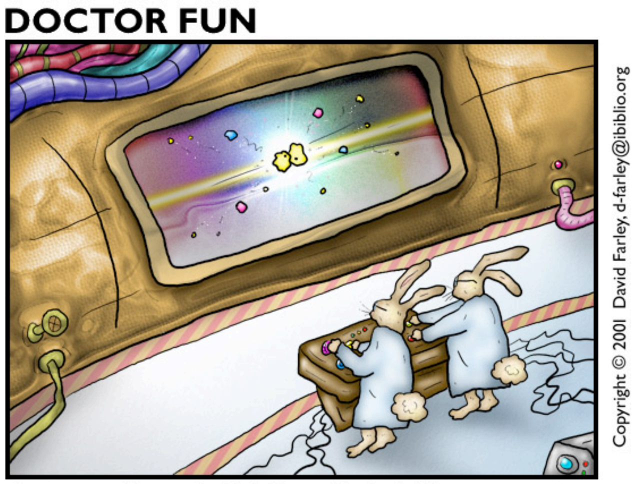
Nuclear and Particle Physics Junior Honours:

Particle Physics

Lecture 4: Accelerators and Detectors

February 19th 2007



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:**
  - Interactions of particles with matter
  - A modern collider detector
  - particle identification

Particle Acceleration

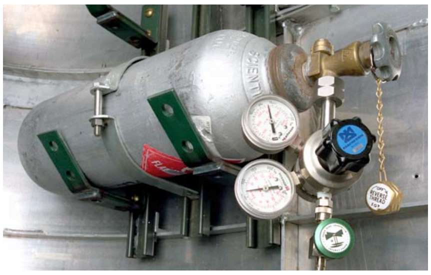
- Charged particles are accelerated to high momenta using electromagnetic fields: e^+, e^-, p, p̄, Au, Pb, Cu nuclei, $\mu^\pm$
- Why accelerate particles?
  - High beam energies ⇒ high E_{CoM} ⇒ more energy to create new particles
  - Higher energies probe shorter physics at shorter distances
  - De-Broglie 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 usually uses a variety of particle acceleration techniques to reach the final energy.

Particle Physics Colliders around the World

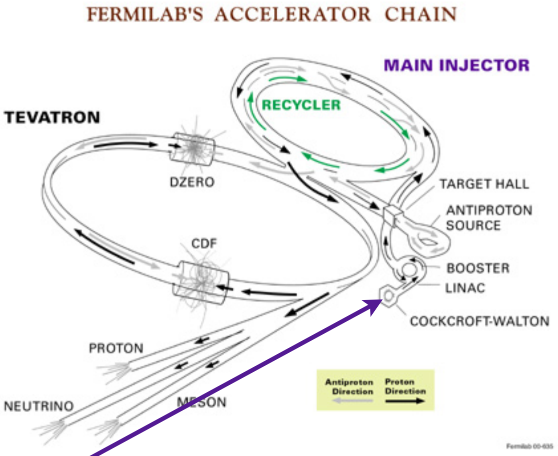
SLAC, California	SLC	$e^- e^+$	50 GeV e^- and 50 GeV e^+
	PEP II	$e^- e^+$	9.0 GeV e^- and 3.1 GeV e^+
Fermilab, near Chicago	Tevatron	$p\,\bar{p}$	980 GeV p and 980 GeV $\bar{p}$
CERN, Geneva	LEP	$e^- e^+$	E_{CoM}: 89 to 206 GeV
	LHC	p p	E_{CoM}: 14 TeV
DESY, Hamburg	HERA	$e^- p$	920 GeV p and 30 GeV e^-
KEK, near Toyko	KEKB	$e^- e^+$	8.0 GeV e^- and 3.5 GeV e^+
Brookhaven National Lab, Long Island	RHIC	AuAu, CuCu	200 GeV/nucleon

