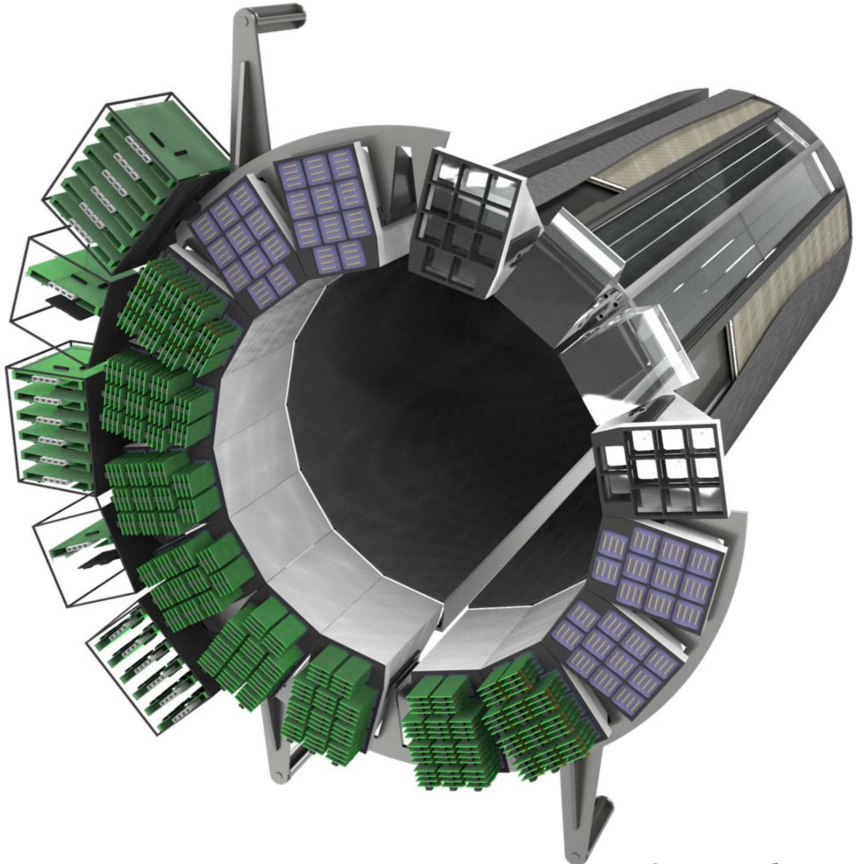
THE PANDA BARREL DIRC DETECTOR

Jochen Schwiening

GSI

for the PANDA Cherenkov Group

- PANDA at FAIR
- Barrel DIRC Technical Design
- PID Performance Validation
- Outlook



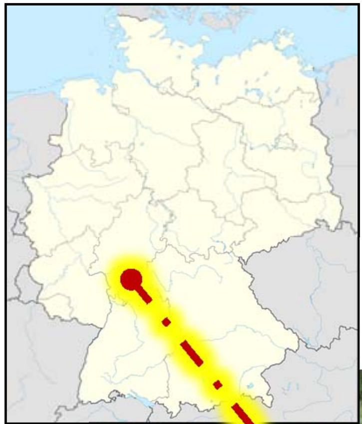
3D rendering of PANDA Barrel DIRC baseline design

The PANDA Cherenkov Group:

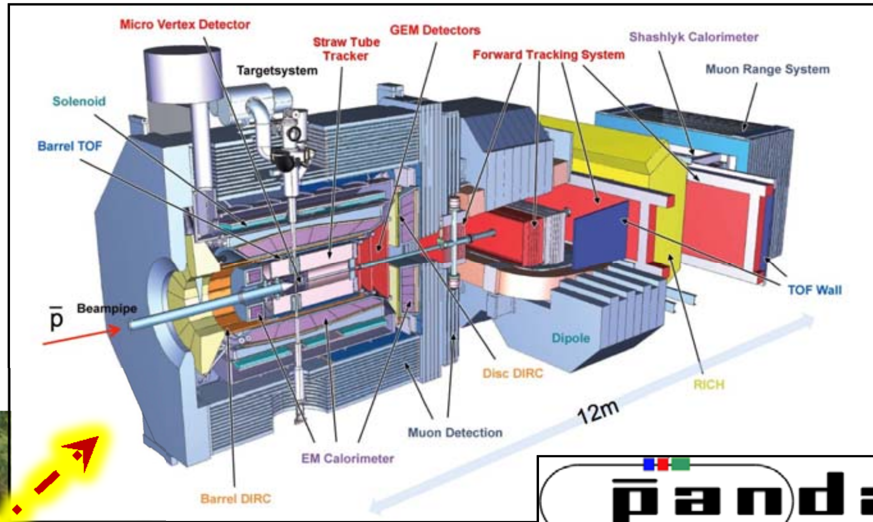
panda · FAU Friedrich-Alexander Universität Erlangen-Nürnberg · Justus-Liebig-Universität Giessen · GSI · JGU Johannes Gutenberg Universität Mainz · FAIR

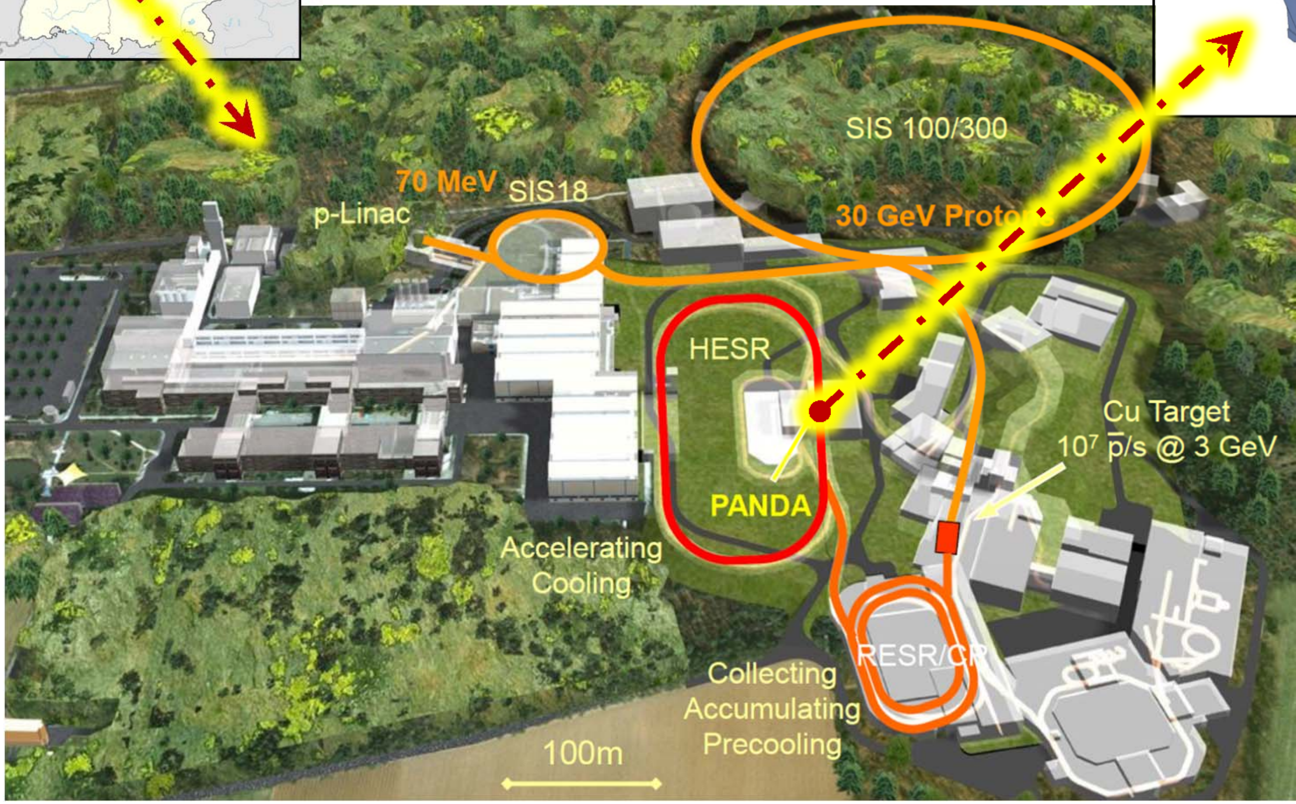
THE PANDA EXPERIMENT AT FAIR

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



- FAIR Accelerator Complex
- PANDA Experiment
- Barrel DIRC Detector

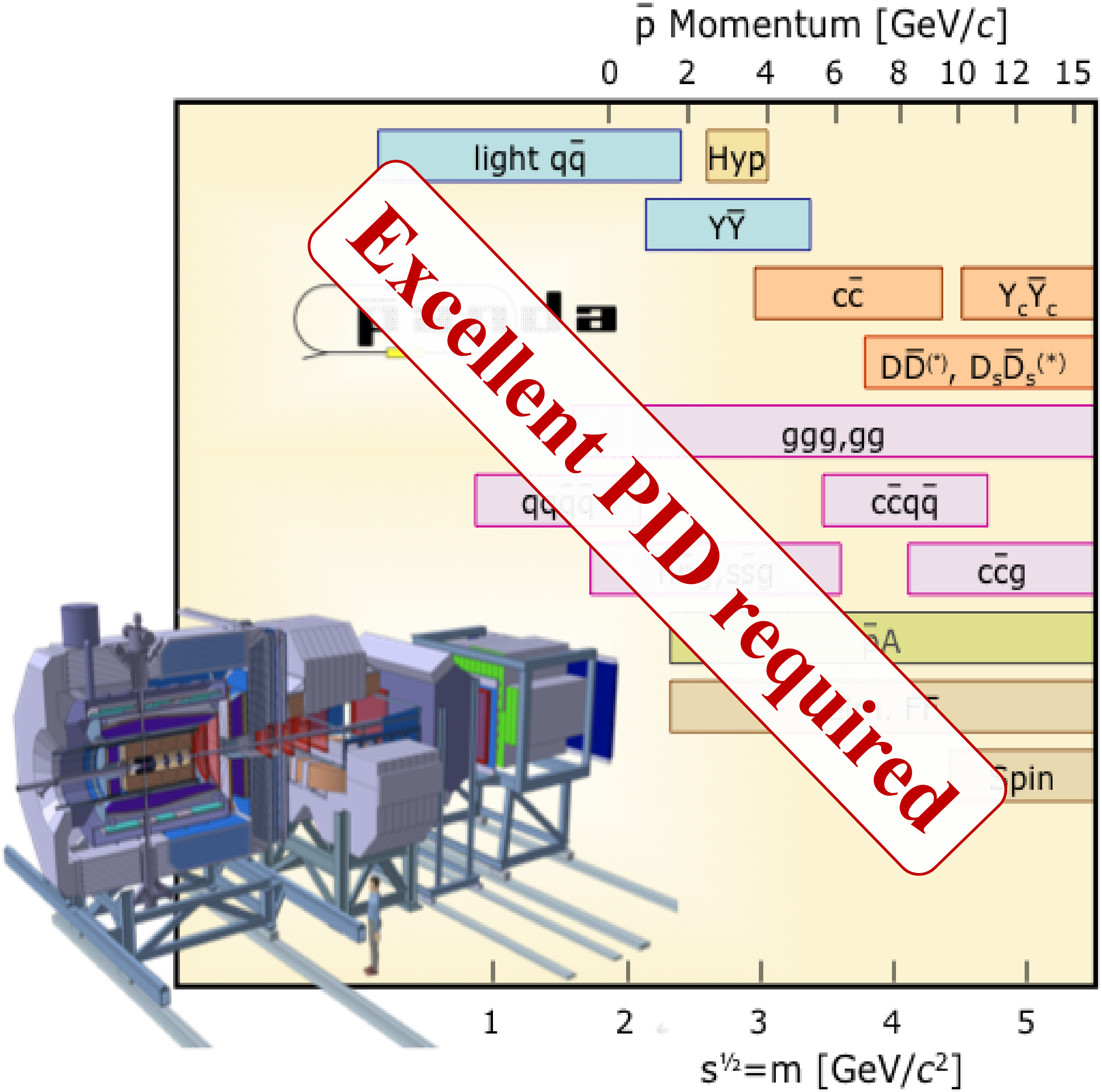




High Energy Storage Ring

- 5×10^{10} stored cooled antiprotons
- 1.5 to 15 GeV/c momentum
- 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}

Study of QCD with Antiprotons



- **Non-perturbative QCD**
- **Hypernuclei**
- **Precision Hadron Spectroscopy**
- **Exotic States (Glueballs, Hybrids)**
- **In-Medium Modifications**
- **Nucleon Structure**

PANDA: two DIRC detectors for hadronic PID

- Barrel DIRC

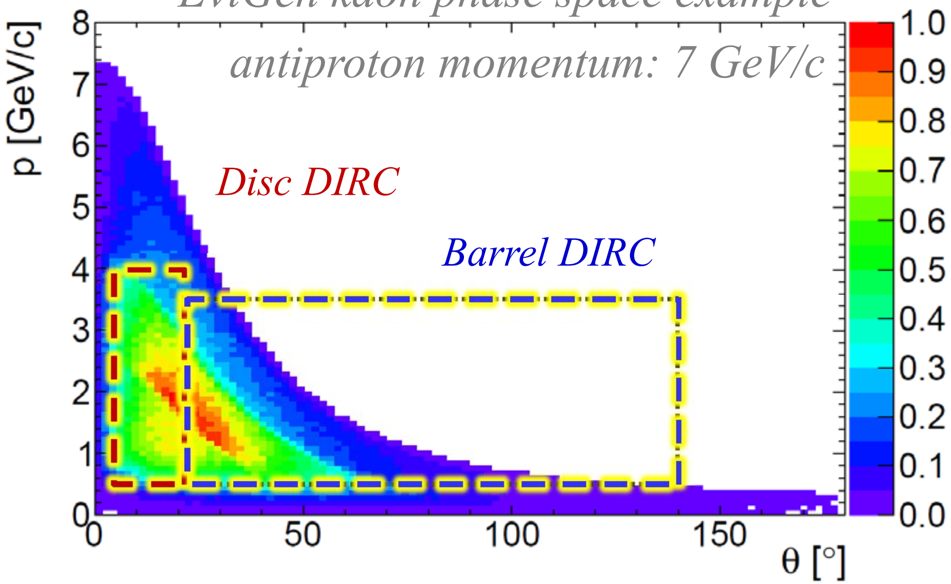
  German in-kind contribution to PANDA

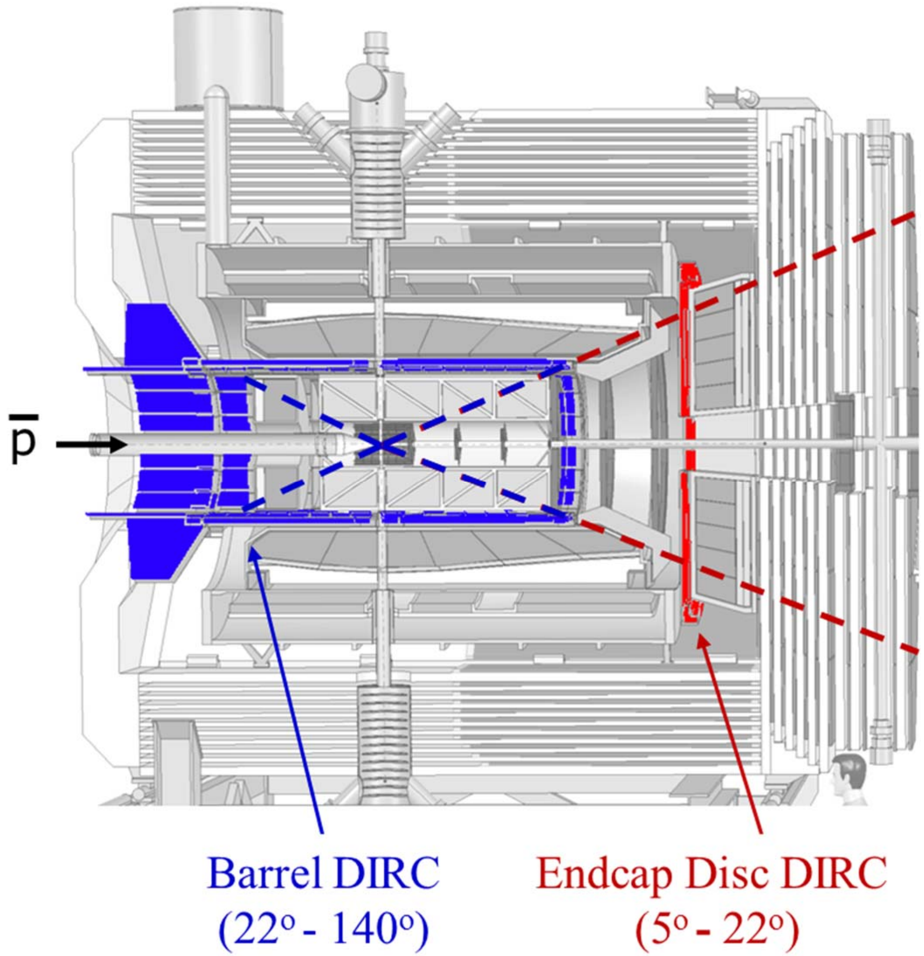
  Goal: 3 s.d. π/K separation up to 3.5 GeV/c

- Endcap Disc DIRC

  ➢ K. Foehl, next talk

  Goal: 3 s.d. π/K separation up to 4 GeV/c





PANDA is back on track; installation to start in 2021.

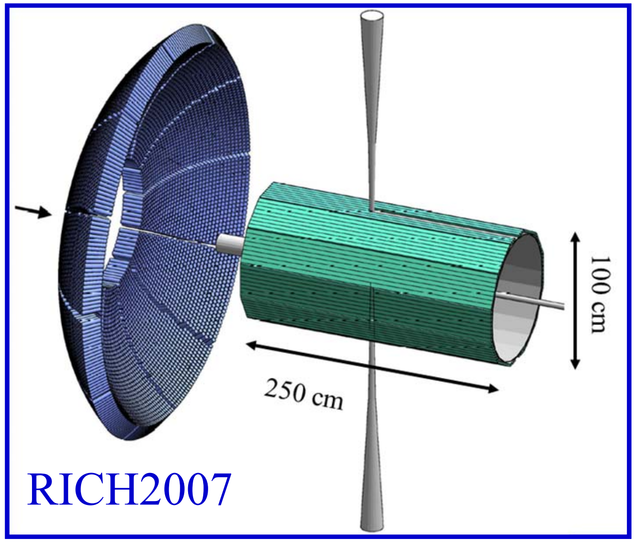
PANDA Barrel DIRC Design

Initial approach: scaled version of BABAR DIRC

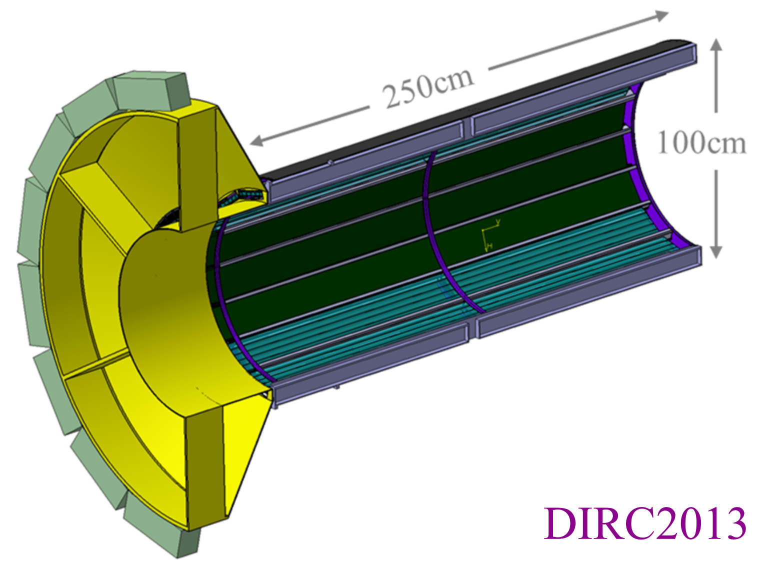
- Radiators: 96 narrow fused silica bars, 2.5m length
- Expansion volume: large water tank
- Sensors: ~ 7,000 conventional PMTs

Fast simulation: design meets PANDA PID goals.

