Simulation and Reconstruction of the PANDA Barrel DIRC

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Outline

- PID requirement of PANDA Barrel DIRC
- Different design options - bar and plate

Bar type geometry:

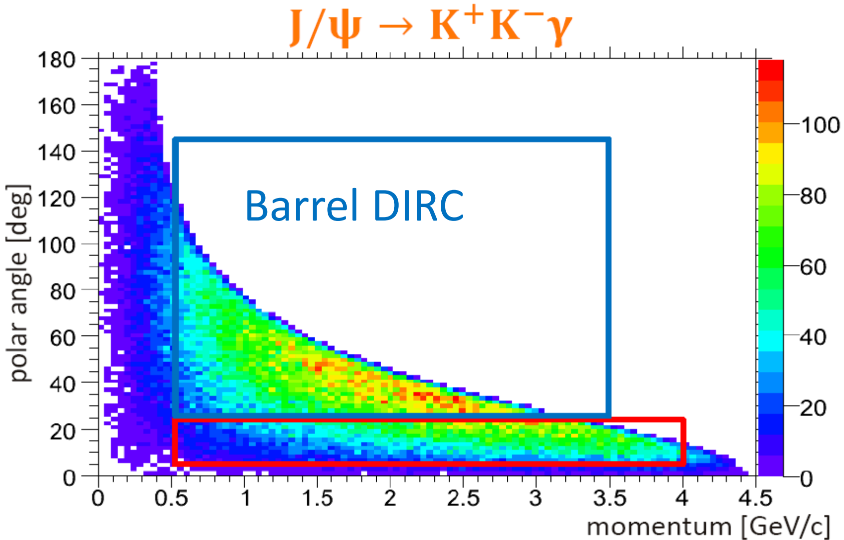
- Geometrical approach to reconstruct Cherenkov angle
- Maximum likelihood method for PID
- Efficiency and mis-identification

Plate type geometry:

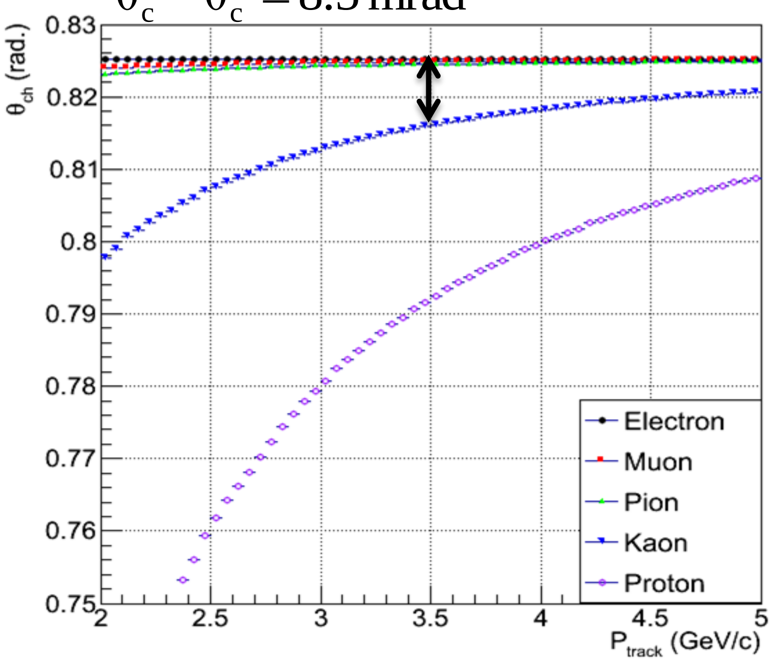
- Geometrical reconstruction of Cherenkov angle
- Time imaging of Cherenkov photons
- Time based maximum likelihood method and separation power

- Summary and outlook

PID Requirement of PANDA Barrel DIRC



$$\theta_c^{\pi} - \theta_c^{k} = 8.5\ \text{mrad}$$



- Typical momentum range of pions and kaons in PANDA will be up to ~3.5GeV/c in the Barrel region as phase space of kaons in one of the radiative decay channel is shown
- The Cherenkov angle difference between pion and kaon is ~ 9mrad at 3.5GeV/c

$$\sigma_{track}^2 = \sigma_c^2 + \sigma_{correlated}^2$$

$$\sigma_c^2 = \frac{\sigma_\gamma^2}{\sqrt{N_{ph}}}$$

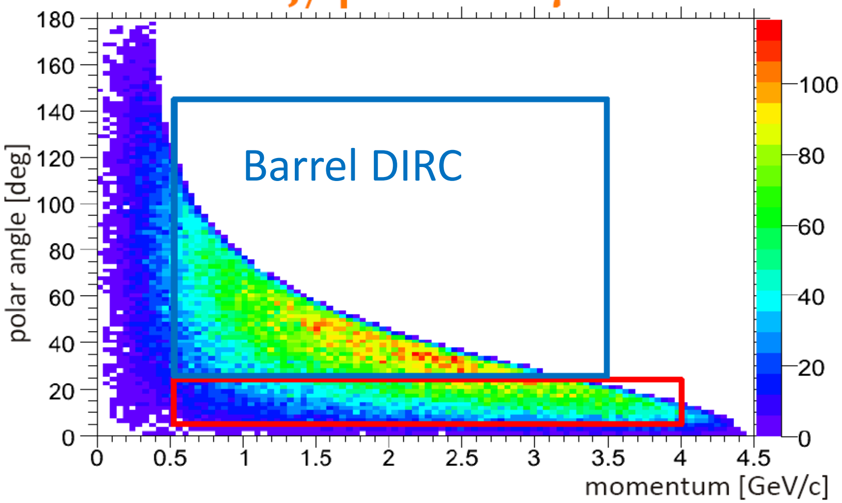
σ_γ= single photon resolution
N_{ph} = detected photons

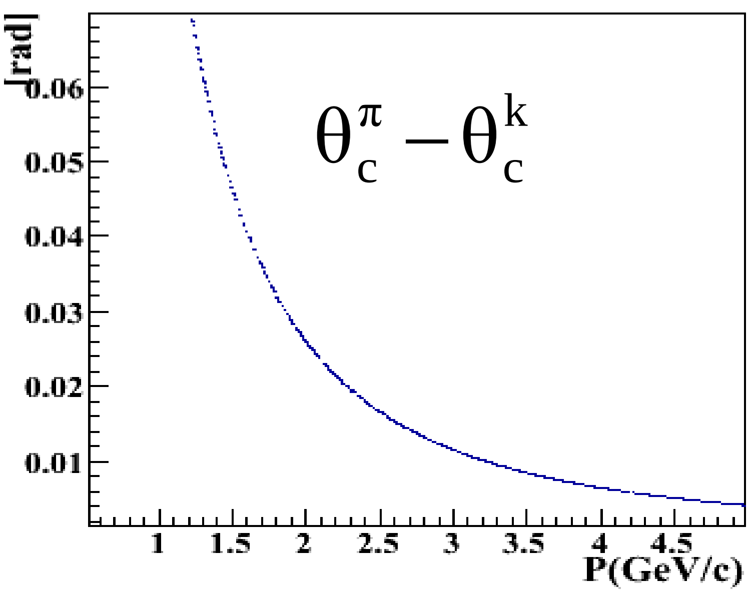
$\sigma_{correlated}$ = multiple scattering, tracking, …

- The maximum required Cherenkov angle resolution for 3σ, π/K separation at highest momentum is better than 2.5 mrad

Example: required σ_γ would be ~11 mrad for N_{ph}=20

PID Requirement of PANDA Barrel DIRC





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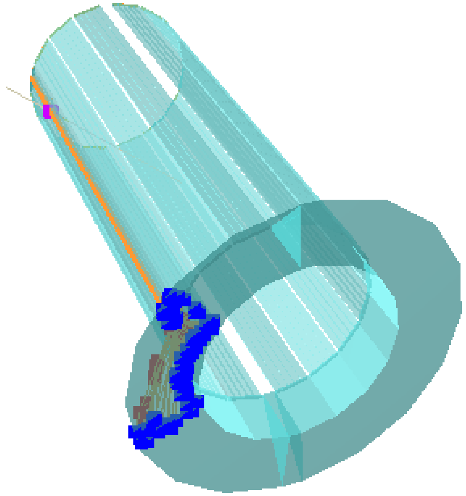
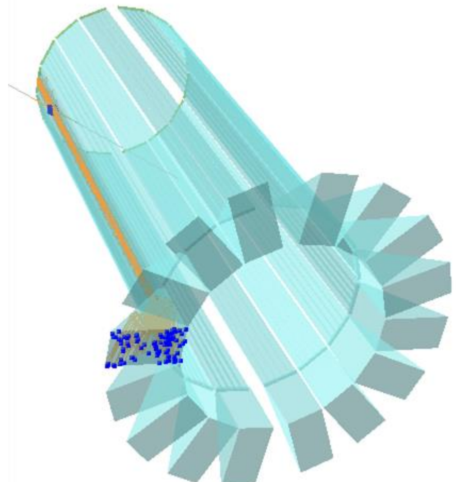
Example: required σ_γ would be ~11 mrad for N_{ph}=20

Different Design Options

Common Features: 16 bar boxes, bar thickness 17mm, length 2.4m.



Bar + Oil tank



Bar + Fused Silica Prism

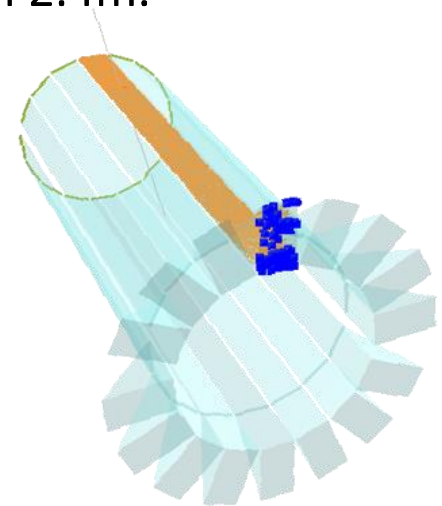


Plate + Fused Silica Prism

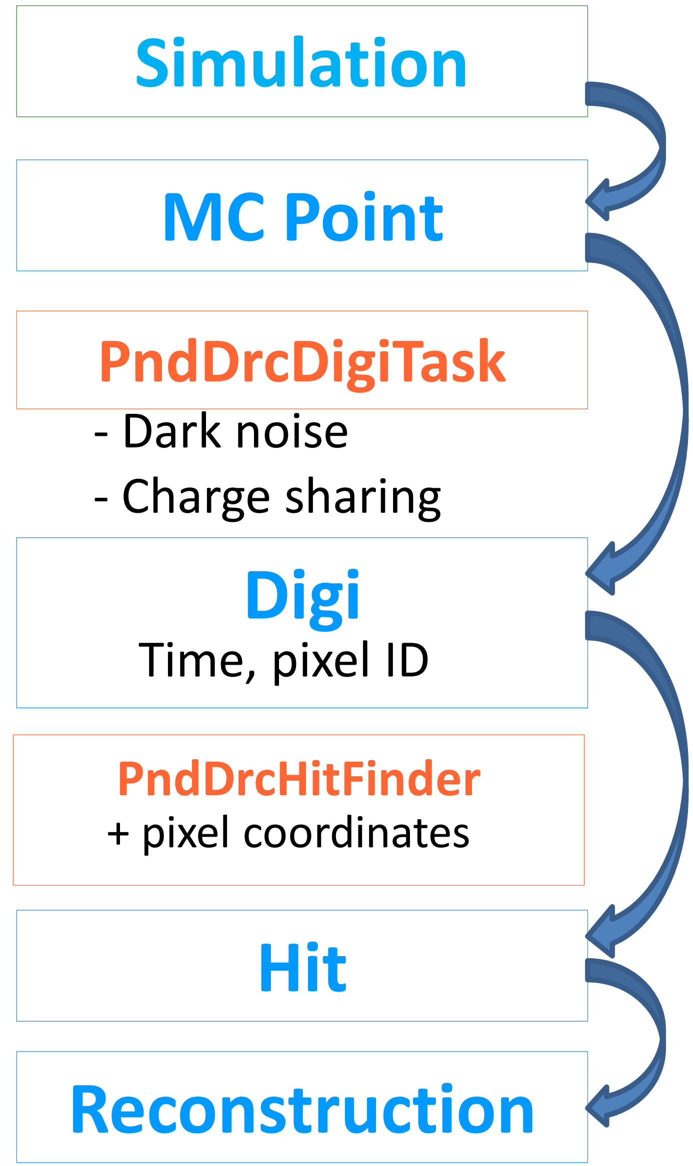
➢ Simple configuration ➢ Significant photon loss in oil compared to fused silica prism	➢ Higher photon yield due to better transmission ➢ Easy in operation but more background due to ambiguities	➢ Bars are replaced with single plate in one bar box ➢ 2-3 times less expensive due to less no. of surfaces to be polished

Different focusing systems with bar type geometry are studied to improve the Cherenkov angle resolution

