Particle Identification by the forward and backward RICHes at Electron Ion Collider

Chandradoy Chatterjee (INFN Trieste)

On behalf of EIC dRICH community.

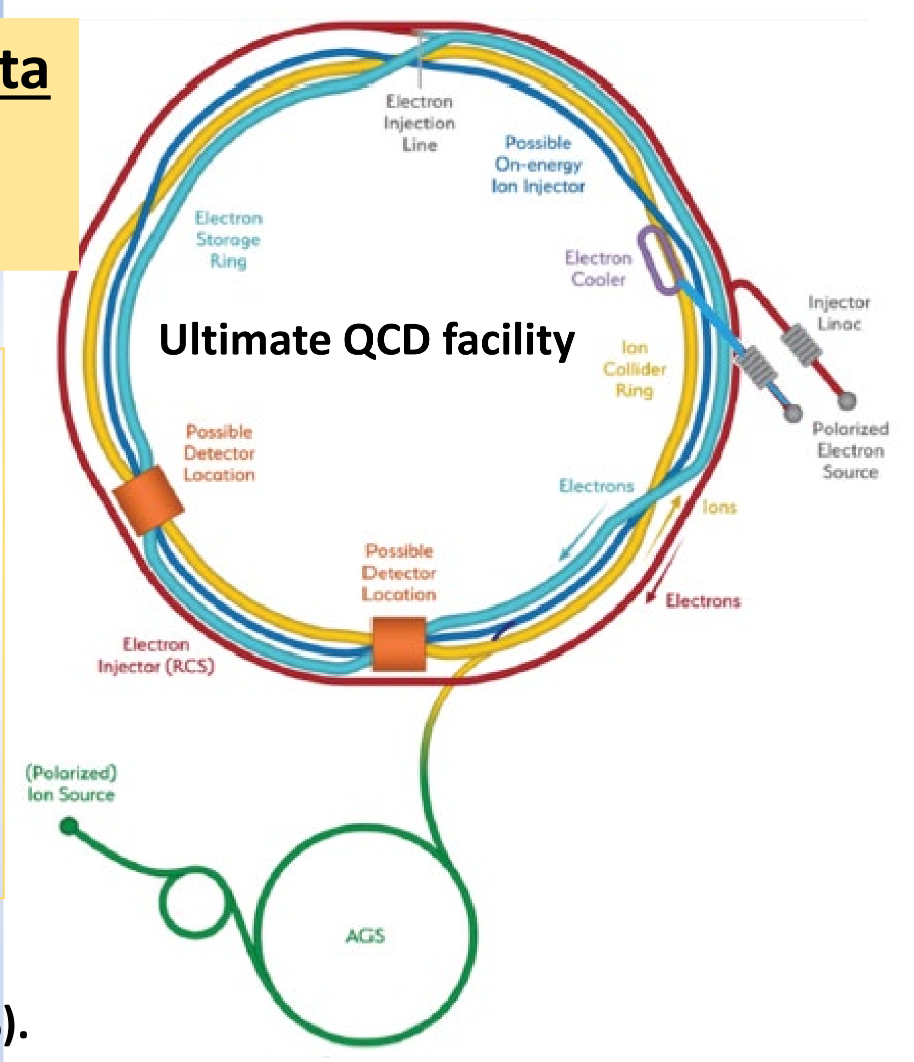
Outline:

a) Introduction to EIC and physics examples depending on efficient particle identification
b) The geometric and physics constraints for the RICHes
c) Simulation studies of the RICHes: Geometric description and performances
d) Current status and conclusions

Istituto Nazionale di Fisica Nucleare

The Electron Ion Collider

Expected to start data taking in the early 2030s at BNL USA



Key Science Topics:

1. **Emergence** of global nucleonic properties such as **spin** and **mass** from partons and their underlying interactions.
2. The **distribution in momentum and position space of the partons inside the nucleon**.
3. The **interaction of nuclear medium** with **color-charged partons** and **jets**. Emergence of confined hadronic states from these partons. **Impact of QCD for nuclear binding**.
4. Saturation of the **Dense gluon environment** inside nuclei.

Main Design Requirements of EIC:

a. **Highly polarized electron and nucleon and light nuclei beam (~70-80%). Polarized electron and heavy ion collision.**

b. **High center of mass energy ~ 20-141 GeV**

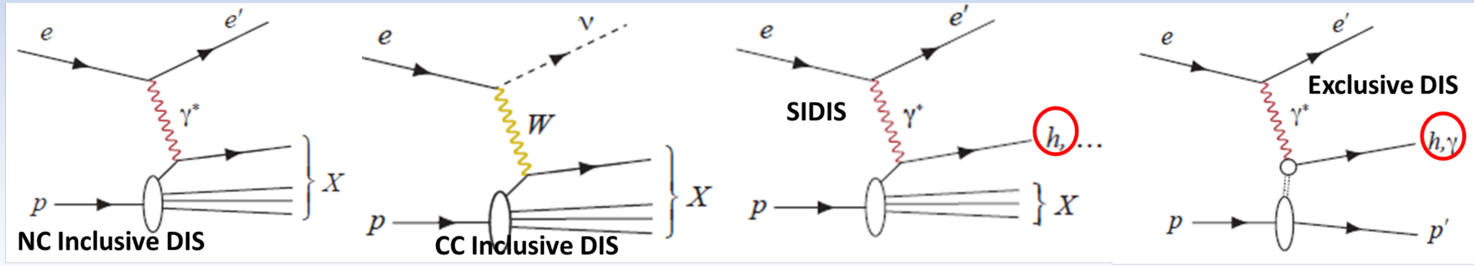
c. **High Luminosity ~10^{34} electron nucleon cm^{-2} s^{-1}**

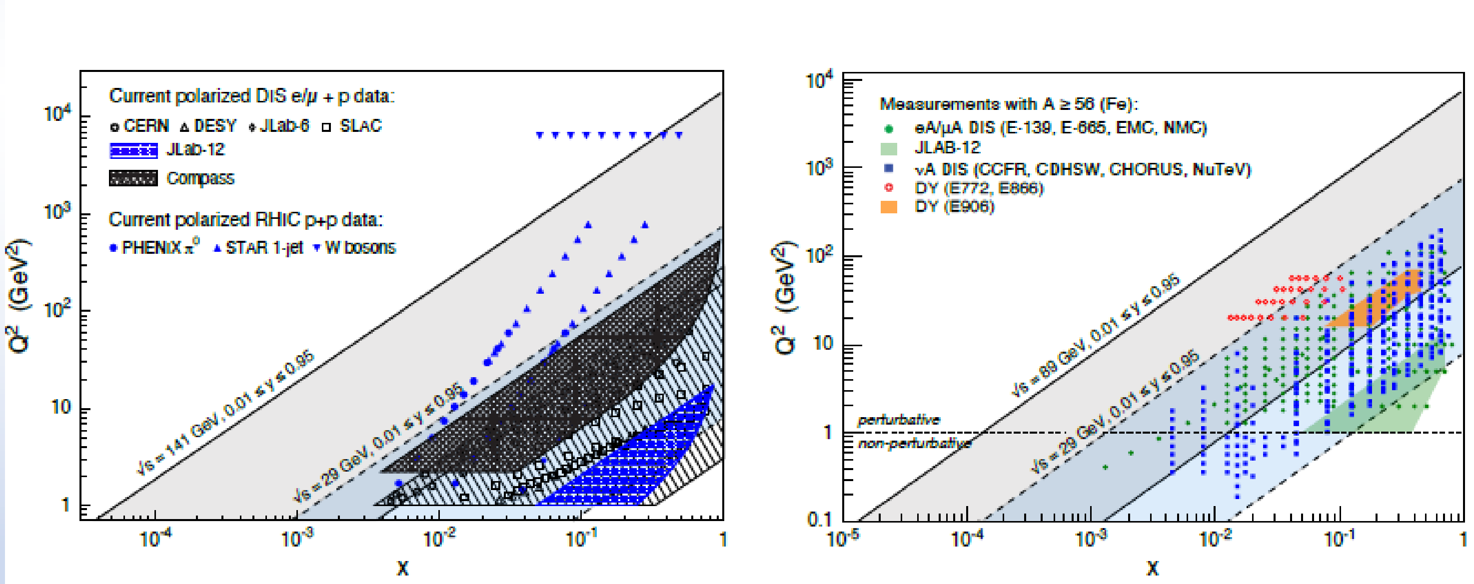
d. **Possibly more than one interaction point**

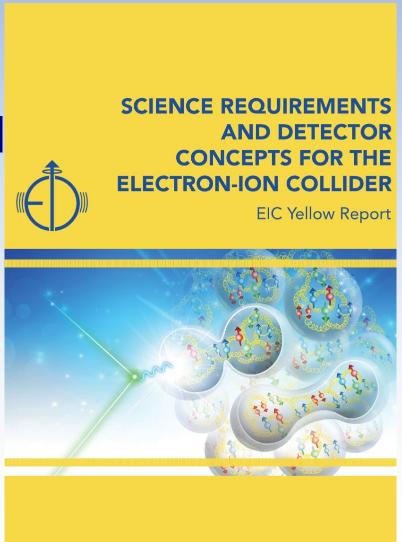
The Electron Ion Collider

R. Abdul Khalek et al. *Science Requirements and Detector Concepts for the Electron-Ion Collider: EIC Yellow Report, 2021*

https://doi.org/10.1016/j.nuclphysa.2022.122447.







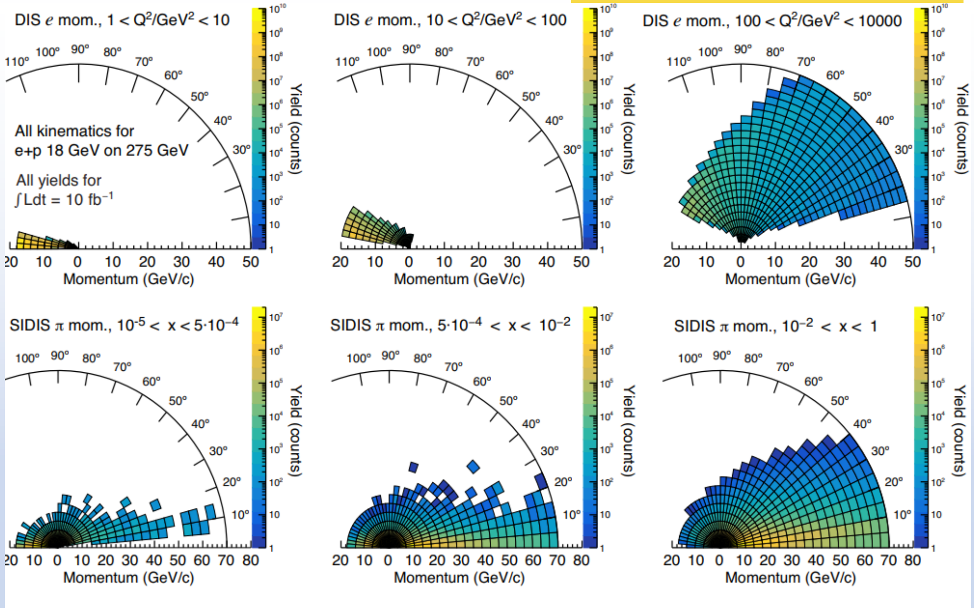
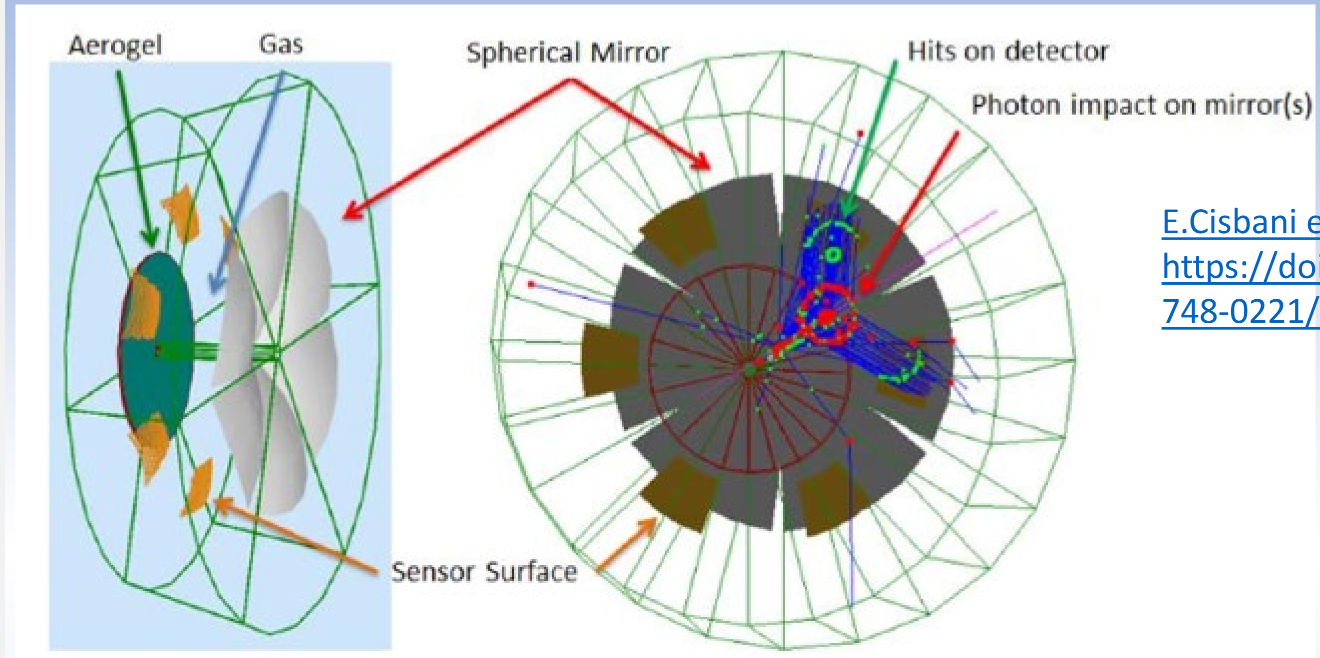


Figure 11.59: DIS electron and SIDIS pion simulated yield for 18 GeV electron on 275 GeV proton collisions. Yield (color scale) is plotted in polar coordinates with the radial coordinate indicating momentum and the azimuthal coordinate indicating ejectile polar angle. The top row is for electrons, the bottom row is for pions. The columns are selected ranges of Q^2 as indicated. The asymmetry of the initial state is reflected as a momentum asymmetry in the ejectiles.

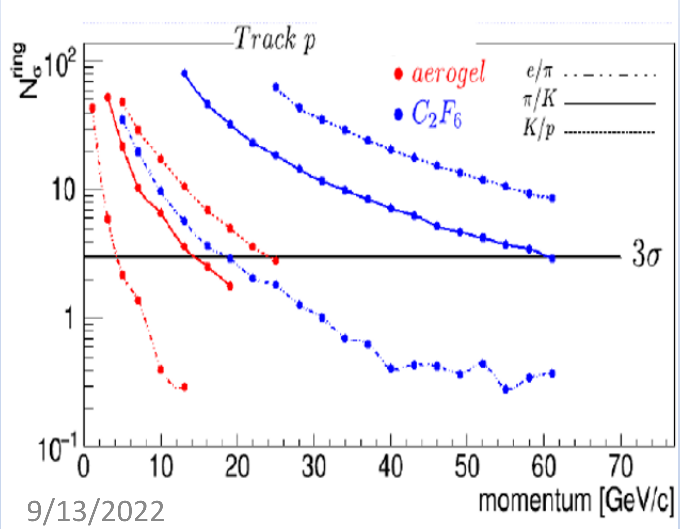
Excellent PID is required at the level of 3 *sigma pi*/K/p separation up to 50 GeV/c in the forward region, up to 10 GeV/c in the central detector region, and up to 10 GeV/c in the backward region.

