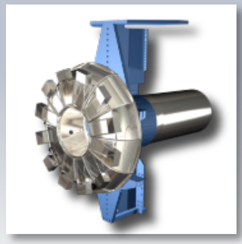
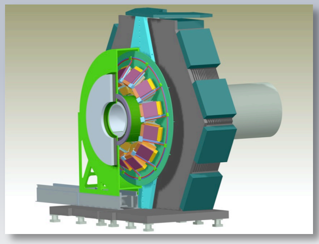
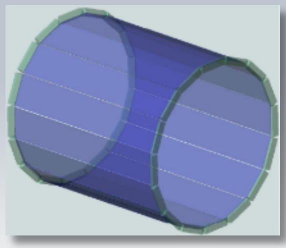
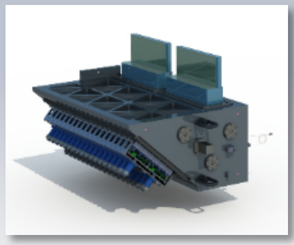
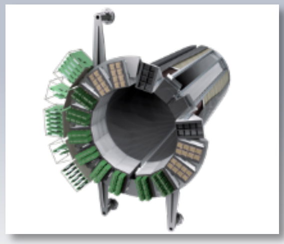
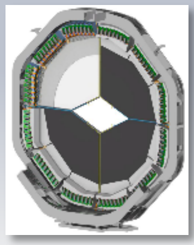
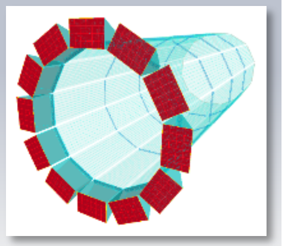
      

BABAR | SuperB | Belle II | GlueX | panda | panda | ePIC

Review of DIRC Detectors
from BABAR to ePIC and Beyond

Jochen SCHWIENING

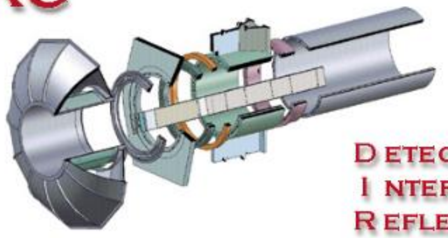
GSI

GSI Helmholtzzentrum für Schwerionenforschung GmbH

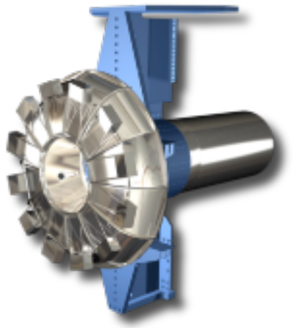
OUTLINE

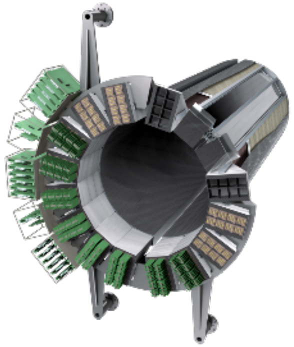
- DIRC Concept
- DIRCs at Past and Current Facilities
- R&D for DIRCs at Future Facilities

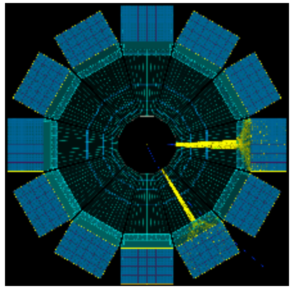
DIRC



DETECTION OF
INTERNALLY
REFLECTED
CHERENKOV LIGHT

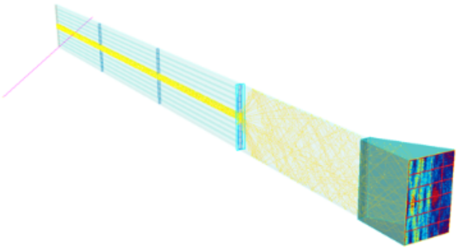






30 years of DIRC detector research with many interesting results,
too much for a 25-minute talk – for more details see:

- *Recent review: B. Ratcliff and J. Va'vra, Nucl.Instrum.Meth. A 970 (2020) 163442*
- *RICH workshop series (most recent: RICH2022, Edinburgh, NIM-A)*
- *DIRC workshop series (most recent: DIRC2019, Rauischholzhausen, JINST)*



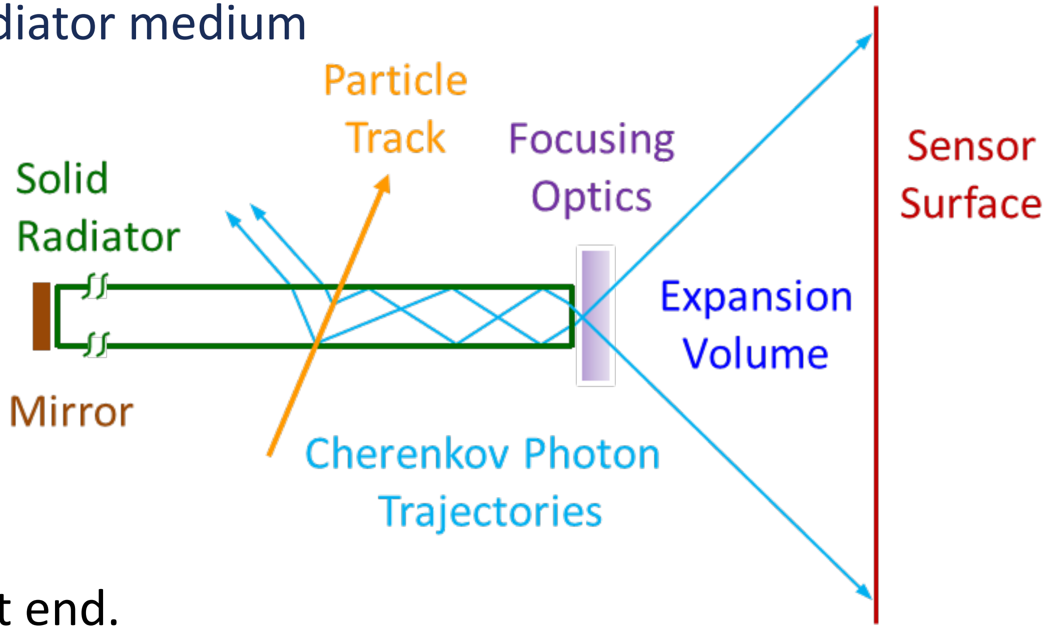
Thanks to my colleagues in the DIRC community who provided information and material.

Detection of Internally Reflected Cherenkov Light

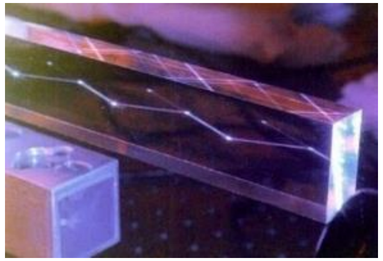
DIRC: Compact subtype of (Ring Imaging CHerenkov) RICH detector

utilizing total internal reflection of Cherenkov photons in a solid radiator medium

- Charged particle traversing solid radiator, refractive index n
- For n>√2 some photons are always
  totally internally reflected for $\beta \approx 1$ tracks
- Radiator: bar, plate, or disk,
  typically made from Synthetic Fused Silica ("Quartz")

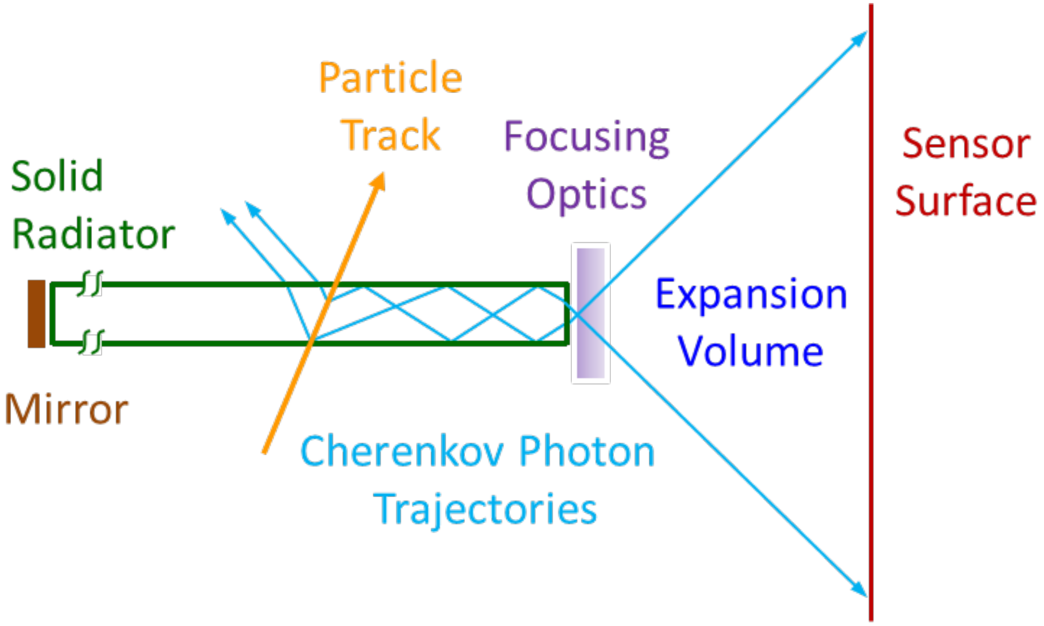


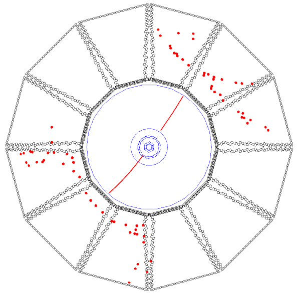
- Mirror attached to one bar end, reflects photon back to readout end.
- Quartz bar/plate/disk both radiator and light guide, transporting photons away from crowded central detector to suitable sensor location



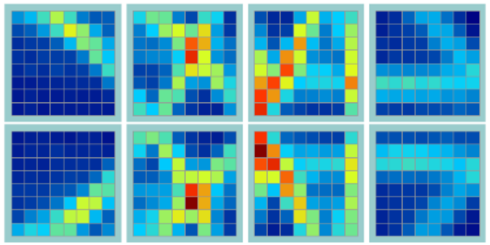
DIRC Concept

- Magnitude of Cherenkov angle conserved during many internal reflections
  (provided radiator surfaces are square, parallel, highly polished)
- 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 likelihoods for observed hit pattern (in detector space or in Cherenkov space) to be produced by e/μ/π/K/p plus event/track background.
- DIRCs requires momentum and position of particle
  measured by tracking system.





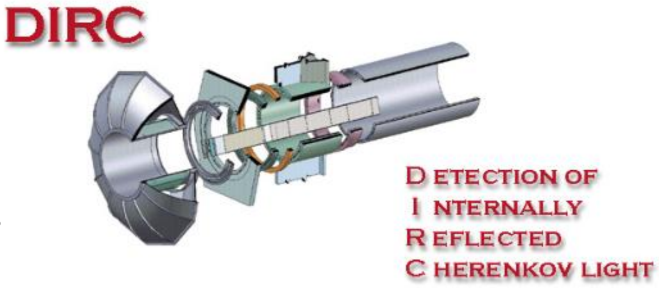
Hit pattern
BABAR DIRC



Accumulated hit pattern
PANDA Barrel DIRC

DIRC Timeline

DIRC used for the first time in BABAR as primary hadronic particle ID system, flavor tagging, primary goal: π/K ID to 4 GeV/c.

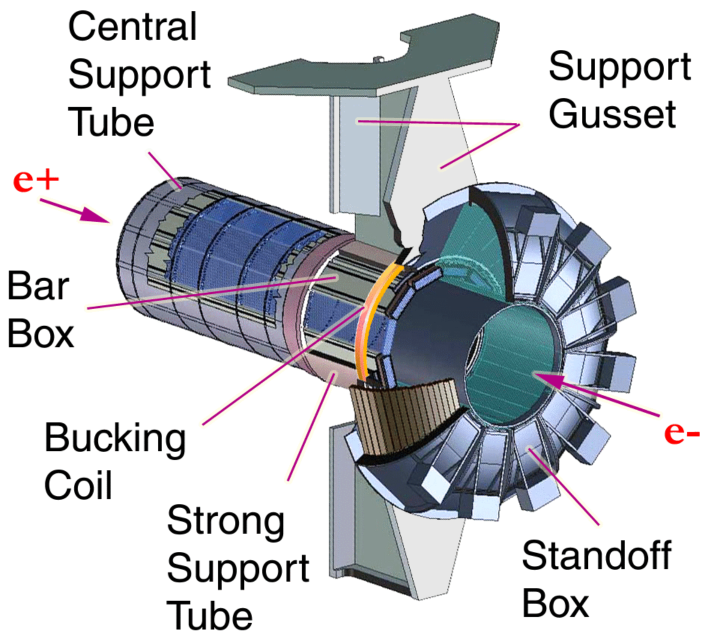


- 1991: first description of DIRC concept; 1992: first DIRC publication[§]
- 1993-1996: DIRC R&D, DIRC prototypes tests with cosmic rays and particle beams
- Nov 1994: decision in favor of DIRC for hadronic PID for BABAR
- Nov 1998: installed first DIRC bar box in BABAR; cosmic ray run, commissioning
- Nov 1998-Apr 1999: installed first 5 DIRC bar boxes in BABAR; commissioning with cosmics and beam
- Nov 1999: all 12 bar boxes installed, start of first BABAR physics run
- early 2000s: growing interest in DIRCs for future experiments (SuperB, Belle II, PANDA) → start of R&D
- April 2008: last event recorded with BABAR
- 2011: start of R&D for EIC high-performance DIRC (eRD14)
- 2016: installation of TOP counter into Belle II
- 2018: installation of DIRC counter into GlueX, reusing four decommissioned BABAR DIRC bar boxes

[§] *B. Ratcliff, SLAC-PUB-5946 (1992) and Conf.Proc.C 921117 (1992) 331*

BABAR DIRC

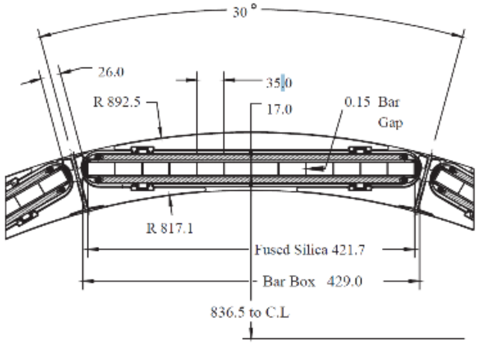
- large expansion volume
- pinhole focusing
- 1'' PMTs
- moderate photon timing
- first DIRC

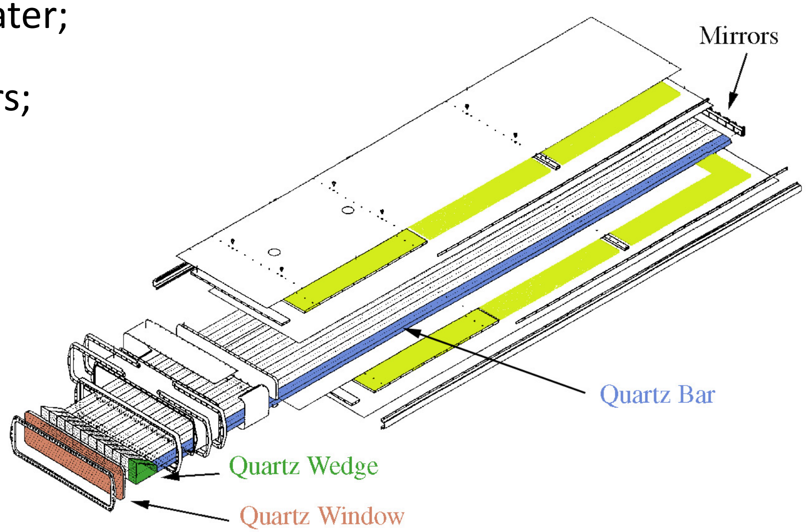


BABAR DIRC

- first DIRC counter, primary hadronic PID in BABAR barrel;
- design goal 3σ π/K separation up to 4 GeV/c;
- compact, 8 cm radial thickness incl. supports;
- pinhole focusing (size of bar small compared to size of expansion volume);
- long narrow synthetic fused silica bars (17mm x 35mm x 4900mm);
- bar boxes penetrate iron of the flux return, sensors outside magnetic field;
- 1.2m-deep expansion volume: tank of 6000 l ultra-pure water;
- sensors: ~11,000 standard 1" PMTs with light concentrators;
- installation in 1998/1999, physics run 1999-2008;
- robust operation, excellent performance.

- large expansion volume
- pinhole focusing
- 1'' PMTs
- moderate photon timing
- first DIRC





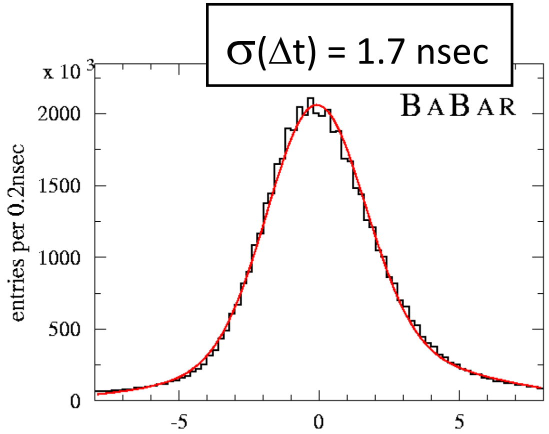
Main operations/performance challenge: accelerator-induced background from large expansion volume

Timing information not used for PID but crucial in separating signal from background

Calculate expected arrival time of Cherenkov photon based on

- track TOF
- reconstructed photon path in radiator bar and in water

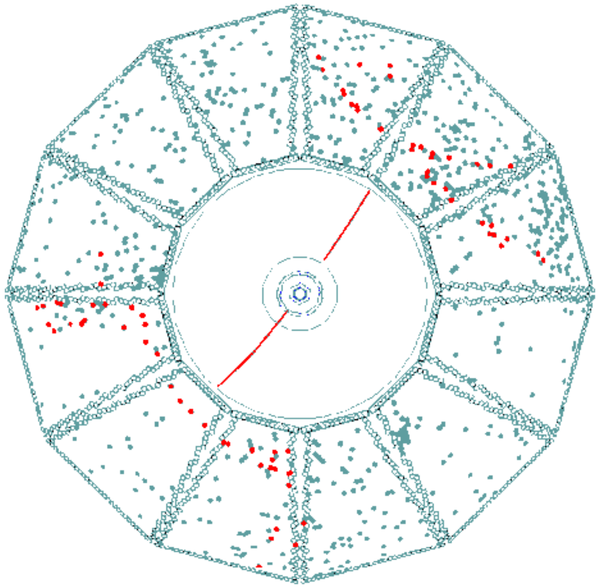
Δt: difference between measured and expected arrival time

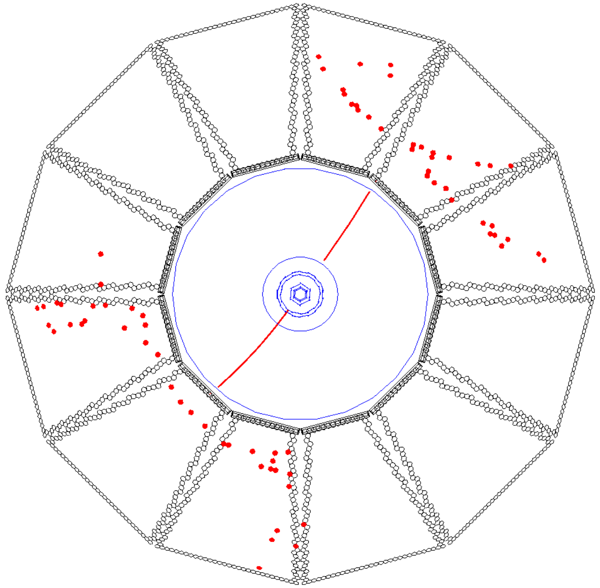


(Δt can provide "DIRC t_0 event time")

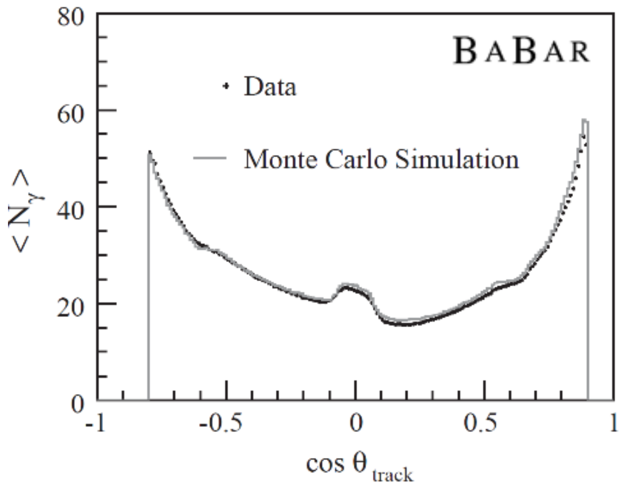
$\pm$ 300 nsec trigger window → $\pm$ 8 nsec Δt window

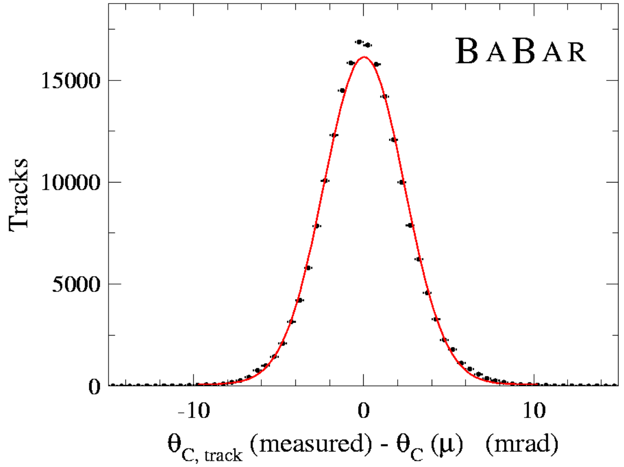
(~500-1300 background hits/event) (1-2 background hits/sector/event)

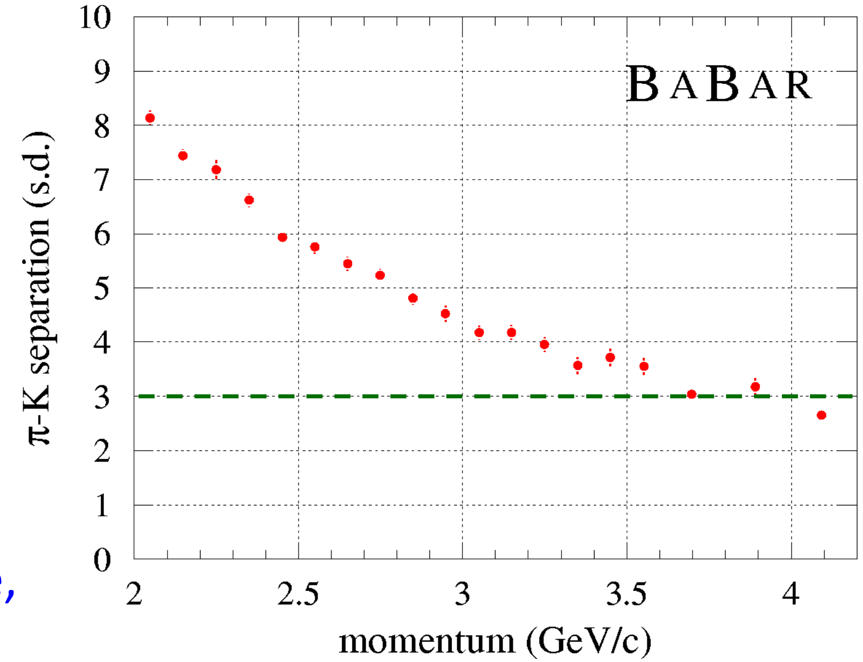




Single photon timing resolution	1.7 ns
Single photon Cherenkov angle resolution	~10 mrad
Photon yield	20-60 photons per track
Track Cherenkov angle resolution	2.4 mrad (di-muons)
π/K separation power	4.3 σ @ 3 GeV/c, ~3σ @ 4 GeV/c





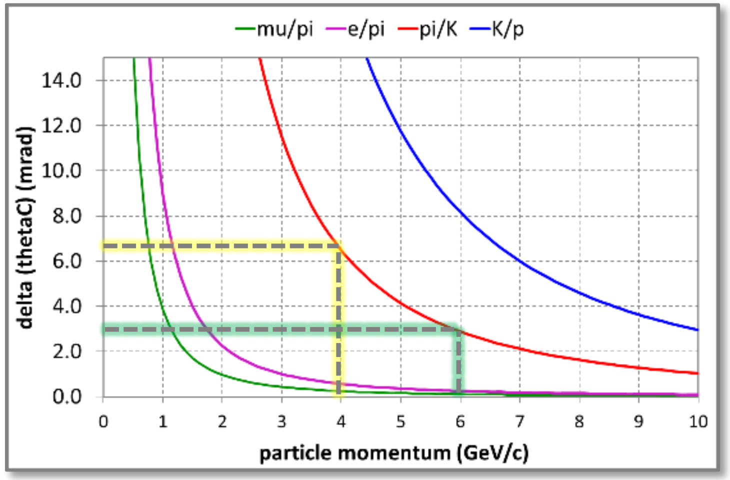


Excellent performance: very reliable, robust, easy to operate, significant contribution to almost all BABAR physics results.

