BEYOND THE STANDARD MODEL

Lecture I

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BEYOND THE STANDARD MODEL



[Murayama]

THE STANDARD MODEL



THE STANDARD MODEL



THE STANDARD MODEL

SM Scorecard	
All measurements made on Earth to date	Yes!*
Dark matter	X
Matter-antimatter asymmetry	X?
Dark energy	X
Inflation	X

* notwithstanding a few outstanding anomalies, and including RH neutrinos

LOOKING BEYOND THE SM

"[I]t seems probable that most of the grand underlying principles have now been firmly established and that further advances are to be sought chiefly in the rigorous application of these principles to all the phenomena which come under our notice.... An eminent physicist has remarked that the future truths of physical science are to be looked for in the sixth place of decimals."

-- Albert Michelson, 1894



Many independent lines of gravitational evidence for DM







We know dark matter:

- exists
- is dark
- is sufficiently cold

...and thus must be something new

ORIGIN OF MATTER

tiny asymmetry between matter and antimatter:

$$\frac{n_p - n_{\bar{p}}}{n_{\gamma}} \approx 6 \times 10^{-10}$$

baryogenesis requires (Sakharov):

- baryon number violation
 - since non-perturbative EW processes can trade B for L, above the weak scale L violation leads to B violation
- CP violation
- departure from thermal equilibrium
- Not satisfied in SM! (* but heavy RH neutrinos might fit the bill?)

PROBLEMS OF THE SM

- Counting RH neutrinos, the SM has 31 continuous parameters:
 - 6 quark masses + 3 mixing angles + 1 phase
 - 9 lepton masses + 3 mixing angles + 3 phases
 - 2 parameters in *V*(*H*)
 - 3 gauge couplings + strong theta angle

Internally consistent for any value of these parameters

PROBLEMS OF THE SM

- Origin of flavor:
 - why three generations?
 - origin of hierarchical Yukawa couplings?
- Strong CP problem
- Unification?
- The hierarchy problem



-- I.I. Rabi, 1936



• Why is $M_{SM} \neq M_{Pl}$?

 spontaneous electroweak symmetry breaking:

 $V(H) = -\mu^2 |H|^2 + \lambda |H|^4$

sets mass scale of the SM

$$v = \sqrt{\frac{\mu^2}{\lambda}}$$

Higgs mass is equivalent to v:

$$m_h = \sqrt{\frac{\lambda}{2}}v$$



- "Who ordered that?" is uniquely acute for *m_h*:
 fundamental scalar mass
- quadratic divergence in loop corrections to scalar mass:



 cutoff: limit of validity of theory, i.e., scale where new physics becomes important

Renormalization: introduce counterterm,

$$m_h^2 = m_0^2 + \delta_{CT} m_h^2$$

This is entirely consistent and predictive.

- Specify renormalization condition, e.g., $m_h = 125$ GeV, to fix counterterm
- Counterterm $\propto \Lambda^2$ cancels UV divergence
- All correlation functions, etc., uniquely determined and finite

• The problem: $\Lambda = M_{pl} \sim 10^{19} \,\text{GeV}$

- Getting $m_h = 125 \text{ GeV}$ requires an extremely delicate cancellation: $\mathcal{O}(10^{19})^2 - \mathcal{O}(10^{19})^2 = \mathcal{O}(100)^2$
- Cancellation profoundly sensitive to physics in the UV:
 - new states \Rightarrow new loops, spoil cancellation
- The generic (natural) expectation is thus $m_h \sim \Lambda$

We only have one universe. So what's wrong with setting up one cancellation?

 $\delta m^2(M) \sim M^2 \ln(M/m_h)$

Λ

 m_h

- cancellation is between value of mass at Λ and the contribution from all intermediate scales
- different microphysical origin!
- no intrinsic reason to expect a cancellation of one part in 10³⁶



This is like saying that the details of atomic-scale physics are important for describing physics on the scale of the moon's orbit.



Bohr radius = $5.3 \times 10^{-11} \text{ m}$



- Solution: what if $\Lambda \sim \text{TeV}$?
 - *m_h* is a message: scale of new physics
 - new physics has to be special: cancel the quadratic divergence

- how massive should new physics be? Subjective
 - is 1 TeV ok? 10 TeV? 100 TeV?



- Bottom line: if the weak scale is natural, new physics should be experimentally accessible by current and/or feasible technology
- Conversely the failure to find new physics near the electroweak scale would tell us nature is fine-tuned: qualitatively new

- "Who ordered that?": flavor
 - Yukawa couplings: $Y_{ij}^U Q_i H u_j$
 - eigenvalues are hierarchical
 - and (mostly) small
- Where does this structure come from?





