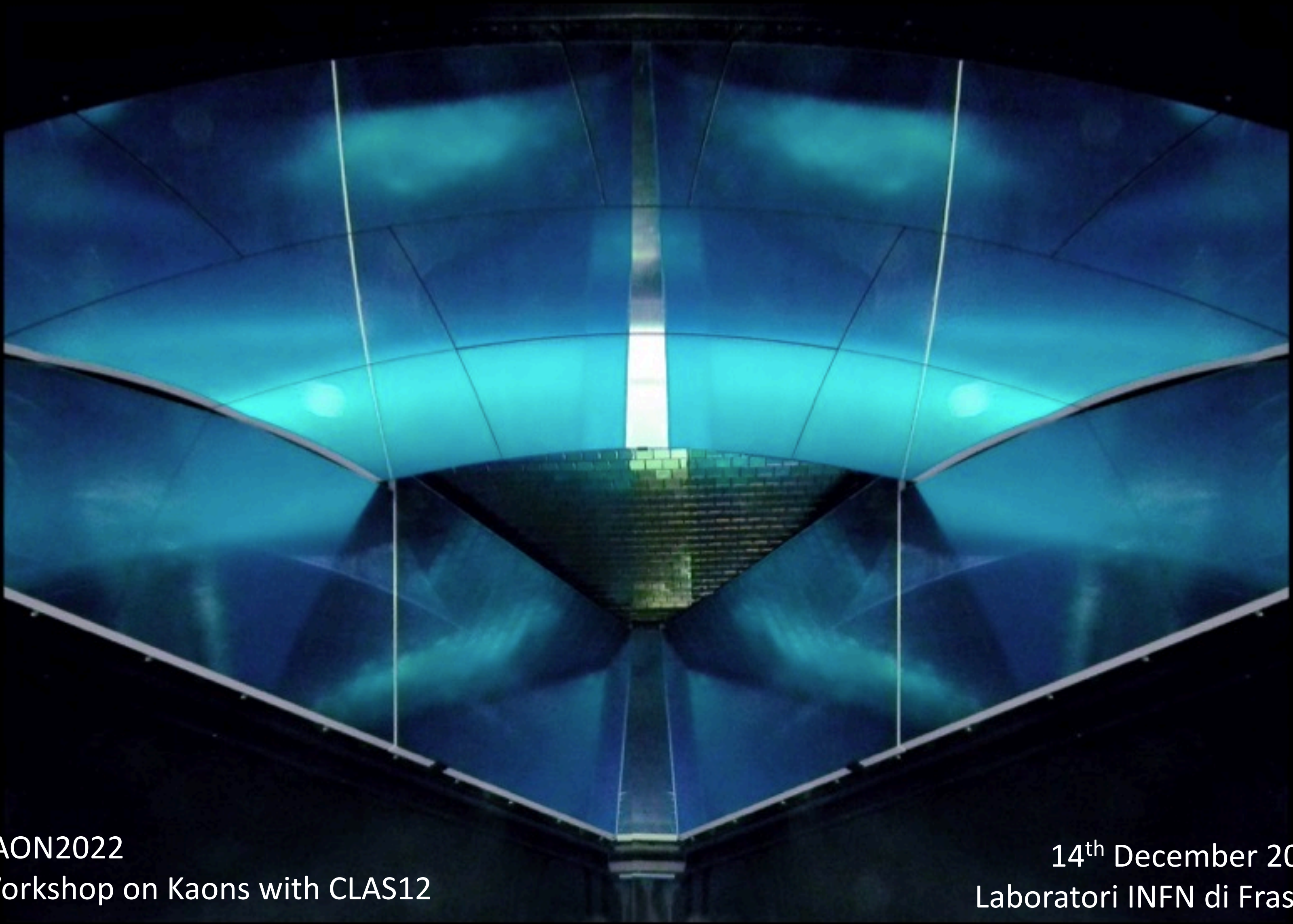
The CLAS12 RICH Reconstruction

M. Contalbrigo – INFN Ferrara – on behalf of the CLAS12 RICH group



KAON2022
Workshop on Kaons with CLAS12

14th December 2022,
Laboratori INFN di Frascati

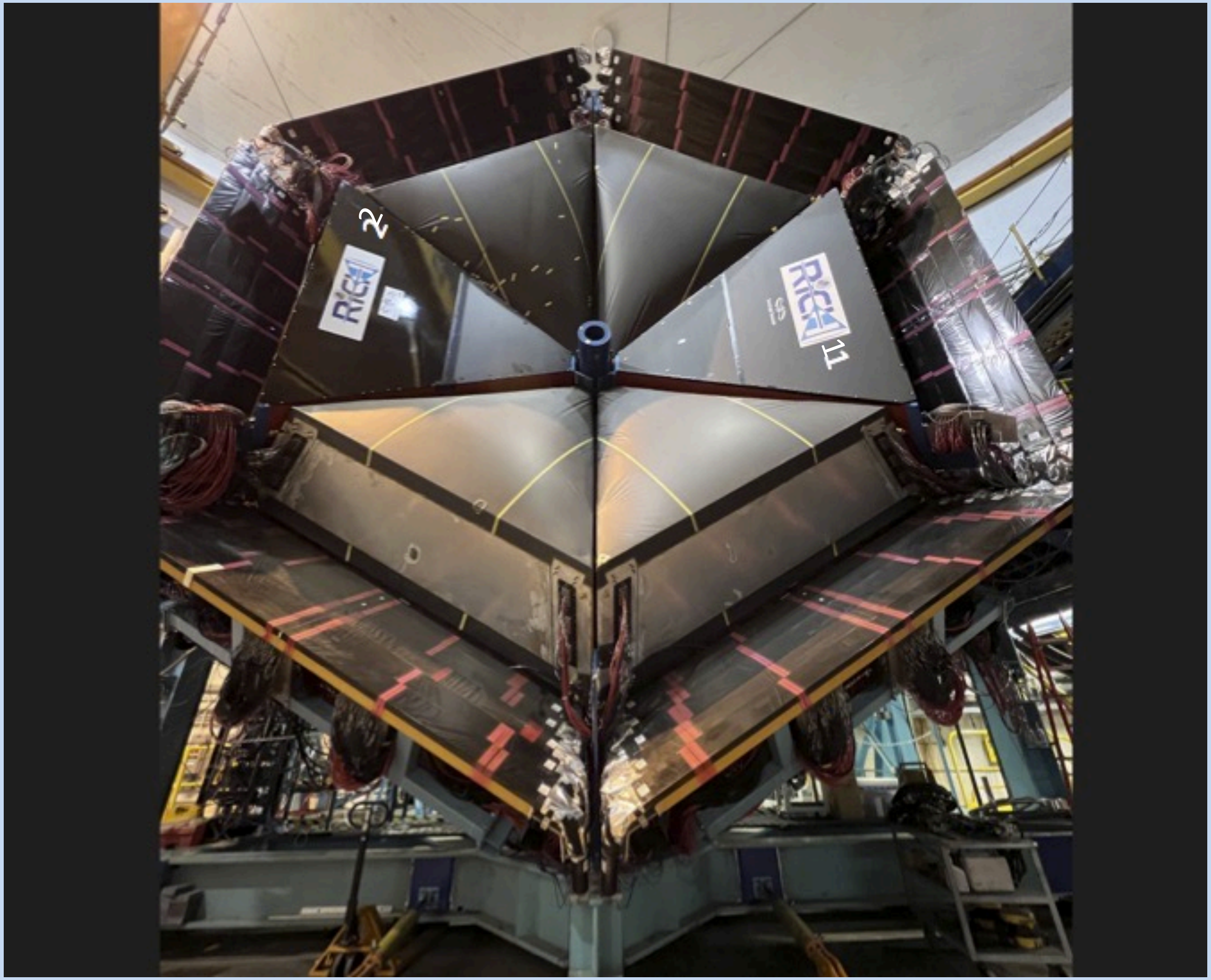
The CLAS12
RICH Reconstruction

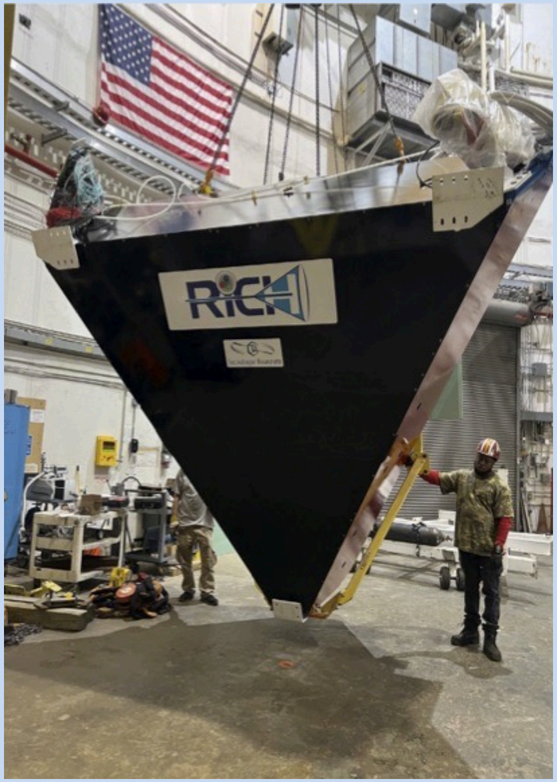
Marco Contalbrigo – INFN Ferrara

KAON 2022: Workshop on kaons at CLAS12 – 14th December 2022

RICH @ CLAS12

Completed in June 2022 with the symmetric configuration dedicated to the runs with polarized targets (now ongoing)





RICH Software

Features: large volume, > 50k readout channels, complicated topology

→ need large statistics for calibration

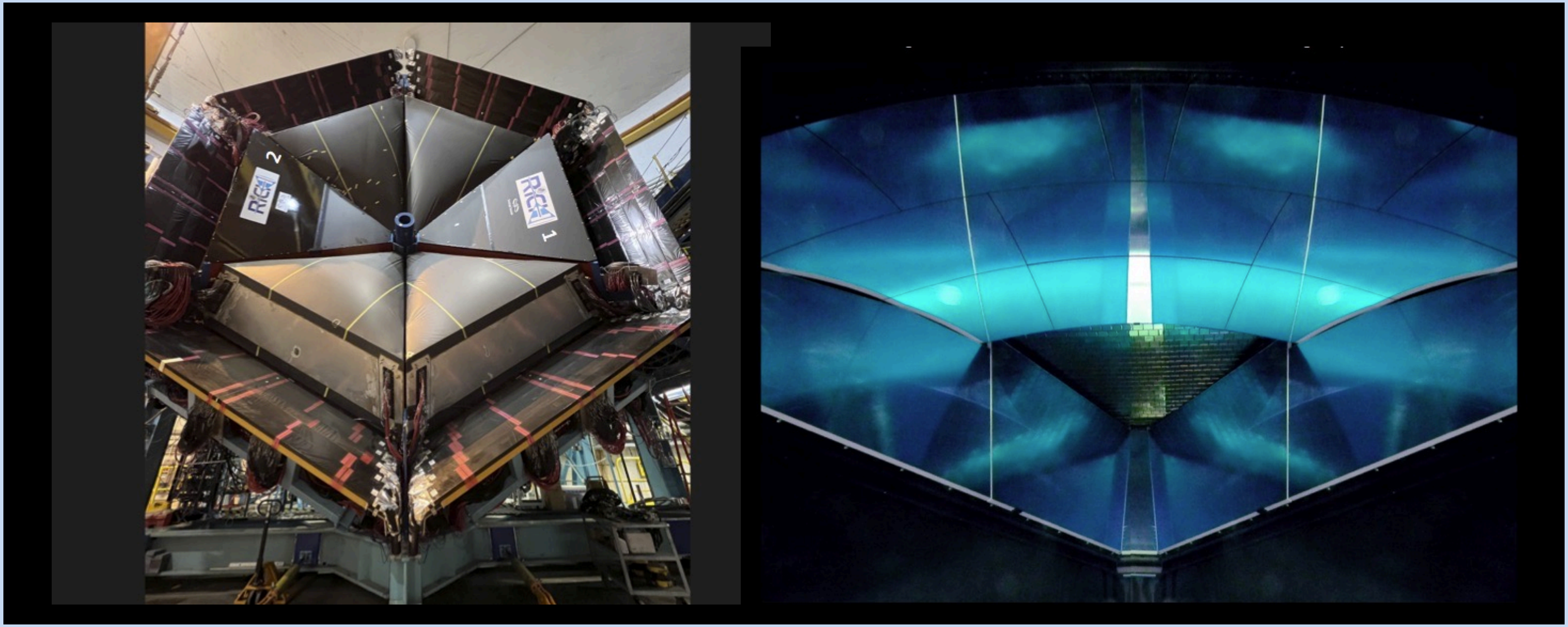
→ calibration possible from DSTs (not only calibration runs)

