PID with the RICH

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Why the CLAS12 RICH?

Experiment	Contact	Title	Rating	PAC days
C12-11-111	M. Contalbrigo	Transverse spin effect in SIDIS at 11 GeV with a transversely polarized target using CLAS12	A	100 + 25
C12-12-009	H. Avakian	Measurement of transversity with di-hadron production in SIDIS with a transversely polarized target	A	100 + 25
C12-12-010	L. Elauadrhiri	Deeply Virtual Compton scattering at 11 GeV with transversely polarized target using the CLAS12 detector	A	100 + 25
C12-11-111A	H. Avakian	Measurements of Single Spin Asymmetries in exclusive production of hadrons with RGH transversely polarized target		100 + 25

C12-11-111:
"The proposed experiment will use the upgraded CLAS12 spectrometer with the low threshold Cherenkov counter replaced by a RICH detector in (at least) two sectors."

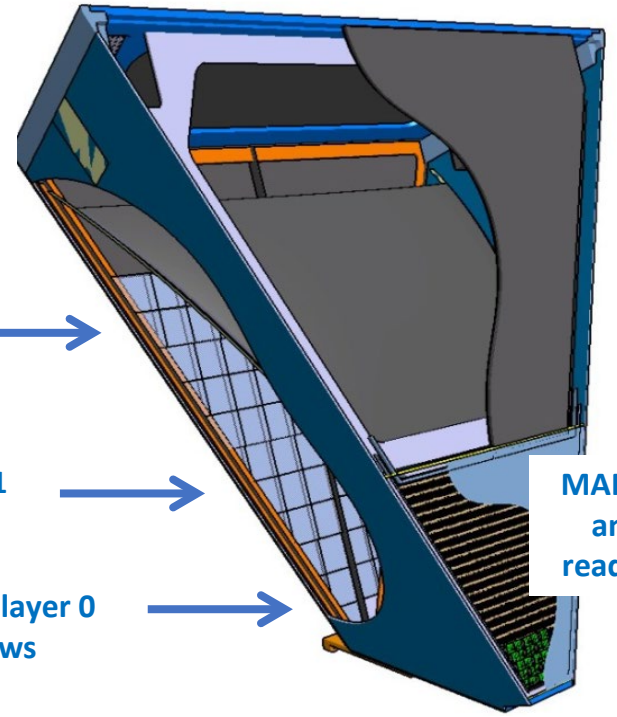
Clean identification of kaons with respect to pions and protons in the momentum range from 3 to 8 GeV/c

- **time resolution better than 1 ns**
- **Cherenkov angle resolution 5 mrad**
- **pi/K rejection factor larger than 500**
- **p/K rejection factor larger than 100**

The RICH detector

RICH design dictated by need to fit in the existing CLAS12 geometry and by cost reduction

- **3 sections of Cherenkov radiator composed by 102 tiles of aerogel with nominal refractive index ~1.05**
- **7 planar mirrors**
- **10 spherical mirrors**
- **391 Multi-Anode PMTs, total of 25024 readout channel**



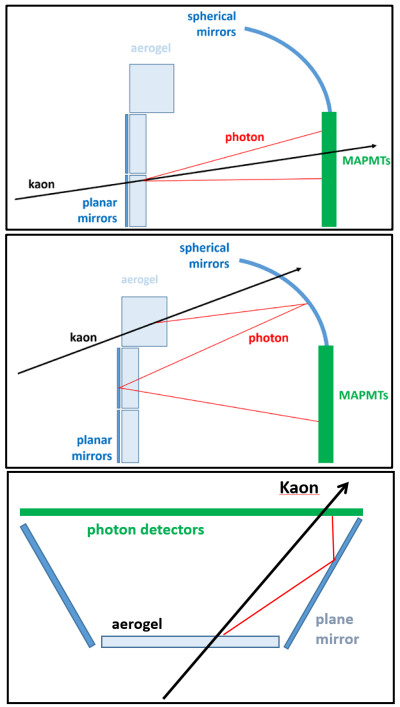
Chrenkov emission thresholds

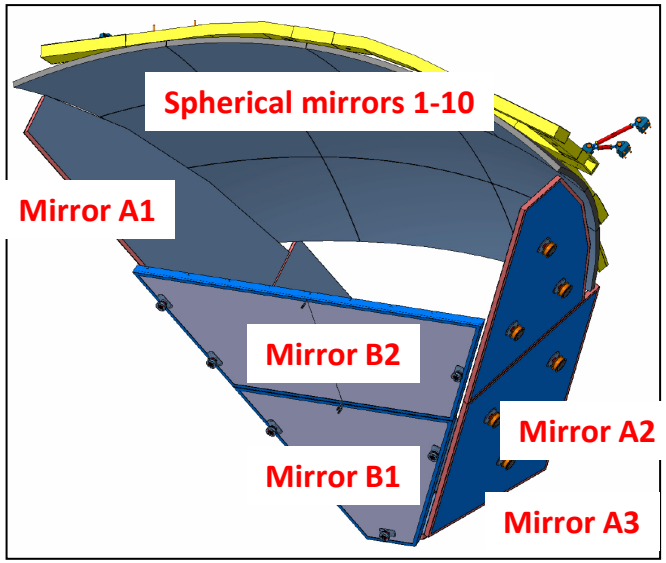
$\beta > 1 / n \approx 0.952$ **with n=1.05**

$P_\pi > 0.45$ GeV/c

$P_K > 1.5$ GeV/c

$P_p > 3.0$ GeV/c





Module 1 installed in sector 4 in January 2018, module 2 installed in sector 1 in June 2022

Alignment

The precise knowledge of the position of the active elements of the detector (aerogel radiators, mirrors, MAPMTs) with respect to the CLAS12 tracking system is a crucial requirement for reliable PID performance

- **large dimensions: at least 54 alignment parameters per sector**
- **highly correlated parameters**
- **the reconstructed Cherenkov angle is the only available information**

The problem has been solved by using a Bayesian optimization method based on the TuRBO algorithm

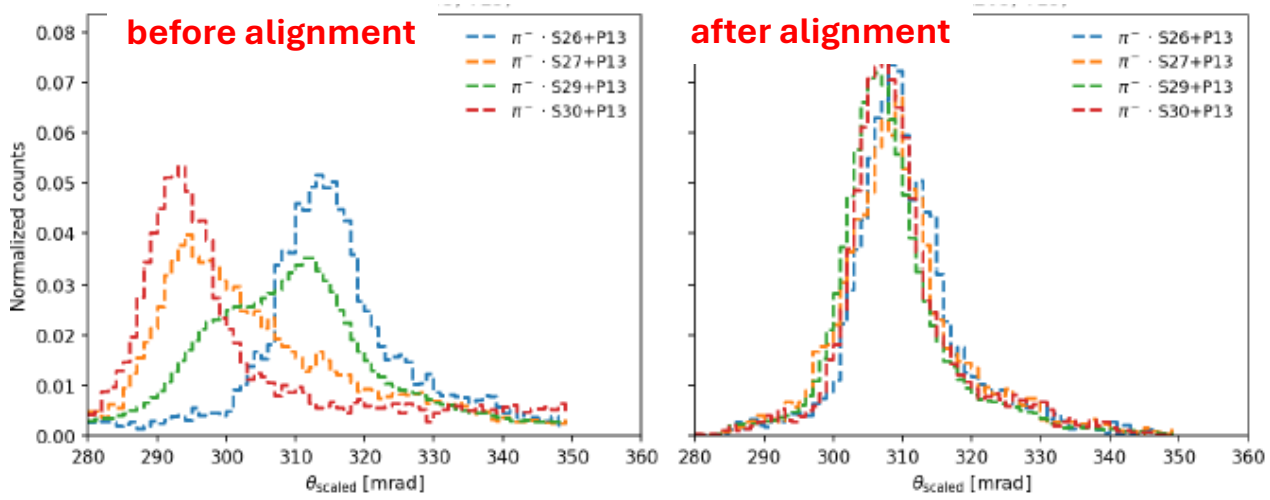
C. Pecar, CLAS Coll. meeting, 10-13 March 2026

First application to the RGK spring 2024 data set

- **few hundreds of pseudo-random initialization trials**
- **few tenths trial per batch ran in parallel for minimization**
- **about 2000 total trials to reach convergence**

Cherenkov angle distributions

- **two reflections, various spherical mirrors**



Alignment software status

The alignment software has been installed on ifarm and an alignment suite has been implemented.
Two alignment steps:

1. **global alignment of the detector with respect to CLAS12: 6 free parameters**
2. **alignment of the mirrors and aerogel layers: 54 free parameters**

The data preparation and the validation results is run interactively on ifarm
The alignment process works through batches of SLURM jobs

