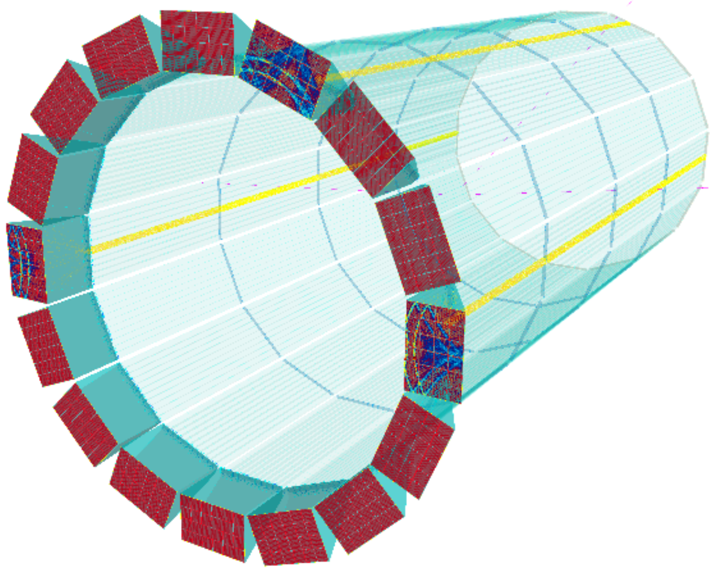
The High-Performance DIRC for the EIC



Greg Kalicy

CUA

for the eRD14 hpDIRC group

- The hpDIRC Concept and Design
- hpDIRC Performance in Simulation
- Experimental Validation
- Plan for TDR-Readiness in 2023

HPDIRC GROUP

hpDIRC: part of the EIC Generic Detector R&D program since day one

- 2011-2015: eRD4 - DIRC-based PID for the EIC
- 2015-now: hpDIRC activity in eRD14

Cooperation between groups from USA and Germany

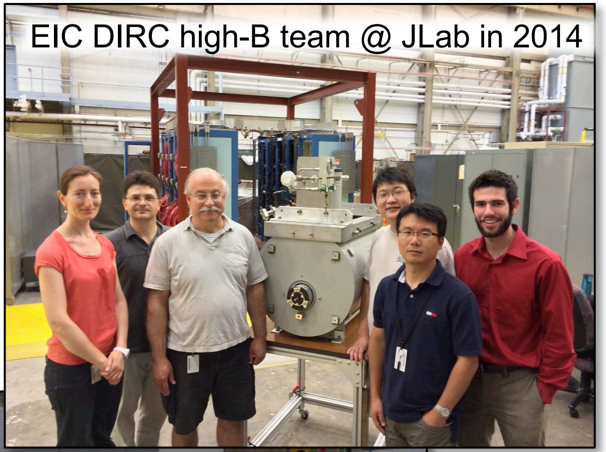
Old Dominion University, CUA, Jefferson Lab, GSI, University of South Carolina, Stony Brook University

DIRC experience ranging from design, software development, R&D, and beam tests to assembly, installation, commissioning, and operation in:

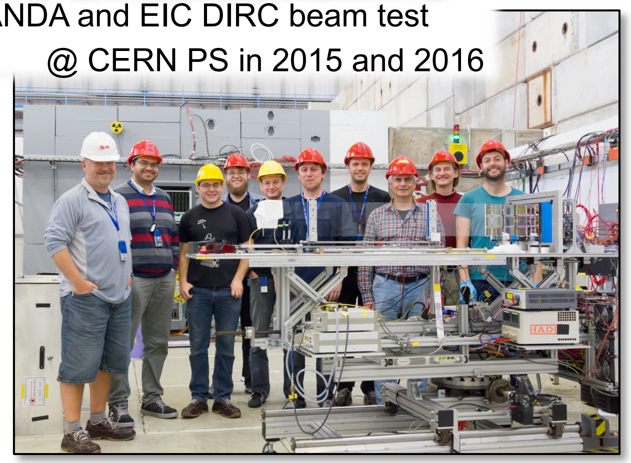
BaBar, SuperB, GlueX, PANDA

Access to DIRC labs and facilities

laser labs: lens & bar measurements; monochromator, X-ray source: material tests; high-B test facility, psec laser pulser: sensor performance; PANDA/EIC DIRC prototype lab space; electronics lab, psec laser pulser: readout tests

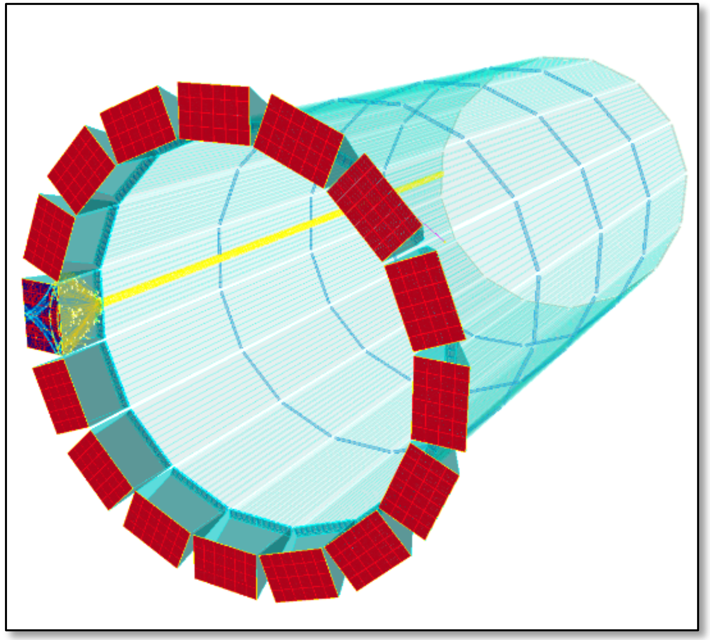


EIC DIRC high-B team @ JLab in 2014



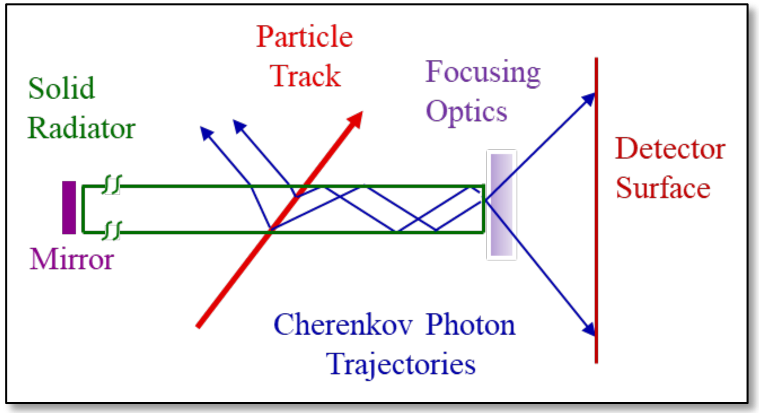
PANDA and EIC DIRC beam test @ CERN PS in 2015 and 2016

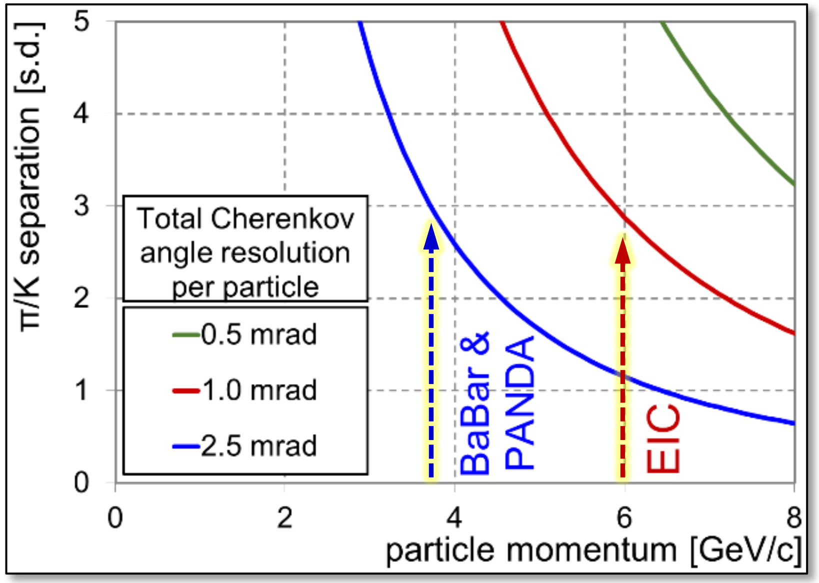
hpDIRC: a high-performance DIRC counter for radially compact hadronic PID in the barrel region of the future EIC experiments



- Designed to provide 3 s.d. separation for π/K up to 6 GeV/c, e/π up to 1.8 GeV/c, K/p up to 10 GeV/c
- Advancing DIRC PID performance by more than 50% beyond the state-of-the-art, improve resolution by factor 2.5

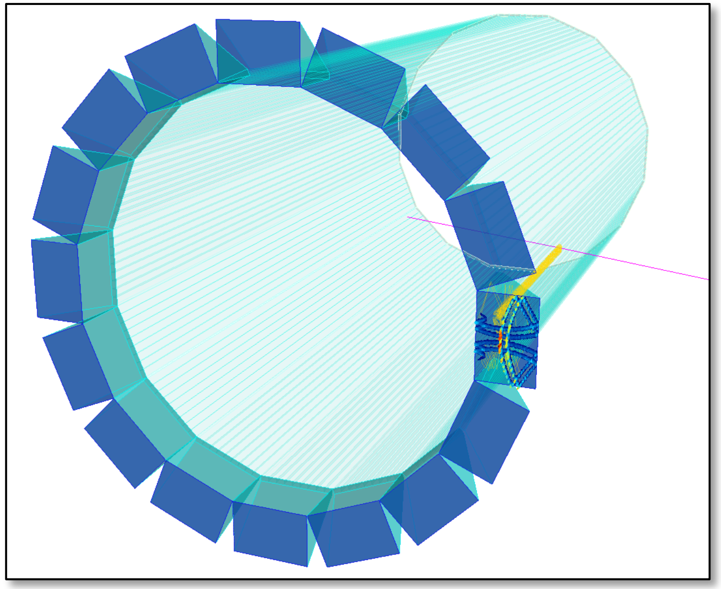
Detection of Internally Reflected Cherenkov Light





Concept: fast focusing DIRC

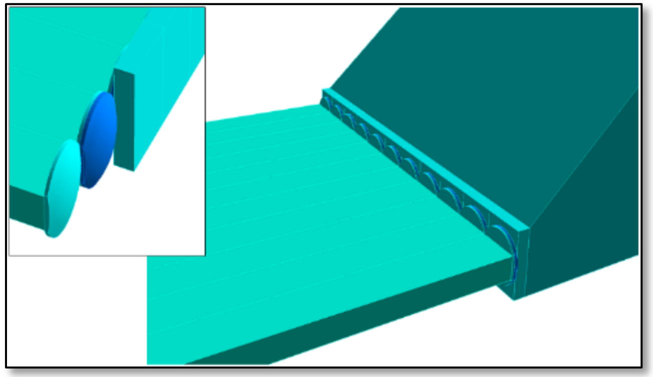
Initial design based on PANDA Barrel DIRC with key improvements



- Generic reference design in Geant4: 1m barrel radius, 16 sectors
- 176 radiator bars (11 per sector), synthetic fused silica,
  17mm (T) × 35mm (W) × 4200mm (L)

  to be optimized
- Focusing optics: innovative rad-hard 3-layer spherical lens
- Compact photon camera:
  30cm-deep solid fused silica prisms as expansion volumes
  lifetime-enhanced MCP-PMTs with 3x3mm^2 pixels
  fast readout electronics (~100,000 channels , <100ps single photon timing)

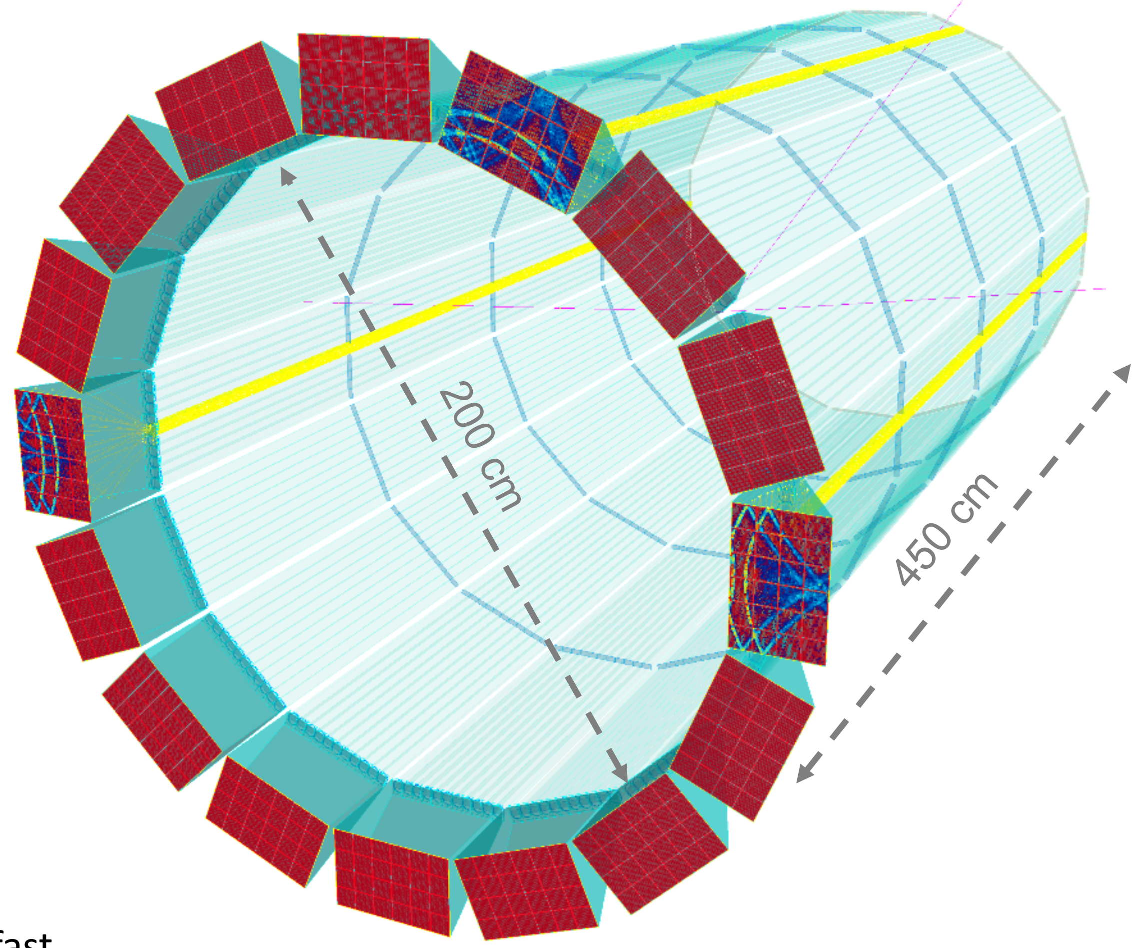
  to be optimized



- Expected performance (Geant4 simulation):
  30-100 detected photons per particle,
  ≥ 3 s.d. π/K separation at 6 GeV/c

