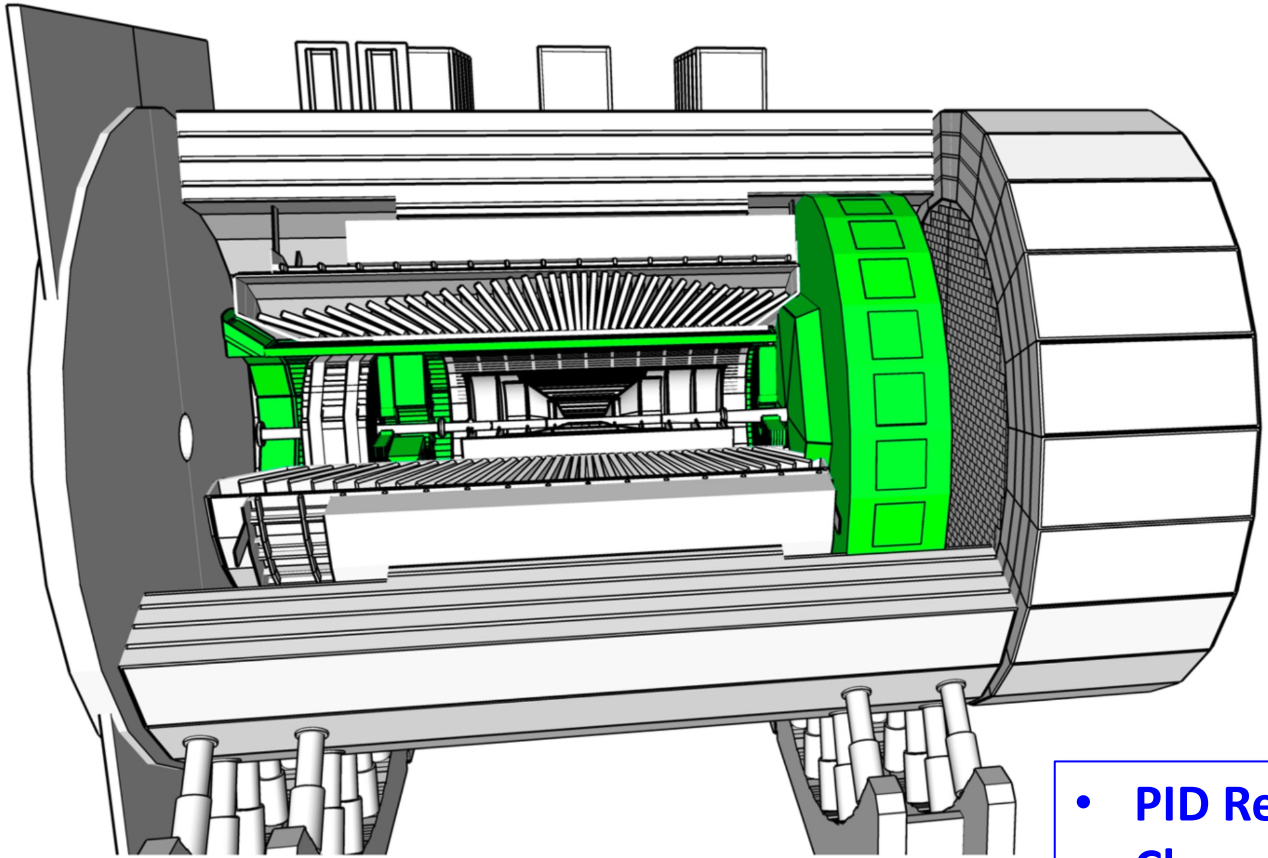
Charged Particle Identification for EIC Detector1



Cherenkov PID

Greg Kalicy — CUA

Roberto Preghenella — INFN

Tom Hemmick — Stony Brook University

Xiaochun He — Georgia State University

TOF PID

Constantin Loizides — Oak Ridge National Laboratory

Frank Geurts — Rice

Wei Li

Zhenyu Ye — UIC

Outlook

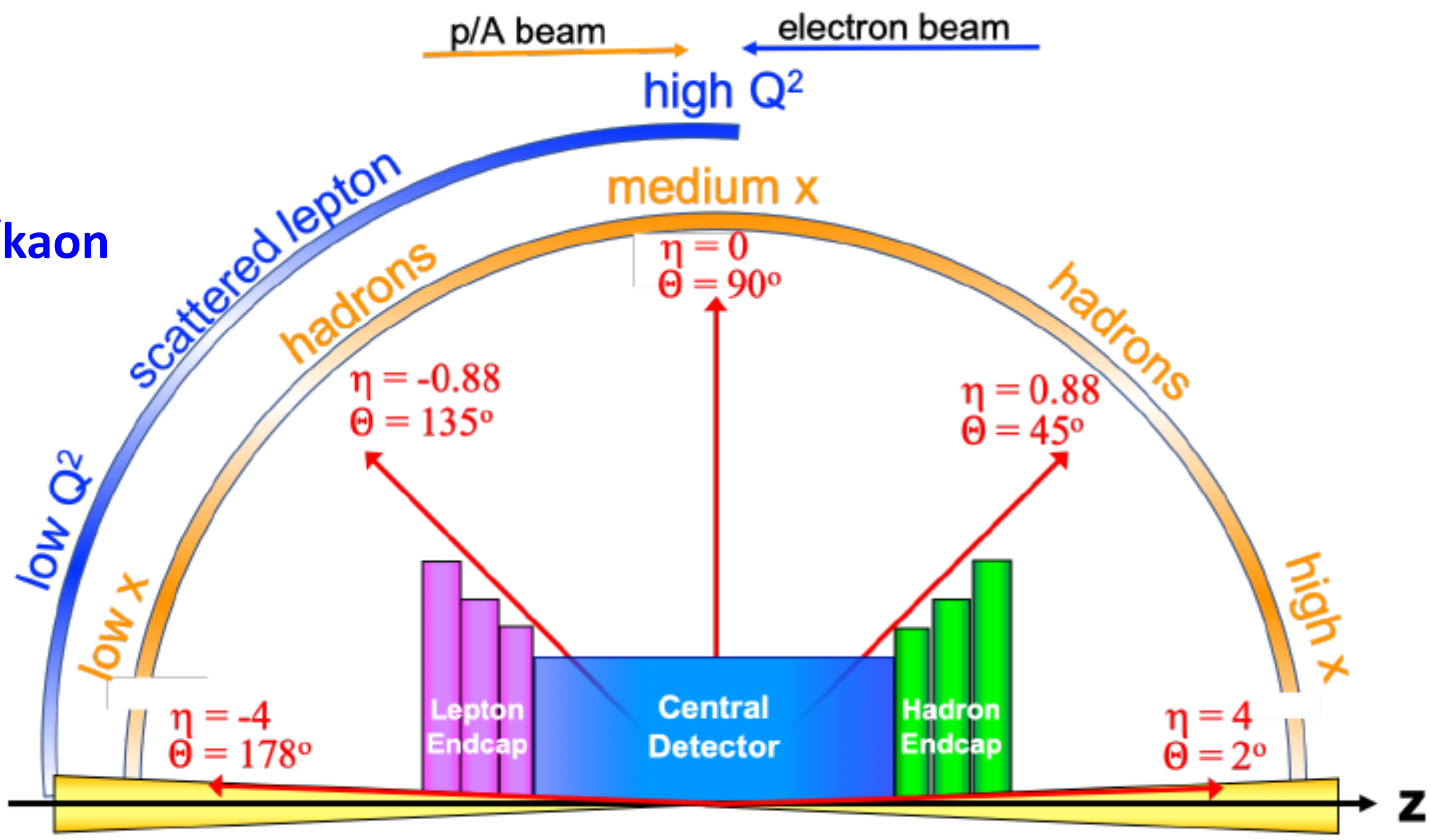
- PID Requirements
- Chosen Technologies
  - Concepts and Designs
  - Performance
- Photosensors & readout

June 8th 2022

CHARGED PARTICLE IDENTIFICATION

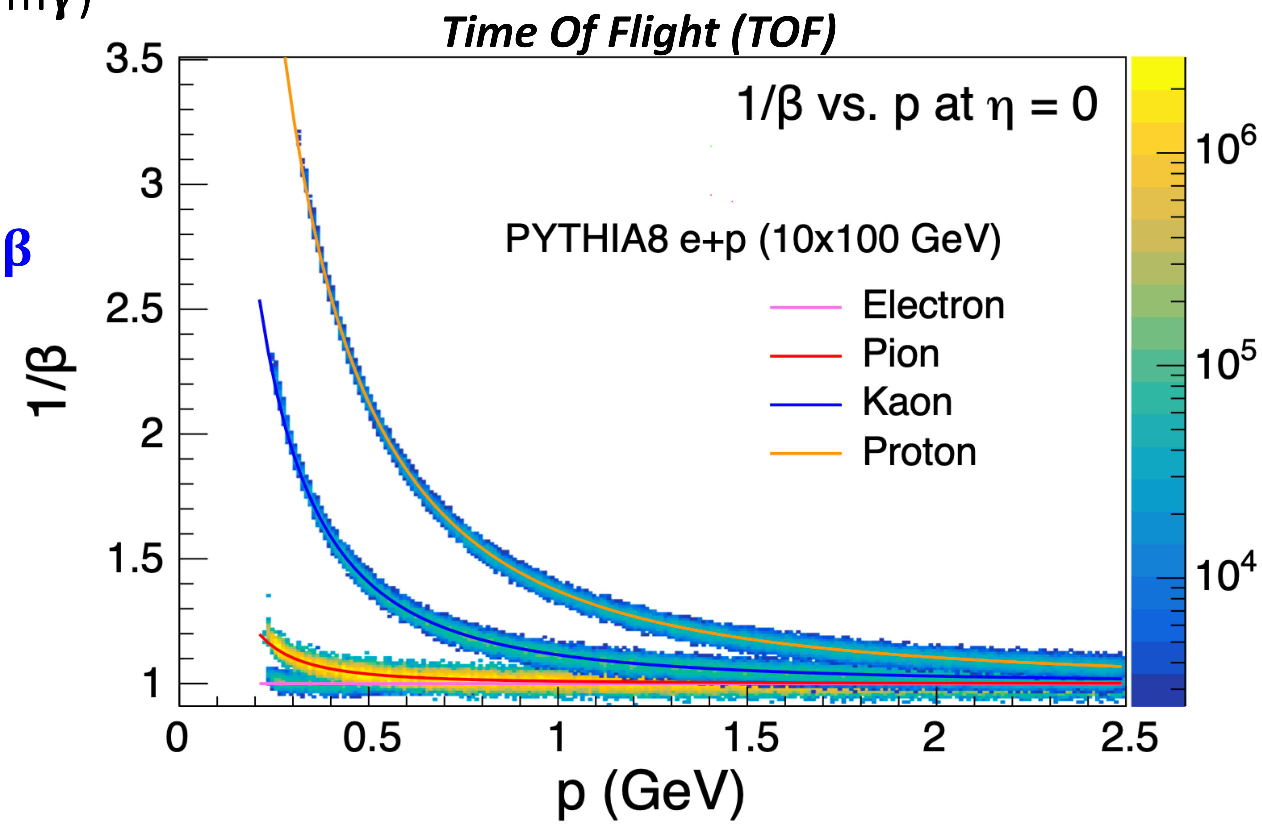
- **Main goal:**
  Separation of charged pions, kaons and protons from each other over a wide range with better than 3σ separation
- **Additional function**:
  Significant pion/electron suppression

- **Challenging momentum coverage for pion/kaon separation:**
  - **Forward**: up to 50 GeV/c
  - **Central**: up to 6 GeV/c
  - **Backward**: up to 10 GeV/c



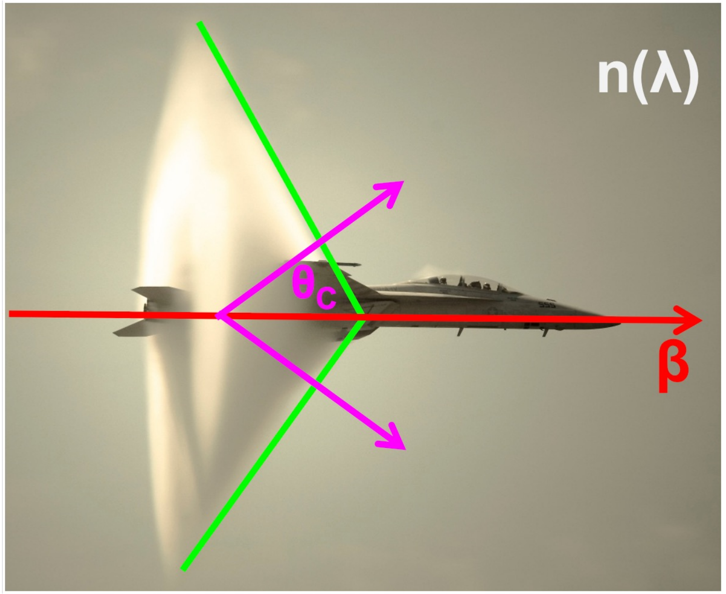
CHARGED PARTICLE IDENTIFICATION

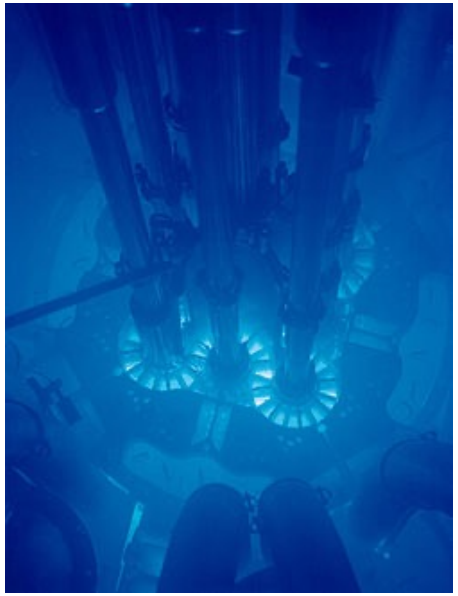
- **Velocity (β) measurement yields mass!** (p = m$\boldsymbol{\gamma\beta}$ E = m$\boldsymbol{\gamma}$)
- **Direct measurement:**
  - **Record signal time at multiple locations, calculate β**
  - "Fast" detector = low transit time spread (most easily achieved at small transit time)
- **Velocity-dependent interactions with detector:**
  - Specific Ionization (aka $\frac{dE}{dx}$)
  - **Cherenkov Radiation**

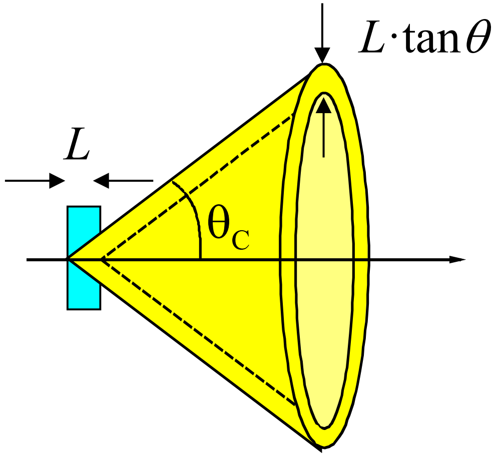


- Equivalent of "sonic boom" for light!
- Particles traveling faster then light in medium irradiate Cherenkov light!
- Cherenkov light produced equally distributed over photon energies, proportional $1/\lambda^2$
  → eery blue light seen in nuclear reactors
- For a given medium, refractive index n, there is a threshold for light production at $\beta = 1/n$
- Angle of cone (θ_C) related to particle velocity (β) in medium with refractive index $n(\lambda)$

$$\cos\theta_c = \frac{1}{\beta n(\lambda)}$$







CHERENKOV DETECTORS

- Select material with refractive index n where particle type A produces Cherenkov light, particle type B does not
→ **threshold counter**

