Q: what is the flux factor @ the LHC?

FF also called $\mathcal{L}$ "instantaneous luminosity"
"luminosity"

$$\mathcal{L} = n_A n_B A_B l \, |v_A - v_B| = \frac{N_A N_B |v_A - v_B|}{Vol}$$

$\hookrightarrow$ Volume of Bunch $= A_B \times l$

Now σ is fixed, so to ~~maximize~~ maximize Events collected, Need to maximize $\mathcal{L}$.

$N = N_A = N_B = 10^{11}$ fixed

$|v_A - v_B| = 2c$ can't get much higher!

$Vol \sim A_B \cdot l$ @ LHC acceleration w/ RF EM field that fixes l (Protons ride the troughs of this field)

$\Rightarrow \lambda$ sets l. $\left(\approx \frac{c}{2 \times 400 \text{ MHz}}\right) \sim \frac{3}{4}$ m

$\hookrightarrow$ wavelength

One handle is A_B, focusing magnets (quadrupoles) act like a lens near the collision points to squeeze the beam. So far focusing magnets have achieved squeezing down to radii of 10 μm! ~ width of human hair.

$$A \approx 10^{-10} \, m^2$$

$$\Rightarrow \mathcal{L} = 2c\frac{N^2}{\ell A} \simeq 2c\, 10^{22}\, \frac{2\times 400\,e6}{c\;\; s}\, \frac{1}{10^{-10}\,m^2}$$

$$\simeq 10^{36}\, cm^{-2}\, s^{-1}$$

Integrated luminosity $L = \int dt\, \mathcal{L}$

Number of Events $= L \cdot \sigma$

Particles moving in a circle accelerating.
Accelerating charged particles radiate. (synchrotron radiation)
Power lost to synchrotron radiation!

$$P \simeq 0.3 \left(\frac{1\,km}{R}\right)^2 \left(\frac{E}{m}\right)^4 \frac{eV}{s}$$

LHC

$\frac{E}{m} \sim 7000$

$R_{LHC} \sim \frac{27\,km}{2\pi}$

$$\simeq 10^5\, GeV/s$$

$\hookrightarrow$ Major draw back of circular colliders

To keep protons in circle need thousands of super conducting bending magnets

$$|\vec{B}| = \frac{|\vec{P}|}{e R_{curv}} \simeq 3\, \frac{E(TeV)}{R(km)}\ \text{Tesla} \Rightarrow E(TeV) \simeq \frac{1}{3} B(T)\, R(km)$$

Most restrictive constraint on increasing energy @ LHC.

Accelerator + Detectors (Cont)

$$E(\text{TeV}) \simeq \frac{1}{3} B(T)\, R(\text{km})$$

Modern super-conducting magnets have max strength $\sim 20\,T$

With current technologies need larger ring to go to significantly higher energy

Efforts now underway for ~ 100 TeV collider
(100 km in geneva)

China also pursuing something similar.

Bunches

$\ell \sim 40\,\text{cm} \qquad A_B \sim (10^{-3}\,m)^2 \quad \Rightarrow \quad Vol_{Bunch} \simeq 10^{-6}\,m^3$

$V_{Protons} = 10^{11}\, r_p^3 \sim 10^{-34}\,m^3$

Proton Beams are mostly empty space!

$$\frac{V_{Proton}}{V_{Bunch}} \sim 10^{-28}$$

Hard to get them to collide.

Focusing Magnets squeeze Beam Size

$A_B \sim (10^{-5}\,m)^2 \quad \Rightarrow \quad V_{Bunch} \sim 10^{-10}\,m^3$

Decrease in Vol Bunch by 10^4 critical for physics program @ LHC

Detectors

Once bunches are accelerated they are made to collide. (Every 25 ns @ LHC)

when protons collide & exchange large amount of momentum, create shower of particles from collision point.

$$|P_1 P_2\rangle_I \longrightarrow |\{P_f^i \cdots P_f^N\}\rangle$$

$t = -\infty$ $\qquad$ $t = +\infty$

Dynamics of the actual collision is imprinted on the final state particles

- Energy Conservation
- mom "
- charge " etc

We want to measure as many particles / + properties as possible.

"Easy" to measure | E + $\vec{p}$ $\left(\Rightarrow m = \sqrt{E^2 - |\vec{p}|^2}\right)$

| charge of leptons hadrons

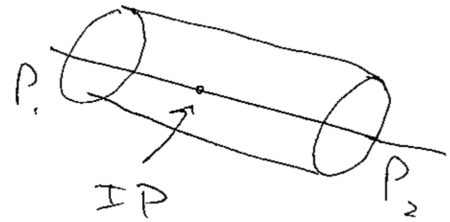
Hard to measure | Angular $\vec{p}$

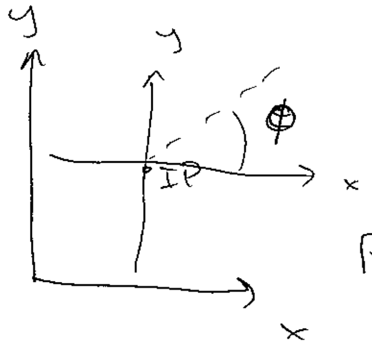
| Spin

Detectors not ~~design~~ built to be sensitive to spins.