See talk by
J. Schwiening

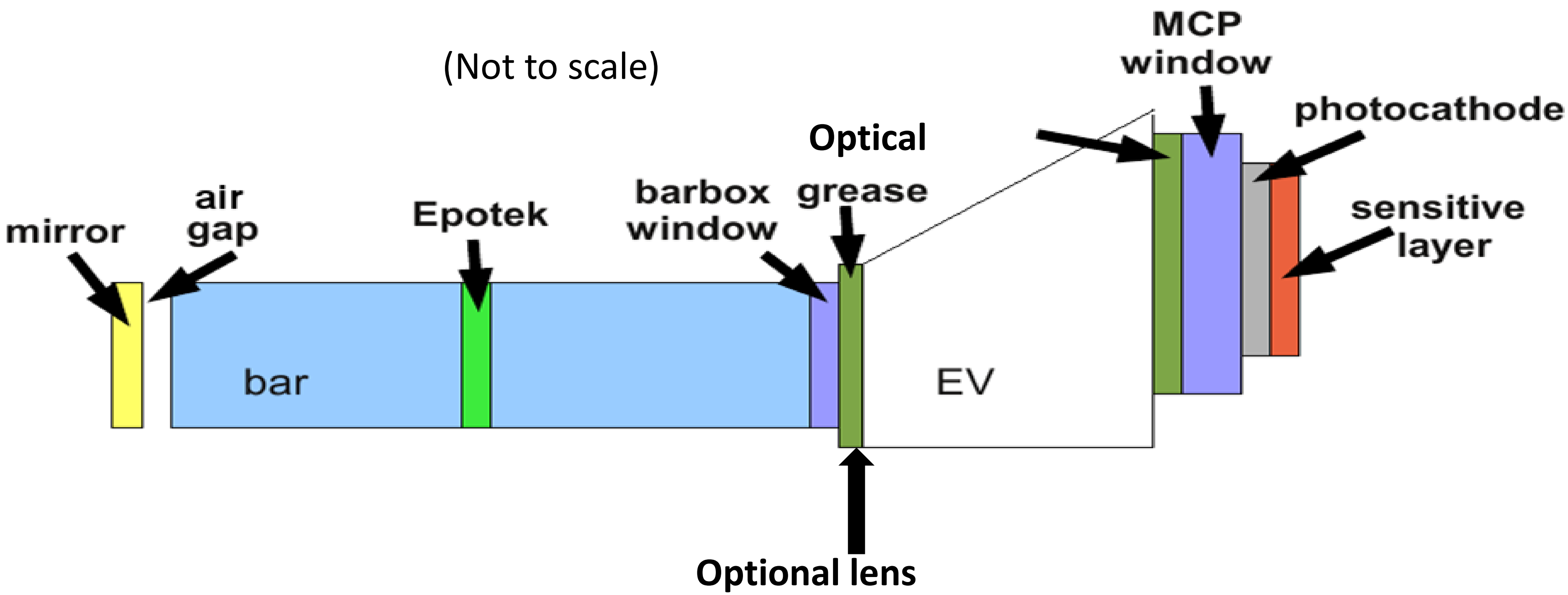
Simulation of the Barrel DIRC

- Geant4 in PandaRoot framework is used for simulation
- Quantum efficiency, collection efficiency, real reflectivity of forward mirror, absorption in fused silica are included
- Complex geometry structure along with MCPs is incorporated
- Dark noise (1 pixel/event) and charge sharing (experimental data from Erlangen group) is included at digitization stage
- Hits are stored along with the pixel coordinates
- Reconstruction of the Cherenkov angle, single photon resolution, track Cherenkov angle resolution, PID study using maximum log-likelihood, efficiency and mis-id studies are done in the final stage



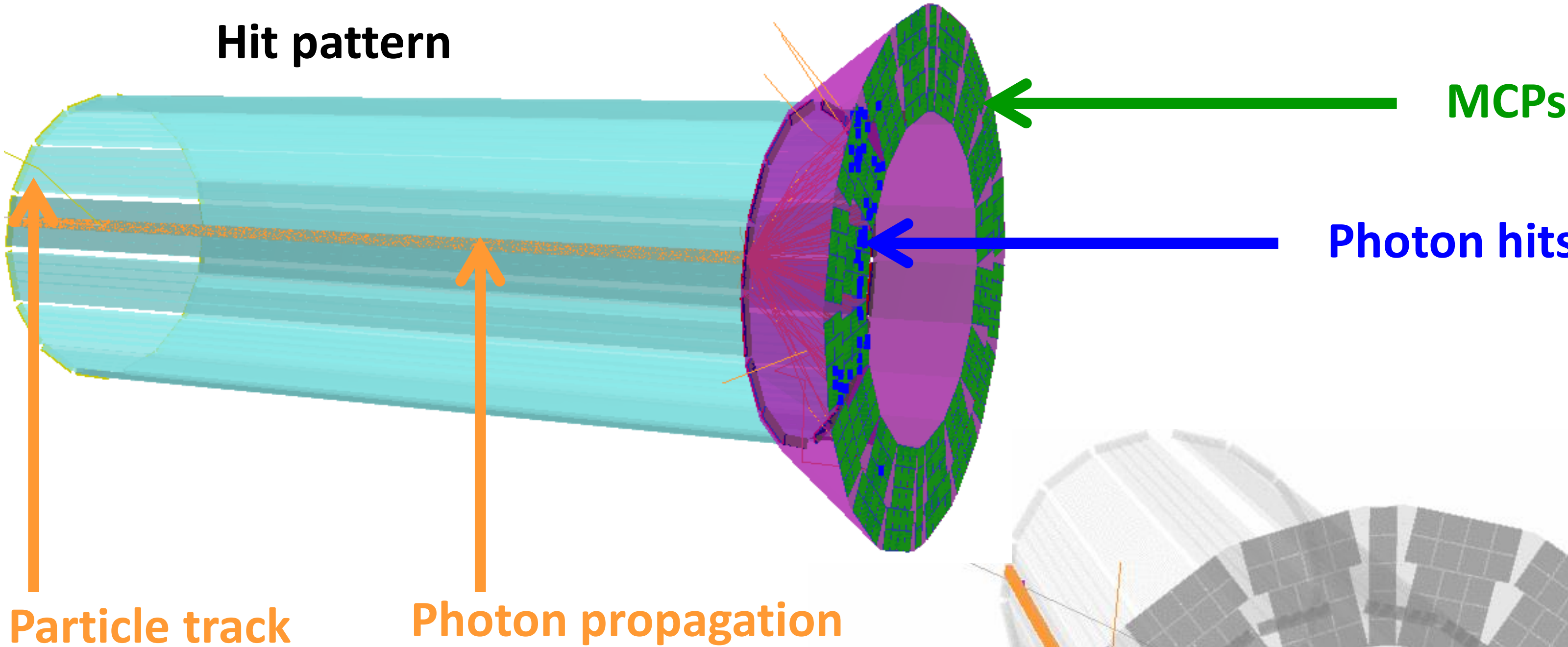
Simulation of the Barrel DIRC

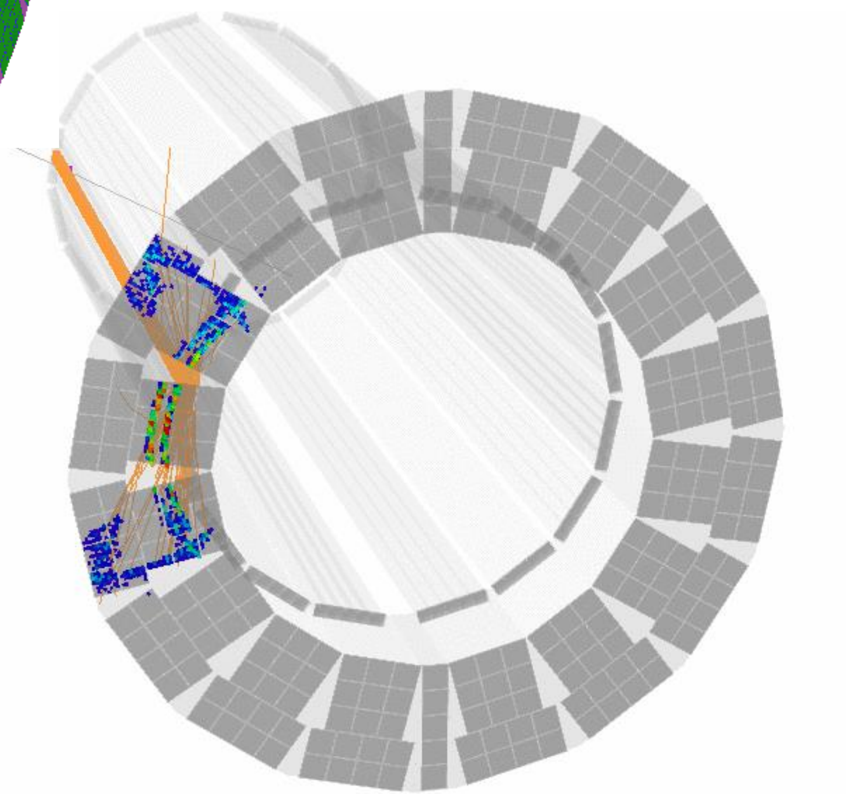
Different components of the complex geometry structures are shown below



Simulation of the Barrel DIRC

Hit pattern





Hit pattern for different polar angles

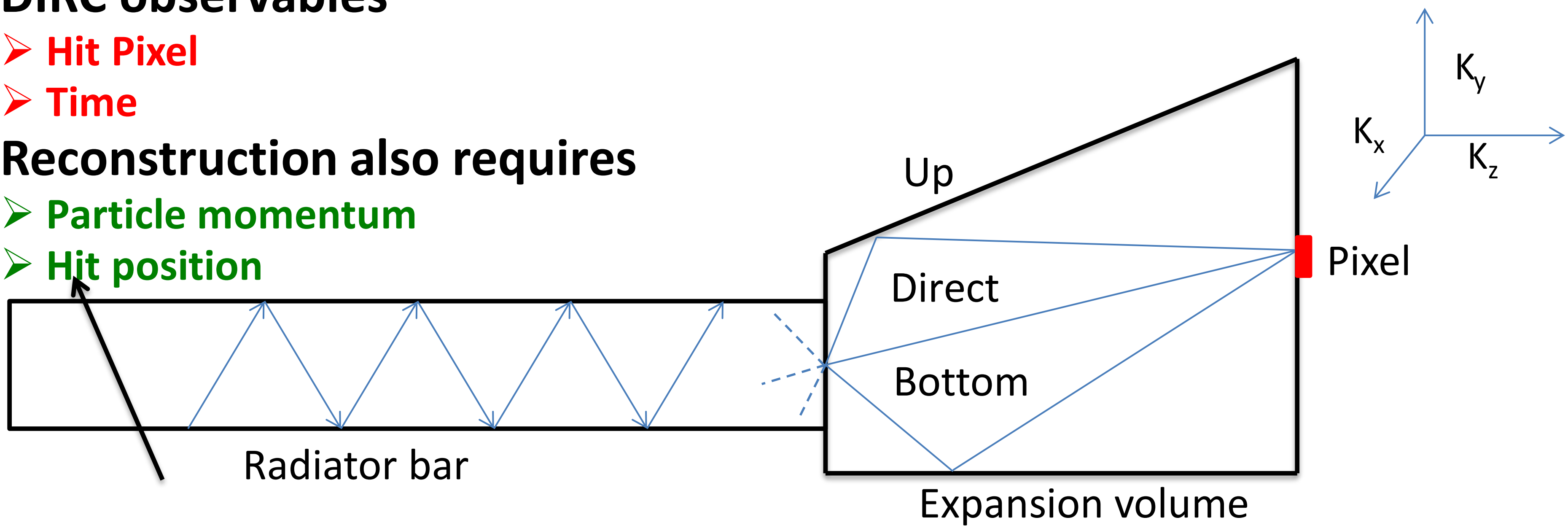
Geometrical Reconstruction Approach

DIRC observables

- **Hit Pixel**
- **Time**

Reconstruction also requires

- **Particle momentum**
- **Hit position**



A proven BABAR-type reconstruction is implemented

Prism/Tank Ambiguities:

- A photon point source is placed at the bar center and photon direction vectors (K_x, K_y and K_z) for each pixel are stored for every identified reflection types (Direct, Bottom, Up, Bottom+up,Left, Right, etc…)

Bar Ambiguities:

- Bar ambiguities are treated by flipping the direction vectors (K_x, K_y, K_z) of the photons inside the bar.

