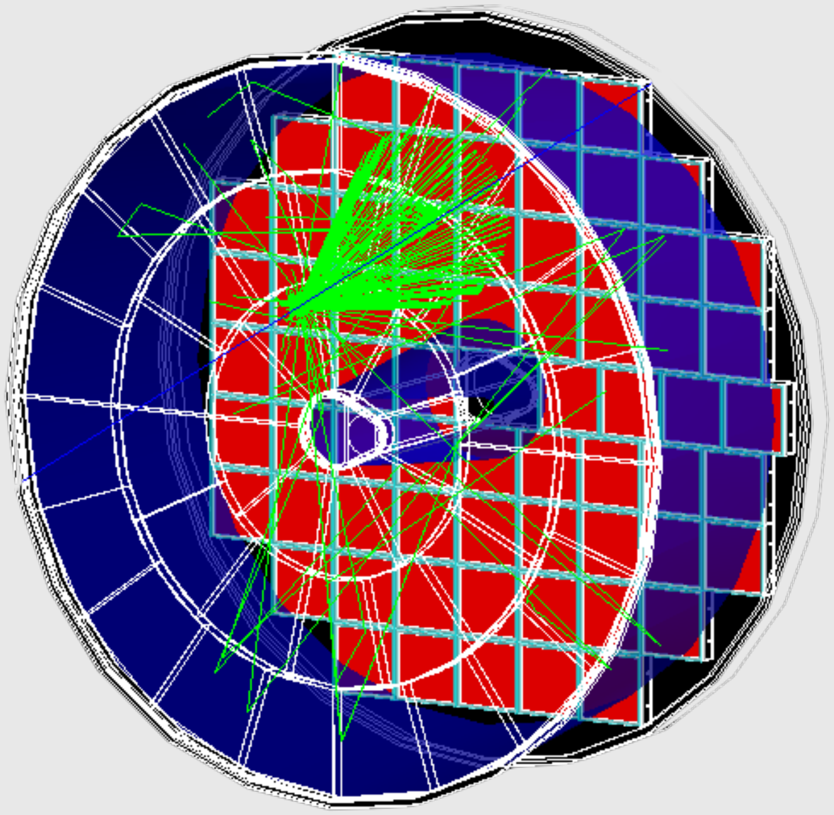
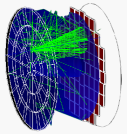
pfRICH Performance Study in ePIC



pfRICH:

- ❑ ⟨Acceptance⟩ > 95%: $-3.5 < \eta < -1.5$
- ❑ e/π separation : $3\sigma \rightarrow p$ = 2.5 GeV
  π/k separation : $3\sigma \rightarrow p$ = 9.0 GeV

Chandradoy Chatterjee (INFN TS)
Kong Tu (BNL)



Outline of this talk

- Introduction to the software
- Geometrical visualization
- **Performance studies**
- Conclusions

Questions to address

A. Comparison of the present assessment of the **Cherenkov PID** detector performance compared with the **YR requirements**?

B. Performance perspectives beyond the YR (if any)?

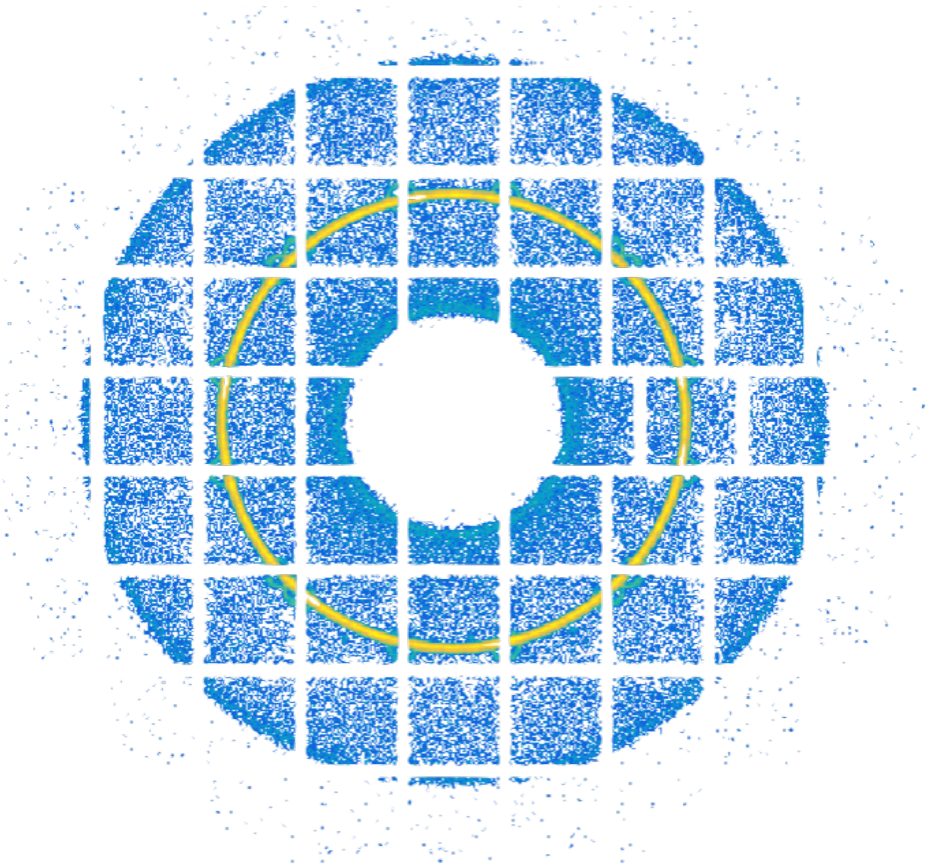
C. Efficiency figures: single particle **π/k/*p*** identified as **π/k/*p*** as a function of the truth momentum in a 3x3-panel figure?

D. Please quantify the performance for **e/h** separation.

E. Active/dead area as 2D function of **η** and ϕ; and comment on the edge effects?

F. Performance or potential as **TOF detector**, providing both timing resolution and acceptance coverage in **η** and ϕ.

G. Under the coordination of the SIDIS working group, provide **Kaon Purity** in the kinematic region of (x. .. Q2…) via parameterized hadron PID performance.



Software

Standalone GEANT simulation environment

- No predefined data model (ROOT C++ serializer interface a la FairRoot)
- No configuration files
- Custom GEANT stepping code
- MC event: a C++ class instance (full history stack of charged particles and optical photons)
- ROOT-based persistency model for events *and optical configuration*
- RC event: identical to the MC one + reconstruction-related fields
- No external dependencies but on ROOT and IRT library from this point on

→ Standalone Geant4 detector description (click)
→ Reconstruction software in EIC stack (click)

Standalone GEANT simulation environment

Simulation

- **Complete** and **precise** geometry description
- Optional import of ePIC geometry pieces in GDML
- ePIC magnetic field

Calibration

- Extensive use of Cherenkov photons which did not pass the QE test (e.g., as a replacement for tracking)

Digitization

- DC-coupled HRPPD, 32x32 pads, no charge sharing
- *Event-level* model (no hit double counting, etc.)

Reconstruction

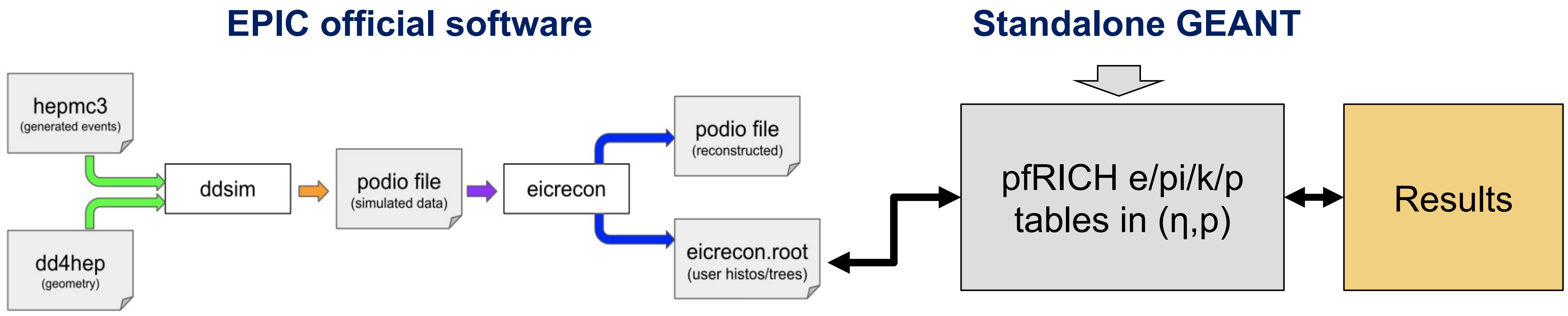
- *Event-level* χ^2 -based statistical model (95% correct PID in Overlapping pion kaon; **first time event based chi-square analysis** in ePIC Cherenkov PID)
- Configurable combinatorial ring finder
- Complete hit-to-track ambiguity resolution

Custom GEANT/ROOT environment

'pfrich' branch in ePIC IRT repository

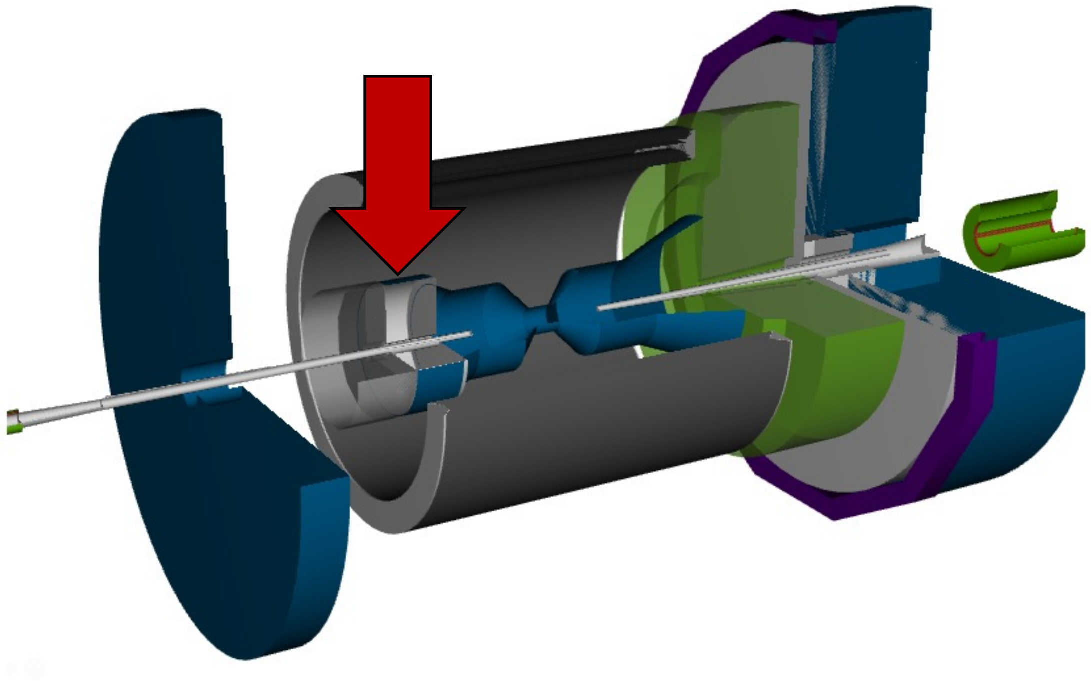
Workflow: standalone G4 + ePIC stack

1. Create Delphes-like PID smearing matrices using **standalone GEANT4** modeling
2. Use **EPIC official software** stack
3. Apply pfRICH delphes-like **parametrization for PID** to the reconstructed particles
4. Make use of the **official simulation** campaign files (e.g., DIS) whenever is possible

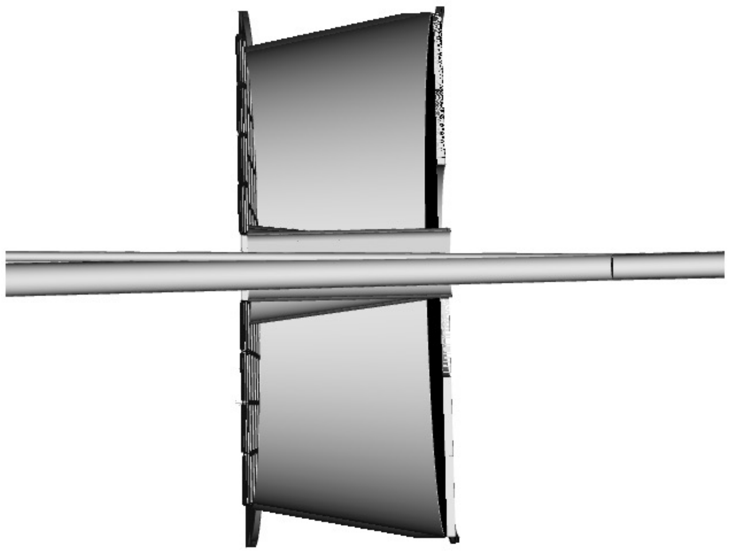


Click for Github repo

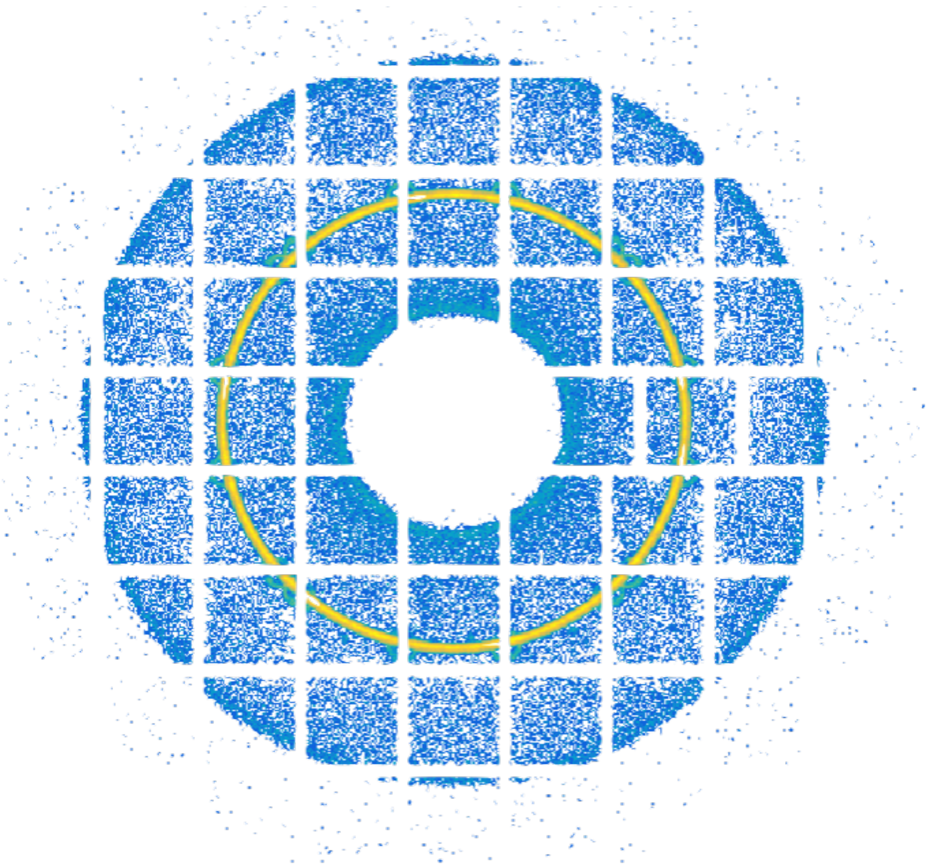
The software in ePIC software stack



By Christopher Dilks

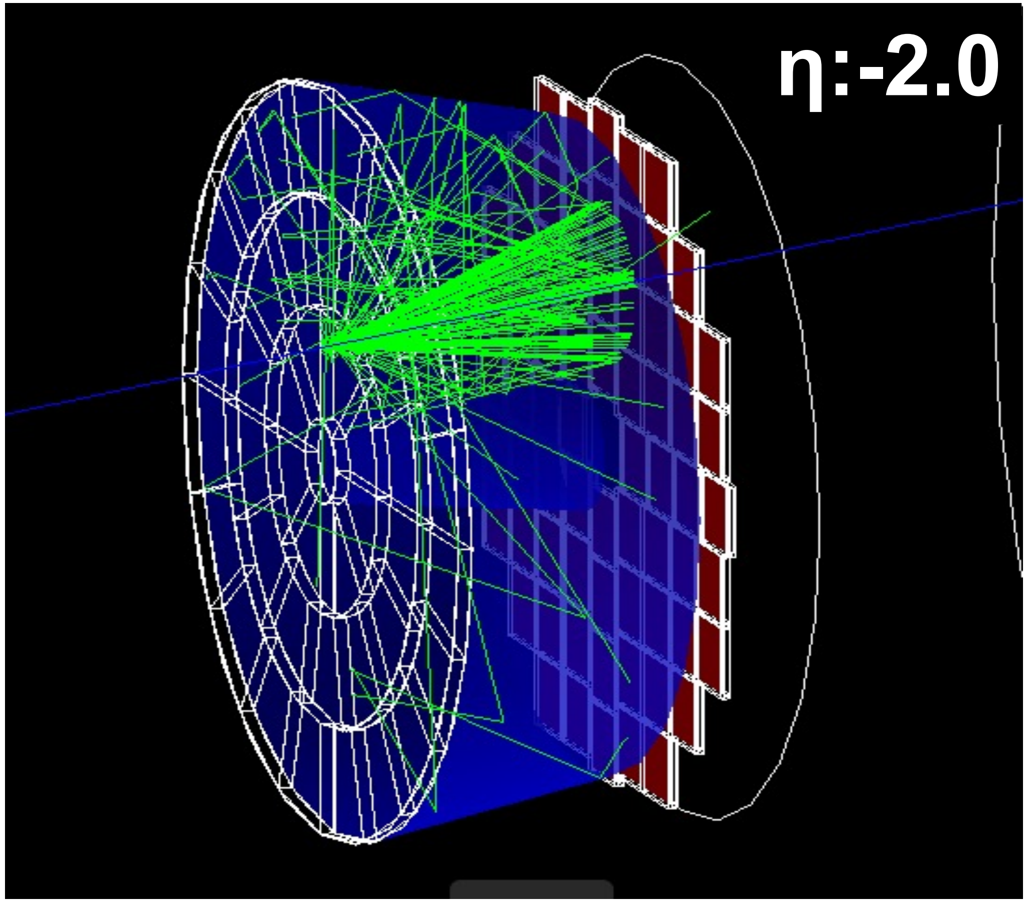


- ➢ pfRICH is in **ePIC official software**. No overlap with other sub-detectors.
- ➢ Previous version of IRT (developed in ATHENA) already exists in official reconstruction framework **EICRecon**.
- ➢ Now, forward dualRICH detector uses the IRT (ATHENA version) for PID.

