Particle Identification by the forward and backward RICHes of ATHENA proto-collaboration at EIC

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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

INFN

Istituto Nazionale di Fisica Nucleare

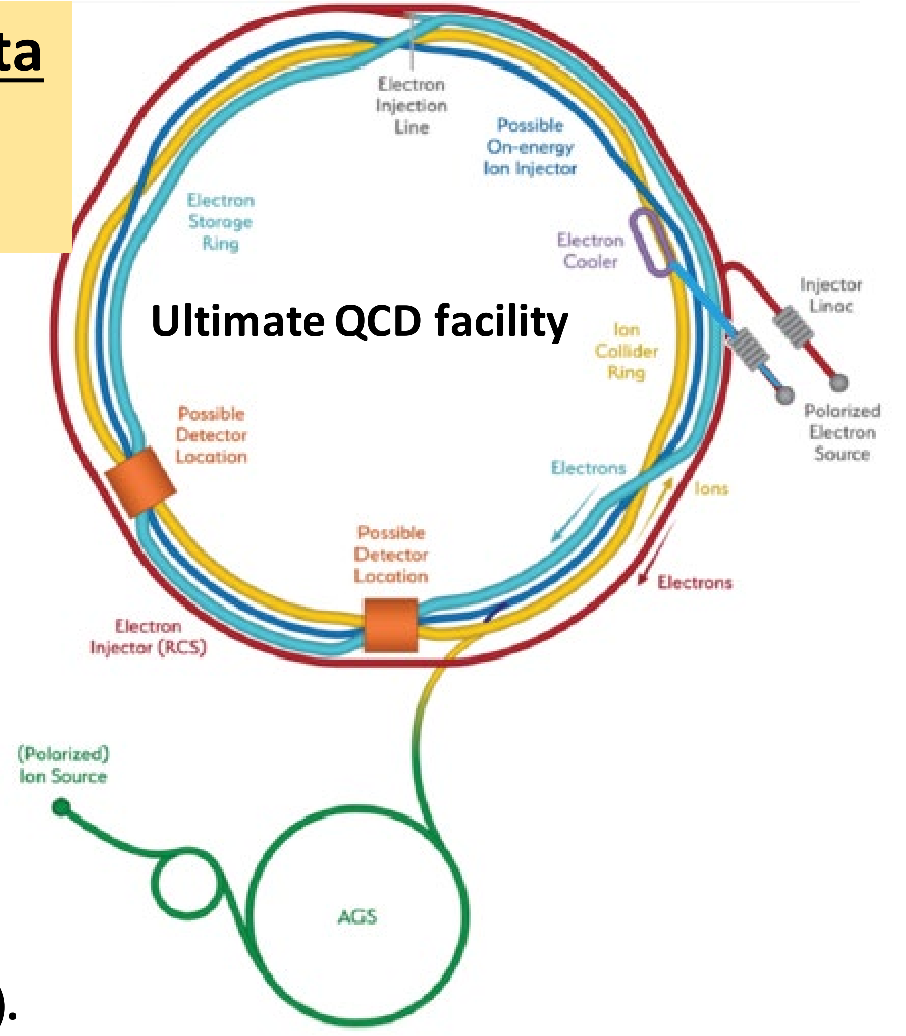
Quinto Incontro Nazionale di Fisica Nucleare INFN 2022

The Electron Ion Collider

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

Key Science Topics:

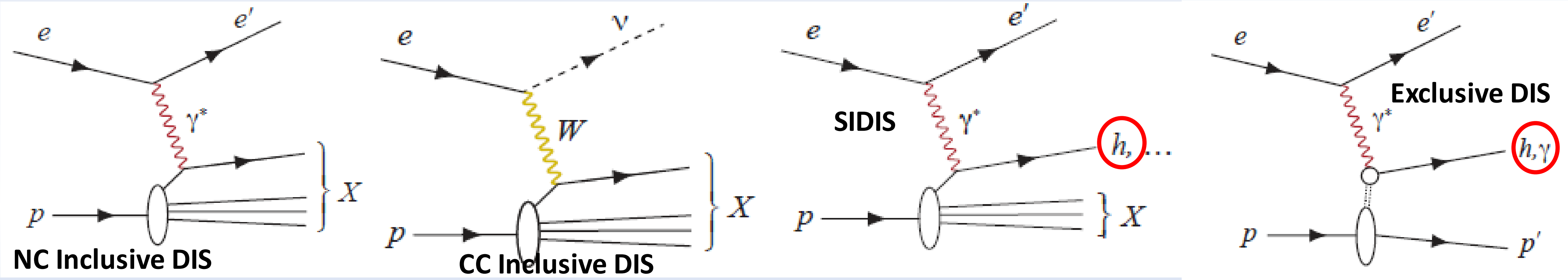
1. **Emergence** of global nucleonic properties such as **spin** and **mass** from partons and their underlying interactions.
2. The **distribution in momentum and position space of the partons inside the nucleon**.
3. The **interaction of nuclear medium** with **color-charged partons** and **jets**.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

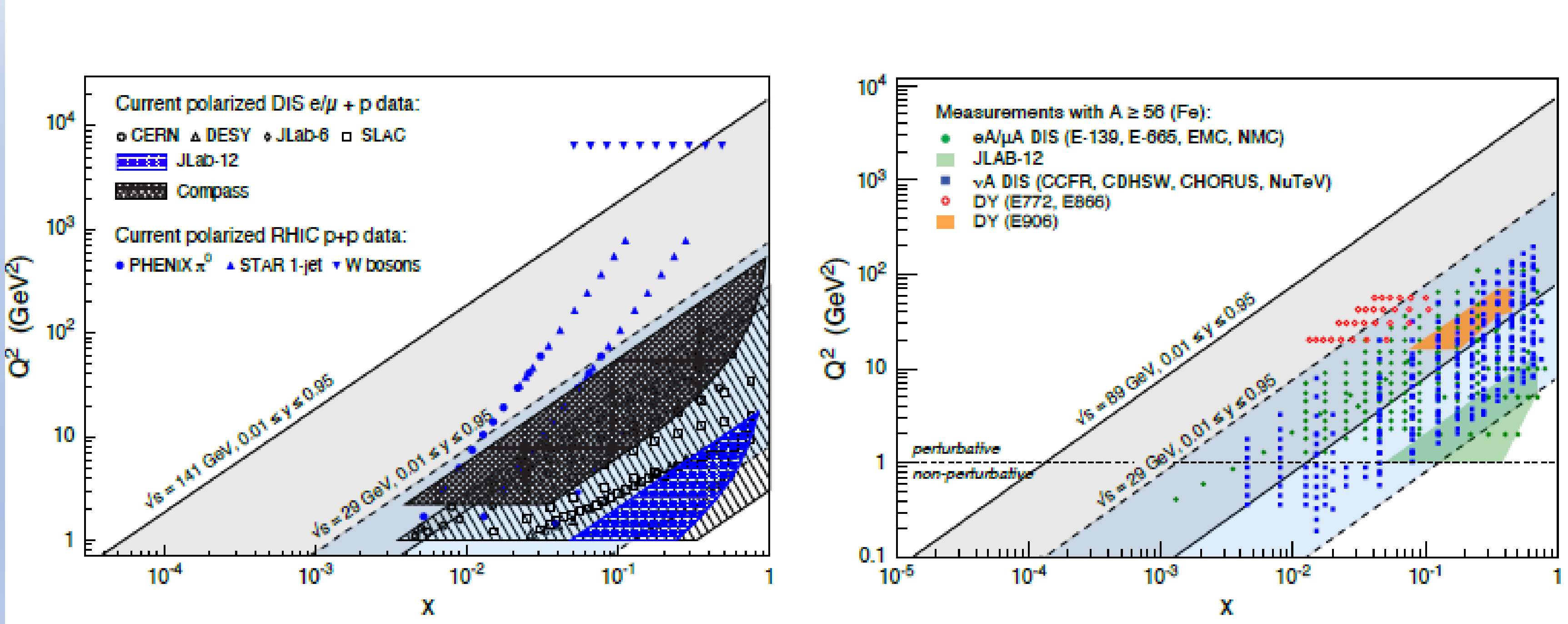


Main Design Requirements of EIC:

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**

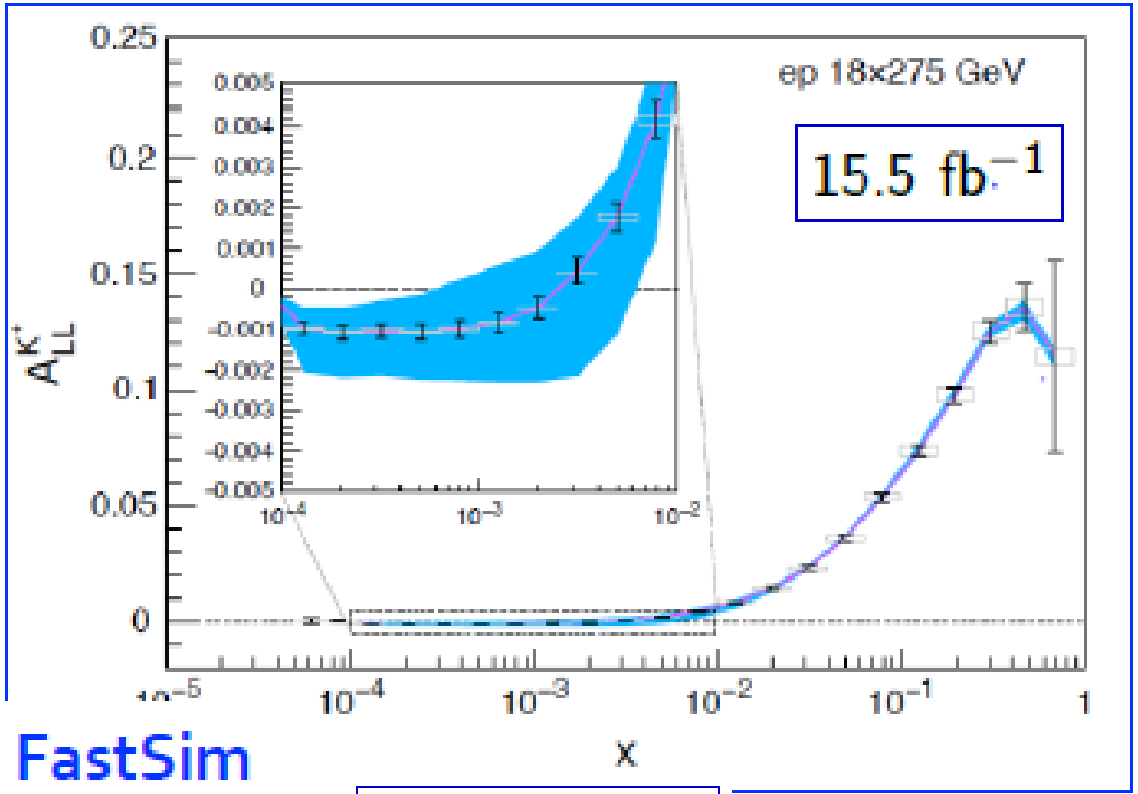
The Electron Ion Collider





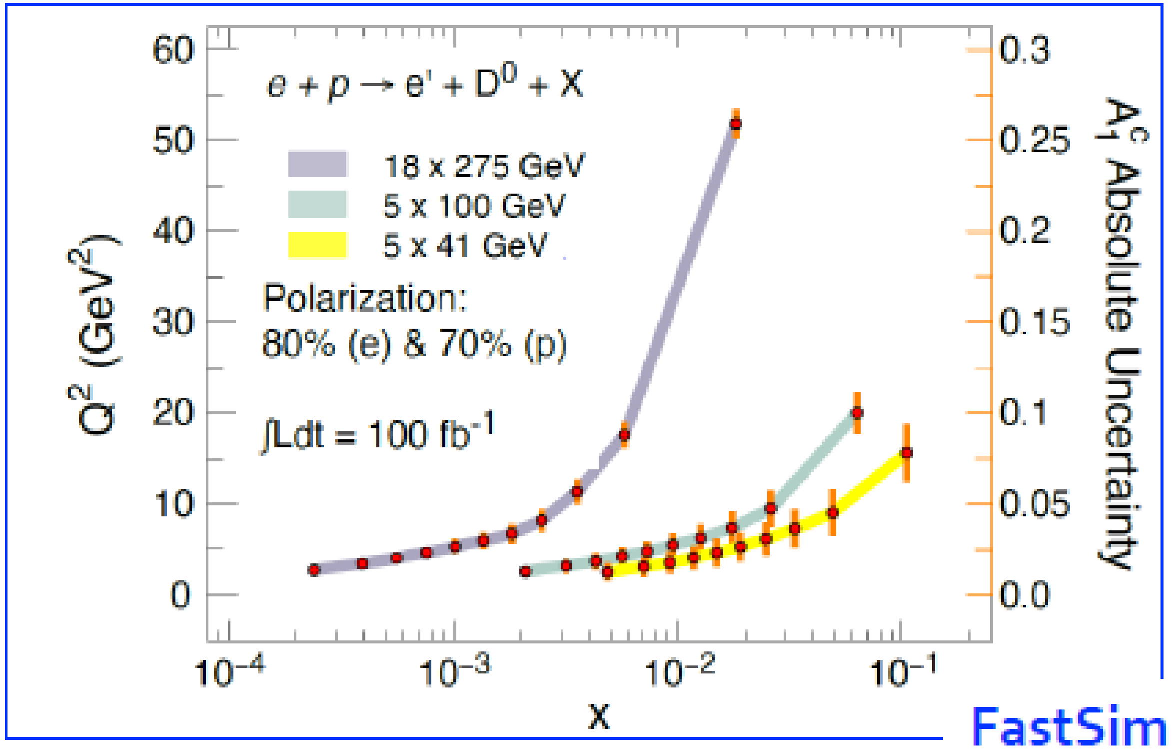
Excellent PID is required at the level of 3 *sigma pi*/K/p separation up to 50 GeV/c in the forward region, up to 10 GeV/c in the central detector region, and up to 10 GeV/c in the backward region.

