Particle Physics
also High-Energy Physics
also (maybe) the Theory of Fundamental Particles

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What is it?

- On the **grand scale** it is the search for the basic building blocks of matter, maybe of energy, and maybe of the universe.
- By “colliding” or “hitting” small “things” together you can sometimes find out what they are made of.

- At the small scale, you need **quantum mechanics** to describe the world, and at high energies and velocities you need QM + Einstein’s Special Theory of Relativity. One such kind of theory is **Quantum Field Theory** and it seems to do a very, very good job describing the Universe (i.e. those experiments that it can calculate).
- We currently have a very good model, if a bit ad-hoc, of the interactions of fundamental particles, and we call it **The Standard Model** (of particle interactions). Mostly in place since the mid-1970’s but predicted particles are still being confirmed, like the Higgs in 2012.

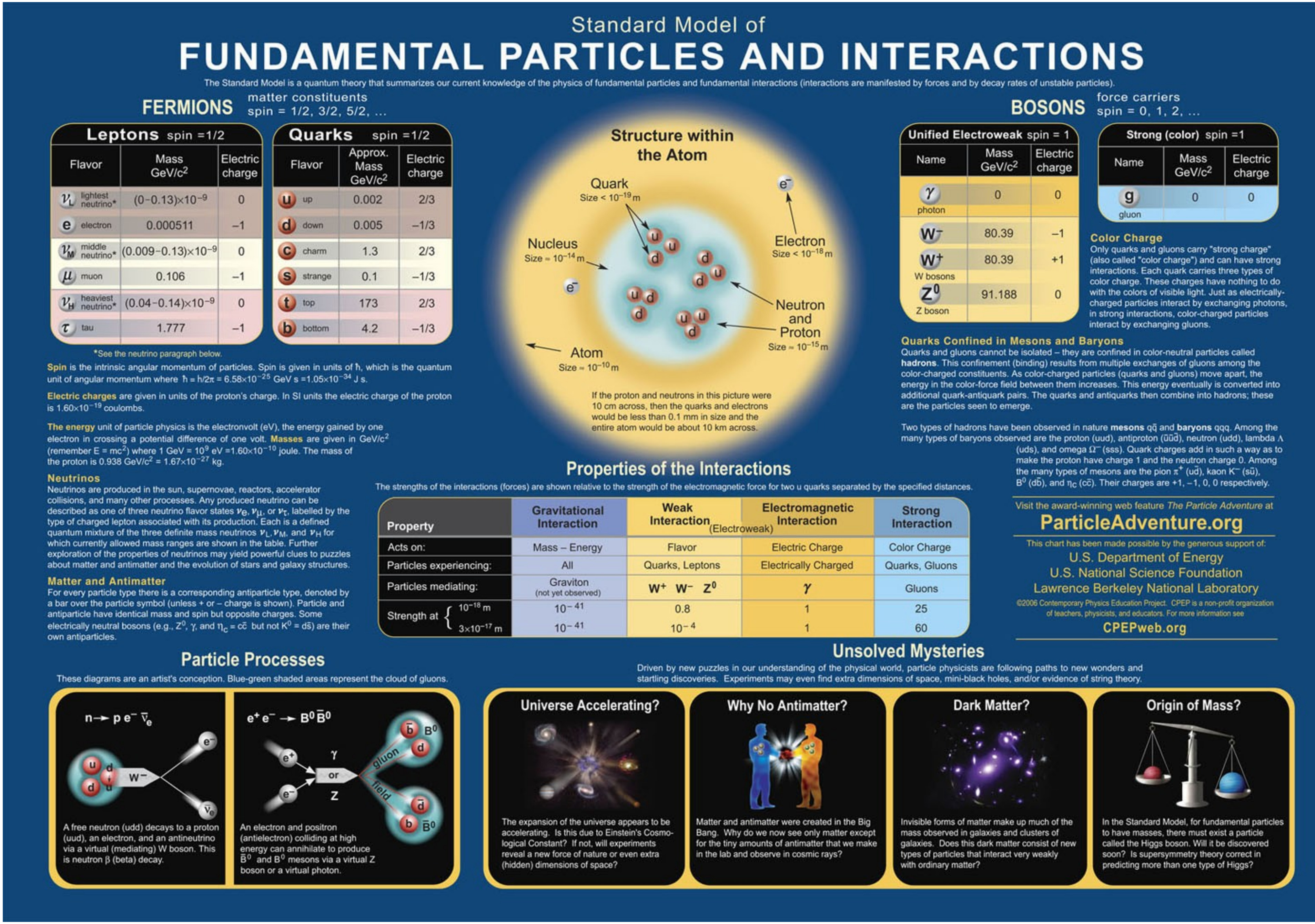
Some Not So Distant History

- Currently call it the Standard Model of Particle Physics (lots of fields have their “Standard Model”).
- Cast of characters we will meet in a few slides.
- Quarks were put on firm footing with the discovery of the J/Psi particle (a charm-anticharm quark pair). “November Revolution of 1974”
  https://en.wikipedia.org/wiki/J/psi_meson
- Because it made sense that at high-energies the ElectroWeak force and the Electromagnetic force be the same, a mechanism was needed to cause them to separate at low energy---The Higgs Mechanism, circa 1967 theoretically proposed, (first) Higgs Boson discovery announced July 4, 2012.