Yellow Report dual RICH prescription



[E.Cisbani et al. https://doi.org/10.1088/1748-0221/15/05/P05009](https://doi.org/10.1088/1748-0221/15/05/P05009)

Collider Setup→ Smaller availability of space to have two Rich detectors in the forward arm to cover different momentum range→ A rich with two radiator→ Single rich to cover entire momentum range.



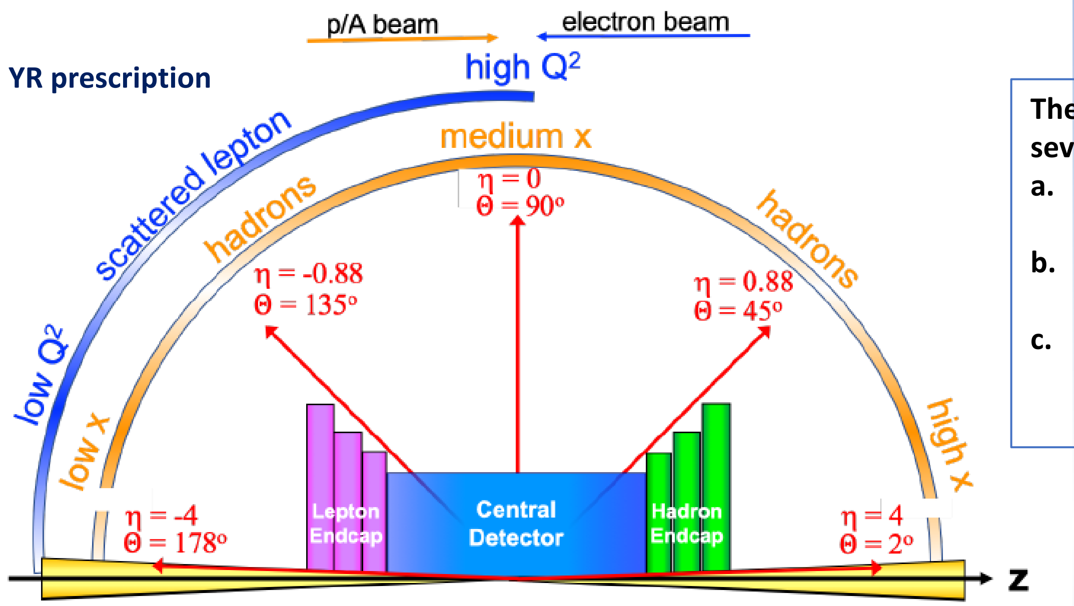
Note:

1. Not only PID application, but excellent eID out to roughly 20 GeV/c.
2. Does not have "holes" in the performance. At low momentum (due to aerogel) at intermediate momentum due to the index match of the aerogel and gas radiator performance. Full coverage.
3. π-K performance achieves the full goals of the PID requirements matrix.

Detector lay out

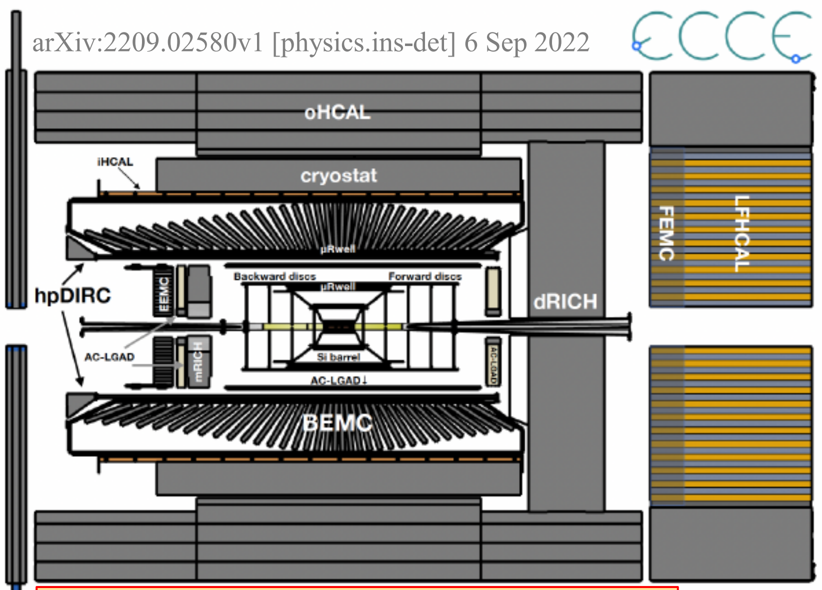
Call for proposals in December 2021

→ Different proposals, independent performance studies of the RICHes in ECCE and ATHENA global detector.



The forward RICH detector has several constraints:

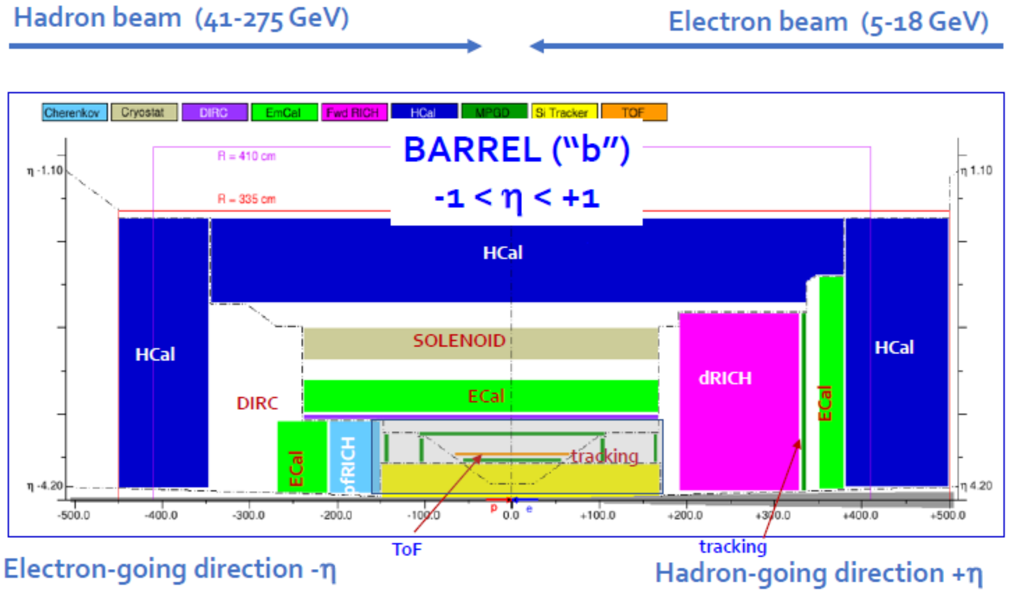
a. Small available space (<150 cm)
b. Need to cover large acceptance(~500 mrad)
c. Need to have wide momentum coverage. (up to 50 GeV/c)



ECCE reuses 1.5 T BaBar magnet

ATHENA employs 3T solenoidal magnet

Backward Endcap ("n")
η < -1



Forward Endcap ("p")
η > +1

Inverse Ray Tracing (IRT): concept

- Originally implemented by HERMES Collaboration
- Recent re-implementations by many colleagues.

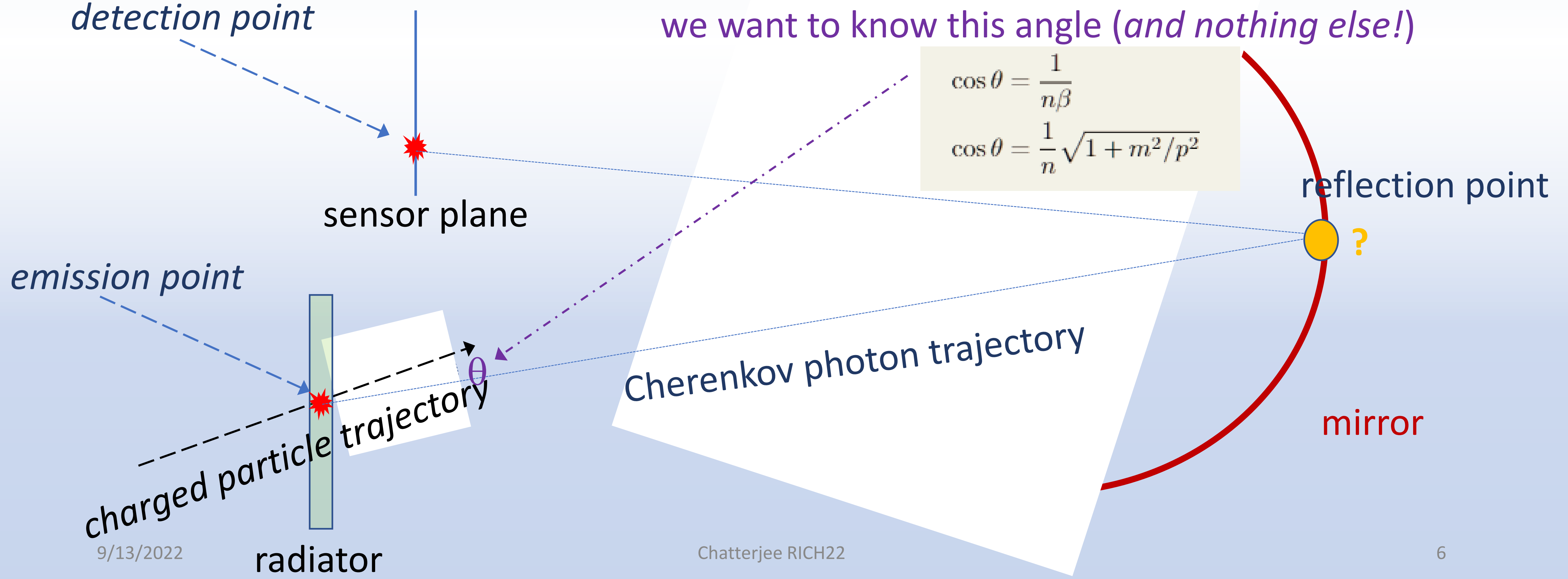
Can be used in a standalone GEANT code as well as in the ATHENA environment

https://eicweb.phy.anl.gov/EIC/irt/-/tree/irt-init-v02

we want to know this angle (*and nothing else!*)

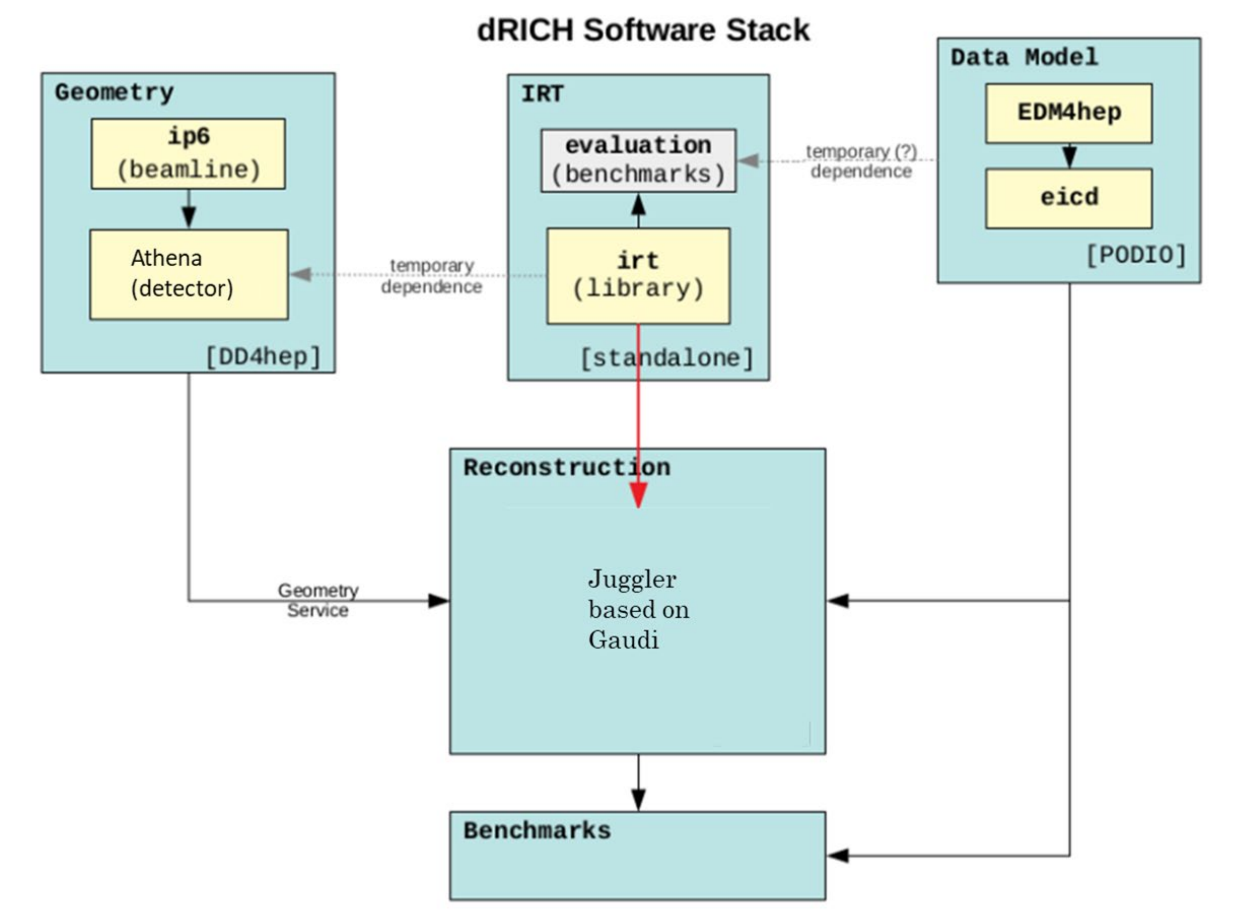
$$\cos\theta = \frac{1}{n\beta}$$

$$\cos\theta = \frac{1}{n}\sqrt{1 + m^2/p^2}$$



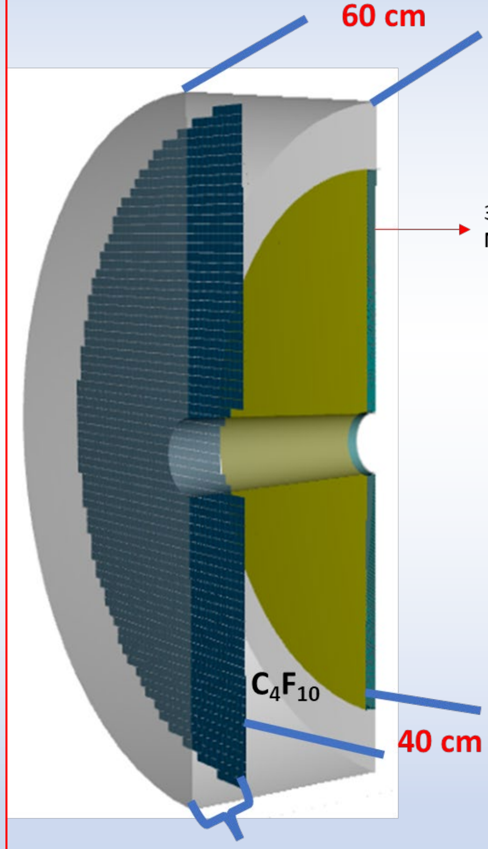
The Workflow in ATHENA

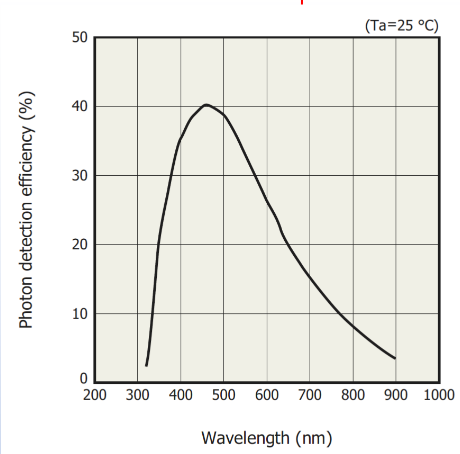
DD4Hep framework



- The ATHENA workflow is same for both proximity focusing RICH and dual RICH. (And now also for the dRICH in EPIC collaboration).
- The software is highly modular.
- Specific geometry can be inserted according to the RICH, and detector of interest.
- The reconstruction algorithm can be the same.
- Standalone analysis of the reconstructed data can be done.