• $\mathcal{O}(\ln 10^{19}) - \mathcal{O}(\ln 10^{19}) = \mathcal{O}(m_b/v)$: no fine-tuning needed

- On the other hand this means no guide to scale of new physics associated with flavor:
 - Yukawa couplings are renormalizable, i.e., are dimensionless ⇒ no intrinsic mass scale
 - No fine tuning ⇒ no scale that could even subjectively point to the need for new physics
- The origin of flavor is one of the biggest mysteries with some of the fewest clues.

- What we do know about flavor: departures from the SM flavor structure are stringently constrained
 - Iow-energy searches for indirect effects of new physics:



• e.g.: heavy Higgs boson can generate 4-fermi operator for $p \ll m_H$

 $\frac{c_{ds}}{m_H^2} (\bar{s}_R \, d_L) (\bar{s}_L \, d_R)$

New contribution to kaon oscillation:



- Limits:
 - $\frac{\text{Re}\,c_{ij}}{m_H^2} < (2 \times 10^4 \,\text{TeV})^{-2} \qquad \frac{\text{Im}\,c_{ij}}{m_H^2} < (3 \times 10^5 \,\text{TeV})^{-2}$
- indirect sensitivity to high scales/small couplings

[e.g., Isidori, Nir, Perez, 1002.0900]

- heavier flavors are somewhat less constrained:
 - neutral D mesons:

 $\frac{\operatorname{Re} c_{cu}}{m_H^2} < (6 \times 10^3 \,\mathrm{TeV})^{-2}$

$$\frac{\mathrm{Im}\,c_{cu}}{m_H^2} < (1.5 \times 10^4\,\mathrm{TeV})^{-2}$$

neutral *B_d* mesons:

$$\frac{\operatorname{Re} c_{bd}}{m_H^2} < (2 \times 10^3 \,\mathrm{TeV})^{-2}$$

$$\frac{\mathrm{Im}\,c_{bd}}{m_H^2} < (4 \times 10^3\,\mathrm{TeV})^{-2}$$

neutral B_s mesons:

$$\frac{|c_{bs}|}{m_H^2} < (4 \times 10^2 \,\mathrm{TeV})^{-2}$$

NEUTRINO MASSES

 In lepton sector, observed neutrino masses may indicate the scale of undiscovered RH neutrinos:

$$\mathcal{L}_{\nu} = y_N N_R H L_L + \frac{1}{2} M_N N_R N_R + H.c. + \dots$$

• If $M_N \gg m_{\nu}$ then:



NEUTRINO MASSES

LH neutrino mass from dim-5 operator:

$$\mathcal{L}_{\nu} = \frac{y_N^2}{2M_N} H L_L H L_L + H.c. + \dots$$

• The coefficient points to the scale of new physics: 2^{2}

$$m_{\nu} = \frac{y_N^2 v^2}{M_N} \approx 0.1 \,\mathrm{eV}$$

Scale of lepton number violation:

$$\frac{M_N}{y_N^2} \approx 10^{14} \,\mathrm{GeV}$$

(but remember the fine print!)

NEUTRINO MASSES

Look for Majorana mass in neutrinoless double beta decay:



Gauge couplings are also dimensionless and evolve logarithmically:

 $\delta g(M) = \beta(g) \delta \ln M$

 m_Z

 evolution is a competition between screening and antiscreening:

$$\beta(g) = -\frac{g^3}{16\pi^2} \left(\frac{11}{3}N_{GB} - \frac{2}{3}N_f\right) + \dots$$

Λ

• Evolution of SM gauge couplings suggests a common origin at a high scale $M_{GUT} \sim 10^{15}$, 10^{16} GeV



common origin of SM gauge interactions in single interaction?

 $SU(3)_c \times SU(2)_L \times U(1)_Y \subset SO(10)$

 Nontrivial: SM fermions have right quantum numbers to fit in single multiplet of SO(10)

Adding new matter adds to the screening and changes the evolution with energy:



- New charged matter in MSSM makes numerical unification work significantly better
- Precision unification requires new charged states between SM and M_{GUT}
- Unification is insensitive to exact value of this scale, but it can't be *too* heavy

- Again: look for high-scale physics indirectly in lowbackground processes
- Grand unified gauge bosons mediate proton decay:



Induces four-fermi operator: $\frac{g_X^2}{M_V^2} \bar{u}_R \gamma^\mu d_L \ \bar{e}_R \gamma_\mu d_L$

- Proton lifetime bounds
 - depend on flavor structure of decay
 - typical scales involved:

 $\tau_p \gtrsim 10^{34} \, \mathrm{years}$

 a powerful constraint on GUTs (and has ruled out several minimal versions)



STRONG CP

Most general renormalizeable SM Lagrangian includes

$$\frac{\alpha_s\theta}{16\pi}\epsilon_{\mu\nu\rho\sigma}G^{a\mu\nu}G^{a\rho\sigma}$$

Violates CP!

