Endcap Disc DIRC for PANDA at FAIR

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on behalf of the PANDA Cherenkov Group

FAIR 2015 - Novosibirsk, Russia

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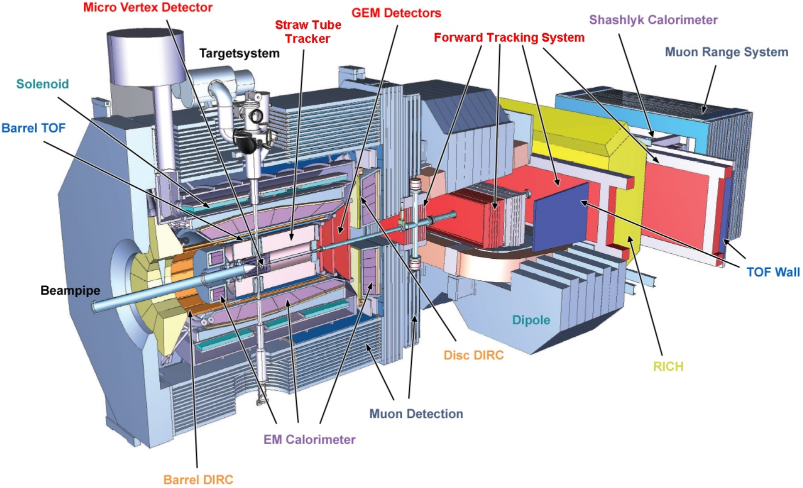
P̄ANDA Spectrometer



Source: <http://www-panda.gsi.de>

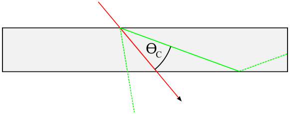
Cherenkov Light

Charged particles with speed higher than photon phase speed in medium emit Chrenkov light

Equation of polar angle θ_C for Cherenkov light cone:

$$\cos\theta_C = \frac{1}{n(\lambda)\beta}$$

Cherenkov Angle θ_C:



with $\beta = \sqrt{1 - 1/\gamma^2} = \sqrt{1 - E_0^2/E^2}$

Number of photons per track length according to Frank-Tamm-Formula:

$$\frac{dN}{dx} = 2\pi\alpha z^2 \int_{\lambda_1}^{\lambda_2} \left(\frac{1}{\lambda^2} - \frac{1}{n^2(\lambda)\beta^2\lambda^2} \right) d\lambda$$

$\alpha \approx 1/137$

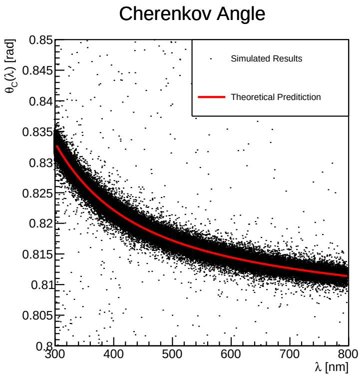
z: charge number of particle

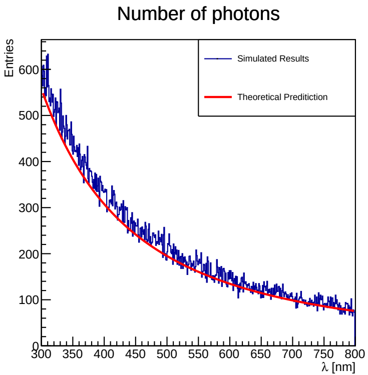
Refractive index n normally a function of wavelength λ (dispersion)

Photon Prediction

Theoretical prediction for 100 π^+ with momentum $p = 4\,\text{GeV/c}$ compared to simulated results with Geant4/PandaRoot

Material thickness: $\Delta x = 2\,\text{cm}$

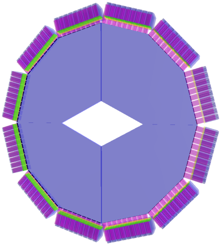




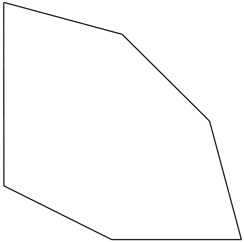
Average photon amount per event: $n = 1103$ for $\lambda = 300 \ldots 800\,\text{nm}$