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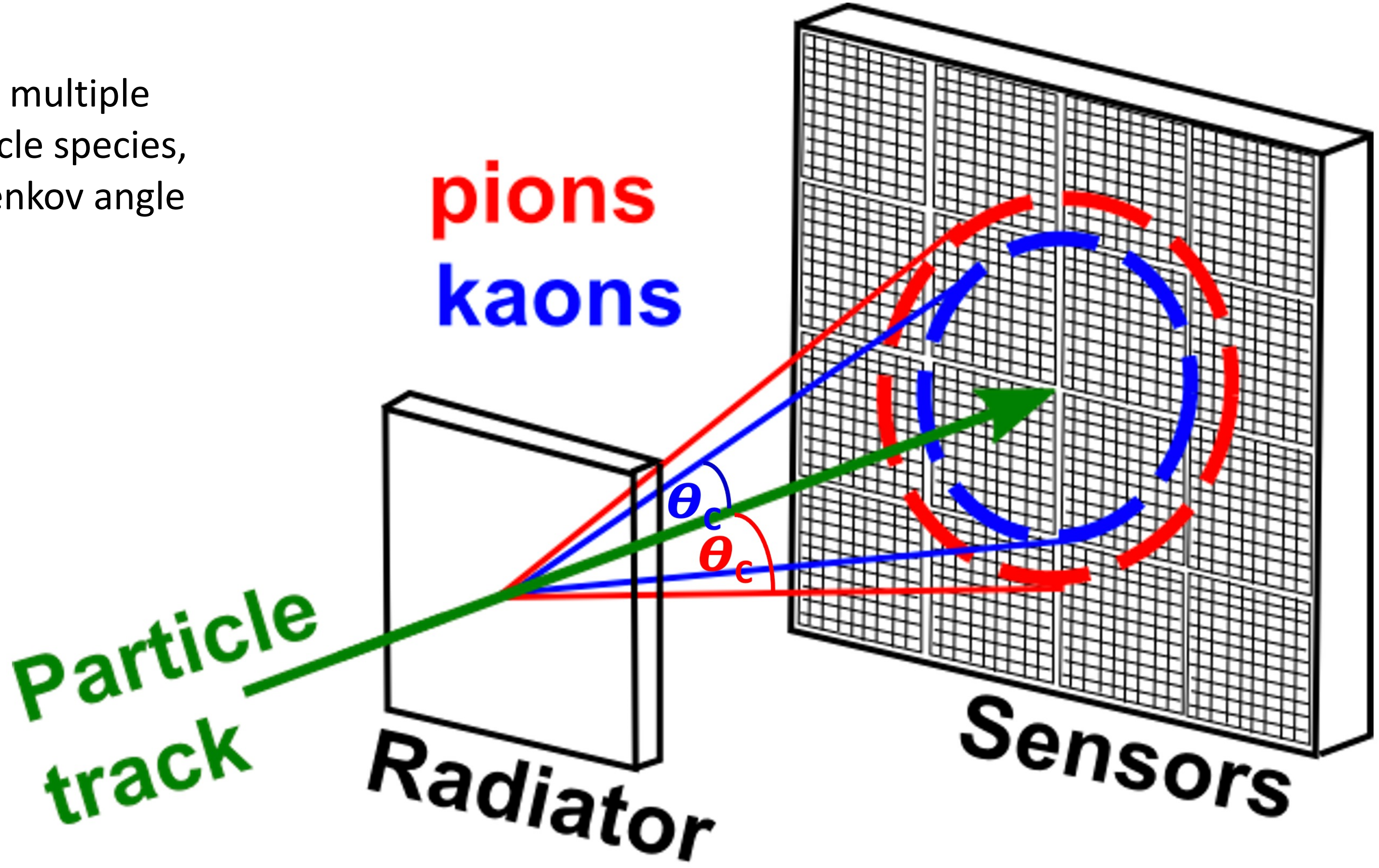
- Select material with refractive index n where multiple Cherenkov photons are detected for most particle species, image Cherenkov ring, precisely measure Cherenkov angle
→ **Ring Imaging Cherenkov counter (RICH)**



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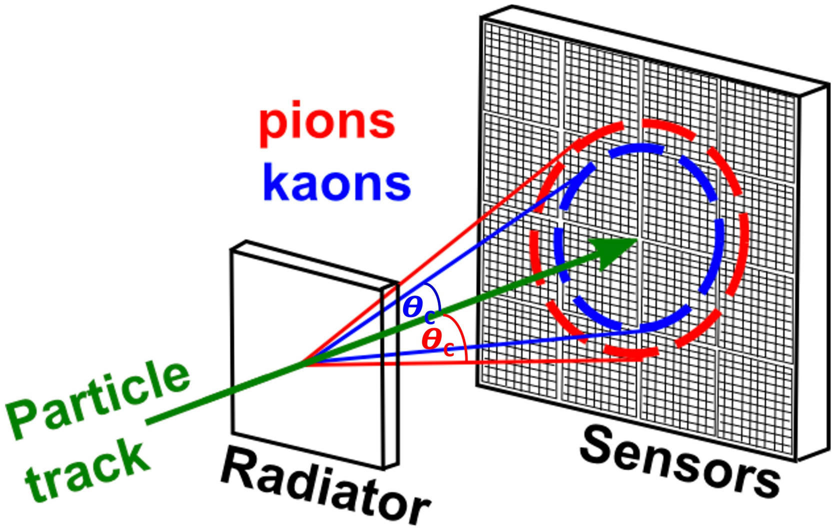

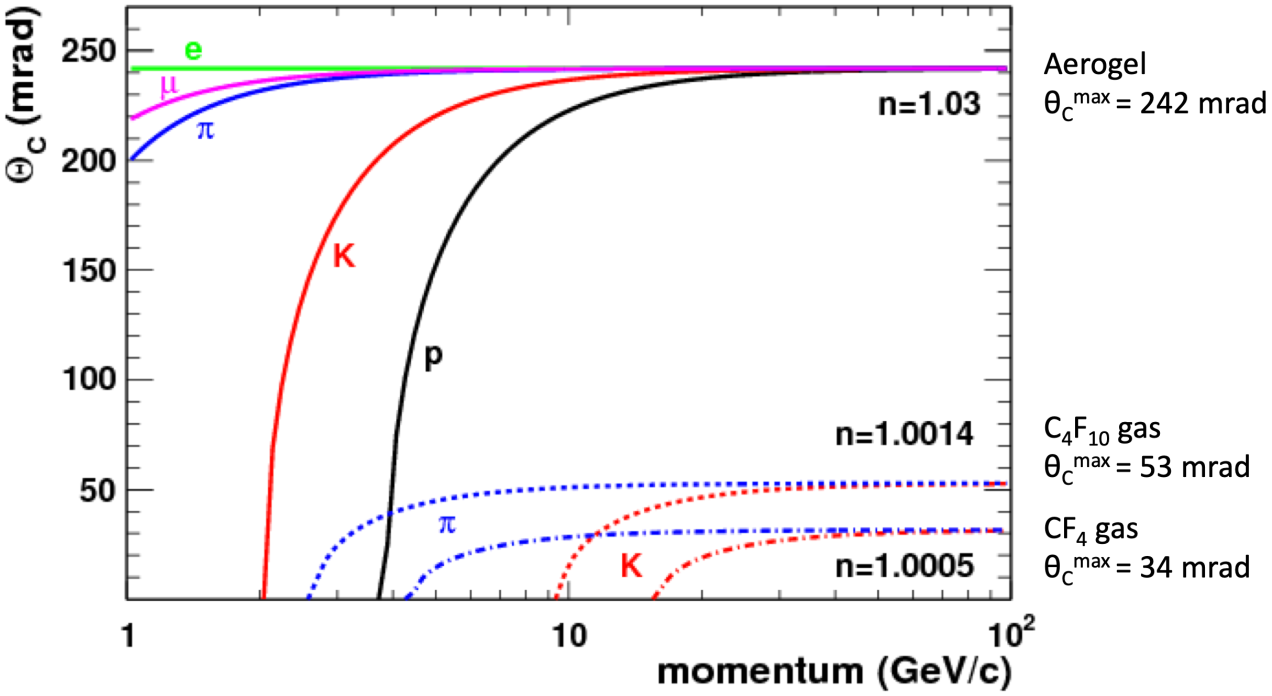

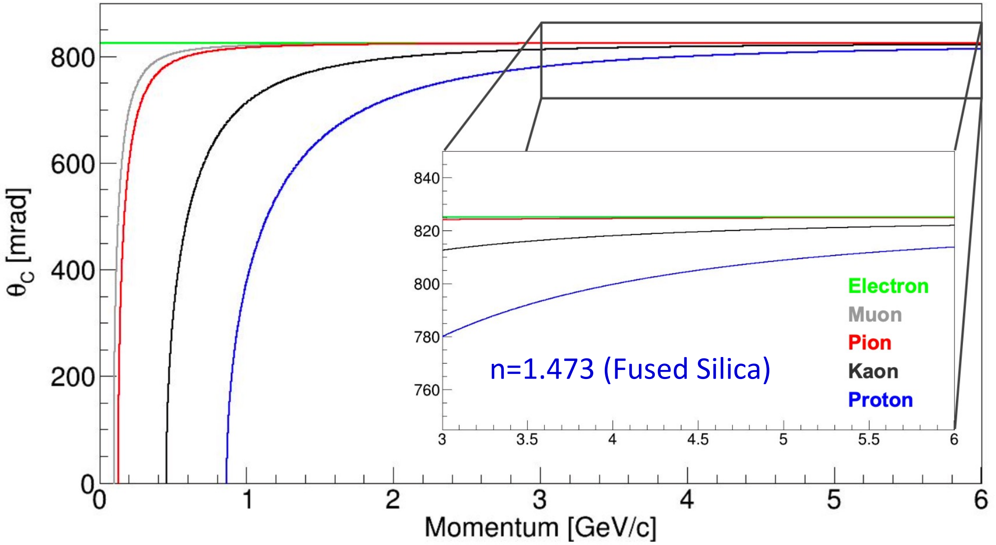

CHERENKOV DETECTORS

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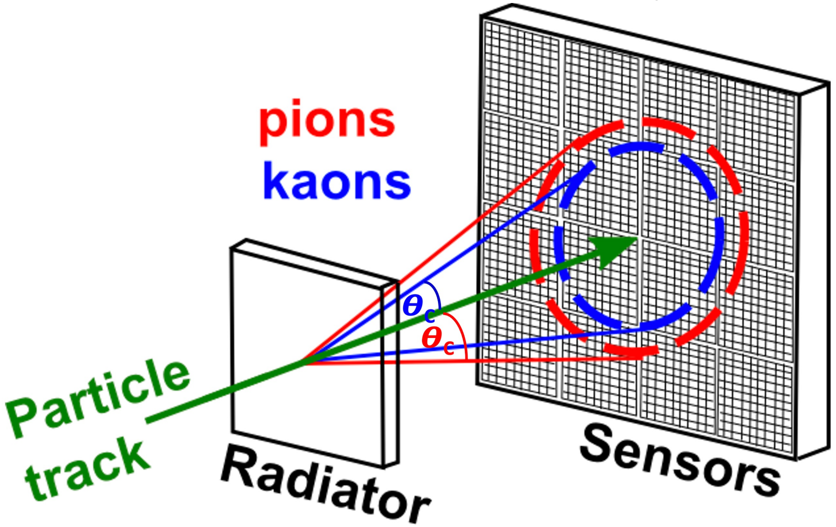
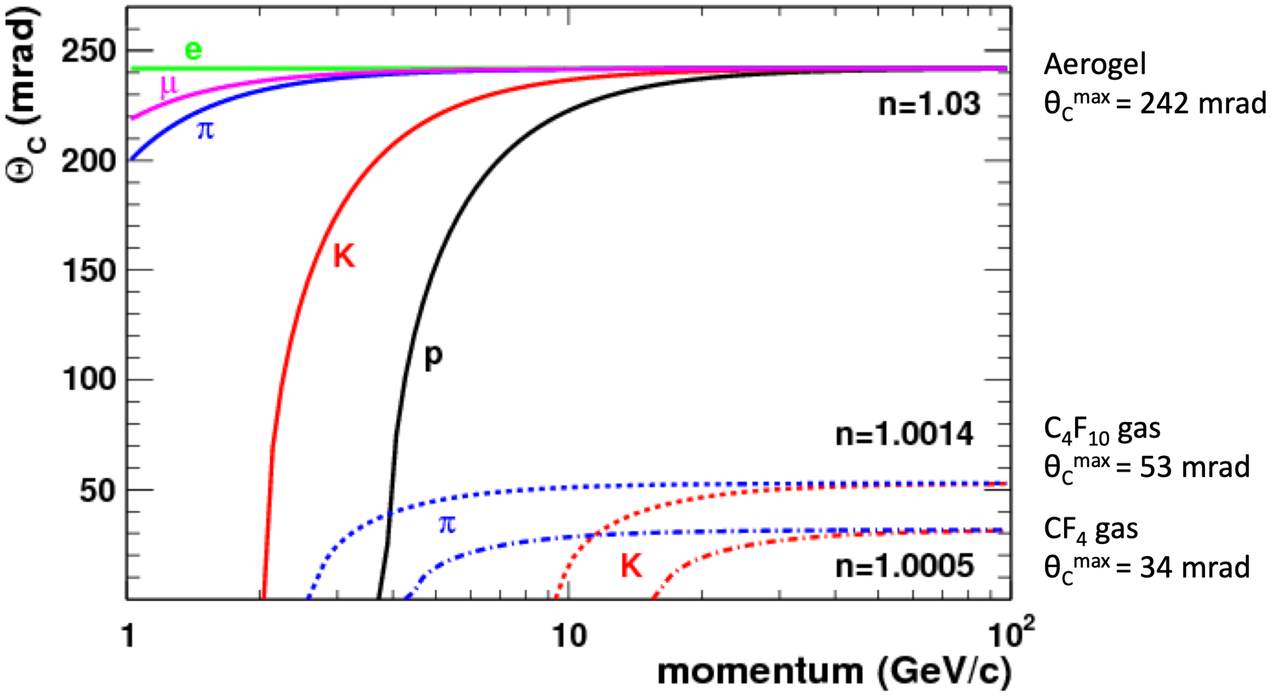
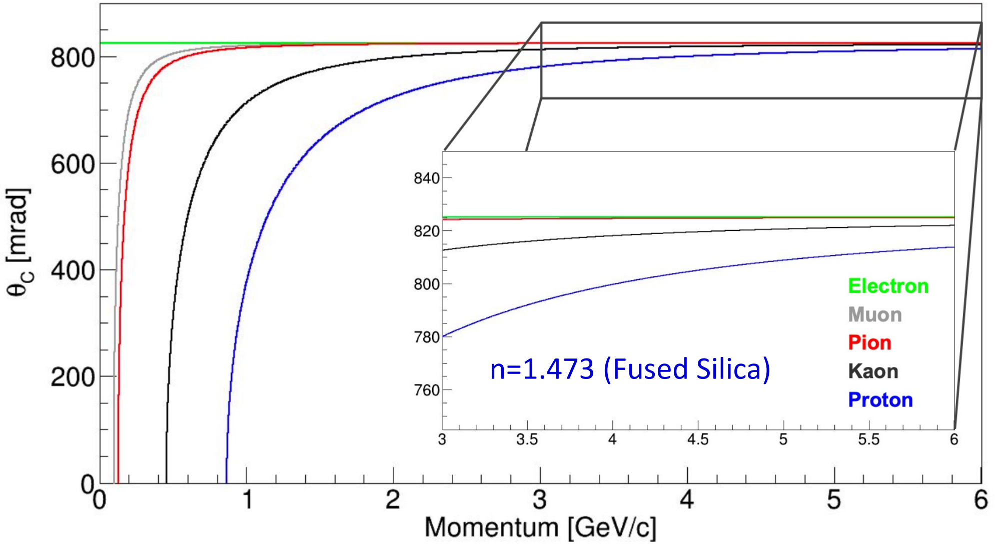
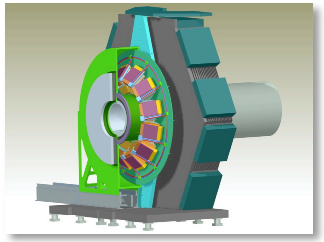
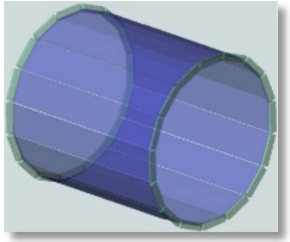
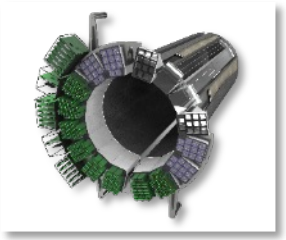
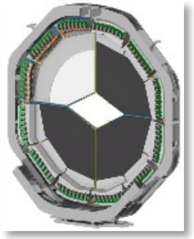
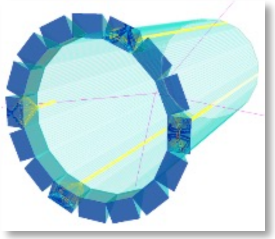
- Select material with refractive index n where multiple Cherenkov photons are detected for most particle species, image Cherenkov ring, precisely measure Cherenkov angle
  → **Ring Imaging Cherenkov counter (RICH)**
- Compare ring image with expected image for e/μ/π/K/p (likelihood test) or calculate mass from track β using independent momentum measurement (B field, tracking).







