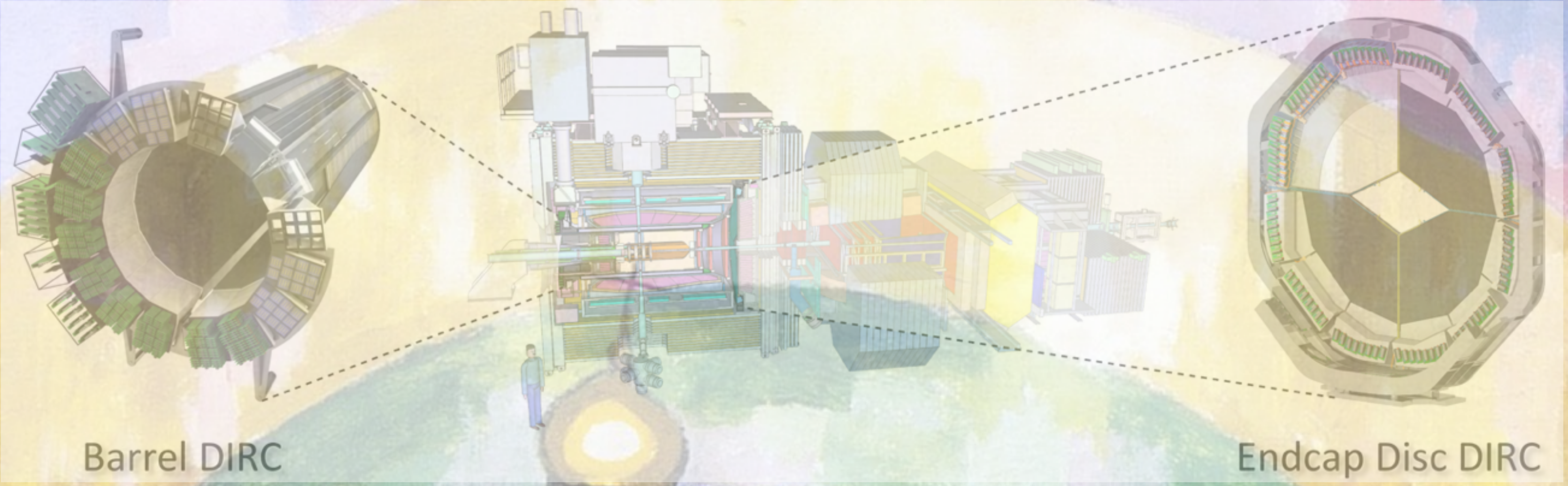


The PANDA DIRC Detectors

Jochen Schwiening

GSI Helmholtzzentrum für Schwerionenforschung GmbH

for the PANDA Cherenkov Group

PANDA Cherenkov Group

FAU Friedrich-Alexander Universität Erlangen-Nürnberg
GSI
FAIR
Justus-Liebig-Universität Giessen
Goethe Universität Frankfurt am Main
JG|U Johannes Gutenberg Universität Mainz

RICH2018, Moscow, Jul 29 – Aug 4, 2018

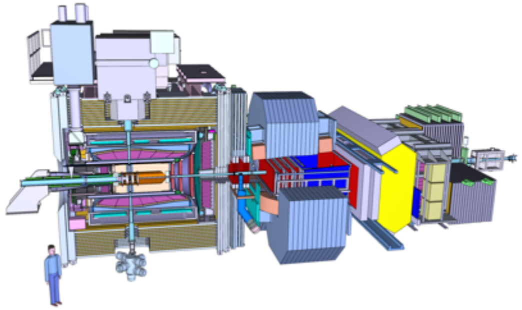
Detection of Internally Reflected Cherenkov Light

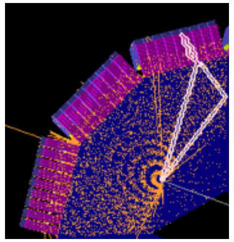
Both PANDA DIRC counters have made excellent progress since RICH2016:

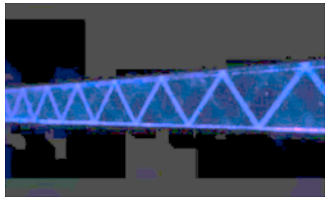
Technical designs have been completed, moving from design to construction stage.

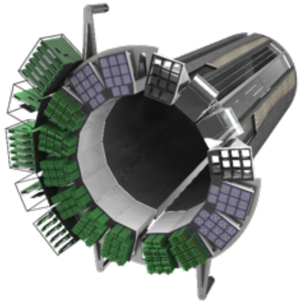
Installation scheduled for 2023, commissioning for 2024.

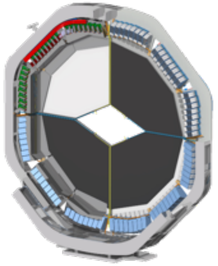
- ➢ PANDA at FAIR
- ➢ DIRC Concept
- ➢ PANDA Barrel DIRC
- ➢ PANDA Endcap Disc DIRC
- ➢ Outlook





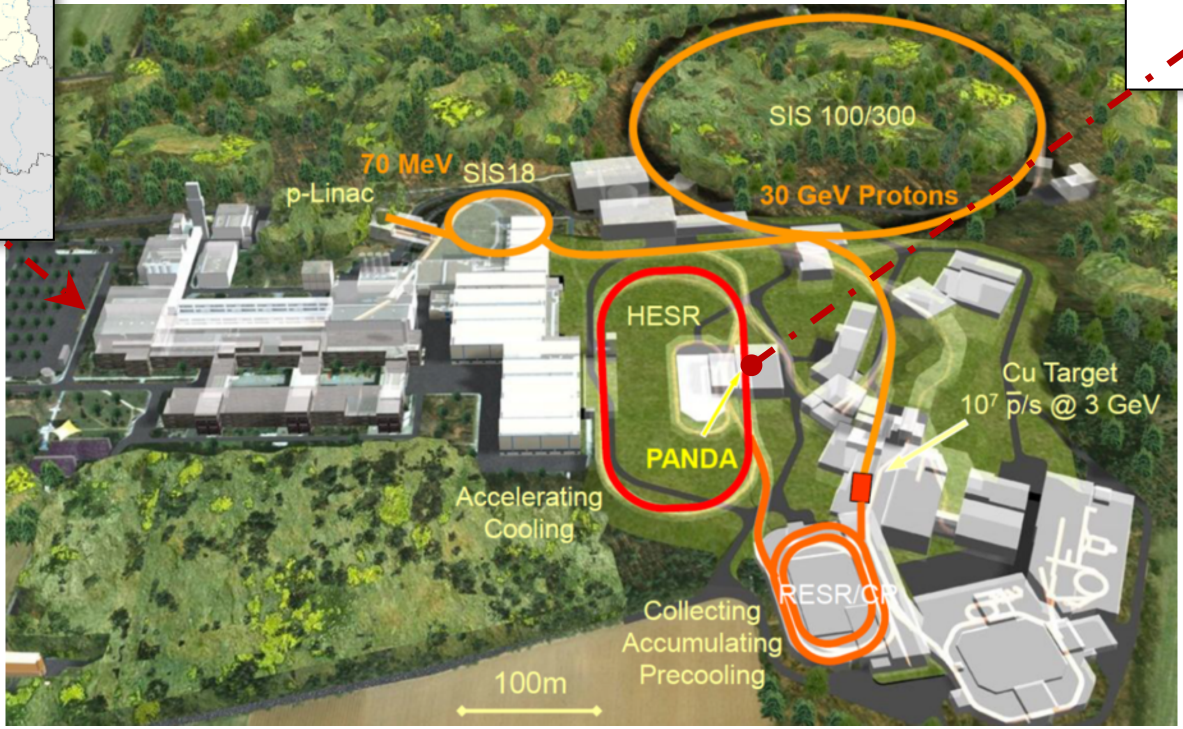


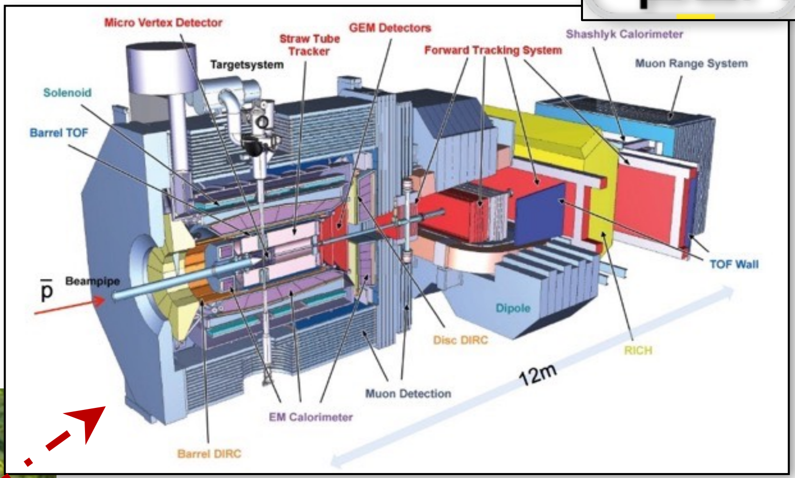




Facility for Antiproton and Ion Research at GSI near Darmstadt, Germany

- ➢ FAIR Accelerator Complex
- ➢ PANDA Experiment
- ➢ Barrel DIRC and Endcap Disc DIRC





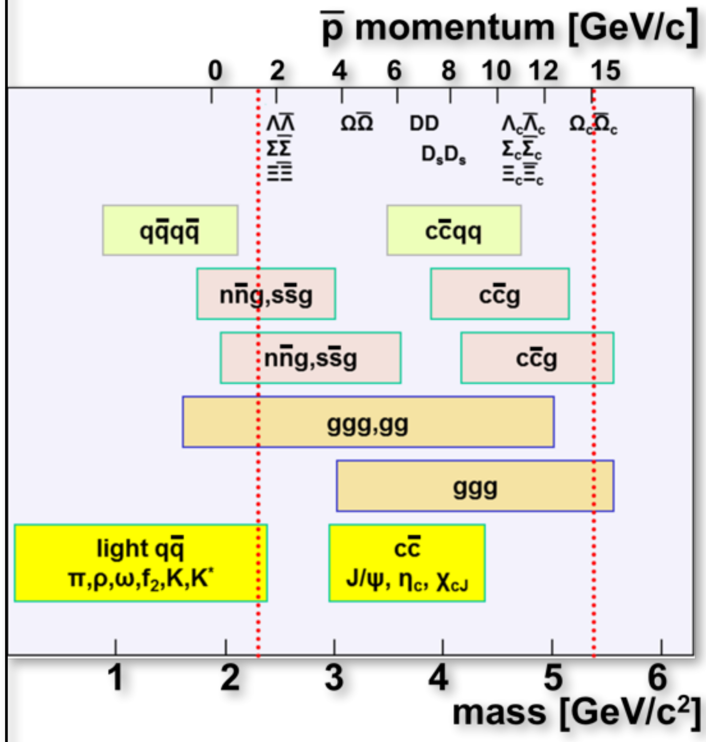
High Energy Storage Ring

- 5×10^{10} stored cooled antiprotons
- 1.5 to 15 GeV/c momentum
- Interaction rate up to 20MHz
- Cluster jet / pellet target
- High luminosity mode
  $\Delta p/p \approx 10^{-4}$ (stochastic cooling)
  $L = 1.6\times10^{32}$ cm^{-2}s^{-1}
- High resolution mode
  $\Delta p/p \approx 5 \times 10^{-5}$ (electron cooling)
  $L = 1.6\times 10^{31}$ cm^{-2}s^{-1}

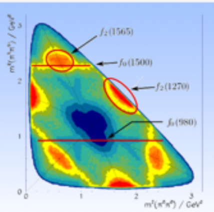
FAIR construction making good progress

(snapshots from recent drone video
https://youtu.be/NN_1t2mrgUI)

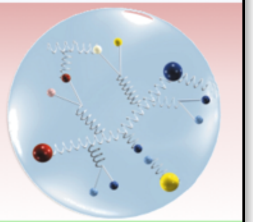
Antiprotons – Unique Probes for Discoveries and Precision Physics



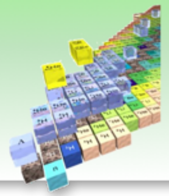
Hadron Spectroscopy
- Charmonium / Charmed hadrons
- Exotic QCD states
- Spectroscopy



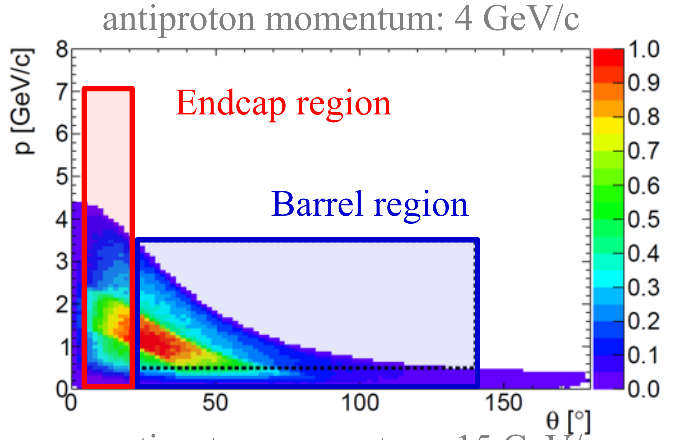
Hadron Structure
- Time-like Nucleon Form Factors
- Generalized Parton Distributions
- Drell-Yan Process

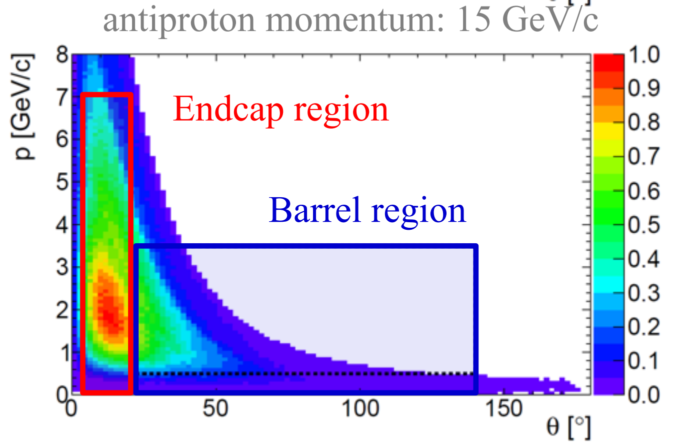


Nuclear Physics
- Production of Λ-Hypernuclei
- Hadrons in Nuclear Medium



Examples: charged kaon phase space for 16 benchmark channels (DPM)





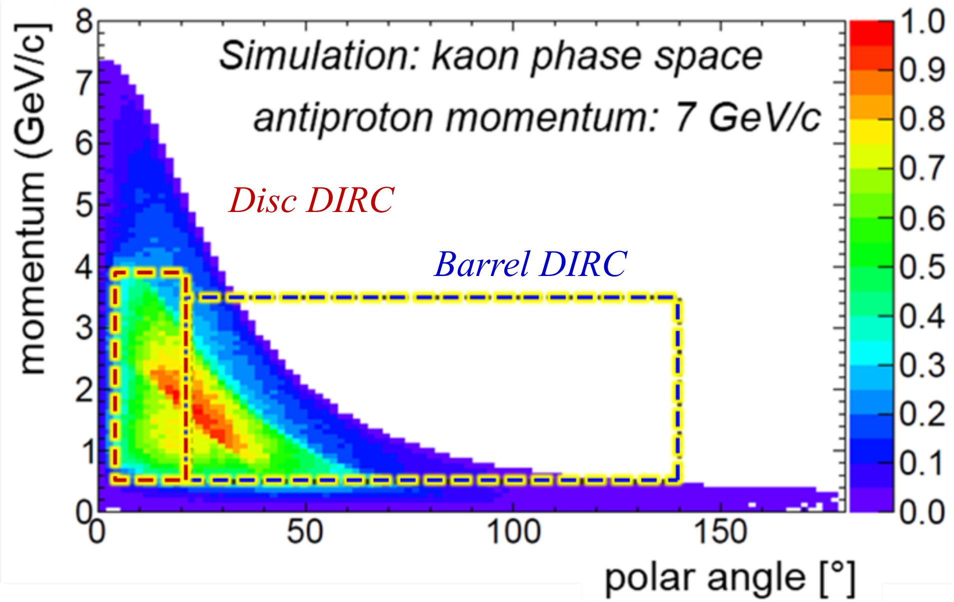
Excellent particle identification required for PANDA physics program

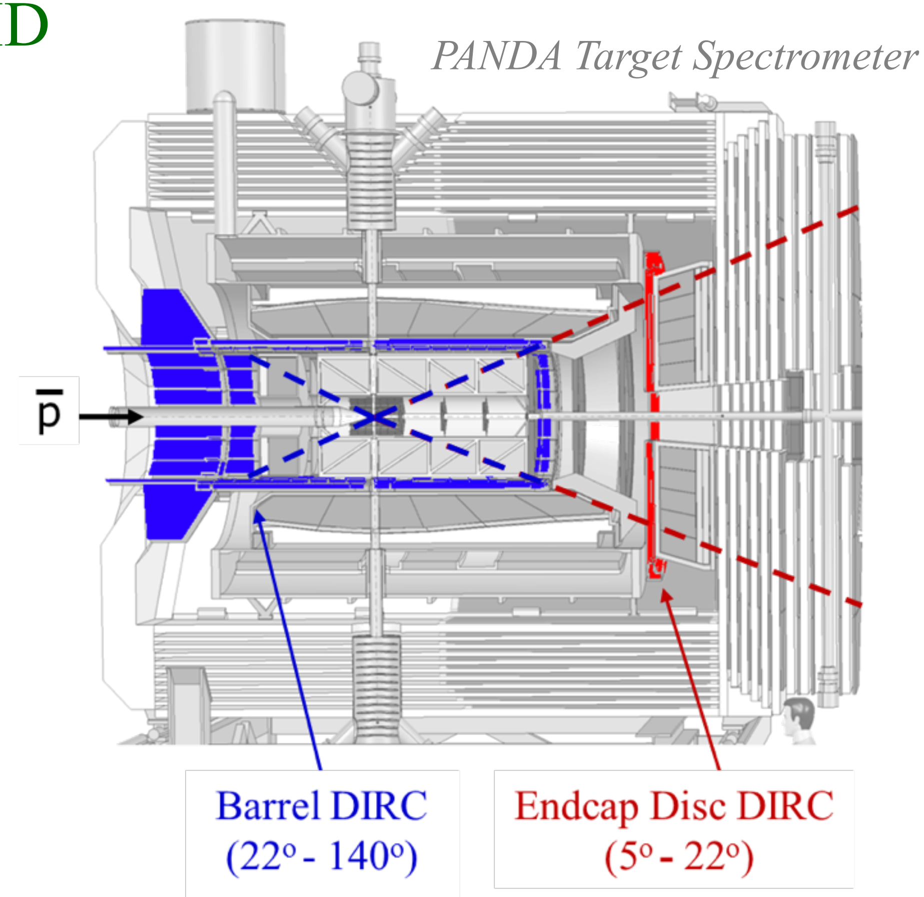
High interaction rate *plus* π/K separation for momenta up to 3-4 GeV/c

plus very compact detector design → excellent case for DIRC counters

PANDA: two innovative DIRC detectors for hadronic PID

- **Barrel DIRC**
  First DIRC with lens focusing.
  Goal: 3 s.d. π/K separation up to 3.5 GeV/c
- **Endcap Disc DIRC**
  First DIRC for detector endcap region.
  Goal: 3 s.d. π/K separation up to 4 GeV/c