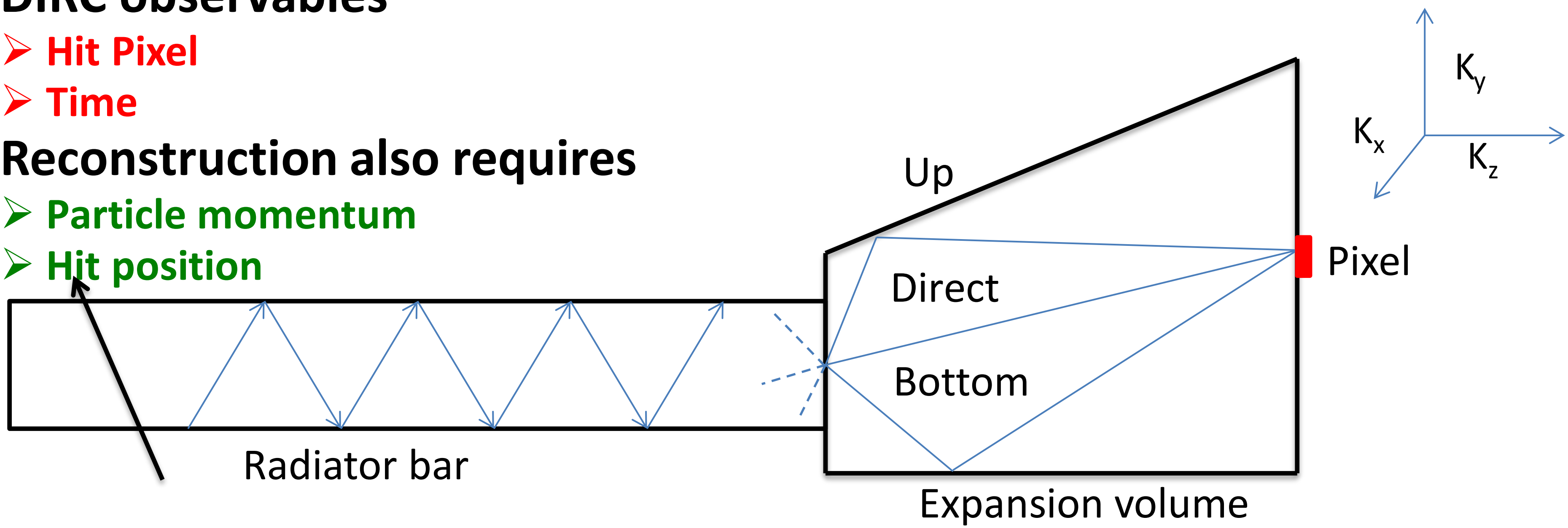
Geometrical Reconstruction Approach

DIRC observables

- **Hit Pixel**
- **Time**

Reconstruction also requires

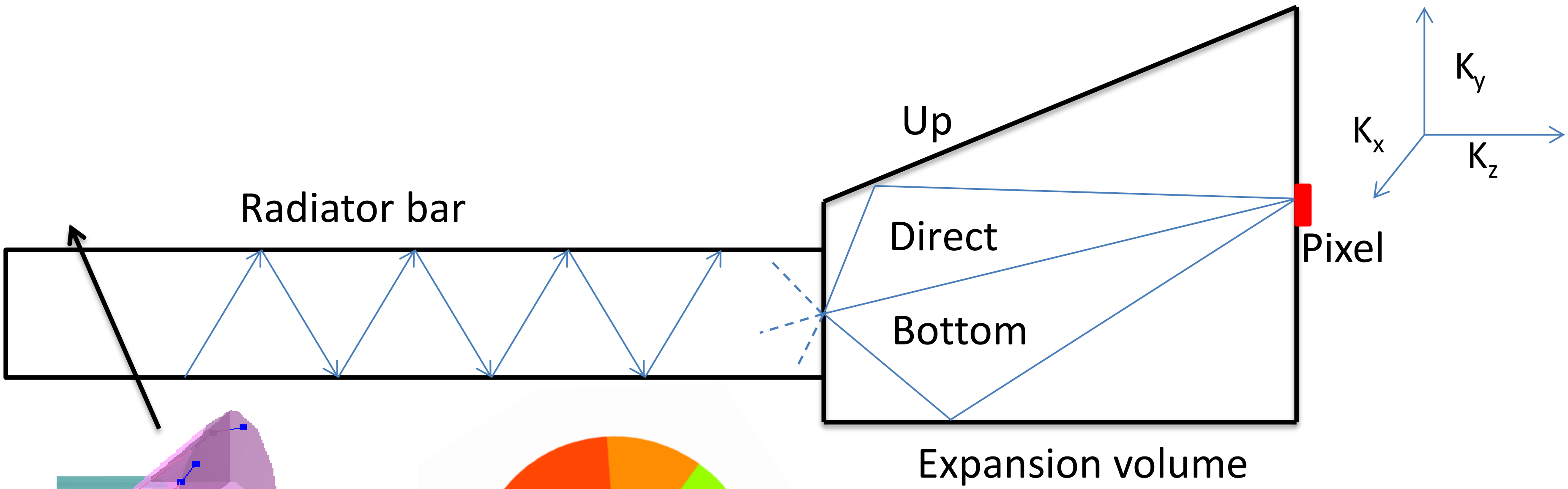
- **Particle momentum**
- **Hit position**

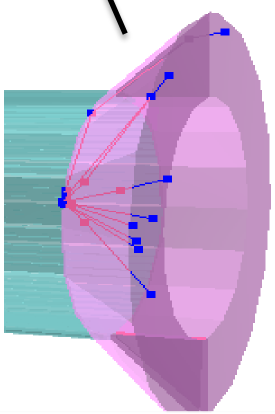


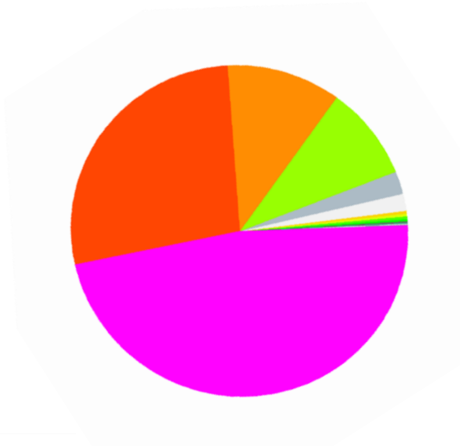
- Cherenkov angle for each photon is calculated from particle and photon direction vectors

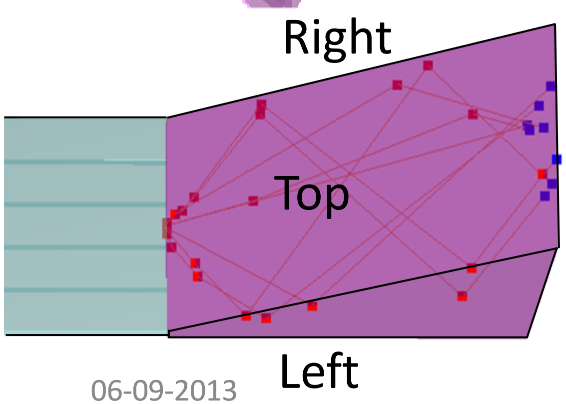
- Out of all reconstructed angles, one is the right Cherenkov angle and other's generate an ambiguity background.

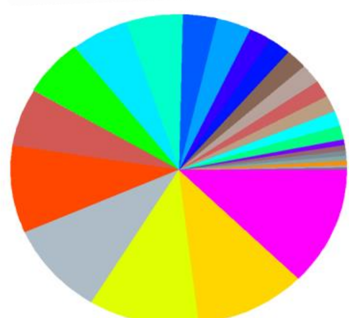
Geometrical Reconstruction Approach







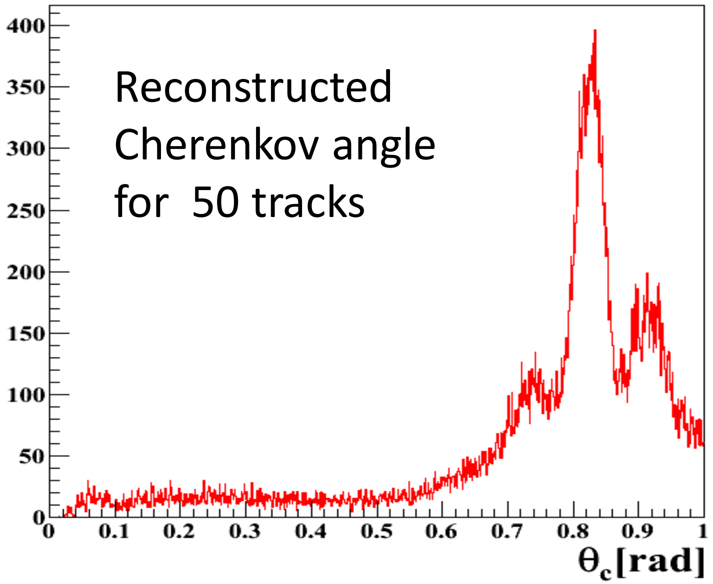


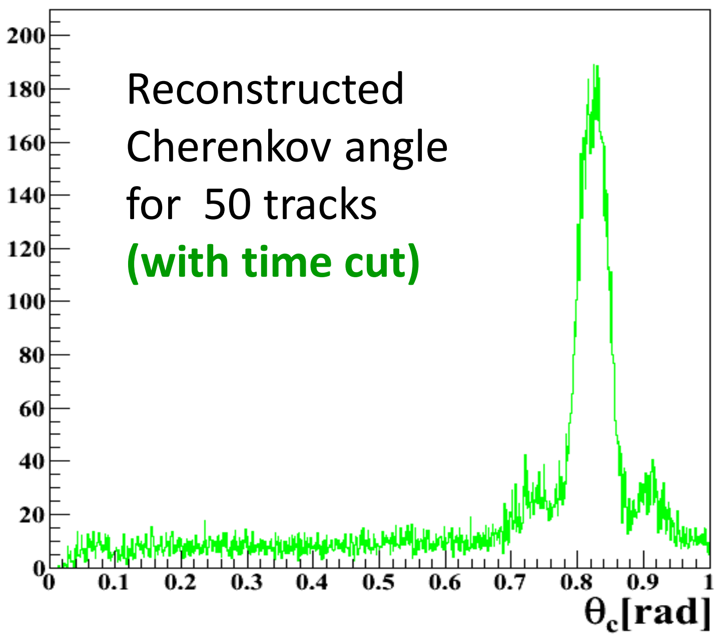


- In the simple tank geometry 4 ambiguities (Direct=48%, Bottom=27%, Up=11%, BottomUp=9%) contribute to 95% photons

- In prism geometry the number of ambiguities is large and more than 25 of them contribute to 95% photons

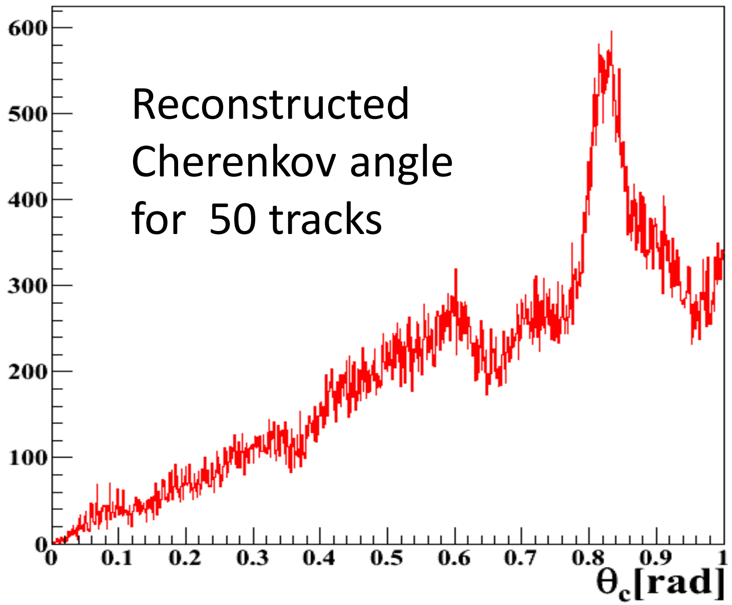
Reconstruction of the Cherenkov Angle

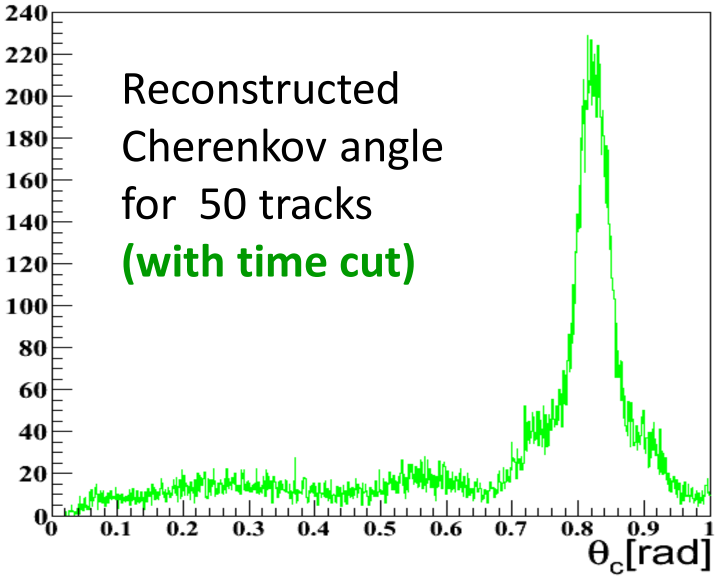




- The reconstructed Cherenkov angle is shown for the **bar + tank type geometry**
- Reconstructed Cherenkov angle peaks at the right position (muons of 3GeV/c, 25° track polar angle)
- The ambiguity background is spread around the true peak
- Photon arrival time information is used to reduce the ambiguity background
- Due to chromatic smearing the time cut is path length dependent