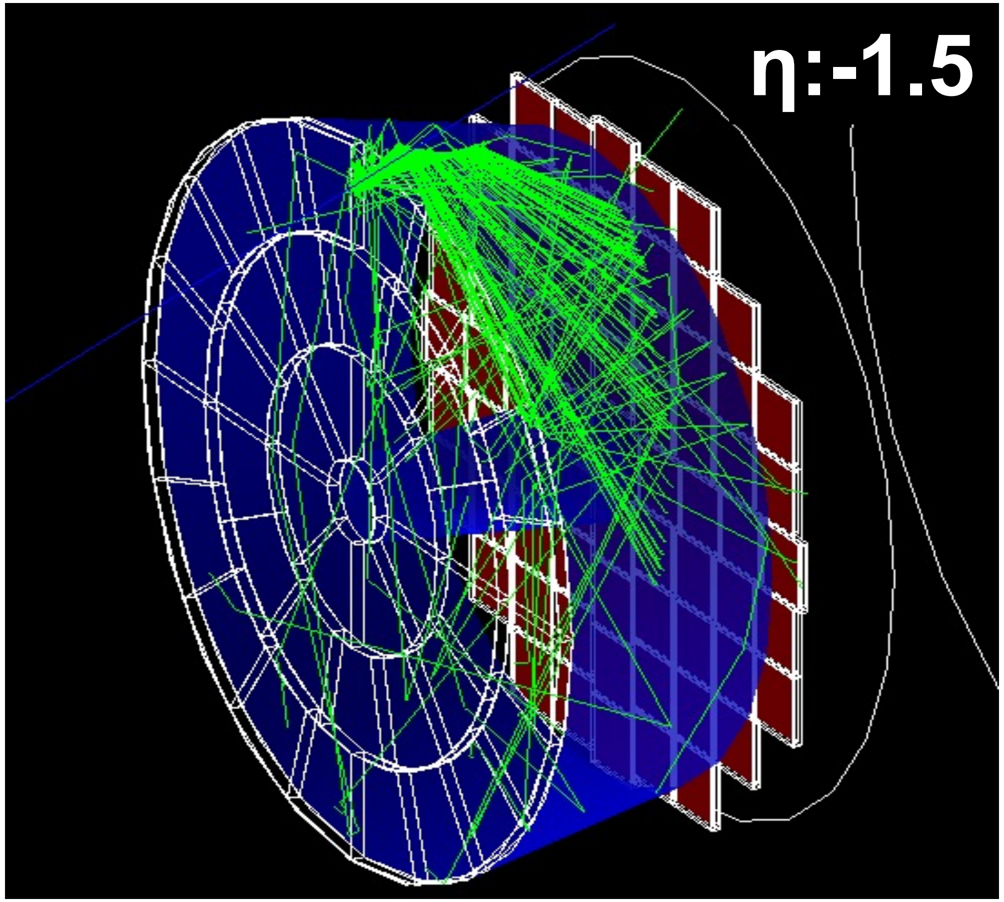


Visualization

Photon image rings by 7 GeV/c pions

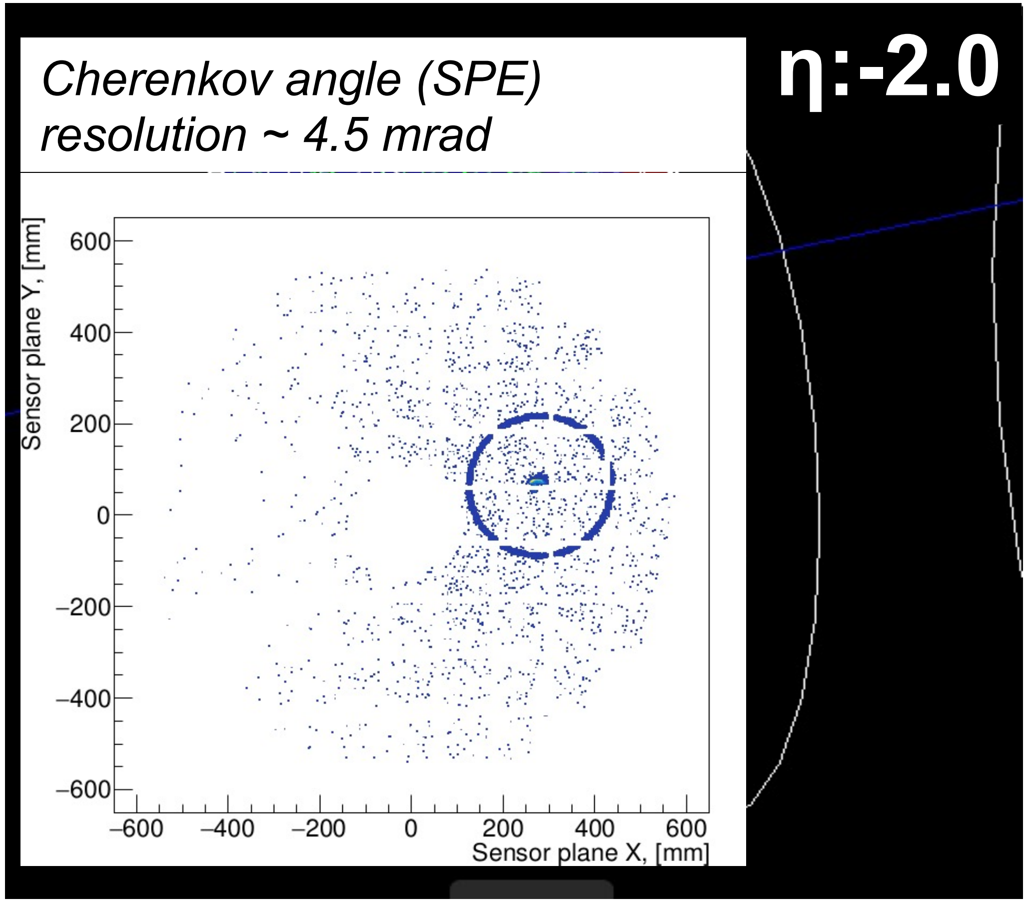


Center of pfRICH

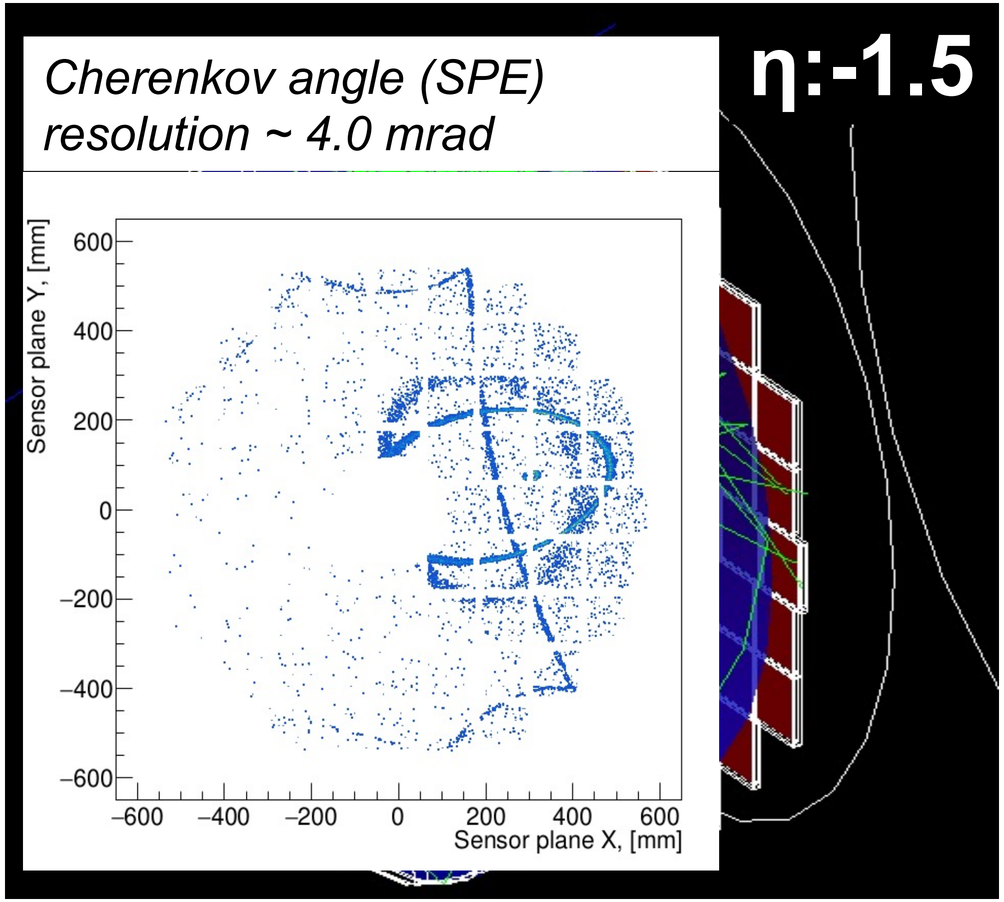


Edge of pfRICH

Photon image rings by 7 GeV/c pions



Center of pfRICH



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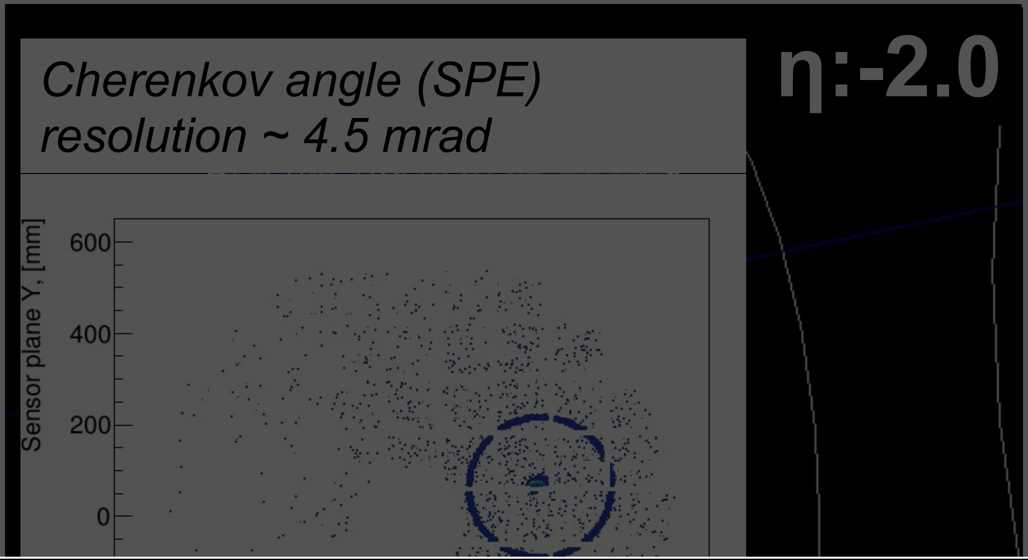
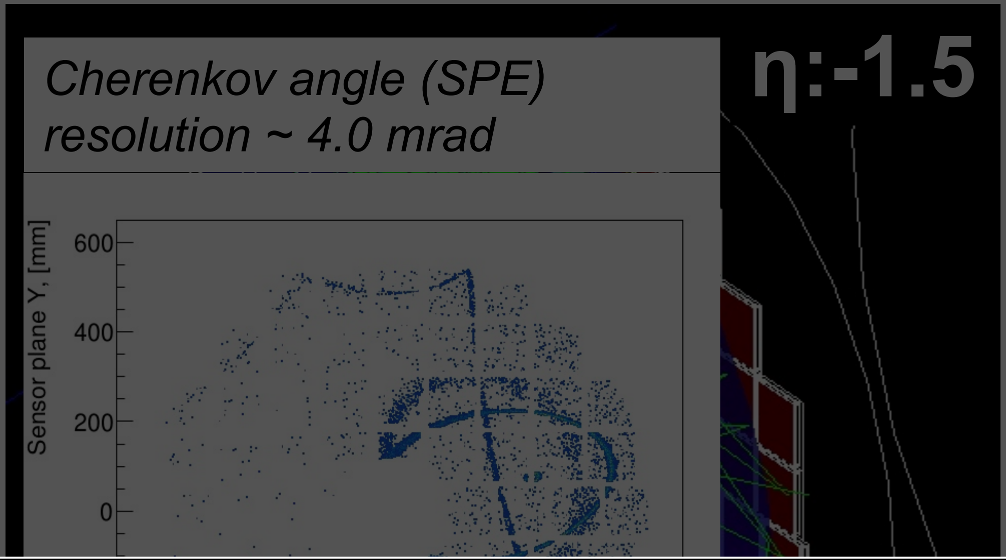
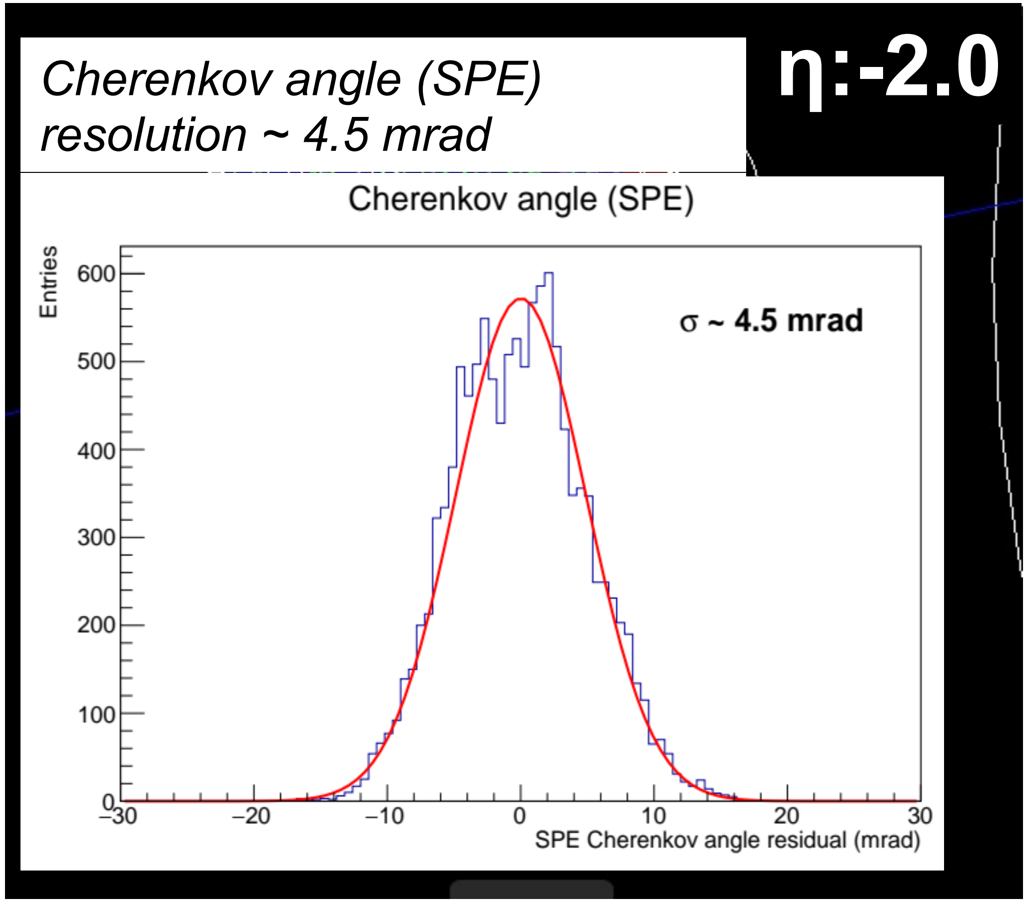




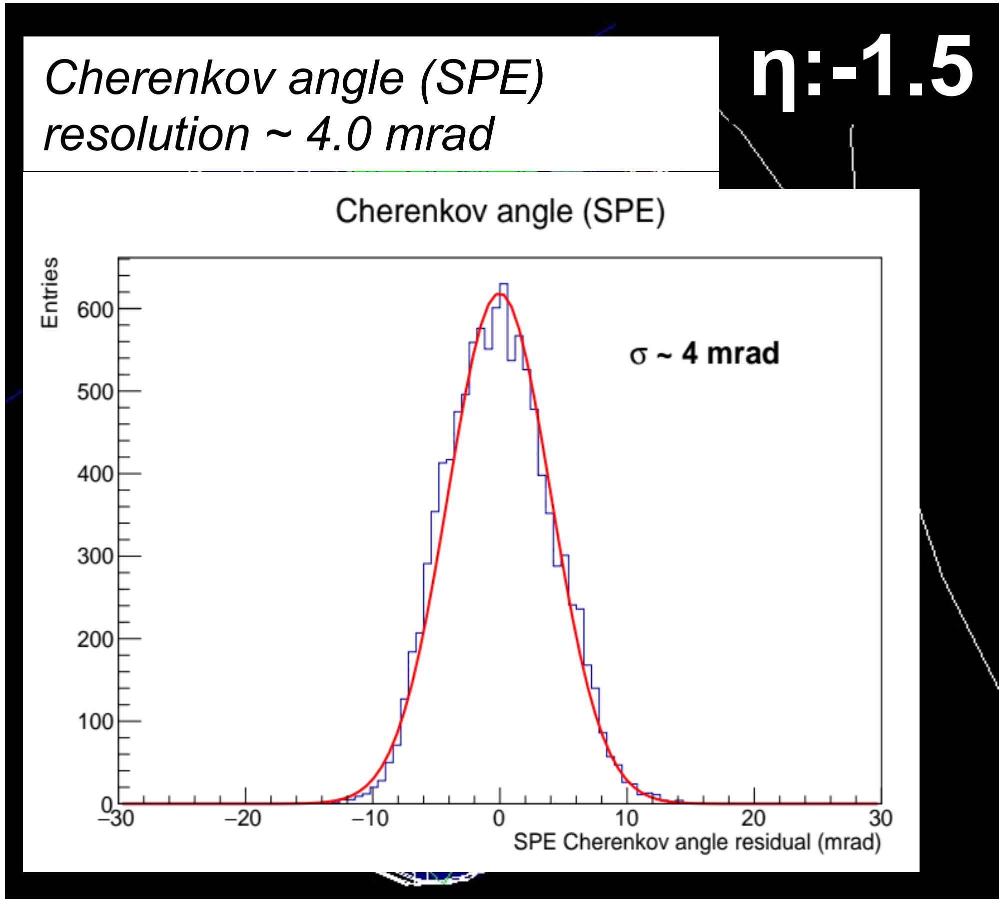
Reflected and **direct** rays generate substantially different hit maps.

→ Reconstruction algorithm is capable to incorporate these categories.
→ Similar single photo-electron resolution.

Similar SPE angular resolution. Small difference?

