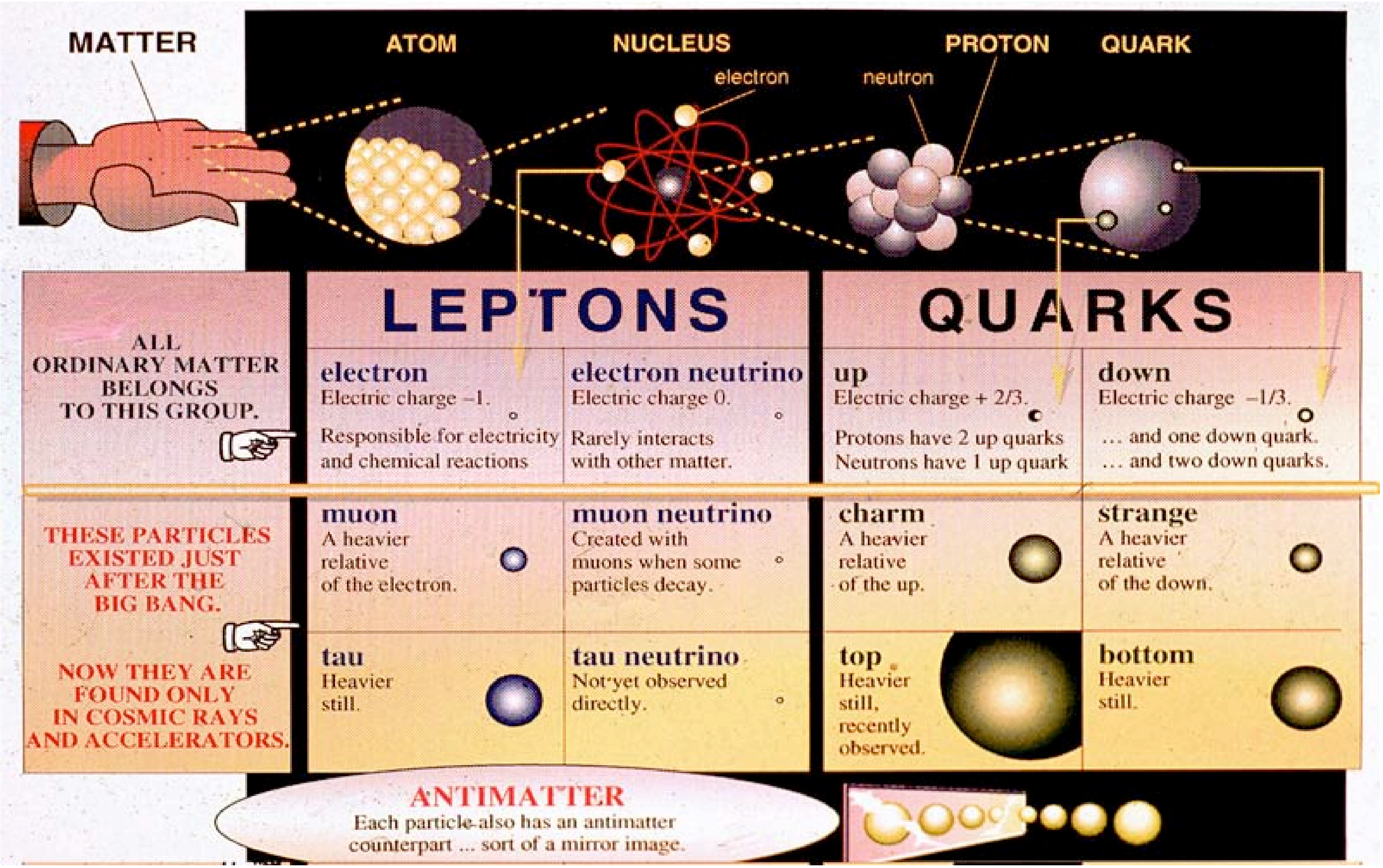
Looking at Quarks

Ritchie Patterson
June 7, 2006

- Introduction to Elementary Particles
- CLEO: Our eye on collisions
- What quarks tell us about nature

The Particles



Mesons and Baryons

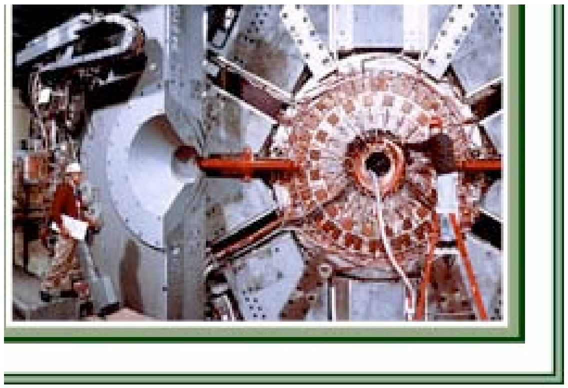
Quarks are never free.
Instead, we always see them either in baryons or mesons

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

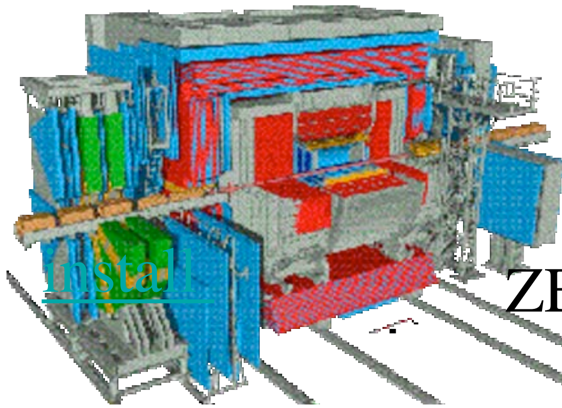
Mesons $q\bar{q}$ Mesons are bosonic hadrons. There are about 140 types of mesons.					
Symbol	Name	Quark content	Electric charge	Mass GeV/c^2	Spin
π^+	pion	$u\bar{d}$	+1	0.140	0
K^-	kaon	$s\bar{u}$	–1	0.494	0
ρ^+	rho	$u\bar{d}$	+1	0.770	1
B^0	B-zero	$d\bar{b}$	0	5.279	0
η_c	eta-c	$c\bar{c}$	0	2 .980	0

The heavy baryons and mesons usually decay quickly into the lighter ones: p, n, π and K