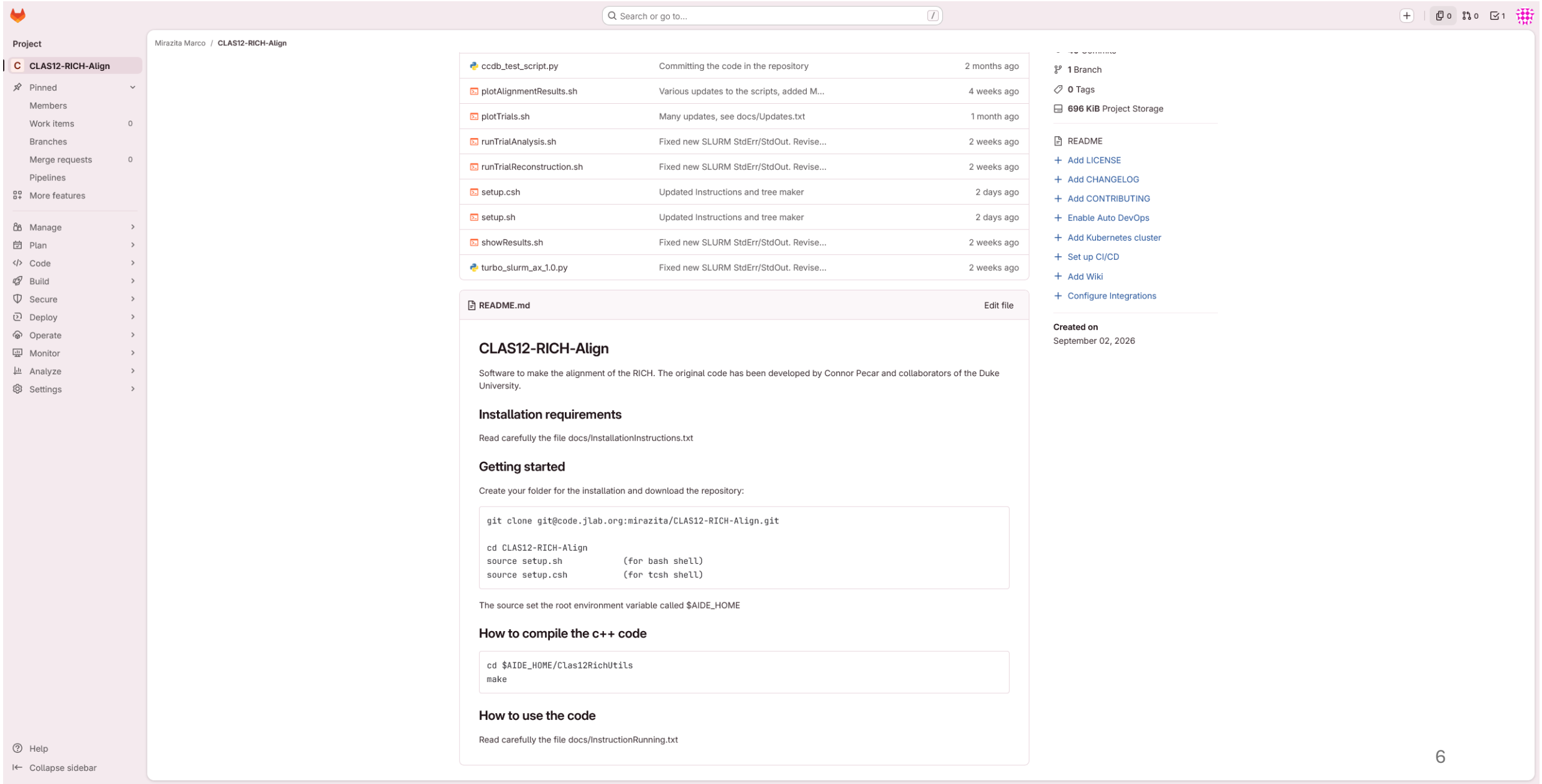
- **o(10 days) to align one sector**
- **2 modules can be run in parallel**

The software can be downloaded from gitlab; it works well, although the scripts and validation plots are still under revision/completion
To be done

- **solve compatibility with latest Ax version (currently running with version 1.0)**
- **implement readout from RICH::calib bank**

→ Now the RICH is fully integrated in the calibration pipeline

Alignment software on gitlab



Run groups

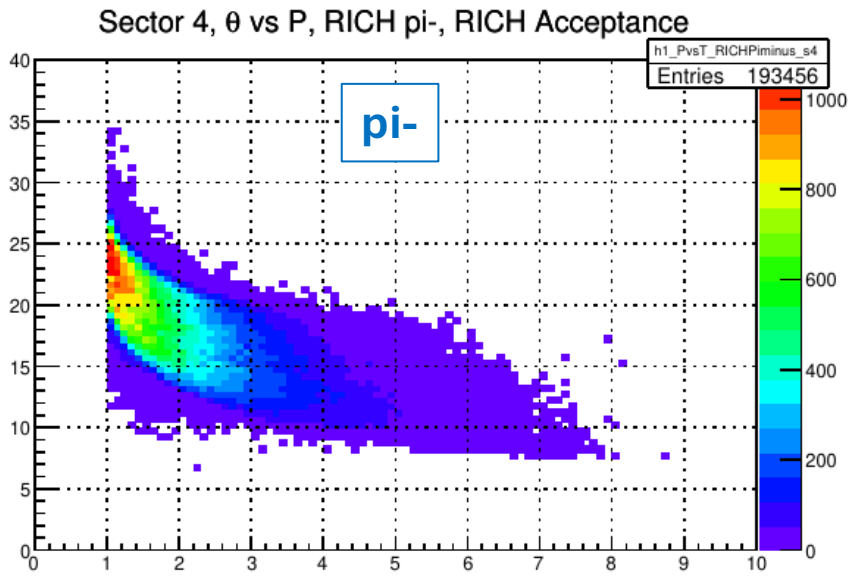
Run Group	Year	Status	
A	2018-19	Alignment in progress	Duquesne (F. Benmokhtar)
K	2018		
B	2019-20		
F	2020		
M	2021		
C	2022-23	Alignment in progress	INFN-Fe (L/ Polizzi)
D	2023		
K	2024	Aligned and calibrated	
E	2024	Aligned and calibrated	
L	2025	Aligned and calibrated	

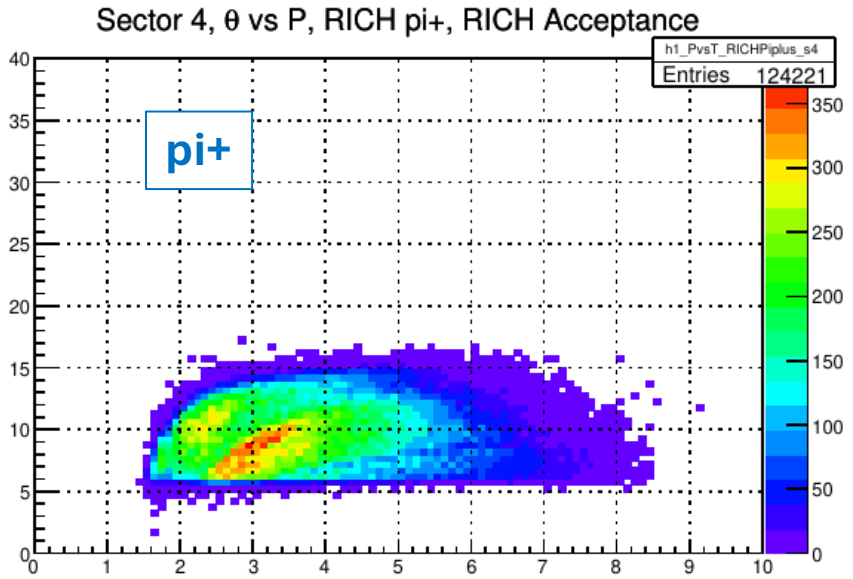
Kinematic coverage

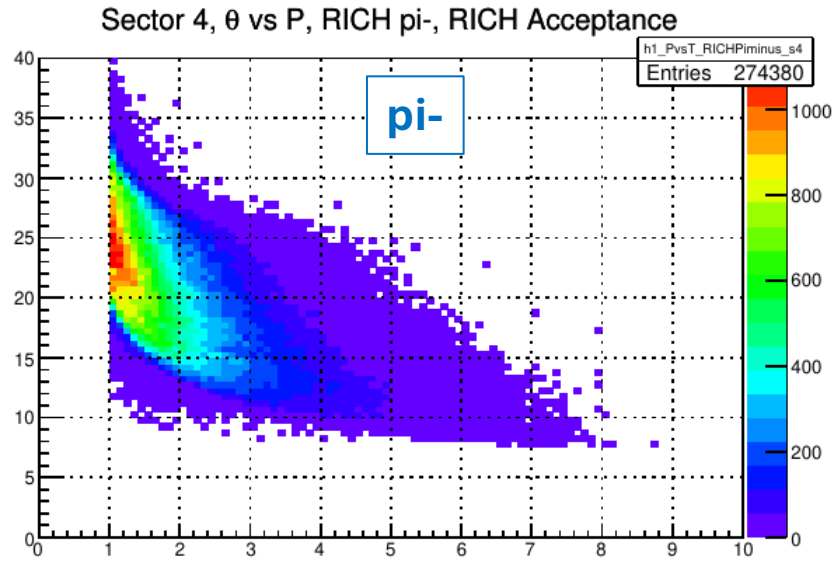
RG-A fall 2018
torus -1

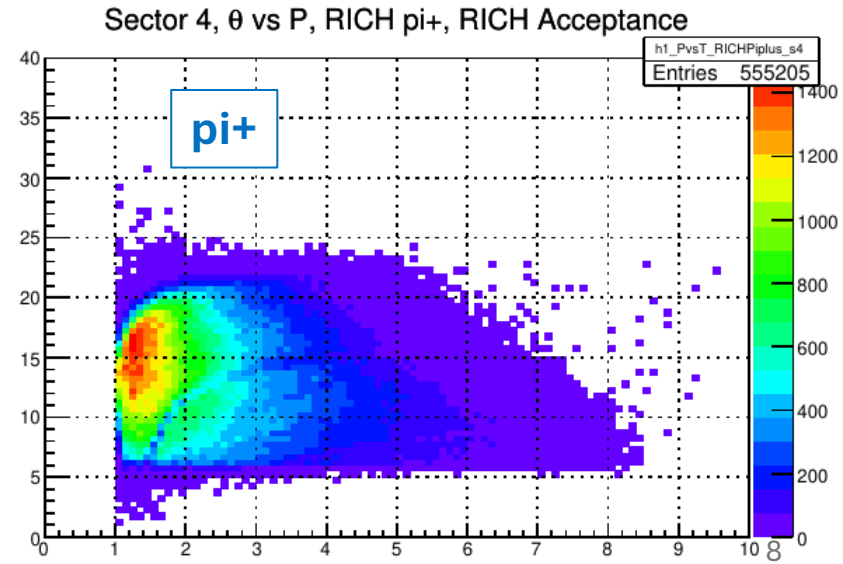
pass2 cooking
- No aerogel layer 2
- No 7 out of 10 spherical mirrors

