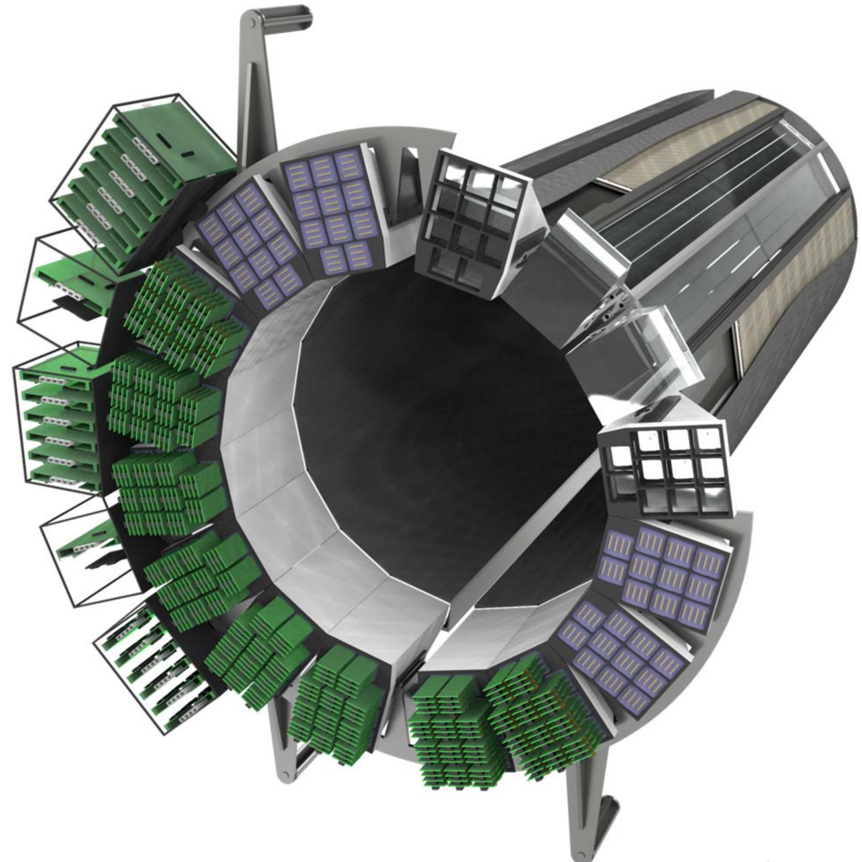
The PANDA Barrel DIRC Detector

Jochen Schwiening

GSI

for the PANDA Cherenkov Group

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



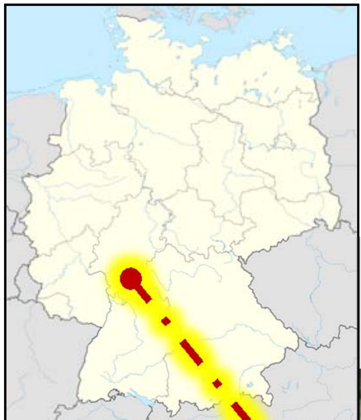
3D rendering of PANDA Barrel DIRC baseline design

The PANDA Cherenkov Group:

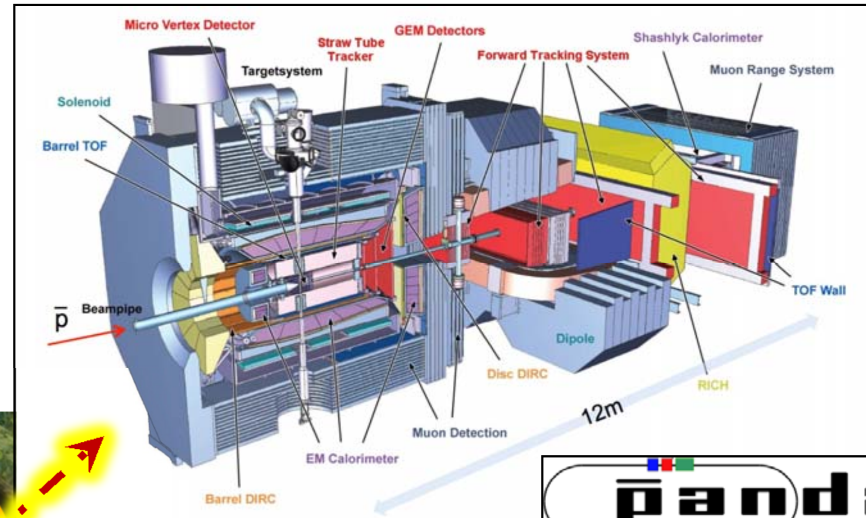
panda · FAU Friedrich-Alexander Universität Erlangen-Nürnberg · Justus-Liebig-Universität Giessen · GSI · JG|U Johannes Gutenberg Universität Mainz · FAIR

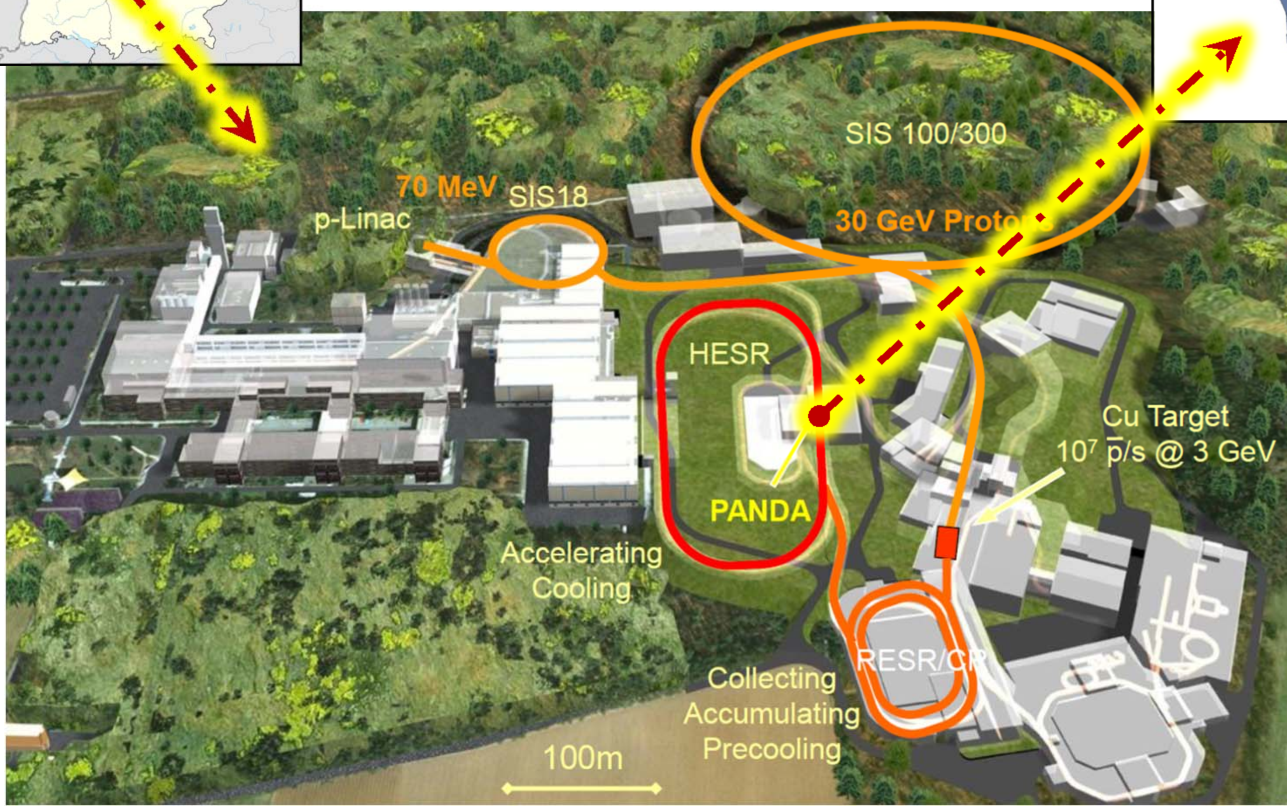
THE PANDA EXPERIMENT AT FAIR

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

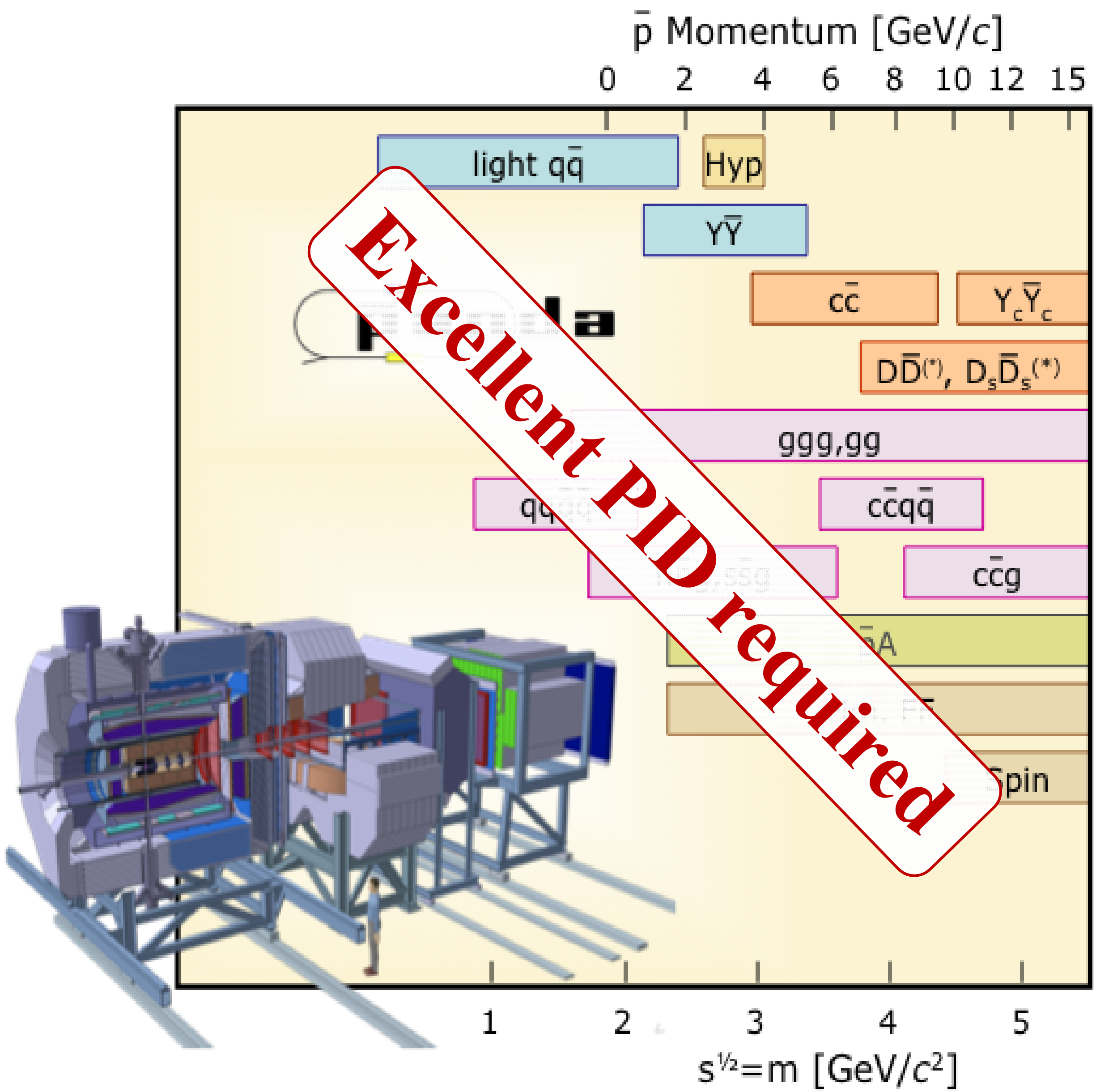
  $\Delta p/p \approx 10^{-4}$ (stochastic cooling)

  $L = 1.6\times10^{32}$ 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**

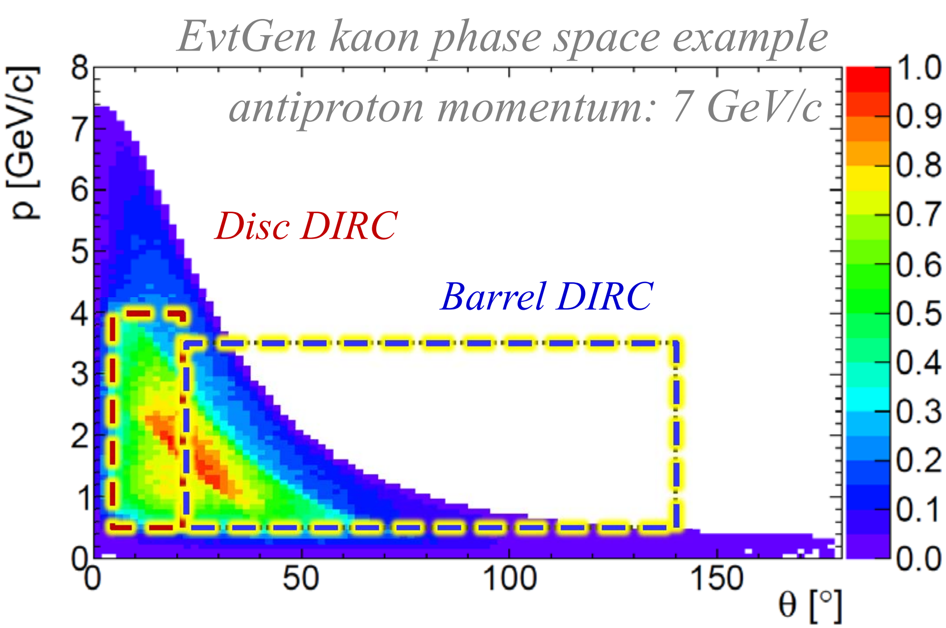
  German in-kind contribution to PANDA

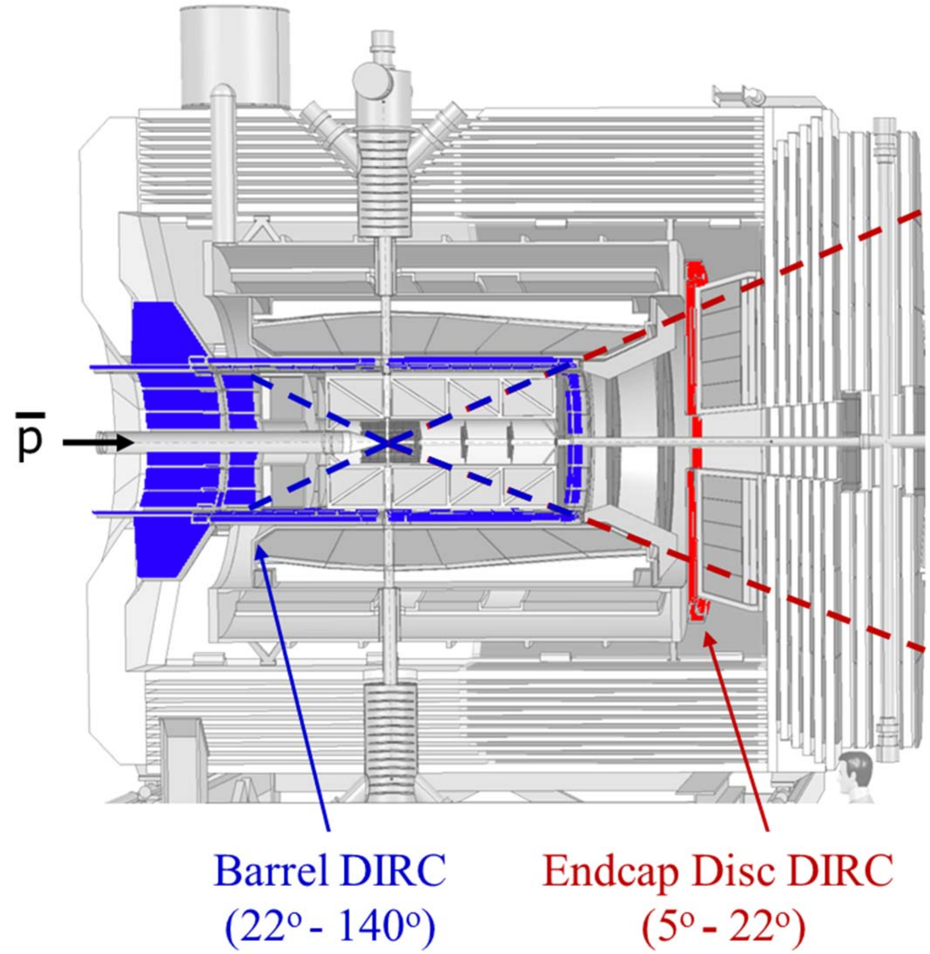
  Goal: 3 s.d. π/K separation up to 3.5 GeV/c

- **Endcap Disc DIRC**

  > M. Dueren, Mon 16:45

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





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

Achieved BaBar DIRC performance exceeds PANDA Barrel DIRC requirement.

