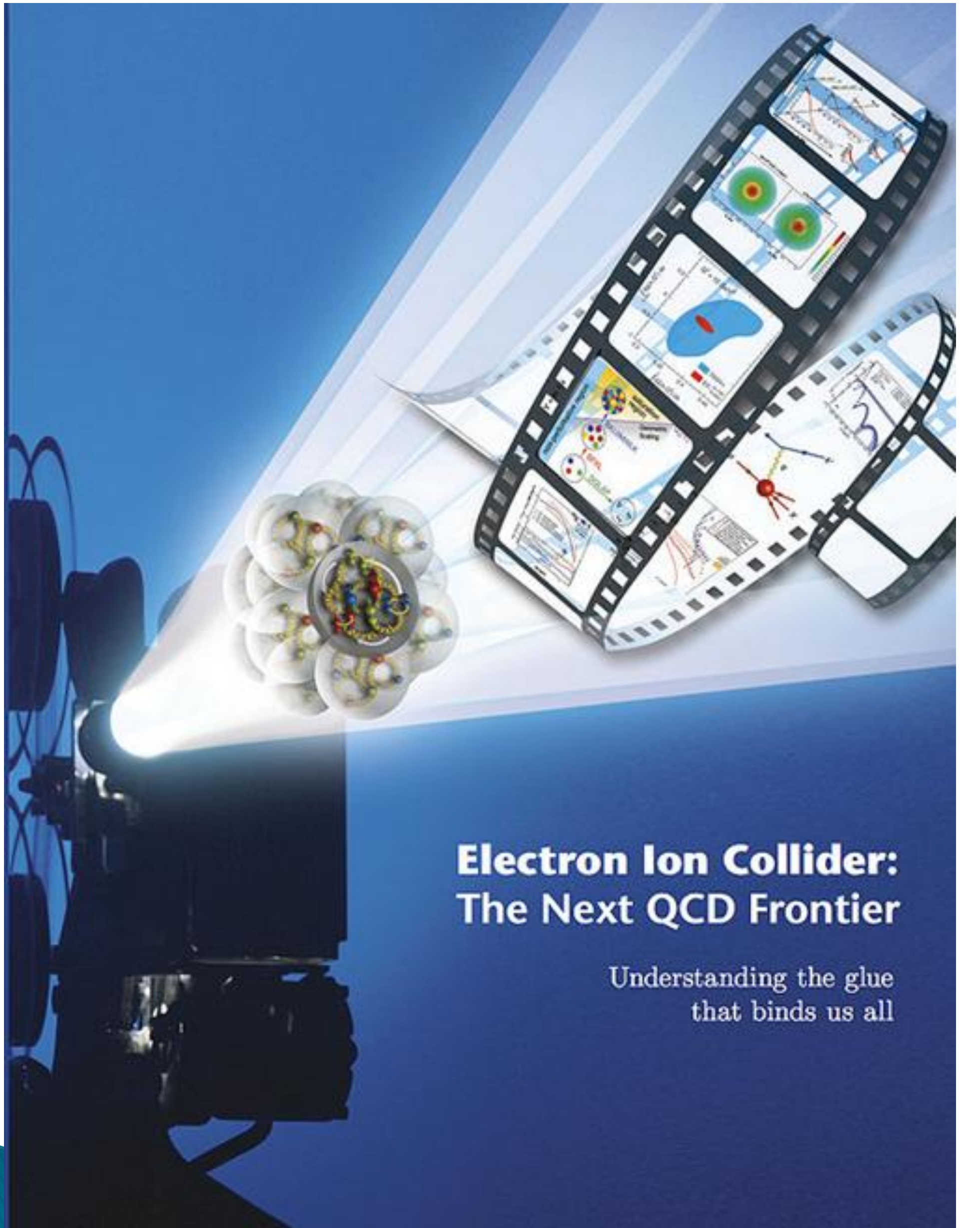


Detectors for an Electron Ion Collider

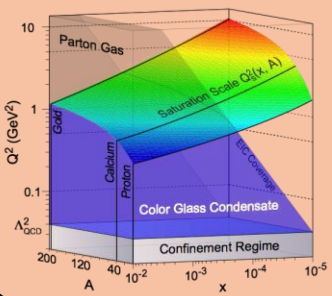
Thomas K Hemmick
Stony Brook University

- RHIC future is viewed by most to center on an "Electron-Ion Collider"
- R&D underway ~few yrs.
- Consortia:
  - Tracking/RICH
    - SBU, BNL, Yale, U Va, Fl Tech.
  - Calorimetry

Today: Overview of "Tracking Consortium" with emphasis on RICH

Most Compelling EIC SCIENCE Questions

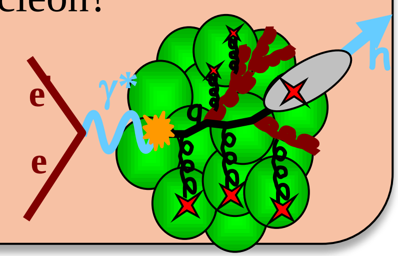
Where does the saturation of gluon densities set in?



- Is there a simple boundary that separates the region from the more dilute quark gluon matter? If so how do the distributions of quarks and gluons change as one crosses the boundary?
- Does this saturation produce matter of universal properties in the nucleon and all nuclei viewed at nearly the speed of light?

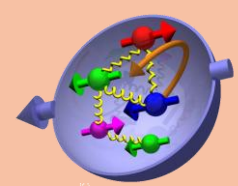
How does the nuclear environment affect the distribution of quarks and gluons and their interaction in nuclei?

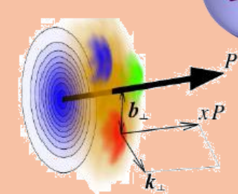
- How does the transverse spatial distribution of gluons compare to that in the nucleon?
- How does matter respond to fast moving color charge passing through it? Is this response different for light and heavy quarks?



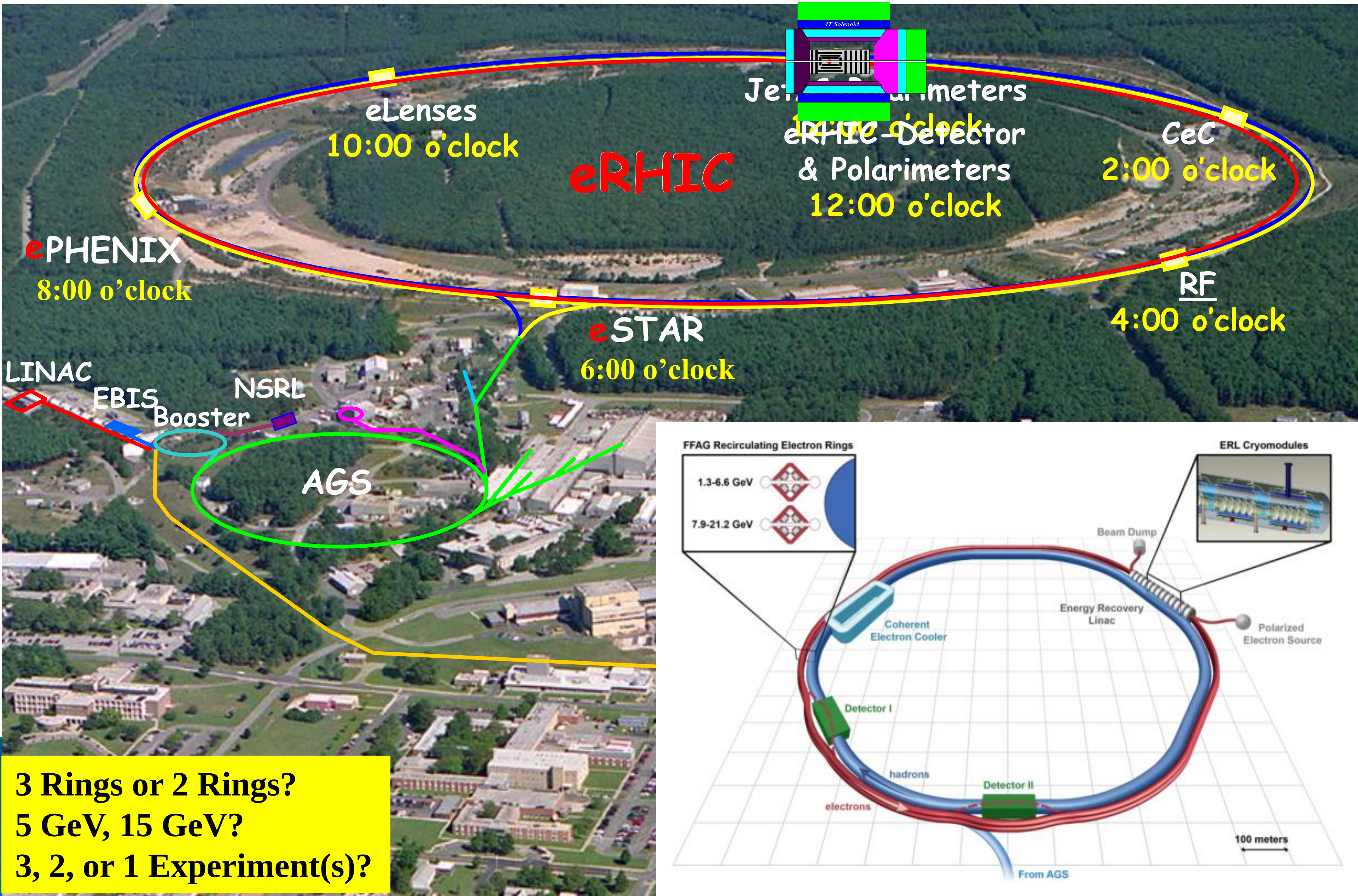
How are sea quarks and gluons and their spin distributed in space and momentum inside the nucleon?

- How are these quark and gluon distributions correlated with the over all nucleon properties, such as spin direction?
- What is the role of the motion of sea quarks and gluons in building the nucleon spin?



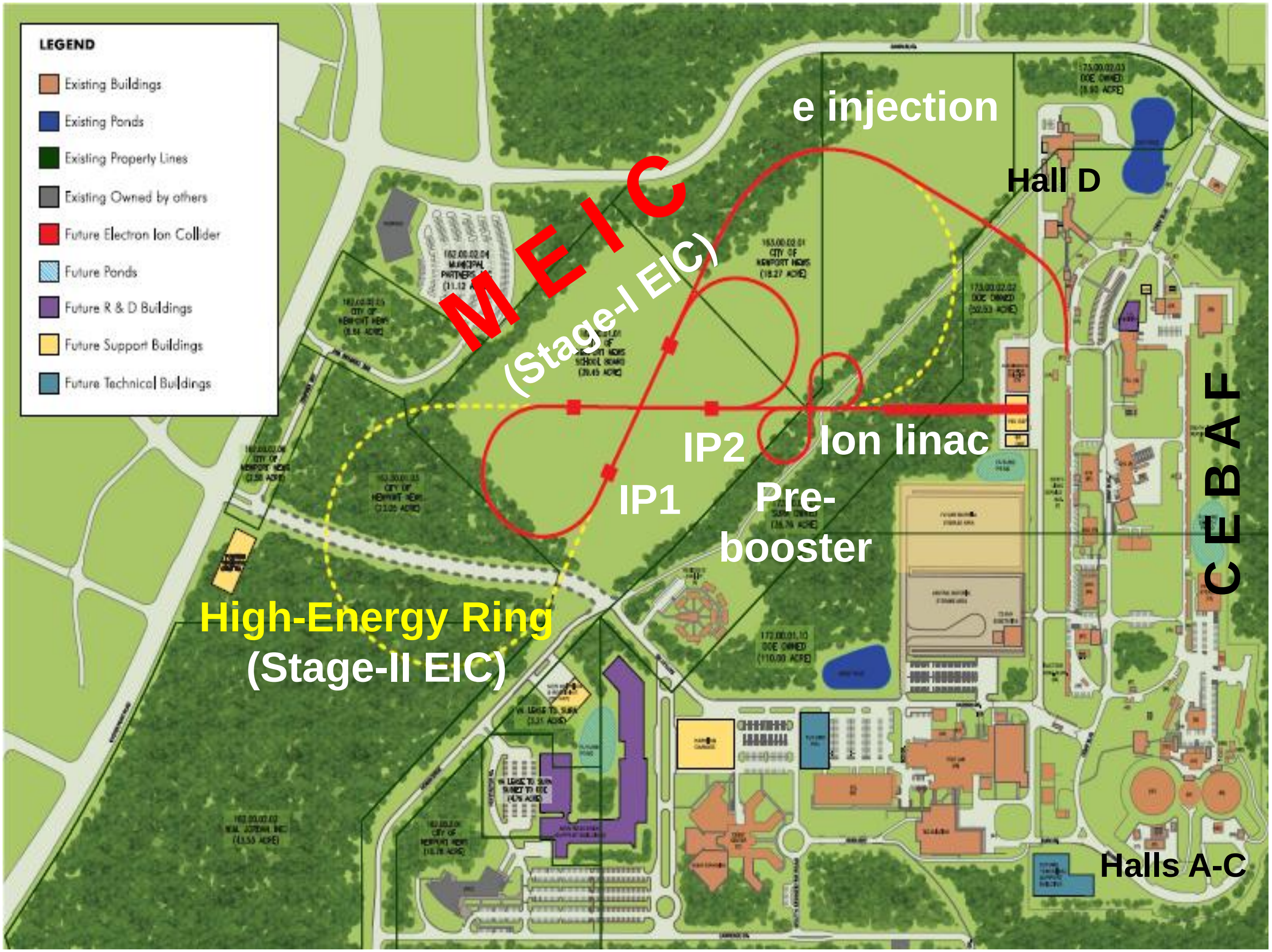


From RHIC to eRHIC



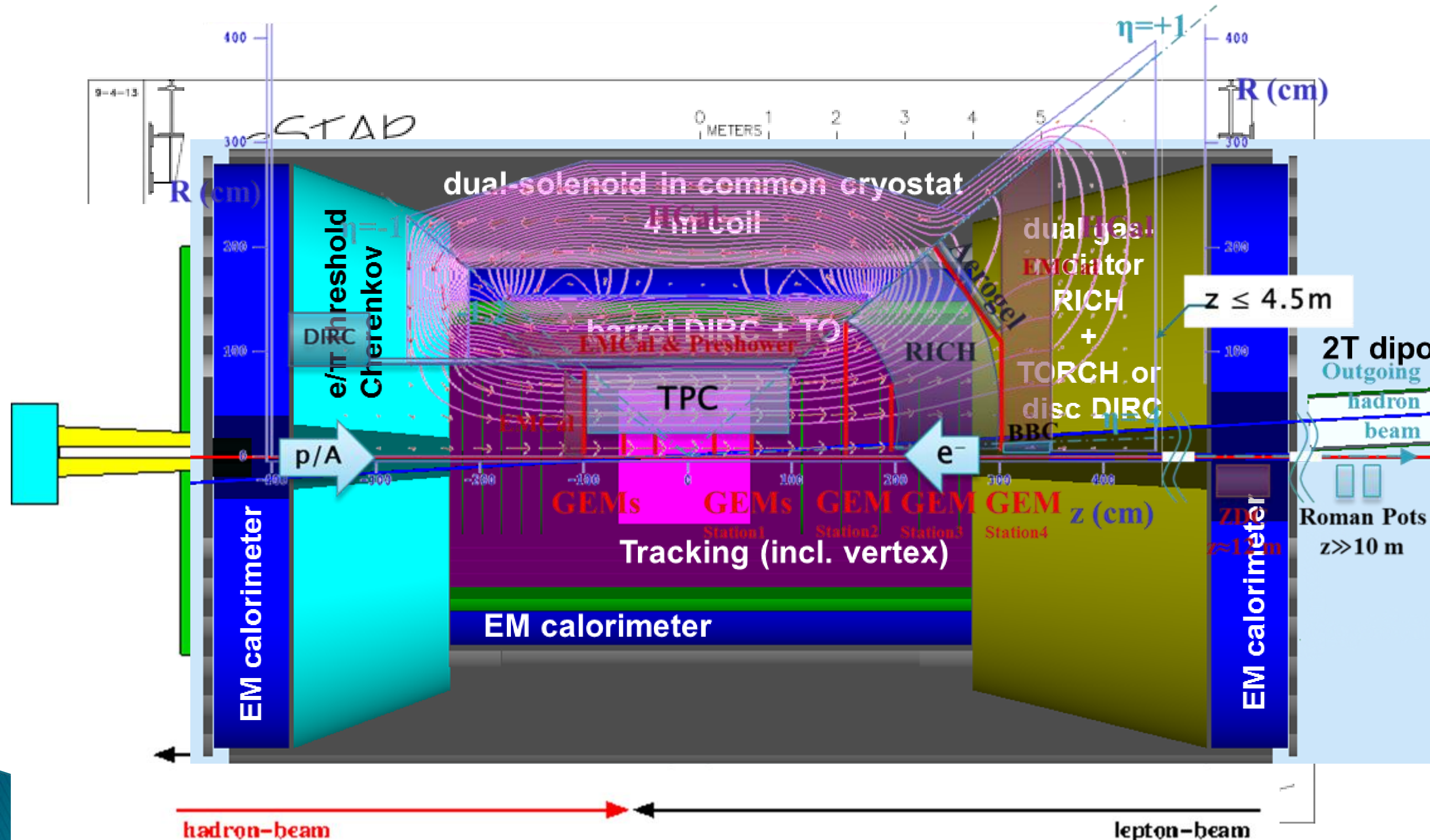
3 Rings or 2 Rings?
5 GeV, 15 GeV?
3, 2, or 1 Experiment(s)?

The EIC at Jefferson Lab



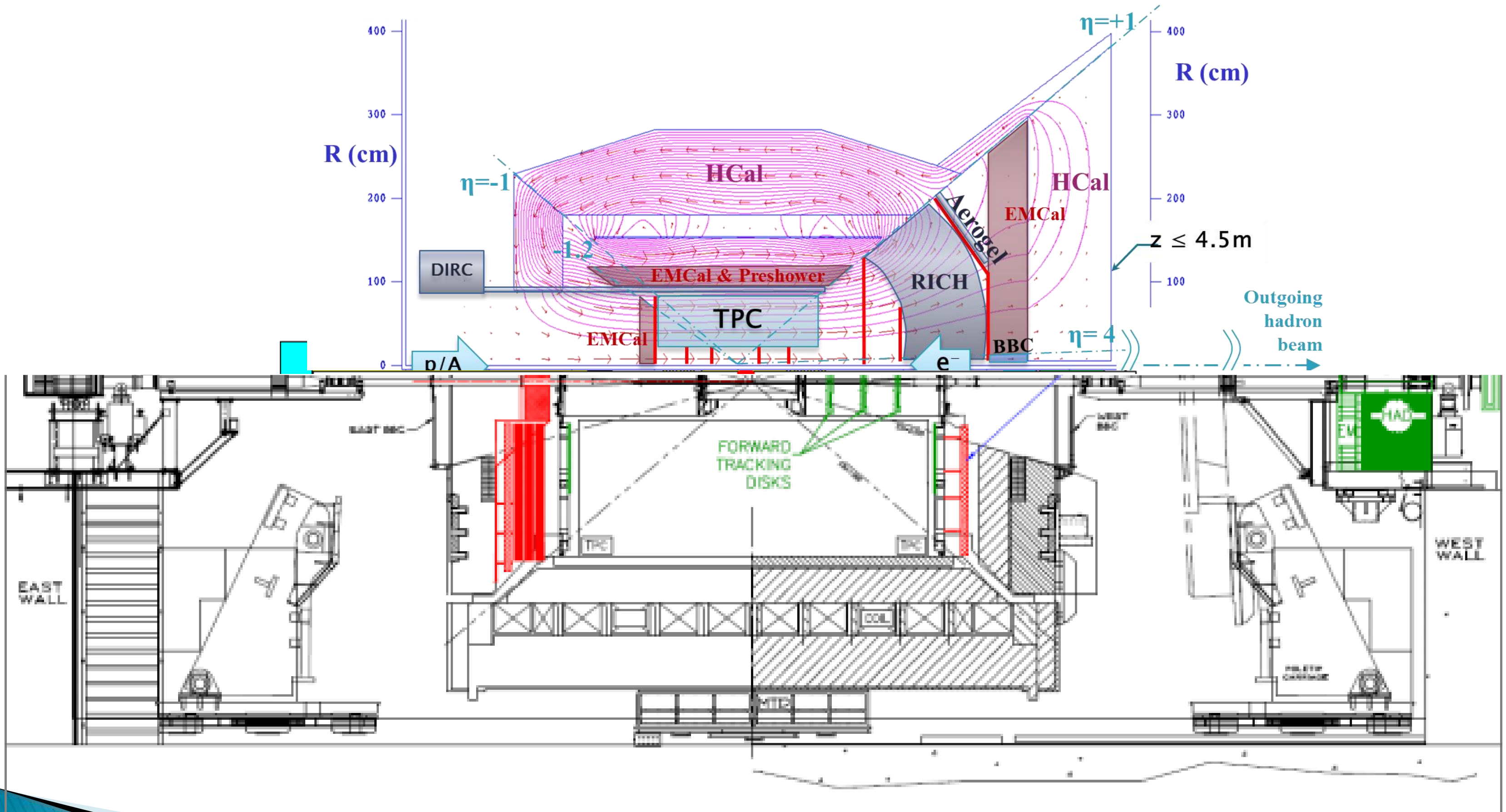
- The MEIC has a circumference similar to CEBAF (1.4 km)

Four Detector Designs

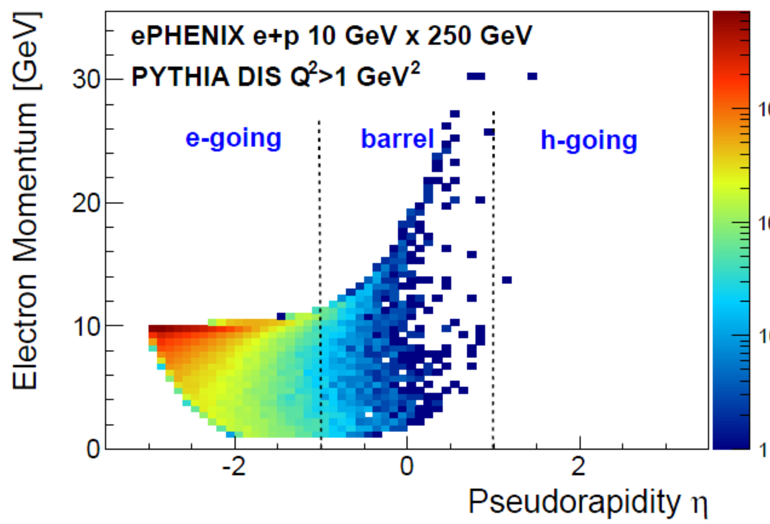


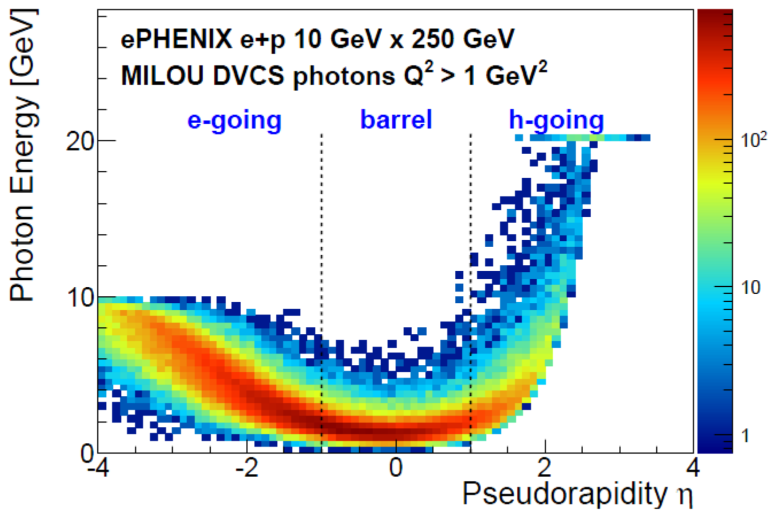
Most designs favor TPC for central tracking due to low momentum PID and low mass

Detector Designs – to scale

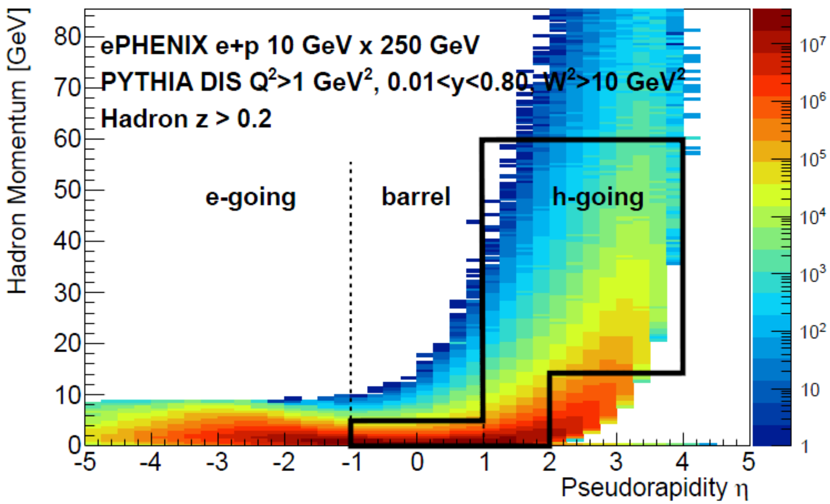


Measure what comes out!