New alignment
Full coverage



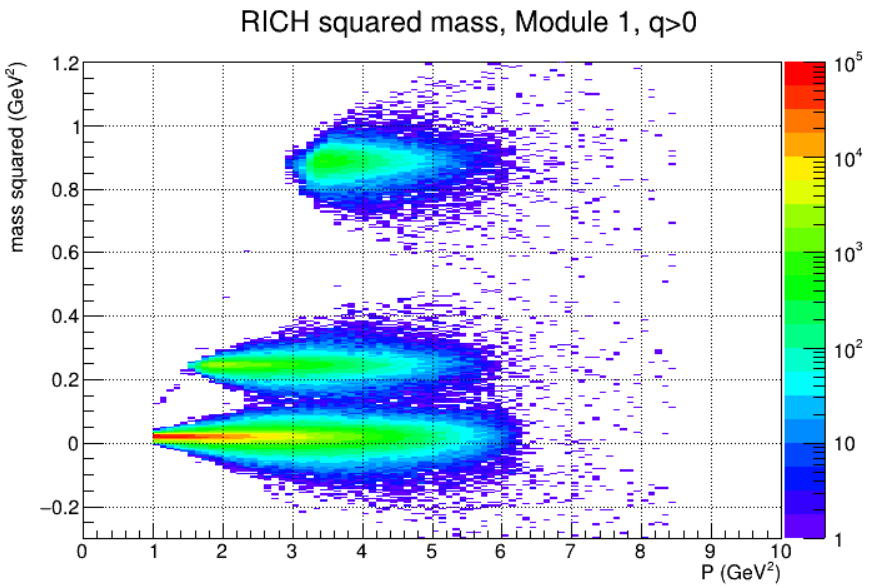


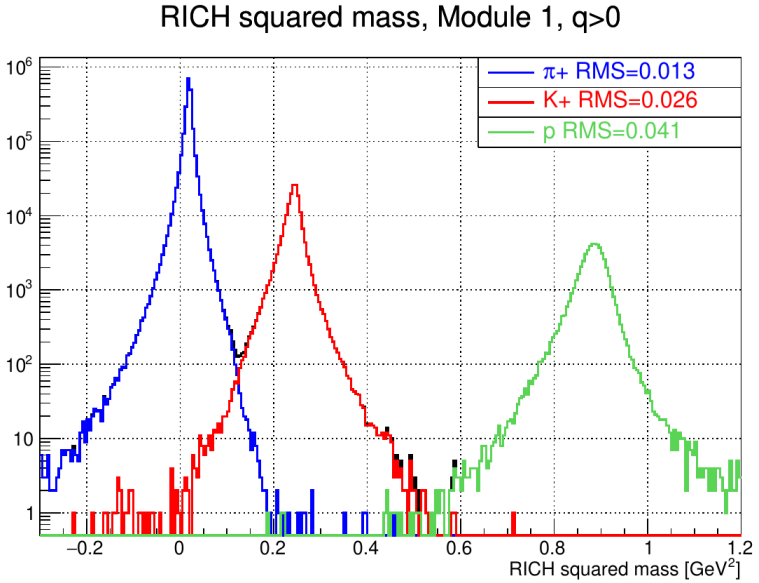




Particle identification

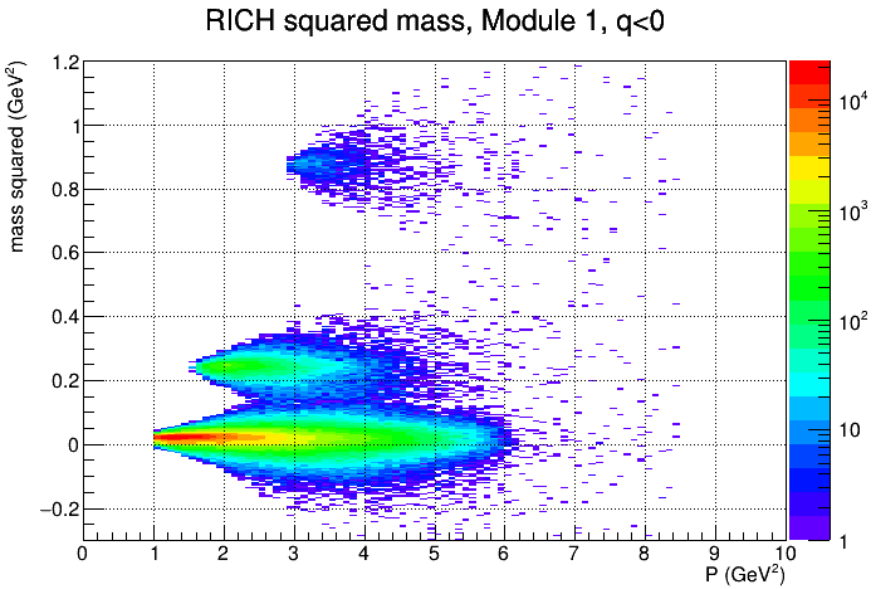
positive hadrons

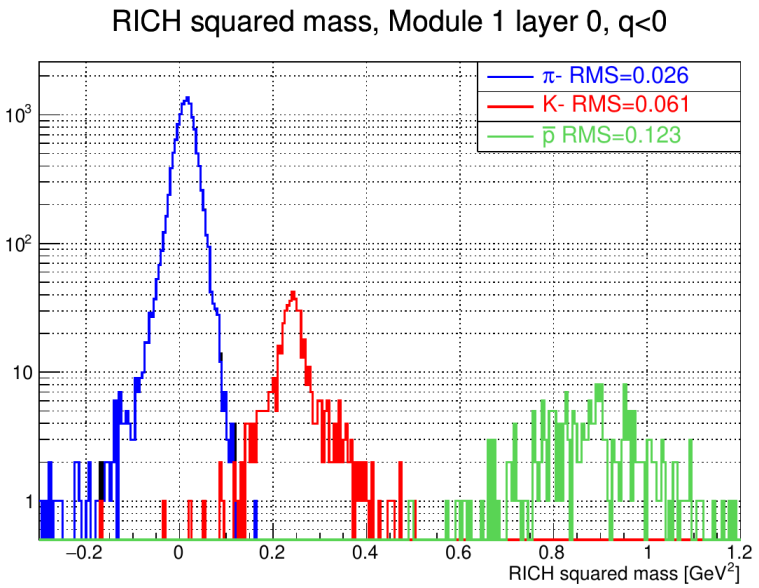




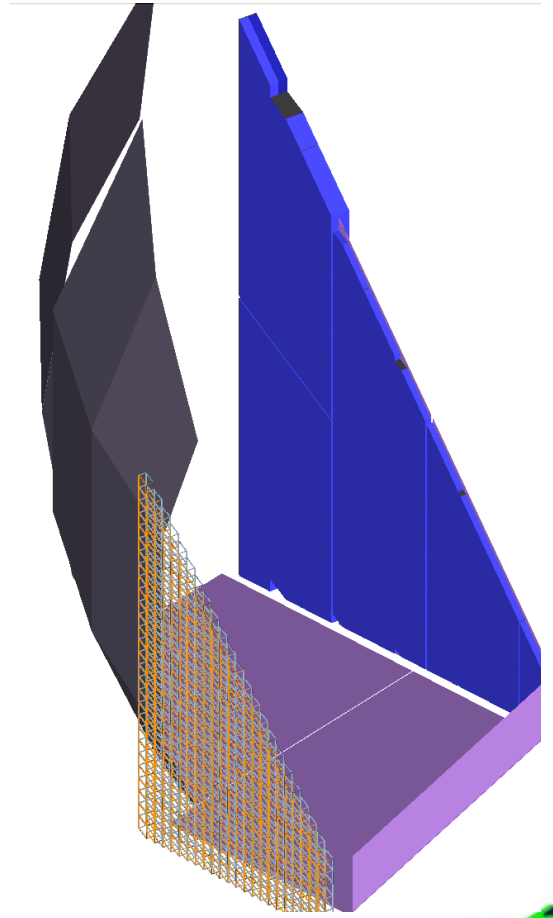
RG-K 2024
torus +1

negative hadrons





Monte Carlo simulation: geometry



GEOMETRY

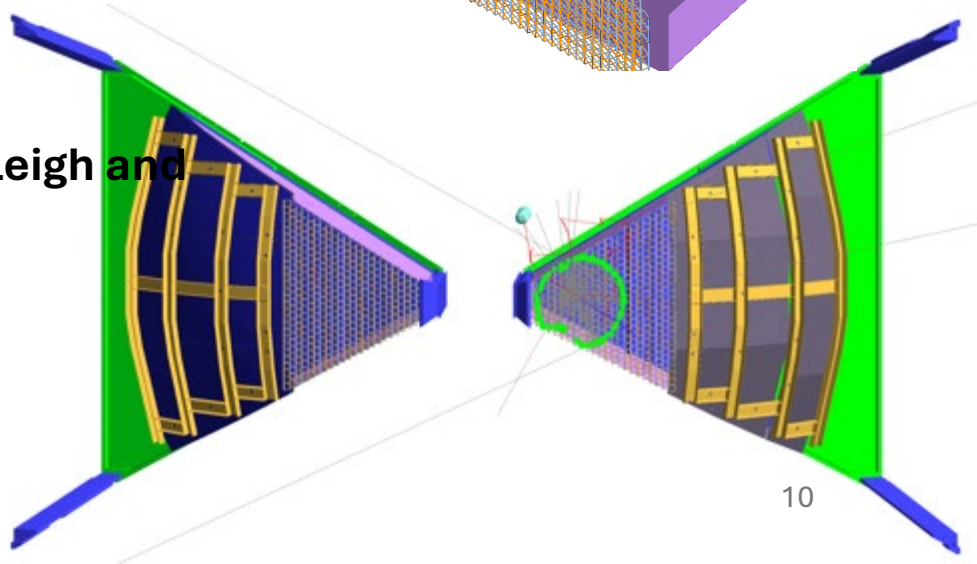
1. **STL files: aerogel, planar mirrors, dead materials**
2. **geant4 shapes: spherical mirrors, MAPMTs**

DIGITIZATION

1. **MAPMT response to single p.e.: quantum efficiency, number of amplification stages, gain, H8500 vs H12700**
2. **TDC: MAPMT time response, MAROC preamp, time walk, conversion to time (1 ns time stamp)**

Optical properties

1. **Aerogel radiator: Cherenkov emission spectrum, absorption, Rayleigh and forward scattering, refraction**
2. **Mirrors: reflectivity, surface accuracy**



