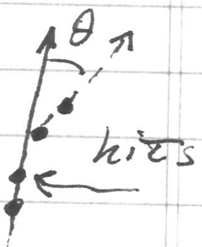
alorimetry

Some experimental challenges:

- not all particles observed in a tracker:
  - neutrals: γ, neutron, π^0, ν
  - new?: WIMPs



- tracker momentum measurement
  - angular deflection of charged particle in magnetic field → momentum
  - as momentum increases → θ decreases
    → hard to measure high-momenta

- sometimes need to stop particles
  ie. absorb all their energy

A Calorimeter puts enough material in path of particles

- to stop them
  - many X_0 for $e^{\pm}$, γ
  - many λ_0 for $\pi^{\pm}$, p, n . . . (if needed)
- to read observable correlating to total energy
- enough coverage to indirectly infer weakly interacting particle
- trigger on occasional weak interaction

There is an enormous dynamic range of energy in natural phenomena

meV (dark matter) energy loss
>TeV (colliders, cosmic rays) particle kinematics

- may need specific detector for appropriate regime

Two most common cases for moderate to high energy:

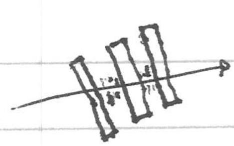
<u>Electromagnetic calorimetry</u>: for particles interacting purely electromagnetically ($e^\pm, \gamma$)

<u>Hadronic calorimetry</u>: interact via both nuclear and electromagnetic processes ($p, n, \pi^\pm \ldots$)

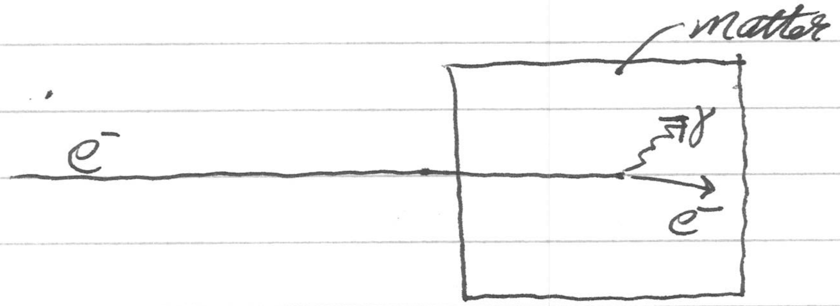
Kinds of calorimeter

- Homogeneous

- Sampling



Electromagnetic Showers



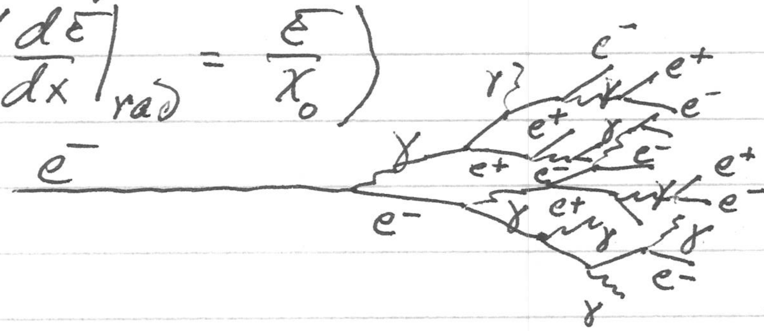
An electron (or e^+) traversing some material:
- if $E > 10-100$ MeV $\Rightarrow$ bremsstrahlung

A photon traversing material
- if $E_\gamma > 10-100$ MeV $\Rightarrow$ pair production

longitudinal direction

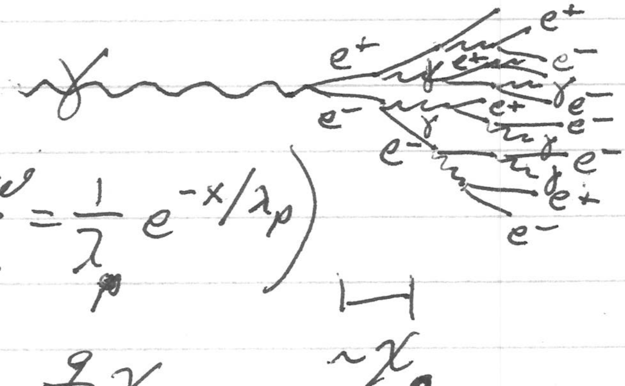
transverse direction

$$\left(\frac{dE}{dx}\bigg|_{rad} = \frac{E}{X_0}\right)$$



Most shower development in longitudinal direction.

particles increase until $\langle E \rangle \sim 10-100$ MeV (other processes take over)



$$\left(\frac{dw}{dx} = \frac{1}{\lambda_p} e^{-x/\lambda_p}\right)$$

$$\lambda_p = \frac{9}{7} X_0$$

Longitudinal EM Shower Development

- Heitler model

when $E >$ $E_{crit.} \sim 100\,MeV$ $\begin{cases} - e^{\pm} \text{ travels } 1\, X_0 + \text{brems} & E_\gamma = \frac{1}{2} E_e \\ - \gamma \text{ travels } 1\, X_0 + \text{pair produces} & E_{e^+} = E_{e^-} = \frac{1}{2} E_\gamma \end{cases}$

