PID AT THE EIC

- Klaus Dehmelt

- The 2022 CFNS Summer School on the Physics of the Electron-Ion-Collider
- July 15, 2022

Stony Brook University | The State University of New York

Center for Frontiers in Nuclear Science

PARTICLE/NUCLEAR PHYSICS EXPERIMENTS

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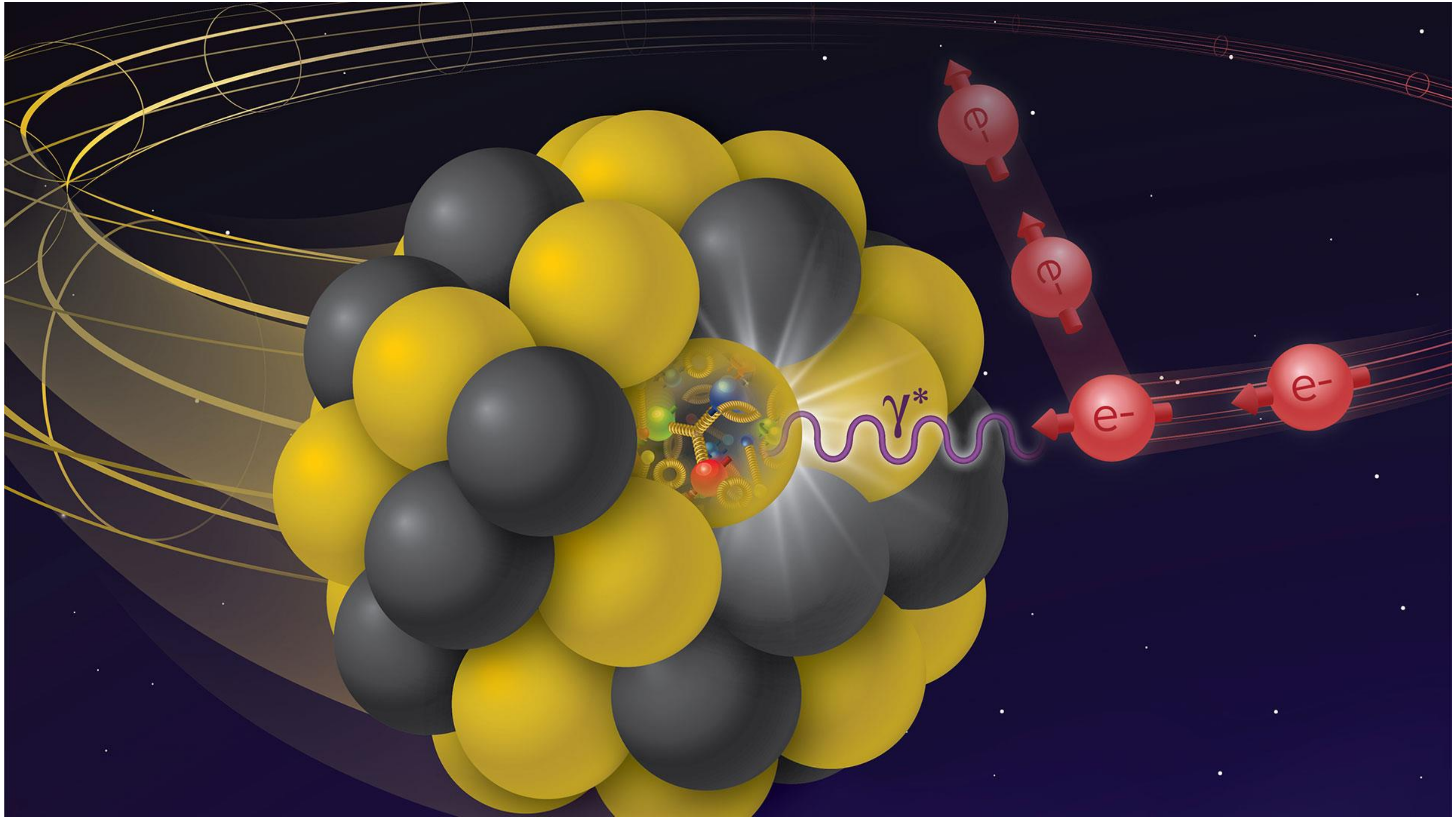
The Electron Ion Collider -EIC-



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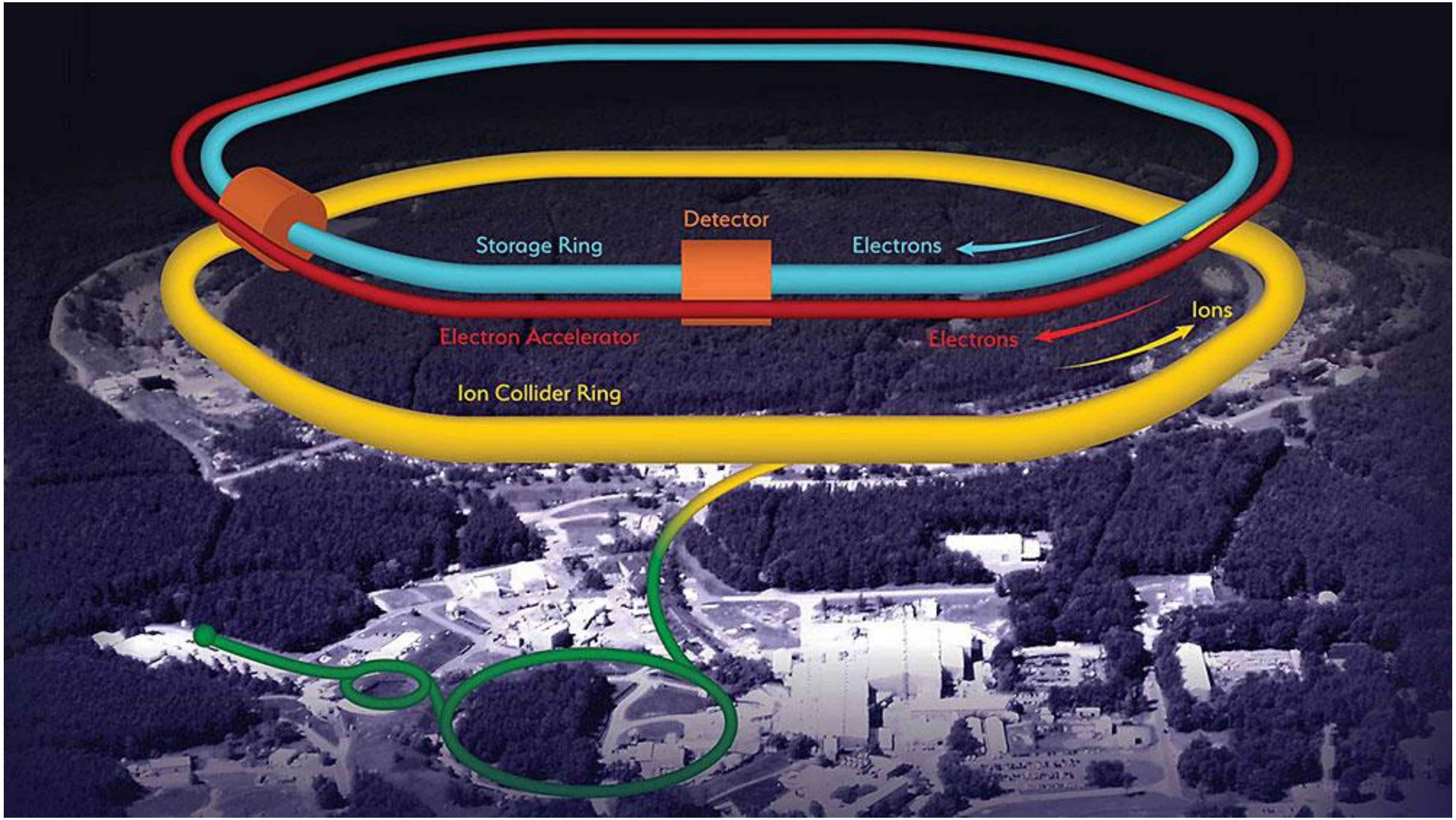

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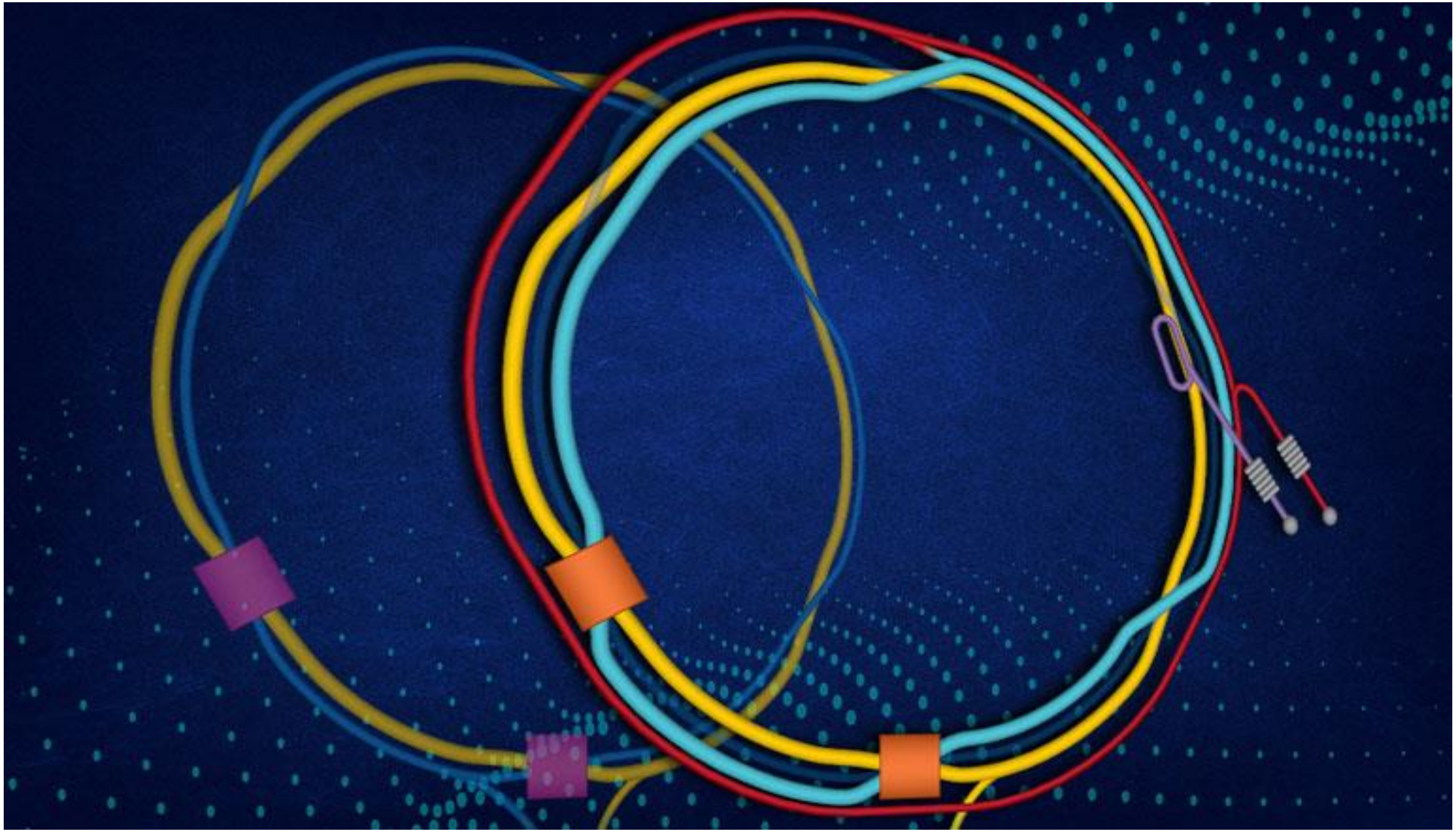

PARTICLE/NUCLEAR PHYSICS EXPERIMENTS

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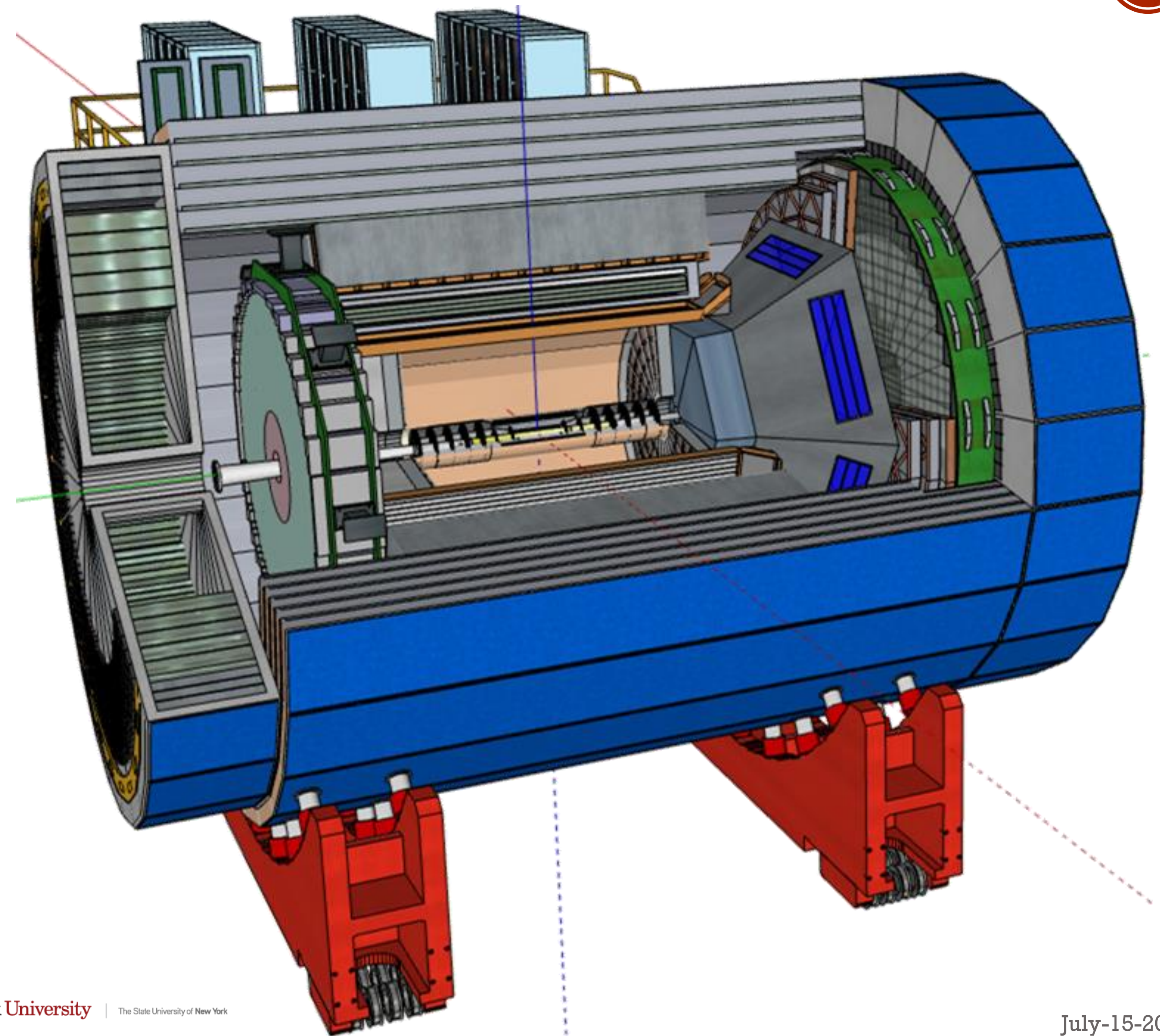
The Electron Ion Collider -EIC-

- Needs Detector(s)
- Measure various observables
  - Momentum → tracking
  - Energy → calorimetry
  - Particle identity
  - Others



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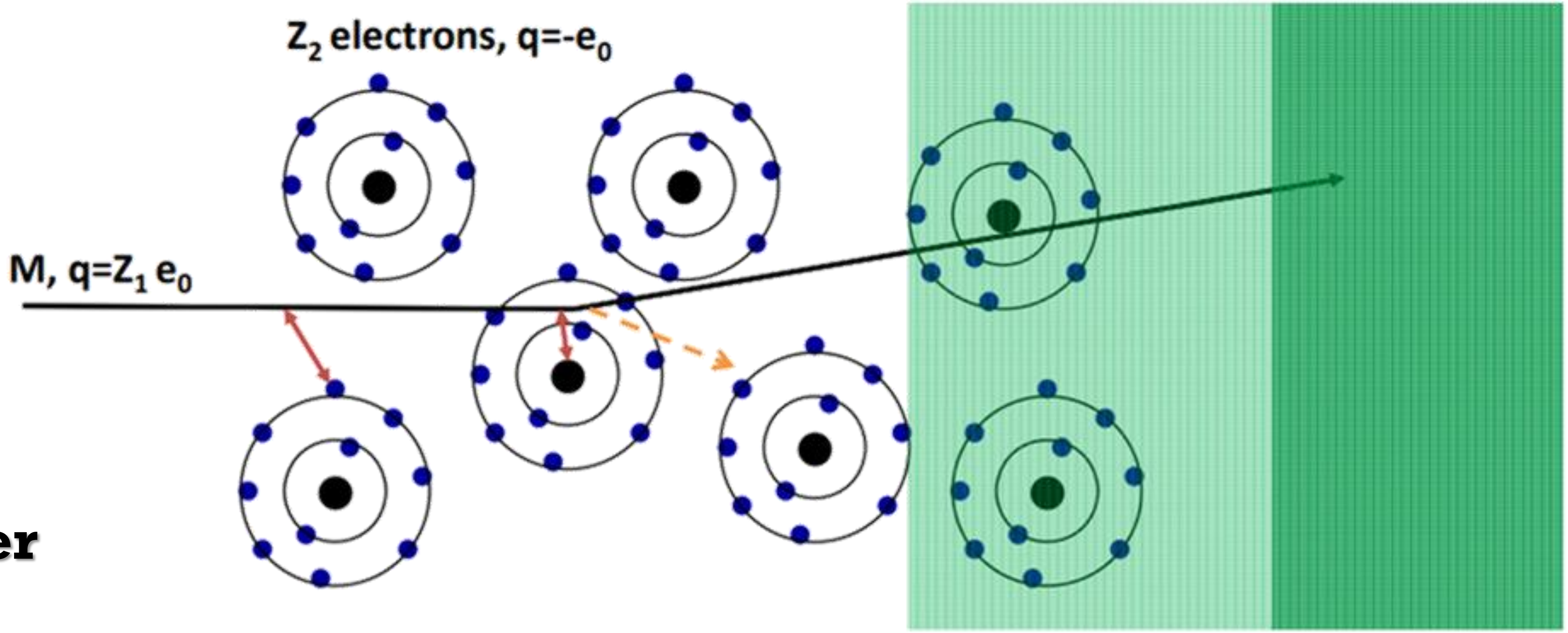


EM Interaction of Particles with Matter

Interaction with the atomic electrons. The incoming particle looses energy and the atoms are excited or ionized.

Interaction with the atomic nucleus. The particle is deflected (scattered) resulting in multiple scattering of the particle in the material. During these scattering events a Bremsstrahlung photons can be emitted.

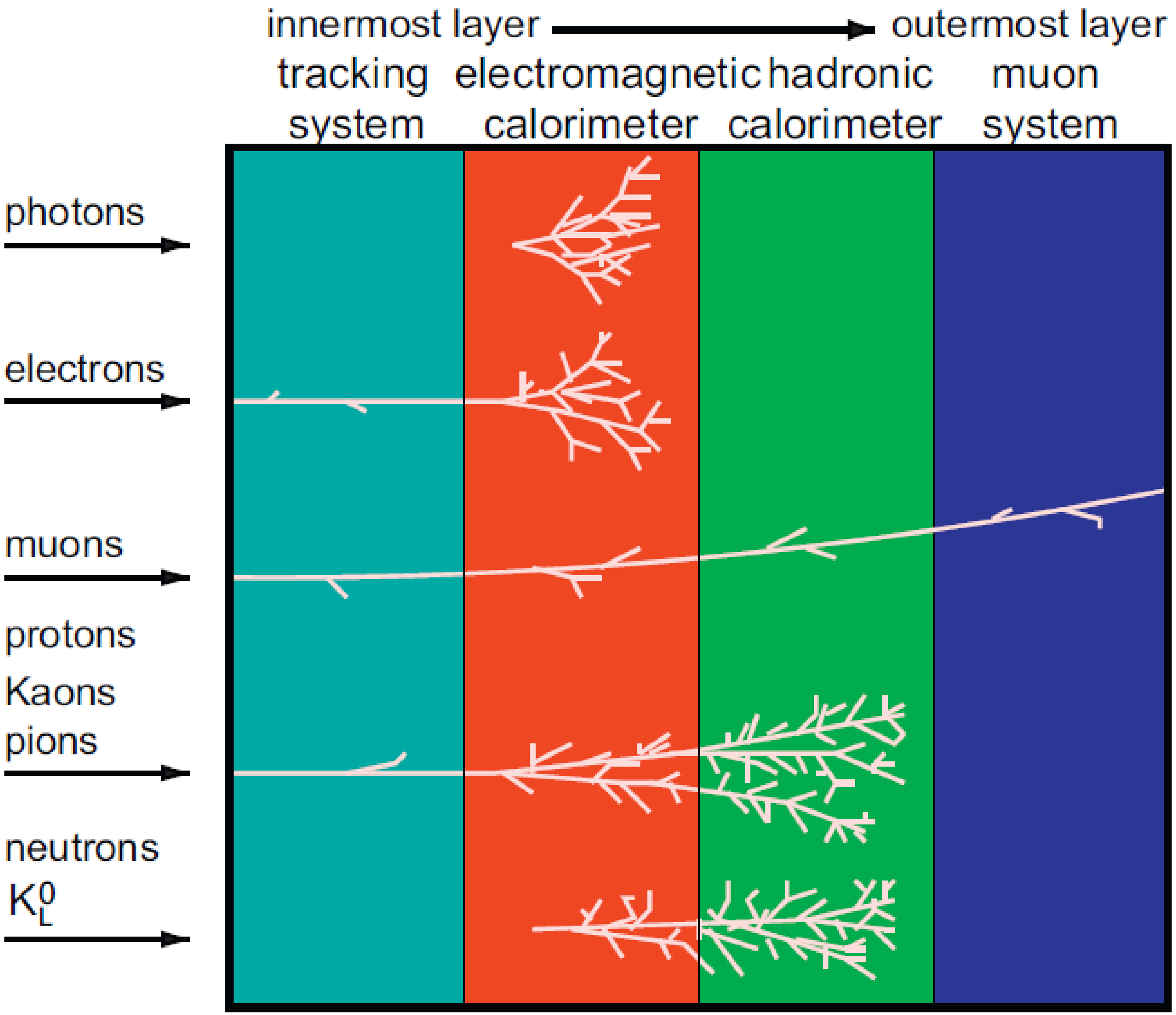
In case the particle's velocity is larger than the velocity of light in the medium, the resulting EM shockwave manifests itself as Cherenkov Radiation. When the particle crosses the boundary between two media, there is a probability of the order of 1% to produce an X ray photon, called Transition radiation.

PARTICLE/NUCLEAR PHYSICS EXPERIMENTS

- Traditional Experiments

  Onion Structure

  - Trackers
    - Momentum measurement
    - Charge measurement
    - Non-destructive
  - Calorimeters
    - Detect neutral particles
    - Measure energy
    - Distinguish EM/Hadron interactions
    - Destructive
  - Others



PARTICLE/NUCLEAR PHYSICS EXPERIMENTS

- Particle Identification -PID-
  - Identify stable particles emerging from the interaction of particle collisions
    - Positive identification
    - Inclusive identification
    - Exclusive identification
  - Determine interaction process
    - Electromagnetic interaction → lepton* and photon identification
  - Determine mass

* basically electrons/positrons

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PARTICLE/NUCLEAR PHYSICS EXPERIMENTS

- Electron and photon identification
  - Photons in material → e^+e^- pair conversion
  - Electrons/Positrons → Bremsstrahlung

  → shower development until energy diminished
- Radiation length → distance in material required for reducing energy by 1/e
- Showers look similar for electrons and photons → distinguish with tracker
- E/p = 1 (pretty much) for electrons
- Muons
  - ~ 200 times heavier than electrons, little Bremsstrahlung, no strong interaction, τ_μ=2.2μs
  - Travel distance d = $\beta\gamma c\tau_\mu$ → 5 GeV muon travels ~30 km before decay → stable
  - Acts most of the times as minimum ionizing particle MIP → detector to measure everything but what's already stopped

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Particle	m [MeV]	Quarks	Main decay	Lifetime	$c\tau$ [cm]
$\pi^{\pm}$	140	$u\bar{d}$	$\mu\nu_{\mu}$	2.6×10^{-8} s	780
$K^{\pm}$	494	$u\bar{s}$	$\mu\nu_{\mu}$, $\pi\pi^{0}$	1.2×10^{-8} s	370
$K_S^{\ 0}$	498	$d\bar{s}$	$\pi\pi$	0.9×10^{-10} s	2.7
$K_L^{\ 0}$	498	$d\bar{s}$	$\pi\pi\pi$, $\pi l\nu$	5×10^{-8} s	1550
p	938	uud	stable	$> 10^{25}$ years	∞
n	940	udd	$pe\nu_{e}$	890 s	2.7×10^{13}
Λ	1116	uds	$p\pi$	2.6×10^{-10} s	7.9

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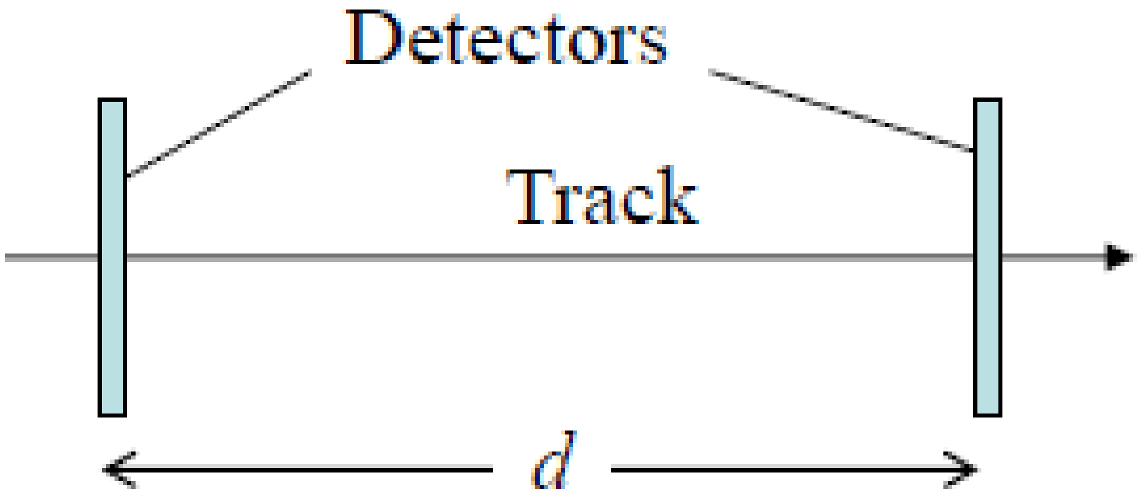
π^0 : $\tau \sim$ 85 attoseconds (10^{-18}s)

PARTICLE IDENTIFICATION -PID-

- Four (4) main PID techniques
  - Time of Flight
    - Fixed distance – fast readout
  - Transition radiation
    - Border crossing between media with different dielectric properties
  - Cherenkov radiation
    - Particle velocity greater than photon velocity in medium
  - Ionization loss – dE/dx
    - Specific energy loss per particle species
- PID techniques → velocity measurements
- These PID techniques aim to identify electrically charged hadrons

TIME OF FLIGHT

- Measure Δt between two planes separated by distance d
  - $\Delta t = d/v \rightarrow \beta = d/c\Delta t$
  - High energy → $\beta \rightarrow 1$
  - Need high timing resolution



TIME OF FLIGHT

- Separation power with Time of Flight TOF
  - Determine mass with velocity measurement → $\beta = d/c\Delta t$

$$\beta = \frac{1}{\sqrt{\left(\frac{mc}{p}\right)^2 + 1}} \Rightarrow m = \frac{p}{c}\sqrt{\left(\frac{ct}{d}\right)^2 - 1}$$

  - Two particles with same momentum → measure $\Delta T = |\, t_a - t_b \,|$

$$|t_A - t_B| = \frac{L}{c}\left|\sqrt{1+\left(\frac{m_A c}{p}\right)^2} - \sqrt{1+\left(\frac{m_B c}{p}\right)^2}\right| \Rightarrow n_{\sigma_{TOF}} = \frac{|t_A - t_B|}{\sigma_{TOF}} = \frac{Lc}{2p^2\sigma_{TOF}}|m_A^2 - m_B^2|$$

σ_{TOF}: TOF resolution

TIME OF FLIGHT

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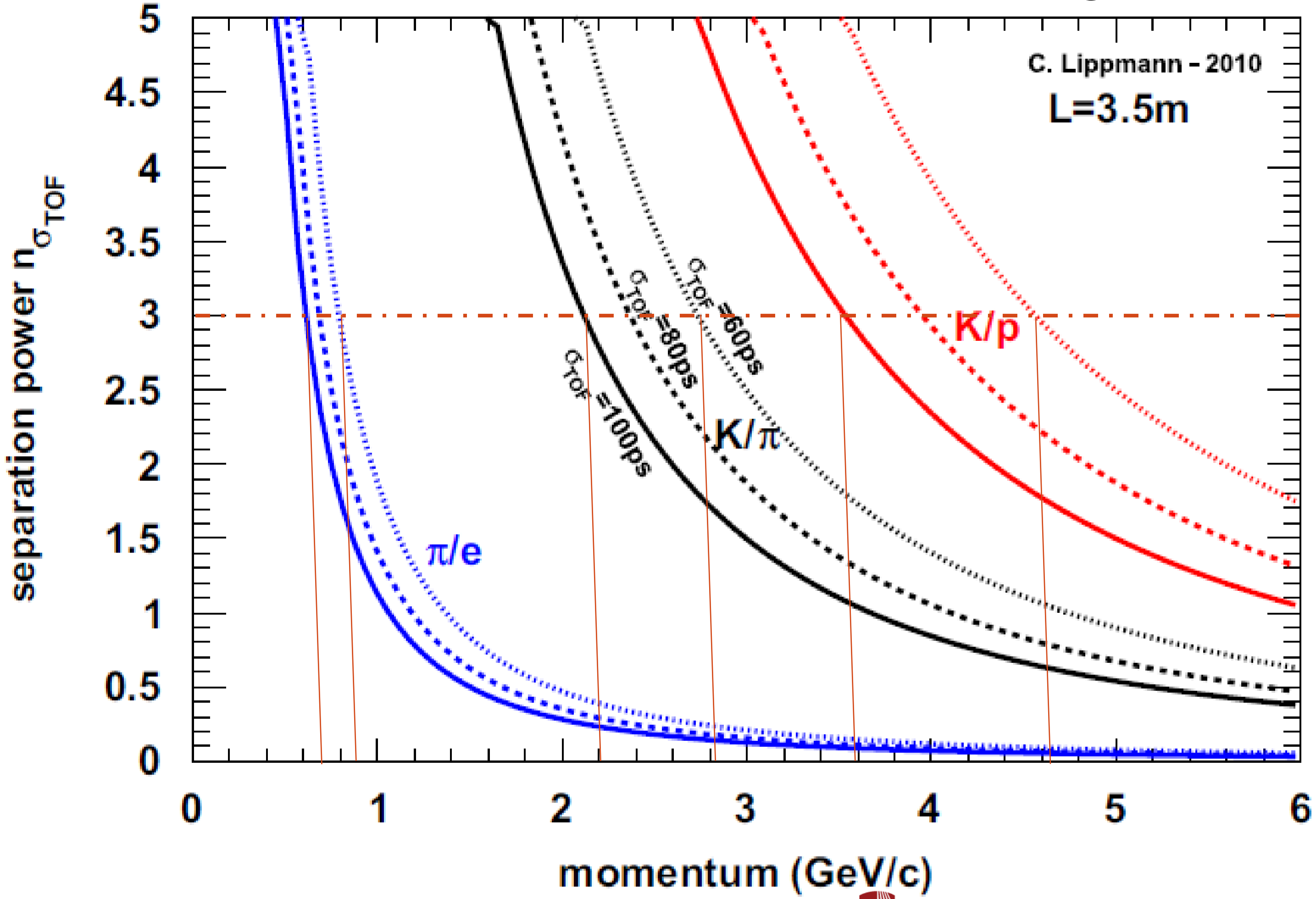
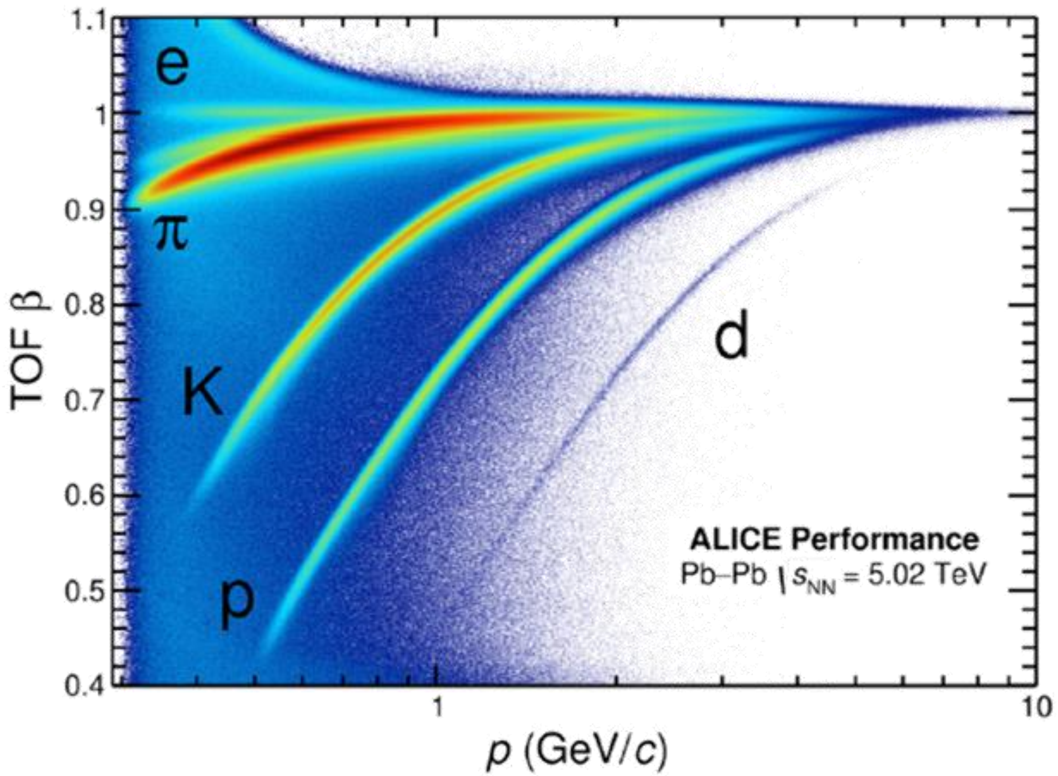