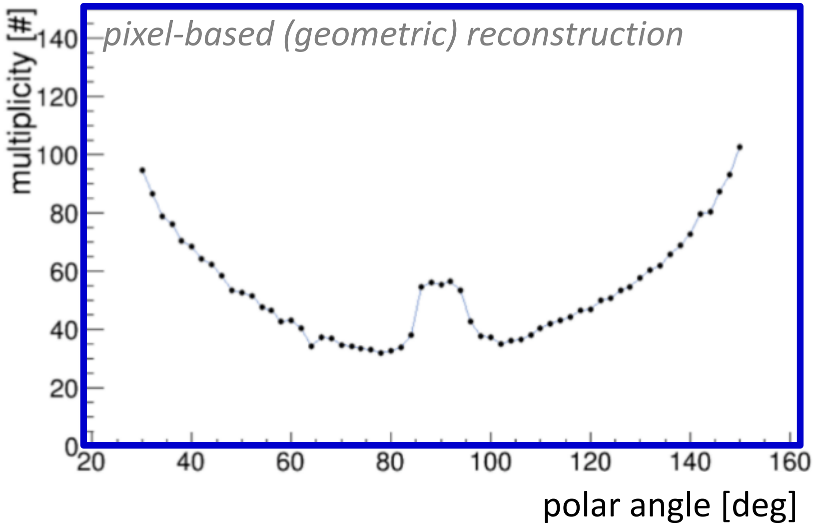
High-performance DIRC: full simulation

- Standalone Geant4 simulation
- Realistic geometry and material properties based on prototypes
  - Polished fused silica bars and prism, glue, optical grease
  - 3-layer spherical lens, MCP-PMT, mirror
- Wavelength-dependent material properties and processes
  - Refractive index, surface scattering, absorption, reflection
  - Photon transport and detection efficiencies
  - Chromatic dispersion in angle and time
- Includes all relevant resolution terms
  - Photon timing precision from MCP-PMT plus readout electronics
  - Tracking resolution
- Two well-tested reconstruction methods
  - Geometrical ("BaBar-like") – relies mostly on space coordinates, robust, fast
  - Time imaging ("Belle II TOP-like") – relies mostly on time measurement, best performance

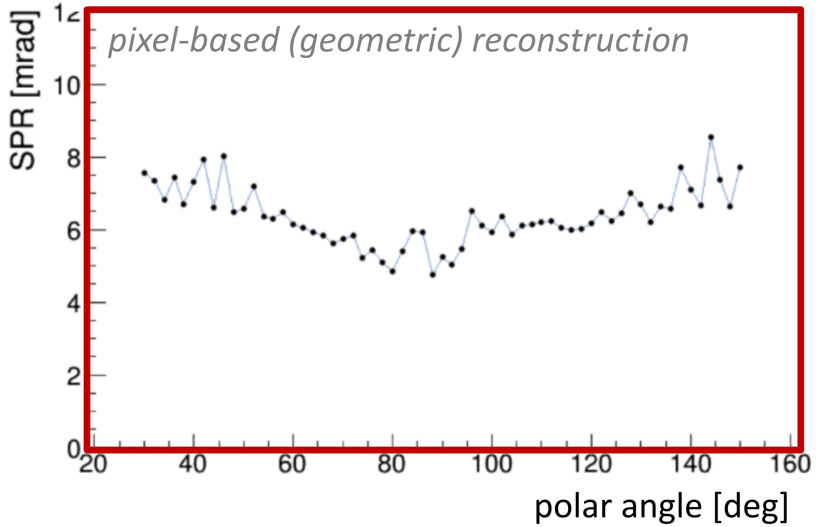


hpDIRC Performance in Geant4

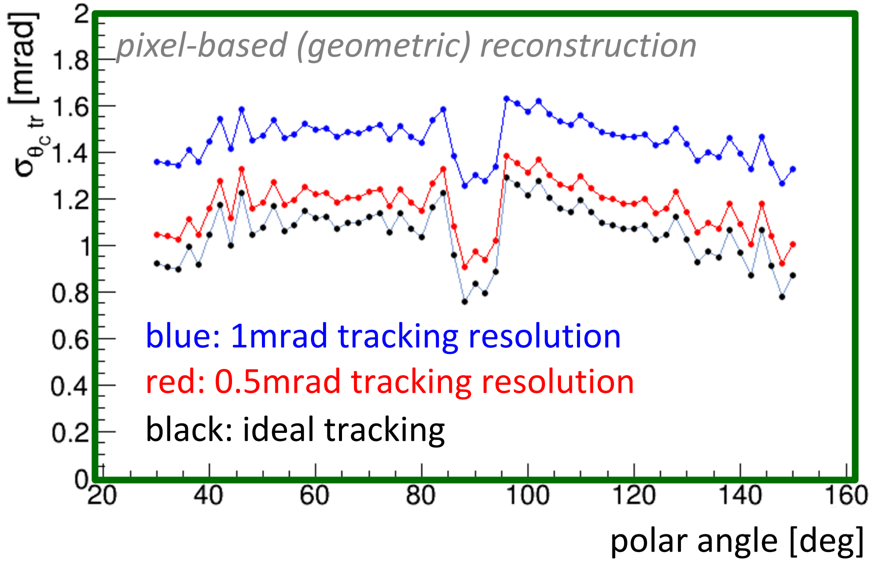
Photon yield per particle



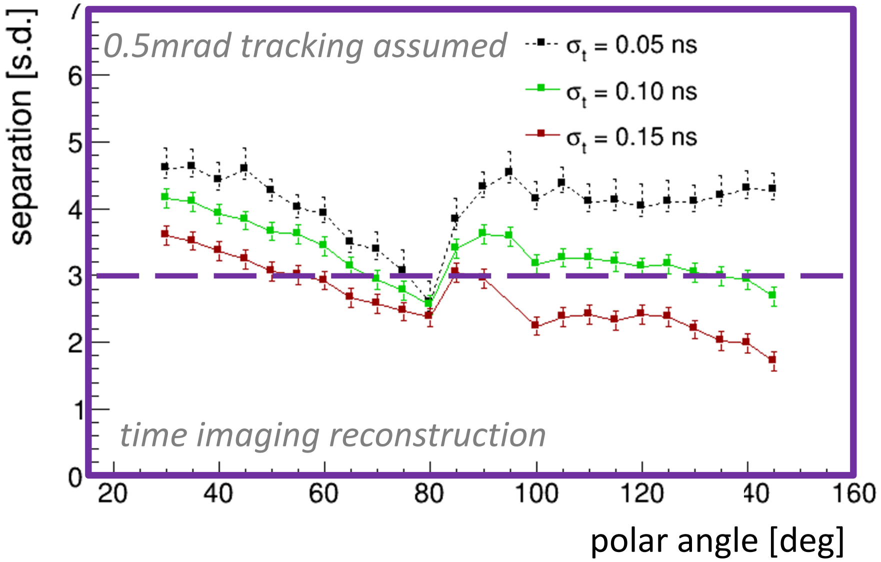
Cherenkov angle resolution per photon (SPR)



Cherenkov angle resolution angle per particle



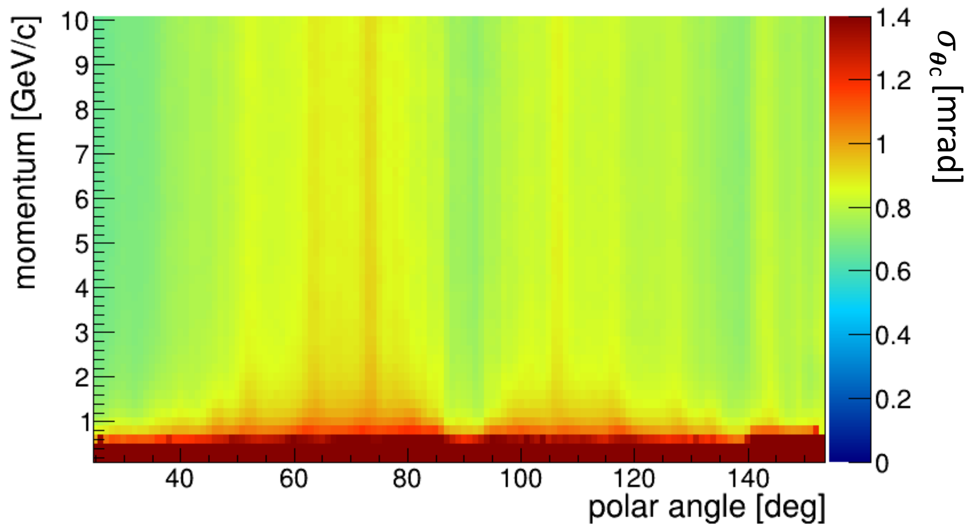
π/K separation power at 6 GeV/c



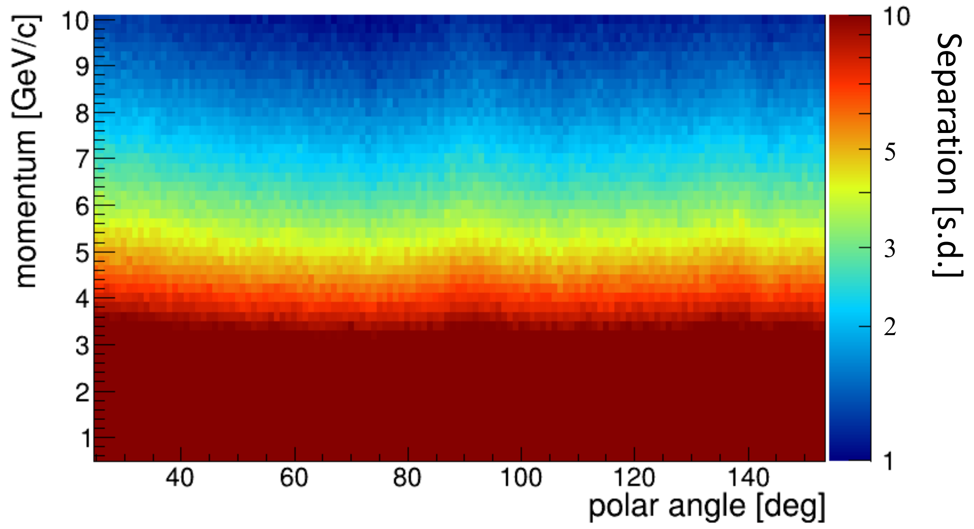
High-performance DIRC: fast simulation

- A fast simulation C++ class was designed and released to the EIC software community in 2019
- Code and documentation available in github
- Based on conservative performance assumptions
- Geant4 simulation of the current hpDIRC baseline design and a pixel-based reconstruction are used to determine
  - the Cherenkov angle resolution per photon
  - the number of detected Cherenkov photons per particle
- These values are used to calculate the Cherenkov angle resolution per particle in combination with the assumed tracking resolution
- Routine provides the normalized probabilities of a given track be an e, μ, π, K or p

Geant4 Cherenkov angle resolution per particle



Example: derived π/K separation power
(tracking resolution of 0.5 mrad)



