The language of particle physics

- In non-relativistic QM you learned about the hydrogen atom, multi-electron atoms, maybe a bit about molecules and nucleii
- To probe short distances (structure of nucleus) requires probes with short de Broglie wavelength, ie, high energy probes, such as relativistic electrons, protons, photons, etc.
- Particle physics is inherently relativistic (as well as quantum mechanical).
- At high energies, it becomes easy and natural to convert matter to different forms ($E = mc^2$); the theory must be many-body (unlike non-rel QM). Classical particle mechanics, x(t), can't accommodate this, but field theory, $\phi(x,t)$, can.
- The language of particle physics is
  Relativistic Quantum Field Theory (QFT)

  A somewhat forced marriage of

  Quantum mechanics, Relativity, Field theory

- Observables (energy levels, reaction rates) in non-trivial QFTs can be computed in perturbation theory.
- A broad class of "gauge invariant" Quantum field theories are "renormalizable" - perturbative calculations converge to a finite (physically meaningful) result (Nobel prize 1999).

The Standard Model on one slide

- The language: Quantum Field Theory
  = QM + Relativity + Field Theory (E&M)
- Origin of forces: Gauge Symmetries
  $-SU(3)_c \times SU(2)_Y \times U(1)$

"Elementary" Particles:

Electric Charge	I	II	III	FAMILY
$+2/3$	u	c	t	QUARKS
$-1/3$	d	s	b	
-1	e	μ	τ	LEPTONS
0	ν_e	ν_μ	ν_τ	

Each fermion has antiparticle: same mass, opposite charges.
The (d, s, b) quarks mix quantum-mechanically (CKM)!

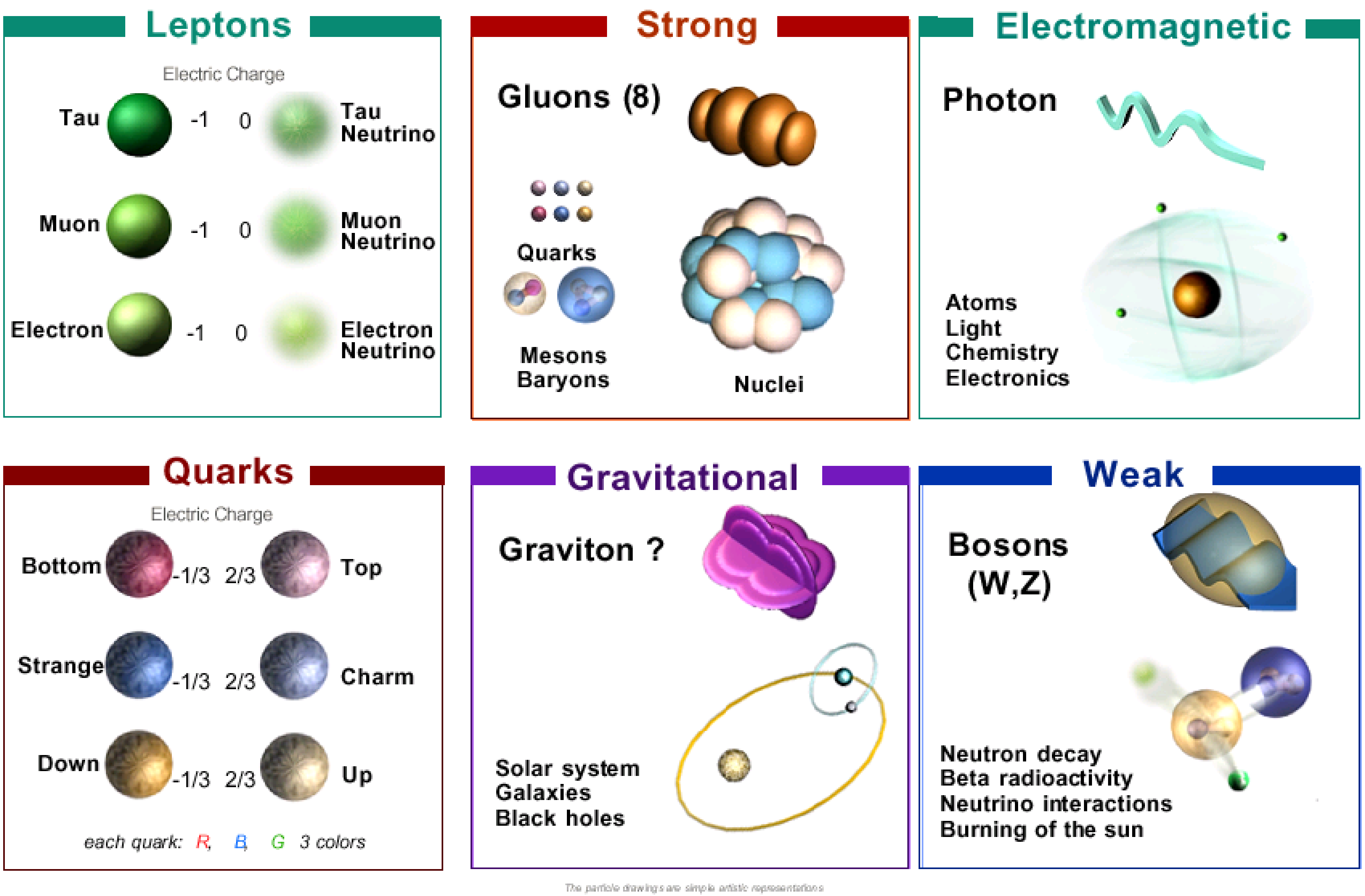
"Elementary" forces:

Force	carrier boson	Spin	Mass	couples to
EM	photon γ	1	0	charged particle
weak	$W^{\pm}$, Z^0	1	80, 91 GeV	all fermions
strong	gluons g	1	0	quarks
gravity	graviton	2	0	all fermions

The incredible success of the Standard model is our boon and our bane. Arising from it are many questions whose answers lie Beyond the Standard Model

+ the Higgs

Particles and forces



Particles and forces

Fundamental Fermions

- Paradigm of Elementary Particle Physics:
  Matter is composed of fundamental fermions
  (Pauli Exclusion) bound together by
  fundamental forces (carried by bosons)

- Fundamental = simply and completely describable

- Ordinary matter: electrons, protons, neutrons
  (fermions) bound by EM (photons),
  nuclear forces, and gravity

- a *simple* fermion is *structureless*
  (no internal degrees of freedom) $\Rightarrow$ pointlike

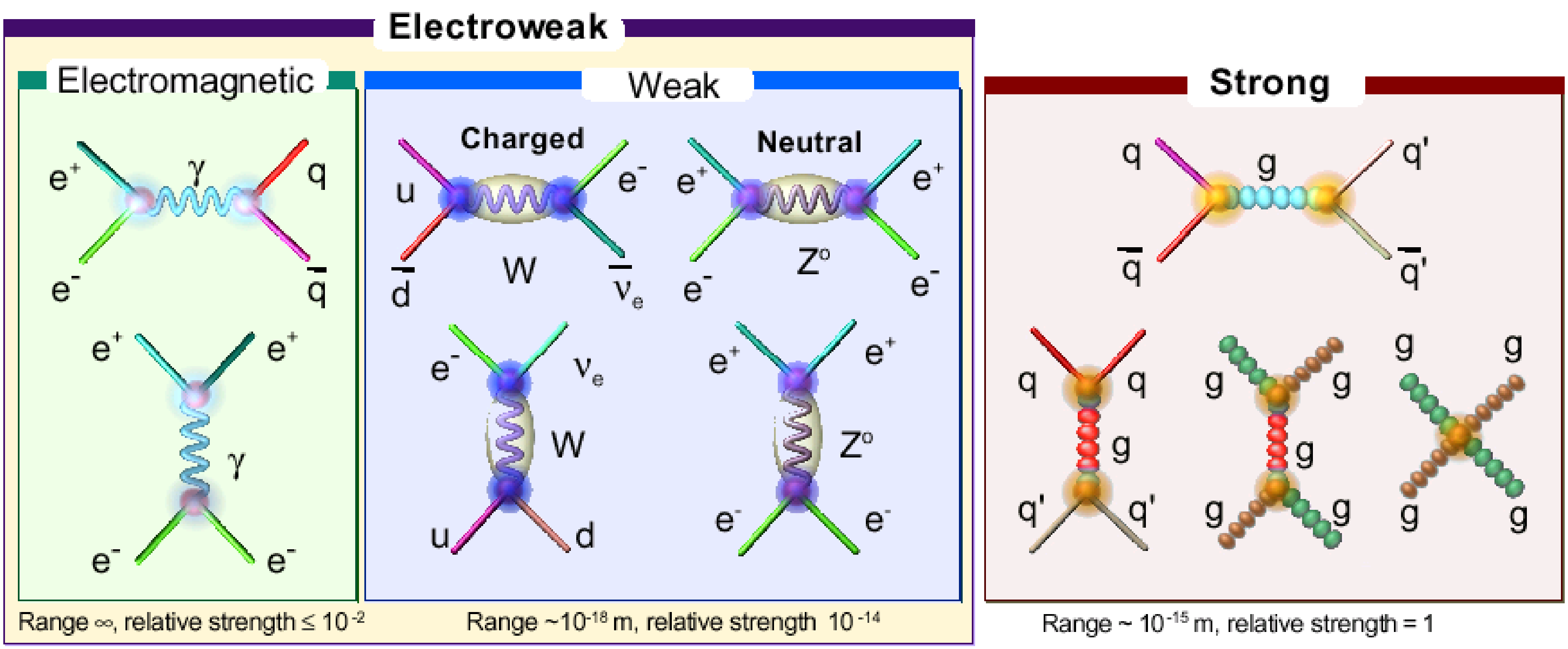
- 1950's: protons, neutrons have structure, $R \sim 1 fm$
  (requires probes with energy > 10 MeV or more)

