Physics Beyond the Standard Model

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Outline

Lecture 1: Evidence and Possible Directions Beyond the Standard Mode

1. Standard Model Overview
2. Evidence for Physics Beyond the Standard Model (BSM)
3. Directions for the BSM

The Standard Model of Particle Physics

- The Standard Model (SM) is a quantum field theory based on the gauge group:

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

- It describes Electromagnetic, weak, and strong interactions
- Particle Content of the Standard Model

Fermions (Matter)

- 3 generations of quarks:

$$\begin{pmatrix} u \\ d \end{pmatrix}, \quad \begin{pmatrix} c \\ s \end{pmatrix}, \quad \begin{pmatrix} t \\ b \end{pmatrix}$$

- 3 generations of leptons:

$$\begin{pmatrix} \nu_e \\ e \end{pmatrix}, \quad \begin{pmatrix} \nu_\mu \\ \mu \end{pmatrix}, \quad \begin{pmatrix} \nu_\tau \\ \tau \end{pmatrix}$$

Gauge Bosons (Forces)

- Gluons (g): strong force ($SU(3)_C$)
- $W^\pm$, Z: weak force ($SU(2)_L$)
- Photon (γ): electromagnetic force ($U(1)_{\text{em}}$)

Scalar Sector

- Higgs boson (H): responsible for electroweak symmetry breaking

Key Features of the Standard Model

- The SM Lagrangian is given by

$$\begin{aligned}\mathcal{L}_{\rm SM} &= -\frac{1}{4}G^a_{\mu\nu}G_a^{\mu\nu} - \frac{1}{4}F^a_{\mu\nu}F_a^{\mu\nu} - \frac{1}{4}B_{\mu\nu}B^{\mu\nu} + \bar{L}_i\, iD_\mu\gamma^\mu\, L_i \\ &+ \bar{e}_{Ri}\, iD_\mu\gamma^\mu\, e_{R_i} + \bar{Q}_i\, iD_\mu\gamma^\mu\, Q_i + \bar{u}_{Ri}\, iD_\mu\gamma^\mu\, u_{R_i} + \bar{d}_{Ri}\, iD_\mu\gamma^\mu\, d_{R_i},\end{aligned}$$

where

$$L_1 = \begin{pmatrix} \nu_e \\ e^- \end{pmatrix}_L, \quad e_{R_1} = e^-_R, \quad Q_1 = \begin{pmatrix} u \\ d \end{pmatrix}_L, \quad u_{R_1} = u_R, \quad d_{R_1} = d_R,$$

$$L_2 = \begin{pmatrix} \nu_\mu \\ \mu^- \end{pmatrix}_L, \quad e_{R_2} = \mu^-_R, \quad Q_2 = \begin{pmatrix} c \\ s \end{pmatrix}_L, \quad u_{R_2} = c_R, \quad d_{R_2} = s_R,$$

$$L_3 = \begin{pmatrix} \nu_\tau \\ \tau^- \end{pmatrix}_L, \quad e_{R_3} = \tau^-_R, \quad Q_3 = \begin{pmatrix} t \\ b \end{pmatrix}_L, \quad u_{R_3} = t_R, \quad d_{R_3} = b_R.$$

- The covariant derivatives D_μ are defined as follows:

$$\begin{aligned}D_\mu\; Q_i &= \left(\partial_\mu - ig_s T_a G^a_\mu - ig_2 T_a W^a_\mu - ig_1 \frac{Y_{Q_i}}{2} B_\mu\right) Q_i, \\ D_\mu L_i &= \left(\partial_\mu - ig_2 T_a W^a_\mu - ig_1 \frac{Y_{L_i}}{2} B_\mu\right) L_i, \\ D_\mu f_R &= \left(\partial_\mu - ig_1 \frac{Y_{f_R}}{2} B_\mu\right) f_R.\end{aligned}$$

Electrweak Symmetry Breaking

- Introducing the Higgs field $\Phi = \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix}, \; Y_\Phi = 1.$