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



RICH2007



DIRC2013

Improved design: 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.

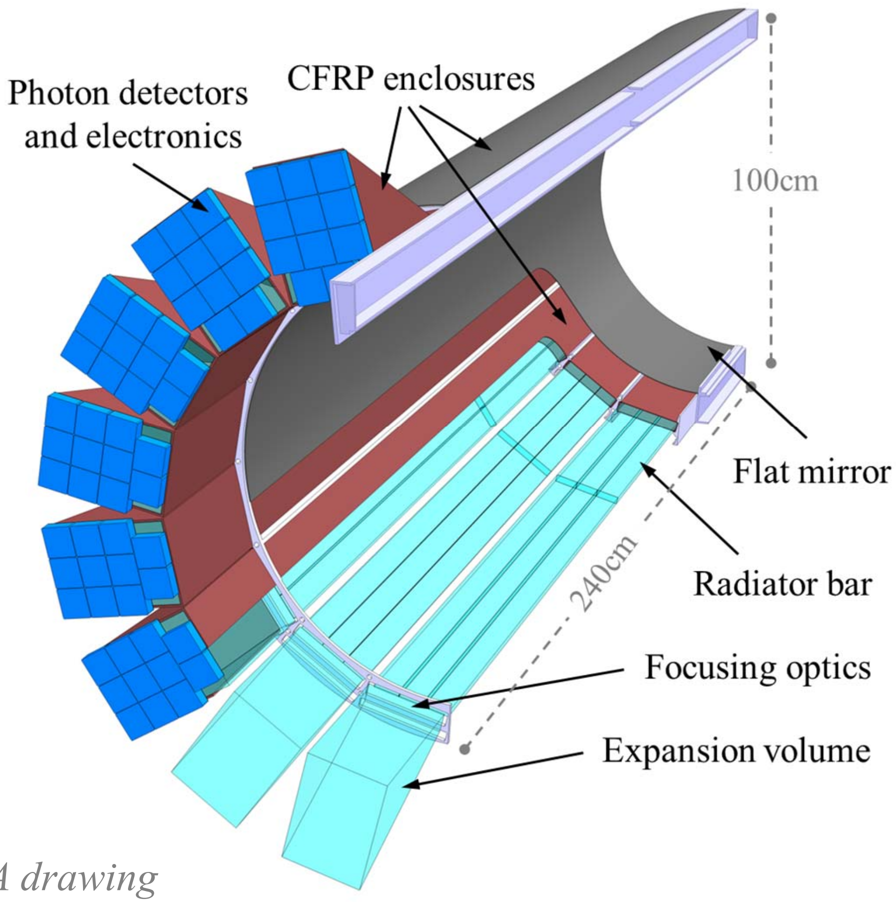
But: production cost ~50% over budget.

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

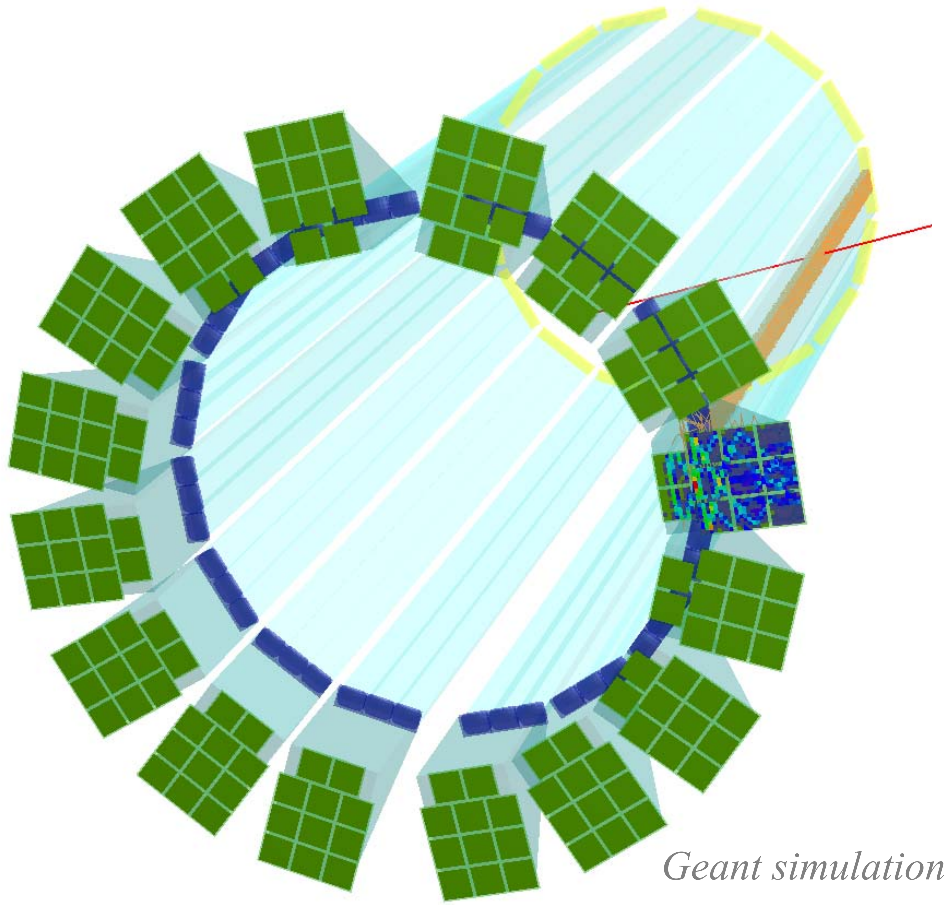
Main results of a comprehensive cost performance optimization in simulation:

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.



CATIA drawing

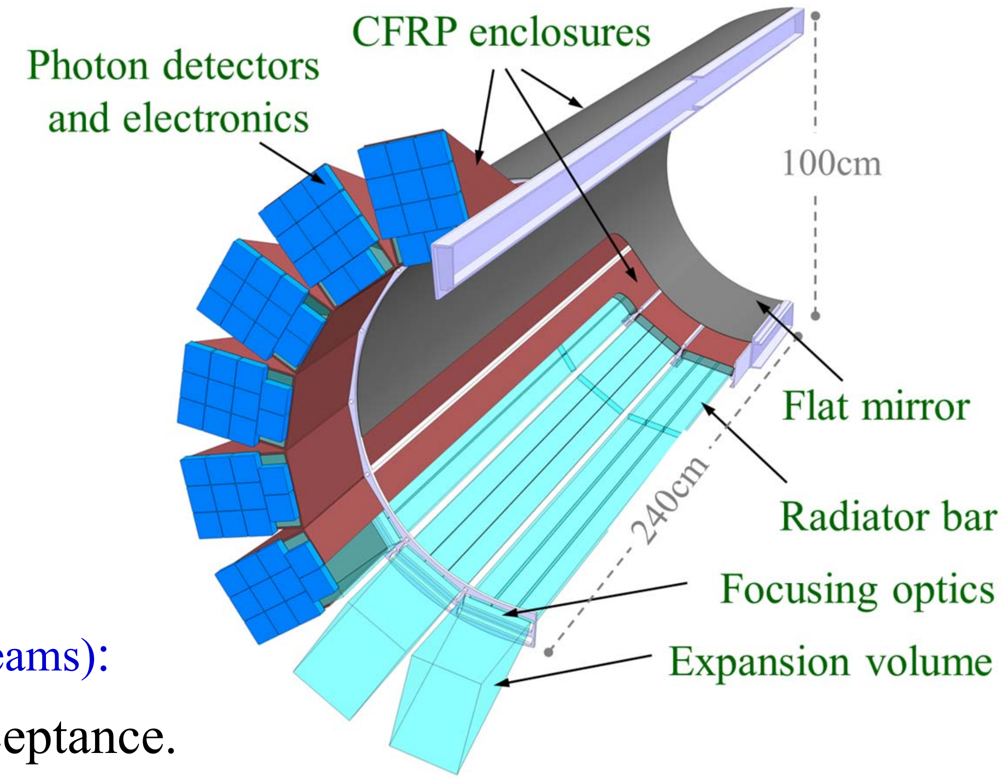


Geant simulation

BASELINE DESIGN

Baseline design – compact fused silica prisms, 3 bars per bar box, spherical lenses.

- 48 radiator bars (16 sectors), synthetic fused silica, *(instead of 80 bars in DIRC2015 design)*
  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 MCP-PMTs
- Fast FPGA-based photon detection.
  ~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, baseline design for TDR.

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

Caveat: still ~20% over budget. *(USD/€ exchange rate recently not our friend...)*

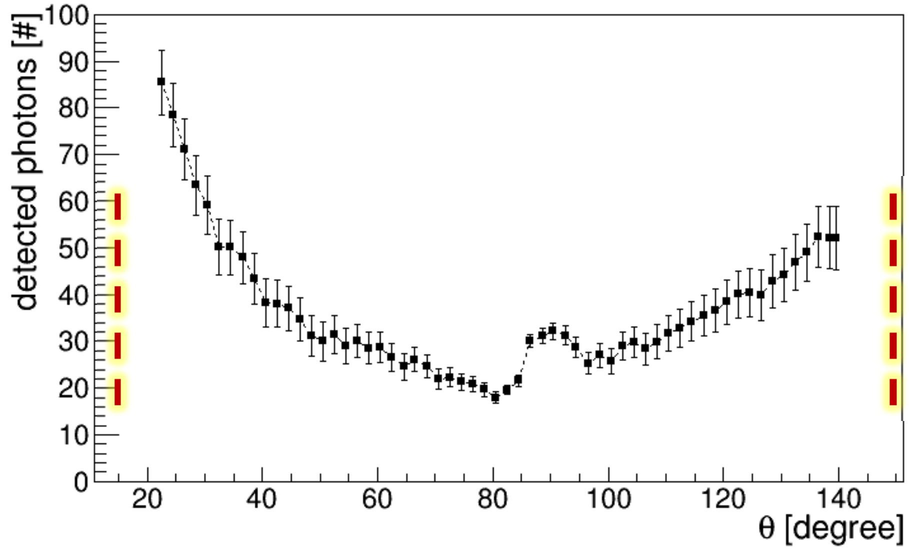
Baseline design, 3 bar per bar box, 3-layer spherical lens, prism

Geant simulation

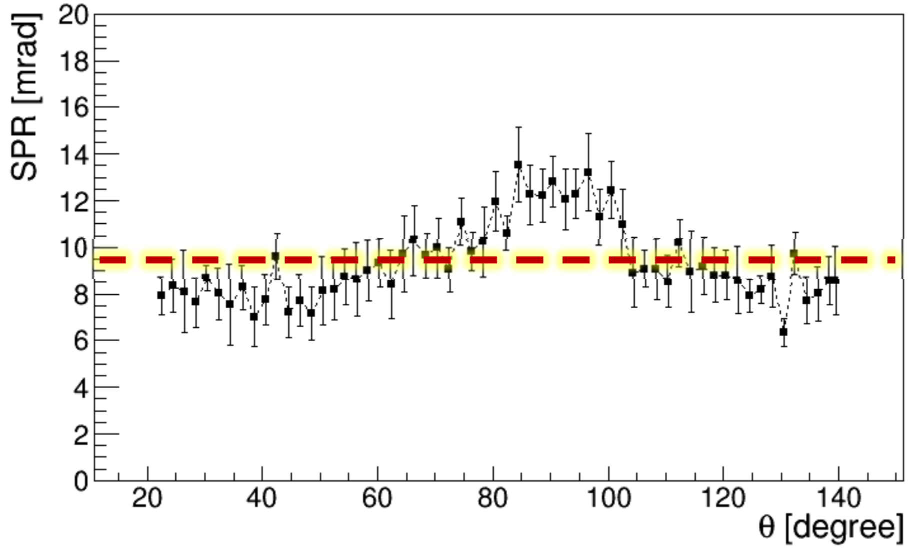
Used geometrical reconstruction (BABAR-like)

to determine photon yield and

single photon Cherenkov angle resolution (SPR)



Yield and SPR reach performance goal.

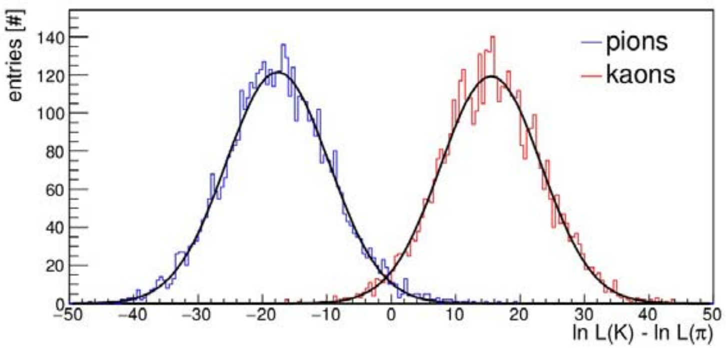


BABAR DIRC FOMs reached or even exceeded,

in particular for most demanding

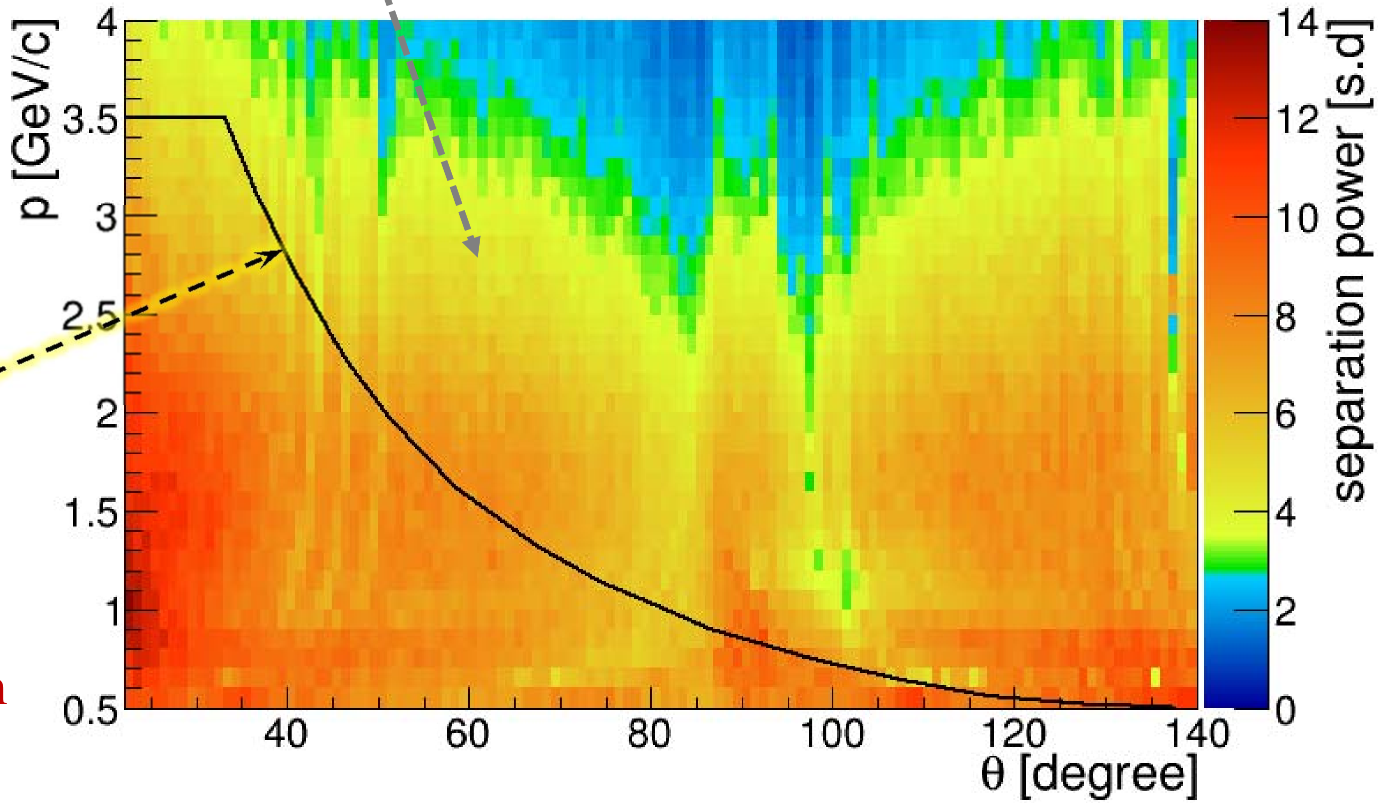
high-momentum forward region.