I. Adam et al., Nucl.Instrum.Meth. A 538 (2005) 281

IMPROVING ON THE BABAR DIRC

DIRC Cherenkov angle difference vs. momentum



- Make DIRC less sensitive to background (main challenge for BABAR and SuperB)
  - decrease size of expansion volume, replace water as medium, add focusing optics;
  - find a way to place photon detector inside magnetic field.
- Investigate alternative radiator shapes (plates, disks), develop endcap device
- Push DIRC π/K separation to higher momentum

$$\sigma_{\theta_c}(particle) \approx \sqrt{\left(\frac{\sigma_{\theta_c}(photon)}{\sqrt{N_\gamma}}\right)^2 + \sigma^2_{correlated}}$$

  - improve angular precision of tracking system, mitigate multiple scattering impact;
  - use photon detectors better PDE, improve Cherenkov angle resolution per photon.

$$\sigma_{\theta_c}(photon) \approx \sqrt{\sigma^2_{bar} + \sigma^2_{pix} + \sigma^2_{chrom}} \qquad \sigma_{correlated} = \sqrt{\sigma^2_{tracking} + \sigma^2_{mult.scatter.}}$$

BABAR DIRC $\sigma_{\theta_c}(photon) = 9.6\ \text{mrad}$

Limited in BABAR by:

- size of bar image ~4.1 mrad
- size of PMT pixel ~5.5 mrad
- chromaticity (n=n(λ)) ~5.4 mrad

Improve for future DIRCs via:

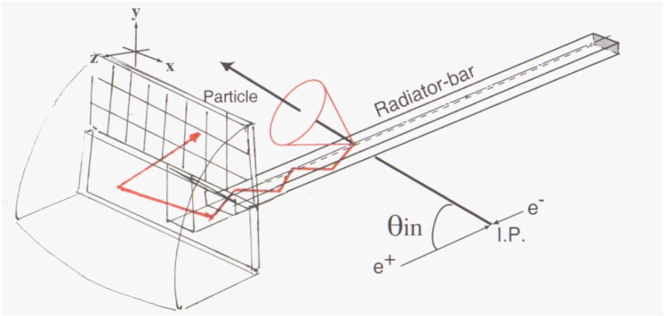
- focusing optics
- smaller pixel size
- better time resolution

SUPERB, BELLE II, PANDA & EIC

9.6 mrad → 5-6 mrad per photon → 1 mrad per particle (EIC goal) in reach

FUTURE DIRC COUNTERS

Initial next-generation DIRC R&D directions can be roughly divided into three imaging approaches using different focusing optics



Early SuperB fDIRC design

- moderate timing, (very) good spatial resolution

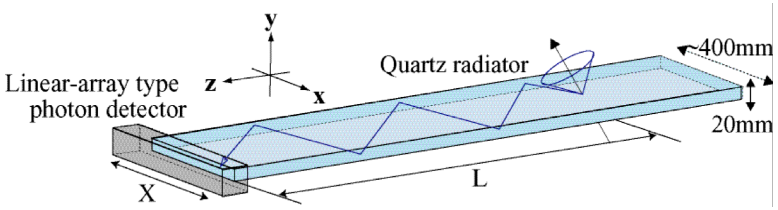
  examples: SuperB fDIRC, GlueX DIRC, early PANDA Barrel DIRC

  200-500 ps photon timing, array of (~6 mm) 2D pixels → PID primarily based on spatial imaging

- very fast timing, moderate/poor spatial resolution

  examples: early Belle II TOP design, early PANDA Disc DIRC design

  ~50 ps photon timing, (~5 mm) 1D pixels → PID emphasizes time imaging



Early Belle II TOP design

- very fast timing, very good spatial resolution

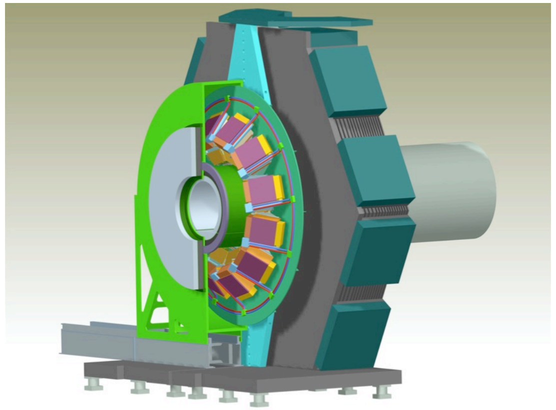
  examples: “ultimate fDIRC”, EIC High-Performance DIRC

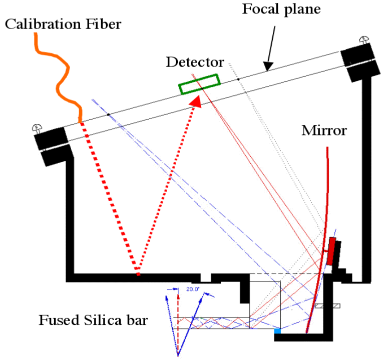
  <100 ps photon timing, large array of (~3 mm) 2D pixels → PID uses full 3D imaging

Final designs for Belle II TOP and PANDA DIRCs are hybrids derived from these initial approaches.

SuperB fDIRC

- compact photon camera
- cylindrical mirror focusing
- small pixels (MAPMT)
- fast photon timing
- dispersion mitigation
- legacy components

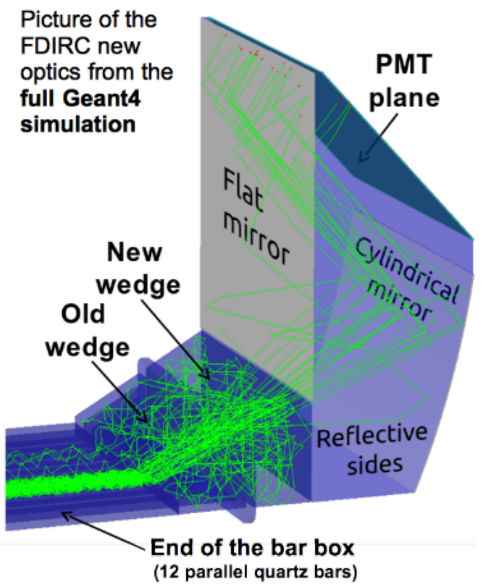




SuperB Focusing DIRC (fDIRC):

- Intended as barrel PID system for the (cancelled) SuperB experiment in Italy
- Design goal 3σ π/K separation up to 4 GeV/c
- Important constraint: reuse BABAR DIRC bar boxes, readout outside magnetic field
- Maintain BABAR DIRC PID performance for much higher backgrounds at 100x luminosity
- Two complex prototypes during 10+ years of R&D (tests with particle beams and cosmic muons)
- Complete redesign of the photon camera (replace water tank with 12 “cameras”)
- New sensors and electronics
- True 3D imaging using (compared to BABAR):
  - 25× smaller volume for expansion region
  - 10× better timing resolution to detect single photons
  - 4x smaller pixels
- Optical design based entirely on solid fused silica to avoid water or oil as optical medium

compact photon camera
cylindrical mirror focusing
small pixels (MAPMT)
fast photon timing
dispersion mitigation
legacy components



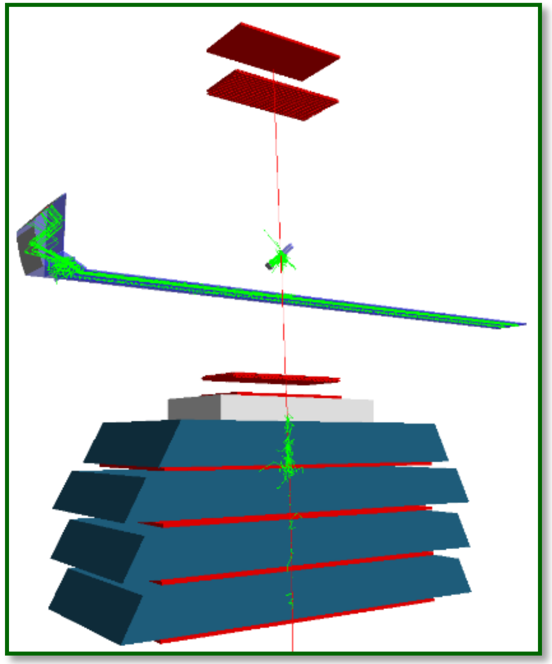
B. Dey et al., Nucl.Instrum.Meth. A 775 (2015) 112

First fDIRC prototype:

- Oil tank expansion volume (KamLand mineral oil), spherical mirror (SLD CRID)
- Mix of multi-anode sensors (MaPMTs, MCP-PMTs) and readout electronics
- Performance evaluation with electron beam at SLAC

Significant upgrade of optics and electronics for second prototype:

- New solid fused silica expansion volume (FBLOCK) with cylindrical mirror focusing
- Additional wedge to couple BABAR DIRC bar box to FBLOCK
- Waveform sampling readout electronics (IRS2, early version of Belle II TOP readout)
- Array of 12 Hamamatsu H8500 MaPMTs (8*8 pixels, 6mm pitch, 140ps TTS)
- Detailed study of SuperB fDIRC phase space using hardened cosmic rays at SLAC.



Achieved required resolution for SuperB fDIRC

Clearly demonstrated resolution improvement

from chromatic dispersion correction with fast timing

D.A. Roberts et al., RICH 2016
Nucl.Instrum.Meth. A 766 (2014) 114

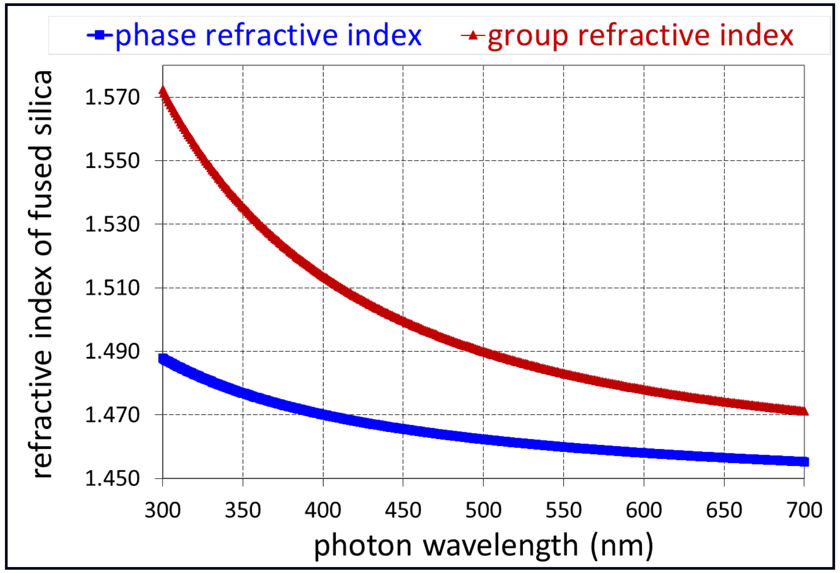
For more details on fDIRC R&D see: J. Va'vra, "Lessons learned from DIRC & FDIRC developments at SLAC", DIRC 2019 workshop, Sep. 2019.

CHROMATIC DISPERSION IN DIRCS

Technical challenge: properties of synthetic fused silica (FS)

Pros:
- Optically transparent over wide wavelength range
- Shown to be radiation hard at Mrad+ levels
- Can be polished to excellent surface finish (few Å *rms* roughness)

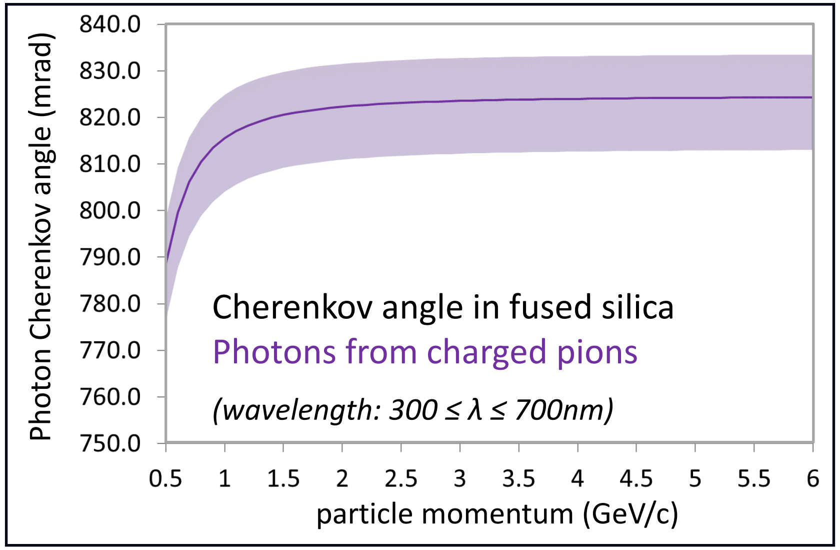
Cons:
- Production process can produce inclusions (bubbles) in bulk material or layers with optical index variations (striae)
- Dispersion of refractive index impacts angular resolution



Impact of chromatic dispersion on Cherenkov angle resolution

For β=1: θ_C=813…834mrad (for 300 ≤ λ ≤ 700nm photons produced in FS)

→ significant contribution to Cherenkov angle resolution per photon



Several approaches to dispersion mitigation are being investigated:

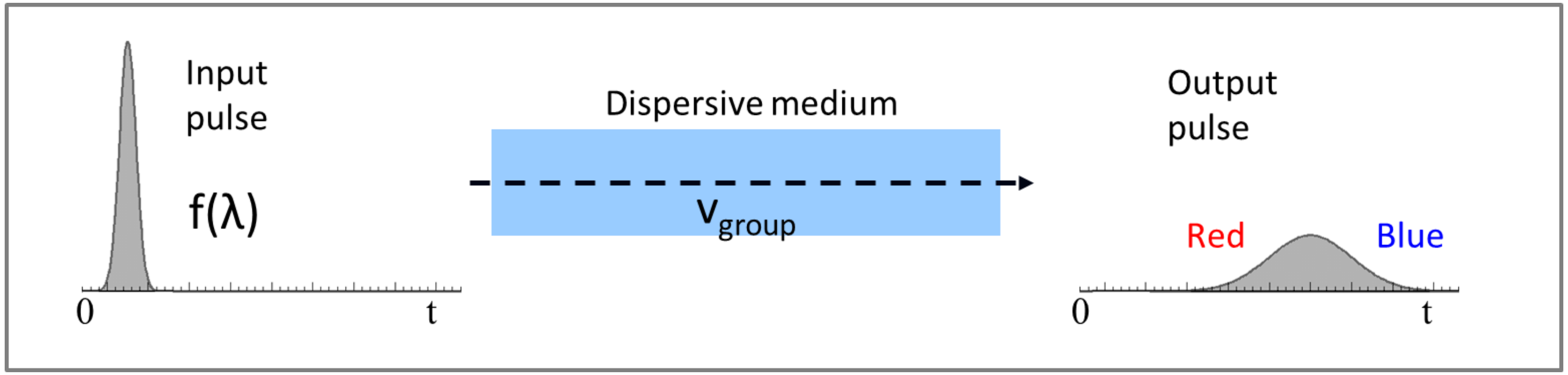
- Limit wavelength range (custom photocathode or band filter)
- Use transition to different refractive index (LiF prism)
- Use fast photon timing to tag photon wavelength using time dispersion
  → SuperB fDIRC first to demonstrate feasibility of this method in 2007

Chromatic Dispersion in DIRCs

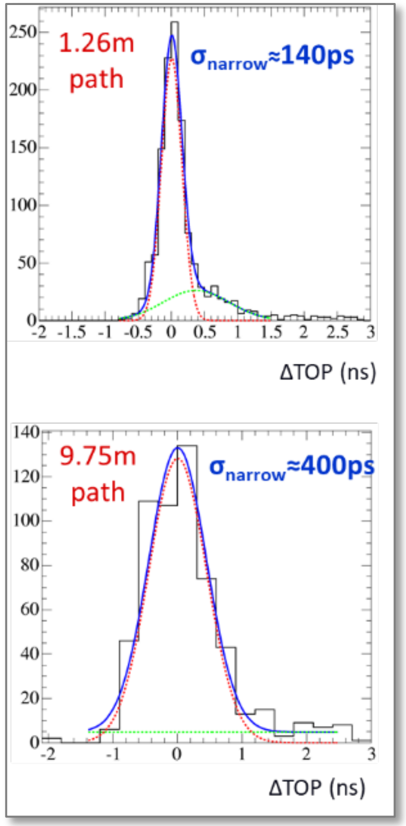
JS, RICH 2007

Cherenkov angle production controlled by n_{phase} ($\cos\theta_c = 1/(n_{phase}\beta)$): θ_c (red) < θ_c (blue)

Propagation of photons controlled by n_{group} ($v_{group} = c_0/n_{group} = c_0/[n_{phase} - \lambda \cdot dn_{phase} \cdot d\lambda]$): v_{group}(red) > v_{group} (blue)



SuperB fDIRC, 1st prototype



Fused silica: n_{phase}(red) < n_{phase}(blue) → v_{group}(red) > v_{group}(blue)

→ red photons arrive before blue photons

Photon color tag dTOP: time difference between the measured propagation time of a photon and the expected propagation time (calculated for photon with the average wavelength)

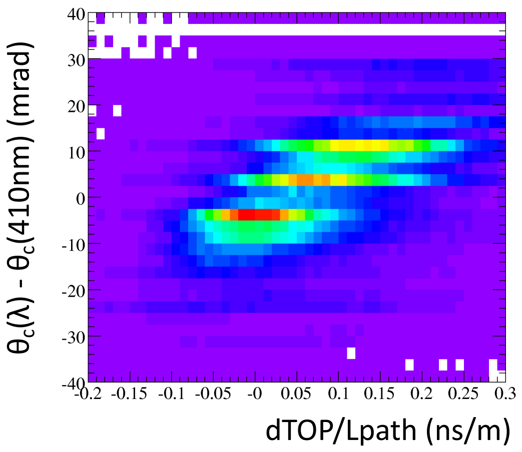
→ negative dTOP: red photons, positive dTOP: blue photons

Use this information to correct the measured Cherenkov angle per photon.