Disc DIRC Detector

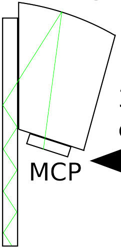
Complete Disc DIRC



4 Quadrants



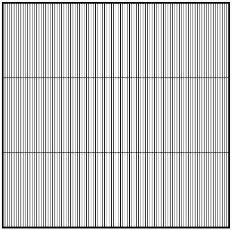
108 Focusing Elements



3 Focusing Elements combined to 1 ROM

1 MCP per ROM

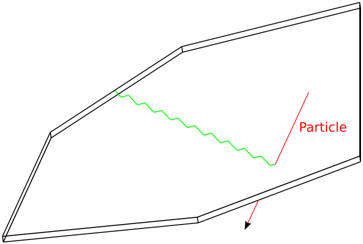
MCP Anode Segmentation

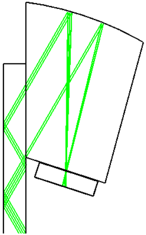


100 pixel per row

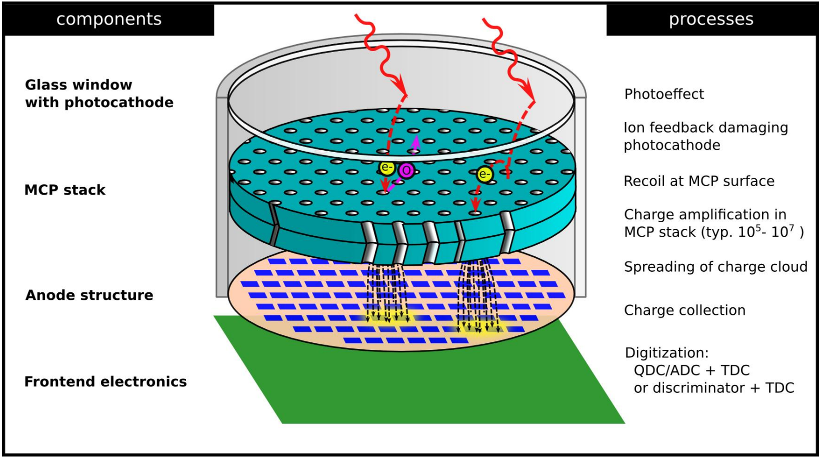
Radiator Disk and Focusing Element

- Internal reflection of light inside radiator disk
- Cylindrical mirror on backside of focusing element for light focusing on readout plane
- Parallel photons focused on one spot
- Photons with different angles focused on different points





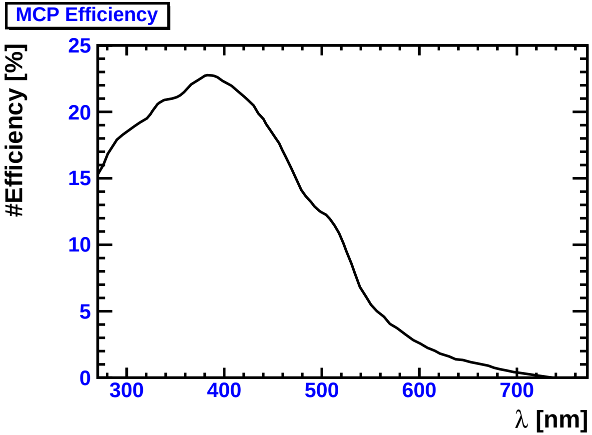
Microchannel Plate PMT



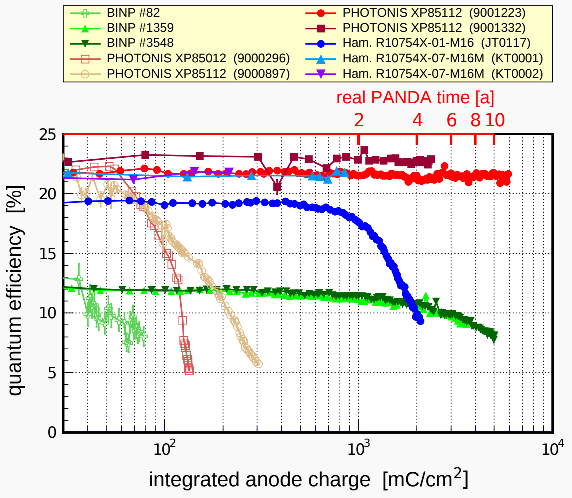
Source: Merle, Oliver: Development, design and optimization of a novel Endcap DIRC for PANDA, Phd Thesis, JLU Giessen, 2015

