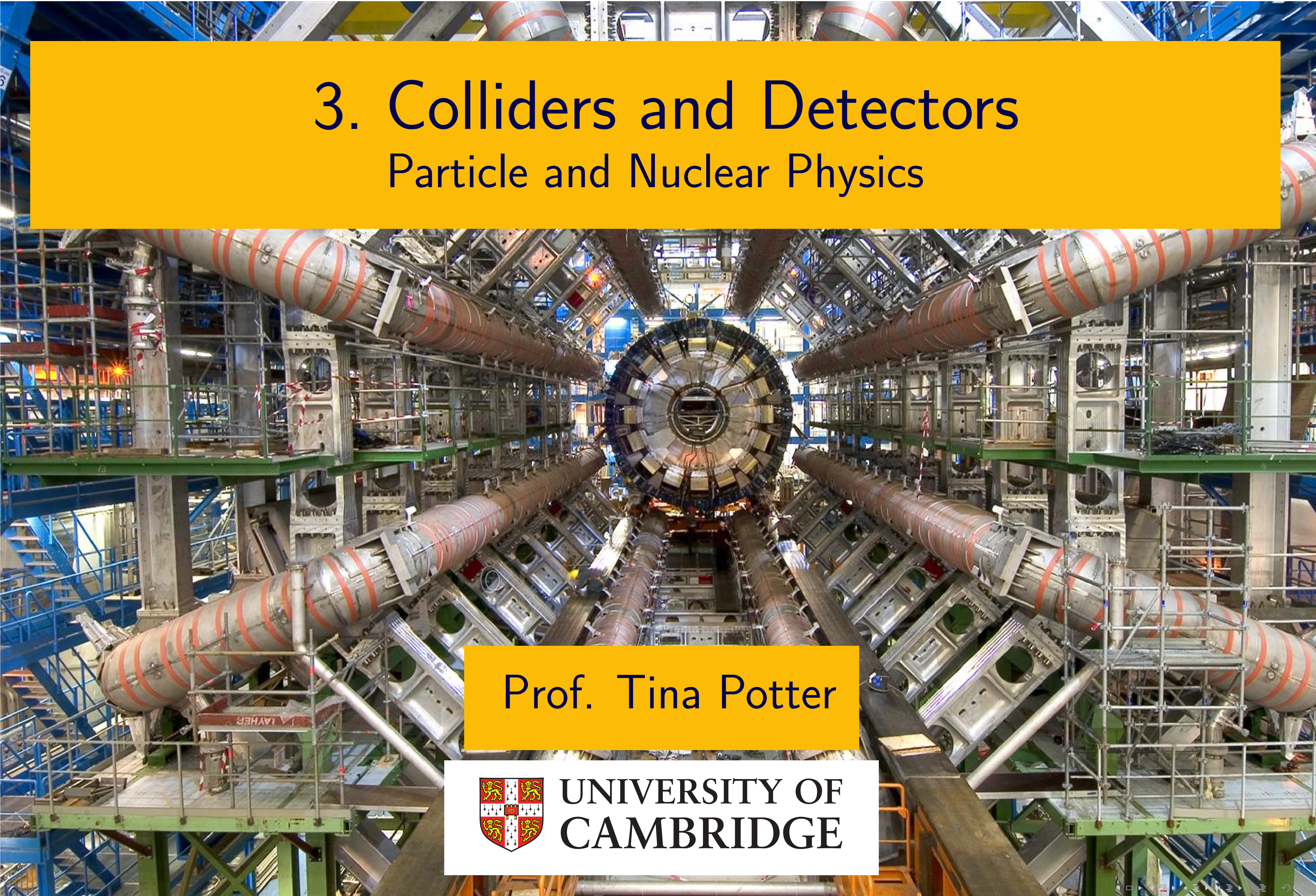
3. Colliders and Detectors

Particle and Nuclear Physics



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In this section...

- Physics of colliders
- Different types of detectors
- How to detect and identify particles

Colliders and $\sqrt{s}$

Consider the collision of two particles:

$$\longrightarrow \quad \cdot \quad \longleftarrow$$

$$p_1 = (E_1, \vec{p}_1) \qquad p_2 = (E_2, \vec{p}_2)$$

The invariant quantity $s = E_{CM}^2 = (p_1 + p_2)^2$

$$= (E_1 + E_2)^2 - (\vec{p}_1 + \vec{p}_2)^2$$

$$= E_1^2 - |\vec{p}_1|^2 + E_2^2 - |\vec{p}_2|^2 + 2E_1E_2 - 2\vec{p}_1.\vec{p}_2$$

$$= m_1^2 + m_2^2 + 2(E_1E_2 - |\vec{p}_1||\vec{p}_2|\cos\theta)$$

θ is the angle between the momentum three-vectors

$\sqrt{s}$ is the energy in the centre-of-mass frame; it is the amount of energy available to the interaction e.g. in particle-antiparticle annihilation it is the maximum energy/mass of particle(s) that can be produced.

