Physics 214
Experimental Particle Physics

Lecture 1

What to expect.

We’ll start with a grand tour.

I do not expect you to understand this tour in detail.

Instead, think of it as an orientation to which we’ll fill in many of the details over the next two quarters.

The big picture

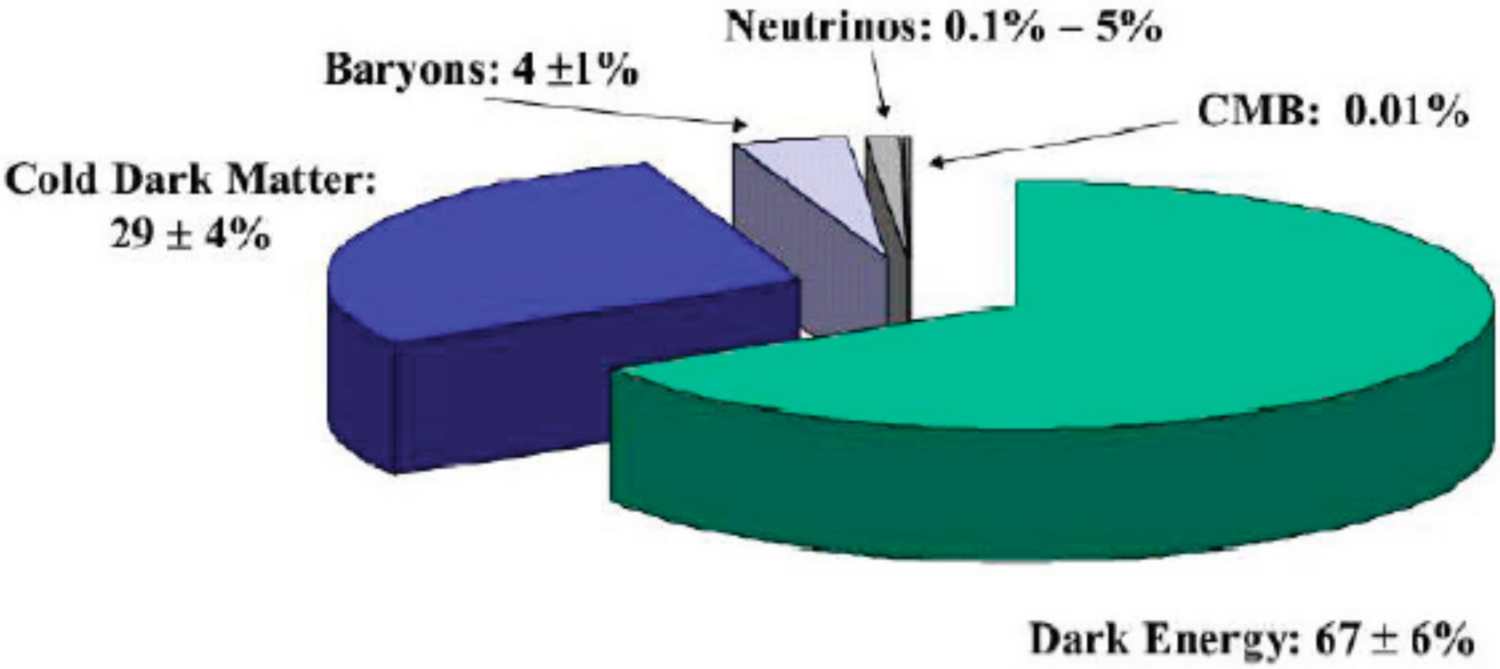
- Standard Model of Particle Physics
- Standard Model of Cosmology
- My taste:
  - Interesting experimental questions today all revolve around these two models.
  - The most promising are those that key in on experimental inconsistencies between them.

Will try to focus on topics that matter for your graduate and post-doc career, with a little bit of general context thrown in.

The **BIG** Experimental Q’s

- Matter content of the universe
  - What is dark matter?
  - What is dark energy?
- Where did all the anti-matter go?
  - CP violation in the lepton sector?
  - New physics with CP violating couplings?
- Electroweak Symmetry breaking
  - Does the higgs exist? And at what mass?