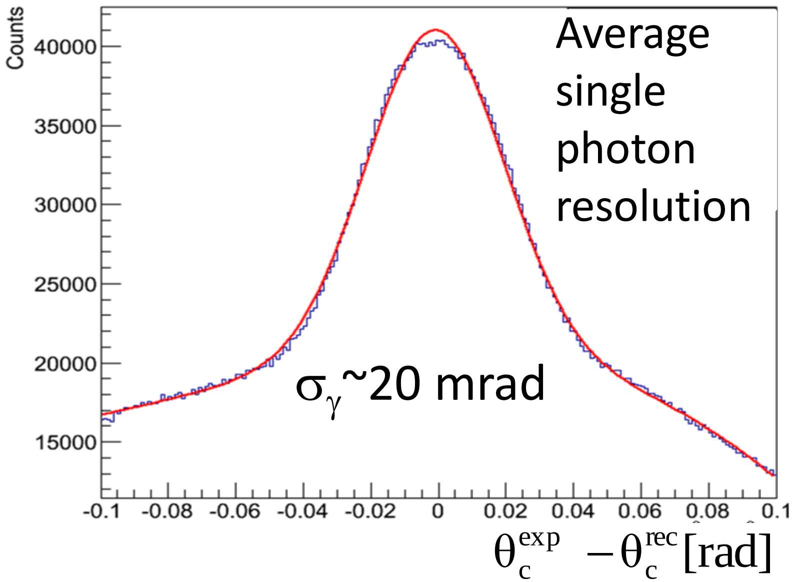
Reconstruction of the Cherenkov Angle

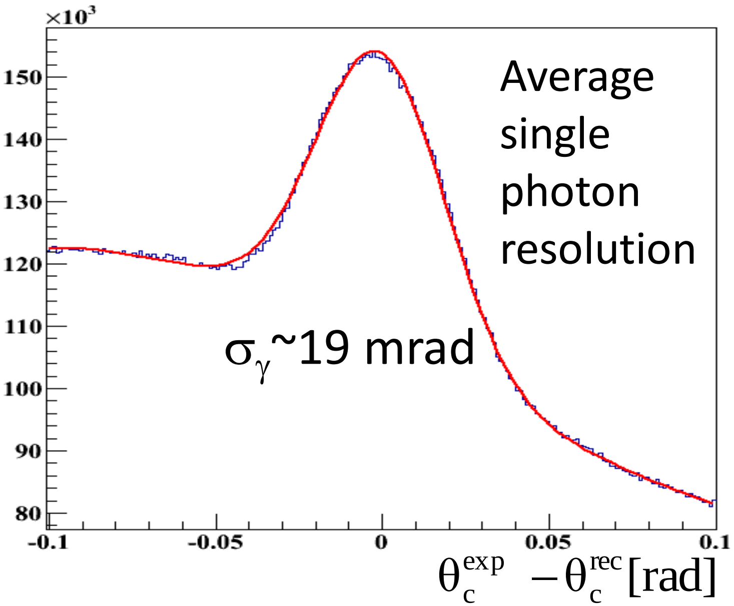




- The reconstructed Cherenkov angle is shown for the **bar + prism type geometry**
- Reconstructed Cherenkov angle peaks at the right position (muons of 3GeV/c, 25° track polar angle)
- The ambiguity background is spread around the true peak and it is much larger compared to the tank type expansion volume
- Photon arrival time information is used to reduce the ambiguity background
- Due to chromatic smearing the time cut is path length dependent

Single Photon Resolution

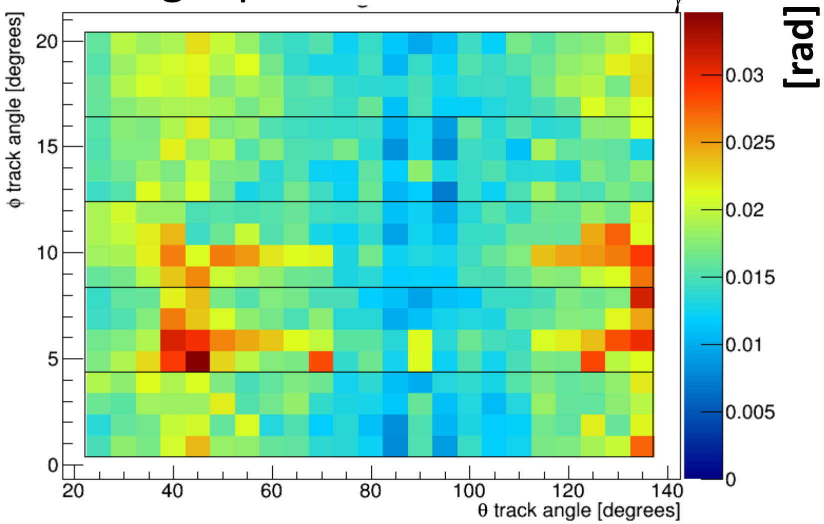




- Single photon resolution (σ_γ) for 0.5-5GeV/c and polar angle 22-140° degree is calculated for many tracks
- The resolution (σ_γ) for **bar + tank type geometry** is ~20 mrad
- The resolution (σ_γ) for **bar + prism type geometry** is ~19 mrad.

Single Photon Resolution, Photon yield

Single photon resolution σ_γ

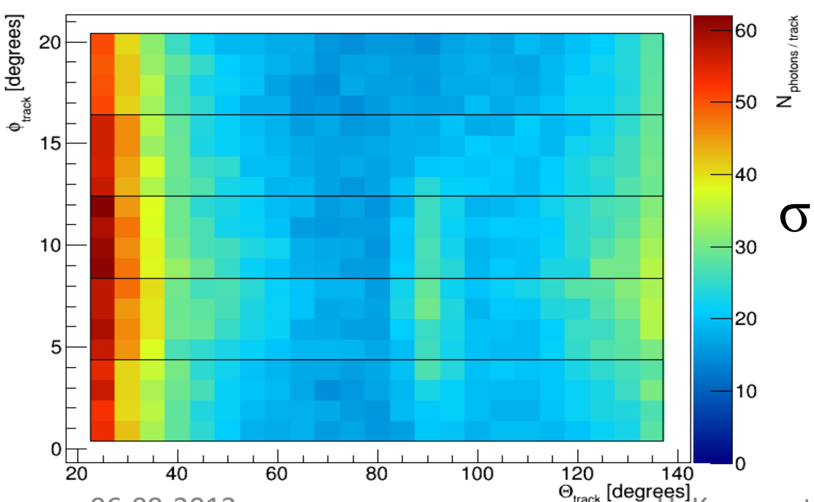


➢ Single photon resolution (σ_γ) in one bar box for a simplified tank type geometry (without lens) is ~10-30 mrad

➢ The resolution is better at 90° compared to forward and backward angles due to chromatic effects and ambiguity separation

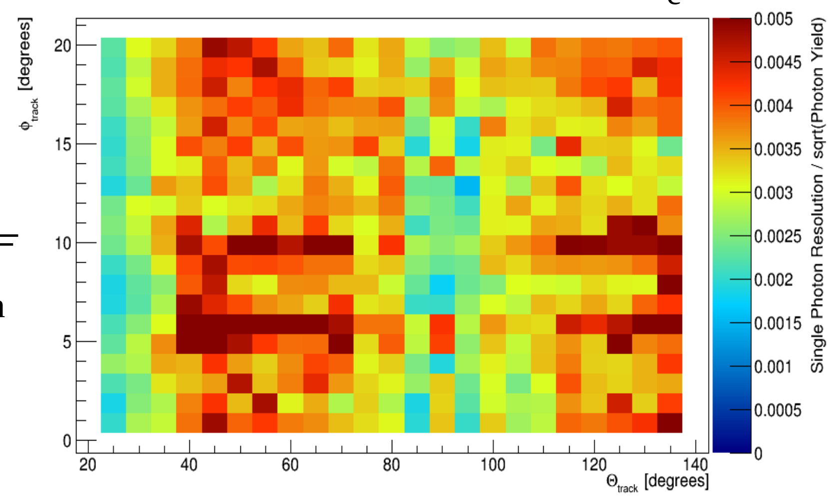
➢ Photon yield is also polar angle dependent which is function of transmission and track length inside bar

Photon yield

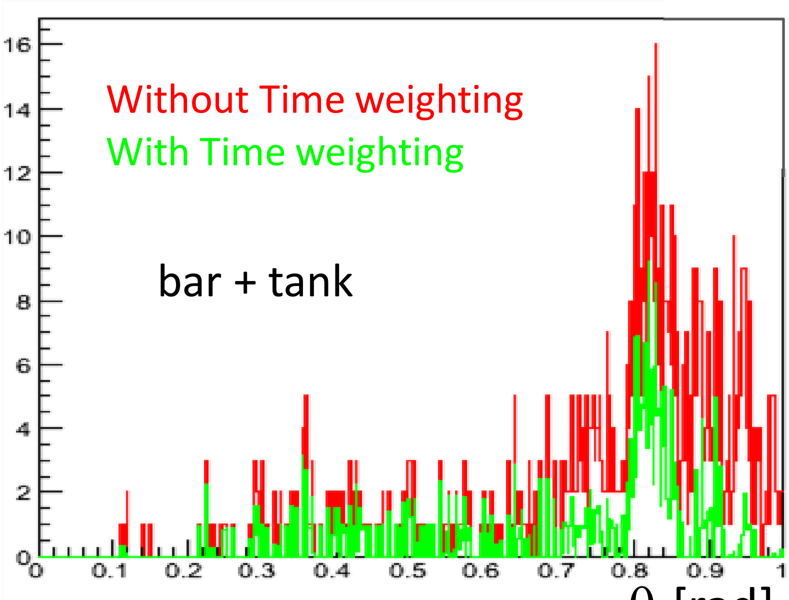


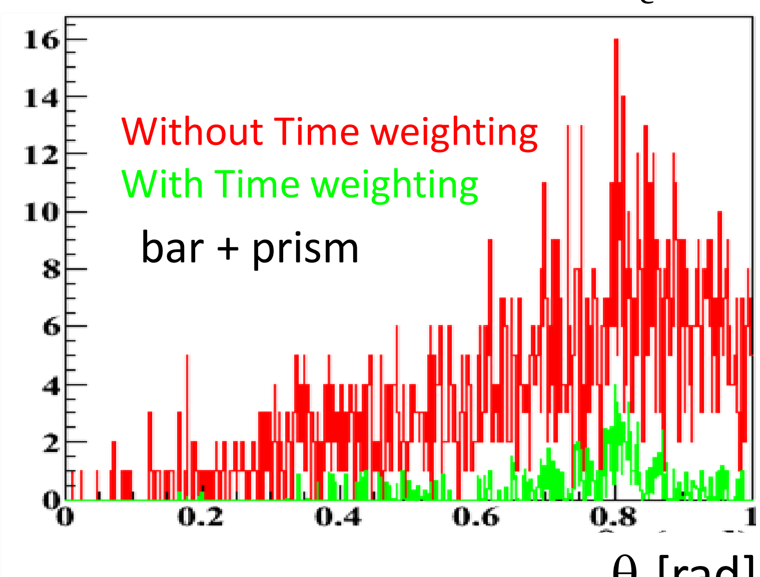
$$\sigma_c = \frac{\sigma_\gamma}{\sqrt{N_{ph}}}$$

Track resolution σ_c



Cherenkov Angle for Single Track





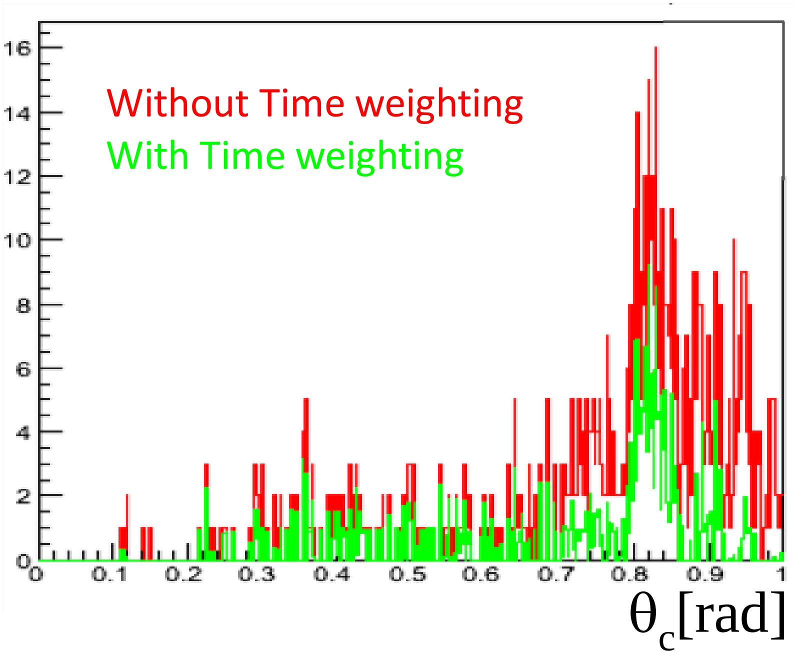
- The reconstructed θ_c for each track is quite clumsy and it is difficult to get the track θ_c by normal fit
- we have used maximum log-likelihood method to calculate track θ_c to study track resolution and PID performance