The Electron Ion Collider (some physics examples that need forward PID)



A_{LL} for charged kaons 18x275 GeV²

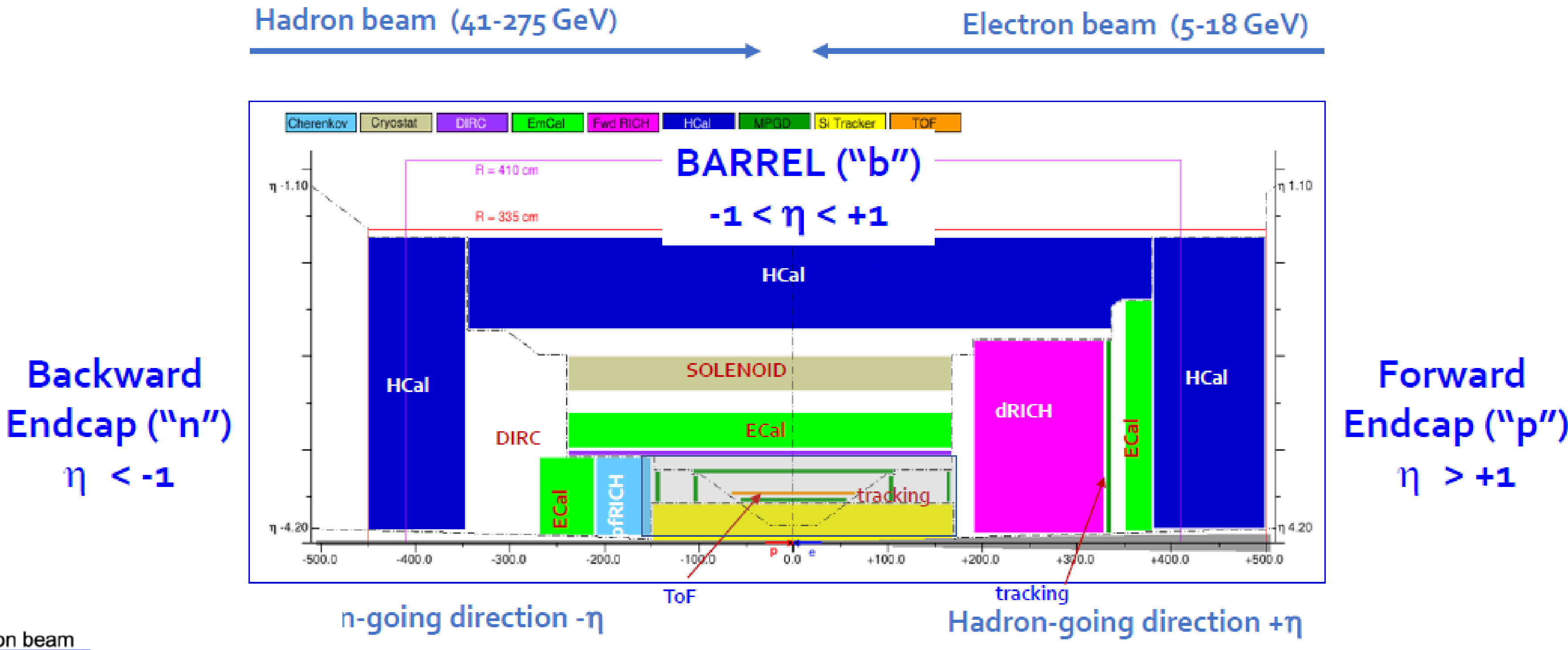
$Q^2 > 1, z > 0.2, y > 0.01$
depolarization factor $D(y) > 0.1$

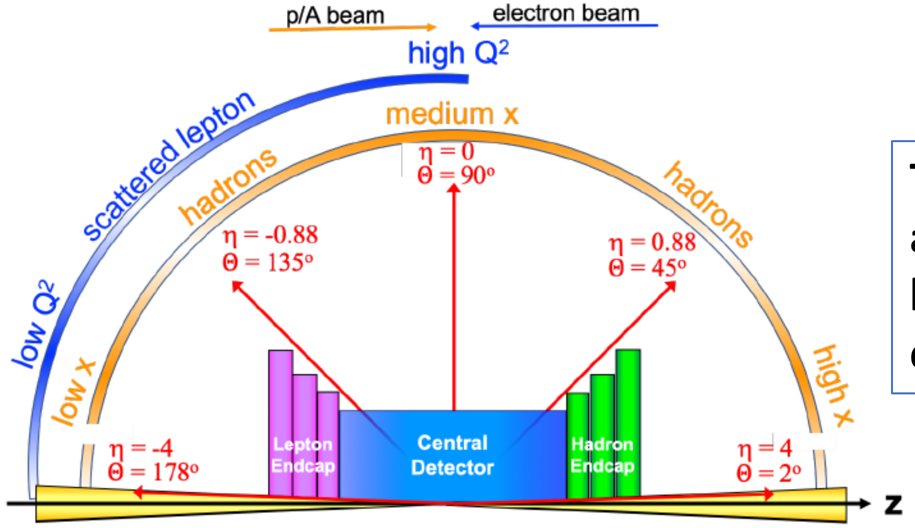


- g helicity at medium and high x from c production; for instance: $A_1^c \sim g_1^c / F_1^c$ in $\vec{e} + \vec{p} \to e' + D^0 + X$

Detector lay out

ATHENA employs 3T solenoidal magnet



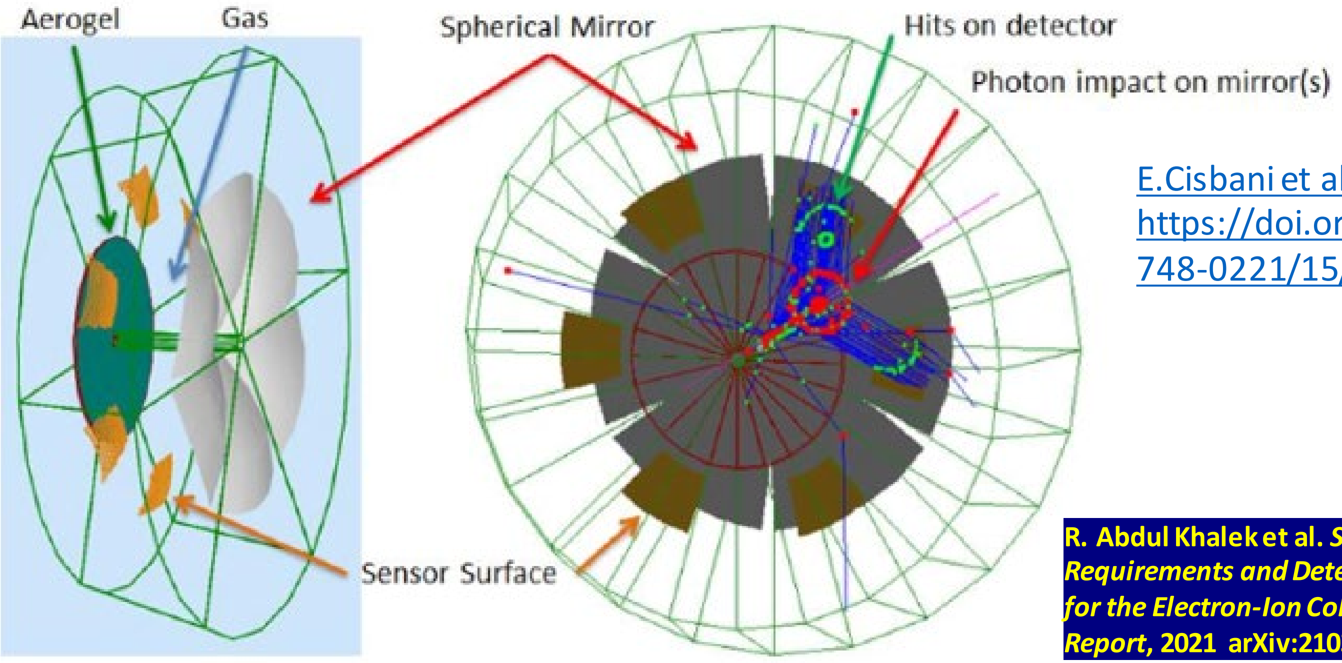


The forward RICH detector has several constraints:

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)**

Yellow Report dual RICH prescription

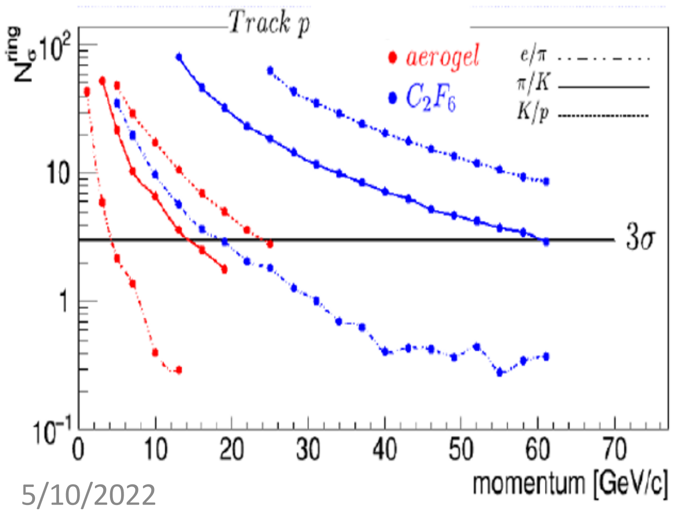
In 2020, common effort of the whole EIC User Group community to produce a detector baseline based on physics requirements resulting in Yellow Report



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

R. Abdul Khalek et al. ***Science Requirements and Detector Concepts for the Electron-Ion Collider: EIC Yellow Report*****, 2021 arXiv:2103.05419**.

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.



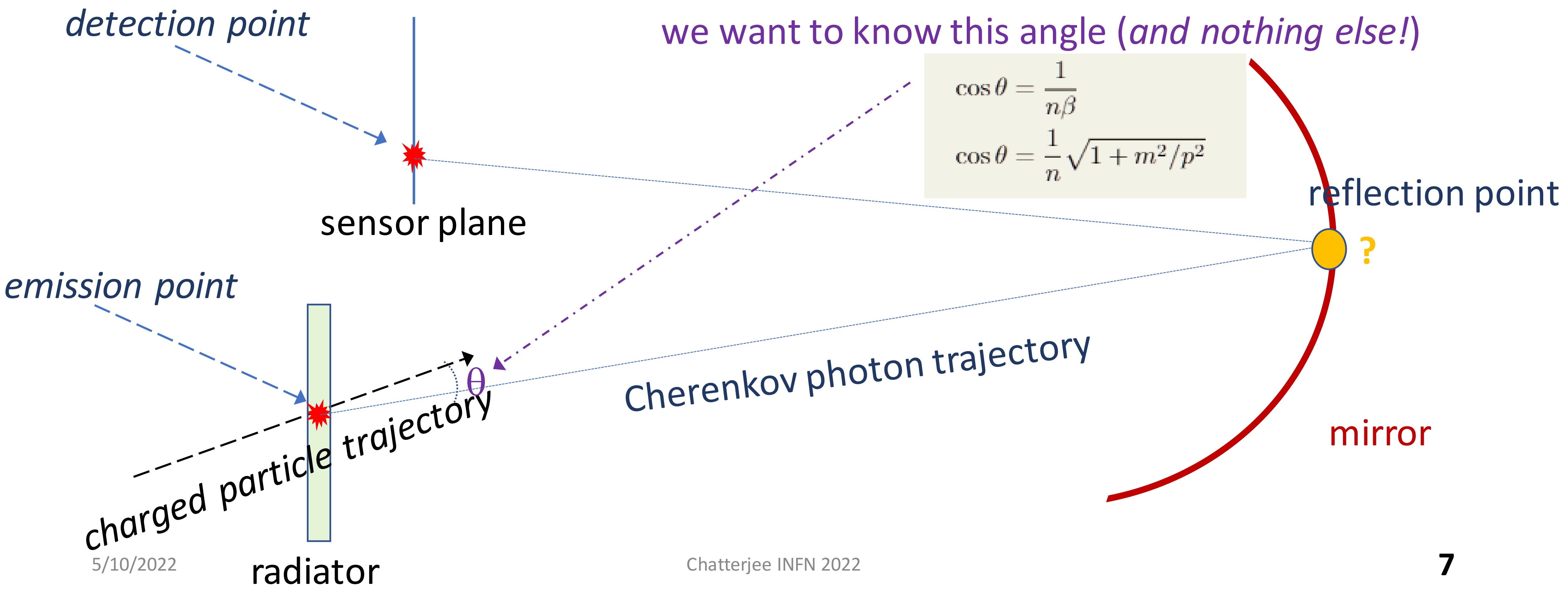
Note:

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.

