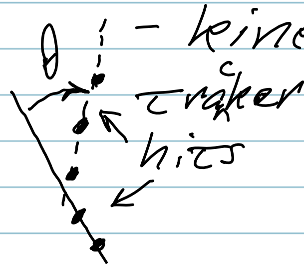
Calorimetry

Some experimental challenges:

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



- kinematic measurement
  - angular deflection of track in B-field $\propto \frac{1}{p_T}$
  - as p_T increases → θ decreases
  - position errors → hard to measure high momenta

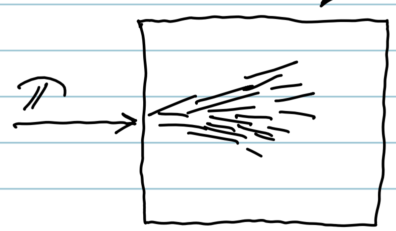
How address these limitations?

→ Calorimetry

Use Energy Loss

Sometimes need to stop particles → ie. absorb all their Energy

A calorimeter puts enough material
- in path of particle
- stops them



- many X for $e^{\pm}$, γ
- many λ_0 for hadrons

- But need also an observable indicating energy lost

Enormous dynamic range in E in natural phenomena

meV (dark matter
>TeV (colliders, cosmic rays)

- may need special or specific technology for appropriate regime

Types of Calorimetry

Two most common cases for moderate to high energy:

Electromagnetic calorimeter:
- particles interacting purely electromagnetically ($e^\pm, \gamma$)

Hadronic calorimeter:
- particles interacting hadronically + electromagnetically $p, n, \pi^\pm, \ldots$

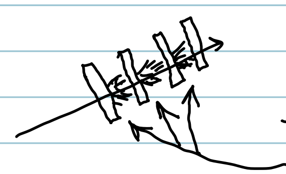
May need enough coverage to infer weakly interacting particles

Kinds of calorimeter

- Homogeneous

eg. CsI scintillato.
- observe all light

- sampling



eg. LAr ionization
- readout charge in gaps

(137) <u>Electromagnetic Showers</u>

Initial stage

- depends on incident specie

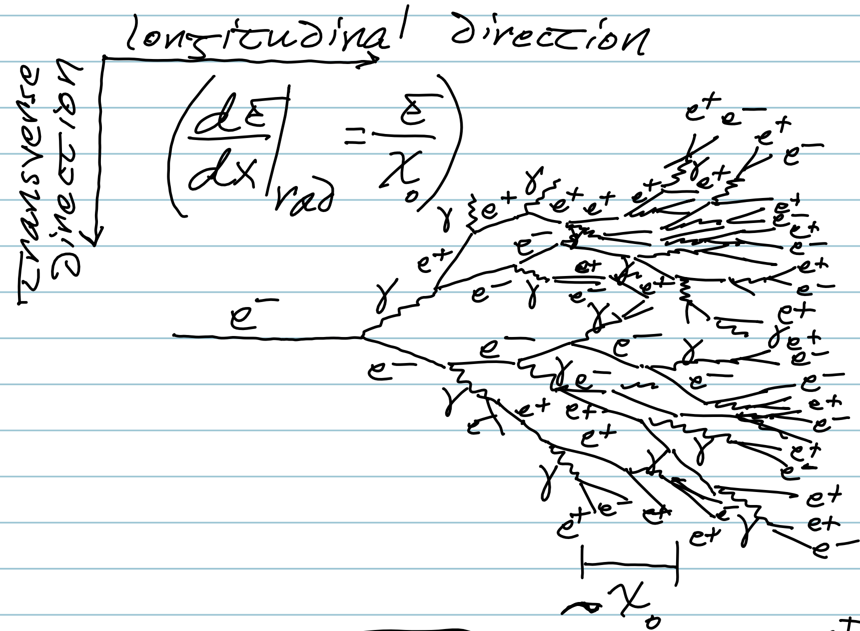
- an $e^\pm$ traversing some material
  - if $E_e > 10$–$100\,MeV$