The -ons

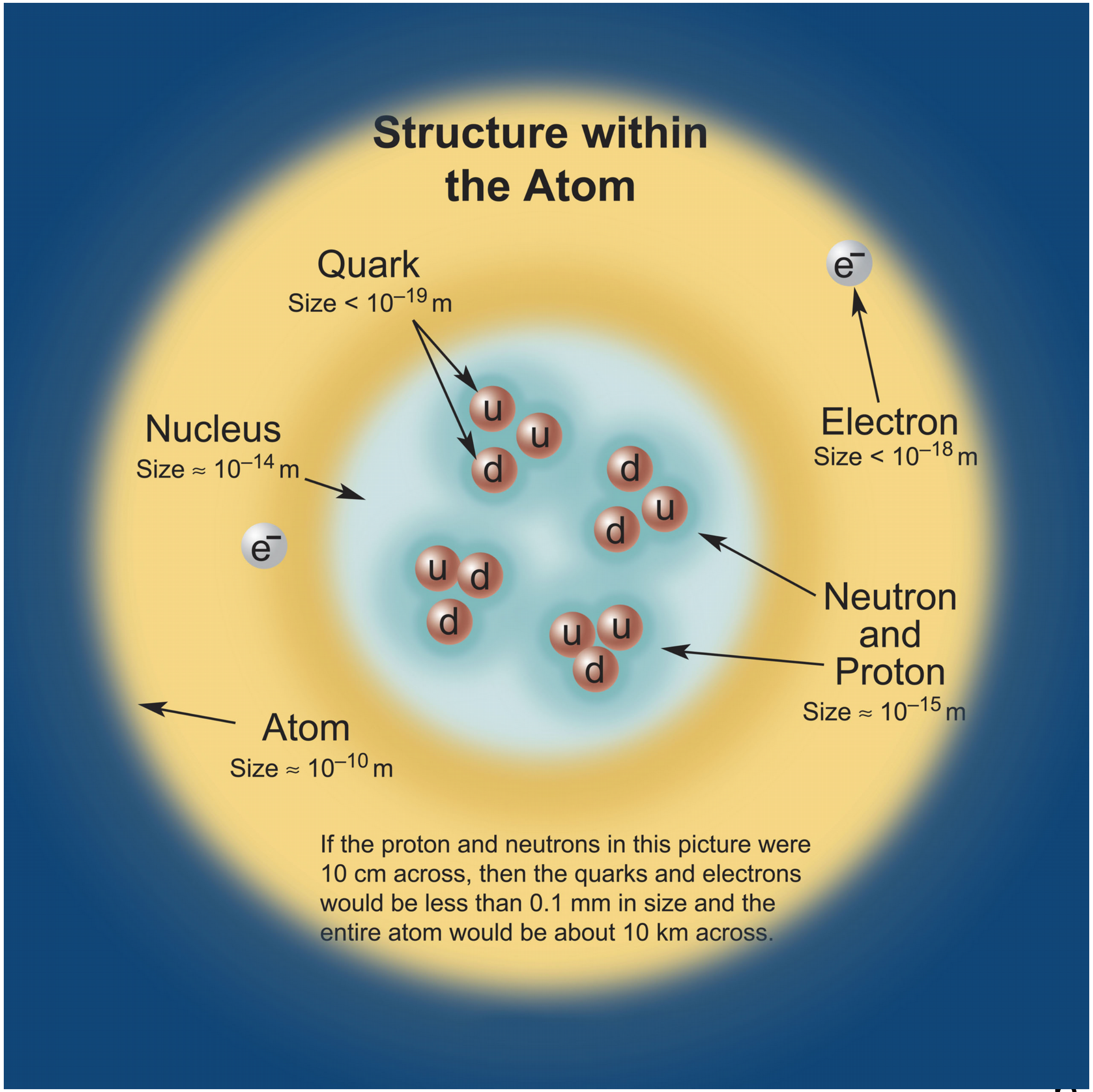
- **Hadron** vs **Lepton**
  - Hadrons ("bulky") are particles link quarks or quark combinations that carry some quark content and can interact with other particles via the Strong (Nuclear) Force.
  - Leptons ("small") are particles like electrons and neutrinos that do NOT interact via the Strong Force.
- **Fermion** vs **Boson**
  - Fermions are the quarks, electron, neutrinos...spin 1/2 (or odd-half) particles that make up all matter.
  - Bosons are the photon, gluons, ElectroWeak (vector) Bosons W+-, Z, and are spin 1 and carry the force between particles.
  - The Higgs is a bit of an odd-ball boson, it is the only spin 0 fundamental particle.
- **Baryon** vs **Meson**
  - Baryons ("heavy") are particles like the proton that have 3 quarks.
  - Mesons ("intermediate") are particles like the pi-meson made up of a quark and anti-quark, i.e. 2 quarks.

The “Poster” --- Our new particle zoo



Helium Nucleus and Two Electrons

- Definitely NOT to scale. The Helium atom in one graphic...2 protons, 2 neutrons, and 2 electrons. Oh and a myriad of “virtual” particles.



Fermions, Spin odd-halves

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

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Bosons, Spin integer (in units of h-bar)

BOSONS

force carriers
spin = 0, 1, 2, …

Unified Electroweak spin = 1

Name	Mass GeV/c²	Electric charge
γ photon	0	0
W^-	80.39	–1
W^+ W bosons	80.39	+1
Z^0 Z boson	91.188	0

Strong (color) spin =1

Name	Mass GeV/c²	Electric charge
g gluon	0	0

Interactions and Their Scale

- Weak, Electromagnetic, and the Strong interaction are described by Quantum Field Theories. Gravity has not been successfully made into a Quantum theory. Maybe String Theory or Quantum Loop Gravity, but not convincing.