- Total derivative: no contribution to observables at any order in perturbation theory
- But extended field configurations of gluons don't necessarily vanish at infinity ⇒ observable effects
- neutron EDM $d_e \propto \theta$: lack of detection requires $\theta < 10^{-10}$

STRONG CP

• Explain smallness of θ : introduce axion, a particle whose potential is dominated by non-perturbative QCD

$$\mathcal{L}_{int} = \frac{a}{f_a} \frac{g^2}{64\pi^2} \epsilon_{\mu\nu\rho\sigma} G^{a\mu\nu} G^{a\rho\sigma}$$

- dim 5: new scale f_a controlling strength of axion interactions
- minimum of axion potential: $\langle a \rangle = -\theta f_a$, no net *CP*-violation!
- Axion is generally accompanied by additional degrees of freedom living near *f_a*

STRONG CP

No *a priori* restrictions on *f_a*, but stringent experimental limits push it far above the weak scale



Meanwhile, in the rest of the universe...



- Many (many, many) ideas for particle DM
- best motivation for DM with terrestrially accessible mass scales and interactions:
 - a particularly simple class of models: WIMPs and their relatives
 - these particles are thermal relics: once a part of hot, dense plasma in the early universe, then left equilibrium when universe expanded and cooled

- Thermal freezeout:
 - particles in early universe are a thermal plasma
 - equilibrium number densities
 - relativistic: $n_i \propto g_i T^3$
 - non-relativistic: $n_i \propto g_i T^3 \left(\frac{m}{T}\right)^{3/2} e^{-m/T}$
 - *T* decreases with adiabatic expansion of universe

Thermal freezeout:



Estimate freezeout:

 $n_{\chi} \langle \sigma v \rangle \lesssim H$

• with x = m/T,

$$H^2 = \frac{8\pi G_N}{3}\rho \approx \frac{1}{M_{Pl}^2} T^4$$

$$m^3 x^{-3/2} e^{-x} \langle \sigma v \rangle \approx \frac{m^2}{x^2 M_{pl}}$$

$$\sqrt{x_{fo}}e^{-x_{fo}} \approx \frac{1}{mM_{pl}\langle\sigma v\rangle}$$

To get the right amount of dark matter:

$$0.2 = \Omega_{DM} = \frac{\rho_{DM}}{\rho_c}$$

DM density today has redshifted:

$$\rho_{DM} = m \, n_{DM} = m \, \frac{T_0^3}{T_{fo}^3} \, n_{fo}$$



So the freezeout and cross-sections we need are:

$$\left(\frac{\Omega_{DM}}{0.2}\right) \approx \left(\frac{x_{fo}}{20}\right) \left(\frac{\text{pb}}{\langle \sigma v \rangle}\right)$$

 Weakly Interacting Massive Particle miracle: weak-scale masses and cross-sections give right estimate for DM

$$\sigma \sim \frac{g^4}{m^2}$$

- WIMP miracle is properly a statement about perturbative thermal relics:
 - upper bound on *m*: $g^2 < 4\pi$

 $\Rightarrow m \lesssim 40 \,\mathrm{TeV}$

 lower bound on *m*: freezeout must happen when DM is relativistic...

 $\Rightarrow m \gtrsim 10 \,\mathrm{eV}$

 but in practice packing DM into galaxies is more stringent



- This is a broad but bounded range of mass scales
- Nontrivial: includes SM electroweak
 - SM weak interactions: only SM gauge interaction with right properties
 - Higgs interactions also fit the bill
 - Is dark matter part of extended model of EWSB?
 - Testable right now!

DM can also freezeout from SM through new BSM mediator:







- still offers weak-scale masses, accessible couplings
- but much wider range of collider, direct detection signatures

• Caveat 1:

 WIMPy freezeout can also happen with little to no involvement of SM; then DM may be weak scale or below, but couplings between DM and the SM too feeble to see at colliders



- Caveat 2: DM may have a non-minimal thermal history
- And a reminder: thermal relics are only one possibility of many





SURPRISES

Be ready for surprises!

- Nature has a track record of giving us particles we had no idea to expect
- Some of the most
 apparently motivated
 theories have not been
 borne out