Inverse Ray Tracing (IRT): concept

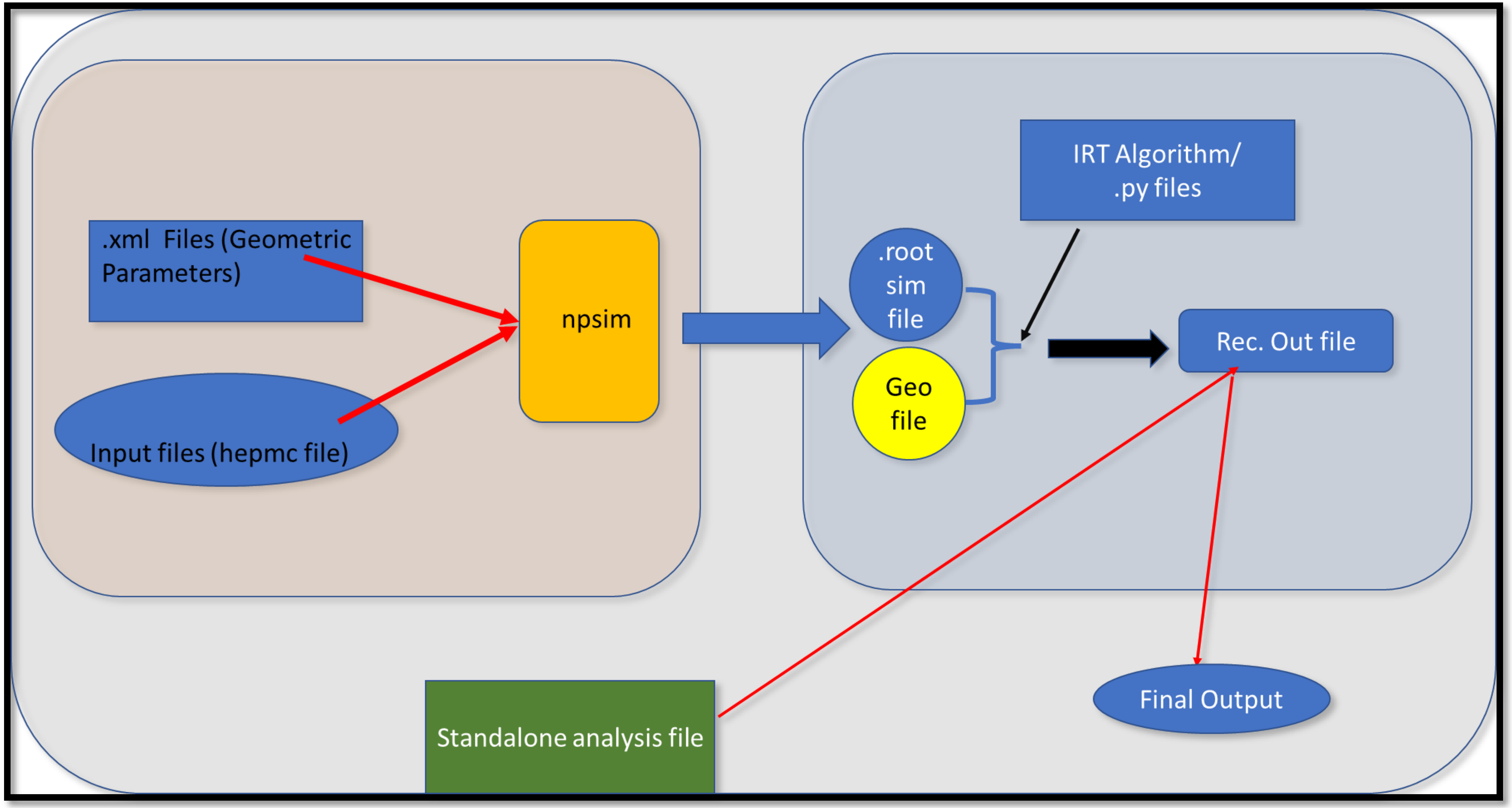
- Originally implemented by HERMES Collaboration
- Recent re-implementations by many colleagues.

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



The Workflow in ATHENA

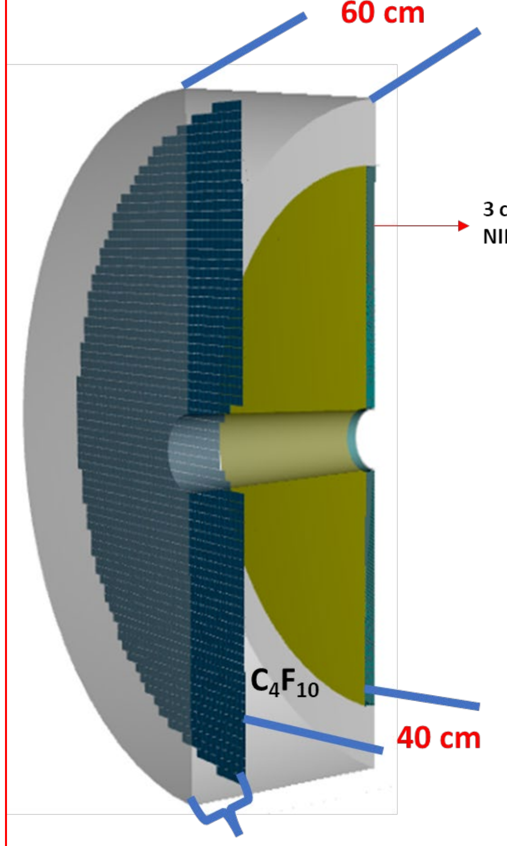
DD4Hep framework



- The Workflow is same for both pfRICH and dRICH
- Specific geometry is inserted according to the RICH of interest.
- The IRT algorithm is the same.

Geometry of pfRICH

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

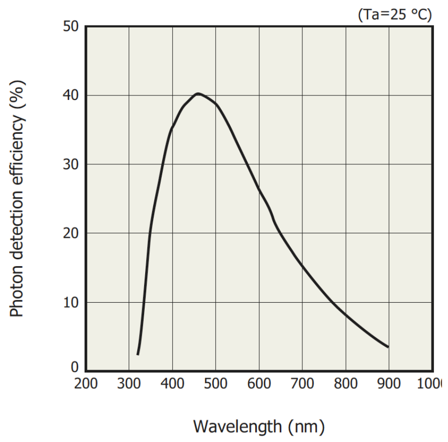


Sensors:

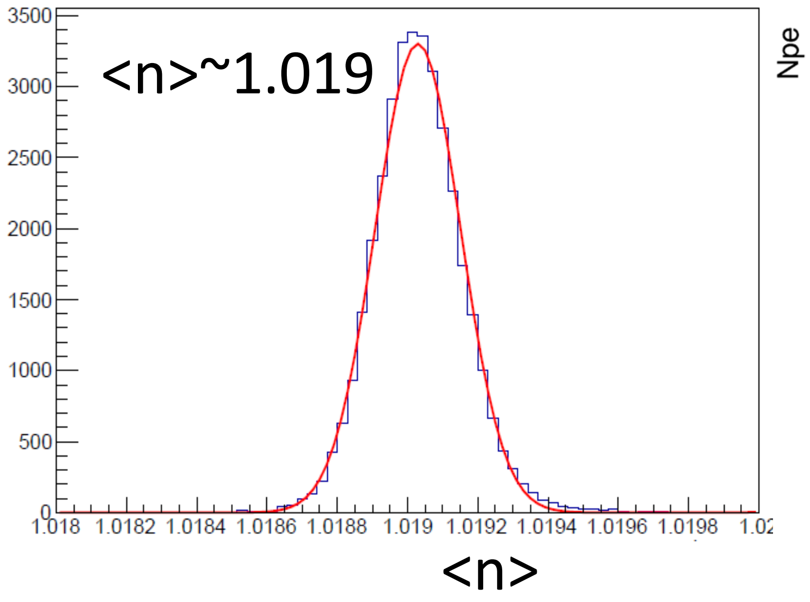
a) Hamamatsu S13361-3050AE-08 8x8 SiPM panels (https://www.hamamatsu.com/us/en/product/type/S13361-3050AE-08/index.html)

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

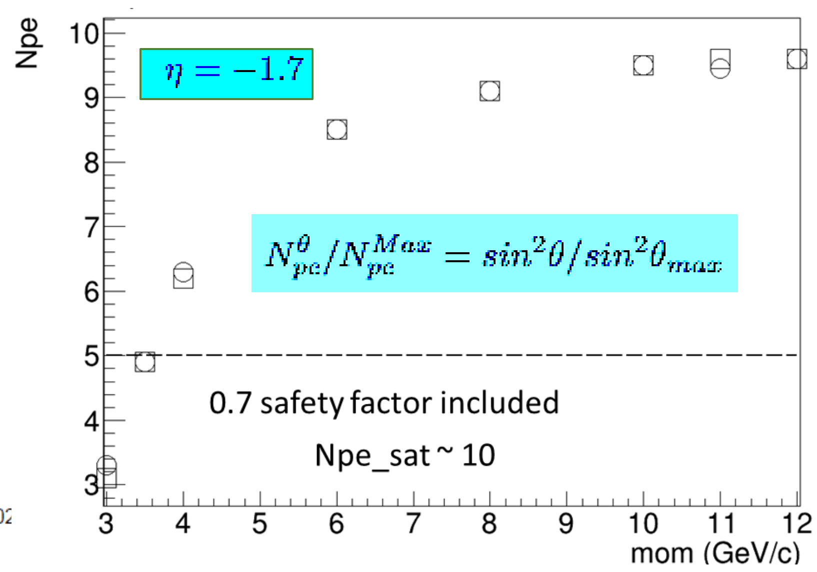
c) Additional safety factor of 0.7 on top of Photo Detection Efficiency provided by Hamamatsu.



Consistency found from RICH Cherenkov angle reconstruction



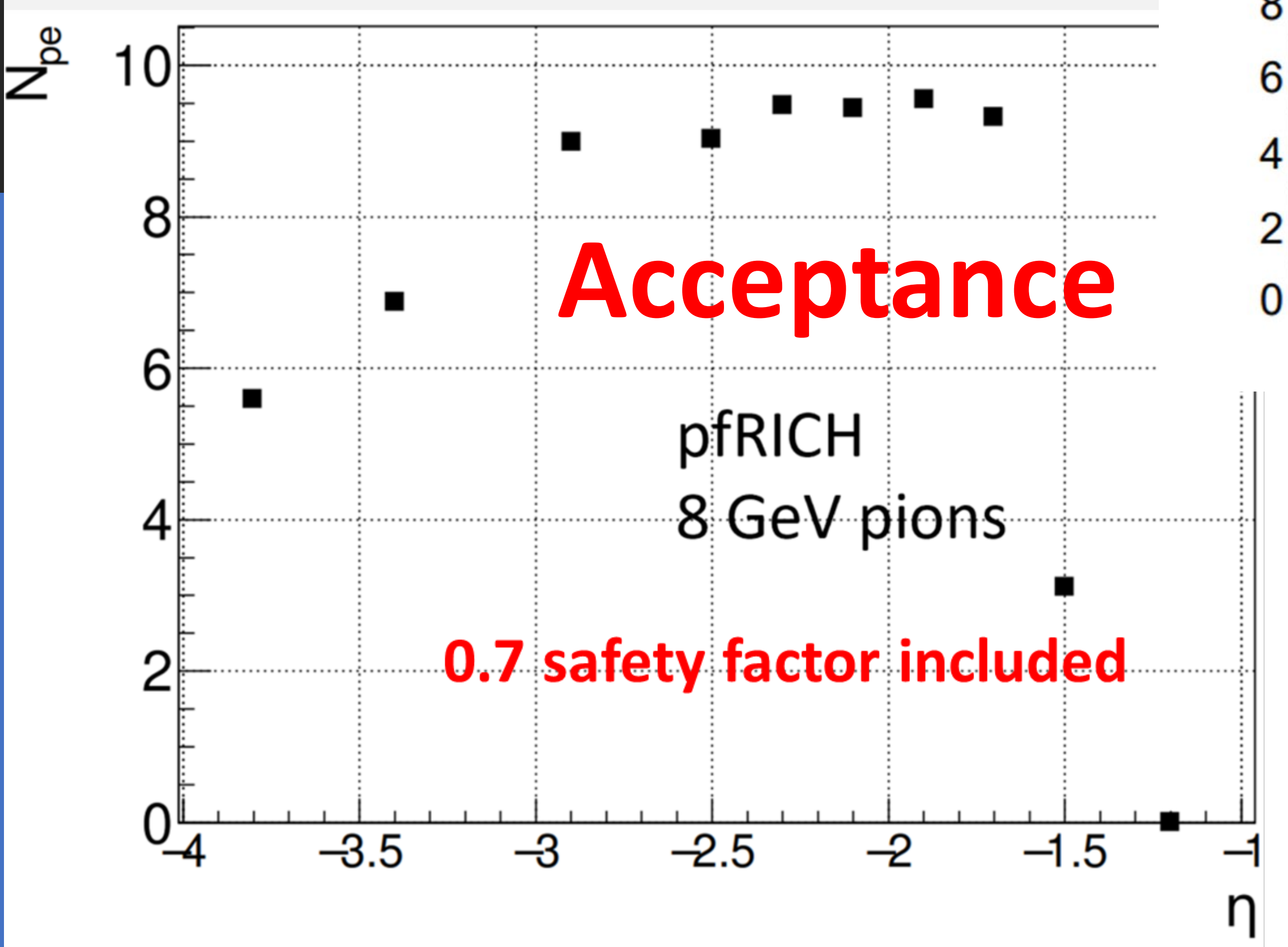
N_{pe} : open box Exp Open Circle Obtained from simulation