    <u>Bremsstrahlung</u>

- a γ traversing material
  - if $E_\gamma > 10$–$100\,MeV$

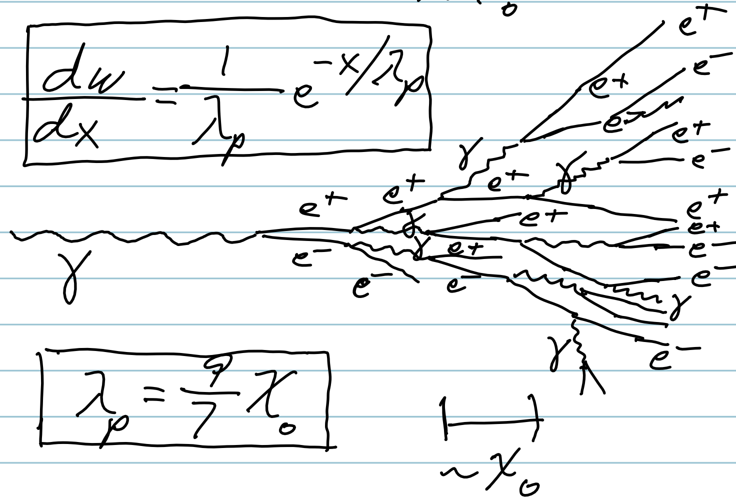
    <u>Pair Production</u>

Longitudinal Shower Development



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

not to scale; Most shower development in longitudinal direction



$$\boxed{\frac{dw}{dx} = \frac{1}{\lambda_p} e^{-x/\lambda_p}}$$

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

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

(139) A Simple Model

- Heitler model
  - when $E > E_{crit} \sim 100\,MeV$
    - $e^{\pm}$ travels $1X_0$ + brems
      $\rightarrow E_\gamma = \frac{1}{2}E_e$, $E_{enew} = \frac{1}{2}E_e$
    - γ travels $1X_0$ + pair produces
      $\rightarrow E_{e^+} = E_{e^-} = \frac{1}{2}E_\gamma$
  - assume high energy $e^{\pm}$ have no collisional losses
  - when $E_e < E_{crit}$
    $\rightarrow e^{\pm}$ stop radiating
      $\rightarrow$ loose energy collisionally

Examples:

e^- shower after $1X_0$:
  $\rightarrow 1\gamma + 1e^-$; $E_\gamma = E_{enew} = \frac{1}{2}E_0$

@ $2X_0$:
  $\rightarrow 2e^-, 1e^-, 1\gamma$
  $\rightarrow$ all have $\frac{1}{4}E_0$

Implications:

particles after 'τ' radiation lengths?

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

Average particle energy @ depth 'τ'

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

Rearranging, we get

- depth where shower $E(\tau) = E'$

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

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

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

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Shower Maximum

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

When $E(t) = E_{crit}$
⟹ "shower maximum" = highest # particles in shower

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

E_0 in GeV

t_{max} → depth of shower max. (in units of X_0)

Particle Multiplicity

Number of particles at maximum:

$$\underline{N_{max.}} = e^{t_{max} \ln 2} = e^{\ln(E_0/E_{crit})}$$
$$= \boxed{E_0/E_{crit}}$$
$$\propto E_0$$

∴ # of particles a linear function of energy

→ very important for calibration purposes

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Example:

A CsI crystal calorimeter has 1 GeV incident γ. The critical energy is 10 MeV.

What is depth of shower max?

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

How many particles at shower max?

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

Example (cont.)

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

$$\underline{\underline{N(E > E')}} = \int_0^{\tau(E')} N(\tau)\, d\tau$$

$$= \int_0^{\tau(E')} e^{\tau \ln 2}\, d\tau$$

$$= \int_0^{\tau(E')} e^{\ln(E_0/E')}\, d\tau$$

$$\boxed{= \frac{1}{\ln 2} \frac{E_0}{E'}}$$

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Photons and Shower Containment

For γ^s around (just below) critical energy, 1-10 MeV

- low cross section
  - interaction length ~3x longer than @ higher energy

Absorbing low E γ^s

- requires a lot of extra material

95% absorption ⇒ + 7 to 9 X_0

(add this to # X_0^s need to get shower max.)

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

Important: must know of calorimeter
- is shower fully contained?
- to what extent is shower not contained

Energy Loss of Shower Particles

When particle "i" ($e^{\pm}$) goes below E_{crit}

- primary energy loss by collisions
  - yields ionization

Interestingly,

$$\underline{\underline{\left.\frac{dE}{dx}\right|_{ioniz.}}} \quad \text{nearly constant vs. } E_i$$

- for relativistic $e^{\pm}$

Also,

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

which means the total ionization observed

$$\sum_i \frac{dE}{dx} \propto N \propto E_0$$

∴ total losses observed
- linearly depend on E_0

Note: a scintillation detector complicates this

A Couple Caveats

Position of shower max.

