The CLAS12 RICH detector

Marco Mirazita
INFN Laboratori Nazionali di Frascati
for the CLAS12 RICH group

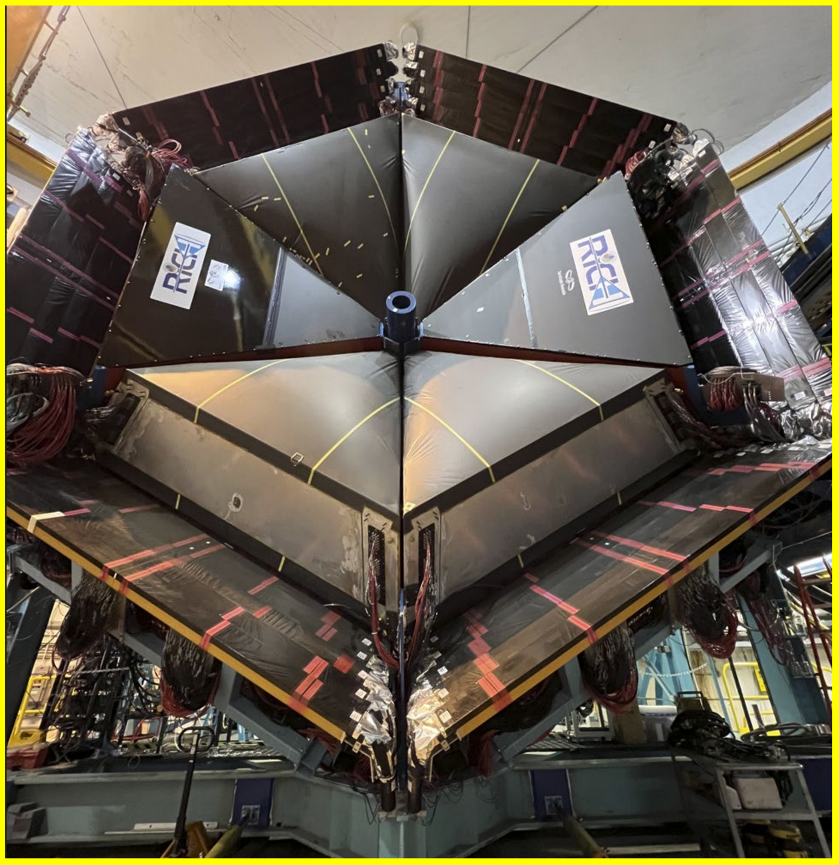
Jefferson Lab

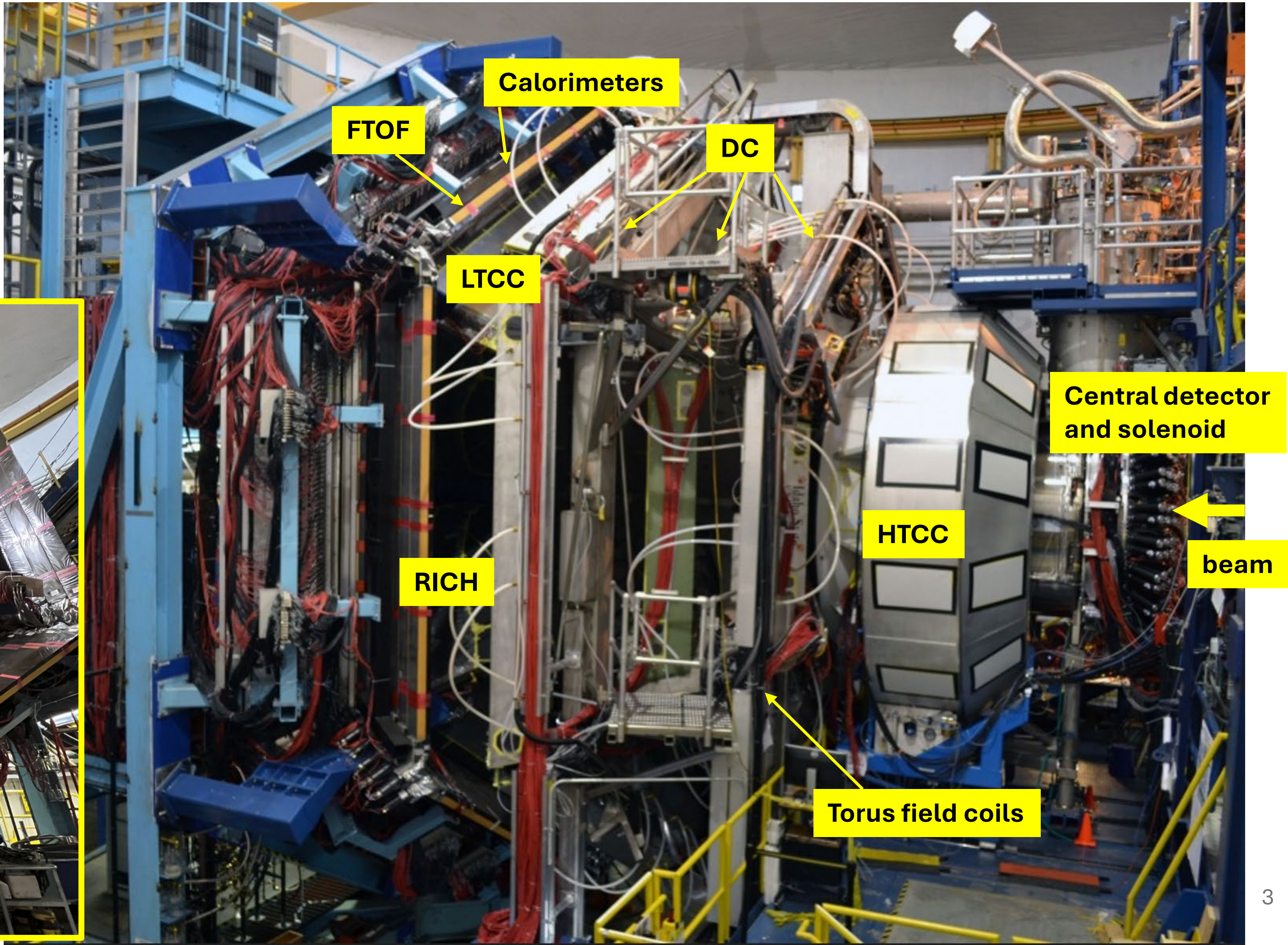
The CLAS12 spectrometer in Hall B

CEBAF Large Acceptance Spectrometer

- **Wide acceptance**
- **Luminosity up to 10^{35} cm^{-1} s^{-1}**
- **Max beam energy 10.6 GeV**
- **Polarization higher than 85%**
- **H and D targets (with polarization)**
- **Nuclear targets**

CLAS12 operative since January 2018





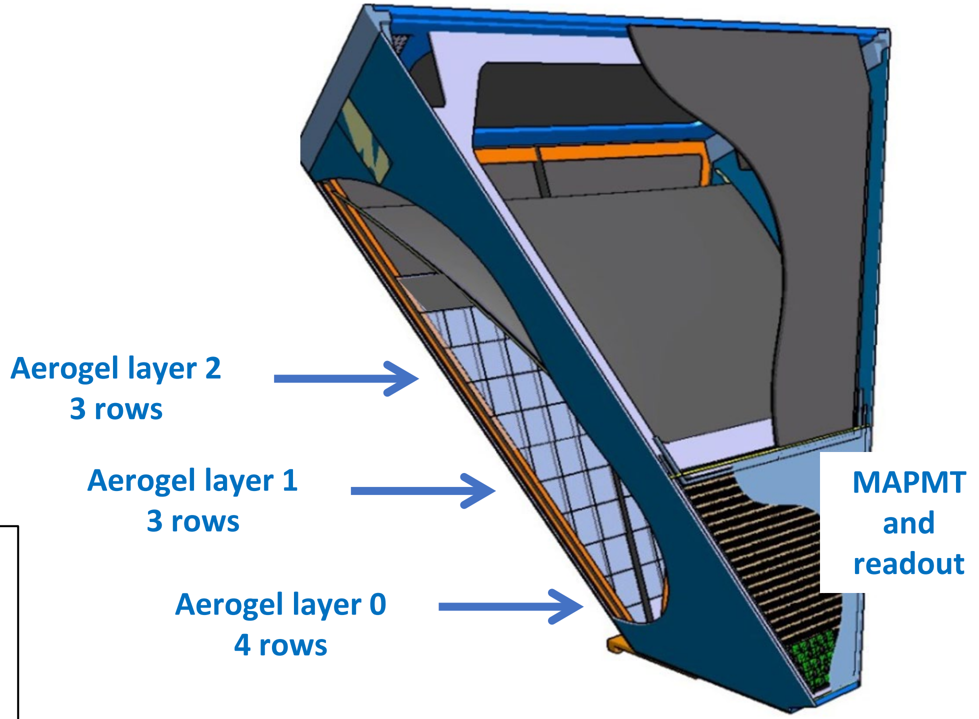
The CLAS12 RICH detector

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
- π/K rejection factor larger than 500
- p/K rejection factor larger than 100

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 n~1.05 (tile-to-tile RMS~10^{-3})
- 7 planar mirrors
- 10 spherical mirrors
- 391 Multi-Anode PMTs Hamamatsu H12700 and H8500
- readout based on the MAROC3 chip, total of 25024 channel



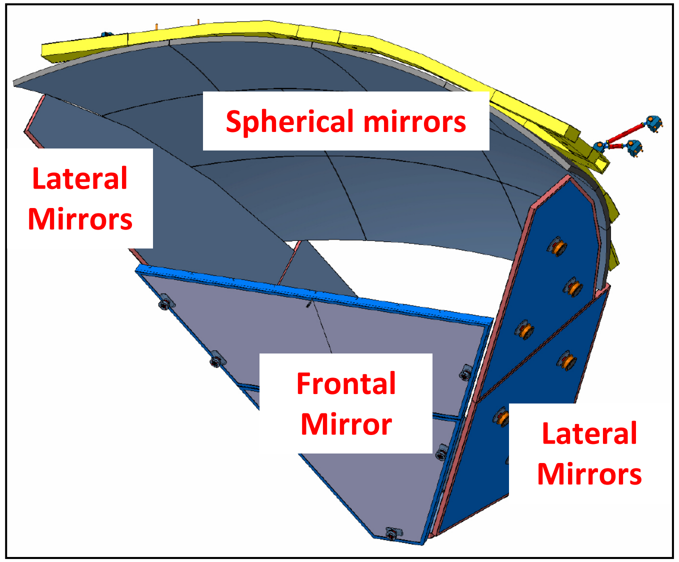
Chrenkov emission thresholds with n=1.05

$\beta > 1 / n \approx 0.952$

$P_{\pi} > 0.45$ GeV/c

$P_{K} > 1.5$ GeV/c

$P_{p} > 3.0$ GeV/c



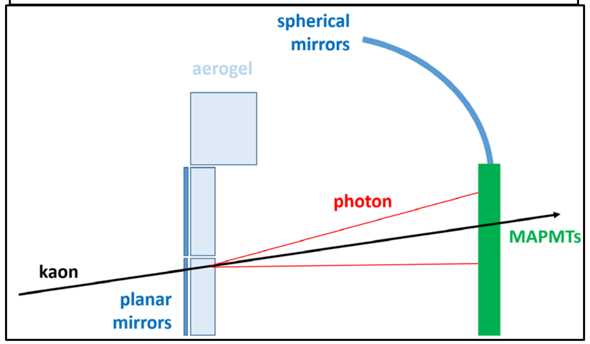
Module 1 installed in January 2018, Module 2 installed in June 2022