single photon reconstruction for high-level pattern recognition and PID

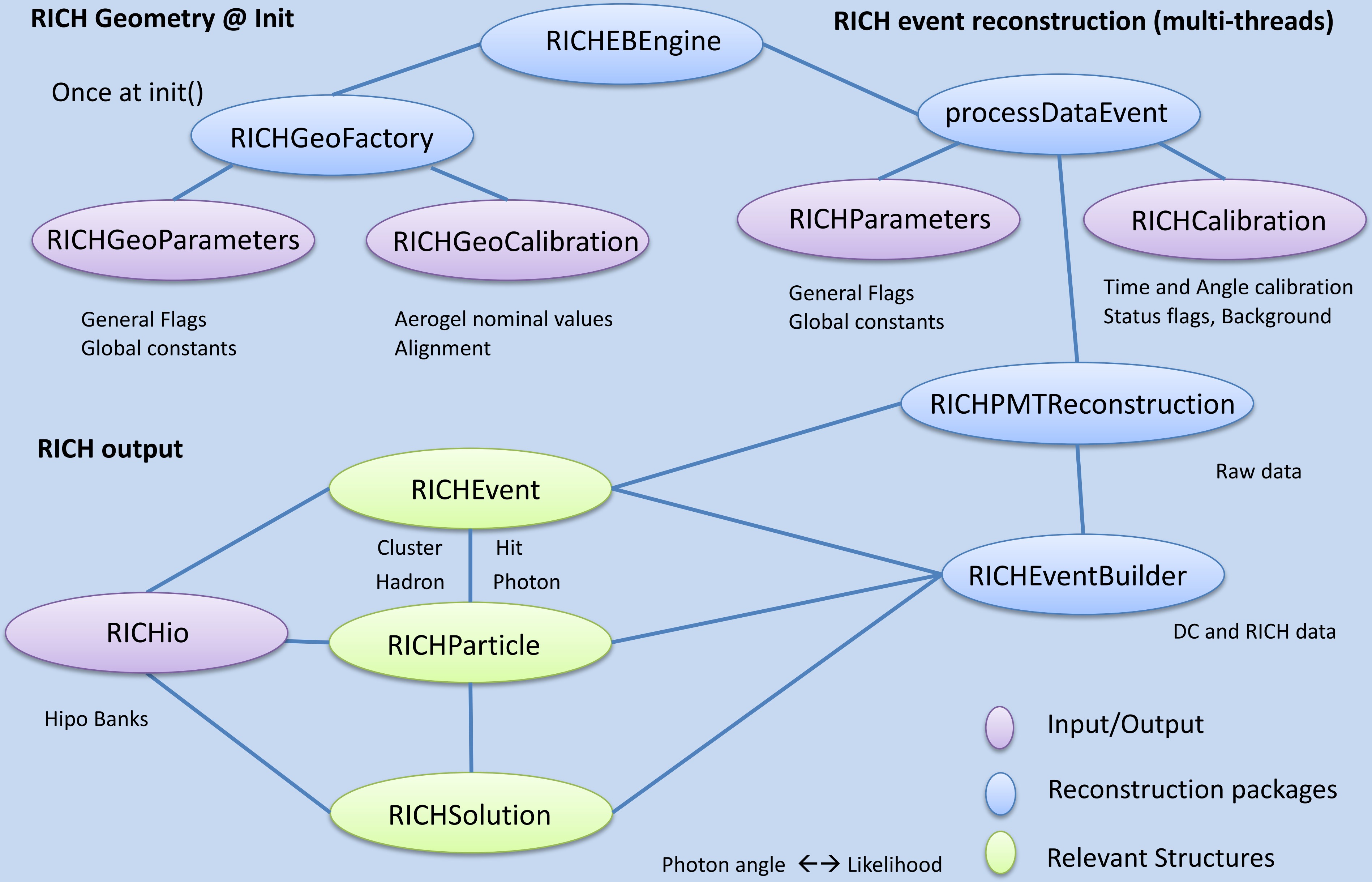
→ require DC track impact point and angle, use EB PID

→ interplay (merge) with EB only possible for two sectors and relevant for multi-particle events

→ post-process with specific hipo banks



Pass2



RICH Geometry @ Init

Once at init()

RICHEBEngine

RICHGeoFactory

RICHGeoParameters

General Flags
Global constants

RICHGeoCalibration

Aerogel nominal values
Alignment

RICH event reconstruction (multi-threads)

processDataEvent

RICHParameters

General Flags
Global constants

RICHCalibration

Time and Angle calibration
Status flags, Background

RICHPMTReconstruction

Raw data

RICHEventBuilder

DC and RICH data

RICH output

RICHEvent

Cluster Hit
Hadron Photon

RICHParticle

RICHio

Hipo Banks

RICHSolution

Photon angle <-> Likelihood

🟣 Input/Output

🔵 Reconstruction packages

🟢 Relevant Structures

RICH Geometry

Read CSG volumes from CAD stl files

Convert volumes into tracking surfaces (Shape3D) and spheres (Sphere3D) with given orientation

Each Sphere3D has an associated Shape3D to define its solid angle of acceptance

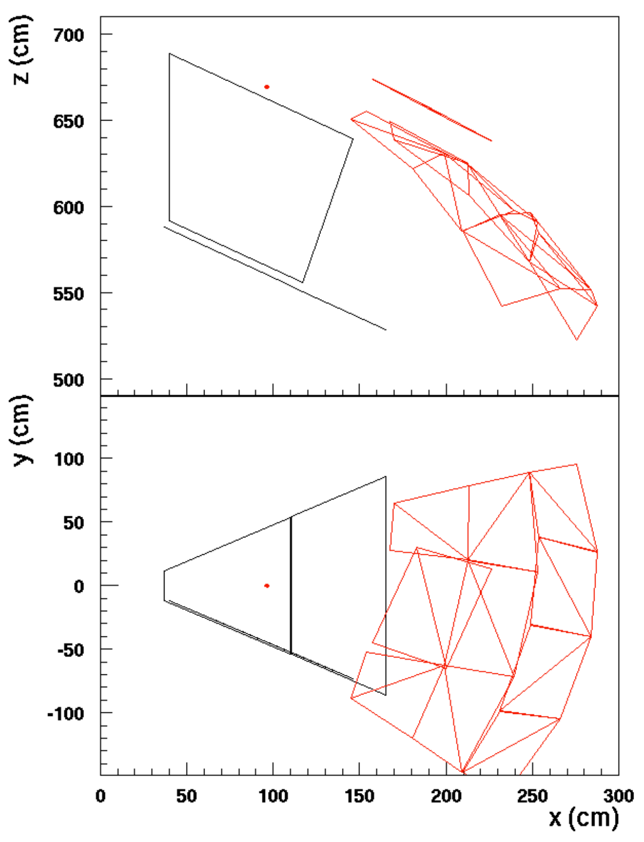
Align the tracking surfaces (as per mounting points)

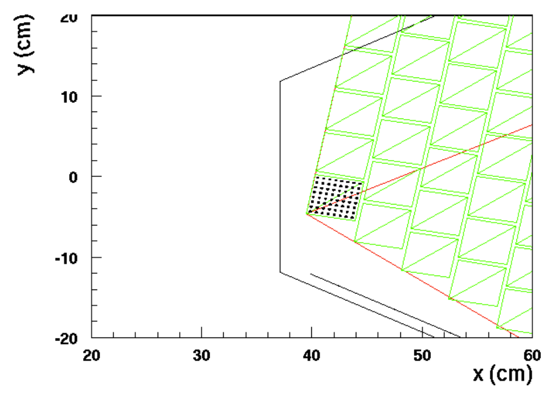
Global RICH

Layer (aerogel, MaPMTs, spherical mirror assembling)

Components (each single mirror, aerogel tile)

Detail MaPMT pixel geometry (on the misaligned plane)





Ray Tracing

Complex geometry with various photon paths (reflections) off the same particle

From CLAS12:

particle momentum
photon emission point

From RICH:

hit time and position

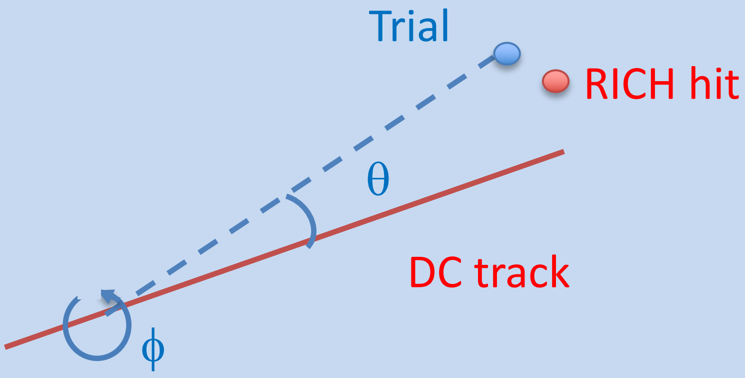
Direct ray-tracing:

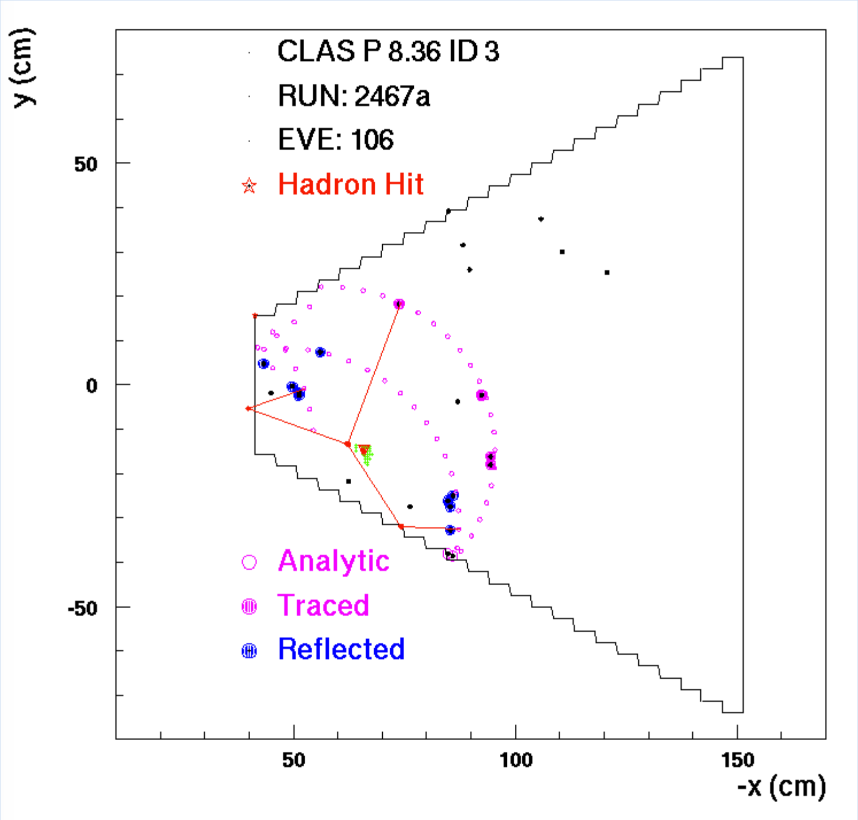
assume an ID hypothesis (e, π, k, p)

ray-trace a limited sample of photon trials (selection of ϕ's for given θ)

adjust the angles to match the hit starting from the closest trial (convergence in 2-3 iterations)

