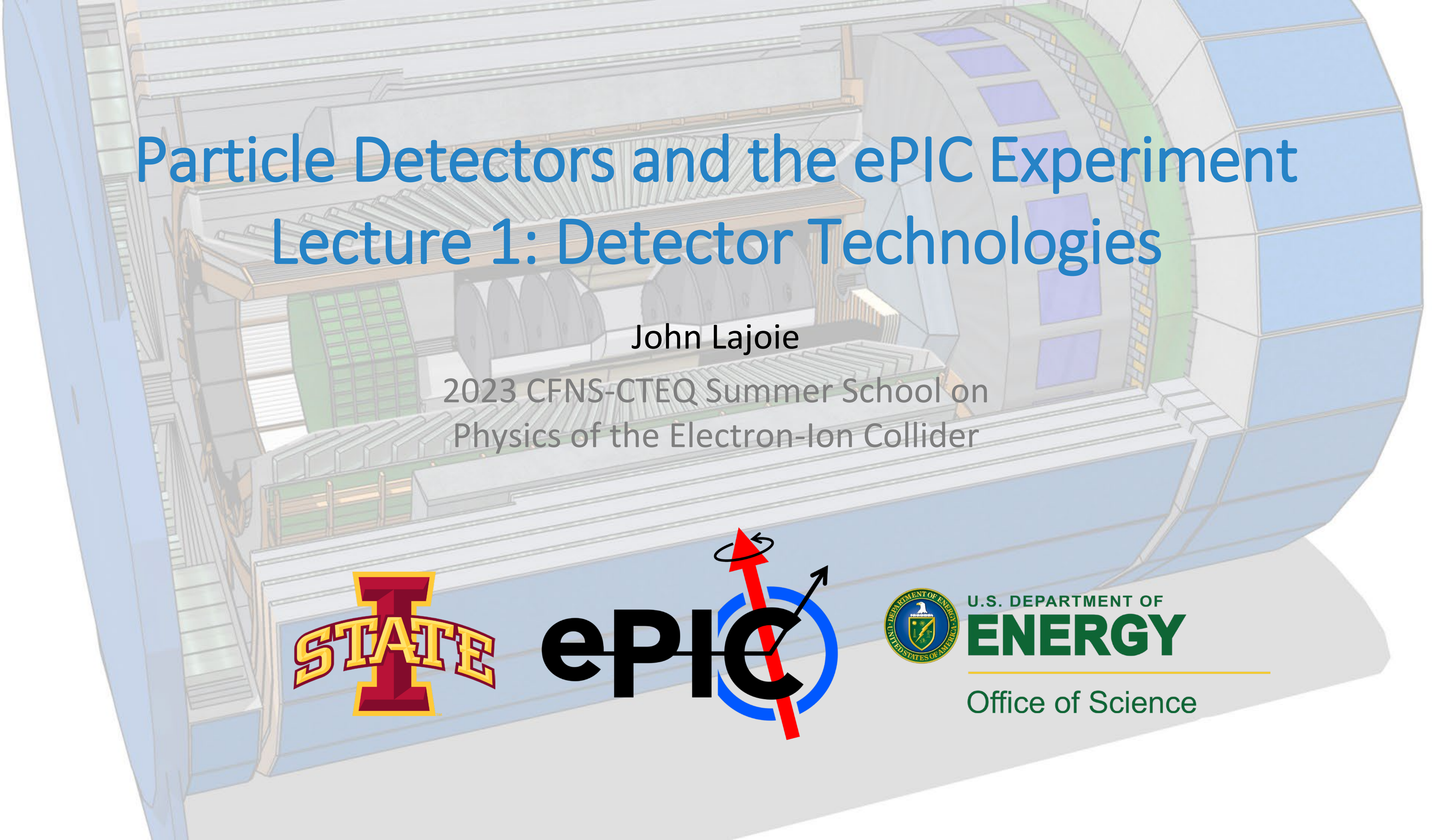

# Particle Detectors and the ePIC Experiment
# Lecture 1: Detector Technologies

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2023 CFNS-CTEQ Summer School on
Physics of the Electron-Ion Collider

U.S. DEPARTMENT OF ENERGY
Office of Science

# Outline of Lectures

- Lecture 1: Particle Physics Detectors
  - Interaction of Particles with Matter
  - Tracking Detectors
  - Calorimetry
  - Particle Identification
- Lecture 2: The ePIC Detector and the EIC
  - Detector requirements at the EIC
  - The design of the ePIC Detector
  - Interaction Region Considerations

# A Comment on Units…

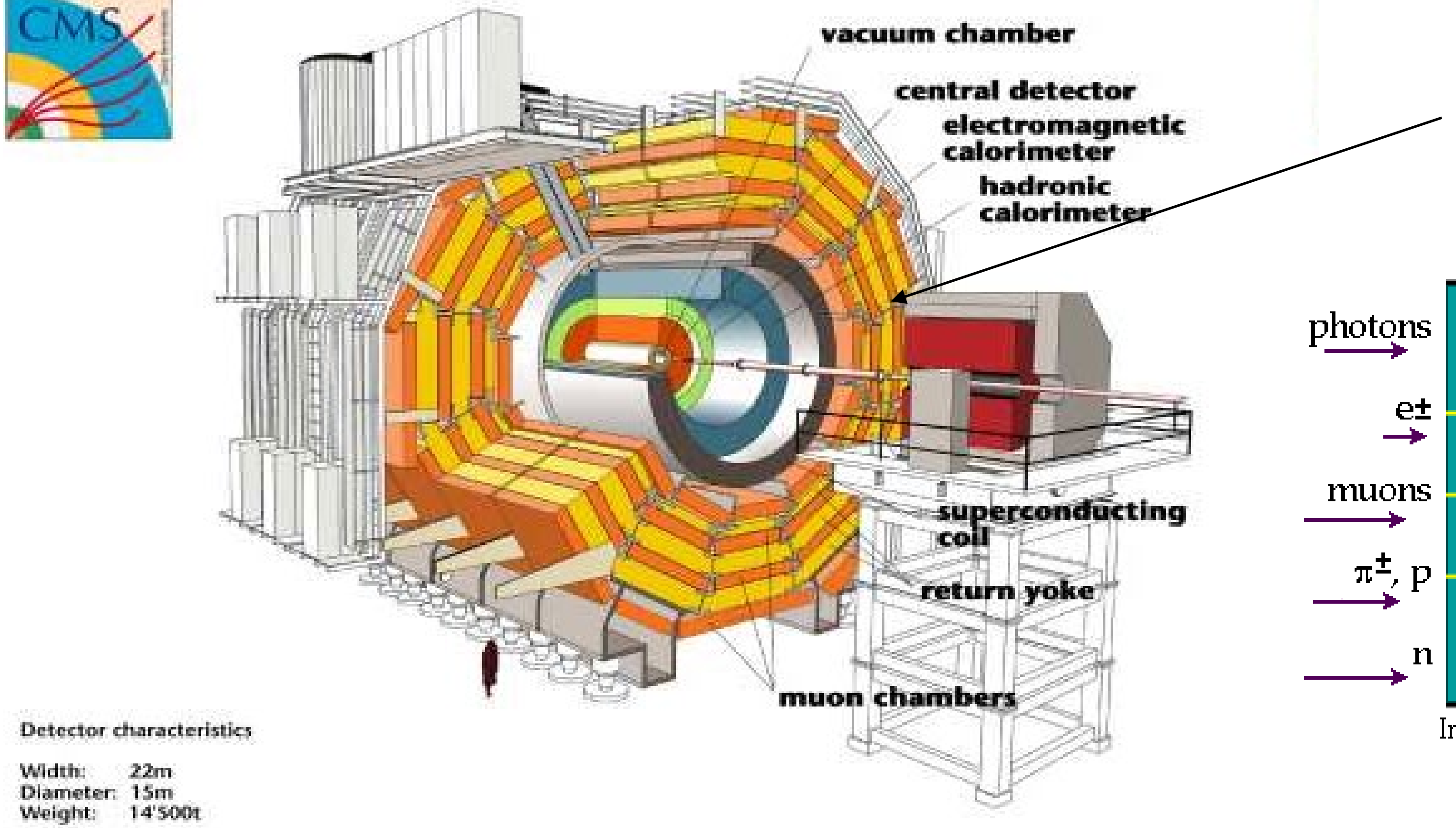
- Particle Physicists are <u>lazy:</u>

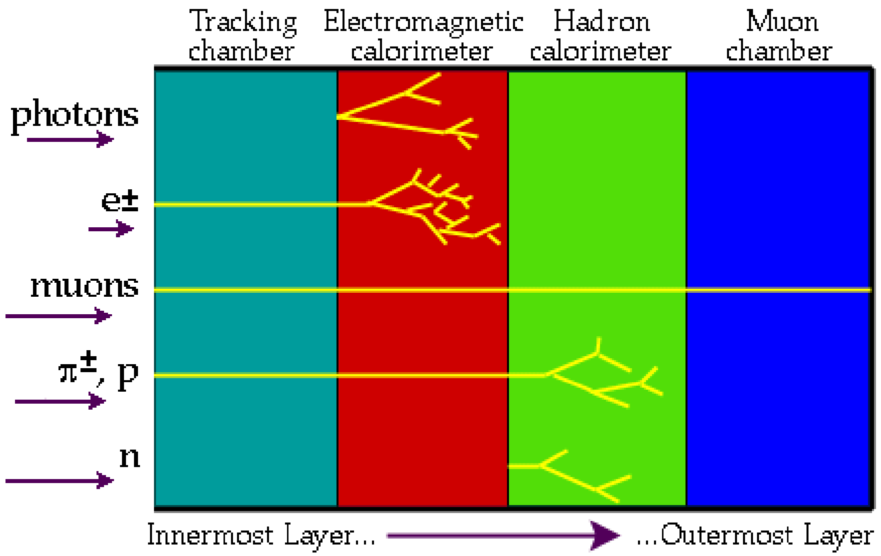
$$E = mc^2 \rightarrow E = m \quad (\text{with c} = 1)$$

$$eV = 1.602 \times 10^{-19}\, J$$

- We will use energy and mass units interchangeably:
  - Also $\hbar = 1$ for simplicity…
  - To get back to mks units just sprinkle $\hbar$, c around until the units work out
  - When I say "MeV" I typically mean $10^6$, not $10^{-3}$ (meV)

# Modern Particle Physics Experiments




**Many common features in modern NP and HEP detectors – inner tracking, magnetic field, EM and hadronic calorimetry, outer muon chambers.**

**Want to determine particle track, charge, momentum, energy, type (id) ….**

# Interaction of Radiation with Matter

## (Heavy Particles, Low Density Matter)

- Heavy Charged Particles (p, $\alpha$, etc)
  - When a charged particle passes through matter, it interacts primarily with the atomic electrons in the material
  - Conservation of energy and momentum for a heavy particle M incident on a light particle m gives:

$$\Delta T = T\left(\frac{4m}{M}\right)$$

**Kinetic energy lost by M**

    - Elastic, head-on collision – this is the maximum energy loss

  - Example: For a 5MeV $\alpha$ particle, $m_\alpha \sim 4m_n$

$$\Delta T = 5MeV\left(\frac{4m_e}{4m_n}\right) \cong 2.6keV$$

# Heavy Particles

- So we already know several Useful Things:
  - A typical particle will undergo thousands of collisions before it loses all its energy!
  - The heavy particle is deflected by a small amount in a collision
  - The Coulomb force has an infinite range, so a particle interacts simultaneously with many electrons and effectively loses energy *continuously* along its path

- The energy required to ionize atoms is a few 10’s of eV, so many collisions will liberate atomic electrons
  - Known as “$\delta$ rays”
  - These $\delta$ rays will have their own collisions and lose energy in the material as well

# Bethe-Block Equation

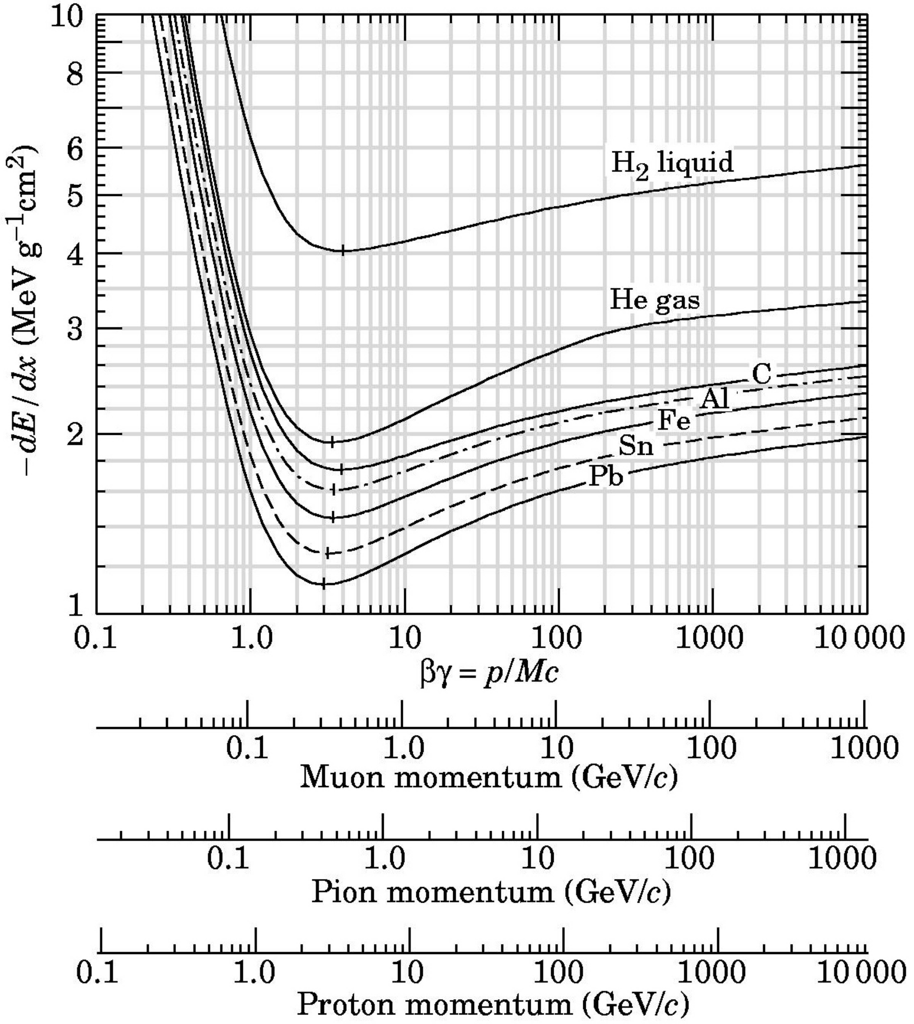
- The original calculation for energy loss of a charged particle is due to Hans Bethe (1930)
  - **Bethe-Block Equation**
    - For a particle of charge *ze*, velocity *v*:

$$-\frac{dE}{dx}=\left(\frac{e^2}{4\pi\varepsilon_0}\right)^2\frac{4\pi}{m_e c^2}\frac{n_e z^2}{\beta^2}\cdot\left[\ln\left(\frac{2m_e c^2\beta^2}{I\cdot\left(1-\beta^2\right)}\right)-\beta^2\right]$$

  - The electron density is given by:

$$n_e=\frac{N_A\cdot Z\cdot\rho}{A}$$

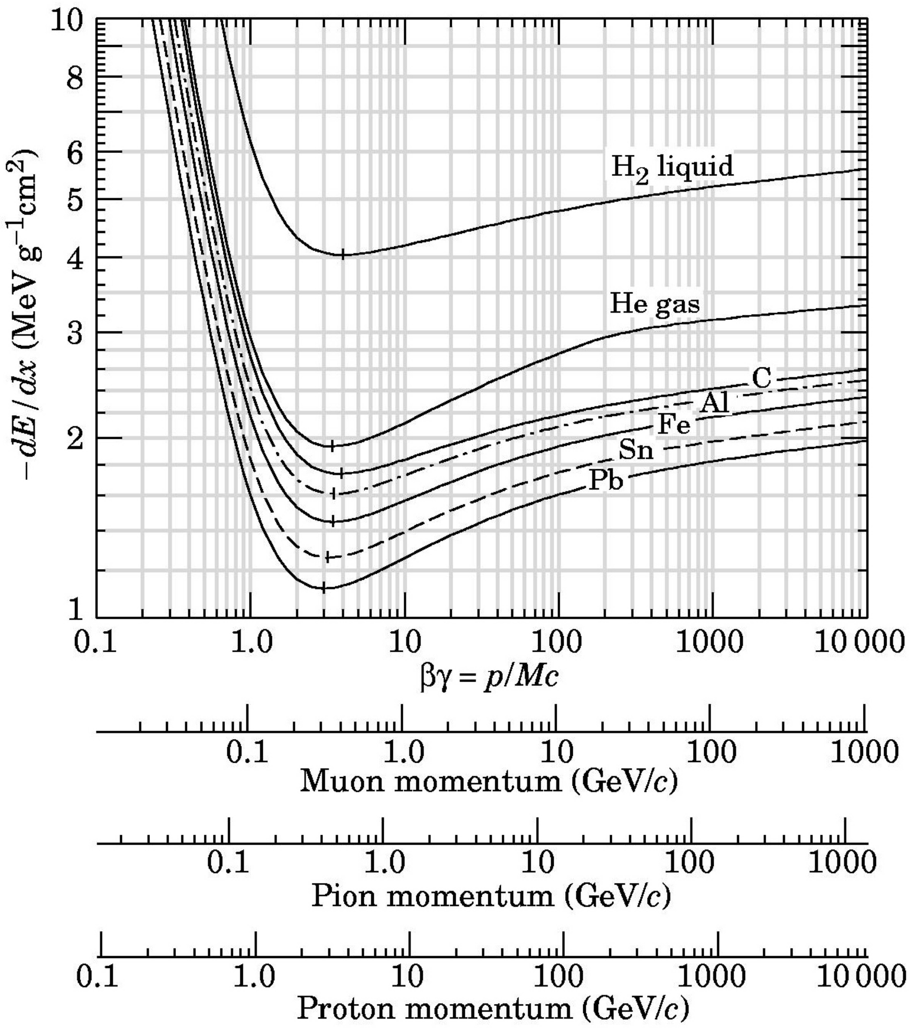
  - *I* is the *mean ionization energy* for the material
    - In principle it is an average over all ionization and excitation processes $I_{AIR}=86eV$ $I_{Al}=163eV$
    - Approximately *I/Z* ~ 10 eV



# Bethe-Block (II)

$$-\frac{dE}{dx} = \left(\frac{e^2}{4\pi\varepsilon_0}\right)^2 \frac{4\pi}{m_e c^2} \frac{n_e z^2}{\beta^2} \cdot \left[ \ln\left(\frac{2 m_e c^2 \beta^2}{I \cdot \left(1-\beta^2\right)}\right) - \beta^2 \right]$$

- Energy loss depends quadratically on *v* and *z*, but not on its mass *M*
- For low energies ($\beta << 1$), the energy loss decreases as ~$1/v^2$
- Reaches a minimum for $E \sim 3Mc^2$
  - $dE/dx \sim 2 MeV\ g^{-1}\ cm^2$ **(note – divided by density!)**
- For $\beta \sim 1$ the energy loss rises logarithmically
  - Referred to as "relativistic rise"
  - Relativistic deformation of Coulomb field of incident particle increases effective impact parameter cutoff (semiclassical)



