PHYSICS 489/1489

WRAPUP

REMINDER

- Problem Set 4 due today
  - arrangements will be made to return these problem sets.
- Final Examination:
  - 1900-2200 on 18 December (Monday) in UC273.
- I will be out of town starting Saturday
  - Happy to answer questions by email or chat by skype

THE HIGGS FIELD

$$\mathcal{L}_K = (\partial_\mu \phi)^\dagger (\partial_\mu \phi) \rightarrow (D_\mu \phi)^\dagger (D^\mu \phi)$$

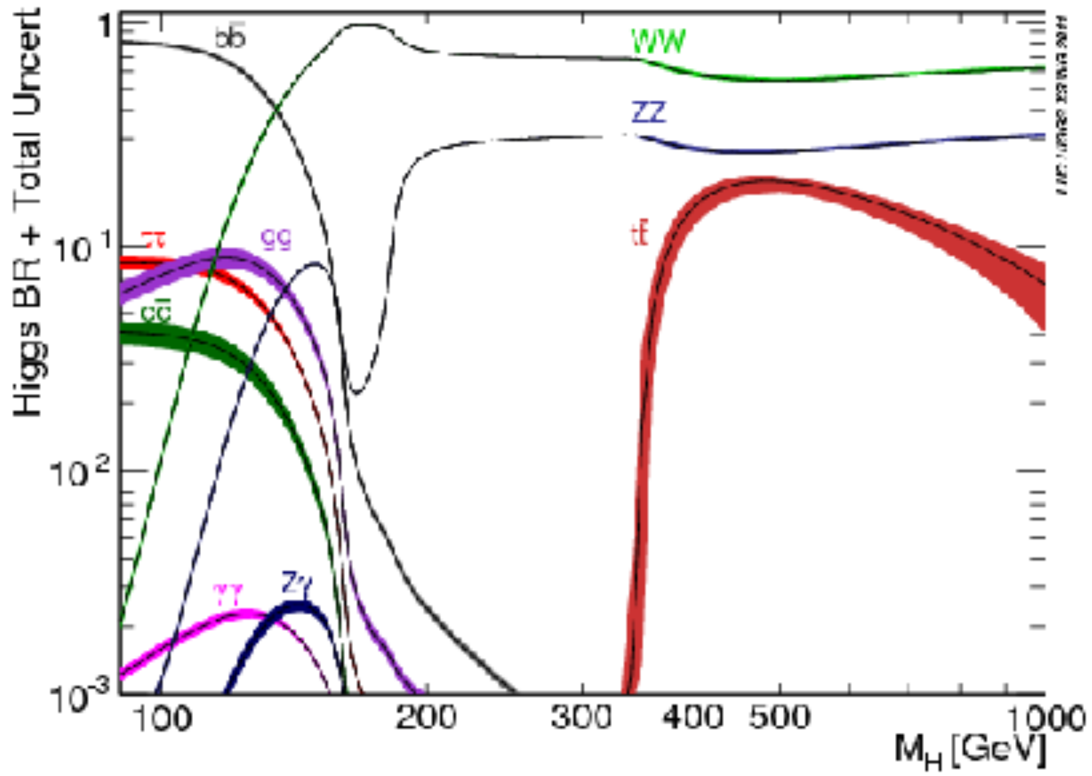
$$D_\mu \phi = \frac{1}{2\sqrt{2}} \begin{pmatrix} ig_w(W_\mu^1 - iW_\mu^2) \\ 2\partial_\mu - ig_W W_\mu^3 + ig' B_\mu \end{pmatrix} (v+h)$$

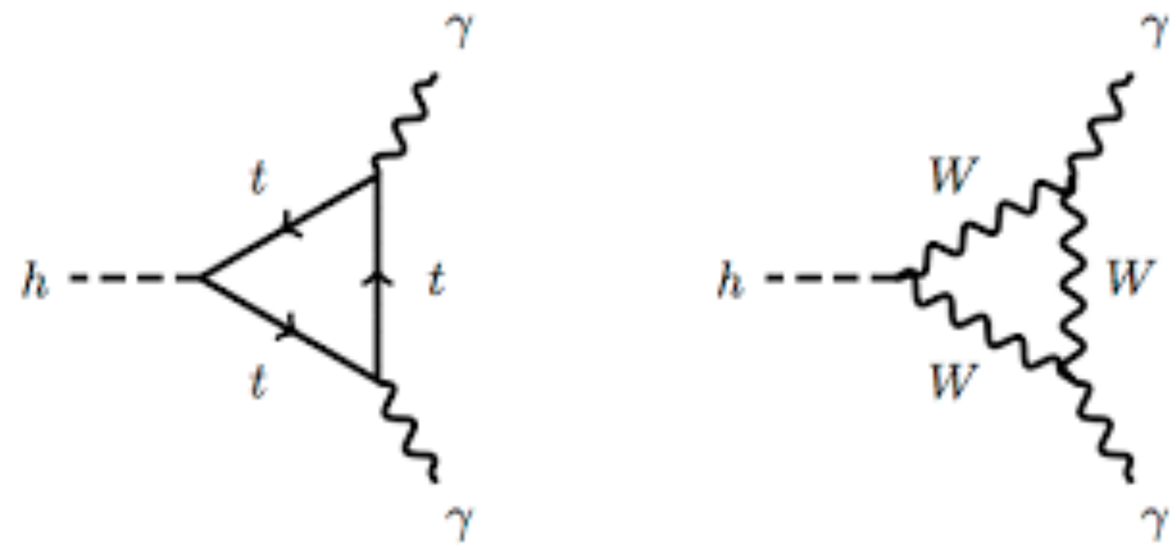
$$\frac{1}{2}(\partial_\mu h)(\partial^\mu h)$$