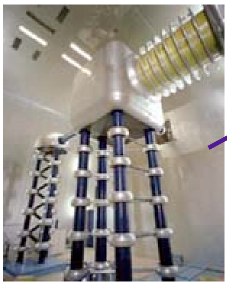
The Tevatron Complex

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



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



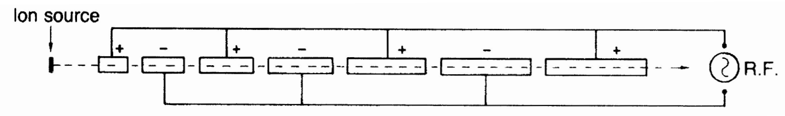


Cockroft-Walton Accelerator
DC Voltage accelerates particles through steps to about 1MV

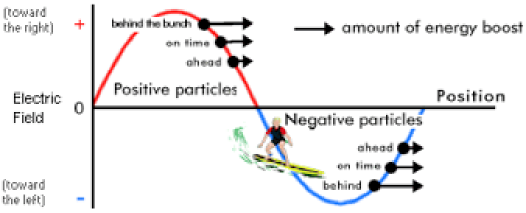
Linac

- After Cockfroft-Wolton is the linac: **lin**ear **ac**celerator.
- Charged particles in vacuum tubes accelerated by an alternating current, with a very high frequency, “Radio Frequency” (RF)
- frequencies typically a few 100 MHz
- Field strengths – few MV/m requires specialised power sources: klystrons

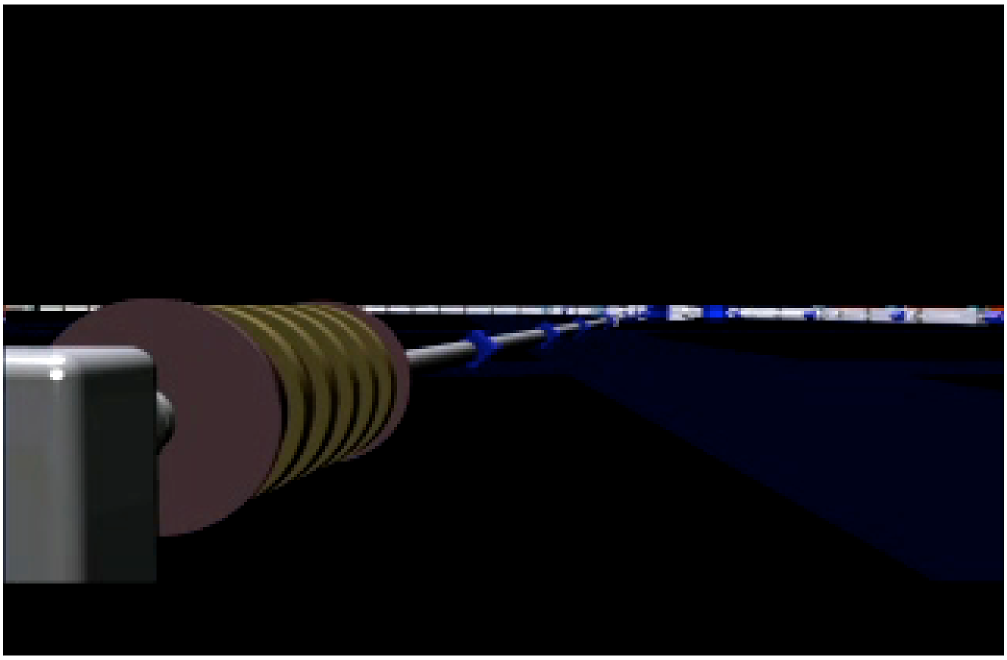
150 m long, accelerates protons to 400 MeV



- 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.

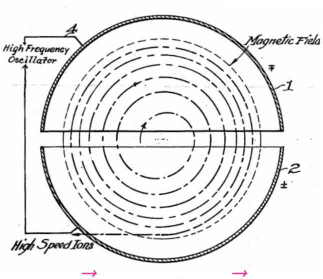


Linac Animation

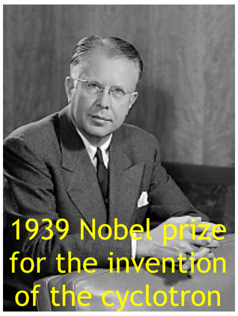


Cyclotrons and Synchrotrons

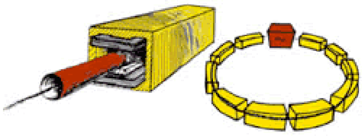
- **The Cyclotron - invented by Ernest Lawerence**
- **Two D-shaped electrodes - perpendicular magnetic field**
    - Constant frequency AC current applied to each electrode
    - Can to accelerate particles to ~10 MeV
    - At higher energies relativistic effects take over, circular path cannot be maintained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