→ Based our design on experience with BaBar DIRC, SuperB FDIRC, Belle II TOP.

Many design options were studied with the full, detailed Geant simulation and with prototypes.

The initial goal: find at least one design that matches the BaBar DIRC figures of merit.

→ Narrow bars (5 per sector), spherical lenses, large oil tank.

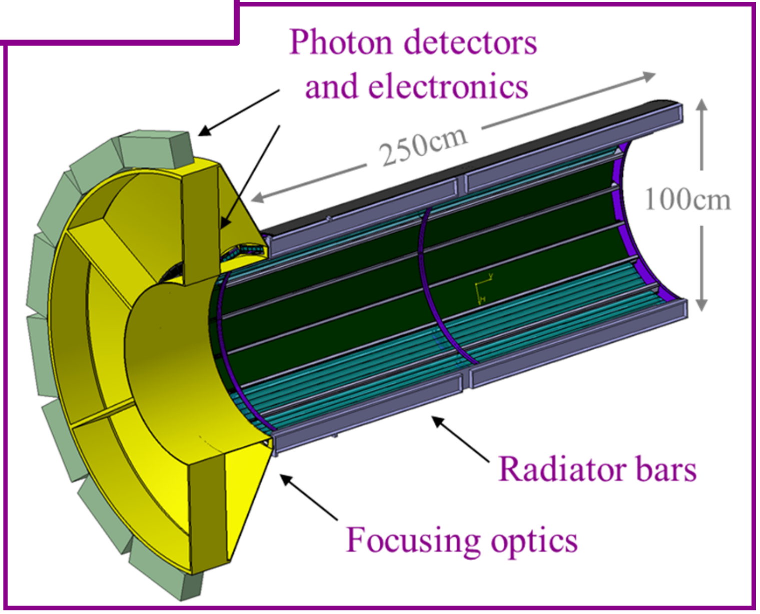
Good performance – but production cost ~50% over budget.

Next goal: cost/performance optimization.

The main cost drivers for the Barrel DIRC are:

- fabrication of the radiator bars (or plates);
- fabrication of the photon detectors.

→ minimize number of bars/sensors.

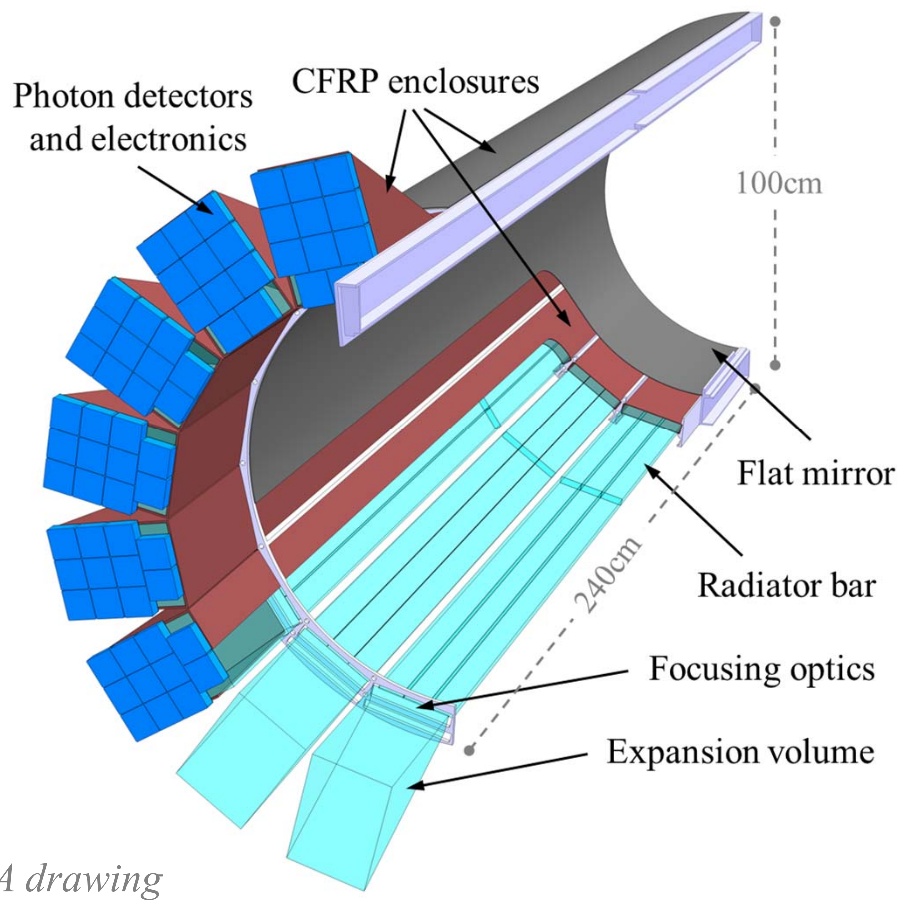


Design from RICH2013.

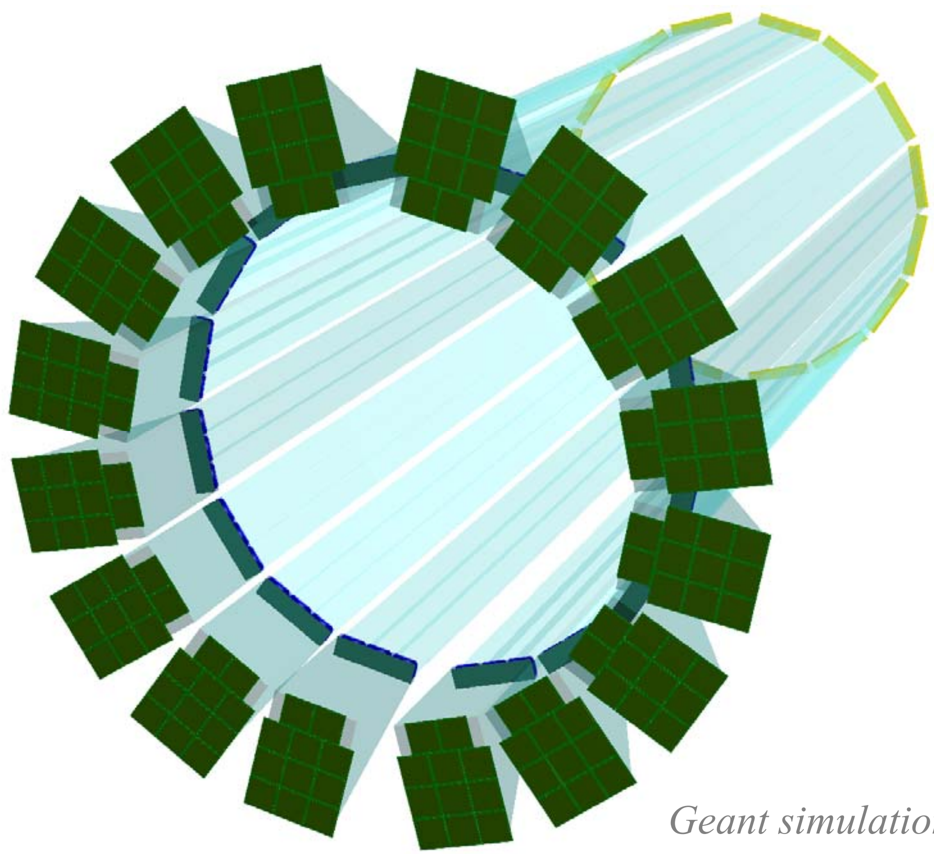
Main results of a comprehensive cost performance optimization in simulation:

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.



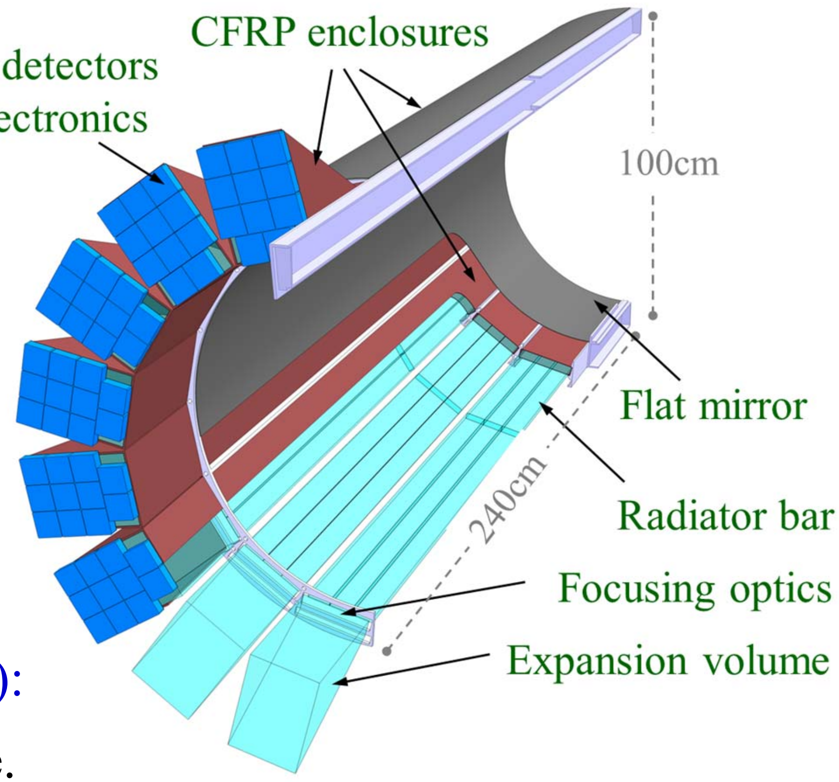
CATIA drawing



Geant simulation

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

- 48 radiator bars (16 sectors), synthetic fused silica, *(instead of 80 bars in 2013 design)*
  17mm (T) × 53mm (W) × 2400mm (L).
- Focusing optics: triplet spherical lens system.
- Compact expansion volume:
  30cm-deep solid fused silical 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 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...)*

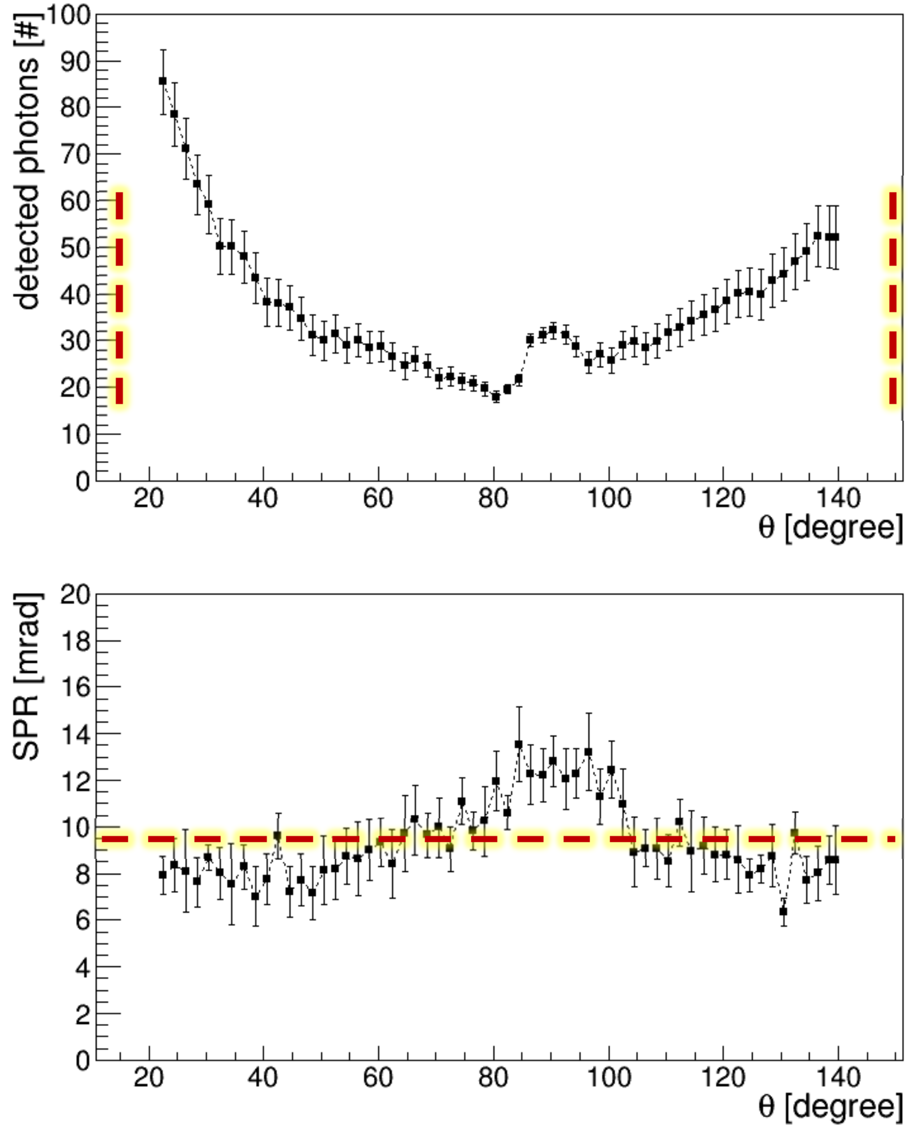
Baseline design, 3 bar per bar box, 3-layer spherical lens, prism

Used geometrical reconstruction (BABAR-like)

to determine photon yield and

single photon Cherenkov angle resolution (SPR)

Geant simulation



Yield and SPR reach performance goal.

