Standard Model (SM) & Beyond the SM physics

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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
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.

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 \((F = ma)\)
  Number of balls? masses, charges, etc? Initial conditions? **Force???** → prediction

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

\[
F_1 = F_2 = G \frac{m_1 m_2}{r^2}
\]

= Quantum Field Theory (QFT)

Which fields? Masses, charges? Initial conditions? **Lagrangian???** → prediction
QFT in 1 min

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

- The properties & interactions of the fields are captured by the **Lagrangian**
  The evolution of the system is determined by minimization of the action: \( \delta S = 0 \).

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

  \[
  S = \int d^4x \ L[\phi_i(x), \partial_\mu \phi_i(x)] \\
  \delta S = 0 \\
  \frac{\partial L}{\partial \phi_i} - \partial^\mu \left( \frac{\partial L}{\partial (\partial^\mu \phi_i)} \right) = 0
  \]

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

- Loop diagrams → Infinities? → OK in some theories ("renormalization")
QFT (1st) example: QED

- QED = QFT describing the interaction of electrons and photons

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

- Most successful scientific theory ever?

\[ F_{\mu\nu} \equiv \partial_\mu A_\nu - \partial_\nu A_\mu \]
QED from the gauge principle

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

\[ \mathcal{L}_0 = i \bar{\psi}(x) \gamma^\mu \partial_\mu \psi(x) - m \bar{\psi}(x) \psi(x). \]

- This Lagrangian is invariant under global U(1) transformations (Q\(\theta\) = arbitrary real constant)

\[ \psi(x) \xrightarrow{U(1)} \psi'(x) \equiv \exp \{iQ\theta\} \psi(x), \]

- Gauge principle: U(1) = local symmetry [ \(\theta = \theta(x)\) ]

This requires the introduction of a new spin-1 field:

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

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

- Thus:

\[ \mathcal{L} \equiv i \bar{\psi}(x) \gamma^\mu D_\mu \psi(x) - m \bar{\psi}(x) \psi(x) - \frac{1}{4} F_{\mu\nu}(x) F^{\mu\nu}(x). \]
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 $\rightarrow$ QED Lagrangian (including gauge field!)

- Electroweak theory:
  
  - Chiral fermions (with their transf. properties) + $SU(2)_L \times U(1)_Y$
  
  \[
  \begin{array}{c|cc|cc|c}
  \text{Quarks} & (u) & u_R & d_R \\
  \text{Leptons} & (\nu_\ell) & \ell_R & \ell^\pm_\ell \\
  \end{array}
  \]
  (+ $Y_i$ hypercharges)

  - A scalar doublet (Higgs) added to accommodate masses
    \[\varphi \equiv \left( \begin{array}{c} \varphi^+ \\ \varphi^0 \end{array} \right)\]

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

  Quarks have 3 colors $\rightarrow$ triplets of $SU(3)_c$
  Leptons have no color $\rightarrow$ singlets of $SU(3)_c$
Standard Model Lagrangian

Fermions + scalars (with their transformation properties)

\[ SU(3)_C \times SU(2)_L \times U(1)_Y \]

\[ \mathcal{L}_{SM}(x) \]

<table>
<thead>
<tr>
<th>Field</th>
<th>SU(3)$_C$</th>
<th>SU(2)$_L$</th>
<th>U(1)$_Y$</th>
<th>Name</th>
<th>Spin</th>
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<tr>
<td>(u_L)</td>
<td>3</td>
<td>2</td>
<td>1/6</td>
<td>LH u &amp; d quarks (doublet)</td>
<td>1/2</td>
</tr>
<tr>
<td>(d_L)</td>
<td>3</td>
<td>1</td>
<td>2/3</td>
<td>RH up quark</td>
<td>1/2</td>
</tr>
<tr>
<td>(\nu_L)</td>
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<td>1</td>
<td>-1/3</td>
<td>RH down quark</td>
<td>1/2</td>
</tr>
<tr>
<td>(e_L)</td>
<td>1</td>
<td>2</td>
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</tr>
<tr>
<td>(f^+ \phi)</td>
<td>1</td>
<td>1</td>
<td>-1</td>
<td>RH electron</td>
<td>1/2</td>
</tr>
<tr>
<td>(\phi^0)</td>
<td>1</td>
<td>2</td>
<td>1/2</td>
<td>Higgs field</td>
<td>0</td>
</tr>
</tbody>
</table>
Standard Model Lagrangian

Fermions + scalars
(with their transformation properties)

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

$$\mathcal{L}_{SM}(x)$$

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

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

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

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

$$W_{\mu\nu}^i = \partial_\mu W_{\nu}^i - \partial_\nu W_{\mu}^i - g e^{ijk} W_{\mu}^j W_{\nu}^k$$

$$D_\mu X = \partial_\mu X + i g_S G^{a}_{\mu} T^a X + i g_L W_{\mu}^i \sigma^i_2 X + i g_Y B_{\mu} X X$$
Standard Model Lagrangian

\[ \mathcal{L}_{SM} = - \frac{1}{4} G^{a \mu \nu} G_{a \mu \nu} - \frac{1}{4} W^k_{\mu \nu} W^k_{\mu \nu} - \frac{1}{4} B^{\mu \nu} B_{\mu \nu} - \bar{\theta} G^{a \mu \nu} \tilde{G}_{a \mu \nu} - i \sum_j \bar{f} D_\mu \gamma^\mu f \\
- (\bar{\tilde{e}} Y_e \varphi e + \bar{\tilde{q}} \varphi Y_d d + \bar{\tilde{q}} \varphi Y_u u) + h.c. \\
+ \left( D_\mu \varphi \right)^\dagger (D^\mu \varphi) - \mu^2 (\varphi^\dagger \varphi) - \lambda (\varphi^\dagger \varphi)^2 \]
SM Lagrangian: charged currents

\[-i \sum_f \bar{f} D_\mu \gamma^\mu f \rightarrow -i \sum_{f=\ell,q} \bar{f} \left( i g_2 \frac{\sigma^i}{2} W^i_\mu \right) \gamma^\mu f\]

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

\[
\mathcal{L}_{CC} = -\frac{g}{2\sqrt{2}} \left\{ W^i_\mu \left[ \bar{u} \gamma^\mu (1 - \gamma_5) d + \bar{e} \gamma^\mu (1 - \gamma_5) e \right] + \text{h.c.} \right\}
\]
**SM Lagrangian: neutral currents**

- $B_\mu$ & $W^3_\mu$ mix $\rightarrow A_\mu$ (massless) & $Z_\mu$ (massive) are the mass eigenstates after EWSB.

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

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

- $A_\mu$ has QED interactions if
  - the hypercharges have the right values ($Y_f = Q_f - T^f_3$), and
  - the gauge couplings satisfy $g_Y \cos \theta_w = e$.

\[
\mathcal{L}_{NC} = -e A_\mu \sum_k \bar{\psi}_k \gamma^\mu Q_k \psi_k + \mathcal{L}^Z_{NC}
\]

\[
Q_1 \equiv \begin{pmatrix}
    Q_{u/\nu} & 0 \\
    0 & Q_{d/e}
\end{pmatrix}
\]

\[
Q_2 = Q_{u/\nu}, \quad Q_3 = Q_{d/e}
\]
\[ ( \begin{pmatrix} W_\mu^3 \\ B_\mu \end{pmatrix} ) \equiv \begin{pmatrix} \cos \theta_W & \sin \theta_W \\ -\sin \theta_W & \cos \theta_W \end{pmatrix} \begin{pmatrix} Z_\mu \\ A_\mu \end{pmatrix} \]

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

- \( B_\mu \) & \( W_\mu^3 \) mix → \( A_\mu \) (massless) & \( Z_\mu \) (massive) are the mass eigenstates after EWSB.

- \( A_\mu \) has QED interactions: \( Y_f = Q_f - T_3^f \), and \( g_Y \cos \theta_w = e \).

- Weak neutral currents (NC) interactions: \( Z_\mu \)

\[ \mathcal{L}_{NC}^Z = -\frac{e}{2 \sin \theta_W \cos \theta_W} Z_\mu \left\{ \bar{\psi}_1 \gamma^\mu \sigma_3 \psi_1 - 2 \sin^2 \theta_W \sum_k \bar{\psi}_k \gamma^\mu Q_k \psi_k \right\} \]

\[ = -\frac{e}{2 \sin \theta_W \cos \theta_W} Z_\mu \sum_f \bar{f} \gamma^\mu (\nu_f - a_f \gamma_5) f \]

\[ a_f = T_3^f \]

\[ \nu_f = T_3^f (1 - 4|Q_f| \sin^2 \theta_W) \]

- No quark-lepton universality;
- LH & RH fermions involved
SM Lagrangian: neutral currents

- $B_\mu$ & $W^3_\mu$ mix $\rightarrow A_\mu$ (massless) & $Z_\mu$ (massive) are the mass eigenstates after EWSB.

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

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

- $A_\mu$ has QED interactions: $Y_f = Q_f - T^f_3$, and $g_Y \cos \theta_w = e$.

