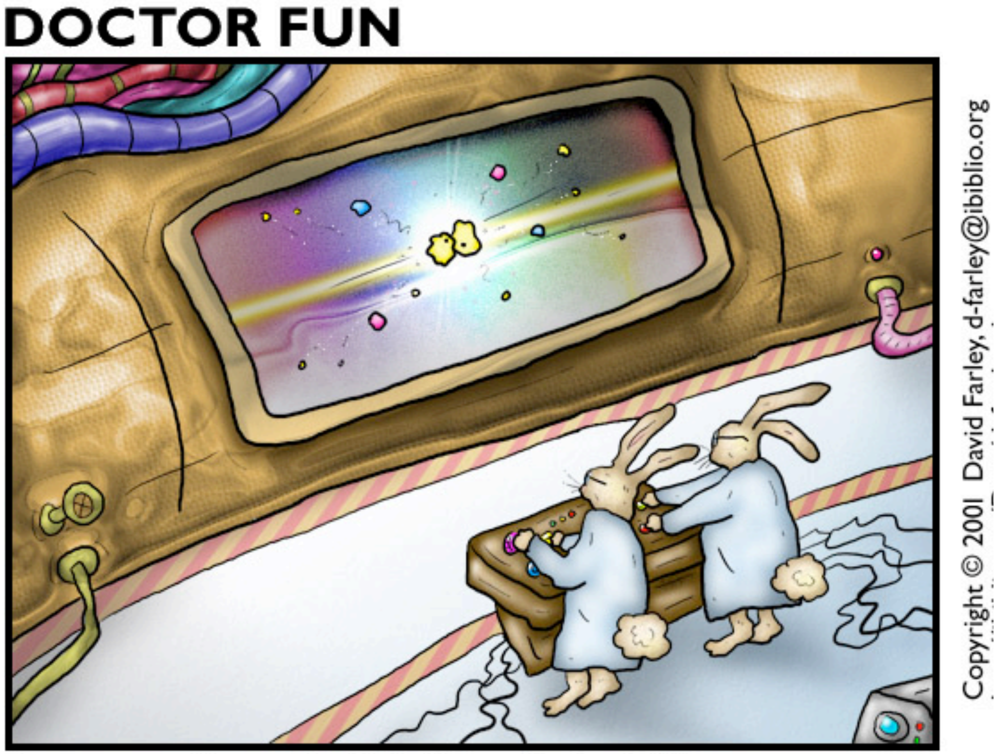
Physics 3:

Particle Physics

Lecture 4: Accelerators and Detectors

February 21st 2008



Bunny researchers at the High Energy Candy Collider generate exotic short-lived isotopes of Peeponium.

* **Particle Beams and Accelerators**
  - Particle Physics Labs
  - Accelerators
  - Synchrotron Radiation
* **Particle Detectors:**
  - A modern collider detector
  - Interactions of particles with matter
  - Particle reconstruction

Particle Acceleration

Long-lived charged particles can be accelerated to high momenta using electromagnetic fields.

- $e^+, e^-, p, \bar{p}, \mu^\pm(?)$ and **Au, Pb & Cu nuclei** have been accelerated so far...

Why accelerate particles?

- High beam energies ⇒ high E_{CM} ⇒ more energy to create new particles
- Higher energies probe shorter physics at shorter distances
- De-Broglie wavelength: $$\frac{\lambda}{2\pi} = \frac{\hbar c}{pc} \approx \frac{197 \text{ MeV fm}}{p\ [\text{MeV}/c]}$$
- *e.g.* **20 GeV/*c*** probes a distance of **0.01 fm**.

