Revisiting the Standard Model of Particle Physics

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LECTURE – 1

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Some questions we shall contemplete . . .

❶ Why Standard Model (SM) is the way it is today?

❷ Are all features of SM fully verfied experimentally?

❸ Are there any SM predictions contrary to our observations?

❹ Does the SM gauge structure allow any Dark Matter particle?

❺ Are there any hidden symmetries in the SM?

Question 1.
Why Standard Model is the way it is today?

Why Standard Model is the way it is today?

- "*Standard Model* of particle physics" is a misnomer – *it is not the final theory of particle physics.*
- SM has
  - phenomenologically motivated symmetries, fields, and Lagrangian,
  - well-defined calculational rules,
  - nice experimental agreement, and
  - many unexplained features too.
- Question: What are the experimental facts that helped in forging the gauge structure of SM, $SU(3)_c \times SU(2)_L \times U(1)_Y$?

Why Standard Model is the way it is today?

Fundamental interactions dealth with in SM

- The SM describes
  - Strong,
  - Electromagnetic,
  - Weak and
  - Higgs interactions.
- $SU(3)_c \implies$ Quantum Chromodynamics (QCD) $\rightarrow$ strong interaction amongst quarks and gluons.
- $SU(2)_L \times U(1)_Y \implies$ Quantum Flavordynamics (QFD) $\rightarrow$ broken at a low energy scale (~ 100 GeV) via spontaneous symmetry breaking (SSB) involving the Higgs scalar $\rightarrow$ weak and electromagnetic interactions amongst quarks and leptons.
- Interaction of Higgs with itself, quarks, leptons and gauge bosons is also included in SM.

Why Standard Model is the way it is today?

Gauge bosons present in SM

- QCD $\Longrightarrow$ 8 gluons: G^i_μ for $i = 1, 2, \ldots, 8$.
- QFD $\Longrightarrow$ 4 vector bosons: W^a_μ for $a = 1, 2, 3$, and B_μ.
  Equivalently, weak interaction $\Longrightarrow$ 3 vector bosons: $W^\pm_\mu$, Z^0_μ, and electromagnetic interaction $\Longrightarrow$ photon A_μ.
- Higgs interaction $\Longrightarrow$ one scalar particle, the Higgs boson.

Why Standard Model is the way it is today?

Families of fermions present in SM

- Fermions (quarks and leptons) come in 3 families (*observation*).
- Taking helicity (L $\equiv$ Left, R $\equiv$ Right) components of fermions under $SU(2)_L$, we have,

Family	**Leptons**	**Quarks**
1st family	$\begin{pmatrix} \nu_e \\ e^- \end{pmatrix}_L, e^-_R, e^+_L, e^+_R, \overline{\nu}_{eR}$	$\begin{pmatrix} u \\ d \end{pmatrix}_L, \begin{pmatrix} \overline{d} \\ \overline{u} \end{pmatrix}_L, u_R, d_R, \overline{u}_R, \overline{d}_R$
2nd family	$\begin{pmatrix} \nu_\mu \\ \mu^- \end{pmatrix}_L, \mu^-_R, \mu^+_L, \mu^+_R, \overline{\nu}_{\mu R}$	$\begin{pmatrix} c \\ s \end{pmatrix}_L, \begin{pmatrix} \overline{s} \\ \overline{c} \end{pmatrix}_L, c_R, s_R, \overline{c}_R, \overline{s}_R$
3rd family	$\begin{pmatrix} \nu_\tau \\ \tau^- \end{pmatrix}_L, \tau^-_R, \tau^+_L, \tau^+_R, \overline{\nu}_{\tau R}$	$\begin{pmatrix} t \\ b \end{pmatrix}_L, \begin{pmatrix} \overline{b} \\ \overline{t} \end{pmatrix}_L, t_R, b_R, \overline{t}_R, \overline{b}_R$

- Greatest puzzle of particle physics today: *why only three families?*
- Total number of fermions is $90 = 18$ leptons $+ (24 \times 3)$ quarks (considering 3 color possibilities for each quark).