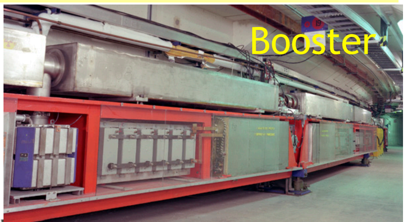


- Series of bending and focussing magnets

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

Synchrotrons at the Tevatron

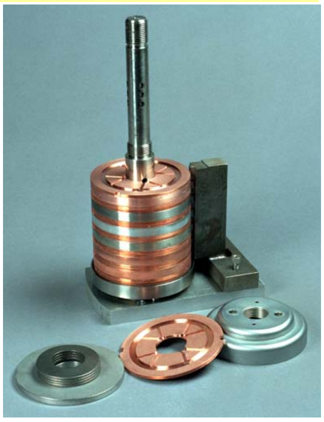
- Many synchrotrons used at the Tevatron:
    - **Booster**: proton energy from 400 MeV to 8 GeV
    - **Accumulator**: stores antiprotons at 8 GeV
    - **Main Injector**: 8 GeV to 120 GeV
    - **Tevatron**: 120 GeV to 980 GeV
- Storage ring: once particles have desired energy, they can be stored. 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).


Booster

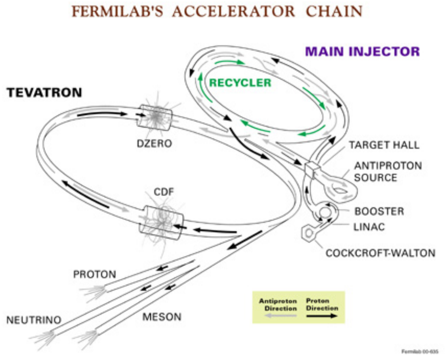

RF Power Supplies for the Main Injector


Tevatron

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 p̄.
- 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...

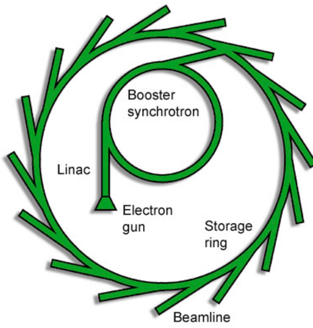
Synchrotron Radiation

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

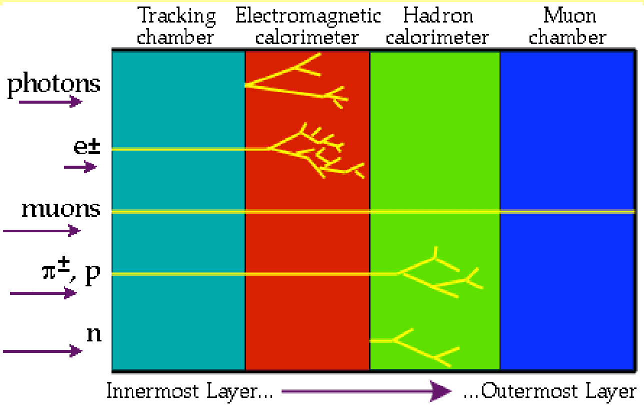
- The energy lost every turn depends of the energy and mass of the particle (**$\gamma = E/m$**) and the radius of the orbit, **ρ**:

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

- 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.



