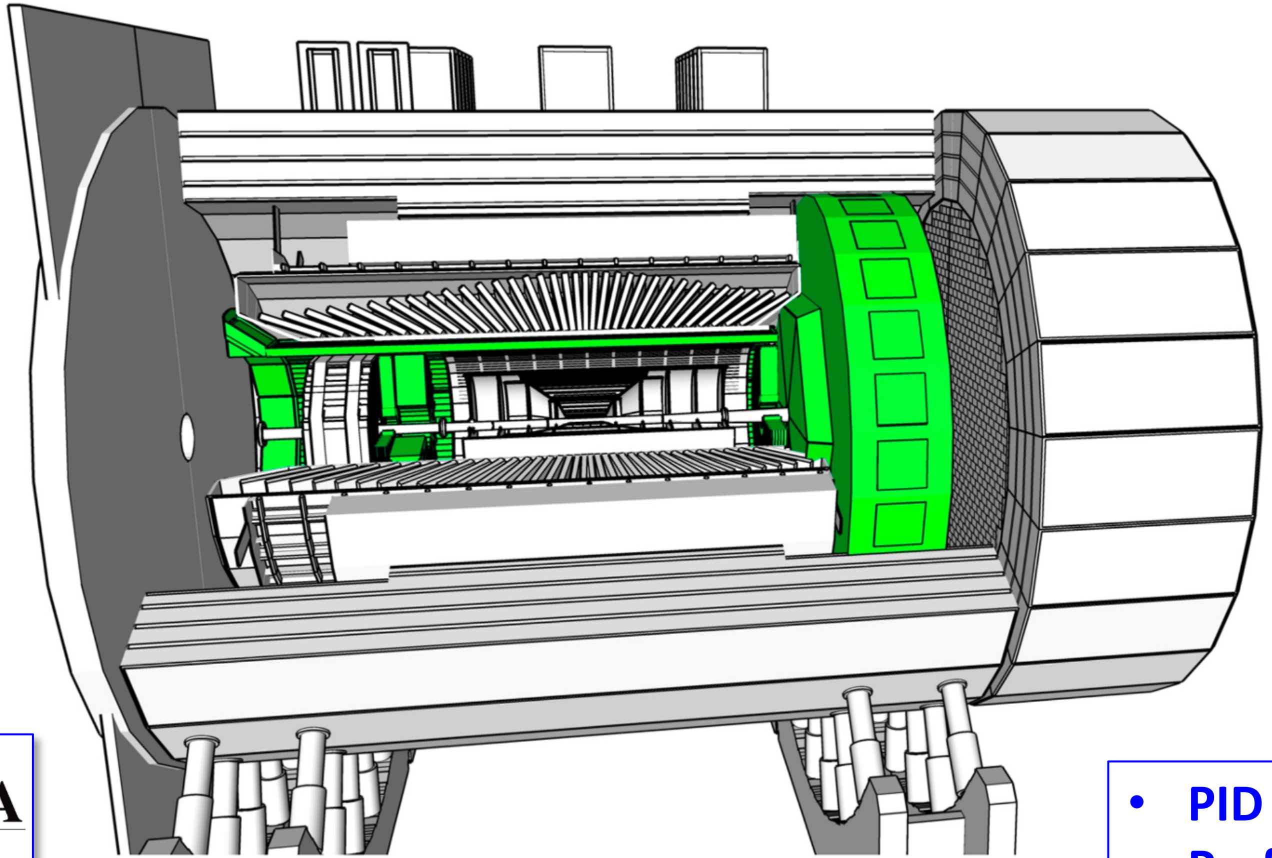
Cherenkov Based Particle Identification for EPIC Detector ☺



Cherenkov PID

Greg Kalicy — CUA

Roberto Preghenella — INFN

Tom Hemmick — Stony Brook University

Xiaochun He — Georgia State University

Outlook

- PID Configuration
- Performance
- Considered Technologies
  - Status of Development

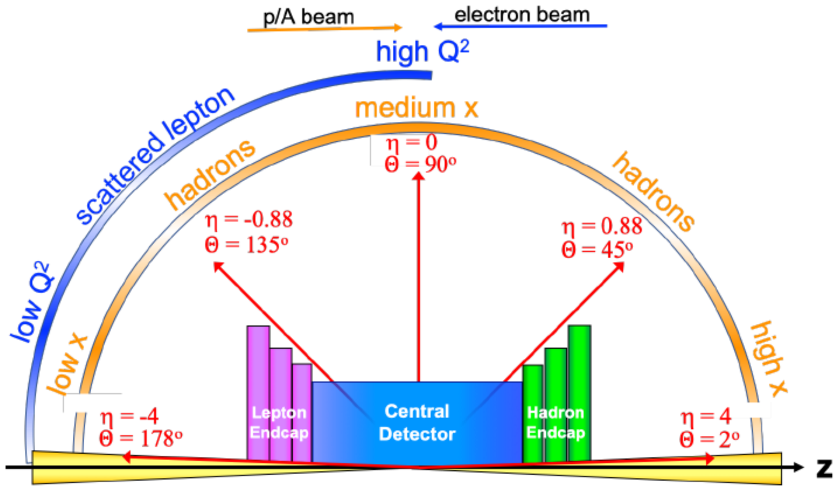
July 26th 2022

PID at EIC EPIC Detector

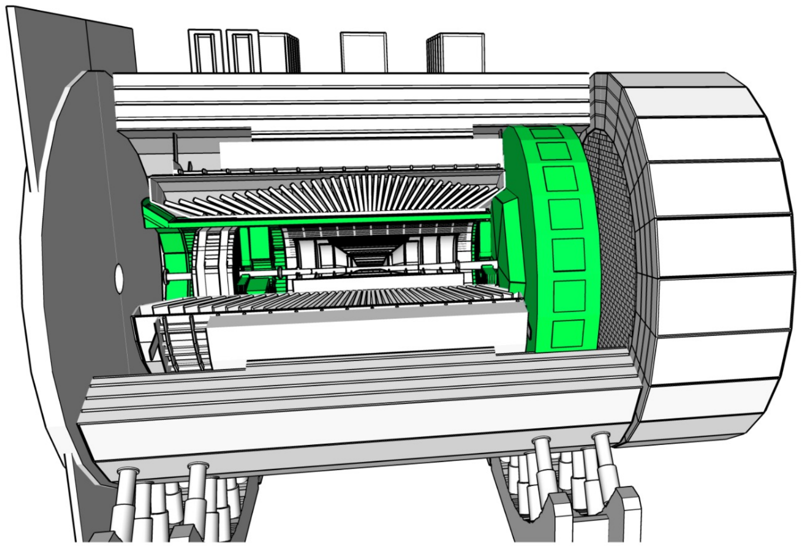
- **INDICO space: https://indico.bnl.gov/category/412/**

- **WIKI: https://wiki.bnl.gov/eic-project-detector/index.php/CherenkovPID**

- **Main goal:**
  Separation of charged pions, kaons and protons from each other over a wide range with better than 3σ separation



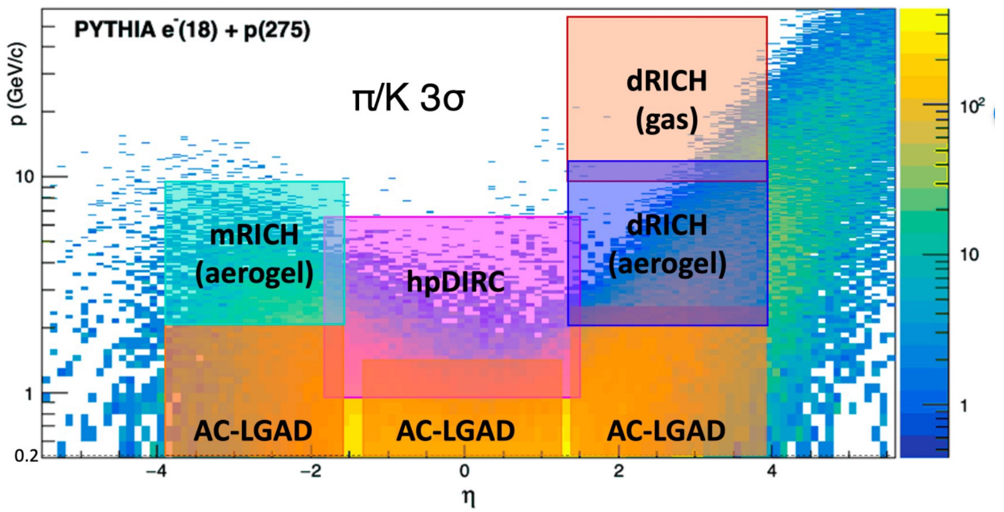
- **Additional function**:
  Significant pion/electron suppression

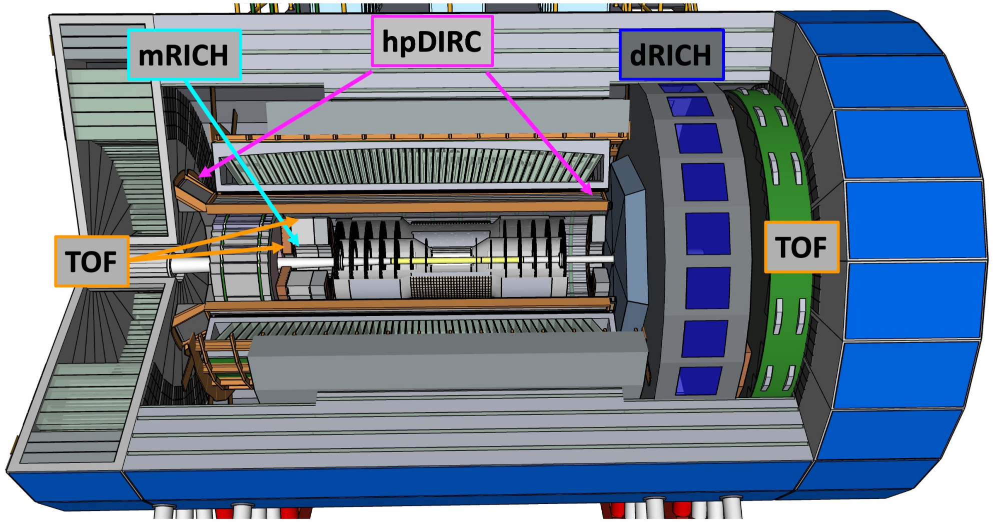


- **Challenging momentum coverage for pion/kaon separation:**
  - **Forward**: up to 50 GeV/c
  - **Central**: up to 6 GeV/c
  - **Backward**: up to 10 GeV/c

PID at EIC EPIC Detector

- **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 detector 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 AT EIC EPIC DETECTOR

- **h-endcap: dRICH**

  Ring imaging:
  - **π/K < 50 GeV/c**
  - **e/π <15 GeV/c**

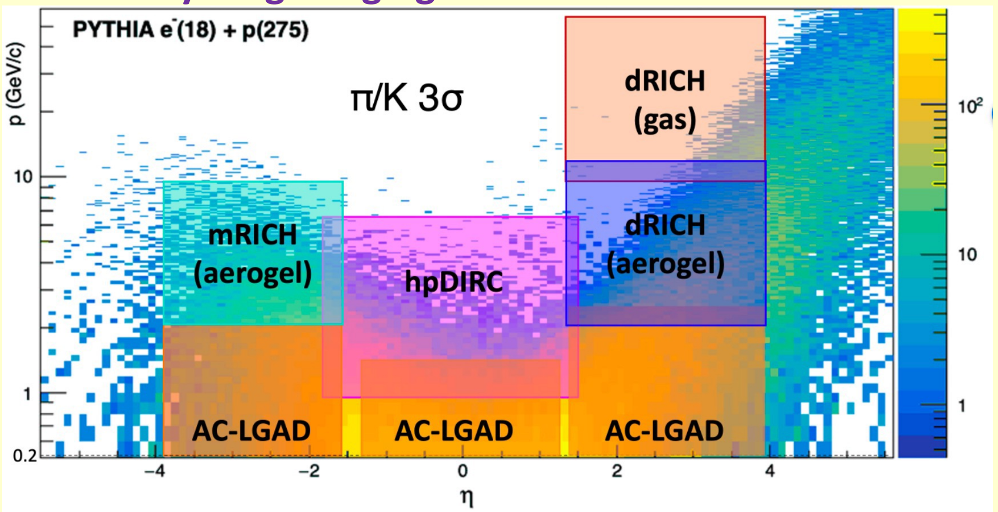
- **e-endcap: mRICH**

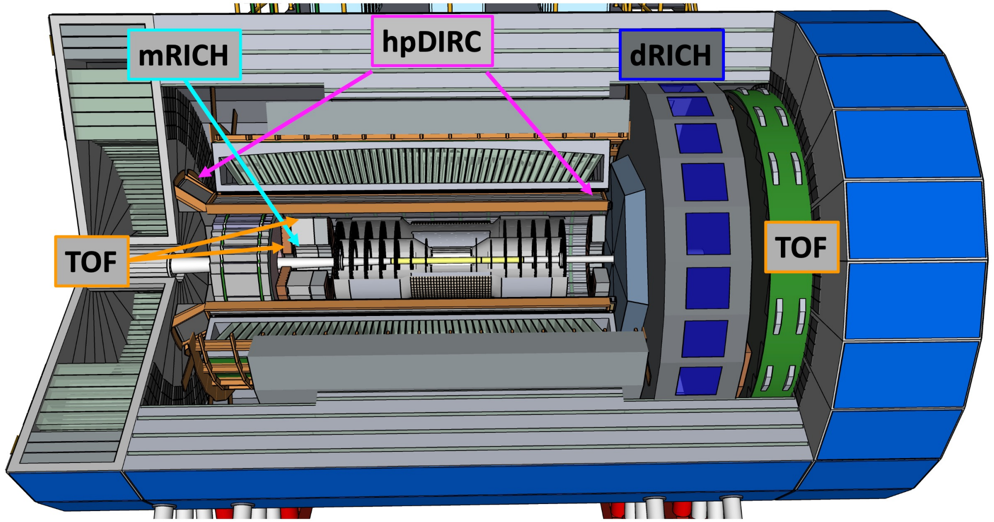
  Ring imaging:
  - ***π/K: 2-10 GeV/c***
  - **e/π : 0.6-2./2.5 GeV/c**

- **barrel: hpDIRC**

  Ring imaging:
  - **π/K <6-7 GeV/c**
  - **e/π <1.2 GeV/c**

Only Ring Imaging for Cherenkov Detectors





PID at EIC EPIC Detector

- **h-endcap: dRICH**

  Ring imaging:
  - **π/K < 50 GeV/c**
  - **e/π <15 GeV/c**

  "Veto" mode:
  - **e/ π above few MeV/c** (up to ~15 GeV/c)
  - **π/K,p above 0.7 GeV/c** (or ~1 GeV/c at "full efficiency")
  - **K/p > 2.5 Gev/c** (or ~3 GeV/c at "full efficiency")

- **e-endcap: mRICH**

  Ring imaging:
  - ***π/K: 2-10 GeV/c***
  - **e/π : 0.6-2./2.5 GeV/c**

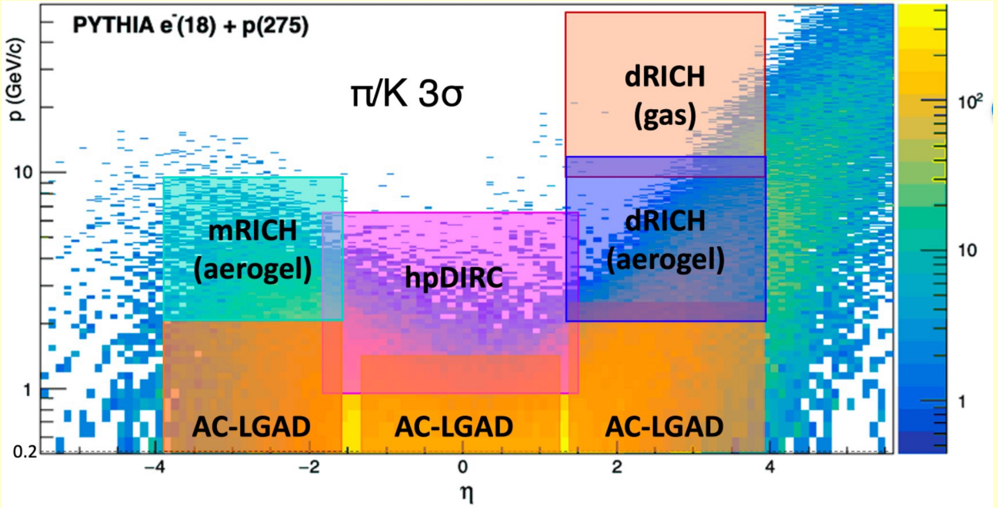
  "Veto" mode:
  - **k/π : 0.6-2 GeV/c**
  - **e/π : <0.6 GeV/c**
  - **K/p <3.8 GeV/c**

