The Standard Model
or Particle Physics 101

Nick Hadley

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Thanks

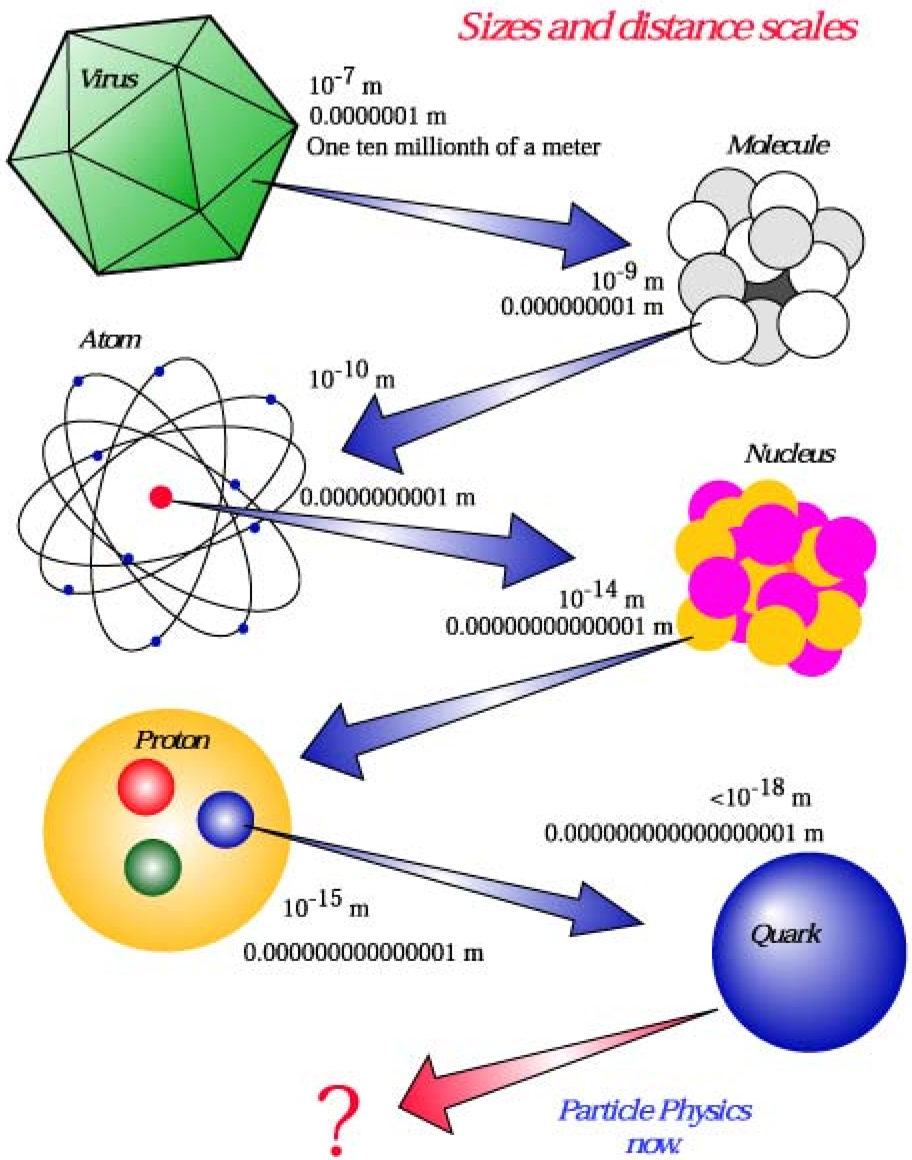
- Thanks to Don Lincoln of Fermilab who provided some of the pictures and slides used in this talk.

- Any errors are mine of course…

Particle Physics

- Particle Physics is the study individual particles
  - (protons, neutrons, electrons,…)
  - There are a lot more (muons, kaons, pions, lambdas, quarks,…)

- And the forces between them. (gravity, electricity/magnetism, strong force, weak force).