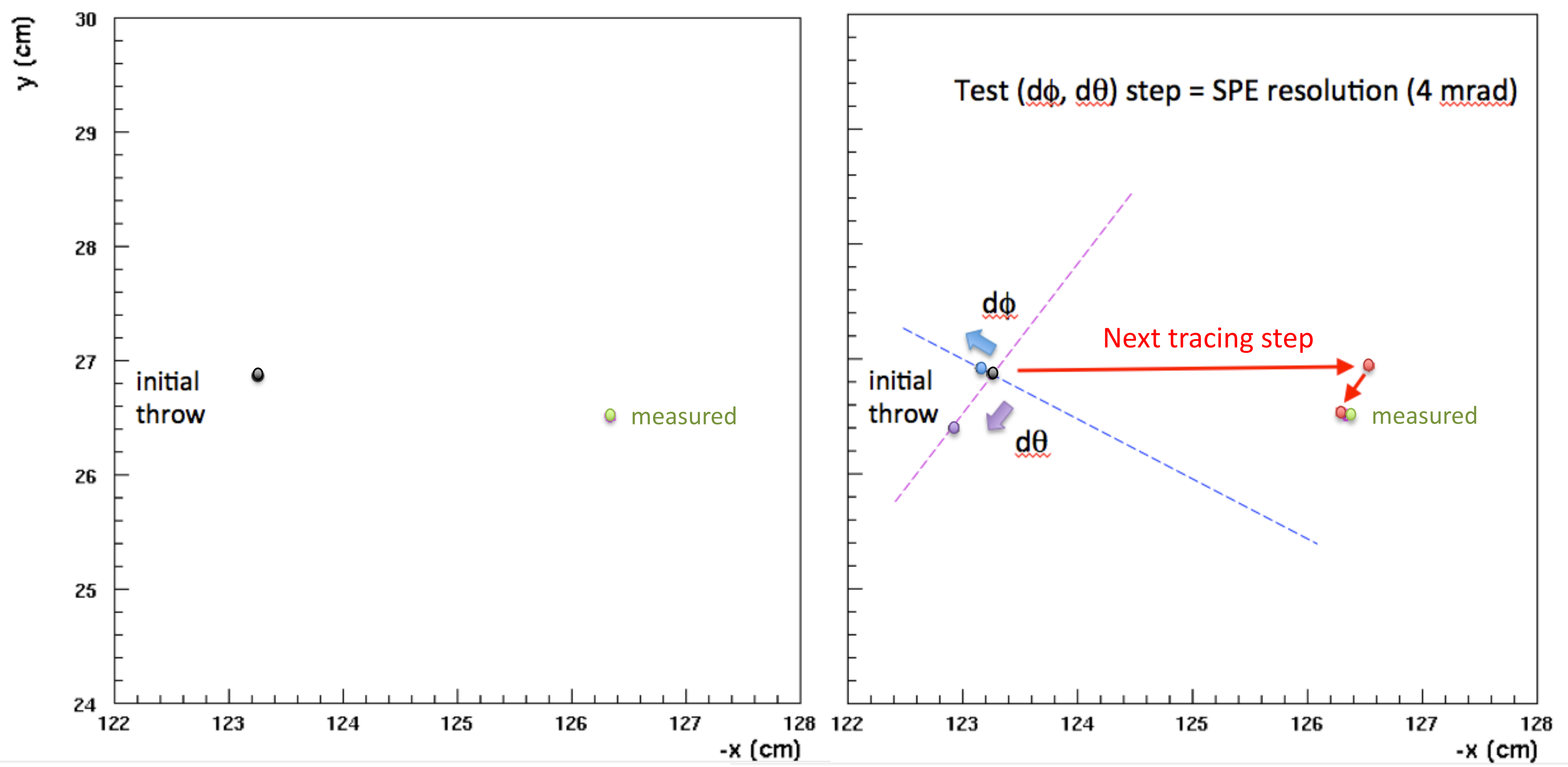
validate photon reconstructed Cherenkov angle and transit time





Ray Tracing

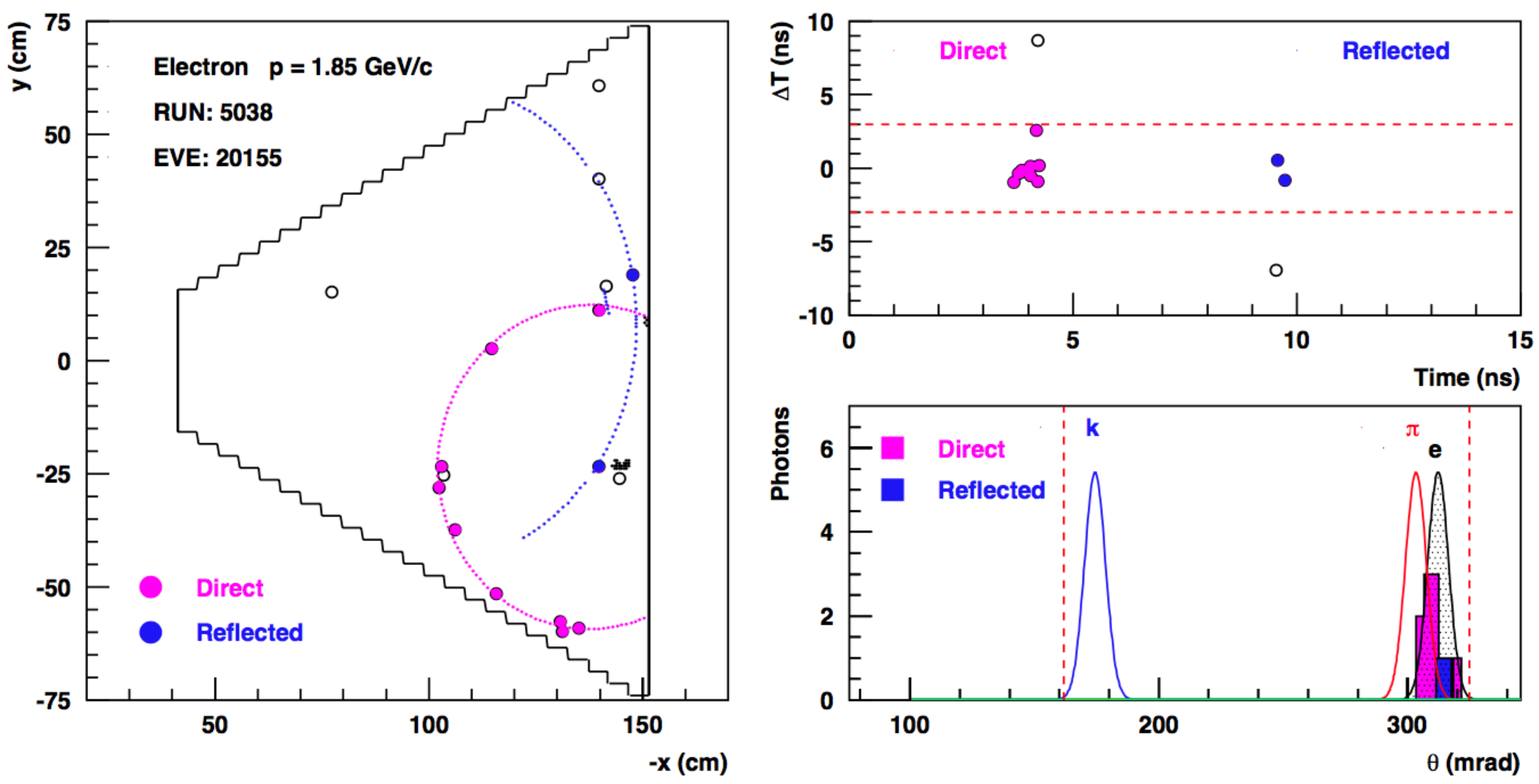
Trial position and refraction at boundaries [θ,n(β)] depend on particle hypothesis
Stop when closer than a given fraction of the expected (angular) resolution



Ray Tracing

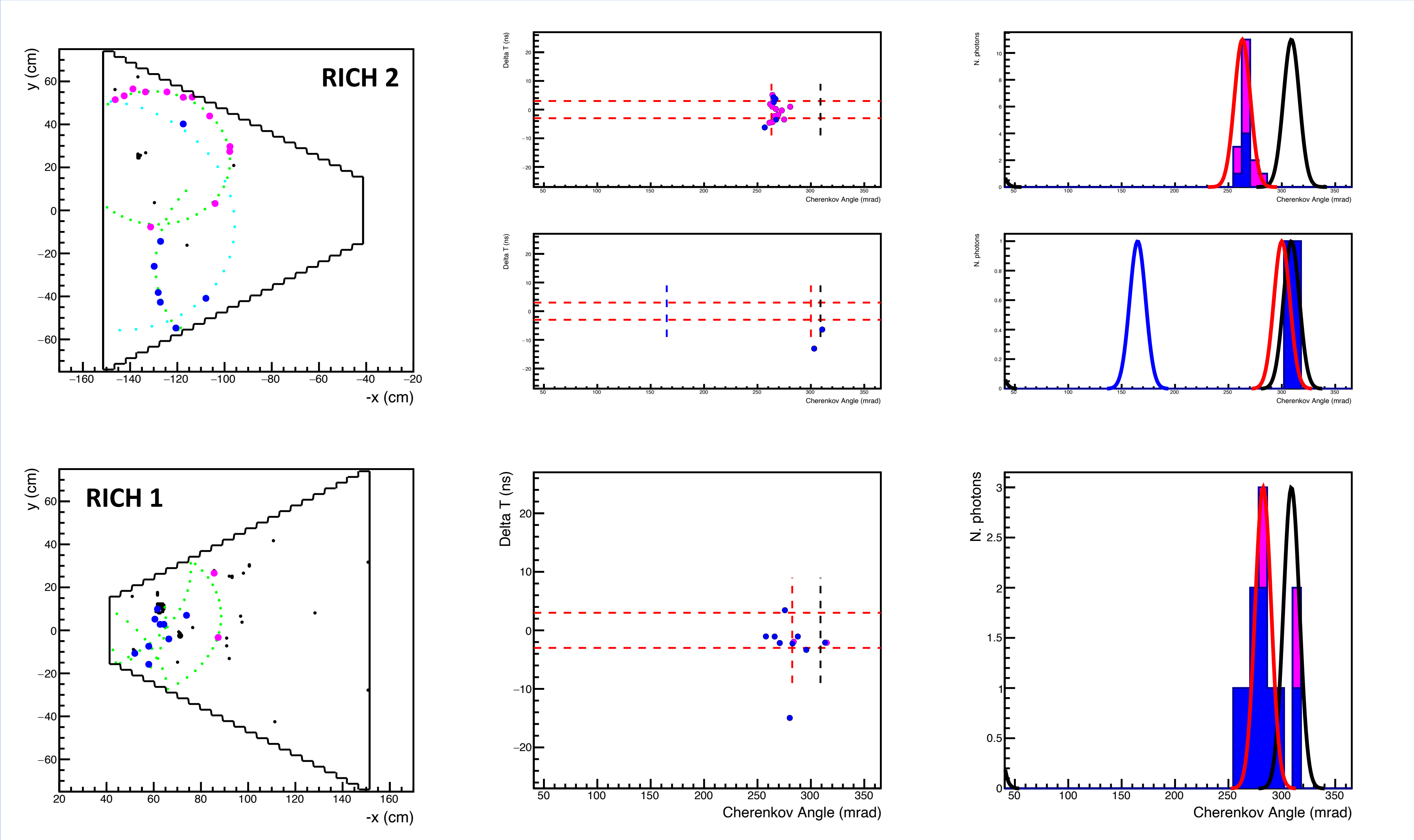
Photon path reconstruction allow to assign the photon to the most likely hypothesis:

- be robust and easy to control (easy to handle multi-reflections, up to e.g. 5)
- discriminate background (hit far from trials, no solution foreseeable)
- provide full information (photon path, time, position and component of each reflection)
- allow relation with nominal optical components, resolution and efficiency



Run Group C

Example of 3 particle event into two RICHes (no calibration)



Extended Maximum Likelihood

Observe n events x_i and expect a total of μ based on model f and parameters θ

$$L(\boldsymbol{\theta}) = \underbrace{\frac{\mu^n}{n!}e^{-\mu}}_{\textbf{Poisson}} \underbrace{\prod_{i=1}^{n} f(x_i;\boldsymbol{\theta})}_{\textbf{Unbinned ML}}$$

In the *logL* any normalization constant is irrelevant, i.e. any term that does not depend on the parameters θ.