# Bethe-Block (III)

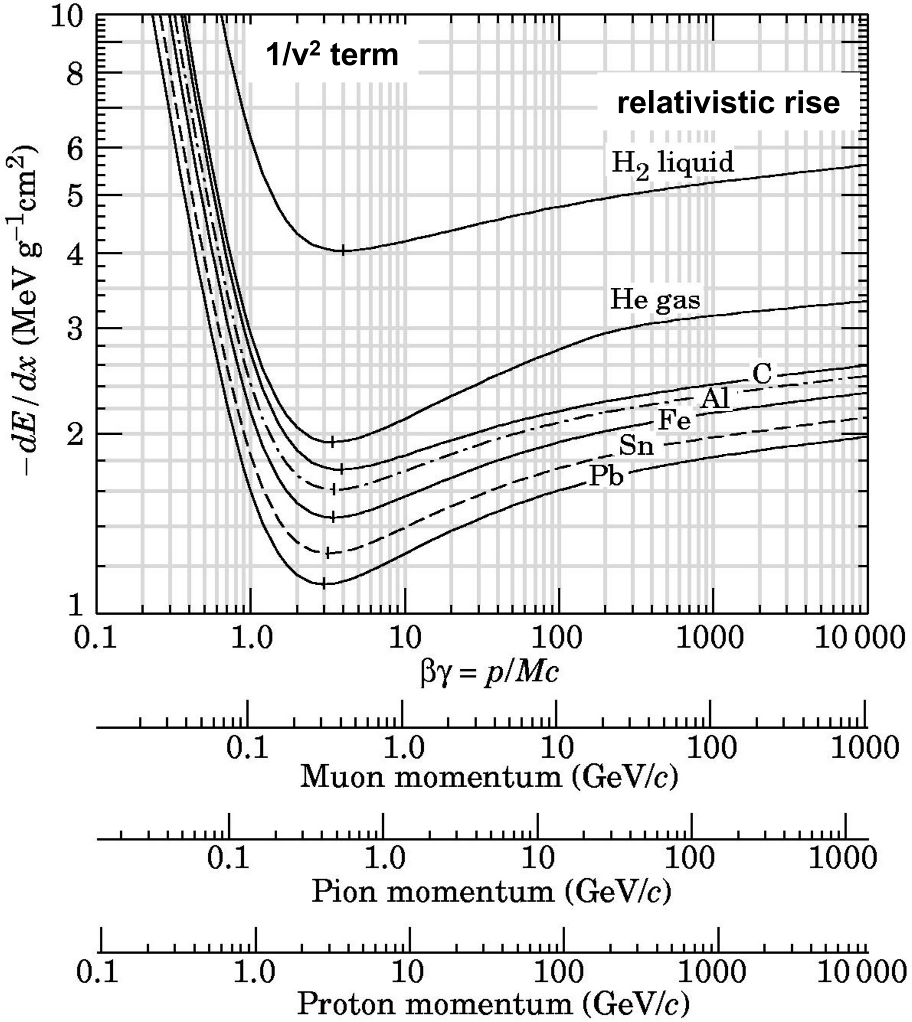


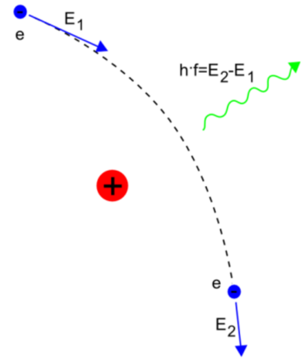

Table 2.1. *Electromagnetic properties of elements*[a]

| Material | $Z$ | $n_a$ ($\times 10^{23}$/cm³) | $n_e$ ($\times 10^{23}$/cm³) | $I$ (eV) | $L_R$ (cm) | $X_R$ (g/cm²) | Density (g/cm³) |
|---|---|---|---|---|---|---|---|
| $H_2$ | 1 | 0.423 | 0.423 | 21.8 | 891 | 63.05 | 0.0708 |
| He | 2 | 0.188 | 0.376 | 41.8 | 755 | 94.32 | 0.125 |
| Li | 3 | 0.463 | 1.39 | 40.0 | 155 | 82.76 | 0.534 |
| Be | 4 | 1.23 | 4.94 | 63.7 | 35.3 | 65.19 | 1.85 |
| B | 5 | 1.32 | 6.60 | 76 | 22.2 | 52.69 | 2.37 |
| C | 6 | 1.146 | 6.82 | 78 | 18.8 | 42.70 | 2.27 |
| $N_2$ | 7 | 0.347 | 2.43 | 85.1 | 47.0 | 37.99 | 0.808 |
| $O_2$ | 8 | 0.429 | 3.43 | 98.3 | 30.0 | 34.24 | 1.14 |
| Ne | 10 | 0.358 | 3.58 | 137[b] | 24.0 | 28.94 | 1.20 |
| Al | 13 | 0.603 | 7.84 | 166 | 8.89 | 24.01 | 2.70 |
| Si | 14 | 0.500 | 6.99 | 173 | 9.36 | 21.82 | 2.33 |
| Ar | 18 | 0.211 | 3.80 | 188[b] | 14.0 | 19.55 | 1.40 |
| Fe | 26 | 0.849 | 22.1 | 286 | 1.76 | 13.84 | 7.87 |
| Cu | 29 | 0.845 | 24.6 | 322 | 1.43 | 12.86 | 8.92 |
| Zn | 30 | 0.658 | 19.6 | 330 | 1.75 | 12.43 | 7.14 |
| Kr | 36 | 0.155 | 5.59 | 352[b] | 5.26 | 11.37 | 2.16 |
| Ag | 47 | 0.586 | 27.6 | 470 | 0.85 | 8.97 | 10.5 |
| Sn | 50 | 0.371 | 18.5 | 488 | 1.21 | 8.82 | 7.31 |
| W | 74 | 0.632 | 46.8 | 727 | 0.35 | 6.76 | 19.3 |
| Pt | 78 | 0.662 | 51.5 | 790 | 0.31 | 6.54 | 21.45 |
| Au | 79 | 0.577 | 45.6 | 790 | 0.34 | 6.46 | 18.88 |
| Pb | 82 | 0.330 | 27.0 | 823 | 0.56 | 6.37 | 11.34 |
| U | 92 | 0.479 | 44.1 | 890 | 0.32 | 6.00 | 18.95 |

[a] Values are for solid and liquid states unless noted.
[b] Gaseous state.
*Source:* Particle Data Group, Rev. Mod. Phys. 56: S1, 1984, S53; S. Ahlen, Rev. Mod. Phys. 52: 121, 1980, Table 6; Y. Tsai, Rev. Mod. Phys. 46: 815, 1974, Table 3.6; *Handbook of Chemistry and Physics,* 64th ed., Boca Raton: CRC Press, 1983, p. B65; R.M. Sternheimer, M.J. Berger, and S.M. Seltzer, Atomic Data and Nuclear Data Tables 30: 261, 1984, Table 1.

# Energy Loss by Electrons and Positrons

- Electrons/Positrons travelling through matter also suffer collisions with atomic electrons
  - However, they will lose energy faster and scatter at larger angles
  - Electrons can lose energy via *bremmstrahlung*
    - Accelerated charge radiates energy!
  - Energy loss (also due to Bethe):




$$-\frac{dE}{dx}\bigg|_{collisions} = \left(\frac{e^2}{4\pi\varepsilon_0}\right)^2 \frac{2\pi}{m_e c^2}\frac{n_e}{\beta^2}\cdot\left[\ln\left(\frac{T(T+m_e c^2)\beta^2}{2I^2 m_e c^2}\right)-(1-\beta^2)\right]$$

$$-\frac{dE}{dx}\bigg|_{bremm.} = \left(\frac{e^2}{4\pi\varepsilon_0}\right)^2 \frac{Z^2 n_e(T+m_e c^2)}{137\cdot m_e^2 c^4}\cdot\left[4\ln\left(\frac{2(T+m_e c^2)}{m_e c^2}\right)-\frac{4}{3}\right]$$

**T = kinetic energy of electron/positron**

# Collision vs. Bremm. Losses

- Which term dominates for electrons/positrons depends on the incident energy of the lepton

$$\frac{\left(\frac{dE}{dx}\right)_{bremm}}{\left(\frac{dE}{dx}\right)_{collisions}} \approx \frac{(T + m_e c^2)}{m_e c^2} \frac{Z}{1600}$$

  - Note that $1/\rho$ dE/dx is plotted

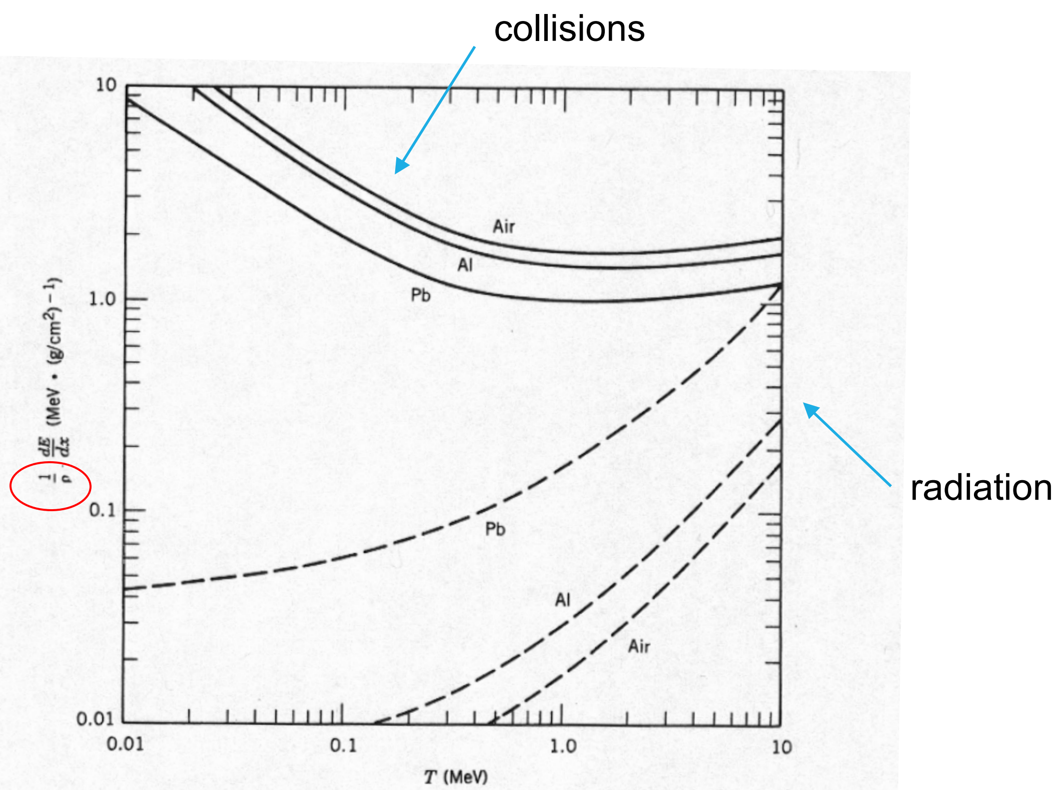
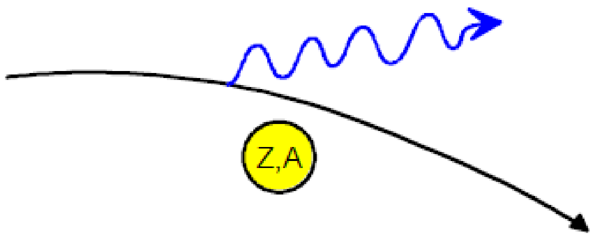



**Figure 7.3** Energy loss by electrons in air, Al, and Pb. To suppress the large variation in *dE/dx* arising from the number of electrons of the material, the quantity $\rho^{-1}(dE/dx)$ is plotted. Solid lines are for collisions; dashed lines are for radiation. For additional tabulated data on energy losses, see L. Pages et al., *Atomic Data* **4**, 1 (1972).

# Radiation Length

Parametrize bremsstrahlung energy loss as:

$$-\frac{dE}{dx} = 4\alpha N_A \frac{Z^2}{A} r_e^2 E \ln\frac{183}{Z^{1/3}} = \frac{E}{X_0} \quad \Rightarrow \quad \mathrm{E} = E_0 e^{-x/X_0}$$




$$X_0 = \frac{A}{4\alpha N_A Z^2 r_e^2 \ln\frac{183}{Z^{1/3}}} \sim 180\, A/Z^2 \ [\mathrm{g\ cm^{-2}}]$$

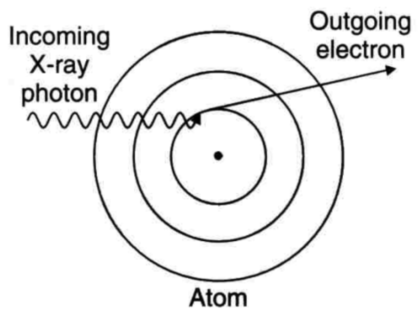
**Example: for Pb (Z=82, A=208), $X_0$ ~ 5.0mm**

A radiation length ($X_0$) is a very convenient quantity to characterize a medium where bremsstrahlung dominates (high energy > ~ 10 MeV).

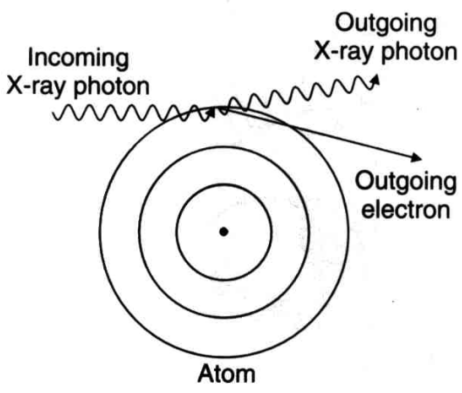
# Photons

- There are three relevant processes for the interaction of photons with matter:
  - Photoelectric Effect, Compton Scattering, Pair Production

- <u>Photoelectric Effect</u>
  - Absorption of a photon by an atomic $e^-$
  - Difficult to calculate but easily measured
  - Most important at low $E_\gamma$




- <u>Compton Scattering</u>
  - Scattering of a photon off an atomic $e^-$
  - Probability depends on scattering angle

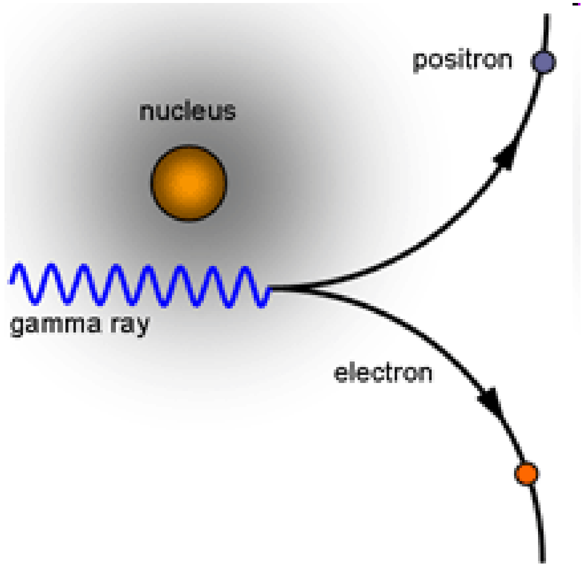


# Photons (cont.)

- Pair Production
  - Photon converts to an $e^+/e^-$ pair
  - Presence of nucleus required for momentum conservation
    - Recoil negligible

$$E_\gamma = T_{e^+} + m_e c^2 + T_{e^-} + m_e c^2$$

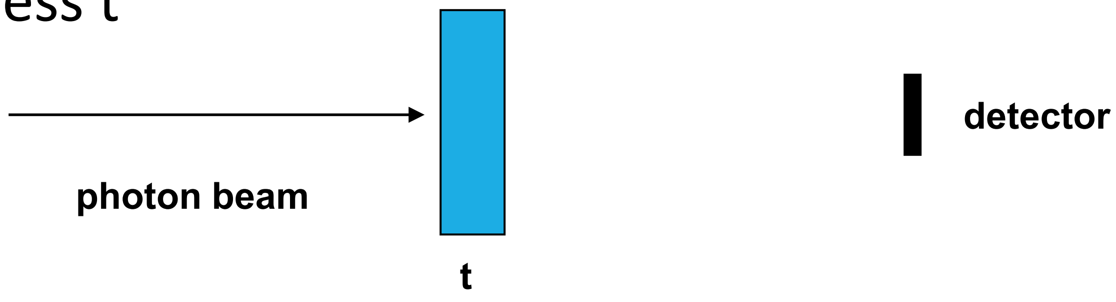
  - Threshold at $2m_ec^2$
    - Important at higher energies
    - Mean free path before pair production: $\lambda_{pair} = 9/7X_0$




- At a given energy, all three processes can contribute, but one process may dominate
- An interacting photon or electron rapidly leads to "shower" of electromagnetic particles in the material

# Attenuation Coefficients

- Consider an experiment where you have a beam of photons incident on a slab of material of thickness t




  - Detected photons will have suffered essentially no interaction at all
    - In contrast with protons of $\alpha$ particles
  - Define $\mu$ = *probability per unit length to remove a photon from the beam (total linear attenuation coefficient)*

$$\mu = \tau + \sigma + \kappa$$

$$\frac{dI}{I} = -\mu dx$$

$$I = I_0 e^{-\mu t}$$

$\tau$ = photoelectric effect probability
$\sigma$ = Compton scattering probability
$\kappa$ = pair production probability

# Photon Attenuation

Linear Attenuation Coefficient:

$$\mu = \tau + \sigma + \kappa$$

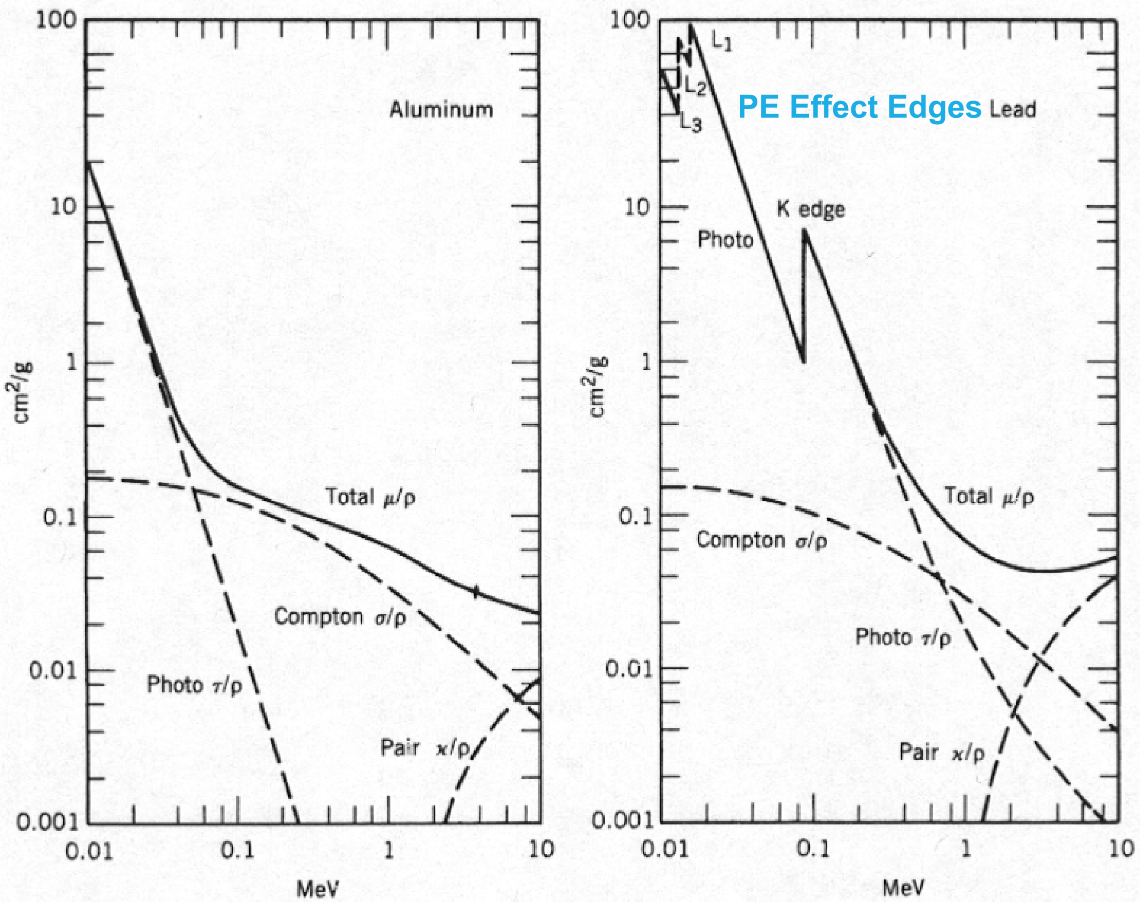



**Figure 7.10** Photon mass attenuation coefficients, equal to the linear attenuation coefficients divided by the density (to suppress effects due simply to the number of electrons in the material) for the three processes in Al and Pb.