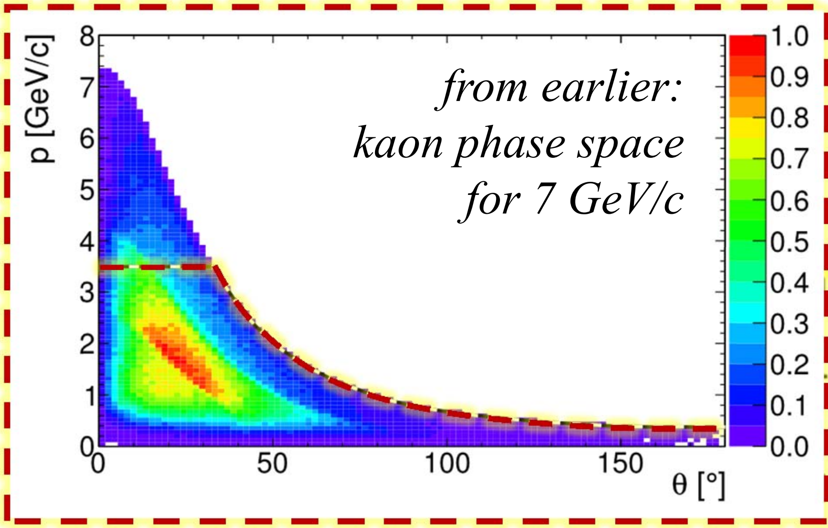
BABAR DIRC FOMs reached or even exceeded,

in particular for most demanding

high-momentum forward region.

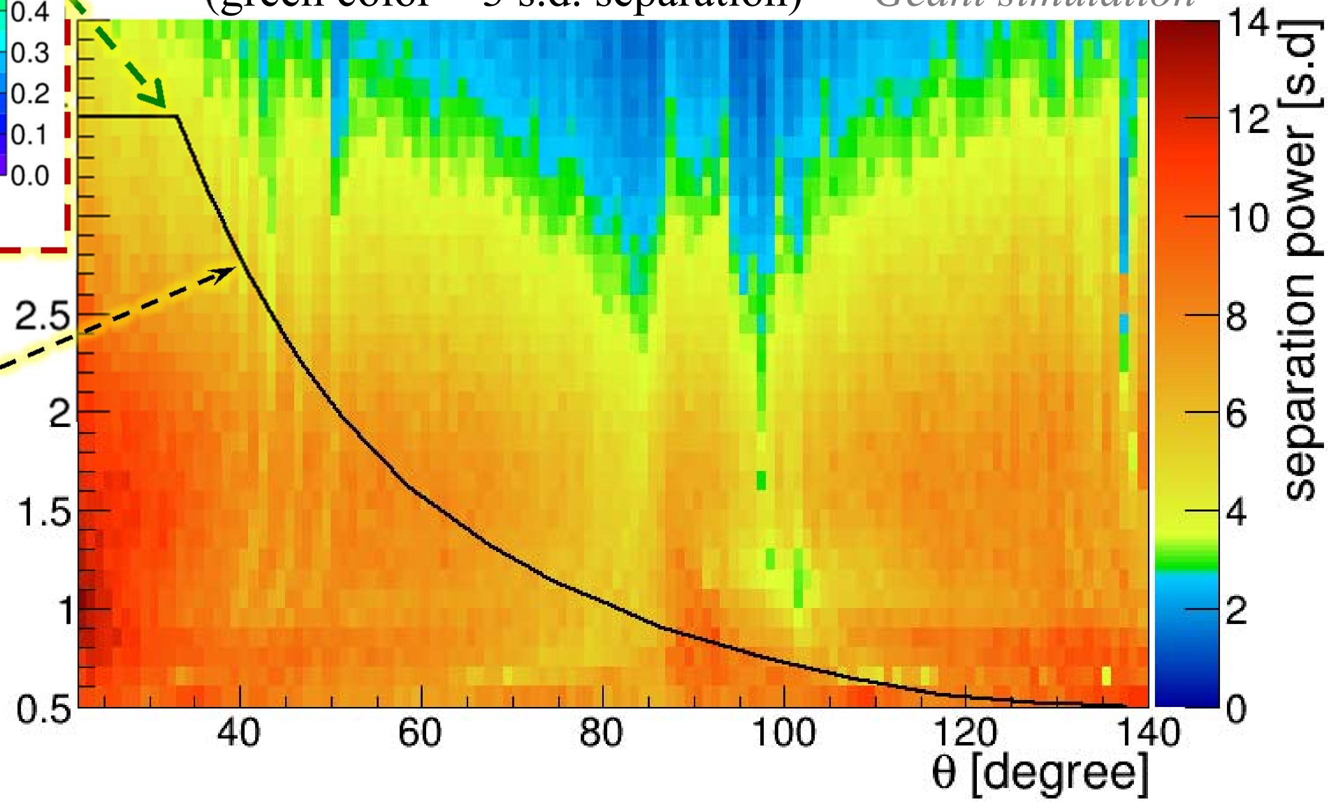
Baseline design, 3 bar per bar box, 3-layer spherical lens, prism

π/K separation power from geometric reconstruction, track-by-track max. likelihood fit



PID requirements for entire acceptance range.

(green color ~ 3 s.d. separation) *Geant simulation*



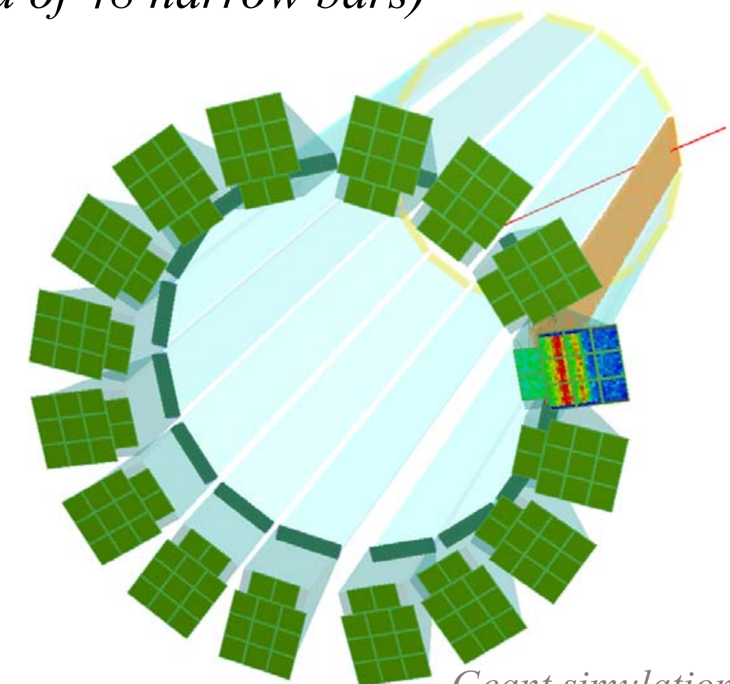
Barrel DIRC PID 3 s.d. goal

(from kaon phase space)

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, still to be validated.



Geant simulation

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

Belle II TOP counter uses wide plates (450mm), completed installation this spring.

May expect similar performance (TOP goal: 3 s.d. π/K up to 4 GeV/c).

Needs PID performance validation from prototype using particle beams.

- J. Fast, Mon 10:55
- M. Staric, Tue 17:00
- K. Suzuki, Fri 9:10

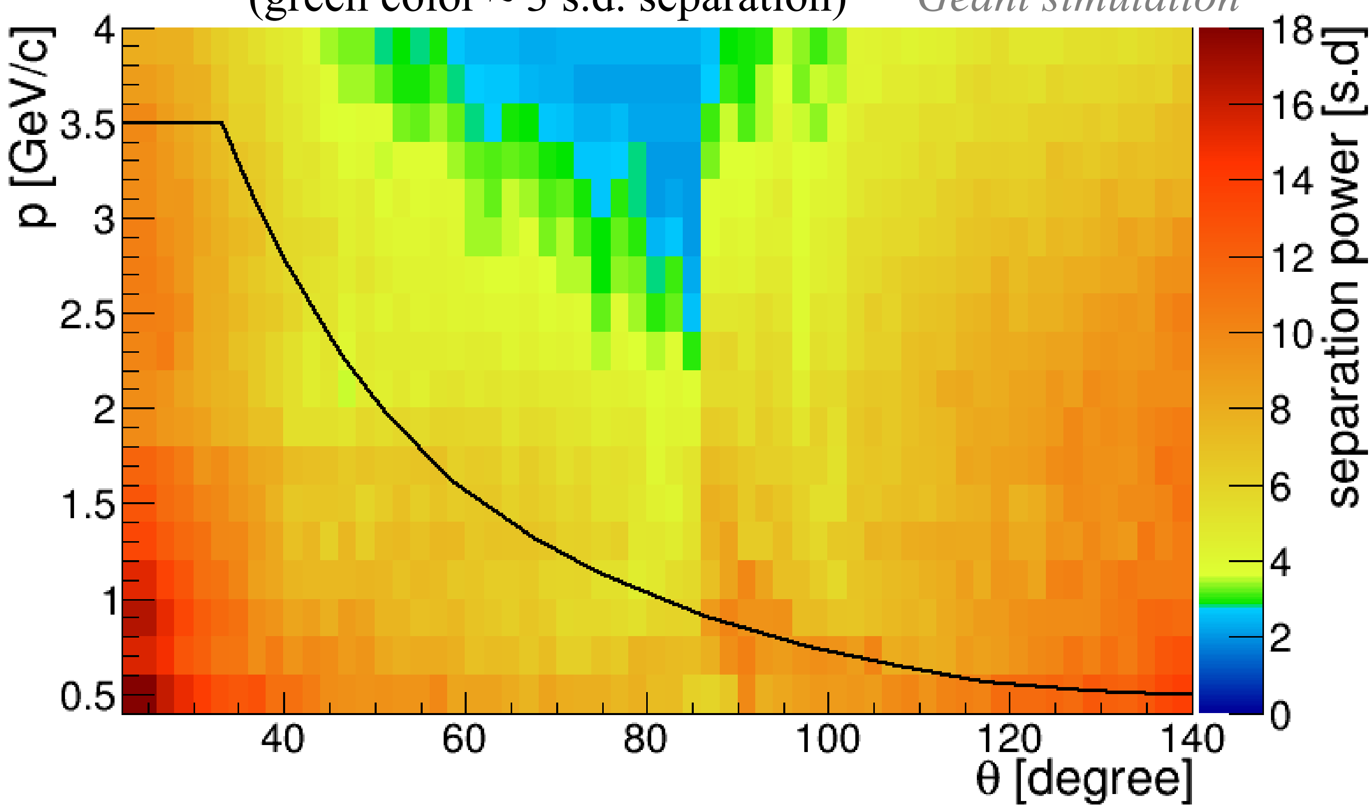
Cost-saving option, 1 plate per bar box, cylindrical lens

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.

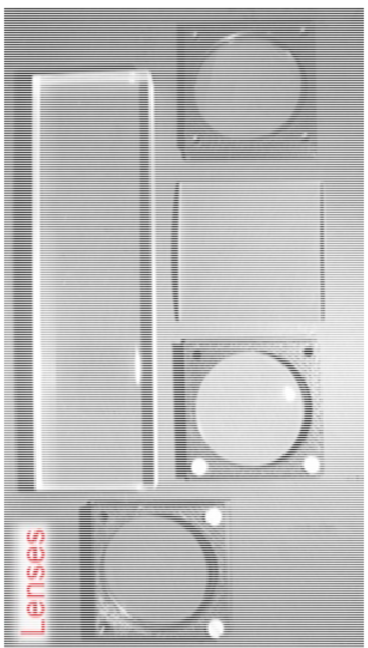
Performance even superior to narrow bar *(possibly due to limitation of geometrical reco).*

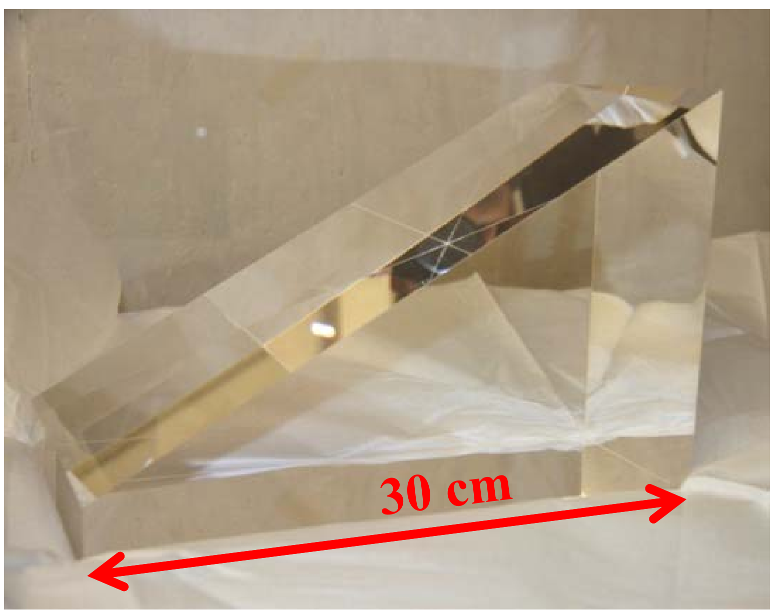
(green color ~ 3 s.d. separation) *Geant simulation*

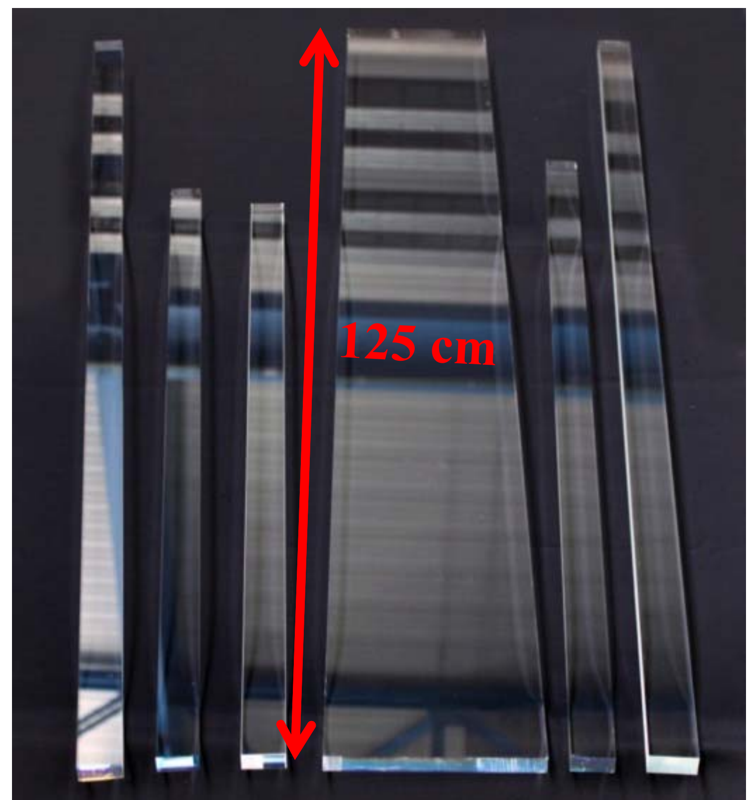


OPTICAL COMPONENTS

- 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*.
- Two solid fused silica prism prototypes (30° and 45° top angle) built by industry.
- Designed several spherical and cylindrical lenses, with and without air gap, several prototypes built by industry.