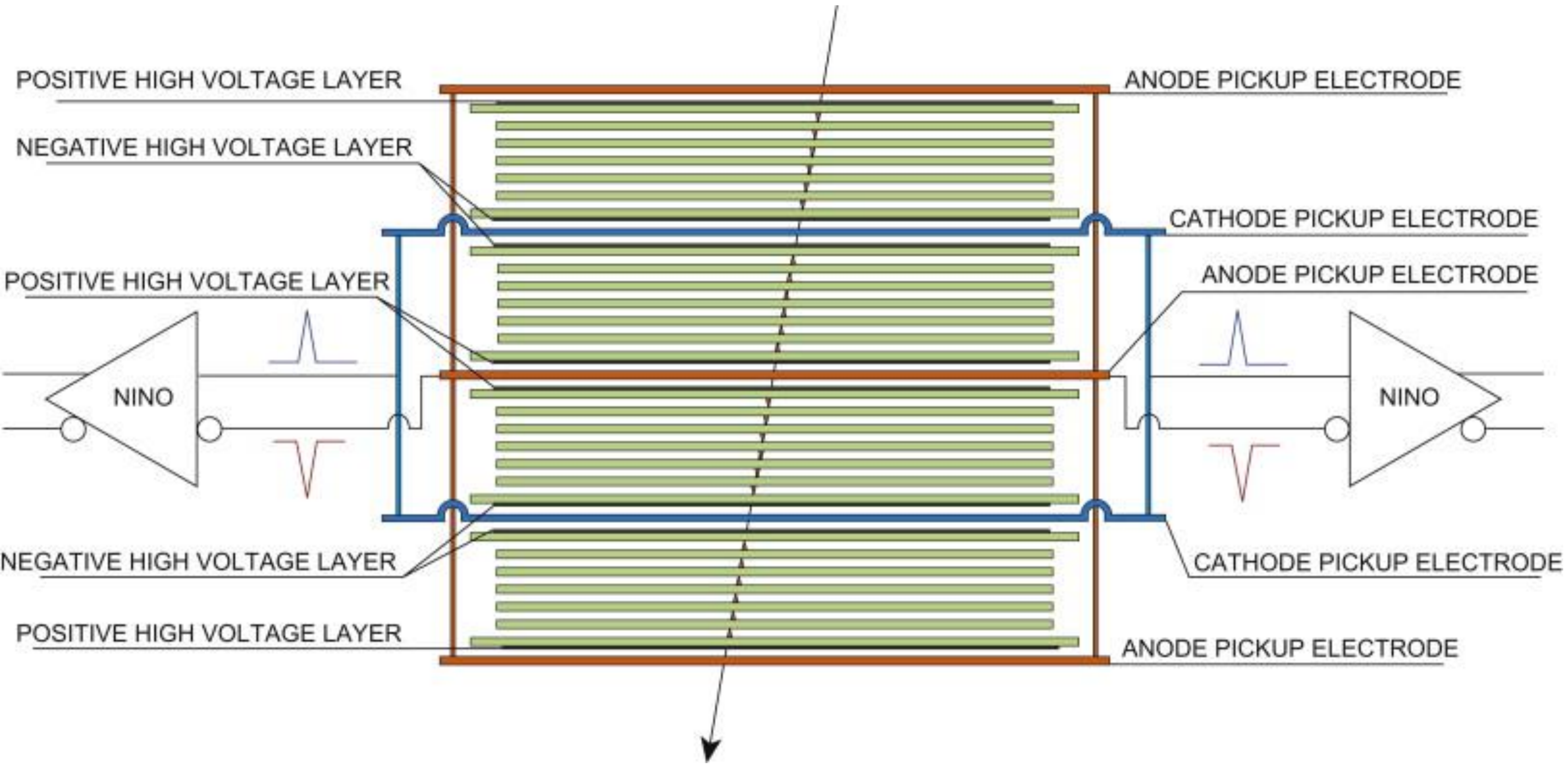
$$\frac{dm}{m} = \frac{dp}{p} + \gamma^2\left(\frac{dt}{t} + \frac{dL}{L}\right)$$

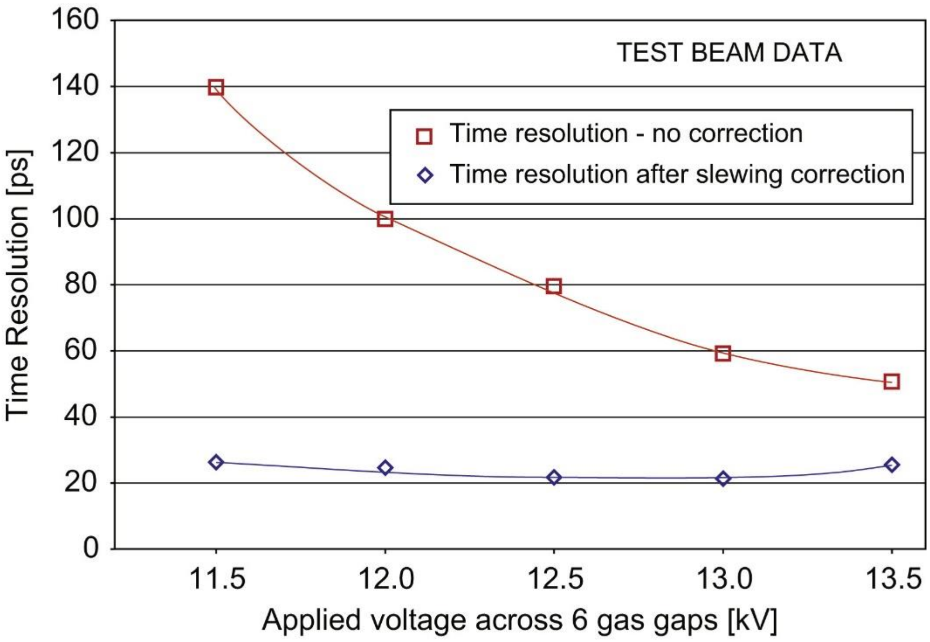
TIME OF FLIGHT

- TOF detector technologies
  - Any sensor that produces a fast/short signal → low transit time spread
    - (m)RPC
    - LGAD
    - PicoSec
    - TOP
    - TORCH
    - …
    - Some have sensor and detector integrated, others need additional detector
  - Fast electronics

TIME OF FLIGHT

- Multigap resistive plate chamber - mRPC





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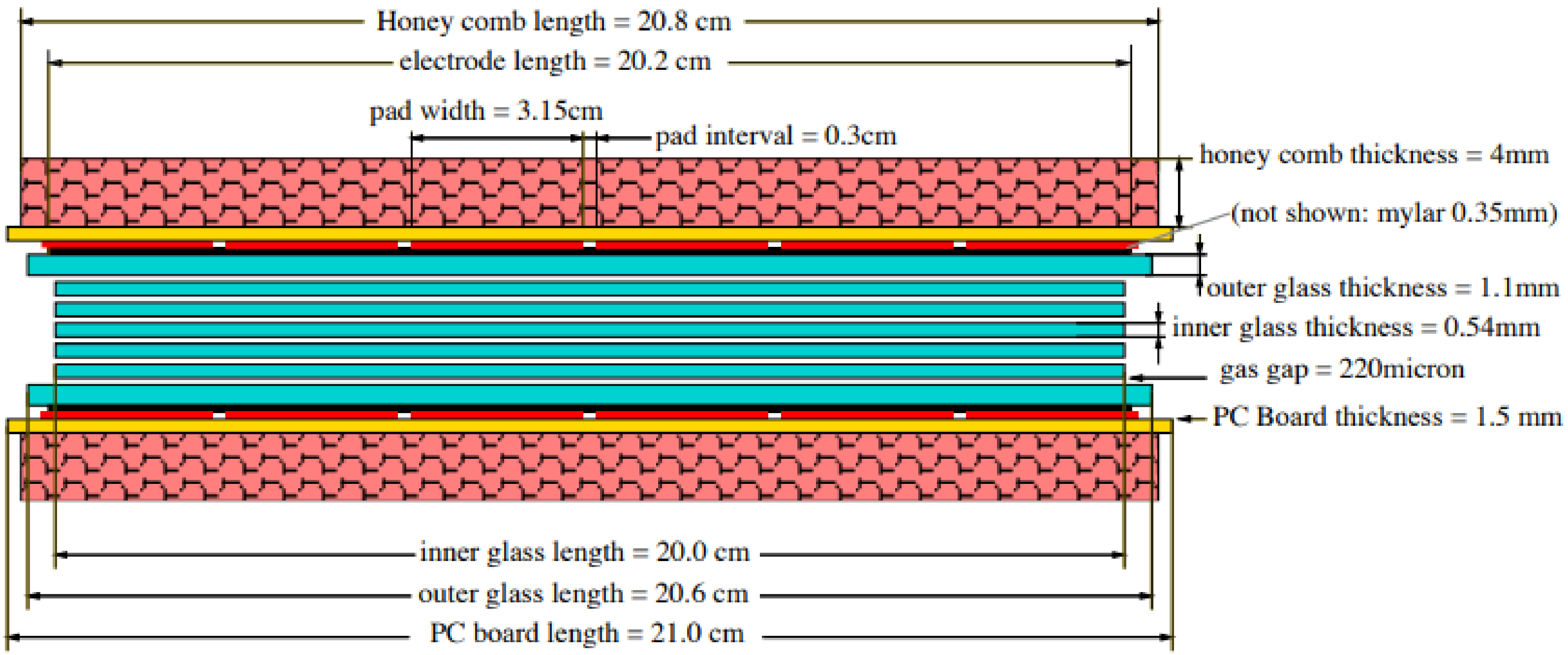
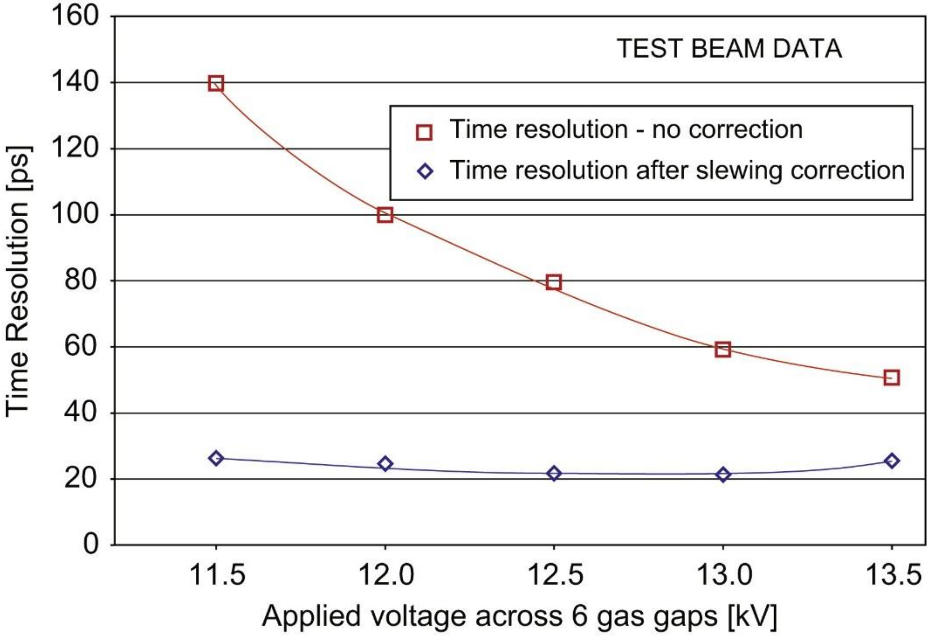
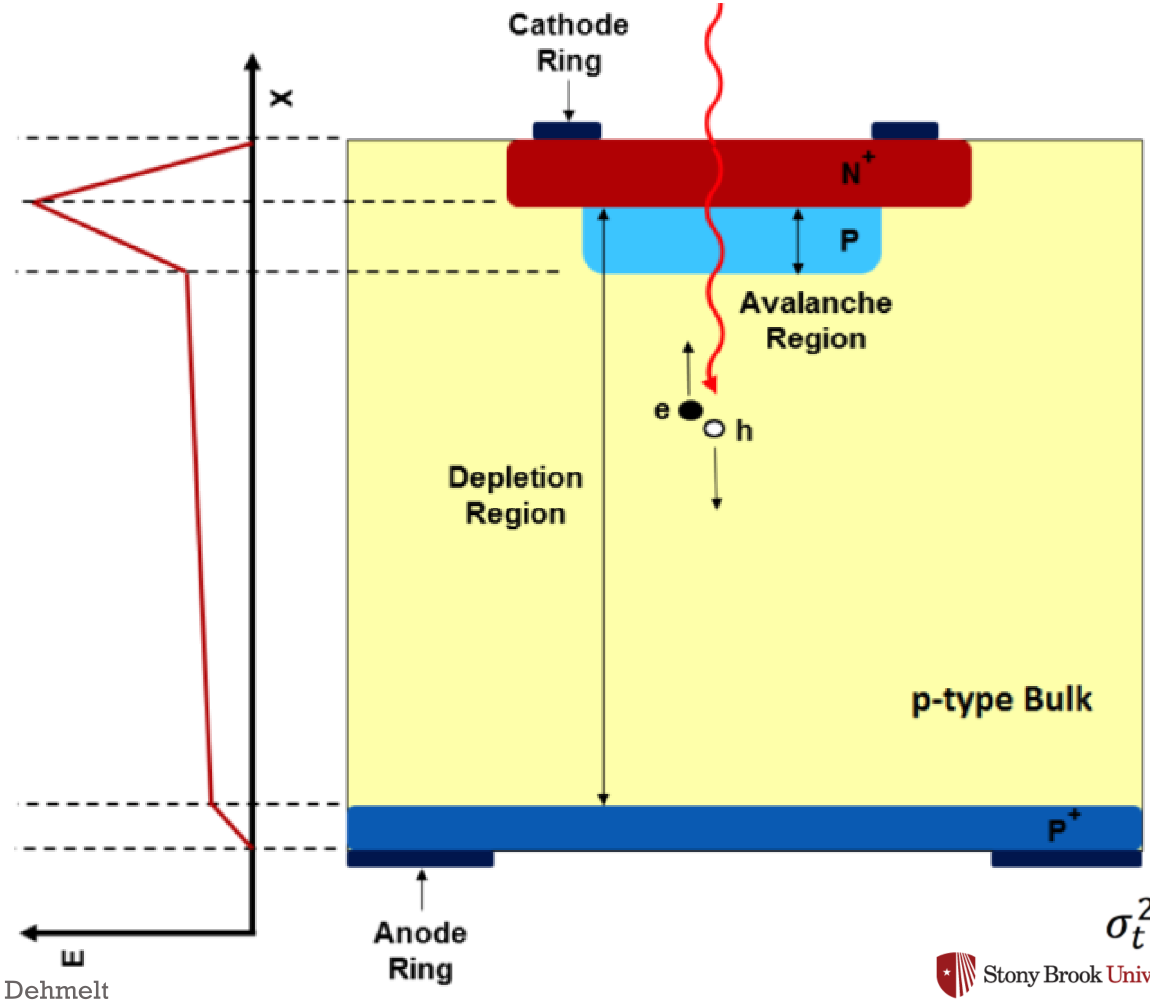


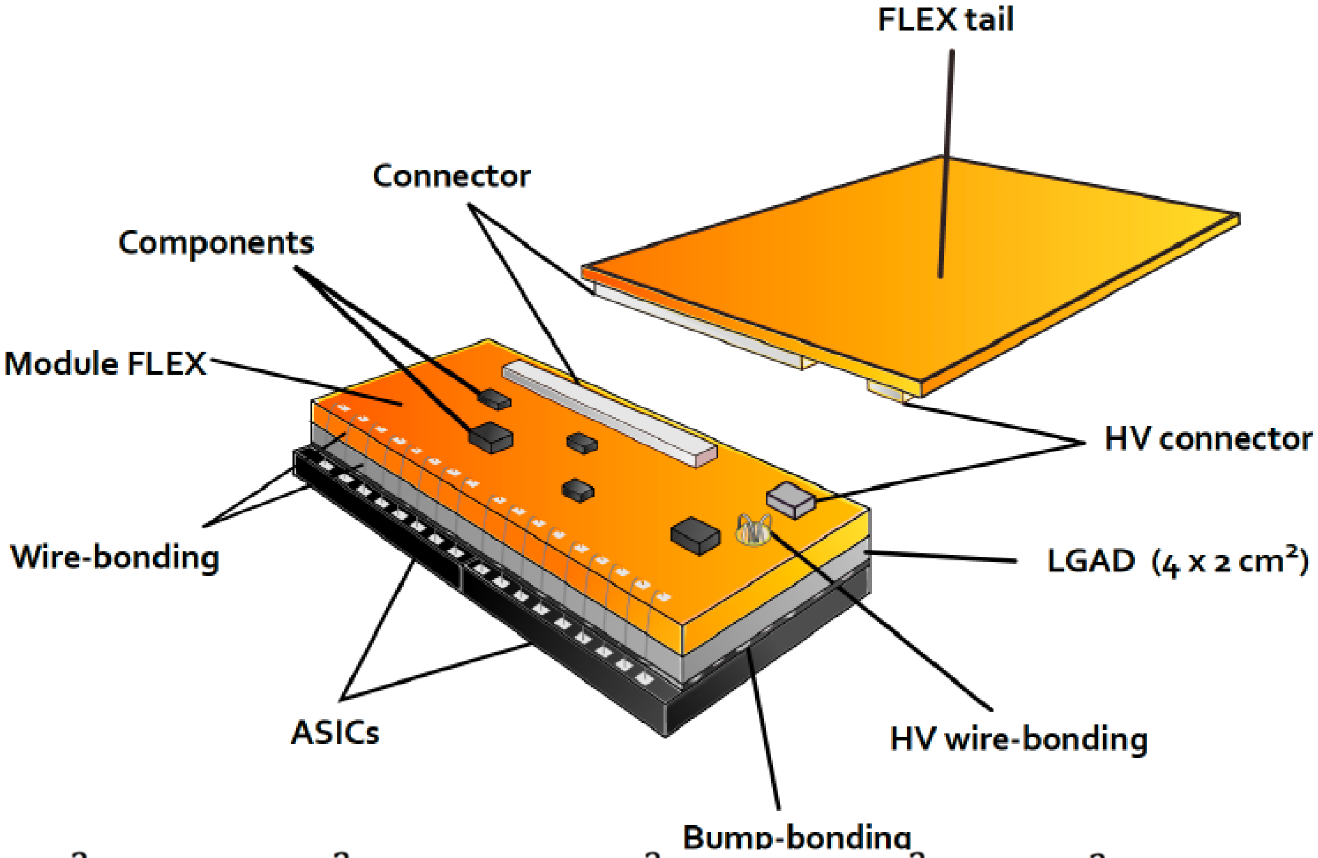


TIME OF FLIGHT

- Low Gain Avalanche Detector LGAD – Si based



CNM LGAD Sensor



$$\sigma_t^2 = \sigma_{TimeWalk}^2 + \sigma_{LandauNoise}^2 + \sigma_{Distortion}^2 + \sigma_{Jitter}^2 + \sigma_{TDC}^2$$

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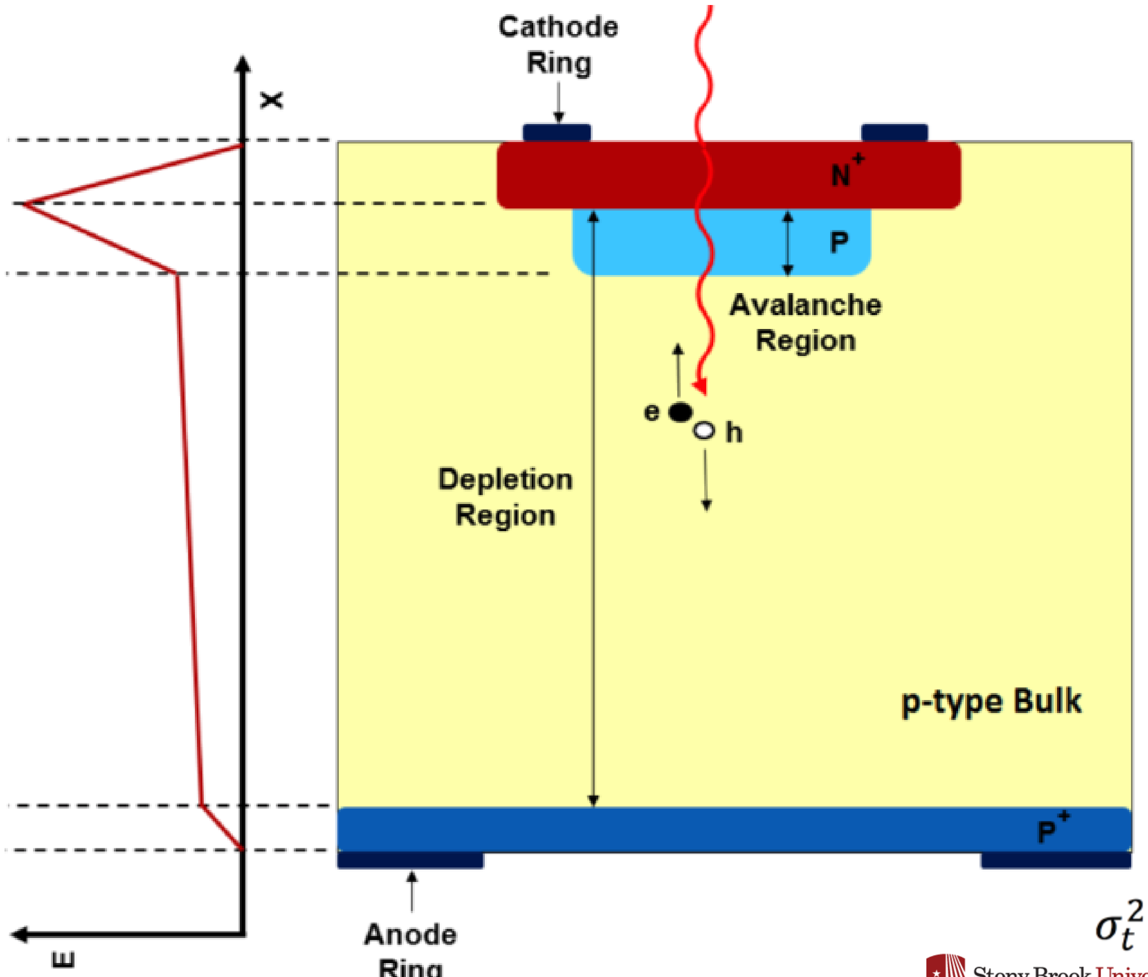

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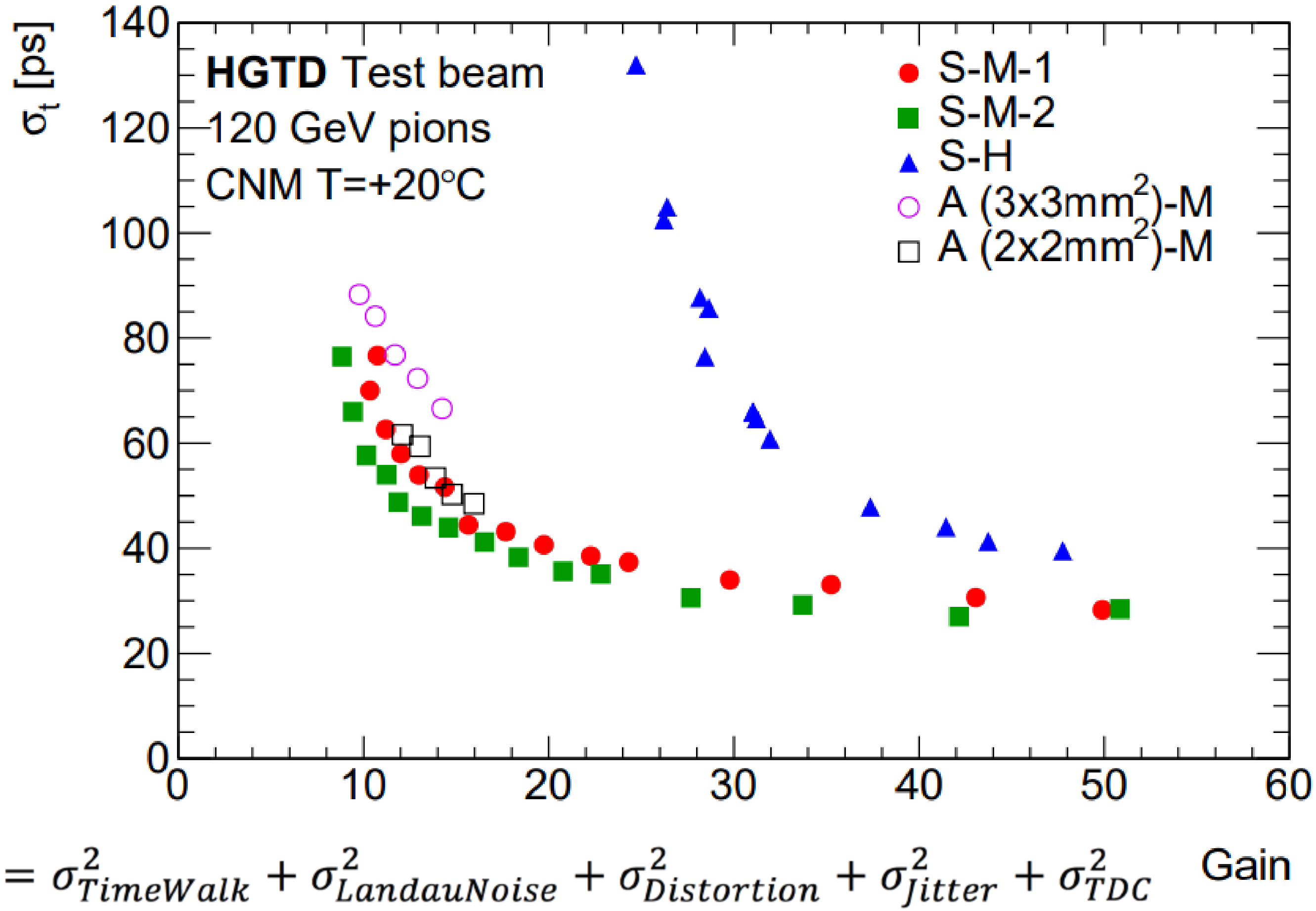
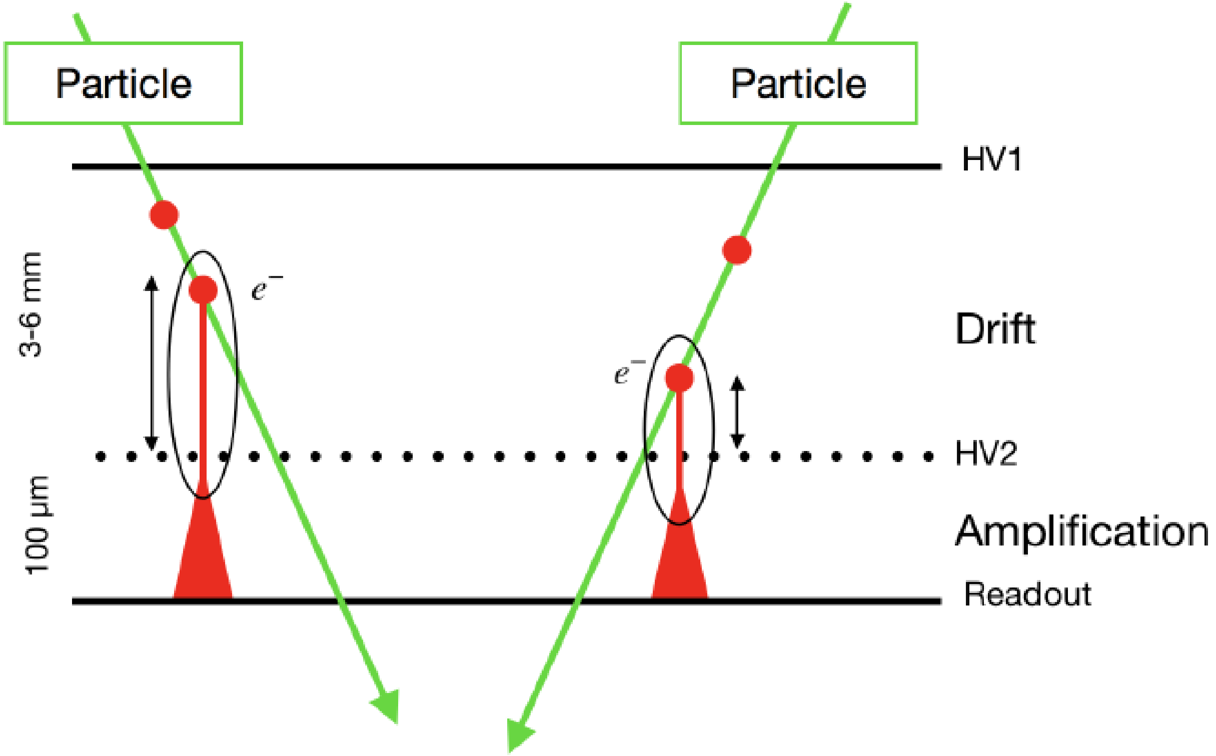


$$\sigma_t^2 = \sigma_{TimeWalk}^2 + \sigma_{LandauNoise}^2 + \sigma_{Distortion}^2 + \sigma_{Jitter}^2 + \sigma_{TDC}^2$$

TIME OF FLIGHT

- PicoSec short for PICOSECOND-MicroMegas



Time resolution limited by last ionization cluster and distance to grid

TIME OF FLIGHT

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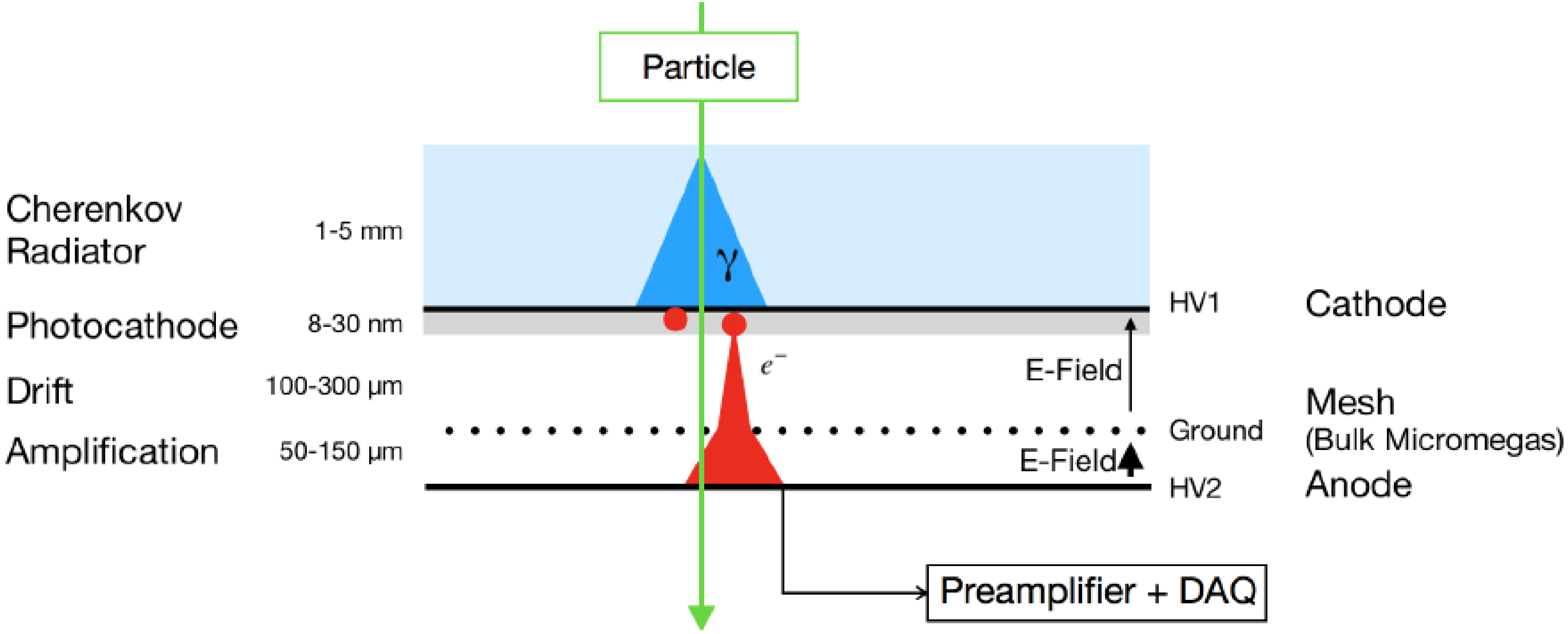

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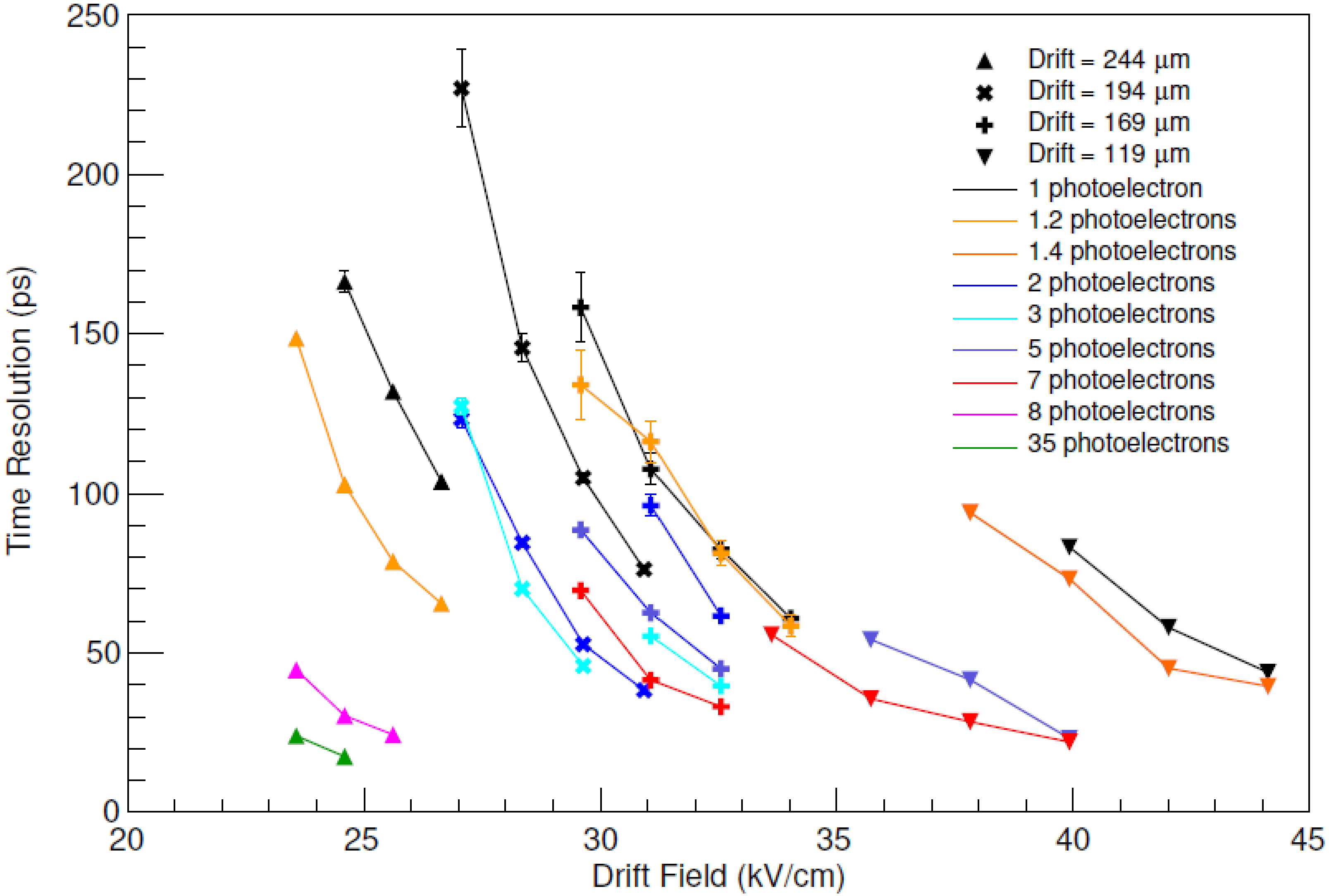
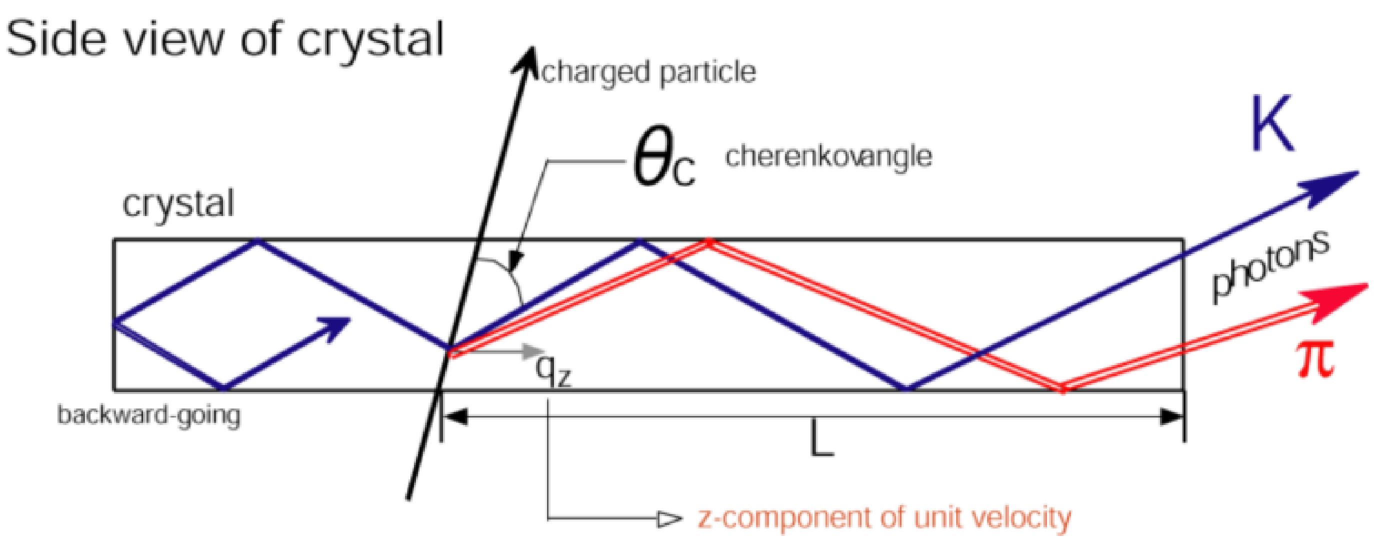
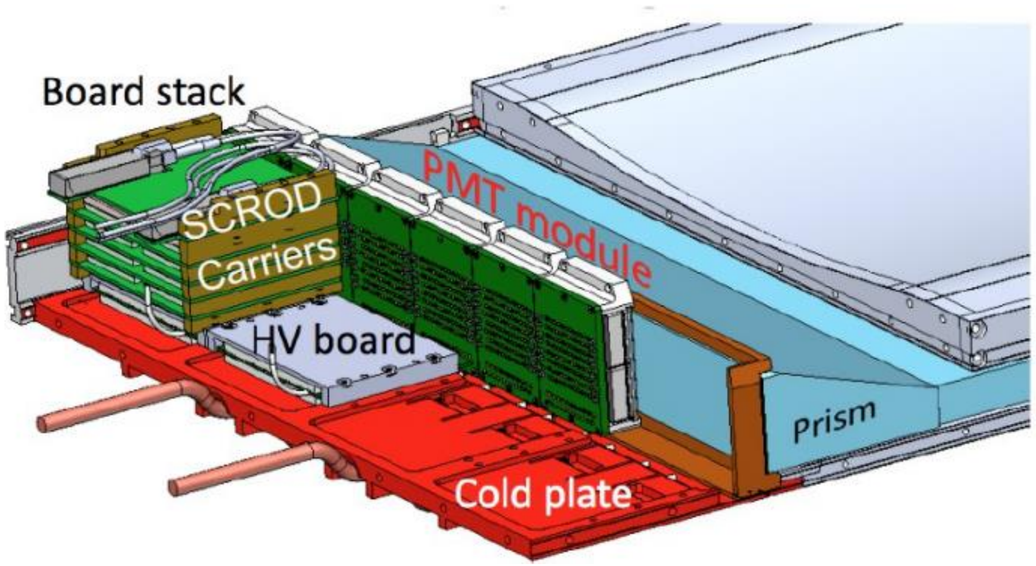