$dt/L = dTOP/L = \lambda \cdot d\lambda \cdot | - d^2n_{phase}/d\lambda^2 | / c_0$ Correlation between propagation time and emission angle

dt is pulse dispersion in time, pathlength L, wavelength bandwidth dλ, refraction index n(λ)

Correlation in data, 10m photon path



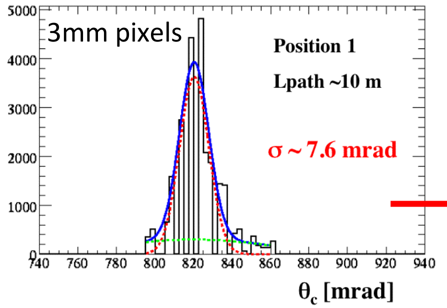
JS, RICH 2007

J. Benitez et al., Nucl.Instrum.Meth. A (2008) 104

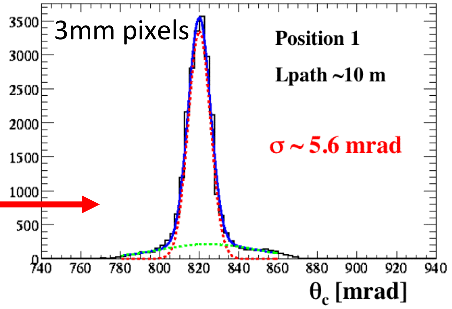
Example from SuperB fDIRC:

- fDIRC prototype in electron beam
- observed photon timing $\sigma_t \approx 200$ps
- correction improves resolution for photon paths > 2-3m
- first experimental demonstration of chromatic dispersion mitigation using fast photon timing

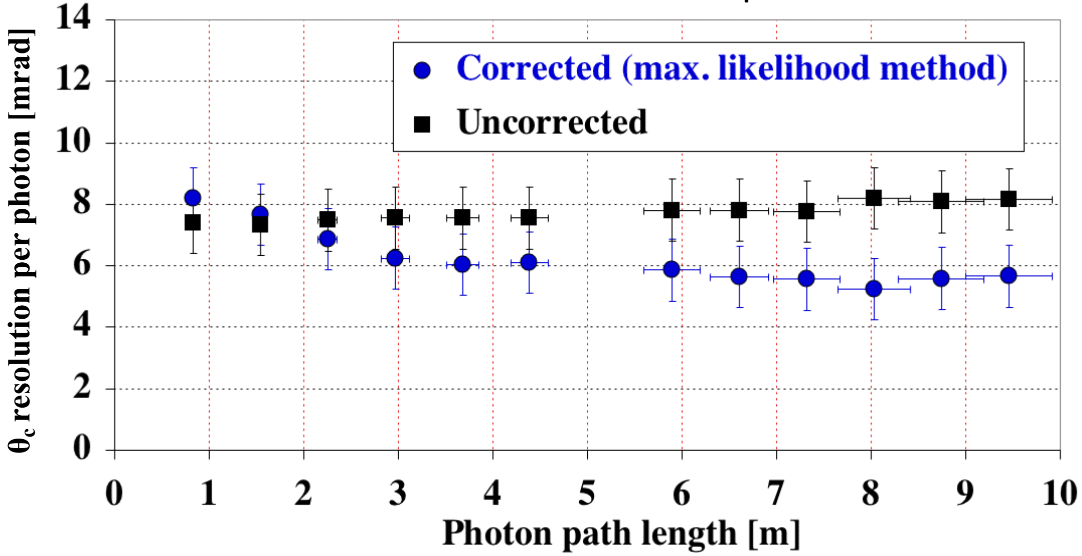
Correction off:



Correction on:



chromatic correction for 3mm pixel MAPMT



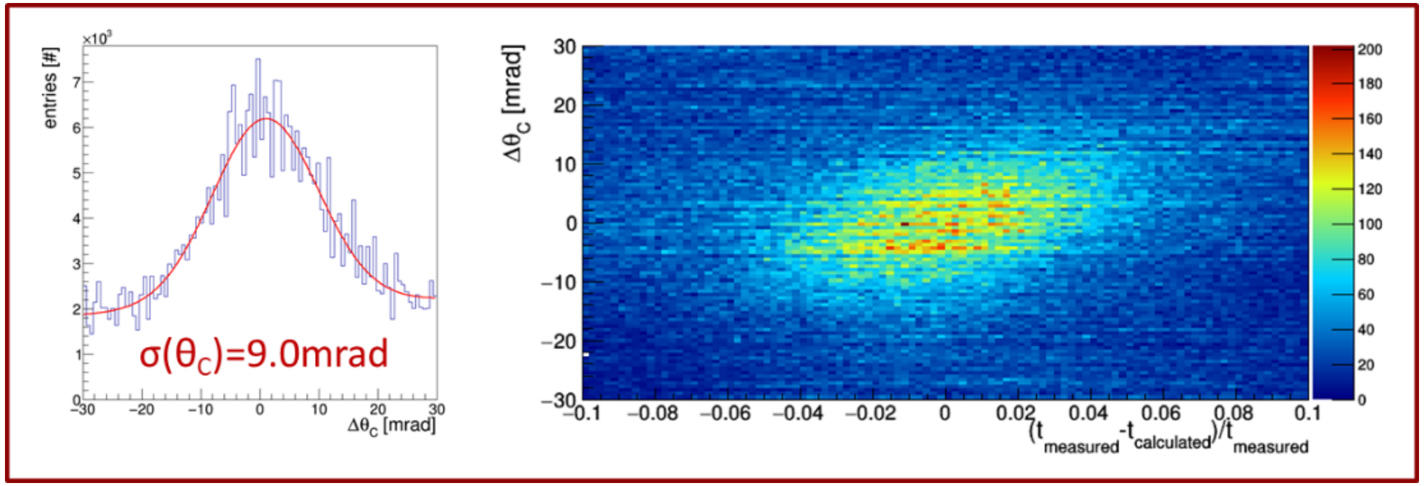
Example from PANDA Barrel DIRC prototype beam test at CERN in 2018:

R. Dzhygadlo, priv. comm.
NIM-A paper in preparation

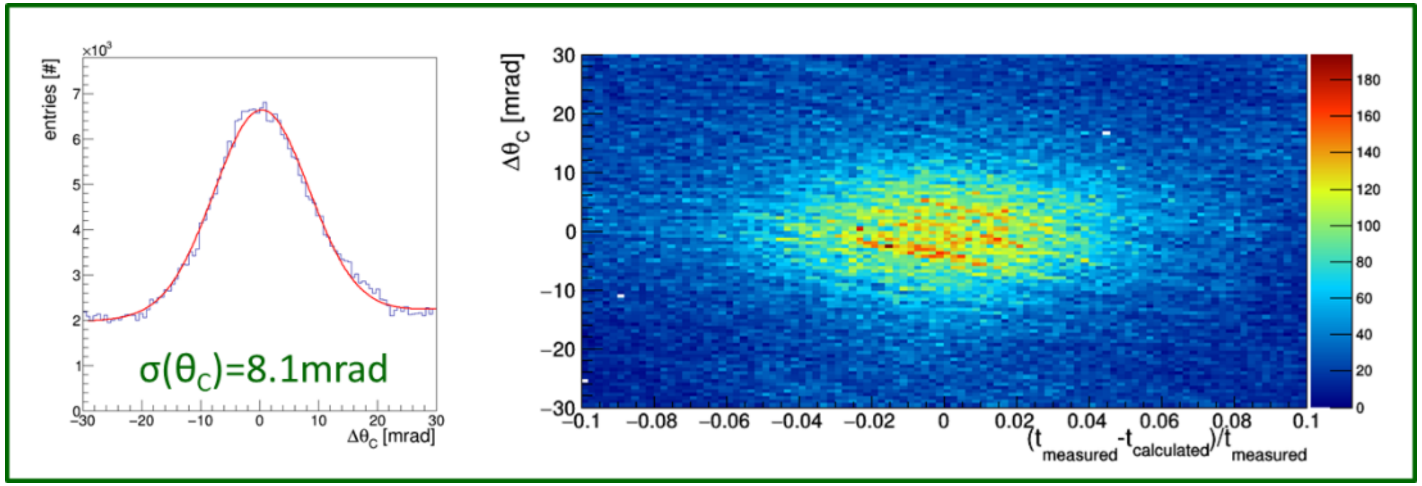
PANDA Barrel DIRC prototype at CERN PS,
7 GeV/c, mixed hadron beam, 90° polar angle

Cherenkov angle corrected by normalized photon propagation time difference
(calculated using average wavelength of 370nm, 196.5mm/ns photon velocity)

before correction



after chromatic correction by photon timing

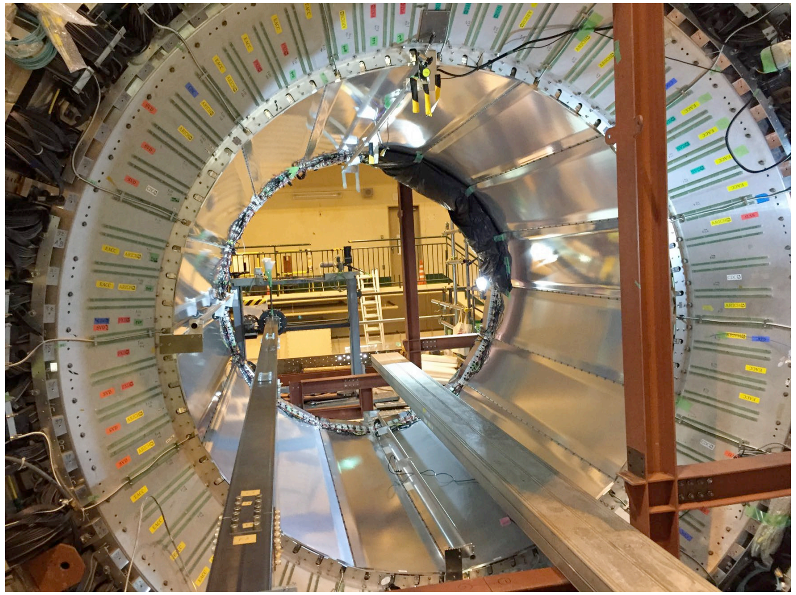


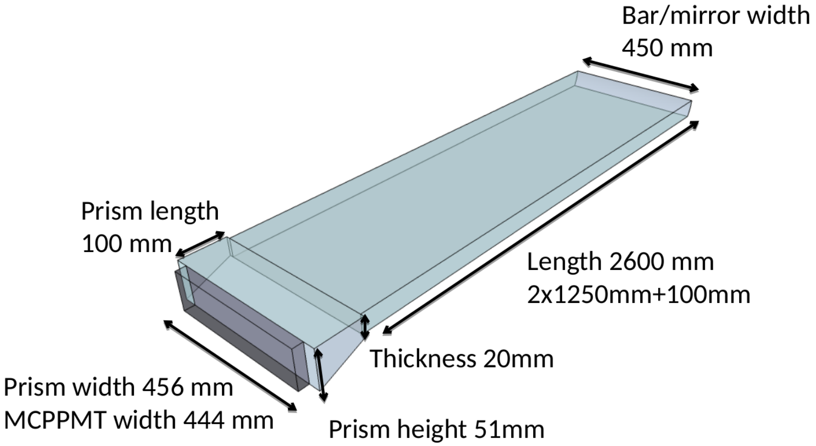
Clear improvement of Cherenkov angle resolution per photon after correction

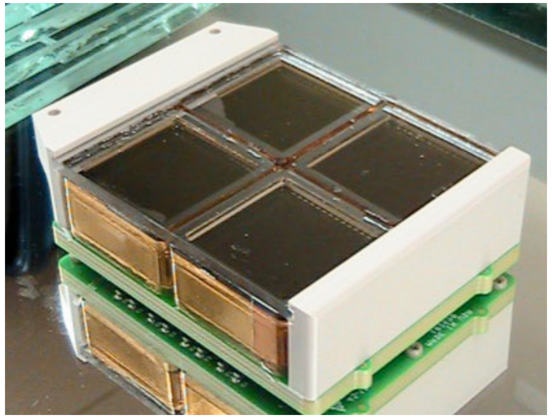
(beam test with modest timing precision (~200ps) and short photon path (1m-3.3m);
expect better timing, longer paths,
bigger improvement in PANDA and ePIC)

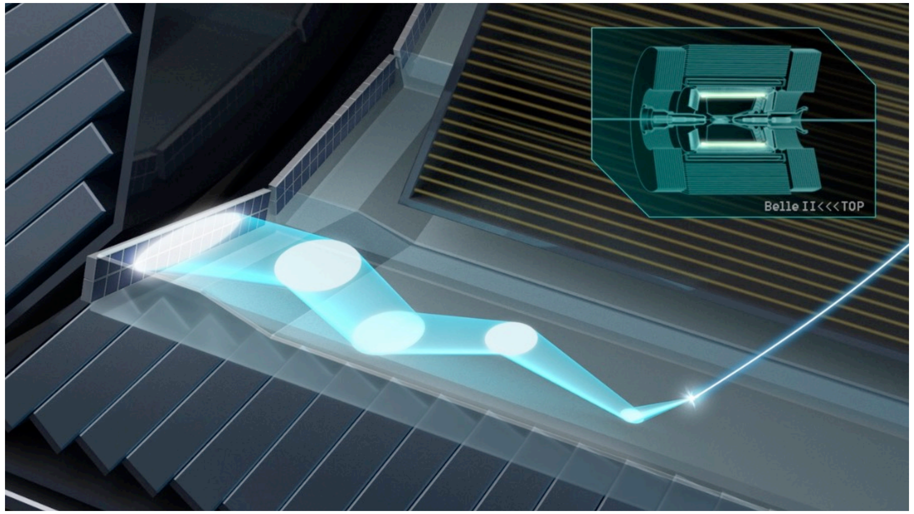
Belle II TOP

compact photon camera
spherical mirror focusing*
small pixels (MCP-PMT)*
fast photon timing
plate geometry









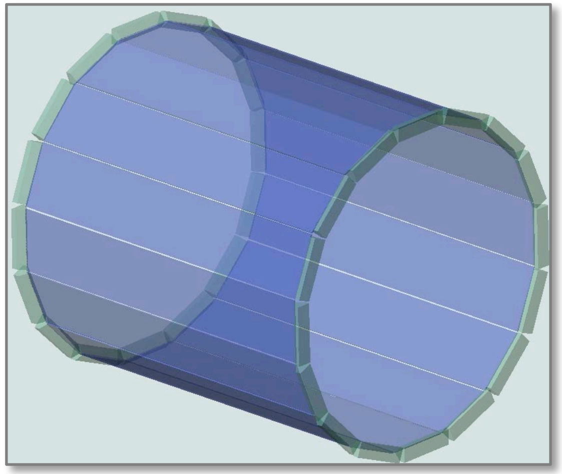
See presentation tomorrow

Ezio Torassa, “**TOP detector for particle identification at Belle II**“

Upgrade of Belle detector for high-luminosity Belle II experiment

- Time-of-Propagation (TOP) DIRC counter, emphasizing high-precision timing;
- design goal 4σ π/K separation up to 4 GeV/c;
- first DIRC using wide plates (~2cm x 45 cm x 250 cm), synthetic fused silica;
- spherical focusing mirror, only for “forward-going” photons;
- MCP-PMTs for fast photon detection in high magnetic field, small expansion prism;
- pioneered innovative time imaging reconstruction/PID method.

- compact photon camera
- spherical mirror focusing*
- small pixels (MCP-PMT)*
- fast photon timing
- plate geometry



TOP PID based on photon time-of-propagation, combined with time-of-flight of particle.

Major technological challenge for Belle II:

Entire TOP system had to fit inside the EM calorimeter space, no room for larger expansion volume, tight fit, no easy access.

Initial design was pure 2D TOP detector:

High precision timing (~50ps per photon) + one space coordinate (~5mm pitch, linear array)

– ultimately rejected due to chromatic dispersion issues and sensitivity to backgrounds.

Final "imaging TOP" design: hybrid of pure TOP and conventional DIRC:

- small expansion volume (10cm depth), spherical focusing mirror on forward end,
- moderate pixel segmentation in x & y (6mm pitch) to mitigate chromatic dispersion,
- fast photon timing (~100ps per photon)

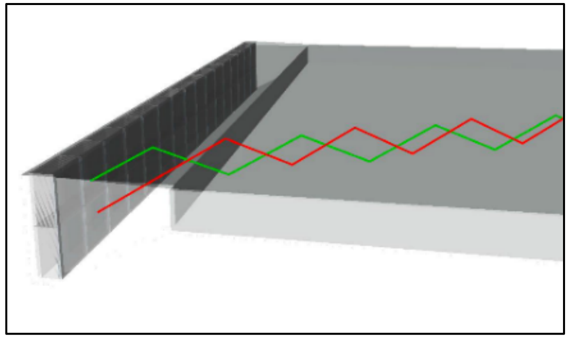
Choice of 45cm-wide plates instead of narrower bars significantly lowers fabrication cost

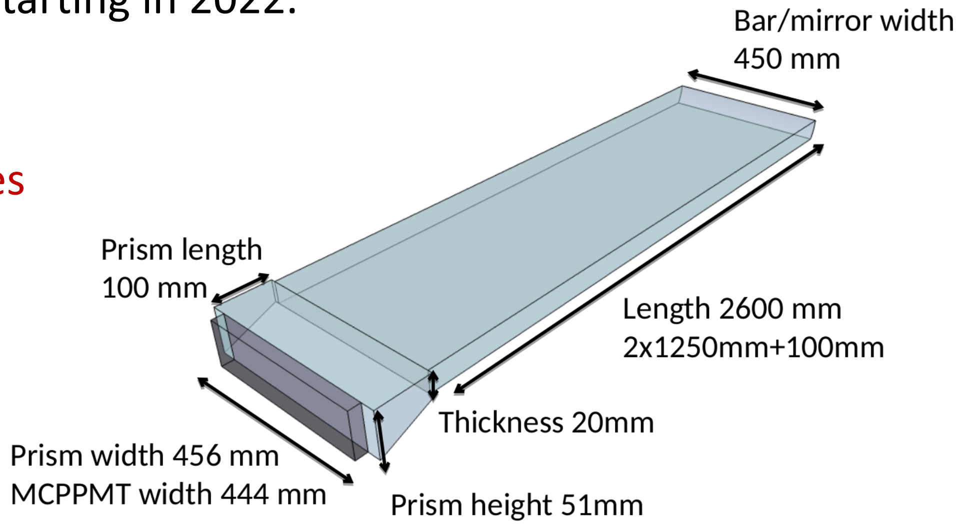
Photon detector: array of 2x16 Hamamatsu SL-10 MCP-PMTs per sector (4x4 pixels each);

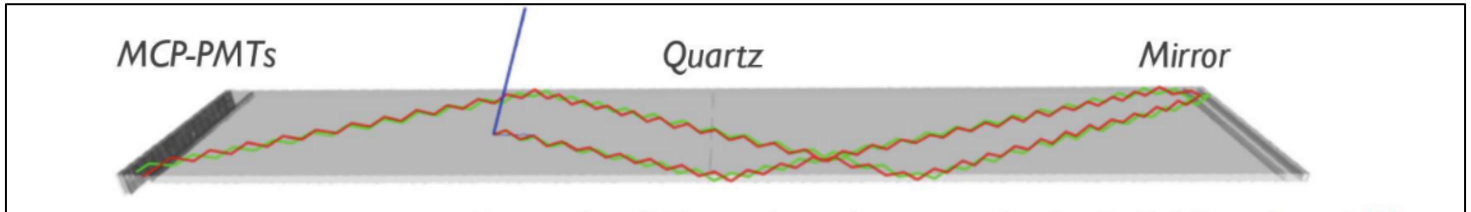
- MCP-PMT lifetime issues will require replacement of (most) MCP-PMTs, starting in 2022.

Readout: IRSx waveform sampling ASIC, <100ps timing precision.

Imaging design with 2D sensor array and small expansion has many advantages (redundancy, robustness, sensor lifetime).



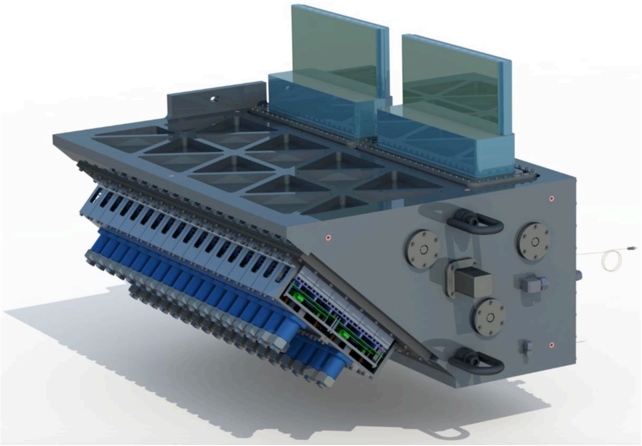




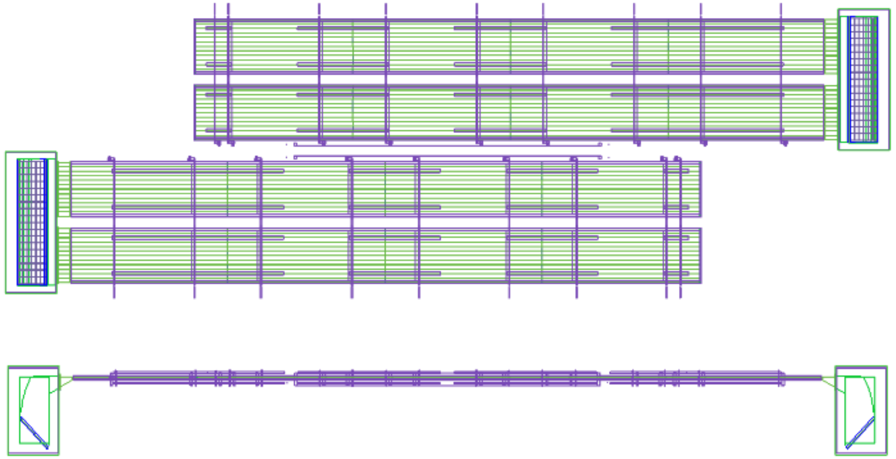
Example of Cherenkov-photon paths for 2 GeV/c $\pi^{\pm}$ and $K^{\pm}$.

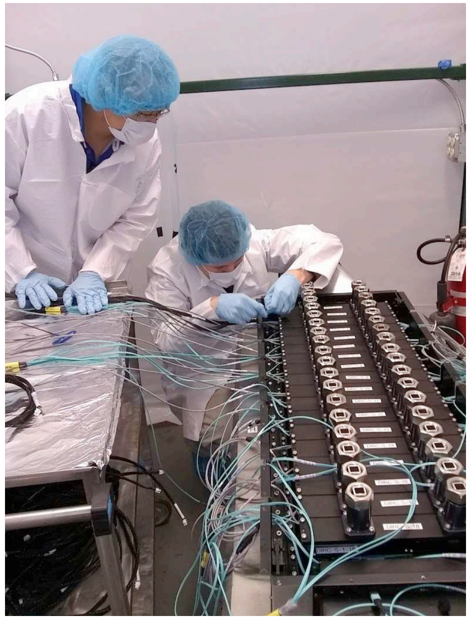
G. Varner, DIRC2019

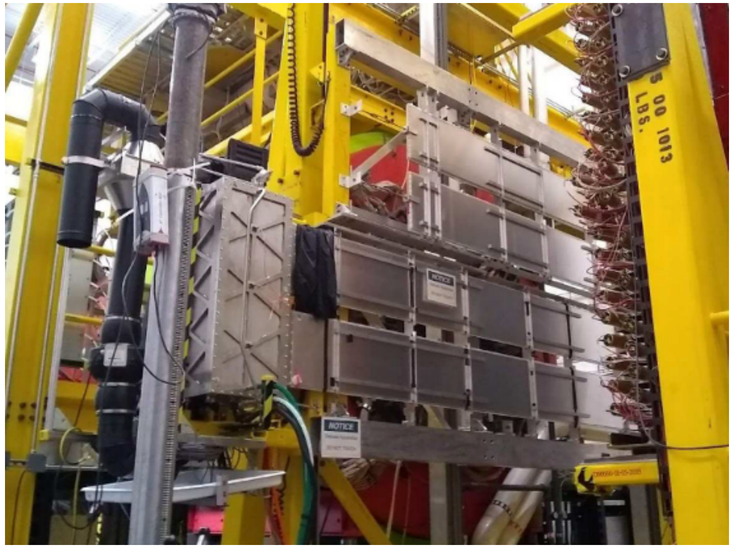
GLUEX DIRC



- compact photon camera
- approx. cyl. mirror focusing
- small pixels (MCP-PMT)
- moderate photon timing
- dispersion mitigation*
- legacy components







GlueX DIRC

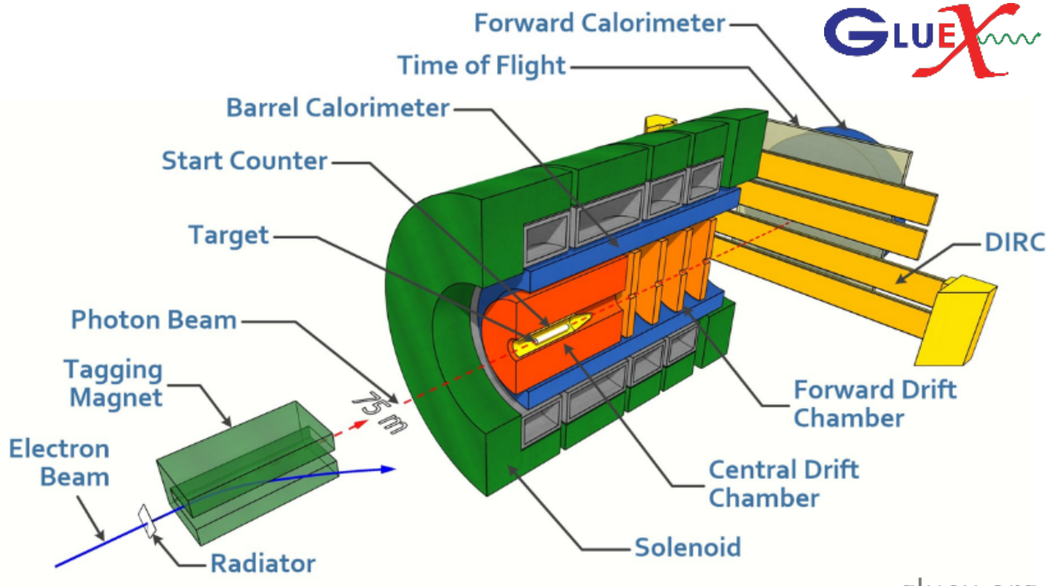
	compact photon camera
	approx. cyl. mirror focusing
	small pixels (MCP-PMT)
	moderate photon timing
	dispersion mitigation*
	legacy components

- forward PID upgrade for GlueX-II, first DIRC used as endcap device;
- extend GlueX physics reach by improving π/K separation from 2 GeV/c (TOF) to 3σ π/K separation at 3.7 GeV/c ;
- cost savings by reusing 4 legacy BABAR DIRC bar boxes (SLAC → JLab in 2017/2018);
- new optics design based on SuperB fDIRC, 3 flat mirrors in DI water to approximate fused silica focusing block;
- two optical boxes as expansion volumes, total of 90 H12700 MaPMTs with 11520 MAROC readout channels;
- installation into GlueX in 2018, commissioning in 2019;
- PID performance close to goal reached in first physics run in 2020.

