The Standard Model of particle physics and beyond

- Lecture 3: Beyond the Standard Model -

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Summary of this lecture

1) Why to go beyond: experimental vs theoretical reasons
2) Experimental reasons
3) Theoretical reasons

Cooking... basically whatever you can imagine
Why to go beyond: experimental vs theoretical reasons
Experimental vs theoretical reasons

**Experimental hints**
- Neutrino masses
- Dark matter
- Baryon asymmetry of the universe

**Theoretical speculation**
- Whatever you can imagine, including:
  - Hierarchy problem
  - Unification
  - Flavor problem
  - ...
Experimental reasons

1) Neutrino masses
2) Dark matter
3) Baryon asymmetry of the universe
Experimental reason 1

Neutrino masses
Neutrinos in the SM

The Standard Model was built with the **assumption** of **massless neutrinos**

\[ m_\nu(SM) = 0 \]

- No **right-handed neutrinos**, and then no Dirac mass \[ \nu_R \]
- Minimal lepton sector
- Accidental lepton number (L) conservation

Our dear friends
Salam, Weinberg and Glashow
Where are my neutrinos??

Solar neutrino problem

\[ N_{\text{observed}} \approx \frac{1}{3} N_{\text{expected}} \]

Atmospheric neutrino problem

\[ \frac{N_\mu}{N_e} < 2 \]

Where are the missing neutrinos?
Neutrino oscillations

Nowadays there is a well established solution to these puzzles:

**Neutrino oscillation**

**Idea:** If neutrinos with definite flavor \((\nu_e, \nu_\mu, \nu_\tau)\) are not **mass eigenstates** they oscillate in their propagation

\[
|i\rangle = |\nu_e\rangle \quad \rightarrow \quad \text{Propagation} \rightarrow \quad |f\rangle = C_e|\nu_e\rangle + C_\mu|\nu_\mu\rangle + C_\tau|\nu_\tau\rangle
\]

And then, when one does a measurement, the probability of finding a given flavor is

\[
P(\nu_e \rightarrow \nu_i) \simeq \text{mixing}^2 \sin^2 \left(\frac{\Delta m^2 L}{4E}\right)
\]

\[\Rightarrow \text{Neutrinos must have non-zero masses and mixing angles!}\]
Leptonic mixing matrix

If neutrinos are massive: \( \nu_L = U_\nu \tilde{\nu}_L \) physical

And then, the leptonic charged current interaction Lagrangian becomes:

\[
\mathcal{L}^\ell_{cc} = \frac{g}{\sqrt{2}} \tilde{\nu}_L \gamma_\mu V_{PMNS} \hat{e}_L W^{+\mu} + \text{h.c.}
\]

\[
V_{PMNS} = U_\nu^\dagger U_e
\]

Pontecorvo-Maki-Nakagawa-Sakata matrix

Determines the relative size of different lepton flavor transitions in CC interactions. Measured in neutrino oscillation experiments.
How can we add neutrino masses to the SM?

Simplest way: just replicate what we do with the other fermions.

(1) Add right-handed neutrinos:

<table>
<thead>
<tr>
<th>Representation</th>
<th>$SU(3)_c$</th>
<th>$SU(2)_L$</th>
<th>$U(1)_Y$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\nu_R$</td>
<td>1</td>
<td>1</td>
<td>0</td>
</tr>
</tbody>
</table>