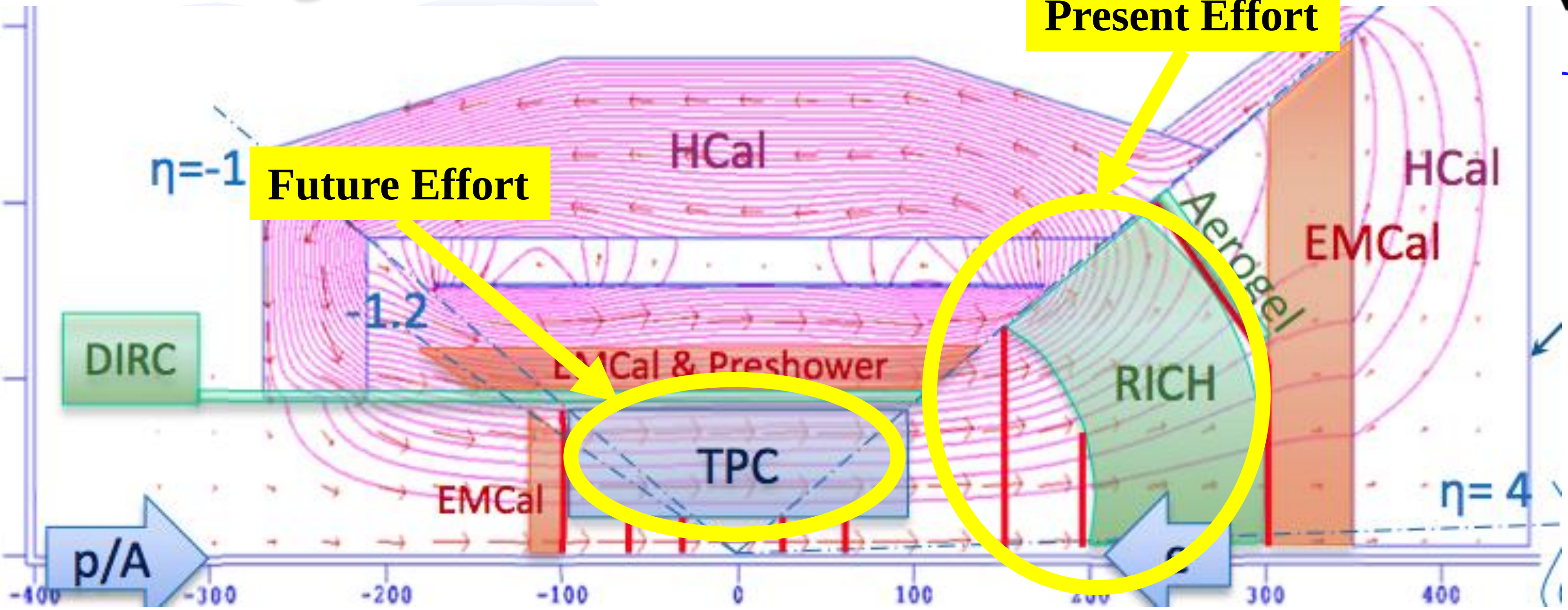


- ep (eA) HIGHLY asymmetric.
- Moderate momenta for ALL species mid- and negative-η.
- At mid-rapidity principally low momentum:
  - dE/dx at lowest p.
  - DIRC to extend to ~8 GeV
- Fwd η <u>BIG challenge</u>
  - Hadron ID req'd to 60 GeV/c!!

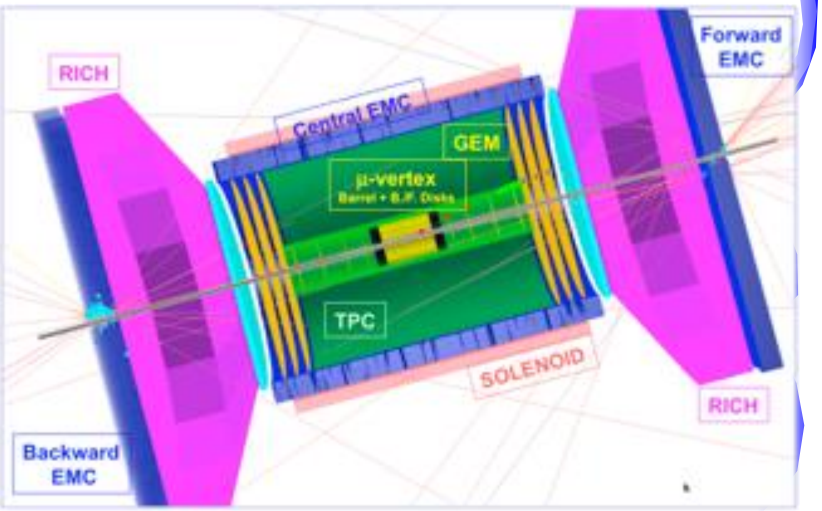


Ring Imaging Cherenkov is only known technology with required momentum reach!

Tracking & RICH



- "Forward" region requires:
  - Planar tracking chambers.
  - High Momentum PID Device.
- Prototypes placed in test beam address issues for:
  - Planar GEM-based trackers.
  - Ring-Imaging Cherenkov (RICH)
- Future has TPC!



RD6: Tracking/PID Consortium

Shift Crew 1

Shift Crew 2

Note: Photo shows Beam Shifters only!

Test Beam Oct 2014:
BNL
Florida Tech
Stony Brook University
Thomas Jefferson Lab
University of Virginia
Yale University

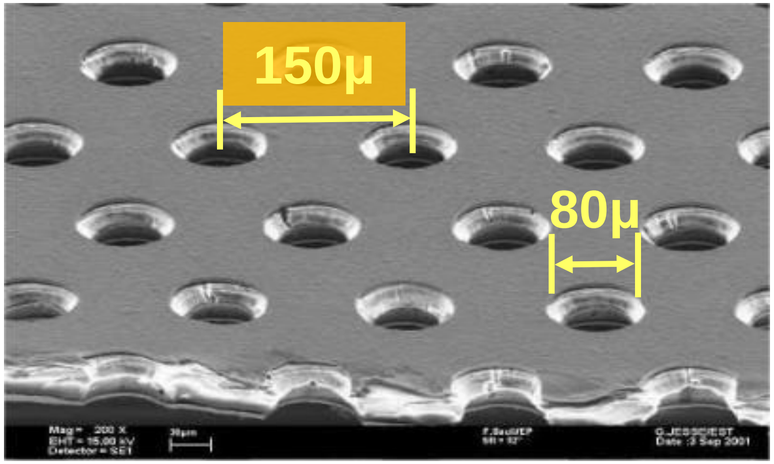
New members (TPC)
LLNL, WIS, LBNL

Principle Focus of "Consortium" Research

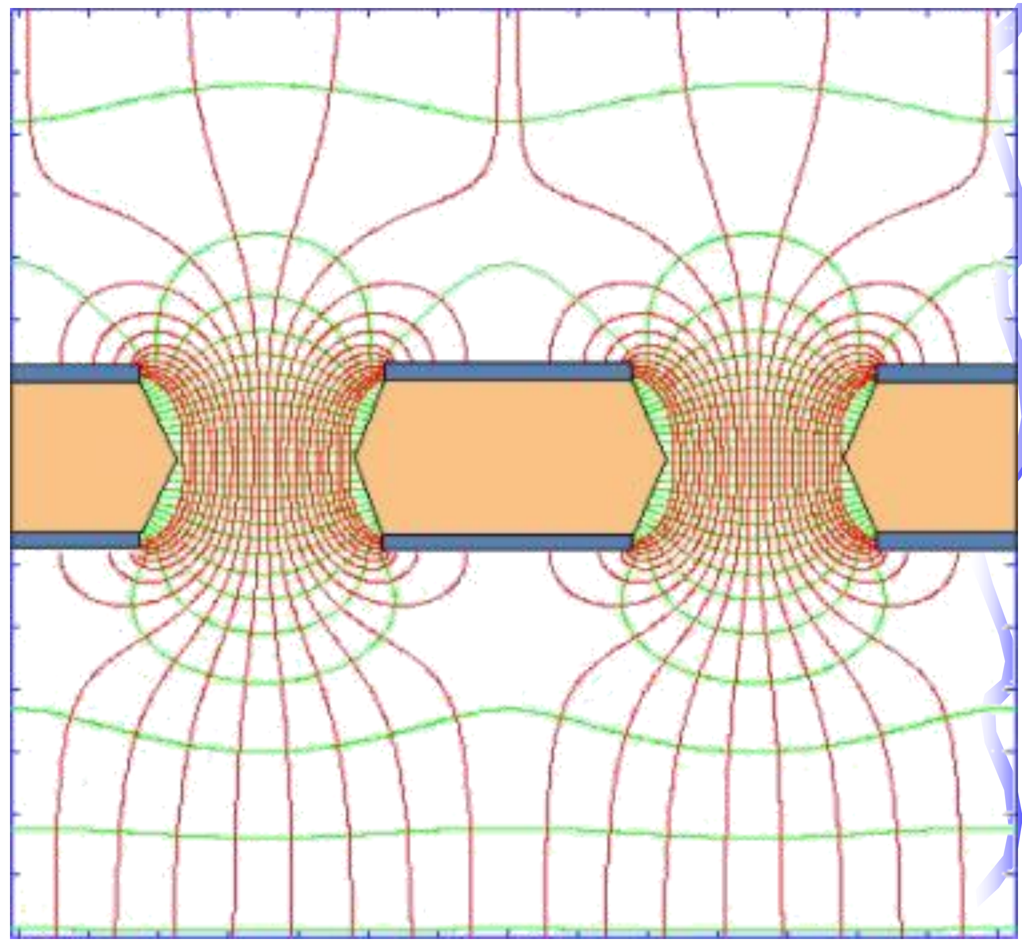
- End-Cap R&D (subject of test beam)
  - Mini-drift GEM chambers:
    - BNL; overcomes degradation of resolution with angle.
  - 3 Coordinate Readout:
    - Yale; X-Y-U match charge & geometry to reduce channel counts
  - Large GEM chambers:
    - UVA; Small angle stereo chamber "Compass Style"
    - FIT; Zig-zag & Stretched foils eliminates spacers.
  - Compact RICH:
    - SBU; CsI/GEM & dielectric mirror reduces radiation 3m→1m
- Barrel R&D (upcoming)
  - TPC with HBD
    - BNL, SBU, Yale
  - New this year: Large TPC (LLNL, WIS).

Common Technology: Gas-Electron Multiplier (GEM)

Gas Electron Multiplier for PHOTONs!

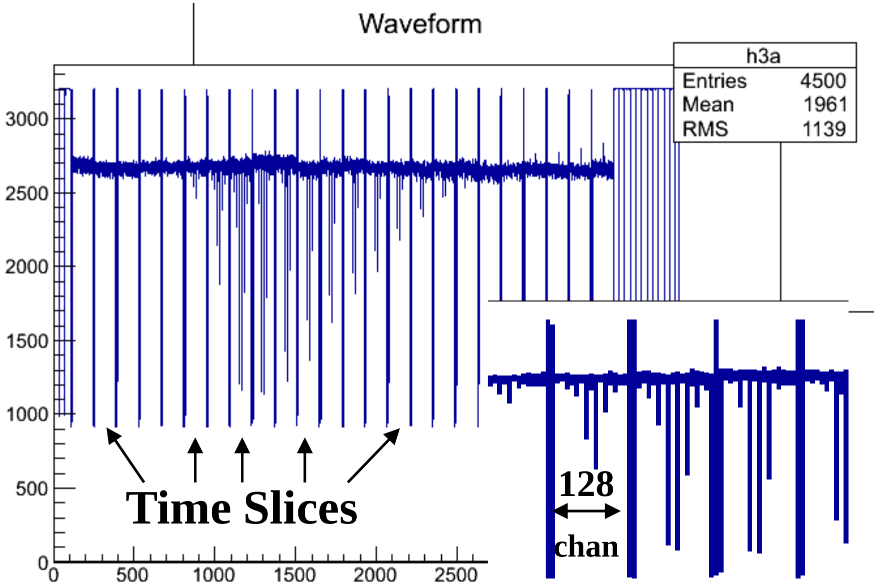


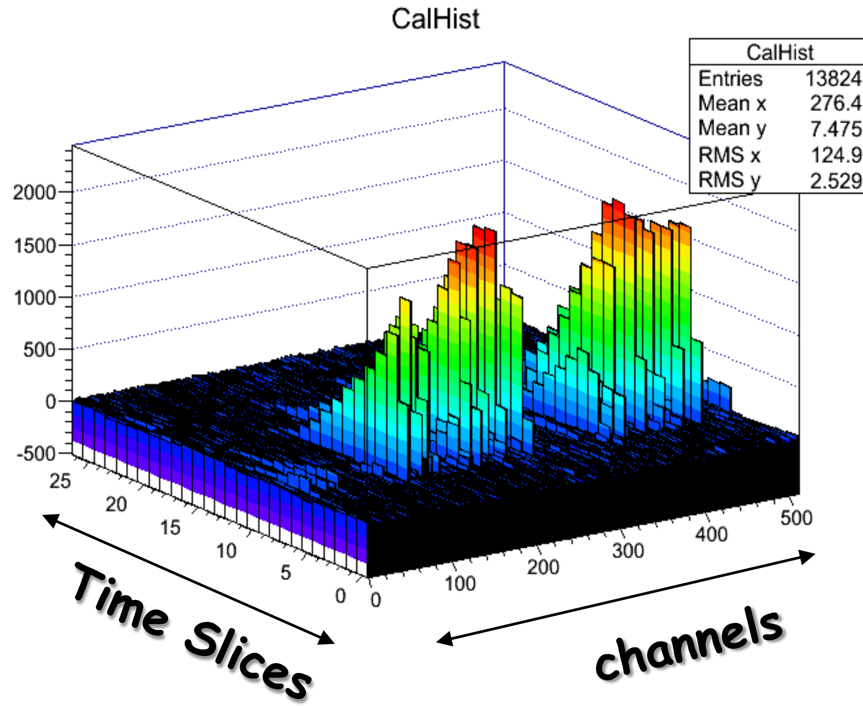
- The original idea by F.Sauli (mid 90s) US Patent 6,011,265
- Traditionally CHARGED PARTICLE detectors (not photons)



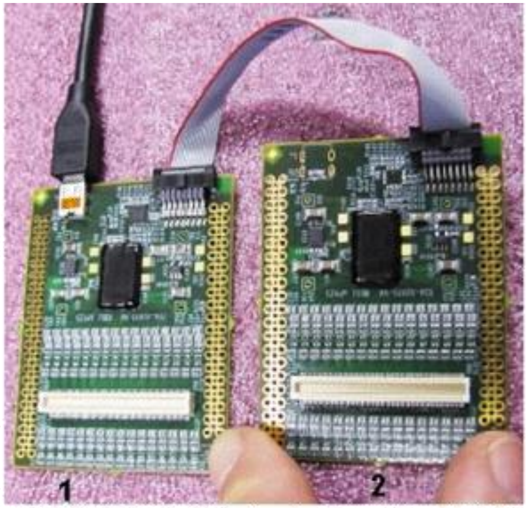
- Two copper layers separated by insulating film with regular pitch of holes.
- HV creates very strong field such that the avalanche develops inside the holes
- Multiple devices can be stacked to increase gain.

SRS Readout for Test Beam (inexpensive)



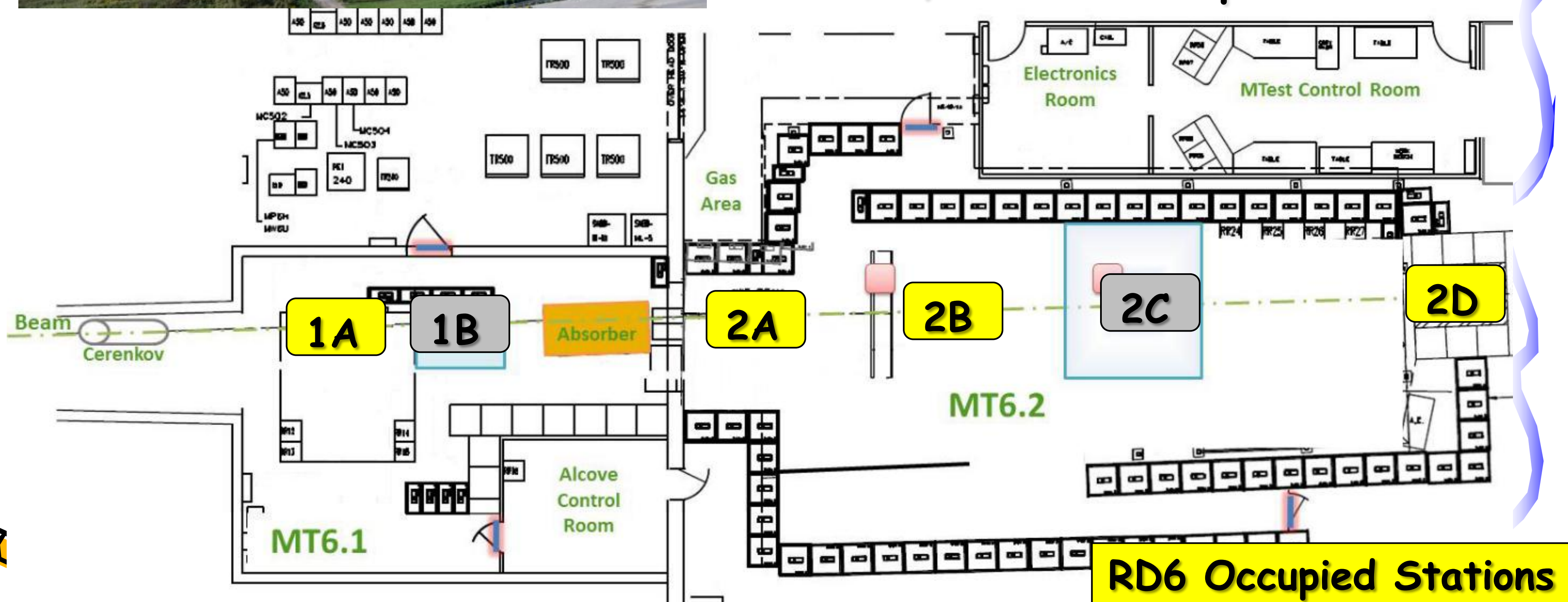


- APV25 chip:
  CMS;128-chan Analog pipeline
- Flash digitized, read through Gbit Ethernet to PC.
- 2048 chan system ~5000 chf