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^- Z^0	γ	Gluons
Strength at	10^{-18} m	10^{-41}	0.8	1	25
	3×10^{-17} m	10^{-41}	10^{-4}	1	60

Baryons, the heavy stuff

- aa

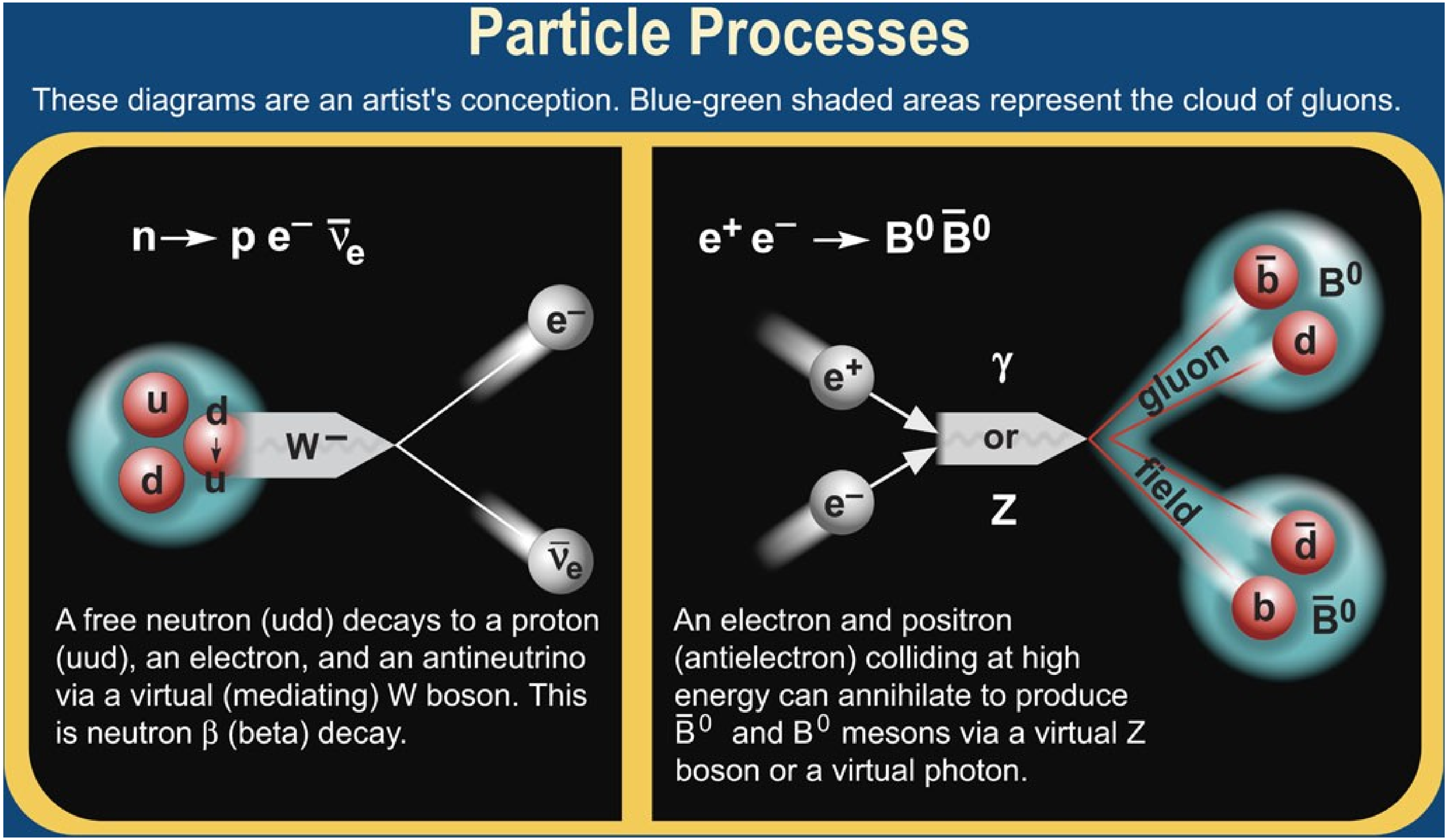
Baryons qqq and Antibaryons $\bar{q}\bar{q}\bar{q}$ Baryons are fermionic hadrons. These are a few of the many types of baryons.					
Symbol	Name	Quark content	Electric charge	Mass GeV/c^2	Spin
p	proton	**uud**	1	0.938	1/2
$\bar{p}$	antiproton	$\bar{u}\bar{u}\bar{d}$	–1	0.938	1/2
n	neutron	**udd**	0	0.940	1/2
Λ	lambda	**uds**	0	1.116	1/2
Ω^-	omega	**sss**	–1	1.672	3/2

Mesons, light and effective force carriers like the pi-meson, and the rho-meson.