- Particle Physics is sometimes called sub-atomic physics

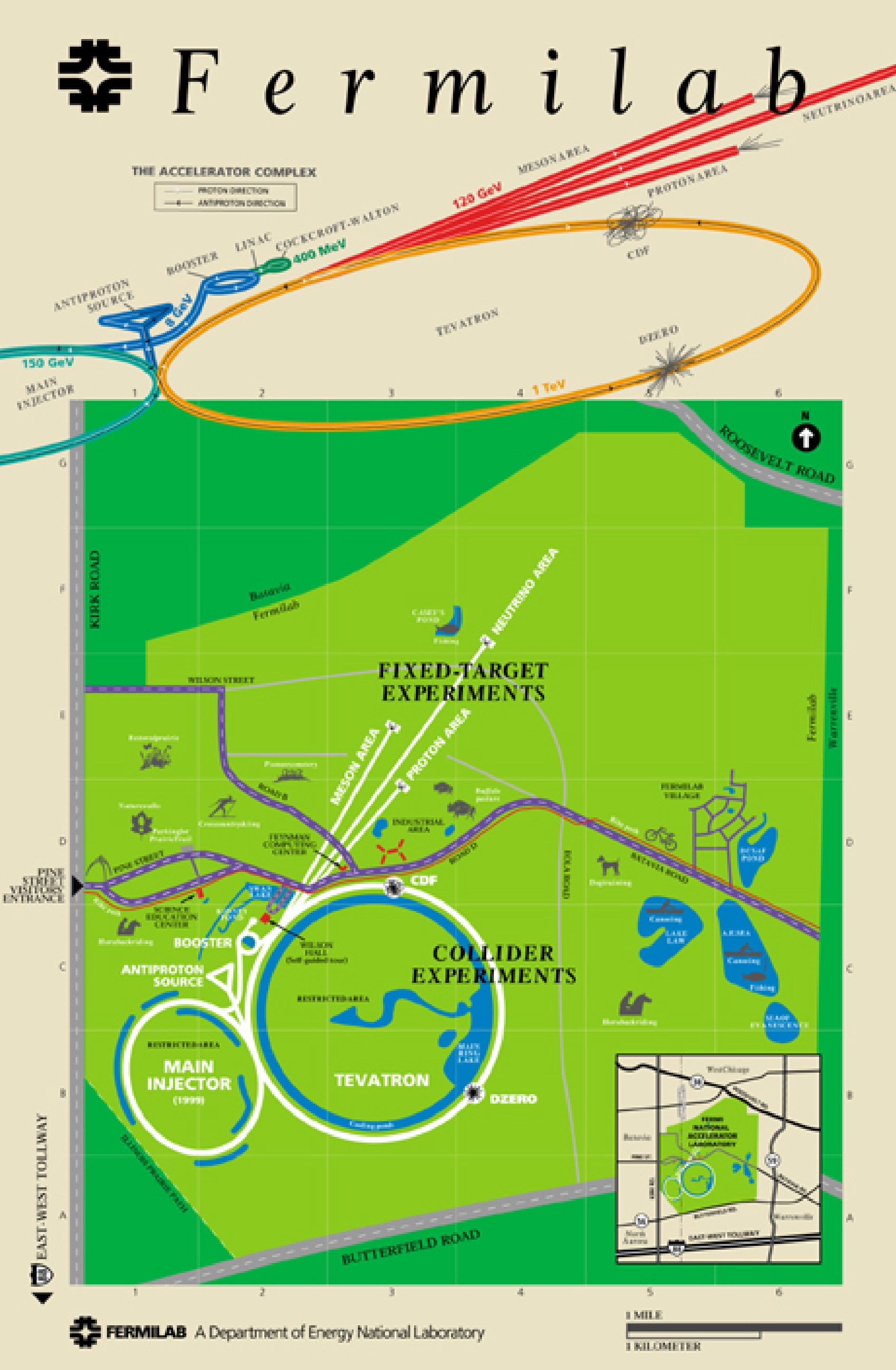
High Energy Physics

- Small distance scales require high energies and momenta.

