The Standard Model

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C T E Q

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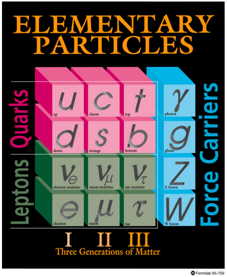
What is the Standard Model?

Definition

The Standard Model is the simplest 4-dimensional low-energy quantum effective field theory description consistent with the known degrees of freedom and their interactions (except gravity), and all experimental data.

- If that sounds a bit fluid, it is ...
  - It basically encapsulates our current knowledge.
  - There is a lot of subtlety built into that definition.
- The quality and quantity of experimental data is astounding, and still growing. I will not concentrate on this.
- The interactions are probably the most interesting part, but I will only concentrate on one type — mass.
- I will focus on the degrees of freedom, and how they are embedded in the Standard Model.

Part I



- The known part

Part II

$+$ Higgs

- The speculative part

Outline

1. **A collection of massless degrees of freedom**
   - Gauge particles — bosons
   - Weyl matter — fermions
   - Embedding fermions without anomalies

2. **Masses are interactions**
   - The Higgs boson vs. the Higgs mechanism
   - Yukawa interactions
   - Neutrino masses (so far)

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Standard Model described by a Lagrangian

- The Standard Model is described by a Lagrangian that is the sum of the gauge, matter, Higgs, and Yukawa interactions:

$$\mathcal{L}_{\rm SM} = \mathcal{L}_{\rm Gauge} + \mathcal{L}_{\rm Matter} + \mathcal{L}_{\rm Higgs} + \mathcal{L}_{\rm Yukawa}$$

- This Lagrangian is not written initially in terms of the (very) low energy degrees of freedom we observe in our ground state, but in terms of
  - massless states
  - fundamental symmetries
- Our ground state is addressed in Part II.
- The fundamental symmetries we have are
  - $\mathsf{SU}(3)_{\rm Color}$
  - $\mathsf{SU}(2)_{\rm Left}$
  - $\mathsf{U}(1)_{\rm hYpercharge}$

    The generators of these groups T^A satisfy graded Lie algebras $[T^A, T^B] = if^{ABC}T^C$.

Gauge transformations

$$\mathcal{L}_{\rm SM} = \mathcal{L}_{\rm Gauge} + \mathcal{L}_{\rm Matter} + \mathcal{L}_{\rm Higgs} + \mathcal{L}_{\rm Yukawa}$$

- Gauge bosons are massless spin-1 particles associated with local (gauge) symmetries

$$T^A G^A_\mu(x) \to U(x) T^A G^A_\mu(x) U^{-1}(x) + \frac{i}{g} \left(\partial_\mu U(x)\right) U^\dagger(x)$$
$$G^A_\mu(x) \to \exp[i T^B_{ad} \theta^B(x)]^{AC} G^C_\mu(x)$$

  T^A are the generators of the fundamental representation
  T^A_{ad} are the generators of the adjoint representation
- The number of adjoint generators $\Longrightarrow$ number of bosonic d.o.f.
  $\mathrm{SU}(3)_C$ has 8 gluons; $\mathrm{SU}(2)_L$ has 3 weak fields A^i_μ;
  $\mathrm{U}(1)_Y$ has 1 hypercharge boson B_μ
- Mass terms are explicitly forbidden for unbroken symmetry

$$\mathcal{L} \neq \tfrac{1}{2} M^2 G_\mu G^\mu = M^2 \mathrm{Tr}\; T^A G^A_\mu T^B G^{B\mu}$$

Gauge kinetic terms

- With some cleverness, we can identify a gauge invariant way to add terms to our Lagrangian by using field strength tensors

$$F_{\mu\nu} = [D_\mu, D_\nu]$$
$$D_\mu = \partial_\mu + igT^A G^A_\mu$$

  D_μ is the covariant derivative, g is the coupling constant

- $F_{\mu\nu} \to U(x) F_{\mu\nu} U^\dagger(x)$;
  $\mathrm{Tr}\,[F_{\mu\nu}F^{\mu\nu}] \to \mathrm{Tr}\,[UF_{\mu\nu}U^\dagger UF^{\mu\nu}U^\dagger] = \mathrm{Tr}\,[F_{\mu\nu}F^{\mu\nu}]$
- We add one kinetic term for each symmetry to get

$$\mathcal{L}_{\mathrm{Gauge}} = \frac{1}{2g_s^2}\mathrm{Tr}\,[G_{\mu\nu}G^{\mu\nu}] + \frac{1}{2g^2}\mathrm{Tr}\,[A_{\mu\nu}A^{\mu\nu}] + \frac{1}{2g'^2}\mathrm{Tr}\,[B_{\mu\nu}B^{\mu\nu}]$$