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



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

Geant simulation, geometric reconstruction



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

Barrel DIRC PID 3 s.d. goal

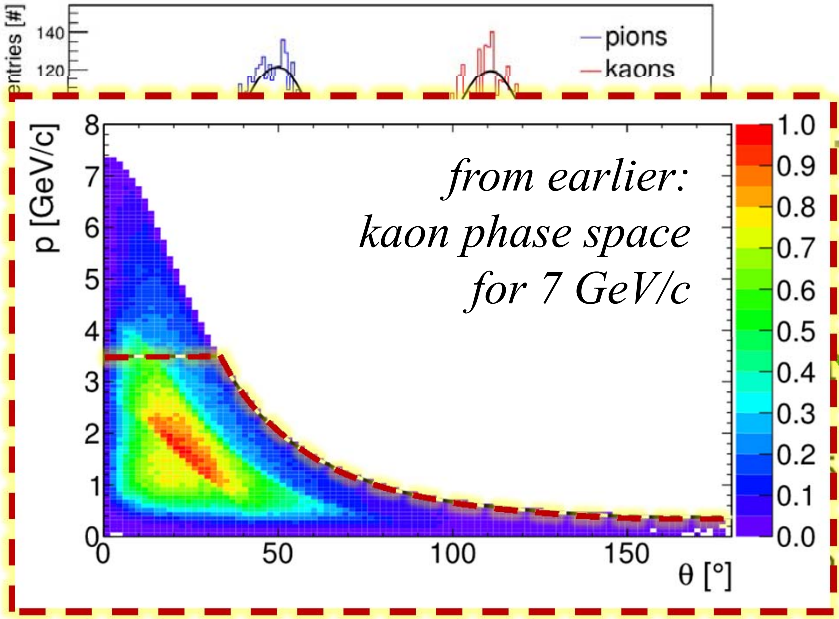
(from kaon phase space)

Design meets PID requirements

- for geometric reconstruction

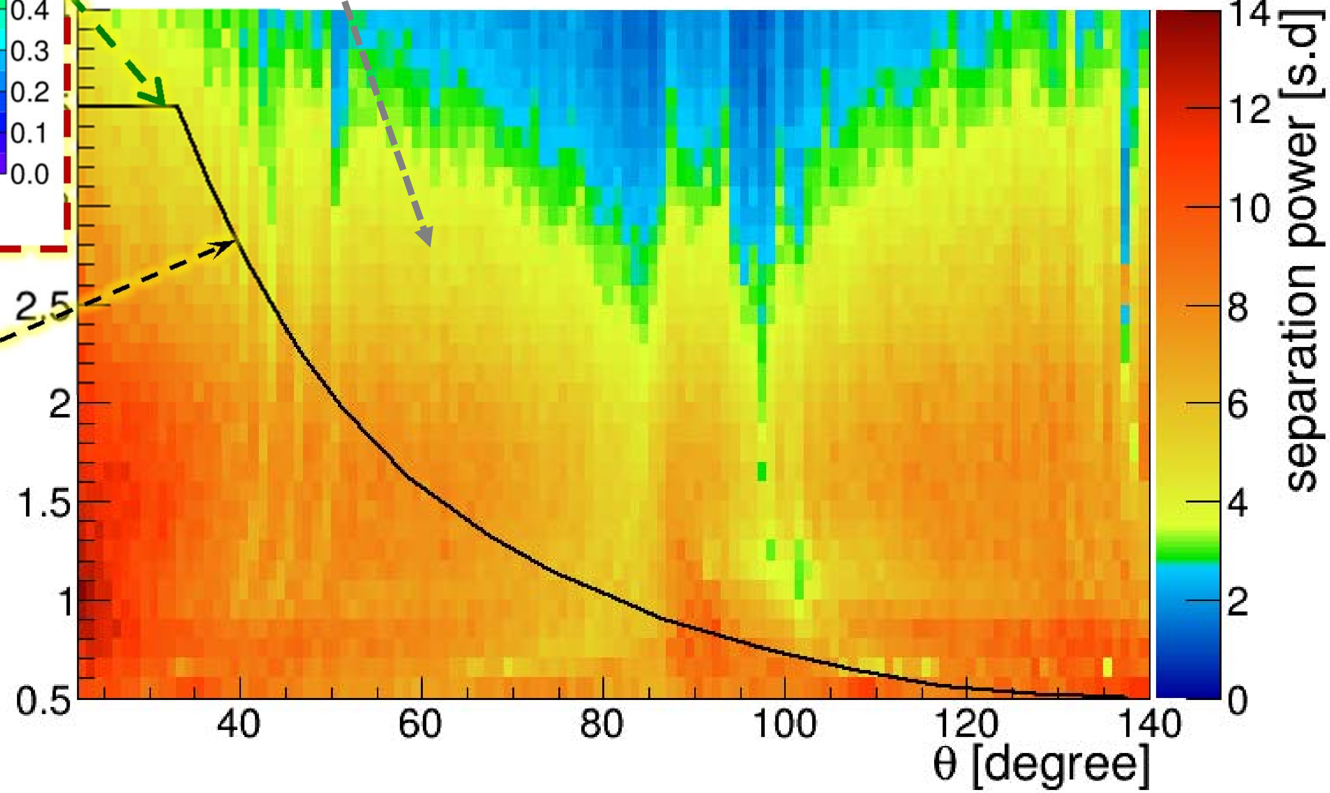
Expected Performance: Baseline

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



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

Geant simulation, geometric reconstruction



Barrel DIRC PID 3 s.d. goal

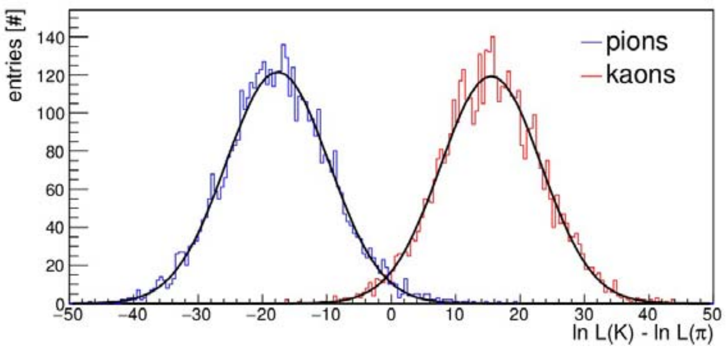
(from kaon phase space)

Design meets PID requirements

- for geometric reconstruction

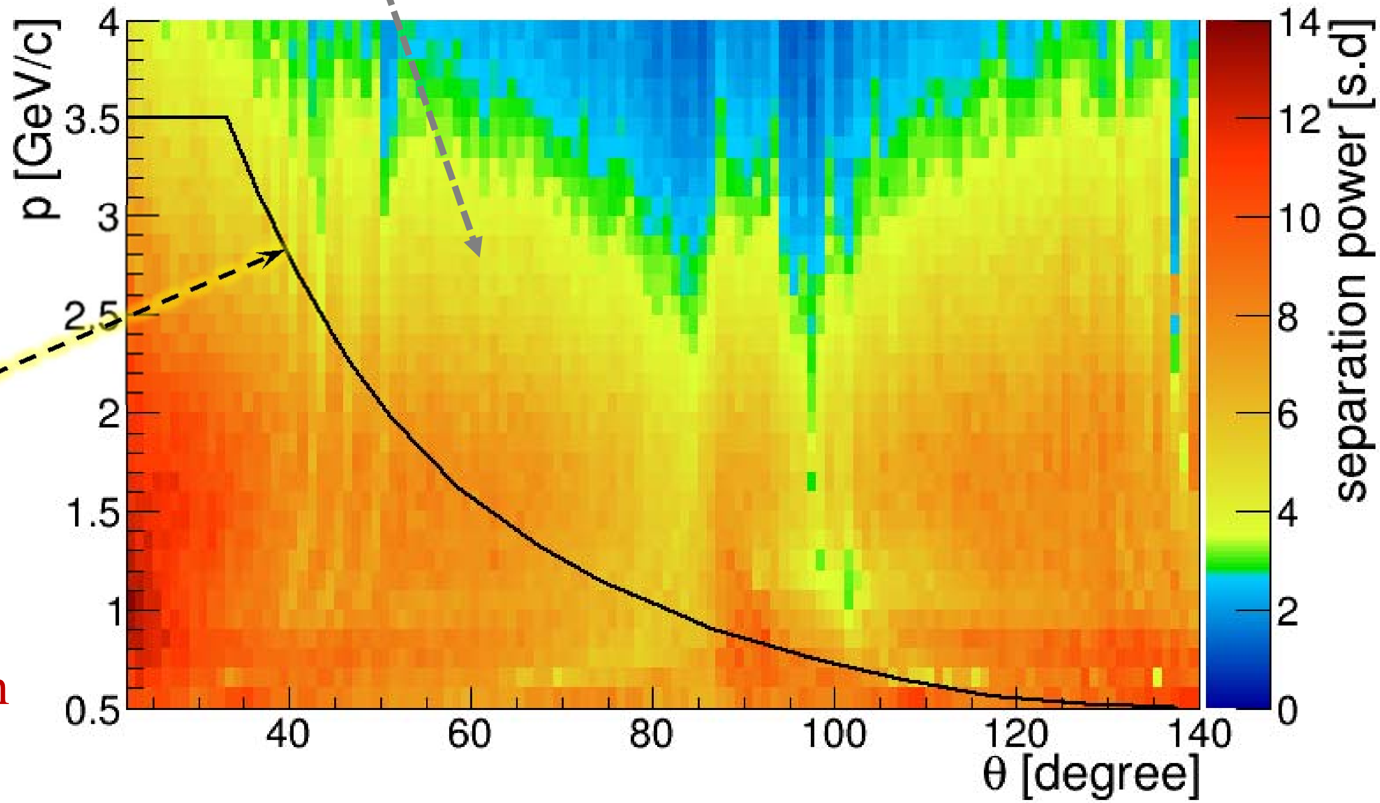
(green color: ~ 3 s.d. separation)

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



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

Geant simulation, geometric reconstruction



Barrel DIRC PID 3 s.d. goal

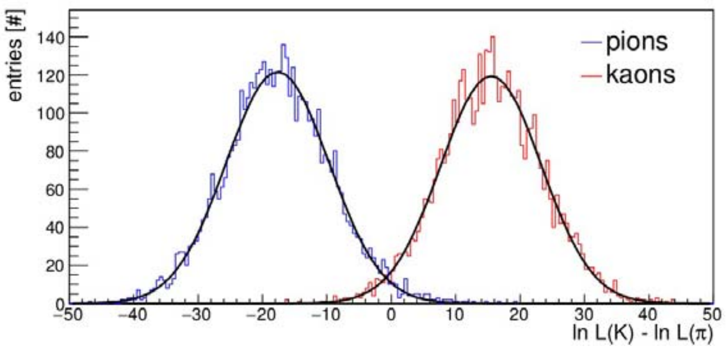
(from kaon phase space)

Design meets PID requirements

- for geometric reconstruction

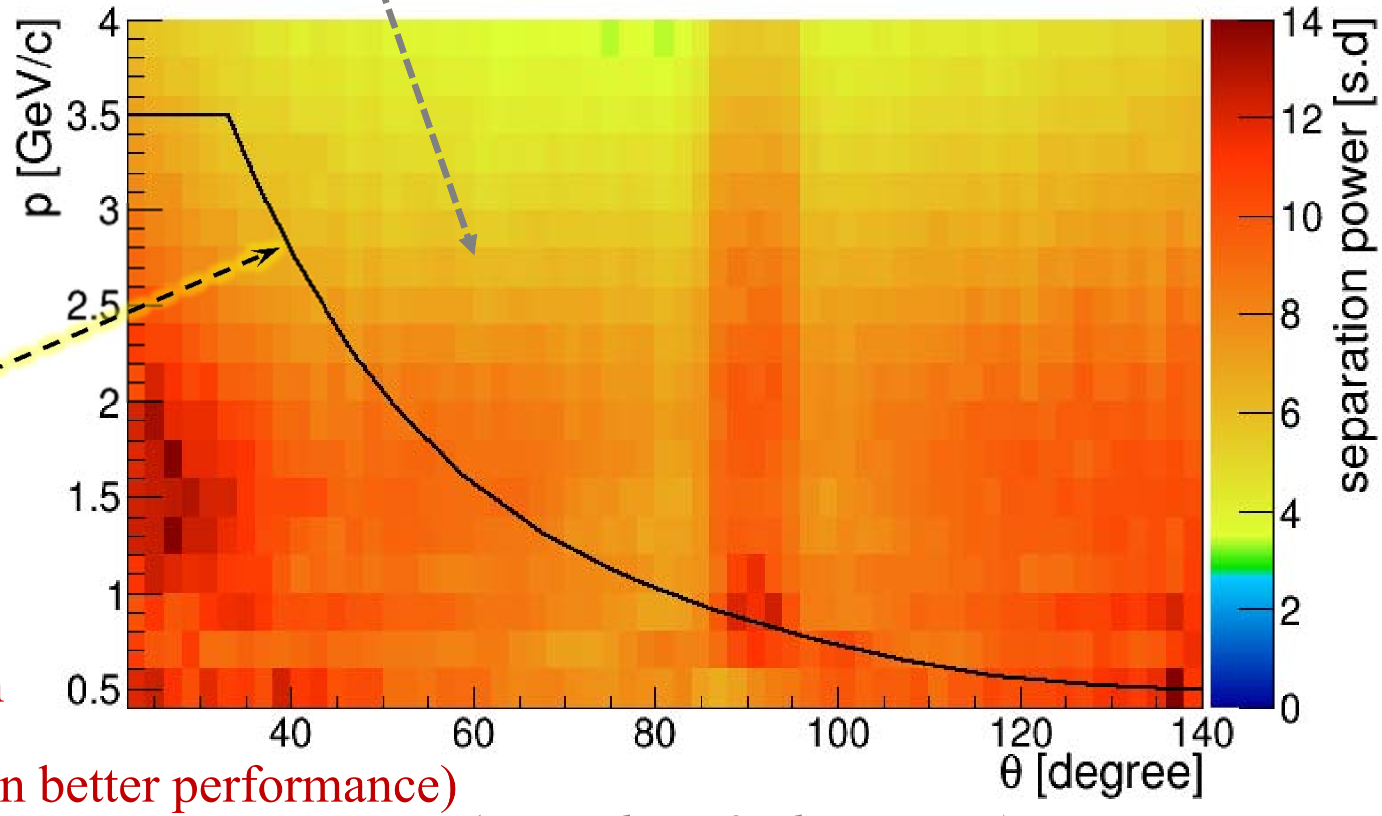
(green color: ~ 3 s.d. separation)

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



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

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



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

Barrel DIRC PID 3 s.d. goal

(from kaon phase space)

Design meets PID requirements

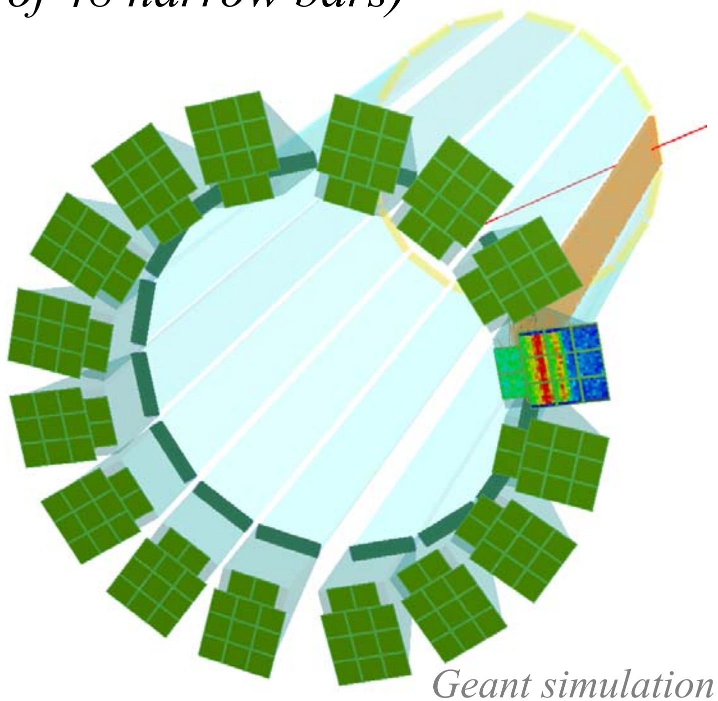
- for geometric reconstruction
- for time-based imaging (even better performance)

COST-SAVING DESIGN OPTION

Second cost optimization result: geometry based on wide plates.

Replacing 3 bars/bar box with 1 wide plate saves significant fabrication costs.

- 16 radiator plates (16 sectors), synthetic fused silica *(instead of 48 narrow bars)*
  17mm (T) × 160mm (W) × 2400mm (L).
- Focusing optics: triplet cylindrical lens system
  (or no lens – to be determined)
- Expansion volume and readout same as baseline.
- Expected performance (according to simulation):
  better than 3 s.d. π/K separation for entire acceptance.
- Included in TDR as design option.



Geant simulation

Wide plate design would fit our budget – but it is no longer a "BABAR-like" DIRC.

Geometric reconstruction approach unavailable, have to rely on time-based imaging PDFs.

Design is more sensitive to timing precision and backgrounds than narrow bars.

Needed to be validated with particle beams.

Cost-saving option, 1 plate per bar box, cylindrical lens

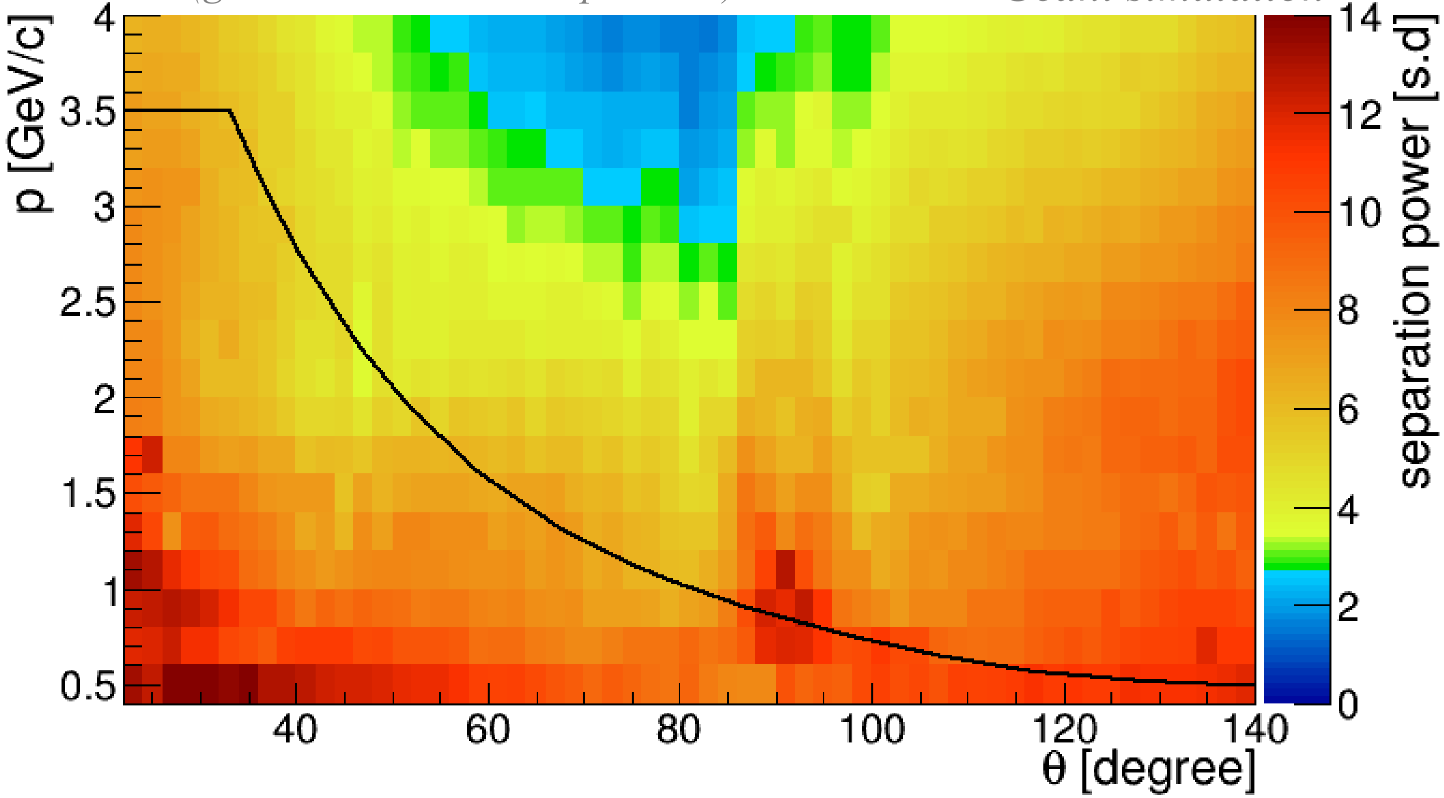
π/K separation power from time-based imaging (Belle II-like algorithm, PDFs from simulation).

Wide plate with focusing exceeds PID requirements for entire acceptance range.

(Performance somewhat worse than narrow bar design.)