Required PID performance great match to DIRC technology
→ BaBar DIRC achieved 3 s.d. π/K sep. up to 4 GeV/c

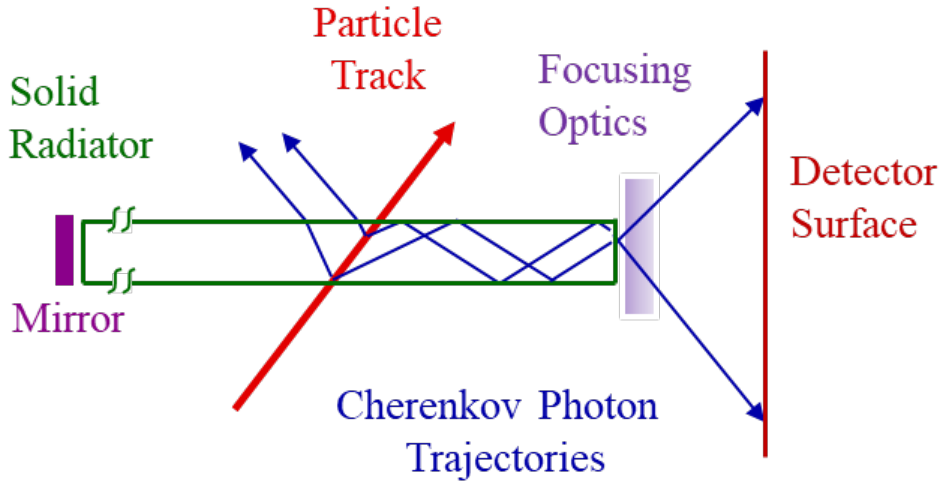
Combination of Barrel and Endcap Disc DIRC: full coverage

DIRC CONCEPT

DIRC counters have been part of every RICH workshop since inaugural meeting in Bari 1993§.

Four DIRC talks this year – still, a brief reminder of the DIRC basics never hurts.

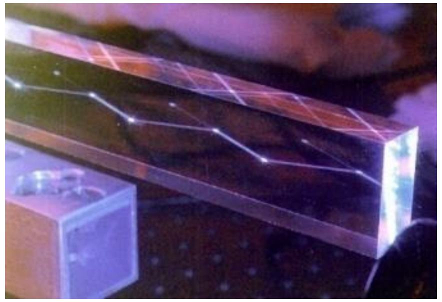
- Charged particle traversing radiator with refractive index n with $\beta = v/c > 1/n$ emits Cherenkov photons on cone with half opening angle $\cos \theta_c = 1/\beta n(\lambda)$.



- For $n>\sqrt{2}$ some photons are always totally internally reflected for $\beta \approx 1$ tracks.

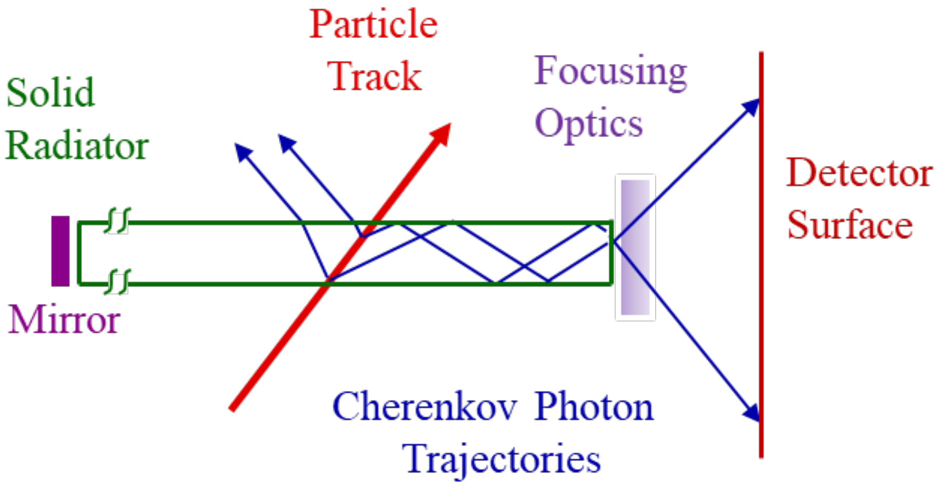
- Radiator and light guide: bar, plate, or disk made from Synthetic Fused Silica ("Quartz") or fused quartz or acrylic glass or …

- Magnitude of Cherenkov angle conserved during internal reflections (provided optical surfaces are square, parallel, highly polished)



§*B.N. Ratcliff, SLAC-PUB-6047 (Jan. 1993); P. Coyle et al., NIM A343 (1994) 292.*

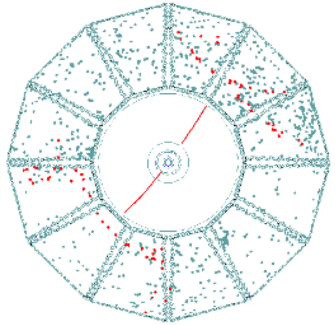
- Mirror attached to one bar end, reflects photon back to readout end.
- Photons exit radiator via optional focusing optics into expansion region, detected on photon detector array.
- DIRC is intrinsically a 3-D device, measuring: x, y, and time of Cherenkov photons, defining θ_c, ϕ_c, $t_{propagation}$.
- Ultimate deliverable for DIRC: PID likelihoods.



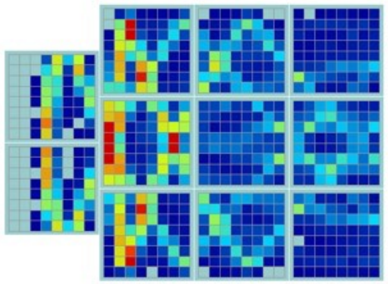
DIRC hit patterns are not your typical Cherenkov rings.

Different DIRCs use different reconstruction approaches to provide likelihood for observed hit pattern (in detector space or in Cherenkov space) to be produced by e/μ/π/K/p plus event/track background.

DIRCs require momentum and position of particle measured by tracking system.



Typical d-muon event BaBar DIRC



Accumulated hit pattern PANDA Barrel DIRC (Geant)

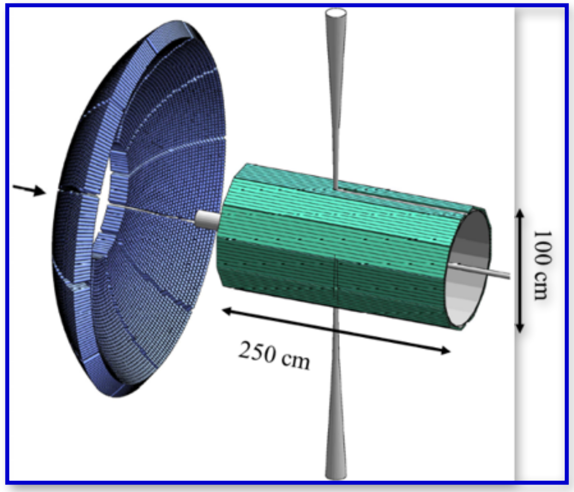
BARREL DIRC: EARLY DESIGNS

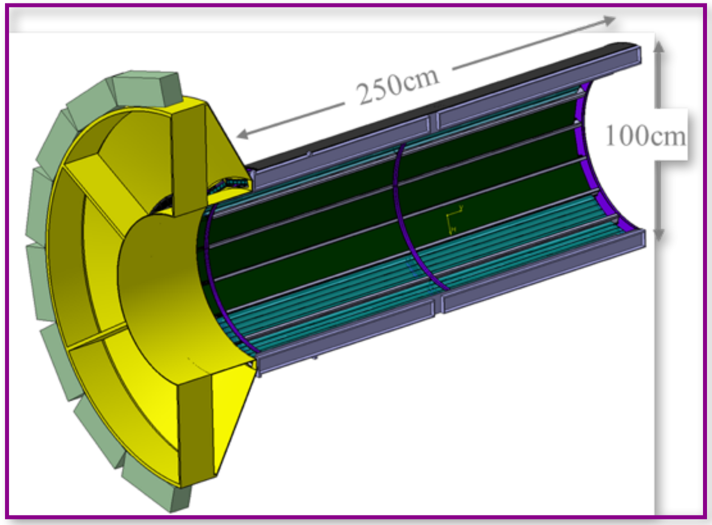
RICH 2007: scaled version of BABAR DIRC

- Radiators: 96 narrow fused silica bars, 2.5m length
- Expansion volume: large water tank
- Sensors: ~ 7,000 conventional PMTs

Fast simulation: design meets PANDA PID goals.

But: increasingly complex PANDA detector design required compact imaging region inside magnet yoke





RICH 2013: compact photon camera

- Radiators: 80 narrow fused silica bars, 2.5m length
- Expansion volume: 30 cm-deep tank (mineral oil)
- Sensors: ~15,000 channels of MCP-PMTs
- Focusing: spherical lenses

Detailed simulation: design meets PANDA PID goals.

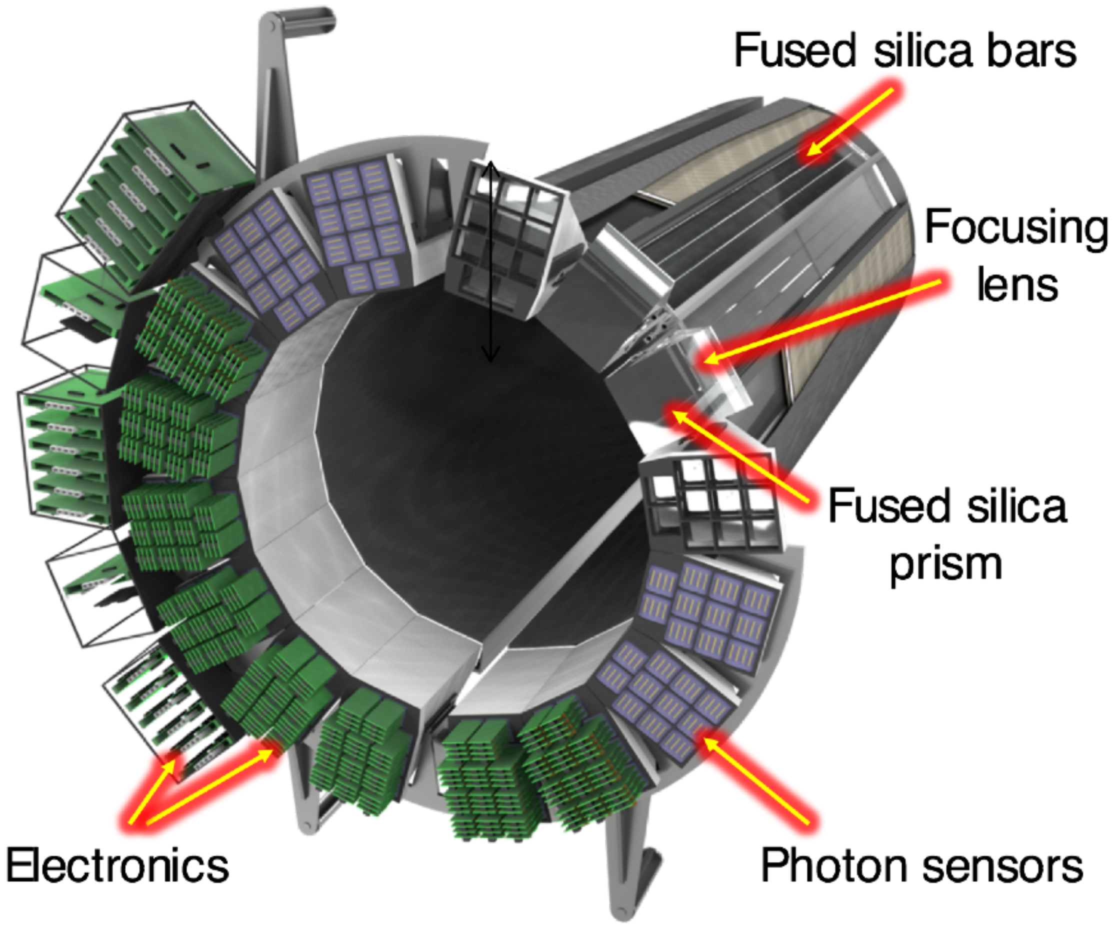
But: production cost ~50% over budget.

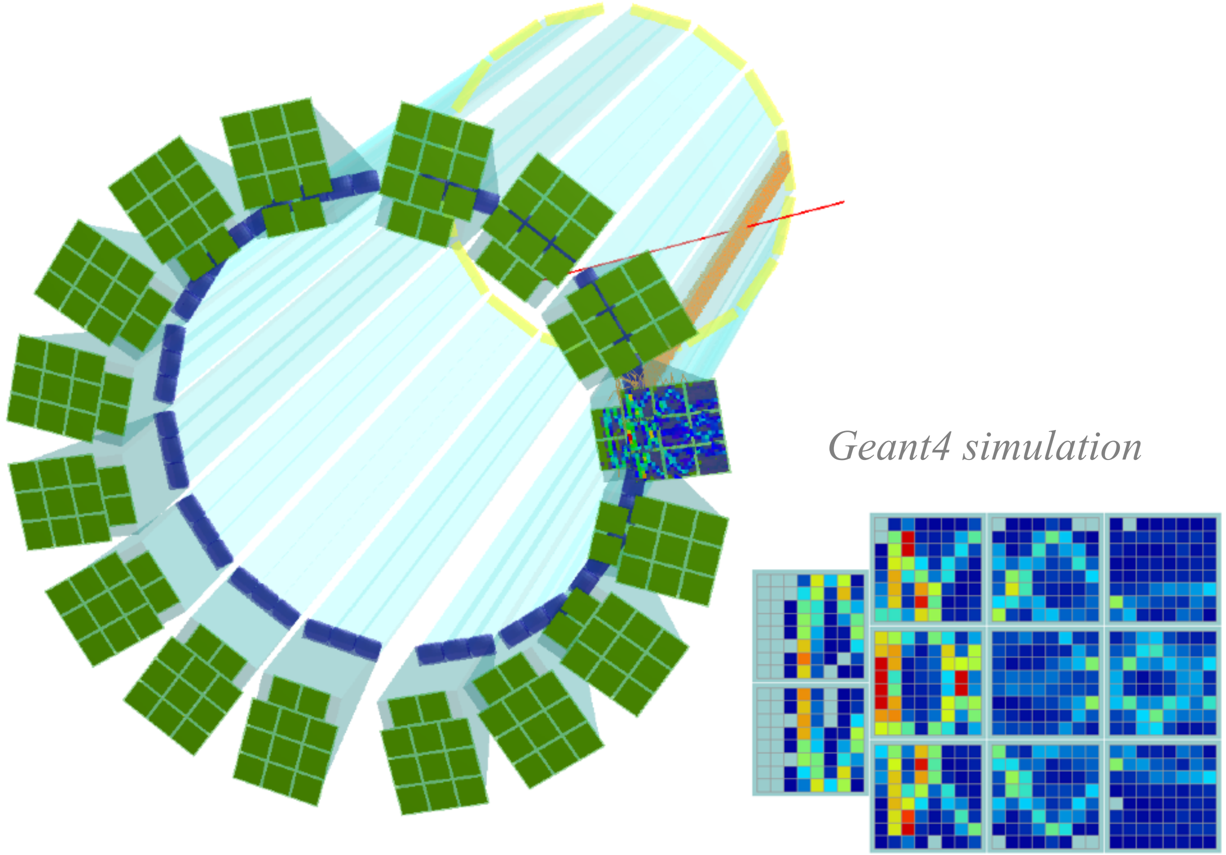
Needed additional cost/performance optimization – cost driver: fabrication of bars and MCP-PMTs.

Main results of a comprehensive cost performance optimization in simulation:

use wider bars (3 per bar box instead of 5) and compact fused silica prisms;

40% fewer bars, 37% fewer MCP-PMTs, lower cost at no performance loss.