TIME OF FLIGHT

- Time of Propagation - TOP
  - Cherenkov angles in a crystal are different for various particle species → different arrival times at different positions in photodetector → 2D
  - Fast photodetector





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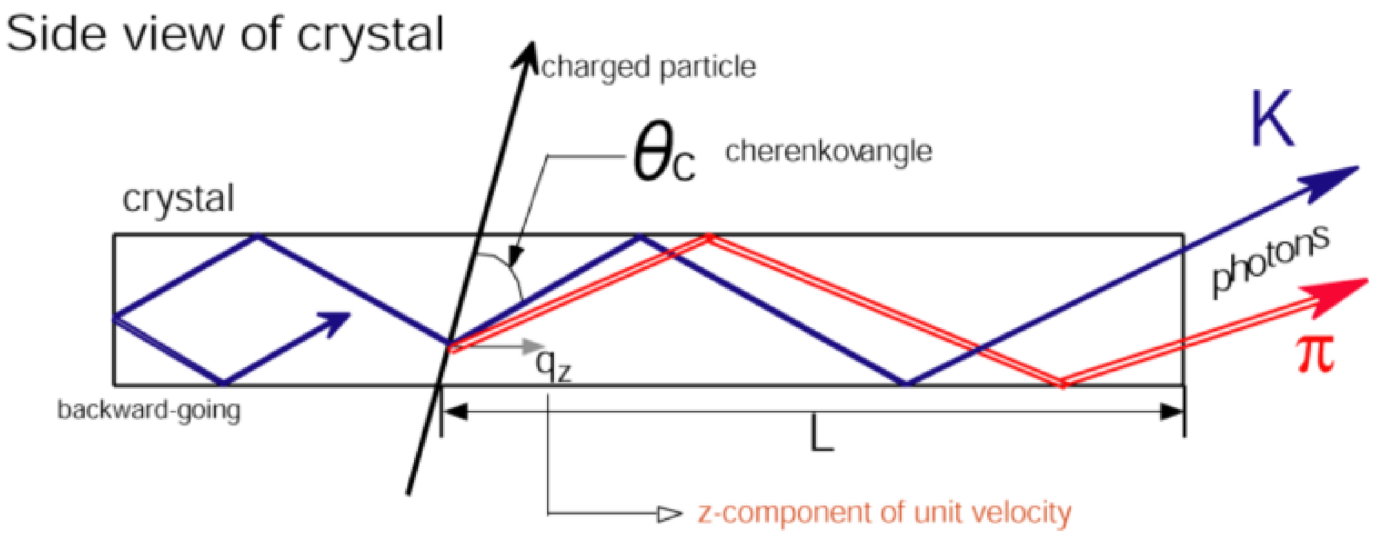
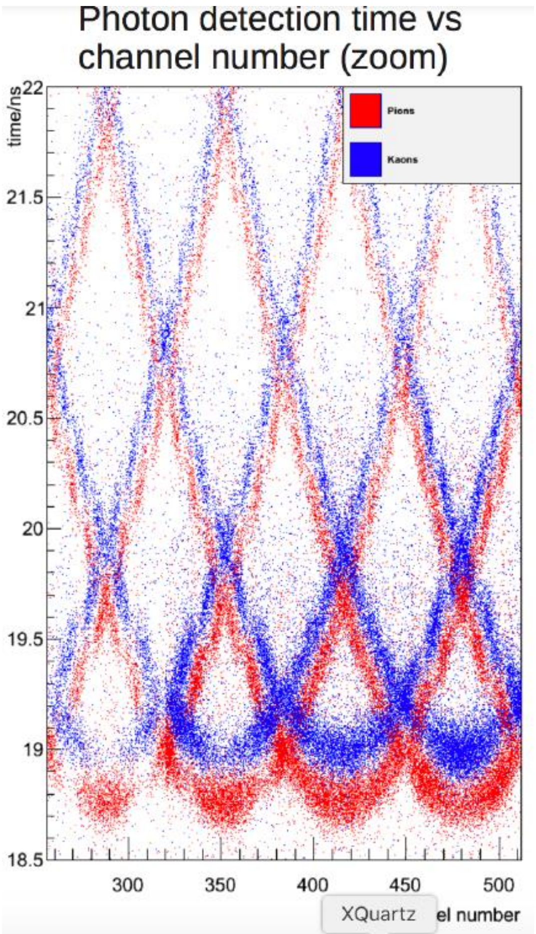
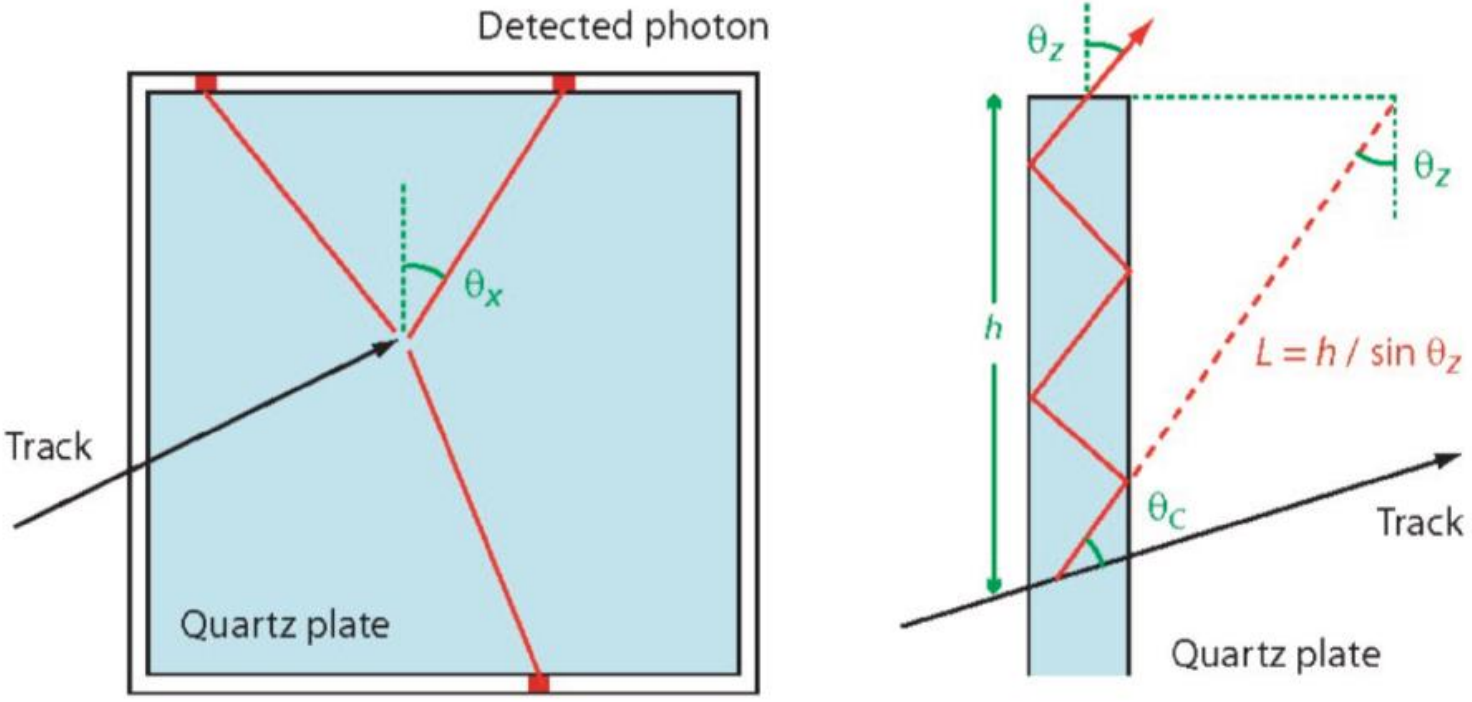




TIME OF FLIGHT

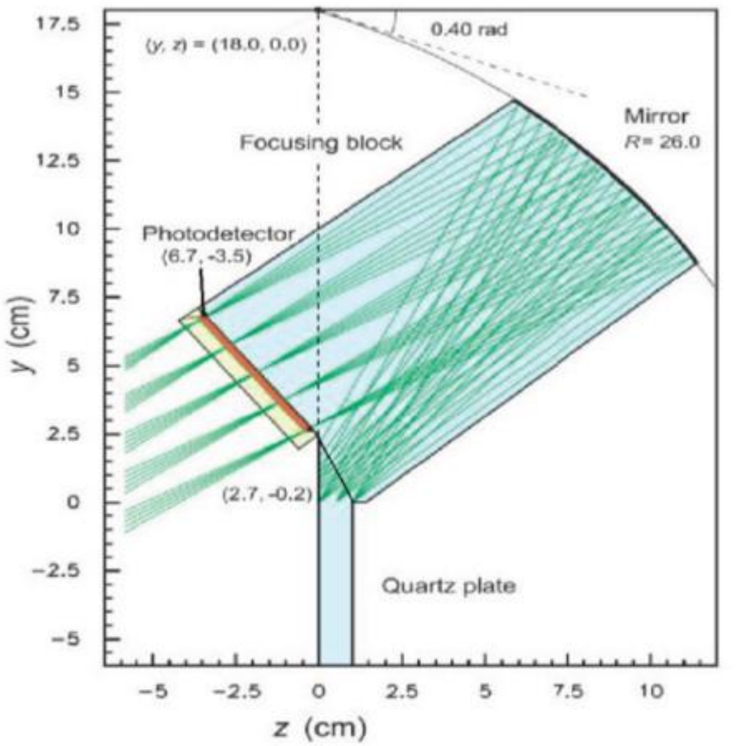
- Time Of internally Reflected Cherenkov light - TORCH

Front and side views of radiator plate



(schematic)

Focusing at edge of plate



Roger Forty

TORCH: a novel concept for PID

TIME OF FLIGHT

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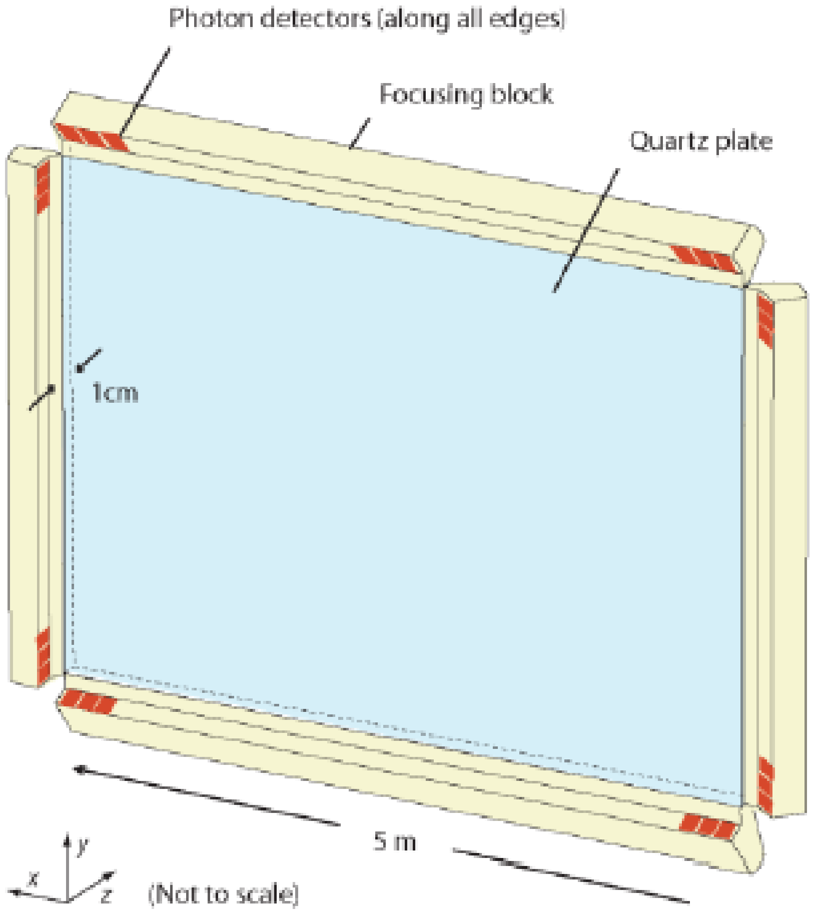
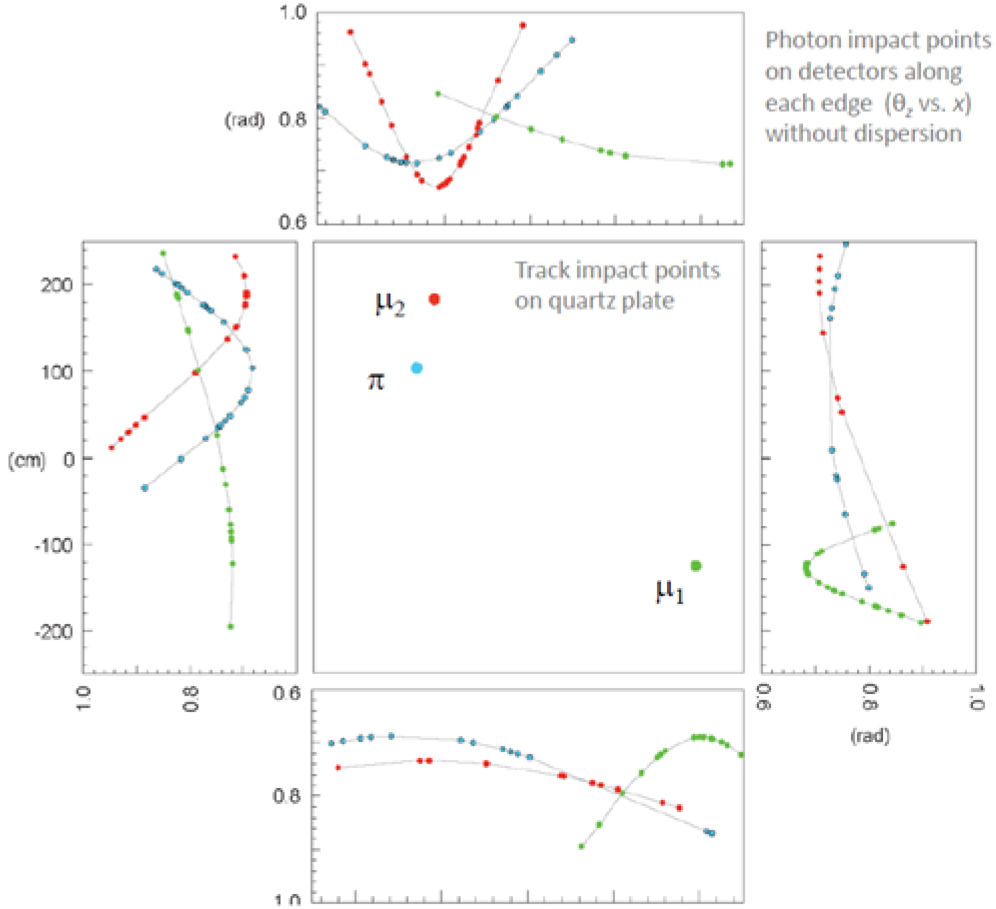
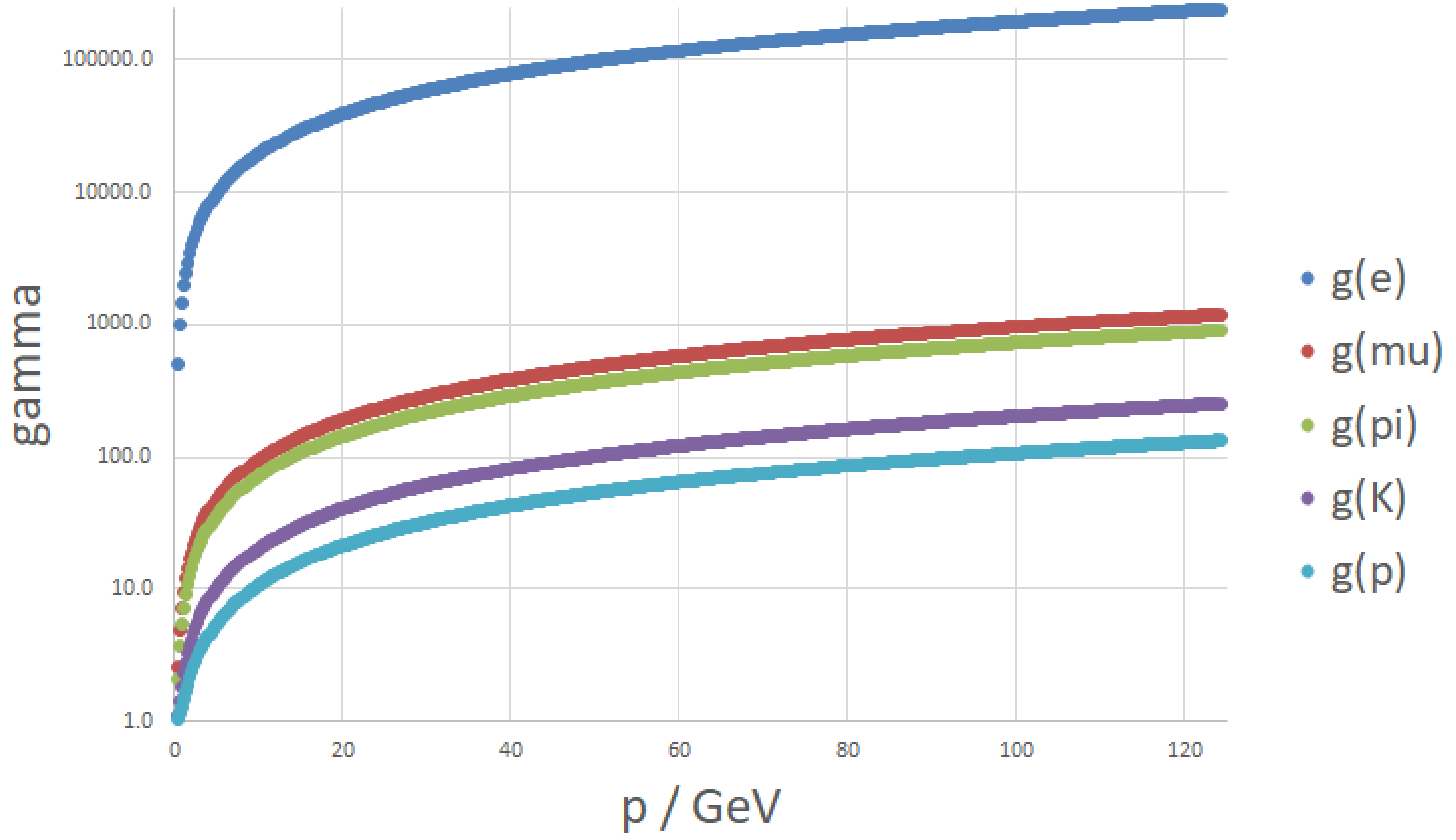


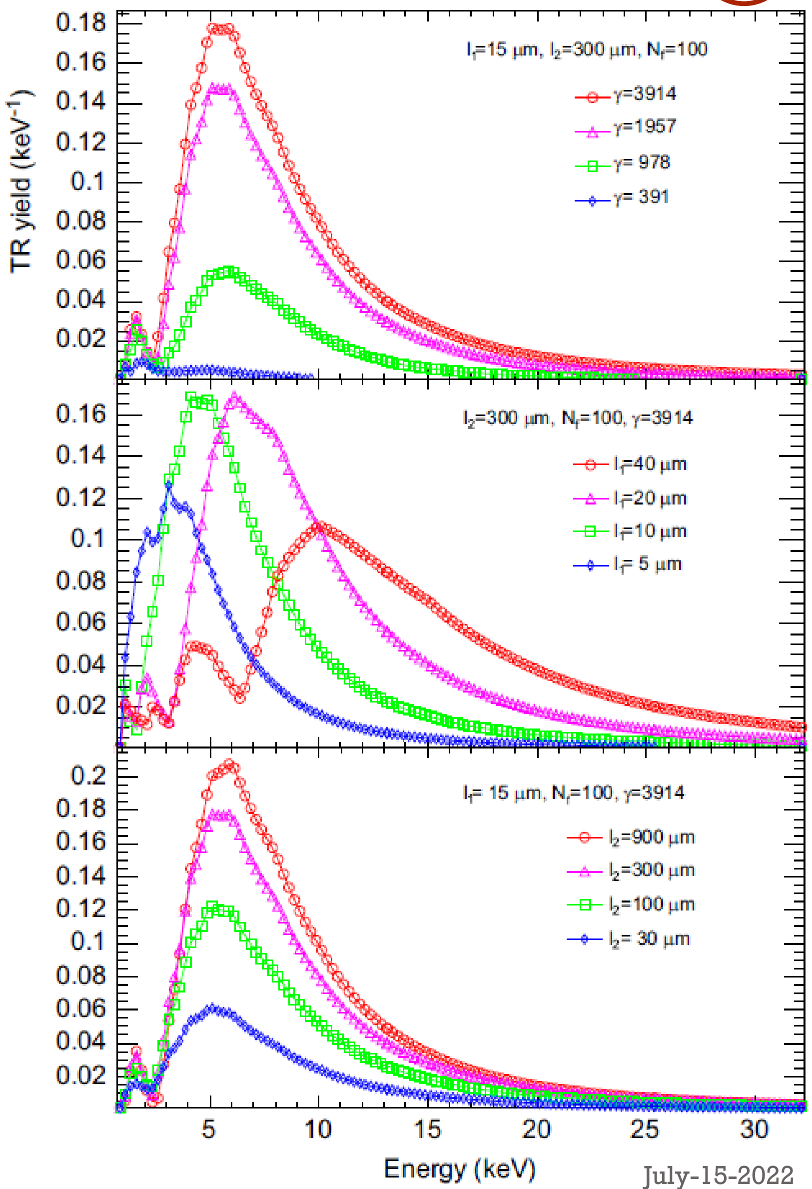


TRANSITION RADIATION

- Transition Radiation – TR
  - Basically eID → γ = Lorentz Factor

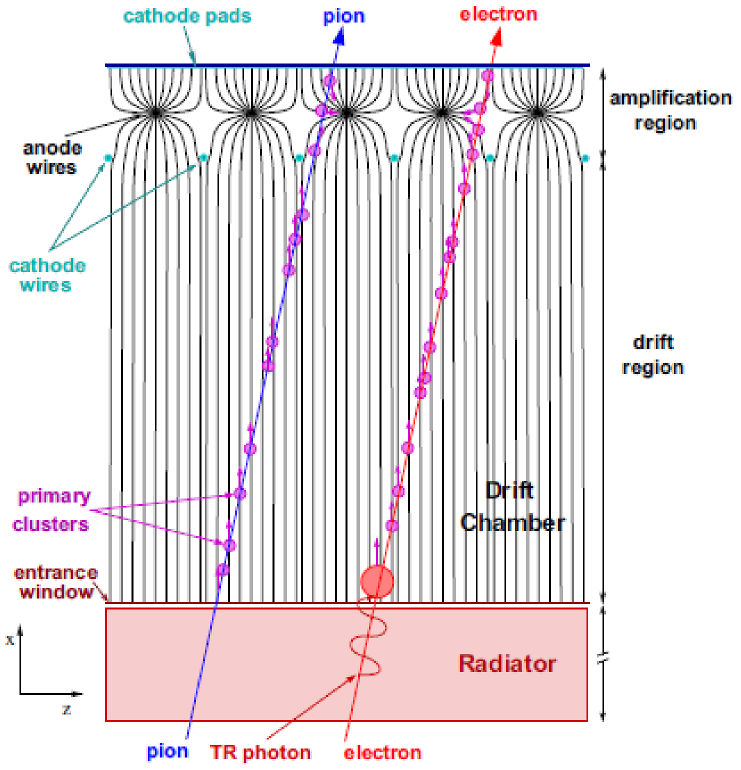
$$I = \frac{(Ze)^2\gamma\omega_p}{3c}$$

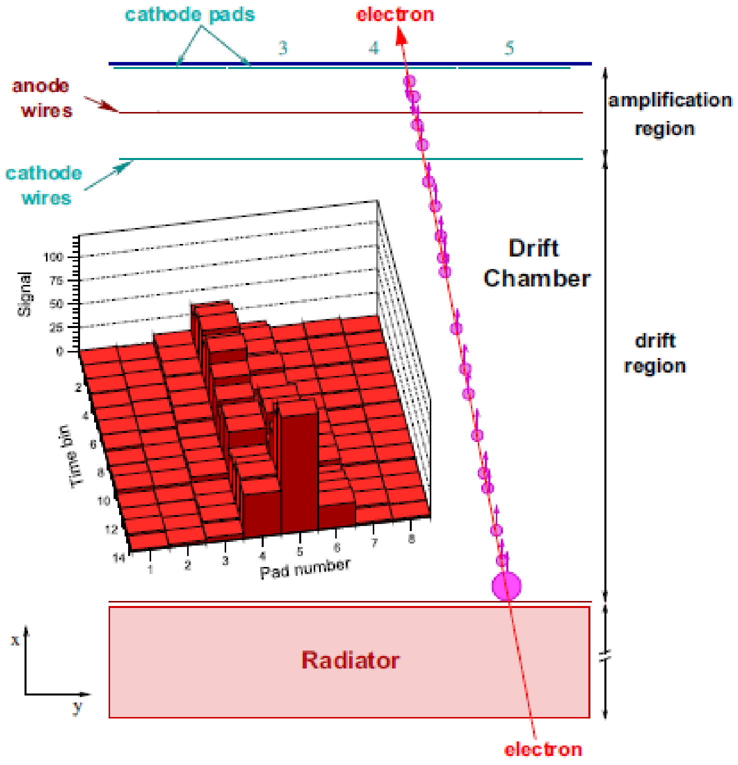


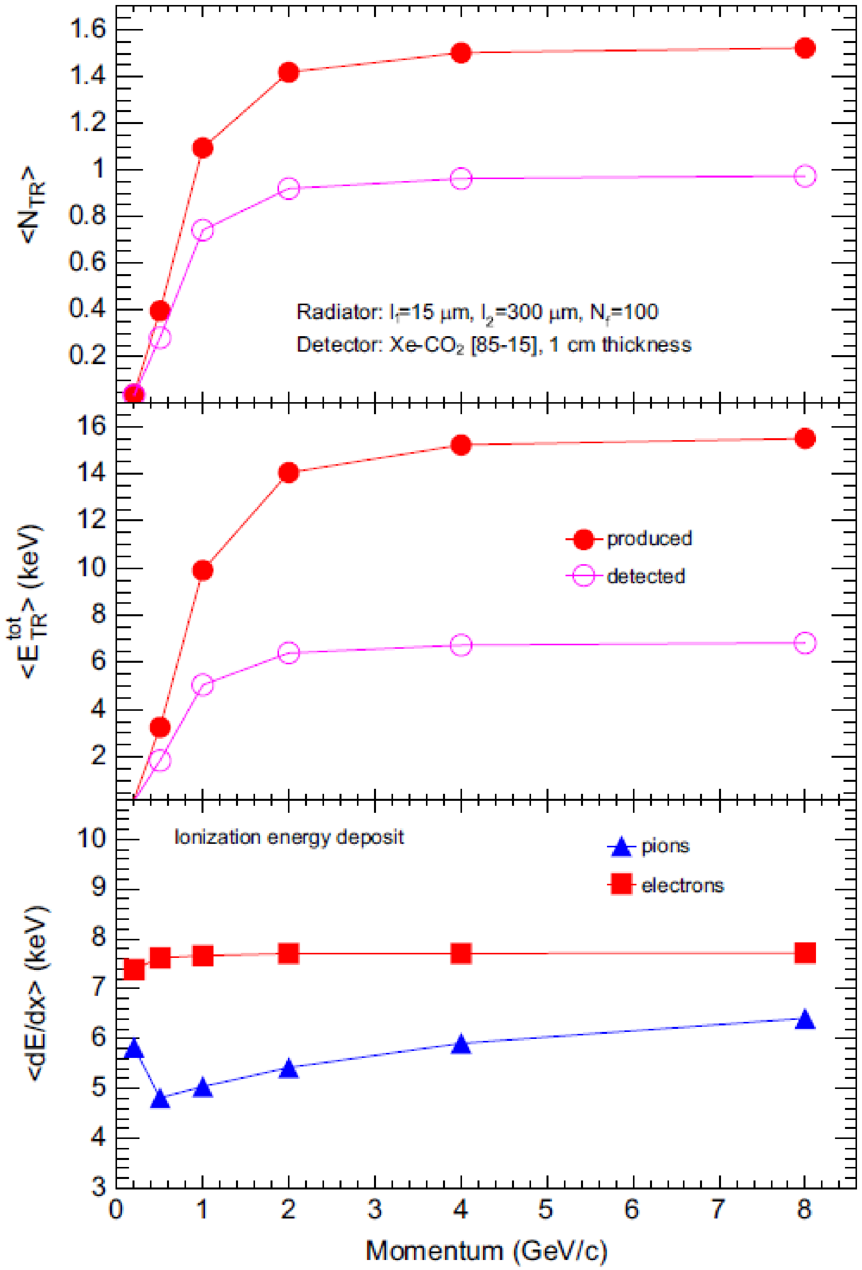


TRANSITION RADIATION

- Transition Radiation Detector – TRD







TRANSITION RADIATION

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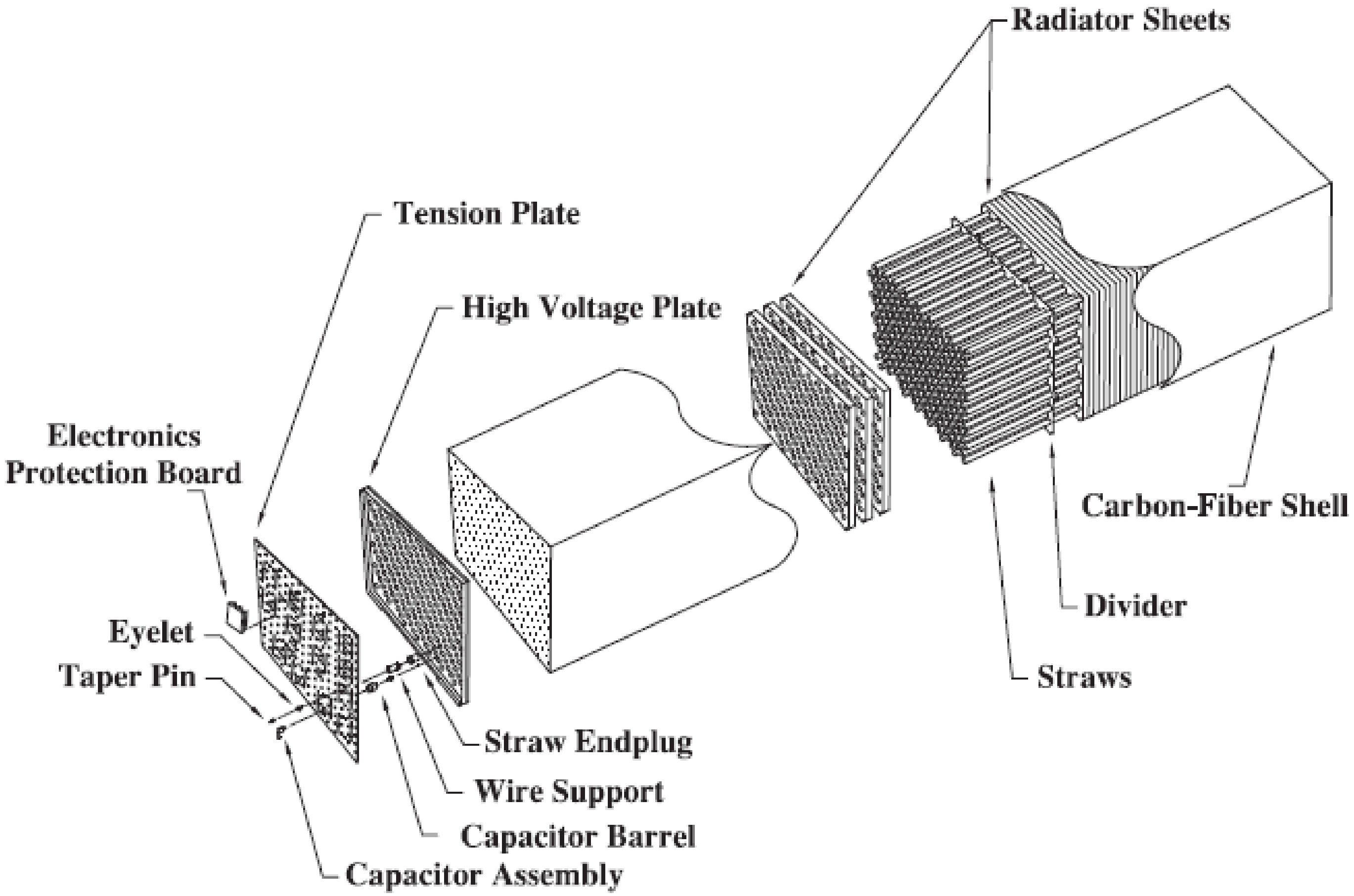
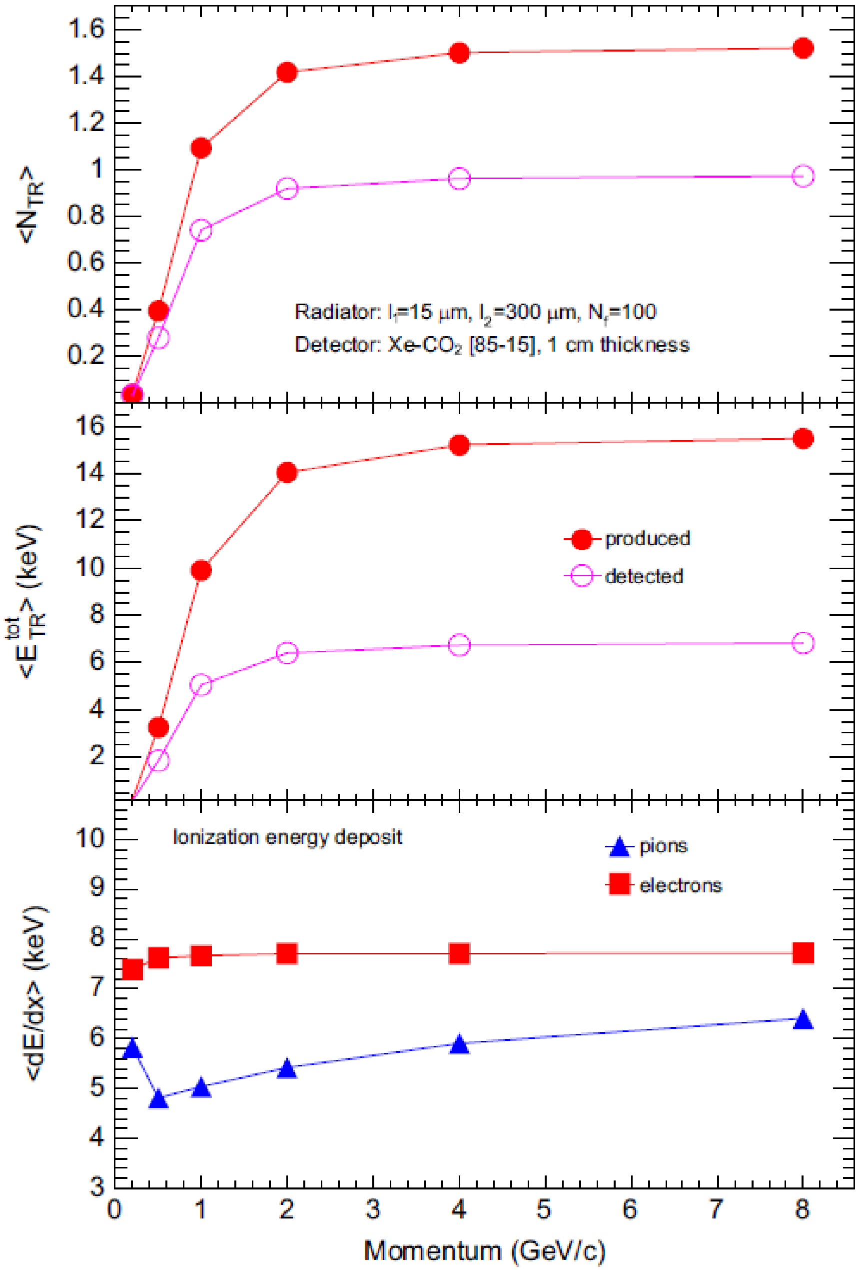