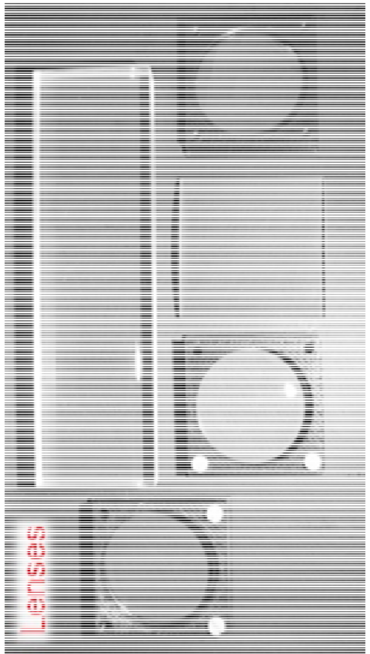
(green color: ~ 3 s.d. separation)

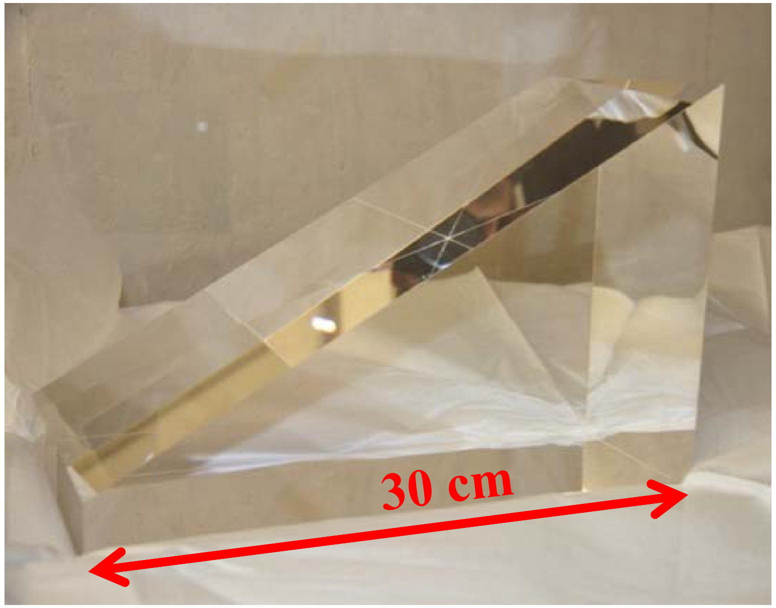
Geant simulation

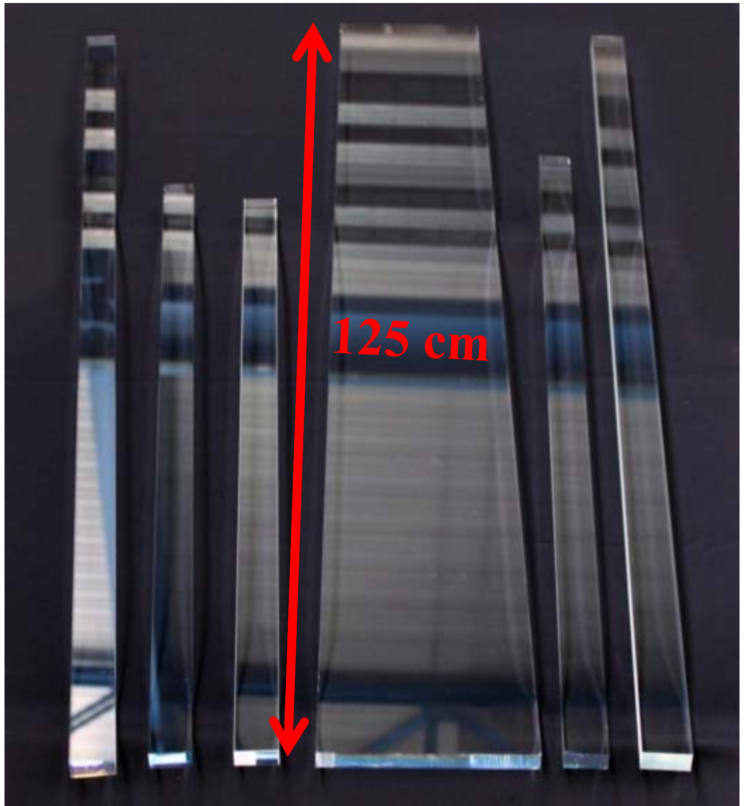


Optical Components

- Radiator prototype program with industry partners in Europe, USA, Japan;
  ~30 bars/plates produced by 8 companies using different materials and techniques
  (pitch polishing, abrasive polishing, even new idea: extrusion and flame polishing).
  → AOS/Okamoto, InSync, Nikon, Zeiss, Zygo; *Heraeus, Lytkarino LZOS, Schott Lithotec*.
- Three solid fused silica prism prototypes (30°, 33°, 45° top angle) built by industry (AGI).
- Designed several spherical and cylindrical lenses, with and without air gap,
  2-layer and 3-layer prototypes built by industry.

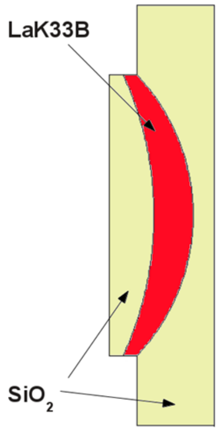


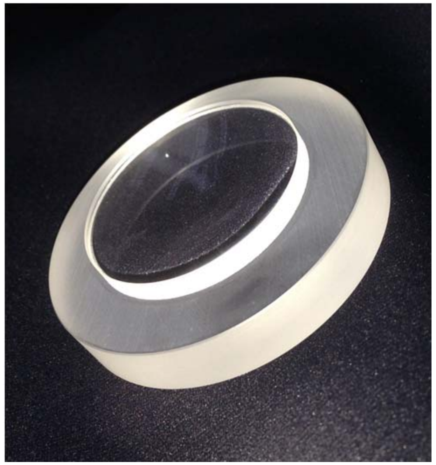




2-layer and 3-layer lenses → minimize photon loss at bar/lens/expansion volume transition.

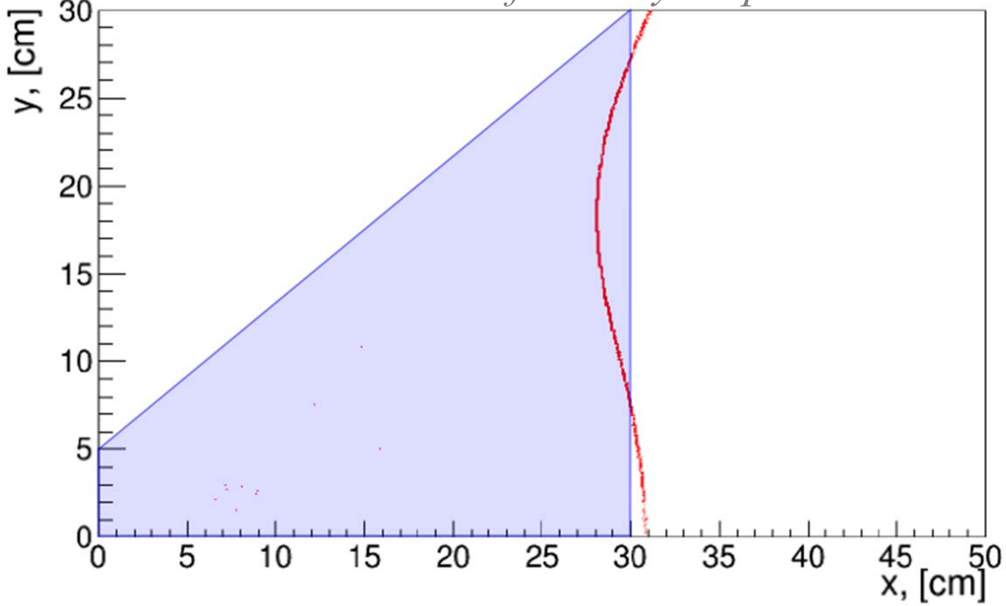
Prototypes built by industry and tested in lab and with particle beams.





3-layer spherical lens prototype

shape of focal plane in Geant simulation for 3-layer spherical lens



➢ G. Kalicy, talk this afternoon

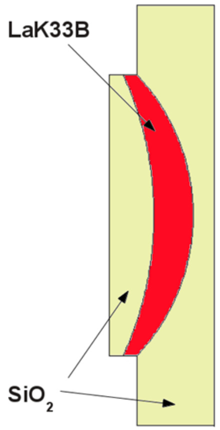
Good imaging properties – but radiation hardness of lanthanum crown glass (LaK33B)?

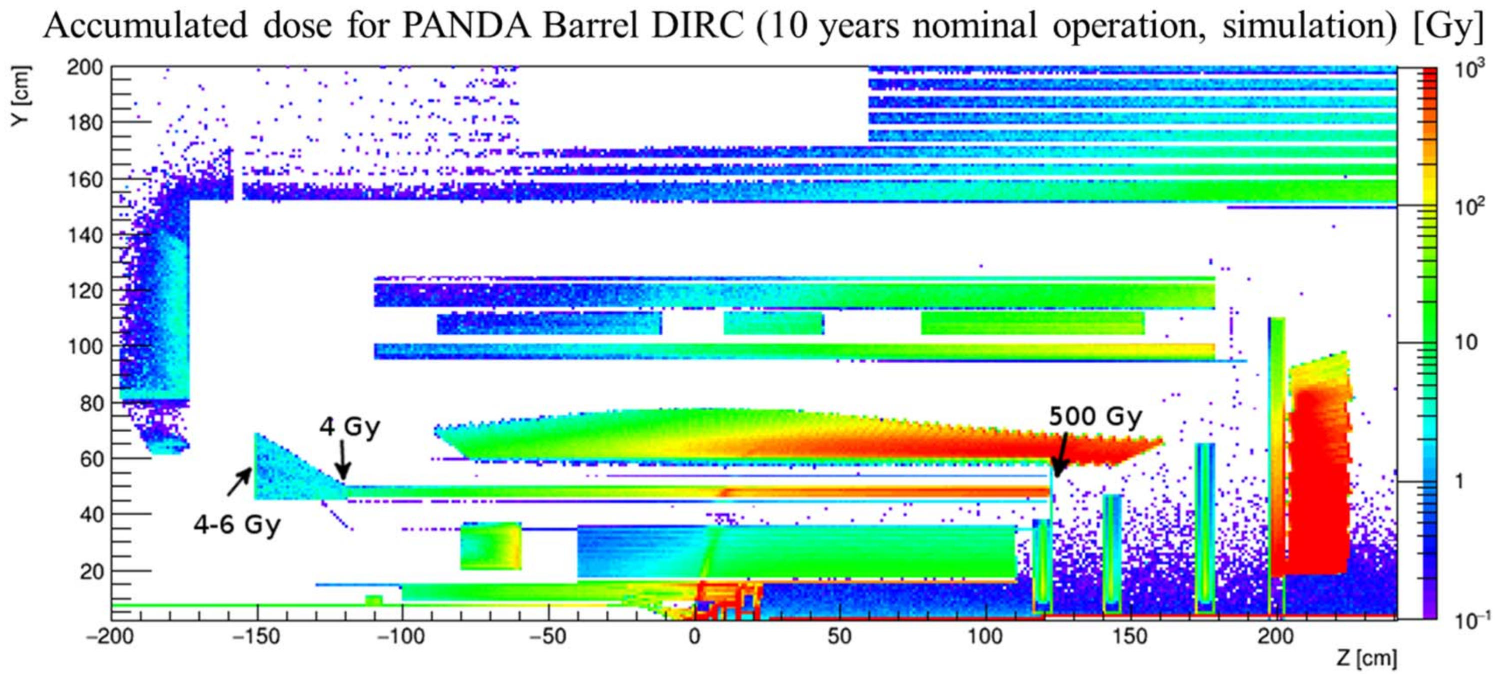
Irradiation test with X-rays ongoing (*DIRC@EIC R&D, eRD14 PID consortium*);

Initial result: LaK33 is sufficiently radiation hard for PANDA *(10 year dose @ lens: <5Gy)*.

2-layer and 3-layer lenses → minimize photon loss at bar/lens/expansion volume transition.

Prototypes built by industry and tested in lab and with particle beams.



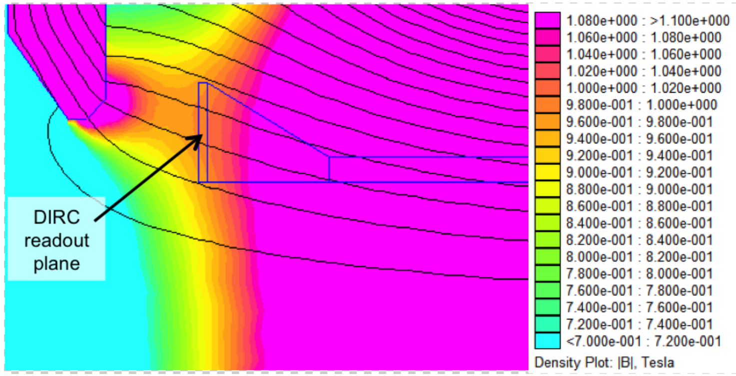


➢ G. Kalicy, talk this afternoon

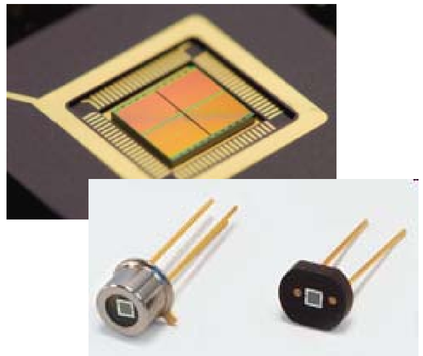
Good imaging properties – but radiation hardness of lanthanum crown glass (LaK33B)?

Irradiation test with X-rays ongoing (*DIRC@EIC R&D, eRD14 PID consortium*);

Initial result: LaK33 is sufficiently radiation hard for PANDA *(10 year dose @ lens: <5Gy)*.



- Multi-anode Photomultipliers (MaPMTs)
  - used successfully in DIRC prototypes,
    - sensors of choice for SuperB FDIRC, GlueX DIRC
  - ruled out by ~1T magnetic field

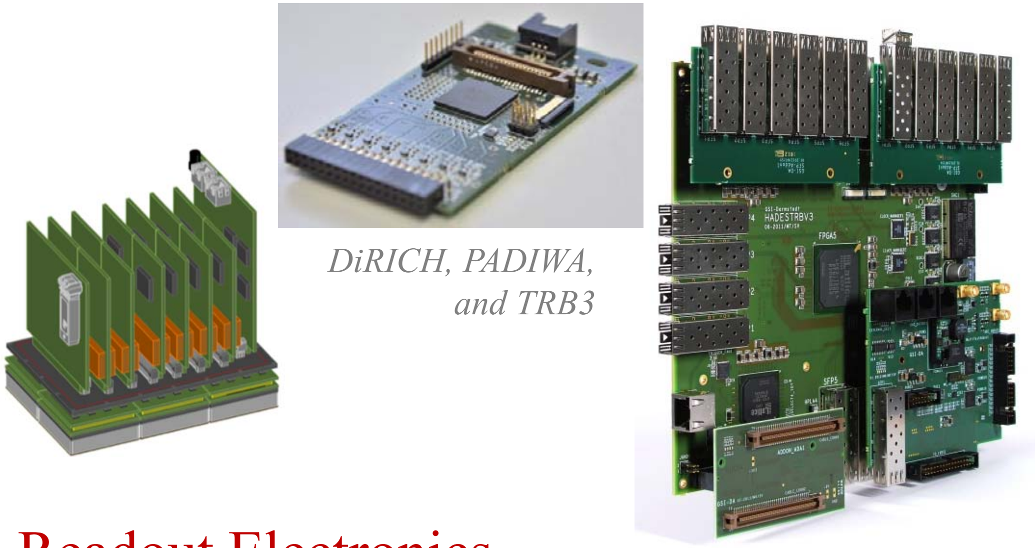


- Geiger-mode Avalanche Photo Diodes (SiPMs)
  - high dark count rate problematic for reconstruction (trigger-less DAQ)
  - radiation hardness an issue in PANDA environment

➢ A. Lehmann, talk yesterday

- Micro-channel Plate Photomultipliers (MCP-PMTs)
  - good PDE, excellent timing and magnetic field performance
  - used to have issues with rate capability and aging, now solved;
    - sensors of choice for Belle II TOP and both PANDA DIRCs.

Readout and Mechanical Design



DiRICH, PADIWA, and TRB3

Readout Electronics

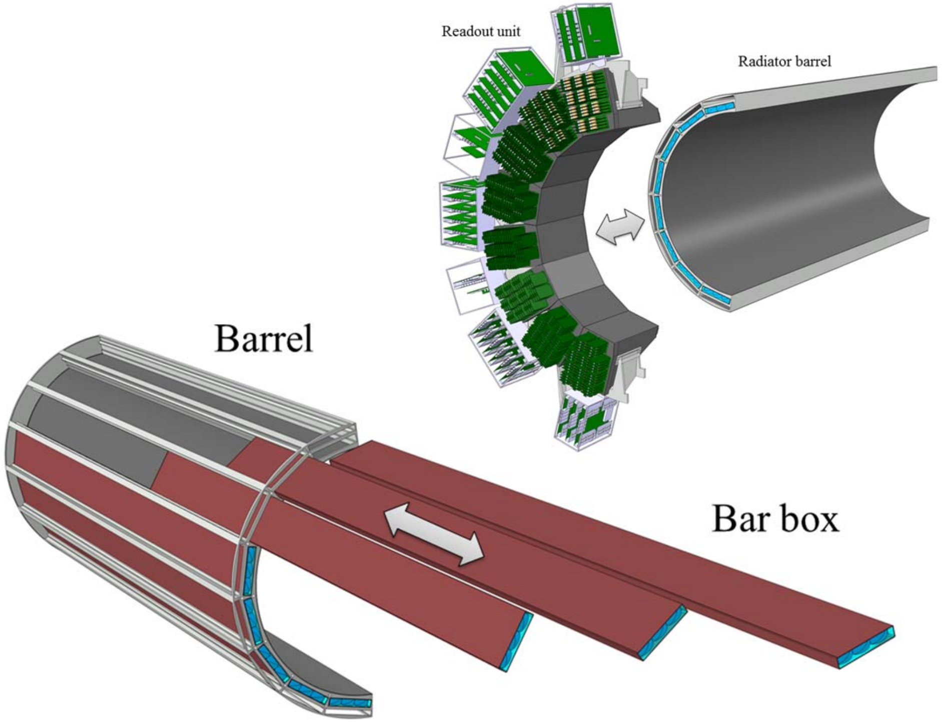
~100ps timing per photon for small MCP-PMT pulses – amplification and bandwith optimization

20MHz average interaction, trigger-less DAQ

Current approach: HADES TRBv3 board with PADIWA amplifier/discriminator.

For PANDA: DiRICH, integrated backplane, joint development with HADES/CBM RICH.

- M. Traxler, talk tomorrow morning



Mechanical Design

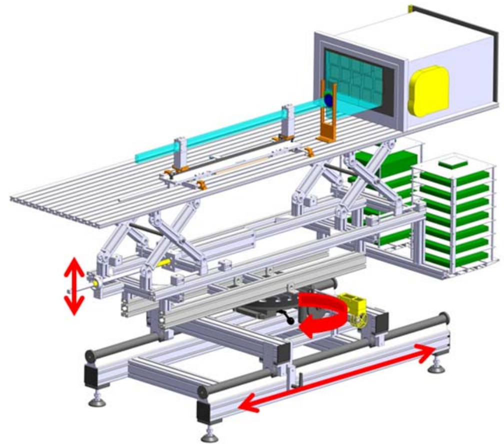
Light-weight and modular, allows staged bar box installation, access to inner detectors.

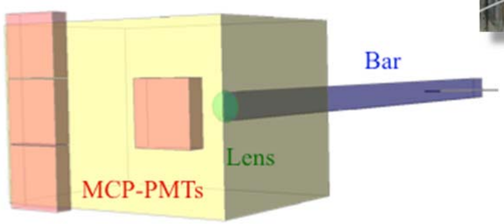
Mechanical support elements made from aluminum alloy or carbon fiber (CFRP).