- Its invariant Lagrangian: $\mathcal{L}_{scalar} = (D_\mu \Phi)^\dagger (D^\mu \Phi) - V(\Phi).$

  where, in this case, D_μ is defined as :

$$D_\mu \Phi = \left(\partial_\mu - i g_2 T_a W^a_\mu - i g_1 \frac{Y_\Phi}{2} B_\mu \right) \Phi$$

- The scalar potential is given by: $V(\Phi) \equiv -\mu^2 \Phi^\dagger \Phi + \lambda (\Phi^\dagger \Phi)^2, \; \mu^2 \;, \lambda > 0.$

  where μ^2 and λ correspond to the square mass and self coupling of the scalar field Φ.

- The scalar doublet should develop a $U(1)_{\rm em}$ symmetric VEV

$$\langle\, \Phi \,\rangle_0 \equiv \langle\, 0 \,|\, \Phi \,|\, 0 \,\rangle = \begin{pmatrix} 0 \\ \frac{v}{\sqrt{2}} \end{pmatrix} \;\; \text{with} \;\; v = \left(\frac{\mu^2}{\lambda} \right)^{1/2}$$

- Note that $I_{3_L} \langle \Phi \rangle_0 = -\frac{1}{2} \langle \Phi \rangle_0$, $Y \langle \Phi \rangle_0 = \langle \Phi \rangle_0$, thus $Q \langle \Phi \rangle_0 = 0$, i.e.,

$$SU(2)_L \times U(1)_Y \to U(1)_{em}$$

Gauge Boson and Fermion Masses

- After symmetry breaking

$$M_Z^2 = \frac{v^2(g_2^2 + g_1^2)}{4}$$

  and

$$M_W^2 = \frac{v^2 g_2^2}{4}$$

- The fermion mass matrices are given by

$$M_r^{ij} = \frac{v}{\sqrt{2}} Y_r^{ij} \quad , \quad r = e, u, d$$

  where Y_r^{ij} are the Yukawa couplings in the Yukawa Lagrangian

$$\mathcal{L}_Y = Y_e^{ij} \; \bar{L}_i \; \Phi \; e_{Rj} + Y_u^{ij} \; \bar{Q}_i \; \tilde{\Phi} \; u_{Rj} + Y_d^{ij} \; \bar{Q}_i \; \Phi \; d_{Rj} + h.c$$

- Since the neutrino has no right-handed component, it is massless.
- The mass of the physical Higgs boson H is also given by

$$M_H = \sqrt{2\lambda} v.$$

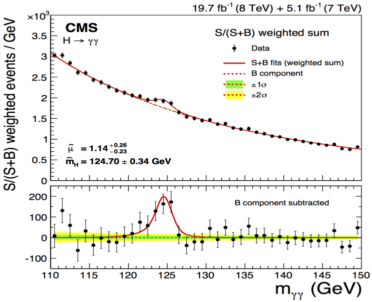
Higgs Prospects at the LHC

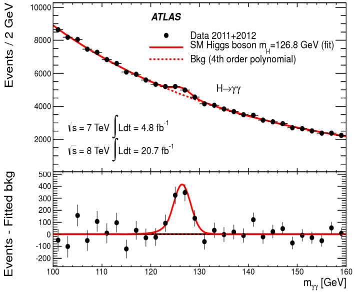
- In July 2012 the ATLAS and CMS collaborations announced the detection of a new particle consistent with a Higgs boson. The combined measured mass is

$$m_h = 125.09 \pm 0.21(\text{stat.}) \pm 0.11(\text{syst.})\ \text{GeV}.$$

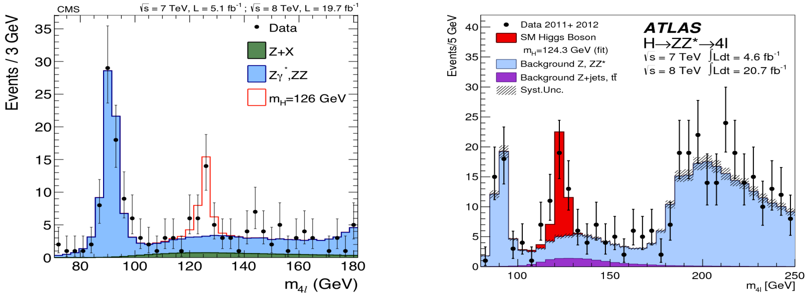
- This discovery was dramatic since a Higgs boson was the last undiscovered particle desperately searched for to complete experimental verification of the SM.