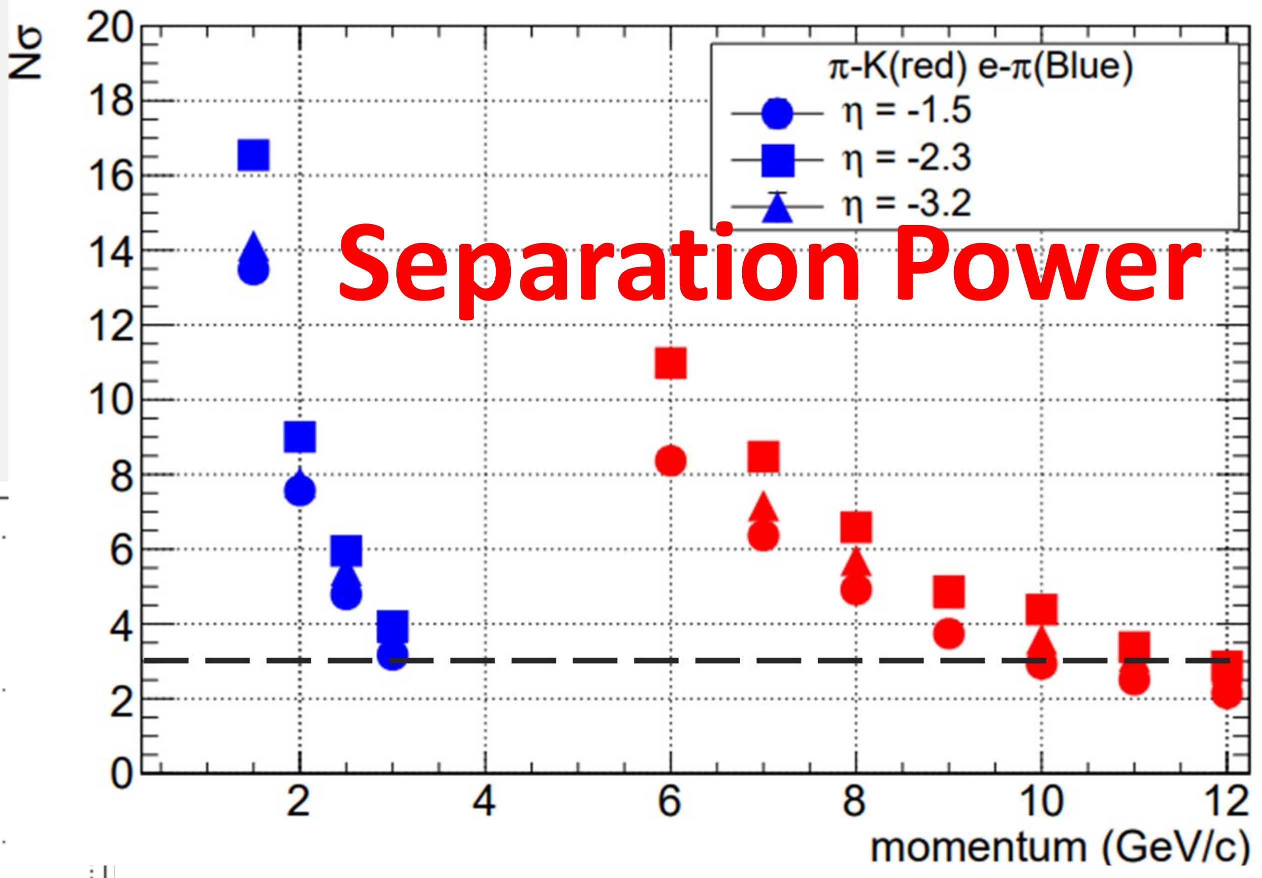


C_4F_{10} **parameters:**
NIMA 510(2003) 262

Performance plot

YR requirement achievable

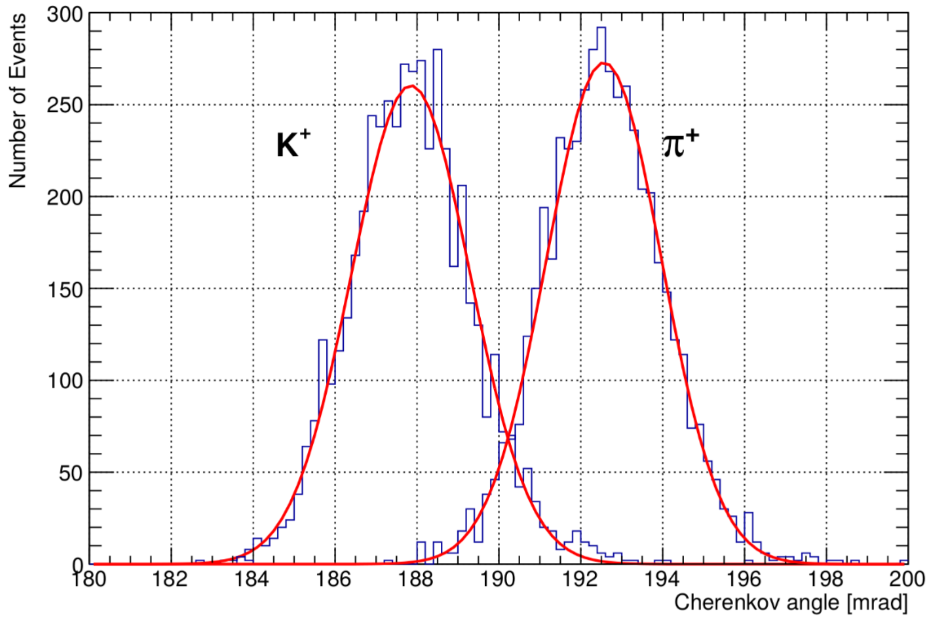


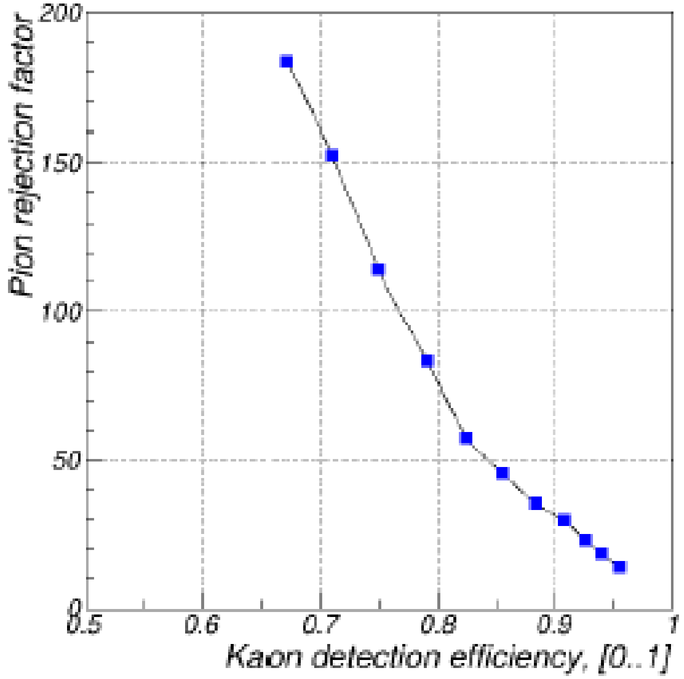


Yellow Report requirement: hadron PID in the electron-going endcap: better than 3σ π/K separation either (1) to 7 GeV/c (pp. 21) (2) up to 10 GeV/c [table 3.1]
We consider the later as a reference!

Performance plot

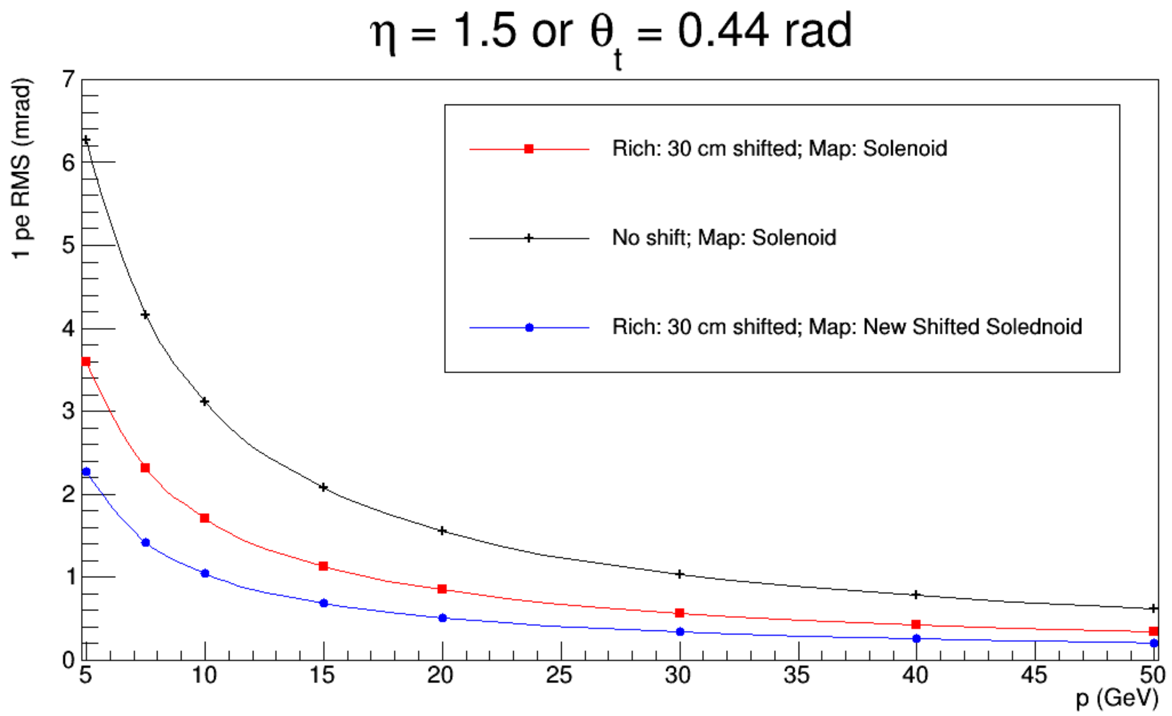
- Expected pfRICH performance in π/K separation.
- **Top**: Reconstructed Cherenkov angle peaks for a **50:50 mix of 10 GeV/c pions and kaons**
- at **η = -1.7**.
- **Bottom**: Dependency of pion rejection factor as a function of kaon identification efficiency with the reconstructed track-by-track Cherenkov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

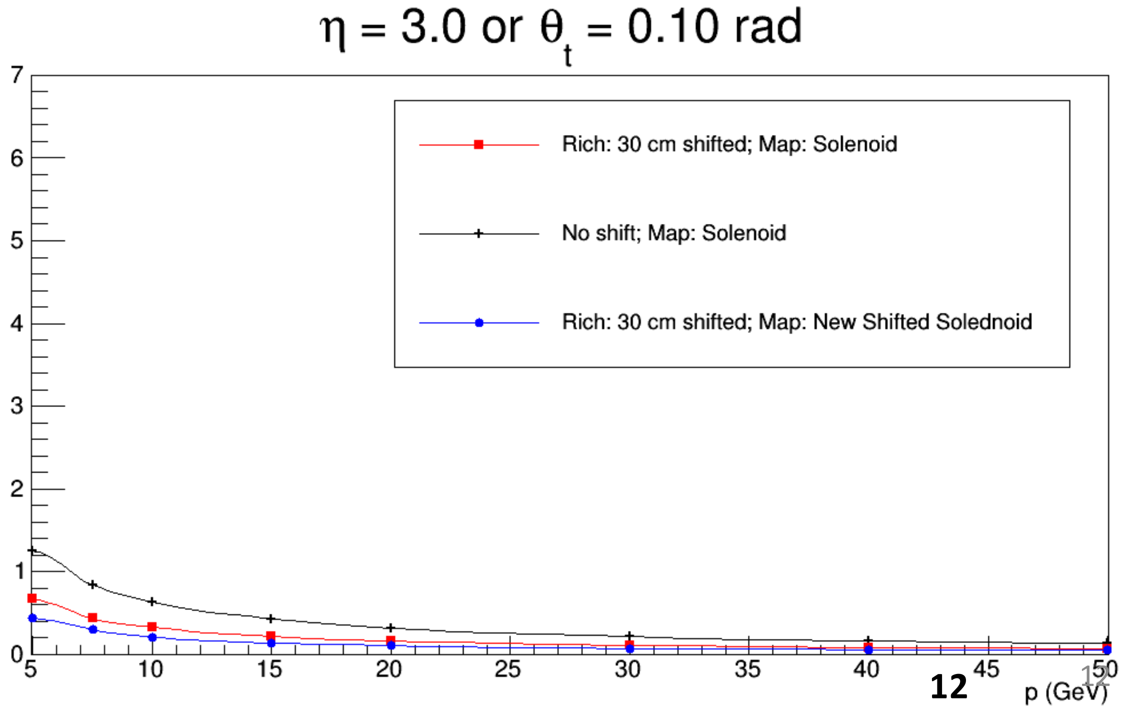




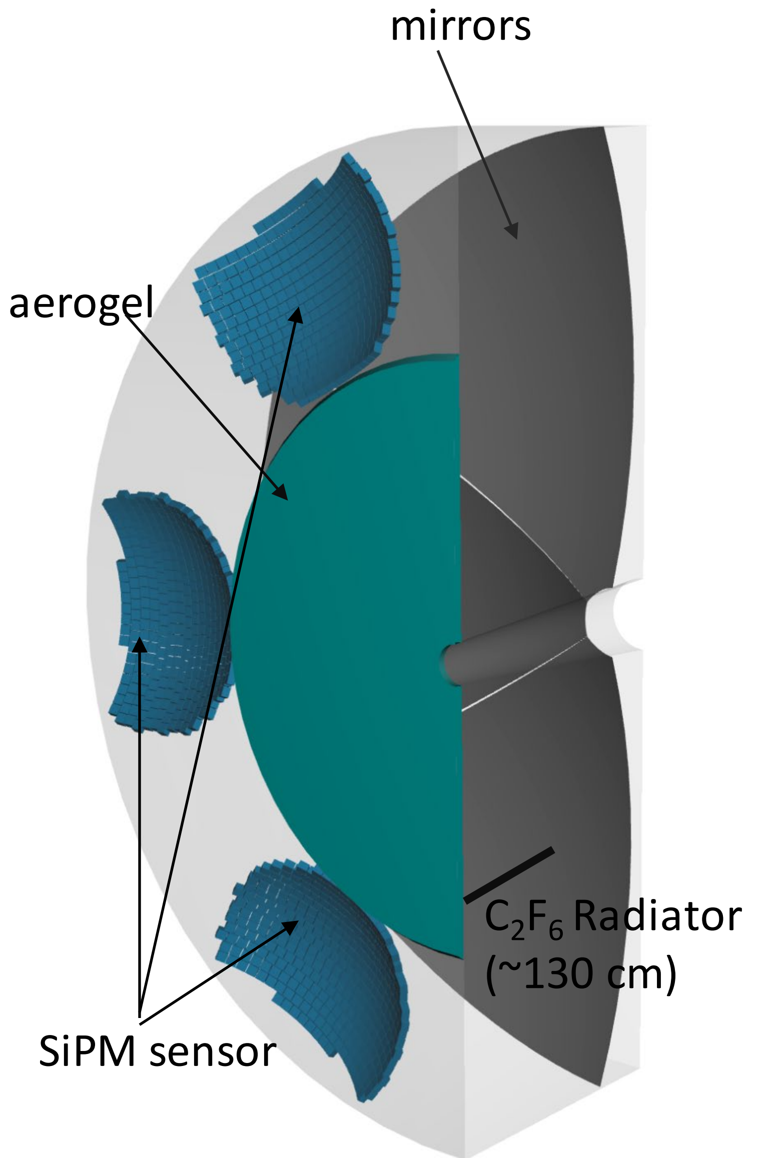
Stand alone Geant4 model : Optimization of dRICH position