- The non-Abelian groups hold a rich nonlinear structure that leads to all of the complexity of QCD and the weak force.

Lorentz transformations and Weyl spinors

- We want a representation of fermions consistent with spacetime

Lorentz group SO(3,1) $\cong$ SU(2)$\times$SU(2)

$$[J_i, J_j] = i\epsilon_{ijk} J_k \qquad [A_i, A_j] = i\epsilon_{ijk} A_k$$
$$[K_i, K_j] = -i\epsilon_{ijk} J_k \qquad [B_i, B_j] = i\epsilon_{ijk} B_k$$
$$[J_i, K_j] = i\epsilon_{ijk} K_k \qquad [A_i, B_j] = 0$$

Rotations J_i are Hermitian
Boosts K_i are anti-Hermitian

A_i/B_i are Hermitian

$$A_i = \frac{1}{2}(J_i + iK_i)$$
$$B_i = \frac{1}{2}(J_i - iK_i)$$

Weyl spinors: simplest nontrivial 2-component representations $(A, B) = (1/2, 0)$, we will denote χ or ξ

Homework: Show $\epsilon\xi^*$ transforms under the $(0, 1/2)$ rep., $\epsilon = i\sigma_2$

Dirac and Majorana spinor notation

- To put things in a more familiar form, create a 4-component spinor that describes particle and anti-particle d.o.f. at the same time:

Using one Weyl spinor χ

$$\psi_M = \begin{pmatrix} \chi \\ \epsilon\chi^* \end{pmatrix}$$

This is a Majorana spinor

The particle is its own antiparticle

Using two Weyl spinors χ, ξ

$$\psi_D = \begin{pmatrix} \chi \\ \epsilon\xi^* \end{pmatrix}$$

This is a Dirac spinor

We've written independent d.o.f. in a single object

- The two Weyl fermions in a Dirac spinor are still independent.
- Chiral projection operators $(1 \pm \gamma_5)/2$ project out Weyl spinors:

$$\psi = \frac{1-\gamma_5}{2}\psi + \frac{1+\gamma_5}{2}\psi = \psi_L + \psi_R$$

$$\psi_L = \begin{pmatrix} \chi \\ 0 \end{pmatrix}, \quad \psi_R = \begin{pmatrix} 0 \\ \epsilon\xi^* \end{pmatrix}$$

Matter Lagrange Density

$$\mathcal{L}_{\rm SM} = \mathcal{L}_{\rm Gauge} + \mathcal{L}_{\rm Matter} + \mathcal{L}_{\rm Higgs} + \mathcal{L}_{\rm Yukawa}$$

- Take our massless Weyl spinors written in 4-component notation and grouped into SU(2) singlets and doublets:

$$u_L = \begin{pmatrix} \chi \\ 0 \end{pmatrix}, \quad (u^c)_L = \begin{pmatrix} \xi \\ 0 \end{pmatrix}; \qquad Q_L \equiv \begin{pmatrix} u_L \\ d_L \end{pmatrix}$$

$$\mathcal{L}_{\rm Mat} = i\overline{Q}^i_L \not{D} Q^i_L + i\overline{(u^c)}^i_L \not{D}(u^c)^i_L + i\overline{(d^c)}^i_L \not{D}(d^c)^i_L + i\overline{L}^i_L \not{D} L^i_L + i\overline{(e^c)}^i_L \not{D}(e^c)^i_L$$