See talk by Greg. Kalicy

Log Likelihood and Hypothesis test

$$\mathrm{LogL} = \sum_{i}^{amb} \mathrm{Log}\left(\frac{1}{\sqrt{2\pi\sigma_{\gamma}^{2}}} \exp\frac{-(\theta_c - \theta_i)^2}{2\sigma_{\gamma}^{2}} + \frac{\theta_c}{\theta_m^2}\right)$$

$$\mathrm{LogL}_{\pi,k,p} = \mathrm{Log}\left(\frac{1}{\sqrt{2\pi\sigma_{c}^{2}}} \exp\frac{-(\theta_c - \theta_{\pi,k,p})^2}{2\sigma_{\gamma}^{2}}\right)$$



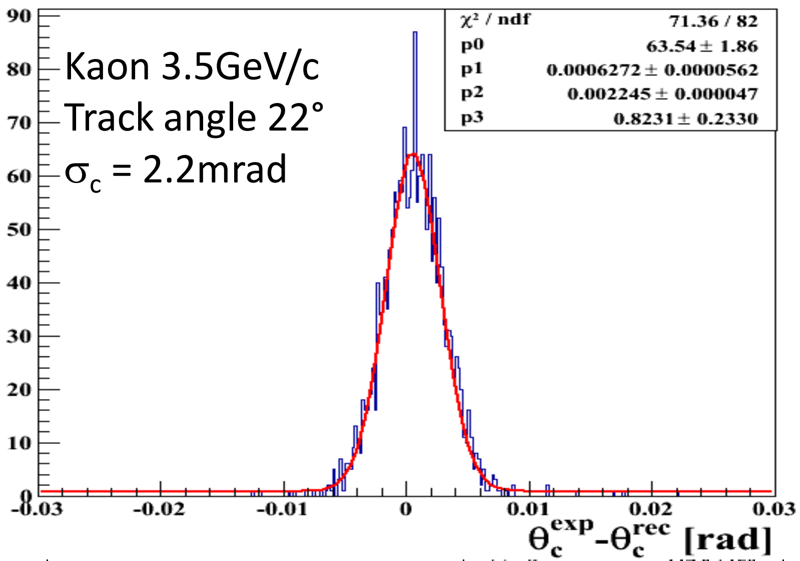
- At first, track θ_c is estimated using reconstructed Cherenkov angle for each track. Probability Density Function (PDF) is taken as Gaussian with linear background function

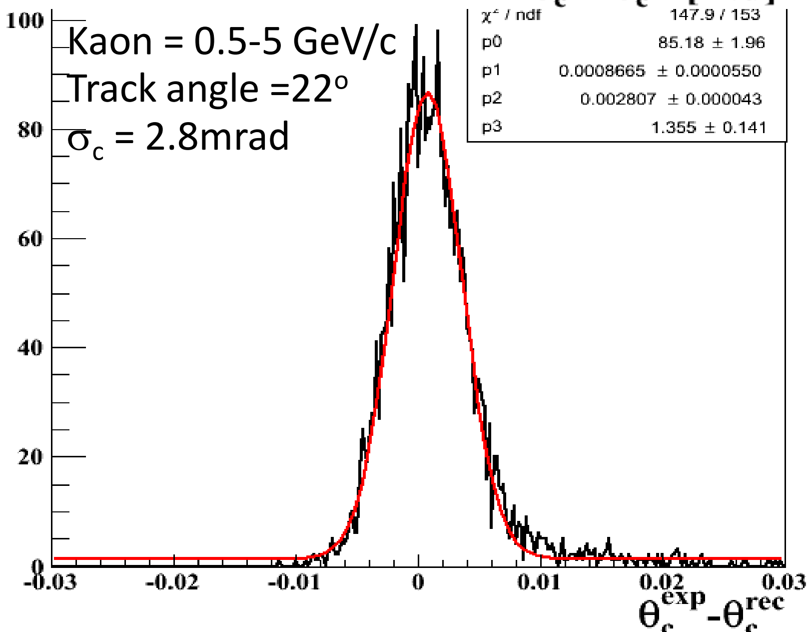
- After calculating the track θ_c we get the track resolution

- The track θ_c is used to test the particle (e, μ, π ,K, P and unknown) hypothesis.

- Selection is based of the required (1σ, 2σ, 3σ,..) separation and the confidence level of the separation

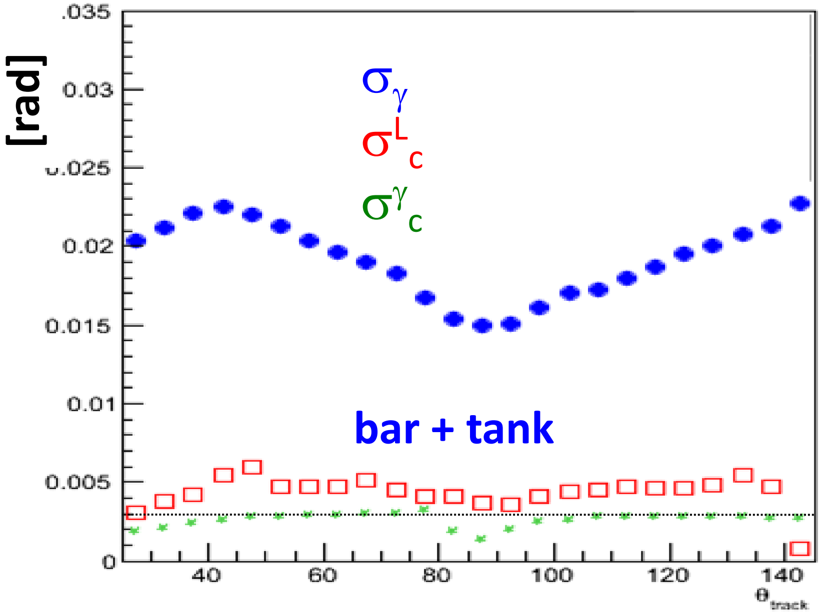
Track Resolution using Likelihood

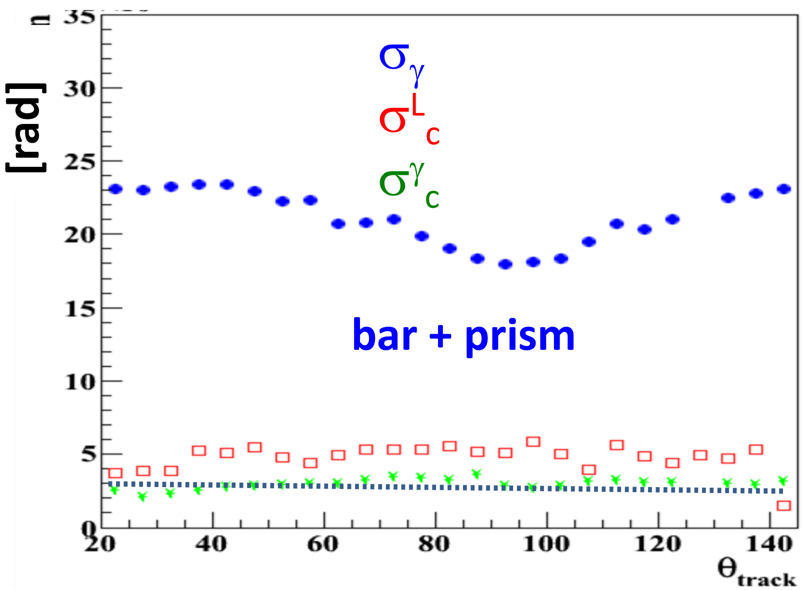




- The stringent resolution requirement is for the forward angles and higher momentums
- The track resolution (σ_{γ}^{L}) for a simplified **bar + tank** geometry for **22º, 3.5GeV/c kaon** tracks is ~2.2mrad. Overall track resolution in the momentum range of 0.5-5GeV/c is 2.8mrad.
- Focusing will further improve it to get the better separation between pions and kaons
- Loss of photon due to grese is not included

Simulation with bar + Tank, Prism (without lens)



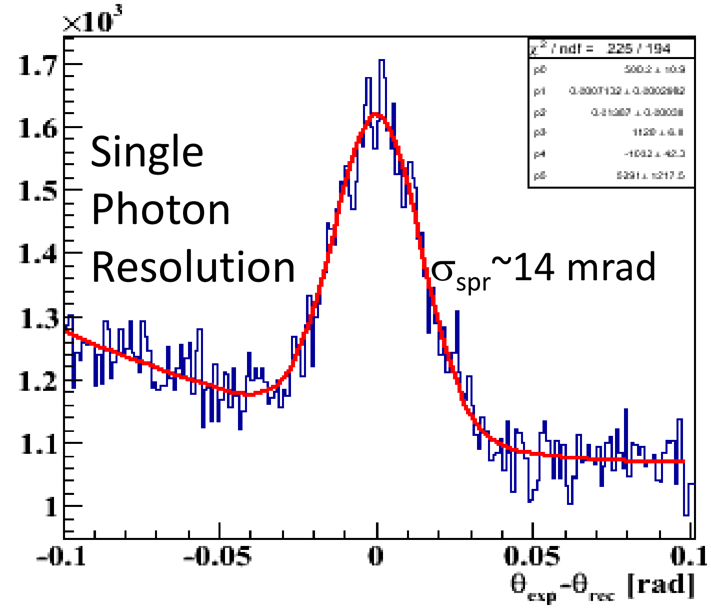


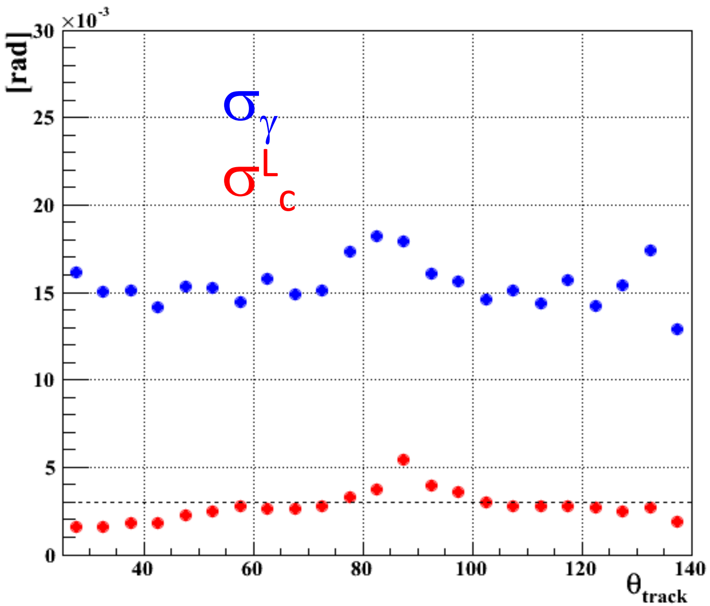
- Single photon resolution (σ_γ) for simplified **bar+tank** and **bar+prism** type geometry is polar angle dependent which is function of photon yield, ambiguity background and transmission of photons

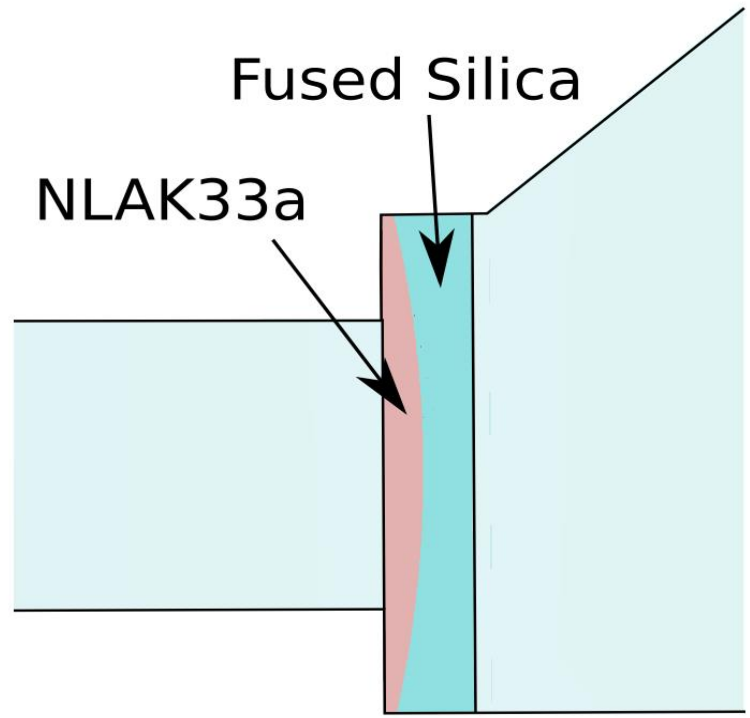
- The photon yield is higher for prism compared to oil tank but the ambiguity background reduces the track resolutions

- Track resolution calculated using maximum likelihood method is ~4mard
- The basic geometry without focusing system does not meet the required expectation of the PANDA Barrel DIRC

