History, Hadron Accelerators, Detectors, & Cross Sections

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History: A Steady Progression to Simplicity and Unification

- **Antiquity:**
  - Democritus names the "atom"
  - Earth, Air, Fire Water
  - Descriptive – Not Predictive

- **Eighteenth Century**
  - Antoine Lavoisier, 1798:
    - Matter consists of chemical elements
    - Conservation of Mass during chemical reactions
  - J.L. Proust, 1799:
    - Law of Definite Proportions, compounds always contain the same elements in the same proportions

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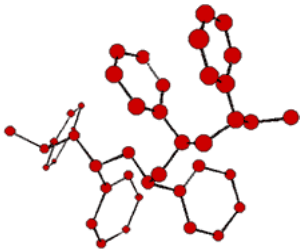
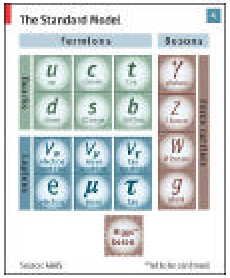


- **Nineteenth Century**
  - **John Dalton, 1803:**
    - **Elements formed from small indivisible particles called <u>atoms</u>**
    - **Identical for a given element but different for any other element.**
    - **Chemical compounds formed by the combining definite number and types of atoms to make various molecular compounds**
  - **Mendeleyev, 1869:**
    - **Devises the Periodic Table.**
    - **Impressive!**
    - **Suggests deeper structure**

H																	He
Li	Be											B	C	N	O	F	Ne
Na	Mg											Al	Si	P	S	Cl	Ar
K	Ca	Sc	Ti	V	Cr	Mn	Fe	Co	Ni	Cu	Zn	Ga	Ge	As	Se	Br	Kr
Rb	Sr	Y	Zr	Nb	Mo	Tc	Ru	Rh	Pd	Ag	Cd	In	Sn	Sb	Te	I	Xe
Cs	Ba		Hf	Ta	W	Re	Os	Ir	Pt	Au	Hg	Tl	Pb	Bi	Po	At	Rn
Fr	Ra		Rf	Db	Sg	Bh	Hs	Mt									
			La	Ce	Pr	Nd	Pm	Sm	Eu	Gd	Tb	Dy	Ho	Er	Tm	Yb	Lu
			Ac	Th	Pa	U	Np	Pu	Am	Cm	Bk	Cf	Es	Fm	Md	No	Lr



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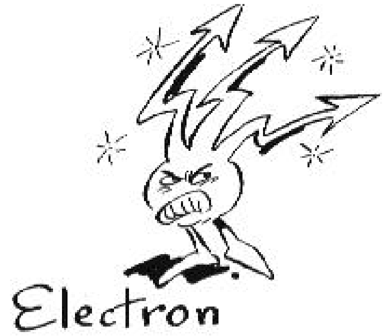
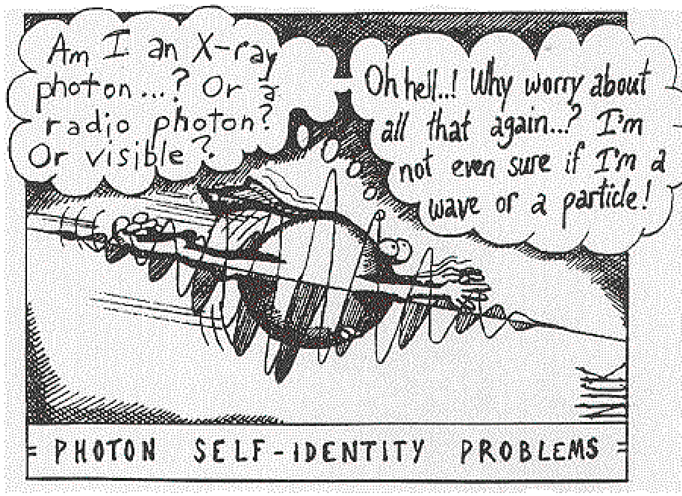
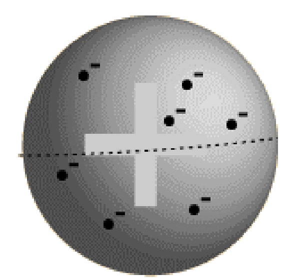
- **Twentieth Century**
  - **J.J.Thomson, 1903**
    - **Discovers the electron**
  - **Rutherford, 1899-1903**
    - **Discovers** a, b, g **as elements of radioactive decay.**
  - **Stark, 1909**
    - **Identifies the photon as a genuine elementary particle**
    - **Posses both momentum and energy**
  - **Thompson, early 1900s**
    - **One of the first models of the atom.**
    - **“Raisin Pudding” - a positive blob with scattered negatively charged electrons**

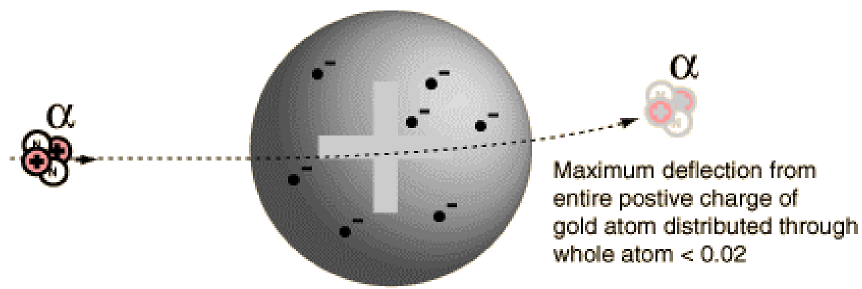






– Geiger, Marsden, Rutherford, 1909-1911

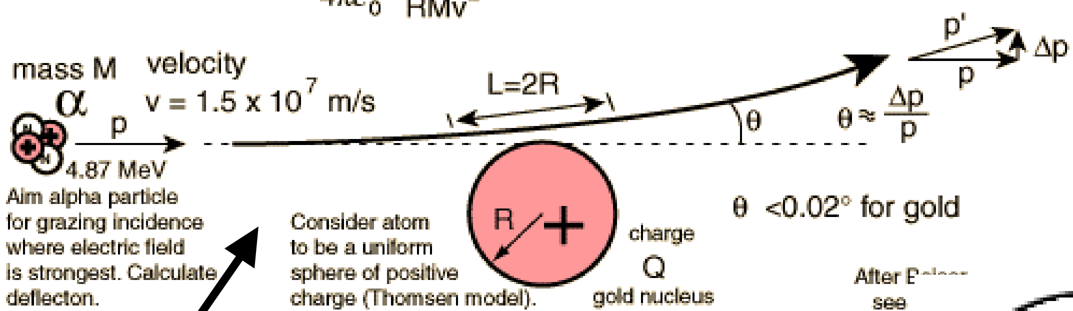
- **Tests model with scattering experiment**



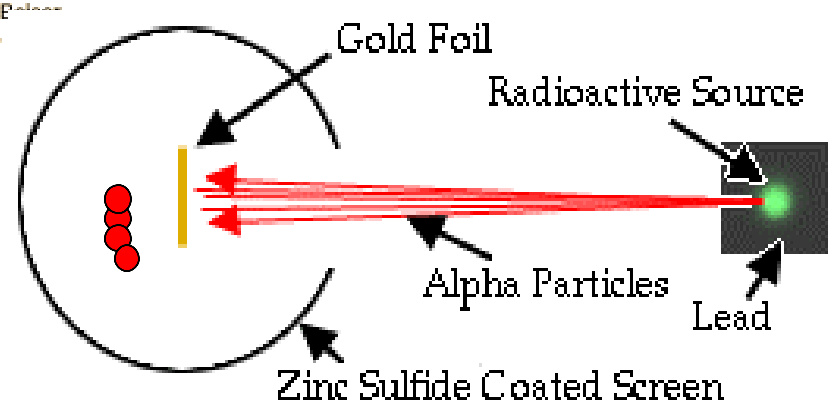
Major Technique of Particle Physics

- **Conservation of E and p predicts a heavy projectile should pass though on relatively straight trajectories**

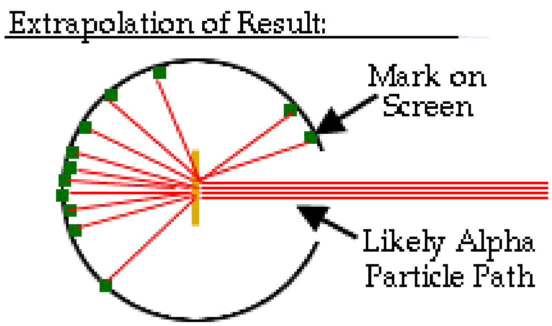
$$\theta_{\text{Thomsen atom}} < \frac{1}{4\pi\varepsilon_0}\frac{4eQ}{RMv^2} < 0.02° \text{ for gold}$$

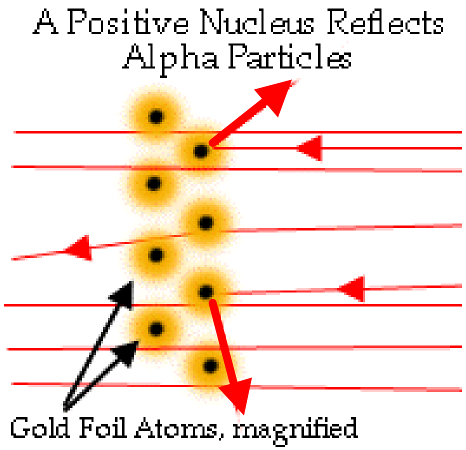


Naturally Leads to the concept of Cross Section



- **To everyone's surprise 1 in 8000 alpha particles scattered more than 90 degrees**



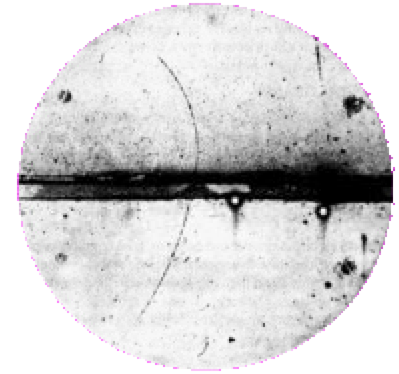


- **Very different than the prediction of raisin pudding and evidence for massive, positive nucleus.**

This experiment nicely illustrates the work of particle physics. Scattering experiments serve as our eyes and ears in the sub-atomic world…

- **Back to the Twentieth Century**
  - **Bohr, 1913**
    - **Model of the atom inspired by Rutherford's work.**
  - **Lawrence, 1920-1930s**
    - **Develops the cyclotron**
  - **Chadwick, 1932**
    - **Discovers the neutron.**