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	$u\bar{d}$	+1	0.140	0
K^-	kaon	$s\bar{u}$	–1	0.494	0
ρ^+	rho	$u\bar{d}$	+1	0.776	1
B^0	B-zero	$d\bar{b}$	0	5.279	0
η_c	eta-c	$c\bar{c}$	0	2.980	0

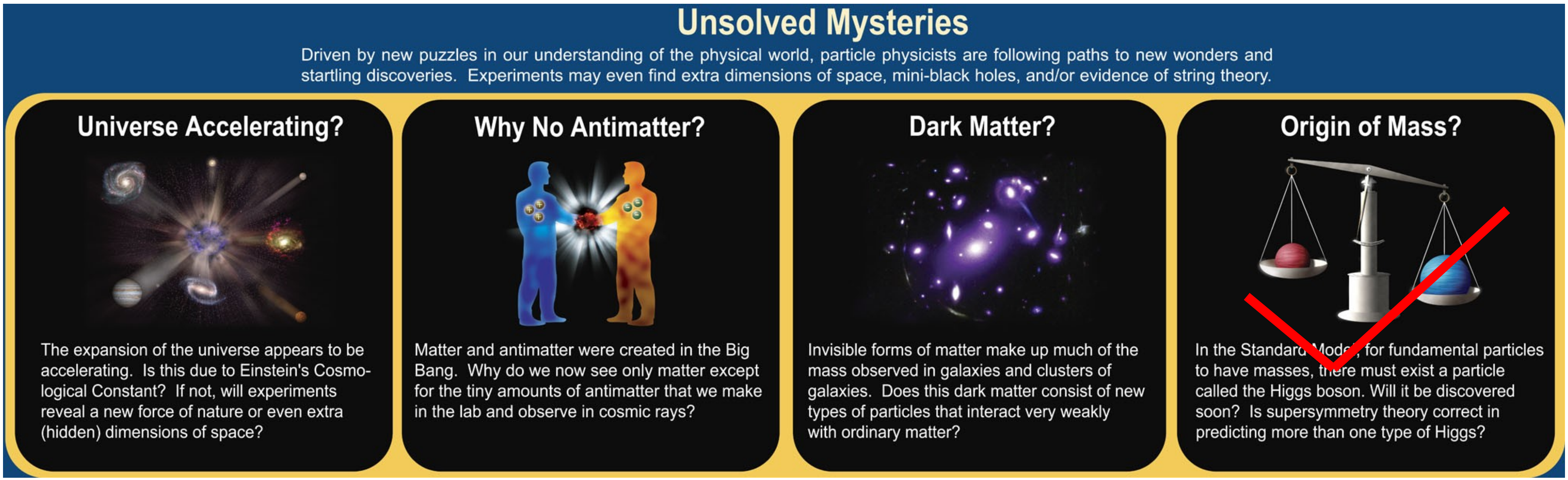
Decay and Annihilation

- processes



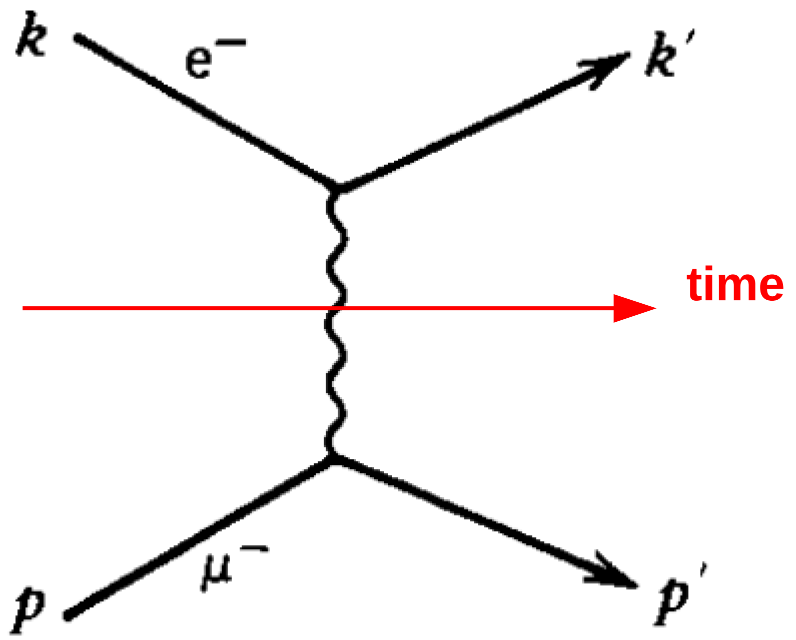
Unsolved Mysteries

- mysteries



Feynman Diagrams

- Always keep in mind that Feynman Diagrams are an artifice, representing some horrible