Colliders and $\sqrt{s}$

Fixed Target Collision

$$\overrightarrow{} \quad \cdot$$

$$p_1 = (E_1, \vec{p}_1) \quad p_2 = (m_2, 0)$$

$$s = m_1^2 + m_2^2 + 2E_1 m_2$$

$$\text{For } E_1 \gg m_1, m_2$$

$$s \sim 2E_1 m_2 \quad \Rightarrow \quad \sqrt{s} \sim \sqrt{2E_1 m_2}$$

e.g. 450 GeV proton hitting a proton at rest:

$$\sqrt{s} \sim \sqrt{2 \times 450 \times 1} \sim 30 \text{ GeV}$$

Collider Experiment

$$\overrightarrow{} \quad \cdot \quad \overleftarrow{}$$

$$p_1 = (E_1, \vec{p}_1) \quad p_2 = (E_2, \vec{p}_2)$$

$$s = m_1^2 + m_2^2 + 2(E_1 E_2 - |\vec{p}_1||\vec{p}_2| \cos\theta)$$

$$\text{For } E_1 \gg m_1, m_2 \quad |\vec{p}| = E, \quad \theta = \pi$$

$$s = 2(E^2 - E^2 \cos\theta) = 4E^2 \Rightarrow \sqrt{s} = 2E$$

e.g. 450 GeV proton colliding with a 450 GeV proton:

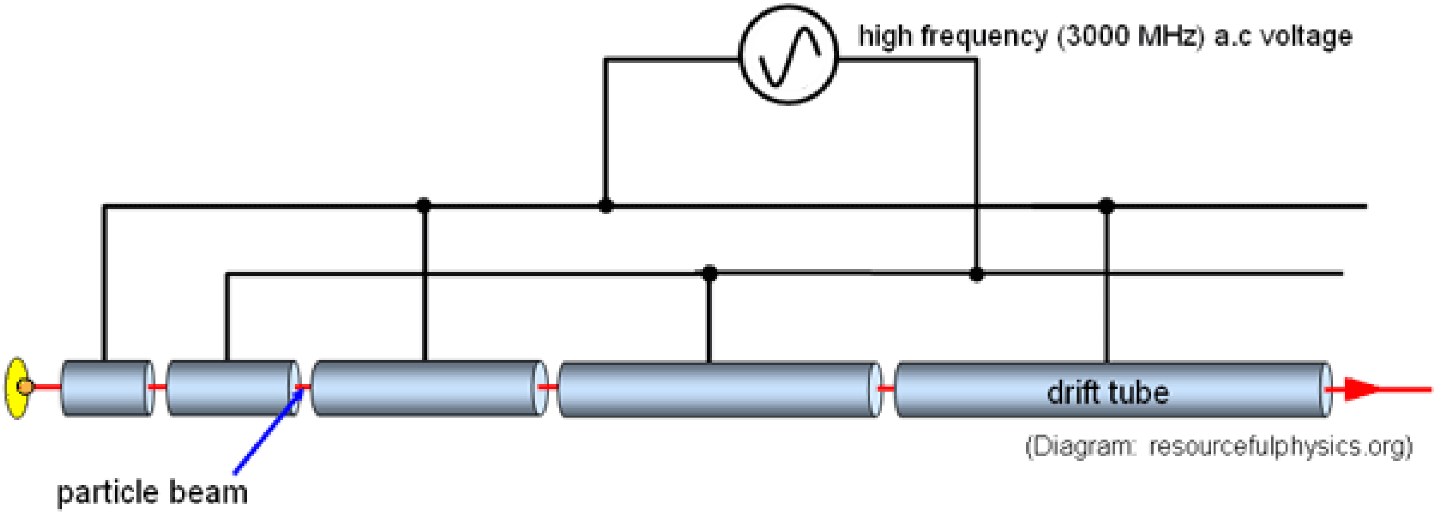
$$\sqrt{s} \sim 2 \times 450 = 900 \text{ GeV}$$

In a fixed target experiment most of the proton's energy is wasted providing forward momentum to the final state particles rather than being available for conversion into interesting particles.

Colliders

To produce and discover heavy new particles, we need high E_{CM}.
Need to collide massive particles at high energies!