CHERENKOV RADIATION

- Photonic Boom
- O. Heaviside (1888) and A. Sommerfeld (1904) predicted luminescence from particles traveling faster than c_m
- M. Curie (1910) observed luminescence
- L. Mallet (1926) described luminous radiation of Ra irradiating H_2O
- P. Cherenkov (1934) observed luminescence
- I. Frank and I. Tamm (1937) developed theory behind Cherenkov's observation
- Cherenkov/Tamm/Frank → Nobel prize in 1958

CHERENKOV RADIATION

Total amount of energy radiated per unit length

$$\left(\frac{dE}{dx}\right)_{rad} = \frac{z^2e^2}{c^2}\int_{\varepsilon(\omega)>\frac{1}{\beta^2}} \omega\left(1-\frac{1}{\beta^2\varepsilon(\omega)}\right)d\omega$$

- Integration over frequencies ω for which $v_{part} > \frac{c}{n(\omega)}$
- Cherenkov radiation is continuous
- Cutoff frequency above which intensity cannot increase $\rightarrow n = n(\omega)$ and out-of-phase relation of driving and radiated em-waves

Photon flux:

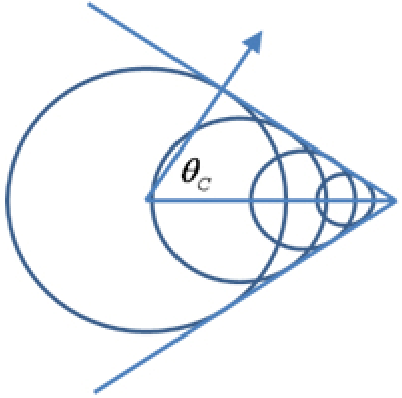
$$\frac{dN}{dx} = 2\pi\alpha\left(1-\frac{1}{(\beta n)^2}\right)\int_{\lambda_1}^{\lambda_2}\frac{1}{\lambda^2}d\lambda = 2\pi\alpha\sin^2\theta\int_{\lambda_1}^{\lambda_2}\frac{1}{\lambda^2}d\lambda$$

This yields

$$\frac{dN}{dx} = 2\pi\alpha\sin^2\theta\frac{1}{\lambda_1} \text{ for } \lambda_2 \rightarrow \infty$$

CHERENKOV RADIATION

- Application of Cherenkov Radiation – CR
  - Threshold counters → HBD
  - Imaging Cherenkov detectors → measure velocity with RICH - DIRC



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

  - Differential counters → restricted narrow interval of velocities

CHERENKOV RADIATION

- Hadron Blind Detector – HBD
  - Highly sensitive to electrons
  - Mostly insensitive to hadrons → high γ needed
- Principle
  - Use radiator that has high momentum reach,
    e.g., gas with small index of refraction n
  - Provide a photocathode for the Cherenkov photons
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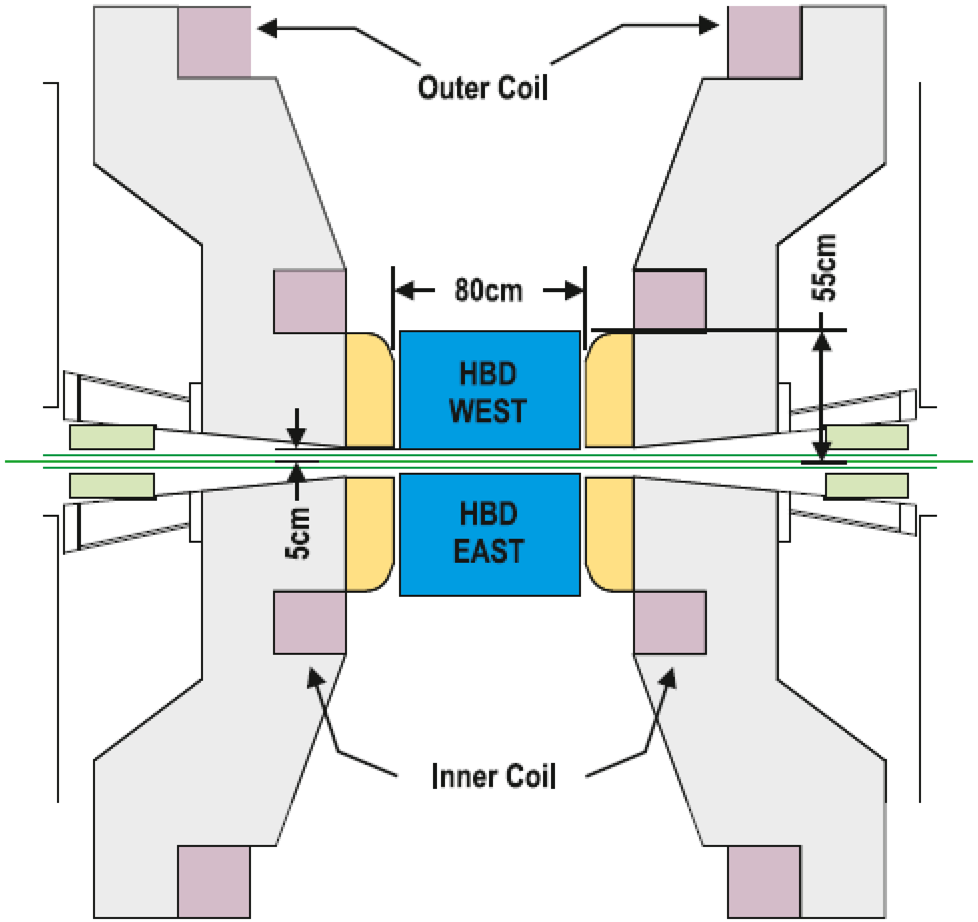
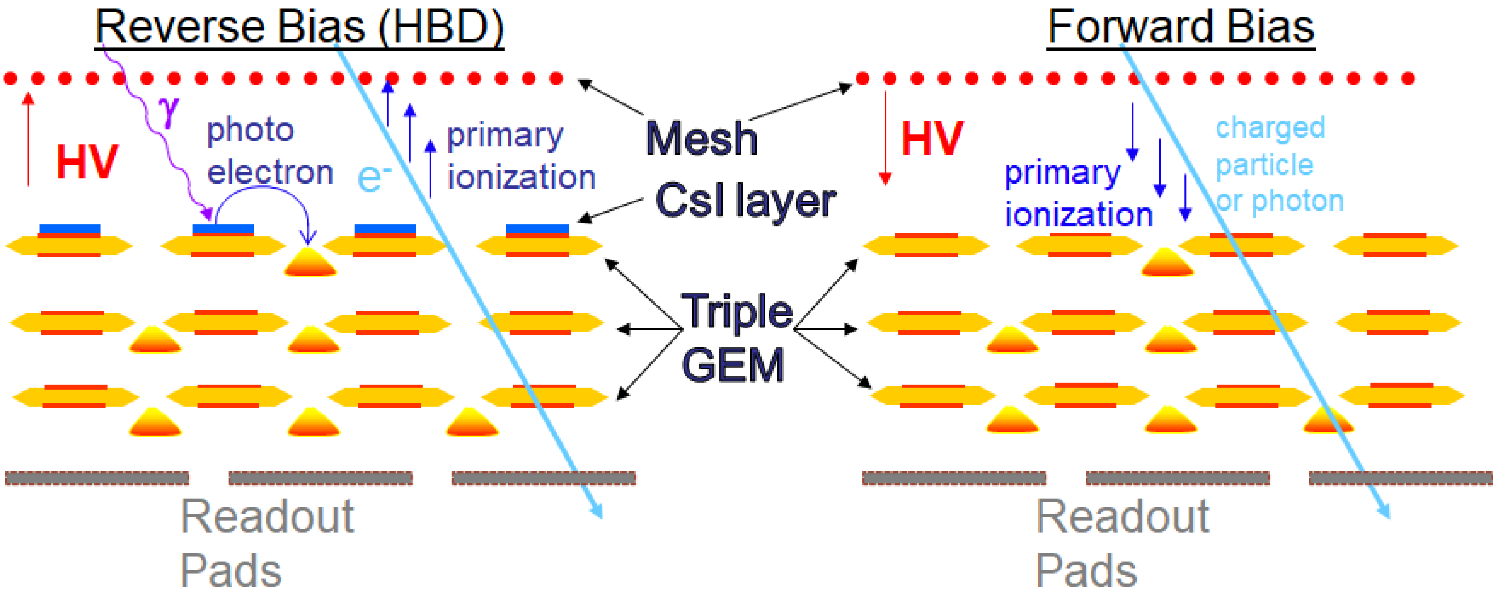
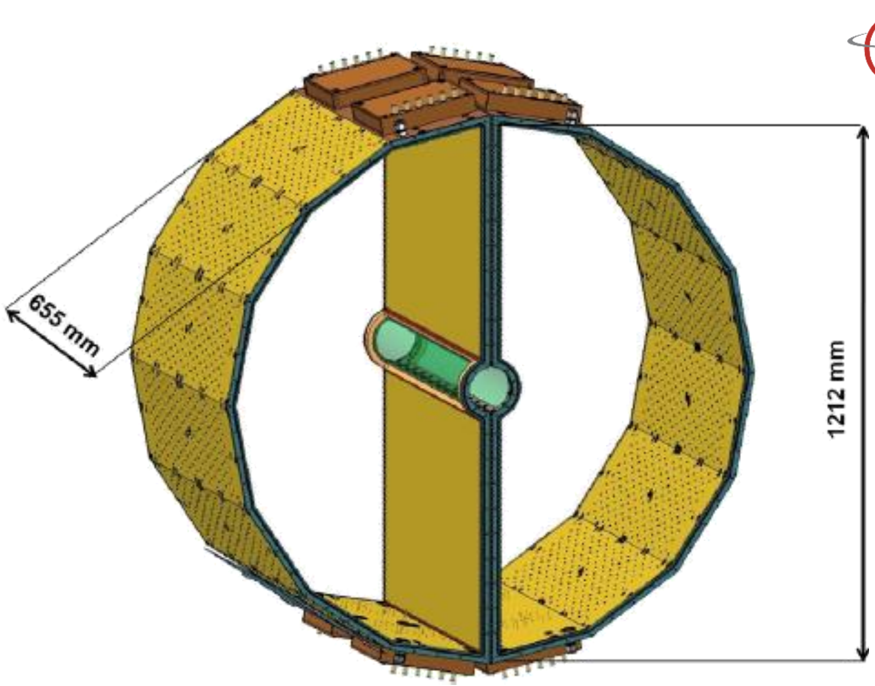
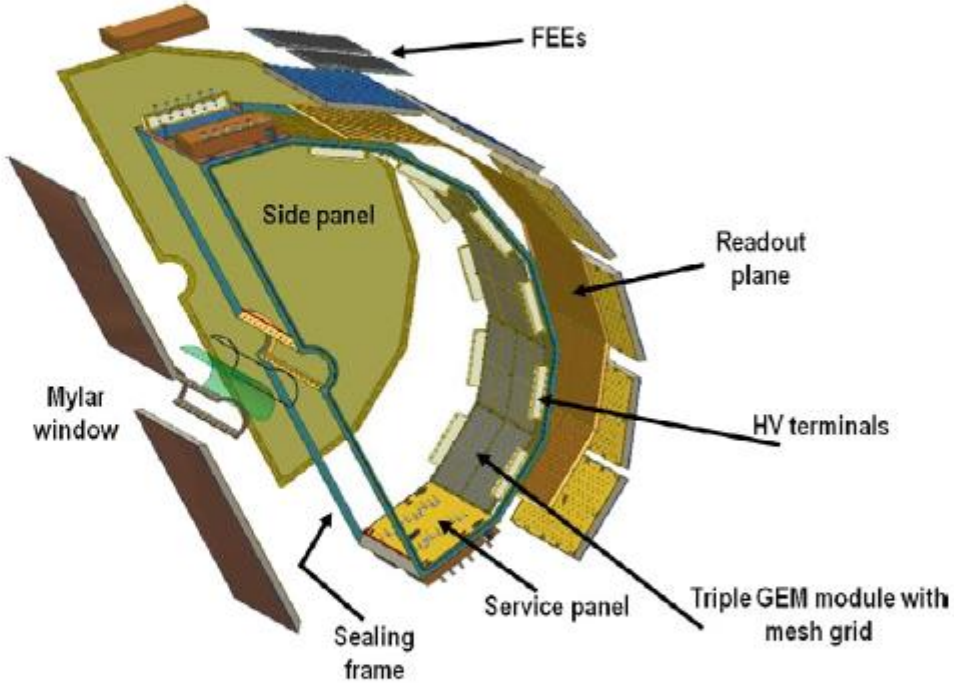


CHERENKOV RADIATION

- Hadron Blind Detector – HBD in PHENIX

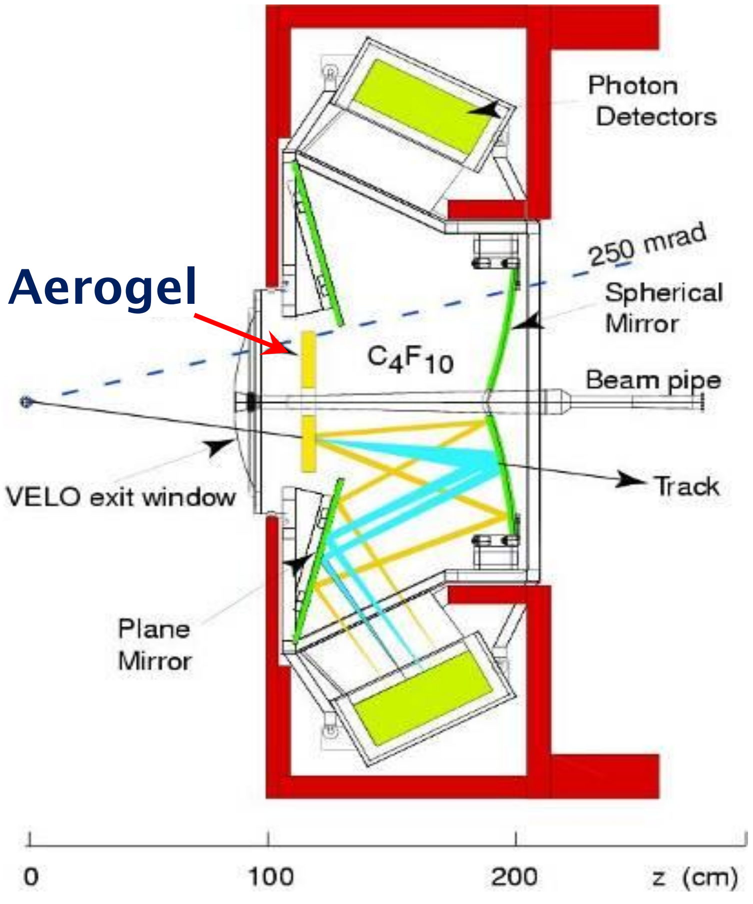


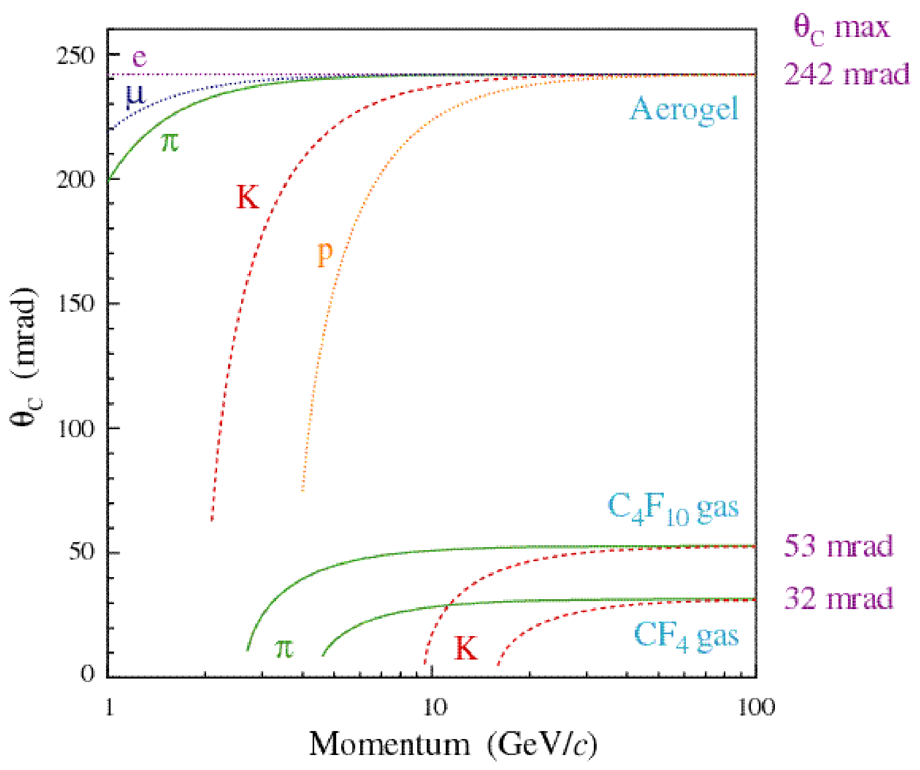




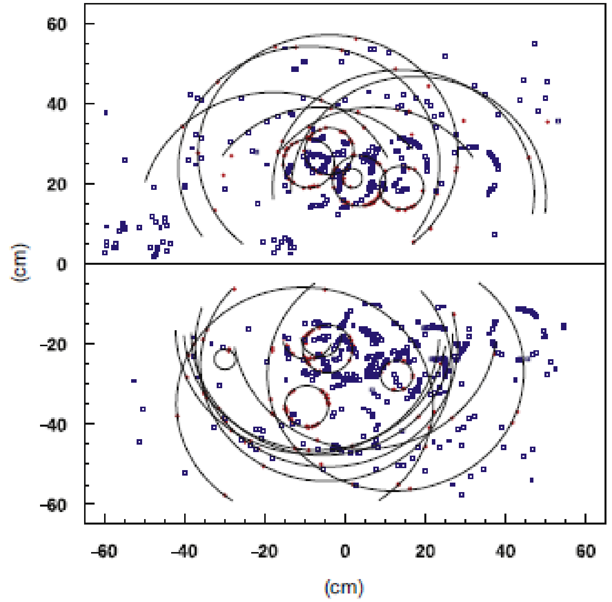
CHERENKOV RADIATION

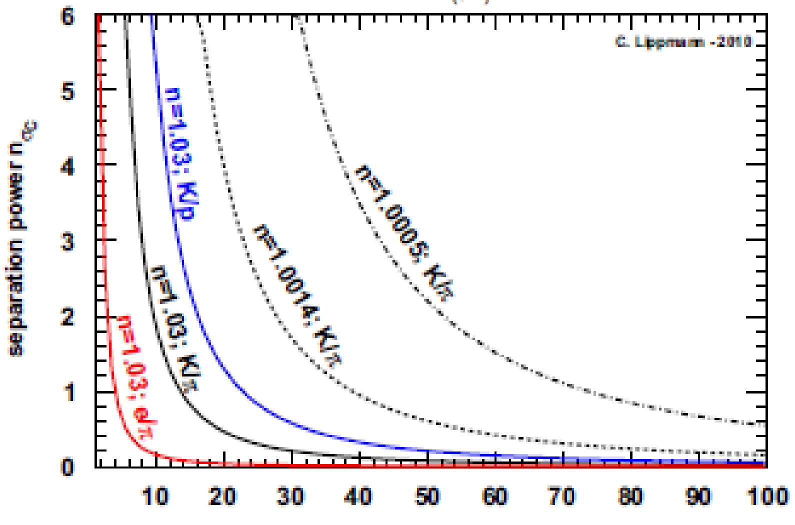
- Ring Imaging Cherenkov counter – RICH @ LHCb





n=1.03, 1.0014, 1.0005

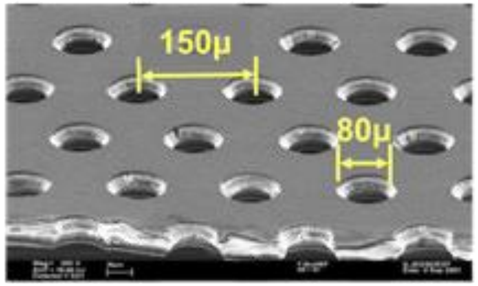




CHERENKOV RADIATION

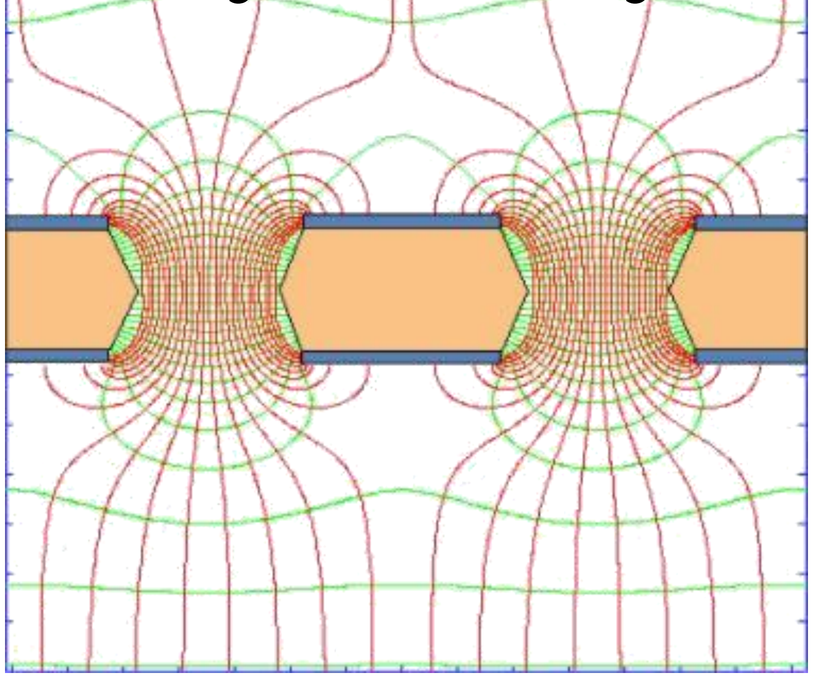
- Ring Imaging Cherenkov counter – RICH @ SBU

Standard GEM



- Challenge 1
  - Hadron ID (π/K/p) @ high lab momenta → CR w/ gas
  - N_γ small in gas → long radiator required
  - Solution: make use of $dN/d\lambda \sim 1/\lambda^2$
    - CsI photocathode sensitive well into VUV (λ<200nm)
    - Very inexpensive per unit area
  - Challenge 2
    - Make use of VUV photons → avoid absorption

Making a GEM Detect Light



CHERENKOV RADIATION

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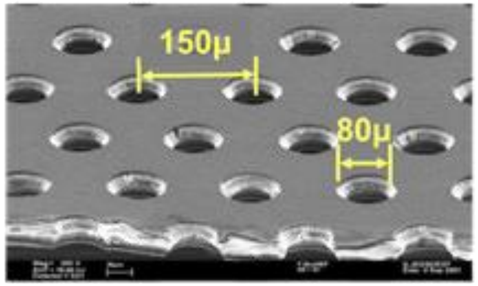

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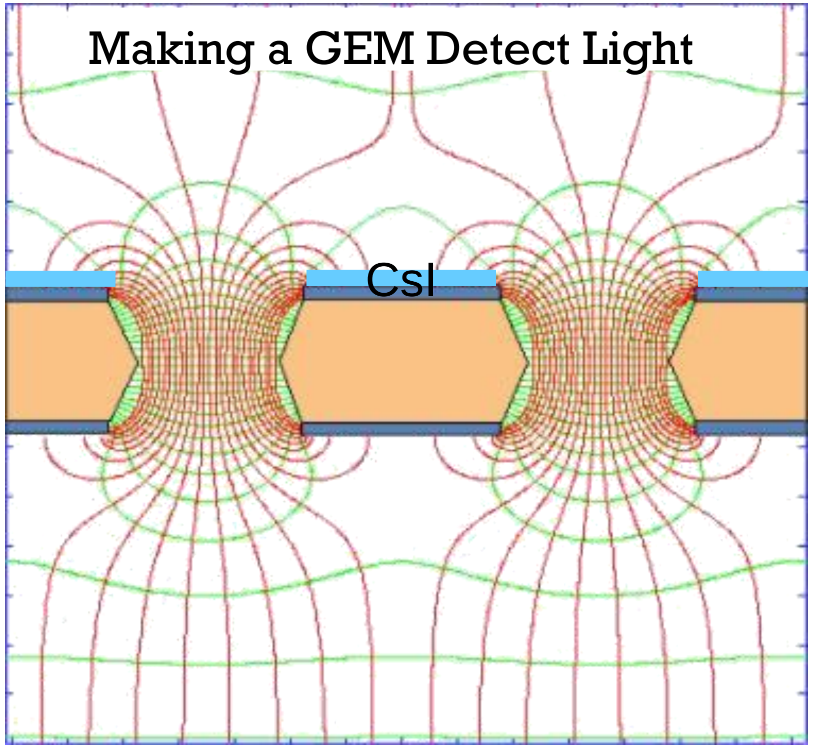

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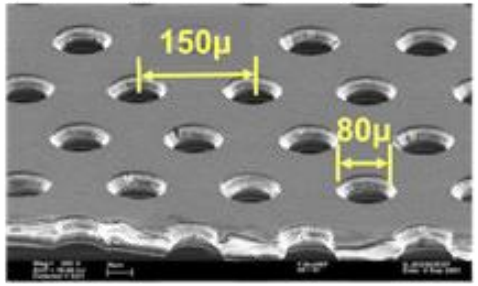

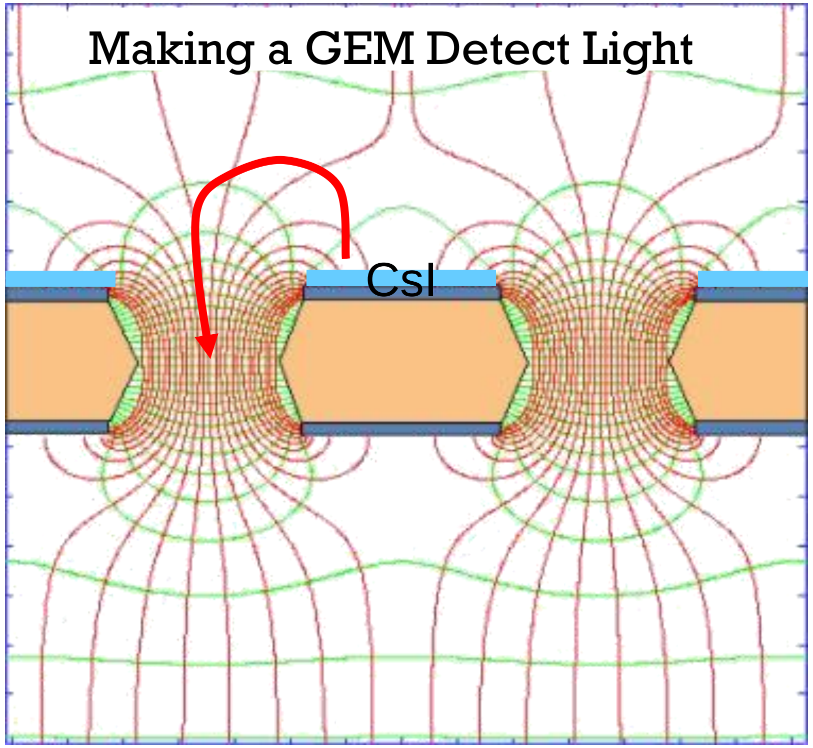

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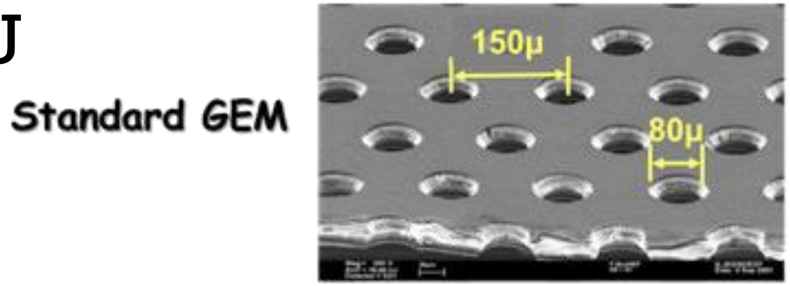
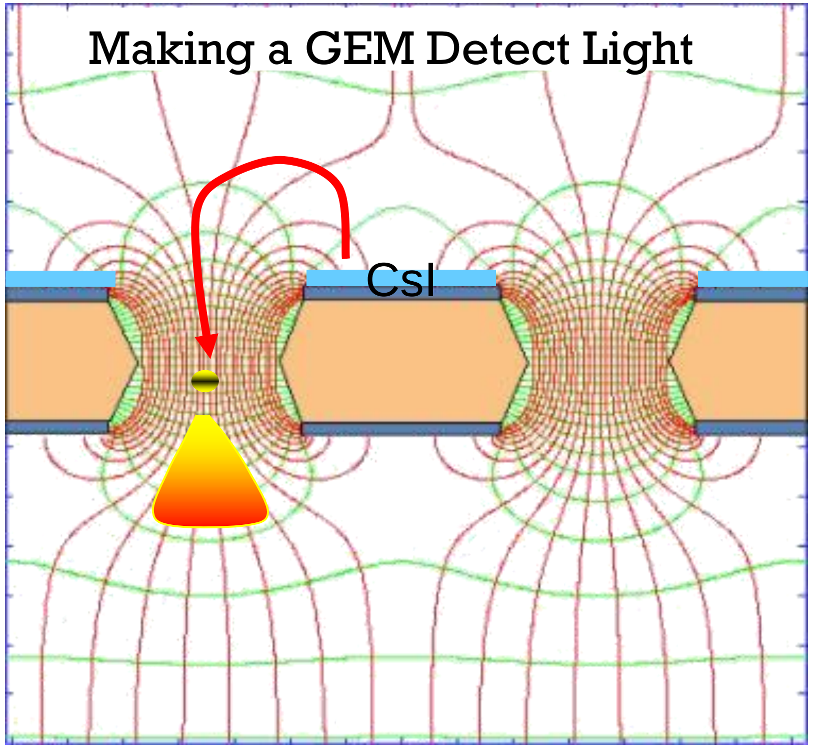
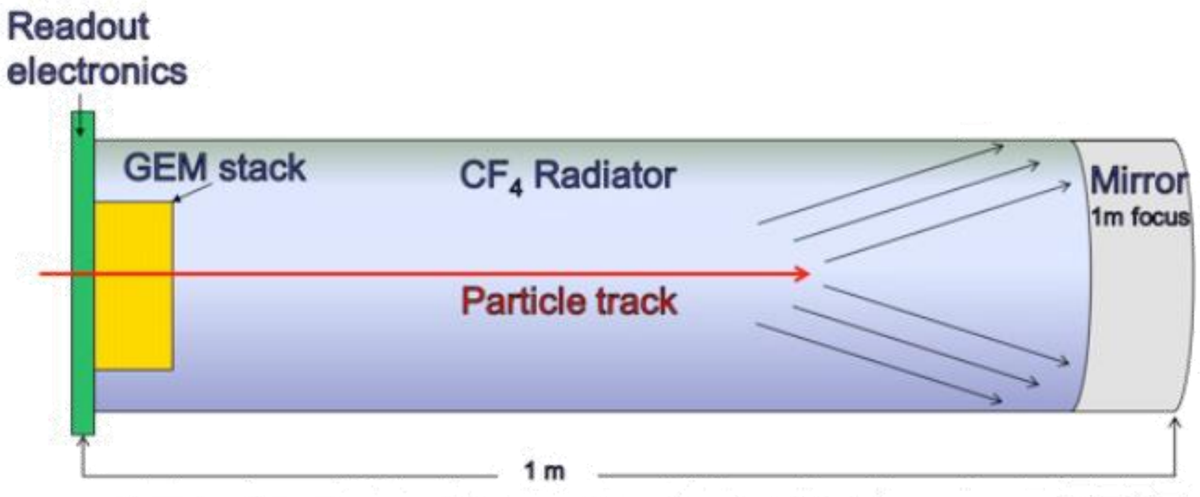