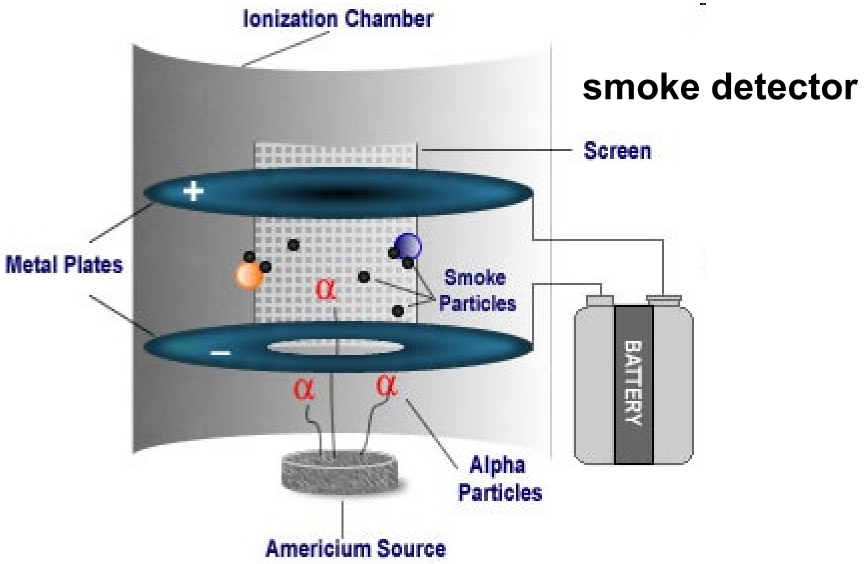
# Particle Detectors

- Now that we know the processes by which radiation and matter interact, let's look at how we can use this detect radiation
- <u>Gas Filled Counters</u>
  - Basic idea is simple – collect and count the ions/electrons formed by the passage of radiation through a gas volume
  - <u>Ionization Chamber</u> – basically a parallel plate capacitor

$$I_{AIR} \sim 86eV$$
$$1\ \mathrm{MeV} \rightarrow\ 1.2\mathrm{x}10^{4}\ \mathrm{ions/e^{-}}$$

$$\Delta V = \frac{1.2 \times 10^{4}(1.602 \times 10^{-19} C/ion)}{\sim 100pf} \sim 19\mu V$$

(100pf ~ 10cm by 10cm by 1cm gap)



# Ionization Chambers

- The ionization chamber gives you relatively small signals, need electronics to amplify the signal
- The size of the voltage/charge you collect is independent of the voltage you apply to the chamber
  - Just determines the drift speed of the ions/electrons

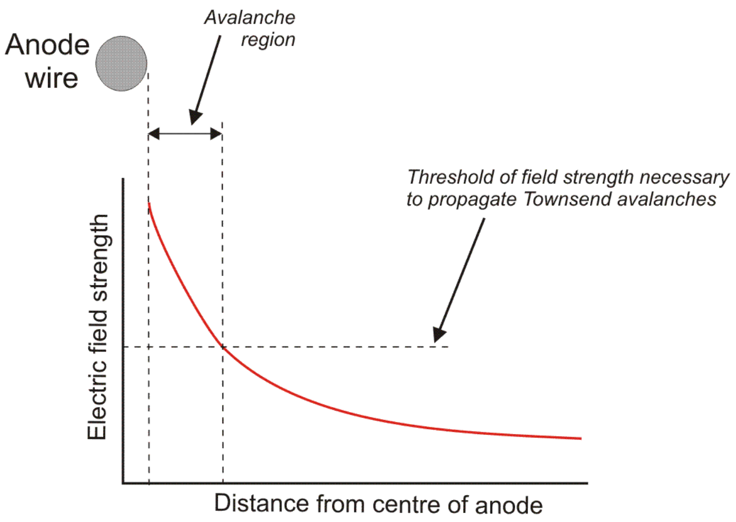
$$v_d(@100V) \approx 1m/s$$

  - To cross a 1cm gap takes about 0.01s – not a very fast detector!

- Ionization chambers are used as radiation monitors, where counting singles pulses is not important, but you want a measure of the total radiation flux.

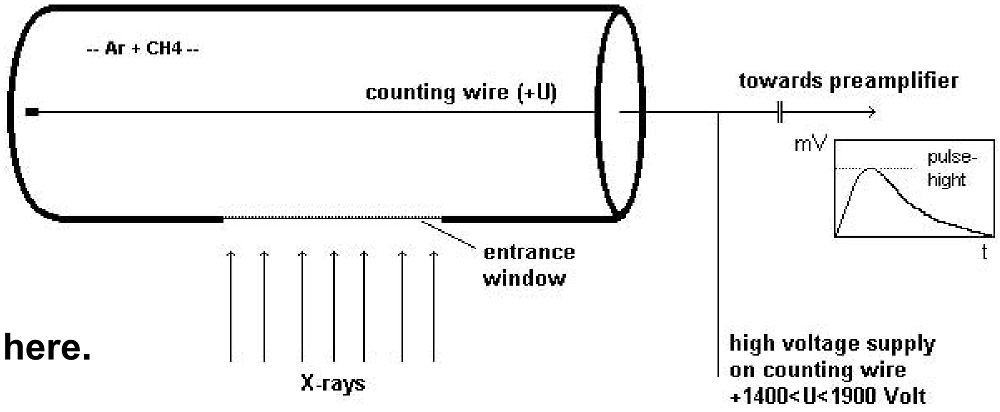
# Proportional Counters

- Designed to be able to count single pulses
- We want a faster drift time, so increase the voltage
  - This accelerates the ions/electrons
  - Faster moving $e^-$ can have inelastic collisions to create more ionization
  - This leads to an amplification of the original signal!
  - Typically use a cylindrical geometry




$$E(r) = \frac{V}{r\ln(b/a)}$$

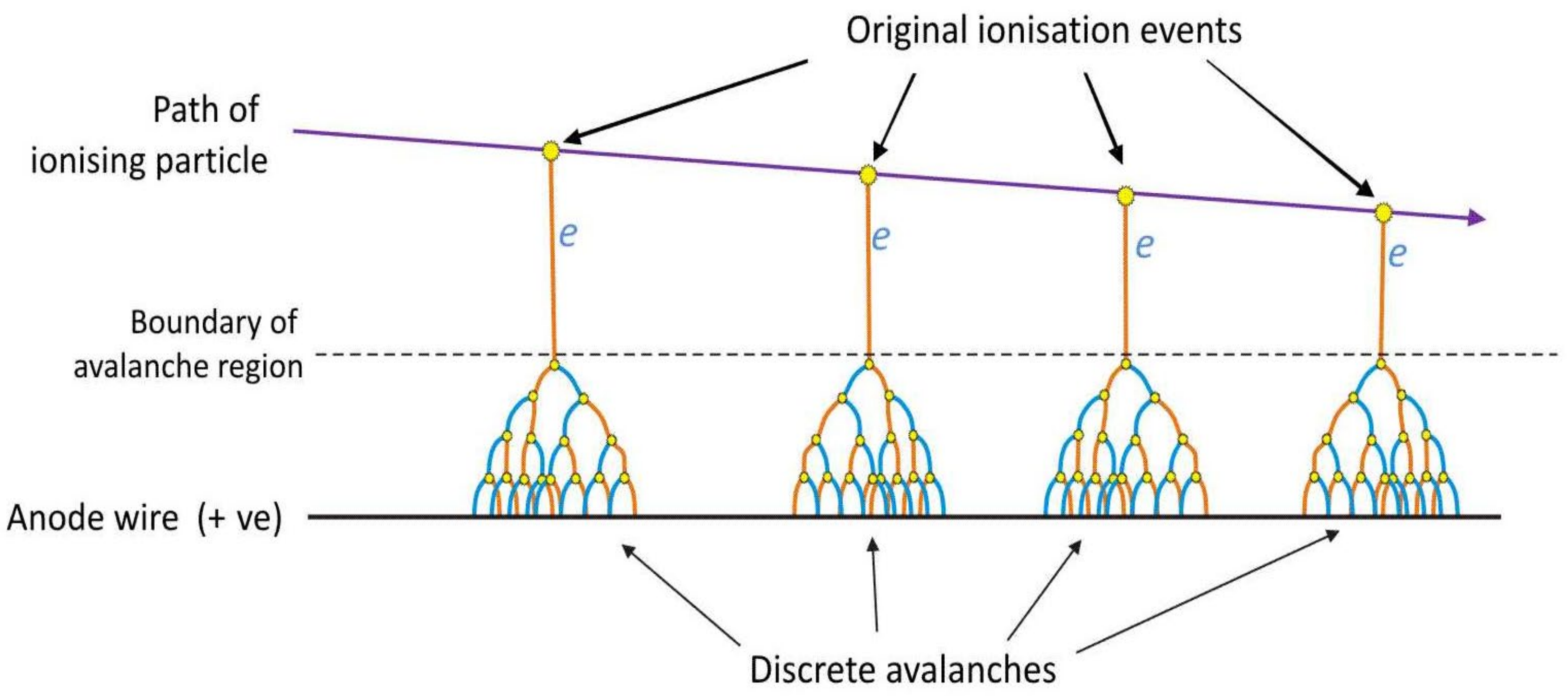
b = cathode cylinder radius
a = anode wire radius




**Very high *E(r)* near the anode wire, most of the amplification takes place here.**

**Size of the signal is still *proportional* to initial ionization. Drift times a few μs.**

# Avalanche




Drift region

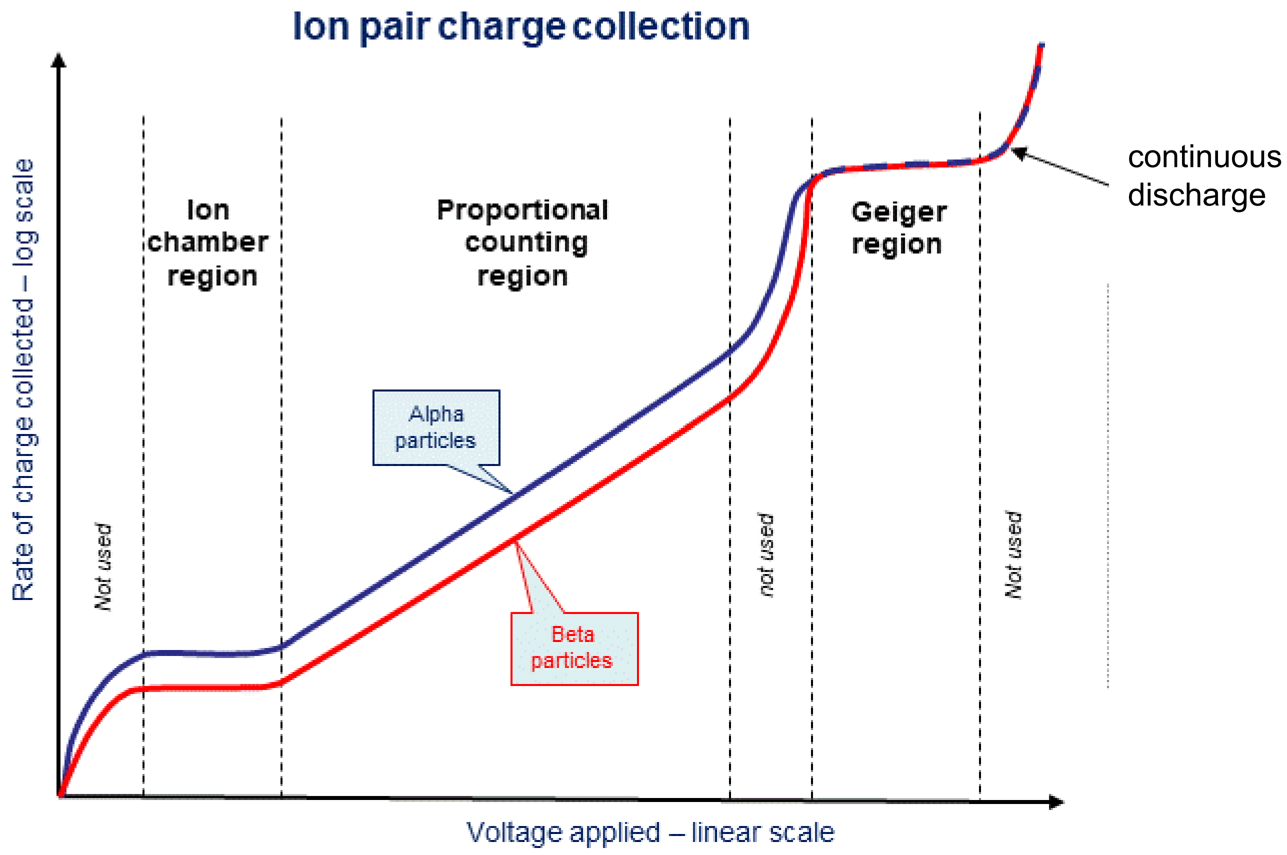
Avalanche region

*M* = multiplication (gain)
*p* = pressure
*V* = operating voltage
K = property of gas
$\Delta V_\lambda$ = change in voltage due to avalanche

$$\ln M = \frac{V}{\ln\left(\frac{b}{a}\right)} \frac{\ln 2}{\Delta V_\lambda}\left[\ln\left(\frac{V}{pa\ln(b/a)}\right) - \ln K\right]$$

# Geiger Counters

- If you increase the voltage further, you will reach a point where amplification can take place anywhere in the cylinder
  - Large ($10^{10}$) amplification, but all incident radiation counts the same
  - Ions striking the cathode could liberate electrons and start the process over again
  - Typically mix in a hydrocarbon gas to *quench* the ions
  - 90%Ar/ 10% Ethane mix (P10)
    - Absorb UV photons from excited states to shut off the cascade



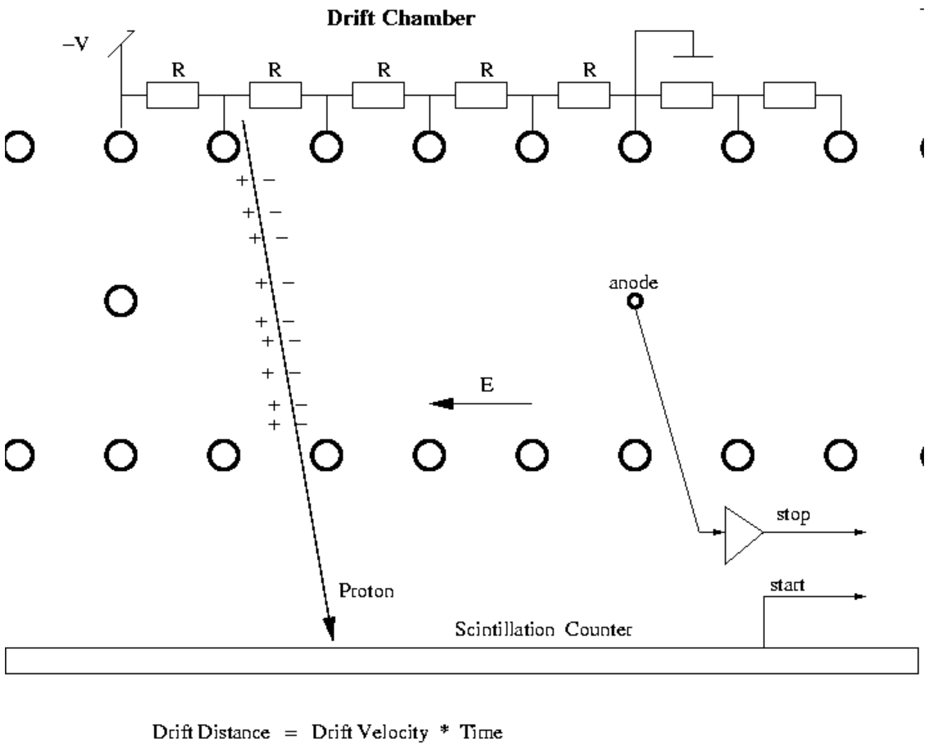
# Drift Chambers

- You can expand a proportional chamber into a multi-wire device (MWPC) or a Drift Chamber
  - Record the time of each pulse and use that information to better localize the particle “hit”
    - Greatly increases the accuracy of the device (50-150 μm)