mathematics in a Taylor-series like expansion in the strength of the interaction.

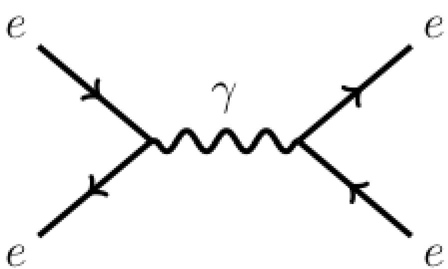


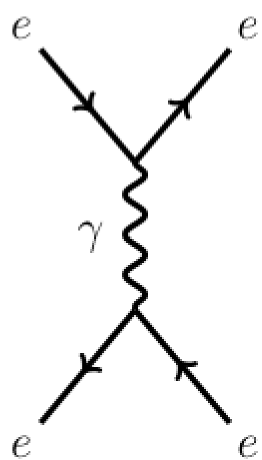
Feynman Diagram for electron-muon scattering. (Halzen & Martin Fig. 6.4)

curly M is the scattering amplitude, and measurements usually involve curly-M-squared.

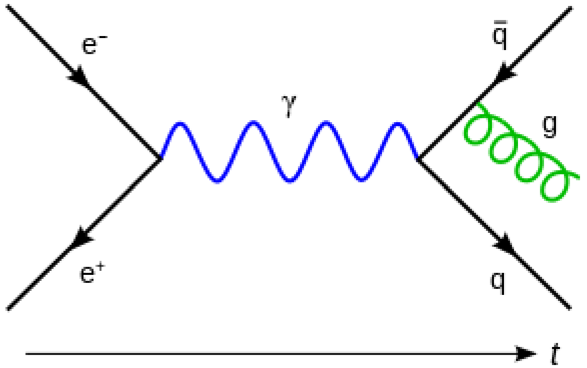
$$\mathfrak{M} = -e^2 \bar{u}(k')\gamma^\mu u(k) \frac{1}{q^2} \bar{u}(p')\gamma_\mu u(p).$$