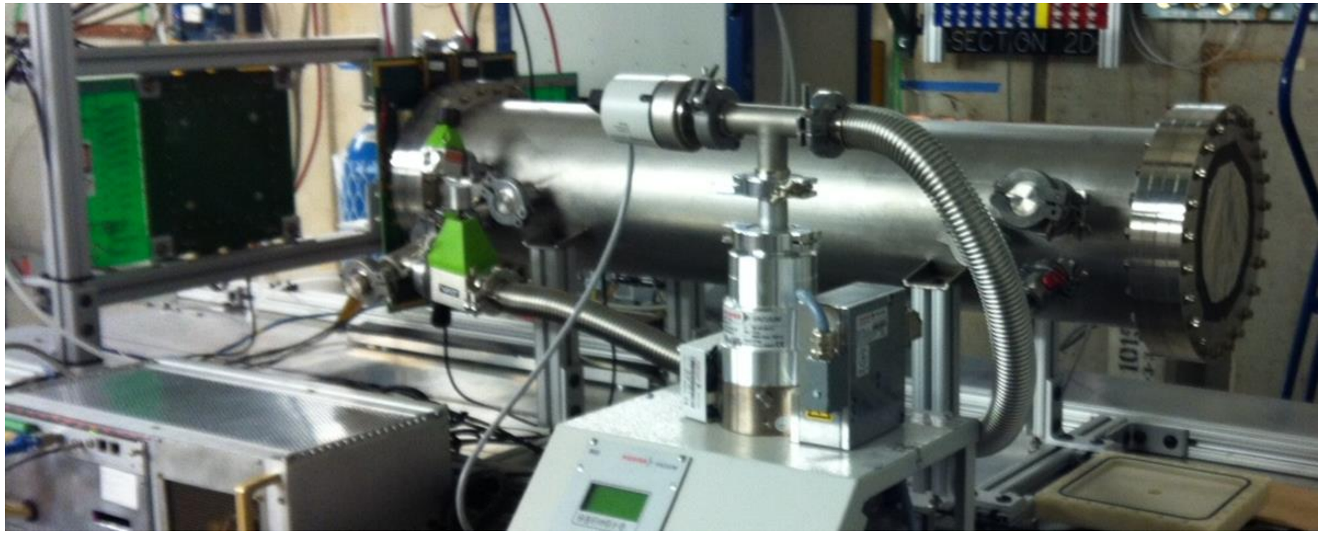


CHERENKOV RADIATION

- Ring Imaging Cherenkov counter – RICH @ SBU
  - Prototype – tested @ SLAC and FermiLab

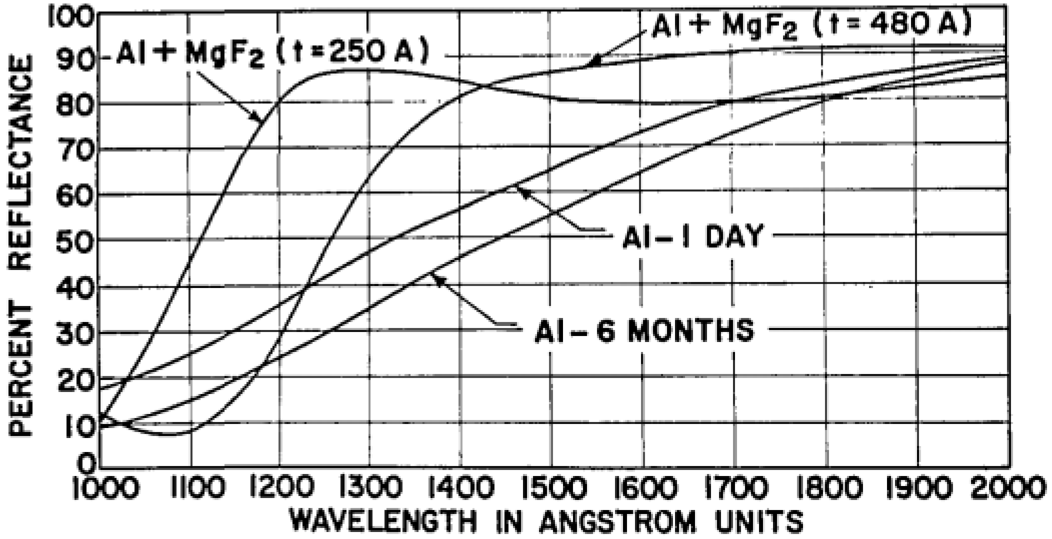
O_2 1.66ppm
H_2O 0.08ppm



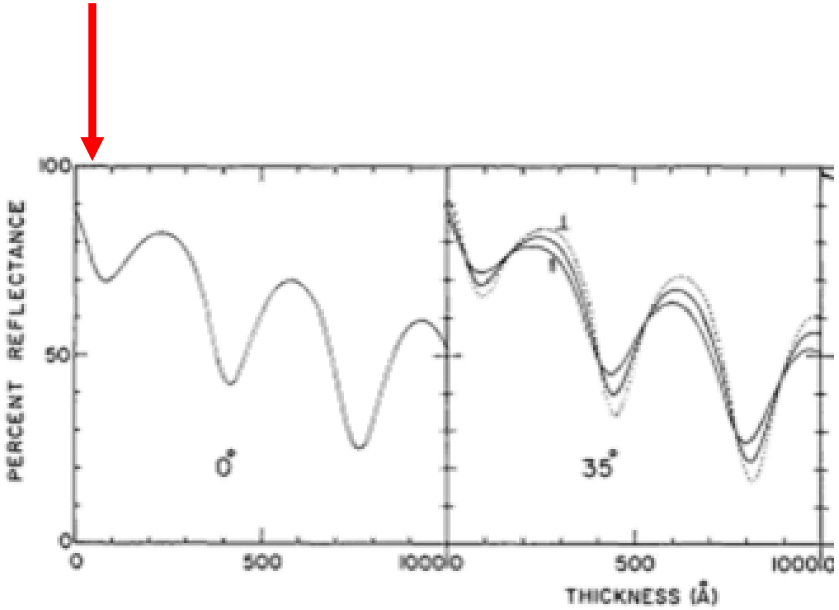


CHERENKOV RADIATION

- Ring Imaging Cherenkov counter – RICH @ SBU
  - Require mirror reflectance deep in the VUV
  - Ordinary MgF_2 cutoff λ<140nm
  - Overcoat thickness = thin film reflection max!
  - Test Beam: Acton Optics – Future: make our own



Interference Maximum



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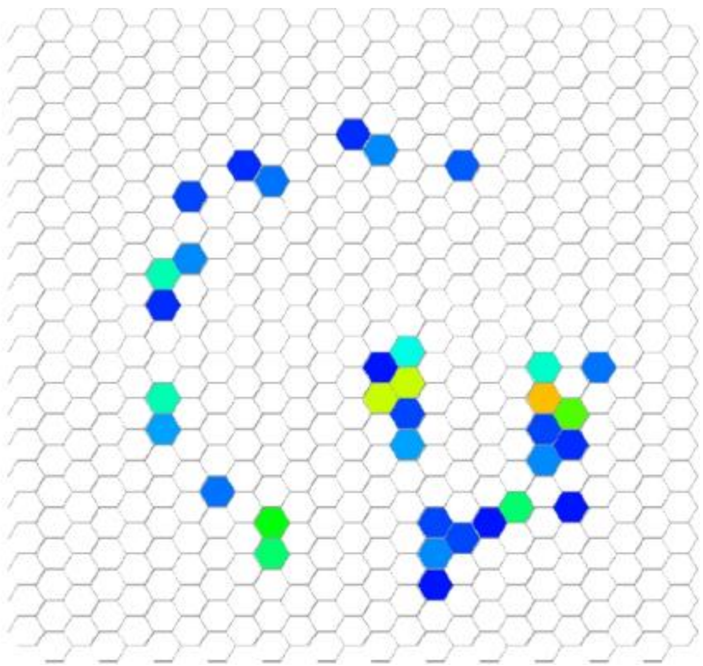

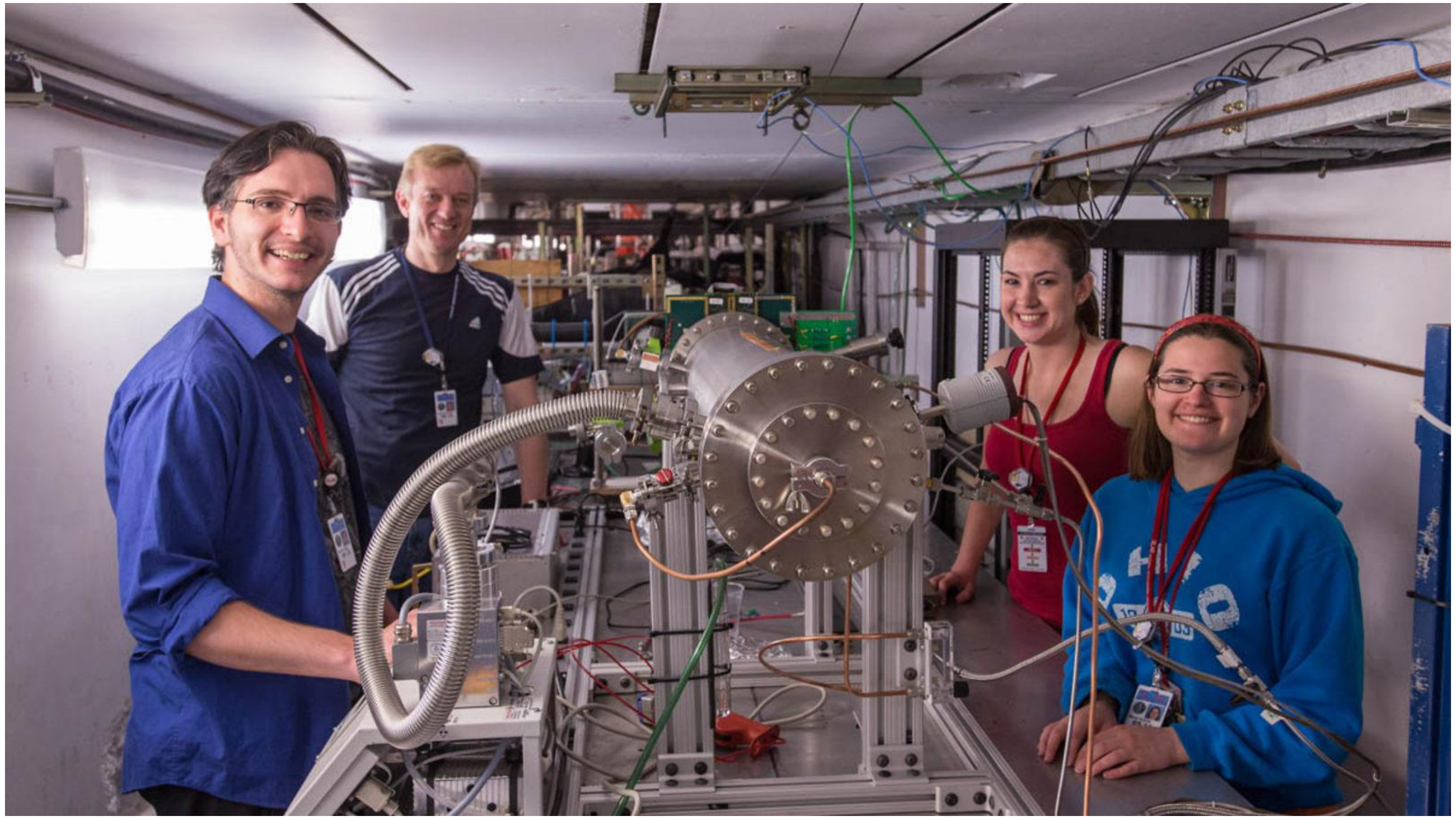

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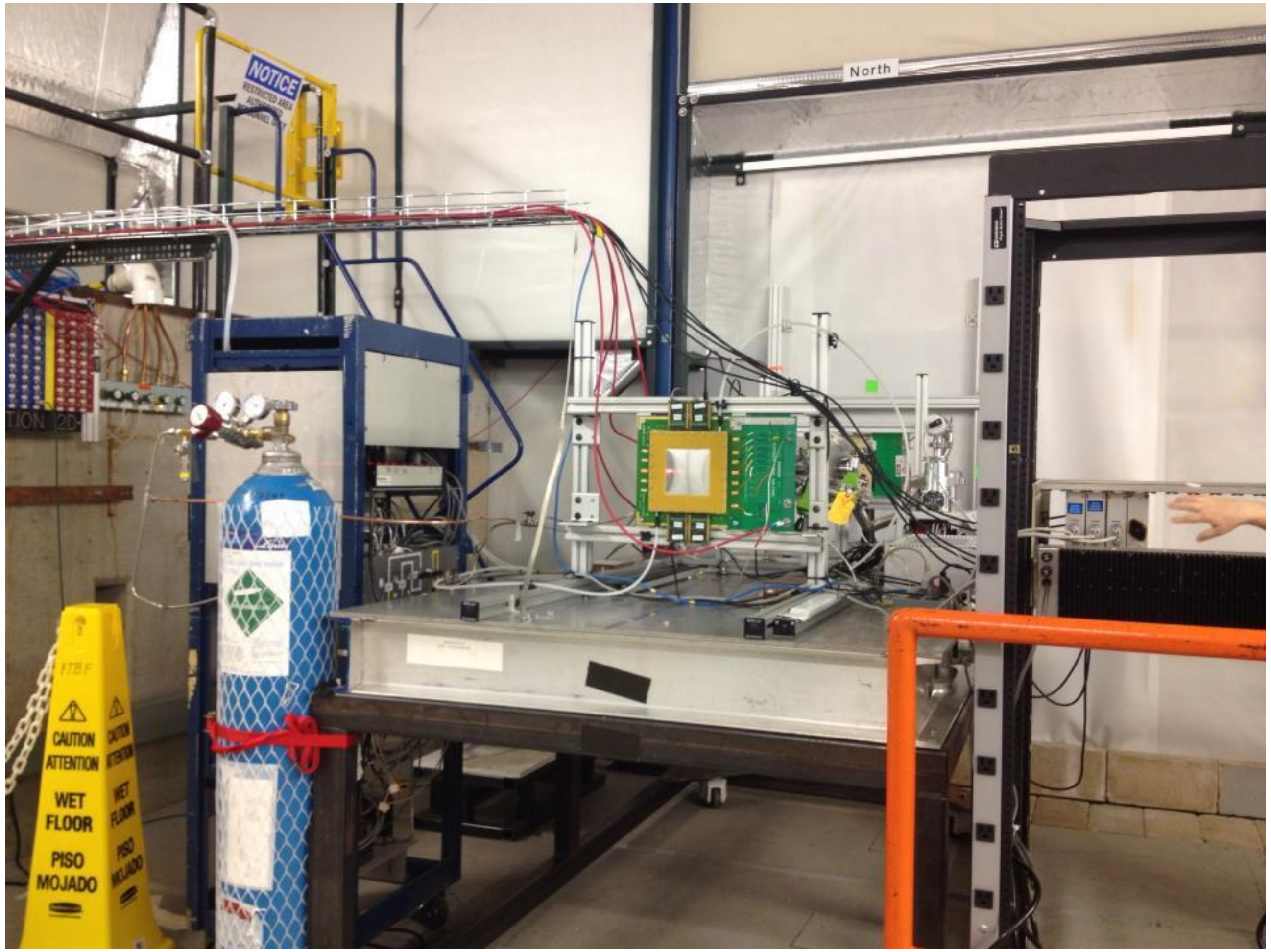

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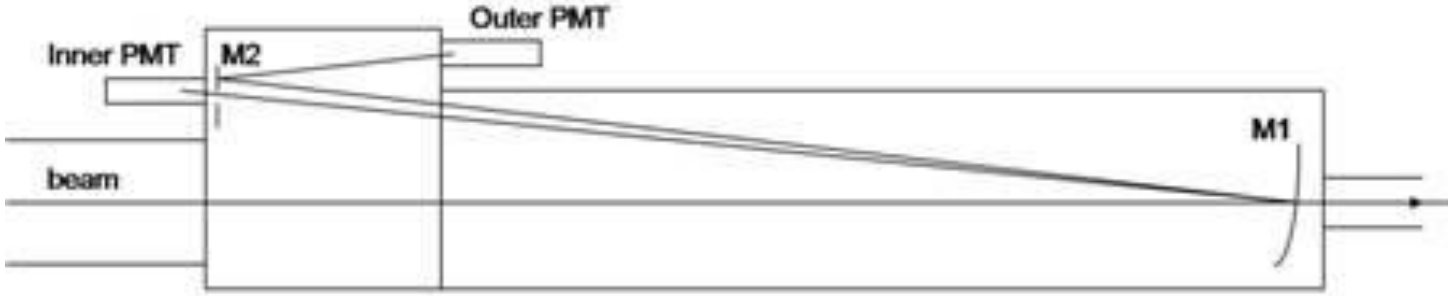

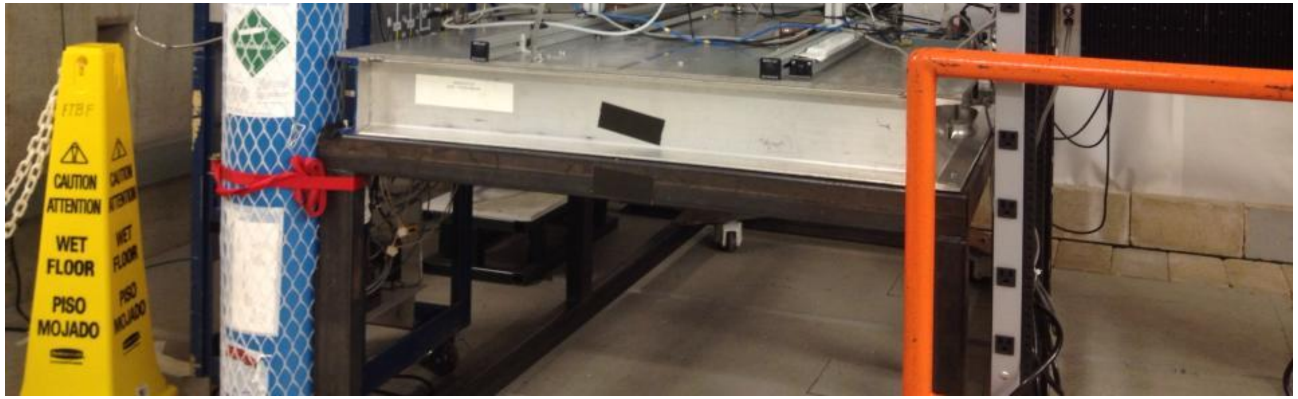

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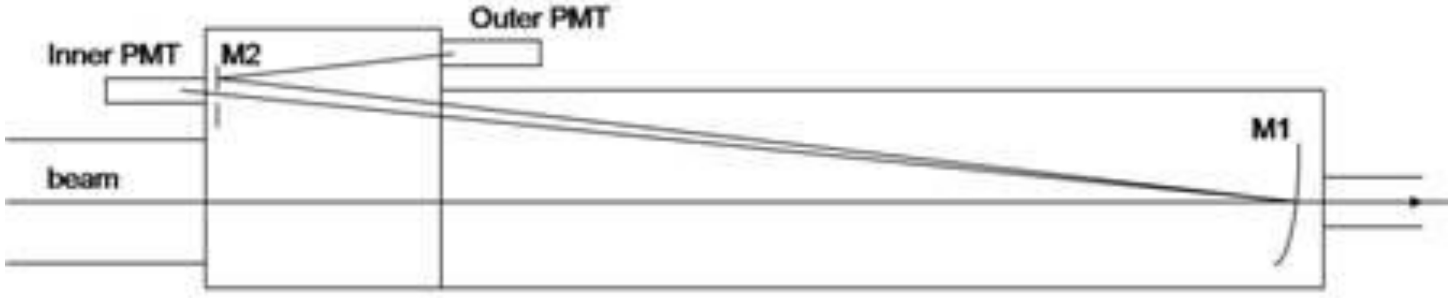
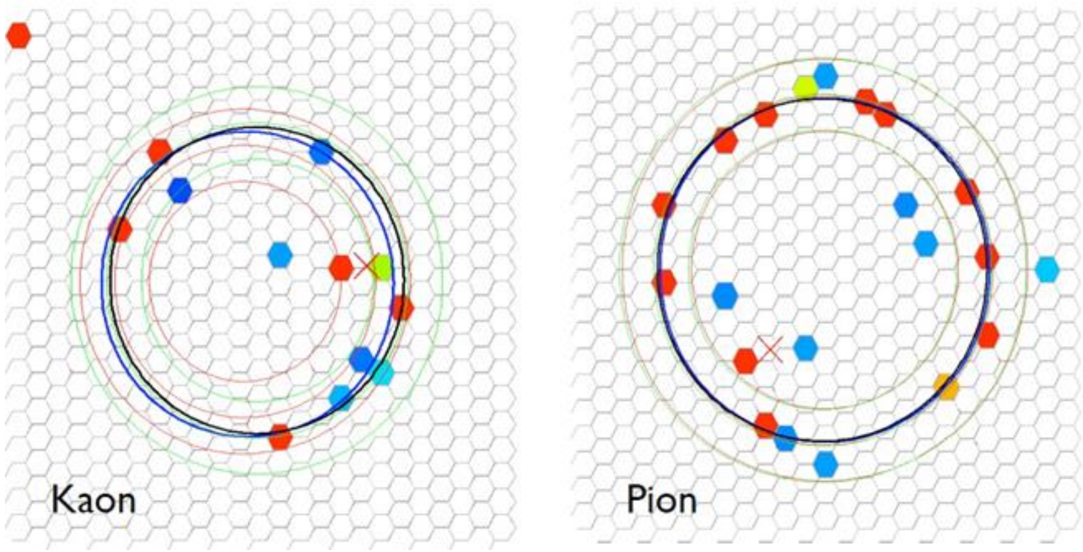
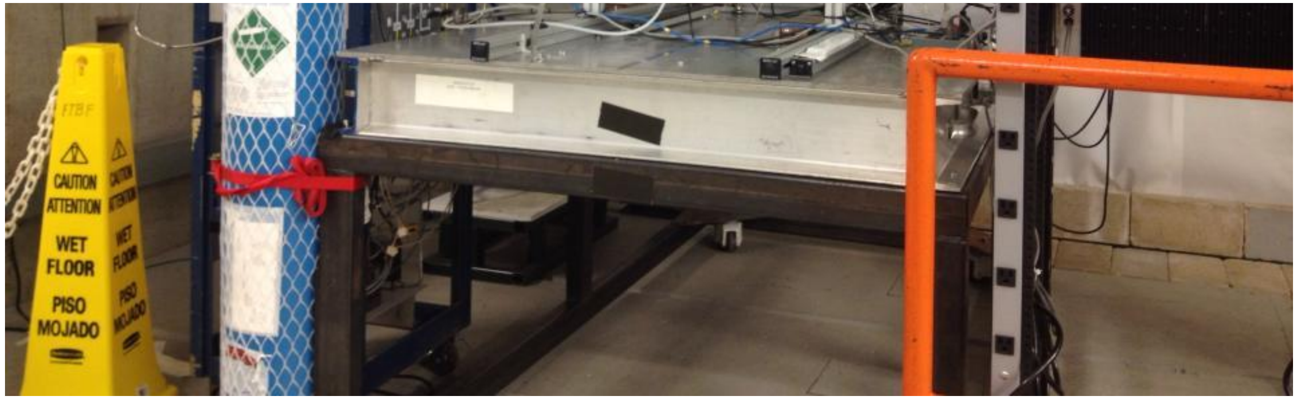


32 GeV Beam Momentum





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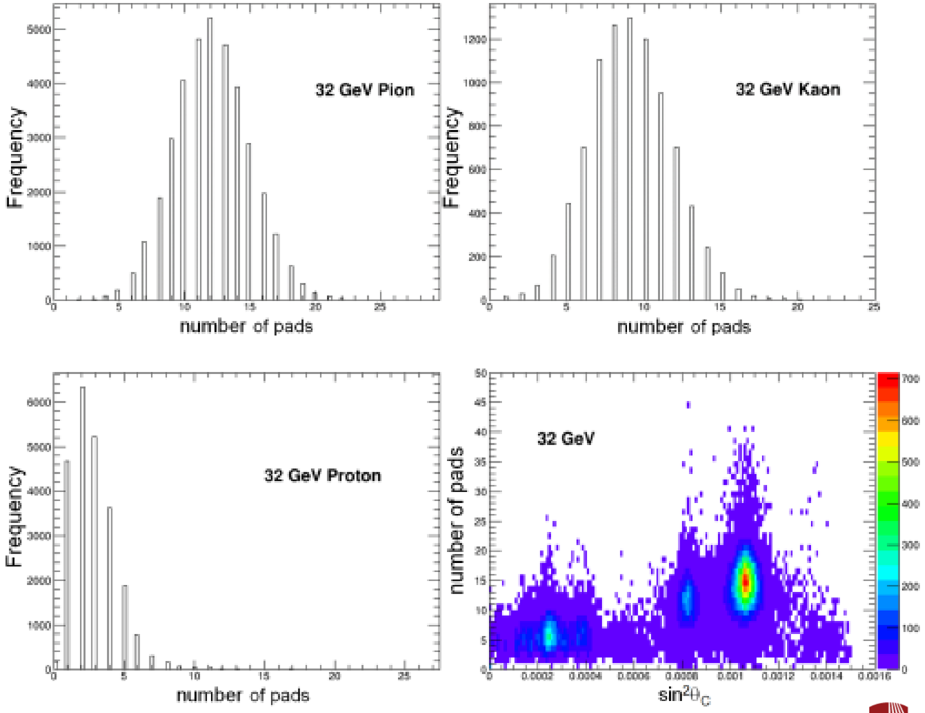
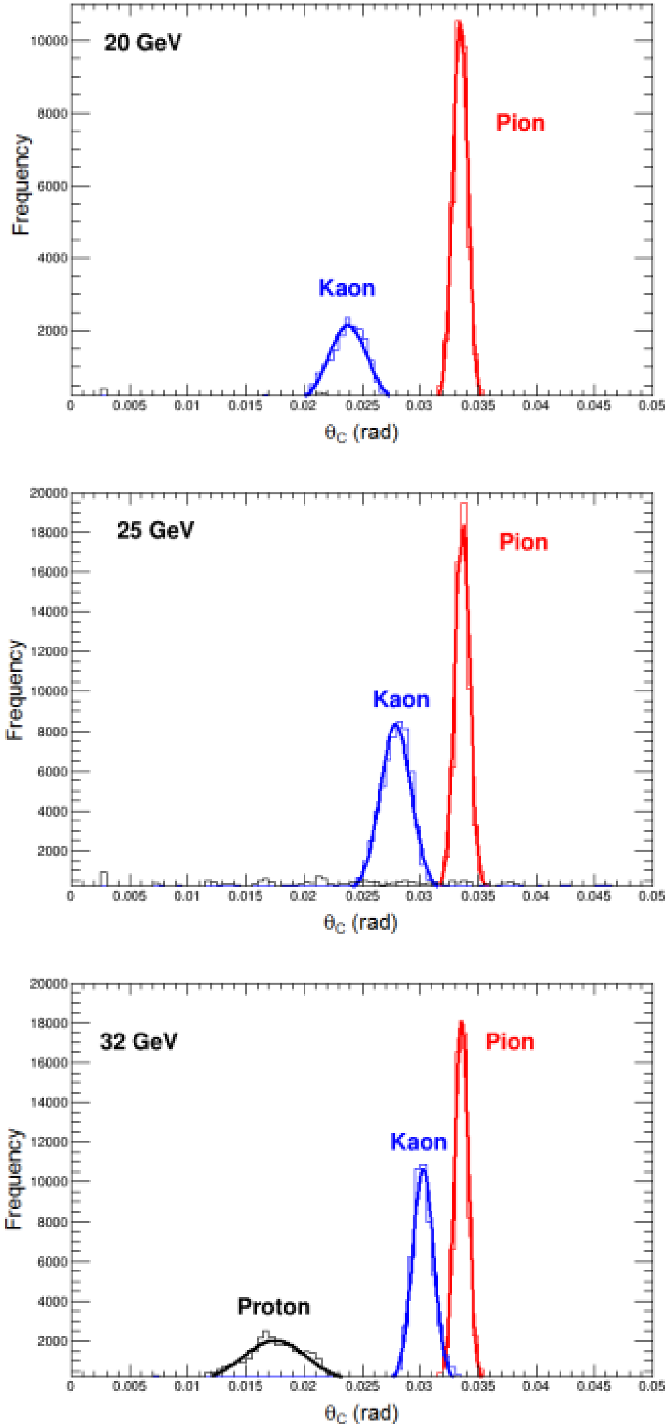
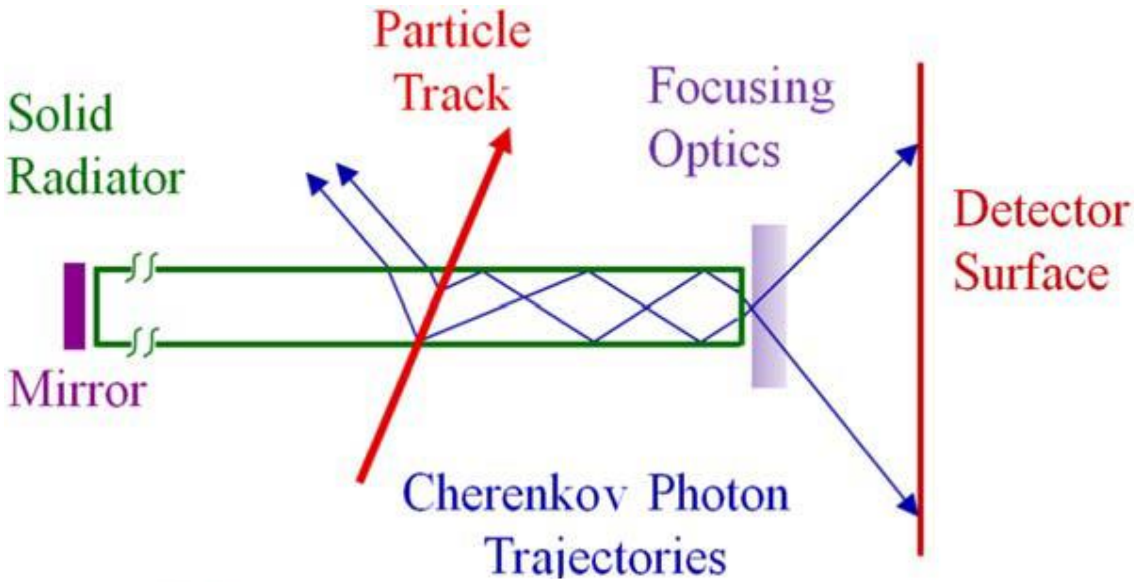
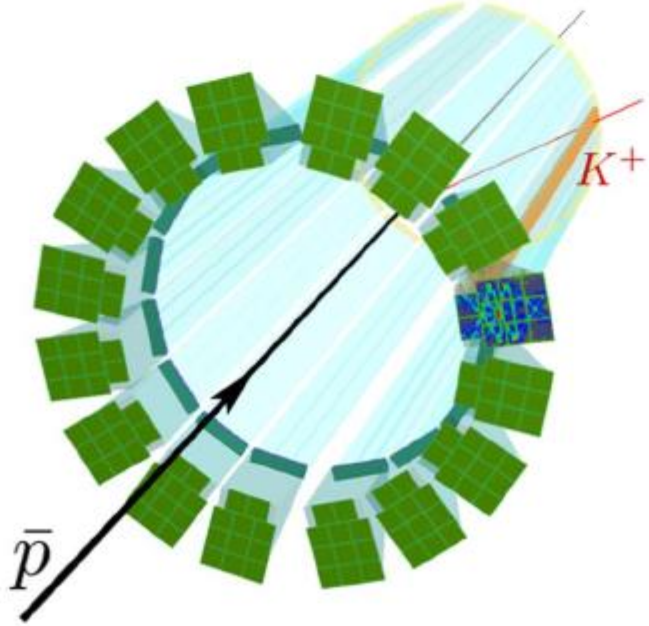


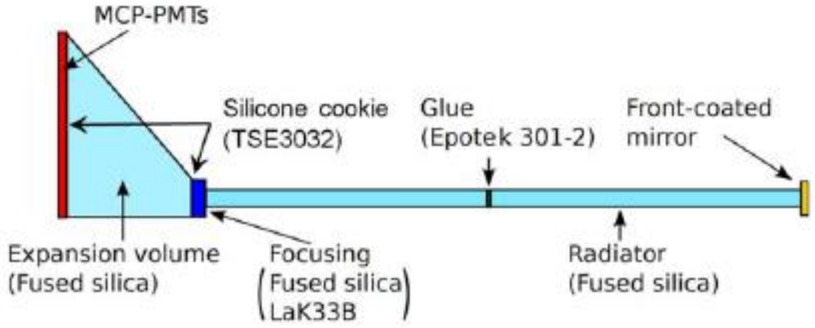


CHERENKOV RADIATION

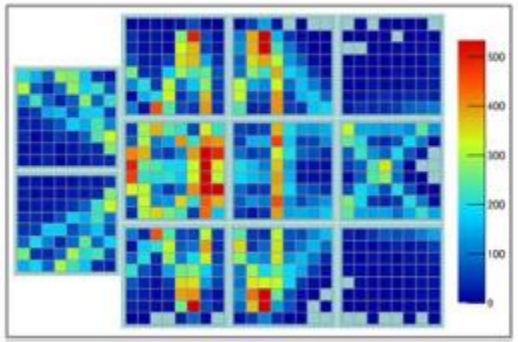
- Detection of Internally Reflected Cherenkov detector – DIRC







