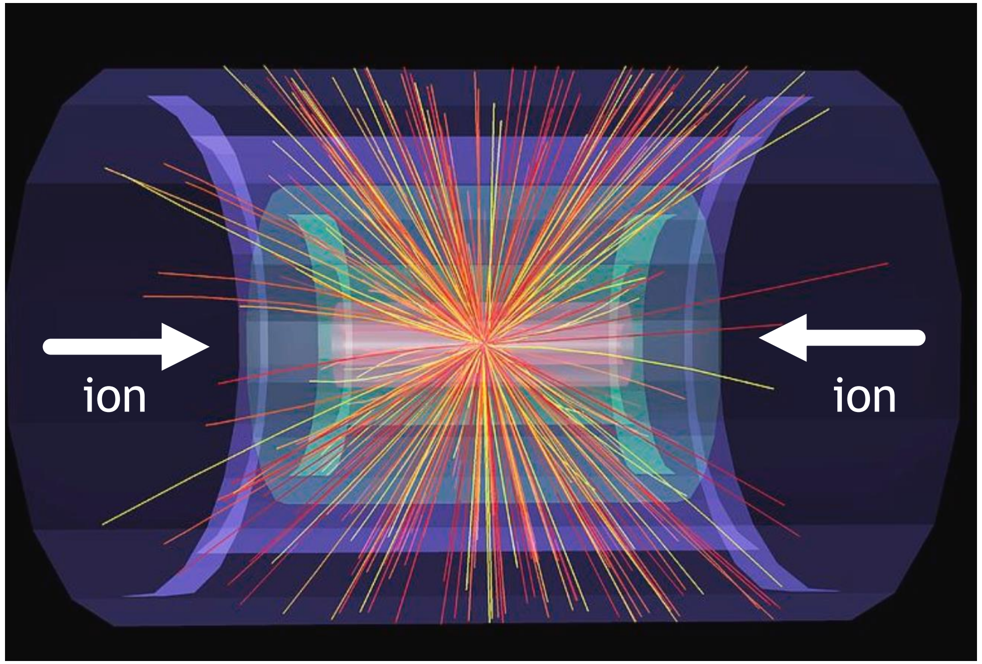
Detectors

TK Hemmick

How do you want to do your physics?



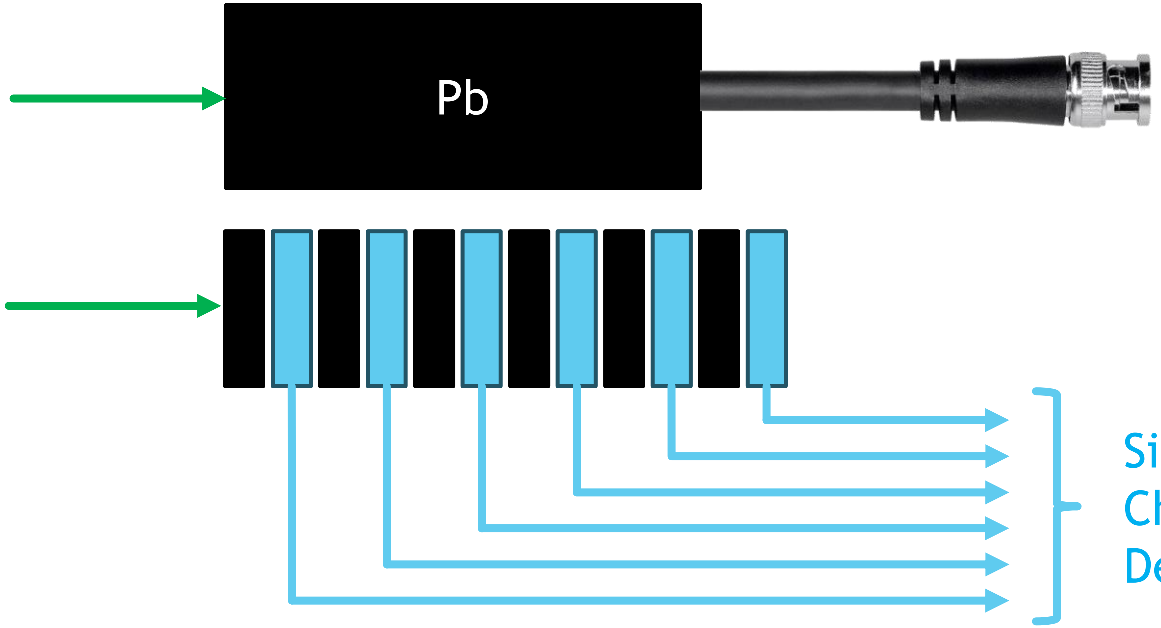
- Beam Species; Beam Energy; (E, p_x, p_y, p_z)
  - Seems logical to use real 4-vectors.
  - Close match to textbook calculations
  - Does this mean $\left(Calorimeter, \overrightarrow{Tracker}\right)$ is ideal?
  - Not exactly…
- All measured particles are "on shell".
  - $E^2 = p^2 + m^2$
  - Past generations have measured on shell masses well.
  - Your precision is enhanced using this knowledge.
    1. Calorimeter-centric $(ID, E\hat{p})$
    2. Spectrometer-centric $(ID, \vec{p})$
    3. Best = properly weighted average of 1 & 2

- Outline of the presentation:
  - Measuring E with Calorimeters
  - Measuring $\vec{p}$ with Tracking
  - Measuring PID

Particles must interact

- Four fundamental forces: Gravity, Weak, E&M, strong
- Participants
  - Pion — Strong, E&M } Medium Range
  - Proton — Strong, E&M } Medium Range
  - Muon — E&M → Long Range
  - Electron — E&M → Short Range
    - Bremsstrahlung sets in for the electron.
    - Allows short detector
    - Allows high precision

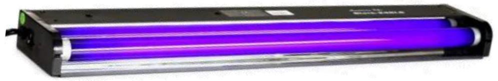
Instrument a Pb Brick

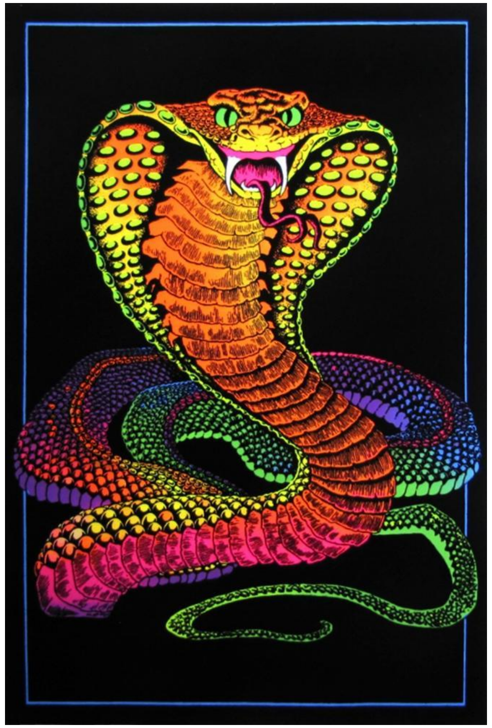


- A piece of Pb does no produce a signal
  - CsI scintillates
  - $PbWO_4$ scintillates

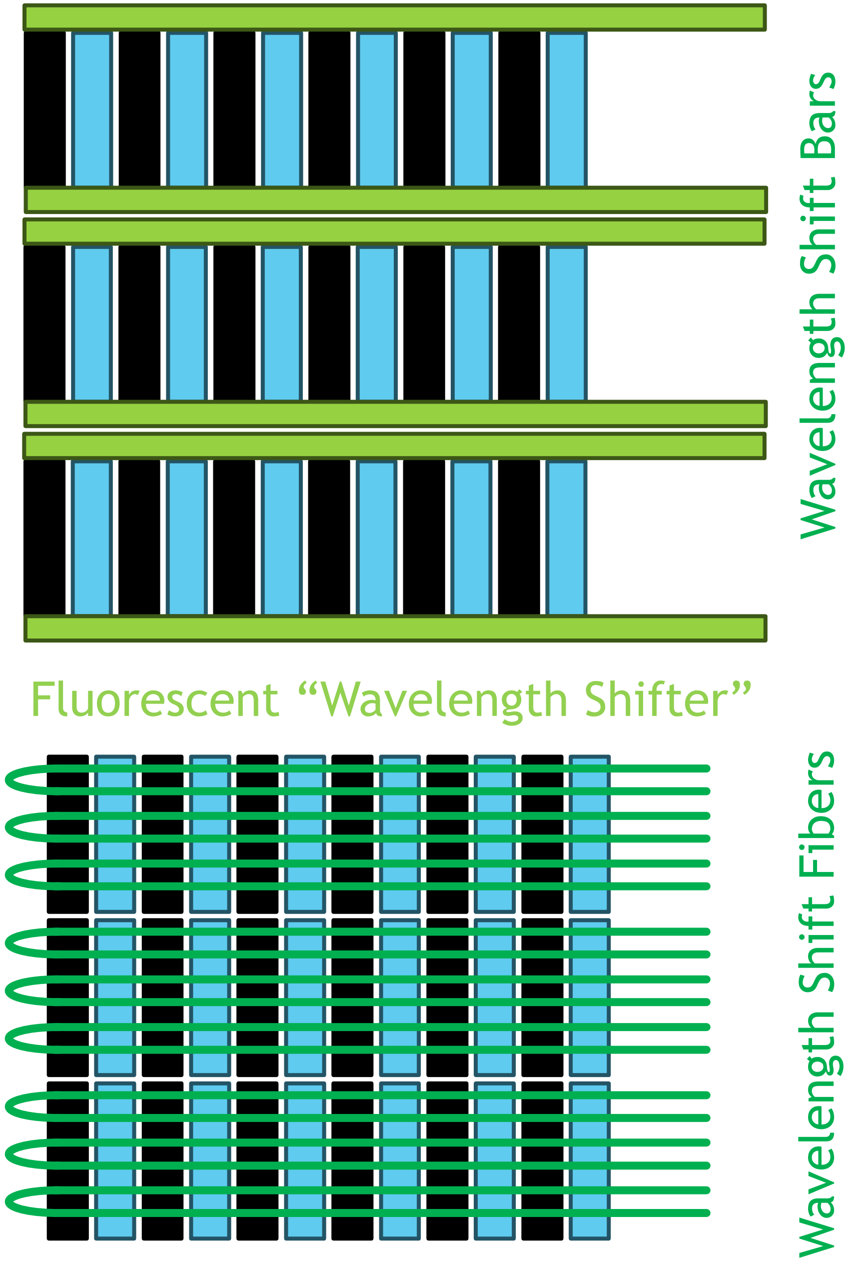
  } Crystal Calorimeters
  - Best Precision
  - Highest Cost
- Slice the Pb brick like bread and insert CP detectors
  - “Sampling Calorimeter”
  - The big question is how the signal gets out