High-performance DIRC: fast simulation

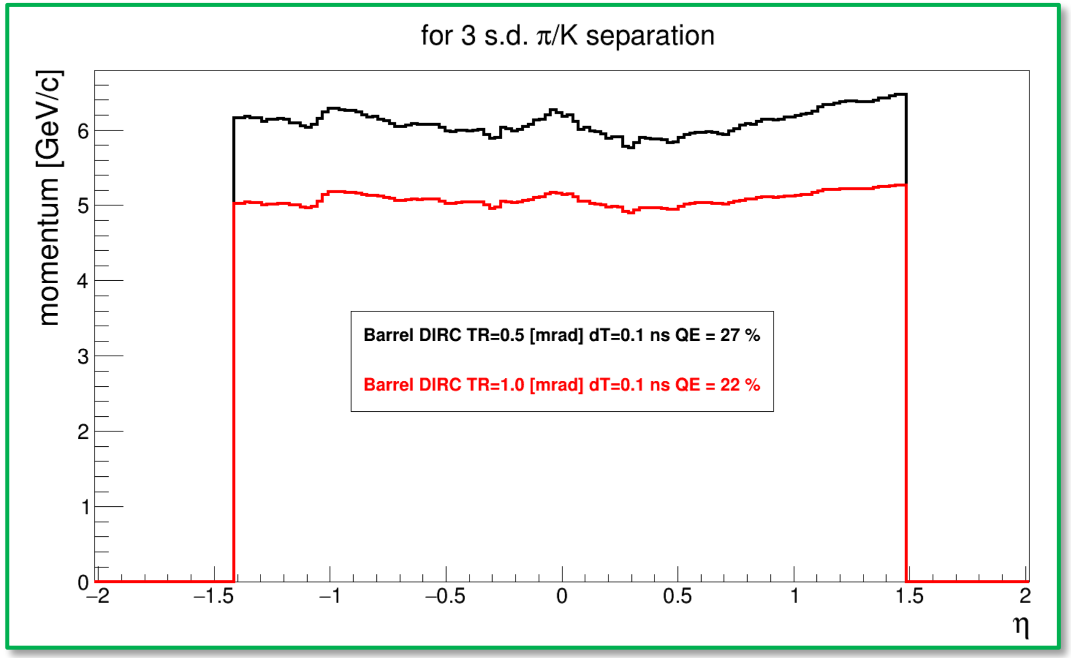
- The DrcPidFast fast simulation code was adapted for the Yellow Report PID evaluation (released on March 9, 2020)
- According to the instruction given by Tom, it provides:
  - numSigma(p, PID)
  - maxP(numSigma, PID)
  - minP(numSigma, PID)

Example of usage:

```
Detectors.push_back( new barrelDirc(trackResolution,timeResolution,QE,etaLow,etaHigh) );
```

Two default scenarios implemented:

- Realistic scenario
  - 0.5 mrad tracking resolution
  - 0.1 ns rms timing precision per photon
  - 27% detective quantum efficiency of the MCP-PMT
- Pessimistic scenario
  - 1.0 mrad tracking resolution;
  - 0.1 ns rms timing precision per photon
  - 22% detective quantum efficiency of the MCP-PMT

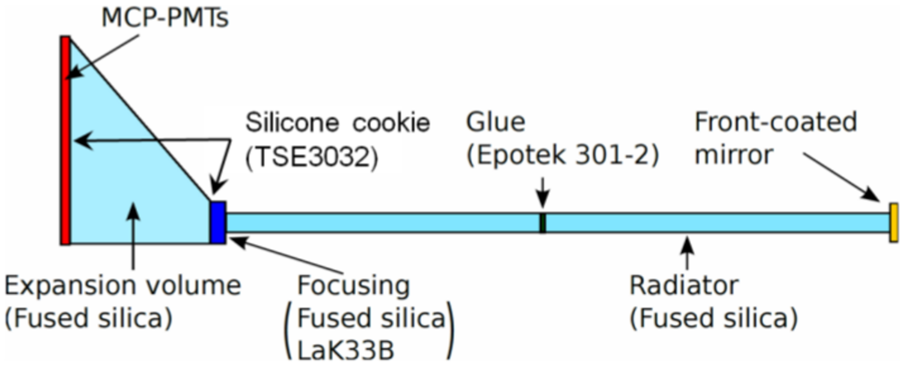


Initial design will be further optimized

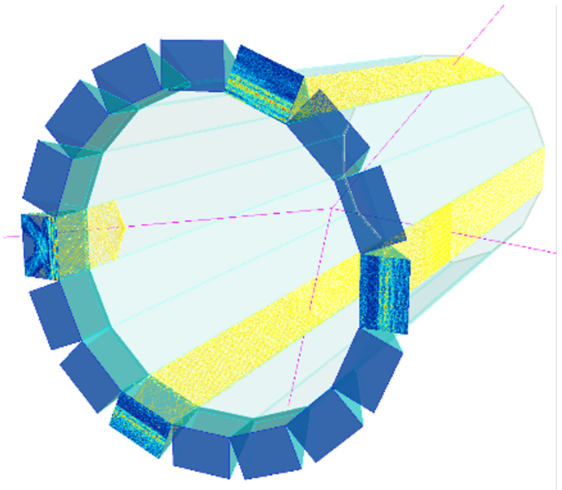
- Number of sectors, length and radius of barrel
- Bar width, pixel size, number of sensors
- Prism size (depth, opening angle) and shape (tilt angle)
- Narrow radiator bars (BaBar/PANDA) or wide plates (Belle II), or hybrid of bars and plate ("SLAC ultimate DIRC")

to be optimized

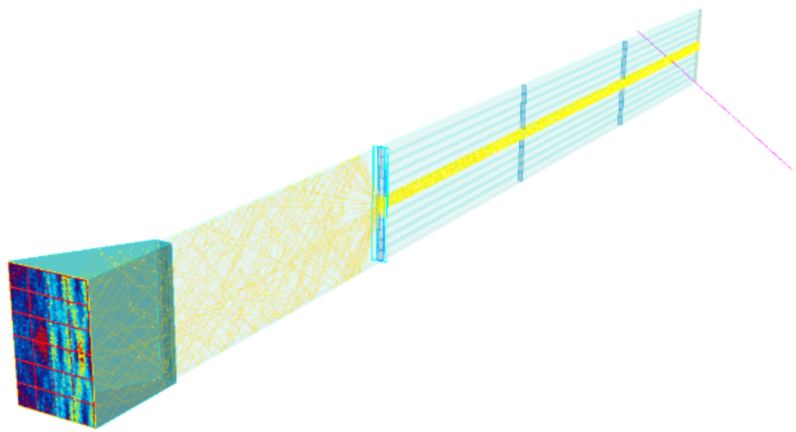
Simplified view of Geant components for one sector:



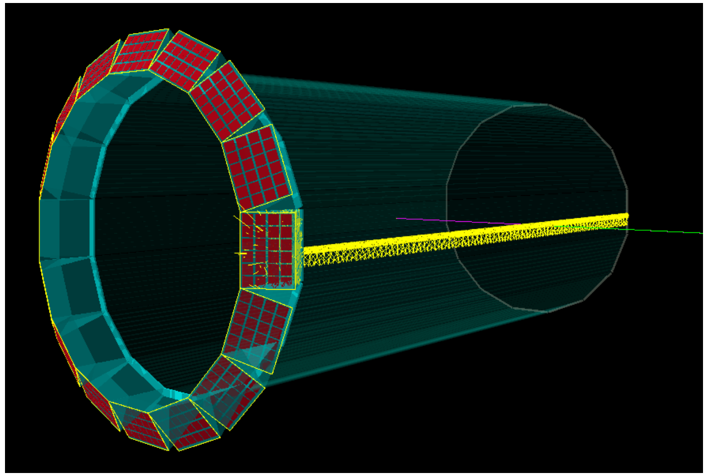
GEANT4 visualization of design concepts:



1 wide bar (plate) in each sector



Hybrid of bars and plate in each sector



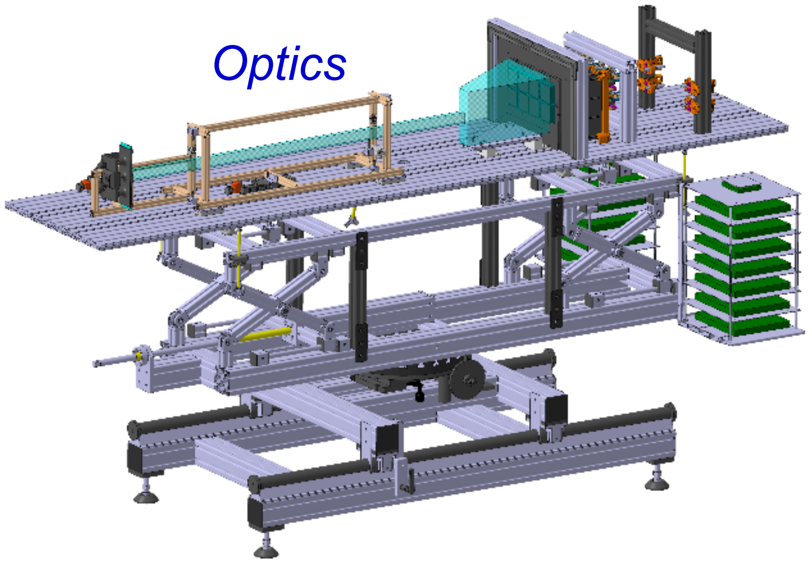
Tilted sensor plane to match B field lines

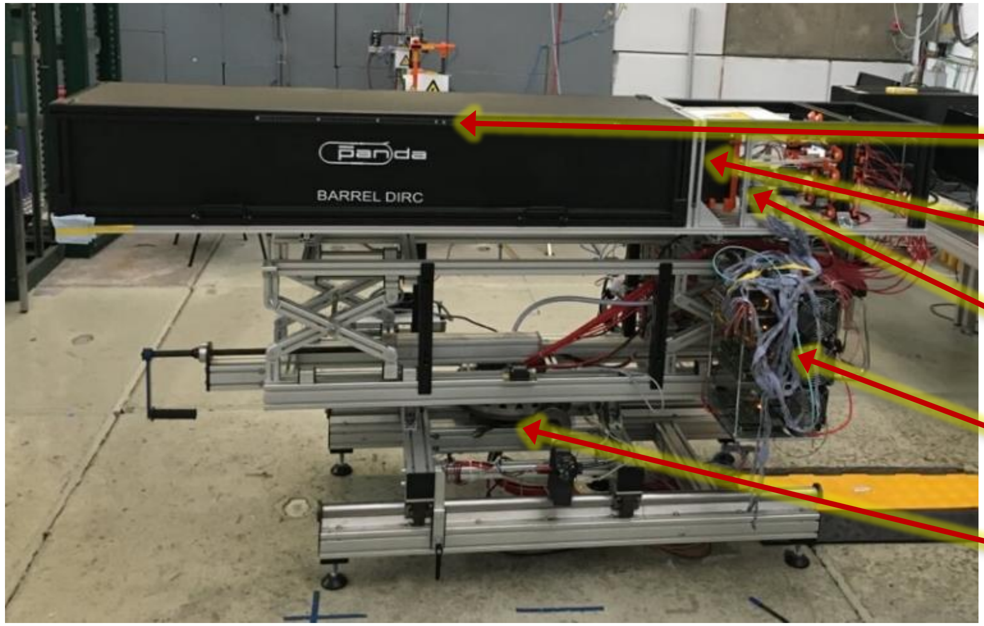
hpDIRC Experimental Validation

PANDA Barrel DIRC prototype

- Modular design modified and improved over 11 years
- Available now due to completion of PANDA DIRC R&D
- Transfer of prototype from GSI to CUA/Stony Brook in 2020

  Includes support mechanics, optics (bars/lenses/plate/prism), DAQ computer, several MCP-PMTs (6.5mm pixels), GSI readout electronics (~200ps timing)
- Start point for hpDIRC prototype, to be set up and tested at Stony Brook





Dark box for optics (bar, lens, prism)

MCP-PMT array

Frontend electronics (PADIWA) (air-cooled)

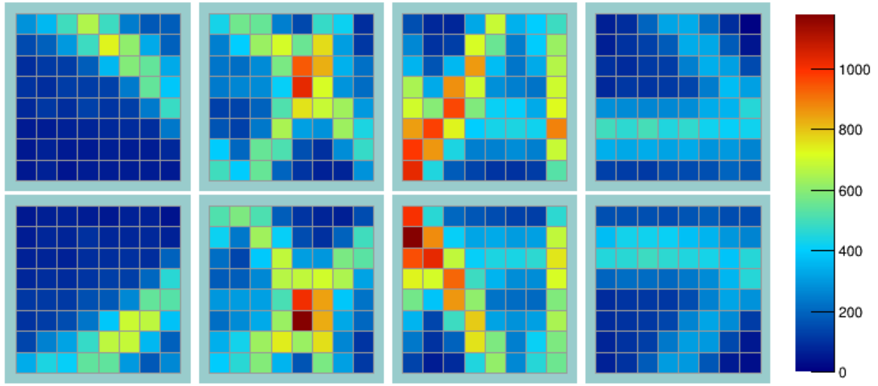
DAQ boards (TRB)

Rotation stage (remote controlled)

HPDIRC EXPERIMENTAL VALIDATION

PANDA Barrel DIRC prototype *(6.5mm pixels, ~200ps photon timing)*

- Goal of PANDA Barrel DIRC: 3σ π/K separation at 3.5 GeV/c
- Achieved up to 4.8 s.d. π/K separation at 3.5 GeV/c and 20° polar angle

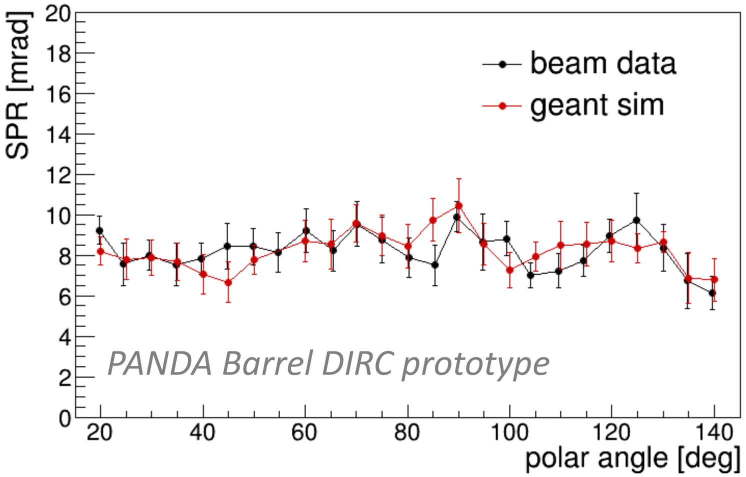


Prototype hit pattern at 20° polar angle

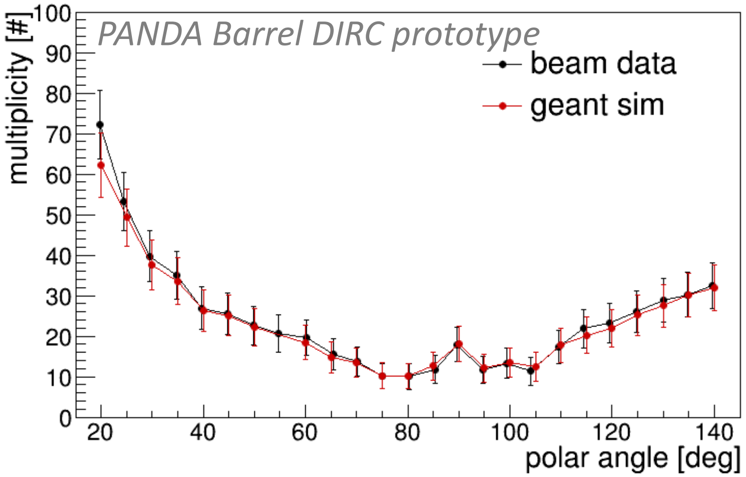
Will be upgraded for 2021 and 2022 beam tests with

- Sensors with smaller pixels (commercial MCP-PMTs or LAPPDs or SiPM)
- Fast readout electronics (SiREAD or TofPET2 or NINO32 or DiRICH or ...)