- increases slowly with E_0
  - but not linearly
- a more careful simulation

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

where

$C_{\gamma e} = +0.5$ for incident γ

$C_{\gamma e} = -0.5$ " " $e^{\pm}$

Particle multiplicity

- particles don't reach E_{crit} simultaneously

$\therefore$ $\underline{N_{max} < 2^{t_{max}}}$

Transverse Profile of EM Showers

Bremsstrahlung γ's
- confined to very narrow angles $\theta(\sim m_e c^2/E_\gamma)$ around e^-
- do not contribute to lateral spreading of the shower

Multiple scattering – main effect

distance from axis of incident particle

scattering of secondaries...

Moliére radius:

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

- note: X_0 means $R_M \propto \frac{1}{Z}$

95% of particles when $r = 2R_M$

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Homogeneous Calorimeter

- Want to see all of signal
- composed of
  - uniform material
  - permits function of absorber AND detector

"detector" is "active medium": material where signal is generated + extracted

Typical example

Crystal calorimeter

- heavy scintillating crystals
- can have very good energy resolution

KTeV calorimeter

(for CP violation @ Fermilab)

- CsI crystals: 50cm deep ($27 X_0$)
- designed for
  - γ's up to 80 GeV (eg. $K_L \to \pi^0\pi^0 \to 4\gamma$)
- resolution often quoted as σ_E/E fractional energy resolution

when $E_\gamma > 5$ GeV

$$\boxed{\frac{\sigma_E}{E} < 1\%}$$

CMS Experiment

- electromagnetic calorimeter
  - 80k lead-tungstate ($PbWO_4$) crystals
  - short X_0 (0.9 cm)
  - small R_M (2.2 cm)
  - fast scintillation
  - radiation-hard

Problem: only 50 γ's/MeV emitted

So what is σ_E/E?

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Energy Resolution

Let's assume energy calibration correct on average

- several effects alter measured energy on a case-by-case basis
  - statistical fluctuations in active media
  - energy leakage
    - "punchthrough"
  - noise in active medium
    - eg. radioactivity
  - gain variations
    - (eg. scintillation or photomultiplier tube gain)
  - electronic noise
  - events overlapping in time window
    - "pileup"

General Description

$$\boxed{\frac{\sigma_E}{E} = \frac{S}{\sqrt{E}} \oplus \frac{N}{E} \oplus C}$$

→ means sum in quadrature ($a \oplus b = \sqrt{a^2+b^2}$)

CMS

↓ N ("noise term"):
- fluctuation from electronic noise or pileup
- same size (in GeV) regardless of incident particle E

$N_{CMS} = 155\,MeV$

∴ important at low E

S ("sampling term"):
- statistical fluctuations in shower particle statistics

$S_{CMS} = 2.7\%$

- scintillation γ's or ionization e
- often dominant over whole E range

C ("constant term"):
- calibration uncertainty due to detector nonuniformity

$C_{CMS} = 0.55\%$

- calibration errors
- limiting factor @ highest energies

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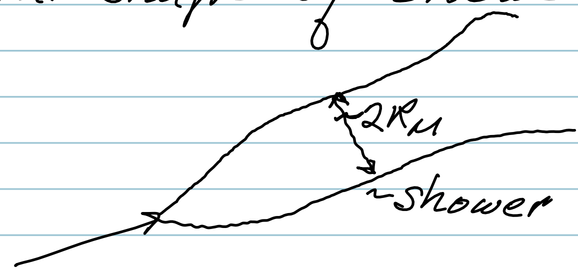
Position Resolution

Lateral shape of shower



- independent of energy
- Since width of shower ~ Moliére radius, R_M
  - position resolution a stastical matter
    - ie. error on mean position of shower

