Standard Model (SM) & Beyond the SM physics

EJC 2023 Sept 2023

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EJC2023 Joliot-Curie ÉCOLE SCHOOL

BEYOND THE STANDARD MODEL OF WEAK INTERACTION:

nuclei, neutrons, neutrinos

I'm a theoretical physicist working at IFIC (Universitat de València / CSIC, Spain). My research focuses on the study of high-precision experiments, their implications for the search of new phenomena and their synergy with high-energy measurements. There is a wide variety of high-precision measurements that I'm interested in, including neutron and nuclear beta decays, flavor physics, precision collider data and neutrino physics. I have worked significantly with Effective Field Theory techniques, which allow one to carry out these studies in a model-independent framework.

Martin GONZALEZ-ALONSO

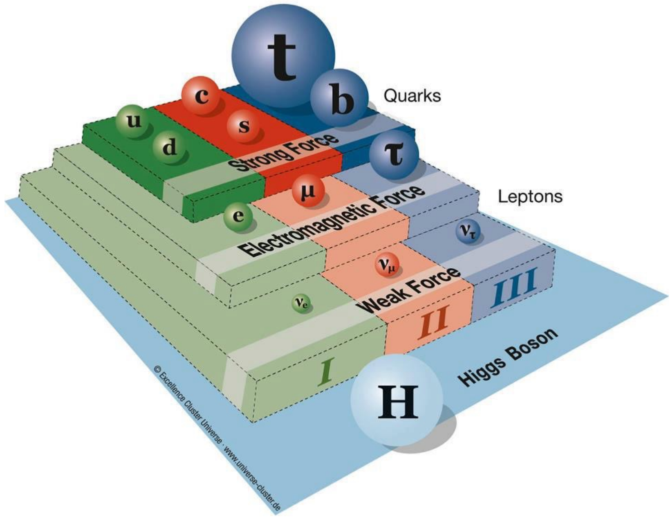
Speaker Participant Committee

Outline of acronyms

- SM → EW

- BSM:
    - EFT
    - SMEFT
    - LEFT

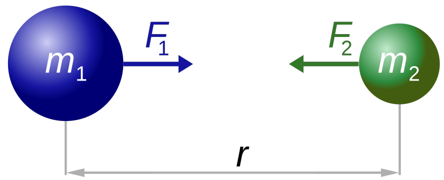
- Neutrino physics



- These lectures are just a (personal) perspective of how to introduce you in the field of EW tests and BSM searches using EFTs, with some emphasis in beta decays and neutrino.
- References: Pich's EW lectures (0705.4264), Adam's SMEFT review (Eur.Phys.J.C 83 (2023) 7, 656), …
- I took advantage of these lectures to go outside my strict comfort zone and learn new things. Fun but risky.

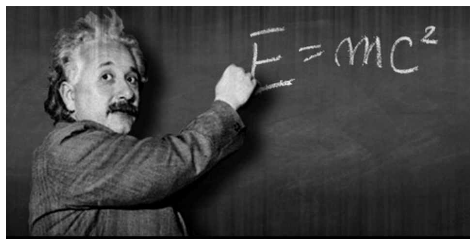
How to play

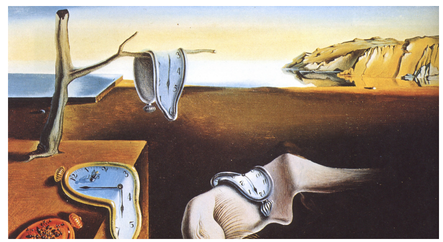
- Classical physics (F = m a)
  Number of balls? masses, charges, etc? Initial conditions? **<u>Force???</u>** → prediction



$$F_1 = F_2 = G\frac{m_1 \times m_2}{r^2}$$

- Particle physics:
  small distances (QM) + high velocities (special relativity)





= Quantum Field Theory (QFT)

Which fields? Masses, charges? Initial conditions? **<u>Lagrangian???</u>** → prediction

QFT in 1min

- Each type of particle is a (quantum) manifestation of a field, which fills spacetime.

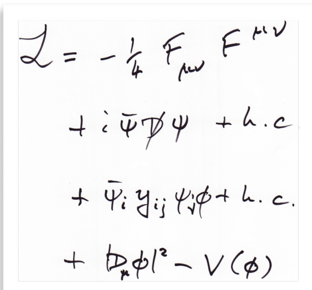
- The properties & interactions of the fields are captured by the **<u>Lagrangian</u>**
The evolution of the system is determined by minimization of the action: δS=0.

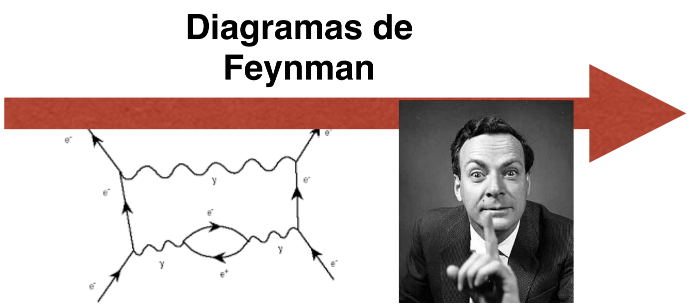
$$S = \int d^4x \;\; \mathcal{L}[\phi_i(x), \partial_\mu \phi_i(x)]$$

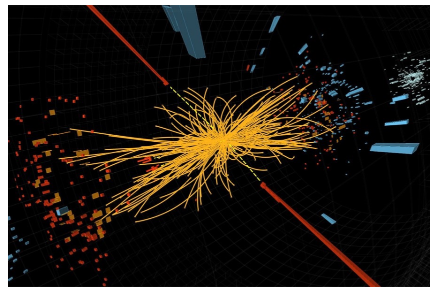
$$\delta S = 0$$

$$\frac{\partial \mathcal{L}}{\partial \phi_i} - \partial^\mu \left(\frac{\partial \mathcal{L}}{\partial(\partial^\mu \phi_i)} \right) = 0$$

- When interactions are present and couplings are small, one can solve the problem perturbatively → Feynman diagrams!







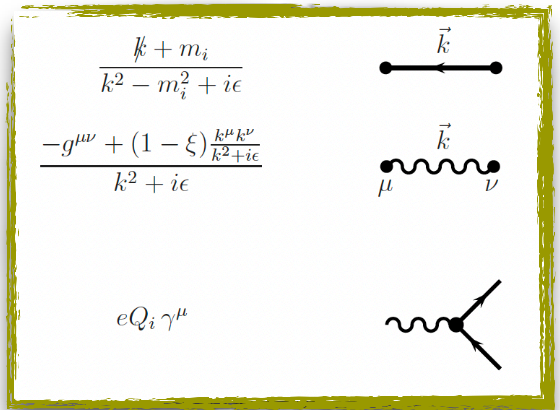
PS: There are also non-perturbative methods to solve QFT (e.g. lattice QCD). They can describe non-pertubative phenomena.

- Loop diagrams → Infinities? → OK in some theories ("renormalization")

QFT (1st) example: QED

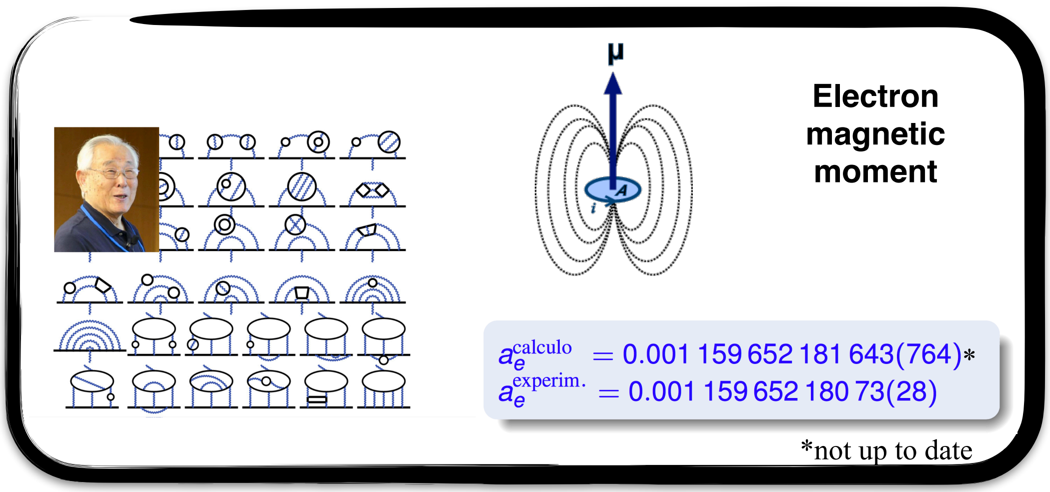
- QED = QFT describing the interaction of electrons and photons

$$\mathscr{L} = i\bar{\psi}(x)\gamma^\mu\partial_\mu\psi(x) - \frac{1}{4}F_{\mu\nu}(x)F^{\mu\nu}(x) - m\bar{\psi}(x)\psi(x) - e\,Q\,\bar{\psi}(x)\gamma^\mu\,\psi(x)\,A_\mu(x)$$



$$F_{\mu\nu} \equiv \partial_\mu A_\nu - \partial_\nu A_\mu$$

- Most successful scientific theory ever?



QED from the gauge principle

- Let us consider the Lagrangian describing a free Dirac fermion:

$$\mathcal{L}_0 = i\,\overline{\psi}(x)\gamma^\mu\partial_\mu\psi(x) - m\,\overline{\psi}(x)\psi(x)\,.$$

- This Lagrangian is invariant under *global* U(1) transformations (Qθ = arbitrary real constant)

$$\psi(x) \quad \xrightarrow{\text{U(1)}} \quad \psi'(x) \equiv \exp\{iQ\theta\}\,\psi(x)\,,$$

- Gauge principle: U(1) = *local* symmetry [θ=θ(x)]
  This requires the introduction of a new spin-1 field:

$$A_\mu(x) \quad \xrightarrow{\text{U(1)}} \quad A'_\mu(x) \equiv A_\mu(x) - \frac{1}{e}\,\partial_\mu\theta\,,$$

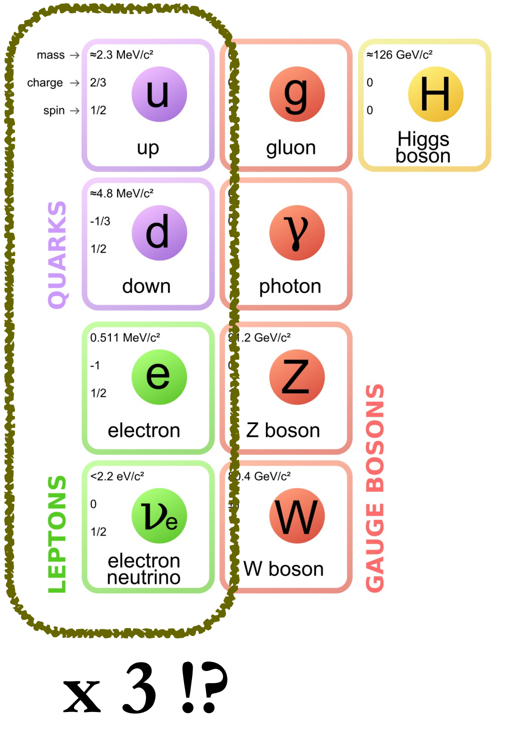
$$D_\mu\psi(x) \equiv \left[\partial_\mu + ieQA_\mu(x)\right]\,\psi(x)\,, \quad \xrightarrow{\text{U(1)}} \quad (D_\mu\psi)'\,(x) \equiv \exp\{iQ\theta\}\,D_\mu\psi(x)\,.$$

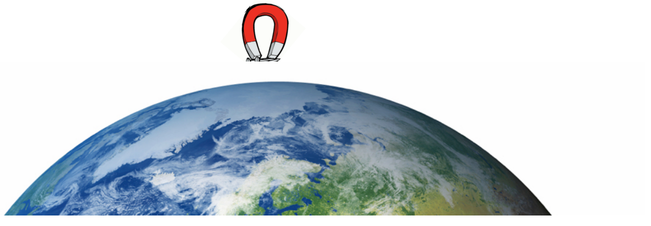
- Thus:

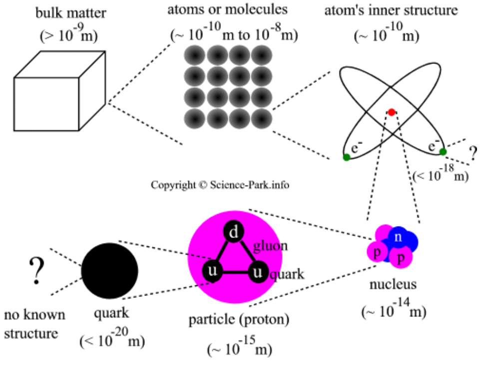
$$\mathcal{L} \equiv i\,\overline{\psi}(x)\gamma^\mu D_\mu\psi(x) - m\,\overline{\psi}(x)\psi(x) - \frac{1}{4}\,F_{\mu\nu}(x)\,F^{\mu\nu}(x)$$

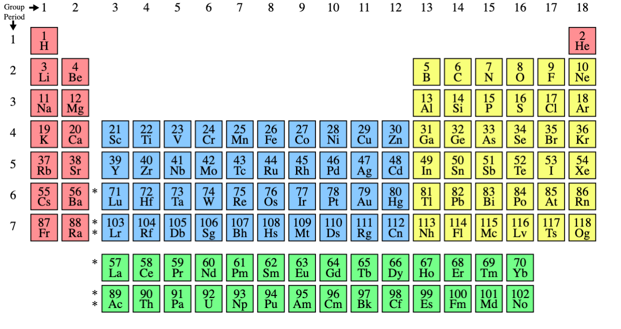
The Standard Model

- The SM is the QFT describing electromagnetic, weak & strong interactions.
- It's the ultimate result of reductionism & unification
  [electromagnetism (→ chemistry), radioactivity, nuclear physics, …]
  Our periodic table.
- ~50 years old, spectacularly confirmed
  [All particles have been observed (Higgs @CERN, 2012)]
- Whatever [future experiments] find, SM has proven to be valid as an effective theory for E < TeV
- *Fortunately* for us (researchers), it can't be the whole thing… we'll come back to that.

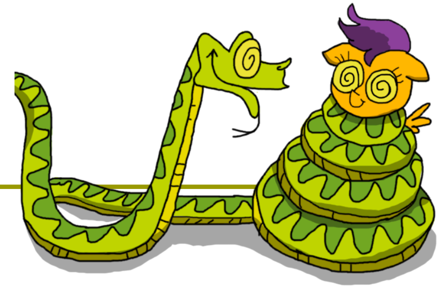








Under the spell of the gauge symmetry



- QED:
  Fermions with Q_i charges + U(1) gauge symmetry → QED Lagrangian (including gauge field!)

- Electroweak theory:

  - Chiral fermions (with their transf. properties) + $SU(2)_L \times U(1)_Y$

x 3 (families)

Quarks	$\begin{pmatrix} u \\ d \end{pmatrix}_L$	u_R	d_R
Leptons	$\begin{pmatrix} \nu_\ell \\ \ell^- \end{pmatrix}_L$	~~ν_R~~	ℓ^-_R

(+ Y_i hypercharges)

  - A scalar doublet (Higgs) added to accommodate masses

$$\varphi \equiv \begin{pmatrix} \varphi^+ \\ \varphi^0 \end{pmatrix}$$

→ Electroweak Lagrangian (including 4 gauge fields)

- QCD:
  Fermions (with their transf. properties) + $SU(3)_c$ gauge symmetry → QCD Lagrangian (including 8 gauge fields)

  Quarks have 3 colors → triplets of $SU(3)_c$
  Leptons have no color → singlets of $SU(3)_c$

Standard Model Lagrangian

Fermions + scalars
(with their transformation properties)

+

$$SU(3)_c \times SU(2)_L \times U(1)_Y$$

$$\rightarrow \mathscr{L}_{SM}(x)$$

Field	$SU(3)_C$	$SU(2)_L$	$U(1)_Y$	Name	Spin
$\begin{pmatrix} u_L \\ d_L \end{pmatrix} = q$	**3**	**2**	1/6	LH u & d quarks (doublet)	1/2
u	**3**	**1**	2/3	RH up quark	1/2
d	**3**	**1**	-1/3	RH down quark	1/2
$\begin{pmatrix} \nu_L \\ e_L \end{pmatrix} = \ell$	**1**	**2**	−1/2	LH l & ν (doublet)	1/2
e	**1**	**1**	-1	RH electron	1/2
$\begin{pmatrix} \varphi^+ \\ \varphi^0 \end{pmatrix} = \varphi$	**1**	**2**	1/2	Higgs field	0

Standard Model Lagrangian

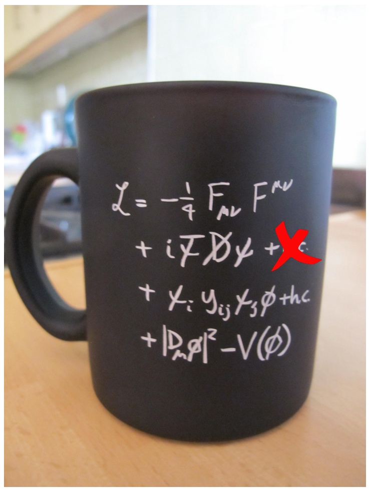
Fermions + scalars
(with their transformation properties)

+

$SU(3)_c \times SU(2)_L \times U(1)_Y$

→ $\mathscr{L}_{SM}(x)$

↓



$$\mathscr{L}_{SM} = -\frac{1}{4} G^{a\mu\nu} G^a_{\mu\nu} - \frac{1}{4} W^{k\mu\nu} W^k_{\mu\nu} - \frac{1}{4} B^{\mu\nu} B_{\mu\nu} - \tilde{\theta}\, G^{a\mu\nu} \tilde{G}^a_{\mu\nu}$$

$$- i \sum_f \bar{f} D_\mu \gamma^\mu f$$

$$- \left(\bar{\ell}\, Y_e \varphi\, e + \bar{q}\, \varphi\, Y_d\, d + \bar{q}\, \tilde{\varphi}\, Y_u\, u \right) + h.c.$$

$$+ \left(D_\mu \varphi \right)^\dagger \left(D^\mu \varphi \right) - \mu^2 \left(\varphi^\dagger \varphi \right) - \lambda \left(\varphi^\dagger \varphi \right)^2$$

$$W^i_{\mu\nu} = \partial_\mu W^i_\nu - \partial_\nu W^i_\mu - g\, \epsilon^{ijk}\, W^j_\mu\, W^k_\nu$$

$$D_\mu X = \partial_\mu X + i g_s G^a_\mu T^a X + i g_L W^i_\mu \tfrac{\sigma^i}{2} X + i g_Y B_\mu Y_X X$$

Standard Model Lagrangian

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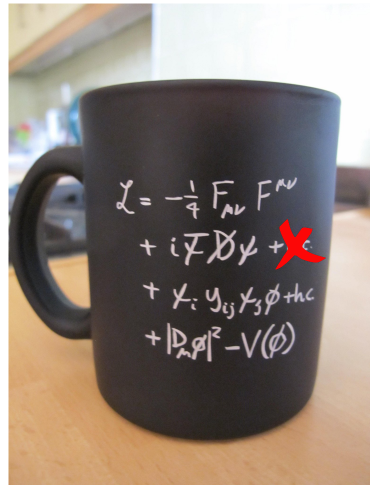


$$W^{i}_{\mu\nu} = \partial_{\mu} W^{i}_{\nu} - \partial_{\nu} W^{i}_{\mu} - g\, \epsilon^{ijk}\, W^{j}_{\mu}\, W^{k}_{\nu}$$

$$D_{\mu} X = \partial_{\mu} X + i g_s G^{a}_{\mu} T^{a} X + i g_L W^{i}_{\mu} \frac{\sigma^i}{2} X + i g_Y B_{\mu} Y_{X} X$$

SM Lagrangian: charged currents

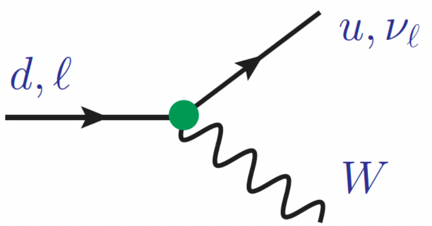
[One family]

$$\ell \equiv \begin{pmatrix} \nu_L \\ e_L \end{pmatrix} \qquad q = \begin{pmatrix} u_L \\ d_L \end{pmatrix}$$

$$-i \sum_f \bar{f} D_\mu \gamma^\mu f \;\rightarrow\; -i \sum_{f=\ell,q} \bar{f} \left(i g_L \frac{\sigma^i}{2} W_\mu^i \right) \gamma^\mu f$$

$$\frac{\sigma^i}{2} W_\mu^i = \frac{1}{2} \begin{pmatrix} W_\mu^3 & \sqrt{2}\, W_\mu^\dagger \\ \sqrt{2}\, W_\mu & -W_\mu^3 \end{pmatrix} \quad , \quad W_\mu \equiv (W_\mu^1 + i\, W_\mu^2)/\sqrt{2}$$

$$\mathcal{L}_{CC} = -\frac{g}{2\sqrt{2}} \left\{ W_\mu^\dagger \left[\bar{u} \gamma^\mu (1-\gamma_5)\, d + \bar{\nu}_e \gamma^\mu (1-\gamma_5)\, e \right] + \text{h.c.} \right\}$$



- **Quark–Lepton Universality**
- **Left-handed Interaction**

SM Lagrangian: neutral currents

- B_μ & W^3_μ mix → A_μ (massless) & Z_μ (massive) are the mass eigenstates after EWSB.

$$\begin{pmatrix} W^3_\mu \\ B_\mu \end{pmatrix} \equiv \begin{pmatrix} \cos\theta_W & \sin\theta_W \\ -\sin\theta_W & \cos\theta_W \end{pmatrix} \begin{pmatrix} Z_\mu \\ A_\mu \end{pmatrix}$$

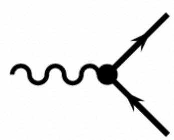
$$\cos\theta_w = \frac{g_L}{\sqrt{g_L^2 + g_Y^2}}$$

- A_μ has QED interactions if
  - the hypercharges have the right values ($Y_f = Q_f - T_3^f$), and
  - the gauge couplings satisfy $g_Y \cos\theta_w = e$.

$$\mathcal{L}_{\mathrm{NC}} = -e\,A_\mu \sum_k \overline{\psi}_k \gamma^\mu Q_k \psi_k + \mathcal{L}^Z_{\mathrm{NC}}$$

$$Q_1 \equiv \begin{pmatrix} Q_{u/\nu} & 0 \\ 0 & Q_{d/e} \end{pmatrix} \quad , \quad Q_2 = Q_{u/\nu} \quad , \quad Q_3 = Q_{d/e}$$

$eQ_i\,\gamma^\mu$



SM Lagrangian: neutral currents

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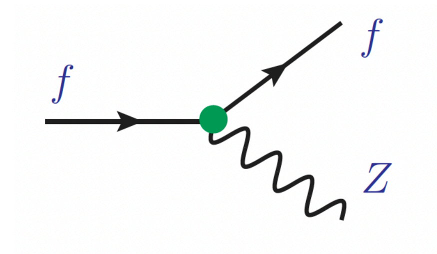
- A_μ has QED interactions: $Y_f = Q_f - T_3^f$, and $g_Y \cos\theta_w = e$.

- Weak neutral currents (NC) interactions: Z_μ

$$\mathcal{L}^Z_{\rm NC} = -\frac{e}{2\sin\theta_W\cos\theta_W} Z_\mu \left\{ \overline{\psi}_1\gamma^\mu\sigma_3\psi_1 - 2\sin^2\theta_W \sum_k \overline{\psi}_k\gamma^\mu Q_k\psi_k \right\}$$

$$= -\frac{e}{2\sin\theta_W\cos\theta_W} Z_\mu \sum_f \bar{f}\gamma^\mu(v_f - a_f\gamma_5)\, f$$



$$a_f = T_3^f$$

$$v_f = T_3^f\left(1 - 4|Q_f|\sin^2\theta_W\right)$$

	u	d	ν_e	e
$2\,v_f$	$1 - \frac{8}{3}\sin^2\theta_W$	$-1 + \frac{4}{3}\sin^2\theta_W$	1	$-1 + 4\sin^2\theta_W$
$2\,a_f$	1	-1	1	-1

- No quark-lepton universality;
- LH & *RH* fermions involved

SM Lagrangian: neutral currents

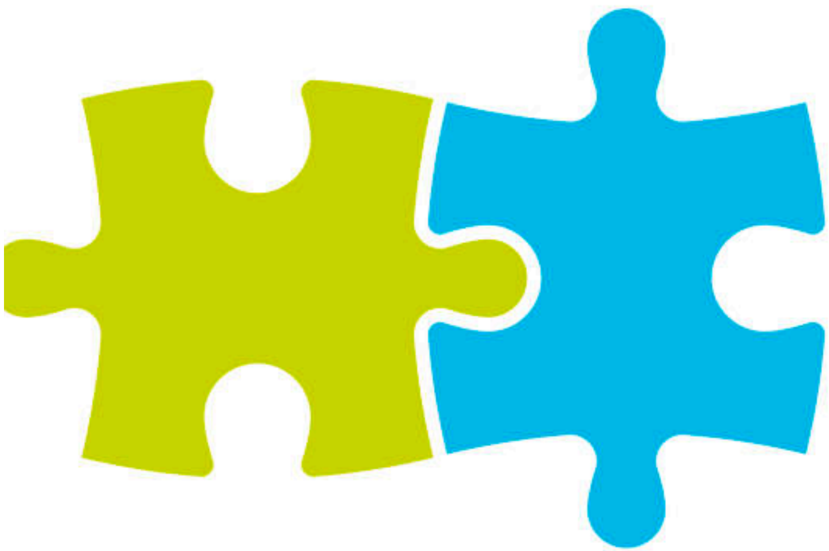
- B_μ & W^3_μ mix → A_μ (massless) & Z_μ (massive) are the mass eigenstates after EWSB.

$$\begin{pmatrix} W^3_\mu \\ B_\mu \end{pmatrix} \equiv \begin{pmatrix} \cos\theta_W & \sin\theta_W \\ -\sin\theta_W & \cos\theta_W \end{pmatrix} \begin{pmatrix} Z_\mu \\ A_\mu \end{pmatrix}$$

$$\cos\theta_w = \frac{g_L}{\sqrt{g_L^2 + g_Y^2}}$$

- A_μ has QED interactions: $Y_f = Q_f - T_3^f$, and $g_Y \cos\theta_w = e$.

- Weak neutral currents (NC) interactions: Z_μ



Electroweak "unification"

Standard Model Lagrangian

$$\mathscr{L}_{SM} = -\frac{1}{4}G^{a\mu\nu}G^a_{\mu\nu} - \frac{1}{4}W^{k\mu\nu}W^k_{\mu\nu} - \frac{1}{4}B^{\mu\nu}B_{\mu\nu} - \tilde{\theta}\, G^{a\mu\nu}\tilde{G}^a_{\mu\nu}$$

$$- i\sum_f \bar{f} D_\mu \gamma^\mu f$$

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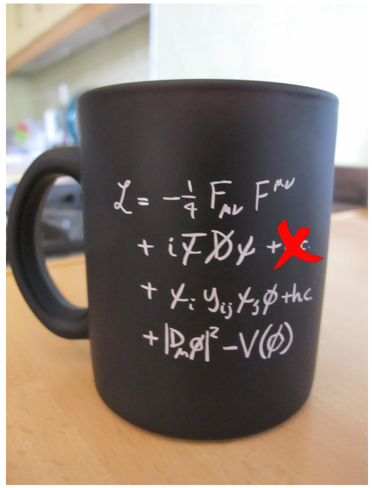


$$W^i_{\mu\nu} = \partial_\mu W^i_\nu - \partial_\nu W^i_\mu - g\, \epsilon^{ijk}\, W^j_\mu W^k_\nu$$

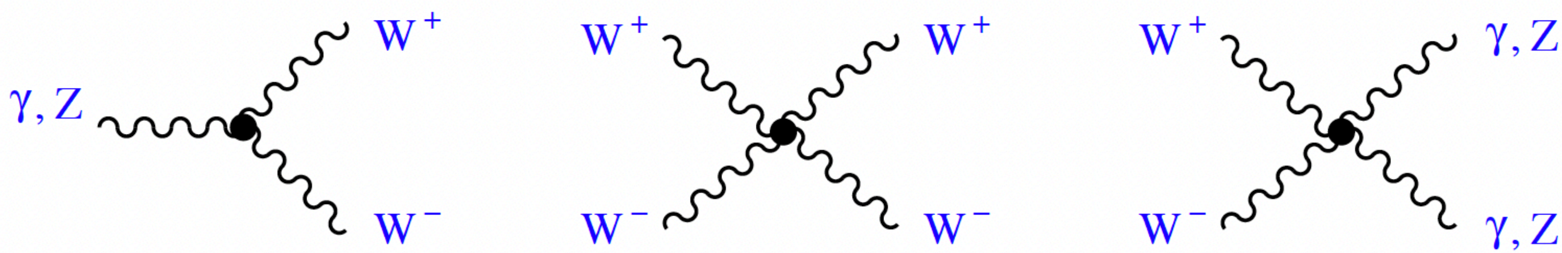
$$D_\mu X = \partial_\mu X + i g_s G^a_\mu T^a X + i g_L W^i_\mu \frac{\sigma^i}{2} X + i g_Y B_\mu Y_X X$$

SM Lagrangian: gauge self interactions

$$-\frac{1}{4}W^{k\mu\nu}W^{k}_{\mu\nu} \quad \rightarrow$$

$$\mathcal{L}_3 = ie\left\{\left(\partial^\mu W^\nu - \partial^\nu W^\mu\right) W^\dagger_\mu A_\nu - \left(\partial^\mu W^{\nu\dagger} - \partial^\nu W^{\mu\dagger}\right) W_\mu A_\nu + W_\mu W^\dagger_\nu \left(\partial^\mu A^\nu - \partial^\nu A^\mu\right)\right\}$$
$$+\, ie\cot\theta_W \left\{\left(\partial^\mu W^\nu - \partial^\nu W^\mu\right) W^\dagger_\mu Z_\nu - \left(\partial^\mu W^{\nu\dagger} - \partial^\nu W^{\mu\dagger}\right) W_\mu Z_\nu + W_\mu W^\dagger_\nu \left(\partial^\mu Z^\nu - \partial^\nu Z^\mu\right)\right\}$$

$$\mathcal{L}_4 = -\,e^2\cot\theta_W \left\{2W^\dagger_\mu W^\mu Z_\nu A^\nu - W^\dagger_\mu Z^\mu W_\nu A^\nu - W^\dagger_\mu A^\mu W_\nu Z^\nu\right\}$$
$$-\,e^2\left\{W^\dagger_\mu W^\mu A_\nu A^\nu - W^\dagger_\mu A^\mu W_\nu A^\nu\right\} - e^2\cot^2\theta_W \left\{W^\dagger_\mu W^\mu Z_\nu Z^\nu - W^\dagger_\mu Z^\mu W_\nu Z^\nu\right\}$$
$$-\,\frac{e^2}{2\sin^2\theta_W}\left\{\left(W^\dagger_\mu W^\mu\right)^2 - W^\dagger_\mu W^{\mu\dagger} W_\nu W^\nu\right\}$$



→ new w.r.t. abelian theories (QED)

→ no vertices involving only neutral gauge bosons (γ, Z) [there is always a W+W- pair].

Standard Model Lagrangian

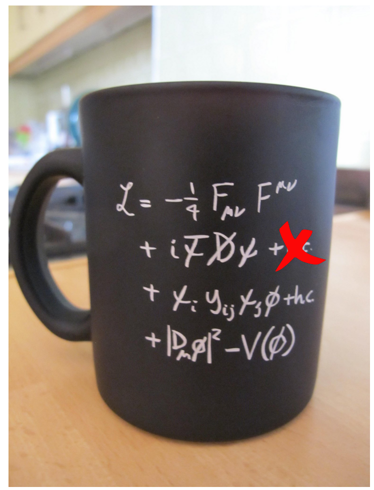
Gauge sector
(everything fixed by gauge symmetry; only 3 free parameters)

$$\mathscr{L}_{SM} = -\frac{1}{4}G^{a\mu\nu}G^{a}_{\mu\nu} - \frac{1}{4}W^{k\mu\nu}W^{k}_{\mu\nu} - \frac{1}{4}B^{\mu\nu}B_{\mu\nu} - \tilde{\theta}\, G^{a\mu\nu}\tilde{G}^{a}_{\mu\nu}$$

$$-i\sum_{f}\bar{f}\, D_{\mu}\gamma^{\mu} f$$

$$-\left(\bar{\ell}\, Y_e \varphi\, e + \bar{q}\,\varphi\, Y_d\, d + \bar{q}\,\tilde{\varphi}\, Y_u\, u\right) + h.c.$$

$$+\left(D_{\mu}\varphi\right)^{\dagger}\left(D^{\mu}\varphi\right) - \mu^2\left(\varphi^{\dagger}\varphi\right) - \lambda\left(\varphi^{\dagger}\varphi\right)^2$$



$$W^{i}_{\mu\nu} = \partial_{\mu}W^{i}_{\nu} - \partial_{\nu}W^{i}_{\mu} - g\,\epsilon^{ijk}\,W^{j}_{\mu}\,W^{k}_{\nu}$$

$$D_{\mu}X = \partial_{\mu}X + i g_s G^{a}_{\mu}T^{a}X + i g_L W^{i}_{\mu}\frac{\sigma^{i}}{2}X + i g_Y B_{\mu} Y_X X$$

Standard Model Lagrangian

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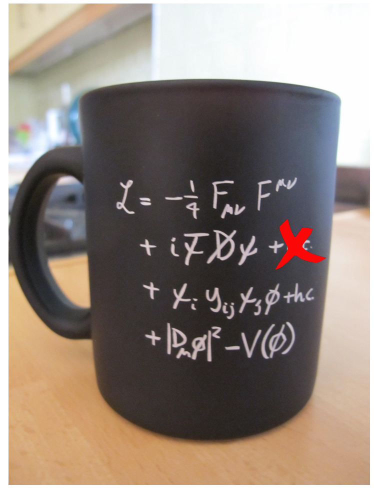
$$+\left(D_{\mu}\varphi\right)^{\dagger}\left(D^{\mu}\varphi\right) - \mu^{2}\left(\varphi^{\dagger}\varphi\right) - \lambda\left(\varphi^{\dagger}\varphi\right)^{2}$$

Scalar sector
(15 free parameters…)



$$W^{i}_{\mu\nu} = \partial_{\mu}W^{i}_{\nu} - \partial_{\nu}W^{i}_{\mu} - g\,\epsilon^{ijk}\,W^{j}_{\mu}W^{k}_{\nu}$$

$$D_{\mu}X = \partial_{\mu}X + ig_{s}G^{a}_{\mu}T^{a}X + ig_{L}W^{i}_{\mu}\frac{\sigma^{i}}{2}X + ig_{Y}B_{\mu}Y_{X}X$$

SM Lagrangian: masses

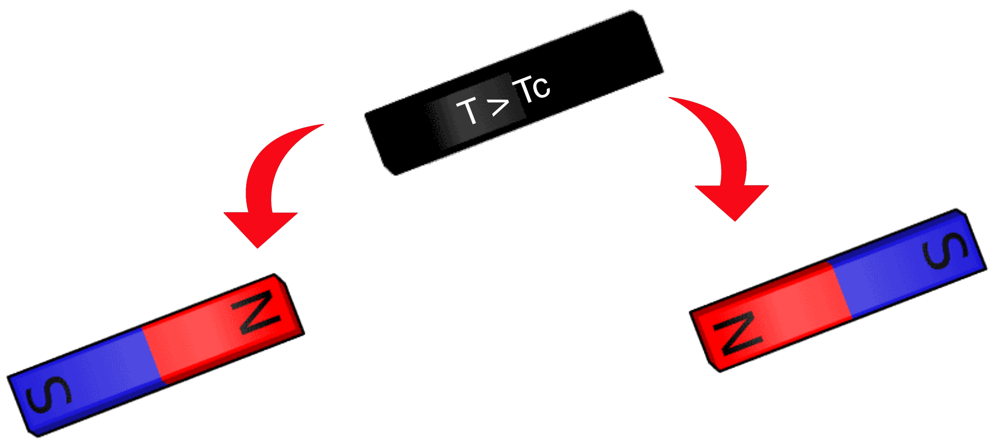
- In the SM Lagrangian, mass terms break gauge symmetry.

$$\mathcal{L}_m = \frac{1}{2} m_B^2 B^\mu B_\mu + \frac{1}{2} m_W^2 W_i^\mu W_\mu \quad \sum_f m_f (\bar{f}_L f_R + \text{h.c.})$$

- But most of the particles have mass!

- Key idea:
  the ground state of a system does not have to display the symmetry of the Lagrangian.
  → One says that the symmetry is spontaneously broken or hidden.

- Example: a ferromagnet chooses a direction when cooled below the Curie temperature.



SM Lagrangian: masses

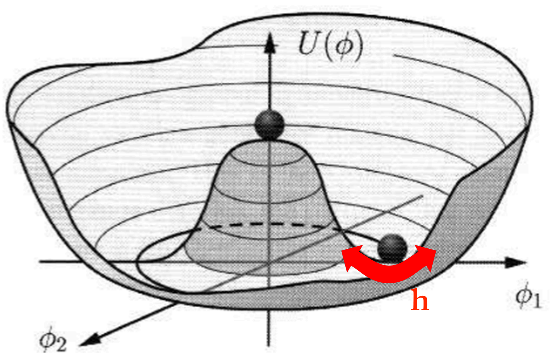
- The SM Lagrangian is invariant under rotations in Φ space

$$\mathscr{L}_S = \left(D_\mu\varphi\right)^\dagger\left(D^\mu\varphi\right) - \mu^2\left(\varphi^\dagger\varphi\right) - \lambda\left(\varphi^\dagger\varphi\right)^2$$

Unitarity gauge ($\varphi_i = 0$)

$$\varphi \equiv \begin{pmatrix}\varphi^+ \\ \varphi^0\end{pmatrix} = \frac{1}{\sqrt{2}}\begin{pmatrix}\varphi_1 + i\,\varphi_2 \\ \varphi_3 + i\,\varphi_4\end{pmatrix} = \exp\left(i\,\vec{\sigma}\cdot\frac{\vec{\theta}}{v}\right)\frac{1}{\sqrt{2}}\begin{pmatrix}0 \\ H\end{pmatrix} \longrightarrow \exp\left(i\,\vec{\sigma}\cdot\frac{\vec{\theta}}{v}\right)\frac{1}{\sqrt{2}}\begin{pmatrix}0 \\ v+h\end{pmatrix}$$

- But the minimum of the potential is not at $\varphi_0 = 0$ (for $\mu^2<0$, h>0)



$$|\langle 0|H|0\rangle| = \sqrt{\frac{-\mu^2}{2\lambda}} \equiv \frac{v}{\sqrt{2}}$$

Higgs vacuum expectation value (VEV) → EW scale

SM Lagrangian: masses

- The SM Lagrangian is invariant under rotations in Φ space.

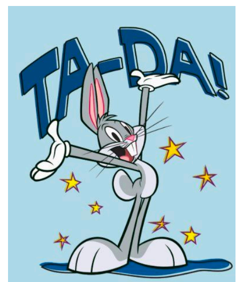
$$\mathscr{L}_S = \left(D_\mu \varphi\right)^\dagger \left(D^\mu \varphi\right) - \mu^2 \left(\varphi^\dagger \varphi\right) - \lambda \left(\varphi^\dagger \varphi\right)^2$$

$$\varphi \to \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v+h \end{pmatrix}$$

$$D_\mu \varphi = \left(\partial_\mu + i\, g_L \frac{\sigma^i}{2} W^i_\mu + i\, g_Y Y_\varphi B_\mu\right) \varphi \qquad \frac{\sigma^i}{2} W^i_\mu = \frac{1}{2} \begin{pmatrix} W^3_\mu & \sqrt{2}\, W^\dagger_\mu \\ \sqrt{2}\, W_\mu & -W^3_\mu \end{pmatrix}$$

$$W_\mu \equiv (W^1_\mu + i\, W^2_\mu)/\sqrt{2}$$

$$\frac{1}{2} \partial_\mu h\, \partial^\mu h + (v+h)^2 \left\{ \frac{g_L^2}{4} W^\dagger_\mu W^\mu + \frac{g_L^2}{8 \cos^2 \theta_w} Z_\mu Z^\mu \right\}$$



$$M_Z \cos\theta_W = M_W = \frac{1}{2}\, v\, g\,.$$

- Counting d.o.f.: 4→1 (the physical Higgs boson). The other 3 d.o.f. were "eaten" by the W+, W- & Z bosons (which have become massive and thus have 3 polarizations instead of 2).

