Beyond SM (BSM): outline of (selected) motivations / ideas

- Just to be clear, (Needless to say,) there are no theoretical inconsistencies within the SM, but there are a few theoretical / aestheic "issues / puzzles" that we will outline below
- First, let us discuss phenomenological / experimental challenges for the SM.
- All of the predictions that have been experimentally tested thus far have been successful (apart from a few "anomalies")
- However there are 3 data where SM clearly can't provide full (or any?) explanation

(a). Observation of non-zero (even if tiny) neutrino masses (based on oscillations): recall that strictly within SM (i.e., with no ν_R and (at renormalizable level), neutrinos are massless

(b). Evidence for dark matter (DM) in the universe, likely in the form of a stable particle. Indeed, a particle with (roughly) weak scale mass and interactions governed by weak scale, called WIMP (weakly interacting massive particle) turns out to be an ideal candidate for DM (if its stable).

Again, SM doesn't have a particle fitting this bill, so we need a new particle. ②

(We might have term papers on above 2 topics.)

(c). As already mentioned, gravitational force is not part of SM, since this interaction being non-renormalizable cannot be described (predictively) within QFT (cf. other 3 forces). So, a quantum theory of gravity is beyond SM. (Of course, one could simply say that gravity is not really relevant for particle physics experiments, i.e., energies much smaller than M_{Pl} (where quantum gravity becomes important)

— Onto theoretical "inadequacies" of SM: we will briefly describe 3 of these as follows.

(1). SM has "too many" parameters (even restricting to 1 generation: see below for more generations), e.g., ③ different gauge groups/couplings, 5 different representations under gauge group for fermions / Higgs doublet (with "arbitrary" hypercharges) ...

... Grand Unified Theories (GUTs) that we will describe in next note (and term paper) address this issue (to begin with) by having single gauge group/coupling and quarks & leptons "unified" into (common) representation of this

[possibly with [same] Yukawa coupling to Higgs field
gauge group], while still explaining why the [3] measured/low-energy gauge [and] quark vs. lepton [Yukawa] couplings are different (as a consequence of spontaneous [breaking] of GUT symmetry, coupled with running of couplings)

(2). Including all [3] generations [again, they all have same gauge quantum numbers, i.e., no new representations vs. (1) above], we have a wide range/hierarchy of masses; e.g, $m_e \sim 0.5$ MeV vs. $m_\tau \sim 2$ GeV (ratio ~ 4000) in lepton sector – and for 2 types of quarks: $m_d \sim$ MeV vs. $m_b \sim 4$ GeV (ratio of ~4000) & [m_u] ~ MeV vs. [m_t] ~ 200 GeV (ratio of ~ [2×10^5])

– Of course, in SM, these masses arise from Yukawa coupling to Higgs VEV, so this is really a [hierarchy] in Yukawa couplings

(3). How about [mass scale] of weak (nuclear) force, i.e., Higgs field mass term/VEV ... but compared to what (?!)

– The point is that there is another (super-large) mass scale in town (again, other than H/W/Z & SM fermion masses, which are all ∝ Higgs VEV), namely, Planck scale, [$M_{Pl} \sim 10^{19}$ GeV] (>> Higgs VEV ~ 250 GeV), again where quantum gravity (not a QFT like SM) becomes relevant.

– So, strictly speaking (although one could "hand-wave" out of it!), one should [not] really extrapolate

the SM, persay, to energy/momentum $\gtrsim M_{Pl}$: again (4)
effective/made dimensionless strength of gravity is $\sim E/M_{Pl} \sim O(1)$ at energies $\sim O(M_{Pl})$

- In other words, M_{Pl} could be considered as a physical UV cut-off for SM: $\Lambda_{UV} \sim M_{Pl}$
[SM is then an effective (quantum) field theory (EFT) valid below $\sim M_{Pl}$]
- So, in the discussion at start of this course (on renormalizability of QED, which "generalizes" to rest of SM), when we regulate UV divergences/calculate loop corrections, we can't really take $\Lambda_{UV} \to$ "∞", since now Λ_{UV} is finite, even if super-large.
- Thus, schematically, the earlier (i.e, with $\Lambda_{UV} \to \infty$) "expression" of renormalization, i.e.,

finite, observed value $\sim$ ∞ bare term ← in order to "cancel" loop
+ ∞ (due to Λ_{UV}) loop correction

becomes now (i.e, with $\Lambda_{UV} \sim M_{Pl}$):

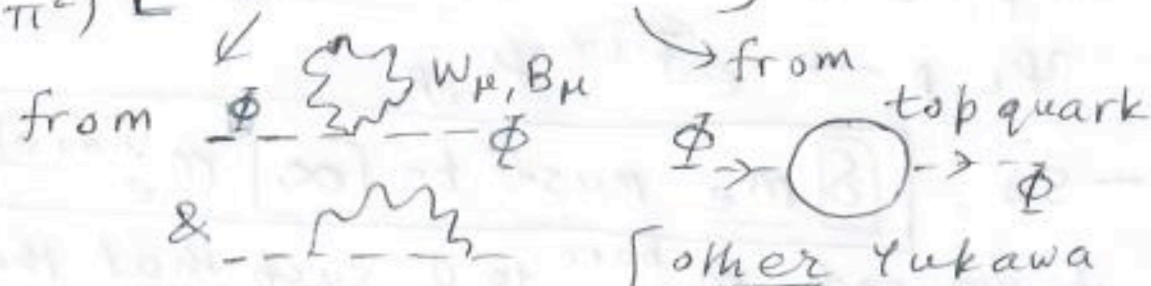
("same") finite, observed $\sim$ finite bare term
+ finite (due to Λ_{UV}) loop correction
← no ∞ anywhere

- So, a question which is legitimate/reasonable now is whether there is any delicate cancellation between bare and loop correction terms (again, both are finite) in order to reproduce [observed] value (i.e., is that observable "fine-tuned") (?!) Again, earlier, i.e., with $\Lambda_{UV} \rightarrow \infty$, when both bare and loop corrections were separately ∞, one couldn't really argue about such an issue.