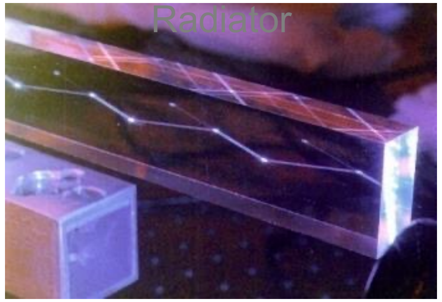




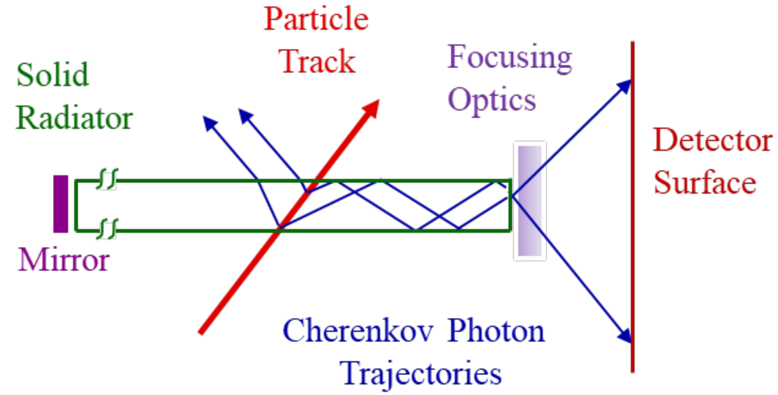
BABAR | SuperB | Belle II | GLUEX | panda | panda | Electron Ion Collider

Detection of Internally Reflected Cherenkov Light

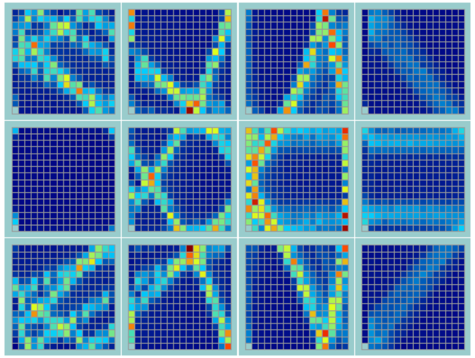
- Pioneered by the BaBar experiment at SLAC National Accelerator Laboratory
- Fused silica radiator is used also as light guide
- Detector surface is outside active volume
- Cherenkov angle is conserved during internal reflections and reconstructed from detected photons
- Ultimate Deliverable: PID likelihoods

Synthetic Fused Silica Radiator

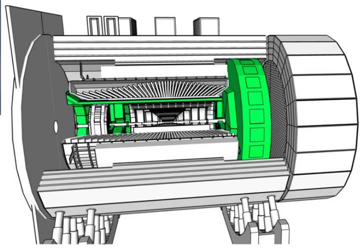




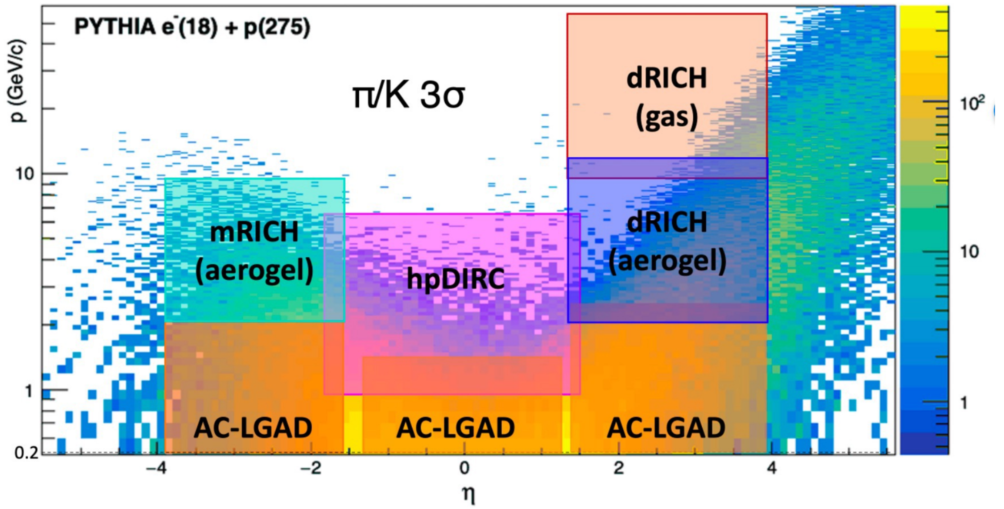
Example Detector Surface hpDIRC simulation

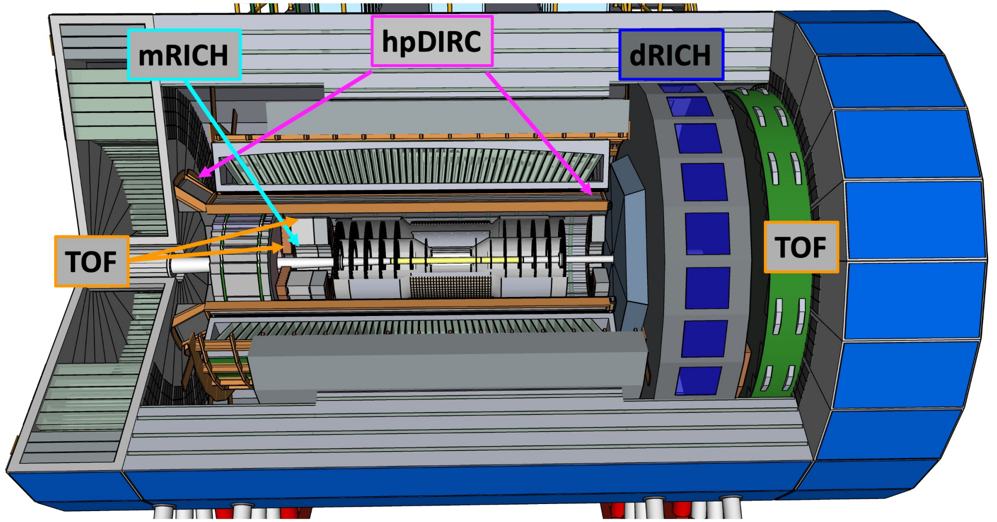


PID AT EIC DETECTOR1

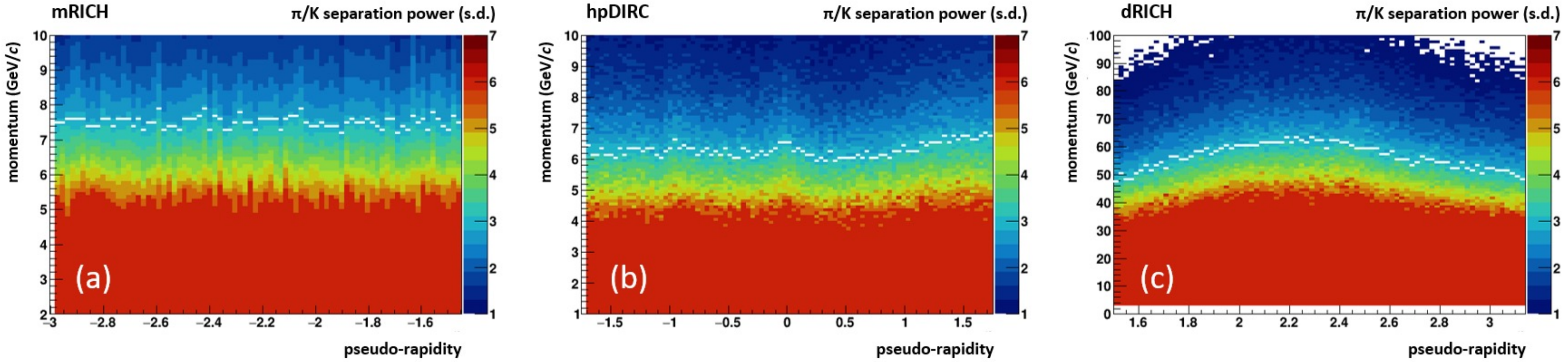


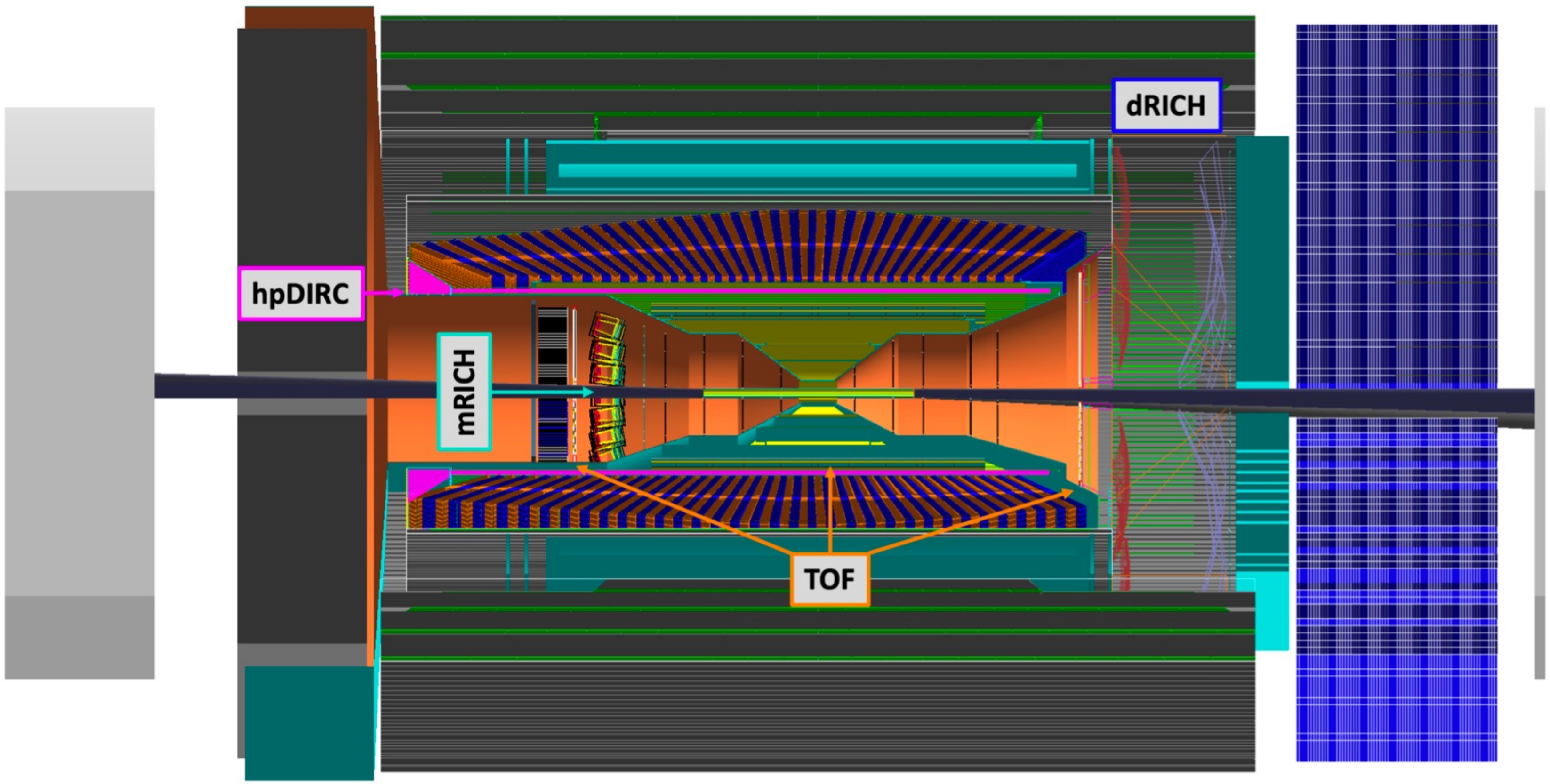
- **EIC PID technologies are based on** the outcome of the **EIC generic R&D program** (eRD14 EIC PID Consortium) and **in line with the reference EIC detector concept in the Yellow Report**
- **Geometries are optimized to fit the reference Detector1 design while maintaining the required performance** to assure wide momentum coverage across the full phase space.
- Backward: Short, modular RICH **(mRICH)**
- Barrel: Radially compact with flexible design high-performance DIRC **(hpDIRC)**
- Forward: Double-radiator RICH **(dRICH)**
- AC-LGAD based time-of-flight (**TOF**) system for hadronic PID in momentum range below the thresholds of the Cherenkov detectors
- Tracking resolution of identified particle has large impact on Cherenkov detectors performance (required 1mrad for mRICH, 0.5mrad for dRICH and hpDIRC!)





PID in EIC Detector1 Simulation

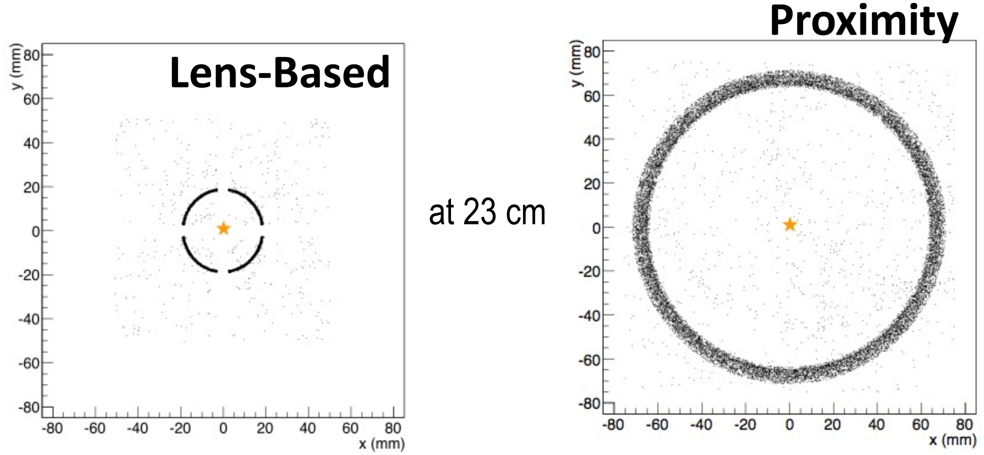




Modular RICH Detector (mRICH)

3-9 GeV/c
-3.0 < η < -1.5

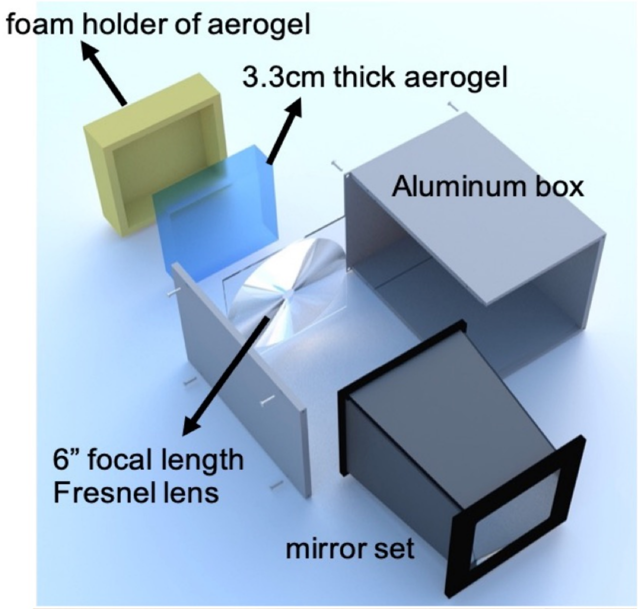
Overview:

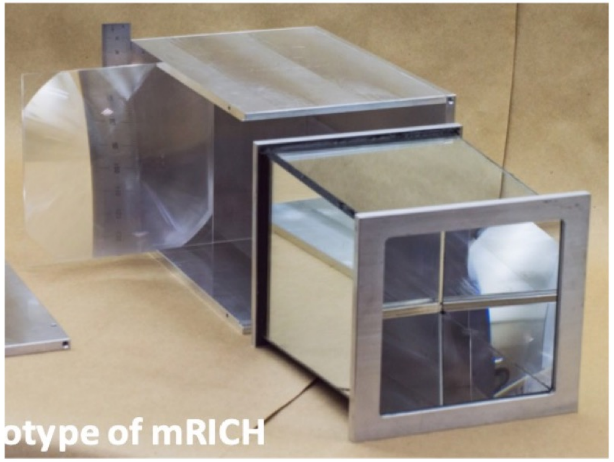
- Modular and compact RICH detector (~15x15x25 cm)
- Radiator: Aerogel, 11x11x3 cm and n=1.03
- Focusing: Fresnel lens with 6" focal length
- 

- π/K separation up to 10 GeV/c and e/π separation up to 2 GeV/c.
- Sensors: Currently **assuming SiPMs but LAPPDs would be good alternative**

Systematic effects

- Emission point error: minimized at the lens focal plane
- Chromatic dispersion error: reduced by UV filtering (acrylic).
- Pixel size error: the uncertainty raised by pixel size, a, error





Modular RICH Detector (mRICH)