SM Lagrangian: masses

- The SM Lagrangian is invariant under rotations in Φ space.

$$\mathcal{L}_S = \left(D_\mu \varphi\right)^\dagger \left(D^\mu \varphi\right) - \mu^2 \left(\varphi^\dagger \varphi\right) - \lambda \left(\varphi^\dagger \varphi\right)^2$$

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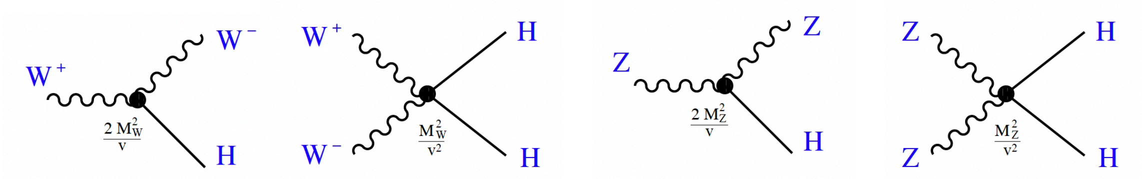
$$D_\mu \varphi = \left(\partial_\mu + i\, g_L \frac{\sigma^i}{2} W_\mu^i + i\, g_Y Y_\varphi B_\mu\right) \varphi \qquad \frac{\sigma^i}{2} W_\mu^i = \frac{1}{2} \begin{pmatrix} W_\mu^3 & \sqrt{2}\, W_\mu^\dagger \\ \sqrt{2}\, W_\mu & -W_\mu^3 \end{pmatrix}$$

$$W_\mu \equiv (W_\mu^1 + i\, W_\mu^2)/\sqrt{2}$$

$$\frac{1}{2} \partial_\mu h\, \partial^\mu h + (v+h)^2 \left\{ \frac{g_L^2}{4} W_\mu^\dagger W^\mu + \frac{g_L^2}{8 \cos^2 \theta_w} Z_\mu Z^\mu \right\}$$

$$= \frac{1}{2} \partial_\mu h\, \partial^\mu h + M_W^2\, W_\mu^\dagger W^\mu \left\{ 1 + 2\frac{h}{v} + \frac{h^2}{v^2} \right\} + \frac{1}{2} M_Z^2\, Z_\mu Z^\mu \left\{ 1 + 2\frac{h}{v} + \frac{h^2}{v^2} \right\}$$



Couplings proportional to masses squared!

SM Lagrangian: masses

- The SM Lagrangian is invariant under rotations in Φ space.

$$\mathscr{L}_S = \left(D_\mu \varphi\right)^\dagger \left(D^\mu \varphi\right) - \mu^2 \left(\varphi^\dagger \varphi\right) - \lambda \left(\varphi^\dagger \varphi\right)^2$$

$$\varphi \rightarrow \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v + h \end{pmatrix}$$

$$D_\mu \varphi = \left(\partial_\mu + i\, g_L \frac{\sigma^i}{2} W^i_\mu + i\, g_Y Y_\varphi B_\mu \right) \varphi \qquad \frac{\sigma^i}{2} W^i_\mu = \frac{1}{2} \begin{pmatrix} W^3_\mu & \sqrt{2}\, W^\dagger_\mu \\ \sqrt{2}\, W_\mu & -W^3_\mu \end{pmatrix}$$

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$$\frac{1}{2} \partial_\mu h\, \partial^\mu h + (v+h)^2 \left\{ \frac{g_L^2}{4} W^\dagger_\mu W^\mu + \frac{g_L^2}{8 \cos^2 \theta_w} Z_\mu Z^\mu \right\}$$

What about fermion masses?

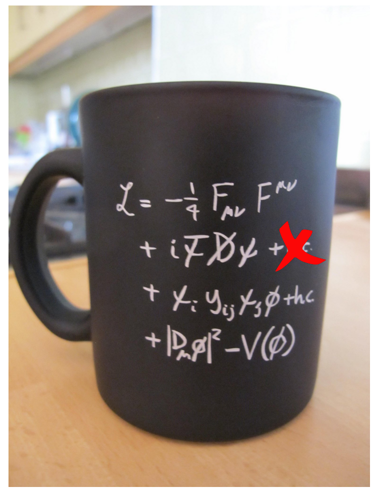
Standard Model Lagrangian

$$\mathscr{L}_{SM} = -\frac{1}{4} G^{a\mu\nu} G^{a}_{\mu\nu} - \frac{1}{4} W^{k\mu\nu} W^{k}_{\mu\nu} - \frac{1}{4} B^{\mu\nu} B_{\mu\nu} - \tilde{\theta}\, G^{a\mu\nu}\, \tilde{G}^{a}_{\mu\nu}$$

$$- i \sum_{f} \bar{f} D_{\mu} \gamma^{\mu} f$$

$$- \left(\bar{\ell}\, Y_e \varphi\, e + \bar{q}\, \varphi\, Y_d\, d + \bar{q}\, \tilde{\varphi}\, Y_u\, u \right) + h.c.$$

$$+ \left(D_{\mu} \varphi \right)^{\dagger} \left(D^{\mu} \varphi \right) - \mu^2 \left(\varphi^{\dagger} \varphi \right) - \lambda \left(\varphi^{\dagger} \varphi \right)^2$$



Scalar sector
(15 free parameters…)

$$W^{i}_{\mu\nu} = \partial_\mu W^i_\nu - \partial_\nu W^i_\mu - g\, \epsilon^{ijk}\, W^j_\mu\, W^k_\nu$$

$$D_\mu X = \partial_\mu X + i g_s G^a_\mu T^a X + i g_L W^i_\mu \frac{\sigma^i}{2} X + i g_Y B_\mu Y_X X$$

SM Lagrangian: masses (fermions)

- 1-family case:

$$\mathscr{L}_Y = -\left(\bar{\ell}\, Y_e \varphi\, e \;+\; \bar{q}\, \varphi\, Y_d\, d \;+\; \bar{q}\, \tilde{\varphi}\, Y_u\, u\right) + h.c.$$

$$\ell \equiv \begin{pmatrix} \nu_L \\ e_L \end{pmatrix}$$

$$q = \begin{pmatrix} u_L \\ d_L \end{pmatrix}$$

$$\tilde{\varphi} \equiv i\,\sigma_2\,\varphi = \begin{pmatrix} (\varphi^0)^* \\ -(\varphi^+)^* \end{pmatrix}$$

SM Lagrangian: masses (fermions)

- 1-family case:

$$\mathscr{L}_Y = -\left(\bar{\ell}\, Y_e \varphi\, e \; + \; \bar{q}\, \varphi\, Y_d\, d \; + \; \bar{q}\, \tilde{\varphi}\, Y_u\, u\right) + h.c.$$

$$\varphi \to \frac{1}{\sqrt{2}}\begin{pmatrix} 0 \\ v+h \end{pmatrix}$$

$$\tilde{\varphi} \to \frac{1}{\sqrt{2}}\begin{pmatrix} v+h \\ 0 \end{pmatrix}$$

$$\ell \equiv \begin{pmatrix} \nu_L \\ e_L \end{pmatrix}$$

$$q = \begin{pmatrix} u_L \\ d_L \end{pmatrix}$$

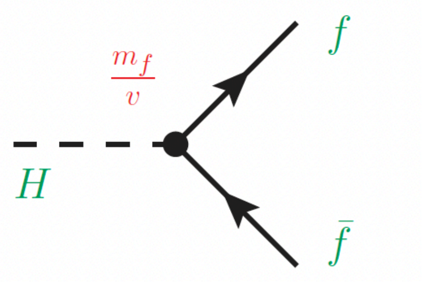
$$\tilde{\varphi} \equiv i\,\sigma_2\,\varphi = \begin{pmatrix} (\varphi^0)^* \\ -(\varphi^+)^* \end{pmatrix}$$

$$\mathscr{L}_Y = -\frac{v+h}{\sqrt{2}}\left(Y_e\, \bar{e}_L\, e_R \; + \; Y_d\, \bar{d}_L\, d_R \; + \; Y_u\, \bar{u}_L\, u_R\right) + h.c.$$

$$= -\left(1+\frac{h}{v}\right)\left(m_e\, \bar{e}_L\, e_R \; + \; m_d\, \bar{d}_L\, d_R \; + \; m_u\, \bar{u}_L\, u_R\right) + h.c.$$

$$m_e = Y_e\, v/\sqrt{2}$$
$$m_d = Y_d\, v/\sqrt{2}$$
$$m_u = Y_u\, v/\sqrt{2}$$

(PS: no mass for the neutrinos)



Hff couplings proportional to masses!

SM Lagrangian: masses (fermions)

- In the real case there are 3 families, and Y_f are matrices
  (only connection between families in the SM before EWSB)

$$\mathcal{L}_Y = -\left(1+\frac{h}{v}\right)\left(\bar{e}'_L\, M'_e\, e'_R + \bar{d}'_L\, M'_d\, d'_R + \bar{u}'_L\, M'_u\, u'_R\right) + h.c.$$

$M'_d = Y_d\, v/\sqrt{2}$

[Non diagonal complex matrices]

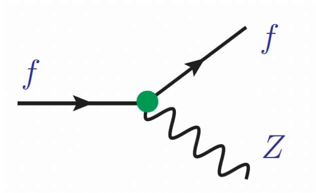
$d_L \equiv U^L_d\, d'_L$

$d_R \equiv U^R_d\, d'_R$

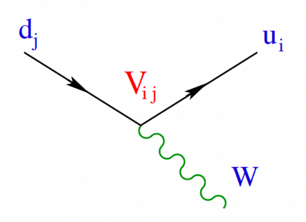
$$\bar{d}_L\, M_{diag}\, d_R$$

[same for u_L, u_R, e_L, e_R]

- NC "unaffected":
  $Z^\mu\, \bar{f}'_L\, \gamma_\mu\, f'_L = Z^\mu\, \bar{f}_L\, \gamma_\mu\, f_L$ [ídem for RH] → No FCNC



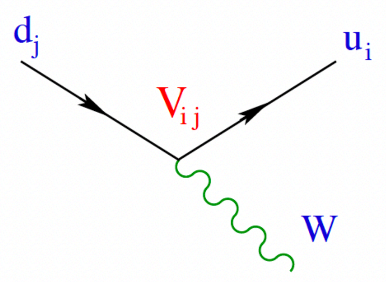
- CC affected (only for quarks):
  $W^\dagger_\mu\, \bar{u}'_L\, \gamma_\mu\, d'_L = W^\dagger_\mu\, \bar{u}_L\, \gamma_\mu\, U^{L\dagger}_u U^L_d\, d_L \equiv W^\dagger_\mu\, \bar{u}_L\, \gamma_\mu\, V_{CKM}\, d_L$

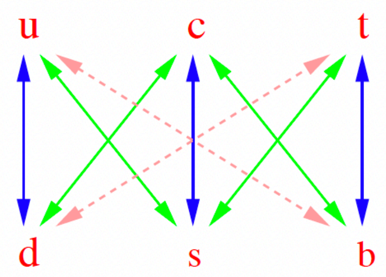


SM Lagrangian: ~~masses~~ → Flavor physics!

- The diagonalization of the quark masses has moved the many parameters in the Yukawa sector (Hff) to the CC interaction → Very rich "flavor physics"!

$$\mathcal{L}_{\rm CC} = -\frac{g}{2\sqrt{2}} \left\{ W_\mu^\dagger \left[\sum_{ij} \bar{u}_i \, \gamma^\mu (1-\gamma_5) \, \mathbf{V}_{ij} \, d_j \; + \; \sum_l \bar{\nu}_l \, \gamma^\mu (1-\gamma_5) \, l \right] + \text{h.c.} \right\}$$





- The CKM matrix: 3 angles + 1 phase

$$\mathbf{V} = \begin{pmatrix} \cos\theta_C & \sin\theta_C \\ -\sin\theta_C & \cos\theta_C \end{pmatrix}$$

$$\mathbf{V} = \begin{bmatrix} c_{12}\, c_{13} & s_{12}\, c_{13} & s_{13}\, e^{-i\delta_{13}} \\ -s_{12}\, c_{23} - c_{12}\, s_{23}\, s_{13}\, e^{i\delta_{13}} & c_{12}\, c_{23} - s_{12}\, s_{23}\, s_{13}\, e^{i\delta_{13}} & s_{23}\, c_{13} \\ s_{12}\, s_{23} - c_{12}\, c_{23}\, s_{13}\, e^{i\delta_{13}} & -c_{12}\, s_{23} - s_{12}\, c_{23}\, s_{13}\, e^{i\delta_{13}} & c_{23}\, c_{13} \end{bmatrix}$$

- The diagonalization of the lepton Yukawa has no physical consequences (→ no LFV)

SM Lagrangian: ~~masses~~ → Flavor physics!

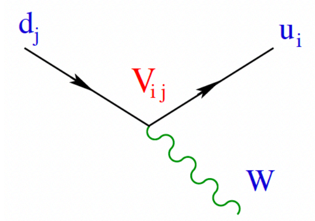
- The CKM matrix is unitary (by construction)

$$V_{CKM} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} = \begin{bmatrix} c_{12}\,c_{13} & s_{12}\,c_{13} & s_{13}\,e^{-i\delta_{13}} \\ -s_{12}\,c_{23} - c_{12}\,s_{23}\,s_{13}\,e^{i\delta_{13}} & c_{12}\,c_{23} - s_{12}\,s_{23}\,s_{13}\,e^{i\delta_{13}} & s_{23}\,c_{13} \\ s_{12}\,s_{23} - c_{12}\,c_{23}\,s_{13}\,e^{i\delta_{13}} & -c_{12}\,s_{23} - s_{12}\,c_{23}\,s_{13}\,e^{i\delta_{13}} & c_{23}\,c_{13} \end{bmatrix}$$

- Let's focus on the first row:

$$|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 = 1$$

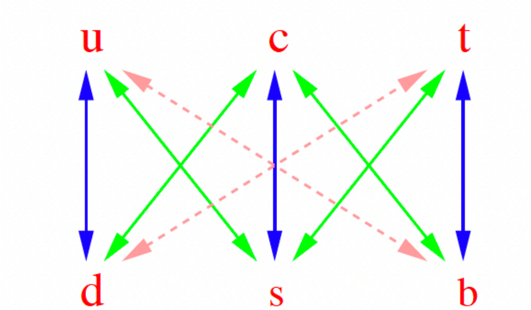
- This is a crucial SM prediction about the W-u-d, W-u-s & W-u-b couplings. A departure from unitarity would require "new physics".



- $V_{ud}: \; d \rightarrow u \ell \nu_\ell \;\; \rightarrow \;\; \beta$ decays !!

  $V_{us}: \; s \rightarrow u \ell \nu_\ell \;\; \rightarrow \;\; K$ decays
  (also hyperon decays & hadronic tau decays)

  $V_{ub}: \; b \rightarrow u \ell \nu_\ell \;\; \rightarrow \;\; B$ decays (negligible)



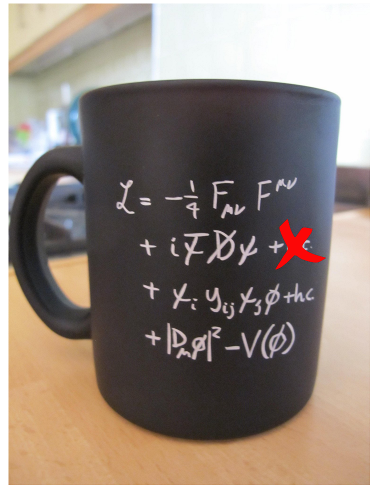
Standard Model Lagrangian

$$\mathscr{L}_{SM} = -\frac{1}{4}G^{a\mu\nu}G^{a}_{\mu\nu} - \frac{1}{4}W^{k\mu\nu}W^{k}_{\mu\nu} - \frac{1}{4}B^{\mu\nu}B_{\mu\nu} - \tilde{\theta}\, G^{a\mu\nu}\tilde{G}^{a}_{\mu\nu}$$

$$-i\sum_{f}\bar{f}\,D_{\mu}\gamma^{\mu} f$$

$$-\left(\bar{\ell}\,Y_e\,\varphi\, e + \bar{q}\,\varphi\, Y_d\, d + \bar{q}\,\tilde{\varphi}\, Y_u\, u\right) + h.c.$$

$$+\left(D_{\mu}\varphi\right)^{\dagger}\left(D^{\mu}\varphi\right) - \mu^2\left(\varphi^{\dagger}\varphi\right) - \lambda\left(\varphi^{\dagger}\varphi\right)^2$$



Scalar sector
(15 free parameters…)

$$W^{i}_{\mu\nu} = \partial_{\mu}W^{i}_{\nu} - \partial_{\nu}W^{i}_{\mu} - g\,\epsilon^{ijk}\,W^{j}_{\mu}\,W^{k}_{\nu}$$

$$D_{\mu}X = \partial_{\mu}X + ig_s G^{a}_{\mu}T^{a}X + ig_L W^{i}_{\mu}\frac{\sigma^i}{2}X + ig_Y B_{\mu}Y_{X}X$$

SM Lagrangian: masses

$$\mathscr{L}_S = \left(D_\mu \varphi\right)^\dagger \left(D^\mu \varphi\right) - \mu^2 \left(\varphi^\dagger \varphi\right) - \lambda \left(\varphi^\dagger \varphi\right)^2$$

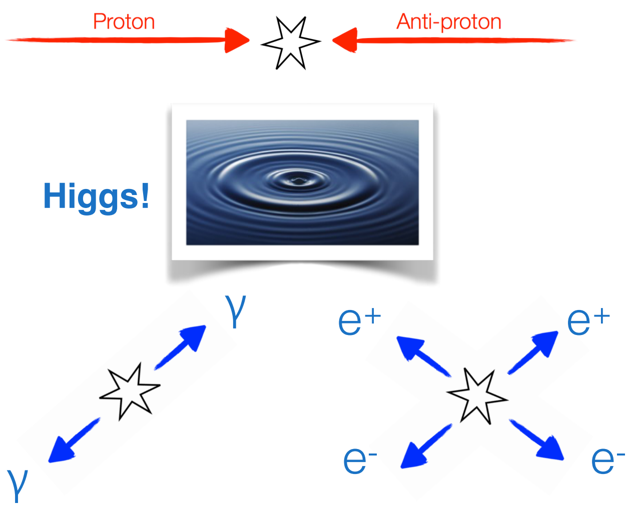
$$\varphi \rightarrow \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v + h \end{pmatrix}$$

$$-\frac{1}{2} M_h^2 h^2 - \frac{M_h^2}{2v} h^3 - \frac{M_h^2}{8v^2} h^4$$

$$M_h = \sqrt{-2\mu^2} = \sqrt{2\lambda}\, v$$

SM Lagrangian: masses

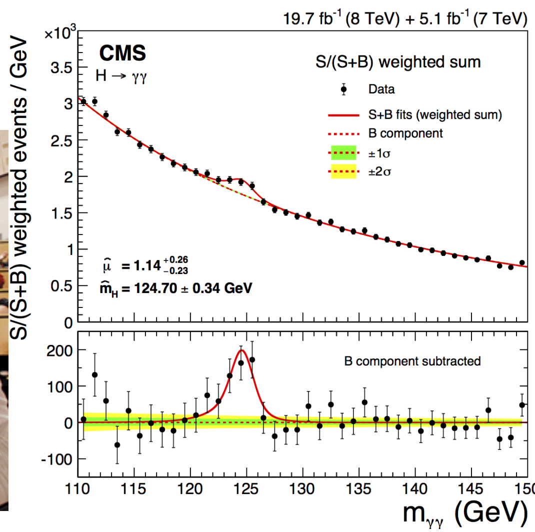
$$\mathscr{L}_S = \left(D_\mu\varphi\right)^\dagger \left(D^\mu\varphi\right) - \mu^2\left(\varphi^\dagger\varphi\right) - \lambda\left(\varphi^\dagger\varphi\right)^2$$

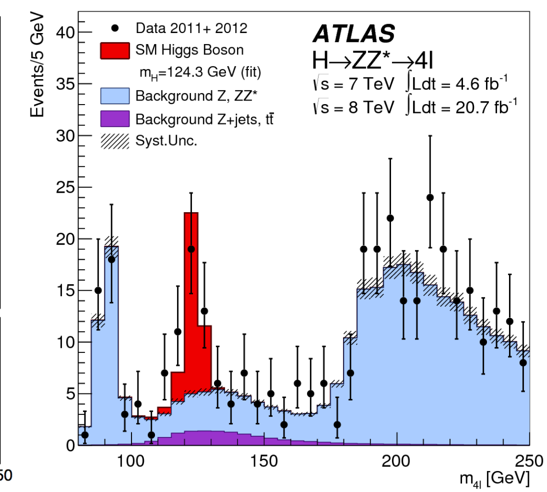


$$-\frac{1}{2}M_h^2\,h^2 - \frac{M_h^2}{2v}h^3 - \frac{M_h^2}{8v^2}h^4$$

$$M_h = \sqrt{-2\mu^2} = \sqrt{2\lambda}\,v$$

2012 (ATLAS & CMS)





SM Lagrangian: free parameters

- 3 gauge couplings (g_s, g, g') → **EW+Higgs free parameters**
- Higgs potential: μ^2, h → **EW+Higgs free parameters**
- 9 fermion masses (up, down & charged leptons)
- 4 CKM parameters: 3 angles + 1 CP phase

→ **Flavor puzzle**

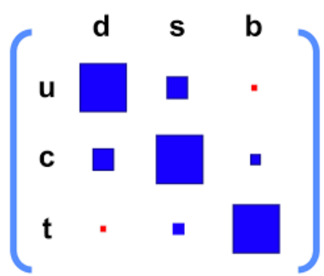
- 1 Theta term (?) → **Strong CP problem**

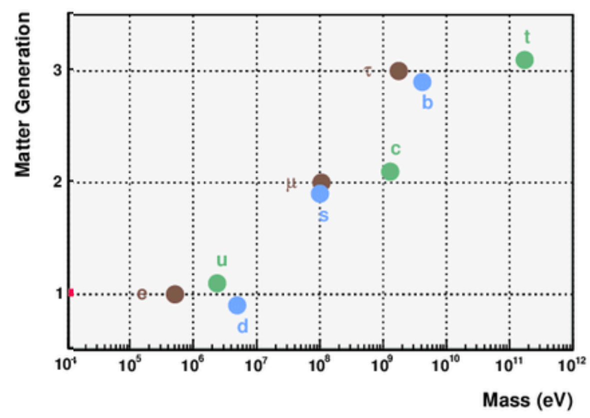
$$\mathscr{L}_{SM} = -\frac{1}{4} G^{a\mu\nu} G^a_{\mu\nu} - \frac{1}{4} W^{k\mu\nu} W^k_{\mu\nu} - \frac{1}{4} B^{\mu\nu} B_{\mu\nu} - \tilde{\theta}\, G^{a\mu\nu} \tilde{G}^a_{\mu\nu}$$

$$- i \sum_f \bar{f} D_\mu \gamma^\mu f$$

$$- \left(\bar{\ell}\, Y_e \varphi\, e + \bar{q}\, \varphi\, Y_d\, d + \bar{q}\, \tilde{\varphi}\, Y_u\, u \right) + h.c.$$

$$+ \left(D_\mu \varphi \right)^\dagger \left(D^\mu \varphi \right) - \mu^2 \left(\varphi^\dagger \varphi \right) - \lambda \left(\varphi^\dagger \varphi \right)^2$$

$V_{CKM} =$ 



$$W^i_{\mu\nu} = \partial_\mu W^i_\nu - \partial_\nu W^i_\mu - g\, \epsilon^{ijk}\, W^j_\mu\, W^k_\nu$$

$$D_\mu X = \partial_\mu X + i g_s G^a_\mu T^a X + i g_L W^i_\mu \frac{\sigma^i}{2} X + i g_Y B_\mu Y_x X$$

EW phenomenology

- Observables:

$$O = f(g_L, g_Y, \mu^2, h)$$

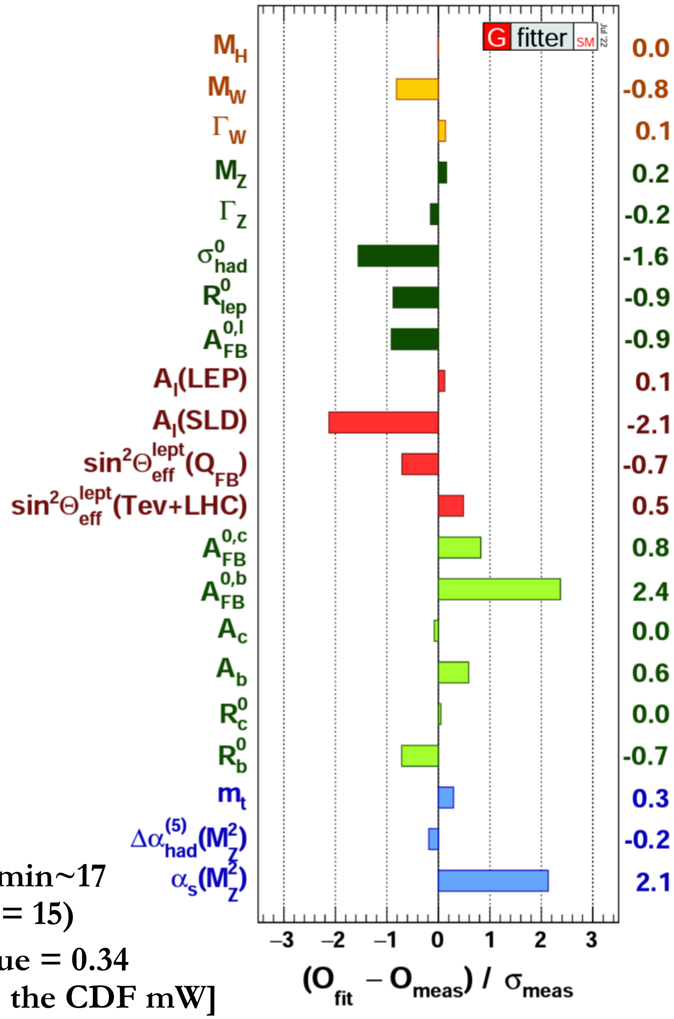
- In general, one should do a global fit to extract g, g', μ^2, h (p-value OK?)
- However, there are 4 measurements that are much more precise than the rest: α, G_F, M_Z, M_h:

$$1/\alpha = 137.035999180(10)$$
$$G_F = 1.1663788(6) \times 10^{-5}\,\text{GeV}^{-2}$$
$$M_Z = 91.1876(21)\,\text{GeV}$$
$$M_h = 125.30(13)\,\text{GeV}$$

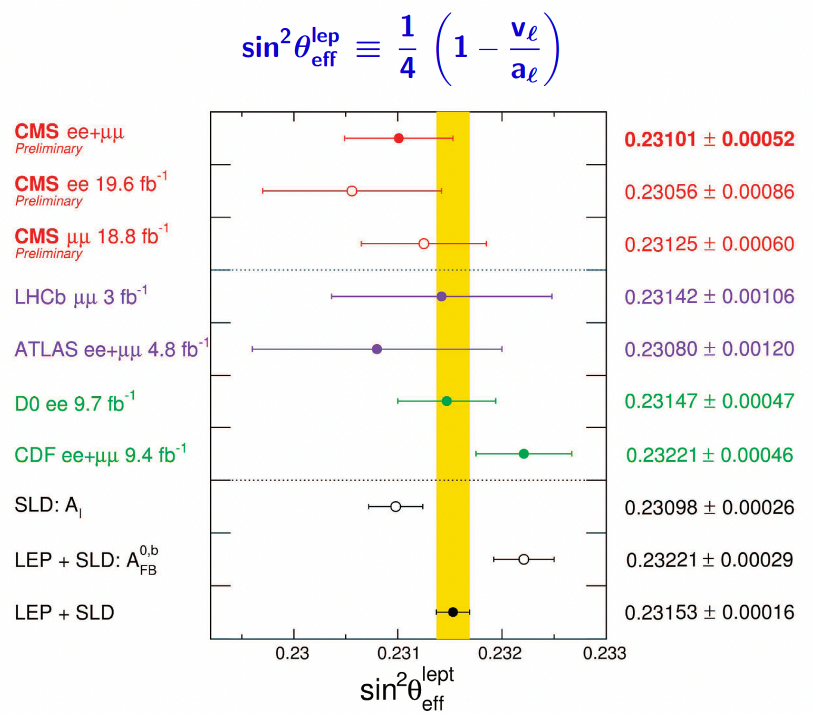
- Thus one can proceed in 2 steps:
  - (α, G_F, M_Z, M_h) → fix EW parameters
  - For the rest of observables, we compare the **SM prediction** with the **measurement**

EW phenomenology

[2211.07665]

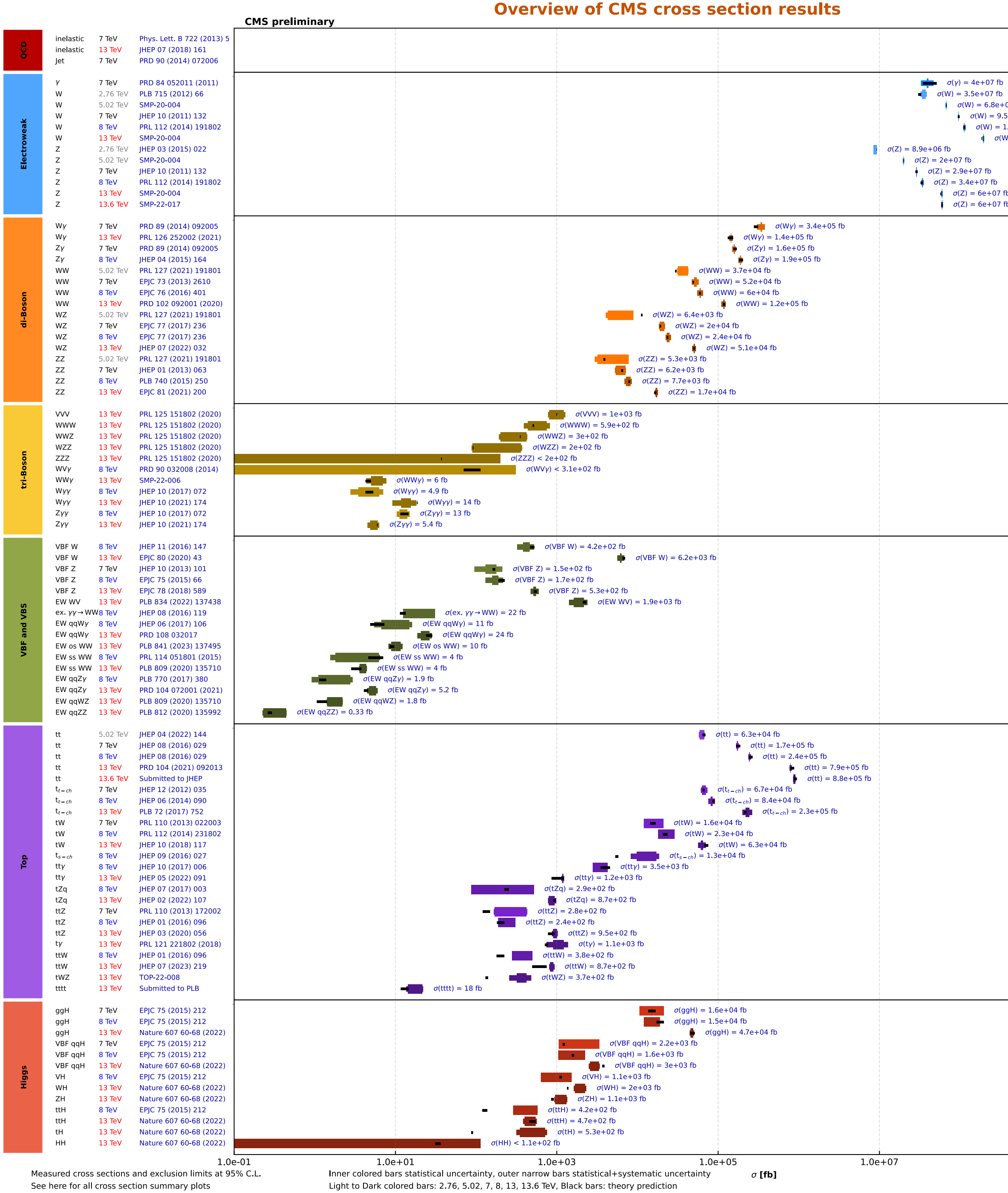


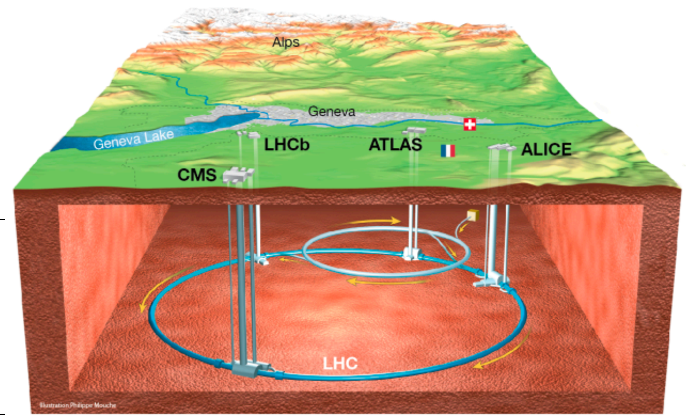
Chi2min~17
(dof = 15)
p value = 0.34
[w/o the CDF mW]

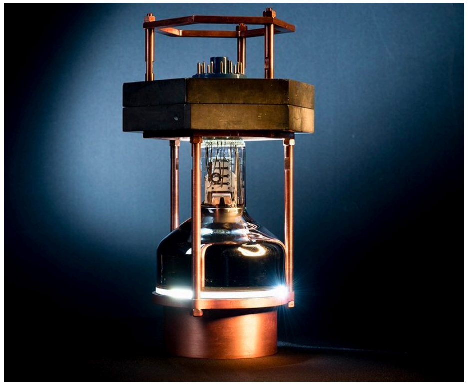


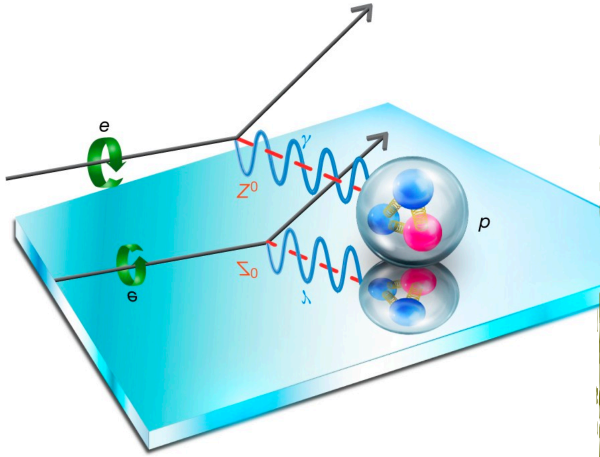
J. Alcaraz, EPS 2017

Overview of CMS cross section results

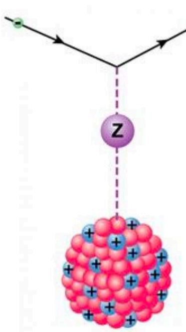


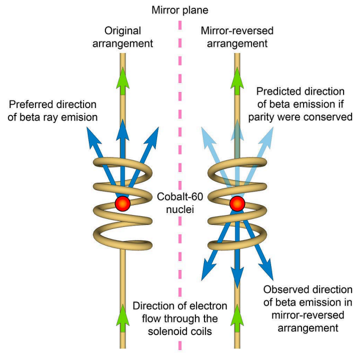


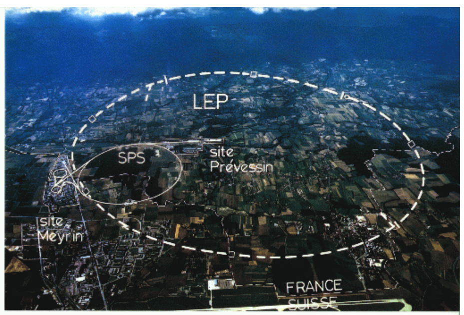


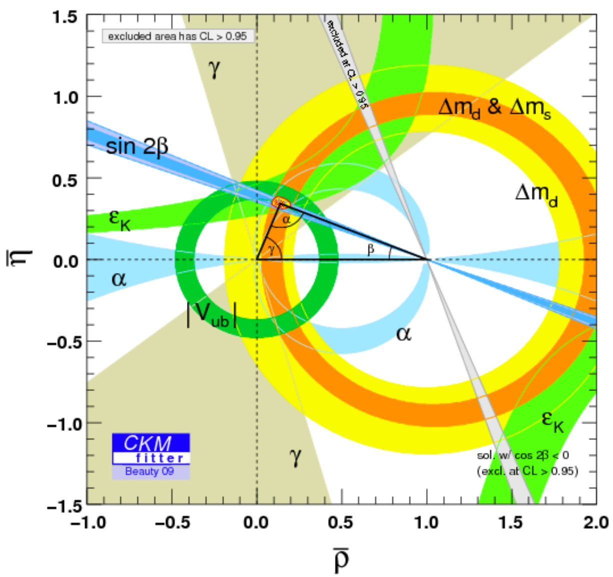


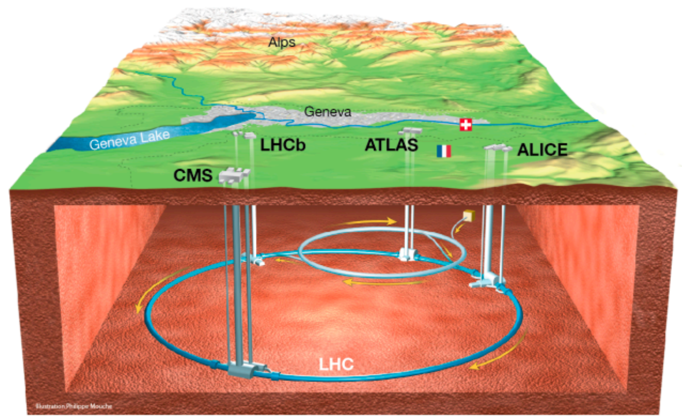
- All interactions observed experimentally (except $\tilde{\theta}$).
- Checked at so many experiments and facilities, using energies that span orders of magnitudes.
- Fantastic agreement, except for occasional tensions that come and go.
- Immense success!







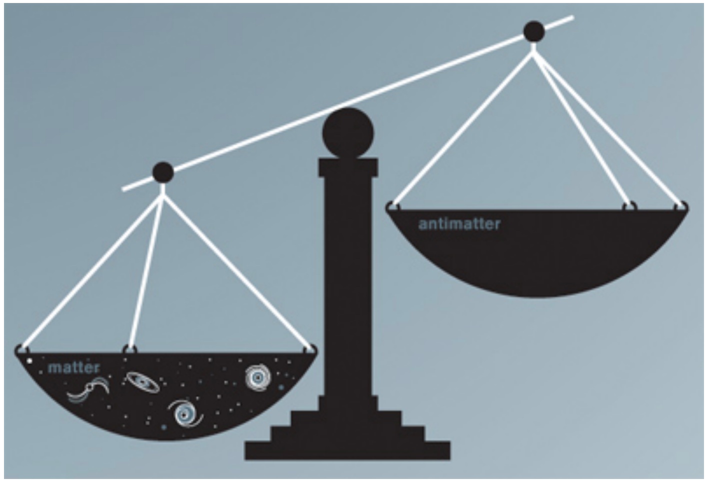




Symmetries and asymmetries

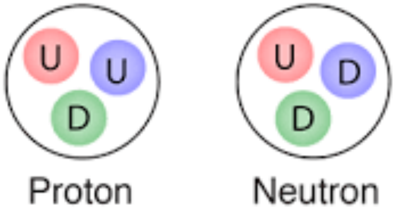
Symmetries & asymmetries

- Observation: huge matter-antimatter asymmetry.

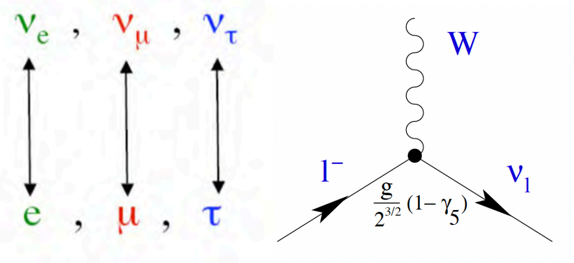


- Sakharov conditions to generate a non-zero matter-antimatter asymmetry
  - B violation → SM?
  - C & CP violation → SM?
  - Out of equilibrium → SM? (or CPT-violation)

Accidental symmetries: B, L, L_i



- Baryon number:
  B(q)=1/3, zero for the rest.
- Lepton number:
  L(e,μ,τ,ν_l)=1, zero for the rest.
- Lepton flavor:
  $L_i(e_i,\nu_i)$=1, zero for the rest.