- **barrel: hpDIRC**

  Ring imaging:
  - **π/K <6-7 GeV/c**
  - **e/π <1.2 GeV/c**

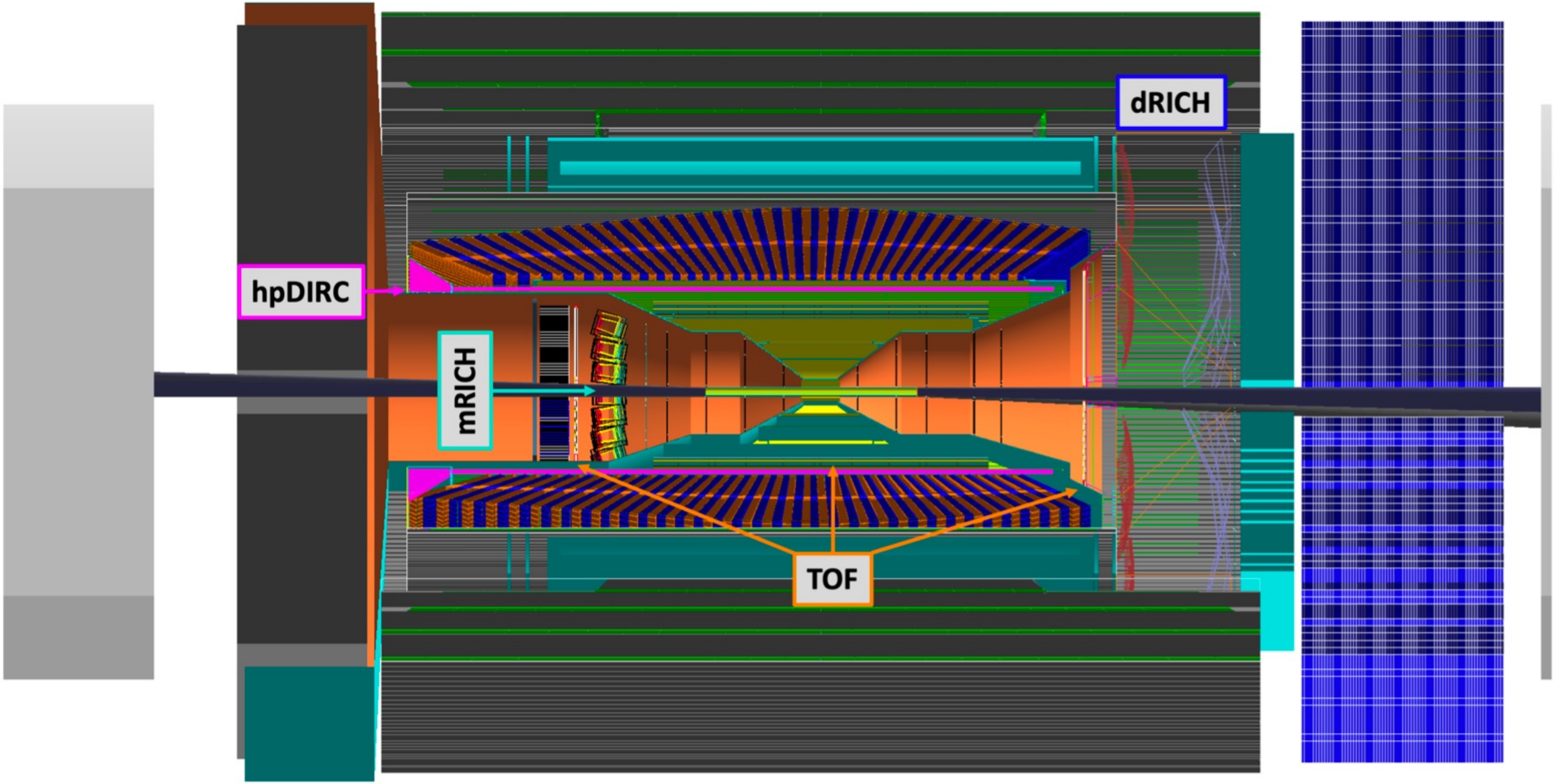
  "Veto" mode:
  - **e,K/π >0.2/0.3GeV/c**
  - **K/p >1 GeV/c**

Only Ring Imaging for Cherenkov Detectors

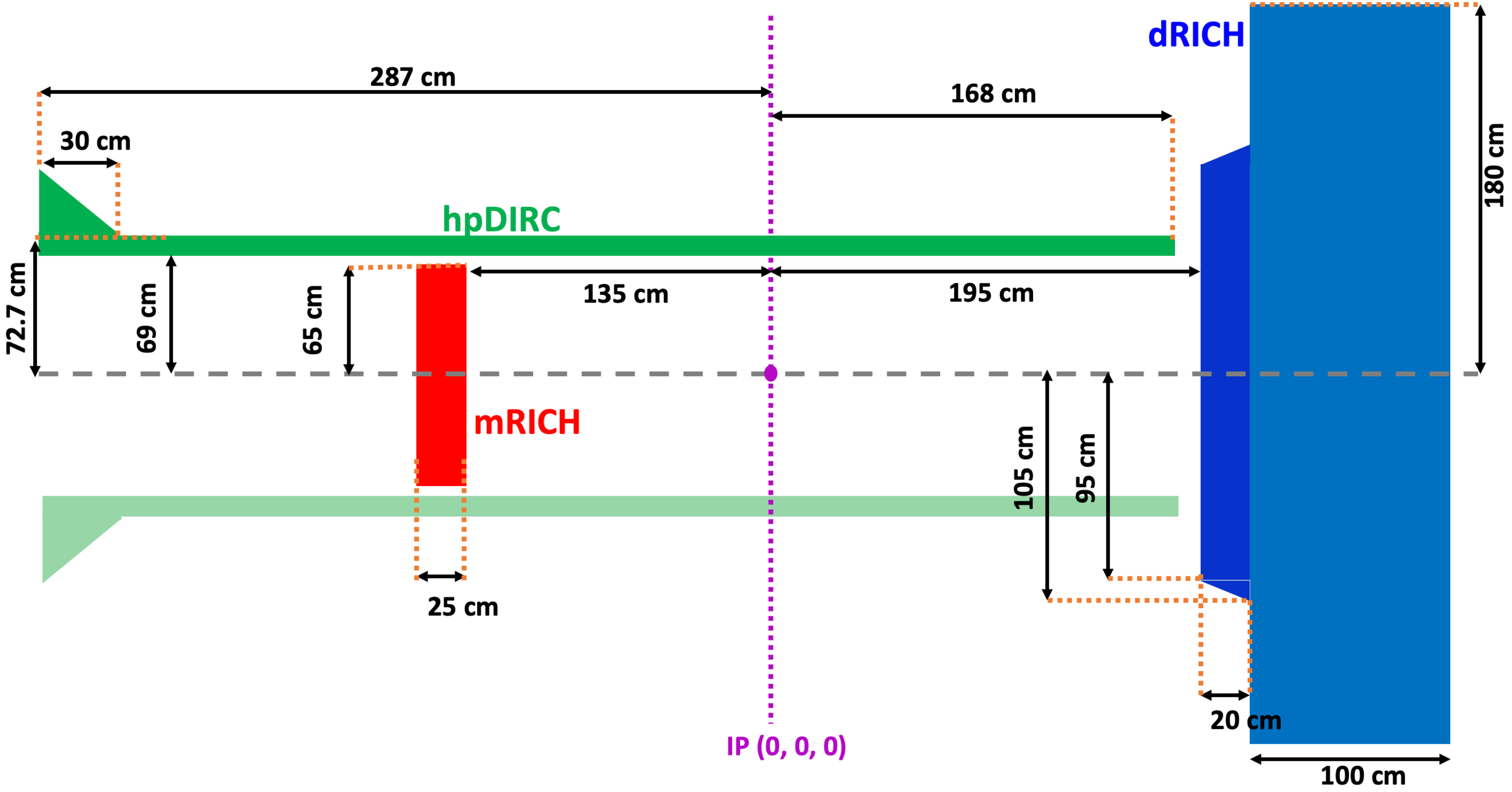


Great talks and discussions lead by Elke and Joe about RICH and DIRC veto/threshold mode: https://indico.bnl.gov/event/16314/

PID in EIC EPIC Detector F4A Simulation

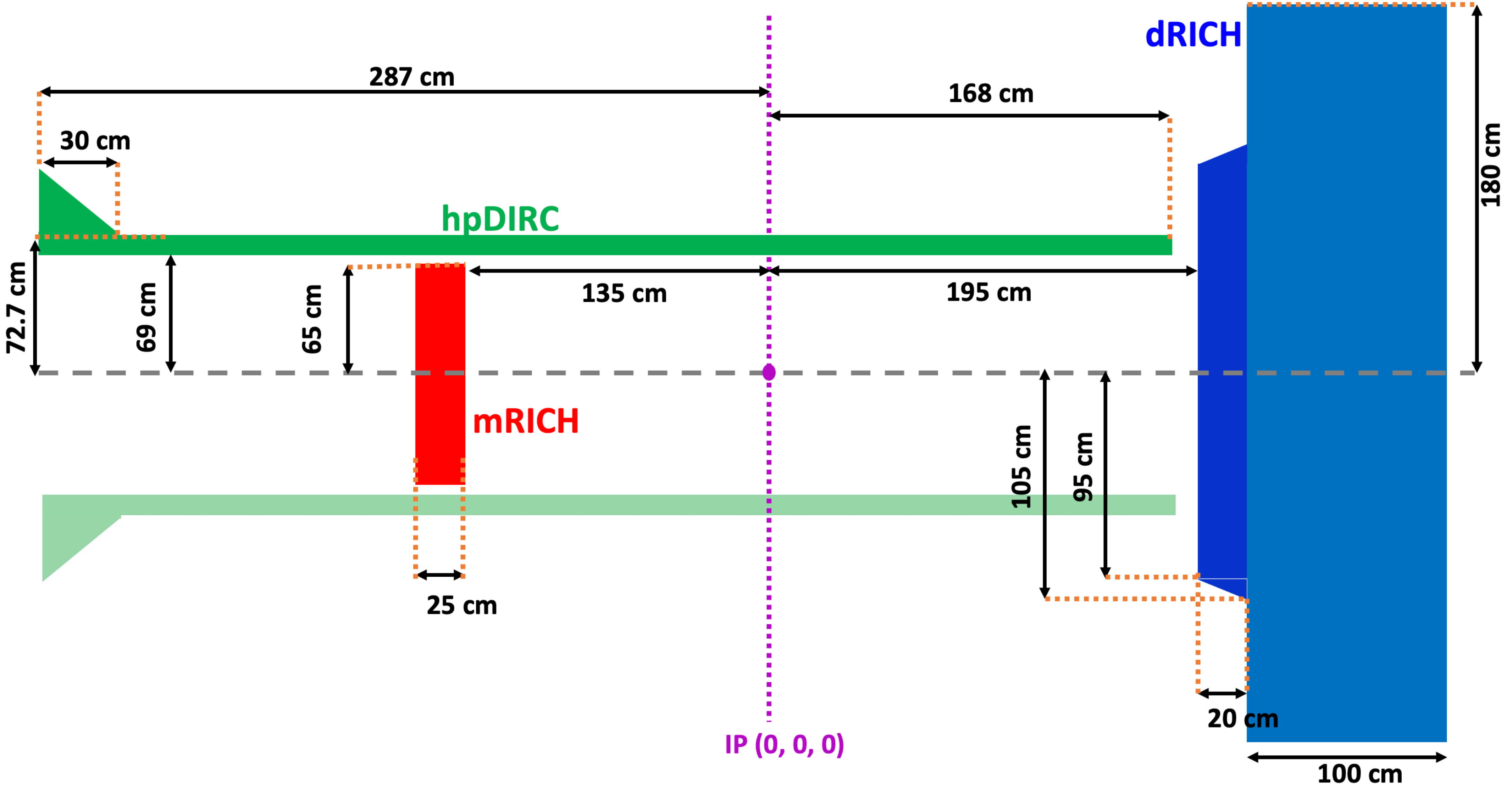


PID IN EIC EPIC DETECTOR INTEGRATION



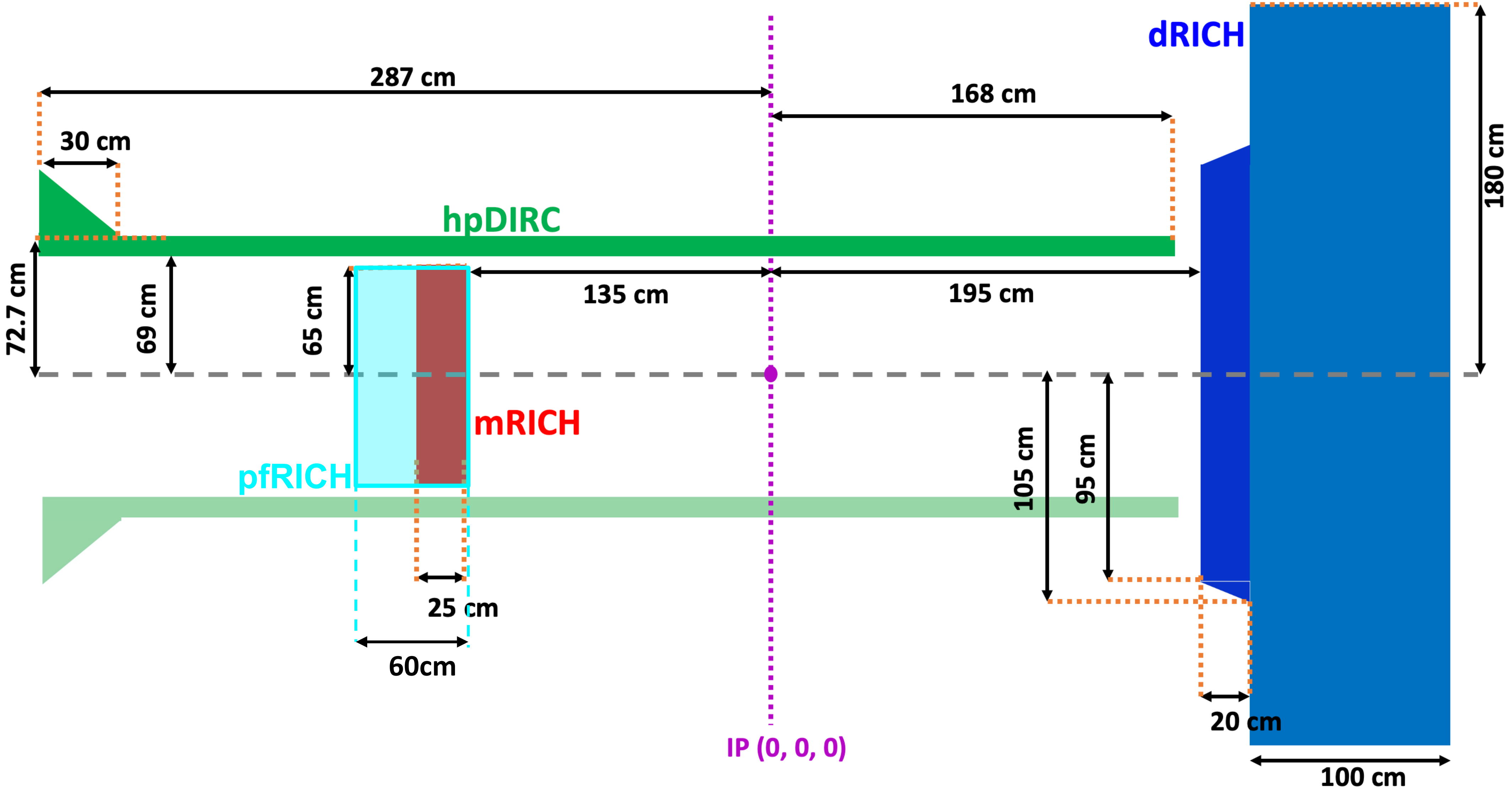
Discussion about the dRICH envelope: https://indico.bnl.gov/event/16314/

PID in EIC EPIC Detector Integration



Discussion about the electron side Cherenkov PID: https://indico.bnl.gov/event/16208/

PID in EIC EPIC Detector Integration

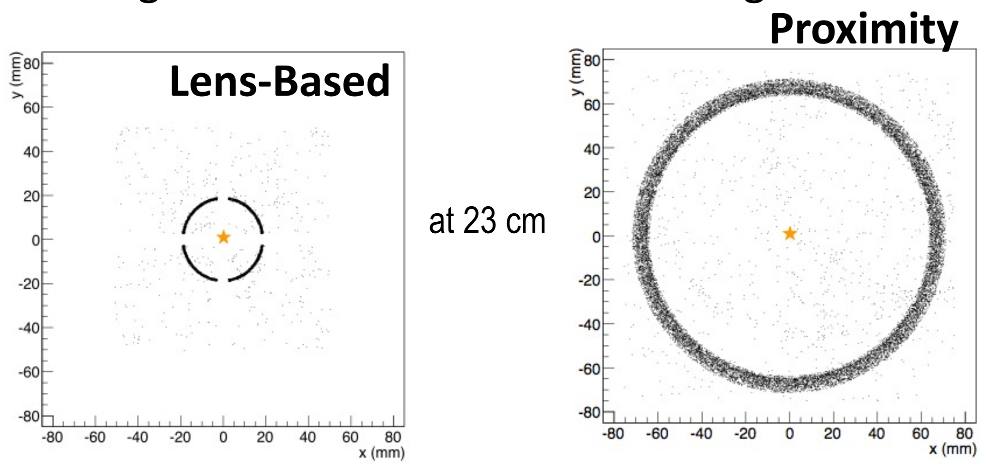


Discussion about the electron side Cherenkov PID: https://indico.bnl.gov/event/16208/