Boil-off nitrogen flush for optical surfaces.

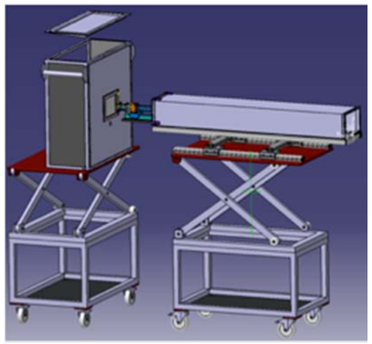
Barrel DIRC Beam Tests

2014, 2015, 2016: GSI, CERN

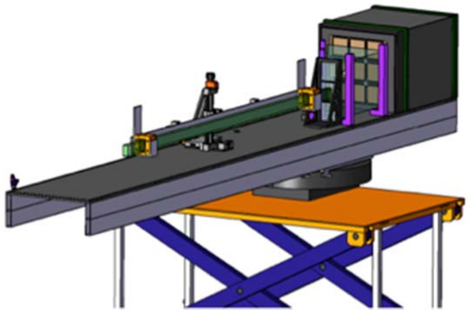




2008, 2009: GSI



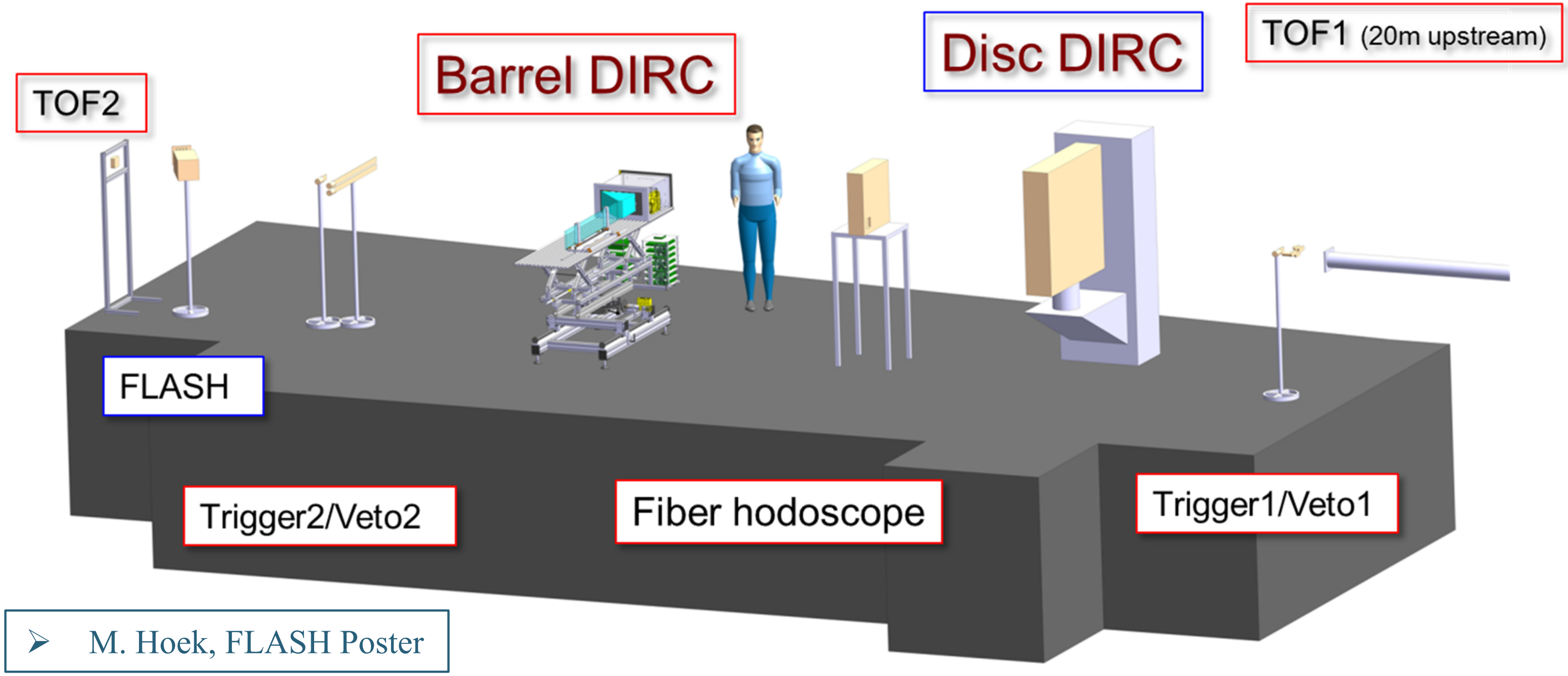
2011: GSI, CERN



2012: CERN

Beam test at CERN PS/T9 (May/June, July 2015)

- Fused silica prism as expansion volume.
- 5 x 3 array of Planacon MCP-PMTs.
- Narrow bar and wide plate as radiator.
- Many different imaging/lens configurations.
- Momentum and angle scans.
- ~500M triggers during 34 days of data taking.

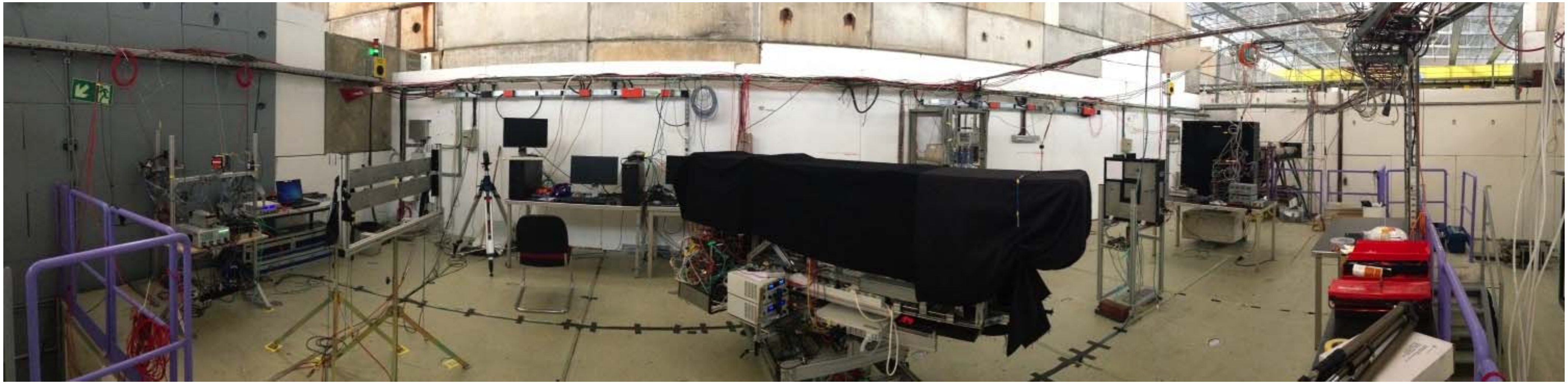


- M. Hoek, FLASH Poster

Beam test at CERN PS/T9 (May/June, July 2015)

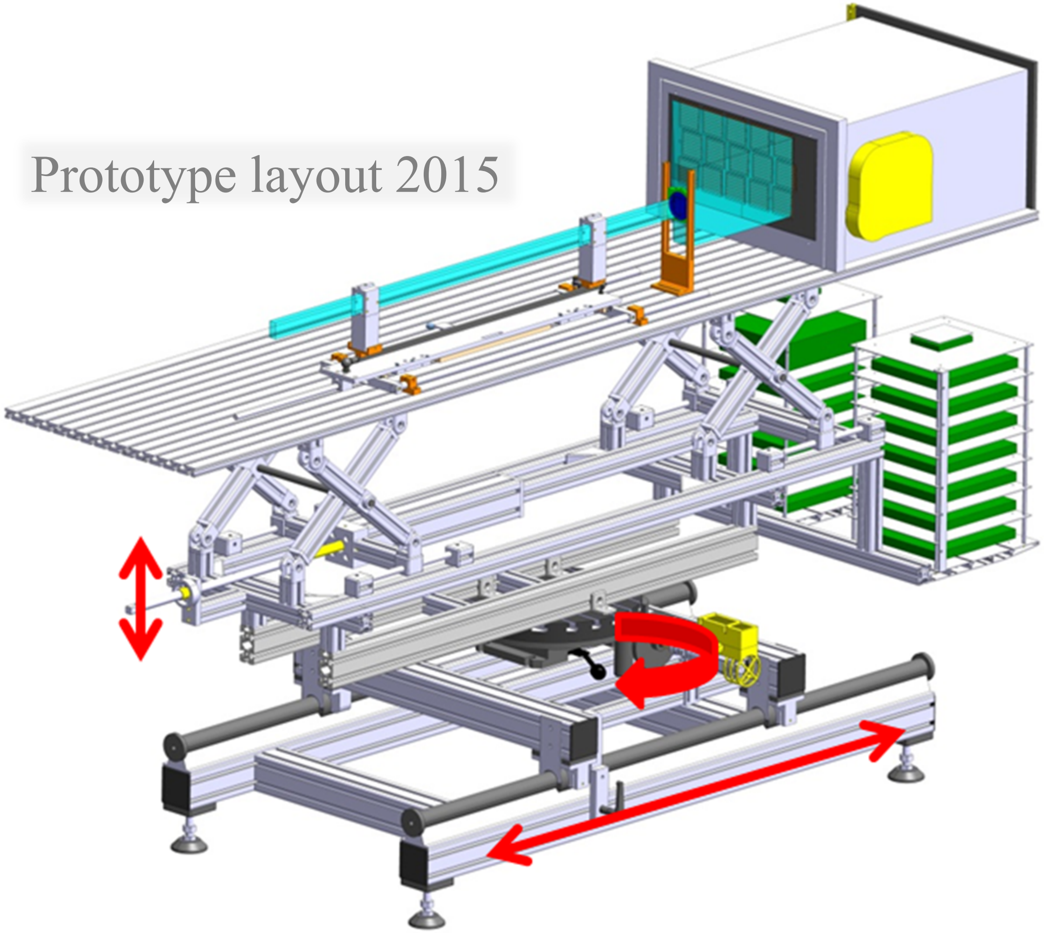
- Fused silica prism as expansion volume.
- 5 x 3 array of Planacon MCP-PMTs.
- Narrow bar and wide plate as radiator.
- Many different imaging/lens configurations.
- Momentum and angle scans.
- ~500M triggers during 34 days of data taking.

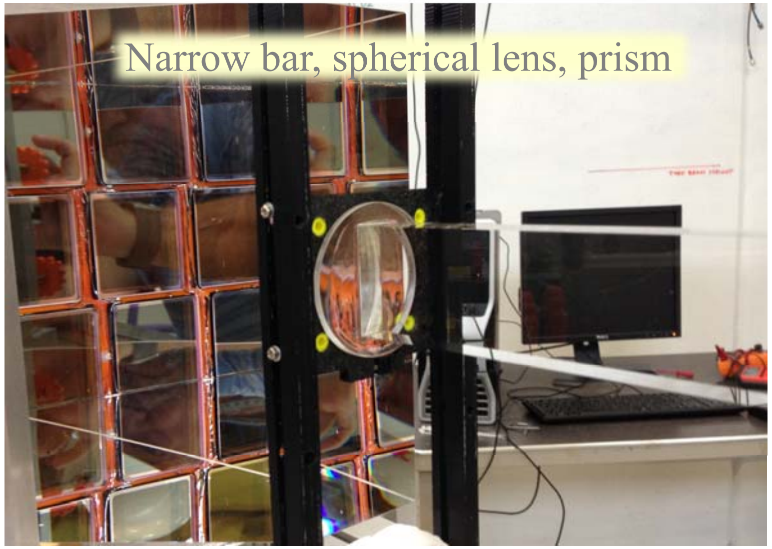
Goal: validation of PID performance of narrow bar and of wide plates.

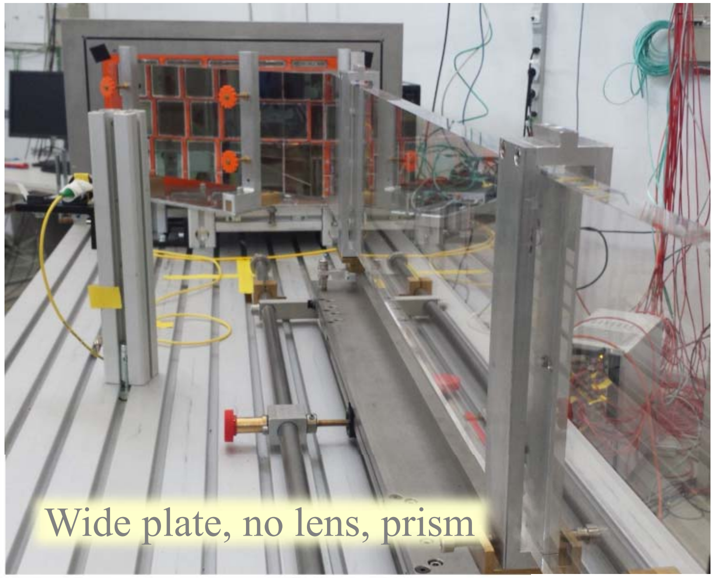


2015 CERN Beam Test

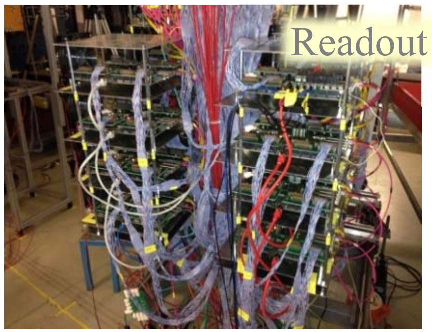
Prototype layout 2015

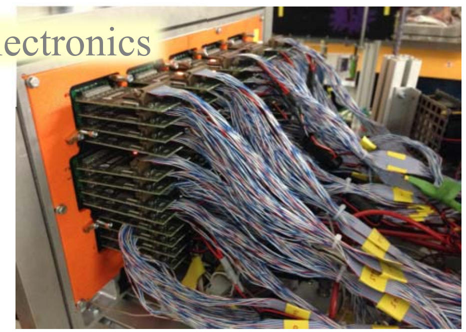




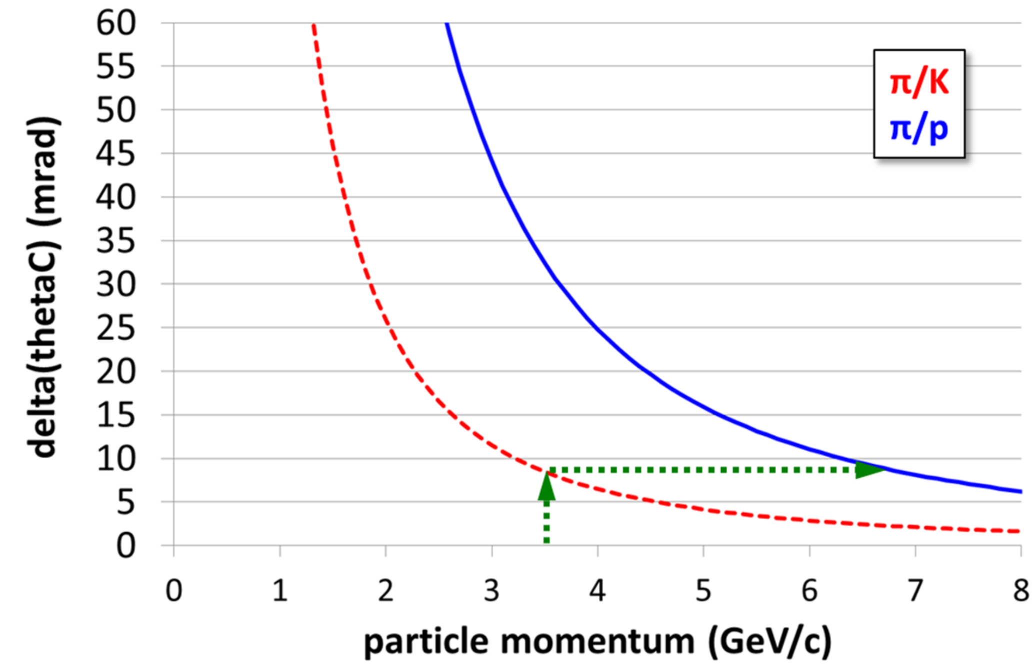


Readout electronics





PID performance ecaluated for π/p at 7 GeV/c.
(Close match to π/K at 3.5 GeV/c.)

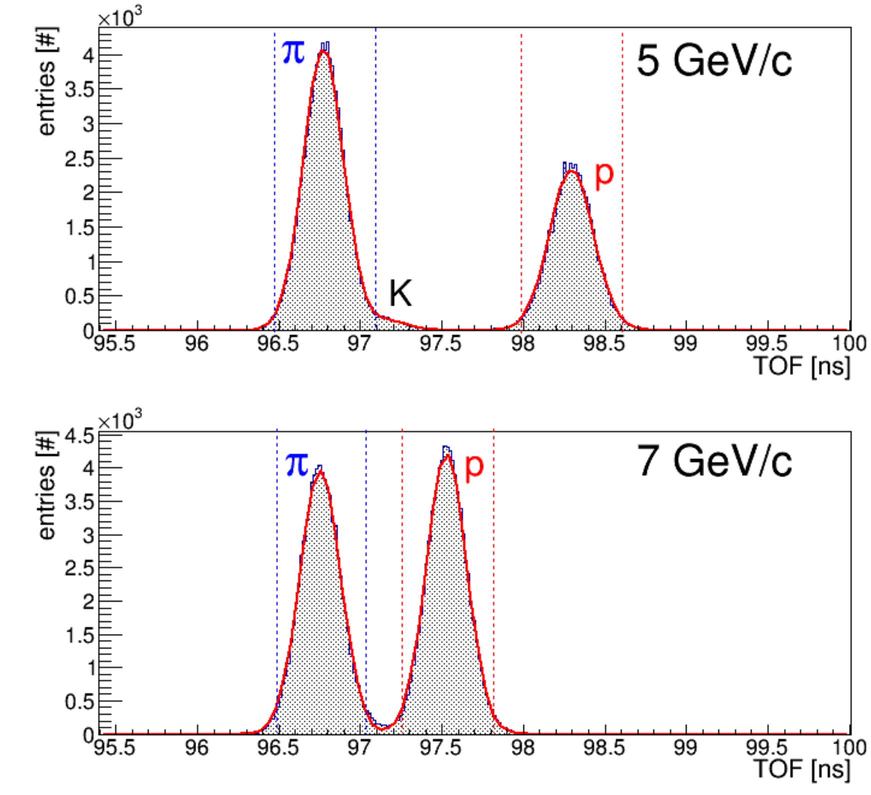


Cherenkov angle difference:

$\Delta\theta_C$ (π-p) = 8.1mrad @ 7GeV/c

$\Delta\theta_C$ (π-K) = 8.5mrad @ 3.5GeV/c

TOF system cleanly tags π/p at 7 GeV/c.



PERFORMANCE OF NARROW BAR

Hit pattern for data and simulation

36 mm-wide bar with 3-layer spherical lens,

5 GeV/c beam momentum.

Observe sharp image with expected structures,

described well by simulation.

Proton image shifted by one column compared

to pion image (Cherenkov angle difference).

Event selection uses fiber hodoscope,

scintillator triggers and time-of-flight.