Quantum Efficiency

Collection efficiency approx. 30% (varying for different MCP-PMTs)



Product of quantum efficiency and collection efficiency equal to probability to detect photon (detection efficiency)



Source: Lehmann, A. et al.: Improved lifetime of microchannel-plate PMTs. Nucl. Instr. and Meth. A, (0):-, 2014.

127, 128, 129

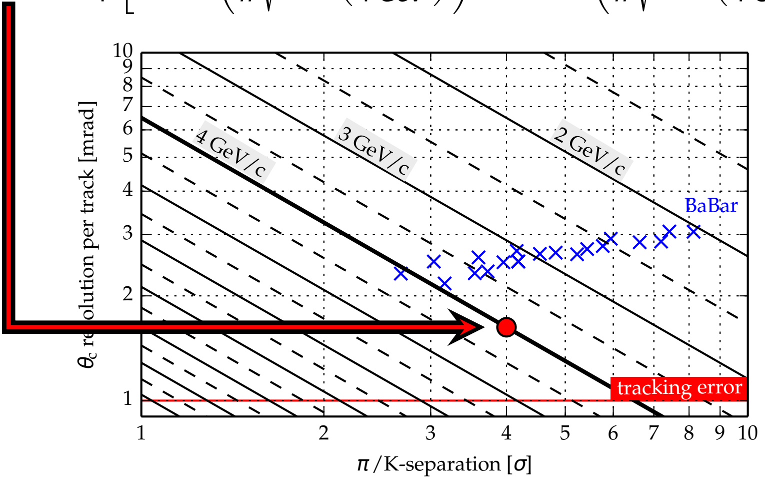
Detector Requirements

Separation power (π, K):	$\geq 4\sigma$
Momentum coverage:	$1.5 \dots 4\,\mathrm{GeV/c}$
Polar acceptance min/max:	$\theta_x = 10^\circ$, $\theta_y = 5^\circ$ $\theta_{x,y} = 22^\circ$
Detector lifetime:	$\geq$ 10 years in duty cycles of 6 m/y
Distance to intersection point:	$\approx 194\,\mathrm{cm}$ in front of EM calorimeter
Magnetic field:	$0.5 \dots 1.3\,\mathrm{T}$
Energy deposit in radiator:	$\approx 500\,\mathrm{Gy}$ for fused silica
Energy deposit in optics:	$\approx 10\,\mathrm{Gy}$ for fused silica
Charged hadron flux:	$\approx 100\,\mathrm{Hz/cm^2}$ ($E_{kin} > 10\,\mathrm{MeV}$)

Required Resolution

Calculation of required resolution for 4-σ-separation-power:

$$\sigma_{\theta_C} \leq \frac{1}{4} \cdot \left[\arccos\left(\frac{1}{n} \sqrt{1 + \left(\frac{m_\pi}{4\ GeV} \right)} \right) - \arccos\left(\frac{1}{n} \sqrt{1 + \left(\frac{m_K}{4\ GeV} \right)} \right) \right]$$



Effects on Photon Transport

- Photon trapping inside radiator due to internal reflection (approx. 70 % constant for $\theta > 10^\circ$)
- Chromatic dispersion influencing photon resolution and time of propagation:

$$t_{prop} = \frac{s}{v} = \frac{s}{c}\left(n - \lambda\frac{dn}{d\lambda}\right)$$

- Bulk losses of photons described by Beer-Lambert law:

$$I = I_0 \exp\left(\frac{x}{-\mu(\lambda)}\right)$$

- Fresnel and surface losses after N reflections due to surface roughness:

$$I = I_0 \cdot R^N \quad \text{with} \;\; R = 1 - (4\pi\cos\theta_i R_q n/\lambda)^2$$

- Losses in filter due to spin vector rotation in strong magnetic field (Faraday effect)