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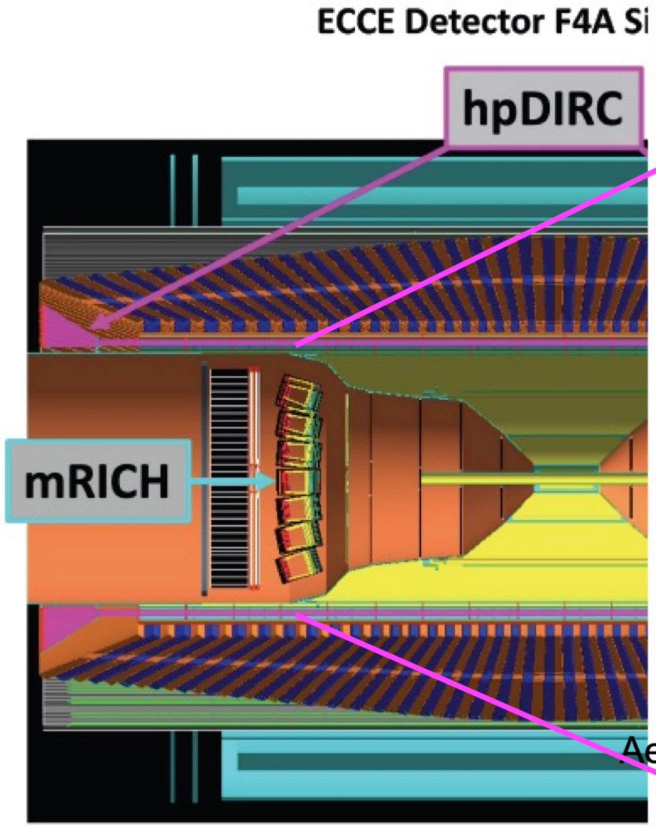
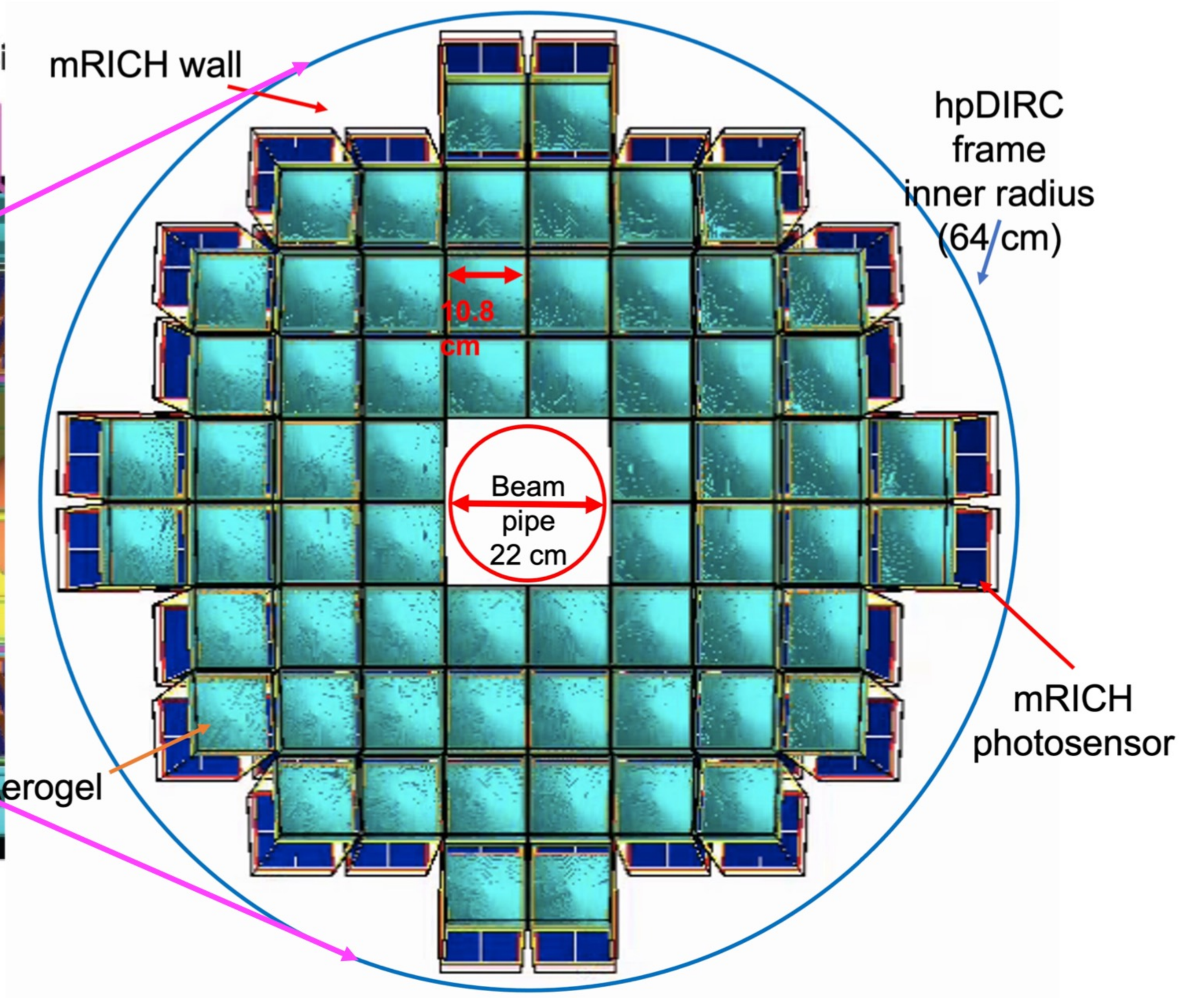
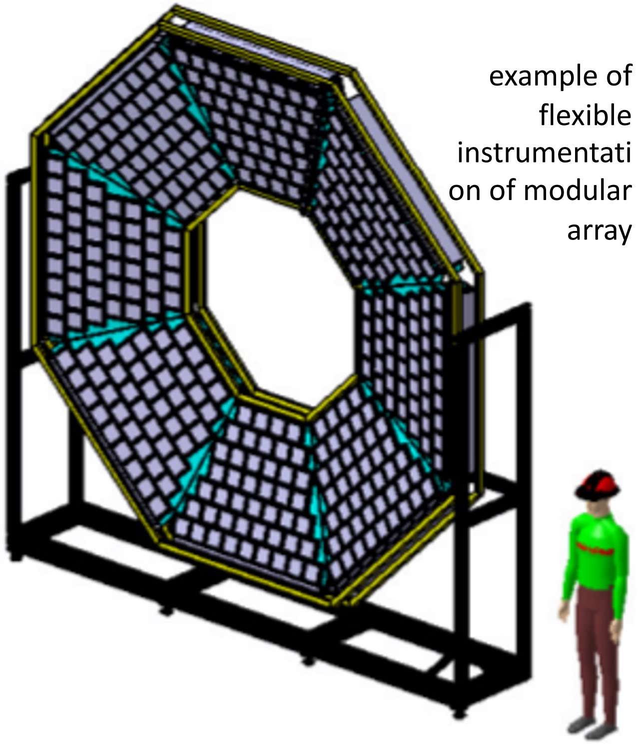


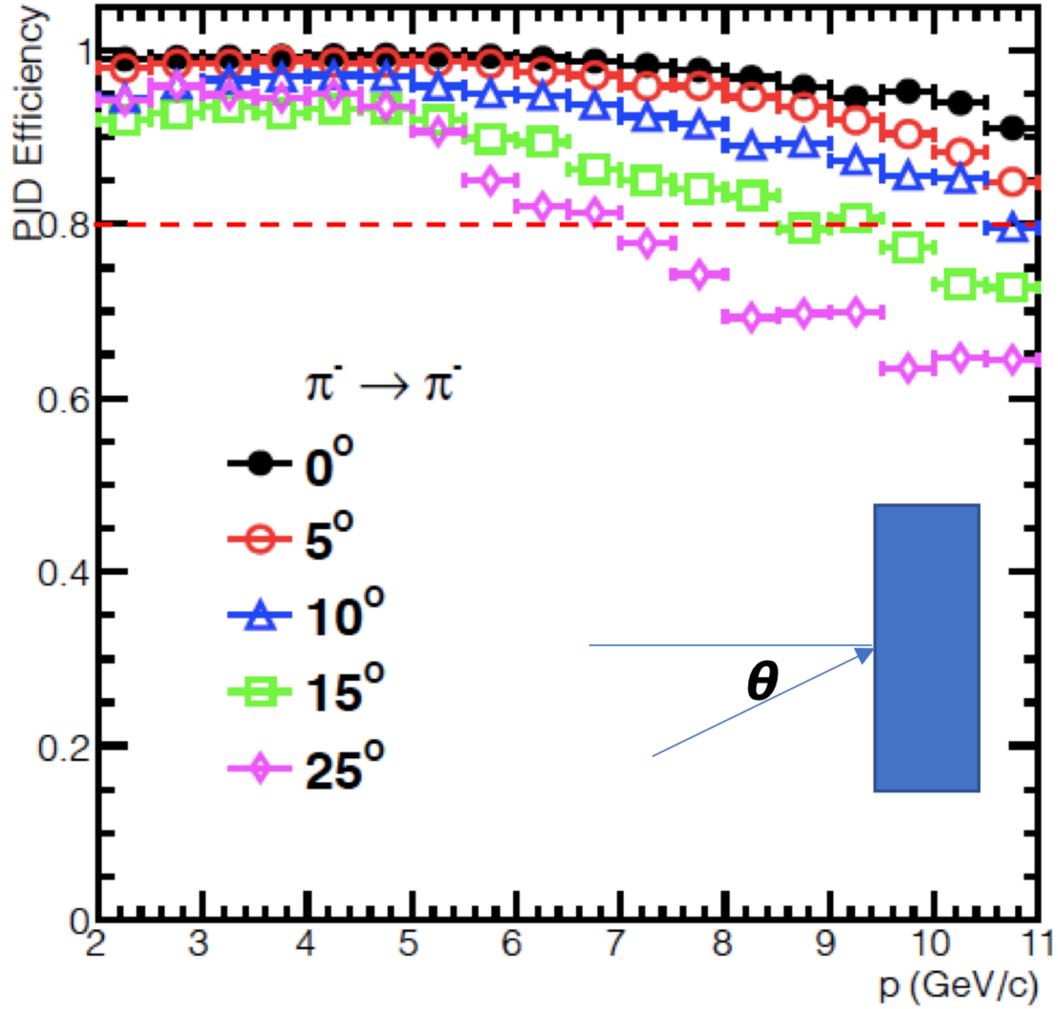


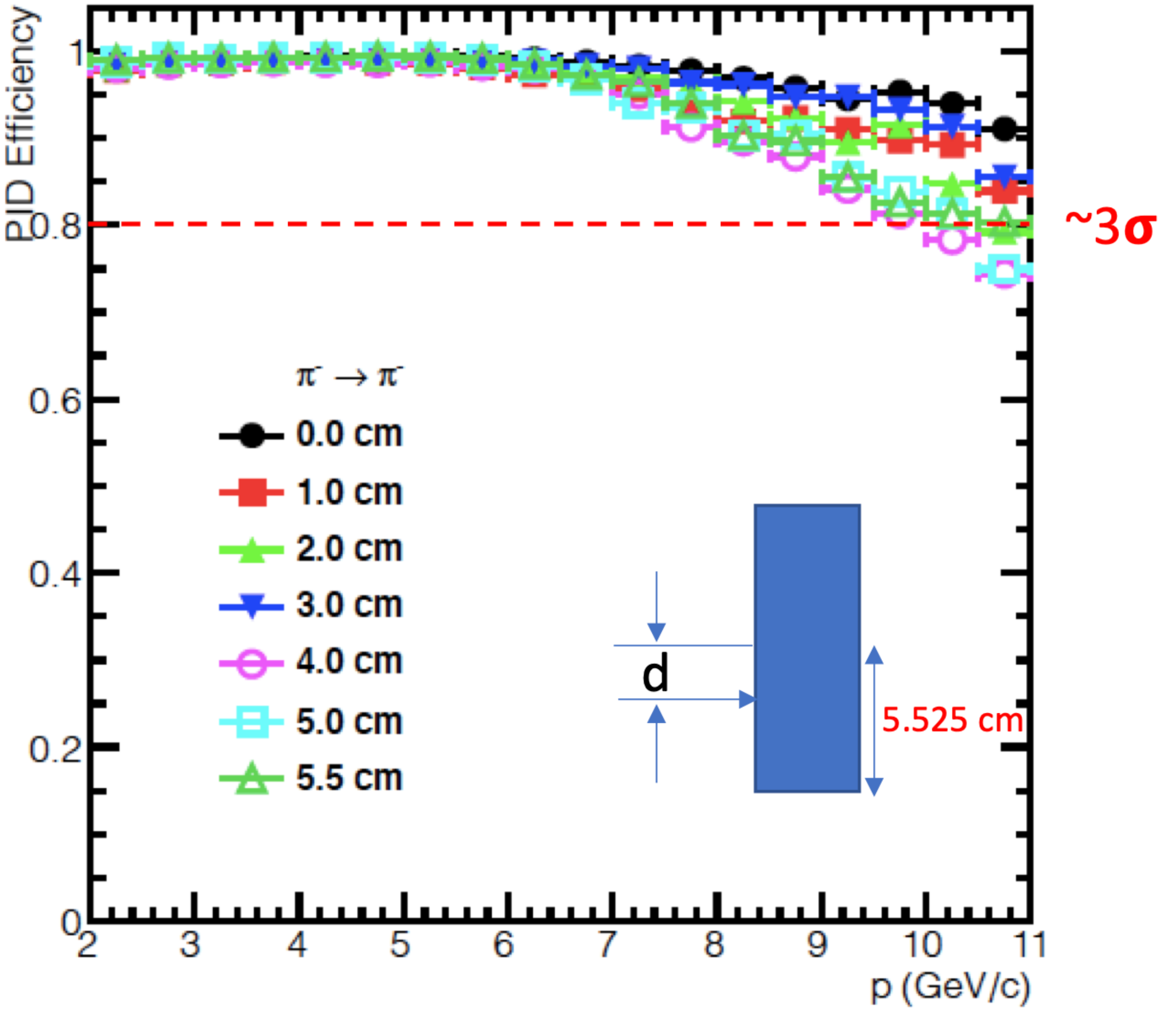


example of flexible instrumentation of modular array

Modular RICH Detector (mRICH)

3-9 GeV/c
$-3.0 < \eta < -1.5$





- Efficiency drops beyond 15°

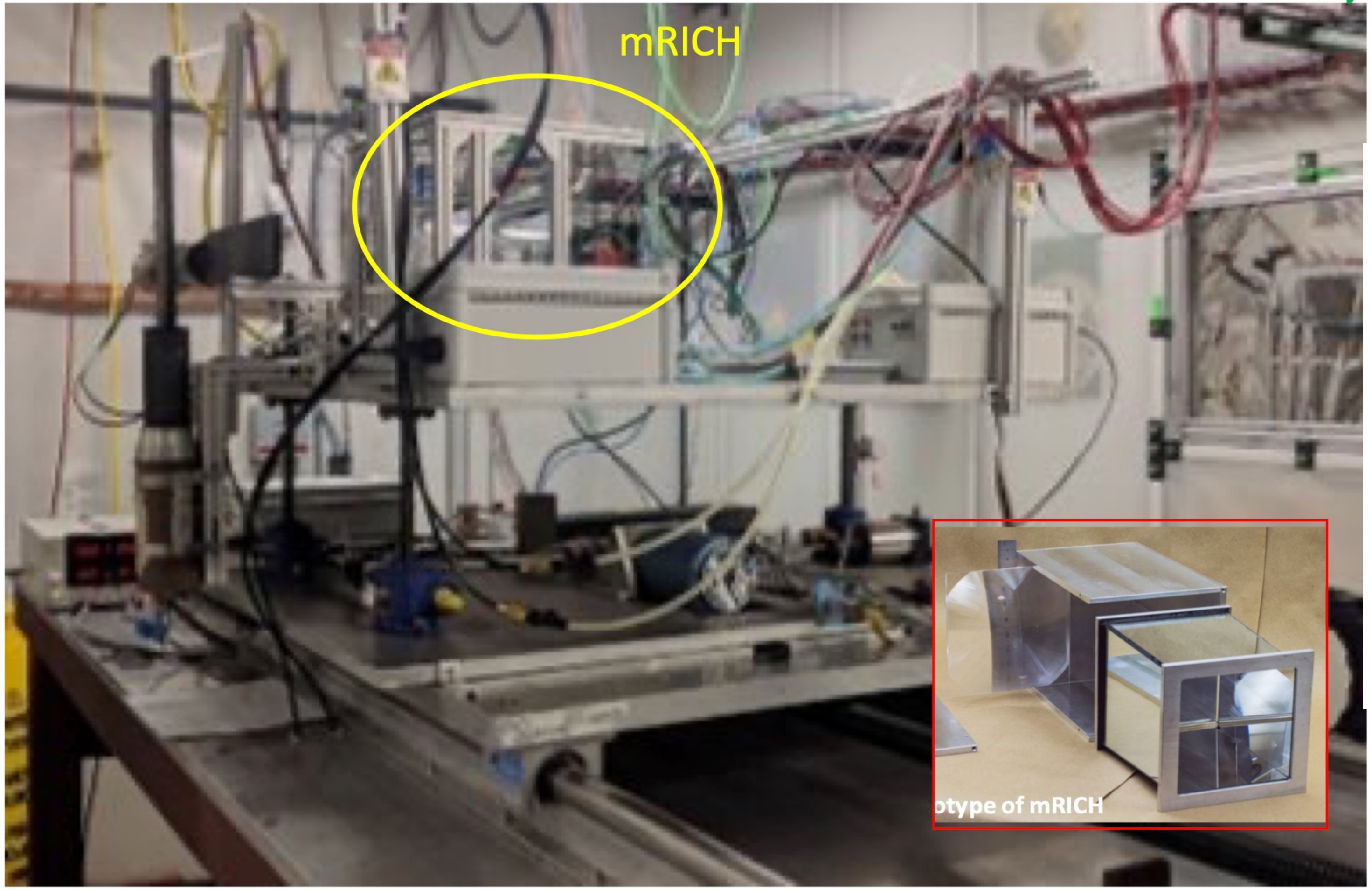
Modular RICH Detector (mRICH)

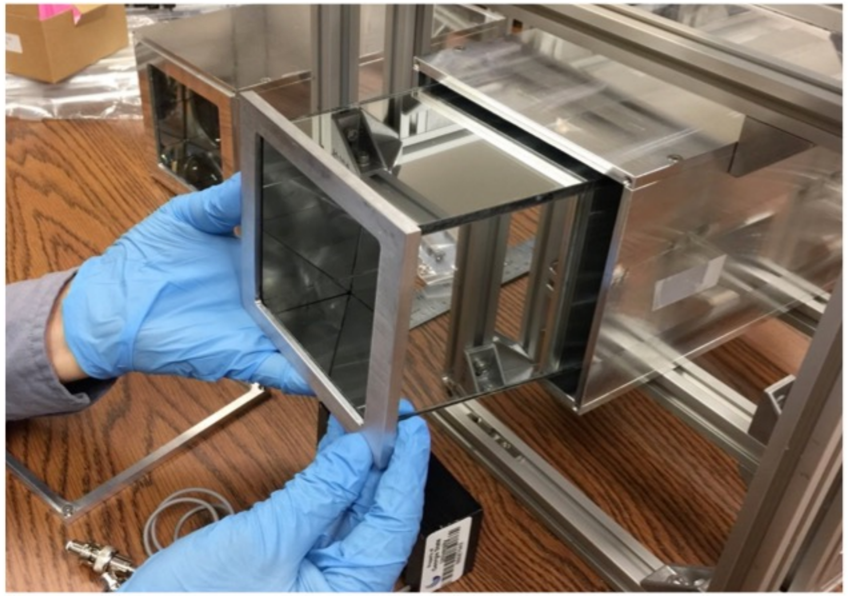
3-9 GeV/c
-3.0 < η < -1.5

- Two beam tests: 2016 and 2018.
  - **1st beam test** - verified mRICH working principle and validated simulation
  - **2nd beam test –** test mRICH performance with improved optical design, and test SiPM sensors.