Photon patterns

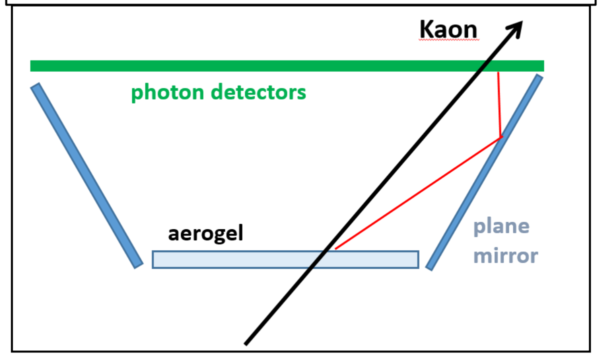
The photon hit patterns depend on the position and angle of the track on the aerogel plane

- **Only central tracks produce a full circle on the photodetector plane**
- **In general, the Cherenkov cone will be imaged onto section of circles with different radius**

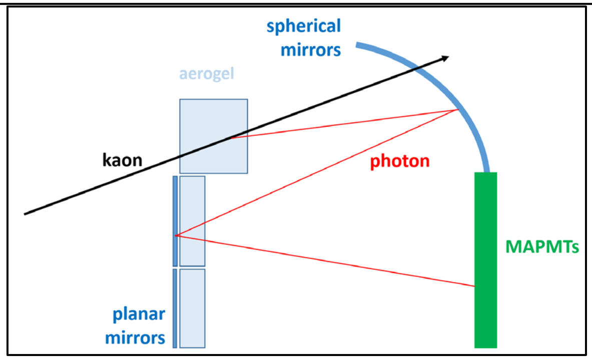
direct detection: no reflections

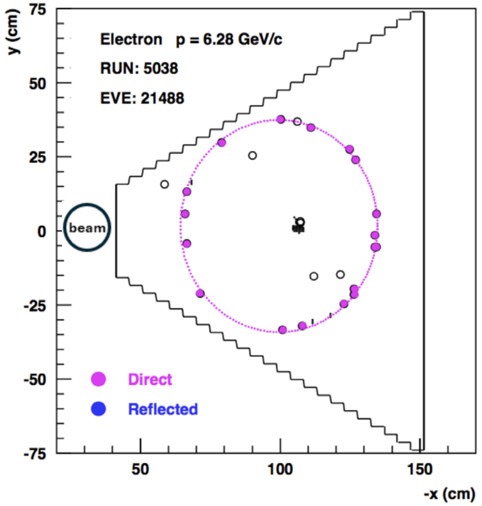


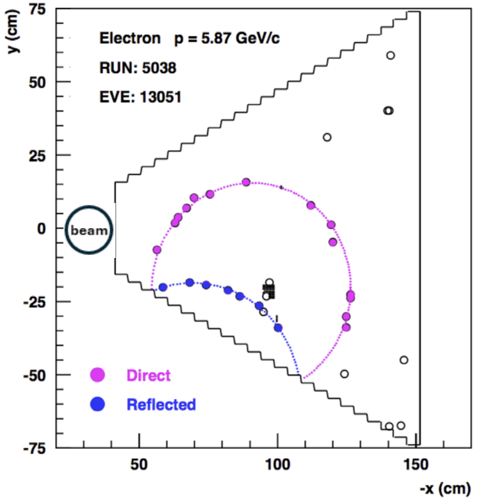
one reflection on a lateral mirror

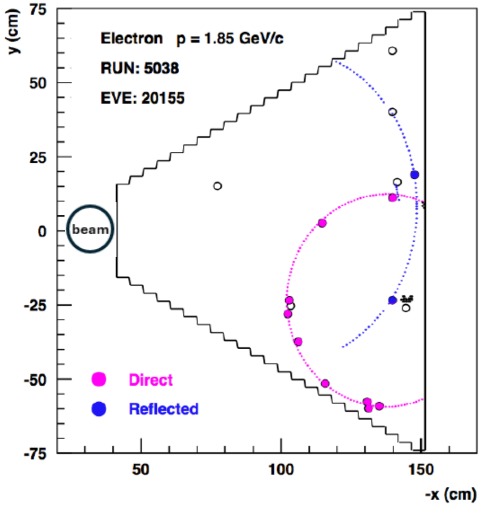


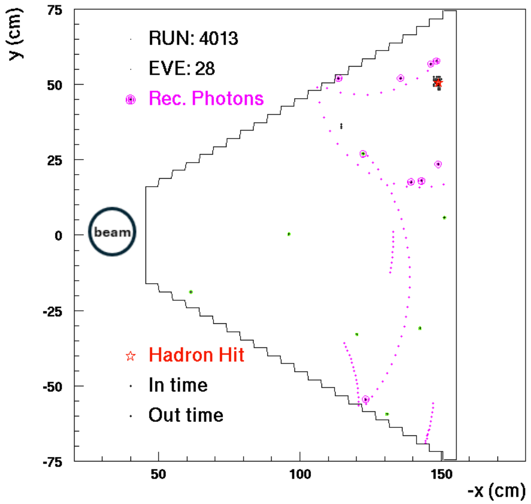
two reflections: spherical plus frontal mirror









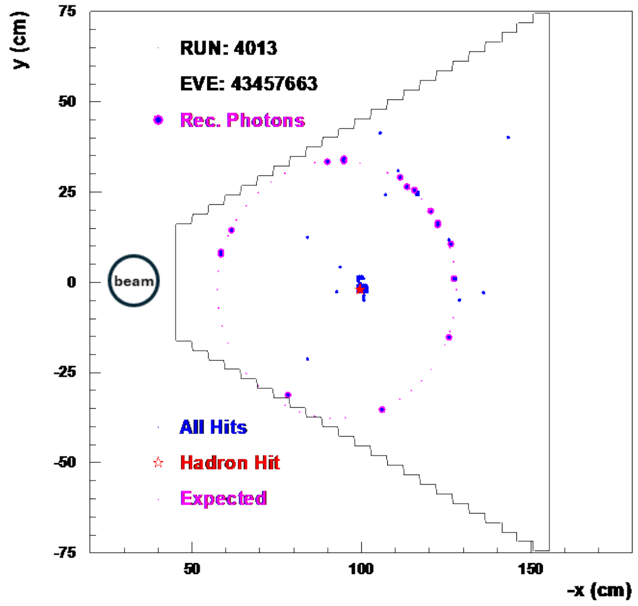


Event reconstruction: direct ray tracing

A sample of photon trials is generated, based on the known refractive index and the charged track kinematics, and traced inside the detector
Starting from the closest trial, the emission angles are adjusted to match the photon hit

- need precise knowledge of the geometry of the detector
- need precise alignment of the detector to the CLAS12 tracking system

→ Cherenkov angle for all the hits and for 3 hadron mass hypotheses: pion, kaon proton



Note on the Cherenkov angle notation:
θ_C represents the measured Cherenkov angle
η_C represents the Cherenkov angle rescaled to particles with $\beta=1$

$$\cos\eta_C = \beta\cos\theta_C \quad \rightarrow \quad \text{no momentum dependence}$$

Alignment

The direct ray tracing requires knowledge of position and angles of all the active elements: aerogel, mirrors, MAPMTs → Alignment

- **total number of free parameters: 126 per module**

A brute force approach has been used:

- **generate a large number of random alignment parameters sets**
- **find the best solution by minimizing based on peak position and resolution**

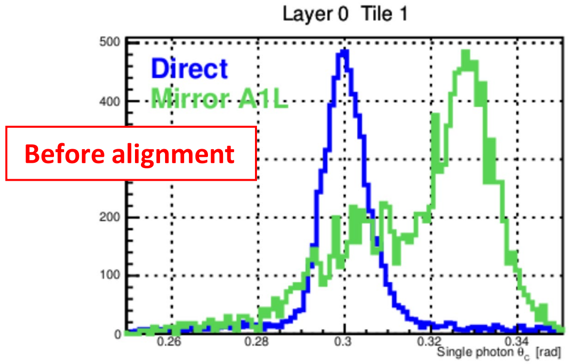
Procedure:

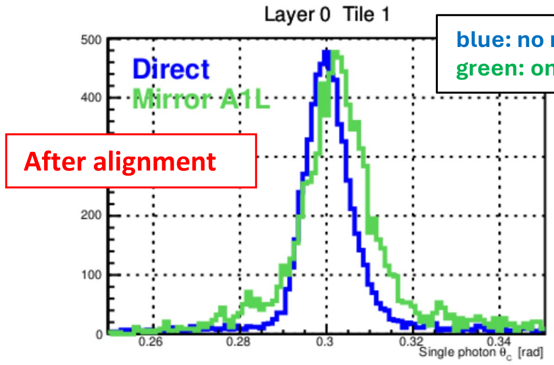
- **determine the relative alignment between the aerogel and MAPMTs using zero reflection photons**
- **align the mirrors one by one selecting specific photon detection topologies**

This approach worked well for simple topologies (up to 2 reflections)

It failed for more complicated topologies and where photons with zero reflections are not available

The third section of aerogel radiator has not been aligned yet
→ no acceptance at the larger polar angles





blue: no reflections
green: one reflection on a lat. mirror

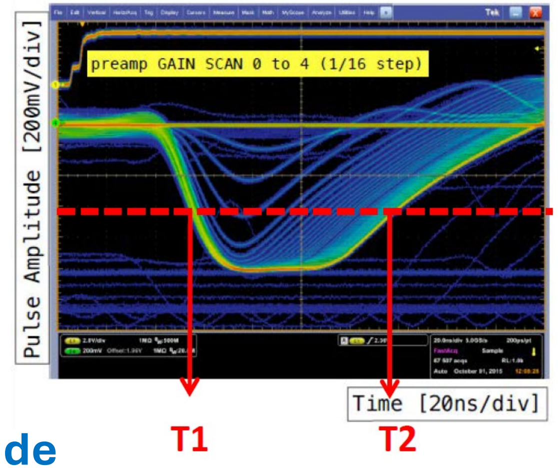
Time reconstruction and calibration

The readous system is composed by:

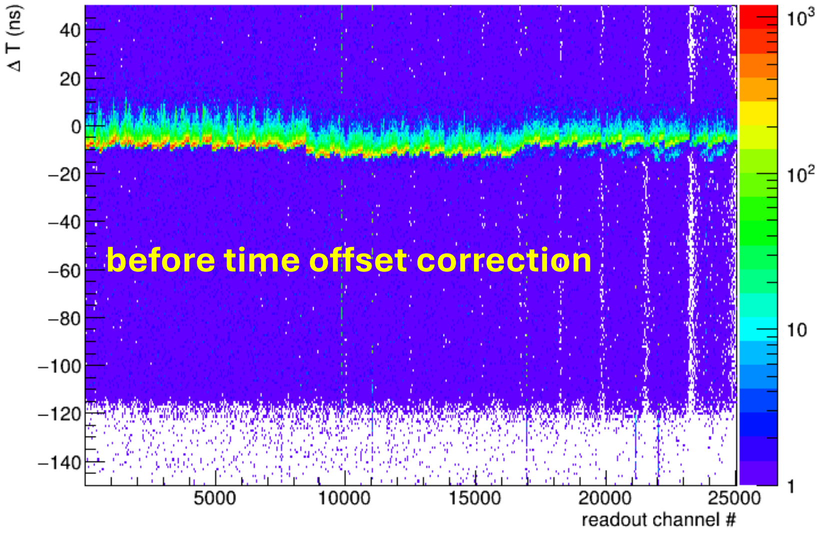
- **MAROC chip: provide a fast (binary) line with programmable amplifier and discriminator threshold for time measurement**
- **FPGA: TDC with 1 ns time stamp**