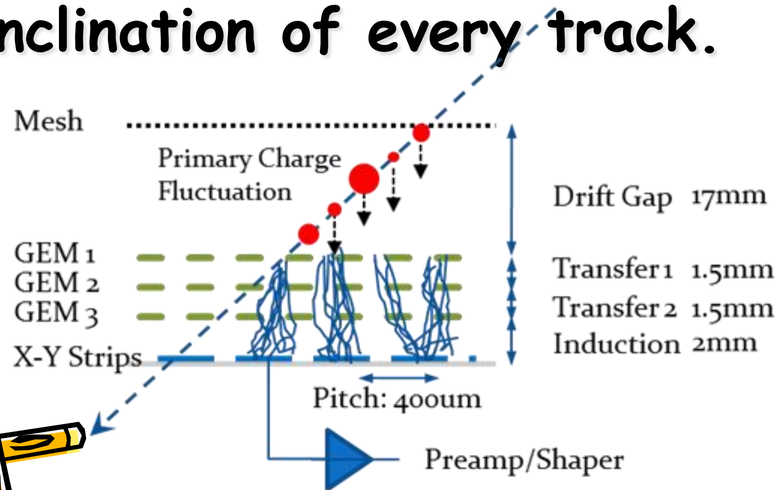
Fermilab Test Beam Facility

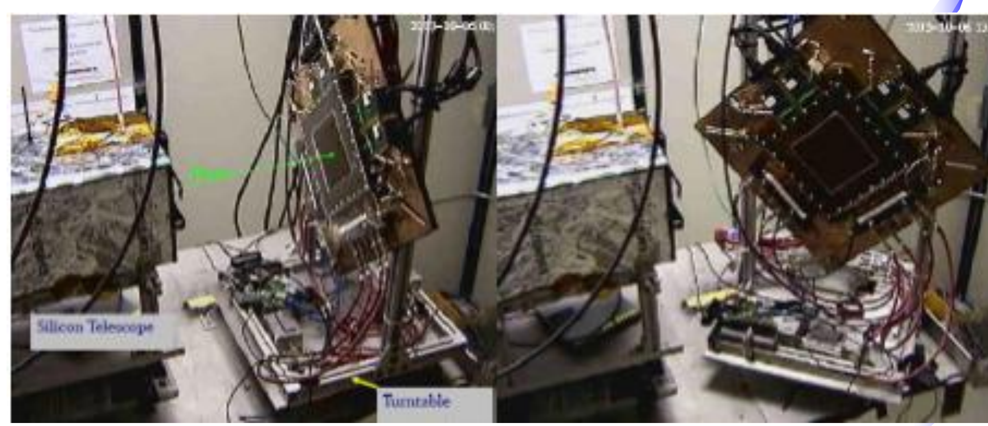
- "Meson Hall" repurposed.
- Beam(s)
  - 120 GeV protons (primary)
  - 1-32 GeV $\pi K p$ (ds-target)
  - 8-66 GeV π (us-target)
- 4 sec spill once per minute.
  - 10,000 counts/spill



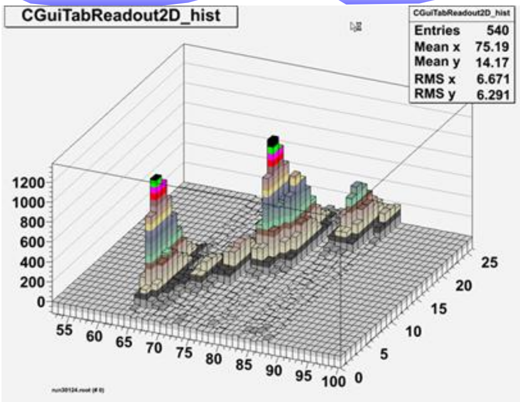
MT6 1A – Minidrift GEM chamber

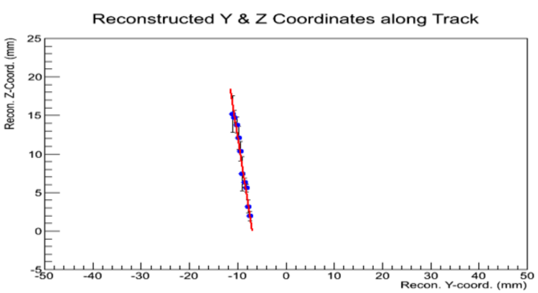
- **Challenge:**
  Standard GEM tracking chambers have their resolution deteriorate with non-normal incidence.
- **Approach:**
  Raising the grid above the first GEM allows each chamber to measure a vector to correct for the inclination of every track.

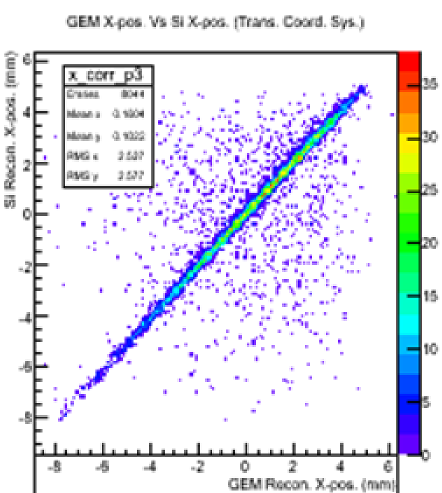


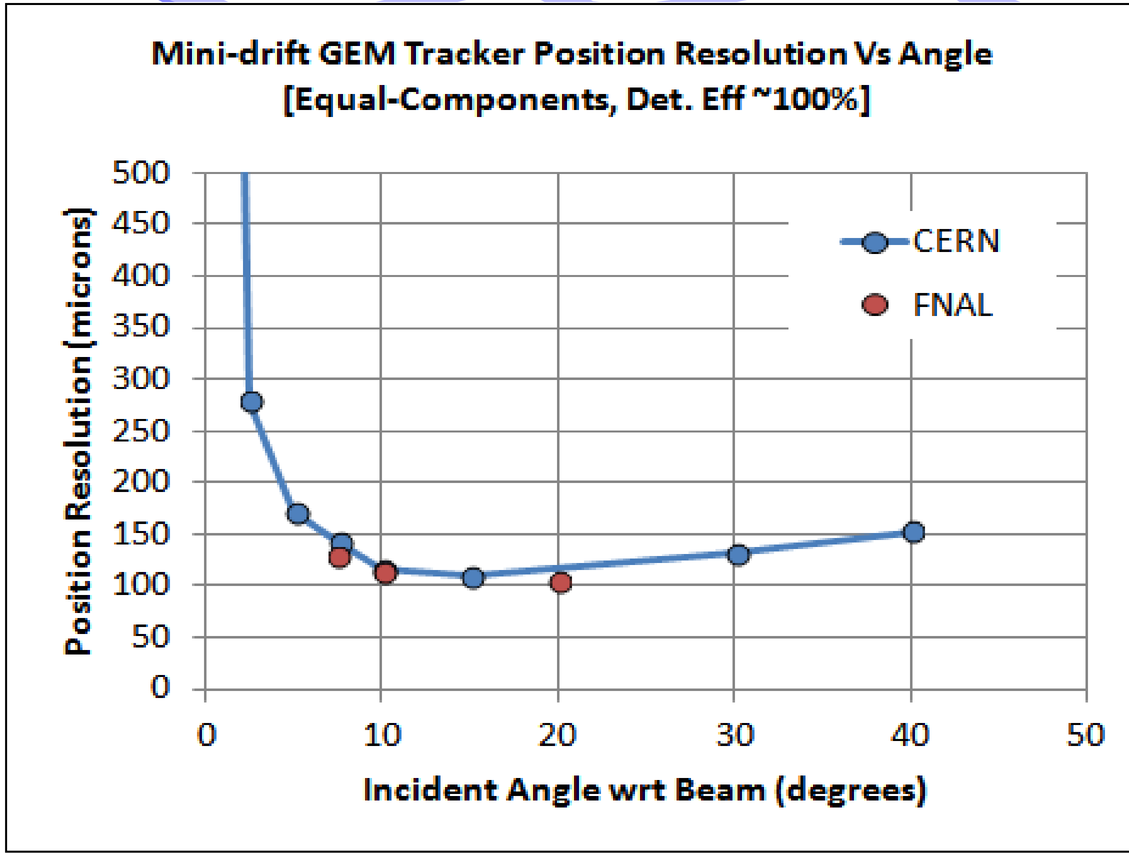


MT6 1A: Mini-Drift Principle Works.





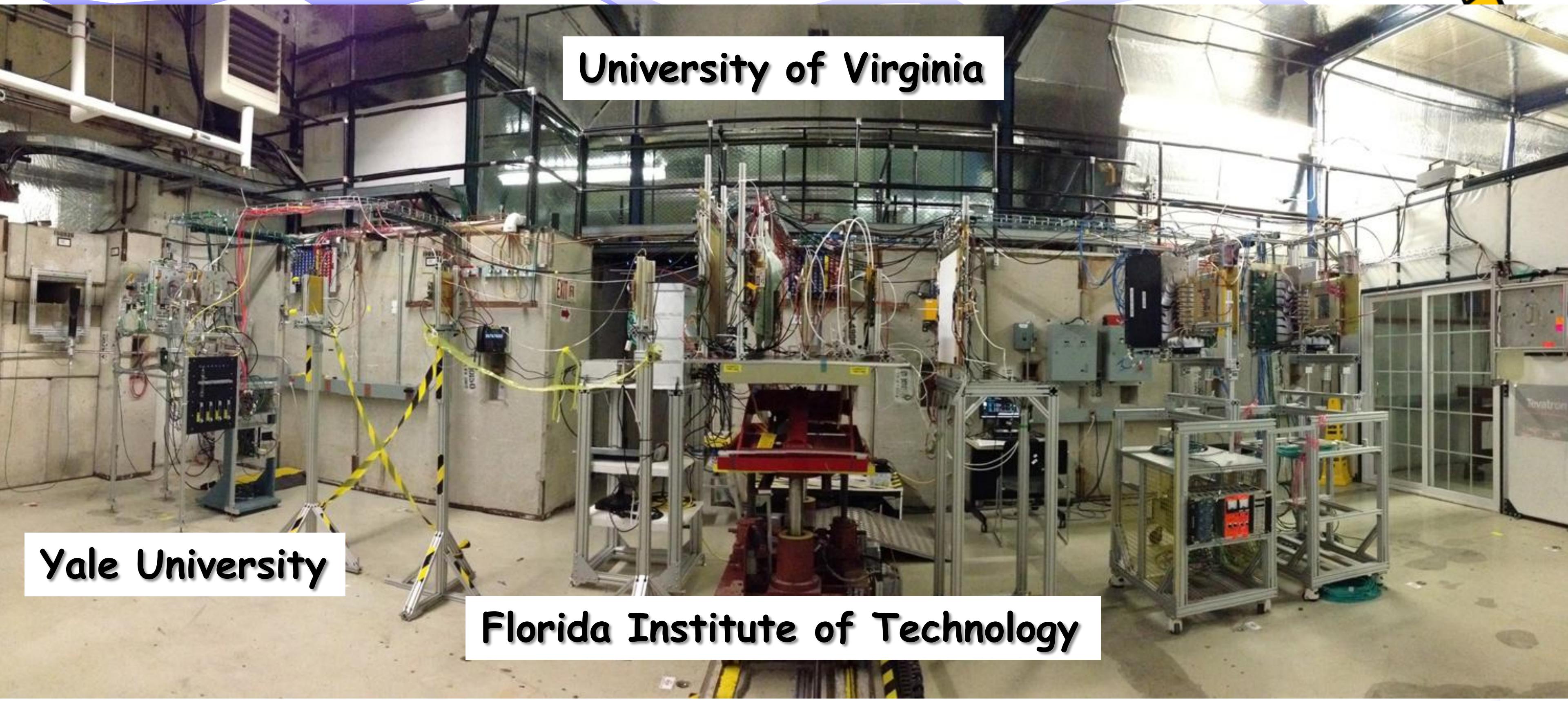




- CERN: Resolution limited by Reference.
- FNAL uses Silicon Tracker Reference.
- FNAL @ 20° = 104 μm (vs 118 μm)!

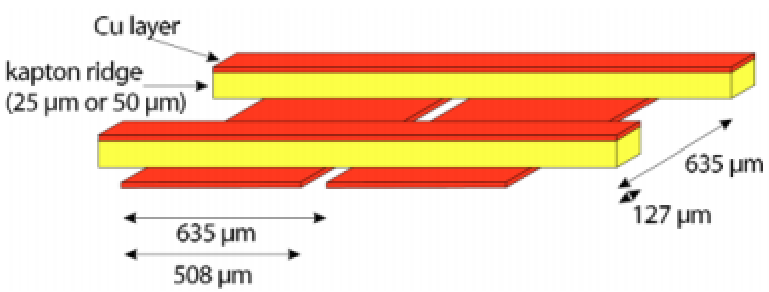
NOTE: Mini-Drift can be added to any chamber.

MT6 2A and 2B

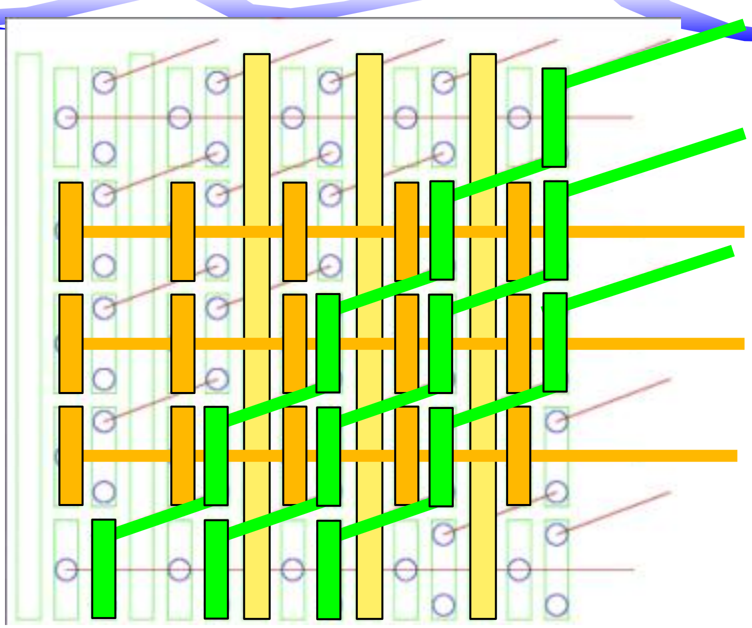


- Extensive setup of trackers at station 2B
- Testing new readout schemes.
- Testing largest area GEM detectors built in the US.

MT6-2A 3-coordinate readout



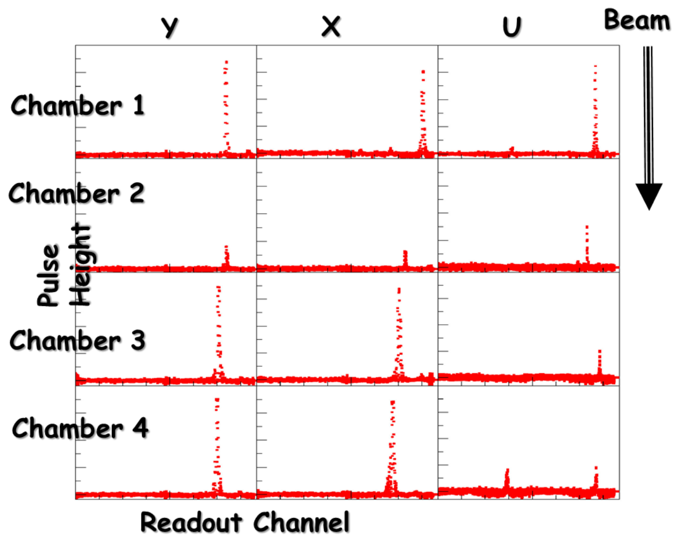
Standard Cartesian Readout
- "Compass Style"
- XY Hit Matching by Charge

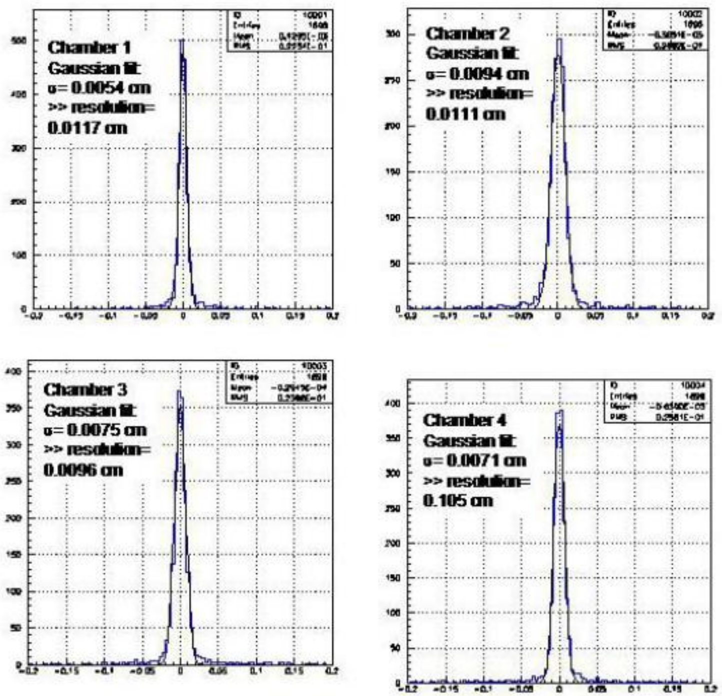


New 3-coordinate Readout
-Hit matching: GEOMETRY & CHARGE

- Challenge:
  Cartesian Readouts can lead to ambiguities in X-Y associations for high multiplicity events.
- Solution:
  3 coordinate readout made on double-sided kapton.
- Goal:
  Increased tracks per "patch" reduces channel count.

MT6 2A





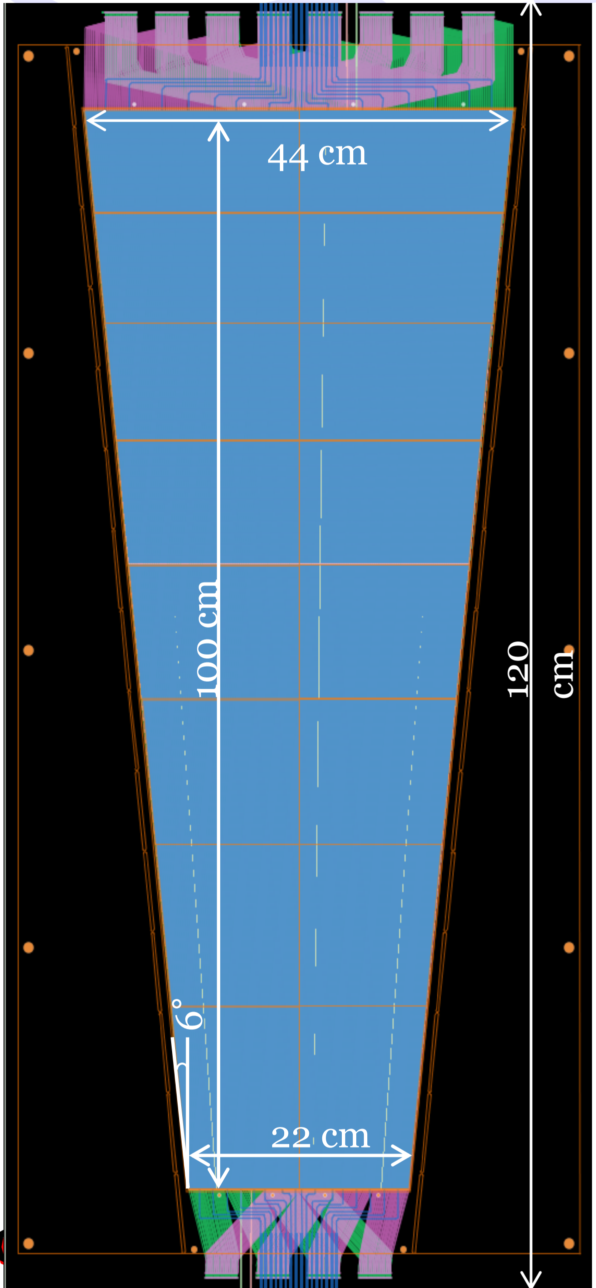
- Event display – four single plane 3-coordinate GEM Chambers
- Single track fires x,u,y in all planes.

- X-residuals in four chambers.
- Resolutions from 97-117 μm.
- Result is superb since the readout pitch is coarse.
- Further analysis to determine maximum hits per region.

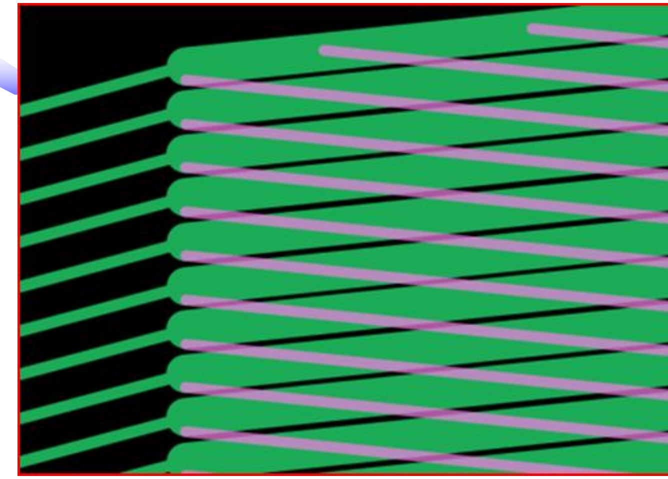
MT6 – 2B Large Area Tracking Chambers

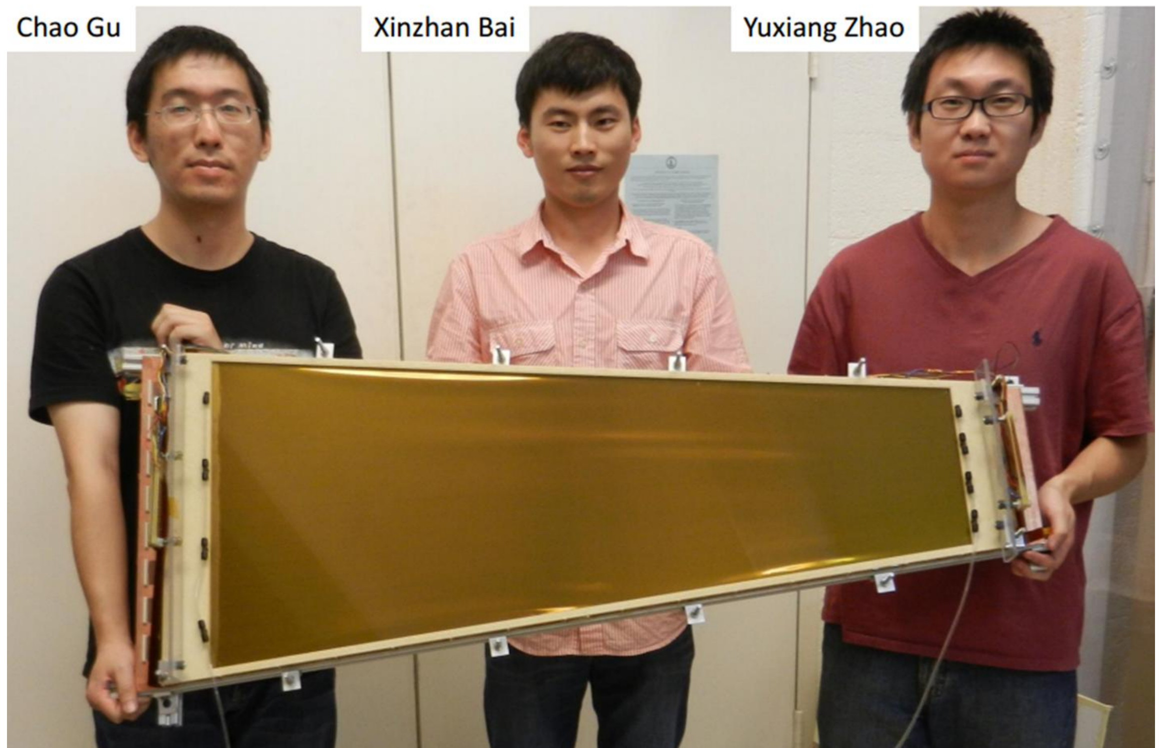
- **Challenge:**
  GEM detector technology must be expanded in size to be useful in large experiments. Other than at CERN, these are the largest area GEM trackers in the world.
- **Furthermore:**
  Alternative Readout using ZigZags & "Stereo-Compass"

"Stereo Compass"



- Strips @ 12º stereo
- Full-sized for EIC.
- Largest "Compass-style" ever produced.