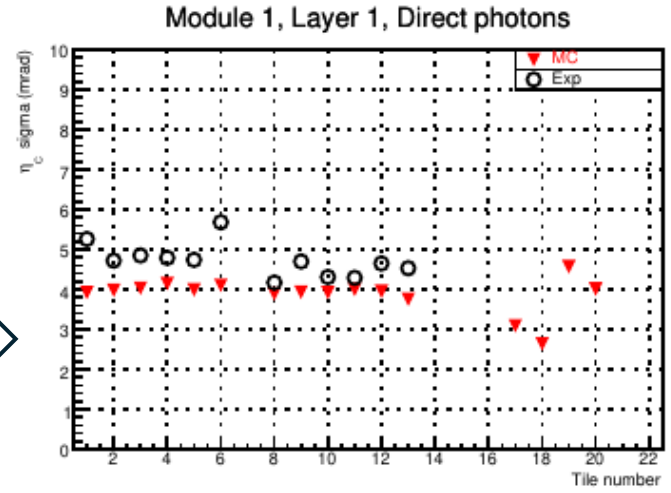
Simulation vs data results

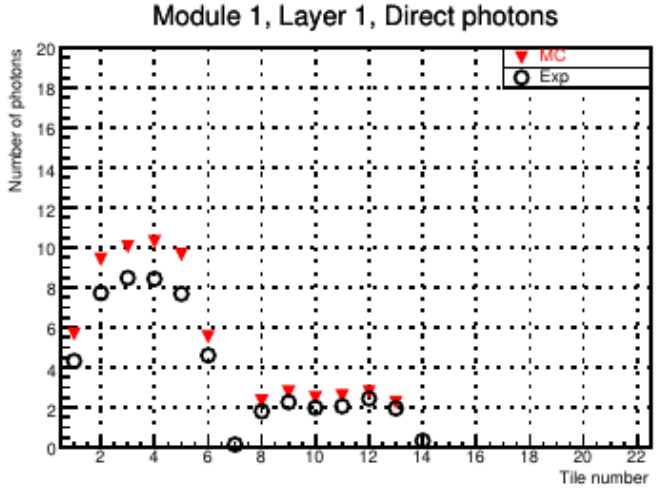
RGA fall 2018 torus -1

RED: MC data
2026 production on OSG

BLACK: Experimental data
RICH realigned (sept. 2026)

0 reflections





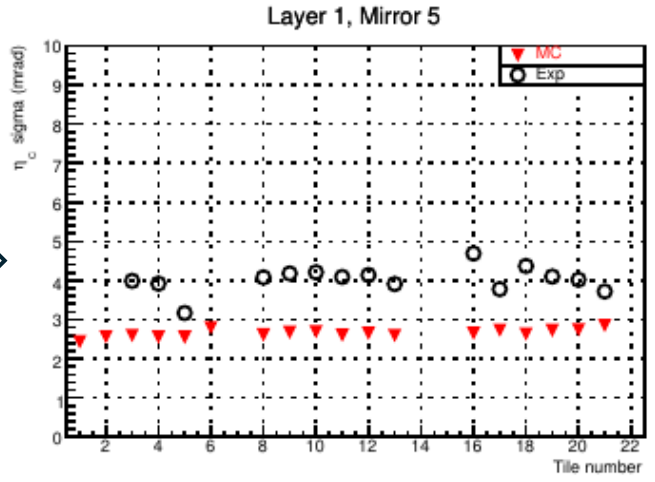
Cherenkov angle resolution

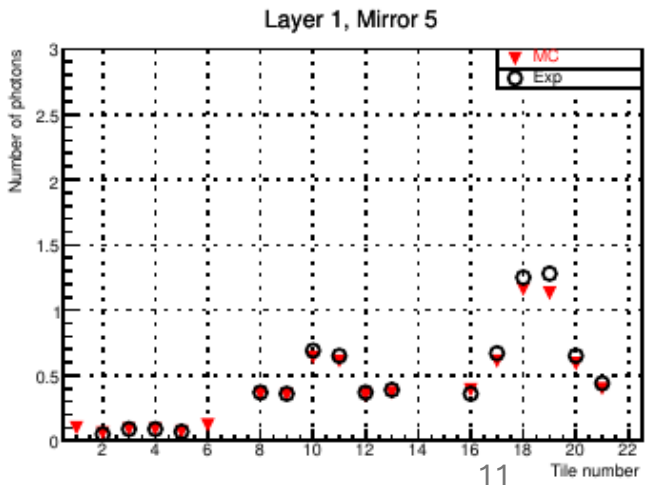
Number of photons per track

About 1 mrad is still missing in the resolution, possible reasons

- **underestimated DC tracking resolution**
- **misalignments (the simulation uses nominal geometry)**
- **optical parameters to be improved**

2 reflections





Particle ID in CLAS12

1. **Event Builder**

   Try FTOF panel 1b first, then 1a, then calorimeter:

   - **calculate the mass $M^2 = p^2 \frac{1-\beta^2}{\beta^2}$**
   - **get PID as the closest mass hypothesis**
   - **quality measure of the ID: $\chi^2_{PID} = \left(\frac{t-\langle t \rangle}{\sigma_t}\right)^2$**
   - **momentum range: P < 3 GeV/c (nominal)**

2. **RICH (Sector 1 and 4)**

   For each hadron mass hypothesis h=pi,K,p:

   - **calculate the likelihood using measured time and Cherenkov angle**
   - **get PID from the hypothesis that maximizes the likelihood**
   - **quality measures of the PID: R_Q, R_L, χ^2 , N_γ (plus likelihoods)**
   - **momentum thresholds: P(π)>0.45 GeV/c, P(K)>1.5 GeV/c, P(p) > 2.8 GeV/c**

3. **Higher level models to improve Kaon ID**
   - **Limited to up ~ 3 GeV/c**
   - **Used to suppress misidentification only**

Combining likelihoods from different detectors

If the likelihoods are properly normalized, likelihoods from different sub-detectors can be easily combined:

$$\mathcal{L}(\pi) = \prod_i \mathcal{L}_i(\pi) \qquad \mathcal{L}(K) = \prod_i \mathcal{L}_i(K) \qquad \mathcal{L}(p) = \prod_i \mathcal{L}_i(p)$$

1. **If one sub-detector has no separation power, it contributes for the same amount for all the mass hypotheses; what matters is the difference of likelihoods**

2. **Best ID by maximizing the likelihood, or by minimizing the LL**

3. **ID quality parameter**
   - **how good is one particle hypothesis? →chisquare, probabilities, etc.**

$$P_{ID} = \frac{\mathcal{L}(best)}{\sum_i \mathcal{L}(i)}$$

   - **how well are two hypotheses separated?**

$$R_Q = 1 - \frac{LL(best)}{LL(second)}$$

First test combing the RICH and the FTOF

RICH likelihood

$$LL = -2\ln\mathcal{L}(\theta) = 2\sum_{i=1}^{N}\left[\mu_i(\theta) - \hat{\mu}_i(\theta) + n_i \ln\frac{\hat{\mu}_i(\theta)}{\mu_i(\theta)}\right]$$

- $\hat{\mu}_i(\theta)$: expected number of hits in pixel i for a "perfect event"
- n_i: number of hits in pixel i (=0,1)
- $\mu_i(\theta)$: expected number of hits in pixel i
- $\sum_{i=1}^{N}$: sum over the MAPMT pixels

perfect event: $n_i = \mu_i \qquad \eta = \langle\eta\rangle \quad t = \langle t\rangle$

$$\mu_i = p_i N_{exp}$$

- N_{exp}: expected total number of hits

$$p_i(\theta) = \varepsilon_i \frac{\Delta\phi}{2\pi} e^{-\frac{(\eta_i - \langle\eta\rangle)^2}{2\sigma_\eta^2}} \frac{\Delta\eta}{\sigma_\eta\sqrt{2\pi}} e^{-\frac{(t_i - \langle t\rangle)^2}{2\sigma_t^2}} \frac{\Delta t}{\sigma_t\sqrt{2\pi}} + B_i\Delta t$$

- ε_i: pixel efficiency (=1)
- $\Delta\phi, \Delta\eta$: ang. acceptance of pixel i
- Δt: TDC time resolution (=1 ns)
- $B_i\Delta t$: background rate

from calibration: $N_{exp}, \langle\eta\rangle, \sigma_\eta, \langle t\rangle, \sigma_t, B_i$

PDG, Section 40. Statistics

FTOF likelihood

expected number of hits in pixel i for a "perfect event"

$$LL = -2\ln\mathcal{L}(\theta) = 2\sum_{i=1}^{N}\left[\mu_i(\theta) - \hat{\mu}_i(\theta) + n_i \ln\frac{\hat{\mu}_i(\theta)}{\mu_i(\theta)}\right]$$

sum over the paddles of panels 1a,1b

number of hits in paddle i (=0,1)

expected number of hits in paddle i

perfect event: $n_i = \mu_i \quad t = \langle t \rangle$

$$\mu_i = p_i N_{exp}$$

expected total number of hits (=2)

TDC time resolution (25/100 ps)

paddle efficiency (=1)

$$p_i(\theta) = \varepsilon_i \frac{\Delta\phi}{2\pi} e^{-\frac{(\eta_i - \langle\eta\rangle)^2}{2\sigma_\eta^2}} \frac{\Delta\eta}{\sigma_\eta\sqrt{2\pi}} e^{-\frac{(t_i - \langle t\rangle)^2}{2\sigma_t^2}} \frac{\Delta t}{\sigma_t\sqrt{2\pi}} + B\Delta t$$