Fluorescence is a Cheap Redirect



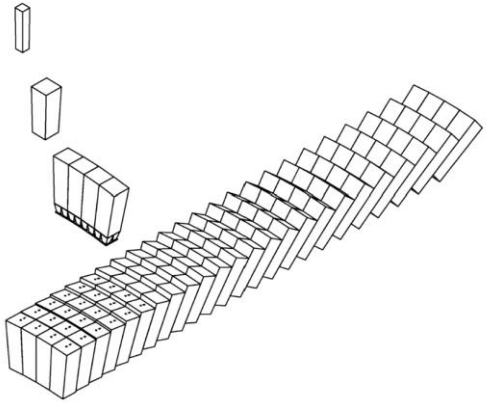


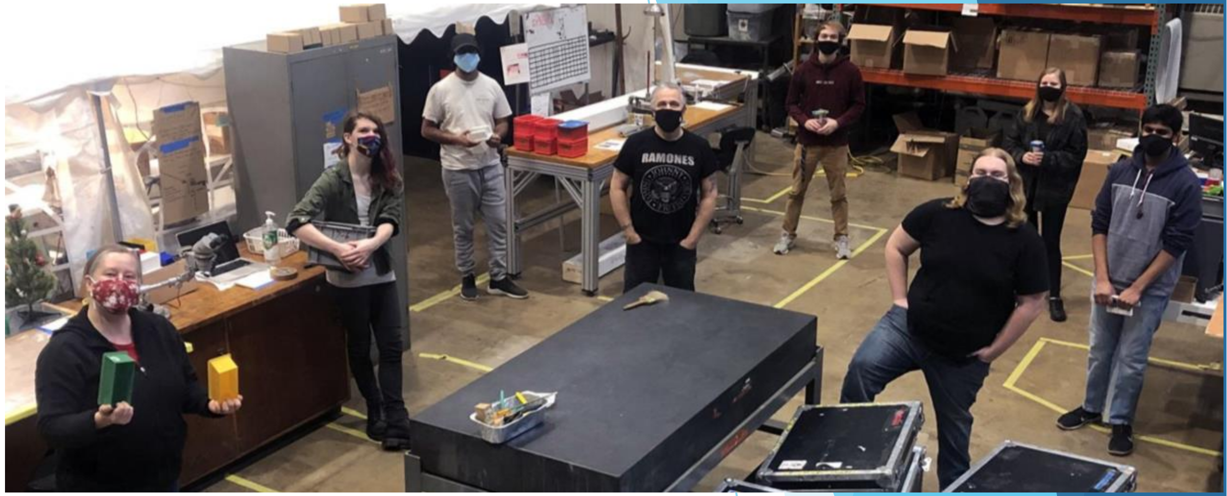
Drug Paraphernalia from the 1970's



- Fluorescence absorbs light at shorter wavelength and re-emits it at a longer wavelength.
- "Blacklight Posters" used inks containing Fluorescent Dye
- Plastic can be purchased with Fluorescent Dye in bars and in fibers.
- Fluorescence "redirects" the light, much of which is totally internally reflected to the back.
- Shashlik or Shish Kebab is best.

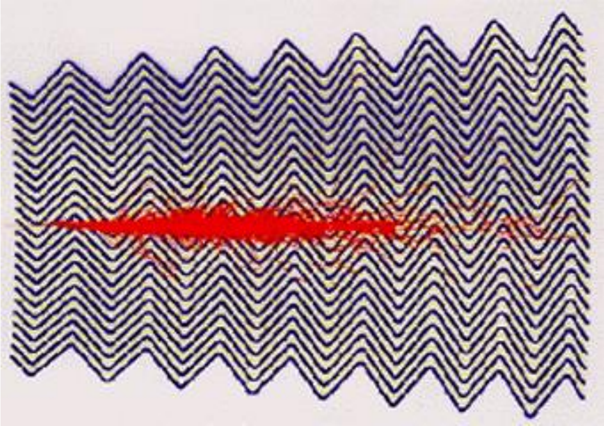
SciFi (aka Scintillating Fibers)

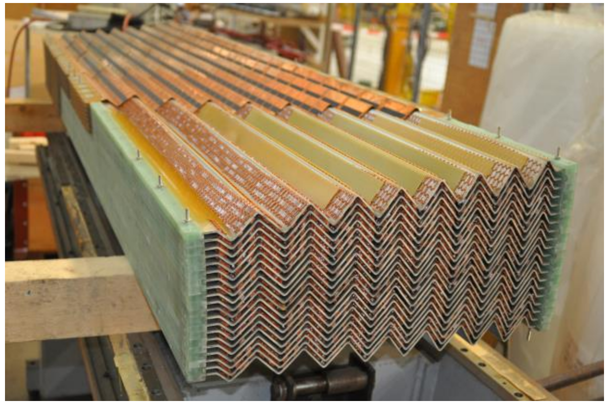




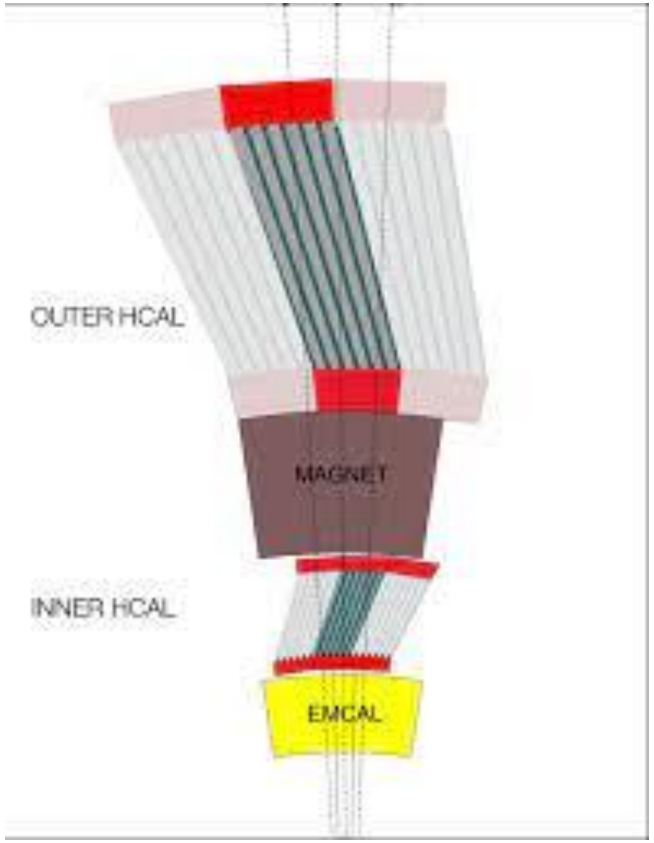
- Scintillating fibers with close spacing direct light out the back without shifters
- Here an sPHENIX EMCAL block is shown.
  - The surrounding material is W powder mixed with a minimal amount of epoxy that is been “injection-molded” around a tight array of scintillating fiber.

Accordion

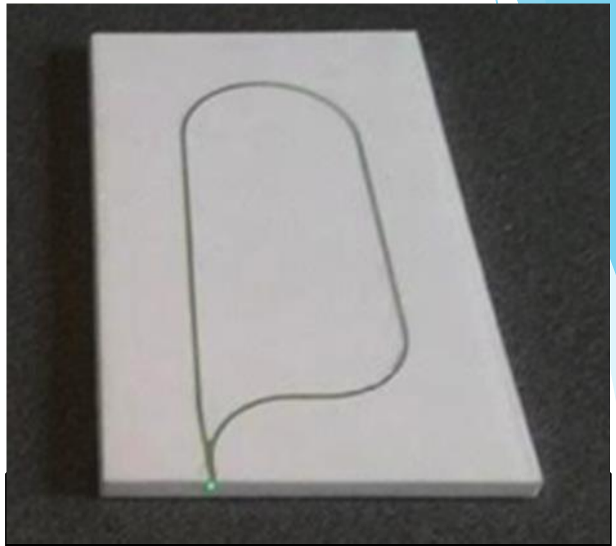




ATLAS Liquid Argon



sPHENIX HCAL



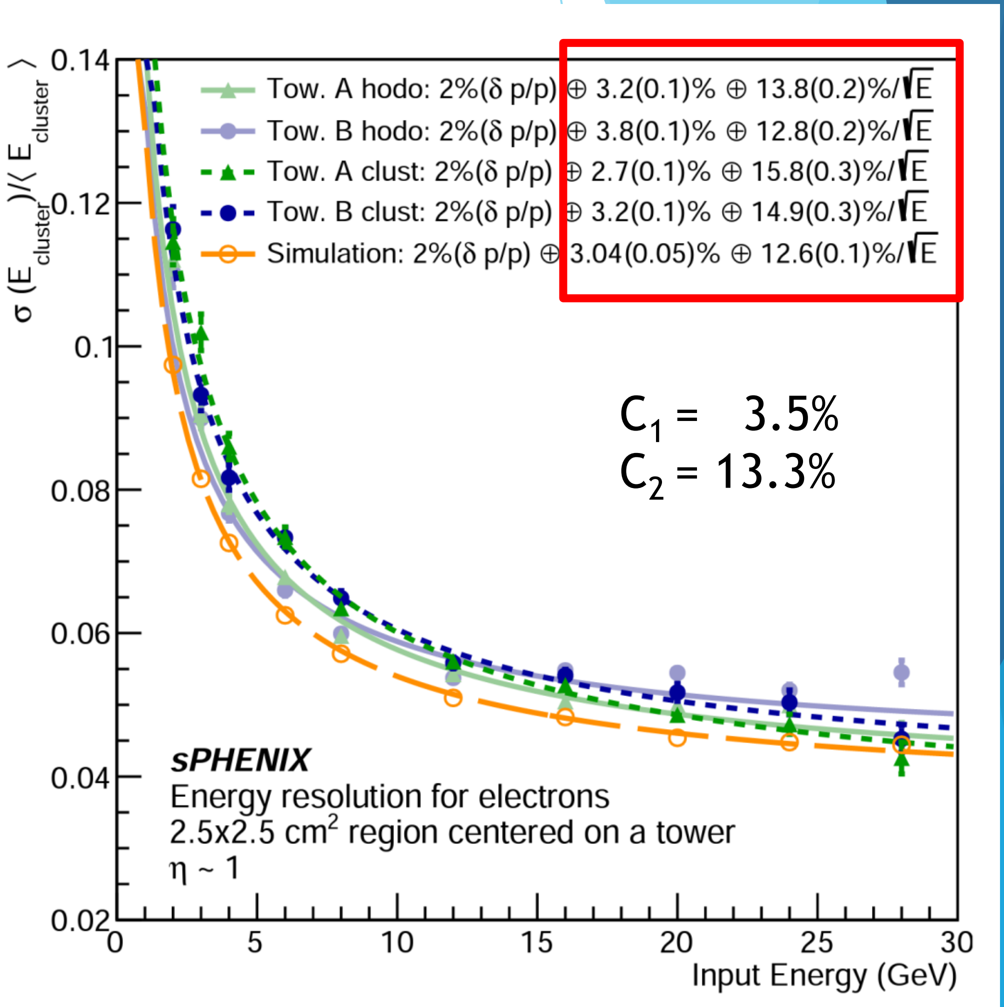
Tile with embedded WLS Fiber

- ATLAS Liquid Argon Calorimeter pioneered the “accordion” to channel ionization charge from within the Argon along the accordion folds.
- sPHENIX mimicked this with a simple “tilt” of each tile and concentrated the light using a wavelength shifting fiber.

