Choice of Materials

Absorber: Generally a dense material with moderate R_M ~~good~~

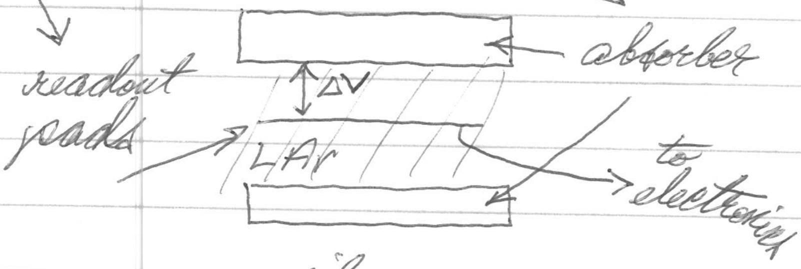
Active Medium: material providing observable which is correlated with particle energy
- → ionization
- → scintillation

- → liquid Argon and scintillators provide better resolution than gaseous active media
  - → latter have larger Landau fluctuations

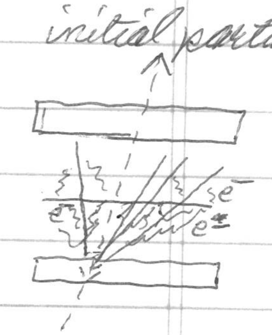
Scintillators
- might be alternating layers of absorber and plastic scintillator
- light sensitive device has large gain
- charged particles in shower produce light in scintillating medium
- fast signals, large amplitude
- if "read out" with photomultiplier tubes
  - difficulty if there's a magnetic field
  - move them outside

Liquid Noble Gases

- → Ar, Kr, Xe : Ar most common (LAr)
- ionization detector
  - metal plates immersed in LAr
  - spacing might be 2-3mm
  - high voltage applied between plates and positive electrodes:



- readout pads can be easily segmented for a 2D position measurement



- charge collection: ionization from propagation in Ar

No gain: i.e. number of electrons is directly read out (∴ very linear for e + γ)
- small amount of charge
  - cryogenically cool (80K) for low noise
  - need preamplifier + electronics

Purity important → don't want impurities in LAr that e^- will recombine with

Notes About Energy Resolution

Because main sampling term

$$\frac{\sigma}{E} = \frac{\sigma_s}{\sqrt{E}}$$

→ means fractional resolution improves as E increases
- tracker $\frac{\sigma_p}{p}$ increases linearly with momentum

- so for very high energy can get very precise measurement

Example EM LAr calorimeter: ATLAS (Fe/LAr)
Dϕ (U/LAr)

Hadronic Calorimeter

Same basic idea as EM calorimeter

- stop particle (absorb all its energy)
- measure parameters that correlate with this energy

IONIZATION
SCINTILLATION

- calorimeter generally sampling,
  - same technology as before

Most particles besides $e^\pm$ or γ

- do not directly create electromagnetic showers
- hadrons
  - more massive than $e^\pm$
    - charged generally loose little energy to ionization
  - interact by nuclear interactions if reach detector

Initiates a hadron shower

Hadronic Showers

Initial hadron interaction with matter
- some ionization
- produce secondary hadron(s)
    - give ionization losses

    - charged pions
        - produce ionization + tertiary particles

    - π^0 (1
        - lifetime, $\tau \sim 10^{-16}$ s
        - $\pi^0 \rightarrow \gamma\gamma$ (EM shower) in hadronic shower
        - about 1/3 of secondaries

    - some K, p, n
    - nuclear breakup fragments
        - binding energy + excitation
        - ν production
    - muons from in-flight decays

    - particle multiplicity $\propto \ln(E)$
    - typical $p_T \sim 0.35$ GeV/c

Very difficult to model well

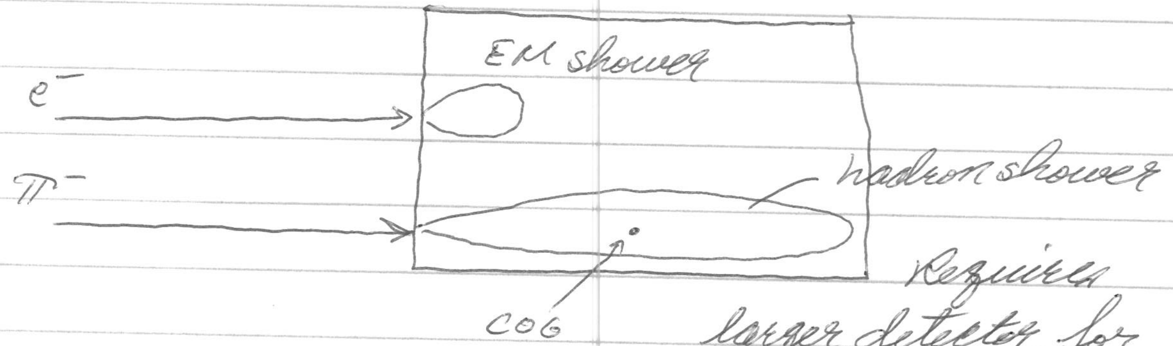
Longitudinal Shower Development

Set by the nuclear absorption length

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

absorption cross section

As we've seen, this is >> X_0 for high Z materials



Requires larger detector for full containment

Define "center of gravity" (COG), and distance within which 95% of energy contained

