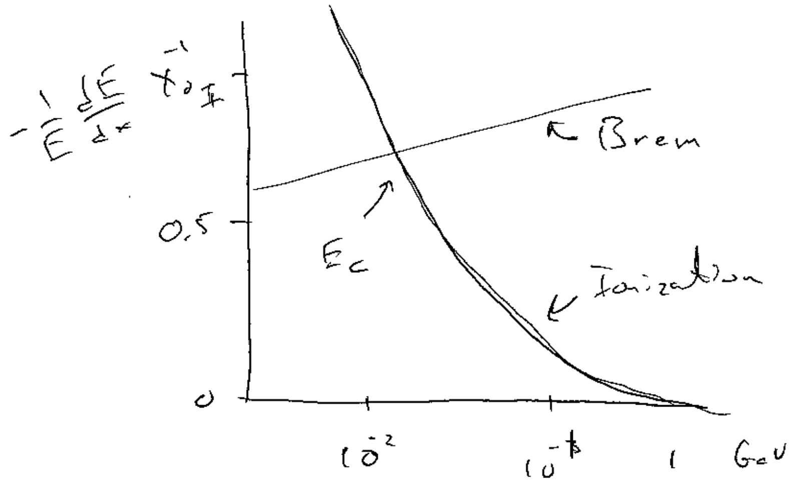
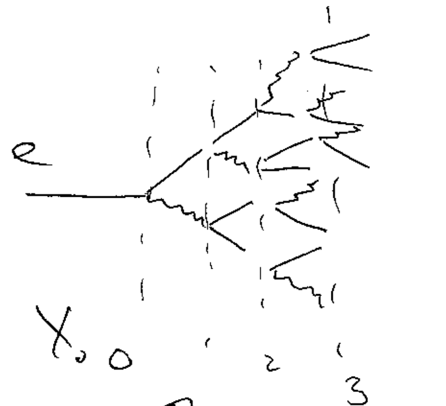
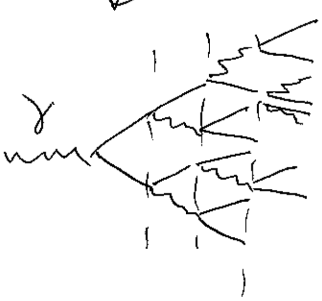


Similar Story for γ's

E_c - critical energy
$\mathcal{O}(10^{-2} - 10^{-1}\ \text{GeV})$



look very similar



"Electro magnetic shower"

- each e (or γ) w $E > E_c$ travels 1 X_0 then gives up $\frac{1}{2}$ energy to γ (or e^+e^-)
- e's, γ's with energy $< E_c$ get absorbed via ionization

If initial Electron $E_0 >> E_c$ then after t - radiation lengths there will be 2^t particles.
~ equal # of electrons / γ's each w/ energy $E(t) = \frac{E_0}{2^t}$

Shower will stop growing when

$$E(t) \simeq E_c \equiv E(t_{max})$$

Point in shower w/ max particles

$$t_{max} = t(E_c) = \frac{\ln(E_0/E_c)}{\ln 2}$$

- shower depth increases ln.
- $N_{max} = \frac{E_0}{E_c}$

For heavier particles Brem does not kick in until much higher energies

eg $E_c \sim 3000$ GeV

↪ for μ in lead

Nuclear Interactions

If particle traversing medium is hadron, can interact via strong interaction.

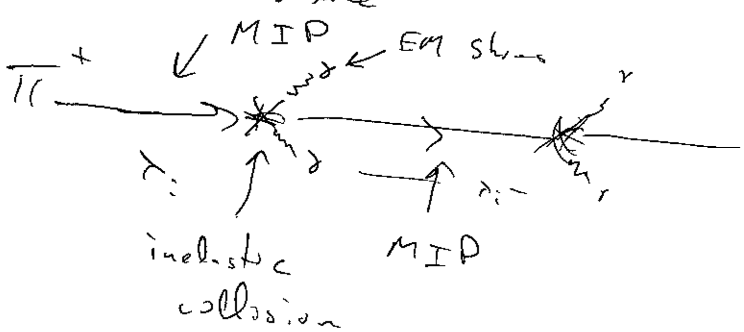
eg $\pi^{\pm}$ moving through detector material will suffer an inelastic collision in distance λ_i

↪ Collision takes energy from π and convert it to additional hadrons (charged + neutral)