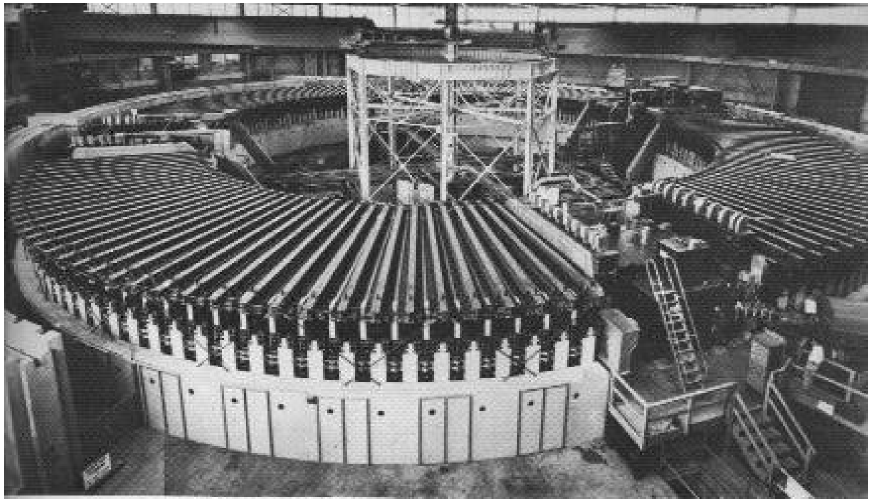
Electrons, proton, neutrons elementary particles of the day



- **Anderson, 1932**
  - Discovers the positron
  - Beginning of a “zoo” of particles
- **Yukawa, 1935**
  - Proposes the pion or a “meson”
  - Mediates the strong force that holds the nucleus together with a mass of ~100 MeV
  - During the 30’s framework for the forces begins to take shape, gravity, electromagnetic, weak interaction for decays and strong…
- **Discovery of the muon, 1937**
  - Correct mass for the meson
  - But interacts weakly – great confusion!
- **Lattes et al., 1947**
  - Discovery of the pion!
  - Confirmation of Yukawa prediction

Bonanza: The Accelerator Era

- Lawrence, 1949
  - Construction of the 6 billon electron volt Bevatron
- Antiproton Discovered, 1955



- The Zoo Grows, 1950-1960s
  - Enormous number of particles discovered with new machines, over 300 species
  - The "dark ages" - the fundamental building blocks appear more numerous than the periodic table.
  - Hadrons
    - Baryons (neutrons, protons, ...) fermions with ½, 3/2 ... spin
    - Mesons (pions, kaons, ...) bosons with integer spin

- **Gellman and Zweig, 1964**
  - **Propose hadrons are not elementary**
  - **Rather composed of quarks.**

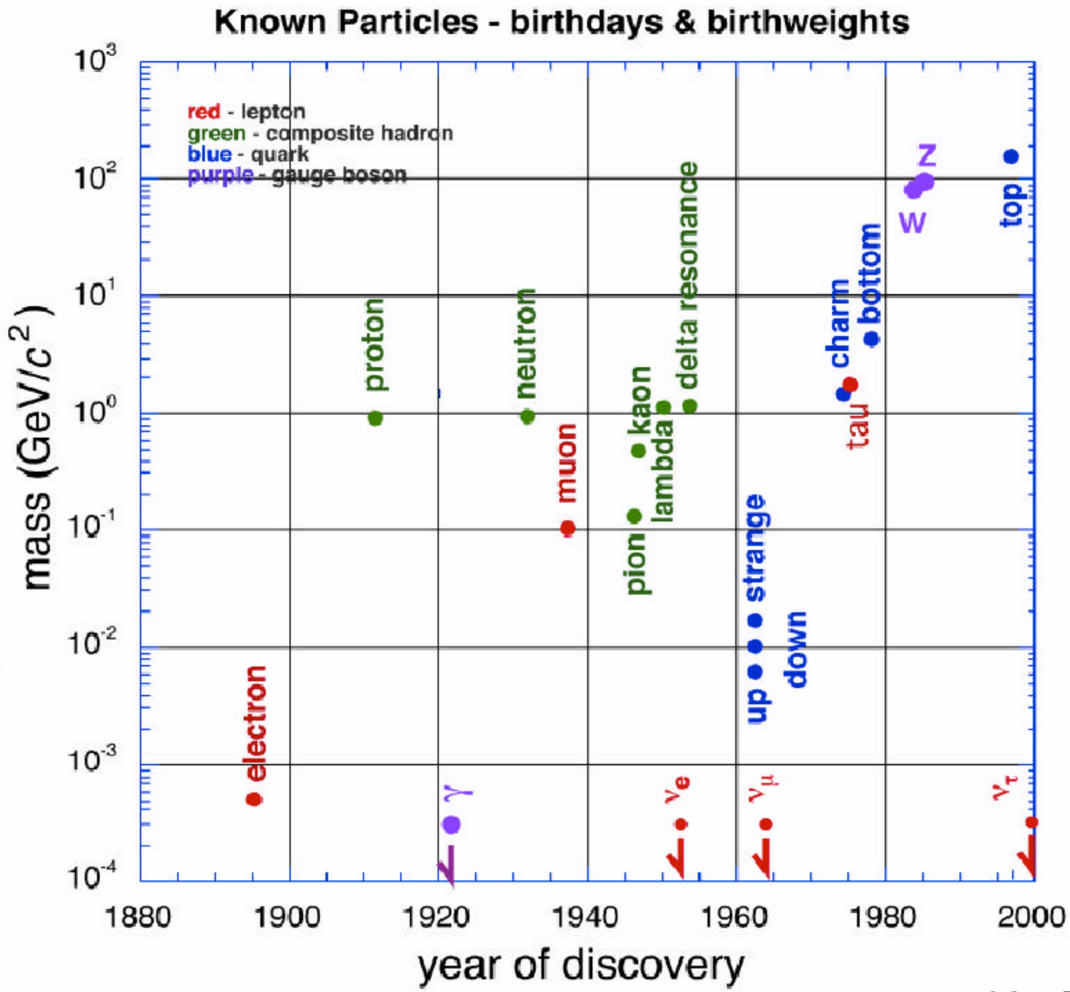
Quark Model cleaned up the mess of 100's of hadrons:

- hadrons are composite with a spectroscopy built on quantized vibrational and rotational degrees of freedom:

$p = uud$; $n = udd$

$\Delta = uud$; $\Lambda = usd$

- fundamental entities are the (point-sized) quarks and (point-sized) leptons

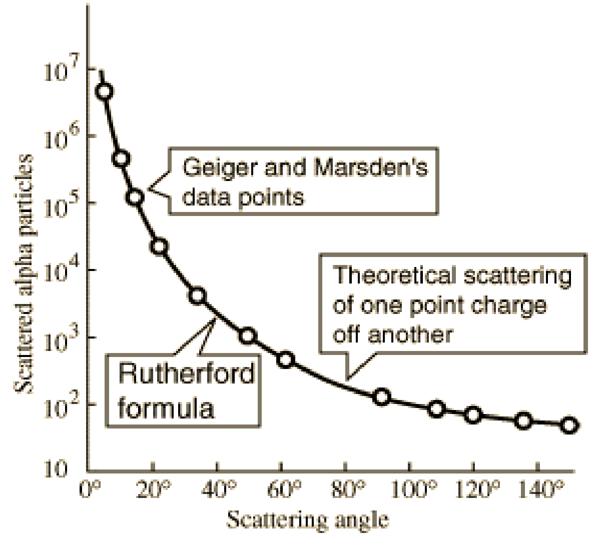


In retrospect, you could have guessed! More on Rutherford Scattering

- **Scattering of alpha particles from nuclei can be modelled**
  - **from the Coulomb force, $1/r^2$**
  - **treated as an orbit (path follows conic section).**
- **Scattering process can be treated statistically in terms of the cross-section or effective area for interaction with a nucleus which is considered to be a point charge Ze.**
- **For a detector at a specific angle with respect to the incident beam, the number of particles per unit area striking the detector is given by the Rutherford formula**

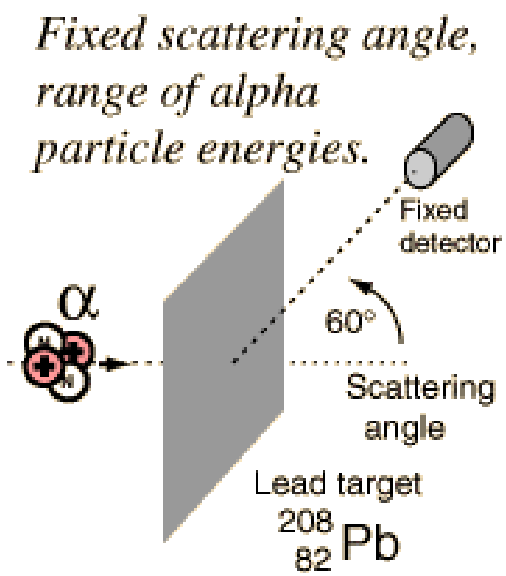
$$N(\theta) = \frac{N_i n L Z^2 k^2 e^4}{4r^2 KE^2 \sin^4(\theta/2)}$$

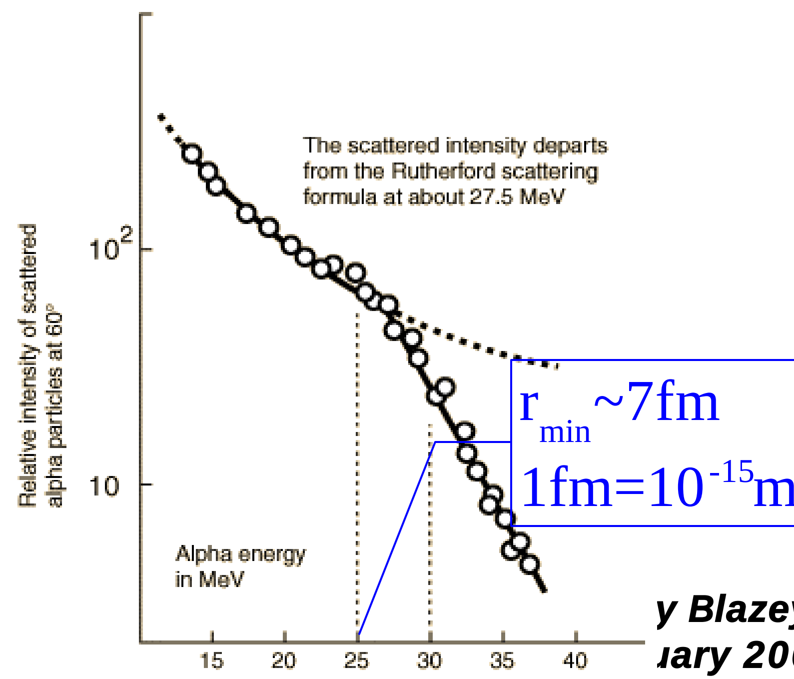
N_i = *number of incident alpha particles*
n = *atoms per unit volume in target*
L = *thickness of target*
Z = *atomic number of target*
e = *electron charge*
k = *Coulomb's constant*
r = *target-to-detector distance*
KE = *kinetic energy of alpha*
θ = *scattering angle*



Rutherford Deviations → Something New?