Why Standard Model is the way it is today?

SM Lagrangian: most general, $SU(3)_c \times SU(2)_L \times U(1)_Y$ invariant, renormalizable Lagrangian

$$
\begin{aligned}
\mathcal{L}_{\rm SM} = & \underbrace{-\frac{1}{4}G^i_{\mu\nu}G^{i\mu\nu}}_{(I)} \underbrace{-\frac{1}{4}W^a_{\mu\nu}W^{a\mu\nu}}_{(II)} \underbrace{-\frac{1}{4}B_{\mu\nu}B^{\mu\nu}}_{(III)} + \underbrace{\Theta\, G^i_{\mu\nu}\, G^i_{\alpha\beta}\, \epsilon^{\mu\nu\alpha\beta}}_{\text{The }\Theta\text{ term}}, \\
& + \underbrace{\sum_{n=1}^{3} \bar{q}_L^{(n)}\gamma^\mu \left(i\partial_\mu - g_3 \frac{\lambda^i}{2} G^i_\mu - g_2 \frac{\tau^a}{2} W^a_\mu - \frac{g_1}{6} B_\mu \right) q_L^{(n)}}_{(IV)} \\
& + \underbrace{\sum_{n=1}^{3} \bar{u}_R^{(n)}\gamma^\mu \left(i\partial_\mu - g_3 \frac{\lambda^i}{2} G^i_\mu - \frac{2g_1}{3} B_\mu \right) u_R^{(n)}}_{(V)} + \underbrace{\sum_{n=1}^{3} \bar{d}_R^{(n)}\gamma^\mu \left(i\partial_\mu - g_3 \frac{\lambda^i}{2} G^i_\mu + \frac{g_1}{3} B_\mu \right) d_R^{(n)}}_{(VI)}, \\
& + \underbrace{\sum_{n} \bar{l}_L^{(n)}\gamma^\mu \left(i\partial_\mu - g_2 \frac{\tau^a}{2} W^a_\mu + \frac{g_1}{2} B_\mu \right) l_L^{(n)}}_{(VII)} + \underbrace{\sum_{n} \bar{e}_R^{(n)}\gamma^\mu \left(i\partial_\mu + g_1 B_\mu \right) e_R^{(n)}}_{(VIII)} \\
& + \underbrace{\left| \left(i\partial_\mu - g_2 \frac{\tau^a}{2} W^a_\mu - g_1 \frac{1}{2} B_\mu \right) \Phi \right|^2}_{(IX)} + \underbrace{\mu^2 \Phi^\dagger \Phi - \frac{\lambda}{2} \left(\Phi^\dagger \Phi \right)^2}_{(X)} \\
& + \underbrace{\sum_{m,n} \left(\Gamma^u_{mn}\, \bar{q}_L^{(m)}\, \Phi^c\, u_R^{(n)} + \Gamma^d_{mn}\, \bar{q}_L^{(m)}\, \Phi\, d_R^{(n)} + \Gamma^e_{mn}\, \bar{l}_L^{(m)}\, \Phi\, e_R^{(n)} + \text{h.c.} \right)}_{(XI)}
\end{aligned}
$$

Why Standard Model is the way it is today?

SM Lagrangian: Fields and Field strength tensors

$$G^i_{\mu\nu} = \partial_\mu\, G^i_\nu - \partial_\nu\, G^i_\mu + g_3\, f^{ijk}\, G^j_\mu G^k_\nu,$$

$$W^a_{\mu\nu} = \partial_\mu\, W^a_\nu - \partial_\nu\, W^a_\mu + g_2\, \epsilon^{abc}\, W^b_\mu W^c_\nu,$$

$$B_{\mu\nu} = \partial_\mu\, B_\nu - \partial_\nu\, B_\mu,$$

$$q^{(n)}_L = \left\{ q^{(1)}_L = \begin{pmatrix} u_\alpha \\ d_\alpha \end{pmatrix}_L, q^{(2)}_L = \begin{pmatrix} c_\alpha \\ s_\alpha \end{pmatrix}_L, q^{(3)}_L = \begin{pmatrix} t_\alpha \\ b_\alpha \end{pmatrix}_L \text{, with } \alpha = r, g, b \right\},$$