Cherenkov angle resolution per photon

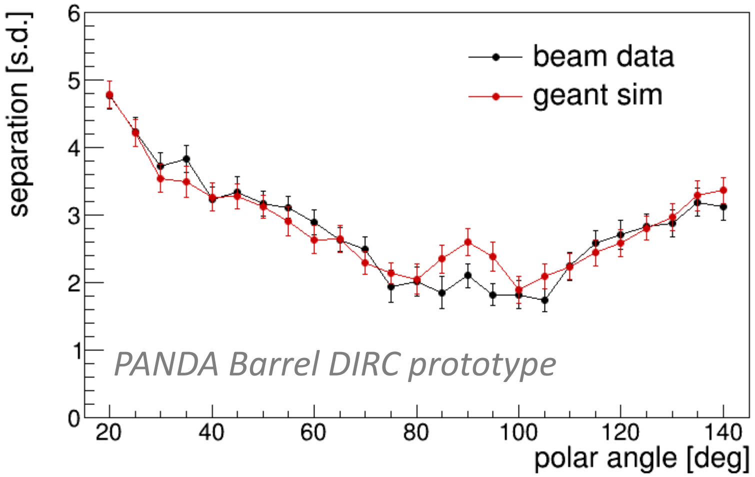


Detected photon multiplicity



π/p separation power at 7 GeV/c

(equivalent to π/K @ 3.5 GeV/c)



- Technology used, risks associated : fast focusing DIRC;

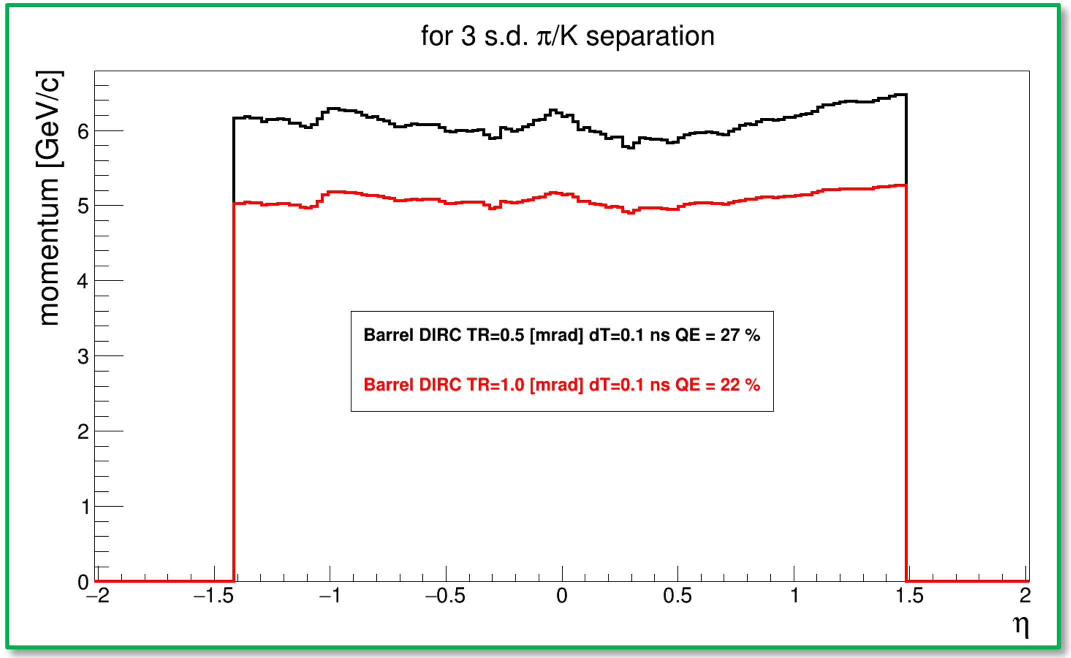
  Key challenges: single photon detection in high B-fields, rad-hard optics, fast readout electronics;

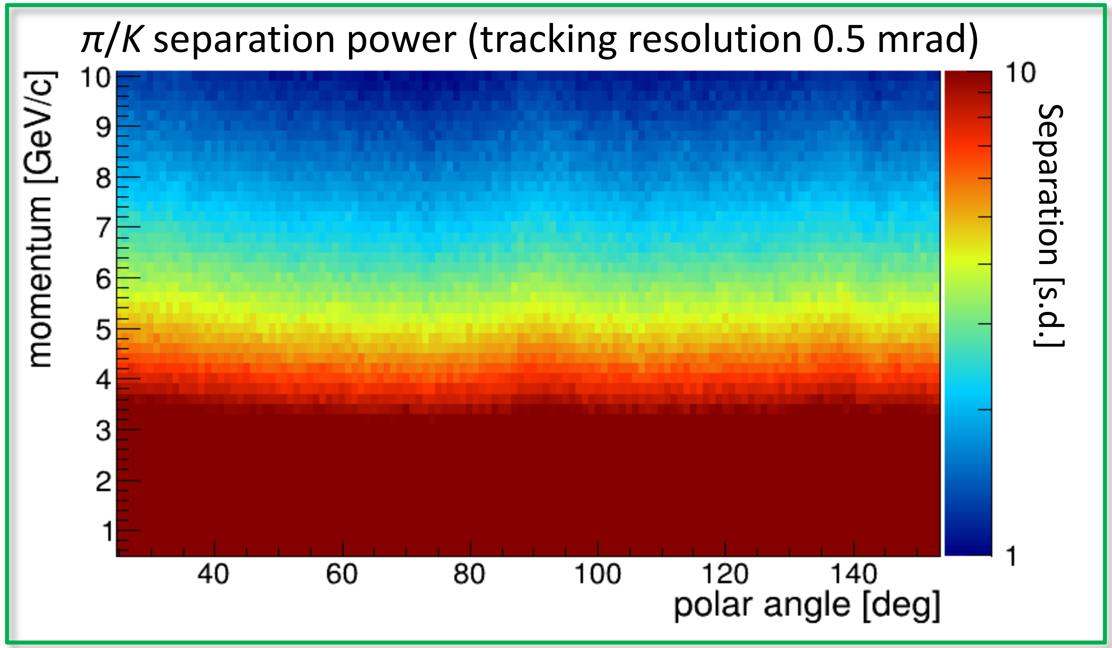
  Risks: availability of sensor for possible 3T field; availability of readout electronics for beam tests,

  insufficient tracking resolution (external risk);

  Risk mitigation: investigating smaller-pore MCP-PMTs and SiPMs, considering alternative readout solutions

- Momentum range covered: 3 s.d. separation for π/K up to 6 GeV/c, e/π up to 1.8 GeV/c, K/p up to 10 GeV/c





HPDIRC: PATRIZIA'S TOPIC LIST

- Robustness of the design (e.g. sensitivity to magnetic field) and has a prototype been built?

  Initial design meets PID goals in Geant simulation, several key design options to be studied;

  Design to be optimized for cost and performance, tilted sensor plane option for B-field performance;

  Final design to be validated with prototype in particle beams, PANDA Barrel DIRC prototype transfer in 2020

- Are the electronics considerations clear (channel count, data size, rate, background)

  Provided requirements to eRD14 experts, working closely with them

- Time needed to complete the R&D and available workforce

  On track for TDR readiness in 2023/24, test of prototype in particle beam at Fermilab in 2021 and 2022;

  Team includes U.S. and German DIRC experts, need more FTEs, hiring new PostDoc now (joint CUA/eRD14 funding)

- Status of Simulation and Reconstruction

  Generic initial design based on PANDA Barrel DIRC implemented in standalone Geant4;

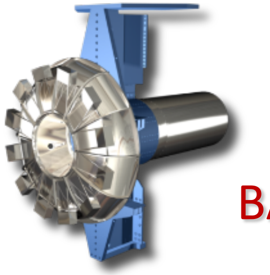
  Geant simulation and reconstruction code validated with PANDA Barrel DIRC prototype and GlueX DIRC;

  Fast simulation, based on full Geant4 implementation, has been made available to YR effort

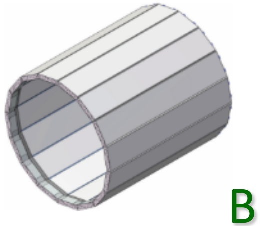
Thank you for your attention

Extra Material

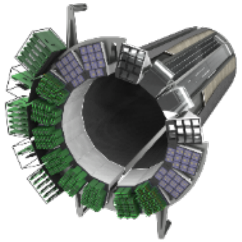
Barrel DIRC Counters



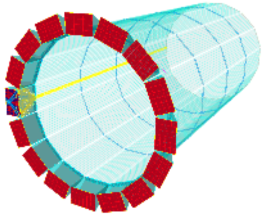
BaBar DIRC



Belle II TOP



PANDA Barrel DIRC

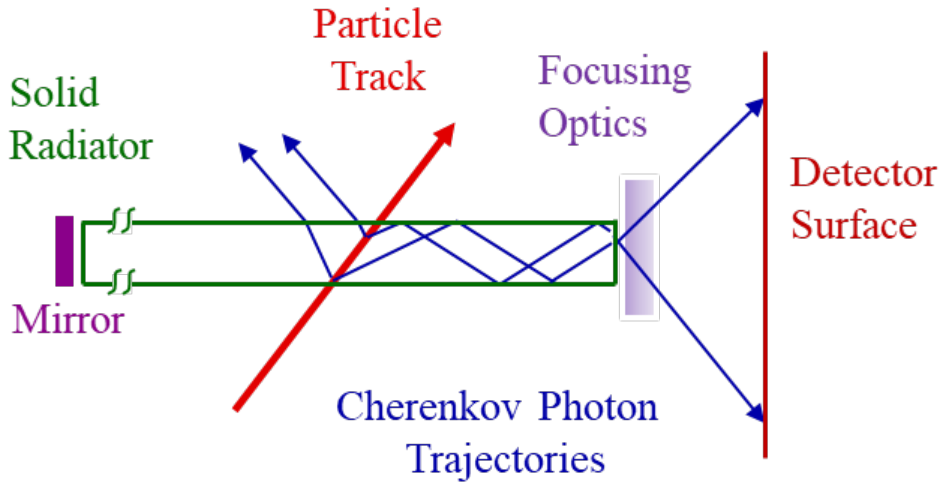


EIC hpDIRC

Radiator geometry	Narrow bars *(35mm)*	Wide plates *(450mm)*	Narrow bars *(53mm)*	Narrow bars *(35mm)*
Barrel radius	85cm	115cm	48cm	100cm
Bar length	490cm *(4×122.5cm)*	250cm *(2×125cm)*	240cm *(2×120cm)*	420cm *(4×105cm)*
Number of long bars	144 *(12×12 bars)*	16 *(16×1 plates)*	48 *(16×3 bars)*	176 *(16×11 bars)*
Expansion volume	110cm, ultrapure water	10cm, fused silica	30cm, fused silica	30cm, fused silica
Focusing	None (pinhole)	Mirror (for some photons)	Spherical lens system	Spherical lens system
Photodetector	~11k PMTs	~8k MCP-PMT pixels	~11k MCP-PMT pixels	~100k MCP-PMT pixels
Timing resolution	~1.5ns	<0.1ns	~0.1ns	~0.1ns
Pixel size	25mm diameter	5.6mm×5.6mm	6.5mm×6.5mm	3.2mm×3.2mm
PID goal	3 s.d. π/K to 4 GeV/c	3 s.d. π/K to 4 GeV/c	3 s.d. π/K to 3.5 GeV/c	3 s.d. π/K to 6 GeV/c
Timeline	1999 - 2008	Installed 2016	Installation 2023/24	TDR-ready in 2023

DIRC Concept

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

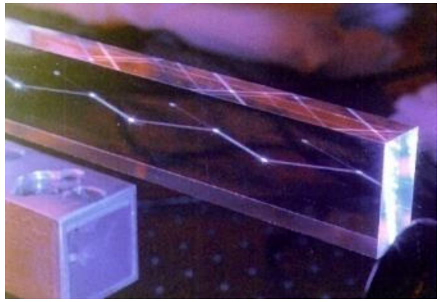


- For n>√2 some photons are always totally internally reflected for $\beta\approx1$ tracks.

- 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)

→ Major technological challenge for BaBar – is it really possible to efficiently and precisely conserve angle during up to 2000 reflections?
... and maintain that surface quality for 10+ years?



