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.

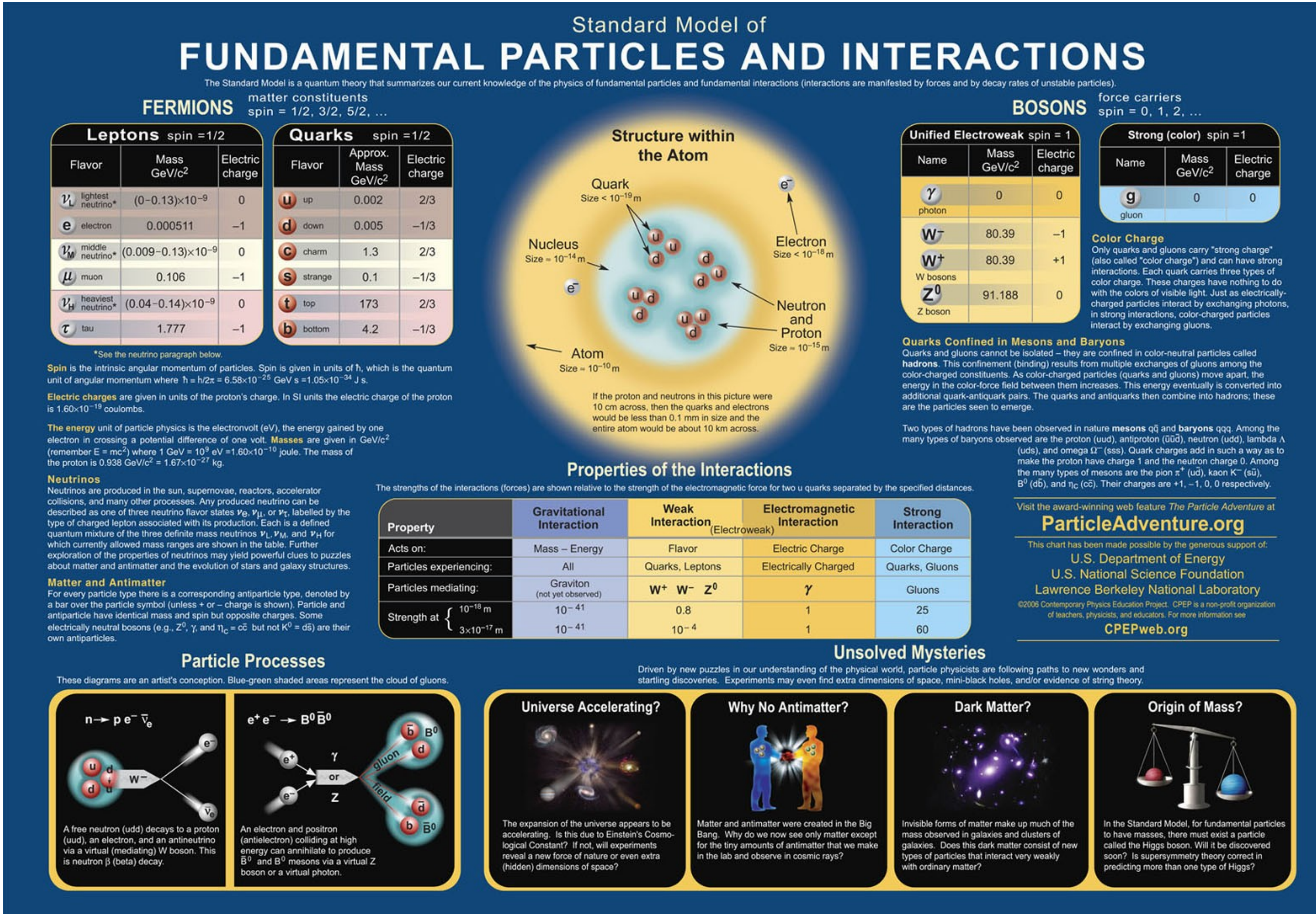
Some Not So Distant History

- 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



Standard Model of

FUNDAMENTAL PARTICLES AND INTERACTIONS

The Standard Model is a quantum theory that summarizes our current knowledge of the physics of fundamental particles and fundamental interactions (interactions are manifested by forces and by decay rates of unstable particles).

FERMIONS matter constituents spin = 1/2, 3/2, 5/2, ...