Fermilab Beam Test Facility

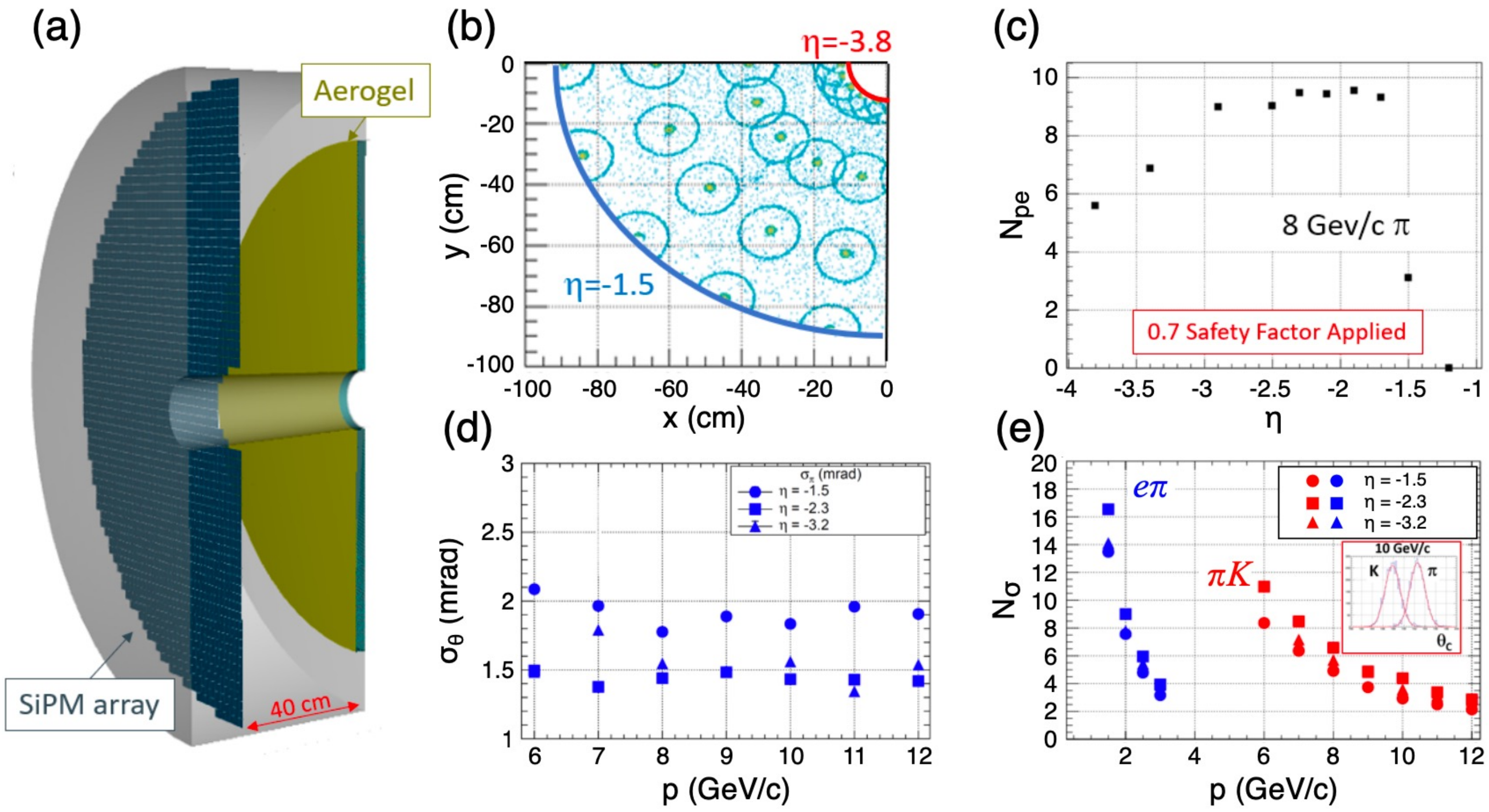
Beam →



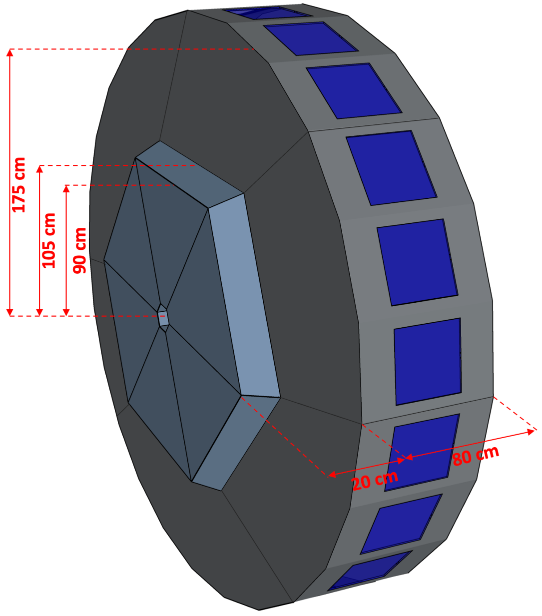


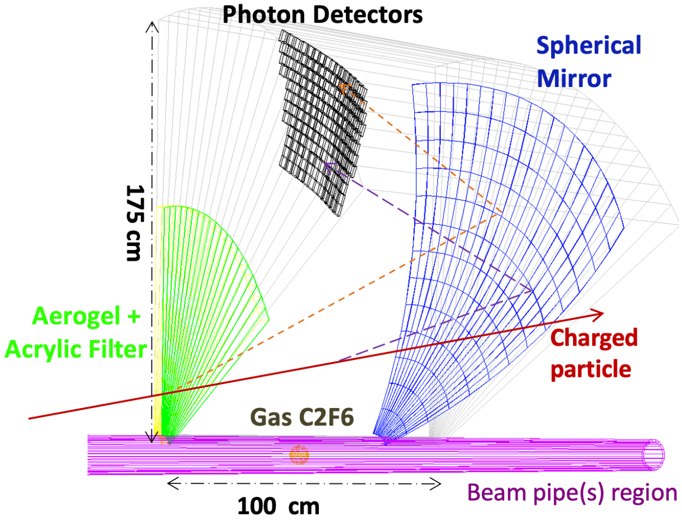
Proximity focusing RICH Detector (pfRICH)

- A proximity-focusing aerogel RICH (pfRICH) with 40 cm proximity gap.
- Alternative proposed in ATHENA, deviates from the mRICH technology used in the Yellow Report.
- Main advantage: no need of lenses and mirrors.
- Needs more detailed simulations for full evaluation.



3-50 GeV/c
1.5 < η < 3.2





Overview:

- **Hadron identification (p/K/p) from 3 to 50 GeV/c** (3 sigma) and **electron identification (e/p) up to 15 GeV/c**
- Covering **polar angles 5-25°** in the current implementation.
- **Photon detector out of acceptance** and far from the beam pipe in moderate magnetic field (~1/2 of central zone): less constraints on material budget (e.g. mechanical supports, shielding, cooling); neutron flux is also reduced
- Currently **assuming SiPMs but LAPPDs would be good alternative**

Radiators:

- Aerogel: 4 cm, $n_{(400nm)}$~1.02 + 3 mm acrylic filter
- Gas: 1m (1.1m ePHENIX), n_{C2F6}~1.0008

6 Identical Open Sectors (Petals):

- Large Focusing Mirror with R ~1.8m (~2.0m ePHENIX)
- Optical sensor elements: ~3500 cm^2/sector, 3 mm pixel size, UV sensitive, out of charged particles acceptance

dRICH: dual-radiator RICH

3-50 GeV/c
1.5 < η < 3.2

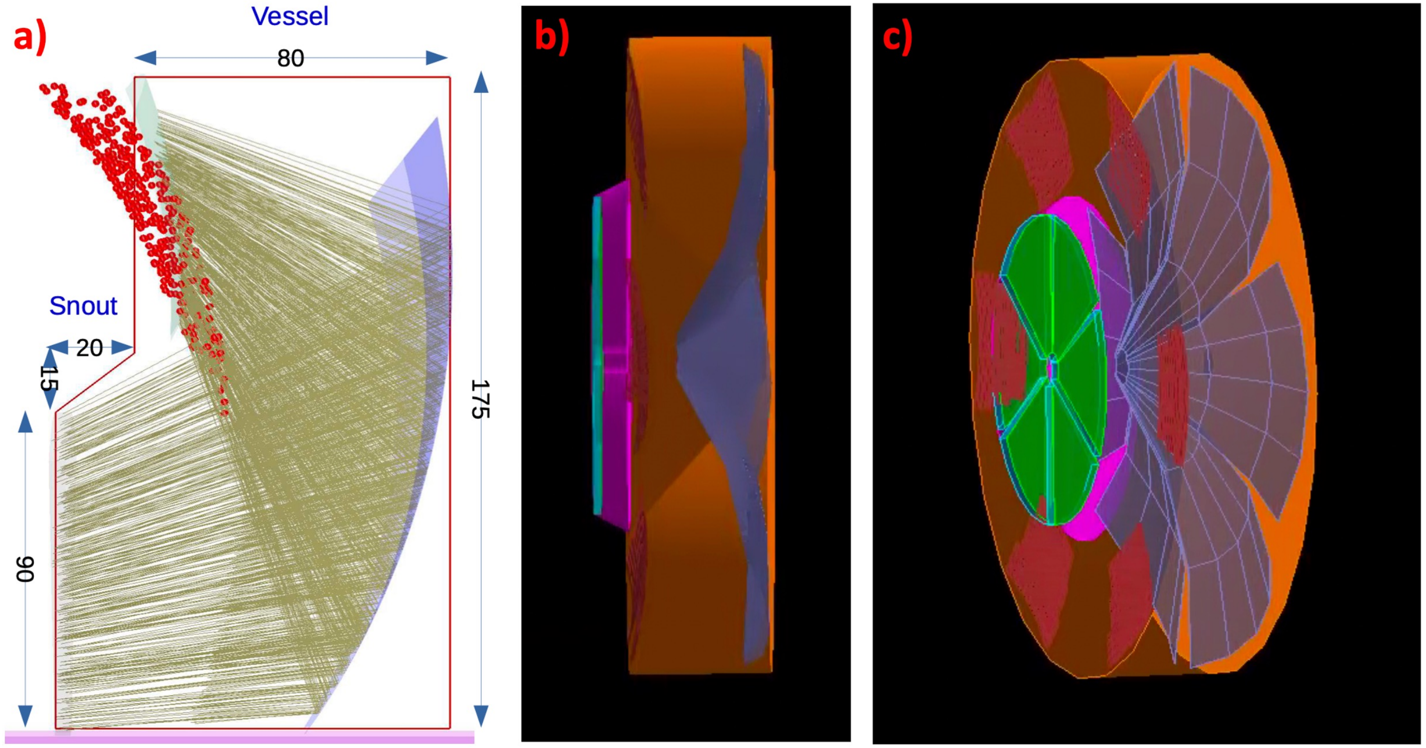
- Adapted eRD14 Generic design

- Decreased longitudinal size:
  - Improve chromatic aberration
  - Potential improve final photon acceptance
  - Reduce number of gas photons

- Decreased transverse size
  - Fits EIC Detector1 space and lowers cost
  - Moved closer to IP to maintain acceptance

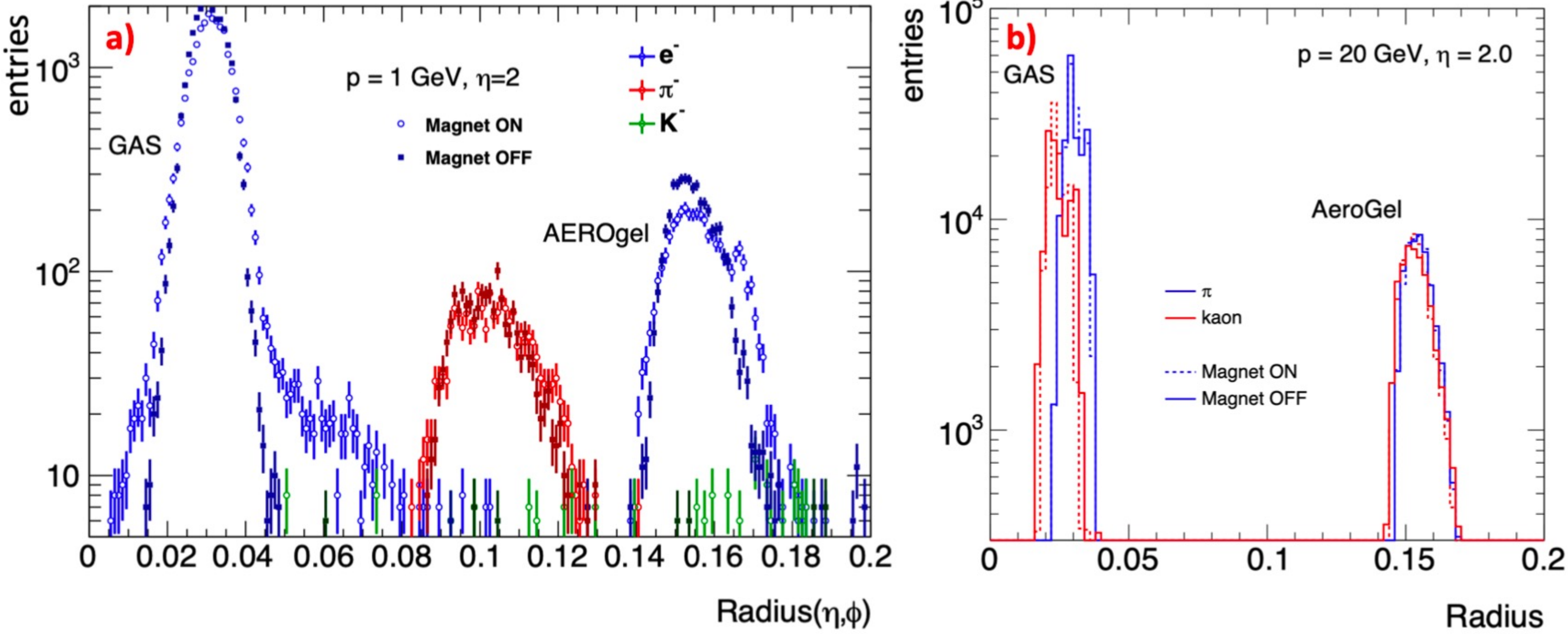
- Location and final shape of detector plane are being optimized

- Gas alternatives are being investigated



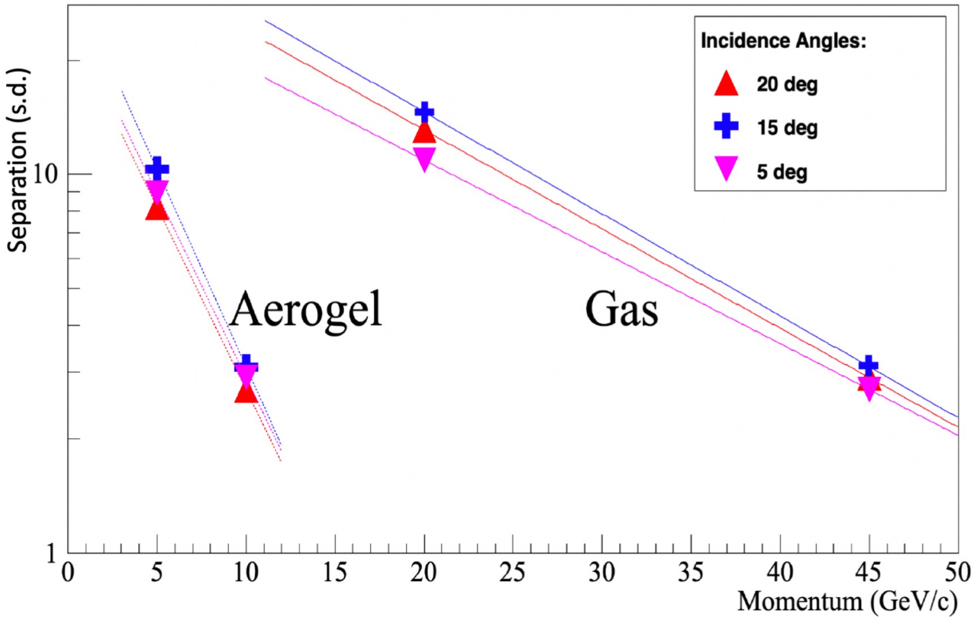
3-50 GeV/c
1.5 < η < 3.2

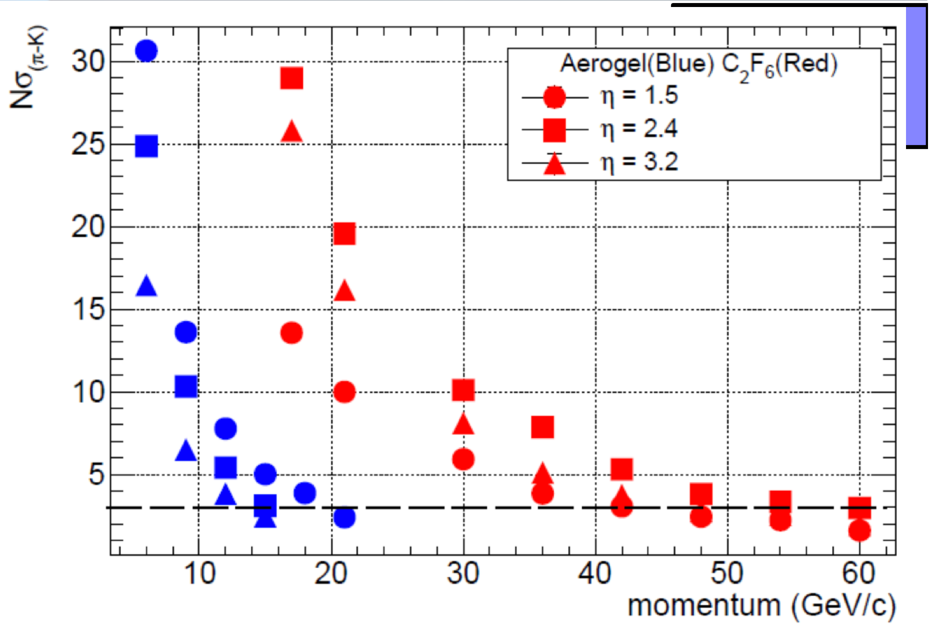
Negligable impact of magnetic field on performance!