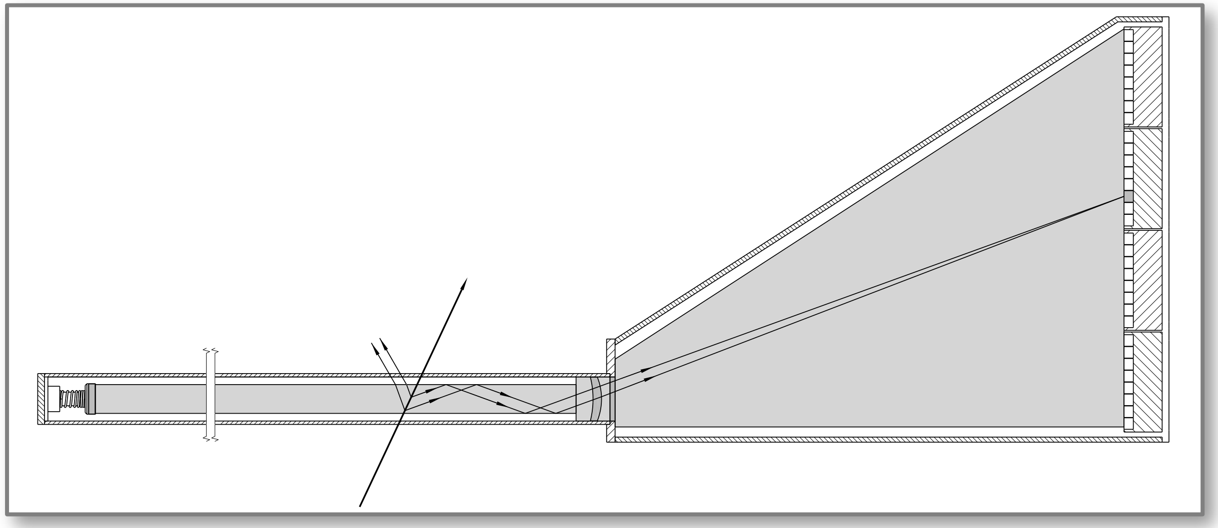
DIRC CONCEPT

- 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.

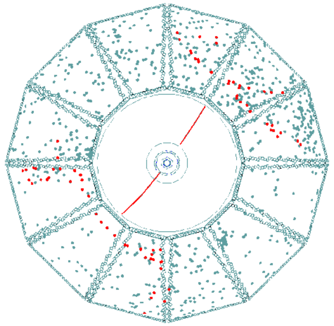
- DIRC is intrinsically a 3-D device,
  measuring: x, y, and time of Cherenkov
  photons, defining θ_c, ϕ_c, $t_{propagation}$.

- Ultimate deliverable for DIRC: PID likelihoods.

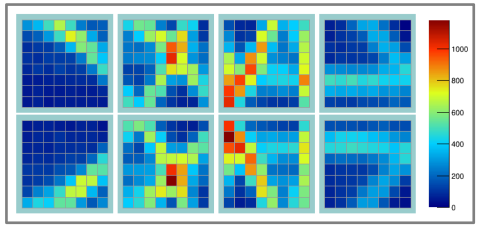


DIRC hit patterns are not typical Cherenkov rings.

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.
DIRC requires momentum and position of particle measured by tracking system.



Typical event
BaBar DIRC

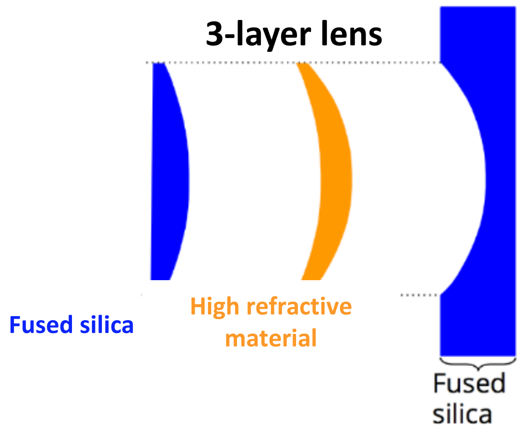


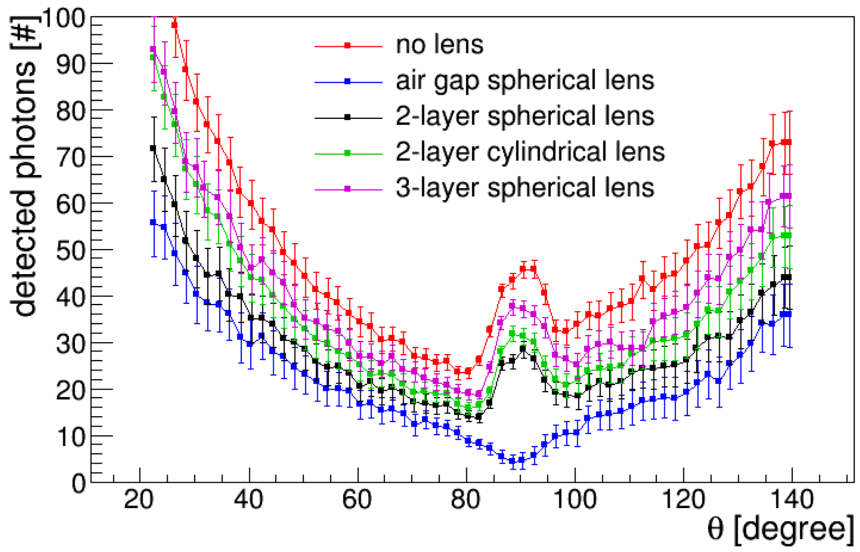
Accumulated hit pattern
PANDA Barrel DIRC

Lens design

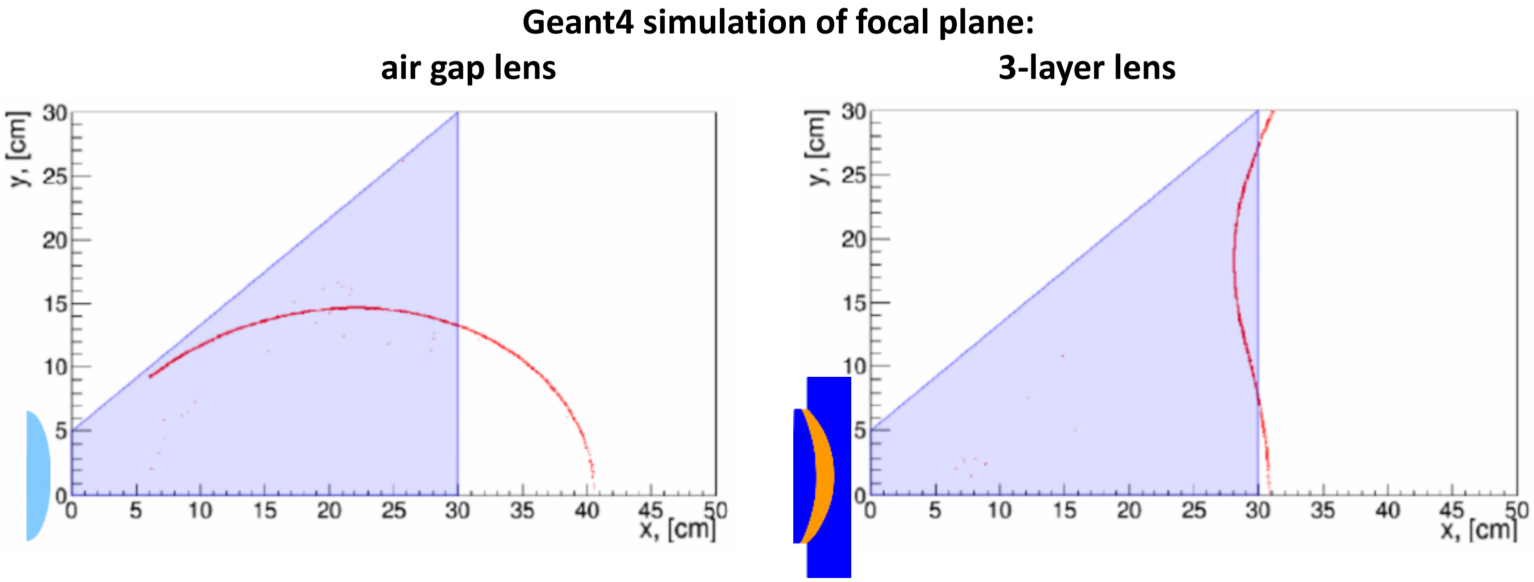
Conventional plano-convex lens with air gap limits DIRC performance

- Significant photon yield loss for particle polar angles around 90°
- Distortion of image plane for photons with steeper propagation angles
- Issues resolved by 3-layer lens with high-refractive index material for middle layer





From PANDA Barrel DIRC TDR: simulation

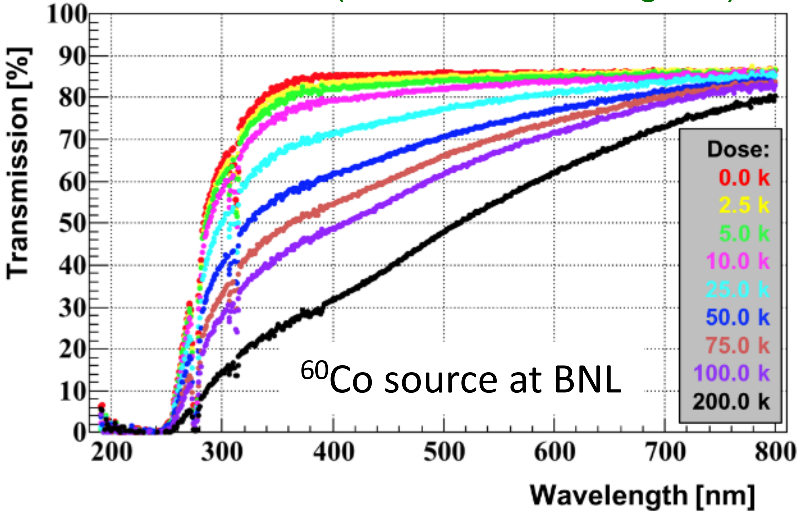


Geant Simulation

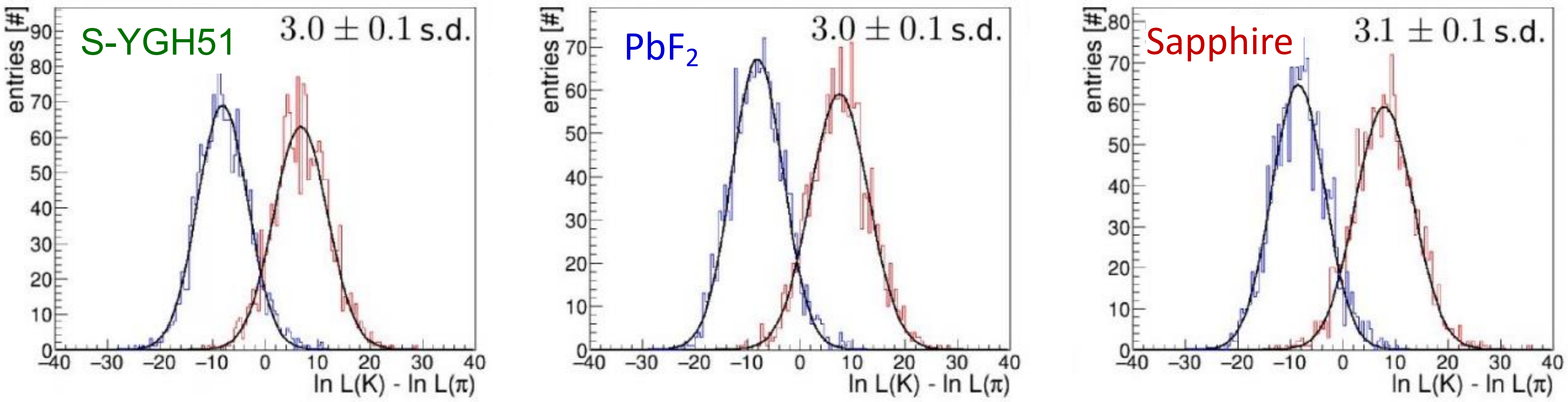
Lens material selection

- Initial lens prototypes used lanthanum crown glass as the middle layer but material was found to be insufficiently radiation hard
- Both Sapphire and PbF_2 are expected to be radiation-hard and to provide good PID performance but are very challenging for industry to process
- Two vendors are building 3-layer lenses with Sapphire and PbF_2, expect delivery by October
- Upgrading ODU laser setup for improved speed, precision, and repeatability

S-YGH51 (lanthanum crown glass)



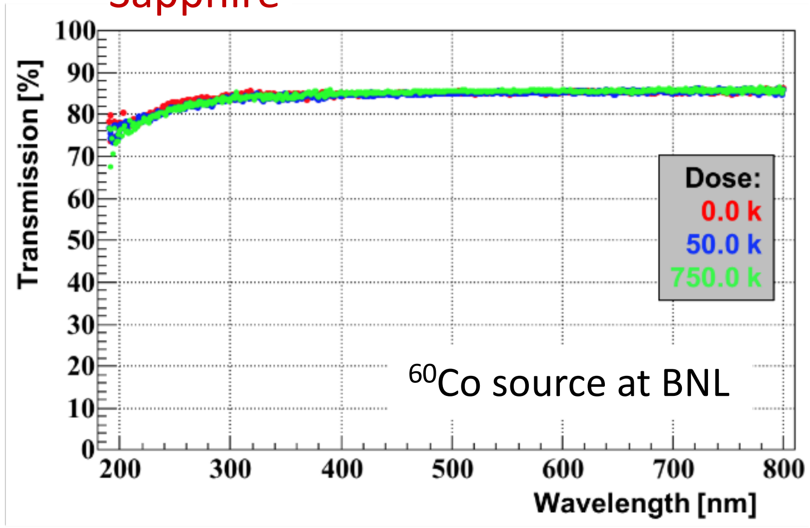
Simulated π/K separation for charged pions and kaons with 6 GeV/c momentum and 30° polar angle, assuming a tracking resolution of 0.5 mrad.