- **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

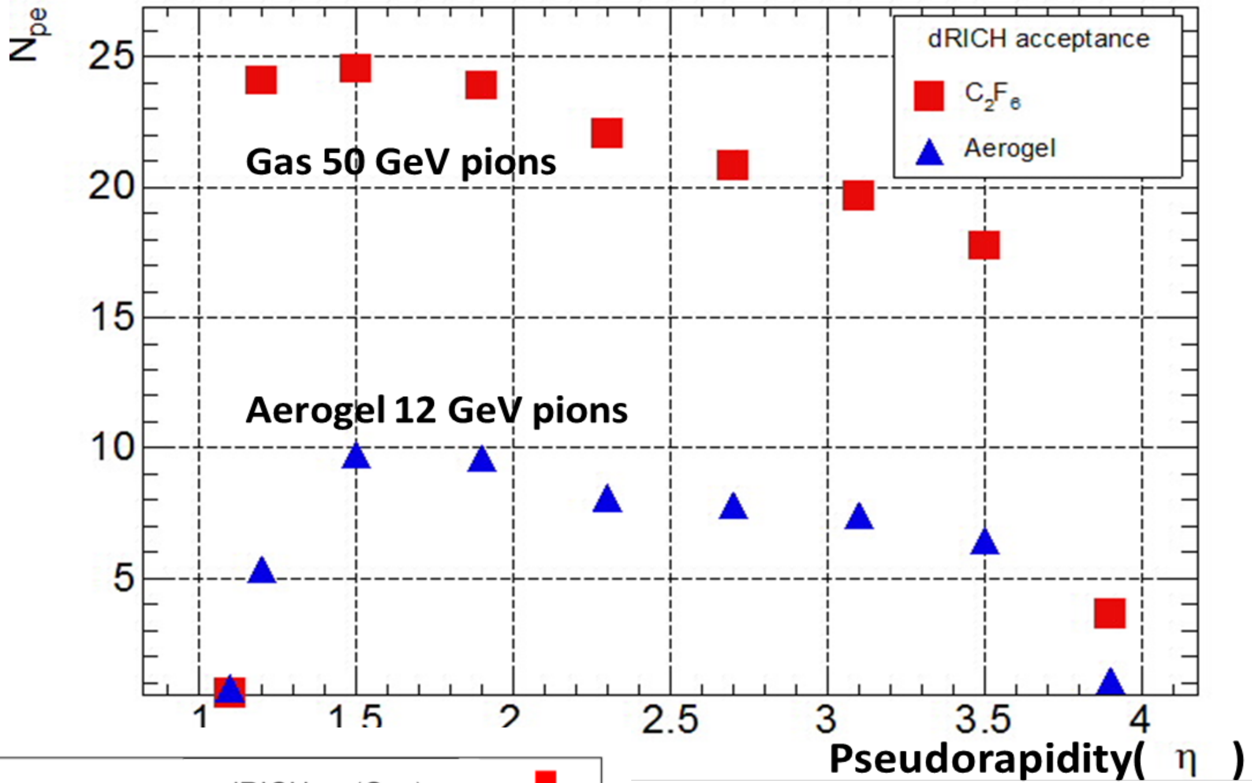


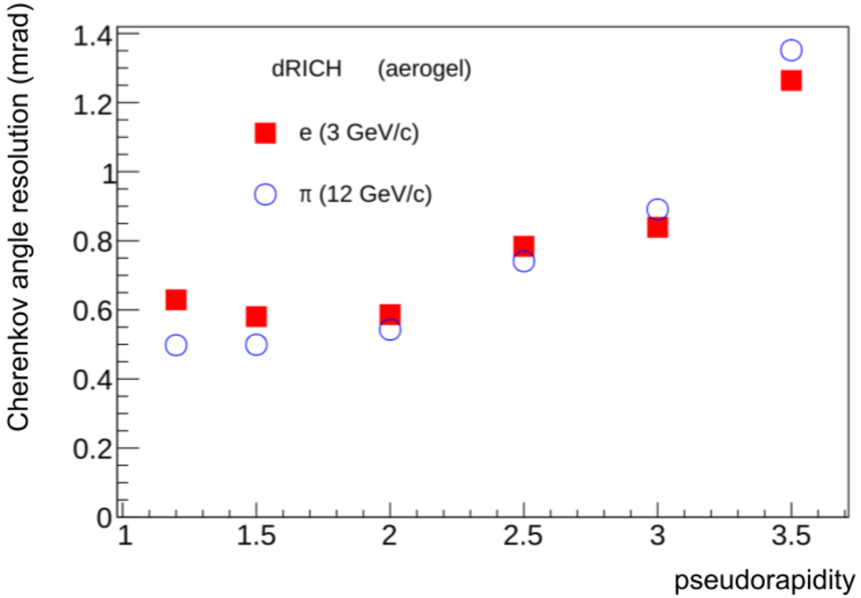
1. 140 cm of total length. Occupying space +190 cm to +330 cm from the IP.
2. Detector will have six 60° sectors, each equipped with its own spherical mirror segment and a sensor plane.
3. Sensor's characteristics are like pfRICH.
4. Focusing mirrors → 6 individual elements (single mirror configuration)
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

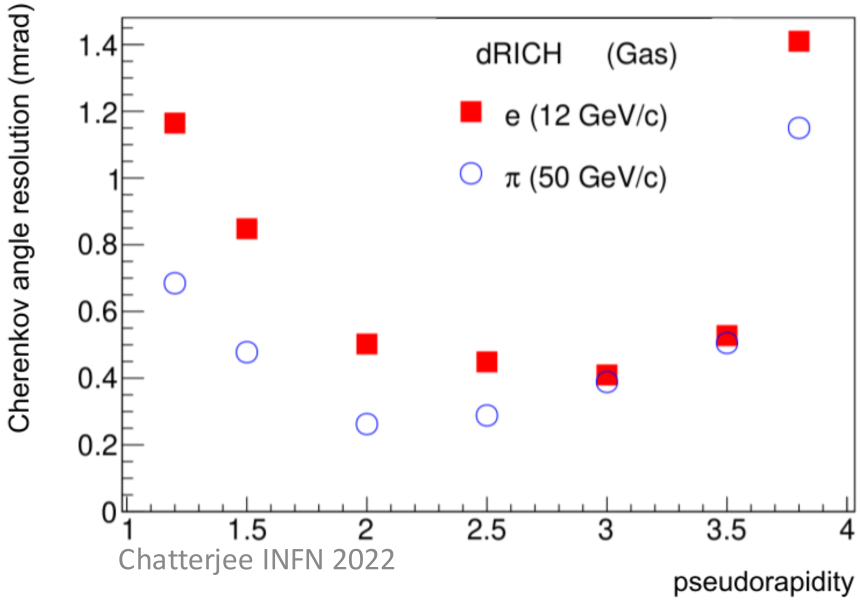
The sensors are positioned on a sphere, with a square tiling algorithm. The spherical mirrors are parameterized by three variables: the z position of the back plane, which is the maximum z the spherical mirror will reach, along with two focus tune parameters f_x and f_z.

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

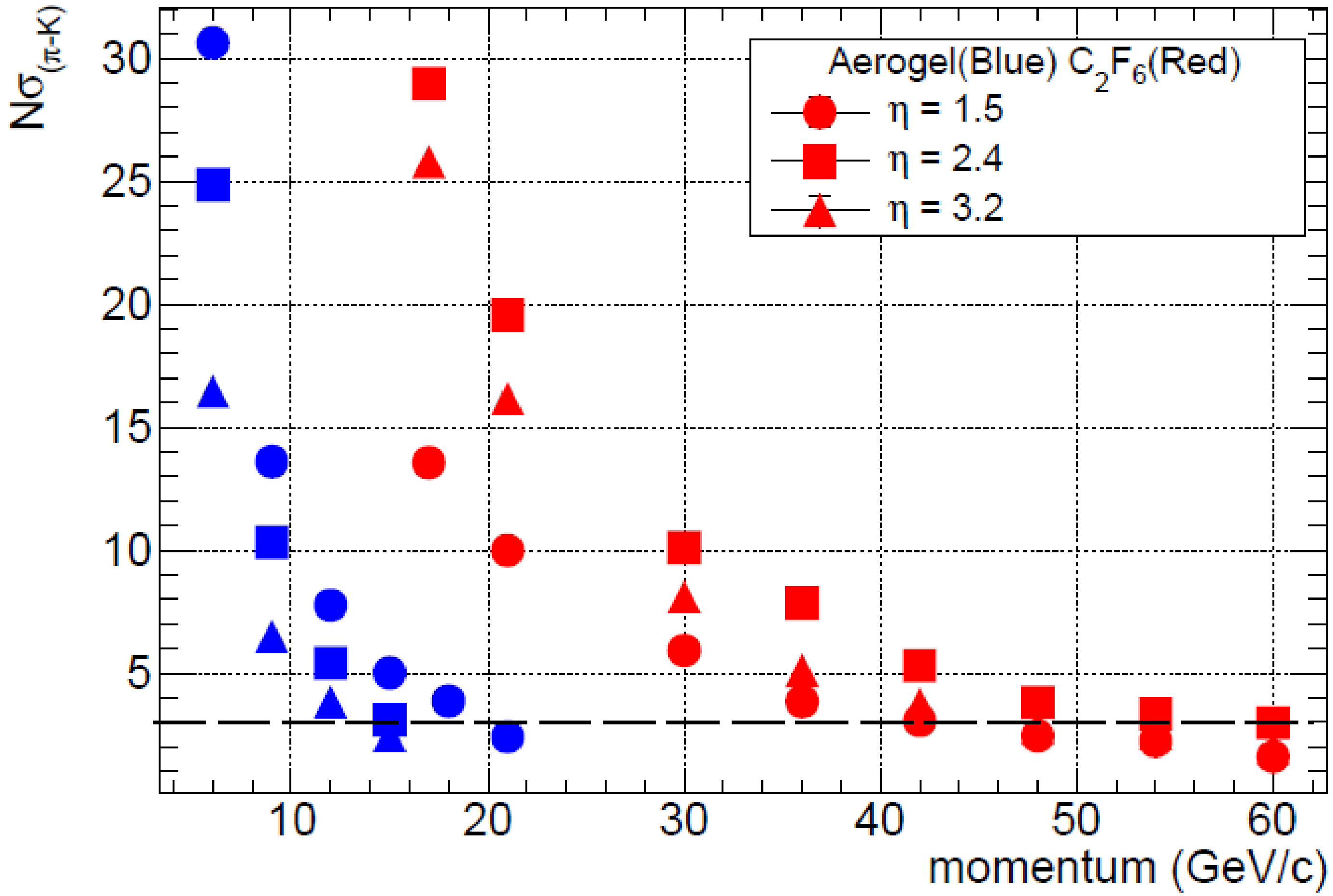


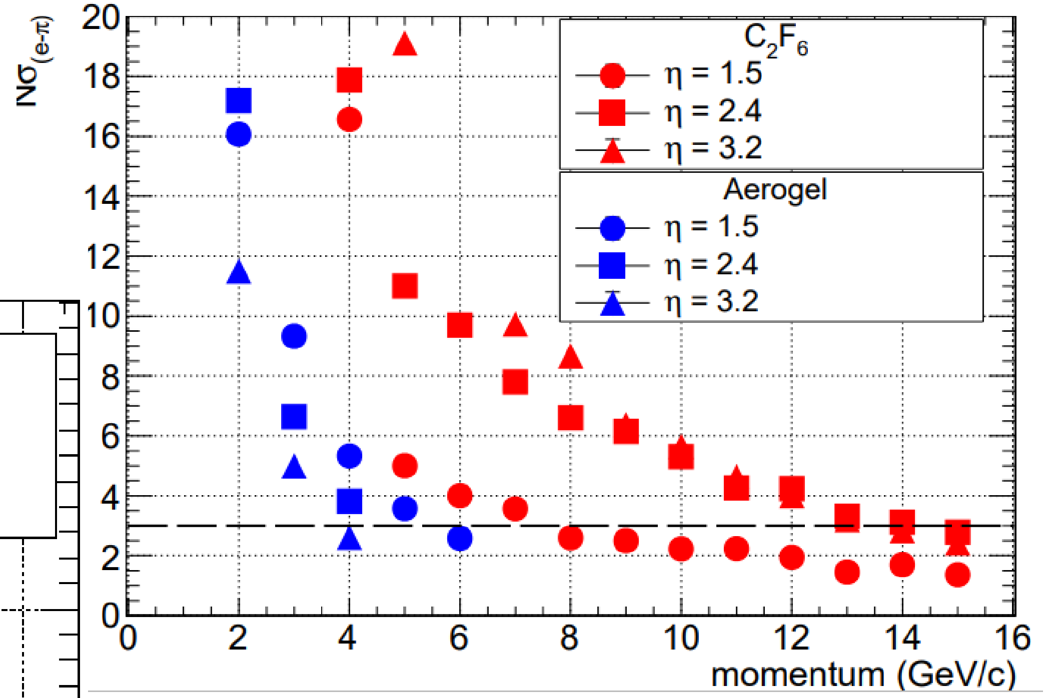




YR requirement: acceptance for the dRICH is 1.0 ≤ η ≤ 3.5. These reference numbers were taken as a guidance for the ATHENA design.