Simulation for Bar + Prism (cylindrical lens)



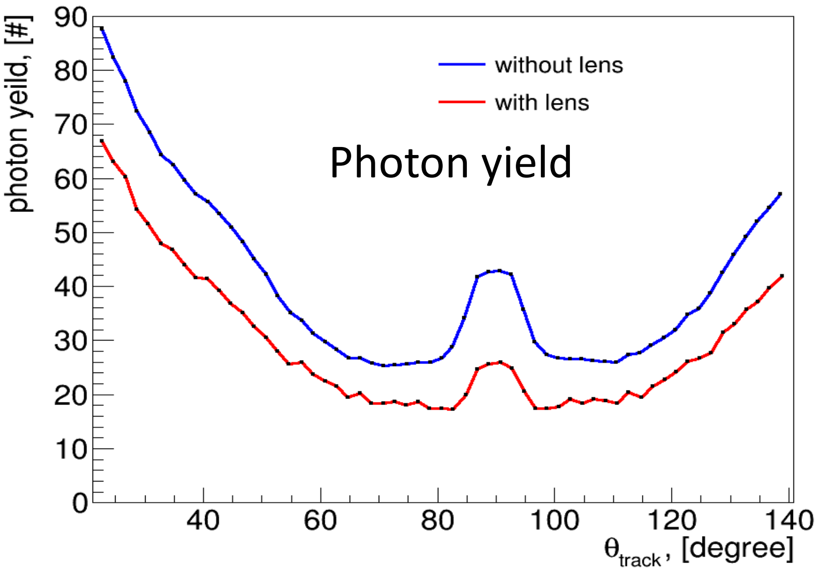


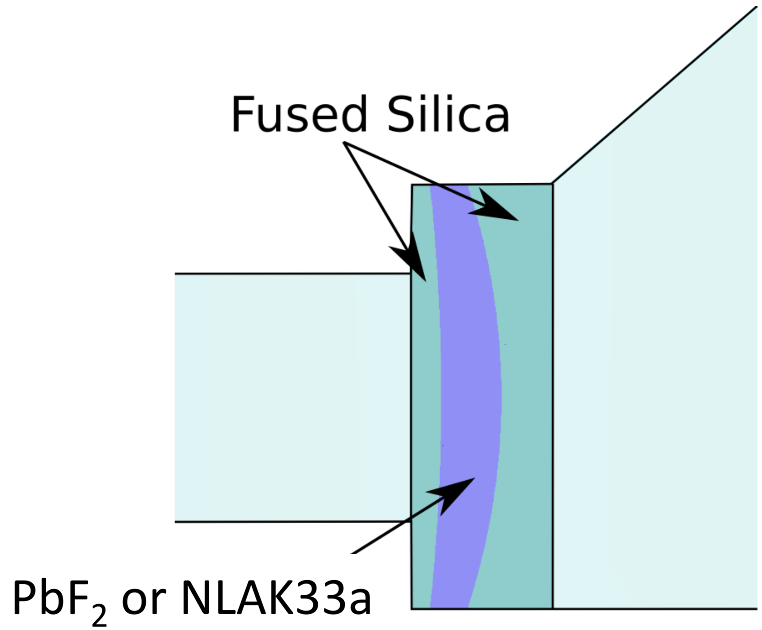


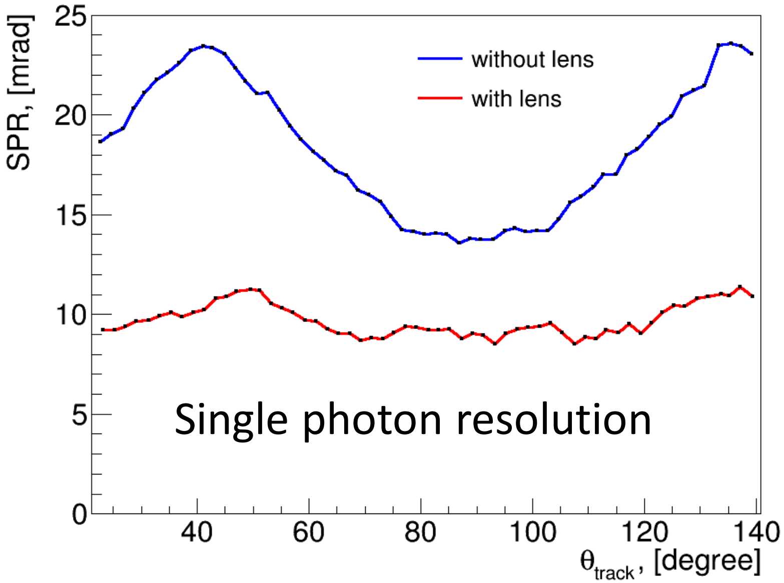
- **Cylindrical lens** improves the single photon resolution (σ_γ) and track resolution (σ_c)

- Track resolution σ^L_c using likelihood is ~2.4mrad

Simulation with Bar + Oil Tank (spherical lens)





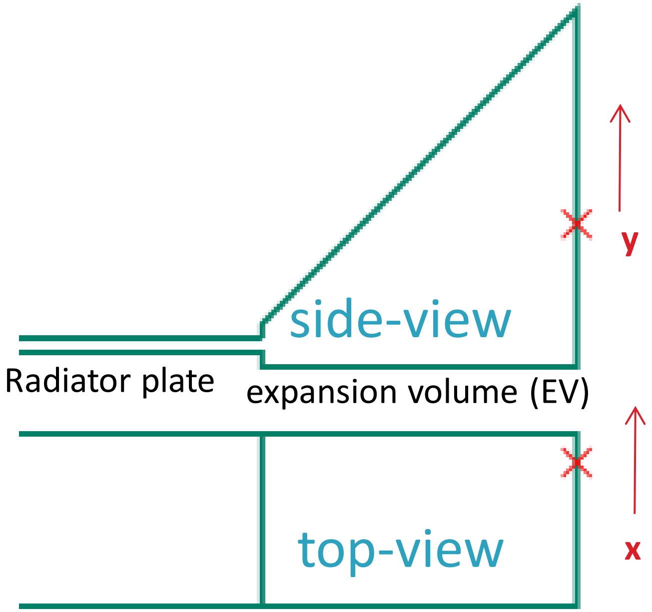


- Photon yield due to scattering in spherical lens decreases by 20-30%
- The single photon resolution (σ_γ) improves to ~10mrad.
- **Spherical lens** with bar type configuration would satisfy the PID requirement of PANDA Barrel DIRC
- Further detailed study is ongoing

Other Design Options: Bar → Plate

- We have studied the basic design options with the bar type geometry
  - The configuration without focusing may satisfy the PID requirement of the PANDA Barrel DIRC but with slightly reduced efficiency
    - Spherical as well as cylindrical focusing system along with basic designs would meet the PID requirements
      - The plate type geometry is an another alternative to be investigated which would lead to significant cost reduction

Reconstruction of the Plate type configuration

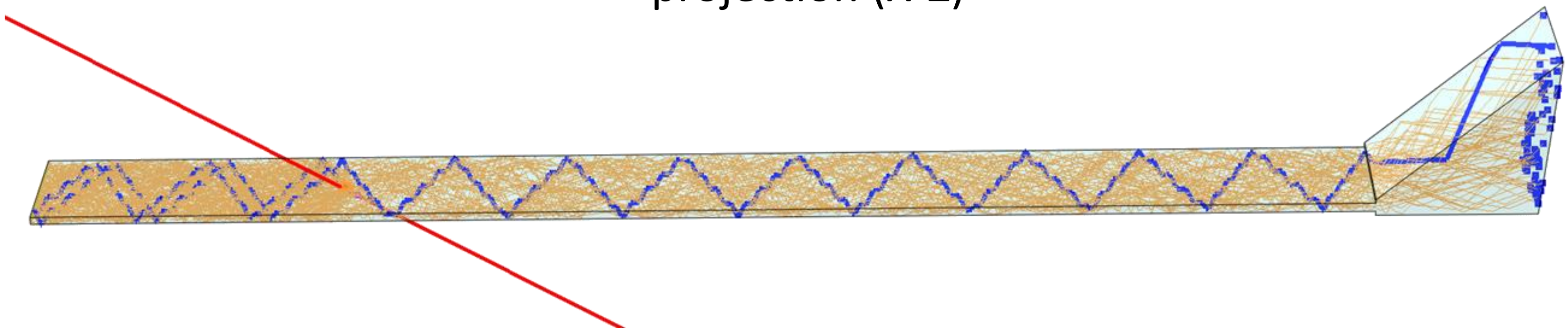


- **Bar type** reconstruction takes bar exit as **point source** and direction vectors are stored to reconstruct Cherenkov angle

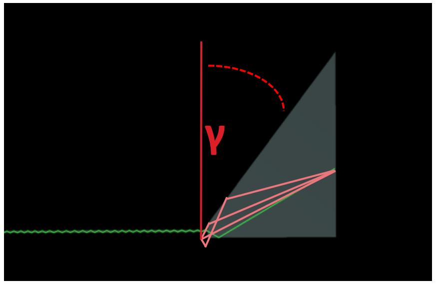
- In case of a wide **plate** a point source assumption is valid only in the 'side'-projection where **radiator thickness** is the same for bar and plate

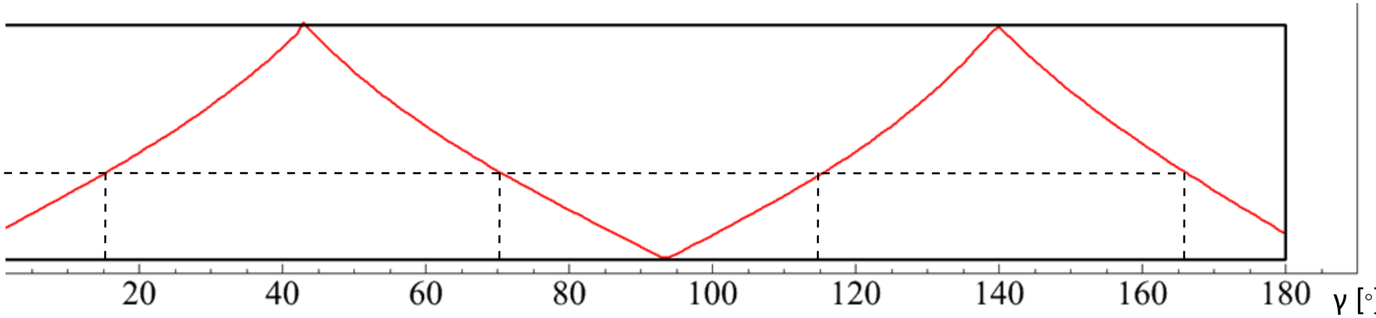
Factorized reconstruction:

- Use **look-up-table** for side-projection (Y-Z)
- **Fully** reconstruct propagation path in top-projection (X-Z)



Reconstruction – 'side'-projection (Y-Z)

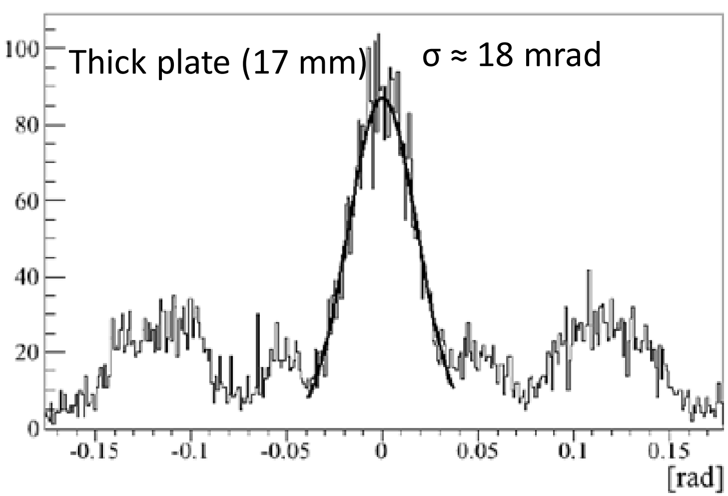


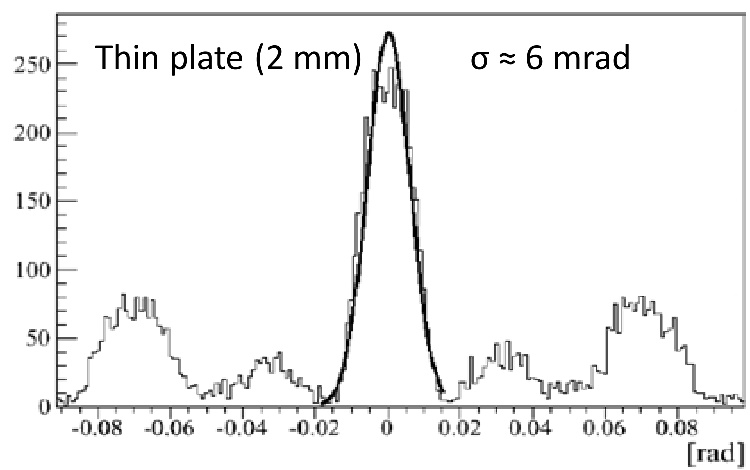


read out plane↑

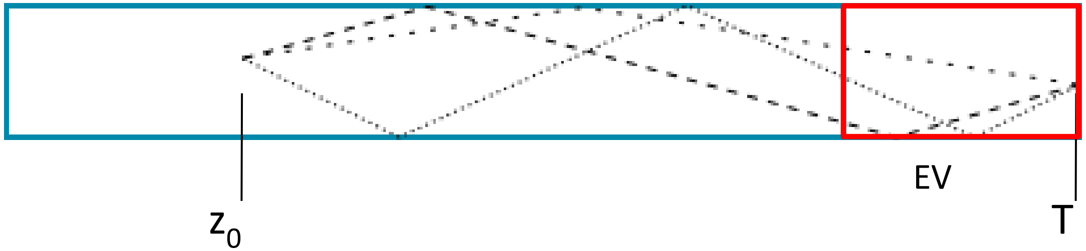
- The γ-angle resolution for side reflections is ~18mrad for 17 mm thick plate and ~6mrad for 2mm thin plate.