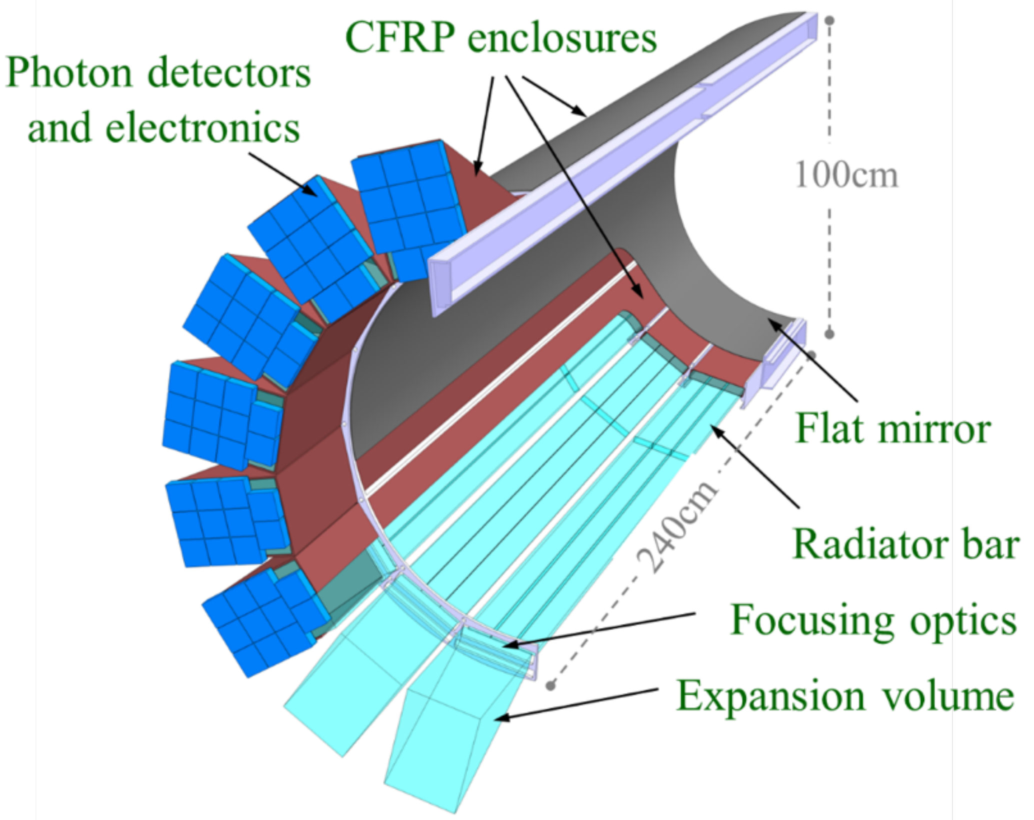
Geant4 simulation

BARREL DIRC: FINAL DESIGN

Compact fused silica prisms, 3 bars per bar box, 3-layer spherical lenses.

For more detail, see
PANDA Barrel DIRC TDR, arXiv:1710.00684

- 48 radiator bars (16 sectors), synthetic fused silica,
  17mm (T) × 53mm (W) × 2400mm (L).
- Focusing optics: 3-layer spherical lens
- Compact expansion volume:
  30cm-deep solid fused silica prisms
  ~11,000 channels of lifetime-enhanced MCP-PMTs
- Fast FPGA-based readout electronics.
  ~100ps per photon timing resolution
- Expected performance (simulation and particle beams):
  better than 3 s.d. π/K separation for entire acceptance.



Conservative design – similar to proven BABAR DIRC, validated in particle beams in 2015.

Excellent performance, robust, little sensitivity to backgrounds and timing deterioration.

Modular design for easy access and optional staged installation of bar boxes.

Multi-layer spherical lens

G. Kalicy, DIRC2013
see also X. He, this conference

Standard fused silica lens with air gap would create large hole in DIRC acceptance for track polar angles for 75-105° (photon captured in lens by internal reflection).

Innovative design: refraction between higher-refractive index material and fused silica.

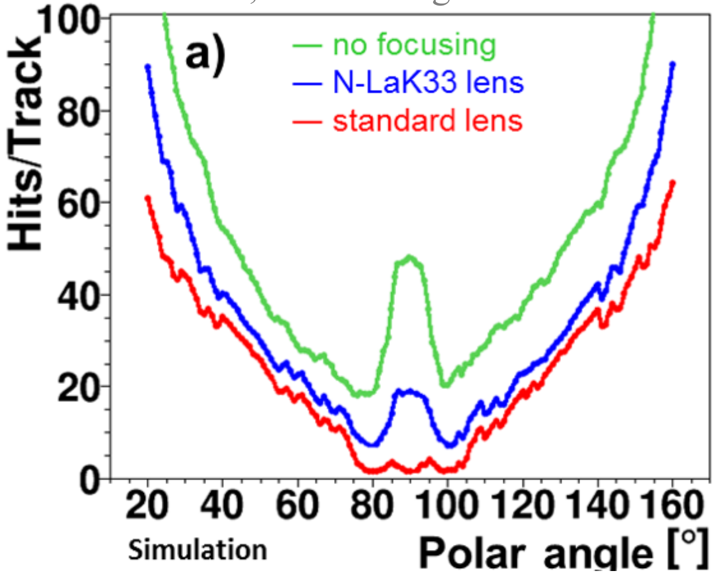
Solution for PANDA Barrel DIRC:
lanthanum crown glass (LaK33B) as middle layer in 3-layer lens,
focusing/defocusing radii inside lens designed to match prism surface.
(λ=380nm: fused silica: n≈1.473, LaK33B: n≈1.786)

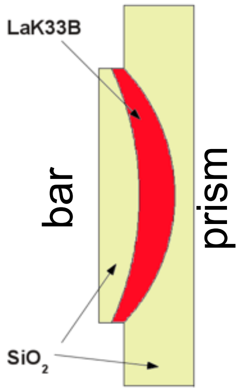
Prototype built by industry, tested with lasers in lab and with PANDA Barrel DIRC prototype using particle beams at CERN.

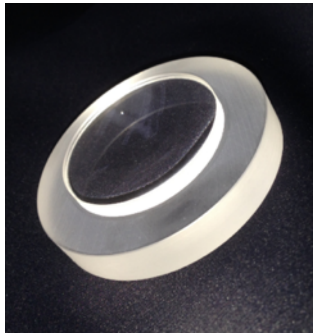
Photon yield, resolution, and shape of focal plane agree with simulation, hole in acceptance closed.

(Note that NLaK33B is "radiation hard enough" for PANDA [expected 10 year dose <5Gy] but not for EIC DIRC. Currently investigating alternatives: PbF_2, sapphire, ...)

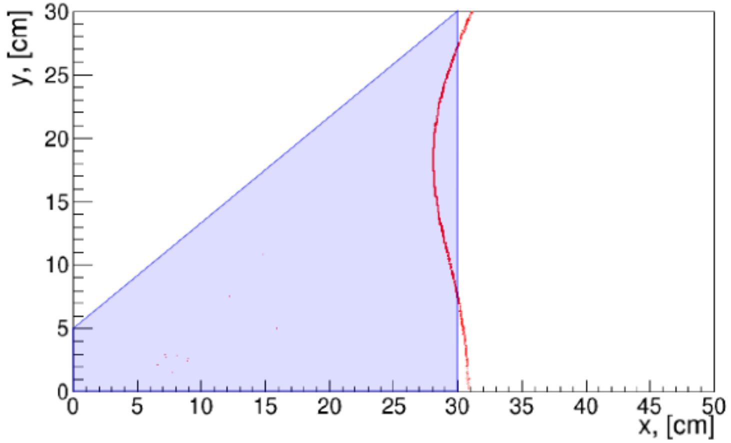
simulation, earlier design







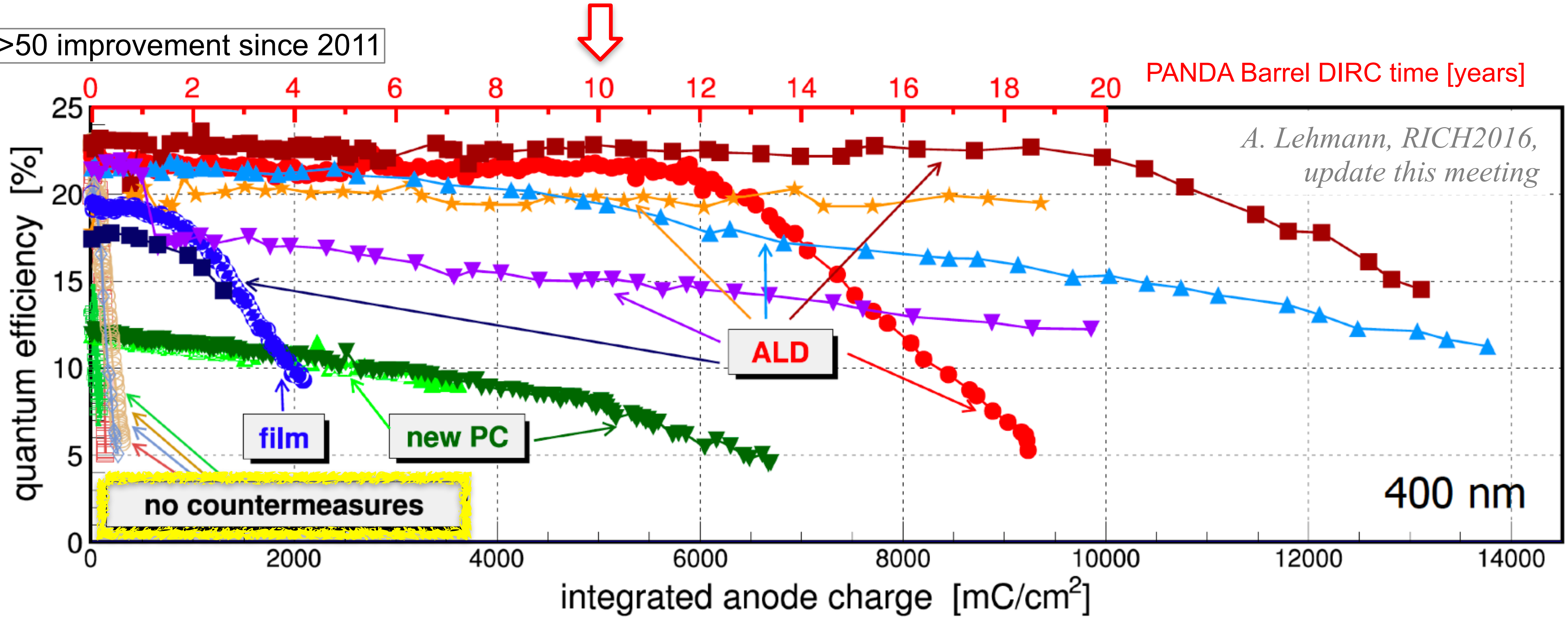
simulation: focal plane of 3-layer lens



Sensor of choice for PANDA DIRCs: MCP-PMTs (due to 1T magnetic field, high rate, low noise, timing precision)

Lifetime of MCP-PMTs was potential showstopper for Belle II and PANDA until a few years ago.

Factor >50 improvement since 2011



Recent MCP-PMTs with atomic layer deposition technique exceed requirements for the PANDA DIRC counters.

BARREL DIRC: EXPECTED PERFORMANCE

Final design, 3 bar per bar box, 3-layer spherical lens, prism

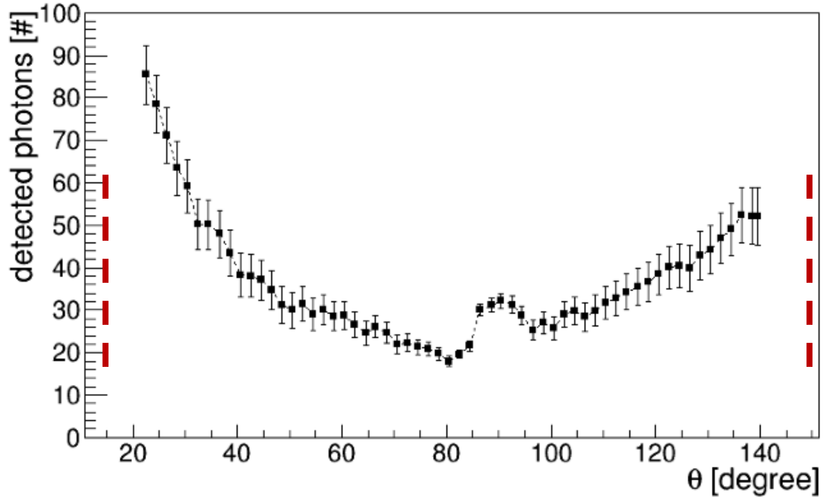
Used geometrical reconstruction (BABAR-like method)
 to determine photon yield and
 single photon Cherenkov angle resolution (SPR).

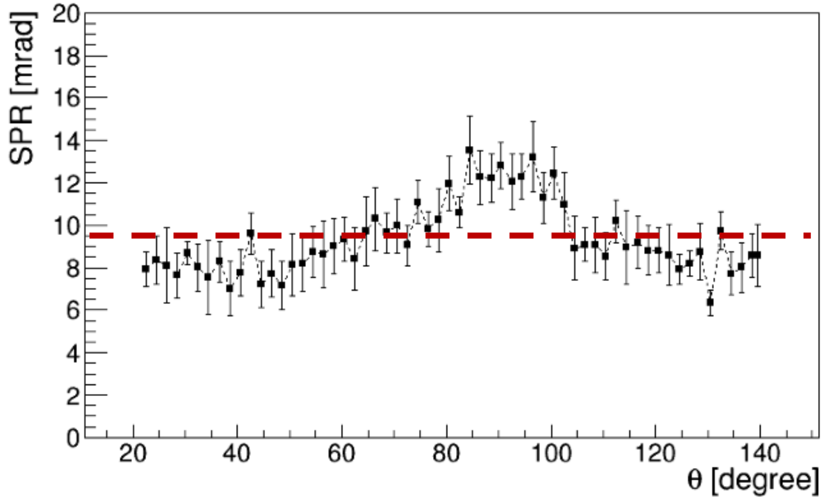
Latest generation of MCP-PMTs expected to
 further increase photon yield by up to 50%.

Yield and SPR reach performance goal.

BABAR DIRC FOMs reached or exceeded,
 in particular for most demanding
 high-momentum forward region.

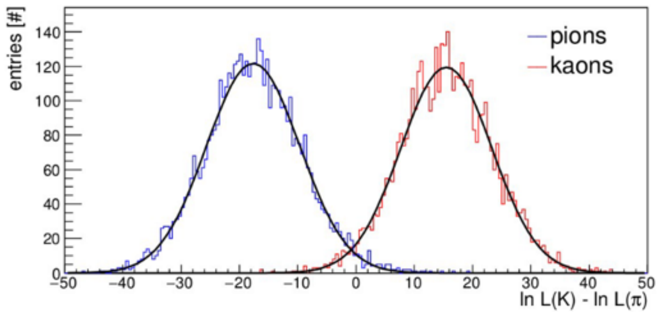
Geant simulation





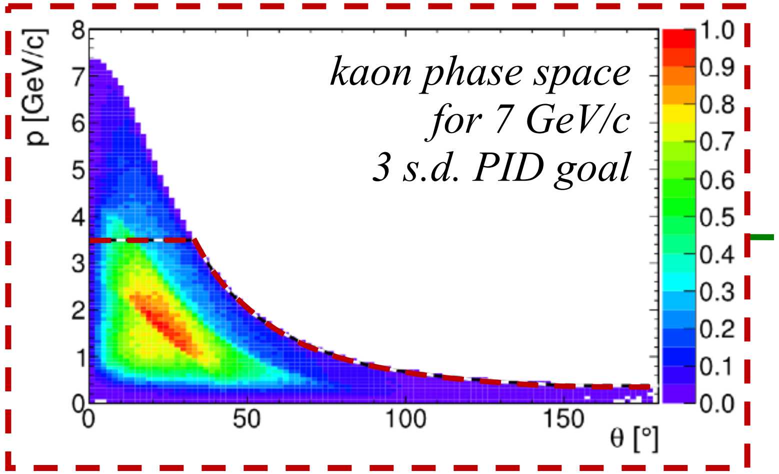
Final design, 3 bar per bar box, 3-layer spherical lens, prism

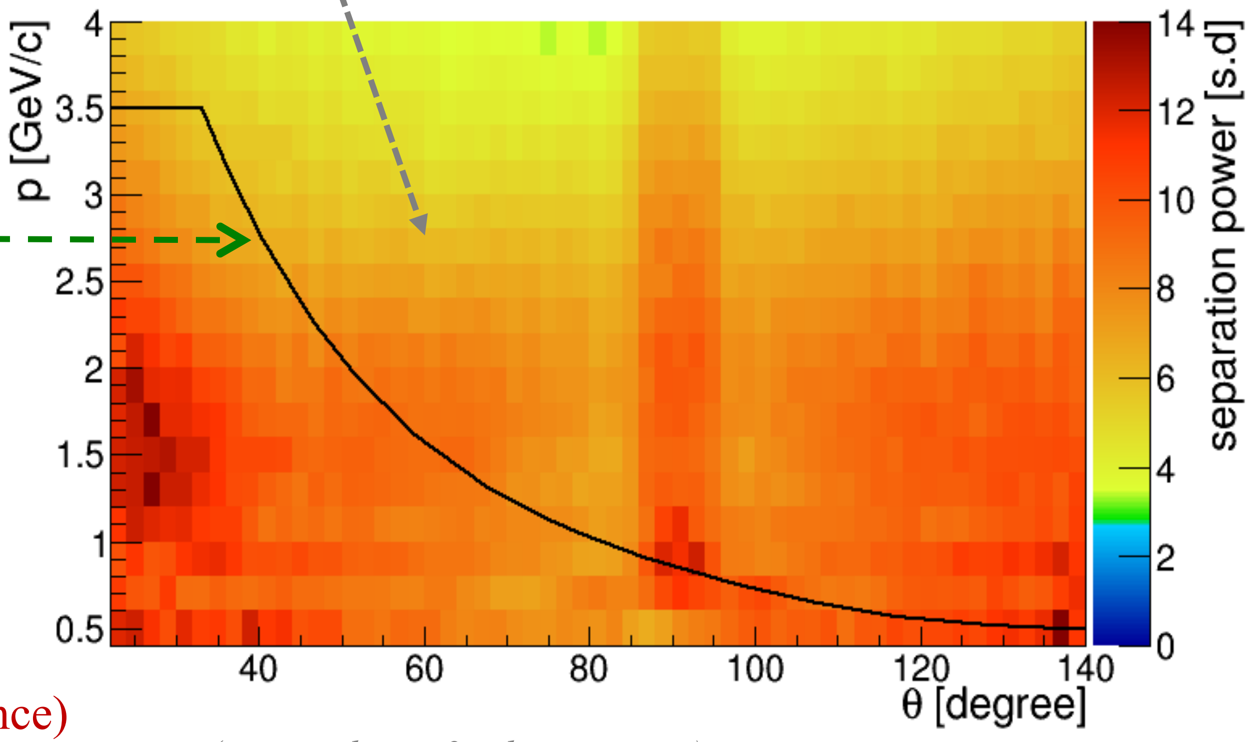
Log-likelihood difference from time-based imaging (Belle II TOP-like method)



$$N_{\mathrm{sep}} = \frac{|\mu_1 - \mu_2|}{0.5(\sigma_1 + \sigma_2)}$$

Geant simulation, time-based imaging, σ_t=100ps



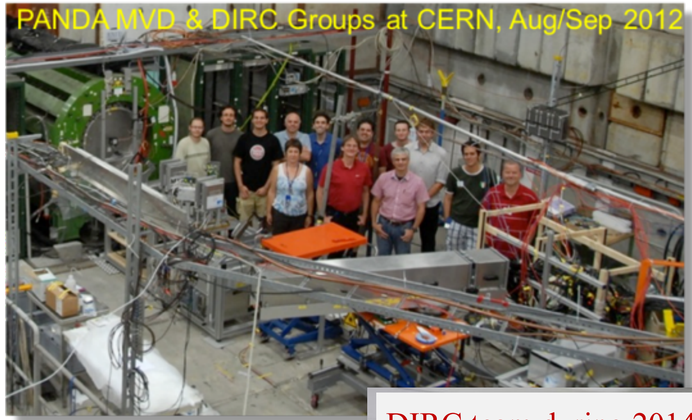


(green color: ~ 3 s.d. separation)