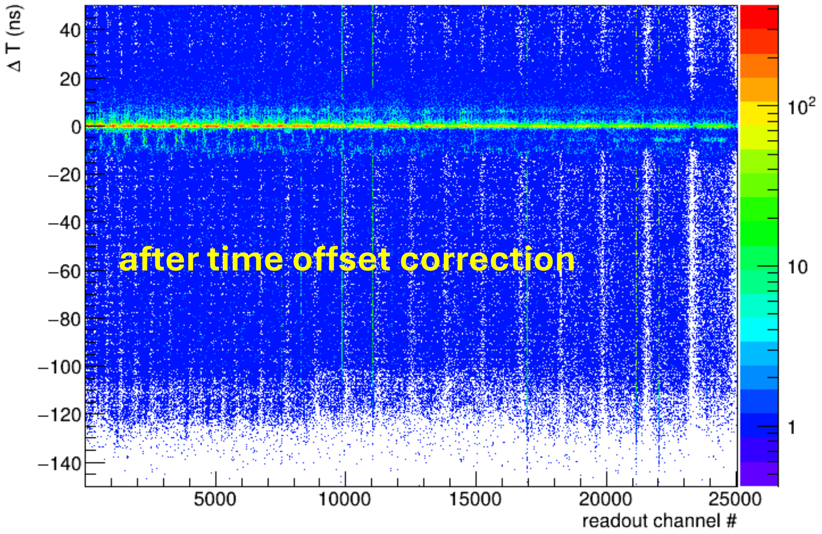
The readout system provides start (T1) and stop (T2) times

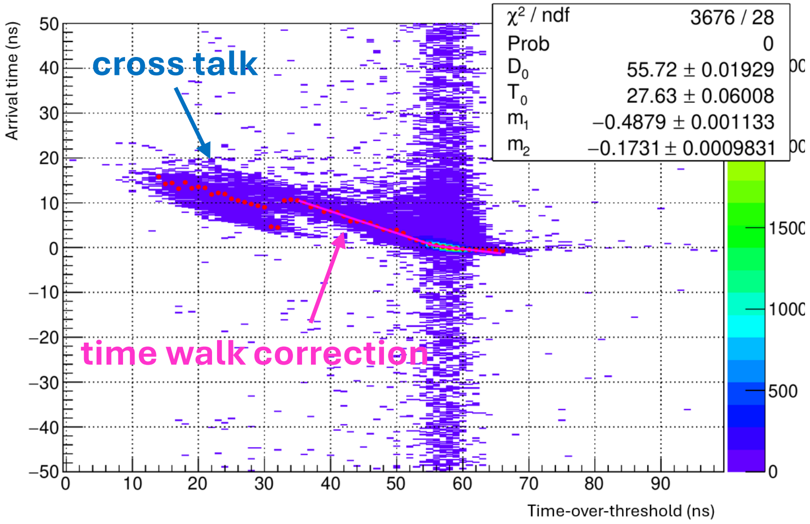
- **T1 determine the photon arrival time**
- **Time-over-threshold (duration) T2-T1: approximately proportional to the signal amplitude**



The time calibration is performed by computing $\Delta T = T1 - T_{calc}$

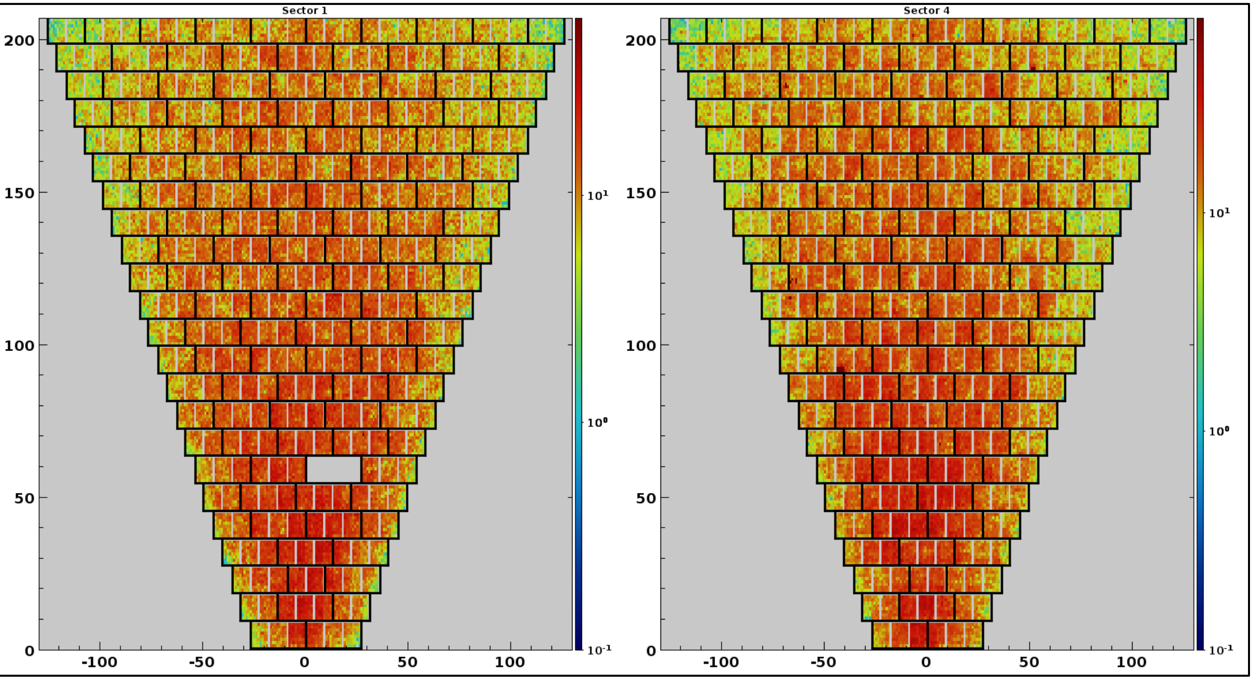




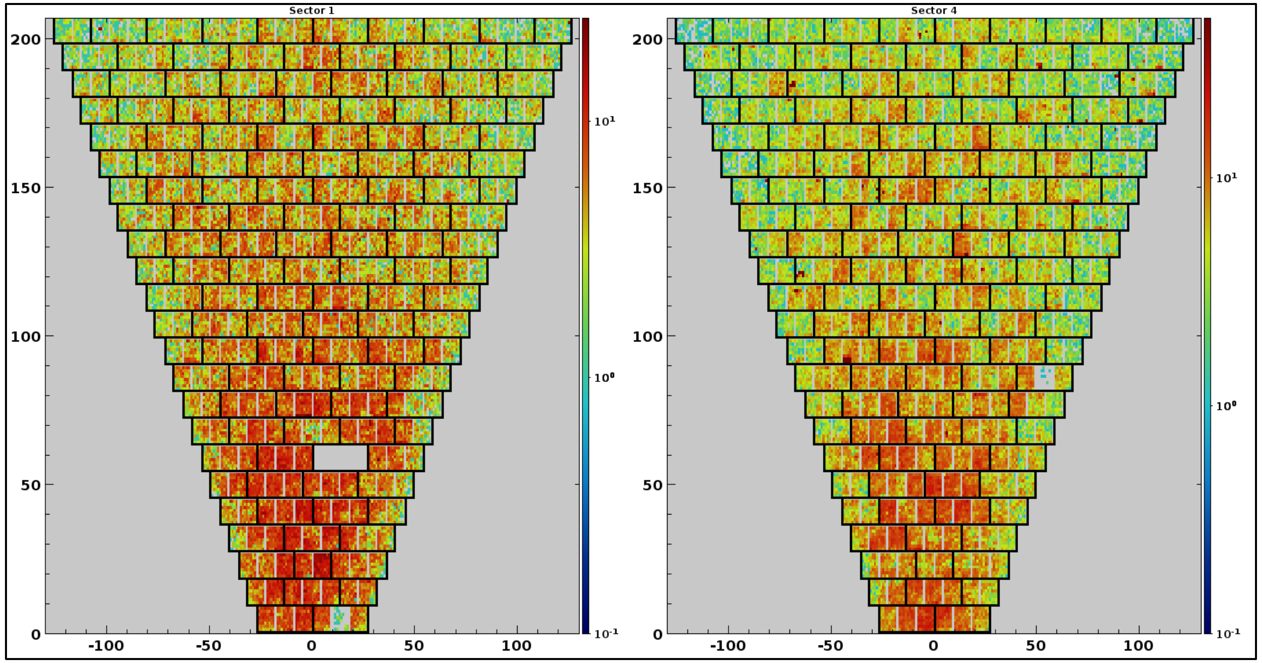


MAPMT ageing

July 2022
NH_3 long. polarized target



April 2025
gaseous deuteron target



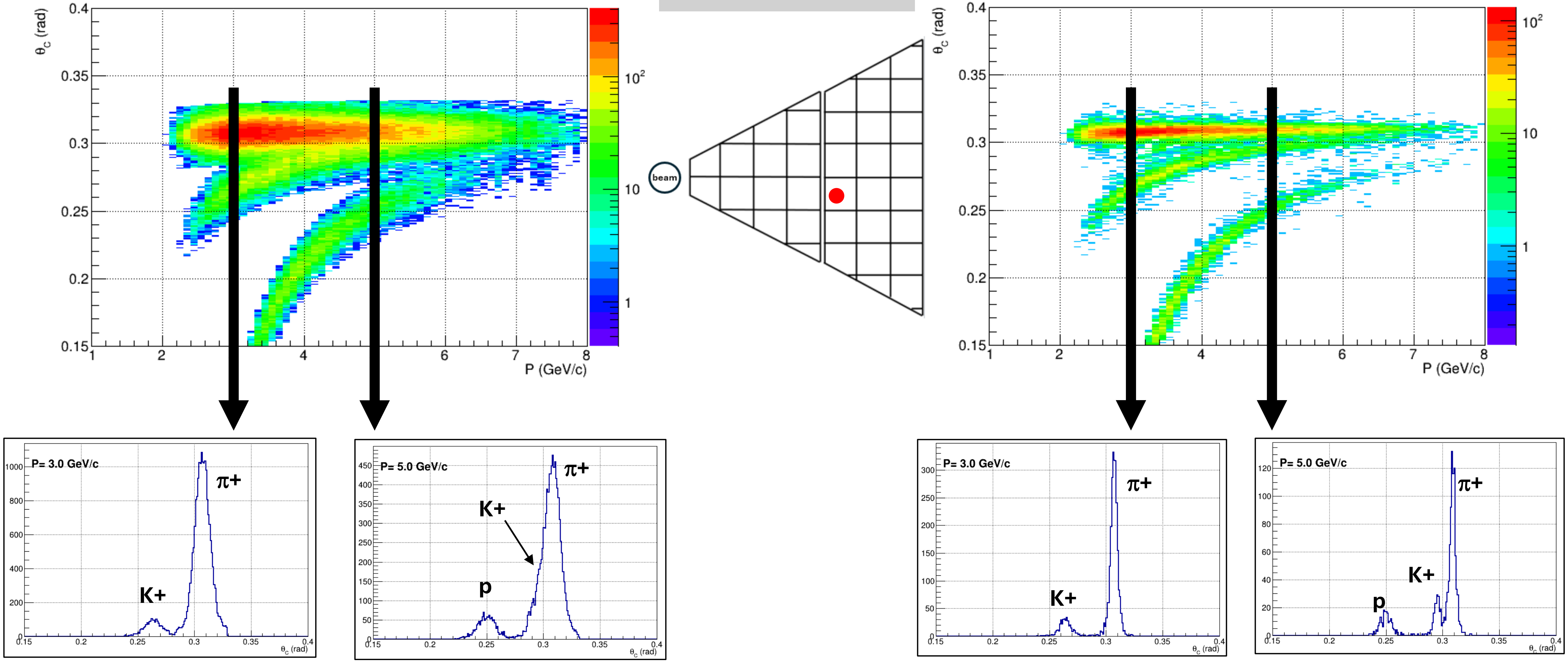
- **One FE board not functioning in module2 due to heat production**
- **2 MAPMT died during nuclear target data taking**
- **less than 1% loss**