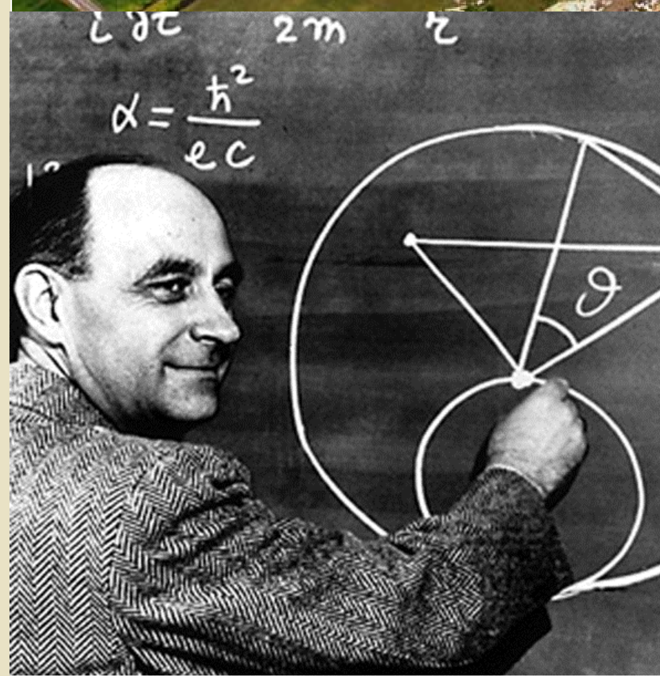
  $\Delta x \, \Delta p > h$

- Particle Physics = High Energy Physics
  = Sub-Atomic Physics

- Also a tie in with the very large, see Jordan's talk on the last day on Cosmology



Fermilab
THE ACCELERATOR COMPLEX
PROTON DIRECTION
ANTIPROTON DIRECTION
NEUTRINO AREA
MESON AREA
PROTON AREA
120 GeV
COCKCROFT-WALTON
LINAC
400 MeV
BOOSTER
8 GeV
ANTIPROTON SOURCE
150 GeV
MAIN INJECTOR
CDF
TEVATRON
DZERO
1 TeV
ROOSEVELT ROAD
KIRK ROAD
WILSON STREET
FIXED-TARGET EXPERIMENTS
MESON AREA
PROTON AREA
NEUTRINO AREA
PINE STREET
PINE STREET VISITORS ENTRANCE
CDF
BOOSTER
ANTIPROTON SOURCE
COLLIDER EXPERIMENTS
MAIN INJECTOR (1999)
TEVATRON
DZERO
BATAVIA ROAD
EOLA ROAD
BUTTERFIELD ROAD
EAST-WEST TOLLWAY
FERMILAB A Department of Energy National Laboratory
1 MILE
1 KILOMETER



$\alpha = \frac{\hbar^2}{ec}$

USA 33
Enrico Fermi

Now
(15 billion years)

Stars form
(1 billion years)

Atoms form
(300,000 years)

Nuclei form
(180 seconds)

Nucleons form
(10^{-10} seconds)

Fermilab
$4x10^{-12}$ seconds

Quarks differentiate
(10^{-34} seconds?)

??? (Before that)

Forces (1)

- Electricity and magnetism – Maxwell/Einstein showed these are one force.
  - Electric motors, lights
  - Keeps electrons tied to atoms.
  - All of chemistry (!)

Forces (2)

- Strong Force
  - Nucleus has protons and neutrons
  - Nucleus stays together
  - Like charges repel
  - Must be a force stronger than EM force holding nucleus together
  - Call it the “Strong Force”
  - Source of Sun’s energy, fusion

Forces (3)

- Weak Force
  - Weaker than EM force
  - Neutron decays into proton + electron + neutrino
  - Most radioactive decays
    - Carbon 14, uranium, …

Forces (4)

- Gravity
  - All masses are attracted to all other masses
  - Much weaker than EM force
    - Calculate force of gravity vs EM (newton vs coulomb) for atom.
  - Important since most objects are electrically neutral
    - Subtext Q(electon) = -Q(proton)
  - Not studied much in particle physics, important for cosmology.

Force Carriers

- EM – photons (EM waves)
  - Long range (R^{-2})
- Weak – W and Z particles discovered 1983
  - Short range (10^{-21} m)
- Strong – gluons seen indirectly in 1970's
  - Short range ($<10^{-15}$ m)
- Gravity – gravitons
  - Long range (R^{-2})

Particles

- Molecules made up of atoms
- Atoms are made up of protons, neutrons, and electrons.
- Electrons (as far as we know) are elementary and are made up of nothing else. Their charge radius is less than 10^{-16} m!
- Protons and neutrons are made of quarks.