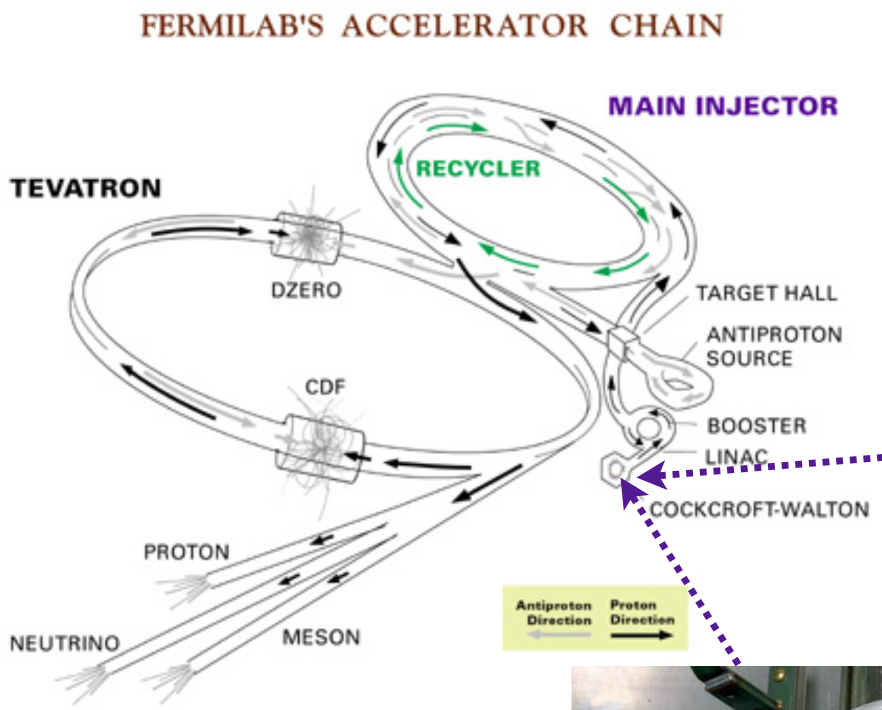
An accelerator complex uses a variety of particle acceleration techniques to reach the final energy.

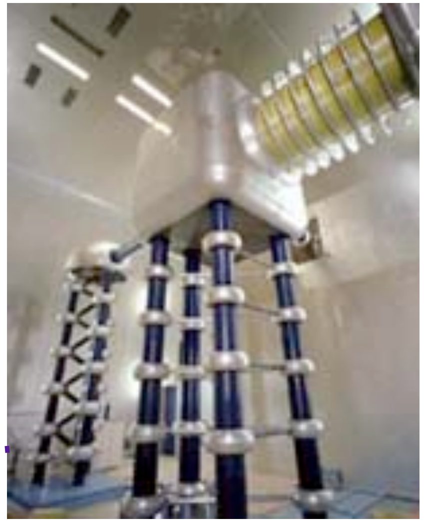
Particle Physics Colliders around the World

SLAC, California	SLC	1989-1998	$e^- e^+$	**50 GeV e^- and 50 GeV e^+**
	PEP II	1997-2008	$e^- e^+$	**9.0 GeV e^- and 3.1 GeV e^+**
Fermilab, nr Chicago	Tevatron	1987-2009	$p\,\bar{p}$	**980 GeV p and 980 GeV $\bar{p}$**
CERN, Geneva	LEP	1989-2000	$e^- e^+$	**E_{CM}: 89 to 206 GeV**
	LHC	2008-...	$p\,p$	**E_{CM}: 14 TeV**
DESY, Hamburg	HERA	1990-2007	$e^- p$	**920 GeV p and 30 GeV e^-**
KEK, near Toyko	KEKB	1999-...	$e^- e^+$	**8.0 GeV e^- and 3.5 GeV e^+**
Brookhaven National Lab, Long Island	RHIC	2000-...	**AuAu, CuCu**	**200 GeV/nucleon**

The Tevatron Complex

- As a example, we'll follow the chain of the Tevatron accelerator.



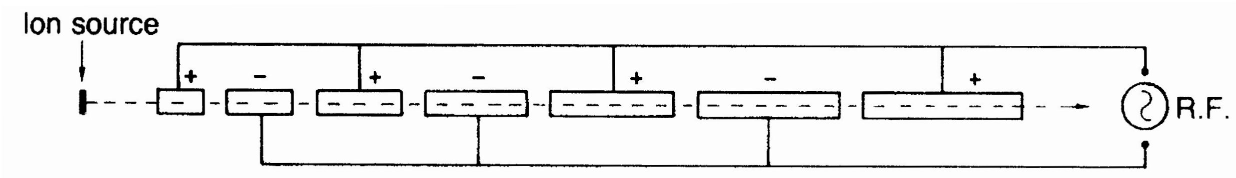


Cockroft-Walton Accelerator
DC Voltage accelerates particles through steps to about 1MV

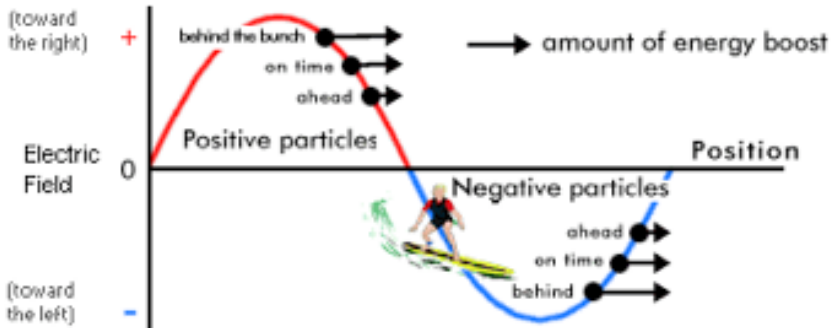
Proton source: 7 litre bottle of hydrogen. Cost US$200. 1 bottle lasts about a year