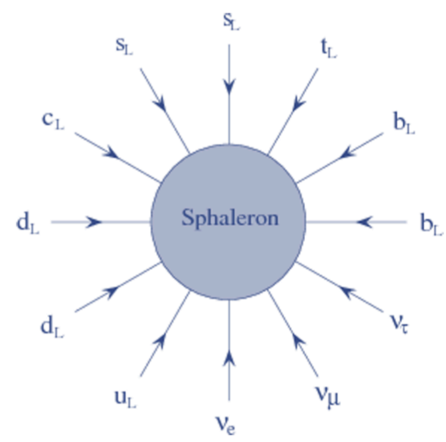
- More formally:
  global symmetries, e.g. $f \to e^{i\beta/3} f \quad (f = u, d, q)$
- In the vanilla SM, B, L & L_i are conserved (perturbatively)
- This was not imposed → "**accidental symmetries**"

Accidental symmetries: B, L, L_i

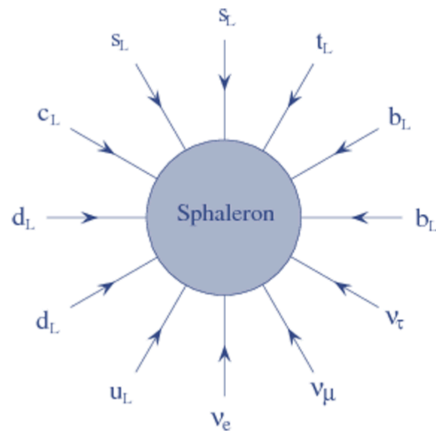
- Symmetries of the Lagrangian can be violated by quantum effects ("anomalous symmetries")

  - B+L (and hence L_i) are violated by non-perturbative effects which generate $\Delta B = \Delta L = \pm 3n$ [*Weinberg'79*].

  - Proton still stable (ΔB=1).
    More complicated processes (e.g. deuteron decay) are extremely suppressed by CKM, G_F factors, …
    We are safe :)



Accidental symmetries: B, L, L_i



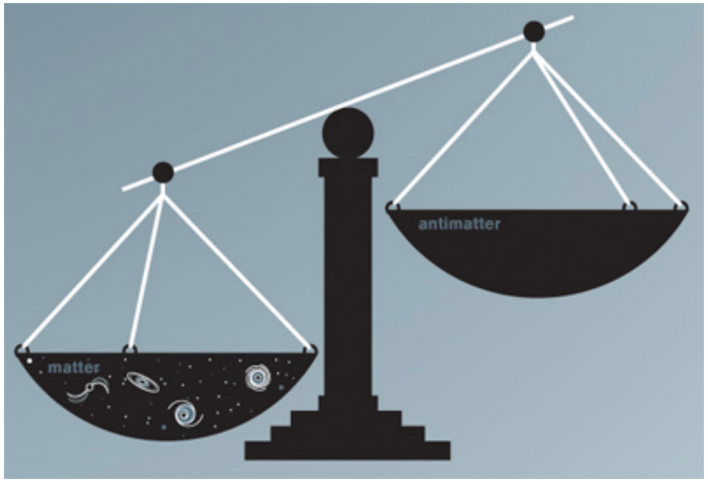
- Symmetries of the Lagrangian can be violated by quantum effects ("anomalous symmetries")
  - B+L (and hence L_i) are violated by non-perturbative effects which generate $\Delta B = \Delta L = \pm 3n$ [*Weinberg'79*].
  - Proton still stable ($\Delta B=1$).
    More complicated processes (e.g. deuteron decay) are extremely suppressed by CKM, G_F factors, …
    We are safe :)
  - Not suppressed at high temperatures (early universe).
    EW sphalerons can create B & L ("baryogenesis") or can transfer a nonzero L to a nonzero B ("leptogenesis").
  - B-L is **not** anomalous.
    Really conserved (accidentally…).

- PS: Neutrino oscillations ($\nu_i \to \nu_j$) tell us that L_i are not conserved.
  L violation: unclear (neutrino mass mechanism not known)
  → Neutrinoless double beta decay ($0\nu\beta\beta$) would indicate LNV!! → [A. Zolotarova's lectures!]

$$(A, Z) \to (A, Z+2) + 2e^-$$

Symmetries & asymmetries

- Observation: huge matter-antimatter asymmetry.



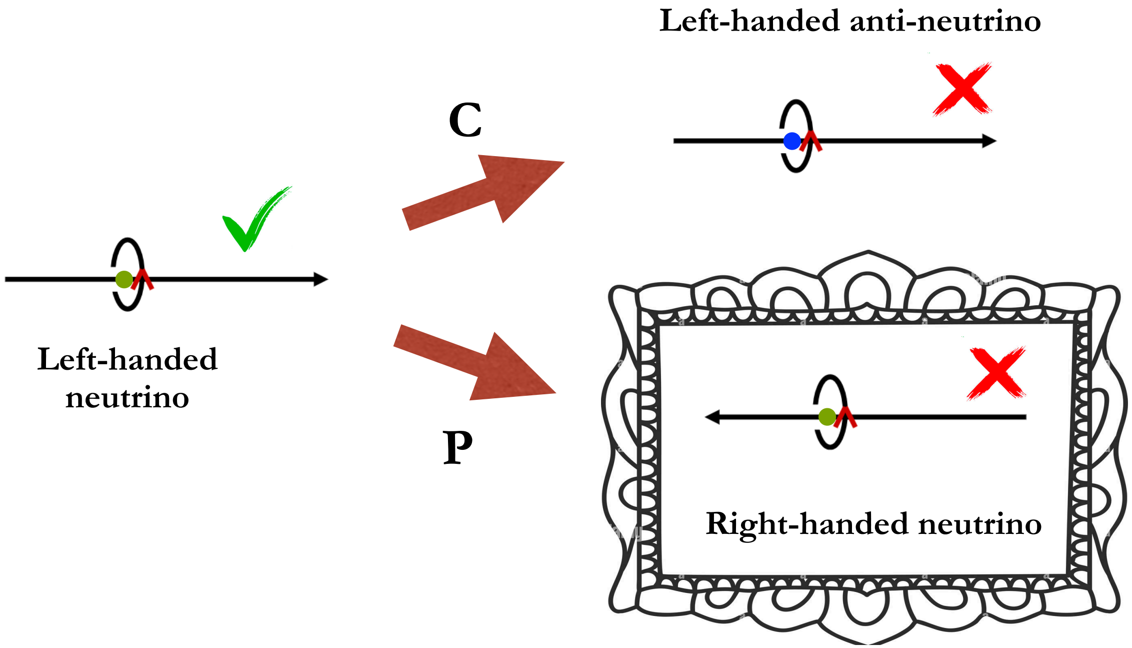
- Sakharov conditions to generate a non-zero matter-antimatter asymmetry
  - B violation → **SM: yes! (EW sphalerons)**
  - C & CP violation → SM?
  - Out of equilibrium → SM?
    (or CPT-violation)

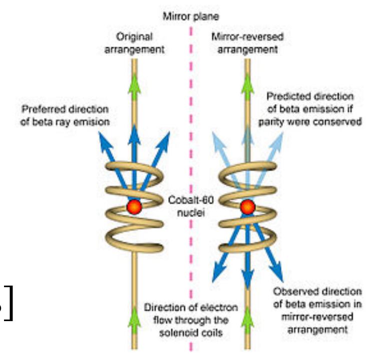
Discrete symmetries: C & P

- C = charge conjugation (particle / antiparticle)
- P = parity (spatial inversion → mirror)

- C & P are completely broken by construction (EW):
  We have LH neutrinos (& RH-antineutrinos)
  but not RH neutrinos (& LH anti-neutrinos)
  → PS: also broken for the other particles.

Fields	ψ_1	ψ_2	ψ_3
Quarks	$\begin{pmatrix} u \\ d \end{pmatrix}_L$	u_R	d_R
Leptons	$\begin{pmatrix} \nu_\ell \\ \ell^- \end{pmatrix}_L$	~~ν_R~~	ℓ^-_R





- Discovered with beta decays (1956, Wu experiment, Co-60, NIST)! → [see Adam's lectures]

Discrete symmetries: C & P

Fields	ψ_1	ψ_2	ψ_3
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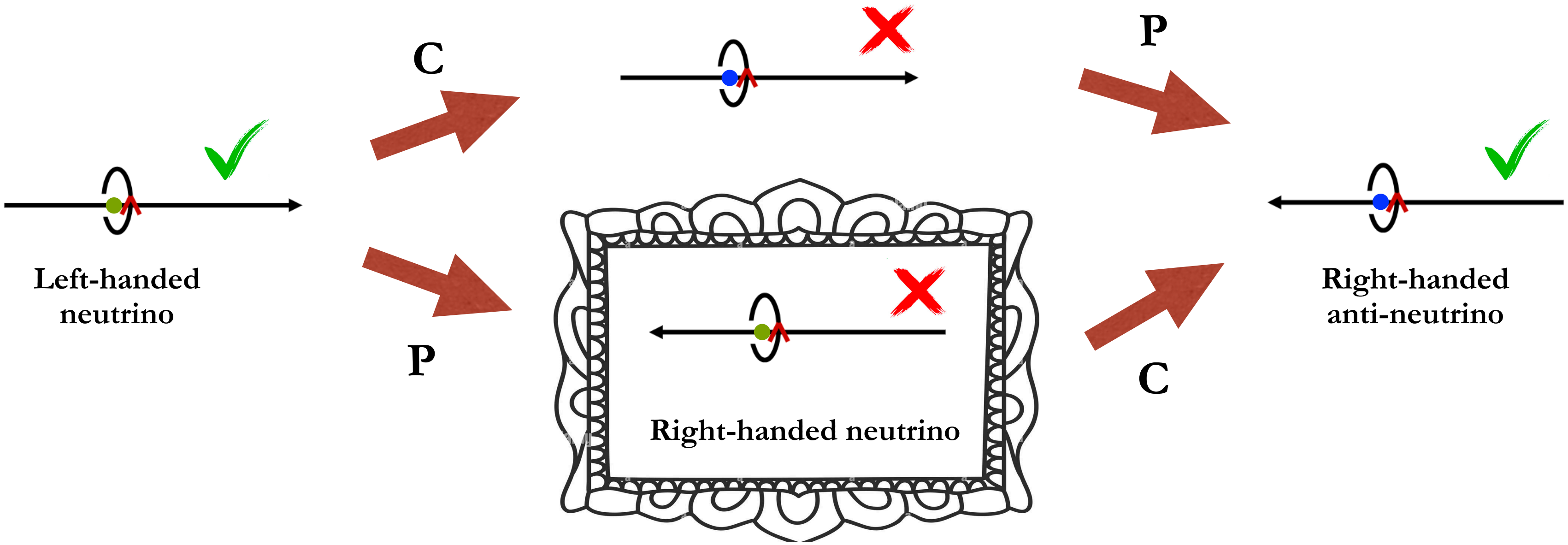


$$\mathscr{L}_{CC} = -\frac{g}{2\sqrt{2}} W_\mu^\dagger \bar{\nu}\gamma^\mu(1-\gamma_5)e + h.c. = -\frac{g}{2\sqrt{2}} W_\mu^\dagger \bar{\nu}\gamma^\mu(1-\gamma_5)e - \frac{g}{2\sqrt{2}} W_\mu \bar{e}\gamma^\mu(1-\gamma_5)\nu$$

Discrete symmetries: CP

- After the 1956 shock, CP was thought to hold.
  - 1964: CP-violation observed in kaon decays (small, ~0.2%).
    Also observed later in B & D mesons.
    But it remains a rare observation
    (almost all phenomena are CP symmetric).
  - The 3rd family was introduced to have CPV in the SM.
- CPT theorem: CP violation → T violation
- The SM has two sources of CPV:
  - Flavor sector:
    CKM phase, which perfectly explains the CPV observed in the lab exp.
  - QCD sector: theta term

Discrete symmetries: CP

- CPV in the flavor sector (EW)

$$\mathscr{L}_{CC} = -\frac{g}{2\sqrt{2}} W_\mu^\dagger \bar{u}_i \gamma^\mu (1-\gamma_5) V_{ij}\, d_j - \frac{g}{2\sqrt{2}} W_\mu \bar{d}_j \gamma^\mu (1-\gamma_5) V_{ij}^*\, u_i$$

- CP is subtle: often phases can be absorbed with redefinitions (not physical).
  Example: SM with 2 families has no CPV!

- A collective endevour: one can't just look at a single interaction term.
  CP invariants are the proper objects to avoid this confusion.
  In the SM, there's only one: the Jarlskog invariant:

$$\mathscr{J} \equiv Im(V_{us} V_{cb} V_{ub}^* V_{cs}^*) = 3.08(14) \times 10^{-5}$$

- CKM matrix:

$$V = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} = \begin{bmatrix} 1-\frac{1}{2}\lambda^2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\frac{1}{2}\lambda^2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{bmatrix} + O(\lambda^4)$$

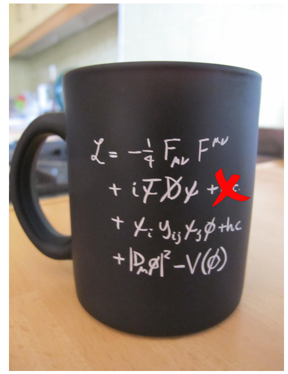
  - Although the CKM phase can be large, J is very small: $J \sim \lambda^6$
  - CP is not a symmetry of the SM, but CPV turns out to be accidentally small or secluded.

Discrete symmetries: CP

- CPV in the QCD sector: the theta term:

$$\tilde{G}^a_{\mu\nu} \equiv \frac{1}{2}\epsilon_{\mu\nu\alpha\beta}G^{a\,\alpha\beta}$$

$$\begin{aligned}\mathscr{L}_{SM} = & -\frac{1}{4}G^{a\mu\nu}G^a_{\mu\nu} - \frac{1}{4}W^{k\mu\nu}W^k_{\mu\nu} - \frac{1}{4}B^{\mu\nu}B_{\mu\nu} - \tilde{\theta}\, G^{a\mu\nu}\,\tilde{G}^a_{\mu\nu} \\ & - i\sum_f \bar{f}\, D_\mu \gamma^\mu f \\ & - \left(\bar{\ell}\, Y_e \varphi\, e + \bar{q}\,\varphi\, Y_d\, d + \bar{q}\,\tilde{\varphi}\, Y_u\, u\right) + h.c. \\ & + \left(D_\mu\varphi\right)^\dagger \left(D^\mu\varphi\right) - \mu^2\left(\varphi^\dagger\varphi\right) - \lambda\left(\varphi^\dagger\varphi\right)^2\end{aligned}$$



- It generates a non-zero nEDM: $d_n = 0.158(36)\,\tilde{\theta}\, e\, fm$

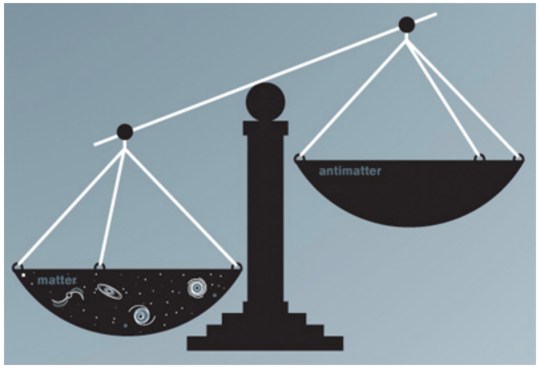
- Strong experimental limits on EDMs: $\tilde{\theta} \lesssim 10^{-12}$!!??
  → Popular possible solution: QCD axion

"Strong CP problem"

- PS: This shows that it's not true that one needs a complex phase to have CPV. That's only true for CP-cons. operators (but not for CPV operators).

Symmetries & asymmetries

- Observation: huge matter-antimatter asymmetry.

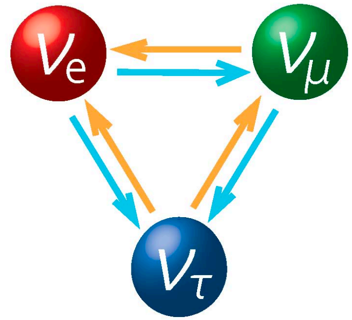


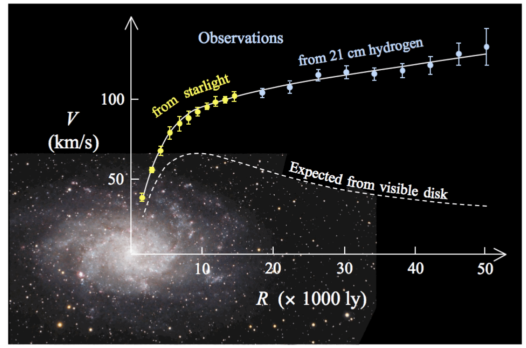
- Sakharov conditions to generate a non-zero matter-antimatter asymmetry
  - B violation → **SM: yes! (EW sphalerons)**
  - C & CP violation → SM: yes, but CPV is **very small**
  - Out of equilibrium → SM: no
    (or CPT-violation)

- Beyond-the-SM physics required!
  (Many ideas in the market…)
  - Models typically require BSM sources of CPV
    → EDMs are ideal experiments to search for them [→ Guillaume's lectures]

The SM is not enough

- In addition to the matter-antimatter asymmetry, there are other reasons that indicate that the SM (despite it's impressive success) is incomplete.
- Neutrinos oscillate → they have a mass!
  - We'll talk about them in detail later
  - Entangled with beta decay physics (production, detection, neutrino mass measurements, …)
- Dark matter!
- What lies under the SM periodic table?
- Strong CP problem
- And many others: hierarchy problem, dark energy, quantum gravity, cosmological problems (why is the universe homogeneous, isotropic & flat?), …
- For some problems there are "good" solutions (axions, inflation, …). For others the situation is less clear.





The SM is not enough

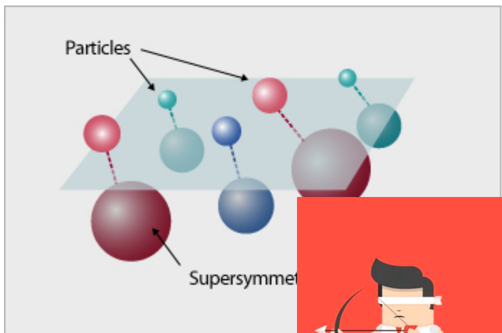
- All SM problems are theoretical or astrophysical/cosmological, except for neutrino masses.
- Too many theories around (often not very convincing)
- The SM works too well. We need new hints. Physics = EXP + TH
- Quite curious crisis

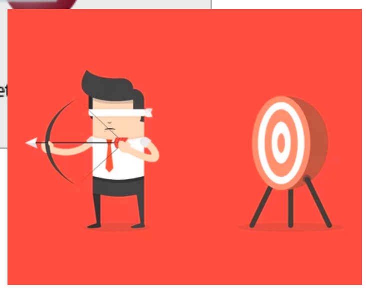
$$\mathcal{L} = -\frac{1}{4} F_{\mu\nu} F^{\mu\nu} + i \bar{\psi} \not{D} \psi + h.c. + \bar{\psi}_i y_{ij} \psi_j \phi + h.c. + |D_\mu \phi|^2 - V(\phi)$$

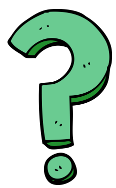
Going beyond the SM

Specific BSM model

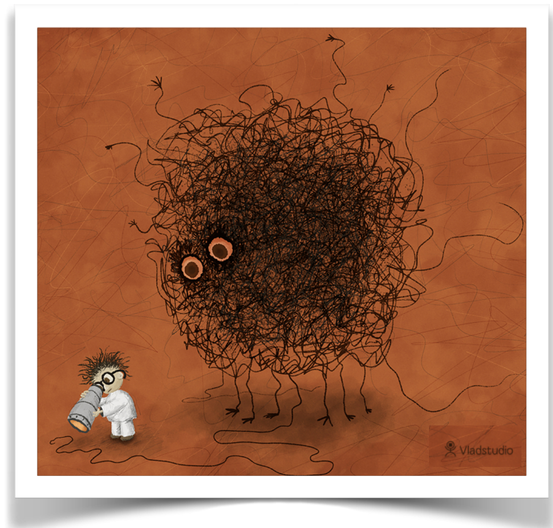
$$\mathscr{L}_{BSM} = \mathscr{L}\left(\phi_{SM}, \Phi_{BSM}\right)$$



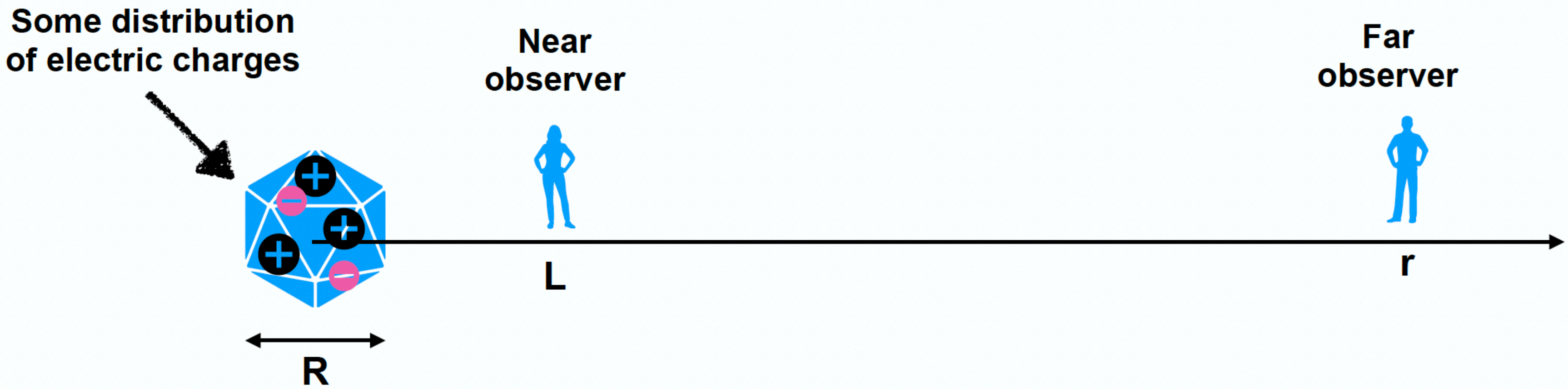




Effective Field Theory (EFT) approach



Detour: EFT



<u>Near observer</u>, L~R, needs to know the position of every charge to describe electric field in her proximity

<u>Far observer</u>, $r \gg R$, can instead use multipole expansion: $V(\vec{r}) = \frac{Q}{r} + \frac{\vec{d} \cdot \vec{r}}{r^3} + \frac{Q_{ij} r_i r_j}{r^5} + \ldots$

$\sim 1/r \qquad \sim R/r^2 \qquad \sim R^2/r^3$

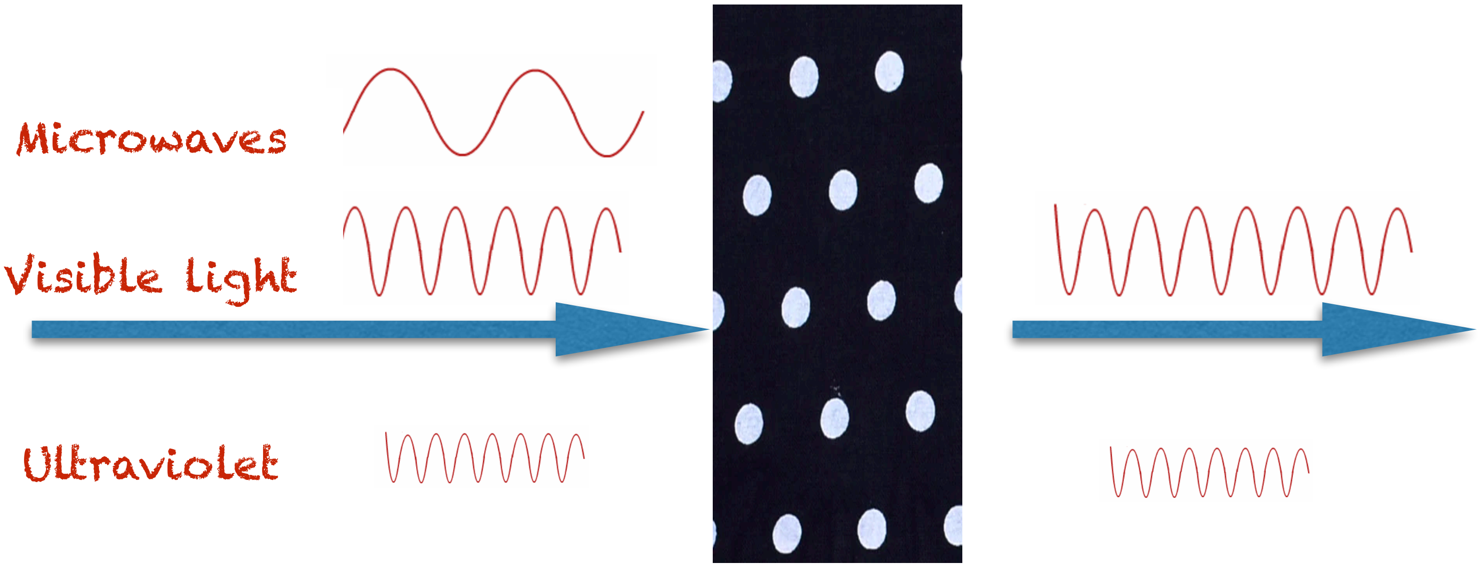
Higher order terms in the multipole expansion are suppressed by powers of the small parameter (R/r). One can truncate the expansion at some order depending on the value of (R/r) and experimental precision

Far observer is able to describe electric field in his vicinity using just a few parameters: the total electric charge Q, the dipole moment $\vec{d}$, eventually the quadrupole moment Q_{ij}, etc.…

On the other hand, far observer can only guess the "fundamental" distributions of the charges, as many distinct distributions lead to the same first few moments

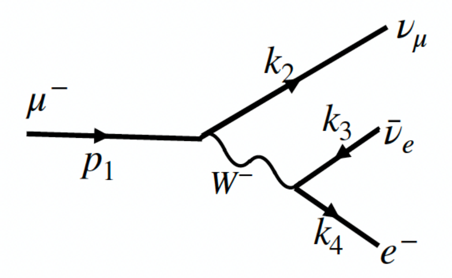
[Adam's CP2023 lectures]

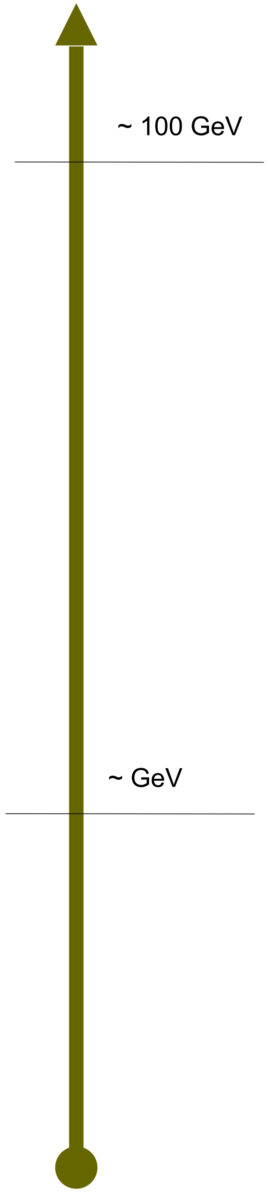
High-E = small distances



$E \sim 1/\lambda$

Detour: EFT in QFT (example)





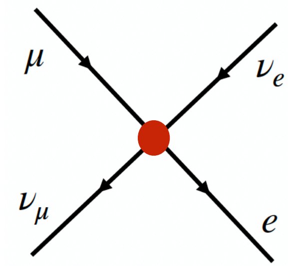
$\mathcal{L}_{SM}$ (EW theory)

$$\mathcal{M} = \frac{g_L^2}{2}\bar{u}(k_2)\gamma_\rho P_L u(p_1)\frac{1}{q^2 - m_W^2}\bar{u}(k_4)\gamma_\rho P_L \mathrm{v}(k_3)$$

$q = p_1 - k_2$

$q^2 \lesssim m_\mu^2 \ll m_W^2$

$$\mathcal{M} = -\frac{g_L^2}{2m_W^2}\bar{u}(k_2)\gamma_\rho P_L u(p_1)\bar{u}(k_4)\gamma_\rho P_L \mathrm{v}(k_3) + \mathcal{O}(q^2/m_W^4)$$

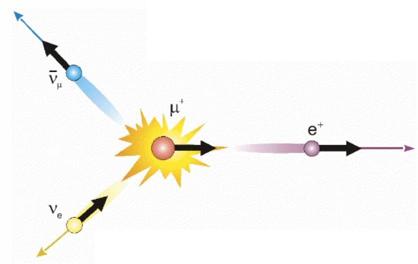


$$\mathcal{L}_{eff} = -\frac{4G_F}{\sqrt{2}}\bar{e}\,\gamma_\mu\,(1-\gamma_5)\,\nu_e \cdot \bar{\nu}_\mu\,\gamma^\mu\,(1-\gamma_5)\,\mu$$

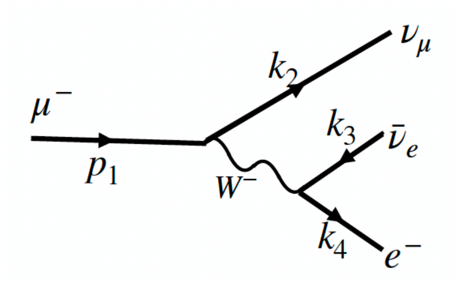
+ higher-dim terms

$$G_F = \frac{g^2}{4\sqrt{2}m_W^2}$$

Wilson coefficient



Detour: EFT in QFT (example)



~ 100 GeV

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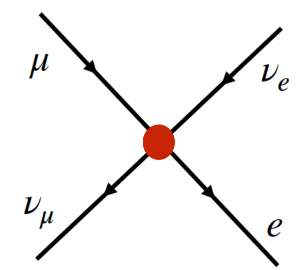


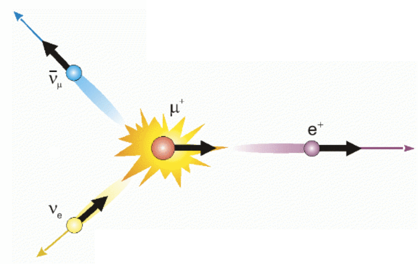
~ GeV

$$\mathcal{L}_{eff} = -\frac{4G_F}{\sqrt{2}}\bar{e}\,\gamma_\mu(1-\gamma_5)\,\nu_e \cdot \bar{\nu}_\mu\gamma^\mu(1-\gamma_5)\,\mu$$

+ *higher-dim terms*

$$G_F = \frac{g^2}{4\sqrt{2}m_W^2}$$

Wilson coefficient



Historically the logic was quite different:
Data → Fermi EFT → SM

Detour: EFT in QFT

Top down

Known theory at high-E

EFT at low-E

Bottom up

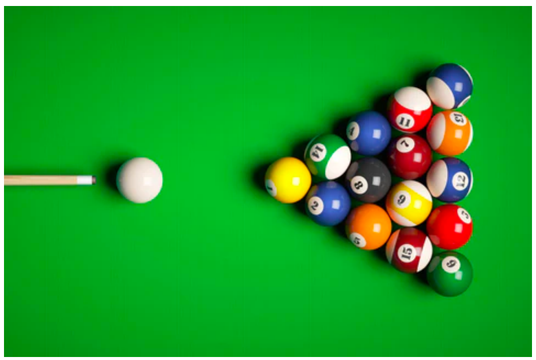
EFT that includes high-E effects

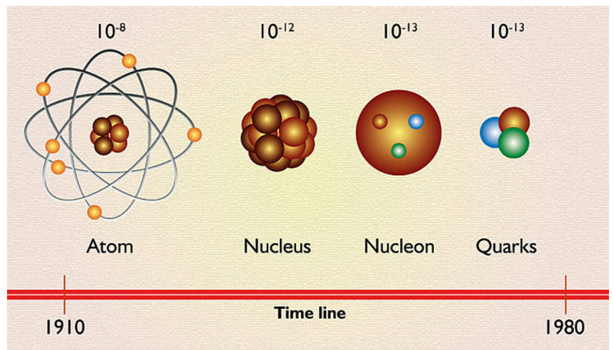
Known theory at low-E
(or at least symmetries & fields)

Given a set of low-E fields & symmetries, one builds an EFT Lagrangian putting all possible interactions and following a power counting

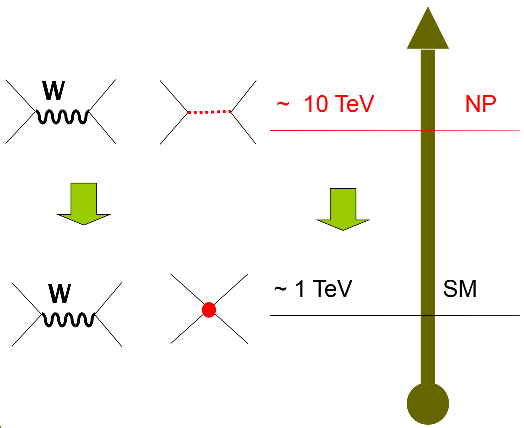
Detour: EFT

- EFT is basically what we do in physics all the time:
  suitable choice of d.o.f. & symmetries + dimensional analysis + perturbative expansion
- We can do it because measurements have finite precision
  (& because often we want approximate predictions)
- It makes our life easier
- It's a general approach to a physics problem: often we don't know the "fundamental" (high-E / small distance) theory, or we can't calculate with it. EFTs allow us to move forward in a general way.
- There's a range of validity (expansion parameter?)





EFT at the EW scale: SM → SMEFT



$$\mathbf{L}^{TeV}(x) = \mathbf{L}(\text{SM-fields, bSM-fields})$$

$$\mathscr{L}_{eff}(x) = \sum_i C_i \mathcal{O}_i$$

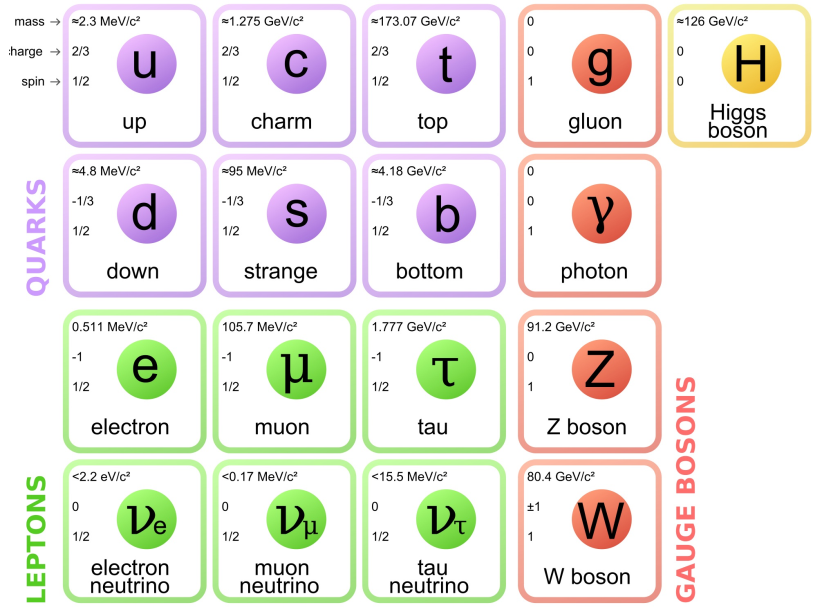
Given a set of low-E fields & symmetries, one builds an EFT Lagrangian putting all possible interactions and following a power counting

C_i: **Wilson coefficients (UV physics)**

EFT = Model-independent approach ≠ Assumption independent

SMEFT: assumptions

Known elementary particles
(masses < 173 GeV)



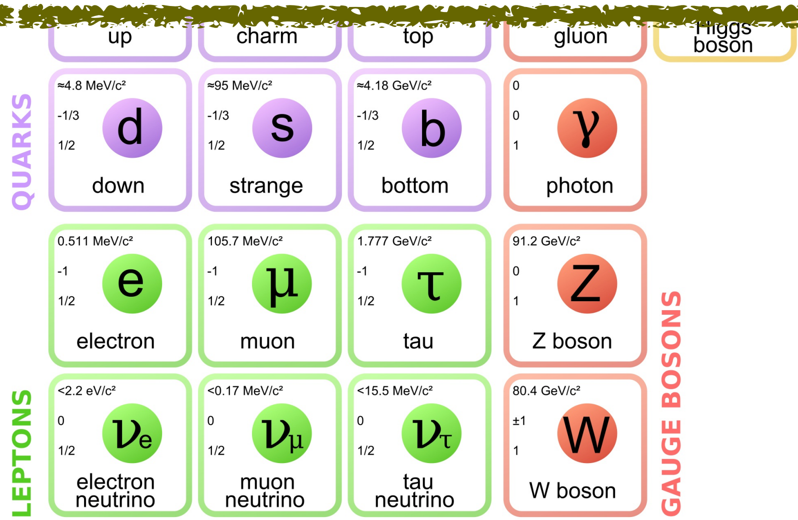
1. QFT

2. SM fields + gap:
   NP scale >> EW scale.

3. Gauge symmetry: local
   SU(3)xSU(2)xU(1) symmetry

SMEFT: assumptions

Physics above the EW scale is described by a manifestly Poincaré-invariant local quantum theory.
Safe assumption.