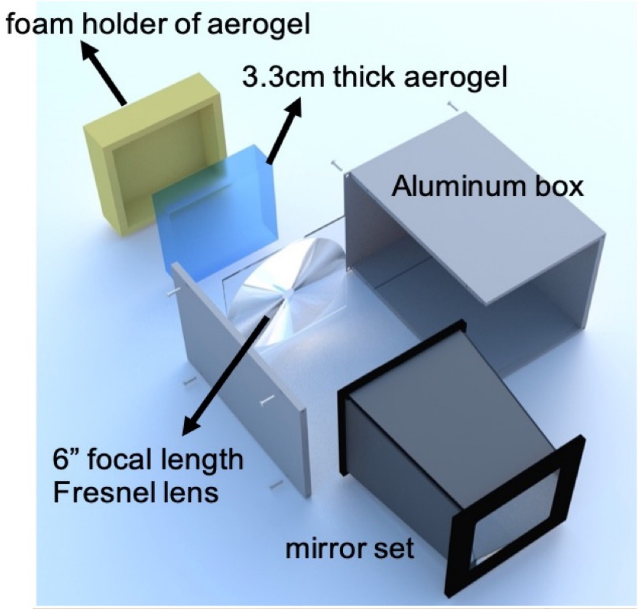
Modular RICH Detector (mRICH)

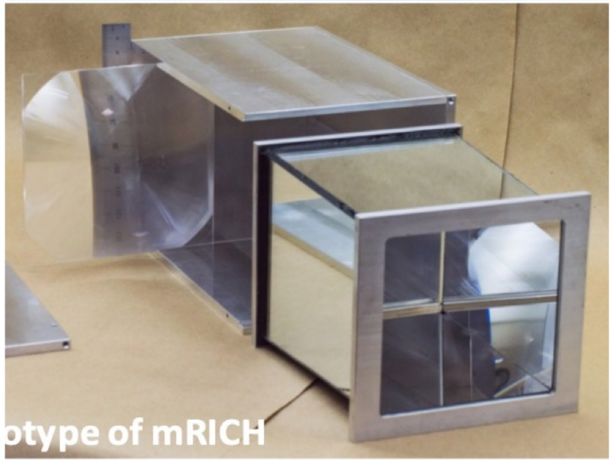
3-10 GeV/c
-3.0 < η < -1.5

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**





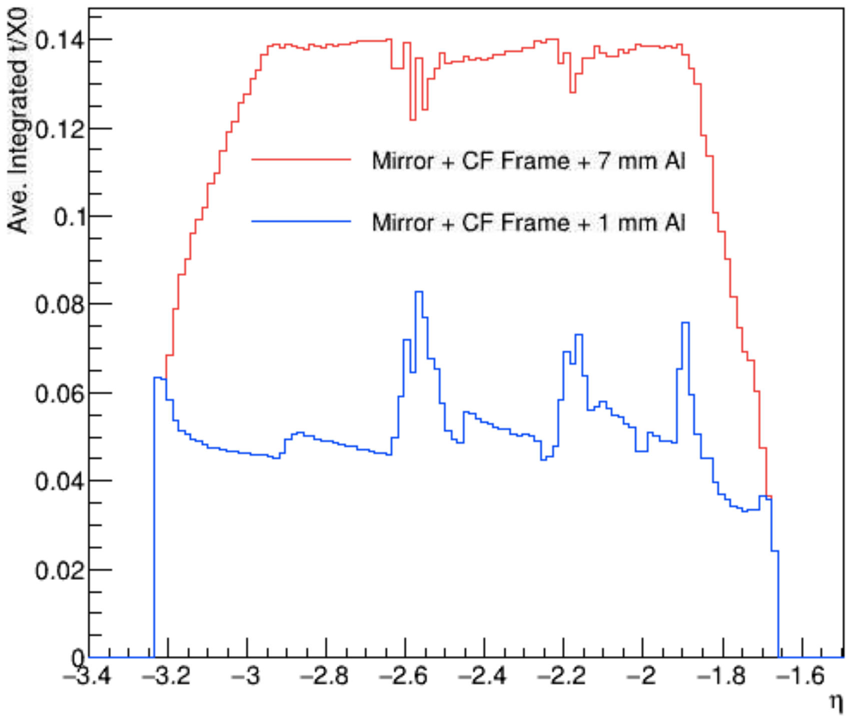
Systematic effects

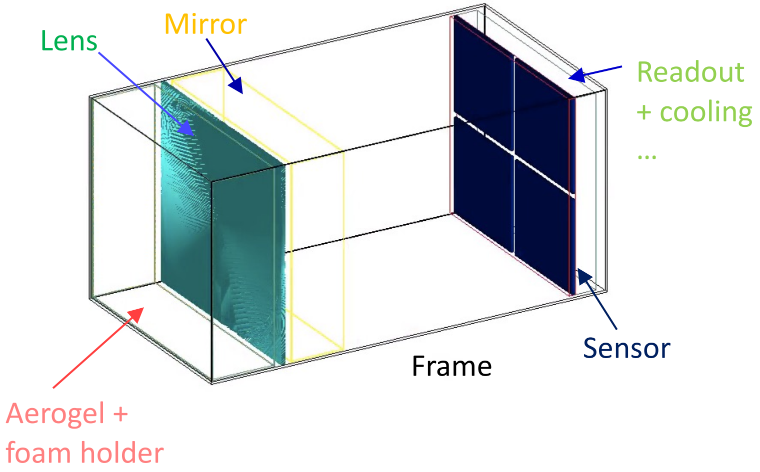
- Emission point error: minimized at the lens focal plane
- Chromatic dispersion error: reduced by UV filtering (acrylic).
- Pixel size error: the uncertainty raised by pixel size, a, error

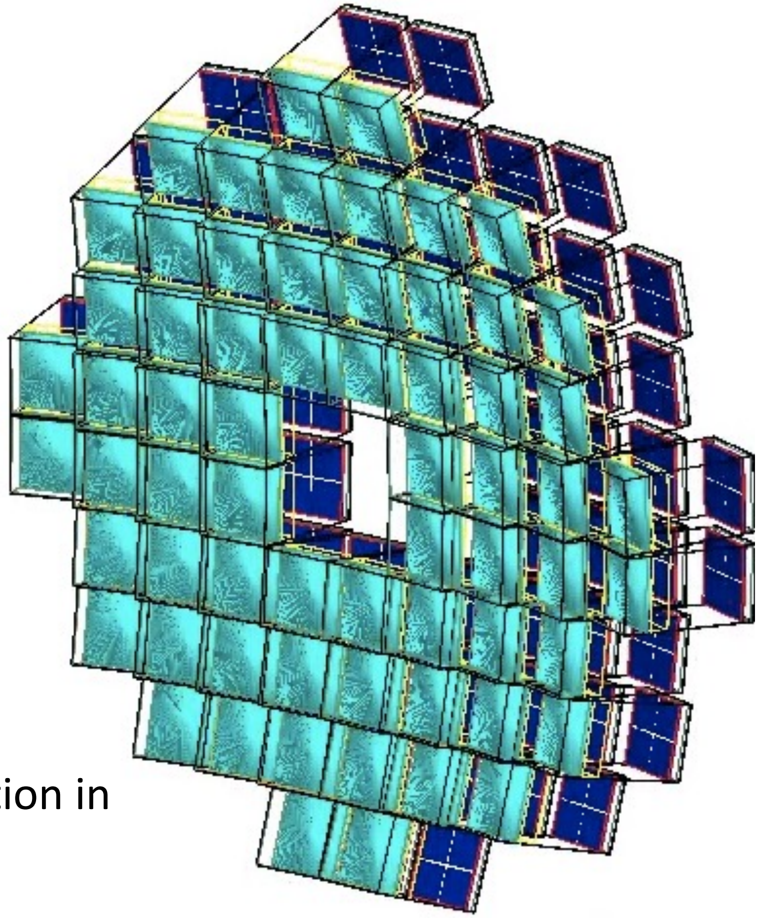
mRICH Material Budget & Design

3-10 GeV/c
$-3.0 < \eta < -1.5$

- 10x10 cm^2 Aerogel blocks @ n=1.02
- Mirrors: 2.54 cm x 10 cm
  @ 0.5 mm thickness / Al
- Frame: 10.8 cm x 20.45 cm
  @ 0.5 mm thickness / carbon fiber
- **The dominant contribution to the material budget is coming from the electronics and services NOT from the mirrors or frame!**
- More efficient modules arrangement in progress to further improve design







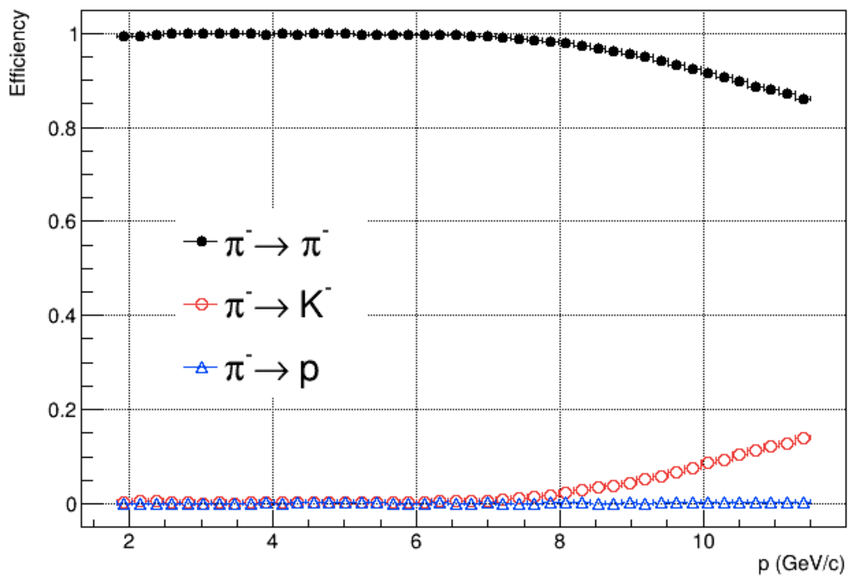
❖ GEANT4 simulation / full implementation in Fun4All!