Nσ Separation

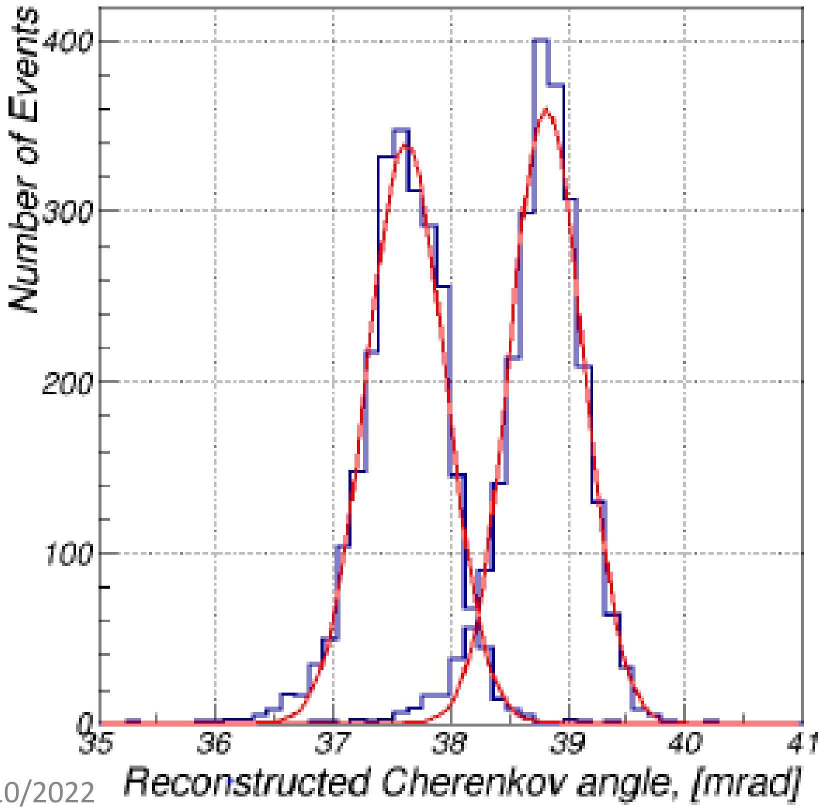


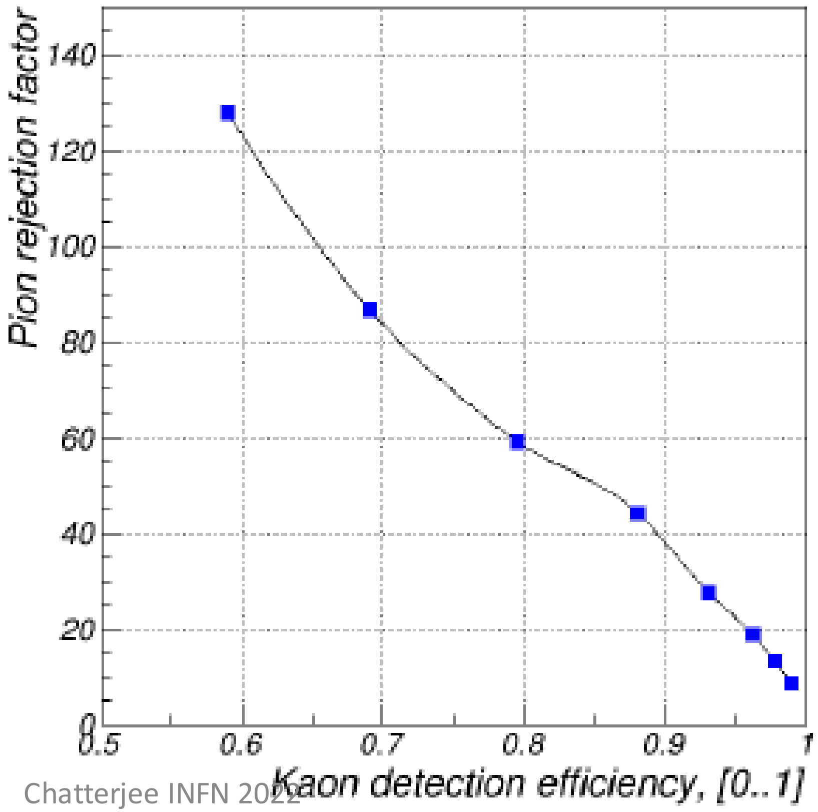


YR prescription achievable.

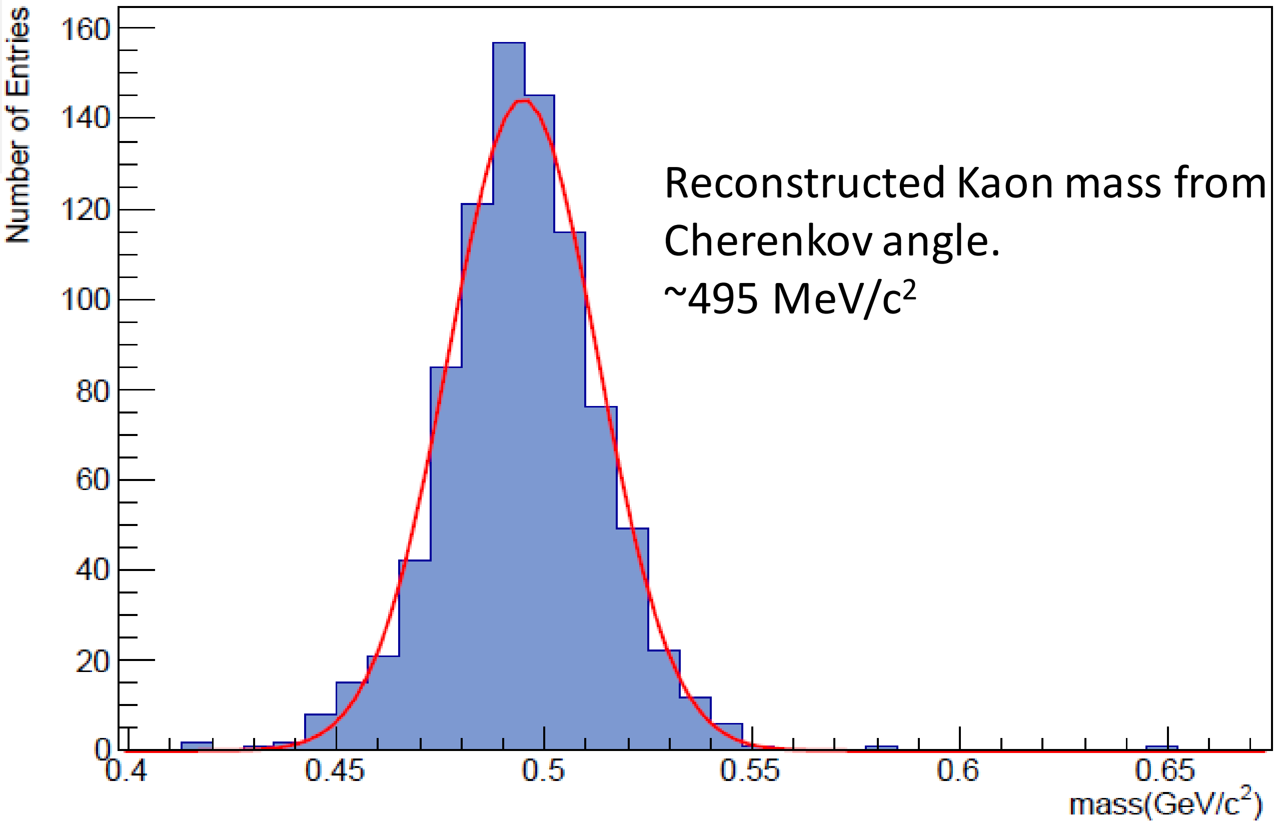
Performance plots

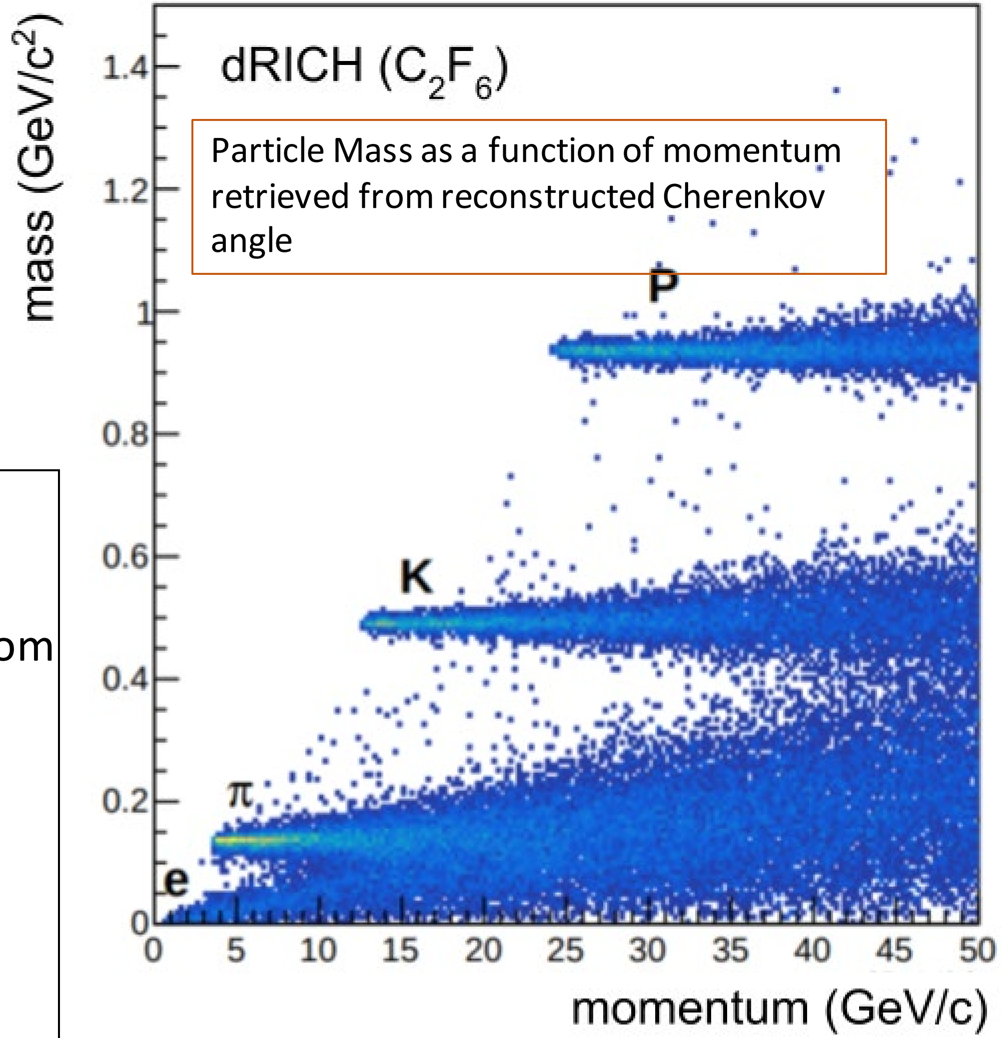
- Left: reconstructed Cherenkov angle peaks for a 50:50 mix of 50 GeV/c kaon and pion tracks at η = 2.4 are ~3σ apart (C2F6 radiator). Right: dependency of pion rejection factor on kaon detection efficiency with the selection cu varying between 37.6 mrad and 38.4 mrad applied to the left hand side plot.





dRICH reconstructed mass





Conclusions

- 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 framework.
- The Yellow Report Requirement has been achieved in the first simulation studies.
- 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.
- During the construction phase these parameters extracted from detailed simulations will be useful for geometrical tuning, mechanical designs and finally to optimize the particle identification.
- Following Detector Advisory Panel advice 1.5 T magnet design chosen as reference detector. EIC community moving toward "Detector 1" final design merging ATHENA and ECCE studies it also includes optimization of the RICH detectors.