Calorimeter Energy Resolution

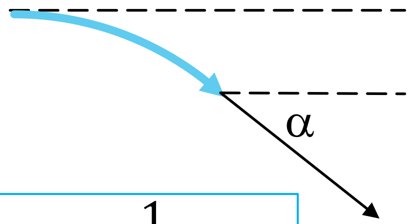
- Fundamentally the calorimeter "counts" something (charge particles, ionization, photons, …) that is proportional to the energy deposit.
  - Statistical Term:
    - $N \propto E$
    - $\partial N = \sqrt{N} \propto \sqrt{E}$
    - $\frac{\partial E}{E} \propto \frac{\partial N}{N} \propto \frac{1}{\sqrt{N}} \propto \frac{1}{\sqrt{E}}$
  - Scale/Calibration Term:
    - $E = aN$
    - $\partial E = \partial a\, N = const * E$
    - $\frac{\partial E}{E} = const$
  - Noise Term:
    - $\partial E = const$
    - $\frac{\partial E}{E} = \frac{const}{E}$
  - Full Resolution
    - $\frac{\partial E}{E} = \sqrt{{c_1}^2 + \left(\frac{c_2}{\sqrt{E}}\right)^2 + \left(\frac{c_3}{E}\right)^2} = c_1 \oplus \frac{c_2}{\sqrt{E}} \oplus \frac{c_3}{E}$

Often negligible



Calorimeters vs Spectrometers

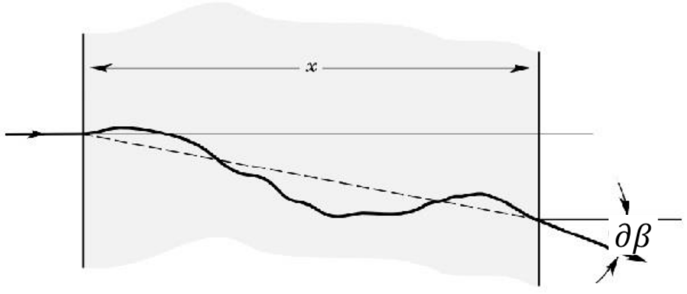
- Calorimeters
  - Measures energy
  - Best energy resolution at highest momentum/energy
  - DESTRUCTIVE to the particle (cannot measure again)
- Magnetic spectrometers
  - Measures momentum
  - Best momentum resolution at lower momentum
    - Position Resolution: $\frac{\partial p}{p} = c_2 p$
    - Multiple Scattering: $\frac{\partial p}{p} = c_1$
    - Total: $\frac{\partial p}{p} = \sqrt{{c_1}^2 + (c_2 p)^2} = c_1 \oplus c_2 p$
  - Non-destructive to the particle



$$\beta \propto \frac{1}{p}$$

$$\partial\beta = const \ \propto \frac{\partial p}{p^2}$$

$$\frac{\partial p}{p} \propto const \ \times p$$



$$\partial\beta = \frac{13.6}{\beta c p} z \sqrt{x/X_0}\,[1 + 0.038 \ln(x/X_0)]$$

$$\partial\beta = \frac{const}{p} \propto \frac{\partial p}{p^2}$$

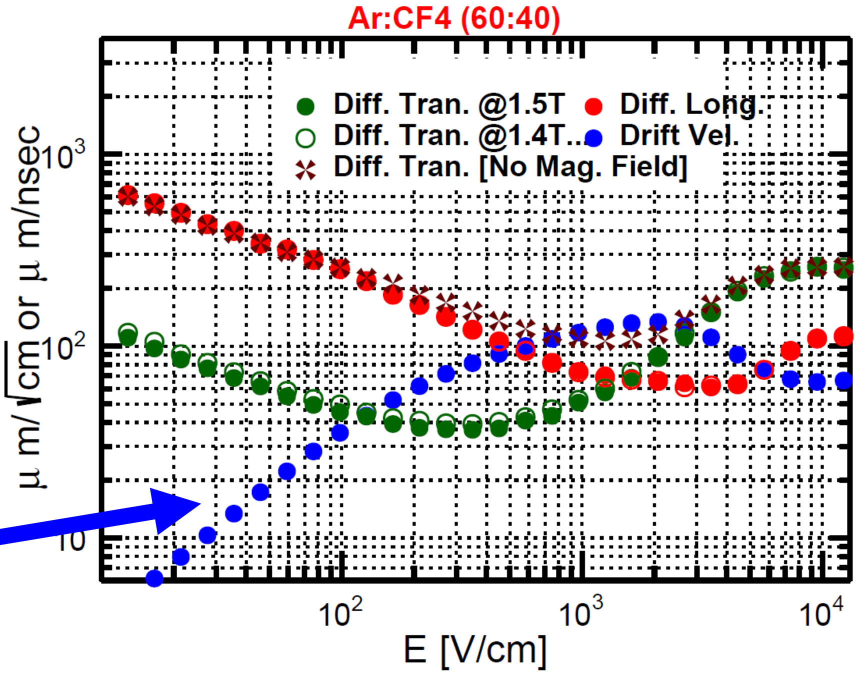
$$\frac{\partial p}{p} = const$$

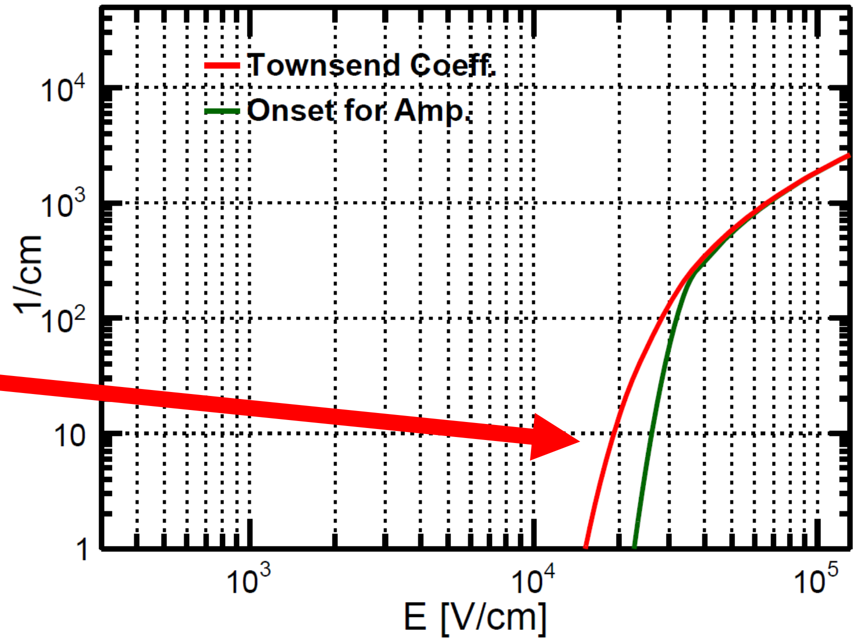
$$X_0 = \frac{716.4A}{Z(Z+1)\ln(287/\sqrt{Z})}$$

Rad.len.	$dE/dx\|_{min}$	Density
X_0	{ MeV	{g cm^{-3}}
{g cm^{-2}}	g^{-1}cm^2}	({gℓ^{-1}})

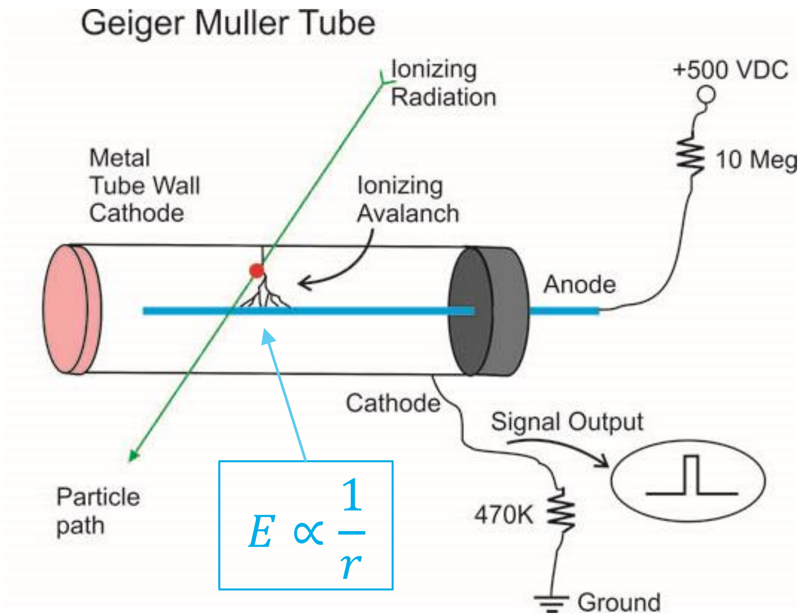
Electron Motion in a Gas

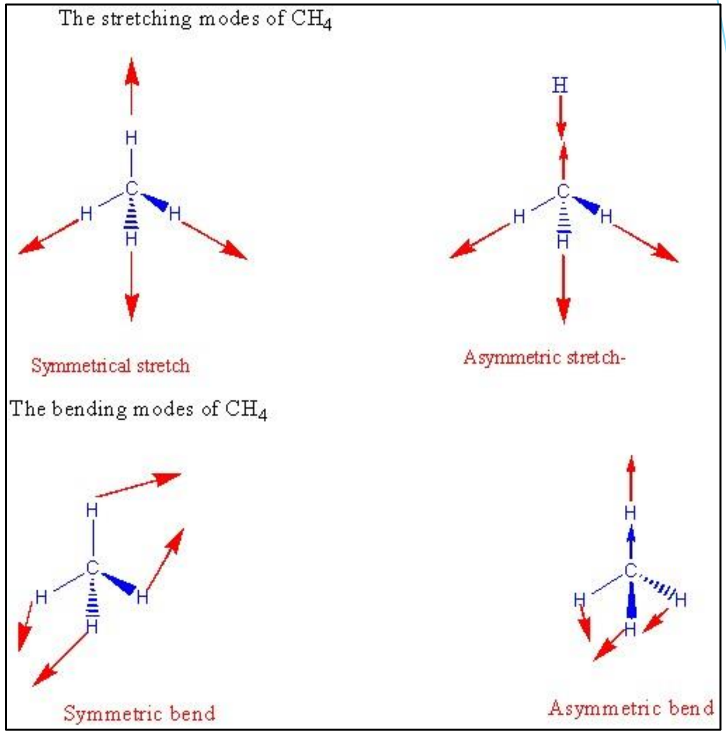
- Low electric fields
  - Collisions of electrons with gas molecules provide an effect backward "Force" on the electron proportional to velocity:
    $$F_B = -bv.$$
  - Terminal velocity when $qE = bv$; $v_T = \frac{q}{b}E$
    - Ions are simple ("b" is effectively constant and $v_T \propto E$
    - Electrons are more complicated as "b" depends upon v
- High Electric Fields
  - Electrons gain enough energy in a mean free path that they are capable of ionizing the gas.
  - Exponential growth in electron current:
    $$\frac{I}{I_0} = e^{\alpha x}$$
  - Growth controlled by the Townsend Coefficient, α.
- Virtually all gas detectors use a low electric field to drift electrons into an avalanche region for detection.





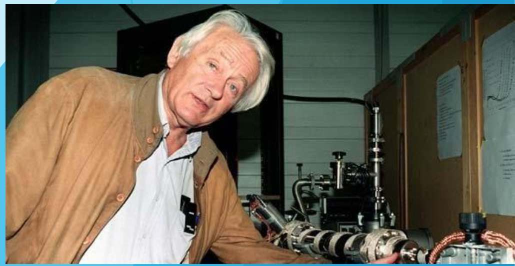
Geiger-Muller → Charpak (Nobel 1993)





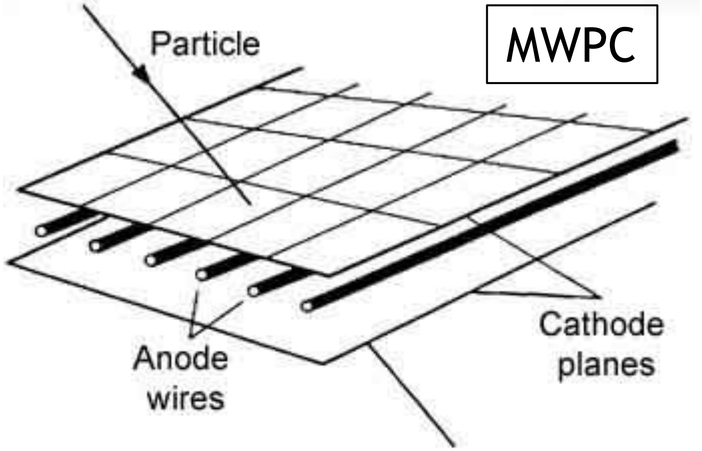
- With a pure noble gas, photons from the avalanche create ionization in the outer region.
- The avalanche "runs away"
  - Good news: BIG signal
  - Bad news:
    - Dead time to recharge wire
    - Insensitive to energy deposited

- Complex molecules have the ability to absorb energy as vibrations and rotations.
- Adding this "quench" to the gas breaks the feedback loop.
- "Proportional Counter"