- Notice that every fermionic degree of freedom is independent.
- In particular, u and u^c do not directly couple to each other.
- Using $(\psi^c)_L = C\gamma^0\psi^*_R$ we can recast $\mathcal{L}$ in a more familiar form

$$\mathcal{L}_{\rm Matter} = i\bar{Q}^i_L \not{D} Q^i_L + i\bar{u}^i_R \not{D} u^i_R + i\bar{d}^i_R \not{D} d^i_R + i\bar{L}^i_L \not{D} L^i_L + i\bar{e}^i_R \not{D} e^i_R$$

Embedding matter in $\mathrm{SU(3)_C \times SU(2)_L \times U(1)_Y}$

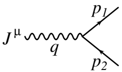
				$SU(3)_C$	$SU(2)_L$	$U(1)_Y$
$Q_L =$	$\begin{pmatrix} u_L \\ d_L \end{pmatrix}$	$\begin{pmatrix} c_L \\ s_L \end{pmatrix}$	$\begin{pmatrix} t_L \\ b_L \end{pmatrix}$	3	2	$\frac{1}{6}$
$(u^c)_L =$	$(u^c)_L$	$(c^c)_L$	$(t^c)_L$	$\bar{3}$	1	$-\frac{2}{3}$
$(d^c)_L =$	$(d^c)_L$	$(s^c)_L$	$(b^c)_L$	$\bar{3}$	1	$\frac{1}{3}$
$L_L =$	$\begin{pmatrix} \nu_{eL} \\ e_L \end{pmatrix}$	$\begin{pmatrix} \nu_{\mu L} \\ \mu_L \end{pmatrix}$	$\begin{pmatrix} \nu_{\tau L} \\ \tau_L \end{pmatrix}$	1	2	$-\frac{1}{2}$
$(e^c)_L =$	$(e^c)_L$	$(\mu^c)_L$	$(\tau^c)_L$	1	1	1

Note: e_R would have hypercharge $Y = -1$.

Anomaly cancellation

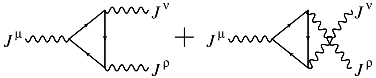
a consequence of current conservation

- Recall gauge invariance implies current conservation, $\partial_\mu J^\mu = 0$



$$q_\mu J^\mu = \overline{u}(p_1)\not{q}v(p_2)$$
$$= \overline{u}(p_1)(\not{p}_1 + \not{p}_2)v(p_2)$$
$$= 0$$

$\overline{u}(p_1)\not{p}_1 = 0$, $\not{p}_2 v(p_2) = 0$



Need $\partial_\mu J^\mu = \partial_\nu J^\nu = \partial_\rho J^\rho = 0$

This is not satisfied unless $\sum_R \mathrm{Tr}\, T_R^A\{T_R^B, T_R^C\} = 0$, where T_R^A is a generator of rep. R.

Homework: Show a vector-like gauge theory is always anomaly-free.

Quantum numbers and anomaly cancellation

1. $SU(N)$–G^2: $T_{\rm G}=1$, so need $\sum_R {\rm Tr}\, T_R^A = 0$, trivial for $N>1$
   - $U(1)_{\rm Y}$: $\sum_{\rm fermions} Y = (+1/6)\cdot 2\cdot 3 + (-2/3)\cdot 3 + (+1/3)\cdot 3$ $+(-1/2)\cdot 2 + 1 = 0$! Quarks and leptons cancel separately.
2. $SU(3)^3$ automatic: QCD is vectorlike (# of 3 = # of $\overline{3}$)
3. $SU(2)^3$ automatic: $\frac{1}{8}\sum_{\rm doublets} {\rm Tr}\,\sigma^A\{\sigma^B,\sigma^C\} = \frac{1}{4}\delta^{BC}{\rm Tr}\,\sigma^A = 0$
4. $U(1)_{\rm Y}^3$: $\sum_{\rm fermions} Y^3 =$ $(+1/6)^3\cdot 2\cdot 3 + (-2/3)^3\cdot 3 + (+1/3)^3\cdot 3 + (-1/2)^3\cdot 2 + 1^3 = 0$
   - Cancellation between quarks and leptons in each generation!
5. $SU(3)^2$–$U(1)_{\rm Y}$: $\propto \sum_{\rm quarks} Y = 0$ (just like gravitational anomaly)
6. $SU(2)^2$–$U(1)_{\rm Y}$: $\propto \sum_{\rm doublets} Y{\rm Tr}\{\sigma^B,\sigma^C\} \propto \sum_{\rm doublets} Y = (+1/6)\cdot 3 + (-1/2) = 0$
   - Cancellation between quarks and leptons again!