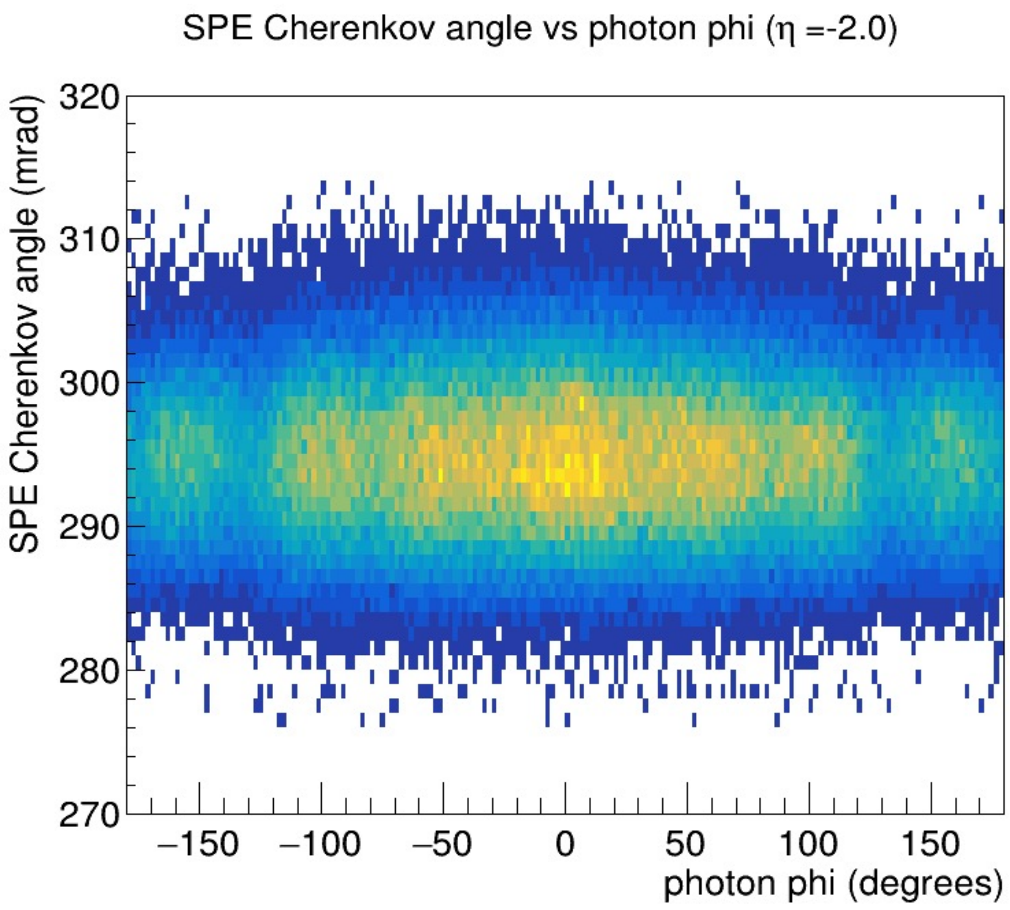


Center of pfRICH

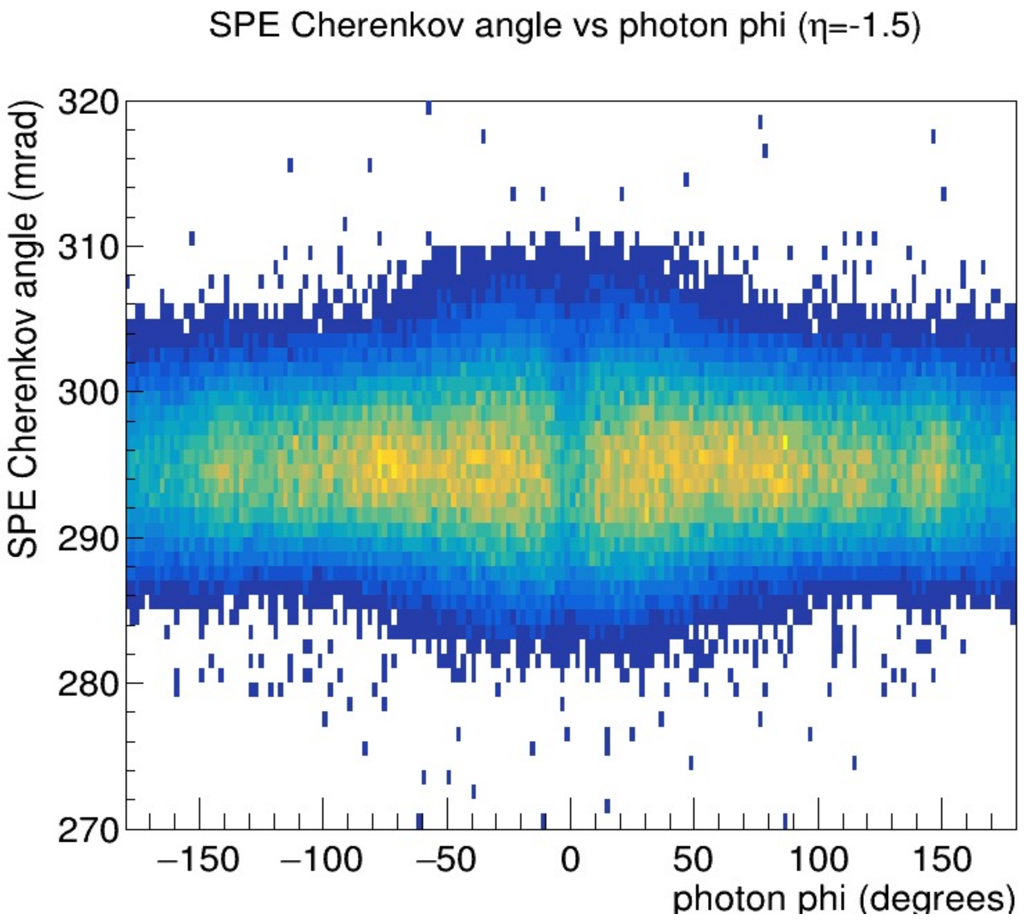


Edge of pfRICH

Less photon scattering at the edge of pfRICH

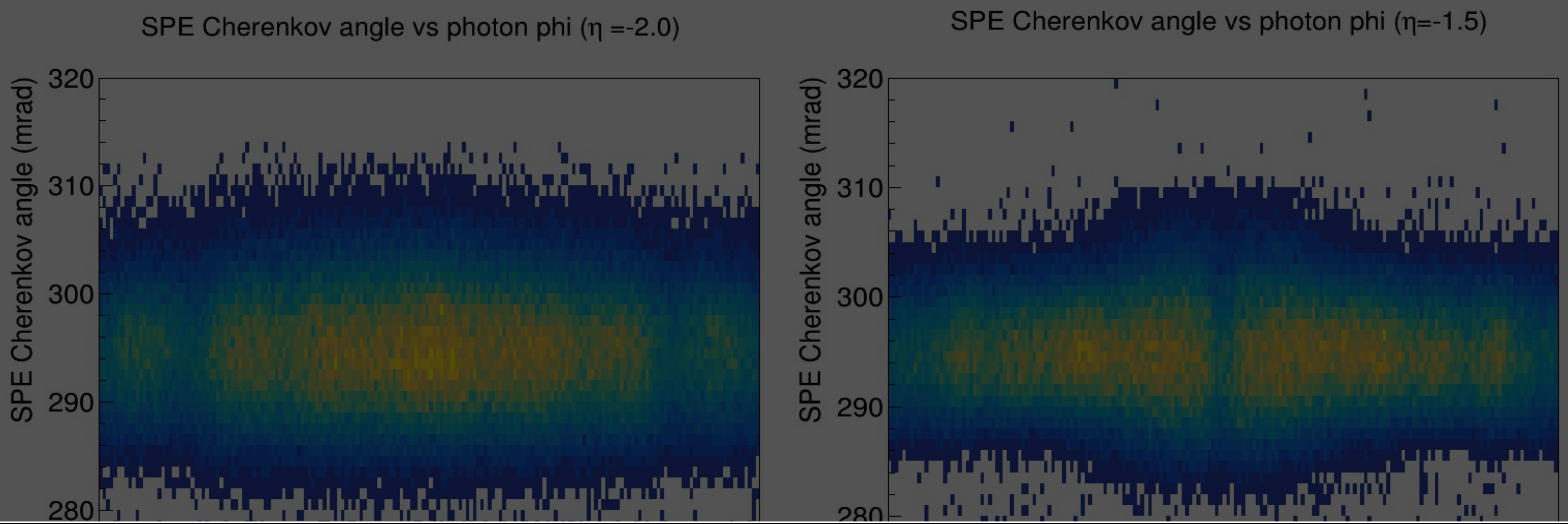


Center of pfRICH



Edge of pfRICH

Less photon scattering at the edge of pfRICH



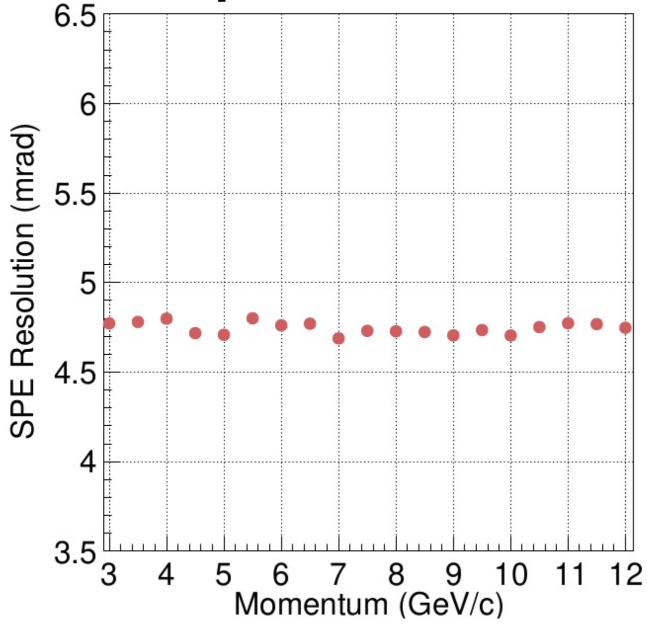
Photons entering at large angles traverse less material inside aerogel in specific ϕ → less emission uncertainty → better resolution.

Center of pfRICH

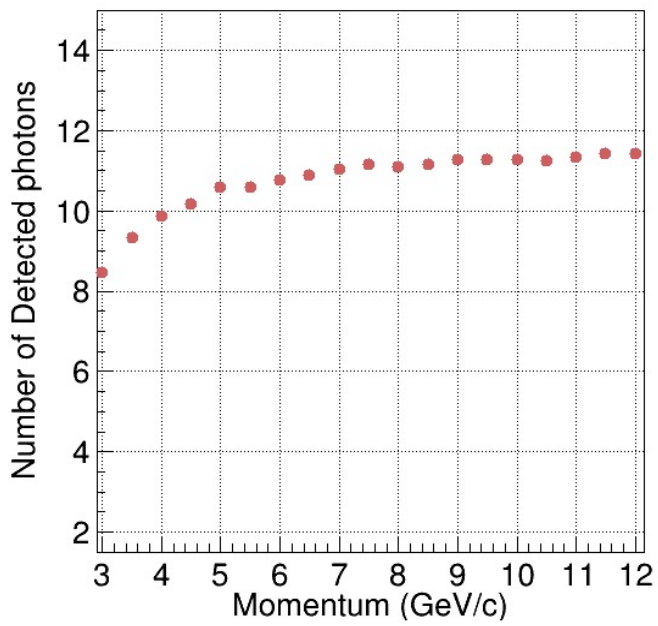
Edge of pfRICH

Consistency Check: scan in momentum

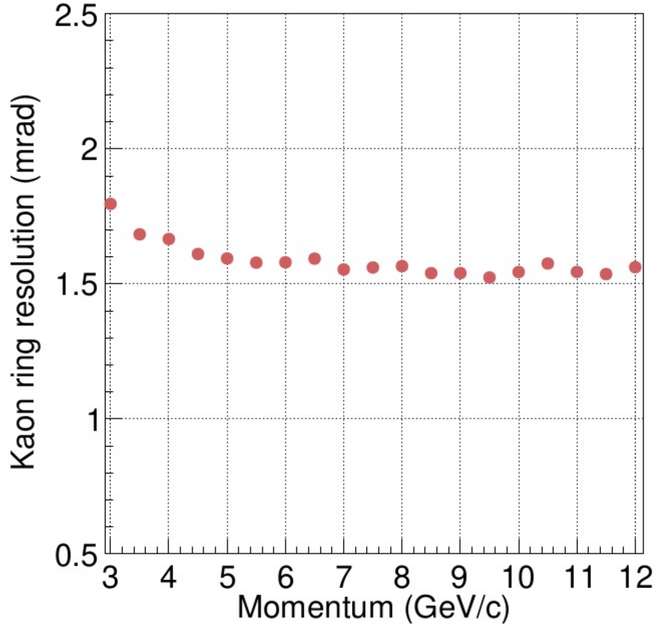
All **η**: SPE resolution



Realistic* QE



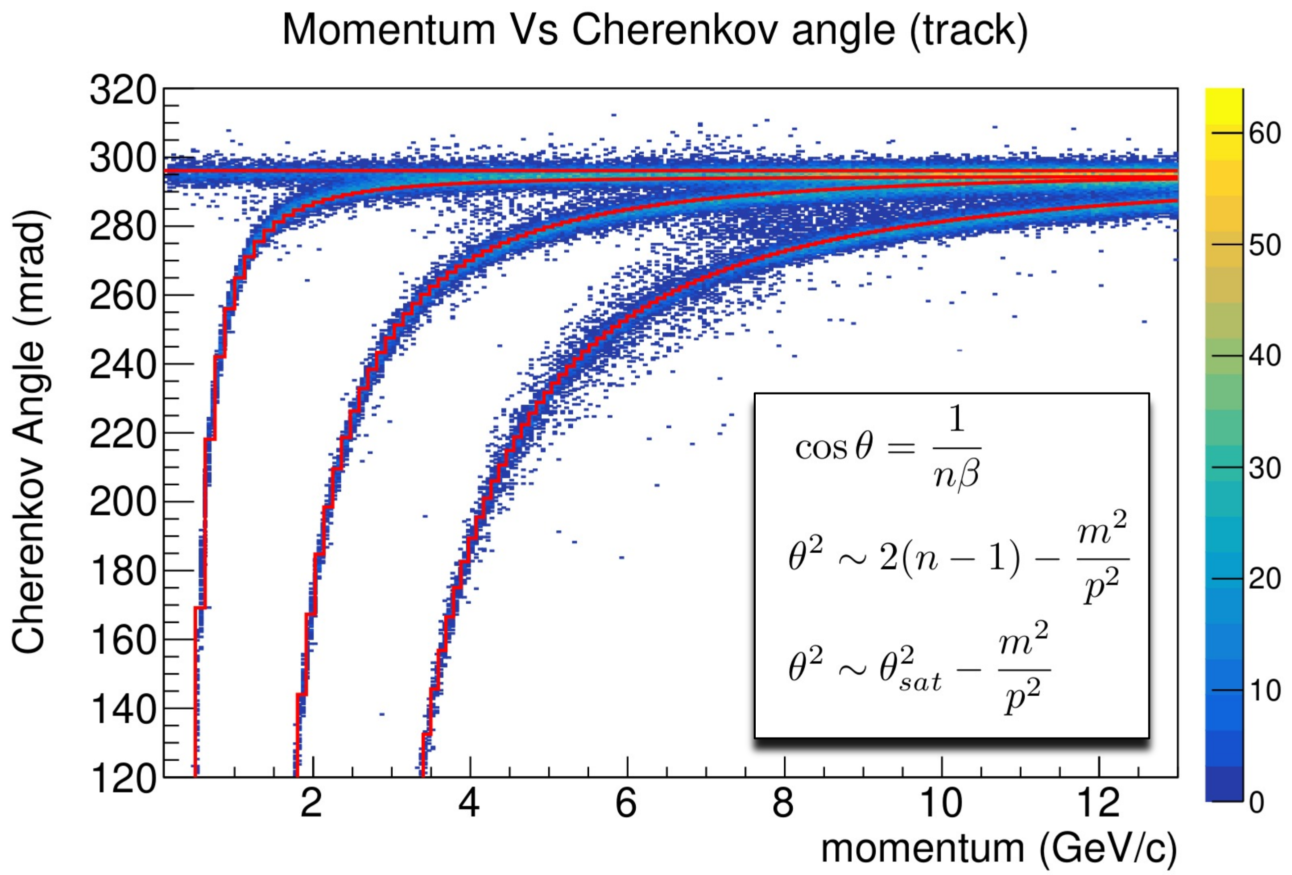
Kaon ring resolution

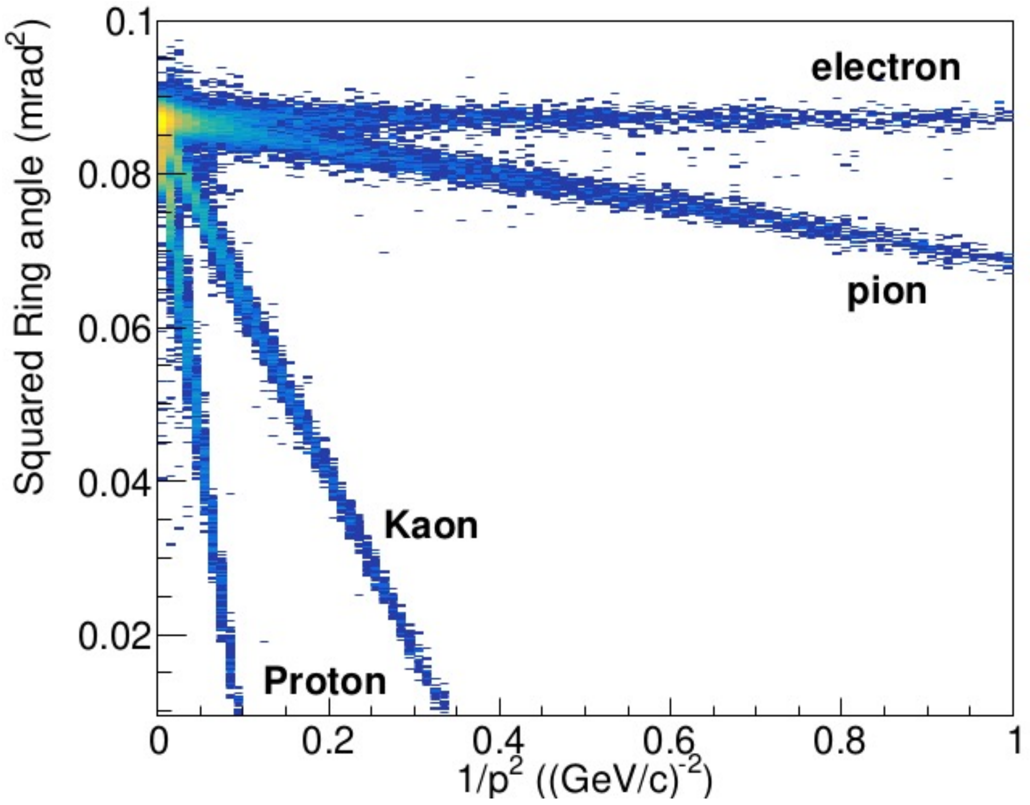


Single photo-electron resolution is constant with momentum (4.5 to 5 mrad).
Track level angular resolution follows N_{pe} evolution.