Quarks

- Protons and neutrons are made of particles called up and down quarks
- Up quark has charge + 2/3
- Down quark has charge –1/3
- Quarks have spin 1/2
- Proton = uud
- Neutron = udd

More particles

- Pions spin 0 particles (π+, π-, π^0)
  - Mass about 1/8 that of proton
  -

$$\pi^+ = u\overline{d}$$

$$\pi^- = \overline{u}d$$

$$\pi^0 = \frac{1}{\sqrt{2}}(u\overline{u} + d\overline{d})$$

Antiparticles

- Yes, antimatter exists
- Anti-electron = positron, antiproton, …

- Opposite charge, same mass and spin
  - Other quantum numbers opposite too
  - We'll explain what those are.

$$\overline{p} = \overline{u}\ \overline{u}\ \overline{d}$$

Terminology

- Integer spin particles are called bosons
  – Photons, W, Z, pions
- Half Integer spin (1/2 or 3/2 or …) are called fermions
  – Protons, electrons, neutrinos
- Fermions are anti-social, no two in the same state.
  – Big consequence, the periodic table.
- Bosons like each other. Infinite number in same state

More Terminology

- Protons, neutrons and quarks feel strong, weak, EM, and gravity
- Electrons feel only weak, EM, and gravity
- Strong force mediated by gluons which couple to quarks thru color charge.
- Electrons have zero color charge.
- Quantum Chromodynamics = QCD = strong force

Is that all there is?

- Neutrinos (ν)
  - $Q = 0$
  - Small mass (almost zero, evidence for mass discovered in past few years, UMD group on experiment)
  - Only feel weak force (and gravity)
  - N -> p e ν

Is that all there is?

- It gets worse (or better!)
- We can explain the particles that make up everyday matter with up and down quarks, electrons and the electron neutrino plus the force carriers.
- However, there’s more. The muon, a heavy electron, was discovered in the 1930s in cosmic rays.

More generations (2)

- Muon and its neutrino
- Strange (1950s) and charm quarks
  - Kaons (strange meson) lambda particles (strange baryons)
- 2^{nd} Generation
- Duplicates first, but heavier
- Big mystery still, who needs it, why the muon???

More generations (3)

- Later, a third generation was found
- Tau lepton and its neutrino
- Bottom and top quark
  - Maryland group played major role in top quark discovery.
- Duplicates first and second, but heavier
- Why three???

Is that all???

- For the Standard Model, yes!!
  - Three generations of quarks and leptons
    - Lepton = electron, muon, tau and their neutrinos
  - Plus the force carriers and the forces
- Essentially all data we have today agrees with Standard Model

Standard Model of

FUNDAMENTAL PARTICLES AND INTERACTIONS

The Standard Model summarizes the current knowledge in Particle Physics. It is the quantum theory that includes the theory of strong interactions (quantum chromodynamics or QCD) and the unified theory of weak and electromagnetic interactions (electroweak). Gravity is included on this chart because it is one of the fundamental interactions even though not part of the "Standard Model."

FERMIONS

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

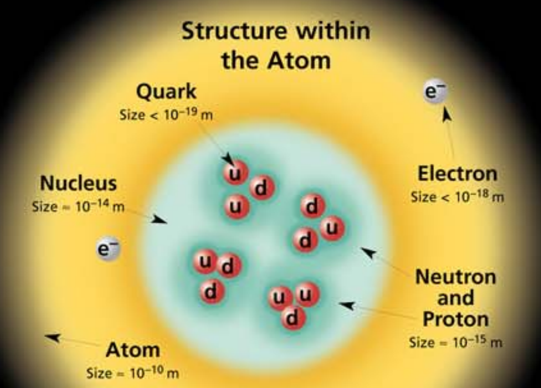
Leptons spin = 1/2		
Flavor	Mass GeV/c^2	Electric charge
ν_e electron neutrino	$<1\times10^{-8}$	0
e electron	0.000511	–1
ν_μ muon neutrino	<0.0002	0
μ muon	0.106	–1
ν_τ tau neutrino	<0.02	0
τ tau	1.7771	–1

Quarks spin = 1/2		
Flavor	Approx. Mass GeV/c^2	Electric charge
u up	0.003	2/3
d down	0.006	–1/3
c charm	1.3	2/3
s strange	0.1	–1/3
t top	175	2/3
b bottom	4.3	–1/3

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/c^2 (remember $E = mc^2$), where 1 GeV $= 10^9$ eV $= 1.60\times10^{-10}$ joule. The mass of the proton is 0.938 GeV/c^2 $= 1.67\times10^{-27}$ kg.