Thank you for your kind attention

Backups

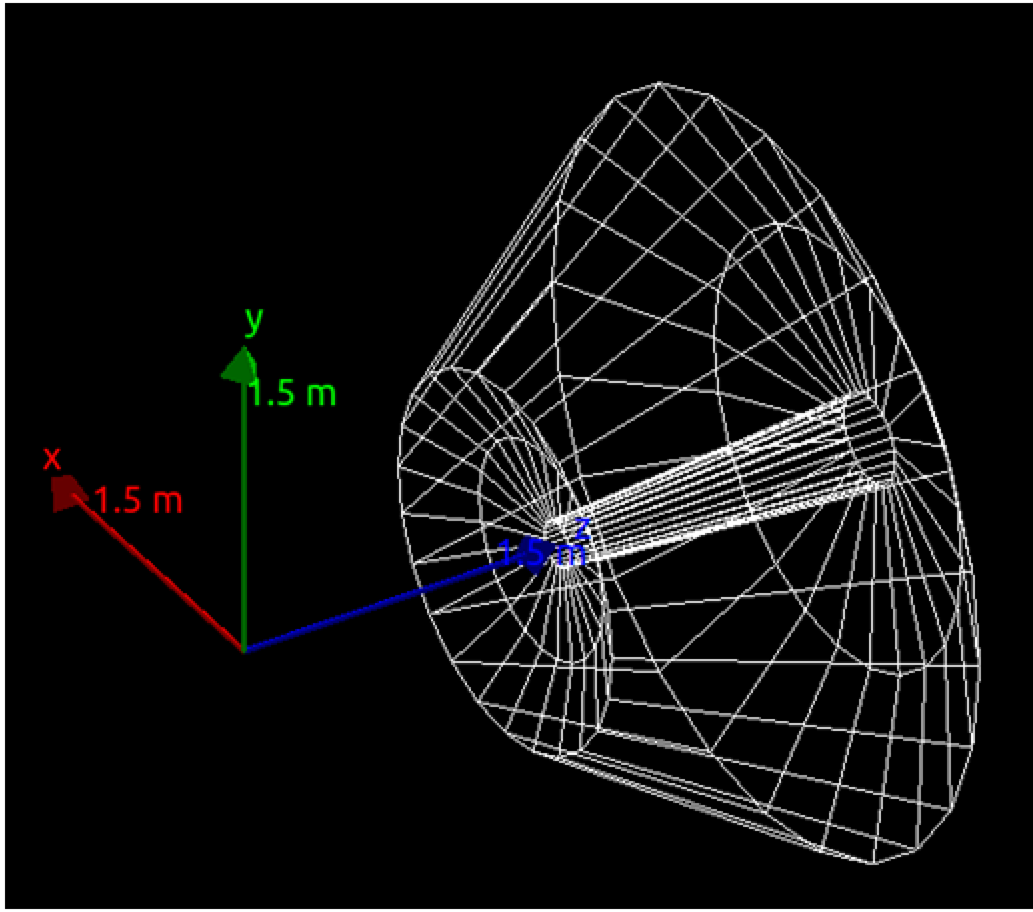
Inverse Ray Tracing: implementation

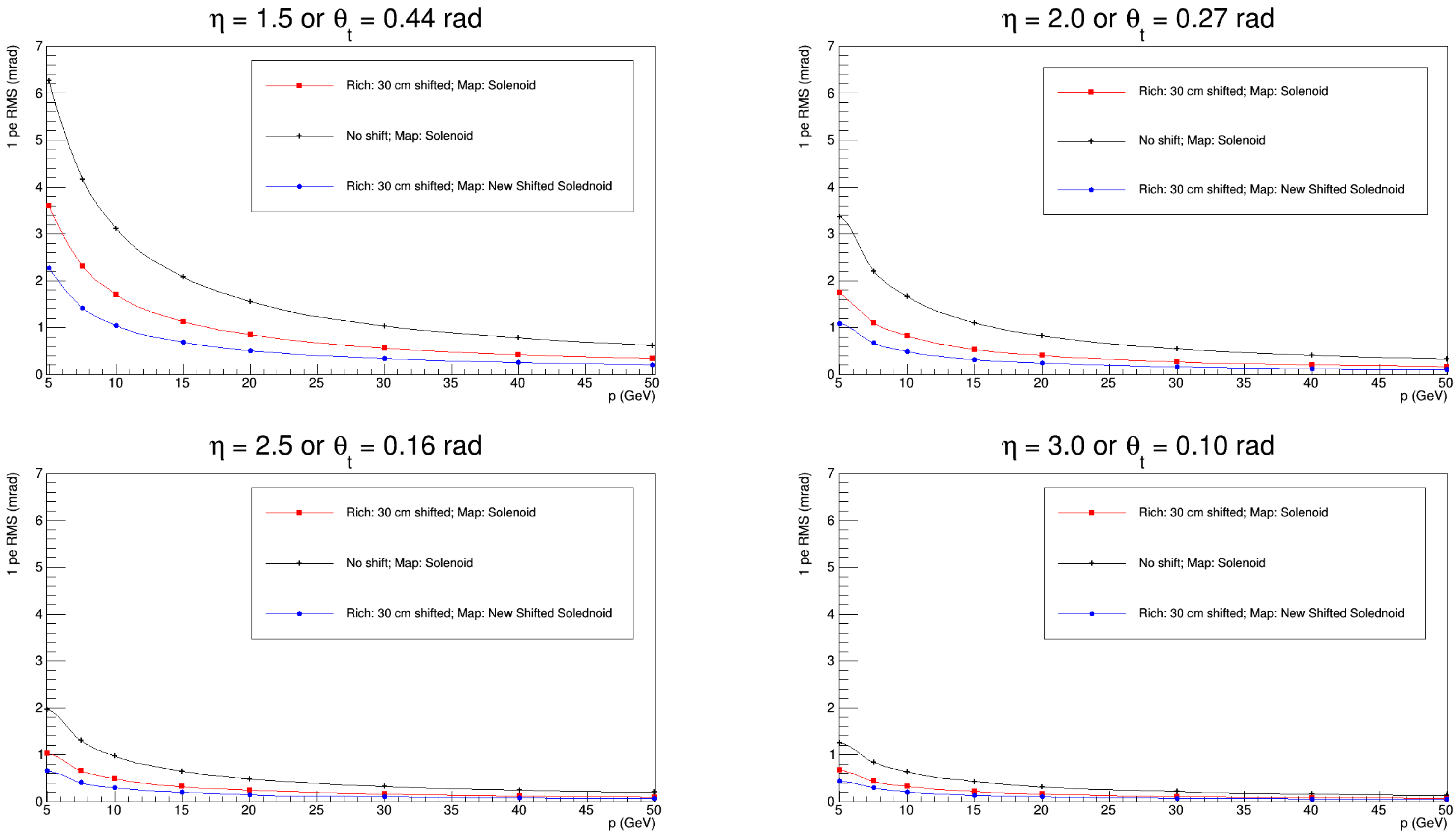
Repository (as of Dec 15, 2021) : https://eicweb.phy.anl.gov/EIC/irt/-/tree/irt-init-v02

- 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.)

Stand alone 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





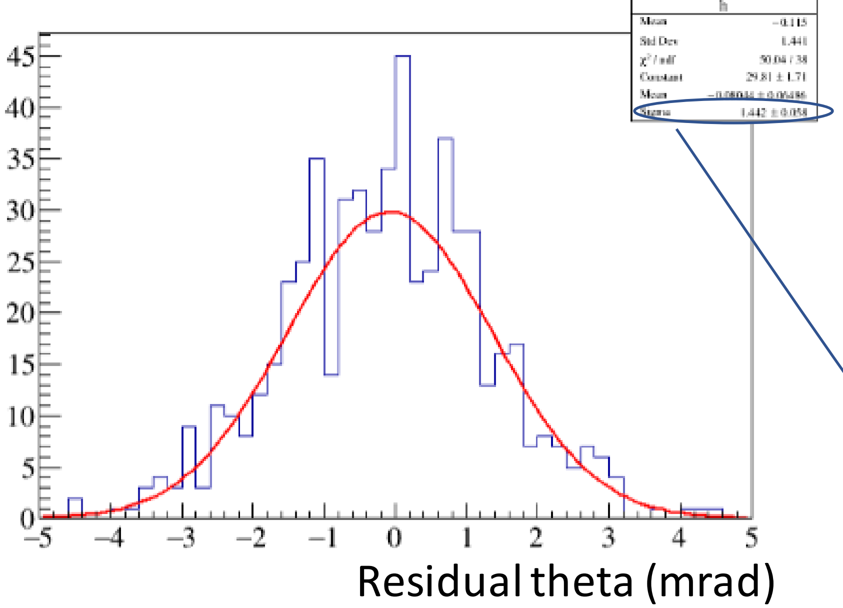
η = 1.5 or θ_t = 0.44 rad
η = 2.0 or θ_t = 0.27 rad
η = 2.5 or θ_t = 0.16 rad
η = 3.0 or θ_t = 0.10 rad
1 pe RMS (mrad)
p (GeV)
Rich: 30 cm shifted; Map: Solenoid
No shift; Map: Solenoid
Rich: 30 cm shifted; Map: New Shifted Solednoid

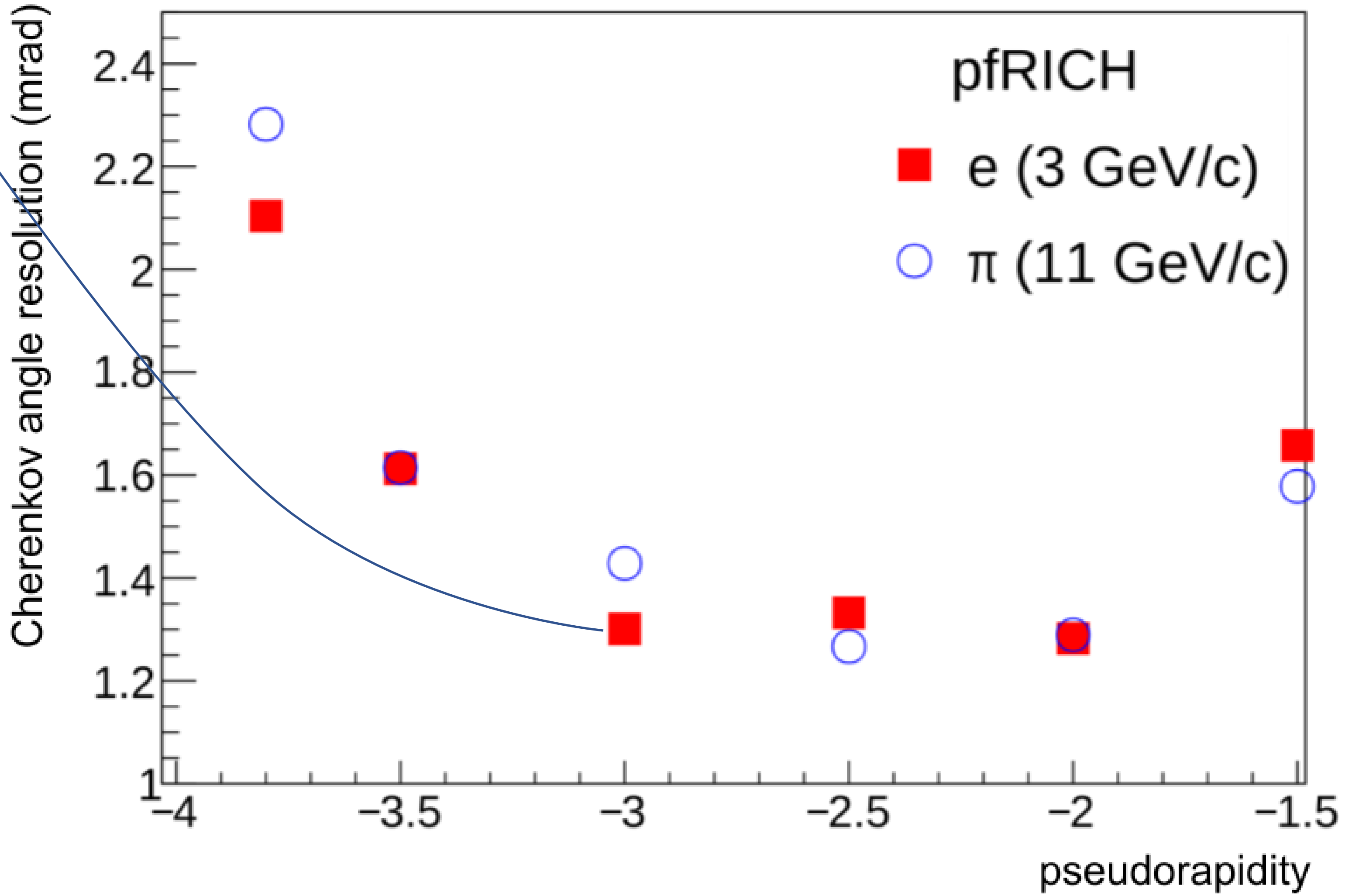
Inverse Ray Tracing: machinery

- 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!

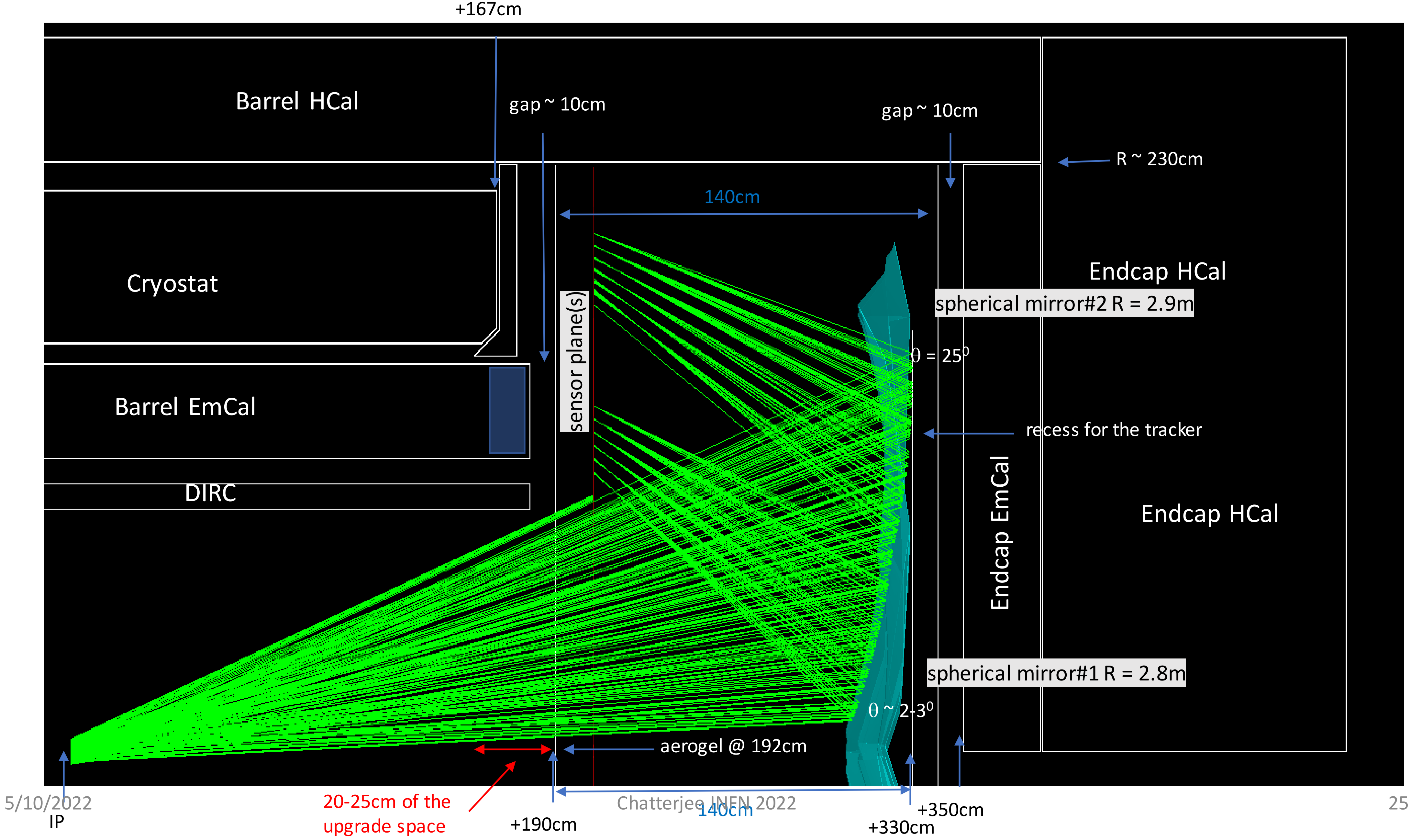
Dependence of ring resolution with pseudo rapidity