Fused silica – quartz
n ≈ 1.5



CHERENKOV RADIATION

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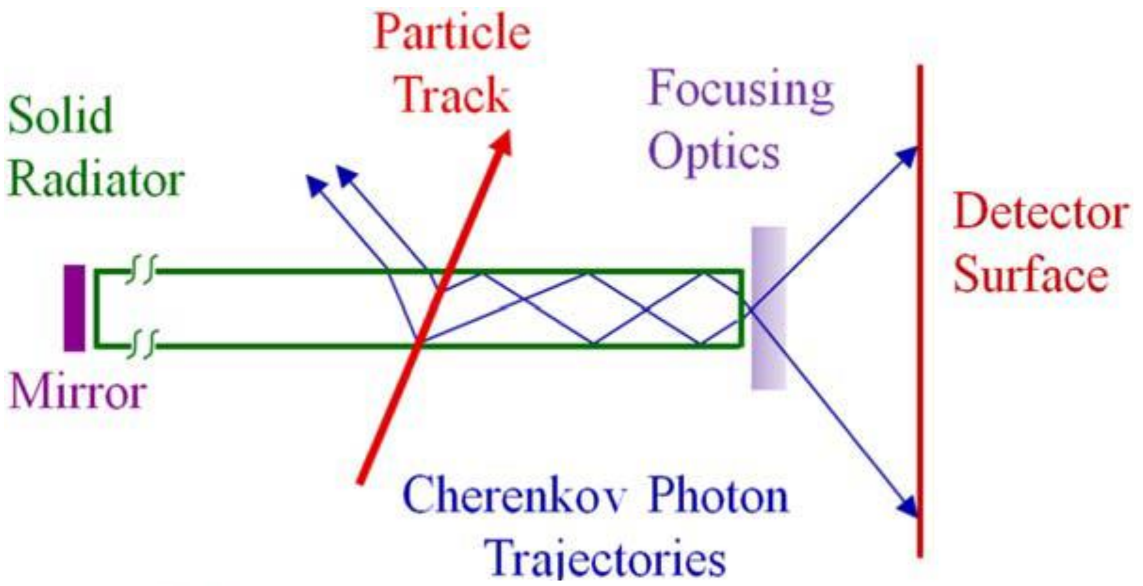
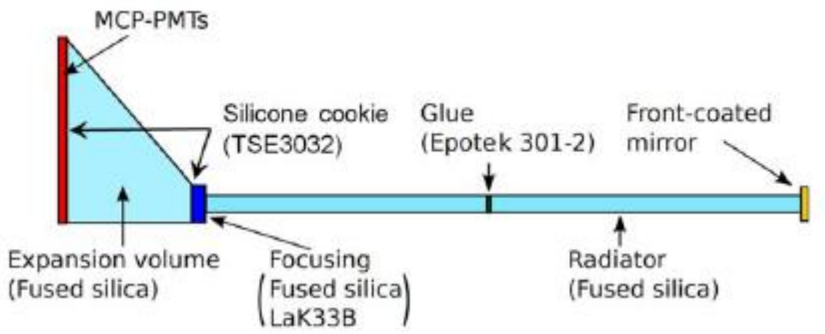
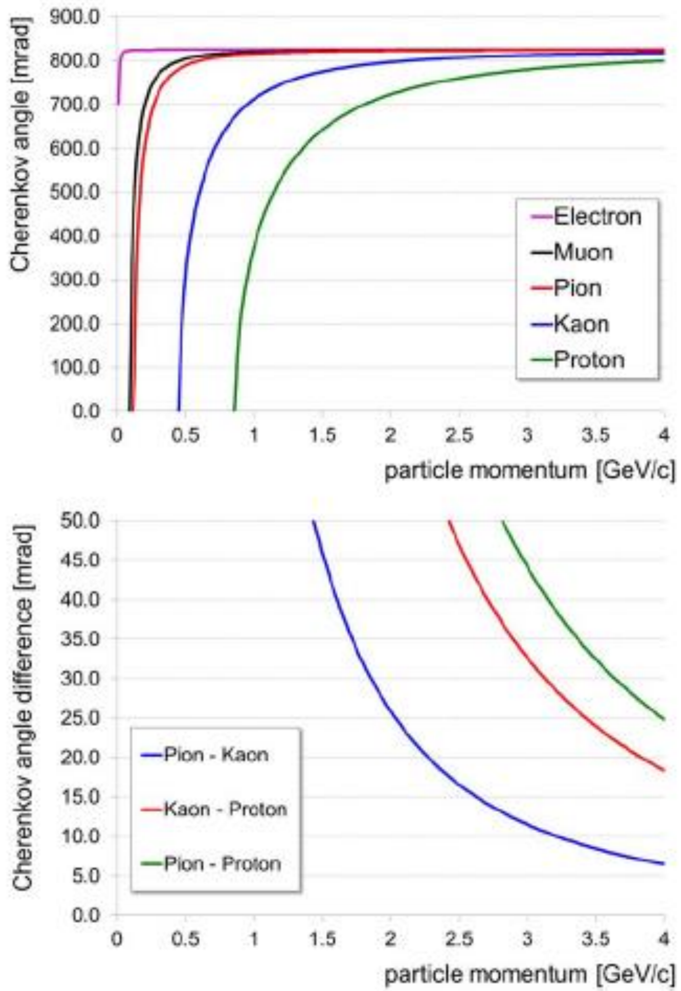


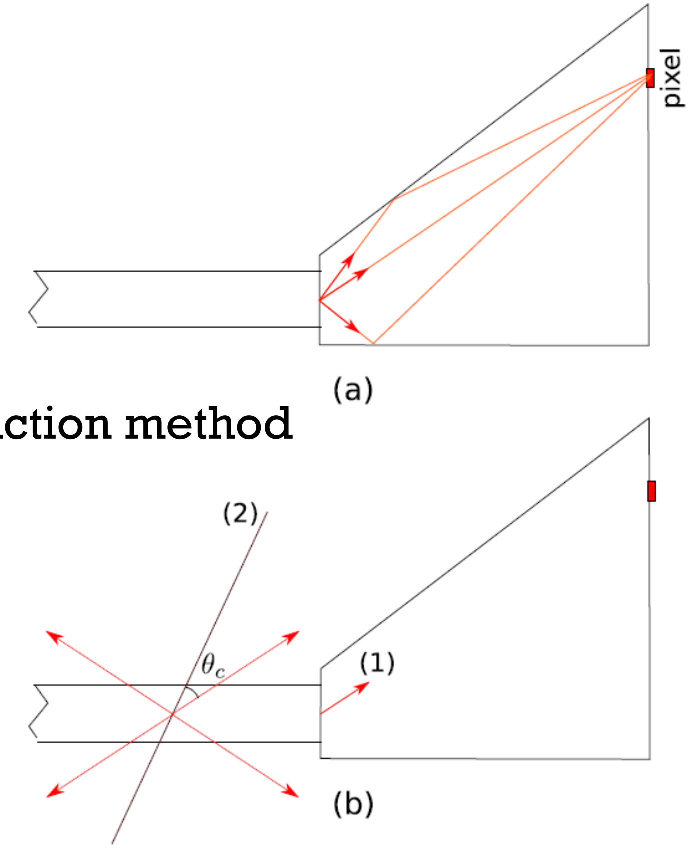


Fused silica – quartz
$n \approx 1.5$

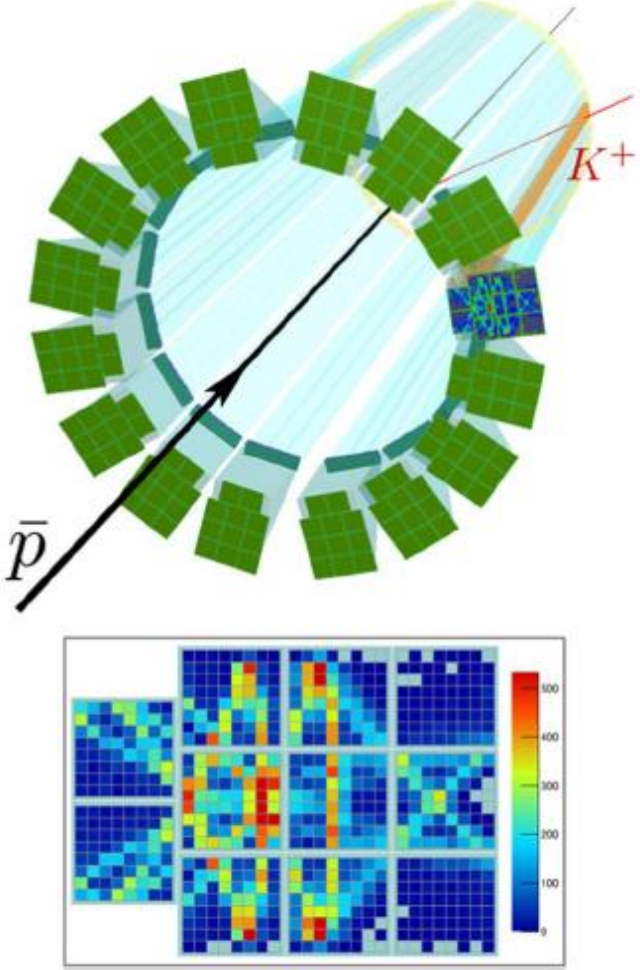


CHERENKOV RADIATION

- Detection of Internally Reflected Cherenkov detector – DIRC
- Ultra-compact



Reconstruction method



CHERENKOV RADIATION

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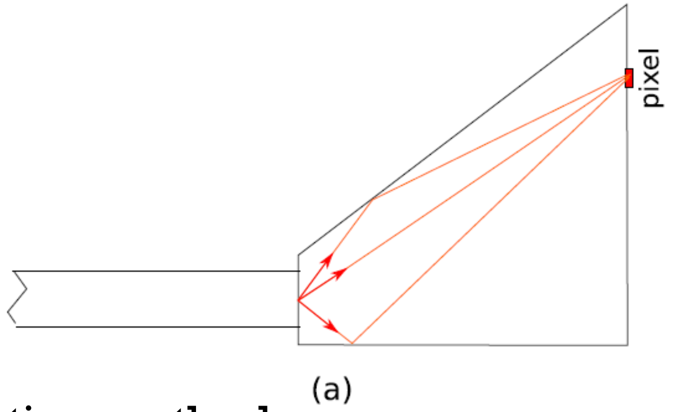

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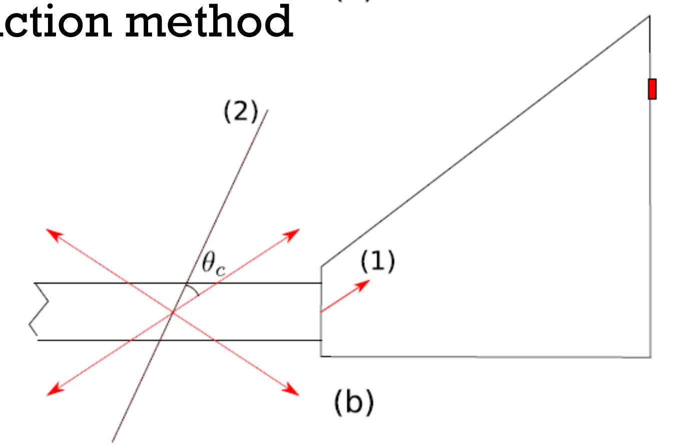
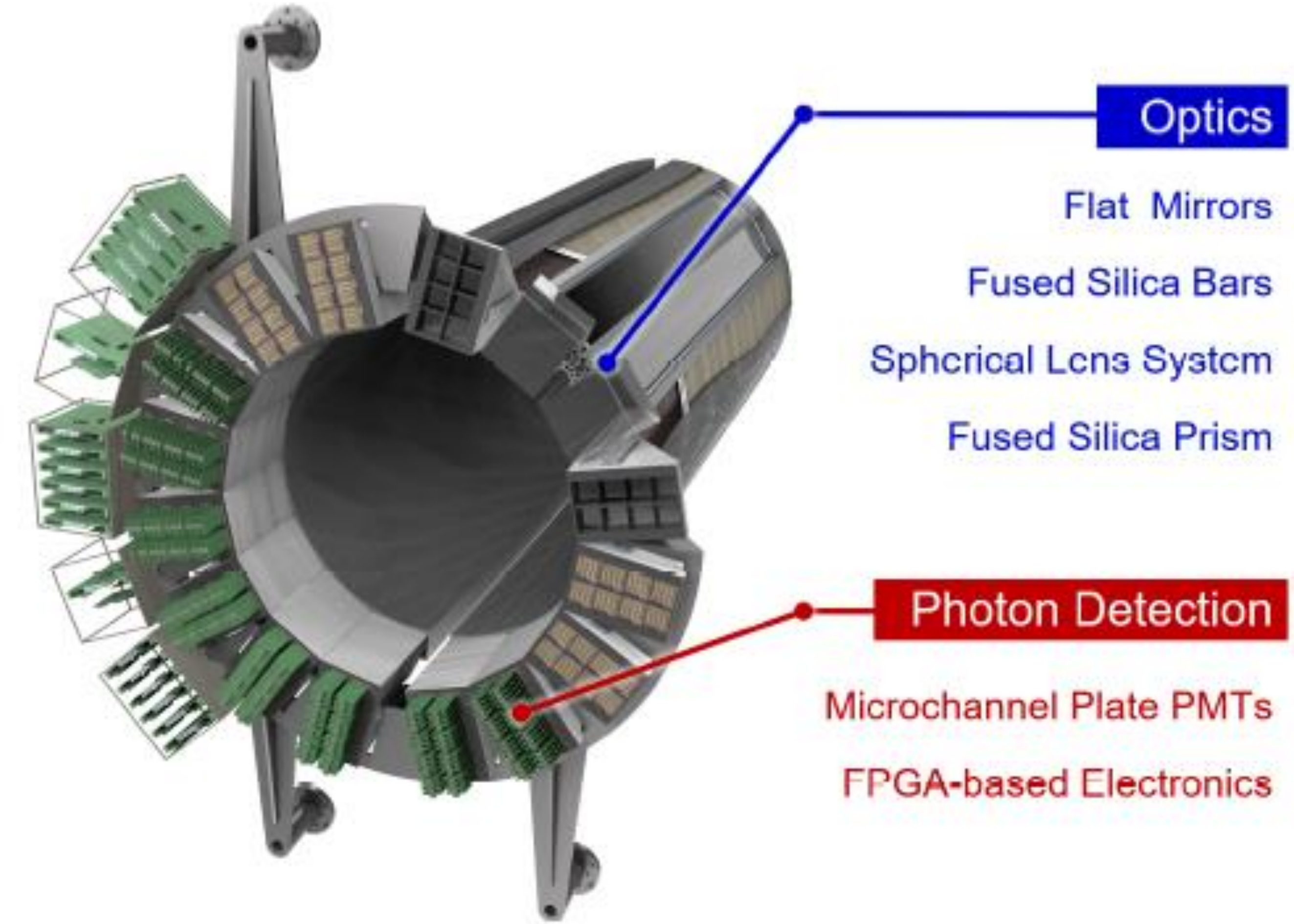
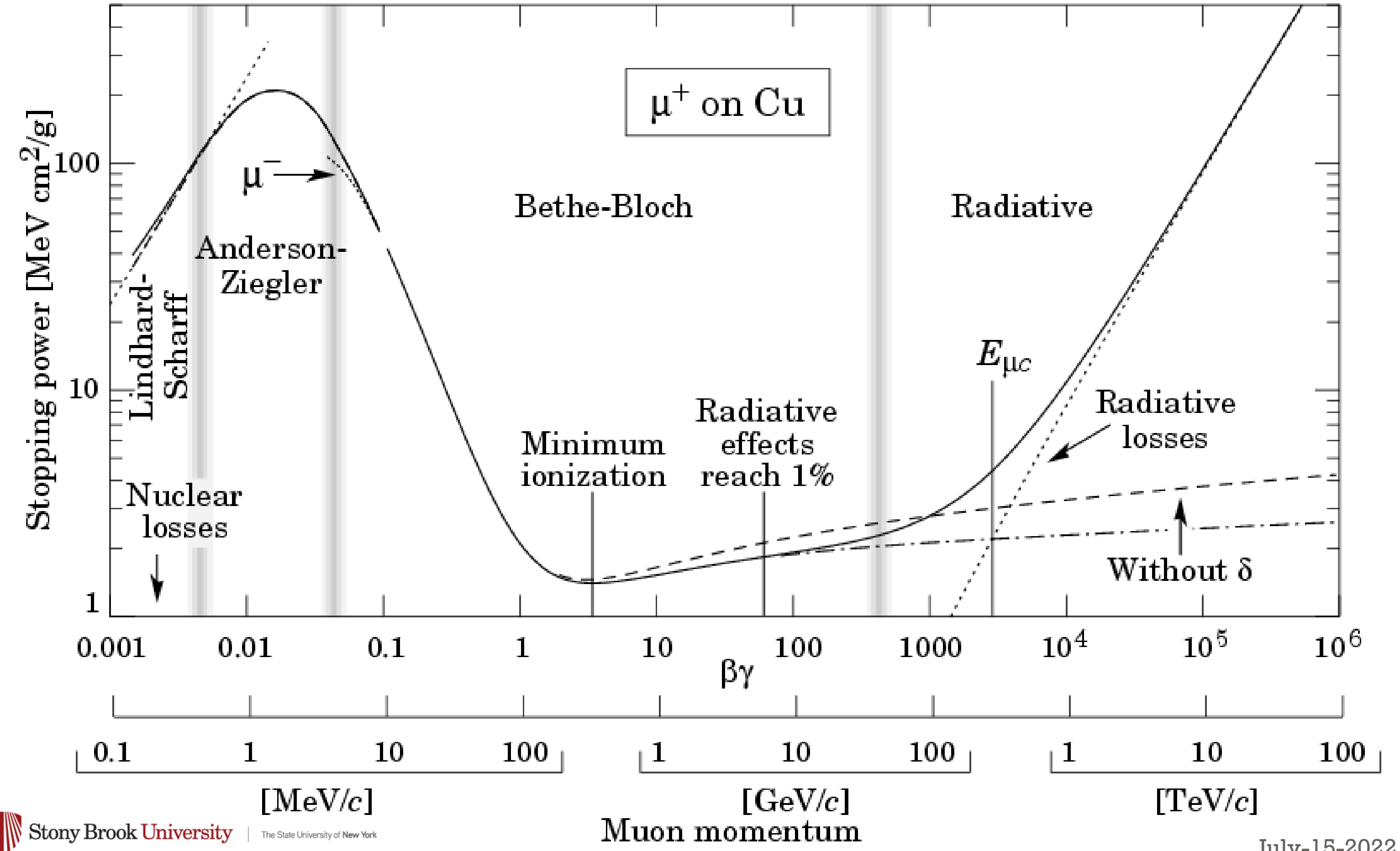




IONIZATION LOSS

- Fast charged particles other than e⁻ traversing matter
  - Inelastic Coulomb collisions with atomic electrons
  - Excited or ionized states
  - Loss of kinetic energy



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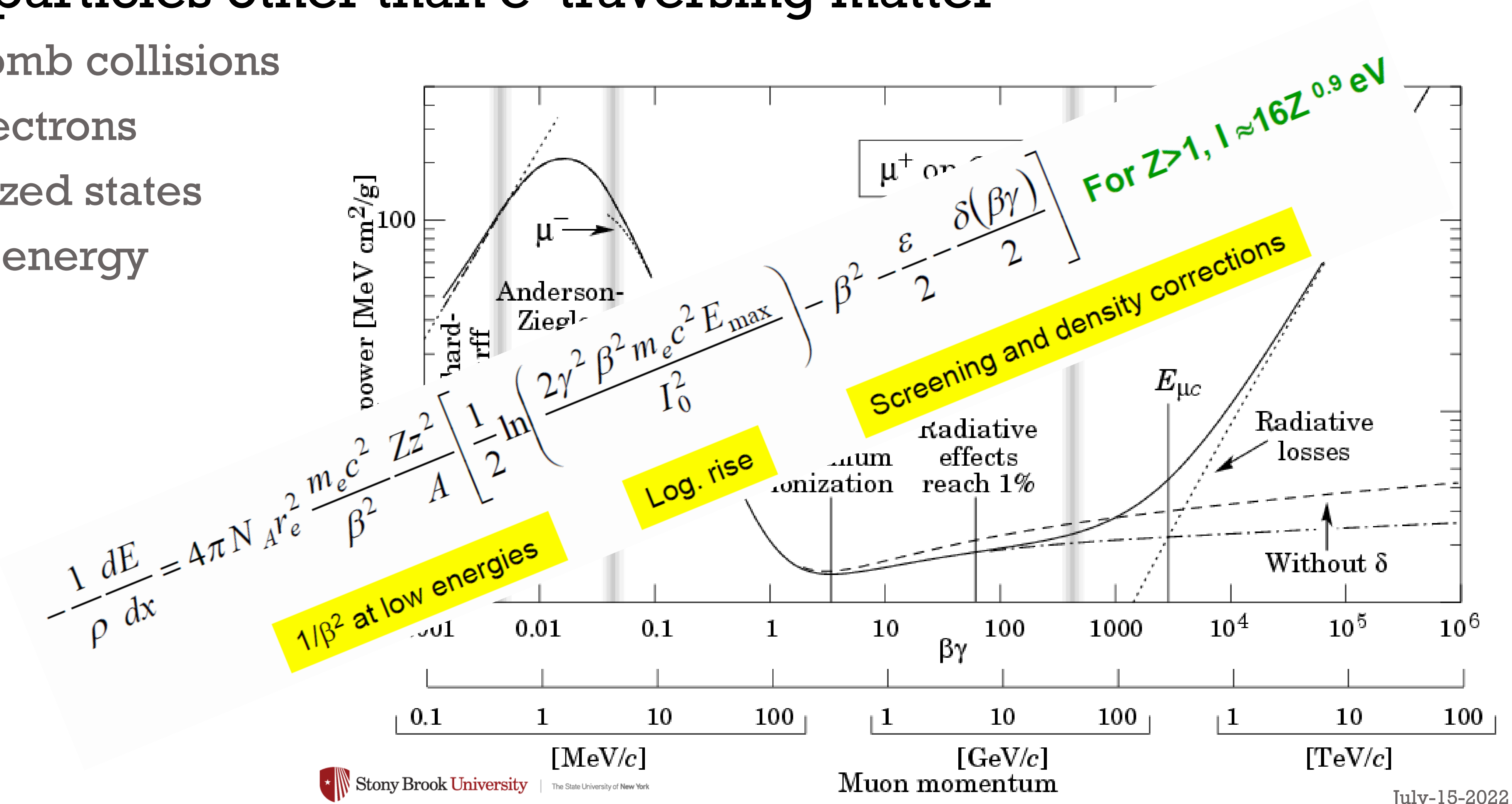

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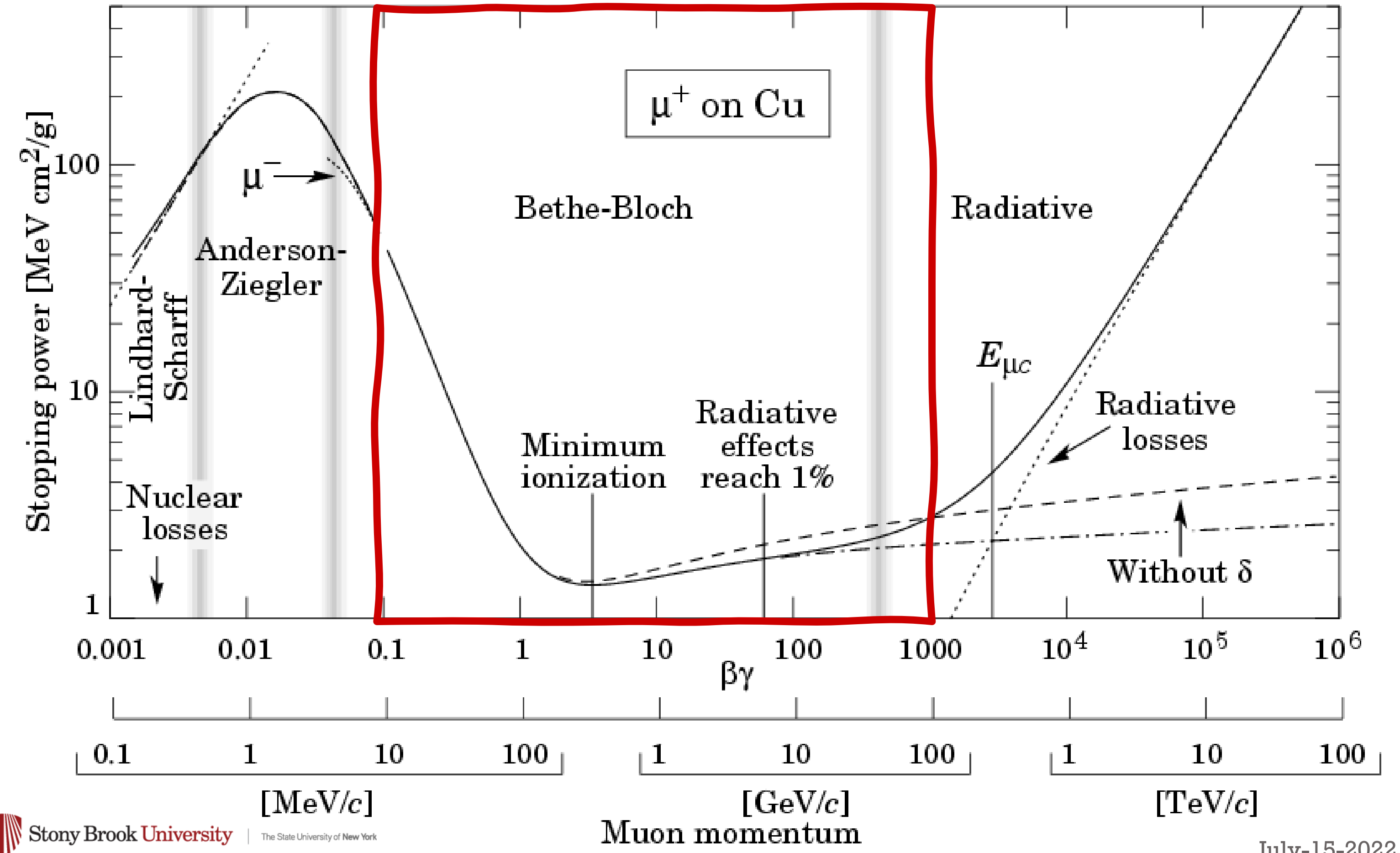
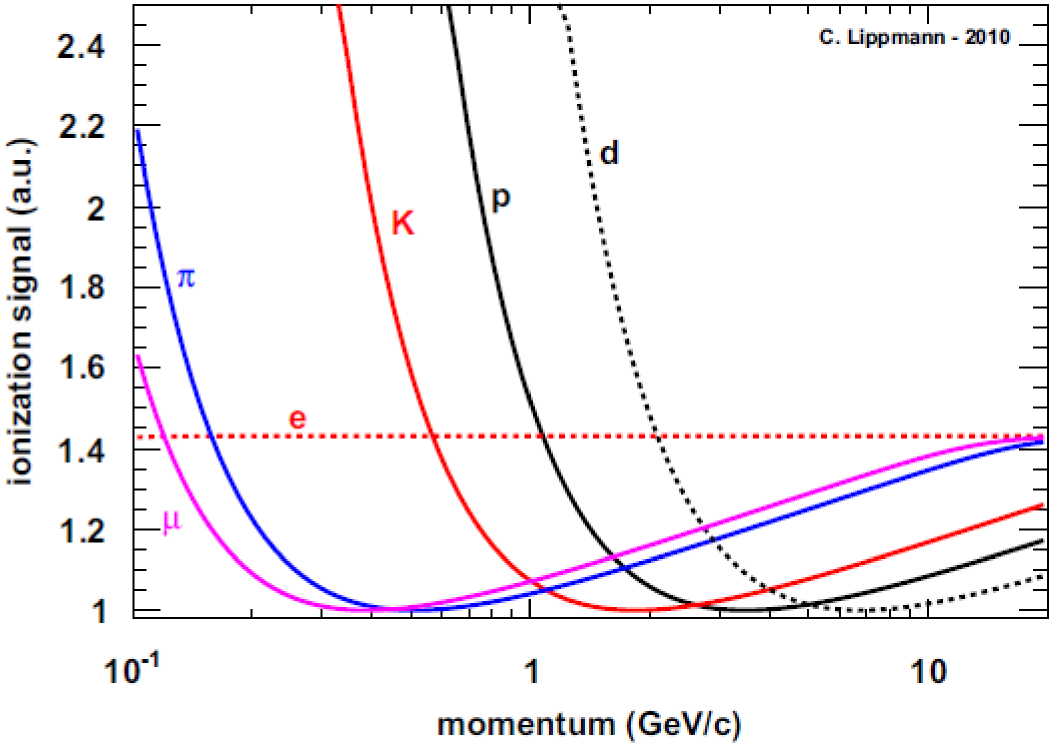
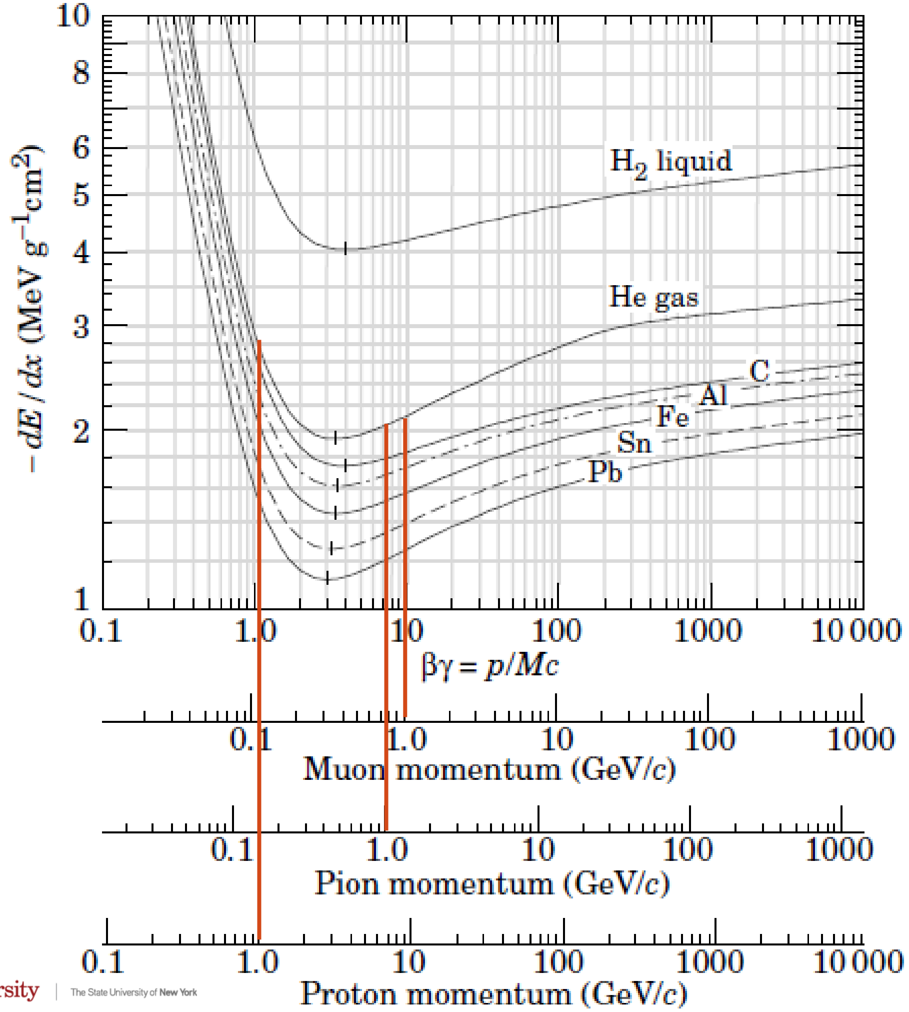


IONIZATION LOSS

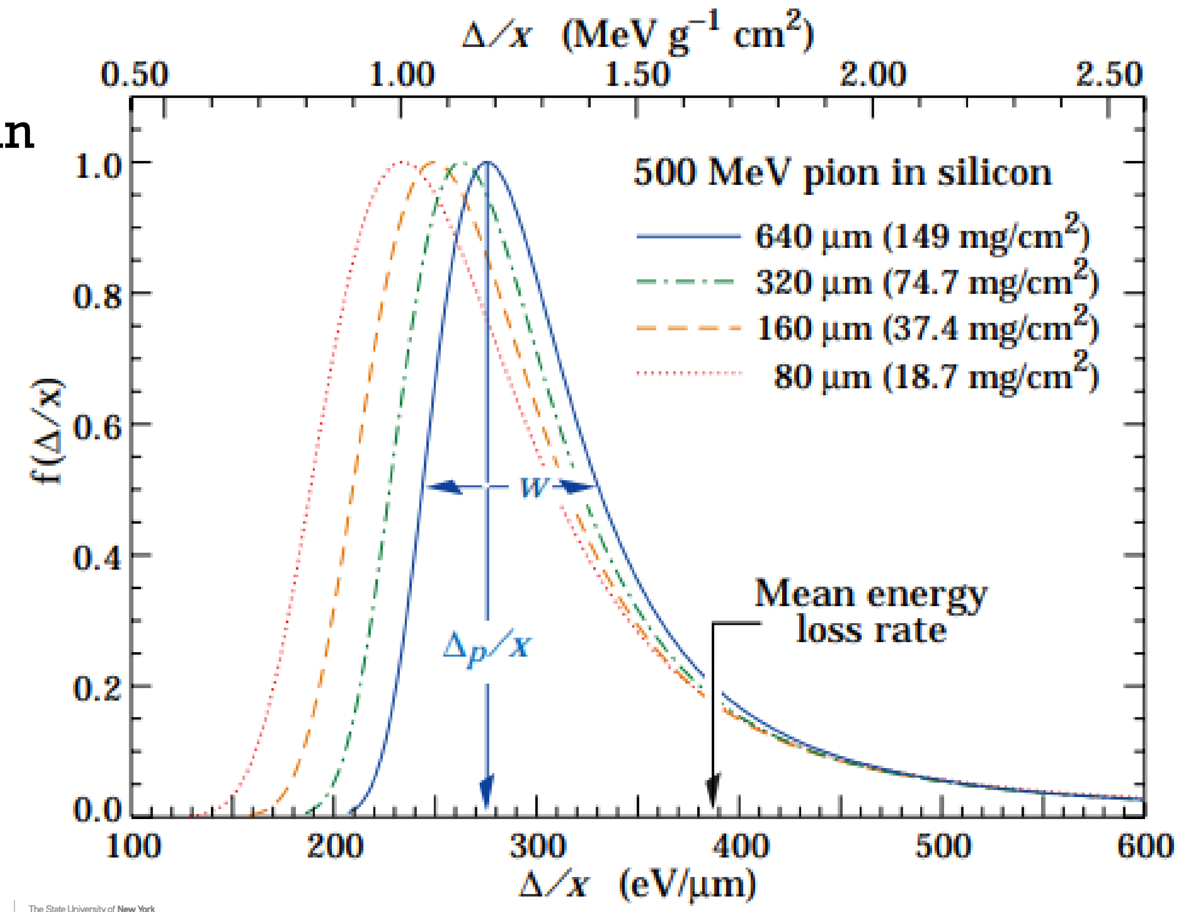
- Fast charged particles other than e⁻ traversing matter
  - Different particle species have different *dE/dx* at same *p*





IONIZATION LOSS

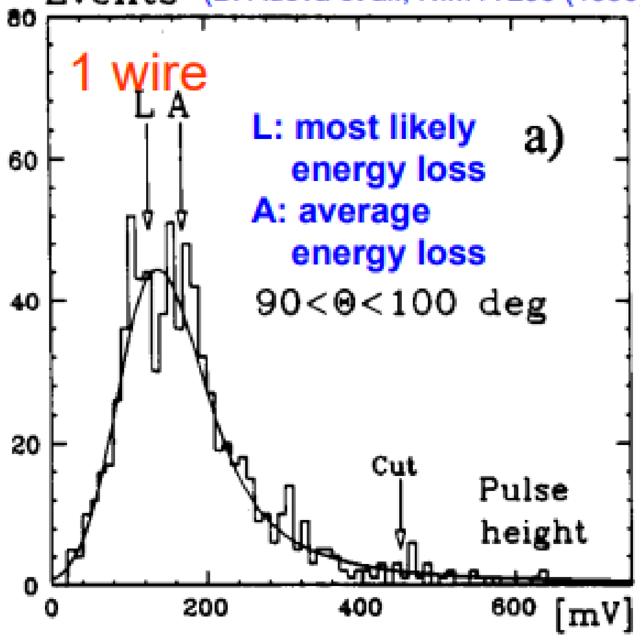
- Fast charged particles traversing matter
  - Measure deposited energy, measure momentum → PID
  - Problem: Straggling
    - E_{loss} distribution not Gaussian around mean
    - Rare cases occur → large energy amount transferred to single electron δ-ray
    - If δ-ray excluded → <E_{loss}> changes
  - "Overcome" straggling by truncating