BABAR DIRC bar boxes

← in storage at SLAC

installed at JLab →

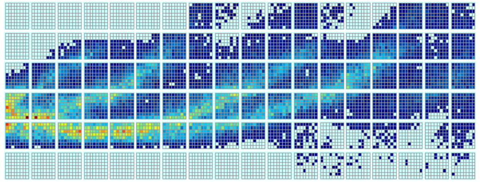


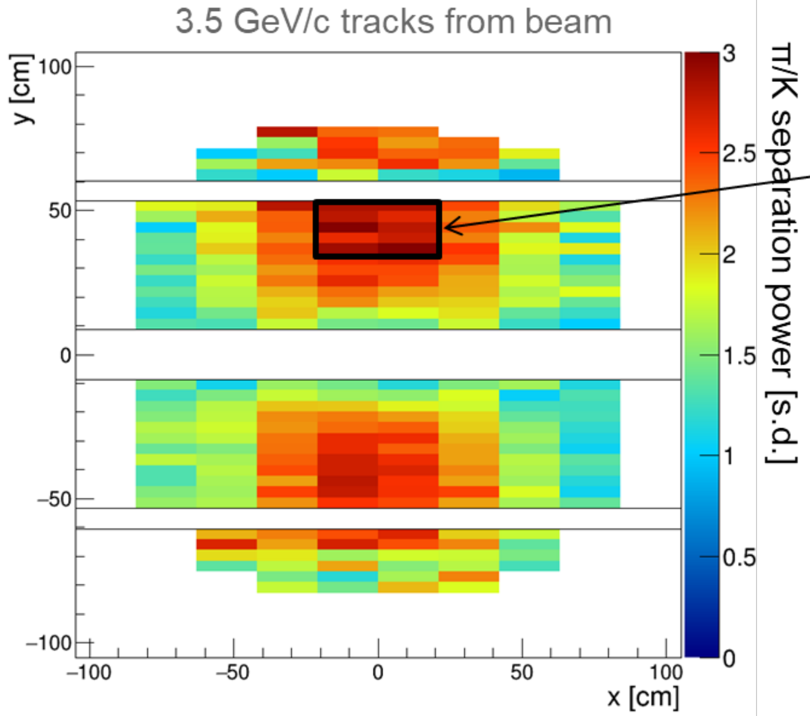
gluex.org

PID performance study using pure samples of kinematically identified π and K from ρ and ϕ decays

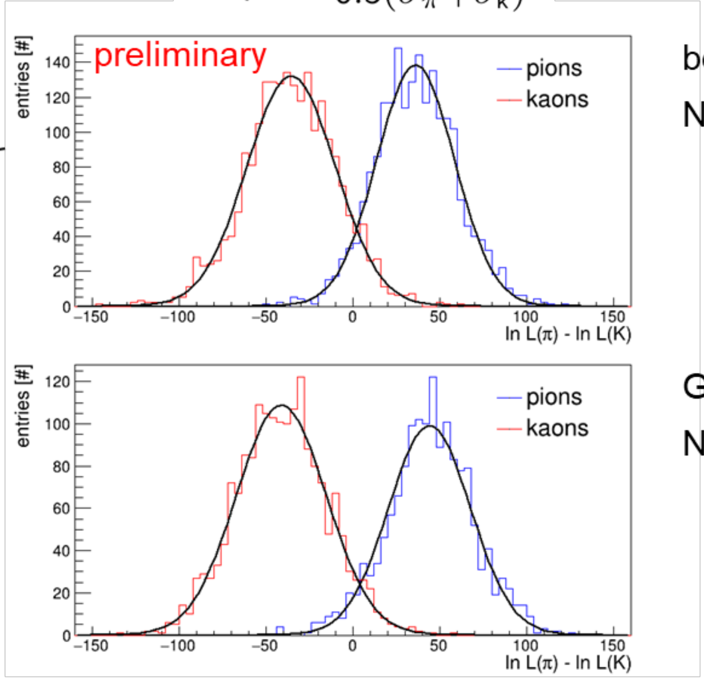
π/K separation power

accumulated hit pattern





$$N_{sep} = \frac{|\mu_\pi - \mu_K|}{0.5(\sigma_\pi + \sigma_K)}$$



beam data:

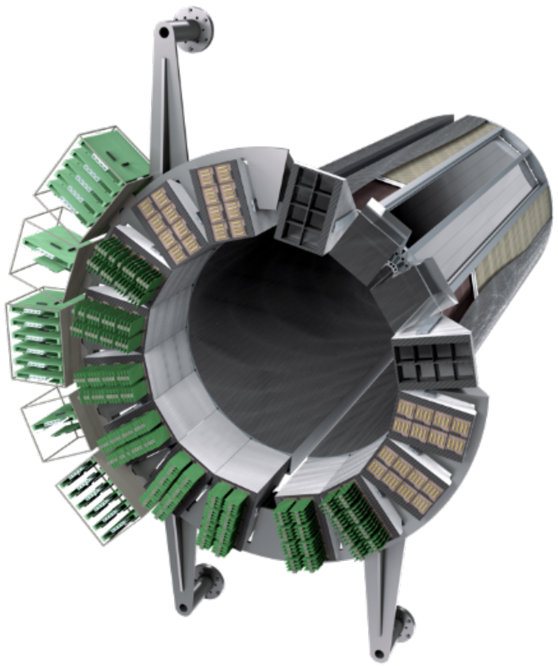
N_{sep} = 3.0 ± 0.1 s.d.

Geant4 simulation:

N_{sep} = 3.4 ± 0.1 s.d.

- π/K separation power already close to goal
- Yield-corrected simulation overestimates separation power by 10-15%
- Performance expected to further improve with better understanding of calibration and alignment and more data – current statistics prevent use of time imaging method *(algorithm with best performance)*

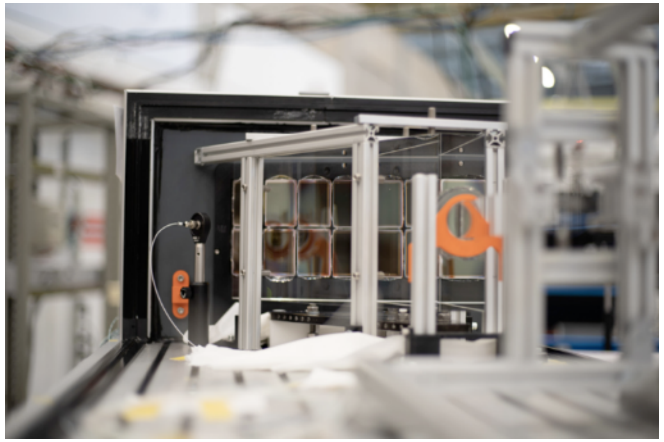
R. Dzhygadlo, TIPP2021 May 2021



	compact photon camera
	spherical lens focusing
	small pixels (MCP-PMT)
	fast photon timing
	dispersion mitigation

PANDA Barrel DIRC

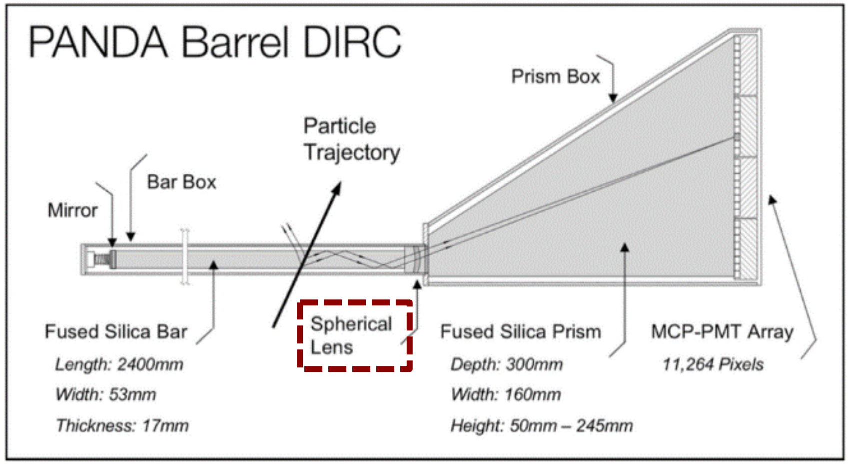
www.gsi.de/en/researchaccelerators/fair/fair_civil_construction/photos_and_videos.htm



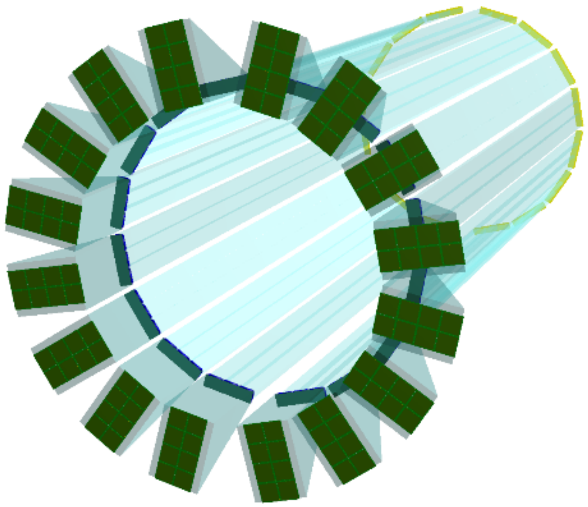
PANDA Barrel DIRC

- compact photon camera
- spherical lens focusing
- small pixels (MCP-PMT)
- fast photon timing
- dispersion mitigation

- design goal 3σ π/K separation up to 3.5 GeV/c for polar angle range 22°-140°;
- PID at high interaction rates, up to 20 MHz;
- narrow bars for robust performance in multi-track events, less sensitive to backgrounds;
- innovative 3-layer spherical lens, first DIRC with lens focusing;
- design aims for comparable precision in time and position measurements;
- suitable for “BABAR-like” pixel-based reconstruction as well as “Belle II-like” time-imaging;
- lifetime-enhanced MCP-PMTs for fast photon detection in high magnetic field.



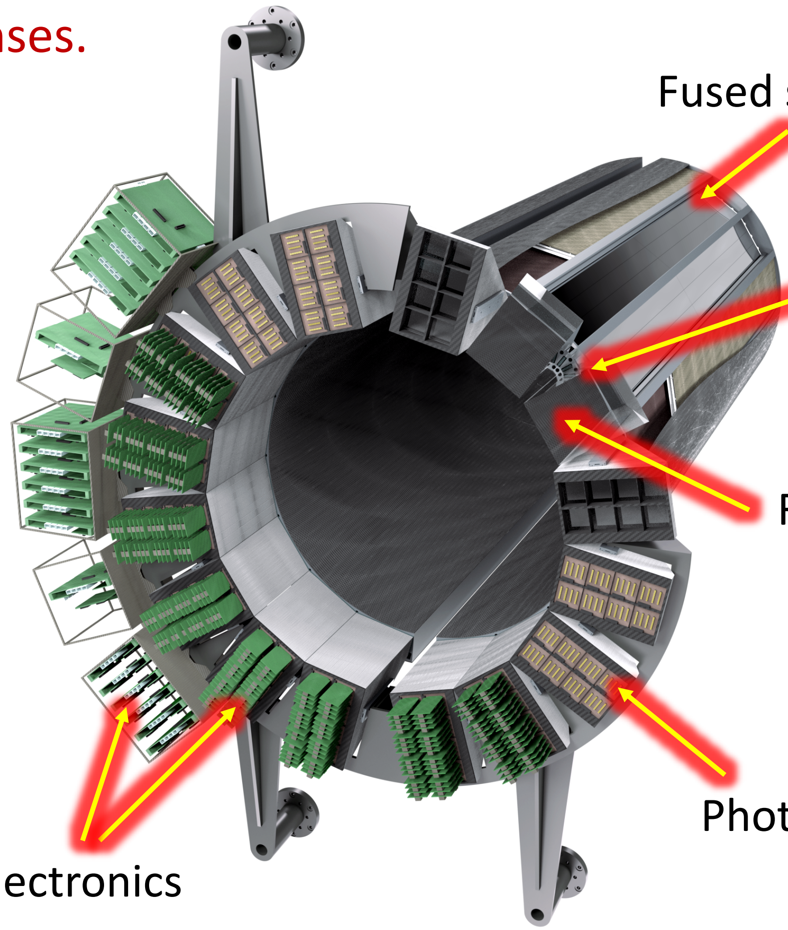
Handbook of Particle Detection and Imaging, Springer, 2021



PANDA Barrel DIRC

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

- 48 radiator bars (16 sectors), synthetic fused silica,
  17mm (T) × 53mm (W) × 2400mm (L)
- Focusing optics: innovative 3-layer spherical lens
- Compact expansion volume:
  30cm-deep solid fused silica prisms
  ~8,000 channels of lifetime-enhanced MCP-PMTs
- Fast FPGA-based readout electronics
  ~100ps per photon timing resolution (DiRICH)



Conservative design – similar to proven BABAR DIRC, performance parameters validated with particle beams since 2015.

TDR published, series production of MCP-PMTs starting, production of bars completed

Optimizing simulation and reconstruction code with experimental data from GlueX DIRC

PANDA Barrel DIRC TDR
J. Phys. G: Nucl. Part. Phys. 46 045001
arXiv:1710.00684

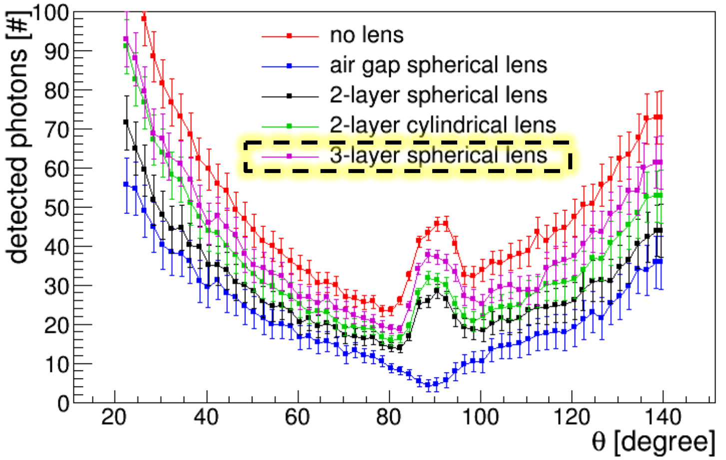
Technical challenge: lens focusing

Barrel DIRC counters require focusing for wide range of photon angles

Conventional plano-convex lens with air gap limits DIRC performance

- Significant photon yield loss for particle polar angles around 90°, gap in DIRC PID
- Distortion of image plane, PID performance deterioration

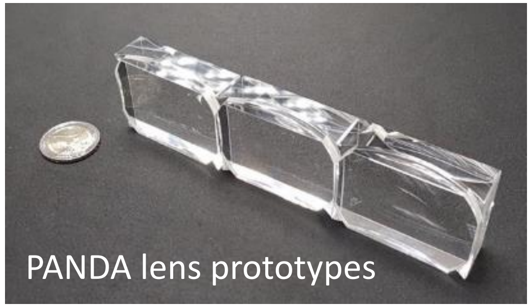
Geant4 simulation: photon yield



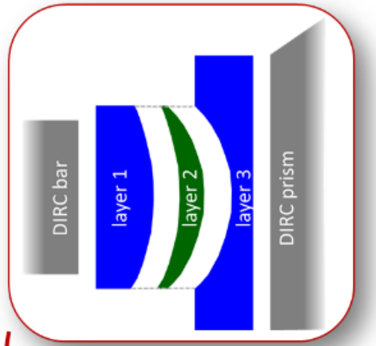
Innovative solution:

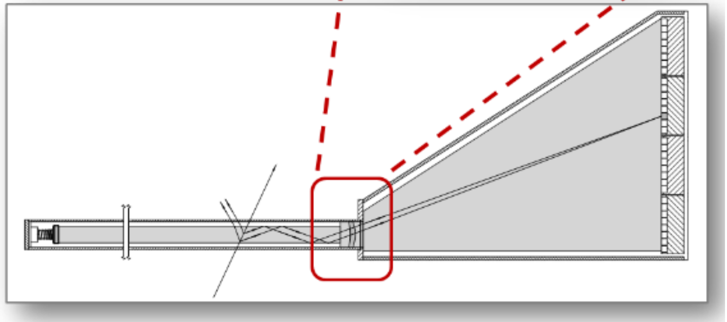
- 3-layer compound lens (without air gap):

layer of high-refractive index material (focusing/defocusing)
sandwiched between two layers of fused silica



PANDA lens prototypes





- Creates flat focal plane – matched to fused silica prism shape
- Avoids photon loss and barrel PID gap
- Current designs use standard spherical shapes – study aspherical shapes for future DIRCs to minimize aberrations?

see also G. Kalicy, RICH2022

Radiation hardness and focusing performance of 3-layer lens

Barrel DIRC counters require focusing for wide range of photon angles

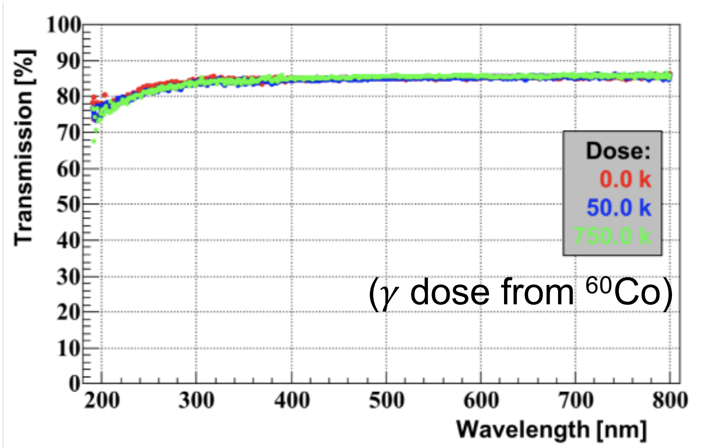
Conventional plano-convex lens with air gap limits DIRC performance

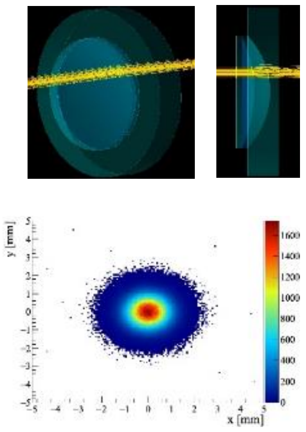
- Significant photon yield loss for particle polar angles around 90°, gap in DIRC PID
- Distortion of image plane, PID performance deterioration

R&D activities for PANDA and EIC/ePIC (eRD program):

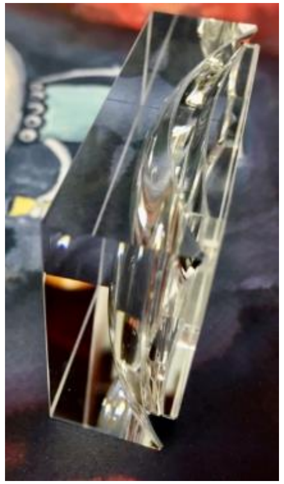
- Identified radiation hard material for middle layer (^{60}Co completed, neutrons next)
  Lanthanum crown glass (LaK33B) for PANDA, rad-hard sapphire for ePIC
- Demonstrate that rad-hard material is suitable for lens fabrication by industry (prototype lenses produced, studied in beams and bench tests)
- Validated focusing properties/flat focal plane with laser scan system

Radiation hardness of sapphire material





Geant4 simulation of laser beam focus



EIC prototype lens (sapphire layer)

G. Kalicy, RICH2022

Expected performance from detailed Geant4 simulation:

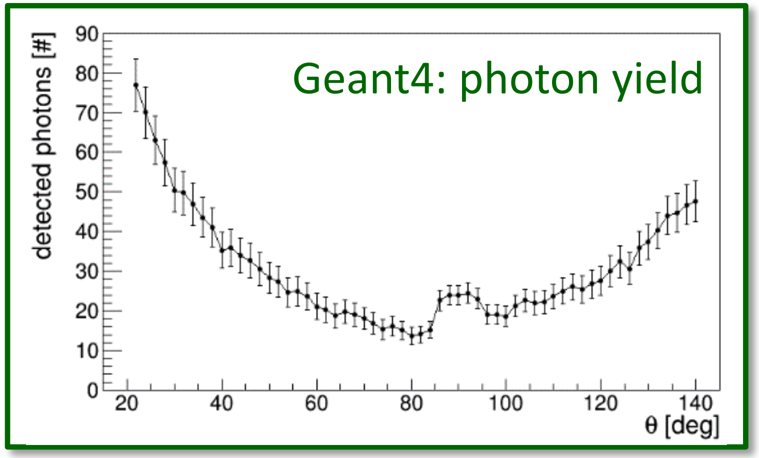
Used geometrical reconstruction (BABAR-like) to determine

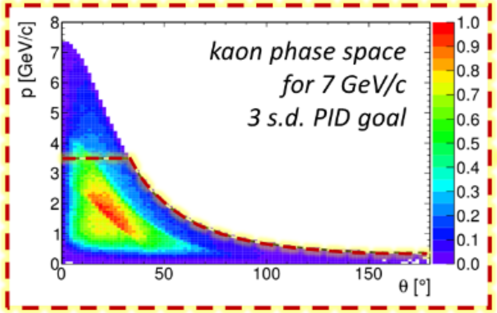
photon yield and single photon Cherenkov angle resolution (SPR).