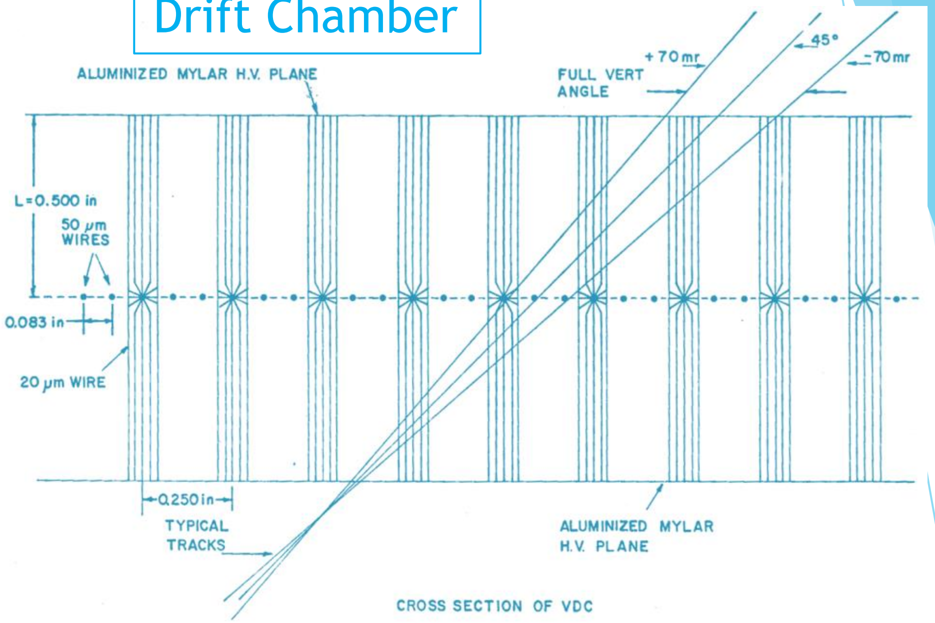


Gas Chamber Evolution

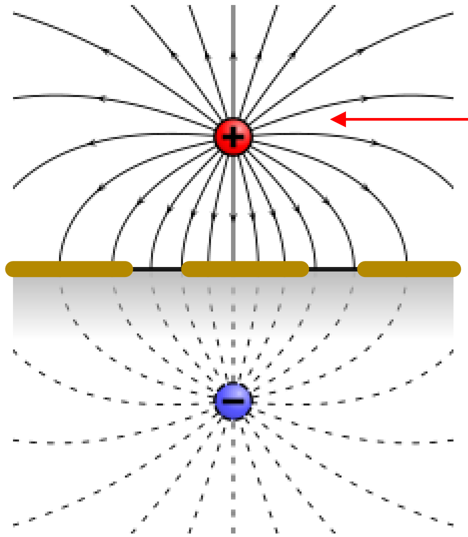
MWPC



Drift Chamber



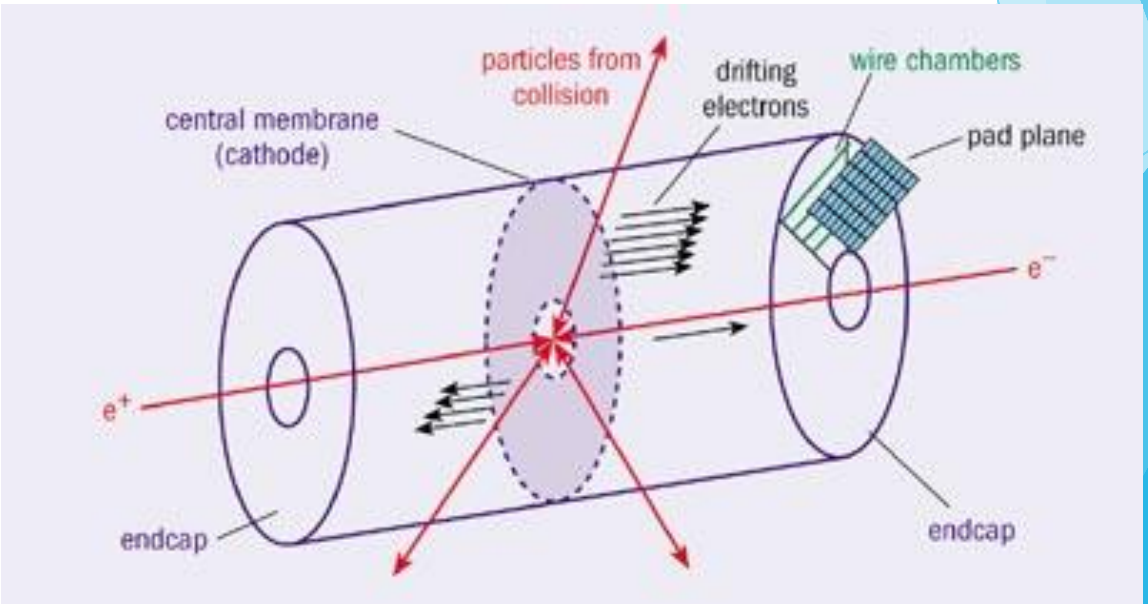
Pad Plane



Positive Cloud Around Wire

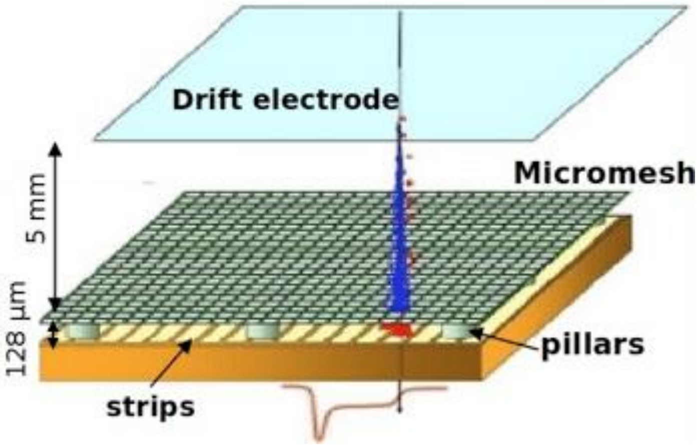
Segmented Pad Plane

Time Projection Chamber

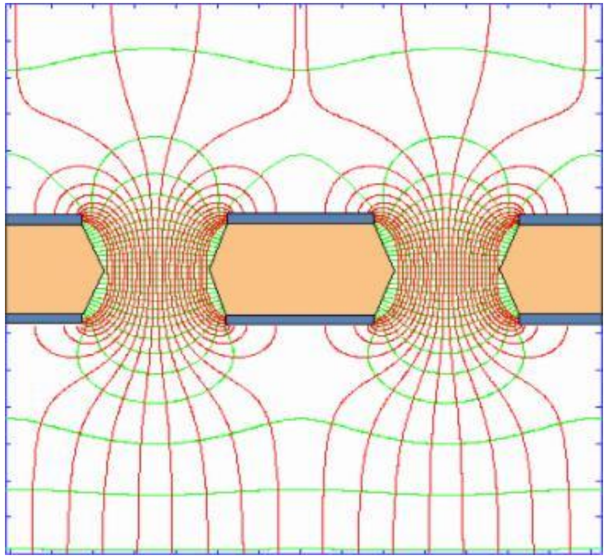


Avalanche Stage Evolution (MPGD)