1. QFT

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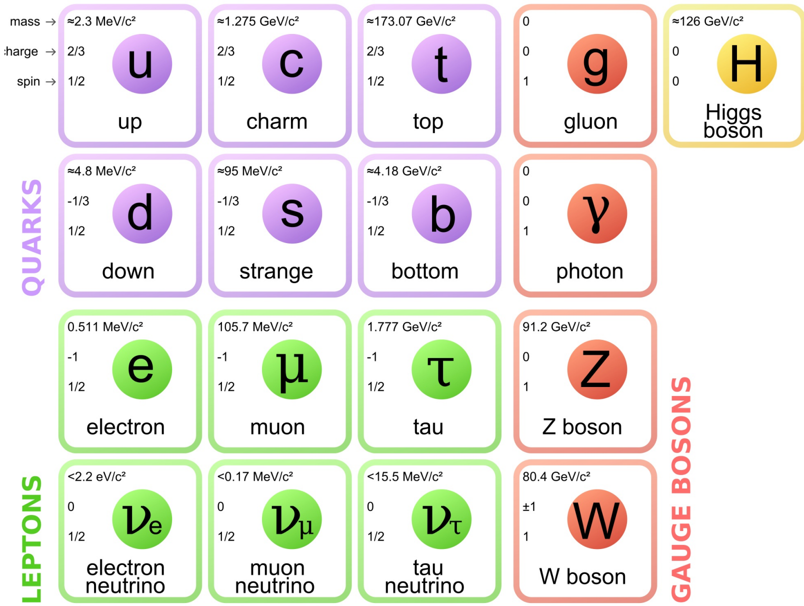
SMEFT: assumptions

Known elementary particles
(masses < 173 GeV)



1. QFT

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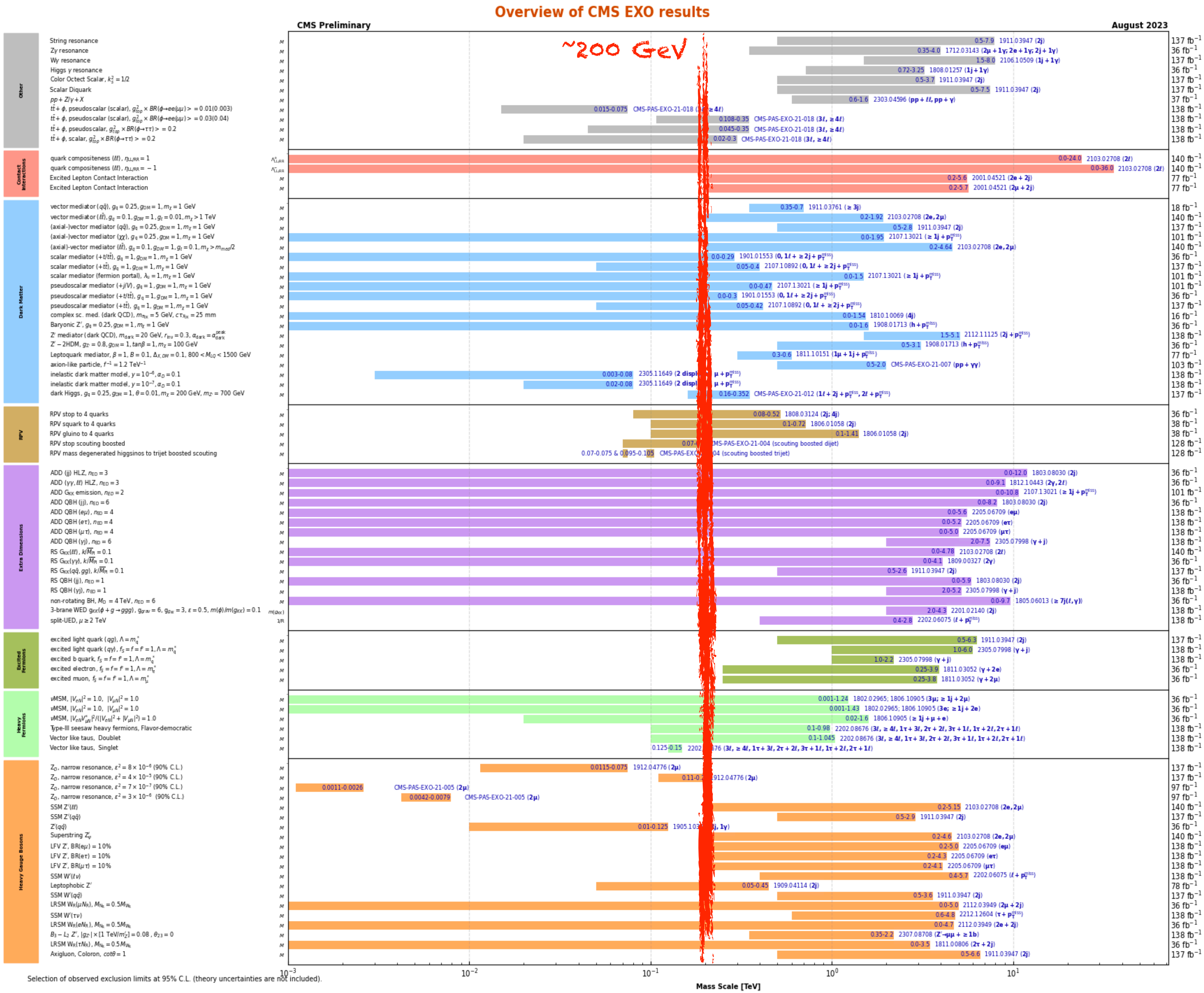
Overview of CMS EXO results
CMS Preliminary
August 2023
~200 GeV
Other
String resonance 0.5-7.9 1911.03947 (2j) 137 fb^{-1}
Zγ resonance 0.35-4.0 1712.03143 (2μ + 1γ; 2e + 1γ; 2j + 1γ) 36 fb^{-1}
Wγ resonance 1.5-8.0 2106.10509 (1j + 1γ) 137 fb^{-1}
Higgs γ resonance 0.72-3.25 1808.01257 (1j + 1γ) 36 fb^{-1}
Color Octect Scalar, $k_s^2 = 1/2$ 0.5-3.7 1911.03947 (2j) 137 fb^{-1}
Scalar Diquark 0.5-7.5 1911.03947 (2j) 137 fb^{-1}
$pp + Z/\gamma + X$ 0.6-1.6 2303.04596 (pp + ℓℓ, pp + γ) 37 fb^{-1}
$t\bar{t} + \phi$, pseudoscalar (scalar), $g_{\phi tt}^2 \times BR(\phi \to ee|\mu\mu) = 0.01(0.003)$ 0.015-0.075 CMS-PAS-EXO-21-018 (3ℓ, ≥ 4ℓ) 138 fb^{-1}
$t\bar{t} + \phi$, pseudoscalar (scalar), $g_{\phi tt}^2 \times BR(\phi \to ee|\mu\mu) = 0.03(0.04)$ 0.108-0.35 CMS-PAS-EXO-21-018 (3ℓ, ≥ 4ℓ) 138 fb^{-1}
$t\bar{t} + \phi$, pseudoscalar, $g_{\phi tt}^2 \times BR(\phi \to \tau\tau) = 0.2$ 0.045-0.35 CMS-PAS-EXO-21-018 (3ℓ, ≥ 4ℓ) 138 fb^{-1}
$t\bar{t} + \phi$, scalar, $g_{\phi tt}^2 \times BR(\phi \to \tau\tau) = 0.2$ 0.02-0.3 CMS-PAS-EXO-21-018 (3ℓ, ≥ 4ℓ) 138 fb^{-1}
Contact Interactions
quark compositeness (ℓℓ), $\eta_{LL,RR} = 1$ 0.0-24.0 2103.02708 (2ℓ) 140 fb^{-1}
quark compositeness (ℓℓ), $\eta_{LL,RR} = -1$ 0.0-36.0 2103.02708 (2ℓ) 140 fb^{-1}
Excited Lepton Contact Interaction 0.2-5.6 2001.04521 (2e + 2j) 77 fb^{-1}
Excited Lepton Contact Interaction 0.2-5.7 2001.04521 (2μ + 2j) 77 fb^{-1}
Dark Matter
vector mediator ($q\bar{q}$), $g_q = 0.25, g_{DM} = 1, m_\chi = 1$ GeV 0.35-0.7 1911.03761 (≥ 3j) 18 fb^{-1}
vector mediator ($\ell\bar{\ell}$), $g_q = 0.1, g_{DM} = 1, g_\ell = 0.01, m_\chi > 1$ TeV 0.2-1.92 2103.02708 (2e, 2μ) 140 fb^{-1}
(axial-)vector mediator ($q\bar{q}$), $g_q = 0.25, g_{DM} = 1, m_\chi = 1$ GeV 0.5-2.8 1911.03947 (2j) 137 fb^{-1}
(axial-)vector mediator ($\chi\chi$), $g_q = 0.25, g_{DM} = 1, m_\chi = 1$ GeV 0.0-1.95 2107.13021 (≥ 1j + p_T^{miss}) 101 fb^{-1}
(axial)-vector mediator ($\ell\bar{\ell}$), $g_q = 0.1, g_{DM} = 1, g_\ell = 0.1, m_\chi > m_{med}/2$ 0.2-4.64 2103.02708 (2e, 2μ) 140 fb^{-1}
scalar mediator ($+t/t\bar{t}$), $g_q = 1, g_{DM} = 1, m_\chi = 1$ GeV 0.0-0.29 1901.01553 (0, 1ℓ + ≥ 2j + p_T^{miss}) 36 fb^{-1}
scalar mediator ($+t\bar{t}$), $g_q = 1, g_{DM} = 1, m_\chi = 1$ GeV 0.05-0.4 2107.10892 (0, 1ℓ + ≥ 2j + p_T^{miss}) 137 fb^{-1}
scalar mediator (fermion portal), $\lambda_u = 1, m_\chi = 1$ GeV 0.0-1.5 2107.13021 (≥ 1j + p_T^{miss}) 101 fb^{-1}
pseudoscalar mediator ($+j/V$), $g_q = 1, g_{DM} = 1, m_\chi = 1$ GeV 0.0-0.47 2107.13021 (≥ 1j + p_T^{miss}) 101 fb^{-1}
pseudoscalar mediator ($+t/t\bar{t}$), $g_q = 1, g_{DM} = 1, m_\chi = 1$ GeV 0.0-0.3 1901.01553 (0, 1ℓ + ≥ 2j + p_T^{miss}) 36 fb^{-1}
pseudoscalar mediator ($+t\bar{t}$), $g_q = 1, g_{DM} = 1, m_\chi = 1$ GeV 0.05-0.42 2107.10892 (0, 1ℓ + ≥ 2j + p_T^{miss}) 137 fb^{-1}
complex sc. med. (dark QCD), $m_{\pi_{DK}} = 5$ GeV, $c\tau_{\pi_{DK}} = 25$ mm 0.0-1.54 1810.10069 (4j) 16 fb^{-1}
Baryonic Z', $g_q = 0.25, g_{DM} = 1, m_\chi = 1$ GeV 0.0-1.6 1908.01713 (h + p_T^{miss}) 36 fb^{-1}
Z' mediator (dark QCD), $m_{dark} = 20$ GeV, $r_{inv} = 0.3$, $\alpha_{dark} = \alpha_{dark}^{peak}$ 1.5-5.1 2112.11125 (2j + p_T^{miss}) 138 fb^{-1}
Z' − 2HDM, $g_{Z'} = 0.8, g_{DM} = 1, tan\beta = 1, m_\chi = 100$ GeV 0.5-3.1 1908.01713 (h + p_T^{miss}) 36 fb^{-1}
Leptoquark mediator, $\beta = 1, B = 0.1, \Delta_{X,DM} = 0.1, 800 < M_{LQ} < 1500$ GeV 0.3-0.6 1811.10151 (1μ + 1j + p_T^{miss}) 77 fb^{-1}
axion-like particle, $f^{-1} = 1.2$ TeV^{-1} 0.5-2.0 CMS-PAS-EXO-21-007 (pp + γγ) 103 fb^{-1}
inelastic dark matter model, $y = 10^{-8}, \alpha_D = 0.1$ 0.003-0.08 2305.11649 (2 displ. μ + p_T^{miss}) 138 fb^{-1}
inelastic dark matter model, $y = 10^{-7}, \alpha_D = 0.1$ 0.02-0.08 2305.11649 (2 displ. μ + p_T^{miss}) 138 fb^{-1}
dark Higgs, $g_q = 0.25, g_{DM} = 1, \theta = 0.01, m_\chi = 200$ GeV, $m_{Z'} = 700$ GeV 0.16-0.352 CMS-PAS-EXO-21-012 (1ℓ + 2j + p_T^{miss}, 2ℓ + p_T^{miss}) 137 fb^{-1}
RPV
RPV stop to 4 quarks 0.08-0.52 1808.03124 (2j; 4j) 36 fb^{-1}
RPV squark to 4 quarks 0.1-0.72 1806.01058 (2j) 38 fb^{-1}
RPV gluino to 4 quarks 0.1-1.41 1806.01058 (2j) 38 fb^{-1}
RPV stop scouting boosted 0.07-0.7 CMS-PAS-EXO-21-004 (scouting boosted dijet) 128 fb^{-1}
RPV mass degenerated higgsinos to trijet boosted scouting 0.07-0.075 & 0.095-0.105 CMS-PAS-EXO-21-004 (scouting boosted trijet) 128 fb^{-1}
Extra Dimensions
ADD (jj) HLZ, $n_{ED} = 3$ 0.0-12.0 1803.08030 (2j) 36 fb^{-1}
ADD (γγ, ℓℓ) HLZ, $n_{ED} = 3$ 0.0-9.1 1812.10443 (2γ, 2ℓ) 36 fb^{-1}
ADD G_{KK} emission, $n_{ED} = 2$ 0.0-10.8 2107.13021 (≥ 1j + p_T^{miss}) 101 fb^{-1}
ADD QBH (jj), $n_{ED} = 6$ 0.0-8.2 1803.08030 (2j) 36 fb^{-1}
ADD QBH (eμ), $n_{ED} = 4$ 0.0-5.6 2205.06709 (eμ) 138 fb^{-1}
ADD QBH (eτ), $n_{ED} = 4$ 0.0-5.2 2205.06709 (eτ) 138 fb^{-1}
ADD QBH (μτ), $n_{ED} = 4$ 0.0-5.0 2205.06709 (μτ) 138 fb^{-1}
ADD QBH (γj), $n_{ED} = 6$ 2.0-7.5 2305.07998 (γ + j) 138 fb^{-1}
RS G_{KK}(ℓℓ), $k/\overline{M}_{Pl} = 0.1$ 0.0-4.78 2103.02708 (2ℓ) 140 fb^{-1}
RS G_{KK}(γγ), $k/\overline{M}_{Pl} = 0.1$ 0.0-4.1 1809.00327 (2γ) 36 fb^{-1}
RS G_{KK}($q\bar{q}$, gg), $k/\overline{M}_{Pl} = 0.1$ 0.5-2.6 1911.03947 (2j) 137 fb^{-1}
RS QBH (jj), $n_{ED} = 1$ 0.0-5.9 1803.08030 (2j) 36 fb^{-1}
RS QBH (γj), $n_{ED} = 1$ 2.0-5.2 2305.07998 (γ + j) 138 fb^{-1}
non-rotating BH, $M_D = 4$ TeV, $n_{ED} = 6$ 0.0-9.7 1805.06013 (≥ 7j(ℓ, γ)) 36 fb^{-1}
3-brane WED $g_{KK}(\phi + g \to ggg)$, $g_{grav} = 6$, $g_{\phi} = 3$, $\epsilon = 0.5$, $m(\phi)/m(g_{KK}) = 0.1$ 2.0-4.3 2201.02140 (2j) 138 fb^{-1}
split-UED, $\mu \geq 2$ TeV 0.4-2.8 2202.06075 (ℓ + p_T^{miss}) 138 fb^{-1}
Excited Fermions
excited light quark (qg), $\Lambda = m_q^*$ 0.5-6.3 1911.03947 (2j) 137 fb^{-1}
excited light quark (qγ), $f_s = f = f' = 1, \Lambda = m_q^*$ 1.0-6.0 2305.07998 (γ + j) 138 fb^{-1}
excited b quark, $f_s = f = f' = 1, \Lambda = m_b^*$ 1.0-2.2 2305.07998 (γ + j) 138 fb^{-1}
excited electron, $f_s = f = f' = 1, \Lambda = m_e^*$ 0.25-3.9 1811.03052 (γ + 2e) 36 fb^{-1}
excited muon, $f_s = f = f' = 1, \Lambda = m_\mu^*$ 0.25-3.8 1811.03052 (γ + 2μ) 36 fb^{-1}
Heavy Fermions
νMSM, $|V_{eN}|^2 = 1.0$, $|V_{\mu N}|^2 = 1.0$ 0.001-1.24 1802.02965; 1806.10905 (3μ; ≥ 1j + 2μ) 36 fb^{-1}
νMSM, $|V_{eN}|^2 = 1.0$, $|V_{\mu N}|^2 = 1.0$ 0.001-1.43 1802.02965; 1806.10905 (3e; ≥ 1j + 2e) 36 fb^{-1}
νMSM, $|V_{eN}V_{\mu N}^*|^2/(|V_{eN}|^2 + |V_{\mu N}|^2) = 1.0$ 0.02-1.6 1806.10905 (≥ 1j + μ + e) 36 fb^{-1}
Type-III seesaw heavy fermions, Flavor-democratic 0.1-0.98 2202.08676 (3ℓ, ≥ 4ℓ, 1τ + 3ℓ, 2τ + 2ℓ, 3τ + 1ℓ, 1τ + 2ℓ, 2τ + 1ℓ) 138 fb^{-1}
Vector like taus, Doublet 0.1-1.045 2202.08676 (3ℓ, ≥ 4ℓ, 1τ + 3ℓ, 2τ + 2ℓ, 3τ + 1ℓ, 1τ + 2ℓ, 2τ + 1ℓ) 138 fb^{-1}
Vector like taus, Singlet 0.125-0.15 2202.08676 (3ℓ, ≥ 4ℓ, 1τ + 3ℓ, 2τ + 2ℓ, 3τ + 1ℓ, 1τ + 2ℓ, 2τ + 1ℓ) 138 fb^{-1}
Heavy Gauge Bosons
Z_D, narrow resonance, $\epsilon^2 = 8 \times 10^{-6}$ (90% C.L.) 0.0115-0.075 1912.04776 (2μ) 137 fb^{-1}
Z_D, narrow resonance, $\epsilon^2 = 4 \times 10^{-5}$ (90% C.L.) 0.11-0.2 1912.04776 (2μ) 137 fb^{-1}
Z_D, narrow resonance, $\epsilon^2 = 7 \times 10^{-7}$ (90% C.L.) 0.0011-0.0026 CMS-PAS-EXO-21-005 (2μ) 97 fb^{-1}
Z_D, narrow resonance, $\epsilon^2 = 3 \times 10^{-6}$ (90% C.L.) 0.0042-0.0079 CMS-PAS-EXO-21-005 (2μ) 97 fb^{-1}
SSM Z'(ℓℓ) 0.2-5.15 2103.02708 (2e, 2μ) 140 fb^{-1}
SSM Z'($q\bar{q}$) 0.5-2.9 1911.03947 (2j) 137 fb^{-1}
Z'($q\bar{q}$) 0.01-0.125 1905.10331 (1j, 1γ) 36 fb^{-1}
Superstring Z'_ψ 0.2-4.6 2103.02708 (2e, 2μ) 140 fb^{-1}
LFV Z', BR(eμ) = 10% 0.2-5.0 2205.06709 (eμ) 138 fb^{-1}
LFV Z', BR(eτ) = 10% 0.2-4.3 2205.06709 (eτ) 138 fb^{-1}
LFV Z', BR(μτ) = 10% 0.2-4.1 2205.06709 (μτ) 138 fb^{-1}
SSM W'(ℓν) 0.4-5.7 2202.06075 (ℓ + p_T^{miss}) 138 fb^{-1}
Leptophobic Z' 0.05-0.45 1909.04114 (2j) 78 fb^{-1}
SSM W'($q\bar{q}$) 0.5-3.6 1911.03947 (2j) 137 fb^{-1}
LRSM $W_R(\mu N_R)$, $M_{N_R} = 0.5 M_{W_R}$ 0.0-5.0 2112.03949 (2μ + 2j) 36 fb^{-1}
SSM W'(τν) 0.6-4.8 2212.12604 (τ + p_T^{miss}) 138 fb^{-1}
LRSM $W_R(eN_R)$, $M_{N_R} = 0.5 M_{W_R}$ 0.0-4.7 2112.03949 (2e + 2j) 36 fb^{-1}
$B_3 - L_2$ Z', $|g_{Z'}| \times [1\ \text{TeV}/m_{Z'}^2] = 0.08$, $\theta_{23} = 0$ 0.35-2.2 2307.08708 (Z' → μμ + ≥ 1b) 138 fb^{-1}
LRSM $W_R(\tau N_R)$, $M_{N_R} = 0.5 M_{W_R}$ 0.0-3.5 1811.00806 (2τ + 2j) 36 fb^{-1}
Axigluon, Coloron, $cot\theta = 1$ 0.5-6.6 1911.03947 (2j) 137 fb^{-1}
10^{-3} 10^{-2} 10^{-1} 10^{0} 10^{1}
Mass Scale [TeV]
Selection of observed exclusion limits at 95% C.L. (theory uncertainties are not included).

SMEFT: assumptions

Known elementary particles
(masses < 173 GeV)

- Reasonable assumption.
- But it could easily be wrong:
  - new O(100 GeV) particles somehow evading LHC searches;
  - light RH neutrinos (→ R-SMEFT), axions (→ALP-SMEFT), light dark matter, …
- In fact it's wrong (graviton!) but unlikely to be relevant for EW physics (→ GRSMEFT).

1. QFT
2. SM fields + gap:
   NP scale >> EW scale.
3. Gauge symmetry: local SU(3)xSU(2)xU(1) symmetry

SMEFT: assumptions

- It can be shown that SU(3)xU(1)$_{em}$ is unavoidable if one wants to write down a Lagrangian with massless gauge bosons (gluons+photon) in a manifestly Lorentz-invariant way.
- One could assume only SU(3)xU(1)$_{em}$ is linearly realized. This takes us to a different EFT called **HEFT**, which covers non-decoupling BSM models (where the masses of new particles vanish in the limit v→0) [Falkowski-Rattazzi, 1902.05936].
  Example: a 4th SM family.
- **SMEFT** describes BSM theories that can be parametrically decoupled, i.e., the mass scale of new particles depends on a free parameter(s) that can be taken to infinity.
- The validity regime of HEFT is limited below ~ 4 π v ~ 3 TeV → mass gap! (Assumption #2)
- Reasonable assumption, given the apparent mass gap.

1. QFT
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SMEFT: assumptions

Known elementary particles
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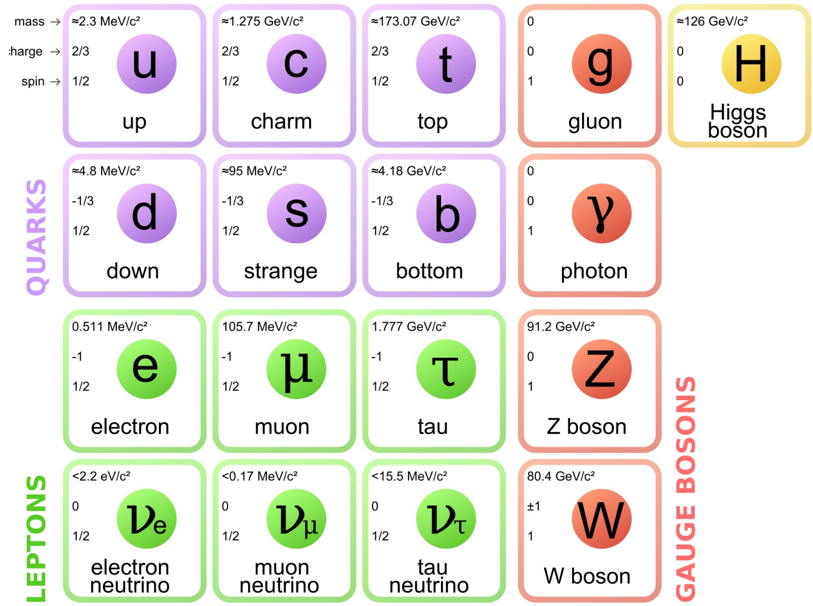


1. QFT

2. SM fields + gap:
   NP scale >> EW scale.

3. Gauge symmetry: local
   SU(3)xSU(2)xU(1) symmetry

SMEFT is the result of very conservative & parsimonious assumptions

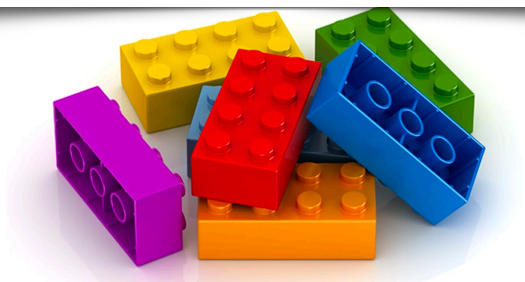
Building the SMEFT

Building the SMEFT

Building blocks:

G_μ^a , W_μ^k , B_μ , q , u , d , ℓ , e , φ

Field	$SU(3)_C$	$SU(2)_L$	$U(1)_Y$	Spin
G_μ^a	**8**	**1**	0	1
W_μ^k	**1**	**3**	0	1
B_μ	**1**	**1**	0	1
Q	**3**	**2**	1/6	1/2
u	**3**	**1**	2/3	1/2
d	**3**	**1**	-1/3	1/2
L	**1**	**2**	−1/2	1/2
e	**1**	**1**	-1	1/2
H	**1**	**2**	1/2	0



Rules

$$SU(3)c \times SU(2)_L \times U(1)_Y$$

$$\mathscr{L} = \sum_i C_i \mathscr{O}_i \left(\phi_j, D_\mu \phi_k\right)$$

Example: $\mathscr{L} = C\ (\varphi^\dagger \varphi)^3$

Building the SMEFT

There are infinite gauge-invariant terms.
But that's OK because there's a well-defined expansion:

- Take an operator (=interaction term) $\mathcal{O}_D$ of dimension D.

- Since $[\mathscr{L}] = E^4 \;\; \rightarrow \;\; \mathscr{L} \supset C_D\, \mathcal{O}_D$ where $[C_D] \sim c_D \,/\, \Lambda^{4-D}$

- Its contribution to a (dimensionless) amplitude associated to a process with E>>m

$$\mathscr{M} \sim C_D\, E^{D-4} \sim \left(\frac{E}{\Lambda}\right)^{D-4}$$

- Thus, for E << Λ:
  a D=5 term gives a larger contribution than a D=6 one,
  a D=6 term gives a larger contribution than a D=7 one,
  and so on.

- For a given precision, we only need a finite amount of terms.

$$\mathscr{L} = \mathscr{L}_{D\leq 4} + \mathscr{L}_5 + \mathscr{L}_6 + \mathscr{L}_7 + \ldots$$

Building the SMEFT

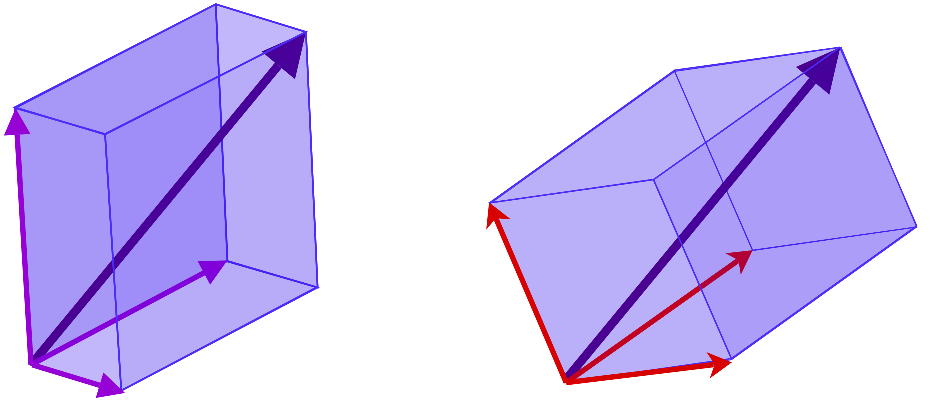
$$\mathscr{L} = \mathscr{L}_{D\leq 4} + \mathscr{L}_5 + \mathscr{L}_6 + \mathscr{L}_7 + \ldots$$

$$\sum_i C_6^i \mathscr{O}_6^i$$

Complete (and minimal) set of operators → "Basis"

- Finding a minimal set of operators is a subtle business.
  - It's not just (O_1, O_2) vs (O_1+O_2, O_1-O_2). Operators can be related through integration by parts, Fierz transformation and field redefinitions.
  - Solved recently.

- Any physical result will be independent of the basis chosen.

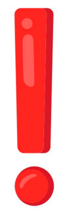


Building the SMEFT

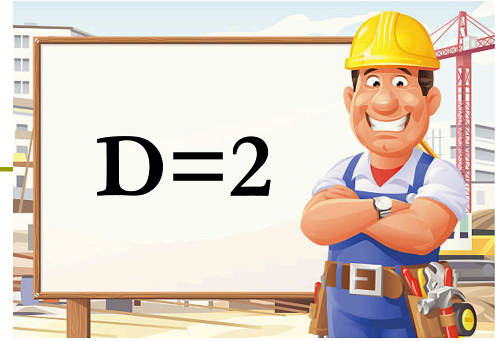
$$\mathscr{L} = \mathscr{L}_{D\leq 4} + \mathscr{L}_5 + \mathscr{L}_6 + \mathscr{L}_7 + \ldots$$

Extra comments:

- This power counting allows us to define SMEFT at the quantum level:
  - The SMEFT is non renormalizable
  - However, it is renormalizable at a any finite order in the EFT expansion
- We'll treat all Wilson Coefficients at a given dimension D on equal footing (c~1), but there can be additional hierarchies: loop vs tree, flavor symmetries, etc. This can alter the naive EFT power counting.



Building the SMEFT



$$\mathscr{L} = \mathscr{L}_2 + \mathscr{L}_3 + \mathscr{L}_4 + \mathscr{L}_5 + \mathscr{L}_6 + \mathscr{L}_7 + \ldots$$

- The first contribution appears at D=2, where we find only one operator:

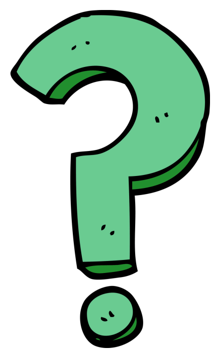
$$\mathscr{L}_2 = \mu^2 \varphi^\dagger \varphi$$

- From the EFT point of view one expects μ' of order Λ >> EW scale (at least ~1 TeV)

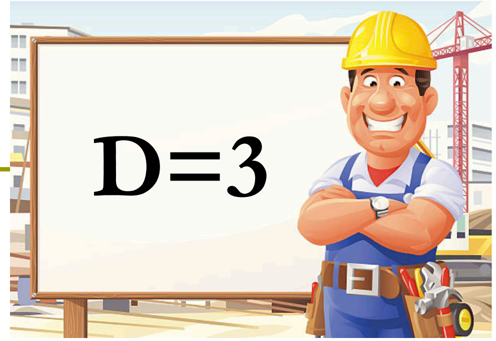
- Data tell us that μ ~ 100 GeV
  (In the SM: $M_h = \mu\sqrt{2}$)

- → **"Hierarchy problem"**.

- The EFT (dimensional analysis!) failed us on the first try.



Building the SMEFT



$$\mathscr{L} = \mathscr{L}_2 + \cancel{\mathscr{L}_3} + \mathscr{L}_4 + \mathscr{L}_5 + \mathscr{L}_6 + \mathscr{L}_7 + \ldots$$

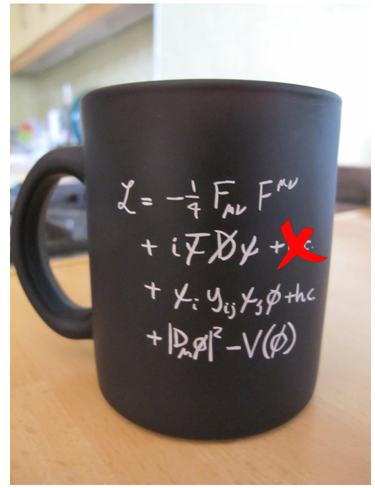
- There are no operators.

- PS: There's nothing fundamental about this.
  If one adds RH neutrinos, a D=3 term is possible (Majorana mass).

$$\mathscr{L}_M = -\frac{1}{2} m_M \bar{\nu}_R^c \nu_R + h.c.\,, \qquad \nu^c \equiv C\bar{\nu}^T$$

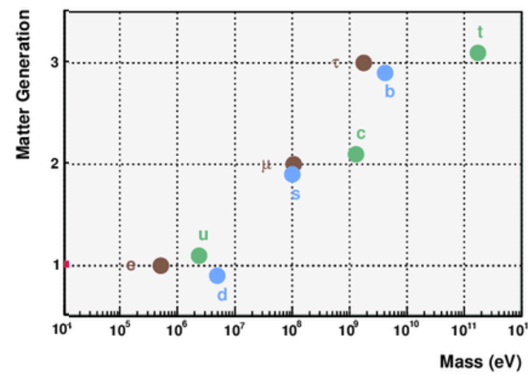
Building the SMEFT

$$\mathscr{L} = \mathscr{L}_2 + \mathscr{L}_3 + \mathscr{L}_4 + \mathscr{L}_5 + \mathscr{L}_6 + \mathscr{L}_7 + \dots$$



- At D=4 we find the rest of the SM
- D=4 is special because it doesn't contain an explicit scale.
  The EFT "predicts" a long list of interactions with coefficients ~O(1)
  - All* coefficients have been measured ✓
  - Interaction size OK in the bosonic sector (gauge and H^4) ✓
  - EFT predicts: $Y_f \sim \mathcal{O}(1) \ \rightarrow \ m_f \sim v, \quad V_{ij} \sim \mathcal{O}(1)$ ✗
    $\rightarrow$ Flavor puzzle
  - *All except the theta term ✗
    $\rightarrow$ Strong CP problem

$$\mathscr{L}_{SM} \supset -\tilde{\theta}\, G^{a\mu\nu} \tilde{G}^a_{\mu\nu}$$



Building the SMEFT

$$\mathscr{L} = \mathscr{L}_2 + \mathscr{L}_3 + \mathscr{L}_4 + \mathscr{L}_5 + \mathscr{L}_6 + \mathscr{L}_7 + \ldots$$

- Only one operator (Weinberg'79)

$$\mathscr{L}_5 = \frac{[c_5]_{pr}}{\Lambda} \left(\tilde{\varphi}^\dagger \ell_p\right)^T C \left(\tilde{\varphi}^\dagger \ell_r\right) + h.c.$$

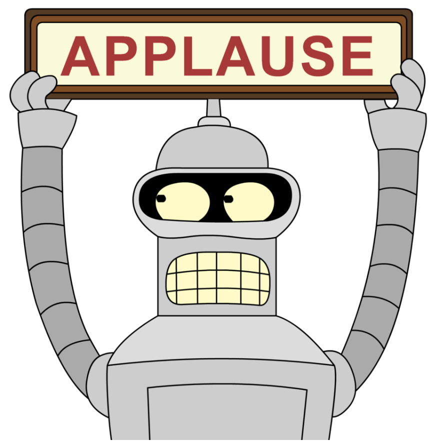
$$\tilde{\varphi} \equiv i\,\sigma_2\,\varphi = \begin{pmatrix} (\varphi^0)^* \\ -(\varphi^+)^* \end{pmatrix} \to \frac{1}{\sqrt{2}} \begin{pmatrix} v + H \\ 0 \end{pmatrix}$$

$$\ell \equiv \begin{pmatrix} \nu_L \\ e_L \end{pmatrix}$$

- After EWSB generates Majorana masses (for LH neutrinos):

$$\mathscr{L}_M = -\frac{1}{2} m_M \bar{\nu}_L^c \nu_L + h.c.\,, \qquad \nu^c \equiv C\bar{\nu}^T$$

- Perfect! (neutrino oscillations → neutrino masses)
  Great success of the SMEFT approach: corrections to the SM Lagrangian predicted at 1st order in the EFT expansion, are indeed observed in



Building the SMEFT

$$\mathcal{L}_5 = \frac{[c_5]_{pr}}{\Lambda}\left(\tilde{\varphi}^\dagger \ell_p\right)^T C\left(\tilde{\varphi}^\dagger \ell_r\right) + h.c. \;\rightarrow\; m_\nu \sim 2\,c_5\,v^2/\Lambda$$

- Oscillation data → Δm^2.
  Other experiments (KATRIN!) /observations → bounds on m.
  All in all, m ~ O(0.01) eV. Thus:

$$v^2/\Lambda \sim 0.1\text{ eV} \;\rightarrow\; \Lambda \sim 10^{15}\text{ GeV !!}$$

- The mass gap is certainly OK

- But then higher dimensional effects are then extremely suppressed
  (only hope: B-number violation)

$$\mathrm{D} = 6 \;\rightarrow\; v^2/\Lambda^2 \sim 10^{-26}\text{ !!}$$

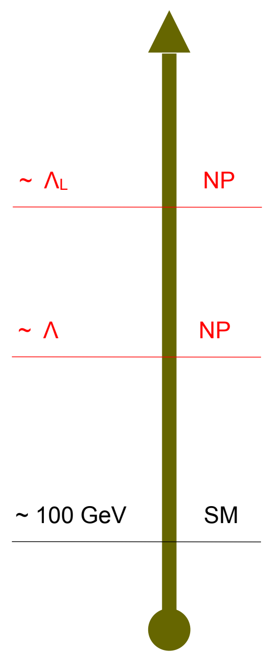
Building the SMEFT

$$\mathscr{L}_5 = \frac{[c_5]_{pr}}{\Lambda} \left(\tilde{\varphi}^\dagger \ell_p\right)^T C \left(\tilde{\varphi}^\dagger \ell_r\right) + h.c. \quad \rightarrow \quad m_\nu \sim 2\, c_5\, v^2/\Lambda$$

- Tiny neutrino masses point to huge NP scale: $\Lambda \sim 10^{15}$ GeV →

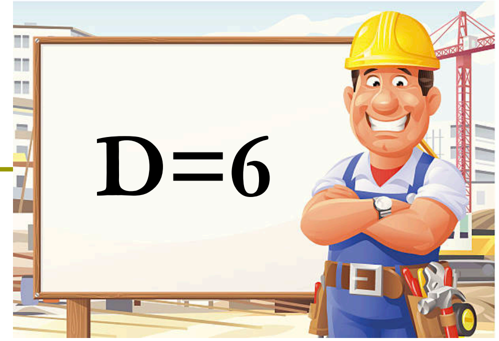
- Alternative:
  It's possible (and even natural) that there's more than one NP scale.
  This is not arbitrary since D=5 is "special": it violates B-L
  - A very high scale Λ_L associated to B-L violating physics (D=5, 7, …)
  - A (hopefully) not so high scale, Λ, associated to B-L conserving physics (D=6, 8, …)

$$\mathscr{L}_{D=5} \sim \frac{1}{\Lambda_L},\ \mathscr{L}_{D=6} \sim \frac{1}{\Lambda^2},\ \mathscr{L}_{D=7} \sim \frac{1}{\Lambda_L^3},\ \mathscr{L}_{D=8} \sim \frac{1}{\Lambda^4},\ \text{and so on}$$



- PS: Outside the SMEFT paradigm there are other explanations for m_ν
  E.g., SM + ν_R → one has D=3 Majorana & D=4 yukawas (→ Dirac mass).

Building the SMEFT



$$\mathscr{L} = \mathscr{L}_2 + \mathscr{L}_3 + \mathscr{L}_4 + \mathscr{L}_5 + \mathscr{L}_6 + \mathscr{L}_7 + \ldots$$

- First B-L conserving corrections to the SM.

- One finds 63 operators [Grzadkowski et al., 1008.4884]
  Flavor structure → 3045 coefficients

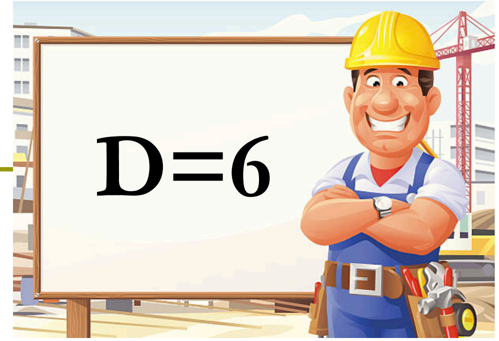
X^3		φ^6 and $\varphi^4 D^2$		$\psi^2\varphi^3$	
Q_G	$f^{ABC} G_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}$	Q_φ	$(\varphi^\dagger\varphi)^3$	$Q_{e\varphi}$	$(\varphi^\dagger\varphi)(\bar l_p e_r \varphi)$
$Q_{\widetilde G}$	$f^{ABC} \widetilde G_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}$	$Q_{\varphi\Box}$	$(\varphi^\dagger\varphi)\Box(\varphi^\dagger\varphi)$	$Q_{u\varphi}$	$(\varphi^\dagger\varphi)(\bar q_p u_r \widetilde\varphi)$
Q_W	$\varepsilon^{IJK} W_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$	$Q_{\varphi D}$	$\left(\varphi^\dagger D^\mu\varphi\right)^\star \left(\varphi^\dagger D_\mu\varphi\right)$	$Q_{d\varphi}$	$(\varphi^\dagger\varphi)(\bar q_p d_r \varphi)$
$Q_{\widetilde W}$	$\varepsilon^{IJK} \widetilde W_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$				
$X^2\varphi^2$		$\psi^2 X\varphi$		$\psi^2\varphi^2 D$	
$Q_{\varphi G}$	$\varphi^\dagger\varphi\, G_{\mu\nu}^A G^{A\mu\nu}$	Q_{eW}	$(\bar l_p \sigma^{\mu\nu} e_r)\tau^I \varphi W_{\mu\nu}^I$	$Q_{\varphi l}^{(1)}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar l_p \gamma^\mu l_r)$
$Q_{\varphi\widetilde G}$	$\varphi^\dagger\varphi\, \widetilde G_{\mu\nu}^A G^{A\mu\nu}$	Q_{eB}	$(\bar l_p \sigma^{\mu\nu} e_r)\varphi B_{\mu\nu}$	$Q_{\varphi l}^{(3)}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu^I \varphi)(\bar l_p \tau^I\gamma^\mu l_r)$
$Q_{\varphi W}$	$\varphi^\dagger\varphi\, W_{\mu\nu}^I W^{I\mu\nu}$	Q_{uG}	$(\bar q_p \sigma^{\mu\nu} T^A u_r)\widetilde\varphi\, G_{\mu\nu}^A$	$Q_{\varphi e}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar e_p \gamma^\mu e_r)$
$Q_{\varphi\widetilde W}$	$\varphi^\dagger\varphi\, \widetilde W_{\mu\nu}^I W^{I\mu\nu}$	Q_{uW}	$(\bar q_p \sigma^{\mu\nu} u_r)\tau^I \widetilde\varphi\, W_{\mu\nu}^I$	$Q_{\varphi q}^{(1)}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar q_p \gamma^\mu q_r)$
$Q_{\varphi B}$	$\varphi^\dagger\varphi\, B_{\mu\nu} B^{\mu\nu}$	Q_{uB}	$(\bar q_p \sigma^{\mu\nu} u_r)\widetilde\varphi\, B_{\mu\nu}$	$Q_{\varphi q}^{(3)}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu^I \varphi)(\bar q_p \tau^I\gamma^\mu q_r)$
$Q_{\varphi\widetilde B}$	$\varphi^\dagger\varphi\, \widetilde B_{\mu\nu} B^{\mu\nu}$	Q_{dG}	$(\bar q_p \sigma^{\mu\nu} T^A d_r)\varphi\, G_{\mu\nu}^A$	$Q_{\varphi u}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar u_p \gamma^\mu u_r)$
$Q_{\varphi WB}$	$\varphi^\dagger\tau^I\varphi\, W_{\mu\nu}^I B^{\mu\nu}$	Q_{dW}	$(\bar q_p \sigma^{\mu\nu} d_r)\tau^I \varphi\, W_{\mu\nu}^I$	$Q_{\varphi d}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar d_p \gamma^\mu d_r)$
$Q_{\varphi\widetilde WB}$	$\varphi^\dagger\tau^I\varphi\, \widetilde W_{\mu\nu}^I B^{\mu\nu}$	Q_{dB}	$(\bar q_p \sigma^{\mu\nu} d_r)\varphi\, B_{\mu\nu}$	$Q_{\varphi ud}$	$i(\widetilde\varphi^\dagger D_\mu\varphi)(\bar u_p \gamma^\mu d_r)$

Table 2: Dimension-six operators other than the four-fermion ones.