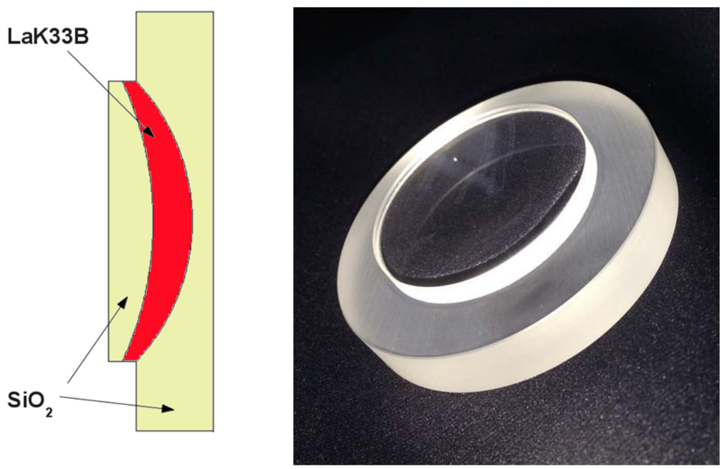




FOCUSING LENSES

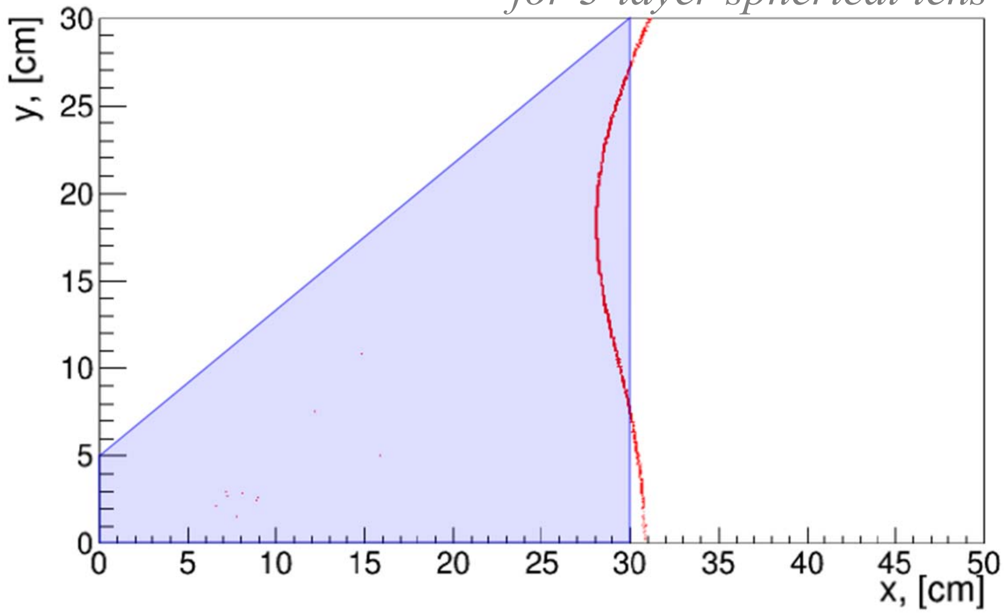
2-layer and 3-layer lens → minimize photon loss at bar/lens/expansion volume transition.

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



Main remaining concern:

radiation hardness of lanthanum crown glass (LaK33B) unknown.

Expected dose in Barrel DIRC is small (<100rad) but performance needs to be validated.

Irradiation test starting soon, results expected this year (fallback solution PbF_2).

(Thanks to DIRC@EIC R&D, eRD14 PID consortium)

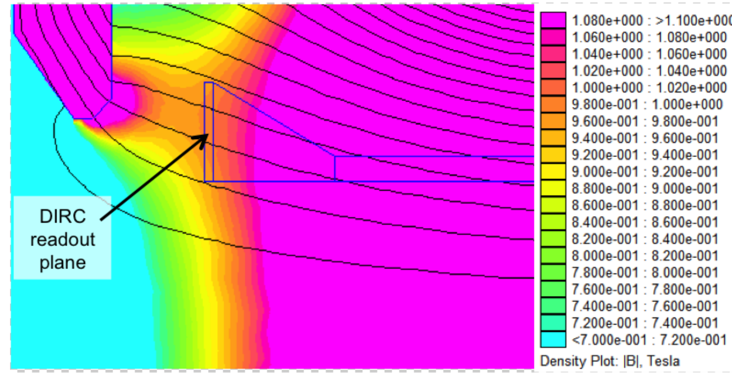
SENSOR CANDIDATES

- Multi-anode Photomultipliers (MaPMTs)

  used successfully in DIRC prototypes,

    sensors of choice for SuperB FDIRC, GlueX DIRC

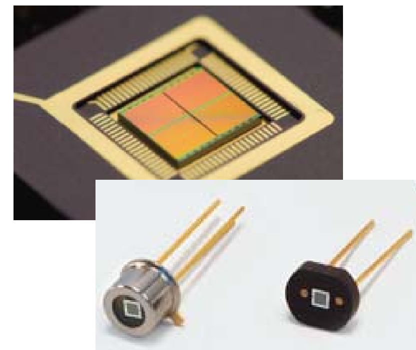
  ruled out by 1T magnetic field



- Geiger-mode Avalanche Photo Diodes (SiPMs)

  high dark count rate problematic for reconstruction (trigger-less DAQ)

  radiation hardness an issue in PANDA environment



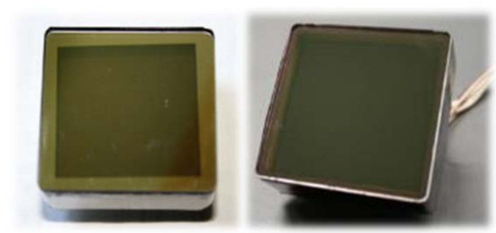
- Micro-channel Plate Photomultipliers (MCP-PMTs)

  good PDE, excellent timing and magnetic field performance

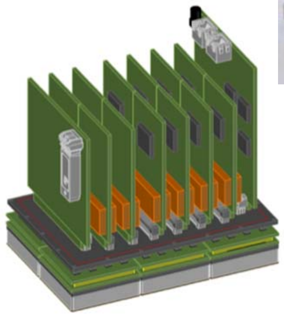
  used to have issues with rate capability and aging, now solved;

    sensors of choice for Belle II TOP and PANDA DIRCs.

> ➢ M. Dueren, Mon 16:45
> ➢ A. Lehmann, Tue 9:35



Readout and Mechanical Design



DiRICH, PADIWA, and TRB3

Readout Electronics

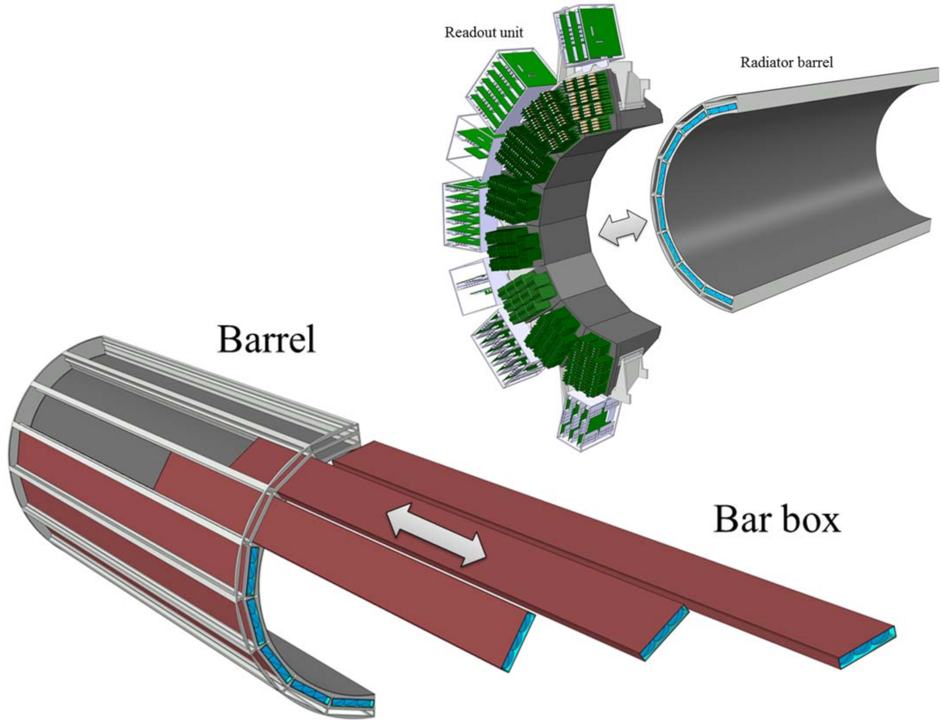
~100ps timing per photon for small MCP-PMT pulses – amplification and bandwith optimization

20MHz average interaction, trigger-less DAQ

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

Near future: DiRICH, integrated backplane, joint development with HADES/CBM RICH.

➢ T. Mahmoud, Mon 16:20



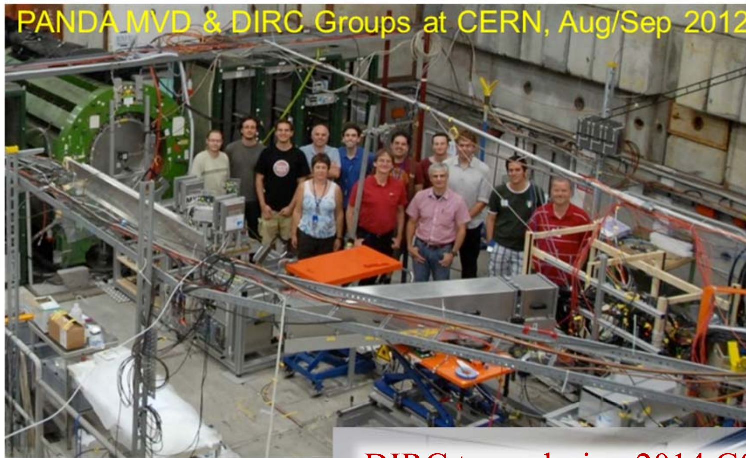
Mechanical Design

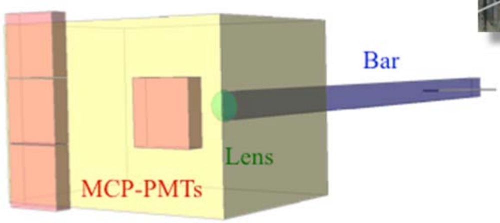
Light-weight and modular, allows staged bar box installation, access to inner detectors.

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

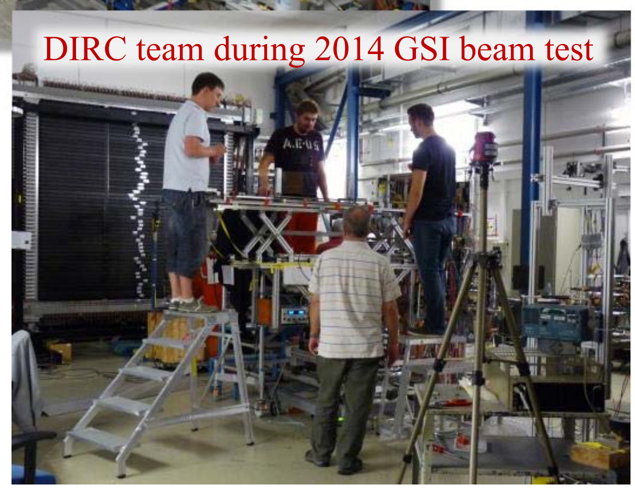
Boil-off nitrogen flush for optical surfaces.

BARREL DIRC BEAM TESTS

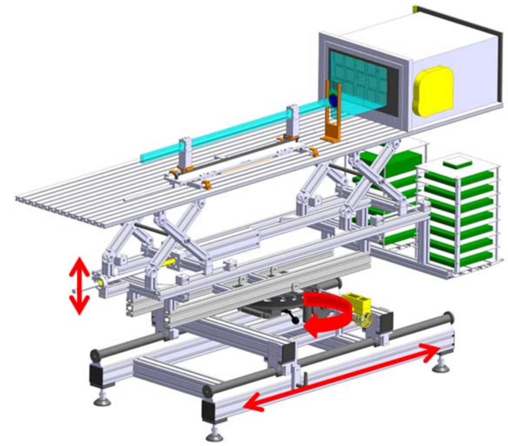


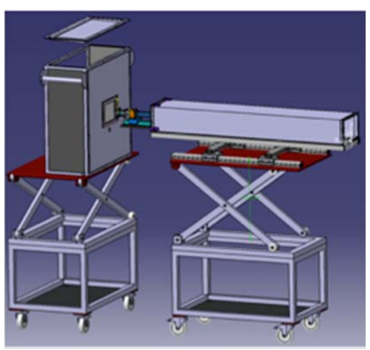


2008, 2009: GSI

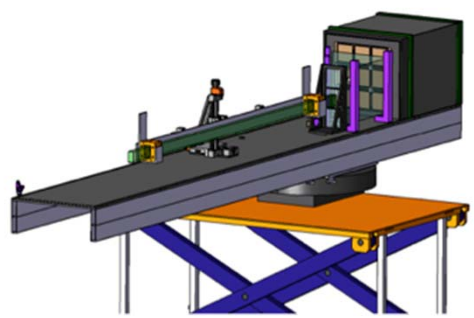


2014, 2015: GSI, CERN





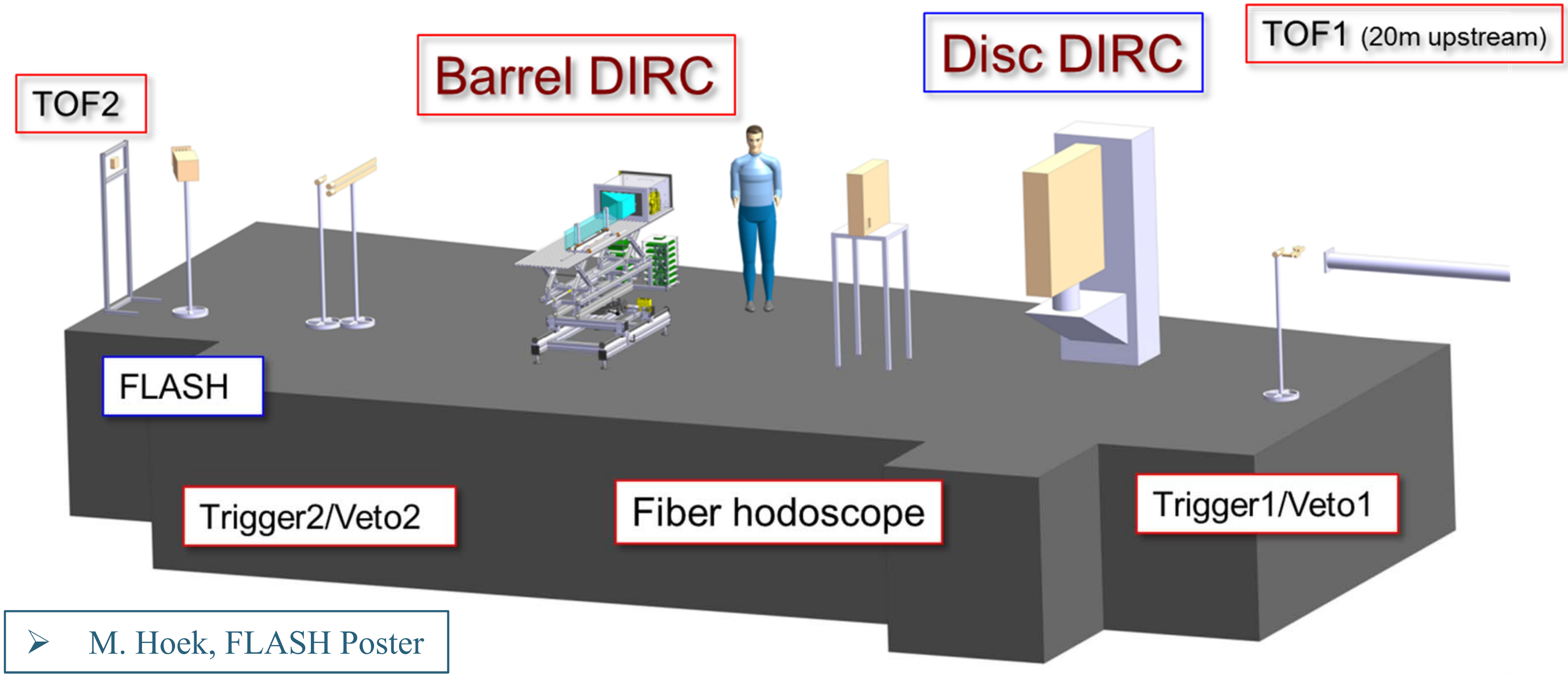
2011: GSI, CERN



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.