Choice of Material

Properties of chosen material:

- Large absorbtion length (less bulk losses)
- Small dispersion
- High radiation hardness

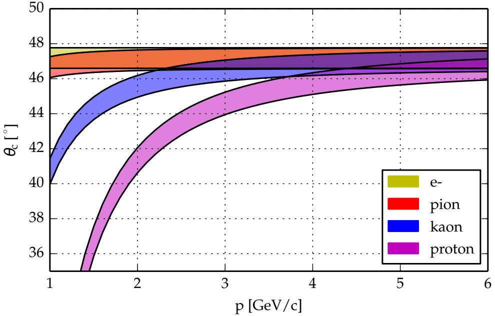
Reasons for using fused silica:

- Already tested at BaBar DIRC
- High transmission for small wavelength
- Well understood technology

Disadvantage: High production cost for polished radiator disk at large scale

Cherenkov Angle Distributions

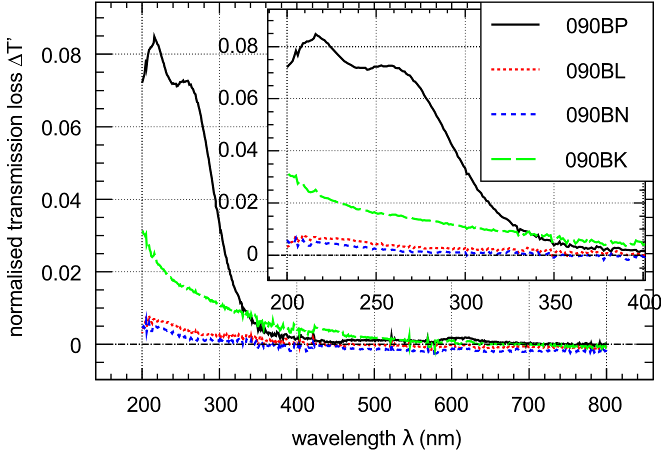
Cherenkov angle in fused silica:



Possible solutions for band width reduction:

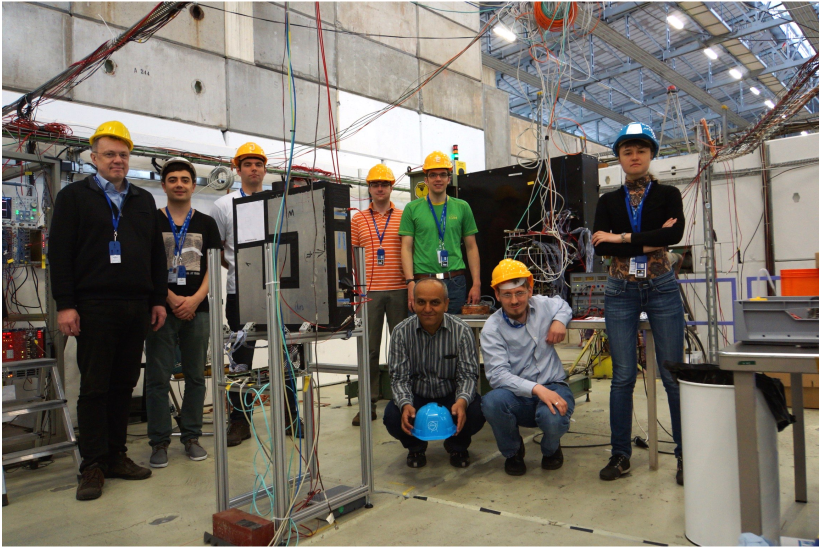
- Higher photon statistics
- Reduction of wavelength acceptance (optical filter)
- Correction of dispersion by achromatic optics
- Correction by means of photons time of flight

Transmission losses of fused silica after radiation with γ-dose of 100 krad:

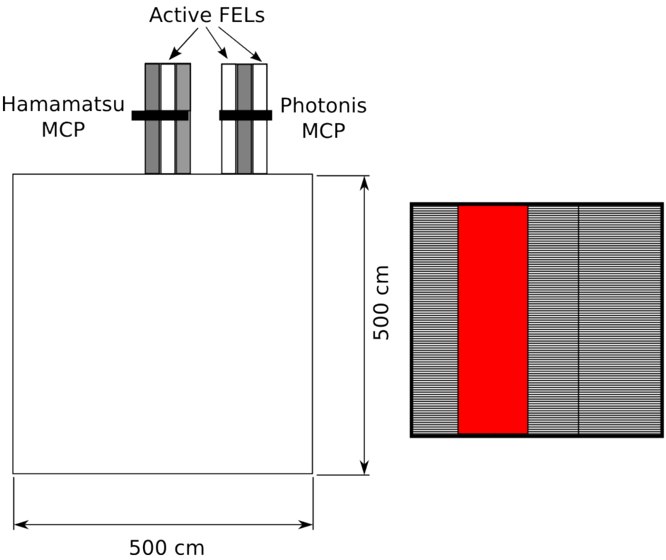


Source: Hoek, M.: Tailoring the radiation hard ness of fused silica. Nucl. Instr. and Meth. A, 639(1):227 – 230, 2011. 107

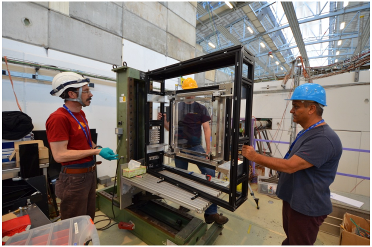
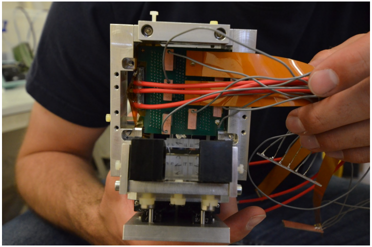
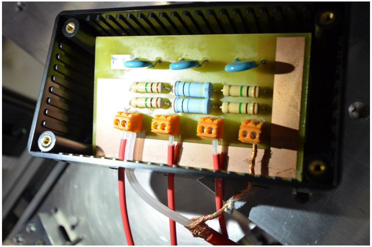
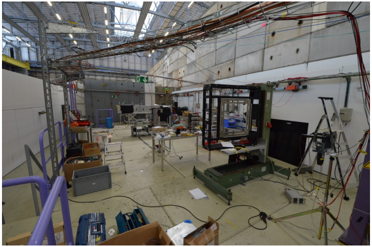
CERN Testbeam



CERN Testbeam



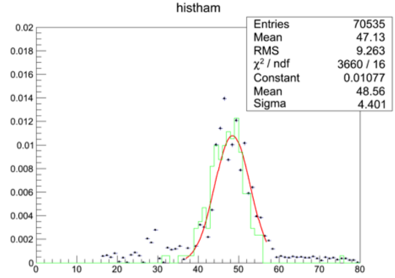
Testbeam at CERN in May 2015 with 3 FELs and 2 MCPs:

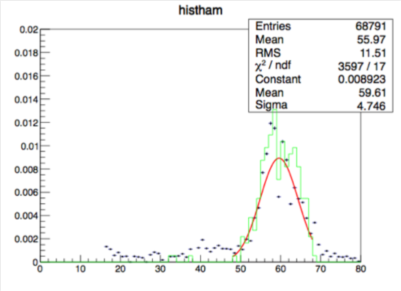
Testbeam Results

Pixel distribution with Monte-Carlo data (green) and testbeam measurements (black) for polar angles...