Accelerate charged particles using RF high-voltage

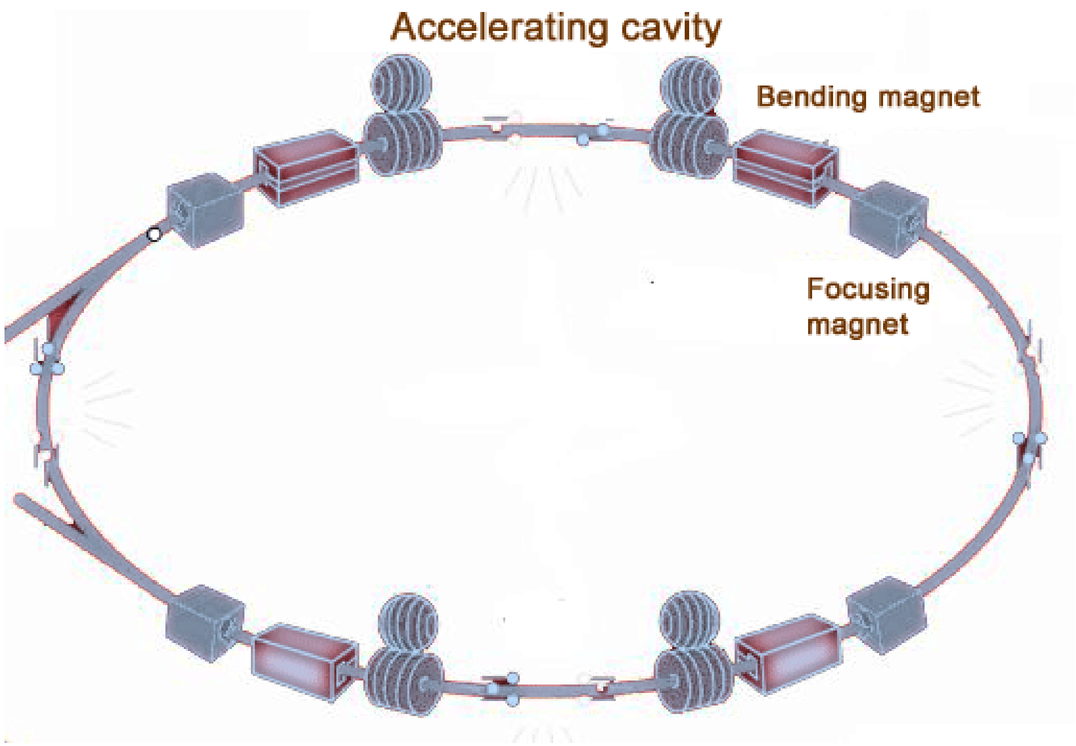


Energy gained with each electric field $\Delta E = qV$
Limited by space! SLAC 3.2 km long, reached $E_e = 50\ \mathrm{GeV}$

Colliders

To produce and discover heavy new particles, we need high E_{CM}.
Need to collide massive particles at high energies!

Accelerate charged particles using RF high-voltage, bend using magnets.



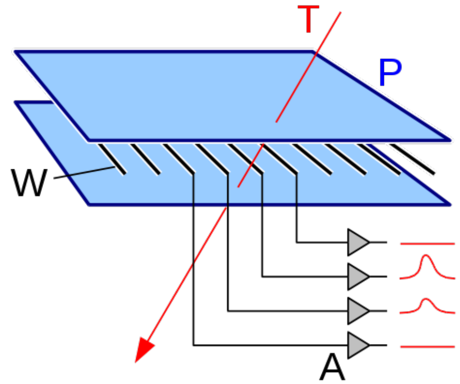
High power magnets needed

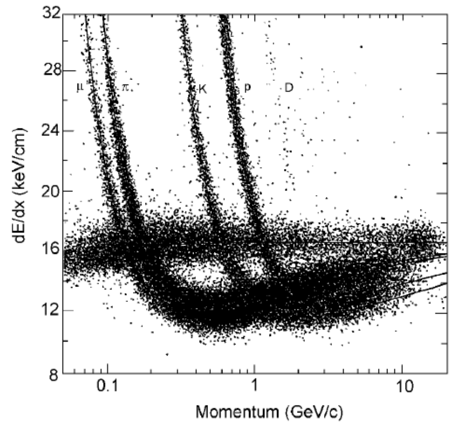
$$B = \frac{p[\text{ GeV}]}{0.3r[\text{m}]}$$

Limited by synchrotron radiation

$$\text{radiated energy per orbit} = \frac{E^4}{m^4 r}$$

Trackers detect ionisation loss
$\Rightarrow$ only detect charged particles
e.g. multiwire proportional chambers, cloud chambers

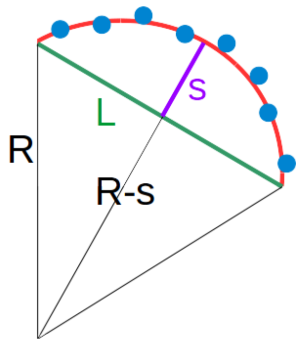




Ionisation loss given by Bethe-Block formula depends on particle charge q and speed β, γ (not mass)

$$-\frac{dE}{dx} = \frac{4\pi N_0 q^2 \alpha^2 (\hbar c)^2}{m_e \beta^2} \frac{Z}{A} \left[\log\left(\frac{2 m_e \gamma^2 \beta^2}{I} \right) - \beta^2 \right]$$

Immerse tracker in $\vec{B}$ to measure track radius, and thus particle momentum p.
Measure sagitta s from track arc $\rightarrow$ curvature R



$$R = \frac{L^2}{8s} + \frac{s}{2} \sim \frac{L^2}{8s}$$

$$p = 0.3B\left(\frac{L^2}{8s}\right)$$

$$\frac{\sigma_p}{p} = \frac{\sigma_s}{s} = \frac{8p}{0.3BL^2}\sigma_s$$

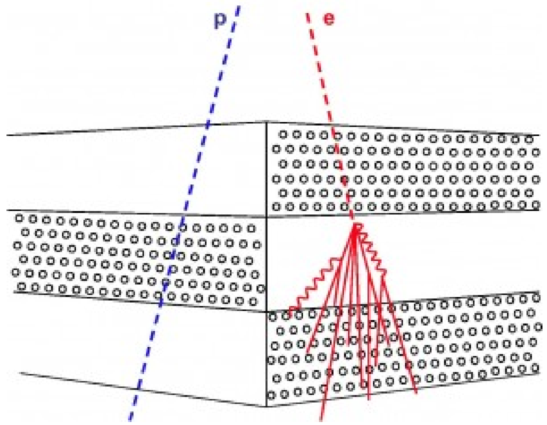
High-p particles have high radius of curvature
$\Rightarrow$ track almost straight.
Low-p particles have small radius of curvature
$\Rightarrow$ measure with high accuracy.

$$\frac{\sigma_p}{p} \propto p$$

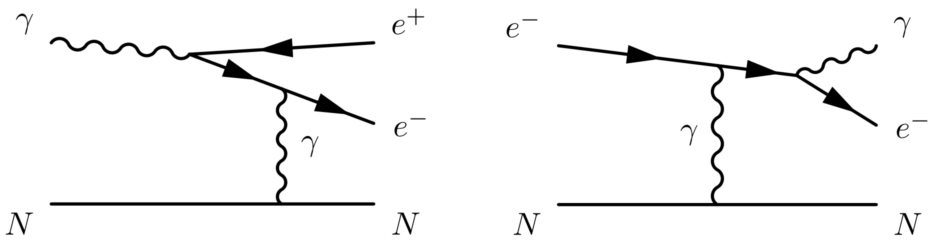
Detecting Particles *Calorimeters*

Calorimeters detect EM/hadronic showers using layers of absorber and scintillating material

High-density material interacts with the particle and initiates shower.