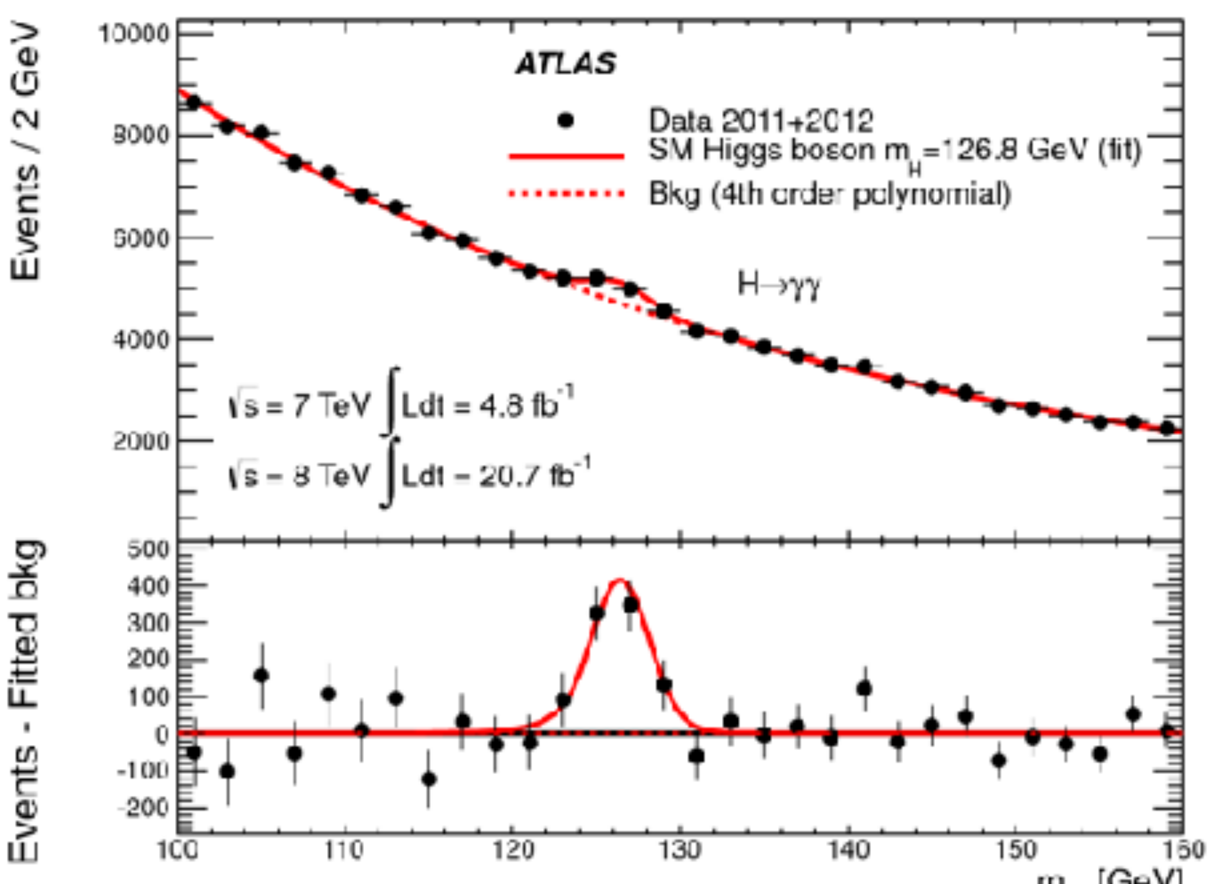
$$\frac{g_W^2}{8}(W_\mu^1 + iW_\mu^2)(W^{1\mu} - iW^{2\mu})(v+h)^2$$

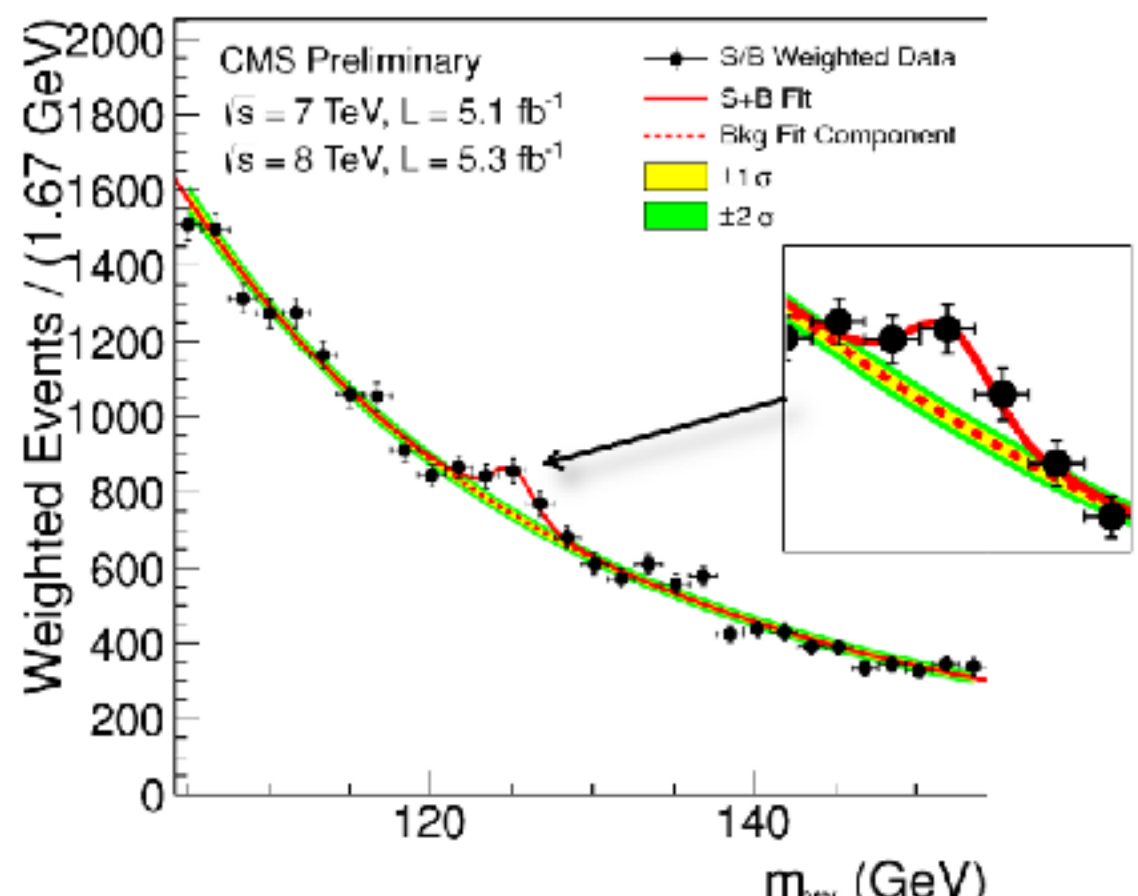
$$\frac{1}{8}(ig_W W_\mu^3 - ig' B_\mu)(-ig_w W^{3\mu} + ig' B^\mu)(v+h)^2$$

HIGGS BOSON DISCOVERY:

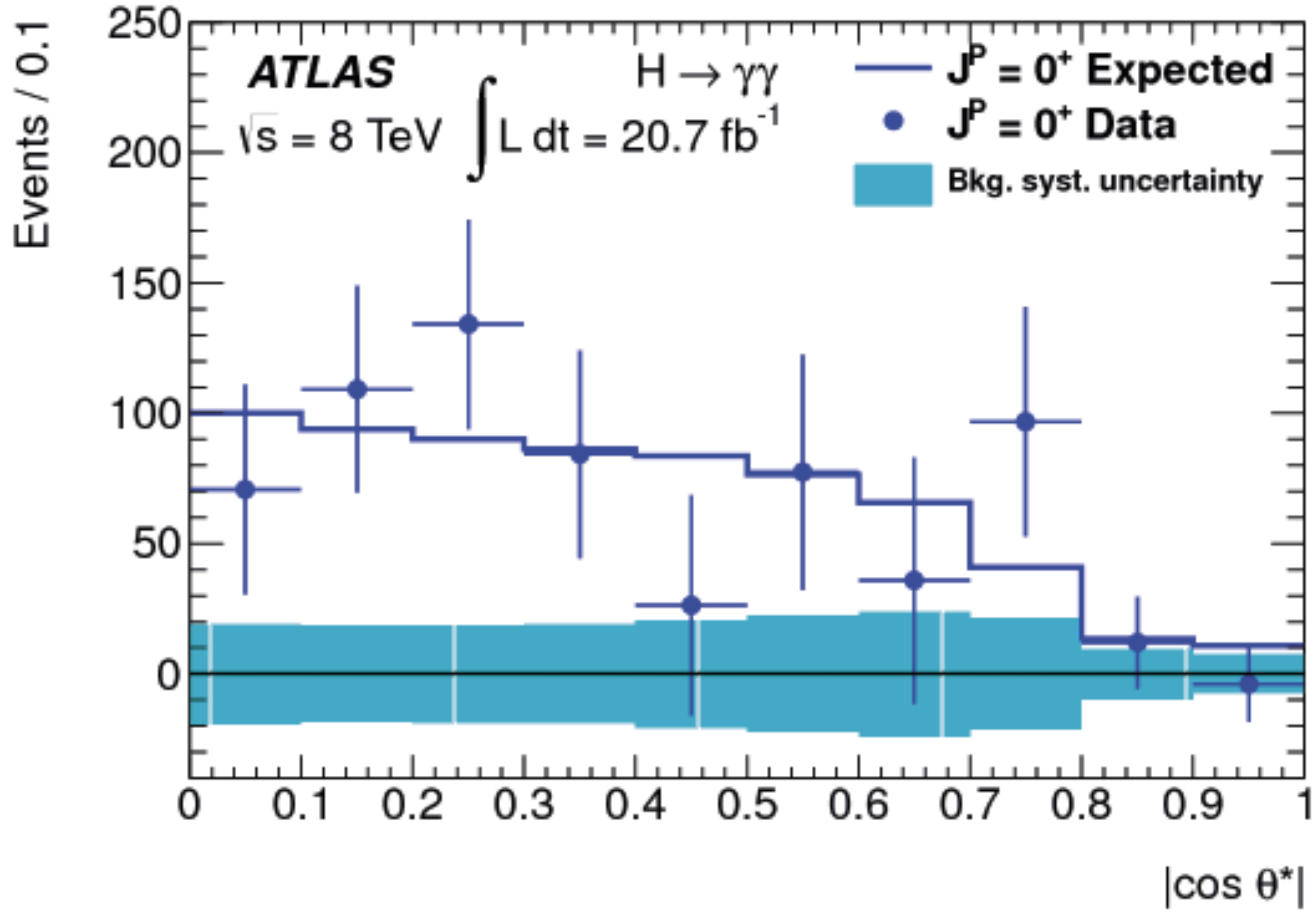


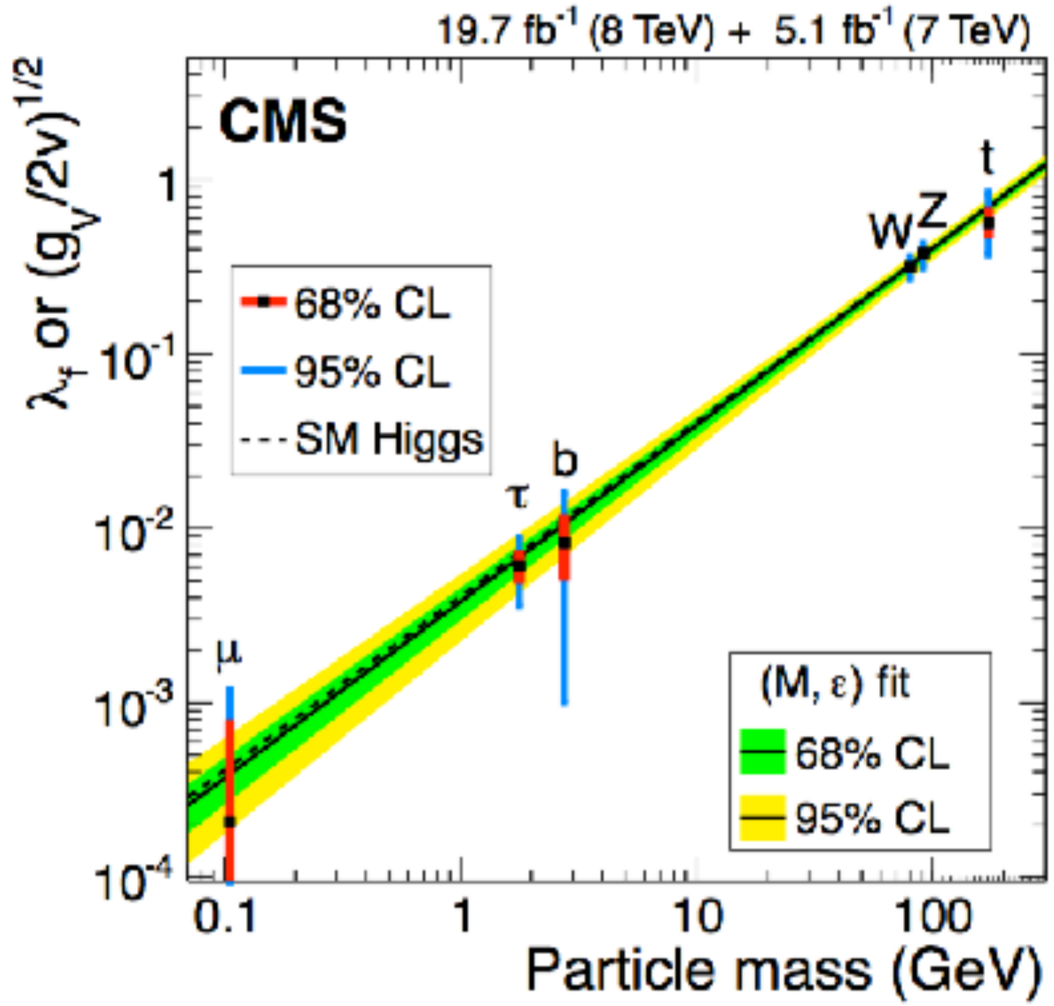






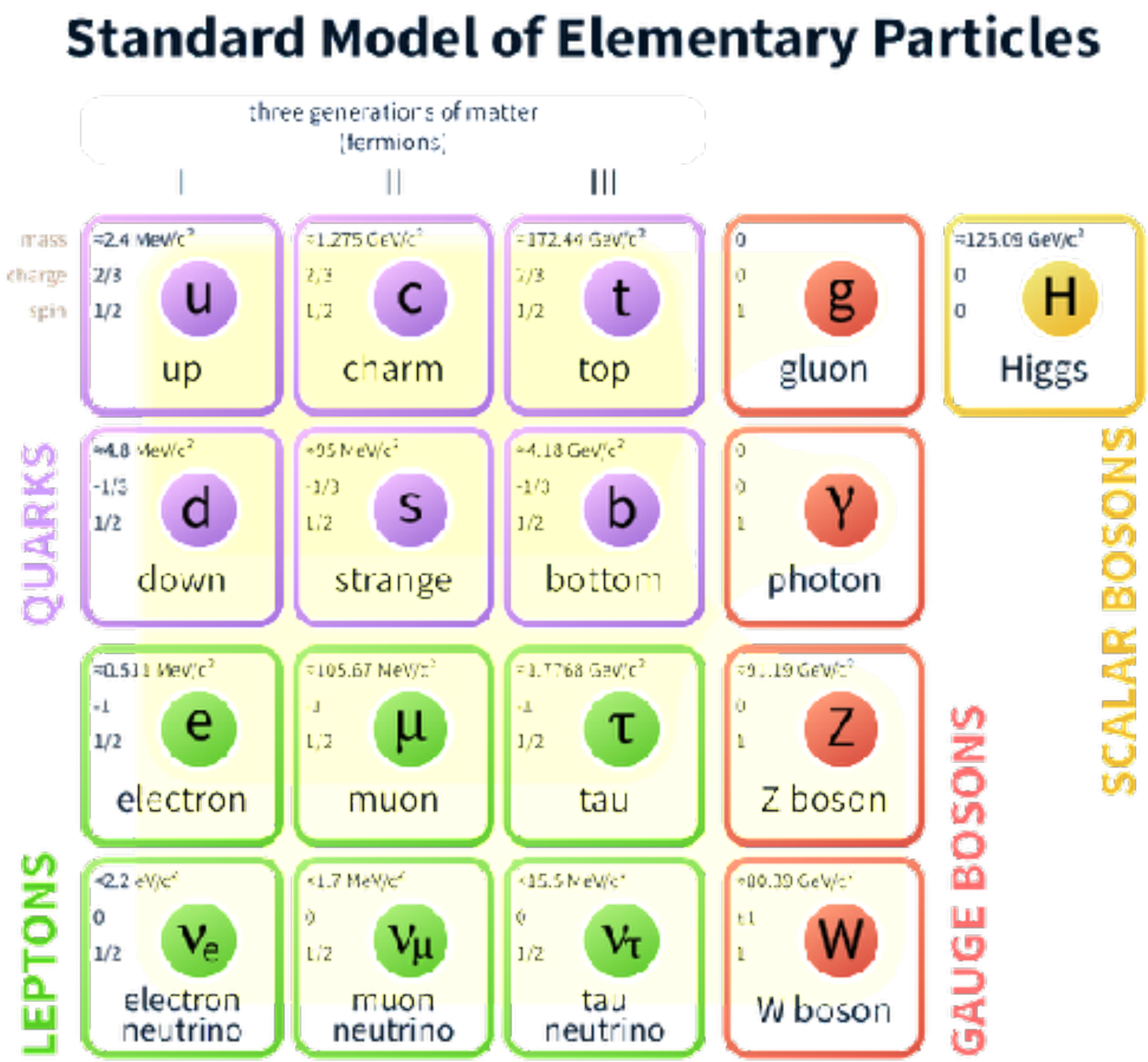
HIGGS PROPERTIES:

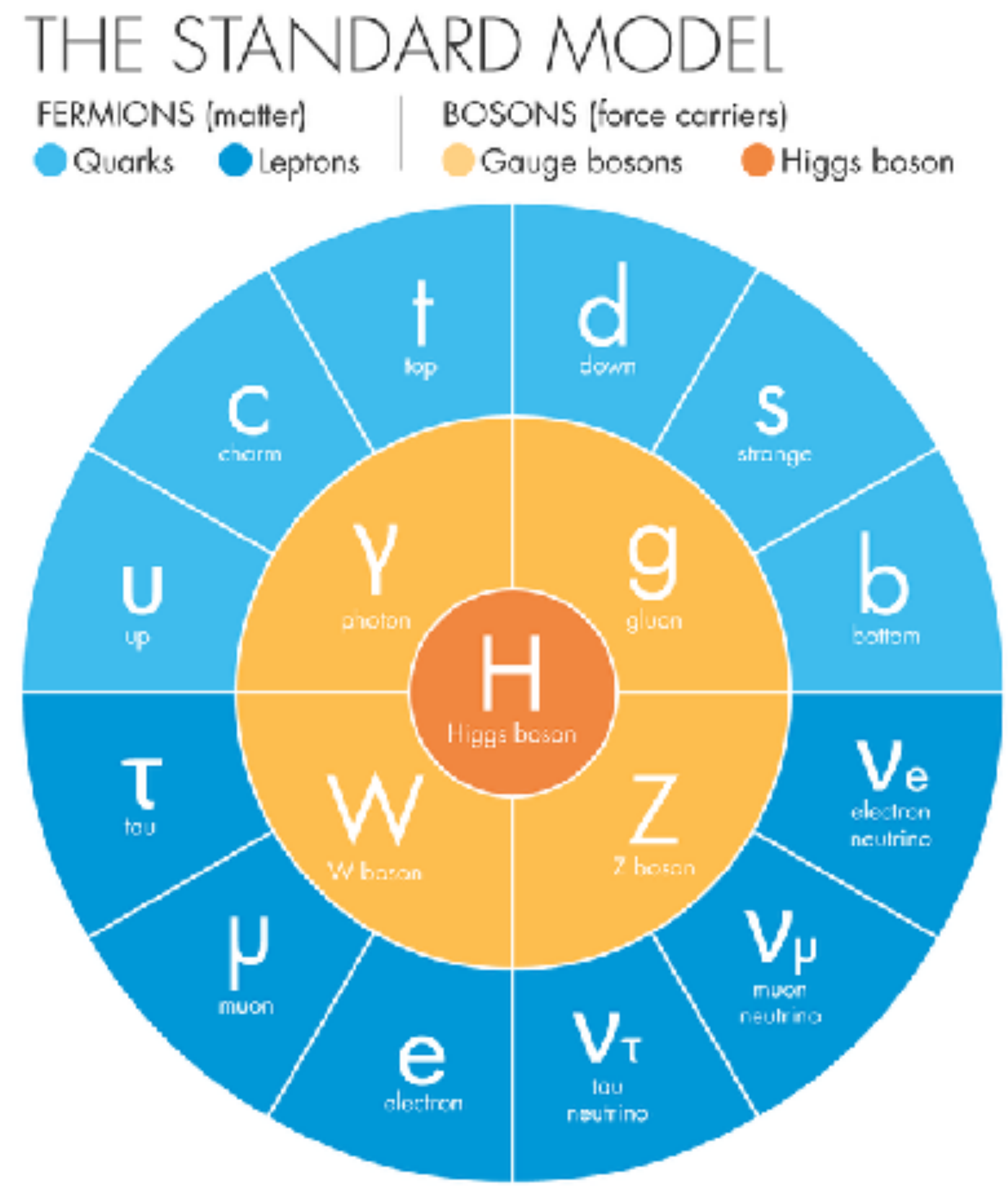




- In the standard model, the Higgs particle is:
  - a scalar (spin 0) particle
  - coupling to other particles determine its mass