Leptons spin =1/2

Flavor	Mass GeV/c²	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/c²	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

*See the neutrino paragraph below.

Spin is the intrinsic angular momentum of particles. Spin is given in units of $\hbar$, which is the quantum unit of angular momentum where $\hbar = h/2\pi = 6.58\times10^{-25}$ GeV s $=1.05\times10^{-34}$ J s.

Electric charges are given in units of the proton's charge. In SI units the electric charge of the proton is 1.60×10^{-19} coulombs.

The energy unit of particle physics is the electronvolt (eV), the energy gained by one electron in crossing a potential difference of one volt. **Masses** are given in GeV/c² (remember $E = mc^2$) where 1 GeV = 10^9 eV $=1.60\times10^{-10}$ joule. The mass of the proton is 0.938 GeV/c² $= 1.67\times10^{-27}$ kg.

Neutrinos
Neutrinos are produced in the sun, supernovae, reactors, accelerator collisions, and many other processes. Any produced neutrino can be described as one of three neutrino flavor states ν_e, ν_μ, or ν_τ, labelled by the type of charged lepton associated with its production. Each is a defined quantum mixture of the three definite mass neutrinos ν_L, ν_M, and ν_H for which currently allowed mass ranges are shown in the table. Further exploration of the properties of neutrinos may yield powerful clues to puzzles about matter and antimatter and the evolution of stars and galaxy structures.

Matter and Antimatter
For every particle type there is a corresponding antiparticle type, denoted by a bar over the particle symbol (unless + or – charge is shown). Particle and antiparticle have identical mass and spin but opposite charges. Some electrically neutral bosons (e.g., Z^0, γ, and $\eta_c = c\bar{c}$ but not $K^0 = d\bar{s}$) are their own antiparticles.

Structure within the Atom

If the proton and neutrons in this picture were 10 cm across, then the quarks and electrons would be less than 0.1 mm in size and the entire atom would be about 10 km across.

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

Color Charge
Only quarks and gluons carry "strong charge" (also called "color charge") and can have strong interactions. Each quark carries three types of color charge. These charges have nothing to do with the colors of visible light. Just as electrically-charged particles interact by exchanging photons, in strong interactions, color-charged particles interact by exchanging gluons.

Quarks Confined in Mesons and Baryons
Quarks and gluons cannot be isolated – they are confined in color-neutral particles called **hadrons**. This confinement (binding) results from multiple exchanges of gluons among the color-charged constituents. As color-charged particles (quarks and gluons) move apart, the energy in the color-force field between them increases. This energy eventually is converted into additional quark-antiquark pairs. The quarks and antiquarks then combine into hadrons; these are the particles seen to emerge.

Two types of hadrons have been observed in nature **mesons** $q\bar{q}$ and **baryons** qqq. Among the many types of baryons observed are the proton (uud), antiproton ($\bar{u}\bar{u}\bar{d}$), neutron (udd), lambda Λ (uds), and omega Ω^- (sss). Quark charges add in such a way as to make the proton have charge 1 and the neutron charge 0. Among the many types of mesons are the pion π^+ ($u\bar{d}$), kaon K^- ($s\bar{u}$), B^0 ($d\bar{b}$), and η_c ($c\bar{c}$). Their charges are +1, –1, 0, 0 respectively.

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
Strength at 3×10^{-17} m	10^{-41}	10^{-4}	1	60

Visit the award-winning web feature *The Particle Adventure* at
ParticleAdventure.org

This chart has been made possible by the generous support of:
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U.S. National Science Foundation
Lawrence Berkeley National Laboratory

CPEPweb.org

Particle Processes

These diagrams are an artist's conception. Blue-green shaded areas represent the cloud of gluons.

A free neutron (udd) decays to a proton (uud), an electron, and an antineutrino via a virtual (mediating) W boson. This is neutron β (beta) decay.

An electron and positron (antielectron) colliding at high energy can annihilate to produce $\bar{B}^0$ and B^0 mesons via a virtual Z boson or a virtual photon.

Unsolved Mysteries

Driven by new puzzles in our understanding of the physical world, particle physicists are following paths to new wonders and startling discoveries. Experiments may even find extra dimensions of space, mini-black holes, and/or evidence of string theory.