- 1960's: nucleon structure is due to quarks (u, d);
  1970's – 1990's: six "flavors" of quarks: u, d, s, c, b, t

- Even structureless fermions have "size" due to
  force couplings: $r_e = \alpha\hbar c/m_e c^2 = 2.8$ fm

- What do the properties of "fundamental" fermions
  tell us about nature?

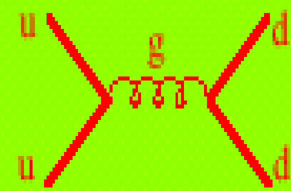
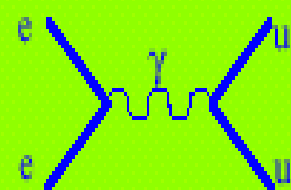
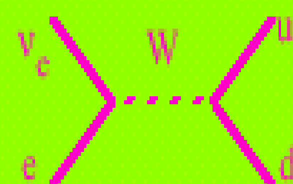
Interactions: coupling of forces to matter



The mathematical description of the fundamental interactions,
all built by analogy to Maxwell's theory of EM,
is based on continuous gauge groups:

$U(1)_Y \times SU(2)_I \times SU(3)_c$

Strengths of fundamental forces

Interaction	exchanged boson	relative strength	example
Strong	Gluon (g)	1	
Electromagnet.	Photon (γ)	$\frac{1}{137}$	
Weak	W^+, W^-, Z^0	10^{-14}	
Gravitation	Graviton (G) ?	10^{-40}	

SU(3)
confining

U(1)
∞ range

SSB
short-range

Tensor field
geometric

Electroweak Lagrangian

- From the PDG review, Ch.10:

$$\mathscr{L}_F = \sum_i \overline{\psi}_i \left(i \not\partial - m_i - \frac{g m_i H}{2M_W} \right) \psi_i$$
$$- \frac{g}{2\sqrt{2}} \sum_i \overline{\psi}_i \, \gamma^\mu \, (1-\gamma^5)(T^+ \, W_\mu^+ + T^- \, W_\mu^-) \, \psi_i$$
$$- e \sum_i q_i \, \overline{\psi}_i \, \gamma^\mu \, \psi_i \, A_\mu$$
$$- \frac{g}{2\cos\theta_W} \sum_i \overline{\psi}_i \, \gamma^\mu (g_V^i - g_A^i \gamma^5) \, \psi_i \, Z_\mu \, . \tag{10.1}$$

$\theta_W \equiv \tan^{-1}(g'/g)$ is the weak angle; $e = g \sin\theta_W$ is the positron electric charge; and $A \equiv B\cos\theta_W + W^3 \sin\theta_W$ is the (massless) photon field. $W^\pm \equiv (W^1 \mp iW^2)/\sqrt{2}$ and $Z \equiv -B\sin\theta_W + W^3\cos\theta_W$ are the massive charged and neutral weak boson fields,

QCD Lagrangian

- From the PDG review, Ch 9:

$$L_{\rm QCD} = -\frac{1}{4} F^{(a)}_{\mu\nu}\, F^{(a)\mu\nu} + i \sum_q \overline{\psi}^i_q \,\gamma^\mu\, (D_\mu)_{ij}\, \psi^j_q - \sum_q m_q\, \overline{\psi}^i_q\, \psi_{qi}\ , \tag{9.1}$$

$$F^{(a)}_{\mu\nu} = \partial_\mu\, A^a_\nu - \partial_\nu\, A^a_\mu - g_s\, f_{abc}\, A^b_\mu\, A^c_\nu\ , \tag{9.2}$$

$$(D_\mu)_{ij} = \delta_{ij}\, \partial_\mu + i g_s \sum_a \frac{\lambda^a_{i,j}}{2} A^a_\mu\ , \tag{9.3}$$

where g_s is the QCD coupling constant, and the f_{abc} are the structure constants of the SU(3) algebra (the λ matrices and values for f_{abc} can be found in "SU(3) Isoscalar Factors and Representation Matrices," Sec. 36 of this *Review*). The $\psi^i_q(x)$ are the 4-component Dirac spinors associated with each quark field of (3) color i and flavor q, and the $A^a_\mu(x)$ are the (8) Yang-Mills (gluon) fields. A complete list of the Feynman rules which derive from this Lagrangian, together with some useful color-algebra identities, can be found in Ref. 1.