- Weak neutral currents (NC) interactions: $Z_\mu$
Standard Model Lagrangian

\[ \mathcal{L}_{SM} = - \frac{1}{4} G^a_{\mu\nu} G^a_{\mu\nu} - \frac{1}{4} W^k_{\mu\nu} W^k_{\mu\nu} - \frac{1}{4} B^{\mu\nu} B_{\mu\nu} - \tilde{\theta} G^{a\mu\nu} \tilde{G}^{a\mu\nu} \\
- i \sum_f \bar{f} D_\mu \gamma^\mu f \\
- (\bar{c} Y_\ell \phi e + \bar{\ell} \phi \bar{Y}_d d + \bar{q} \phi Y_u u) + h.c. \\
+ \left( D_\mu \phi \right)^\dagger \left( D^\mu \phi \right) - \mu^2 (\phi^\dagger \phi) - \lambda (\phi^\dagger \phi)^2 \]
SM Lagrangian: gauge self interactions

\[-\frac{1}{4} W^{\mu\nu} W_{\mu\nu} \rightarrow \]

\[\mathcal{L}_3 = ie \left\{ (\partial^\mu W^\nu - \partial^\nu W^\mu) W_\mu^\dagger A_\nu - (\partial^\mu W^\nu_{\dagger} - \partial^\nu W^\mu_{\dagger}) \right\} W_\mu A_\nu + W_\mu W_\nu^\dagger \left( \partial^\mu A^\nu - \partial^\nu A^\mu \right) \]

\[+ ie \cot \theta_W \left\{ (\partial^\mu W^\nu - \partial^\nu W^\mu) W_\mu^\dagger Z_\nu - (\partial^\mu W^\nu_{\dagger} - \partial^\nu W^\mu_{\dagger}) \right\} W_\mu Z_\nu + W_\mu W_\nu^\dagger \left( \partial^\mu Z^\nu - \partial^\nu Z^\mu \right) \]

\[\mathcal{L}_4 = -e^2 \cot \theta_W \left\{ 2W_\mu^\dagger W^\mu Z_\nu A^\nu - W_\mu^\dagger Z^\mu W_\nu A^\nu - W_\mu^\dagger A^\mu W_\nu Z^\nu \right\} \]

\[- e^2 \left\{ W_\mu^\dagger W^\mu A^\nu A^\nu - W_\mu^\dagger A^\mu W_\nu A^\nu \right\} + e^2 \cot^2 \theta_W \left\{ W_\mu^\dagger W^\mu Z_\nu Z^\nu - W_\mu^\dagger Z^\mu W_\nu Z^\nu \right\} \]

\[- \frac{e^2}{2 \sin^2 \theta_W} \left\{ (W_\mu^\dagger W^\mu)^2 - W_\mu^\dagger W^\mu W_\nu W_\nu \right\} \]

→ 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

\[ \mathcal{L}_{SM} = - \frac{1}{4} G^{a\mu\nu} G_{a}^{\mu\nu} - \frac{1}{4} W^{k\mu\nu} W_{k}^{\mu\nu} - \frac{1}{4} B^{\mu\nu} B_{\mu\nu} - \tilde{\theta} G^{a\mu\nu} \tilde{G}_{a}^{\mu\nu} - i \sum_{f} \bar{f} D_{\mu} \gamma^{\mu} f \\
- (\bar{\ell} Y_{e} \phi e + \bar{q} \phi Y_{d} d + \bar{q} \phi Y_{u} u) + h.c. + \left( D_{\mu} \phi \right)^{\dagger} (D^{\mu} \phi) - \mu^{2} (\phi^{\dagger} \phi) - \lambda (\phi^{\dagger} \phi)^{2} \]

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

\[ W_{\mu\nu}^{i} = \partial_{\mu} W_{\nu}^{i} - \partial_{\nu} W_{\mu}^{i} - g \epsilon^{ijk} W_{\mu}^{j} W_{\nu}^{k} \]
\[ D_{\mu} X = \partial_{\mu} X + i g_{s} G_{\mu}^{a} T^{a} X + i g_{L} W_{\mu}^{a} \sigma_{\mu}^{a} X + i g_{Y} B_{\mu} X X \]
\[ \mathcal{L}_{SM} = -\frac{1}{4} G^{a\mu\nu} G_{\mu\nu}^a - \frac{1}{4} W^{k\mu\nu} W_{\mu\nu}^k - \frac{1}{4} B^{\mu\nu} B_{\mu\nu} - \tilde{\theta} G^{a\mu\nu} \tilde{G}^a_{\mu\nu} \]

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

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

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

**Scalar sector**

(15 free parameters…)

\[ W_{\mu \nu}^i = \partial_\mu W_{\nu}^i - \partial_\nu W_{\mu}^i - g \epsilon^{ijk} W_{\mu}^j W_{\nu}^k \]

\[ D_\mu X = \partial_\mu X + ig_S G^a_\mu T^a X + ig_L W^i_\mu \sigma^i_\mu X + ig_Y B_\mu X X \]
In the SM Lagrangian, mass terms break gauge symmetry.

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

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.
The SM Lagrangian is invariant under rotations in $\Phi$ space

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

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

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

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

Unitarity gauge ($\varphi_i = 0$)

Higgs vacuum expectation value (VEV) $\rightarrow$ EW scale
The SM Lagrangian is invariant under rotations in $\Phi$ space.

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

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

$$D_\mu \varphi = \left( \partial_\mu + i g_L \frac{\sigma^i}{2} W^i_\mu + i g_Y Y_\varphi B_\mu \right) \varphi$$

$$\frac{\sigma^i}{2} W^i_\mu = \frac{1}{2} \begin{pmatrix} W^3_\mu & \sqrt{2} W^i_\mu \\ \sqrt{2} W^i_\mu & -W^3_\mu \end{pmatrix}$$

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

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

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

Counting d.o.f.: $4 \rightarrow 1$ (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).
The SM Lagrangian is invariant under rotations in $\Phi$ space.

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

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

$$D_\mu \phi = \left( \partial_\mu + i g_L \frac{\sigma^i}{2} W^i_\mu + i g_Y Y_\phi B_\mu \right) \phi$$

$$\frac{g_L^2}{2} \frac{W^{\dagger}_\mu W^\mu}{4} + \frac{g_L^2}{8 \cos^2 \theta_w} Z^\dagger_\mu Z^\mu$$

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

$$\frac{1}{2} \partial_\mu h \partial^\mu h + M^2_W W^{\dagger}_\mu W^\mu \left\{ 1 + 2 \frac{h}{v} + \frac{h^2}{v^2} \right\} + \frac{1}{2} M^2_Z Z^{\dagger}_\mu Z^\mu \left\{ 1 + 2 \frac{h}{v} + \frac{h^2}{v^2} \right\}$$

Couplings proportional to masses squared!
The SM Lagrangian is invariant under rotations in \( \Phi \) space.

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

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

\[
D_\mu \varphi = \left( \partial_\mu + ig_L \frac{\sigma^i}{2} W^i_\mu + ig_Y Y_\varphi B_\mu \right) \varphi
\]

\[
\frac{\sigma^i}{2} W^i_\mu = \frac{1}{2} \begin{pmatrix} W^3_\mu & \sqrt{2} W^1_\mu \\ \sqrt{2} W^1_\mu & -W^3_\mu \end{pmatrix}
\]

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

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

What about fermion masses?
Standard Model Lagrangian

\[ \mathcal{L}_{SM} = - \frac{1}{4} G^{a\mu\nu} G_{a}^{\mu\nu} - \frac{1}{4} W^{k\mu\nu} W_{k}^{\mu\nu} - \frac{1}{4} B^{\mu\nu} B_{\mu\nu} - \bar{\theta} G^{a\mu\nu} \tilde{G}_{a}^{\mu\nu} \]

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

\[- (\bar{\epsilon} Y_{e} \varphi e + \bar{q} \varphi Y_{d} d + \bar{q} \bar{\varphi} Y_{u} u ) + h.c. \]

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

Scalar sector
(15 free parameters...)

\[ W_{\mu\nu}^{i} = \partial_{\mu} W_{\nu}^{i} - \partial_{\nu} W_{\mu}^{i} - g \epsilon^{ijk} W_{\mu}^{j} W_{\nu}^{k} \]

\[ D_{\mu} X = \partial_{\mu} X + i g_{s} G_{\mu}^{a} T^{a} X + i g_{L} W_{\mu}^{i} \sigma_{i}^{j} X + i g_{Y} B_{\mu} X X \]
SM Lagrangian: masses (fermions)

- 1-family case:

\[ \mathcal{L}_Y = - \left( \bar{\ell} Y_\ell \varphi e + \bar{q} \varphi Y_d d + \bar{q} \bar{\varphi} Y_u u \right) + h.c. \]
SM Lagrangian: masses (fermions)

- 1-family case:

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

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

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

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

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

- \( m_e = Y_e v / \sqrt{2} \)
- \( m_d = Y_d v / \sqrt{2} \)
- \( m_u = Y_u v / \sqrt{2} \)

