Particle Identification PID
PID detector concepts

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$\bar{\text{P}}$ANDA Spectrometer

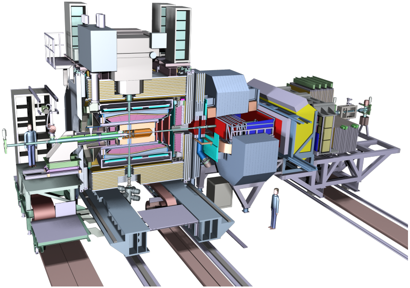
FAIR

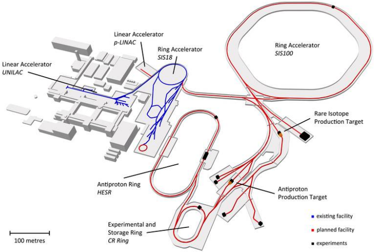
- Antiprotons $\bar{p}$ from HESR
- High luminosity mode:

$$\mathcal{L} = 2 \cdot 10^{32}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$$

- Average interaction rate:

$$\dot{N} = 2 \cdot 10^{7}\,\mathrm{s}^{-1}$$



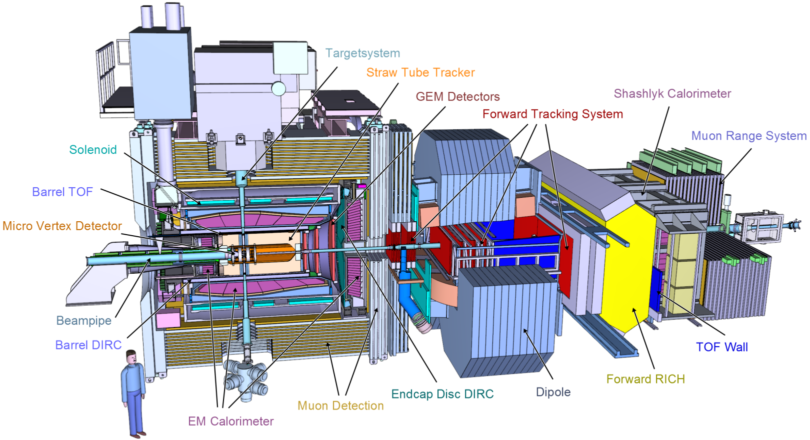


PANDA

- $p\bar{p}$ collisions with hydrogen target
- Created particles with forward boost in z-direction
- Excellent PID necessary to fulfill physics program goals

PANDA

PANDA (Antiproton Annihilation at Darmstadt) for studying collisions between antiprotons and fixed proton target



PANDA Physics Program

Nucleon Structure

- Generalized parton distributions
- Drell Yan process
- Time-like form factors

Hadron Spectroscopy

- Production of exotic QCD states
- Understanding new XYZ states
- Investigation of charm hadrons
- Production of states with all quantum numbers

Nuclear Physics

- Hypernuclear physics
- Hadrons in nuclei

PID Channels

Physics Case	Signal Channel	Background Channel	Final State	$\sigma \cdot \mathcal{BR}$ (estimate)	s/bg ratio	PID challenge
Charmonium	$Y(4260) \to J/\psi 2\pi^{\pm}$		$2e^{\pm}2\pi^{\pm}$	60 pb		e/π
Spectroscopy		$2\pi^+2\pi^-$	$4\pi^{\pm}$	46 μb	$1 \cdot 10^{-6}$	sep.
	$Y(4260) \to J/\psi 2\pi^0$		$e^+e^-4\gamma$	30 pb		e/π
		$\pi^+\pi^-2\pi^0$	$2\pi^{\pm}4\gamma$	50 μb	$6 \cdot 10^{-7}$	sep.
	$X(3872) \to J/\psi\eta$		$e^+e^-2\gamma$	20 pb		e/π
		$\pi^+\pi^-\pi^0$	$2\pi^{\pm}2\gamma$	290 μb	$7 \cdot 10^{-8}$	sep.
	$\chi_c \to J/\psi\gamma$		$e^+e^-\gamma$	0.8 nb		e/π
		$\pi^+\pi^-\pi^0$	$2\pi^{\pm}2\gamma$	0.29 mb	$2 \cdot 10^{-6}$	sep.
	$h_c \to \eta_c\gamma \to 2\Phi\gamma$		$4K^{\pm}\gamma$	20 pb		p/K/π
		$\Delta^{++}\Delta^{--}\pi^0$	$\bar{p}p2\pi^{\pm}2\gamma$	530 μb	$4 \cdot 10^{-8}$	sep.
		$4\pi^{\pm}\pi^0$	$4\pi^{\pm}2\gamma$	750 μb	$3 \cdot 10^{-8}$	
	$\psi(3770)$		$2K^{\pm}\ 4\pi^{\pm}$	14 pb		K/π
		$\bar{p}p \to X$	X	60 mb	$2 \cdot 10^{-10}$	sep.
	$\psi(4040) \to D^*\bar{D}^*$		$2K^{\pm}\ 4\pi^{\pm}$	0.46 pb		K/π
		$\bar{p}p \to X$	X	60 mb	$1 \cdot 10^{-11}$	sep.
Exotics	$\eta_{c1}\eta \to DD^*\eta$		$2K^{\pm}2\pi^{\pm}8\gamma$	0.06 pb		K/π
		$\bar{p}p \to X$	X	50 mb	$1 \cdot 10^{-12}$	sep.
	$\xi(2230) \to 2\Phi$		$4K^{\pm}$	3 nb		K/π
		$\bar{p}p \to X$	X	60 mb	$5 \cdot 10^{-8}$	sep.
Baryon	$\Xi^+\Xi^-$		$\bar{p}p4\pi^{\pm}$	1 μb		
Production		$\bar{p}p \to X$	X	60 mb	$2 \cdot 10^{-5}$	
Electromagn.	$\bar{p}p \to e^+e^-$ [a]		e^+e^-			e/π
Formfactors		$\bar{p}p \to \pi^+\pi^-$	$\pi^+\pi^-$		$2 \cdot 10^{-6}$	sep.
Drell-Yan	$\bar{p}p \to \mu^+\mu^-X$		$\mu^+\mu^-X$			μ/π
Process		$\bar{p}p \to X$	X	60 mb	?	sep.
Hadrons in	$\bar{p}\,^{40}Ca \to J/\psi X$		e^+e^-X	0.3 nb		e/π
Nuclear Medium		$\bar{p}\,^{40}Ca \to X$	X	1 b	$3 \cdot 10^{-10}$	sep.