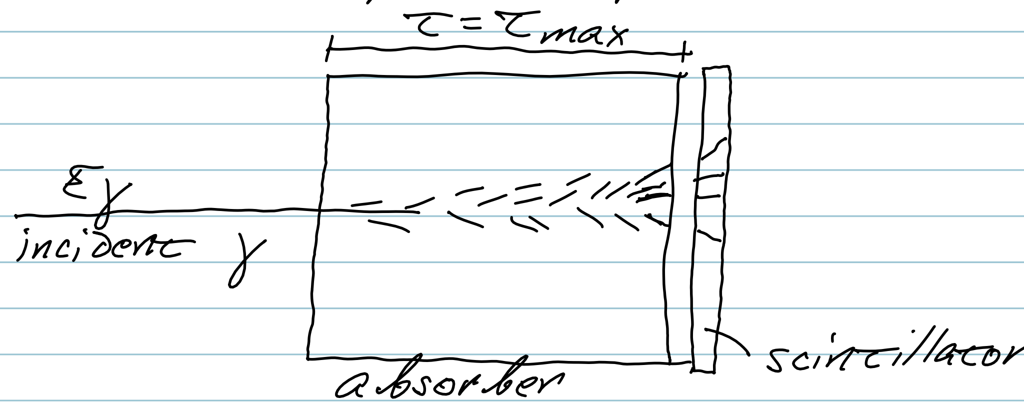
$$\sigma_{pos.} = \frac{R_M}{\sqrt{N_{shwr}}}$$

consider to be N_{max}

$$\boxed{\sigma_{pos} = \frac{R_M}{\sqrt{E_0/E_c}}}$$

Sampling Calorimeter

Consider simple setup:



The # of γ particles $= E_\gamma / E_{crit}$

$$\therefore \; N_{e^\pm} = \frac{2}{3} N_{max} = \frac{2}{3}\frac{E_\gamma}{E_{crit}}$$

Fractional fluctuations on N_e

$$\frac{\sigma(N_e)}{N_e} \simeq \frac{1}{\sqrt{N_e}}$$

Since $N_e \propto E_\gamma$, we have

$$\boxed{\frac{\sigma_E}{E}} \simeq \frac{1}{\sqrt{N_e}} \simeq \boxed{\frac{1}{\sqrt{2E_\gamma / 3E_{crit}}}}$$

"sampling term"

tends to be more dominant than homogeneous calorimeter

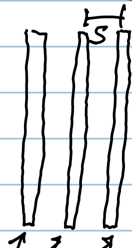
Resolution improves with energy

→ Tracker $\frac{\sigma_p}{p}$ increases linearly in p

Sampling Fluctuations

A general form in a sampling calorimeter

$$\boxed{\frac{\sigma_s}{E} = \frac{2.7\%}{\sqrt{E[\mathrm{GeV}]}} \sqrt{\frac{s[\mathrm{mm}]}{f_{samp}}}}$$



s = gap spacing
→ size of active region with sensitive material

absorber

<u>sampling fraction, f_{samp}:</u>

- ratio of energy loss $\left(\frac{dE}{dx}\Big|_{MIP}\right)$ in active medium

- vs. - energy loss (MIP) in absorber + active

<u>Example:</u> DØ EM calorimeter

$s = 2\,\mathrm{mm} \qquad \langle f_{samp} \rangle \sim 10\%$

$\therefore \frac{\sigma_s}{E} = \frac{2.7\%}{\sqrt{E}}(5) \sim \frac{14\%}{\sqrt{E}}$

→ actual value → $15\%/\sqrt{E}$

Choice of Materials

Absorber: Generally dense material
- moderate R_M

Active Medium: material providing observable correlated with particle energy
→ ionization
→ scintillation

→ liquid argon (LAr) & scintillators
- ~~pd~~ better resolution than gaseous media
- gases give larger Landau fluctuations

Scintillators
- might use alternating layers of absorber & plastic scintillator
- light sensitive device has large gain
- charged particles in shower produce light in active medium.
- fast signals, large amplitude if "read out" with PMTs
- problem if a magnetic field
- move them outside

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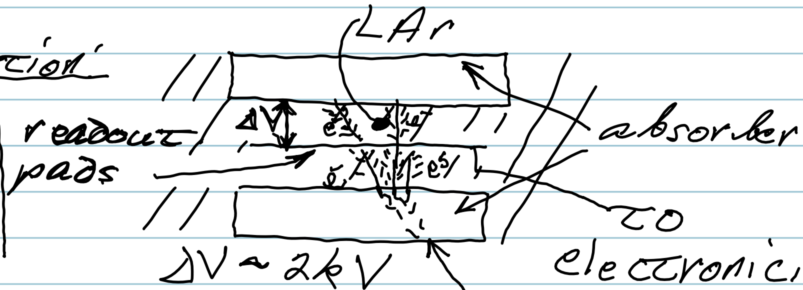
Examples: ATLAS (Fe/LAr)
DØ (U/LAr)