In case f(x_i ; θ) is a binned PDF with poisson probability the above reduces (except for an irrelevant normalization constant) to the binned maximum likelihood

$$L\ f_{\mathrm{P}}(\boldsymbol{n};\boldsymbol{\theta}) = \prod_{i=1}^{N} \frac{\mu_i^{n_i}}{n_i!}e^{-\mu_i}$$

Binned Log Likelihood

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

Taking a likelihood ratio, vs an ideal model corresponding to the "observed pattern" ($\mu_i = n_i$), provides a chi2-like estimator (goodness of fit) if μ_i are not too small

* pdf normalization to 1 is given by Poisson

* the $\mu_i - n_i$ term is optional (less stringent except close to threshold)

* one can have bins with zero counts (last term is taken to be zero)

* there is some arbitrary choice in the bin selection (N)
(i.e. total PMT surface or just the area potentially illuminated by the photons)

* μ_i is the expected yield in bin i (signal + background)

$$f_{PIXEL}(i;\theta) = 1 - \underbrace{e^{-\mu(i,\theta)}}_{\text{Poisson probability to have zero (no hit)}} \sim \mu(i,\theta)$$

Expected Photon Yield

Measured values

$$\mu(i,\theta) = N_0\ \varepsilon(i)\ \underbrace{\frac{d\phi}{2\pi}}_{\text{Flat probability}}\ e^{-\frac{(\theta-\theta_i)^2}{2\sigma^2}}\ \frac{d\theta}{\sqrt{2\pi}\sigma}\ \underbrace{e^{-\frac{(t(\theta)-t_i)^2}{2\sigma_t^2}}}_{\text{Despite t depends on }\theta\text{ it does not change much for a given path (direct or reflected)}}\ \frac{dt}{\sqrt{2\pi}\sigma_t}\ +\ B(i)$$

All these quantities are defined at pixel level

dθ and **dϕ** define the pixel solid angle and are known by RICH reconstruction

N_0, ε, θ, t , σ, σ_t,, B can be extracted from data (control samples) and enter the CCDB database

ε(i) can reflect dead (0), hot (1), or the quantum/reflection efficiency ([0:1])

B(i) can be derived from random triggers or electron control sample

This definition is effectively pretty close to the simpler ones used in pass1
However it is more general, seems better defined and could accounts for second order effects (photon path and pattern change among various mass hypotheses).

RICH Calibration

RICH Calibration Suites:

ε, B

1. **Dark count measurement** with scaler readout and random triggers
   1. extended to 2 modules
   2. dedicated data taking
   3. extract hot channel list, estimate dark count rate and pixel efficiency

t , σ_t

2. **Time calibration** from CLAS data
   1. extended to two modules
   2. input is calibration data (full runs)
   3. extract time offsets and time walk corrections

N_0, θ, σ

3. **Cherenkov angle calibration** from CLAS data
   1. new software
   2. input is DST data (high statistics)
   3. extract measured Cherenkov angle mean and sigma per photon
   4. detection topology and particle charge

4. **Alignment** from CLAS data and MC
   - Check response for specific photon paths
   - Account for correlations at once with AI

Likelihood Ratio

$$\mu(i,\theta) = \varepsilon(i)\ \frac{d\phi}{2\pi}\ \boxed{e^{-\frac{(\theta-\theta_i)^2}{2\sigma^2}}}\ \frac{d\theta}{\sqrt{2\pi}\sigma}\ \boxed{e^{-\frac{(t(\theta)-t_i)^2}{2\sigma_t^2}}}\ \frac{dt}{\sqrt{2\pi}\sigma_t}$$

With negligible B(i), at first order all the terms not depending on θ change the likelihood value but not the minimum location (best θ , or mass, estimator).

One might take the likelihood ratio with a model corresponding to the "observed pattern" in which all the hit are at the right (expected) angle:

$$\mu'^{(i,\theta)} = \varepsilon(i)\ \frac{d\phi}{2\pi}\ \underbrace{1}_{\theta=\theta_i}\ \frac{d\theta}{\sqrt{2\pi}\sigma}\ \underbrace{1}_{t=t_i}\ \frac{dt}{\sqrt{2\pi}\sigma_t}$$

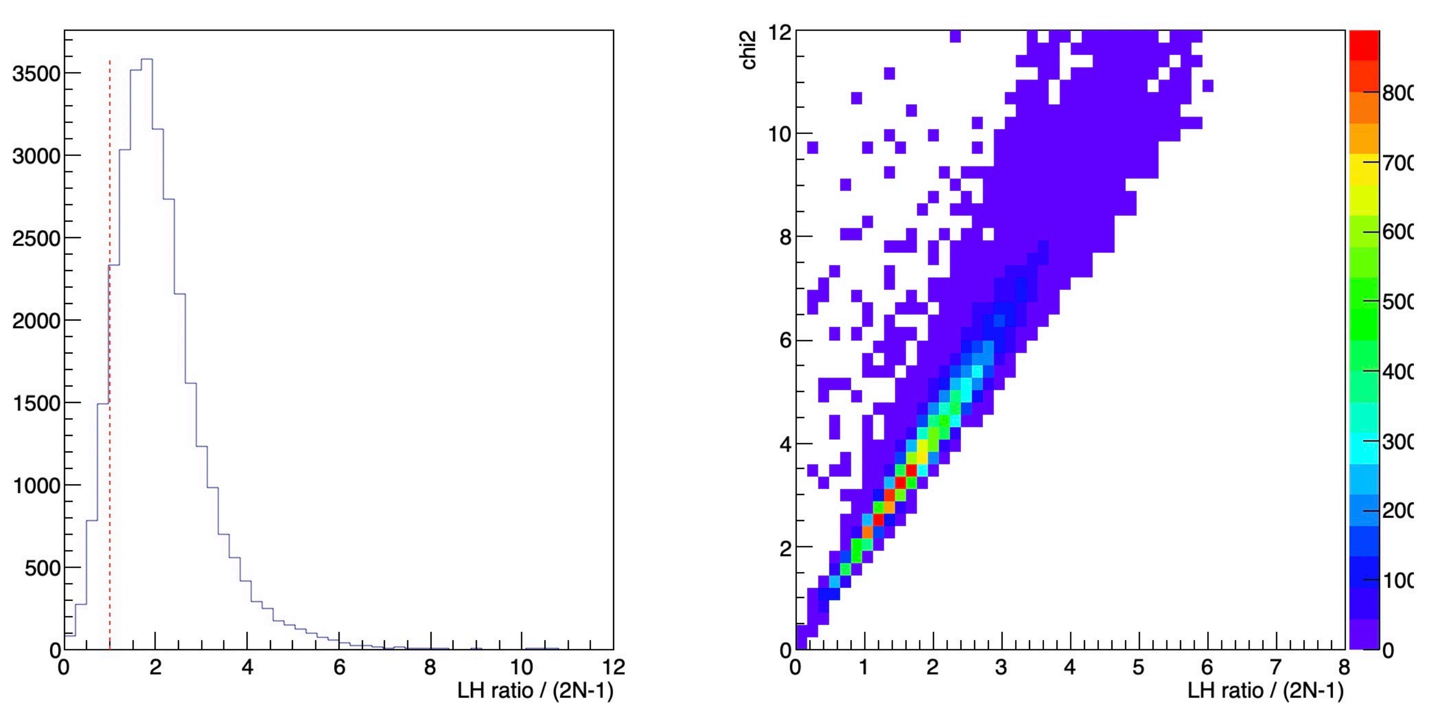
$$-2ln\lambda(\theta) = 2\sum_{i=1}^{N}\left[\mu_i(\theta)\ - n_i + n_i ln\frac{\mu_i'(\theta)}{\mu_i(\theta)}\right]$$

Likelihood Ratio

As expected, the log ratio should reduce to a sort of chi2.

$$-2ln\lambda(\theta) = 2\left(N_{exp} - N\right) + \sum_{i=1}^{N}\left[\frac{(\theta - \theta_i)^2}{\sigma^2}\right] + \left[\frac{(t(\theta) - t_i)^2}{\sigma_t^2}\right]$$

Except for second order effects, the real difference is in the background that defines a sort of cutoff: an accepted hit that is background for all the hypotheses does not count in the likelihood, whereas the ordinary chi2 weights anyway its distance from the expected value (provides a preference)



RICH::Particle

Providing best particle hypothesis (PID) with quality estimators

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"name": "RICH::Particle",
 "group": 21800,
 "item" : 37,
 "info": "Reconstructed Cherenov information per track",
 "entries": [
      {"name":"id",           "type":"B", "info":"id"},
      {"name":"hindex",       "type":"S", "info":"related row in the RICH::clusters bank (if any)"},
      {"name":"pindex",       "type":"B", "info":"related row in the REC::Particle bank"},

      {"name":"emilay",       "type":"B", "info":"aerogel layer of photon emission"},
      {"name":"emico",        "type":"B", "info":"aerogel component of photon emission"},
      {"name":”t",       "type":"B", "info":"aerogel component of particle entrance point"},
      {"name":"emqua",        "type":"S", "info":"aerogel quadrant of photon emission"},
      {"name":"mchi2",        "type":"F", "info":"track-cluster matching chi2 (if any)"},

      {"name":"best_PID",     "type":"S", "info":"most probable PID choice"},
      {"name":"RQ_prob",      "type":"F", "info":"goodness of hadron choice parameter (1=anambiguos, 0=random)"},
      {"name":"ReQ_prob",     "type":"F", "info":"goodness of elecgtron choice parameter (1=anambiguos, 0=random)"},
      {"name":"el_prob",      "type":"F", "info":"probability to be an electron"},
      {"name":"pi_prob",      "type":"F", "info":"probability to be an pion"},
      {"name":"k_prob",       "type":"F", "info":"probability to be an kaon"},
      {"name":"pr_prob",      "type":"F", "info":"probability to be an proton"},