PANDA PID Subsystems

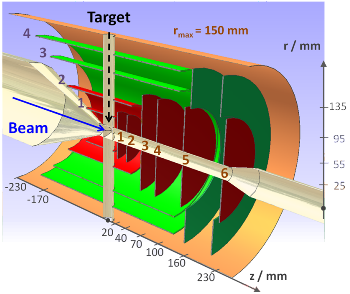
PID Subsystems in target spectrometer of PANDA

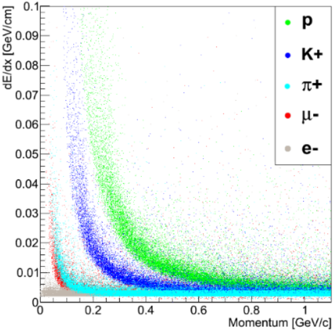
- Micro Vertex Detector (MVD)
- Straw Tube Tracker
- Barrel Time of Flight
- Barrel DIRC
- Disc DIRC
- Electromagnetic Calorimeter
- Muon counters

Redundancy in the forward spectrometer

Micro Vertex Detector (MVD)

- Micro Vertex Detector (MVD) inner most detector
- Closest to primary interaction vertices
- 4 barrels around IP
- 6 disks in forward direction
- Inner layers: hybrid pixels ($100\,\mu$m $\times$ $100\,\mu$m)
- Outer layers: double sided pixels
- Time resolution: 6 ns
- Pixel resolution: 28 μm
- Strip resolution: 14 μm
- Vertex resolution: 50 μm
- PID using energy loss



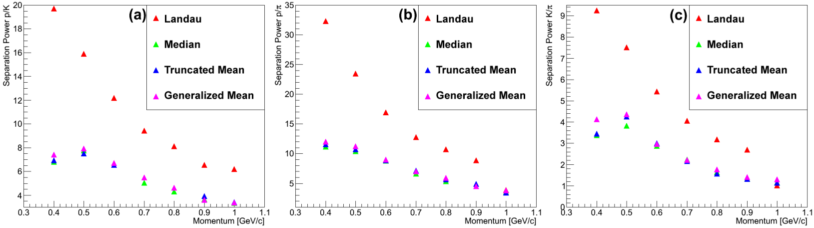


Micro Vertex Detector

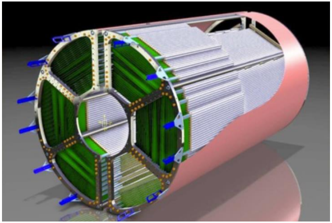
- Good PID performance especially for low particle momenta (below MIP) because of the steep falling of Bethe-Bloch
- Possibility to estimate dE/dx via energy loss ΔE per layer and Δx layer thickness:

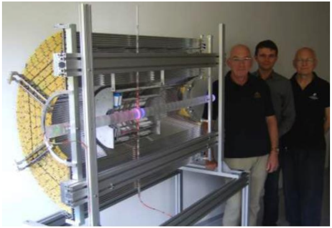
$$\frac{\Delta E}{\Delta x} = \frac{\sum_{k=1}^{N} E_k}{\sum_{k=1}^{N} x_k}$$

with N being number of hits per track



Straw Tube Tracker (STT)