Liquid Noble Gases

→ Ar, Kr, Xe: Ar is common in liquid form
- ionization detector

charge collection: ionization from propagation in Ar



- readout → metal pads
- absorber → metal plates immersed in LAr

No gain: # e's directly read out
∴ very linear for $e^{\pm}$, γ

- small amount of charge
- cryogenically cool (80 K) for low noise
- need preamplifier and electronics

Purity: important as impurities in Ar allow $e^{\pm}$ recombination
- loss of signal,
- energy dependent

Hadronic Calorimeter

Same basic idea as EM Calorimeter

- stop particle (absorb all its energy)
- measure parameters correlated with this energy
  - IONIZATION
  - SKINTILLATION

- calorimeter generally sampling
  - same technology as before

Most particles besides $e^{\pm}$ or γ

- do not directly create EM showers
- hadrons
  - more massive than $e^{\pm}$
    - charged ones generally lose little energy to ionization

  - interact via nuclear interactions
    - if reach detector
    - initiates a shower

Hadronic Showers

Initial hadron interactions with matter
- some ionization
- produce secondary hadrons)
  - charged pions
    - produce ionization
    - tertiary particles
  - π^0
    - lifetime, $\tau \sim 10^{-16}$ s
    - decay $\to \gamma\gamma$
      - EM shower in hadron shower
    - about 1/3 of secondaries
  - some K, p, n
  - nuclear breakup fragments
    - binding energy + excitation
    - ν production
  - μ's from in-flight decays
- particle multiplicity $\propto \ln(E)$
- typical $p_T \sim 0.35$ GeV/c

Very difficult to model well

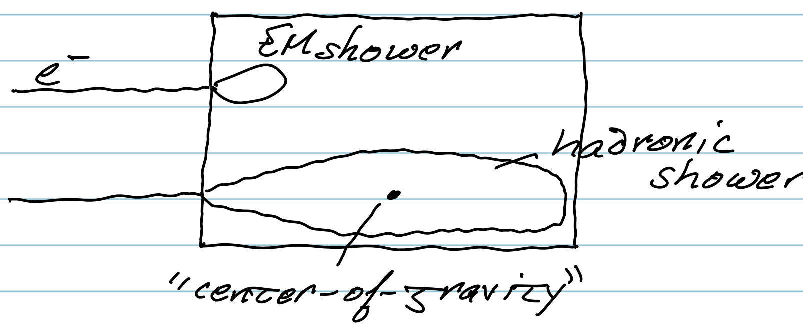
Longitudinal Shower Development

Set by nuclear absorption length

$$\boxed{\lambda_0 = A/(N_A\,\sigma_{abs})} \propto A^{1/3}$$

absorption cross section

As we've seen, this is $\gg X_0$ for high Z materials



Distance with which 95% of energy contained

$$\boxed{L(95\%) \sim \frac{\lambda_0^X}{\lambda_0^{Fe}}\left(9.4\ln\left(\frac{E}{GeV}\right)+3.9\right)} \{cm\}$$

- where "X" is some material (e.g. Pb) and "Fe" is iron

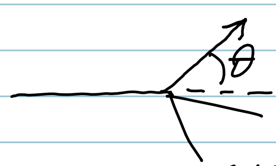
Require a larger detector (than EM) for full containment