microMEGAS



Gas Electron Multipliers GEMs

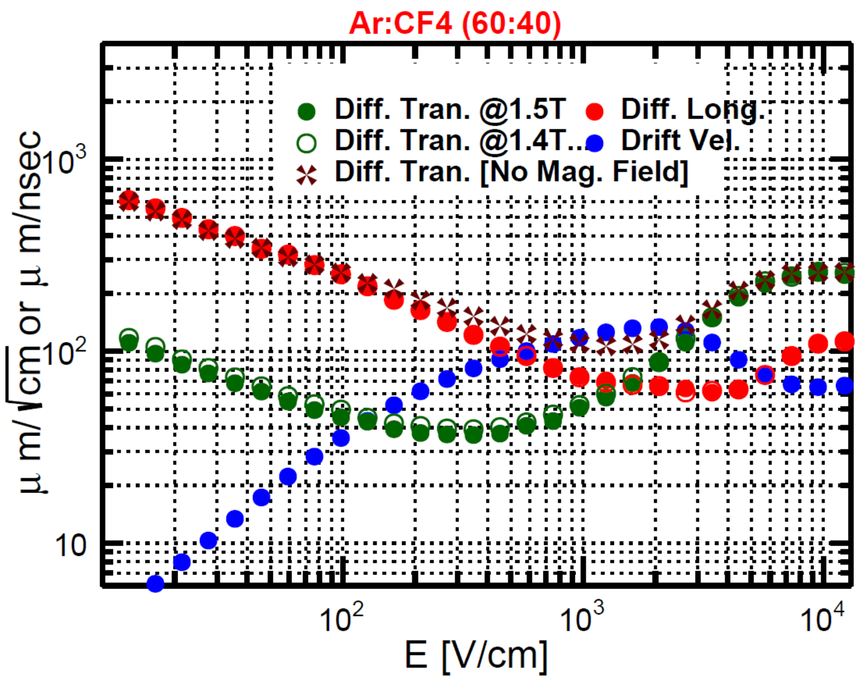


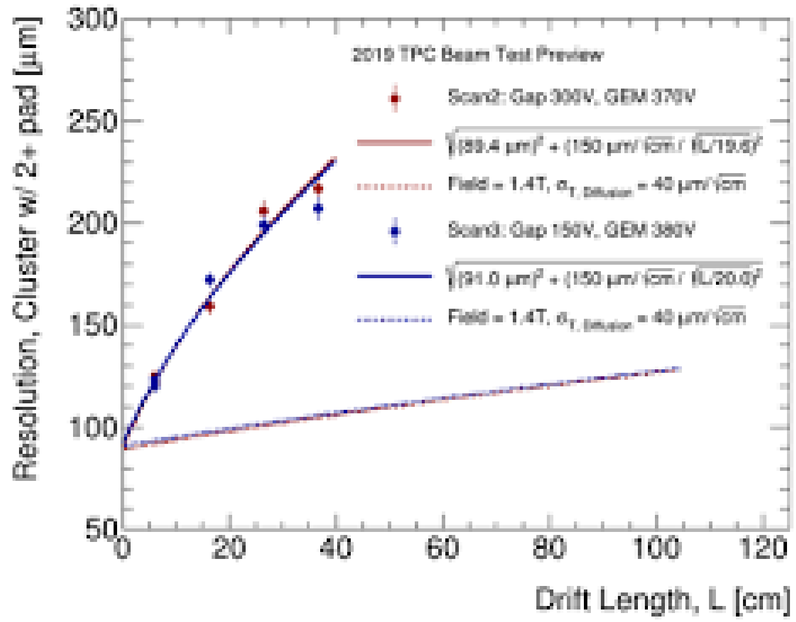
Ioannas Giomataris

Fabio Sauli

Precision of Gas Measurements

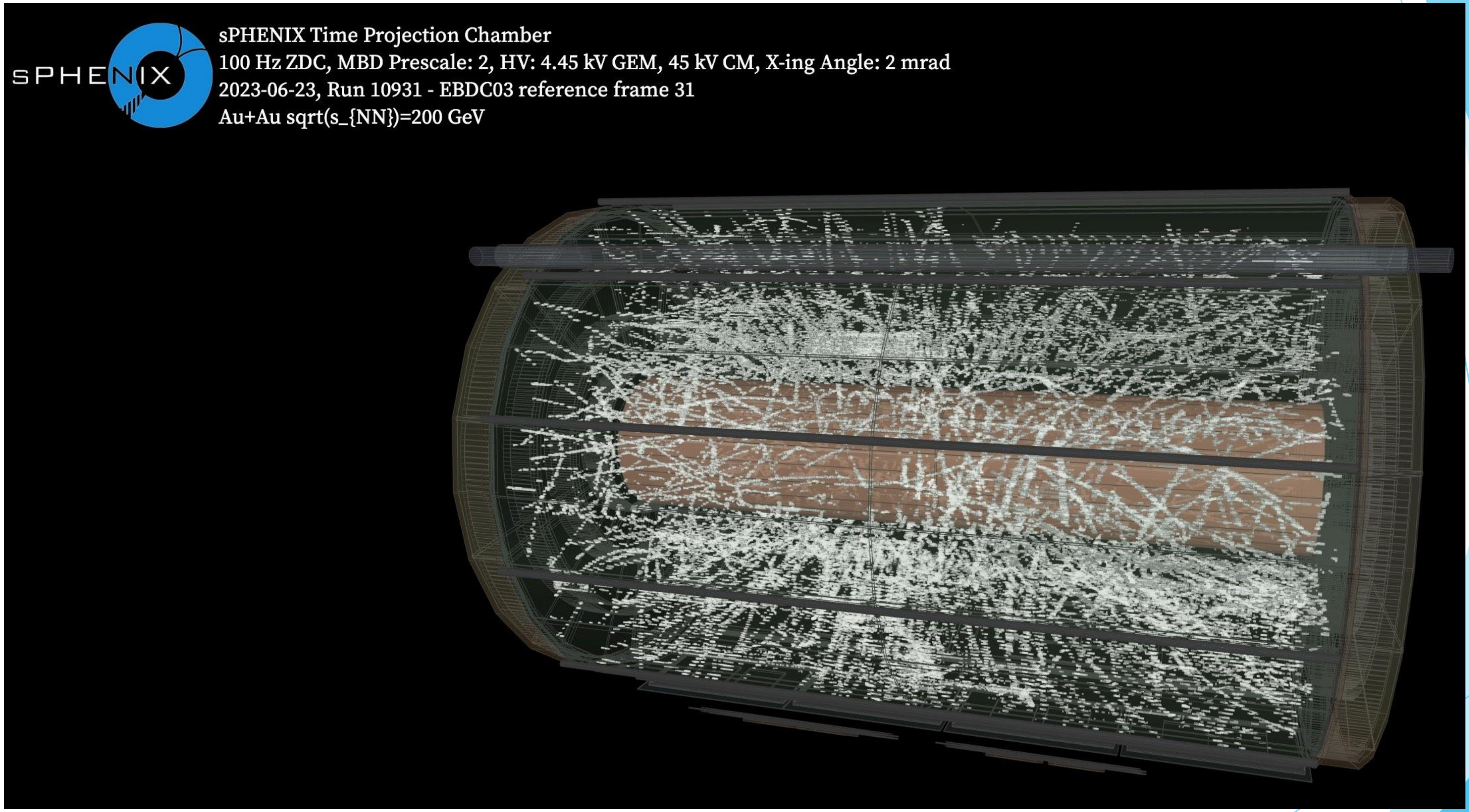
- Many factors can affect resolution, but two terms affect all detectors.
  - Readout Intrinsic Resolution
    - Constant…segmentation, noise, etc…
    - σ_I
  - Diffusion
    - Diffusion is a transverse kick due to electron-molecule collisions
    - Diffusion follows the mathematics of a random walk.
    - A single electron “misses” it’s target by $\sigma_1 = D_T\sqrt{L}$
    - The error on the mean of N electrons revied is $\sigma_T = \frac{\sigma_1}{\sqrt{N}}$
  - Other effects are either sensitive to the number of electrons in a signal or not. The typical formula becomes: $\sigma = \sigma_i \oplus \frac{D_T}{\sqrt{N_{eff}}}\sqrt{L}$
  - Notice that transverse diffusion falls STEEPLY with magnetic field.



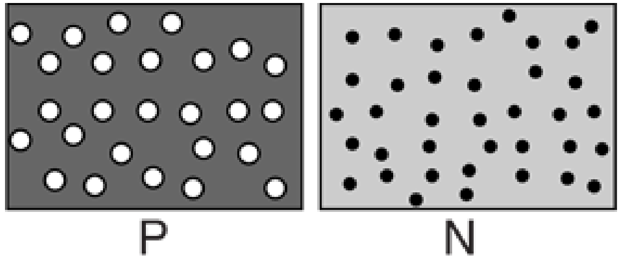


D_T has units of $\frac{\mu m}{\sqrt{cm}}$

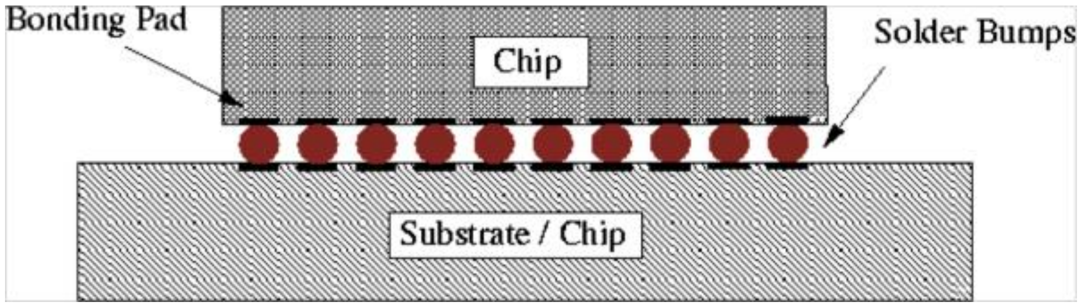
sPHENIX TPC Example



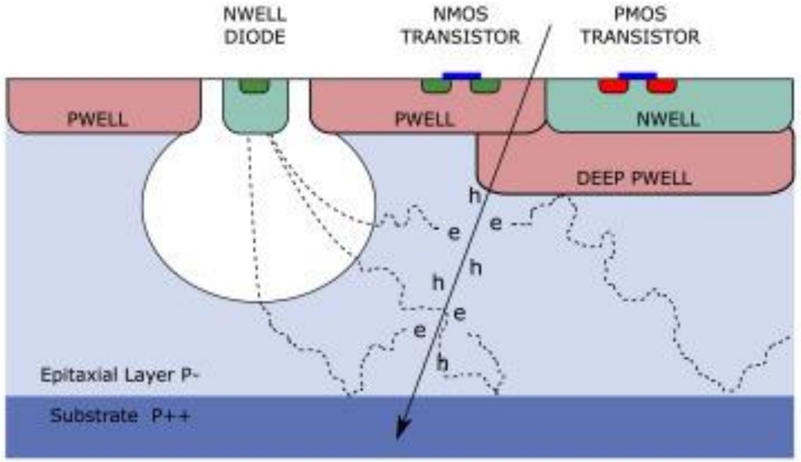
Silicon Detectors



- Reverse bias diode ideally flows no current and created a depletion region in the middle.
- A charge particle energy deposit in the depleted region makes current surge.

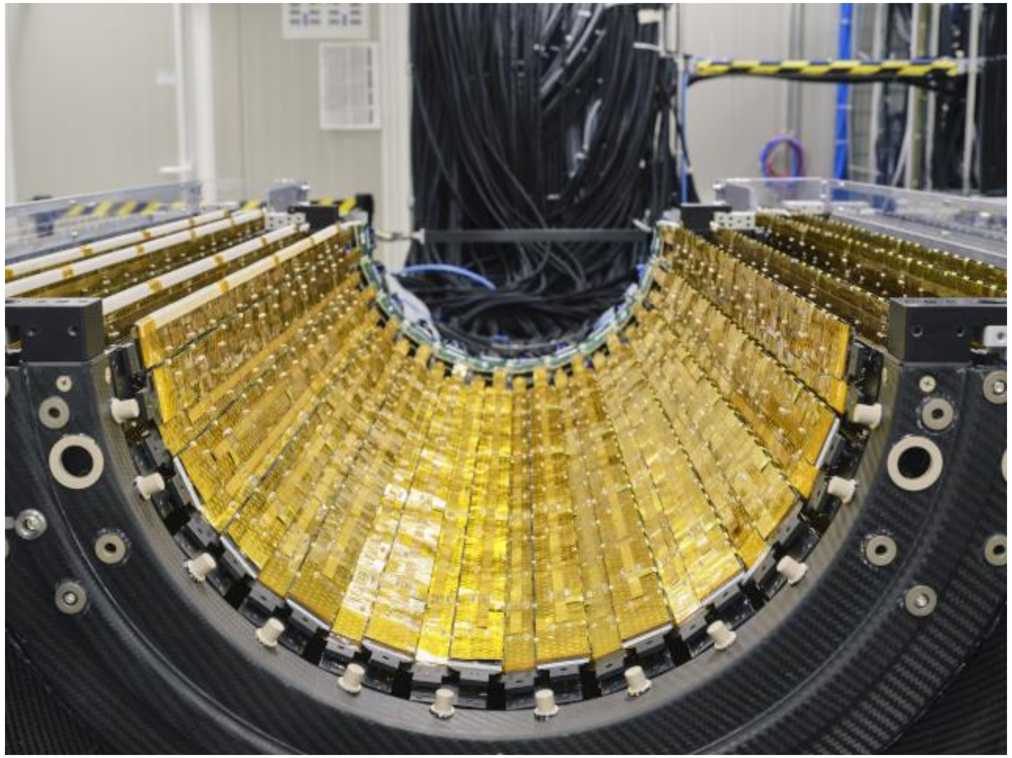


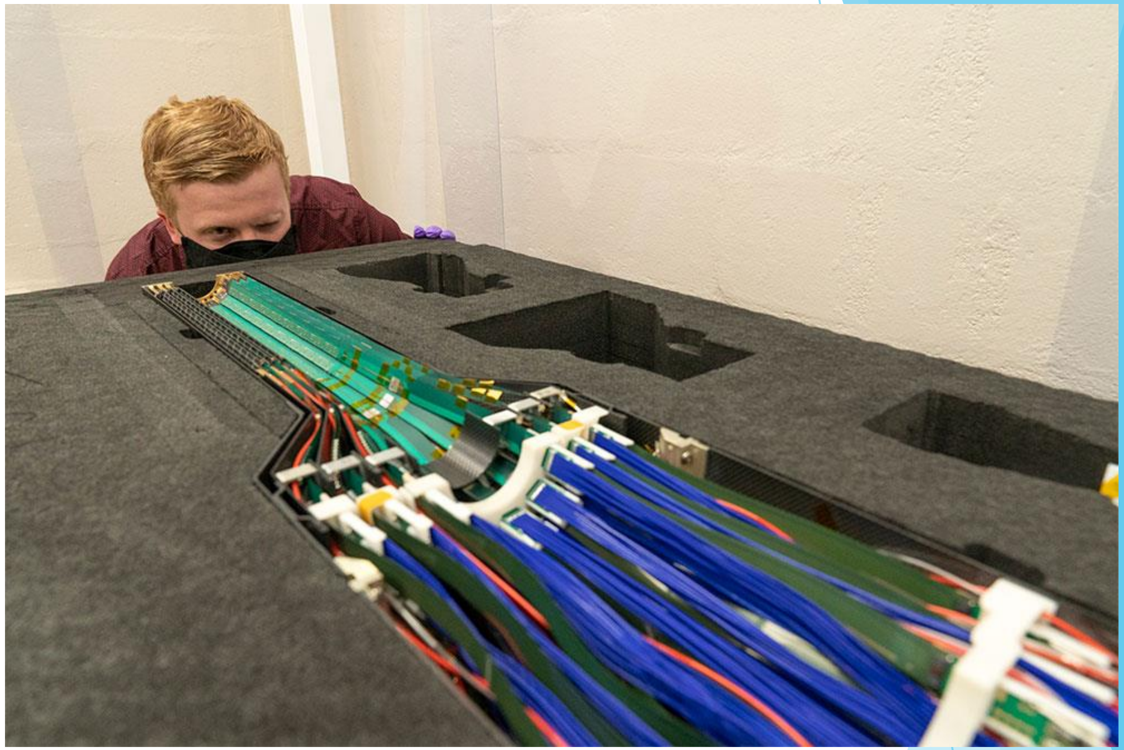
- Chip technology allows a pattern of sensors to be printed onto a chip.
- “Bump bonding” allows individual sensors to be connected to a readout chip.