- **With higher alpha energies the projectile punches close to the nuclear center and comes into the range of the nuclear strong force**
- **The distribution of scattered alphas departs from the Rutherford formula.**
- **Departure point from the Rutherford scattering gives estimate of the nuclear radius, onset of new physics....**
- **Much better measurements attained w/ electron scattering, but Rutherford was able to show that the nucleus was more than 10^4 times smaller than previously thought!**





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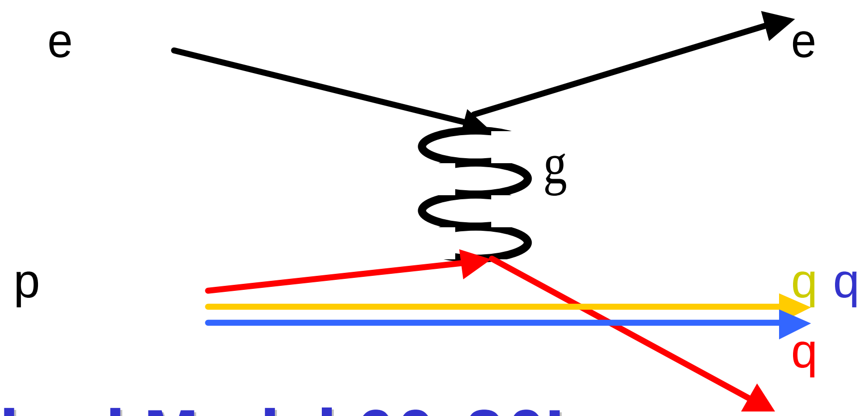
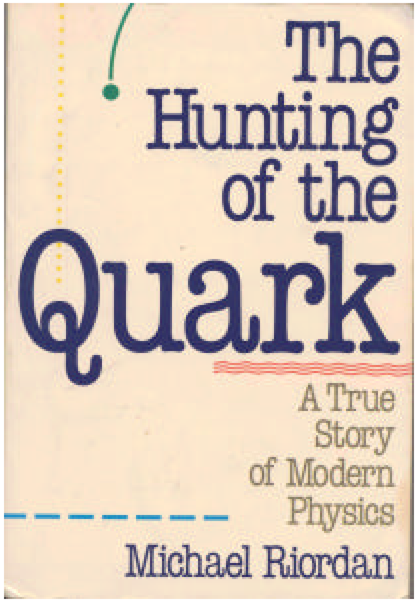
- **The quark, 1967**
  - **First evidence in electron proton scattering at Stanford Linear Accelerator**
  - **Completely analogous to Rutherford Scattering.**
  - **Proton and neutron show internal structure**





- **Standard Model 60-80's**

Matter consists of two types of elementary particles: **Leptons** and **Quarks**.	1970s-1980s Weinberg, Salam, Glashow, Rubbia

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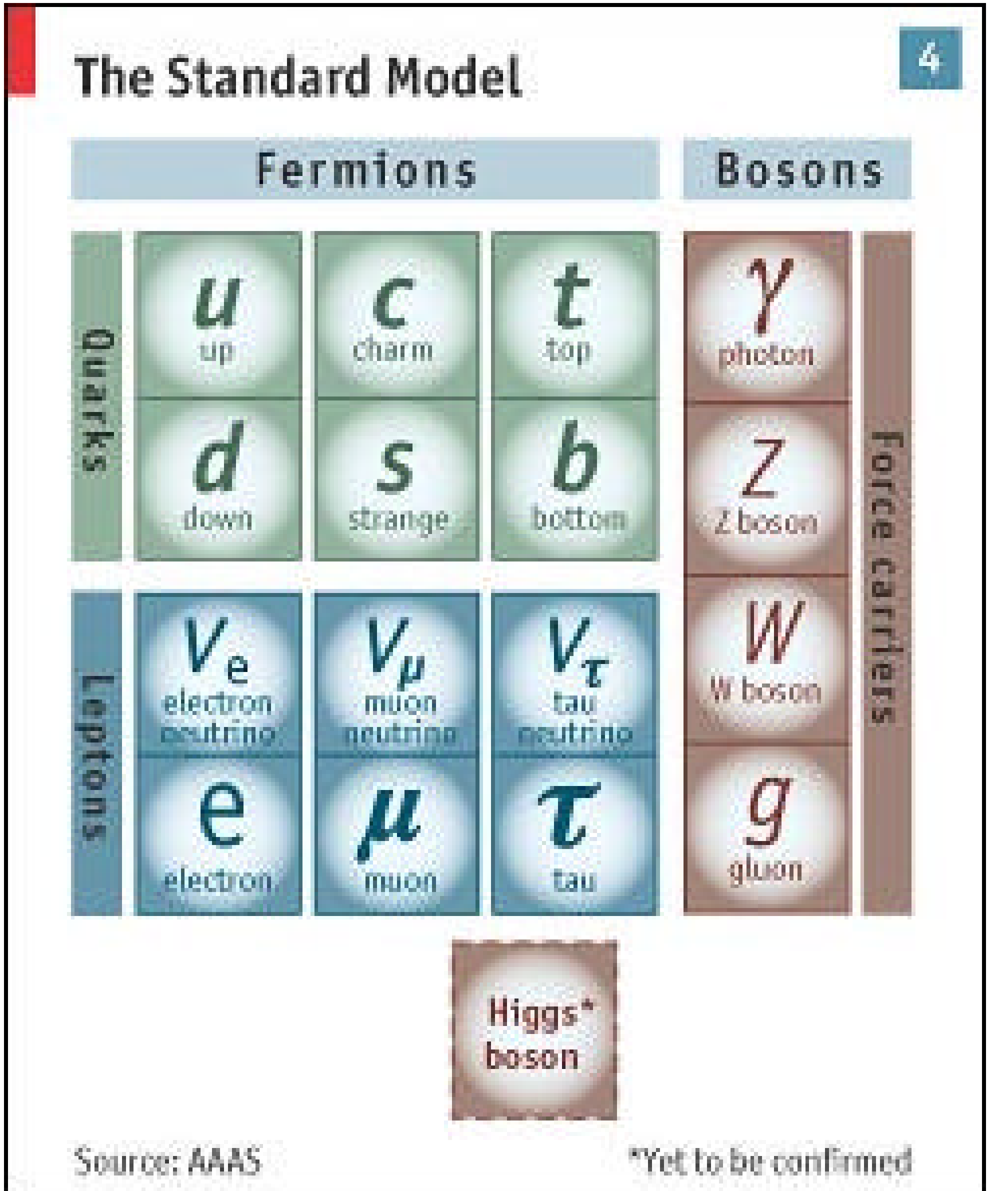
The non-relativistic quark model

- Proton = uud, antiproton = $\bar{u}\bar{u}\bar{d}$
- Neutron = udd
- Charged Pions = $\bar{u}d$, $u\bar{d}$
- And so on…

1. Homework (using the charges given in the periodic chart of fundamental particles on Slide 5 of Lecture 1):
   - What is the charge of the W particle, which has three strange quarks?
   - The top quark can decay into a W and bottom quark. What is the charge of the W?
   - Same for antitop into a W and an antibottom quark?
   - A W^- can decay into two second generation quarks, which ones?
   - Same for the W^+ ?

Today: The Standard Model



All point-like (down to 10^{-18} m)

Families reflect increasing mass and a theoretical organization

u, d, n_e, e are "normal matter"

Rubbia et al., 1983 Discovery of the W

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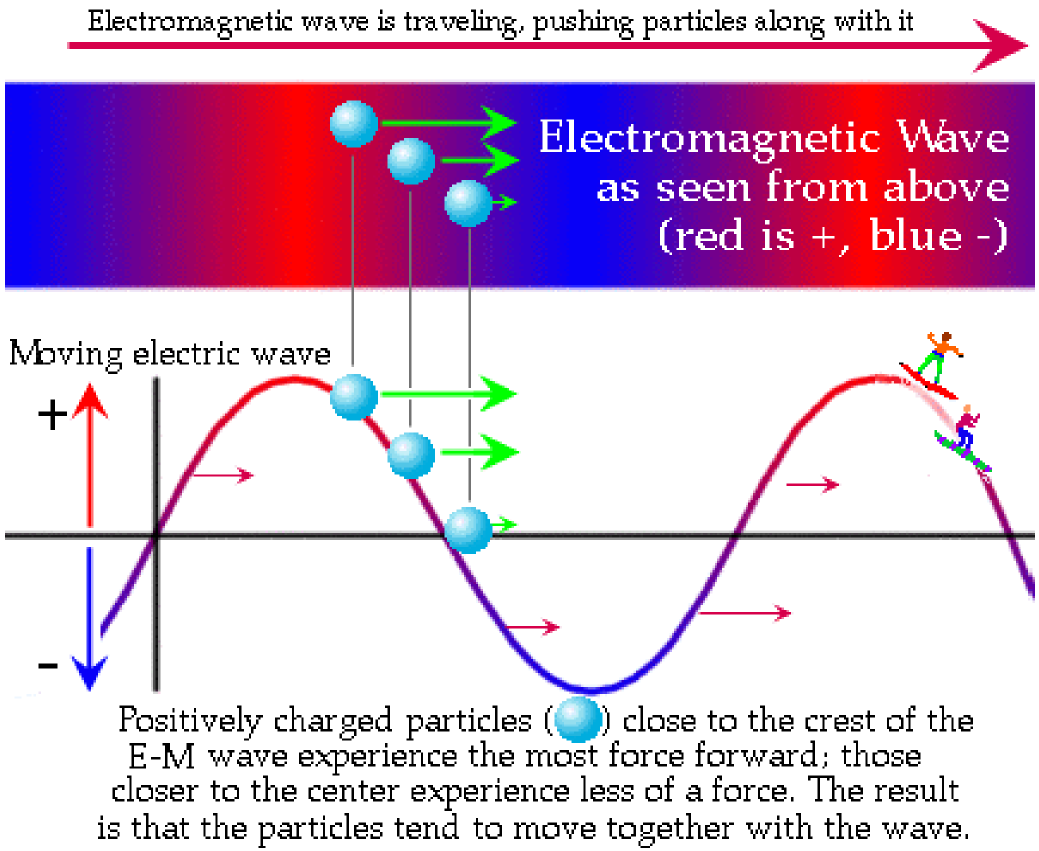
Accelerators: The Basic Principles

- **Particles are easy to obtain:**
  - **Electrons by heating metals**
  - **Protons by robbing hydrogen of its electron**
- **Accelerators speed up charged particles by creating large electric fields which attract or repel the particles**
- **This field is then moved down the accelerator, "pushing" the particles along.**



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The Colliding Beams Advantage

- ***Fixed Target Experiment*** : Experiments like Rutherford's may be performed when a beam of particles is made to collide with a stationary target
- ***Colliding-beam experiment*** : Two beams of high-energy particles can be made to cross each other.
  - Both beams have significant kinetic energy, more energy available in center-of-mass of the collision compared to a single beam.
  - Since we are dealing with particles with a lot of relative momentum, these particles have short wavelengths and make excellent probes.
  - Currently dominating the world program.