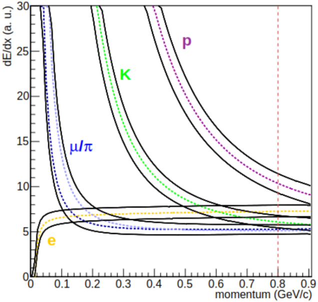


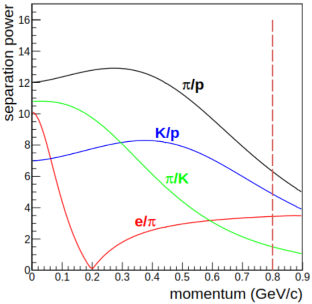


- Cylindrical shape around MVD
- 4,200 Al-mylar drift tubes filled with Ar/CO_2 in 21 – 27 layer
- 8 layers skewed by 3°
- Avalanche gain: approx. 100
- Inner radius: 15 cm
- Outer radius: 42 cm
- Tube diameter: 10 mm
- Tube length: 150 cm
- ϱ/ϕ plane resolution: 150 μm
- z resolution: 1 mm

Straw Tube Tracker

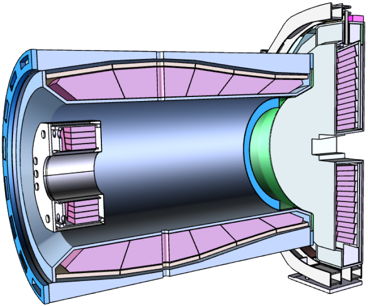
- Good PID for particles below 1 GeV/c momentum
- Approx. 25 measurements of energy loss per layer
- Simulated, digitized, and reconstructed in PandaROOT
- Simulations helped to optimize PID for different gas mixing ratios and pressures (pressure largest influence)





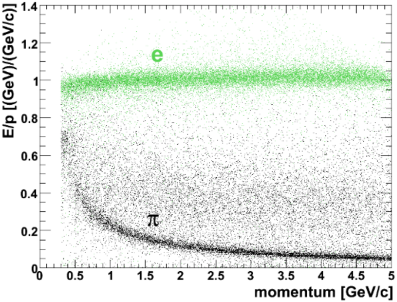
Electromagnetic Calorimeter (EMC)

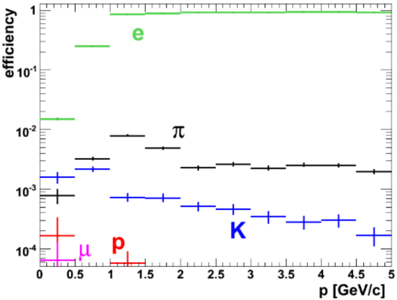
- 2[nd] generation $PbWO_4$ crystals (improved photon yield and radiation hardness)
- In total 15744 crystals
- Operation temperature: $(-25 \pm 0.1)^\circ$C (4x photon yield)
- Radiation length: 0.9 cm
- Molière radius: 2.1 cm
- Typical crystal dimensions: $20\,\text{cm} \times 2.5\,\text{cm} \times 2.5\,\text{cm}$
- Time resolution: $\leq 1\,\text{ns}$ ($\geq 100\,\text{MeV}$)
- Energy resolution: $1\% \oplus 2\%/\sqrt{E[\text{GeV}]}$
- Spatial resolution $\leq 1.5\,\text{mm}$
- 75% of crystals in phase 1



Electromagnetic Calorimeter (EMC)

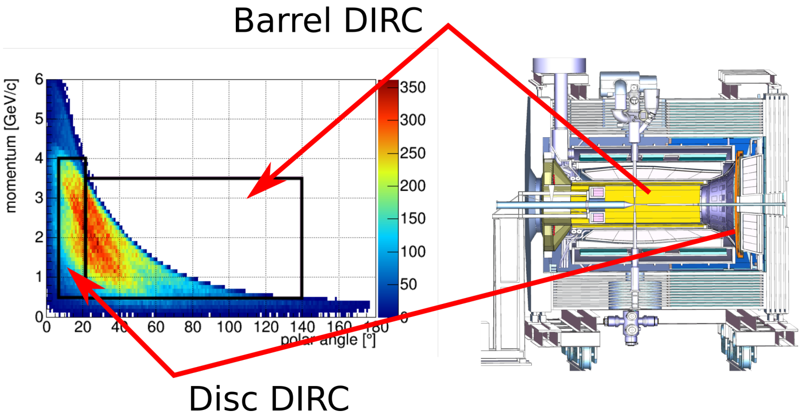
- Ratio of deposited energy to reconstructed momentum E/p almost unity
- Hadronic interactions can lead to a higher energy deposition
- Shower shape (smaller for electrons, larger for hadrons) additional important for PID





Cherenkov Detectors in PANDA

- Two DIRC (Detection of Internally Reflected Cherenkov Light) in PANDA: Barrel & Disc DIRC
- Goal: $\pi^{\pm}/K^{\pm}$ separation (covering full phase space)



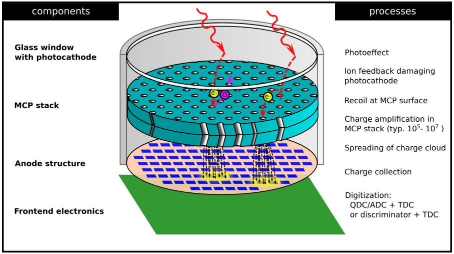
Example: Benchmark channel $J/\psi \to K^+K^-\gamma$