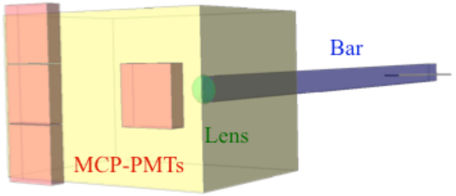
Design meets PID requirements

- for geometric reconstruction
- for time-based imaging (even better performance)

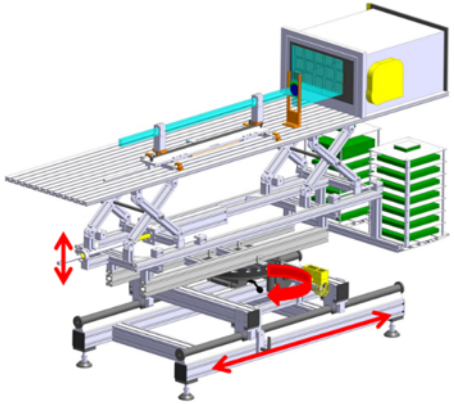
BARREL DIRC BEAM TESTS

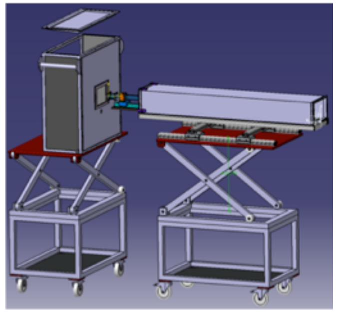


2014, 2015, 2016, 2017, 2018: GSI, CERN

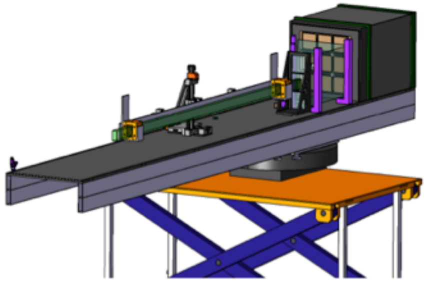


2008, 2009: GSI





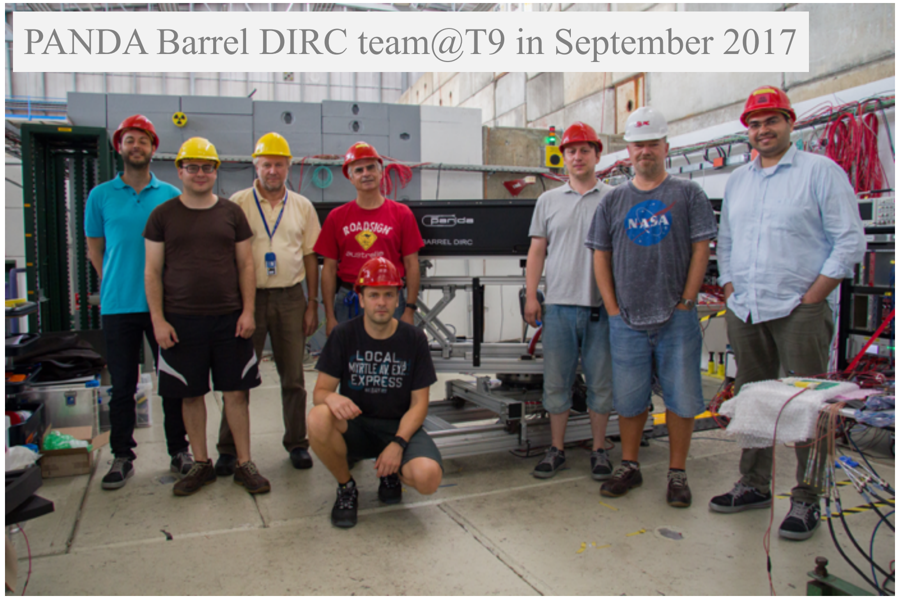
2011: GSI, CERN

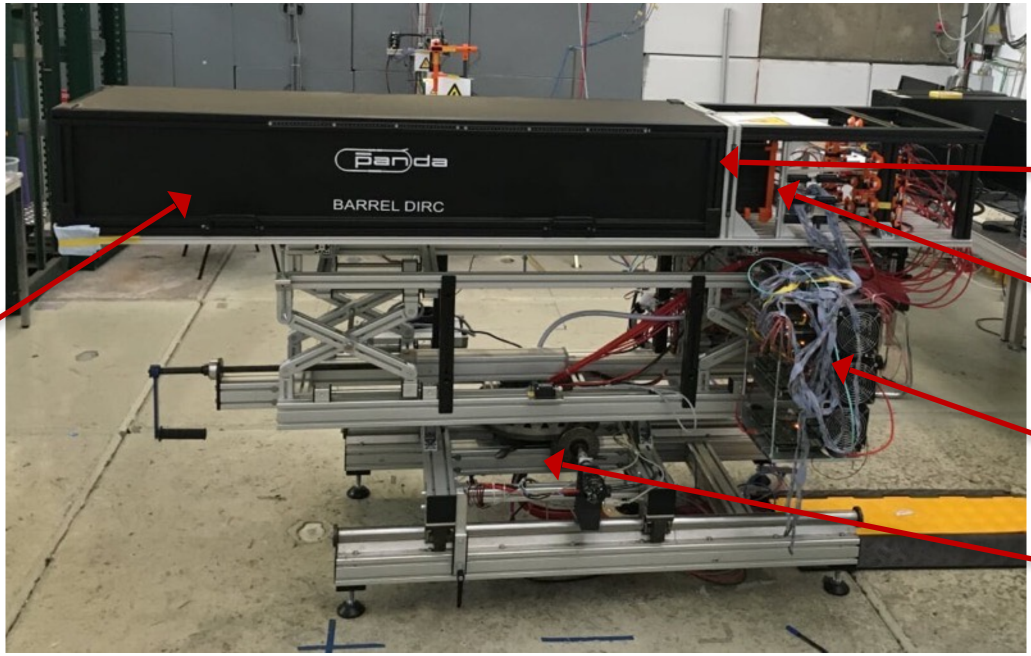


2012: CERN

Beam test at CERN PS/T9

- Fused silica prism as expansion volume.
- 4 x 3 array of PHOTONIS Planacon XP85012 MCP-PMTs.
- Narrow bar or wide plate as radiator.
- 3-layer spherical or cylindrical lenses.
- Momentum and angle scans similar to PANDA phase space.
- Goal: PID validation of near-final design (also: test of EIC DIRC lens)





Dark box for optics (bar, lens, prism)

MCP-PMT array

Frontend electronics (PADIWA) (air-cooled)

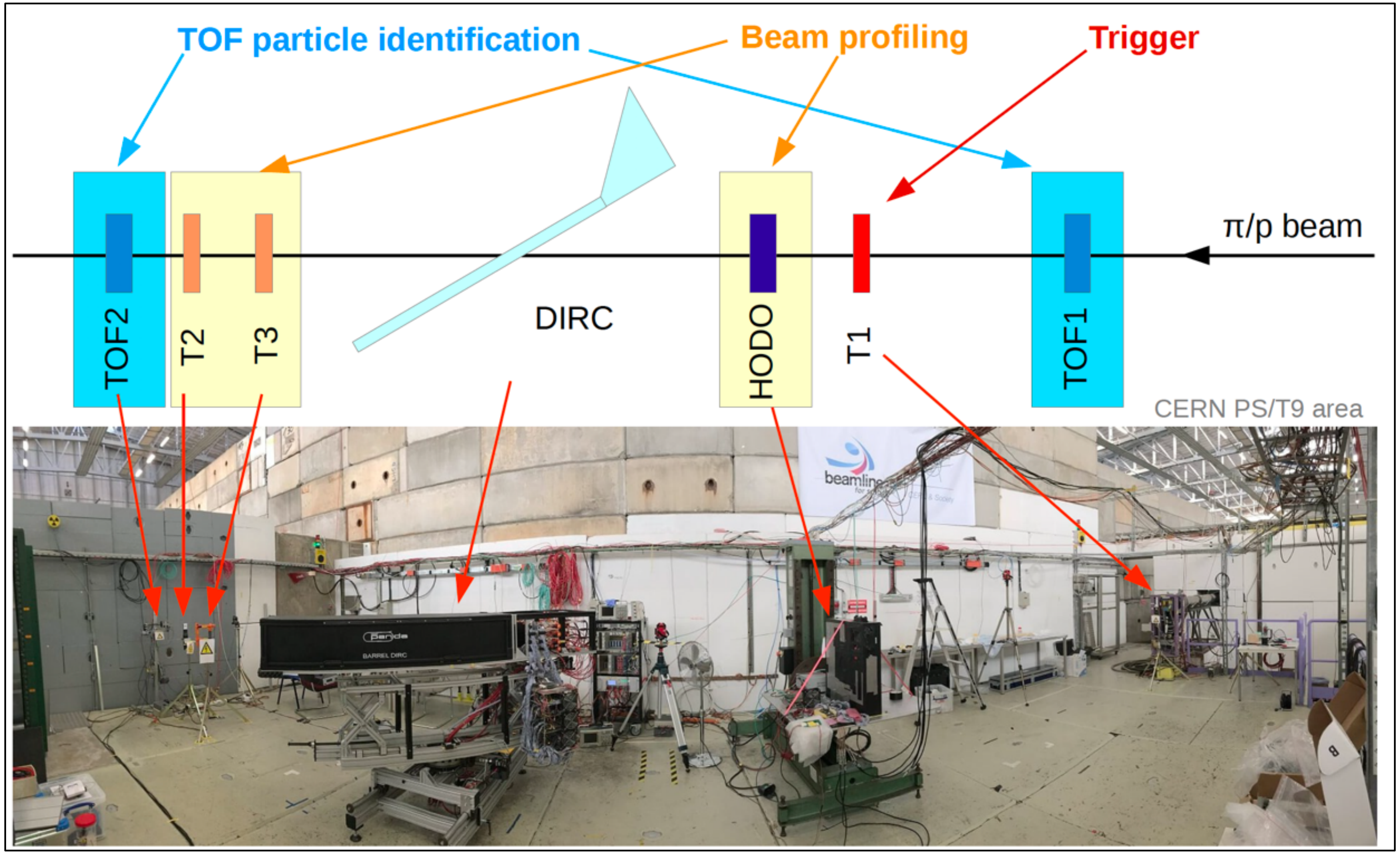
DAQ boards (TRB)

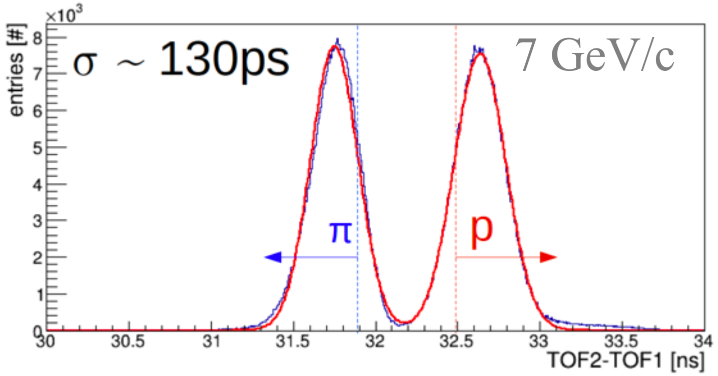
Rotation stage (remote controlled)

T9 beamline: mixed hadrons (mostly π and p), available momentum range 1.5-10 GeV/c

Most measurements at 7 GeV/c – π/p Cherenkov angle difference (8.1 mrad) approx. same as π/K at 3.5 GeV/c (8.5 mrad).

Scintillators for trigger (T1-3) and beam spot selection in combination with fiber hodoscope.





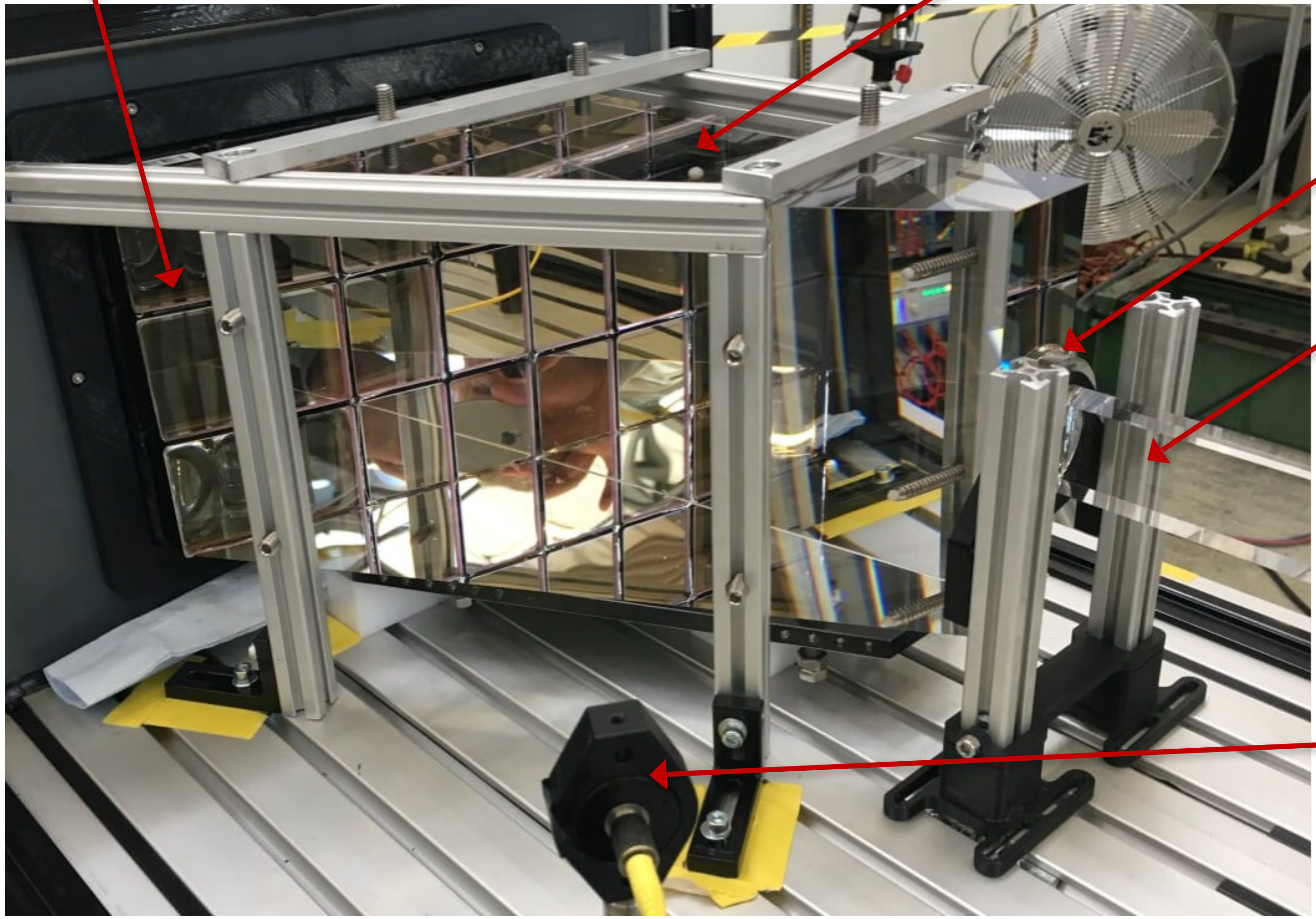
Time-of-flight system

Two TOF stations, ~28m distance

Clean tag for pions and protons up to 10 GeV/c.