For a 100 GeV beam
E fixed = 14 GeV
E collider = 200 GeV

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Some Kinematics

- **For high energy physics we set c = 1.**
- **Definition of the four vector: $p = (E, \vec{p})$**
- **Addition of four vector: $p_1 + p_2 = (E_1+E_2, \vec{p}_1+\vec{p}_2)$**
- **Product of four vector: $p_1 \cdot p_2 = E_1E_2 - \vec{p}_1 \cdot \vec{p}_2$**
- ***Mandalstam Variables: u*, *s*, *t*, are four vector quantities describing the kinematics of particle interactions**
- ***s*, which is the total energy available in a system, for a two particle system is $s^2 = (p_1+p_2)^2$.**
- ***s* is invariant and has the same value in all frames before and after collisions, decays…**

Homework Problems

2. **Show that for a single particle s^2 is just equal to the mass of the particle squared and another form of the relativistic equation: $E^2 = p^2 + m^2$.**
3. **Using the definition of s^2, for the electromagnetic decay of a neutral pion ($p \rightarrow gg$) at rest (mass = 0.135 GeV) , what is the energy of the final state photons (mass = 0)**

Prove the Boxed Claim, Slide 17

4. **Proton beam on fixed proton target:**
   - $p_1 = (m_1, 0)$, $p_2 = (E_2, \vec{p}_2)$
   - $s^2 = (p_1 + p_2)^2 = (m_1 + E_2, 0 + \vec{p}_2) = (m_1 + E_2)^2 - \vec{p}_2^{\,2}$
   - But $m = m_1 = m_2$ and $E >> m$, so $s^2 = 2mE_{beam}$
   - Energy available is roughly $(2\ \text{GeV} * E_{beam})^{1/2}$

5. **Colliding proton beams:**
   - $p_1 = (E_1, \vec{p}_1)$, $p_2 = (E_2, \vec{p}_2)$
   - $s^2 = (p_1 + p_2)^2 = (E_1 + E_2, \vec{p}_1 + \vec{p}_2)^2$
   - But $m = m_1 = m_2$ and $E >> m$, so $s^2 = 4E^2$
   - Energy available is $2E_{beam}$

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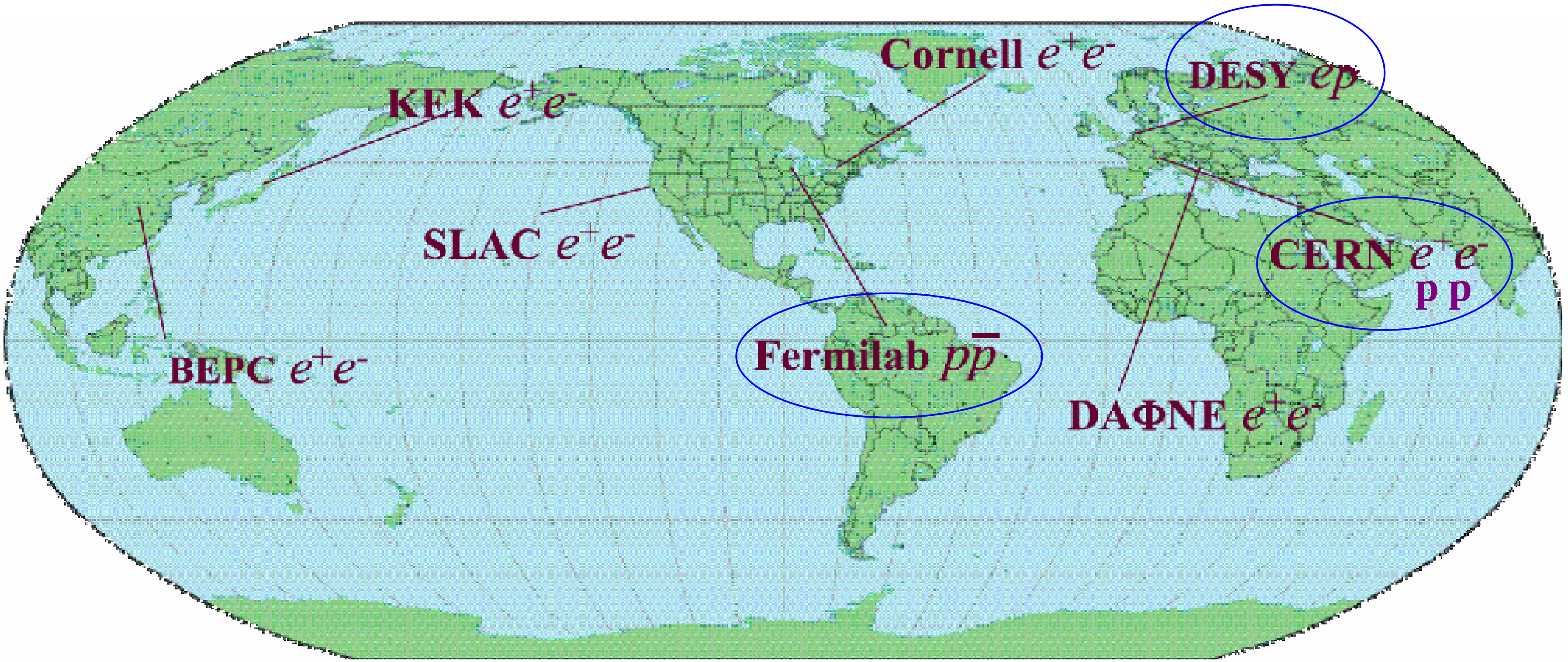
Major Worldwide Labs



7 laboratories in the world dedicated to HEP

- **US: SLAC(e^+e^-), CESR(e^+e^-), FERMILAB(pp & assorted)**
- **Europe: HERA(ep); CERN: $LEP_{finished}$(e^+e^-), LHC_{2007}(pp)**
- **Asia: BEPC(e^+e^-), KEK(e^+e^-)**

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Complementary Approaches

electron-positron

Emphasis on precision measurements

Past

- SPEAR at SLAC
- PETRA at DESY
- LEP at CERN

Present

- SPEARIII at SLAC
- BEPC
- KEK

Future

- International Linear Collider

hadron-hadron

Emphasis on maximum energy → maximum physics reach for new discoveries

Past

- ISR at CERN
- SPS at CERN

Present

- Tevatron at Fermilab

Future

- LHC at CERN

electron-hadron

Emphasis on precise measurements of hadron structure

Present

- DESY at HERA

LEP

- **Location: CERN, Geneva Switzerland**
- **e^+e^- machine**
- **$P_{e+} = P_{e-}$**
- **Maximum center-of-mass Energy = 209 GeV**
- **Circumference of machine = 26.7km**
- **Program Ended.**

HERA

- ? Location: DESY, Hamburg Germany
- ? e-p machine
- ? P_e=27.5 GeV/c
- ? P_p=920 GeV/c
- ? Center-of-mass Energy = 318 GeV
- ? Circumference of machine=6.3km

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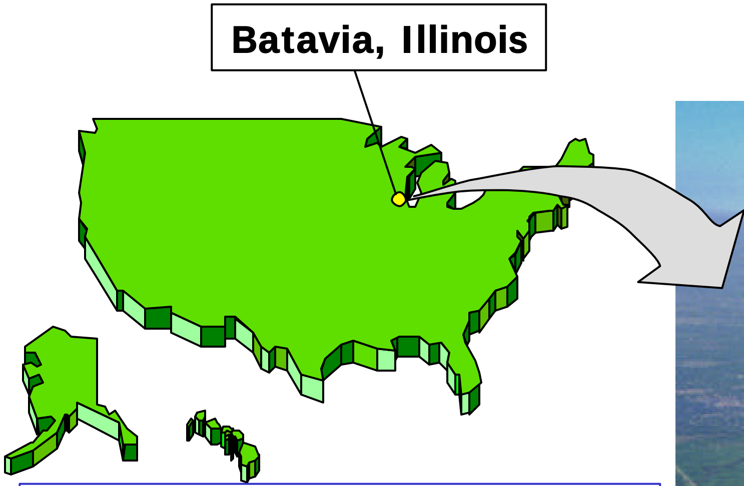
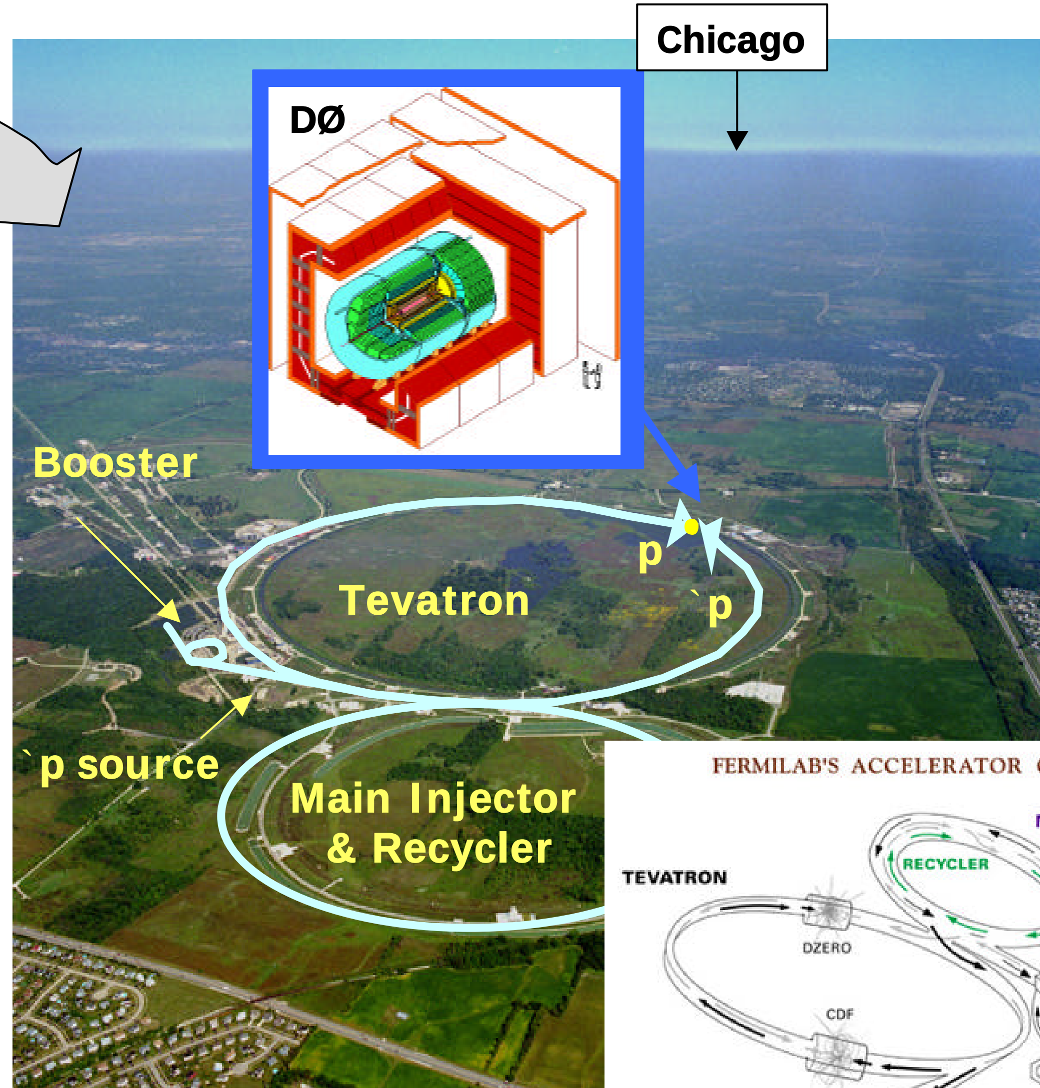
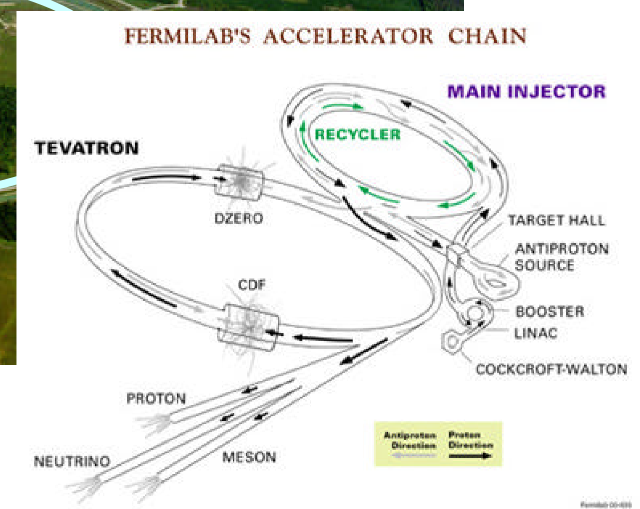
Fermilab: Proton-Antiproton Collider