reconstructed angle - true MC angle





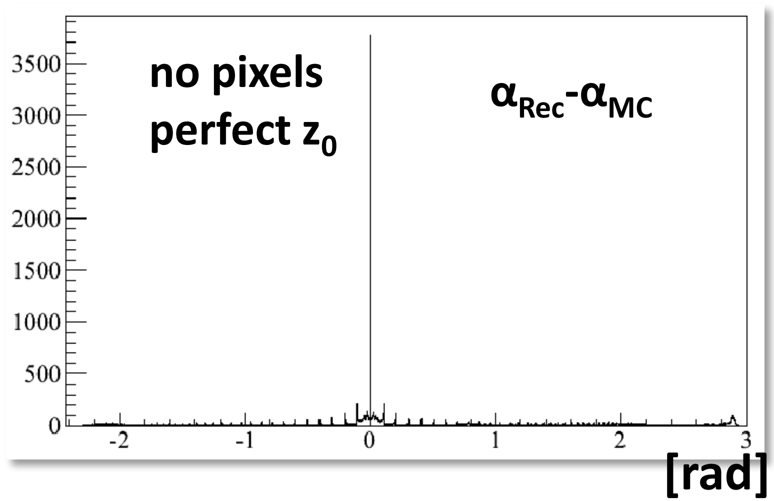
Reconstruction – ‘top’-projection (X-Z)

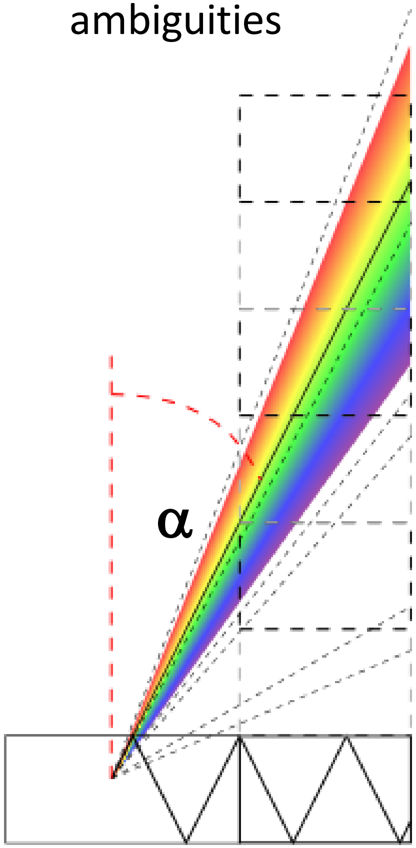


Possible paths in wavelength range are treated as ambiguities

z_0 = Hit position of the particle in the plate
T = Photon hit time
c_n = Group velocity of photons
γ = previously reconstructed angle

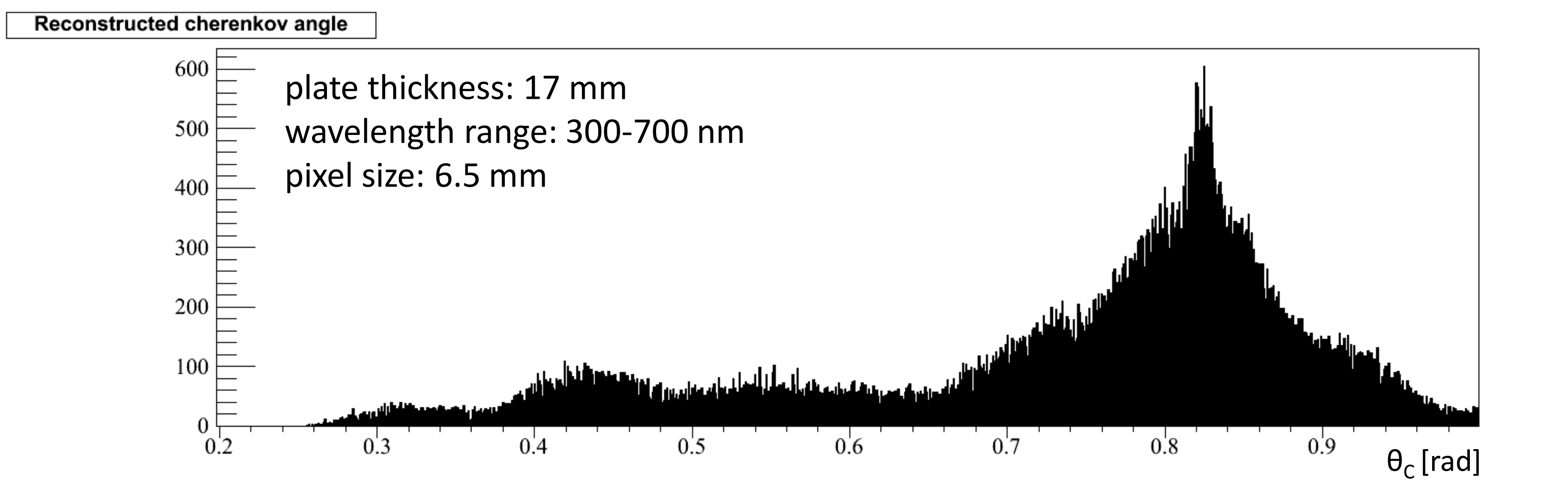
$$\alpha = \arcsin\left(\frac{z_0}{T \cdot c_n \cdot \sin\gamma}\right)$$





Geometrical Reconstruction - results

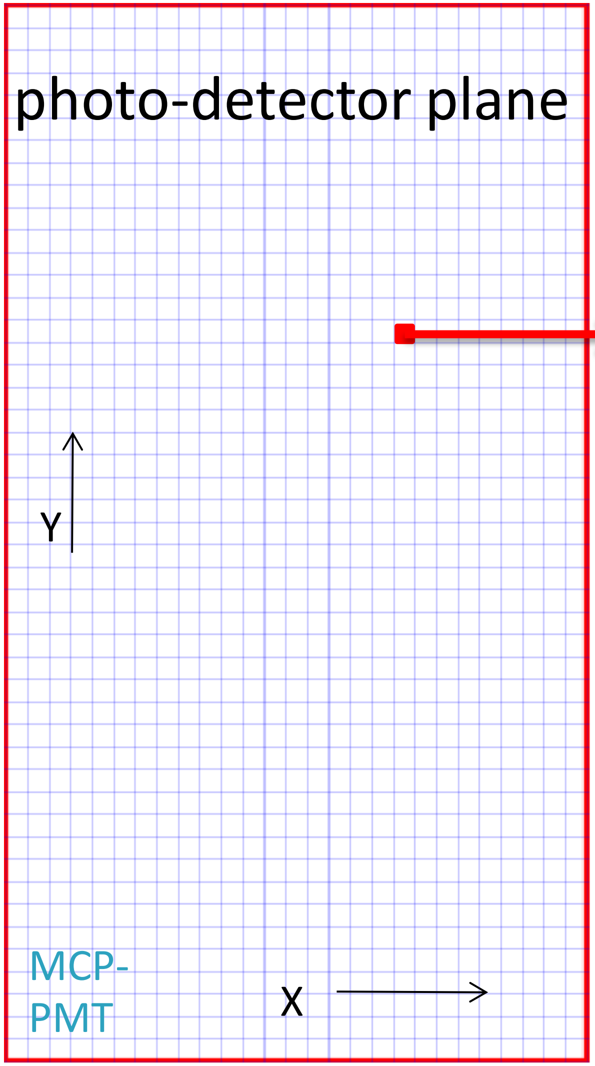
Muons, 35° θ_{Track}, 2 GeV/c

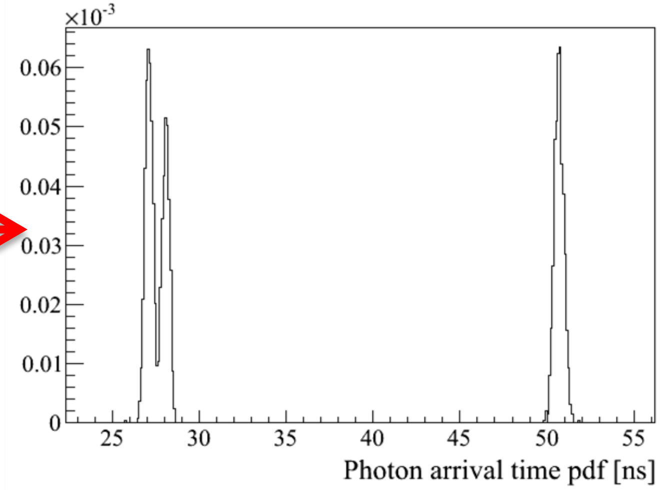


- Peak visible at the right position
- Large number of ambiguities gives a poor signal/background ratio
- Single photon Cherenkov angle resolution is difficult to interpret

Time Imaging of Cherenkov Photons

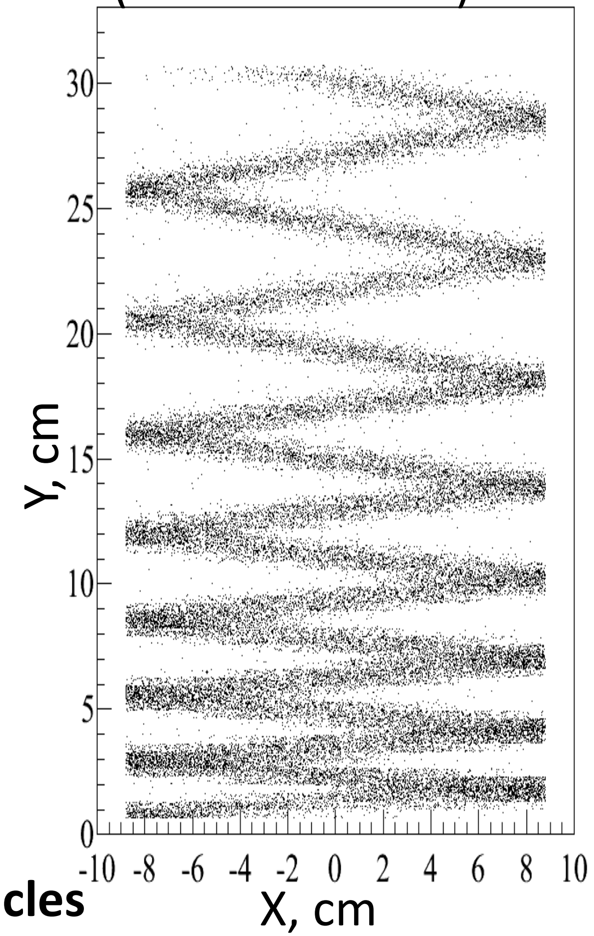
This approach is inspired by **BELLE II** collaboration





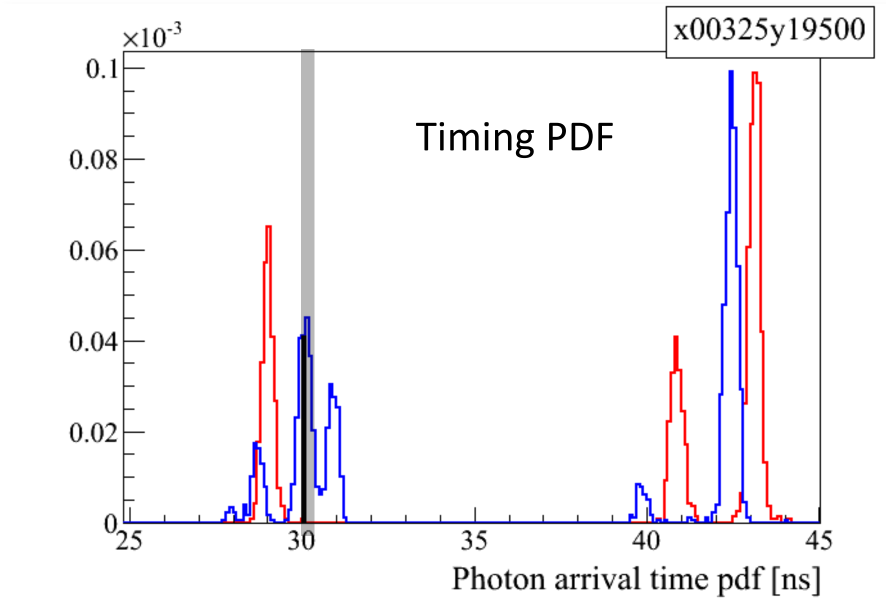
Probability Distribution of time for one pixel