$(\bar LL)(\bar LL)$		$(\bar RR)(\bar RR)$		$(\bar LL)(\bar RR)$	
Q_{ll}	$(\bar l_p\gamma_\mu l_r)(\bar l_s\gamma^\mu l_t)$	Q_{ee}	$(\bar e_p\gamma_\mu e_r)(\bar e_s\gamma^\mu e_t)$	Q_{le}	$(\bar l_p\gamma_\mu l_r)(\bar e_s\gamma^\mu e_t)$
$Q_{qq}^{(1)}$	$(\bar q_p\gamma_\mu q_r)(\bar q_s\gamma^\mu q_t)$	Q_{uu}	$(\bar u_p\gamma_\mu u_r)(\bar u_s\gamma^\mu u_t)$	Q_{lu}	$(\bar l_p\gamma_\mu l_r)(\bar u_s\gamma^\mu u_t)$
$Q_{qq}^{(3)}$	$(\bar q_p\gamma_\mu\tau^I q_r)(\bar q_s\gamma^\mu\tau^I q_t)$	Q_{dd}	$(\bar d_p\gamma_\mu d_r)(\bar d_s\gamma^\mu d_t)$	Q_{ld}	$(\bar l_p\gamma_\mu l_r)(\bar d_s\gamma^\mu d_t)$
$Q_{lq}^{(1)}$	$(\bar l_p\gamma_\mu l_r)(\bar q_s\gamma^\mu q_t)$	Q_{eu}	$(\bar e_p\gamma_\mu e_r)(\bar u_s\gamma^\mu u_t)$	Q_{qe}	$(\bar q_p\gamma_\mu q_r)(\bar e_s\gamma^\mu e_t)$
$Q_{lq}^{(3)}$	$(\bar l_p\gamma_\mu\tau^I l_r)(\bar q_s\gamma^\mu\tau^I q_t)$	Q_{ed}	$(\bar e_p\gamma_\mu e_r)(\bar d_s\gamma^\mu d_t)$	$Q_{qu}^{(1)}$	$(\bar q_p\gamma_\mu q_r)(\bar u_s\gamma^\mu u_t)$
		$Q_{ud}^{(1)}$	$(\bar u_p\gamma_\mu u_r)(\bar d_s\gamma^\mu d_t)$	$Q_{qu}^{(8)}$	$(\bar q_p\gamma_\mu T^A q_r)(\bar u_s\gamma^\mu T^A u_t)$
		$Q_{ud}^{(8)}$	$(\bar u_p\gamma_\mu T^A u_r)(\bar d_s\gamma^\mu T^A d_t)$	$Q_{qd}^{(1)}$	$(\bar q_p\gamma_\mu q_r)(\bar d_s\gamma^\mu d_t)$
				$Q_{qd}^{(8)}$	$(\bar q_p\gamma_\mu T^A q_r)(\bar d_s\gamma^\mu T^A d_t)$
$(\bar LR)(\bar RL)$ and $(\bar LR)(\bar LR)$		B-violating			
Q_{ledq}	$(\bar l_p^j e_r)(\bar d_s q_t^j)$	Q_{duq}	$\varepsilon^{\alpha\beta\gamma}\varepsilon_{jk}\left[(d_p^\alpha)^T C u_r^\beta\right]\left[(q_s^{\gamma j})^T C l_t^k\right]$		
$Q_{quqd}^{(1)}$	$(\bar q_p^j u_r)\varepsilon_{jk}(\bar q_s^k d_t)$	Q_{qqu}	$\varepsilon^{\alpha\beta\gamma}\varepsilon_{jk}\left[(q_p^{\alpha j})^T C q_r^{\beta k}\right]\left[(u_s^\gamma)^T C e_t\right]$		
$Q_{quqd}^{(8)}$	$(\bar q_p^j T^A u_r)\varepsilon_{jk}(\bar q_s^k T^A d_t)$	Q_{qqq}	$\varepsilon^{\alpha\beta\gamma}\varepsilon_{jn}\varepsilon_{km}\left[(q_p^{\alpha j})^T C q_r^{\beta k}\right]\left[(q_s^{\gamma m})^T C l_t^n\right]$		
$Q_{lequ}^{(1)}$	$(\bar l_p^j e_r)\varepsilon_{jk}(\bar q_s^k u_t)$	Q_{duu}	$\varepsilon^{\alpha\beta\gamma}\left[(d_p^\alpha)^T C u_r^\beta\right]\left[(u_s^\gamma)^T C e_t\right]$		
$Q_{lequ}^{(3)}$	$(\bar l_p^j \sigma_{\mu\nu} e_r)\varepsilon_{jk}(\bar q_s^k \sigma^{\mu\nu} u_t)$				

Table 3: Four-fermion operators.

Building the SMEFT

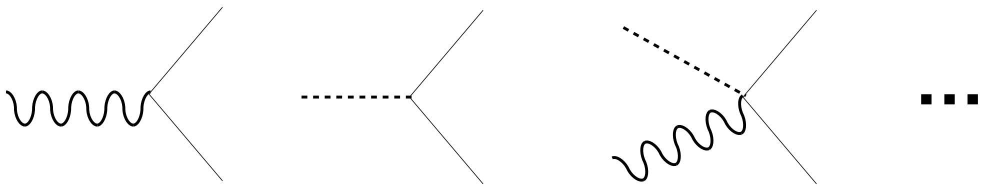


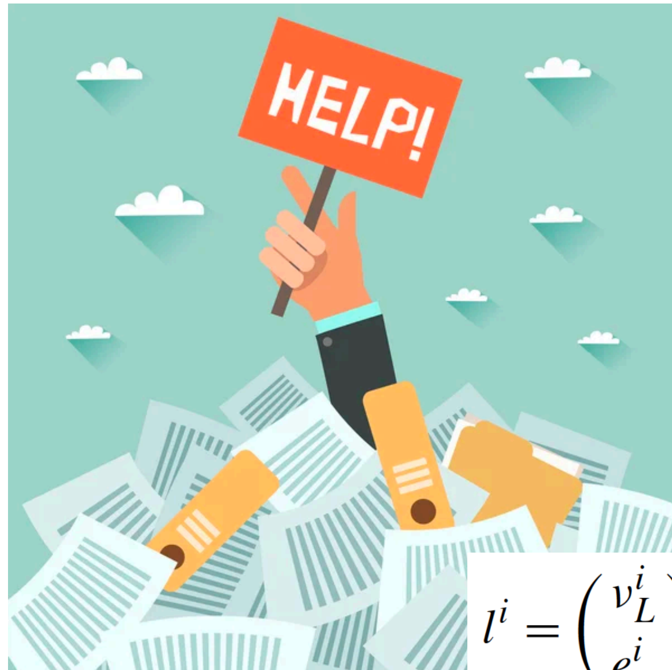
$$\mathscr{L} = \mathscr{L}_2 + \mathscr{L}_3 + \mathscr{L}_4 + \mathscr{L}_5 + \mathscr{L}_6 + \mathscr{L}_7 + \ldots$$

- First B-L conserving corrections to the SM.

- One finds 63 operators [Grzadkowski et al., 1008.4884]
  Flavor structure → 3045 coefficients

$$(\varphi^\dagger i D_\mu \varphi)(l_p \gamma^\mu l_r)$$



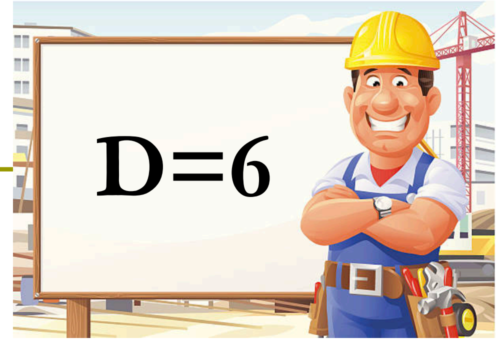


$$l^i = \begin{pmatrix} \nu_L^i \\ e_L^i \end{pmatrix}$$

$$\varphi = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v + h(x) \end{pmatrix}$$

$$D_\mu = I \partial_\mu - i g_s \frac{\lambda^A}{2} G_\mu^A - i g \frac{\sigma^a}{2} W_\mu^a - i g' Y B_\mu$$

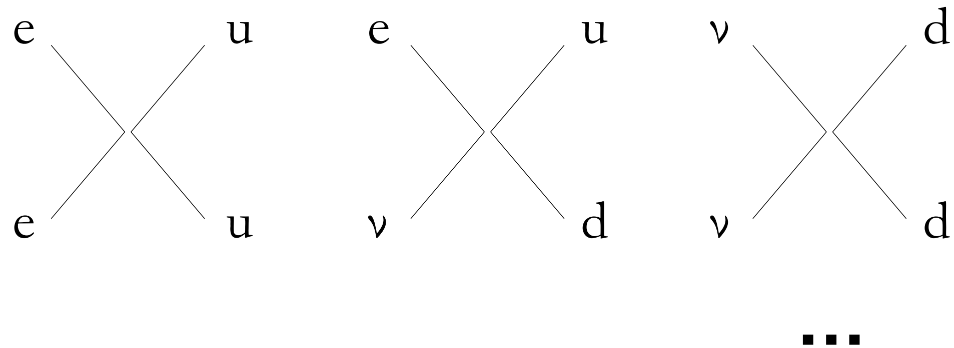
Building the SMEFT

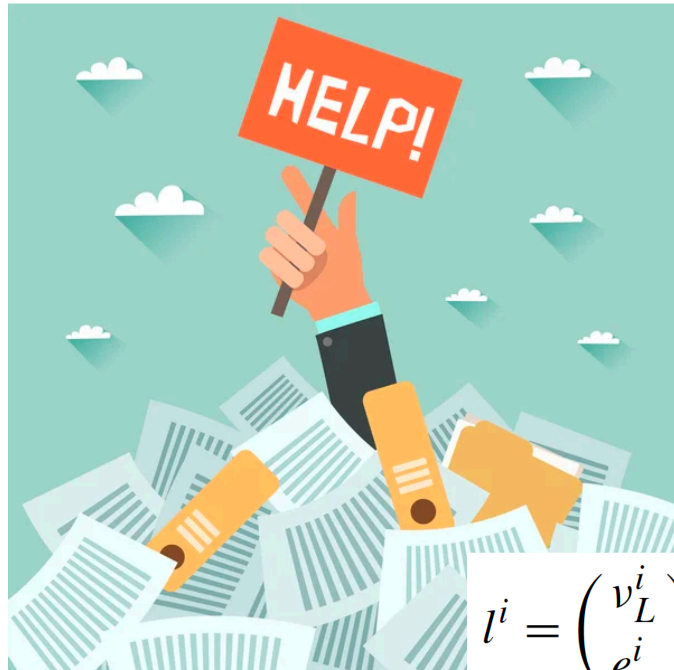


$$\mathscr{L} = \mathscr{L}_2 + \mathscr{L}_3 + \mathscr{L}_4 + \mathscr{L}_5 + \mathscr{L}_6 + \mathscr{L}_7 + \ldots$$

- First B-L conserving corrections to the SM.
- One finds 63 operators [Grzadkowski et al., 1008.4884]
  Flavor structure → 3045 coefficients

$$(\bar{l}_p \gamma_\mu \tau^I l_r)(\bar{q}_s \gamma^\mu \tau^I q_t)$$





$$l^i = \begin{pmatrix} \nu_L^i \\ e_L^i \end{pmatrix}$$

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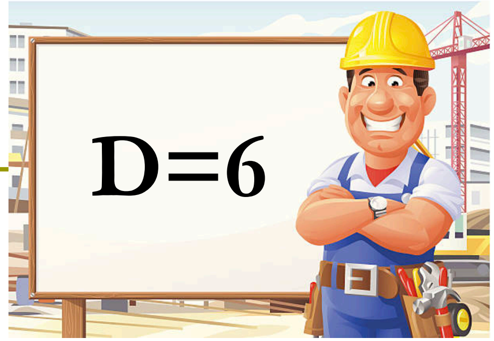
$$D_\mu = I\partial_\mu - i g_s \frac{\lambda^A}{2} G_\mu^A - i g \frac{\sigma^a}{2} W_\mu^a - i g' Y B_\mu$$

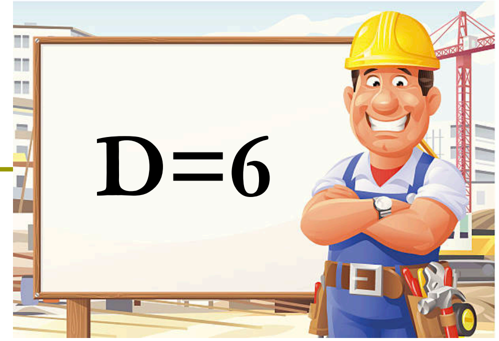
Building the SMEFT



$$\mathscr{L} = \mathscr{L}_2 + \mathscr{L}_3 + \mathscr{L}_4 + \mathscr{L}_5 + \mathscr{L}_6 + \mathscr{L}_7 + \dots$$

- First B-L conserving corrections to the SM.
- One finds 63 operators [Grzadkowski et al., 1008.4884]
  Flavor structure → 3045 coefficients
- Extremely rich phenomenology:
  colliders,
  flavor,
  low-energy searches (beta decay!),
  neutrino physics,
  proton decay,
  CP violation (EDMs!),
  …
- All results compatible with zero → Bounds on Λ

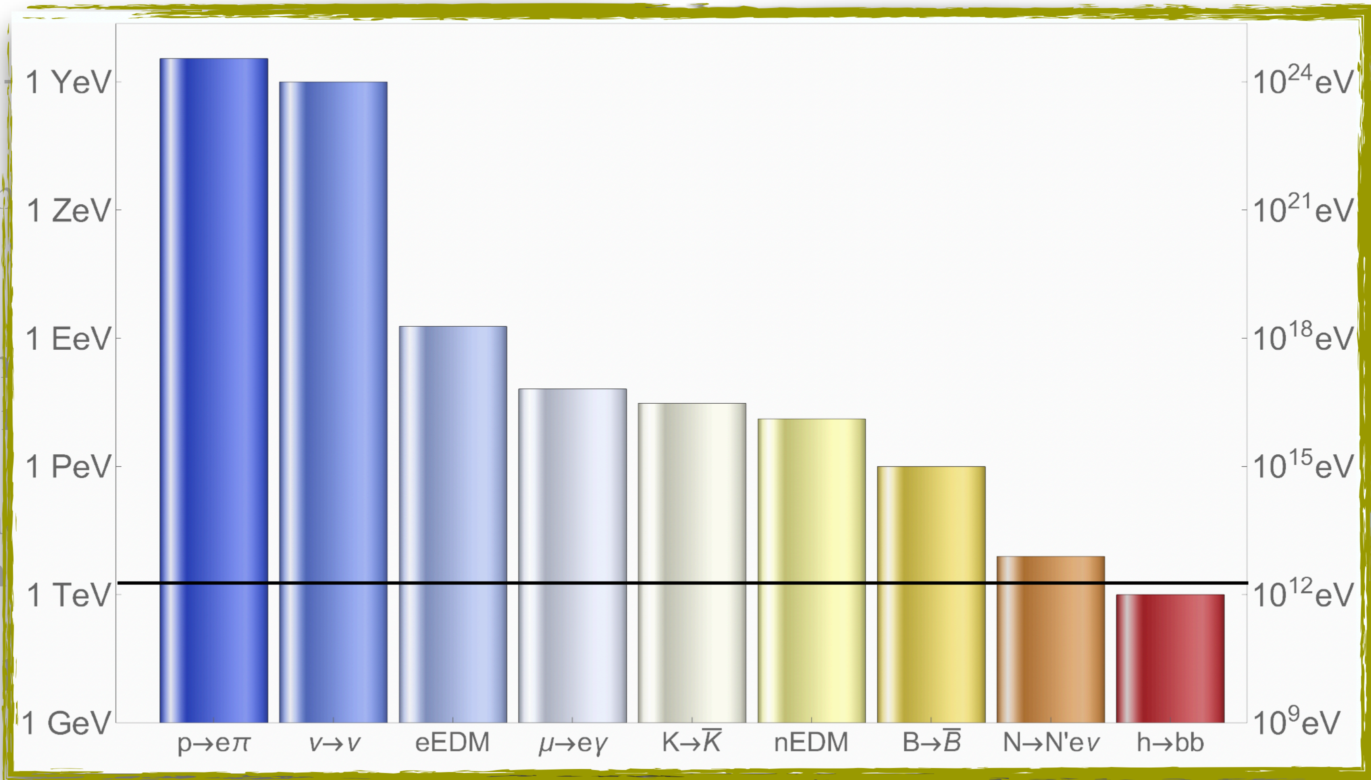
Building the SMEFT



$$\mathscr{L} = \mathscr{L}_2 + \mathscr{L}_3 + \mathscr{L}_4 + \mathscr{L}_5 + \mathscr{L}_6 + \mathscr{L}_7 + \ldots$$

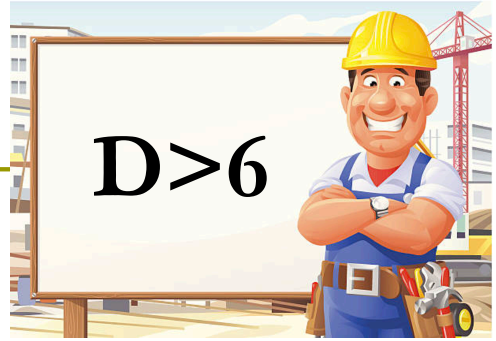
[A. Falkowski, Eur.Phys.J.C 83 (2023) 7, 656]

- First B
- One fi Flavor
- Extrem collide flavor, low-en neutrin proton CP vio …



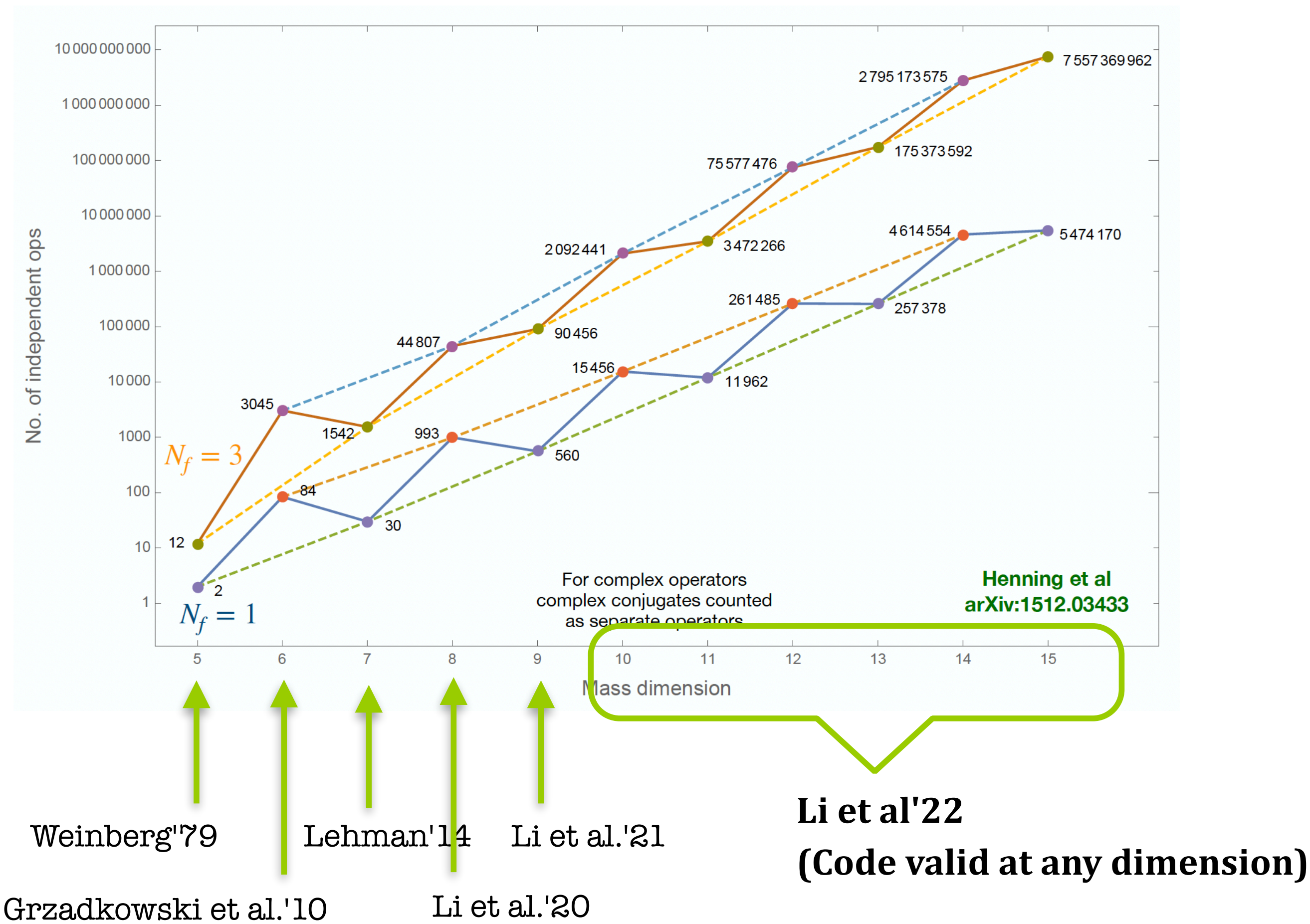
- All results compatible with zero → Bounds on Λ

Building the SMEFT



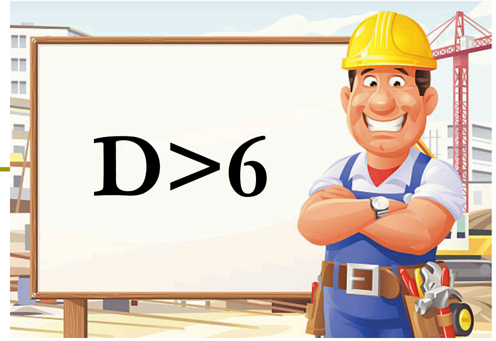
$$\mathscr{L} = \mathscr{L}_2 + \mathscr{L}_3 + \mathscr{L}_4 + \mathscr{L}_5 + \mathscr{L}_6 + \mathscr{L}_7 + \ldots$$

- At dim-6 is where all the fun starts, but it's also where it ends



Exponential growth with D

Building the SMEFT



$$\mathscr{L} = \mathscr{L}_2 + \mathscr{L}_3 + \mathscr{L}_4 + \mathscr{L}_5 + \mathscr{L}_6 + \mathscr{L}_7 + \ldots$$

- At dim-6 is where all the fun starts, but it's also where it ends
  - Really too many operators
  - For D=7, 9, … the effect is expected to be tiny
  - For D=8, 10, … not easy to imagine situations where terms that are so suppressed (if the EFT works) give measurable effects in observable X whereas all D=6 terms do not give measurable effects in so many other observables.

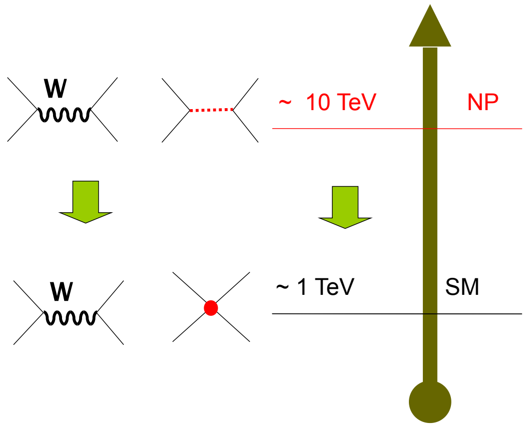
- A few processes receive their first tree-level correction at D>6:
  light-by-light scattering (dim-8), neutron-antineutron oscillation (dim-9), …
  Depending on the mass gap, they could compete with loop effects from lower-dimension operators.

- It's crucial to keep in mind that these operators exist.
  E.g. (dim-6)^2 vs dim-8 contributions (validity of the EFT expansion)

Building the SMEFT

$$\mathscr{L} = \mathscr{L}_{SM} + \text{Majorana neutrino masses} + \sum c_6^i \mathcal{O}_6^i + \ldots$$

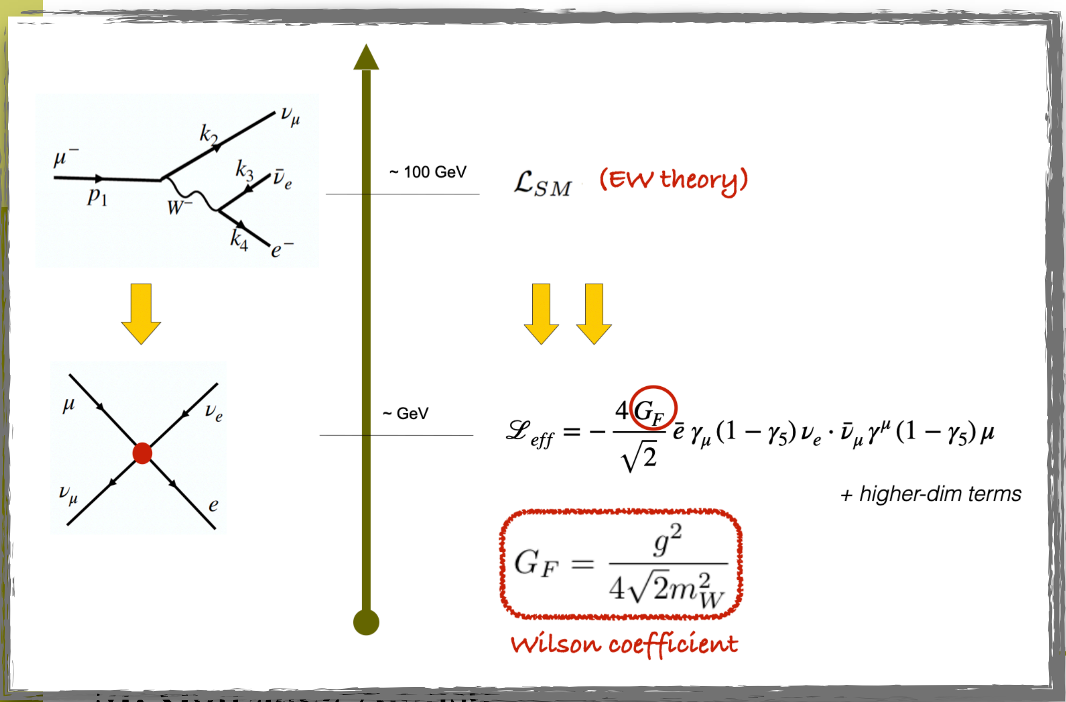
Matching to NP models



$$\mathscr{L}_{multi-TeV} = \mathscr{L}\left(\phi_{SM}, \Phi_{BSM}\right)$$

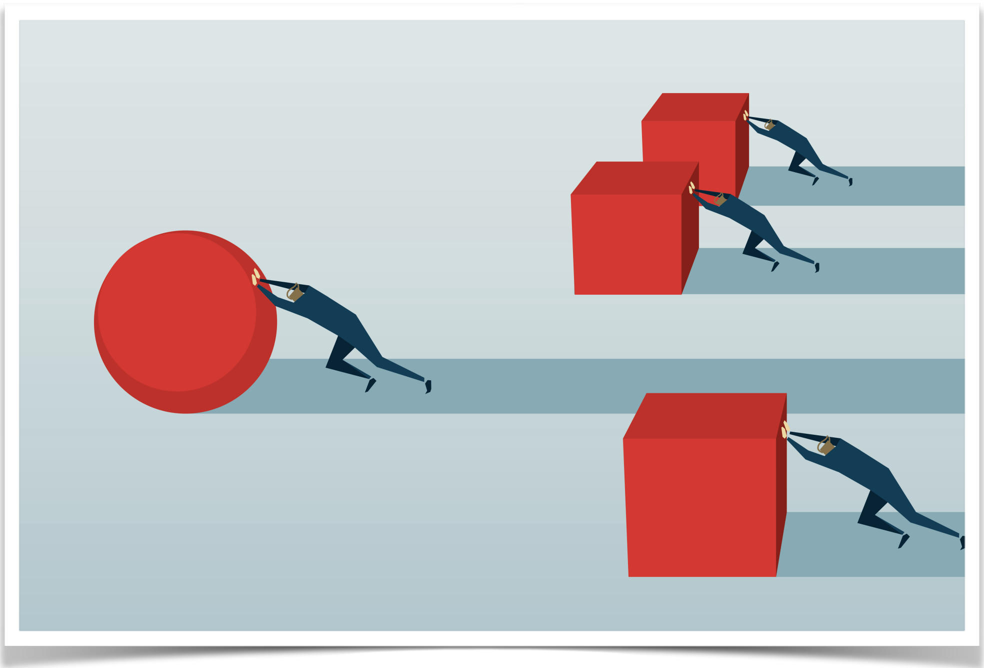
$$\mathscr{L}_{SMEFT} = \mathscr{L}_{SM} + \sum C_6^i \mathcal{O}_6^i + \ldots$$

$$C_6^i = f\left(g_{NP}, M_{NP}\right)$$

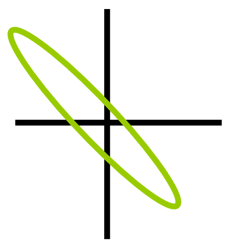


SMEFT: an efficient approach

Data → **(Correlated) bounds on the EFT Wilson Coefficients** → **Matching with a specific NP model** → $\frac{\alpha_6^{(i)}}{\Lambda^2} = f_i\left(g_{NP}, M_{NP}\right)$



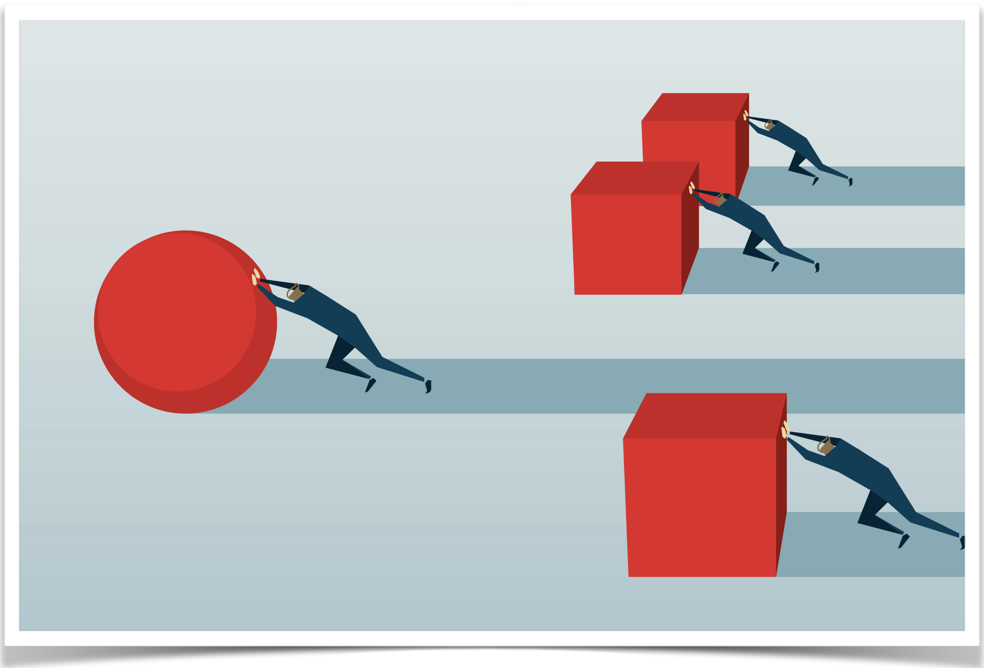
- Analysis (bkg, PDFs, FF, simulations, …) done once and for all!
- Useful especially if…
  - Global analysis
  - Final likelihood public (correlation matrix!)
  - Avoid additional assumptions



- Valid also if NP is found!

SMEFT: an efficient approach

Data → (Correlated) bounds on the EFT Wilson Coefficients → Matching with a specific NP model → $\frac{\alpha_6^{(i)}}{\Lambda^2} = f_i\left(g_{NP}, M_{NP}\right)$



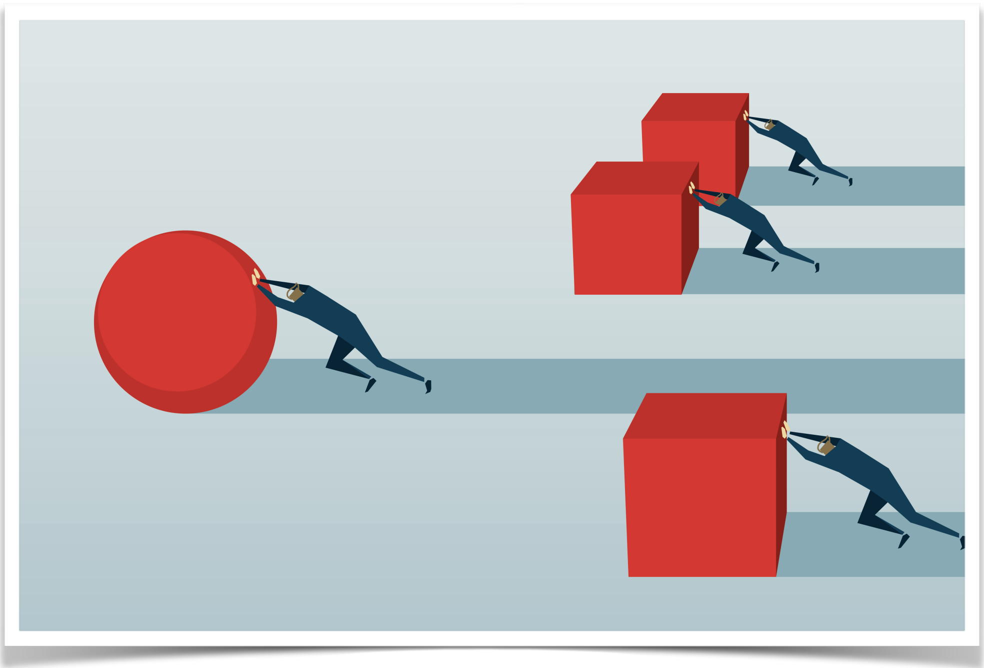
The EFT setup allows us to…

- obtain results that can be applied to any given model later;
- assess the interplay between processes (related by symmetries) in a general setup;
- Turn every stone

$$\frac{d\Gamma}{dq^2} = \frac{d\Gamma_{SM}}{dq^2} + f(\alpha_4; q^2)$$

SMEFT: an efficient approach

Data → (Correlated) bounds on the EFT Wilson Coefficients → Matching with a specific NP model → $\frac{\alpha_6^{(i)}}{\Lambda^2} = f_i\left(g_{NP}, M_{NP}\right)$



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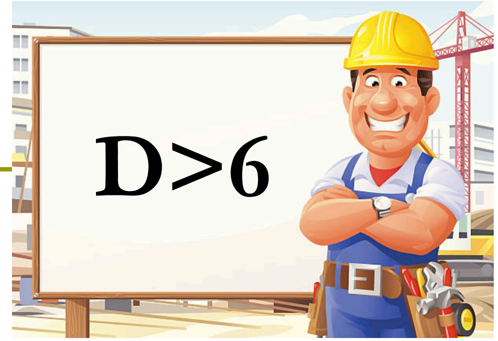
$$\frac{d\Gamma}{dq^2} = \frac{d\Gamma_{SM}}{dq^2} + f(\alpha_4; q^2)$$

Linear vs. Quadratic



$$\mathscr{L} = \mathscr{L}_2 + \mathscr{L}_3 + \mathscr{L}_4 + \mathscr{L}_5 + \mathscr{L}_6 + \mathscr{L}_7 + \ldots$$

- It's crucial to keep in mind that these operators exist.
  E.g. (dim-6)^2 vs dim-8 contributions (validity of the EFT expansion)

- Let's think in a low-E process (E<<v):

$$\mathscr{M} = \mathscr{M}_{SM}\left(1 \;+\; c_6\,\mathscr{O}\left(\frac{v^2}{\Lambda^2}\right) \;+\; c_8\,\mathscr{O}\left(\frac{v^4}{\Lambda^4}\right) \;+\; \ldots\right)$$

$$\mathscr{R} \sim |\mathscr{M}|^2 = |\mathscr{M}_{SM}|^2\left(1 \;+\; c_6\,\mathscr{O}\left(\frac{v^2}{\Lambda^2}\right) \;+\; c_6^2\,\mathscr{O}\left(\frac{v^4}{\Lambda^4}\right) \;+\; c_8\,\mathscr{O}\left(\frac{v^4}{\Lambda^4}\right) \;+\; \ldots\right)$$

- One should *not* include quadratic terms
  (equivalently: results should not depend strongly on quadratic terms)

- The reasoning is the same for E~v or higher energies.

SMEFT: a global effort

- Experiment!
- SM calculation:
  - Perturbative calculations
  - Non-perturbative input (PDFs, form factors -lattice!-)
- EFT analysis:
  - Conceptual issues (basis, EFT @ LHC?, ...)
  - RGEs
  - Fitting
  - New non-perturbative input
- Matching
- Model building

Correlating measurements (or how to play the EFT game)

- Choose an operator basis $\{O_1, O_2, \ldots, O_n\}$, *e.g. the Warsaw basis*
  $\mathcal{L}_{\text{eff}} = \mathcal{L}_{\text{SM}} + \Sigma\, C_i\, O_i$

- Calculate the observable you like in the EFT, *e.g.* $O = O_{SM} + 3C_1 - C_6$

- What are the known limits on the Wilson coefficients?
  e.g. from LEP… $C_1 = 0.001(3)$, *C_2 unkown, …*
  More precisely: χ^2 with (*LEP*) measurements gives you central values and error matrix.

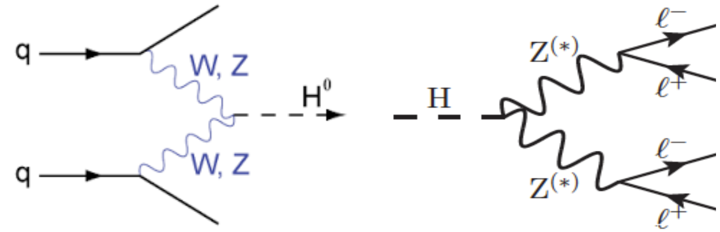
- Implications for your observable?
  e.g. error matrix $\rightarrow 3C_1 - C_6 = 0.02(4)$
  - ~ 4% sensitivity (th+exp) to be competitive (or to check a LEP anomaly);
  - If your sensitivity is better than that, you are exploring new SMEFT territory and your measurement should be added to the big fit.
  - A deviation larger than that indicates some wrong assumptions in your EFT!

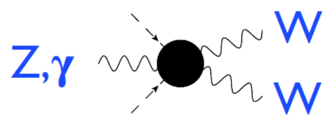
- Often we have a dataset (instead of a single data point O). The same logic applies, but it's often better to look at the (C_1 , C_6) space → example.

Example: LEP2 WW vs Higgs

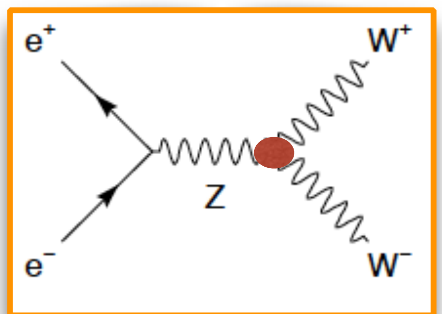
- EFT (symmetry) connects these processes. See e.g.

$$(D^{\mu}H)^{\dagger}(D^{\nu}H)B_{\mu\nu}$$

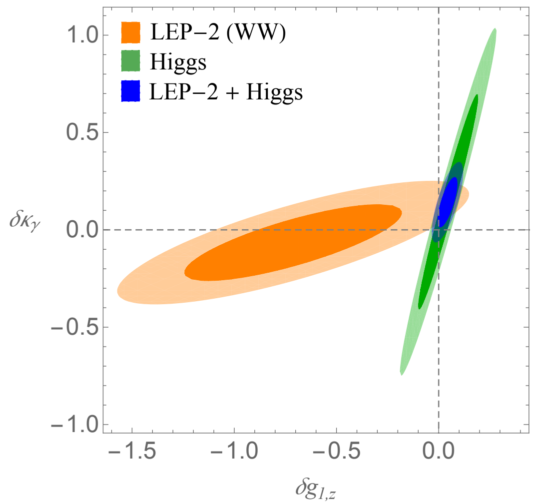




$e^+e^- \rightarrow W^+W^-$ (LEP2)



(Taking into account LEP1),
LEP2 probes 3 directions of the EFT space:
Triple Gauge Couplings… TGC = f (WC)



Can Higgs data cover this region?