Interactions with Matter

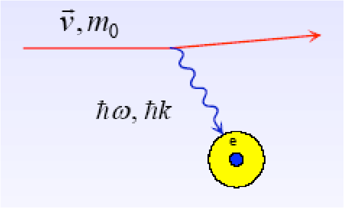


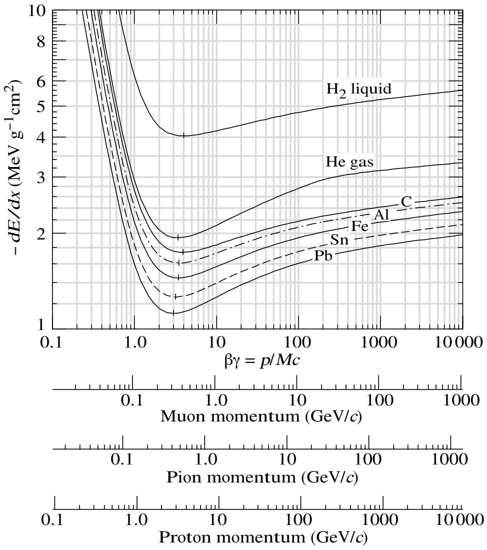
- At an experiment we have to be able to detect all the particle that live long enough to interact with the detector.
- Detector is generally a few centimetres from the interaction point.
- Length travelled before decay is $L=\beta\gamma c\tau$, anything with $\tau>\sim10^{-10}$ s might appear in detector
    - $e^{\pm}$, $\mu^{\pm}$, $\pi^{\pm}$, $K^{\pm}$, K^0, p, n, γ, ν
- 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.
- Energy loss of charged particles by ionisation is given by Bethe-Bloch formula:

$$\left\langle \frac{dE}{dx} \right\rangle = -4\pi N_A r_e^2 c^2 z^2 \frac{Z}{A}\frac{1}{\beta}^2 \left[\log\left(\frac{2m_e\gamma^2\beta^2c^2T^{\max}}{I^2}\right) - \beta^2 - \frac{\delta}{2}\right]$$

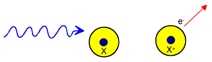




- N_A: Avogadro's number
- Z, A atomic and mass number of medium
- r_e=2.82 fm (classical radius of electron)
- T^{max} - maximum kinetic energy of particle
- I - excitation energy
- $x=\rho d$ density times distance
- dE/dx - energy lost per x [MeVg^{-1}cm^2]

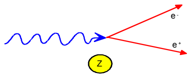
Interactions of Photons

- Photons are neutral, Bethe-Bloch formula does not apply.
- Photons can create charged particles (*e.g.* $\gamma \rightarrow e^+e^-$) or transfer energy to charged particles:
    - low energies (<100 keV): Photoelectric effect



$\gamma + \text{atom} \rightarrow \text{atom}^+ + e^-$

- medium energies (~1 MeV): Compton scattering
- high energies (> 10 MeV): e+e– pair production in electric field of nucleus



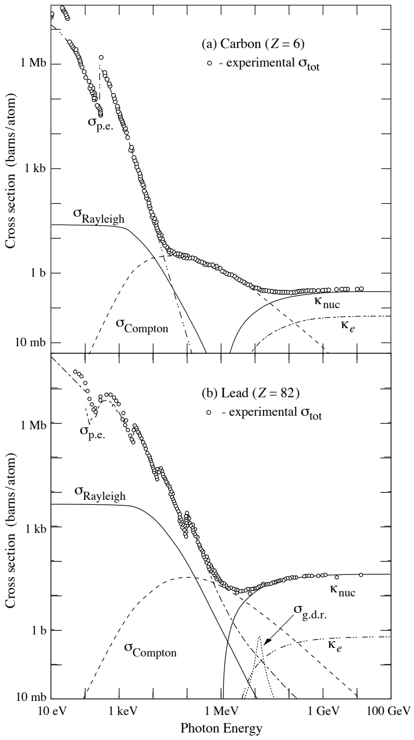
$\gamma + \textit{nucleus} \rightarrow e^+e^- + \textit{nucleus}$