Geometry of pfRICH





Sensors:

a) Hamamatsu S13361-3050AE-08 8x8 SiPM panels (https://www.hamamatsu.com/us/en/product/type/S13361-3050AE-08/index.html)

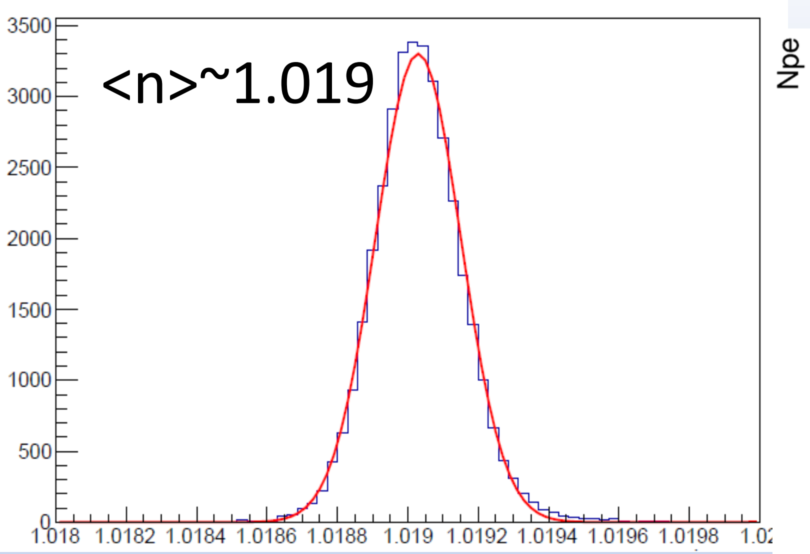
b) 3x3 mm^2 single SiPM with 8X8 pixels in each sensor. Sensor full size = 25.8x25.8 mm2. → 0.85 geometric efficiency.

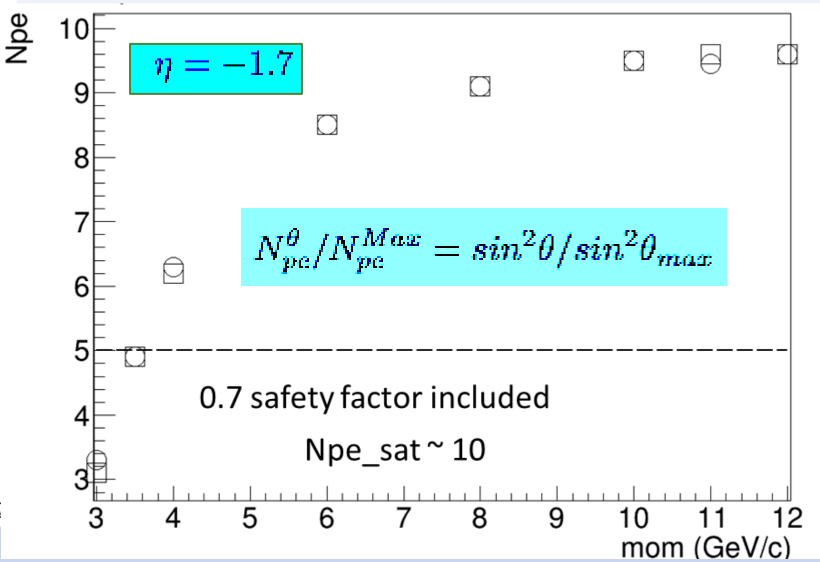
c) Additional safety factor of 0.7 on top of Photo Detection Efficiency provided by Hamamatsu.

Aerogel (3 cm) Example:
Absorption length->@ 400 nm 157 mm
Rayleigh->@ 400 nm ~40 mm
R_{index}->@ 400 nm 1.01933

Consistency found from RICH Cherenkov angle reconstruction

N_{pe} : open box Exp Open Circle Obtained from simulation

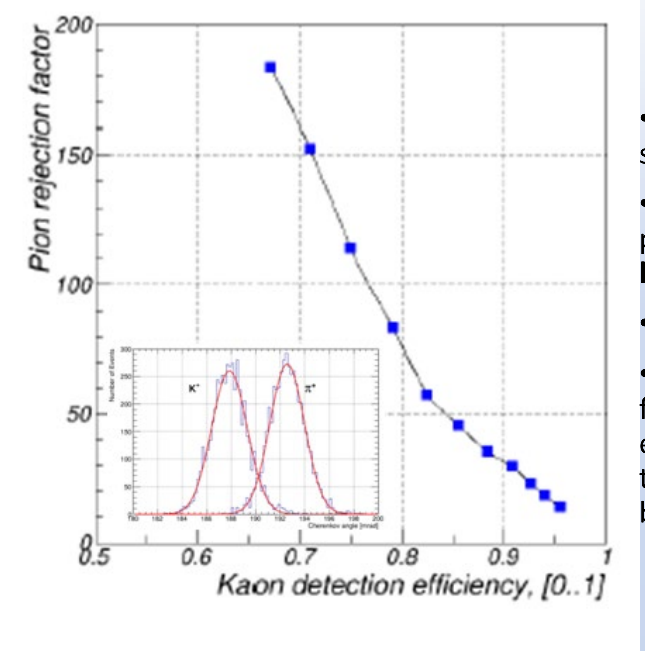




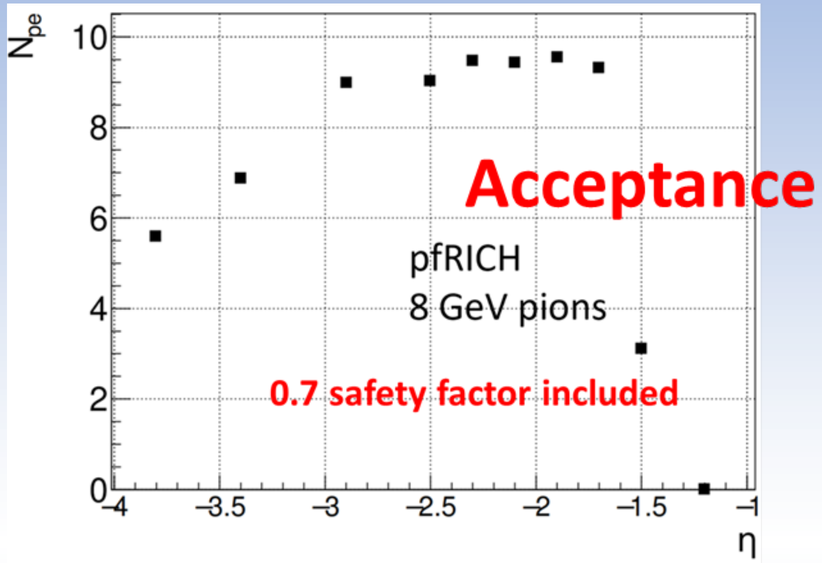
C_4F_{10} parameters:
NIMA 510(2003) 262

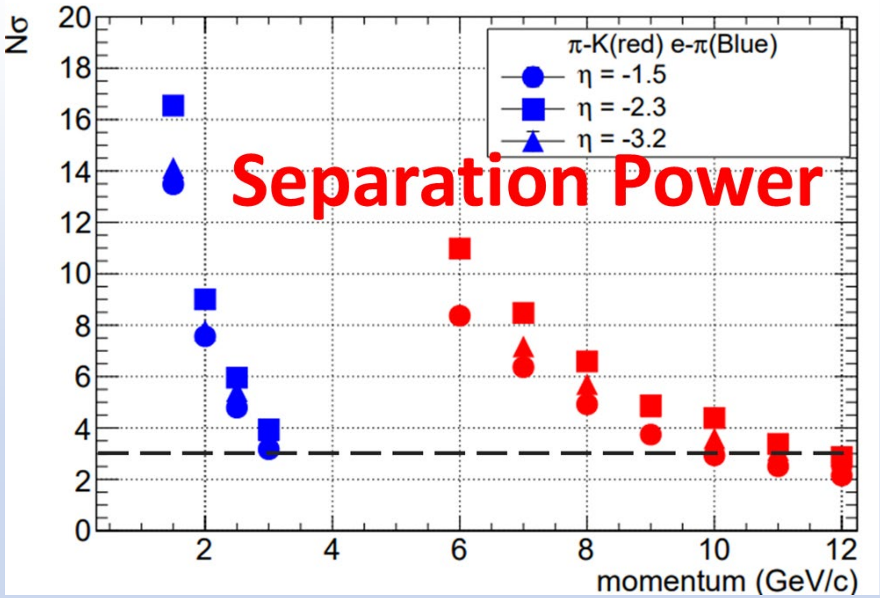
Performance plot

YR requirement achievable



- Expected pfRICH performance in π/K separation.
- **Top**: Reconstructed Cherenkov angle peaks for a **50:50 mix of 10 GeV/c pions and kaons**
- at **η = -1.7**.
- **Bottom**: Dependency of pion rejection factor as a function of kaon identification efficiency with the reconstructed track-by-track Cherenkov ring angle cut varying between 187.8 mrad and 190.2 mrad.

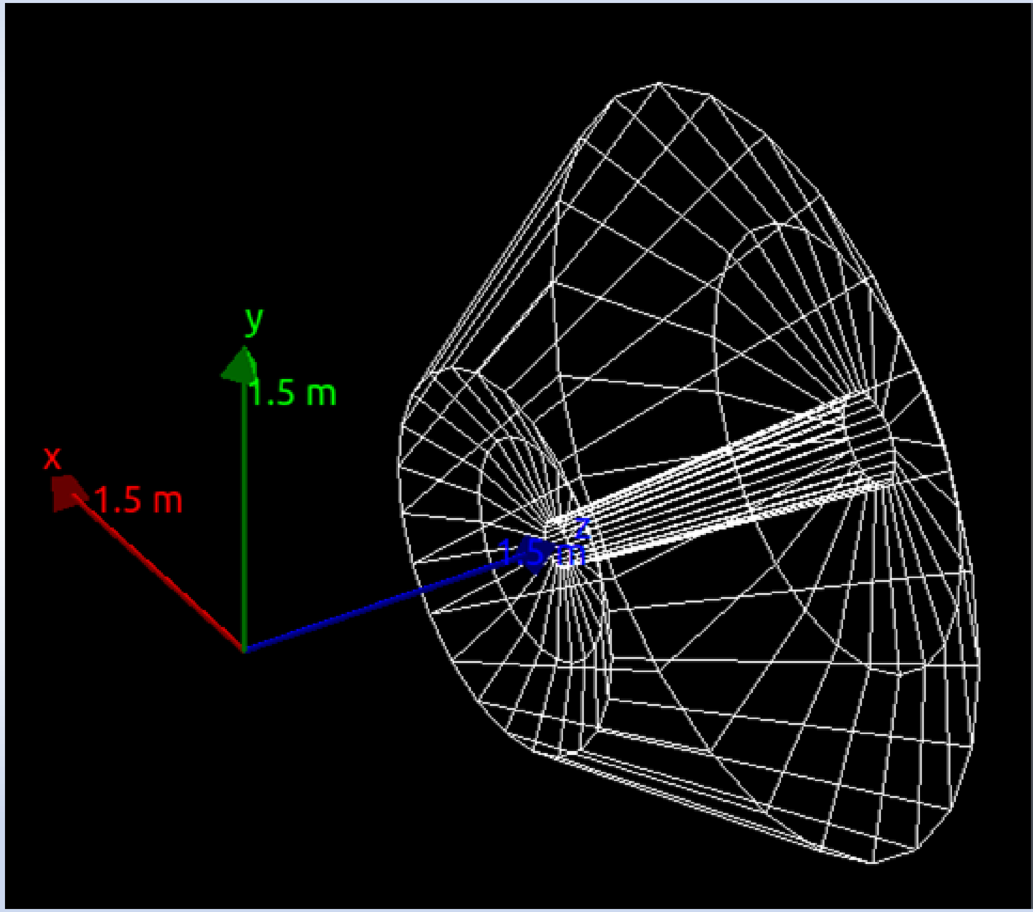




Yellow Report requirement: hadron PID in the electron-going endcap: better than 3σ π/K separation either (1) to 7 GeV/c (pp. 21) (2) up to 10 GeV/c [table 3.1] We consider the later as a reference!