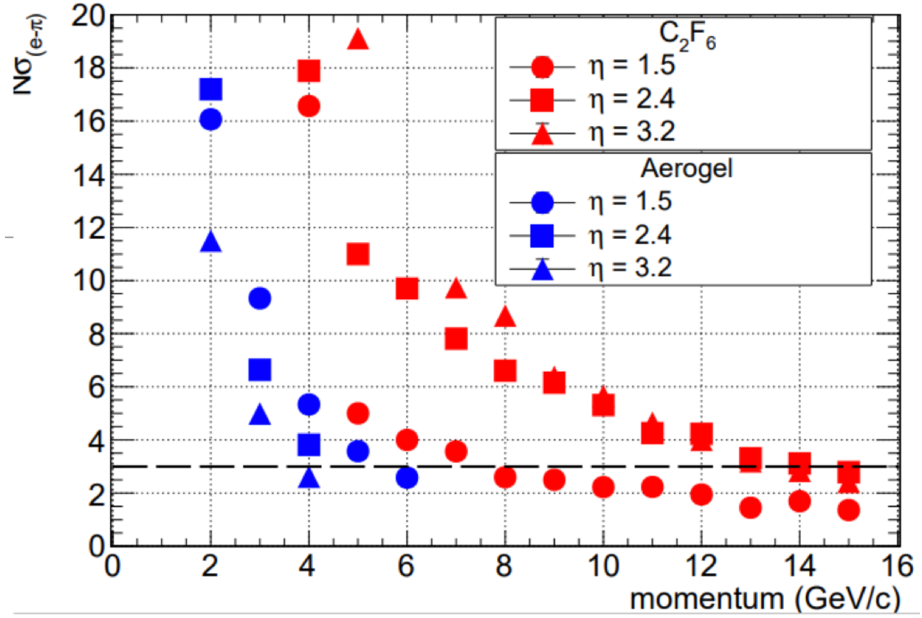


Reconstructed radius for electrons, pions, and kaons at 1 GeV/c with and without magnetic field

Capability of reaching desired separation power!







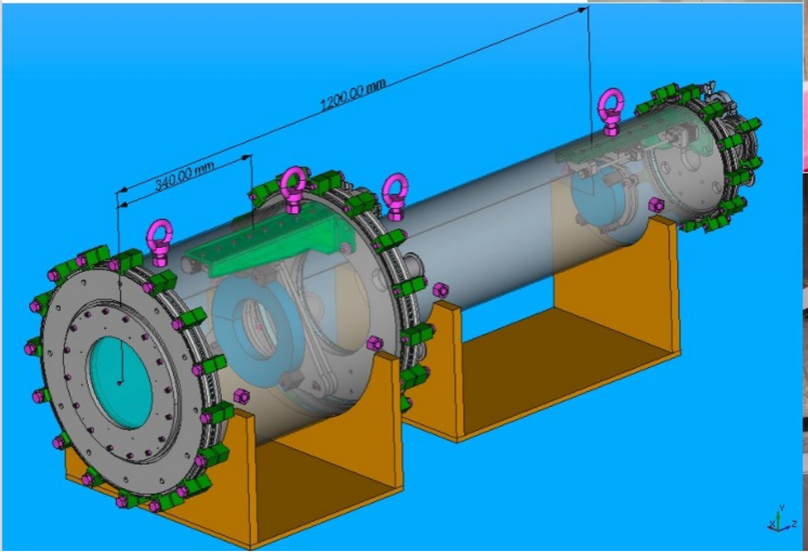
dRICH: dual-radiator RICH

first test-beams in September (SPS) and October 2021 (PS, in synergy with ALICE) at CERN

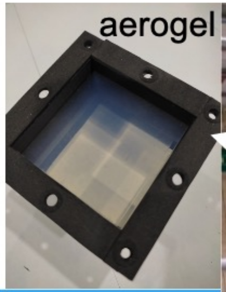
- **goals**
  - study dual radiator performance and interplay
  - study specifications and alternatives for optical components
  - test alternate single-photon detection systems

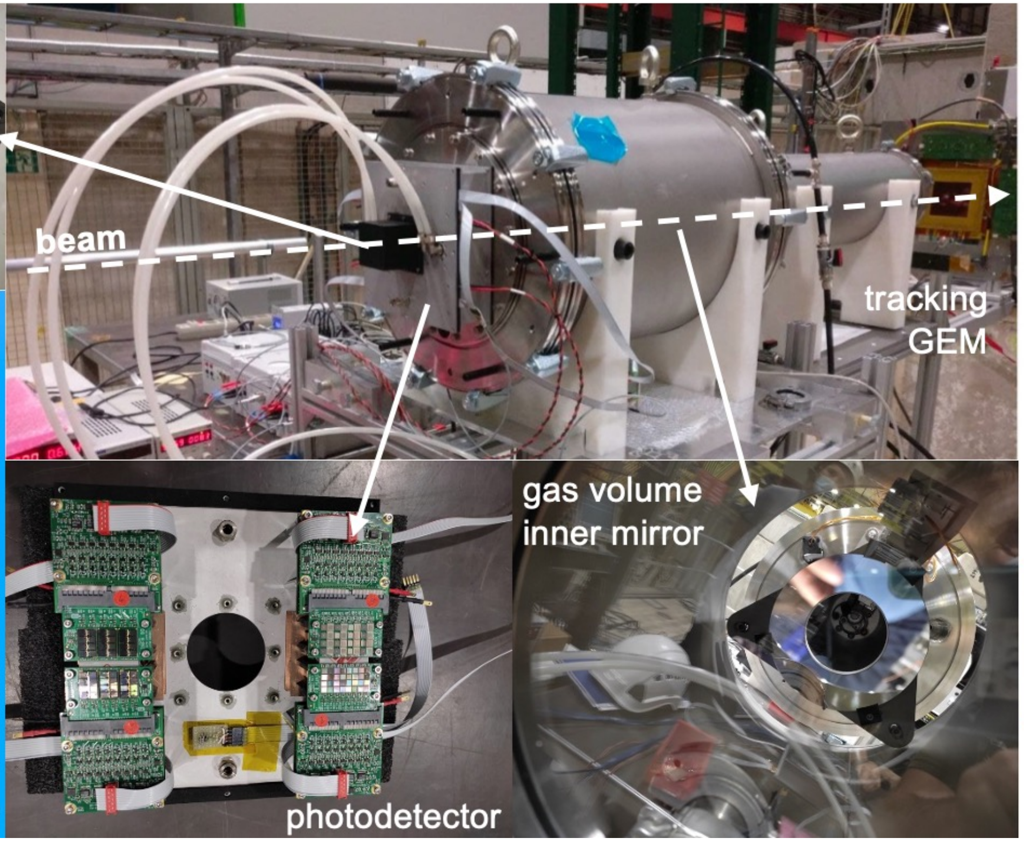
dRICH prototype

dual-radiator imaging
vessel for gas and n tune
sensor & readout friendly

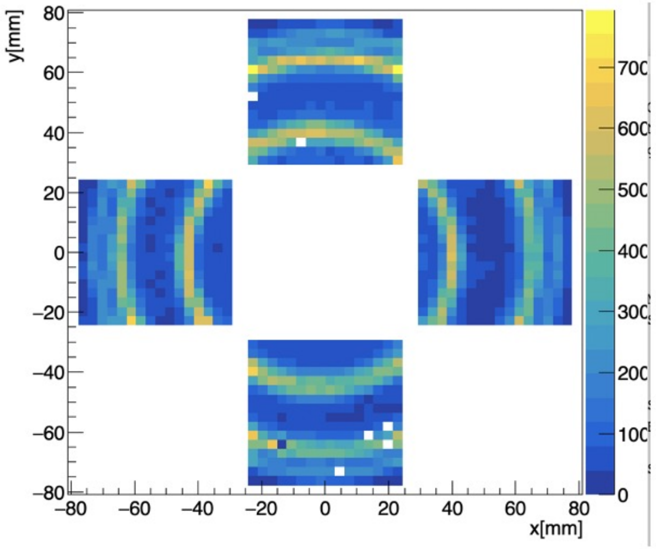


dRICH prototype @ CERN-SPS

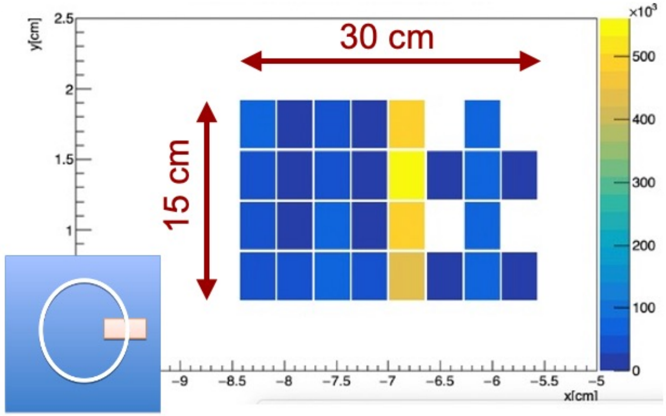




working principle + optical performance with H13700 PMT and MAROC readout



dRICH online monitor results



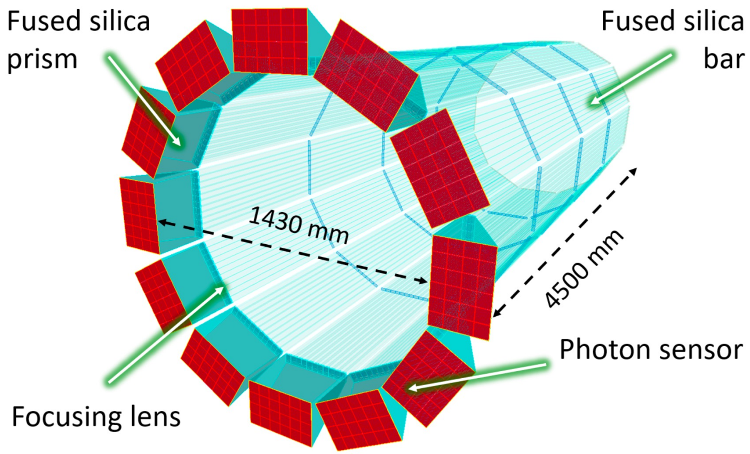
test of SiPM Cherenkov application with new ALCOR chip (ToT, streaming)

EIC hpDIRC

Concept:

- Fast focusing DIRC, utilizing high-resolution 3D (x,y,t) reconstruction
- Innovative 3-layer spherical lenses, compact fused silica expansion volumes
- Fast photon detection using small-pixel MCP-PMTs *(eRD14)* and high-density readout electronics *(eRD14)*

1-6 GeV/c
$-1.64 < \eta < 1.6$

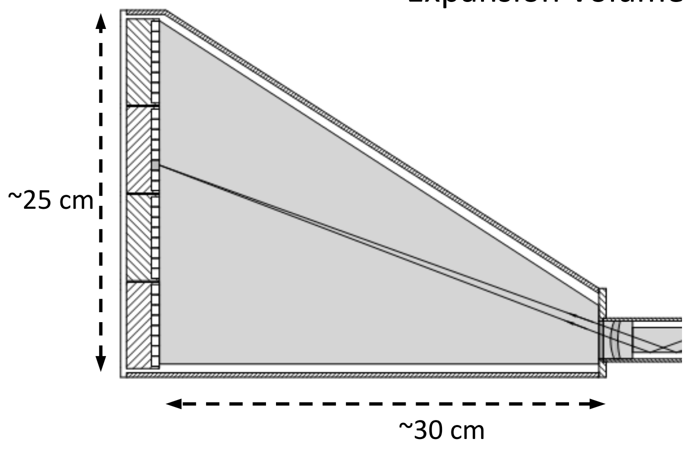


Excellent performance over wide angular range:

- ≥ 3 s.d. π/K up to 6 GeV/c, ≥ 3 s.d. e/π up to ~1.2 GeV/c
- Low momentum π/K identification in "veto mode" down to 0.2-0.3 GeV/c

Key Features:

- **Radially compact** (~6 cm; impact on cost of post-DIRC systems)
- **Flexible design** (to deal with sensor in B-field and detector integration)
- **Low demand on detector infrastructure** (no cryogenic cooling, no flammable gases)
- **R&D at advanced stage** (PID performance estimate based on test beam results, excellent agreement between detailed simulation and prototype data, fast simulation available)



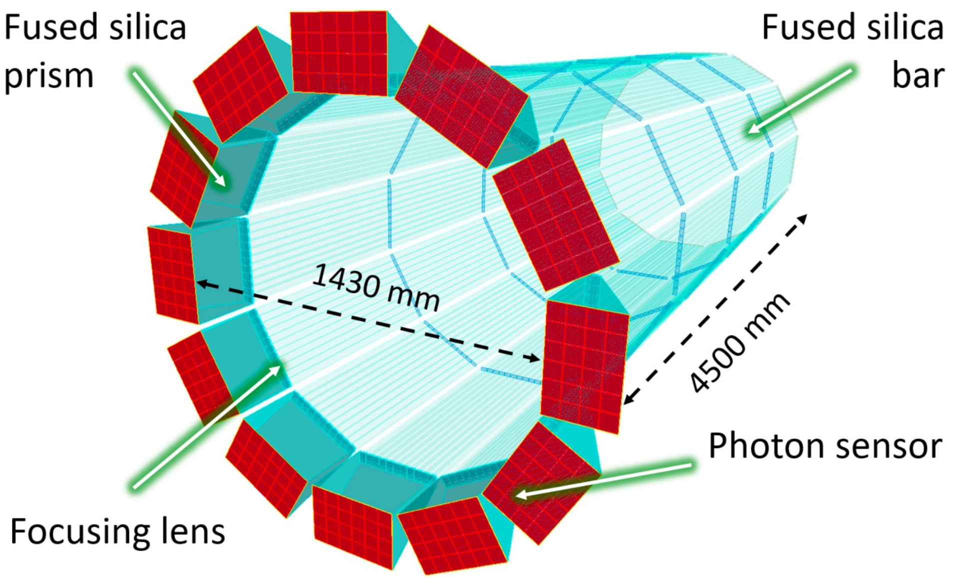
EIC HPDIRC

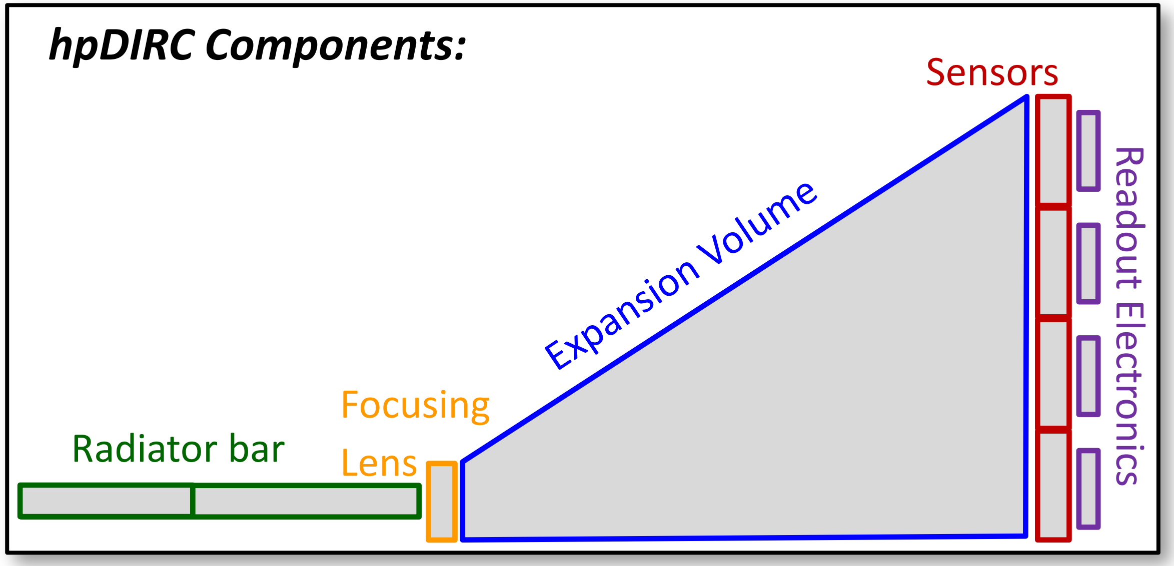
- **Barrel hpDIRC with 72cm radius**
- **Radiator bars:**
  - **420cm bar length** (works with both reused BaBar DIRC bars or new bars)
  - **12 bar boxes**, 10 long bars side-by-side in a bar box, 3 BaBar DIRC bars plus one half BaBar DIRC bar glued to form one long bar (or 3 BaBar DIRC bars plus one new short plate)
- **Focusing optics:**