Some Results on Large Compass-Style Chamber

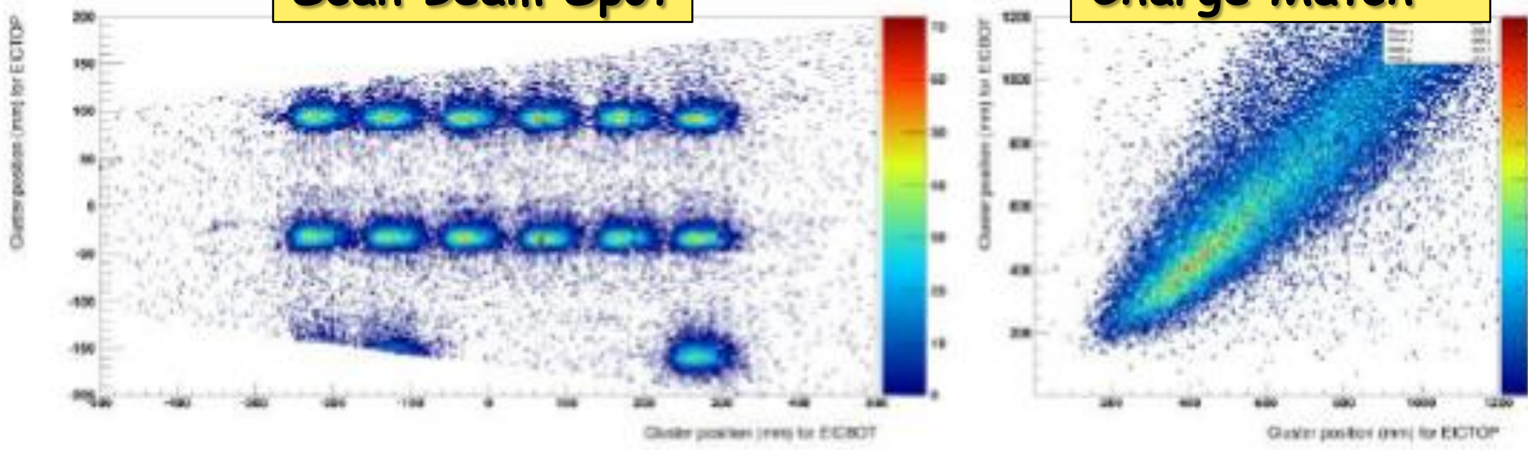


Figure 29: 25 GeV Hadron beam position scan (left); u-v strips charge sharing correlation (right).

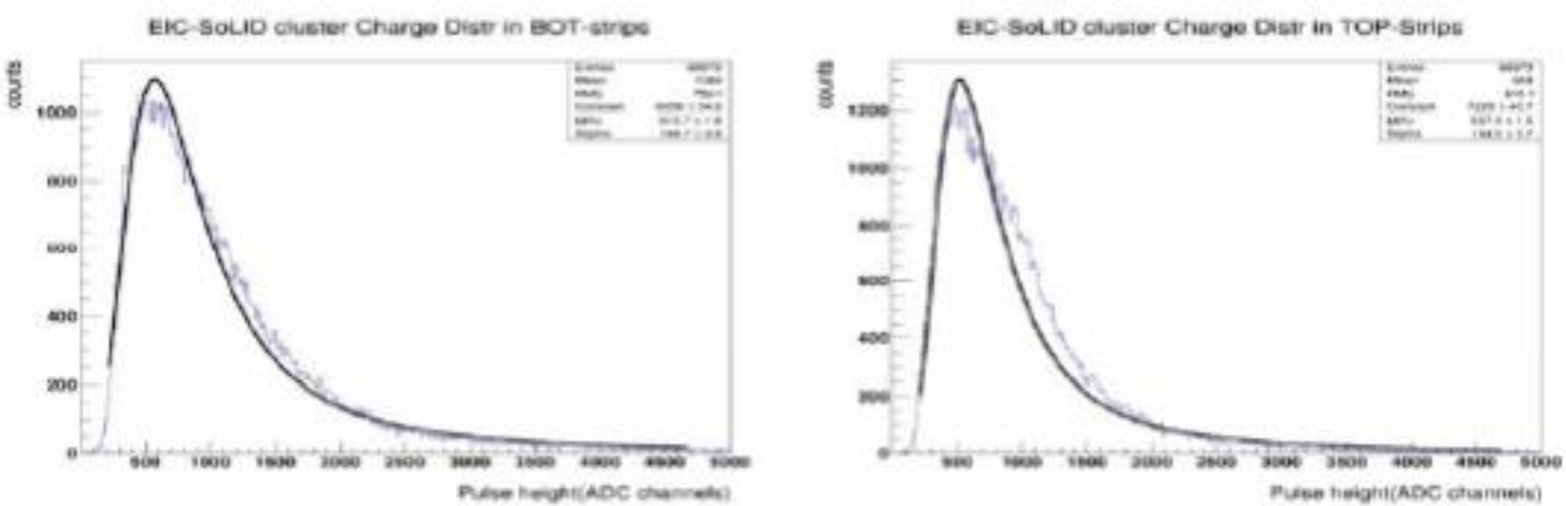
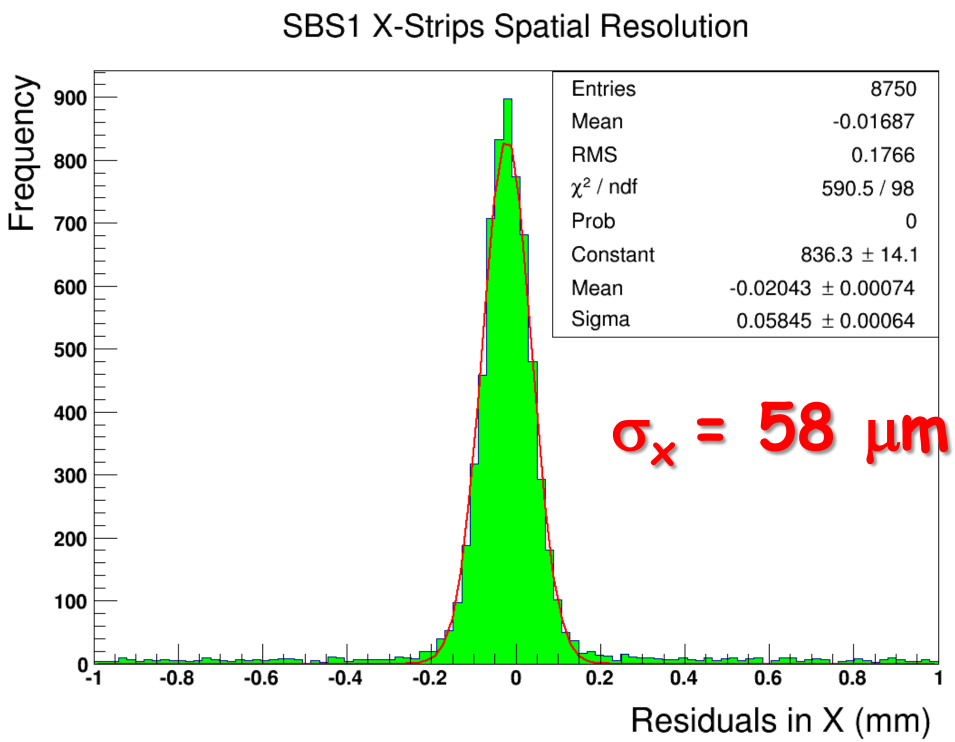
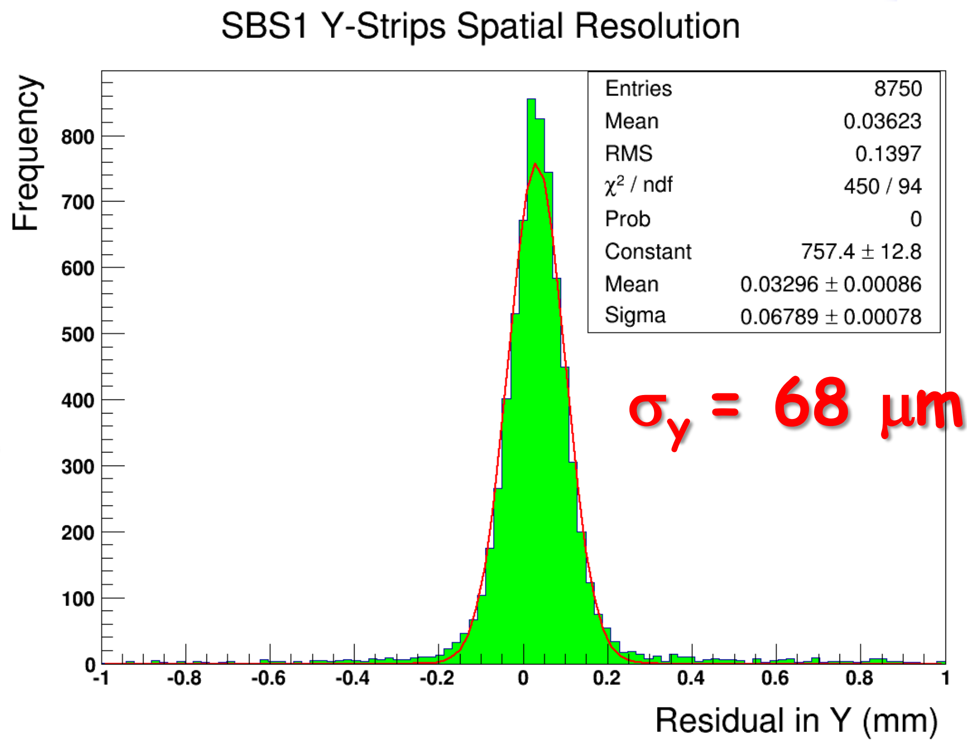


Figure 30: cluster charges distribution with Landau fit on v-strips (left) and u-strips (right).

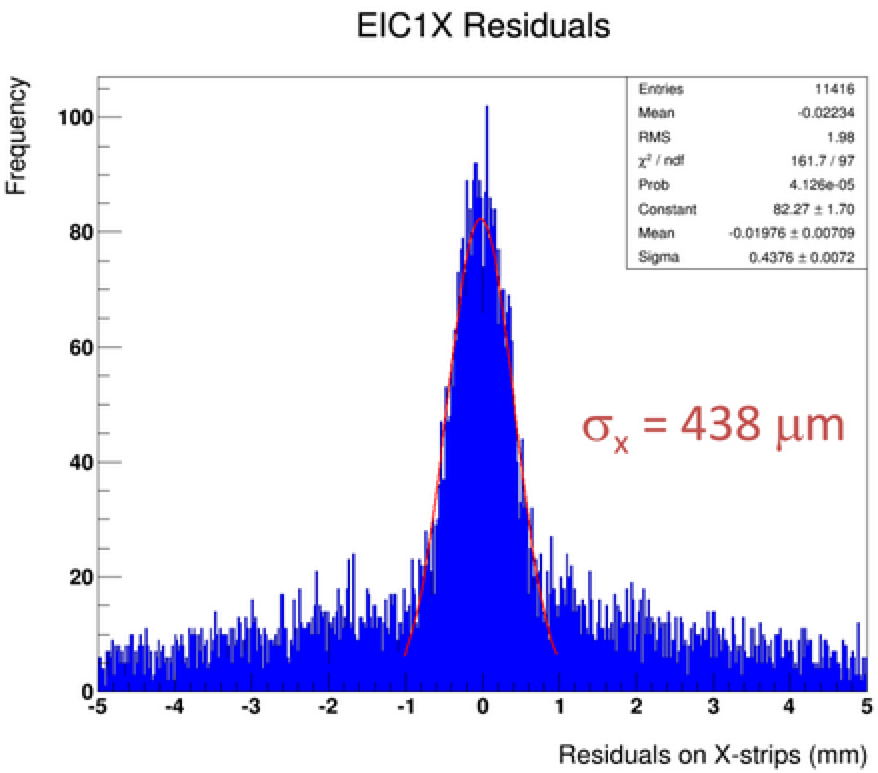
Spatial Resolution of SBS1

- **Combined distribution** : Exclusive and Inclusive residual distribution are merged
- **Resolution:** Width ($\sigma_{resolution}$) of the Gaussian fit to the combined residual distribution
- **Resolution:** $\sigma_{resolution} = sqrt(\sigma_{exclusive} \times \sigma_{inclusive})$





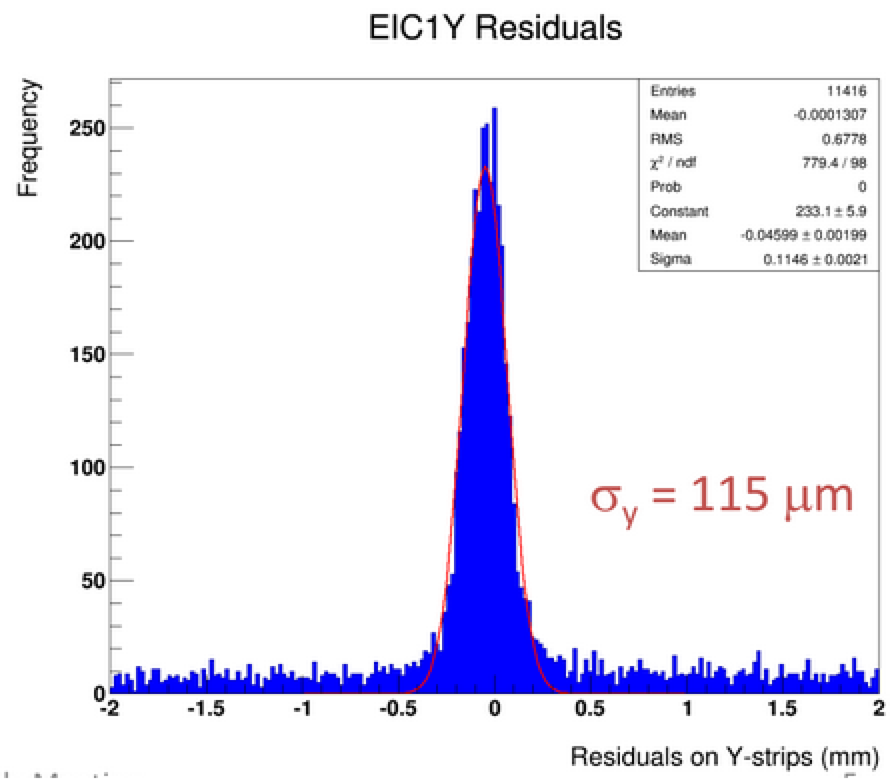
120 GeV Proton: Residuals of the EIC-SoLID with 430 mm



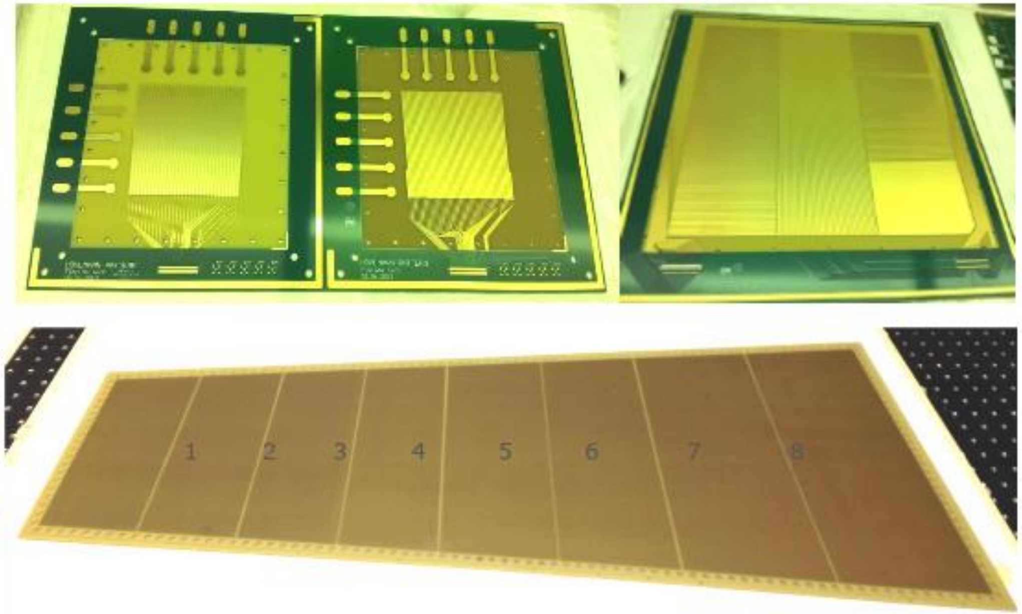
Now with the correct dimensions:

Large base: 430 mm, Stereo angle: 12.14°

Double pic in Y residual distribution is gone



Zig-Zags (aka Chevrons)

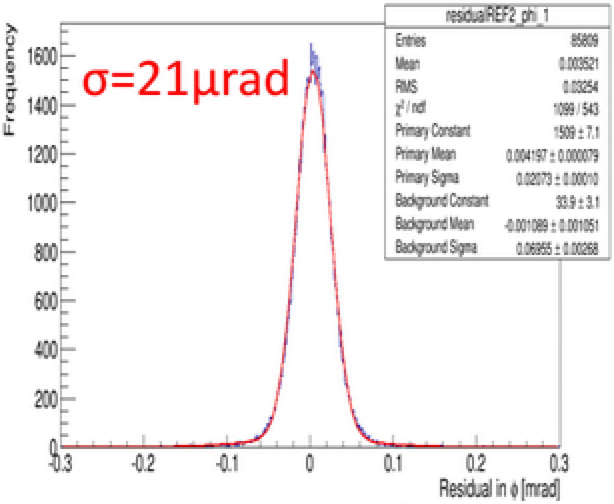


- Various patterns measured with cosmics in small chambers lead eventually to single choice for wedge chamber.

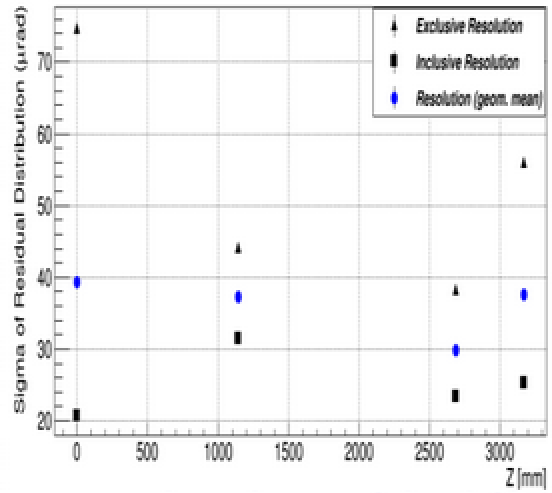
- HUGE savings in channel count.
- High resol. Only in bend direction, coarse in η.