$$l^{(n)}_L = \left\{ l^{(1)}_L = \begin{pmatrix} \nu_e \\ e^- \end{pmatrix}_L, l^{(2)}_L = \begin{pmatrix} \nu_\mu \\ \mu^- \end{pmatrix}_L, l^{(3)}_L = \begin{pmatrix} \nu_\tau \\ \tau^- \end{pmatrix}_L \right\},$$

$$u^{(n)}_R = \left\{ u^{(1)}_R = u_{\alpha R}, u^{(2)}_R = c_{\alpha R}, u^{(3)}_R = t_{\alpha R} \text{, with } \alpha = r, g, b \right\},$$

$$d^{(n)}_R = \left\{ d^{(1)}_R = d_{\alpha R}, d^{(2)}_R = s_{\alpha R}, d^{(3)}_R = b_{\alpha R} \text{, with } \alpha = r, g, b \right\},$$

$$e^{(n)}_R = \left\{ e^{(1)}_R = e_R, e^{(2)}_R = \mu_R, e^{(3)}_R = \tau_R \right\}$$

$$\Phi = \begin{pmatrix} \phi_a \\ \phi_b \end{pmatrix} = \frac{1}{\sqrt{2}} \begin{pmatrix} \phi_1 + i\phi_2 \\ \phi_3 + i\phi_4 \end{pmatrix} \Longrightarrow \Phi^c = i\, \tau_2\, \Phi^*.$$

❶ g_1, g_2, and g_3 are the $U(1)_Y$, $SU(2)_L$, and $SU(3)_c$ coupling constants.

❷ $\lambda^i \equiv$ Eight Gell-Mann Matrices, and $\tau^a \equiv$ Three Pauli Matrices.

❸ $f^{ijk} \equiv$ completely antisymmetric $\left(f^{ijk} = -f^{ikj} = f^{kij}\right)$ structure constants, $\left[\lambda^i, \lambda^j\right] = 2i f^{ijk}\, \lambda^k$. The non-zero structure constants are, $f^{123} = 1, f^{147} = f^{246} = f^{257} = f^{345} = f^{516} = f^{637} = \frac{1}{2}, f^{458} = f^{678} = \frac{\sqrt{3}}{2}$.

❹ $\epsilon^{abc} \equiv$ Levi-Civita symbol, $\left[\tau^a, \tau^b\right] = 2i\epsilon^{abc}\, \tau^c$.

1. Terms I, II, and III $\Longrightarrow$ kinetic energies + self-interactions of the pure gauge field part of the $SU(3)_c \times SU(2)_L \times U(1)_Y$ non-abelian gauge theory.

2. Θ term violates P, T, and CP symmetries (for $\Theta \neq 0$). It contributes to the electric dipole moment (EDM) of neutron, d_n. There is stringent experimental limit on the possible value of EDM for neutron. The best experimental upper limit[1] amounts to $|d_n| < 2.9 \times 10^{-26} e$-cm. This gives an extremely small upper bound[2] on Θ: $|\Theta| < 0.7 \times 10^{-11}$.

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[1] With 90% confidence level, Baker et.al., Phys. Rev. Lett. 97. (2006)
[2] Jihn E. Kim and Gianpaolo Carosi, Rev. Mod. Phys. **82**, 557-601 (2010).

Why Standard Model is the way it is today?

SM Lagrangian: Discussion

❸ Terms *IV*, *V*, *VI*, *VII* and *VIII* $\Longrightarrow$ kinetic energies + interaction of fermions with the gauge fields.

❹ No mass terms for the fermions[3]. Mass terms are generated via Brout-Englert-Higgs Mechanism.

❺ Terms *IX*, *X* and *XI* $\Longrightarrow$ interactions of the Higgs field with itself, with the gauge bosons, and fermions $\Longrightarrow$ SSB, generation of masses of $W^{\pm}$, Z^0, quarks and leptons[4]. In the Higgs part of the Lagrangian (terms *IX* and *X*), we have $\mu^2 > 0$ and $\lambda > 0$ for SSB.