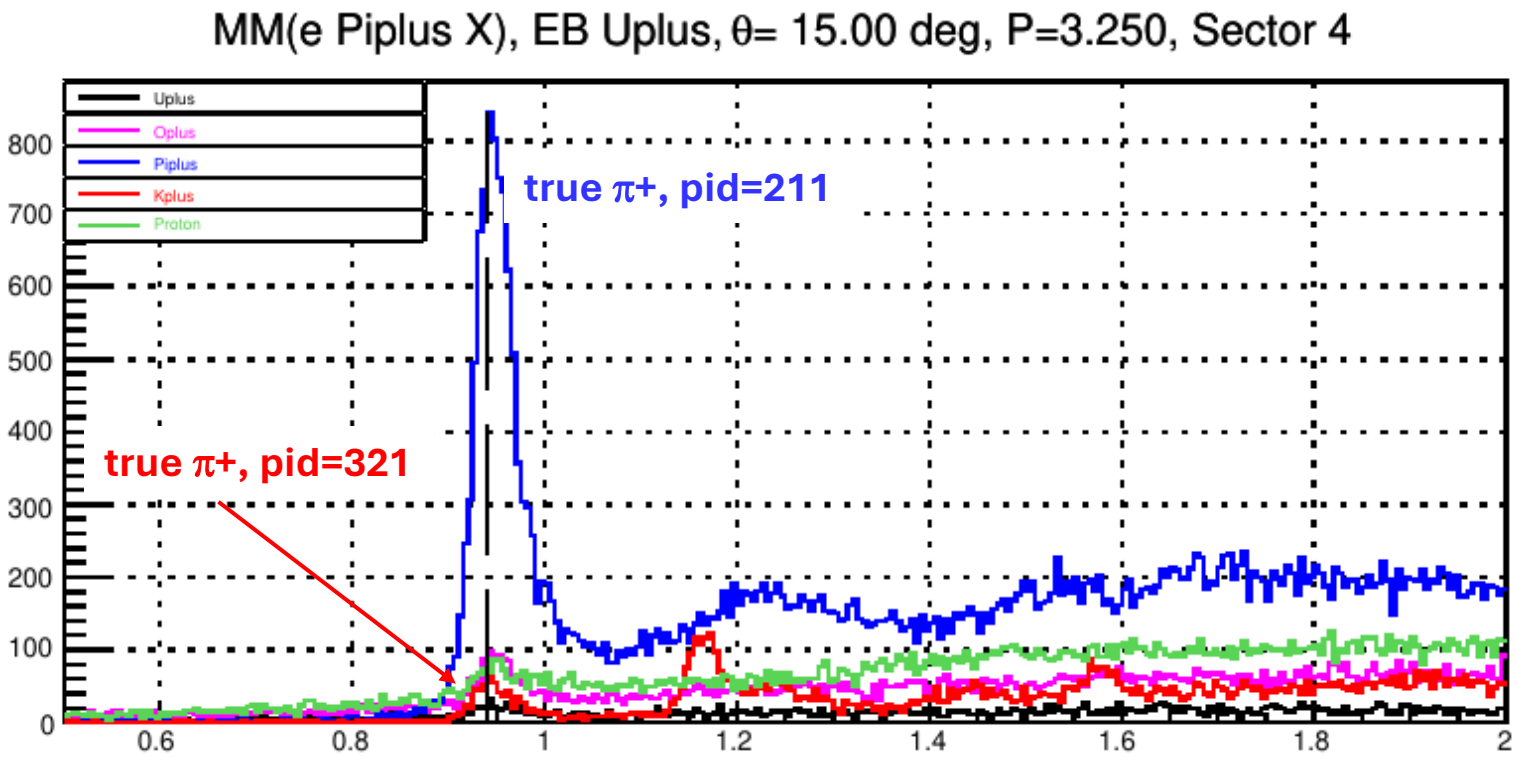
from calibration: $\langle t \rangle = 0, \sigma_t$

Pion identification study

Efficiency calculation procedure

- **select events: e p →e' h+ X**
- **apply fiducial cuts**
- **impose pion mass to h+**
- **plot MM(e h+ X) depending on the ID of the h+**
- **fit the MM around the nucleon mass**
- **true pions are the events in the neutron peak (N_n), after the background subtraction**

RGK spring 2024 data set
E_{beam} = 8.5 GeV
torus +1
Results for sector 1



Efficiency and mis-ID calculation

$N_{\pi \to j}$ **Number of true pions with reconstructed ID=j**

$\sum_j N_{\pi \to j}$ **Total number of true pions**

- **Ratios to the total number of true pions**

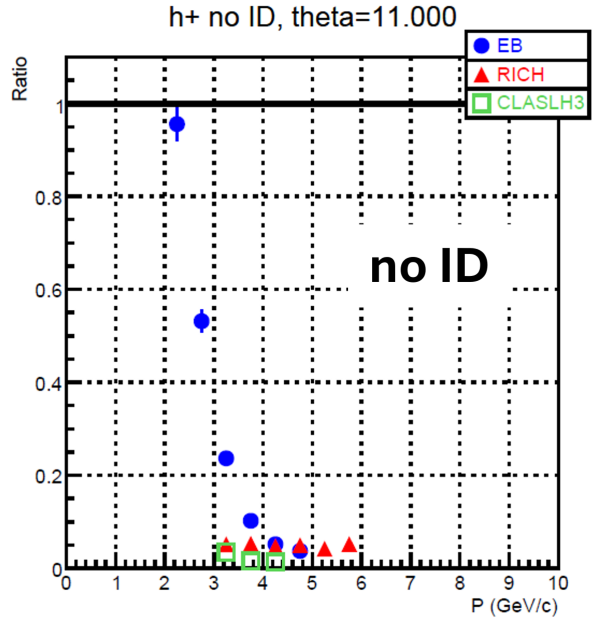
Efficiency	$\epsilon_\pi = \frac{N_{\pi \to \pi}}{\sum_j N_{\pi \to j}}$	Fraction of true pions correctly ID
Mis-ID	$M_{\pi \to j} = \frac{N_{\pi \to j}}{\sum_k N_{\pi \to k}}$	Fraction of true pions with wrong ID, j=321,2212
No ID	$M_{\pi \to 0} = \frac{N_{\pi \to 0}}{\sum_k N_{\pi \to k}}$	Fraction of event with no ID, j=0
Loss	$M_{\pi \to noFC} = \frac{N_{\pi \to noFC}}{\sum_k N_{\pi \to k}}$	Fraction of events out of the fiducial cuts

- $1 = \epsilon_\pi + \sum_{j \neq \pi} M_{\pi \to j}$

- Efficiency, mis-ID, no ID, loss depend on the detector only (if fully unintegrated)
- The efficiency includes everything, except DC tracking efficiency

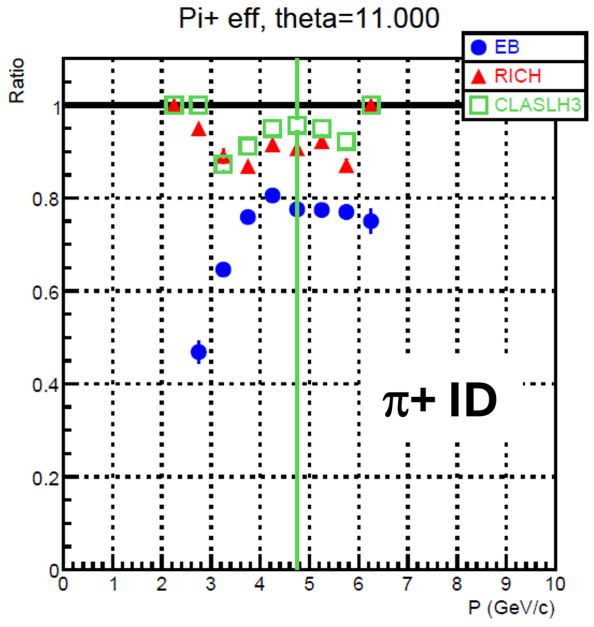
- To better understand the PID detector performance, it may be convenient to take out the loss due to fiducial cuts

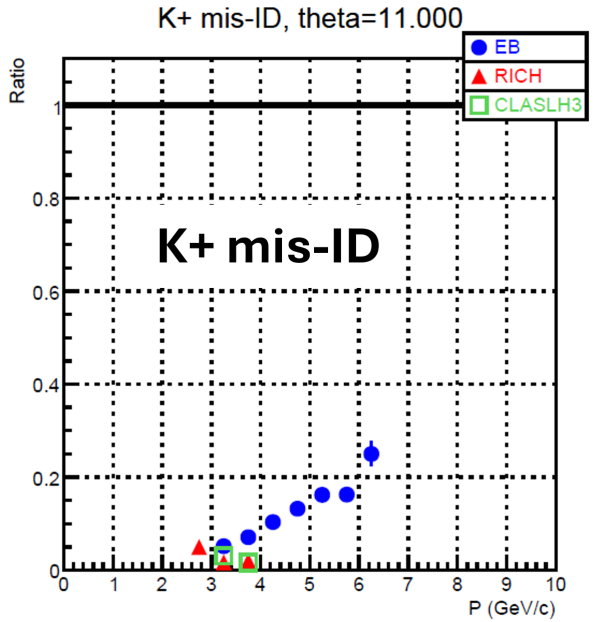
Efficiency and mis-ID vs PID detector

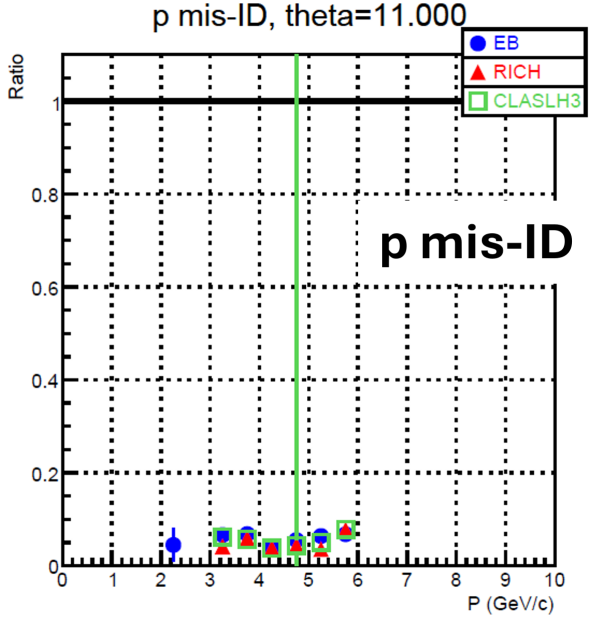


Fixed angle θ=11 deg, momentum dependence

blue filled circles:	EB
red filled up triangles:	RICH
green filled down triangles:	LH RICH+FTOF