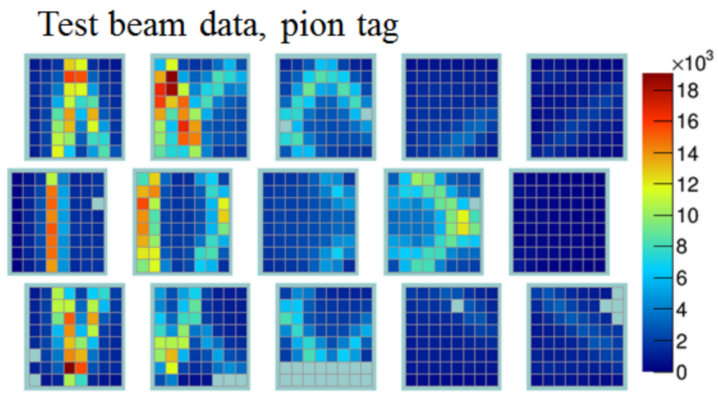
Data calibrated using picosecond laser pulser.

Specific prototype simulation, tuned to beam

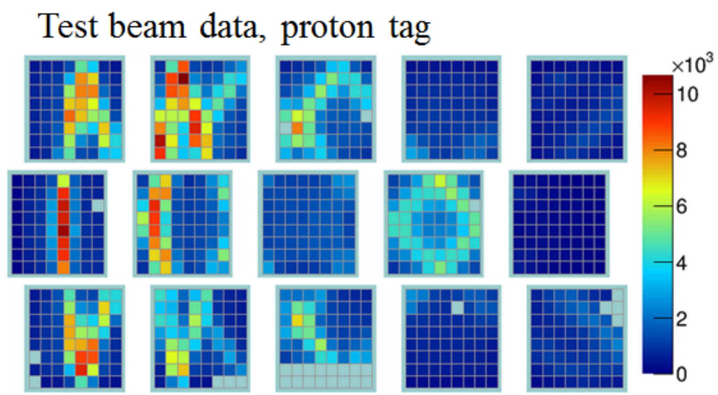
parameters, includes quantum efficiencyies

from 2D scan data for each MCP-PMT.

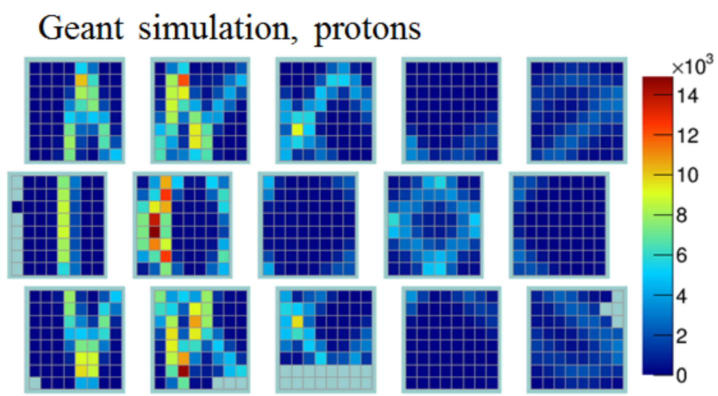
beam
pion tag

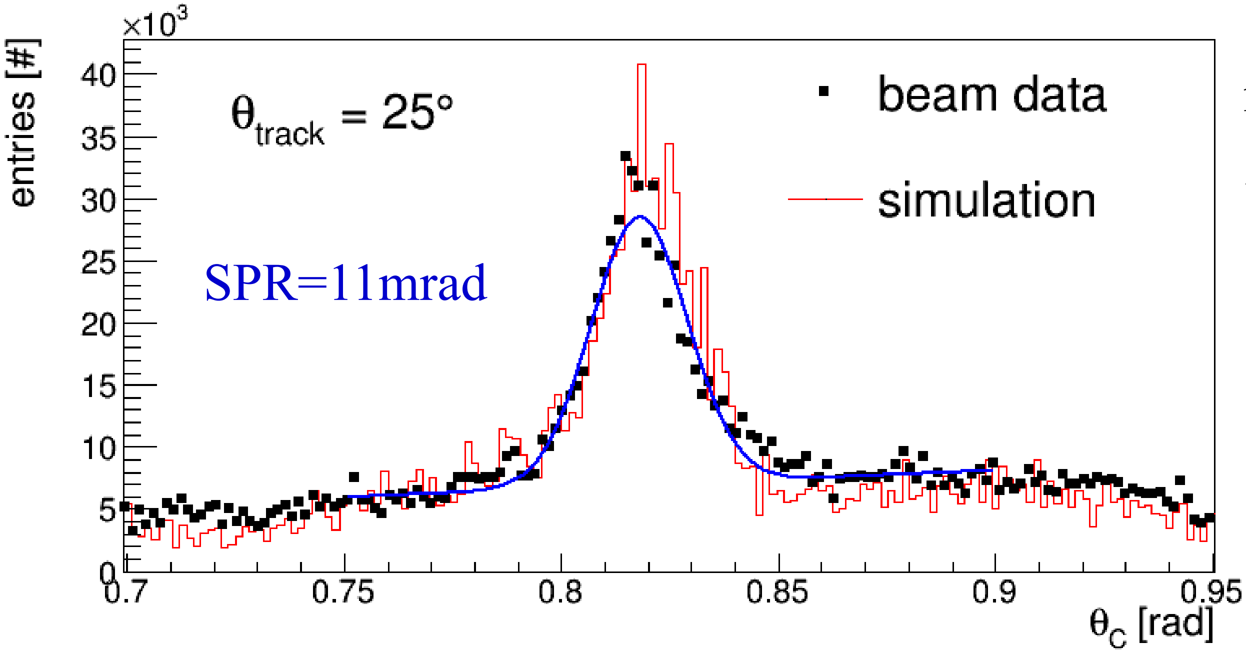


beam
proton tag



simulation
protons



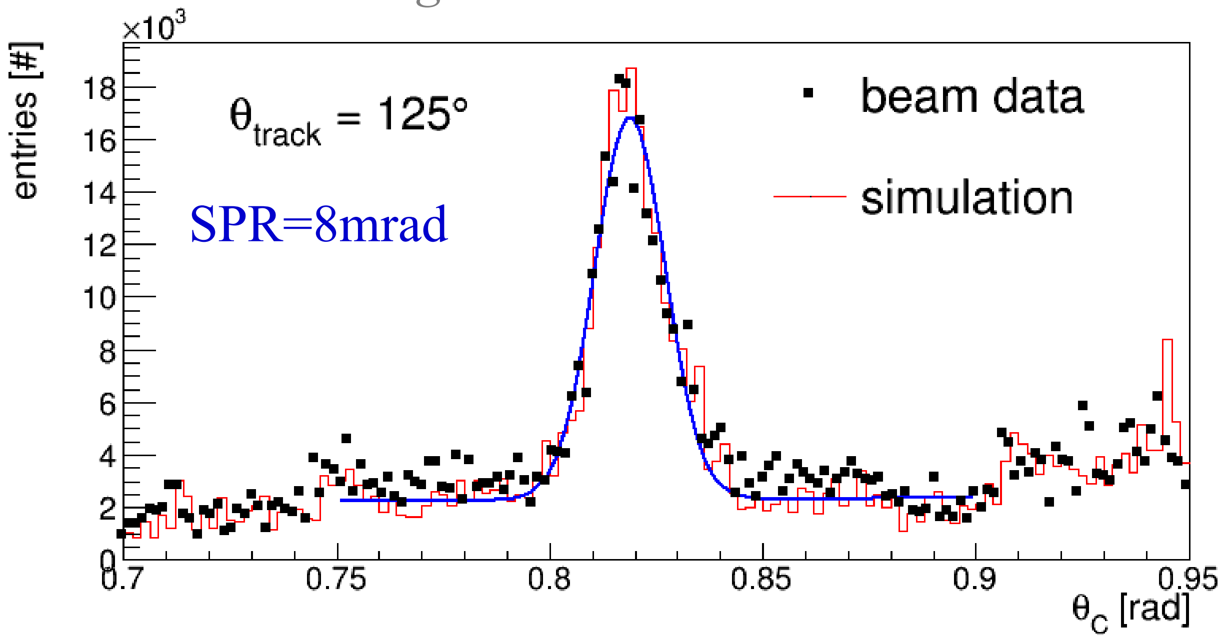


narrow bar with 3-layer spherical lens

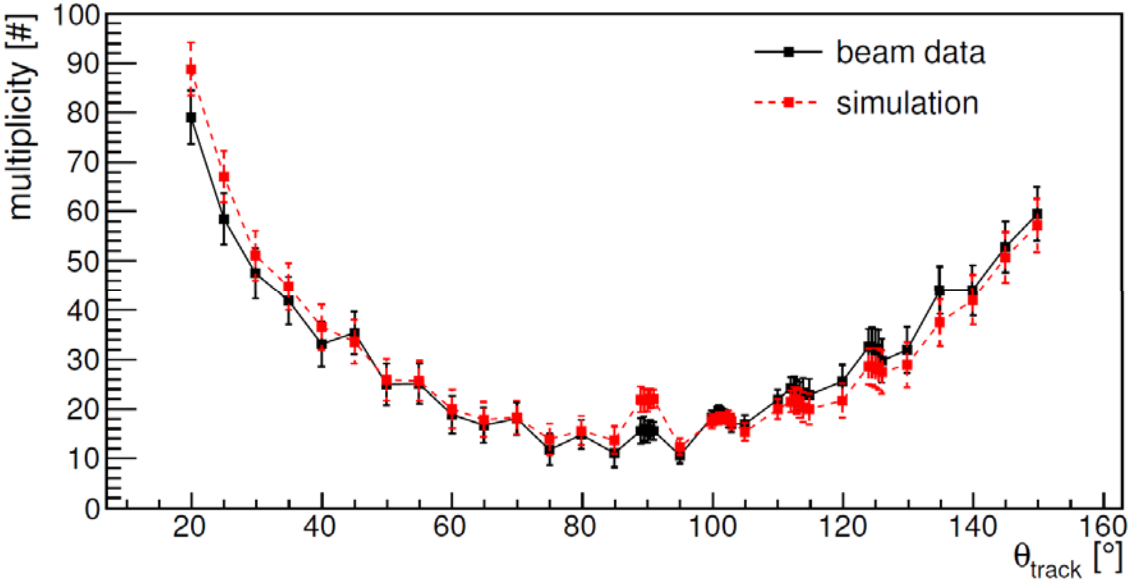
7 GeV/c proton tag

Single photon Cherenkov angle resolution (SPR)

geometric reconstruction



Simulation describes data quite well.

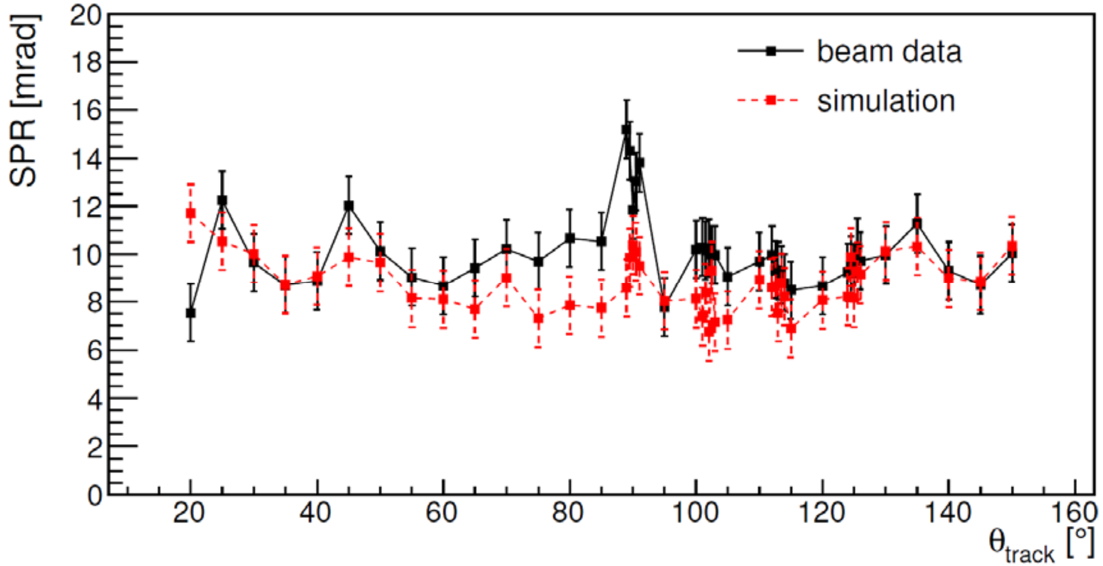


narrow bar, 3-layer spherical lens

7 GeV/c proton tag

Figures of merit meet PANDA requirements

geometric reconstruction

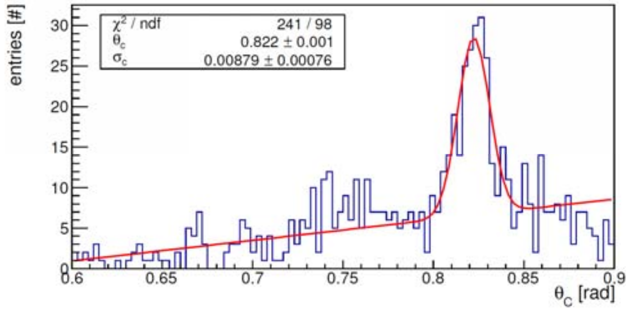


Simulation describes data reasonably well.

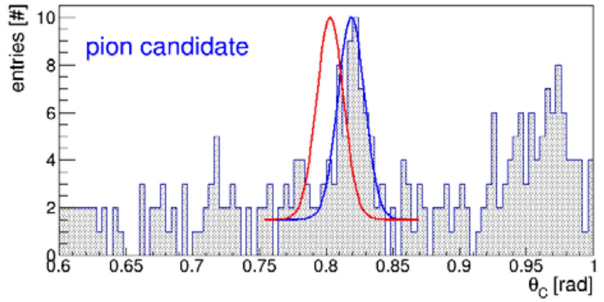
Some differences due to group of older, less efficient MCP-PMTs, issues with thresholds and noise in data (see hit pattern).

Used three methods to evaluate PID performance of geometry with the narrow bar

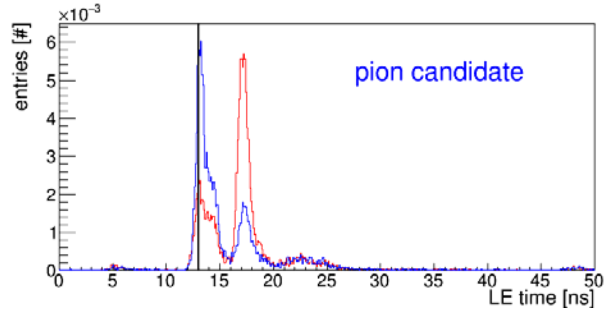
- track-by-track fit of single photon Cherenkov angle distribution to extract track Cherenkov angle (geom. reco)

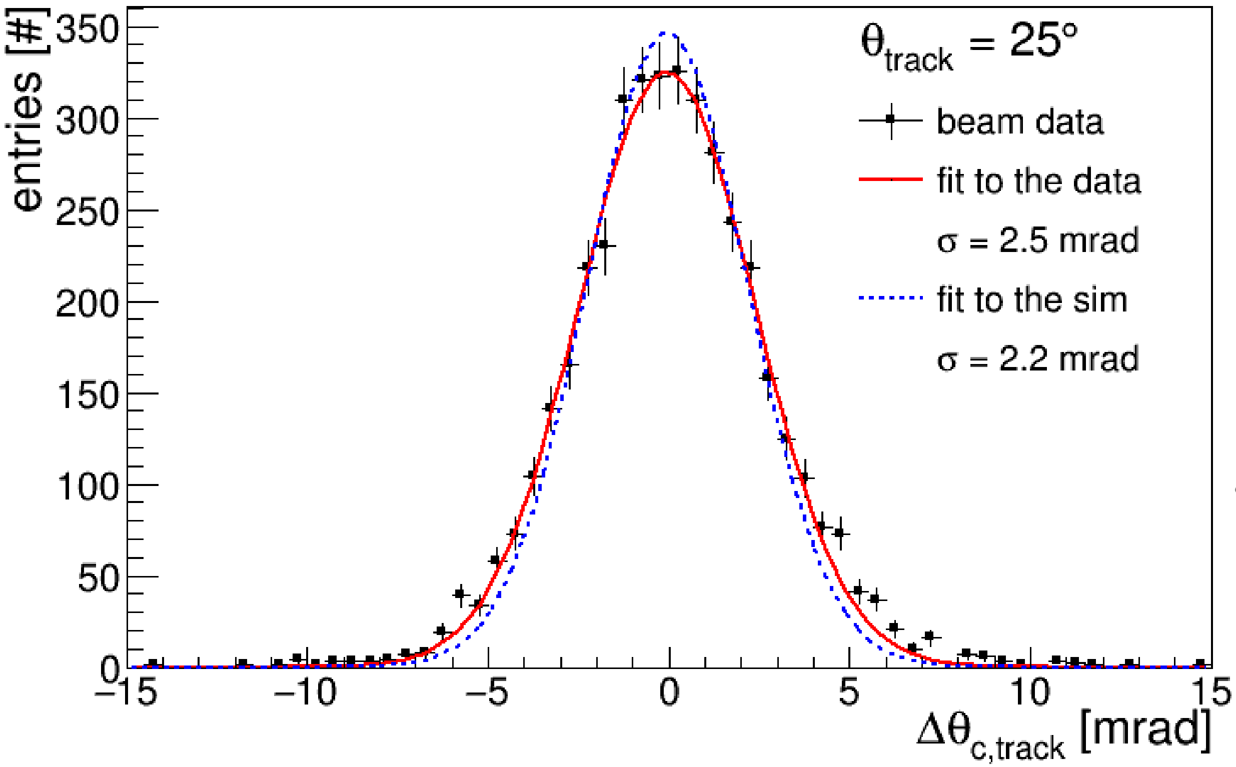


- track-by-track unbinned likelihood hypothesis test to extract log-likelihood differences (geom. reco)



- time-based imaging to extract log-likelihood differences (PDFs were generated from beam data directly using time-of-flight tag, statistically independent data sets)