(2) Write Yukawa couplings:

$$\mathcal{L}_Y^\nu = Y_\nu \ell_L \tilde{\Phi} \nu_R + \text{h.c.}$$

(3) Generate neutrino masses through the Higgs VEV:

$$\mathcal{L}_m^\nu = M_\nu \bar{\nu}_L \nu_R + \text{h.c.}$$

However...
### SM particle masses

<table>
<thead>
<tr>
<th>Particle</th>
<th>Log10 ( m eV )</th>
</tr>
</thead>
<tbody>
<tr>
<td>neutrino</td>
<td>0</td>
</tr>
<tr>
<td>electron</td>
<td>5.71</td>
</tr>
<tr>
<td>muon</td>
<td>8.02</td>
</tr>
<tr>
<td>tau</td>
<td>9.23</td>
</tr>
<tr>
<td>u quark</td>
<td>6.6</td>
</tr>
<tr>
<td>d quark</td>
<td>6.85</td>
</tr>
<tr>
<td>s quark</td>
<td>8</td>
</tr>
<tr>
<td>c quark</td>
<td>9.08</td>
</tr>
<tr>
<td>b quark</td>
<td>9.6</td>
</tr>
<tr>
<td>t quark</td>
<td>11.24</td>
</tr>
<tr>
<td>W boson</td>
<td>10.9</td>
</tr>
<tr>
<td>Z boson</td>
<td>10.96</td>
</tr>
<tr>
<td>Higgs</td>
<td>11.06</td>
</tr>
</tbody>
</table>

The neutrino looks special, right?
Neutrinos have tiny masses

The SM must be extended to account for them
(and we should try to understand why they are small!)

- “Classical” seesaw
- Low scale seesaw (example: inverse seesaw)
- Radiative models (also scotogenic variations)
- SUSY with R-parity violation
- Dirac neutrinos
- …
Dirac vs Majorana

A brief détour...

Paul Dirac

\[ m_D \bar{f}_L f_R + \text{h.c.} = m_D \bar{f} f \]

\[ f \neq f^c \]

Ettore Majorana

\[ \frac{1}{2} m_M \bar{f}_X f_X + \text{h.c.} \]

\[ f = f^c \]

Only neutral fermions can be Majorana
The right-handed neutrino is a singlet under all symmetries: **Majorana masses are allowed!**

\[ \mathcal{L}^\nu_Y = Y_\nu \ell_L \tilde{\Phi} \nu_R + \frac{1}{2} \nu_R^c M_R \nu_R + \text{h.c.} \]

After SSB:

\[ \mathcal{L}_m = m_D \bar{\nu}_L \nu_R + \frac{1}{2} \nu_R^c M_R \nu_R + \text{h.c.} = \frac{1}{2} \chi^c \mathcal{M}_\chi \chi + \text{h.c.} \]

\[ \mathcal{M}_\chi = \begin{pmatrix} 0 & m_D \\ m_D^T & M_R \end{pmatrix} \]

We define \( \chi = \begin{pmatrix} \nu_L^c \\ \nu_R \end{pmatrix}^T \) which violates lepton number.
The right-handed neutrino is a singlet under all symmetries: Majorana masses are allowed!

\[ \mathcal{L}_Y^\nu = Y_\nu \ell_L \tilde{\Phi} \nu_R + \frac{1}{2} \overline{\nu_R^c} M_R \nu_R + \text{h.c.} \]

After SSB:

\[ \mathcal{L}_m^\nu = m_D \overline{\nu}_L \nu_R + \frac{1}{2} \overline{\nu_R^c} M_R \nu_R + \text{h.c.} = \frac{1}{2} \overline{\chi^c} \mathcal{M}_\chi \chi + \text{h.c.} \]

\[ \mathcal{M}_\chi = \begin{pmatrix} 0 & m_D \\ m_D^T & M_R \end{pmatrix} \quad \text{m}_D \ll M_R \quad \xrightarrow{\text{Type-I Seesaw}} \quad \widetilde{\mathcal{M}}_\chi \simeq \begin{pmatrix} m_{\text{light}} & 0 \\ 0 & M_{\text{heavy}} \end{pmatrix} \]

\[ m_{\text{light}} = -m_D^T \cdot M_R^{-1} \cdot m_D \]

\[ M_{\text{heavy}} = M_R \]

We define

\[ \chi = \begin{pmatrix} \nu_L^c \\ \nu_R \end{pmatrix}^T \]
The Seesaw mechanism