(PS: no mass for the neutrinos)
In the real case there are 3 families, and $Y_f$ are matrices (only connection between families in the SM before EWSB)

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

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

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

$$\bar{d}_L M_{\text{diag}} d_R \quad \text{[same for } u_L, u_R, e_L, e_R\text{]}$$

NC "unaffected":
$$Z^\mu \bar{f}'_L \gamma_\mu f'_L = Z^\mu \bar{f}'_L \gamma_\mu f'_L \quad \text{[idem for RH]} \rightarrow \text{No FCNC}$$

CC affected (only for quarks):
$$W^\mu_\mu \bar{u}'_L \gamma_\mu d'_L = W^\mu_\mu \bar{u}'_L \gamma_\mu U^L_{u} U^L_{d} d_L \equiv W^\mu_\mu \bar{u}'_L \gamma_\mu V_{CKM} d_L$$
The diagonalization of the quark masses has moved the many parameters in the Yukawa sector (H_{ff}) to the CC interaction $\rightarrow$ Very rich "flavor physics"!

\[
\mathcal{L}_{CC} = -\frac{g}{2\sqrt{2}} \left\{ W^\dagger_\mu \left[ \sum_{ij} \bar{u}_i \gamma^\mu (1 - \gamma_5) V_{ij} d_j + \sum_l \bar{\nu}_l \gamma^\mu (1 - \gamma_5) l \right] \right\} + \text{h.c.}
\]

The CKM matrix: 3 angles + 1 phase

\[
V = \begin{pmatrix}
\cos \theta_C & \sin \theta_C \\
-\sin \theta_C & \cos \theta_C
\end{pmatrix}
\]

The diagonalization of the lepton Yukawa has no physical consequences ($\rightarrow$ no LFV)
The CKM matrix is unitary (by construction)

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

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

\[ \mathcal{L}_{SM} = -\frac{1}{4} G^{a\mu\nu} G_{\mu\nu}^a - \frac{1}{4} W^{k\mu\nu} W_{\mu\nu}^k - \frac{1}{4} B^{\mu\nu} B_{\mu\nu} - \bar{\theta} G^{a\mu\nu} \tilde{G}_{\mu\nu}^a \]

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

\[-(\bar{\epsilon} Y_e \phi e + \bar{q} \phi Y_d d + \bar{q} \bar{\phi} Y_u u) + h.c.\]

\[+ \left( D_\mu \phi \right) ^\dagger \left( D^\mu \phi \right) - \mu^2 (\phi ^\dagger \phi) - \lambda (\phi ^\dagger \phi)^2\]

**Scalar sector**

(15 free parameters...)

\[ W_{\mu\nu}^i = \partial_\mu W_{\nu}^i - \partial_\nu W_{\mu}^i - g \epsilon^{ijk} W_{\mu}^j W_{\nu}^k \]

\[ D_\mu X = \partial_\mu X + i g_s G^{a\mu}_{\mu} T^a X + i g_L W^i_{\mu} \sigma^i_{\mu} X + i g_Y B_\mu X X \]
SM Lagrangian: masses

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

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

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

\[ M_h = \sqrt{-2\mu^2} = \sqrt{2\lambda} v \]
SM Lagrangian: masses

\[ \mathcal{L}_S = \left( D_\mu \phi \right)^\dagger \left( D^\mu \phi \right) - \mu^2 \left( \phi^\dagger \phi \right) - \lambda \left( \phi^\dagger \phi \right)^2 \]

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

\[ M_h = \sqrt{-2\mu^2} = \sqrt{2\lambda} v \]
SM Lagrangian: free parameters

- 3 gauge couplings ($g_s, g, g'$)
- Higgs potential: $\mu^2, h$
- 9 fermion masses (up, down & charged leptons)
- 4 CKM parameters: 3 angles + 1 CP phase
- 1 Theta term (?)

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

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

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

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

$V_{CKM} =$

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

$D_\mu X = \partial_\mu X + ig_s G^a_\mu T^a X + ig_L W^i_\mu g^i_2 X + ig_Y B_\mu Y X$
EW phenomenology

- Observables:
  \[ O = f(g_L, g_Y, \mu^2, h) \]

- In general, one should do a global fit to extract \( g, g', \mu^2, h \) (p-value OK?)

- However, there are 4 measurements that are much more precise than the rest: \( \alpha, G_F, M_Z, M_h \):
  \[
  \begin{align*}
  1/\alpha &= 137.035999180(10) \\
  G_F &= 1.1663788(6) \times 10^{-5} \text{GeV}^{-2} \\
  M_Z &= 91.1876(21) \text{GeV} \\
  M_h &= 125.30(13) \text{GeV}
  \end{align*}
  \]

- Thus one can proceed in 2 steps:
  \[
  (\alpha, G_F, M_Z, M_h) \rightarrow \text{fix EW parameters}
  \]
  
  For the rest of observables, we compare the **SM prediction** with the **measurement**
Chi2min~17
(dof = 15)
p value = 0.34
[w/o the CDF mW]

\[ \sin^2 \theta_{\text{lep}}^{\text{eff}} \equiv \frac{1}{4} \left( 1 - \frac{\nu_\ell}{\alpha_\ell} \right) \]
๏ 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:**
  $L(e, \mu, \tau, \nu_l) = 1$, zero for the rest.

- **Lepton flavor:**
  $L_i(e_i, \nu_i) = 1$, zero for the rest.

- More formally:
  global symmetries, e.g. $f \to e^{i\beta/3}f$ ($f = u, d, q$)

- 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 ($\Delta B = 1$).
    More complicated processes (e.g. deuteron decay) are extremely suppressed by CKM, $G_F$ factors, …
    We are safe :)

![Diagram of Sphaleron](image)
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 ($\nu_i \rightarrow \nu_j$) 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!]
    \[
    (A, Z) \rightarrow (A, Z + 2) + 2e^- \]
Symmetries & asymmetries

- Observation: huge matter-antimatter asymmetry.

- Sakharov conditions to generate a non-zero matter-antimatter asymmetry
  - B violation $\rightarrow$ SM: yes! (EW sphalerons)
  - C & CP violation $\rightarrow$ SM?
  - Out of equilibrium $\rightarrow$ 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.

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

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

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

- 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:

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

- 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~\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:

\[ \mathcal{L}_{SM} = -\frac{1}{4} G^{a \mu \nu} G_{\mu \nu}^a - \frac{1}{4} W^{k \mu \nu} W_{\mu \nu}^k - \frac{1}{4} B^{\mu \nu} B_{\mu \nu} - \tilde{\theta} G^{a \mu \nu} \tilde{G}_{\mu \nu}^a \]

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

- (\bar{e} Y_e \varphi e + \bar{\bar{q}} \varphi Y_d d + \bar{\bar{q}} \varphi Y_u u) + h.c.

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

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

- Strong experimental limits on EDMs: \( \tilde{\theta} \lesssim 10^{-12} \) !!??

- 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).
Observation: huge matter-antimatter asymmetry.

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

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

Specific BSM model

\[ \mathcal{L}_{BSM} = \mathcal{L}(\phi_{SM}, \Phi_{BSM}) \]

Effective Field Theory (EFT) approach
Detour: EFT

Some distribution of electric charges

Near observer, $L \sim R$, needs to know the position of every charge to describe electric field in her proximity.

Far observer, $r \gg R$, can instead use multipole expansion:

$$V(\vec{r}) = \frac{Q}{r} + \frac{\vec{d} \cdot \vec{r}}{r^3} + \frac{Q_{ij} r_i r_j}{r^5} + \ldots$$

$$\sim \frac{1}{r} \quad \sim \frac{R}{r^2} \quad \sim \frac{R^2}{r^3}$$

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)

\[ \mathcal{L}_{SM} \quad (EW \text{ theory}) \]

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

\[ q = p_1 - k_2 \]

\[ q^2 \lesssim m_\mu^2 \ll m_W^2 \]

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

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

+ higher-dim terms

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

Wilson coefficient
Detour: EFT in QFT (example)

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

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

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

\( q = p_1 - k_2 \)

\( q^2 \lesssim m_\mu^2 \ll m_W^2 \)

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

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

+ higher-dim terms

Wilson coefficient

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

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

\[ \mathcal{L}_{\text{eff}}(x) = \sum_i C_i \mathcal{O}_i \]

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

EFT = Model-independent approach ≠ Assumption independent
SMEFT: assumptions

1. QFT

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

3. Gauge symmetry: local
   $SU(3) \times SU(2) \times U(1)$ symmetry
SMEFT: assumptions

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

1. QFT

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

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

1. QFT

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

3. Gauge symmetry: local SU(3)xSU(2)xU(1) symmetry
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 ($\rightarrow$ R-SMEFT), axions ($\rightarrow$ ALP-SMEFT), light dark matter, …
- In fact it's wrong (graviton!) but unlikely to be relevant for EW physics ($\rightarrow$ GRSMEFT).