- Monolithic Active Pixel Sensor (MAPS)
- Point-like collection of the signal frees space on chip to allow readout.
- Point-like collection reduces input capacitance and makes noise low.
- ALPIDE (shown) is a leading MAPs chip.

ALPIDE in ALICE and sPHENIX

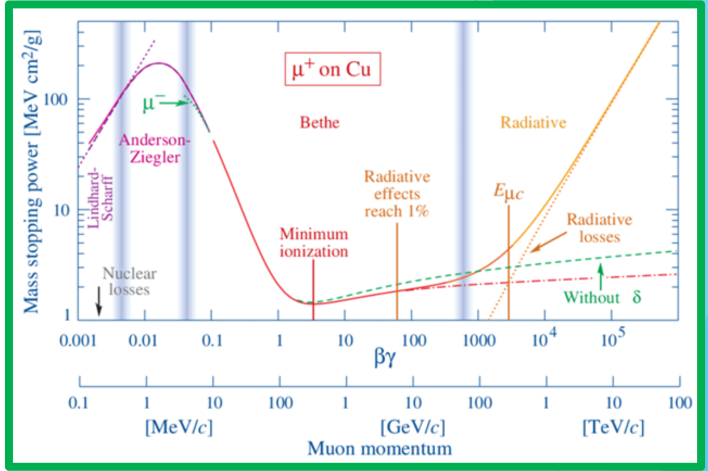


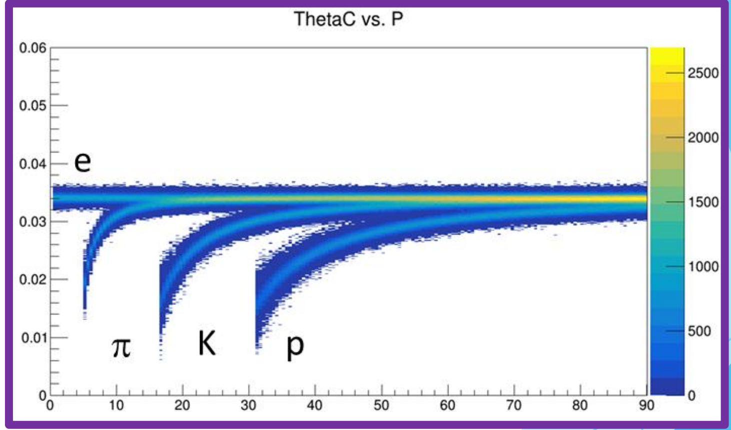


- ALPIDE sensors developed by ALICE.
- Same technology also used in sPHENIX.
- NOTE: Silicon and Gas resolutions use different units!
  - Silicon uses pixel size; gas uses sigma (factor of $\sqrt{12}$)
  - 29 x 27 μm^2 means sigmas of 8.4 x 7.8 μm^2

PID ~ Velocity

- p = mγβ E = mγ velocity(β) measurement yields mass.
- Direct measurement:
  - Record signal time at multiple locations, calculate v.
  - "Fast" detector = low transit time spread (most easily achieved at small transit time)
- Velocity-dependent interaction(s) with detector:
  - Specific Ionization (aka $\frac{dE}{dx}$)
  - Cherenkov Radiation: $\cos\theta_C = \frac{1}{n\beta}$
    - θ_C measured wrt track direction.
    - Thus dependent upon deliverables from tracking





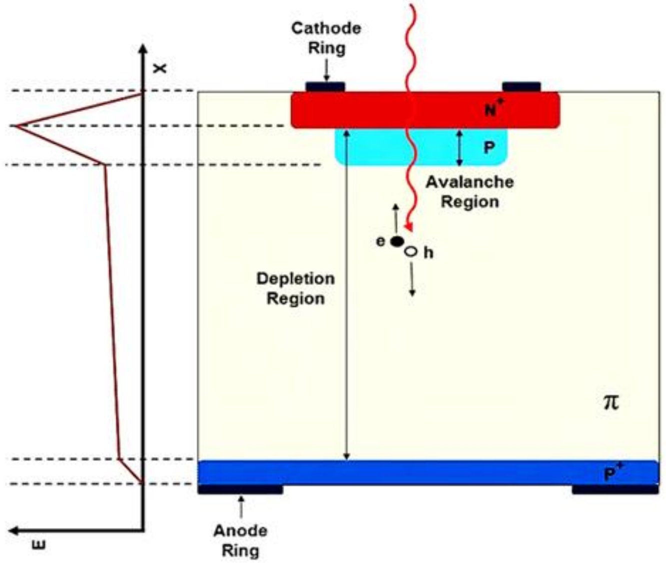
  - Bremsstrahlung: $P = \frac{q^2\gamma^4}{6\pi\varepsilon_0 c}\left(\dot{\beta}^2 + \frac{(\vec{\beta}\cdot\dot{\vec{\beta}})^2}{1-\beta^2}\right)$
  - Transition Radiation: $I = \frac{Z^2 e^2 \gamma \omega_p}{3c}$

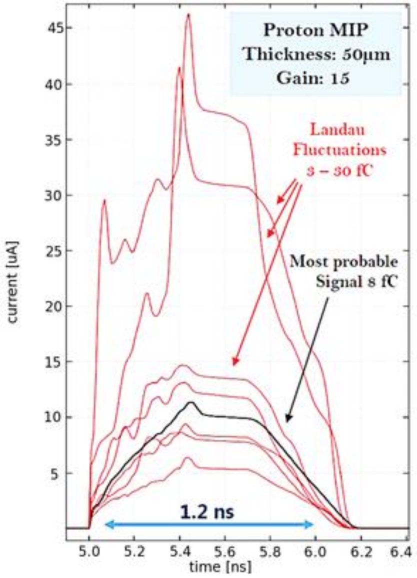
eID mechanisms

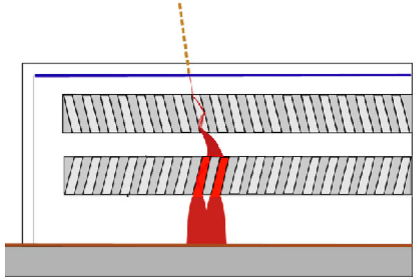
TOF covered well in prior presentations, not repeated here