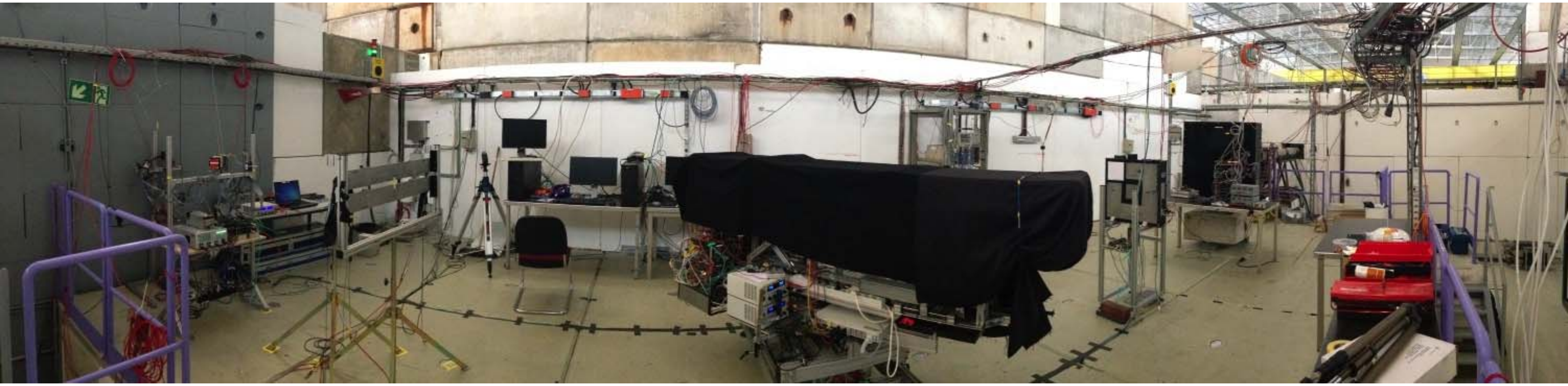
- M. Hoek, FLASH Poster

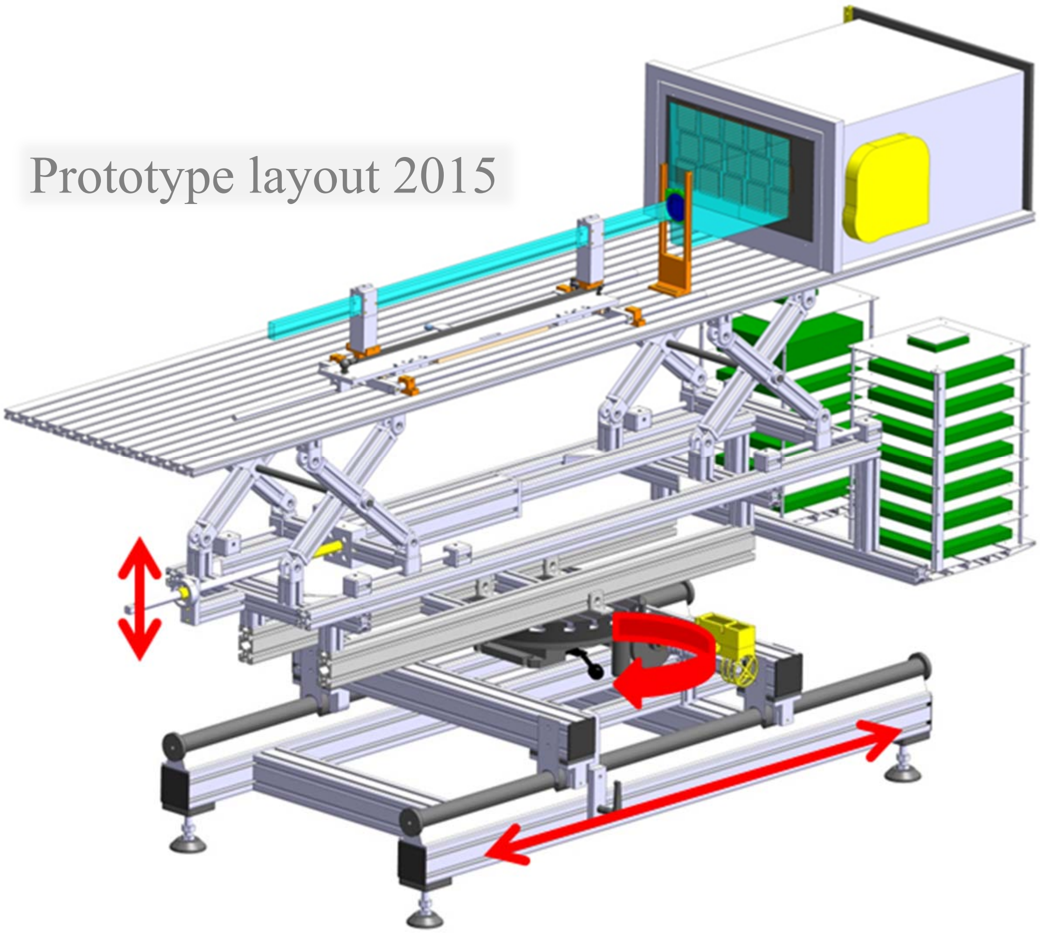
2015 CERN BEAM TEST

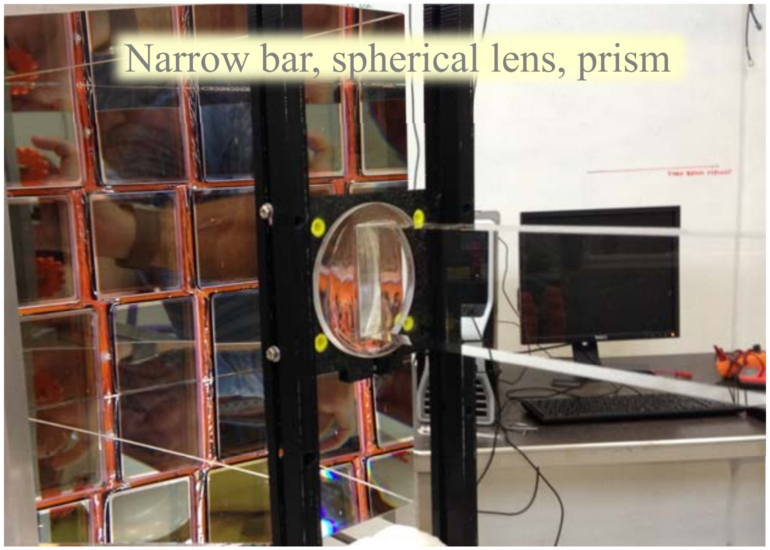
Beam test at CERN PS/T9 (May/June, July 2015)

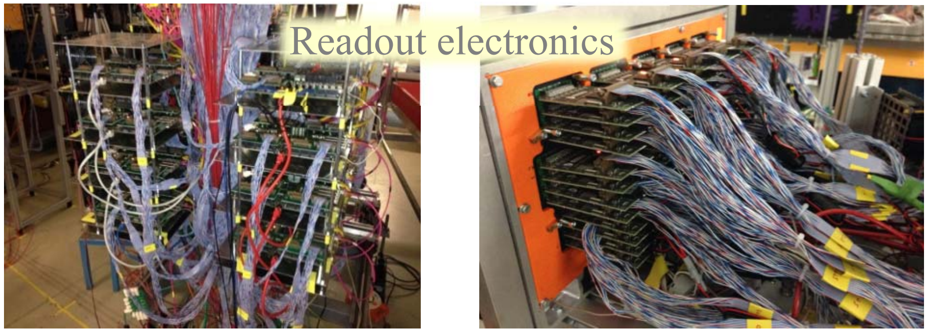
- Fused silica prism as expansion volume.
- 5 x 3 array of Planacon MCP-PMTs.
- Narrow bar and wide plate as radiator.
- Many different imaging/lens configurations.
- Momentum and angle scans.
- ~500M triggers during 34 days of data taking.

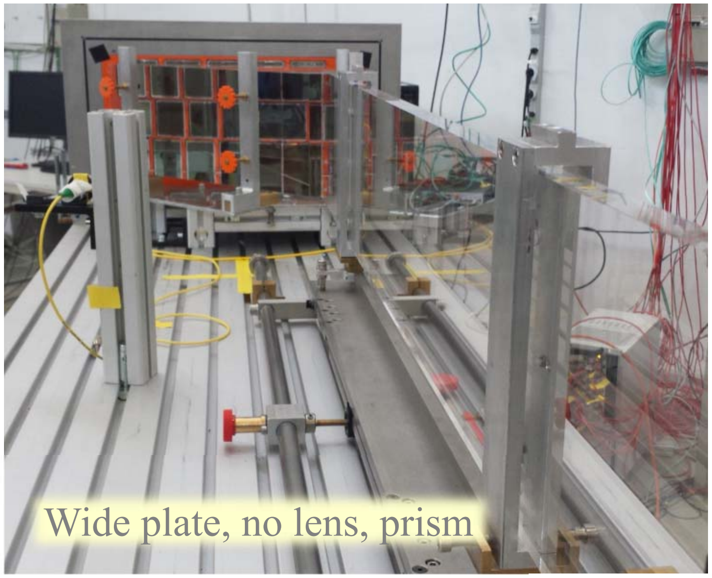
Goal: validation of PID performance of baseline design and cost-saving option.




Prototype layout 2015

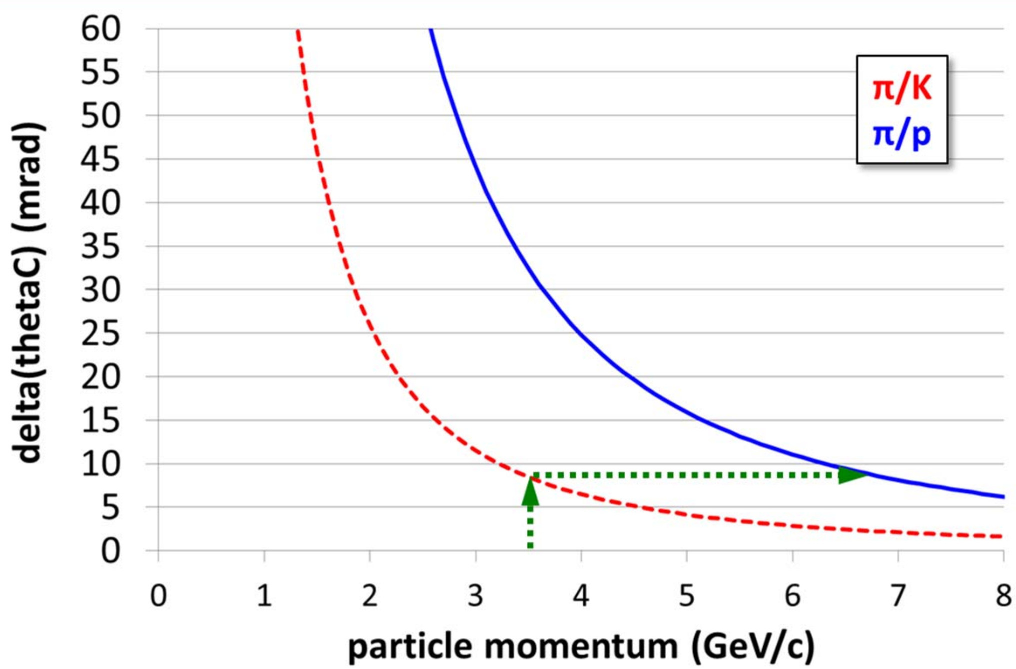

Narrow bar, spherical lens, prism


Readout electronics


Wide plate, no lens, prism

2015 CERN BEAM TEST

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

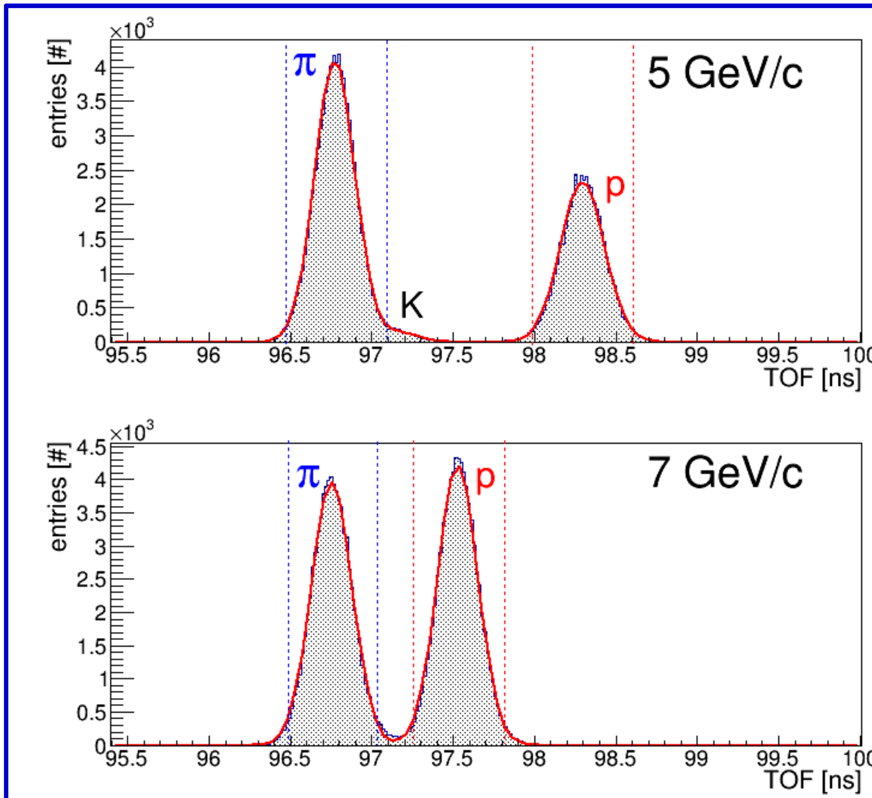


Cherenkov angle difference:

$\Delta\theta_C$ (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.