❻ Coefficients Γ^x_{mn}, where $x \in \{u, d, e\}$, in term *XI* are Yukawa Couplings. These are arbitrary parameters in the SM. They couple the Right and Left helicities. Each of the Γ^x matrix is a 3×3 matrix of Yukawa Couplings, with the Γ^x_{mn} term giving the coupling between the generation m and the generation n.

[3] Such terms violate the $SU(3)_c \times SU(2)_L \times U(1)_Y$ invariance of the Lagrangian $\mathscr{L}_{SM}$.

[4] Neutrinos are massless in SM. If we can put a term like $\Gamma^{\nu}_{mn}\, \bar{l}_{mL}\, \Phi\, \nu_{nR}$ in term *XI* of $\mathscr{L}_{SM}$, then neutrinos can get mass by SSB (**Dirac Mass**). Also all the gluons and the photon remain massless. However, mass of the Higgs boson can not be predicted in SM. It is sensitive to the shape of the scalar potential.

- The SM predicted existence of $W^{\pm}, Z^0$, top quark and Higgs before they were discovered.
- All neutral current measurements suggest $\sin^2\theta_W \approx 0.23$, where θ_W is the weak mixing angle (or Weinberg angle) defined as,

$$\tan\theta_W = g_1/g_2.$$

  The predicted masses of $W^{\pm}_{\mu}$ and Z^0 from SM are:

$$M_W = 37.3/\sin\theta_W \text{ GeV} \approx 84 \text{ GeV},$$
$$M_Z = M_W/\cos\theta_W \approx 94 \text{ GeV}.$$

  The experimental values are in close agreement with these values.
- SM also predicts CP violation in the quark sector which is also well observed in experiments.

Why Standard Model is the way it is today?

Answering the question

The gauge structure $SU(3)_c \times SU(2)_L \times U(1)_Y$ of the SM is justified by many experiments, but most importantly it helps explain,

- ❖ why $W^{\pm}$ and Z^0 have the particular masses they have,
- ❖ why number of lepton and quark families should be equal and why 3 colored states must exist for each quark (hint: chiral anomaly cancellation in triangle diagrams for *VVA* and *AAA*),
- ❖ why CP violation occurs in the meson sector,
- ❖ why Higgs boson must exist with properties as per SM (hint: taming divergence in the scattering $W^+W^- \to W^+W^-$, to guarantee renormalizability),

and many more. However, the SM despite being the best experimentally verified theoretical framework, is definitely not the ultimate theory of elementary particles, it has many shortcomings as well.

Why Standard Model is the way it is today?

Why should we extend SM? Two pragmatic reasons (!?).

- In SM neutrinos are massless. *Neutrino oscillation experiments* suggest that they have non-zero finite mass. This can be achieved in SM by proposing existence of *right-handed* neutrinos which are singlet under $SU(3)_c \times SU(2)_L$ and have hypercharge[5] $Y = 0$. But if neutrino were Majorana fermion, SM cannot accomodate massive neutrinos as Majorana mass term gives $I_3 = 1$, $Y = 2$ and in SM there is no weak isospin triplet with $Y = 2$. So existence of Majorana neutrino will necessarily push for extension of gauge structure of SM. **It is, therefore, important to ascertain the nature of sub-eV neutrinos.**
- Our universe has some matter which is ~ 5 times more abundant than ordinary matter but has no electromagnetic interaction, its presence is only felt gravitationally. This is the *dark matter* (DM). Since all SM particles form visible baryonic matter, DM demands (really?) extension of SM.

[5] Gell-Mann–Nishijima formula: $Q = I_3 + Y/2$, where Q is electric charge, I_3 is 3rd component of weak isospin, and Y is hypercharge.

Question 2.
Are all features of the Standard Model fully verfied experimentally?

Are all features of the SM fully verfied experimentally?

Context of the question

- When we have enough reason to extend the SM, it is very pertinent to know which parts of SM are not yet experimentally tested. This tells us where our new physics models still have freedom.