- both vary logarithmically

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

where "X" is some material (eg. Pb) and "Fe" is iron

Lateral Shower Development

- EM shower width: due mainly to multiple scattering

Nuclear processes

- large momentum transfer
  ∴ $p_\perp$ can be large: large angle of secondary relative to primary

- collisions, nuclear or particle decay
- produce very wide showers

Width of shower

- diameter of cylinder (in cm) containing 99% of energy

$$\boxed{W(E) = -17.3 + 14.3\ln(\underbrace{E}_{\text{in GeV}})}$$

Very strong fluctuations in hadronic showers

- produces wide variation in shower structure compared to purely EM showers

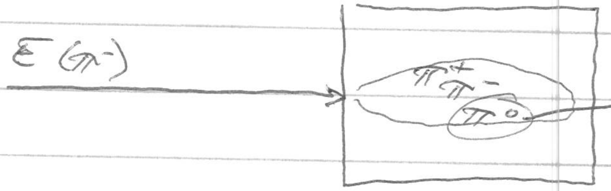
Electromagnetic Content of Hadronic Showers

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

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

- next nuclear interaction : $\frac{1}{3}\pi^0 \to EM$
  - etc, Naively EM energy fraction, f_{EM}

$$\sim 1 - \left(\frac{2}{3}\right)^{n}$$ — # of shower generations



$$\frac{N_{\pi^0}}{N_{TOT}} = f_{EM}$$

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

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

∴ in iron the EM content is lower at a particular energy than Pb
- but rises more quickly with E

Varies alot shower-to-shower

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Non-Electromagnetic Components

Ionization losses: small for hadrons

Must be translated into EM components to be observed

Some secondaries can be "invisible"

- nuclear fragments
  - short-lived
  - absorbed before can be detected
- long-lived neutrals
  - n, K_L^0, ν
    - escape detector leaving little or no energy
- muons
  - created in decay of hadrons
  - only leave small ionization losses
- total contribution 30-40% of the hadronic shower

Result:

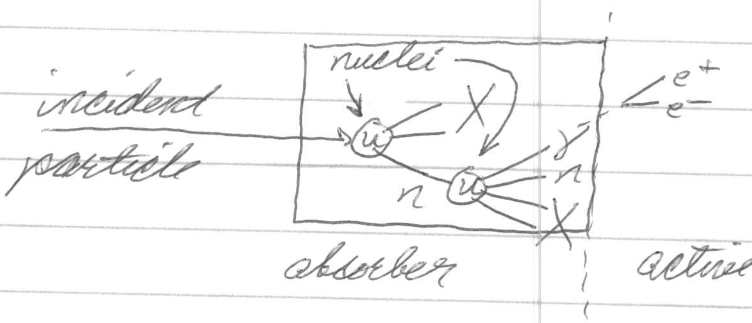
- Hadron energies usually undermeasured relative to $e^\pm$ or γ energies

  i.e. $\frac{"e"}{\pi} > 1$ (and it's energy dependent)
- makes hadronic calibration much more difficult

Compensation

It is possible to recover or "compensate" for the lost signal in hadronic showers

- consider a fissile material, eg. U
- neutrons produced in nuclear interactions
  - if caught by other nuclei
    - ⇒ fission: emission of more $n^s + \underline{\underline{\underline{\gamma^s}}}$
- the photons can produce a signal in the sampling medium



Need to be above a few GeV to get good compensation
→ improves with energy

Example: DØ U/LAr calorimeter

$e/\pi \sim 1.05$

㉗

Energy Resolution

Use same general expression as for EM calorimetry:

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

Now we have large variations in hadronic shower evolution

- Composition of each shower (# neutrals, f_{EM})
  - dominates statistical term S of resolution

Best hadron sampling calorimeters
- still significantly worse than EM calorimeter
- U absorber (compensating)

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

- non-compensating

$$\underline{\frac{\sigma}{E} = \frac{42\%}{\sqrt{E\,[\mathrm{GeV}]}}} \quad \text{(ATLAS)}$$

(Note $\frac{e}{\pi} \sim 1.37$)

Still, for 50 GeV π^-

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

So 5% precision possible.