  Radiation-hard 3-layer spherical lens
- **Expansion volume:**

  Solid fused silica prism: 24 x 36 x 30 cm^3 (H x W x L)
- **Readout:**

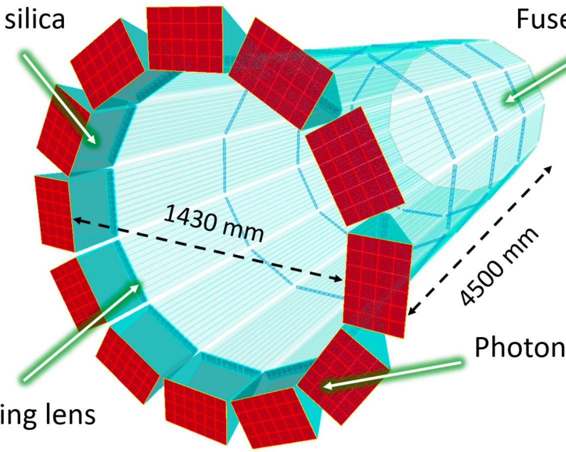
  PHOTONIS MCP-PMT Sensors + NALU's ASIC based Readout Electronics

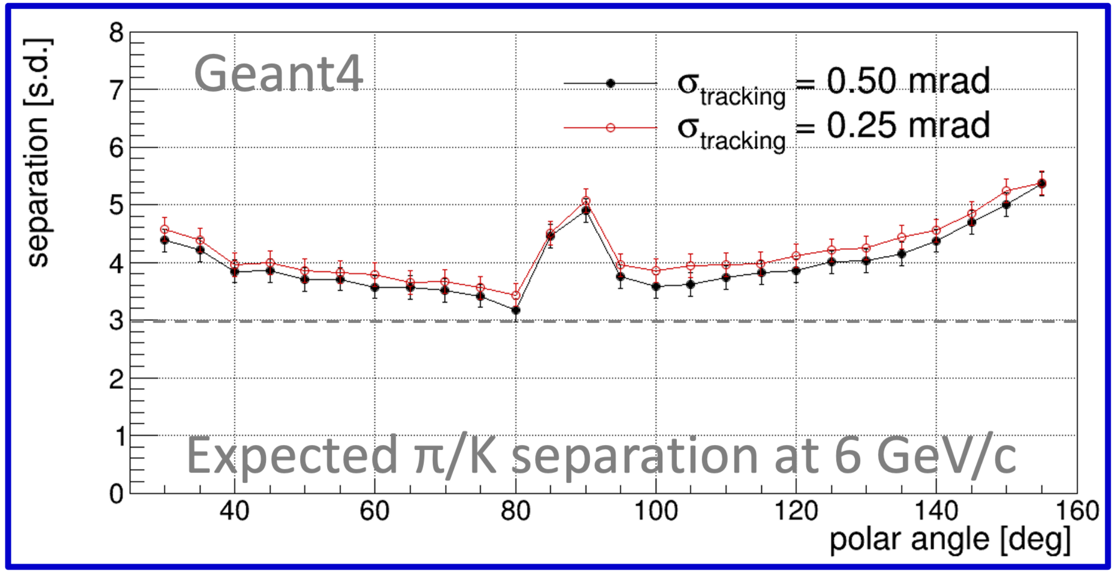


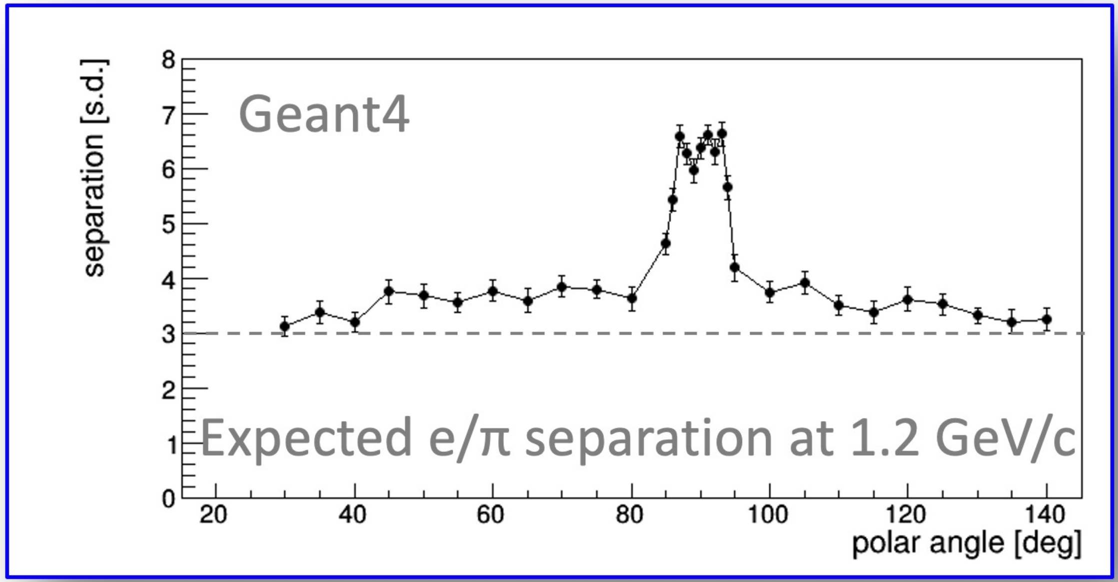


hpDIRC

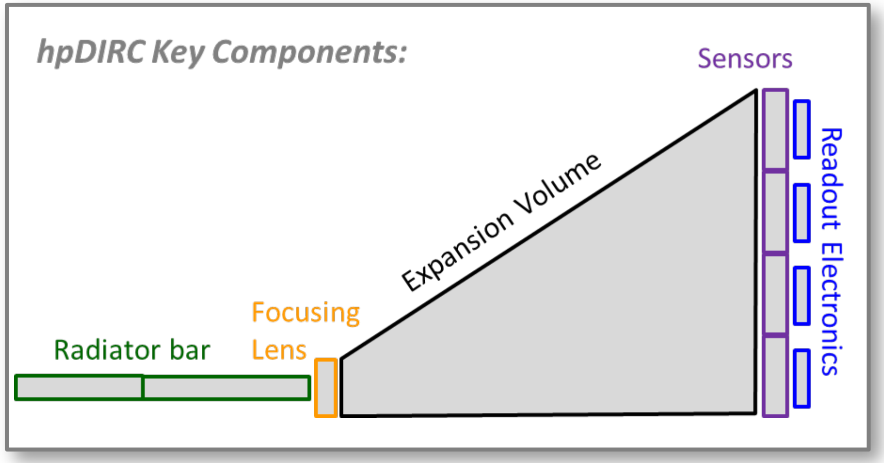
- **Simulation validated in test beam**
- **Excellent performance over wide angular range:**
  - ≥ 3 s.d. π/K up to 6 GeV/c, ≥ 3 s.d. e/π up to ~1.2 GeV/c
  - Low momentum π/K identification in “veto mode” down to 0.2-0.3 GeV/c
- Performance evaluation in full Detector1 Simulation with physical events in progress!



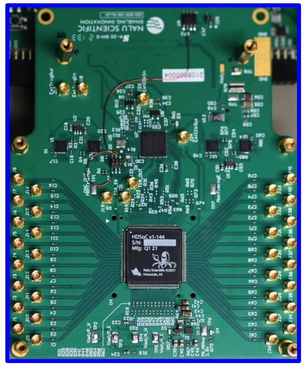


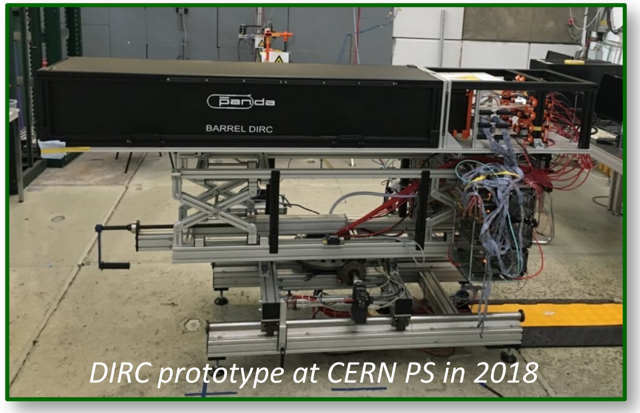


hpDIRC: high-performance DIRC

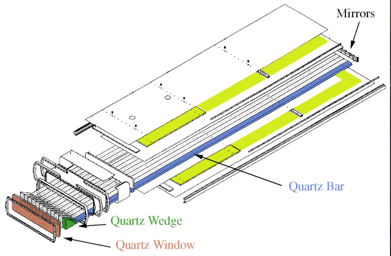


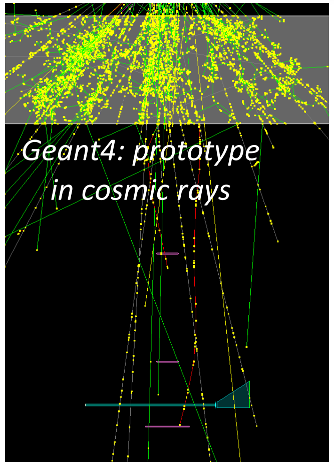
Prototype readout stack at UH/Nalu

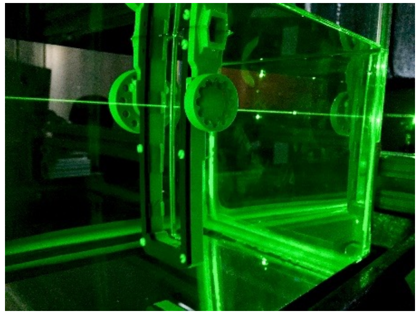




BaBar DIRC barboxes @ SLAC

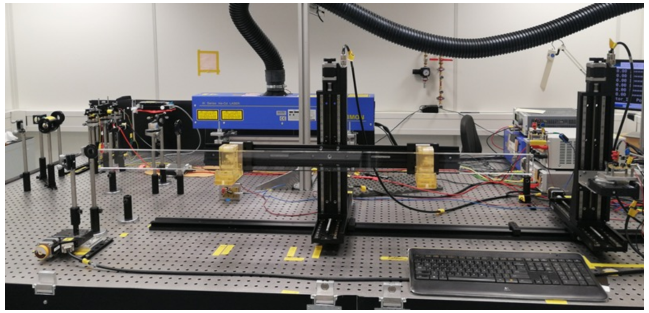






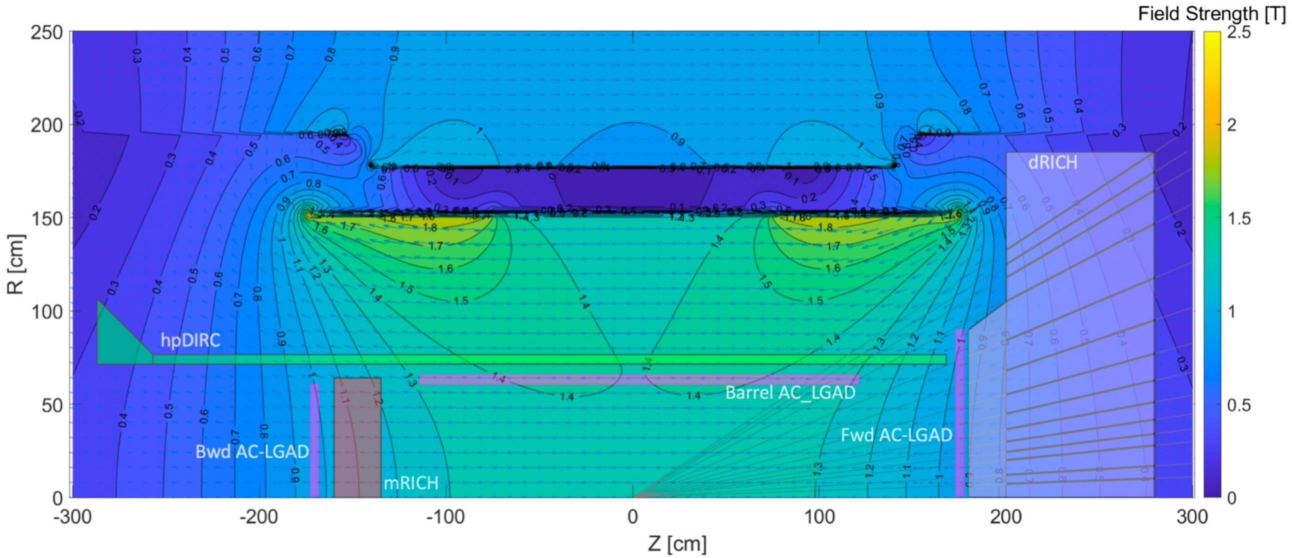
DIRC lab @ ODU

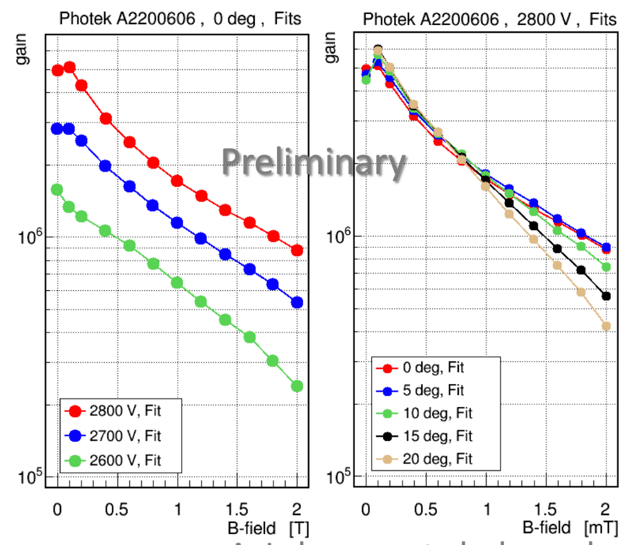
DIRC lab @ GSI



Photosensors

- Pixelated sensor with 3mm pixel size capable of single photon detection are common goal.
- Some detailed demands differ for each system
- Different maturity of **MCP-PMT** sensors development:
  - **Established:** PHOTONIS XP85122-S
  - **Freshly Developed:** Photek MAPMT 253
  - **Under development:** INCOM Gen III HRPPD
  - Small-pore MCP-PMTs shown to be OK for fields up to 2 Tesla (see result from A. Lehmann et al. for 6µm-pore 2'' Photek AuraTek MCP-PMT)
- **SiPMs** are potential solution (less likely for hpDIRC)
  - A lot of progress on usual challenges like dark noise, radiation damage, cooling, integration issues)



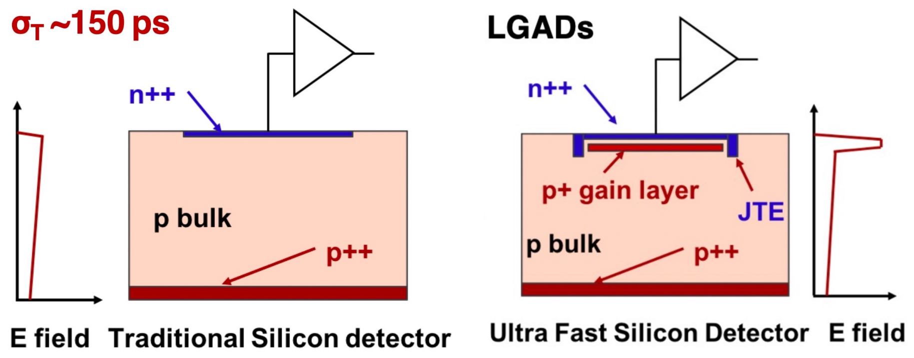


A. Lehmann et al, shown by J. Milnes, IEEE NSS, Nov. 2020

TOF Detector Technology for EIC Detector-1

Overview:

- Low Gain Avalanche Diodes (LGADs)
- High E field → larger, faster signal → better timing resolution
- Cover low to intermediate momentum range
- Capability of providing additional tracking points taking advantage of excellent position resolution of LGADs

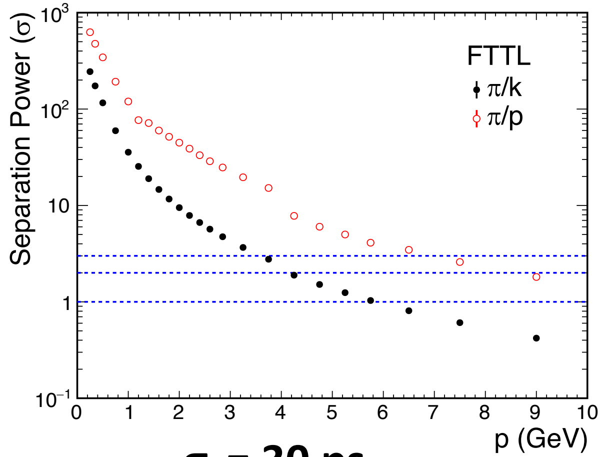


ATLAS/CMS LGAD Specs:

- **Position resolution: ~1mm**
- **Time resolution: ~30 ps**
- **Fill Factor: 55% per layer**

Potential upgrades:

- Trench-isolated LGAD and AC-LGAD with nearly 100% fill factor per layer and significantly improved position resolution