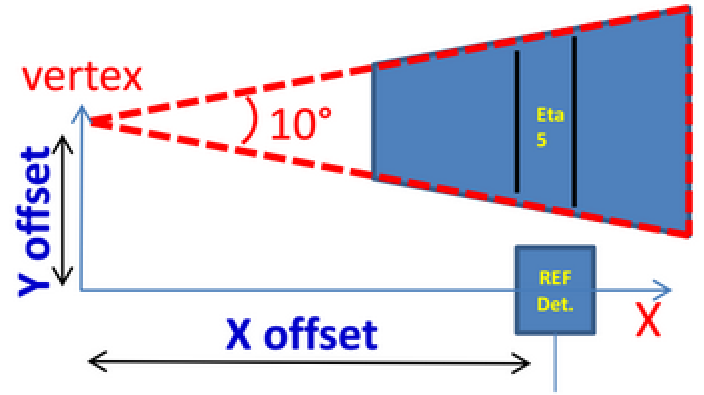
Tracking method for the zigzag GEM detector

Inclusive residual for 1st tracker



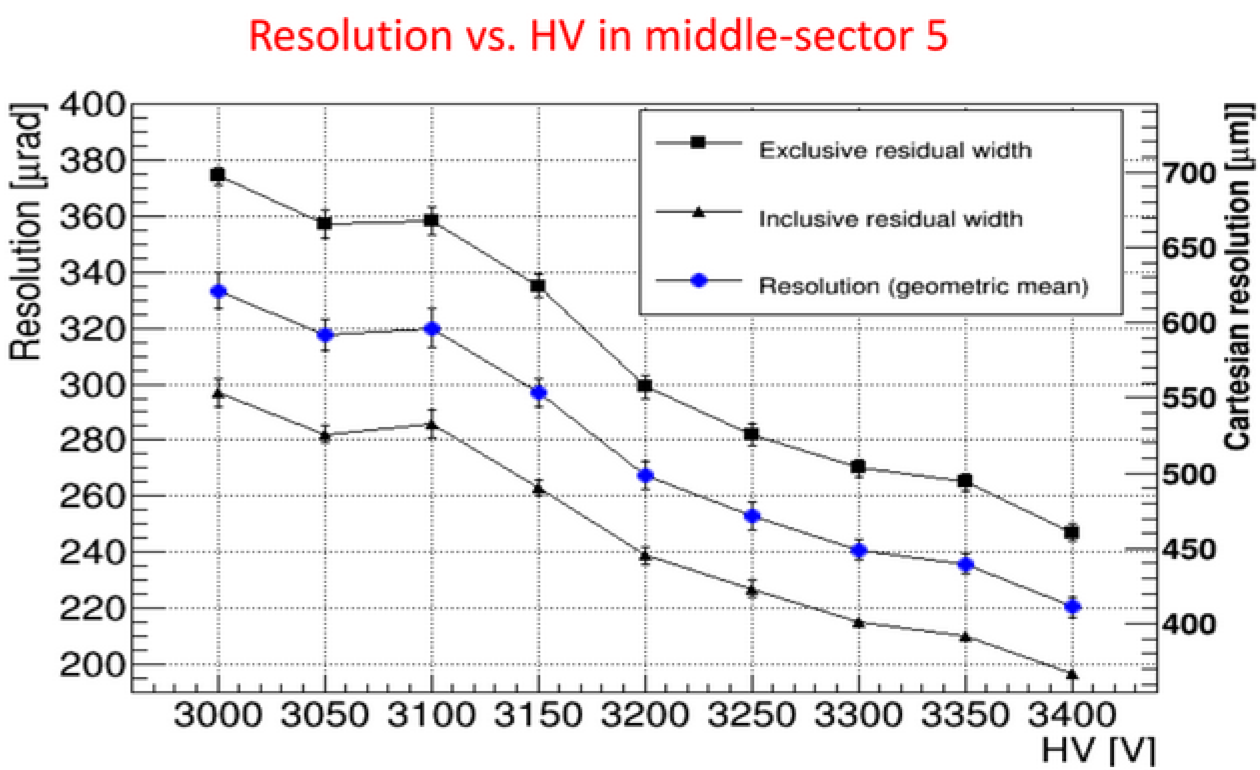
Resolution in φ for trackers





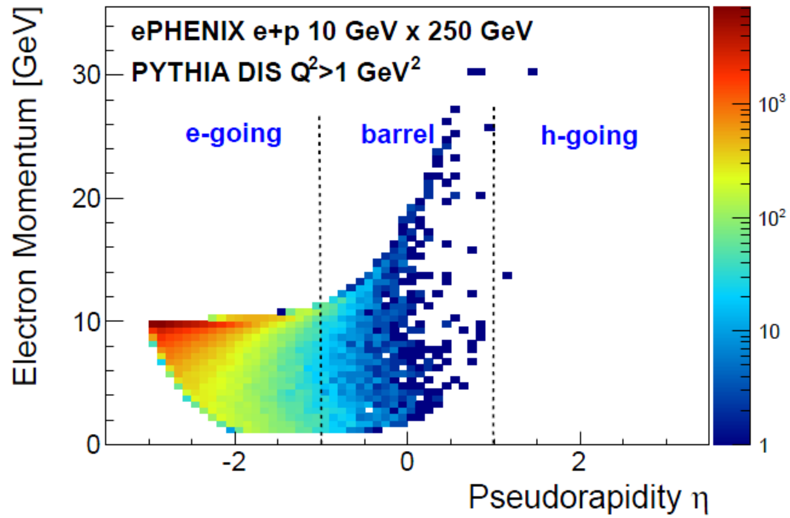
- After aligning the trackers to each other with shifts and rotations, they are giving resolutions around **70μm** (the typical spatial resolution for GEM detectors) in both X and Y.
- The radial zigzag strips have a pitch of 1.37mrad, so we study the resolution in its natural polar coordinate (φ).
- Tracking in polar system was demonstrated to be working as well as in Cartesian system. The trackers have azimuthal resolutions around **30μrad**.
- The φ resolution of the zigzag GEM detector can be studied if its vertex is taken as the origin of the tracking system. **(X,Y) offsets** need to be optimized for the trackers to match that origin.

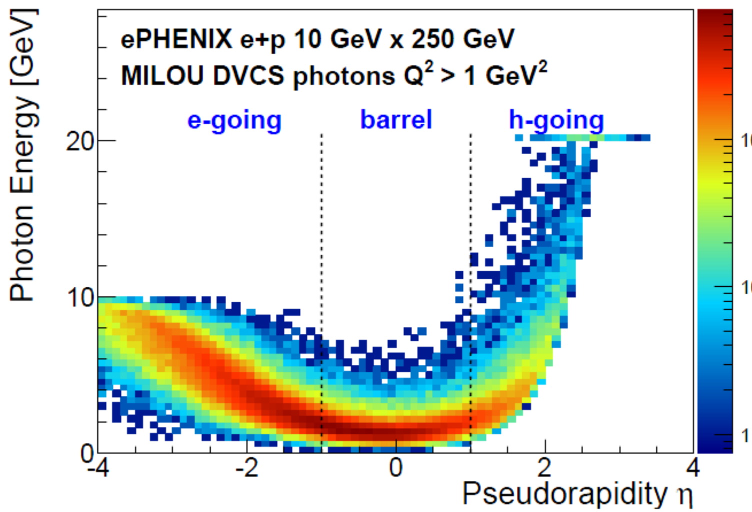
Spatial resolution results for the zigzag GEM detector



- The resolution of the detector is calculated as the geometric mean of the exclusive and inclusive residual widths: $\sigma = \sqrt{\sigma_{ex} \times \sigma_{in}}$
- Resolution @ 3300V is **(241±3)μrad** (17.6% of strip pitch), which corresponds to **(449±6)μm** at R=1866mm.

Measure what comes out!





- ep (eA) HIGHLY asymmetric.
- Moderate momenta for ALL species mid- and negative-η.
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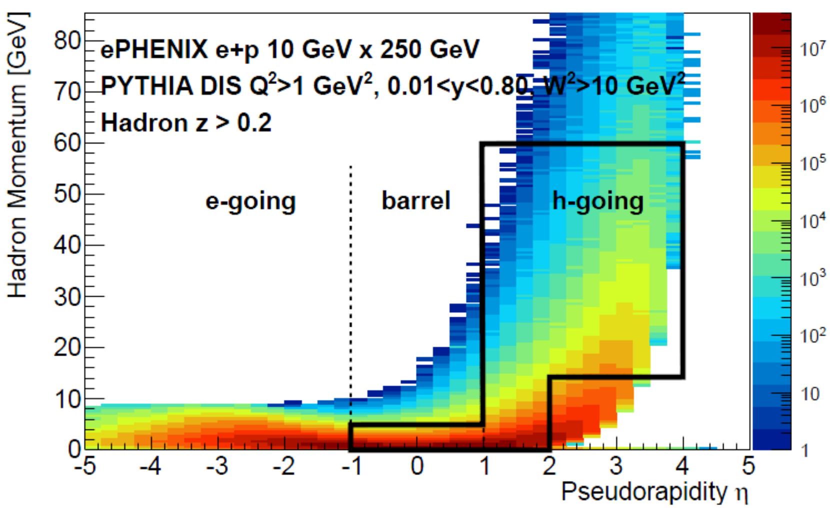
  - DIRC to extend to ~8 GeV
- Fwd η BIG challenge
  - Hadron ID req'd to 60 GeV/c!!



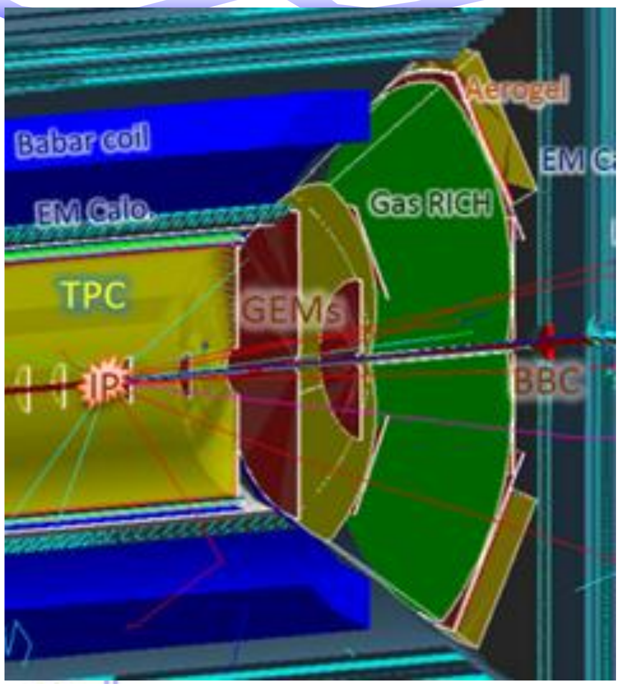
Ring Imaging Cherenkov is only known technology with required momentum reach!

Compact RICH? Impossible!

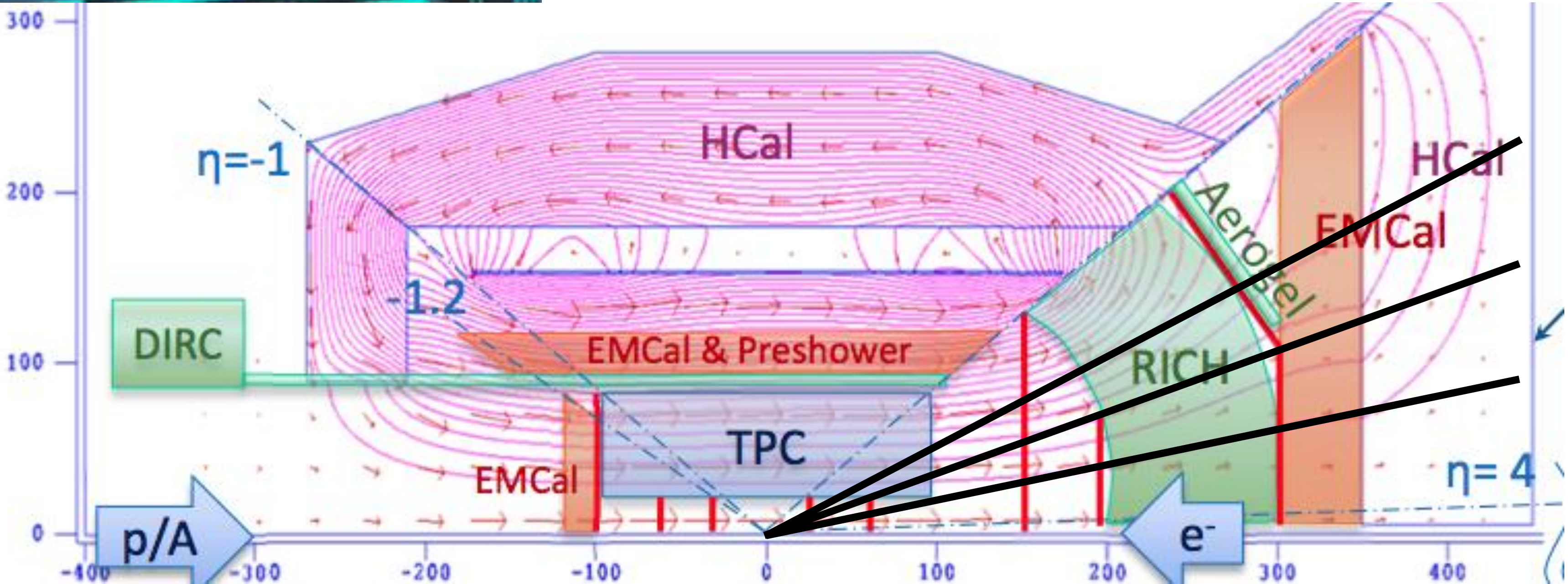
- LHCb required 3 meters of radiator (each) for C_4F_{10} AND CF_4. At 4.5 meters, you hit the accelerator!
- If the RICH is small it is close to the interaction.
- There will be B-field in the RICH, bending smears rings!
- The B-field will kill PMTs and m^2 of SiPM breaks the bank.
- Single photons are tough.
- LHCb (and PHENIX) direct focused light to the side. You have no room, hermiticity lost!
- How can you measure rings for particle near beam pipe?

- We've budgeted one meter for the radiator a RICH that can perform Kaon ID to 60 GeV/c
.
- Indeed.
.
- Our field will not bend tracks while inside the RICH.
- We have a cheap tech to cover m^2 areas at low cost.
- Our tech can handle it.
- Our tech is thin enough for the particle beam to go directly through the sensors.
- Clever Optics.

RICH drives Magnetic Field Shape

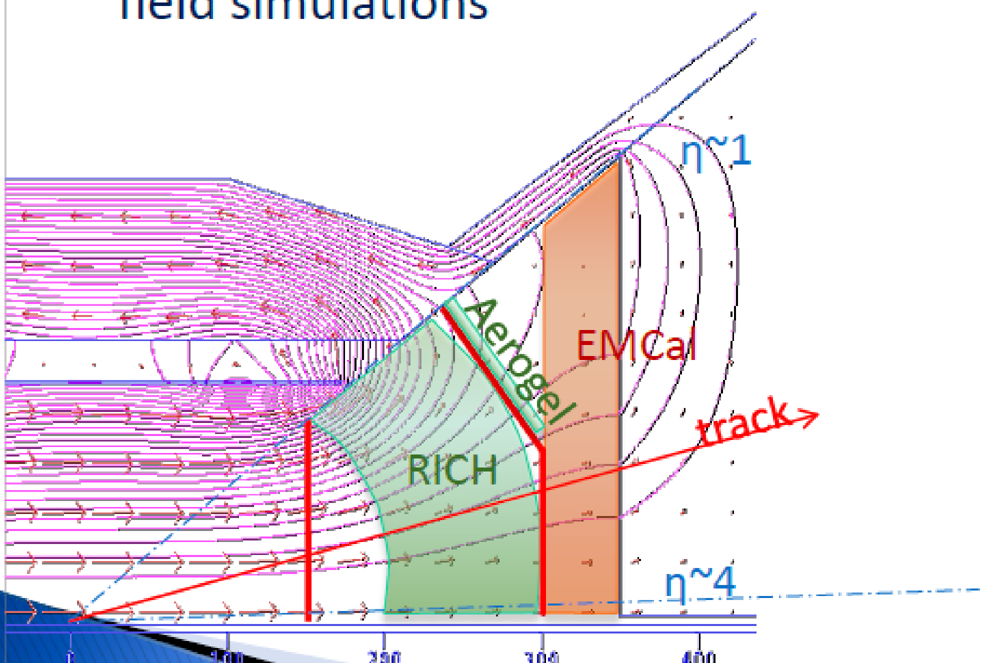


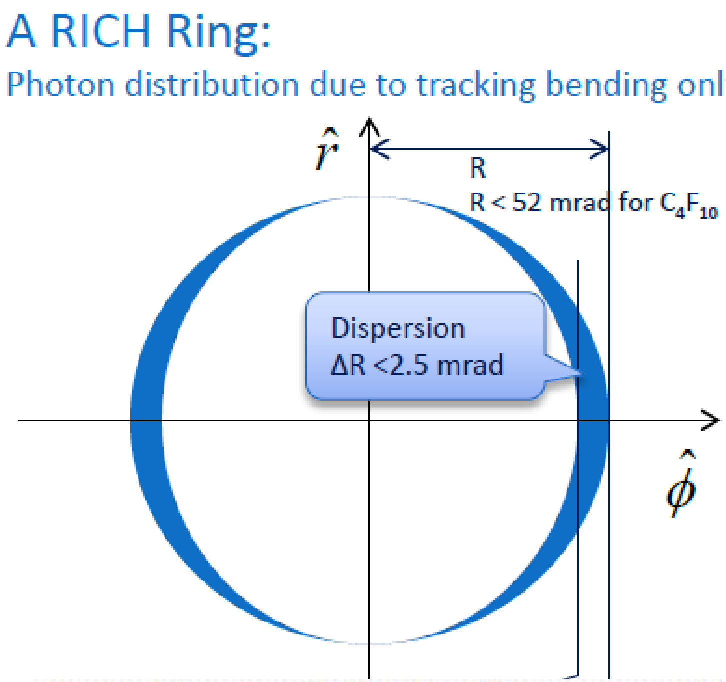
- The RICH will necessarily be tucked close to the solenoid.
- There will necessarily be field.
- Since we cannot set $\vec{B} = 0$, we instead approximate $\vec{v} \times \vec{B} = 0$ using shaped field lines:

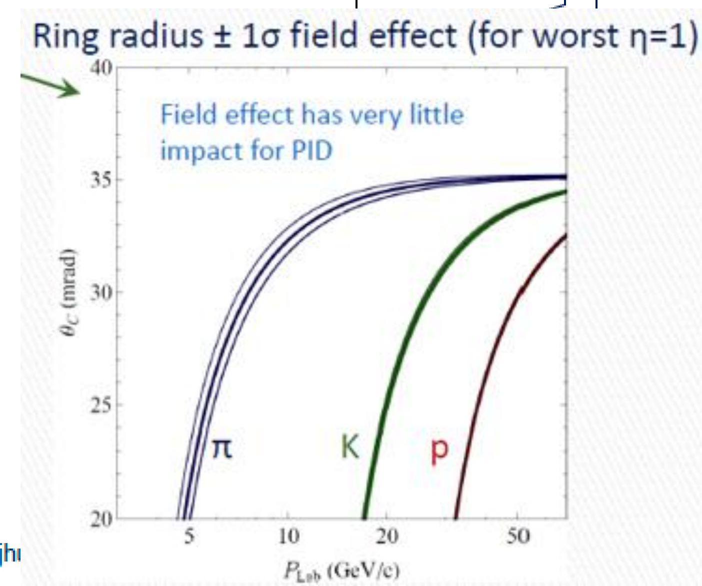


Field effect - distortion for RICH

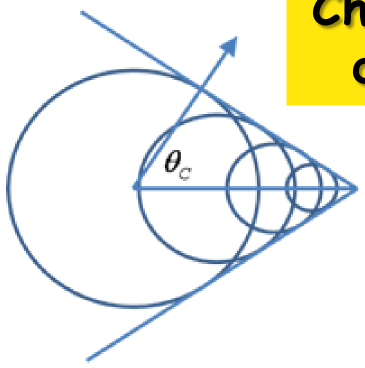
- Field calculated numerically with field return
- Field lines mostly parallel to tracks in the RICH volume with the yoke
- We can estimate the effect through field simulations





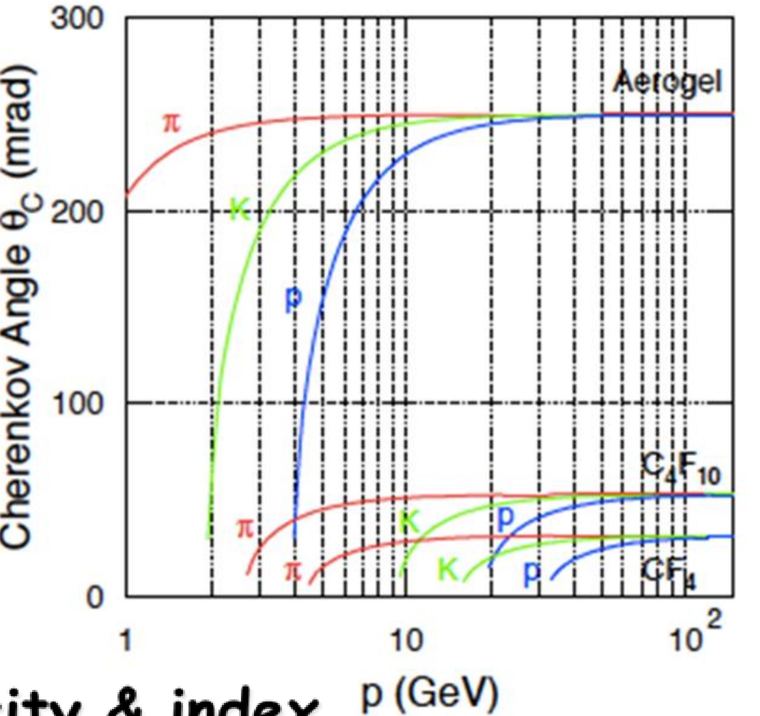


Cherenkov Light



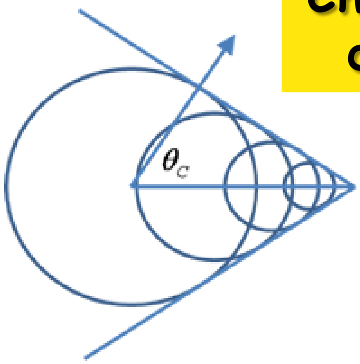
Cherenkov Angle determines β

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



- 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?
  - PHENIX HBD: No Optics allows for VERY low λ_{min}
  - But a RICH requires optics! What to do?