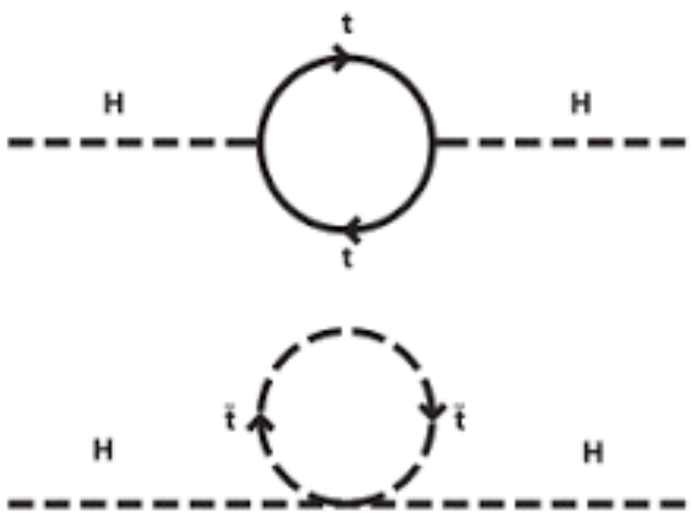
THE STANDARD MODEL





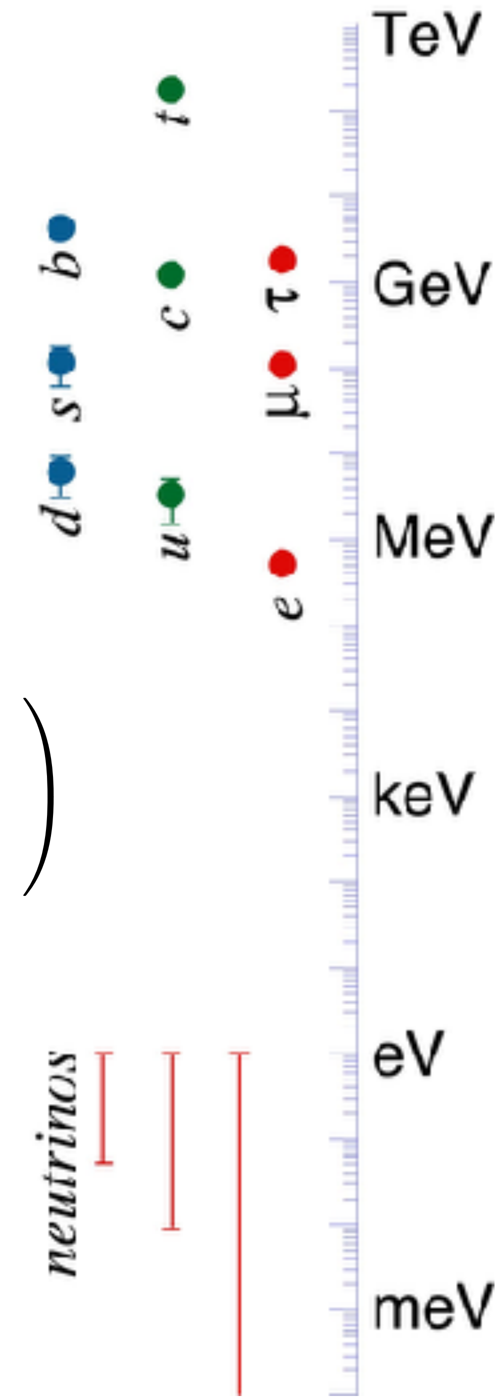
- The Higgs boson is unique in being the only elementary scale field/particle in the Standard Model
- In principle, this is everything . . . .
  - searching for "**physics beyond the standard model**" (BSM)

ISSUES



$$|U_{LEPTON}| \sim \begin{pmatrix} 0.8 & 0.5 & 0.15 \\ 0.4 & 0.6 & 0.7 \\ 0.4 & 0.6 & 0.7 \end{pmatrix}$$

$$|U_{QUARK}| \sim \begin{pmatrix} 0.97428 & 0.2253 & 0.0034 \\ 0.2252 & 0.93745 & 0.0410 \\ 0.00862 & 0.0403 & 0.99915 \end{pmatrix}$$



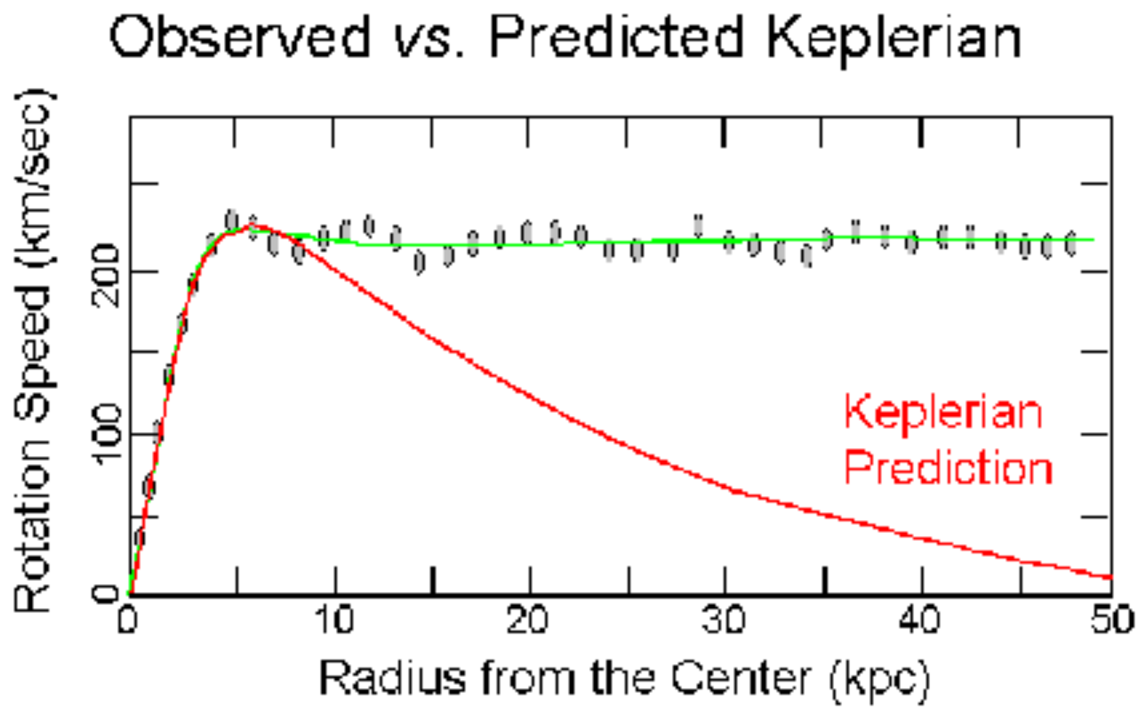
- The Higgs mass term is unstable to higher order corrections
- Is there a mechanism that stabilizes this?