Coordinates

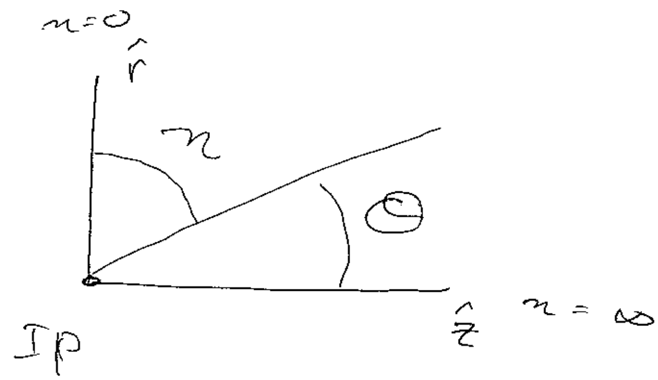
Cylindrical Symmetry





p_x, p_y

$p_T = \sqrt{p_x^2 + p_y^2}$



$\eta = -\ln \tan \frac{\Theta}{2}$ "pseudo-rapidity" $\boxed{\text{Explore this in HW}}$

$y = \frac{1}{2} \ln \frac{E + p_z}{E - p_z}$ "rapidity" $\eta = y$ for $m = 0$

We know $p_T^I = 0$, we don't know p_z^I so often interested in variables (like p_T) that are independent of Boosts along z.

massless particle: $p = p_T(\cosh\eta, \cos\phi, \sin\phi, \sinh\eta)$

massive particle: $= (\underbrace{\sqrt{p_T^2+m^2}}_{m_T} \cosh y, p_T\cos\phi, p_T\sin\phi, \sqrt{p_T^2+m^2}\sinh y)$

m_T m_T - "transverse mass" invariant to Boosts along z.

In order to be detected, a particle must undergo an interaction w/ detector material.

(Agian this is an enourmous subject, scratch surface)

Typically talk about how particles loose energy to the detectors.

3 key mechinisms.

Long range EM force → (Ionisation Energy loss → Interaction w/ electrons in atoms.

Radiation " "

Strong/weak interaction, Both short range → Nuclear interaction) → Interaction w/ atomic nucleus

2 Basic types of detectors

Trackers - Sensitive to Ionisation loss.

- non-destructive $\vec{P}_{in} \simeq \vec{P}_{out}$
- small fraction of energy deposited indicating particle position

Calorimeter - Use Radiation / Nuclear interaction to extract Partical energy

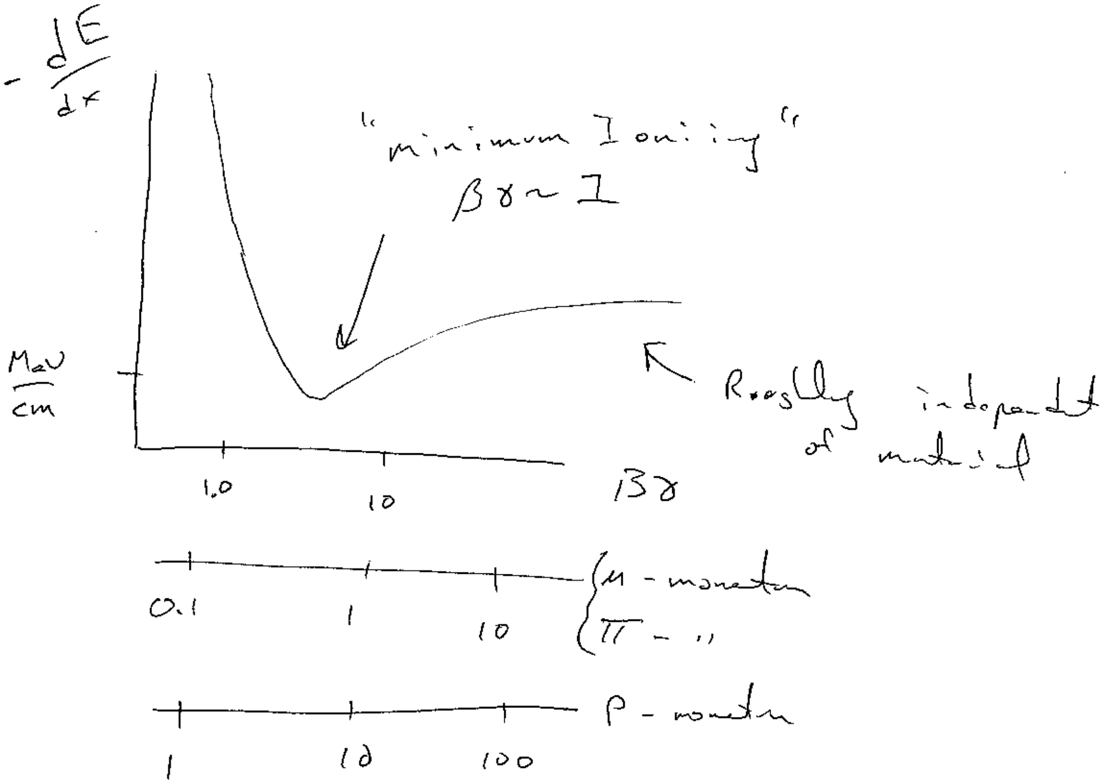
- destructive $\vec{P}_{out} = 0$
- Use ionisation loss to measure energy of Radiation / nuclear loss