PHOTONIS Planacon MCP-PMT array

Fused silica prism (33° opening angle)



Spherical 3-layer lens

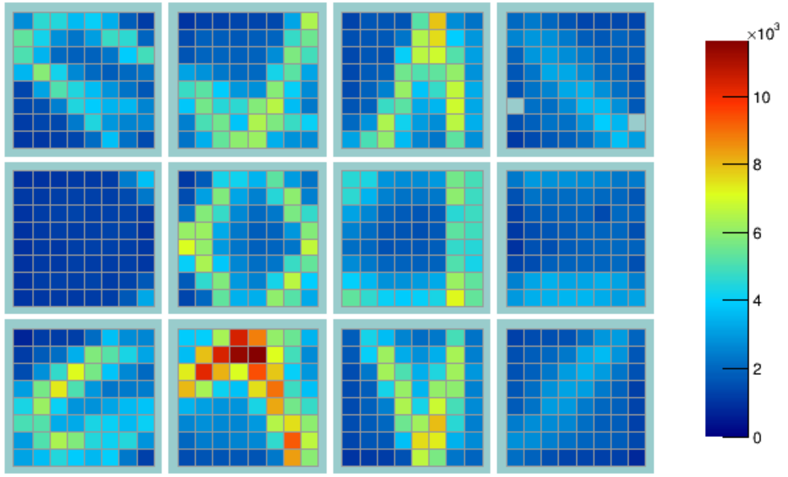
Narrow bar (35mm width)

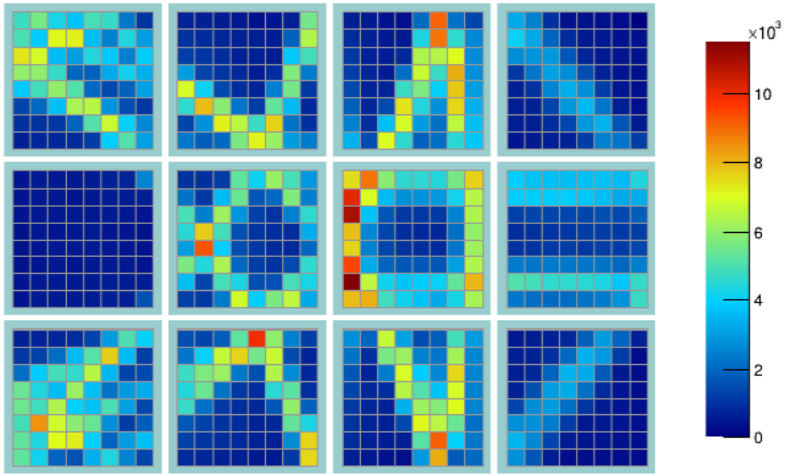
Diffuser for PiLas laser pulser

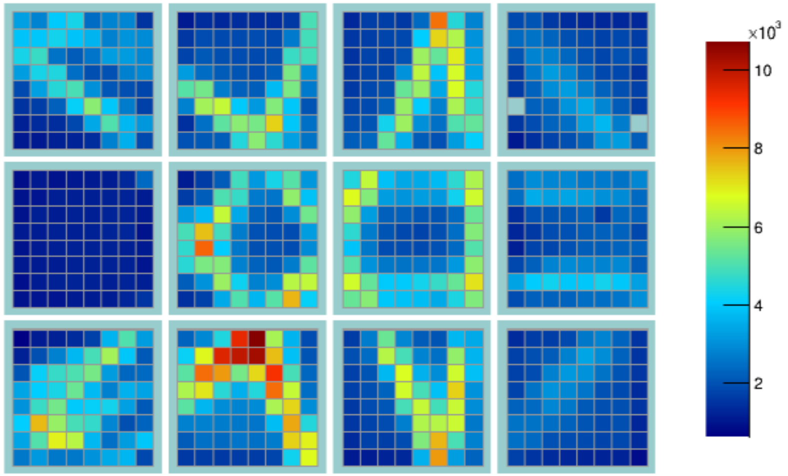
Examples of the Hit Pattern

- 20 degree polar angle
- pions and protons @ 7 GeV/c
- bar + 3 layer spherical lens

- beam data with proton tag
- beam data with pion tag
- geant simulation for pions





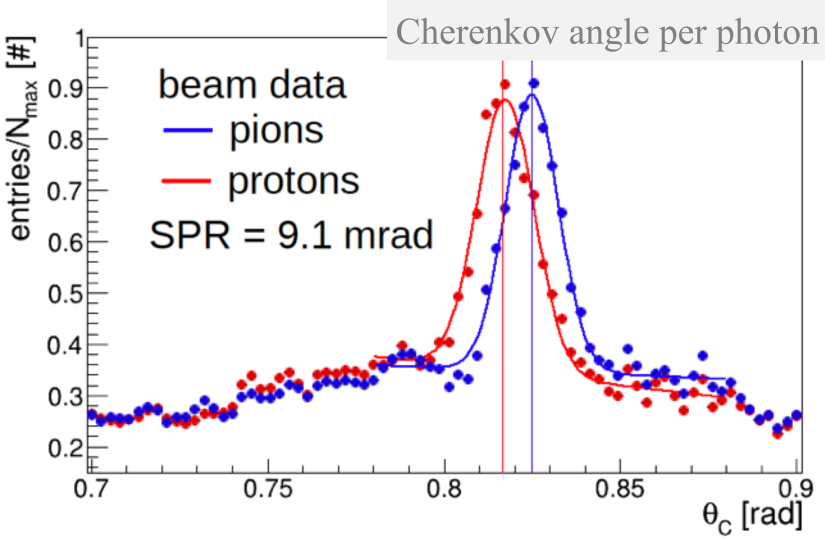


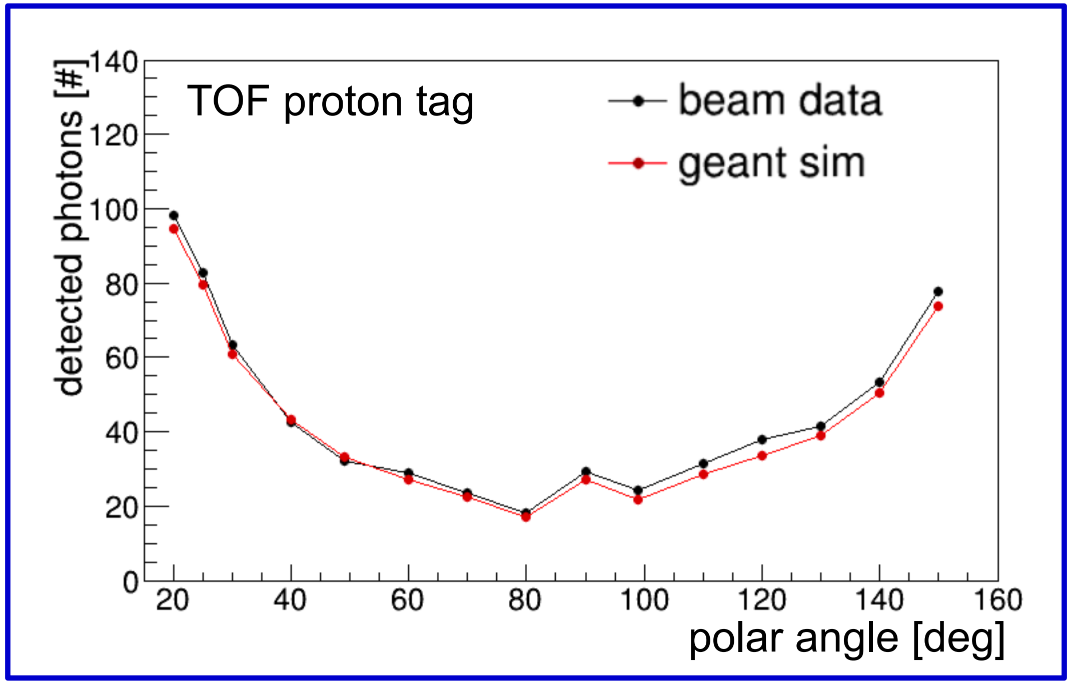
Photon yield and single photon Cherenkov angle resolution (SPR)
at 7 GeV/c (equivalent to 3.5 GeV/c π/K).

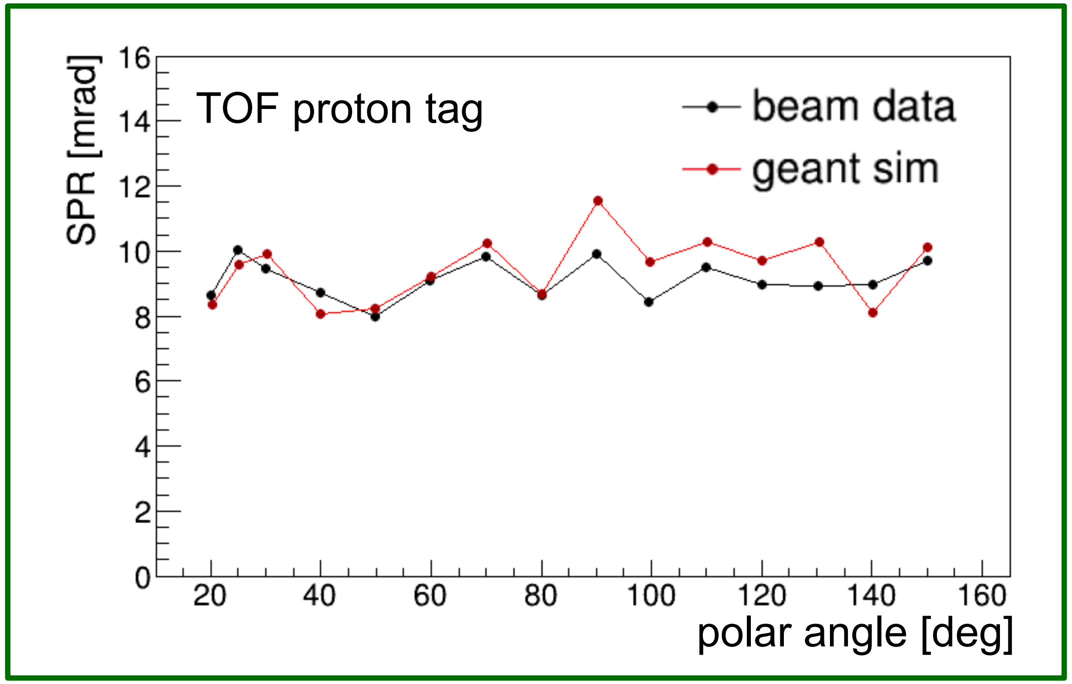
Geometric (“BaBar-like”) reconstruction method.

Very good agreement with detailed prototype Geant simulation.

Calibration of data still ongoing
All results still preliminary







SELECTED 2017 BARREL DIRC PROTOTYPE RESULTS

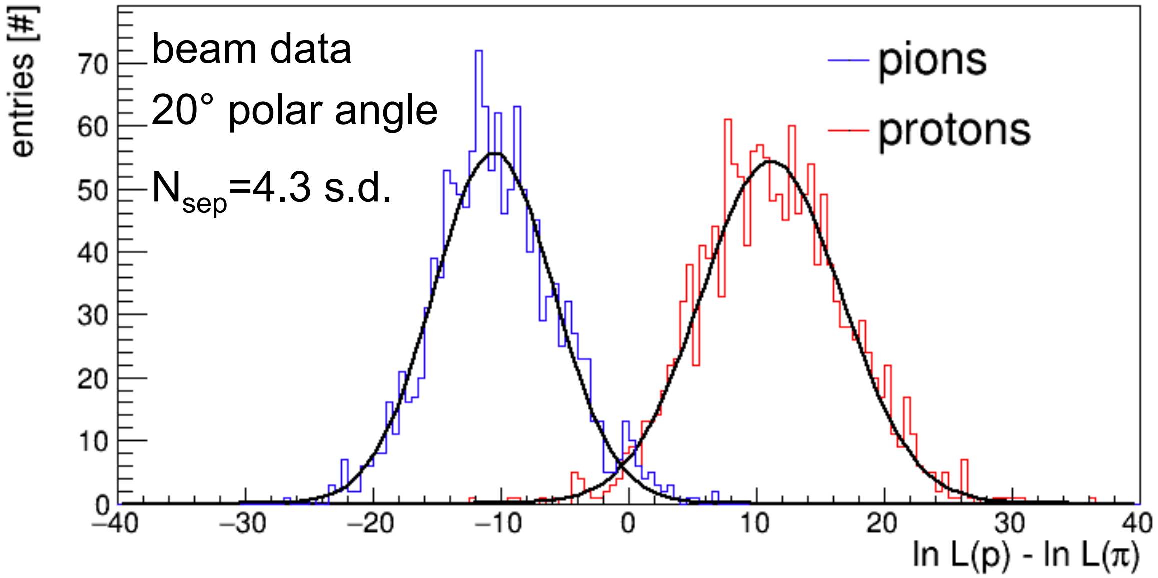
Calibration of data still ongoing
All results still preliminary

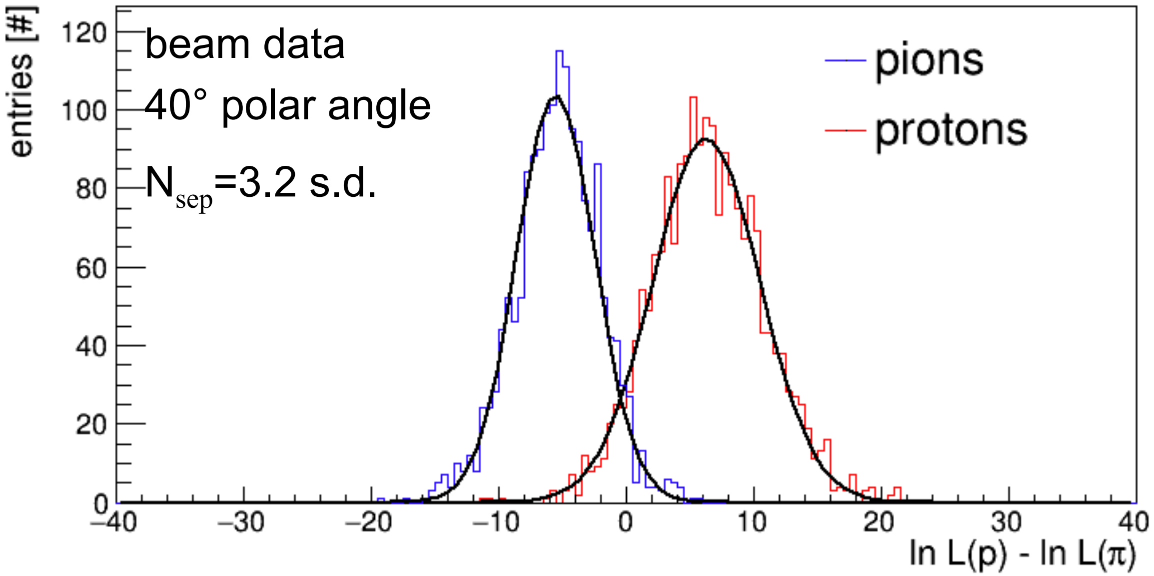
Separation power (N_{sep}) for TOF-tagged pions and protons
at 7 GeV/c (equivalent to 3.5 GeV/c π/K).

Time-based imaging reconstruction method, PDFs from beam data (250ps average timing precision).

PID performance exceeds PANDA requirements, validates narrow bar/spherical lens design.

Result extrapolates to 6.6 s.d. π/K at 3.5 GeV/c, 22° for
fully equipped PANDA Barrel DIRC (simulation with 100 ps timing).



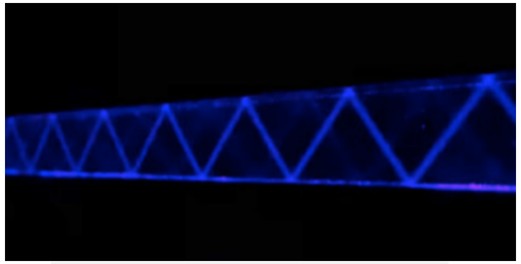


Cost-optimized design completed, performance validated in particle beams

TDR available at arXiv:1710.00684, accepted for publication by Journal of Physics G

Optimizing simulation and reconstruction code with experimental data at GlueX DIRC ("FAIR Phase 0") ➞ see talk by M. Patsyuk today.

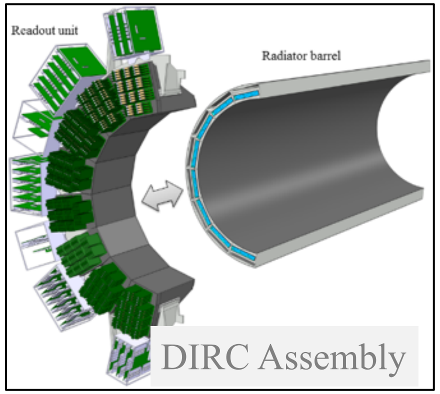
Starting construction phase, first round of call for tenders this summer.



DIRC bar with blue laser

2018-2023: Component Fabrication, Assembly, Installation

- 2018/2019: Finalize specifications, MoUs, call for tenders and contracts
- 2019-2021: Industrial fabrication of main components (sensors, bars, lenses, prisms)
- 2019-2020: Production and QA of readout electronics
- 2019-2022: Industrial fabrication of bar boxes and mechanical support frame; QA of all components; gluing of long bars, assembly of complete sectors
- 2023/2024: Installation in PANDA, commissioning



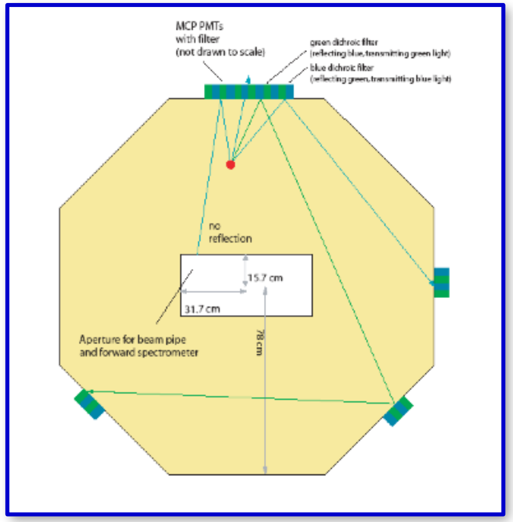
DIRC Assembly

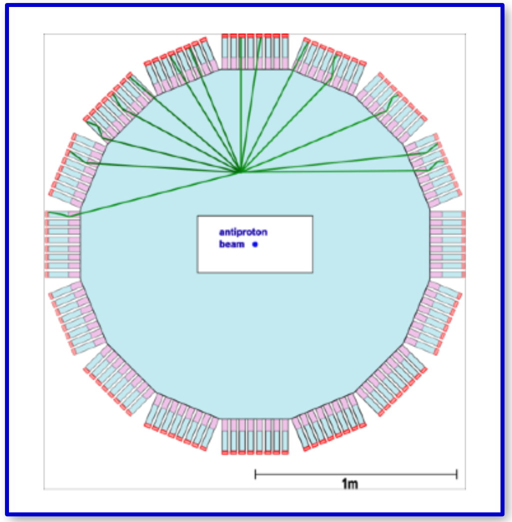
ENDCAP DISC DIRC: EARLY DESIGNS

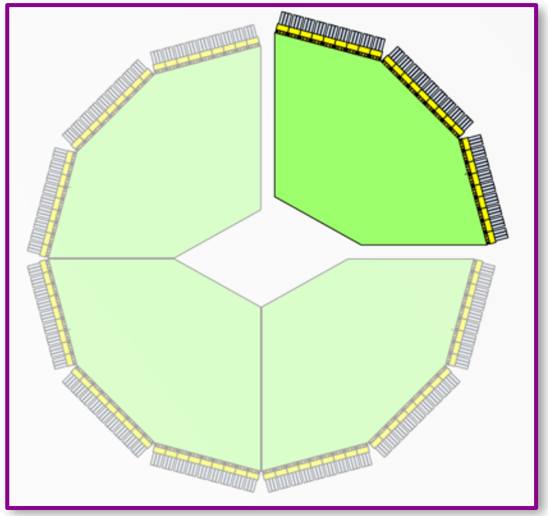
RICH 2007: two design options

- Time-of-Propagation design
  - linear array of pixels, very fast photon timing
  - dichroic mirrors for dispersion mitigation
- Focusing Lightguide design
  - 2D pixels plus fast photon timing and focusing
  - LiF block for dispersion mitigation
- Radiator: single large plate

Both designs showed potential to reach required performance.