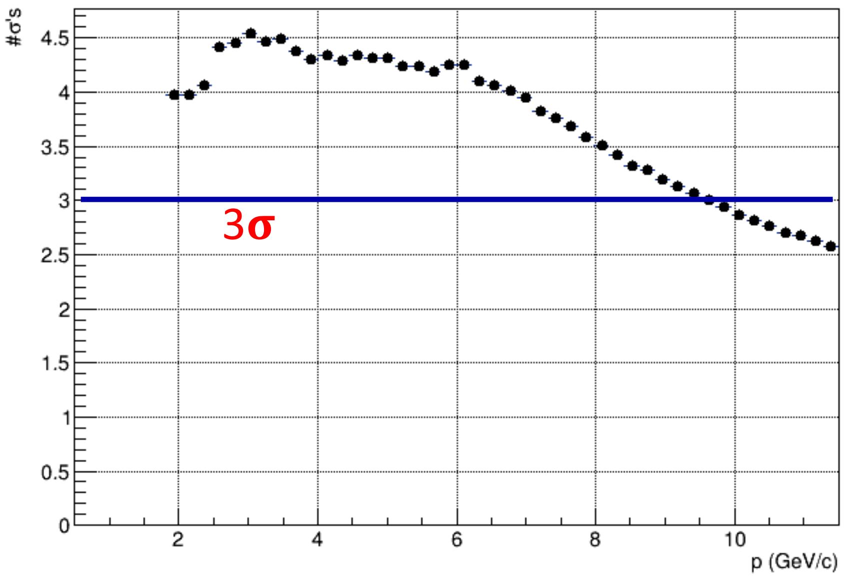
mRICH PID Performance

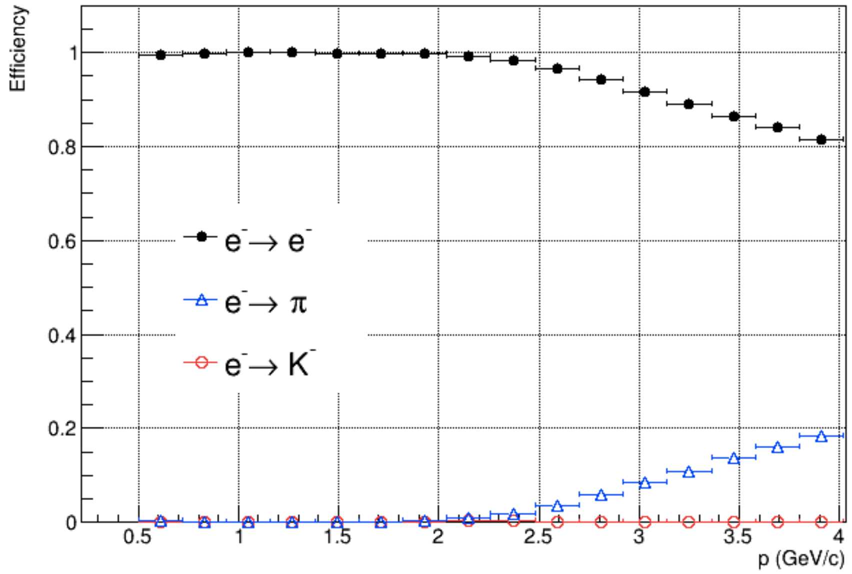
- Single particle studies

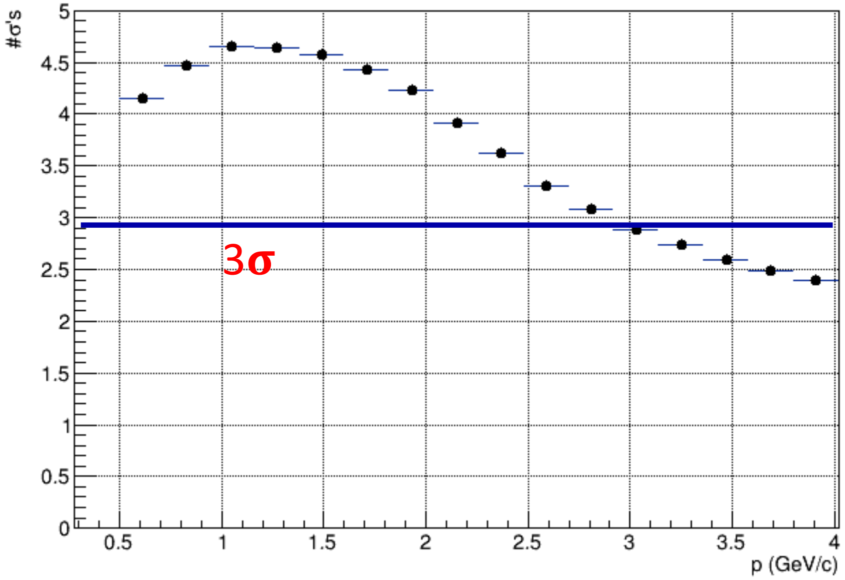
Assuming SIPM Q.E. n=1.02 Aerogel

3-10 GeV/c
-3.0 < η < -1.5







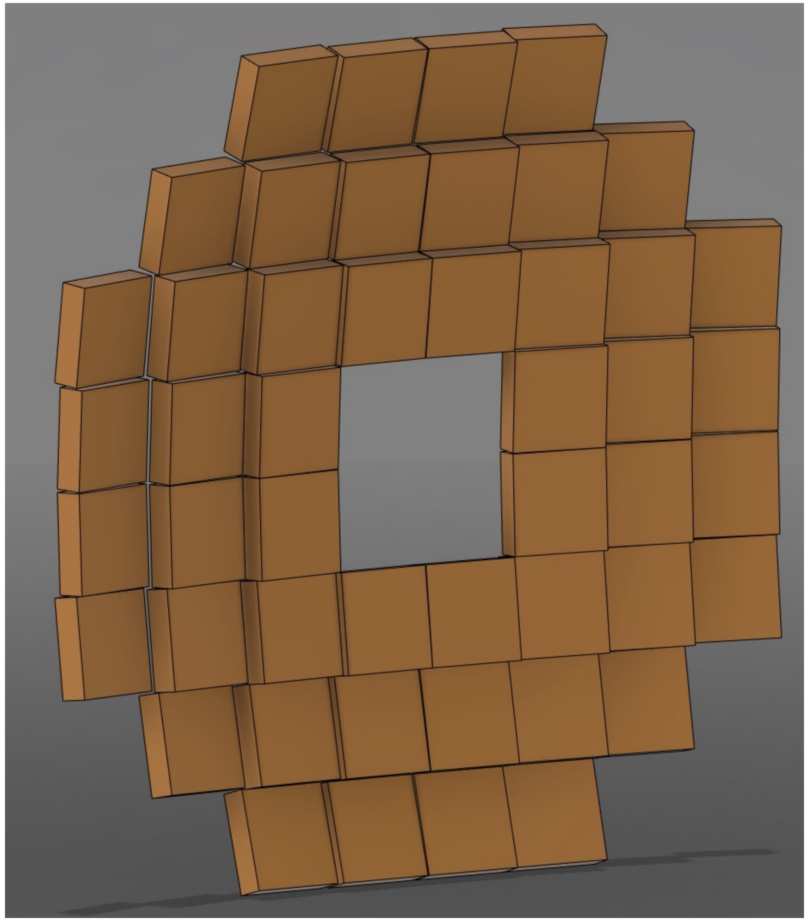


Simulation study with different efficiencies and aerogel

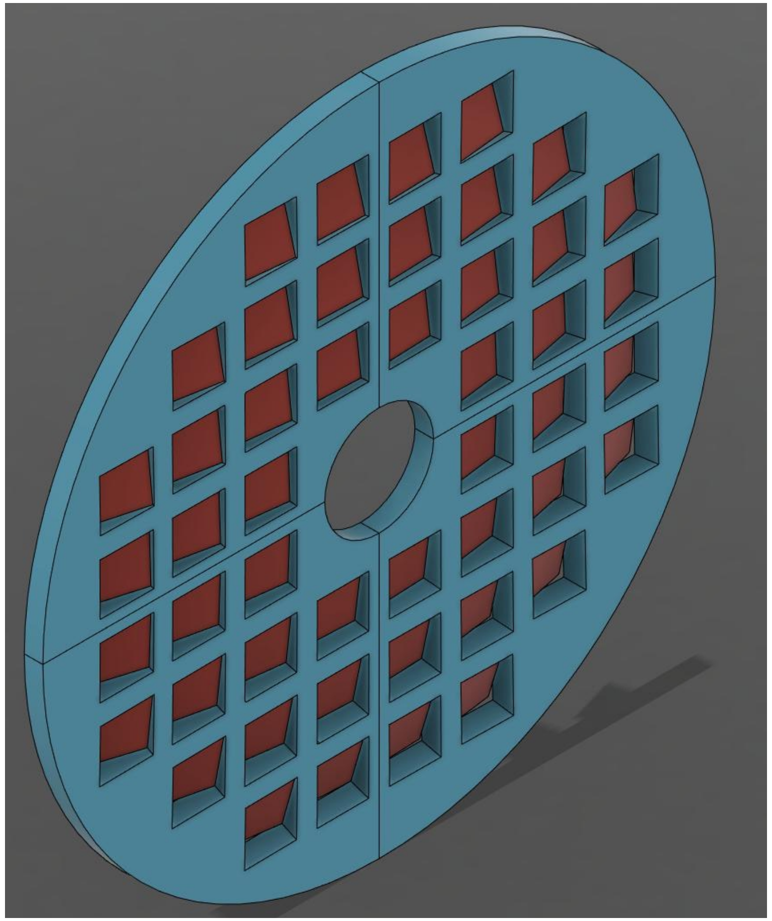
mRICH R&D: Support Frame Design and Services

3-10 GeV/c
-3.0 < η < -1.5

- Collaboration with Alex Eslinger - JLab engineer

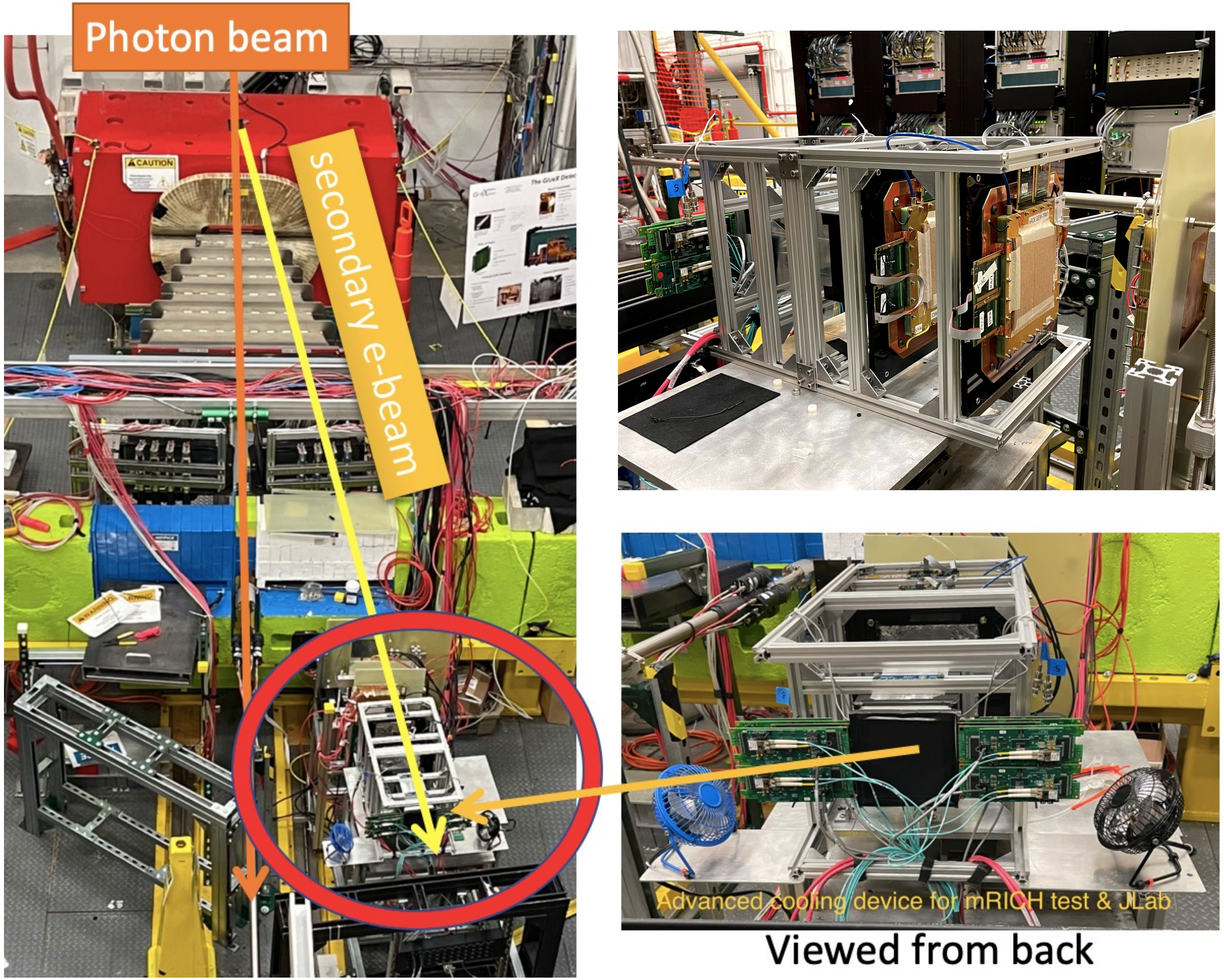


Back view, frame is being updated



mRICH R&D

3-10 GeV/c
-3.0 < η < -1.5

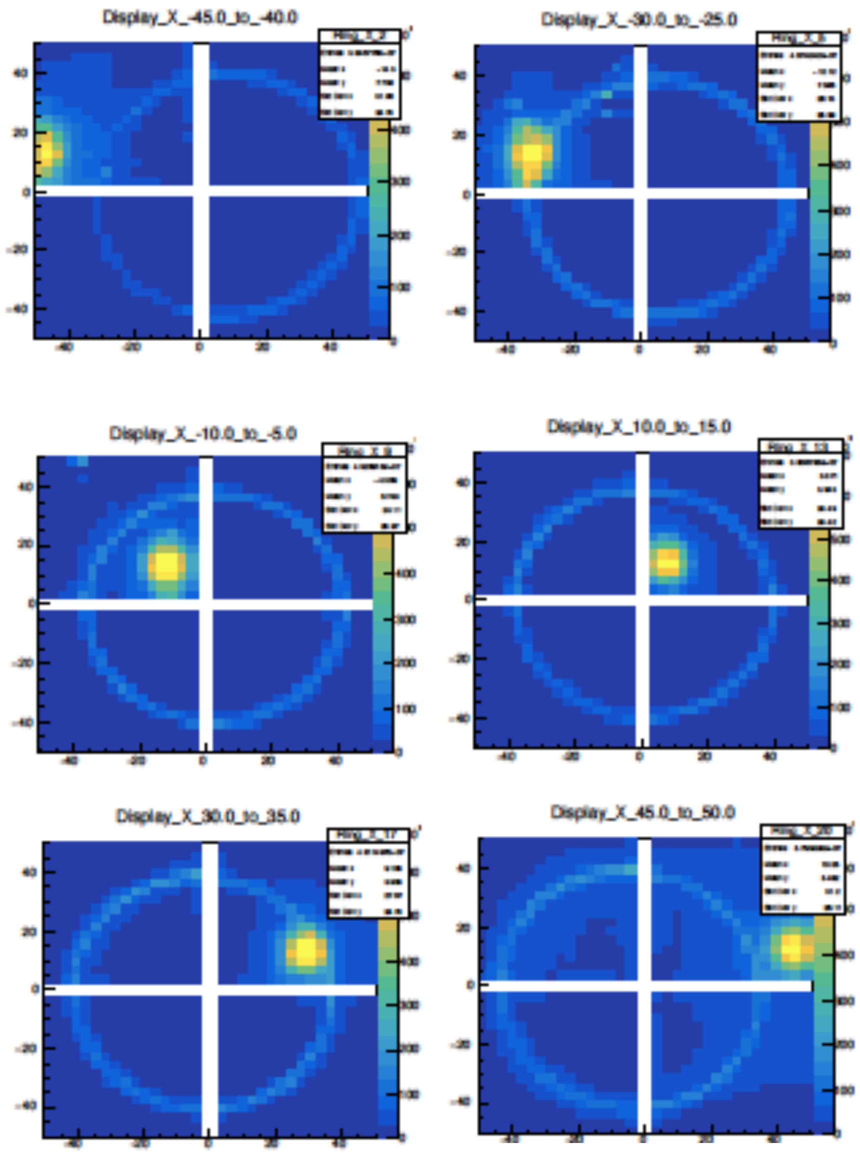


Viewed from back

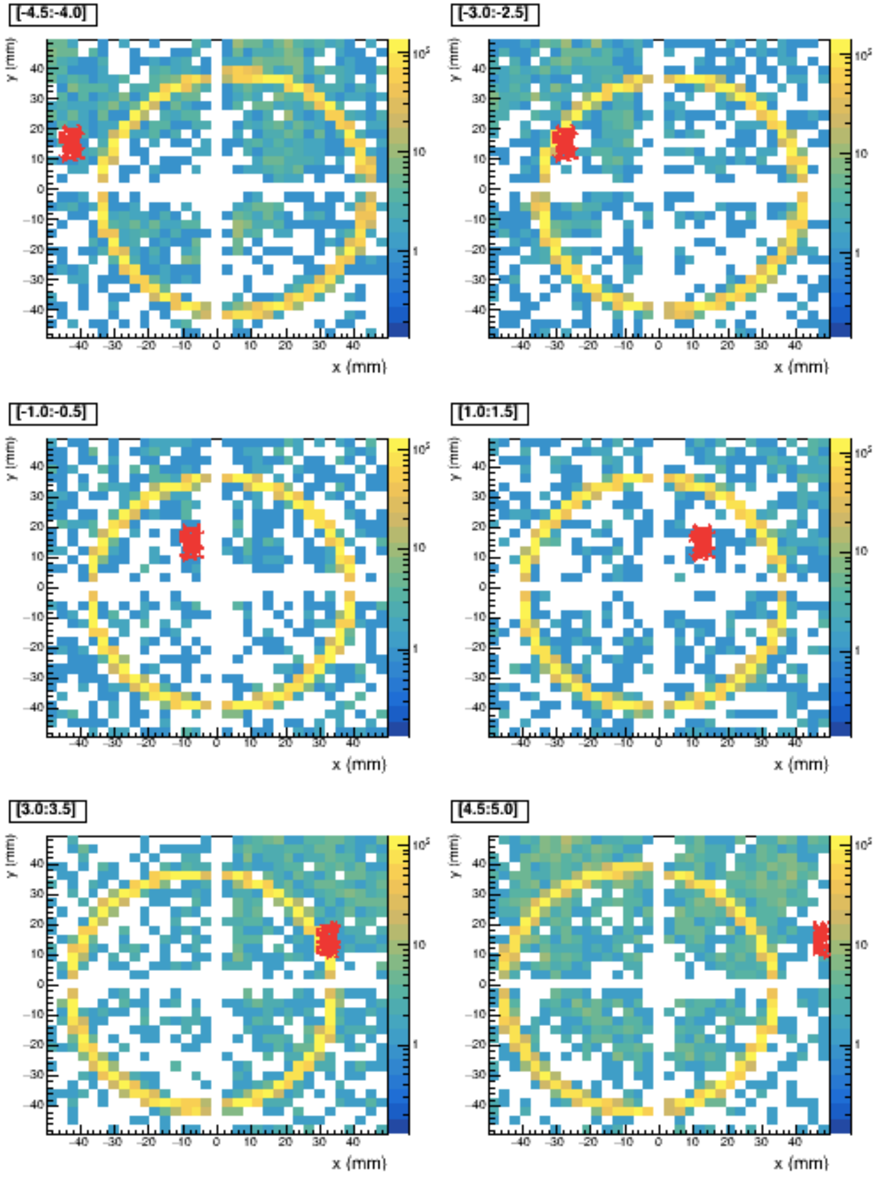
- **2022 JLab Beam Test**
  (1-6 GeV/c Secondary Electron Beam)

mRICH R&D

2022 Beam Data



GEANT4 Simulation



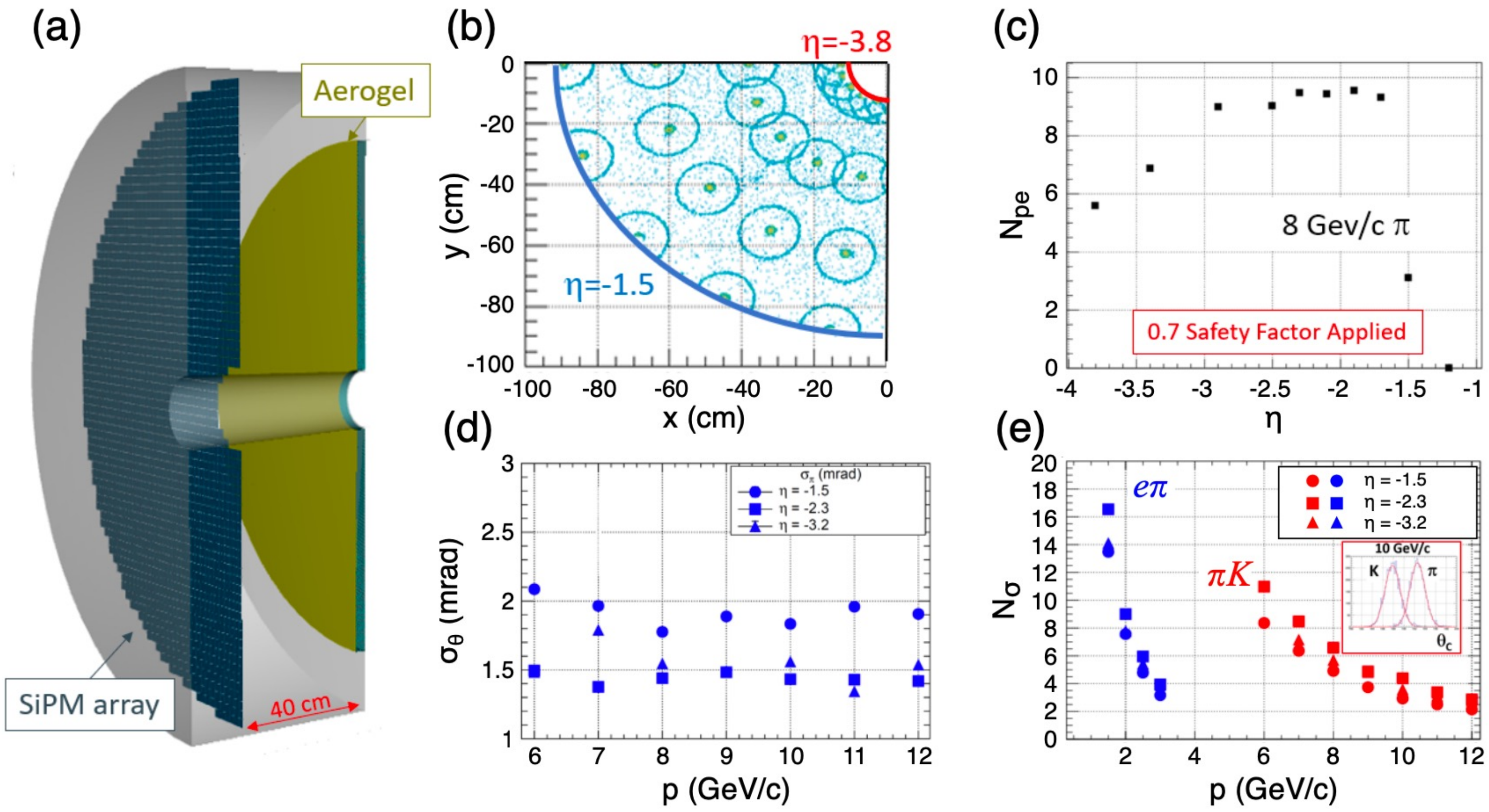
3-10 GeV/c
-3.0 < η < -1.5

2022 JLab Beam Test:

- **Rings as a Function of Incident Beam Position**
- **Determination of Single Photon Resolution in progress!**