Cherenkov angle reconstruction

Positive hadrons
No reflections

Single photon Cherenkov angle

Track average Cherenkov angle



Cherenkov angle vs photon detection topology

For photons with no reflections, the Cherenkov angle resolution can be written as

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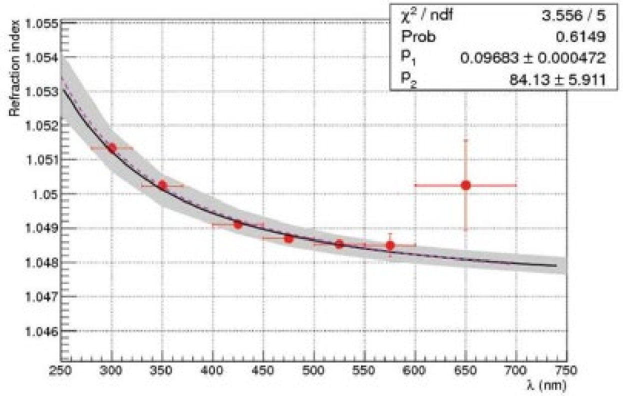
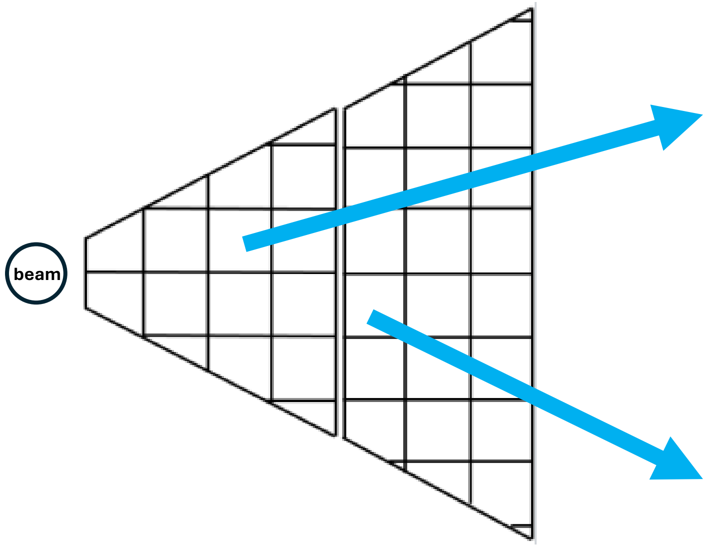


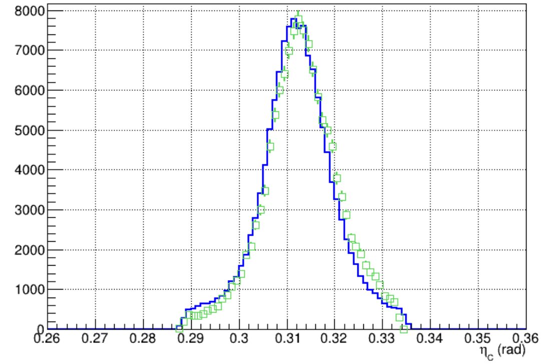
$$\sigma_{dir}^2 = \sigma_{trk}^2 + \sigma_{chr}^2 + \sigma_{det}^2 + \sigma_{emi}^2$$

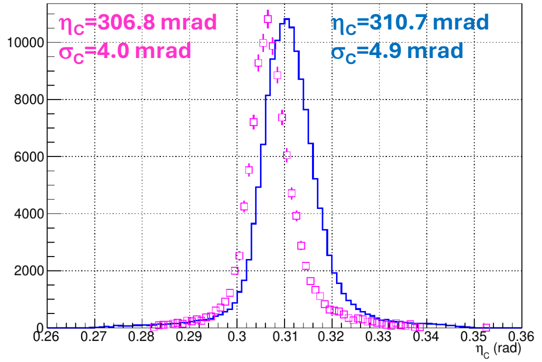
- **bigger contribution coming from the chromatic dispersion**
- **expected value around 5 mrad or better**

For reflected photons, one must add:

- **mirror contribution: small with smooth wavelength dependence**
- **double passage through the aerogel: suppression of UV and blue photons**





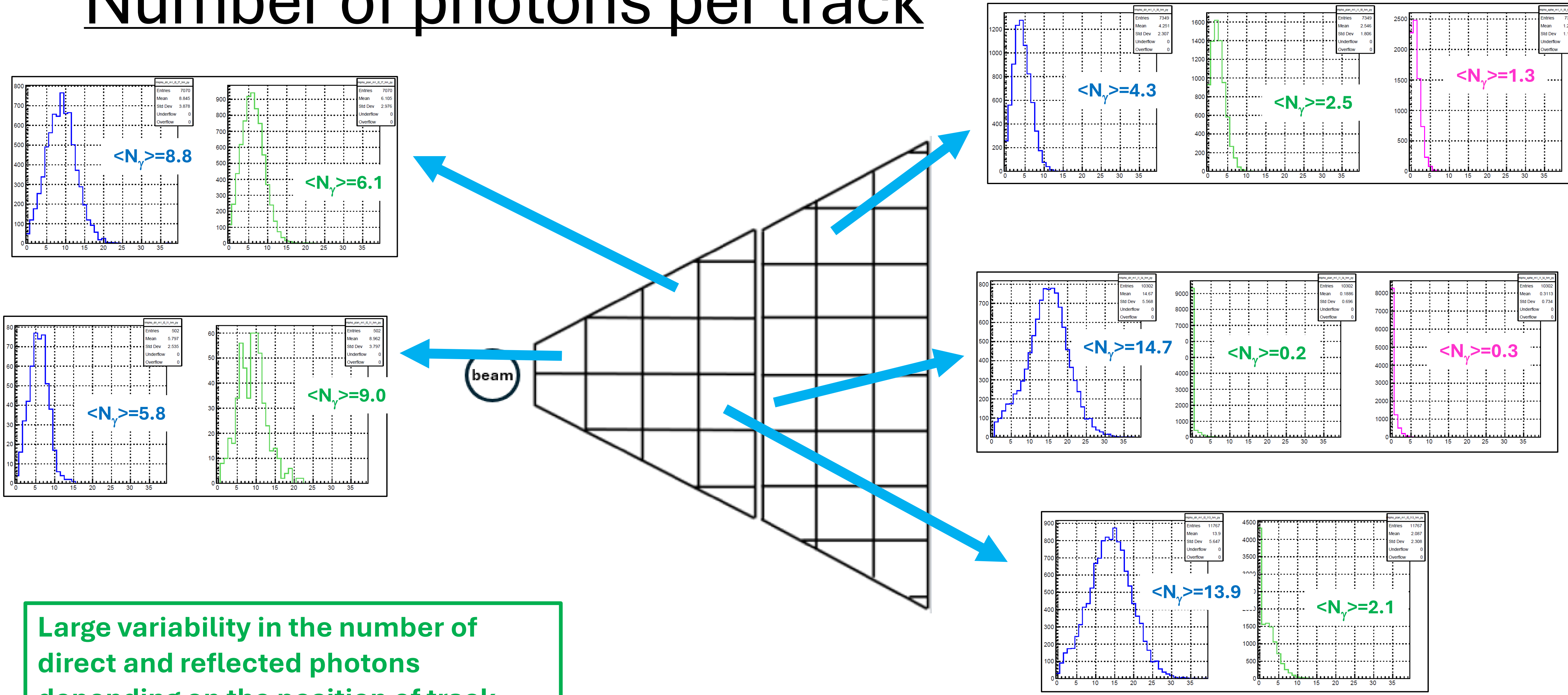


Results for π-

- **No appreciable difference between 0 and 1 reflection photons**
- **For photons with 2 reflections, about 4 mrad shift and 20% better resolution**

blue: no reflections
green: first reflection on a lateral mirror
purple: first reflection on a spherical mirror

Number of photons per track



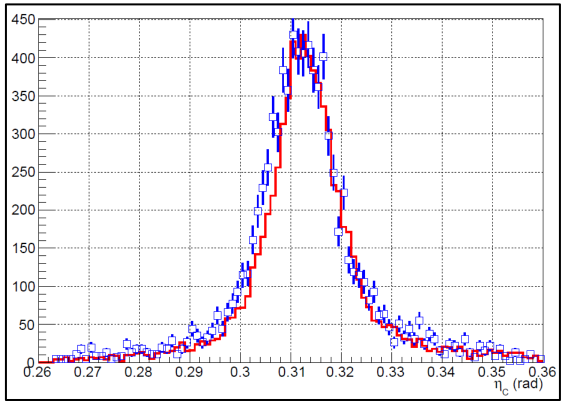
Large variability in the number of direct and reflected photons depending on the position of track

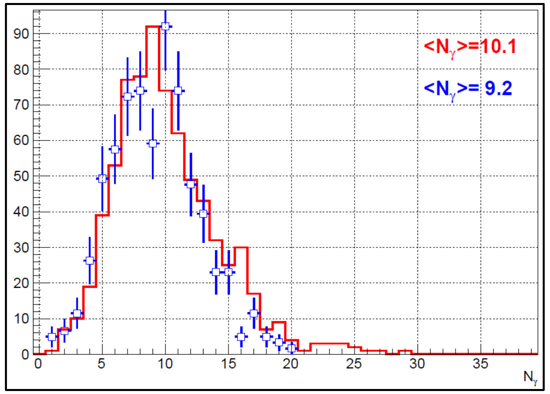
blue: no reflections
green: first reflection on a lateral mirror
purple: first reflection on a spherical mirror