***** *estimated with 30% safety margin*

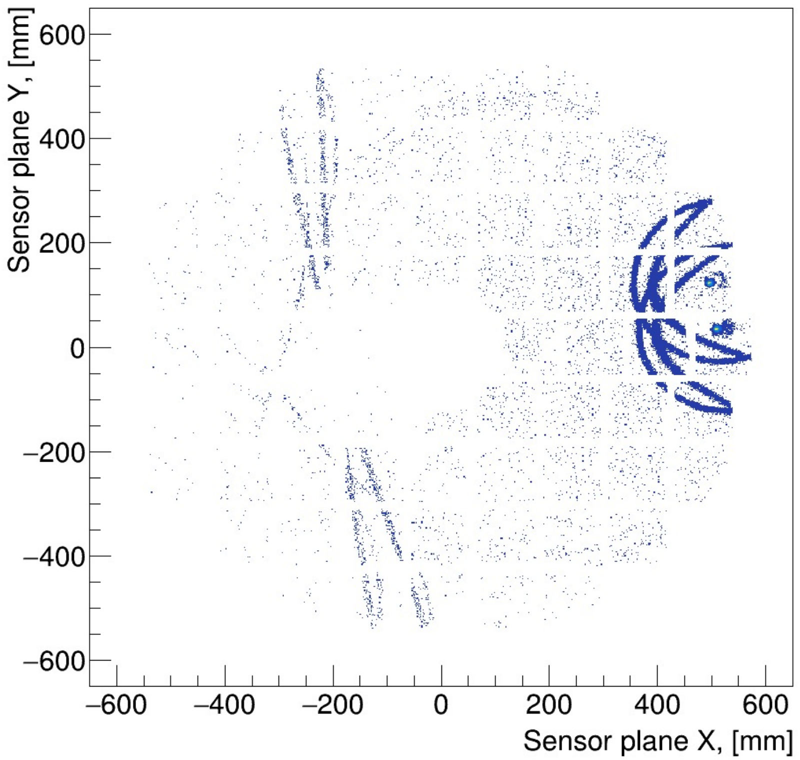
Cherenkov angle and momentum

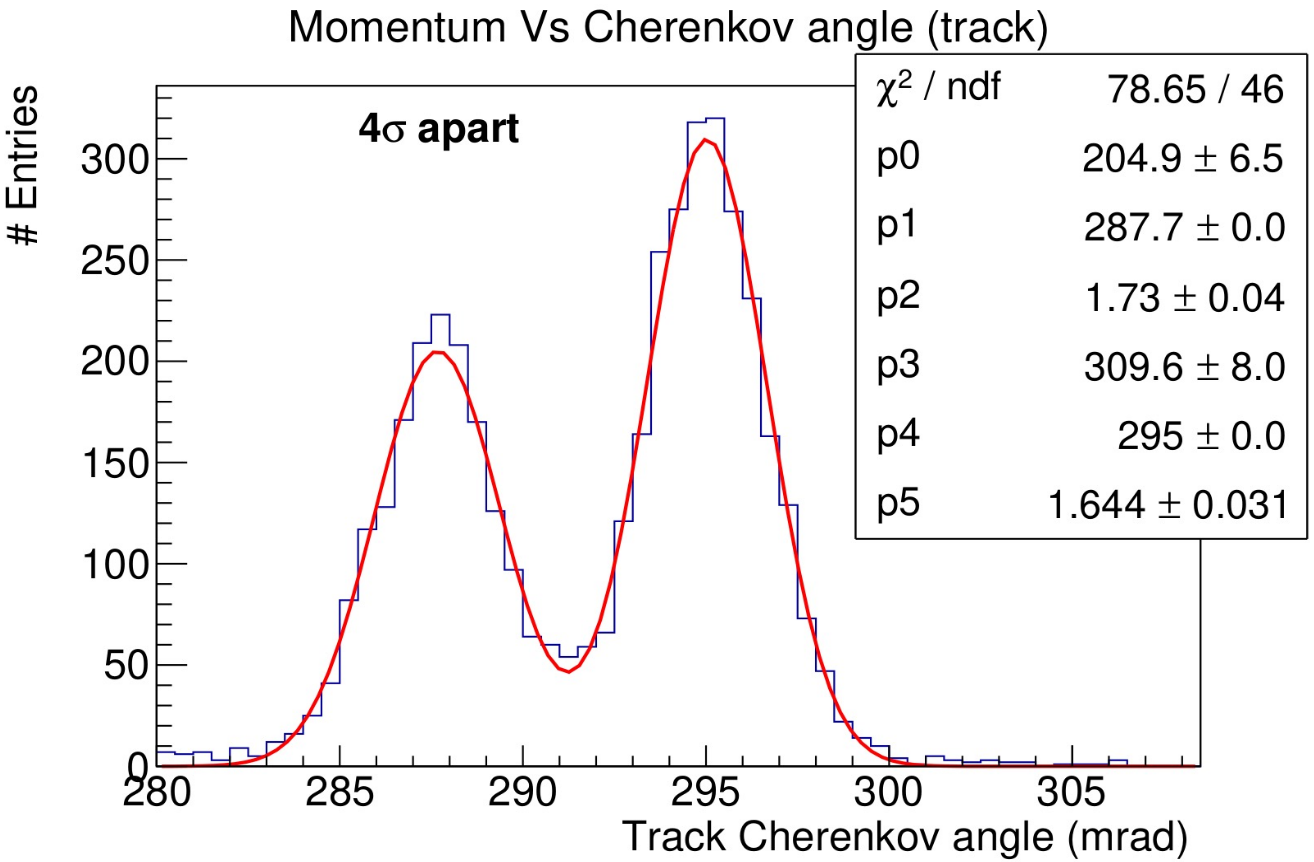




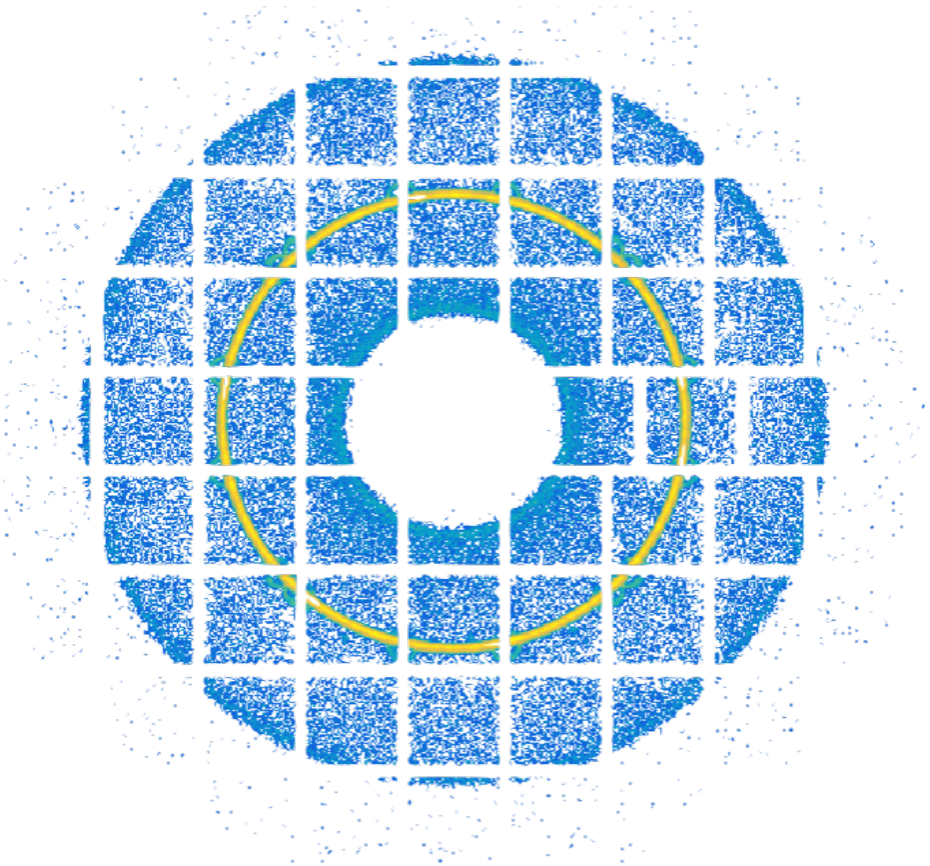
Reconstructed angles well in agreement with expected values.

pfRICH can separate extreme multi-particle cases





- **π** and kaon generated in same event.
- particle ϕ angle chosen to have overlapping rings at border pseudorapidity
- Event-based χ^2 model has a **95% accuracy** separating multi-particles

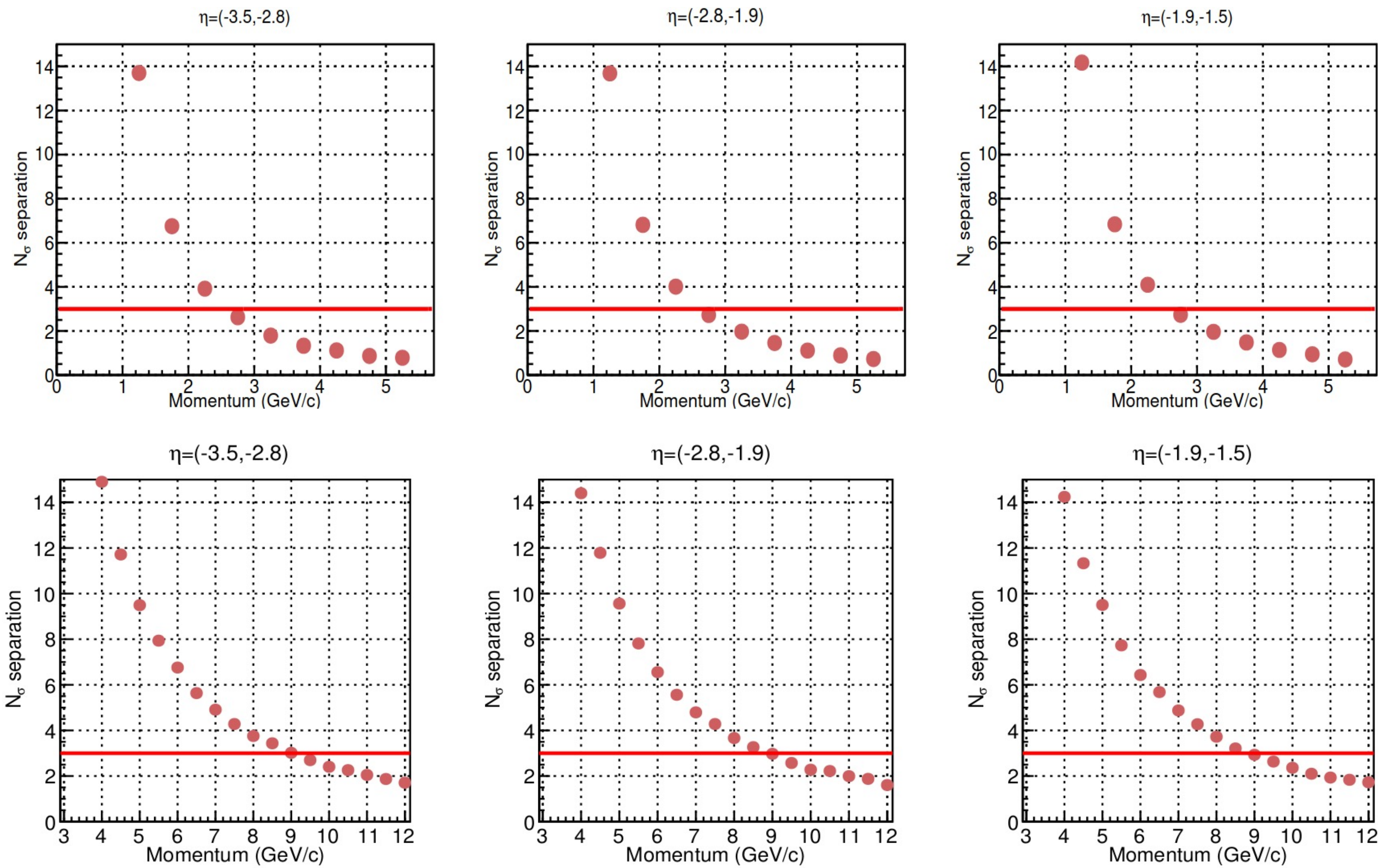


Performance

Performance: e/π & π/k separation

e/π

π/k



3σ at ~2.5 GeV

3σ at ~9.0 GeV

A & B. Comparison to the YR requirement

Table 8.6: Requested PID momentum coverage for 3σ pion/kaon separation.

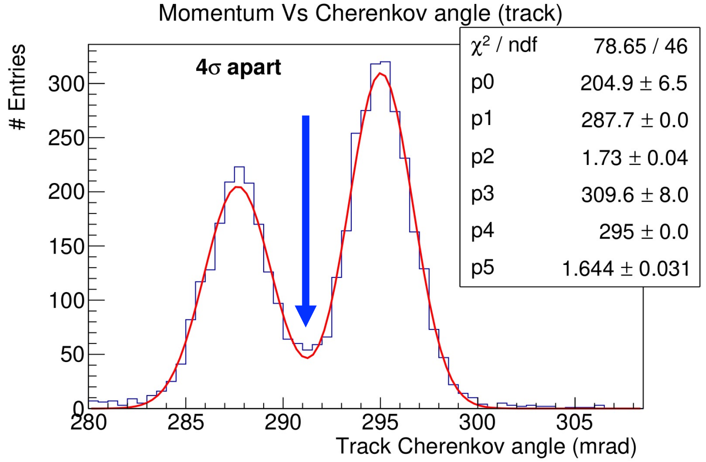
Pseudorapidity Range	Momentum Range
$-3.5 < \eta < -1.0$	≤ 7 GeV/c
$-1.0 < \eta < 0.5$	≤ 10 GeV/c
$0.5 < \eta < 1.0$	≤ 15 GeV/c
$1.0 < \eta < 1.5$	≤ 30 GeV/c
$1.5 < \eta < 2.5$	≤ 50 GeV/c
$2.5 < \eta < 3.0$	≤ 30 GeV/c
$3.0 < \eta < 3.5$	≤ 20 GeV/c

e/π separation ~ 2.5 GeV for 3σ

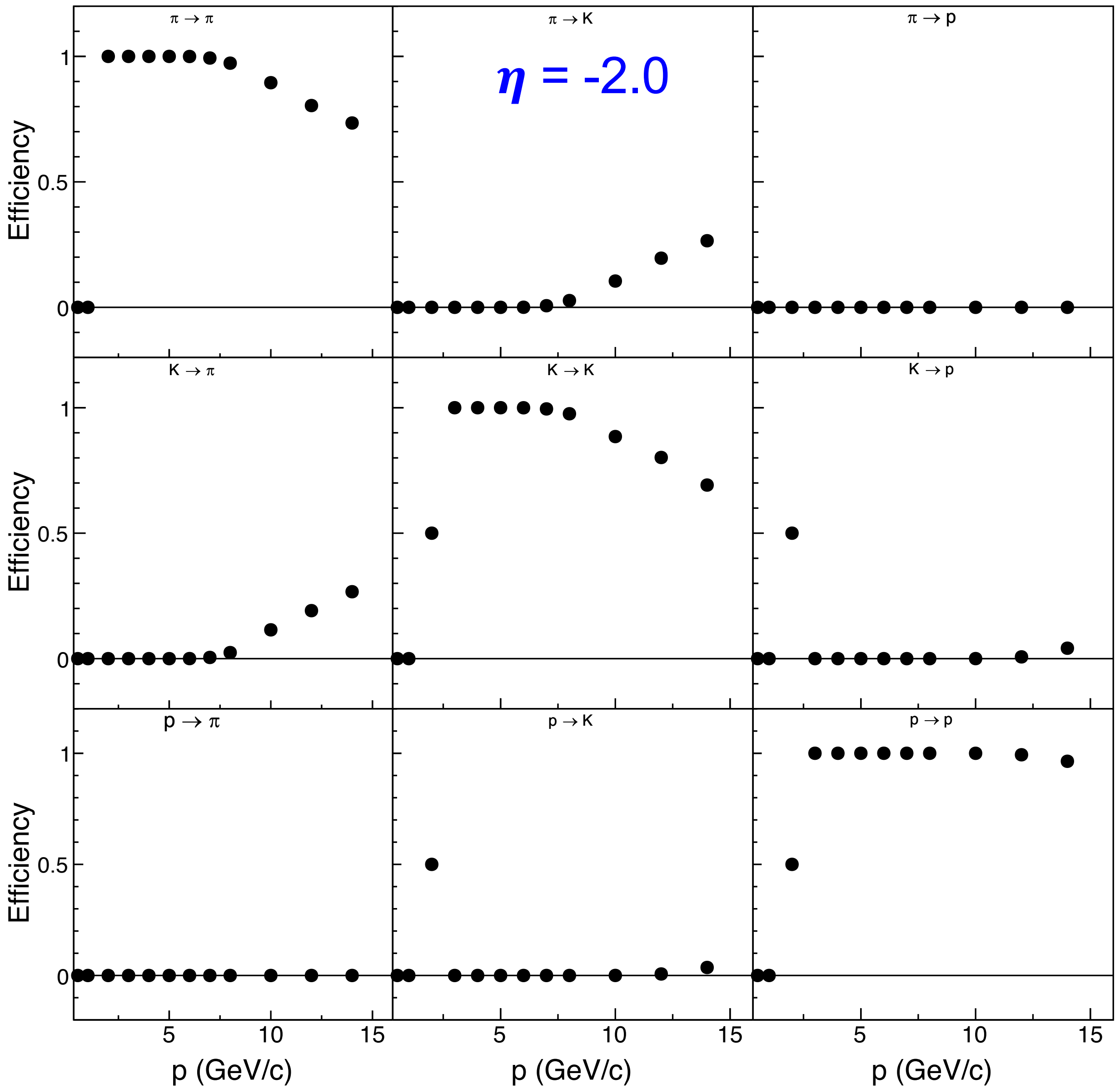
π/k separation ~ 9 GeV for 3σ (Beyond the YR requirement)