1. QFT

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

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

1. QFT

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

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

- 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 $v \to 0$) [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 $\sim 4 \pi v \sim 3$ TeV $\to$ mass gap! (Assumption #2)

- Reasonable assumption, given the apparent mass gap.
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 is the result of very conservative & parsimonious assumptions
Building the SMEFT
Building the SMEFT

Building blocks:

\[ G_{\mu}^{a}, \, W_{\mu}^{k}, \, B_{\mu}, \, q, \, u, \, d, \, \ell, \, e, \, \phi \]

Rules

\[ SU(3)_{C} \times SU(2)_{L} \times U(1)_{Y} \]

Example:

\[ \mathcal{L} = C \left( \phi^\dagger \phi \right)^3 \]
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 $[\mathcal{L}] = E^4 \rightarrow \mathcal{L} \supset C_D \mathcal{O}_D$ where $[C_D] \sim c_D / \Lambda^{4-D}$
- Its contribution to a (dimensionless) amplitude associated to a process with $E \gg m$

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

- Thus, for $E \ll \Lambda$:
  - 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.

$$\mathcal{L} = \mathcal{L}_{D \leq 4} + \mathcal{L}_5 + \mathcal{L}_6 + \mathcal{L}_7 + \ldots$$
Building the SMEFT

\[ \mathcal{L} = \mathcal{L}_{D\leq 4} + \mathcal{L}_5 + \mathcal{L}_6 + \mathcal{L}_7 + \ldots \]

\[ \sum_i C^i_6 \phi^i_6 \]

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

\[ \mathcal{L} = \mathcal{L}_{D\leq 4} + \mathcal{L}_5 + \mathcal{L}_6 + \mathcal{L}_7 + \ldots \]

Extra comments:

- This power counting allows us to define SMEFT at the quantum level:
  - The SMEFT is non renormalizable
  - However, it is renormalizable at 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.
The first contribution appears at D=2, where we find only one operator:

\[ \mathcal{L} = L_2 + L_3 + L_4 + L_5 + L_6 + L_7 + \ldots \]

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

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

- \( \rightarrow \) "Hierarchy problem".

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

\[ \mathcal{L} = \mathcal{L}_2 + \mathcal{L}_3 + \mathcal{L}_4 + \mathcal{L}_5 + \mathcal{L}_6 + \mathcal{L}_7 + \ldots \]

- There are no operators.

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

\[ \mathcal{L}_M = -\frac{1}{2} m_M \bar{\nu}_R^c \nu_R + h.c., \quad \nu^c \equiv C \bar{\nu}^T \]
Building the SMEFT

\[ \mathcal{L} = \mathcal{L}_2 + \mathcal{L}_3 + \mathcal{L}_4 + \mathcal{L}_5 + \mathcal{L}_6 + \mathcal{L}_7 + \ldots \]

- 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 \( \sim O(1) \)
  - All* coefficients have been measured
  - Interaction size OK in the bosonic sector (gauge and \( H^4 \))
  - EFT predicts: \( Y_f \sim \mathcal{O}(1) \rightarrow m_f \sim \nu \), \( V_{ij} \sim \mathcal{O}(1) \) \( \times \)
    \rightarrow Flavor\ puzzle
  - *All except the theta term
    \rightarrow Strong CP problem

\[ \mathcal{L}_{SM} \supset - \tilde{\theta} G^{a \mu \nu} \tilde{G}^a_{\mu \nu} \]
Building the SMEFT

\[ \mathcal{L} = \mathcal{L}_2 + \mathcal{L}_3 + \mathcal{L}_4 + \mathcal{L}_5 + \mathcal{L}_6 + \mathcal{L}_7 + \ldots \]

- Only one operator (Weinberg‘79)

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

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

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

\[ \ell \equiv \begin{pmatrix} \nu_L \\ e_L \end{pmatrix} \]

- 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

\[ \mathcal{L}_5 = \frac{[c_5]_{pr}}{\Lambda} \left( \tilde{\phi}^\dagger \ell_\rho \right)^T C \left( \tilde{\phi}^\dagger \ell_\rho \right) + h.c. \rightarrow m_\nu \sim 2 c_5 v^2 / \Lambda \]

- Oscillation data \( \rightarrow \Delta m^2 \).
  Other experiments (KATRIN!) /observations \( \rightarrow \) bounds on \( m \).
  All in all, \( m \sim O(0.01) \) eV. Thus:

\[ \frac{v^2}{\Lambda} \sim 0.1 \text{ eV} \rightarrow \Lambda \sim 10^{15} \text{ GeV} \]

- The mass gap is certainly OK

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

\[ D = 6 \rightarrow \frac{v^2}{\Lambda^2} \sim 10^{-26} \]
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 $\Lambda_L$ associated to B-L violating physics (D=5, 7, …)
- A (hopefully) not so high scale, $\Lambda$, associated to B-L conserving physics (D=6, 8, …)

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

PS: Outside the SMEFT paradigm there are other explanations for $m_\nu$
E.g., SM + $\nu_R$ → one has D=3 Majorana & D=4 yukawas (→ Dirac mass).
First B-L conserving corrections to the SM.

One finds 63 operators [Grzadkowski et al., 1008.4884]

Flavor structure → 3045 coefficients

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

<table>
<thead>
<tr>
<th>$X^3$</th>
<th>$\varphi^6$ and $\varphi^4D^2$</th>
<th>$\psi^2\varphi^3$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$Q_G$</td>
<td>$(\varphi^1 \varphi^3)$</td>
<td>$(\varphi^1 \varphi^3)(i\gamma_\mu \gamma_5)$</td>
</tr>
<tr>
<td>$Q_{\bar{G}}$</td>
<td>$(\varphi^1 \varphi^3 \varphi^4)$</td>
<td>$(\varphi^1 \varphi^3)(\bar{q}_\mu \gamma_5)$</td>
</tr>
<tr>
<td>$Q_W$</td>
<td>$(\varphi^1 D^3 \varphi)(\varphi^1 D_\mu \varphi)$</td>
<td>$(\varphi^1 \varphi^3)(\bar{q}_\mu \gamma_5)$</td>
</tr>
<tr>
<td>$Q_{\bar{W}}$</td>
<td>$(\varphi^1 D^3 \varphi)(\varphi^1 D_\mu \varphi)$</td>
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</tbody>
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<tr>
<th>$X^2\varphi^2$</th>
<th>$\psi^2X\varphi$</th>
<th>$\psi^2\varphi^2D$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$Q_{eW}$</td>
<td>$(i\gamma_5 \sigma_{\mu\nu} e_\mu)(i\gamma_\mu \gamma_5)$</td>
<td>$(\bar{q}<em>\mu \gamma_5 e</em>\mu)(i\gamma_\mu \gamma_5)$</td>
</tr>
<tr>
<td>$Q_{eB}$</td>
<td>$(\bar{q}<em>\mu \gamma_5 \sigma</em>{\mu\nu} e_\mu)(i\gamma_\mu \gamma_5)$</td>
<td>$(\bar{q}<em>\mu \gamma_5 \sigma</em>{\mu\nu} e_\mu)(i\gamma_\mu \gamma_5)$</td>
</tr>
<tr>
<td>$Q_{eC}$</td>
<td>$(\bar{q}<em>\mu \gamma_5 \sigma</em>{\mu\nu} e_\mu)(i\gamma_\mu \gamma_5)$</td>
<td>$(\bar{q}<em>\mu \gamma_5 \sigma</em>{\mu\nu} e_\mu)(i\gamma_\mu \gamma_5)$</td>
</tr>
<tr>
<td>$Q_{eG}$</td>
<td>$(\bar{q}<em>\mu \gamma_5 \sigma</em>{\mu\nu} e_\mu)(i\gamma_\mu \gamma_5)$</td>
<td>$(\bar{q}<em>\mu \gamma_5 \sigma</em>{\mu\nu} e_\mu)(i\gamma_\mu \gamma_5)$</td>
</tr>
<tr>
<td>$Q_{eQ}$</td>
<td>$(\bar{q}<em>\mu \gamma_5 \sigma</em>{\mu\nu} e_\mu)(i\gamma_\mu \gamma_5)$</td>
<td>$(\bar{q}<em>\mu \gamma_5 \sigma</em>{\mu\nu} e_\mu)(i\gamma_\mu \gamma_5)$</td>
</tr>
<tr>
<td>$Q_{e\bar{Q}}$</td>
<td>$(\bar{q}<em>\mu \gamma_5 \sigma</em>{\mu\nu} e_\mu)(i\gamma_\mu \gamma_5)$</td>
<td>$(\bar{q}<em>\mu \gamma_5 \sigma</em>{\mu\nu} e_\mu)(i\gamma_\mu \gamma_5)$</td>
</tr>
<tr>
<td>$Q_{eB^{-}}$</td>
<td>$(\bar{q}<em>\mu \gamma_5 \sigma</em>{\mu\nu} e_\mu)(i\gamma_\mu \gamma_5)$</td>
<td>$(\bar{q}<em>\mu \gamma_5 \sigma</em>{\mu\nu} e_\mu)(i\gamma_\mu \gamma_5)$</td>
</tr>
<tr>
<td>$Q_{eB^{+}}$</td>
<td>$(\bar{q}<em>\mu \gamma_5 \sigma</em>{\mu\nu} e_\mu)(i\gamma_\mu \gamma_5)$</td>
<td>$(\bar{q}<em>\mu \gamma_5 \sigma</em>{\mu\nu} e_\mu)(i\gamma_\mu \gamma_5)$</td>
</tr>
</tbody>
</table>