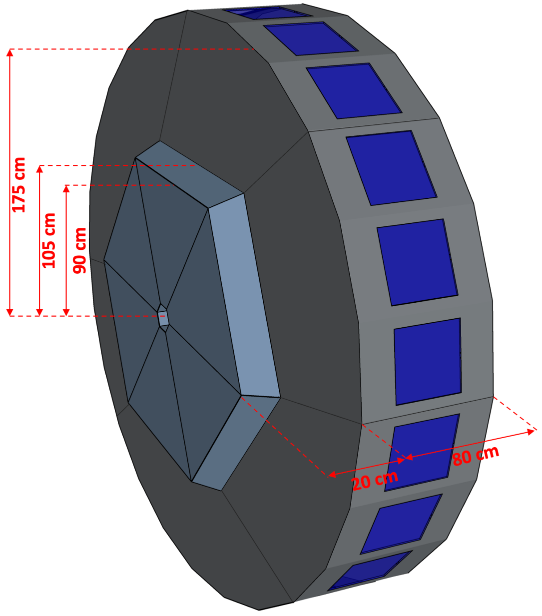
Proximity focusing RICH Detector (pfRICH)

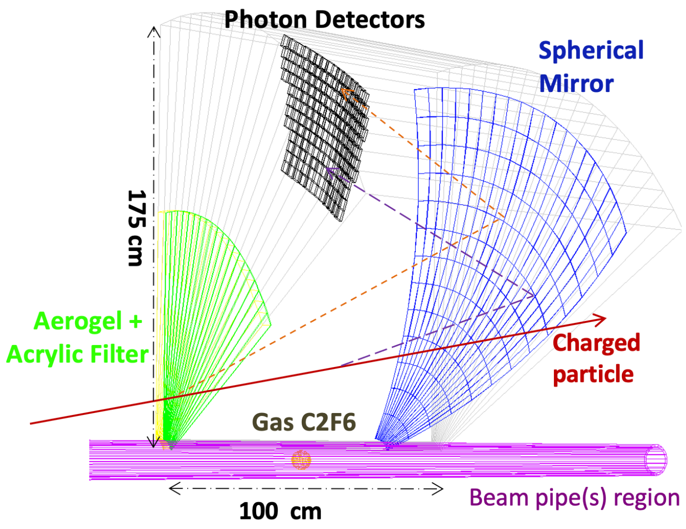
- **A proximity-focusing aerogel RICH (pfRICH) with 40 cm proximity gap (~60 cm full length).**
- Alternative proposed in ATHENA, deviates from the mRICH technology used in the Yellow Report.
- **Main advantage: no need of lenses and mirrors.**
- **Needs more detailed simulations for full evaluation:**
  - Implementing aerogel frame
  - Realistic implementation of sensors
  - Adopting geometry to reference detector space



dRICH: dual-radiator RICH

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:

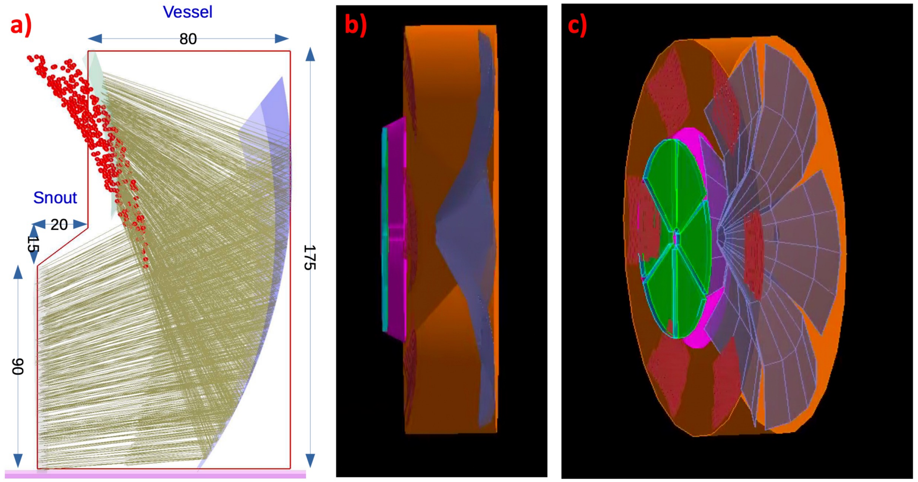
- Aerogel: 4 cm, $n_{(400nm)}$~1.02 + 3 mm acrylic filter
- Gas: 1m (1.1m ePHENIX), n_{C2F6}~1.0008

6 Identical Open Sectors (Petals):

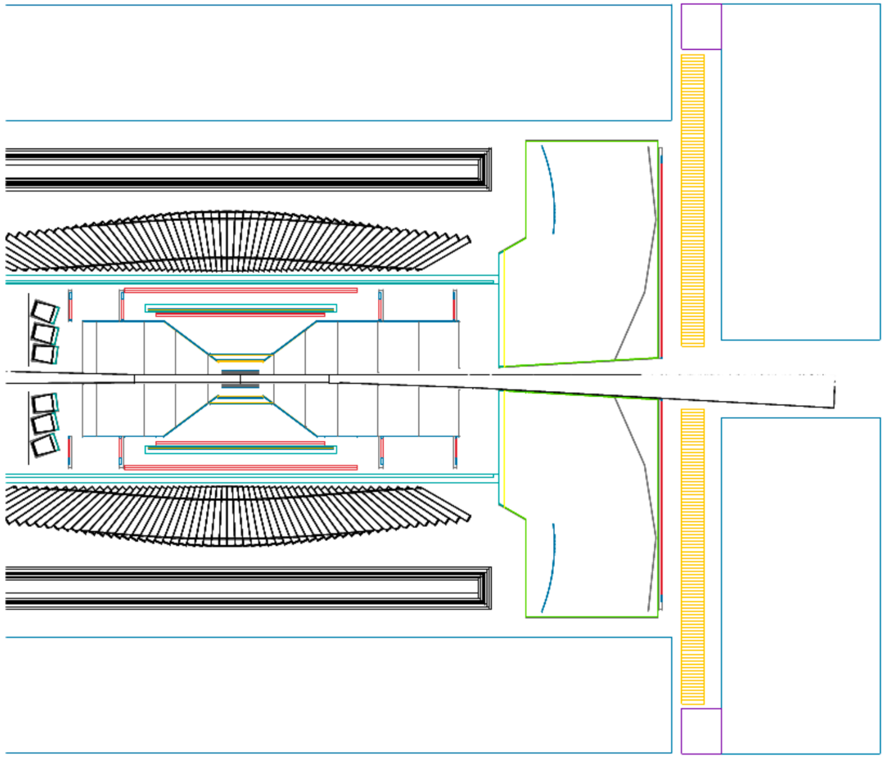
- Large Focusing Mirror with R ~1.8m (~2.0m ePHENIX)
- Optical sensor elements: ~3500 cm^2/sector, 3 mm pixel size, UV sensitive, out of charged particles acceptance

dRICH Studies

- **Adapted eRD14 Generic design**
- **Decreased transverse size of Generic design**
  - Fits EIC Detector1 space and lowers cost
  - Moved closer to IP to maintain acceptance
- **Simulation efforts:**
  - Work on reliable and efficient reconstruction
  - Longitudinal dimension impact on performance
  - Location and final shape of detector plane are being optimized
  - Ensuring proper space for all services
  - Tracking layer behind dRICH?
  - Cost/Performance optimization
- **Gas alternatives are being investigated**



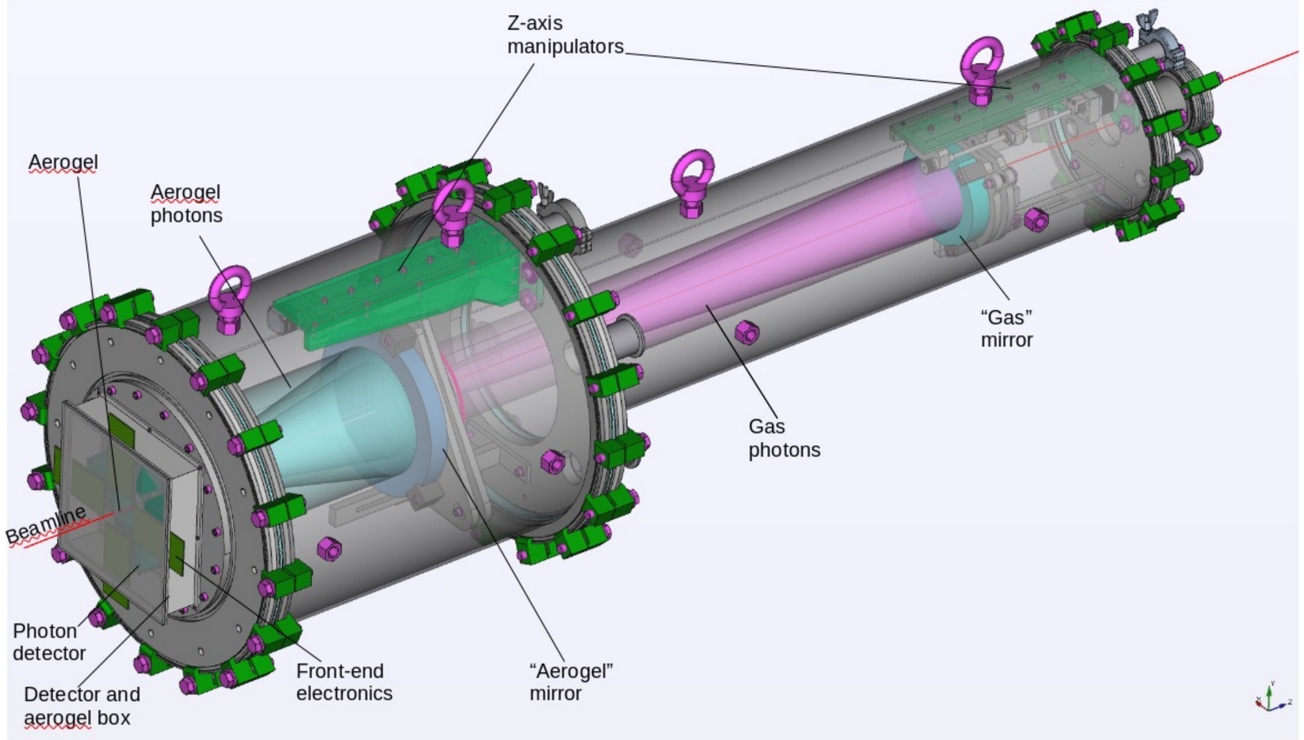
3-50 GeV/c
$1.5 < \eta < 3.2$



dRICH R&D

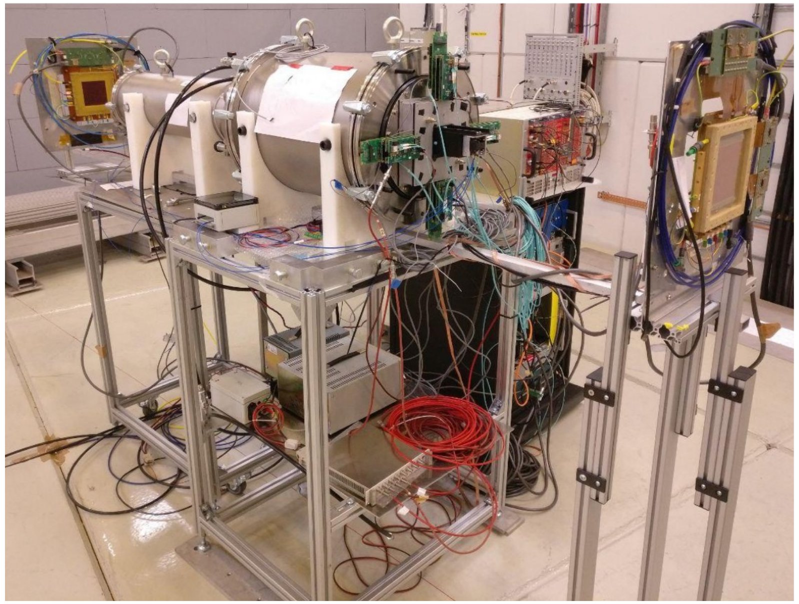
3-50 GeV/c
1.5 < η < 3.2

- A study of radiation effects on SiPM and recover by annealing is ongoing.
- The September test main goal was to implement the readout chain based on ALCOR (with not irradiated SiPMs)
- The ALCOR chip and ARCADIA DAQ are INFN developments designed to readout SiPM with precise time resolution (50 ps time binning) and at high rate (up to 500 kHz per channel).



dRICH R&D

- A larger amount of data will be acquired in the new test beams in fall 2022, making it possible to carry out systematic studies on the dRICH performance towards the design resolution.
- A new version of the reconstruction and analysis software is under development, which will allow an improved resolution and online monitoring.
- An improvement of the simulations is on going, based on the ongoing optical characterization of the dRICH components.



3-50 GeV/c
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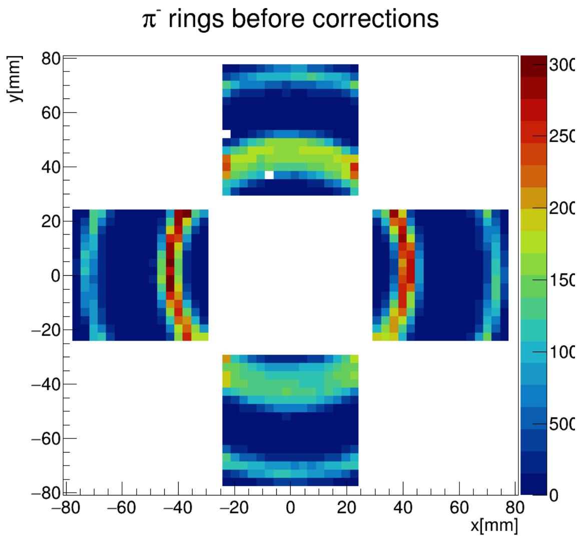
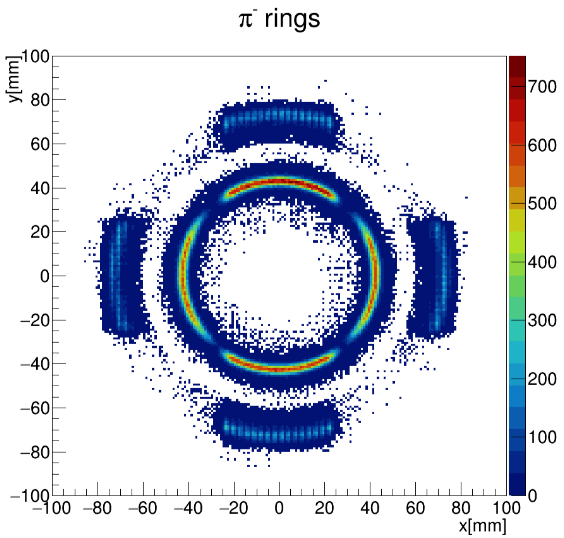
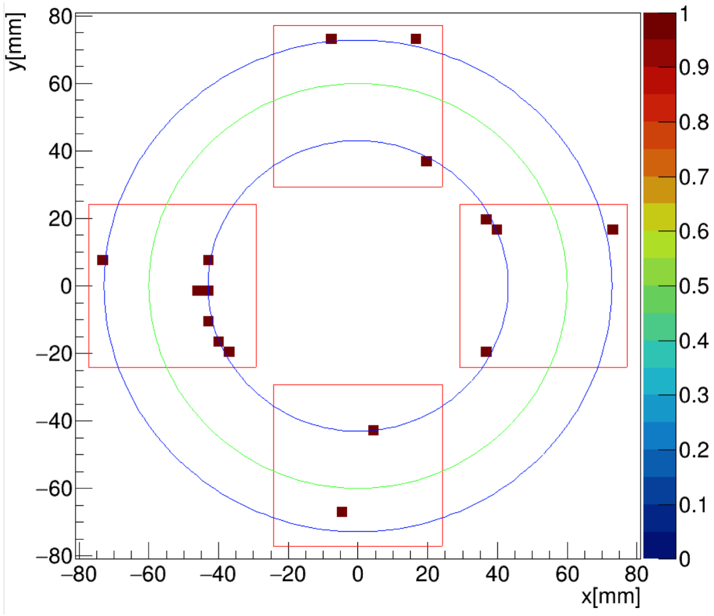