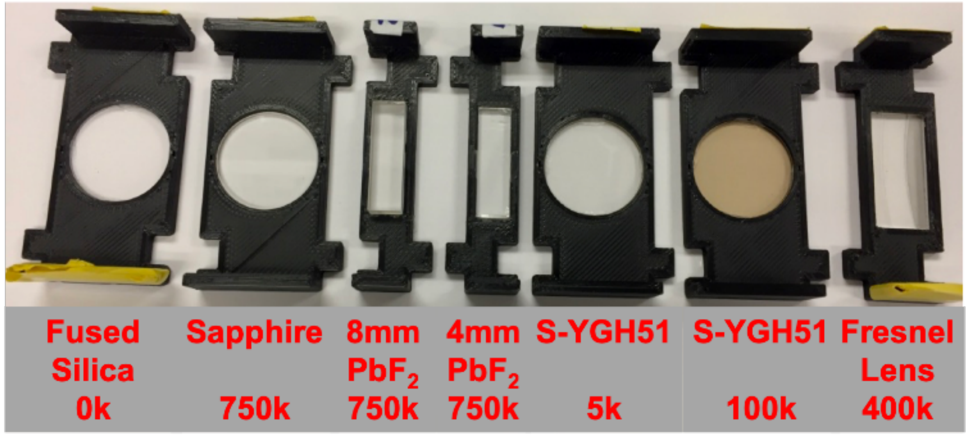
Radiation hardness study

- Seven materials studied with ^{60}Co source and monochromator at BNL
- Radiation hardness of Sapphire and PbF_2 confirmed
- Luminescence still to be investigated
- Neutron damage will be studied next

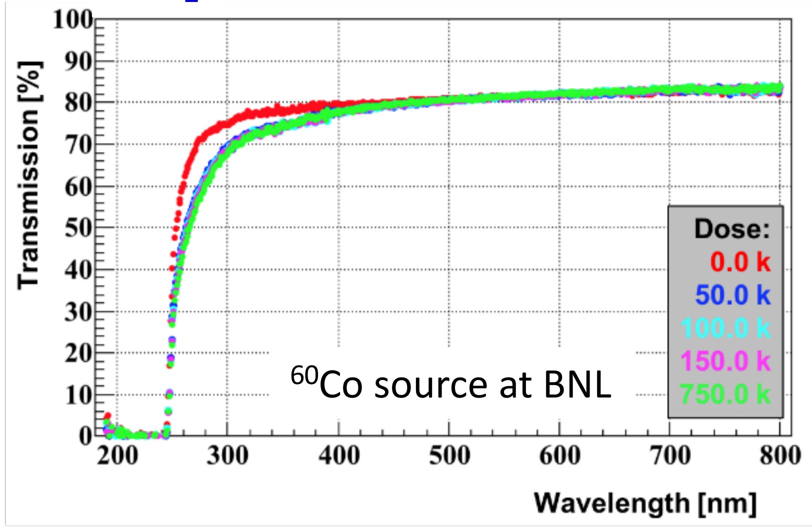
Sapphire



Tested samples



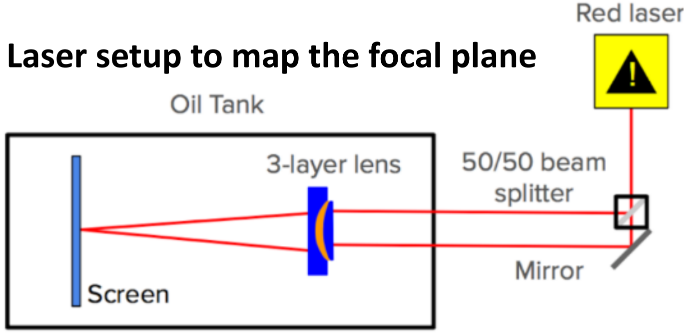
PbF_2

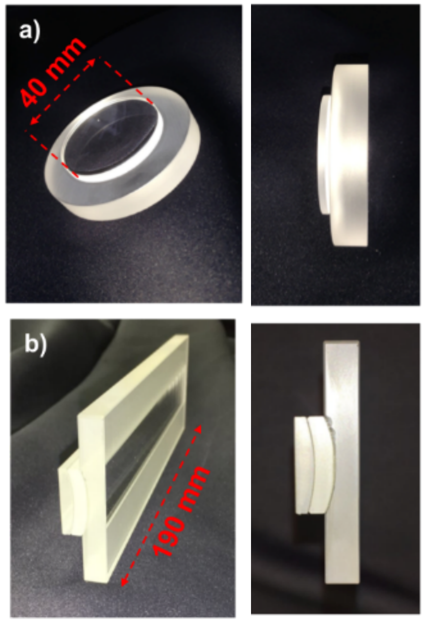


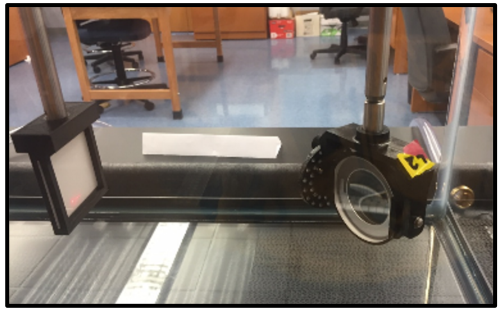
Lens measurements in ODU optical lab

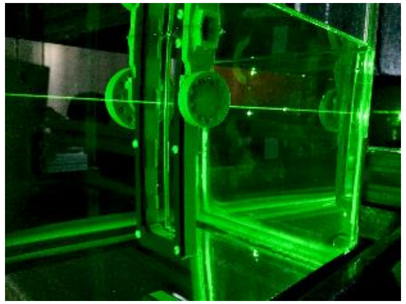
- Confirmed flat focal plane, matching prism shape
- Geant in excellent agreement with data

Laser setup to map the focal plane

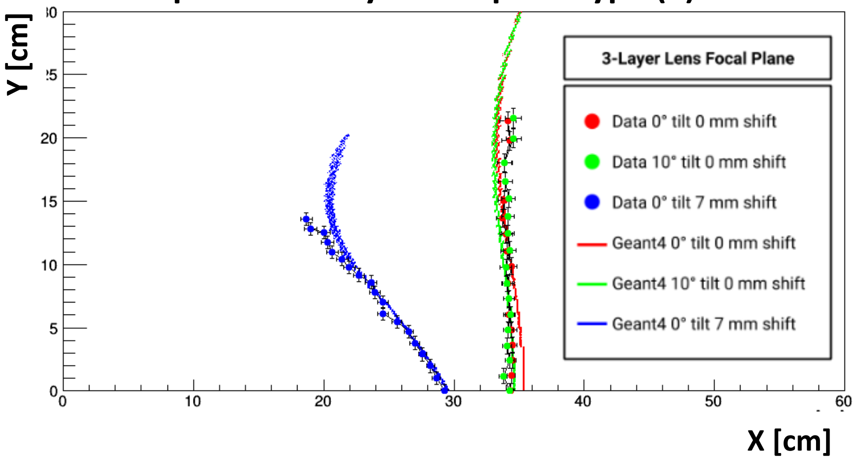




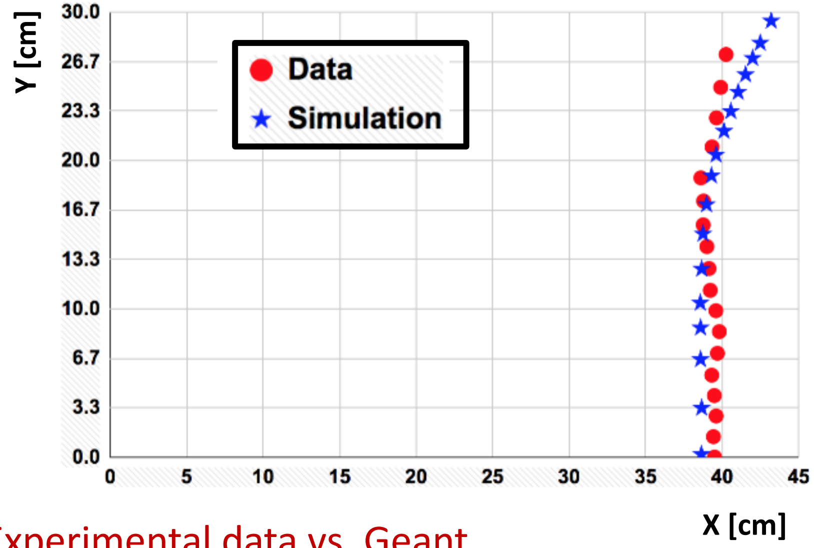




Spherical 3-layer lens prototype (a)



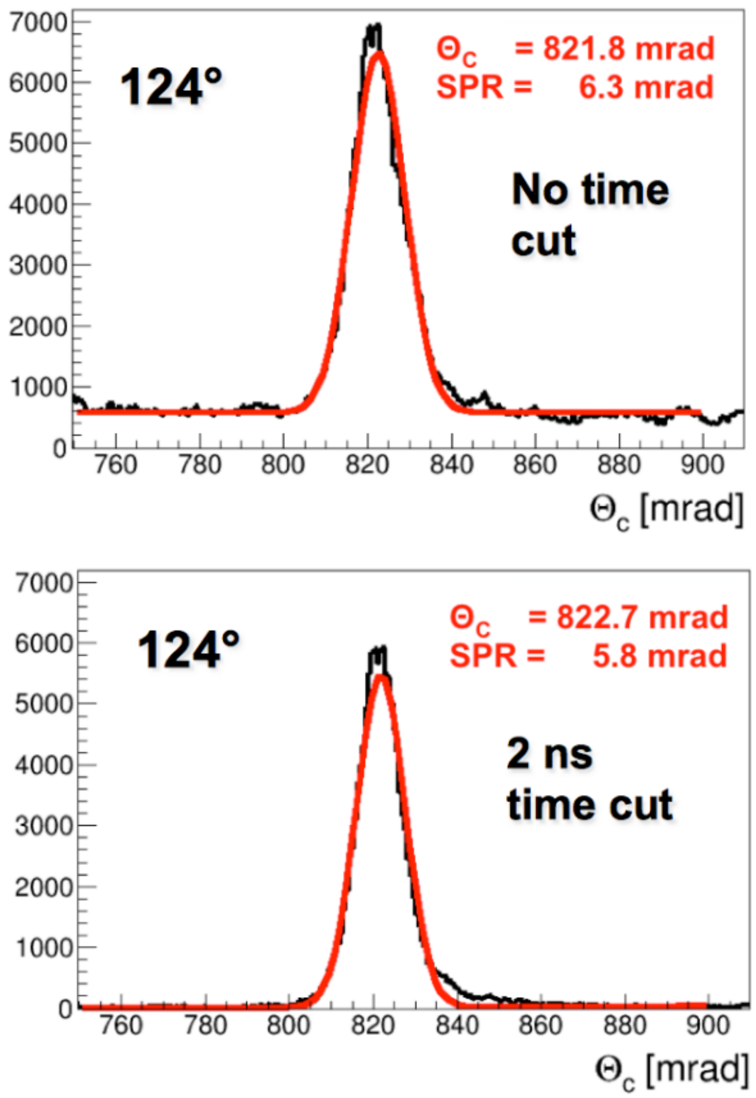
Cylindrical 3-layer prototype (b)