- [Specifically], we will see below that (in general) scalar mass (e.g., for Higgs field in SM) [is] fine-tuned (if measured mass $\ll M_{Pl}$), while [fermion] mass (even if it is $\ll M_{Pl}$) is [not].
- In the SM, we have [$\delta \mu^2$] (shift due to loops in mass term for [Higgs] doublet Φ)

schematically

$$\sim \boxed{\Lambda^2_{UV}} / (16\pi^2) \left[g^2 + h_t^2 \right]$$



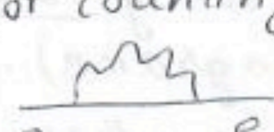
[other Yukawa couplings are (much) smaller]

- The quadratic [divergence] is expected based on simple [dimensional] analysis, i.e., superficial degree of divergence (we can easily count powers of loop momenta in above (1)-loop diagrams). It is backed-up by an explicit calculation, there being [no] symmetry argument to "save the day" here (cf. for fermions : see below)

- Setting $\Lambda_{UV} \sim M_{Pl}$ (and using $\mu^2_{bare} + \delta\mu^2 = \mu^2_{observed} \sim (\text{few } 100 \text{ GeV})^2$ (as per above discussion)) clearly shows that observed Higgs field mass term (or weak scale) is fine-tuned to 1 part in about $(M_{Pl} / \text{a few } 100 \text{ GeV})^2 \sim 10^{30}$! [this is called Planck-weak hierarchy problem]
- Onto fermion masses, e.g., is $m_e \ll M_{Pl}$ fine-tuned (say in just QED) ?! Answer is No due (in short) to chiral symmetry, i.e., mass term for fermion (whether bare or loop correction to it) breaks symmetry under which L, R chiralities transform independently / oppositely, since the 2 chiralities are "connected" by mass term :

$$m_\psi \bar{\psi}_L \psi_R \longrightarrow m_\psi \, e^{2i\alpha} \, \bar{\psi}_L \psi_R \text{ for}$$

$$\psi_{L,R} \rightarrow e^{\mp i\alpha} \psi_{L,R}$$

- So, δm_e must be $\propto m_e^{bare}$ itself, i.e, if we set m_e^{bare} to 0 such that theory has chiral symmetry classically ("to begin with"), then loop corrections must respect that symmetry, i.e., δm_e is also 0.
- Dimensional analysis (or counting of propagators in 1-loop diagram : ) gives $\delta m_e \sim m_e^{bare} \times \frac{e^2}{16\pi^2} \times \log \Lambda_{UV}/m_e^{bare}$

(Again, it is backed-up by an actual calculation: see early part of this course)

- The point is that with a "finite" Λ_{UV} - even if it is as large as M_{Pl}, we see that there is basically no fine-tuning : $\log \Lambda_{UV}/m_e \sim 40$ so that $\delta m_e \sim m_e^{bare} \sim m_e^{observed}$ (very roughly), cf. Higgs field mass term above.
- Re-phrasing the "problem" for Higgs/scalar field (in general), we see that even if $\mu^2_{bare} = 0$, loop corrections will still be non-zero : $\delta\mu^2 \not\propto \mu^2_{bare}$, since there is no symmetry at play here...

... unless we extend the SM, e.g.

(i). Supersymmetry (SUSY) relates fermions to bosons, so chiral symmetry "protection" for mass term ("originally" present for fermions only) now can "extend" to bosons, including scalar fields such as Higgs. This framework entails adding "superpartners" (i.e., new particles) for every particle of SM, with a spin differing by $1/2$ from SM particle.

SUSY has to be broken in nature, since we haven't seen a scalar partner of electron (or "fermionic" photon) with same mass as SM particle ⑧

- However as long as these superpartners have ~TeV mass, we still get sufficient suppression of $\delta\mu^2$ for Higgs field

(ii). Alternatively, one can extend 4D spacetime with an extra, spatial dimension. A (5)D gauge field (A_5) $(A_M = A_\mu + A_5)$ has an "extra" polarization as compared to 4D gauge field (A_μ), which from 4D viewpoint is a scalar. Thus, if Higgs field of SM can be suitably identified with A_5, then the (5D) (gauge) symmmetry protection carries over to Higgs field also.

- Once again, the "symmetry" relating Higgs (as A_5) to A_μ has to be broken, i.e., extra dimension has to be compact (of size L cf. ∞ 4D). One can show that (roughly) the extra-dimensional excitations of SM particles appear (from 4D viewpoint) as a tower of new particles (called Kaluza-Klein or KK modes) with masses quantized in units of $\sim 1/L$. As long as this KK mass is ~TeV, we still address the Planck-weak hierarchy problem

- So, we see that such solutions (SUSY or extra dimensions) predict new particles at weak/TeV scale, with other phenomenlogical implications, e.g., they can be directly produced at the LHC; one of them could be a stable WIMP, thus provide DM of the universe (see term papers for more details)