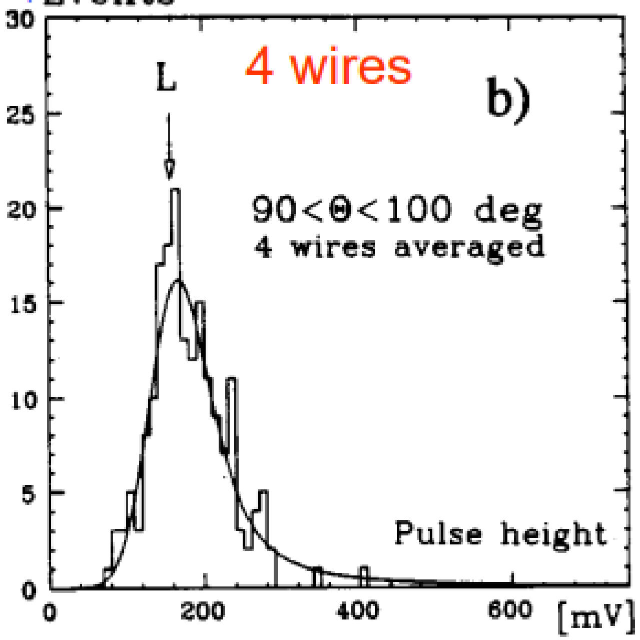


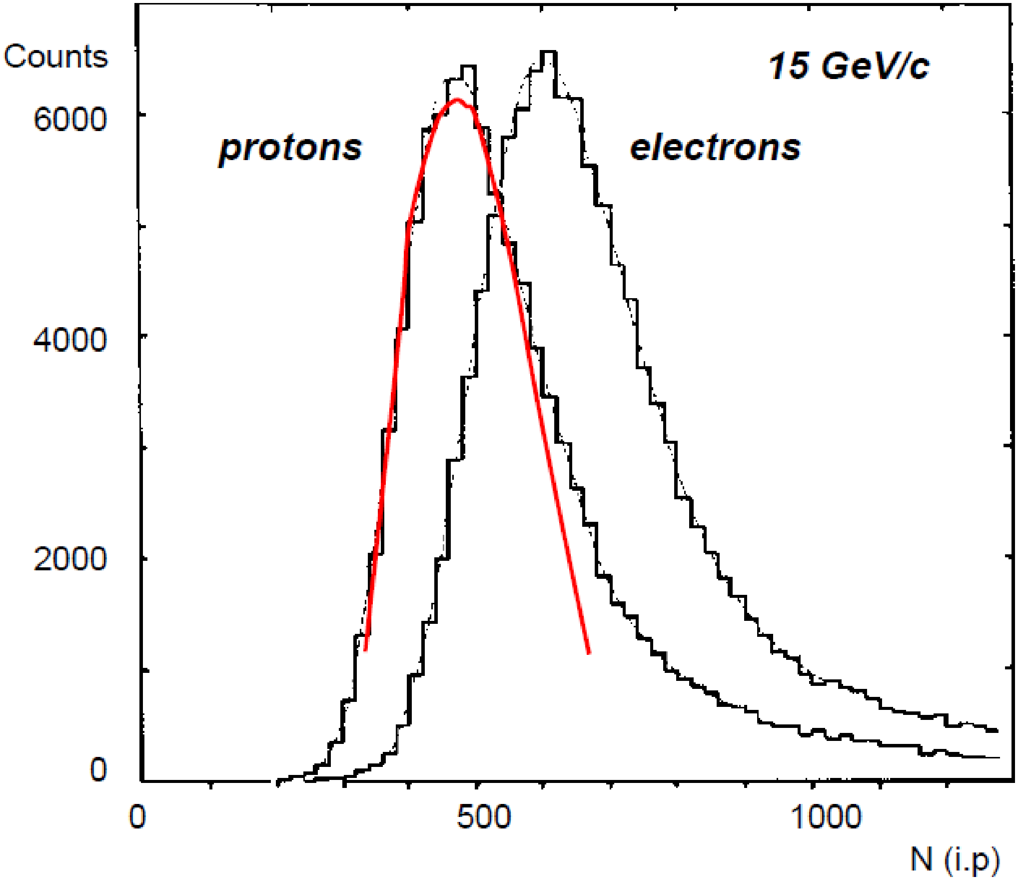
IONIZATION LOSS

- Fast charged particles traversing matter
  - Truncated Mean
    - Remove outliers
    - Increase number of samples

(B. Adeva et al., NIM A 290 (1990) 115)







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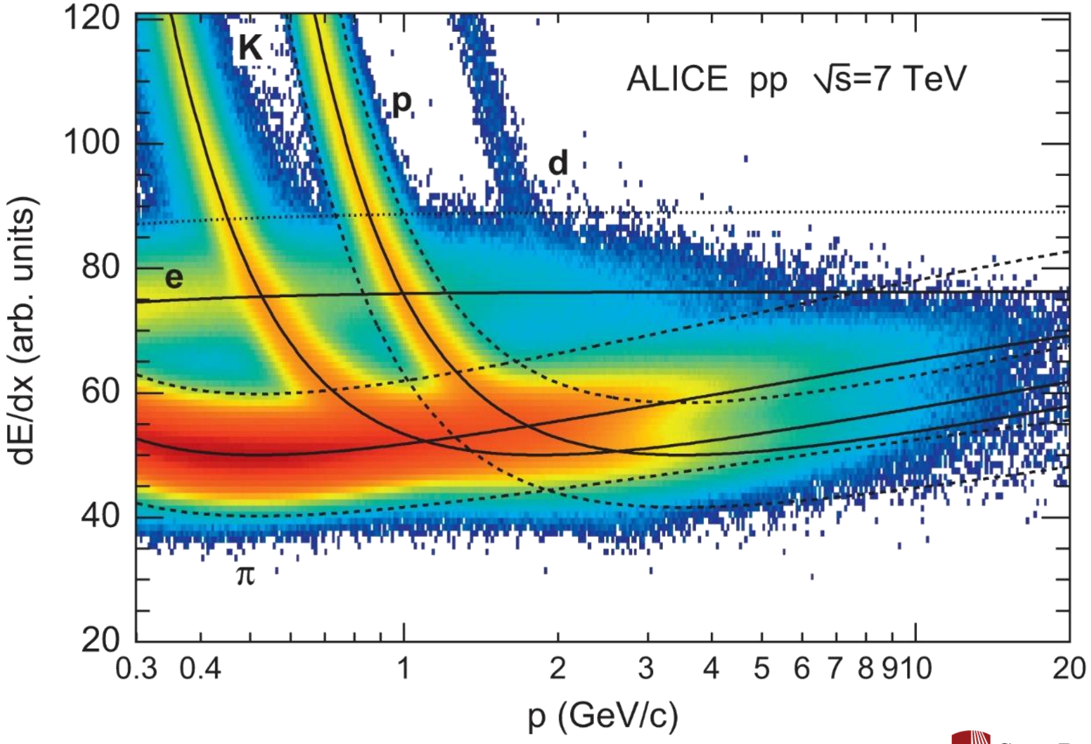
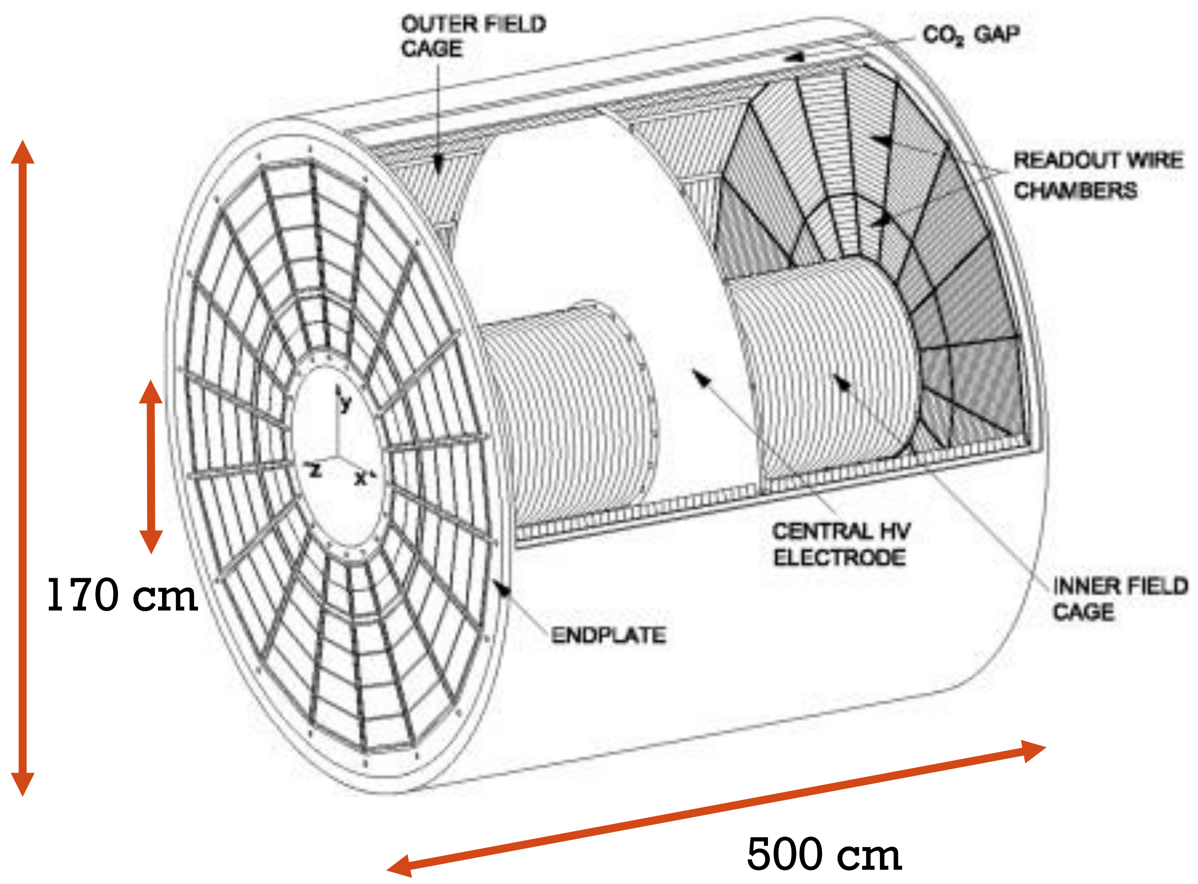


ALICE TPC



IONIZATION LOSS

- Fast charged particles traversing matter
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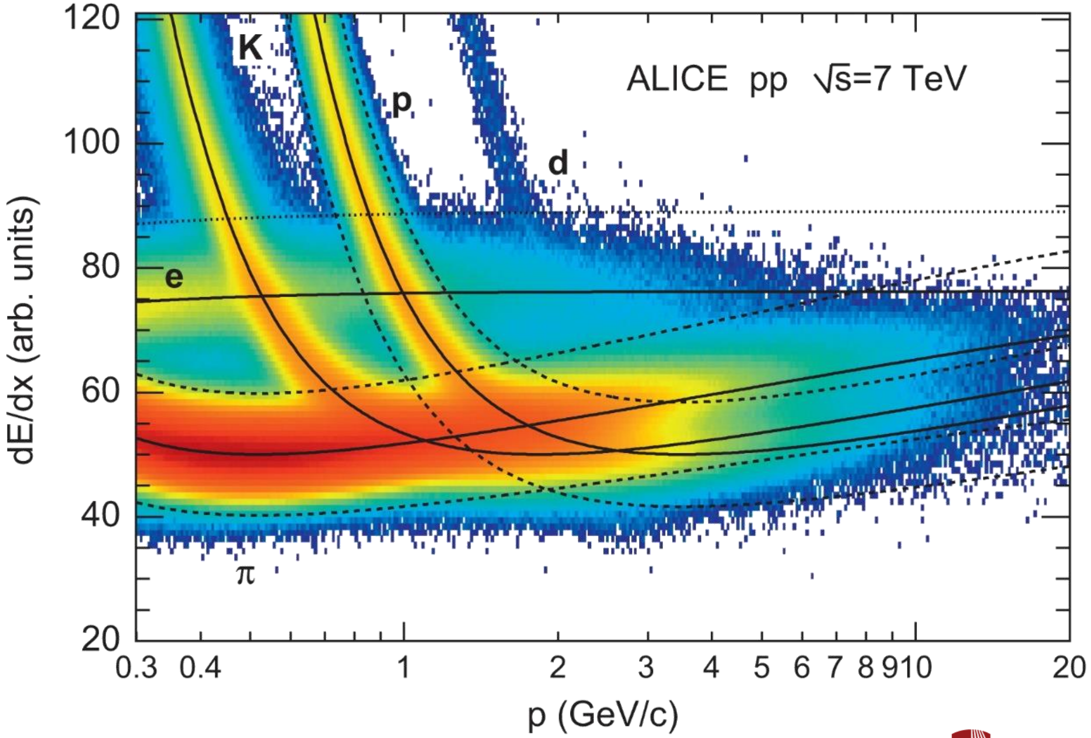

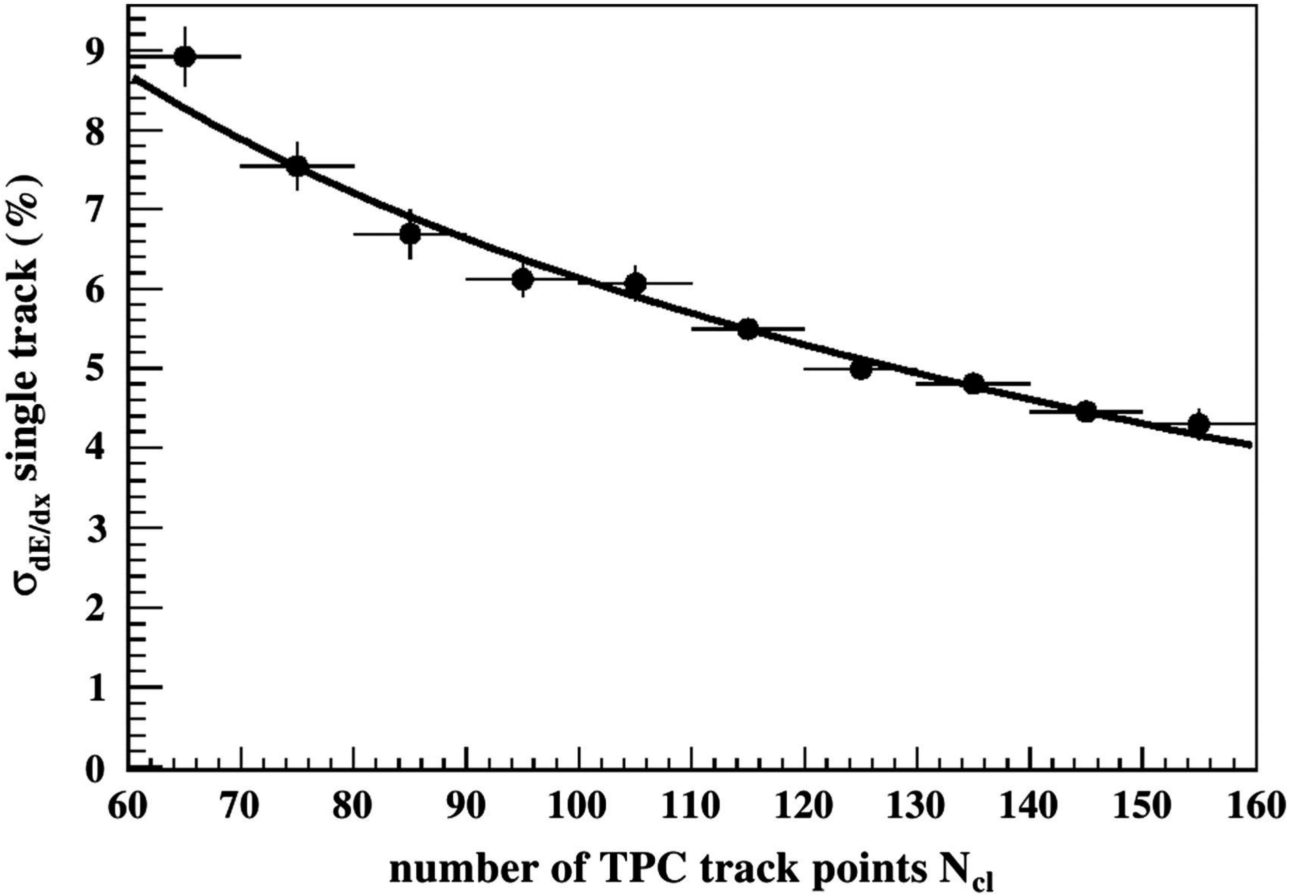

IONIZATION LOSS

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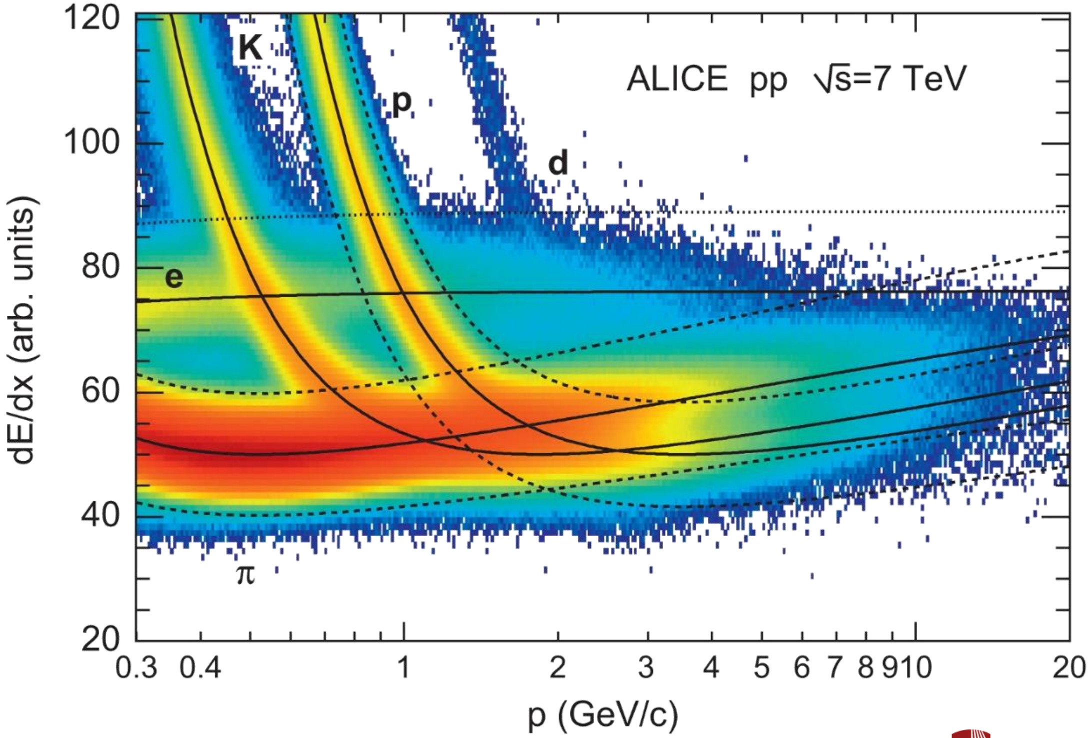
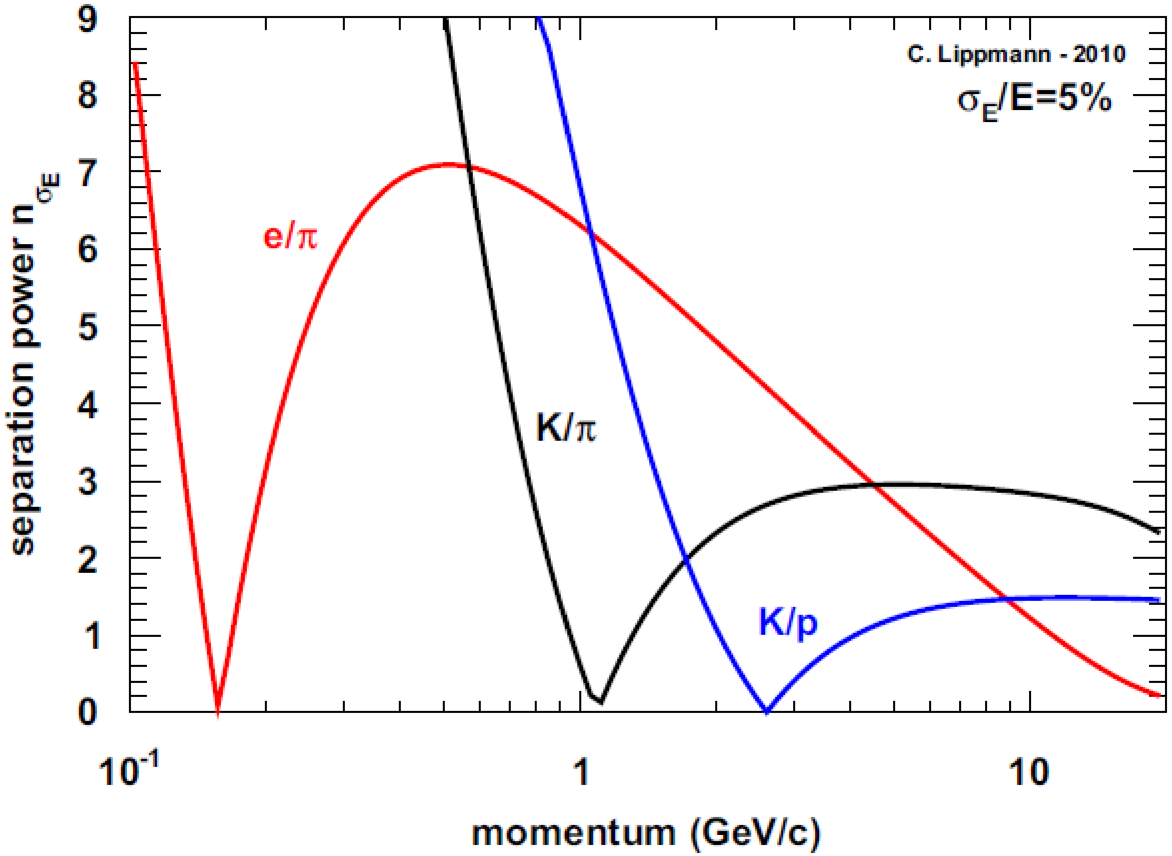
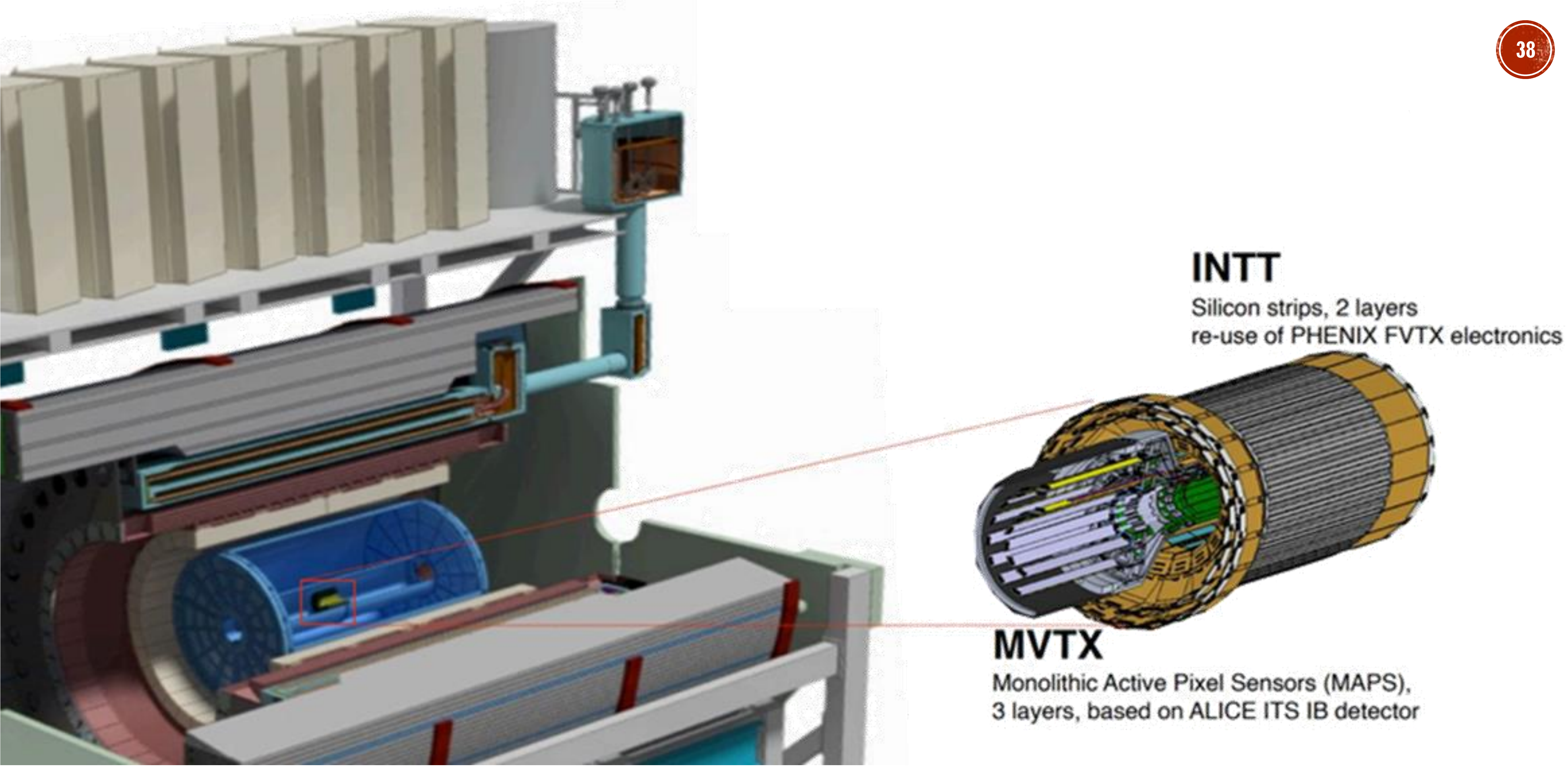
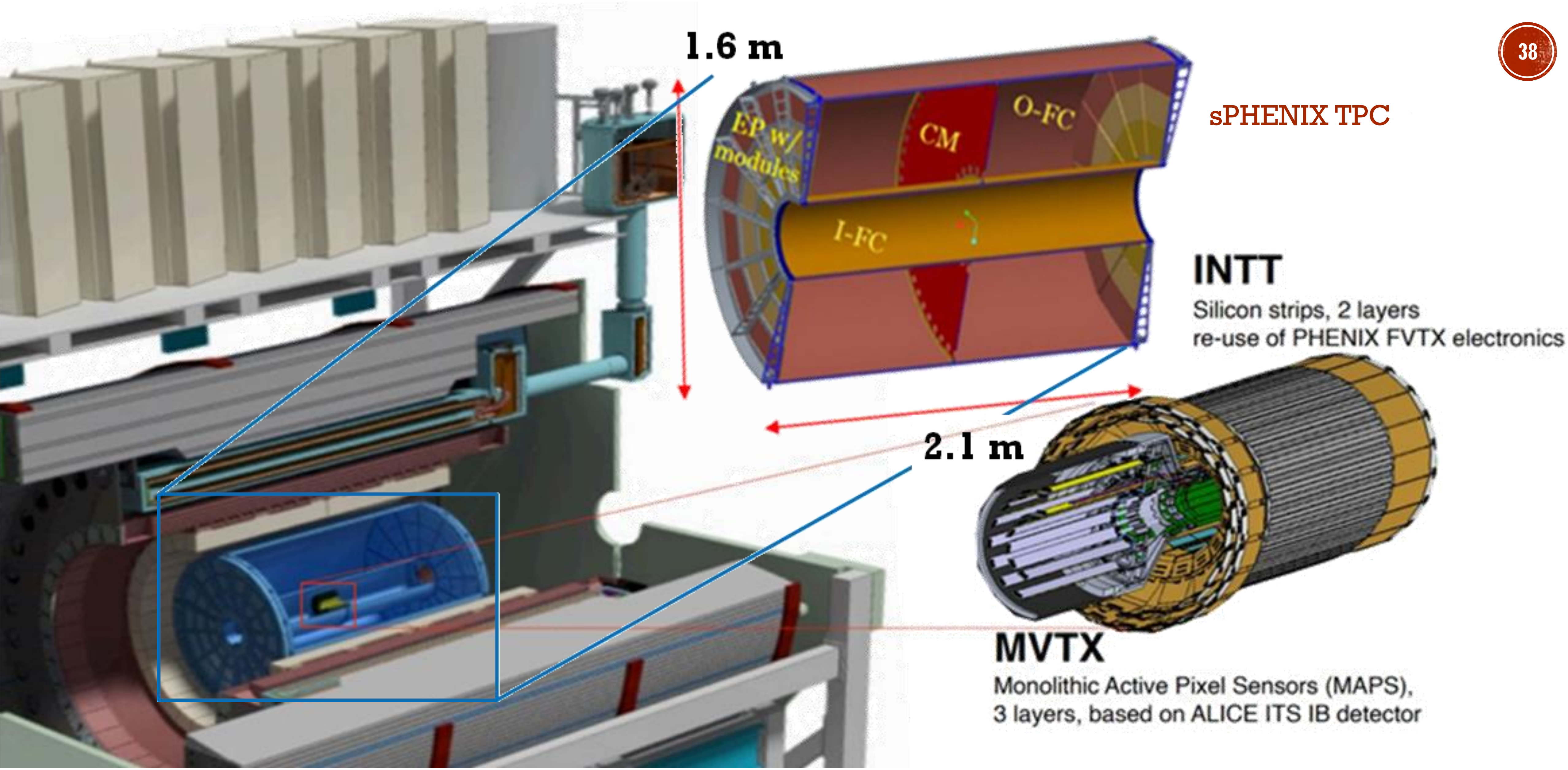




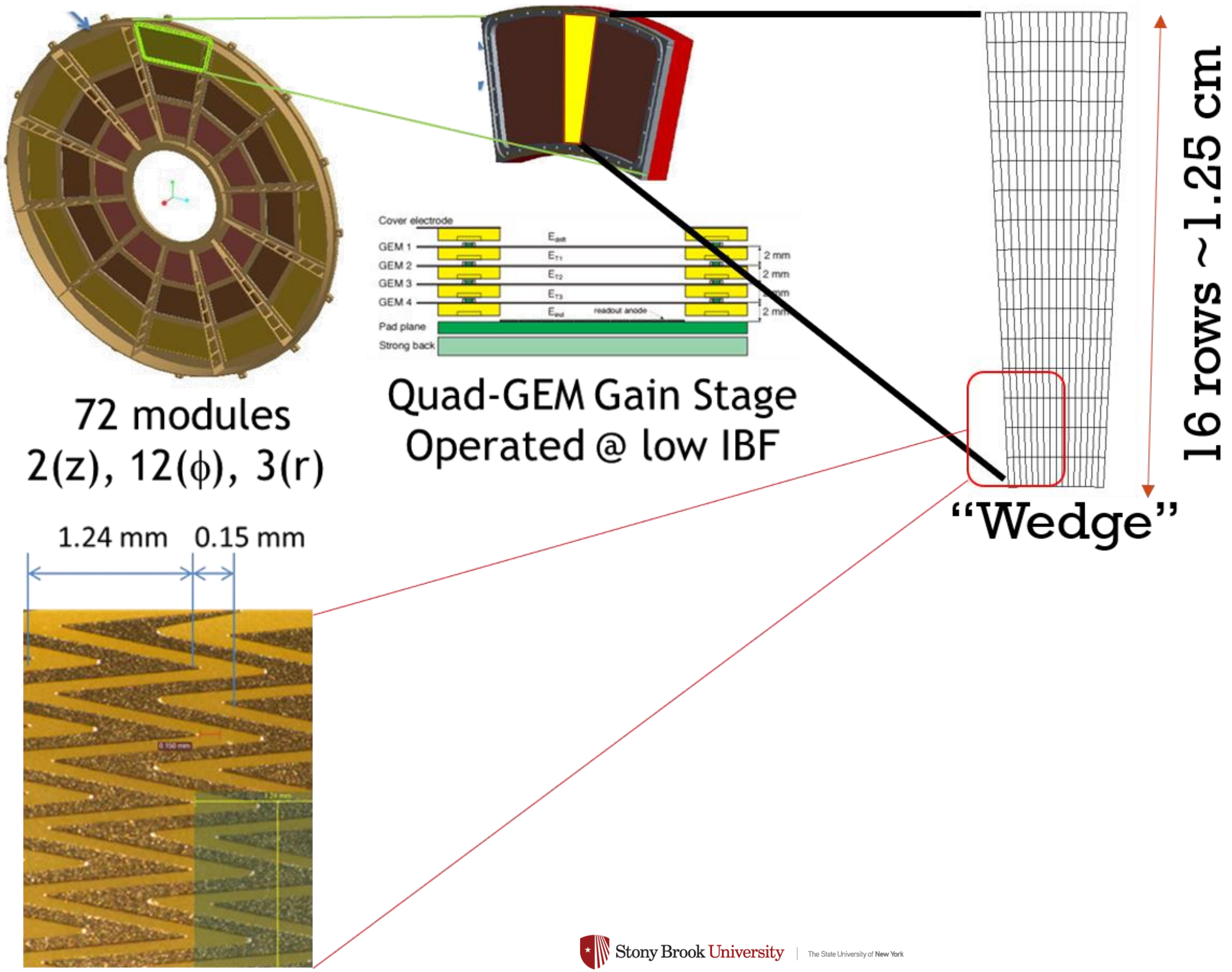
IONIZATION LOSS



IONIZATION LOSS

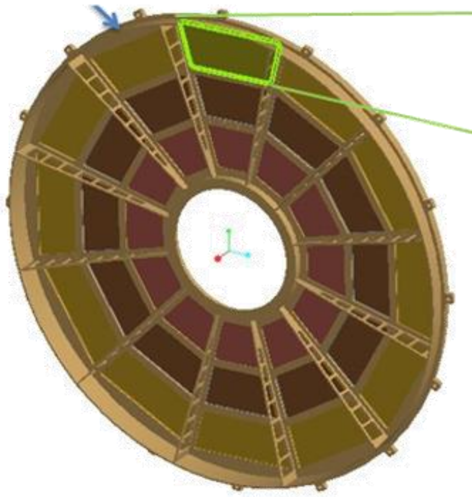


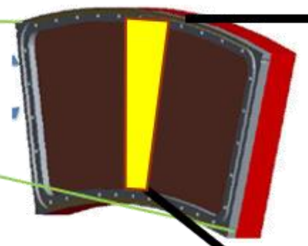
IONIZATION LOSS



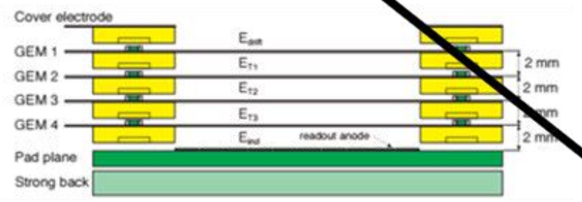
sPHENIX TPC

IONIZATION LOSS

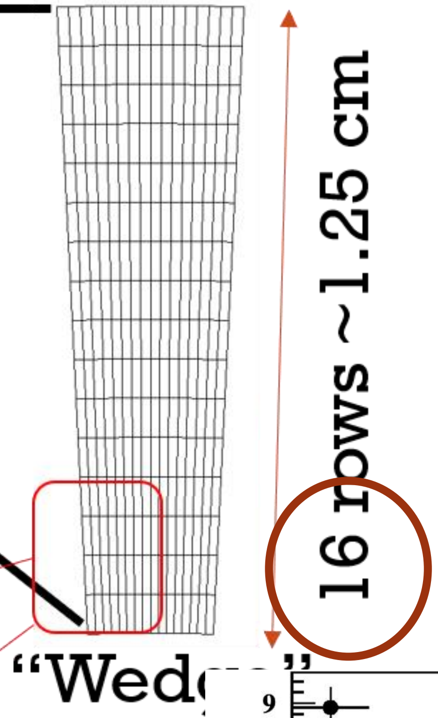




72 modules
2(z), 12(ϕ), 3(r)