YES!

[Falkowski, MGA, Greljo & Marzocca, 2015]

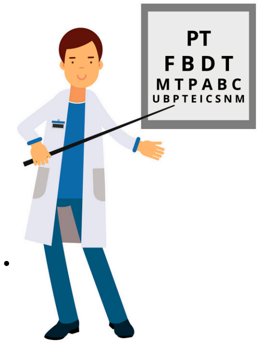
[Higgs signal strengths]

SMEFT fit to EWPO

[Breso-Pla, Falkowski, MGA, Monsálvez-Pozo, 2301.07036 JHEP]

Update of [Falkowski, MGA & Mimouni, 1706.03783 JHEP]

- General (flavorful) SMEFT
- Global fit to Electroweak precision observables:
  - Z- & W-pole data
  - $e^+e^- \to l^+l^-$, qq
  - Low-energy processes: Atomic PV, $d \to ul\nu$, tau decays, ν scattering, …
- 65 (combinations of) Wilson Coefficients (<<< datapoints !)

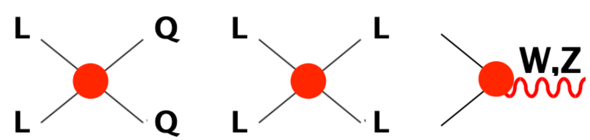


Observable	Experimental value	Ref.	SM prediction	Definition
Γ_Z [GeV]	2.4952 ± 0.0023	[47]	2.4950	$\sum_f \Gamma(Z \to f f)$
$\sigma_{\rm had}$ [nb]	41.541 ± 0.037	[47]	41.484	$\frac{12\pi}{m_Z^2}\frac{\Gamma(Z\to e^+e^-)\Gamma(Z\to q\bar{q})}{\Gamma_Z^2}$
R_e	20.804 ± 0.050	[47]	20.743	$\frac{\sum_q \Gamma(Z\to q\bar{q})}{\Gamma(Z\to e^+e^-)}$
R_μ	20.785 ± 0.033	[47]	20.743	$\frac{\sum_q \Gamma(Z\to q\bar{q})}{\Gamma(Z\to \mu^+\mu^-)}$
R_τ	20.764 ± 0.045	[47]	20.743	$\frac{\sum_q \Gamma(Z\to q\bar{q})}{\Gamma(Z\to \tau^+\tau^-)}$
$A_{\rm FB}^{0,e}$	0.0145 ± 0.0025	[47]	0.0163	$\frac{3}{4}A_e^2$
$A_{\rm FB}^{0,\mu}$	0.0169 ± 0.0013	[47]	0.0163	$\frac{3}{4}A_e A_\mu$
$A_{\rm FB}^{0,\tau}$	0.0188 ± 0.0017	[47]	0.0163	$\frac{3}{4}A_e A_\tau$
R_b	0.21629 ± 0.00066	[47]	0.21578	$\frac{\Gamma(Z\to b\bar{b})}{\sum_q \Gamma(Z\to q\bar{q})}$
R_c	0.1721 ± 0.0030	[47]	0.17226	$\frac{\Gamma(Z\to c\bar{c})}{\sum_q \Gamma(Z\to q\bar{q})}$
$A_b^{\rm FB}$	0.0992 ± 0.0016	[47]	0.1032	$\frac{3}{4}A_e A_b$
$A_c^{\rm FB}$	0.0707 ± 0.0035	[47]	0.0738	$\frac{3}{4}A_e A_c$
A_e	0.1516 ± 0.0021	[47]	0.1472	$\frac{\Gamma(Z\to e_L^+e_L^-)-\Gamma(Z\to e_R^+e_R^-)}{\Gamma(Z\to e^+e^-)}$
A_μ	0.142 ± 0.015	[47]	0.1472	$\frac{\Gamma(Z\to \mu_L^+\mu_L^-)-\Gamma(Z\to \mu_R^+\mu_R^-)}{\Gamma(Z\to \mu^+\mu^-)}$
A_τ	0.136 ± 0.015	[47]	0.1472	$\frac{\Gamma(Z\to \tau_L^+\tau_L^-)-\Gamma(Z\to \tau_R^+\tau_R^-)}{\Gamma(Z\to \tau^+\tau^-)}$
A_e	0.1498 ± 0.0049	[47]	0.1472	$\frac{\Gamma(Z\to e_L^+e_L^-)-\Gamma(Z\to e_R^+e_R^-)}{\Gamma(Z\to \tau^+\tau^-)}$
A_τ	0.1439 ± 0.0043	[47]	0.1472	$\frac{\Gamma(Z\to \tau_L^+\tau_L^-)-\Gamma(Z\to \tau_R^+\tau_R^-)}{\Gamma(Z\to \tau^+\tau^-)}$
A_b	0.923 ± 0.020	[47]	0.935	$\frac{\Gamma(Z\to b_L b_L)-\Gamma(Z\to b_R b_R)}{\Gamma(Z\to b\bar{b})}$
A_c	0.670 ± 0.027	[47]	0.668	$\frac{\Gamma(Z\to c_L\bar{c}_L)-\Gamma(Z\to c_R\bar{c}_R)}{\Gamma(Z\to c\bar{c})}$
A_s	0.895 ± 0.091	[48]	0.935	$\frac{\Gamma(Z\to s_L\bar{s}_L)-\Gamma(Z\to s_R\bar{s}_R)}{\Gamma(Z\to s\bar{s})}$
R_{uc}	0.166 ± 0.009	[45]	0.1724	$\frac{\Gamma(Z\to u\bar{u})+\Gamma(Z\to c\bar{c})}{2\sum_q \Gamma(Z\to q\bar{q})}$

Observable	Experimental value	Ref.	SM prediction	Definition
m_W [GeV]	80.385 ± 0.015	[50]	80.364	$\frac{g_L v}{2}(1+\delta m)$
Γ_W [GeV]	2.085 ± 0.042	[45]	2.091	$\sum_f \Gamma(W \to f f')$
$\mathrm{Br}(W \to e\nu)$	0.1071 ± 0.0016	[51]	0.1083	$\frac{\Gamma(W\to e\nu)}{\sum_f \Gamma(W\to f f')}$
$\mathrm{Br}(W \to \mu\nu)$	0.1063 ± 0.0015	[51]	0.1083	$\frac{\Gamma(W\to \mu\nu)}{\sum_f \Gamma(W\to f f')}$
$\mathrm{Br}(W \to \tau\nu)$	0.1138 ± 0.0021	[51]	0.1083	$\frac{\Gamma(W\to \tau\nu)}{\sum_f \Gamma(W\to f f')}$
R_{Wc}	0.49 ± 0.04	[45]	0.50	$\frac{\Gamma(W\to cs)}{\Gamma(W\to ud)+\Gamma(W\to cs)}$
R_σ	0.998 ± 0.041	[52]	1.000	$g_L^{Wq_3}/g_{L,\rm SM}^{Wq_3}$

Quantity	$\sqrt{s}$ (GeV)	Average value	SM	$\sqrt{s}$ (GeV)	Average value	SM
$\sigma(q\overline{q})$	130	82.445±2.197±0.766	83.090	192	22.064±0.507±0.107	21.259
$\sigma(\mu^+\mu^-)$	130	8.606±0.699±0.131	8.455	192	2.926±0.181±0.018	3.096
$\sigma(\tau^+\tau^-)$	130	9.020±0.944±0.175	8.452	192	2.860±0.246±0.032	3.096
$A_{\rm fb}(\mu^+\mu^-)$	130	0.694±0.059±0.012	0.705	192	0.551±0.051±0.007	0.566
$A_{\rm fb}(\tau^+\tau^-)$	130	0.682±0.079±0.016	0.705	192	0.590±0.067±0.008	0.565
$\sigma(q\overline{q})$	136	66.984±1.954±0.630	66.787	196	20.307±0.294±0.096	20.148
$\sigma(\mu^+\mu^-)$	136	8.325±0.692±0.109	7.292	196	2.994±0.110±0.018	2.961
$\sigma(\tau^+\tau^-)$	136	7.167±0.851±0.143	7.290	196	2.961±0.152±0.029	2.961
$A_{\rm fb}(\mu^+\mu^-)$	136	0.707±0.061±0.011	0.684	196	0.592±0.030±0.005	0.562
$A_{\rm fb}(\tau^+\tau^-)$	136	0.761±0.089±0.013	0.684	196	0.464±0.044±0.008	0.561
$\sigma(q\overline{q})$	161	37.166±1.063±0.398	35.234	200	19.170±0.283±0.095	19.105
$\sigma(\mu^+\mu^-)$	161	4.580±0.376±0.062	4.610	200	3.072±0.108±0.018	2.833
$\sigma(\tau^+\tau^-)$	161	5.715±0.553±0.139	4.610	200	2.952±0.148±0.029	2.832
$A_{\rm fb}(\mu^+\mu^-)$	161	0.542±0.069±0.012	0.610	200	0.519±0.031±0.005	0.558
$A_{\rm fb}(\tau^+\tau^-)$	161	0.764±0.061±0.013	0.610	200	0.539±0.041±0.007	0.558
$\sigma(q\overline{q})$	172	29.350±0.989±0.336	28.775	202	18.873±0.408±0.098	18.569
$\sigma(\mu^+\mu^-)$	172	3.562±0.331±0.058	3.950	202	2.709±0.146±0.017	2.766
$\sigma(\tau^+\tau^-)$	172	4.053±0.469±0.092	3.950	202	2.838±0.208±0.022	2.765
$A_{\rm fb}(\mu^+\mu^-)$	172	0.673±0.077±0.012	0.591	202	0.547±0.045±0.005	0.556
$A_{\rm fb}(\tau^+\tau^-)$	172	0.357±0.098±0.013	0.591	202	0.535±0.058±0.009	0.556
$\sigma(q\overline{q})$	183	24.599±0.393±0.182	24.215	205	18.137±0.282±0.087	17.832
$\sigma(\mu^+\mu^-)$	183	3.505±0.145±0.042	3.444	205	2.464±0.098±0.015	2.673
$\sigma(\tau^+\tau^-)$	183	3.367±0.174±0.049	3.444	205	2.783±0.149±0.028	2.672
$A_{\rm fb}(\mu^+\mu^-)$	183	0.564±0.034±0.008	0.576	205	0.556±0.034±0.004	0.553
$A_{\rm fb}(\tau^+\tau^-)$	183	0.604±0.044±0.011	0.576	205	0.618±0.040±0.008	0.553
$\sigma(q\overline{q})$	189	22.492±0.206±0.119	22.184	207	17.316±0.212±0.083	17.482
$\sigma(\mu^+\mu^-)$	189	3.150±0.075±0.016	3.207	207	2.618±0.078±0.014	2.628
$\sigma(\tau^+\tau^-)$	189	3.204±0.107±0.032	3.206	207	2.502±0.109±0.029	2.628
$A_{\rm fb}(\mu^+\mu^-)$	189	0.571±0.020±0.005	0.569	207	0.535±0.028±0.004	0.552
$A_{\rm fb}(\tau^+\tau^-)$	189	0.590±0.026±0.007	0.569	207	0.590±0.034±0.010	0.552

$O = O_{SM} + O(c_1, c_2, \ldots, c_{65}) \to$ Correlated bounds on c_i



[Breso-Pla, Falkowski, MGA, Monsálvez-Pozo, 2301.07036 JHEP]

SMEFT fit to EWPO

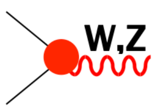
Update of [Falkowski, MGA & Mimouni, 1706.03783 JHEP']

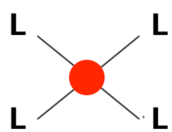
$$
\begin{pmatrix}
[\delta g_L^{Wl}]_{ee} \\ [\delta g_L^{Wl}]_{\mu\mu} \\ [\delta g_L^{Wl}]_{\tau\tau} \\ [\delta g_L^{Ze}]_{ee} \\ [\delta g_R^{Ze}]_{ee} \\ [\delta g_L^{Ze}]_{\mu\mu} \\ [\delta g_R^{Ze}]_{\mu\mu} \\ [\delta g_L^{Ze}]_{\tau\tau} \\ [\delta g_R^{Ze}]_{\tau\tau} \\ [\delta g_R^{Wq}]_{11} \\ [\delta g_L^{Zu}]_{11} \\ [\delta g_R^{Zu}]_{11} \\ [\delta g_L^{Zd}]_{11} \\ [\delta g_R^{Zd}]_{11} \\ [\delta g_L^{Zu}]_{22} \\ [\delta g_R^{Zu}]_{22} \\ [\delta g_L^{Zd}]_{22} \\ [\delta g_R^{Zd}]_{22} \\ [\delta g_L^{Zd}]_{33} \\ [\delta g_R^{Zd}]_{33}
\end{pmatrix}
=
\begin{pmatrix}
-1.8(2.6) \\ -0.6(2.2) \\ 0.2(3.5) \\ -0.21(28) \\ -0.42(27) \\ 0.2(1.2) \\ 0.0(1.4) \\ -0.09(59) \\ 0.61(62) \\ -3.8(8.1) \\ -7(22) \\ 4(29) \\ -13(35) \\ 10(120) \\ -1.5(3.6) \\ -3.3(5.3) \\ 14(27) \\ 34(46) \\ 3.2(1.7) \\ 22(8.8)
\end{pmatrix}
\times 10^{-3},
\qquad
\begin{pmatrix}
[c_{ll}]_{eeee} \\ [c_{le}]_{eeee} \\ [c_{ee}]_{eeee} \\ [c_{ll}]_{e\mu\mu e} \\ [c_{ll}]_{ee\mu\mu} \\ [c_{le}]_{e\mu\mu e} \\ [c_{le}]_{ee\mu\mu} \\ [c_{le}]_{\mu\mu ee} \\ [c_{ee}]_{ee\mu\mu} \\ [c_{ll}]_{e\tau\tau e} \\ [c_{ll}]_{ee\tau\tau} \\ [c_{le}]_{ee\tau\tau} \\ [c_{le}]_{\tau\tau ee} \\ [c_{ee}]_{ee\tau\tau} \\ [\hat{c}_{ll}]_{\mu\mu\mu\mu} \\ [c_{ll}]_{\mu\tau\tau\mu} \\ [c_{le}]_{\mu\tau\tau\mu}
\end{pmatrix}
=
\begin{pmatrix}
1.03(38) \\ -0.22(22) \\ 0.19(38) \\ -0.56(80) \\ 0.1(2.0) \\ 11.4(6.8) \\ 0.3(2.2) \\ -0.2(2.1) \\ 0.2(2.3) \\ -0.60(68) \\ 2(11) \\ -2.3(7.2) \\ 1.7(7.2) \\ -1(12) \\ 2(21) \\ 1.5(1.9) \\ 19(15)
\end{pmatrix}
\times 10^{-2},
$$

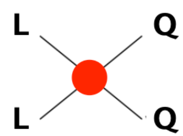
$$
\begin{pmatrix}
[c_{lq}^{(3)}]_{ee11} \\ {\color{red}[\hat{c}_{eq}]_{ee11}} \\ [\hat{c}_{lu}]_{ee11} \\ [\hat{c}_{ld}]_{ee11} \\ [\hat{c}_{eu}]_{ee11} \\ [\hat{c}_{ed}]_{ee11} \\ [c_{lequ}^{(1)}]_{ee11} \\ [c_{ledq}]_{ee11} \\ [c_{lequ}^{(3)}]_{ee11} \\ [\hat{c}_{lq}^{(3)}]_{ee22} \\ [c_{lu}]_{ee22} \\ [\hat{c}_{ld}]_{ee22} \\ [c_{eq}]_{ee22} \\ [c_{eu}]_{ee22} \\ [\hat{c}_{ed}]_{ee22} \\ [\hat{c}_{lq}^{(3)}]_{ee33} \\ [c_{ld}]_{ee33} \\ [c_{eq}]_{ee33} \\ [c_{ed}]_{ee33}
\end{pmatrix}
=
\begin{pmatrix}
0.1(\ldots \\ {\color{red}4(\ldots} \\ -2.5(8.7) \\ -2(18) \\ -3.1(9.4) \\ -2(17) \\ -0.017(60) \\ -0.018(57) \\ 0.023(66) \\ -61(32) \\ 2.4(8.0) \\ -300(130) \\ -21(28) \\ -87(46) \\ 250(140) \\ -8.5(8.0) \\ -1(10) \\ -3.1(5.1) \\ 18(20)
\end{pmatrix}
\times 10^{-2},
\qquad
\begin{pmatrix}
\ldots \\ \ldots \\ \ldots \\ {\color{red}[c_{ld}]_{\mu\mu 11}} \\ [\hat{c}_{eq}]_{\mu\mu 11} \\ \epsilon_P^{d\mu}(2\ \text{GeV}) \\ [c_{lq}^{(3)}]_{\tau\tau 11} \\ [c_{lequ}^{(3)}]_{\tau\tau 11} \\ \epsilon_P^{d\tau}(2\ \text{GeV})
\end{pmatrix}
=
\begin{pmatrix}
\ldots 5) \\ \ldots .8) \\ {\color{red}\ldots 5)} \\ {\color{red}5(24)} \\ 3(41) \\ -0.080(95) \\ -0.3(2.8) \\ -0.3(1.2) \\ 0.93(85)
\end{pmatrix}
\times 10^{-2}.
$$

$$[\hat{c}_{eq}]_{1111} = [c_{eq}]_{1111} + [c_{\ell q}]_{1111}$$

$$\bar{e}\gamma_\mu e \cdot \bar{q}\gamma^\mu q$$
$$\bar{\ell}\gamma_\mu \ell \cdot \bar{q}\gamma^\mu q$$





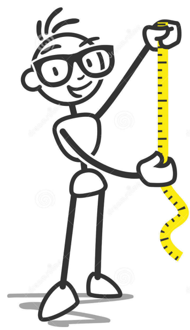


+ correlation matrix (65x65 !!)

$$\mathbf{O = O_{SM} + O\,(c_1, c_2, \ldots, c_{65}) \rightarrow \chi^2 = \chi^2\,(c_i)}$$

Precision:

O(0.01 – 1)% !!



Correlating measurements (or how to play the EFT game)

- Choose an operator basis $\{O_1, O_2, \ldots, O_n\}$, *e.g. the Warsaw basis*
  $\mathcal{L}_{\text{eff}} = \mathcal{L}_{\text{SM}} + \Sigma\, C_i\, O_i$

- Calculate the observable you like in the EFT, *e.g.* $O = O_{SM} + 3C_1 - C_6$

- What are the known limits on the Wilson coefficients?
  e.g. from LEP… C_1 =0.001(3), C_2 unkown, …
  More precisely: χ^2 with (*LEP*) measurements gives you central values and error matrix.

- Implications for your observable?
  e.g. error matrix $\rightarrow 3C_1 - C_6 = 0.02(4)$
  - ~ 4% sensitivity (th+exp) to be competitive (or to check a LEP anomaly);
  - If your sensitivity is better than that, you are exploring new SMEFT territory and your measurement should be added to the big fit.
  - A deviation larger than that indicates some wrong assumptions in your EFT!

- Often we have a dataset (instead of a single data point O). The same logic applies, but it's often better to look at the (C_1 , C_6) space → example.

Down the EFT stairs

Top down

Known theory at high-E

↓

EFT at low-E

Bottom up

EFT that includes high-E effects

SMEFT

↑

Low-E symmetries & fields

Down the EFT stairs

Top down

Known theory at high-E

SMEFT

EFT at low-E

Low-energy (~GeV) EFT (LEFT)

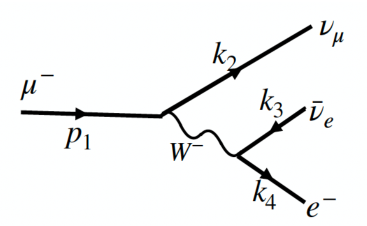
Bottom up

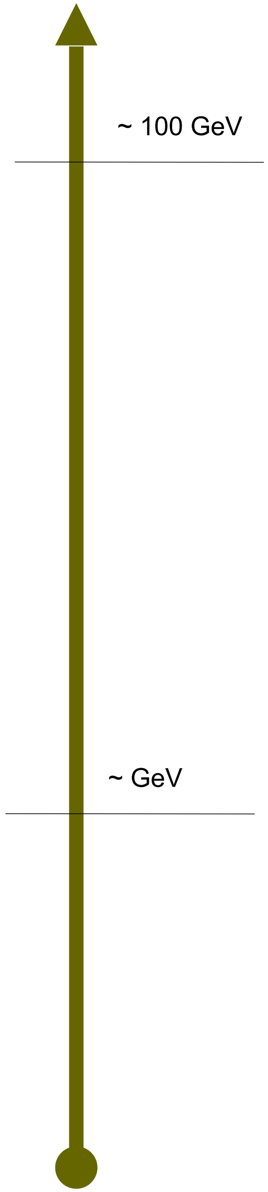
EFT that includes high-E effects

SMEFT

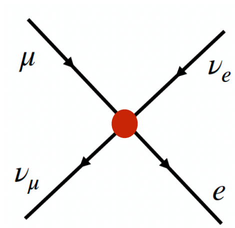
Low-E symmetries & fields

Down the EFT stairs





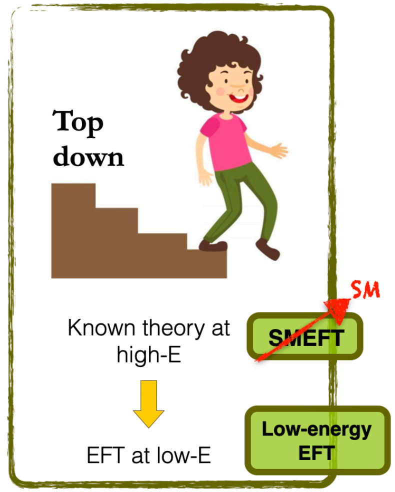
$$\mathscr{L}_{eff} = \mathscr{L}_{SM}$$



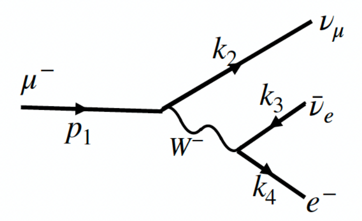
$$G_F = \frac{g^2}{4\sqrt{2}\, m_W^2}$$

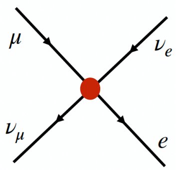
$$\mathscr{L}_{eff} = -\frac{4 G_F}{\sqrt{2}} \bar{e}\, \gamma_\mu (1-\gamma_5)\, \nu_e \cdot \bar{\nu}_\mu \gamma^\mu (1-\gamma_5)\, \mu$$

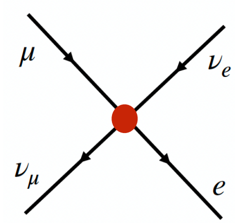
+ higher-dim terms

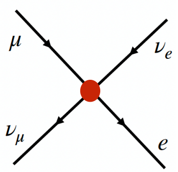


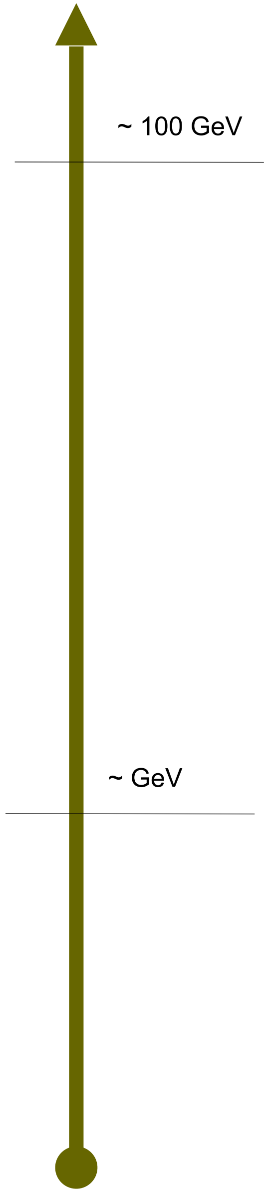
Down the EFT stairs











$$\mathscr{L}_{eff} = \mathscr{L}_{SM}$$

$$+ C_5 \mathscr{O}_5 + \sum_i C_6^i \mathscr{O}_6^i + \ldots$$

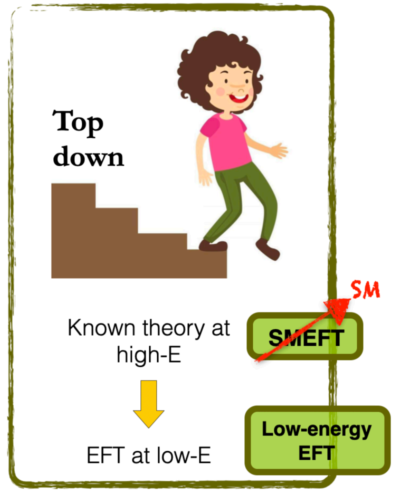
$$G_F = \frac{g^2}{4\sqrt{2}\, m_W^2} + f(C_6^i)$$

$$\mathscr{L}_{eff} = -\frac{4 G_F}{\sqrt{2}} \bar{e}\, \gamma_\mu (1-\gamma_5)\, \nu_e \cdot \bar{\nu}_\mu \gamma^\mu (1-\gamma_5)\, \mu$$

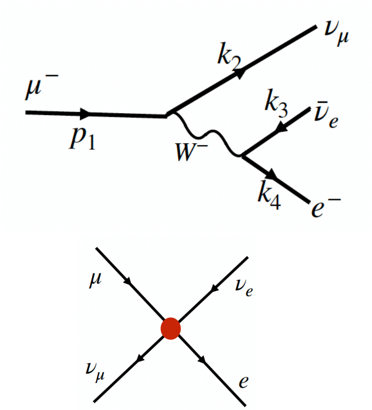
+ *higher-dim terms*

$$+ \frac{4\epsilon}{\sqrt{2}} \bar{e}\, (1-\gamma_5)\, \nu_e \cdot \bar{\nu}_\mu (1+\gamma_5)\, \mu$$

$$\epsilon = g(C_6^i)$$



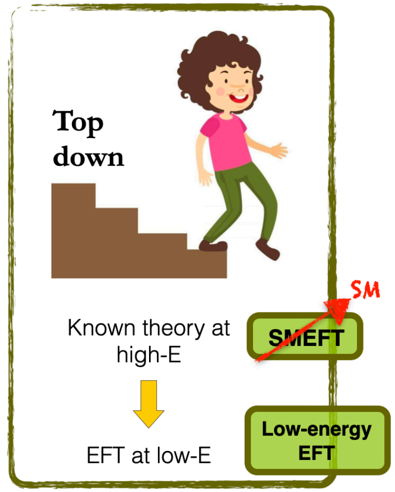
Down the EFT stairs



~ 100 GeV

$$\mathscr{L}_{eff} = \mathscr{L}_{SM}$$

$$+ C_5\,\mathcal{O}_5 + \sum_i C_6^i\,\mathcal{O}_6^i + \ldots$$



$$G_F = \frac{g^2}{4\sqrt{2}\,m_W^2} + f(C_6^i)$$

$$\mathscr{L}_{eff} = -\frac{4G_F}{\sqrt{2}}\,\bar{e}\,\gamma_\mu\,(1-\gamma_5)\,\nu_e \cdot \bar{\nu}_\mu\,\gamma^\mu\,(1-\gamma_5)\,\mu$$

+ higher-dim terms

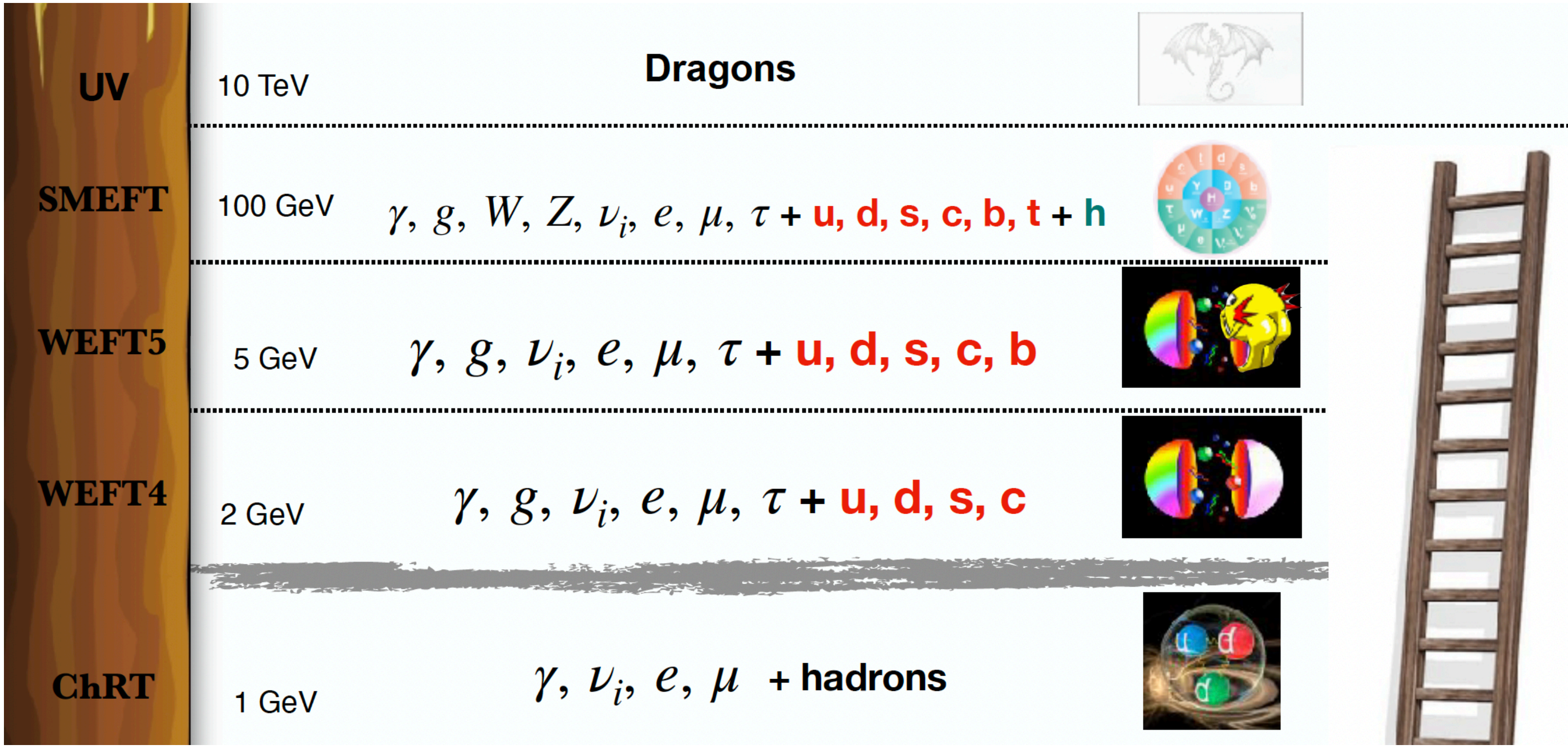
$$+\frac{4\epsilon}{\sqrt{2}}\,\bar{e}\,(1-\gamma_5)\,\nu_e \cdot \bar{\nu}_\mu\,(1+\gamma_5)\,\mu$$

$$\epsilon = g(C_6^i)$$

The SMEFT has ~3K coefficients, but it generates only one new term to the muon decay low-energy EFT Lagrangian.

- Moreover this term can be neglected in most cases (contributions $\sim m_e/m_\mu$)

SMEFT → Low-energy EFT

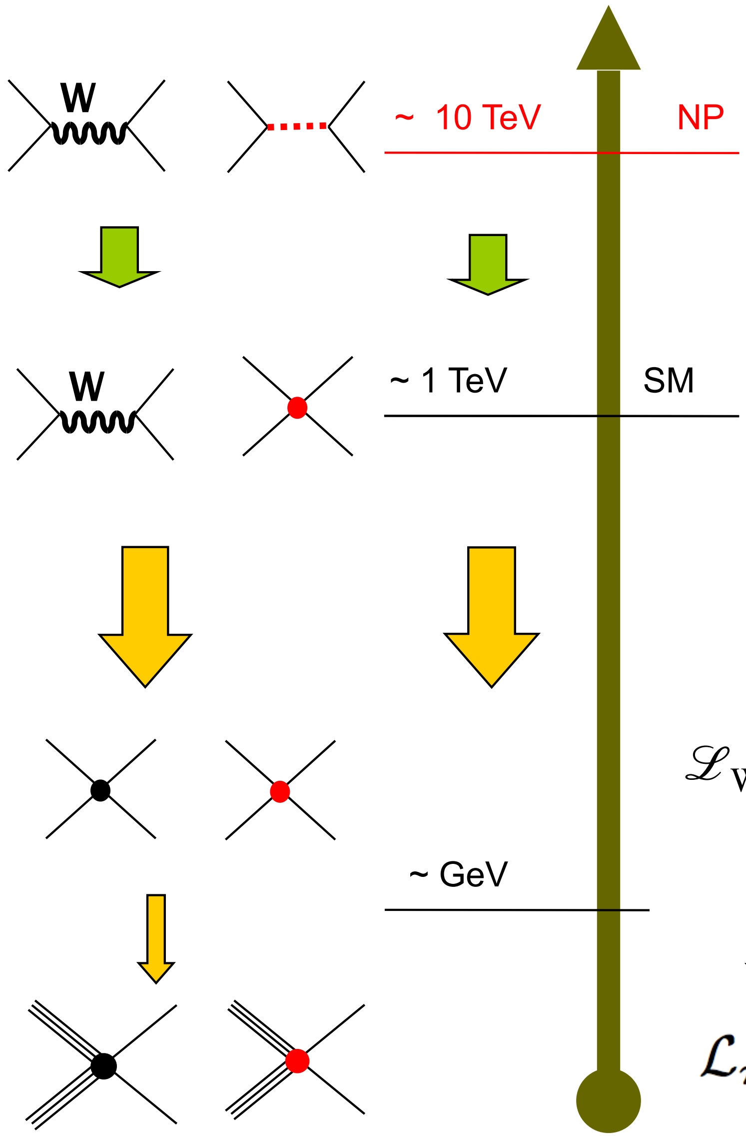


- Various names: LEFT, WEFT, WET, …
    - Variants: LEFT-5, LEFT-4, …

- In any case, the full LEFT (generated by the SMEFT) has of course many many terms. The matching between LEFT & SMEFT is known at 1-loop [Jenkins et al., 1709.04486; Dekens & Stoffer, 1908.05295].

- For concreteness, I'll focus on beta decays.