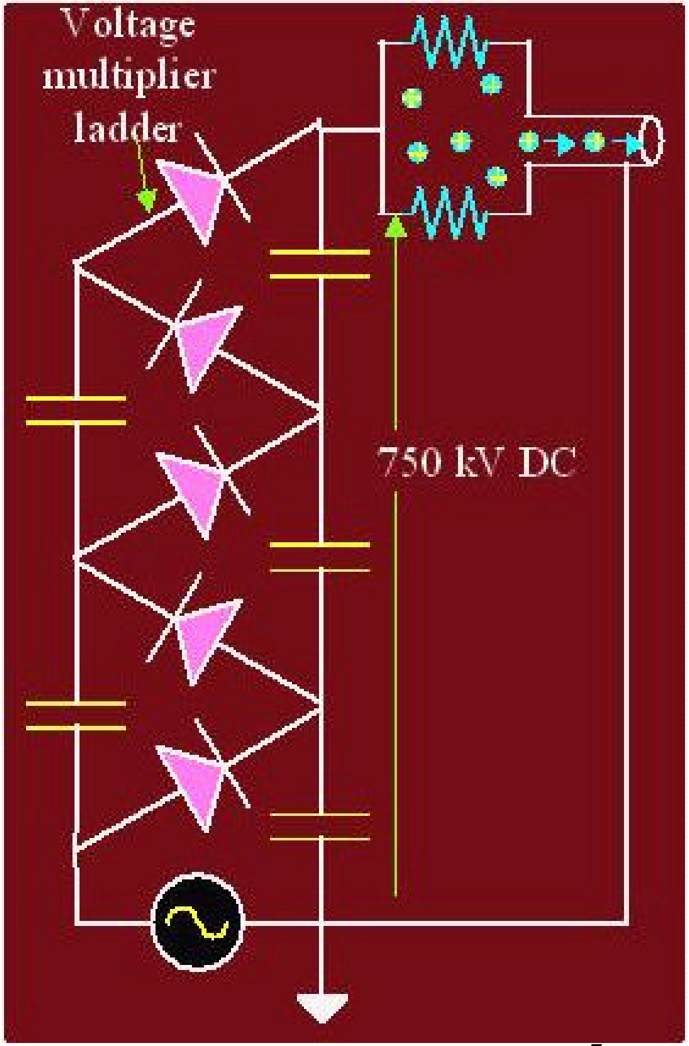
Complex:
1)Hydrogen Bottle
2)Linear Accelerator
3)Booster
4)Main / Injector
5)Antiproton Source
6)Tevatron

Energy:
1)Proton, Antiproton Beam = 1 TeV
2)Center-of-mass = 2 TeV



Cockcroft-Walton

H- to 0.75 MeV



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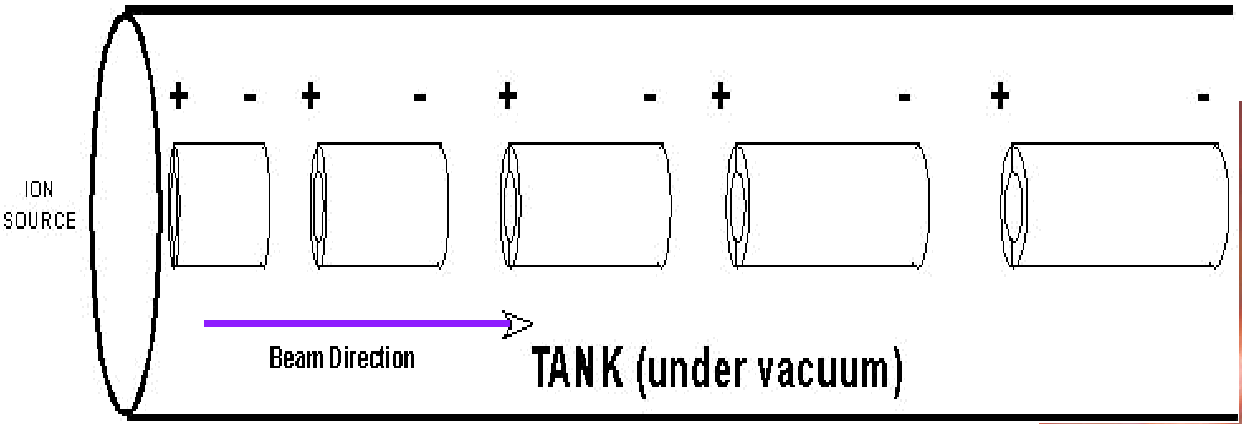
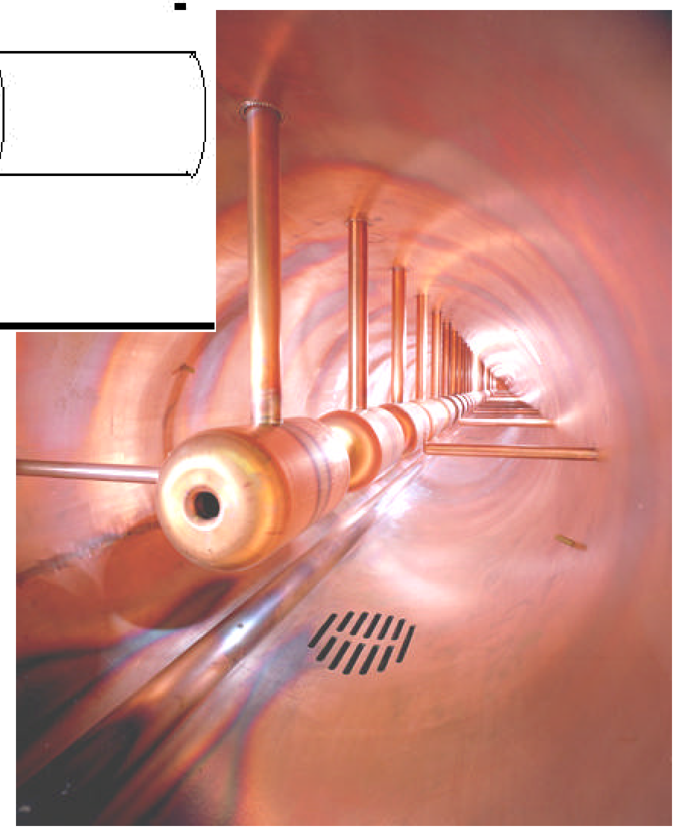
The Alvarez Linac





H- to 400 MeV
130 Meters Long

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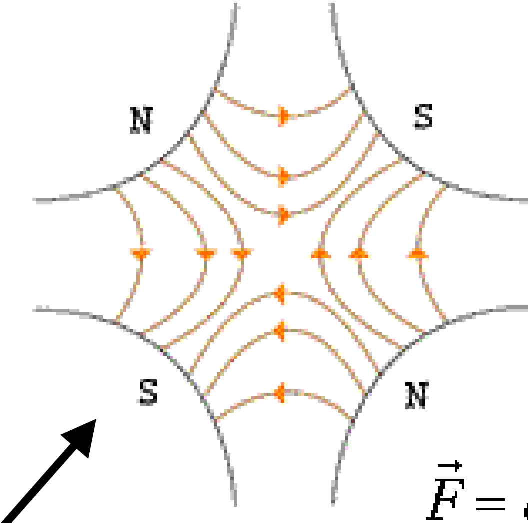
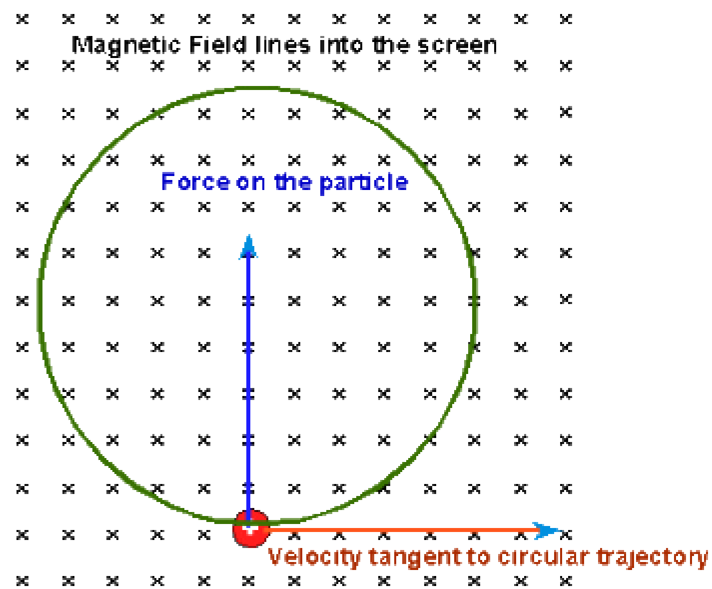
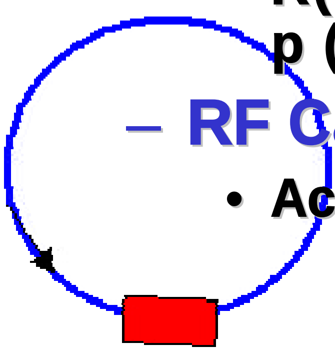
Proton Synchrotrons



$$\vec{F} = q\vec{E} + q\vec{v} \times \vec{B}$$

- **Six on site:**
  - **Booster, Debuncher, Accumulator, Recycler, Main Injector, TeVatron**
- **Two Main Components**
  - **Magnetic Fields**
    - **Guide and Focus Beam**
    - **Curvature Constant so Field Changes with Time**
    - **R(in meters) = p (GeV/c)/0.3B(Tesla)**
  - **RF Cavities**
    - **Accelerate Particles.**





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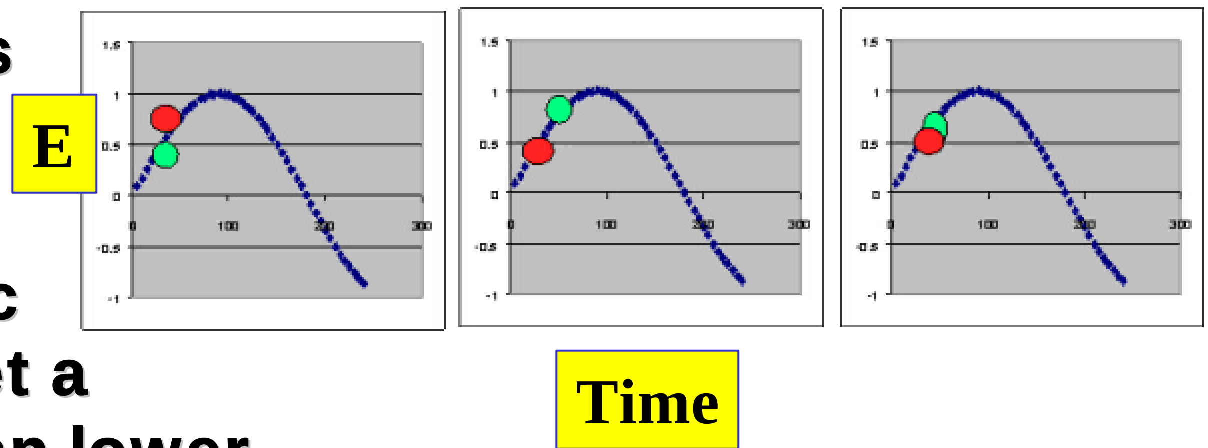
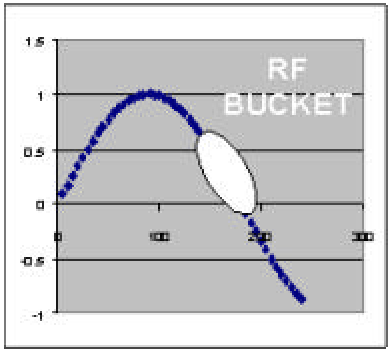
Radio Freq. Cavities and Phase Stability