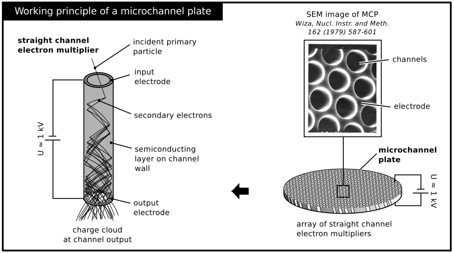
Detector Requirements

Separation power (π, K):	$\geq 4\sigma$
Momentum coverage:	$1.5 \ldots 4\,\mathrm{GeV/c}$
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:	$0.5 \ldots 1.3\,\mathrm{T}$
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:	$\approx 100\,\mathrm{Hz/cm^2}$ ($E_{kin} > 10\,\mathrm{MeV}$)

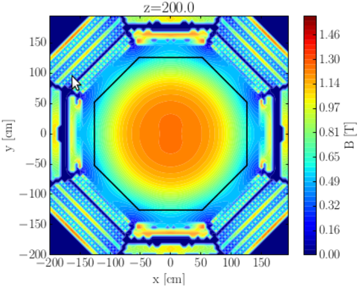
Microchannel Plate PMTs

MCP-PMT working principle

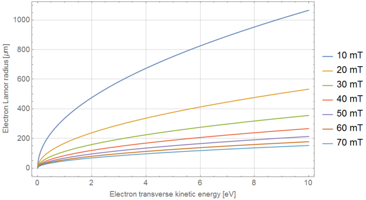




B-field at Disc DIRC

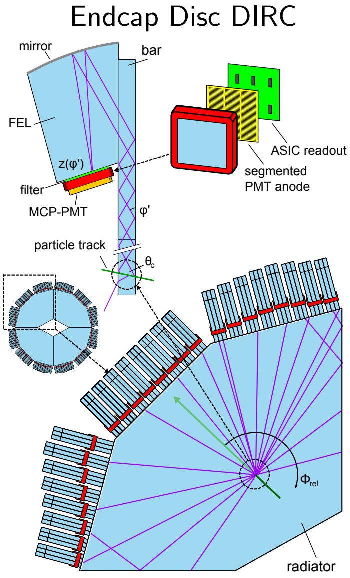


Larmor radius for electrons

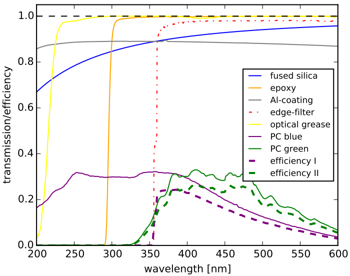


PANDA Disc DIRC

- Fused silica plate containing 4 independent quadrants
- Cherenkov light internally propagated to outer rim
- 8 Readout Modules (ROMs) per side with 3 Focusing Elements (FELs) per ROM sharing one MCP-PMT
- FELs focusing parallel light to same spot
- MCP-PMT with segmented anode (3 cols, 100 rows)
- PMTs connected to PCB with ASIC readout (TOF-PET from PETsys) for digitizing signals



Optical Parameters



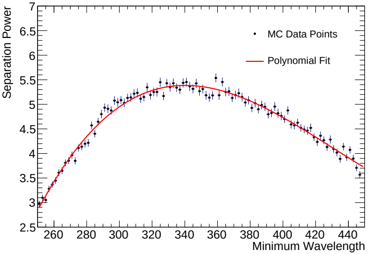
- Mirror reflectivity of focusing elements
- MCP-PMT detection efficiency
- Transmission coefficiencies, refractive indices and absorption lengths of used materials
- Using bandpass filter with minimum wavelength cut off

Expected Resolution

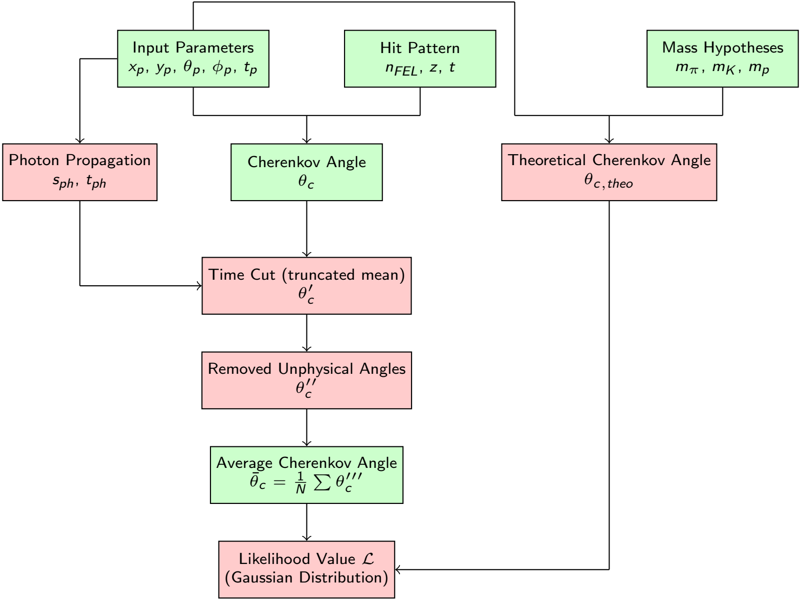
- Detector resolution::