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.

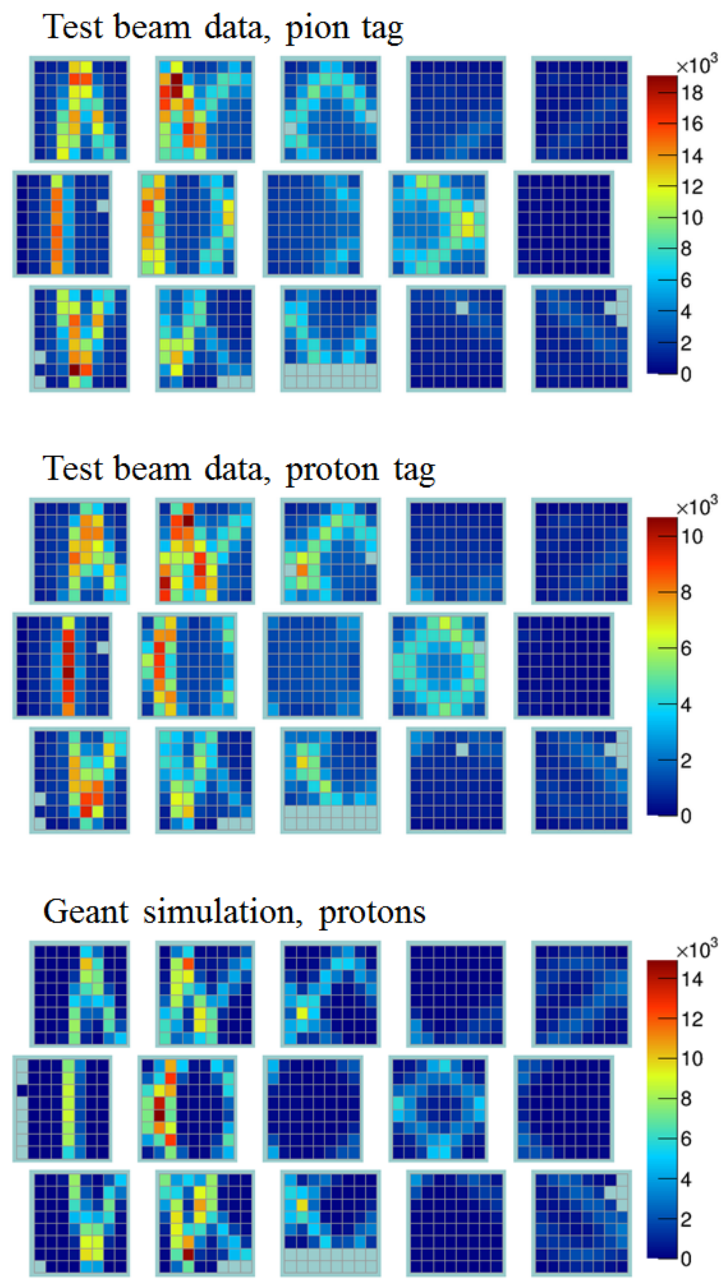
Data calibrated using picosecond laser pulser.

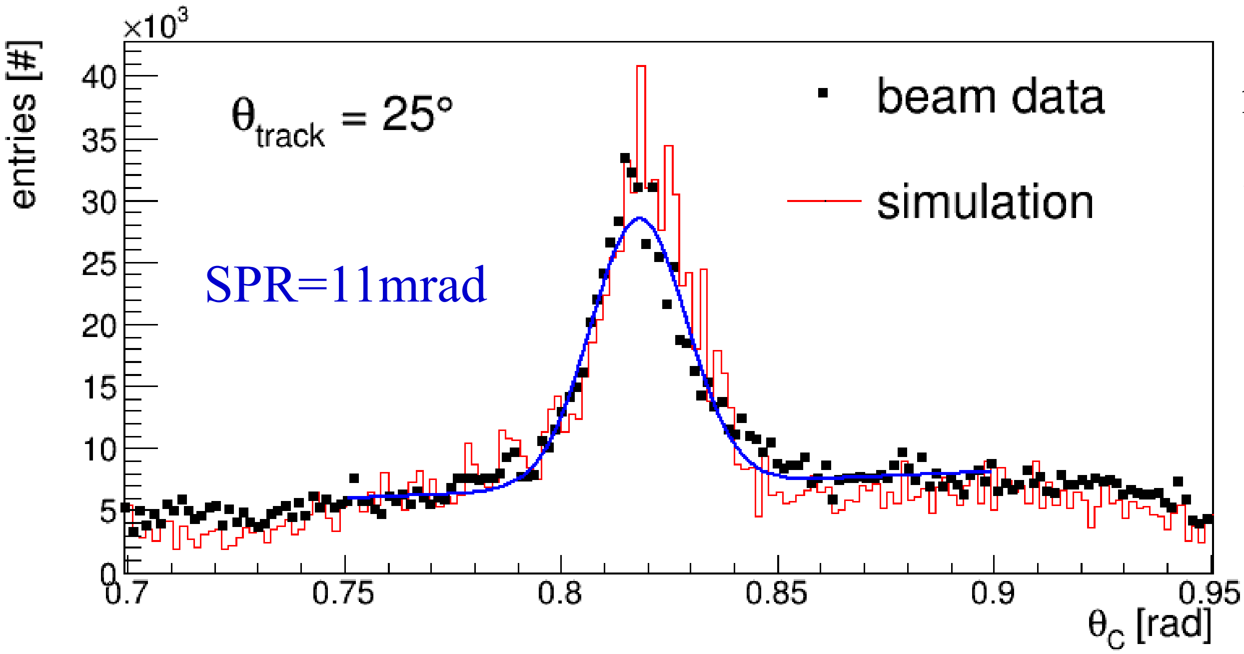
Specific prototype simulation, tuned to beam
parameters, includes quantum efficiencyies
from 2D scan data for each MCP-PMT.

beam
pion tag

beam
proton tag

simulation
protons

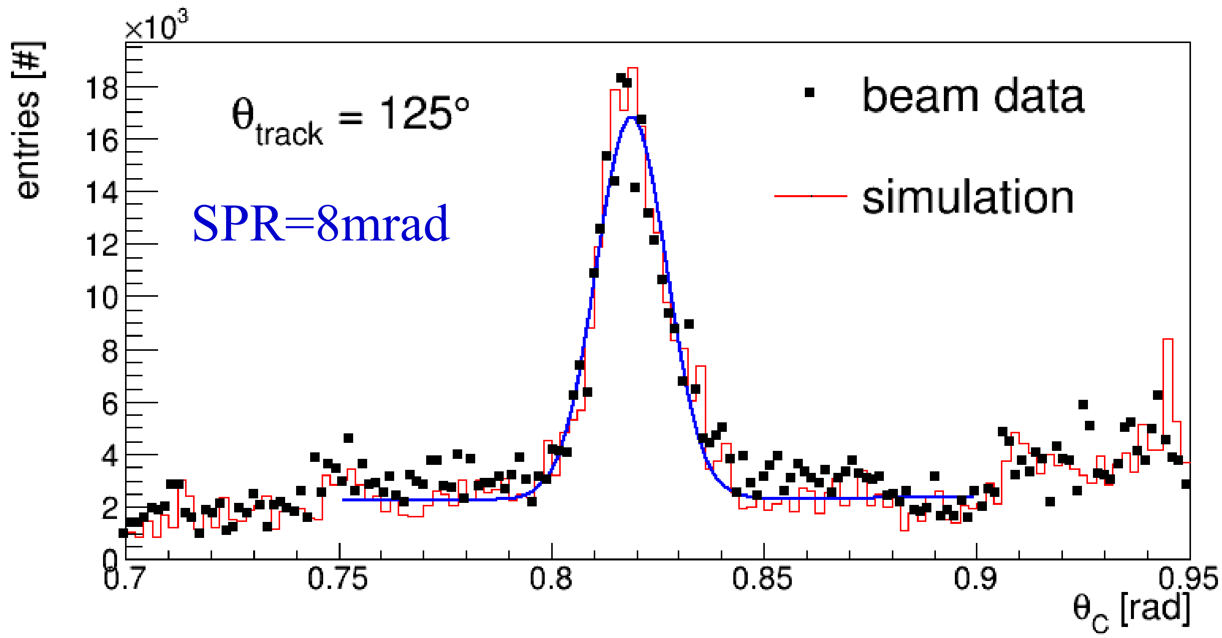




narrow bar with 3-layer spherical lens

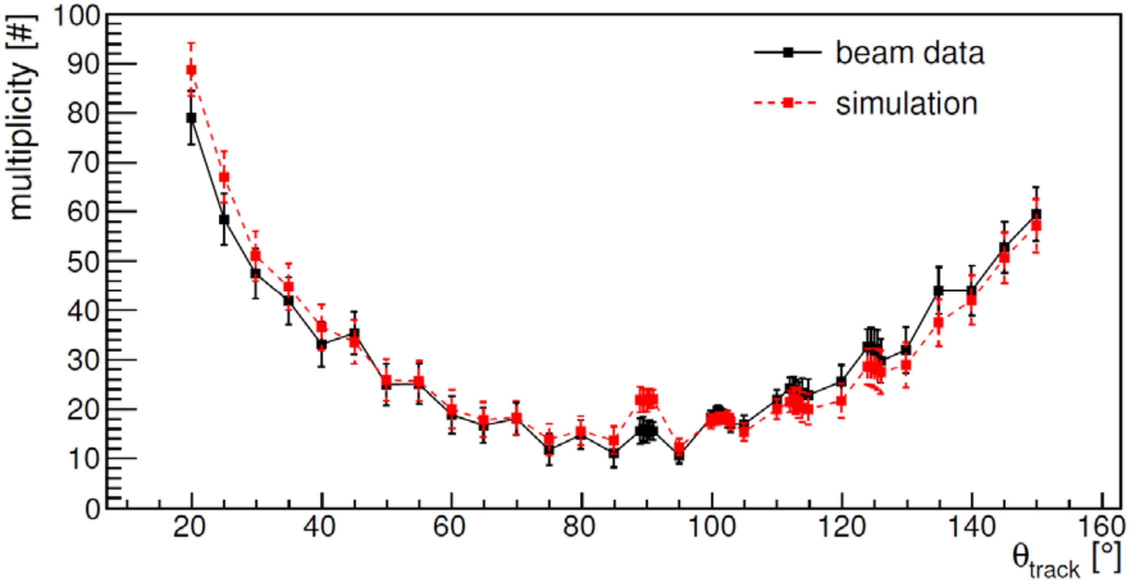
7 GeV/c proton tag

Single photon Cherenkov angle resolution (SPR)



Simulation describes data quite well.

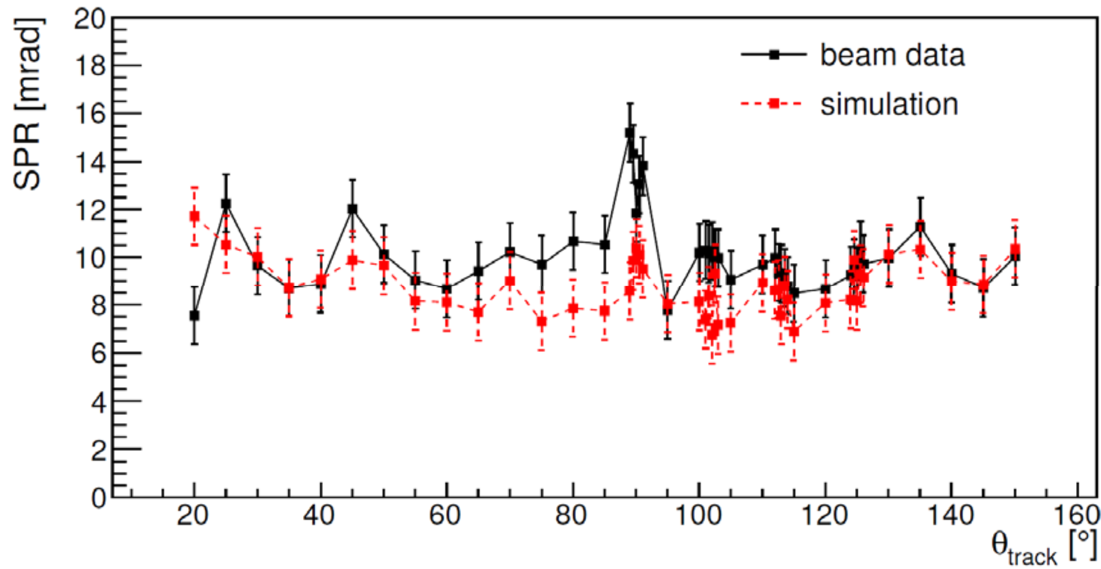
Performance of Narrow Bar



narrow bar with 3-layer spherical lens

7 GeV/c proton tag

Figures of merit meet PANDA requirements

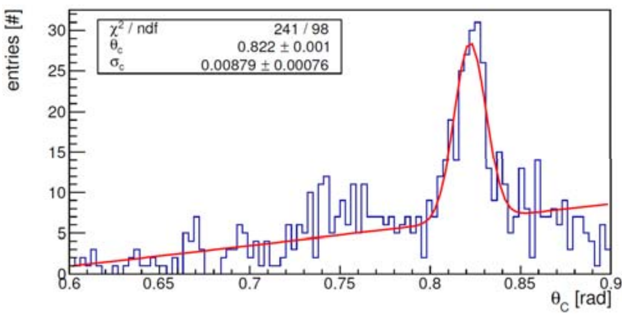


Simulation describes data reasonably well.

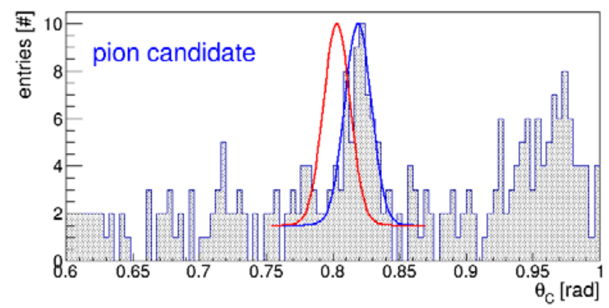
Some differences due to group of older, less efficient MCP-PMTs, issues with thresholds and noise in data (see hit pattern).