C. π/k/*p* Efficiency

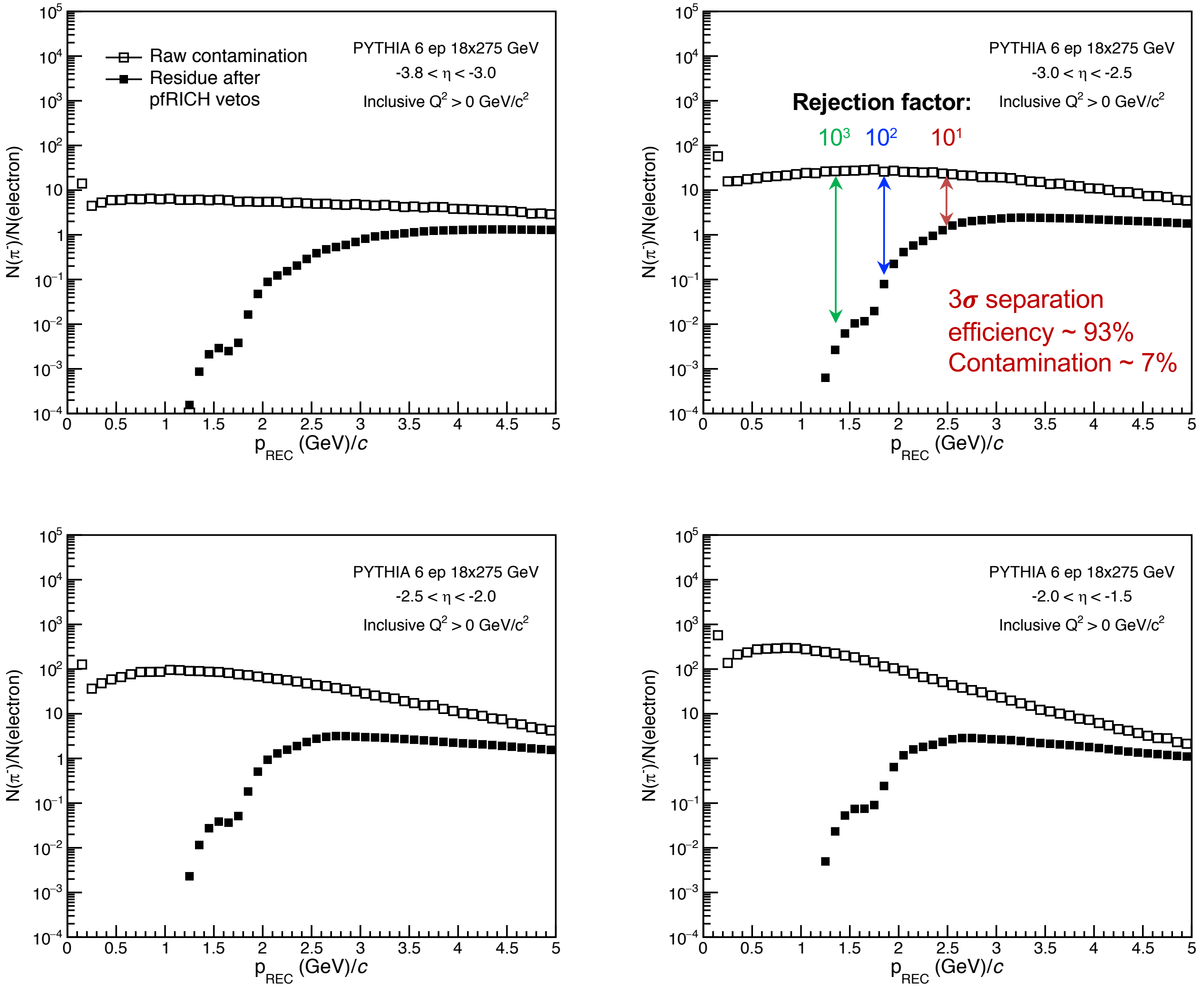
- Efficiency = PID probability for **π/k/*p* → π/k/*p* (3x3)**
- Nominal selection: place **Cherenkov angle cut at the Gaussian overlap.**



example



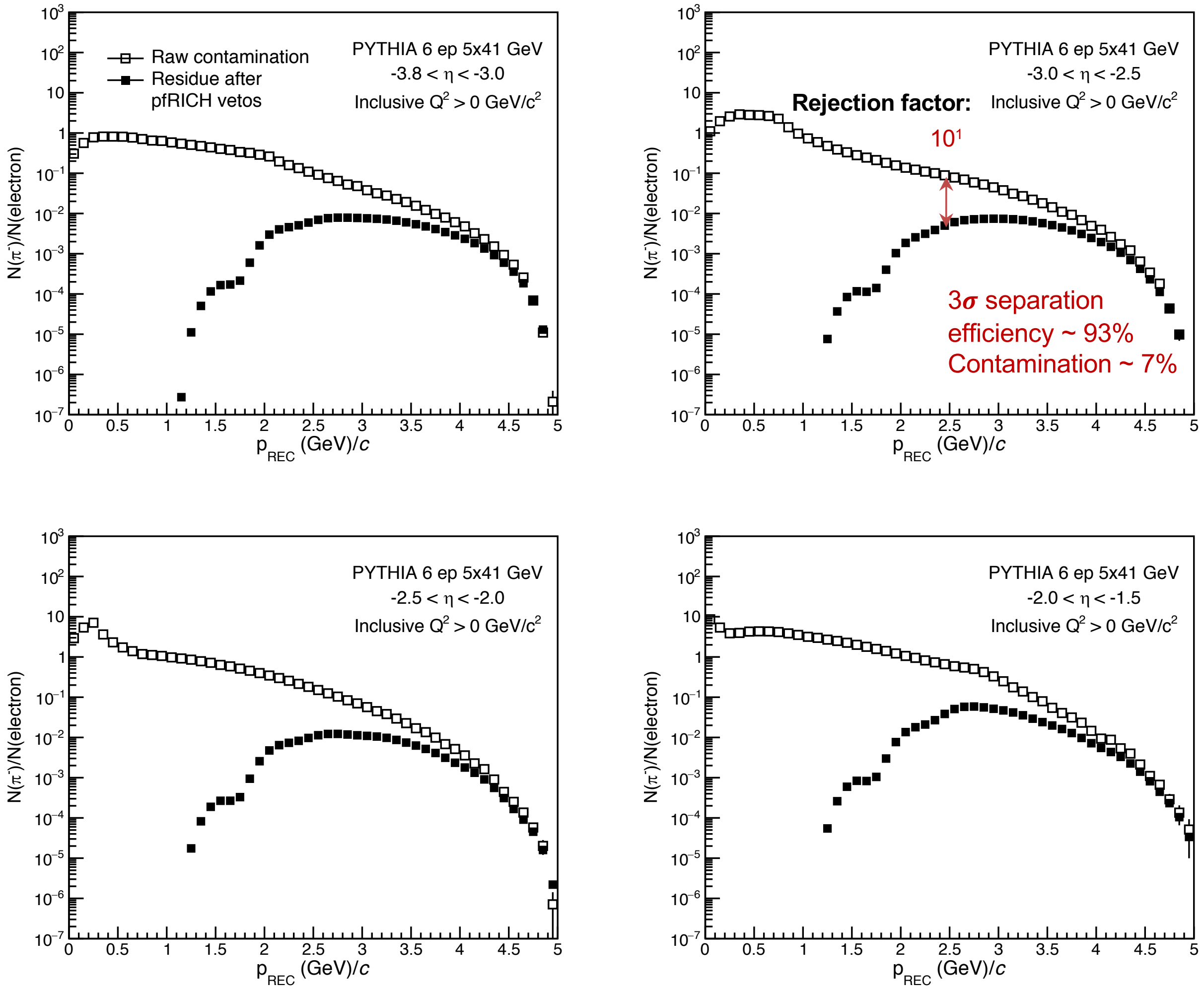
D. pfRICH to separate electron and hadron (π)



ep 18x275 (high energy)

- Ratio = N(**π**)/N(**e**); only pfRICH rejection power considered.
- Low momentum region corresponds to **low-x** region - important for **Saturation** related physics.
- EMCal: pion rejection performance worsen at low momentum. However, **pfRICH can complement.**
- PYTHIA 6 sample with ePIC tracking resolution effect implemented. *(Impact of smearing is small*)

D. pfRICH to separate electron and hadron (π)

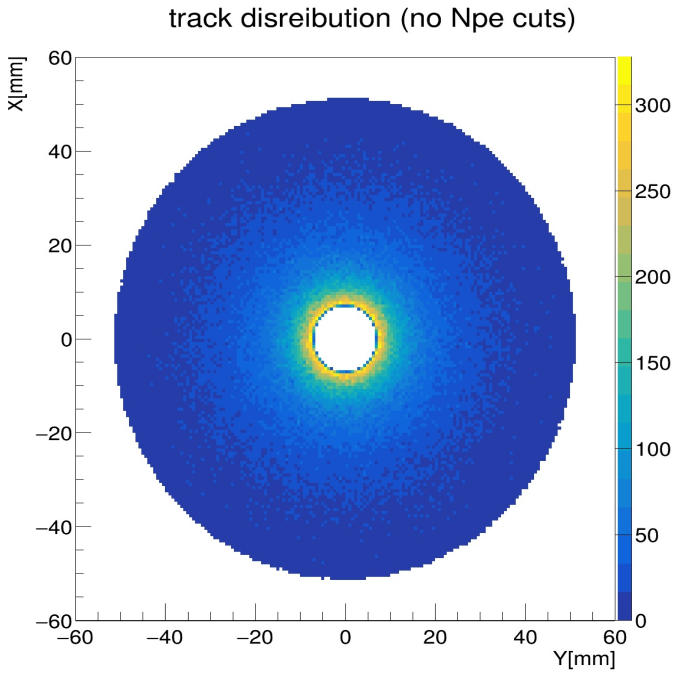


ep 5x41 (low energy)

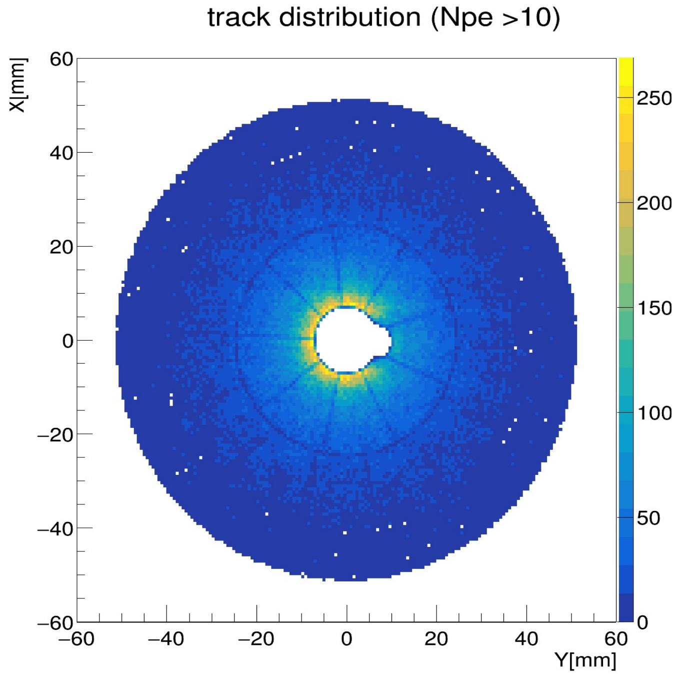
- Ratio = N(**π**)/N(**e**); only pfRICH rejection power considered.
- Momentum range correspond to **high(er)-x physics.** Important for **anti-shadowing** region **& EMC** region
- EMCal: pion rejection performance worsen at low momentum. However, **pfRICH can complement.**
- PYTHIA 6 sample with ePIC tracking resolution effect implemented. *(Impact of smearing is small)*

E. Active and dead area

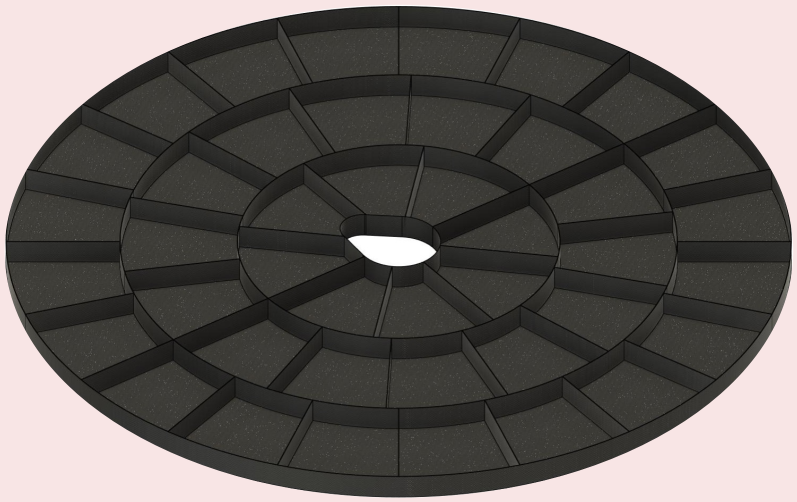
7 GeV pions $\langle N_{pe} \rangle \sim 12$



Uniform track distribution w/o N_{pe} cut

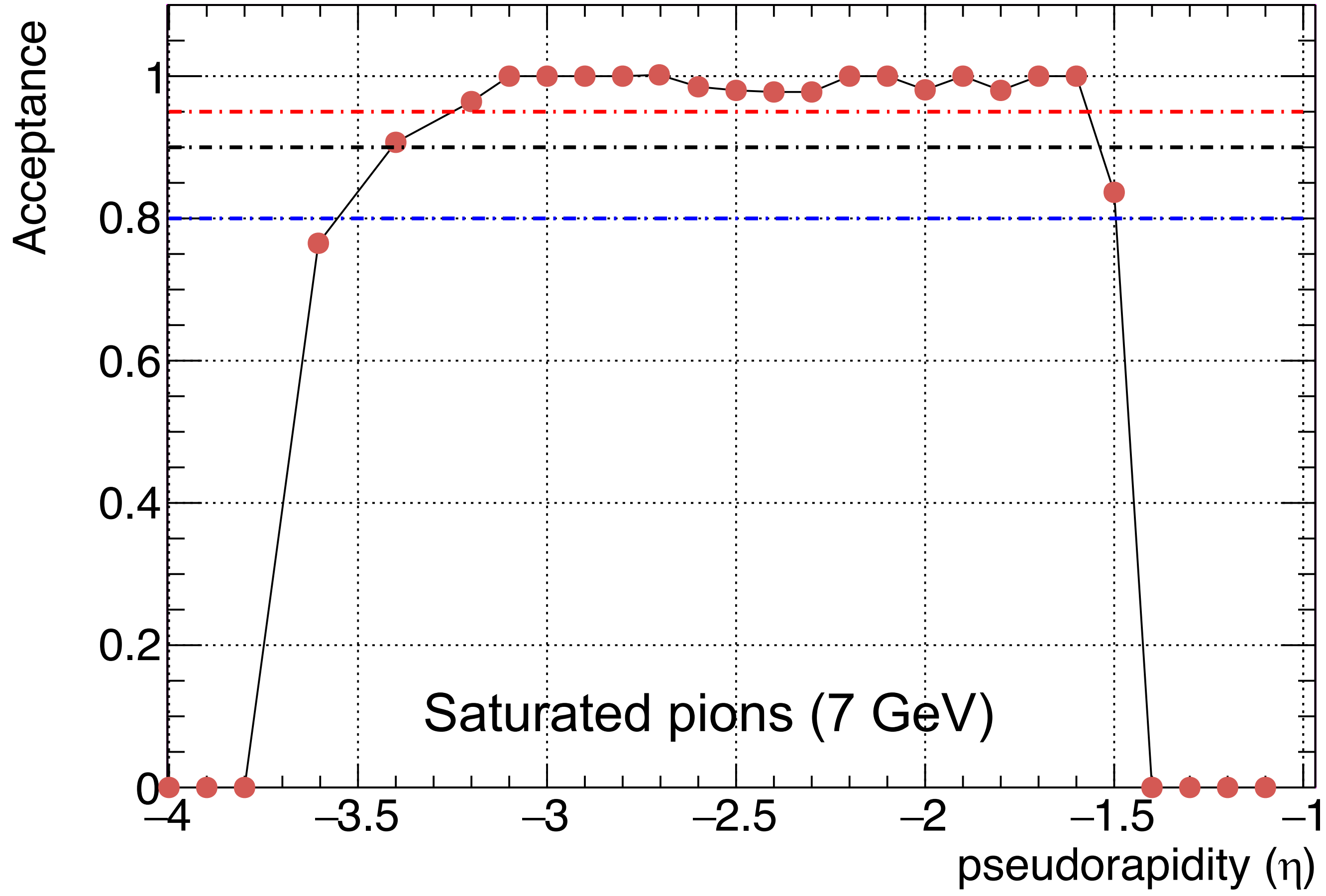


Track distribution with more than **10 photons**

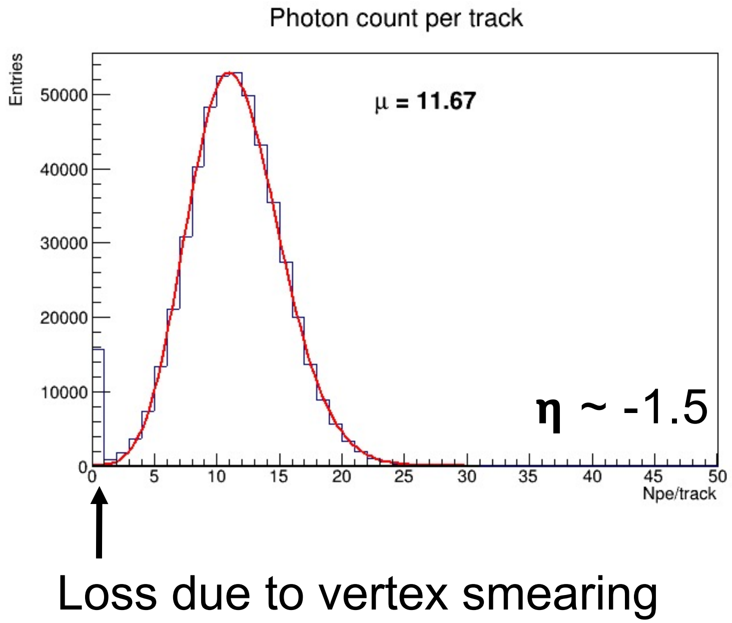


- Aerogel **holder ribs** absorbs photons.
- No discontinuity compared to initial track distribution. Tracks with $N_{pe}>10$ is uniform in eta-phi space

E. Edge effect and acceptance



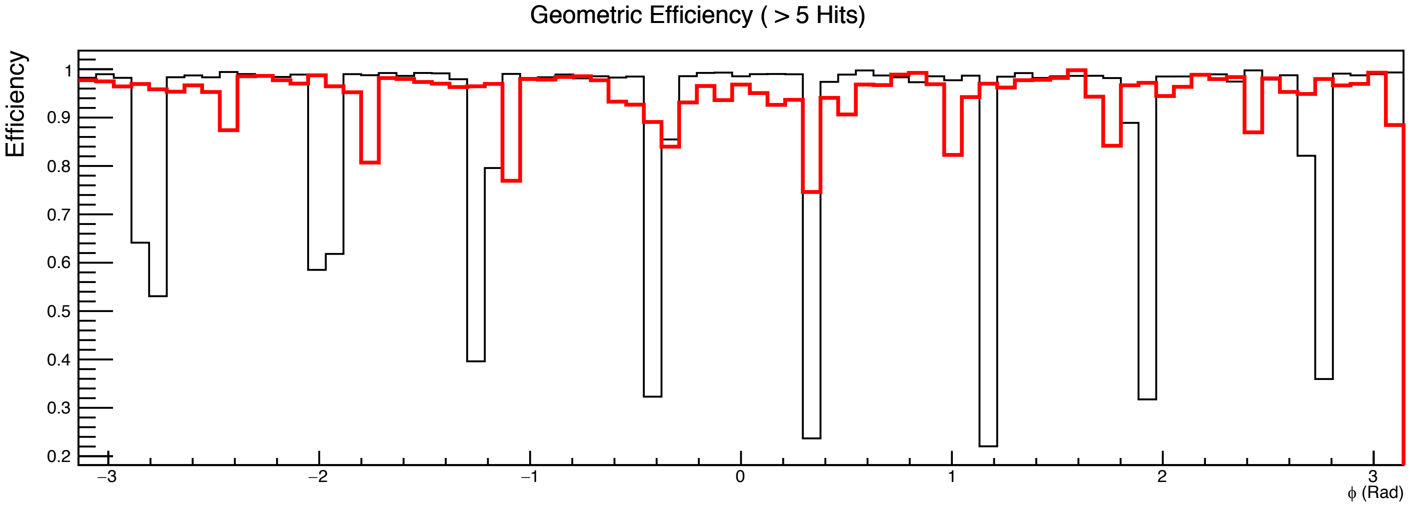
$$\text{acceptance} = \frac{N_{\text{charged tracks}}(N_{pe} > 0)}{N_{\text{charged tracks}}}$$



⟨Acceptance⟩ > 95 % for -3.5 < **η** < -1.5

pfRICH Time-of-Flight Perspectives

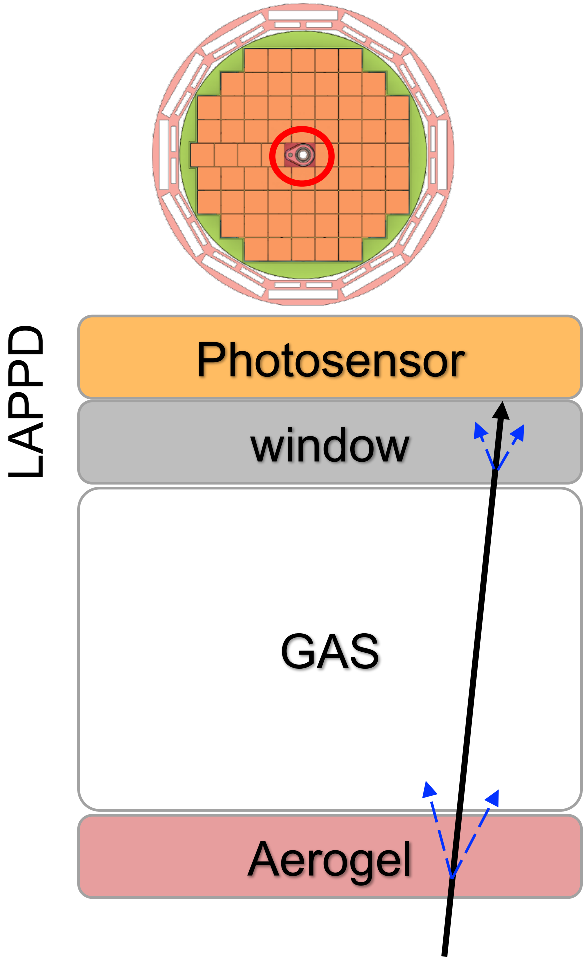
- **ToF** meas. ← # photon hits created by particles
  - pfRICH receives photon hits from aerogel, acrylic filter, gas in expansion volume, and **LAPPD window**
- **Efficiency** (η, ϕ): prob. of particle creating $N_{pe} > 5$.
  - **20 ps t_0 resolution** by having 6 photons, assuming 50 ps single photon time resolution (timing resolution **20ps = 50ps /** $\sqrt{6}$).