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

<table>
<thead>
<tr>
<th>$(LL)(LL)$</th>
<th>$(RR)(RR)$</th>
<th>$(LL)(RR)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$Q_{ee}$</td>
<td>$(\bar{e}<em>\mu \gamma_5 e</em>\mu)(\bar{e}<em>\mu \gamma_5 e</em>\mu)$</td>
<td>$(\bar{e}<em>\mu \gamma_5 e</em>\mu)(\bar{e}<em>\mu \gamma_5 e</em>\mu)$</td>
</tr>
<tr>
<td>$Q_{uu}$</td>
<td>$(\bar{u}<em>\mu \gamma_5 u</em>\mu)(\bar{u}<em>\mu \gamma_5 u</em>\mu)$</td>
<td>$(\bar{u}<em>\mu \gamma_5 u</em>\mu)(\bar{u}<em>\mu \gamma_5 u</em>\mu)$</td>
</tr>
<tr>
<td>$Q_{dd}$</td>
<td>$(\bar{d}<em>\mu \gamma_5 d</em>\mu)(\bar{d}<em>\mu \gamma_5 d</em>\mu)$</td>
<td>$(\bar{d}<em>\mu \gamma_5 d</em>\mu)(\bar{d}<em>\mu \gamma_5 d</em>\mu)$</td>
</tr>
<tr>
<td>$Q_{c\ell}$</td>
<td>$(\bar{c}<em>\mu \gamma_5 e</em>\mu)(\bar{c}<em>\mu \gamma_5 e</em>\mu)$</td>
<td>$(\bar{c}<em>\mu \gamma_5 e</em>\mu)(\bar{c}<em>\mu \gamma_5 e</em>\mu)$</td>
</tr>
<tr>
<td>$Q_{d\ell}$</td>
<td>$(\bar{d}<em>\mu \gamma_5 e</em>\mu)(\bar{d}<em>\mu \gamma_5 e</em>\mu)$</td>
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Table 3: Four-fermion operators.
Building the SMEFT

\[ \mathcal{L} = \mathcal{L}_2 + \mathcal{L}_3 + \mathcal{L}_4 + \mathcal{L}_5 + \mathcal{L}_6 + \mathcal{L}_7 + \ldots \]

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

\[
\left( \varphi^\dagger i D_\mu \varphi \right) \left( l_p \gamma^\mu l_r \right)
\]

\[
l^i = \begin{pmatrix} v^i_L \\ e^i_L \end{pmatrix}
\]

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

\[
D_\mu = i \partial_\mu - i g_s \frac{\lambda^A}{2} G^A_\mu - i g \frac{\sigma^a}{2} W^a_\mu - i g' Y B_\mu
\]
Building the SMEFT

\[ \mathcal{L} = \mathcal{L}_2 + \mathcal{L}_3 + \mathcal{L}_4 + \mathcal{L}_5 + \mathcal{L}_6 + \mathcal{L}_7 + \ldots \]

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

\[
\begin{pmatrix}
\bar{l}_p \gamma^\mu \tau^I l_r \\
\bar{q}_s \gamma^\mu \tau^I q_t
\end{pmatrix}
\]

\[
\begin{array}{cccccc}
e & u & e & u & \nu & d \\
\times & & \times & & \times & \\
e & u & \nu & d & \nu & d
\end{array}
\]

\[
\begin{pmatrix}
v^i_L \\
e^i_L
\end{pmatrix}
\]

\[
\varphi = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v + h(x) \end{pmatrix}
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\[
D_\mu = i \partial_\mu - i g_s \frac{\lambda^A}{2} G^A_\mu - i g \frac{\sigma^a}{2} W^a_\mu - i g' Y B_\mu
\]
Building the SMEFT

\[ \mathcal{L} = \mathcal{L}_2 + \mathcal{L}_3 + \mathcal{L}_4 + \mathcal{L}_5 + \mathcal{L}_6 + \mathcal{L}_7 + \ldots \]

- 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 \( \Lambda \)
Building the SMEFT

\[ \mathcal{L} = \mathcal{L}_2 + \mathcal{L}_3 + \mathcal{L}_4 + \mathcal{L}_5 + \mathcal{L}_6 + \mathcal{L}_7 + \ldots \]

- First B-L conserving corrections to the SM.
- One finds 63 operators [Grzadkowski et al., 1008.4884].
- Flavor structure leads to 3045 coefficients.
- Extremely rich phenomenology: colliders, flavor, low-energy searches (beta decay!), neutrino physics, proton decay, CP violation, ...

- All results compatible with zero → Bounds on \( \Lambda \)
Building the SMEFT

\[ \mathcal{L} = \mathcal{L}_2 + \mathcal{L}_3 + \mathcal{L}_4 + \mathcal{L}_5 + \mathcal{L}_6 + \mathcal{L}_7 + \ldots \]

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

---

Exponential growth with D

For complex operators complex conjugates counted as separate operators

Henning et al. arXiv:1512.03433

---

\( N_f = 1 \)

\( N_f = 3 \)

Weinberg’79
Lehman’14
Grzadkowski et al.’10
Li et al.’21
Li et al.’20

Li et al’22
(Code valid at any dimension)
Building the SMEFT

\[ \mathcal{L} = \mathcal{L}_2 + \mathcal{L}_3 + \mathcal{L}_4 + \mathcal{L}_5 + \mathcal{L}_6 + \mathcal{L}_7 + \ldots \]

- 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

\[ \mathcal{L} = \mathcal{L}_{SM} + \text{Majorana neutrino masses} + \sum \sigma_{6}^{i} \mathcal{O}_{6}^{i} + \ldots \]
Matching to NP models

\[ \mathcal{L}_{\text{multi-TeV}} = \mathcal{L}(\phi_{SM}, \Phi_{BSM}) \]

\[ \mathcal{L}_{\text{SMEFT}} = \mathcal{L}_{SM} + \sum C^i_6 \mathcal{O}^i_6 + \ldots \]

\[ C^i_6 = f(g_{NP}, M_{NP}) \]
SMEFT: an efficient approach

- 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

**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

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

\[
\frac{d\Gamma}{dq^2} = \frac{d\Gamma_{SM}}{dq^2} + f(\alpha_4; q^2)
\]
Linear vs. Quadratic

\[ L = L_2 + L_3 + L_4 + L_5 + L_6 + L_7 + \ldots \]

- 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):

  \[ M = M_{SM} \left( 1 + c_6 \mathcal{O} \left( \frac{v^2}{\Lambda^2} \right) + c_8 \mathcal{O} \left( \frac{v^4}{\Lambda^4} \right) + \ldots \right) \]

  \[ R \sim |M|^2 = |M_{SM}|^2 \left( 1 + c_6 \mathcal{O} \left( \frac{v^2}{\Lambda^2} \right) + c_6^2 \mathcal{O} \left( \frac{v^4}{\Lambda^4} \right) + c_8 \mathcal{O} \left( \frac{v^4}{\Lambda^4} \right) + \ldots \right) \]

- 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
  \[ \mathcal{L}_{\text{eff}} = \mathcal{L}_{\text{SM}} + \sum C_i O_i \]

- Calculate the observable you like in the EFT, e.g. \( O = O_{\text{SM}} + 3C_1 - C_6 \)

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

- Implications for your observable?
  e.g. error matrix \( \rightarrow 3C_1 - C_6 = 0.02(4) \)
  - \( \sim 4\% \) 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 \( \rightarrow \) example.
Example: LEP2 WW vs Higgs