Electromagnetic calorimeter ($e^{\pm}, \gamma$)

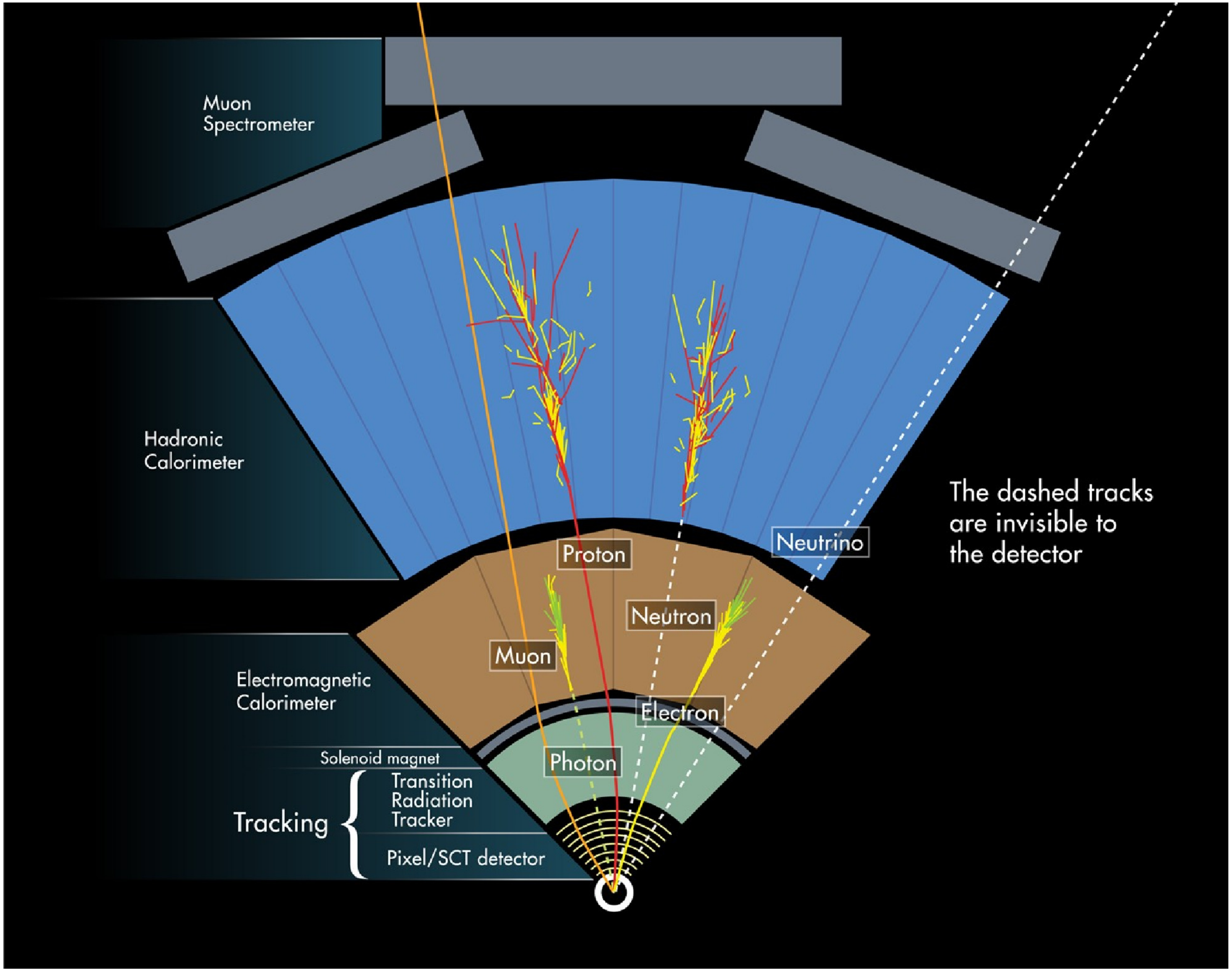


Hadronic calorimeter ($p, n, \pi, K\ldots$)
Nuclear interaction length > radiation length.
Use more (denser) material.