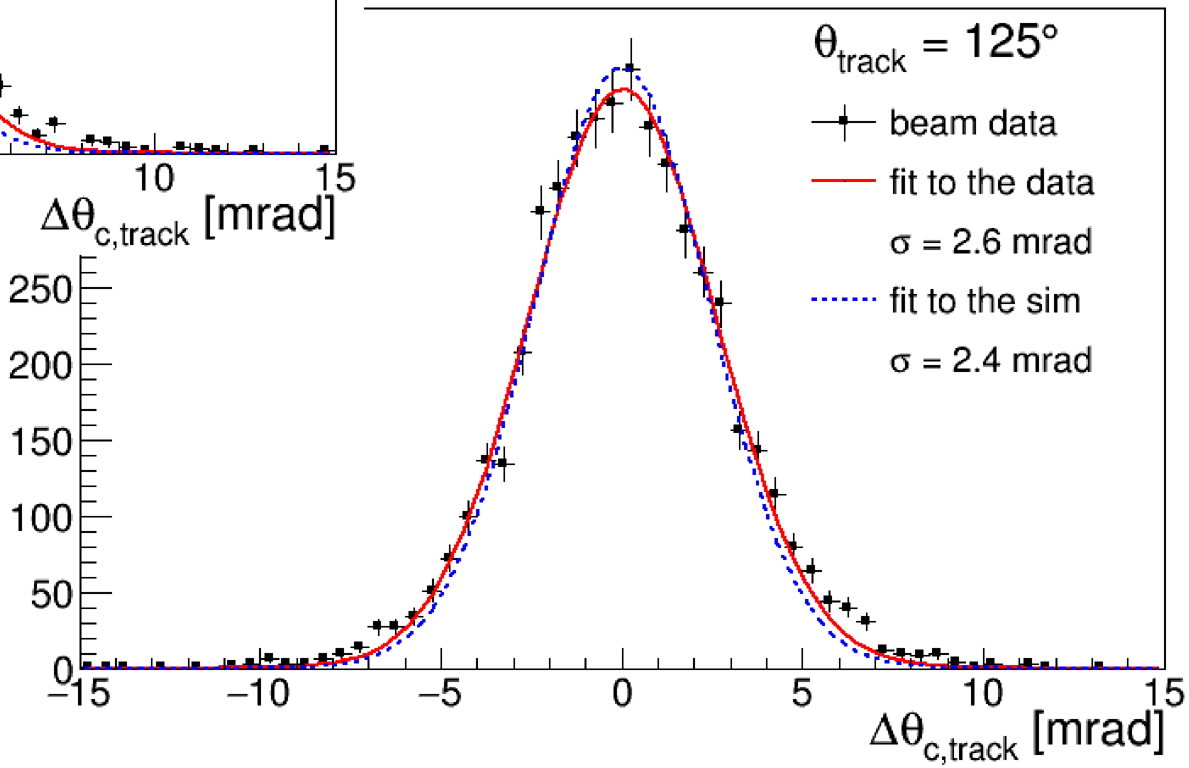


narrow bar, 3-layer spherical lens

7 GeV/c proton tag

track-by-track Cherenkov angle fit

geometric reconstruction



Calculate separation power with

$\Delta\theta_C$ (π-K)=8.5mrad

$\Delta\theta_C$ (π-K)/σ = 3.5 s.d. @ 25°

→ meets PANDA requirement

narrow bar, 3-layer spherical lens

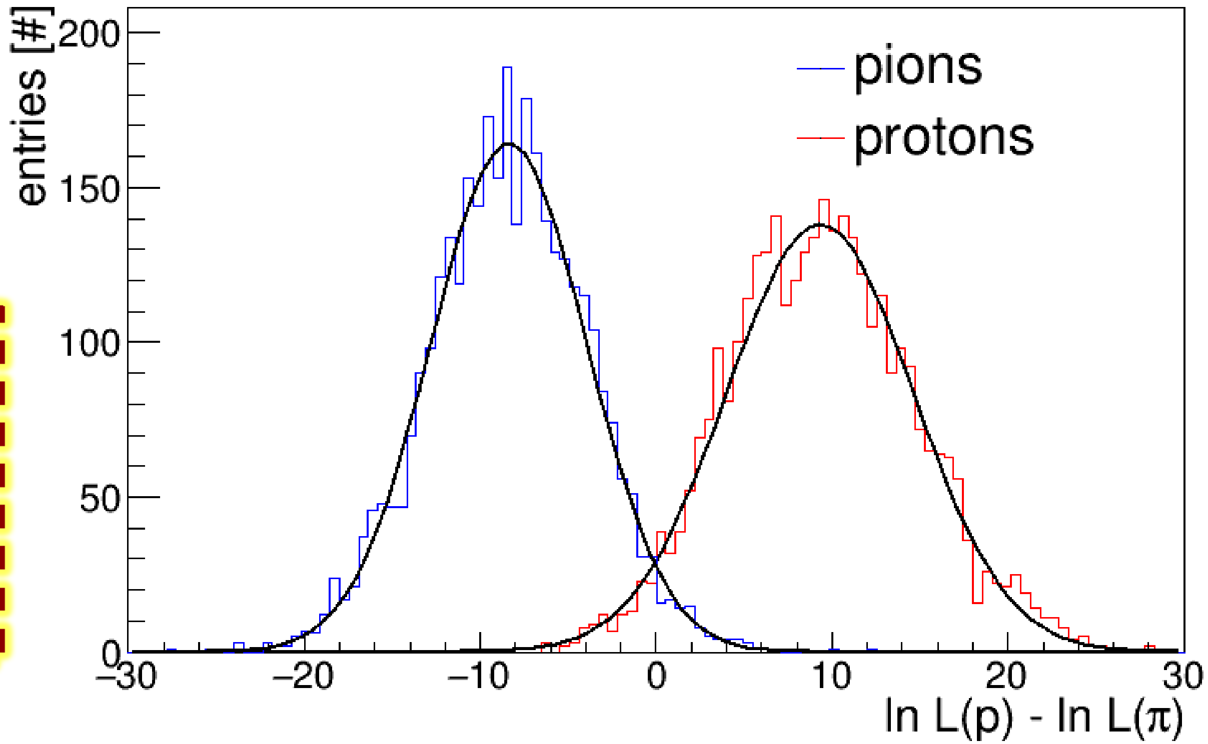
7 GeV/c proton tag, 25° polar angle

time-based imaging method (PDFs from beam data, timing precision ~150-300 ps)

π/p separation power = 3.6 s.d.

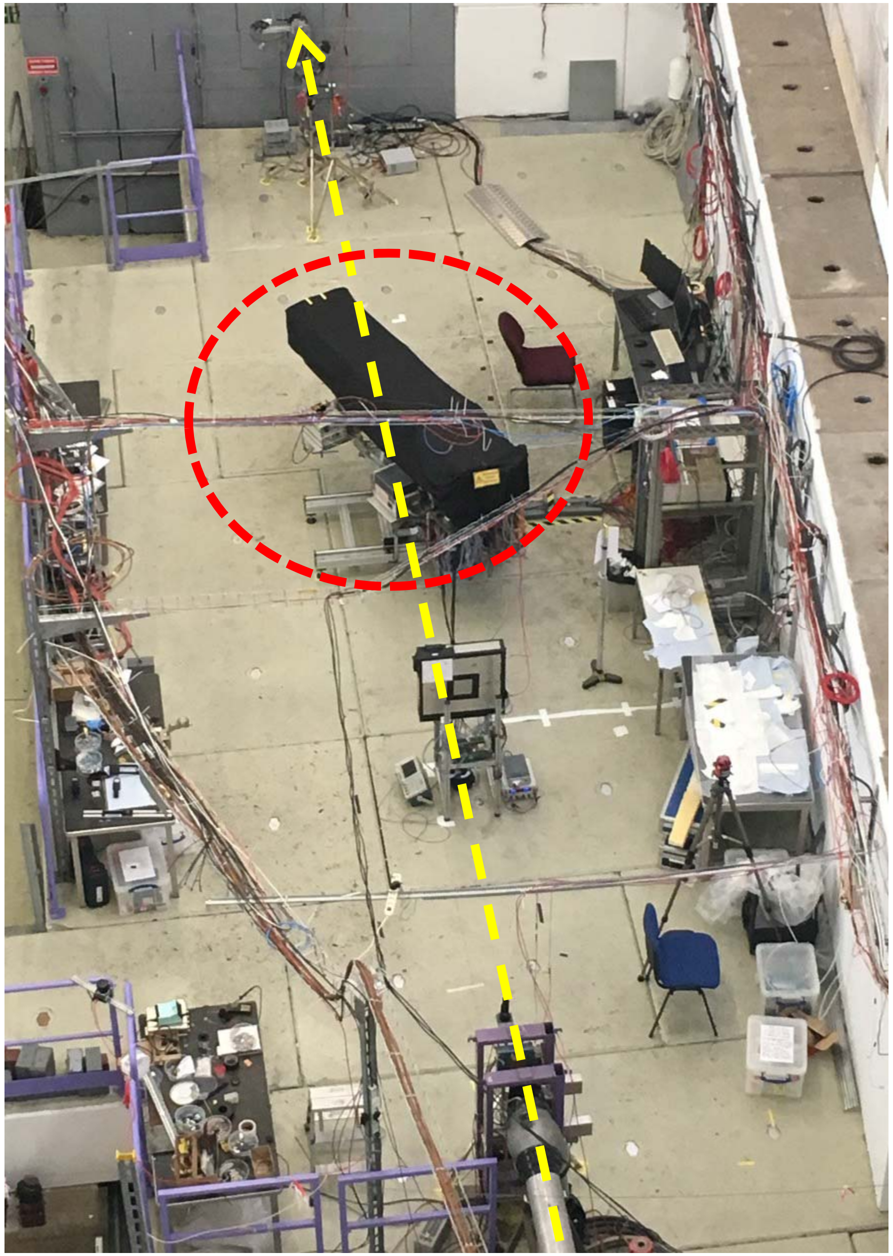
(equivalent to 3.8 s.d. π/K @ 3.5 GeV/c)

→ meets PANDA requirement



Time-based imaging provides best performance for narrow bar.

Corresponds to 5+ s.d. π/K @ 3.5 GeV/c for the fully equipped PANDA Barrel DIRC.

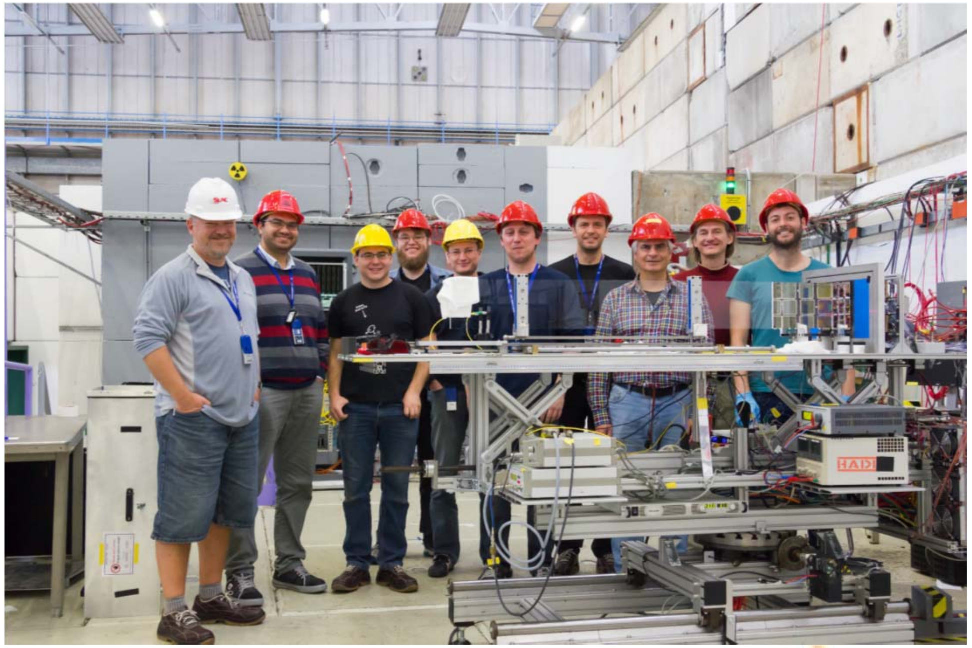


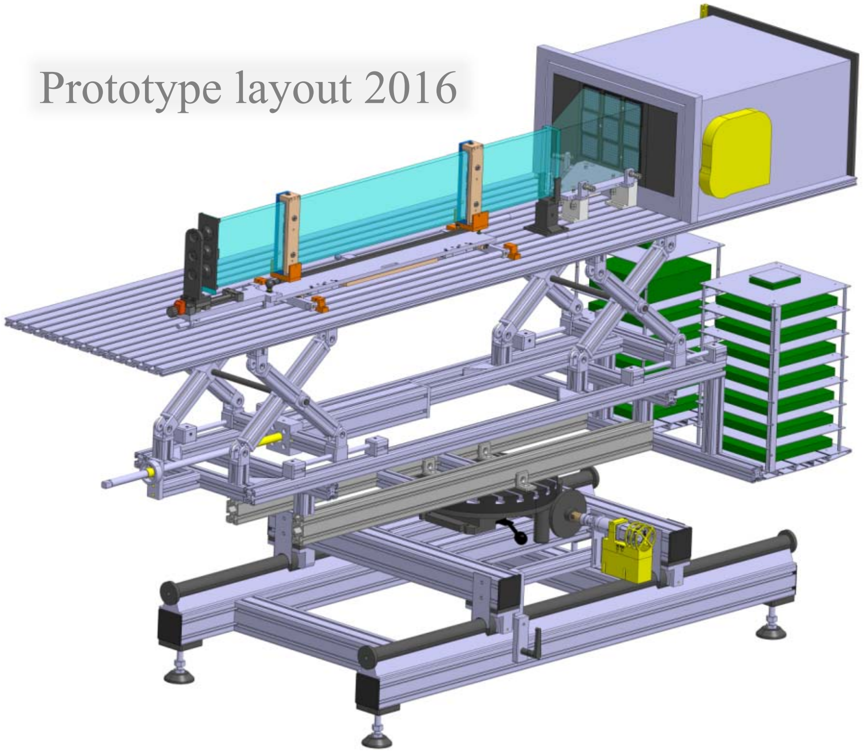
Barrel DIRC beam test at CERN PS/T9

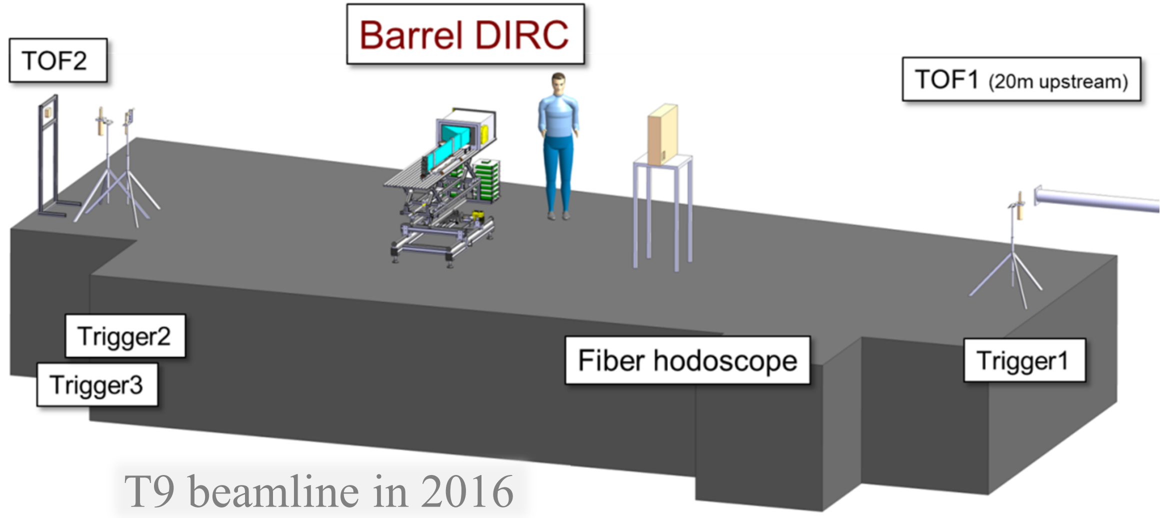
Goal: validate PID performance of
cost-saving design option (wide plates)

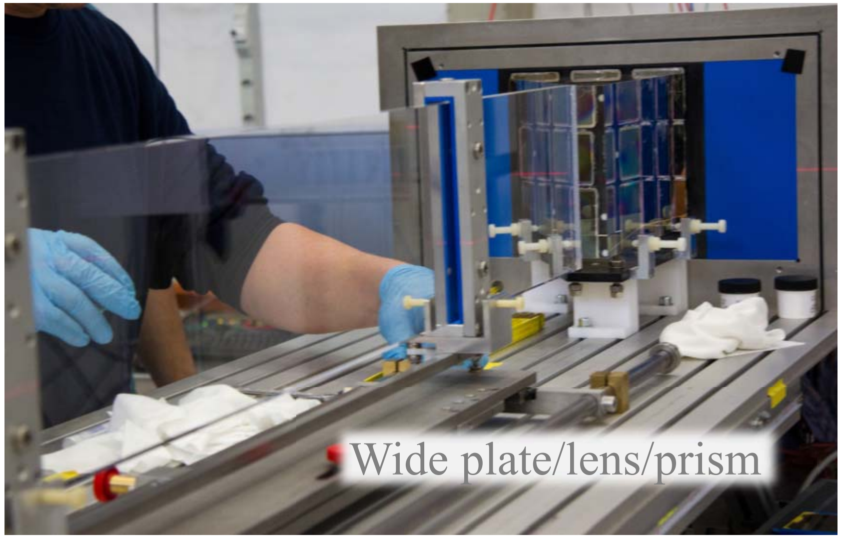
Improved prototype layout and electronics

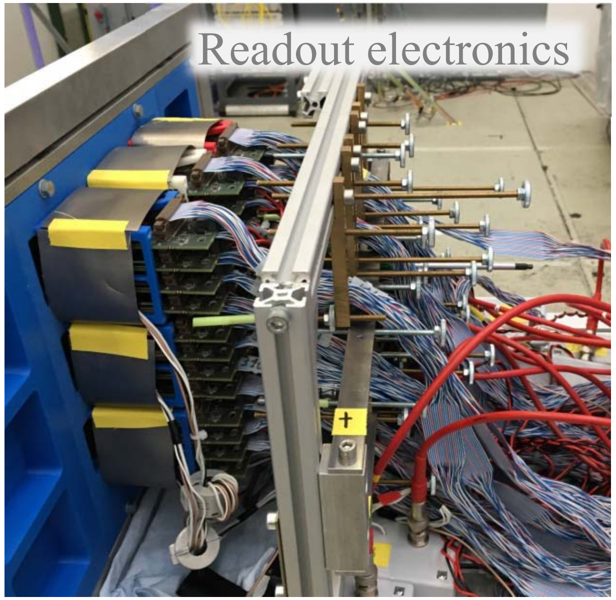
Three weeks of beam (Oct 14-Nov 2), 500M triggers




Prototype layout 2016


TOF2
Barrel DIRC
TOF1 (20m upstream)
Trigger2
Trigger3
Fiber hodoscope
Trigger1
T9 beamline in 2016


Wide plate/lens/prism


Readout electronics

Results for data and simulation

175mm-wide plate with 2-layer cylindrical lens,

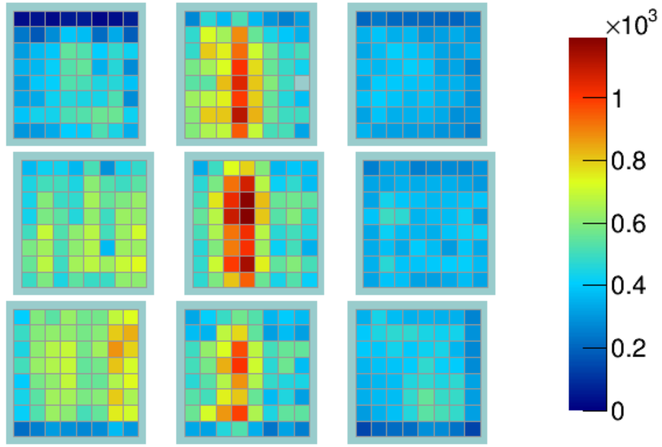
7 GeV/c beam momentum.

Plate image looks different from bar, less structure.

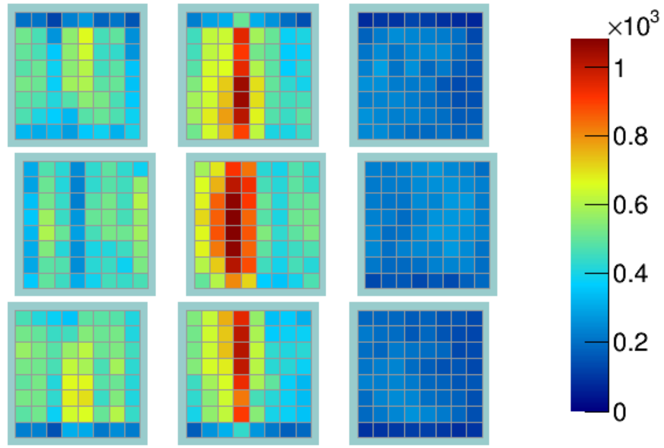
Pattern and photon yield agree with simulation.