$\theta = 6^\circ$

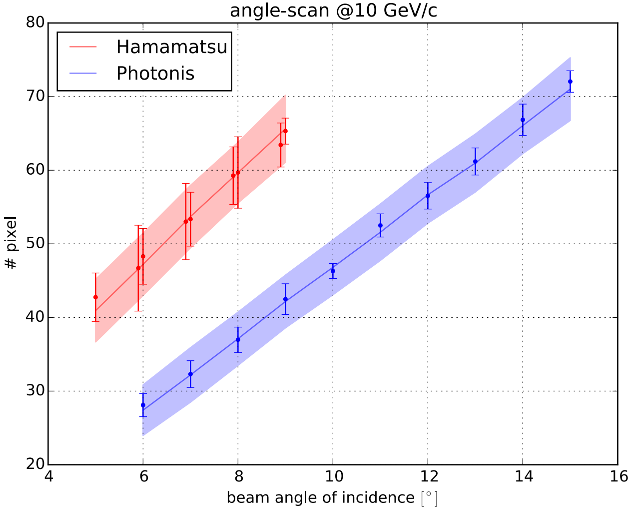


$\theta = 7^\circ$



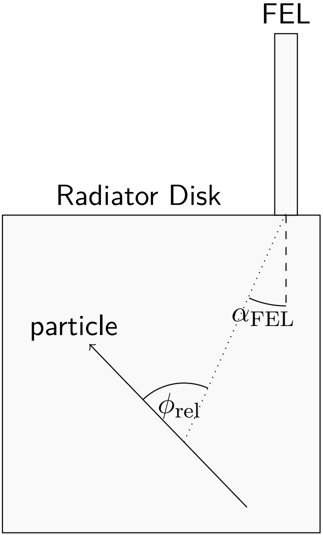
Source: Etzelmüller, Erik: DIRC 2015

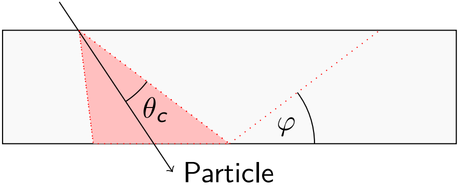
Testbeam Results



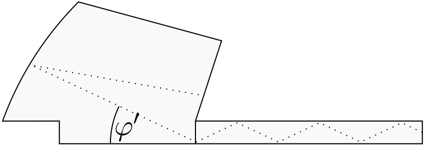
Source: Etzelmüller, Erik: DIRC 2015

Angle Definitions:





$$\tan\varphi' = \frac{\tan\varphi}{\tan\alpha_{FEL}}$$



Disc DIRC Model

Calculation of the Cherenkov angle:

$$\theta_c = \arccos(\sin\theta_p \cos\phi_{rel} \cos\varphi + \cos\theta_p \sin\varphi) \tag{1}$$

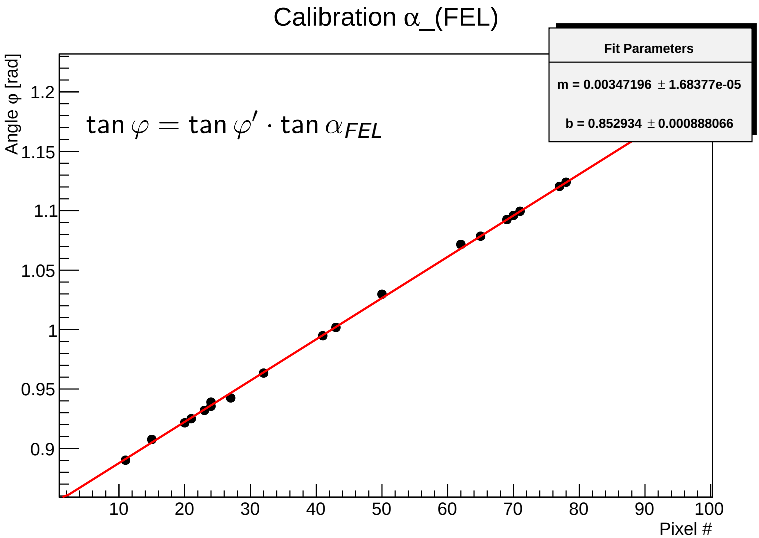
- θ_p: θ angle of particle
- ϕ_{rel}: angular difference between ϕ angle of particle and photon
- φ: Angle between total reflected photon and radiator disk surface

Calculation of φ if θ_c is known:

$$\cos\varphi = \frac{A\cos\theta_c}{B} \pm \sqrt{\frac{\cos^2\theta_p - \cos^2\theta_c}{B} + \left(\frac{A\cos\theta_c}{B}\right)} \tag{2}$$