More Feynman Diagrams

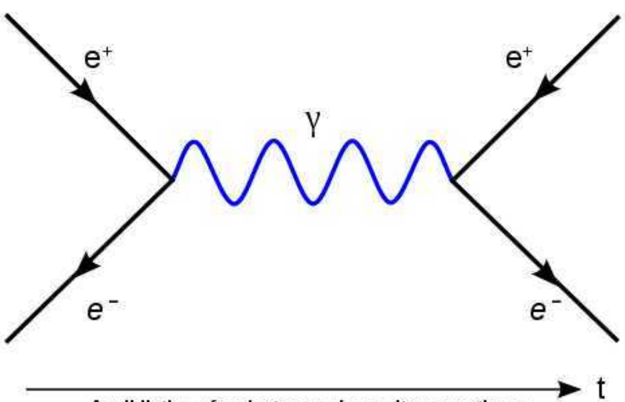




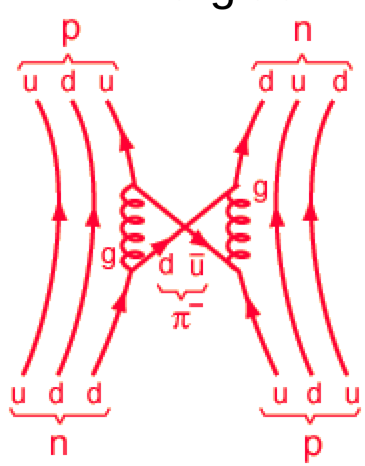
electron & positron annhiliate creating an electron & positron

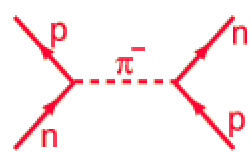


electron & positron annhiliate creating a quark & anti-quark pair in which one of them emits a gluon.



Annihilation of a electron and a positron creating a photon which decays into an new electron positron pair