- Our new physics models can not challenge SM in those places where SM has strong agreement with experiments.

- If some predictions from SM are found to disagree significantly from the corresponding experimental measurements, it would call for new physics even if one were to put a blind-eye to neutrino oscillation and dark matter.

Are all features of the SM fully verfied experimentally?

In the strong interaction sector

- QCD has *no direct* experimental evidence, because quarks and gluons are confined to the interior of hadrons due to *color confinement*.

- However, top quark which is the heaviest of all quarks (in fact, of all particles in the SM) is the only one to decay as a free quark. How can color non-neutrality be tested in case of single top decays?

- The gauge structure of QCD allows for color-singlet states made up of quark-antiquark pair or of three quarks or three antiquarks. However, recently experimental studies have hinted at tetraquark and pentaquark states. How do their properties fare when compared with those predicted from QCD?

- QCD is non-perturbative in nature at very low energies as the strong coupling constant becomes very large at such energy scale leading to the concept of asymptotic freedom. It is theoretically very challenging to deduce all properties of known low mass mesons starting from basic principles. Lattice QCD plays a major role in such theoretical endeavours.

Are all features of the SM fully verfied experimentally?

In the electroweak sector

- How precisely do $W^{\pm}$ and Z^{0} couplings to 3rd generation of quarks follow the prediction from the SM?
- Are the couplings of $W^{\pm}$ and Z^{0} to the leptons completely family independent as in the SM? Recent experimental data regarding $R(K)$, $R(K^{*})$, $R(D)$, $R(D^{*})$, angular distribution of $B \to K^{*}\ell^{+}\ell^{-}$, and decay rate measurement of $B_s \to \mu^{+}\mu^{-}$ suggest some sort of violation of lepton universality.
- Neutrino, introduced by Pauli to save the conservation of energy and momentum, also strengthens the spin-statistics theorem. However, contrary to usual beliefs the neutrinos might violate spin-statistics theorem, by obeying Bose-Einstein statistics instead of the usual Fermi-Dirac statistics[6]. Such scenarios must be directly tested in laboratory experiments, in addition to the cosmological and astrophysical tests suggested in the literature.

[6] See (a) L. Cucurull, J.A. Grifols and R. Toldra, Astropart. Phys. 4 (1996) 391, and (b) A.D. Dolgov and A.Yu. Smirnov, Phys. Lett. B 621 (2005) 1–10.

Are all features of the SM fully verfied experimentally?

In the Higgs sector

- ❖ How does Higgs couple to light fermions, such as electron and muon, up, down and strange quarks?
- ❖ How does Higgs trilinear coupling measurement fare up with the SM loop prediction? What about Higgs quartic coupling strength?
- ❖ Does the 125 GeV Higgs follow a Mexican hat potential as suggested by the SM for stability of vacuum?
- ❖ How does the invisible Higgs decay rate measurement fare with the prediction from SM?

Are all features of the SM fully verfied experimentally?

Answer to the question

- Definitely, not all aspects of SM has been thoroughly tested experimentally. We must probe SM as minutely as possible.
- SM is a fully renormalizable theory, quantum corrections to processes allowed in SM have miniscule contributions from new physics if any. Thus SM has got a very good reputation of being very close to the experiments. However, fundamental features of SM must be thoroughly tested by considering new techniques or methodologies.

Question 3.
Are there any SM predictions contrary to our observations?

Are there any SM predictions contrary to our observations?

Answer to the question

Yes, there are the following two interesting cases, both in the strong interaction sector.

- ❖ The SM predicts that there must exist gluonic condensates called as 'glue-balls' due to the self-interaction property of gluons. However, despite fervent searches for glue-balls we are yet to find out any such color singlet state which has no quark content.
- ❖ We observe the quarks and gluons to obey 'infrared slavery' / 'color confinement' and 'asymptotic freedom'. However, it is not yet known how to derive this result mathematically starting from the theoretical framework of QCD in the SM. This is a reverse problem according to our question.