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

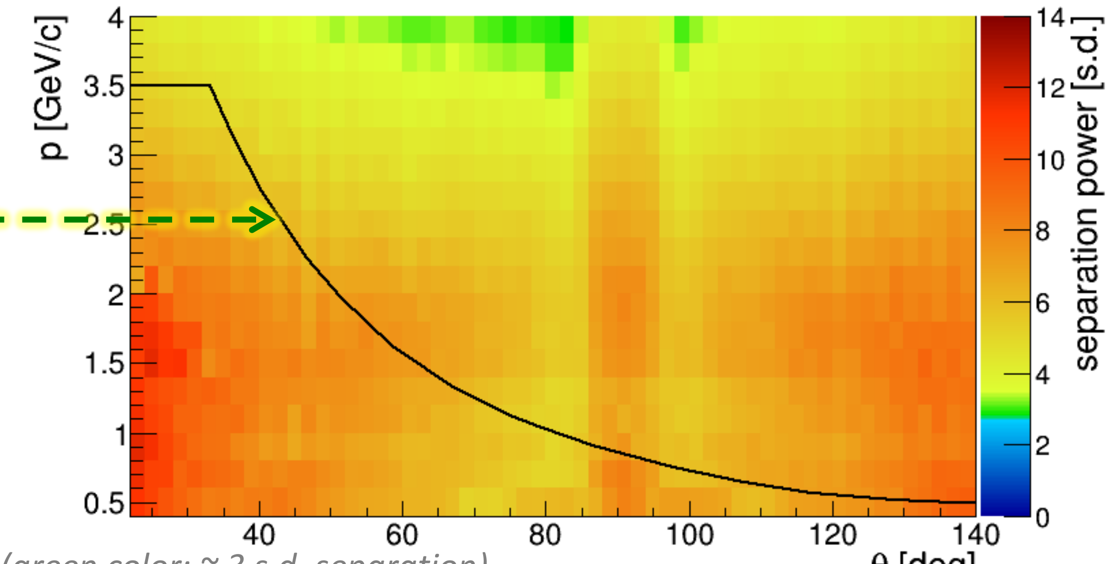
Time-imaging delivers best performance for π/K separation power map,

PANDA PID performance goal exceeded for entire phase space

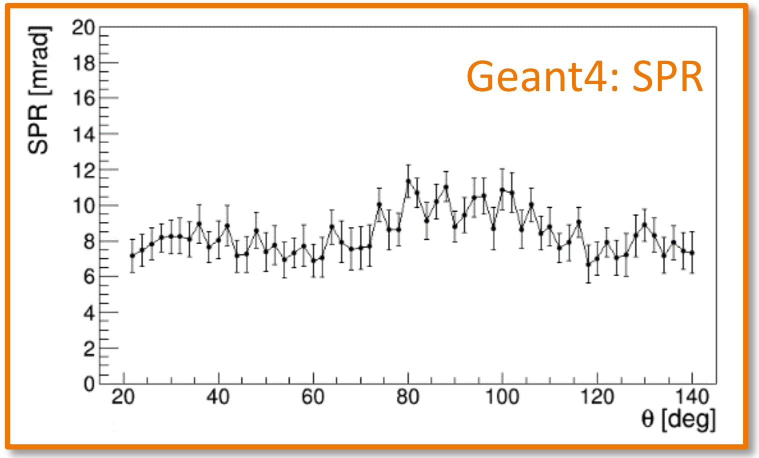




Geant4: π/K separation power map *time-imaging*

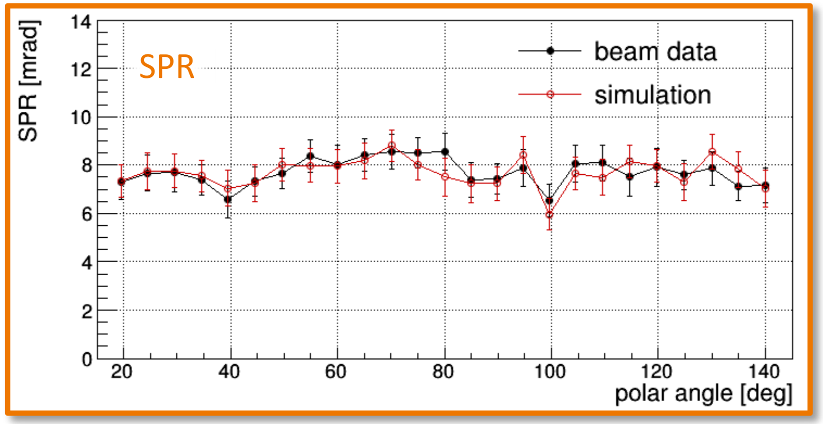


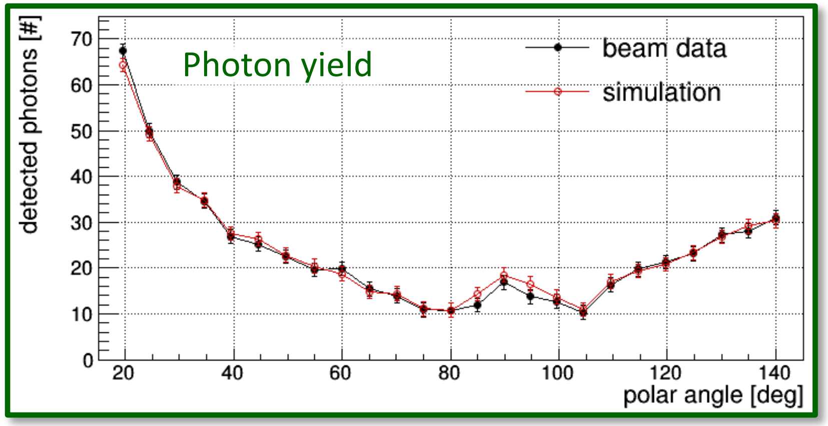
(green color: ~ 3 s.d. separation)



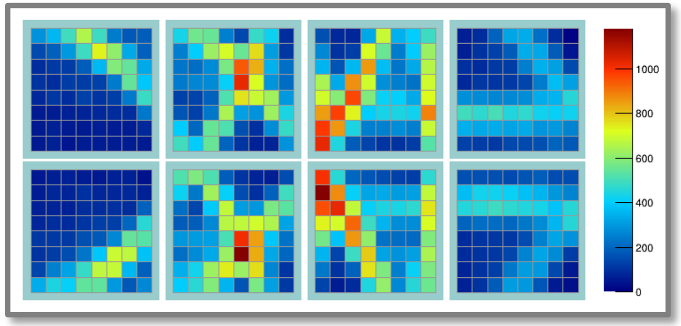
R. Dzhygadlo, priv. comm.

Performance validation: 2018 prototype at CERN PS

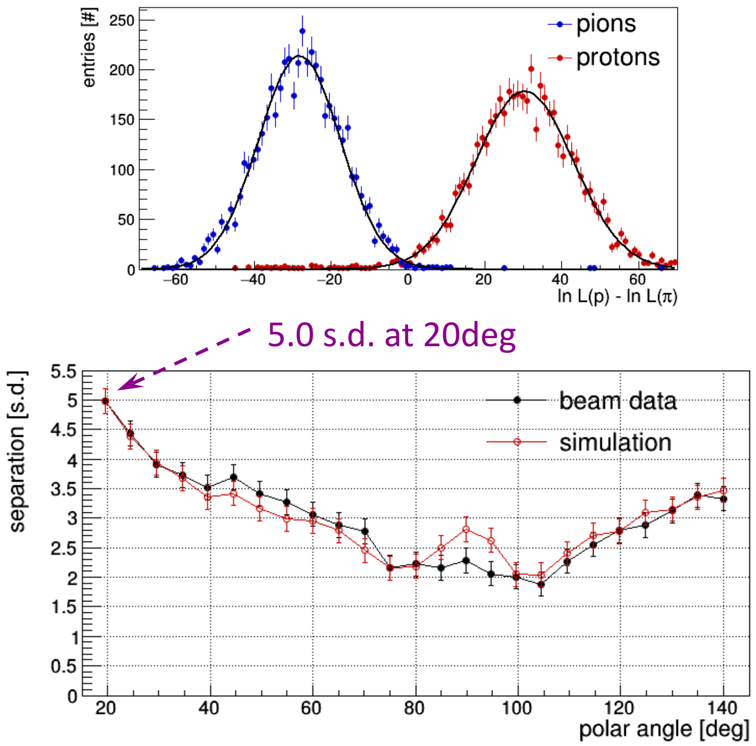




observed hit pattern at polar angle 20°

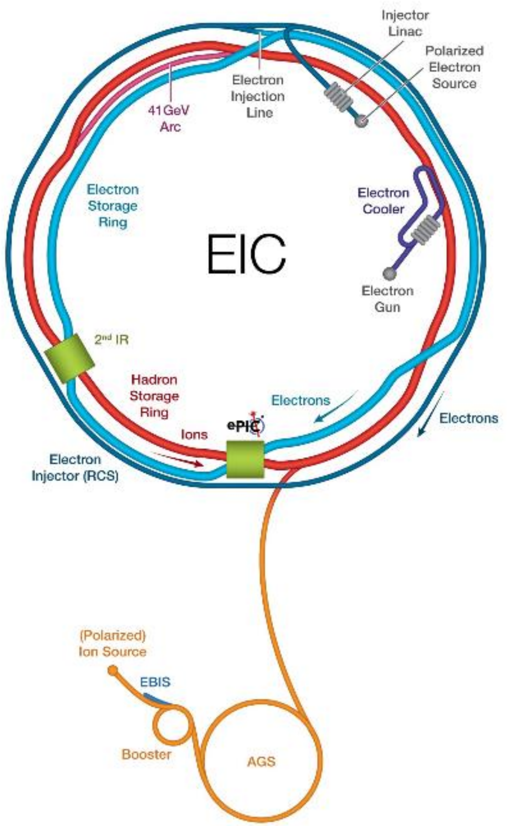


π/p separation power @ 7 GeV/c



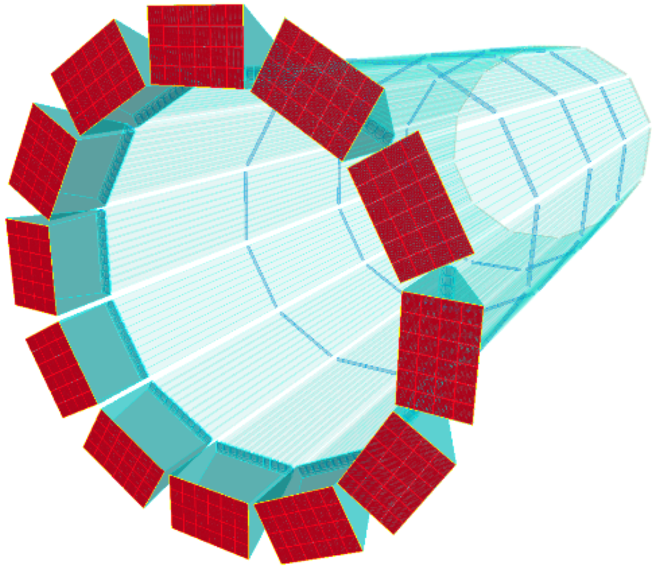
- Scans of beam incident angle and position for different momenta
- Measured Cherenkov angle resolution per photon (SPR), photon yield, and π/K separation in excellent agreement with expectation and Geant4 simulation
- Achieved π/K separation power of N_{sep}=5.0 s.d. with time imaging reconstruction for most challenging phase space region (expect better photon timing in PANDA)
- Design and simulation/reconstruction validated
- Same simulation/reconstruction code used for GlueX DIRC and EIC/ePIC high-performance DIRC

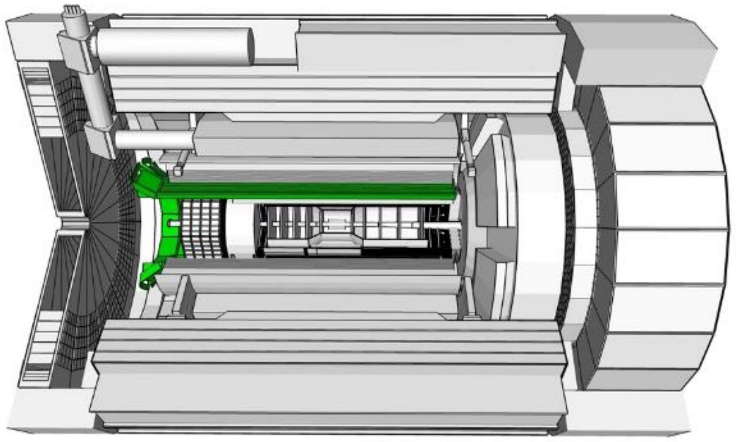
R. Dzhygadlo
RICH2022



ePIC High-Performance DIRC

- compact photon camera
- spherical lens focusing
- small pixels (MCP-PMT)
- fast photon timing
- dispersion mitigation
- precision tracking
- mult. scattering mitigation
- legacy components (?)



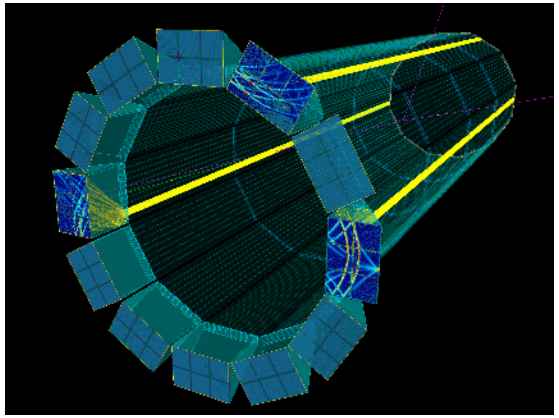


EIC Yellow Report, Nucl.Phys.A 1026 (2022) 122447, arXiv:2103.05419
https://www.bnl.gov/eic/epic.php

EIC High-Performance DIRC (hpDIRC) for the ePIC Experiment

- R&D since 2011 within EIC generic detector R&D program (eRD4, eRD14, eRD103)
- Push DIRC performance significantly past state-of-the-art, increase π/K range by 50%
- 3σ π/K separation up to at least 6 GeV/c for rapidity range $-1 \leq \eta \leq +1$ (Cherenkov angle resolution ≤1mrad), add supplemental e/π separation up to ~1.2 GeV/c
- Narrow bars for robust performance in high-multiplicity jet events
- 3-layer spherical lens, compact prism, small-pixel MCP-PMTs, fast ASIC readout
- Fast photon timing for chromatic dispersion mitigation
- High-precision tracking, expect 0.5mrad polar angle resolution at 6 GeV/c
- Post-DIRC track point (EMCal AstroPix sensor) for multiple scattering mitigation
- Key target dates: EIC/ePIC TDR in late 2024, hpDIRC installation into ePIC in 2030

- compact photon camera
- spherical lens focusing
- small pixels (MCP-PMT)
- fast photon timing
- dispersion mitigation
- precision tracking
- mult. scattering mitigation
- legacy components (?)

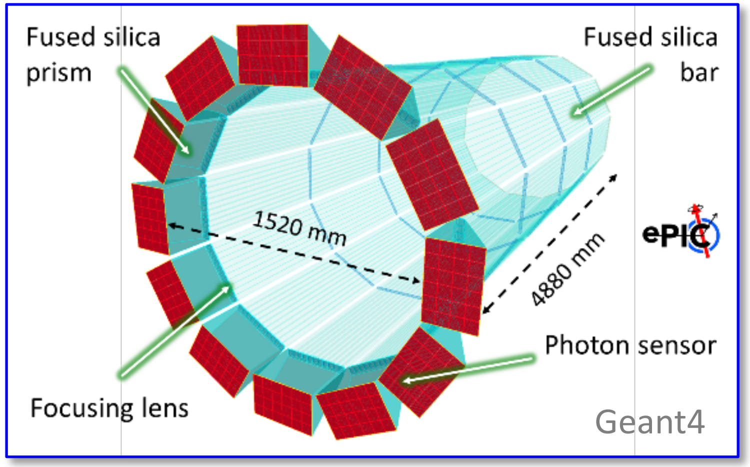


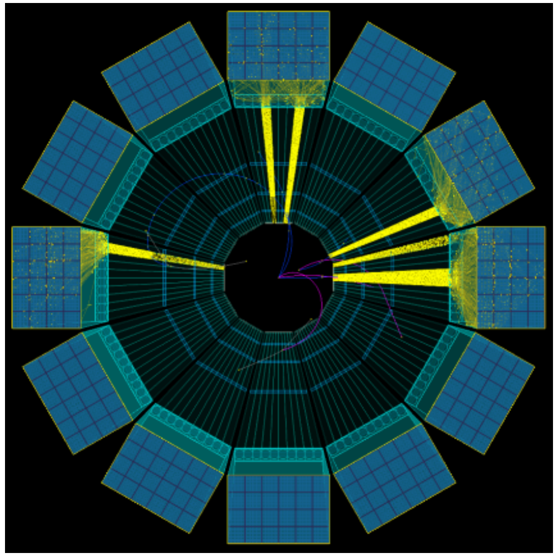
EPIC HIGH-PERFORMANCE DIRC

Preliminary ePIC hpDIRC design

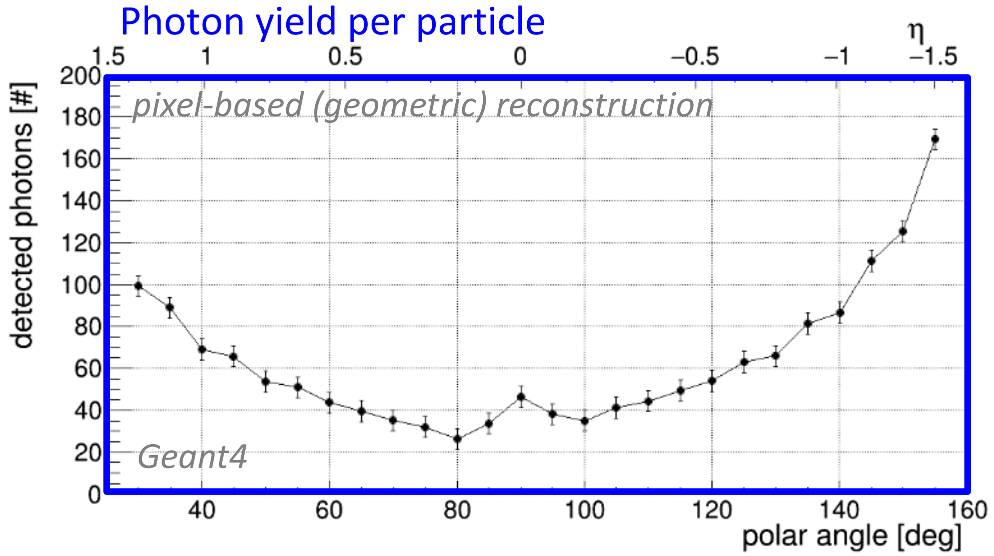
Compact fused silica prisms, narrow bars, 3-layer spherical lenses

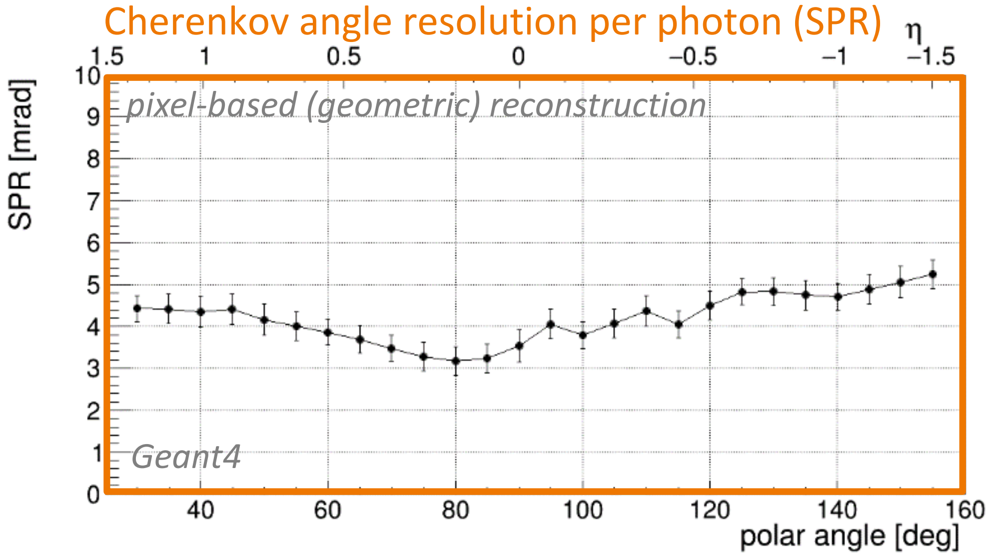
- Barrel radius: 762 mm, 12 sectors, 10 long bars per sector
- Reuse bars from decommissioned BABAR DIRC
  (SLAC-JLab transport planned for March/April, followed by disassembly of the bar boxes and detailed optical/mechanical QA this summer to determine if bars are usable)
- Focusing optics: innovative radiation-hard 3-layer spherical lens
- Compact expansion volume: 30cm-deep solid fused silica prism
- Readout system:
  - small-pixel MCP-PMT sensors (~3 mm pixel pitch, e.g. Photek or Incom)
  - fast ASIC-based readout (e.g. EICROC)
- Full Geant4 simulation based on validated PANDA Barrel DIRC code
  (joint EIC/PANDA CERN beam tests 2015-2018)

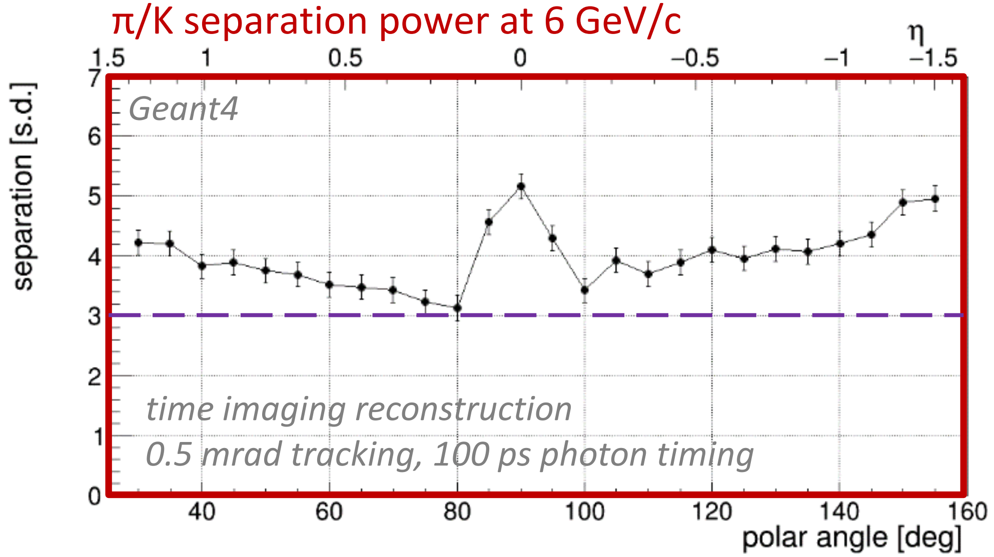




PYTHIA events in ePIC hpDIRC (Geant4)
Bill Llope, Wayne U.