Ionisation

fast moving particle that interacts electromagnetically w/ an electron in atom. Kick out electrons from the atom, loose energy

$$\frac{dE}{dx} = -\alpha^2 Q^2 \frac{nZ}{m_e v^2}\left[\log \frac{2\gamma^2 m_e v^2}{\omega} - v^2\right]$$

char. energy difference between states in atom

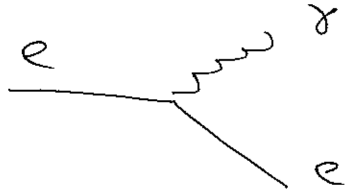


Ionisation dominates as long as particles are not too relativistic. $\beta\gamma \lesssim 1000$

Above this a new effect takes over ...

Radiation loss

At very high energy



← roughly colinear, carries large fraction of initial energy.

"Bremsstrahlung"
German for Braking

Same effect works for γ's

"pair-production"

Typically involve interactions w/ nuclei to conserve 4-mom
← will explore in H.W.

Processes occur infrequently, but very significant events when they occur.

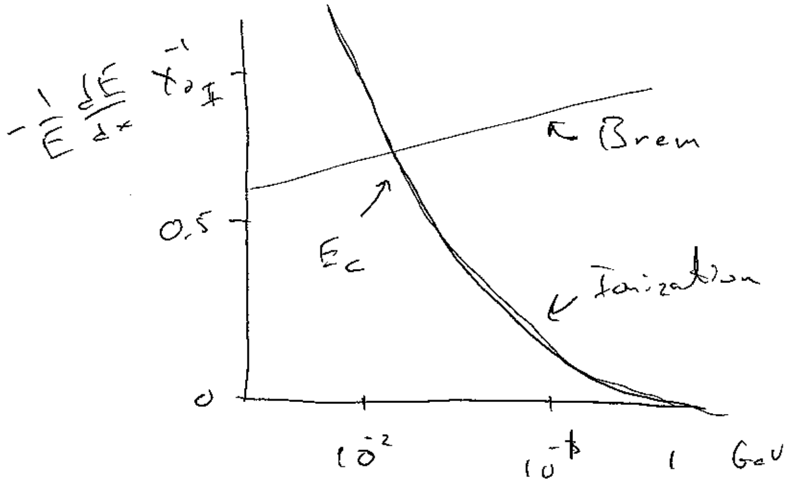
So unlike ionization makes sense to talk about the probability for ~~...~~ Energy loss, not by average along path.

Skip the details

Bottom line,

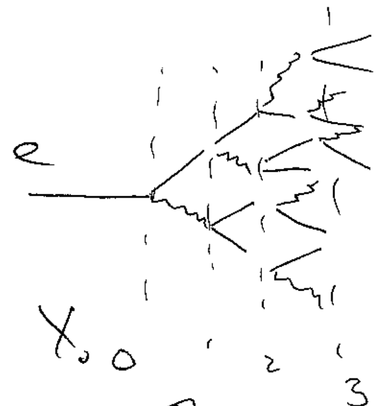
$$\frac{dE}{dx} \simeq -\frac{E}{X_0}$$

X_0: $\mathcal{O}(cm)$ → "radiation length" distance over which electron ~~...~~ looses e^{-1} of its energy.

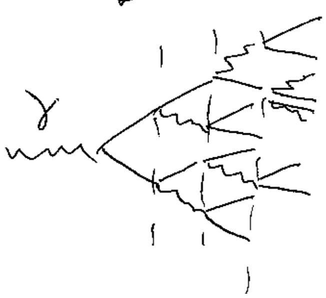


Similar story for γ's

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 ½ energy to γ (or e^+e^-)
- e's, γ's with energy $< E_c$ get absorbed via ionisation

If initial Electron $E_0 \gg E_c$ 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.
- $N_{max} = \frac{E_0}{E_c}$