Matter Content of the Universe



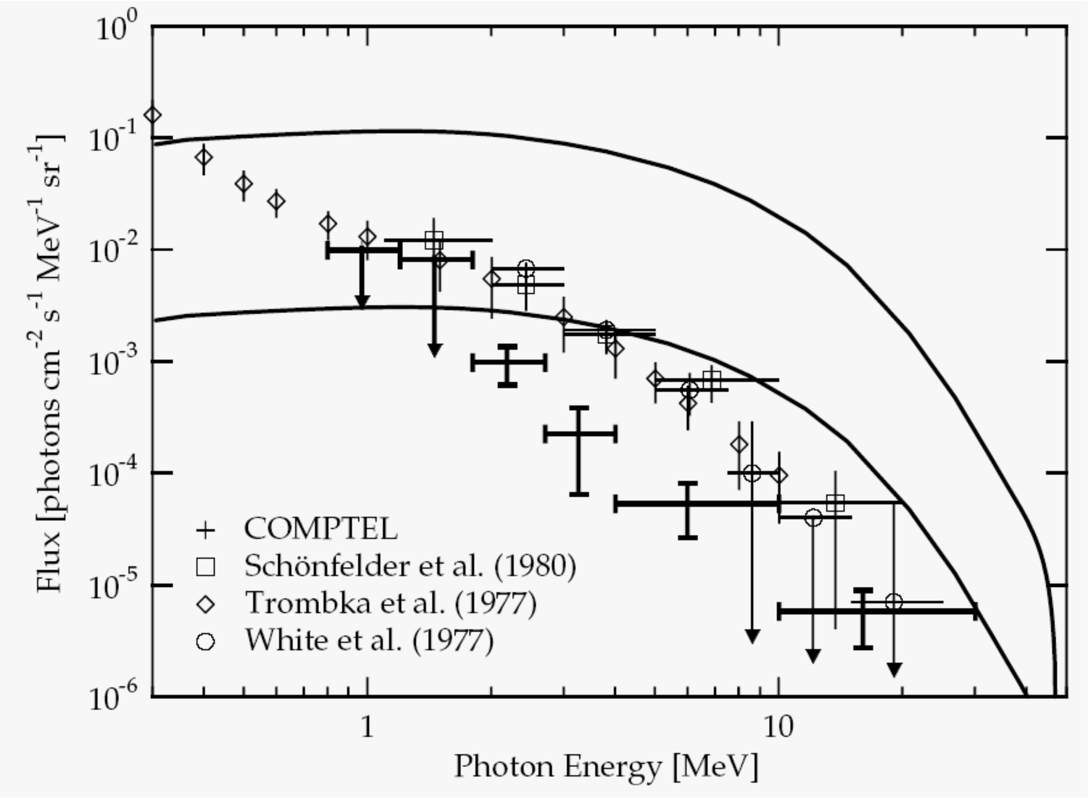
I will not cover cosmology in this class!
It's covered in detail in Physics 227 at UCSD.
Or read up on it in references at course web site.

Observation of dark matter.

- Collision of two galaxies.
  - Gas clouds collide, drag slows them down as they interact.
- Use grav. lensing to measure mass in collission area.

- Find that there is additional mass outside the drag region.
  - There must be mass that does not shine nor interact with the gas in the galaxy.

Matter/anti-matter Asymmetry



The cosmic diffuse gamma ray spectrum observed rules out the existence of equal number of matter and anti-matter domains with domain sizes smaller than the size of the visible universe.

Matter-antimatter symmetry must be broken at some as yet unknown scale.