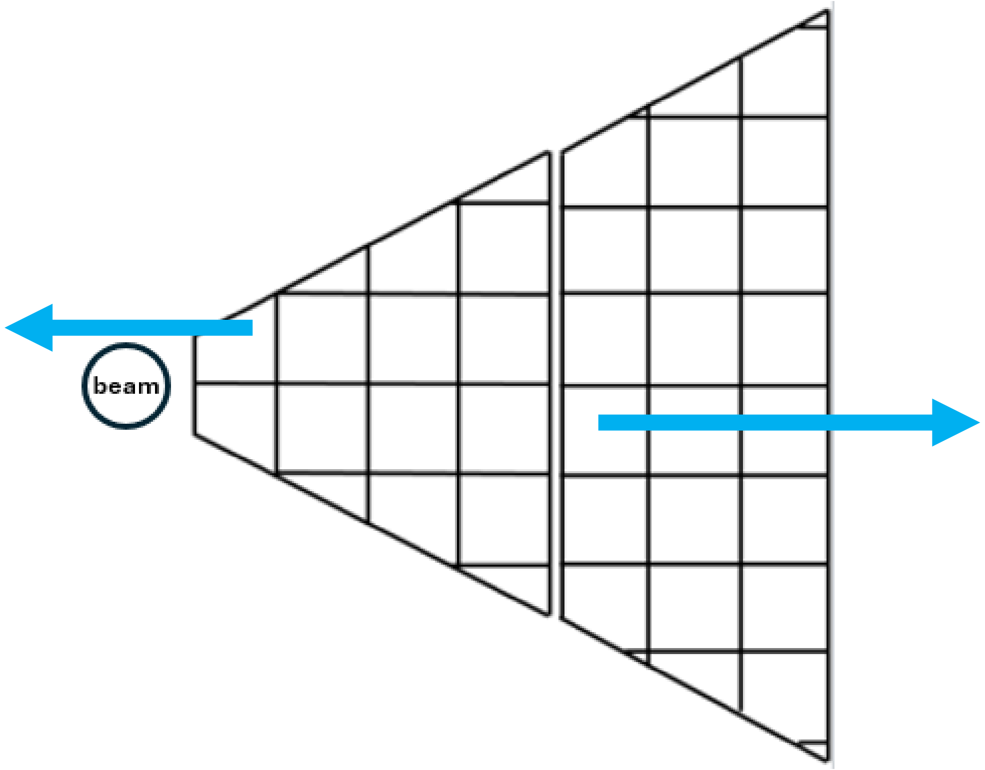
RICH performance: time dependence

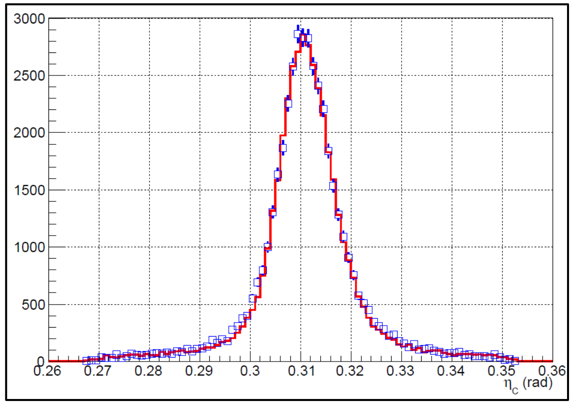
Comparison between data on an
unpolarized Hydrogen target taken in fall 2018
with data taken on a
longitudinally polarized NH3 target in fall 2022

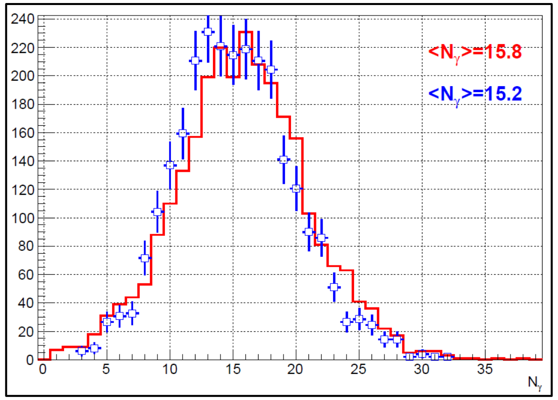
Results for π-
Plots for photons with 0 reflections











Particle ID

Based on a binned likelihood approach as described in the PDG (Section 40 Statistics), where the **bin** is the **MAPMT pixel**

$$LL = -2\log\lambda(\theta) = 2\sum_{i=1}^{N}\left[\mu_i(\theta) - n_i + n_i\,log\frac{n_i}{\mu_i(\theta)}\right]$$

n_i = number of hits in the pixel i (= 0,1)

$$\mu_i(\theta) = \underbrace{\varepsilon_i\frac{\Delta\phi}{2\pi}}_{\text{flat }\phi}\underbrace{e^{-\frac{(\theta_i-\langle\theta\rangle)^2}{2\sigma_\theta^2}}\frac{\Delta\theta}{\sigma_\theta\sqrt{2\pi}}}_{\text{gauss }\theta}\underbrace{e^{-\frac{(t_i-\langle t\rangle)^2}{2\sigma_t^2}}\frac{\Delta t}{\sigma_t\sqrt{2\pi}}}_{\text{gauss }t} + B_i$$

θ_i and t_i measured quantities for the hit

ε_i = efficiency of the pixel i (=0 dead, =1 ok)

B_i = expected background of the pixel i (typical few hertz from calibration data)

For a reliable PID, a crucial ingredient is the precise knowledge of <t>, σ_t, <θ>, σ_θ for every detected photon

- **they depend on the aerogel block crossed by the particle and its β**
- **due to alignment and calibration uncertainty, they may depend also on the path of the photons in the detector, in particular on the charge of the particle and on the number of reflections**

→ stored in the CLAS calibration database

Particle ID quality parameters:
- **number of photons per track**
- **R_L = LL(PID_1) / LL(max)**
- **R_Q = 1 – LL(PID_2) / LL(PID_1)**
- **χ^2 (time and Cherenkov angle)**

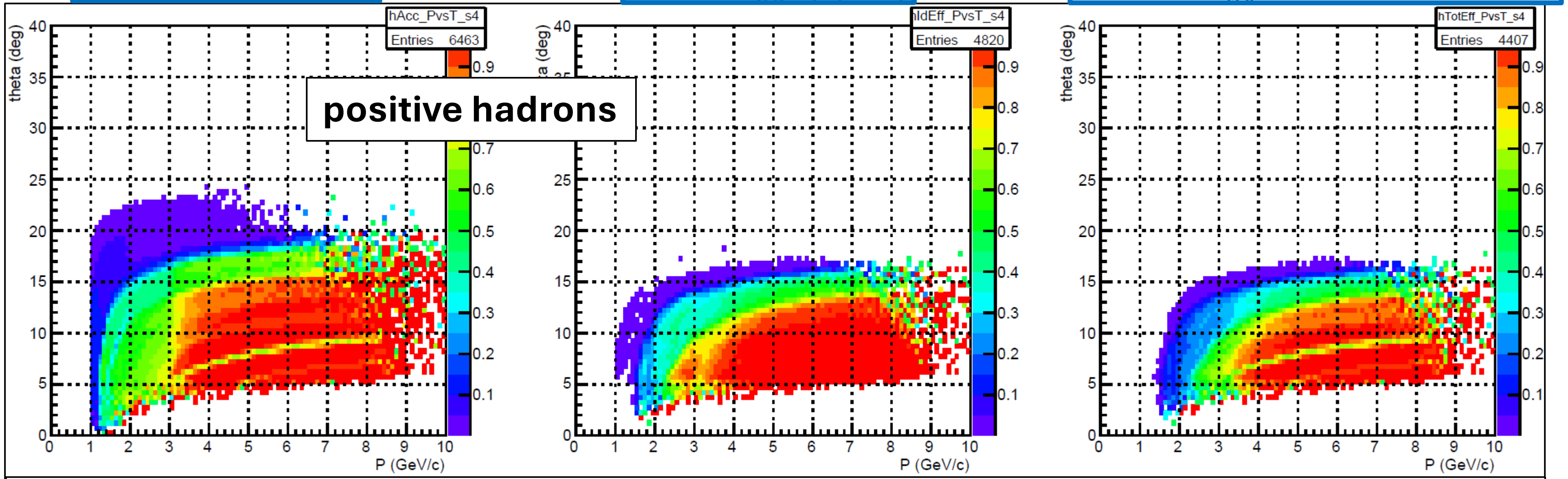
Kinematic coverage

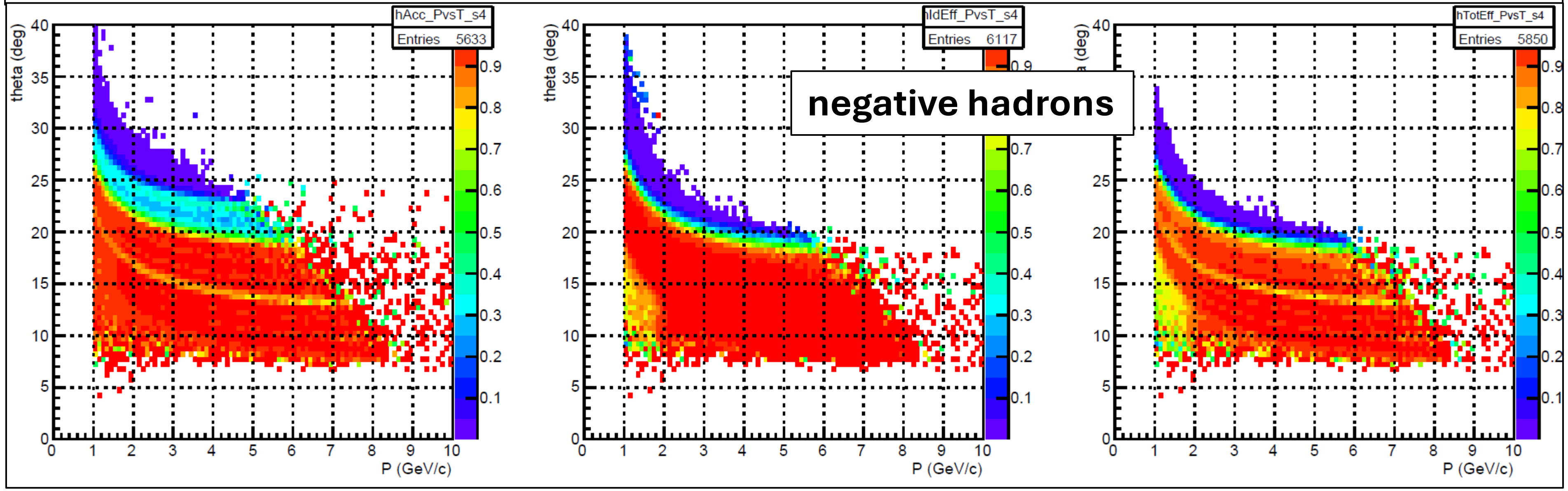
- **SIDIS kinematics**
  e p → e h X
- **RICH ID: N_γ>2.5**

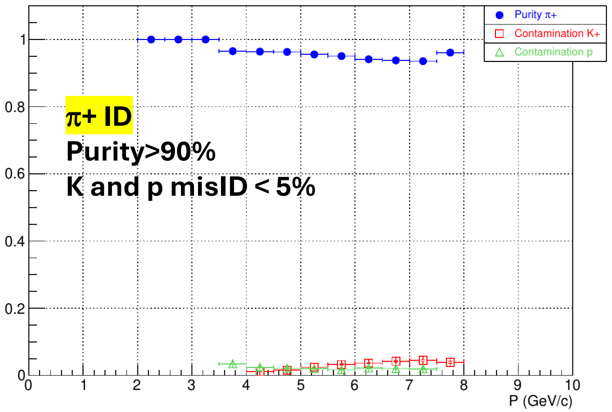
$$GeoAcc = \frac{N_{trk}^{RICH}(N_\gamma > 0)}{N_{trk}^{RICH}}$$

$$IdEff = \frac{N_{trk}^{RICH}(ID \neq 0)}{N_{trk}^{RICH}(N_\gamma > 0)}$$

$$Eff = \frac{N_{trk}^{RICH}(ID \neq 0)}{N_{trk}^{RICH}} \equiv GeoAcc \times IdEff$$