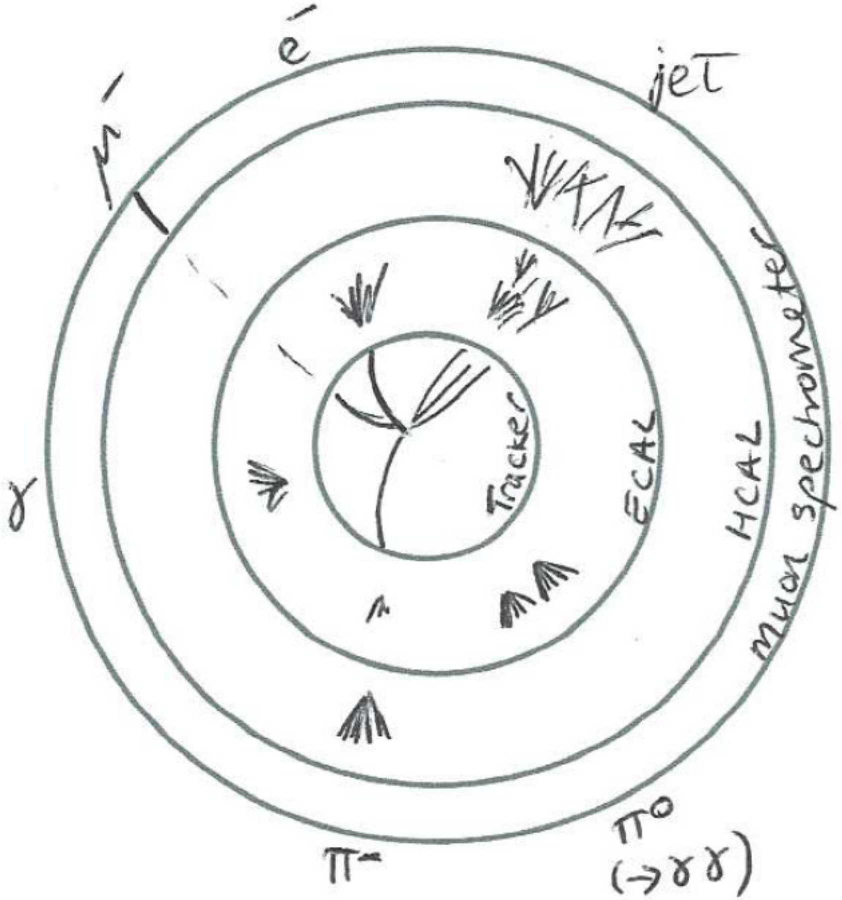
High-energy particles produce showers with many particles
$\Rightarrow$ measure with high accuracy.
Low-energy particles produce showers with few particles
$\Rightarrow$ low accuracy.

$$\frac{\sigma_E}{E} \propto \frac{\sqrt{N}}{E} = \frac{1}{\sqrt{E}}$$

Detector design

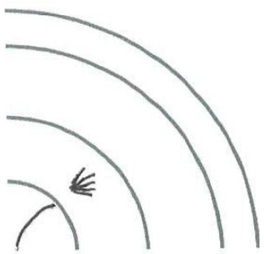


Particle Signatures

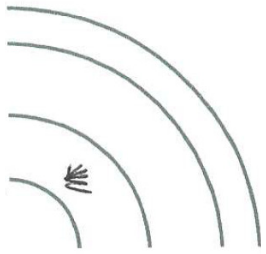


Different particles leave different signals in the various detector components allowing almost unambiguous identification.

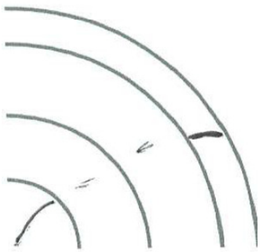
$e^{\pm}$: Track + EM energy
γ: No track + EM energy
$\mu^{\pm}$: Track, small calo energy deposits, penetrating
$\tau^{\pm}$: decay, observe decay products
ν: not detected (need specialised detectors)
hadrons: track (if charged) + calo energy deposits
quarks: seen as jets of hadrons