The Seesaw
Seesaw paradigm: Neutrino mass is generated at a very high scale

\[ m_\nu \propto \frac{v^2}{M_{SS}} \]

Naturally small if \( M_{SS} \gg v \)

(close to the GUT scale)
Open questions

What is the origin of neutrinos masses?
Are they Dirac or Majorana?
What is the absolute scale of neutrino masses?
What is the mass ordering?
Are there more than three neutrinos? Maybe sterile?
Is there CP violation in the lepton sector?
Experimental reason 2

Dark matter
Evidences for **Dark Matter** come from many different sources:

- Galactic rotation curves
- Clusters dynamics
- Gravitational lensing
- Cosmic microwave background
- Large scale structure simulations
- Bullet cluster
- ...
Evidences for Dark Matter

\[ V \text{ (km/s)} \]

\[ R \times 1000 \text{ ly} \]

Observations

- from starlight
- from 21 cm hydrogen

Expected from visible disk
Evidences for Dark Matter

Composition of the universe:

Remember:
DE is not the same as DM
Hypothesis: DM is made of particles

Requirements for the DM particle:

- **Electrically neutral**: Since DM is dark, it should not interact with photons, at least at tree-level. Otherwise they would scatter light becoming visible.

- **Colorless**: If DM particles were strongly interacting, like quarks, they would form bound states. This is strongly constrained by different cosmological searches.

- **Stable or long-lived**: We need the DM particles to be stable or long-lived (with a life-time of the order of the age of the universe) or otherwise they would have disappeared with the evolution of the universe.
Neutrinos: do not work... they destroy structures.

⇒ Beyond the SM
DM for particle physicists

**Neutrinos:** do not work... they destroy structures.

⇒ **Beyond the SM**

**Stabilization mechanism:** analogous to proton stability in the SM (protected by symmetry)
Neutrinos: do not work... they destroy structures.

⇒ Beyond the SM

Stabilization mechanism: analogous to proton stability in the SM (protected by symmetry)

Example: Scalar Singlet DM = SM + real scalar $S_{(1,1)_0} + \mathbb{Z}_2$

$S \rightarrow S' = -S$

$$\mathcal{L}_S = \frac{1}{2} \partial_\mu S \partial^\mu S - \frac{1}{2} \mu_S^2 S^2 - \frac{1}{4} \lambda_S S^4 - \frac{1}{2} \lambda_P S^2 |\Phi|^2$$
Experimental reason 3

Baryon asymmetry of the universe
The baryon asymmetry of the universe

Why is there **more matter than antimatter**?

\[ Y_B \equiv \frac{n_B - n_{\overline{B}}}{s} \bigg|_0 = (8.65 \pm 0.08) \times 10^{-11} \]

CMB + BBN:

If the universe has started from a state with equal number of baryons and antibaryons \( \Rightarrow \) The BAU must be generated dynamically

**Chuck Norris fact of the day**

*Chuck Norris lost his virginity before his dad*
Sakharov’s conditions

[ 1967, Sakharov ]

- **B violation**: baryon number must be violated in order to evolve from a state with $Y_B = 0$ to a current universe with $Y_B \neq 0$.

- **C and CP violation**: If either C or CP were conserved, processes involving baryons would proceed at the same rate as those involving antibaryons, thus compensating each other and leading to a vanishing overall effect.

- **Departure from thermal equilibrium**: In thermal equilibrium it is not possible to generate an asymmetry since direct ($A \rightarrow B$) and inverse ($A \leftarrow B$) processes would take place at the same rate.
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[ 1967, Sakharov ]

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In the SM

- Sphalerons
- Not enough
- Not enough (phase transition not 1st order)

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Andrei

Sakharov
Sakharov’s conditions

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**In the SM**

- **Sphalerons**
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Andrei Sakharov

Badly

Beyond the SM
Leptogenesis: Lepton asymmetry from out-of-equilibrium decay of heavy Majorana neutrinos converted into baryon asymmetry through sphaleron interactions.