Red dips → ribs from Aerogel wall

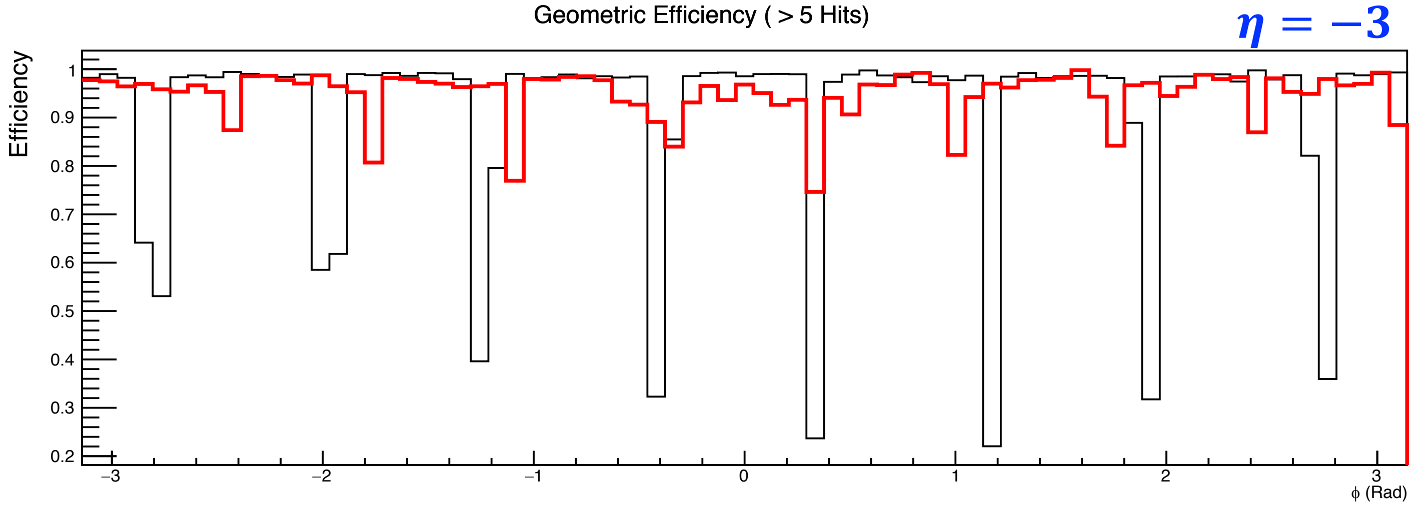
Black dips → ribs from window ceramic boundary

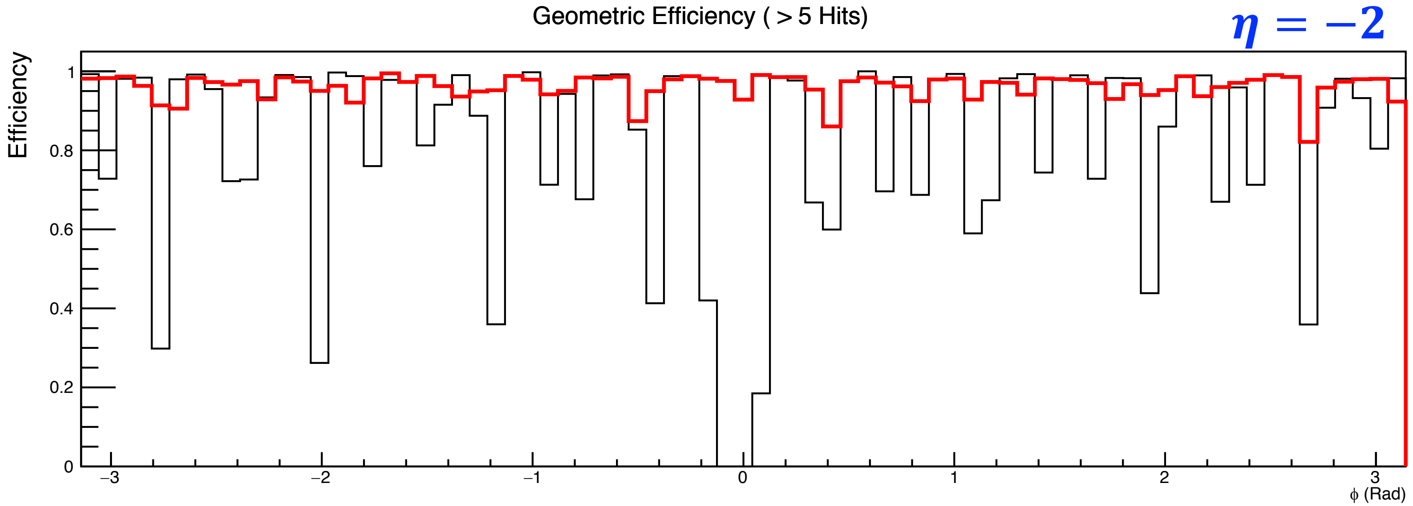
Number of photon hits



Single Particles fired at $\eta = -3$

Geometric ToF Efficiency vs. φ





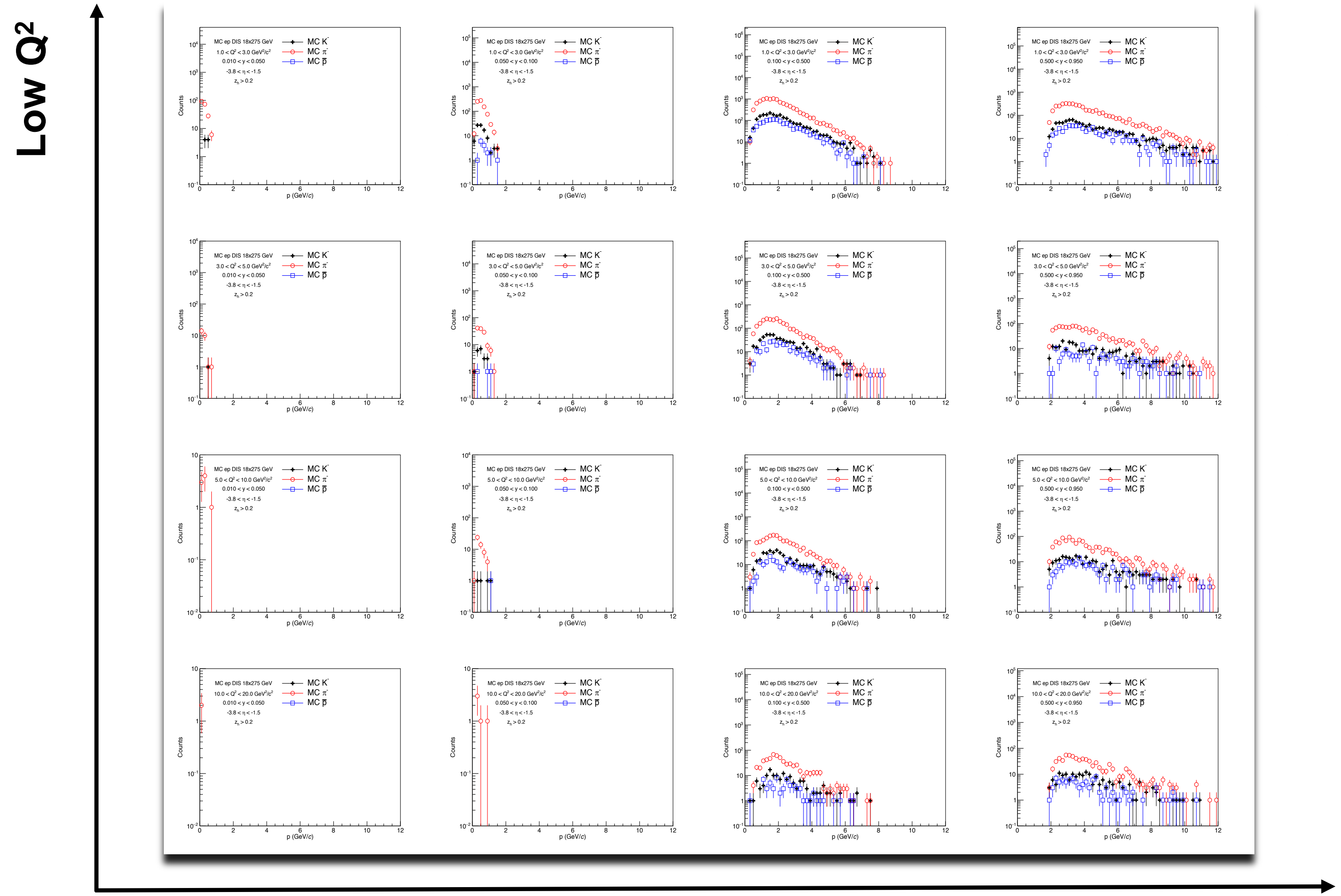
N_{Hits}	Window	Aerogel
>1	95%	99%
>2	94%	99%
>3	93%	99%
>4	91%	98%
>5	90%	96%

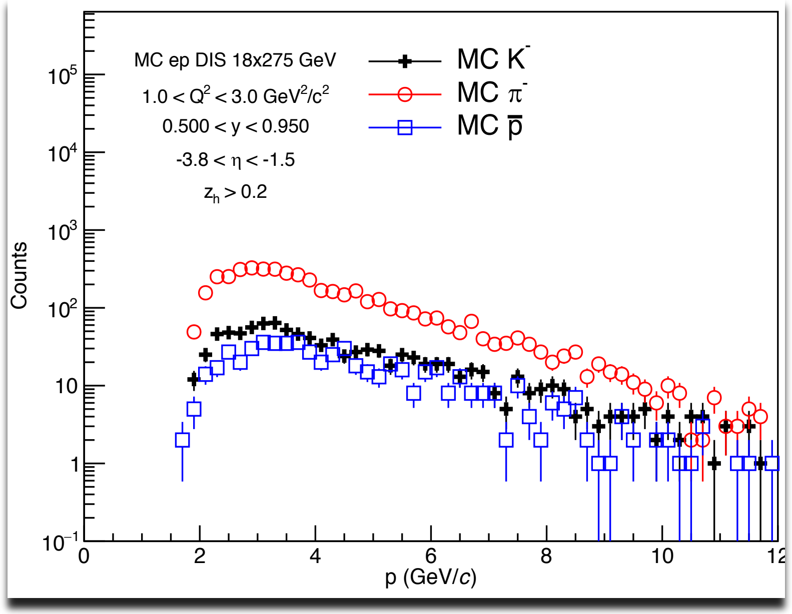
Using Photons from LAPPD Window **Only**

Using Photons from Aerogel **Only**

N_{Hits}	Window	Aerogel
>1	90%	99%
>2	87%	99%
>3	84%	99%
>4	83%	98%
>5	81%	96%

G. SIDIS Impact study



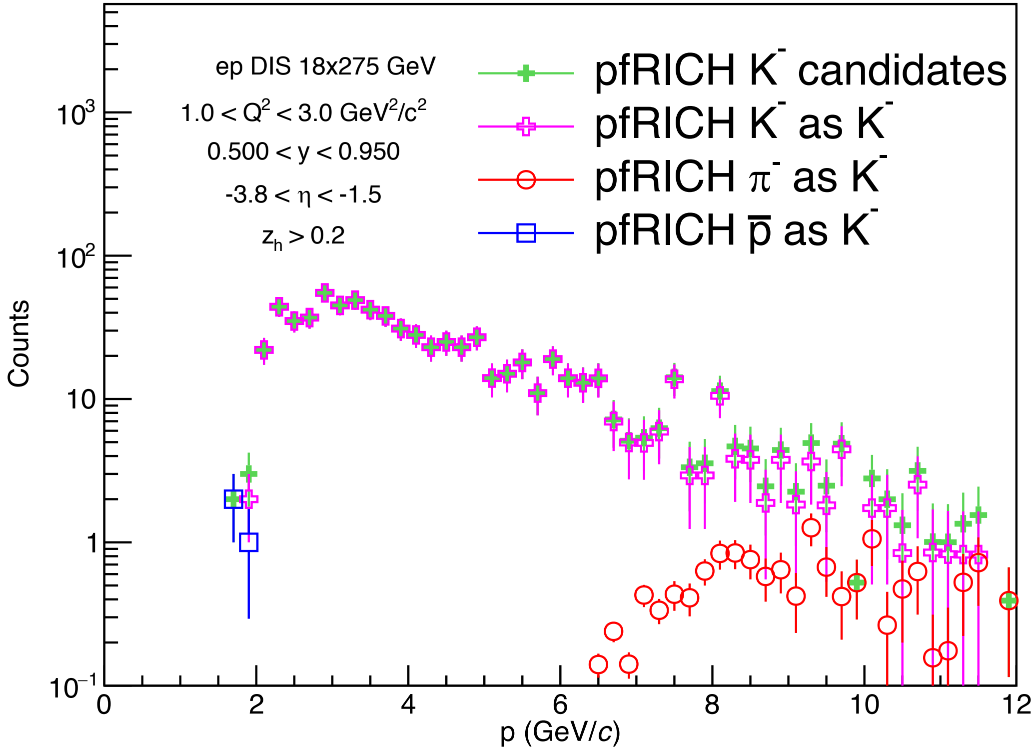


- Leading momentum selected by $z_h > 0.2$

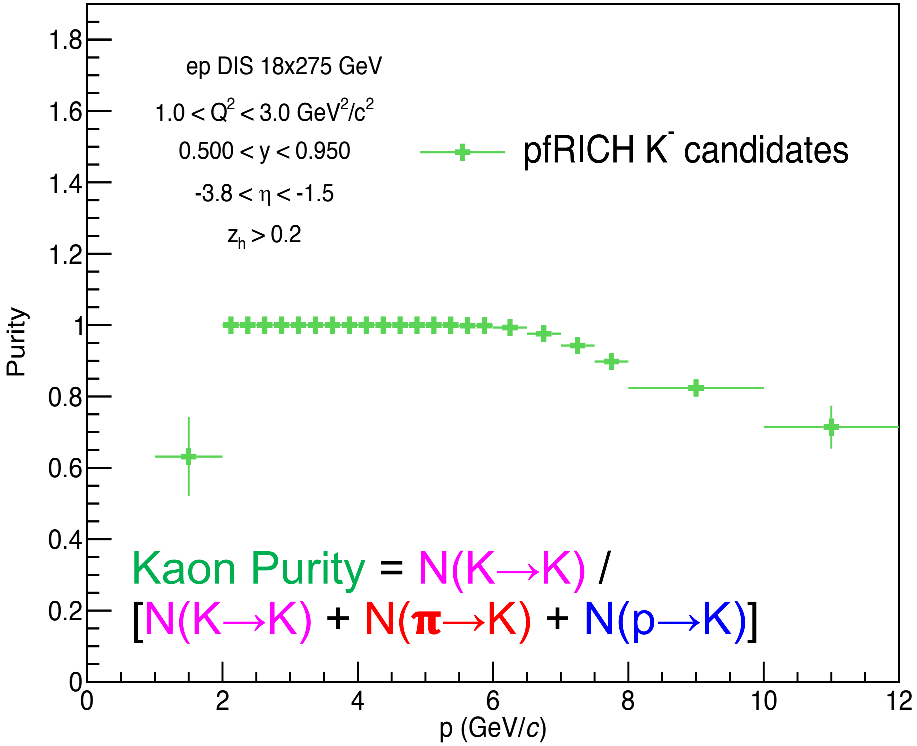
$$z_{\mathrm{h}} = \frac{P \cdot h}{P \cdot q}$$

G. SIDIS Impact study

RECO level



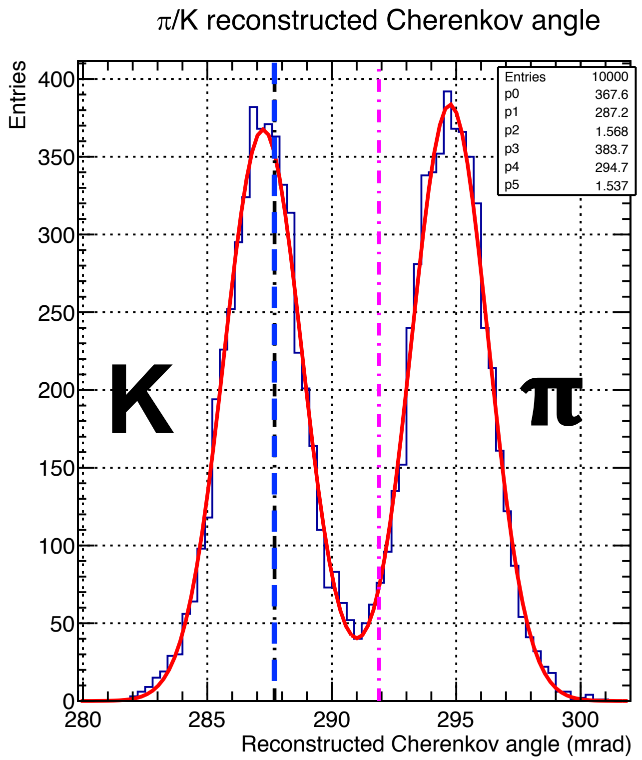
RECO level



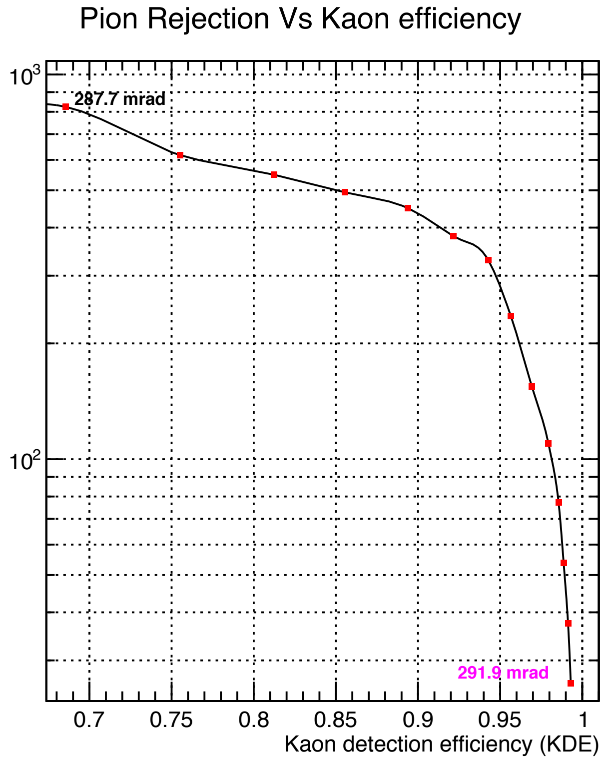
High Kaon Purity ~ 95% at 7 GeV/c

→ this **goes beyond** the requirement of SIDIS physics in the YR

Kaon detection efficiency and pion rejection



High purity High efficiency



For 7 GeV/c pions and kaons:

- Pion Rejection Factor (PRF) as a function of Kaon detection efficiency (KDE) is computed.
- The tunable theta cut is varied from Kaon Cherenkov angle (~287 mrad) to the overlap region (292 mrad).
- PRF > 250 is at 95% KDE.