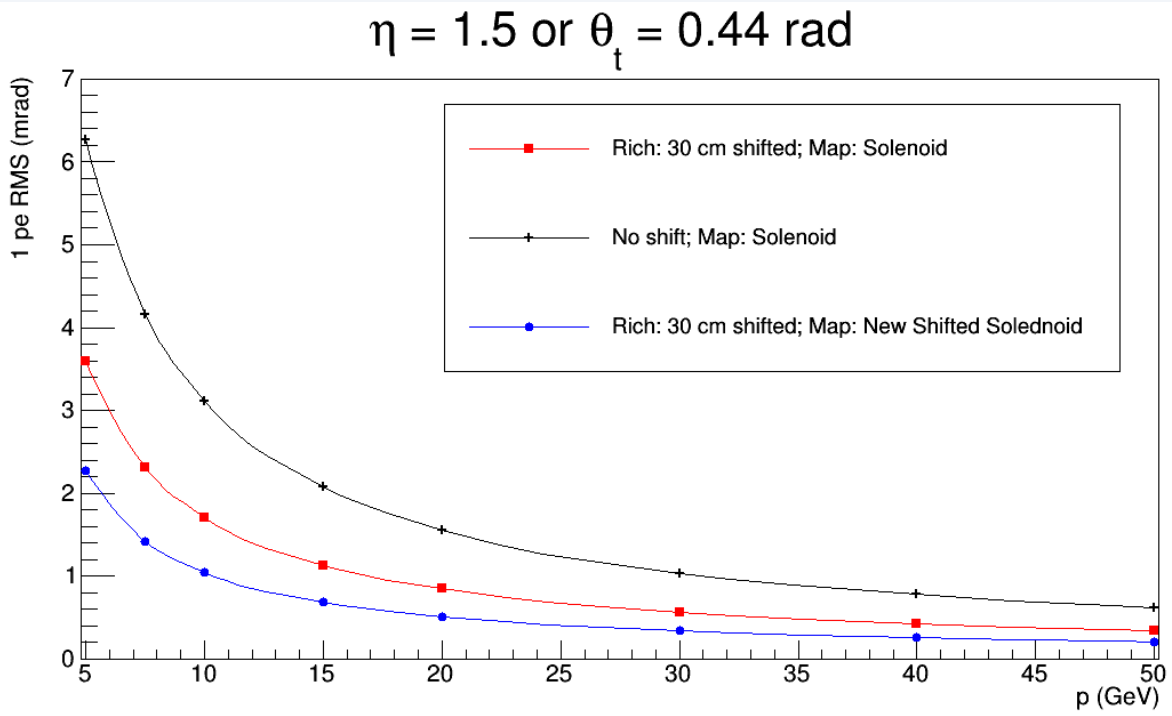
Standalone Geant4 model : Optimisation of position

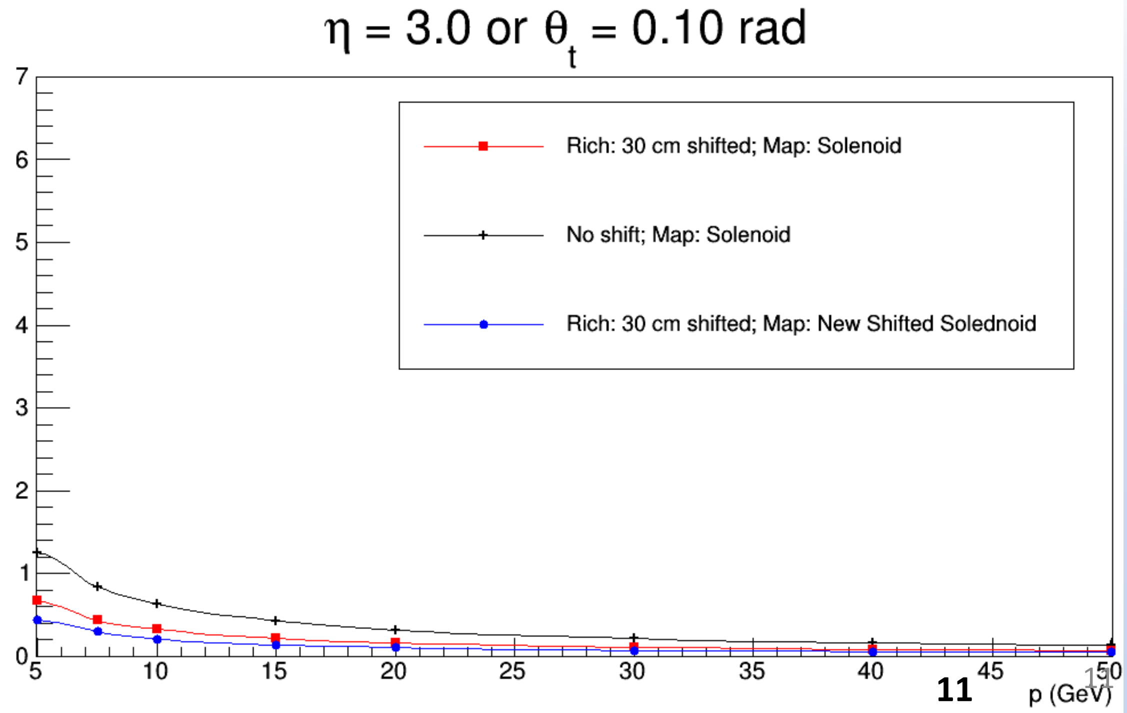
- **C2F6 refractive index for the radiator**
  - with chromatic dispersion
  - realistic C_2F_6 material
- **spherical mirror with perfect reflection**
  - R = 300 cm
- **spherical sensor surface**
  - R = 150 cm
- **basically an ideal RICH detector**
- **inverse ray-tracing reconstruction**
  - from HERMES papers
  - fix emission at mid-point of the radiator
  - assumes perfect tracking information
    - namely the actual track position / direction at the emission point



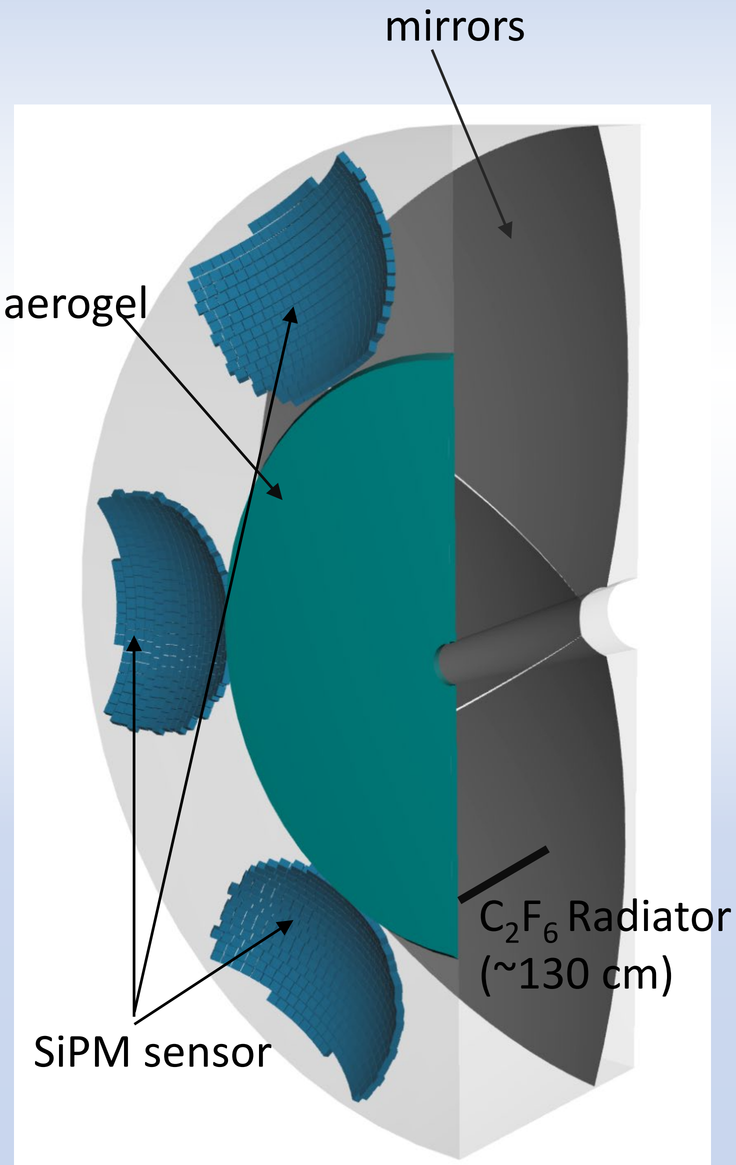
Stand alone Geant4 model : Optimization of dRICH position

- **C2F6 refractive index for the radiator**
  - with chromatic dispersion realistic C_2F_6 material
- **spherical mirror with perfect reflection**
  - R = 300 cm
- **spherical sensor surface**
  - R = 150 cm
- **inverse ray-tracing reconstruction**
  - from HERMES papers fix emission at mid-point of the radiator
  - assumes perfect tracking information: namely the actual track position / direction at the emission point





Geometry of dRICH

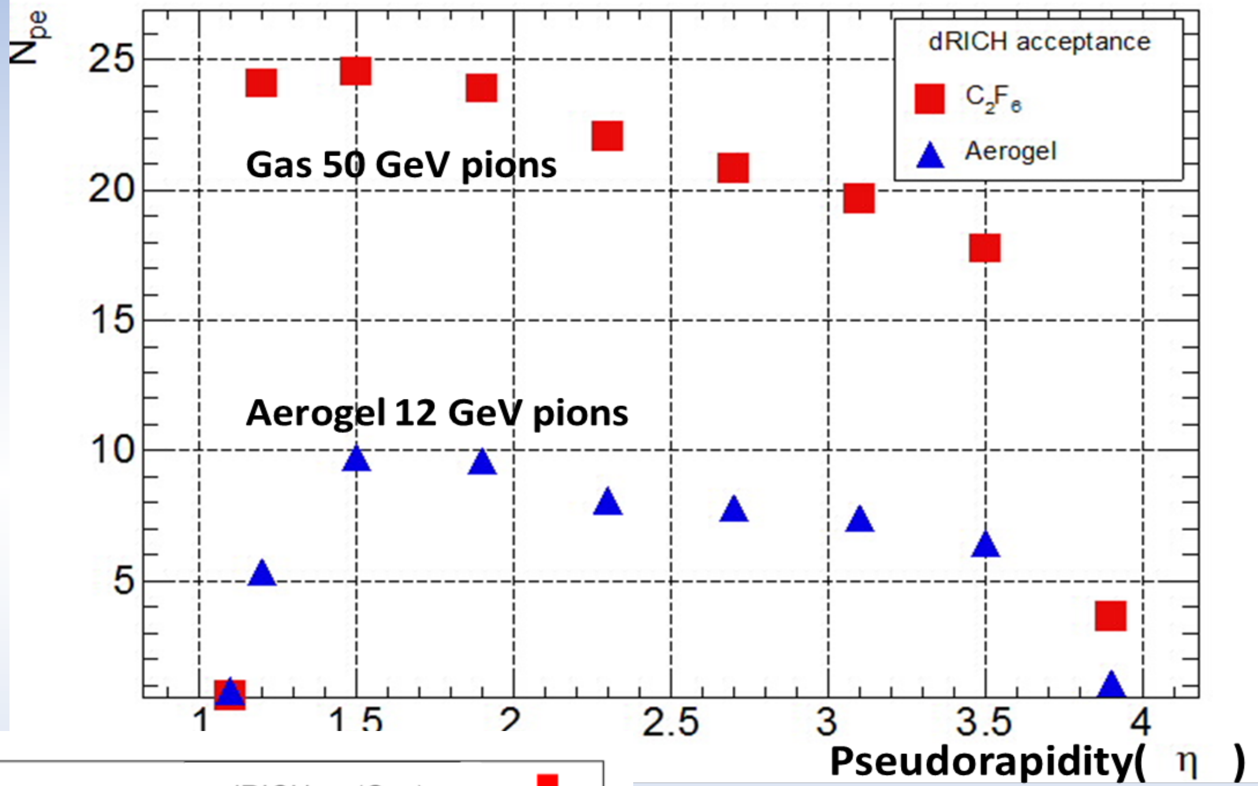


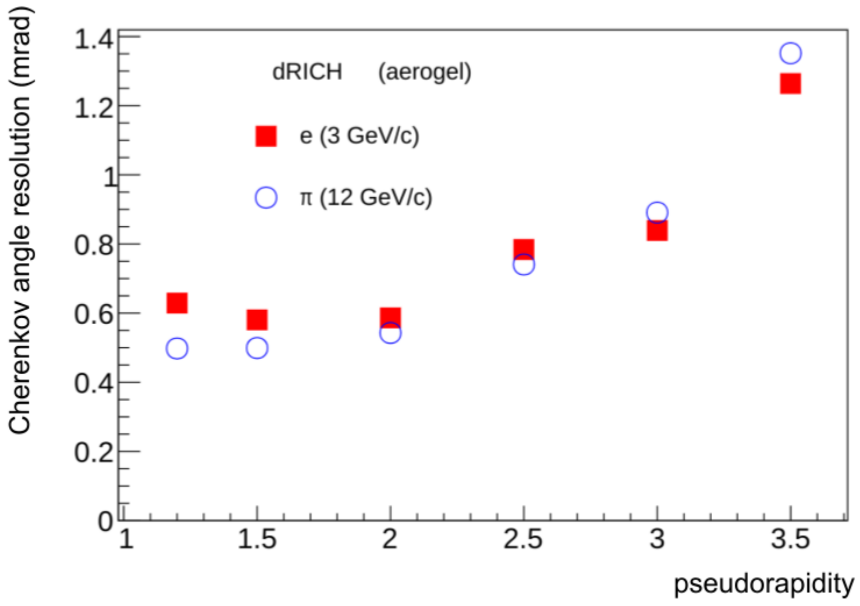
1. 140 cm of total length. Occupying space +190 cm to +330 cm from the IP.
2. Detector will have six 60° sectors, each equipped with its own spherical mirror segment and a sensor plane.
3. Sensor's characteristics are like pfRICH.
4. Focusing mirrors → 6 individual elements (single mirror configuration)
5. More complicated beam pipe geometry.
6. C_2F_6 radiator. Fully parameterized (The Journal of Chemical Physics 73.2 (1980), p. 990., NIMA 354.2 (1995), pp. 417). Conservative absorption length (10 m).
7. Aerogel properties are like pfRICH. → 4 cm thick

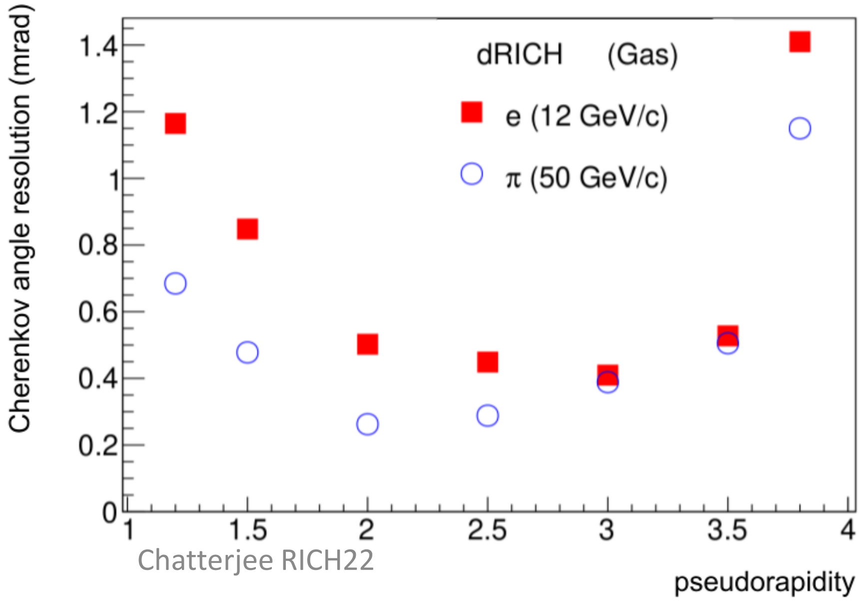
The sensors are positioned on a sphere, with a square tiling algorithm. The spherical mirrors are parameterized by three variables: the z position of the back plane, which is the maximum z the spherical mirror will reach, along with two focus tune parameters f_x and f_z.