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

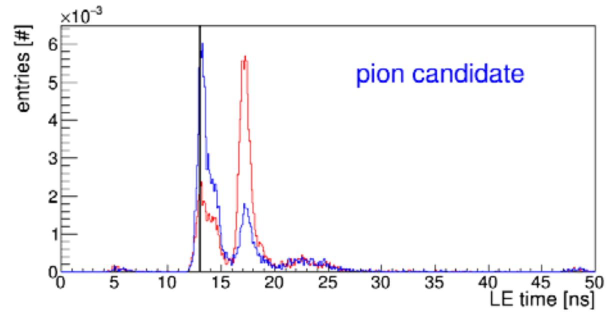
- track-by-track fit of single photon Cherenkov angle distribution to extract track Cherenkov angle (geom. reco)



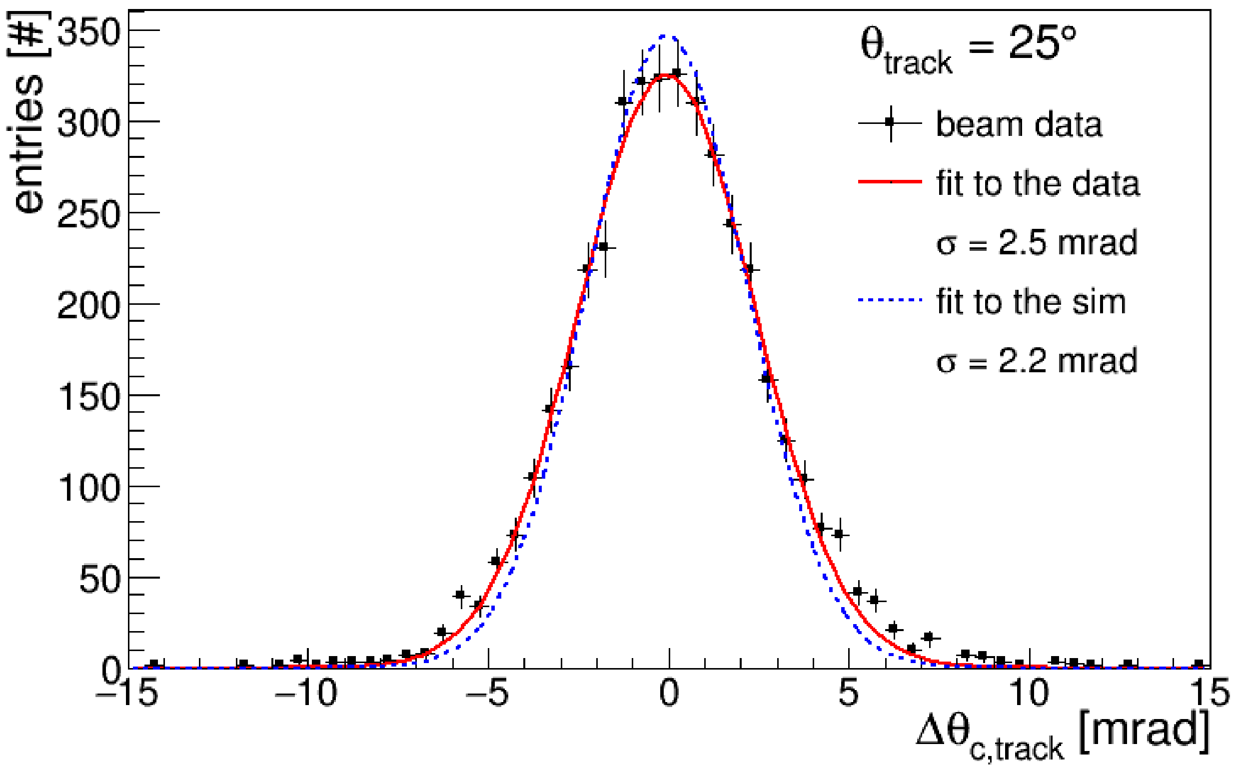
- track-by-track unbinned likelihood hypothesis test to extract log-likelihood differences (geom. reco)



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



Performance of Narrow Bar



narrow bar

3-layer spherical lens

7 GeV/c proton tag

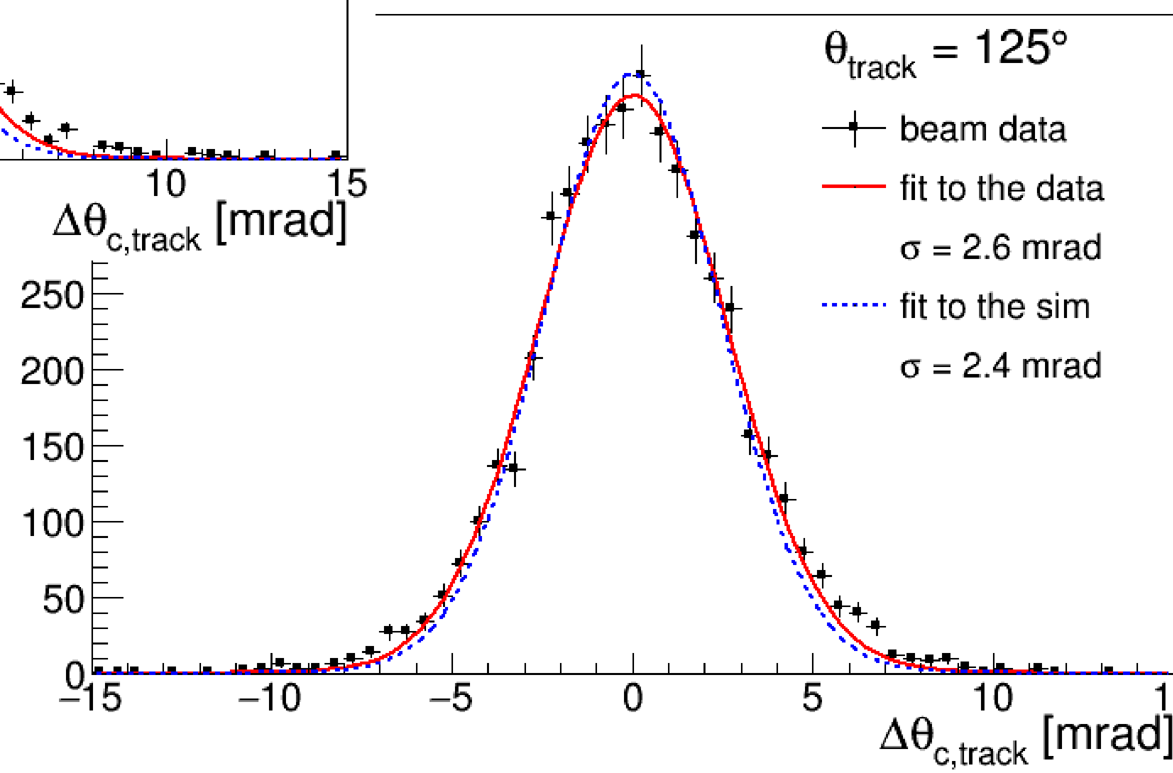
track-by-track Cherenkov angle fit

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

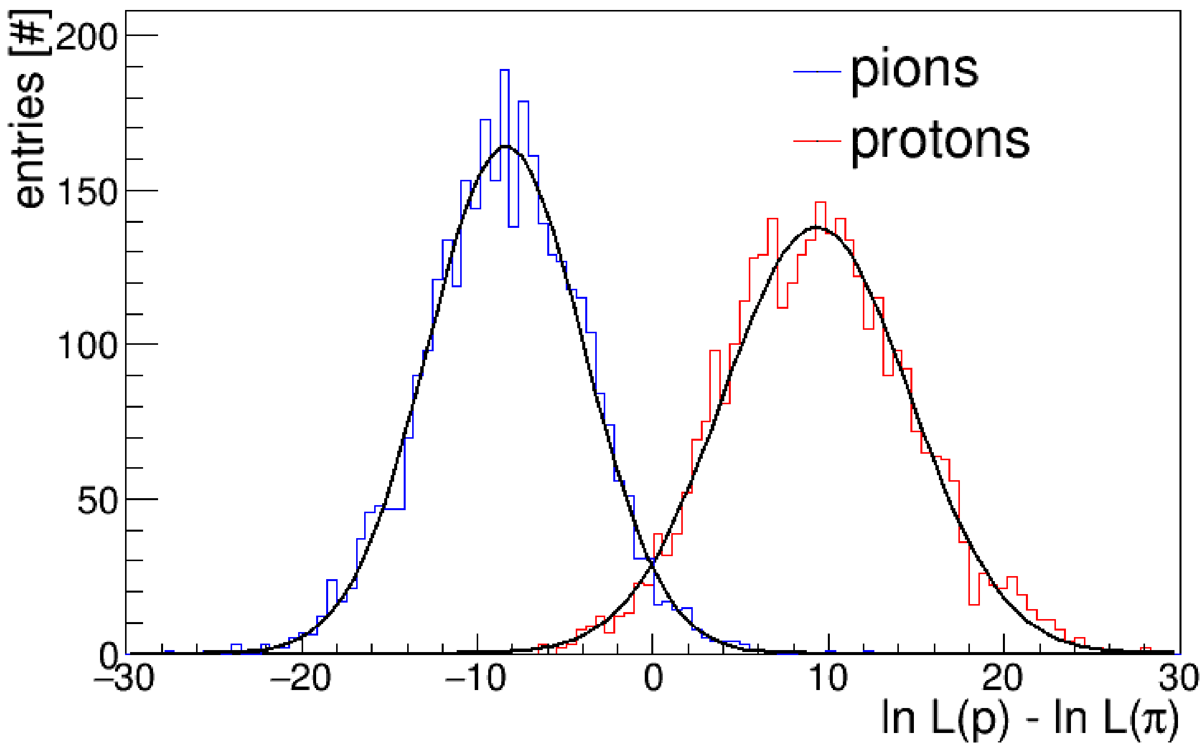


narrow bar with 3-layer spherical lens

7 GeV/c proton tag, 25° polar angle

time-based imaging method (PDFs from beam data)

time-based imaging



π/p separation power = 3.6 s.d.

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

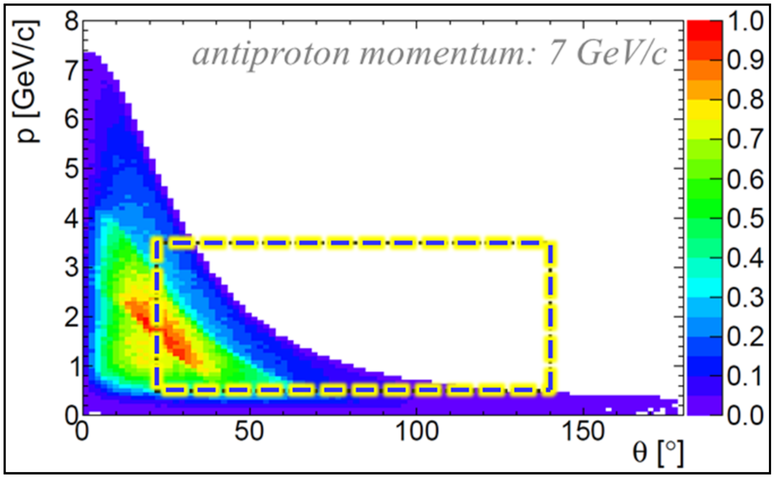
→ meets PANDA requirement

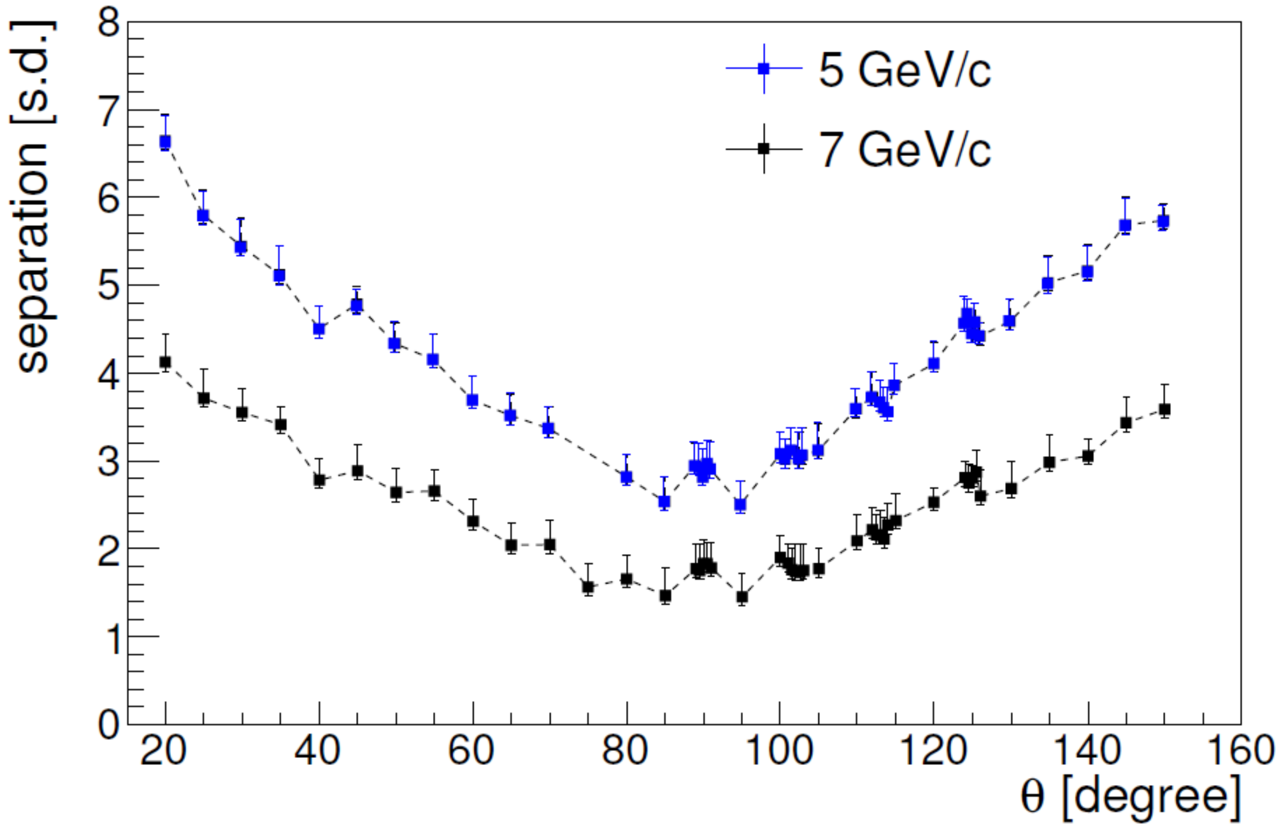
Time-based imaging shows best performance for narrow bar.

narrow bar with 3-layer spherical lens

time-based imaging method (PDFs from beam data)

π/p separation power meets PANDA requirement





Note that in PANDA π/K separation at up to 3.5 GeV/c is only required for steep forward angles; lower momenta at larger angles.