RICH 2013: merged into compact 3D design

- Radiator: four optically isolated quadrants
- Imaging: 2D spatial plus fast timing
- Sensors: (d)SiPMs or MCP-PMTs
- Focusing: cylindrical focusing elements
- Fits into tight available space in PANDA endcap

Detailed simulation: design meets PANDA PID goals.

ENDCAP DISC DIRC (EDD) DESIGN

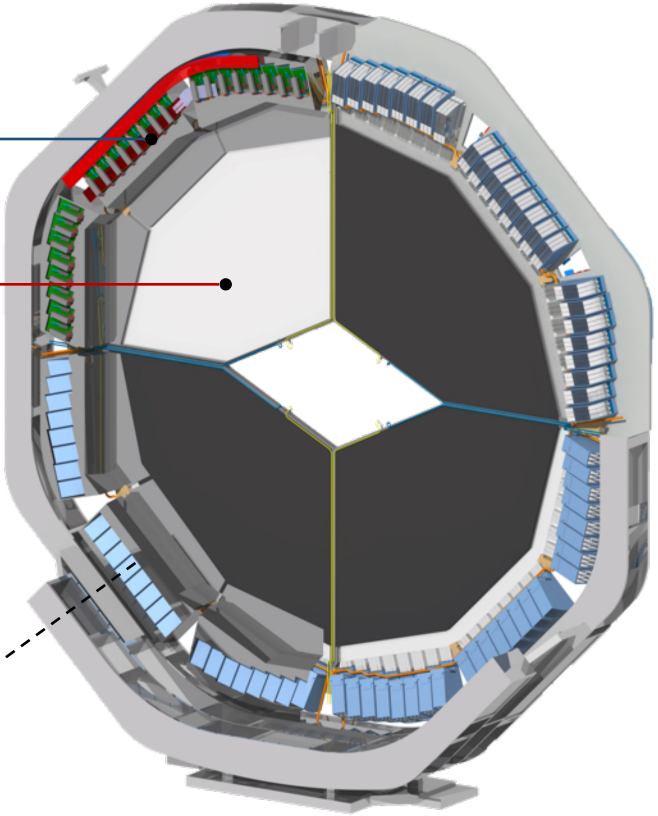
optics made of synthetic fused silica

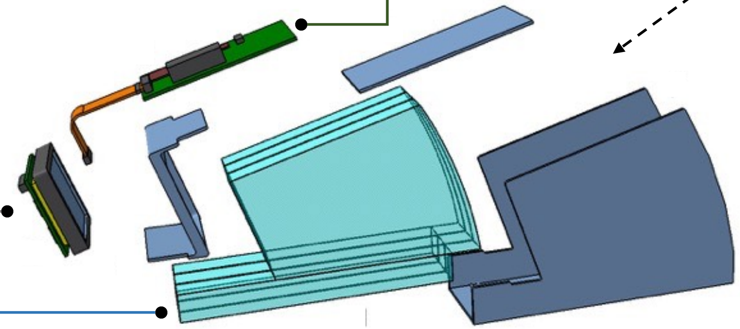
4 independent quadrants

focusing elements convert angle to position information

2-inch MCP-PMT with a pitch of 0.5 mm

ASIC based readout





Quadrant plate dimension:

20mm thickness

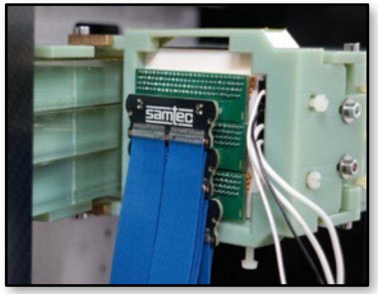
1056mm outer radius

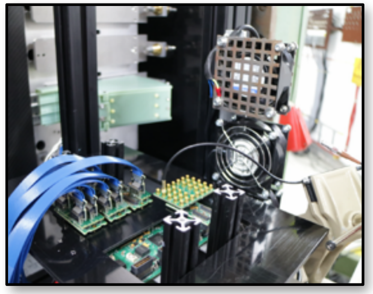
Sensors: 96 MCP-PMTs (lifetime-enhanced, ~3x100 pixels)

Optical band pass filter for chromatic dispersion mitigation

TOFPET ASIC readout

~30k channels

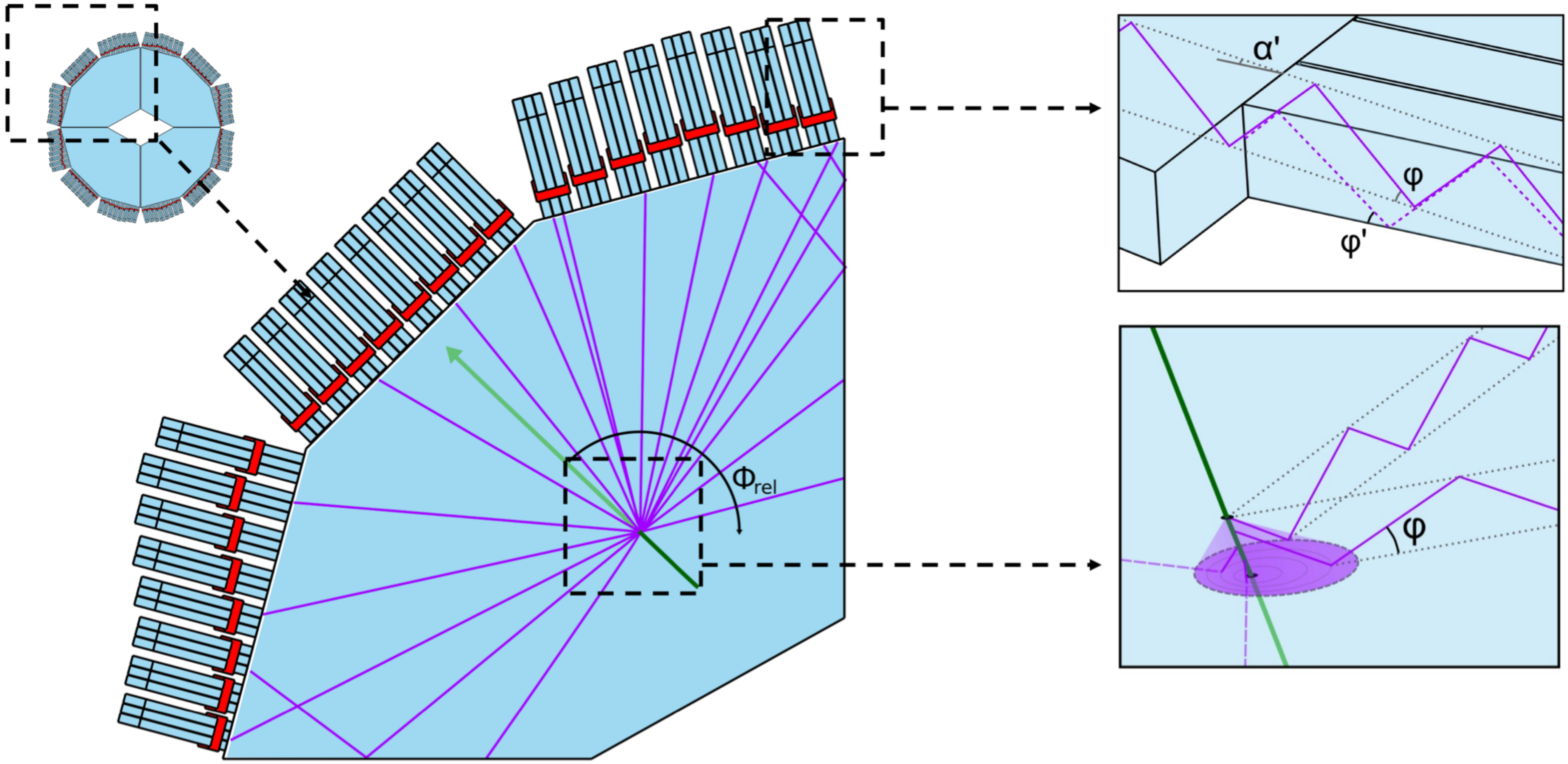


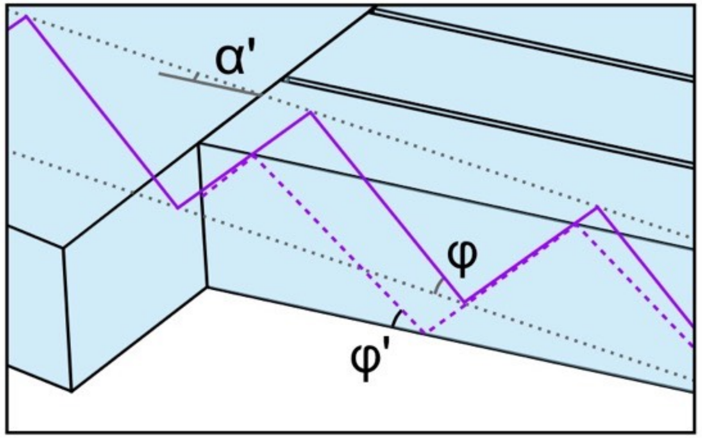


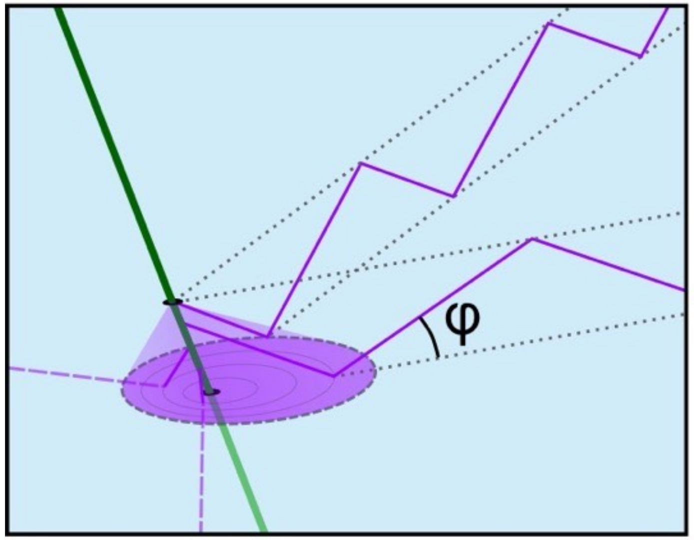
Beam tests at CERN in 2015 and at DESY in 2016 validated basic performance parameters.

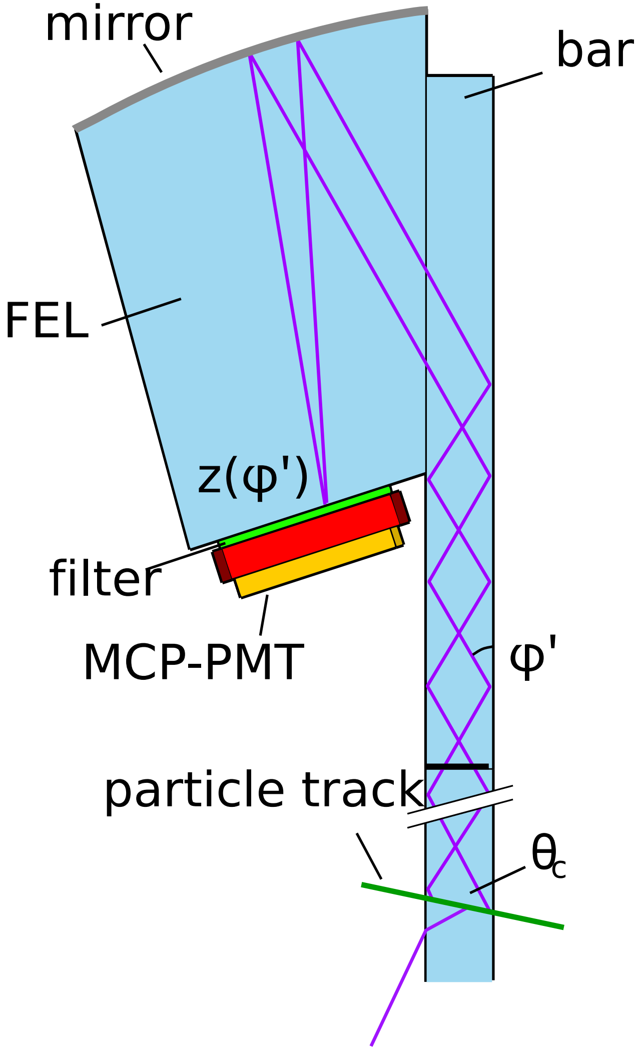
TDR recently completed

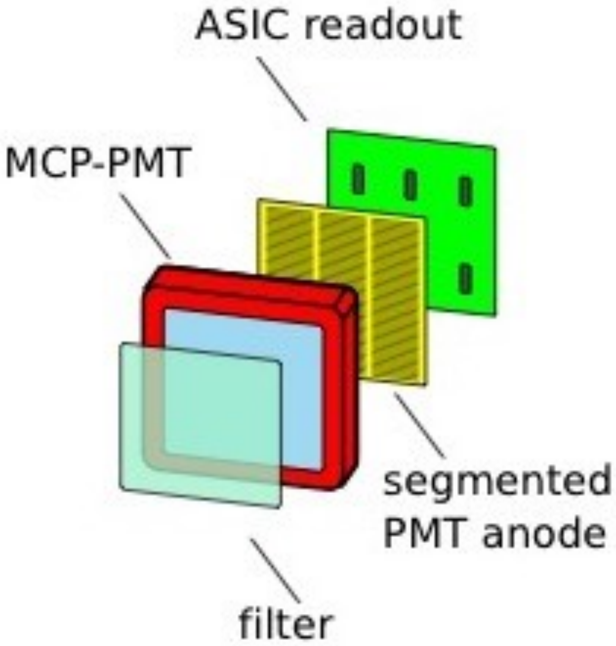
ENDCAP DISC DIRC PRINCIPLE







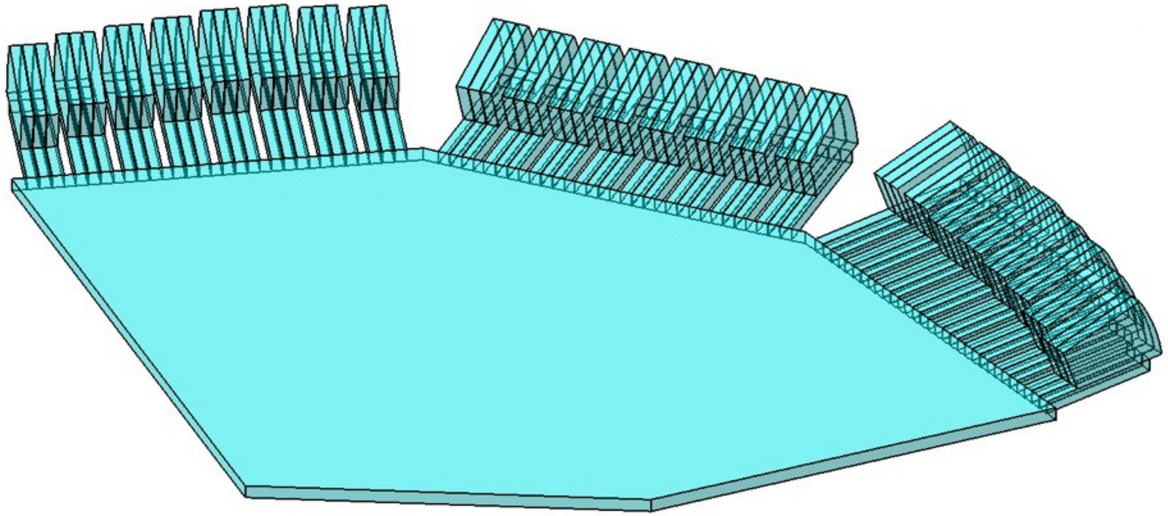


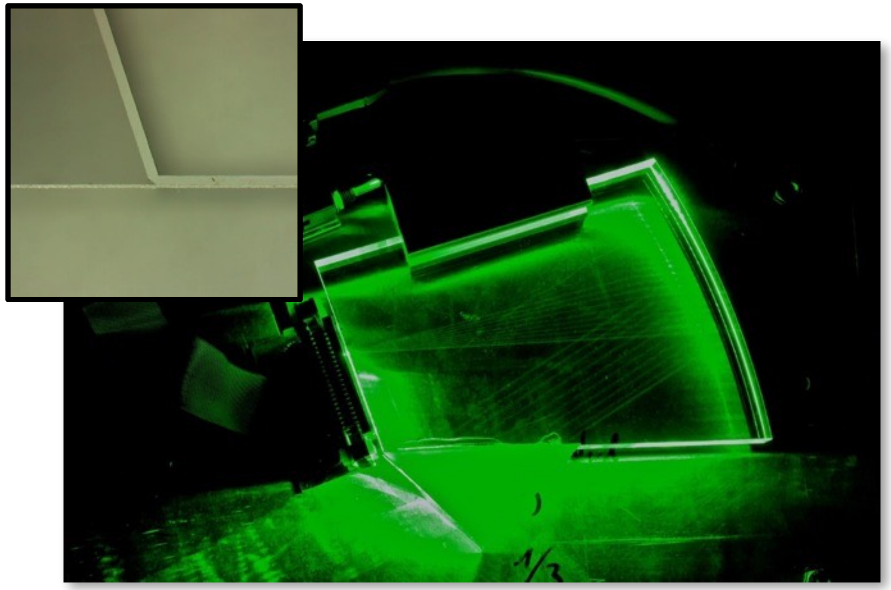


$$\theta_c = \arccos\left(\sin\theta_p \cos\phi_{\text{rel}} \cos\varphi + \cos\theta_p \sin\varphi\right)$$

EDD Optical System

- Thin design for very tight forward endcap space in PANDA
- Large plate surfaces parallel with excellent polish (<1.5nm *rms*)
- Tight tolerances on dimensions
- Lightguide bars of different lengths needed to place spherical focusing elements into available locations





- Custom 2" MCP-PMTs, asymmetric pixels
- Optical filter to limit photon wavelength range → n(λ)
- Optical contact bonding for best possible transmission
- Position resolution better than 150 µm

EDD: Key Technology

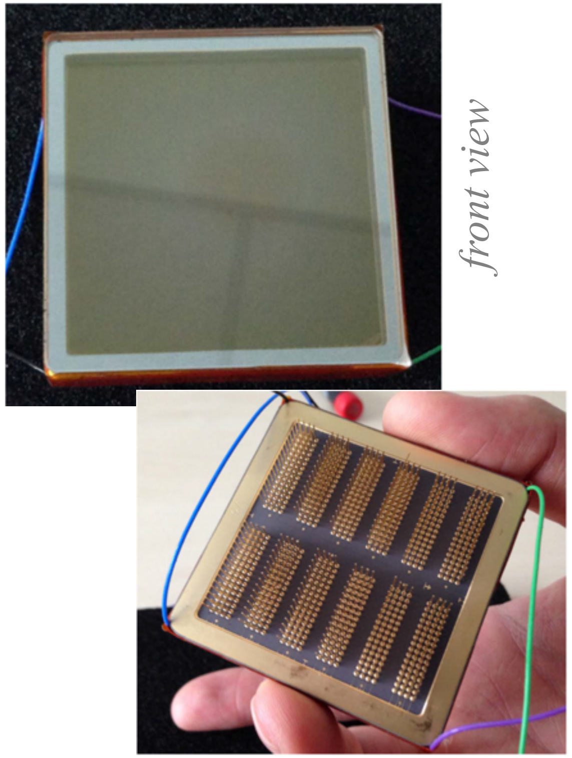
J. Rieke, IEEE 2014,

EDD needs sensor with very small pixels (0.5mm pitch) in one direction, coarse pixels (1-2cm pitch) in the other.