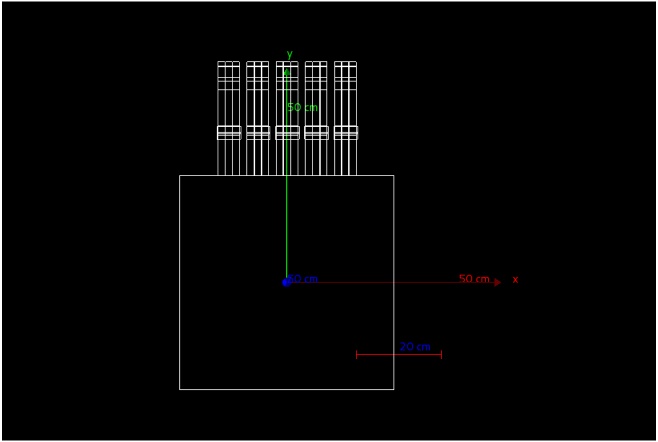
with $A = \sin\theta_p \cos\phi_{\mathrm{rel}}$ and $B = A^2 + \cos^2\theta_p$

Correlation between pixel number and angle φ':



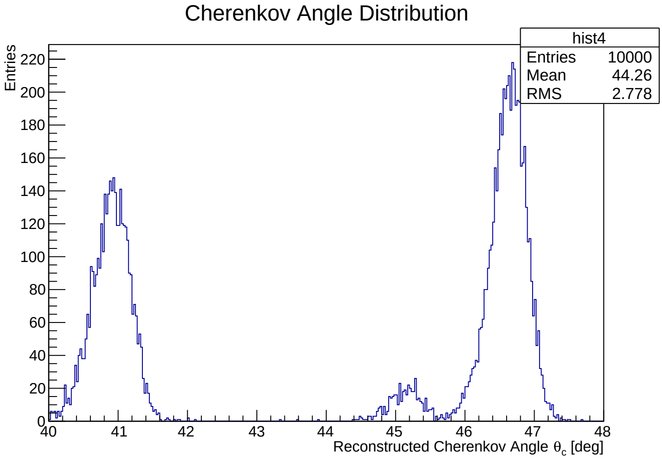
Future Disc DIRC Prototype

Test simulations with new Disc DIRC prototype in Geant4:



Reconstruction of Cherenkov Angles

Testbeam simulations with 55% π^+, 30% p, 5% K
Beam momentum: $p = 2\,\mathrm{GeV/c}$ (diameter: $2\,\mathrm{cm}$ uniform)



Reconstruction results without removing outliers

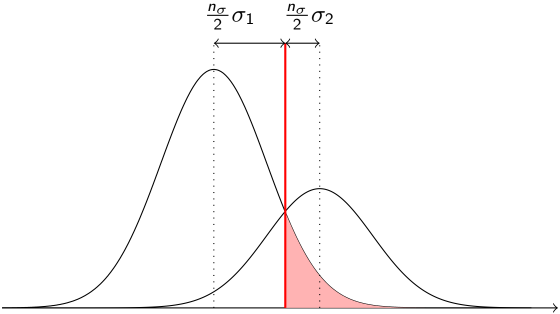
Separation Power

Calculation of separation power for $p = 3\,\mathrm{GeV/c}$:

$$n_\sigma = \frac{\bar{\theta}_{c,\pi} - \bar{\theta}_{c,k}}{\frac{1}{2}(\sigma_{\bar{\theta}_{c,\pi}} + \sigma_{\bar{\theta}_{c,k}})} = 2.9$$

Probability for misidentification:

$$P_{\mathrm{misid}}(n_\sigma) = \frac{1}{2}\left[1 - \mathrm{erf}\left(\frac{n_\sigma}{2\cdot\sqrt{2}}\right)\right] = 7.1\,\%$$