quarks interact and looks like an effective theory where a pion is exchanged.

Useful Links

- Vanderbilt QuarkNet Site:
  http://www.hep.vanderbilt.edu/~gabellwe/qnweb/
- Some details here
  http://www.leptonica.com/particle-primer.html
- Contemporary Physics Education Project, particle physics materials
  http://www.cpepphysics.org/particles.html

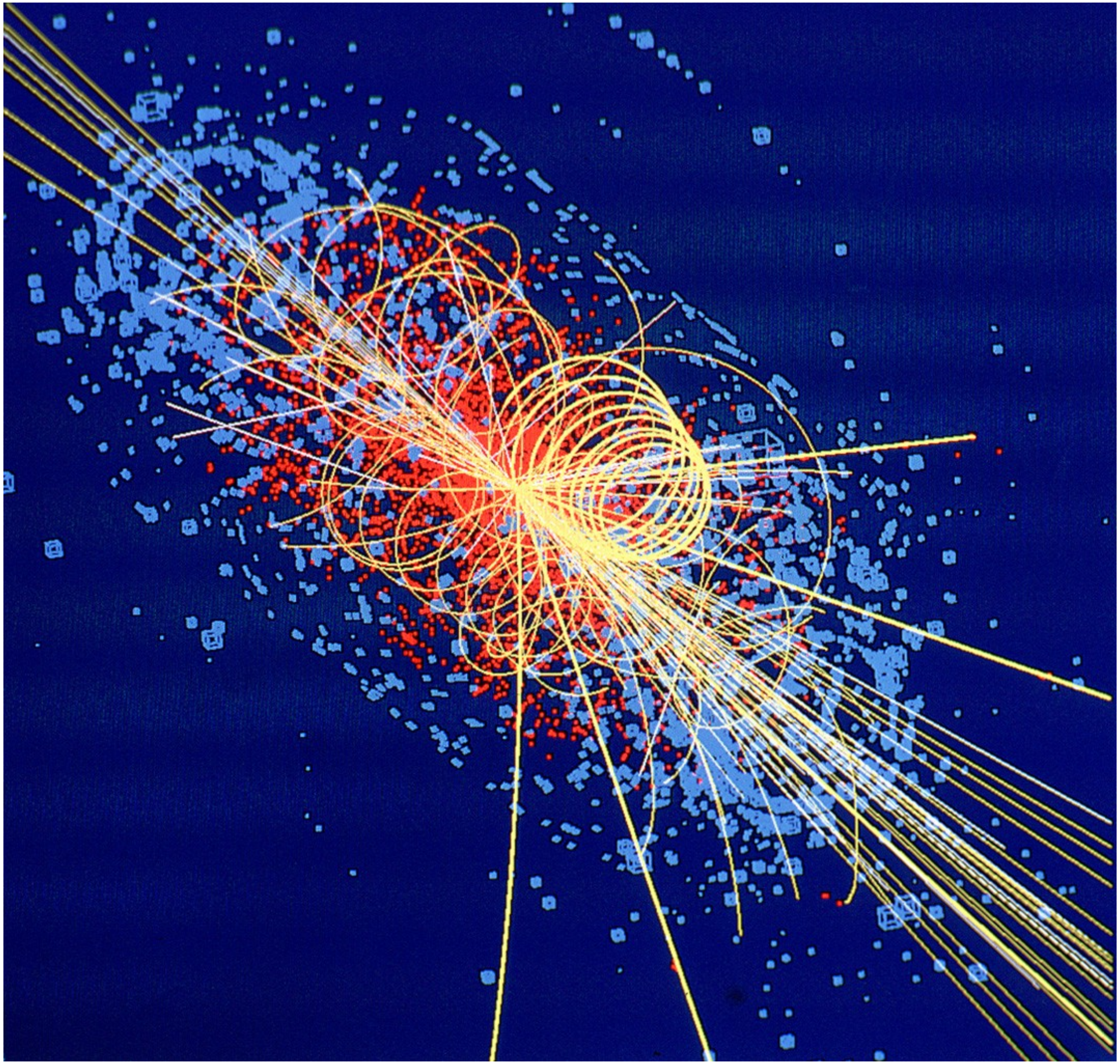
Next Discoveries?