Heavy neutrino decay

\[ N_1 \rightarrow \Phi \ell_\alpha \]
\[ N_1 \rightarrow \Phi^* \ell_\alpha \]

\[ \epsilon_{\alpha\alpha} = \frac{\Gamma (N_1 \rightarrow \Phi \ell_\alpha) - \Gamma (N_1 \rightarrow \Phi^* \ell_\alpha)}{\Gamma (N_1 \rightarrow \Phi \ell) + \Gamma (N_1 \rightarrow \Phi^* \ell)} \]

CP asymmetry

Out of equilibrium: expansion of the universe

relates the BAU with neutrino masses (seesaw)

Sphalerons

B asymmetry
Theoretical reasons

1) Hierarchy problem
2) Unification
3) Flavor problem
Theoretical reason 1

Hierarchy problem

It’s a little too hot for 125 GeV...
The hierarchy problem: perhaps the most influential driving force in particle physics in the last decades

Tree-level Higgs mass: \( m_h^2 = -2\mu^2 \)

Loop corrections?
The hierarchy problem: perhaps the most influential driving force in particle physics in the last decades

Tree-level Higgs mass: \( m_h^2 = -2\mu^2 \)

Loop corrections?

\[
-\lambda_S |h|^2 |S|^2
\]

\[
(\Delta m_h^2)_S \sim \lambda_S \int \frac{d^4p}{(2\pi)^4} \frac{1}{p^2 - m_S^2} \propto m_S^2
\]
The hierarchy problem: perhaps the most influential driving force in particle physics in the last decades

Tree-level Higgs mass: \( m_h^2 = -2\mu^2 \)

Loop corrections?

\[
-\lambda_S |h|^2 |S|^2 \\
(\Delta m_h^2)_S \sim \lambda_S \int \frac{d^4 p}{(2\pi)^4} \frac{1}{p^2 - m_S^2} \propto m_S^2
\]

\[
-\lambda_f h \bar{f} P_L f + \text{h.c.} \\
(\Delta m_h^2)_f \propto -|\lambda_f|^2 \int \frac{d^4 p}{(2\pi)^4} \frac{\text{TR}}{(p^2 - m_f^2)^2} \propto m_f^2
\]
The hierarchy problem

Suppose the new particles are very heavy \( m \sim 10^{16} \text{ GeV} \)

\[
(m^2_h)_{1\text{-loop}} = -2\mu^2 + (\Delta m^2_h)_S + (\Delta m^2_h)_f \\
\sim (100 \text{ GeV})^2 + (10^{16} \text{ GeV})^2 + (10^{16} \text{ GeV})^2 \sim (100 \text{ GeV})^2
\]

How come the final result is so much smaller than the individual terms?

“Naturalness problem”

Caused by a large hierarchy between energy scales
Remark

The hierarchy problem is **not** a problem of the SM *per se*

In fact, the SM does not have any hierarchy problem

The naturalness problem only appears when we add new physics at very high energies
Let us have another look at the scalar and fermion loops...

Observation:

\[
\begin{align*}
    m_s^2 &= m_f^2 \\
    \lambda_s &= |\lambda_f|^2
\end{align*}
\]

\[\implies\]

Exact cancellation between scalar and fermion contributions!

Note:
Other solutions exist
This is just the most popular one

Symmetry between scalars and fermions

Supersymmetry

(SUSY)
Supersymmetry

Supersymmetry is a symmetry that relates scalars and fermions

Duplication of the particle content
Example: electron (e) + selectron (ē)

If supersymmetry is realized in nature, it cannot be an exact symmetry

SUSY breaking
Ignorance about the mechanism: many free parameters

Supersymmetric models are typically supplemented with R-parity (a discrete symmetry)

Forbids L and B violating terms
Stabilizes the lightest supersymmetric particle (LSP): DM candidate
Characteristic collider signatures (pair production)
The MSSM