$$\sigma_\theta^2 = \frac{\sigma_{ph}^2}{N} + \sigma_{track}^2$$

- σ_{ph} containing chromatic and geometric error

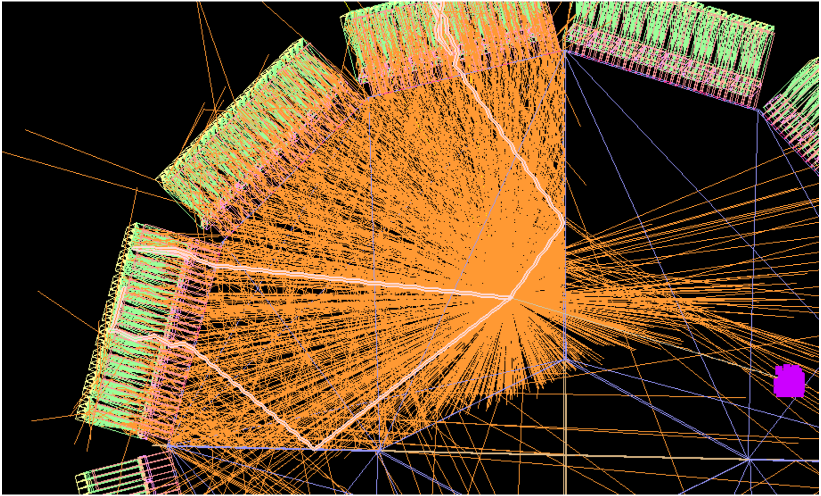


Reconstruction Algorithm

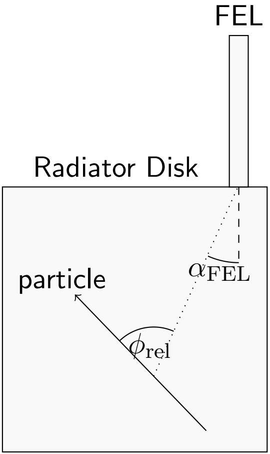


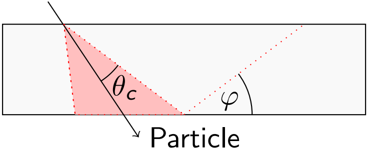
PANDA Disc DIRC

Monte-Carlo Simulations performed with Geant4

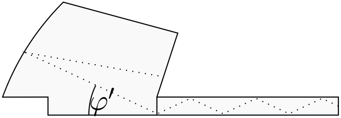


Geometrical Model





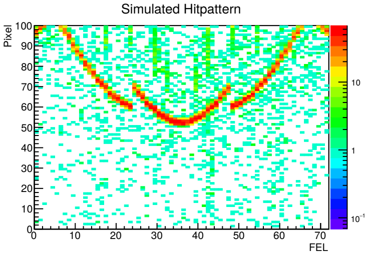
$$\tan\varphi' = \frac{\tan\varphi}{\tan\alpha_{FEL}}$$

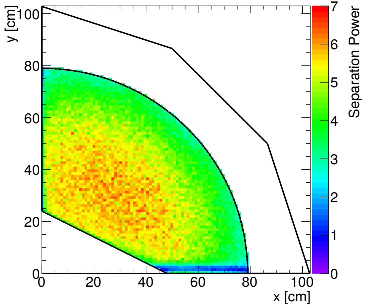


$$\theta_c = \arccos(\sin\theta_p \cos\phi_{rel} \cos\varphi + \cos\theta_p \sin\varphi)$$

PANDA Disc DIRC

- All performance studies based on Monte-Carlo simulations
- Background induced mainly by additional reflections
- Simulated and measured hit pattern: Projection of Cherenkov ring into 2D sensor space (Cherenkov smile)
- Separation power decreasing for larger polar angles (ambiguities due to non-zero bar width)
- Small band with deteriorated performance as a result of mirror reflections



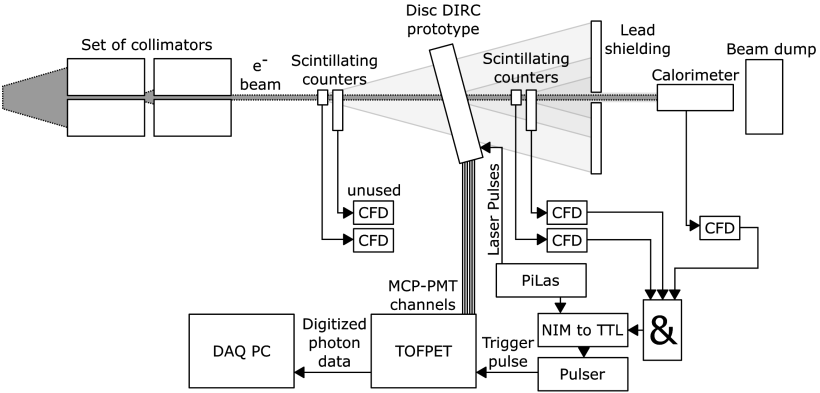


CERN Testbeam

Testbeam in T9 area at CERN in 2015

DESY Testbeam 2016

DESY testbeam setup for T24/1 hall:

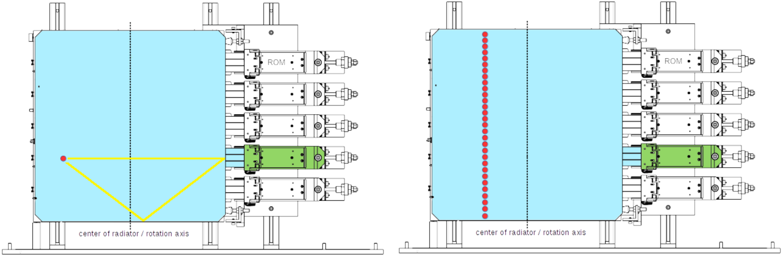


TOFPET: Free running readout device with 50 ps time resolution

Radiator Setup

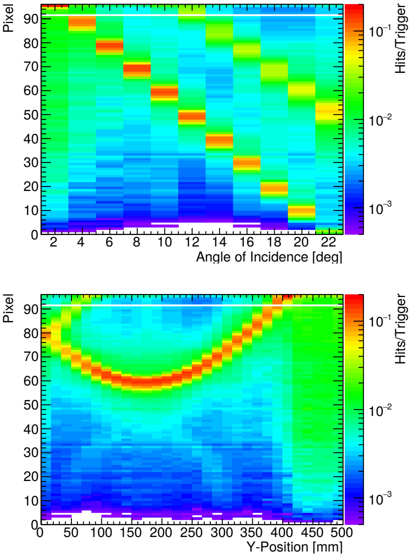
- Polar angle scan with fixed position
- y-axis scan with fixed angle
- One ROM with MCP-PMT attached to testbeam radiator plate

Radiator with Beam Position



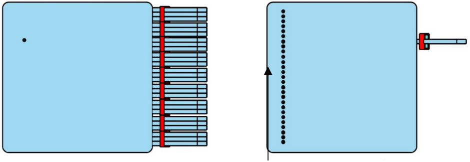
Testbeam radiator: Fused silica plate (50 cm $\times$ 50 cm)

Measured Hitpattern



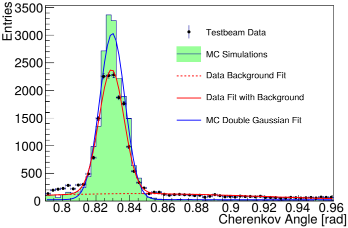
- Electrons at 3 GeV/c momentum for high statistics
- Linear dependency between pixel and angle of incidence
- "Cherenkov smile" for vertical scan
- Additional reflection on rim clearly visible
- Background hits from delta-electrons (housing) and additional reflections

Event Combination

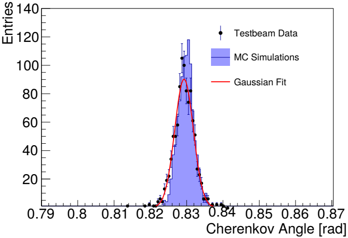


- Combining each event from every position to one new event
- Making a coarse time cut according to photon propagation time
- Reduction of background with truncated mean of pixel hits
- Obtained resolutions:
  $\sigma_{\theta} = 7.4\,\text{mrad}$
  $\sigma_{\bar{\theta}} = 2.5\,\text{mrad}$

Single photon distribution

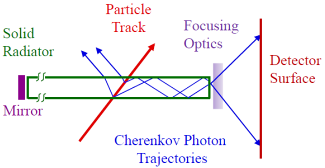


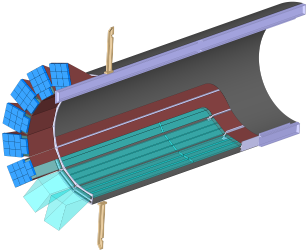
Cherenkov distribution

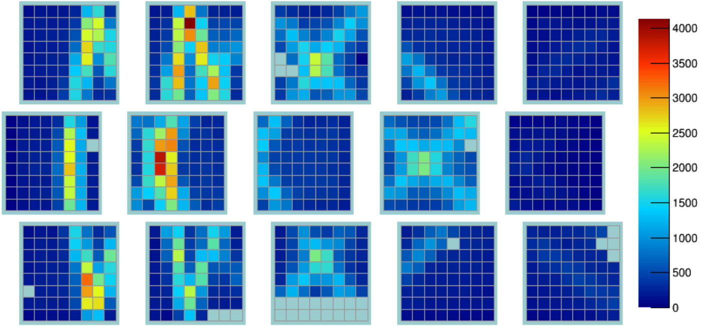


PANDA Barrel DIRC

- Cherenkov light internally reflected to the rim (sensors)