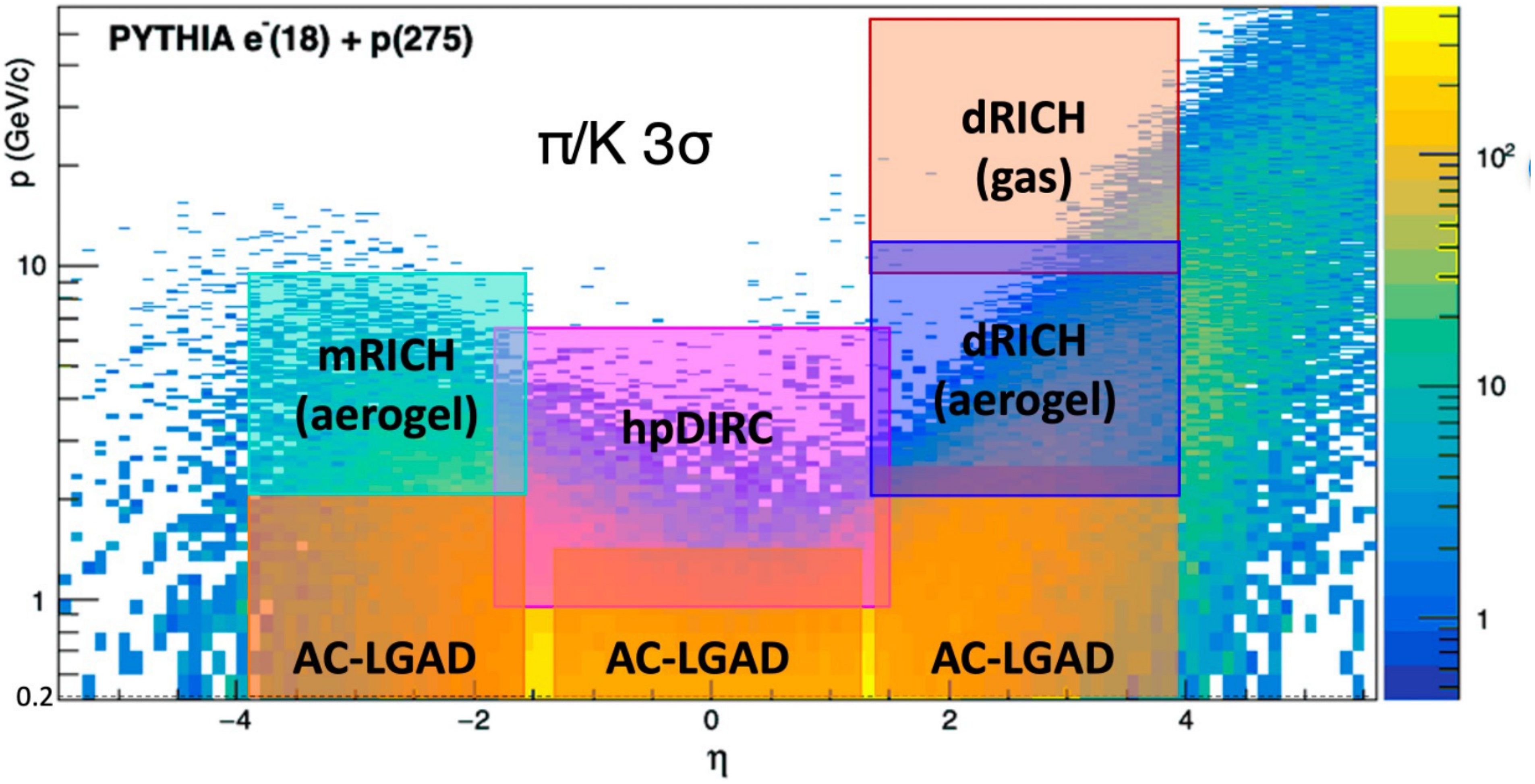


σ_t = 30 ps

Coverage: 0.2-3 GeV/c

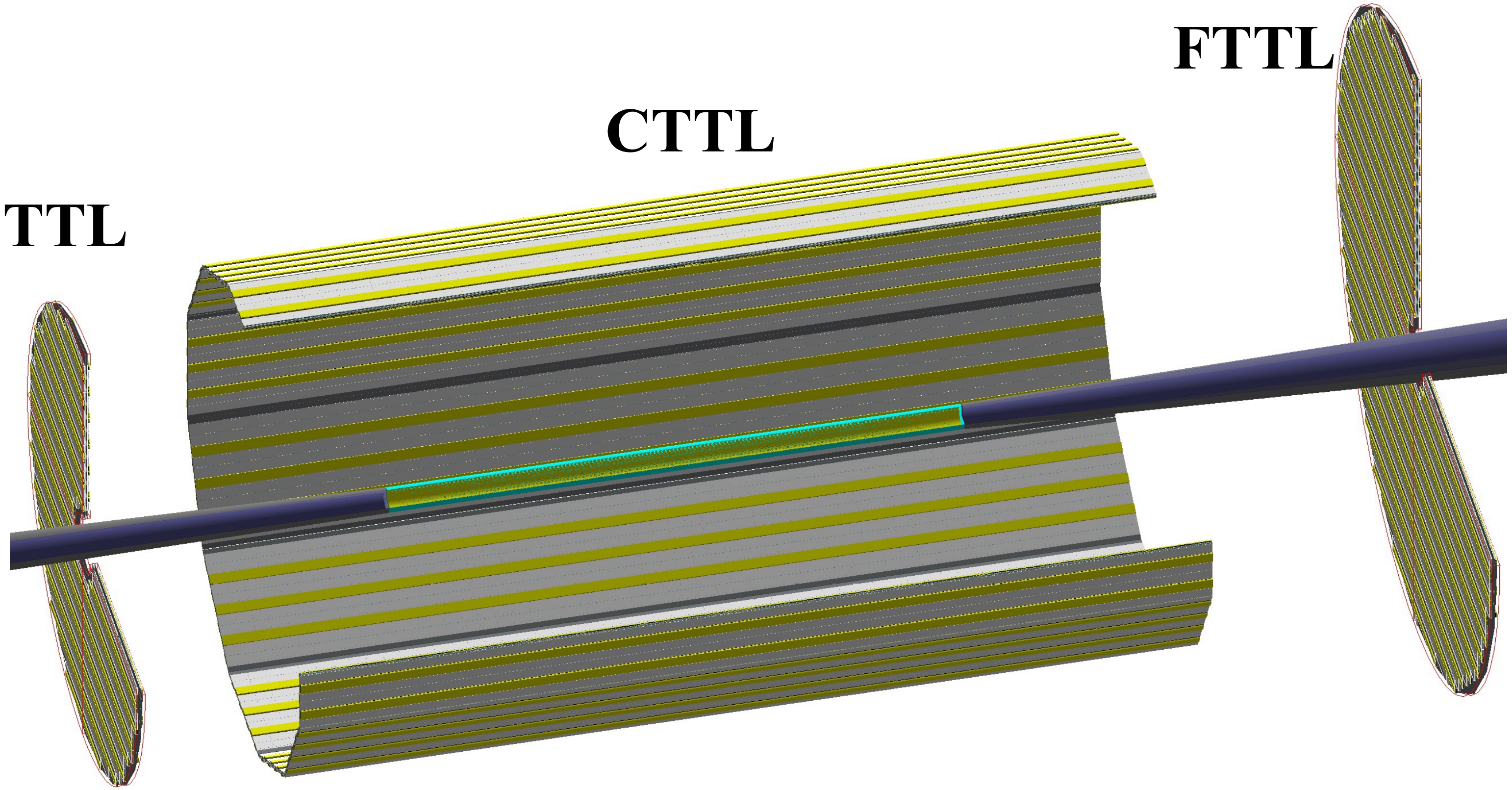
TOF Detector Technology for EIC Detector-1

- A nearly 4π TOF coverage for e/π/K/p PID at low-to-intermediate p range that sufficiently overlaps with RICH-based PID detectors to cover the interesting phase space at EIC.



TOF Detector Technology for EIC Detector-1

- Explore novel technology (AC-LGADs, benefit the tracking) and leverage established designs (DC-LGADs for CMS/ATLAS) to minimize the cost.



- **Timing resolution: ~25 ps per hit**
- **Position resolution: ~30 µm with 500 µm pitch**
- **Total area: ~ 15 m²**

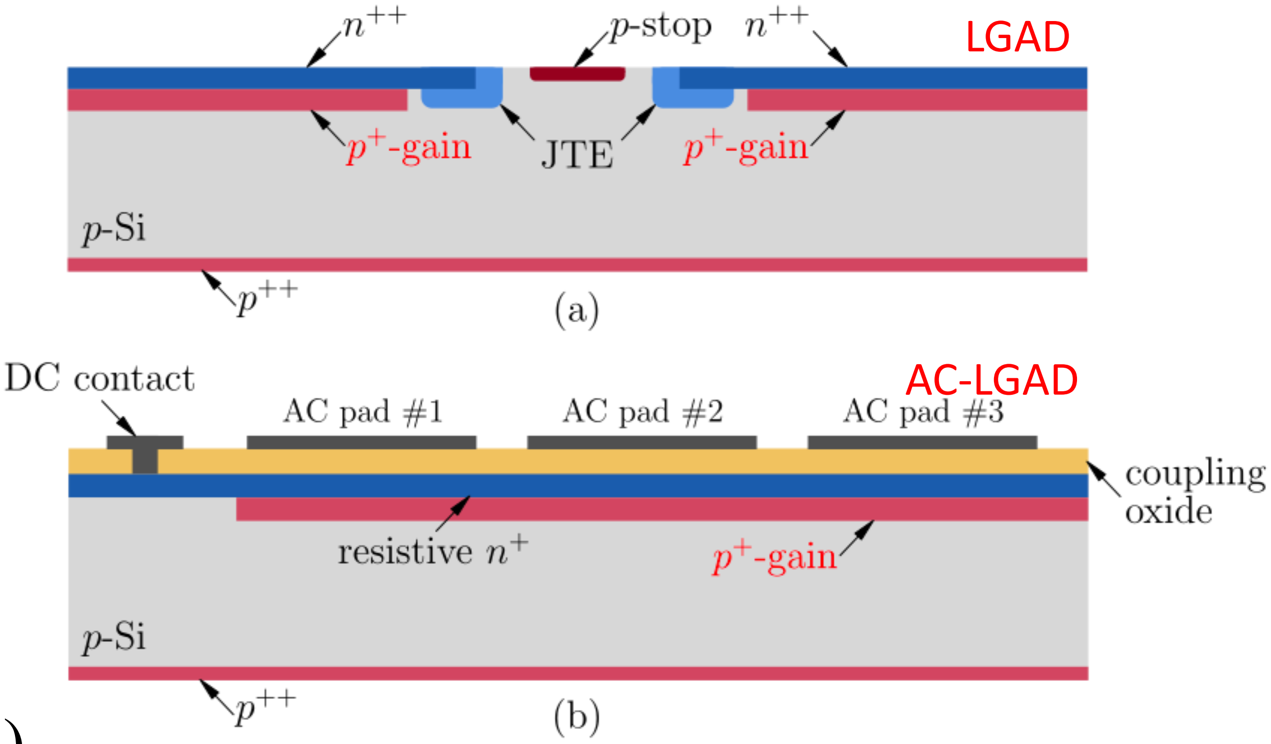
- FTTL ($1.5<\eta<3.5$): $0.15 < p < 2$ GeV
- CTTL ($|\eta|<1.4$): $0.15 < p_T < 1.5$ GeV
- ETTL ($-3.7<\eta<-1.74$): $0.15 < p < 2.5$ GeV

AC-LGAD for EIC

- Large area LGAD detectors are being built by ATLAS (6.4 m^2) and CMS (14 m^2) for data taking starting in 2029.

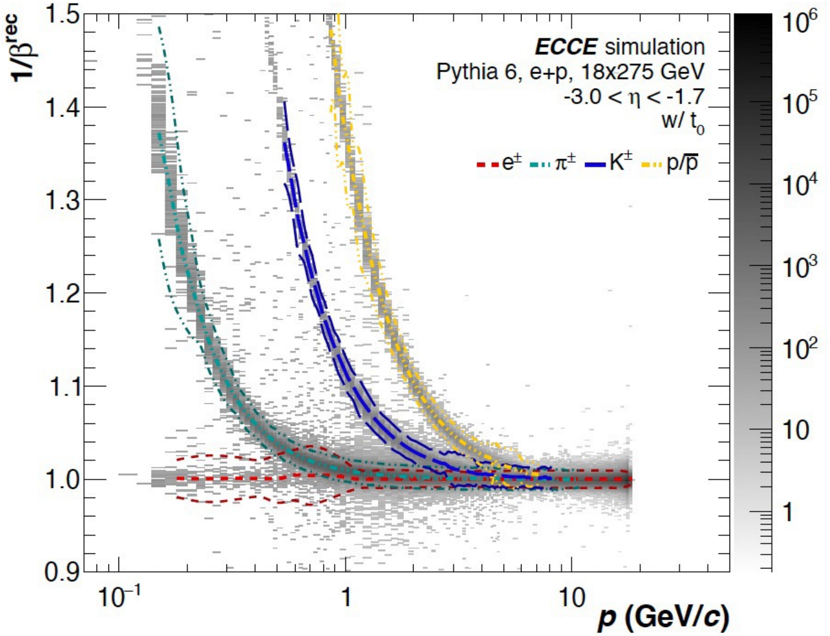
- AC LGAD detectors proposed for EIC
  - Roman Pots and B0
  - TOF for PID (and tracking)

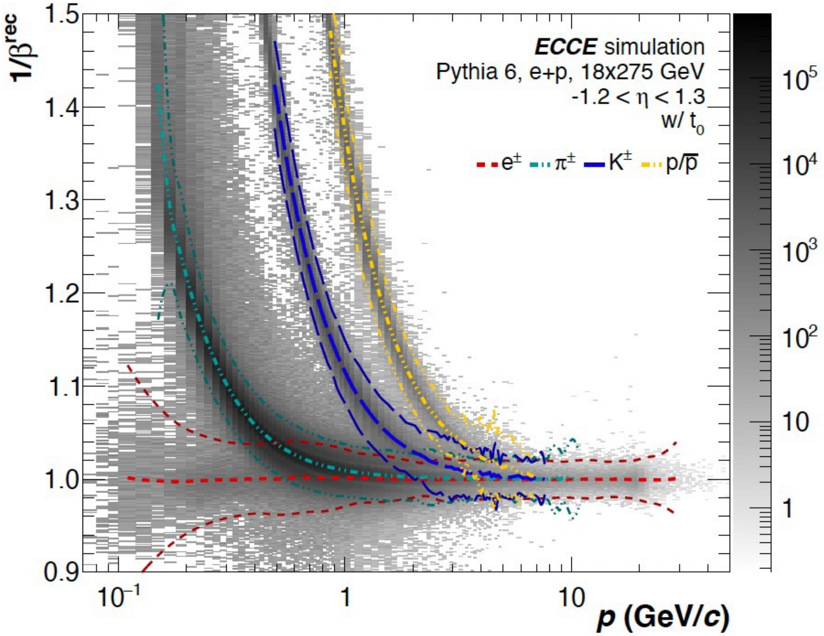
- Have common designs in sensor, ASIC etc. when possible, combine R&D efforts (eRD112)

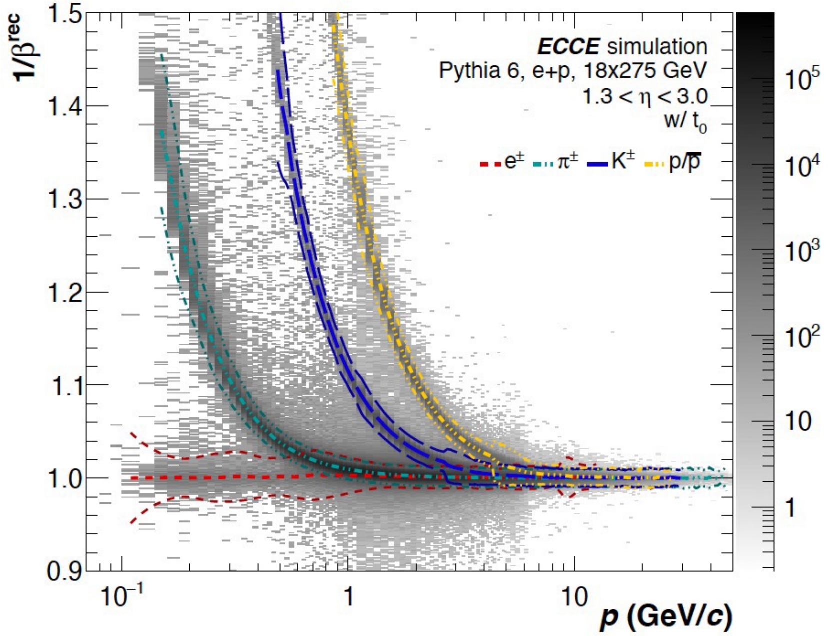


	Time resolution / hit	Position resolution / hit	Material budget / layer
Barrel ToF (Tracker)	<30 ps	(3-30 μm for Tracker)	$< 0.01\ X_0$
Endcap ToF (Tracker)	<25 ps	(30-50 μm for Tracker)	e-direction $< 0.05 X_0$ h-direction $< 0.15 X_0$
Roman Pots	<50 ps	$< 500/\sqrt{12}\ \mu m$	N/A
B0	<50 ps	$O(50)\ \mu m$	$< 0.01\ X_0$

TOF Performance at EIC Detector-1







T0 included

SUMMARY

- **EIC PID technologies are based on** the outcome of the **EIC generic R&D program** (eRD14 EIC PID Consortium) and **in line with the reference EIC detector concept in the Yellow Report**

- **Geometries are being further optimized to fit the reference Detector1 design while maintaining the required performance** to assure wide momentum coverage across the full phase space and minimize the cost!

  - Backward: Short, modular RICH **(mRICH)**
  - Barrel: Radially compact with flexible design high-performance DIRC **(hpDIRC)**
  - Forward: Double-radiator RICH **(dRICH)**
  - AC-LGAD based time-of-flight (**TOF**) system for hadronic PID in momentum range below the thresholds of the Cherenkov detectors

- All four technologies are supported in direct R&D program

- Separate eRD programs for Photosensors and readout electronics