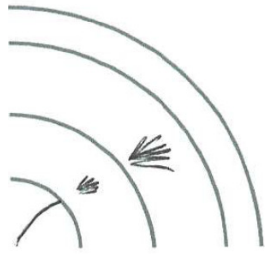
electron



photon



muon



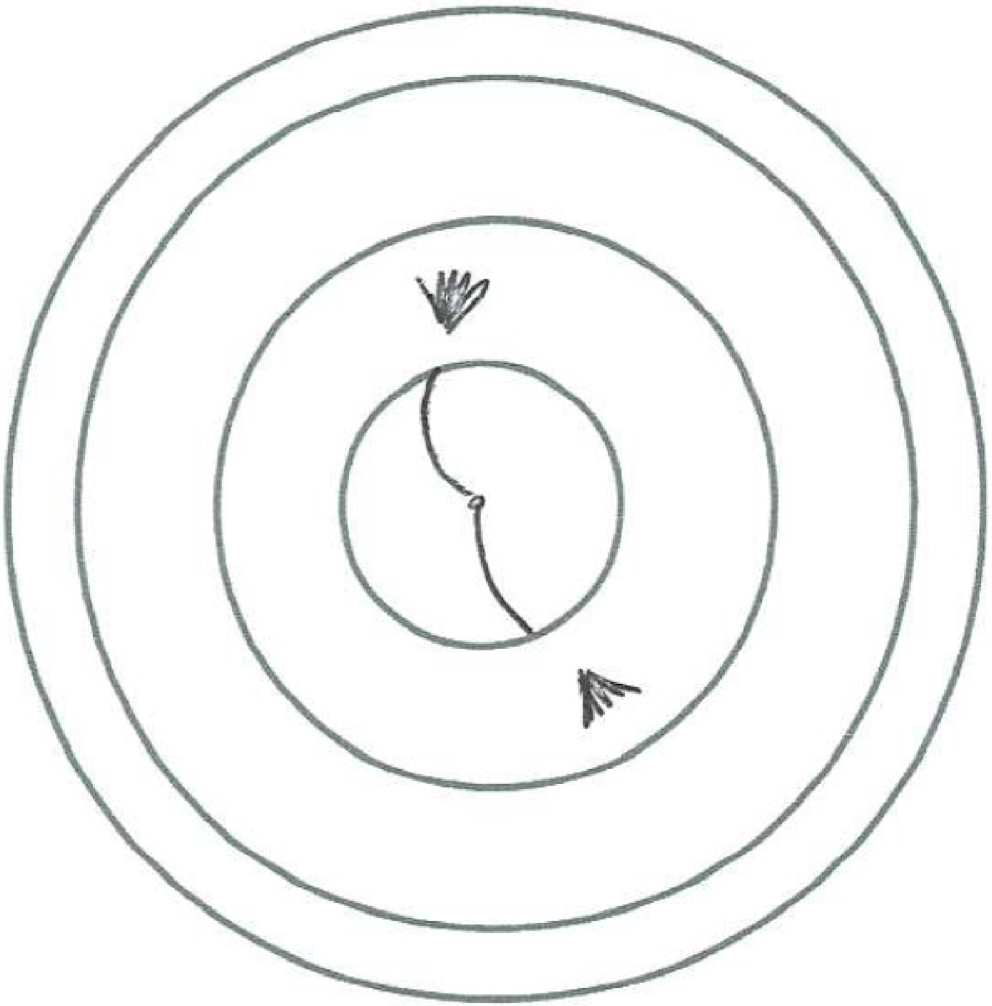
pion

neutrino

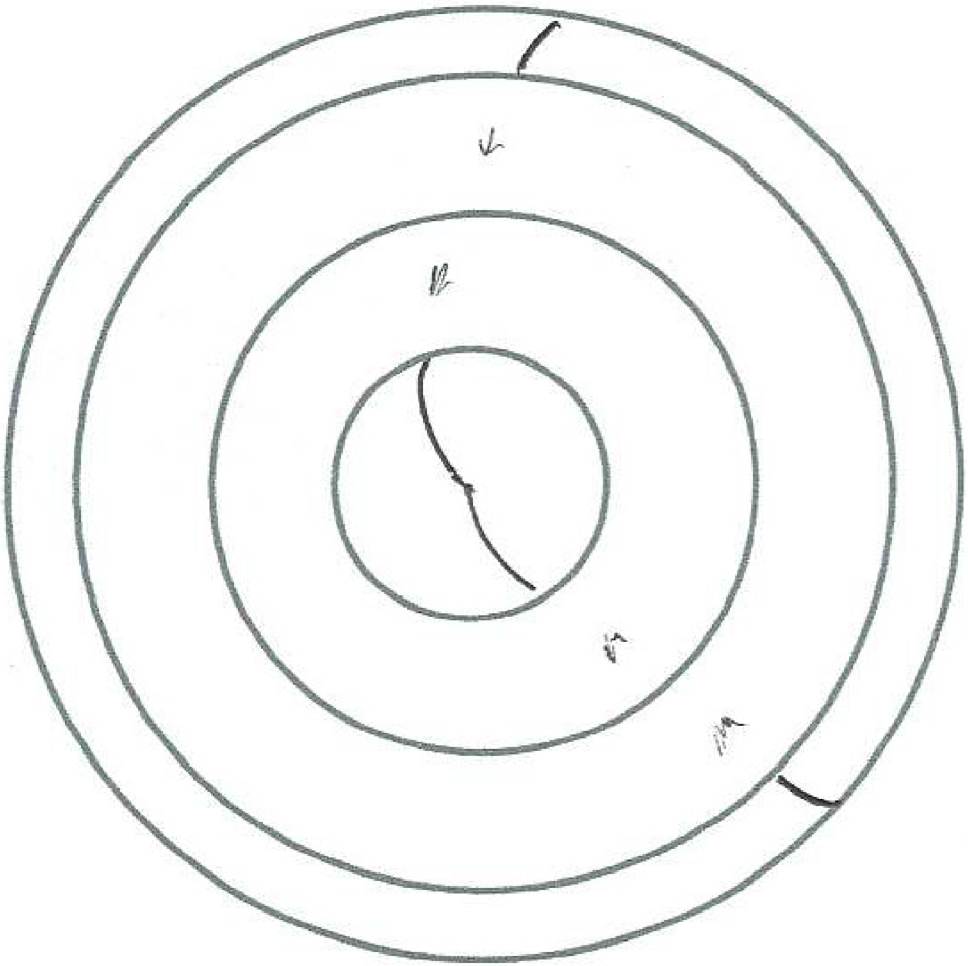
jet

Particle Signatures *Examples*

$e^+e^- \to Z \to e^+e^-$

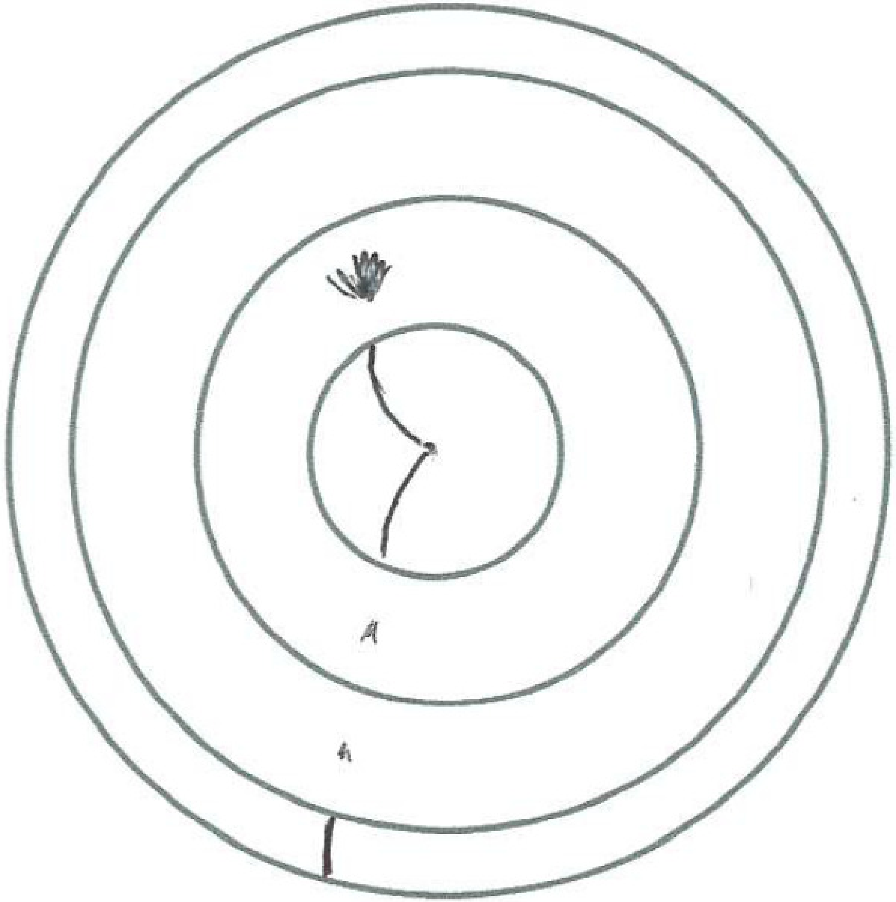