Lateral Shower Development

- EM shower width: due mainly to multiple scattering

Nuclear processes
- large momentum transfer in collisions

$\therefore$ p_T can be large: large angle of secondary relative to primary

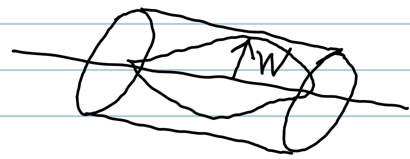


- nuclear or particle decay
- produce very wide showers

~~Width of a shower~~

163 Width of a shower

Diameter of a cylinder (in cm) containing 99% of energy



$$\boxed{W(E) = -17.3 + 14.3 \ln(E)}$$

in GeV

Very strong fluctuations in hadronic showers

- produces wide variations in hadronic showers structure

- much more than EM showers

Electromagnetic Content of Hadronic Showers

$\frac{1}{3}$ of secondaries are π^0 for each interaction

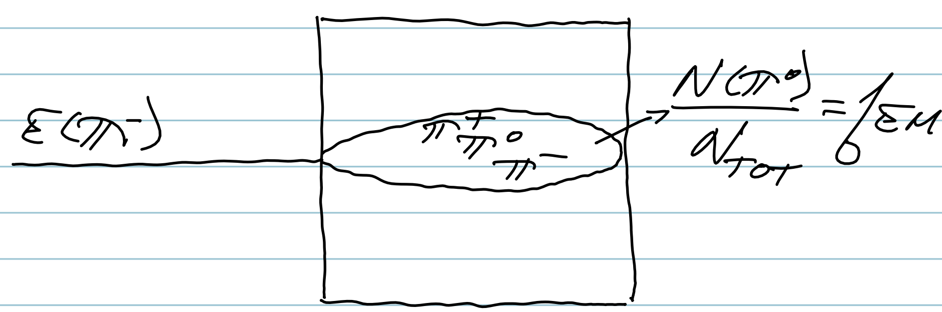
- Since $\pi^0 \to 2\gamma$: $\frac{1}{3}$ of shower goes to EM sub-shower

- next nuclear interaction $\frac{1}{3}$ are π^0's $\to$ EM showers

- et cetera...

Naively, EM fraction of a shower should rise vs. Energy

$$f_{EM} \overset{?}{\simeq} 1 - \left(\frac{2}{3}\right)^{n}$$ — # of shower generations



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- Each element (nucleus) interacts differently with incident hadron

- more than just π's produced

$$\boxed{f_{EM} = 1 - \left(\frac{E}{E_0}\right)^{k-1}}$$

$E_0 = 0.7$ GeV (Fe), 1.3 GeV (Pb)
$k = 0.8$ " , 0.85 "

$\therefore$ in iron, EM content lower at a given E than lead

- but rises more quickly with E

Varies a lot shower-to-shower

Non-Electromagnetic Components

- some secondaries can be "invisible
  - nuclear fragments
    - short lived
    - absorbed before can be detected
  - long-lived neutrals
    - n, K_L, ν
      - escape detector leaving little or no energy
  - muons
    - created in decay of hadrons
    - only small ionization losses
  - can ~~t~~ contribute up to 40% of hadronic shower

Result:

- hadron energies usually undermeasured relative to $e^{\pm}$, γ

$\frac{"e"}{h} > 1$ (+ it's Energy dependent)

- makes hadronic calibration much more difficult

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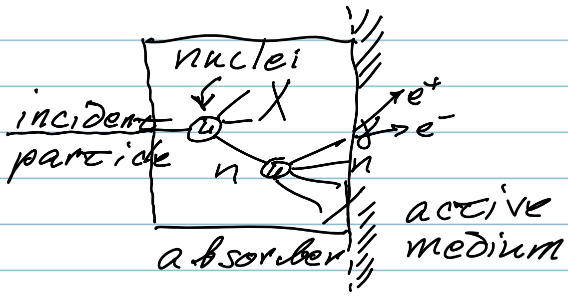
Compensation

Possible to recover, or "compensate" for lost signal in hadronic showers

- consider fissile material, e.g. U
  - neutrons produced in nuclear interactions



1) - caught by other nuclei
2) fission + emission of more n^s + γ^s
3) conversion of $\gamma^s \to e^+e^-$ yields a signal

Need to be above a few GeV
- for good compensation
- improves with energy

Example: DØ U/LAr calorimeter

$e/\pi \sim 1.05$

Energy Resolution

Use same general expression as for EM calorimetry

$$\boxed{\frac{\sigma}{E} = \frac{N}{E^2} \oplus \frac{S}{E} \oplus C}$$

$\oplus$ = addition in quadrature

Now we have large variations in hadronic shower evolution

- composition of each shower (ie. # π^0's, f_{EM})
  - dominates statistical term, S, of resolution

Best hadron sampling calorimeters

- less performant than EM calorimeter
- two examples, DØ (U absorber, compensating)

$$\boxed{\frac{\sigma(E)}{E} = \frac{35\%}{\sqrt{E[GeV]}}}$$

- ATLAS (Fe absorber + Scintillator, $e/\pi \sim 1.37$)

$$\frac{\sigma(E)}{E} = \frac{42\%}{\sqrt{E[GeV]}}$$

Still, for 50 GeV π^-

$$\frac{\sigma}{E} \sim \frac{0.35}{\sqrt{E}} = 0.05$$

so 5% precision possible