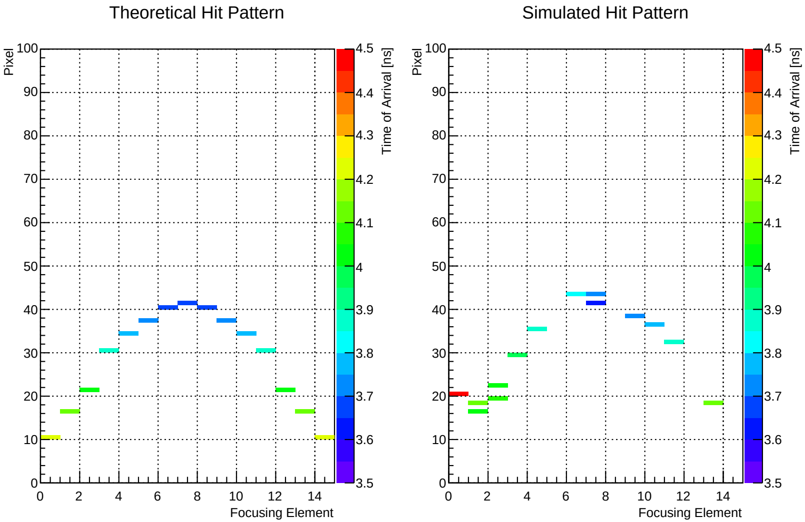
Reconstruction & PID Algorithm

- Input parameters:
  - Particle momentum vector $\vec{p}$
  - Particle angle and position (θ_p, ϕ_p, x, y)
  - Hit pattern $(z_i, t_i, \text{sensor id})$
  - Mass hypotheses (m_π, m_K, m_p)
- Calculation of all possible photon paths
- Computation of theoretical hit pattern and time of propagation
- Removing unwanted bhits with $|z - z_{pred}| < z_{thresh}$
- Matching of arrival times and removing of outliers: $|t - t_{pred}| < t_{thres}$
- Assuming gaussian probability density function and calculating pseudo likelihood function for each hypothesis:

$$\ln \mathcal{L} = \sum_{i=0}^{N} [\ln \mathcal{L}(z_i | z_{pred,i}; \sigma_z) + \ln \mathcal{L}(t_i | t_{pred,i}; \sigma_t)]$$

Example for Hit Pattern Prediction

Particle: π^+, momentum $p = 4\,\mathrm{GeV/c}$, polar angle $\theta = 10^\circ$, azimuth angle $\phi = 0^\circ$

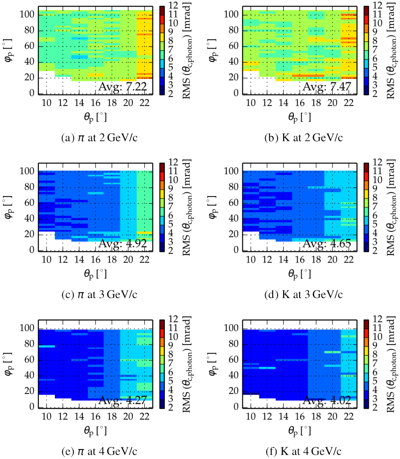


Simulation Parameters for Performance Study

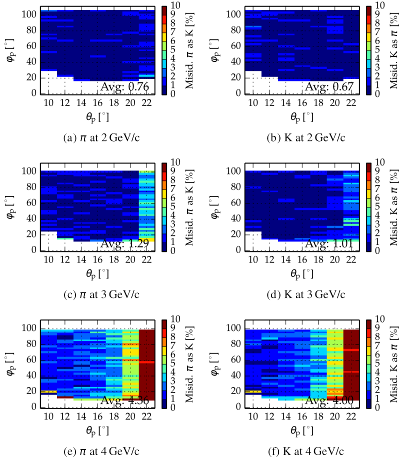
Simulation parameters for final detector with TOFPET readout system:

- Material: Fused silica (definition of refractive index, absorption length and reyleigh length)
- Mirror coating
  - Type: Dielectric metal
  - Gaussian scatter angle: 0.6 mrad
  - Reflectivity: 85%
- Time resolution (RMS): 21 ps
- TDC binning (LSB): 50 ps
- Pixel line height: 0.5 mm
- Surface roughness: 1.0 nm
- Track position error $\sigma_{x,y}$: 1.0 mm
- Track angular error σ_{θ_p,ϕ_p} : 1 mrad

RMS values



Misidentificaion for π and K



Source: Merle, Oliver: Development, design and optimization of a novel Endcap DIRC for PANDA, Phd Thesis, JLU Giessen, 2015

Summary & Outlook

- Full simulation (Geant4/PandaRoot), reconstruction and PID algorithm available
- Disc DIRC prototype with 15 FELs development in progress
- Possibilities for testing in cosmics test stand at University of Giessen and test beam facilities (DESY, Jülich, CERN etc.)
- Influences of magnetic fields have to be studied further
- Photon yields of simulation and measurement must be analyzed

Thank you very much for your attention!