**External device gives a time reference.**

**Electric fields adjusted to be almost constant within a drift “cell”.**

**Timing of hit and known drift velocity used to produce accurate hit location.**

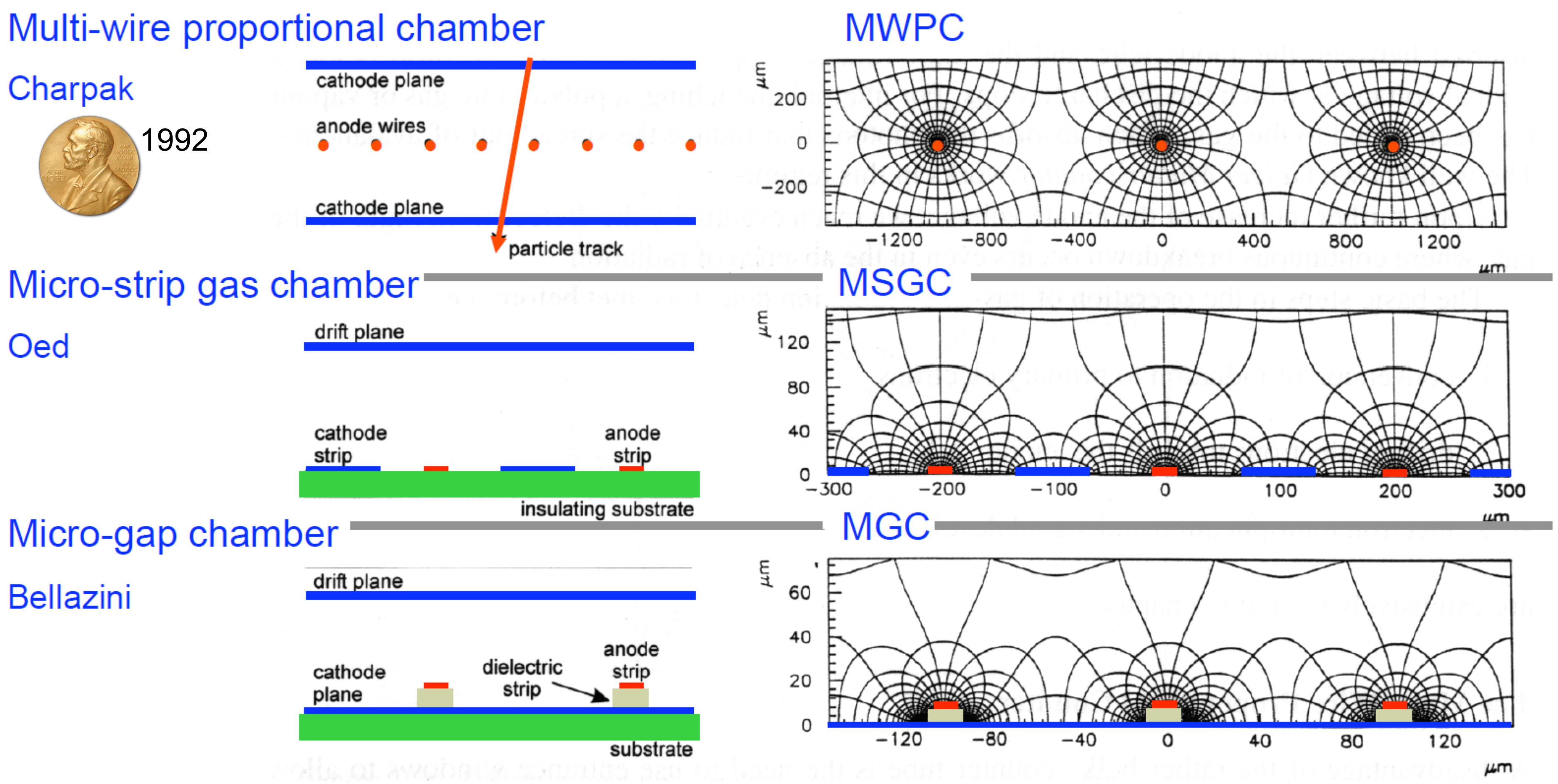


# MWPC's, MSGC's, MGC's, …

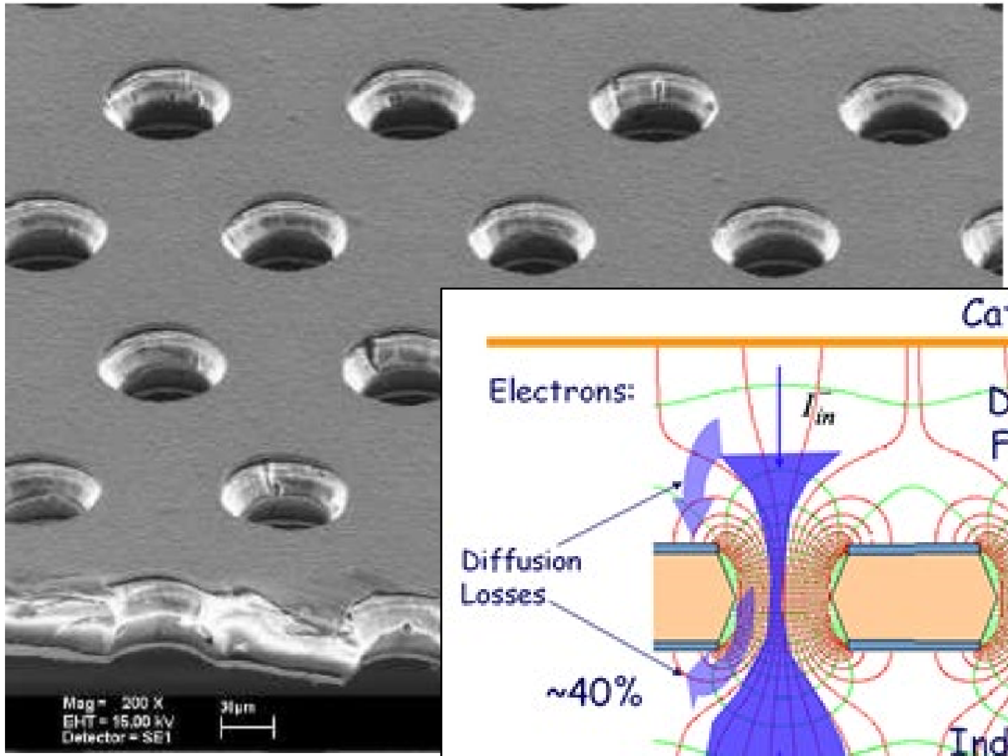
Movement of the positive ions to the cathode plane generate a large part of the signal – but the ions are heavy (and slow!).

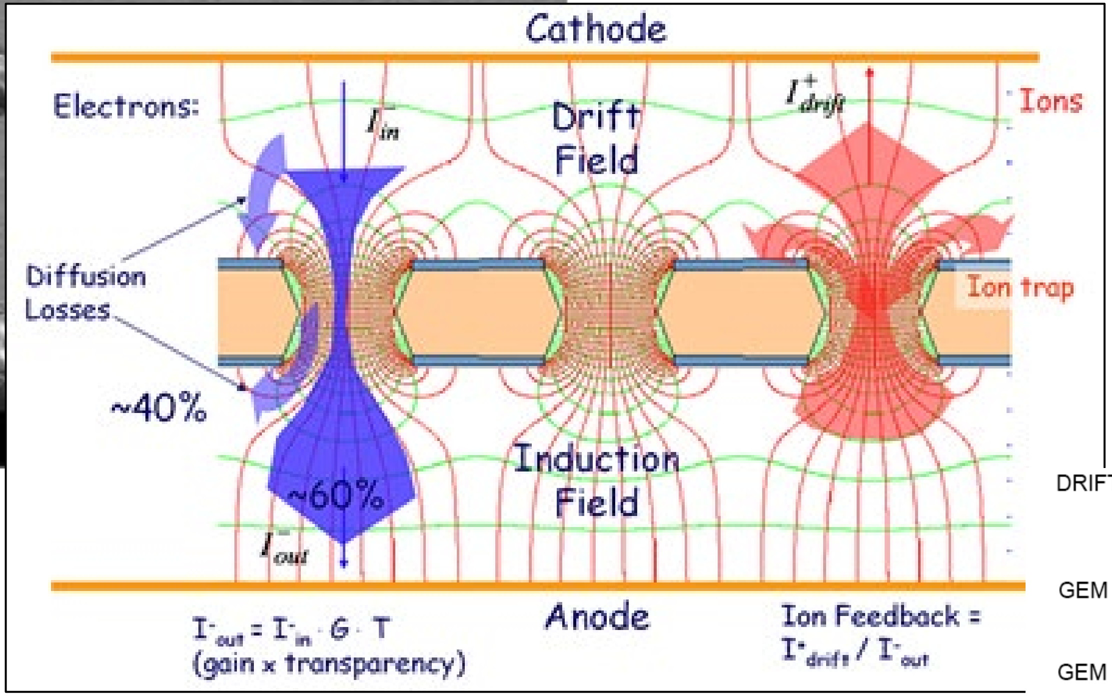
Different field configurations can create small anodes (good position resolution) and small distances for ions to travel to the cathode.

Photoetching is easy, but must be supported by relatively thick material



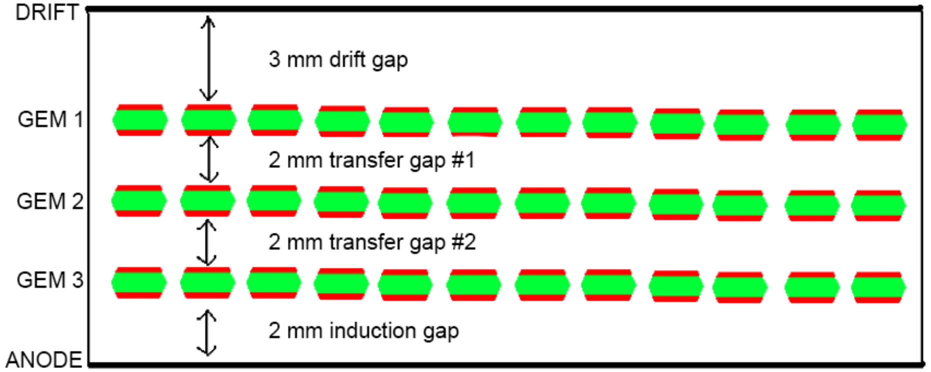
# GEMs (Gas Electron Multiplier)



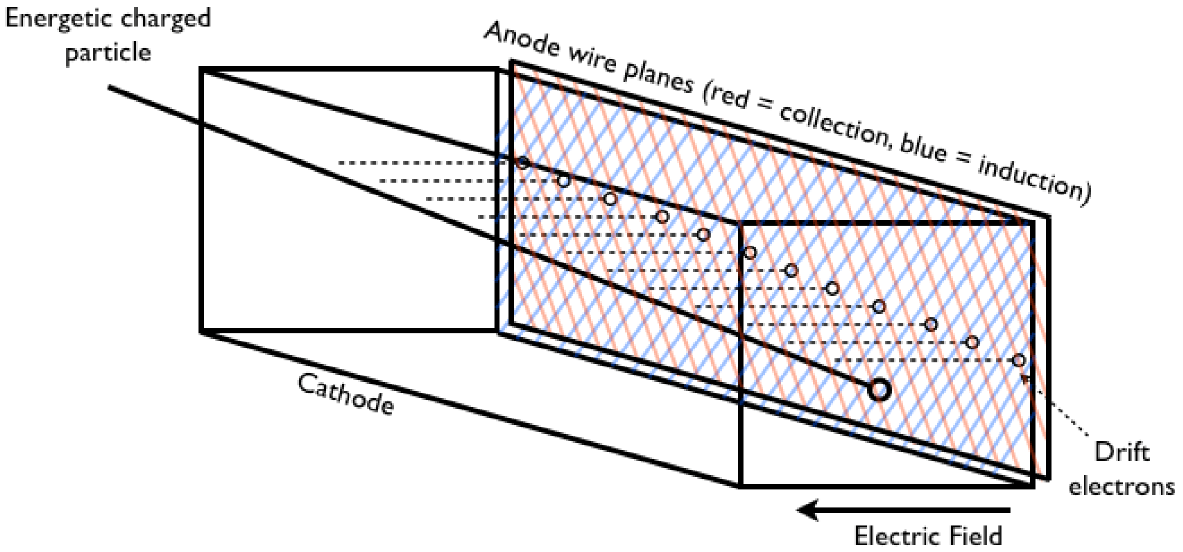




A GEM uses a thin metallized mylar with precision holes in a regular pattern – the hole provides the amplification region.

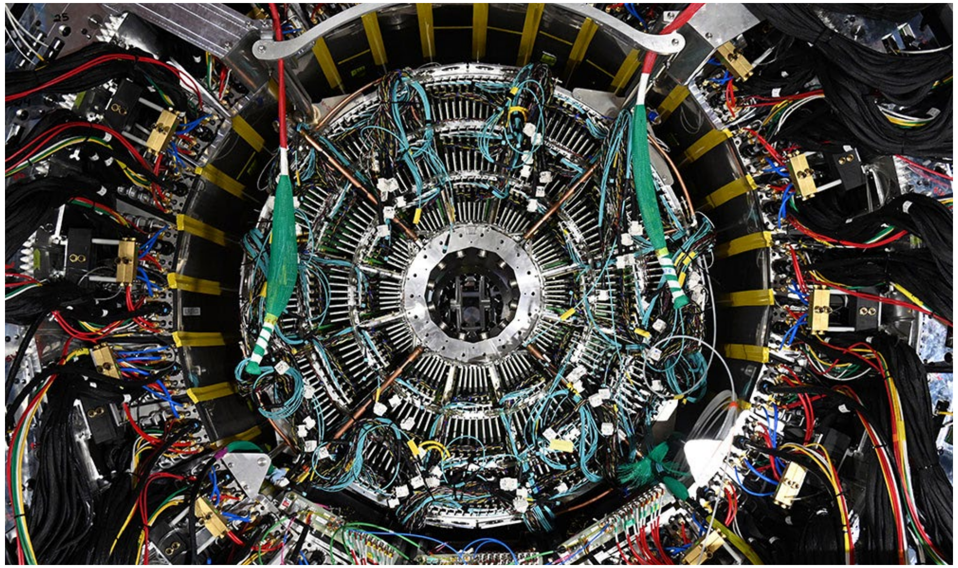
Layers of GEMs can be uses to provide high gain, readout provided by an instrumented anode plane.

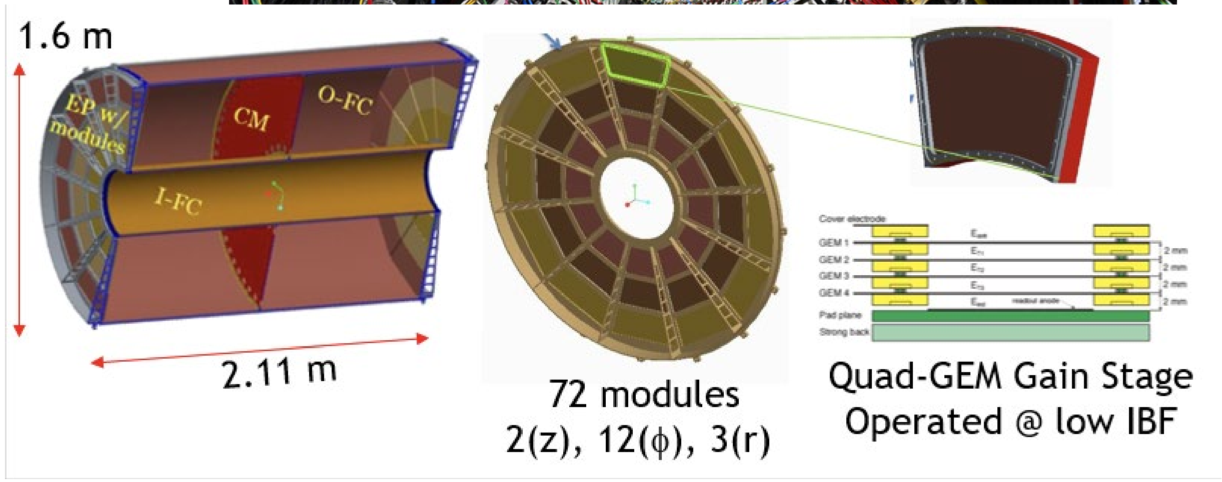


# Time Projection Chamber




sPHENIX TPC






A time projection chamber uses the drift time of the ionization to determine the third coordinate of the “hit” – well suited to a solenoidal magnetic field configuration where E||B.

Readout at the ends has typically been some sort of MWPC, which had to be gated to prevent ion backflow back into the gas volume. Newer TPC’s (sPHENIX, ALICE) use GEM’s in a configuration that suppresses ion backflow and can operate continuously.

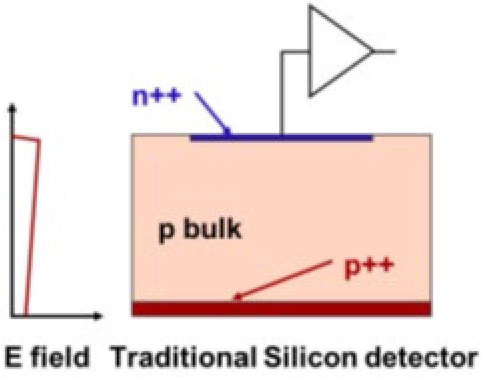
Charge buildup in the TPC is still an issue and will distort particle tracks!

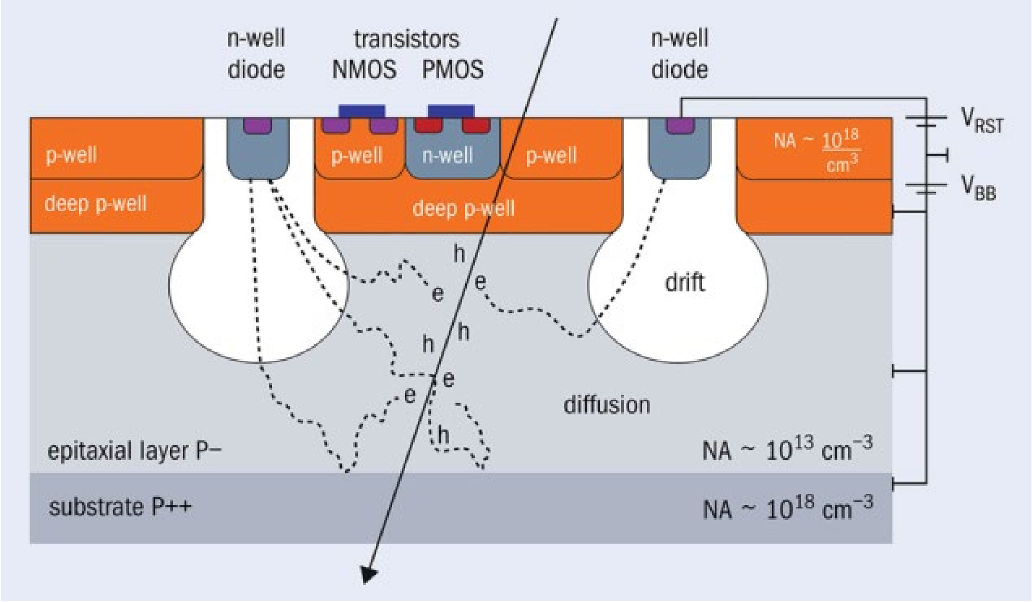
# Silicon Detectors (SS Drift Chamber)

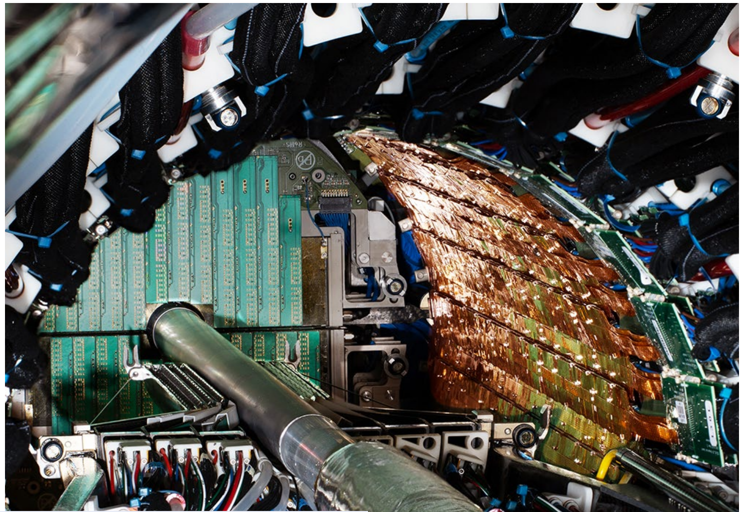
- A silicon detector is essentially a reverse biased diode, the bulk Si is used as the medium

Hybrid sensors bond the electronics to the Si sensor.

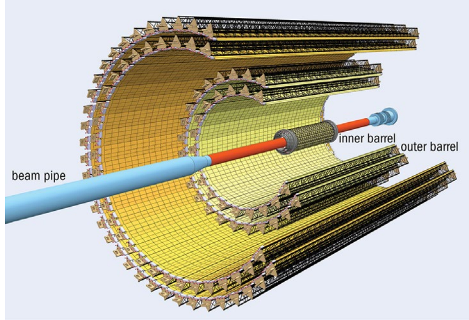
MAPS (Monolithic Active Pixel) devices allow for integration of the sensor and electronics.



ALICE ITS2 Inner Tracker




  - Charge deposition by a charged particle creates a current
  - Small feature size – excellent resolution (down to 10’s of $\mu$m)
    - Even better if charge sharing is taken into account.