      {"name":"best_etaC",    "type":"F", "info":"Average etaC for best hypothesis"},
      {"name":"best_c2",      "type":"F", "info":"chi2 for best hypothesis"},
      {"name":"best_RL",      "type":"F", "info":"Likelihood ratio for best hypothesis"},
      {"name":"best_ntot",    "type":"F", "info":"Number of photon used for likelihood"},
      {"name":"best_mass",    "type":"F", "info":"Reconstructed mass for best hypothesis"}
 ]
```

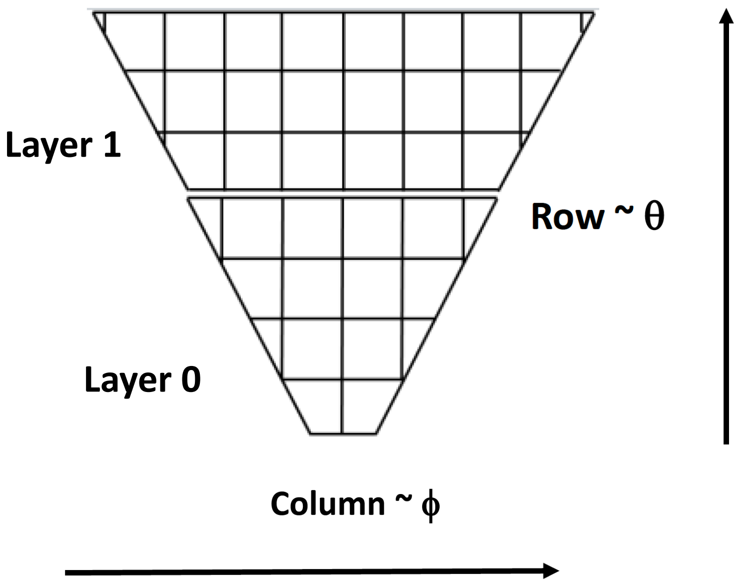
RICH PID

- Pass 1 inbending data
- Particles selection based on the EB
- One good trigger electron
- Only 1 charged track in the RICH

- RICH with direct photons only
  - alignment to be completed
- Average Cherenkov angle of the track
  - 4 p.e. minimum

NOTE:

- No fiducial cuts
- No PID refinements (chi2pid, calo SF, etc.)
- No kinematical cuts (SIDIS)

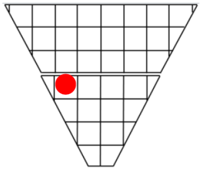


“Natural” binning for the RICH analysis:

- tile number (variation in the refractive index)
- particle momentum (beta dependence of Cherenkov angle)

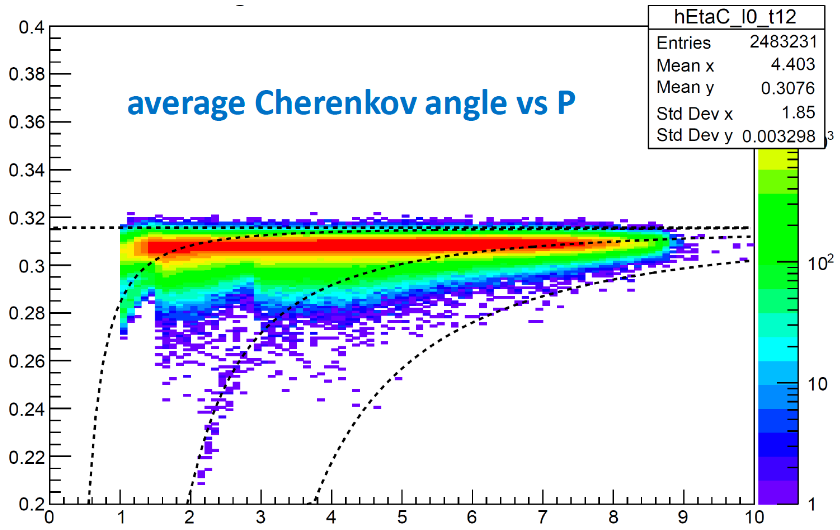
M. Mirazita pass1 analysis

pi- to electron contamination

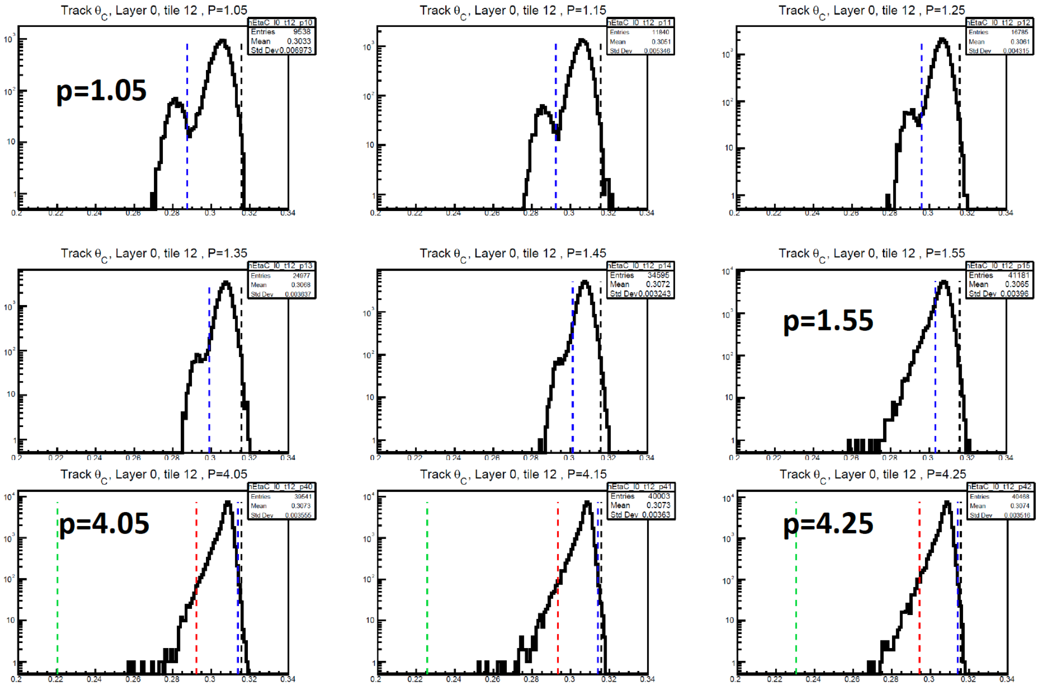


Layer 0
Tile 12
row 3

1. Select electron with EB
2. Look at the RICH Cherenkov angle



Momentum bins



NOTE: reference lines for e/pi/k/p are shifted because of misalignments

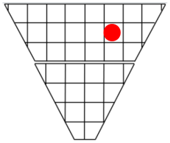
- Contamination estimate possible only at p < 1.4 GeV/c
- The momentum range of sensitivity could be slightly extended with better alignment (i.e. more photons)
- Too low momenta for SIDIS kinematics

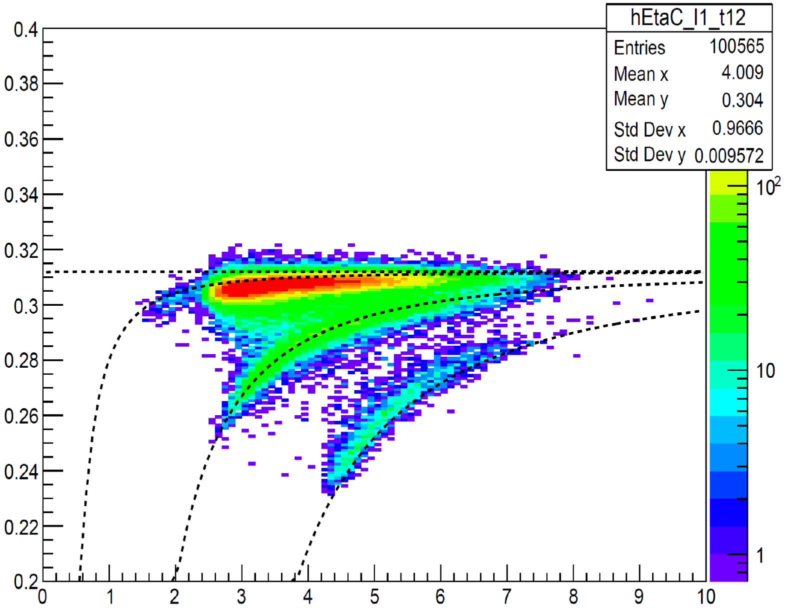
M. Mirazita pass1 analysis

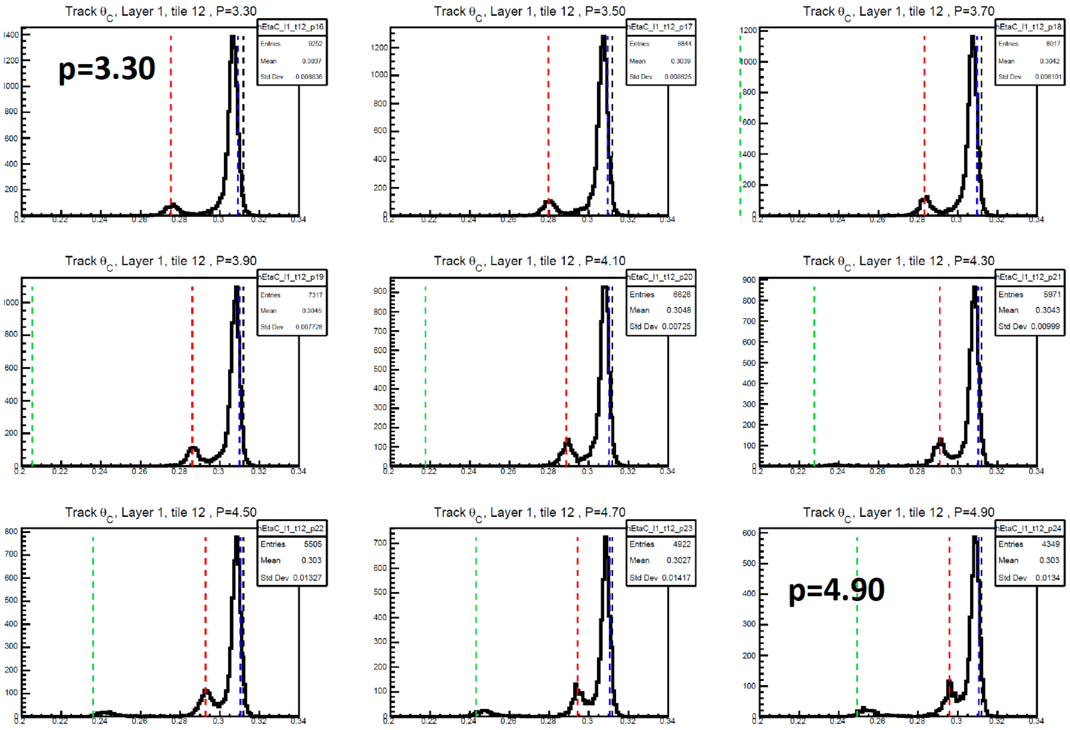
Positive Hadrons

1. **Select positive hadrons with EB**
2. **Look at the RICH Cherenkov angle**

Layer 1
Tile 12
row 1





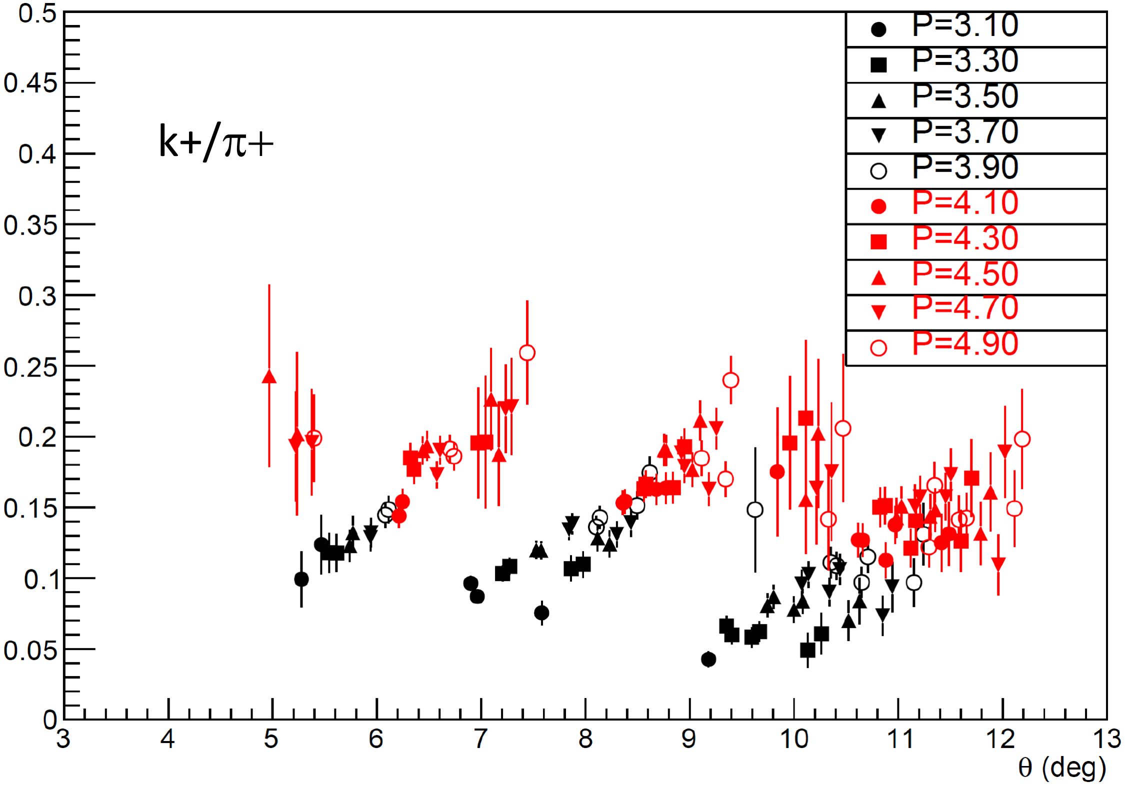


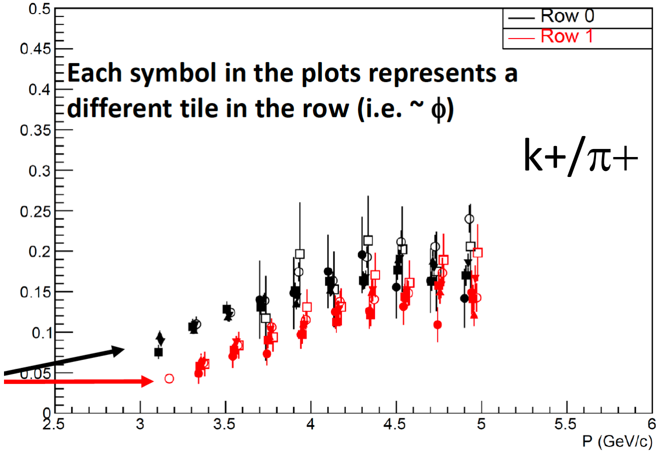
- **Extension to higher momenta requires better alignment (i.e. more photons)**

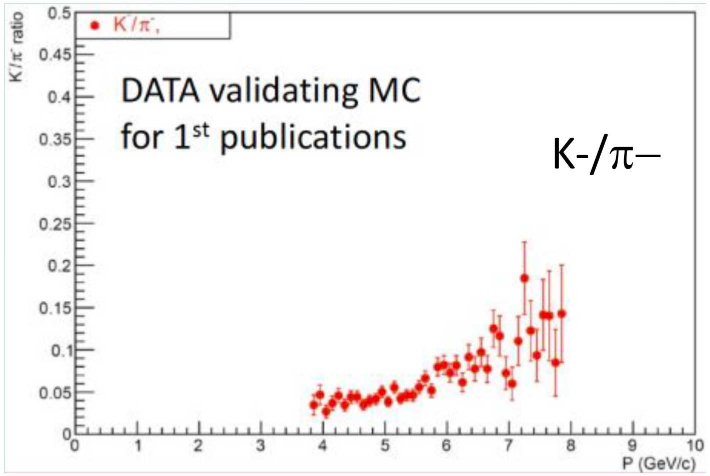
M. Mirazita pass1 analysis

Kaon Yield

k/π ratio as a function of momentum and angle
Points are from diffrent tiles




Each symbol in the plots represents a different tile in the row (i.e. ~ ϕ)

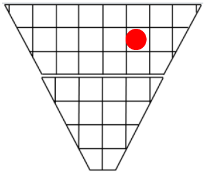

DATA validating MC for 1st publications

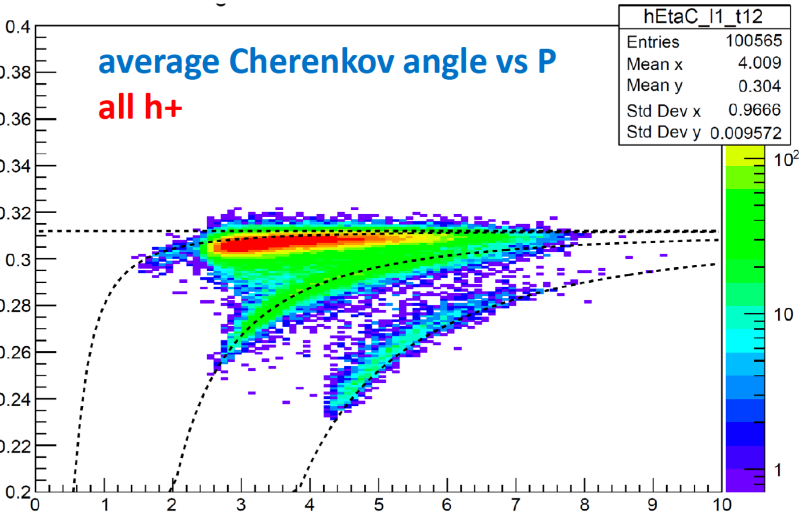
M. Mirazita pass1 analysis

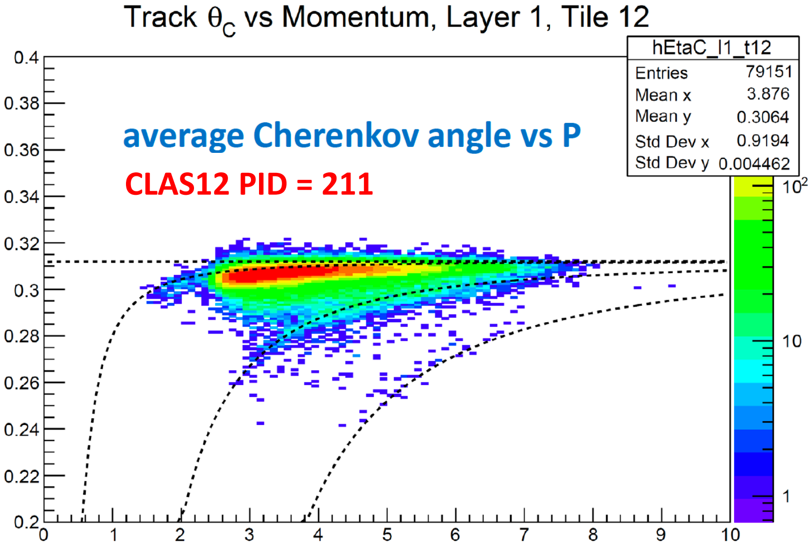
Kaon identification

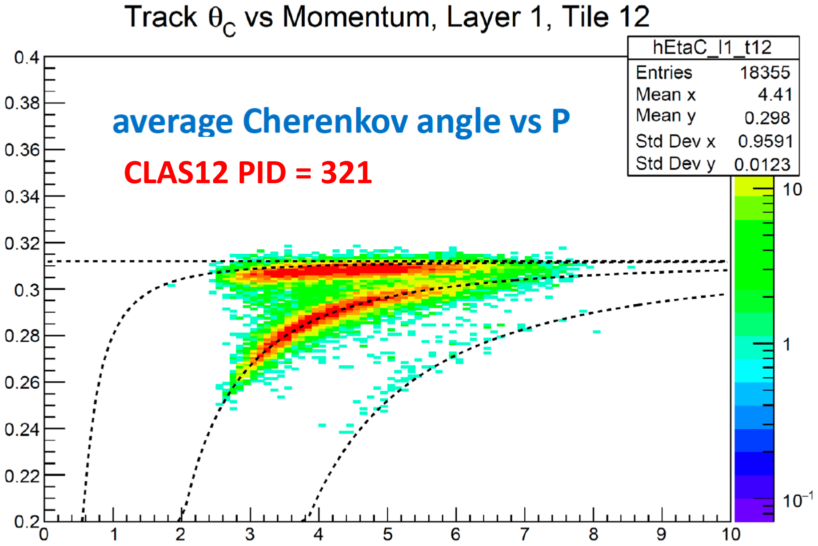
pi+/k+ misidentification

Layer 1
Tile 12
row 1







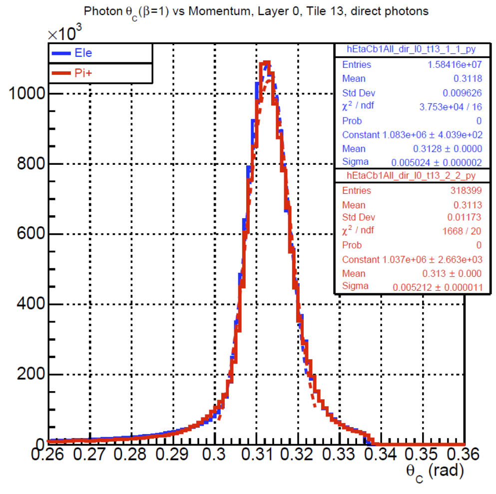


M. Mirazita pass1 analysis

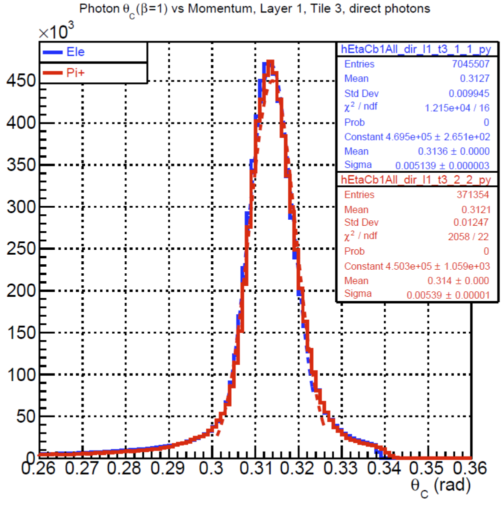
Alignment & Resolution

Alignment requires large statistics and full reconstruction to deal with the various photon paths
Angular resolution is comparable for direct and reflected photons

Direct photons: electrons vs pi+

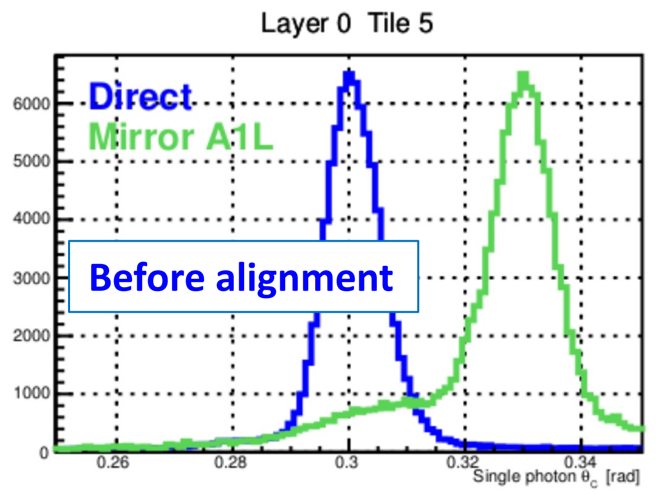

Photon $\theta_c(\beta=1)$ vs Momentum, Layer 0, Tile 13, direct photons