Universe Accelerating?
The expansion of the universe appears to be accelerating. Is this due to Einstein's Cosmological Constant? If not, will experiments reveal a new force of nature or even extra (hidden) dimensions of space?

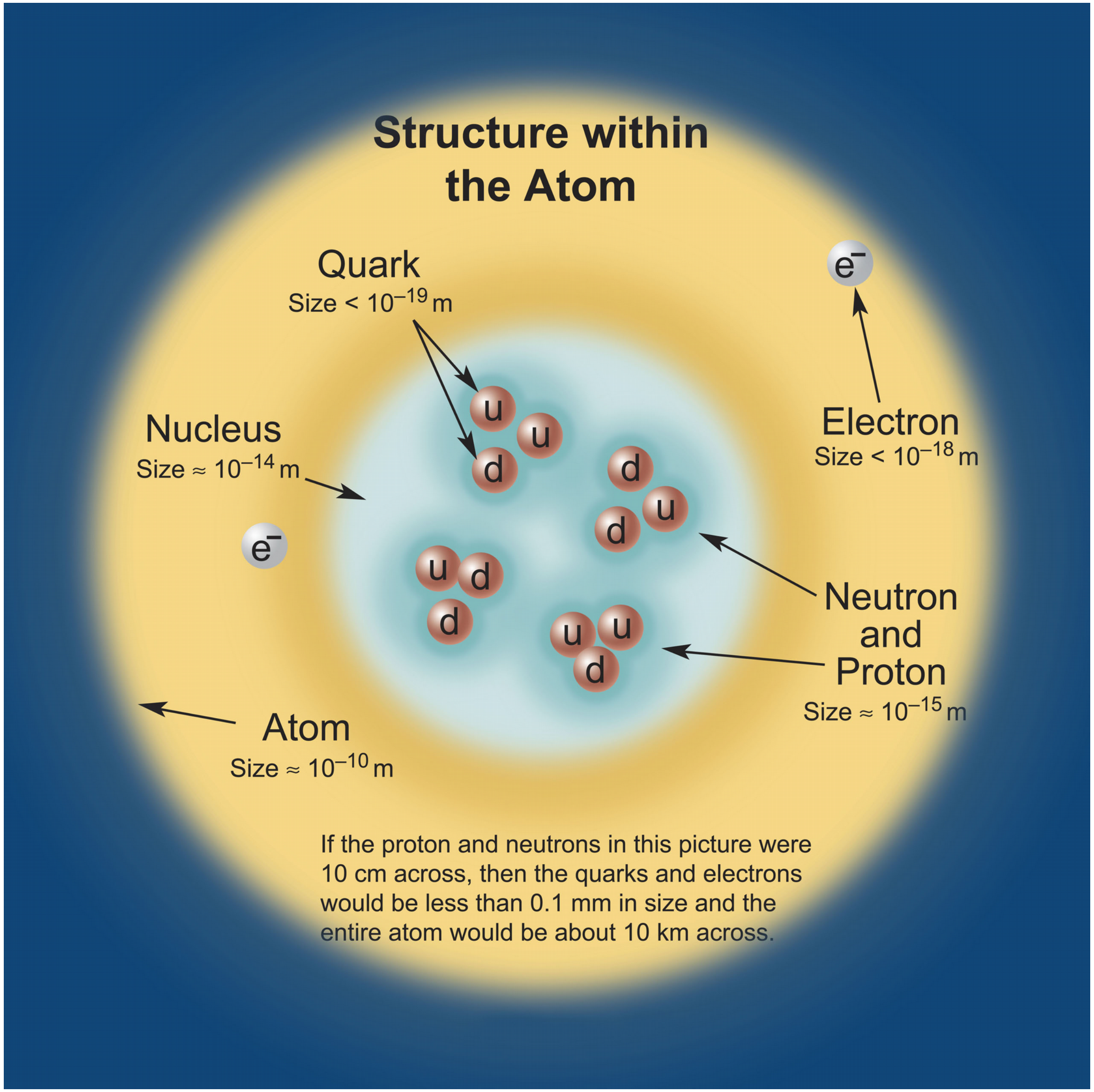
Why No Antimatter?
Matter and antimatter were created in the Big Bang. Why do we now see only matter except for the tiny amounts of antimatter that we make in the lab and observe in cosmic rays?