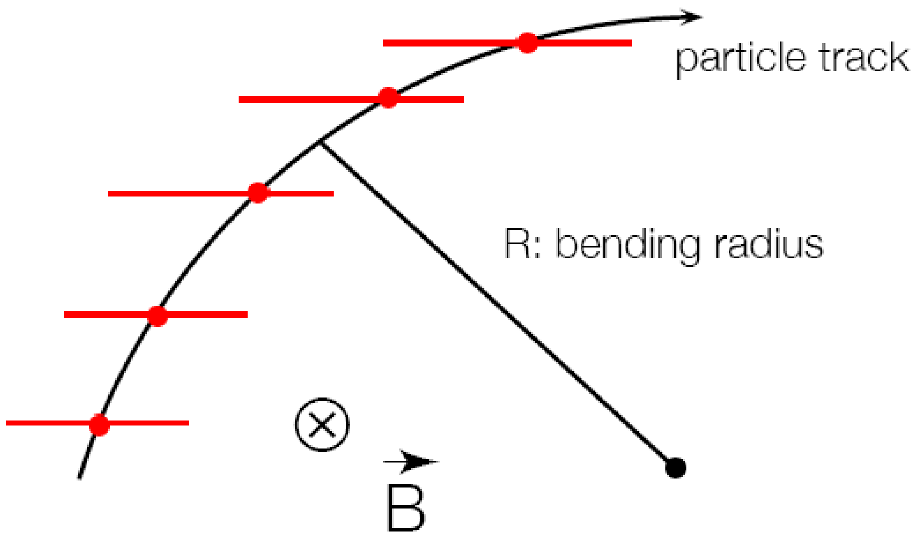
# Tracking

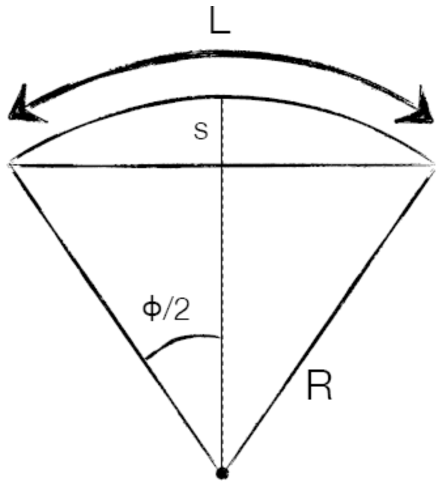
$$\vec{F} = q\vec{v} \times \vec{B}$$

$$\frac{mv^2}{R} = evB \quad \rightarrow \quad p = eB \cdot R$$

$$\boxed{p\left[\frac{\mathrm{GeV}}{c}\right] = 0.3B\,[\mathrm{m}] \cdot R\,[\mathrm{T}]}$$

Use layers of position sensitive detectors in a magnetic field to measure the trajectory of a charged particle.




$$s = R - R\cos\frac{\phi}{2} \approx R\frac{\phi^2}{8} \qquad \text{with } \phi = \frac{L}{R}$$

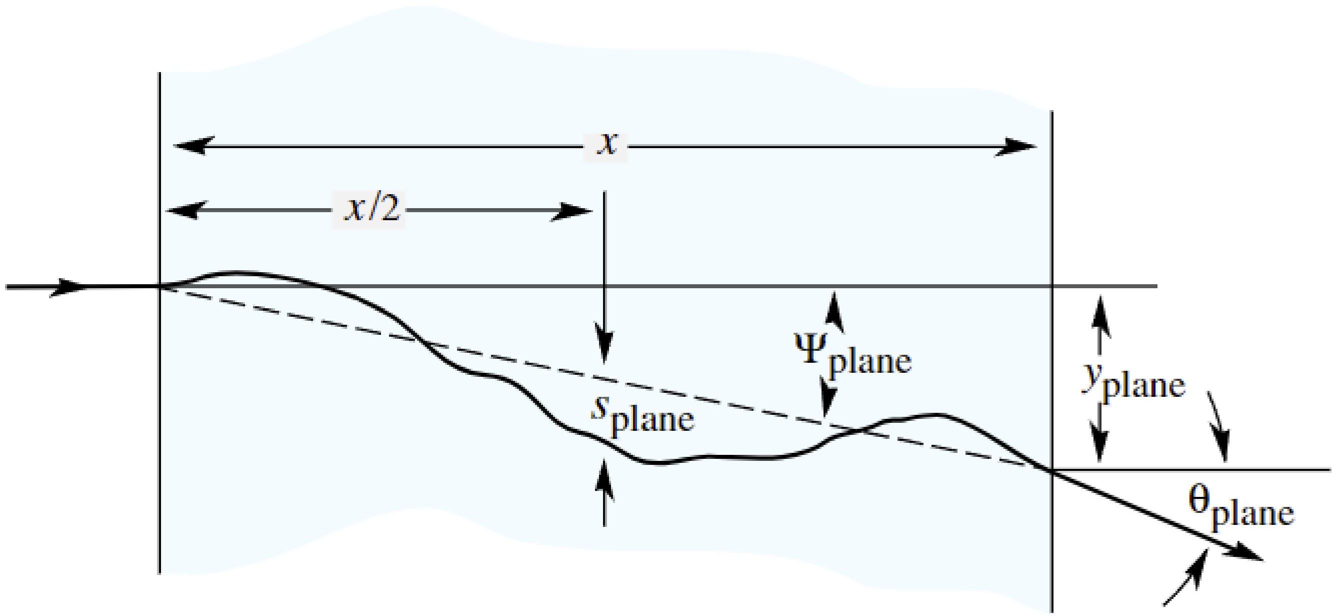
$$s = R\frac{L^2}{8R^2} = \frac{L^2}{8R} \quad \text{and} \quad R = \frac{L^2}{8s}$$

$$\rightarrow \quad \frac{\Delta p}{p} = \frac{\Delta R}{R} = \frac{L^2}{8Rs} \cdot \frac{\Delta s}{s}$$

➔ radius is obtained by a circle fit through measurement points along the track with point resolution $\sigma_{r\phi}$

# Multiple Scattering

- Particles passing through matter can also undergo scattering from the atomic nuclei (Rutherford scattering). This will deflect the direction of the particle through many small-angle scatters:




Thickness of material in radiation lengths

$$\theta_0 = \frac{13.6\ \text{MeV}}{\beta c p}\, z \sqrt{\frac{x}{X_0}}\left[1 + 0.088 \log_{10}\left(\frac{x\,z^2}{X_0 \beta^2}\right)\right]$$
$$= \frac{13.6\ \text{MeV}}{\beta c p}\, z \sqrt{\frac{x}{X_0}}\left[1 + 0.038 \ln\left(\frac{x\,z^2}{X_0 \beta^2}\right)\right]$$

Many small scatters leads to an approximately Gaussian distribution with tails from "hard" scatters.

$$\frac{1}{2\pi\,\theta_0^2} \exp\left(-\frac{\theta_{\text{space}}^2}{2\theta_0^2}\right) d\Omega,$$

$$\frac{1}{\sqrt{2\pi}\,\theta_0} \exp\left(-\frac{\theta_{\text{plane}}^2}{2\theta_0^2}\right) d\theta_{\text{plane}}$$

**For tracking detectors, you want it all - high precision, large signal, low mass, …**

# Momentum Resolution

Momentum measurement uncertainty:

$$\frac{\sigma_p}{p} = \frac{L^2}{8Rs} \cdot \frac{\sigma_s}{s} = \frac{L^2}{8R} \cdot \frac{\sigma_s}{L^4/64R^2} = \frac{\sigma_s}{L^2} \cdot 8R = \frac{\sigma_s}{L^2} \cdot \frac{8p}{eB} \sim p \cdot \frac{\sigma_s}{BL^2}$$

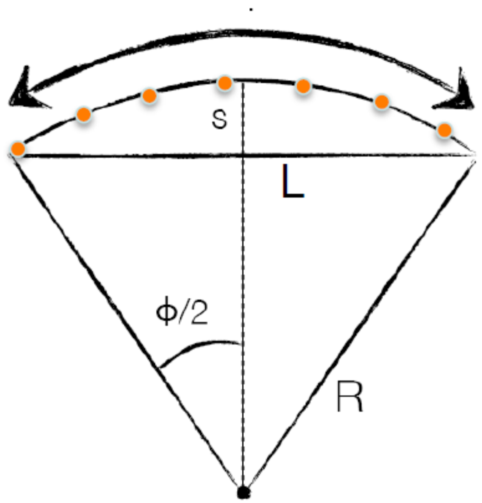
Uncertainty $\sigma_s$ depends on number and spacing of track point measurements; for equal spacing and large N:

$$\sigma_s = \frac{\sigma_{r\phi}}{8}\sqrt{\frac{720}{N+5}}$$

see: Glückstern, NIM 24 (1963) 381 or Blum & Rolandi, Particle Detection ...

Good momentum resolution:

- large path length L
- large magnetic field B
- good Sagitta measurement




For momentum p:

generally in experiment measure $p_t$

$$\left(\frac{\sigma_p}{p}\right)^2 = \left(\frac{\sigma_{p_t}}{p_t}\right)^2 + \left(\frac{\sigma_\theta}{\sin\theta}\right)^2$$

multiple scattering term conts. in $p_t$

using $p = \frac{p_t}{\tan\theta}$

# Scintillation Counters

- Basic idea is to convert the ionization to light, then collect the light
  - Has the advantage of a high efficiency even at low energies
- <u>Organic Scintillators</u> are typically a plastic (or oil) doped with a fluorescing chemical.
  - Passage of ionizing radiation excites the molecules and sets them into motion (vibration)
  - Excited state spacings are of order ~eV, vibrational spacings around 1/10 eV
  - Excited states decay to the vibrational ground state quickly (~ps), then later to the electronic ground state (~10ns)
  - As a result, the material is essentially transparent to its own radiation!
    - Since most molecules are in the ground only one of many possible transition photons is likely to be absorbed.
    - The doping elements shift the UV light to visible

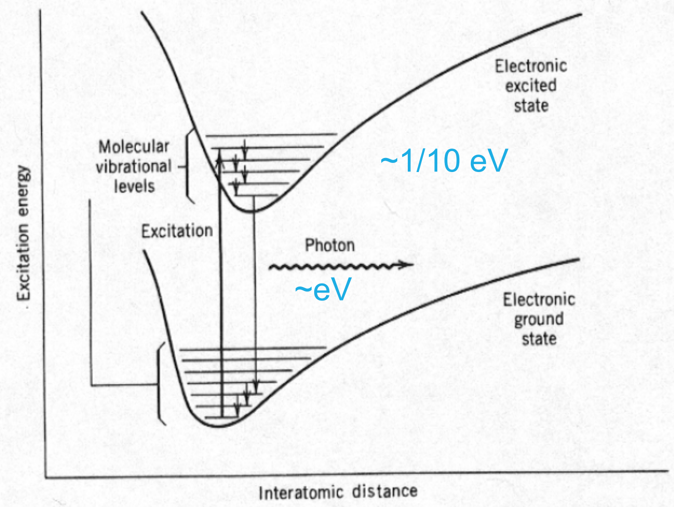



**Figure 7.15** Electronic structure in an organic scintillator. The electronic states are represented as a potential minimum, resulting from the combined effects of the molecular attraction that keeps us from separating the atoms to greater distances and the repulsion that keeps us from forcing the atoms closer together (because the Pauli principle does not let the atomic wave functions overlap). Inside the electronic potential minimum is a sequence of levels that result from the atoms of the molecule vibrating against one another.

# Photomultiplier Tube

- A PMT is a device that can detect a single photon, and amplify the signal to usable levels
  - Signal amplified at dynodes (~100V potential difference)
  - Typically, a gain of 5-10 at each dynode, total gain ~$10^7$

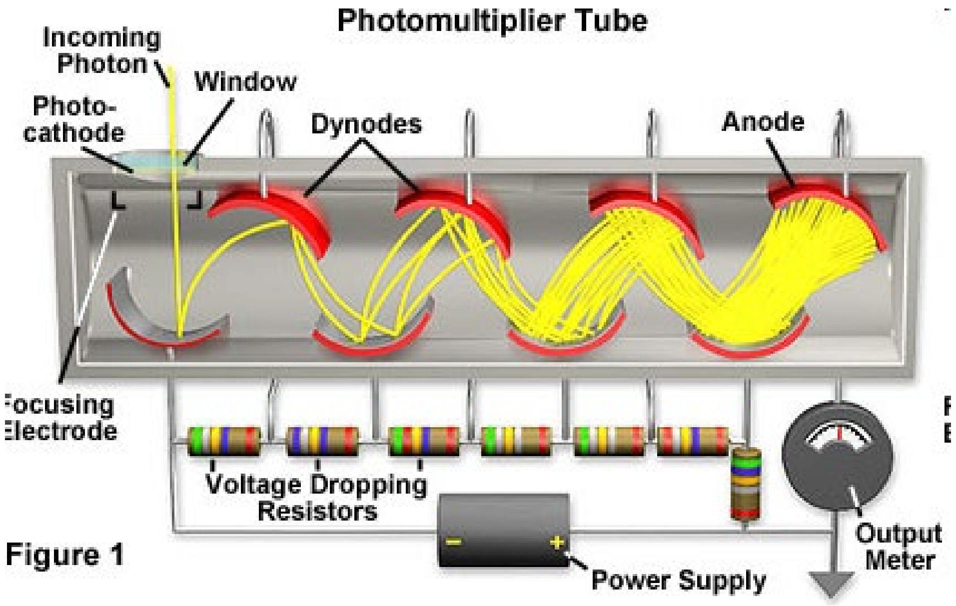
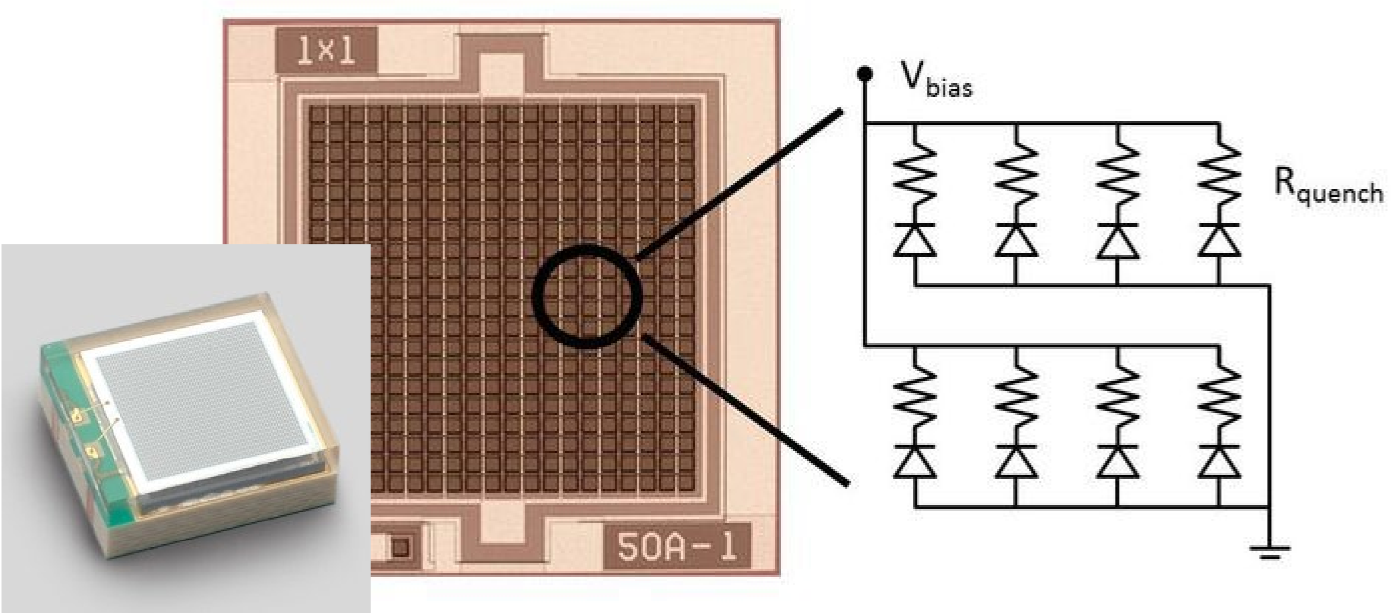


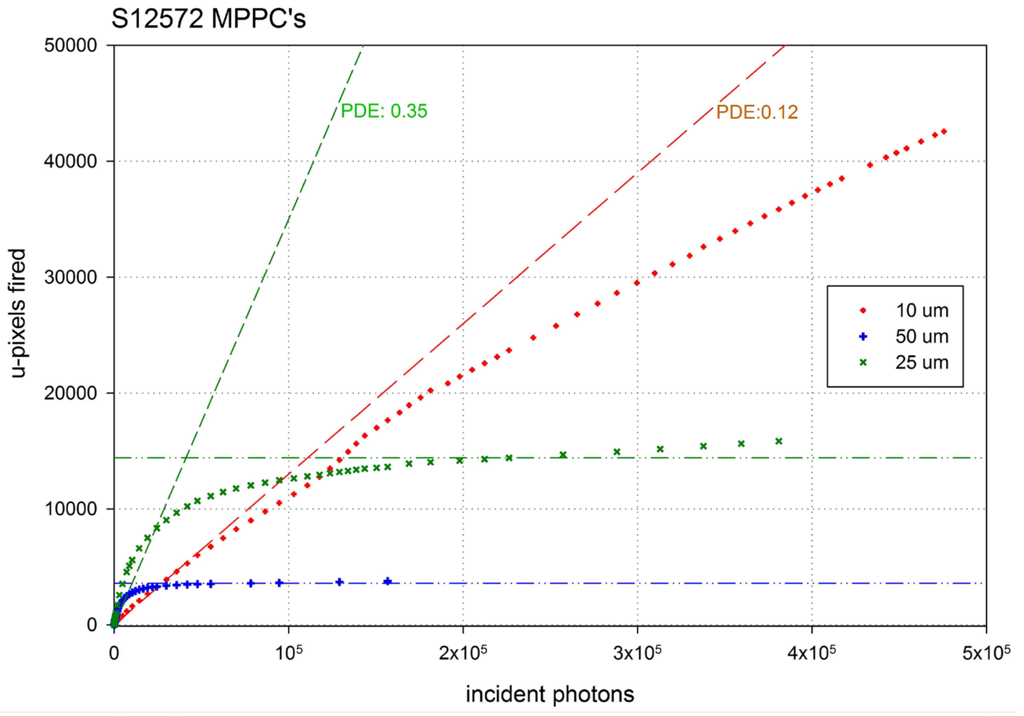
Figure 1

- Scintillator/phototube combinations used extensively as single particle detectors (~ns transit times, ~10ps time resolution)

# Si PMT's (SiPM)

- Potential replacement for a PMT




An array of parallel connected avalanche photodiodes (Geiger mode) with a quenching resistor.
A single photon can trigger the avalanche breakdown with very high internal gain.
Individual microcell response independent of light intensity, device response is summed output of microcells. High QE, fast response, independent of magnetic field – but – ***gain is temp dependent*** and they are ***susceptible to radiation damage***!