Different placement geometries of the sensors, as well as a dual or multi-mirror configuration are under consideration → IMPROVE OPTIMIZATION!

dRICH acceptance and resolution as a function of pseudo-rapidity

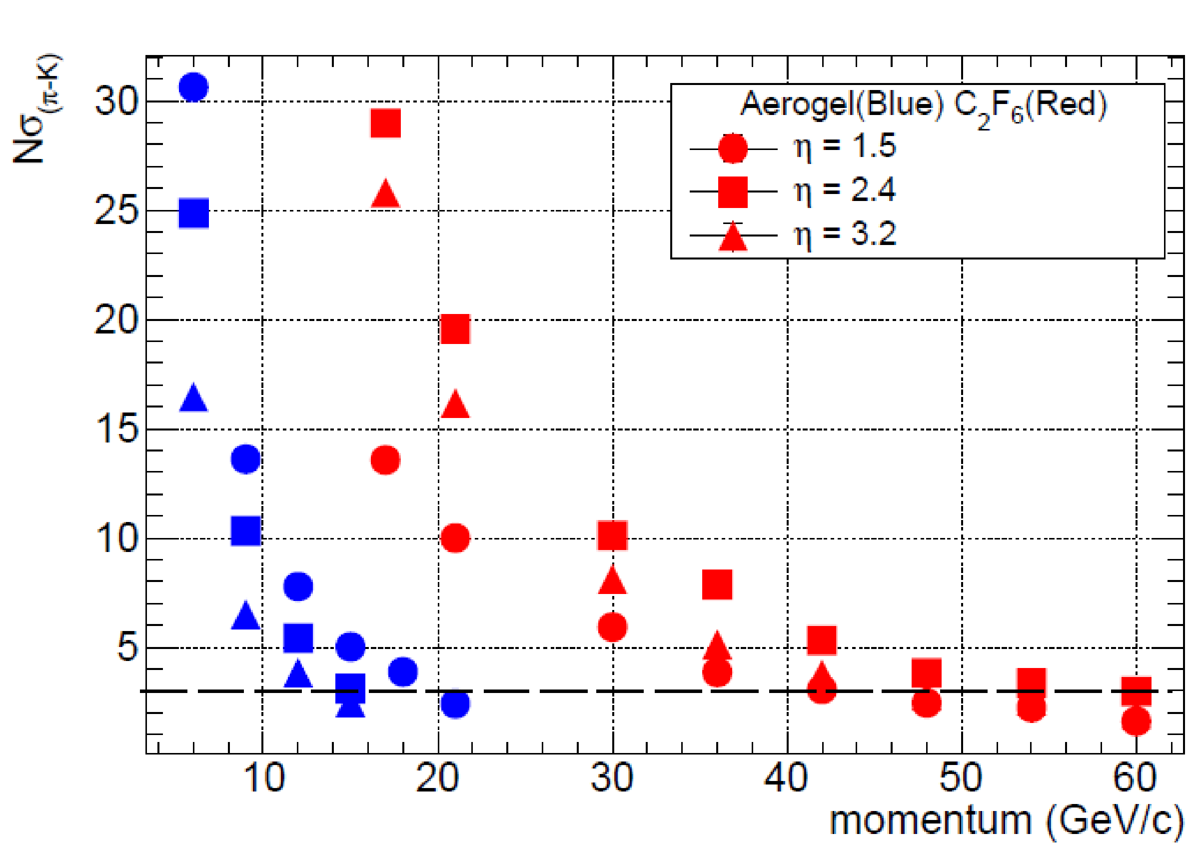






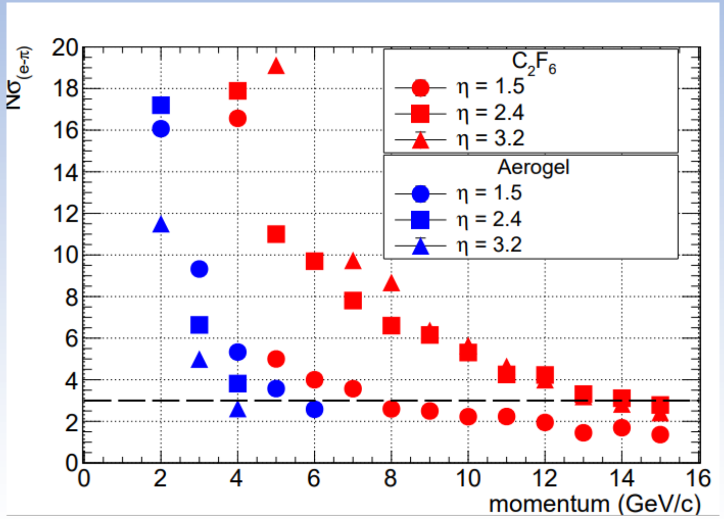
YR requirement: acceptance for the dRICH is 1.0 ≤ η ≤ 3.5. These reference numbers were taken as a guidance for the ATHENA design.

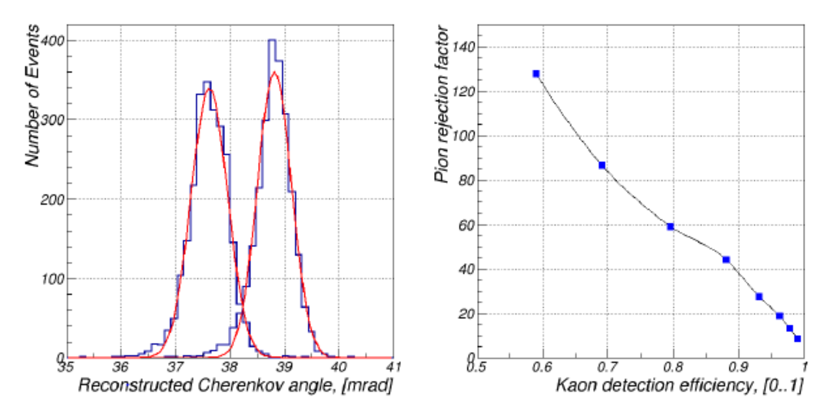
Performance dRICH



YR prescription achievable.

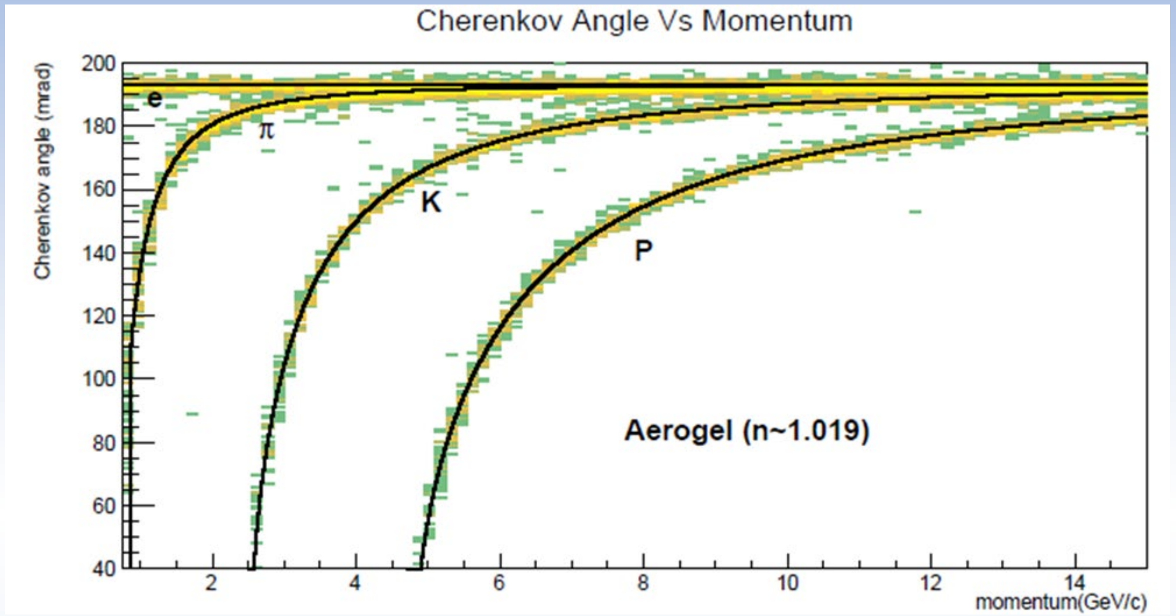
Translated to DELPHES to apply PID cut!

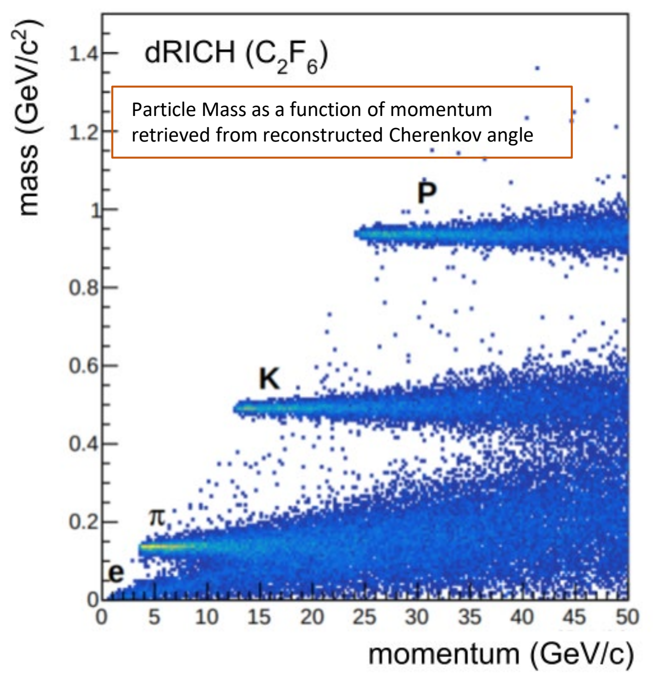


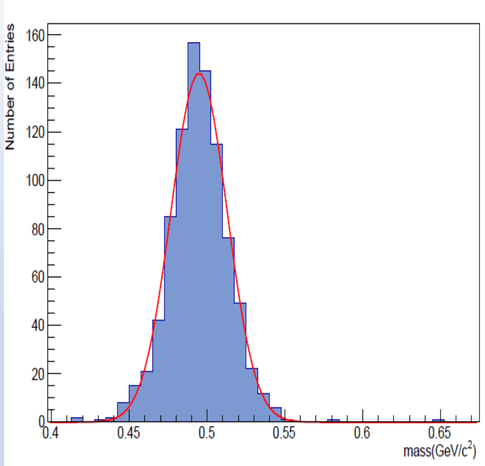


- Left: reconstructed Cherenkov angle peaks for a 50:50 mix of 50 GeV/c kaon and pion tracks at η = 2.4 are ∼3σ apart (C2F6 radiator). Right: dependency of pion rejection factor on kaon detection efficiency with the selection cu varying between 37.6 mrad and 38.4 mrad applied to the left hand side plot.

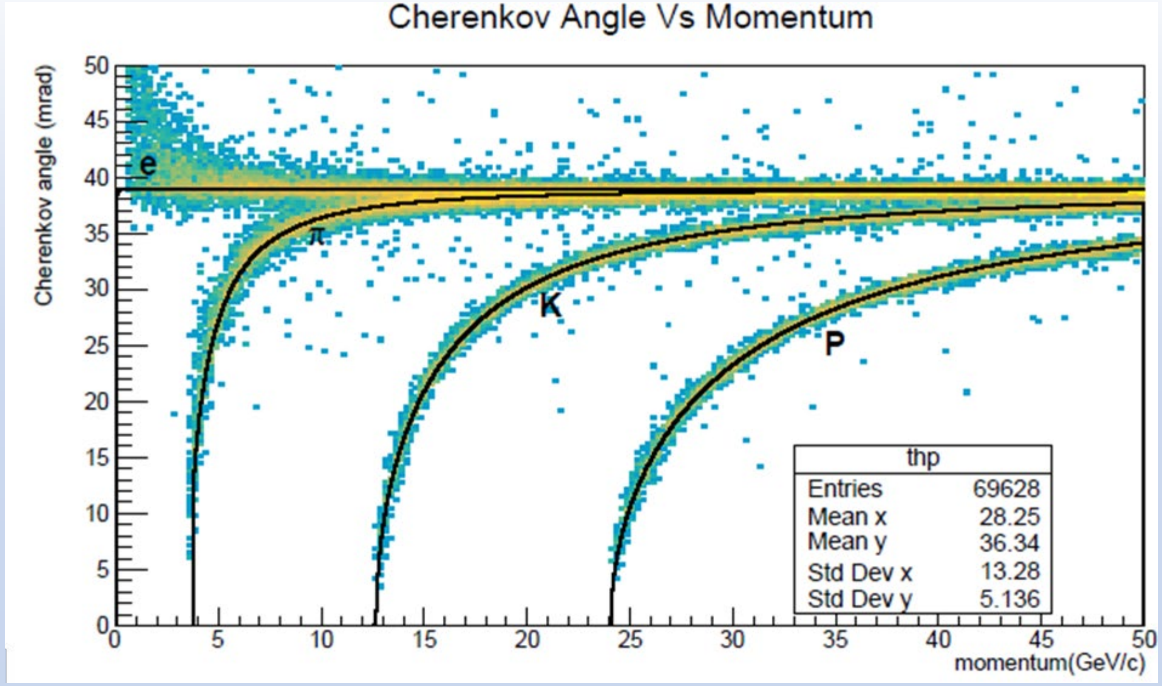
ATHENA dRICH reconstructed Cherenkov angle and mass







Reconstructed Kaon mass from Cherenkov angle.
~495 MeV/c^2



ECCE Performance plot

arXiv:2209.02580v1 [physics.ins-det] 6 Sep 2022

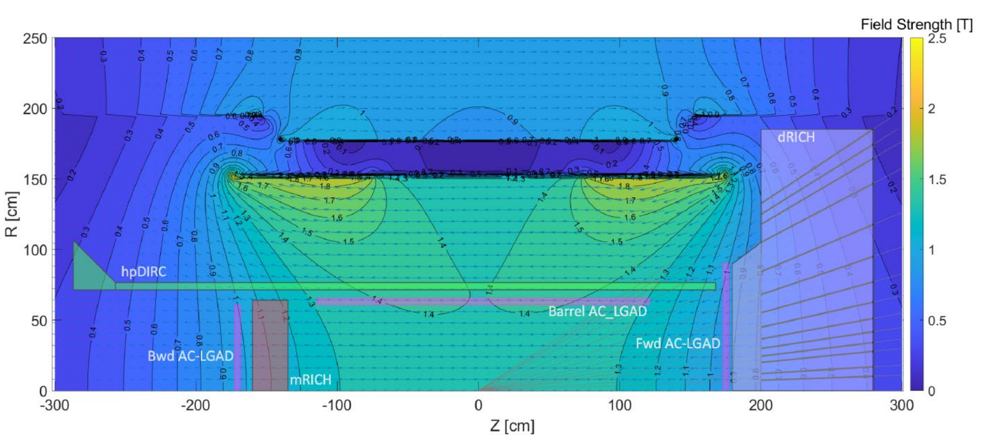


Figure 13: ECCE magnetic field map with the PID detector envelopes overlaid.