```
hEtaCb1All_dir_l0_t13_1_1_py
Entries            1.58416e+07
Mean                    0.3118
Std Dev               0.009626
χ² / ndf        3.753e+04 / 16
Prob                         0
Constant 1.083e+06 ± 4.039e+02
Mean           0.3128 ± 0.0000
Sigma     0.005024 ± 0.000002
hEtaCb1All_dir_l0_t13_2_2_py
Entries                 318399
Mean                    0.3113
Std Dev                0.01173
χ² / ndf             1668 / 20
Prob                         0
Constant 1.037e+06 ± 2.663e+03
Mean             0.313 ± 0.000
Sigma     0.005212 ± 0.000011
```

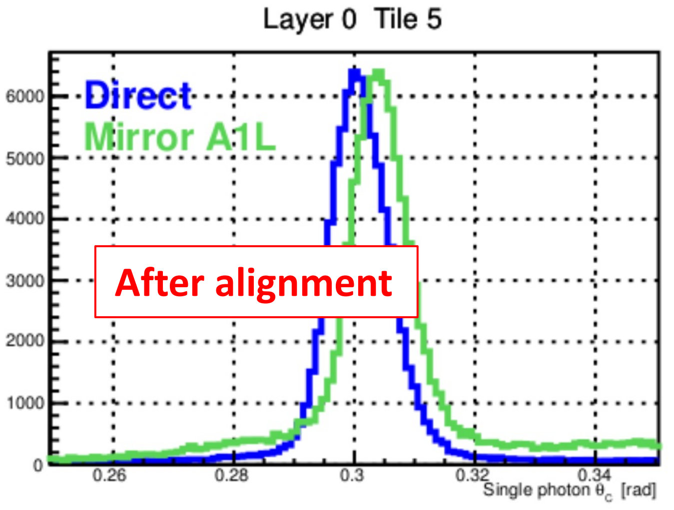

Photon $\theta_c(\beta=1)$ vs Momentum, Layer 1, Tile 3, direct photons