- The need to cancel anomalies explains why charges are quantized in the fractions they are, i.e. defines generations.

Homework: Prove there are exactly 3 generations... just kidding

Summary of the Standard Model matter content

- The Starting from $\mathrm{SU}(3)_C \times \mathrm{SU}(2)_L \times \mathrm{U}(1)_Y$ local symmetries of Lagrangian, we found kinetic terms for gauge particles G, A, B

$$\mathcal{L}_{\text{Gauge}} = \frac{1}{2g_s^2}\mathrm{Tr}\left[G_{\mu\nu}G^{\mu\nu}\right] + \frac{1}{2g^2}\mathrm{Tr}\left[A_{\mu\nu}A^{\mu\nu}\right] + \frac{1}{2g'^2}\mathrm{Tr}\left[B_{\mu\nu}B^{\mu\nu}\right]$$

- A large number of 2-component (Weyl) massless fermions are charged under these gauge groups, and also acquire kinetic terms

$$\mathcal{L}_{\text{Mat}} = i\overline{Q}^i_L \not{D} Q^i_L + i\overline{(u^c)}^i_L \not{D}(u^c)^i_L + i\overline{(d^c)}^i_L \not{D}(d^c)^i_L + i\overline{L}^i_L \not{D} L^i_L + i\overline{(e^c)}^i_L \not{D}(e^c)^i_L$$

  - The pattern of quantum numbers and distinction between "quarks" and "leptons" is attributed to writing a consistent (anomaly-free) theory.
  - The fields and conjugate fields (e.g., u, u^c) have independent d.o.f..

- We've identified the fundamental degrees of freedom and interactions.
  - The low energy world we observe is not composed of independent L and R worlds with all massless particles. Something must have happened.

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Higgs mechanism breaks electroweak symmetry

$$\mathcal{L}_{\rm SM} = \mathcal{L}_{\rm Gauge} + \mathcal{L}_{\rm Matter} + \mathcal{L}_{\rm Higgs} + \mathcal{L}_{\rm Yukawa}$$

- Imagine a complex scalar SU(2)$_L$ doublet $\phi = \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix}$ w/ $Y = +1/2$
- We can add this "Higgs" field to our Lagrange density

$$\mathcal{L}_{\rm Higgs} = (D_\mu \phi)^\dagger D^\mu \phi + \mu^2 \phi^\dagger \phi - \lambda (\phi^\dagger \phi)^2$$

where $D_\mu = (\partial_\mu + i\frac{g}{2}\sigma^i A^i_\mu + i\frac{g'}{2} B_\mu)$

Higgs mechanism By assigning a non-zero vacuum expectation value $< \phi^\dagger \phi >_0 = v^2/2$, $v = 246$ GeV, the ground state explicitly breaks SU(2)$_L \times$U(1)$_Y$ down to U(1)$_{EM}$

- Recast ϕ in the language of a nonlinear sigma model

$$\phi \to \frac{1}{2}(\sigma + v)\exp[iT^1\theta^1 + iT^2\theta^2 + i(T^3 - Y)\theta^3] \binom{0}{1}$$

- We can gauge away θ^i, and are left with 1 real d.o.f. σ

Acquiring massive $W^{\pm}$, Z, and massless photon

- Of course θ^i are just hiding. Under this gauge transformation, the Higgs kinetic term rearranges itself so the A^i_μ, B_μ mix:

$$
\begin{aligned}
W^{\pm}_\mu &= \tfrac{1}{\sqrt{2}}(A^1_\mu \mp iA^2_\mu) \qquad && M_W = \tfrac{1}{2}gv \\
Z_\mu &= \tfrac{1}{\sqrt{g^2+g'^2}}(gA^3_\mu - g'B_\mu) \qquad && M_Z = \tfrac{1}{2}\sqrt{g^2+g'^2}\,v \\
A_\mu &= \tfrac{1}{\sqrt{g^2+g'^2}}(g'A^3_\mu + gB_\mu) \qquad && M_A = 0
\end{aligned}
$$

