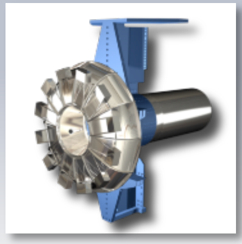
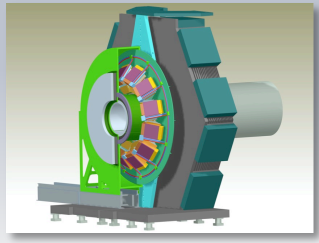
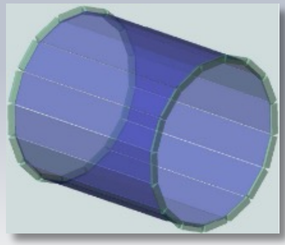
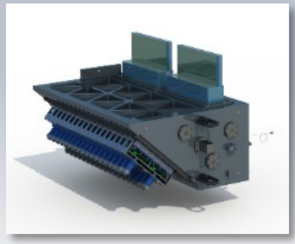
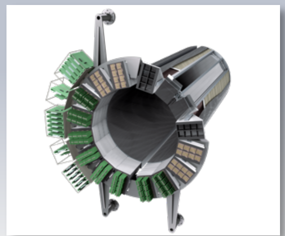
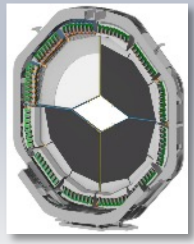
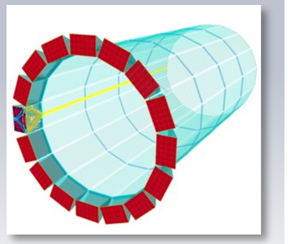
      

BaBar SuperB Belle II GlueX panda panda EIC

DIRC Technology Requirements

ECFA Detector R&D Roadmap Symposium of Task Force 4, May 6, 2021

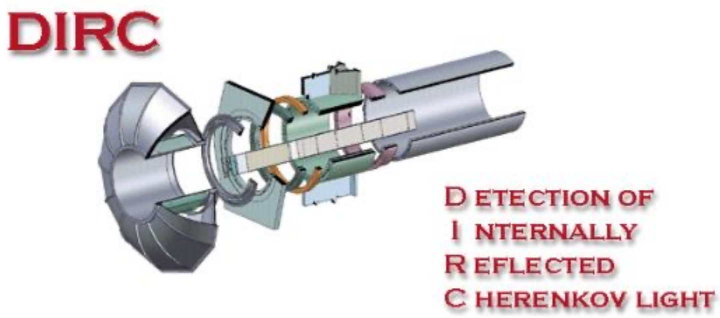
ECFA
European Committee for Future Accelerators

Jochen Schwiening

GSI

GSI Helmholtzzentrum für Schwerionenforschung GmbH

OUTLINE



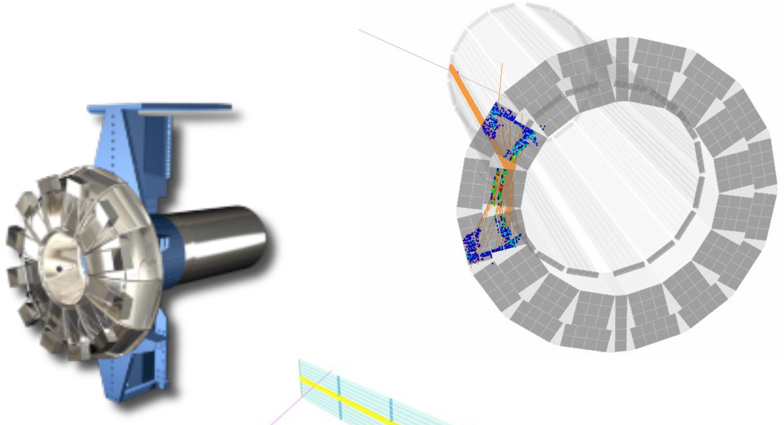
- DIRC Concept
- DIRCs at Past and Current Facilities
- R&D for DIRCs at Future Facilities

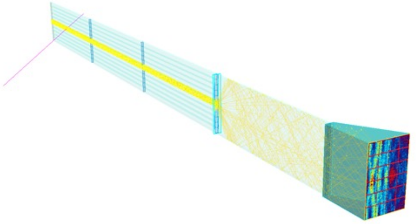
A lot of activities with many interesting results,
too much for a 25-minute talk – for more details see:

- *Recent review: B. Ratcliff and J. Va'vra, Nucl.Instrum.Meth. A 970 (2020) 163442*
- *RICH workshop series (most recent: RICH2018, Moscow)*
- *DIRC workshop series (most recent: DIRC2019, Rauischholzhausen)*

Not covered in this talk: DIRC-based time-of-flight counters → see Roger's TOF talk
More about sensor development → session this afternoon
More about fast readout electronics development → TF7 symposium, March 25