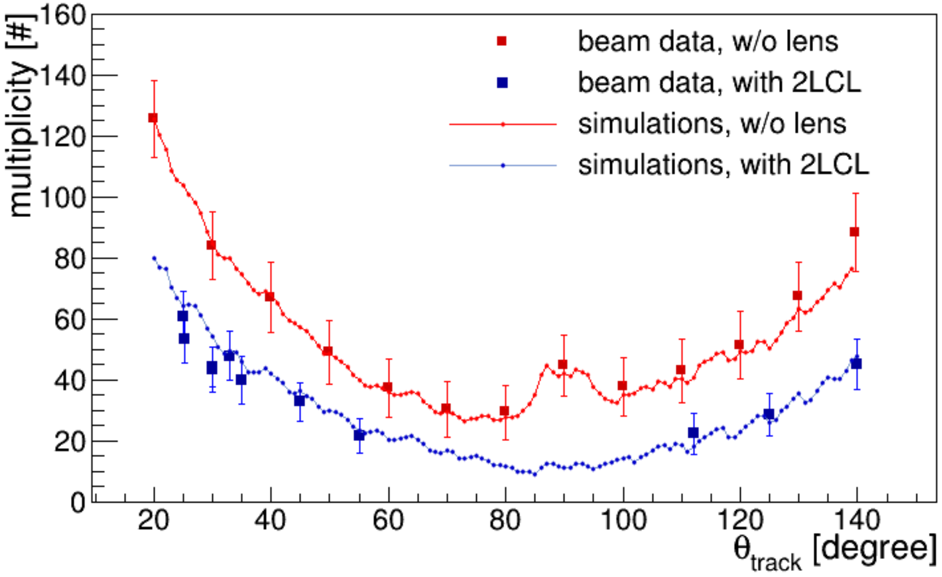
(lens/prism size mismatch caused some photon loss and performance degradation)

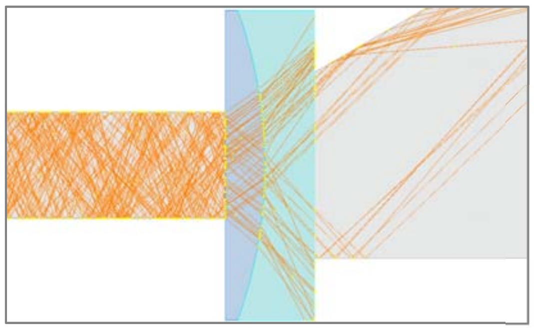
beam proton tag



simulation protons







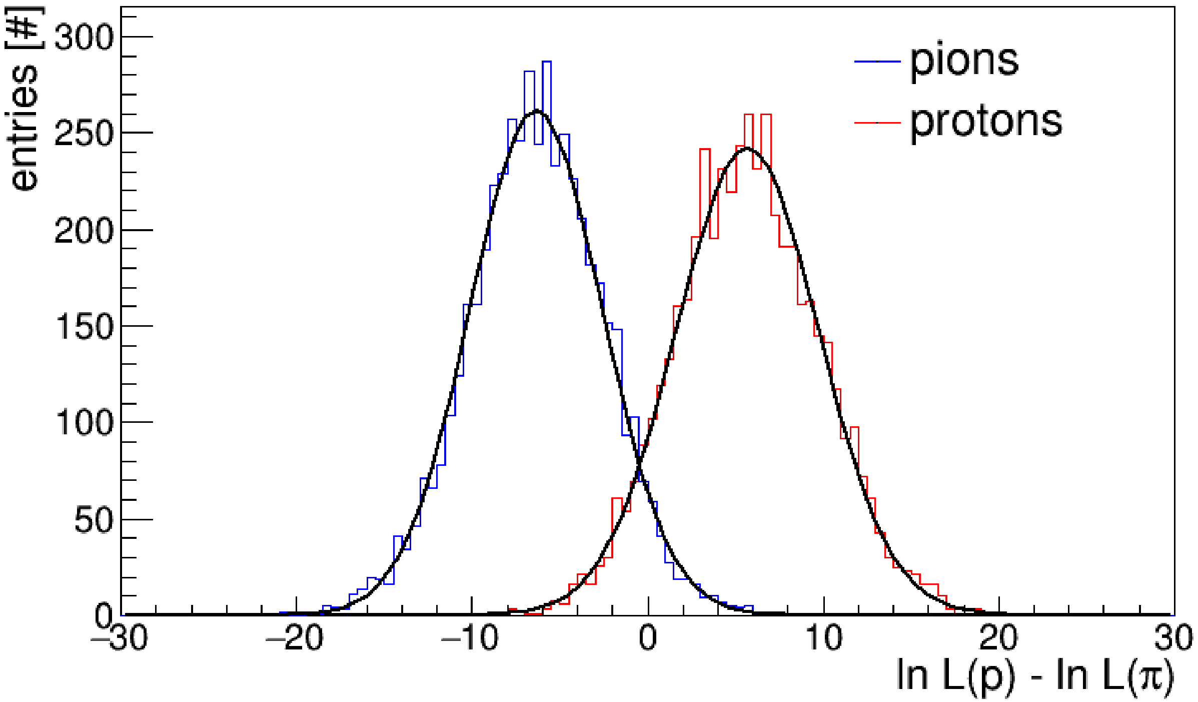
lens/prism size mismatch in 2016

wide plate, 2-layer cylindrical lens

7 GeV/c proton tag, 25° polar angle

time-based imaging method (PDFs from beam data, timing precision ~150-200 ps)

time-based imaging

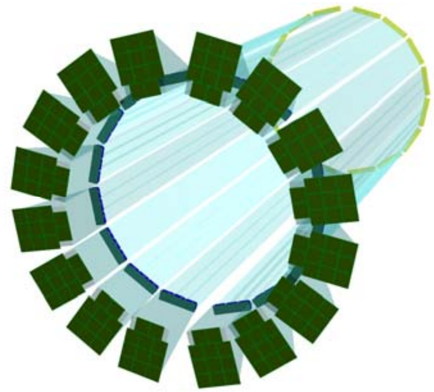


π/p separation power = 3.1 s.d.

(equivalent to 3.2 s.d. π/K @ 3.5 GeV/c)

→ meets PANDA requirement

Wide plate without 2-layer cylindrical lens does not quite meet PID goal (2.8 s.d. π/p separation).



Design with narrow bars, 3-layer spherical lens, and compact prisms meets or exceeds the PANDA PID requirements.

Performance robust in terms of background and timing resolution.

Simulation and PID performance validated with particle beams in 2015.

Wide plate with 2-layer cylindrical lens also meets PANDA PID requirements.

Performance validated with particle beam in 2016.

- PID performance of narrow bars slightly better than for wide plates.
- System cost of narrow bar design ~15% higher than for wide plates.
- Wide plate more sensitive to background, multiple tracks per sector, pile-up effects, and timing precision degradation.
- Geometric reconstruction algorithm only possible for narrow bar geometry.

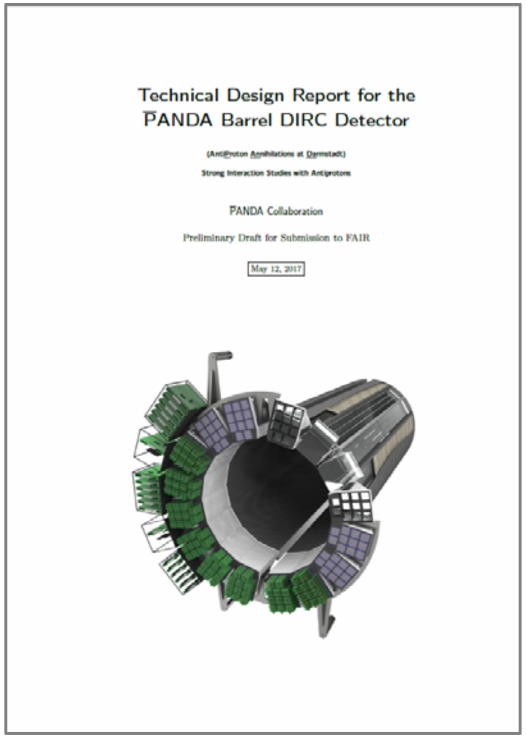
Decision in favor of narrow bars, baseline design in TDR.

PANDA Barrel DIRC: Status

The PANDA Barrel DIRC design has been completed, the performance validated.

Important milestone: Technical Design Report submitted in Sep. 2016,

received positive FAIR review, approval expected this month.



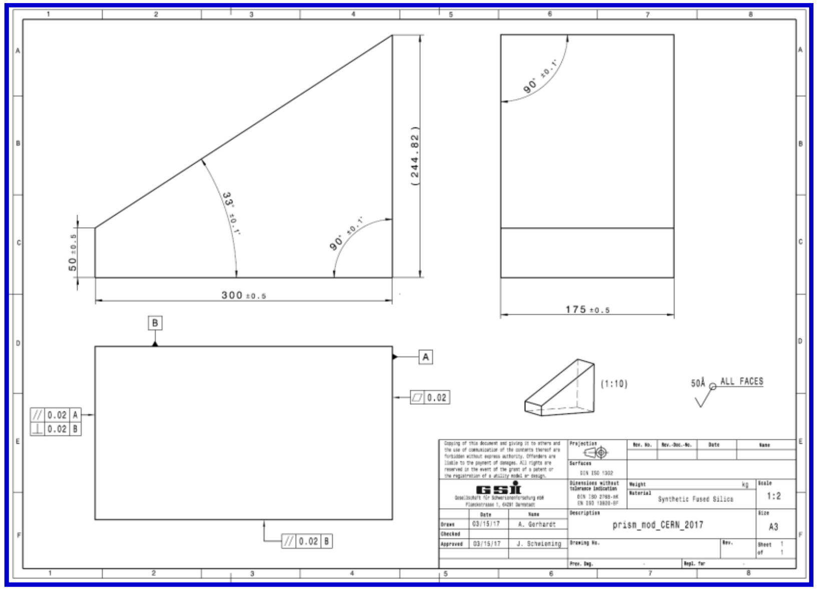
But: we know that we're not done yet, exciting times are ahead.

A lot of technical issues still need to be resolved

(discussions at this DIRC workshop are very helpful):

- gluing of bars, bar box assembly
- detailed design of mechanical support (CFRP bar boxes?)
- mechanical and optical coupling of bar boxes and MCP-PMTs to prism
- readout electronics (DiRICH) validation (HADES RICH) and optimization for MCP-PMTs
- ...and we all know how much fun the mass production and QA of bars and MCP-PMTs can be...

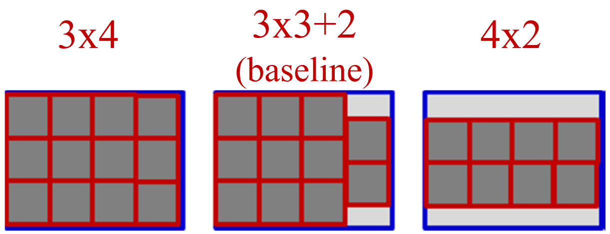
One more (final?) beam test opportunity: Aug 23 – Sep 13, 2017 at the CERN PS/T9.



New prism, 33° opening angle

→ hit patterns closer to PANDA reality,
better MCP-PMT coverage.

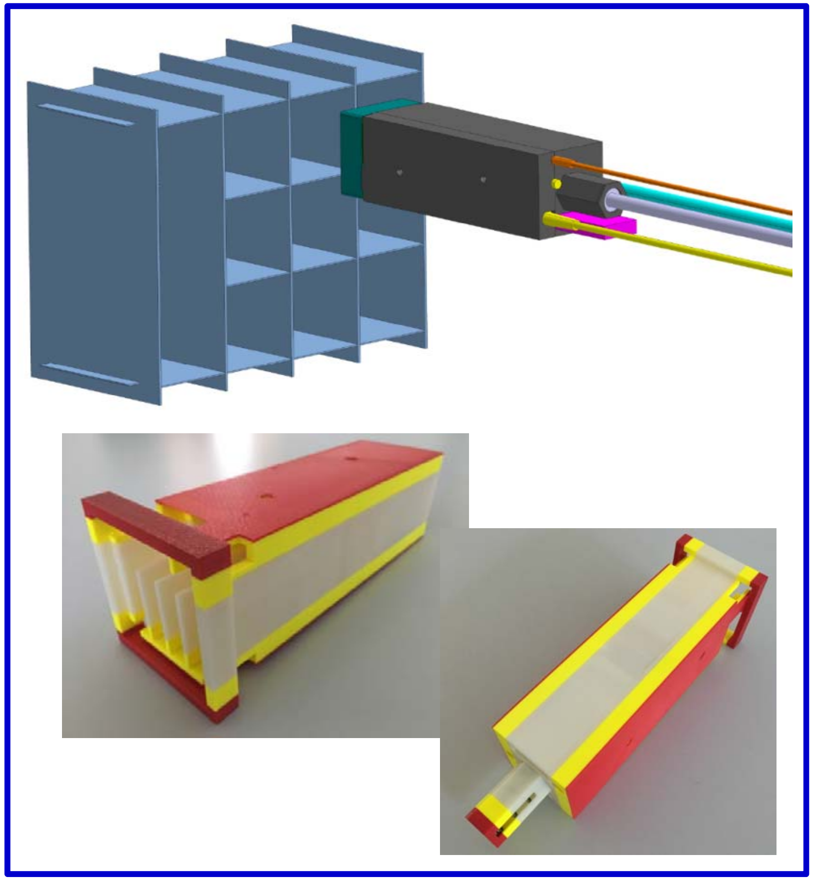
Will test different MCP-PMT layouts:
possible cost-reduction for PANDA.



Primary goals for Barrel DIRC prototype:

- study hit patterns for near-final prism size, compare MCP-PMT layouts
- study quality of optical coupling using silicone sheets/cookies
- new MCP-PMT/readout electronics assembly
- study time-based imaging PDFs
- study impact of azimuthal track angle
- study performance of new 3-layer cylindrical lens (with bar or plate)

One more (final?) beam test opportunity: Aug 23 – Sep 13, 2017 at the CERN PS/T9.

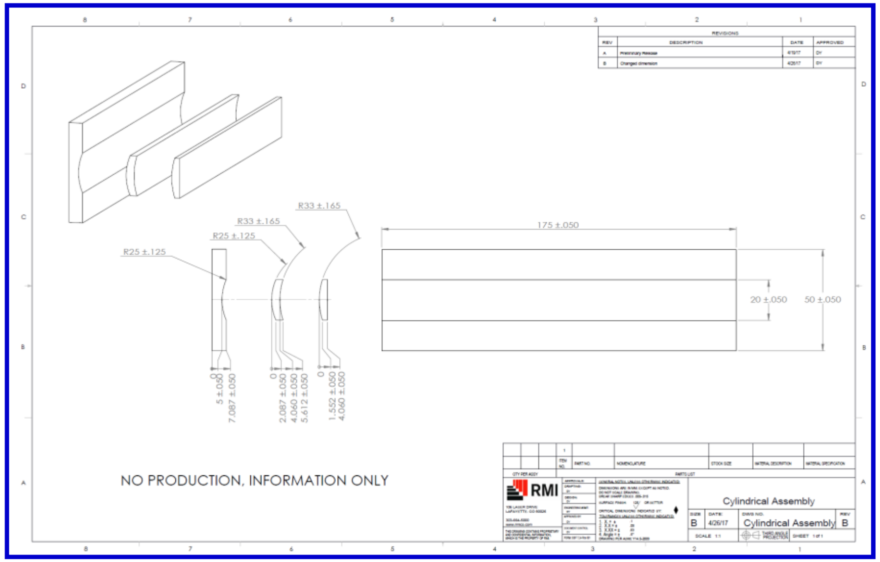


New 3D-printed readout modules
in new shielded module array holder
→ better sensor coverage, cleaner cable routing, less electronics noise

Primary goals for Barrel DIRC prototype:

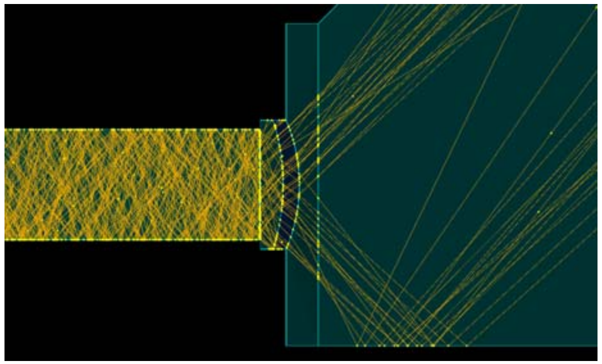
- study hit patterns for near-final prism size, compare MCP-PMT layouts
- study quality of optical coupling using silicone sheets/cookies
- new MCP-PMT/readout electronics assembly
- study time-based imaging PDFs
- study impact of azimuthal track angle
- study performance of new 3-layer cylindrical lens (with bar or plate)

One more (final?) beam test opportunity: Aug 23 – Sep 13, 2017 at the CERN PS/T9.



New 3-layer cylindrical lens *(eRD14 funding)*,
important for future DIRC@EIC design.

→ improved flatness of focal plane

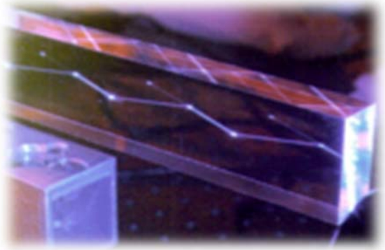


Primary goals for Barrel DIRC prototype:

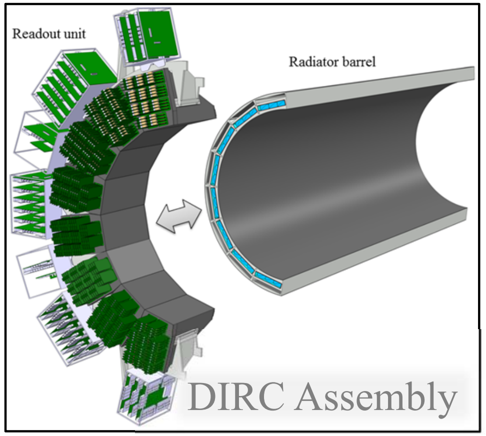
- study hit patterns for near-final prism size, compare MCP-PMT layouts
- study quality of optical coupling using silicone sheets/cookies
- new MCP-PMT/readout electronics assembly
- study time-based imaging PDFs
- study impact of azimuthal track angle
- study performance of new 3-layer cylindrical lens (with bar or plate)

2017-2023: Component Fabrication, Assembly, Installation.

- 2017/2018: Finalize specifications, MoUs, tender, contracts.
- 2018-2021: Industrial fabrication of fused silica bars, lenses, and prisms. Industrial production of Micro-channel Plate PMTs.


DIRC bar with laser

- 2019-2020: Production and QA of readout electronics.
- 2018-2022: Industrial fabrication of bar containers and mechanical support frame; QA of bars, gluing of long bars, assembly of complete bar boxes. Detailed QA (scans, aging study) of MCP-PMTs. Assembly of readout units.
- 2022/2023: Installation of mechanical support frame in PANDA, insert bar boxes, mount readout modules.



DIRC Assembly

Ready as “Start Setup / Day One” detector in PANDA.

THANK YOU FOR YOUR ATTENTION.