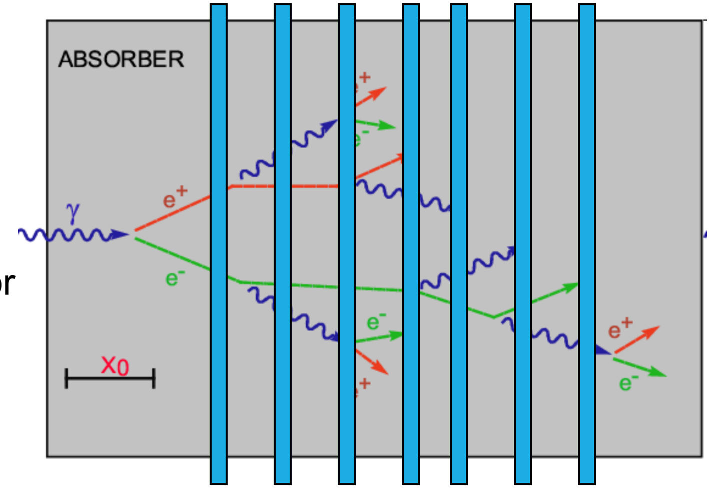
Larger cells -> higher QE, nonlinearity
Smaller cells -> lower QE, better linearity

# Calorimeters

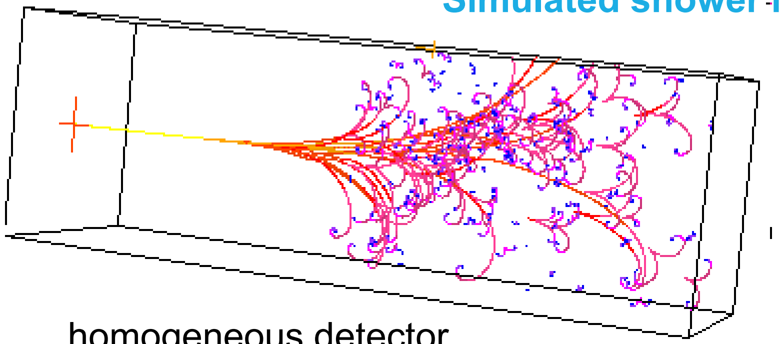
- A calorimeter is a device that measures the energy of a particle.
- Incident particles interact and initiate a shower in the high-density calorimeter material
  - Electromagnetic Calorimeter: photons, $e^{+/-}$
    - Radiation Length ($X_0$): 6.37 g/cm$^2$ for Pb (0.57 cm)
  - Hadronic Calorimeter: hadrons ($p,\pi,K$, etc.)
    - Hadronic Interaction Length ($\lambda_I$): 119.6 g/cm$^2$ for Pb (10.5 cm)

Both define 1/e distance

sampling detector



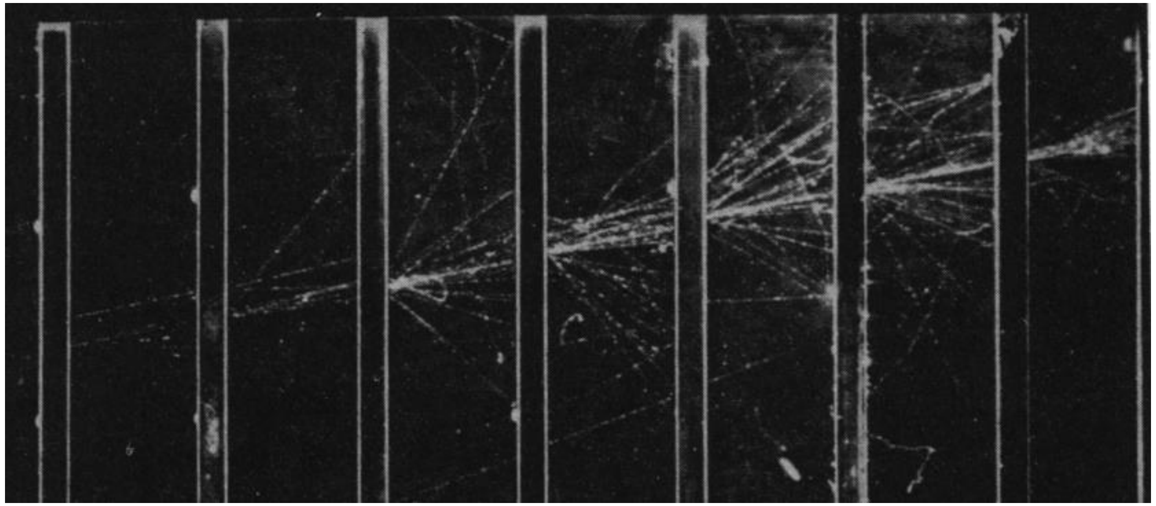

Simulated shower in a PbW crystal.



homogeneous detector

# Electromagnetic Cascade (Model)

Consider a high energy incident photon or electron, incident energy = $E_0$, $\lambda_{pair} = X_0$:
After each $X_0$ the number of particles doubles.



Electron shower in a cloud chamber with Pb absorbers

After t layers of thickness $X_0$: $\mathrm{N(t)} = 2^t$

Average energy per particle: $\mathrm{E(t)} = {E_0}/{2^t}$

This continues until $E(t) < E_C \sim \frac{610\ MeV}{Z+1.24}$ (7.3 MeV for Pb)

$$t_{max} = \frac{\ln {E_0}/{E_C}}{\ln 2}$$

$$N_{tot} = \sum_{t=0}^{t_{max}} 2^t \approx 2\frac{E_0}{E_C}$$

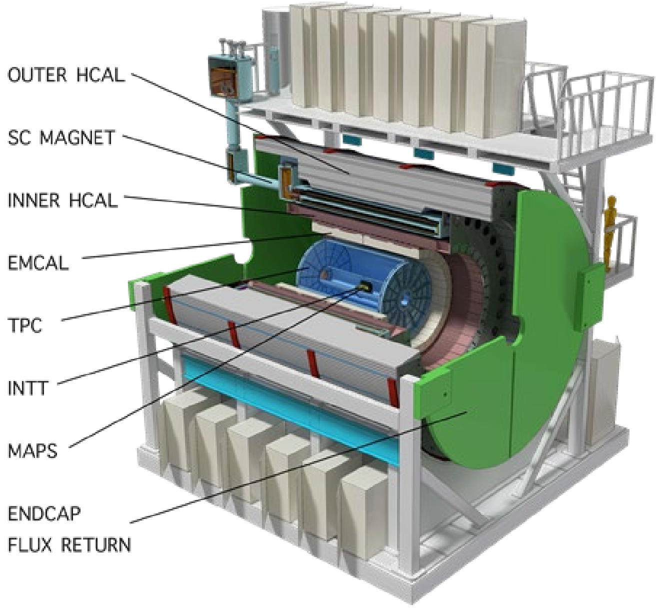
**<u>For a 50 GeV electron on Pb:</u>**
**$N_{tot}$ ~ 14000**
**$t_{max}$ ~ 13 $X_0$ (overestimate)**

# Electromagnetic Calorimeter (Sampling)

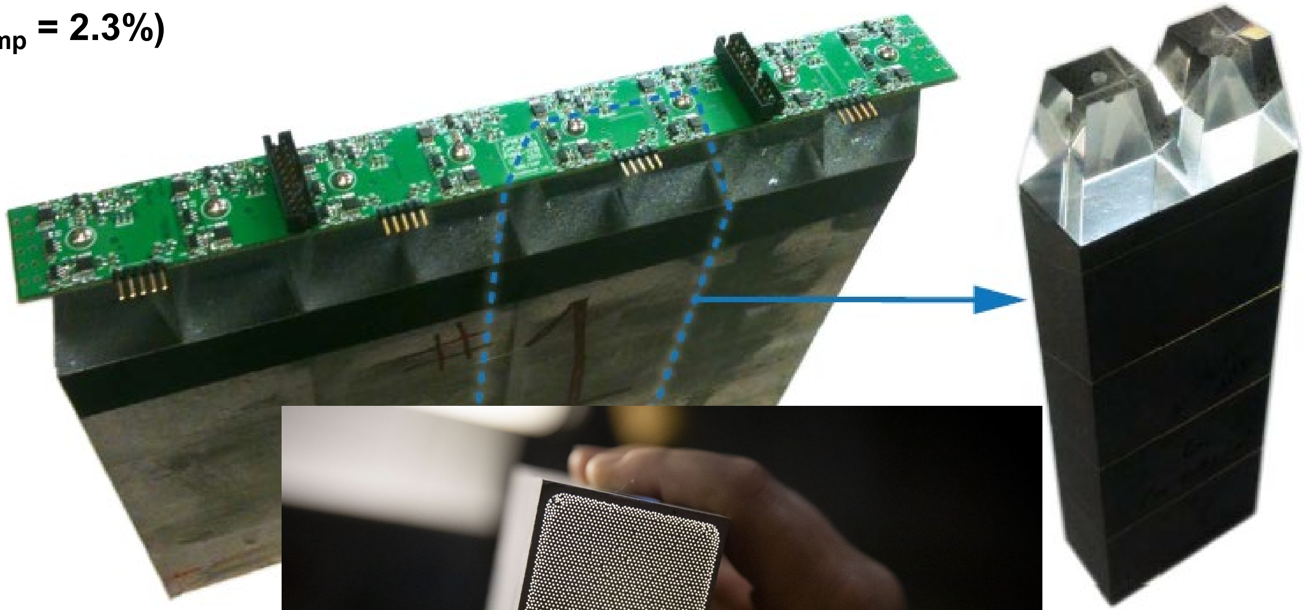
For a sampling calorimeter:

$$E_{meas} = \frac{E_{samp}}{f_{samp}}$$

Sampling fraction




**sPHENIX barrel EM Calorimeter W/SciFi ($f_{samp}$ = 2.3%)**



**Each block has 2688 fibers in a Tungsten-epoxy matrix**

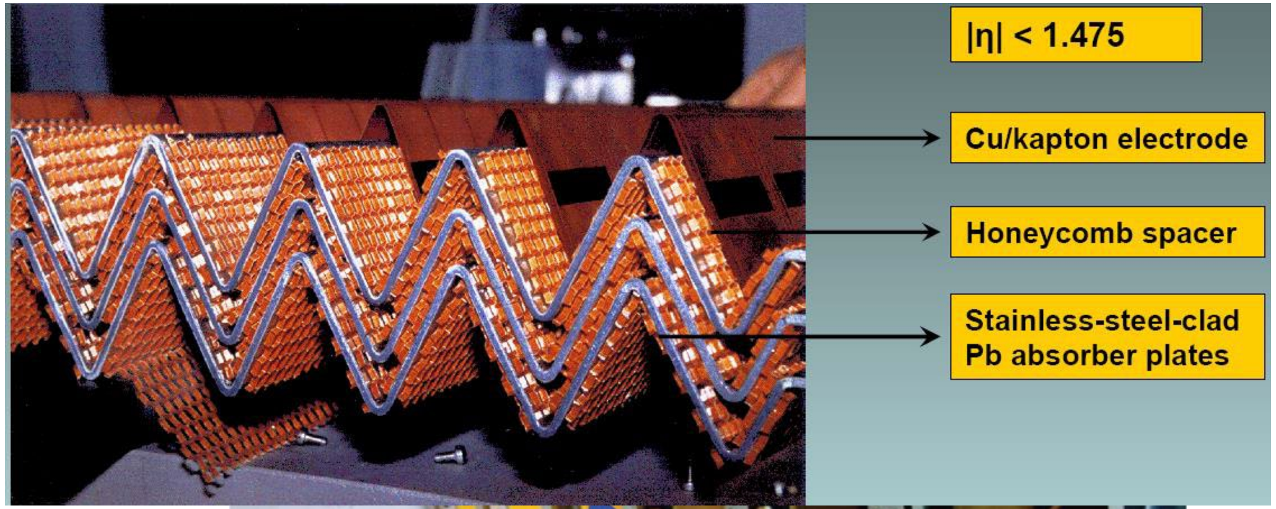
# Electromagnetic Calorimeters (Sampling)

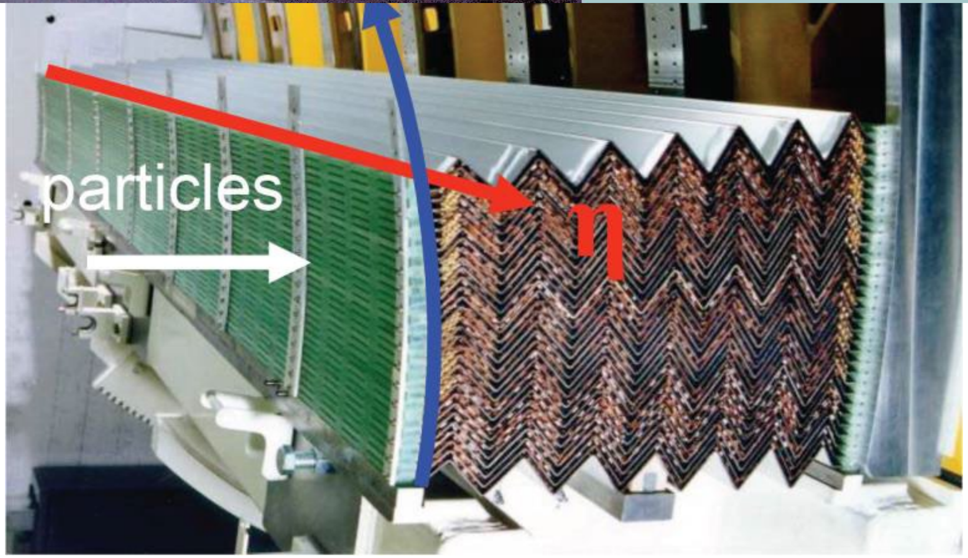
**ATLAS 'Accordion' sampling liquid Ar calorimeter at the LHC**

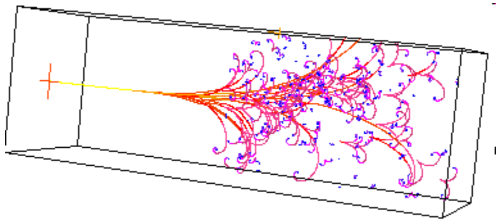
Corrugated stainless steel clad Pb absorber sheets (1-2mm thick), immersed in liquid Ar (90K)

Ionization electrons in liquid Ar collected via and electric field across a 2.1mm drift gap

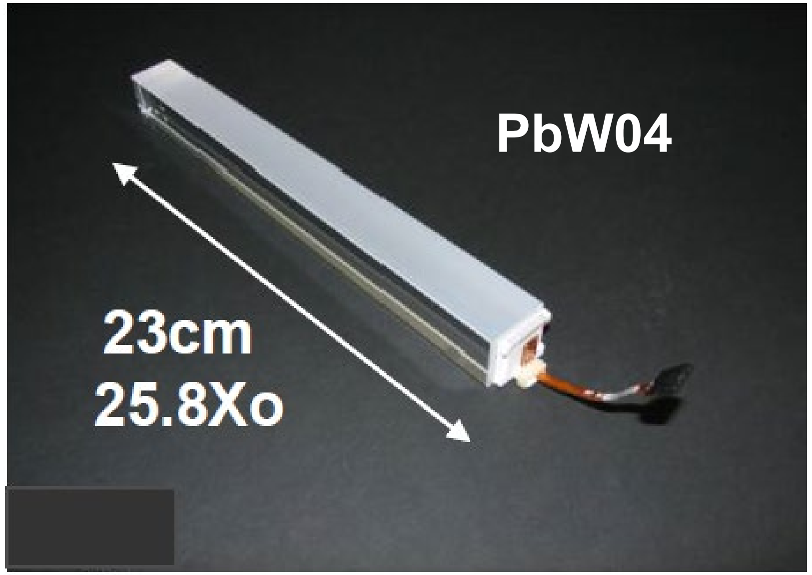
1 GeV deposit -> 5.0 x $10^6$ $e^-$



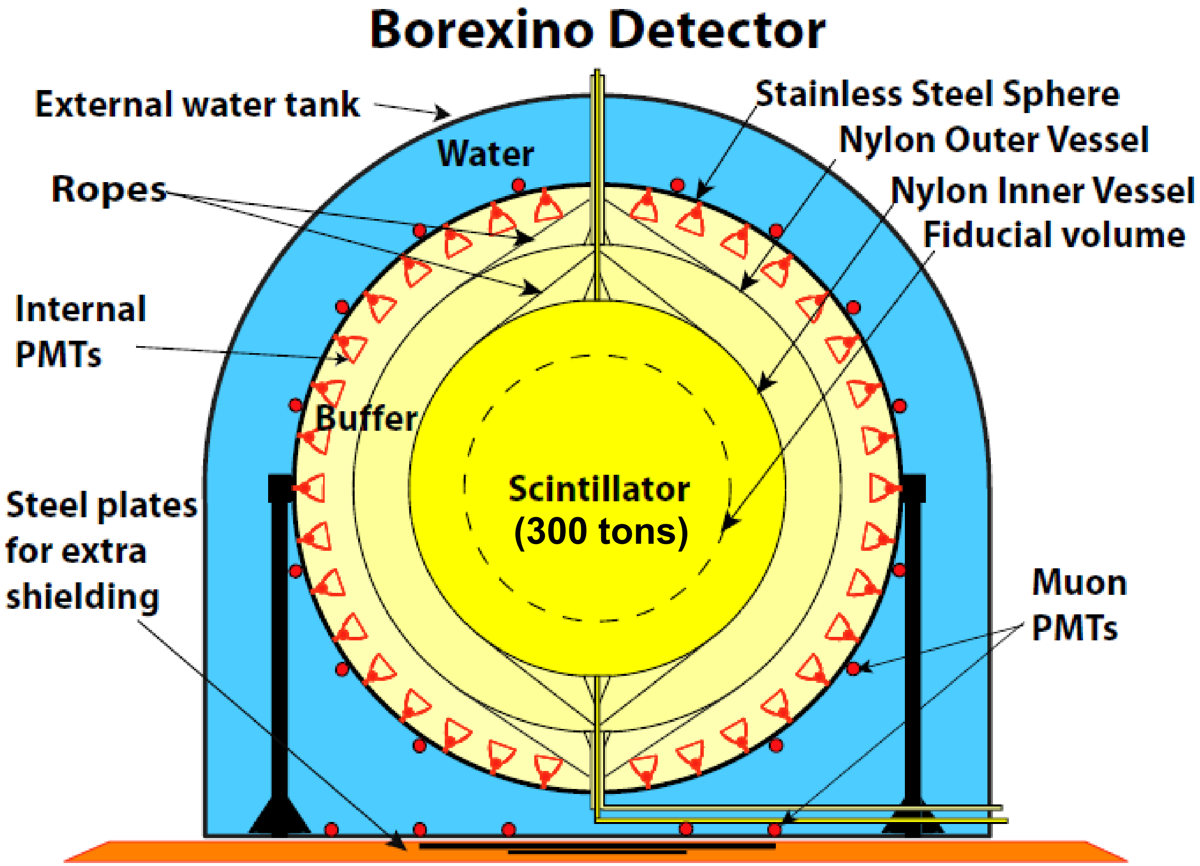





# Electromagnetic Calorimeters (Homogeneous)

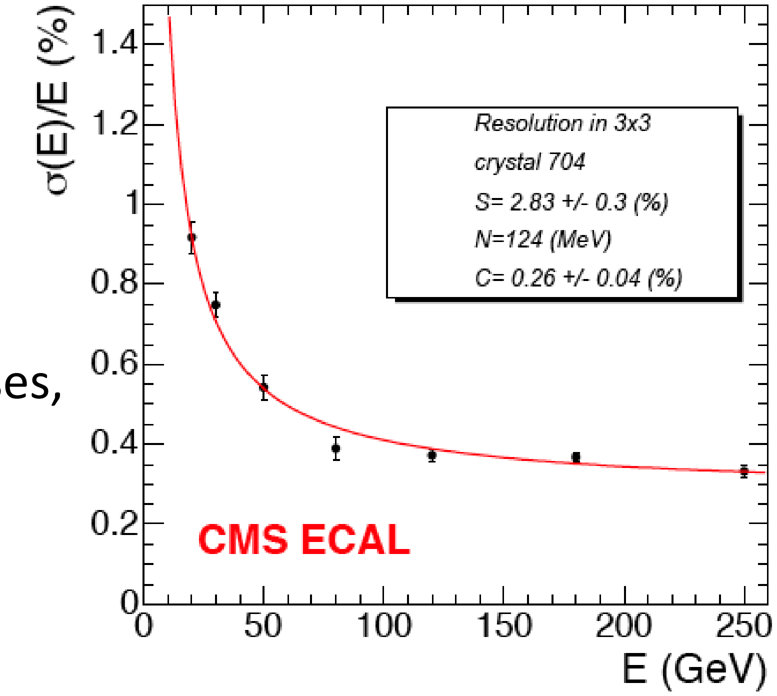



**CMS Barrel crystal, tapered ~2.6x2.6 cm$^2$ at rear**
**Avalanche Photo Diode readout, gain = 50**



# Energy Resolution in Calorimetry

$$\frac{\sigma}{E} = \frac{a}{\sqrt{E}} \oplus \frac{b}{E} \oplus c$$




**Stochastic term (a):** Fluctuations in the number of signal generating processes, for example the number of electrons that are detected as signals

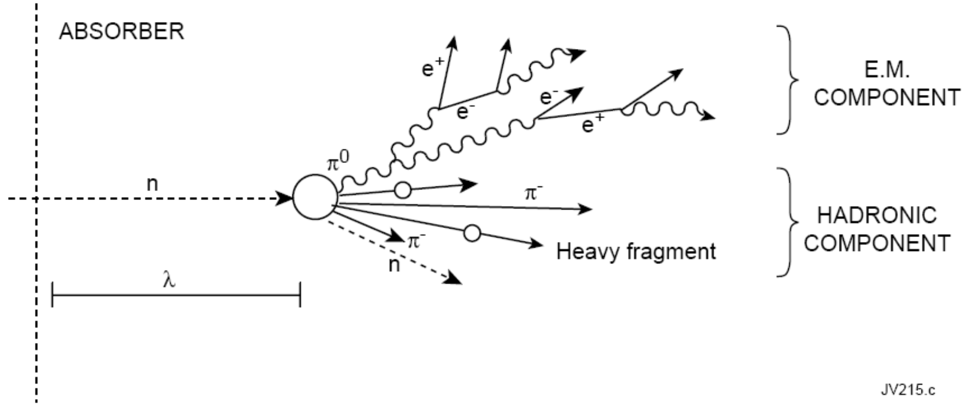
**Noise term (b):** Noise in readout electronics, 'pile up' from other collision events close in time, etc.