Explanation Attempts

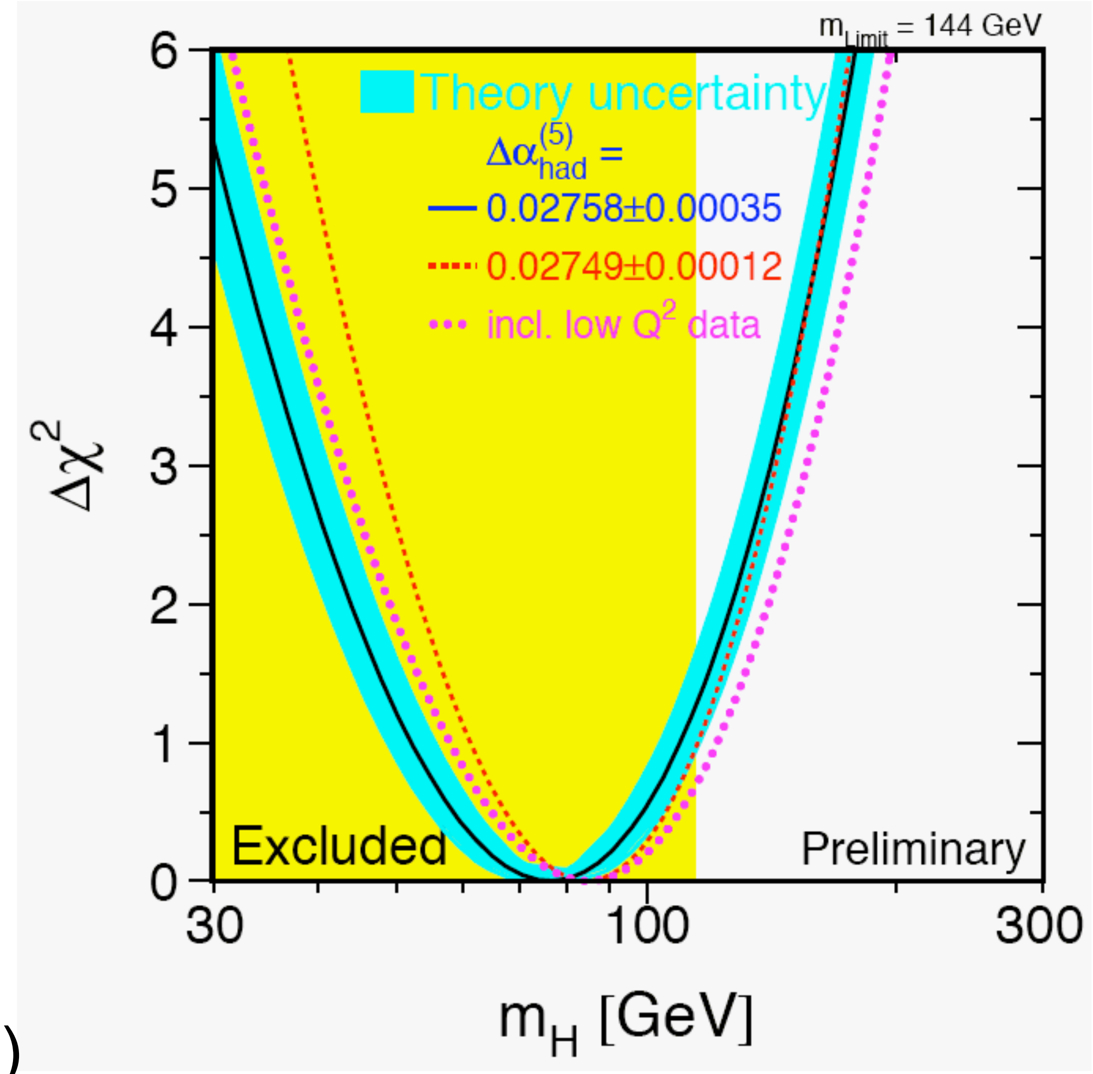
- CP violation in quark sector
  - Well measured and insignificant compared to what's needed.
- CP violation in lepton sector
  - Measure sinθ_{13} in neutrino sector to assess experimental feasibility.
  - If feasible, build neutrino factory to measure CP violation in lepton sector.
- New physics at higher energies.
  - E.g. Most general SUSY model has 44 CP violating couplings in Lagrangian, most of which enter via SUSY breaking mechanism.

Standard model predicts higgs

$m_H = 76^{+33}_{-24}$GeV
$m_H < 144$GeV at 95% C.L.

Direct searches rule out
$m_H < 114$ GeV.

All of MSSM requires
a light Higgs ($m_H < 130$GeV)



There are plenty of other ways for nature to implement EWK symmetry breaking, incl. more than one higgs doublet. We will discuss this in some detail next quarter.

… lot’s of smaller q’s as well

- Is the neutrino its own anti-particle?
- The strong CP problem
  - Do Axions exist?
- … and lot’s more that are more pedestrian in nature.