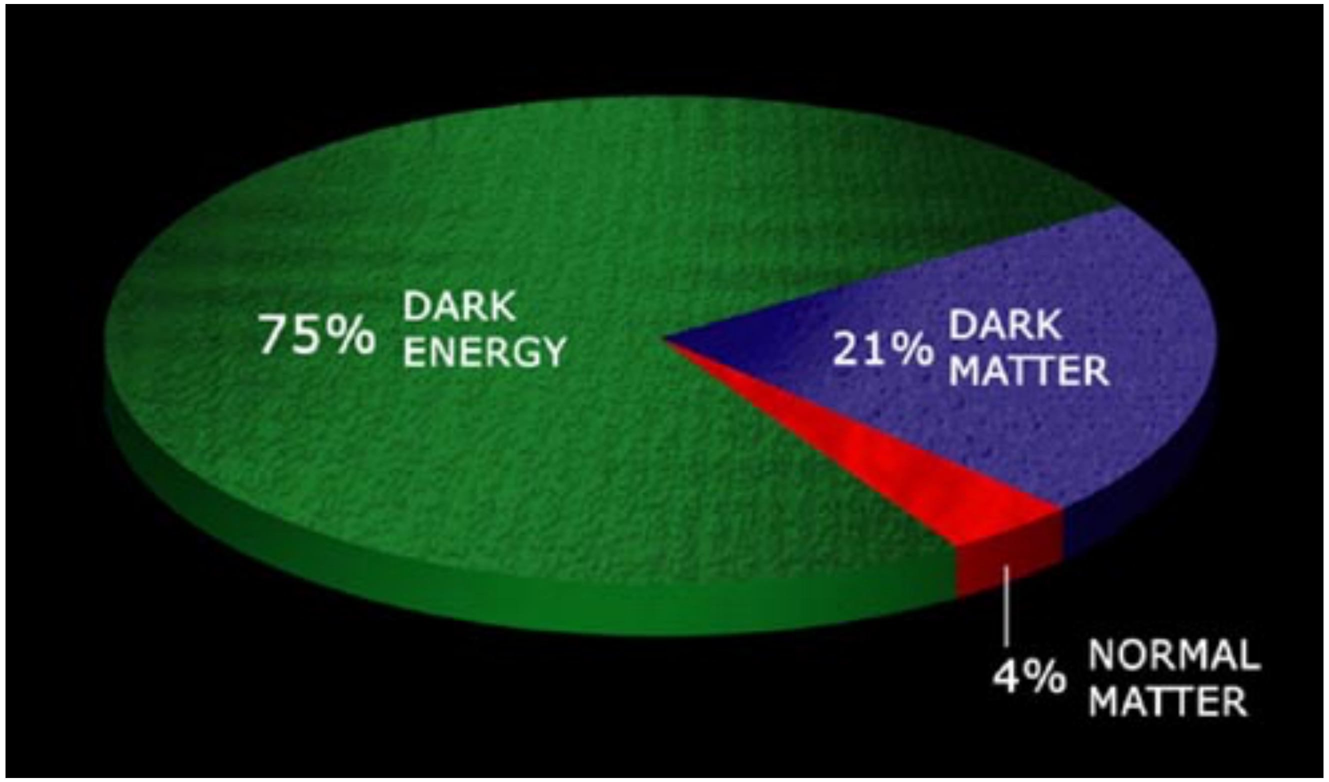
- Why are quark and lepton mixing matrices so different?
- Why are neutrinos so much lighter than all the other particles?

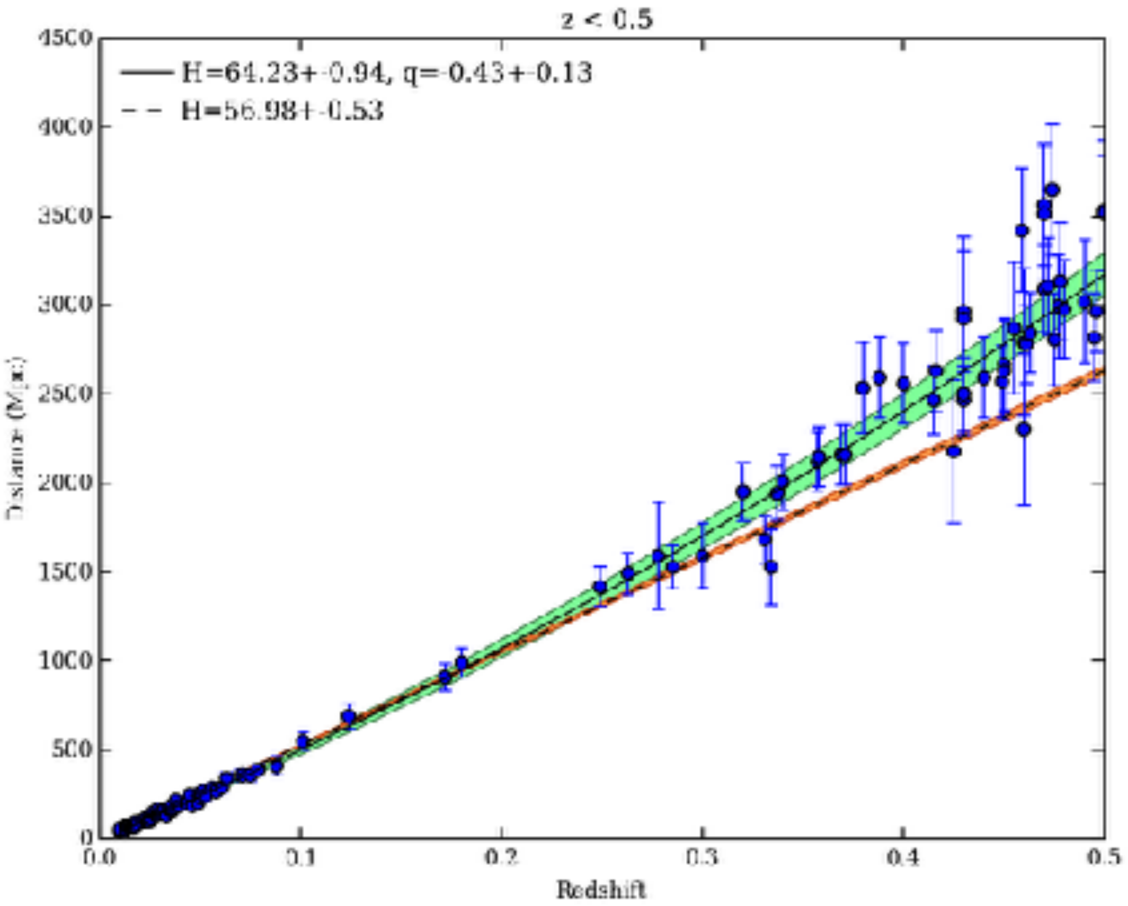
- Could be that's "just the way it is"