Single photon sensitivity in high magnetic field (~1T) with long lifetime (~7C/cm^2), fast timing (<100ps)

(d)SiPM initially a promising candidate but rejected due to concerns about radiation hardness.

Hamamatsu (6x128)



front view

anode pin array

Obtained prototype 2” MCP-PMTs from Hamamatsu and PHOTONIS

Options with custom photocathode available.

Excellent gain and timing performance.

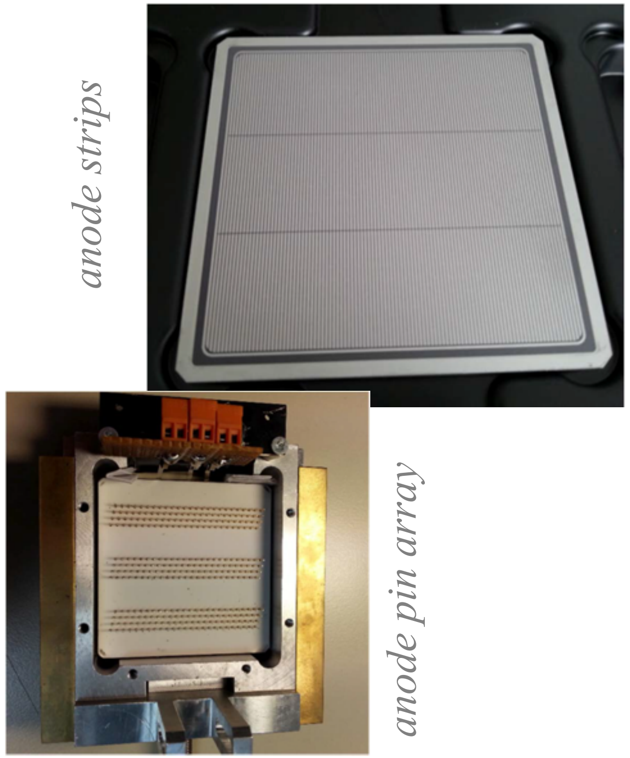
Charge sharing suppressed in magnetic field.

Tubes meet position resolution requirement.

Both good candidates for the PANDA EDD.

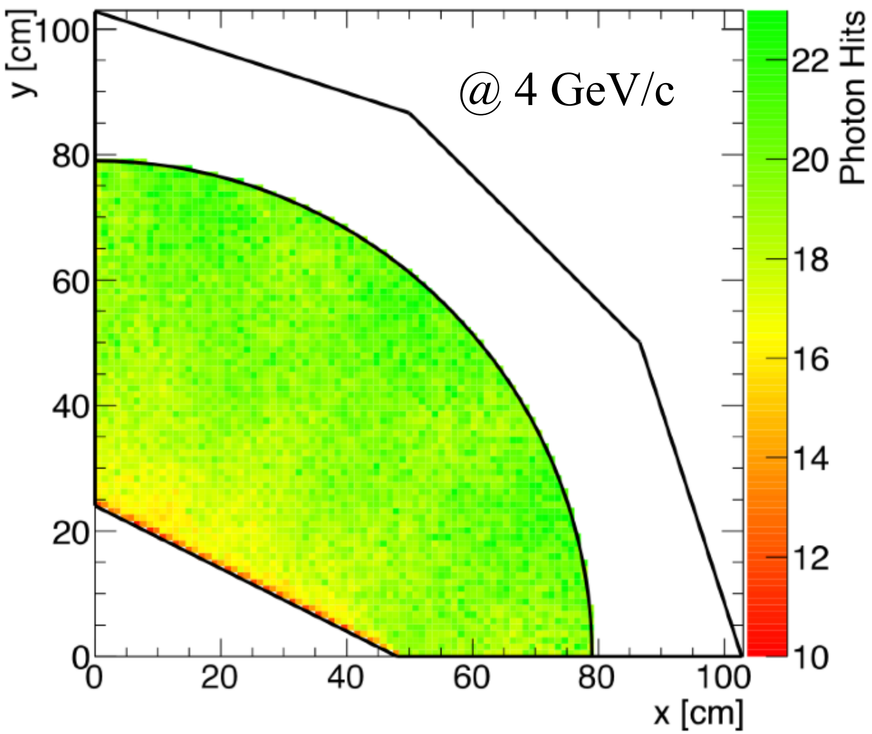
PHOTONIS (3x100)

anode strips

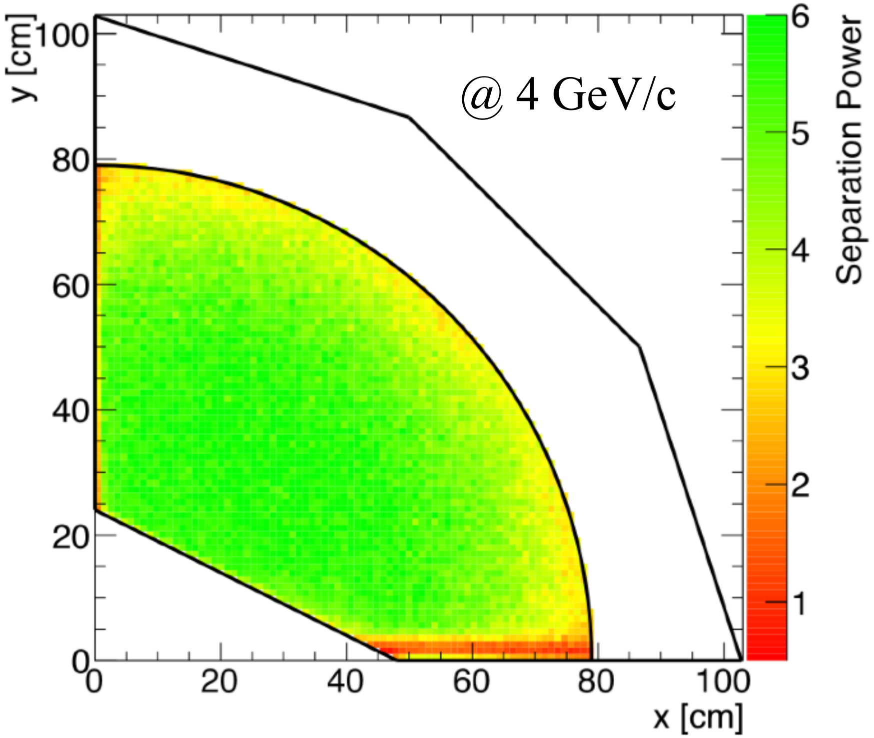


anode pin array

Photon yield (Geant)



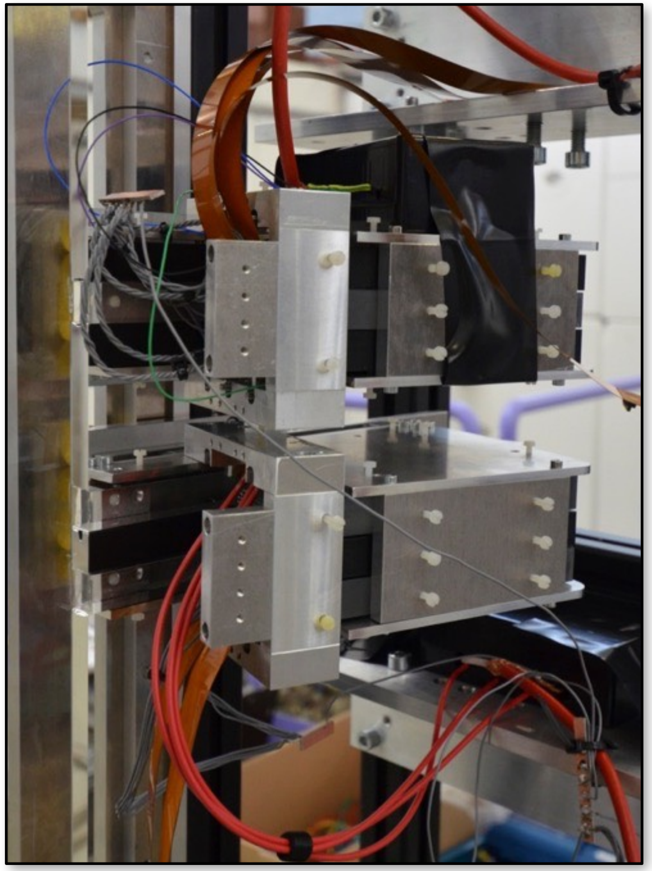
π/K separation power (Geant)



- simulation expects about 20 detected photons per charged particle
- the target of 3 s.d. separation power will be achieved for almost the entire active area

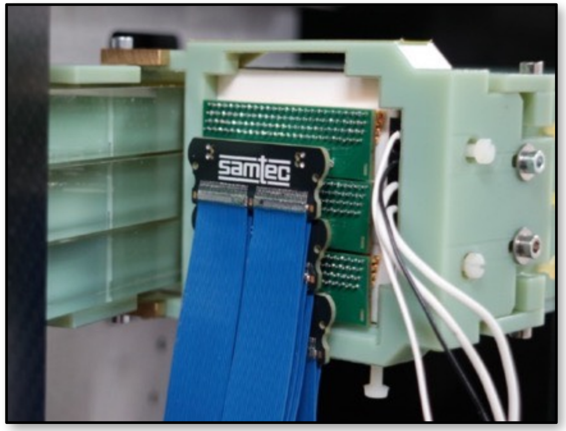
EDD Prototypes in Particle Beams

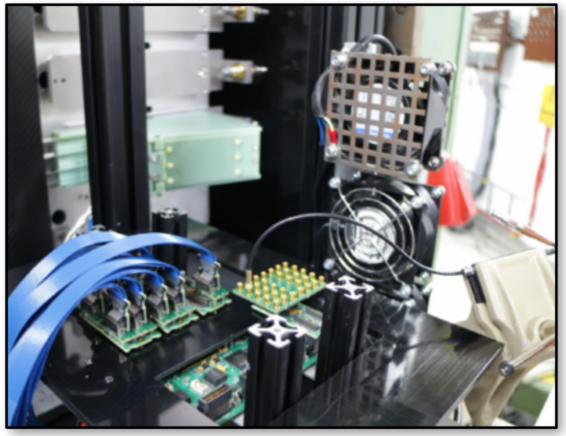
2015 testbeam @ CERN



- mixed hadron beam up to 10 GeV/c
- TRBv3 readout

2016 testbeam @ DESY



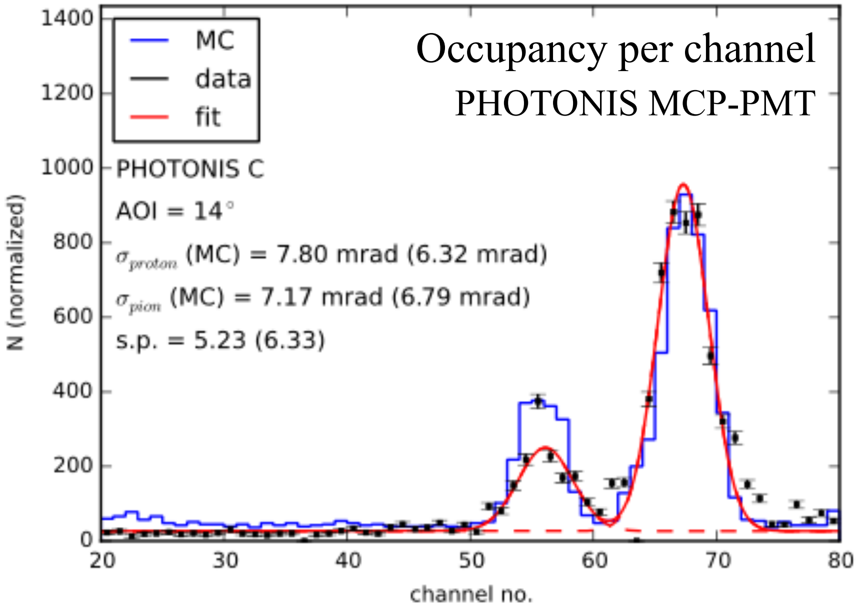


- 3 GeV/c electron beam
- TOFPET ASIC readout
- fully equipped ROM

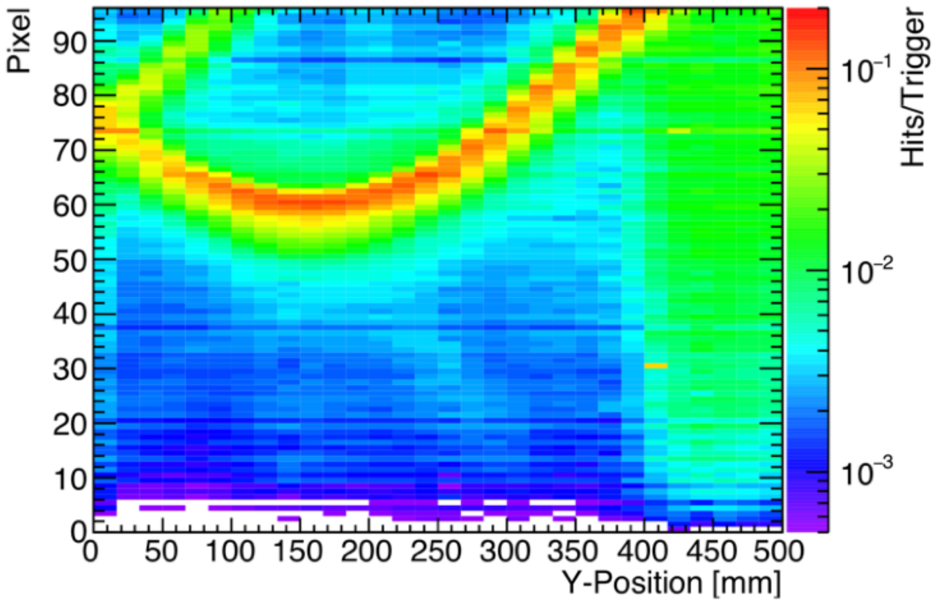
Common features:

- fused silica optics
- 50x50x2 cm^3 radiator
- MCP-PMTs with high anode granularity

2015



2016

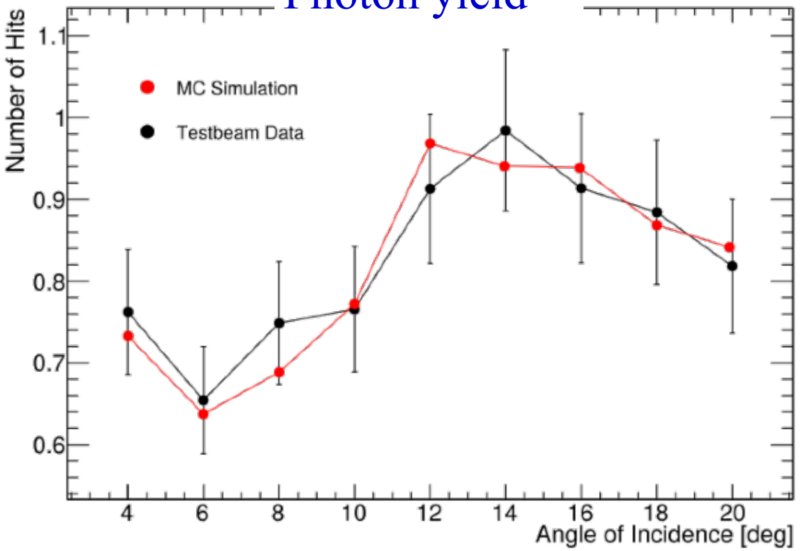


- single photon resolution of 5.7 mrad was measured
- 5σ π/p-separation at 3 GeV/c with single photons

- Cherenkov pattern observed
- resolution of both testbeam campaigns limited by tracking and chromatic dispersion