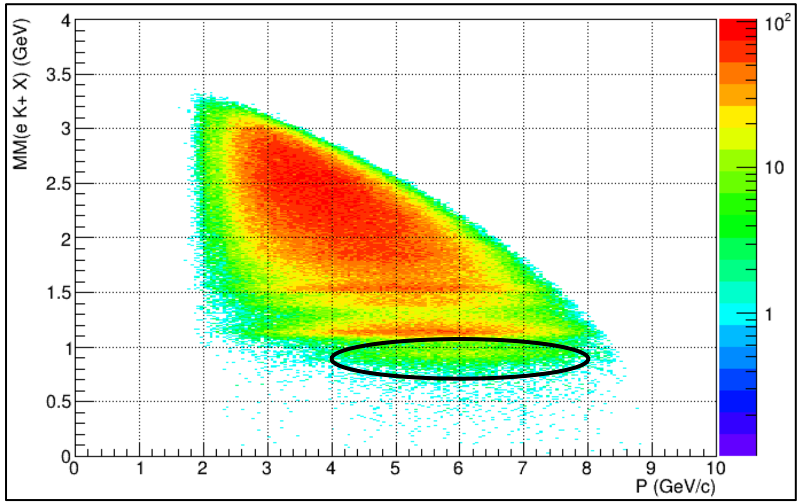


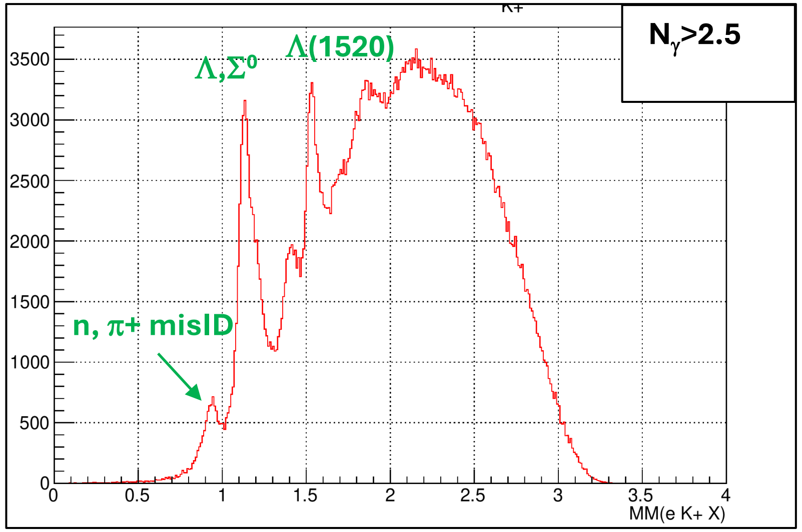


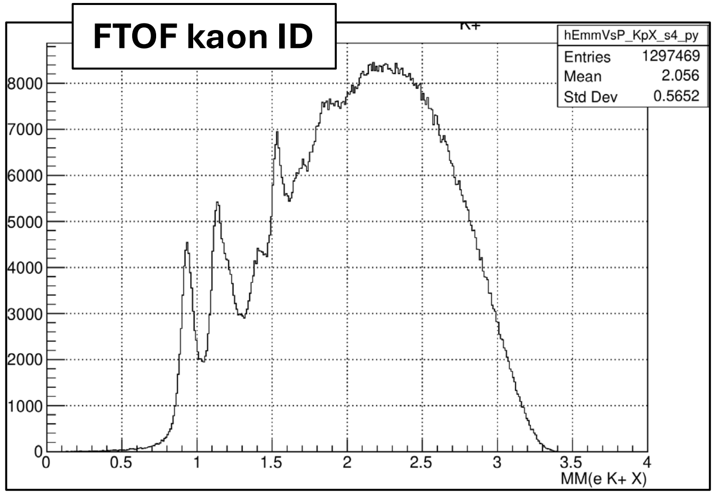


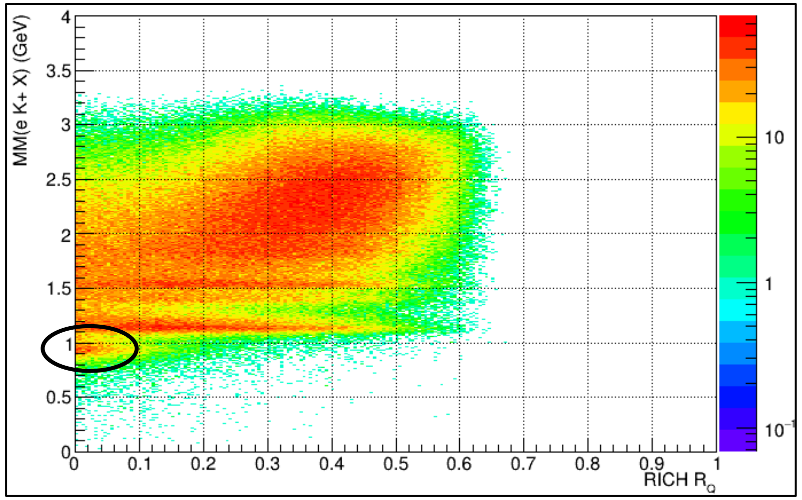
- **High ID efficiency within the acceptance**
- **Low misID contaminaion**

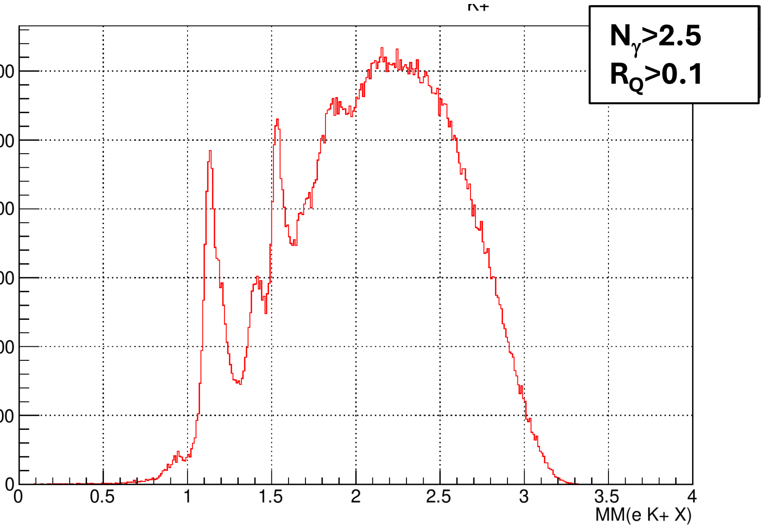
Physics observables: MM(e K X)









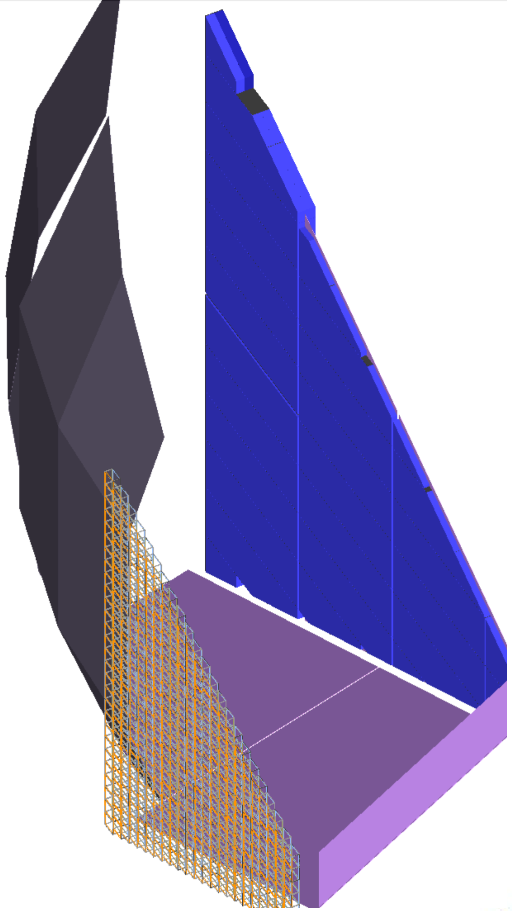


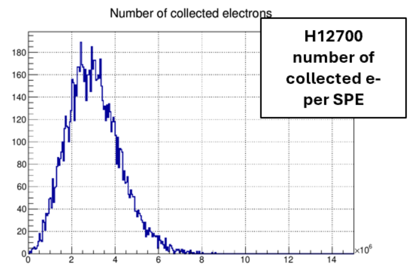
- **Pion to Kaon misID effectively suppressed by a cut on R_Q**
- **Higher R_Q cut required at higher momentum**

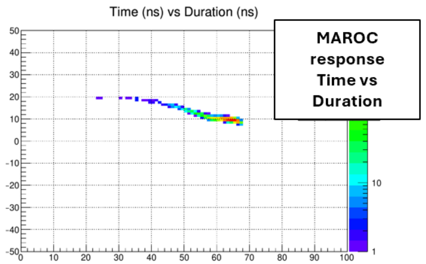
The quality parameter cuts must be studied for each final state to optimize efficiency vs low misID

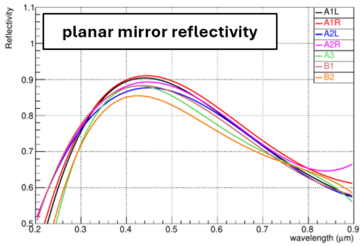
Monte Carlo simulations

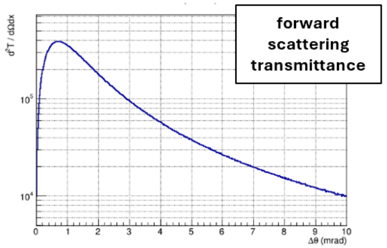
- The RICH geometry is a mix of STL files extracted from CAD (aerogel, planar mirrors, dead volumes) and geant4 shapes (spherical mirrors, MAPMTs)
- Optical properties tuned from characterization measurements
  - aerogel:
    - Cherenkov emission spectrum
    - volumeeffects: transmission or absorption, Rayleigh and forward scattering
    - surface effects:refraction with smearing
  - mirrors
    - reflectivity
    - surface smearing
- Readout digitization
  - MAPMT response to single photon (H1270 and H8500)
  - binary readout of the MAROC chip
  - TDC conversion