PRF = 1/efficiency

This analysis can be done in real data to improve purity.

pfRICH Performance Study Team:

- **BNL :** A. Kiselev, B. Page, J. Vanek, Z. Tu
  (Software, geometrical optimization, timing, physics...)
- **SBU/CFNS :** C. Naim, J. Datta, H. Klest
  (validation, analytical calculations, gas)
- **INFN:** C. Chatterjee, Mikhail Osipenko, S. Dalla Torre
  (validation, recons &, performance studies, gas)
- **Duke :** Chris Dilks (ePIC RICH detector hero)

Review: pfRICH addresses all questions raised

Review Charge Questions

A. Comparison of the present assessment of the **Cherenkov PID** detector performance compared with the **YR requirements**?
B. Performance perspectives beyond the YR (if any)?
C. **Efficiency figures:** single particle **π/k/*p*** identified as **π/k/*p*** as a function of the truth momentum in a 3x3-panel figure?
D. Please quantify the performance for **e/h** separation.
E. **Active/dead area** as 2D function of **η** and ϕ; and comment on the edge effects?
F. Performance or potential as **TOF detector**, providing both timing resolution and acceptance coverage in **η** and ϕ.
G. Under the coordination of the SIDIS working group, provide **Kaon Purity** in the kinematic region of (x. .. Q2…) via parameterized hadron PID performance.

Answers to Charge Questions

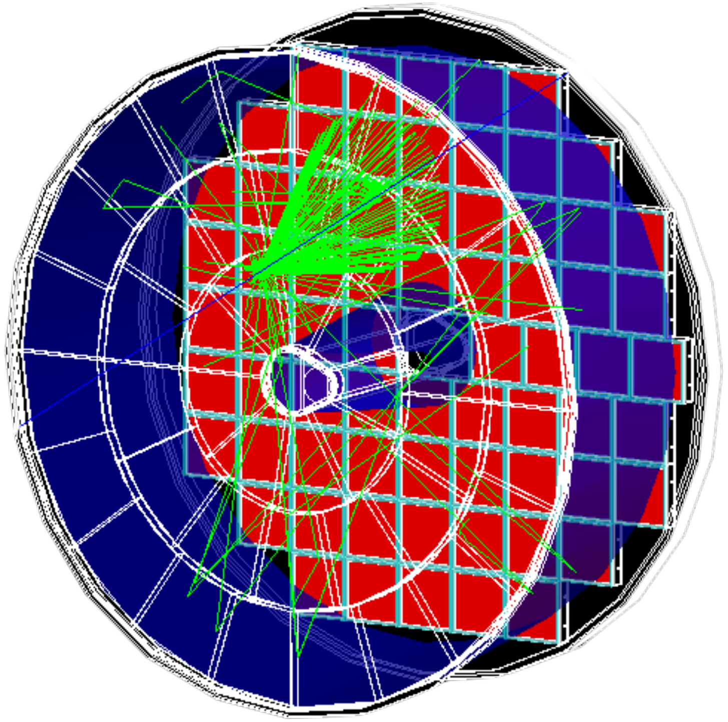
A. pfRICH **meets** the YR requirements.
B. e/π & π/k separations **exceeds the YR requirements.**
C. Provided the 3x3 full **PID efficiency**.
D. Pion suppression: $\mathbf{10^3}$**–**$\mathbf{10^1}$ up to *p*(1,2.5) GeV/c. Impactful for 5x41 ep program.
E. Some dead areas from the ribs, and above **95% acceptance -3.5 < η < -1.5.**
F. Achieve **25ps timing resolution** by having 6 and more photons from aerogel and LAPPD window.
G. Kaon Purity is high, above **95% purity at 7 GeV**. SIDIS impact study performed.

Summary: pfRICH performance study in ePIC

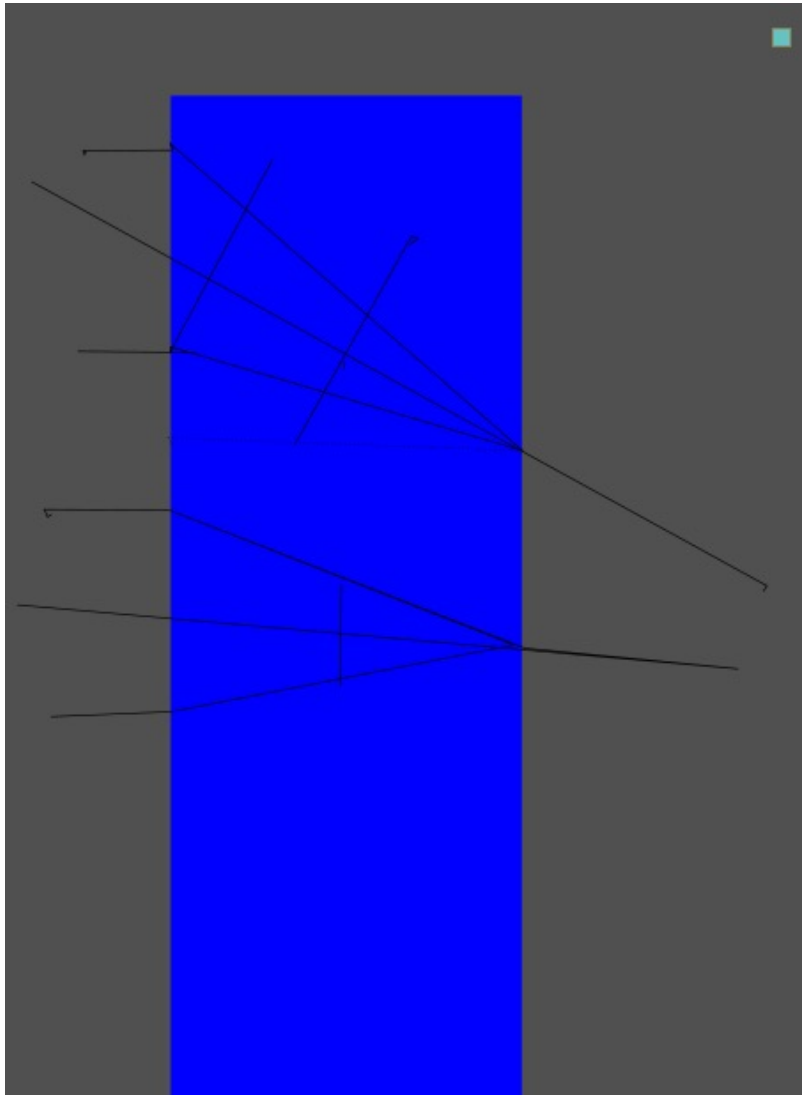
- Comprehensive performance studies
  - ✓ Accept x Efficiency in (p, η)
  - ✓ Edge effect and dead areas
  - ✓ e/**π** & **π**/k separations
  - ✓ SIDIS impact
  - ✓ ToF capabilities
  - ✓ Kaon purity

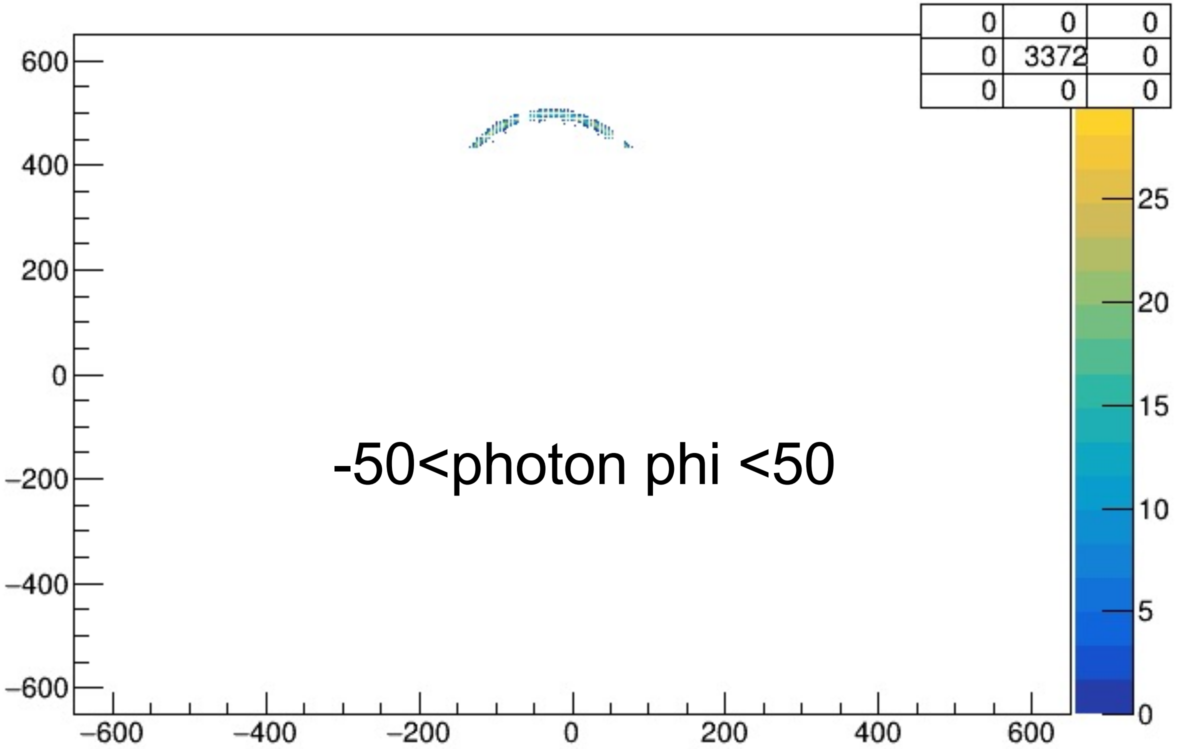
pfRICH Performance:

- ⟨Acceptance⟩ > 95%: $-3.5 < \boldsymbol{\eta} < -1.5$
- e/**π** separation : 3$\boldsymbol{\sigma}$ → p = 2.5 GeV
  π/k separation : 3$\boldsymbol{\sigma}$ → p = 9 GeV



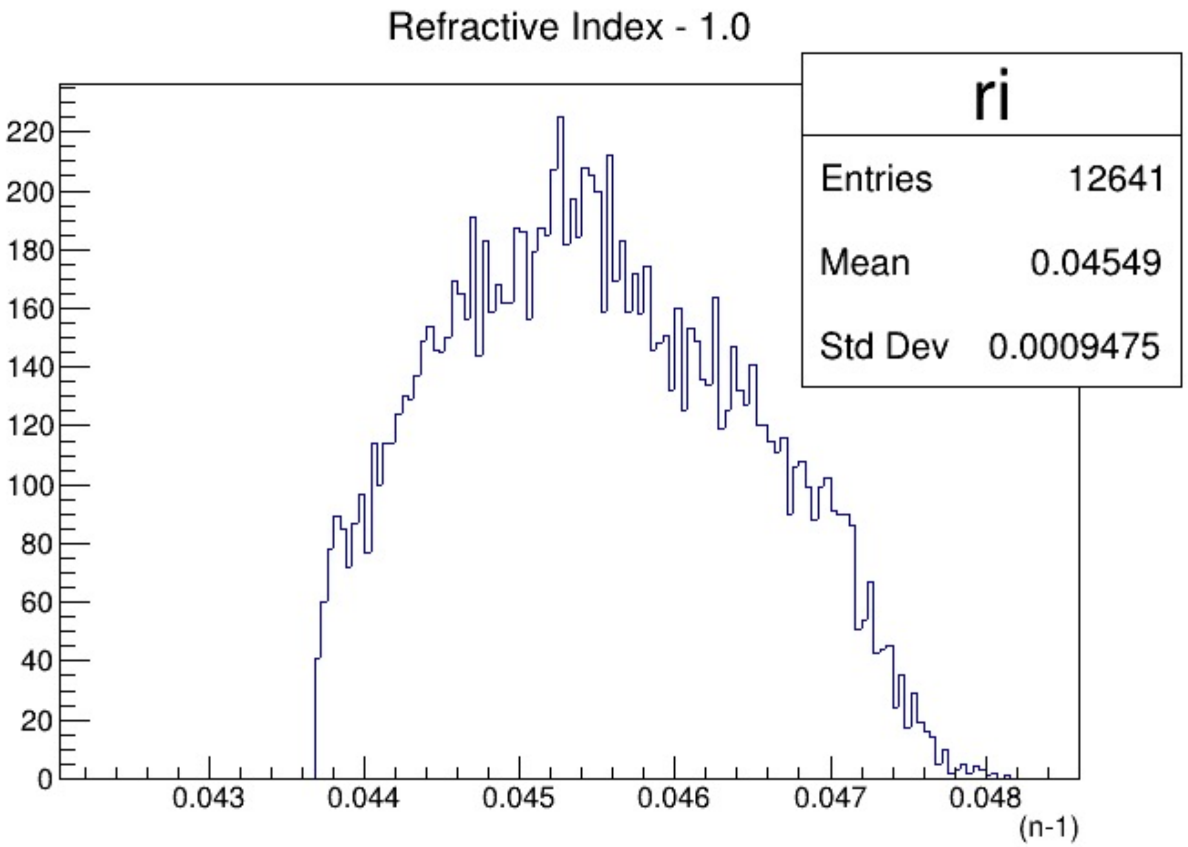
Backup





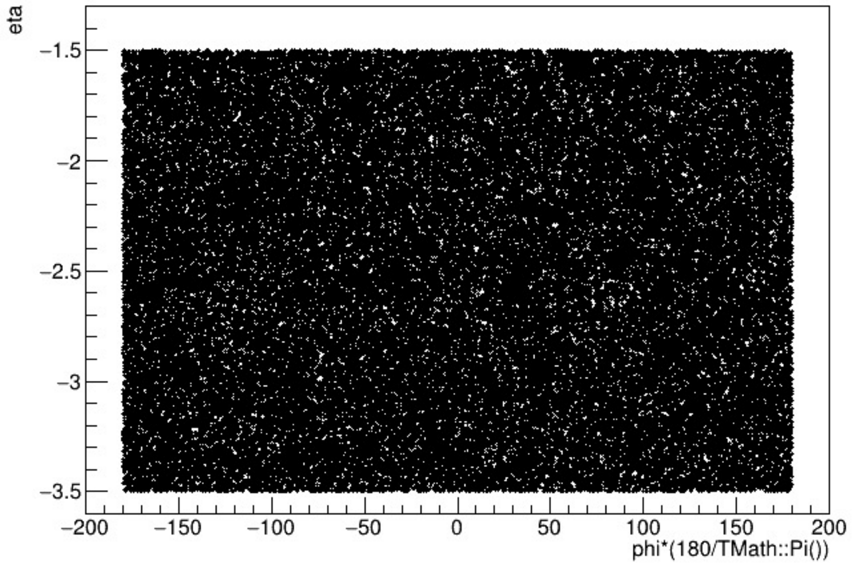
0 0 0
0 3372 0
0 0 0
600
400
200
0
−200
−400
−600
−600 −400 −200 0 200 400 600
25
20
15
10
5
0
-50<photon phi <50