Linac

- After Cockroft-Wolton comes the linac (linear accelerator)
- Charged particles in vacuum tubes accelerated by an alternating current, with a very high frequency: “Radio Frequency” (RF)
- RF frequencies typically a few 100 MHz
- Field strengths – few MV/m requires specialised power sources: “klystrons”

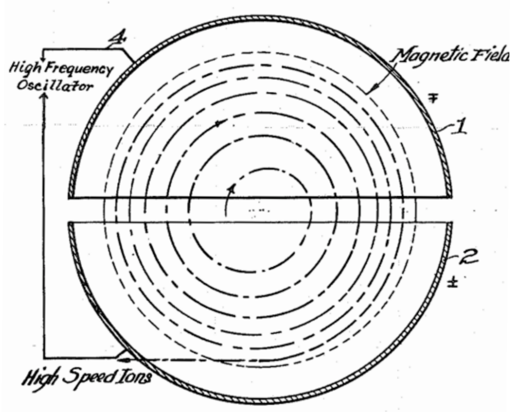


- The tubes act as Faraday cages: when the particles are in the tubes they feel no force
- Outside of the tubes they feel the potential difference between successive tubes, they accelerate forward
- Alternating current ensures that the difference always has the correct sign for acceleration.

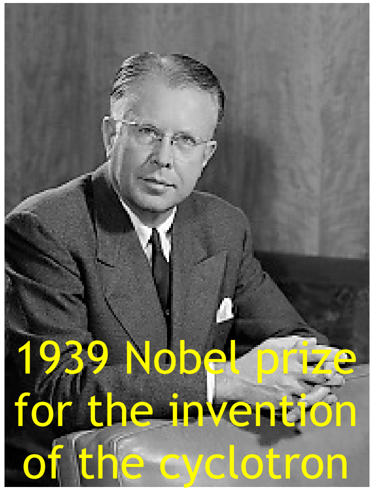


Cyclotrons and Synchrotrons

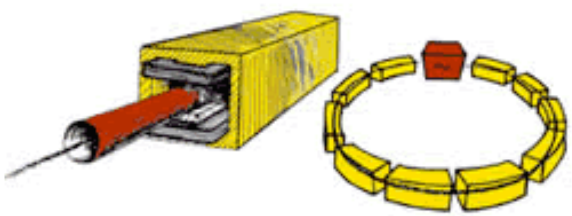
- **The Cyclotron - invented by Ernest Lawerence**
- **Two D-shaped electrodes - perpendicular magnetic field**
  - Constant frequency AC current applied to each electrode
  - Can to accelerate particles to **~10 MeV**
  - At higher energies relativistic effects take over, circular path cannot be maintained need...



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


1939 Nobel prize for the invention of the cyclotron

- Synchrotron accelerators use variable ***B***-field strength and radio frequency ***E***-field, synchronised with particle speed to accelerate charged particles to relativistic energies.

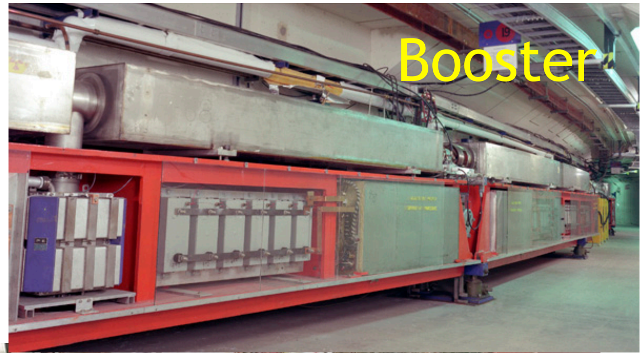


- Series of bending and focussing magnets

- Beams have a constant radius in a synchrotron.
- Synchrotrons used as storage rings and colliders.