Therefore, our experimental search for 'glue-balls' must continue and all theoretical efforts for deriving asymptotic freedom and color confinement must also be vigorously pursued.

Question 4.
Does the SM gauge structure allow any Dark Matter particle?

Does the SM gauge structure allow any DM particle?

Look again at SM

- In the SM,
  - Quarks have color, weak isospin and hypercharge. Gluons are bi-colored (not white) color-octet states.
  - Leptons have no color, but have both weak isospin and hypercharge. Gauge bosons $W^{\pm}, Z^0$ also have weak isospin and hypercharge. Photon has no weak isospin and no hypercharge.
- Can we have a fermion which has no color, no weak isospin, but only hypercharge and hence only electric charge?
  Yes, such a particle is allowed to exist by the SM gauge group[7].

[7] See G. Rajasekaran, arXiv:1105.5213 [hep-ph].

Does the SM gauge structure allow any DM particle?

Christening the new fermion

- Thus, such charged massive particles (CHAMPs) when stable and have integer electric charge can form very tightly bound neutral bound states with electron, proton, alpha particle etc. and act as *atomic dark matter*.
- If such a fermion has zero electric charge, it would be absolutely stable and can be a component of dark matter directly. Due to its mass, it would have only gravitational interaction. Due to being neutral, it is possible that this particle can be a Majorana fermion.
- The fermion can have irrational or fractional electric charge as well and this would help it to be stable, but a cluster of such fermions would necessarily carry a net electric charge, and hence would have finite non-zero non-gravitational interaction with another such cluster of fermions.
- This new CHAMP, which is neither a quark nor a lepton, can be called **erebon** (*Erebos*: primordial Greek deity of darkness).

Does the SM gauge structure allow any DM particle?

Stability of the new fermion

- The erebon ψ would imply adding the following terms to SM Lagrangian,

$$\mathscr{L}_{\text{Erebon}} = i\overline{\psi}\gamma^\mu \left(\partial_\mu - i\frac{g_1}{2} YB_\mu\right)\psi - m_\psi \overline{\psi}\psi,$$

  where the mass term is now allowed and m_ψ is fully arbitrary so as the electric charge $Q = Y/2$ of the erebon.

- After SSB, we get

$$\mathscr{L}_{\text{Erebon}} = i\overline{\psi}\gamma^\mu \left(\partial_\mu - ieQA_\mu - ig_2 Q \tan\theta_W \sin\theta_W Z_\mu\right)\psi - m_\psi \overline{\psi}\psi,$$

  implying that $\psi\overline{\psi}$ can be produced in high-enegy collisions via virtual photon or Z^0 boson. To prevent $Z^0 \to \psi\overline{\psi}$ decay we demand $m_\psi > M_Z/2$.

- To prevent coupling of ψ_1 $(Q = -1)$ with SM Higgs, we can invoke a discrete Z_2 symmetry. For $Q = -2$, i.e. ψ_2 such extra symmetry is not required.

Does the SM gauge structure allow any DM particle?

Erebonic atomic dark matter

- Erebonic atoms such as $\psi_1 + p$, $\psi_2 + \mathrm{He}$ are candidates for atomic dark matter.
- These atoms, depending on m_ψ, can have binding energy in the hard X-ray or γ-ray region, and hyperfine line in the infrared or microwave region. May be spectral search in these regions of electromagnetic wave would reveal if there are such dark atoms present or not. However, by going to masses $m_\psi \gg 100$ GeV one can go to very high binding energies and similar shift in hyperfine line as well.
- The erebonic dark atoms present an exciting set of dark atom models that can be falsified by experimental data. Also if mass is very high, its required number density would be very small so as to easily avoid direct detection limits.

Question 5.
Are there any hidden symmetries in the SM?

Are there any hidden symmetries in the SM?

Answer to the question

Yes, the SM Lagrangian has a few hidden symmetries. These are some space-time symmetries, flavor symmetry, custodial symmetry and scale symmetry. For a nice discussion see Scott Willenbrock, ‘Symmetries of the Standard Model’, arXiV:hep-ph/0410370v2.

Thank you