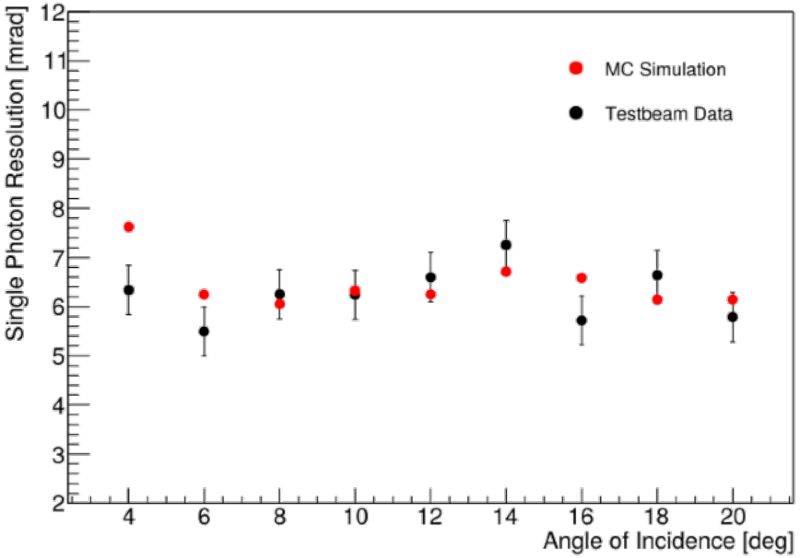
2016

Photon yield

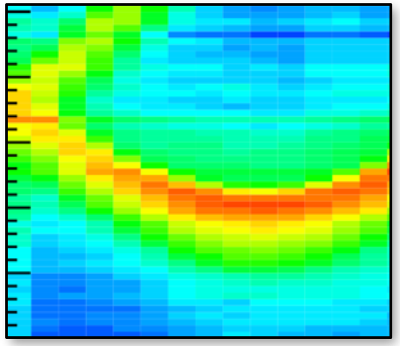


2016

Single photon Cherenkov angle resolution

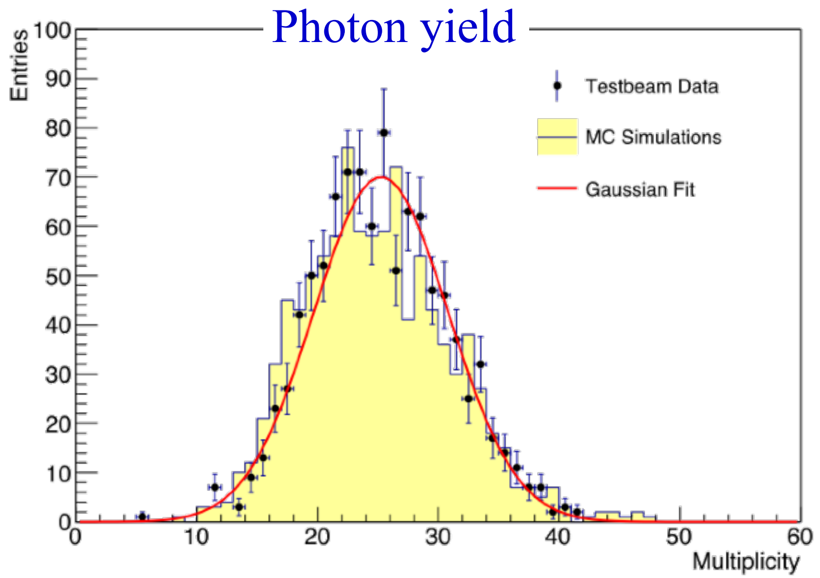


- photon yield for single MCP-PMT column in agreement with MC data
- increase at 12° due to overlapping Cherenkov patterns (side reflection)

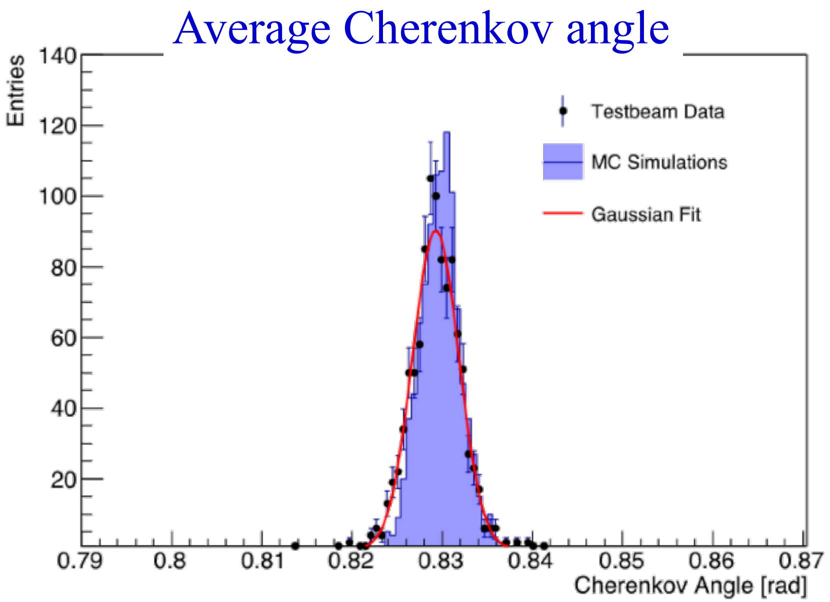


- good agreement for single photon resolution for all angles and positions
- fluctuations are caused by different paths inside the FEL

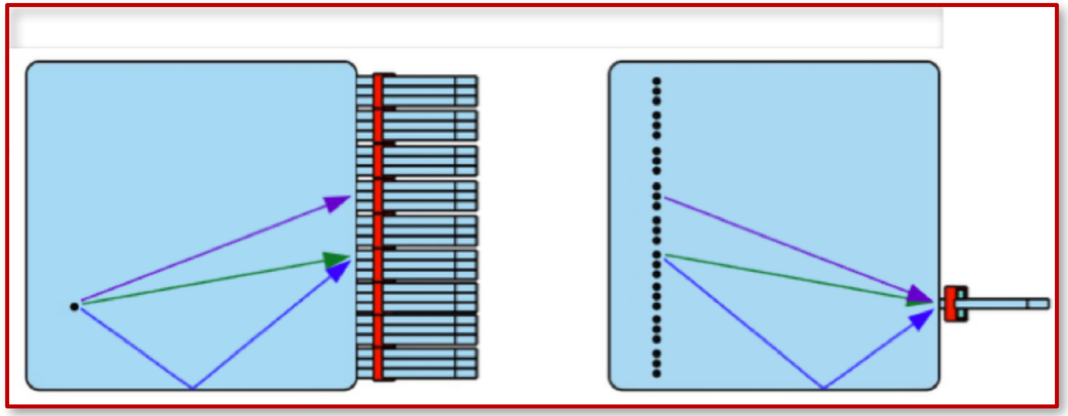
2016



2016



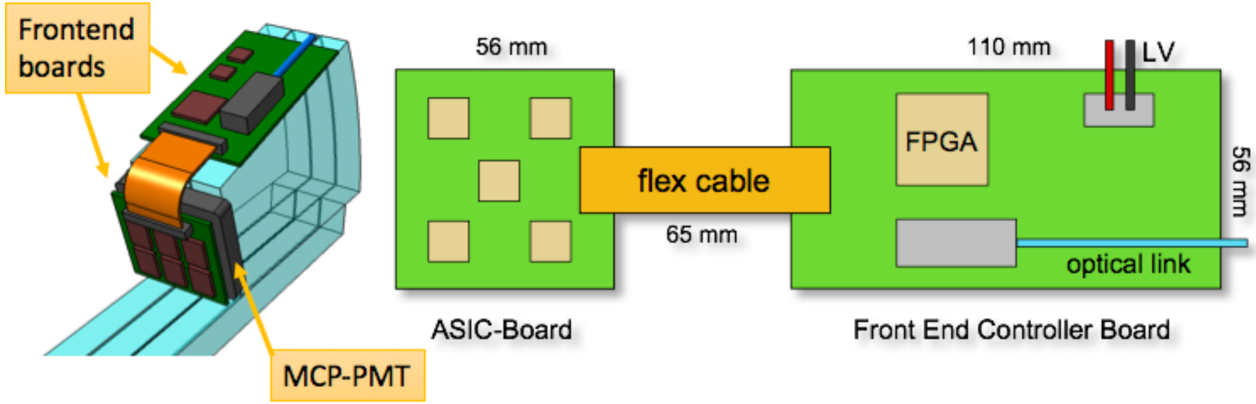
- „Combined event" data set is constructed by combining events from different vertical positions to overcome limitation of single sensor/FEL.

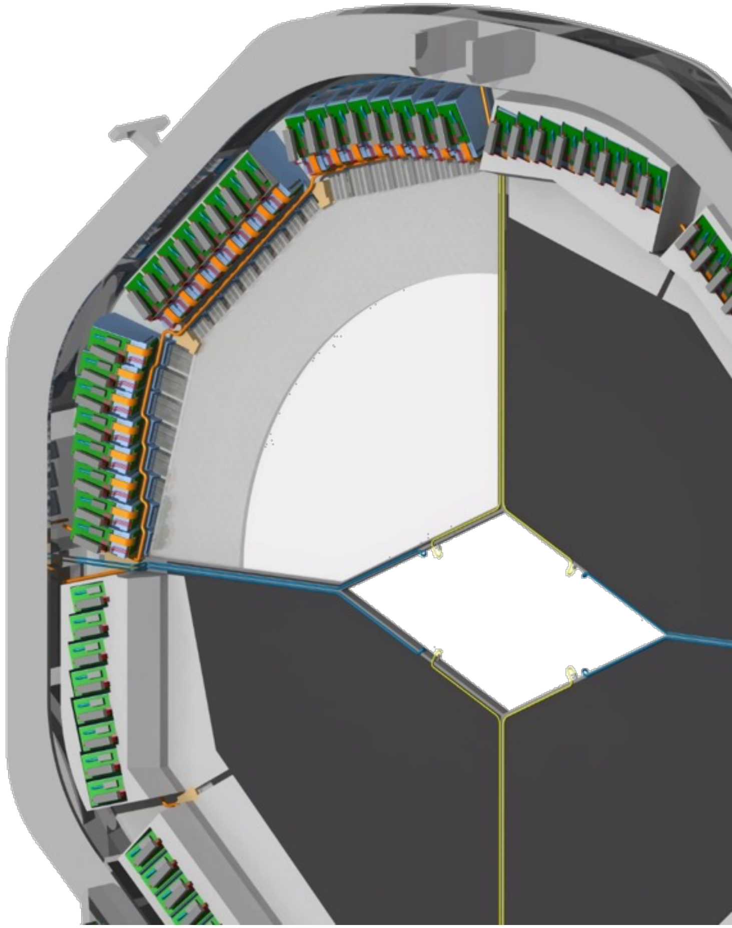


- Photon yield and single photon resolution in good agreement with MC predictions
- Cherenkov angle resolution "per particle" obtained: 2.5 mrad for data (2.2 mrad Geant)
- Performance meets PANDA PID requirements

Endcap Disc DIRC Summary

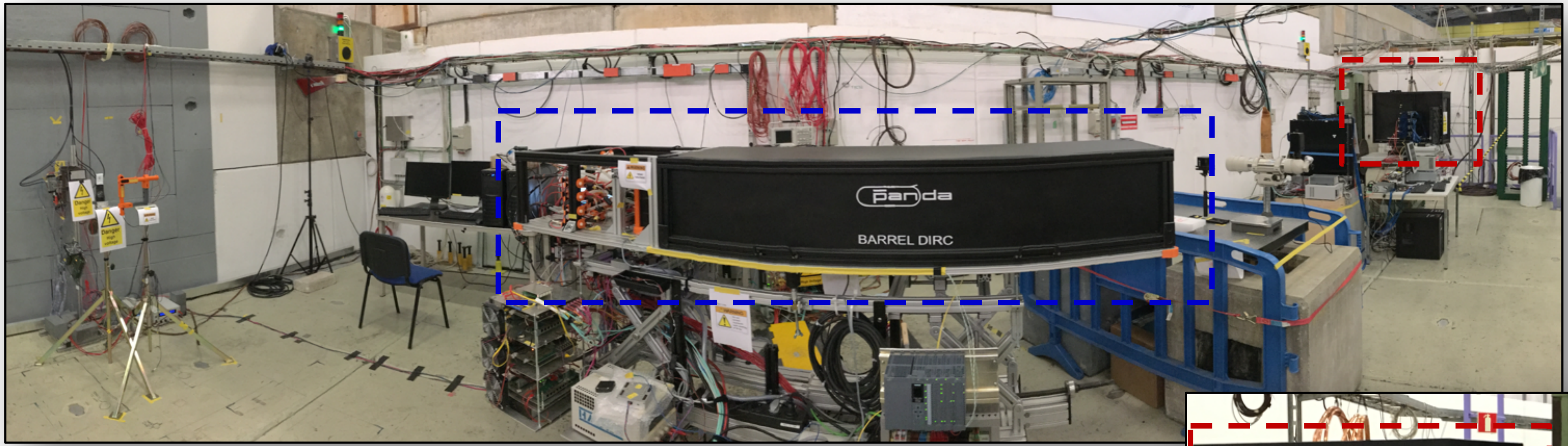
- The main technical challenges have been solved (optics, photon sensors, readout)
- Final detector design has been described in a Technical Design Report
- Readout very compact to meet spatial requirements in PANDA





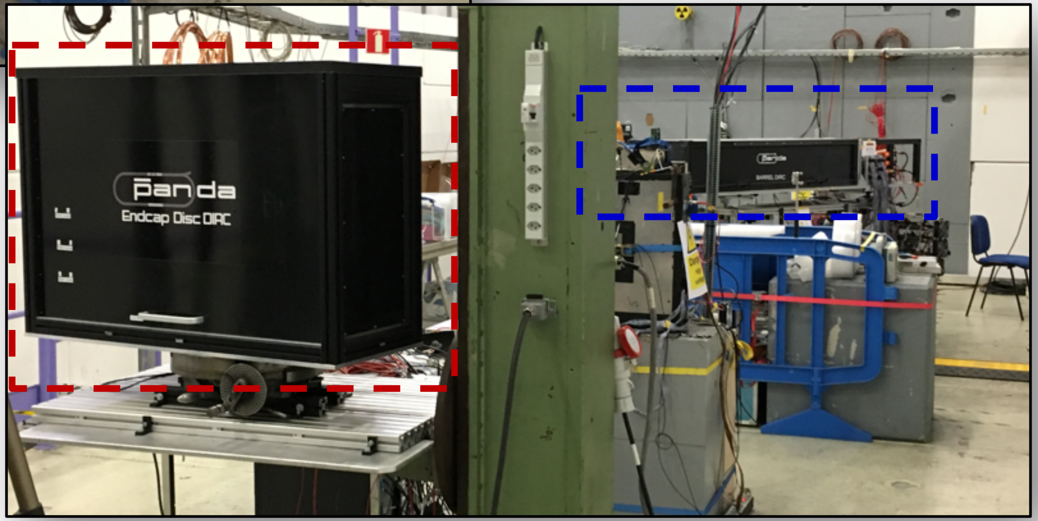
- Goal is to build a full size prototype quadrant until 2021
- Installation of full detector for phase 2 of PANDA in 2025

Both PANDA DIRC prototypes currently in T9 beamline at CERN PS until Aug 15, 2018.



Barrel DIRC

Endcap Disc DIRC



→ direct measurement of PID performance across PANDA phase space

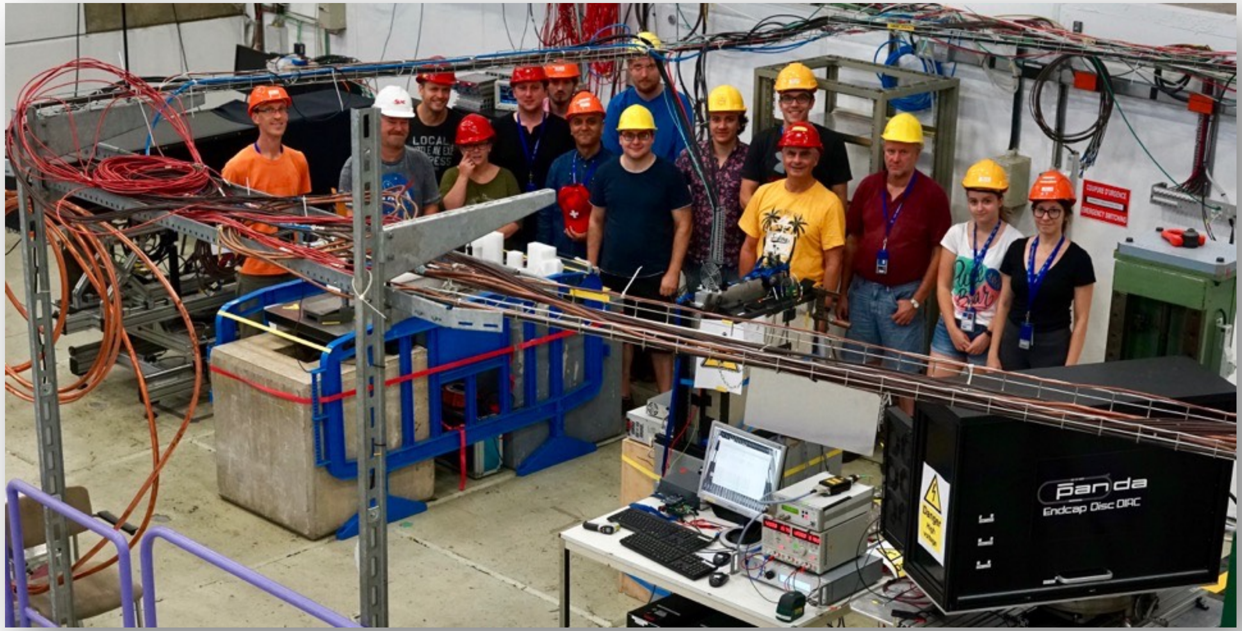
→ test cost-saving design options

The PANDA DIRC counters are key components for the PANDA physics program.

The designs have matured and both detectors are now moving on to the construction phase.

Looking forward to reporting on the component fabrication progress at the next RICH.

PANDA Cherenkov Team at CERN, July 28, 2018



On behalf of the PANDA Cherenkov group,
especially the team currently taking
exciting DIRC data at the CERN PS:

Thank you all for your attention.