Beyond I

Two standard models:

Cosmology "concordance" ΛCDM

Particle "SM" $SU(3)\times SU(2)\times U(1)$

Reconciling these 2 provide best opportunity to go beyond our current knowledge.

I. Particle Physics

1) Higgs mass (hierarchy) problem

Must have $M_H^2 = O(100 \text{ GeV})$ but

quantum corrections to $M_{h_{\text{bare}}}^2$ are quadratically divergent. Planck scale is where we
expect quantum gravity to be important.

$$M_{Pl} = \left(\frac{\hbar c}{G_N}\right)^{1/2} = 10^{-19} \text{ GeV}$$

corresponding to $L_P = 10^{-33} \text{ cm}$. For cutoff of $M_{Pl}$,

$$M_H^2 = (M_{h_{\text{bare}}})^2 + \delta M_H^2$$

"fine-tuning" of $M_{h_{\text{bare}}}$ to 1 part in $10^{17}$
Some theoretical solutions:

a. Composite Higgs "technicolor"

Higgs as bound state of some new strong color-like force, "technicolor" and "techniquark" constituents. Provides lower cut-off.

b. Supersymmetry

Boson-fermion symmetry reduces quadratic divergence to log.

c. Extra dimensions

+ others

Solutions must remain consistent with current SM tests, for example, smallness of FCNC
(2) SM gauge group is complicated.

Is there a grand unified theory, GUT? Is there left-right symmetry at high energy?

(3) Fermion families

masses, mixings

Is it its own antiparticle (Majorana)?

(4) Strong CP.

Quantum corrections to QCD break CP.

breaking parameter $\theta < 10^{-8}$ from neutron EDM.

(5) Cosmological constant ($\Lambda$) problem

GR gravity couples to energy.

Another quantum field divergence we have not mentioned - zero point energy.

Effective cosmological constant $10^{50} \times$ observed
Experimental hints:

(1) Neutrino mass.

In SM, neutrino is taken to be its own antiparticle ("Majorana"), and therefore massless.

Either the ν is not Majorana, implying additional "sterile" neutrino states; or there is a lepton # violating "Majorana mass".

Search for ννββ which is observed proves ν has "Majorana mass".

(2) Running Couplings:

Quantum corrections lead to effective couplings ("running couplings") depending on distance scale probed in interactions.

QED vacuum polarization:

\[ e_{bare} \quad \text{antielectron} \]
Running couplings:

\[
\alpha(g^2) = \frac{\alpha(\mu^2)}{1 + R \alpha(\mu^2) \ln \left( g^2/\mu^2 \right)}
\]

\[
R = \frac{11 n_b - 4 n_f}{12 \pi}
\]

\[
n_f = 3 \quad (# \text{ fermion families})
\]

\[
n_b = 0, 2, 3 \quad \text{for } U(1), SU(2), SU(3)
\]

So for \( \alpha_{\text{em}} = 1/137 \) @ \( \mu = 1 \text{MeV} \)

\[
\alpha(m_Z) \approx 1/129
\]

Effective coupling increases for \( U(1) \); decreases for \( SU(2), SU(3) \).

Hint of grand unification:

\[
\begin{array}{c}
\alpha_1^{-1} \\
\alpha_2^{-1} \\
\alpha_3^{-1}
\end{array}
\]

\[
\log E \quad \sim 10^{16} \text{ GeV} \equiv \text{GUT scale}
\]
II Cosmology $\Lambda$CDM

1. Baryon asymmetry (matter vs antimatter)
   not enough CP in S.M.!

2. Dark energy $\approx 70\%$ of total energy density of universe ($\Omega=1$)

3. Dark matter particle $\Omega_{\text{DM}} \approx 30\%$
   structure formation, rotation curves, gravitational lensing

4. Inflaton
   Inflation needed in $\Lambda$CDM to explain
   "horizon problem", predicted $\Omega = 1$
   (flat universe).

* Sakhnov criteria:
  (i) $B$ violating
  (ii) non-equilibrium
  (iii) $C, CP$ violating