→ assume high energy $e^{\pm}$ have no collisional loss
- when $E_e < E_{crit}$, $e^{\pm}$ stops radiating + loses energy collisionally

Examples:
→ e^- after $1\, X_0 \rightarrow 1\gamma + 1e^-$: $E_\gamma = E_{e\,new} = \frac{1}{2} E_{old}$
→ $2 X_0$: $2e^-$, $1e^+$, 1γ all with $\langle E \rangle = \frac{1}{4} E_{old}$

Implications:
→ # particles after τ radiation lengths

$$N(\tau) = 2^{\tau} = e^{\tau \ln 2}$$

→ average particle energy @ depth τ

$$\langle E(\tau) \rangle = E_0 / 2^{\tau}$$

Rearranging we get depth where shower $E(\tau) = E'$

$$\ln(2^{\tau}) = \ln(E_0/E')$$

$$\tau(E') \ln 2 = \ln(E_0/E')$$

$$\boxed{\tau(E') = \ln(E_0/E') / \ln 2}$$

Shower Maximum

→ Shower grows but $\langle E_i \rangle$ decreases
- at some point $\langle E_i \rangle$ for electrons goes below E_{crit} + ionization dominates
- for γ's → Photoelectric + Compton dominate
- production of new particles slows + stops

When $E(\tau) = E_{crit}$, maximum # particles in the shower ("shower max.")

$$\boxed{\tau_{max} = \frac{\ln(E_0/E_{crit})}{\ln 2}} \propto \ln E_0$$

in GeV

→ depth of shower max. (in units of X_0)

Number of particles at max.:

$$\underline{\underline{N_{max}}} = e^{\tau_{max} \ln 2} = \boxed{E_0/E_{crit}}$$

$$\underline{\underline{\propto E_0}}$$

∴ # particles a linear function of energy
→ useful for calibration purposes

Example: CsI crystal calorimeter
1 GeV incident photon
10 MeV critical energy

$$\tau_{max} = \ln(1000/10)/\ln 2 = 4.6/0.7$$
$$= 6.6 \; X_0\text{'s}$$

$$N = E_0/E_{crit} = 100$$

If we want to know the number of particles with $E > E'$, where $E' \ll E_0$

$$N(E>E') = \int_0^{\tau(E')} N(\tau)\, d\tau$$
$$= \int_0^{\tau(E')} e^{\tau \ln 2}\, d\tau$$
$$= \int_0^{\tau(E')} e^{\ln(E_0/E')}\, d\tau$$
$$= \boxed{\frac{1}{\ln 2} \frac{E_0}{E'}}$$

Photons & Shower Containment

For photons around (just below) the critical energy, 1-10 MeV

- a low cross-section: the interaction length is $\sim 3\times$ longer than at high energy.

Absorbing these γ^s requires alot of extra material

95% absorption requires 7-9 X_0
→ add this to the # X_0^s to get to shower max.

$\tau_{total} \sim 15\, X_0$

This is important because a fully contained shower, or the degree to which you know it's not contained, is a key for calorimetry

Energy Loss of Shower Particles

As particle $\langle E_i \rangle$ goes below E_{crit}

- primary energy loss by $e^{\pm}$: collisions (i.e. ionization)

$$\left.\frac{dE}{dx}\right|_{ioniz.}$$ almost constant vs. E_i for relativistic $e^{\pm}$'s

Since $N \propto E_0$, and $\left.\frac{dE}{dx}\right|_{ioniz} \propto N$

$\therefore$ energy losses observed ~ linearly depend on initial particle energy

- for ionization detector
- scintillation complicates this

Main Qualitative Points

For total EM shower containment

- calorimeter thickness $\sim 15 X_0$ (larger as E rises)
- main leakage issue with photons of a few MeV

("depth")
Position of shower max.

- increases slowly with E, but not linearly
- more careful simulation

$$\boxed{t_{max} = \ln\left(\frac{E_0}{E_{crit}}\right) + C_{\gamma e}}$$

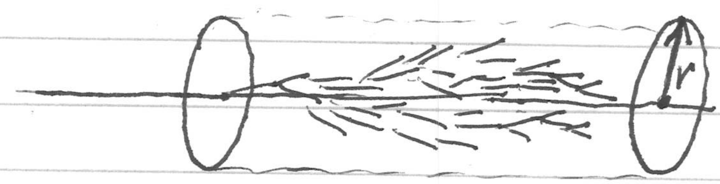
$C_{\gamma e} = +0.5$ when incident γ
$C_{\gamma e} = -0.5$ when incident $e^{\pm}$

→ also $N_{max} < 2^{t_{max}}$ because particles do not reach E_{crit} all at once

Transverse Profile of EM Showers

Bremsstrahlung γ's are confined to very narrow angles ($\sim m_e c^2/E_\gamma$) around $e^\pm$ – do not contribute to lateral spreading

Multiple scattering is main effect



→ Molière radius: $\boxed{R_M = \frac{21\,\text{MeV}}{E_{crit}} X_0}$ {g/cm^2}

→ note: X_0 means $\underline{\underline{R_M \propto 1/Z}}$ ($= \frac{7.4}{Z}$ g/cm^2)

95% of particles are contained in $2R_M$ from axis