- The discovery has been achieved via the decay channel $h \to \gamma\gamma$ with Higgs mass around 125 GeV





- The signal for the golden decay channel $h \to ZZ \to 4\ell$ is easier to recognize from the background

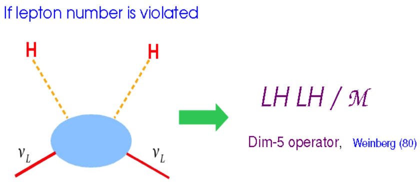


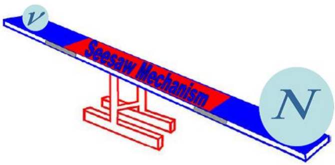
SM Summary

- Standard Model is defined by
  - 4-dimension QFT (Invariant under Poincare group).
  - Symmetry: Local $SU(3)_C \times SU(2)_L \times U(1)_Y$.
  - Particle content (Point particles):
  - 3 fermion (quark and Lepton) Generations.
  - No Right-handed neutrinos: Massless Neutrinos.
- Symmetry breaking: one Higgs doublet.
- No candidate for Dark Matter.
- SM does not include gravity.

1- Neutrino Mass:

- In the SM, quarks and electrons acquire masses through Yukawa couplings : $\mathcal{L}_{Yuk} \sim \bar{Q}_L \phi u_R$.
- Neutrinos remain massless because there are no RH ν in the SM.
- However, it has proven experimentally (from neurino oscillations) that $m_\nu \neq 0$.
- Needs a mechanism to give ν masses...





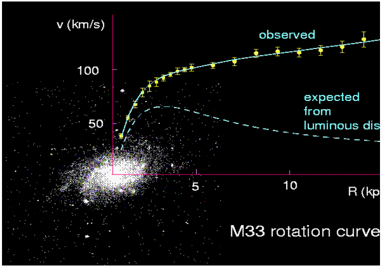
2- Dark Matter:

- In 1933, Zwicky noticed that the mass of luminous matter in the Coma cluster is much smaller than its total mass.
- In 1970, the existence of DM be considered, as the explanation for the anomalous rotation curves of spiral galaxies.

- **The velocity of rotating objects**

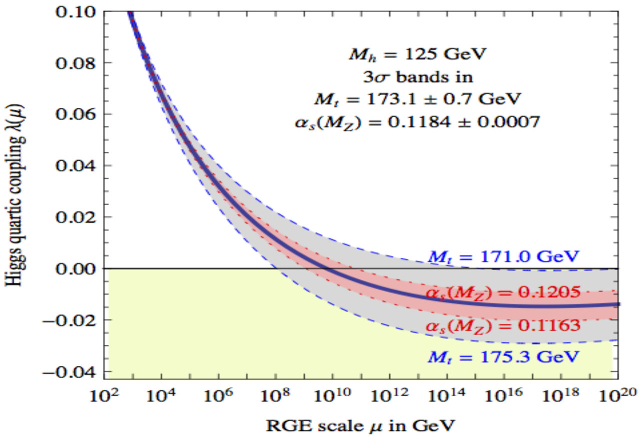
$$v(r) = \sqrt{\frac{G\ M(r)}{r}}$$

- **The observation of 1000 spiral galaxies showed that away from the centre of galaxies the rotation velocities do not drop off with distance.**
- **The explanation for these is to assume that disk galaxies are immersed in extended DM halos.**