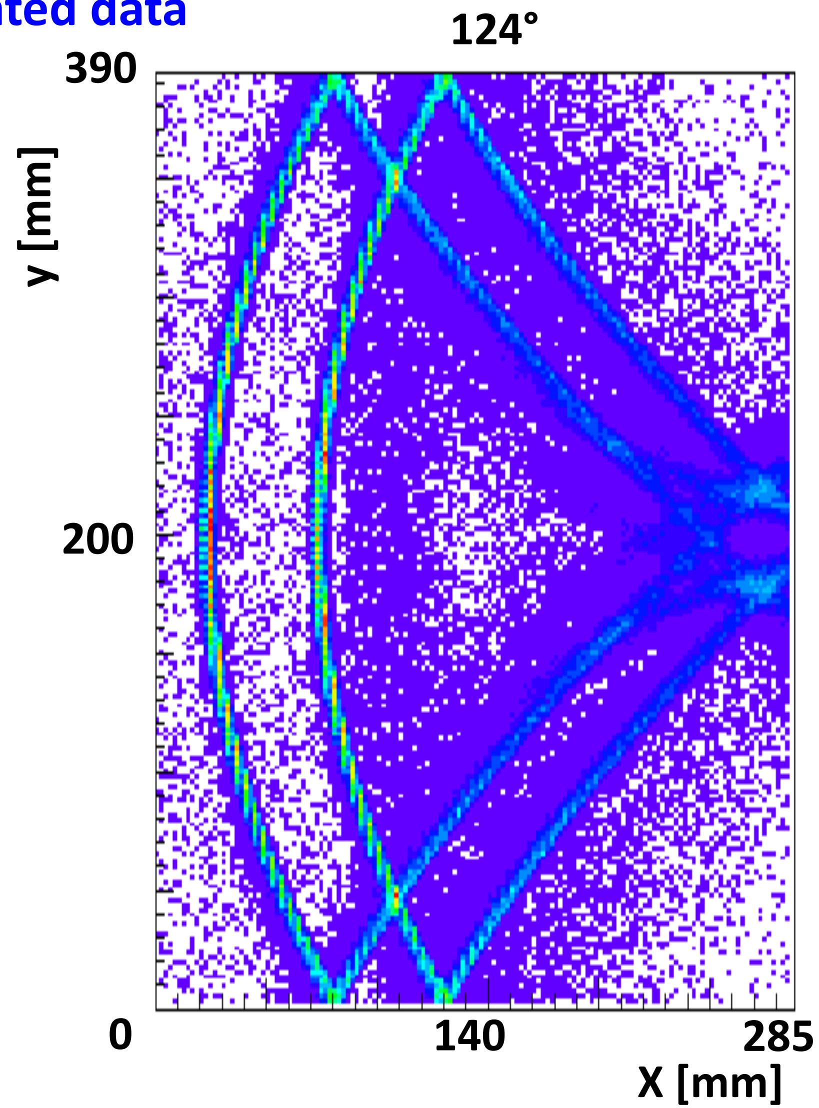


Experimental data vs. Geant

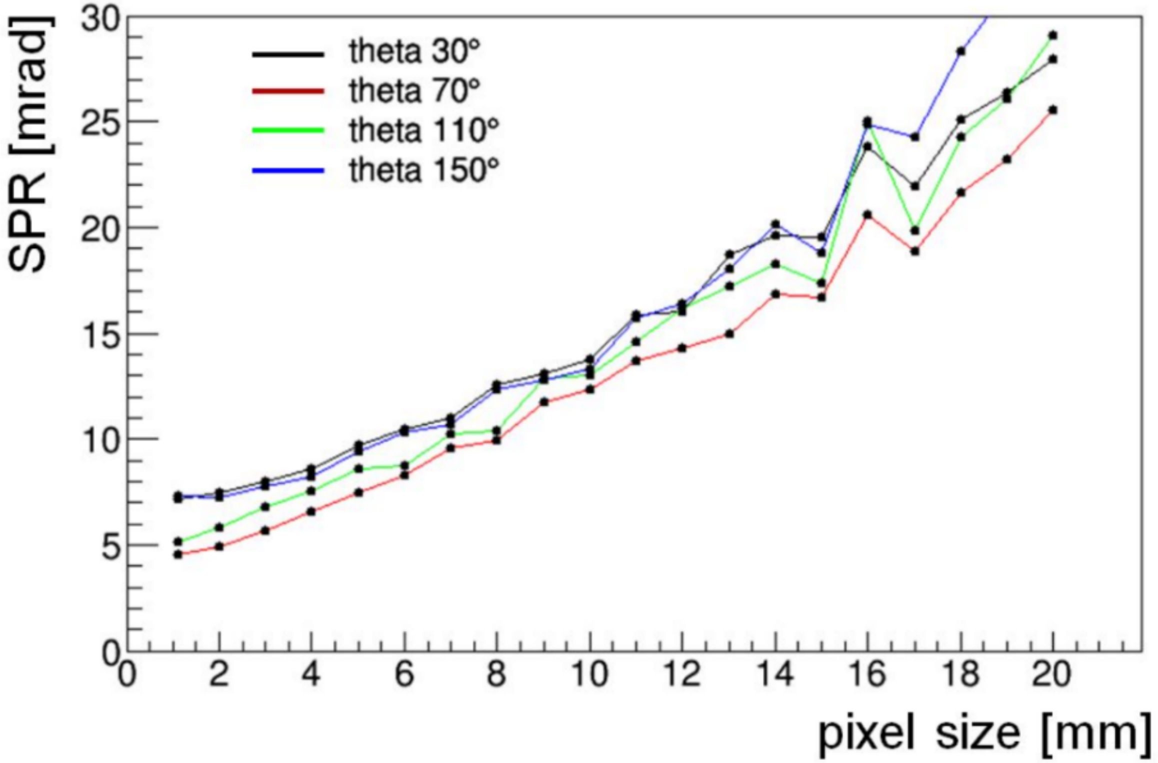
hpDIRC Simulation: Performance

Simulated data

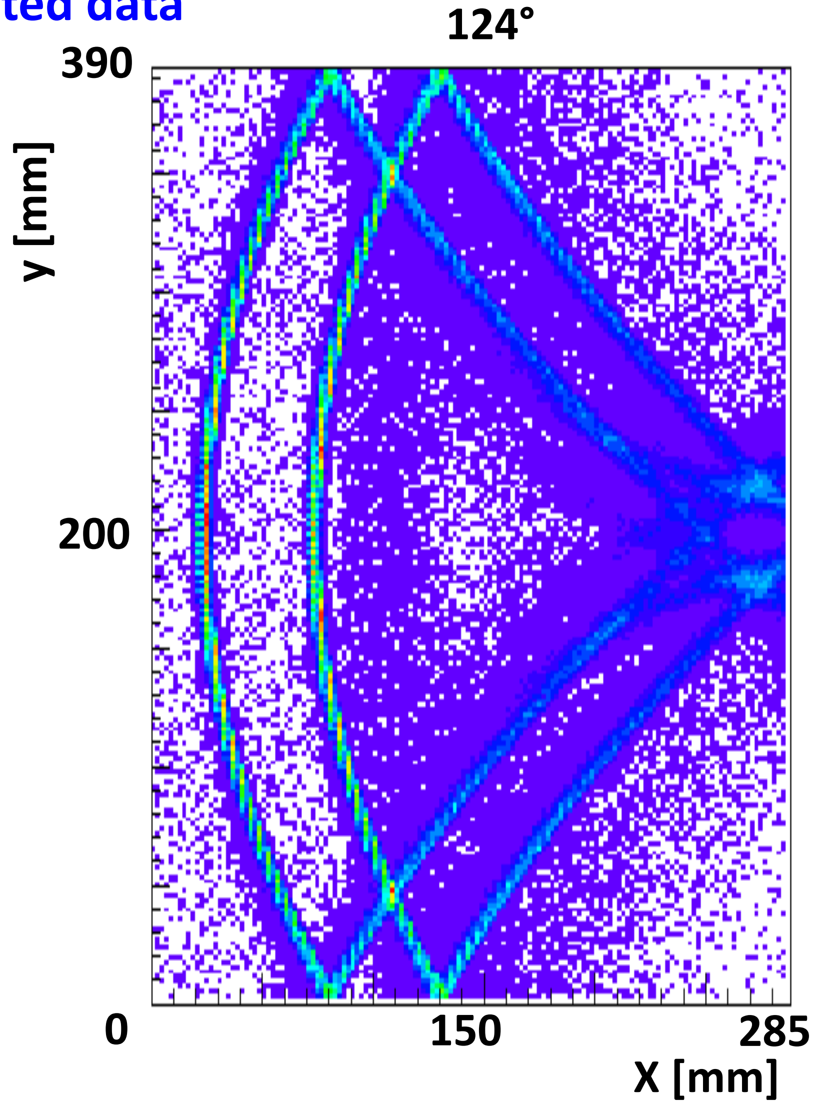




Influence of the pixel size on SPR for selected track polar angles

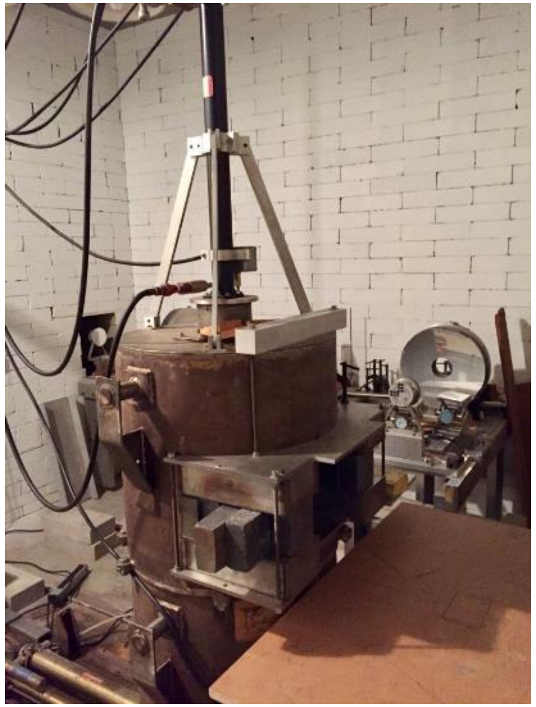


Simulated data

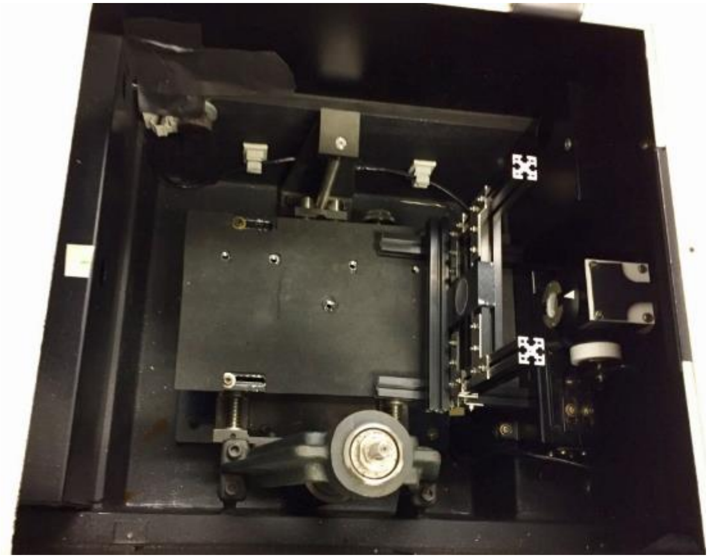


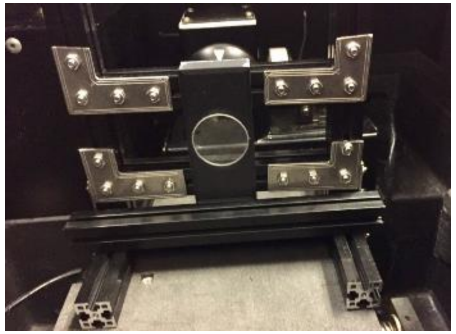
hpDIRC Radiation Tests

Co^{60} Chamber



Monochromator





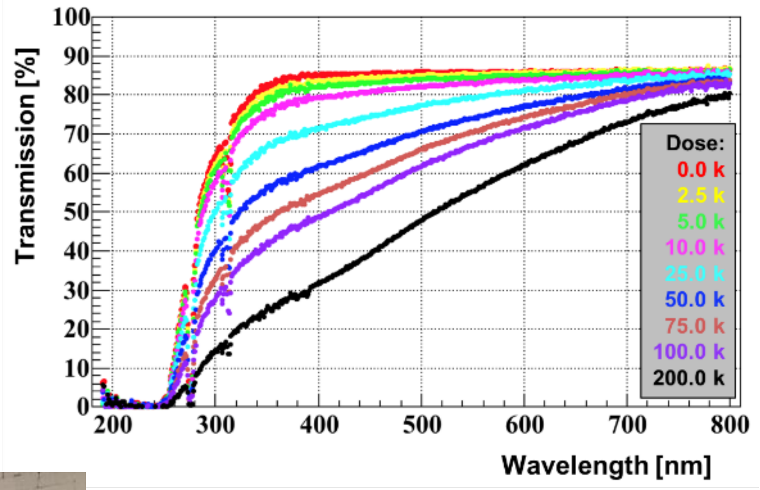
HPDIRC RADIATION TESTS

- ^{60}Co irradiation results

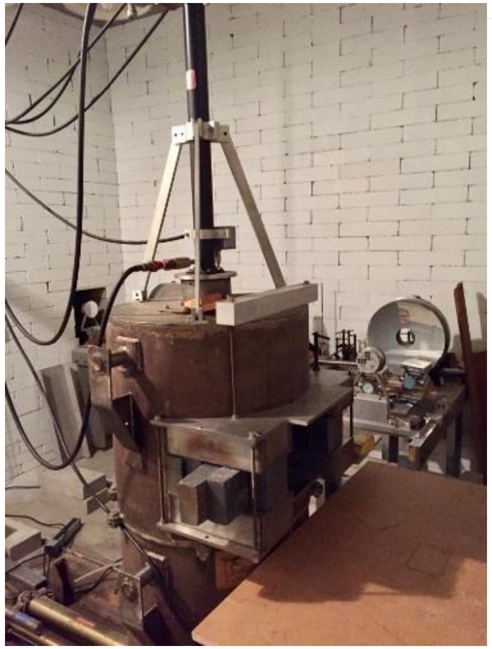
- Radiation damage quantified by measuring the transmission in the 190-800 nm range in a monochromator

- Transmission loss of alternate lanthanum crown glass material (S-YGH51) confirmed

S-YGH51 (NLaK33 equivalent)