$e^+e^- \to Z \to \mu^+\mu^-$



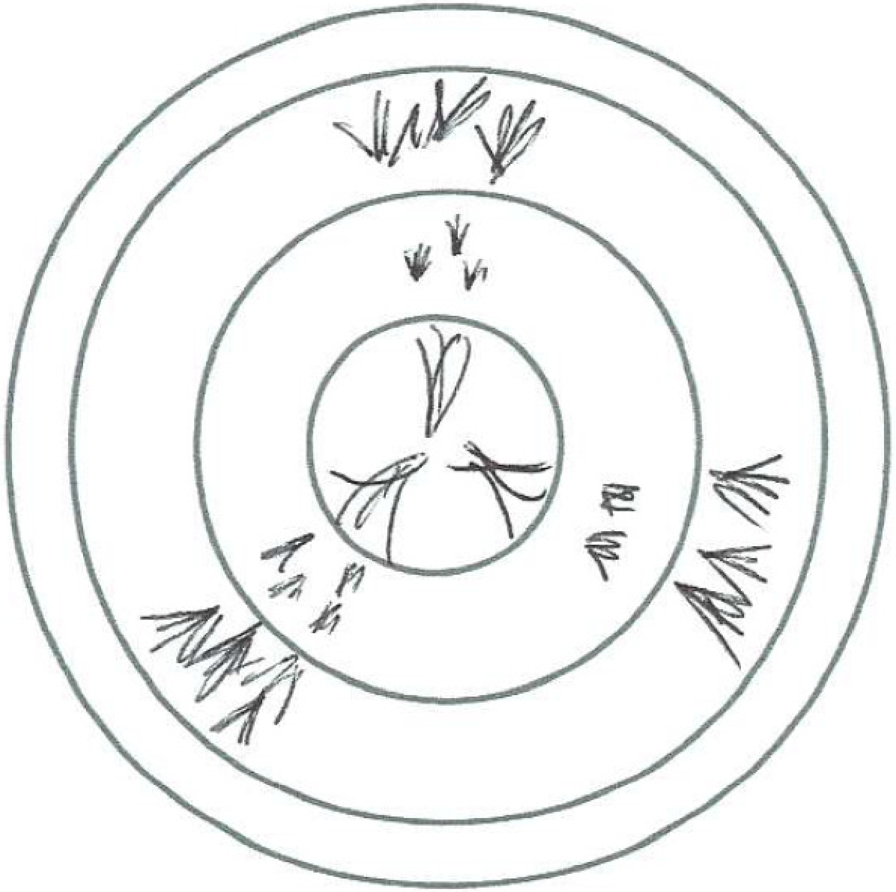
Particle Signatures *Examples*

$e^+e^- \to Z \to \tau^+\tau^-$



Taus decay within the detector (lifetime $\sim 10^{-13}$ s).
Here $\tau^- \to e^-\bar{\nu}_e\nu_\tau$, $\tau^+ \to \mu^+\nu_\mu\bar{\nu}_\tau$