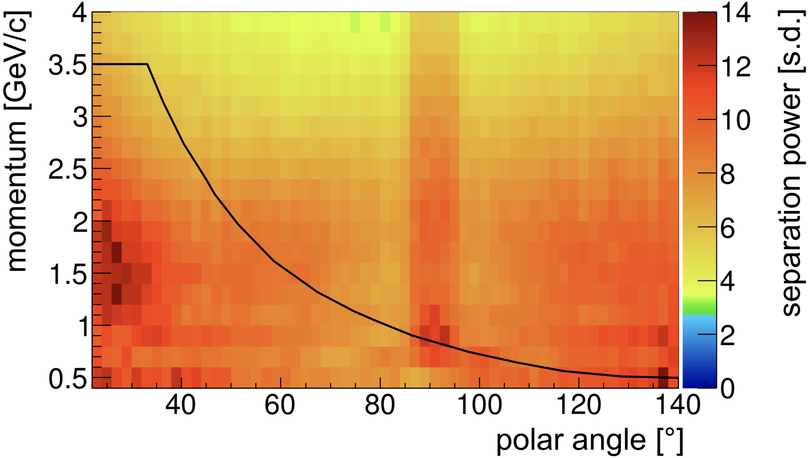






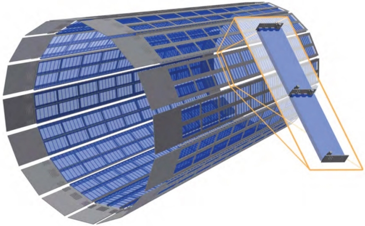
PANDA Barrel DIRC

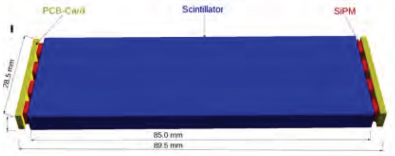
PANDA Barrel DIRC meeting the requirement of 4σ π/K separation at 4 GeV/c particle momentum



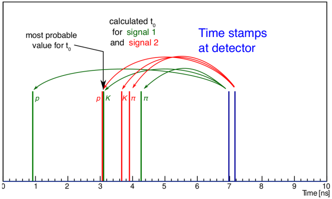
Barrel ToF

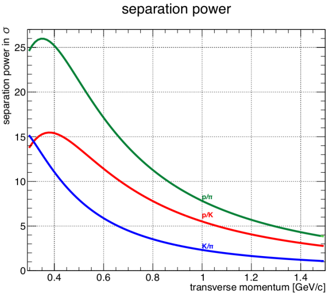
- PID of low momentum particles $p \leq 1\,\mathrm{GeV/c}$
- Excellent time resolution of approx. 100 ps
- 5,760 scintillator tiles with sizes about $30\,\mathrm{mm} \times 30\,\mathrm{mm} \times 5\,\mathrm{mm}$
- Light weight construction
- Scintillator material: plastic (EJ-228 or EJ-232)
- Readout: Hamamatsu SiPM
- Front-end electronics: PETsys TOFPET ASICs





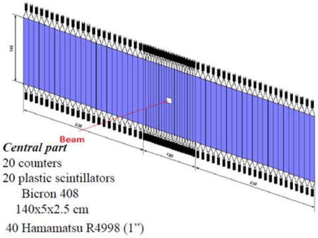
Barrel ToF

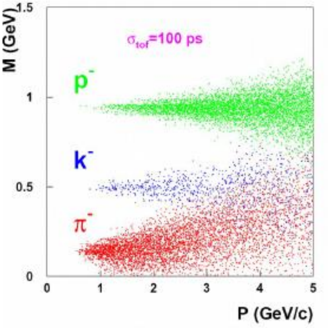




- Different particle masses are assumed and corresponding t0 calculated from track and momentum information
- Time resolution for 3 or more track of 167 ps
- Very good separation power for particles with low momentum
- Very good separation power for particles with low momentum

Forward ToF

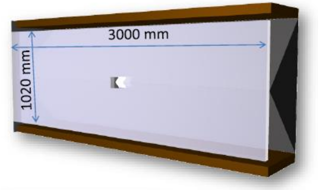


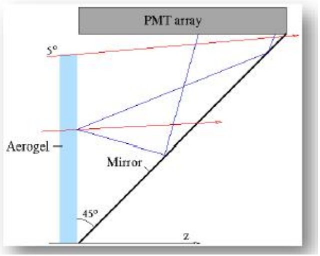


- Time of flight in forward spectrometer essential
- No start counter ⇒ relative timing to Barrel ToF
- Scintillator wall of slabs
- Distance to target: 7.5 m
- Slab geometry: 140 cm × 10 cm (sides), 140 cm × 10 cm (center)
- Material: Bicron 409 scintillator
- Photon read out with PMTs on both ends
- Side part: 2 × 32 counters ⇒ 92 PMTs for photon readout