**SUPERSYMMETRY**

Standard particles  SUSY particles

Minimal Supersymmetric Standard Model (MSSM)

Minimal realistic model

And many other variations exist...
Experimental limits

Supersymmetry is a great theoretical idea... but nature does not seem to like it

Many SUSY searches at the Large Hadron Collider (LHC)

Results presented at the ICHEP’16 conference
Chicago, August 2016
Theoretical reason 2

Unification

The graph shows the relative strength of different forces (strong, electromagnetic, weak, electroweak, gravity) as a function of temperature (K). The forces are expected to unify at a certain temperature, marked as GUT force or “super force”. The graph indicates that gravity might be stronger at very high temperatures compared to the other forces.
Gauge coupling unification

In QFT: the strength of the interactions changes with the energy

Reminder:

\[ \alpha_i = \frac{g_i^2}{4\pi} \]

The SM gauge couplings approach a common region at high energies.

In the MSSM the coincidence is really good.

Unification?
Gauge coupling unification
Grand Unified Theories

Some properties of GUTs:

\[ SU(3)_c \times SU(2)_L \times U(1)_Y \supset G_{\text{GUT}} \]

The SM fermions are embedded into big multiplets of \( G_{\text{GUT}} \) [possibly including new particles]

The breaking of \( G_{\text{GUT}} \) is analogous to the breaking of \( G_{\text{SM}} \): Higgs mechanism

“Famous” GUTs: \( SU(5), SO(10) \) [1974, Georgi, Glashow, Fritzsch, Minkowski]

“Postdiction”: Charge quantization [why \( q_e + q_p = 0 \) ?]

Prediction: Proton decay [however: never observed]

for example \( p \to e^+ \pi^0 \)
Theoretical reason 3

Flavor problem
The flavor problem

Why are there 3 fermionic replicas?

What is the origin of the quark and lepton masses?

What is the origin of the observed patterns of the Yukawa couplings?
The flavor problem

Why are there 3 fermionic replicas?

What is the origin of the quark and lepton masses?

What is the origin of the observed patterns of the Yukawa couplings?

\[
|V_{\text{CKM}}| = \begin{pmatrix}
0.974254 & 0.22542 & 0.003714 \\
0.22529 & 0.973394 & 0.04180 \\
0.008676 & 0.04107 & 0.999118 \\
\end{pmatrix}
\]  
Quark mixing matrix
Almost diagonal
Small mixing angles

\[
|V_{\text{PMNS}}| = \begin{pmatrix}
0.813449 & 0.561872 & 0.150333 \\
0.467118 & 0.47709 & 0.744437 \\
0.346556 & 0.675785 & 0.650549 \\
\end{pmatrix}
\]  
Lepton mixing matrix
No clear structure
Large mixing angles
The flavor problem

A flavor ("horizontal") symmetry at work?
Summary of the lecture
Exercises
The Type-II Seesaw

SM extended with a scalar triplet

\[ \Delta \sim (1, 3)_1 \quad \text{under} \quad SU(3)_c \times SU(2)_L \times U(1)_Y \]

\[ \Delta = \begin{pmatrix} \Delta^{++} \\ \Delta^+ \\ \Delta^0 \end{pmatrix} \]

Show that \( \langle \Delta^0 \rangle \neq 0 \) induces Majorana masses for the left-handed neutrinos

Exercise 3.1

Gauge coupling unification in the SM and in the MSSM

\[ \frac{d}{dt} \alpha_i^{-1} = -\frac{b_i}{2\pi} \]

\[ t = \log Q \]

Reproduce the results shown in this lecture for the running of the gauge couplings in the SM / MSSM

Hint:

Use these expressions

\[ (b_1, b_2, b_3) = \begin{cases} \\ (41/10, -19/6, -7) & \text{SM} \\ (33/5, 1, -3) & \text{MSSM} \end{cases} \]

Exercise 3.2