Refractive index

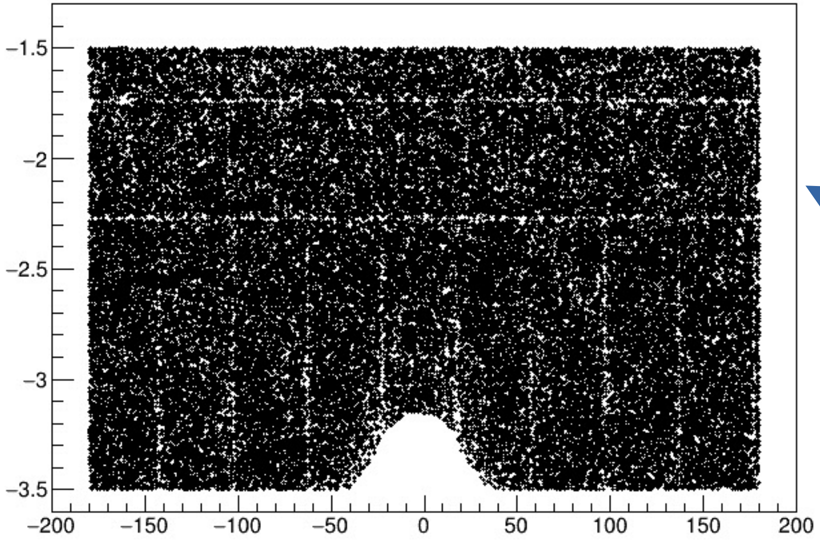


E. Active and dead area

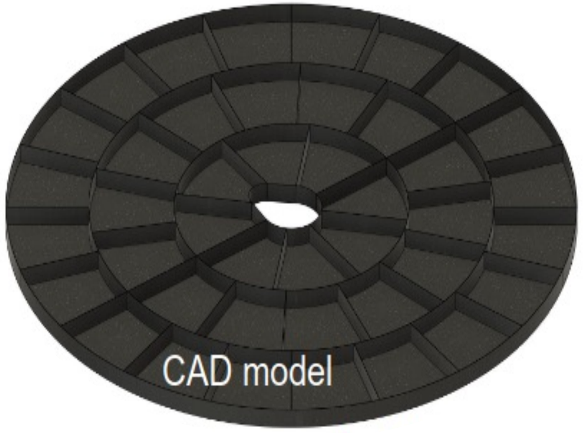
7 GeV pions <Npe>~ 12

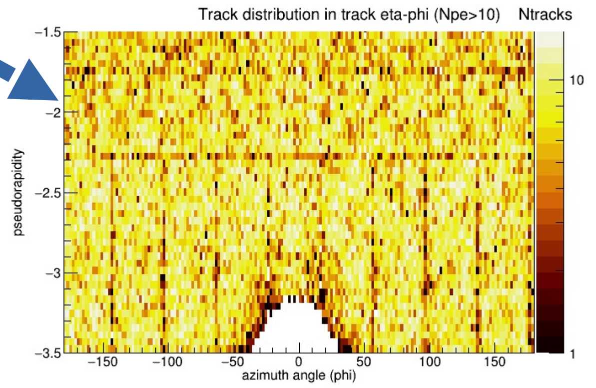


Uniform track distribution w/o Npe cut



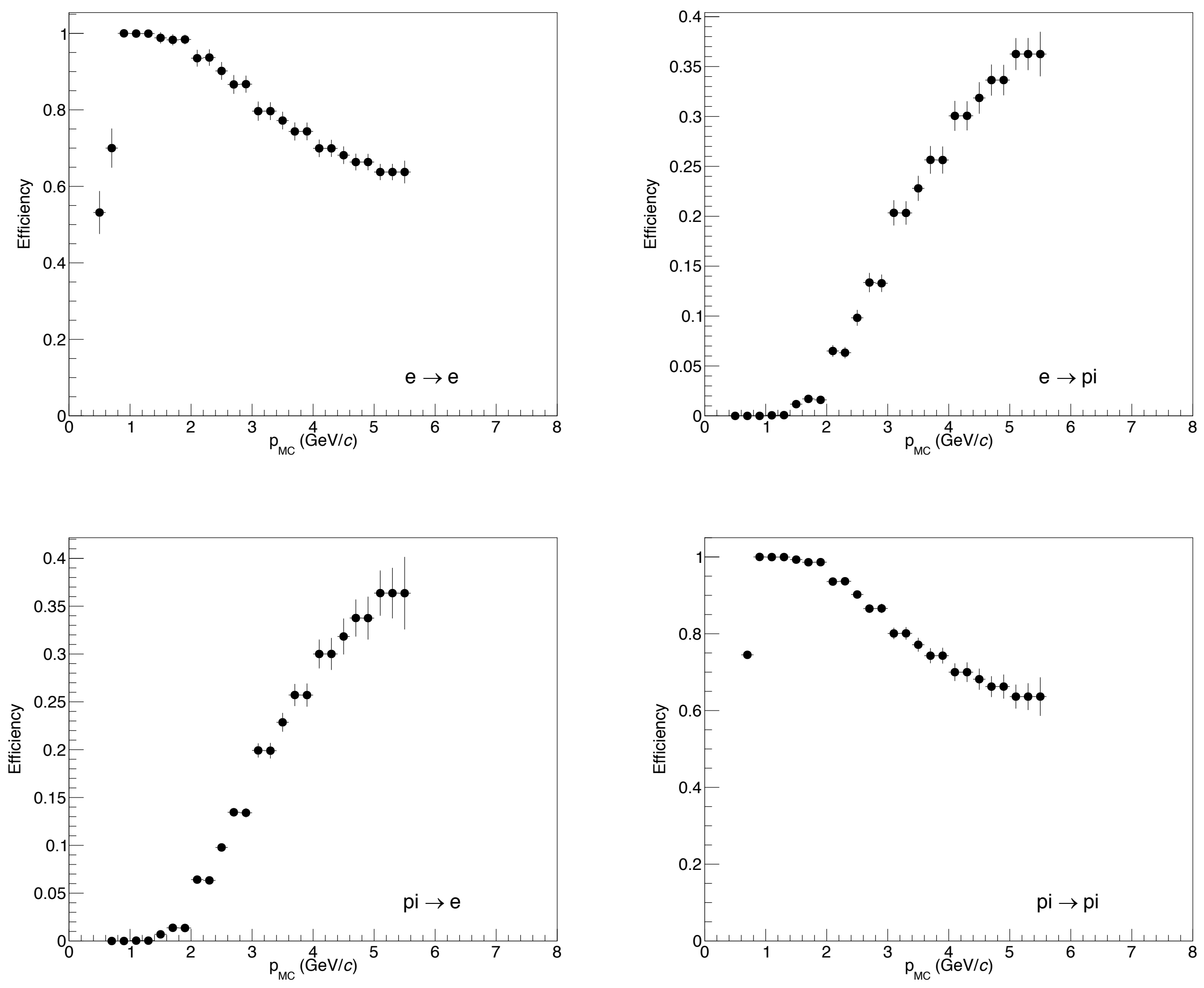
Track distribution with more than **10 photons**





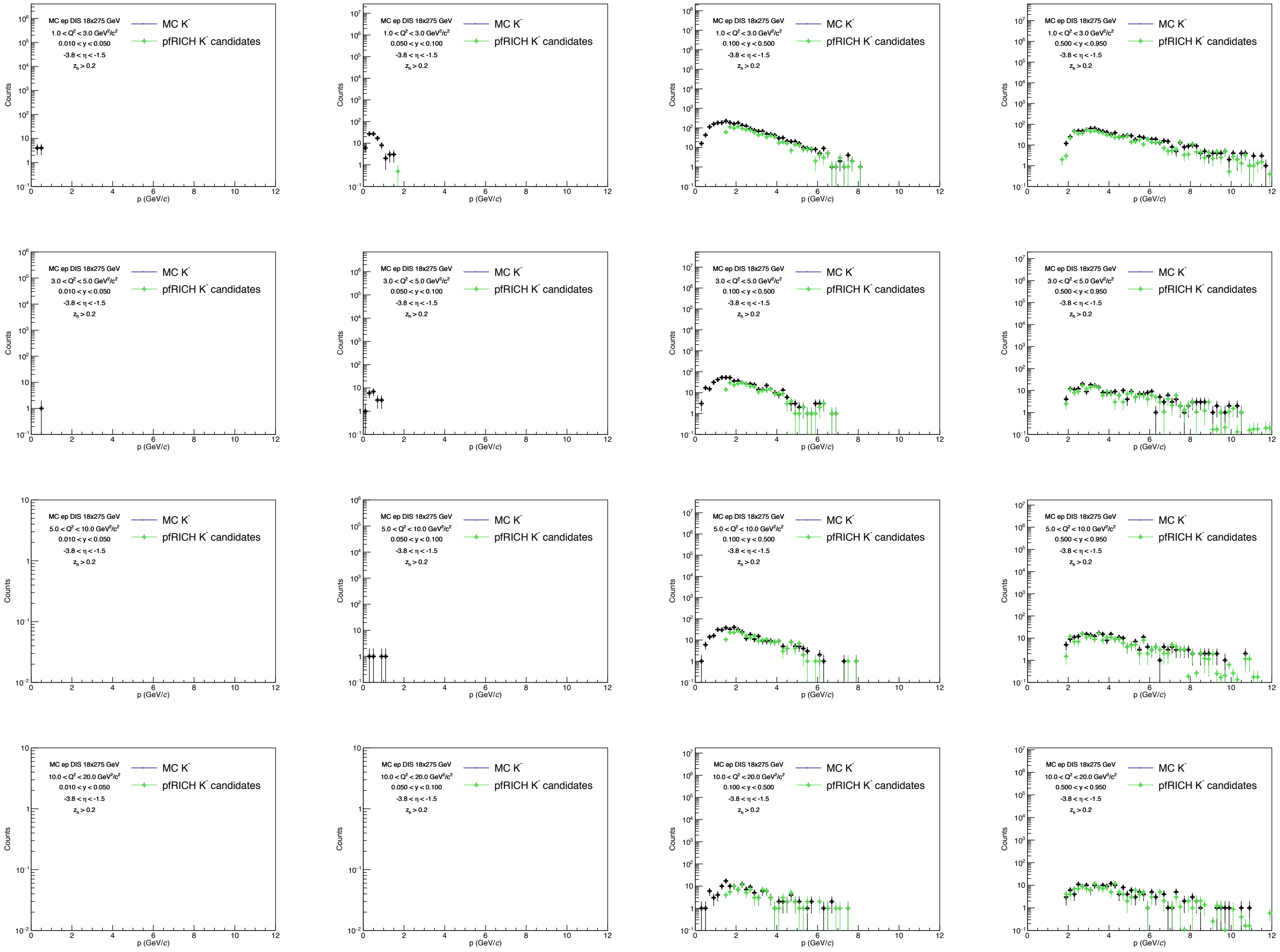
No discontinuity in eta-phi

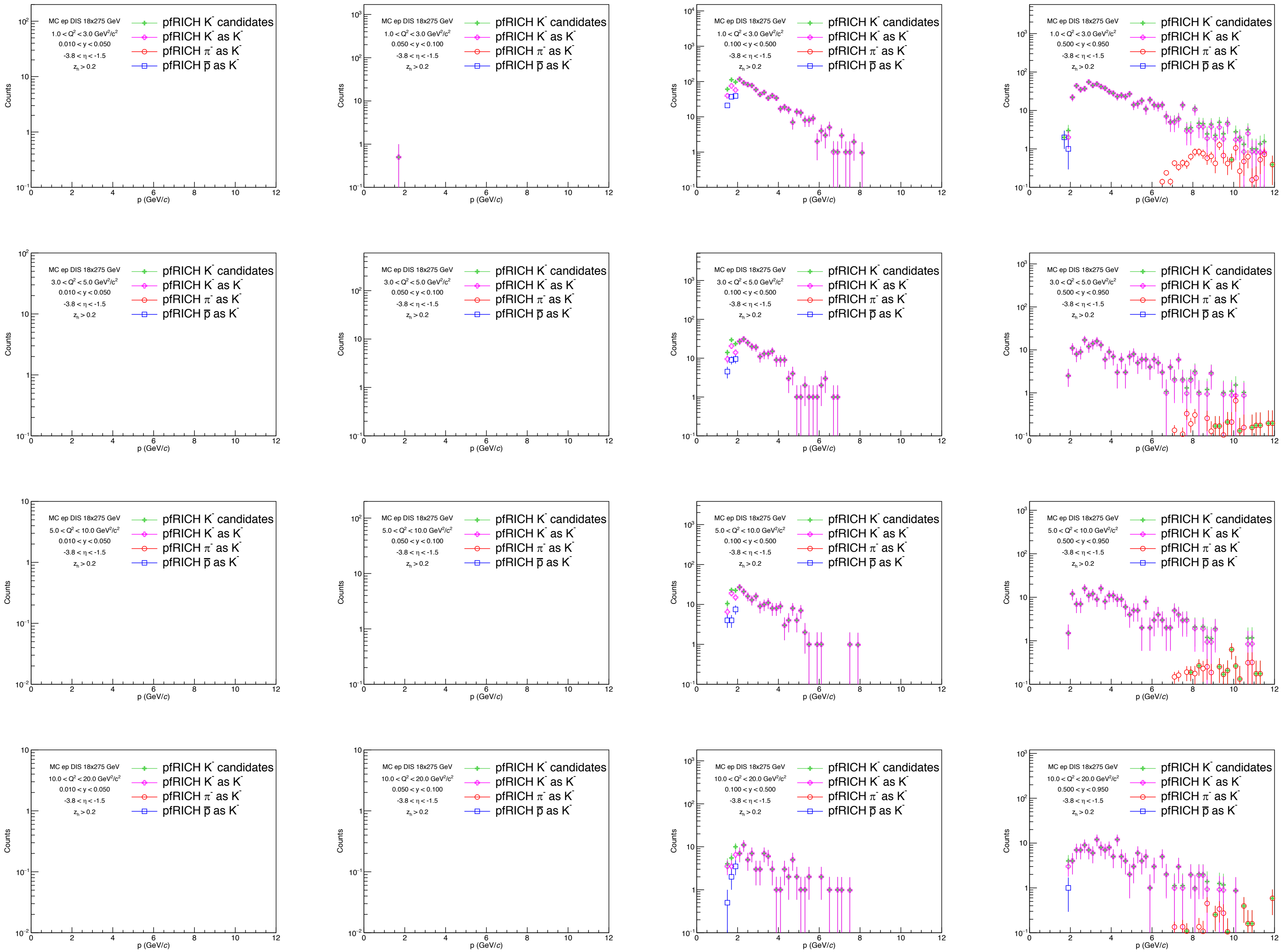
Dead areas created by the structure of the Aerogel holder (?) ribs

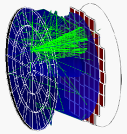


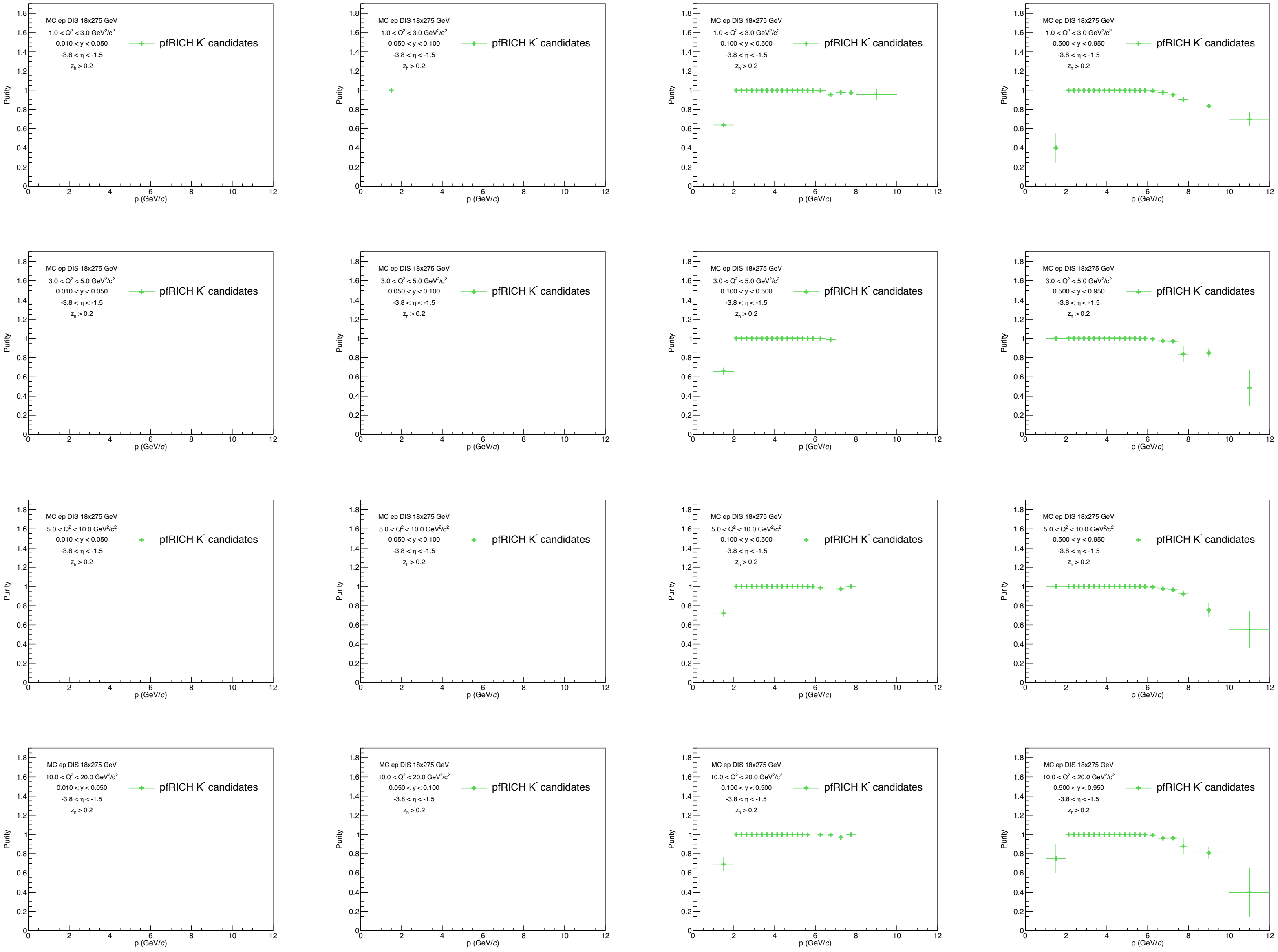
Measured ratio = N(**π**)/N(**e**);

N(**π**) = N^{truth}(**π**) * (1-eff (**π**→**π**))
N(**e**) = N^{truth}(e)*[1-eff(e→ **π**)]*eff (e→e) **+** N^{truth}**(π)** eff (**π**→e)


MC ep DIS 18x275 GeV
1.0 < Q² < 3.0 GeV²/c²
0.010 < y < 0.050
0.050 < y < 0.100
0.100 < y < 0.500
0.500 < y < 0.950
3.0 < Q² < 5.0 GeV²/c²
5.0 < Q² < 10.0 GeV²/c²
10.0 < Q² < 20.0 GeV²/c²
-3.8 < η < -1.5
z_h > 0.2
MC K⁻
pfRICH K⁻ candidates
Counts
p (GeV/c)


MC ep DIS 18x275 GeV
1.0 < Q² < 3.0 GeV²/c²
0.010 < y < 0.050
0.050 < y < 0.100
0.100 < y < 0.500
0.500 < y < 0.950
3.0 < Q² < 5.0 GeV²/c²
5.0 < Q² < 10.0 GeV²/c²
10.0 < Q² < 20.0 GeV²/c²
-3.8 < η < -1.5
z_h > 0.2
pfRICH K⁻ candidates
pfRICH K⁻ as K⁻
pfRICH π⁻ as K⁻
pfRICH p̄ as K⁻
Counts
p (GeV/c)




MC ep DIS 18x275 GeV
$1.0 < Q^2 < 3.0$ GeV^2/c^2
$0.010 < y < 0.050$
$0.050 < y < 0.100$
$0.100 < y < 0.500$
$0.500 < y < 0.950$
$3.0 < Q^2 < 5.0$ GeV^2/c^2
$5.0 < Q^2 < 10.0$ GeV^2/c^2
$10.0 < Q^2 < 20.0$ GeV^2/c^2
$-3.8 < \eta < -1.5$
$z_h > 0.2$
pfRICH K^- candidates
Purity
p (GeV/c)