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

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

(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

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

\[ O = O_{\text{SM}} + O(c_1, c_2, \ldots, c_{65}) \rightarrow \text{Correlated bounds on } c_i \]
### SMEFT fit to EWPO

\[ \left( \frac{\delta g_{\mu}^{[W]}}{\sigma} \right)_{ee} = \begin{pmatrix} -1.8(2.6) \\ -0.6(2.2) \\ 0.2(3.5) \\ -0.21(28) \\ -0.42(27) \\ 0.2(1.2) \\ 0.0(1.4) \\ -0.09(59) \\ -3.8(8.1) \\ -7(22) \\ 4(29) \\ -13(35) \\ 10(120) \\ -1.5(3.6) \\ -3.3(5.3) \\ 14(27) \\ 34(46) \\ 3.2(1.7) \\ 22(8.8) \end{pmatrix} \times 10^{-3}, \]

\[ \left( \frac{\delta g_{\mu}^{[W]}_{\mu\mu}}{\sigma} \right)_{ee} = \begin{pmatrix} [c_{\mu}]_{\mu\mu} \\ [c_{\mu}]_{\mu\mu} \\ [c_{\mu}]_{\mu\mu} \\ [c_{\mu}]_{\mu\mu} \\ [c_{\mu}]_{\mu\mu} \\ [c_{\mu}]_{\mu\mu} \\ [c_{\mu}]_{\mu\mu} \\ [c_{\mu}]_{\mu\mu} \\ [c_{\mu}]_{\mu\mu} \\ [c_{\mu}]_{\mu\mu} \end{pmatrix} = 1.03(38) \\
-0.22(22) \\
0.19(38) \\
-0.56(80) \\
0.1(2.0) \\
11.4(6.8) \\
0.3(2.2) \\
-0.2(2.1) \\
0.2(2.3) \\
-0.60(68) \\
2(11) \\
-2.3(7.2) \\
1.7(7.2) \\
-1(12) \\
2(21) \\
1.5(19) \\
19(15) \right) \times 10^{-2}, \]

\[ \left( \frac{c_{\mu}^{(3)}}{\sigma} \right)_{\mu\mu} = \begin{pmatrix} \hat{c}_{\mu\mu}^{(3)} \end{pmatrix} = \begin{pmatrix} 0.25(8.7) \\ -2(18) \\ -3.1(9.4) \\ -2(17) \\ -0.017(60) \\ -0.018(57) \\ 0.023(9) \\ 0.2(3.2) \\ -61(32) \\ 2.4(8.0) \\ -300(130) \\ -21(28) \\ -87(16) \\ 250(140) \\ -8.5(8.0) \\ -1(10) \\ -3.1(5.1) \\ 18(20) \end{pmatrix} \times 10^{-2}, \]

\[ \left( \frac{c_{\mu\ell}}{\sigma} \right)_{\mu\mu} = \begin{pmatrix} \hat{c}_{\mu\ell} \end{pmatrix} = \begin{pmatrix} -0.05(95) \\ -0.3(2.8) \\ -0.3(1.2) \\ 0.93(85) \end{pmatrix} \times 10^{-2}. \]

\[ \bar{e}_{\gamma}\mu e \cdot \tilde{q}_{\gamma} \gamma^{\mu} q \]

\[ \bar{\ell}_{\gamma}\mu \ell \cdot \tilde{q}_{\gamma} \gamma^{\mu} q \]

+ correlation matrix (65x65 !!)

\[ O = O_{\text{SM}} + O (c_{1}, c_{2}, \ldots, c_{65}) \rightarrow \chi^{2} = \chi^{2} (c_{i}) \]

**Precision:**

\[ 0(0.01 - 1)\% !! \]
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*
  \[ \mathcal{L}_{\text{eff}} = \mathcal{L}_{\text{SM}} + \sum C_i O_i \]

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Down the EFT stairs

**Top down**
- Known theory at high-E
- EFT at low-E

**Bottom up**
- EFT that includes high-E effects
- Low-E symmetries & fields

SMEFT
Down the EFT stairs

**Top down**
- Known theory at high-E
- EFT at low-E
- SMEFT

**Bottom up**
- EFT that includes high-E effects
- Low-E symmetries & fields
- SMEFT
Down the EFT stairs

\[ \mathcal{L}_{\text{eff}} = \mathcal{L}_{\text{SM}} \]

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

+ higher-dim terms

\[ G_F = \frac{g^2}{4\sqrt{2} m_W^2} \]
Down the EFT stairs

\[ \mathcal{L}_{\text{eff}} = \mathcal{L}_{\text{SM}} \]

\[ + C_5 \, \mathcal{O}_5 + \sum_i C_{6}^i \, \mathcal{O}_{6}^i + \ldots \]

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

\[ + \text{higher-dim terms} \]

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

\[ \epsilon = g(C_{6}^i) \]
The SMEFT has $\sim$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 $\sim m_e/m_\mu$)

$$\mathcal{L}_{\text{eff}} = \mathcal{L}_{\text{SM}} + C_5 \phi_5 + \sum_i C_6^i \phi_6^i + \ldots$$

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

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

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

$$\epsilon = g(C_6^i)$$
**SMEFT → Low-energy EFT**

<table>
<thead>
<tr>
<th>MeV</th>
<th>Terms</th>
</tr>
</thead>
<tbody>
<tr>
<td>10 TeV</td>
<td>γ, g, W, Z, ν_i, e, μ, τ + u, d, s, c, b, t + h</td>
</tr>
<tr>
<td>100 GeV</td>
<td>γ, g, ν_i, e, μ, τ + u, d, s, c, b</td>
</tr>
<tr>
<td>5 GeV</td>
<td>γ, g, ν_i, e, μ, τ + u, d, s, c</td>
</tr>
<tr>
<td>2 GeV</td>
<td>γ, ν_i, e, μ + hadrons</td>
</tr>
</tbody>
</table>

- 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**

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

\[ \mathcal{L}_{SMEFT} = \mathcal{L}_{SM} + \sum_i \frac{c_i^6}{\Lambda^2} \mathcal{O}_6^i + \ldots \]

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

\[ \mathcal{L}_{\pi, N, \ldots} = \ldots \]

\[ \frac{\epsilon_\Gamma}{v^2} = f \left( \frac{c_i^6}{\Lambda^2} \right) \rightarrow \epsilon_\Gamma = f \left( \frac{c_i^6 v^2}{\Lambda^2} \right) \]
\[
\mathcal{L} (x) = \mathcal{L} (\text{SM fields, bSM fields}) \\
\mathcal{L}_{\text{SMEFT}} = \mathcal{L}_{\text{SM}} + \sum_i \frac{c_i^6}{\Lambda^2} \sigma^i_6 + \ldots \\
\mathcal{L}_{\text{WFEFT}} \supset -\frac{2V_{ud}}{v^2} \left\{ (1+\epsilon_L) (\bar{u} \gamma^\mu P_L d) (\bar{e} \gamma_\mu P_L \nu_e) + \epsilon_R (\bar{u} \gamma^\mu P_R d) (\bar{e} \gamma_\mu P_L \nu_e) + \frac{1}{2} \epsilon_S (\bar{u} d) (\bar{e} P_L \nu_e) - \frac{1}{2} \epsilon_P (\bar{u} \gamma_5 d) (e P_L \nu_e) + \frac{1}{4} \epsilon_T (\bar{u} \sigma^{\mu\nu} P_L d) (\bar{e} \sigma_{\mu\nu} P_L \nu_e) + \text{h.c.} \right\}, \\
\epsilon_\Gamma = f^i \left( \frac{c_i^6 v^2}{\Lambda^2} \right) 
\]
The SMEFT → Beta-decay LEFT

\[ \mathcal{L}_{\text{SMEFT}} = \mathcal{L}_{\text{SM}} + \sum_i \frac{c^i_6}{\Lambda^2} \mathcal{O}^i_6 + \ldots \]

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

\[ \epsilon_L \approx \frac{v^2}{\Lambda^2 V_{ud}} \left( V_{ud} [c^{(3)}_{H_1}]_{11} + V_{jd} [c^{(3)}_{H_2}]_{11} - V_{jd} [c^{(3)}_{lq}]_{111} \right) , \]

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

\[ \epsilon_S \approx -\frac{v^2}{2\Lambda^2 V_{ud}} \left( V_{jd} [c_{leq}]^*_{11} + [c_{ledq}]^*_{111} \right) , \]

\[ \epsilon_p \approx -\frac{v^2}{2\Lambda^2 V_{ud}} \left( V_{jd} [c_{leq}]^*_{111} - [c_{ledq}]^*_{1111} \right) , \]

\[ \epsilon_T \approx -\frac{2v^2}{\Lambda^2 V_{ud}} V_{jd} [c^{(3)}_{leq}]^*_{11} , \]

\[ \epsilon_\Gamma = f \left( \frac{c^i_6}{\Lambda^2} \right) \]
SMEFT → Beta-decay LEFT

\[ \mathcal{L}_{\text{SMEFT}} = \mathcal{L}_{\text{SM}} + \sum_i \frac{c_i^6}{\Lambda^2} \mathcal{Q}^i + \ldots \]

\[ \mathcal{L}_{\text{WEFT}} \supset - \frac{2 V_{ud}}{v^2} \left\{ (1 + \epsilon_L)(\bar{u} \gamma^\mu P_L d)(\bar{e} \gamma^\mu P_L \nu_e) + \epsilon_R(\bar{u} \gamma^\mu P_R d)(\bar{e} \gamma^\mu P_L \nu_e) \right. \\
\left. + \frac{1}{2} \epsilon_S(\bar{u} d)(\bar{e} P_L \nu_e) - \frac{1}{2} \epsilon_P(\bar{u} d)(e P_L \nu_e) \right. \\
\left. + \frac{1}{4} \epsilon_T(\bar{u} \sigma^{\mu \nu} P_L d)(\bar{e} \sigma_{\mu \nu} P_L \nu_e) + \text{h.c.} \right\} , \]