SMEFT → Beta-decay LEFT



$$\mathcal{L}(x) = \mathcal{L}\,(\text{SM fields, bSM fields})$$

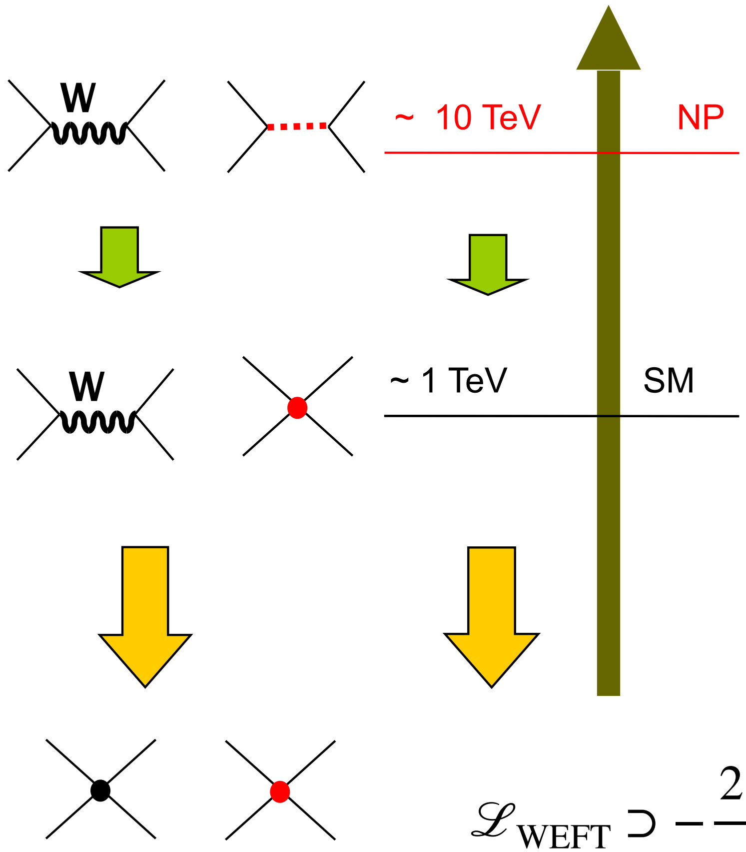
$$\mathscr{L}_{SMEFT} = \mathscr{L}_{SM} + \sum_i \frac{c_6^i}{\Lambda^2}\mathscr{O}_6^i + \ldots$$

$$\mathscr{L}_{\text{WEFT}} \supset -\frac{2V_{ud}}{v^2}\left\{(\bar{u}\gamma^\mu P_L d)(\bar{e}\gamma_\mu P_L \nu_e) + \sum_\Gamma \epsilon_\Gamma\,(\bar{u}\Gamma d)(\bar{e}\Gamma\nu_e)\right\} \,,$$

$$\mathcal{L}_{\pi,N,\ldots} = \ldots$$

$$\frac{\epsilon_\Gamma}{v^2} = f\left(\frac{c_6^i}{\Lambda^2}\right) \rightarrow \epsilon_\Gamma = f\left(c_6^i\frac{v^2}{\Lambda^2}\right)$$

SMEFT → Beta-decay LEFT



$$\mathcal{L}(x) = \mathcal{L}\,(\text{SM fields, } \text{bSM fields})$$

$$\mathscr{L}_{SMEFT} = \mathscr{L}_{SM} + \sum_i \frac{c_6^i}{\Lambda^2}\mathscr{O}_6^i + \ldots$$

$$\mathscr{L}_{\text{WEFT}} \supset -\frac{2V_{ud}}{v^2}\Big\{(1+\epsilon_L)(\bar{u}\gamma^\mu P_L d)(\bar{e}\gamma_\mu P_L \nu_e) + \epsilon_R(\bar{u}\gamma^\mu P_R d)(\bar{e}\gamma_\mu P_L \nu_e)$$

$$+ \frac{1}{2}\epsilon_S(\bar{u}d)(\bar{e}P_L\nu_e) - \frac{1}{2}\epsilon_P(\bar{u}\gamma_5 d)(eP_L\nu_e)$$

$$+ \frac{1}{4}\epsilon_T(\bar{u}\sigma^{\mu\nu}P_L d)(\bar{e}\sigma_{\mu\nu}P_L\nu_e) + \text{h.c.}\Big\},$$

$$\epsilon_\Gamma = f\left(c_6^i\frac{v^2}{\Lambda^2}\right)$$

SMEFT → Beta-decay LEFT

$$\mathscr{L}_{SMEFT} = \mathscr{L}_{SM} + \sum_i \frac{c_6^i}{\Lambda^2}\mathscr{O}_6^i + \dots$$

$$\mathscr{L}_{\rm WEFT} \supset -\frac{2V_{ud}}{v^2}\Big\{(1+\epsilon_L)(\bar{u}\gamma^\mu P_L d)(\bar{e}\gamma_\mu P_L \nu_e) + \epsilon_R(\bar{u}\gamma^\mu P_R d)(\bar{e}\gamma_\mu P_L\nu_e) + \frac{1}{2}\epsilon_S(\bar{u}d)(\bar{e}P_L\nu_e) - \frac{1}{2}\epsilon_P(\bar{u}\gamma_5 d)(eP_L\nu_e) + \frac{1}{4}\epsilon_T(\bar{u}\sigma^{\mu\nu}P_L d)(\bar{e}\sigma_{\mu\nu}P_L\nu_e) + {\rm h.c.}\Big\},$$

$$\epsilon_L \approx \frac{v^2}{\Lambda^2 V_{ud}}\left(V_{ud}\,[c_{Hl}^{(3)}]_{11} + V_{jd}\,[c_{Hq}^{(3)}]_{1j} - V_{jd}\,[c_{lq}^{(3)}]_{111j}\right),$$

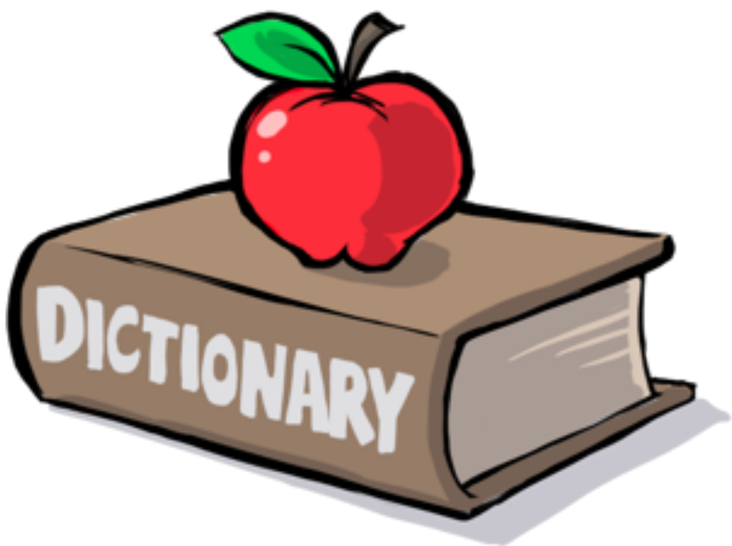
$$\epsilon_R \approx \frac{v^2}{2\Lambda^2 V_{ud}}[c_{Hud}]_{11}$$

$$\epsilon_S \approx -\frac{v^2}{2\Lambda^2 V_{ud}}\left(V_{jd}[c_{lequ}]^*_{11j1} + [c_{ledq}]^*_{1111}\right),$$

$$\epsilon_P \approx -\frac{v^2}{2\Lambda^2 V_{ud}}\left(V_{jd}[c_{lequ}]^*_{11j1} - [c_{ledq}]^*_{1111}\right),$$

$$\epsilon_T \approx -\frac{2v^2}{\Lambda^2 V_{ud}}V_{jd}\,[c_{lequ}^{(3)}]^*_{11j1},$$

$$\epsilon_\Gamma = f\left(c_6^i\frac{v^2}{\Lambda^2}\right)$$



SMEFT → Beta-decay LEFT

$$\mathcal{L}_{SMEFT} = \mathcal{L}_{SM} + \sum_i \frac{c_6^i}{\Lambda^2}\mathcal{O}_6^i + \ldots$$

$$\mathcal{L}_{\rm WEFT} \supset -\frac{2V_{ud}}{v^2}\Big\{(1+\epsilon_L)(\bar{u}\gamma^\mu P_L d)(\bar{e}\gamma_\mu P_L \nu_e) + \epsilon_R(\bar{u}\gamma^\mu P_R d)(\bar{e}\gamma_\mu P_L \nu_e)$$
$$+ \frac{1}{2}\epsilon_S(\bar{u}d)(\bar{e}P_L\nu_e) - \frac{1}{2}\epsilon_P(\bar{u}\gamma_5 d)(eP_L\nu_e)$$
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$$\epsilon_L \approx \frac{v^2}{\Lambda^2 V_{ud}}\Big(V_{ud}\,[c_{Hl}^{(3)}]_{11} + V_{jd}\,[c_{Hq}^{(3)}]_{1j} - V_{jd}\,[c_{lq}^{(3)}]_{111j}\Big),$$

$$\epsilon_R \approx \frac{v^2}{2\Lambda^2 V_{ud}}[c_{Hud}]_{11}$$

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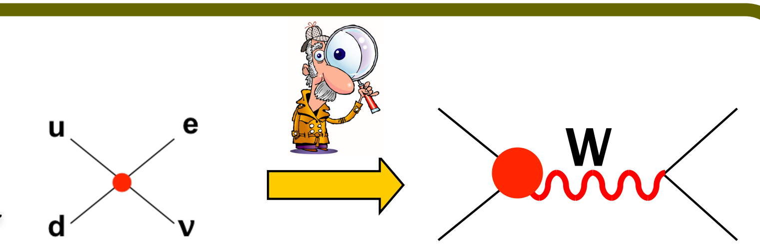
$$\epsilon_T \approx -\frac{2v^2}{\Lambda^2 V_{ud}}V_{jd}\,[c_{lequ}^{(3)}]^*_{11j1}\,,$$



$$\bar{e}_L\gamma_\mu\nu_L \cdot \bar{u}_R\gamma^\mu d_R \qquad i(\varphi^T\epsilon D_\mu\varphi)(\bar{u}\gamma^\mu d)$$

(V-A) x (V+A)

→ ***RH currents are lepton flavor universal!***
(SMEFT prediction)

SMEFT → Beta-decay LEFT

$$\mathcal{L}_{SMEFT} = \mathcal{L}_{SM} + \sum_i \frac{c_6^i}{\Lambda^2} \mathcal{O}_6^i + \ldots$$

$$\mathcal{L}_{\rm WEFT} \supset -\frac{2V_{ud}}{v^2}\Big\{(1+\epsilon_L)(\bar{u}\gamma^\mu P_L d)(\bar{e}\gamma_\mu P_L \nu_e) + \epsilon_R(\bar{u}\gamma^\mu P_R d)(\bar{e}\gamma_\mu P_L \nu_e)$$
$$+ \frac{1}{2}\epsilon_S(\bar{u}d)(\bar{e}P_L\nu_e) - \frac{1}{2}\epsilon_P(\bar{u}\gamma_5 d)(eP_L\nu_e)$$
$$+ \frac{1}{4}\epsilon_T(\bar{u}\sigma^{\mu\nu}P_L d)(\bar{e}\sigma_{\mu\nu}P_L\nu_e) + \mathrm{h.c.}\Big\},$$

Reminder:

$$\ell \equiv \begin{pmatrix} \nu_L \\ e_L \end{pmatrix} \qquad q = \begin{pmatrix} u_L \\ d_L \end{pmatrix}$$

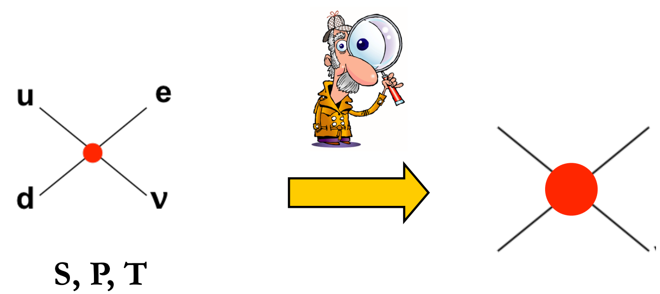
$$\epsilon_L \approx \frac{v^2}{\Lambda^2 V_{ud}}\left(V_{ud}\,[c_{Hl}^{(3)}]_{11} + V_{jd}\,[c_{Hq}^{(3)}]_{1j} - V_{jd}\,[c_{lq}^{(3)}]_{111j}\right),$$

$$\epsilon_R \approx \frac{v^2}{2\Lambda^2 V_{ud}}[c_{Hud}]_{11}$$

$$\epsilon_S \approx -\frac{v^2}{2\Lambda^2 V_{ud}}\left(V_{jd}[c_{lequ}]^*_{11j1} + [c_{ledq}]^*_{1111}\right),$$

$$\epsilon_P \approx -\frac{v^2}{2\Lambda^2 V_{ud}}\left(V_{jd}[c_{lequ}]^*_{11j1} - [c_{ledq}]^*_{1111}\right),$$

$$\epsilon_T \approx -\frac{2v^2}{\Lambda^2 V_{ud}} V_{jd}\,[c_{lequ}^{(3)}]^*_{11j1}\,,$$

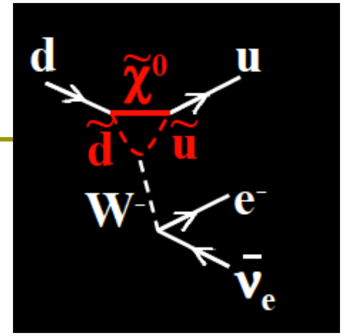


$(\bar{\ell}e)(\bar{d}q)$

$(\bar{\ell}_a e)\epsilon^{ab}(\bar{q}_b u)$

$(\bar{\ell}_a\sigma^{\mu\nu}e)\epsilon^{ab}(\bar{q}_b\sigma_{\mu\nu}u)$

SMEFT → Beta-decay LEFT

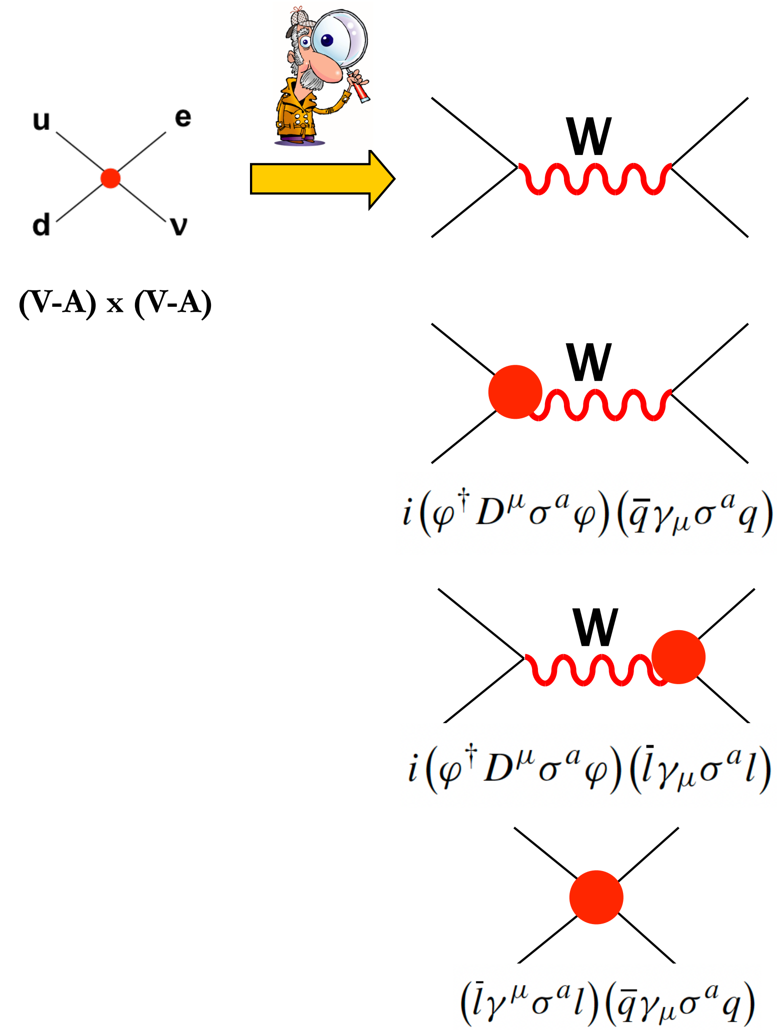


$$\mathscr{L}_{SMEFT} = \mathscr{L}_{SM} + \sum_i \frac{c_6^i}{\Lambda^2}\mathcal{O}_6^i + \ldots$$

$$\mathscr{L}_{\rm WEFT} \supset -\frac{2V_{ud}}{v^2}\{(1+\epsilon_L)(\bar u\gamma^\mu P_L d)(\bar e\gamma_\mu P_L\nu_e) + \epsilon_R(\bar u\gamma^\mu P_R d)(\bar e\gamma_\mu P_L\nu_e)$$

$$+ \frac{1}{2}\epsilon_S(\bar u d)(\bar e P_L\nu_e) - \frac{1}{2}\epsilon_P(\bar u\gamma_5 d)(\bar e P_L\nu_e)$$

$$+ \frac{1}{4}\epsilon_T(\bar u\sigma^{\mu\nu}P_L d)(\bar e\sigma_{\mu\nu}P_L\nu_e) + \mathrm{h.c.}\}$$



$$\epsilon_L \approx \frac{v^2}{\Lambda^2 V_{ud}}\left(V_{ud}\,[c_{Hl}^{(3)}]_{11} + V_{jd}\,[c_{Hq}^{(3)}]_{1j} - V_{jd}\,[c_{lq}^{(3)}]_{111j}\right),$$

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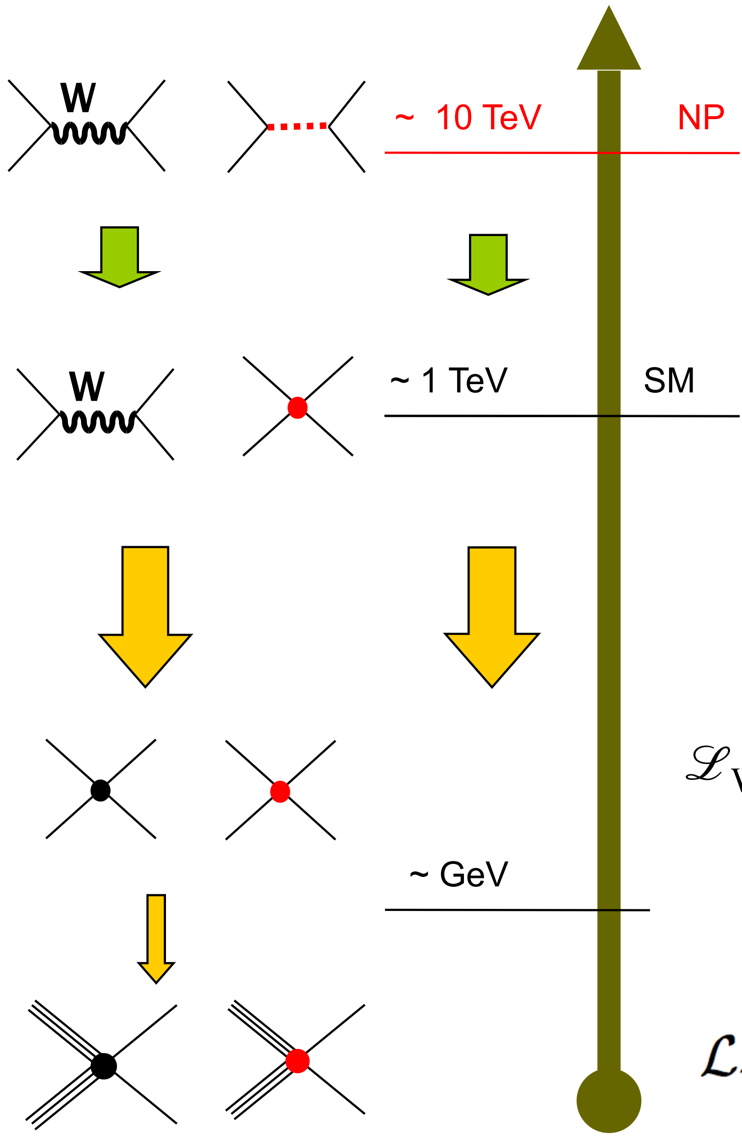
$$\epsilon_P \approx -\frac{v^2}{2\Lambda^2 V_{ud}}\left(V_{jd}[c_{lequ}]^*_{11j1} - [c_{ledq}]^*_{1111}\right),$$

$$\epsilon_T \approx -\frac{2v^2}{\Lambda^2 V_{ud}}V_{jd}\,[c_{lequ}^{(3)}]^*_{11j1}\ ,$$

LEFT from SMEFT



$$\mathcal{L}(x) = \mathcal{L}\,(\text{SM fields, bSM fields})$$

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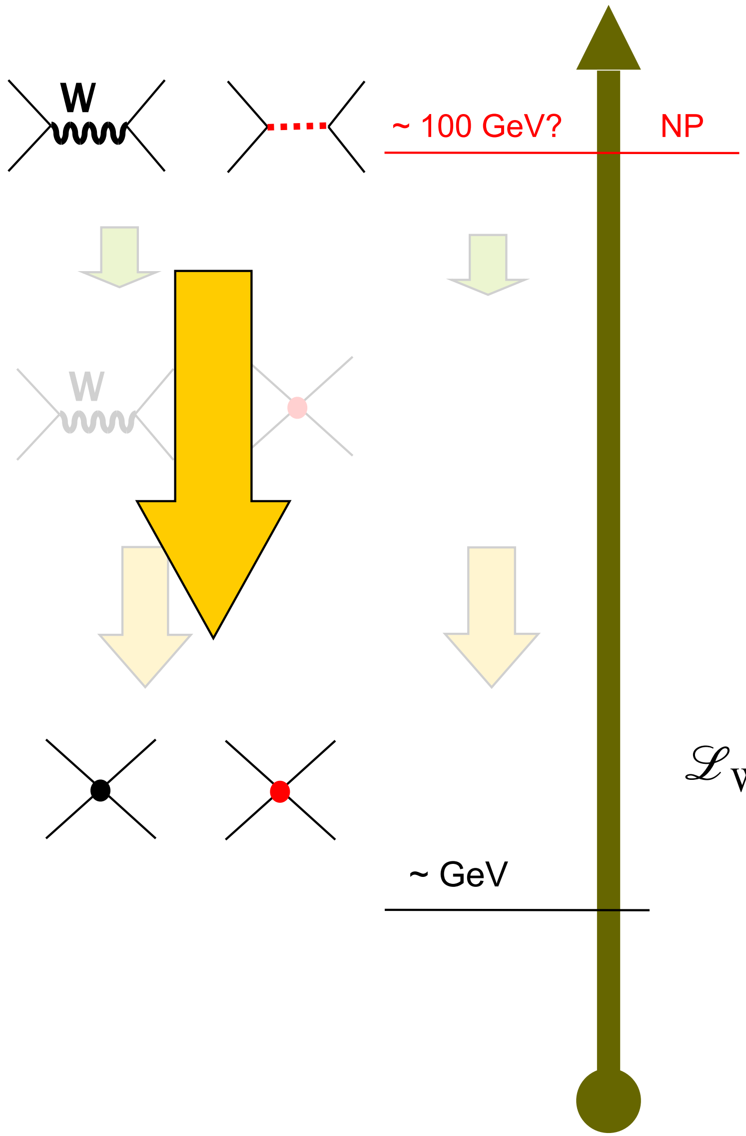
$$\mathcal{L}_{\pi,N,\ldots} = \ldots$$

$$\epsilon_\Gamma = f\left(\frac{c_6^i}{\Lambda^2}\right)$$

LEFT ~~from~~ without SMEFT



$$\mathcal{L}(x) = \mathcal{L}\,(\text{SM fields, bSM fields})$$

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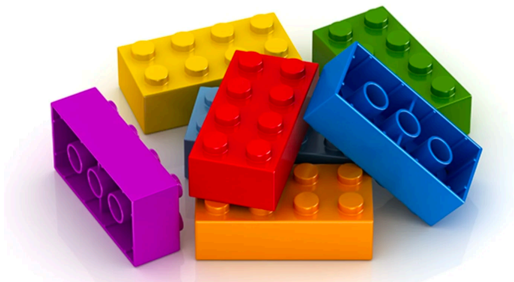
$$\mathscr{L}_{\text{WEFT}} \supset -\frac{2V_{ud}}{v^2}\left\{(\bar{u}\gamma^\mu P_L d)(\bar{e}\gamma_\mu P_L \nu_e) + \sum_\Gamma \epsilon_\Gamma (\bar{u}\Gamma d)(\bar{e}\Gamma \nu_e)\right\}\ ,$$

Building the LEFT

Building blocks:

$G_\mu^a \,,\, A_\mu \,,\, q_L^i \,,\, q_R^i \,,\, e_L^i \,,\, e_R^i \,,\, \nu_L^i$



Rules

$SU(3)c \times U(1)_{em}$

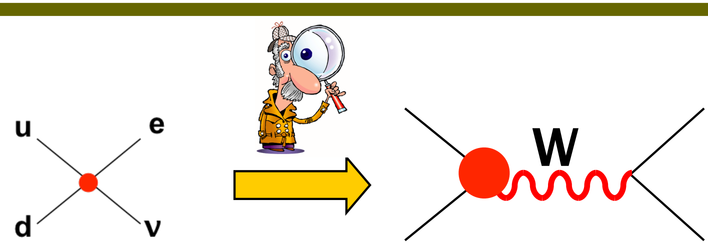
$$\mathscr{L} = \mathscr{L}_2 + \mathscr{L}_3 + \mathscr{L}_4 + \mathscr{L}_5 + \mathscr{L}_6 + \mathscr{L}_7 + \ldots$$

[Jenkins et al., 1709.04486]

Beta-decay LEFT (not necessarily from SMEFT)

$$\mathscr{L}_{\rm WEFT} \supset -\frac{2V_{ud}}{v^2}\Big\{(1+\epsilon_L)(\bar{u}\gamma^\mu P_L d)(\bar{e}\gamma_\mu P_L \nu_e) \;+\; \epsilon_R(\bar{u}\gamma^\mu P_R d)(\bar{e}\gamma_\mu P_L \nu_e)$$
$$+\;\frac{1}{2}\epsilon_S(\bar{u}d)(\bar{e}P_L\nu_e) \;-\; \frac{1}{2}\epsilon_P(\bar{u}\gamma_5 d)(eP_L\nu_e)$$
$$+\;\frac{1}{4}\epsilon_T(\bar{u}\sigma^{\mu\nu}P_L d)(\bar{e}\sigma_{\mu\nu}P_L\nu_e) + {\rm h.c.}\Big\}\;,$$

No new operators (SMEFT generates them all)*



$\bar{e}_L\gamma_\mu\nu_L \cdot \bar{u}_R\gamma^\mu d_R$ $\qquad$ $i(\varphi^T\epsilon D_\mu\varphi)(\overline{u}\gamma^\mu d)$

(V-A) x (V+A)

Not necessarily true anymore ← ~~*RH currents are lepton flavor universal!*~~

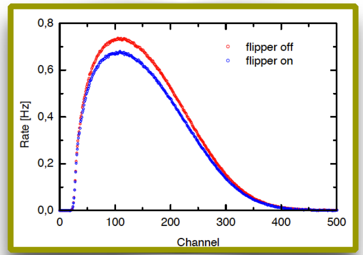
(SMEFT prediction)

*Not always the case. E.g., in b → s e⁺e⁻ some structures are forbidden!
[Alonso, Grinstein & Camalich'2014]

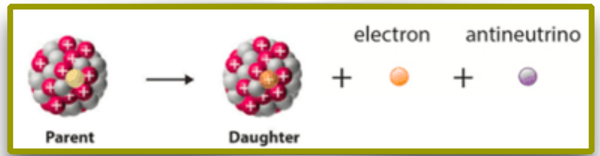
Neutrino

Neutrino prehistory (<1956)

- 1914: The **β spectrum is continuous**! (Chadwick);
  - Letter to Rutherford:
    "There's probably some silly mistake somewhere"



- 1930: Pauli postulates the **neutrino** ("a desperate remedy");



- 1956: The neutrino is detected by Cowan & Reines [Polergeist project]
  - 12th June 1956, telegram to Pauli:
    "We are happy to inform you that we have definitely detected neutrinos from fission fragments by observing the inverse beta decay of protons. Observed cross section agrees well with expected six times ten to minus forty-four square centimeters"
  - "Thanks for the message. Everything comes to him who knows how to wait. Pauli"
  - Pauli died in 1958

Neutrino prehistory (<1956)

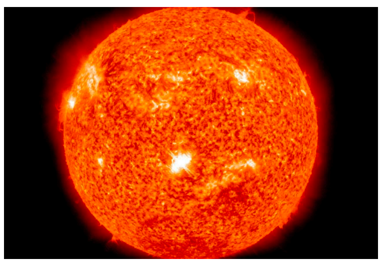
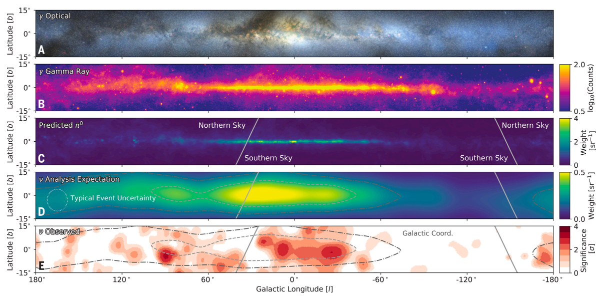
- 1959: Pontecorvo suggest the existence of the **muon neutrino**.
  → Discovered in 1962 (Lederman, Schwartz and Steinberger) → Nobel prize 1988

$$\pi^+ \rightarrow \mu^+ \nu_\mu$$
$$\nu_\mu n \rightarrow p \mu^-$$

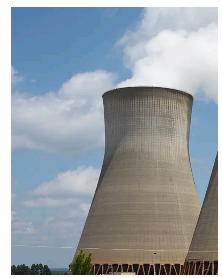
Not an electron!

- 1978: Discovery of the tau lepton (→ tau neutrino?)
  → Tau neutrino discovered in 2000 (DONUT coll.)

- The extremely low cross section made the neutrino discovery incredibly hard.
  But this property makes neutrino a unique probe.
  E.g.: 1987: Observation of neutrinos from a supernova (SN1987A)

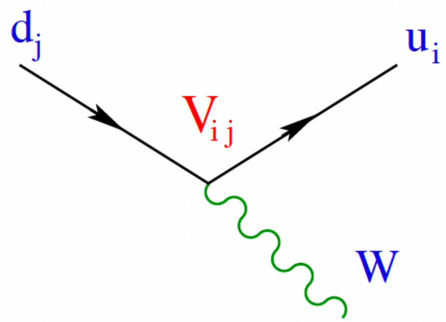



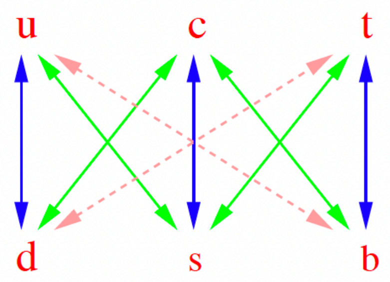


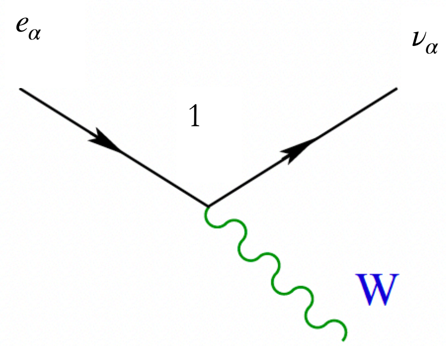


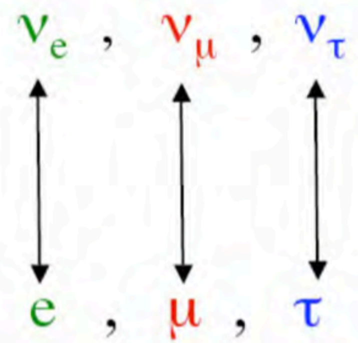
Neutrinos in the SM

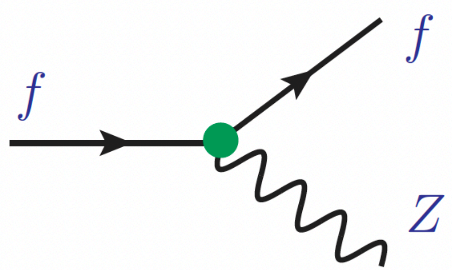
$$\mathcal{L} = -\frac{1}{4} F_{\mu\nu} F^{\mu\nu} + i \bar{\psi} \not{D} \psi + h.c. + \bar{\psi}_i y_{ij} \psi_j \phi + h.c. + |D_\mu \phi|^2 - V(\phi)$$









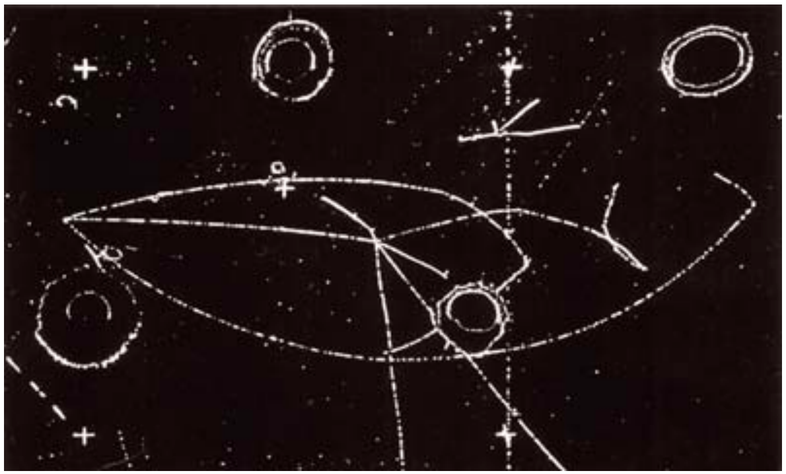


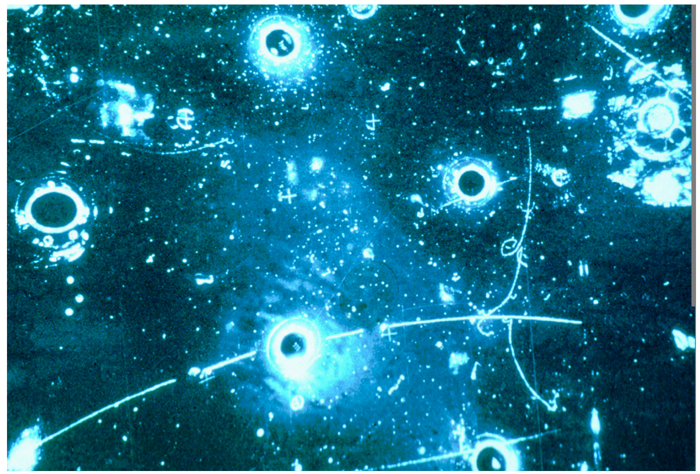
Neutrinos in the SM

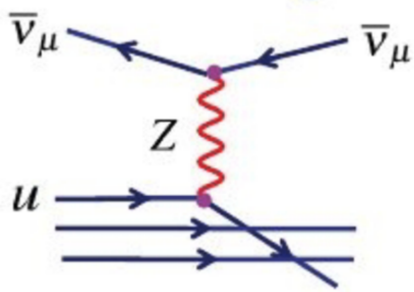
- 1973 (Gargamelle bubble chamber @ CERN): first observation of Neutral Current interactions (using neutrinos!)

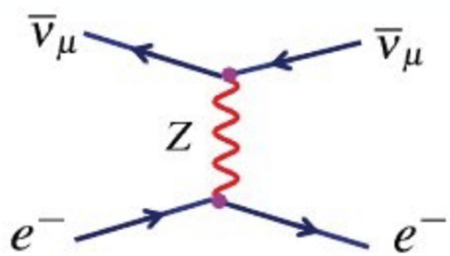
$\overline{\nu}_\mu + N \to \overline{\nu}_\mu + \text{hadrons}$

$\overline{\nu}_\mu + e^- \to \overline{\nu}_\mu + e^-$



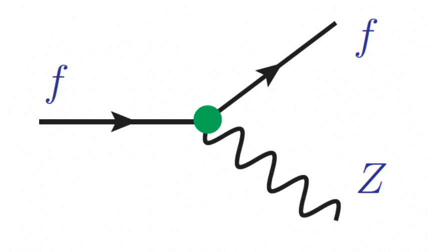






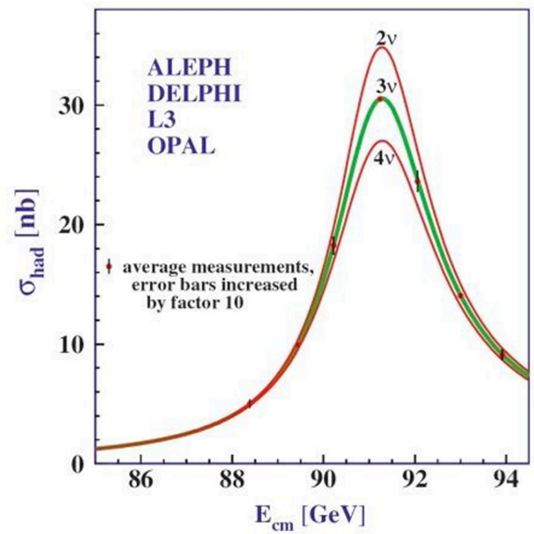
Neutrinos in the SM

- 1989 (before the ν_τ discovery): LEP1



$$\frac{\Gamma_{inv}}{\Gamma_e} = \frac{N_\nu \Gamma(Z \to \bar{\nu}\nu)}{\Gamma_e} = \frac{2N_\nu}{1 + (1 - 4\sin^2\theta)^2} \approx 2N_\nu$$

$$\Gamma_{inv} = \Gamma_Z - \Gamma_{had} - \Gamma_{e+\mu+\tau}$$



$$N_\nu = 2.984 \pm 0.008$$

(+NLO EW corrections)

$$\Gamma(Z \to \bar{f}f) = N_f \frac{G_F M_Z^3}{6\pi\sqrt{2}} \left(|v_f|^2 + |a_f|^2\right)$$

Neutrinos in the SM: masses

$$\mathcal{L}_Y = -\left(\bar{\ell}\, Y_e \varphi\, e \;+\; \bar{q}\,\varphi\, Y_d\, d \;+\; \bar{q}\,\tilde{\varphi}\, Y_u\, u\right) + h.c.$$

$$\ell \equiv \begin{pmatrix} \nu_L \\ e_L \end{pmatrix} \qquad q = \begin{pmatrix} u_L \\ d_L \end{pmatrix} \qquad \tilde{\varphi} \equiv i\,\sigma_2\,\varphi = \begin{pmatrix} (\varphi^0)^* \\ -(\varphi^+)^* \end{pmatrix}$$

$$\varphi \to \frac{1}{\sqrt{2}}\begin{pmatrix} 0 \\ v+h \end{pmatrix} \qquad \tilde{\varphi} \to \frac{1}{\sqrt{2}}\begin{pmatrix} v+h \\ 0 \end{pmatrix}$$

$$\mathcal{L}_Y = -\frac{v+h}{\sqrt{2}}\left(Y_e\, \bar{e}_L\, e_R \;+\; Y_d\, \bar{d}_L\, d_R \;+\; Y_u\, \bar{u}_L\, u_R\right) + h.c.$$

$$= -\left(1+\frac{h}{v}\right)\left(m_e\, \bar{e}_L\, e_R \;+\; m_d\, \bar{d}_L\, d_R \;+\; m_u\, \bar{u}_L\, u_R\right) + h.c.$$

$$m_e = Y_e\, v/\sqrt{2} \qquad m_d = Y_d\, v/\sqrt{2} \qquad m_u = Y_u\, v/\sqrt{2}$$

- The Higgs can't give masses to neutrinos because there's no RH neutrino (by construction)
- Note that a Majorana mass term (which can be built only with LH neutrinos) is NOT gauge invariant, so it's not possible either

$$\mathcal{L}_M = -\frac{1}{2} m_M \bar{\nu}_L^c \nu_L + h.c.\,, \qquad \nu^c \equiv C\bar{\nu}^T$$

- Conclusions: neutrinos are massless in the (vanilla) SM

Neutrinos in the SM: masses

$$\ell \equiv \begin{pmatrix} \nu_L \\ e_L \end{pmatrix} \qquad q = \begin{pmatrix} u_L \\ d_L \end{pmatrix} \qquad \tilde{\varphi} \equiv i\,\sigma_2\,\varphi = \begin{pmatrix} (\varphi^0)^* \\ -(\varphi^+)^* \end{pmatrix}$$

$$\mathscr{L}_Y = -\left(\bar{\ell}\, Y_e\, \varphi\, e \;+\; \bar{q}\,\varphi\, Y_d\, d \;+\; \bar{q}\,\tilde{\varphi}\, Y_u\, u\right) + h.c.$$

$$\varphi \to \frac{1}{\sqrt{2}}\begin{pmatrix} 0 \\ v+h \end{pmatrix} \qquad \tilde{\varphi} \to \frac{1}{\sqrt{2}}\begin{pmatrix} v+h \\ 0 \end{pmatrix}$$

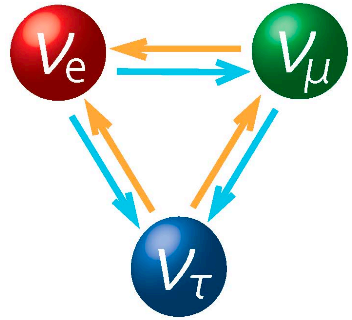
$$\mathscr{L}_Y = -\frac{v+h}{\sqrt{2}}\left(Y_e\,\bar{e}_L\, e_R \;+\; Y_d\,\bar{d}_L\, d_R \;+\; Y_u\,\bar{u}_L\, u_R\right) + h.c.$$

$$= -\left(1+\frac{h}{v}\right)\left(m_e\,\bar{e}_L\, e_R \;+\; m_d\,\bar{d}_L\, d_R \;+\; m_u\,\bar{u}_L\, u_R\right) + h.c.$$

$$m_e = Y_e\, v/\sqrt{2} \qquad m_d = Y_d\, v/\sqrt{2} \qquad m_u = Y_u\, v/\sqrt{2}$$

- Additional reminders:
  - L is (accidentally) conserved, up to non-perturbative effects only relevant at high T
  - Same for Lepton flavor numbers: L_e, L_μ, L_τ

Neutrino oscillations (1968-2001)



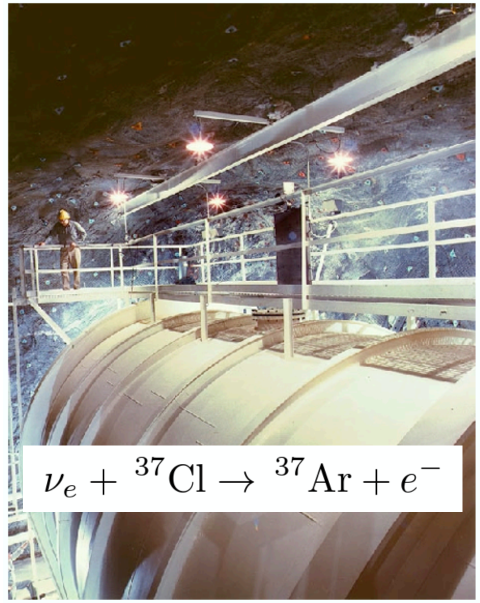
- 1957-1962 Pontecorvo & Maki, Nagakawa & Sakata (PMNS) put forward the idea of neutrino mixing & the associated oscillations

- 1968: R. Davis detects solar neutrinos for the first time (Homestake)

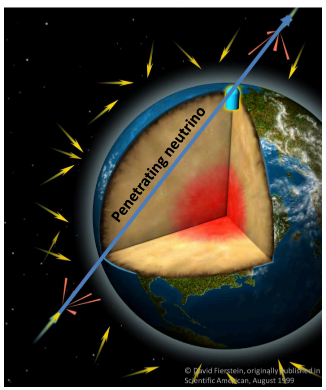
  → He detected 1/3 of the theory prediction (SM + solar model)!!

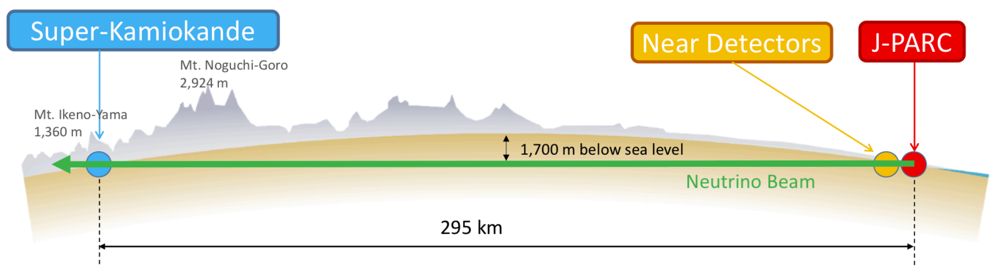
  → Confirmed by subsequent solar experiments

  → 2002 Nobel prize to Davis

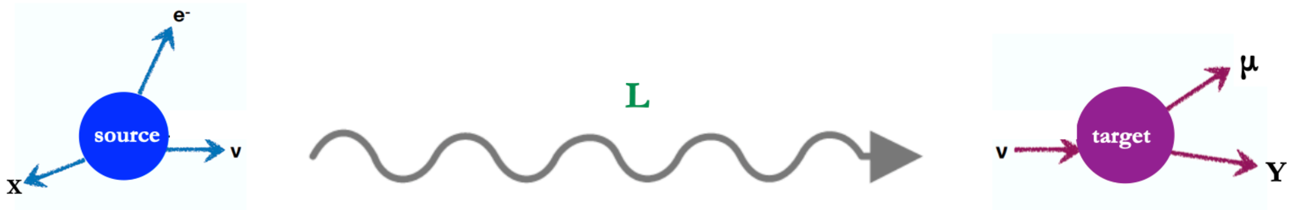


- 90's-2000's: oscillation confirmed by atmospheric, reactor & accelerator experiments





Neutrino oscillations: QM



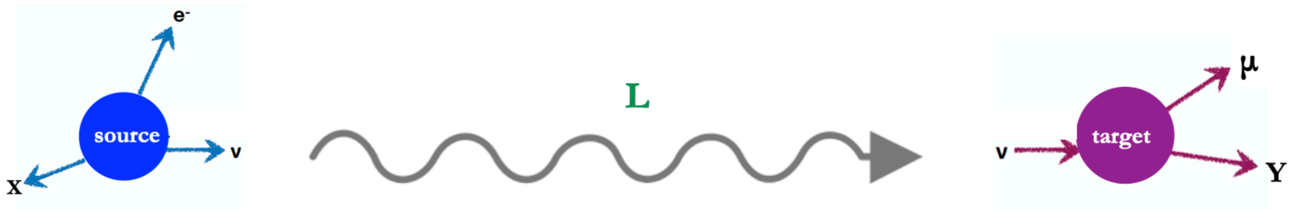
- If the dynamics (Lagrangian) are such that neutrinos have (almost degenerate) masses and these mass eigenstates are not the weak eigenstates, then weak interactions will produce a charged lepton (e.g. electron) together with a quantum superposition of neutrino mass eigenstates.