```
hEtaCb1All_dir_l1_t3_1_1_py
Entries                7045507
Mean                    0.3127
Std Dev               0.009945
χ² / ndf        1.215e+04 / 16
Prob                         0
Constant 4.695e+05 ± 2.651e+02
Mean           0.3136 ± 0.0000
Sigma     0.005139 ± 0.000003
hEtaCb1All_dir_l1_t3_2_2_py
Entries                 371354
Mean                    0.3121
Std Dev                0.01247
χ² / ndf             2058 / 22
Prob                         0
Constant 4.503e+05 ± 1.059e+03
Mean             0.314 ± 0.000
Sigma      0.00539 ± 0.00001
```

Electrons: direct vs planar reflection

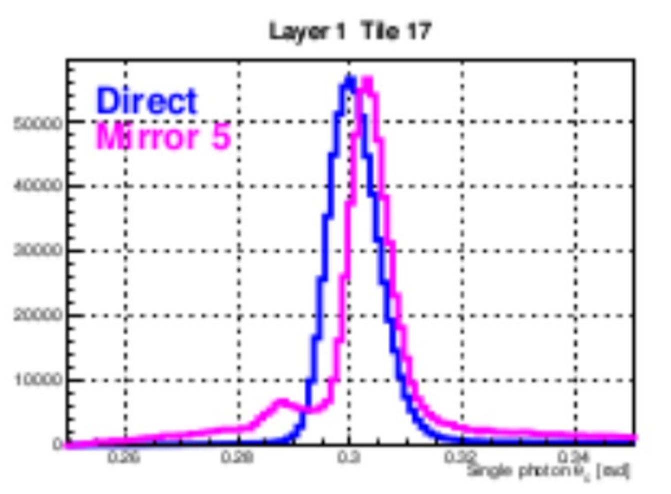

Layer 0 Tile 5

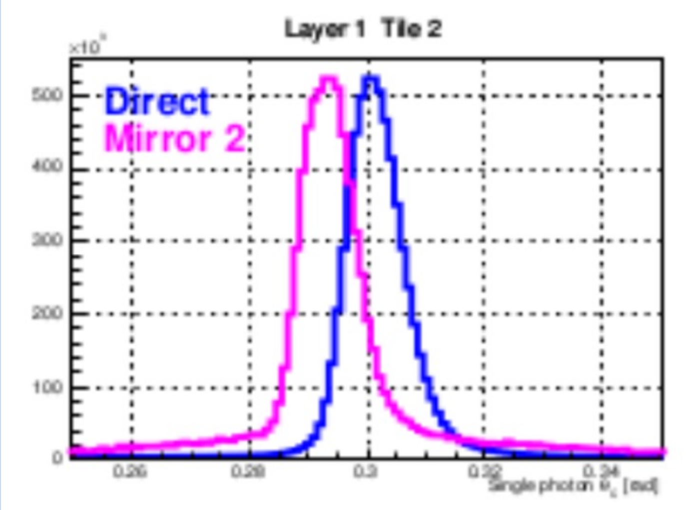
Before alignment


Layer 0 Tile 5

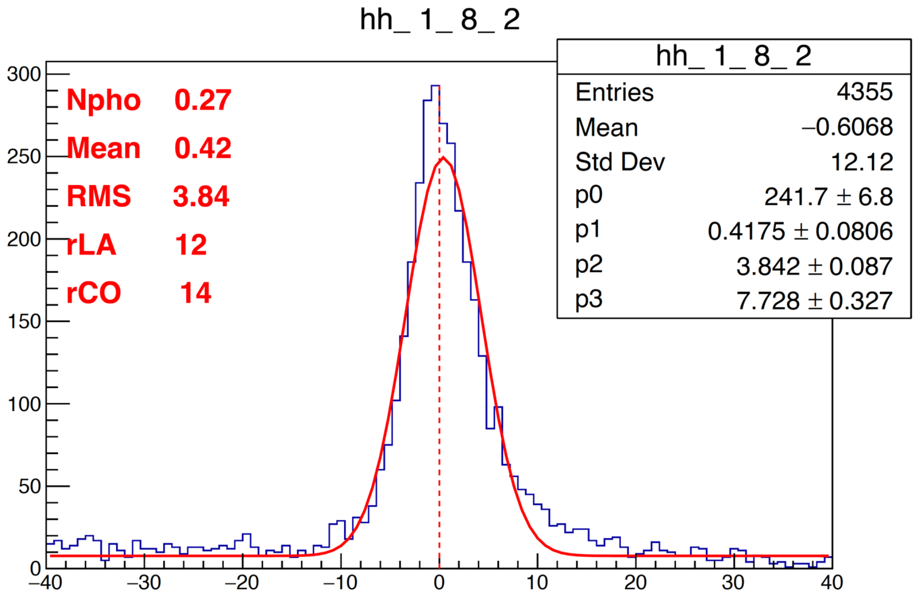
After alignment

Electrons: direct vs spherical reflection


Layer 1 Tile 17

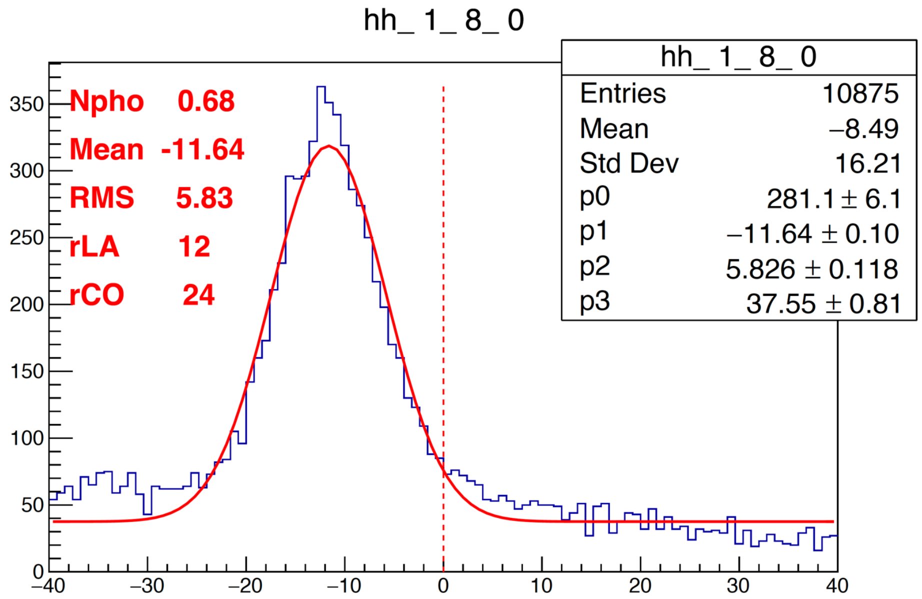

Layer 1 Tile 2

Pass2 Alignment



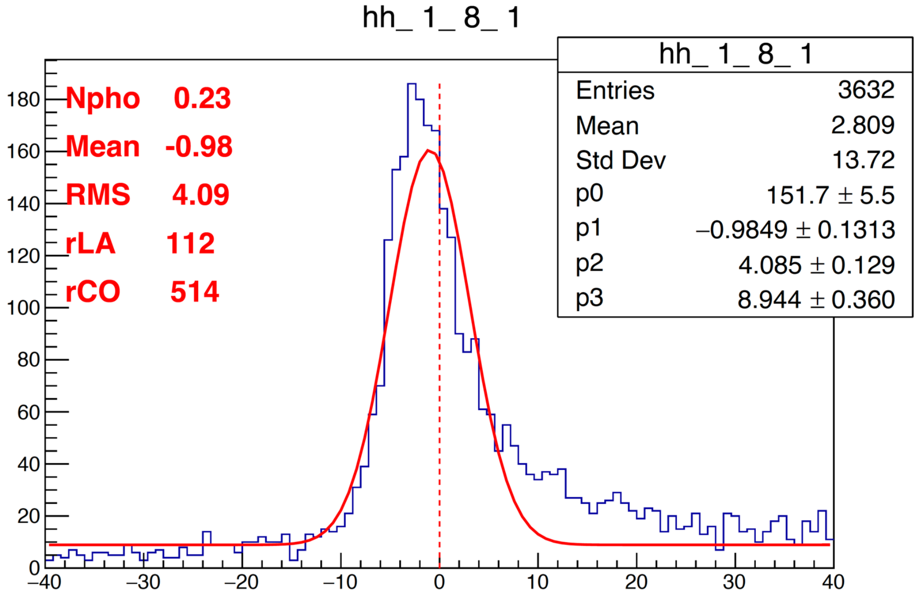
Npho 0.27
Mean 0.42
RMS 3.84
rLA 12
rCO 14

hh_ 1_ 8_ 2	
Entries	4355
Mean	−0.6068
Std Dev	12.12
p0	241.7 ± 6.8
p1	0.4175 ± 0.0806
p2	3.842 ± 0.087
p3	7.728 ± 0.327



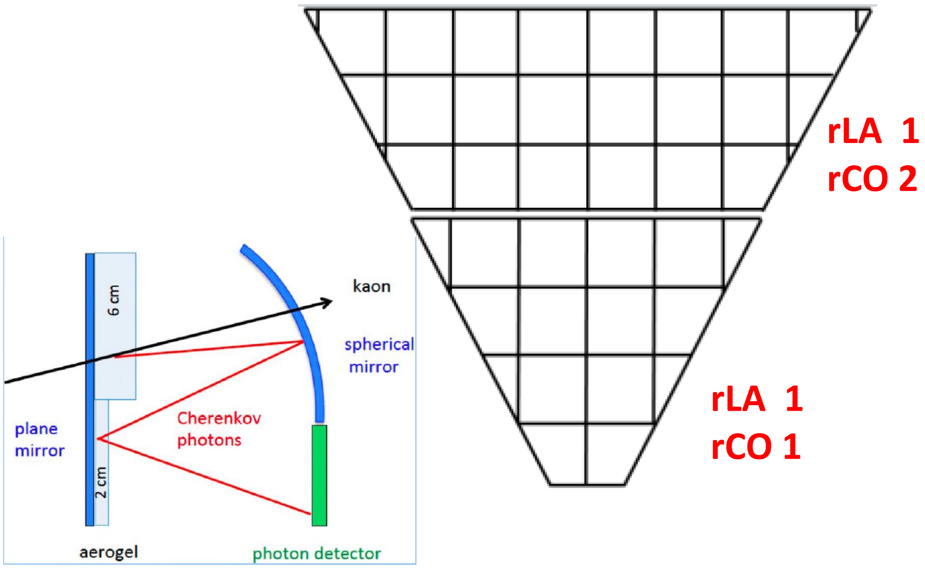
Npho 0.68
Mean -11.64
RMS 5.83
rLA 12
rCO 24

hh_ 1_ 8_ 0	
Entries	10875
Mean	−8.49
Std Dev	16.21
p0	281.1 ± 6.1
p1	−11.64 ± 0.10
p2	5.826 ± 0.118
p3	37.55 ± 0.81



Npho 0.23
Mean -0.98
RMS 4.09
rLA 112
rCO 514

hh_ 1_ 8_ 1	
Entries	3632
Mean	2.809
Std Dev	13.72
p0	151.7 ± 5.5
p1	−0.9849 ± 0.1313
p2	4.085 ± 0.129