- Intensity of photon energy decreases over distance:

$$I_\gamma = I_0 \exp(-\mu x)$$

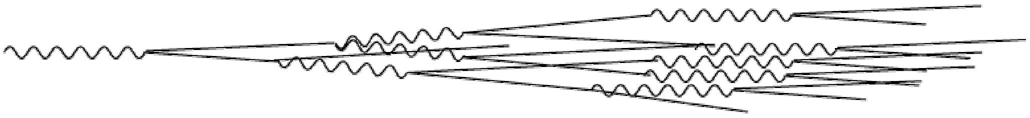
$$\mu = \mu_{\text{photo}} + \mu_{\text{Compton}} + \mu_{\text{pair}}$$

$$\mu_i = \frac{N_A}{A}\sigma_i \quad [\text{cm}^2/\text{g}]$$



Interactions of electrons and positrons

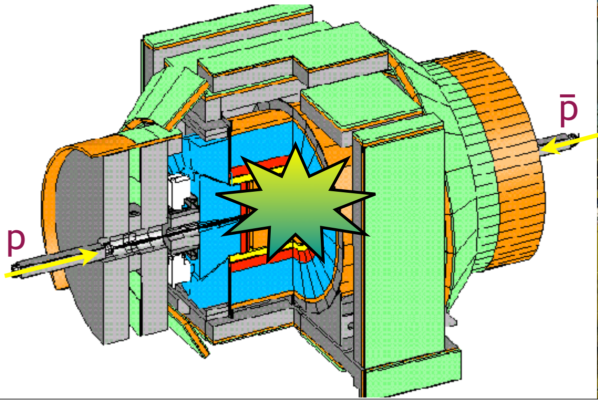
- Response of electrons, positrons and photons are inter-linked.
- In addition to ionisation energy loss, electrons lose energy by Bremsstrahlung: $e^- \rightarrow e^-\gamma$
- Positrons annihilate with electrons in matter making pairs of photons: $e^+e^- \rightarrow \gamma\gamma$
- For **e+, e−, γ**: end result is an **electromagnetic shower**. Total energy transferred to detector is related to initial energy of the particle.

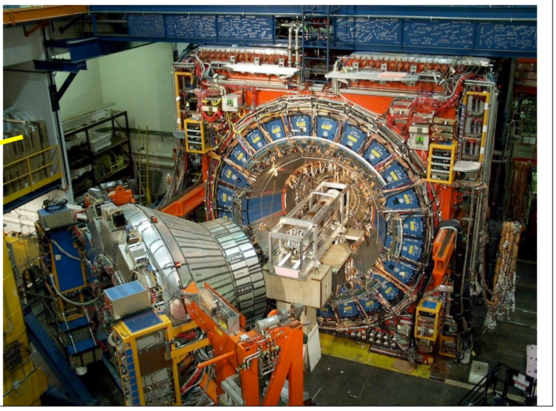


A Modern Collider Detector

- Use CDF at the Tevatron as an example.
- Most collider detectors are quite similar - same components blocks: 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



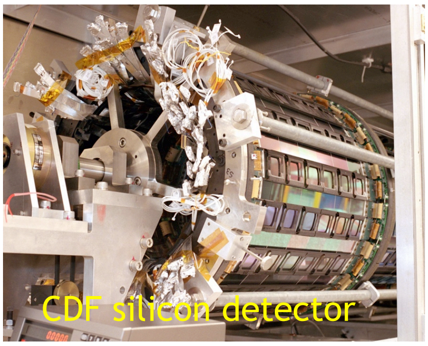


Charged Particle Tracking

- Charged particle trajectories are curved in magnetic fields.
- Measure the momentum transverse to the field.

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

- **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**'
- **Silicon detector**: charged particle ionises silicon semiconductor. Six very accurate position measurements.
- **Drift chamber:** large volume filled with argonne-ethane-CF_4 mixture. Gas is ionised and drifts towards cathode and anode wires. 96 position measurements per track.



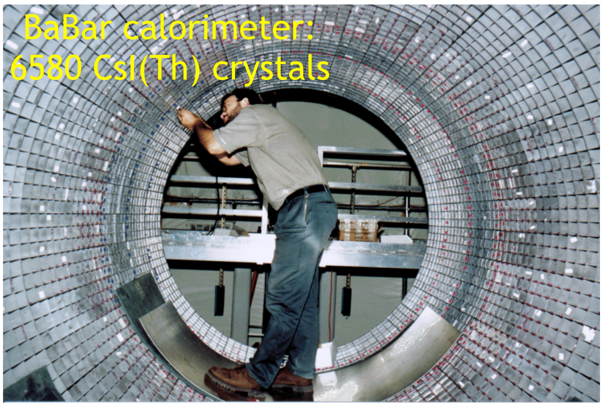
CDF silicon detector

CDF gaseous tracker

Electromagnetic and Hadronic Calorimeters

- Electrons, positrons and photons produce **electromagnetic showers**
- Hadrons: ($\pi^{\pm}$, $K^{\pm}$, K^0, p, n) produce **hadronic showers**
- Calorimeters measures the energy deposited.
- 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.