Detectors for Particle Physics

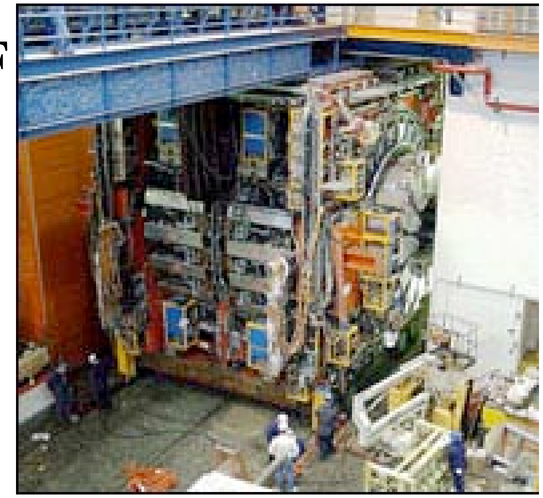


BaBar



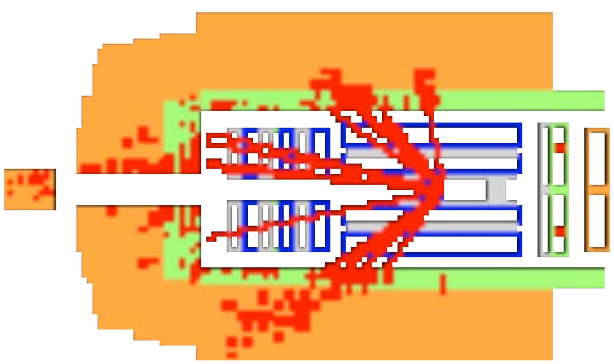
ZEUS

CDF

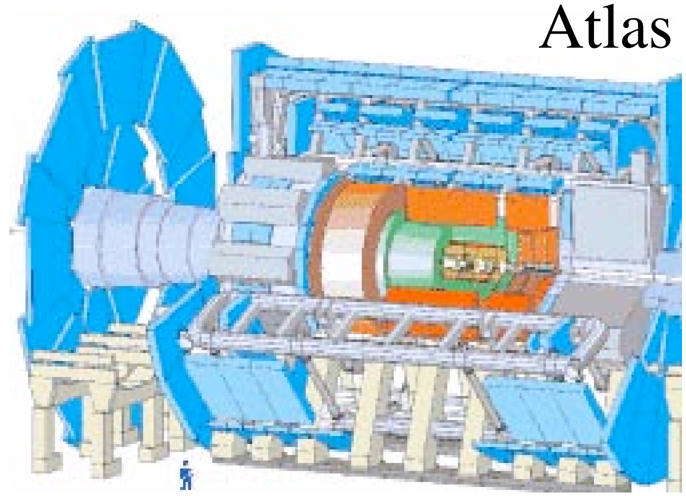


D0

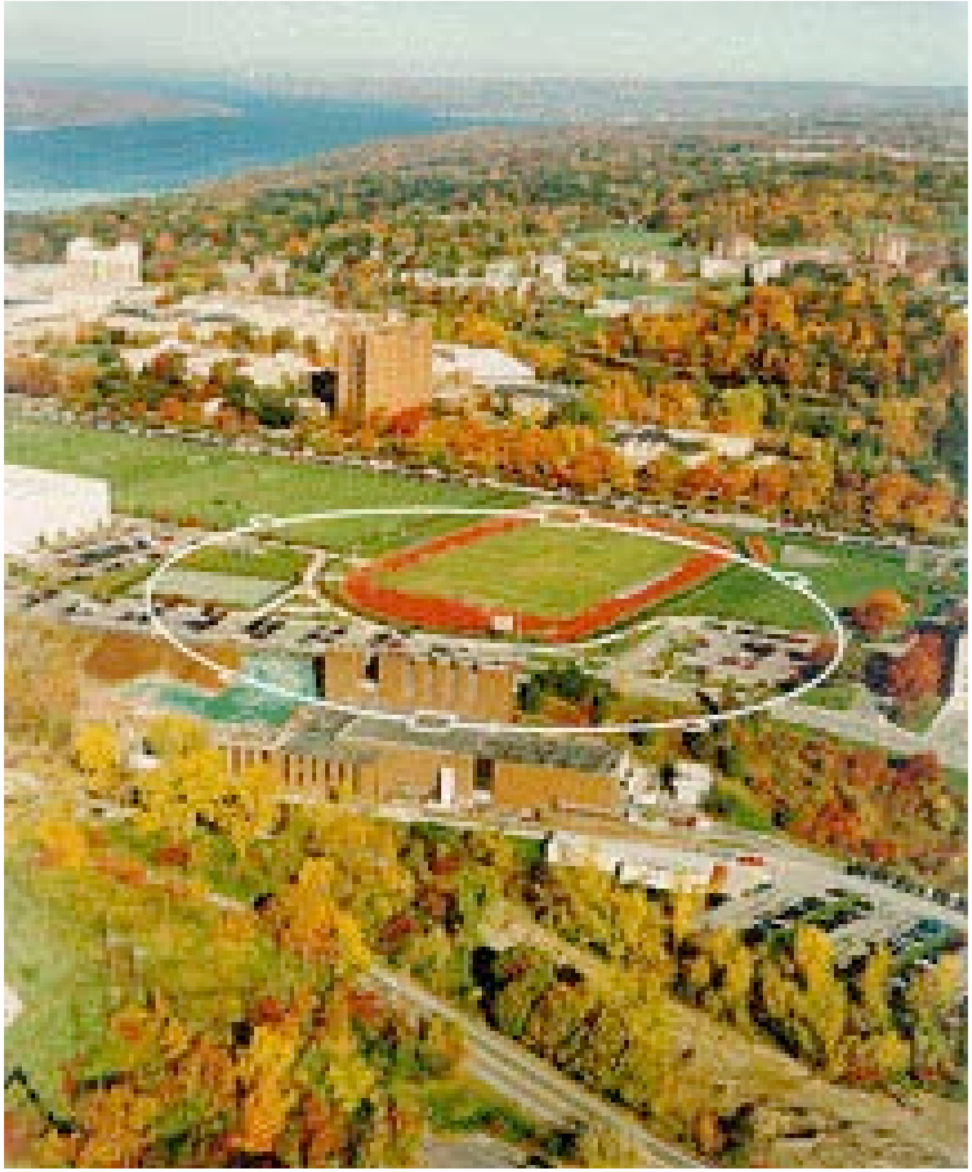
H1 DETECTOR



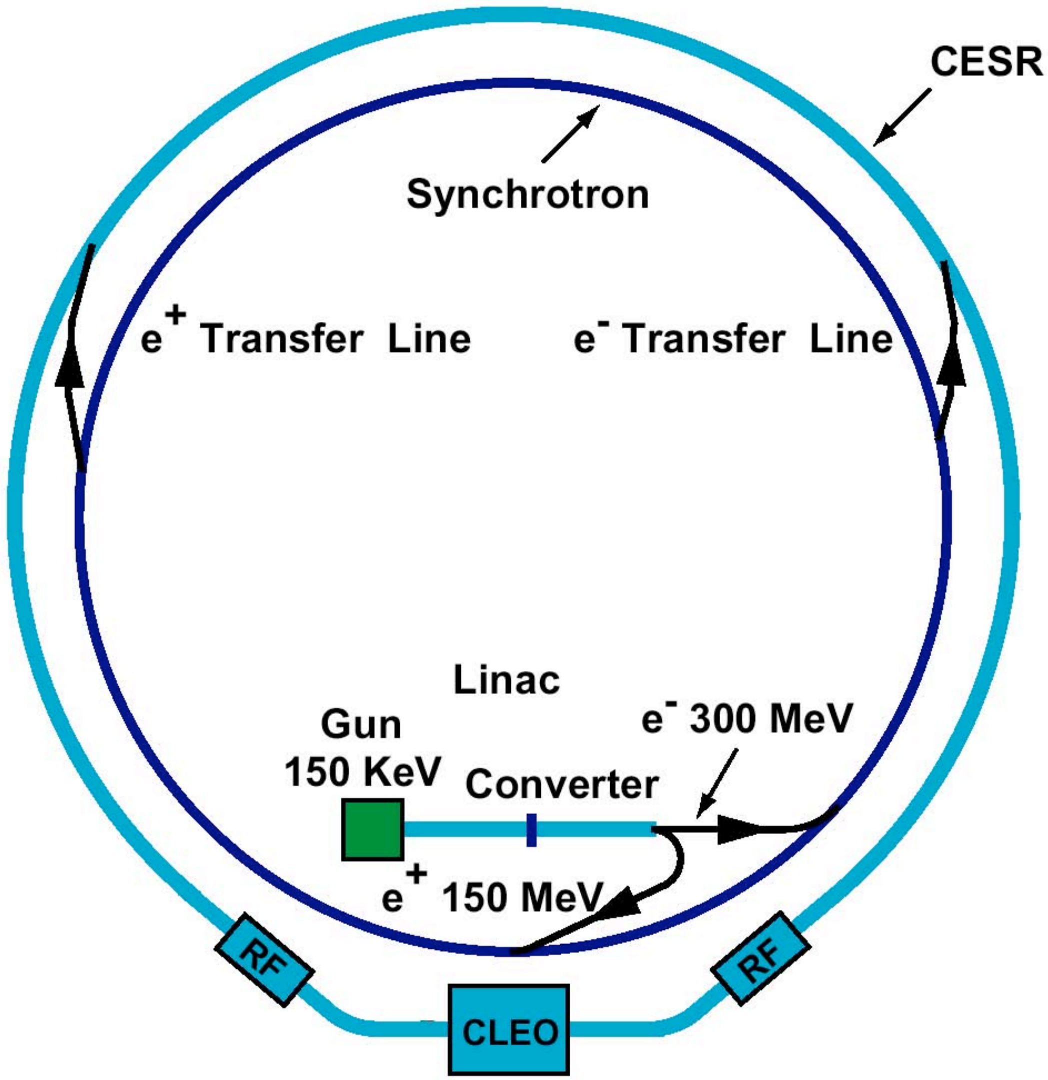
Atlas



Today: CESR and CLEO



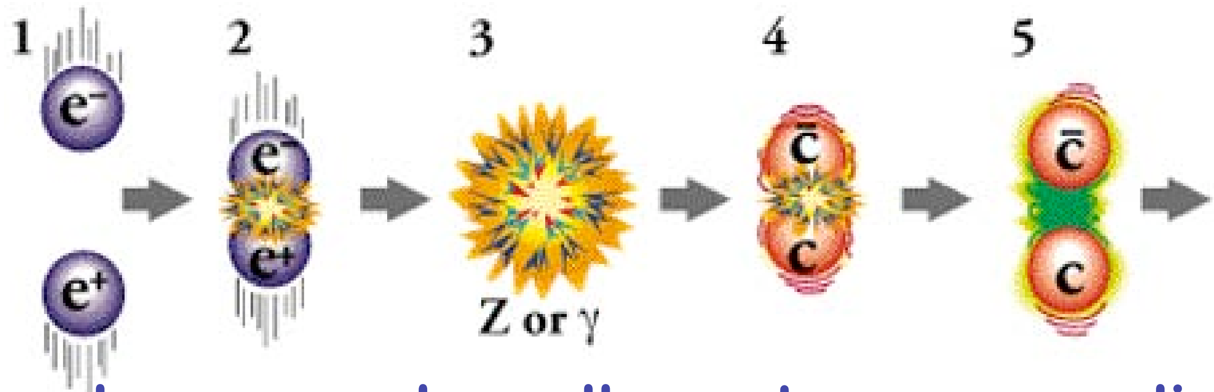
CESR



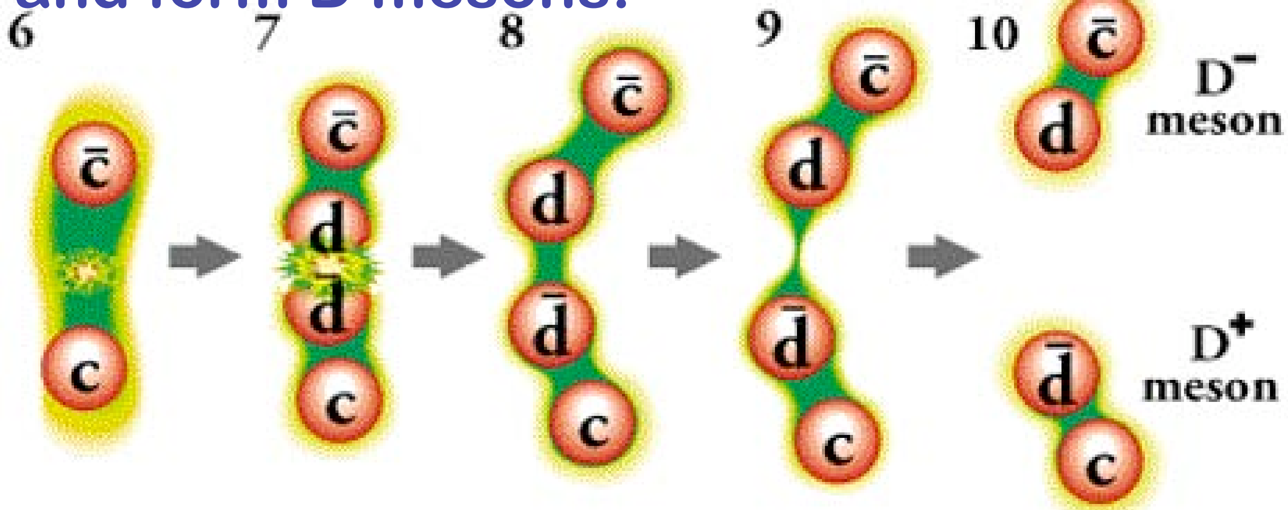
CESR
Synchrotron
e+ Transfer Line
e- Transfer Line
Linac
Gun
150 KeV
Converter
e- 300 MeV
e+ 150 MeV
RF
RF
CLEO

Collisions

First, e^+ and e^- annihilate to make a pair of charm quarks:



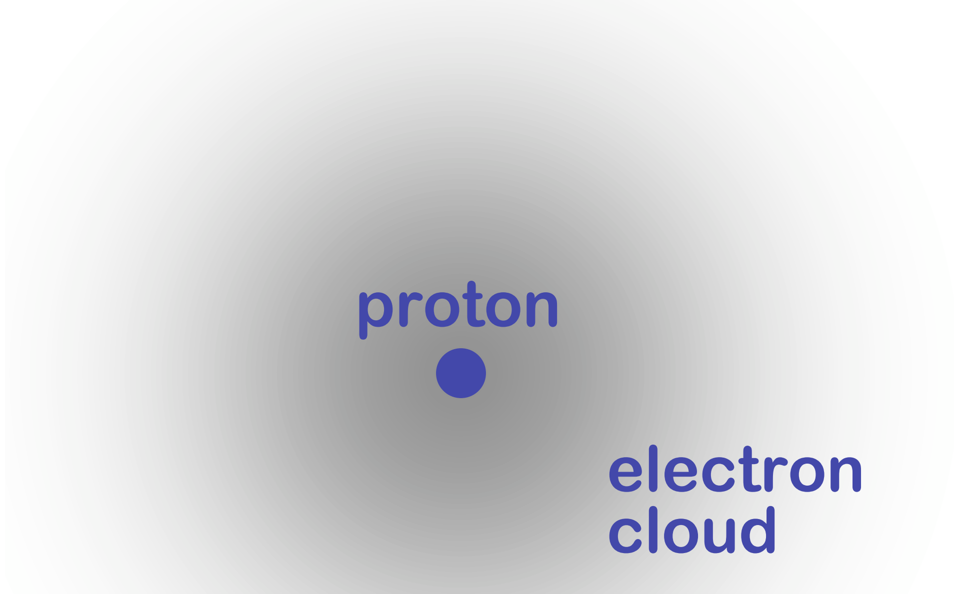
Then the charm quarks pull apart, pop some light quarks, and form D mesons:



D mesons decay after 1ps into particles that CLEO detects

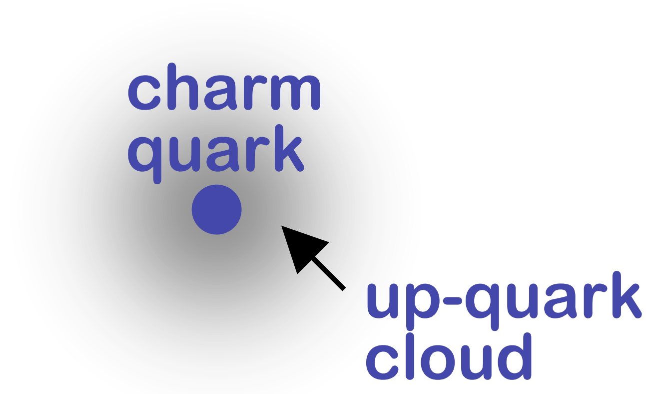
What's a D meson?

Hydrogen Atom



Electromagnetism binds electron to proton

D Meson



Strong Force binds up-quark to charm-quark

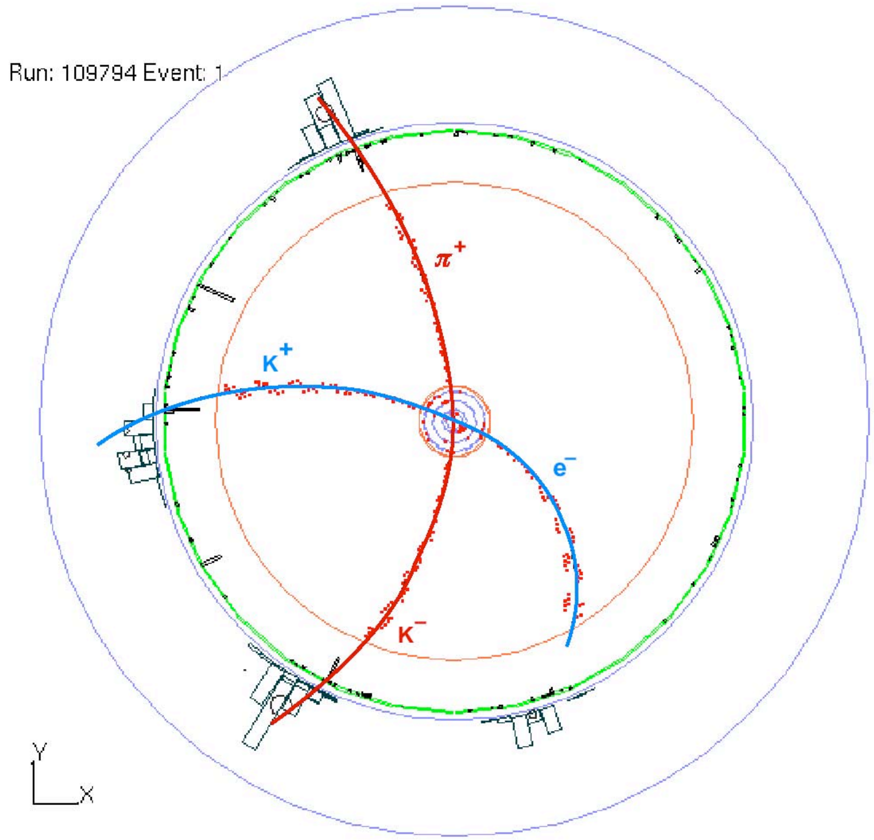
Decays via weak interaction:
charm → strange quark.
The lost mass materializes as new particles (pions, kaons, etc)

Why D mesons?