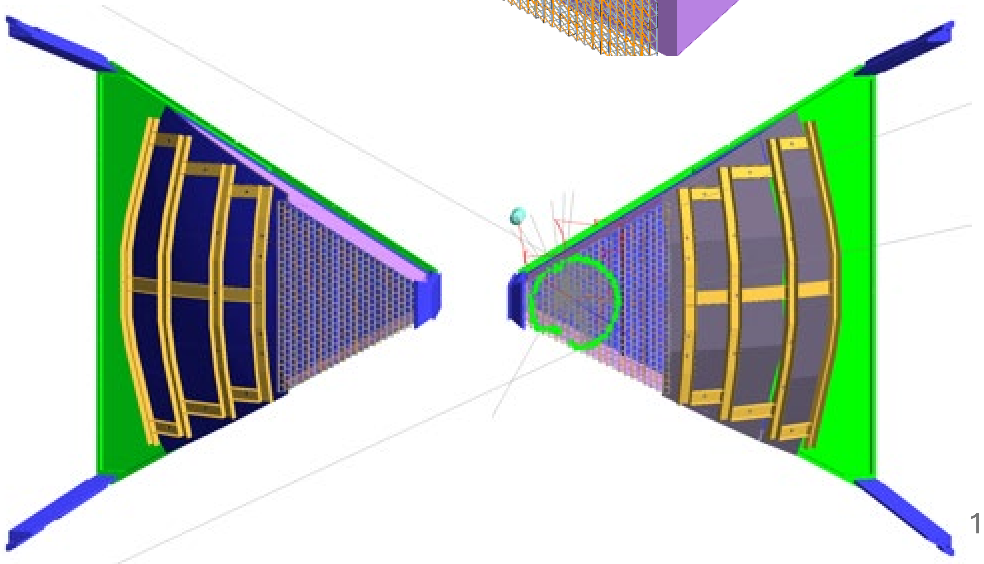










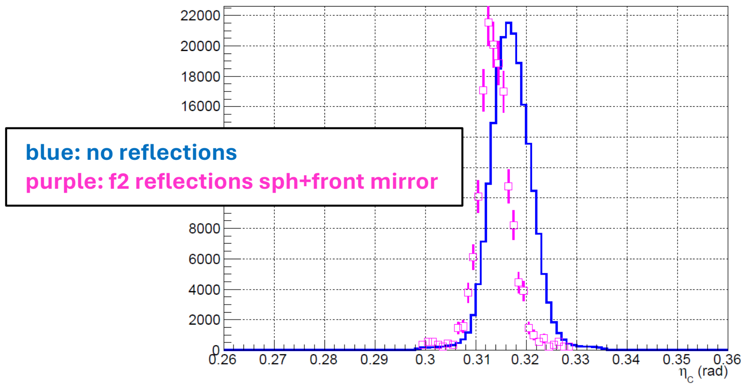


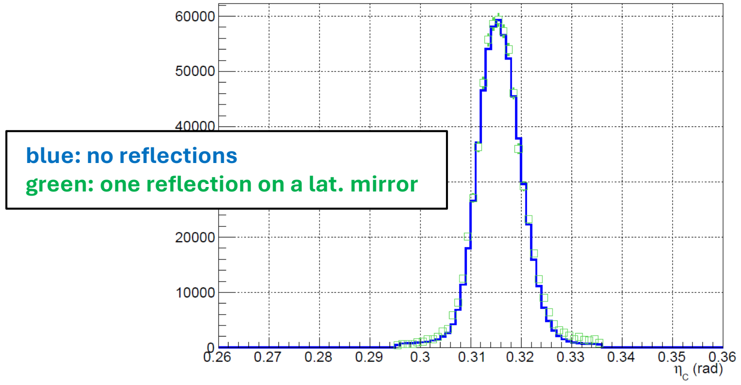
Monte Carlo simulation results

Simulation results for perfect geometry

- **misalignments not implemented yet**
- **expected worsening of the resolutions with misalignments**

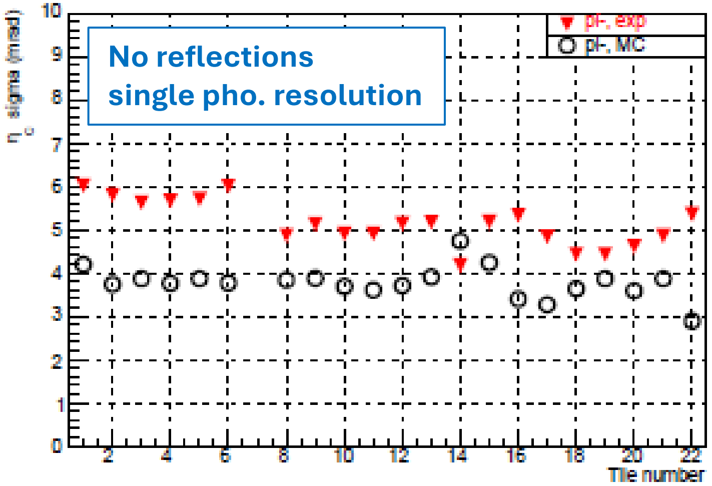
Cherenkov angle vs photon detection topology

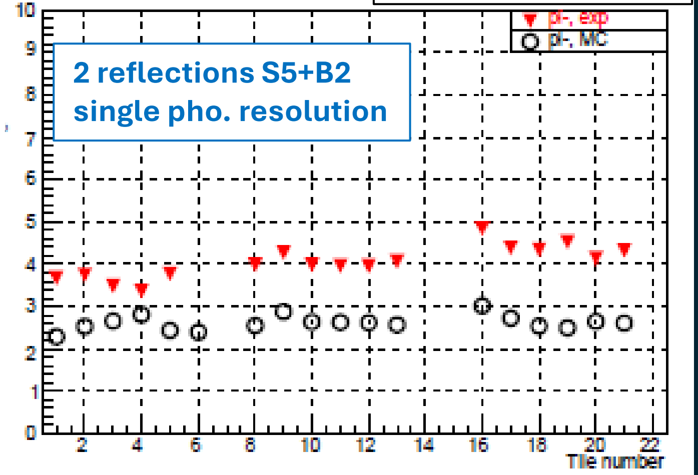


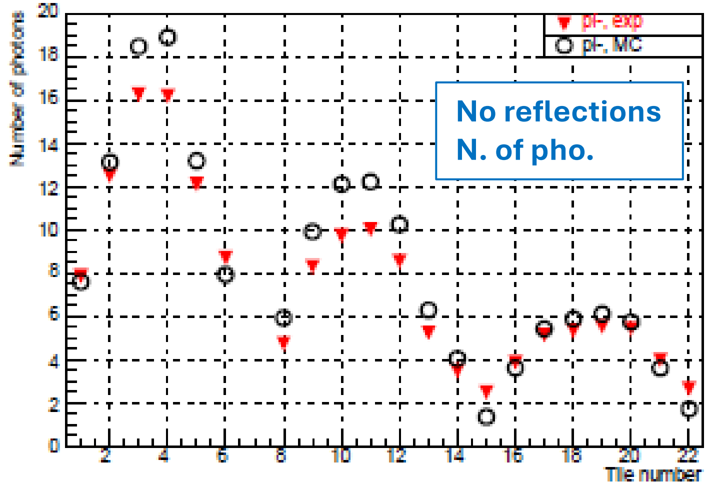


Comparison between exp. data and simulations

red triangles: exp. data
black circle: MC







- **about 1 mrad resolution missing**
- **number of photons in agreement within 20% or better**

New developments for alignment

The alignment of the CLAS12 RICH detector is a complex problems with a large number of correlated parameters to be determined that can be effectively treated with Bayesian Optimization (BO) algorithm

- **initial survey of the parameter space using Sobol generation**
- **using TuRBO (1910.01739v4) for best alignment finding**

Define the objective to minimize as:

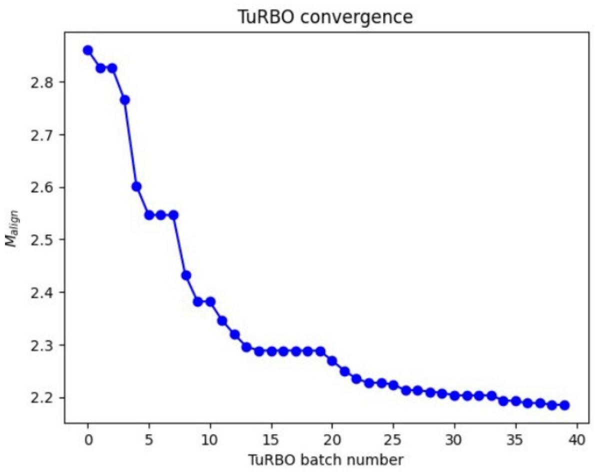
$$M_{align} = \sqrt{(R^2_{direct} + R^2_{sphe,2} + \cdots)}$$

with:

$$R^2_{topology} = \frac{1}{N_{tiles}} \sum_l^{N_{layers}} \sum_t^{N_{tiles}} \sum_i^{N_{photons}} \left(\frac{\theta^{rec,i}_{l,t} - \theta^{expected}_{l,t}}{4} \right)^2$$

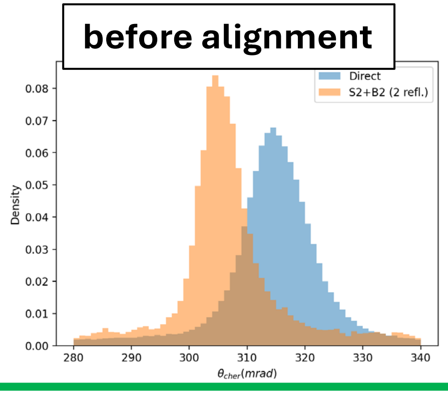
First test: align two aerogel layers, 2 frontal mirrors and 3 spherical mirrors

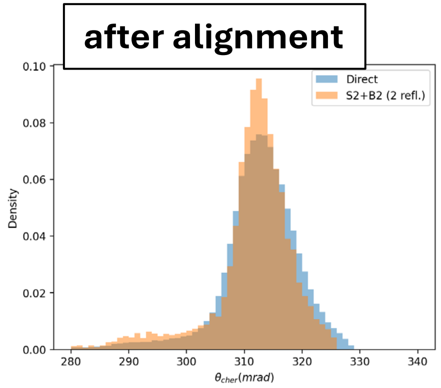
- **15 free parameters simultaneously determined**

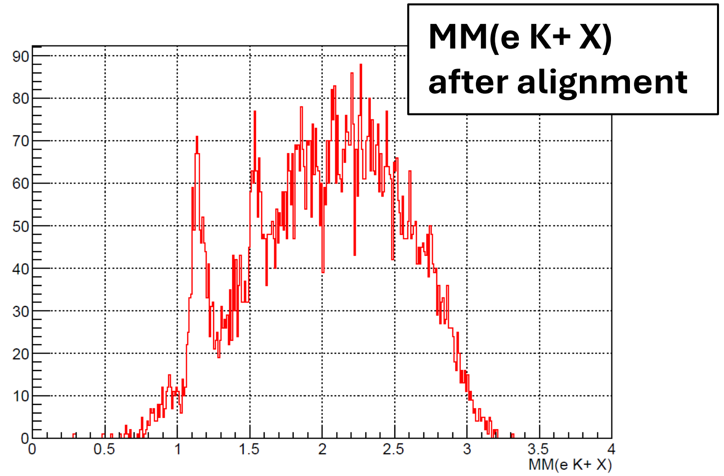


blue: zero reflections

yellow: 2 reflection photons







Conclusions

The CLAS12 RICH detector is designed to provide hadron identification in the momentum range 3-8 GeV/c

The detector is taking data in the CLAS12 experiment with one module since January 2018 and in the final configuration with two modules in opposite position since June 2022

Due to the constraints imposed by the existing spectrometer, the detector exploits a complicated optics, with photons imaged either directly or after one or more reflections on the mirror system

A considerable effort has been required to calibrate and align the detector and optimize the PID algorithm

At present, the detector reached its design performance in the forward region (two out of three aerogel sections)

New projects based on more powerful software tools (BO, AI/ML) have been initiated to reach the design performance in the whole detector acceptance

backup slides

RICH detection purity and contamination

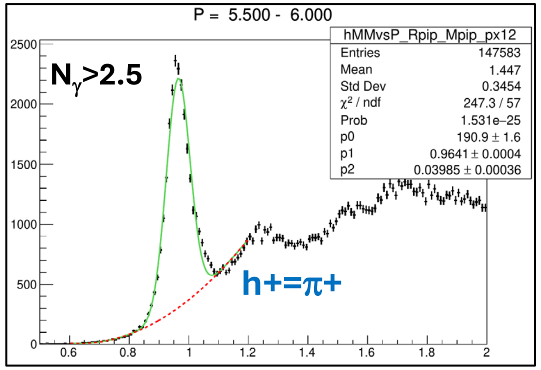
Look at e p → e h+ X events and plot the MM for h+=π+/K+/p