EIC HPDIRC

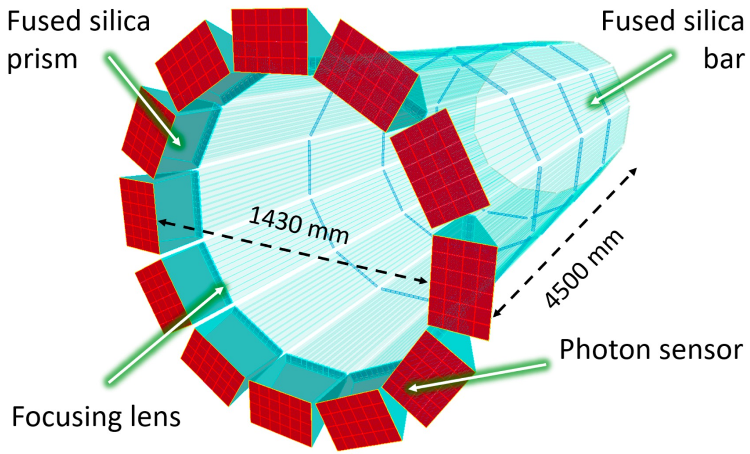
1-6 GeV/c
$-1.64 < \eta < 1.6$

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)*

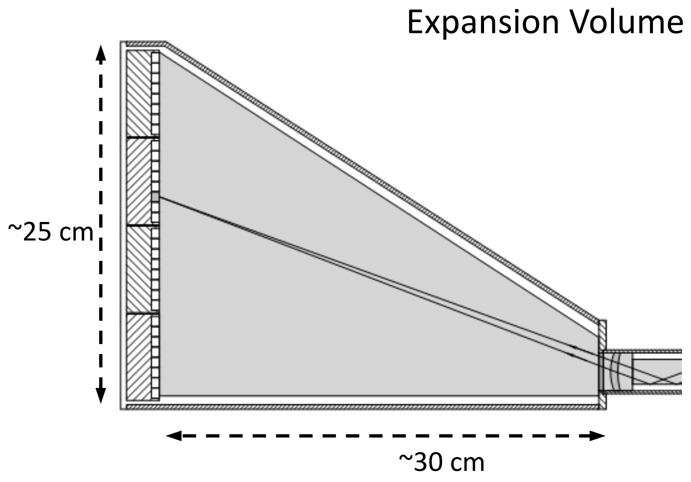
Excellent performance over wide angular range:

- ≥ 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)

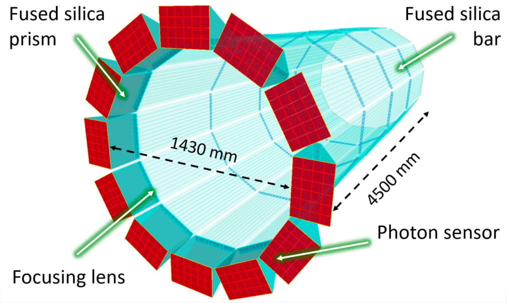


EIC hpDIRC

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

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)*



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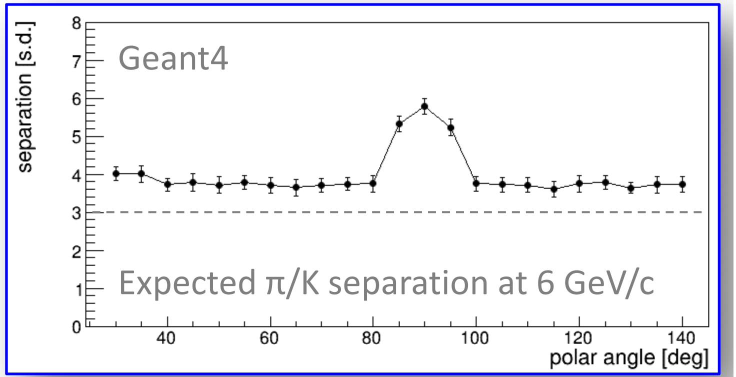

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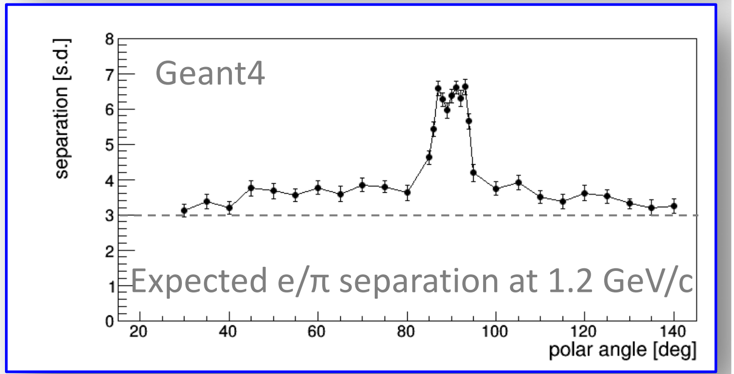
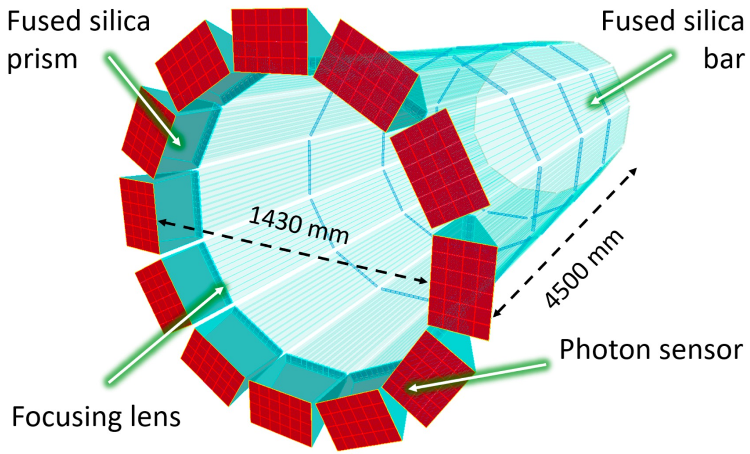
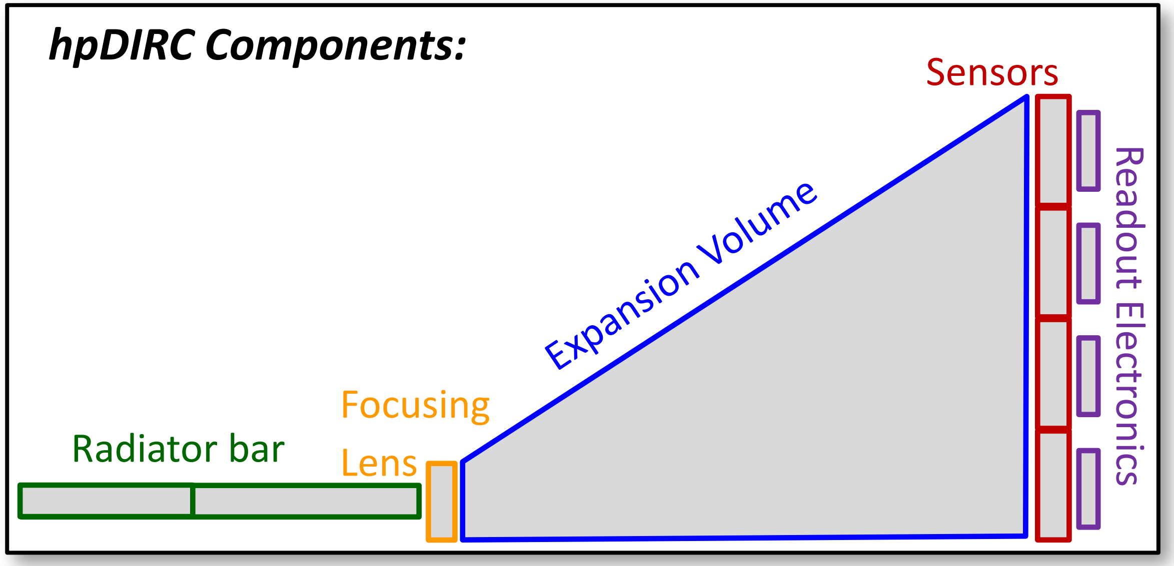


EIC hpDIRC

1-6 GeV/c
-1.64 < η < 1.6

- **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**

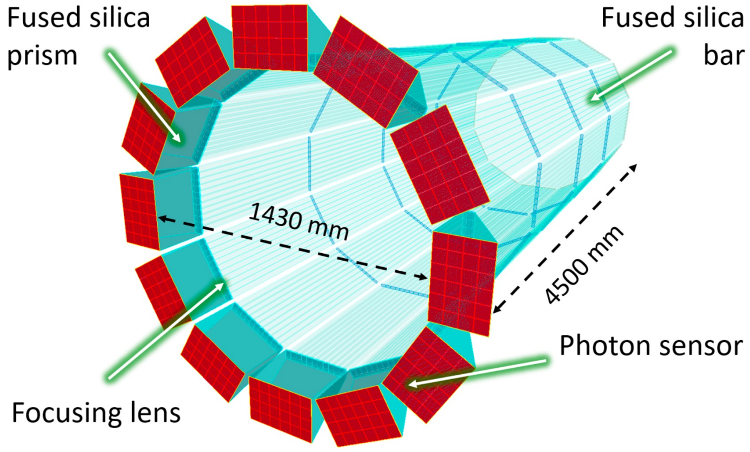


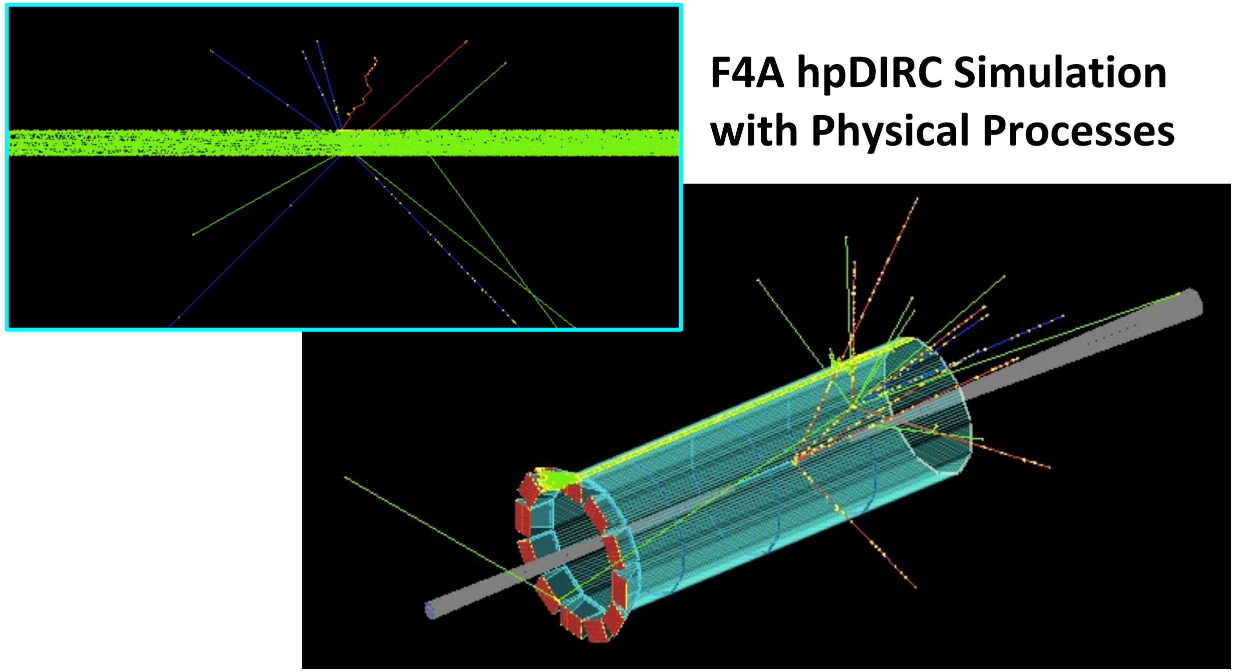


hpDIRC Simulations

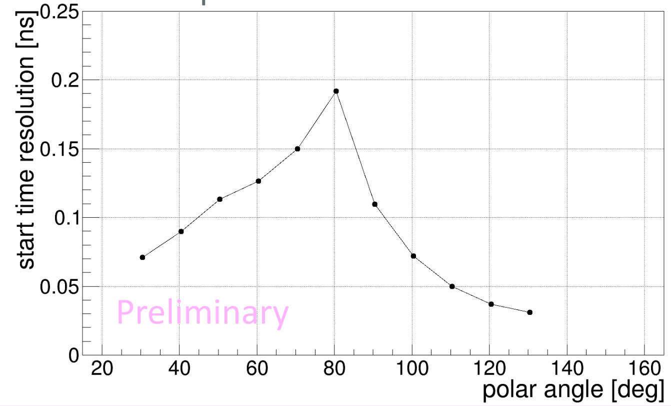
- **Simulation validated in test beam**
- **Excellent performance with particle gun over wide angular range:**
  - ≥ 3 s.d. π/K up to 6 GeV/c, ≥ 3 s.d. e/π up to ~1.2 GeV/c
  - Low momentum π/K identification in "veto mode" down to 0.2-0.3 GeV/c
- Performance evaluation in full Detector1 Simulation with physical events in progress!
- Start time using only hpDIRC information study
- Feasibility studies of "light-guide" section (Generic R&D)

1-6 GeV/c
-1.64 < η < 1.6





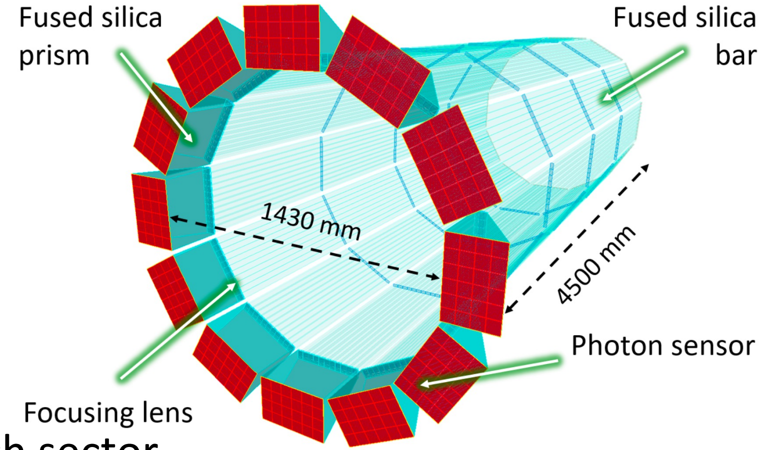
F4A hpDIRC Simulation with Physical Processes