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = U_{\text{PMNS}} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

- The emitted state is a superposition of energy eigenstates ν_i (free Hamiltonian)
  $\rightarrow$ ν_i states do not change with time (=distance).
  $\rightarrow$ But the emitted state (ν_e) will evolve, since it's a superposition.
  $\rightarrow$ After some time/distance we don't have anymore a pure ν_e (but instead a combination of ν_e, ν_μ, ν_τ).
  $\rightarrow$ If we measure (detection process) we can measure it has *oscillated* to, e.g., ν_μ)

$$-i\frac{d}{dt}|\nu\rangle = H|\nu\rangle \qquad H = \begin{pmatrix} E_1 & 0 & 0 \\ 0 & E_2 & 0 \\ 0 & 0 & E_3 \end{pmatrix} \qquad E_i = \sqrt{p_i^2 + m_i^2} \approx p_i + \frac{m_i^2}{2p_i}$$

Neutrino oscillations: QM



- If the dynamics (Lagrangian) are such that neutrinos have (almost degenerate) masses and these mass eigenstates are not the weak eigenstates, then weak interactions will produce a charged lepton (e.g. electron) together with a quantum superposition of neutrino mass eigenstates.

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = U_{\text{PMNS}} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix} \Rightarrow P_{\nu_e \to \nu_\mu} = |\langle \nu_\mu | \nu(L) \rangle|^2 = f\left(U_{\alpha k}, \Delta m^2_{ij}\right)$$

$$\begin{pmatrix} \nu_e \\ \nu_\mu \end{pmatrix} = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \end{pmatrix} \Rightarrow P_{\nu_e \to \nu_\mu} = |\langle \nu_\mu | \nu(L) \rangle|^2 = \sin^2 2\theta \, \sin^2\left(\underbrace{\frac{\Delta m^2_{21} L}{4E}}_{\Phi}\right)$$

- $\Phi \approx 1.3 \frac{\Delta m^2_{21}[\text{eV}^2]\, L[\text{km}]}{E[\text{GeV}]}$
  - "Short" distance (or large energy): $\Phi << 1 \rightarrow$ no oscillation: $\sin^2\Phi \approx 0$
  - "Long" distance (or small energies): $\Phi >> 1 \rightarrow$ oscillations averaged out: $\sin^2\Phi \approx 1/2$
  - Intermediate region: $\Phi \sim 1 \rightarrow$ oscillations!

Neutrino oscillations

- Neutrino oscillations violate lepton flavor number ($\nu_e \to \nu_\mu$), but not total lepton number.

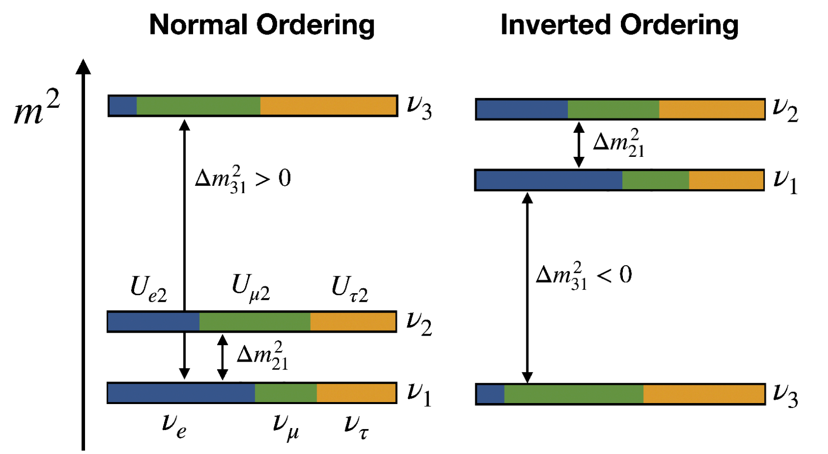
- PMNS matrix (unitary) → 3 mixing angles + 1 Dirac phase, like in the CKM case.

$$U_{PMNS} = \begin{bmatrix} c_{12}\, c_{13} & s_{12}\, c_{13} & s_{13}\, e^{-i\delta_{13}} \\ -s_{12}\, c_{23} - c_{12}\, s_{23}\, s_{13}\, e^{i\delta_{13}} & c_{12}\, c_{23} - s_{12}\, s_{23}\, s_{13}\, e^{i\delta_{13}} & s_{23}\, c_{13} \\ s_{12}\, s_{23} - c_{12}\, c_{23}\, s_{13}\, e^{i\delta_{13}} & -c_{12}\, s_{23} - s_{12}\, c_{23}\, s_{13}\, e^{i\delta_{13}} & c_{23}\, c_{13} \end{bmatrix}$$

  - Majorana mass $\neq 0$ → Additional phases! [they don't affect oscillations, they do affect 0νββ)
  - Dirac phase → CPV: $P(\nu_\alpha \to \nu_\beta) \neq P(\bar{\nu}_\alpha \to \bar{\nu}_\beta)$

- Oscillations are sensitive to $\Delta m^2_{ij} \equiv m^2_i - m^2_j$, but not to the absolute mass.

- Oscillation data:
  - $\Delta m^2_{sol} = \Delta m^2_{21} \equiv m^2_2 - m^2_1 \sim 7 \times 10^{-5}\,\mathrm{eV}^2$
  - $|\Delta m^2_{atm}| = |m^2_{31}| \equiv |m^2_3 - m^2_1| \sim 2 \times 10^{-3}\,\mathrm{eV}^2$
  - Thus, at least 2 neutrinos are massive!
  - No sensitivity to the lightest mass (it could be massless)
  - The heaviest one is at least ~0.05 eV.



[Phys. Sci. Forum **2023**, 8(1), 7]

Neutrino mass

- Oscillation data:
  - 3 non-degenerate neutrinos.
  - The heaviest one is at least ~0.05 eV.

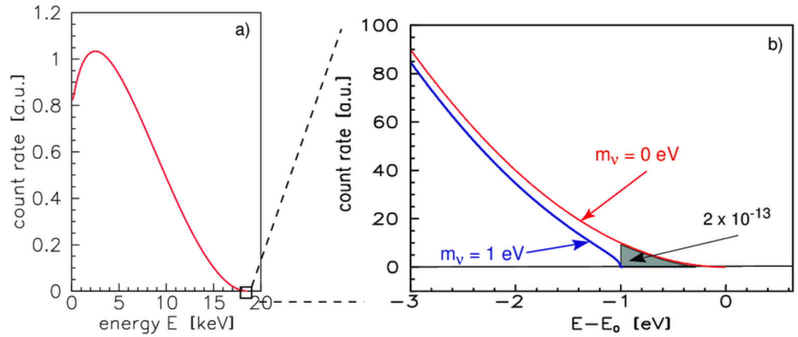
- Cosmology:

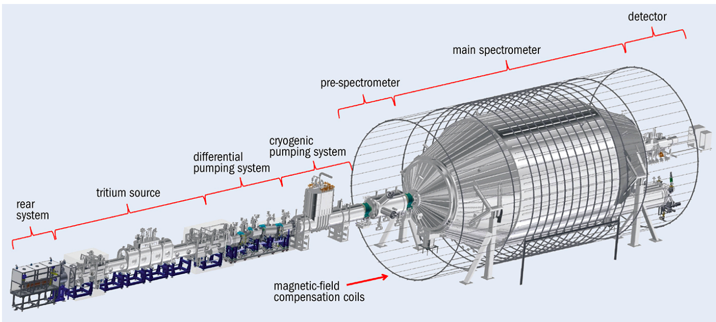
$$\sum_i m_i \lesssim 0.1 \text{ eV}$$

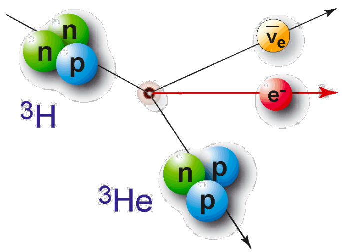
- Beta decay (tritium):

$$m_\beta \equiv \sum_i |U_{ei}|^2 m_i^2 \;<\; 0.8 \text{ eV (90\% CL)}$$

  - Final sensitivity: 0.2-0.3 eV.







- Neutrinoless 2β decay:

$$m_{\beta\beta} = |\sum U_{ei}^2 m_i| \lesssim 0.2 \text{ eV}$$

Neutrino mass

- Oscillation data:
  - 3 non-degenerate neutrinos.
  - The heaviest one is at least ~0.05 eV.

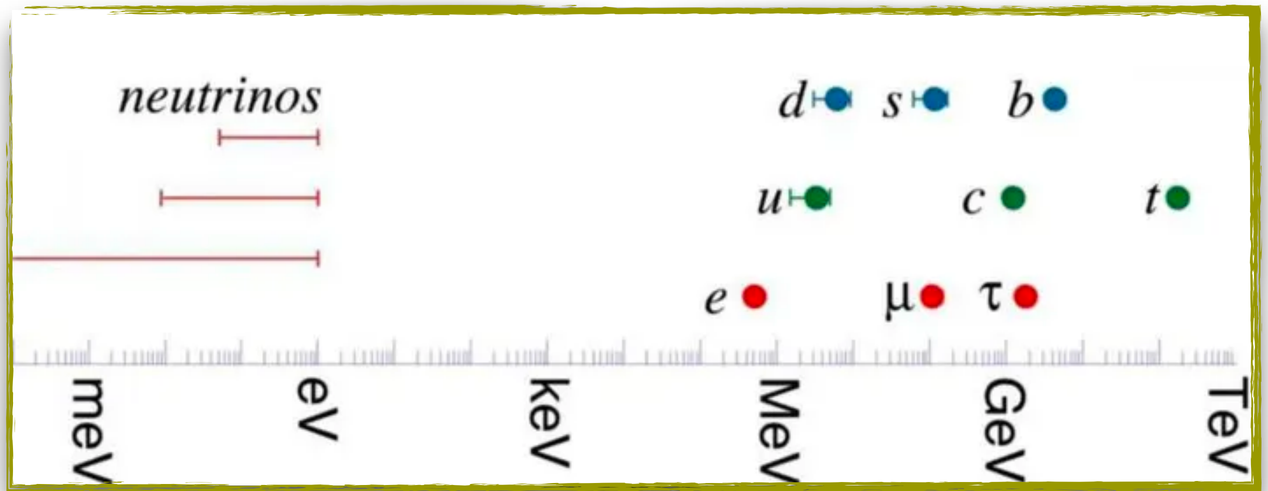
- Cosmology:

$$\sum_i m_i \lesssim 0.1 \text{ eV}$$

- Beta decay (tritium):

$$m_\beta \equiv \sum_i |U_{ei}|^2 m_i^2 \; < \; 0.8 \text{ eV (90\% CL)}$$

- The window is getting smaller…



Neutrino masses are zero
in the vanilla SM.

How can we generate
them with BSM physics?

Neutrino masses in the SMEFT

$$\mathscr{L} = \mathscr{L}_2 + \mathscr{L}_3 + \mathscr{L}_4 + \mathscr{L}_5 + \mathscr{L}_6 + \mathscr{L}_7 + \ldots$$

- Only one operator (Weinberg'79)

$$\mathscr{L}_5 = \frac{[c_5]_{pr}}{\Lambda} \left(\tilde{\varphi}^\dagger \ell_p\right)^T C \left(\tilde{\varphi}^\dagger \ell_r\right) + h.c.$$

$$\tilde{\varphi} \equiv i\,\sigma_2\,\varphi = \begin{pmatrix} (\varphi^0)^* \\ -(\varphi^+)^* \end{pmatrix} \rightarrow \frac{1}{\sqrt{2}} \begin{pmatrix} v + H \\ 0 \end{pmatrix}$$

$$\ell \equiv \begin{pmatrix} \nu_L \\ e_L \end{pmatrix}$$

- After EWSB generates Majorana masses (for LH neutrinos):

$$\mathscr{L}_M = -\frac{1}{2} m_M \bar{\nu}_L^c \nu_L + h.c.\,, \qquad \rightarrow \qquad m_\nu \sim 2\,c_5\,v^2/\Lambda$$

- It implies (perturbative) LNV
- There are many NP models that generate this term

- For 3 families, m_M is a matrix, which has to be diagonalized.
  Much like in the quark sector, this leads to a mixing matrix: PMNS

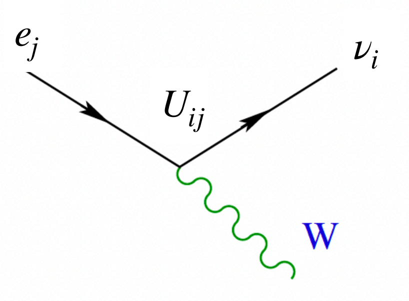
Neutrino masses in the SMEFT

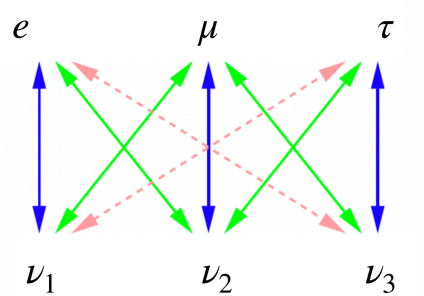
- The PMNS matrix has 3 angles + 1 Dirac phase, as the CKM matrix.
  But it also has new 2 phases (which now can't be rotated away).

$$U = \begin{pmatrix} 1 & & \\ & c_{23} & s_{23} \\ & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & & s_{13}e^{-i\delta} \\ & 1 & \\ -s_{13}e^{i\delta} & & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & \\ -s_{12} & c_{12} & \\ & & 1 \end{pmatrix} \begin{pmatrix} e^{i\alpha} & & \\ & e^{i\beta} & \\ & & 1 \end{pmatrix}$$

$$W_\mu^\dagger \bar{\nu}'_L \gamma_\mu e'_L = W_\mu^\dagger \bar{\nu}_L \gamma_\mu U_\nu^{L\dagger} U_e^L e_L \equiv W_\mu^\dagger \bar{\nu}_L \gamma_\mu U_{PMNS} e_L$$

$$\mathscr{L}_{CC} = -\frac{g}{\sqrt{2}} W_\mu^\dagger \left\{ \bar{u}_L \gamma_\mu V_{CKM} d_L + \bar{\nu}_L \gamma_\mu U_{PMNS} e_L \right\} + \mathrm{h.c.}$$





SM + ν_R

- Minimal SM modification

Fields	ψ_1	ψ_2	ψ_3
Quarks	$\begin{pmatrix} u \\ d \end{pmatrix}_L$	u_R	d_R
Leptons	$\begin{pmatrix} \nu_\ell \\ \ell^- \end{pmatrix}_L$	~~$\nu_{\ell,R}$~~	ℓ^-_R

→

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- Then neutrinos obtain a mass exactly like the rest of particles (Higgs mechanism, EWSB)

$$\mathscr{L}_Y = -\left(\bar{\ell}\,\varphi\,Y_e\,e \;+\; \bar{\ell}\,\tilde{\varphi}\,Y_\nu\,\nu \;+\; \bar{q}\,\varphi\,Y_d\,d \;+\; \bar{q}\,\tilde{\varphi}\,Y_u\,u\right) + h.c.$$

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$$\mathscr{L}_Y = -\frac{v+h}{\sqrt{2}}\left(Y_e\,\bar{e}_L\,e_R \;+\; Y_d\,\bar{d}_L\,d_R \;+\; Y_u\,\bar{u}_L\,u_R\right) + h.c.$$

$$\mathscr{L}_Y = -\left(1+\frac{h}{v}\right)\left(m_e\,\bar{e}_L\,e_R \;+\; m_\nu\,\bar{\nu}_L\,\nu_R \;+\; m_d\,\bar{d}_L\,d_R \;+\; m_u\,\bar{u}_L\,u_R\right) + h.c.$$

$$m_e = Y_e\,v/\sqrt{2}$$
$$m_\nu = Y_\nu\,v/\sqrt{2}$$
$$m_d = Y_d\,v/\sqrt{2}$$
$$m_u = Y_u\,v/\sqrt{2}$$

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- Then neutrinos obtain a mass exactly like the rest of particles (Higgs mechanism, EWSB)

  $\rightarrow Y_\nu \sim 10^{-13} \ll Y_e \sim 10^{-5}$!!??

- However, note that a d=3 Majorana mass for the ν_R is also possible (unless we impose L conv.)

$$\mathscr{L}_M = -\frac{1}{2} m_M \bar{\nu}^c_R \nu_R + h.c.\,, \qquad \nu^c_R \equiv C\bar{\nu}^T_R$$

  - It's not connected with EWSB. It would be a completely new scale.
  - This term violates (perturbatively) Lepton number by 2 units (→ 0νββ)
  - No other SM particle can have such term

SM + ν_R

- Minimal SM modification

Fields	ψ_1	ψ_2	ψ_3
Quarks	$\begin{pmatrix} u \\ d \end{pmatrix}_L$	u_R	d_R
Leptons	$\begin{pmatrix} \nu_\ell \\ \ell^- \end{pmatrix}_L$	~~$\nu_{\ell,R}$~~	ℓ^-_R

Fields	ψ_1	ψ_2	ψ_3
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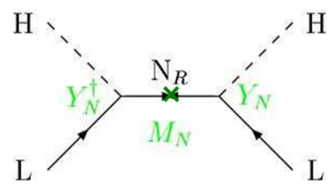
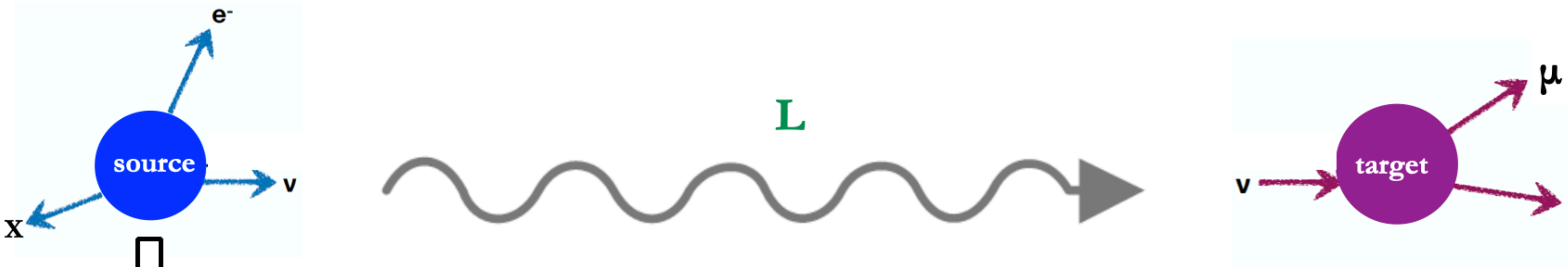
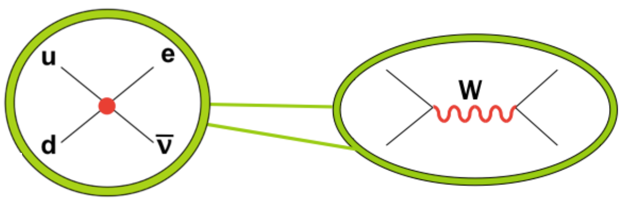
$$\mathscr{L}_M = -\frac{1}{2} m_M \bar{\nu}_R^c \nu_R + h.c.\,, \qquad \nu_R^c \equiv C\bar{\nu}_R^T$$

- One family: ν_L & ν_R mix $\rightarrow \nu_1$ and ν_2 are the massive eigenstates (2 Majorana particles). If $m_M \gg v$ then ν_2 is heavy $\rightarrow$ D=5 SMEFT operator (see-saw)



Oscillation as precision experiments





[Same in detection]

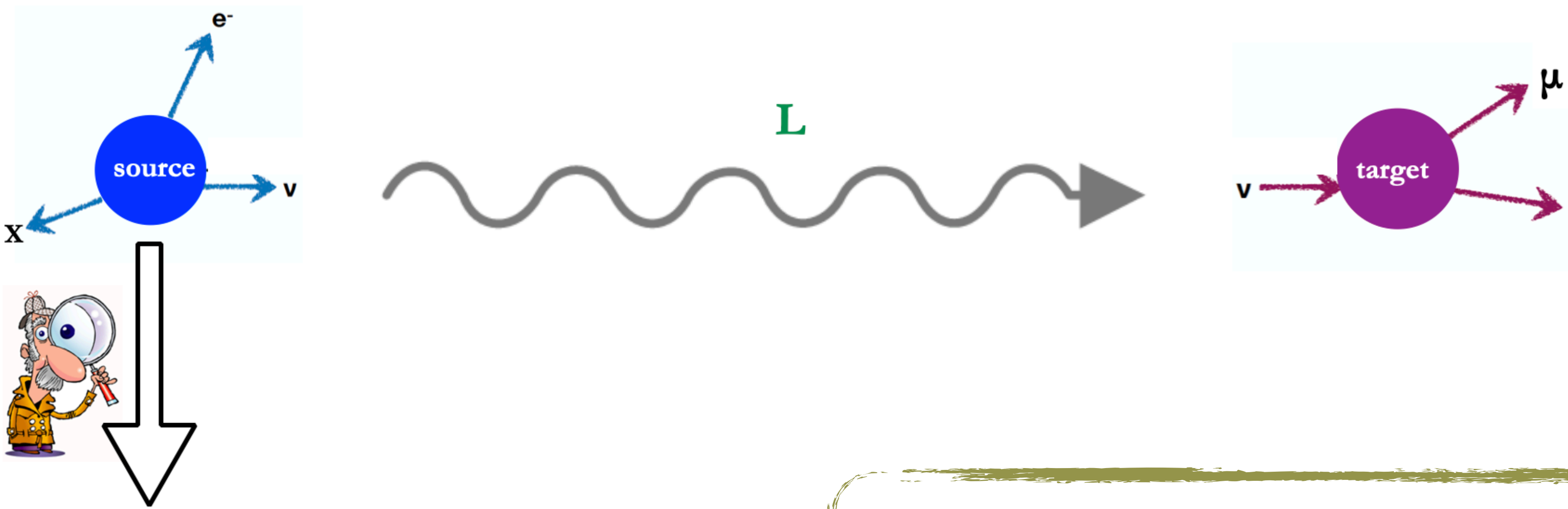
In the SM*: $O = O\,(\theta_i, \Delta m^2)$

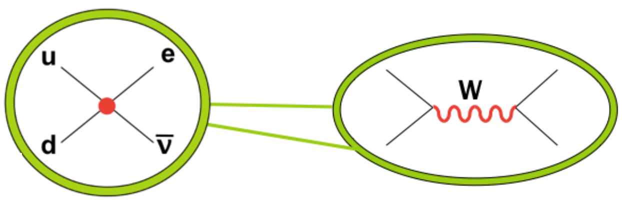
Beyond the SM*: $O = O\,(\theta_i, \Delta m^2, \varepsilon_j)$

		Normal Ordering (best fit)		Inverted Ordering ($\Delta\chi^2 = 7.1$)	
		bfp $\pm 1\sigma$	3σ range	bfp $\pm 1\sigma$	3σ range
with SK atmospheric data	$\sin^2\theta_{12}$	$0.304^{+0.012}_{-0.012}$	$0.269 \to 0.343$	$0.304^{+0.013}_{-0.012}$	$0.269 \to 0.343$
	$\theta_{12}/^\circ$	$33.44^{+0.77}_{-0.74}$	$31.27 \to 35.86$	$33.45^{+0.78}_{-0.75}$	$31.27 \to 35.87$
	$\sin^2\theta_{23}$	$0.573^{+0.016}_{-0.020}$	$0.415 \to 0.616$	$0.575^{+0.016}_{-0.019}$	$0.419 \to 0.617$
	$\theta_{23}/^\circ$	$49.2^{+0.9}_{-1.2}$	$40.1 \to 51.7$	$49.3^{+0.9}_{-1.1}$	$40.3 \to 51.8$
	$\sin^2\theta_{13}$	$0.02219^{+0.00062}_{-0.00063}$	$0.02032 \to 0.02410$	$0.02238^{+0.00063}_{-0.00062}$	$0.02052 \to 0.02428$
	$\theta_{13}/^\circ$	$8.57^{+0.12}_{-0.12}$	$8.20 \to 8.93$	$8.60^{+0.12}_{-0.12}$	$8.24 \to 8.96$
	$\delta_{CP}/^\circ$	197^{+27}_{-24}	$120 \to 369$	282^{+26}_{-30}	$193 \to 352$
	$\frac{\Delta m^2_{21}}{10^{-5}\ \mathrm{eV}^2}$	$7.42^{+0.21}_{-0.20}$	$6.82 \to 8.04$	$7.42^{+0.21}_{-0.20}$	$6.82 \to 8.04$
	$\frac{\Delta m^2_{3\ell}}{10^{-3}\ \mathrm{eV}^2}$	$+2.517^{+0.026}_{-0.028}$	$+2.435 \to +2.598$	$-2.498^{+0.028}_{-0.028}$	$-2.581 \to -2.414$

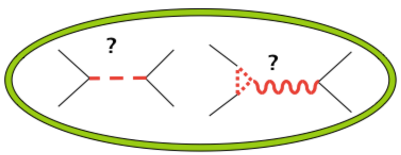
[I.Esteban et al., 2007.14792 JHEP]

Oscillation as precision experiments





[Same in detection]



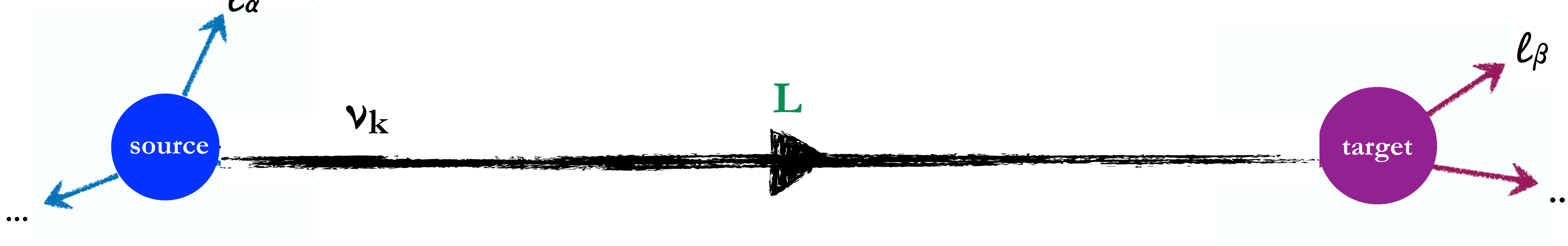
In the SM*: $O = O(\theta_i, \Delta m^2)$

Beyond the SM*: $O = O(\theta_i, \Delta m^2, \varepsilon_j)$

- QM approach not useful ("source/detector NSI") → QFT approach needed

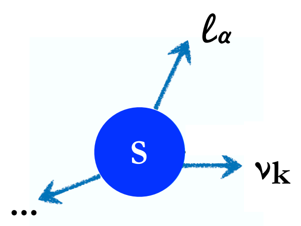
Oscillations in QFT→ EFT

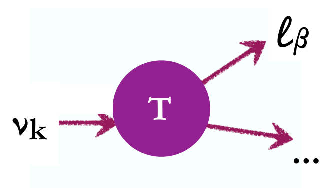
[A. Falkowski, MGA, & Z. Tabrizi, JHEP'20]



$$R_{\alpha\beta} \equiv \frac{dN_{\alpha\beta}}{dt dE_\nu} = \ \dots \ = \frac{\kappa}{E_\nu} \sum_{k,l} e^{-i\frac{L\Delta m^2_{kl}}{2E_\nu}} \int d\Pi_{P'} \mathcal{M}^P_{\alpha k} \bar{\mathcal{M}}^P_{\alpha l} \int d\Pi_D \mathcal{M}^D_{\beta k} \bar{\mathcal{M}}^D_{\beta l}$$

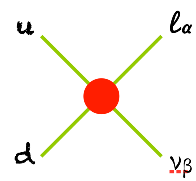
- The rest is "straightforward":
  specify the Lagrangian and calculate the production & detection amplitudes.





$$\mathcal{M}^P_{\alpha k} \equiv \mathcal{M}(S \to X_\alpha \nu_k) \qquad \mathcal{M}^D_{\beta k} \equiv \mathcal{M}(\nu_k T \to Y_\beta)$$

- SMEFT / LEFT → $O = O\,(\theta_i, \Delta m^2, \varepsilon_j)$



Oscillations in EFT

- Oscillation observable calculated in the LEFT: $O = O\,(\theta_i,\ \Delta m^2,\ \varepsilon_j)$

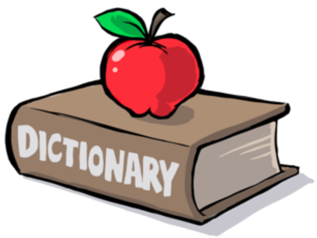
  [A. Falkowski, MGA, & Z. Tabrizi, JHEP'20]

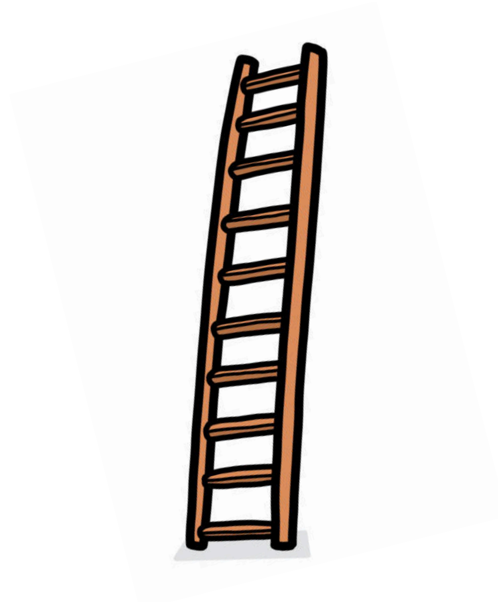
- Choose your favourite oscillation experiment:

$$O = O\,(\theta_i,\ \Delta m^2,\ \varepsilon_j) \Longrightarrow \varepsilon_j$$

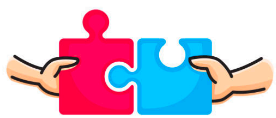
- Now you use the EFT ladder / dictionary

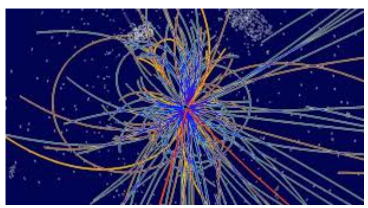
$$\epsilon_\Gamma = f\left(c_6^i \frac{v^2}{\Lambda^2}\right)$$

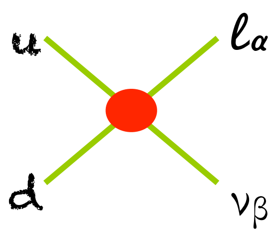




- Compare and combine with other searches.





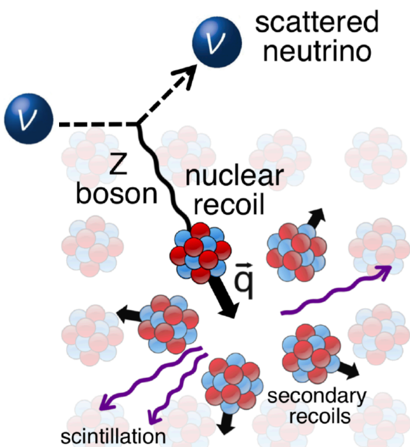


EFT analysis of NP at COHERENT

- COHERENT observed for the first time CEνNS (Coherent Elastic Neutrino-Nucleus Scattering): $\nu N \to \nu N$

- It occurs for E_ν small enough so that the neutrino does not resolve the nucleus → CEνNS cross section enhanced by N^2.
  Theoretically known since the 70's
  [Freedman'74; Kopeliovich & Frankfurt'74]

- Extremely challenging experimentally (very small nuclear recoil)

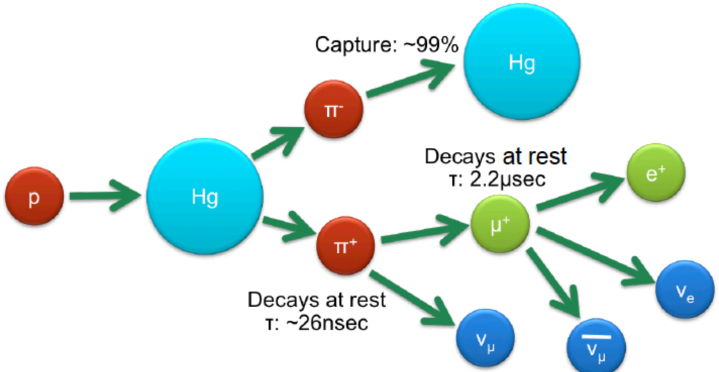


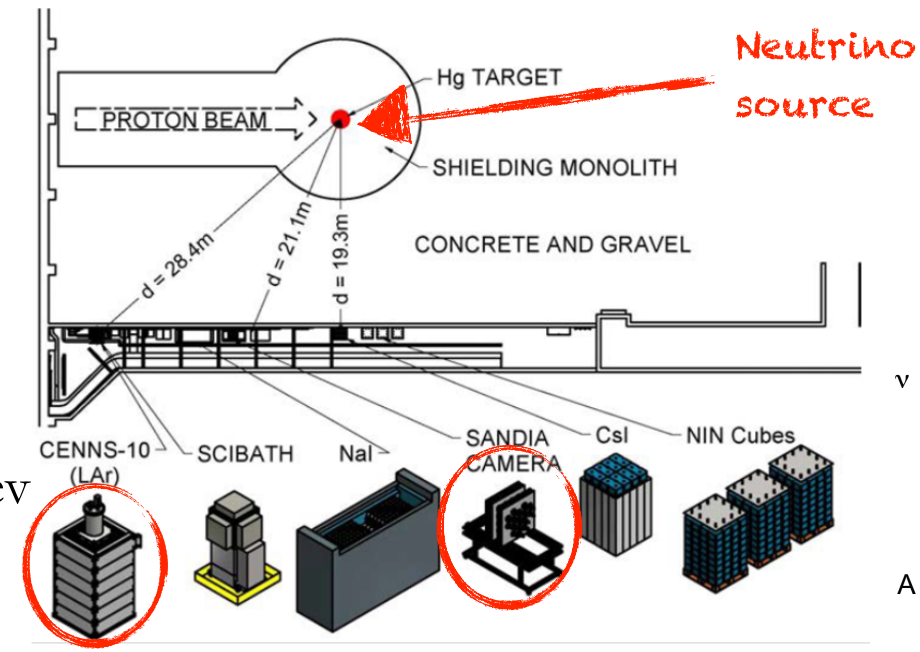
[from COHERENT coll.]

[Akimov et al.'17]


[Image credit: Duke U.]

EFT analysis of NP at COHERENT





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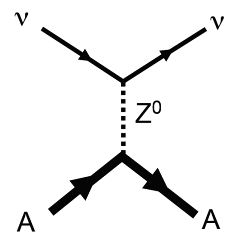
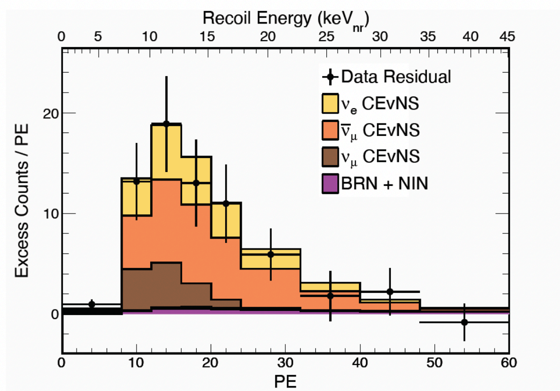
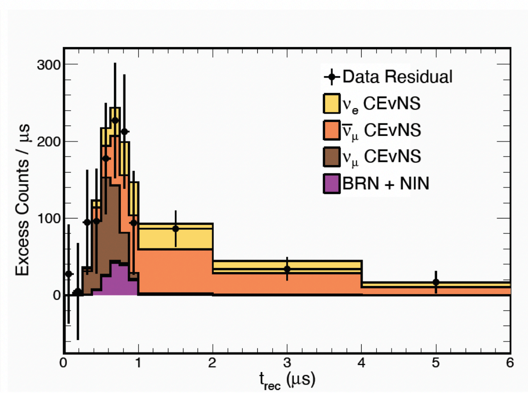


[from Scholberg's talk at IPA18]

$\pi^+ \to \mu^+ \, \nu_\mu$ (prompt)

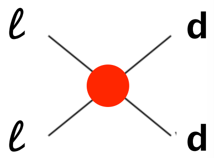
$\hookrightarrow \mu^+ \to e^+ \, \bar{\nu}_\mu \, \nu_e$ (delayed)



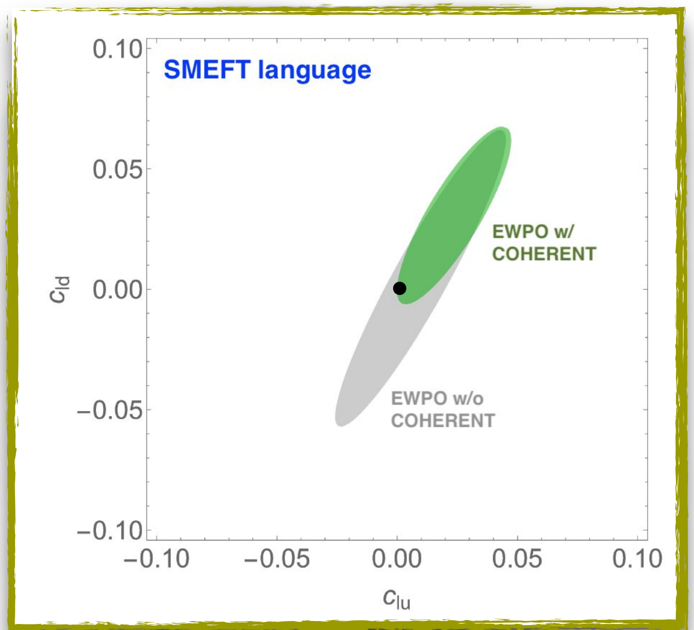


COHERENT in the SMEFT

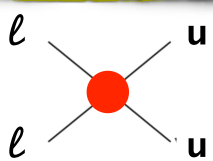
- COHERENT is an Electroweak Precision Observable



$\bar{\ell}\gamma_\mu \ell \ \bar{d}\gamma^\mu d$



$\bar{\ell}\gamma_\mu \ell \ \bar{u}\gamma^\mu u$



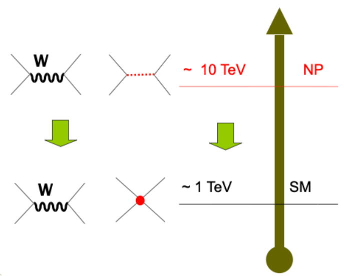
18 free parameters
"Flavor-blind" SMEFT
(→ $U(3)^5$ symmetry)

[Breso-Pla, Falkowski, MGA, Monsálvez-Pozo, 2301.07036 JHEP]

~~Outline~~ Summary

$$\mathcal{L} = -\frac{1}{4} F_{\mu\nu} F^{\mu\nu} + i \bar{\Psi} \not{D} \psi + h.c + \bar{\Psi}_i y_{ij} \psi_j \phi + h.c. + |D_\mu \phi|^2 - V(\phi)$$

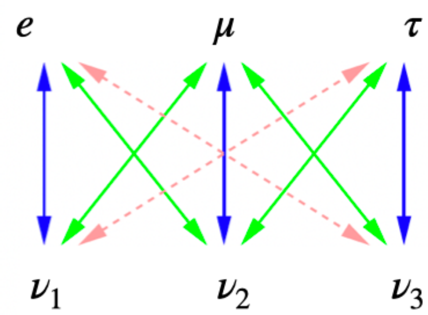
- SM → EW
- BSM:
  - EFT
  - SMEFT
  - LEFT



$$\mathscr{L}_{multi-TeV} = \mathscr{L}\left(\phi_{SM}, \Phi_{BSM}\right)$$

$$\mathscr{L}_{SMEFT} = \mathscr{L}_{SM} + \sum C_6^i \mathcal{O}_6^i + \ldots$$

- Neutrino physics




NEUTRINO
NEUTRINO
NEUTRINO
Credit: Sandbox Studio, Chicago

Thanks!