… and then there's speculation …

- Supersymmetry
- Extra dimensions
- Grand Unified Theories et al.
- Lepton flavor violation
- Proton decay
- Black holes made in the lab

Most of this I will stay away from in this course, except maybe towards the end of the second quarter.

Experimental facilities coming up

- Collider Physics:
  - 1st results from LHC ~2009, expect to run for ~10years.
  - Next Linear Collider not before 2015
- Neutrino physics:
  - 1st results on $\sin\theta_{13}$ ~2012
  - CP violation physics not before 2020
- Dedicated Dark Matter Searches
  - Direct searches with cryogenic detectors
    - Reach sensitivity where dark matter candidates possibly observed at LHC might be confirmed within the next decade.
  - Indirect searches via astrophysical objects
    - Many projects both currently running as well as planned
- Dark Energy
  - A variety of projects with timescales from few years to more than a decade.

Switch gears now …

Talk a little about the mechanics of this course.

http://physics.ucsd.edu/students/courses/fall2007/physics214/

Lectures

- Twice a week:
  - Mo,We 2-3:20pm
- Hope to have some transparencies up at the website by lunch of the day of the lecture.
- Will use transparencies as guide for content, but do all derivations by hand.
- Hope to capture my scribbling, and put it online after each lecture.

Seminars

- Each student needs to give a seminar talk that accounts for 20% of the total grade.
- I’m expecting a 30min talk on one of the topics listed on the website.
- I’m expecting serious preparation for this, and will want to see the slides one week prior to the day they are given!!!
- We will schedule those seminars outside the regular lecture time.

Grades

- 50% take home final
  - Most likely during week before finals week.
- 30% homework
  - I will reuse some of the homework assignments from last year, and expect you to not look up solutions from your friends !!!
  - I have no grader, and thus might decide not to grade all problems on all homework assignments.
- 20% seminar

If you are a theorist, and don’t want to put in the effort required to get a decent grade, then please sign up pass/fail. I won’t fail anybody who does ok on the final or gives a decent seminar.

Any Questions?

If not, let’s get started
with an introductory “fly through”
Particle Physics.

Elementary Particle Physics

- The quest to understand matter and how it interacts.
  - Discover which particles are elementary
  - Develop theory of their interactions
- What’s an *elementary* particle ?
  - Something without further constituents
  - Point-like

Probing the size via scattering

- Shine light (or some other quantum) on an object.
- Your resolution depends on energy of quantum
  - Remember Rutherford scattering!

$$E = h\nu = \frac{hc}{\lambda} \Rightarrow \lambda = \frac{hc}{E}$$

$$R \geq \frac{hc}{E}$$

Need high energy to probe short distances!

Structure of matter

- $R \sim 10^{-8}$ cm atoms
- $R \sim 10^{-12}$ cm nuclei
- $R \sim 10^{-13}$ cm proton
- $R < 10^{-18}$ cm quarks, leptons

At present, we consider quarks & leptons
To be point-particles and elementary.

Natural Units

- Energy [E]
  - eV, keV, MeV, GeV, TeV, PeV, …

    10^0, 10^3, 10^6, 10^9, 10^{12}, 10^{15}

    1eV = 1.6 10^{-19} J

  eV is more useful unit in particle physics

  than Joule for obvious reasons.

- Largest energy colliders:
  - Tevatron ~ 2TeV CoM for proton-antiproton collission
  - LHC ~ 14TeV CoM for proton-proton collission.

Natural Units (2)

- Mass:

  $E = m c^2$

  $[E] = [m] [v]^2 = [m]$

  In natural units velocity is dimensionless because

  Special relativity treats length and time on equal footing. [length]/[time] = dimensionless !

  The only fixed, and thus natural scale is c.

  Accordingly, we set c=1.

Natural Units (3)

- Momentum

  [P] = [m] [v] = [m] = [E]
- Angular momentum

  [J] = [length] [P] = [length] [E]

  but angular momentum is quantized

  with natural scale being ħ

It is thus natural to set ħ = 1

(Recall h ~ 10^{-34} J sec ~ 6.6 10^{-22} MeV/sec)

Natural Units (4)

- Charge

  Coulomb force: $F \sim Q^2/L^2$

$$[Q] = \sqrt{[F][length]^2} = \sqrt{[M]\frac{[length]^3}{[time]^2}}$$

Charge is dimensionless.
It's scale is defined by the electromagnetic interaction.
We'll get back to this later.