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

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

\[ \epsilon_S \approx - \frac{v^2}{2 \Lambda^2 V_{ud}} \left( V_{jd} [c_{lequ}]^*_{1nj1} + [c_{ledq}]^*_{1111} \right) , \]

\[ \epsilon_P \approx - \frac{v^2}{2 \Lambda^2 V_{ud}} \left( V_{jd} [c_{lequ}]^*_{1nj1} - [c_{ledq}]^*_{1111} \right) , \]

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

\[ \bar{e} L \gamma^\mu \nu_L \cdot \bar{u} R \gamma^\mu d_R \]

\[ i(\varphi^T e D_\mu \varphi)(\bar{u} \gamma^\mu d) \]

\[ \rightarrow \text{RH currents are lepton flavor universal! (SMEFT prediction)} \]
SMEFT $\rightarrow$ Beta-decay LEFT

\[ \mathcal{L}_{SMEFT} = \mathcal{L}_{SM} + \sum_i \frac{c_i^6}{\Lambda^2} \mathcal{O}_i^6 + \ldots \]

\[ \mathcal{L}_{WEFT} \supset -\frac{2V_{ud}}{v^2} \left\{ (1+\epsilon_L)(\bar{u}\gamma^\mu P_L d)(\bar{e}\gamma^\mu P_L \nu_e) + \epsilon_R(\bar{u}\gamma^\mu \gamma^\nu P_R d)(\bar{e}\gamma^\nu P_L \nu_e) \right. \]

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

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

\[ \ell \equiv \begin{pmatrix} \nu_L \\ e_L \end{pmatrix}, \quad q = \begin{pmatrix} u_L \\ d_L \end{pmatrix} \]

Reminder:

\[ \epsilon_L \approx \frac{v^2}{\Lambda^2 V_{ud}} \left( V_{ud} [c_{H_{I11}}^{(3)}]_{11} + V_{jd} [c_{H_{Ij}}^{(3)}]_{1j} - V_{jd} [c_{I_{ij}}^{(3)}]_{11j} \right), \]

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

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

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

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

\[ (\bar{e}e)(\bar{d}q) \]

\[ (\bar{e}_{a} e)\epsilon^{ab}(\bar{q}_{b} u) \]

\[ (\bar{e}_{a} \sigma^{\mu\nu} e)\epsilon^{ab}(\bar{q}_{b} \sigma_{\mu\nu} u) \]
SMEFT → Beta-decay LEFT

\[ \mathcal{L}_{\text{SMEFT}} = \mathcal{L}_{\text{SM}} + \sum_i \frac{c_i^6}{\Lambda^2} \mathcal{O}_i^6 + \ldots \]

\[ \mathcal{L}_{\text{WEFT}} \ni -\frac{2V_{ud}}{v^2} \left\{ (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{\nu}_\mu P_R \nu_e) \right\} \\
+ \frac{1}{2} \epsilon_S (\bar{u}d)(\bar{e}P_L \nu_e) - \frac{1}{2} \epsilon_p (\bar{\nu}_5 d)(eP_L) \\
+ \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.} \right\}.

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

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

\[ \epsilon_S \approx -\frac{v^2}{2\Lambda^2 V_{ud}} \left( V_{jd} [c_{leq}^{(3)}]_{1j1} + [c_{leq}^{(3)}]_{1111} \right), \]

\[ \epsilon_p \approx -\frac{v^2}{2\Lambda^2 V_{ud}} \left( V_{jd} [c_{leq}^{(3)}]_{1j1} - [c_{leq}^{(3)}]_{1111} \right), \]

\[ \epsilon_T \approx -\frac{2v^2}{\Lambda^2 V_{ud}} V_{jd} [c_{leq}^{(3)}]_{1j1} \].
LEFT from SMEFT

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

\[ \mathcal{L}_{SMEFT} = \mathcal{L}_{SM} + \sum_i \frac{c_i^i}{\Lambda^2} \mathcal{O}_6^i + \ldots \]

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

\[ \mathcal{L}_{\pi,N,\ldots} = \ldots \]

\[ \epsilon_{\Gamma} = f \left( \frac{c_i^i}{\Lambda^2} \right) \]
LEFT from SMEFT

\[ \mathcal{L}(x) = \mathcal{L} (\text{SM fields}, \ b\text{SM fields}) \]

\[ \mathcal{L}_{\text{SMEFT}} = \mathcal{L}_{\text{SM}} + \sum_i \frac{c_i^6}{\Lambda^2} \mathcal{O}_6^i + \ldots \]

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

\[ \text{~100 GeV?} \]

M. González-Alonso
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**

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

\[ \mathcal{L} = \mathcal{L}_2 + \mathcal{L}_3 + \mathcal{L}_4 + \mathcal{L}_5 + \mathcal{L}_6 + \mathcal{L}_7 + \ldots \]

[Jenkins et al., 1709.04486]
Beta-decay LEFT (not necessarily from SMEFT)

\[ L_{\text{WEFT}} \supset -\frac{2V_{ud}}{v^2} \left\{ (1 + \epsilon_L)(\bar{u}\gamma^\mu P_L d)(\bar{e}\gamma^\mu P_L \nu_e) + \epsilon_R(\bar{u}\gamma^\mu P_R d)(\bar{e}\gamma^\mu P_L \nu_e) + \frac{1}{2} \epsilon_S(\bar{u}d)(\bar{e}P_L \nu_e) - \frac{1}{2} \epsilon_P(\bar{u}\gamma_5 d)(eP_L \nu_e) + \frac{1}{4} \epsilon_T(\bar{u}\sigma^{\mu\nu} P_L d)(\bar{e}\sigma_{\mu\nu} P_L \nu_e) + \text{h.c.} \right\} , \]

RH currents are lepton flavor universal! (SMEFT prediction)

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

No new operators (SMEFT generates them all)*
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
  
\[
\pi^+ \rightarrow \mu^+ \nu_\mu \quad \nu_\mu n \rightarrow p \mu^- 
\]
  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

\[ L = -\frac{1}{4} F_{\mu\nu} F^{\mu\nu} + i \bar{\psi} \gamma^\mu \gamma^5 \psi + \text{h.c.} 
+ \bar{\psi}_d \gamma^\mu \chi \gamma^5 \psi + \text{h.c.} 
+ \partial_{\mu} \phi \partial^\mu \phi - V(\phi) \]
1973 (Gargamelle bubble chamber @ CERN): first observation of Neutral Current interactions (using neutrinos!)

\[ \bar{\nu}_\mu + N \rightarrow \bar{\nu}_\mu + \text{hadrons} \]

\[ \bar{\nu}_\mu + e^- \rightarrow \bar{\nu}_\mu + e^- \]
Neutrinos in the SM

- 1989 (before the $\nu_\tau$ discovery): LEP1

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

\[
\Gamma_{\text{inv}} = \Gamma_Z - \Gamma_{\text{had}} - \Gamma_{\mu+\tau+e}
\]

\[
N_\nu = 2.984 \pm 0.008
\]

(+NLO EW corrections)

\[
\Gamma(Z \to \bar{f}f) = N_f \frac{G_F M_Z^3}{6\pi \sqrt{2}} (|v_f|^2 + |a_f|^2)
\]
Neutrinos in the SM: masses

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

- 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

\[ \mathcal{L}_M = - \frac{1}{2} m_M \tilde{\nu}_L \nu_L + h.c., \quad \nu^c \equiv C \tilde{\nu}^T \]

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

\[ \mathcal{L}_Y = - \left( \bar{e} Y_e \phi e + \bar{q} \phi Y_d d + \bar{q} \tilde{\phi} Y_u u \right) + h.c. \]

\[ \phi \rightarrow \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v + h \end{pmatrix} \]

\[ \tilde{\phi} \rightarrow \frac{1}{\sqrt{2}} \begin{pmatrix} v + h \\ 0 \end{pmatrix} \]

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

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

- Additional reminders:
  - L is (accidentally) conserved, up to non-perturbative effects only relevant at high T
  - Same for Lepton flavor numbers: \( L_e, L_\mu, L_\tau \)
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
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.

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

$$-i \frac{d}{dt} |\nu\rangle = H |\nu\rangle$$

$$H = \begin{pmatrix}
E_1 & 0 & 0 \\
0 & E_2 & 0 \\
0 & 0 & E_3 
\end{pmatrix}$$

$$E_i = \sqrt{p^2_i + m_i^2} \approx p_i + \frac{m_i^2}{2p_i}$$
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.