- **Magnetic strength and radiofrequency must be synchronized for stability (Veksler & McMillan Nobel)**
- **Each revolution the cavity boosts the particles in a bunch**
- **Early or energetic particles (red) get a smaller boost than lower energy particles.**
- **Eventually the coalesce into an RF Bucket.**





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Booster and Main Injector

Proton 8 GeV

P/Pbar 150 GeV

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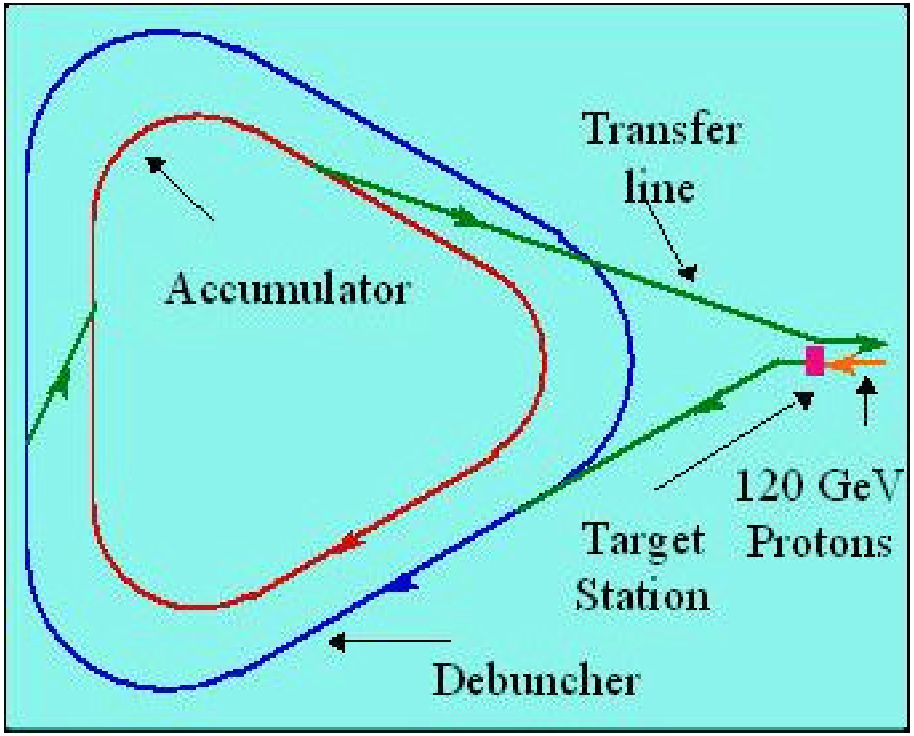
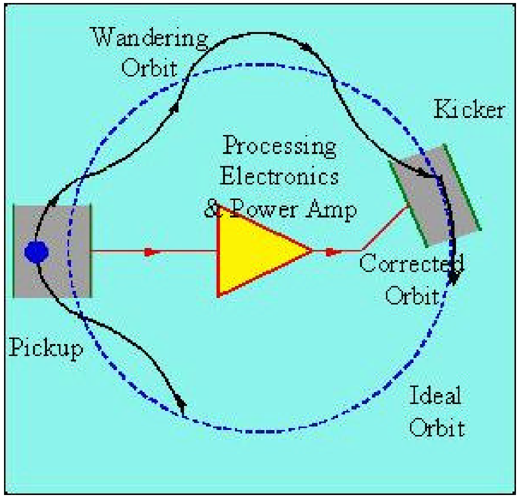
Antiproton Source

- **Three Components**
  - **Target**
  - **Debuncher**
    - **removes RF structure of proton beam**
    - **in favor of narrow energy spread**
  - **Accumulator**
    - **Stores antiprotons**
    - **Uses RF and stochastic cooling to**





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Accumulator and Tevatron

Stores Antiprotons

p/pbar 980 GeV

Super Conducting

2 TeV Collisions!

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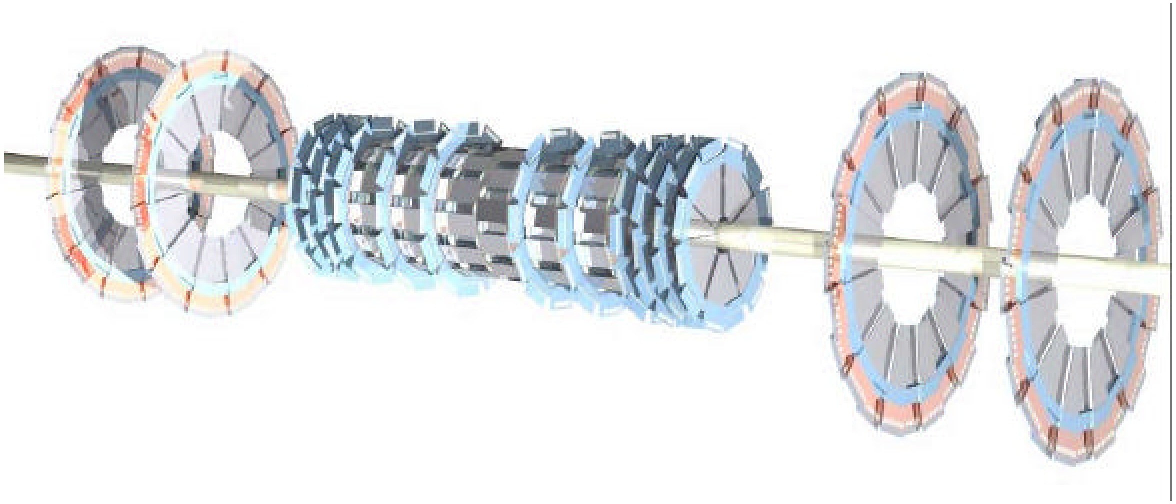
Detectors: Basic Ideas

- **Charged particles (leptons, mesons, hadrons) ionize detecting medium.**
- **Charged Particle Tracking:**
  - The ionization (in many forms) can be amplified and detected.
  - The passage of single particles can be detected at many points to measure a trajectory.
  - The bend of the trajectory in a magnetic field provides momentum measurement.
- **Calorimetry:**
  - A particle, charged or neutral, will interact with dense medium to create a shower of charged particles.
  - The shower energy can be sampled as a measure of the particle energy
  - The shape of the shower provides information on direction and particle type.
- **Other techniques are available but these are the most prevalent.**

Tracking in Silicon



- Silicon is etched in narrow strips ~40 microns.
- With the Si held at voltage, ionizing radiation can be detected and amplified
- Typical Detectors have 1M channels
- Barrel/Disk structure ensures good coverage

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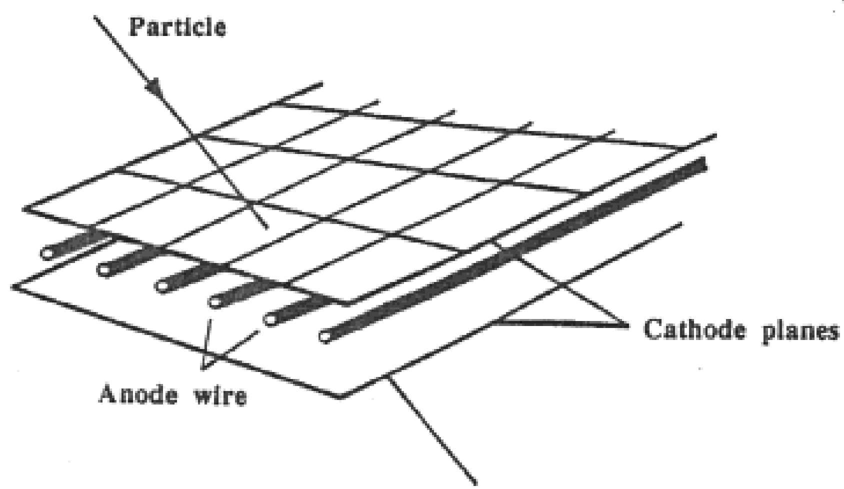
Tracking in Gaseous Detectors

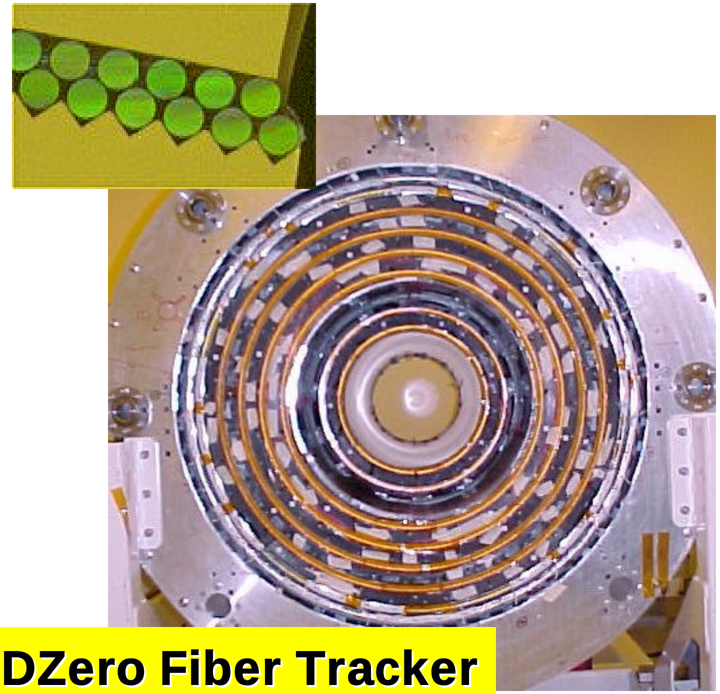
- **When a charged particle traverses a gas-filled chamber, it ionizes the gas atoms along its path.**
- **Thin wires inside the chamber at high voltage attracts the charge**
- **The signals caused by gas ions attracted to the wires can be amplified and recorded.**
- **The data reveal the arrival time of a particle as well as its track.**
- **In 1992, Georges Charpak received the Nobel Prize for the invention of the**

  wire chamber.
- **Many varieties, proportional and drift...**

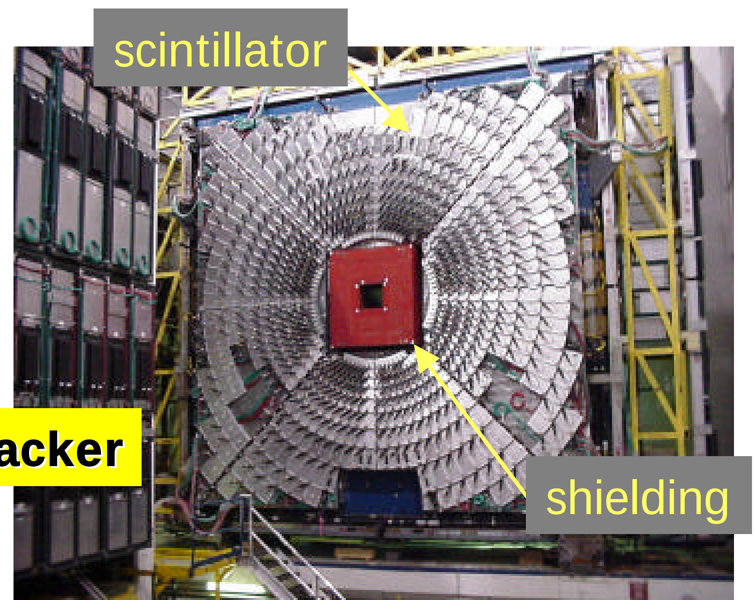


Tracking in Scintillator

- Scintillator emits light with passage of ionizing radiation
- Can be shaped as small fibers with good 1mm resolution
- Or as panels for wide are coverage.
- The light is converted to electrical signals with phototubes or solid state detectors