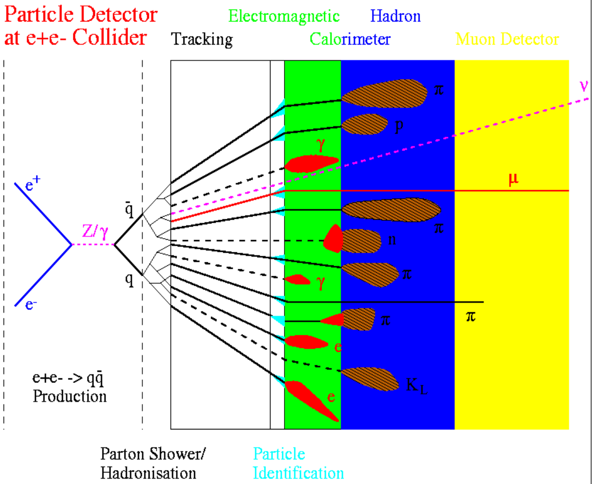
- Better energy measurements may be made using a **homogeneous calorimeter** - measures *all* deposited energy *e.g.* scintillating crystals (NaJ, CsI, BGO, ...) or cryogenic liquids(argon, krypton, xenon).


BaBar calorimeter:
6580 CsI(Th) crystals

Particle Identification

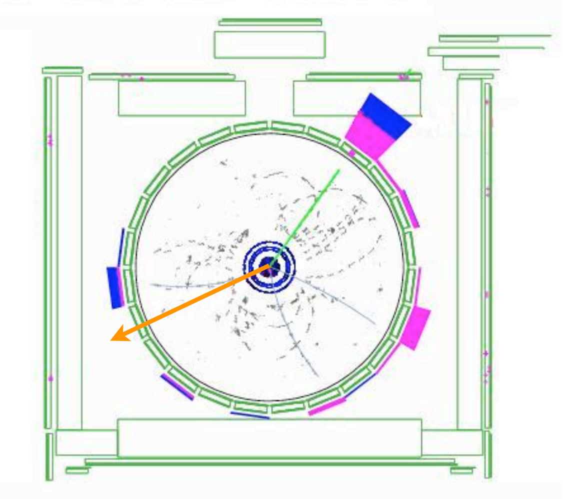
- All charged particles: Hits in the tracking detectors are linked together to reconstruct the ‘tracks’.
- Electrons: A track and a narrow cluster of energy in the electromagnetic calorimeter.
- Muons: Tracks matching to hits in the muon detector.
- Photons: A narrow cluster of energy in the electromagnetic calorimeter, and no track.
- Neutrinos: Inferred from their absence, using an energy balance technique.
- Pions/Kaons/protons: Track and calorimeter energy. energy loss dE/dx can be used to separate p, π and K.
- Neutrons energy in electromagnetic and hadronic calorimeter.

- Use information from all detector subsystems to identify which particle was seen.



Neutrino Identification at Colliders

- **Neutrinos:** Neutrinos are not charged, very small cross section ⇒ they do not interact at all in the detector.
  - Incoming momentum of the collision is along beam direction. Momentum in the detector should balance perpendicular to beam.
  - We infer neutrinos for absence of momentum seen in a particular direction.



Direction of momentum carried away by neutrino

Summary

- We accelerate particles to obtain more E_{CoM} to produce new particles.
- Probes very short distance scales, very short lived particles.

- Linacs and Synchrotrons are main accelerating structures.
- 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 light

- Particle detectors strive to reconstruct all long-lived particles.
- System of complex subdetector systems used to reconstruct position, momentum, energy and particle type.