Natural Units Summary

Quantity	N.U.	Conv. Factor to SI
E	GeV	1GeV = 1.6 10^{-19}J
P	GeV	
M	GeV	1kg = 5.61 10^{26}GeV
length	1/GeV	1m = 5.07 10^{15} GeV^{-1}
time	1/GeV	1sec = 1.52 10^{24} GeV^{-1}
J	dimensionless	
Q	dimensionless	

Some more useful facts

- 1 fermi = 10^{-13}cm = 5.07 GeV^{-1}
- 1 fermi^2 = 10 mb
- 1 GeV^{-2} = 0.389 mb

$$\alpha = \frac{e^2}{4\pi} \approx \frac{1}{137}$$

$$e = \sqrt{4\pi\alpha} \approx 0.303$$

Fundamental Particles

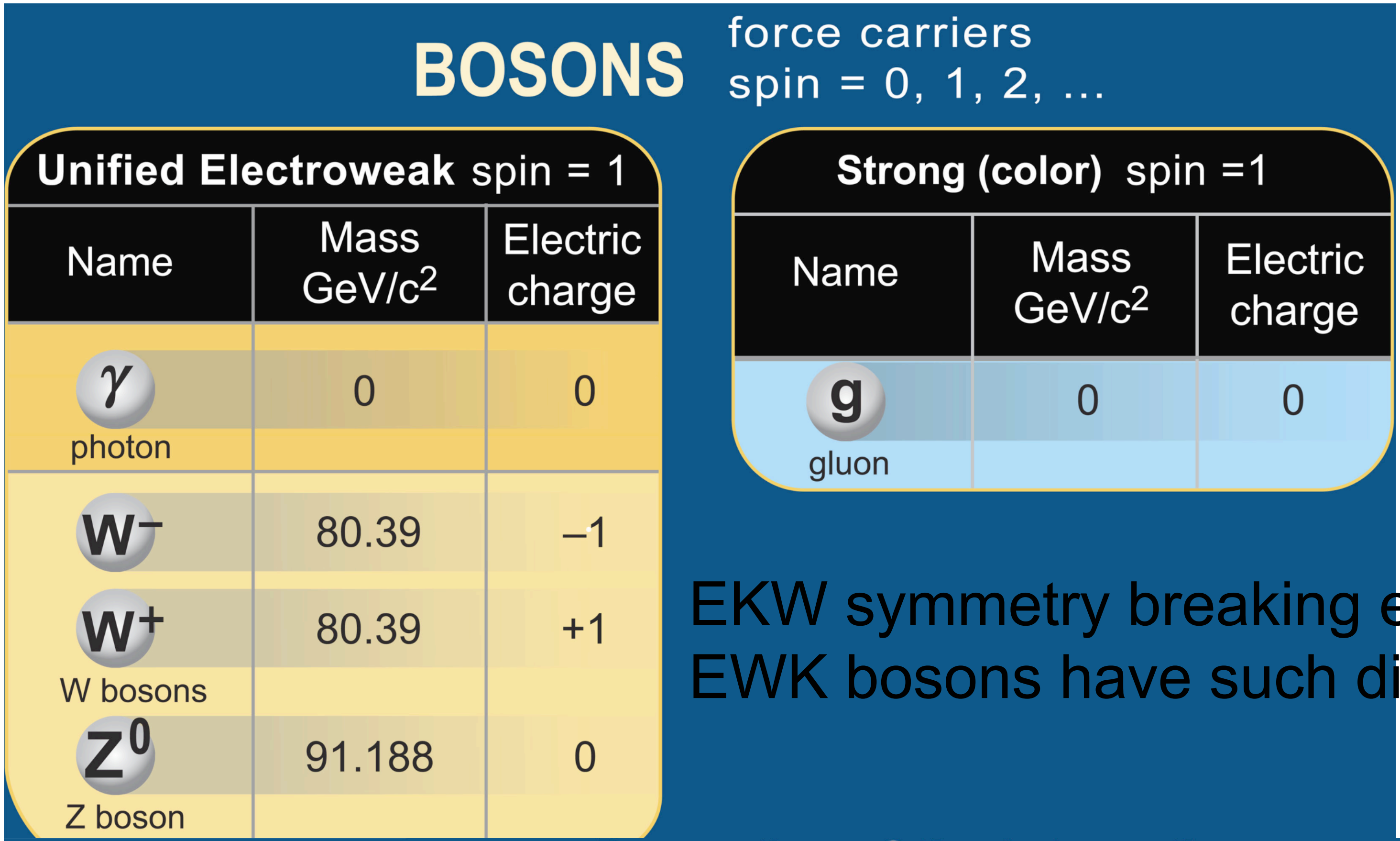
- Fermions:
  - Spin 1/2 -> Fermi-Dirac statistics
  - All matter is made of fermions
- Bosons:
  - Integer spin -> Bose-Einstein statistics
  - All forces are mediated via bosons