Cherenkov Light



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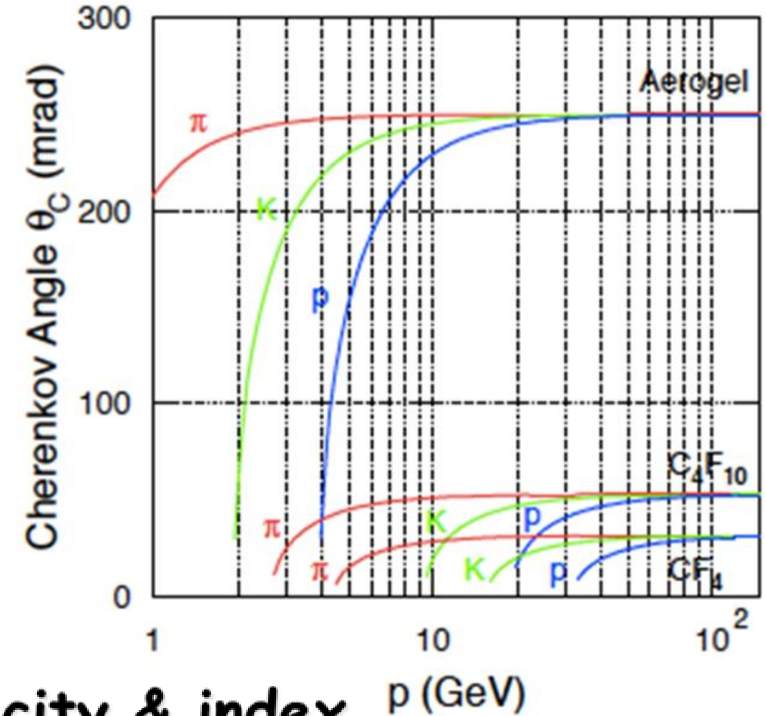

- ❑ Cherenkov Light – "Optical Boom"
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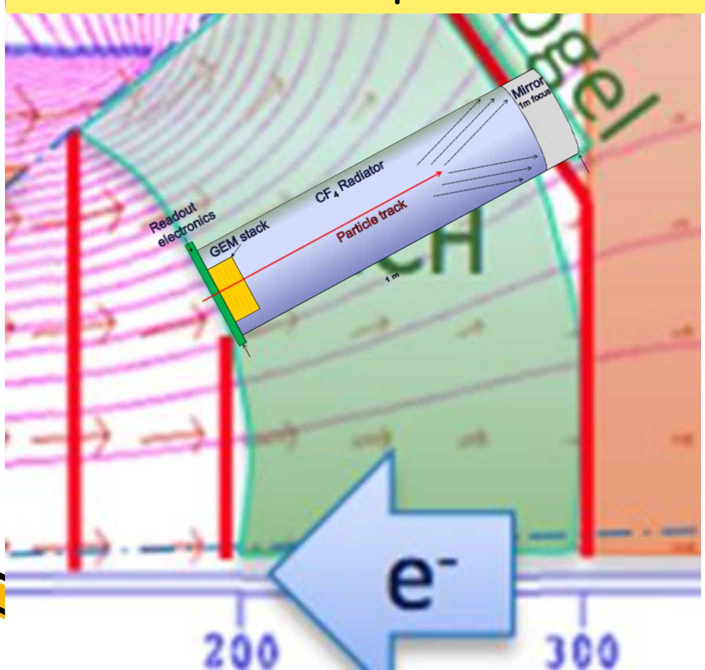
  - Deep UV Cherenkov yield is highest…how to get there?

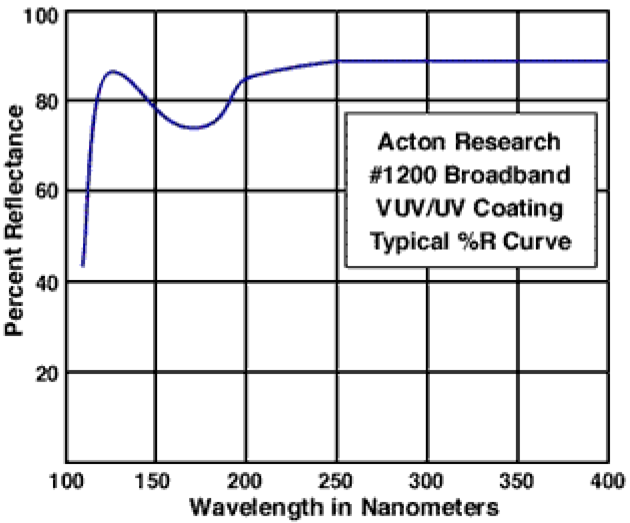
Outline of Requirements

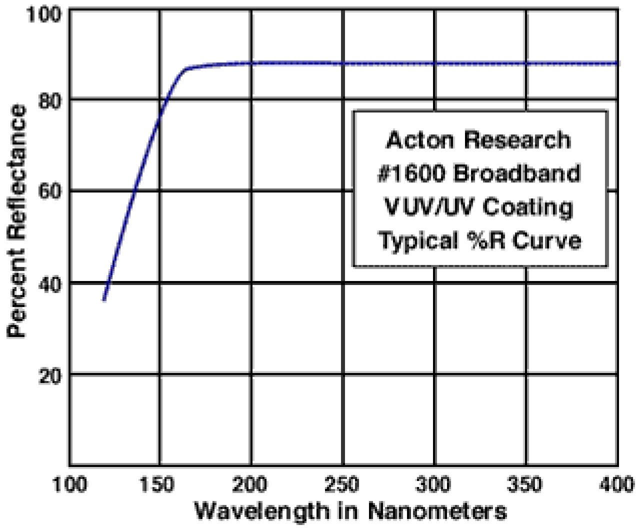
Requirement	Technology	Status
Low index gas w/ high light yield by UV transparency	CF_4	Achieved: PHENIX HBD
Photon Detectors in Field	Photo-sensitive GEM	Achieved: PHENIX HBD
m^2 focal plane coverage	Photo-sensitive GEM	Achieved: PHENIX HBD
Hermetic Acceptance	Particles pass through focal plane	Achieved: PHENIX HBD
Single photon detection	Gain 10^5 or higher	R&D
DEEP UV Optics	Dielectric Film Mirror	R&D



- R&D to develop small prototype
- 1 meter radiator
- Photo-sensitive GEM readout
- Test Beams:
  - SLAC May/June 2013
  - FNAL October 2013

Commercial (small) mirror Reflectivities





- Bare aluminum mirrors no good (AlO…high cutoff).
- Better has MgF_2 overcoat (right hand).
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- Thin Film Interference!
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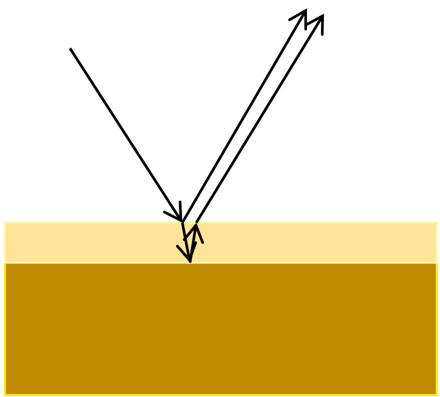
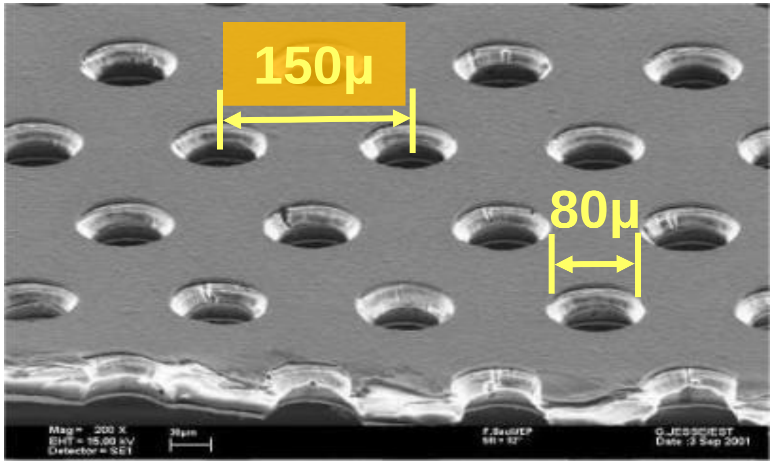
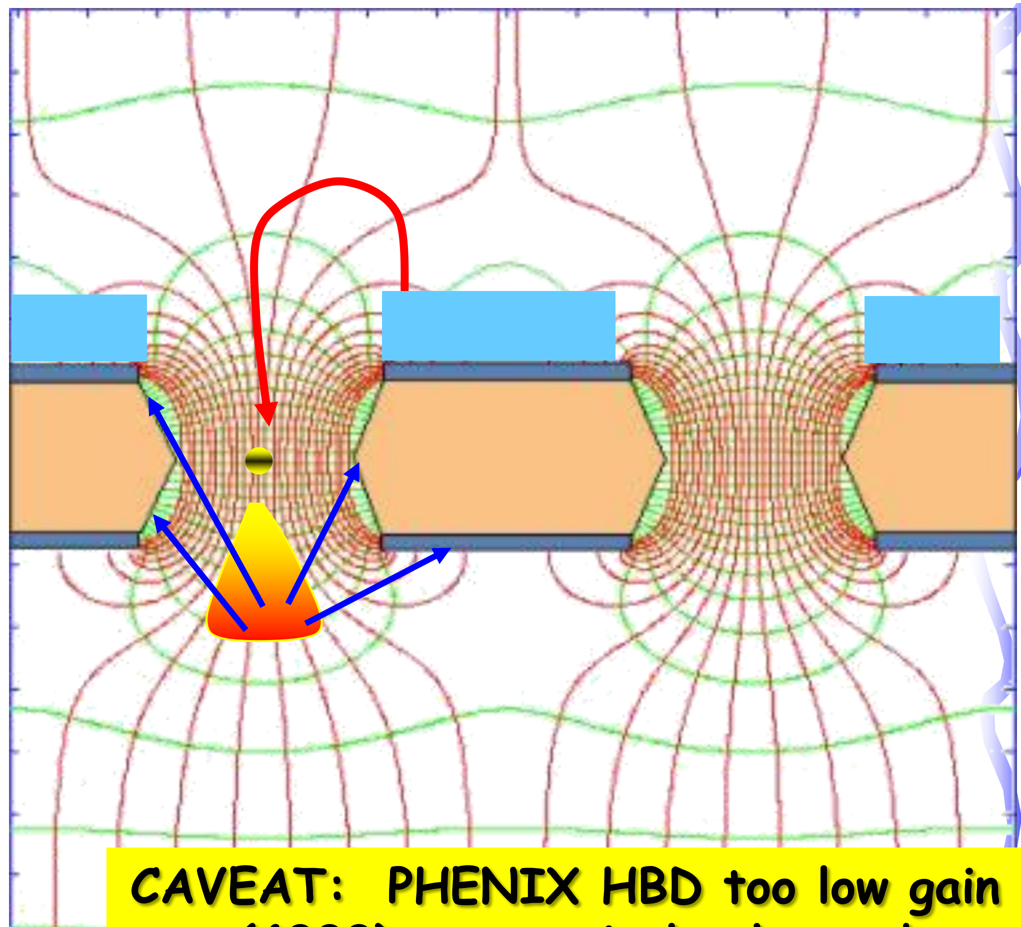


Thin Film Interference

Gas Electron Multiplier for PHOTONs!



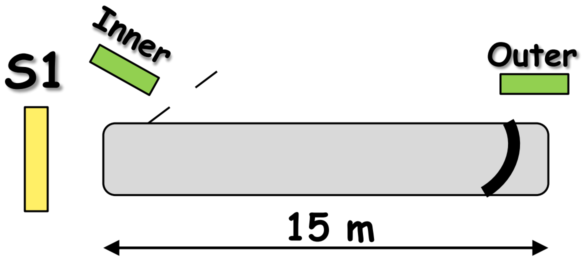
- The original idea by F.Sauli (mid 90s) US Patent 6,011,265
- Traditionally CHARGED PARTICLE detectors (not photons)

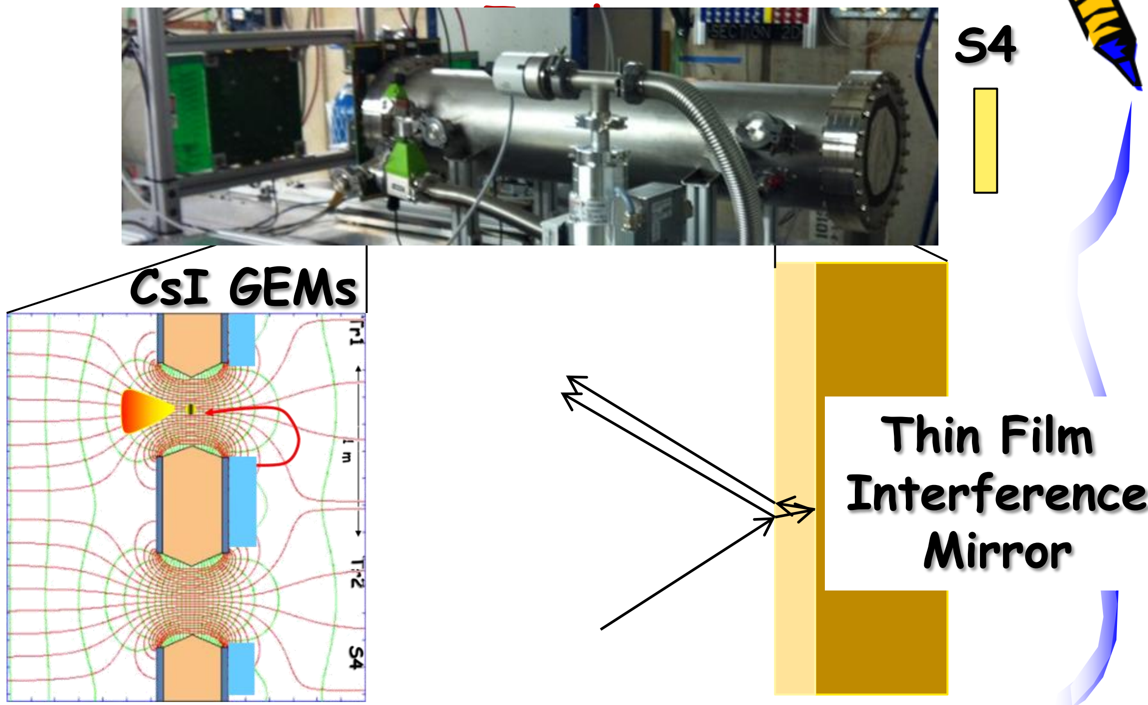


- Two copper layers separated by insulating film with regular pitch of holes.
- HV creates very strong field such that the avalanche develops inside the holes
- Just add the photocathode
- By the way: no photon feedback onto photocathode

CAVEAT: PHENIX HBD too low gain (4000) to see single photons!

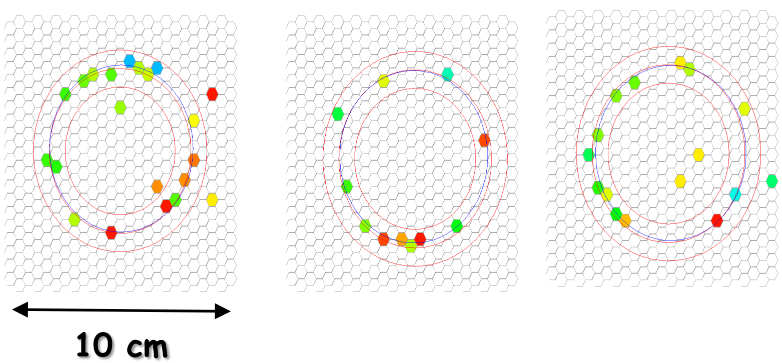
MT6 2D: RICH Detector



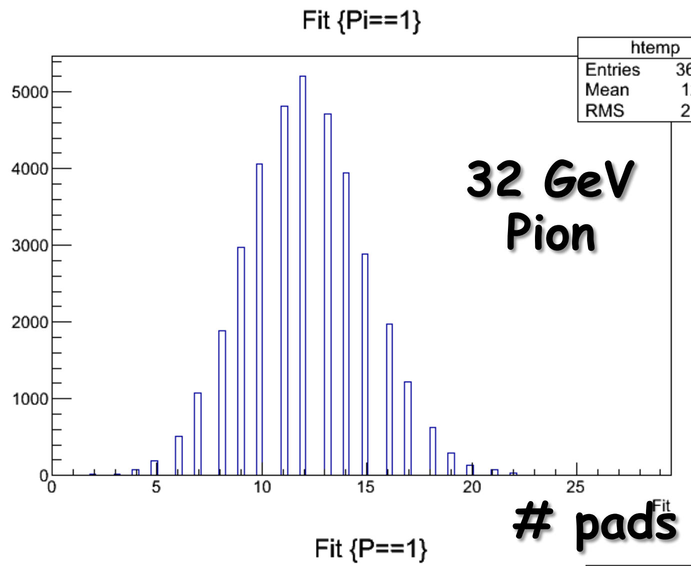


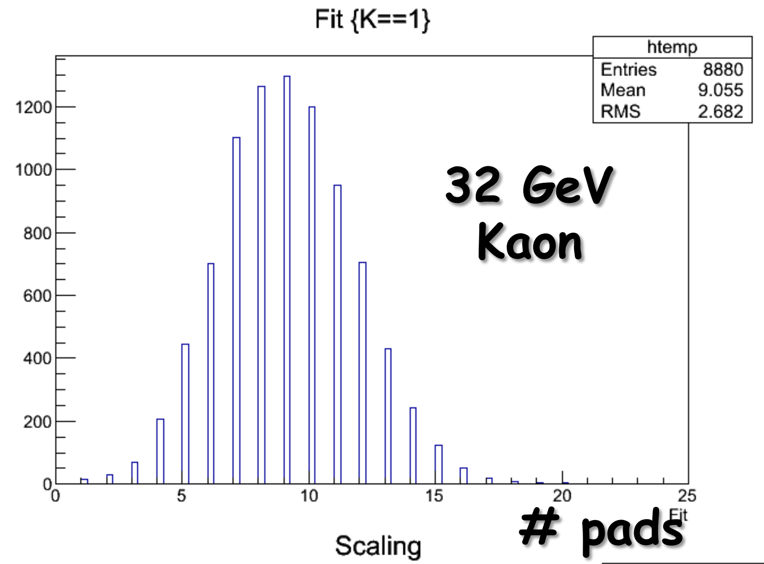
- ❑ Beamline Cerenkov
- ❑ PID offline
- ❑ K-Trigger

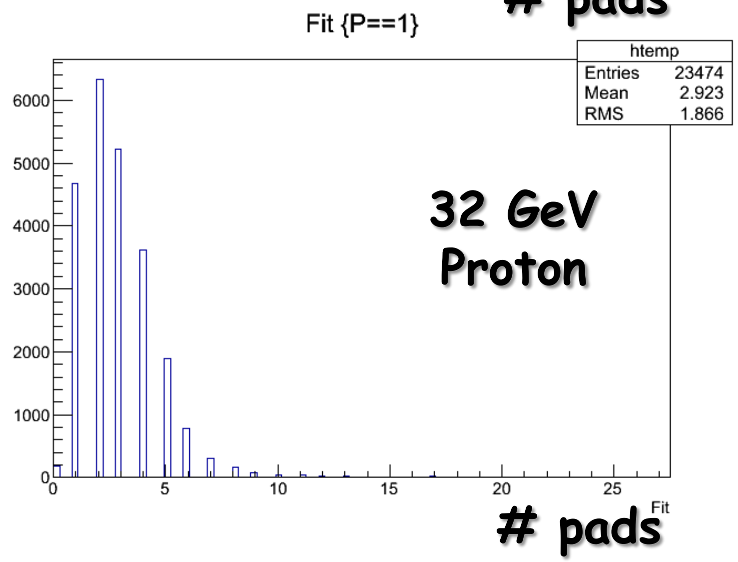
- ❑ Goal: PID to 60 GeV/c
- ❑ Rings in only 1 meter of gas
  - ➢ LHCb uses 3 meters
- ❑ Technique:
  - Deep UV mirror
  - CsI GEMs

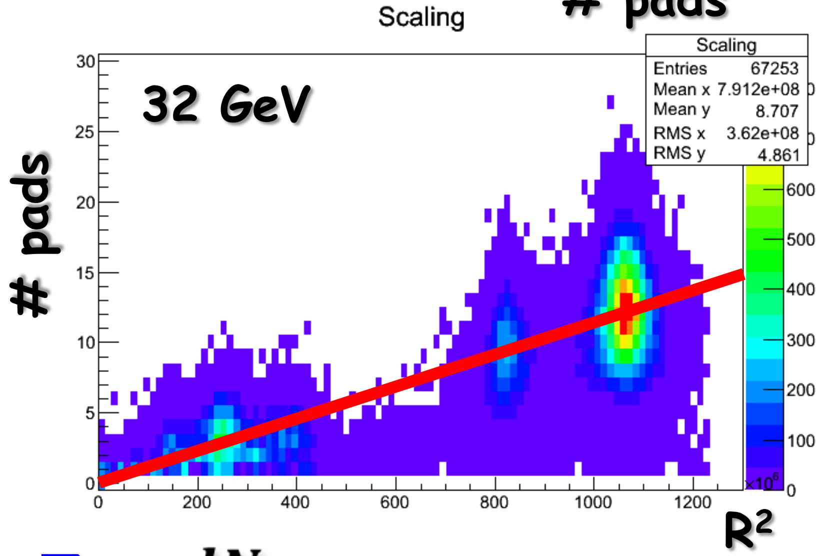


Number of Pads Included in the Fit:



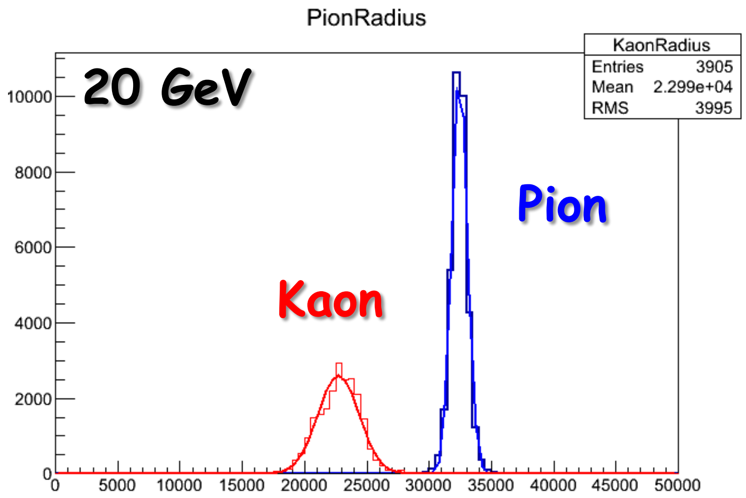


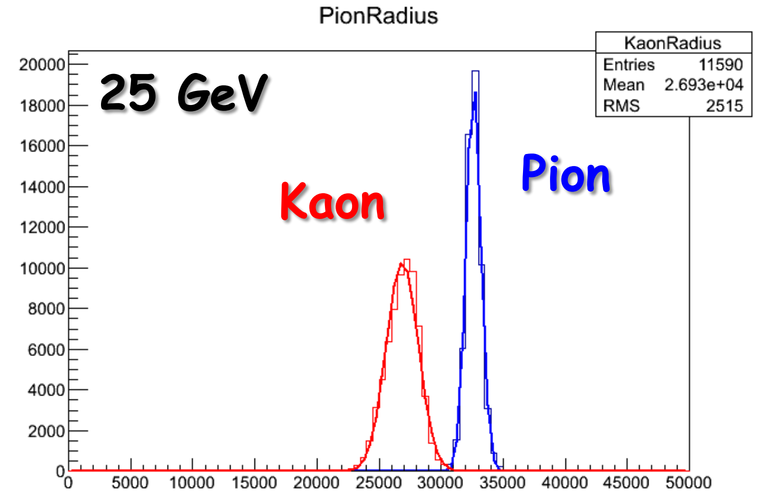




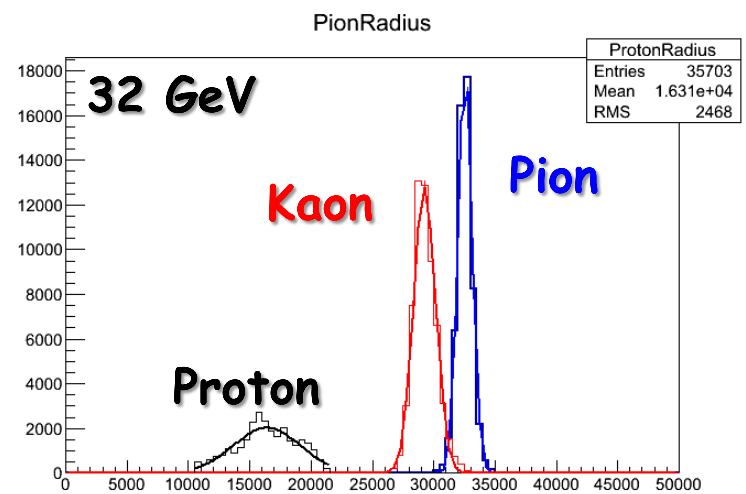
- $$\frac{dN_\gamma}{dL} \approx sin^2\theta_c \approx R^2$$

Radii Results:

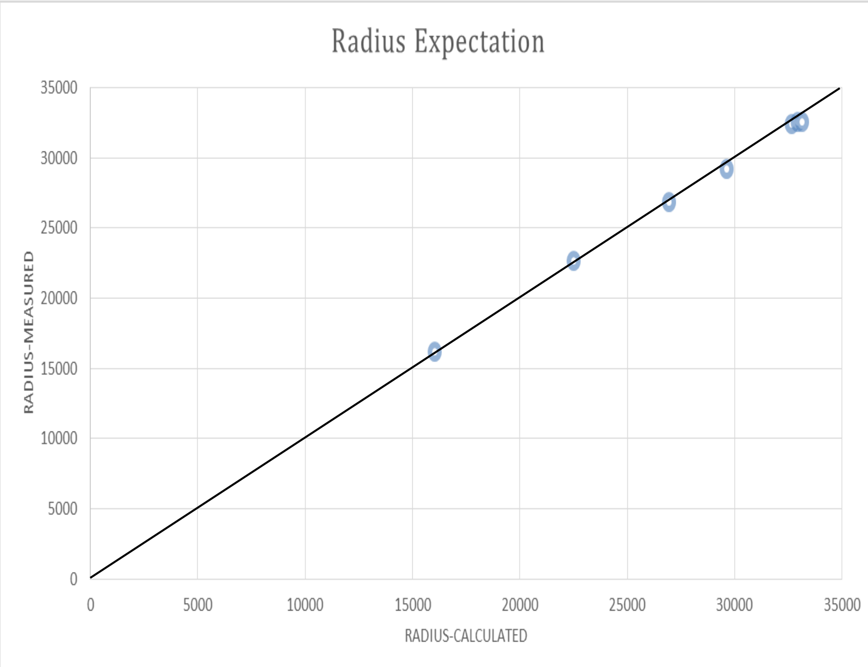


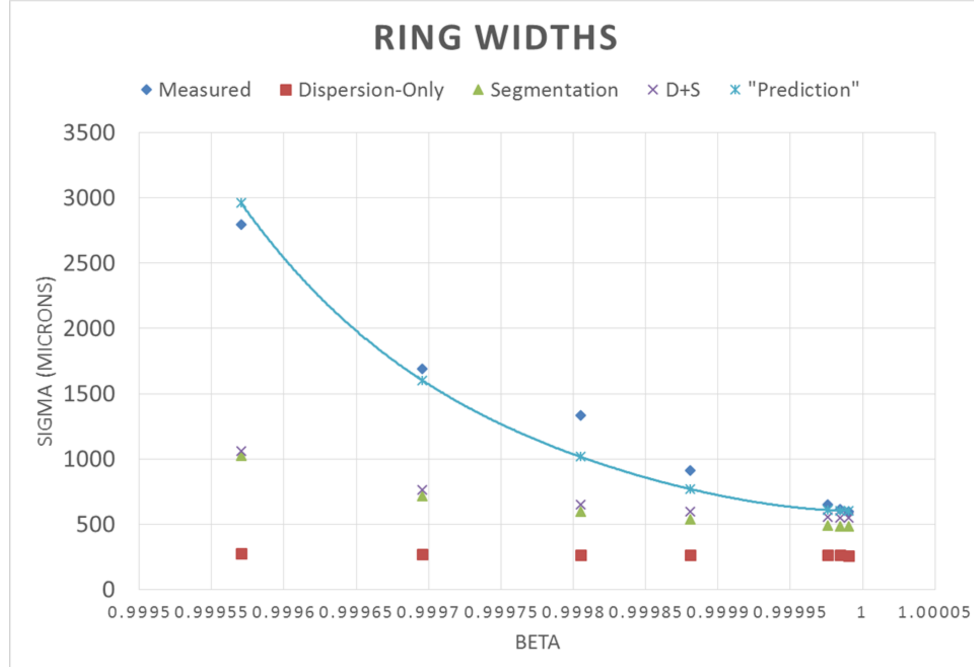


- Reasonable results at all measured energies.
- NOTE: 32 GeV is the highest available energy for Kaons at FTBF.



Radius & Width Matches Expectation.

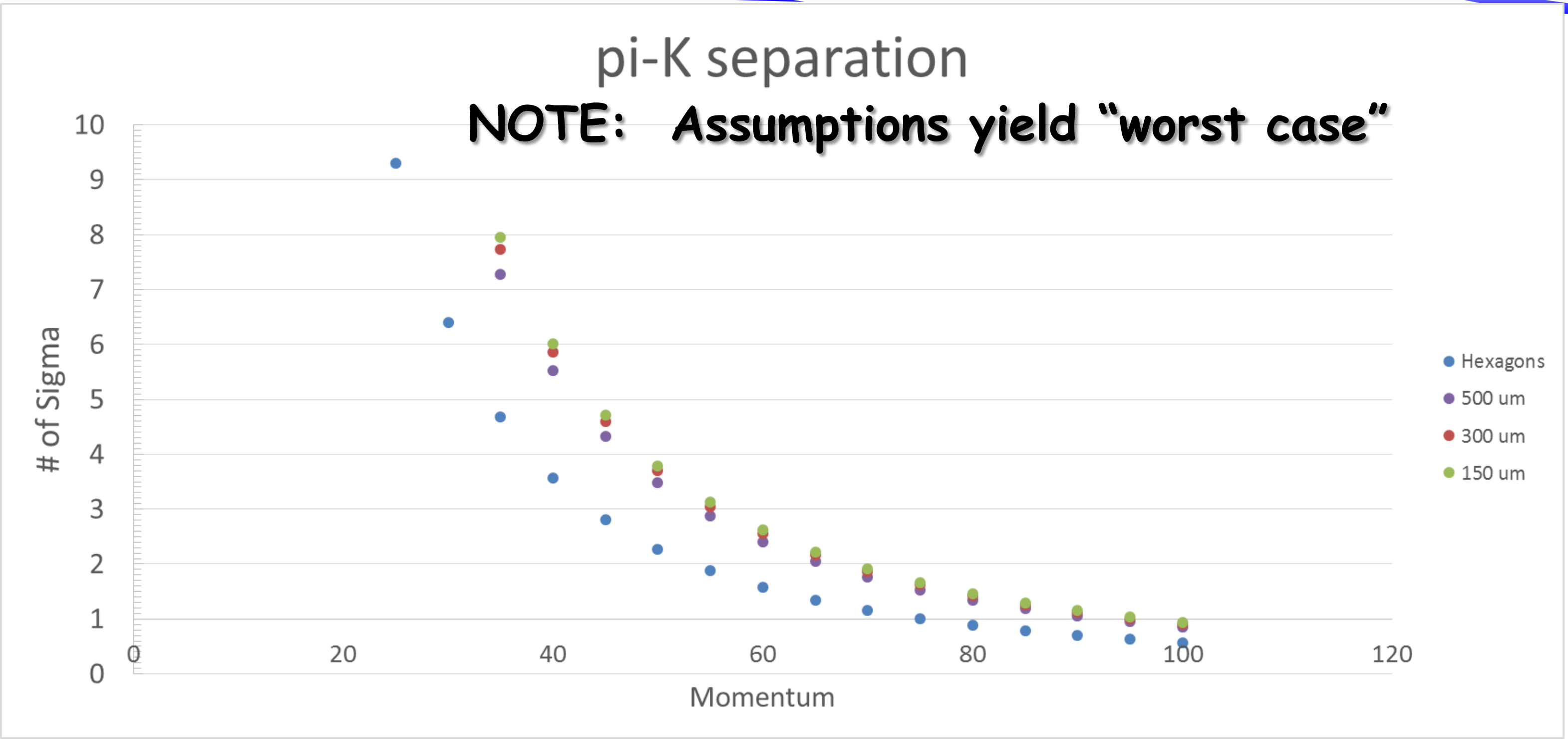




- Index = free parameter.
- n = 1.000558
- n matches literature.

- Influenced by momentum spread delivered in beam.
- Assume $\frac{\delta p}{p} = const.$
- Fit $\frac{\delta p}{p} = 5\%$ (reasonable)

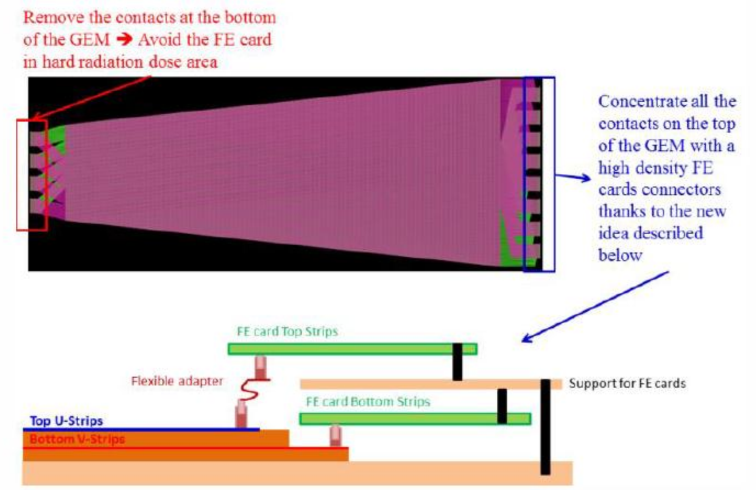
PID to 60 GeV w/ better position resolution



- Dispersion eventually becomes limiting factor.
- 500 micron (sigma) photon position resolution is easy goal.
  - Hence proposed R&D for Resistive Charge Division.
- ~2.5 sigma separation at 60 GeV!

Next Steps: Core Research

- Core Tracking:
  - Move stereo readouts away from beam pipe.
  - Complete & Test TPC/HBD Concept
  - Improved uniformity of response for zig-zag chamber and improved test station.
  - $251k



- Core Mirror:
  - Refurbish Big Mac vacuum chamber to become evaporator.
    - Postponed as lower priority to deal with budget profile.
  - $83k

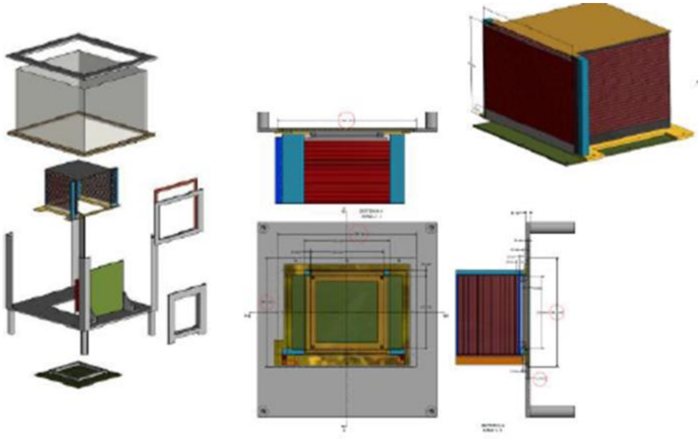
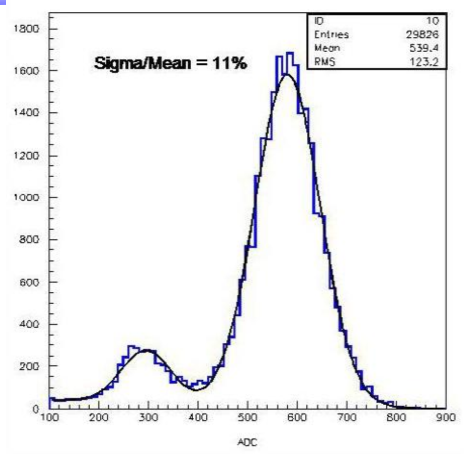


Figure 6 3D model of the prototype TPC/ Cherenkov detector.

Next Steps: New Ideas

- Hybrid Gain Stages GEM+MMG
  - Very low ion feedback
  - Peaked single-e response
  - $35k



- Resistive Charge Division
  - Avalanche spot in RICH has σ=132 μm.
  - Cannot use geometrical charge division.
  - Alternative to high channel count is resistive division.
  - $10k

- Central Barrel Tracking TPC
  - TPC/HBD is most useful for 2nd phase EIC.
  - Fast TPC necessary for 1st phase in most designs.
  - New Collaborators to pursue new research.
  - $100k (to be defended in May/June).

Summary

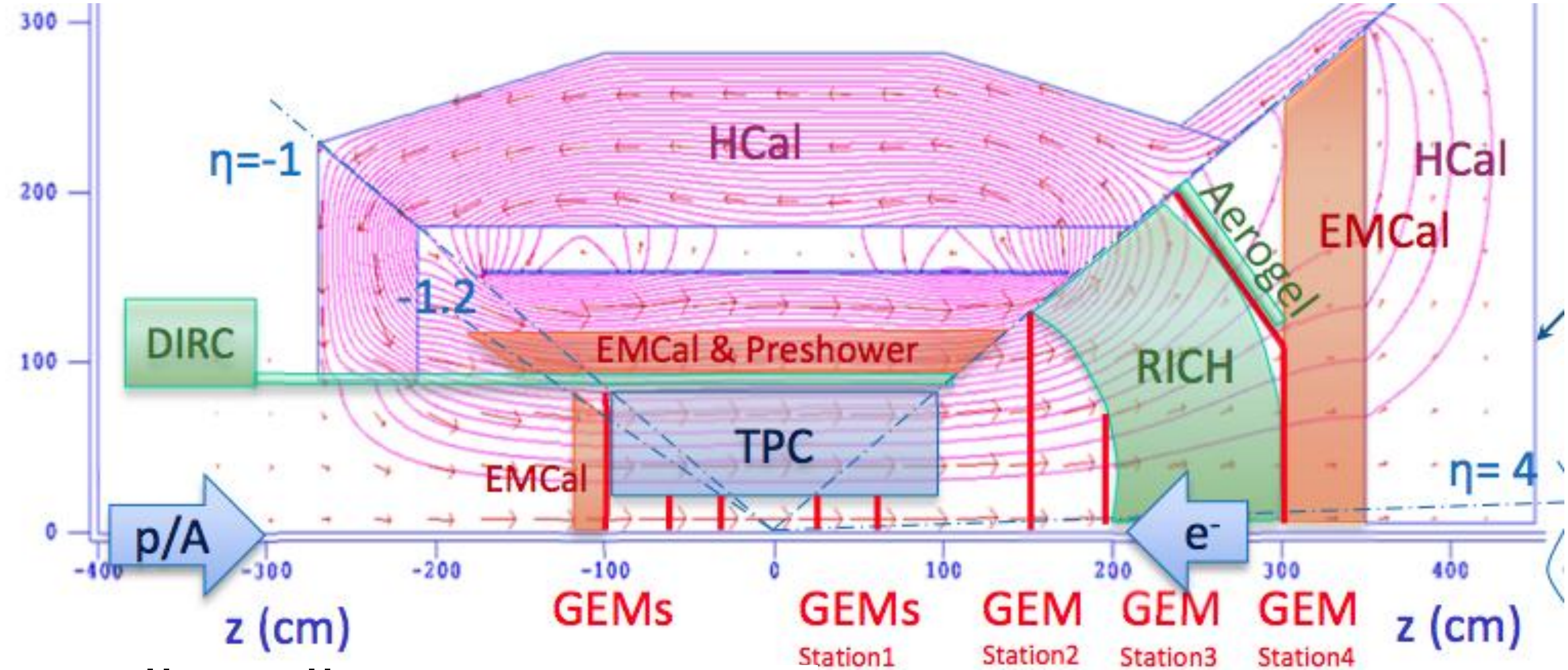
- The EIC Tracking/PID Consortium has completed our sector test for forward tracking & RICH in October 2013 (ahead of schedule).
- Results are uniformly excellent; at or near EIC specs.
- Hemmick believes this is among the most productive R&D efforts he has witnessed in his career.
- Consortium funding "per institution" very cost effective.
- FY14 Outlook (not including salaries).
  - Core Tracking: $251k
  - Core Mirror: $83k
  - New Hybrid Gain: $35k
  - New Resistive Div: $10k
  - New TPC (May/June): $100k

Backups…

Summary

- TPC provides PID, low mass, hermetic tracking.
- TPC is principle choice of most EIC designs.
- ALL EIC designs require RICH which constrains TPC to be small/compact device.
- Fast/low diffusion gas for Au+Au.
- Likely wish un-gated:
  - Quad-GEM or mixed mode GEM/μMEGA.
  - Follow ALICE upgrade plans?
- Electronics:
  - Follow ALICE upgrade plans? (Anders Oskarsson)

TPC Constraint Summary:



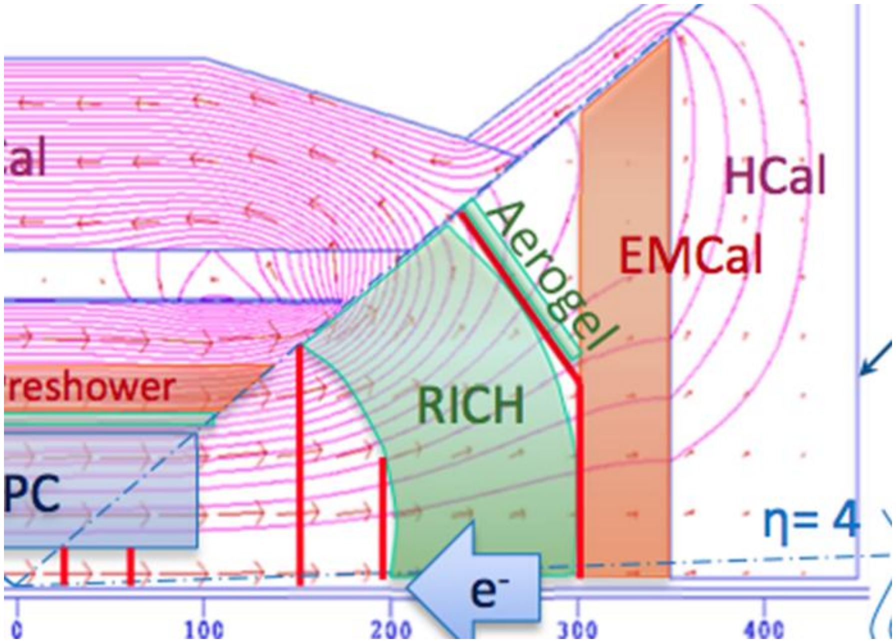
- Overall Small Device:
  - B-field "Sweet Spot"
- Outer radius:
  - Driven by BaBar DIRC→ <80 cm
- Length:
  - η-accept → ~2 meters full length.
- Inner radius:
  - Not tightly constrained
  - Leave room for Silicon?
- Resolution
  - eA not challenging.
  - AuAu Υ(1s), Υ(2s), Υ(3s) is doable (I. Ravinovich/B. Selihan)
- Gating(?)
  - ~ 10kHz for Q^2>1 GeV^2
  - Likely want un-gated solution.