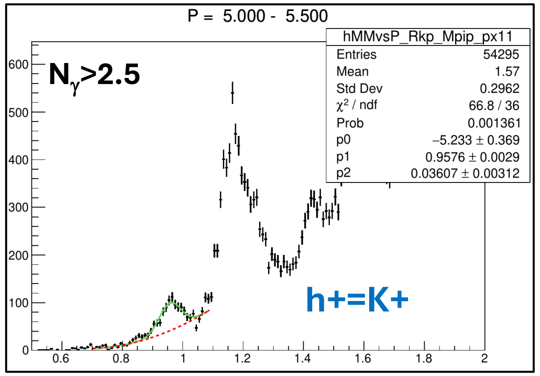
- **Minimal cut on the RICH ID N_γ>2.5**

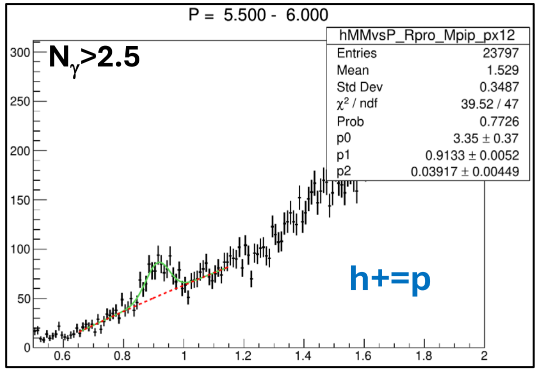
Fit the MM plots in the neutron mass region

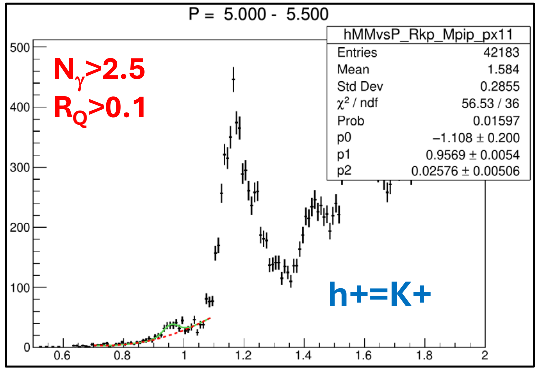
$$P_\pi = \frac{N_{PID=\pi}^{ep\to ep(n)}}{N_{PID=\pi}^{ep\to ep(n)} + N_{PID=K}^{ep\to ep(n)} + N_{PID=p}^{ep\to ep(n)}}$$

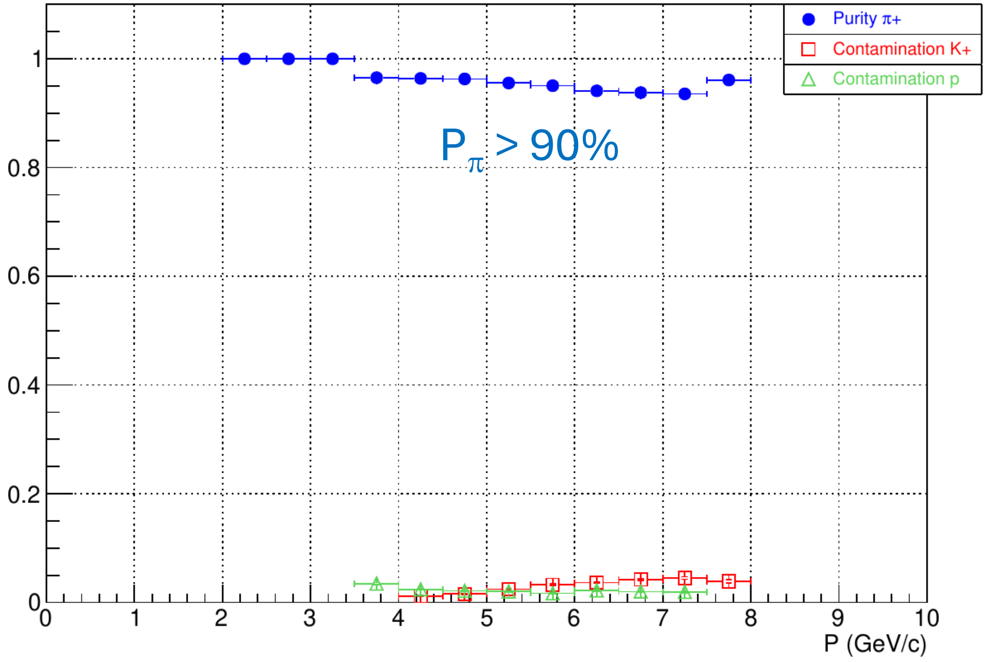
$$C_{K,p} = \frac{N_{PID=K,p}^{ep\to ep(n)}}{N_{PID=\pi}^{ep\to ep(n)} + N_{PID=K}^{ep\to ep(n)} + N_{PID=p}^{ep\to ep(n)}}$$







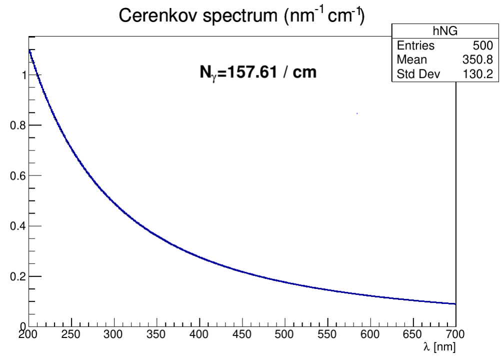


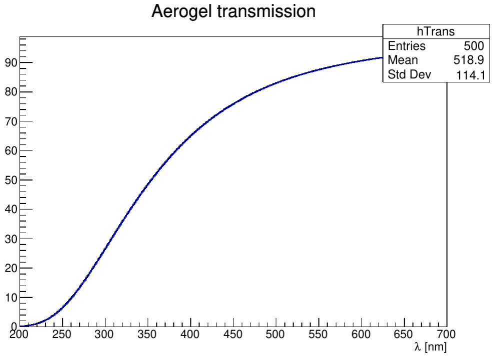


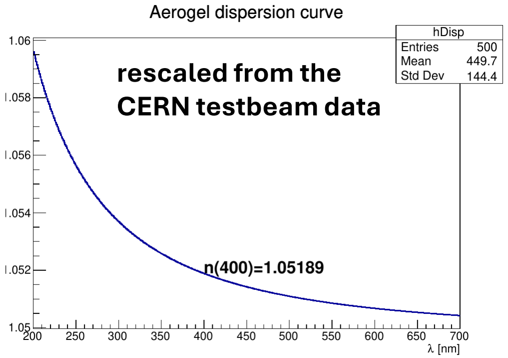
Cherenkov angle spectrum calculation (tile op424f22)

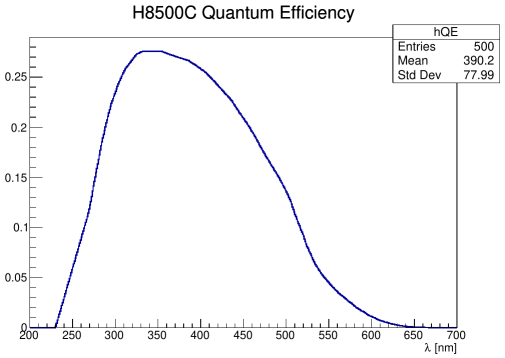
The detected Cherenkov spectrum is a convolution of:

- **the Cherenkov emission spectrum**
- **the transmission of the aerogel**
- **the dispersion curve**
- **the MAPMT quantum efficiency**
- **the mirror reflectivity (assumed flat here)**

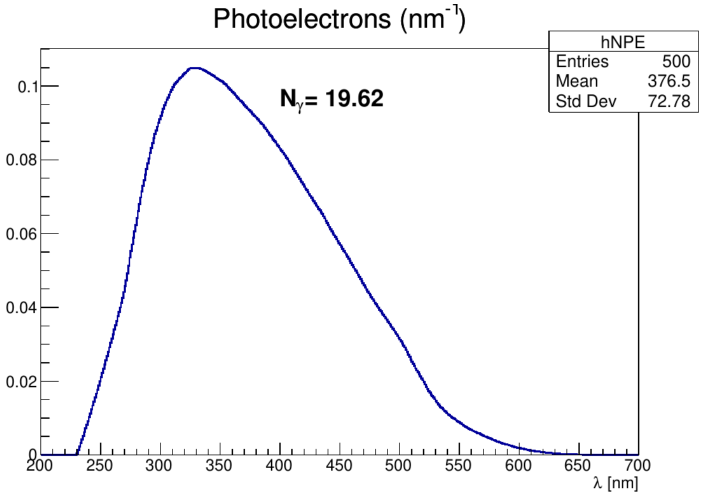




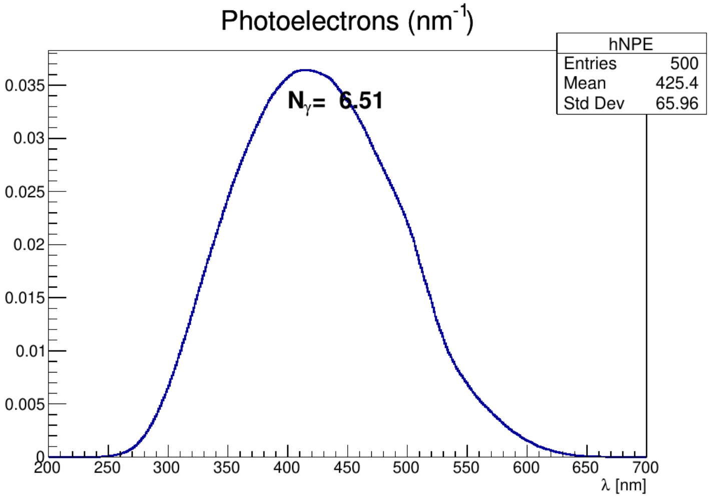




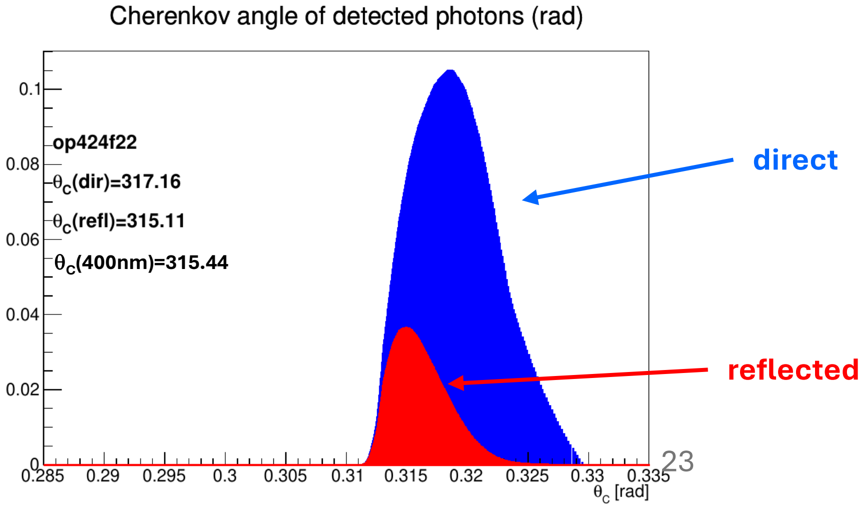
wavelength spectrum for direct photons



wavelength spectrum for photons reflected by the spherical mirrors with an additional contribution of the aerogel transmission through 2+2 cm



The double passage through the aerogel substantially kills the large angle components of the spectrum



MM(e p → e K X)

Negative torus field

Positive torus field

RICH ID
$N_\gamma > 2.5$
$R_Q > 0.1$