Simulation studies performed with

- Stand-alone Geant4 simulation
- Single particles from particle gun
- 6 GeV/c momentum
- No magnetic field, no other ePIC subsystems

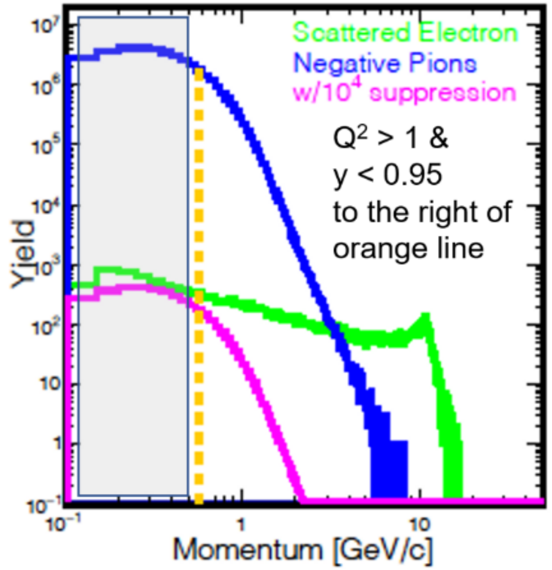
→ Performance goal reached: ≥ 3 s.d. π/K separation at 6 GeV/c for full hpDIRC acceptance

G. Kalicy
RICH2022, Sep 2022

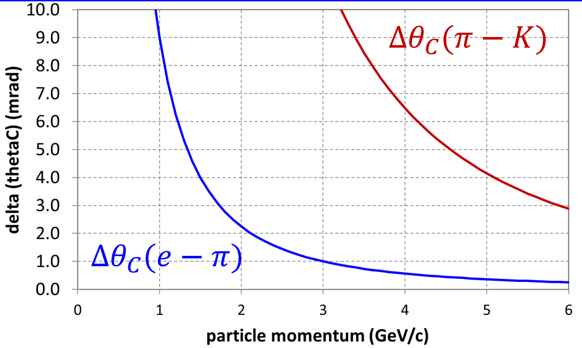
Challenge: e/π separation at low momentum

- Yellow report effort identified need for supplemental e/π suppression from PID systems to support EM calorimeter at lower momentum
- Simulation shows that ID of scattered electron requires $O(10^4)$ suppression of large pionic background
- hpDIRC e/π performance at low momentum very different from high-momentum domain, dominated by multiple scattering (MS) and EM showers in DIRC bars
- Even without any MS mitigation: > 3 s.d. e/π separation at 1.2 GeV/c (caveat: tails)
- Study of potential improvements from DIRC "ring center fit" and impact of track point from AstroPix sensor (barrel EMCal) outside hpDIRC radius underway (also expected to further improve high-momentum π/K separation)

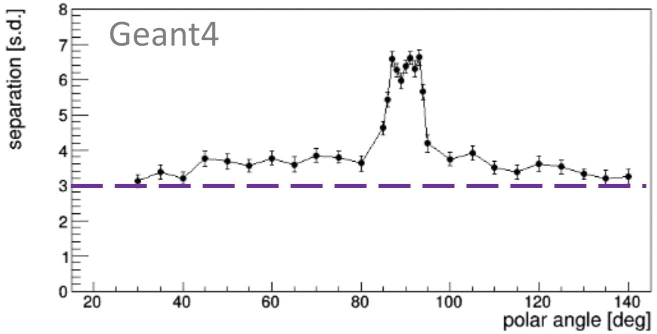
-1.0 < η < 0.0 (half of DIRC Barrel)

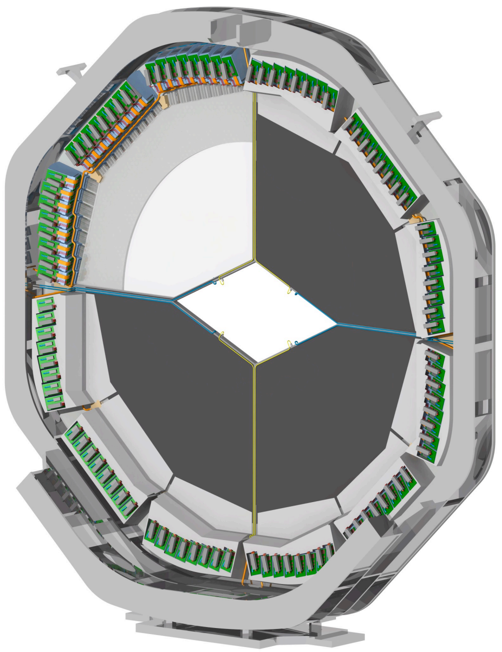


CORE proposal simulation, B. Schmookler



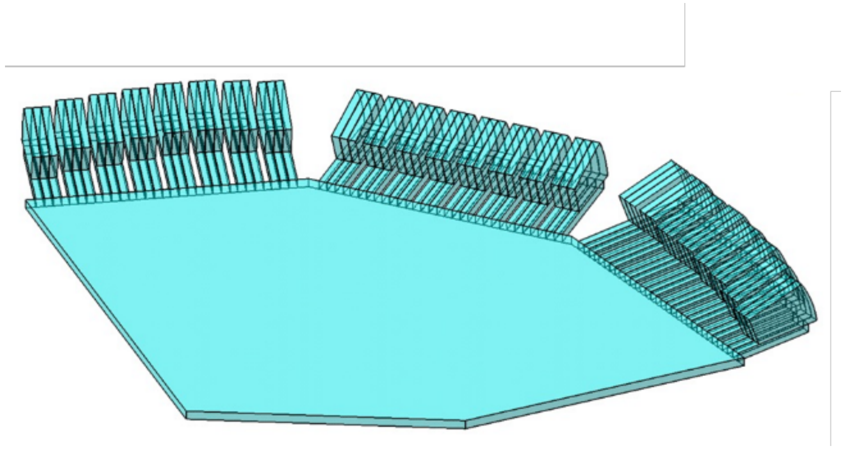
hpDIRC e/π separation at 1.2 GeV/c without MS mitigation

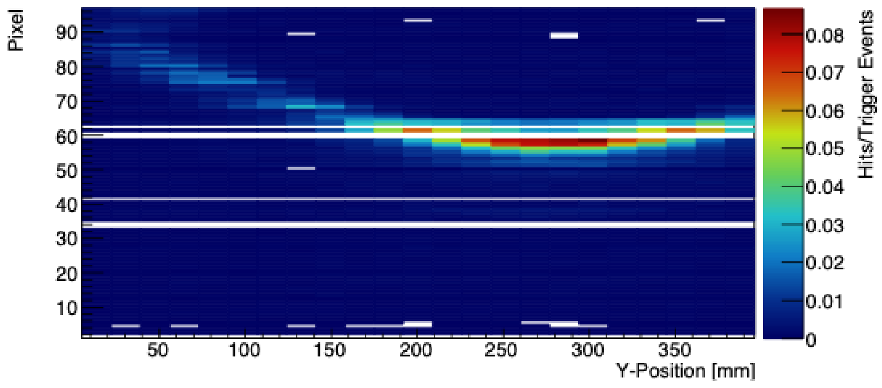




PANDA Endcap Disc DIRC

- compact photon camera
- cylindrical mirror focusing
- small pixels (MCP-PMT)
- fast photon timing
- endcap geometry

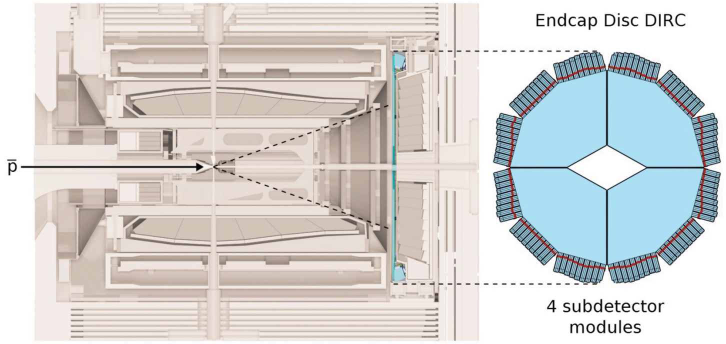


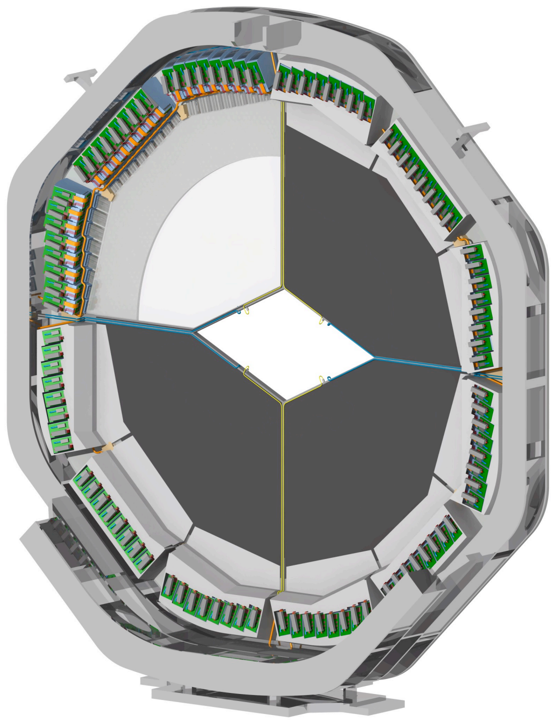


- compact photon camera
- cylindrical mirror focusing
- small pixels (MCP-PMT)
- fast photon timing
- endcap geometry

PANDA Endcap Disc DIRC (EDD)

- design goal 3σ π/K separation up to 4 GeV/c for polar angle range 5°-22°;
- PID at high interaction rates, up to 20 MHz;
- first DIRC designed for PID in forward endcap;
- must fit into tight space between forward GEM and EM Calorimeter;
- ~2m diameter plate, made from 4 optically independent quadrants;
- fused silica bars and cylindrical focusing block attached to rim of plate;
- lifetime-enhanced MCP-PMTs with highly-segmented anode (~3x100 pixels);
- MCP-PMT placement optimized for B-field line orientation;
- fast ASIC readout (TofPET2).





PANDA EDD TDR
arXiv:1912.12638

PANDA Endcap Disc DIRC

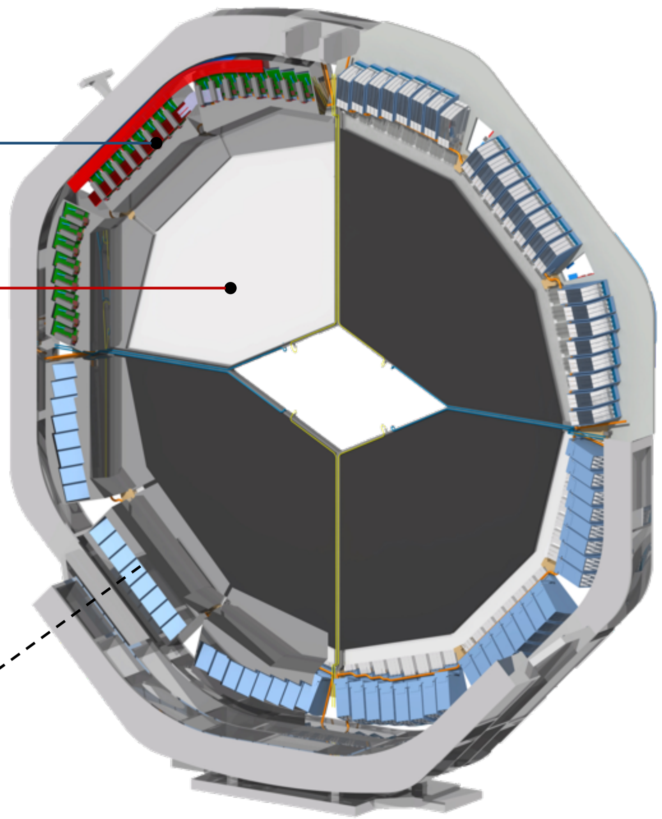
Optics made of synthetic fused silica

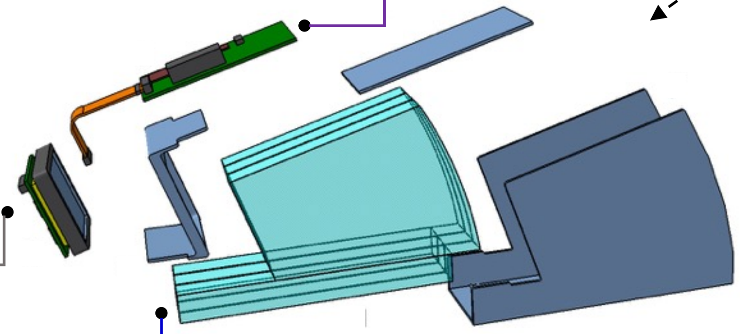
4 independent quadrants

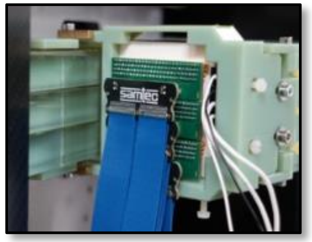
Focusing elements convert angle to position information

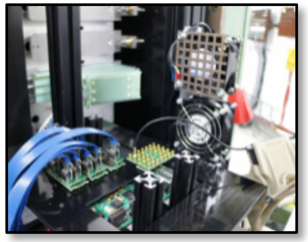
2-inch MCP-PMT with a pitch of 0.5 mm

ASIC-based readout









Quadrant plate dimension:

20mm thickness

1056mm outer radius

Sensors: 96 MCP-PMTs

(lifetime-enhanced,~3x100 pixels)

Optional: Optical band pass filter for chromatic dispersion mitigation

TOFPET ASIC readout

~29k channels

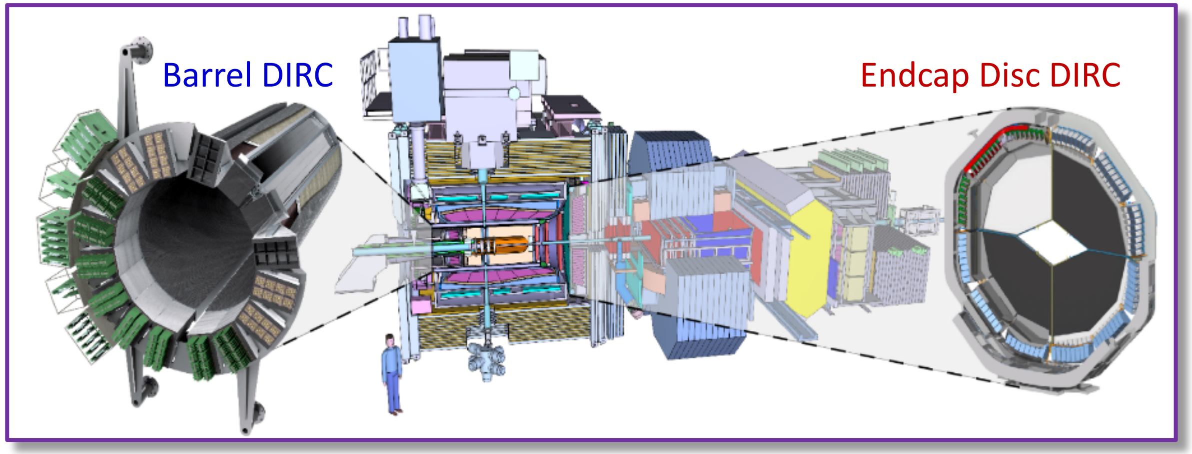
Novel design, validated with particle beams since 2016.

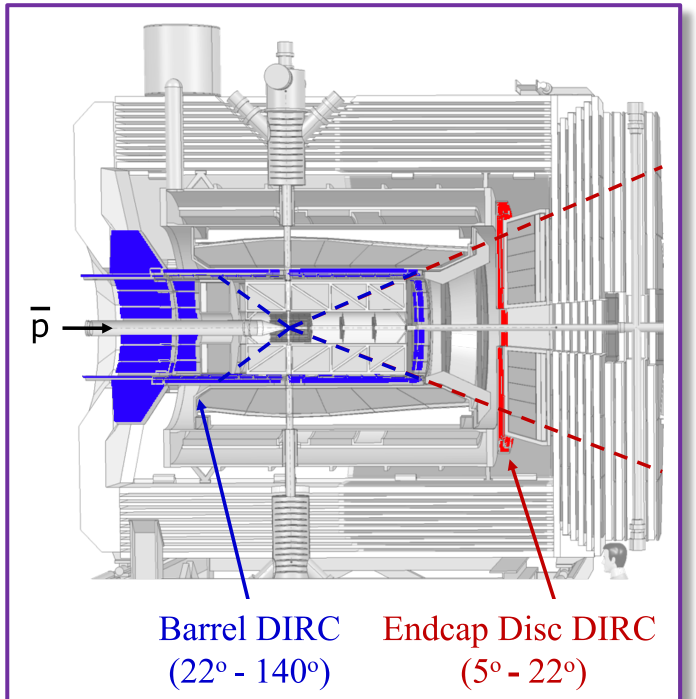
goal: first-of-series quadrant in 2025

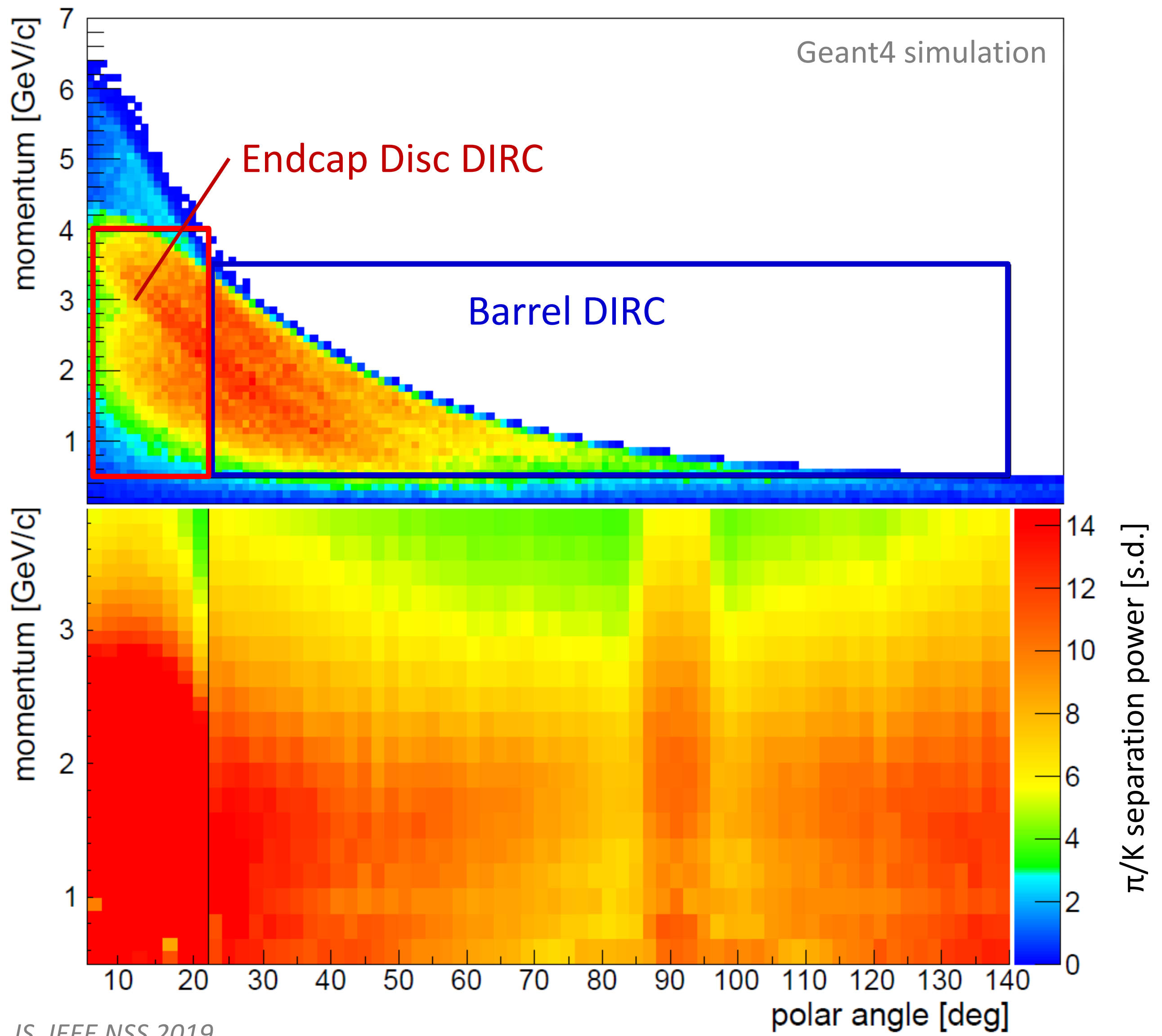
TDR available at arXiv:1912.12638

JS RICH2018

PANDA DIRCs





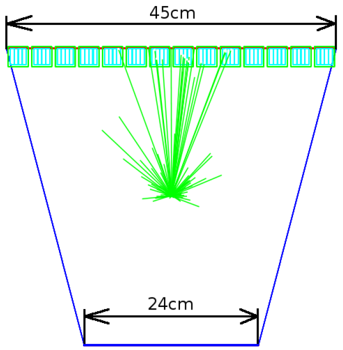


JS, IEEE NSS 2019

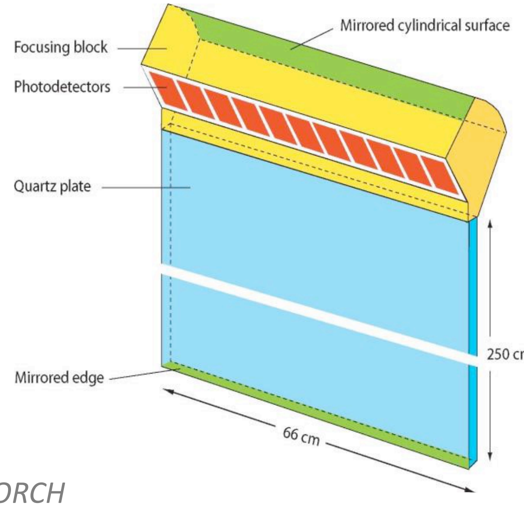
For an update, see presentation tomorrow