Their decays teach us about

- Weak interactions
  - Fundamental parameters
- Strong interactions
  - Binding of the daughter particles
    - Checks new calculations
    - Enables rigorous studies of matter-antimatter asymmetry & searches for new phenomena
  - Charm quark bound states may decay into exotic forms of matter known as glueballs

Detecting Particles



$D^0 \rightarrow K^- \pi^+$ $D^0 \rightarrow K^+ e^- \nu$

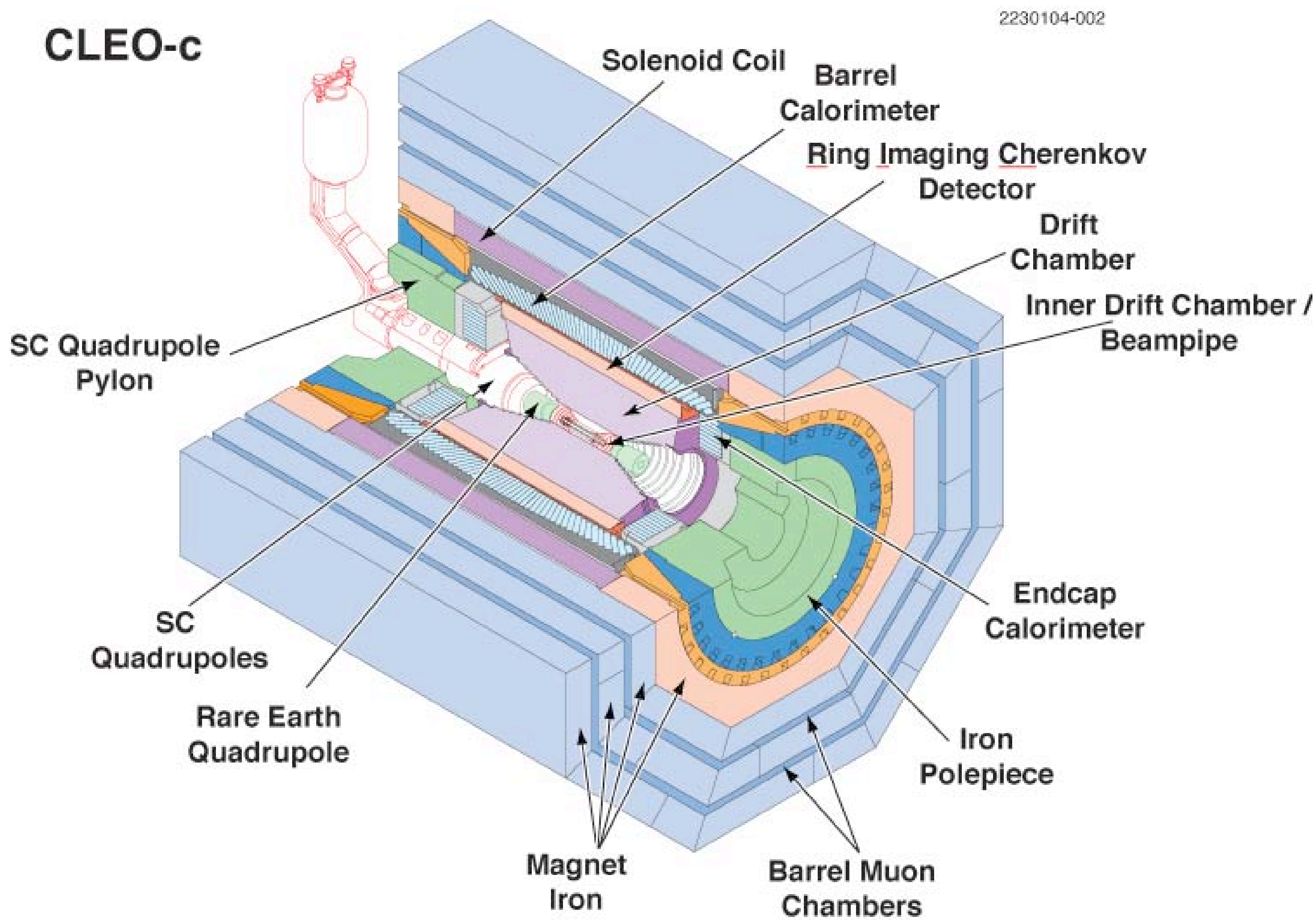
What do we want from our detector?

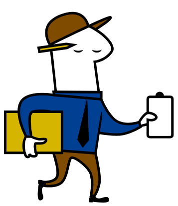
Imagine that a bomb explodes mid-air, and you want to study the fragments to find out everything you can about the bomb.

What properties of the fragments would you want to measure?

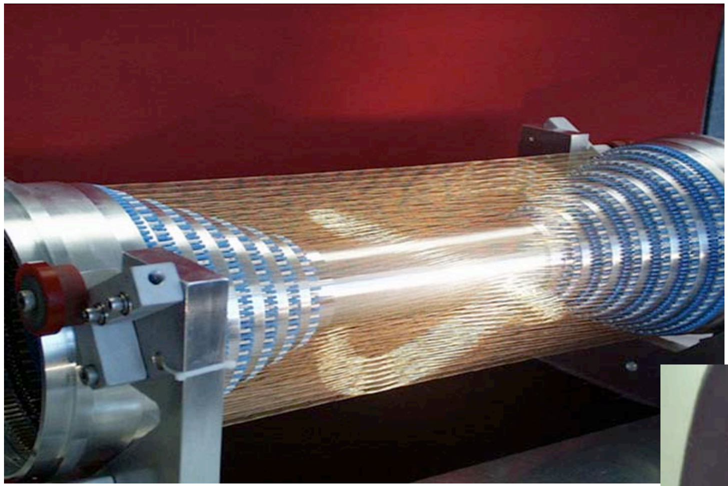
- Direction of motion of each fragment just after explosion
- Speed (or momentum) of each fragment
- Mass of each fragment

CLEO-c Detector

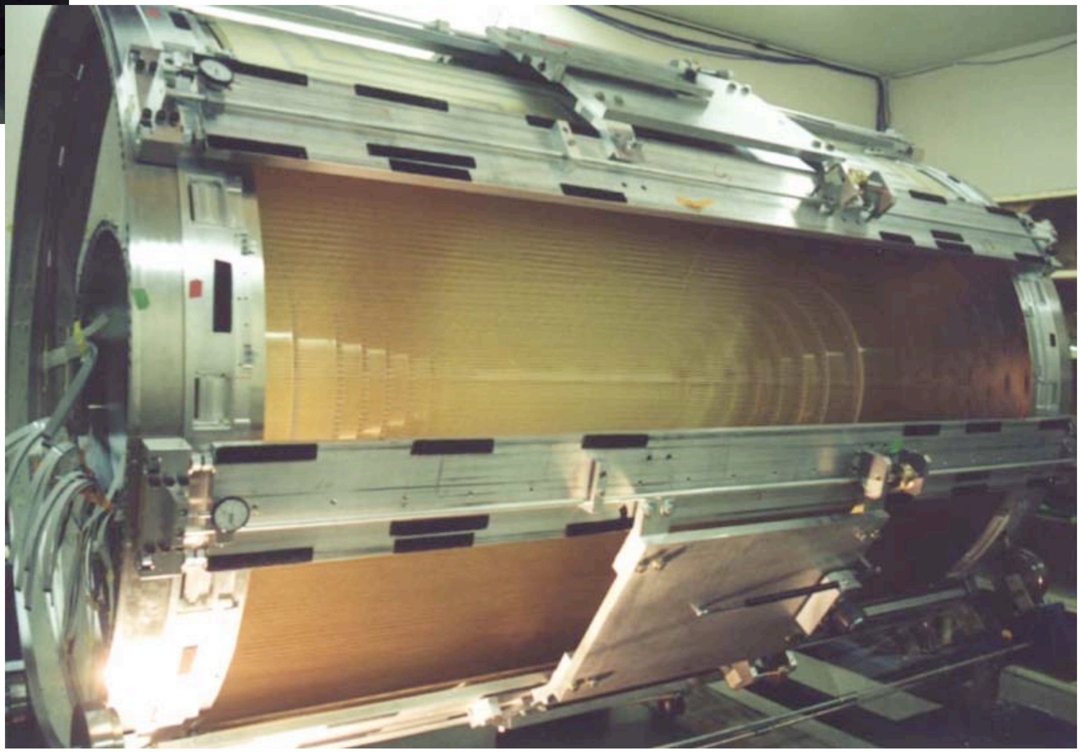




Tracking Chambers

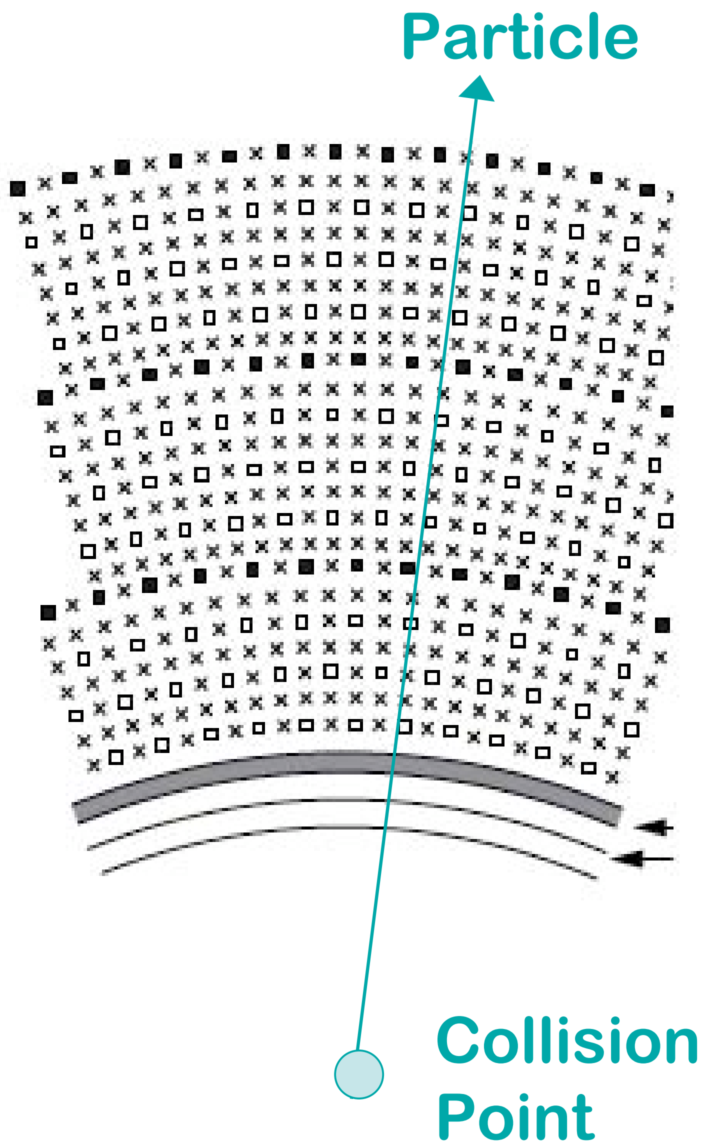


ZD
6 layers



DR
48 layers
10,000 sense wires!