Dark Matter?
Invisible forms of matter make up much of the mass observed in galaxies and clusters of galaxies. Does this dark matter consist of new types of particles that interact very weakly with ordinary matter?

Origin of Mass?
In the Standard Model, for fundamental particles to have masses, there must exist a particle called the Higgs boson. Will it be discovered soon? Is supersymmetry theory correct in predicting more than one type of Higgs?

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.



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Fermions, Spin odd-halves

FERMIONS

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

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

BOSONS

force carriers
spin = 0, 1, 2, ...

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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

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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
$\bar{\textbf{p}}$	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	$\mathbf{u\bar{d}}$	+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

Decay and Scattering

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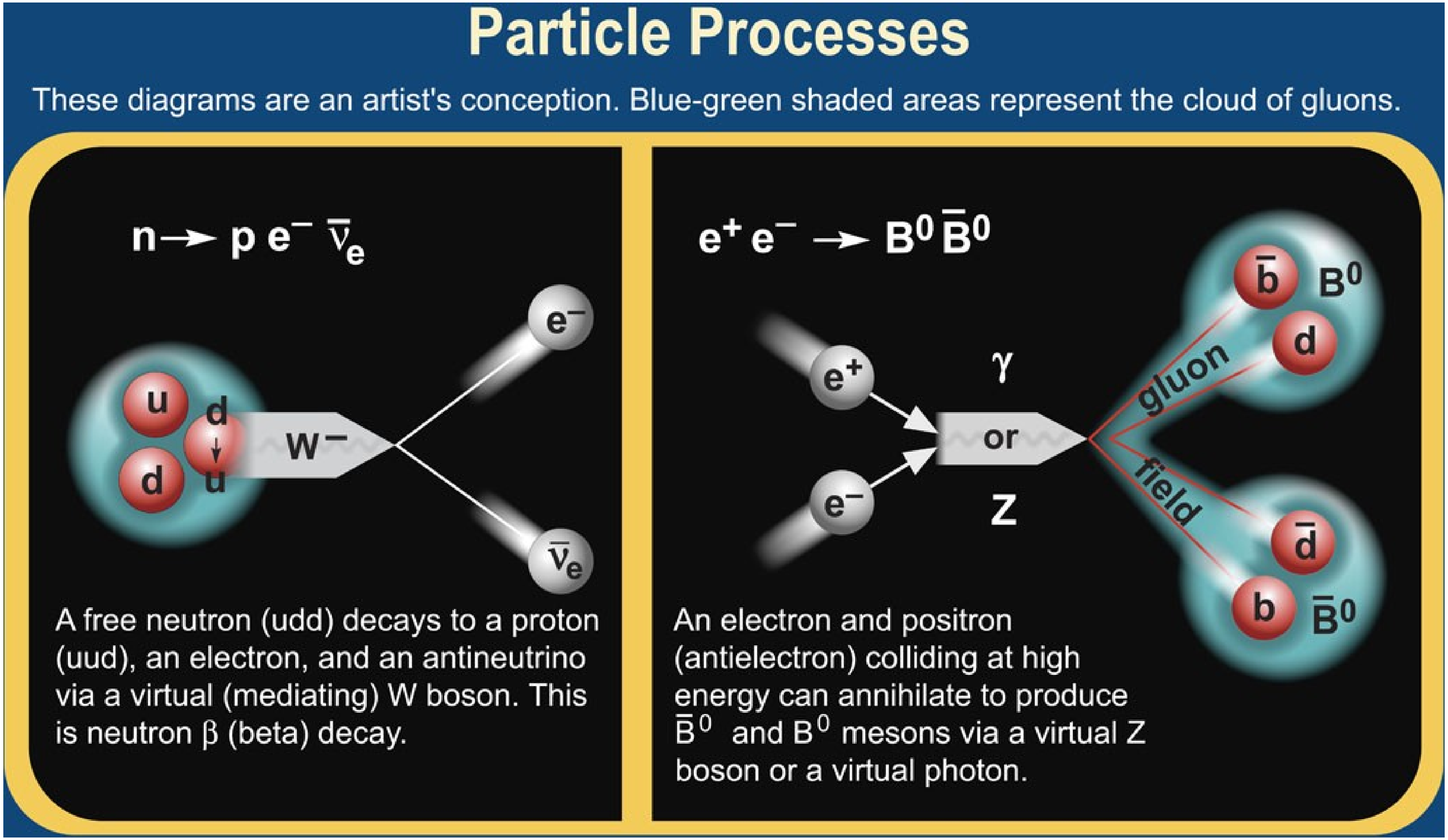
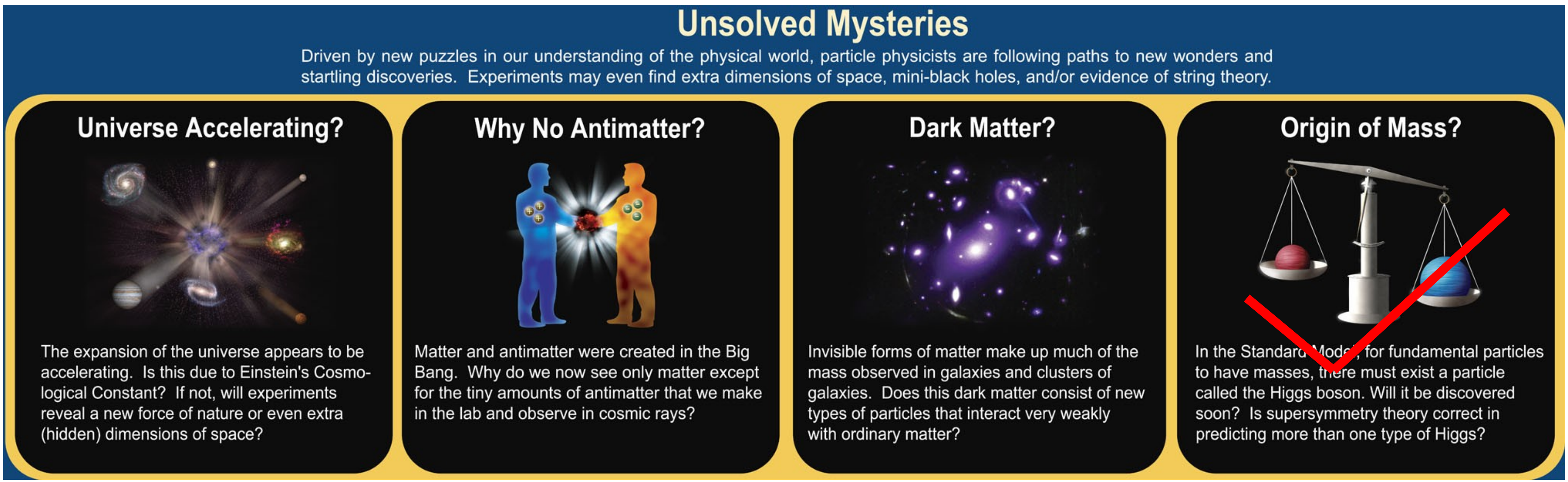