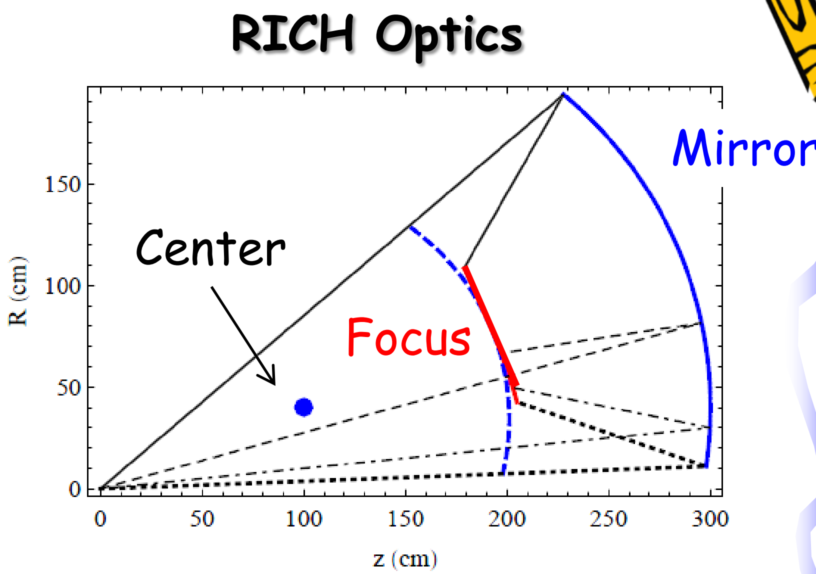
"Full Disclosure"

Item	Comment	Total
Salaries	Must be Fully Funded. Top Priority Includes $180k of EIC-wide Simulation Effort	$269k
Core: Tracking	Lean @ 75%; Dead at 50%.	$251k
Core: Mirrors	Approved June 2013, Can be postponed.	$83k
New: Hybrid Gain	Lean Proposal. Requires full funds to execute.	$35k
New: Resistive Div	Lean Proposal. Requires full funds to execute.	$10k
New: TPC	Placeholder. New colleagues. Full Prop. In May	$100k

- **ALL FY14 monies associated with our consortium.**
  - **Some already "allocated" (e.g. Salaries/Core-Mirrors).**
- **Urge committee to remember that these funds are distributed across 7 institutions.**
- **We believe our consortium is exceptionally productive.**
- **We believe our per-institution requests are minimal.**

ePHENIX: Gas RICH



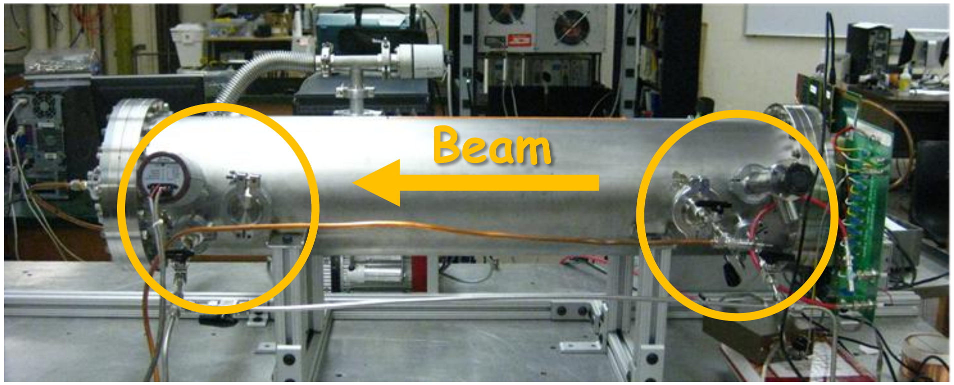


- Magnetic Field in RICH!
- Field shaped to "point at collision vertex".
- $\vec{v} \times \vec{B} \approx 0.$
- Not true near beam pipe!
  - OK, p is very large there.

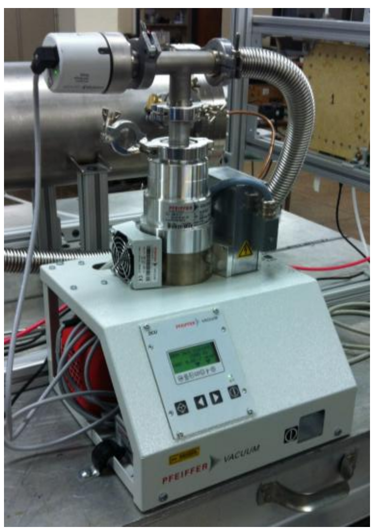
- Mirror(s) break symmetry.
  - Reduced focal plane size: no dead area at edge.
  - Improved acceptance for light from high η particles
  - 6 segments around phi

Detector Design

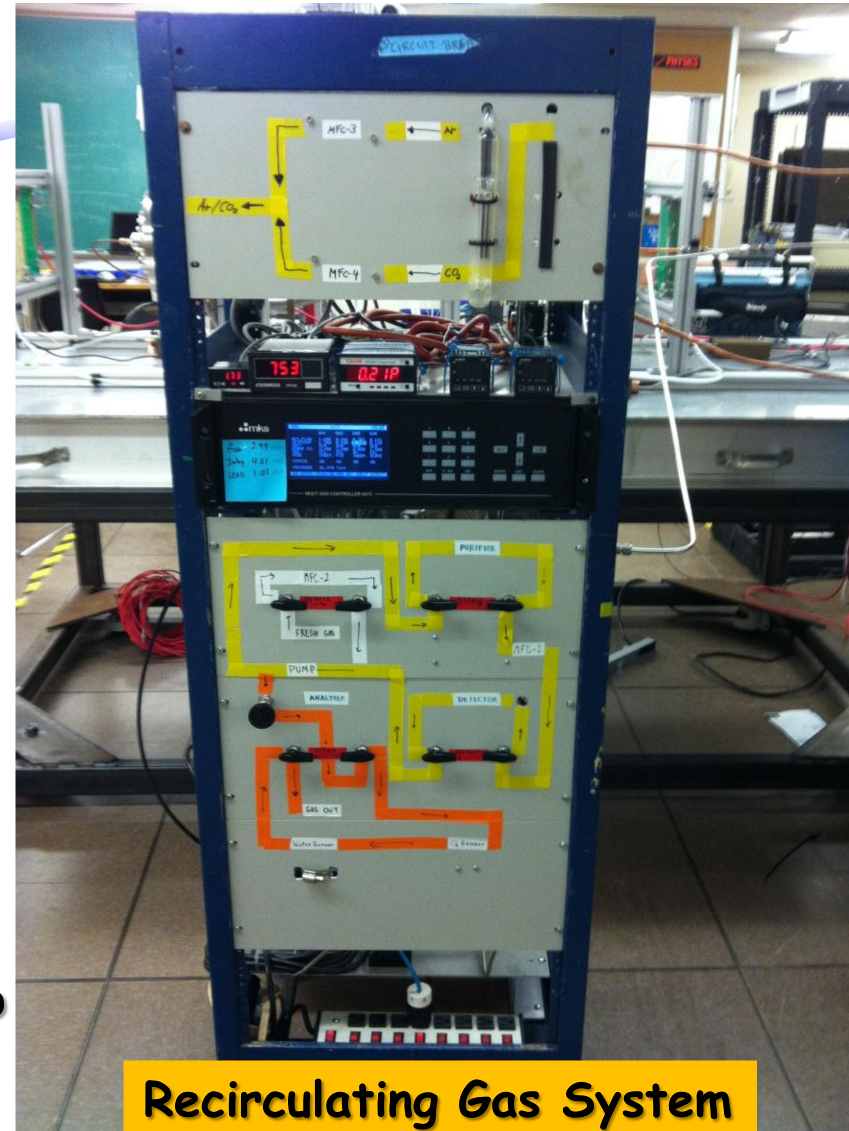
8" Conflat Flanges @ Ends



Clusters of KF Fittings



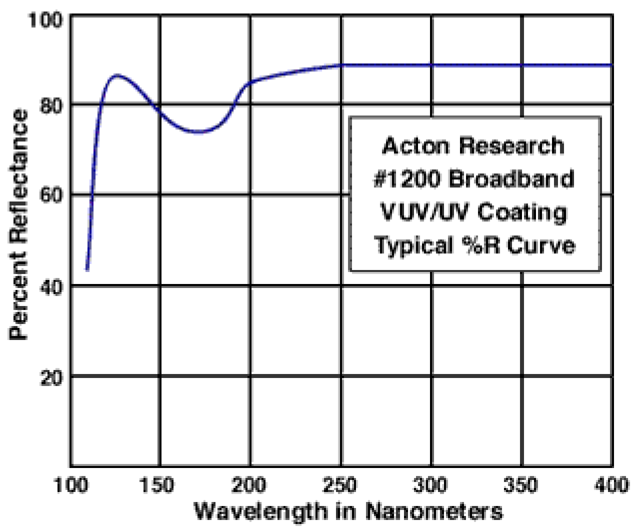
Molecular Drag Pump
Backed by Diaphragm Pump

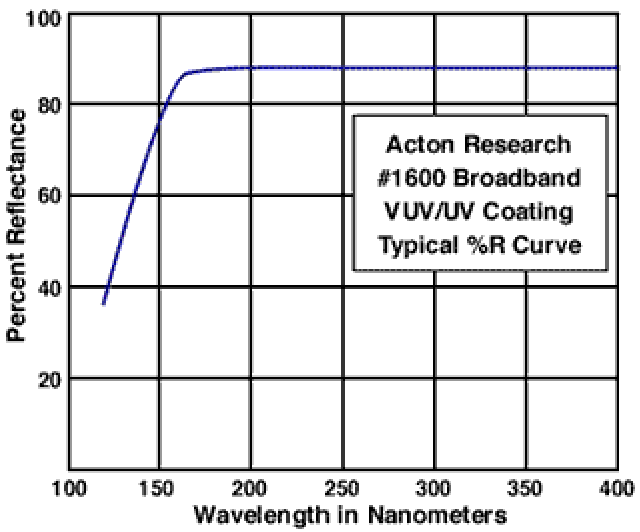


Recirculating Gas System

- All SS construction
- Commercial parts for EVERYTHING except GEM plane.

Commercial (small) mirror Reflectivities





- Bare aluminum mirrors no good (AlO…high cutoff).
- Better has MgF_2 overcoat (right hand).
  - Exists and has been made to large scale.
  - Not good enough.
- Thin Film Interference!
  - Tuned for peak at 120 nm.
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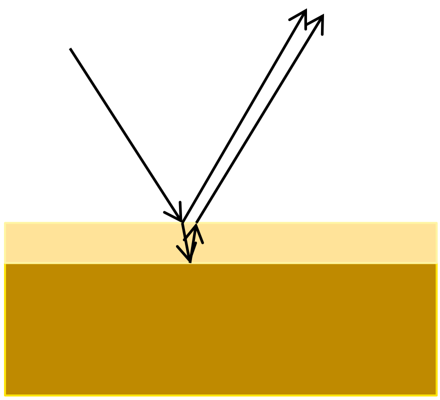
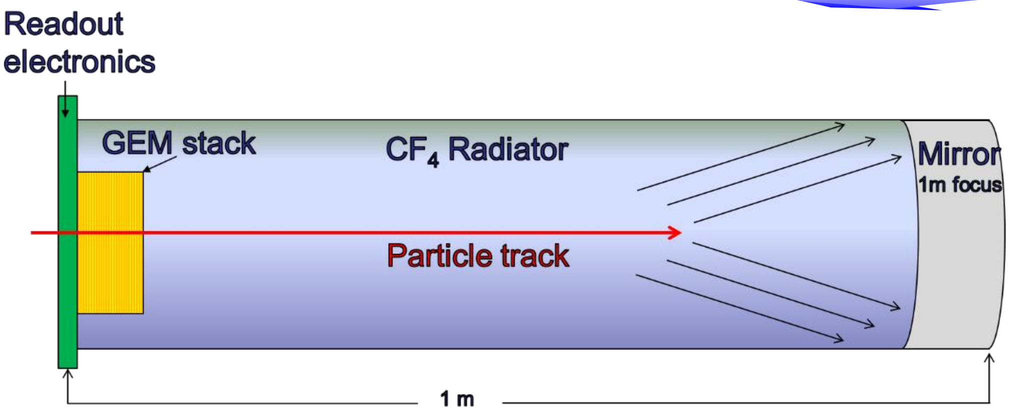
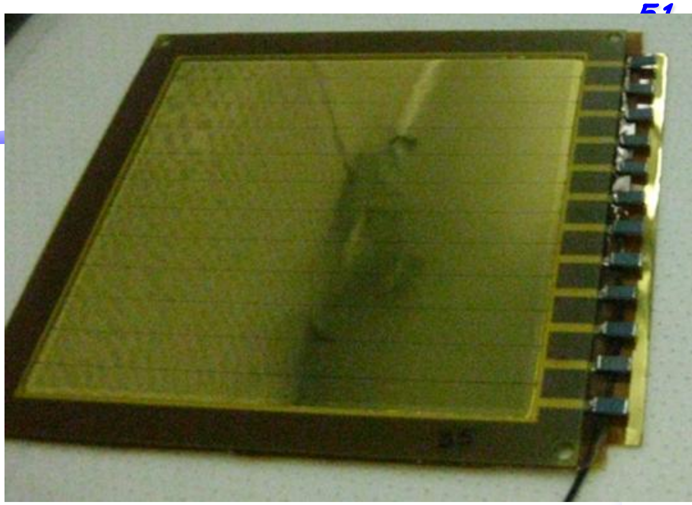
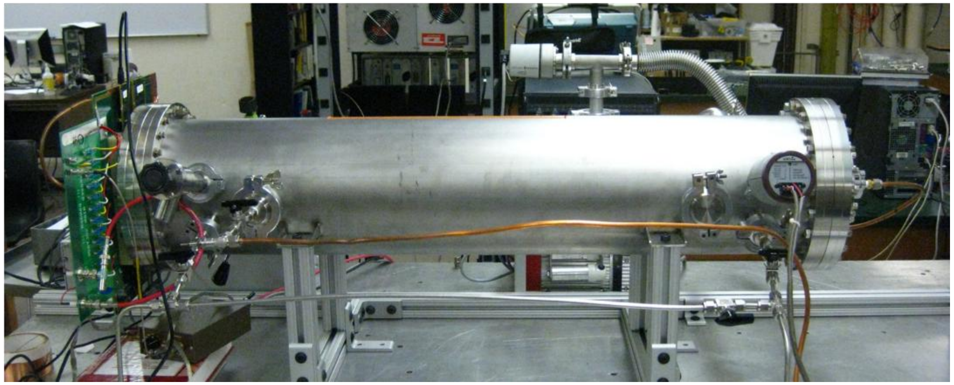


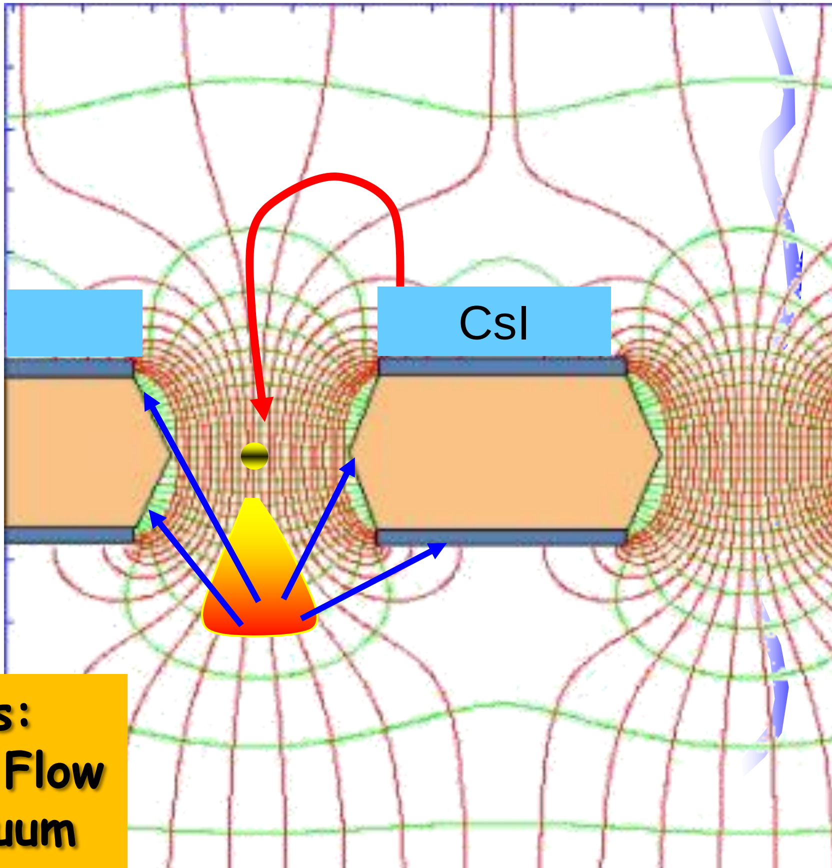
Thin Film Interference

Detector Overview







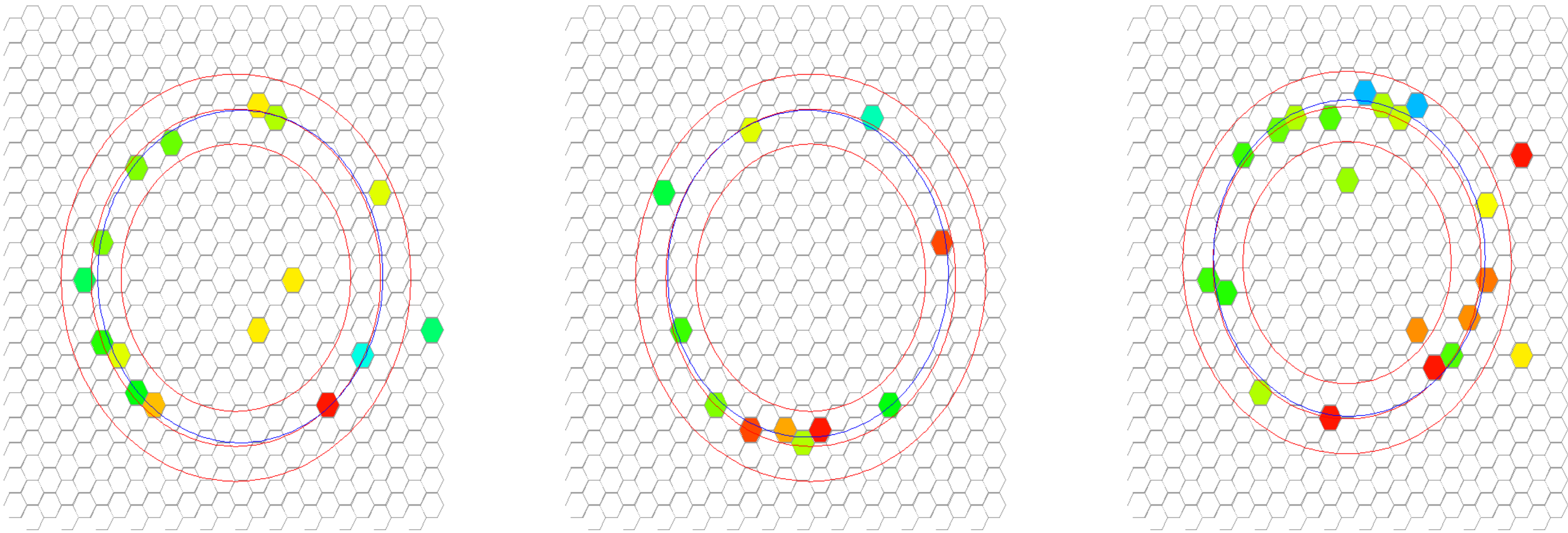


- Spherical mirror makes ring:
  - Ring → Cherenkov Angle
- Use photo-sensitive GEMs!
- Readout APV25 via SRS.

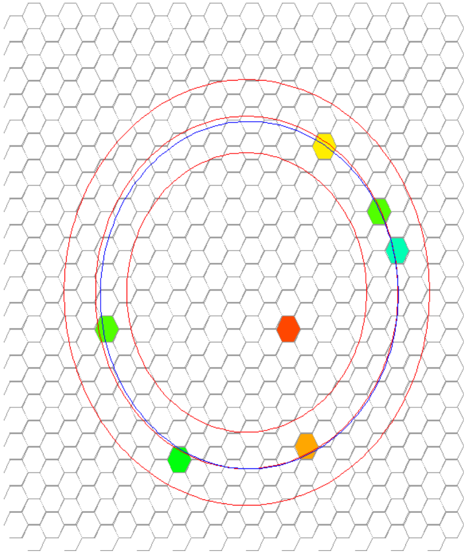
Detector dies when:
- Dust kills GEMs
- Water @ 20 ppm kills CsI

24-7 Status:
- UHP Gas Flow
- High Vacuum

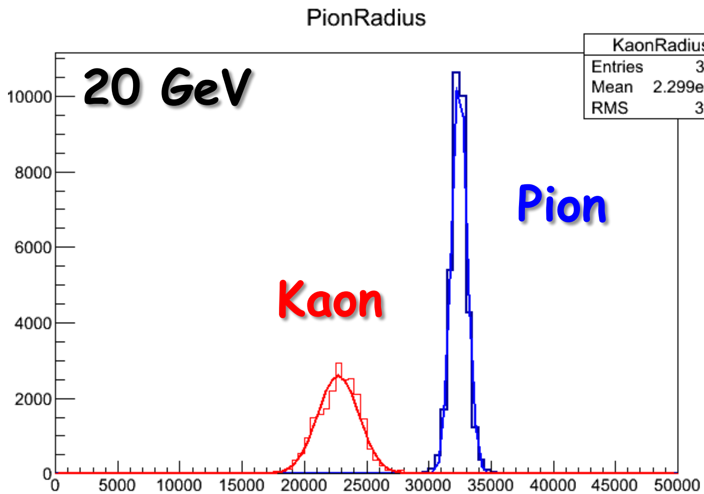
Look at the “Hit” pads… See Rings!

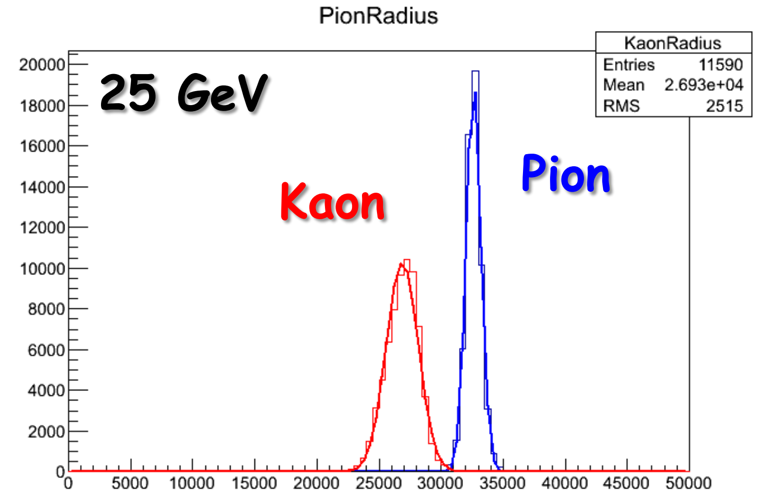


- Your eyes see the Rings very easily.
- Red Circles: Pattern Recognition.
- Blue Circles: Robust Fit.



Radii Results:





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