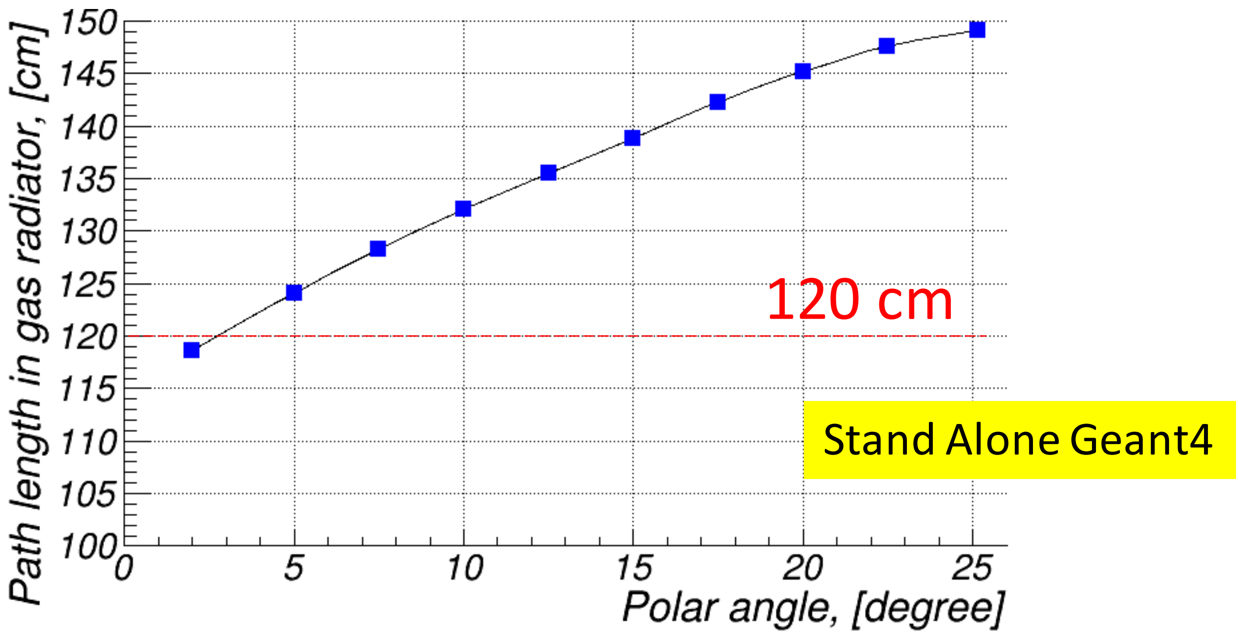


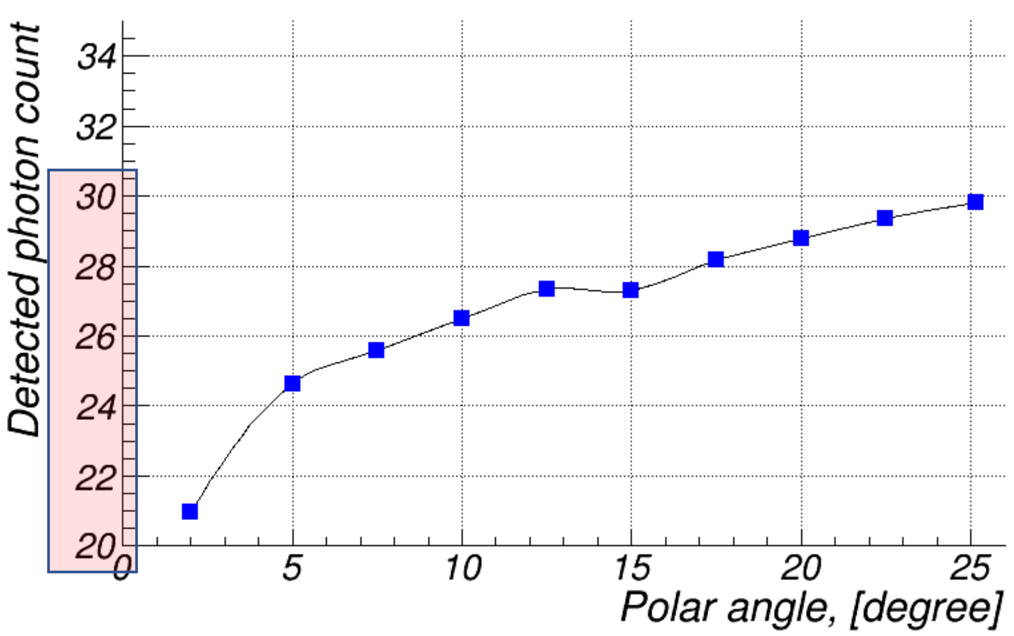
Track level resolution:
pixel size, emission point uncertainty, and chromaticity to the track-level Cherenkov photon angle resolution were taken together to estimate ~1.5 mrad.

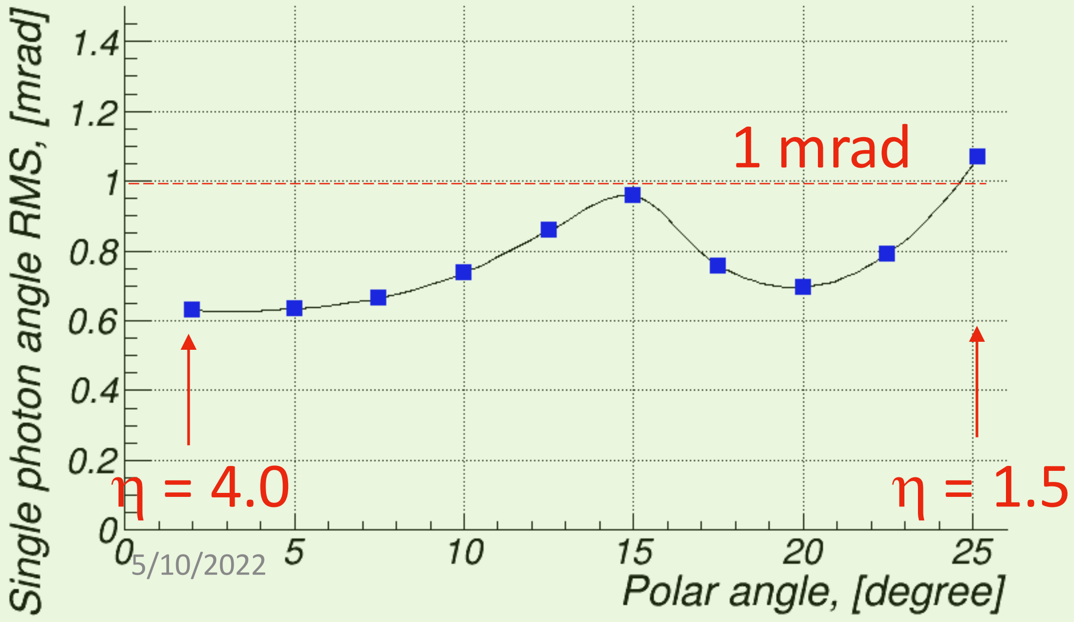
Inverse Ray Tracing: application (standalone GEANT4)

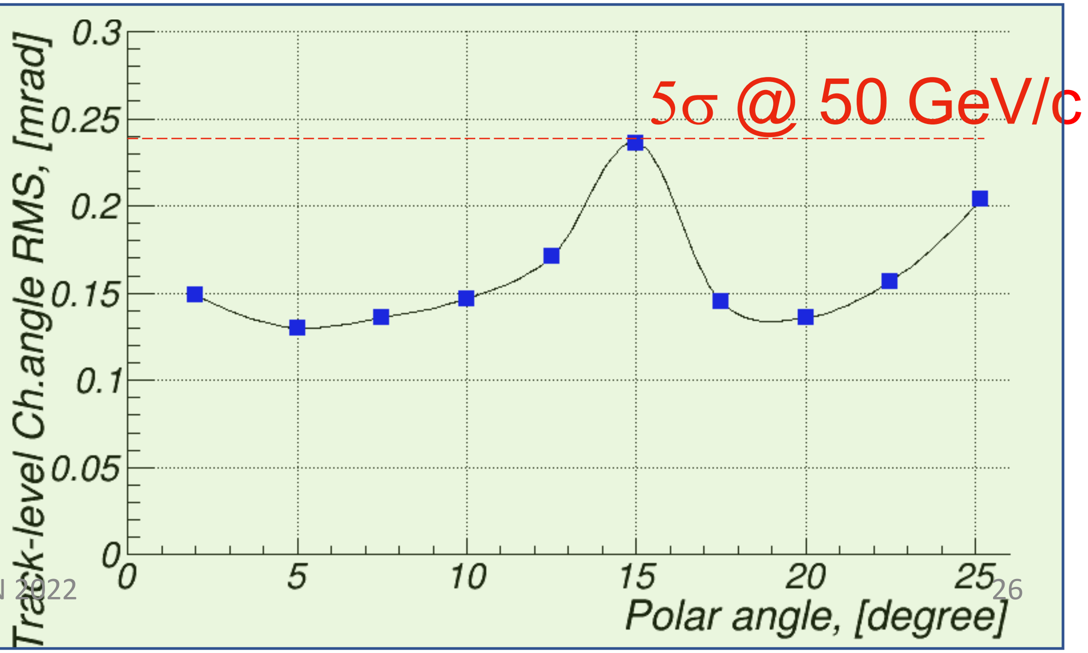


Inverse Ray Tracing: performance plots (C_2F_6, 50 GeV/c π^+)

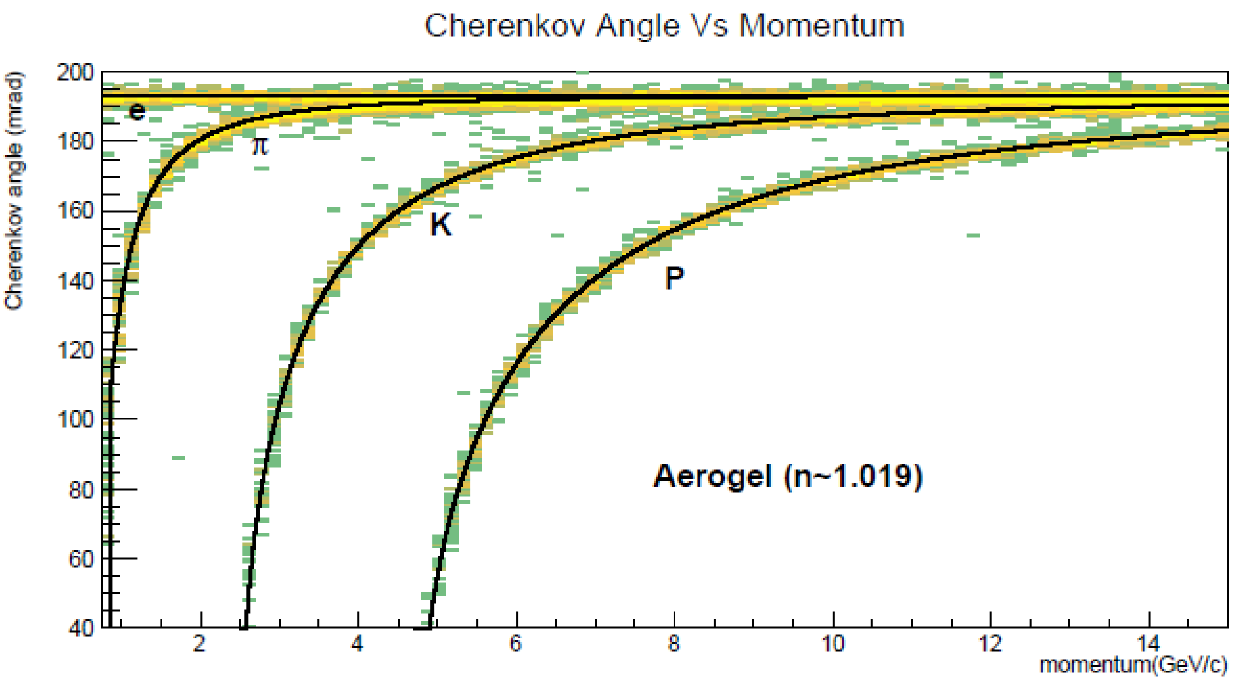


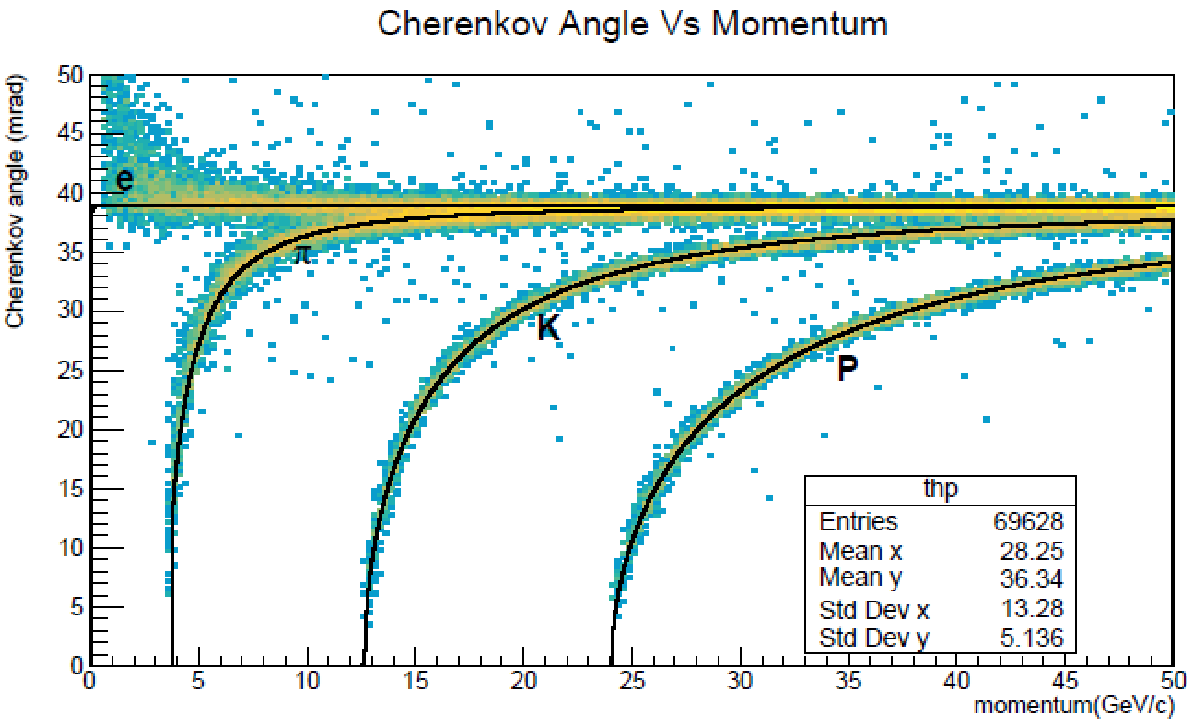






Reconstructed Cherenkov Angle Vs momentum





@ pseudo rapidity = 2.4