DARK MATTER AND ENERGY

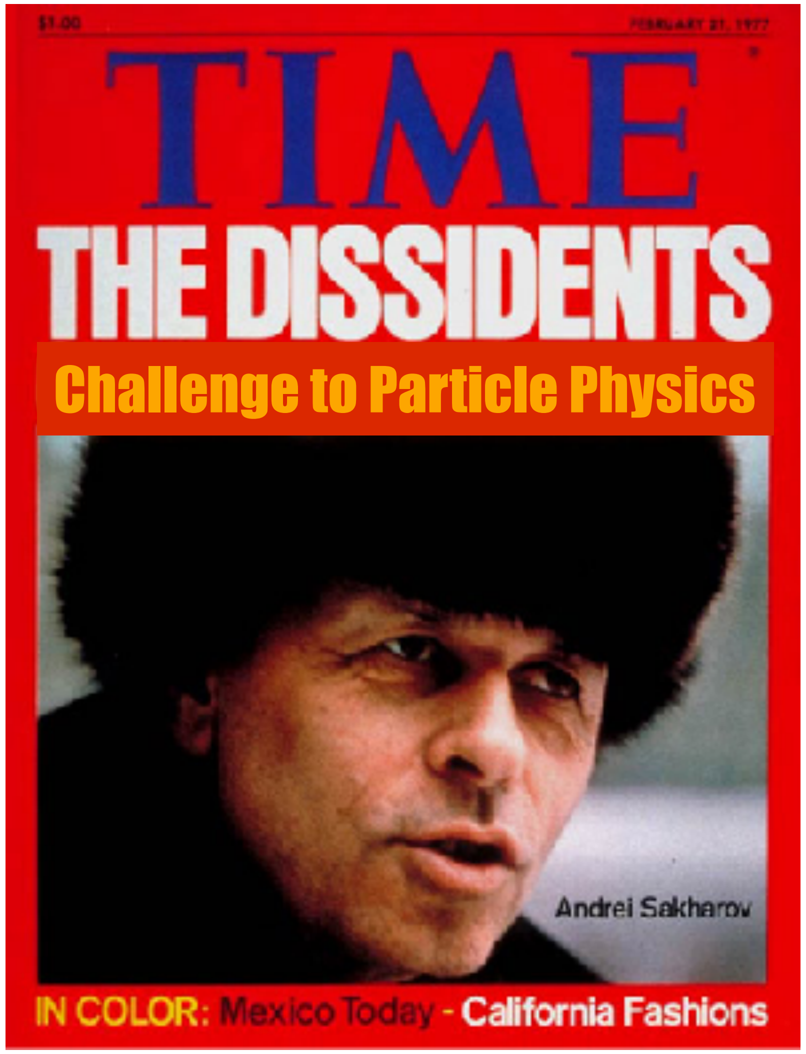
- Cosmological observations indicate sources of energy and mass that cannot be explained by the Standard Model:
  - Dark Matter
  - Dark Energy





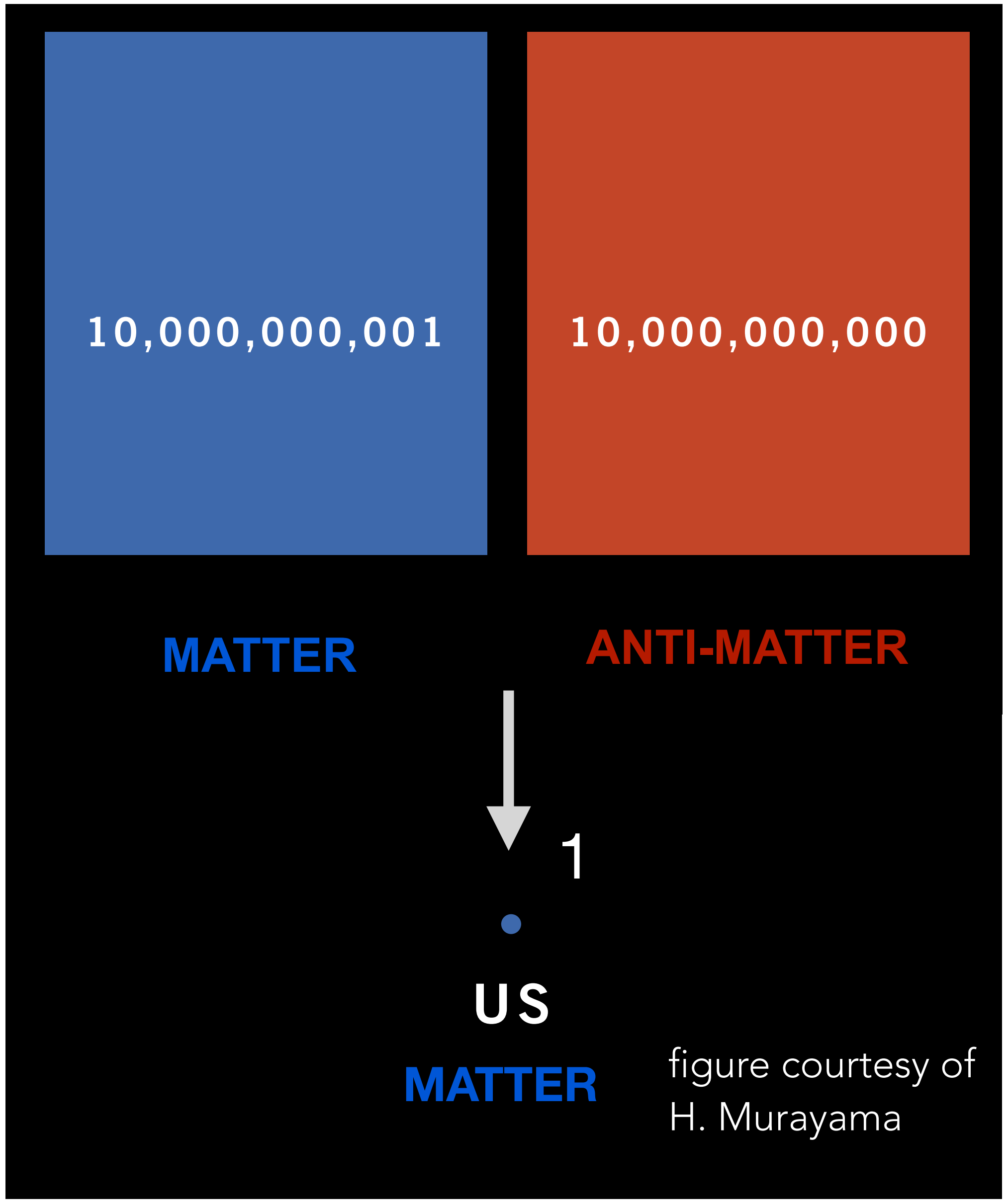


MATTER DOMINATED UNIVERSE



SAKHAROV CONDITIONS:

- BARYON NUMBER (B) VIOLATION
- VIOLATION OF C, CP SYMMETRY (CPV)
- DEPARTURE FROM THERMAL EQUILIBRIUM



$$\frac{\Delta B}{N_\gamma} \sim \mathcal{O}(10^{-10})$$

- Extremely small?
- Extremely large?
  - Known sources of CPV (quark CKM) cannot produce this asymmetry

REVIEW: WEAK INTERACTIONS

- Chiral interaction vertex:
  - parity violation
  - helicity suppression
- Massive gauge bosons (W, Z)
  - impacts strength of interaction
- Mixing of flavor/mass states of quarks and leptons
  - flavour change: hierarchy of transition strengths based on matrix
    - "CKM/Cabibbo" favored/suppressed processes
  - CP violation
    - relation to number of generations
  - GIM mechanism:
    - cancellation at the amplitude level for "flavor changing neutral currents"