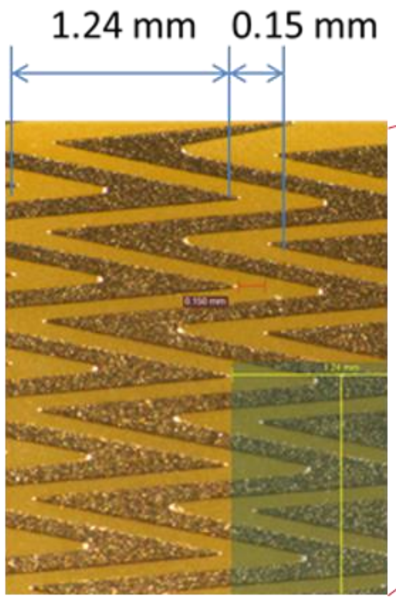


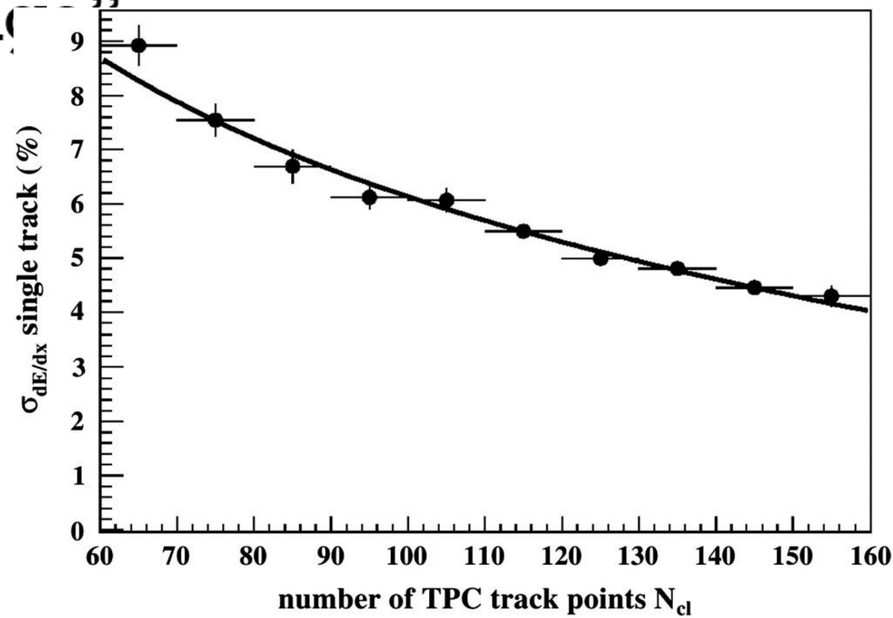
Quad-GEM Gain Stage
Operated @ low IBF



sPHENIX TPC

x 3 → 48 pad rows





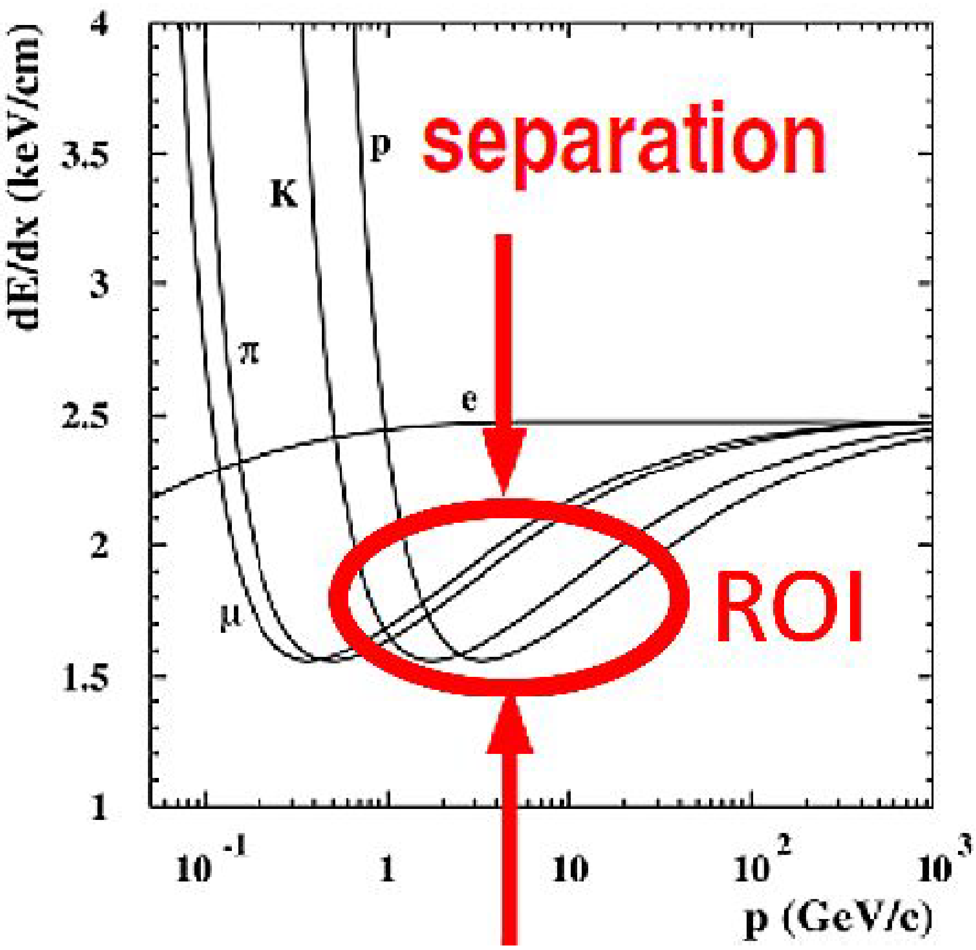
IONIZATION LOSS

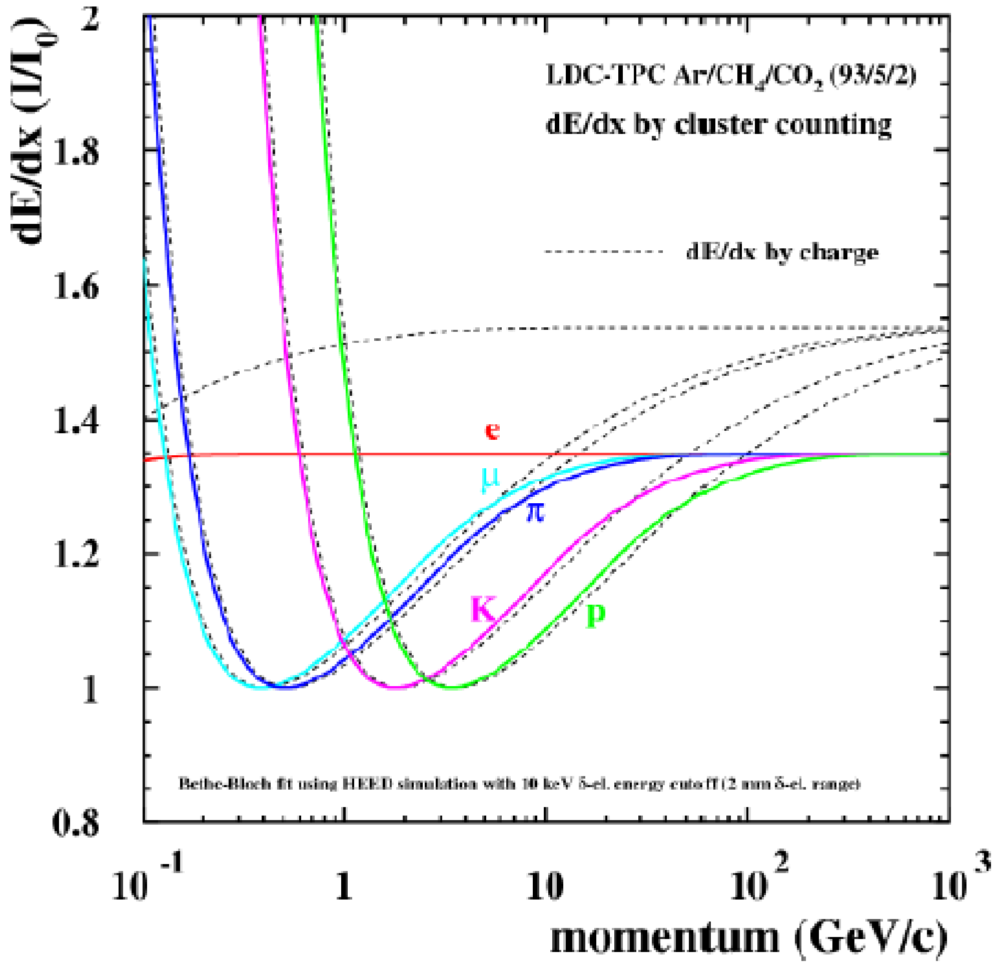
- Procedure most widely used: count charge and truncate mean $\rightarrow$ lowest $p\%$ (typically p = 60 - 80) of the pulse heights
  - Cut reduces effect of fluctuations due to long tail
  - Cut also removes fraction of track samples $\rightarrow$ worsens the ionization resolution
- Alternative: count number of clusters $\rightarrow$ complete suppression of Landau tail
  - Every cluster -big or small- has the same weight $\rightarrow$ Poissonian distribution with significantly smaller width
  - Better correlation and particle identification power

$$\text{separation power} = \frac{\text{separation}}{\text{resolution}}$$

  - Improvement in pattern recognition and track fitting $\rightarrow$ better double hit/track resolution

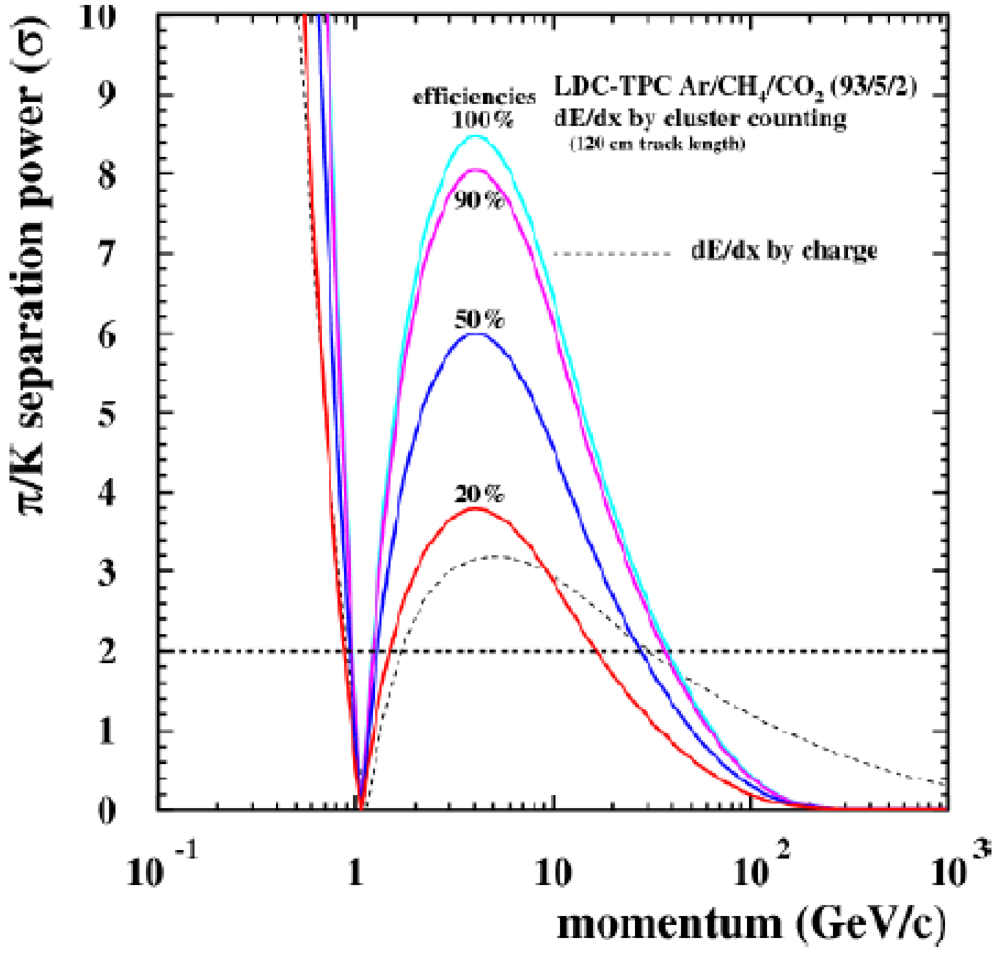
IONIZATION LOSS

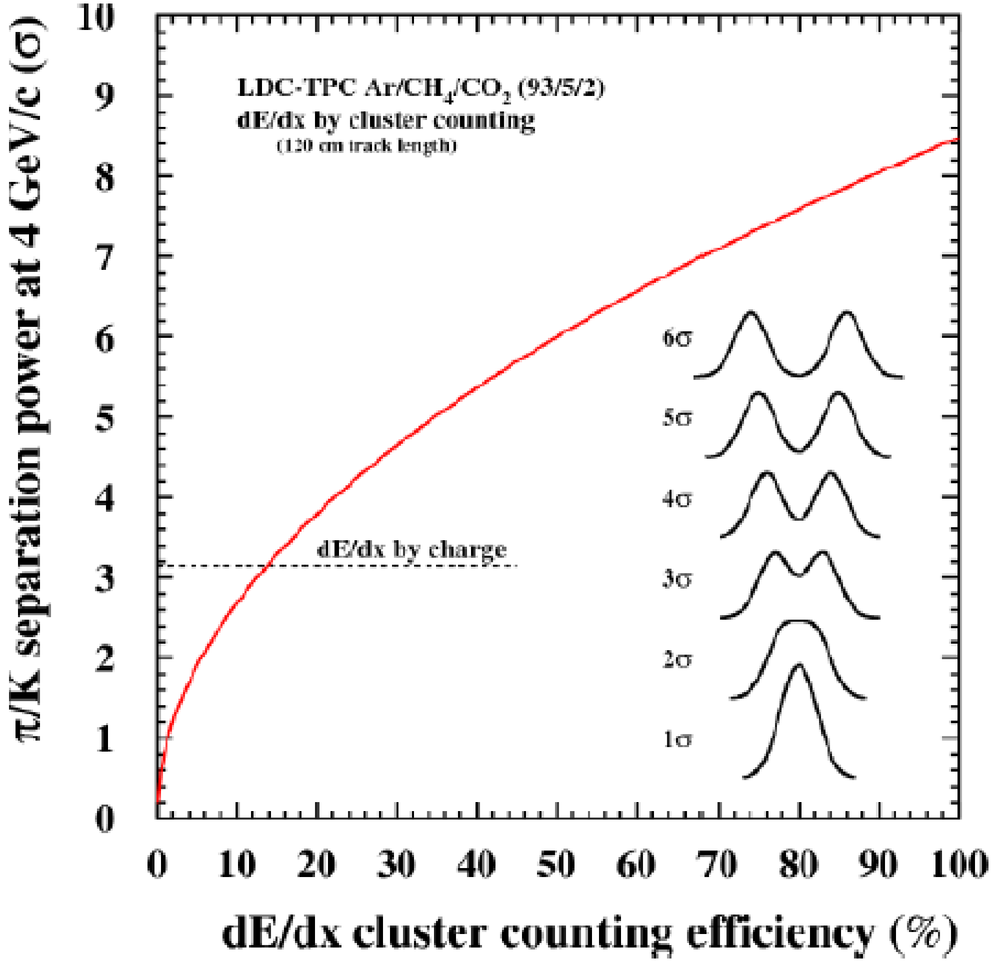




IONIZATION LOSS

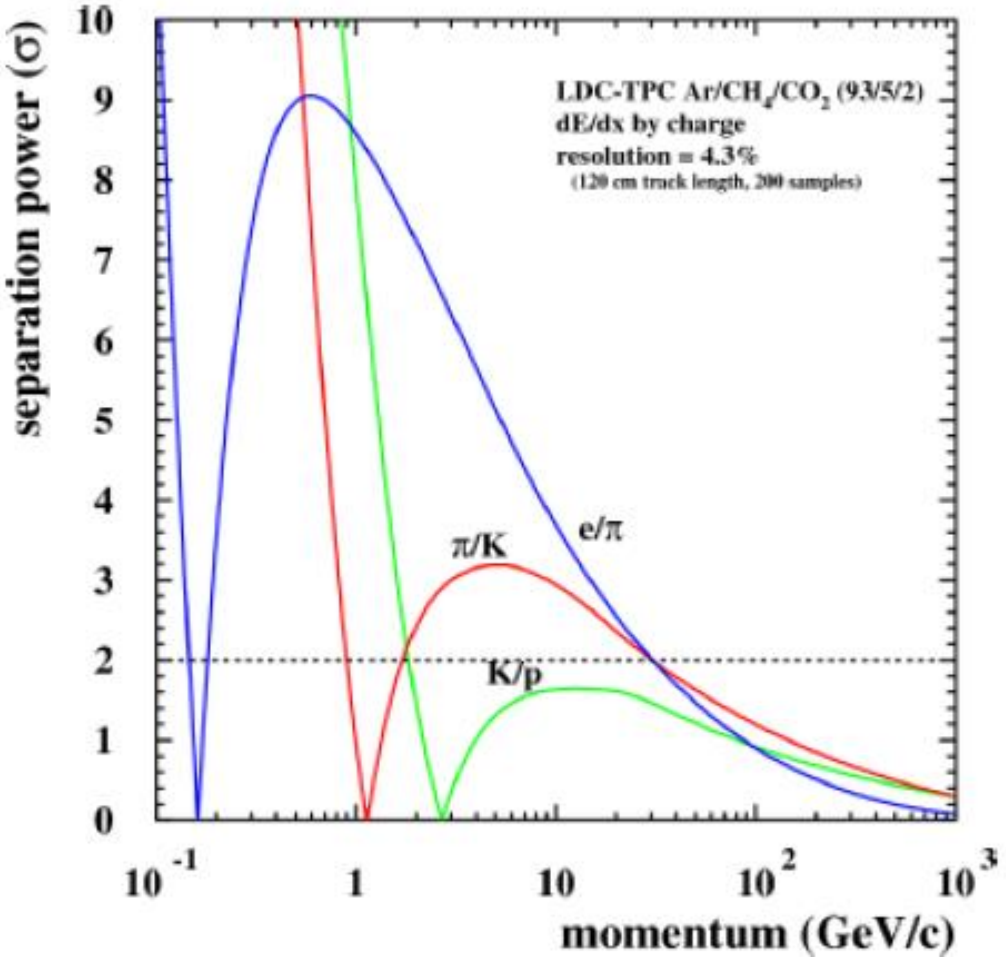
Compare separation power obtained with charge counting and cluster counting with inefficiencies

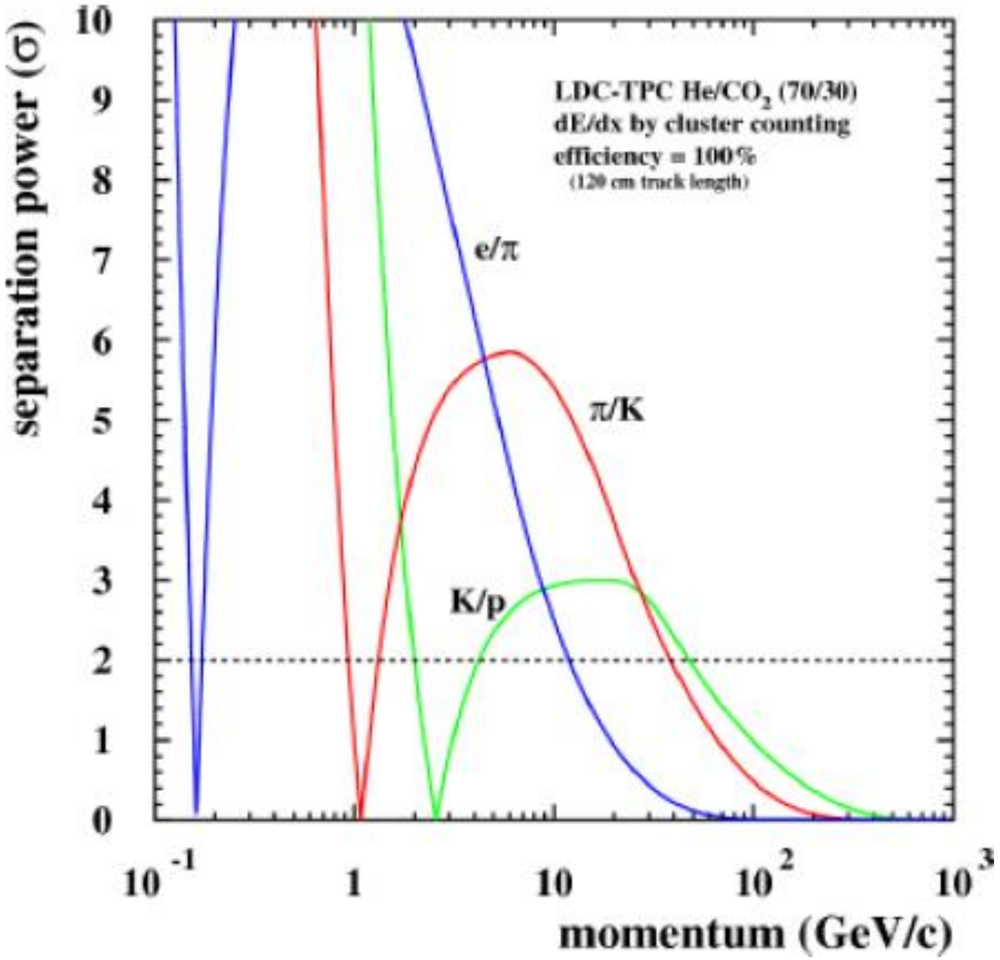




IONIZATION LOSS

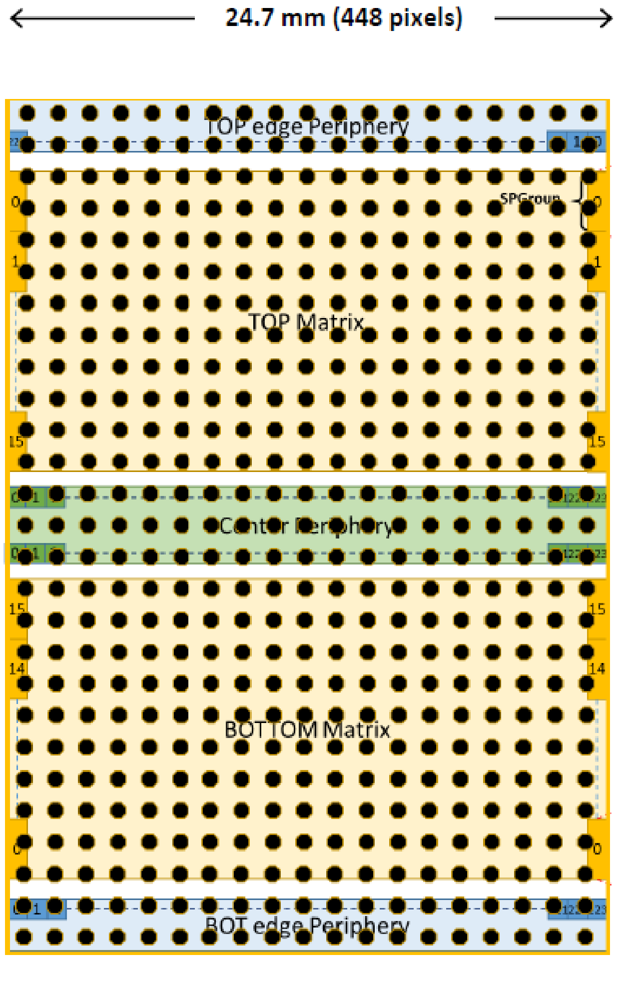
Compare separation power obtained with charge counting (LDC-TPC gas) and cluster counting (He-CO_2 gas: 70-30)

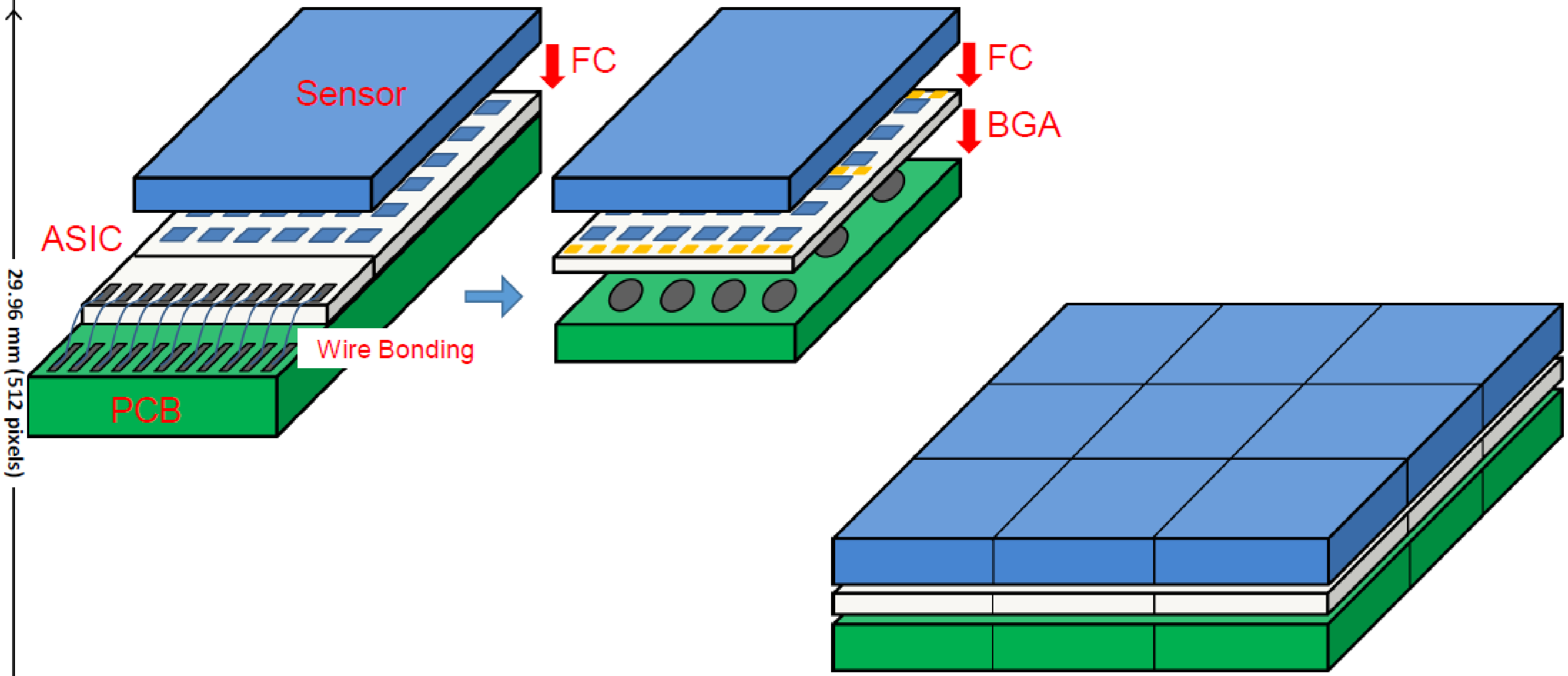




IONIZATION LOSS

- Provide readout with sufficiently high granularity

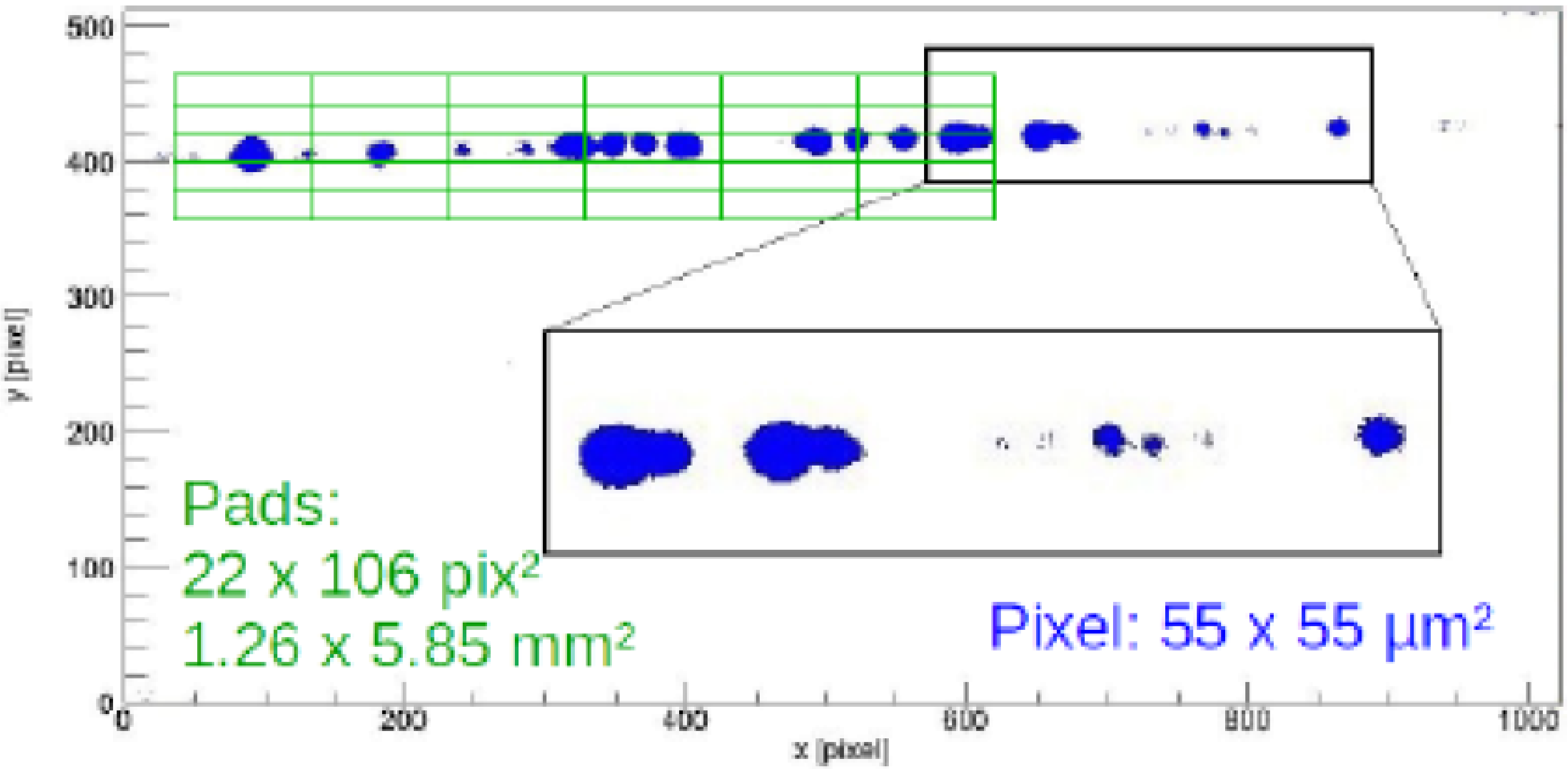




→ TimePix ASIC with appropriate pad size

IONIZATION LOSS

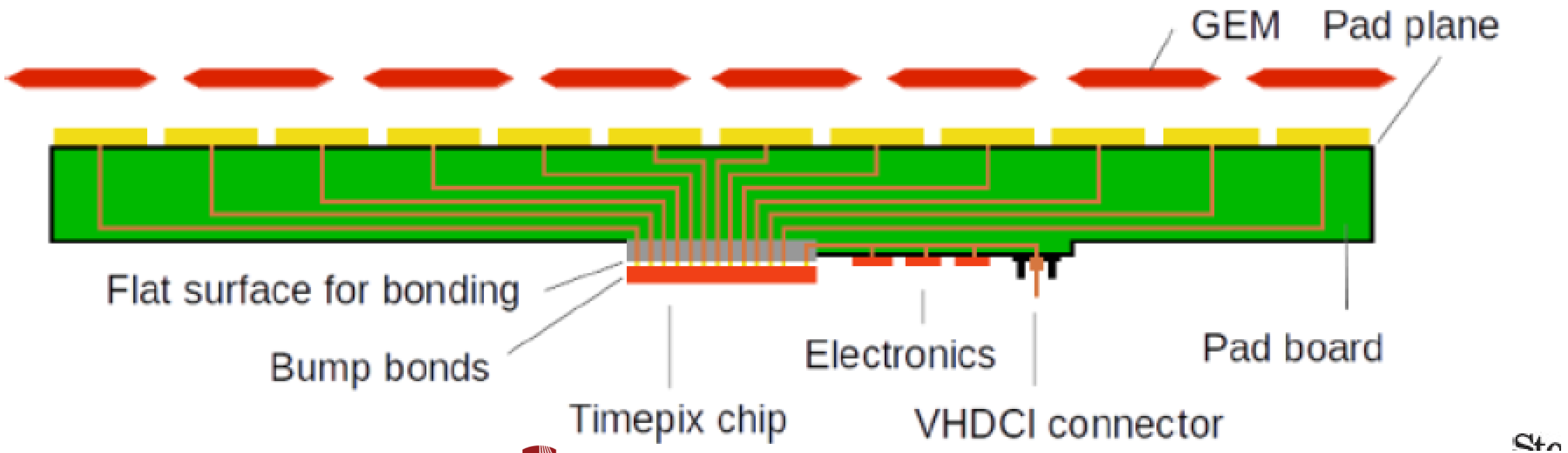
- Provide readout with sufficiently high granularity



→ TimePix ASIC with appropriate pad size

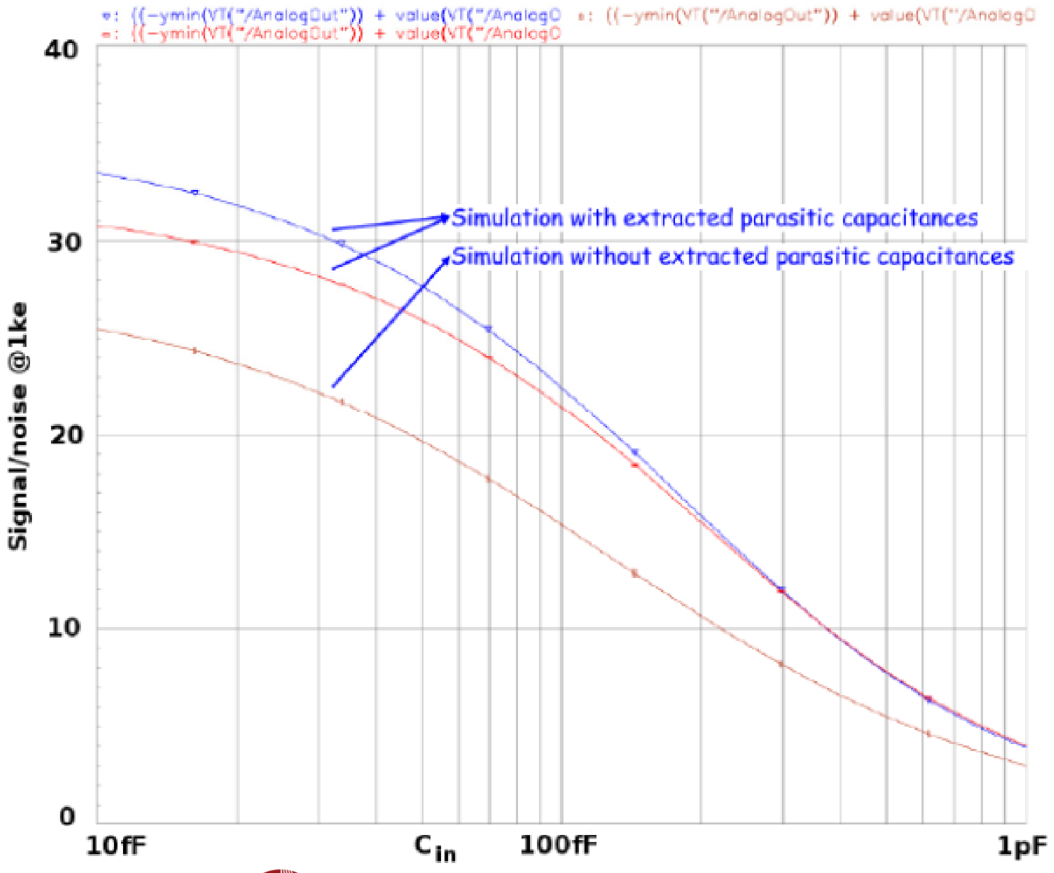
IONIZATION LOSS

- Based on TimePix ASIC
  - TDC readout per channel in highly integrated package
  - $256 \times 256 = 65{,}536$ pixels, pixel pitch 55 μm $\times$ 55 μm
  - Each pixel can record either time of arrival or charge collected (ToT)
- Combine TimePix with traditional PCB
  - Larger pad size, pitch: ~ 300 μm
  - Connections from pads routed through PCB to ASIC $\rightarrow$ bump bonded to PCB surface



IONIZATION LOSS

- TimePix optimized for low input capacitance (10-100 fF)
- TimePix chip with its small pixels to be connected to readout plane
- Routing on PCB between bump bond pads and charge collection pads is non-trivial



SUMMARY

- Large variety of PID techniques
- Must be adapted to physics goal/reach
- Complementarity
- Hot topics for future (near and far) projects
- Produce own ideas