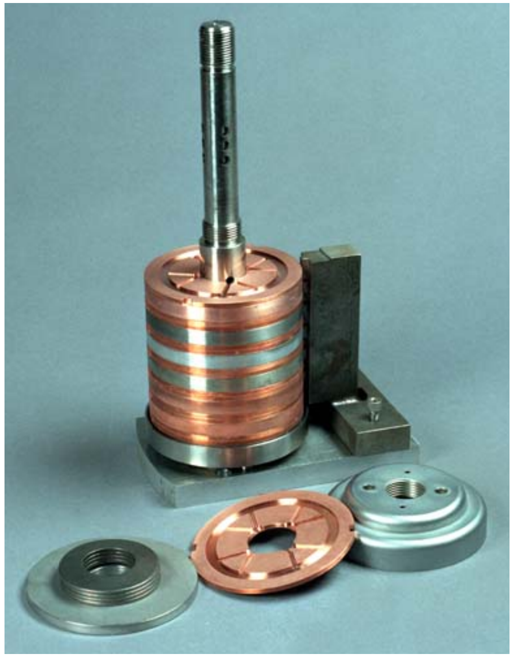
Synchrotrons at the Tevatron

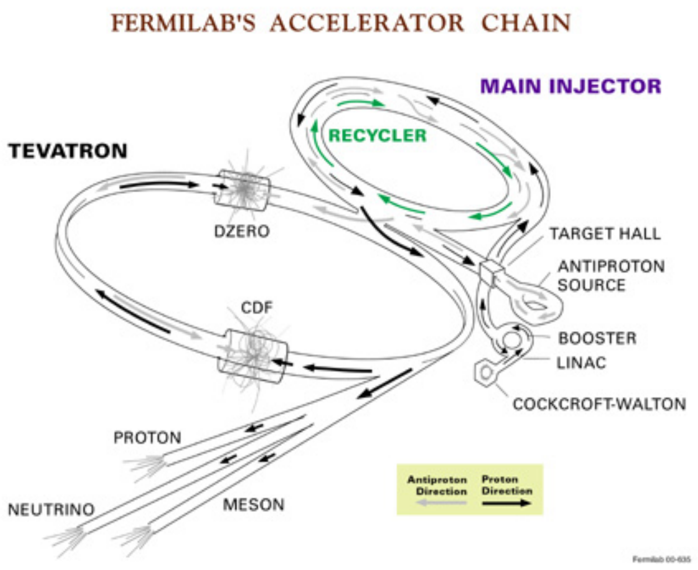
- Many synchrotrons used at the Tevatron:
  - **Booster**: proton energy from 400 MeV to 8 GeV
  - **Recycler**: stores antiprotons at 8 GeV
  - **Main Injector**: 8 GeV to 120 GeV
  - **Tevatron**: 120 GeV to 980 GeV
- **Storage ring**: once particles have desired energy, they can be stored. Typically 8-24h.
- The Tevatron stores both the proton and anti-proton beam travelling in opposite directions.
- **Collider**: two beams are steered to collide at two points in the (CDF and DØ experiments).



Antiproton Production

- Protons from the main injector are fired onto a nickel target.
- 1 million protons produces 20-30 8 GeV antiprotons.
- Magnetic field used to separate p from $\bar{p}$.
- Stored in the accumulator synchrotron for several hour to several days - until required for collision in Tevatron.
- At the end of a 'store' in the Tevatron any remaining antiprotons are stored in the **Recycler** synchrotron.





- Two collision points in the Tevatron: CDF and DØ
- We'll see the CDF detector in a moment...

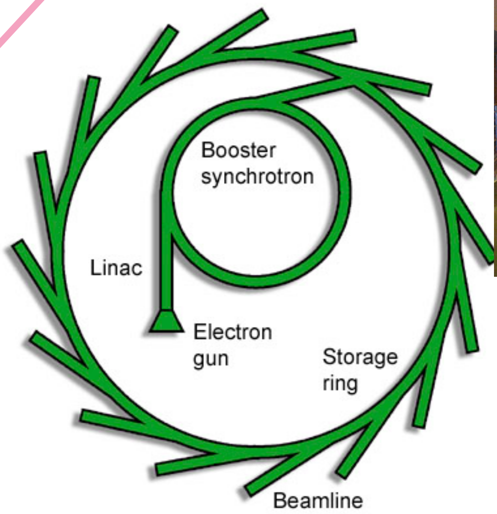
Synchrotron Radiation

- In a synchrotron the accelerated charged particles emit photons: **synchrotron radiation.**

- The energy lost every turn depends of the energy and mass of the particle (*γ=E/m*) and the radius of the orbit, *ρ*:

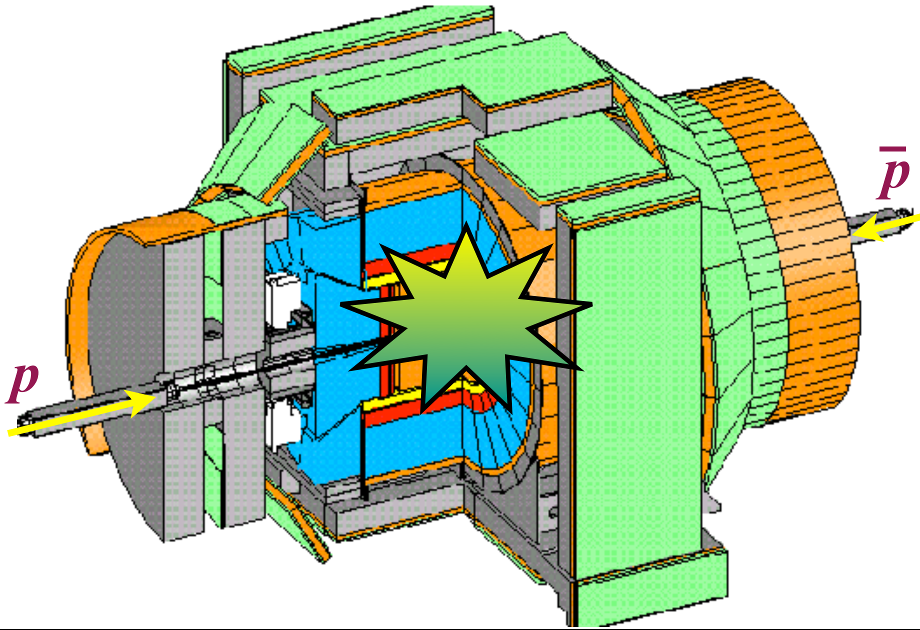
$$\Delta E = \frac{q^2 \beta^3 \gamma^4}{3\epsilon_0 \rho}$$

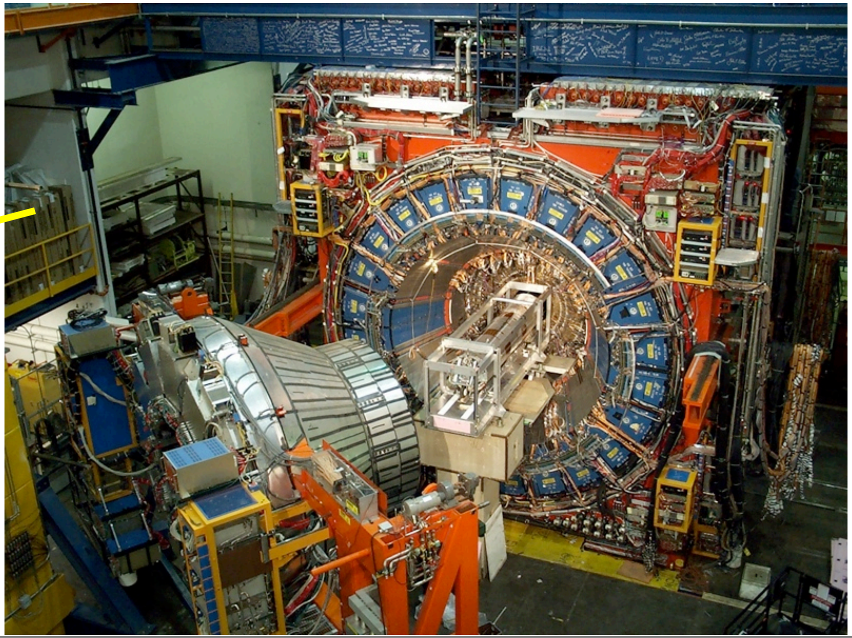
- Synchrotrons are used as high-energy photon sources
- In a storage ring, the energy lost due to synchrotron radiation must be returned to the beam to keep the collision energy constant.