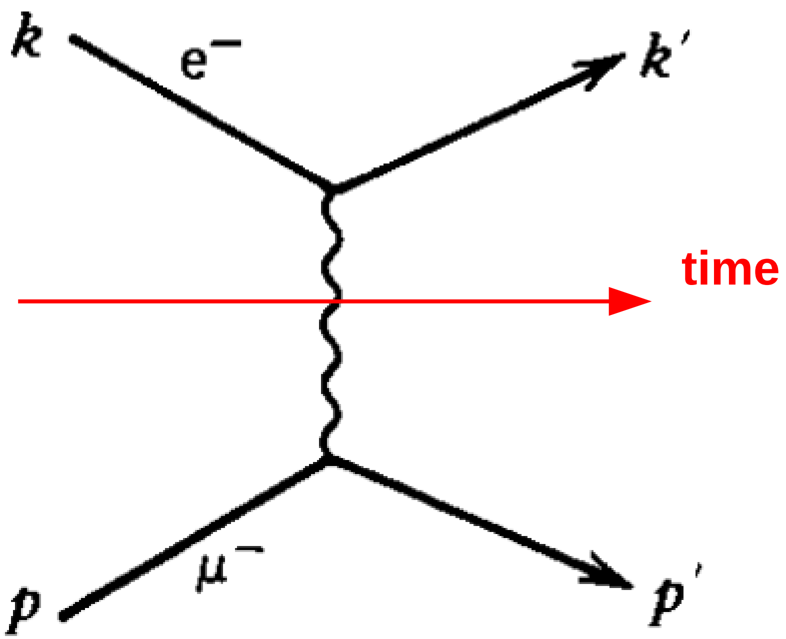
Unsolved Mysteries

- aa



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.