Forces = Interactions

- Strong (QCD)
  - Mediated by gluons
  - Holds nuclei together
- Electroweak
  - E&M mediated by photon
  - Weak mediated by W,Z
  - Electroweak symmetry breaking requires Higgs boson.
- Gravity
  - Mediated by graviton
  - Beyond the scope of this course

Photon, gluon, W, Z all spin=1
Higgs is spin=0
Graviton is spin=2

Photon, gluon,graviton m=0
W,Z,Higgs roughly 100GeV



BOSONS

force carriers
spin = 0, 1, 2, …

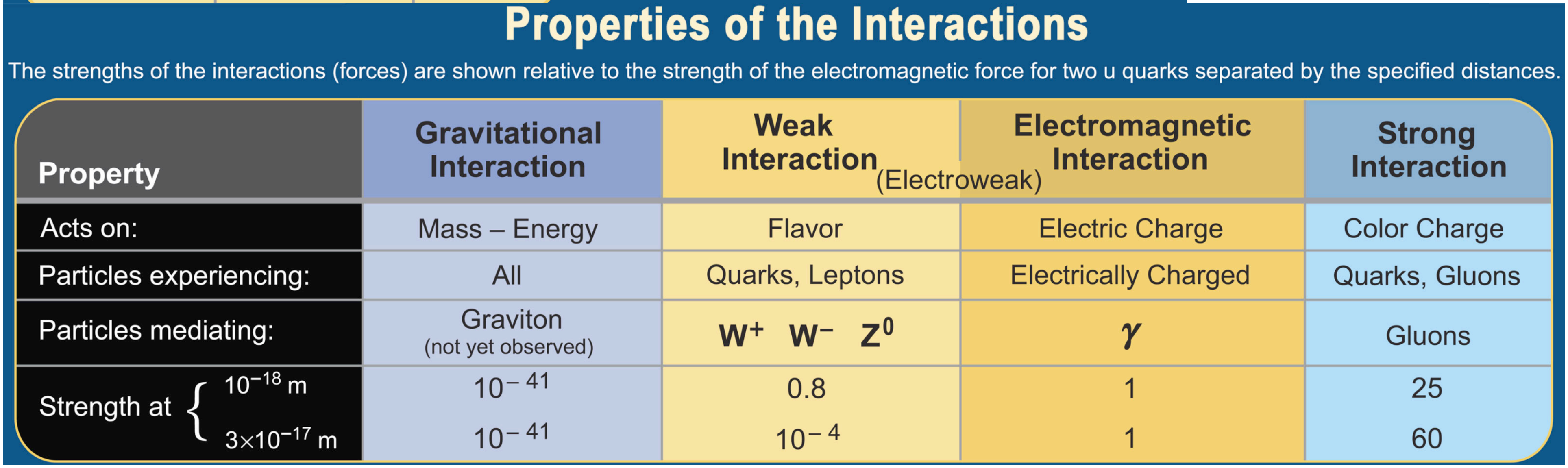
Unified Electroweak spin = 1

Name	Mass GeV/c^2	Electric charge
γ photon	0	0
W⁻	80.39	–1
W⁺ W bosons	80.39	+1
Z⁰ Z boson	91.188	0

Strong (color) spin =1

Name	Mass GeV/c^2	Electric charge
g gluon	0	0

EKW symmetry breaking explains why EWK bosons have such different masses.