Tracking Chamber Operation



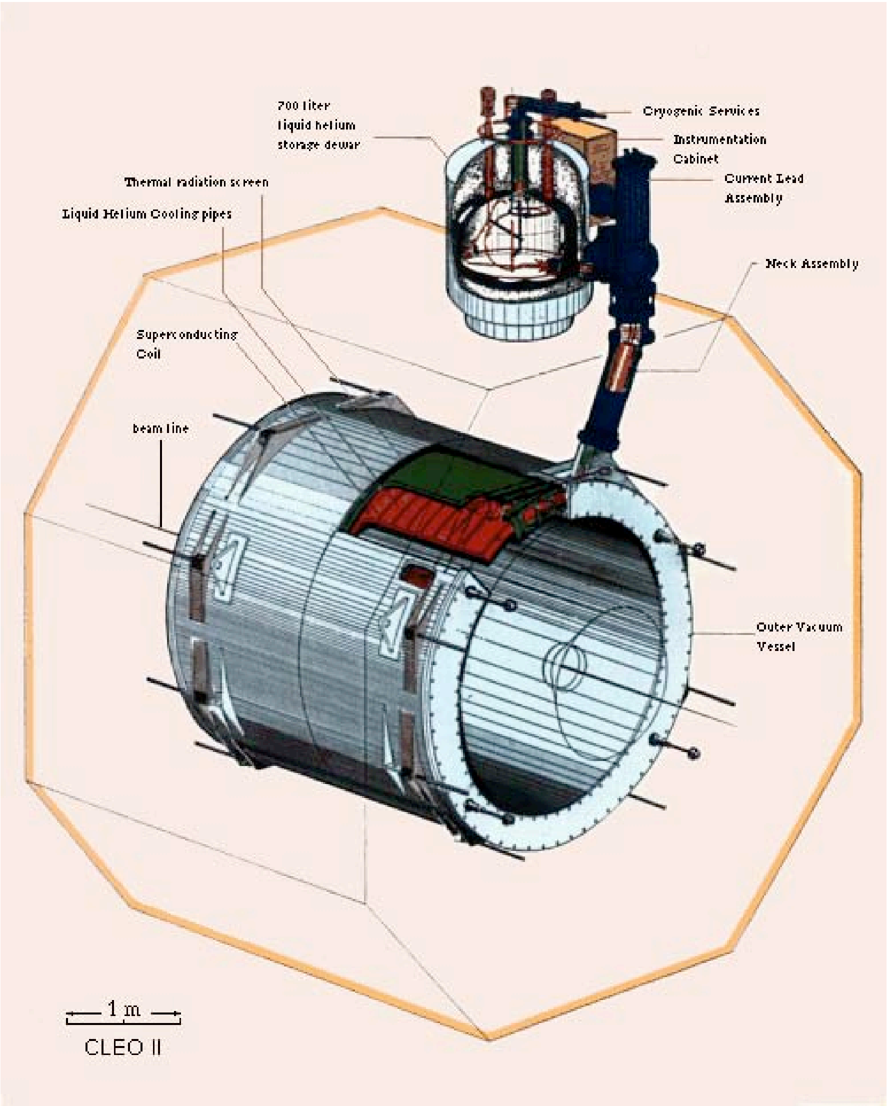
End View of Chamber

X - wire at 0V (field wire)
o - wire at 2000V (sense wire)

1. Particle ionizes the gas that fills the chamber.
2. Each released electron travels to nearest sense wire.
3. We measure arrival time of the electrons -- precision of 1/10 mm

Trick of the trade: Particles bend (why?), and their curvature gives momentum

The Magnetic Field

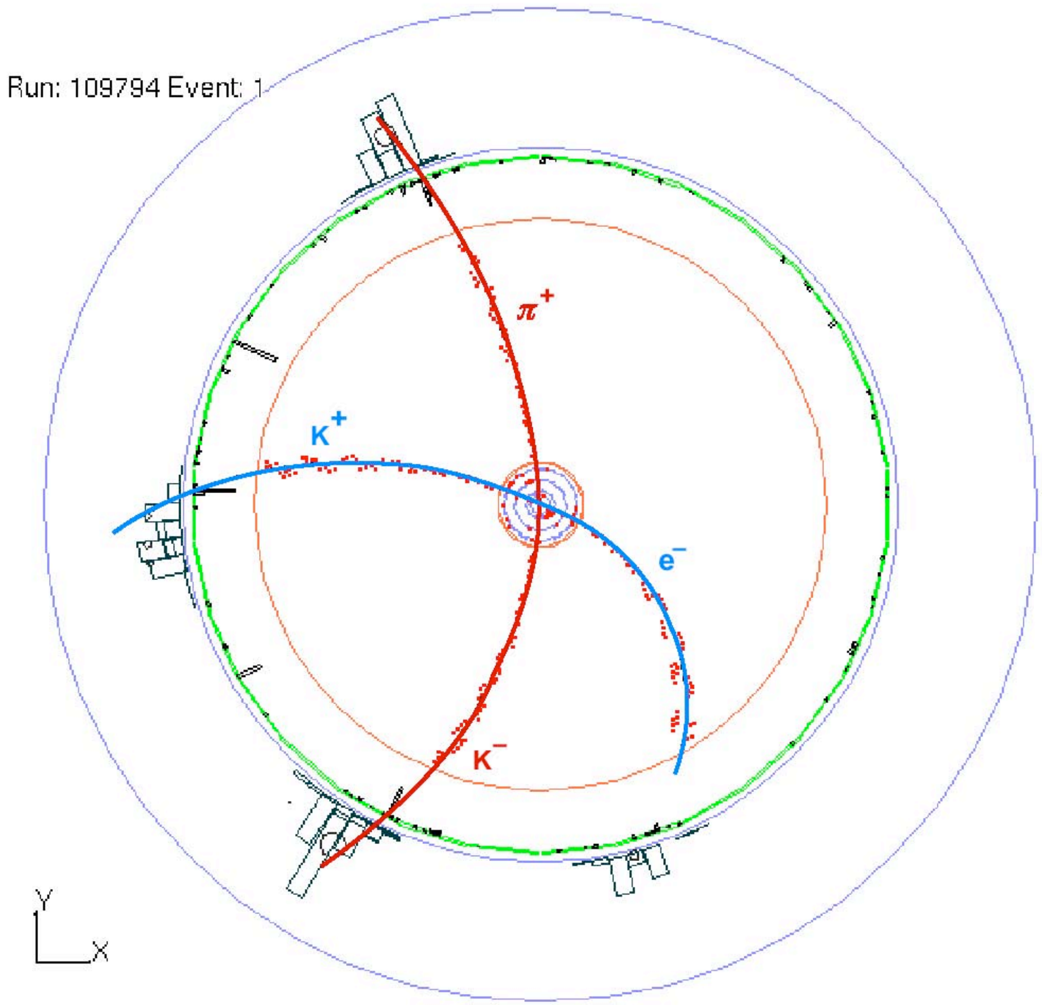


Superconducting coil surrounds the tracking chambers and produces a 1 Tesla magnetic field.

As a result, charged particles follow curved paths.

- **The direction of curvature reveals the sign of their electric charge.**
- **The amount of curvature varies inversely with momentum.**

Our “Event”



$D^0 \rightarrow K^- \pi^+$ $\quad$ $D^0 \rightarrow K^+ e^- \nu$

Notice

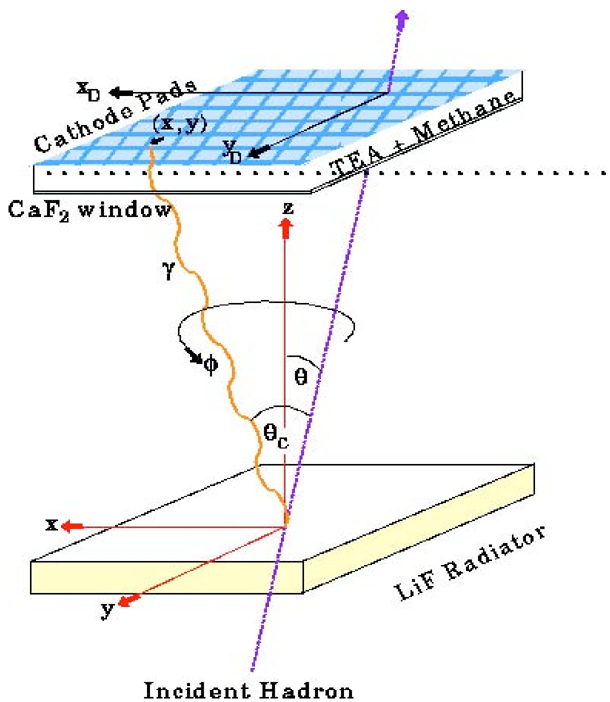
- the paths of the charged particles in the chambers
- their curvature

Which particle has the highest momentum? The lowest?

Distinguishing pions from kaons

Ring Imaging Cerenkov Counter (RICH)

The opening angle of the Cerenkov radiation gives the particle speed. Then momentum/speed reveals the mass.

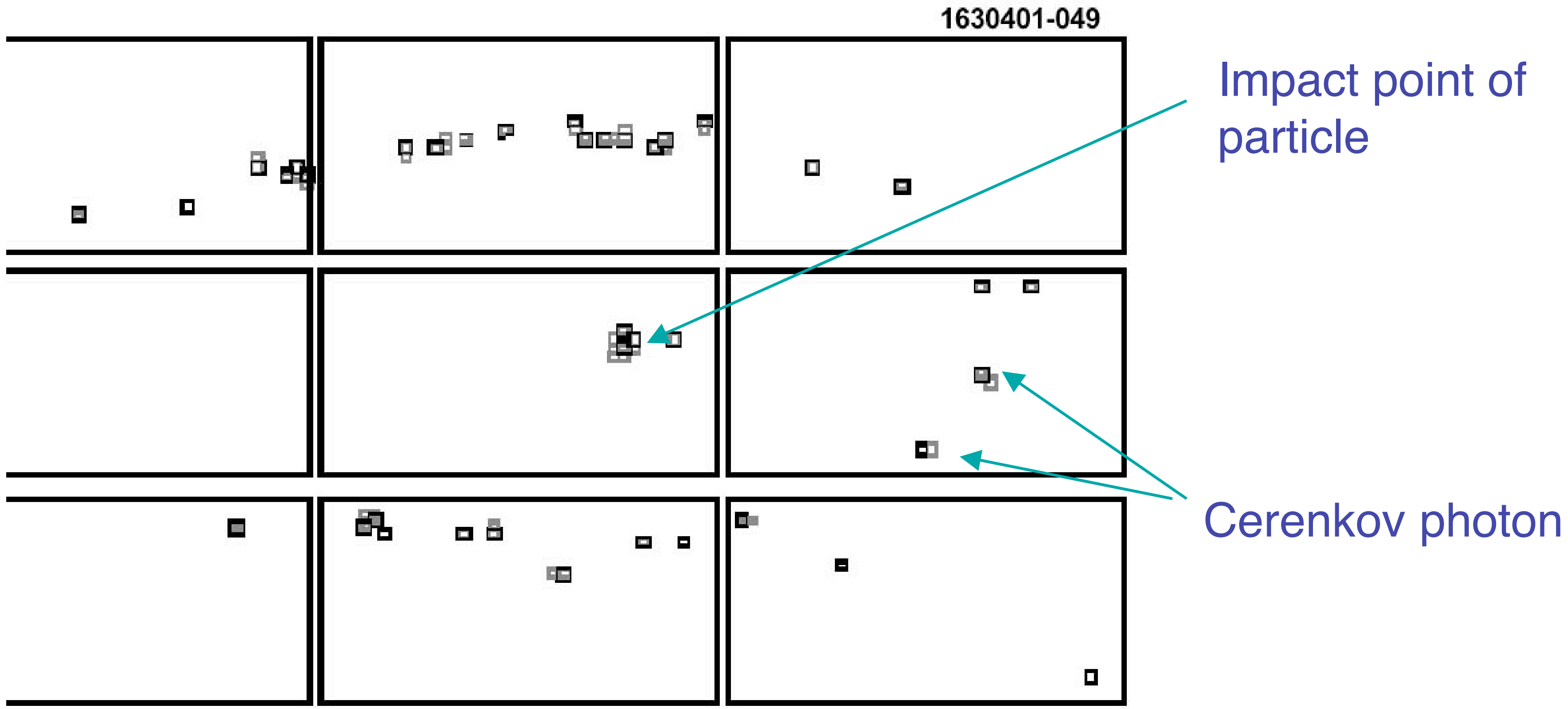


Cerenkov Radiation - Blue light produced when a fast particle goes through material, analagous to a sonic boom. The direction of the light depends on particle speed.