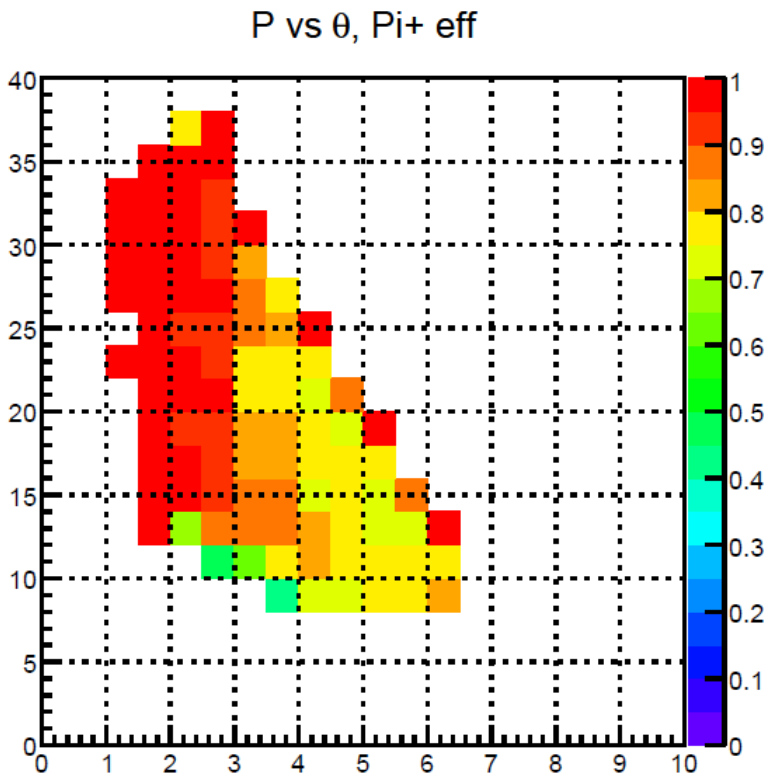




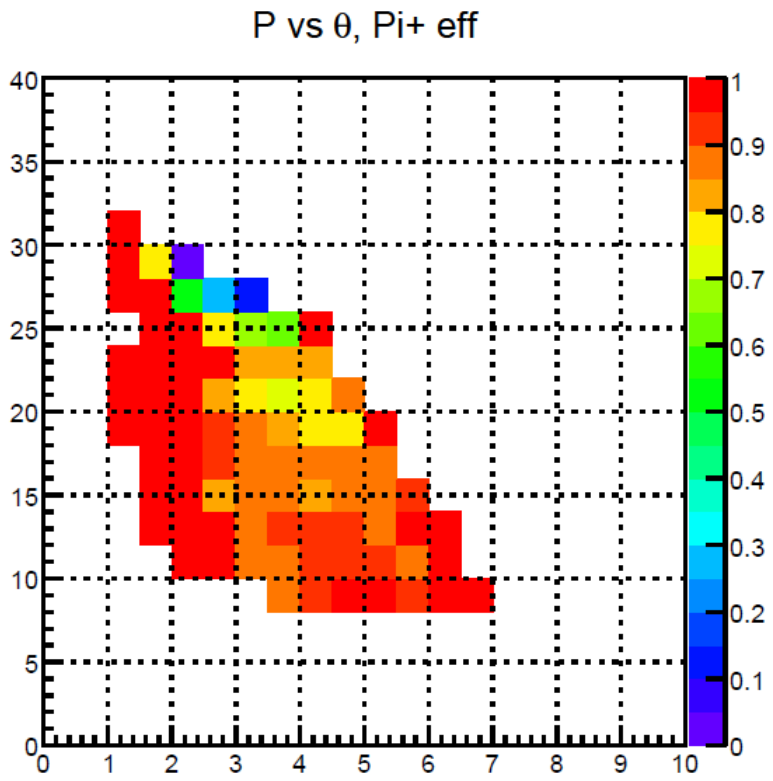


pi+ efficiency maps

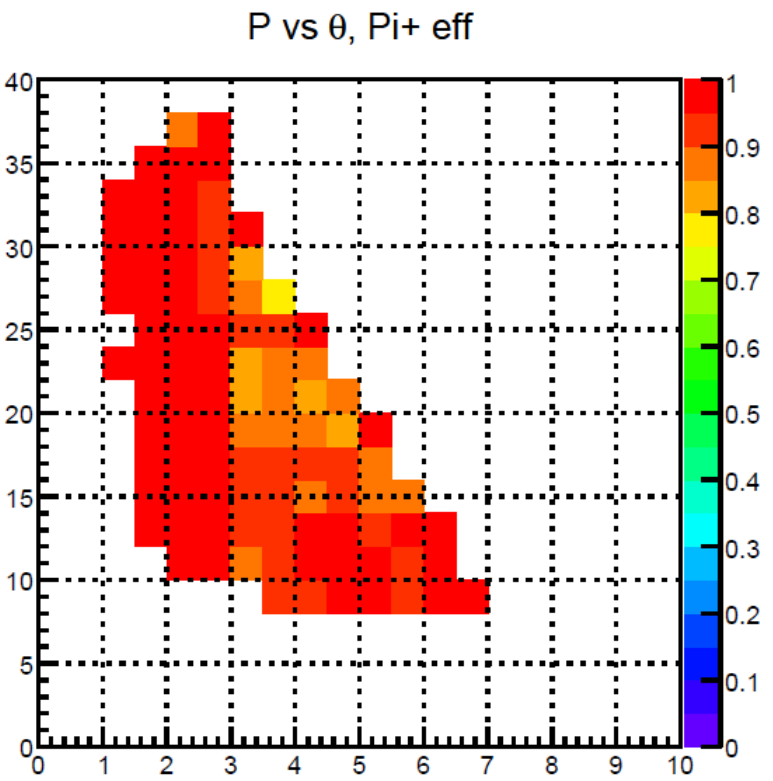
Event Builder



RICH



LH RICH+FTOF



Combining FTOF and RICH provides a flat efficiency over the entire kinematic plane

The RICH at RGH

The RICH is finally fully operative on its whole kinematic coverage

- **tools are available to perform regular alignment and calibration together with all the other CLAS12 components**

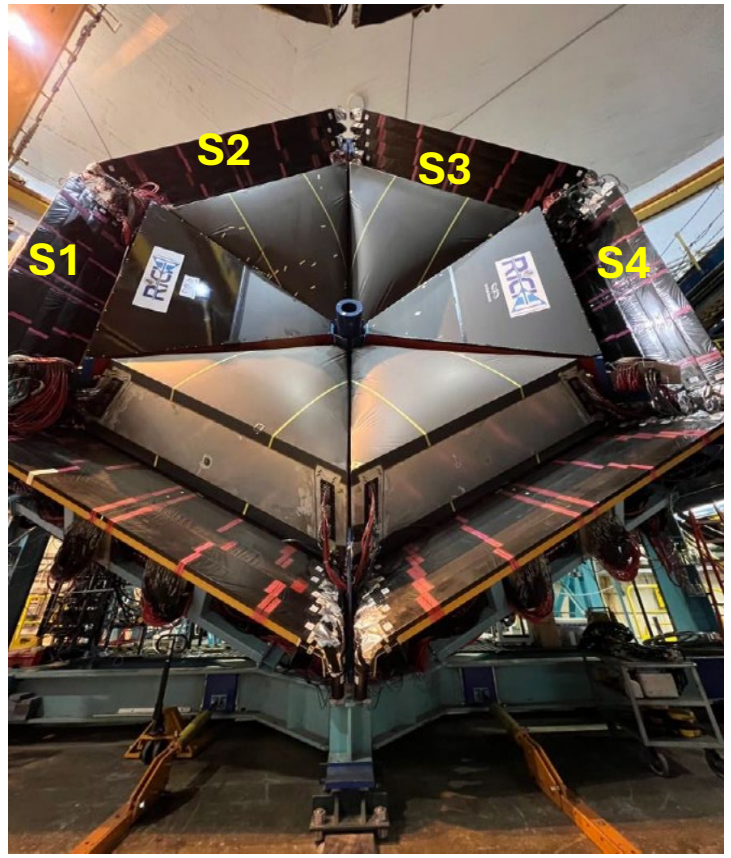
No degradation of the response has been found after several years of operation

Studies to combine the information of PID detector in a global CLAS12 ID have been started

Running the RICH at RGH, the luminosity is not a problem

- **RGA with LH target run at 10^{35}**
- **RGC with NH3 target run at 5 10^{34}**
- **RGH will run at 5 10^{33}**

The background level in Sector 4 is an issue: the sector will be turned off
→ the RICH sector 4 module must be moved to sector 2 or 3
→ need simulations to determine the best configuration