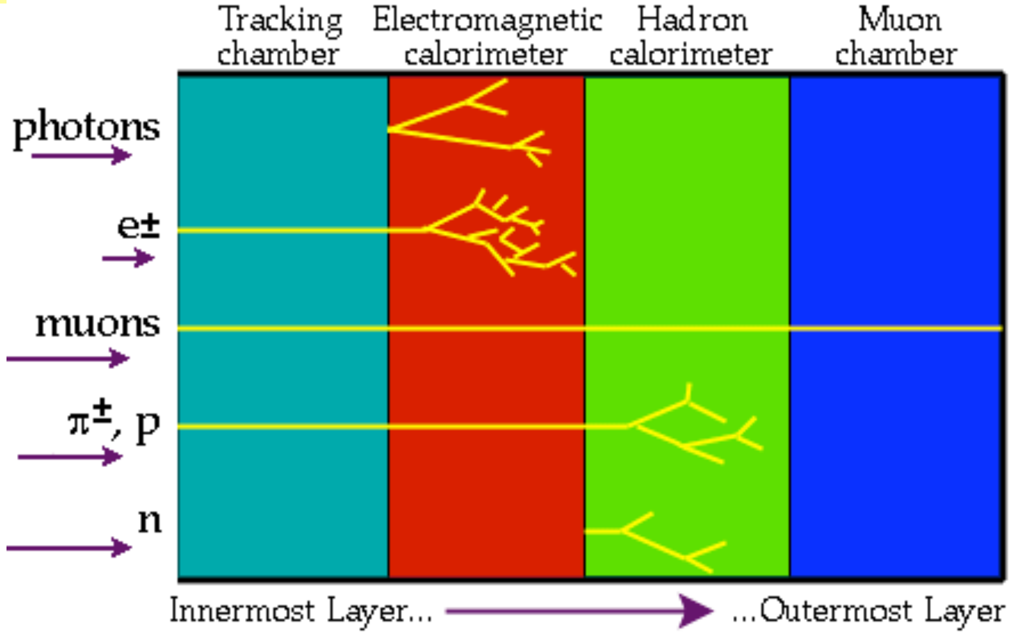
A Modern Collider Detector

- Use CDF at the Tevatron as an example.
- Most collider detectors are quite similar - same component pieces, different implementations
    - From inside to out:
        1. Silicon tracker
        2. Gaseous tracker
        3. 1.4 T Solenoid Magnet
        4. Electromagnetic Calorimeter
        5. Hadronic Calorimeter
        6. Muon detectors



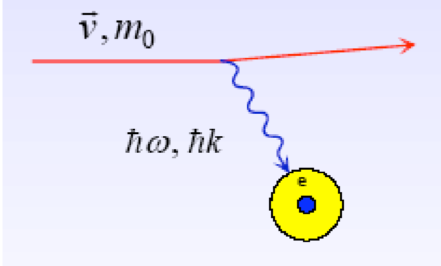


Interactions with Matter



- An experiment should detect all particles that live long enough to interact with the detector.
- Detector generally starts a few centimetres from the interaction point.
- Length travelled before decay is $L=\beta\gamma c\tau$, therefore particles with $\tau > \sim 10^{-10}$ s appear in detector
  - $e^{\pm}, \mu^{\pm}, \pi^{\pm}, K^{\pm}, K^{0}, p, n, \gamma, \nu$
- Use series of different detection techniques to identify these particles.
- Infer the existence of shorter-lived particles from the decay produces.

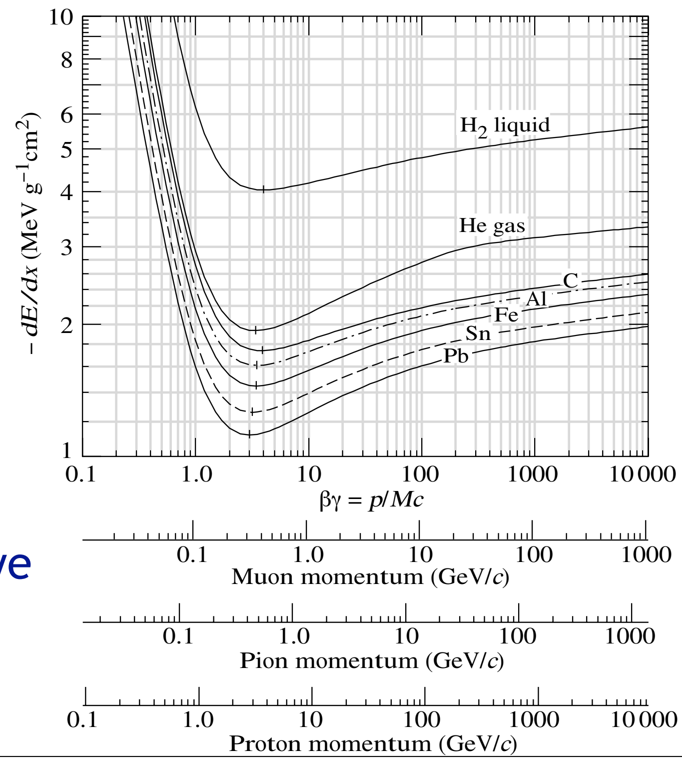
Charged Particle Energy Loss



- Energy loss of charged particle through matter is described by **Coulomb scattering**. Moving charged particles scatter off atomic electrons causing ionisation.
- Ionisation energy loss given by **Bethe-Bloch** formula:

$$-\frac{dE}{dx} = \frac{4\pi}{m_e c^2} \cdot \frac{N_A Z \rho}{A} \cdot \frac{Q^2}{\beta^2} \cdot \left(\frac{e^2}{4\pi\varepsilon_0}\right)^2 \cdot \left[\ln\left(\frac{2m_e c^2\beta^2}{I\cdot(1-\beta^2)}\right) - \beta^2\right]$$