PID Performance of Wide Plate

Hit pattern for data and simulation

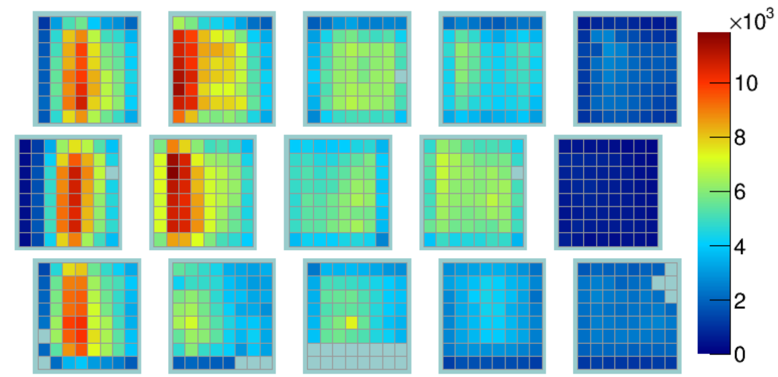
175mm-wide plate without focusing,

7 GeV/c beam momentum.

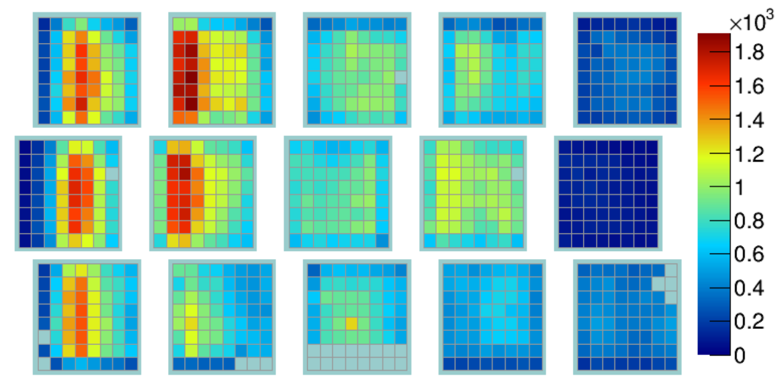
Plate image looks different, less structure.

Reasonably well described by simulation.

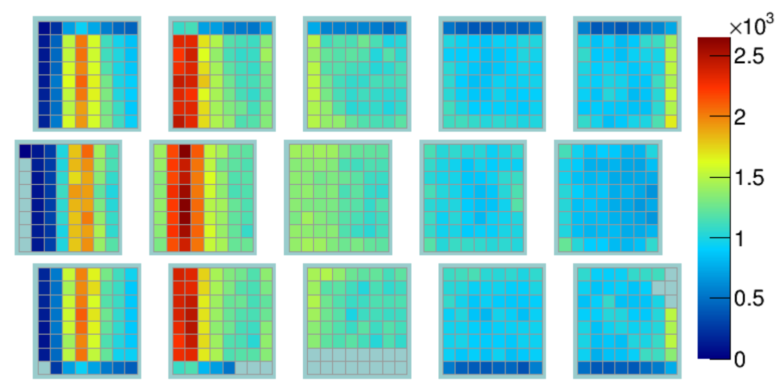
beam
pion tag



beam
proton tag



simulation
protons



Impact of less efficient MCP-PMTs, sub-optimum thresholds on right side of array visible.

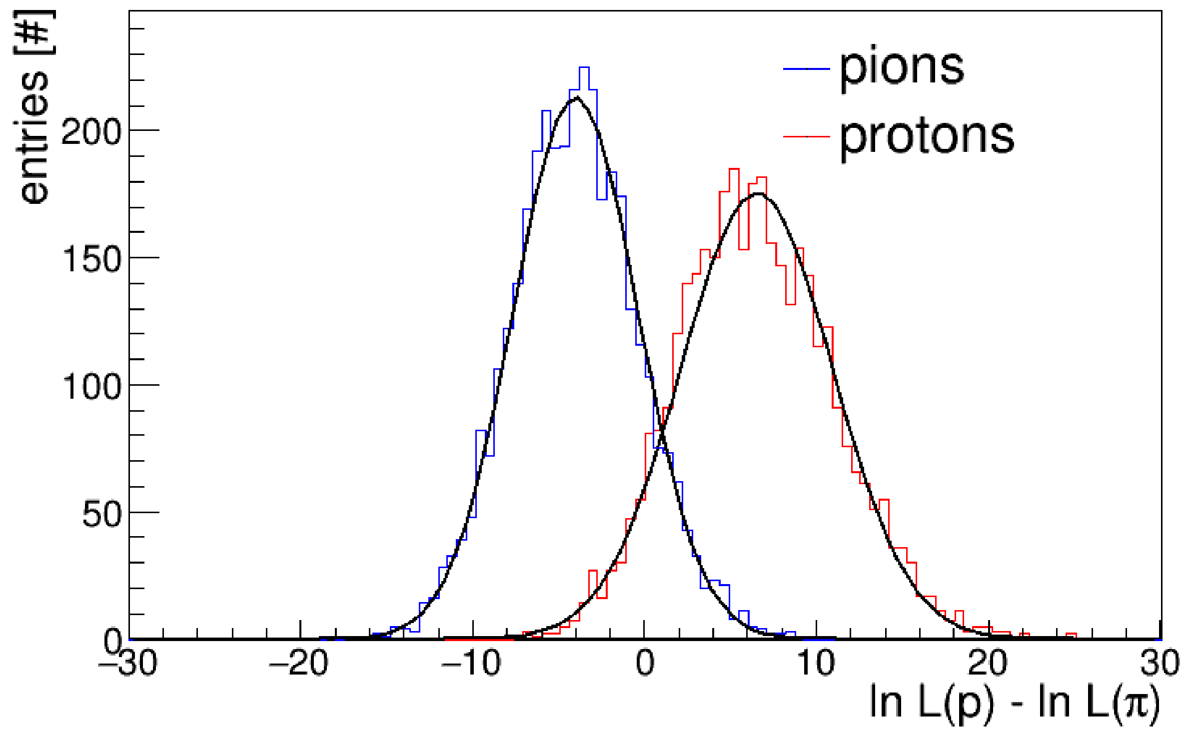
wide plate without lens

7 GeV/c proton tag, 25° polar angle

time-based imaging method (PDFs from beam data)

Plate performance does not quite meet PANDA requirement.

time-based imaging



π/p separation power = 2.6 s.d.

(equivalent to 2.7 s.d. π/K @ 3.5 GeV/c)

Wide plate with 2-layer cylindrical lens also does not meet PID goal (2.7 s.d. π/p separation).

wide plate without lens

7 GeV/c proton tag beam data compared to proton beam simulation

time-based imaging method

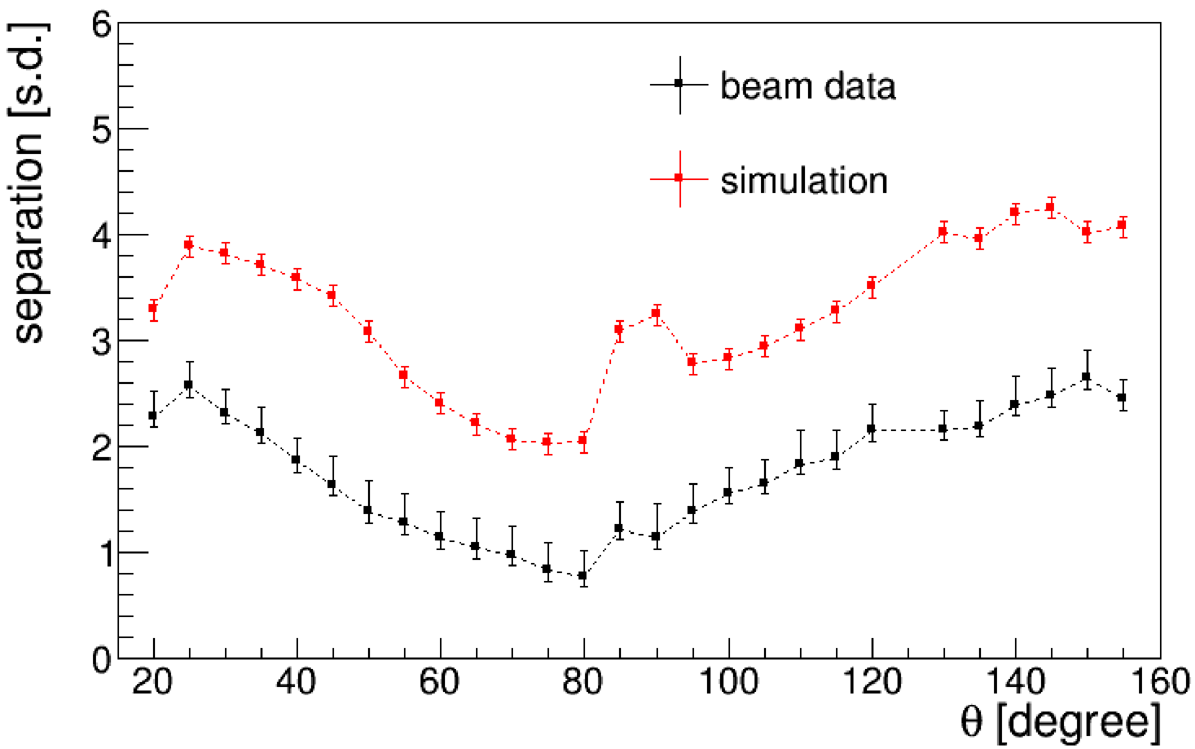
Plate performance in the beam data significantly worse than predicted by simulation.

Plate performance does not quite meet PANDA requirement.

Simulation assumes 100ps timing resolution per photon and 3mm rms beam spot.

Suggests that prototype with good timing and small beam spot is capable of PID validation.

Problems in 2015 due to timing resolution.



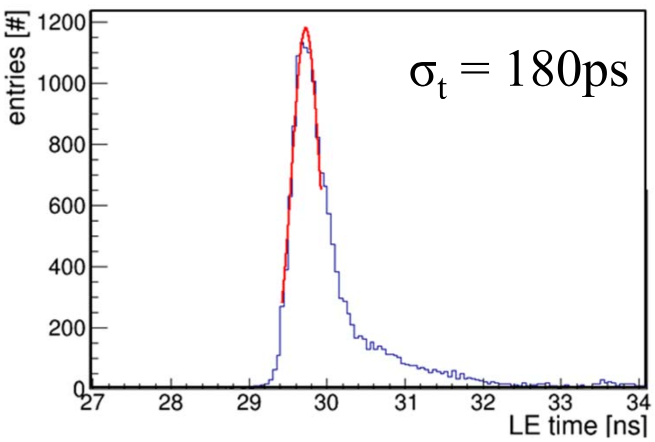
PERFORMANCE OF WIDE PLATE

Timing resolution very important for time-based imaging method,

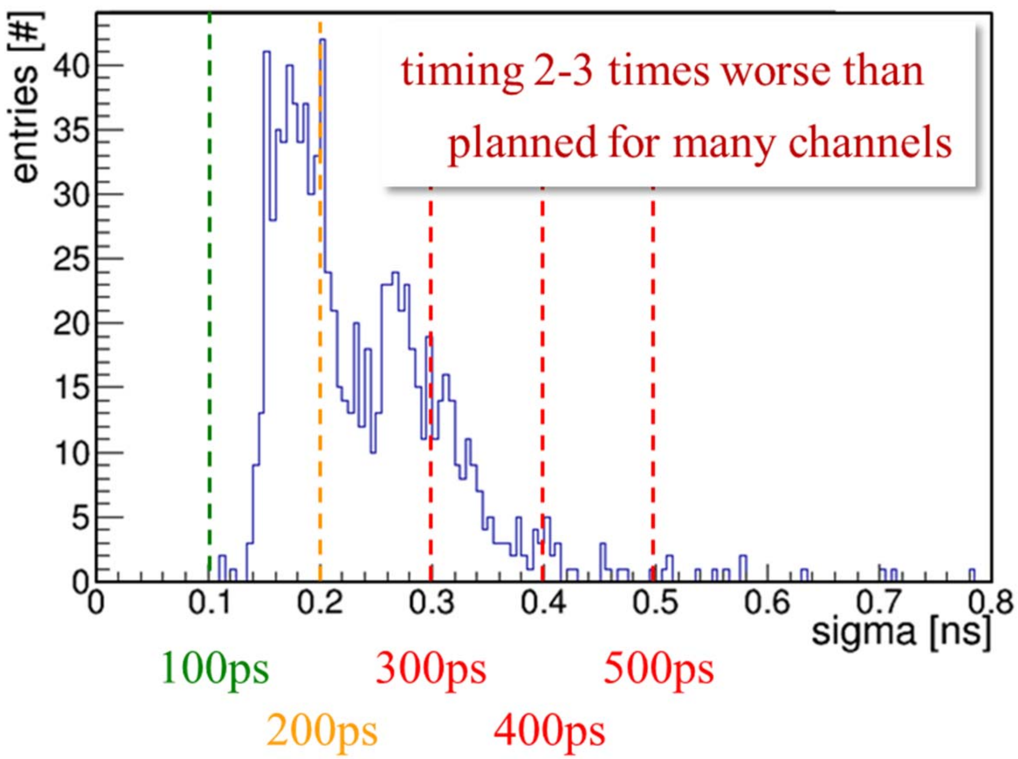
expect that ~100ps single photon timing is required for PID.

Used laser pulser to determine time resolution after time walk correction.

Hit time for typical "good" channel



Timing resolution summary for all channels.



Reason for poor timing has been studied with prototoype in electronics lab.

TRB/PADIWA capable of much better timing, needed further optimization of PADIWA to deal with small MCP-PMT signals.

PANDA BARREL DIRC: STATUS

The PANDA Barrel DIRC is a key component of the PANDA PID system.

Completed Technical Design Report, currently in review.

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

- The design is robust in terms of background and timing resolution.
- Simulation and PID performance validated with particle beams.

Cost-saving option with wide plates and 3-layer cylindrical lens is very promising in simulation, excellent PID performance.

- But PID validation with particle beam 2015 not quite successful due to poor photon timing.

Next (final?) validation opportunity: Oct 14 – Nov 2, 2016 at the CERN PS/T9.

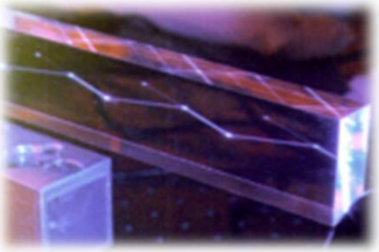
- Modified readout electronics (PADIWA cards) for higher bandwidth and larger amplification.
- Achieved <100ps timing for single channels, still studying performance of large system.

PANDA BARREL DIRC: OUTLOOK

Sep. 2016: Completed technical design, TDR in review, to be submitted to FAIR.

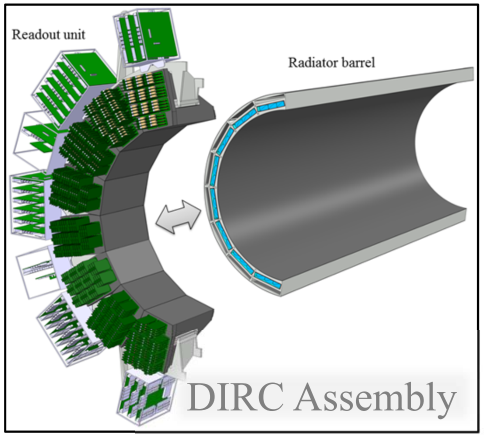
2017-2021: Component Fabrication, Assembly, Installation.

- 2017: TDR approval, finalize specifications, tender, contracts.
- 2018-2020: Industrial fabrication of fused silica bars/plates and prisms.
  Industrial production of photon sensors.



DIRC bar with laser

- 2018-2019: Production and QA of readout electronics at GSI/Mainz.
- 2018-2021: Industrial fabrication of bar containers and mechanical support frame,
  gluing of bars/plates, construction of complete bar boxes in Mainz.
  Detailed scans of all sensors in Erlangen.
  Assembly of readout units at GSI/Mainz.



DIRC Assembly

- 2021: Installation of mechanical support frame in PANDA,
  insert bar boxes, mount readout modules.
  Ready as “Start Setup / Day One” detector.