Binbin Qi, “**STCF DIRC-like TOF detector R&D**“

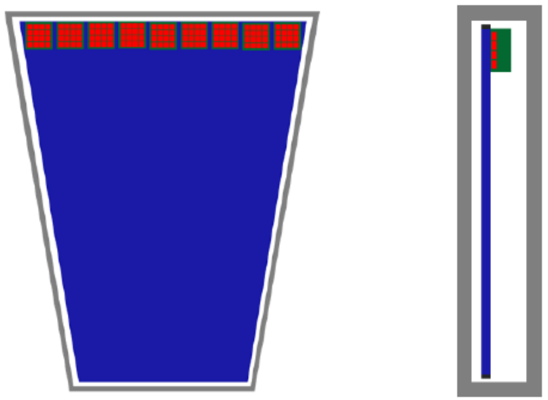
DIRC-Based Time-of-Flight



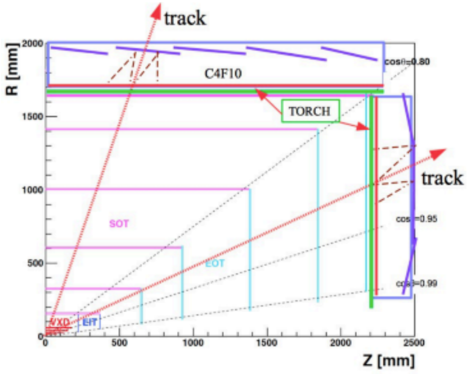
SuperB FTOF concept
N. Arnaud et al, NIM-A 718 (2013) 557



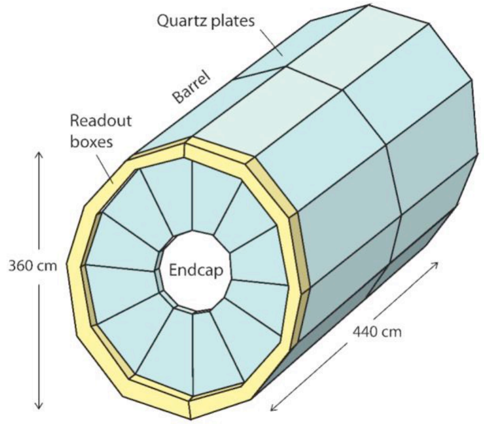
TORCH
M. Charles and R. Forty, NIM-A 639 (2011) 173
S. Bhasin et al, NIM-A 1050 (2023) 168181



Tau Charm DTOF concept
Binbin Qi et al, JINST 16 (2021) 08, P08021
Ziwei Li et al, NIM-A 1051 (2023) 168202
SCTF CDR Front. Phys. 19(1), 14701 (2024)



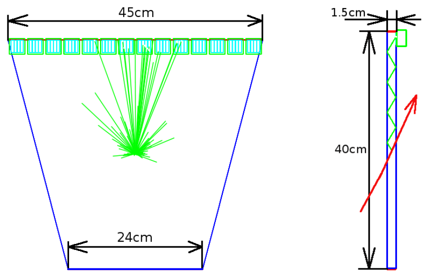
TORCH-like concept for CEPC
(Z. Liang, IAS-HEP2021)



TORCH-like concept for FCC-ee
(R. Forty, ECFA TF4, May 2021)

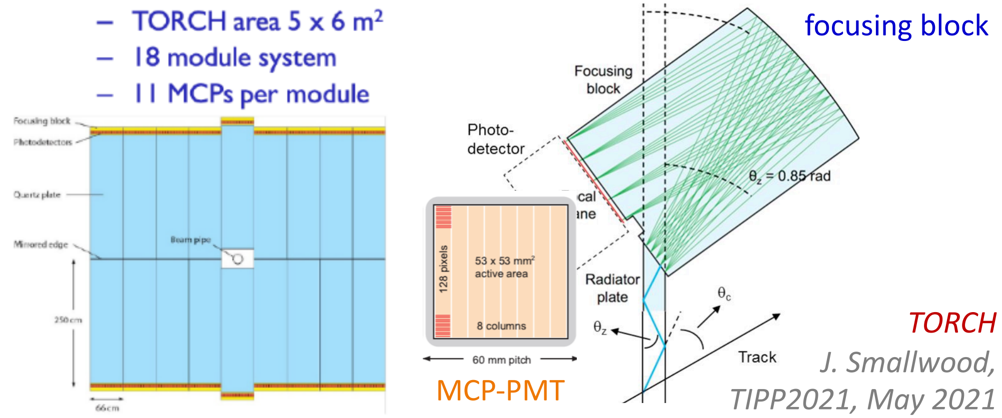
DIRC-Based Time-of-Flight

Generate Cherenkov light in DIRC bar or plate, image photons, reconstruct 3D photon propagation path, calculate time of particle crossing DIRC radiator



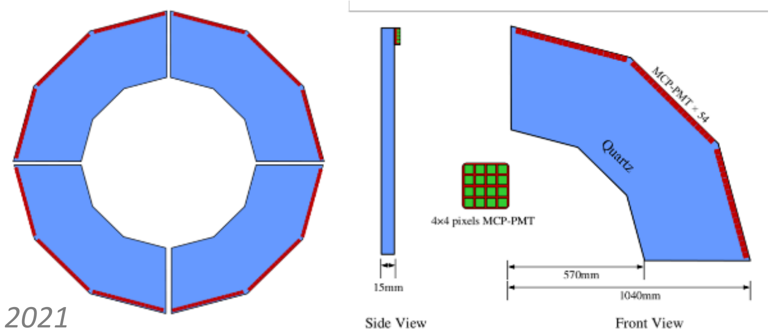
FTOF
L. Burmistrov
Acta Phys. Pol. B Proc. Suppl. 4, 91 (2011)

- FTOF: proposed for endcap of cancelled SuperB experiment
  - goal 3σ π/K separation up to 3 GeV/c
  - 2m flight path, 30ps time resolution goal



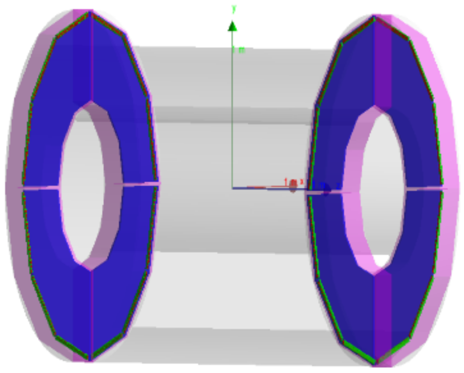
TORCH
J. Smallwood,
TIPP2021, May 2021

- TORCH (Timing Of internally Reflected CHerenkov light) goal: 3σ π/K separation up to 10 GeV/c
  - proposed for upgrade of LHCb in ~2027
  - use measured Cherenkov angle to correct chromatic dispersion
  - 10m flight path, per-particle resolution of 10-15ps required, → 70ps resolution per photon for ~30 detected photons per particle
  - beam test results with complex prototype (plate from Nikon, small-pixel MCP-PMTs from Photek, NINO ASICs), per-photon performance approaching design goals



DTOF
Ming Shao,
Future SCTF, Nov 2021

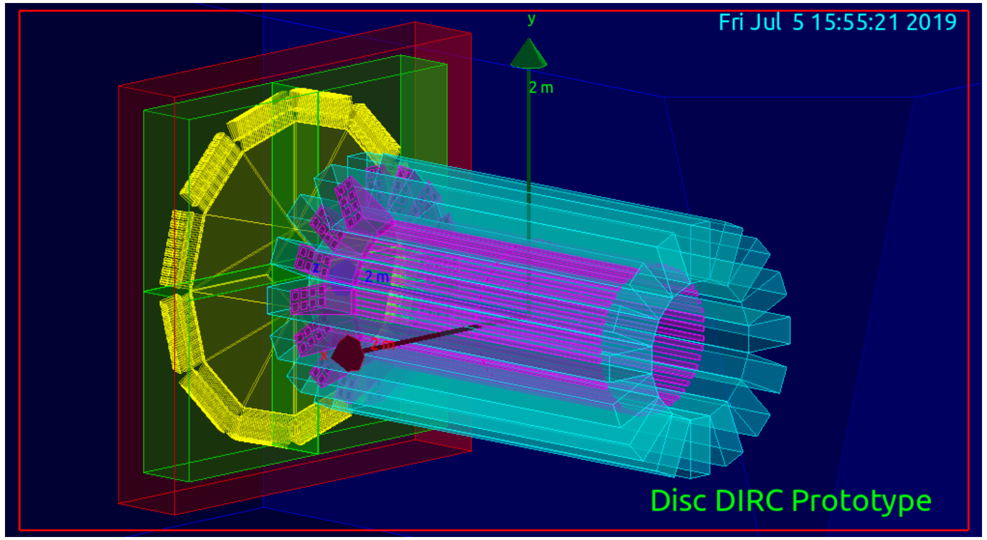
- DTOF: proposed for endcap of future Super Charm Tau Factory
  - goal 3σ π/K separation up to 2 GeV/c
  - 1.4m flight path, 50ps time resolution goal



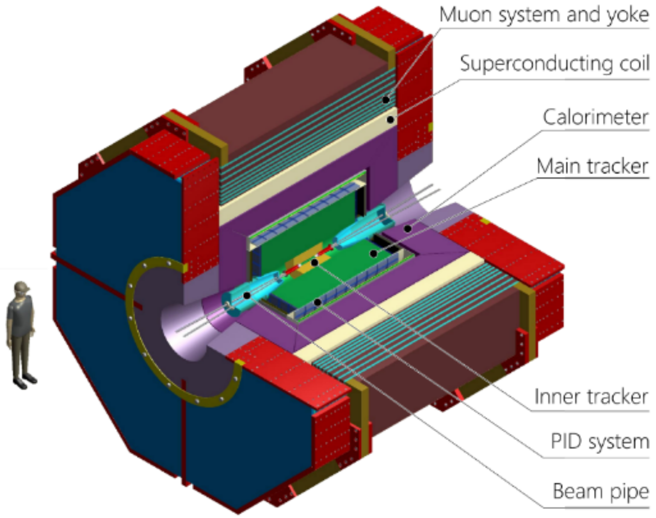
Qian LIU, STCF workshop 2020

Future Tau Charm DIRCs

- compact photon camera
- lens/mirror focusing
- small pixels (MCP-PMT/SiPM)
- fast photon timing
- dispersion mitigation
- barrel and endcap?
- mult. scattering mitigation



M. Schmidt, DIRC2019

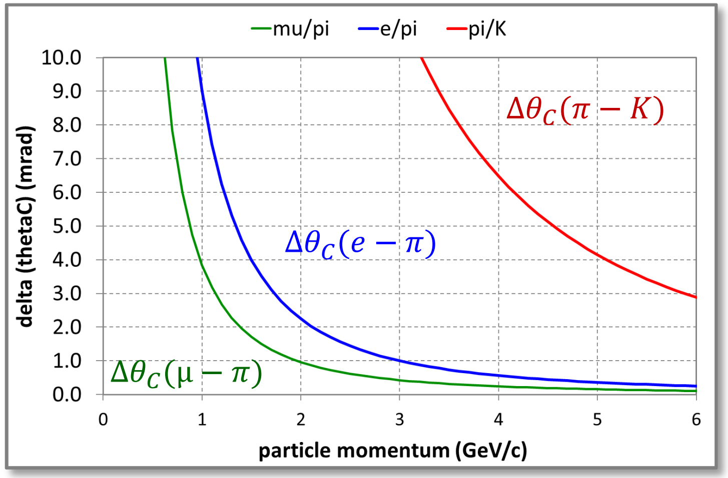


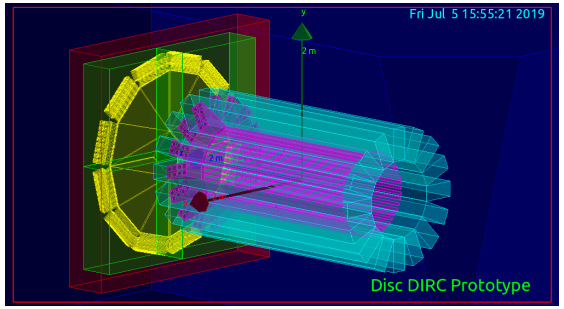
Tau Charm DIRC Concepts

Tau Charm DIRCs

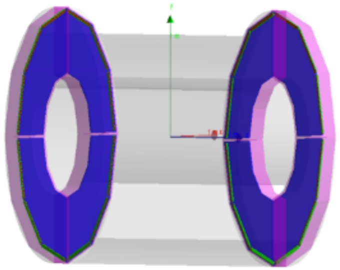
- barrel and/or endcap PID for the future (super) Charm-Tau/Tau-Charm facilities
- unique and challenging task for DIRCs: 3σ μ/π separation up to 1.2 GeV/c
- μ/π separation at 1.2 GeV/c close to π/K separation at 6 GeV/c,
  ~1mrad Cherenkov angle resolution per particle required for 3σ separation
- EIC hpDIRC or PANDA Barrel and Endcap Disc DIRC designs may be able to meet requirements but would need significant design optimization, including
  - chromatic dispersion mitigation using hardware or software correction
  - multiple scattering mitigation at low momentum using post-DIRC track points
- early stage of R&D and detector simulation studies, evaluating technologies (also considering gas RICH, focusing aerogel RICH, and DIRC-based TOF).

- compact photon camera
- lens/mirror focusing
- small pixels (MCP-PMT/SiPM)
- fast photon timing
- dispersion mitigation
- barrel and endcap?
- mult. scattering mitigation





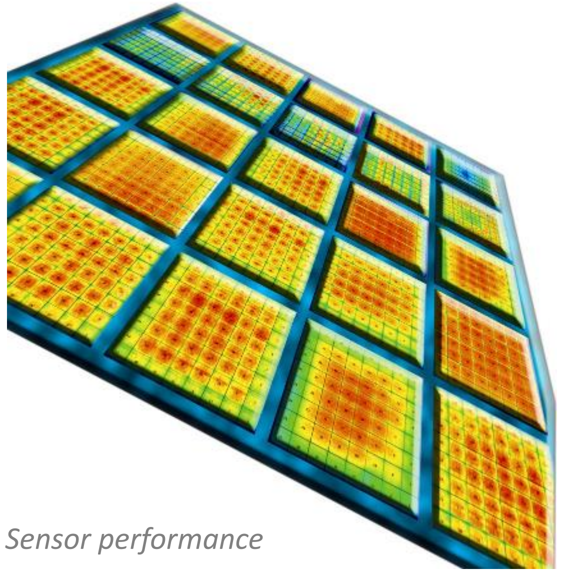
Barrel/endcap disc DIRC options, M. Schmidt, DIRC2019


Endcap DIRC/TOF option, Qian Liu
Future charm-tau factory workshop, Nov 2020

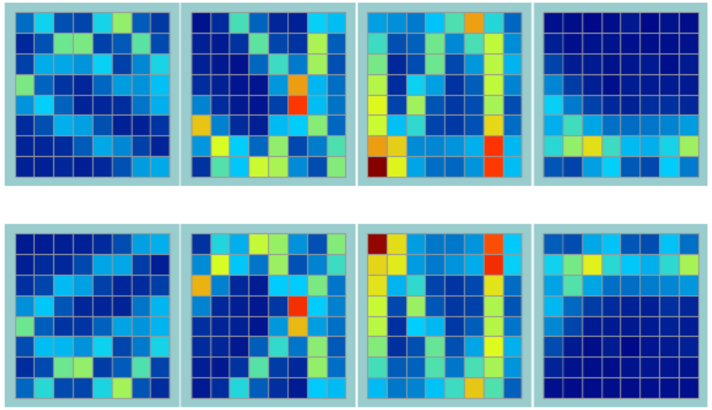
Recommended further reading:
"DIRC options for the Super Charm Tau Factory"
M. Schmidt et al 2020 JINST 15 C02032

Progress of Key Technologies

Bar/plate fabrication



Sensor performance



Reconstruction/PID algorithms

Production of large fused silica pieces (bars, plates) has been challenging

DIRC radiators require mechanical tolerances on flatness, squareness, and parallelism,
for large objects with optical finish and long sharp edges → not a turnkey operation

Excellent surface polish required across entire bar/plate, typical local roughness < 5 Å,
to ensure high photon transport efficiency (reflection coefficient > 0.999 at 400nm)

Parallel and square bar/plate surfaces required to maintain Cherenkov angle during reflections;
non-squareness of cross-section < 0.1 mrad for Belle II TOP, <0.25 mrad for BABAR DIRC

Few qualified vendors worldwide → cost and schedule risk

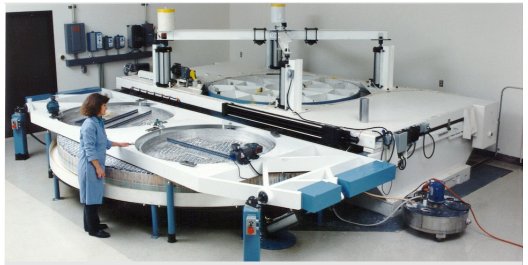
Radiator production source of significant DIRC project delays for BABAR and Belle II

Extensive PANDA Barrel DIRC R&D prototype program with eight optical companies

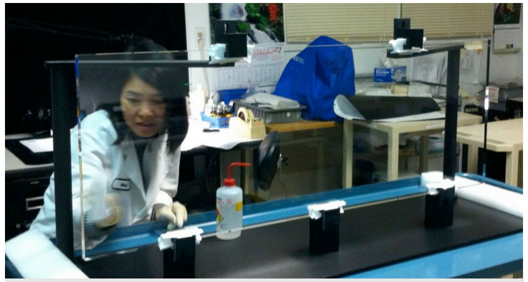
Tested both abrasive and pitch polishing methods *(future: magnetorheological finishing (MRF)?)*

Tested new synthetic fused silica materials (Corning, Heraeus, Nikon), all suitable for PANDA

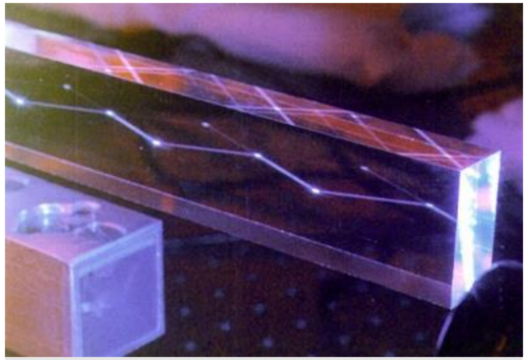
Successful series production with Nikon encouraging for future DIRC projects



4.2m-diameter planetary polisher at InSync Inc (BABAR DIRC)



Cleaning of Belle II TOP plate (Zygo)

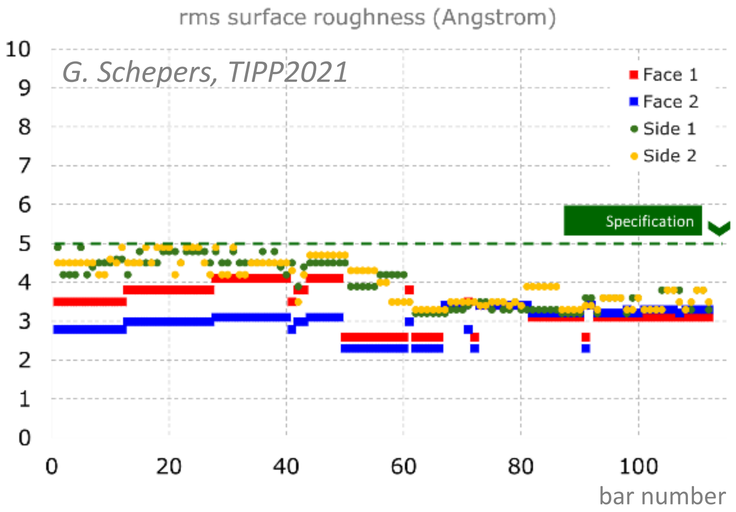


BABAR DIRC bar in laser beam

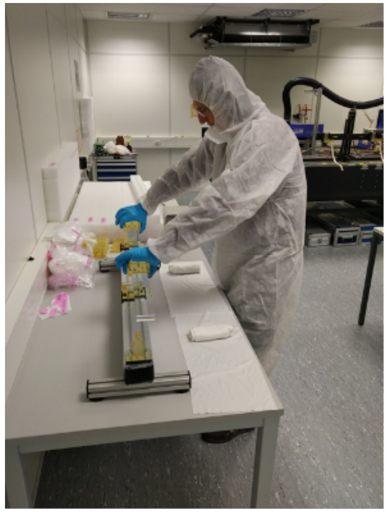
DIRC RADIATOR PRODUCTION

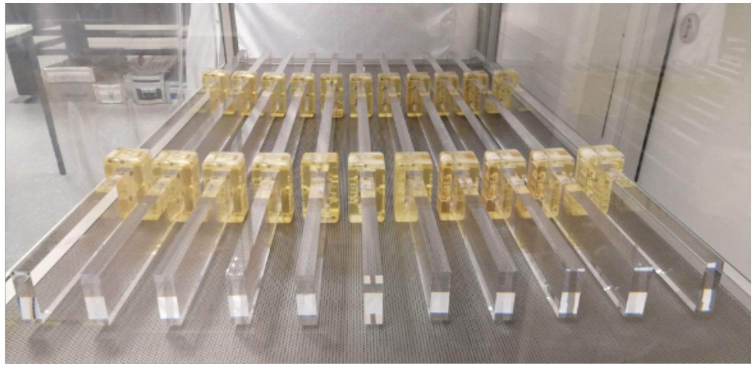
PANDA Barrel DIRC Experience

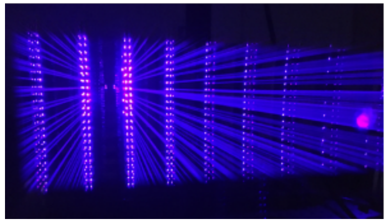
- series production of components started in 2019
- contract for fused silica bars awarded to Nikon Corp, Japan in Sep 2019
- smooth production, excellent communication
- 112 DIRC bars delivered by Feb 2021, ahead of schedule
- all bars meet or exceed specifications (example: surface roughness)

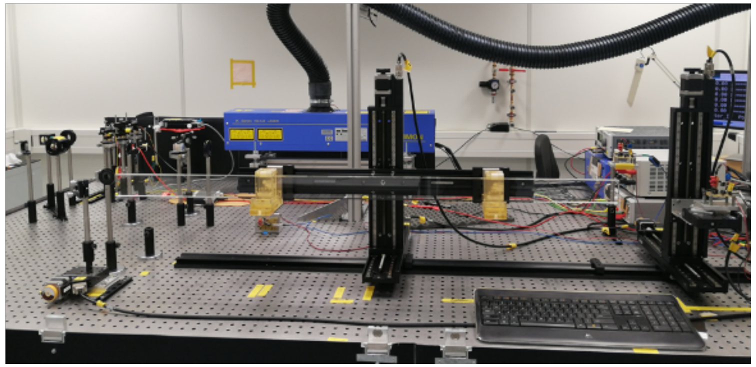


Nikon bars in DIRC lab at GSI



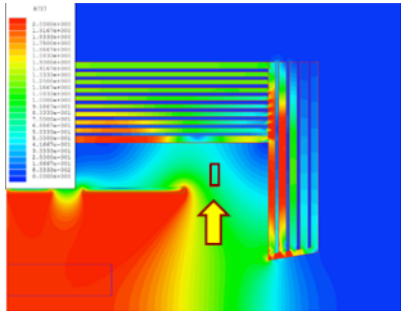






DIRC SENSOR OPTIONS

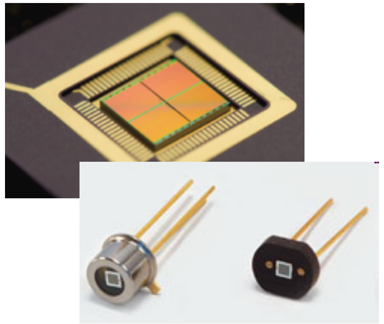
DIRC sensor location in PANDA, B≈1T



- **Multi-anode Photomultipliers (MaPMTs)**

  used successfully in DIRC prototypes, sensor of choice for SuperB FDIRC, GlueX DIRC

  does not work in magnetic fields, serious challenge for DIRC integration



- **Geiger-mode Avalanche Photo Diodes (SiPMs)**

  high dark count rate problematic for reconstruction (DIRC photon arrival time spread)

  radiation hardness a serious issue → cryogenic operation and annealing?