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

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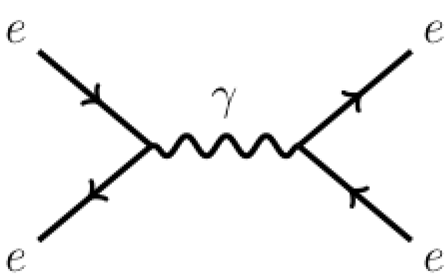
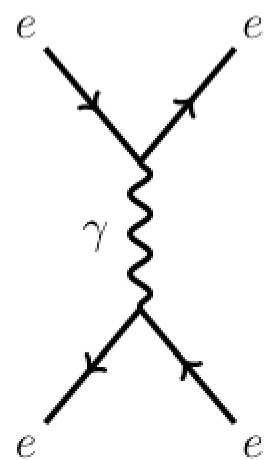
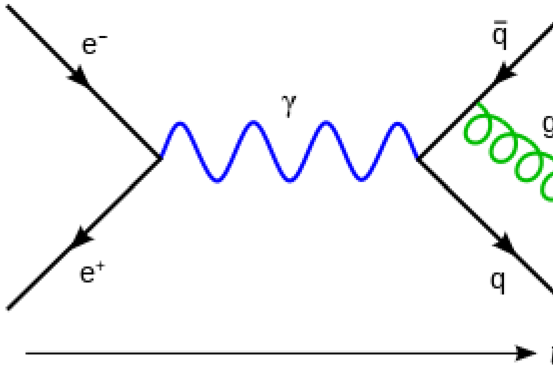
More Feynman Diagrams

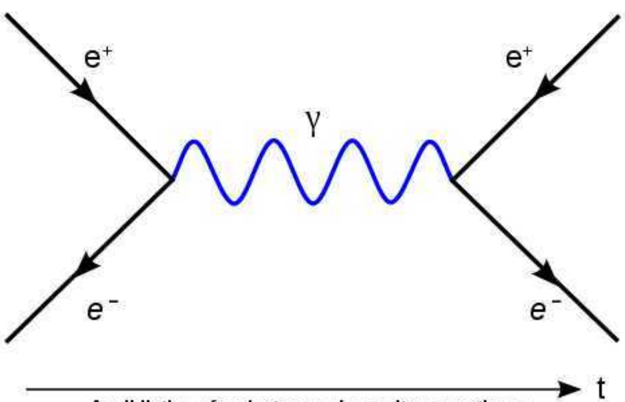




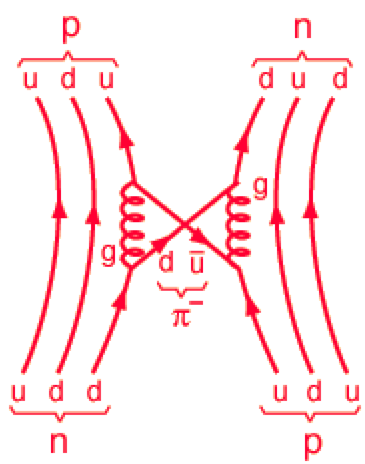
electron & positron annhiliate creating an electron & positron

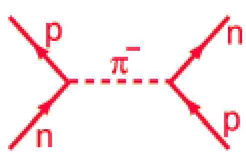


electron & positron annhiliate creating a quark & anti-quark pair in which one of them emits a gluon.