- ➡ dE/dx - particle energy lost per x [$\mathrm{MeVg^{-1}cm^2}$]
- ➡ x - distance travelled by particle
- ➡ Q - particle charge (e)
- ➡ N_A - Avogadro's number
- ➡ Z, A - atomic and mass number of medium
- ➡ I - excitation energy of medium
- ➡ ρ - density of medium



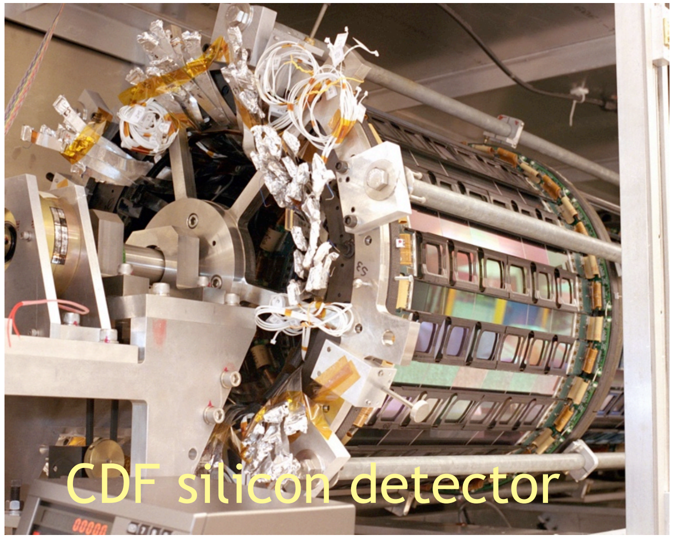
- Measure dE/dx to identify the type of particle (as we know the medium we are using for our detector).
- Also measure total energy absorbed by detector.

Charged Particle Tracking

- Charged particle trajectories are curved in magnetic fields.
- Use the curvature, ρ, to measure the momentum transverse to the field, p_T.

$$p_T[\mathrm{GeV}/c] = 0.3\, B[\mathrm{T}]\, \rho[\mathrm{m}]$$

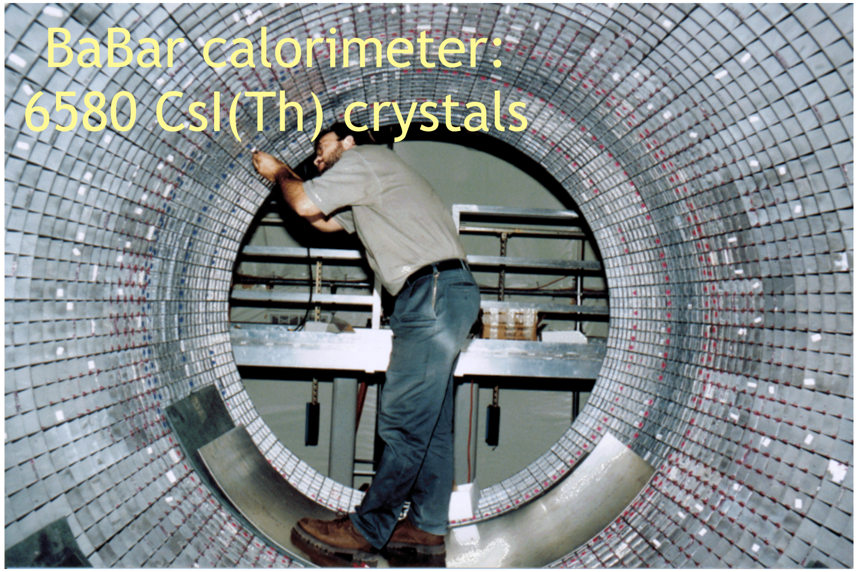
- **Old method**: use a homogenous substance to trace out the entire motion.
- **Modern method**: take several position measurements as charged particle passes. Reconstruct a '**track**'
- **CDF Silicon detector**: charged particle ionises silicon semiconductor. Six very accurate position measurements per track
- **CDF Drift chamber:** large volume filled with argonne-ethane-CF_4 mixture. Gas is ionised and drifts towards cathode and anode wires. Up to 96 position measurements per track.