DZero Fiber Tracker



DZero Muon Tracker

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January 2005
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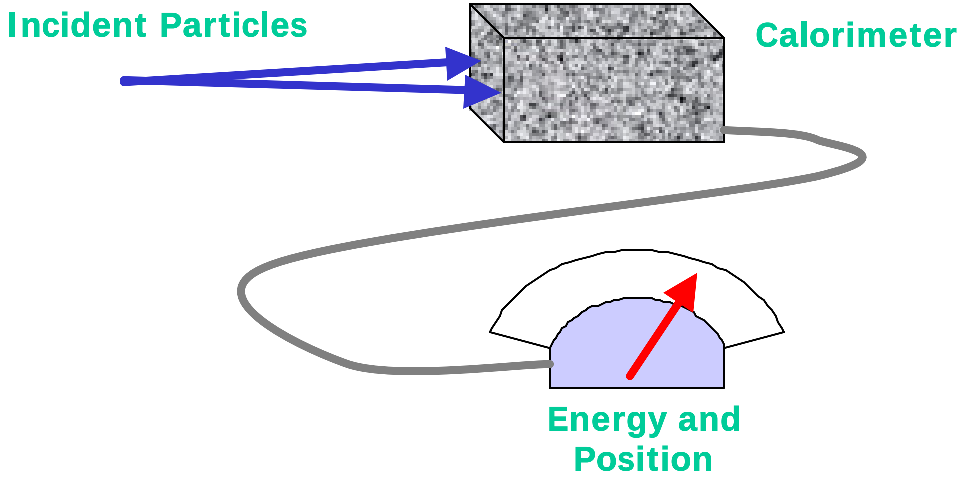
Calorimetry

- Induce a shower of interactions between incident particle and denser material
- Collect ionization as an energy measurement of charged and neutral particles.
- In a collider primarily electrons, photons, and pions. To a lesser extend protons, kaons, neutrons...
- To measure energy and position a segmented calorimeter surrounds tracking



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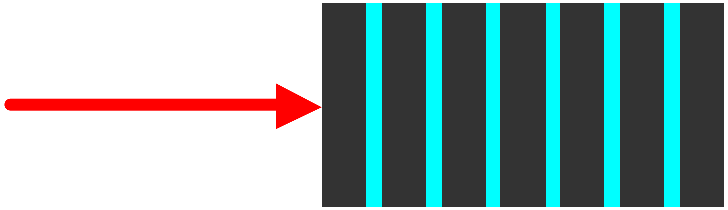
Sampling calorimeters

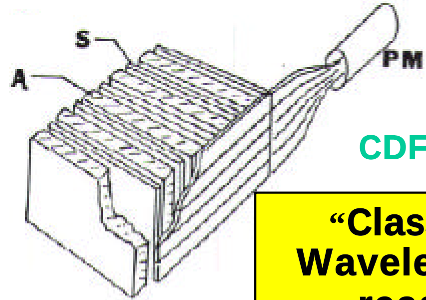
- For reasons of cost and compactness, typically measure only a fixed fraction of the ionization, the "sampling fraction"



- Alternate dense absorber with sensitive medium
- Absorber can be
  - lead, uranium (for maximum density), steel, copper, iron (for magnetic field), tungsten
- Sensitive layers can be
  - Wire chambers, silicon, scintillator, liquid argon
- Choices depend on cost, space, resolution desired.

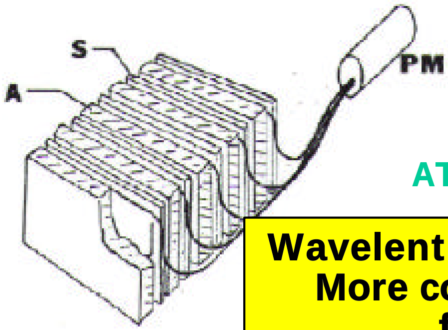
Scintillator calorimeters

Cheap, straightforward to build, but suffer from radiation damage



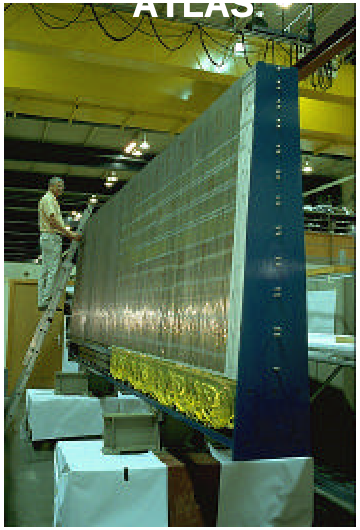
CDF, ZEUS

"Classic" design
Wavelength-shifter readout bars



ATLAS, CMS

Wavelenth-shifting fibres
More compact, more flexible



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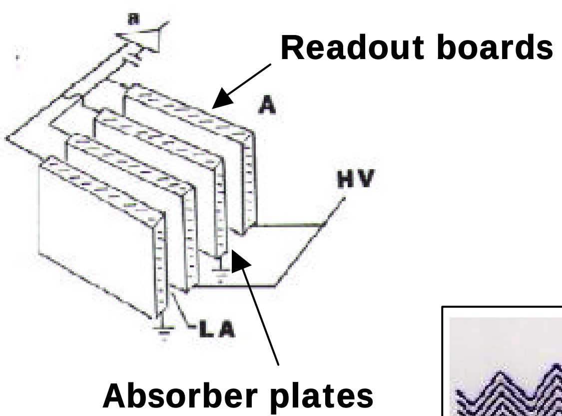
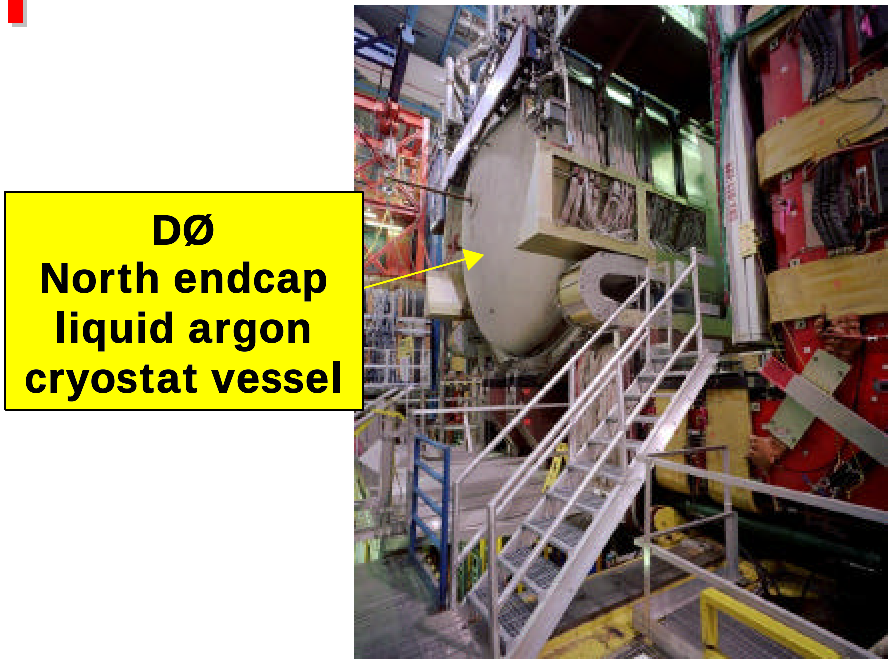
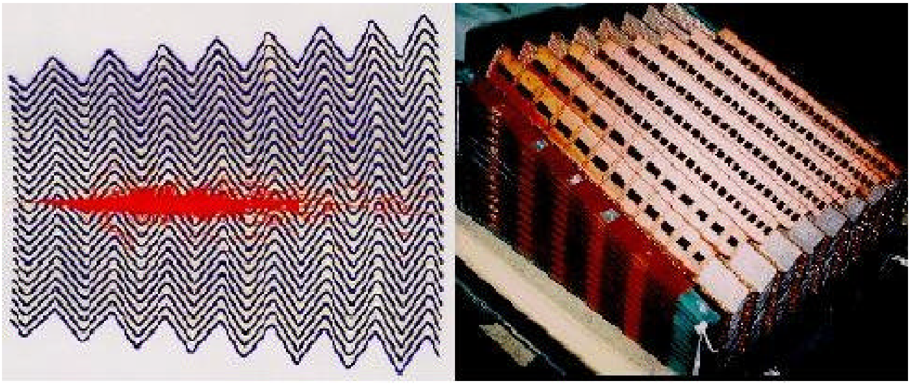
Liquid Argon

- **Stable, linear, radiation hard**
- **BUT operates at 80K: cryostat and LN_2 cooling required**