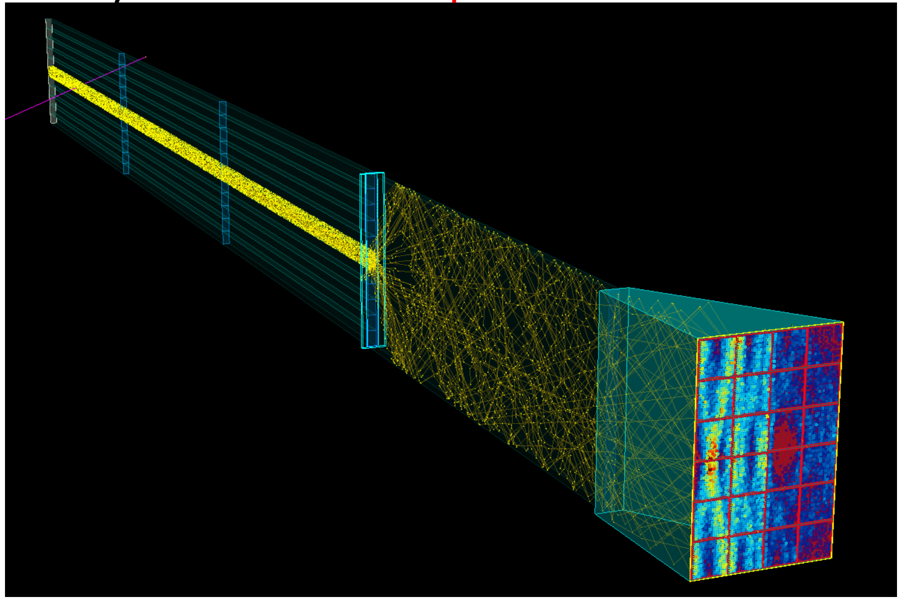
HPDIRC SIMULATIONS

1-6 GeV/c
-1.64 < η < 1.6

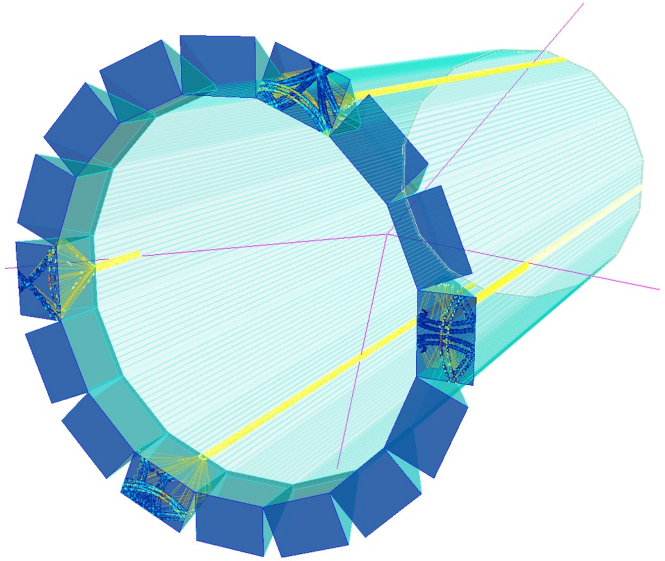
- **Simulation validated in test beam**
- **Excellent performance with particle gun over wide angular range:**
  - ≥ 3 s.d. π/K up to 6 GeV/c, ≥ 3 s.d. e/π up to ~1.2 GeV/c
  - Low momentum π/K identification in "veto mode" down to 0.2-0.3 GeV/c
- Performance evaluation in full Detector1 Simulation with physical events in progress!
- Start time using only hpDIRC information study
- Feasibility studies of "light-guide" section (Generic R&D)



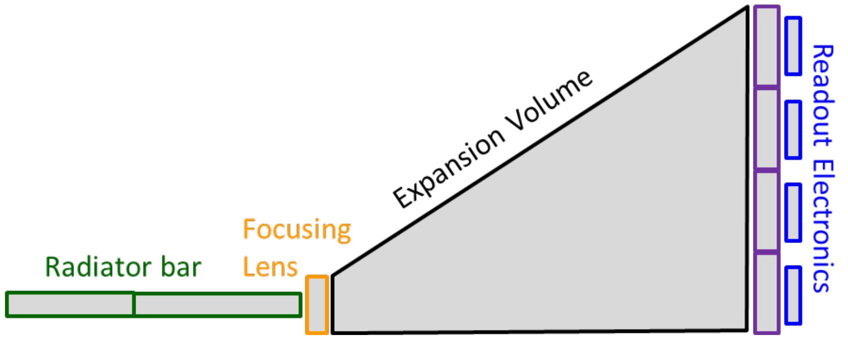
Hybrid of bars and plate in each sector



Narrow bars in each sector

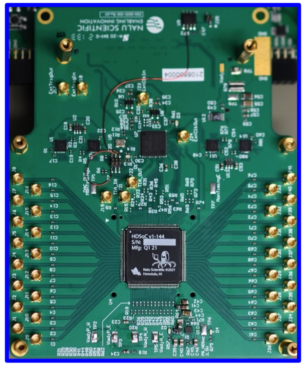


hpDIRC R&D

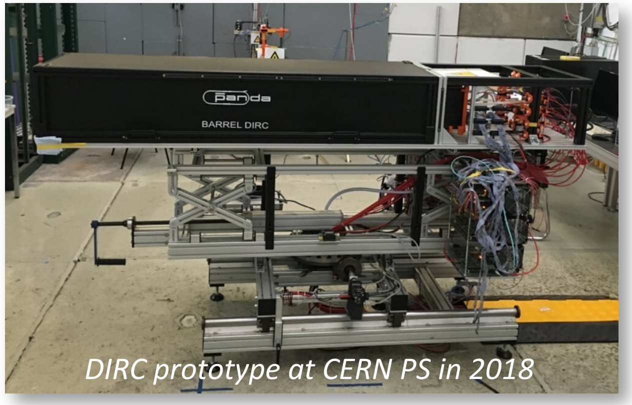


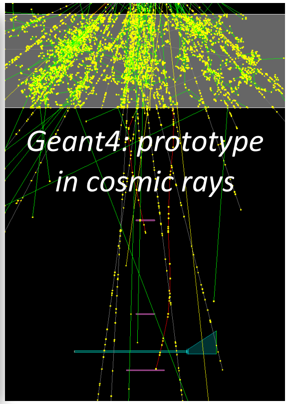
Readout Development

Prototype readout stack at UH/Nalu

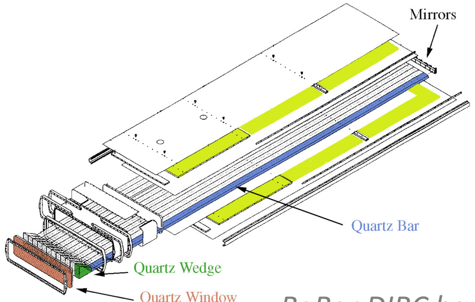


hpDIRC Prototype in CRT



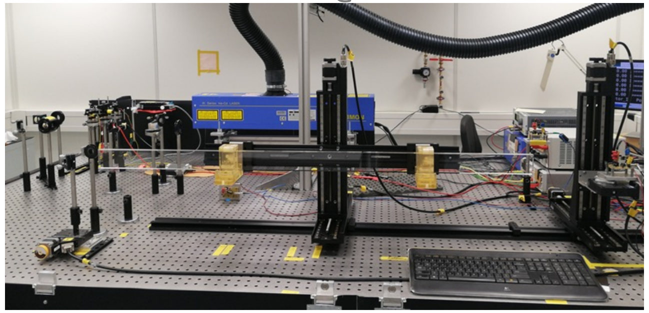


BaBar Bars Dissasambly

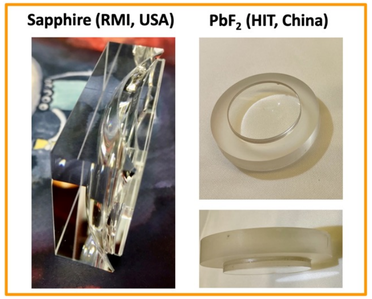


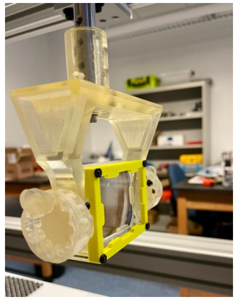
BaBar DIRC barboxes @ SLAC

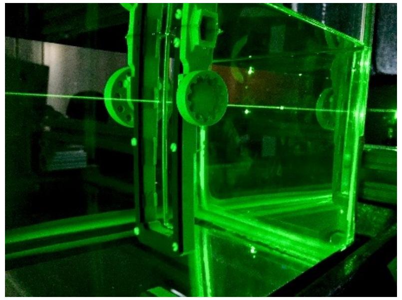
DIRC lab @ GSI



3-Layer Lens Development







DIRC lab @ ODU

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**

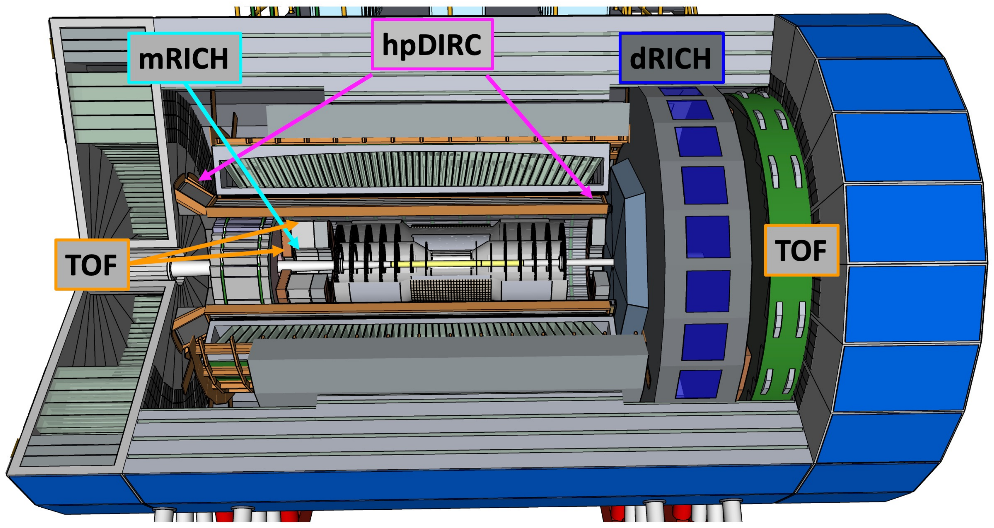
- **Geometries are being further optimized to fit the reference EPIC Detector design while maintaining the required performance** to assure wide momentum coverage across the full phase space and minimize the cost!

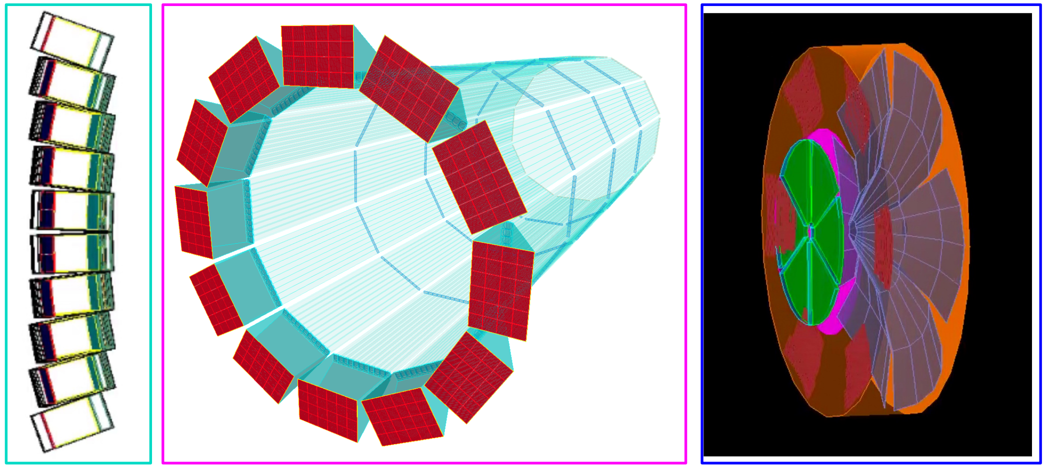
  - Backward: Short, modular RICH **(mRICH)**
  - Barrel: Radially compact with flexible design high-performance DIRC **(hpDIRC)**
  - Forward: Double-radiator RICH **(dRICH)**

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

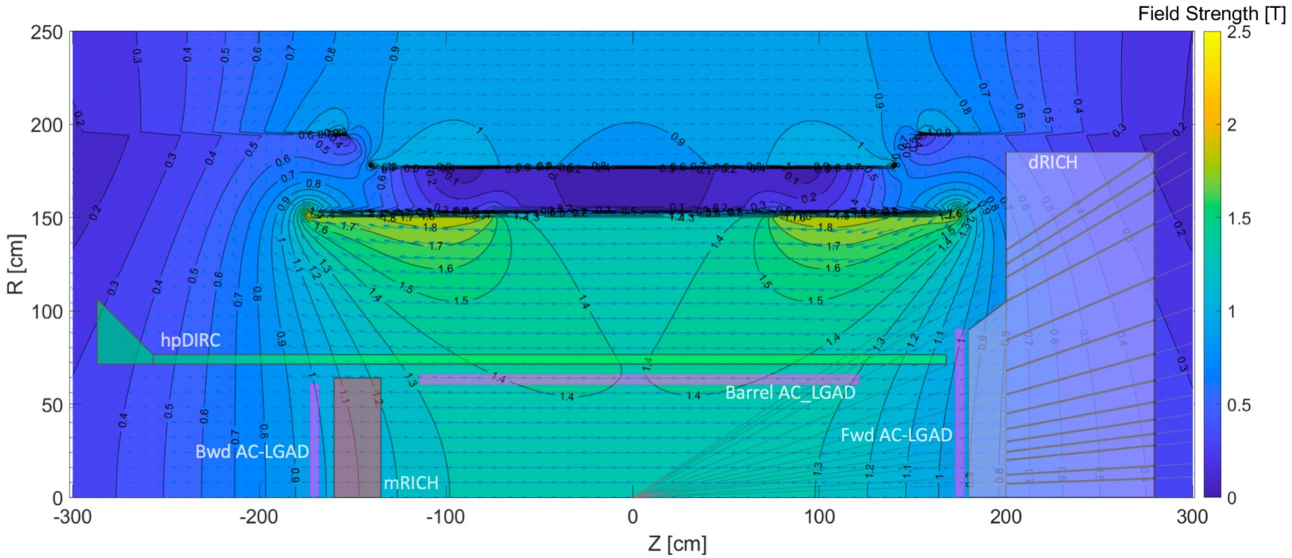
- Separate eRD programs for Photosensors and readout electronics

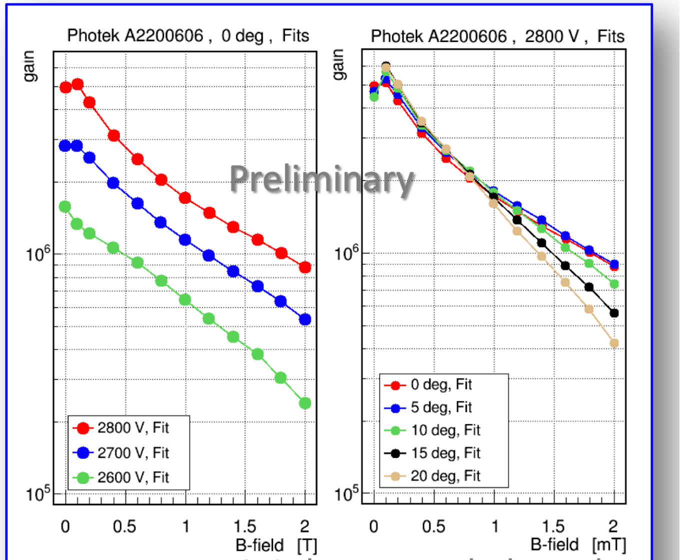
- EPIC Detector deserves EPIC PID ☺





- 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)

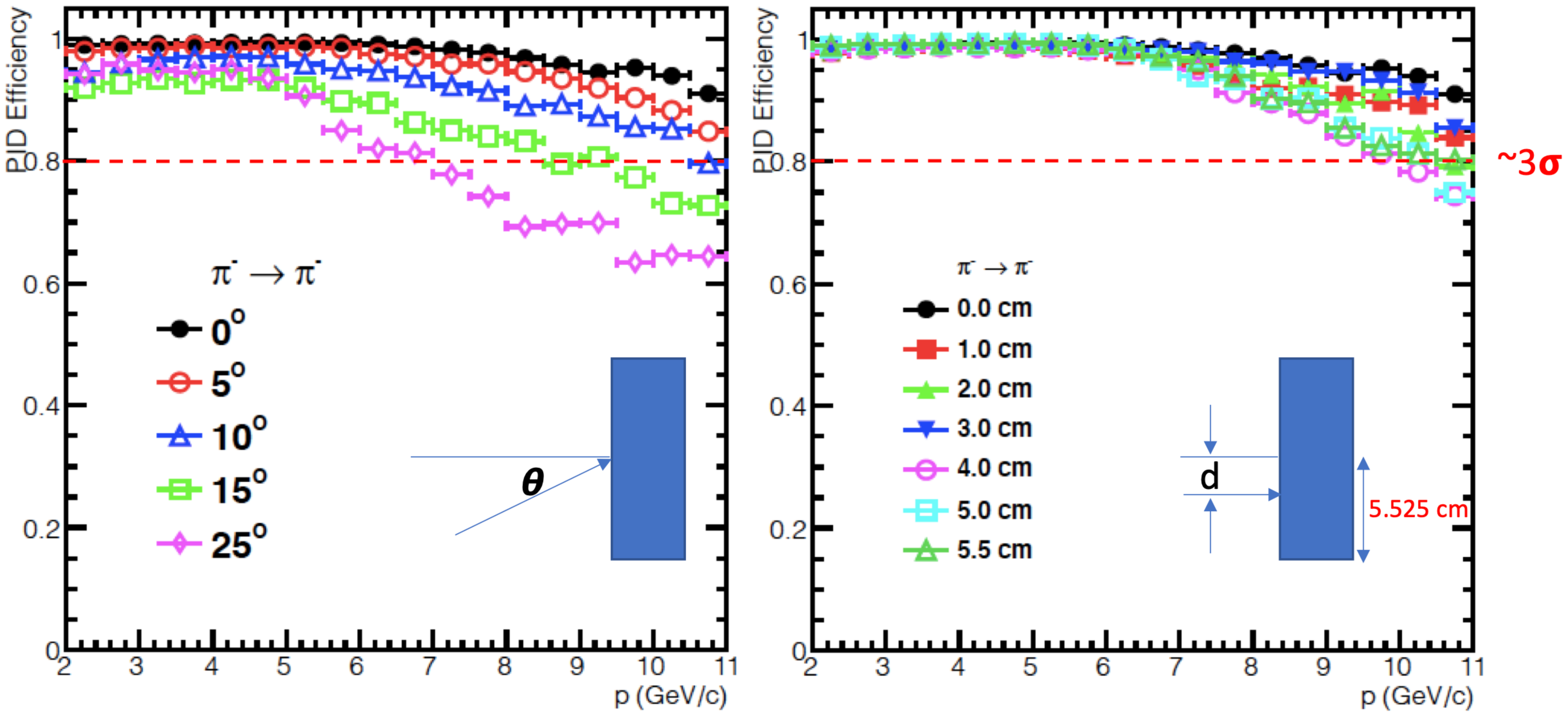




A. Lehmann et al, shown by J. Milnes, IEEE NSS, Nov. 2020

Modular RICH Detector (mRICH)