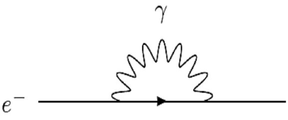


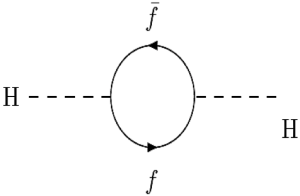
3- Higgs Vacuum Stability:

- Qadratic coupling evolves to zero or negative values. Recall that in SM $M_H = \sqrt{\lambda} v$



4- Higgs Mass Hierarchy:





$$\delta m_e = 2\frac{\alpha_{em}}{\pi} m_e \log\frac{\Lambda}{m_e} + \ \ldots$$

$$\delta m_H^2(f) = -2N_f \frac{|\lambda_f|^2}{16\pi^2}[\Lambda^2 - 2m_f^2 \ln\frac{\Lambda}{m_f} \ + \ldots]$$

$m_e \to 0$, Chiral Symmetry

m_H^2 no symmetry, Quadratic div.!!

$$\Lambda = 10^{19} \text{ GeV}$$

$$\delta m_e \ = \ 0.24 \ m_e$$

$$\delta m_H^2 \ \simeq \ 10^{30} \text{ GeV}$$

Evidence for Physics Beyond the SM

5. Baryon Asymmetry of the Universe (BAU)

- Observationally, the universe is composed almost entirely of matter.
  Why is there no significant amount of antimatter?
- Neither the Standard Model (SM) nor General Relativity can fully explain this asymmetry.
- In 1967, Andrei Sakharov identified three necessary conditions for generating a net baryon asymmetry:
  - **Baryon number violation**
  - **C and CP violation**
  - **Departure from thermal equilibrium**
- These conditions were, in principle, satisfied in the early universe. However:
  - CP violation in the SM is insufficient to explain the observed asymmetry.
  - The electroweak phase transition is not strongly first-order in the SM.
- Key question: *Can we calculate the BAU from first principles?*
- Current observational value:

$$\frac{n_B - n_{\bar{B}}}{n_\gamma} \approx 6.1 \times 10^{-10}$$

Other Evidences for Physics Beyond the SM

- There are a number of questions we hope will be answered:
  - Electroweak symmetry breaking, which is not explained within the SM.
  - Why is the symmetry group is $SU(3) \times SU(2) \times U(1)$?
  - Can forces be unified?
  - Why are there three families of quarks and leptons?
  - Why do the quarks and leptons have the masses they do?
  - Can we have a quantum theory of gravity?
  - Why is the cosmological constant much smaller than simple estimates would suggest?

Directions Beyond the Standard Model (BSM)

- **Gauge Symmetry Extensions:**
  Enlarging the SM group to include new symmetries (e.g., Left-Right symmetry, Grand Unified Theories (GUTs), $U(1)_{B-L}$, etc.).
- **Higgs Sector Extensions:**
  Introducing additional scalar fields (e.g., Two-Higgs-Doublet Models, singlets, triplets) to address flavor, CP violation, or baryogenesis.
- **Matter Content Extensions:**
  Adding new fermions such as sterile neutrinos, vector-like fermions, or mirror sectors.
- **Flavor Symmetries:**
  Implementing horizontal (family) symmetries to explain fermion mass hierarchies and mixing patterns.
- **Extra Spatial Dimensions:**
  Embedding the SM in higher-dimensional space-time (e.g., ADD, Randall?Sundrum) to address the hierarchy problem.

Directions Beyond the Standard Model (BSM)

- **Supersymmetry (SUSY):**
  Extending space-time symmetry to include fermion-boson symmetry, stabilizing the Higgs mass and enabling unification.

- **Supergravity and Gravity Unification:**
  Including gravity via local supersymmetry and aiming at a unified quantum description of all interactions.

- **Superstring Theory:**
  Proposing fundamental one-dimensional objects to unify all forces, including gravity, within a consistent quantum framework.