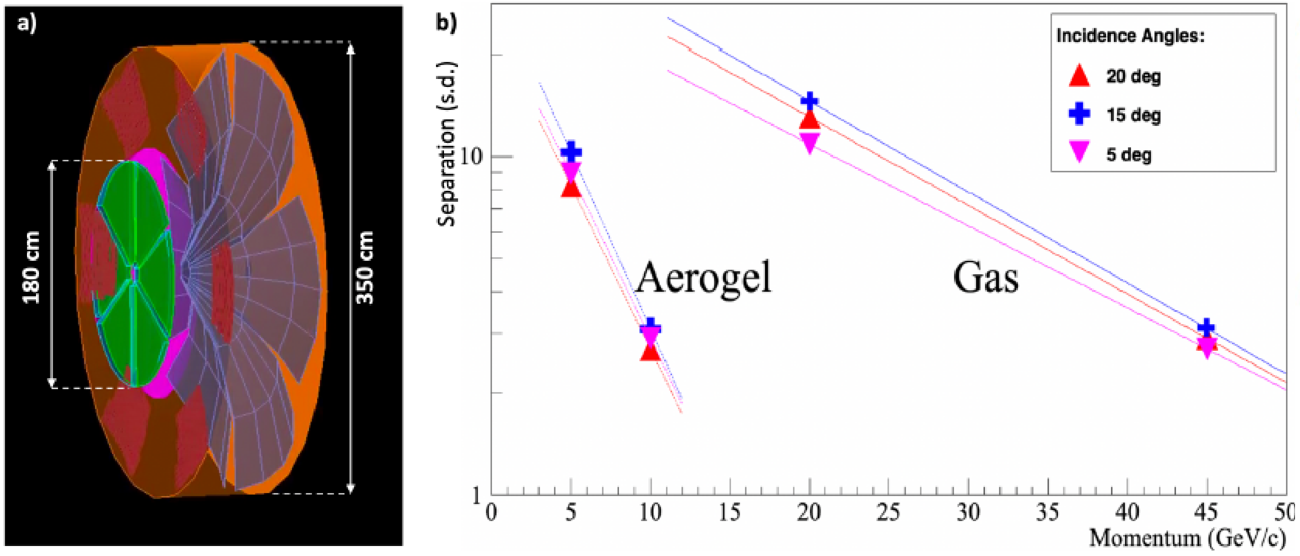
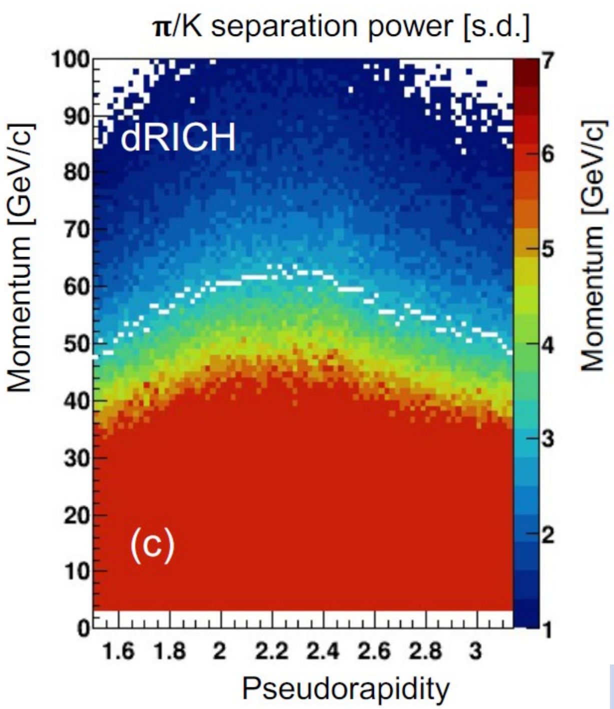
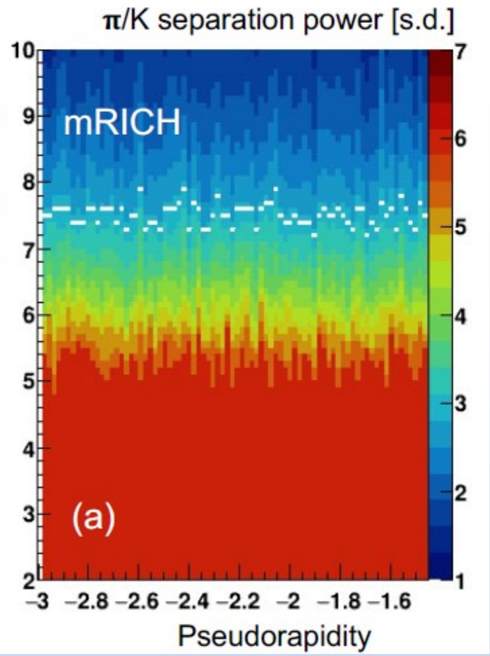


Figure 16: dRICH geometry (a) and expected performance (b) from the ECCE GEANT4 simulation. The K/π separation power is shown as a function of momentum for a simplified dRICH geometry (flat detector plane).





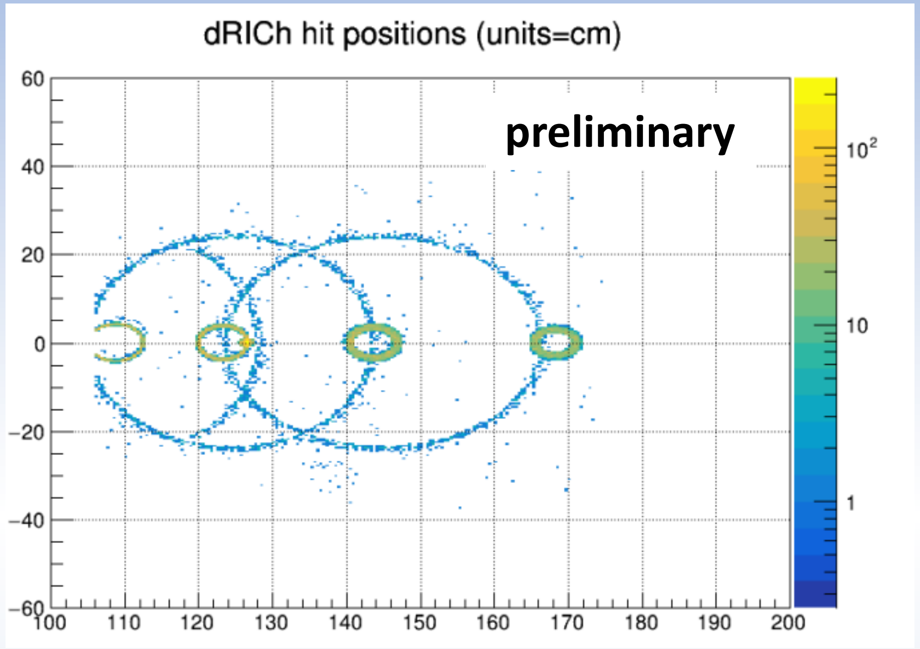
YR requirement achieved

EPIC detector collaboration

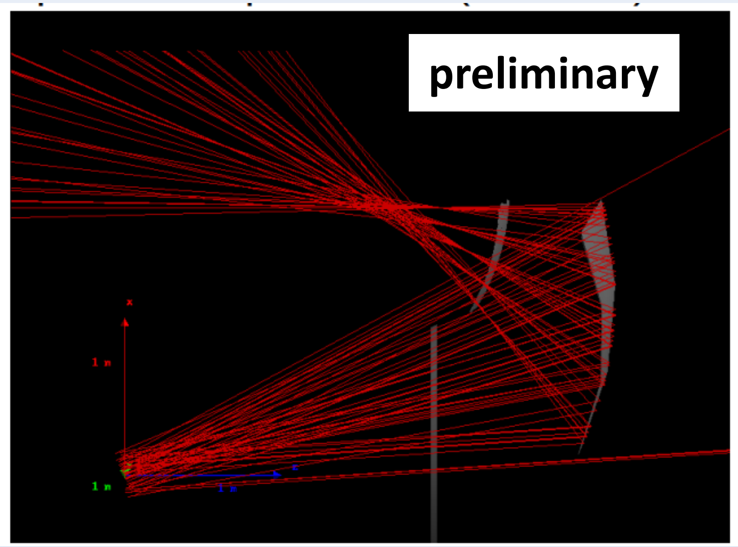
Evaluating the proposals, the detector advisory committee stated both ECCE and ATHENA was capable to deliver full physics program of EIC.

The RICHes employed in both the detectors demonstrated yellow report requirements can be achieved, based on independent simulation studies using different software stacks.

DPAP advised 1.5T magnetic field to be chosen as the base line detector for detector-1. A new collaboration, EPIC, is formed. EPIC foresees a 1.7 T magnet.



Example of EPIC dRICH sensor hit positions



- The software chain will most likely be based on DD4Hep, reconstruction framework is still under discussion.
- Already several upstream changes have been made in and refactoring of the downstream codes have been performed. Full software chain is working.
- Optimization of the dRICH geometry, optics tuning is ongoing within the framework.

Conclusions

Thank you for your kind attention

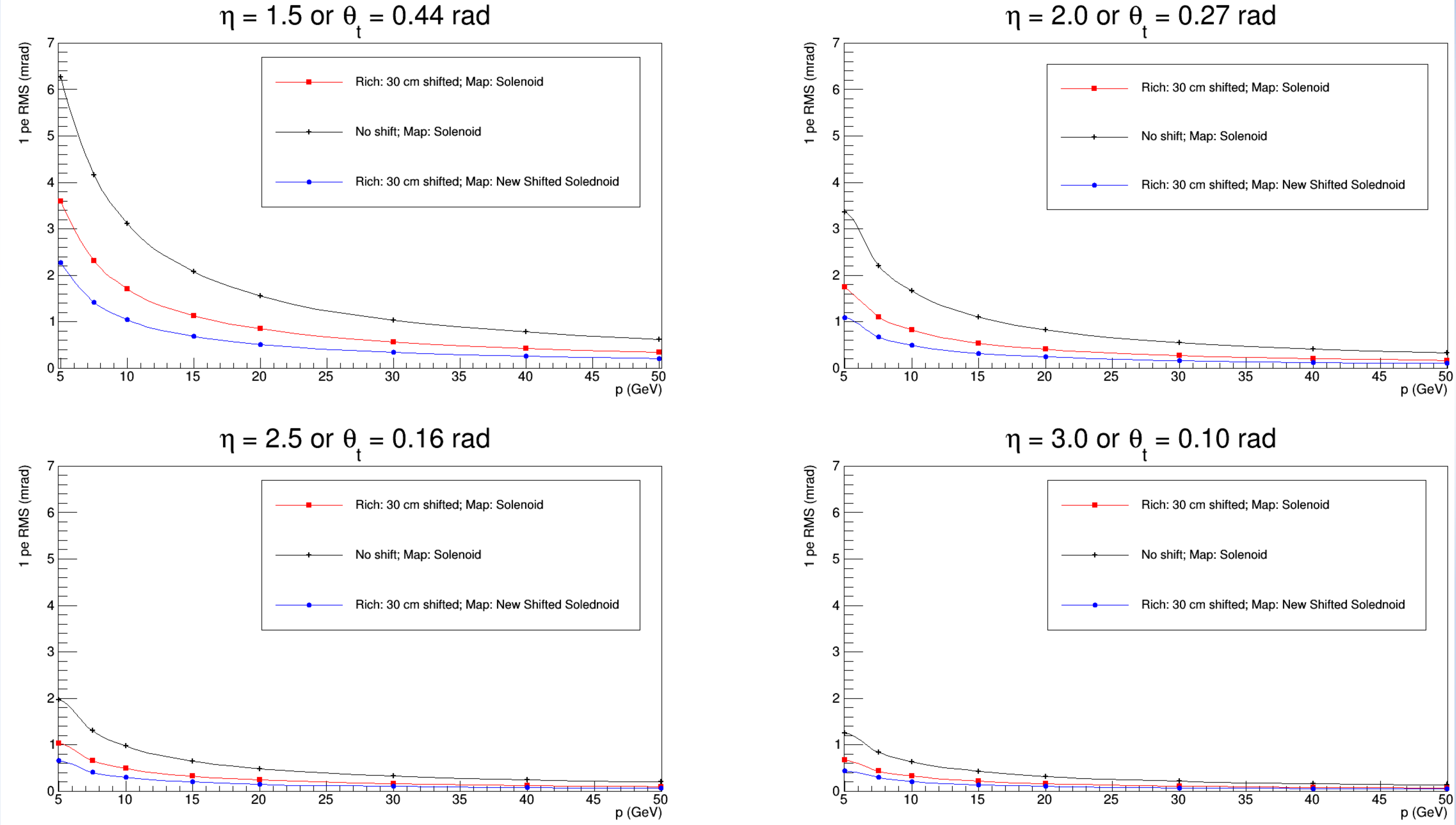
- The simulation studies reported for the dRICH has been adopted from the geometry and principle prescribed in EIC yellow report and had been integrated to ATHENA software framework.
- The Yellow Report Requirement has been achieved in the first simulation studies by both ATHENA and ECCE.
- An optimized software foresees to deliver two lines of tasks:
  A) The Particle Identification
  B) The RICH characterization parameters namely Cherenkov angle resolutions, number of detected photons etc.
- Following Detector Advisory Panel advice 1.5 T magnet design chosen as reference detector. EIC community is moving toward a new collaboration, EPIC which employs 1.7 T magnetic field.
- EPIC dRICH is under ongoing optimization. Optical and geometrical tuning and dRICH performance studies are ongoing in DD4Hep framework.
- The software chain has adopted all the upstream changes. Robust PID algorithm and possibility to move towards sophisticated PID algorithms will be implemented in near future.

Backups

Inverse Ray Tracing: implementation

Repository (as of Dec 15, 2021) : https://eicweb.phy.anl.gov/EIC/irt/-/tree/irt-init-v02

- A compact C++ library
  - Can be used in a standalone GEANT code as well as in the ATHENA environment
  - Optical geometry ROOT class instance is created *in the same code, which creates RICH detector* (therefore simulation-vs-reconstruction consistency is guaranteed)
  - Persistency model: optical setup dump in ROOT format
  - Newton-Gauss iterative solver for optical path defined by arbitrary sequence of refractive and reflective surfaces in 3D (presently flat and spherical boundaries only)
  - Absorbtion length accounting (azimuthally-asymmetric shift of emission point)
  - Emission angle uncertainly calculation (it does depend on the azimuthal angle!)
  - A wrapper for sampling along the charged particle trajectory (magnetic field case, etc.)