- The 3 θ^i are "eaten" by the W, Z giving them masses $\propto v$.
- These mass relationships are predictive. At leading order

$$\rho = \frac{M_W^2}{M_Z^2}\frac{g^2+g'^2}{g^2} = 1$$

  - $M_W = 80.4$ GeV was used to predict $M_Z = 91$ GeV
  - The Higgs Mechanism was validated when the Z was found.
- The job of the Higgs Mechanism is to explain gauge boson masses and relationships. It succeeds.

The Higgs boson

The Higgs boson is the remaining degree of freedom, the σ

- The Higgs boson played NO ROLE in hiding electroweak symmetry
  The σ was just a placeholder in front of the exponent that held the θ^i d.o.f. eaten by the W and Z. ($\phi = \sigma \exp[iT^i\theta^i]$)
- There is no direct evidence of a Higgs boson.
- Is a Higgs boson necessary then? NO!
- Models that go Beyond the Standard Model (BSM) explore alternates to a simple 1 d.o.f. σ particle.
  - Technicolor replaces σ with a fermion condensate.
  - Supersymmetry adds more d.o.f., one combination of which looks like σ
  - "Little Higgs" models mimic σ by collective breaking of larger symmetries
  - Extra dimensional models can use extra d.o.f. instead of σ
- Remember: The Higgs Mechanism is tested with data, the Higgs boson is a mnemonic device to remind us the picture is incomplete...

Giving mass to fermions — Yukawa interactions

$$\mathcal{L}_{\rm SM} = \mathcal{L}_{\rm Gauge} + \mathcal{L}_{\rm Matter} + \mathcal{L}_{\rm Higgs} + \mathcal{L}_{\rm Yukawa}$$

- Once we have the Higgs hammer... we can add a coupling of a Higgs field to different fermions to generate Dirac mass terms.

$$\mathcal{L}_{\rm Yukawa} = -\Gamma_u^{ij}\overline{Q}_L^i\epsilon\phi^* u_R^j - \Gamma_d^{ij}\overline{Q}_L^i\phi d_R^j - \Gamma_e^{ij}\overline{L}_L^i\phi e_R^j + H.c.$$

$\Gamma_u, \Gamma_d, \Gamma_e$ are 3×3 complex matrices

- Using $M^{ij} = \Gamma^{ij}v/\sqrt{2}$ we have (after EWSB, $\phi \to v/\sqrt{2}$)

$$\mathcal{L}_{\rm Mass} = -M_u^{ij}\overline{u}_L^i u_R^j - M_d^{ij}\overline{d}_L^i d_R^j - M_e^{ij}\overline{e}_L^i e_R^j + H.c.$$

- Fermion mass is a dynamical effect of coupling to a Higgs boson.
  - Reminder: there may not be a Higgs boson, and this may not be the whole story — mass generation is accommodated, but not explained

Diagonalizing quark mass matrices

- As written above, the quark fields u_L, u_R, etc., are not written as mass eigenstates (of propagating particles).
- We can use unitary field redefinitions to diagonalize the mass matrices $u_L^i = A_{u_L}^{ij} u_L'^j$, $u_R^i = A_{u_R}^{ij} u_R'^j$, $d_L^i = A_{d_L}^{ij} d_L'^j$, $d_R^i = A_{d_R}^{ij} d_R'^j$, etc.
  - E.g., M_u is diagonalized by $M_u^{\mathrm{Diag}} = A_{u_L}^\dagger M_u A_{u_R}$
  - Notice both u_L and u_R fields are simultaneously redefined
- How are gauge couplings to fermions modified?
  - $\overline{u}_L \not{Z} u_L \to \overline{u}'_L A_{u_L}^\dagger A_{u_L} \not{Z} u'_L = \overline{u}'_L \not{Z} u'_L$ Z, γ, and gluon are unaffected
  - $\overline{d}_L \not{W} u_L \to \overline{d}'_L A_{d_L}^\dagger A_{u_L} \not{W} u'_L = \overline{d}'_L V_{CKM} \not{W} u'_L$ W-q-q' is modified
- The Cabibbo-Kobayashi-Maskawa (CKM) matrix encodes $A_{d_L}^\dagger A_{u_L}$

$$\begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} = \begin{pmatrix} 0.9743 & 0.2253 & 0.0035 \\ 0.2252 & 0.9735 & 0.0410 \\ 0.0086 & 0.0403 & 0.9992 \end{pmatrix}$$