"Hadronic Shower" - much more complex than EM showers

Involve a variety of processes @ different length scales.

tracks like



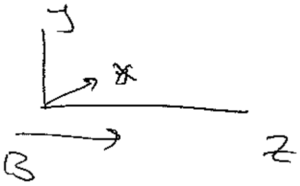
↪ $\begin{cases} \pi^+ \sim 1/3 \\ \pi^0 \sim 1/3 \leftarrow Br(\gamma\gamma) \sim 100\% \Rightarrow \text{EM shower w/ scale } X_0 \\ \pi^- \sim 1/3 \quad \text{travels} \sim 10\text{nm} \end{cases}$

$\pi^{\pm}$ MIPs order λ_i

$\Rightarrow$ Hadronic Showers develop over longer distances and contain much more fluctuations.

Trackers (Ionisation detectors in magnetic field) (1)

Charged particles travelling in magnetic field move in circles



$$\frac{1}{R(m)} = Q\, B(T)\, \frac{0.3}{P_T(\mathrm{GeV})}$$

Particle positions are measured by finely etched Si sensors

$\sim 10\,\mu m$ resolution

What is measured is the curvature $\propto \frac{1}{R} \propto \frac{1}{P_T}$

H.W.

We actually measure Sagitta s

$$\Rightarrow \Delta \frac{1}{P_T} = \frac{\Delta P_T}{P_T^2} \Rightarrow$$ Relative uncertainty in P_T degrades w/ P_T

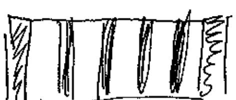
LHC typical performance

$S = \frac{q B L^2}{8 P_T}$ More important to have bigger length than B

$$\frac{\Delta P}{P_T} \sim (\text{few } \%)\left(\frac{P_T}{100\ \mathrm{GeV}}\right)$$

EM Calorimeter

Contains & Measures e's γ's $\pi^0 \to \gamma\gamma$



lead → maximize $\frac{X_0}{m}$

medium sensitive to ionization

Si / LAr

total depth $\sim 20\, X_0$ (Enough to contain high P_T showers).

measure e's here

Only energy deposited in Si / LAr is measured. Rest is lost in lead

Unmeasured

Only a small fraction of total EM shower energy is collected.

$E \sim N_e$ ← Amount that is collected scales like # electrons produced.

~~$\frac{\Delta E}{E} \sim \frac{10\%}{\sqrt{E}}$~~

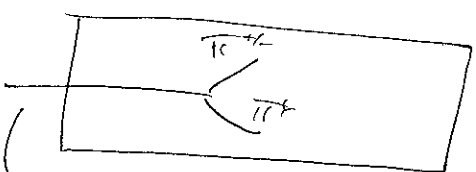
$$\frac{\Delta E}{E} \sim \frac{\Delta N}{N} \sim \frac{1}{\sqrt{N}} \sim \frac{1}{\sqrt{E}}$$

At the LHC typical performance

$$\frac{\Delta E}{E} \sim \frac{10\%}{\sqrt{E}}$$ ← Unlike tracks the relative energy measurement improves with E.

Hadron Calorimeters

Imagine putting a $\pi^{+/-}$ into the detector instead of an e



- total depth $\sim 11 \lambda_I$

→ π will travel further B/c has to interact via strong force (~~[illegible]~~ shorter range than EM)

$\pi^{+/-}$ will make other $\pi^{+/0}$'s & π^0s
- Compared to e's / γ's you will make less particles B/c the π mass is bigger (fewer @ fixed E)

  ⇒ more fluctuations

- Also have much more varied showers depending on what particles are produced $\pi^{+/-}$ vs π^0

Typical performance for hadrons

$$\frac{\Delta E}{E} \sim \frac{50\%}{\sqrt{E}}$$

Muon Detectors

Put tracking detectors outside of the calorimeters
And if any charged particle makes it through
~3 m of lead it has to be a μ.

μ - | no strong interaction
| only rarely radiate γ's (below ~3 TeV)

Neutrino Detectors @ LHC

ν's leave no energy in detector. Can infer
there presence from ~~the~~ momentum imbalance in
transverse plane.

Poor Resolution, B/c have to measure
everything in Event

Trigger

LHC provides bunch crossing @ 40 MHz
each event is ~2 kb => 80 Tb/s
↳ Library of Congress
~10 Tb

Can only afford to keep ~2 Gb/s

Only keep 1/40k events