  could be a good candidate for future DIRCs

  active R&D for RICH and DIRC counters (LHC, Belle II, EIC, …)

- **Micro-channel Plate Photomultipliers (MCP-PMTs)**

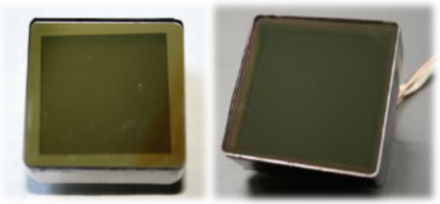
  good gain and PDE, excellent timing and magnetic field performance up to 2T

  issues with rate capability and aging resolved in recent years

  main downside: cost per area

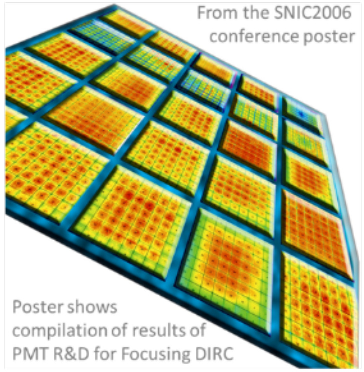
  availability of vendors for large (2-inch or larger) MCP-PMTs becoming an issue

  (Photek and Incom main candidates, Hamamatsu and Photonis availability questionable)



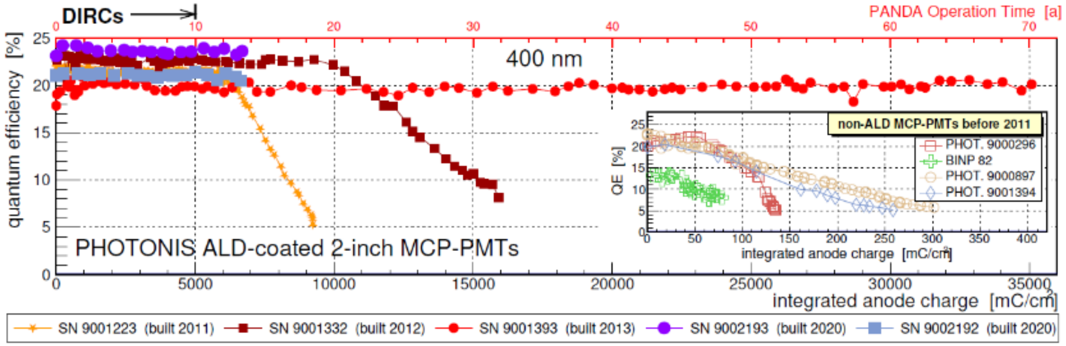
DIRC Sensor Requirements

Sensor development has been crucial to DIRC progress



Main DIRC development directions: Smaller pixels and faster single photon timing

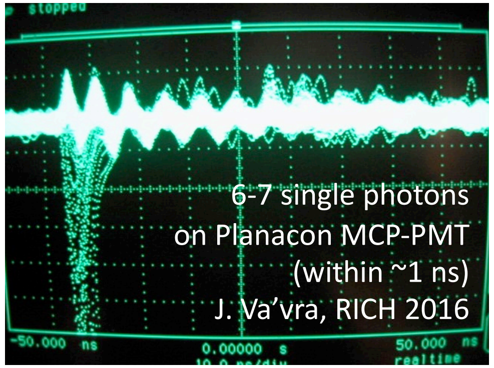
- reduces sensitivity to backgrounds
- improves Cherenkov angle resolution per photon
- allows chromatic dispersion mitigation
- anode design needs to match required angular resolution (required pitch may be asymmetric – see PANDA EDD)



A. Lehmann et al., GSI scientific report 2022
DOI:10.15120/GSI-2023-00462

Main challenge: Maintain fast timing and single photon sensitivity

- in high magnetic fields for compact camera designs (up to 3 Tesla for EIC?)
- after large ionizing radiation doses and neutron fluxes
- during long lifetime (10-20+ C/cm^2 integrated anode charge)
- during high interaction rates and photon hit rates (MHz/cm^2)
- for high hit multiplicities per event (coherent oscillation?)



Sensor development has been crucial to DIRC progress

Single photon detection

- excellent rms timing precision, more important than simple TTS
- reduce tails in timing distribution by increasing PC-MCP voltage

High photon yield (up to 100 photoelectrons per particle)

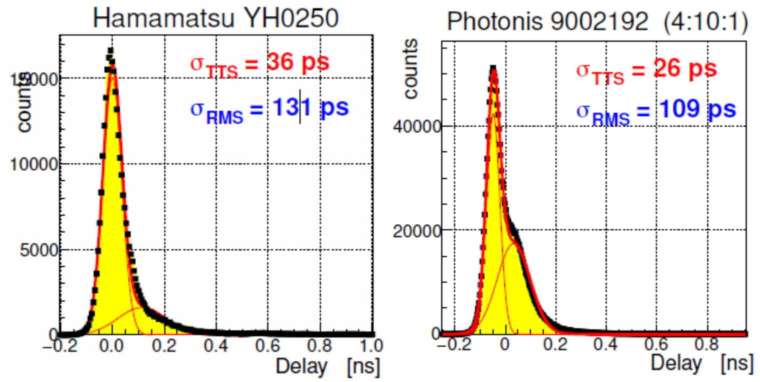
- need pixelated readout to determine position without ambiguities
- need tolerance for high occupancy per sensor

Long photon propagation paths in bar (arrival time often spread over >30ns)

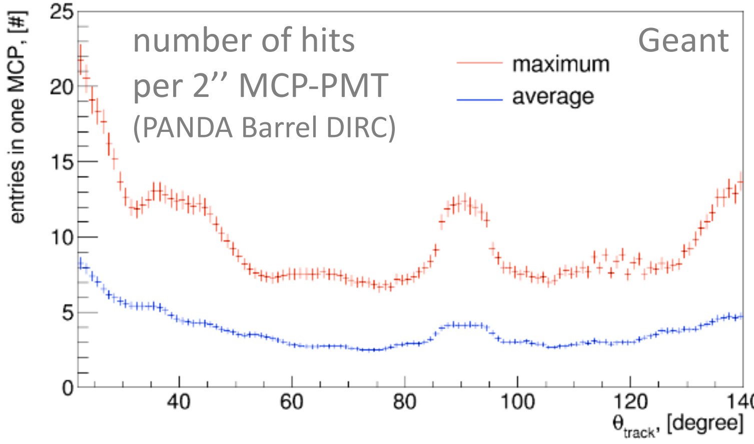
- need low noise rates (coincidence timing very difficult/impossible to use)
- High dark count rate and radiation damage currently showstoppers for SiPM

Leading candidate for DIRCs: MCP-PMT

- Commercial MCP-PMTs baseline solution for PANDA DIRCs and ePIC hpDIRC
- Hoping for significant cost reduction soon due to LAPPD™ effort (Incom)

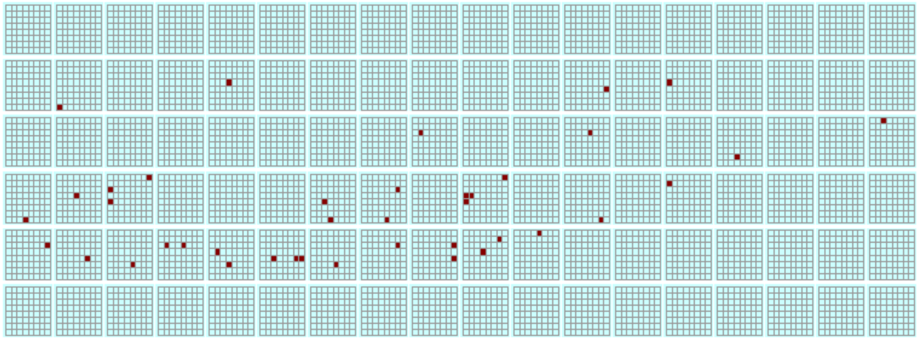


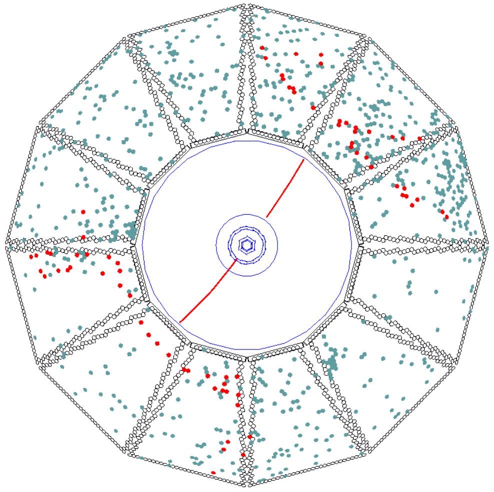
A. Lehmann TIPP2021



JS ANL MCP-PMT Workshop 2014

Single 3.5 GeV/c pion event, GlueX DIRC beam data





Single dimuon event, BABAR beam data

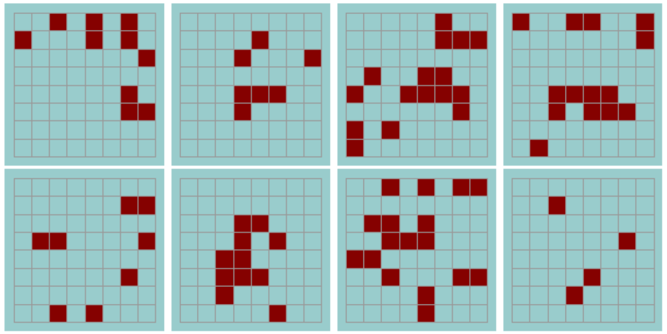
DIRC hit patterns do not look like your typical RICH "rings"

Patterns complicated by internal reflections inside bar/plate, mirror, expansion volume, shape of sensor plane.

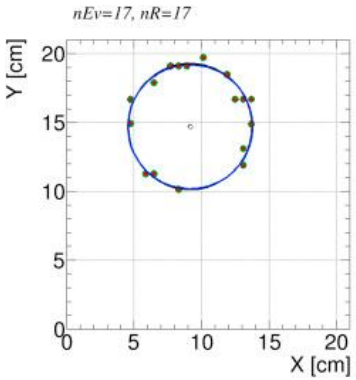
Detector space is often not the best space for DIRC reconstruction, no "simple" ring fits

Performing reconstruction and PID in Cherenkov space instead

Leading candidates: position-based geometric reconstruction and time-based imaging



Single 3.5 GeV/c pion event,
PANDA Barrel DIRC prototype



For comparison:
Single event in
CMB RICH (CO_2) prototype

Geometric reconstruction, example for PANDA Barrel DIRC

$$\log\mathcal{L}_h = \sum_{i=1}^{N} \log(S_h(c_i) + B_h(c_i)) + \log P_h(N)$$

Developed for BABAR DIRC, approximates Cherenkov photon direction as

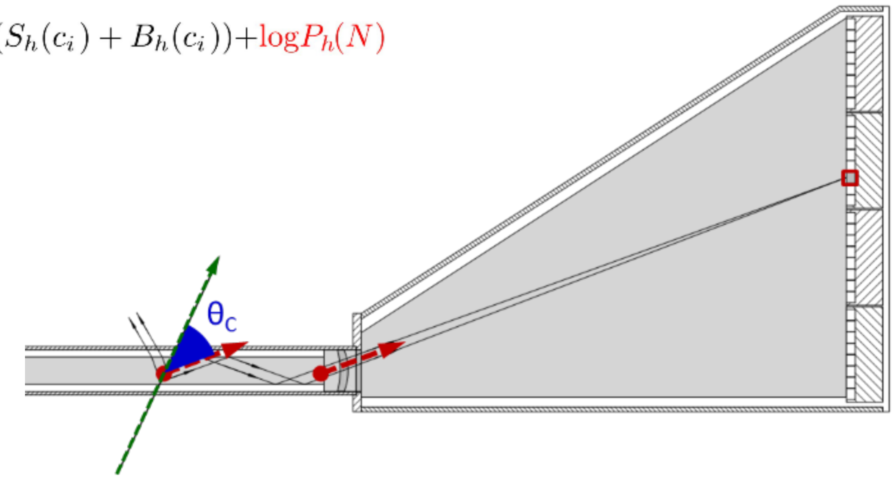
3D vector from center of end of bar to center of pixel (allowing for reflections)

Use photon gun in simulation to create look-up tables (LUT)

of photon vectors for every pixel/bar combination

Robust approach, fewer requirements on photon timing precision

Fast method, one LUT for all particle tracks



Time-based imaging, example for PANDA Barrel DIRC

$$\log\mathcal{L}_h = \sum_{i=1}^{N} \log(S_h(c_i, t_i) + B_h(c_i, t_i)) + \log P_h(N)$$

Developed for Belle-II TOP, calculate probability for times of all

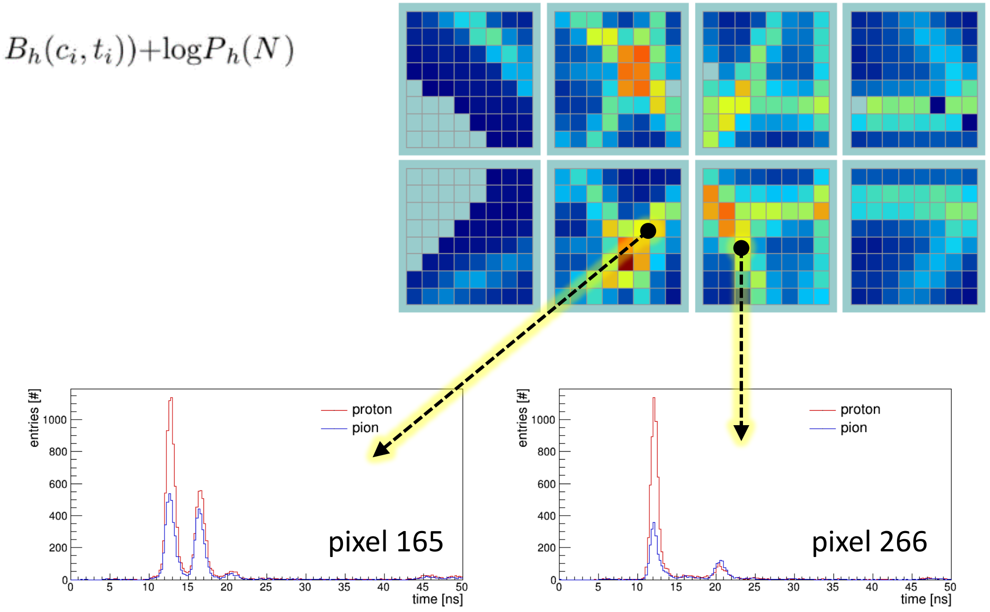
observed hits in all pixels to come from e/μ/π/K/p

Requires probability density functions of expected photon times

Three possible methods for creating PDFs:

simulation, data (from calibration samples), analytical

Makes optimum use of high-precision hit location and time precision



DIRC Reconstruction/PID in PANDA

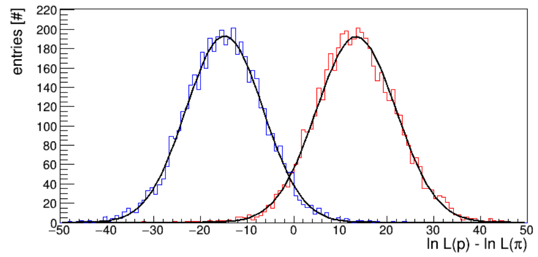
PANDA Barrel DIRC prototype, CERN 2018, 20° polar angle
7 GeV/c π/p beam, equiv. to 3.5 GeV/c π/K

Examples of reconstruction/PID methods from PANDA Barrel DIRC

- track-by-track fit of single photon Cherenkov angle distribution based on look-up tables to extract track Cherenkov angle ("BABAR-like")
- track-by-track unbinned likelihood hypothesis test to determine log-likelihood differences ("geometrical reconstruction")
- "Belle II-like" time imaging to extract log-likelihood differences (PDFs were generated either analytically or from beam data directly using time-of-flight tag, statistically independent data sets)
- best performance from time imaging
- first applications of advanced AI/ML techniques underway

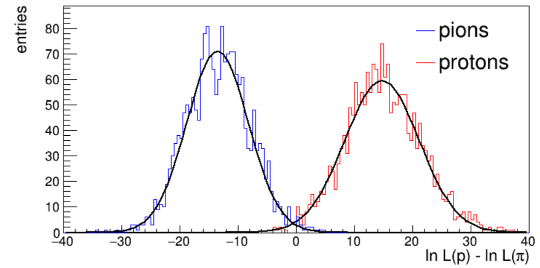
geometrical reconstruction

π/K separation: 3.5 s.d.

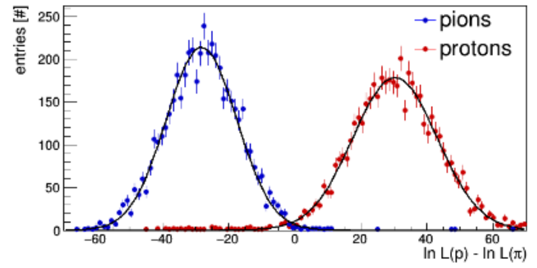


time imaging

analytical PDF: π/K separation: 4.4 s.d



beam data PDF: π/K separation: 5.0 s.d



R. Dzhygadlo, CHEP2019

What about a design based on the "best of…" of DIRC design R&D in recent years?

At RICH 2016 J. Va'vra showed the "ultimate fDIRC" concept:

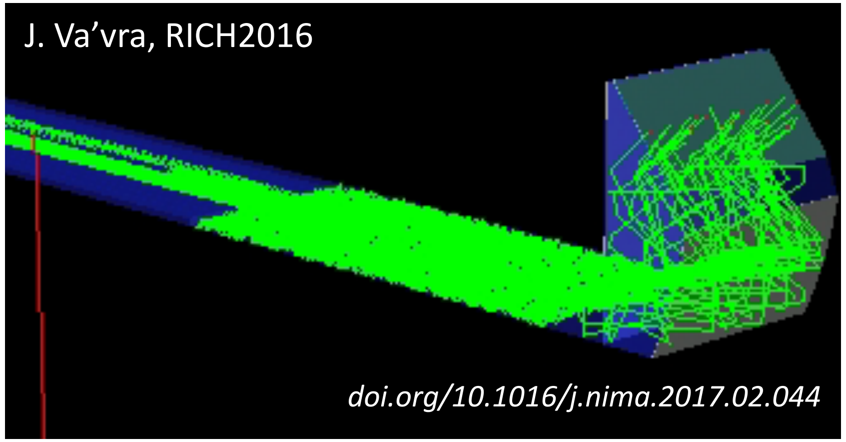
- smaller fused silica block, cylindrical mirror, sensors with 3mm pixel pitch;
- disassemble BABAR DIRC bar boxes, remove wedges;
- replace last bar with one common plate for all 12 bars in box.

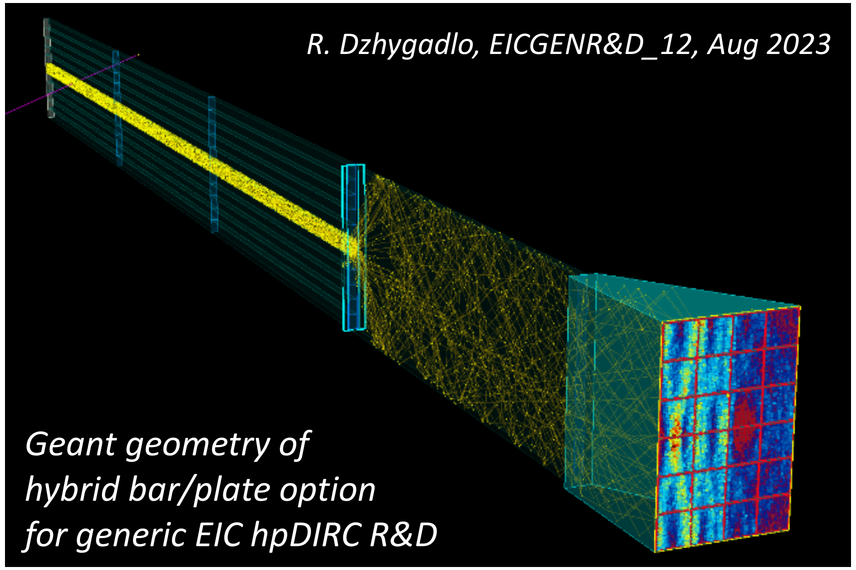
Best of both worlds:

- narrow bars in "active area" ensure robust performance in multi-track events;
- wide plate effectively part of the expansion volume in horizontal direction, provides better angular precision;
- SuperB fDIRC simulation predicts 3-5mrad Cherenkov angle resolution per photon, best-in-class single photon resolution prediction as of 2016.

Combining this hybrid design with time-based imaging with faster photon timing and better tracking should lead to further improvement.

Simulation project for EIC hpDIRC suggests even better performance for lens-focused bar-plate hybrid (EICGENR&D program).





SUMMARY

30 years after Blair Ratcliff's original paper, DIRC counters are a popular solution for hadronic PID

DIRCs are radially very compact, providing more space for calorimeters or tracking detectors

BABAR DIRC was the first DIRC, PID for barrel region, very successful, π/K up to ~4 GeV/c (1999-2008)

Prompted DIRC interest by several experiments: Belle II, SuperB, PANDA, and others

R&D to make DIRC readout more compact, expand momentum reach, use for endcap

Very active and complex R&D, applying advances in sensors, electronics, imaging, algorithms

Main R&D directions *(with significant overlap/synergy)*:

(a) focusing design emphasizing spatial resolution, x&y pixels (fDIRC, GlueX)

(b) focusing design emphasizing high-precision photon timing (Belle II)

(c) focusing design with time and space coordinates with similarly high precision (PANDA, EIC)

(d) DIRC-based time-of-flight counters (LHCb, Tau-Charm) – *not covered in this talk*

Exploring mitigation of previously "irreducible" RICH resolution terms: chromatic dispersion, multiple scattering

20+ years of next-gen DIRC R&D, active field, designs pushing DIRC performance limits

THANK YOU FOR YOUR ATTENTION