**Constant term (c):** Imperfections in calorimeter construction, non-uniform response, calibration errors, energy lost in dead material (before or in detector)

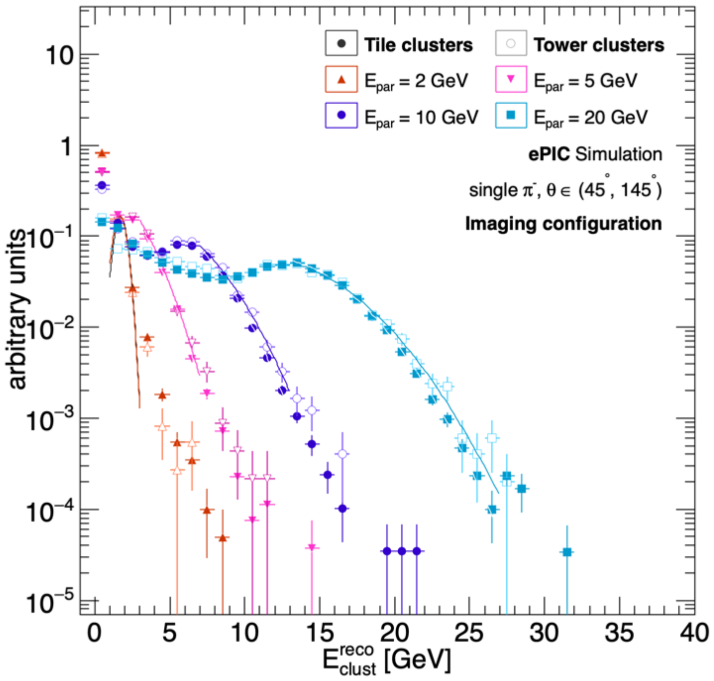
A small constant term is crucial for good energy resolution at the highest particle energies.

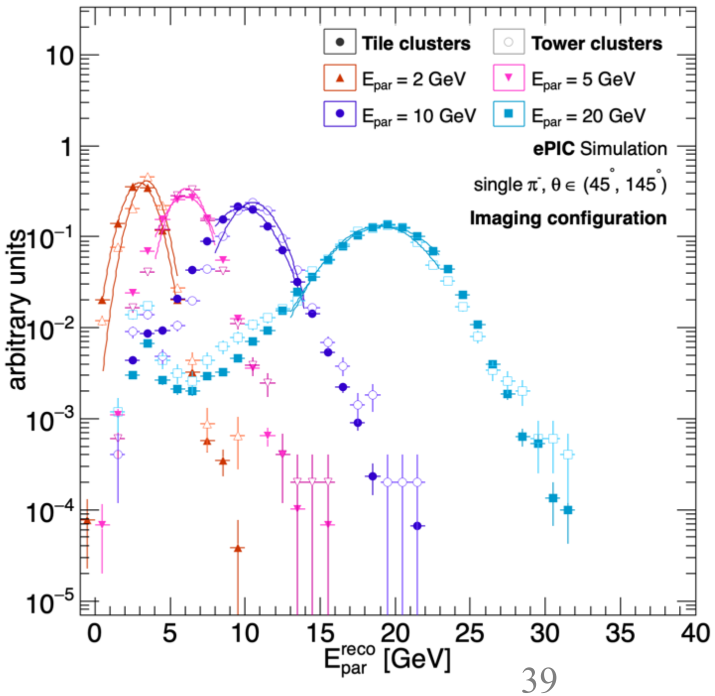
# Hadronic Calorimetry

A hadronic calorimeter generates a particle cascade by interactions with nuclei in the absorber material.  This cascade will have an *electromagnetic* and *hadronic* component.



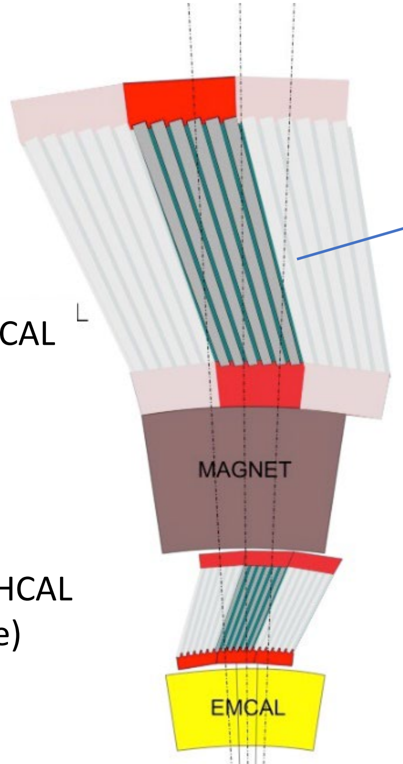

This makes good hadronic calorimetry complicated!  The EM and hadronic components will be sampled differently in the calorimeter $\left(\frac{e}{h} \neq 1\right)$ so fluctuations in the different components will limit the energy resolution that can be achieved.  There are ways around this…

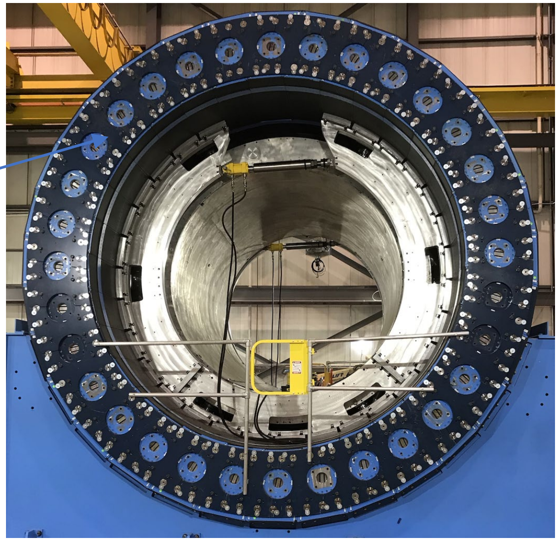



Must also calibrate for losses to nuclear binding energy, etc.

# Hadronic Calorimetry (sPHENIX)



- HCAL steel and scintillating tiles with wavelength shifting fiber
  - **Outer HCal (outside the solenoid)**
  - **$\Delta\eta \times \Delta\phi \approx 0.1 \times 0.1$**
  - **1,536 readout channels**
- SiPM Readout

- Outer HCAL $\approx 3.5\lambda_I$
- Magnet $\approx 1.4X_0$
- (Frame $\approx 0.25\lambda_I$) (sPHENIX)
- (EMCAL $\approx 18X_0 \approx 0.7\lambda_I$)

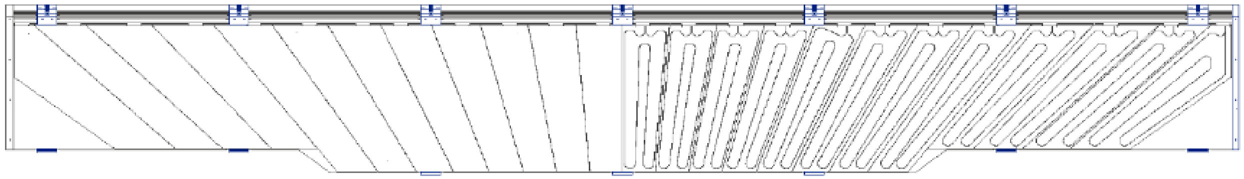
(sPHENIX)

HCAL performance requirements driven by jet physics in HI collisions

- Uniform fiducial acceptance $-1<\eta<1$ and $0<\phi<2\pi$
  - Extended coverage $-1.1<\eta<1.1$ to account for jet cone
- **(sPHENIX)** Absorb >95% of energy from a 30 GeV jet
  - Requires ~4.9 nuclear interaction length depth
- **(sPHENIX)** Hadronic energy resolution of *combined* calorimetry:
  - UPP: $\frac{\sigma}{E} < \frac{150\%}{\sqrt{E}}$ (in central Au+Au collisions)
  - Gaussian response (limited tails)
- HCAL created by instrumenting barrel magnetic flux return

# Outer HCAL Design

tiles in sector gap:



**Assembly Detail:**
5 scintillators/tower
48 towers per sector
32 sectors;
1536 channels (7680 SiPMs)

32 assembled and tested sectors - 1.9m inner radius, 2.6m outer radius

10 rows of 8mm scint. tiles (24 tiles per row), 12$^{o}$ tilt angle

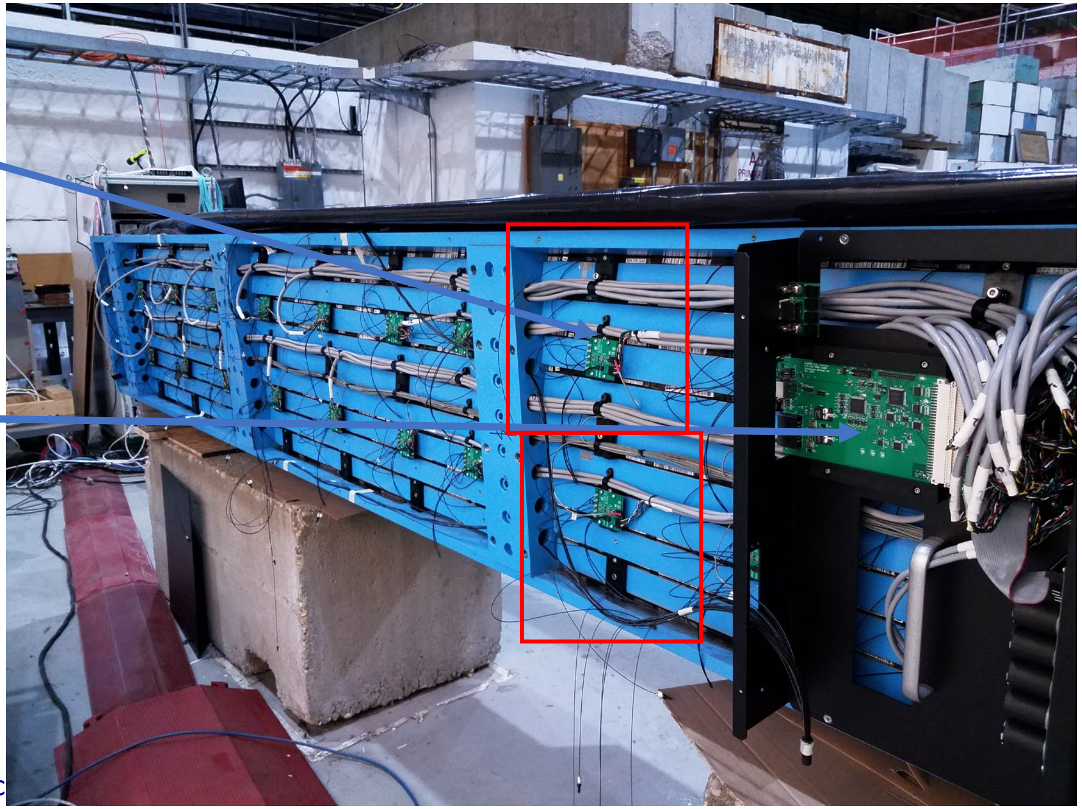
Tapered 1020 steel plates ~26.1mm - ~42.4mm

**Completed sector is 6.3m long, 13.5 tons**

Tower preamplifiers

LV/Bias and slow controls.

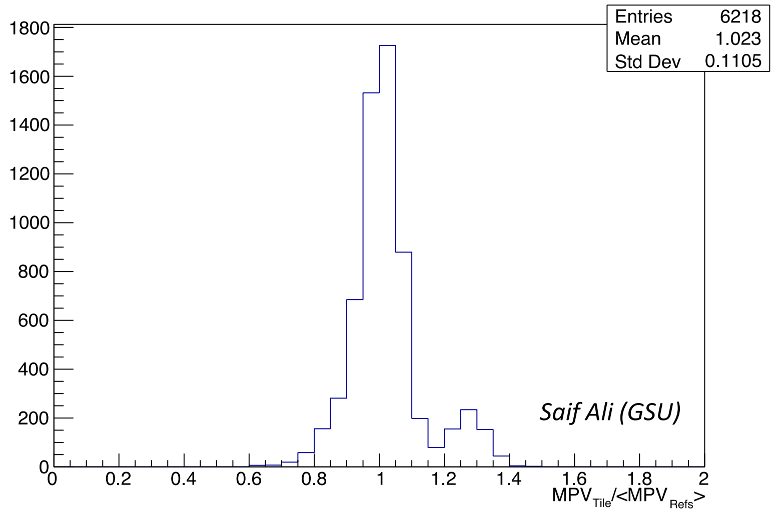
Tower signals cabled out to digitizers

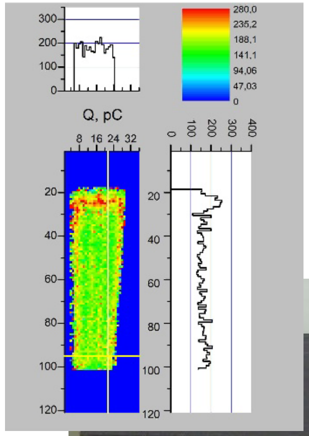


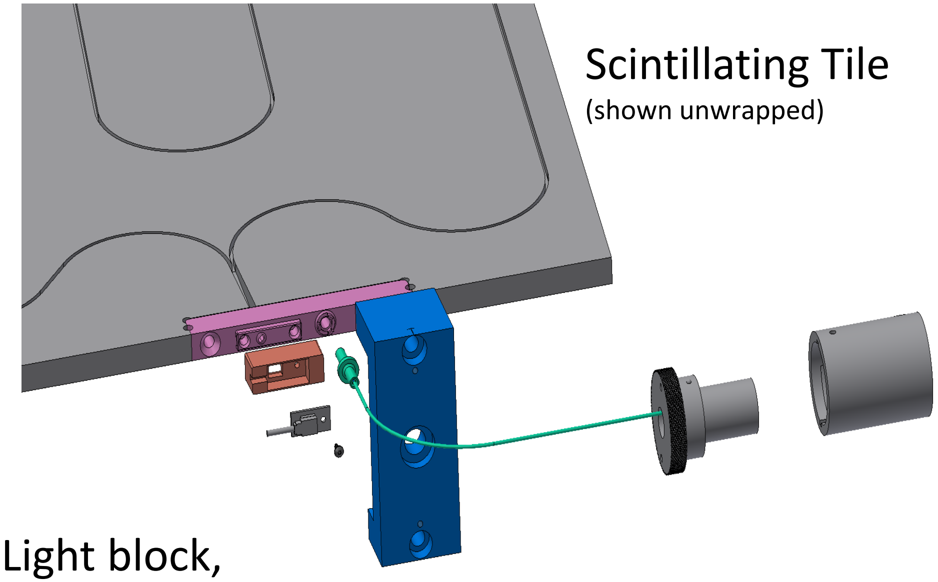
# Scintillating Tiles

Scintillating tiles are integrated units manufactured by Uniplast. Detailed cosmic ray response maps from MEPHI (Urugan), integrated into simulations.  Detailed testing/PR categorization by GSU.