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

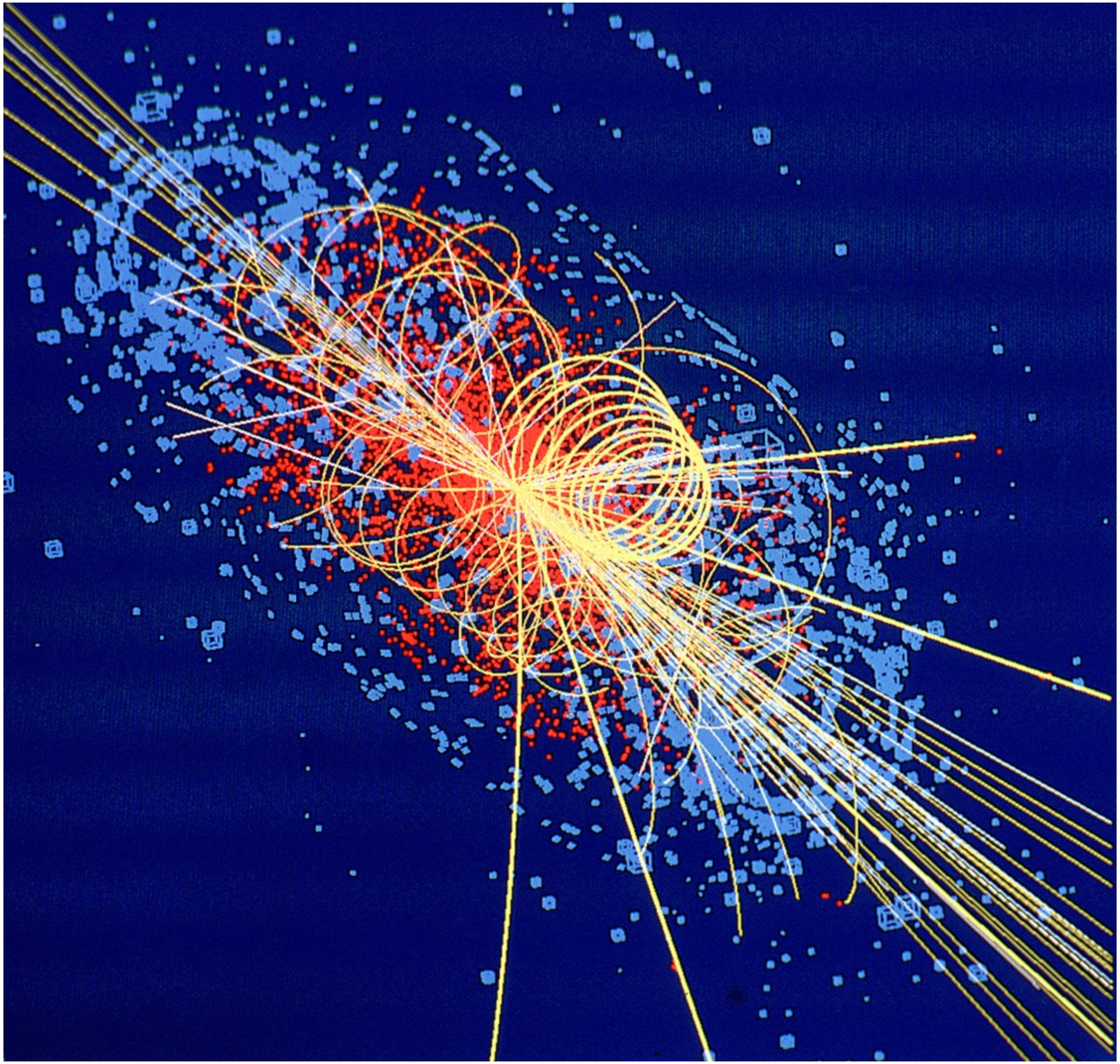
Next Discoveries?

- **Higgs Boson**, the particle the 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

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



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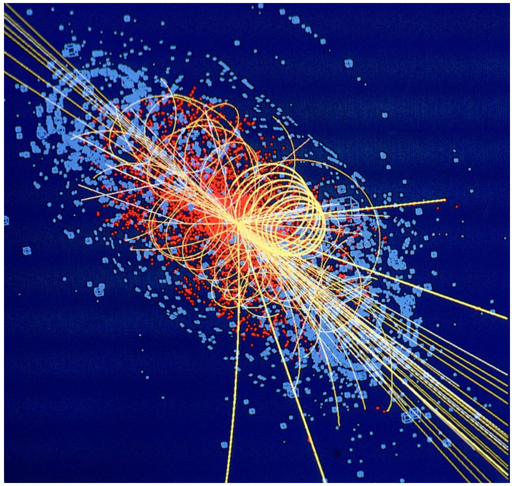

Infer from this picture that it can get pretty messy inside the detector, that is it takes a fair bit of cleverness to learn new things.