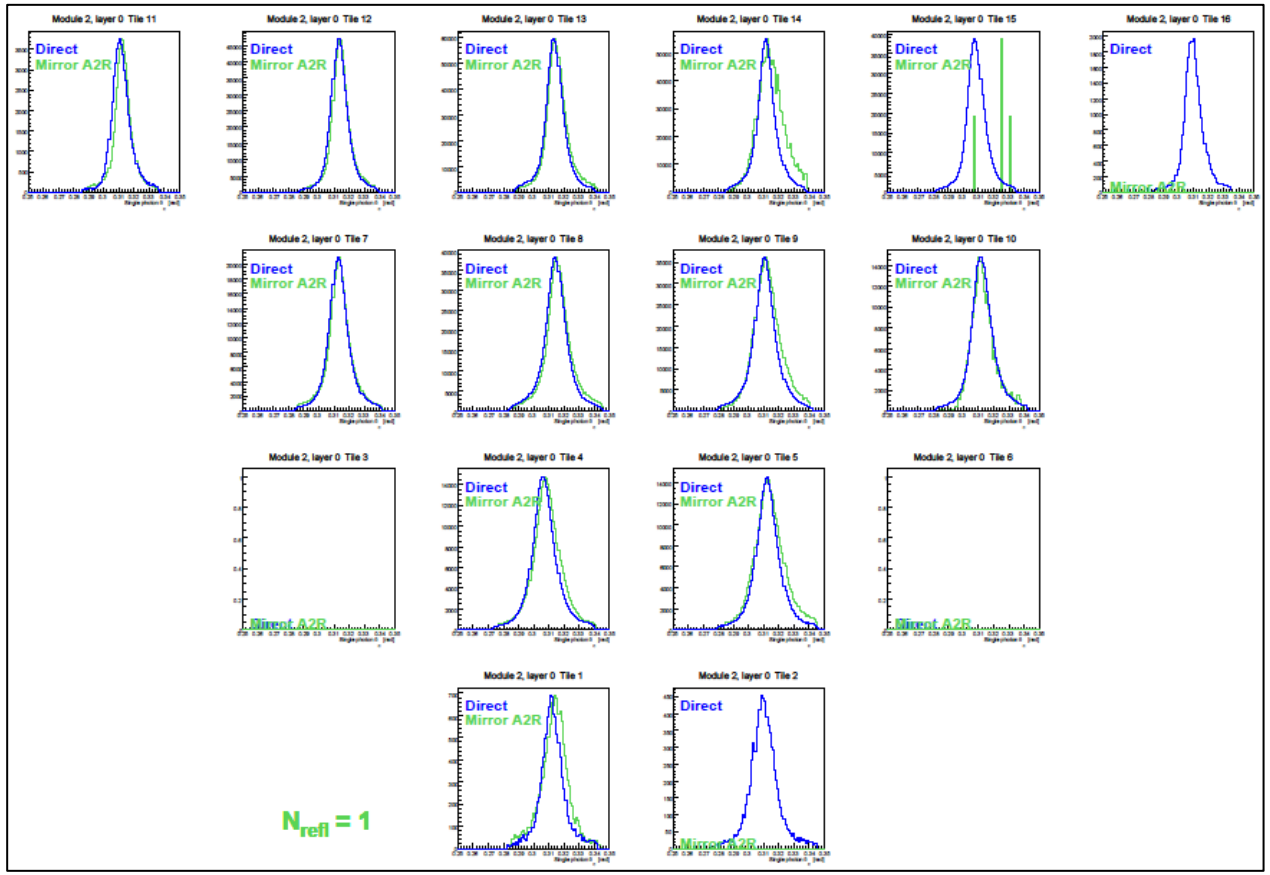


additional slides

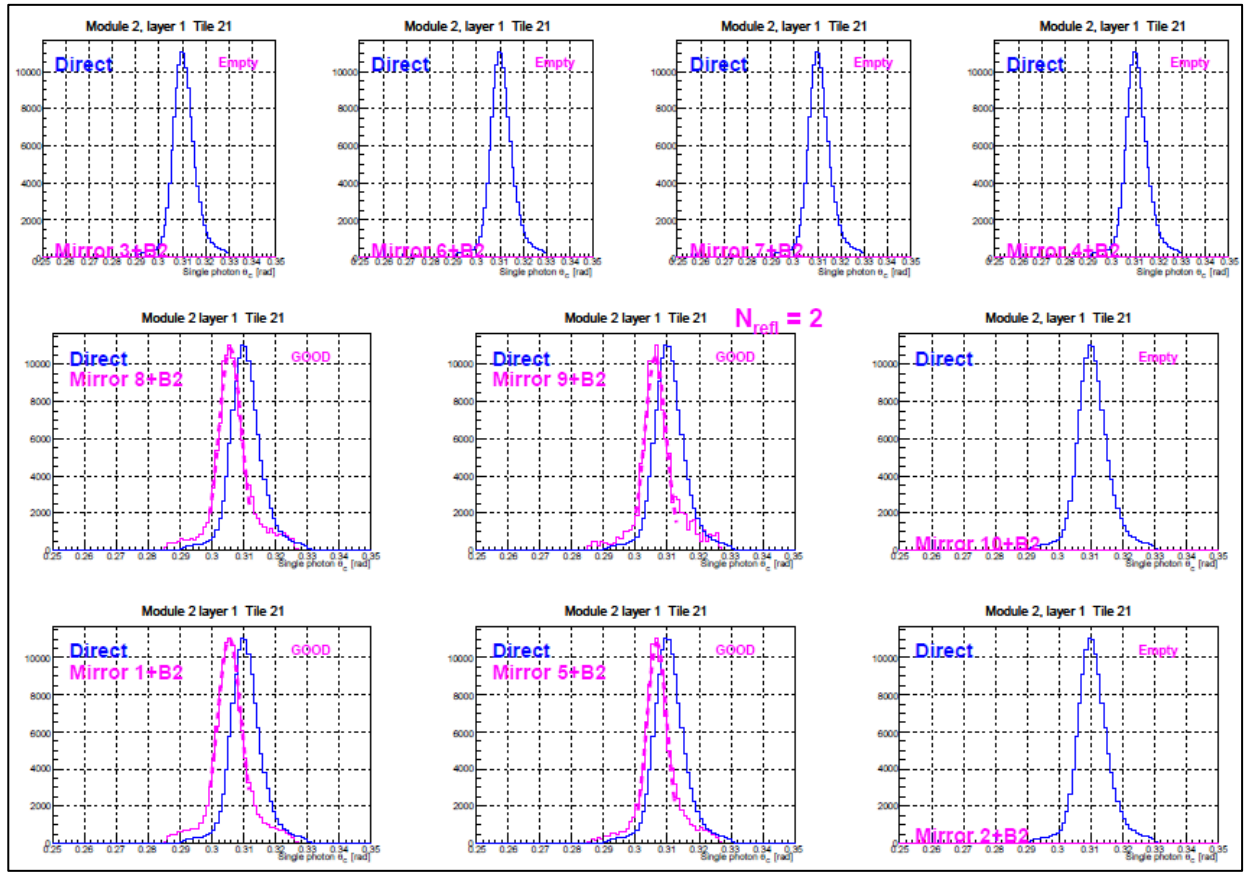
Cherenkov angle results

RGK spring 2024
Sector 1

pi+, all aerogel tiles of layer 0
blue: no reflections
green: one reflection on the lateral mirror A2R



pi+, tile 21 of layer 1
blue: no reflections
green: two reflections, spherical mirror plus frontal mirror B2



Optical properties

The optical properties in GEMC are defined by a number of parameters that have been tuned to the characterization measurements performed on the mirrors and aerogel

Aerogel

1. **Cherenkov photon generation**
   - **nominal refractive index at λ=400nm, dispersion law**
2. **Volume effects**
   - **transmition or absorption:** $T = Ae^{-t/L_{scatt}(\lambda)}$
   - **Rayleigh scattering:** $f(\theta) \propto 1 + \cos^2\theta$
   - **forward scattering:** $f(\theta) \propto \frac{1+g^2}{(1+g^2\cos\theta)^{3/2}}$
3. **Surface effects**
   - **refraction (Snell law)**
   - **angular smearing from the RMS of the surface roughness (μm scale)**

no tile dependence

Mirrors

1. **Surface accuracy**
   - **planar mirrors: angular smearing from the RMS of the surface accuracy**
   - **spherical mirrors: angular smearing from D_0 measurements**
2. **Reflectivity**

no mirror dependence

Ageing

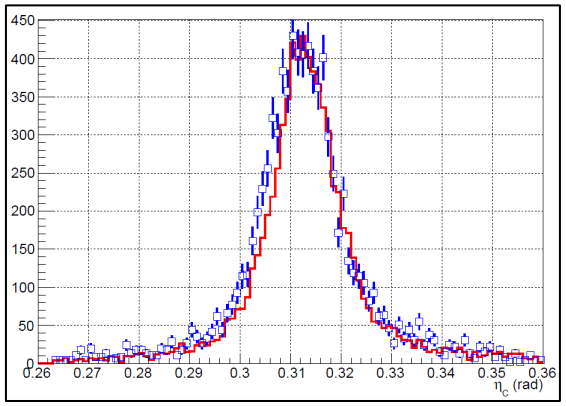
Comparison between data on an

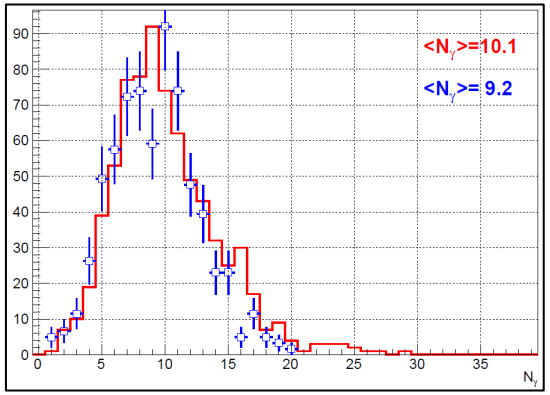
unpolarized Hydrogen target taken in fall 2018