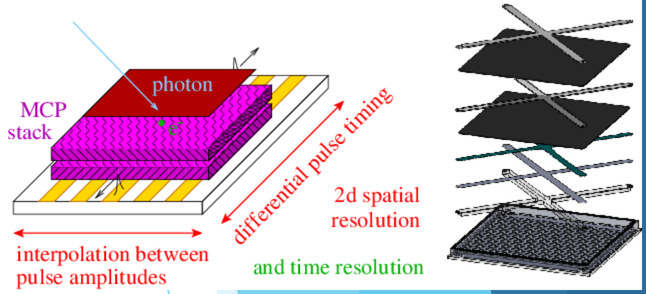
Time-of-Flight

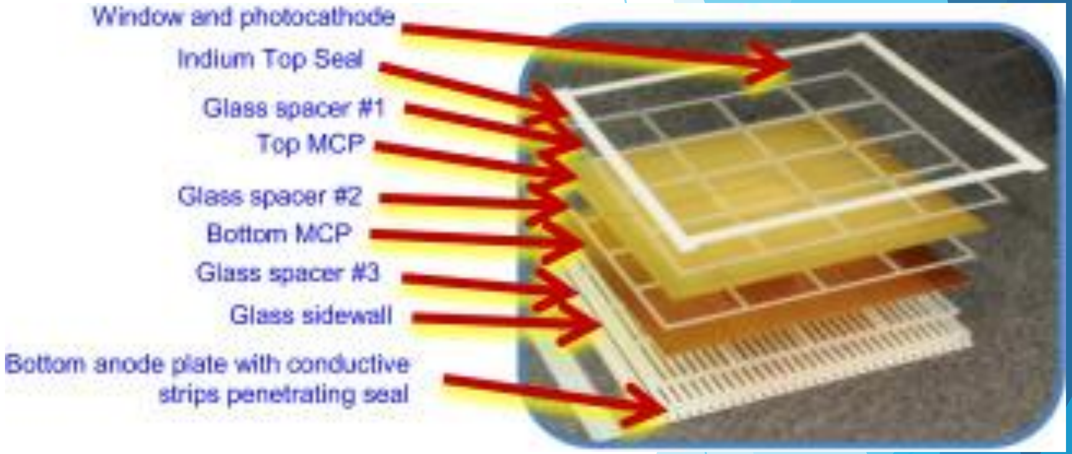
MCP: Micro Channel Plate





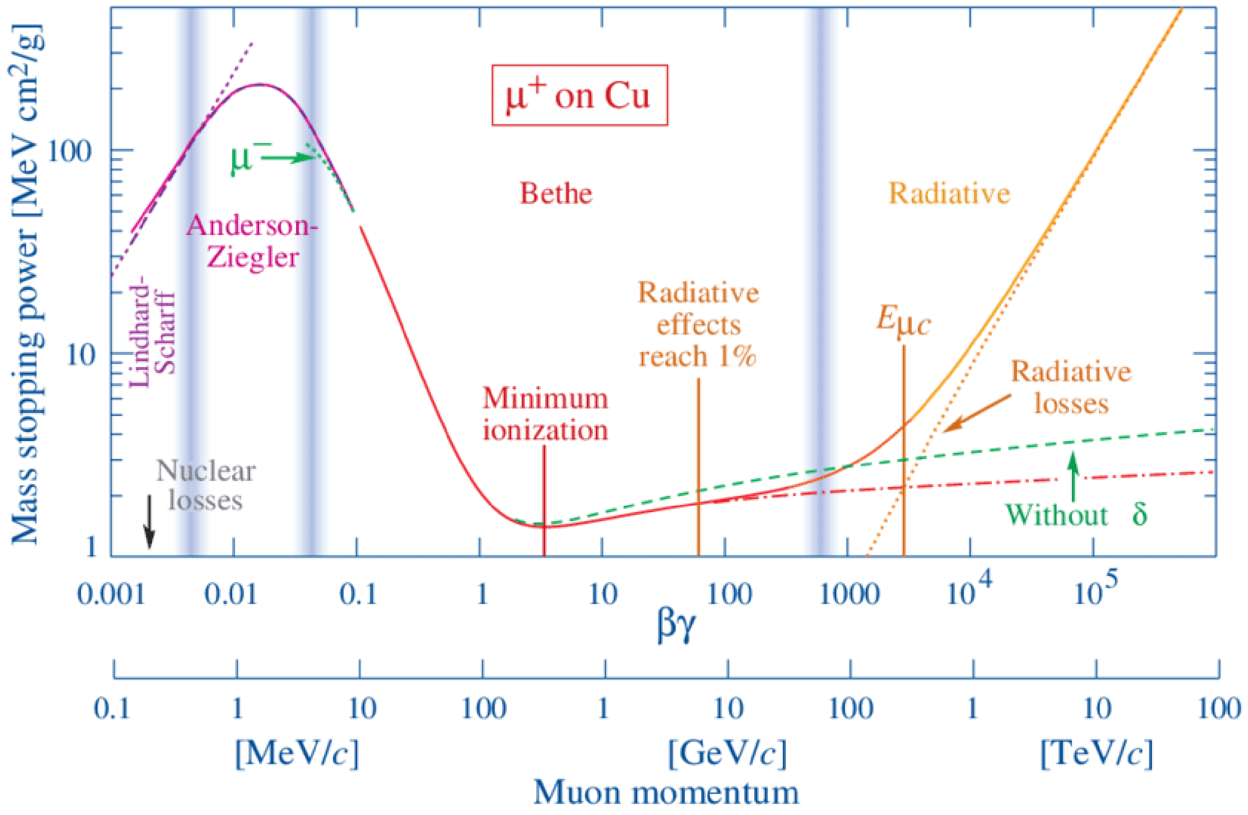


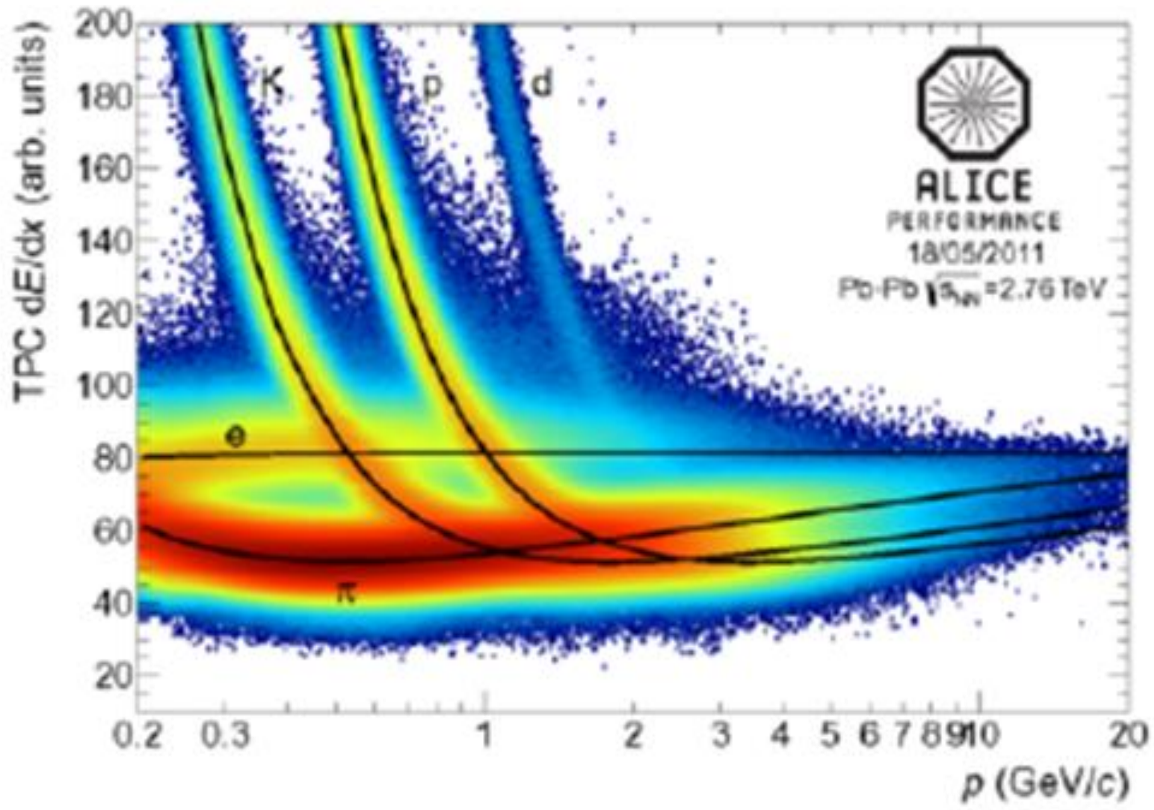




- Direct measurements of velocity require a fast charge collection device.
- The time resolution is automatically helped by small devices:
  - LGAD: Low Gain Avalanche Device. Instantly small.
  - MCP: Micro Channel Plate ➔ LAPPD (Large Area Picosecond Photon Detector)

dE/dx

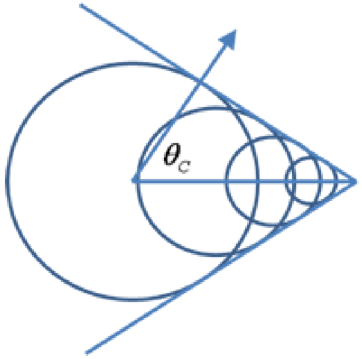




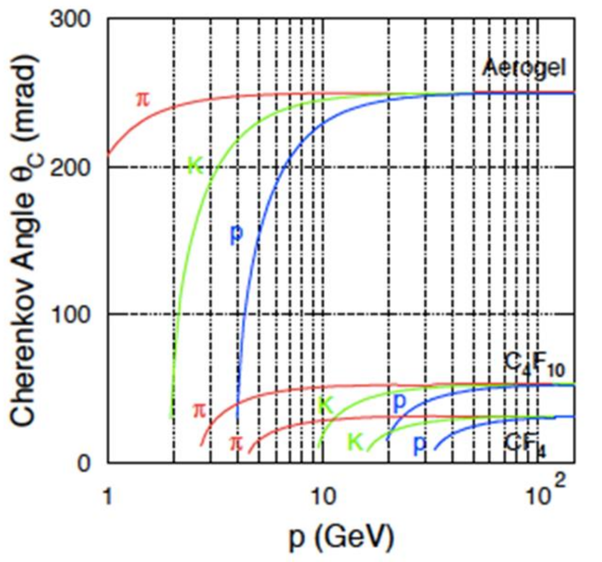
- dE/dx is a velocity-dependent interaction with the detector.
- Combined with momentum it provides PID.
- "Band crossings" are at β~0.7 and can be distinguished many ways.

Cherenkov Light

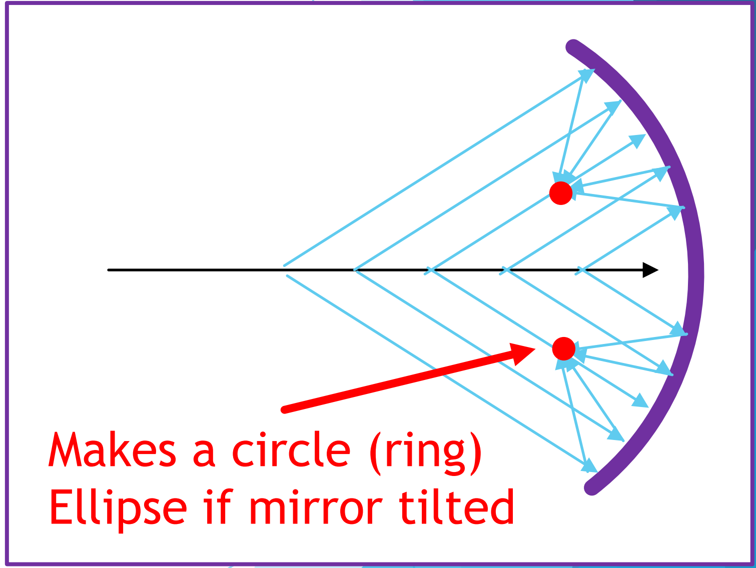
Cherenkov Angle determines β



$$\theta_C = \cos^{-1}\left(\frac{1}{\beta n}\right)$$



- Cherenkov Light – "Optical Boom"
- Cherenkov angle depends upon velocity & index
  - Low n distinguishes particles to high momentum.
  - Low n yields less light!
- Go where the light is:
  - $$\frac{dN}{dL} = 2\pi\alpha_{EM}\sin^2\theta_C \int_{\lambda_{MIN}}^{\infty} \varepsilon(\lambda)QE(\lambda)\frac{1}{\lambda^2}\,d\lambda$$
  - Deep UV Cherenkov yield is highest…how to get there?



Dual RICH

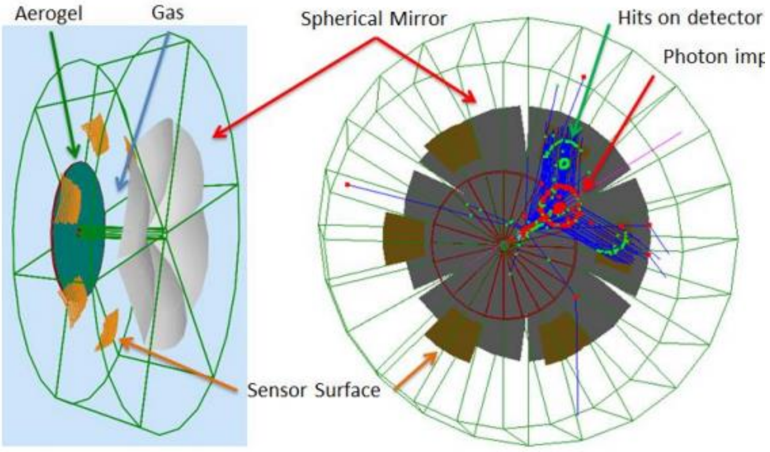
- Cherenkov radiator
  - Refractive Index

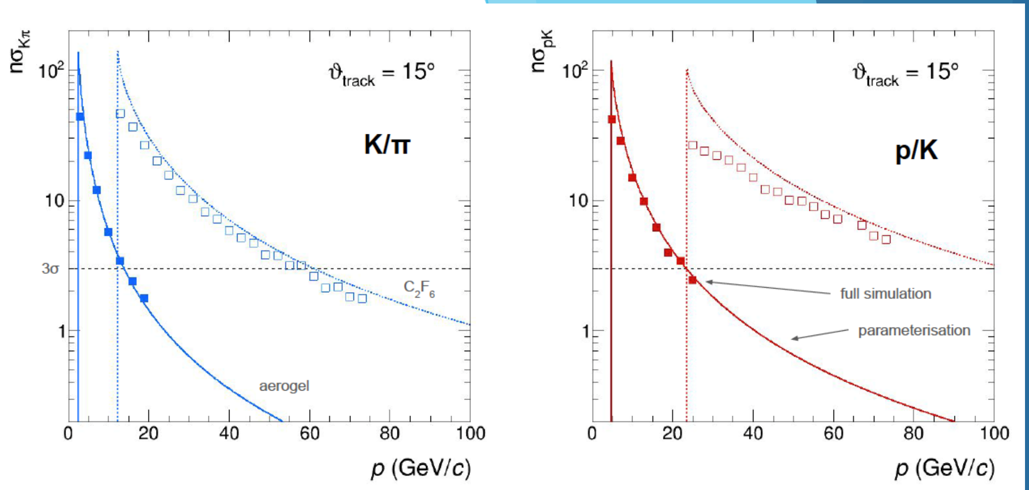
  n = 1.02 (aerogel)   1.0008 (C_2F_6)
  - Length of the radiator

  L = 4 cm (aerogel) , 160 cm (C_2F_6)
- Mirrors
- Photon Detector

  3 mm pixel size; 200-500 nm MAPMT
- Particle Generation

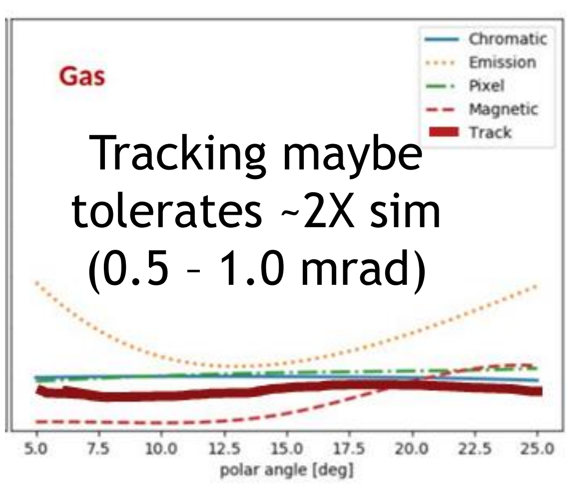
  Originate from the vertex





K/π and p/K separation as a function of momentum

- Exquisite detail in simulation.
- AI-based optimization.
- Uses constant external angular resolution assumption.
- Similar external constraint assumed as deduced for separate gas & aerogel RICHes