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

\[
P_{\nu_e \rightarrow \nu_\mu} = |\langle \nu_\mu | \nu(L) \rangle |^2 = f \left( U_{ak}, \Delta m^2_{ij} \right)
\]

\[
P_{\nu_e \rightarrow \nu_\mu} = |\langle \nu_\mu | \nu(L) \rangle |^2 = \sin^2 2\theta \sin^2 \left( \frac{\Delta m^2_{21} L}{4E} \right)
\]

\[
\Phi \approx 1.3 \frac{\Delta m^2_{21}[eV^2] L[km]}{E[GeV]}
\]

- "Short" distance (or large energy): \( \Phi \ll 1 \rightarrow \text{no oscillation: } \sin^2 \Phi \approx 0 \)
- "Long" distance (or small energies): \( \Phi \gg 1 \rightarrow \text{oscillations averaged out: } \sin^2 \Phi \approx 1/2 \)
- Intermediate region: \( \Phi \sim 1 \rightarrow \text{oscillations!} \)
Neutrino oscillations

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

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

\[
U_{PMNS} = \begin{pmatrix}
    c_{12} c_{13} & s_{12} c_{13} & s_{13} e^{-i \delta_{13}} \\
    -s_{12} c_{23} + c_{12} s_{23} s_{13} e^{i \delta_{13}} & c_{12} c_{23} - s_{12} s_{23} s_{13} e^{i \delta_{13}} & s_{23} c_{13} \\
    s_{12} s_{23} - c_{12} c_{23} s_{13} e^{i \delta_{13}} & -c_{12} s_{23} - s_{12} c_{23} s_{13} e^{i \delta_{13}} & c_{23} c_{13}
\end{pmatrix}
\]

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

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

- Oscillation data:
  - $\Delta m^2_{sol} = \Delta m^2_{21} \equiv m_2^2 - m_1^2 \sim 7 \times 10^{-5}\text{eV}^2$
  - $|\Delta m^2_{atm}| = |m_3^2 - m_1^2| \sim 2 \times 10^{-3}\text{eV}^2$
  - Thus, at least 2 neutrinos are massive!
  - No sensitivity to the lightest mass (it could be massless)
  - The heaviest one is at least $\sim 0.05\text{eV}$.
Neutrino mass

- Oscillation data:
  - 3 non-degenerate neutrinos.
  - The heaviest one is at least \( \sim 0.05 \) 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 2\( \beta \) 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

\[ \mathcal{L} = \mathcal{L}_2 + \mathcal{L}_3 + \mathcal{L}_4 + \mathcal{L}_5 + \mathcal{L}_6 + \mathcal{L}_7 + \ldots \]

- Only one operator (Weinberg'79)

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

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

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

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

- 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).

\[
U = \begin{pmatrix}
1 & c_{23} & s_{23} \\
-c_{23} & s_{23} & c_{23} \\
-s_{13}e^{i\delta} & -c_{13}e^{-i\delta} & 1
\end{pmatrix}
\begin{pmatrix}
c_{12} & s_{12} \\
-s_{12} & c_{12} \\
1 & 0
\end{pmatrix}
\begin{pmatrix}
e^{i\alpha} & 0 \\
0 & e^{i\beta} \\
0 & 0
\end{pmatrix}
\]

\[
W_{\mu}^\dagger \bar{\nu}_L \gamma_\mu e'_L = W_{\mu}^\dagger \bar{\nu}_L \gamma_\mu U^L_L U^L e_L \equiv W_{\mu}^\dagger \bar{\nu}_L \gamma_\mu U_{\text{PMNS}} e_L
\]

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

- Minimal SM modification

<table>
<thead>
<tr>
<th>Fields</th>
<th>$\psi_1$</th>
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<th>$\psi_3$</th>
</tr>
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<tbody>
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<td>$d_R$</td>
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<tr>
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<td>$\ell_R$</td>
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- Then neutrinos obtain a mass exactly like the rest of particles (Higgs mechanism, EWSB)

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

- Minimal SM modification

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\[ Y_\nu \sim 10^{-13} \ll Y_\ell \sim 10^{-5} \]

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

\[ \mathcal{L}_M = -\frac{1}{2}m_M \bar{\nu}_R^c \nu_R + h.c., \quad \nu_R^c \equiv C \bar{\nu}_R^T \]

- It's not connected with EWSB. It would be a completely new scale.
- This term violates (perturbatively) Lepton number by 2 units (\(\rightarrow 0\nu\beta\beta\))
- No other SM particle can have such term
**SM + \( \nu_R \)**

- Minimal SM modification

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- One family: \( \nu_L \& \nu_R \) mix \( \rightarrow \nu_1 \) and \( \nu_2 \) are the massive eigenstates (2 Majorana particles).
  If \( m_M \gg v \) then \( \nu_2 \) is heavy \( \rightarrow \) D=5 SMEFT operator (see-saw)
Oscillation as precision experiments

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

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

<table>
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<tr>
<th></th>
<th>Normal Ordering (best fit)</th>
<th>Inverted Ordering (( \Delta \chi^2 = 7.1 ))</th>
</tr>
</thead>
</table>
|                    | bfp ±1σ  
| \( \sin^2 \theta_{12} \) | 0.304\( \pm 0.012 \) 0.269 → 0.343 | 0.304\( \pm 0.013 \) 0.269 → 0.343 |
| \( \theta_{13} /^\circ \) | 33.44\( \pm 0.77 \) 31.27 → 35.86 | 33.45\( \pm 0.78 \) 31.27 → 35.87 |
| \( \sin^2 \theta_{23} \) | 0.573\( \pm 0.029 \) 0.415 → 0.616 | 0.575\( \pm 0.019 \) 0.419 → 0.617 |
| \( \theta_{23} /^\circ \) | 49.2\( \pm 0.9 \) 40.1 → 51.7 | 49.3\( \pm 0.9 \) 40.3 → 51.8 |
| \( \sin^2 \theta_{13} \) | 0.02219\( \pm 0.00062 \) 0.02032 → 0.02410 | 0.02238\( \pm 0.00063 \) 0.02062 → 0.02428 |
| \( \theta_{13} /^\circ \) | 8.57\( \pm 0.12 \) 8.20 → 8.93 | 8.60\( \pm 0.12 \) 8.24 → 8.96 |
| \( \delta_{CP} /^\circ \) | 197\( \pm 27 \) 120 → 369 | 282\( \pm 26 \) 193 → 352 |
| \( \Delta m^2_{31} \) | 7.42\( \pm 0.21 \) 6.82 → 8.04 | 7.42\( \pm 0.21 \) 6.82 → 8.04 |
| \( \Delta m^2_{32} \) | +2.51\( \pm 0.026 \) +2.435 → +2.598 | -2.498\( \pm 0.028 \) -2.581 → -2.414 |

[Esteban et al., 2007.14792 JHEP]
Oscillation as precision experiments

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

\[ R_{\alpha\beta} \equiv \frac{dN_{\alpha\beta}}{dtdE_\nu} = \cdots = \frac{\kappa}{E_\nu} \sum_{k,l} e^{-i \frac{L \Delta m_{kl}^2}{2E_\nu}} \int d\Pi_P \mathcal{M}_P^{\alpha k} \mathcal{M}_P^{\alpha l} \int d\Pi_D \mathcal{M}_D^{\beta k} \mathcal{M}_D^{\beta l} \]

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

\[ \mathcal{L}_\nu \equiv \mathcal{L}(S \rightarrow X_\alpha \nu_k) \]

\[ \mathcal{M}_P^{\alpha k} \equiv \mathcal{M}(S \rightarrow X_\alpha \nu_k) \]

\[ \mathcal{M}_D^{\beta k} \equiv \mathcal{M}(\nu_k T \rightarrow Y_\beta) \]

- SMEFT / LEFT → 0 = 0 (\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:

  $O = O (\theta_i, \Delta m^2, \varepsilon_j) \xrightarrow{} \varepsilon_j$

- Now you use the EFT ladder / dictionary

  $\varepsilon_\Gamma = f \left( c_i^j \frac{v^2}{\Lambda^2} \right)$

- Compare and combine with other searches.
COHERENT observed for the first time CEvNS (Coherent Elastic Neutrino-Nucleus Scattering): $\nu N \rightarrow \nu N$

It occurs for $E_\nu$ small enough so that the neutrino does not resolve the nucleus $\rightarrow$ CEvNS cross section enhanced by $N^2$.
Theoretically known since the 70's
[Freedman'74; Kopeliovich & Frankfurt'74]

Extremely challenging experimentally (very small nuclear recoil)
EFT analysis of NP at COHERENT

[from Scholberg's talk at IPA18]

\[ \pi^+ \rightarrow \mu^+ \nu_\mu \text{ (prompt)} \]

\[ \mu^+ \rightarrow e^+ \bar{\nu}_\mu \nu_e \text{ (delayed)} \]
COHERENT in the SMEFT

- COHERENT is an Electroweak Precision Observable

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

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

SM → EW

BSM:
- EFT
- SMEFT
- LEFT

Neutrino physics

Summary

\[ L = -\frac{1}{4} F_{\mu\nu} F^{\mu\nu} + i \bar{\Psi} D \Psi + h.c. + \bar{\Psi} m_\chi \Psi + h.c. + \partial_i \phi^2 - V(\phi) \]

\[ \mathcal{L}_{\text{SMEFT}} = \mathcal{L}_{\text{SM}} + \sum C_i^i \phi^i + \ldots \]
Thanks!