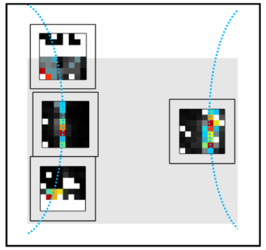


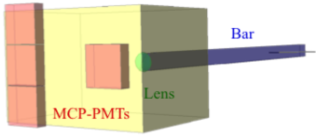
Monochromator



Co^{60} Chamber

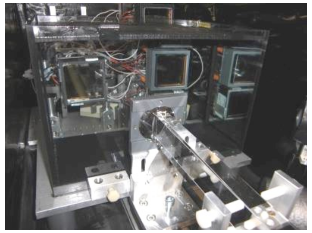
PANDA BARREL DIRC BEAM TESTS

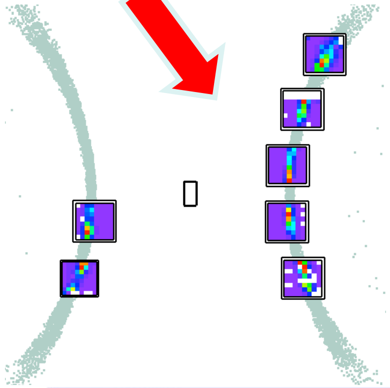




GSI

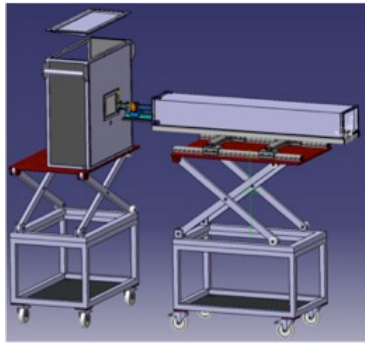
2008/2009

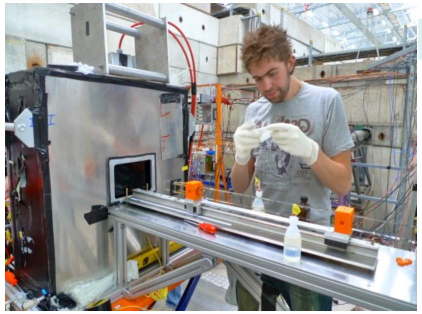


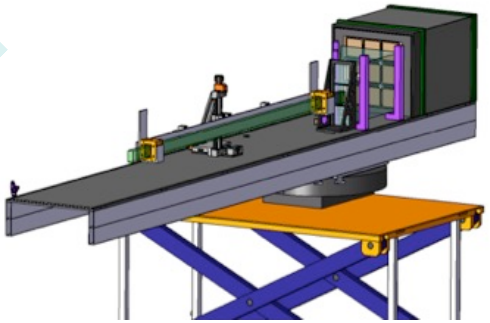


GSI, CERN

2011

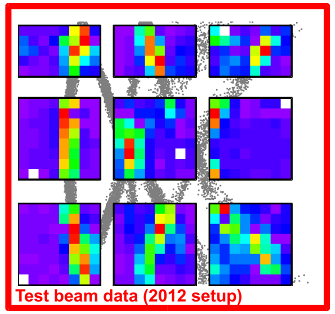


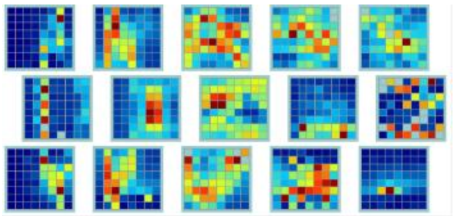




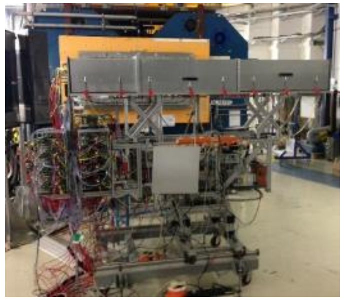
CERN

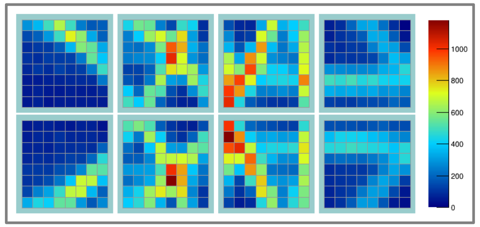
2012





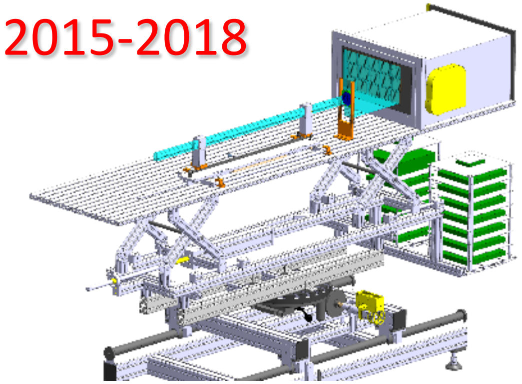
GSI 2014





CERN

2015-2018



Example of validated cost/performance optimization, based on simulation study:

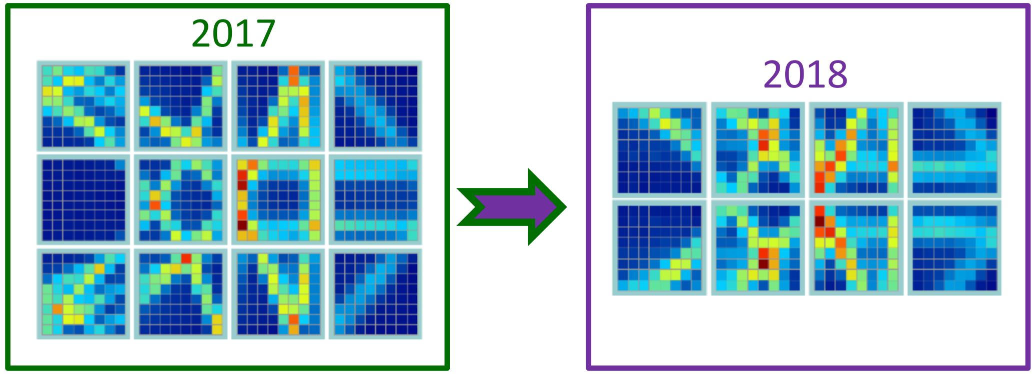
PANDA Barrel DIRC beam test at CERN in 2017 and 2018

2017: prism covered with 12 MCP-PMTs (3x4)

Simulation: 1/3 of the MCP-PMTs can be removed with

no significant impact on PID ⟹ major cost savings.

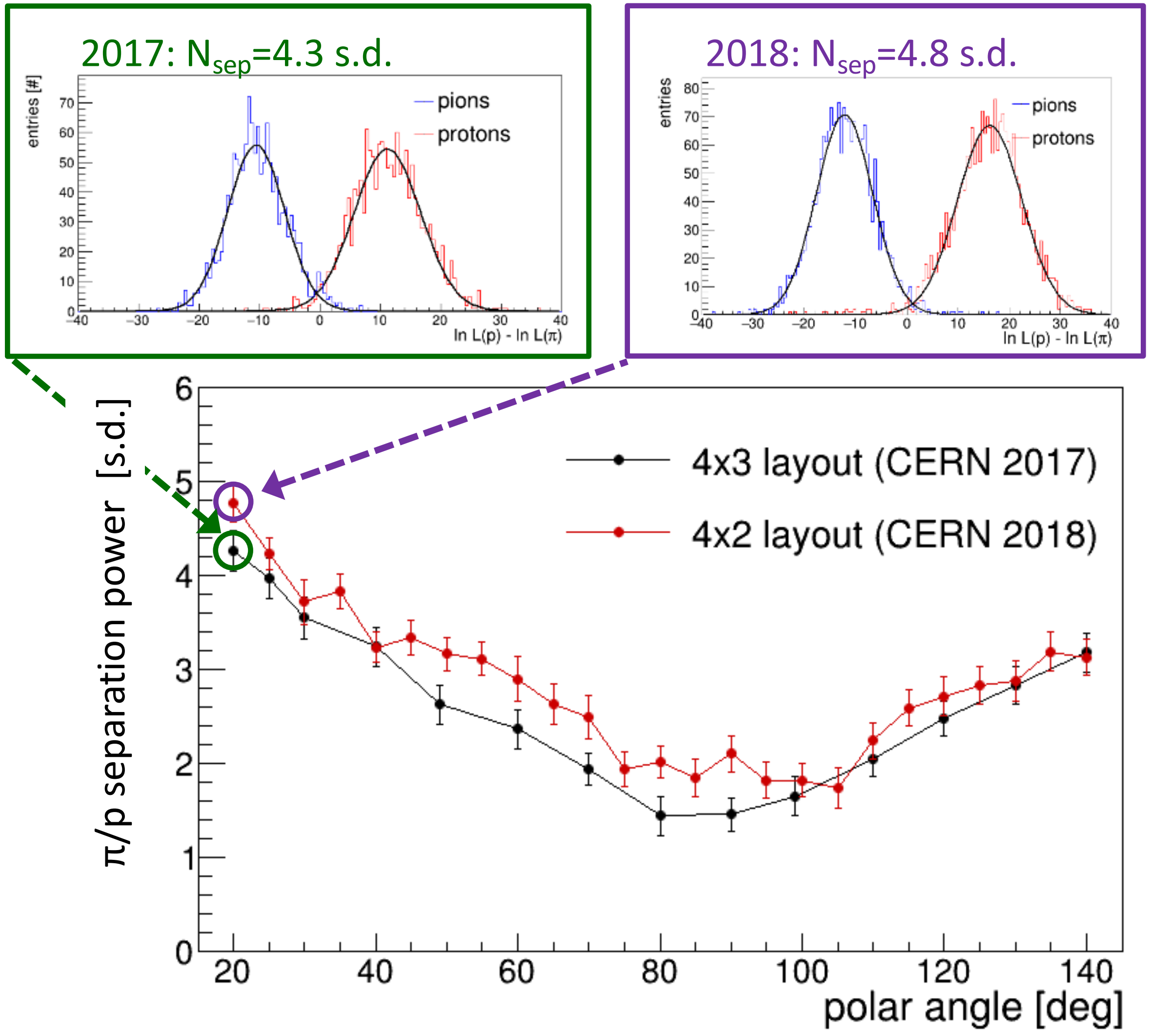
2018: beam test with reduced coverage to 8 MCP-PMTs (2x4)



accumulated hit pattern

beam data, 7 GeV/c

Note: π/p at 7 GeV/c ≈ π/K at 3.5 GeV/c



Found expected photon loss rate (30-40%)

with no observable loss of PID performance.

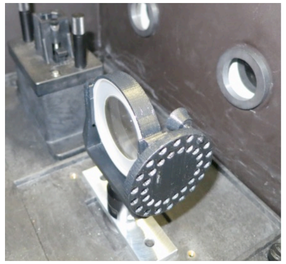
(Small improvement is due to better timing precision in 2018.)

HPDIRC TEAM

Greg Kalicy — co-PI, tenure track faculty, DIRC experience at GSI, ODU, and CUA since 2010

→ PANDA Barrel DIRC (2010-2014), hpDIRC (since 2013), GlueX DIRC (since 2015)

Optical tests of DIRC components*, Geant and ray-tracing simulation, prototype beam tests at GSI and CERN, radiation hardness tests, high-B tests, DIRC installation and commissioning

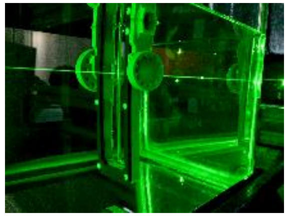


CUA facilities: X-ray source and monochromator

Former CUA hpDIRC members: T. Horn, M. Boer

Charles Hyde — faculty, hpDIRC since 2011

DIRC design, EIC physics with PID focus, simulation, optical lab support, cosmic ray test facility



Thomas Hartlove — laboratory specialist

Optical lab design and support

ODU facility: laser lab for lens measurements, picosecond laser pulser

Former ODU hpDIRC members: L. Allison, K. Park, H. Seraydaryan

**responsibilities within hpDIRC group highlighted in blue*

HPDIRC TEAM

Pawel Nadel-Turonski adjunct faculty, hpDIRC since 2011 at JLab and SBU

DIRC design, EIC physics with PID focus, mini-DIRC

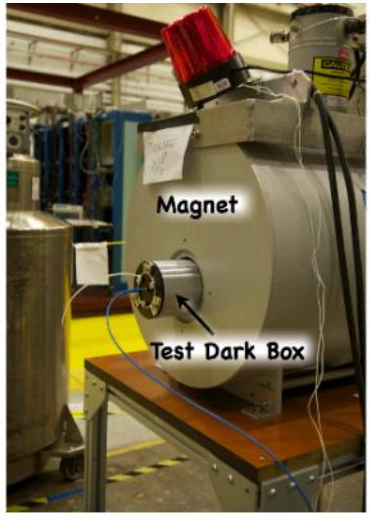
SBU facility: lab space for hpDIRC prototype preparation

Yordanka Ilieva faculty, hpDIRC since 2012

Photodetectors, high-B performance evaluation at JLab test facility

Former and current USC members involved in high-B tests at JLab:

T. Cao, C. Gleason, N. Zachariou plus undergraduate students



Carl Zorn senior scientist, hpDIRC since 2012

Photodetectors, high-B performance evaluation at JLab test facility

JLab facility: high-B sensor test setup, picosecond laser pulser

Former JLab hpDIRC members: J. Stevens, W. Xie

hpDIRC Team

Jochen Schwiening co-PI, senior scientist, DIRC experience at SLAC and GSI since 1995

→ BaBar DIRC (1995-2008), SuperB fDIRC (2001-2008), PANDA Barrel DIRC (since 2009), hpDIRC (since 2011), GlueX DIRC (since 2015)

DIRC design, optical properties and radiation hardness of DIRC bars, simulation and reconstruction, prototype beam tests at SLAC, GSI, and CERN, construction, installation, commissioning, operations and system management

Carsten Schwarz staff scientist, DIRC experience since 2004

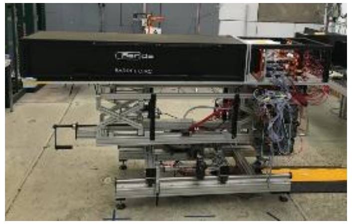
→ PANDA Barrel DIRC (since 2007), hpDIRC (since 2011)

Lens design, ray-tracing simulation, readout electronics, prototype beam tests at GSI and CERN

Roman Dzhygadlo staff scientist, DIRC experience since 2014

→ PANDA Barrel DIRC (since 2013), hpDIRC (since 2013), GlueX DIRC (since 2015)

DIRC design, simulation and reconstruction, prototype beam tests at GSI and CERN, commissioning



Klaus Peters faculty and staff scientist, hpDIRC (since 2011), EIC physics

GSI facilities: optical lab, electronics lab, mechanical lab, PANDA Barrel DIRC prototype

Engineering support for prototype and beam tests: A. Gerhardt, D. Lehmann