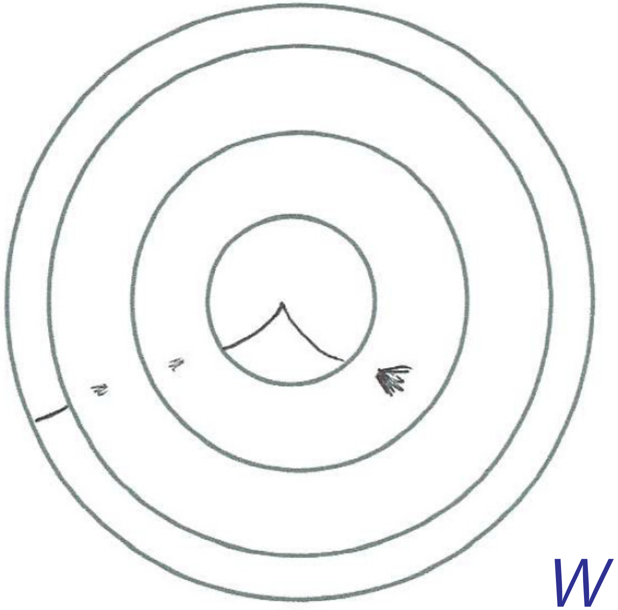
$e^+e^- \to Z \to q\bar{q}$



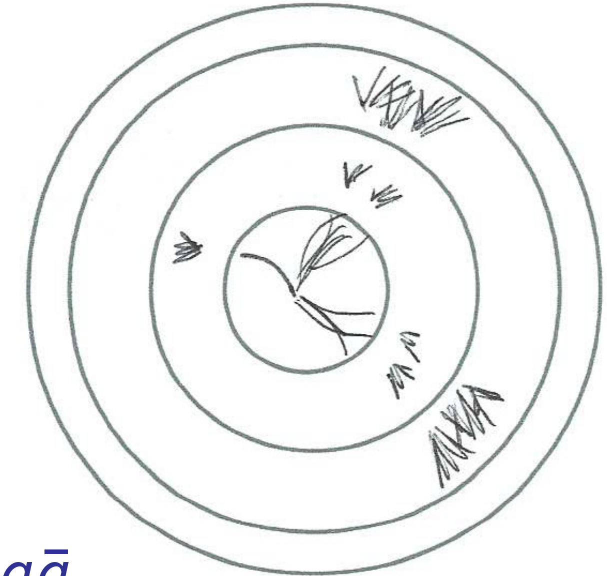
3-jet event (gluon emitted by $q/\bar{q}$)

Particle Signatures *Examples*

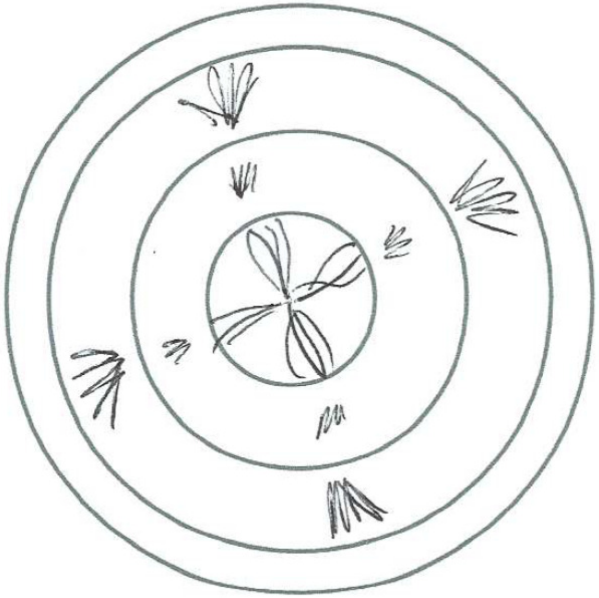
$W^+W^- \to e\nu\mu\nu$



$W^+W^- \to q\bar{q}e\nu$



$W^+W^- \to q\bar{q}q\bar{q}$



Example

e^+e^- collider with typical cylinder detector.
In one event, two electrons are detected:

1. e^+, $E_{\mathrm{cluster}} = 44.7 \pm 1.2$ GeV, $|\vec{p}_{\mathrm{track}}| = 46.0 \pm 3.2$ GeV
2. e^-, $E_{\mathrm{cluster}} = 46.0 \pm 1.2$ GeV, $|\vec{p}_{\mathrm{track}}| = 49.5 \pm 3.5$ GeV

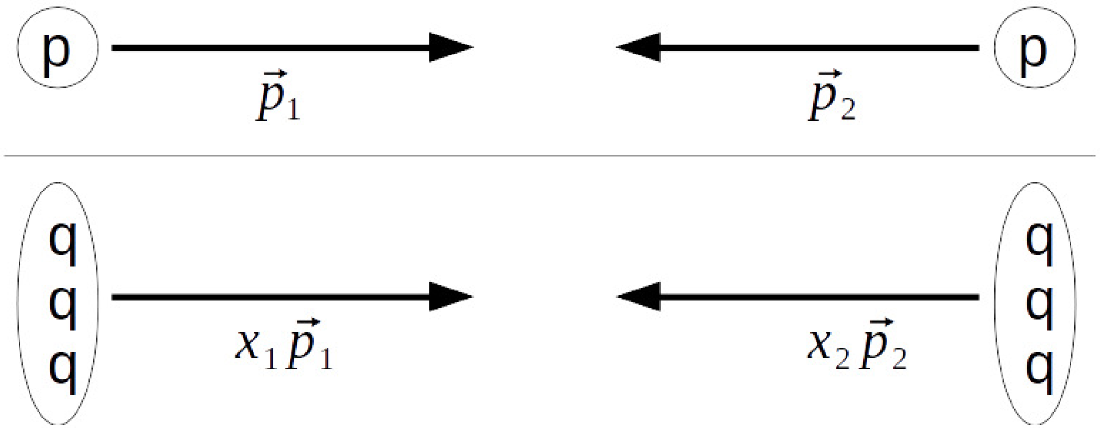
For this event we need

- Lowest order Feynman diagram
- Detector signature
- Invariant mass

Example

Consider *pp* collisions.

Calculate the reduced E_{CM} assuming the colliding quarks carry a fraction x_1 and x_2 of the proton energy.



Summary

- For high $\sqrt{s}$:
  - Prefer colliders over fixed target collisions
  - Prefer circular colliders with high power magnets
  - Prefer to collide high mass particles
- Trackers to trace the path of charged particles
- Calorimeters to stop and measure the energy of particles
- Detector design and particle signatures

Problem Sheet: q.7-9

Up next...
Section 4: The Standard Model