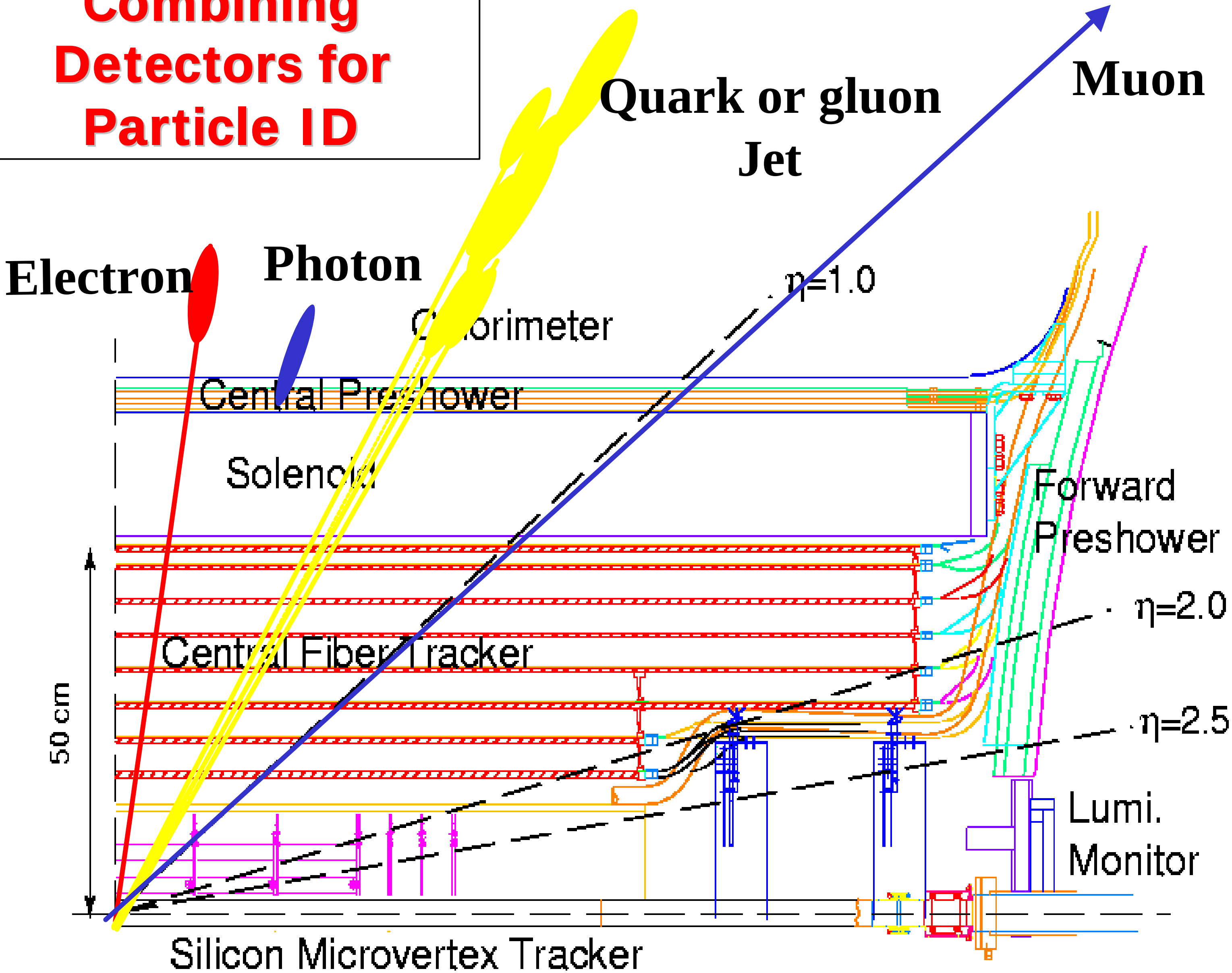


e.g. H1, SLD, DØ, ATLAS



ATLAS “accordion” EM calorimeter

Combining Detectors for Particle ID



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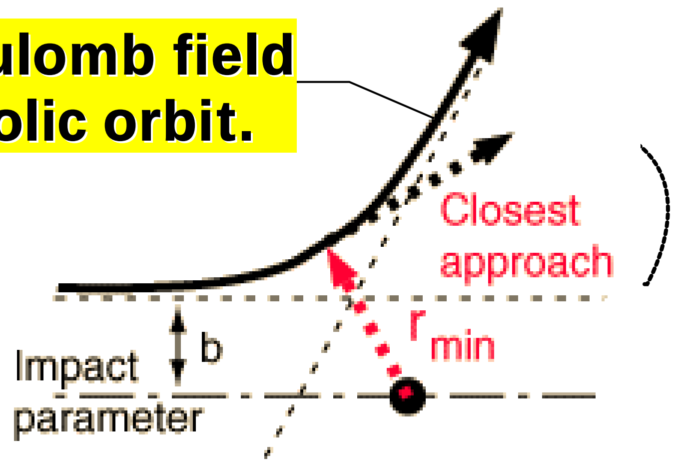
A Return to Rutherford Scattering → Cross Sections

Scattering from Coulomb field
Treated as hyperbolic orbit.



q = scattering angle

$$b = \frac{kq_1q_2}{mv^2}\sqrt{\frac{1+\cos\theta}{1-\cos\theta}}$$

$$r_{\min} = \frac{b\cos\left(\frac{\theta}{2}\right)}{1-\sin\left(\frac{\theta}{2}\right)}$$

$$\lim_{\theta \to 180^\circ} r_{\min} = \frac{Zke^2}{\mathrm{KE}}$$

b is characteristic size of nucleus.

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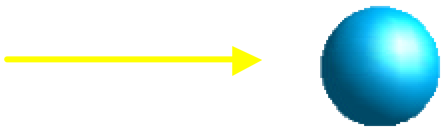
- **The concept of cross section, as its name suggests, is that of effective area for collision.**

- **For a spherical target:**

$$\sigma = \pi r^2$$



- **The cross section for scattering off something smaller than the impact parameter b = r, or equivalently, at greater angle than q is:**

$$\sigma = \pi Z^2 \left(\frac{ke^2}{KE} \right)^2 \left(\frac{1+\cos\theta}{1-\cos\theta} \right)$$

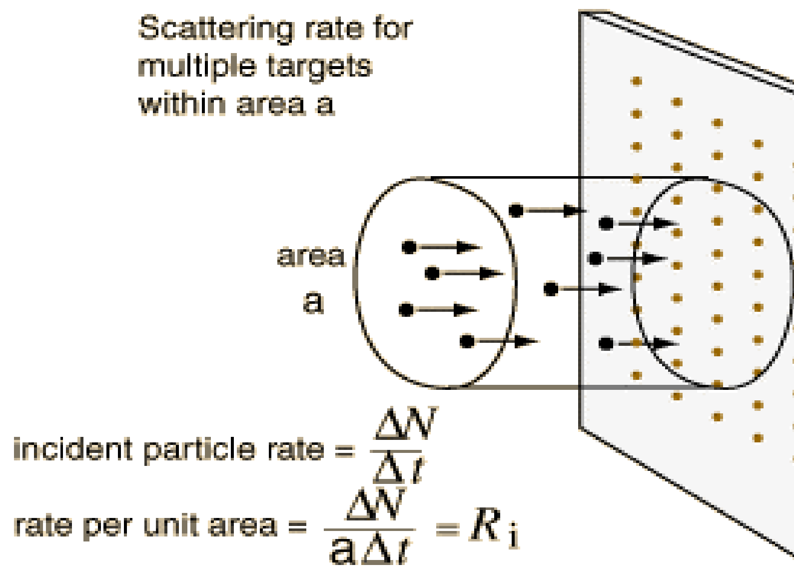
- **The scattering cross section depends on the strength of the force involved (e.g. ke^2) and the energy scale involved (KE of alpha). This will be true even for particle interactions.**

- **Since the cross section gives us an *effective area* for a target, we can determine a scattering rate for a beam of particles as follows:**

Incident flux

$$\text{Rate} = S \text{ x } \frac{N_{\text{incident particles}}}{(\text{Unit Area})(\text{Unit time})}$$

- **In aiming a beam of particles at a target which is much smaller than the beam, as in the Rutherford scattering experiment, the cross section takes on a statistical nature.**



Cross Sections at a Proton Antiproton Collider

$$\frac{dN}{dt} = S \frac{f * N_b * n_p * n_{pbar}}{S_x S_y}$$

$$N = S \int L \, dt$$

$$N = S \, L$$

Reminder: 1pb^{-1} of integrated luminosity means 1 event will be produced for a process of 1pb cross section.

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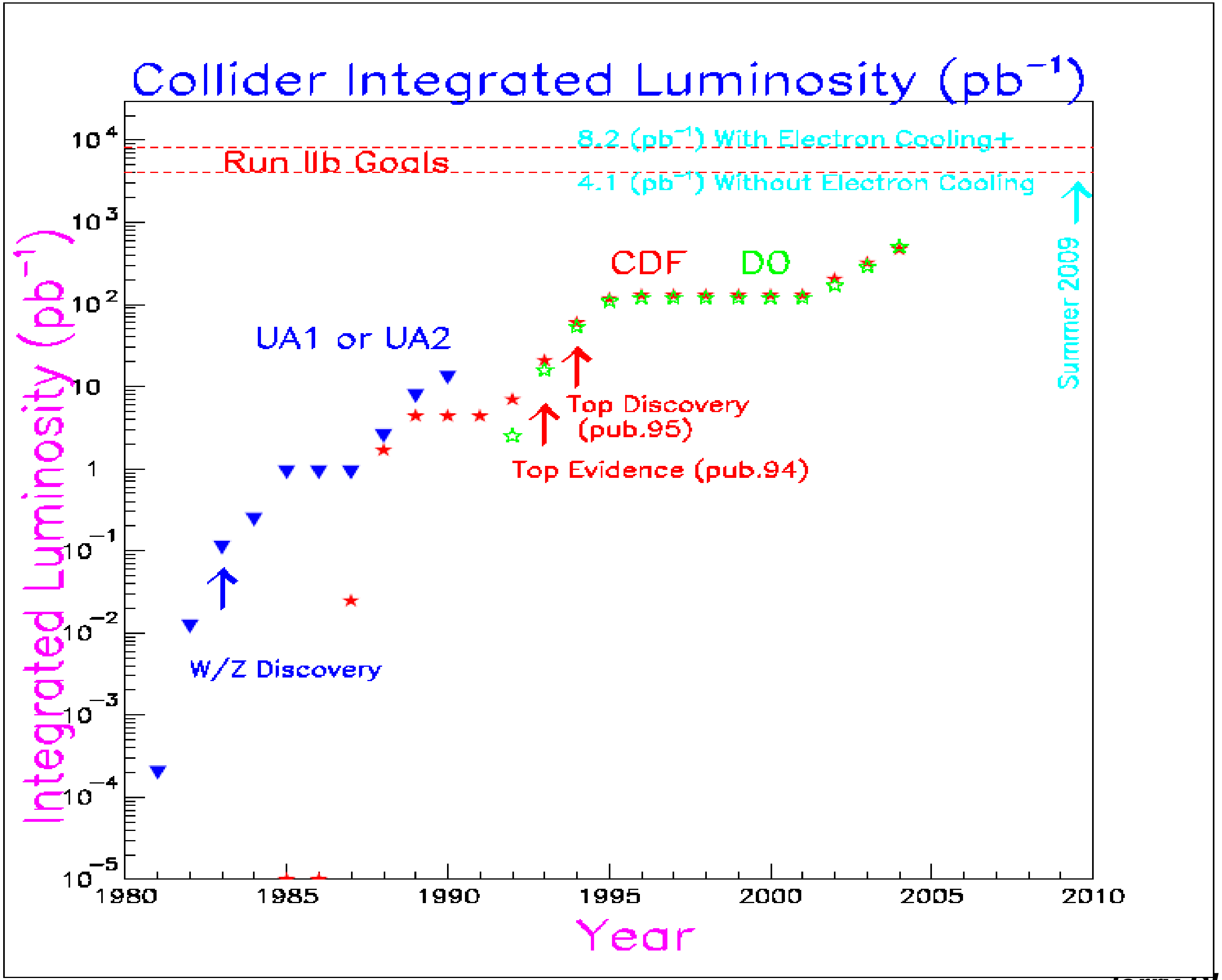

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- ✓ History, Accelerators, Detectors, & Cross Sections
- QCD Electroweak Physics
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