Properties of the Interactions

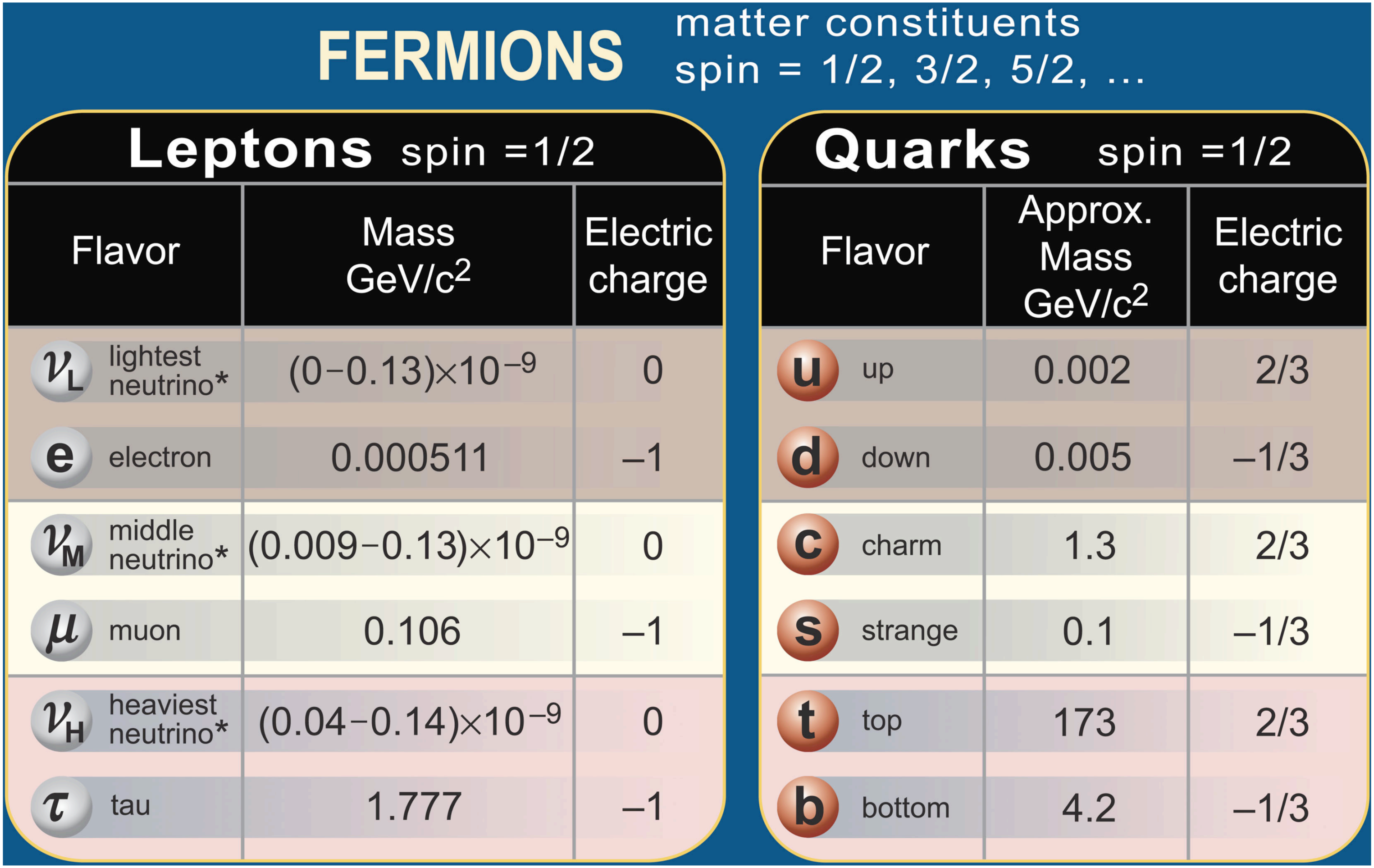
The strengths of the interactions (forces) are shown relative to the strength of the electromagnetic force for two u quarks separated by the specified distances.