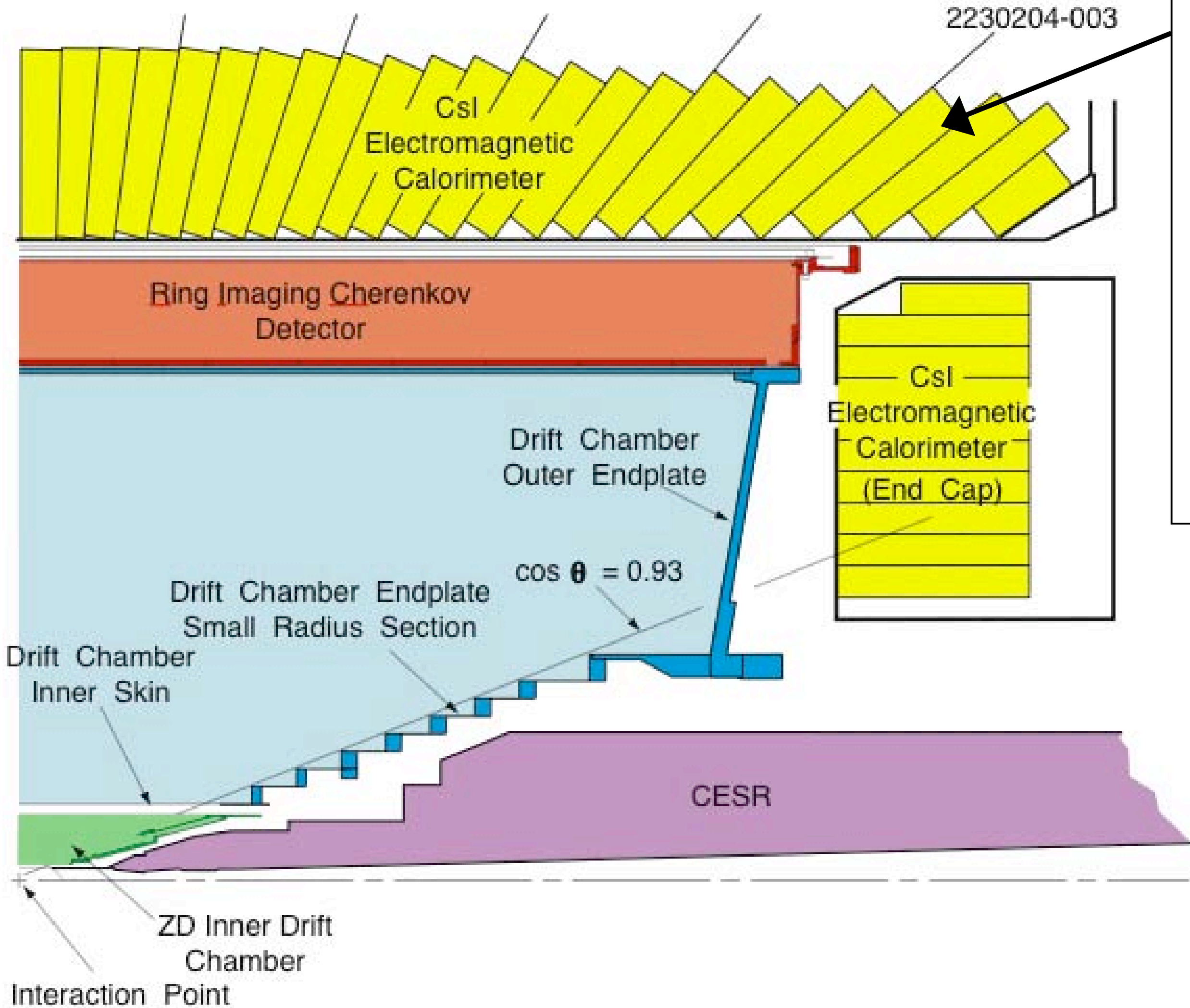
$v_{light} = c/n$

$\theta_c = \arccos(v_{light}/v_{particle})$

A particle in the RICH



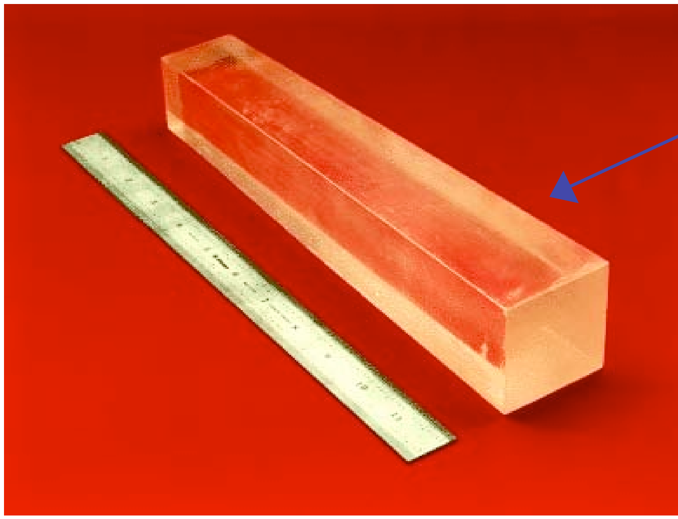
Next: Electromagnetic Calorimeter



Electromagnetic Calorimeter

Measures the energy of light particles, ie photons and electrons

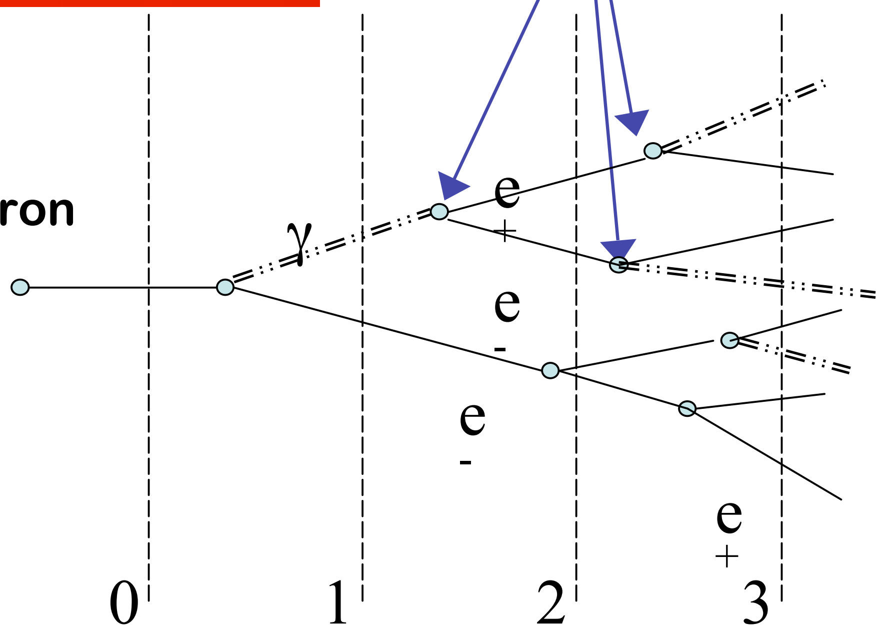
Electromagnetic Calorimeter



CsI crystal
CLEO has 7800
like this one.