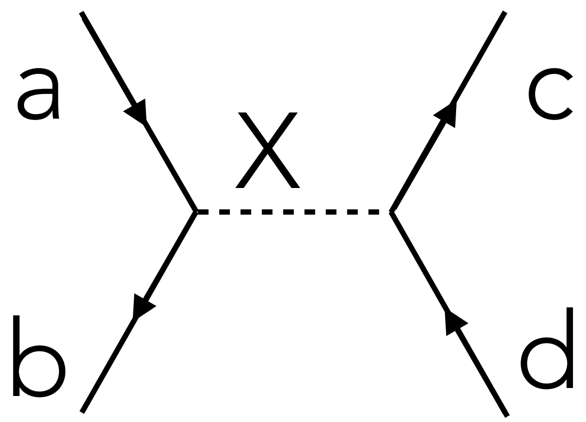
ELECTROWEAK MIXING

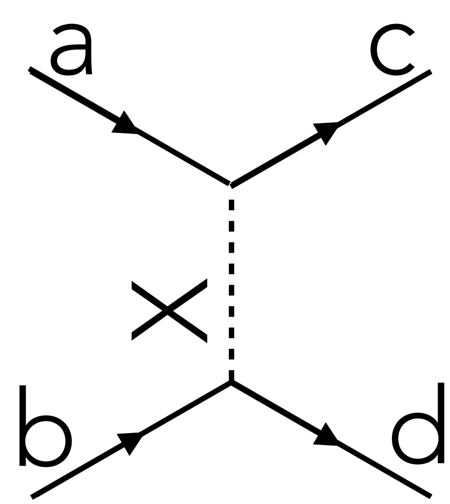
- local gauge invariance
- $SU(2)_L \times U(1)_Y$ gauge group
  - Chiral properties of the gauge coupling
  - 4 gauge bosons arise
    - how do they correspond to the $W^{\pm}$, Z, γ?
    - where does electromagnetism come from?
  - What is θ_W and where does it "show up?
  - masses:
    - why can't we add mass terms for the gauge bosons?
    - why can't we add mass terms for the fermions (quarks/leptons)?

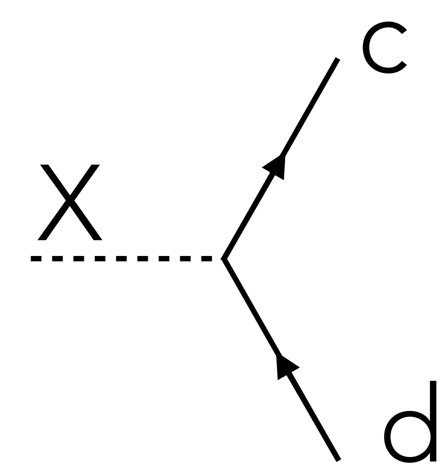
SSB AND HIGGS MECHANISM

- Vacuum expectation value (VEV)
  - how does a field acquire a non-zero VEV?
  - how can it result in a mass term for the gauge boson?
  - how can it result in a mass term for fermions?
- Goldstone boson:
  - massless vector bosons have only transverse polarization.
  - how does the massive gauge boson acquire longitudinal polarization?

CALCULATIONS:





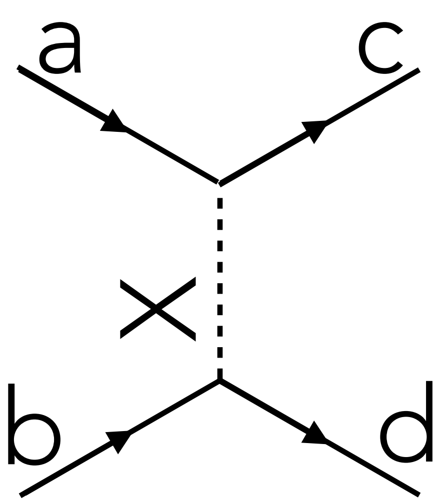


$$\bar{b}\,\Gamma^{\mu}\;a\;P_{\mu\nu}(X)\;\bar{c}\,\Gamma^{\nu}\;d \qquad \bar{c}\,\Gamma^{\mu}\;a\,P_{\mu\nu}(X)\,\bar{d}\,\Gamma^{\nu}\;b \qquad \epsilon_{\mu}(X)\,\bar{c}\,\Gamma^{\mu}\;d$$

- Most calculations are one of the above
  - annihilation diagram (s-channel)
  - exchange digram (t,u channel)
  - boson decay
- a, b, c, d are u,v spinors
  - reverse arrows→reverse ordering of spinors
- Γ^{μ} is the vertex factor (usually a constant, γ, γ^5)
- P is the propagator for boson (γ, W, Z)
- ε_{μ} is the polarization for an initial state boson
- Notes
  - the amplitude is a number. Note Dirac and Lorentz structure of terms
    - beware "-" in spatial components of Lorentz contraction
  - when γ^5 is present, the amplitude can be broken down into vector currents with chiral spinors
    - explicit forms of relevant currents will be given
  - propagator for W, Z can be simplified if energies ≪ M_W, M_Z
  - averaging factors for initial state

NEUTRINO-QUARK SCATTERING

- $\nu_e + d \rightarrow e + u$



$$\bar{c}\,\Gamma^\mu\; a \qquad \bar{e}\frac{-ig_W}{2\sqrt{2}}\gamma^\mu(1-\gamma^5)\nu$$

$$P_{\mu\nu}(X) \qquad \frac{-i(g_{\mu\nu} - q_\mu q_\nu / M_W^2)}{q^2 - M_W^2} \qquad \sim \frac{ig_{\mu\nu}}{M_W^2}$$

$$\bar{d}\,\Gamma^\nu\; b \qquad \bar{d}\frac{-ig_W}{2\sqrt{2}}\gamma^\nu(1-\gamma^5)u$$

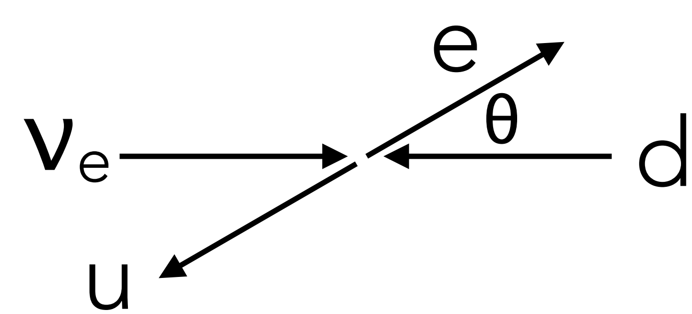
- $\nu \rightarrow$ "1"
- $e \rightarrow$ "2"
- $d \rightarrow$ "3"
- $u \rightarrow$ "4"

$$\mathcal{M} = \frac{g_W^2}{8M_W^2}\;\left[\bar{u}_3\gamma^\mu(1-\gamma^5)u_1\right]\left[\bar{u}_4\gamma_\mu(1-\gamma^5)u_2\right]$$

$$\mathcal{M} = \frac{g_W^2}{2M_W^2}\;\left[\bar{u}_{3L}\gamma^\mu u_{1L}\right]\left[\bar{u}_{4L}\gamma_\mu u_{2L}\right]$$

$$\mathcal{M} = 4g_W^2\,\frac{E^2}{M_W^2}$$

- Center-of-mass scattering



$$\left[\bar{u}_{3L}\gamma^\mu u_{1L}\right] = 2E(c, s, -is, c)$$

$$\left[\bar{u}_{4L}\gamma^\mu u_{2L}\right] = 2E(c, -s, is, ic)$$

c, s = cos θ/2, sin θ/2