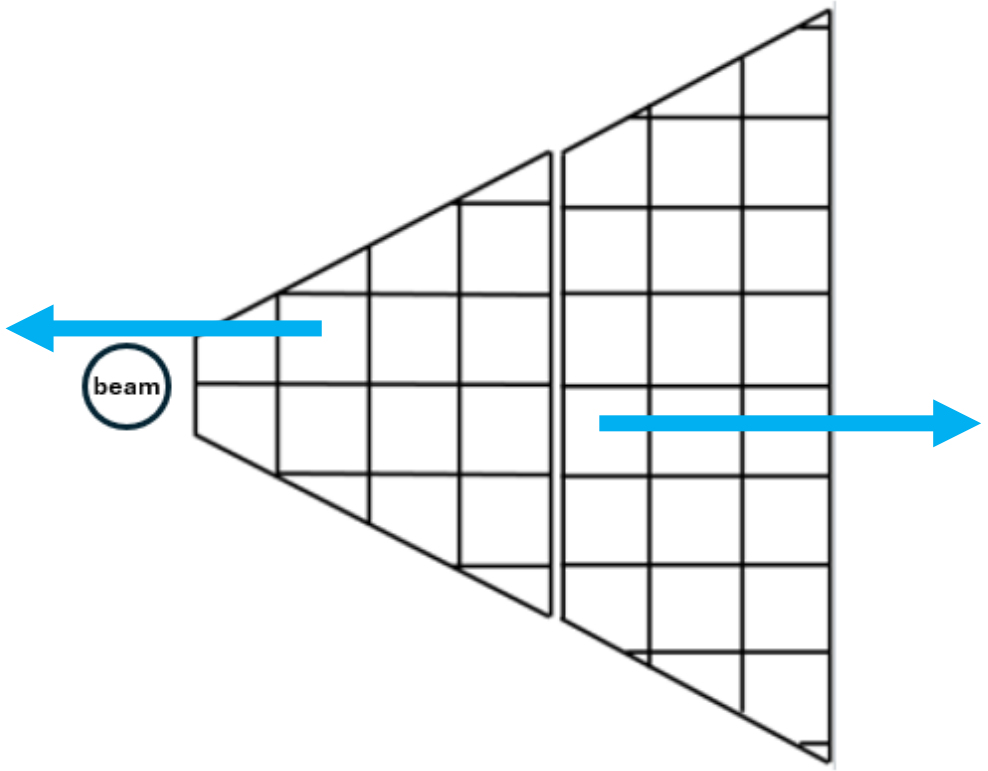
with data taken on a

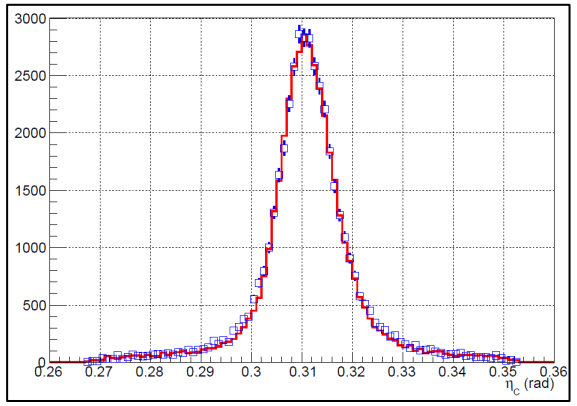
longitudinally polarized NH3 target in fall 2022

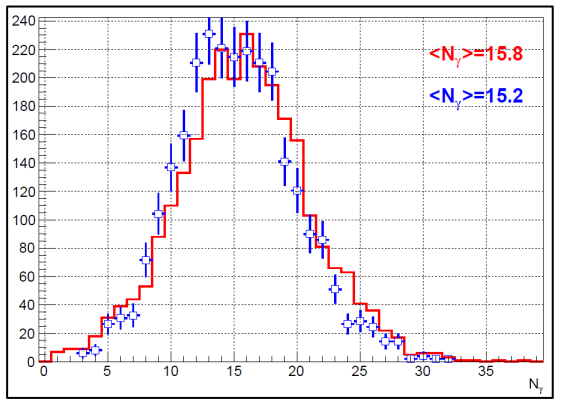
Results for π-
Plots for photons with 0 reflections









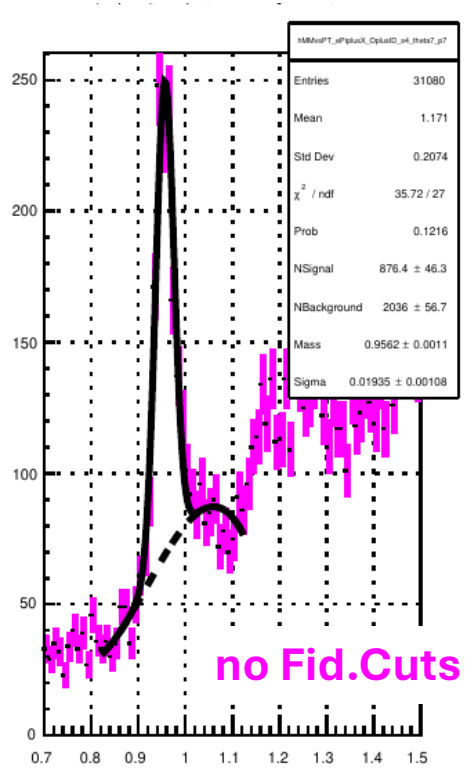


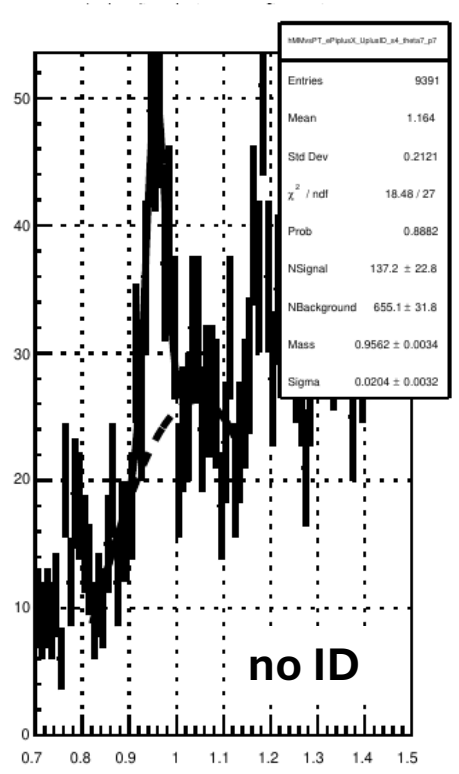
MM Fits

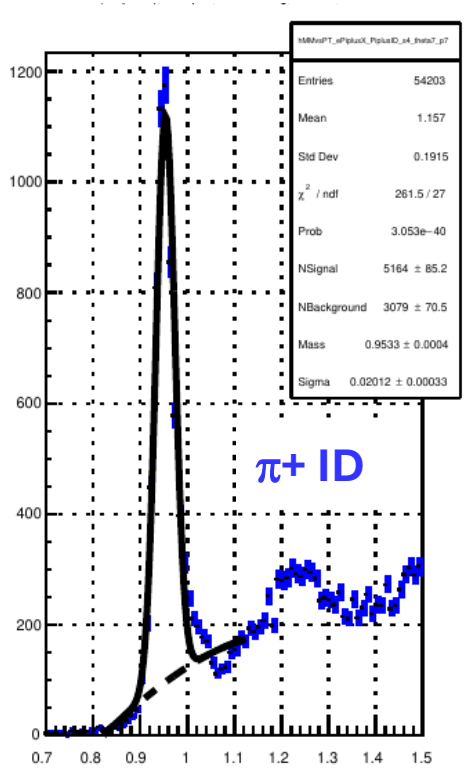
Fit function: $f(x) = N_n G(x) + N_b P_3(x)$

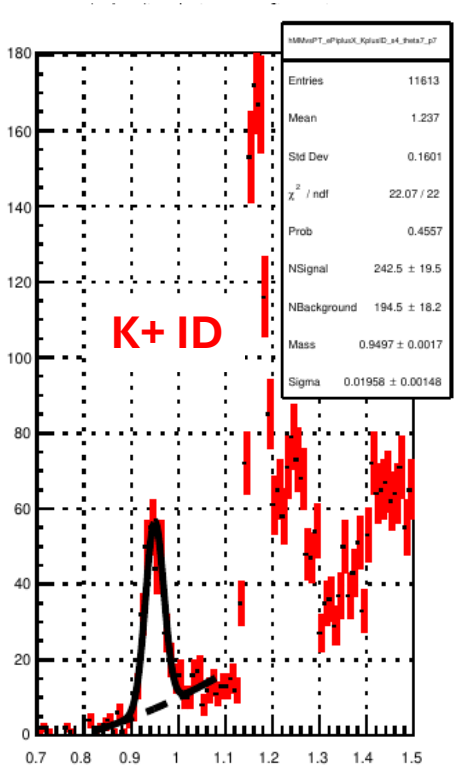
- $G(x)$ and $P_3(x)$ are gauss and 3rd order polynomial, normalized to 1 in the fit range
- free parameters
  - Number of events: N_n, N_b
  - mass and width of the gauss
  - parameters of the polynomial
- binned Likelihood fit

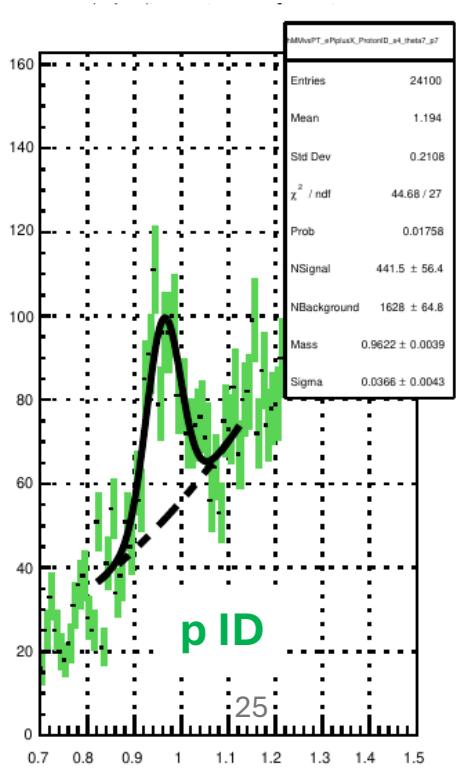
Proton ID: wider peak, more background



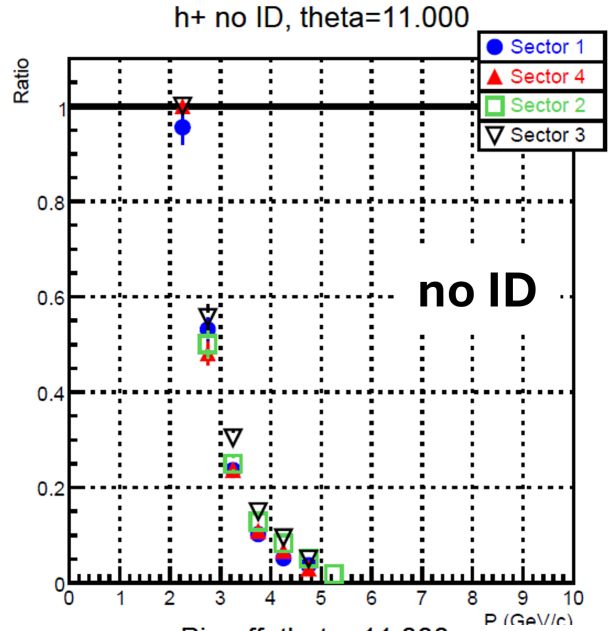








EB efficiency vs Sector



Fixed angle θ=11 deg, momentum dependence

Sector 1 and 4: with RICH
Sector 2 and 3: with LTCC??