Property	Gravitational Interaction	Weak Interaction (Electroweak)	Electromagnetic Interaction	Strong Interaction
Acts on:	Mass – Energy	Flavor	Electric Charge	Color Charge
Particles experiencing:	All	Quarks, Leptons	Electrically Charged	Quarks, Gluons
Particles mediating:	Graviton (not yet observed)	W⁺ W⁻ Z⁰	γ	Gluons
Strength at 10^{-18} m	10^{-41}	0.8	1	25
Strength at $3{\times}10^{-17}$ m	10^{-41}	10^{-4}	1	60

Matter comes in 2 types

- Leptons:
  - EWK & gravity
- Quarks:
  - EWK & gravity & strong

Both types come in 3 families (or flavors) of doublets.



FERMIONS

matter constituents
spin = 1/2, 3/2, 5/2, …

Leptons spin =1/2

Flavor	Mass GeV/c^2	Electric charge
ν_L lightest neutrino*	$(0-0.13)\times10^{-9}$	0
e electron	0.000511	–1
ν_M middle neutrino*	$(0.009-0.13)\times10^{-9}$	0
μ muon	0.106	–1
ν_H heaviest neutrino*	$(0.04-0.14)\times10^{-9}$	0
τ tau	1.777	–1

Quarks spin =1/2

Flavor	Approx. Mass GeV/c^2	Electric charge
u up	0.002	2/3
d down	0.005	–1/3
c charm	1.3	2/3
s strange	0.1	–1/3
t top	173	2/3
b bottom	4.2	–1/3

Charged particles couple to photon, W, Z
Neutral particles couple only to W,Z

Quarks are bound into hadrons

- Strong force increase with distance, thus making it impossible to have free quarks.
- The “charge” of the strong force is called color because it’s a triplet.
  - Color neutrality can be achieved either via
    - color-anticolor pair
    - Color triplet with one of each color
    - Anticolor triplet with one of each color

Baryons qqq and Antibaryons $\bar{q}\bar{q}\bar{q}$

Baryons are fermionic hadrons.

These are a few of the many types of baryons.

Symbol	Name	Quark content	Electric charge	Mass GeV/c^2	Spin
p	proton	**uud**	1	0.938	1/2
$\bar{\mathbf{p}}$	antiproton	$\bar{\mathbf{u}}\bar{\mathbf{u}}\bar{\mathbf{d}}$	–1	0.938	1/2
n	neutron	**udd**	0	0.940	1/2
Λ	lambda	**uds**	0	1.116	1/2
Ω^-	omega	**sss**	–1	1.672	3/2

Mesons $q\bar{q}$

Mesons are bosonic hadrons

These are a few of the many types of mesons.

Symbol	Name	Quark content	Electric charge	Mass GeV/c^2	Spin
π^+	pion	$\mathbf{u\bar{d}}$	+1	0.140	0
$\mathbf{K}^-$	kaon	$\mathbf{s\bar{u}}$	–1	0.494	0
ρ^+	rho	$\mathbf{u\bar{d}}$	+1	0.776	1
B^0	B-zero	$\mathbf{d\bar{b}}$	0	5.279	0
η_c	eta-c	$\mathbf{c\bar{c}}$	0	2.980	0

Quark Model

- At this point it should be obvious that you can construct a large variety of baryons and mesons simply by angular momentum addition.
- All of them will be color neutral.
- Lowest lying states for a given flavor composition are stable with regard to strong interaction but not weak interaction.
- Excited states can be made by adding orbital angular momentum of the quarks with respect to each other.
- Excited states are not stable with respect to strong interactions.

However, nature's more complicated still.

The quarks from quantum fluctuations are called see quarks. You can probe see quarks and gluons inside hadrons by scattering electrons off hadrons at high momentum transfer.

Interactions mediated by vector bosons

Tempting to think about the exchange as a quantum fluctuation.

Range of “force” as quantum fluctuation

$$\Delta E \Delta t \approx h$$

$$\Delta E = mc^2$$

$$\Rightarrow \Delta t \approx \frac{h}{mc^2}$$

$$R \approx c\Delta t = \frac{h}{mc}$$

Range of force is inverse proportional to mass of mediator.

Well, I’m cheating a little

- We will see that this works because:
  - Cross section $\propto |A|^2$
  - A is perturbative expansion in Feynman diagrams.
  - Diagrams include vertex factors and propagators.
  - Propagators are interpreted as “mediators” of the interaction.
- If you wish, the mental picture works because perturbation theory works.

Perturbation Cartoon

Rate per unit time for i->f