CsI nucleus

Incident electron
or photon

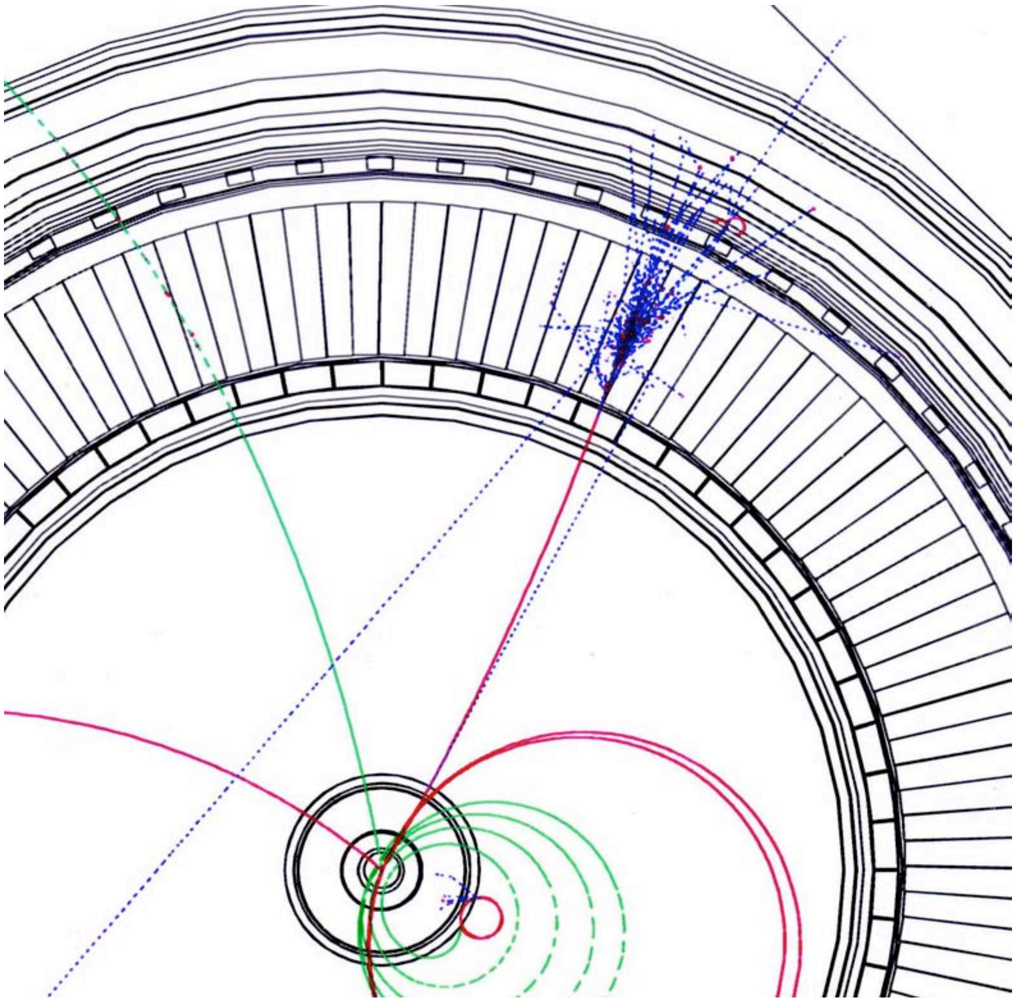


Light output is
proportional to
incident electron or
photon energy

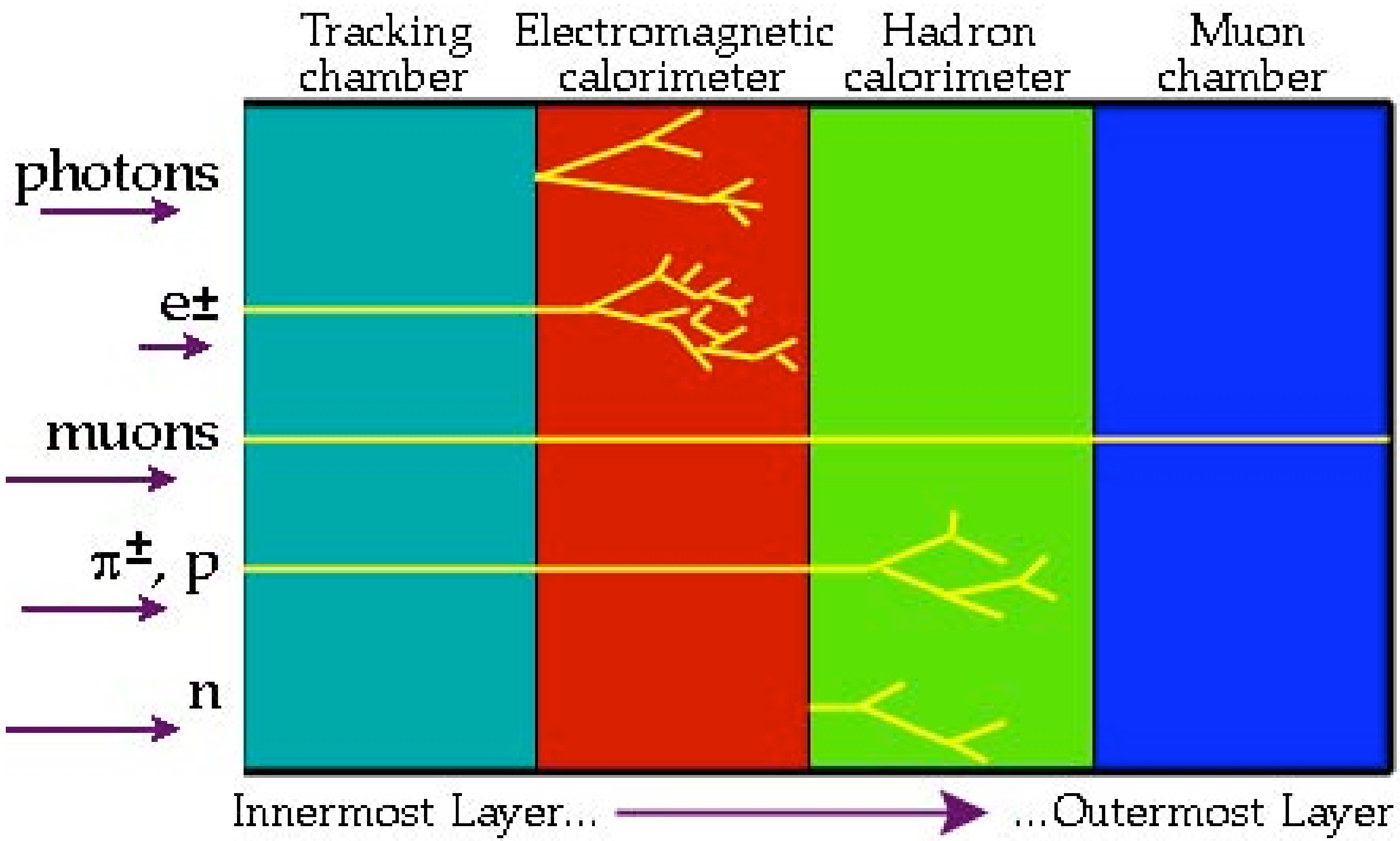
Electromagnetic Calorimeter

Simulation of an electron showering in the calorimeter

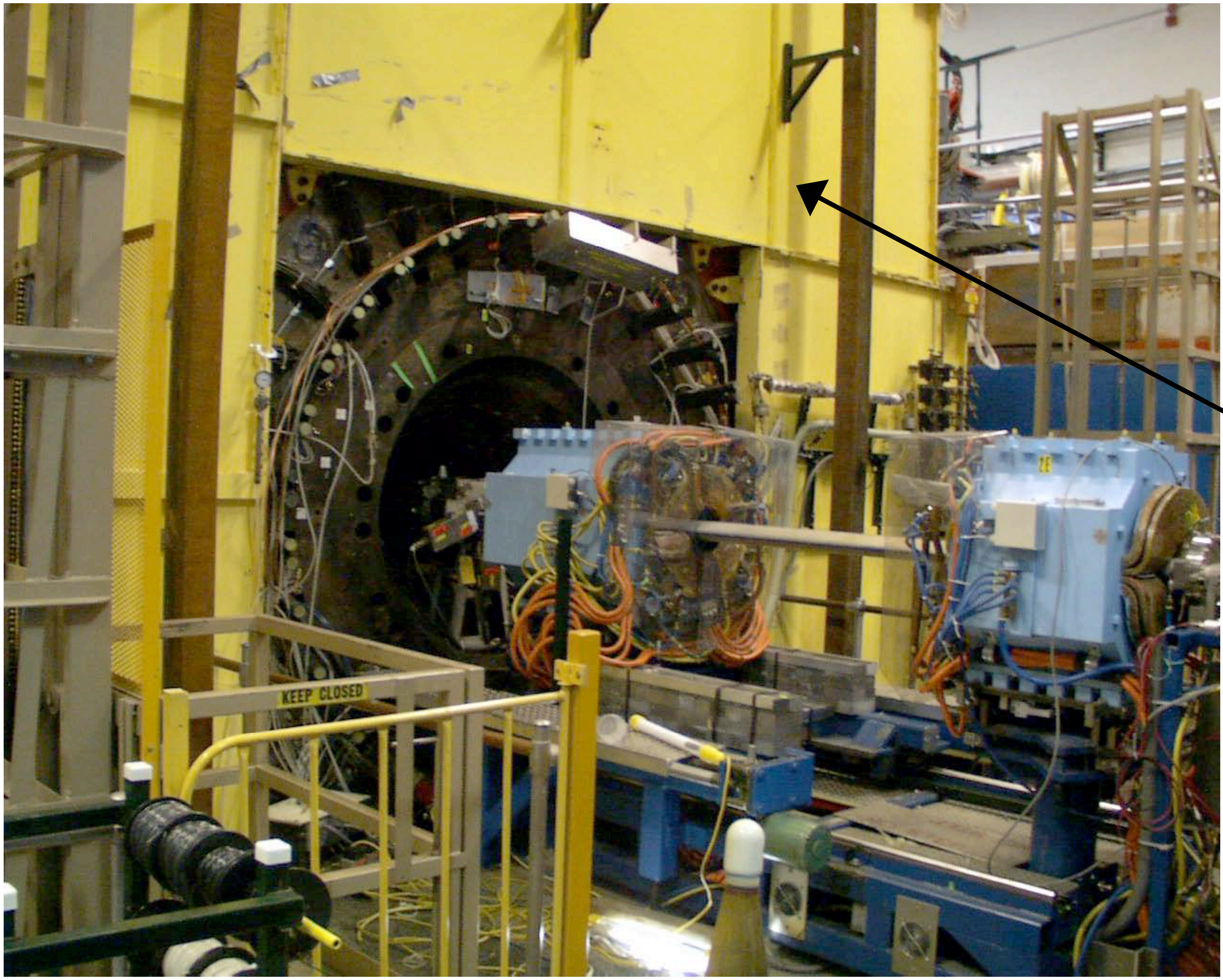
Pink - electron
Blue - photon



Particle Detectors



Muon Detection



Muon steel

Also serves as solenoid return yoke

What has CLEO measured so far?

- Direction of motion of charged particles -- Drift Chamber
- Momentum magnitude of charged particles -- Drift Chamber
- Speed of charged particles -- RICH (together with momentum gives mass)
- Energy of photons -- Electromagnetic calorimeter
- Muon ID -- Muon counters

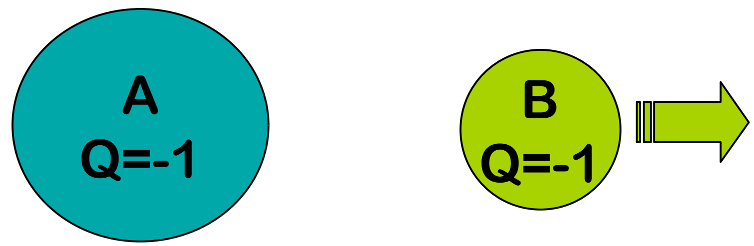
All detectors for particle physics look more or less like this one.

A thought question: in general, the higher the energy of the accelerator, the bigger the detector. Why is this?

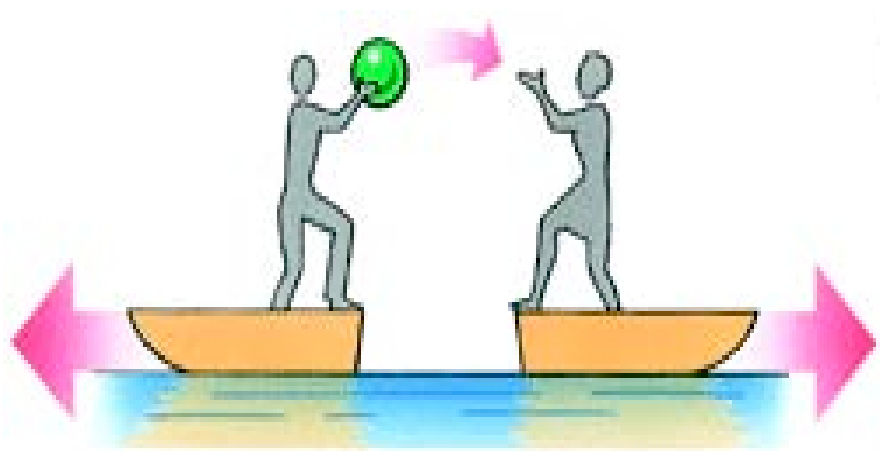
The Upshot

- You now know the tricks of the trade that have led to most of our knowledge about how the quarks and leptons interact with one another.
- So what have we learned?
  Where does particle physics go from here?

The Forces



Classical view: "B accelerates because it feels A's electric field"
Quantum view: "B accelerates because it absorbs a photon produced by A"



Photon (γ) - the carrier of the electro-magnetic force.

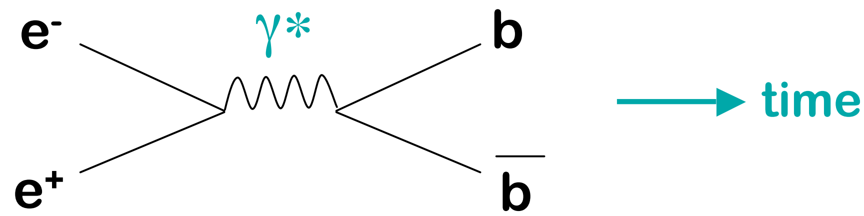
Gluon (g) - the carrier of the strong force. Binds quarks *e.g.* in protons and neutrons.

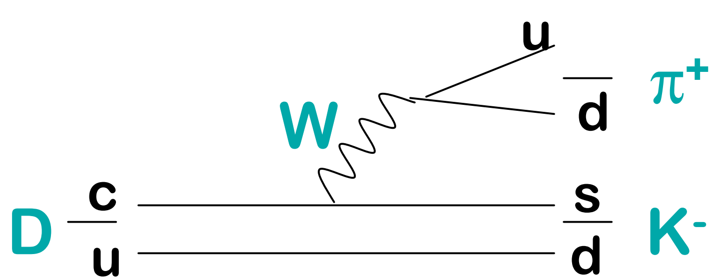
***W* and *Z* - the weak force carriers.**

Graviton - not observed, but postulated to exist for gravity.