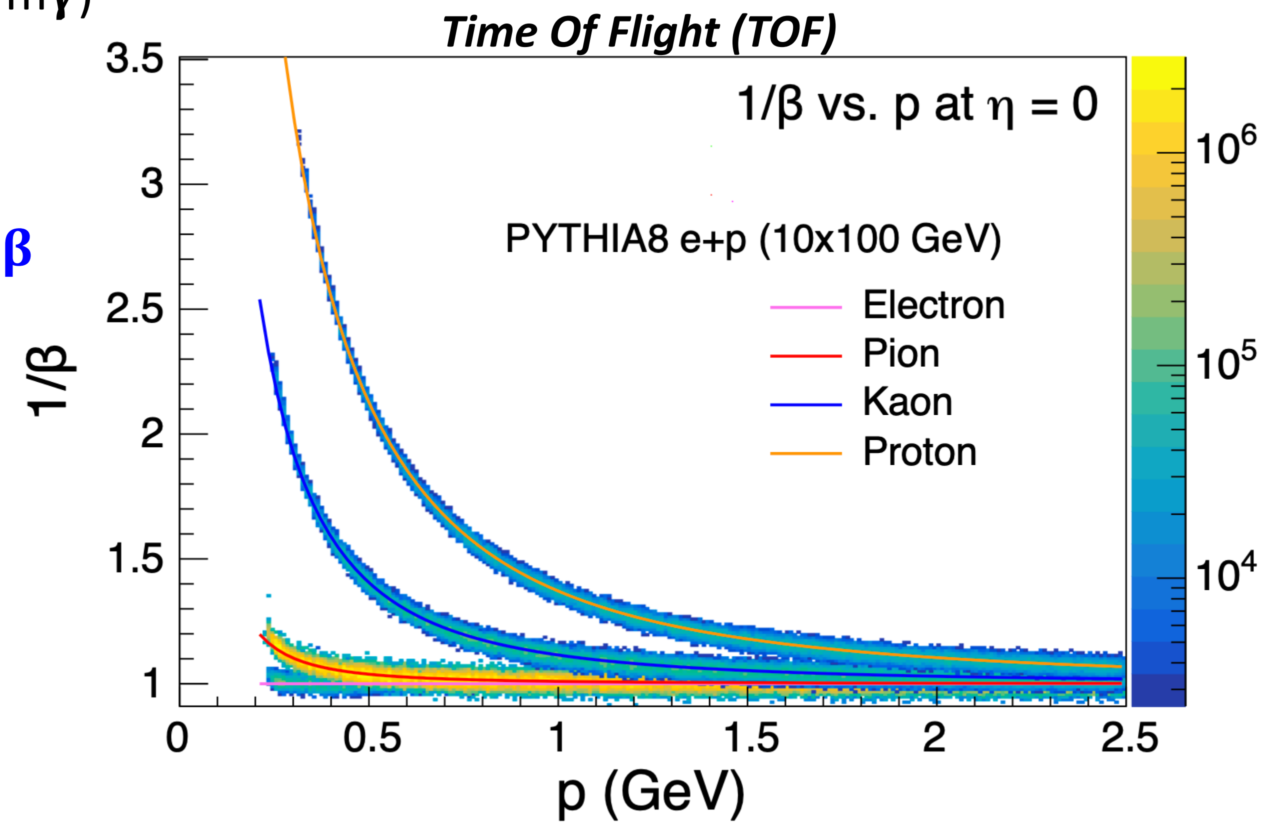
3-9 GeV/c
$-3.0 < \eta < -1.5$



- Efficiency drops beyond 15°

CHARGED PARTICLE IDENTIFICATION

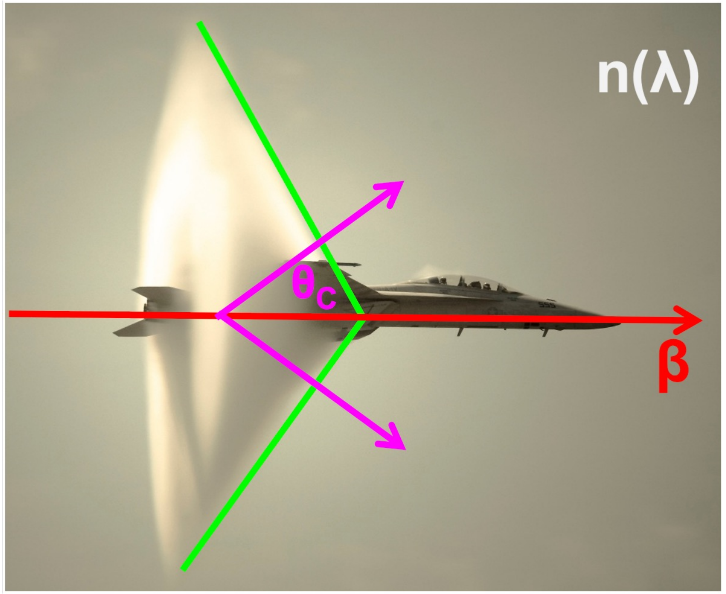
- **Velocity (β) measurement yields mass!** (p = m$\gamma\beta$ E = mγ)
- **Direct measurement:**
  - **Record signal time at multiple locations, calculate β**
  - "Fast" detector = low transit time spread (most easily achieved at small transit time)
- **Velocity-dependent interactions with detector:**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

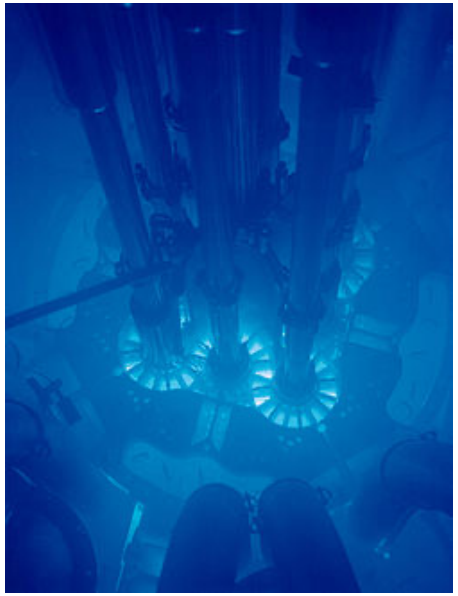


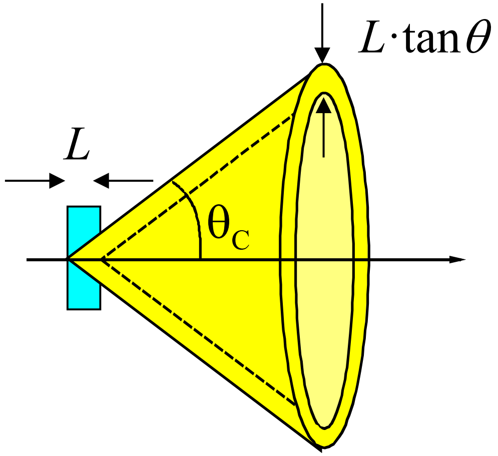
CHERENKOV RADIATION

- 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 $n(\lambda)$

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





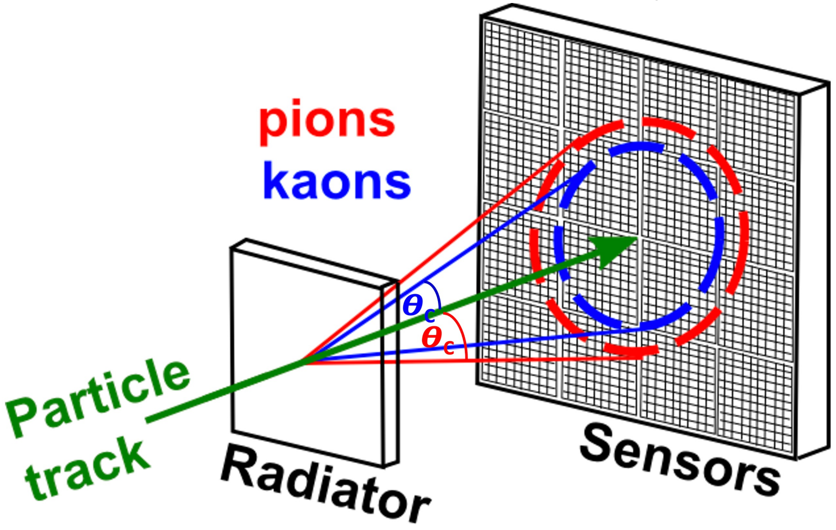


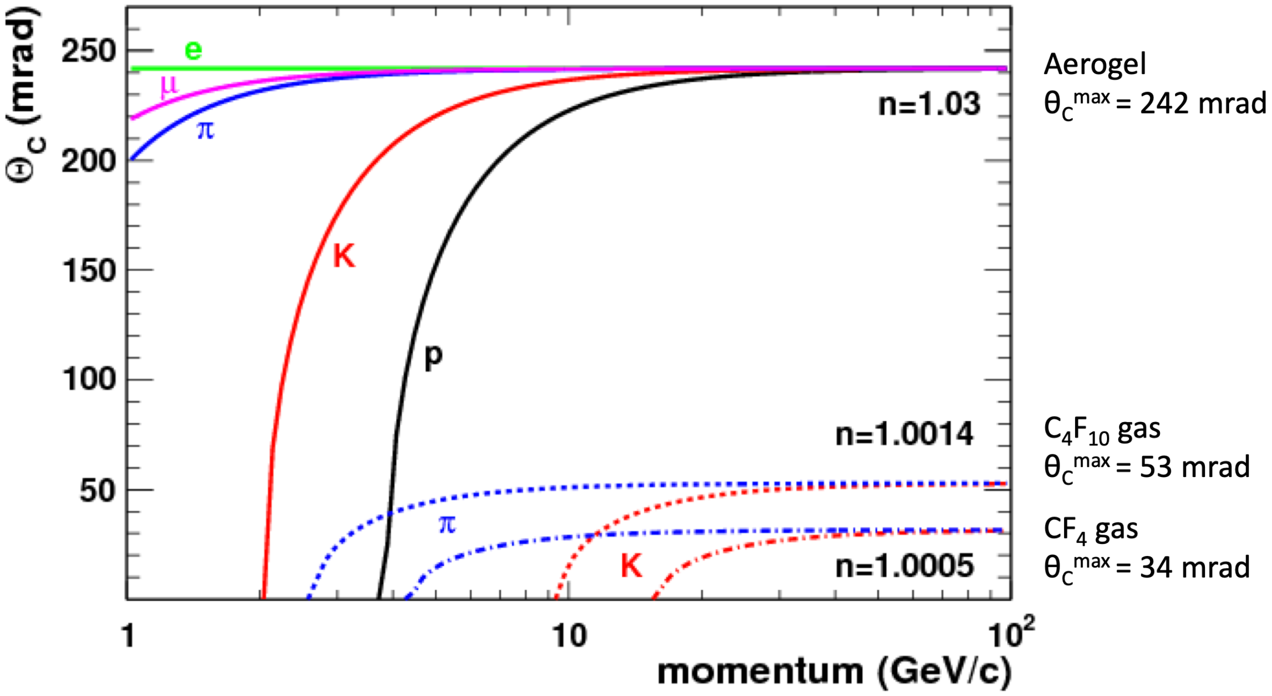
CHERENKOV DETECTORS

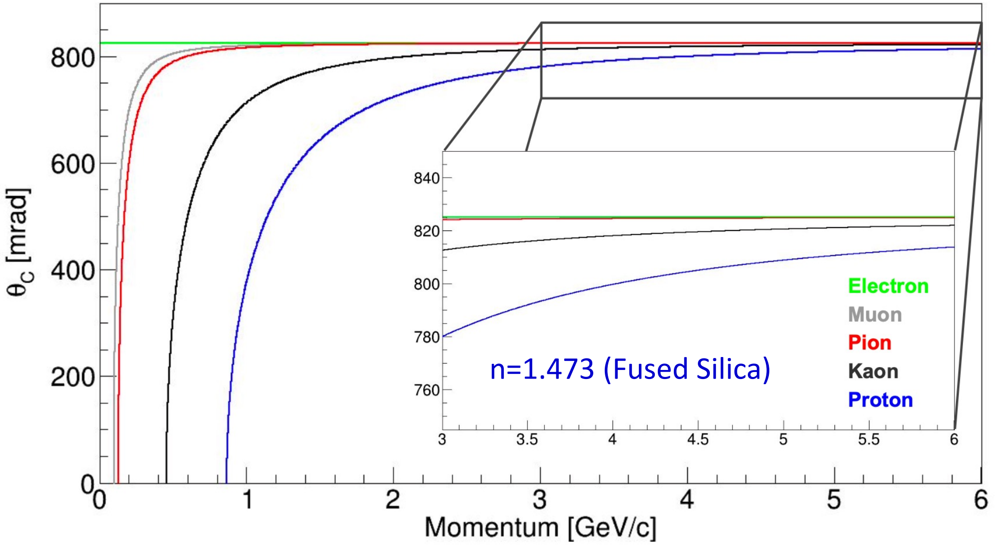
- Select material with refractive index n where particle type A produces Cherenkov light, particle type B does not
  → threshold counter

- 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)

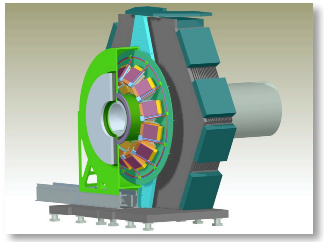
- Compare ring image with expected image for e/μ/π/K/p (likelihood test) or calculate mass from track β using independent momentum measurement (B field, tracking).

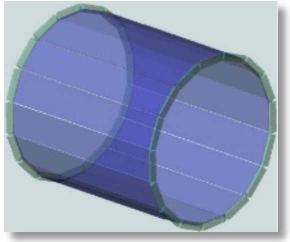


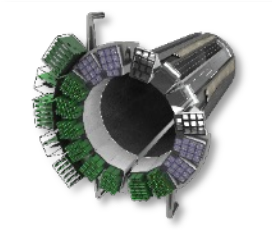


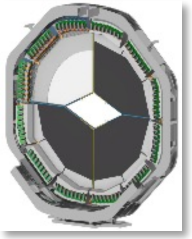


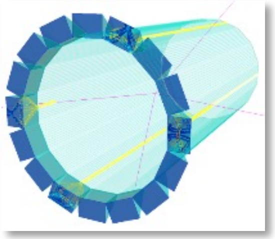
Cherenkov Detectors









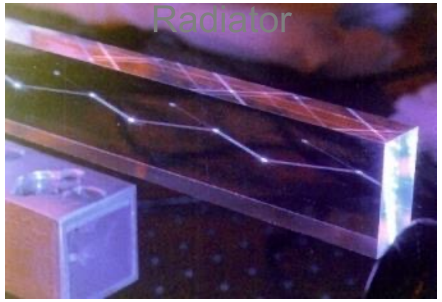


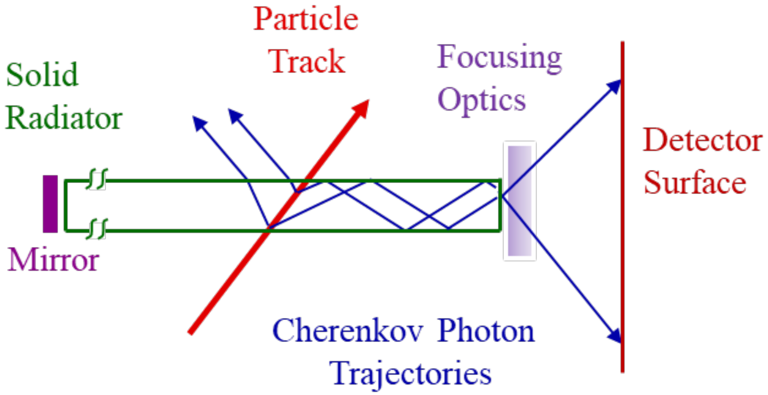
BaBar | SuperB | Belle II | GlueX | panda | panda | Electron Ion Collider

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