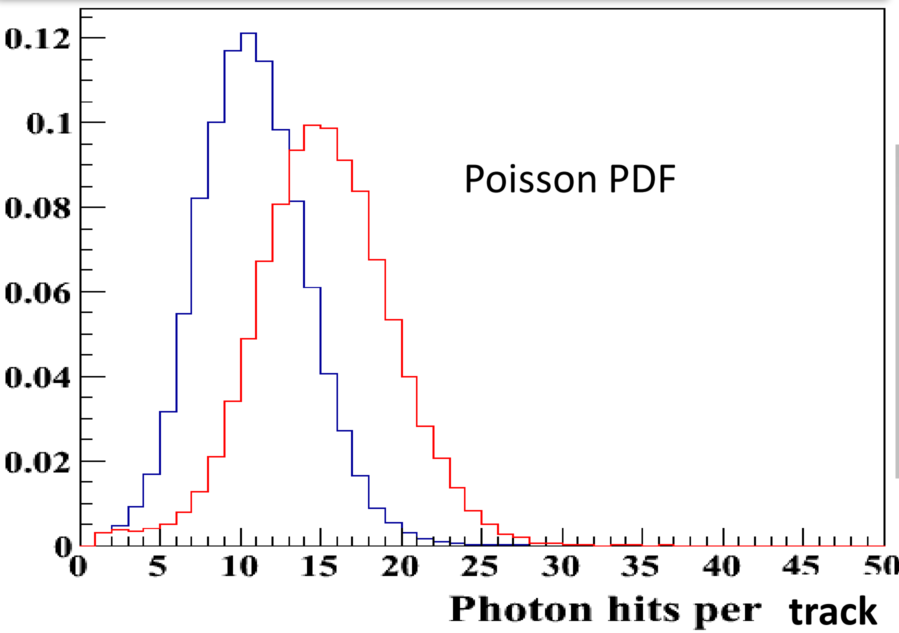
A 'typical' **hit pattern** in X-Y (with some cuts)



MC: 400 000 identical particles with identical event parameters

Time Based Likelihood Test





- Timing and Poissonion PDFs are calculated for each pixel and particle types
- Log likelihood values are added for a track to test different hypothesis

Blue: Kaon hypothesis
Red: Pion hypothesis

$$L_H = \prod_N pdf(x_i, y_i, t_i; H) \times P_{N_0}(N)$$

$$\log L_H = \sum_N \log[pdf(x_i, y_i, t_i; H)] + \log P_{N_0}(N)$$

Kaon and Pion Hypothesis Test

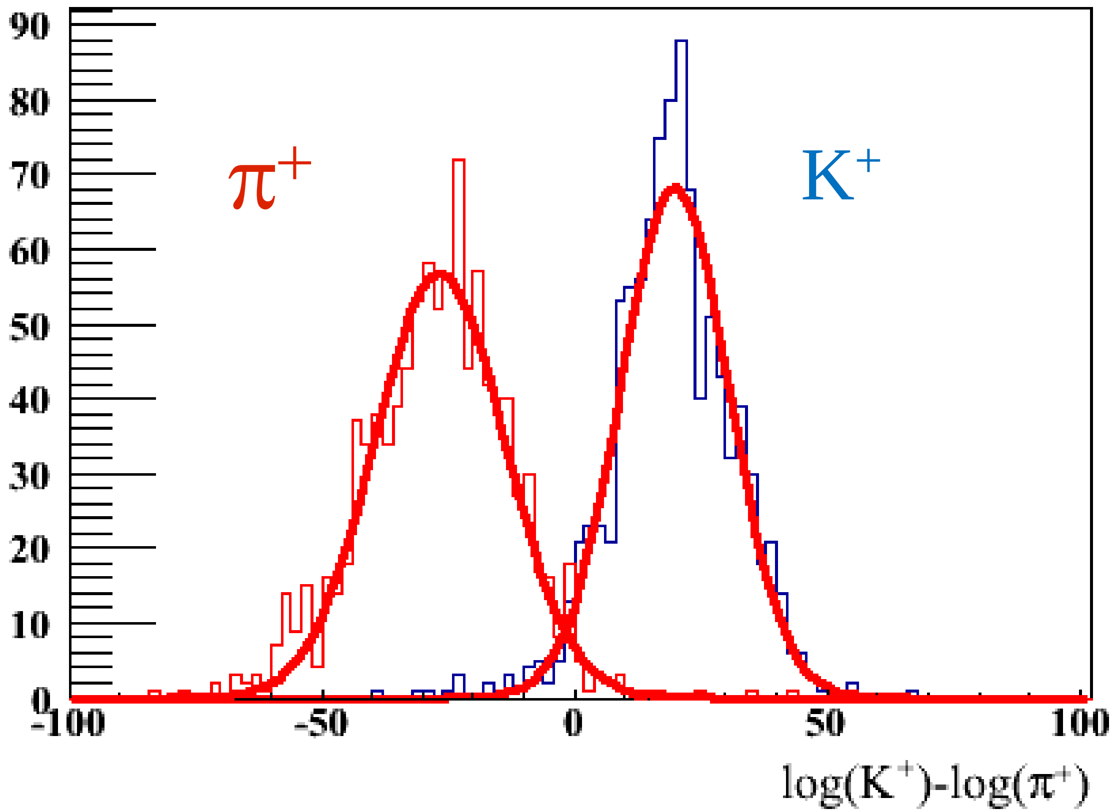
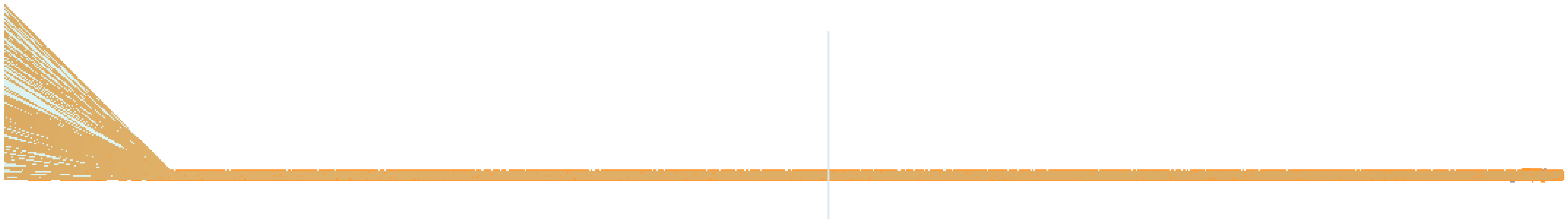


Plate thickness (17mm)
B-field
1000 (π^+, K^+) tested
3.5GeV/c, θ_{Track} = 22°

Kaon and Pion Hypothesis Test



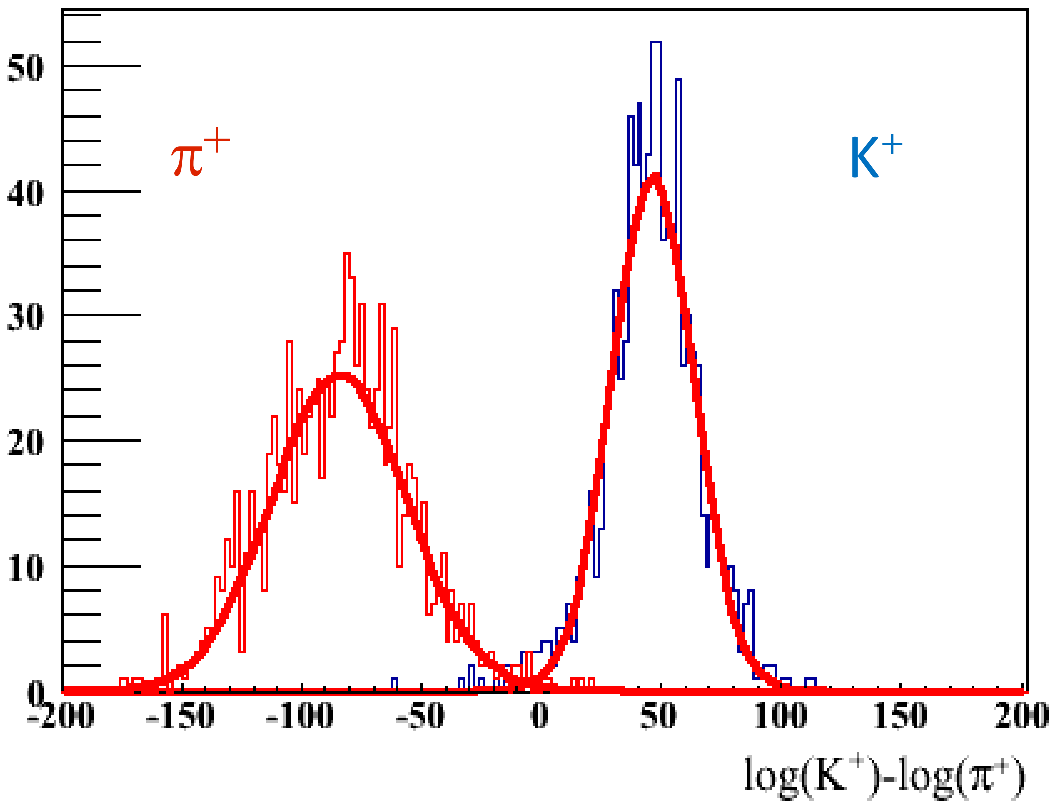


Plate thickness (17mm)
B-field
1000 (π^+, K^+) tested
1.0GeV/c, θ_{Track} = 90°

Kaon and Pion Hypothesis Test

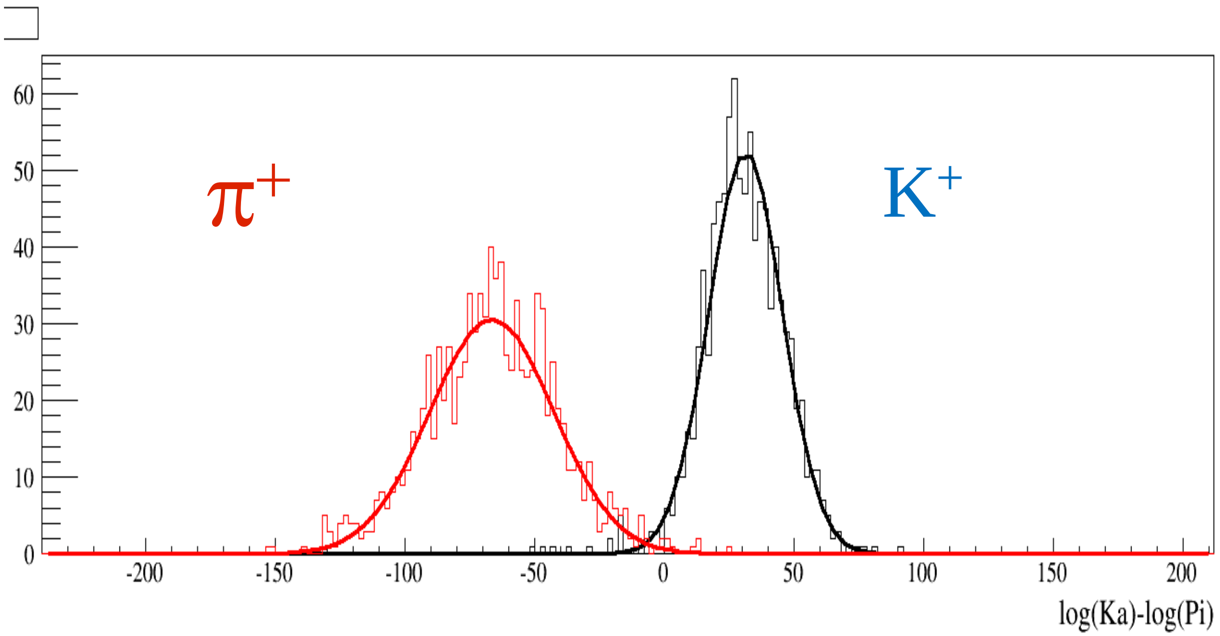


Plate thickness (17mm)
B-field
1000 (π^+, K^+) tested
1.0GeV/c, θ_{Track} = 70°

Summary and outlook

- Different design options with bar type geometry of the PANDA Barrel DIRC has been studied
- The single photon resolution and track Cherenkov resolution have been mapped in momentum and polar angle space
- Single photon resolution and track resolution using focusing system satisfy PANDA Barrel DIRC requirements.
- Plate type configuration with possibility of significant cost reduction shows promising results
- An analytical approach to calculate PDFs needs to be developed
- Focusing system with plate type geometry is to be studied
- Further detailed study along with tracking uncertainties will be carried out to test different hypothesis of an real physics event for all geometries

Thank you for your attention!