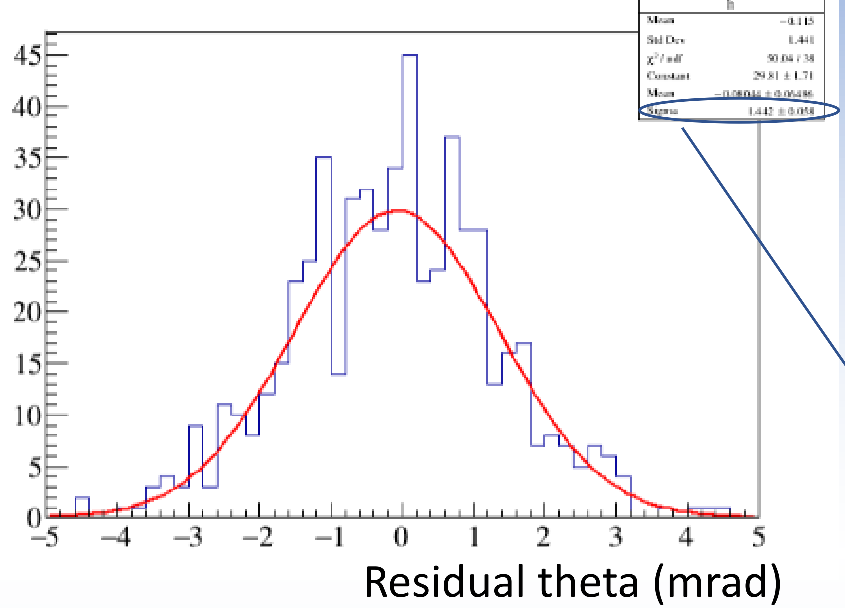

η = 1.5 or θt = 0.44 rad
η = 2.0 or θt = 0.27 rad
η = 2.5 or θt = 0.16 rad
η = 3.0 or θt = 0.10 rad
1 pe RMS (mrad)
p (GeV)
Rich: 30 cm shifted; Map: Solenoid
No shift; Map: Solenoid
Rich: 30 cm shifted; Map: New Shifted Solednoid

Inverse Ray Tracing: machinery

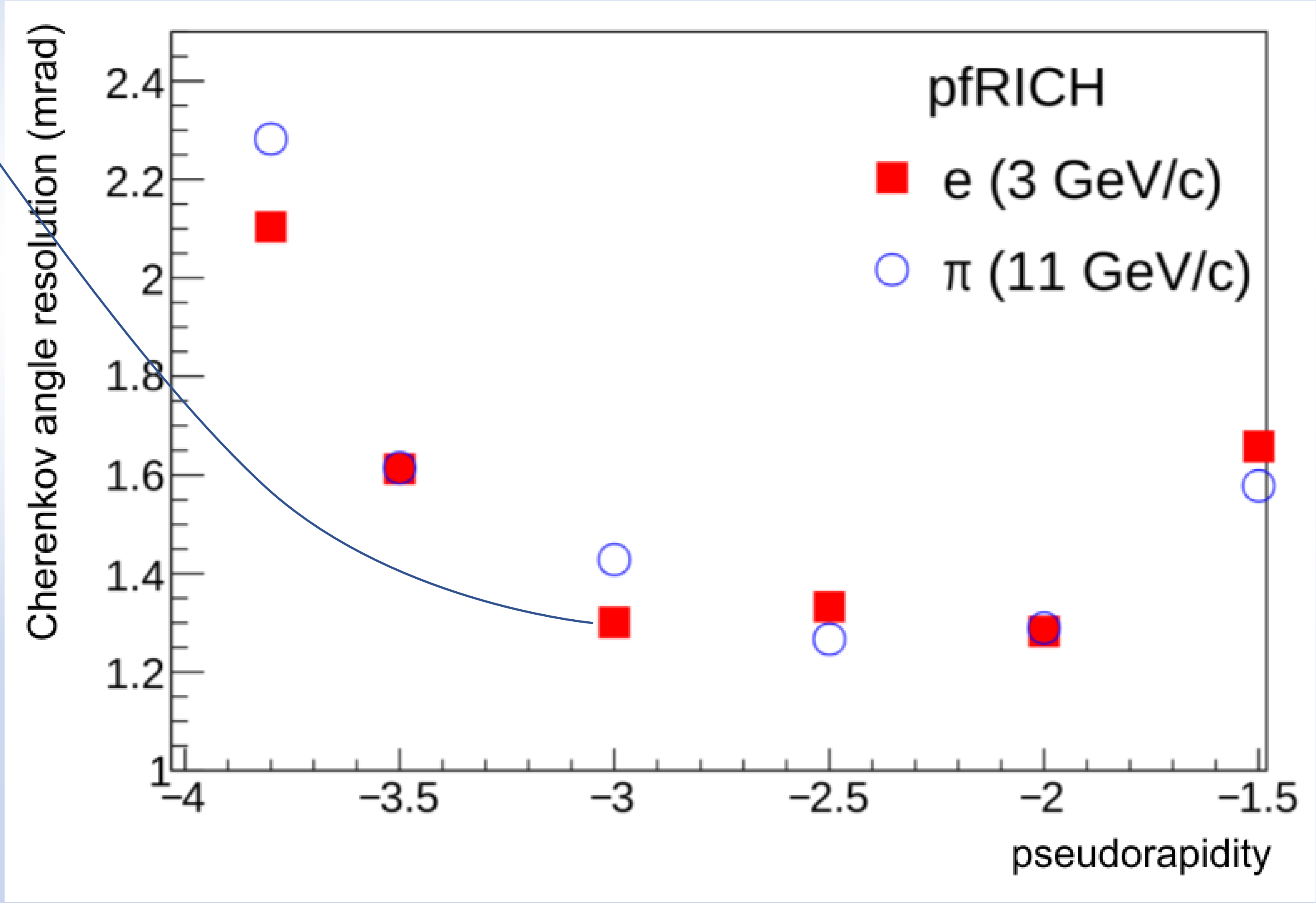
- In case of a single (unknown!) reflection point the task is reduced to a 2D case, a quartic equation follows, can be solved iteratively (e.g. using the Newton method)
- The math can be extended to a case with a second (flat!) mirror
- For dRICH the refraction on aerogel boundary can be accounted in a more or less consistent way a posteriori

- More complicated cases (tilted aerogel tiles, acrylic layer, 2-d spherical mirror) require generalization into 3D space
- Some sort of bookkeeping is required when
  - a single charged particle produces Cherenkov photons detected in different sectors
  - a pair of [emission, detection] 3D points allows for more than one optical path (like in a dual mirror configuration)
- Very important: GEANT geometry should be consistent with the optical setup!

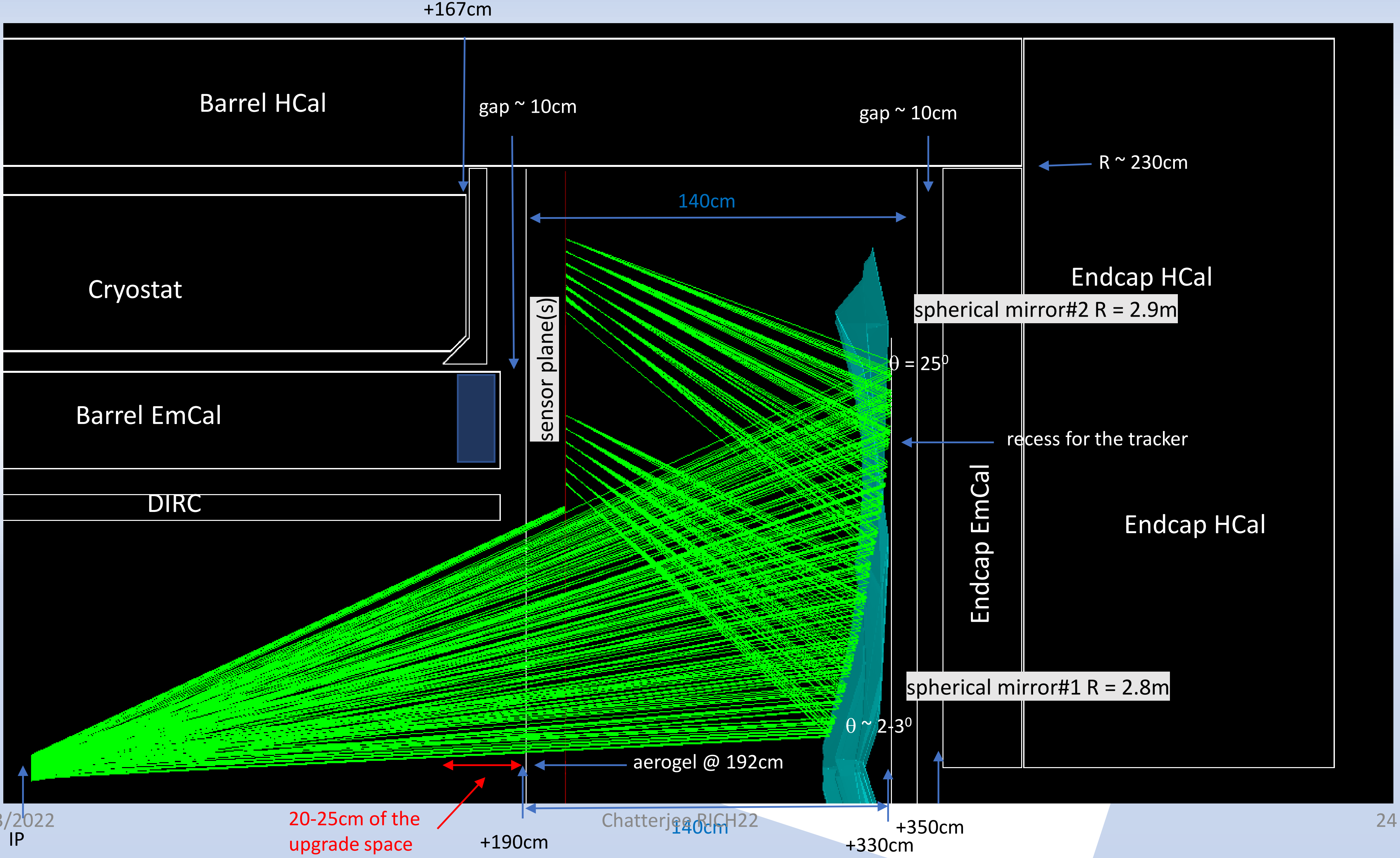
Dependence of ring resolution with pseudo rapidity



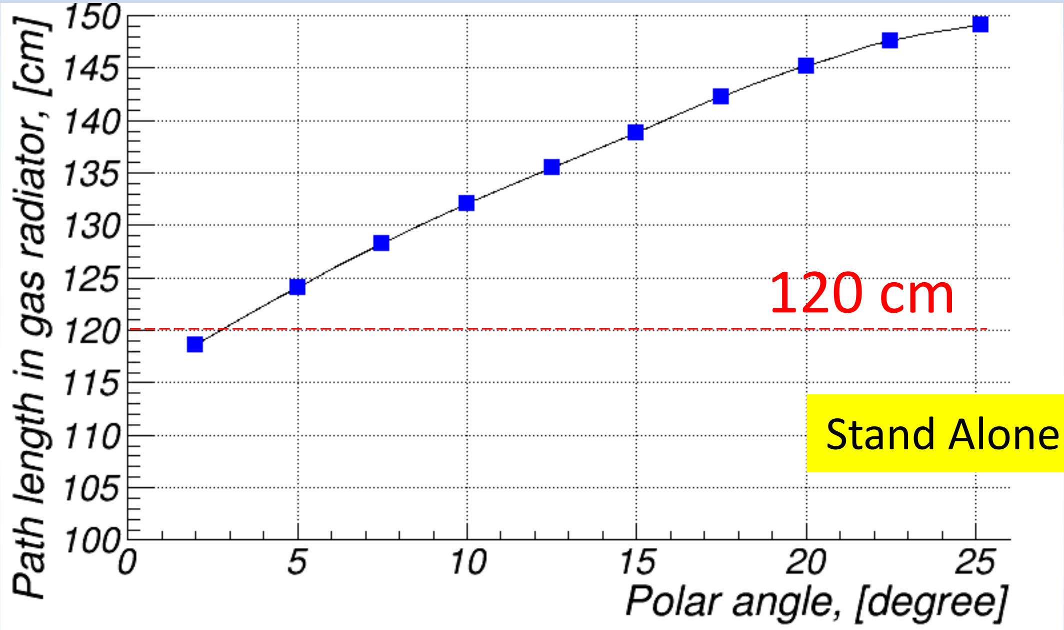
Track level resolution:
pixel size, emission point uncertainty, and chromaticity to the track-level
Cherenkov photon angle resolution were taken together to estimate ~1.5 mrad.



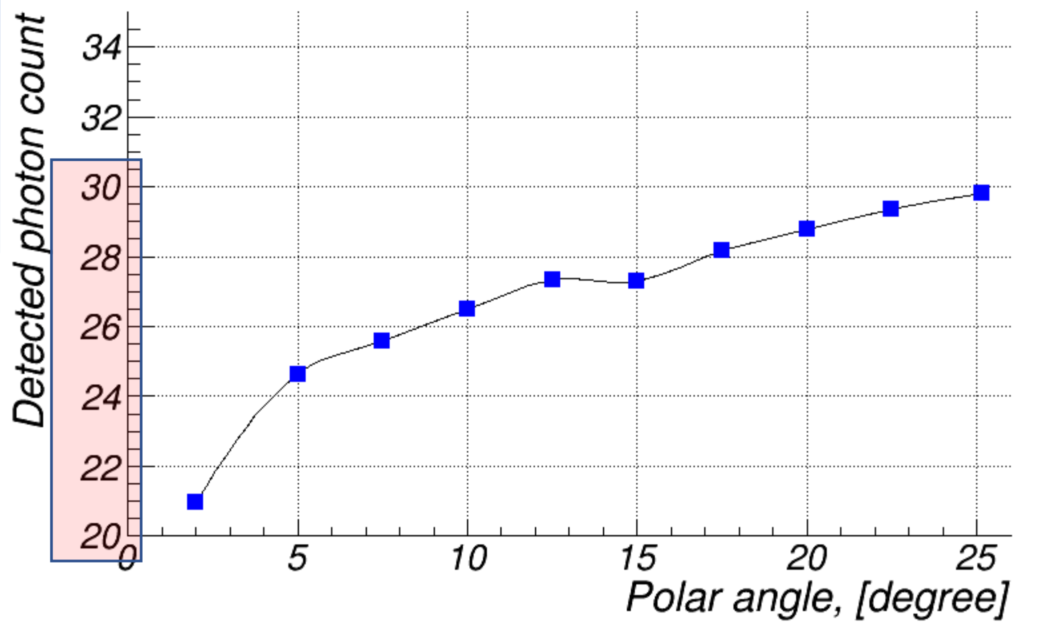
Inverse Ray Tracing: application (standalone GEANT4)