- **Higgs Boson**, the particle that permeates all of space and that every other particle moves through and acquires **MASS** (read Inertia or resistance to changes in motion). More to learn? Other Higgs particles?
- **SUperSYmmetric (SUSY) Particles**, candidate for cold dark matter in theories of galaxy formation, but...been looking for it for 40 years!
- **Neutrinos** have a small mass and the convert one into the other as the travel in free-space. What?
- **New stuff?** Mini-blackholes, new particles, extra dimensions

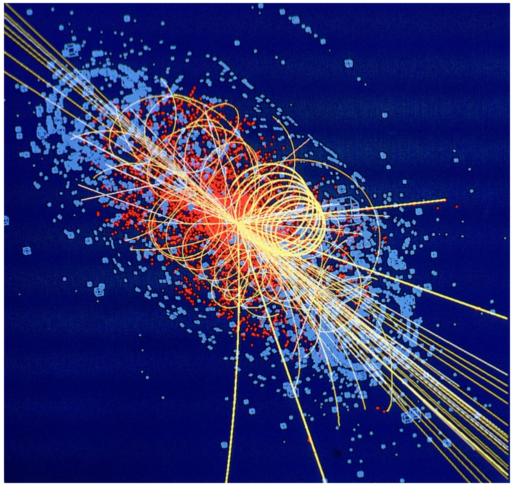
Old Pixel Numerology

- Barrel has 11520 ROCs, 48 MPxl
- Forward has 4320 ROCs, 18 MPxl
- 1 ROC has 4160 pixels
- Si Sensor pixel size is 100 microns by 150 microns
- Fpix has 3 plaquette and 4 plaquette config to its panels: 3 plaquette: 2x5 + 2x4 + 2x3 (ROCs), and the 4 plaquette: 1x5 + 2x4 + 2x3 + 1x2 (ROCs)
- Urs shows fpix: (3x24+3x21)/4320 = 2.6% and bpix (3x16+6x8+3)/1152 = 0.9% not working.

An Event: Higgs to 4 muons



An Event: Higgs to 4 muons



Infer from this picture that it can get pretty messy inside the detector, that is it takes a fair bit of cleverness to learn new things.