Feynman Diagrams

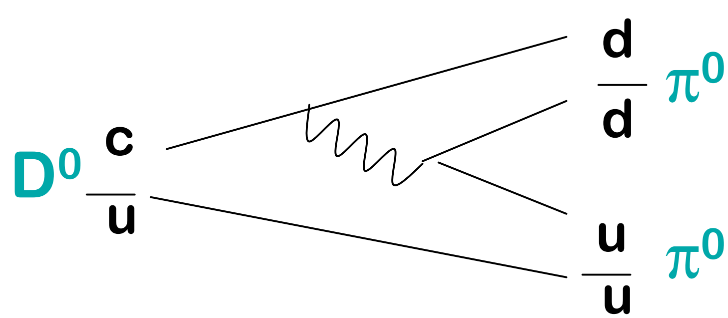
$e^+e^- \to b\bar{b}$





$D \to K^-\pi^+$

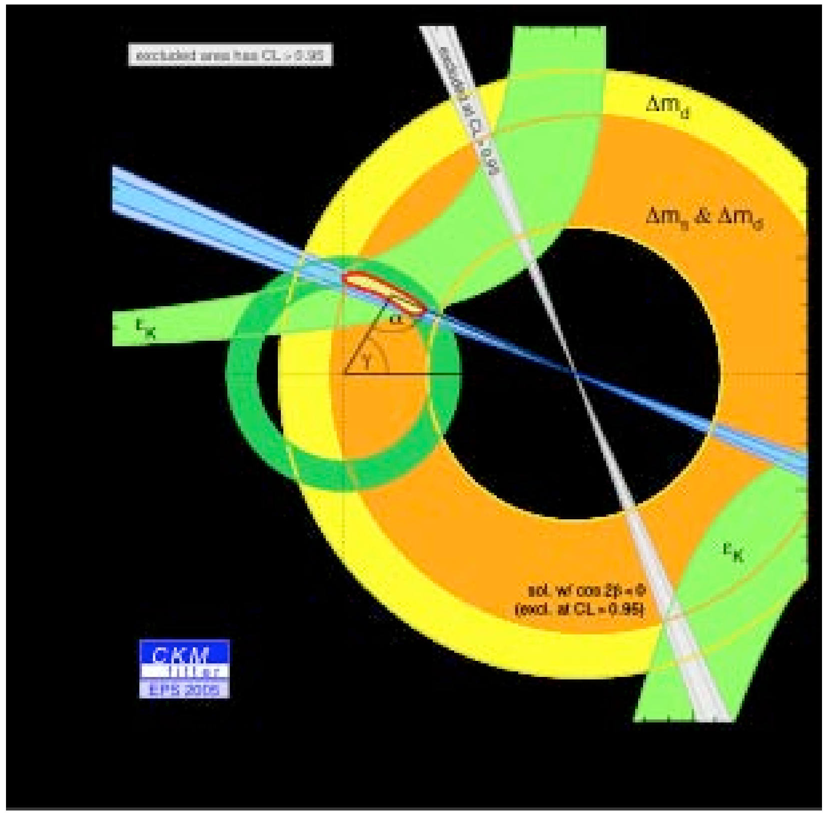
$D^0 \to \pi^0\pi^0$



At CLEO:

- Look for new physics by looking for decays that are forbidden in the Standard Model
- Understand the Standard Model better so that we can recognize deviations that signal new physics
  - Measure the fundamental parameters of the weak interaction
  - Understand strong interactions

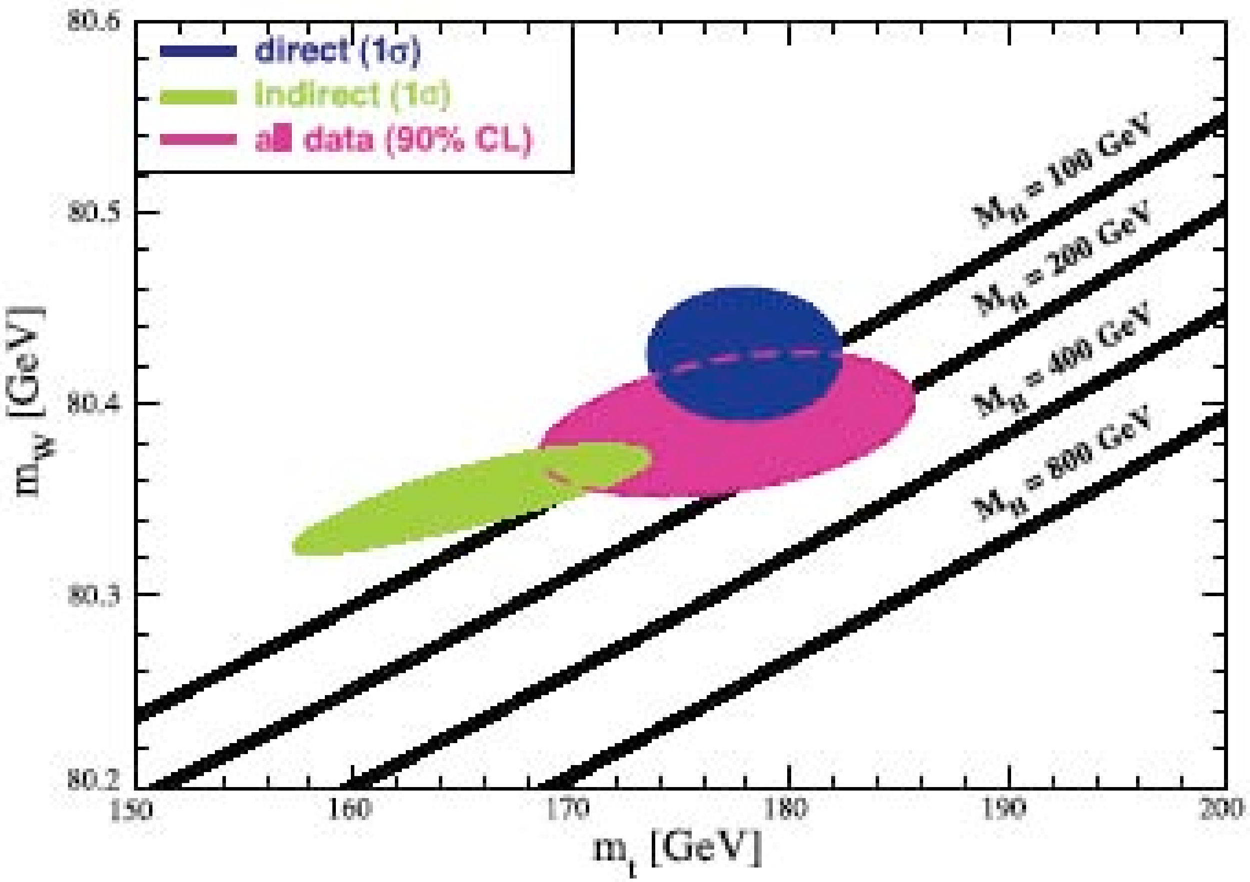
Quark interactions



- This plot checks that the Standard Model describes disparate, complex weak interaction processes. So far, it does.

The Standard Model

Quarks & Leptons	+	Strong, EM & Weak Forces	=	The Standard Model



It works!

The Standard Model is accurate at the parts per thousand level

But it’s Incomplete

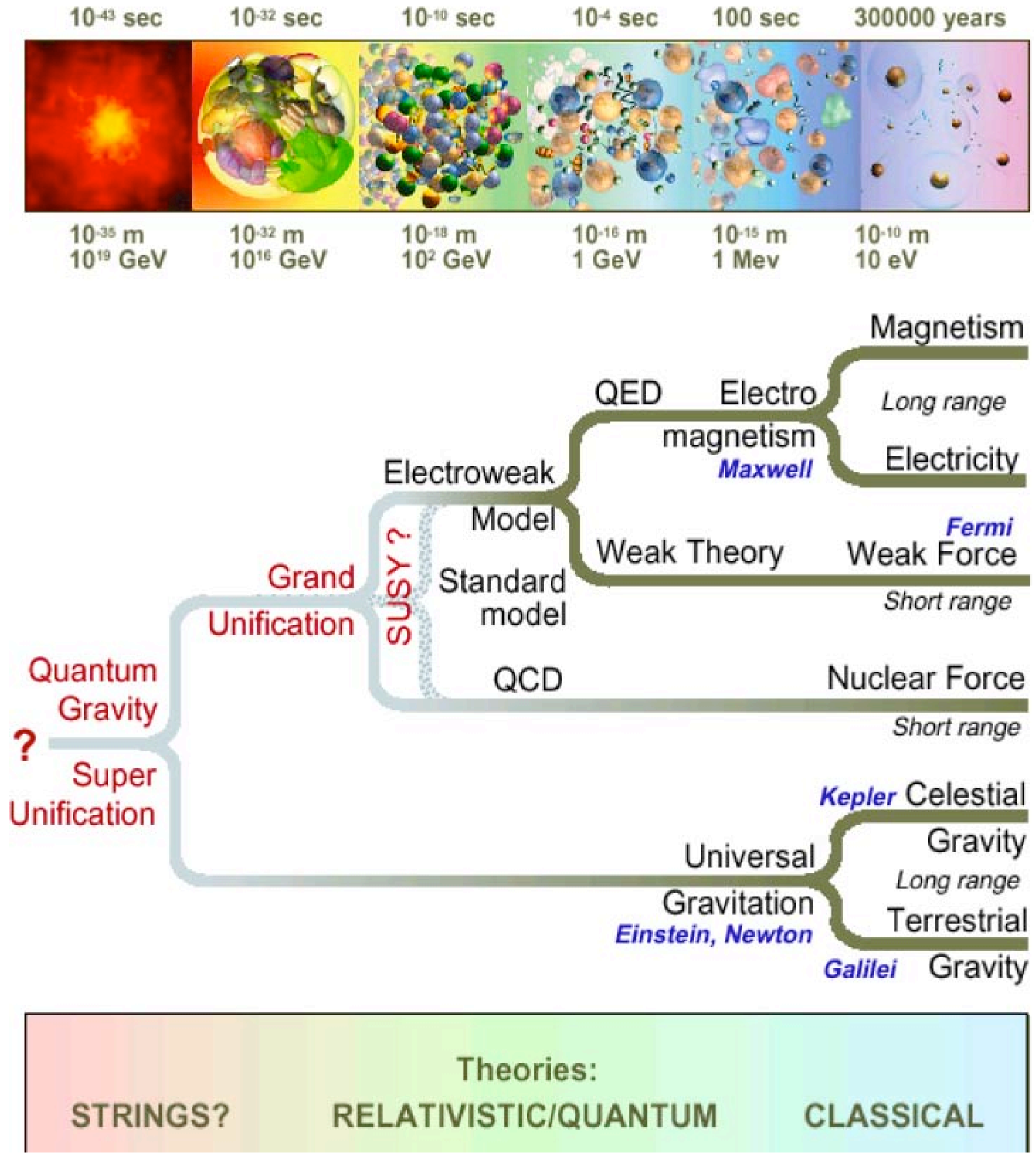
Unanswered questions:

- How did the antimatter disappear?
- What is the dark matter?
- How does gravity fit in?
- What’s the sludge (aka Higgs particle)?
  We need a sludge-filled Universe to give the W and Z their masses.

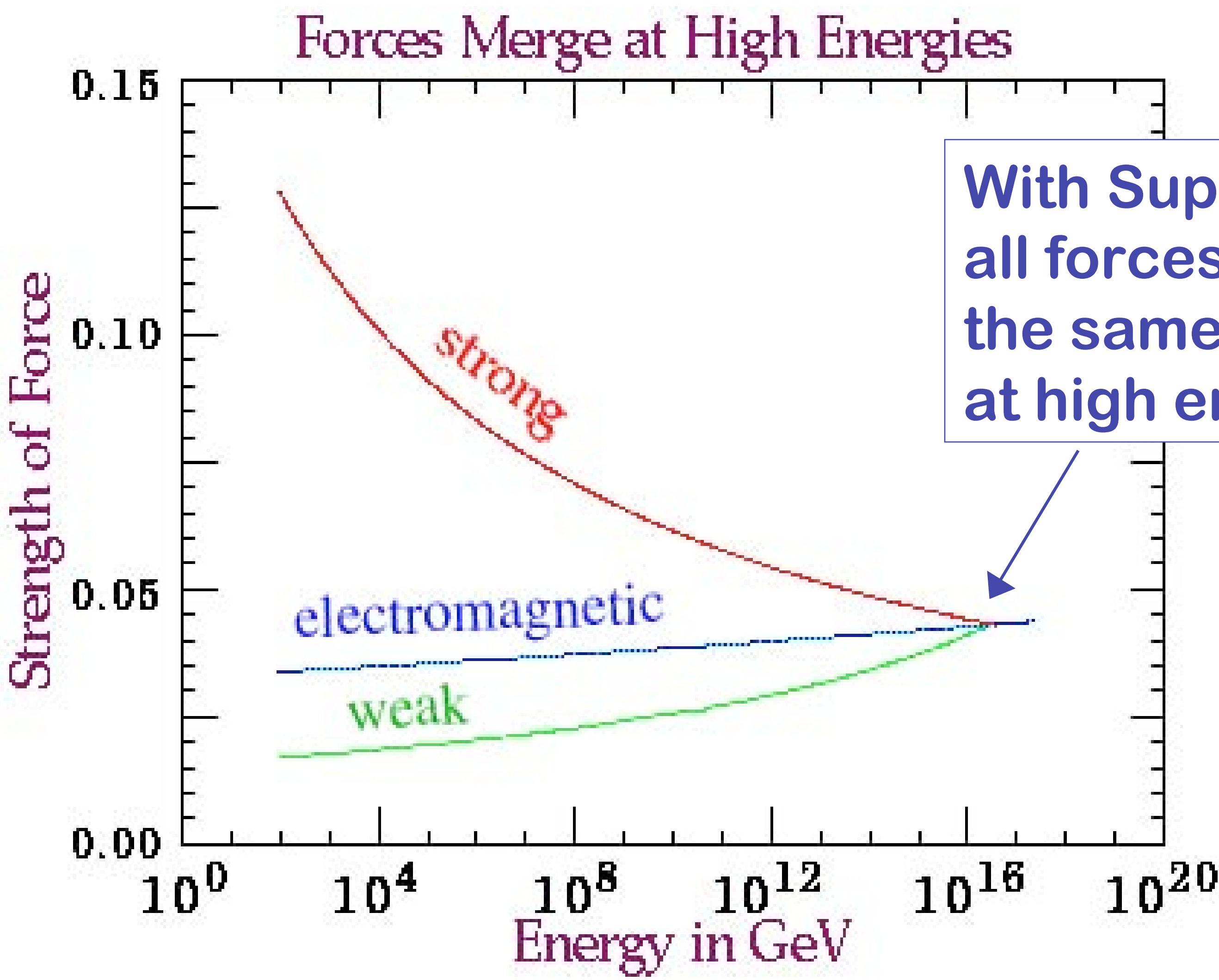
Unsatisfying situations:

- The forces don’t “unify”
- If you calculate the Higgs mass, you get the wrong answer

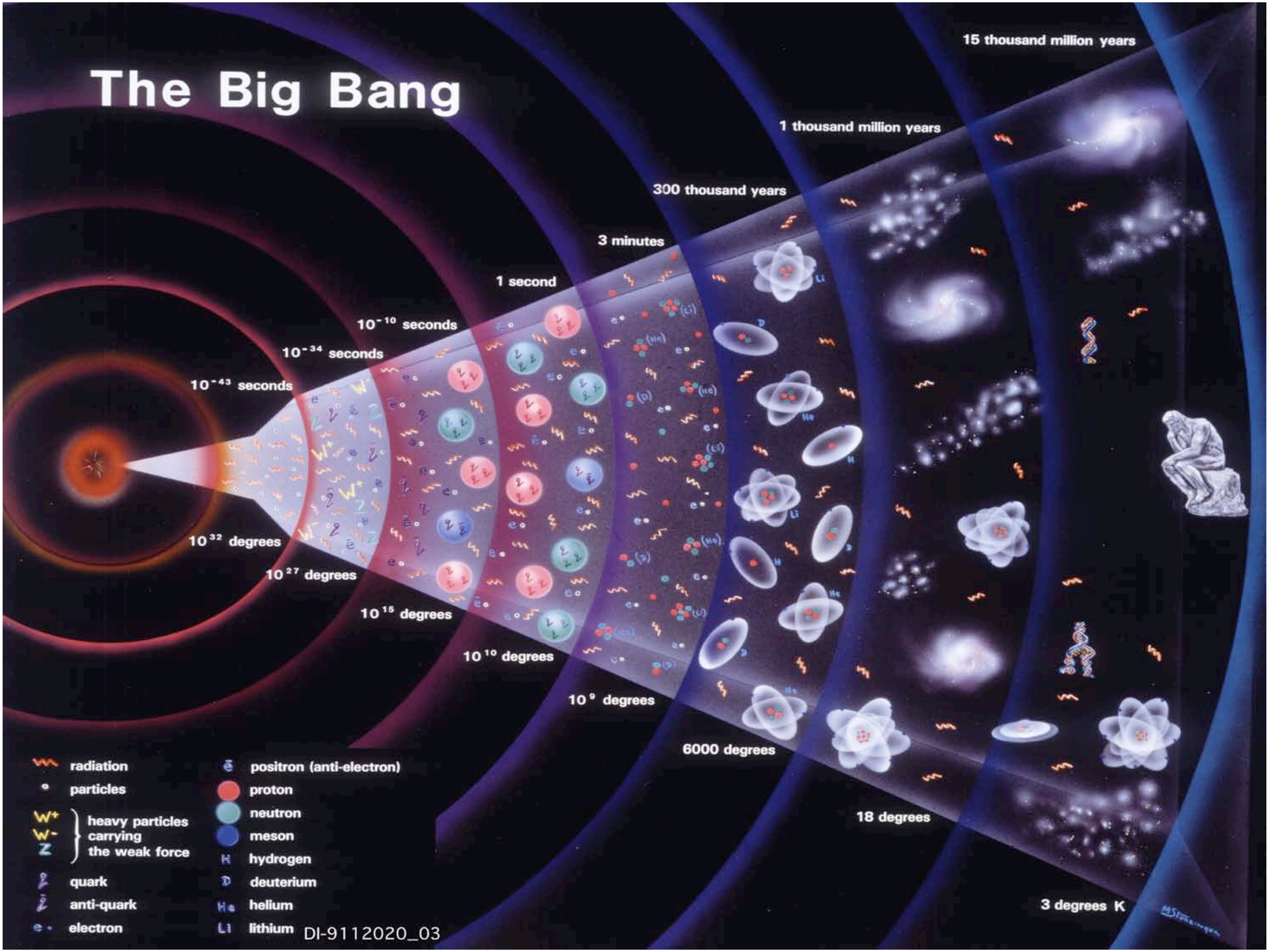
Unification



Supersymmetry?

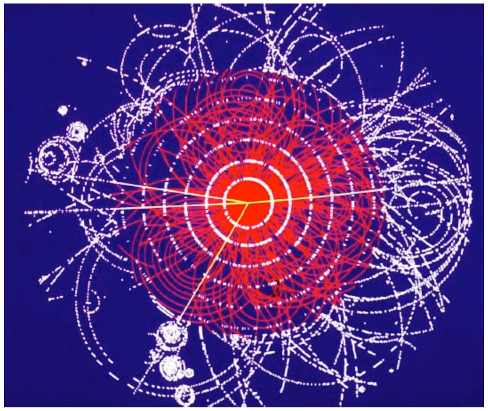


With Supersymmetry,
all forces have
the same strength
at high energies

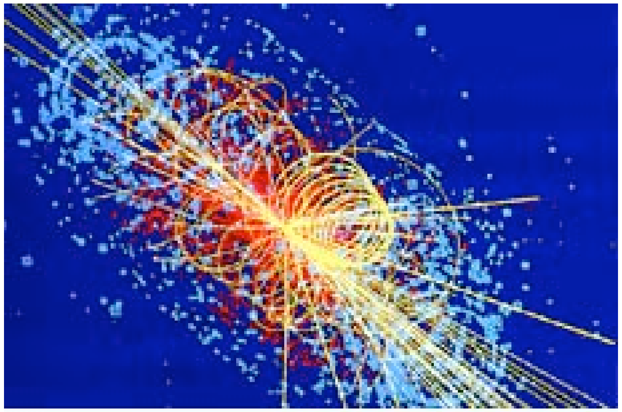

The Big Bang
15 thousand million years
1 thousand million years
300 thousand years
3 minutes
1 second
10^{-10} seconds
10^{-34} seconds
10^{-43} seconds
10^{32} degrees
10^{27} degrees
10^{15} degrees
10^{10} degrees
10^{9} degrees
6000 degrees
18 degrees
3 degrees K
radiation
particles
W+ W- Z heavy particles carrying the weak force
quark
anti-quark
electron
positron (anti-electron)
proton
neutron
meson
hydrogen
deuterium
helium
lithium
DI-9112020_03

The Future

- Large Hadon Collider (LHC) will collide p and p starting in 2007. ATLAS and CMS experiments at the LHC may see Higgs-like particles and new, weird phenomena.

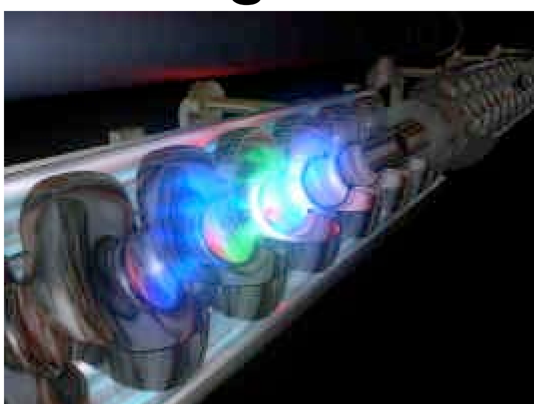


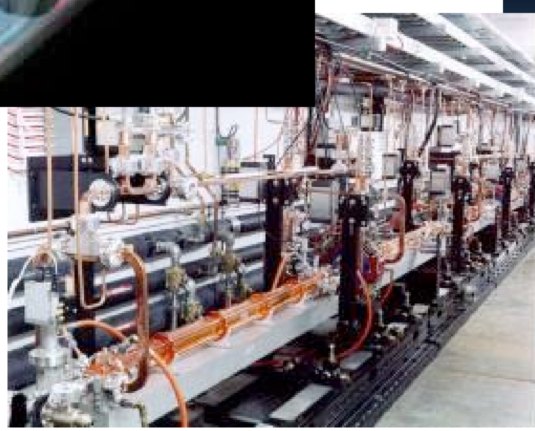


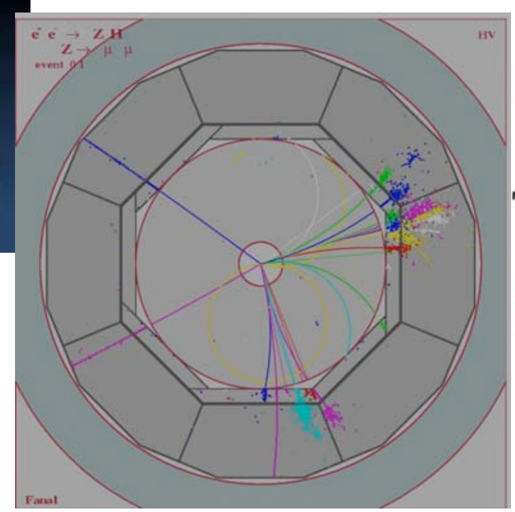



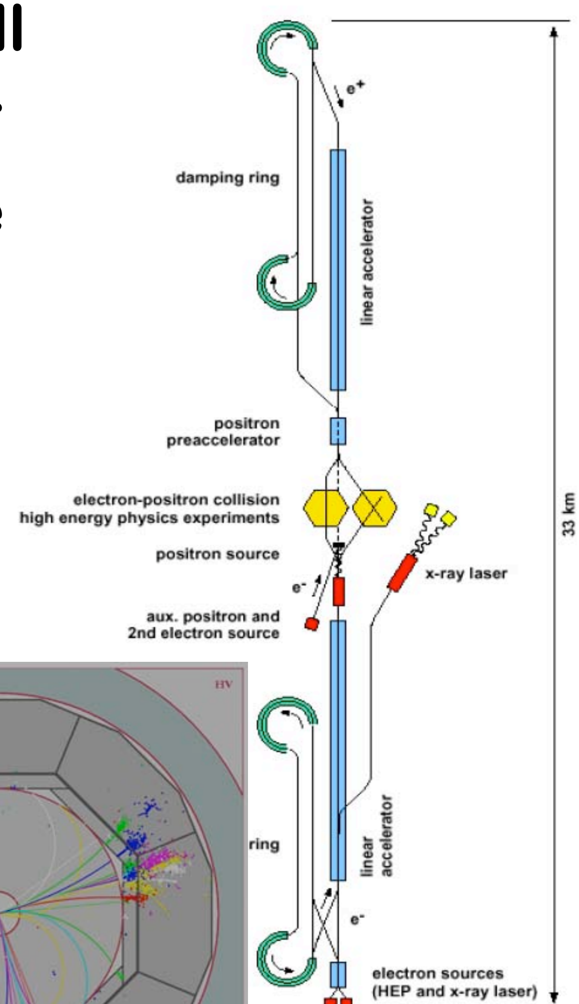
The Future

- International Linear Collider (ILC) will collide e and anti-e starting in ~2015. Will explore the phenomena seen at the LHC. Does the Higgs travel alone or with partners? Is one of the discovered particles dark matter? A sign of extra dimensions of space?









Conclusion

At LEPP

- We are addressing some of the great mysteries of the particle world and the Universe.
- Our particle detectors and software push the envelope of precision and scope.
- Our accelerators press the frontier in the development of particle sources, accelerating structures and the control of dense beams.

Welcome to this enterprise.