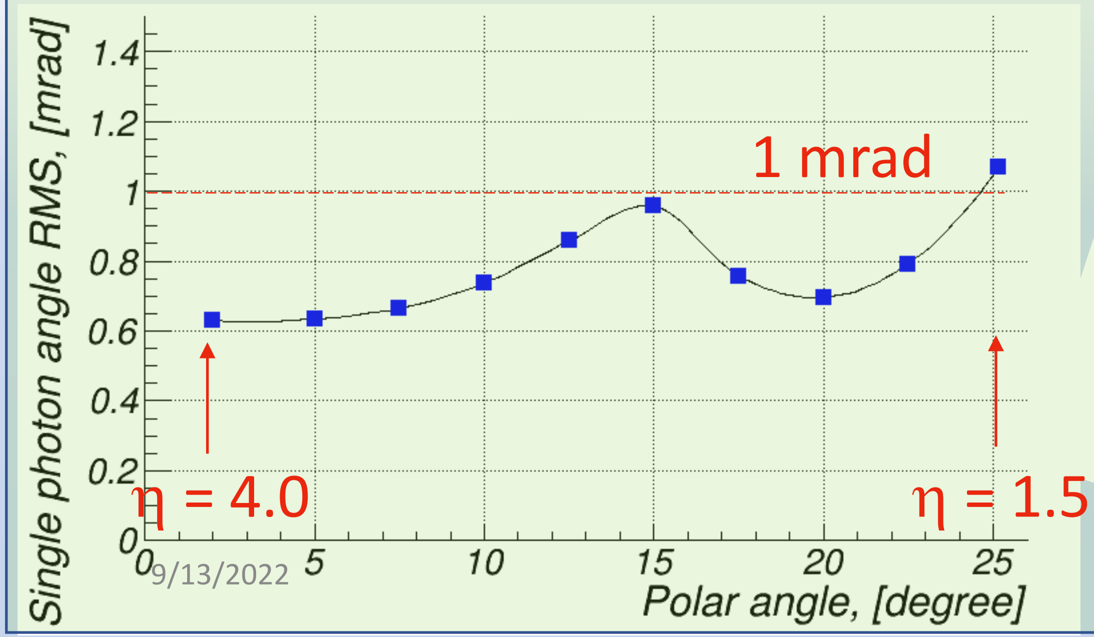


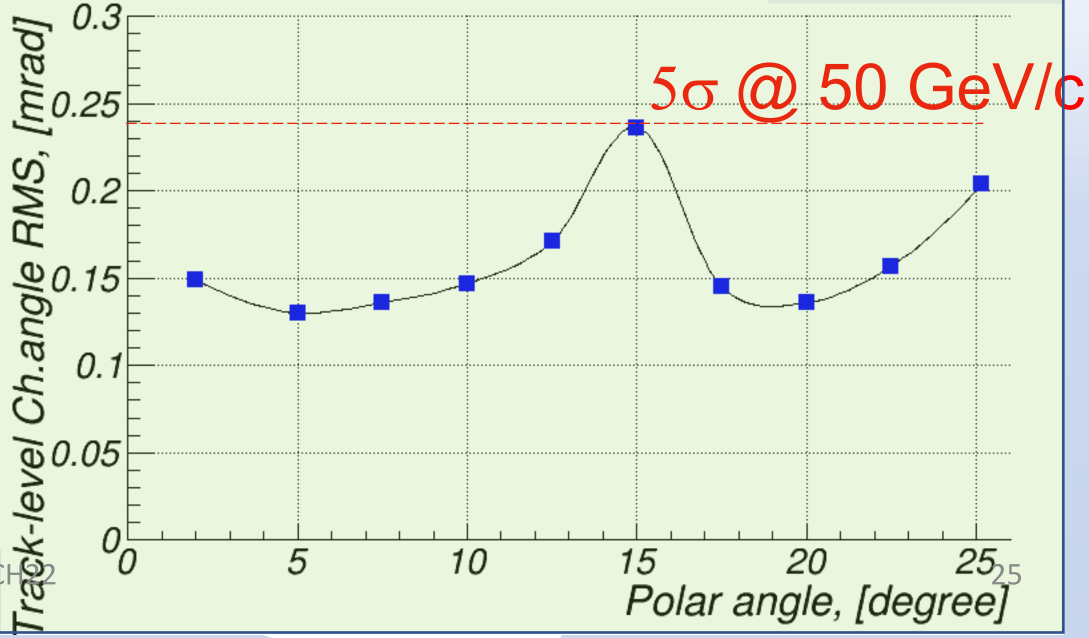
Inverse Ray Tracing: performance plots (C_2F_6, 50 GeV/c π^+)



Stand Alone Geant4







EPIC dRICH geometry compared to ATHENA

All Units are in cm!

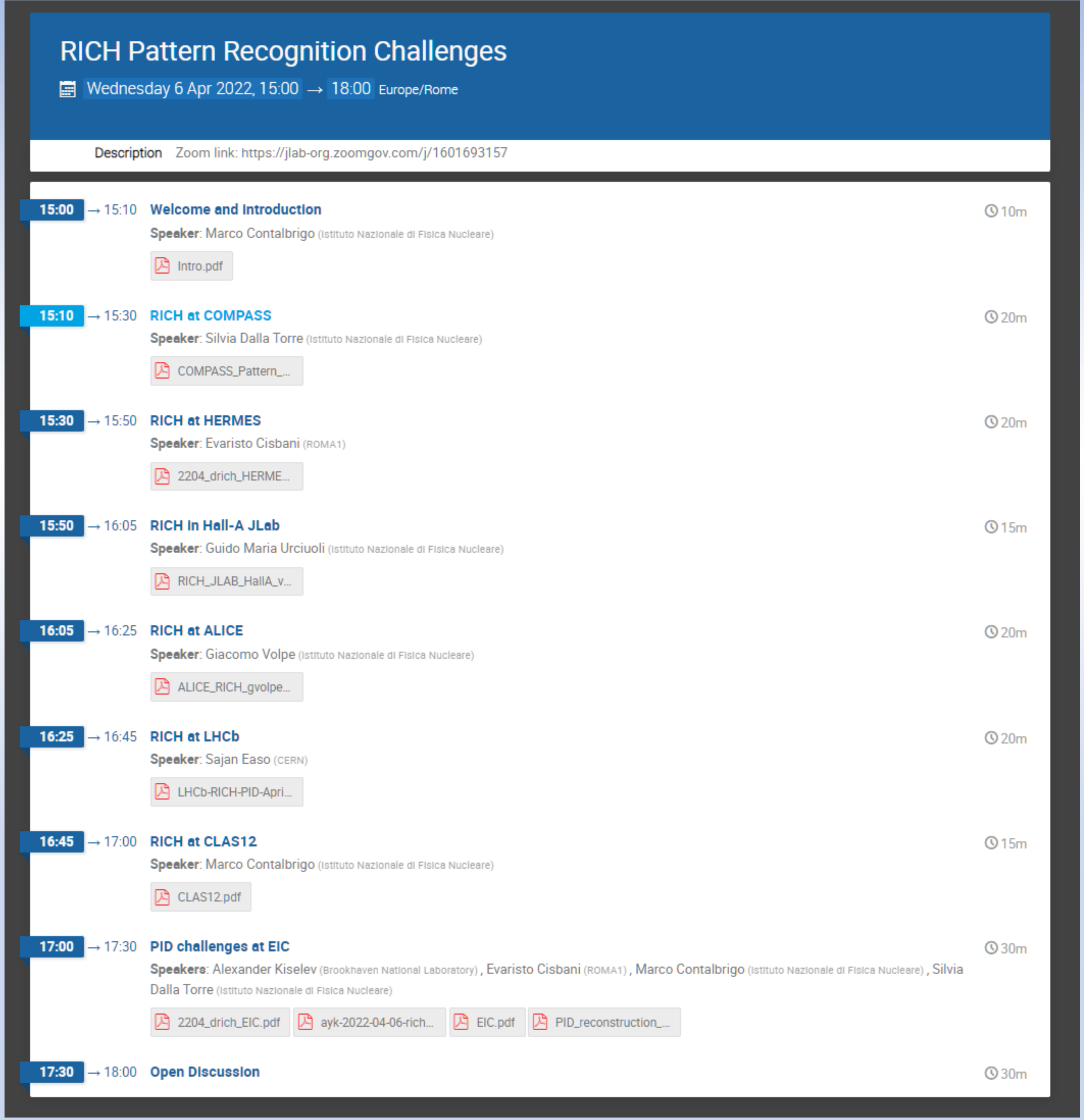
ATHENA

DRICH_Length	=	140.000
DRICH_SnoutLength	=	4.000
DRICH_SnoutSlope	=	0.667
DRICH_aerogel_thickness	=	4.000
DRICH_create_irt_file	=	0.000
DRICH_debug_mirror	=	0.000
DRICH_debug_optics	=	0.000
DRICH_debug_sensors	=	0.000
DRICH_num_px	=	8.000
DRICH_rmax0	=	126.667
DRICH_rmax1	=	129.333
DRICH_rmax2	=	220.000
DRICH_rmin0	=	8.273
DRICH_rmin1	=	16.062
DRICH_sensor_pixel_pitch	=	0.320
DRICH_sensor_pixel_size	=	0.300
DRICH_sensor_size	=	2.580
DRICH_sensor_thickness	=	0.050
DRICH_wall_thickness	=	0.500
DRICH_window_thickness	=	0.100
DRICH_zmin	=	190.000

EPIC (current version after increasing the radiator length of ecce)

DRICH_Length	=	120.000
DRICH_SnoutLength	=	20.000
DRICH_SnoutSlope	=	0.487
DRICH_aerogel_thickness	=	4.000
DRICH_create_irt_file	=	0.000
DRICH_debug_mirror	=	0.000
DRICH_debug_optics	=	0.000
DRICH_debug_sensors	=	0.000
DRICH_num_px	=	8.000
DRICH_rmax0	=	95.000
DRICH_rmax1	=	104.744
DRICH_rmax2	=	180.000
DRICH_rmin0	=	8.490
DRICH_rmin1	=	15.332
DRICH_sensor_pixel_pitch	=	0.320
DRICH_sensor_pixel_size	=	0.300
DRICH_sensor_size	=	2.580
DRICH_sensor_thickness	=	0.050
DRICH_wall_thickness	=	0.500
DRICH_window_thickness	=	0.100
DRICH_zmax	=	315.000
DRICH_zmin	=	195.000

Pattern Recognition challenge at EIC



RICH Pattern Recognition Challenges

Wednesday 6 Apr 2022, 15:00 → 18:00 Europe/Rome

Description Zoom link: https://jlab-org.zoomgov.com/j/1601693157

15:00 → 15:10 **Welcome and Introduction** 10m
Speaker: Marco Contalbrigo (Istituto Nazionale di Fisica Nucleare)
Intro.pdf

15:10 → 15:30 **RICH at COMPASS** 20m
Speaker: Silvia Dalla Torre (Istituto Nazionale di Fisica Nucleare)
COMPASS_Pattern_...

15:30 → 15:50 **RICH at HERMES** 20m
Speaker: Evaristo Cisbani (ROMA1)
2204_drich_HERME...

15:50 → 16:05 **RICH in Hall-A JLab** 15m
Speaker: Guido Maria Urciuoli (Istituto Nazionale di Fisica Nucleare)
RICH_JLAB_HallA_v...

16:05 → 16:25 **RICH at ALICE** 20m
Speaker: Giacomo Volpe (Istituto Nazionale di Fisica Nucleare)
ALICE_RICH_gvolpe...

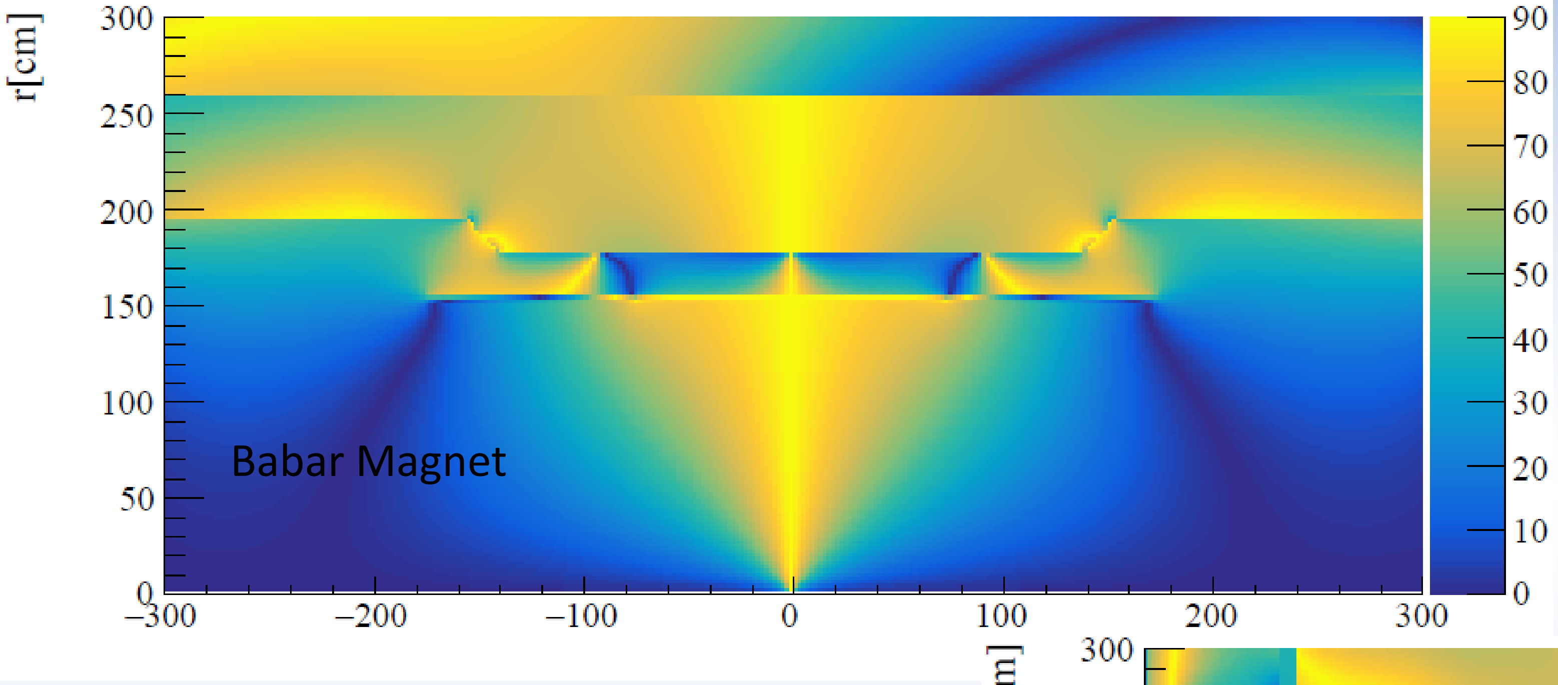
16:25 → 16:45 **RICH at LHCb** 20m
Speaker: Sajan Easo (CERN)
LHCb-RICH-PID-Apri...

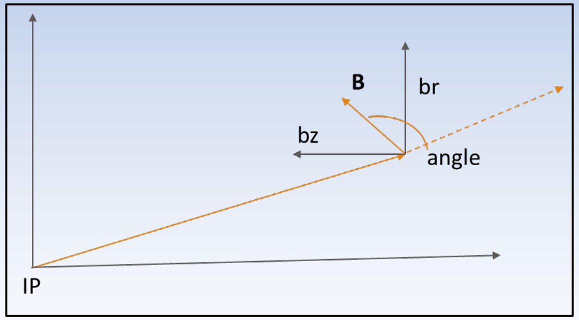
16:45 → 17:00 **RICH at CLAS12** 15m
Speaker: Marco Contalbrigo (Istituto Nazionale di Fisica Nucleare)
CLAS12.pdf

17:00 → 17:30 **PID challenges at EIC** 30m
Speakers: Alexander Kiselev (Brookhaven National Laboratory), Evaristo Cisbani (ROMA1), Marco Contalbrigo (Istituto Nazionale di Fisica Nucleare), Silvia Dalla Torre (Istituto Nazionale di Fisica Nucleare)
2204_drich_EIC.pdf ayk-2022-04-06-rich... EIC.pdf PID_reconstruction_...

17:30 → 18:00 **Open Discussion** 30m

Choice of PID algorithm is still an open question.
Different experiences are discussed. More to come ...





No apparent large difference in the projective nature of the field lines

ATHENA Magnet