p3	8.944 ± 0.360



rLA 1
rCO 2

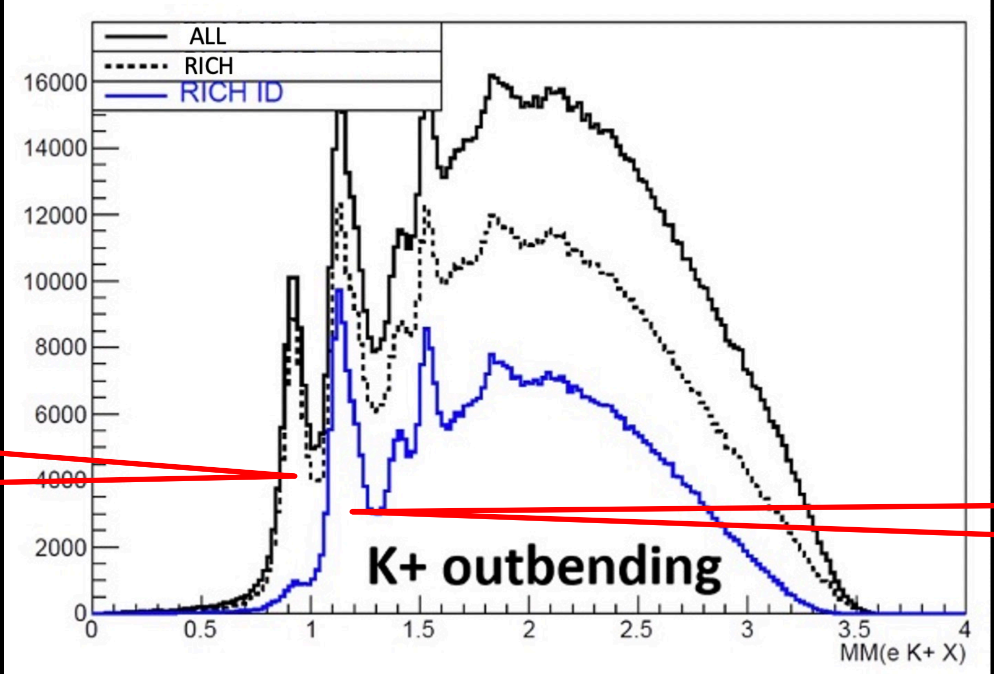
rLA 1
rCO 1

RICH Pass2 Reconstruction

Pass1: direct photons and single reflection

Pass2: full acceptance (multiple reflections), RICH PID and 2nd module

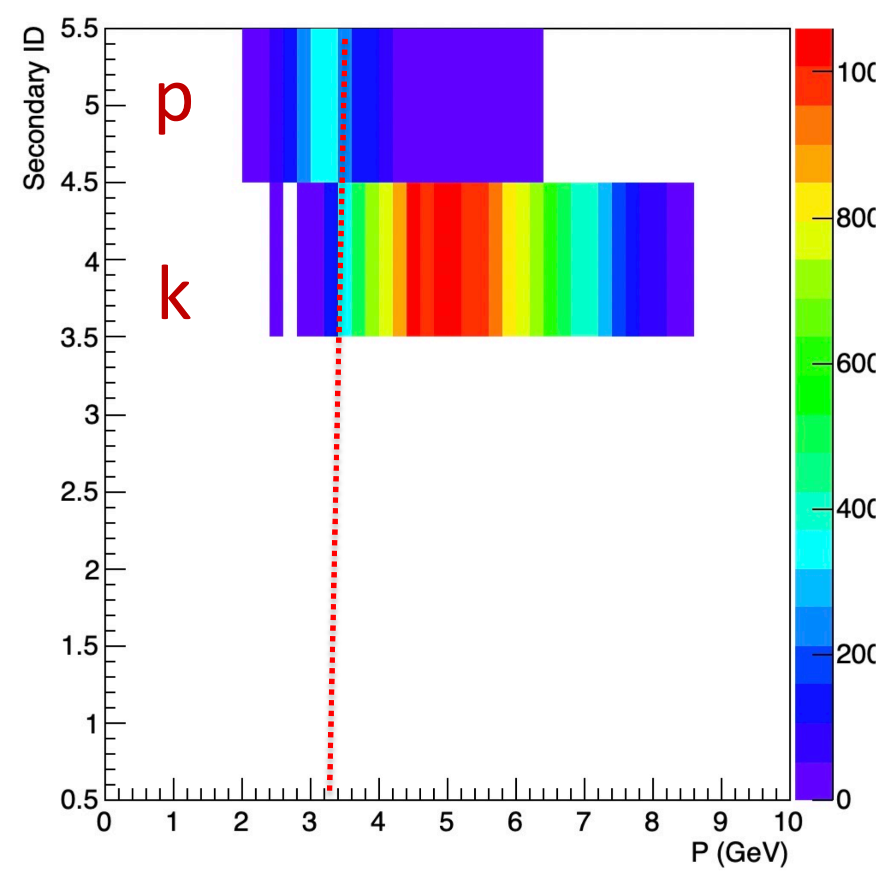
multi-thread safe, all particle ID hypothesis, multi-particles
likelihood PID for single photon and single particle
complete photon path tagging for proper calibration and alignment

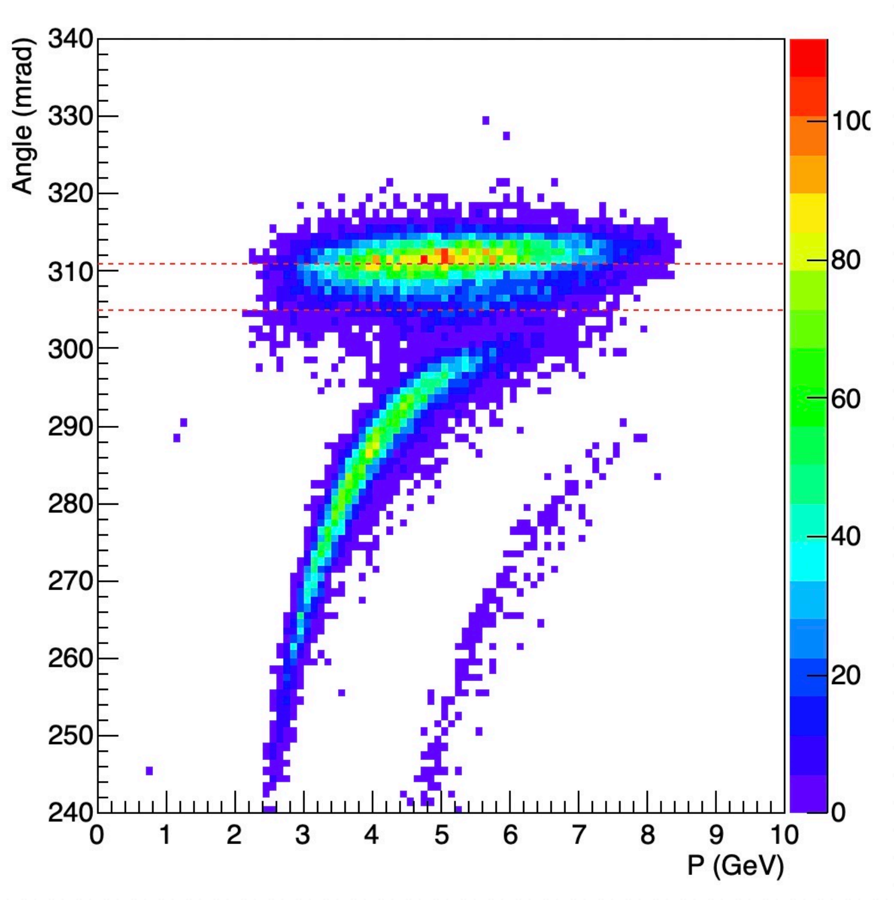


$ep \rightarrow e\pi^+ n$
background

$ep \rightarrow eK^+\Lambda$
signal

Secondary ID





RICH N_{exp} N Bck. $\Sigma n_i \log(n_i/\mu_i)$ $2(N_{exp}-N)$ LH

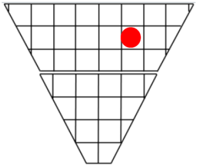
```
[    11]     11 [  13.00]    8     1 [     152.7     -117.6     12.00] -->     164.7
[   211]     11 [  12.66]    8     1 [     153.6     -118.8     11.33] -->     164.9
[   321]     11 [   8.79]    8     6 [     208.6     -129.3     13.57] -->     222.2
[  2212]     11 [   0.00]    8     7 [     216.0     -216.0    -2.000] -->     214.0
```

Clear pion (electron). Equally bad kaon and proton, but LH with N term prefers smaller expected yield.

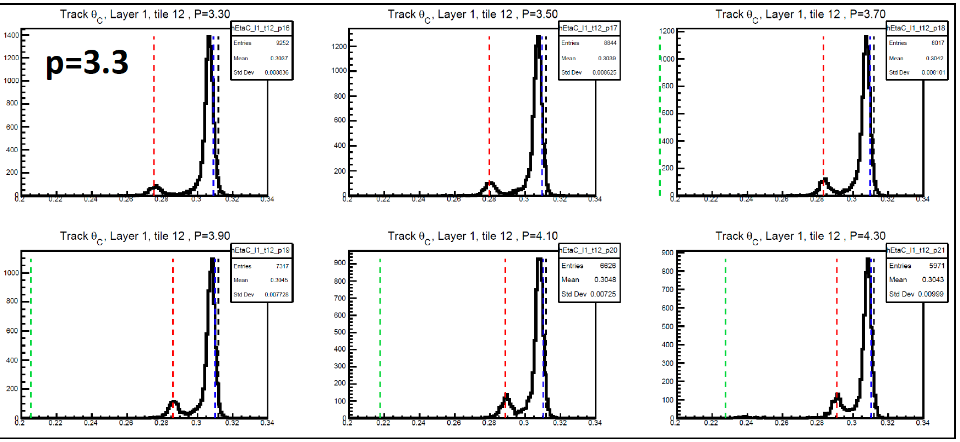
Pion vs Kaon

pi+/K+ misidentification

Layer 1
Tile 12
row 1

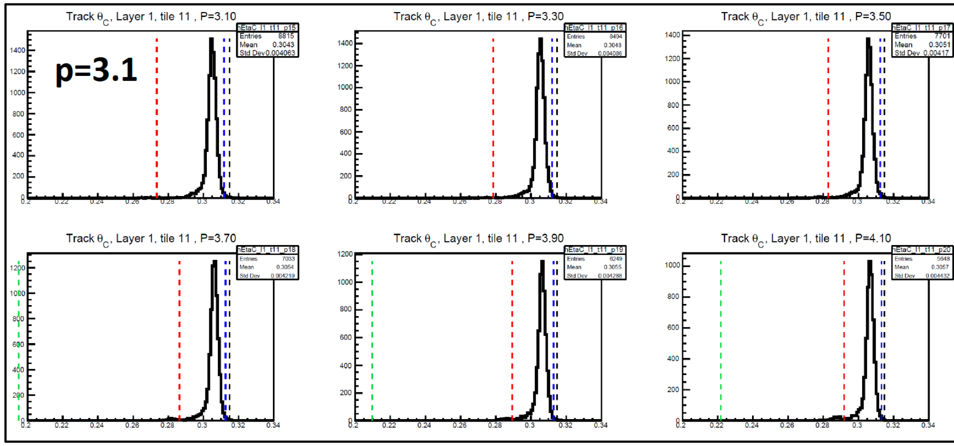


all h+

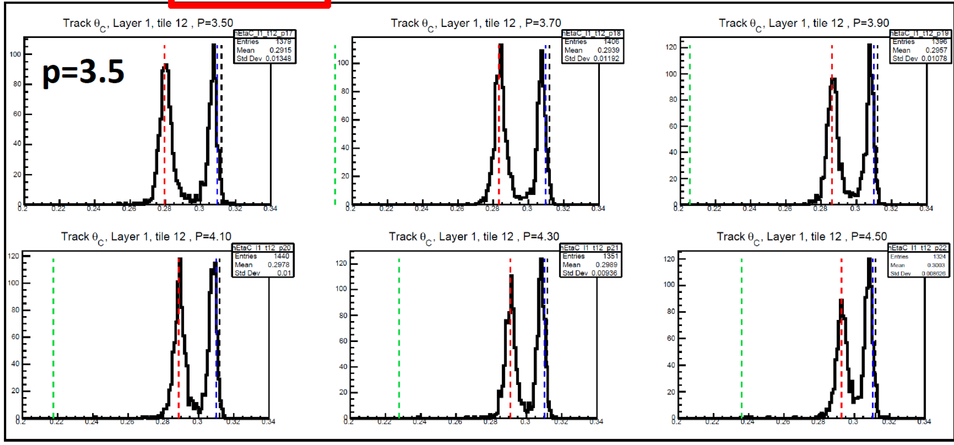


- **Very small contamination from Kaons**
- **<u>About 50% or more of ID Kaons above RICH threshold were pions</u>**

PID=211



PID=321



M. Mirazita analysis