Forward RICH

- 2 layers of aerogel
- Refractive index: $n_1 = 1.050$ and $n_2 = 1.047$
- Only flat mirrors
- π/K separation up to $p = 10\,\text{GeV/c}$
- mu/K separation up to $p = 10\,\text{GeV/c}$
- Read out with Hamamatsu MaPMTs
  - 8×8 anode pixels with 6 mm size
  - Relatively cheap $\approx 1800\,\text{EUR/unit}$
  - Robust and long life time



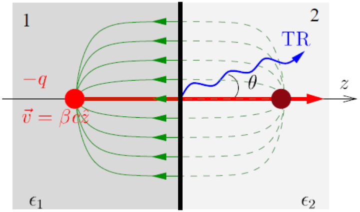


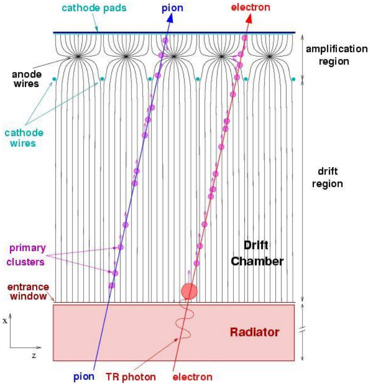
Transition Radiation

- Transition Radiation (TR): highly relativistic charged particles $\gamma > 1000$ pass boundary between two media with different primitive constants
- Induced mirror charge create a dipole together with the charged particle
- Emitting angle:

$$\theta = \frac{1}{\gamma}$$

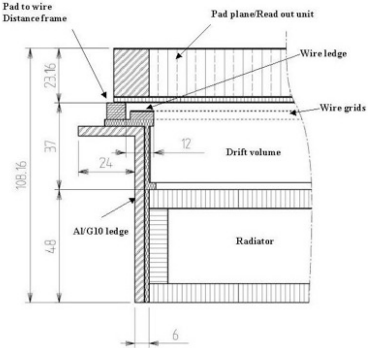
- Photon energy between 5 and 15 keV
- Small photon yield: multilayers

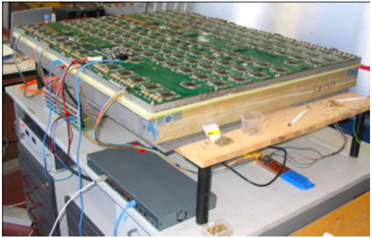




ALICE TRD

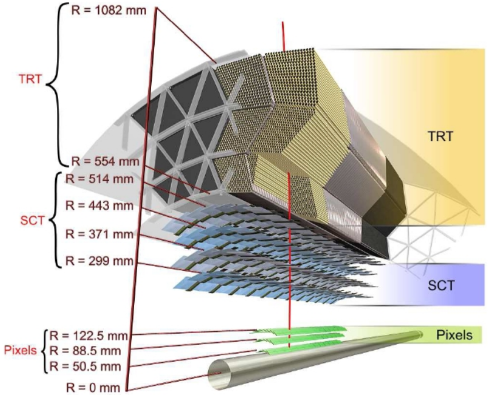
- energy of radiated photons: $\propto \gamma$
- Number of radiated photons: αz^2

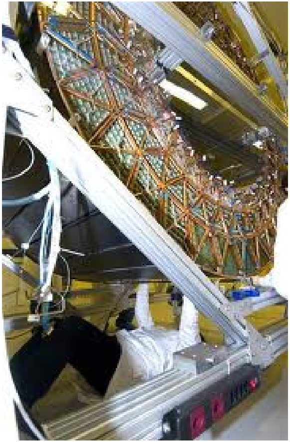




ATLAS TRD

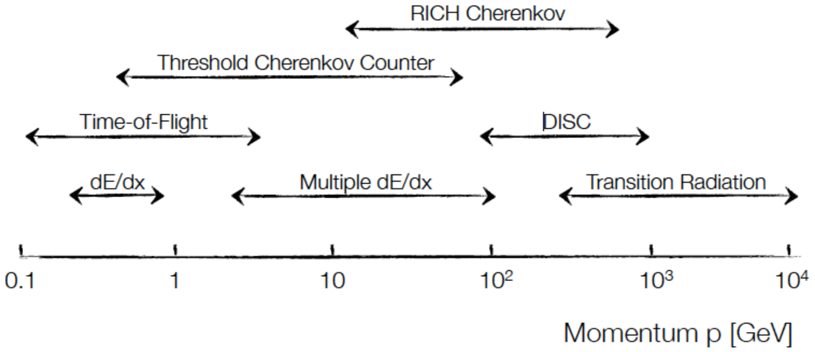
- Transition radiation tracker (TRT)
- 300,000 straw tubes with a xenon-based gas mixture
- 4 mm diameter equipped with 30 μm diameter gold-plated tungsted wire





PID Methods Comparison

- Different momenta for π/K separation require different methods
- Small momentum: Time of Flight and energy loss measurements
- Medium momentum: DIRC and RICH detectors
- Large momentum: Transition radiation



Thank you very much for your attention!