  - The CKM matrix has 4 d.o.f., 3 (unique) real and 1 complex phase δ

Diagonalizing lepton mass matrices

How did we treat quarks?

$$A^\dagger_{d_L} A_{u_L} = V_{CKM}$$
$$A^\dagger_{d_L} M_d A_{d_R} = (d, s, b) \text{ masses}$$
$$A^\dagger_{u_L} M_u A_{u_R} = (u, c, t) \text{ masses}$$

How about the leptons?

$$A^\dagger_{e_L} A_{\nu_L} = V_{PMNS}$$
$$A^\dagger_{e_L} M_e A_{e_R} = (e, \mu, \tau) \text{ masses}$$
$$A^\dagger_{\nu_L} M_\nu A_{\nu_R} = (\nu_1, \nu_2, \nu_3) \text{ masses?}$$

- The Pontecorvo-Maki-Nakagawa-Sakata (PMNS) matrix is the leptonic equivalent of the CKM for quarks.

$$\begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} = \begin{pmatrix} 0.85 & 0.53 & <0.01\ ? \\ \text{-}0.37 & 0.60 & 0.71 \\ 0.37 & \text{-}0.60 & 0.71 \end{pmatrix}$$

Homework: If the entries of V_{PMNS} are so large, explain why we never see charged leptons mix.

- The SM naturally accommodates an SU(3)×SU(2)×U(1) singlet ν^c (sometimes called ν_R) that generates a Dirac neutrino mass $-M^{ij}_\nu \overline{\nu}^i_L \nu^j_R$
  - ν^c was ignored historically, but that does NOT mean it is unexpected

Majorana masses may play a role

- One canard is with the addition of ν_R a Majorana mass "must" show up in the Lagrangian because it is allowed by local symmetry:

$$\mathcal{L}_{\mathrm{Mass}} = -\tfrac{1}{2} M_R^{ij} \nu_R^{iT} C \nu_R^j + H.c.$$

  - Lepton number is an *accidental* global symmetry of the Lagrangian.
  - A Majorana term breaks L (and $B - L$), but global symmetries are made to be broken, and so... the story goes... this term must appear.
- There is no experimental evidence that L or B are broken.
  - Finding such a term would be radical new physics, as there are no known Majorana states in nature.
- Is a Majorana mass term reasonable?
  - The Standard Model is an effective field theory. The only allowed dimension 5 operator is mass suppressed, and gives ν_L a Majorana mass

$$\mathcal{L}_5 = \tfrac{1}{M}\dim 5 = \frac{c^{ij}}{M} L_L^{iT} \epsilon\phi C \phi^T \epsilon L_L^j + H.c. \to \mathcal{L}_{\mathrm{Maj}} = -\frac{c^{ij}}{2}\frac{v^2}{M} \nu_L^{iT} C \nu_L^j + H.c.$$

  - Diagonalizing the Dirac and Majorana mass terms could lead to 1 light/1 heavy Majorana neutrino — This is the "seesaw" mechanism.

A current view of the Standard Model

- The Standard Model collects of our current knowledge about the strong, weak, and electromagnetic forces, and the degrees of freedom on which they act.
- We saw the pieces we know:
  - Which gauge bosons exist, which fermions
  - How complete generations are required for consistency
  - How the Higgs Mechanism explains W and Z masses
  - Mass is not fundamental — it's an artifact of interactions
- We saw some of the speculative parts
  (and questions that were simply ignored for lack of data)
  - In the Standard Model there is 1 undiscovered degree of freedom: the Higgs boson
  - Is there a ν^c that only interacts gravitationally?
  - Is Lepton or Baryon number, or a combination really conserved?
- I've discussed structure, but ignored the rich phenomenology of the Standard Model. You will hear more about this these next two weeks.