Extensive testing of produced tiles for unform response, results used to sort tiles into a tower with variation <5%



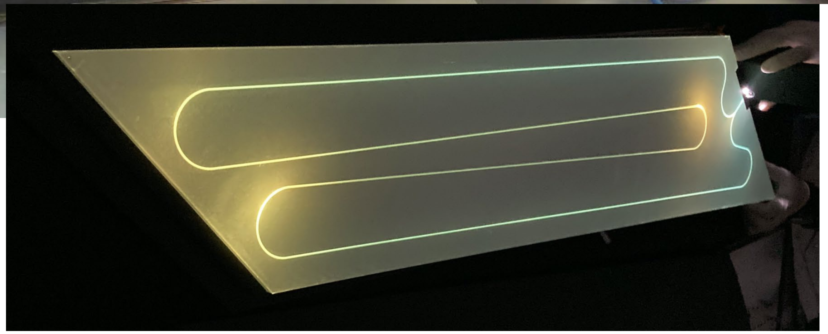



Scintillating Tile
(shown unwrapped)

Light block, SiPM mount and SiPM

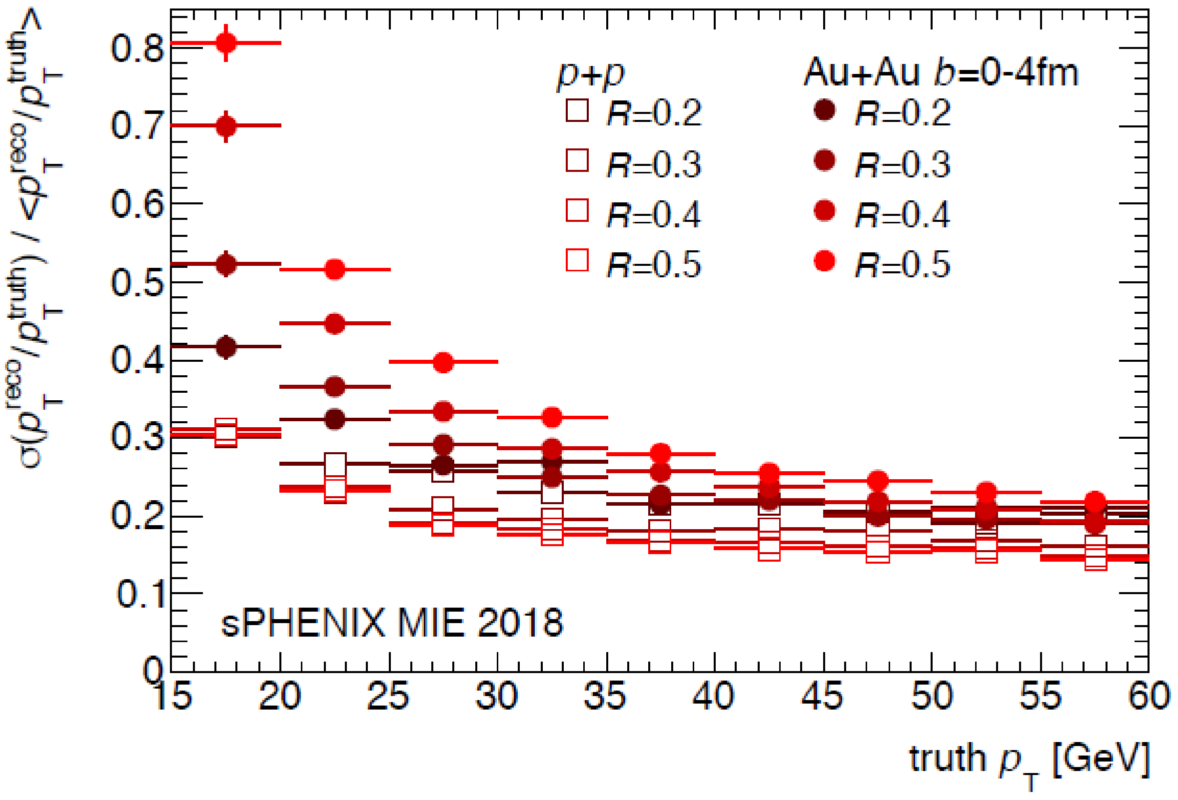
Tile Retainer Clip

Calibration Fiber



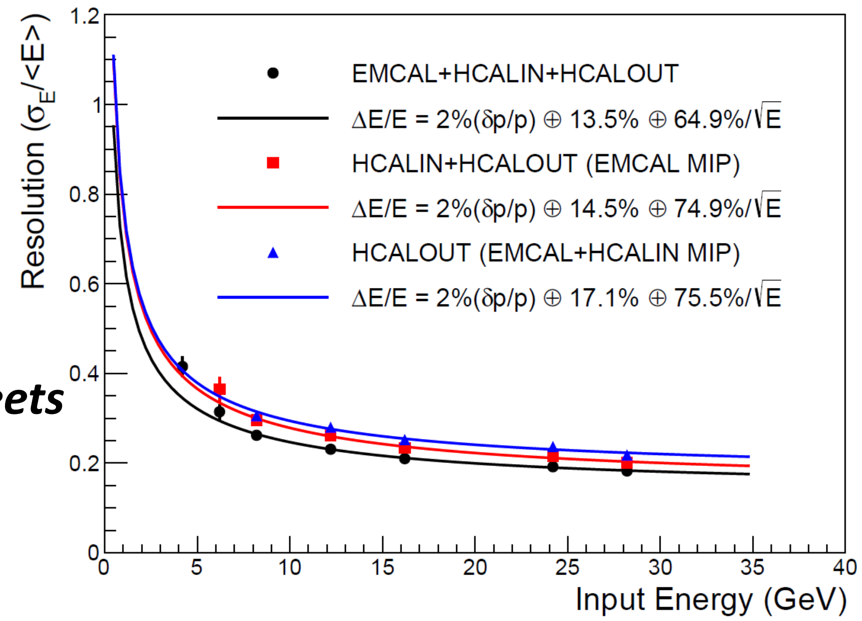
# Physics to Detector Specs.

- The HCAL enables the measurement of calorimetric jets in sPHENIX:




Plot from G4 Simulations
by D. Perepelitsa

HI jets determined with iterative background subtraction procedure. Note resolution comparison between Au+Au and p+p – jet resolution in HI determined by *fluctuations in underlying event*.



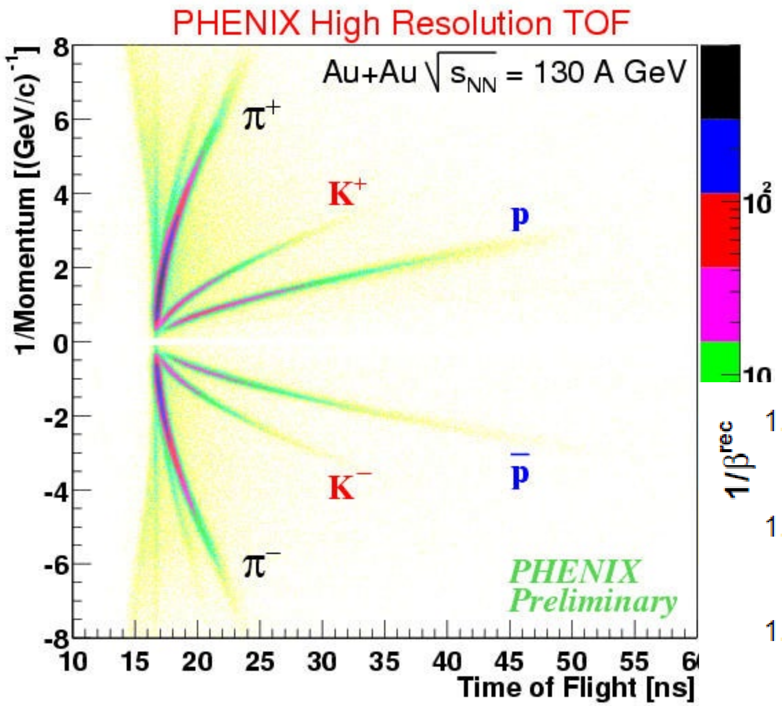

Performance in test beam – ***meets specifications!***

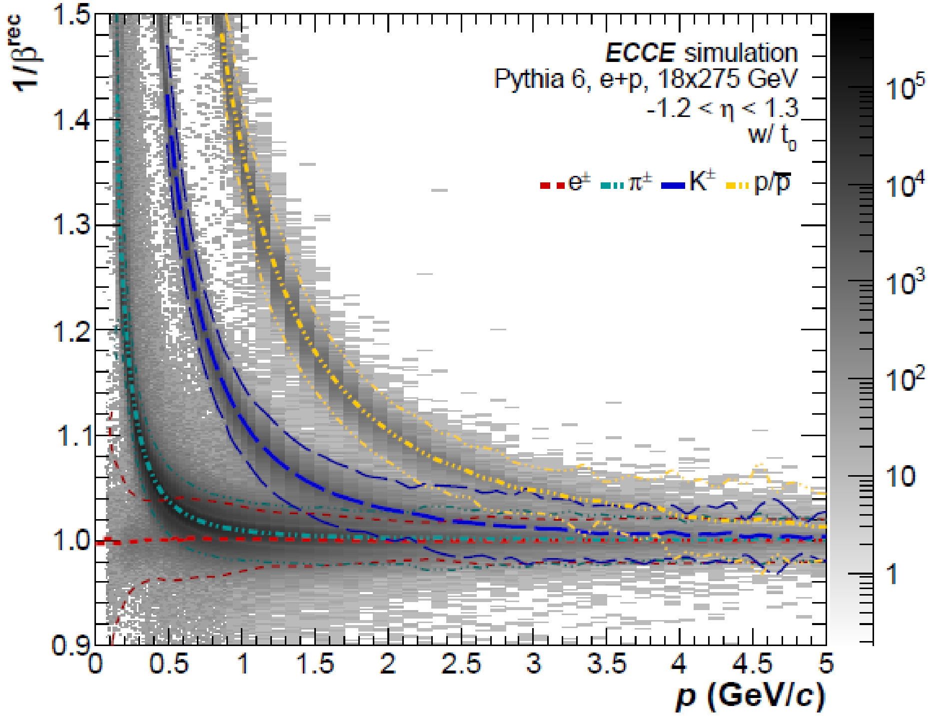
# Particle Identification

- Sometimes it's just not enough to know that a particle passed by (and maybe it's charge). Some physics requires that we *identify* the particle as an electron, muon, proton, pion, kaon, etc.

- Many techniques:
  - Electrons: match momentum (tracking) and calorimetry (energy)
  - Reconstruct a decay (calculate invariant mass)
  - Penetration depth (muons)
  - Time of Flight (sensitive to velocity)
  - Cerenkov radiation (sensitive to velocity)
  - …

# PID by Time-of-Flight



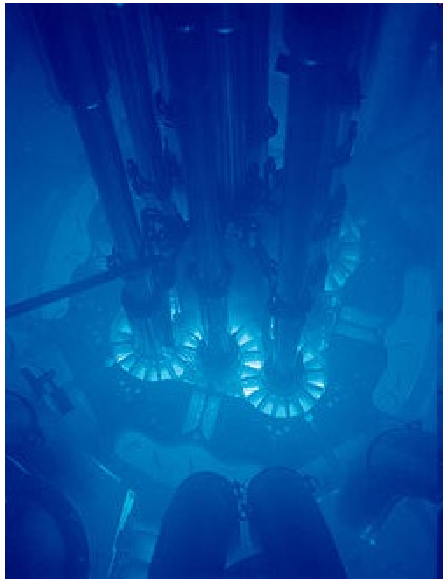

**High resolution scintillation counters can achieve a time resolution of 80-100ps or less. New technologies (LGADs) can achieve a time resolution of 20-30ps.**

**"Walls" of scintillation counters/ timing detectors can be used in conjunction with a "start time" to determine particle ID by comparing momentum and TOF.**

**Define "bands" by particle type, tag particles with a controlled background fraction.**

# Cerenkov Counters

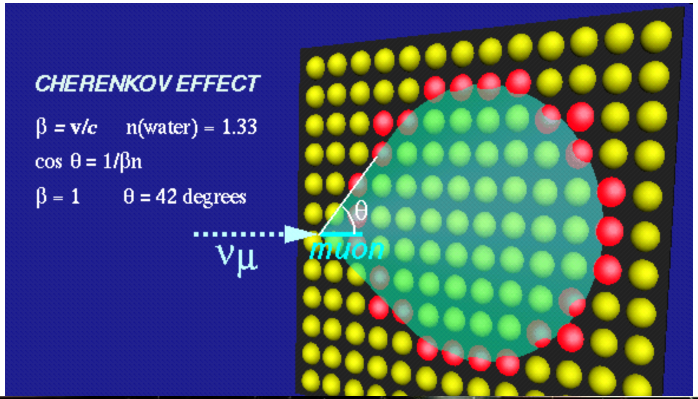
- Cerenkov light is emitted when a particle travels faster than the speed of light in a medium
  - Similar to a sonic boom (but optical)
  - Light emitted at a characteristic angle: $\cos\theta_C = \frac{1}{n\beta}$
  - Light depends on particle velocity
    - Different momentum for different masses
  - Threshold Counter:
    - Just detect the light
  - Ring Imaging Cerenkov (RICH):
    - Image the ring, measure the angle
    - Can be used to identify different particle types
    - Typically, only a few photons, measurements are delicate!

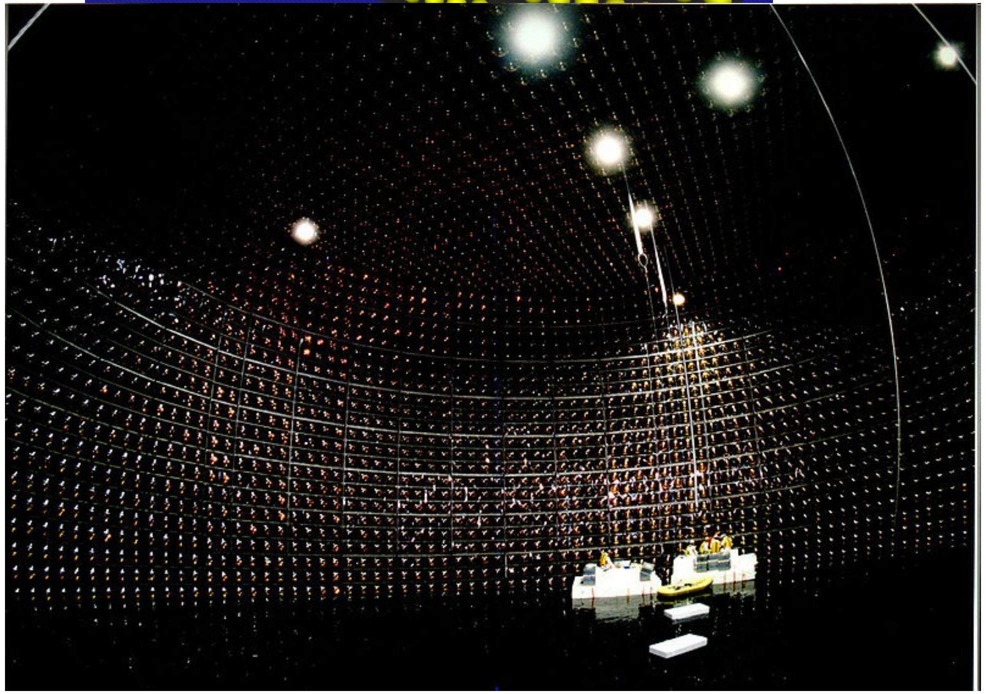


**Cerenkov radiation from nuclear fission reactor core.**

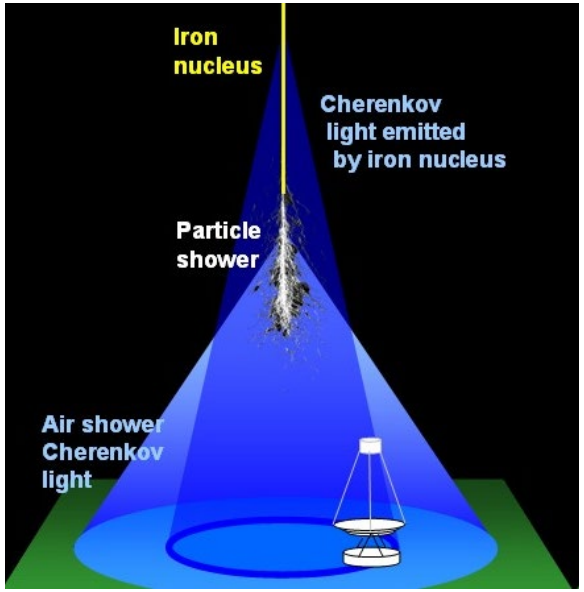
# Cerenkov Counters (II)

- Large, underground water Cerenkov counters were instrumental in demonstrating solar neutrino oscillations.
- Cerenkov light is used to detect cosmic rays in air showers

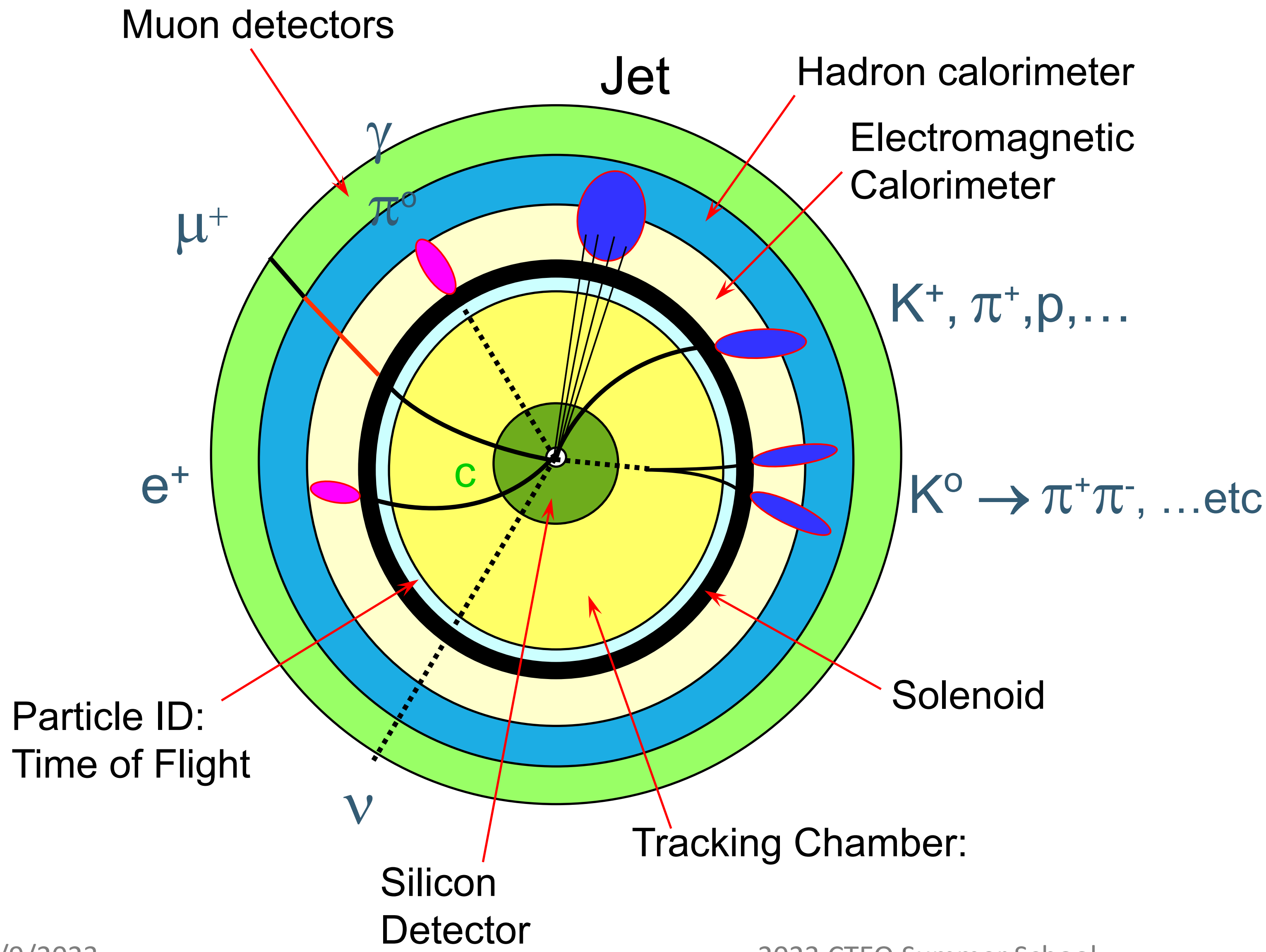


Super Kamiokande



# Collider Detector Schematic




A modern collider detector is a combination of detector technologies designed to work in concert to achieve a specific set of physics goals.

# Summary

- This is only a sampling of some basic detector types and techniques – this field is limited only by the imagination and the desire to do (really) hard work!

- So far we have only discussed the detectors themselves, but equally important are things like the readout electronics, cooling, radiation damage, etc.

- The next lecture will try to put some of these techniques in context by showing you how a modern particle physics detector was designed to address the wide-ranging physics program at the EIC.


BACK UP

# Seed Question #1

- The neutron has no charge, so therefore is does not lose energy by electromagnetic interactions.
  - Can a neutron lose energy passing through material? If so, how?
  - How might you detect a high energy neutron (few GeV)?
  - How might you detect a low energy neutron (few MeV)?
  - How might you detect a very low energy neutron (thermal energies)?

# Seed Question #2

- A sampling calorimeter is made up of repeated absorber section of length *s* and sampling sections of length *d*.  How do you define the *sampling fraction* for this calorimeter?