Electromagnetic and Hadronic Calorimeters

- **Calorimeters** measure the energy deposited when particles are absorbed.
- Electrons, positrons and photons are mainly absorbed in the **electromagnetic calorimeter**.
- Hadrons: ($\pi^{\pm}, K^{\pm}, K^{0}, p, n$) are mainly absorbed in the **hadronic calorimeter.**
- CDF uses a **sampling calorimeter**: sample parts of the shower. Extrapolate to obtain the full amount of energy.
  - CDF electromagnetic calorimeter: Lead + light sensitive scintillator.
  - CDF hadronic calorimeter: Iron + light sensitive scintillator.

- Better energy measurements may be made using a **homogeneous calorimeter** -
- A **homogeneous calorimeter** measured *all* deposited energy
  - scintillating crystals (*e.g.* Caesium Iodide)
  - Cryogenic liquids (argon, krypton, xenon).

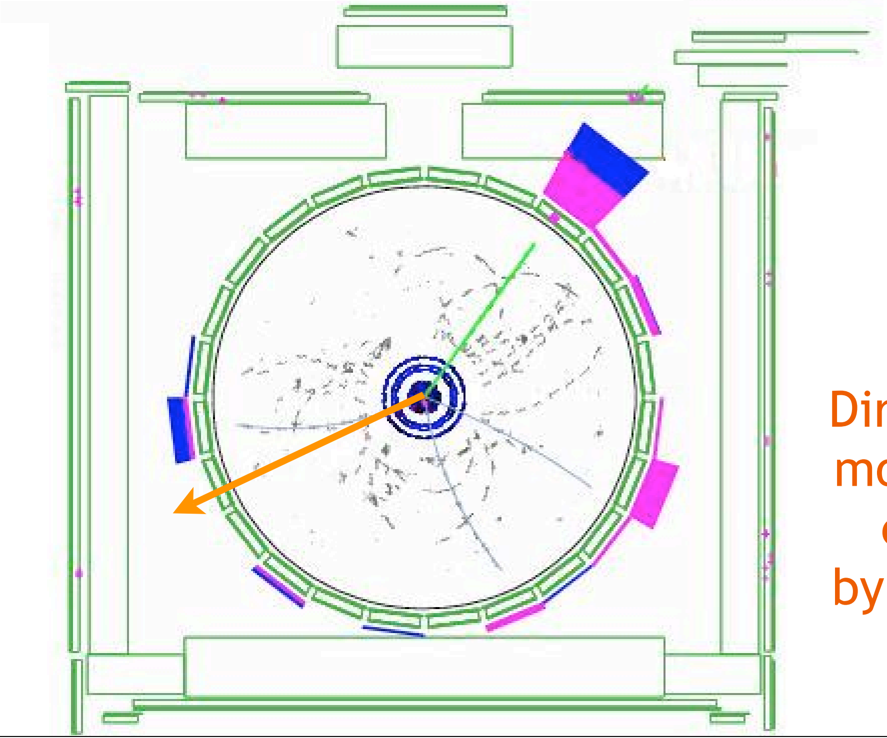


Neutrino Identification at Colliders

- Neutrinos are not charged and only interact via the weak force
  ⇒ they do not interact at all in the detector.

$$\sum \vec{p}_{\text{initial}} = \sum \vec{p}_{\text{final}}$$

  - The initial momentum of the collision is along beam direction, no perpendicular component.
  - Total reconstructed momentum perpendicular to the beam should sum to zero.
  - We infer neutrinos from absence of momentum seen in a particular direction.



Direction of momentum carried by neutrino

We'll talk about the signal produced by quarks in a detector in lecture 6.

Summary

- We accelerate particles to obtain more E_{CM} in order to produce new, as yet, undiscovered particles.

- Long-lived charged particles may be accelerated in a magnetic field.
- An accelerator complex uses a system of **Linacs** and **Synchrotrons** to accelerate particles to the desired energy.
- Synchrotrons can also be used to store energetic particles.
- Synchrotron radiation: energy loss due to photon emission
  - ➡ energy need to be added back to beam at a collider
  - ➡ can be exploited produce high frequency gamma rays

- **Particle detectors** strive to reconstruct all long-lived particles.
- System of complex subdetector systems used to reconstruct position, momentum, energy and particle type.
- Charged particles leave several position measurements in the tracking detector. Positions are joined up to trace out a ‘track’, used to reconstruct the momentum.
- Most particles (except muons and neutrinos) loose their energy in calorimeters, allowing the energies of these particles to be measured.