If the protons 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/c^2	Electric charge
γ photon	0	0
W^-	80.4	–1
W^+	80.4	+1
Z^0	91.187	0

Strong (color) spin = 1		
Name	Mass GeV/c^2	Electric charge
g gluon	0	0

Color Charge

Each quark carries one of three types of "strong charge," also called "color charge." These charges have nothing to do with the colors of visible light. There are eight possible types of color charge for gluons. Just as electrically-charged particles interact by exchanging photons, in strong interactions color-charged particles interact by exchanging gluons. Leptons, photons, and ***W*** and ***Z*** bosons have no strong interactions and hence no color charge.

Quarks Confined in Mesons and Baryons

One cannot isolate quarks and gluons; 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 (see figure below). 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.

Residual Strong Interaction

The strong binding of color-neutral protons and neutrons to form nuclei is due to residual strong interactions between their color-charged constituents. It is similar to the residual electrical interaction that binds electrically neutral atoms to form molecules. It can also be viewed as the exchange of mesons between the hadrons.

PROPERTIES OF THE INTERACTIONS

Property \ Interaction	Gravitational	Weak (Electroweak)	Electromagnetic (Electroweak)	Strong: Fundamental	Strong: Residual
Acts on:	Mass – Energy	Flavor	Electric Charge	Color Charge	See Residual Strong Interaction Note
Particles experiencing:	All	Quarks, Leptons	Electrically charged	Quarks, Gluons	Hadrons
Particles mediating:	Graviton (not yet observed)	W^+ W^- Z^0	γ	Gluons	Mesons
Strength relative to electromag for two u quarks at: 10^{-18} m	10^{-41}	0.8	1	25	Not applicable to quarks
Strength relative to electromag for two u quarks at: 3×10^{-17} m	10^{-41}	10^{-4}	1	60	Not applicable to quarks
for two protons in nucleus	10^{-36}	10^{-7}	1	Not applicable to hadrons	20

Baryons qqq and Antibaryons $\bar{q}\bar{q}\bar{q}$
Baryons are fermionic hadrons. There are about 120 types of baryons.

Symbol	Name	Quark content	Electric charge	Mass GeV/c^2	Spin
p	proton	uud	1	0.938	1/2
$\bar{p}$	anti-proton	$\bar{u}\bar{u}\bar{d}$	–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 $q\bar{q}$
Mesons are bosonic hadrons. There are about 140 types of mesons.

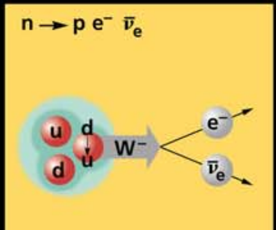
Symbol	Name	Quark content	Electric charge	Mass GeV/c^2	Spin
π^+	pion	$u\bar{d}$	+1	0.140	0
K^-	kaon	$s\bar{u}$	–1	0.494	0
ρ^+	rho	$u\bar{d}$	+1	0.770	1
B^0	B-zero	$d\bar{b}$	0	5.279	0
η_c	eta-c	$c\bar{c}$	0	2 .980	0

Matter and Antimatter

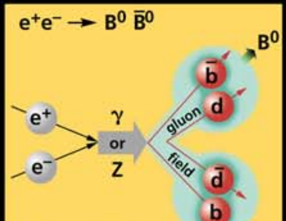
For every particle type there is a corresponding antiparticle type, denoted by a bar over the particle symbol (unless + or – charge is shown). Particle and antiparticle have identical mass and spin but opposite charges. Some electrically neutral bosons (e.g., Z^0, γ, and $\eta_c = c\bar{c}$, but not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

Figures

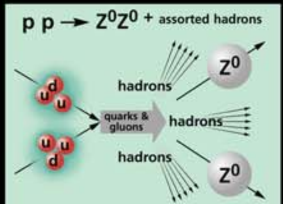
These diagrams are an artist's conception of physical processes. They are *not* exact and have *no* meaningful scale. Green shaded areas represent the cloud of gluons or the gluon field, and red lines the quark paths.



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



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



Two protons colliding at high energy can produce various hadrons plus very high mass particles such as Z bosons. Events such as this one are rare but can yield vital clues to the structure of matter.

The Particle Adventure

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

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BURLE INDUSTRIES, INC.

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Conclusions

- Is this the end?
- Despite all its successes, many questions unanswered by Standard Model
  - Why 3 generations, particle masses, why do the generations mix, anti-matter vs matter
- Unanswered questions -> new theories -> new particles (supersymmetry, leptoquarks,…)
- Still more questions than answers!
- Not done yet!