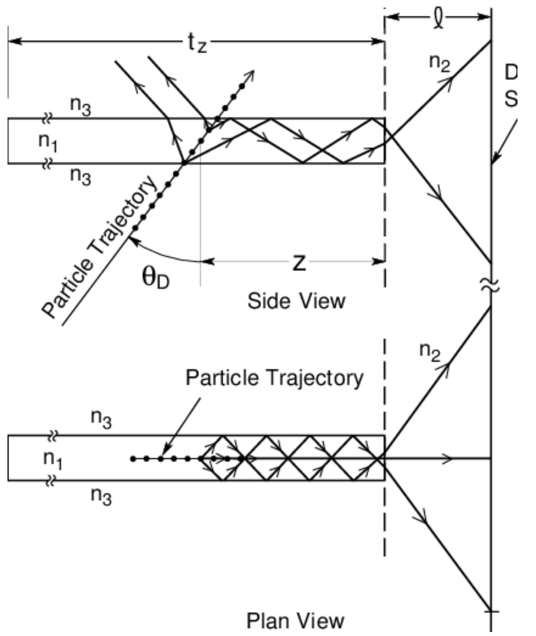
Tracking maybe tolerates ~2X sim (0.5 – 1.0 mrad)

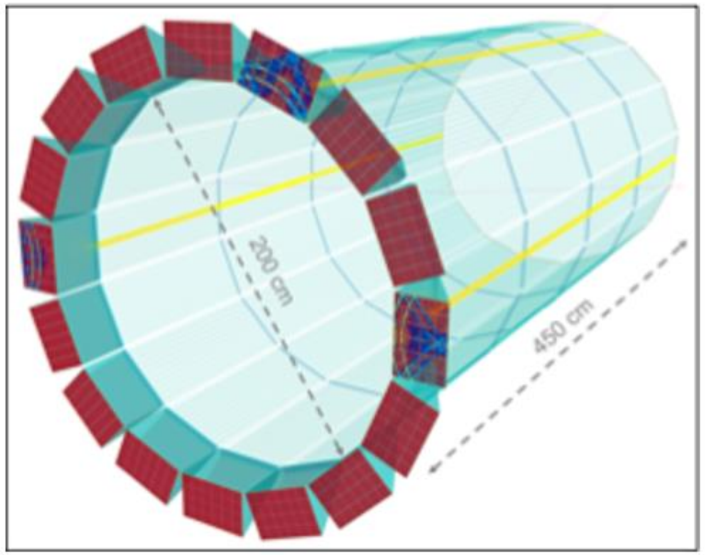
Tracking	
Angular resolution	σ = 0.5 mrad (1 mm over 2 m) – whole momentum range
Impact point resolution	σ = 0.3 mm
Momentum resolution dP/P	+/- few percent negligible effects in Cherenkov angle reconstruction
Magnetic Field	3 Tesla Central Field in JL-MEIC spectrometer
Space Requirement	(based on original spectrometer constraints)
longitudinal length	JLEIC: ≈1.6 m, ePHENIX: ≈1.0 m
transverse radius	JLEIC: ≈2.5 m, ePHENIX: ≈2 m
beam pipe radius	<10 cm
Background	no direct external background only backrground produced by the simulated charged particle: Delta rays, Rayleigh scattering …

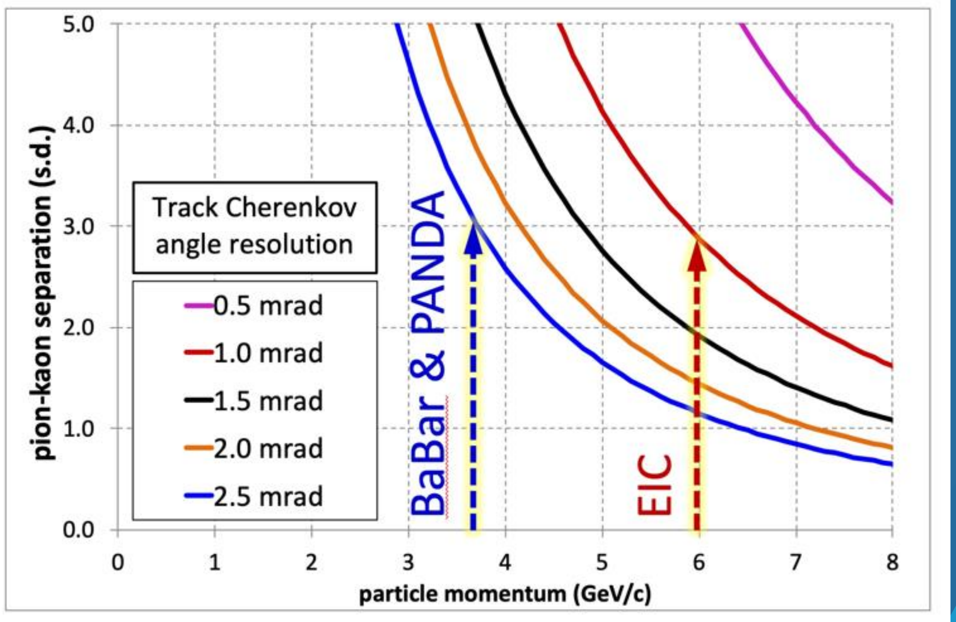
External Assumption

NOTE: PMTs to the side makes optical aberration ("Emission") dominant

Detection of Internally Reflected Cherenkov: DIRC







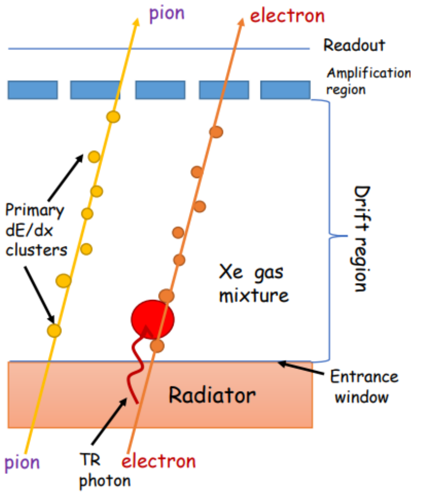
hpDIRC

- At normal incidence, Cerenkov light is internally reflected for $n > \sqrt{2}$
- Cerenkov angle preserved if bars meticulously flat with 90 degree corners.
  - If you “back up the photon sensors” this is a proximity focus. (original BaBar)
  - If you use focusing elements it becomes a high performance hpDIRC
- Spectacularly compact PID device with photon detection at end.

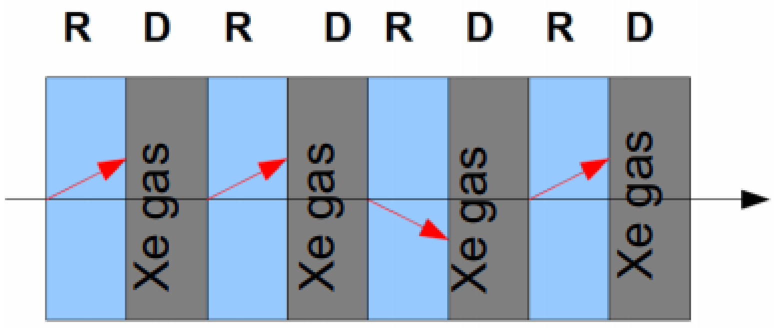
eID by Transition Radiation (TRD)

1: Make TR photons:

- Index, n, change
- X-ray regime

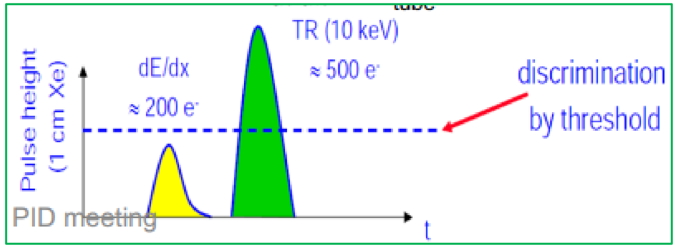


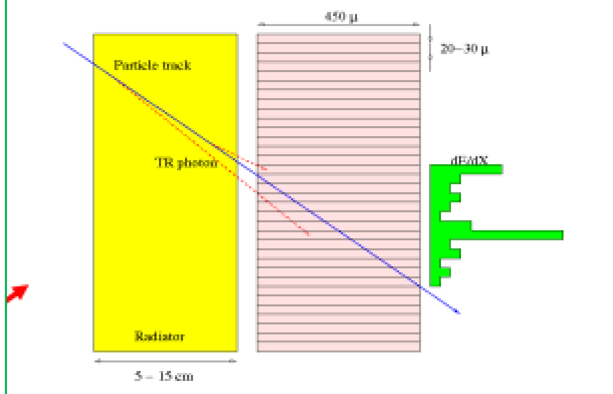
Film, foam, fleece

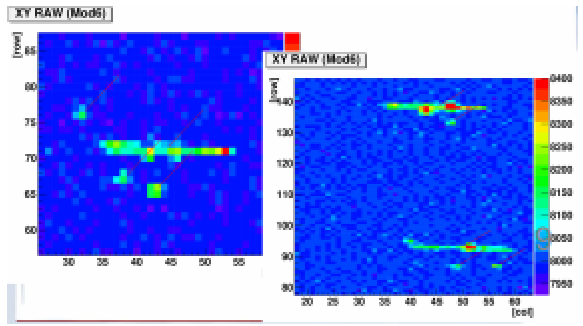


2: Layered to get more photons

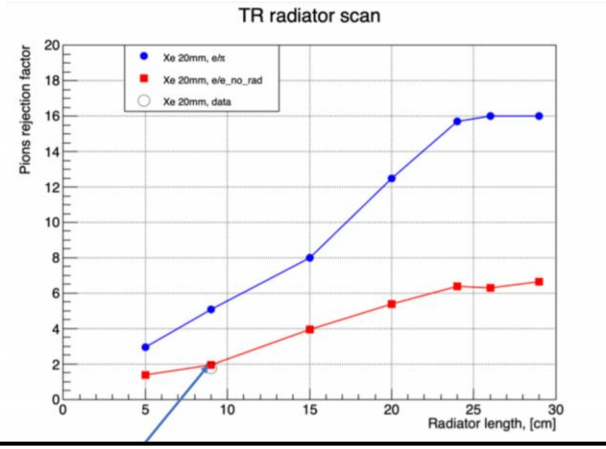
3: ID TR photons by energy/pos

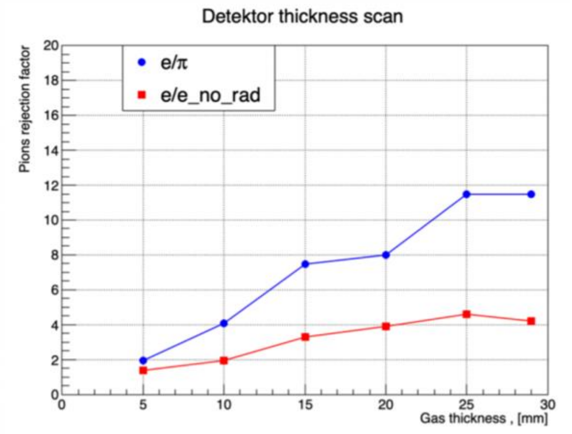






4: Reject Pions





- "Threshold detector" (TR X-rays produced or not)
- P_{min} ~ 1 GeV (rejection ~constant at higher momentum)

Balance between X_0 and rejection

Summary

- Welcome to Nuclear Physics!!!
- Detector Technology is fun and exciting.
- No time for so many things SiPM, readout electronics, streaming mode.
- Present capabilities are excellent and the future is better.
- You are entering the nuclear physics at an amazing time.
- Financial investments are excellent, particularly with the future electron-ion collider.