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





Detection of Internally Reflected Cherenkov Light

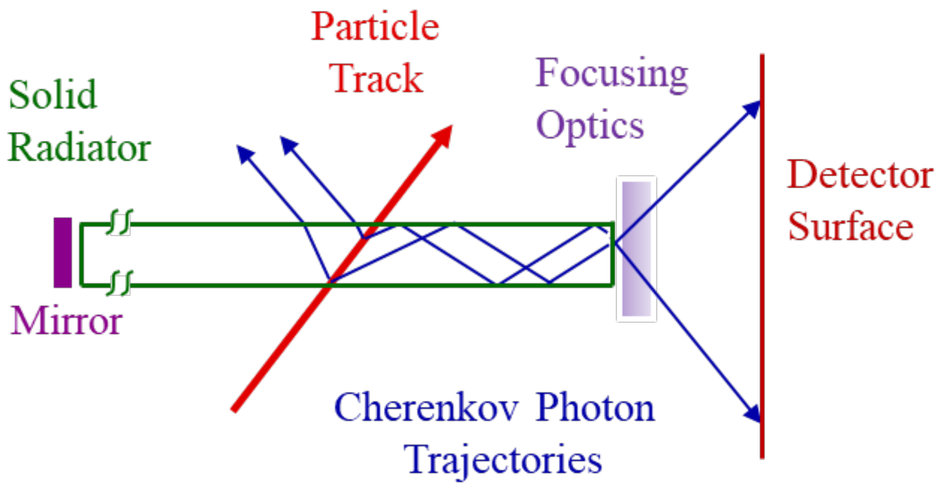
- DIRC: Compact subtype of RICH (Ring Imaging CHerenkov) detector
  utilizing total internal reflection of Cherenkov photons in a solid radiator medium

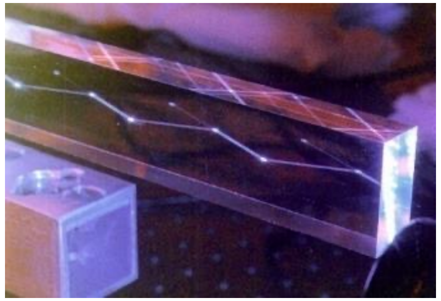
- Charged particle traversing radiator with refractive index n
  with $\beta = v/c > 1/n$ emits Cherenkov photons on cone
  with half opening angle $\cos\theta_c = 1/\beta n(\lambda)$.

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

- Radiator and light guide: bar, plate, or disk,
  typically made from Synthetic Fused Silica ("Quartz")

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

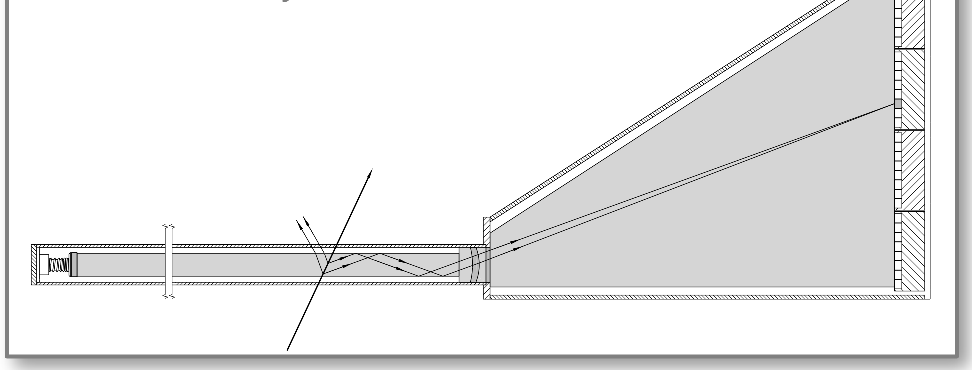




DIRC CONCEPT

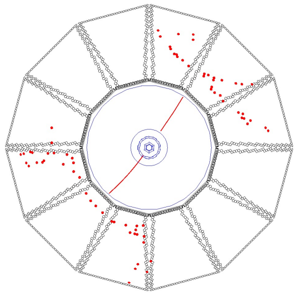
- Mirror attached to one bar end, reflects photon back to readout end.
- Photons exit radiator via optional focusing optics
  into expansion region, detected
  on photon detector array.
- DIRC is intrinsically a 3-D device,
  measuring: x, y, and time of Cherenkov
  photons, defining θ_c, ϕ_c, $t_{propagation}$.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

Schematic view of PANDA Barrel DIRC

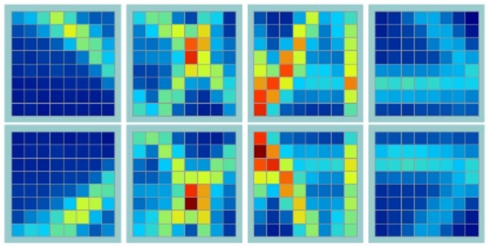


DIRC hit patterns are not typical Cherenkov rings.

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.

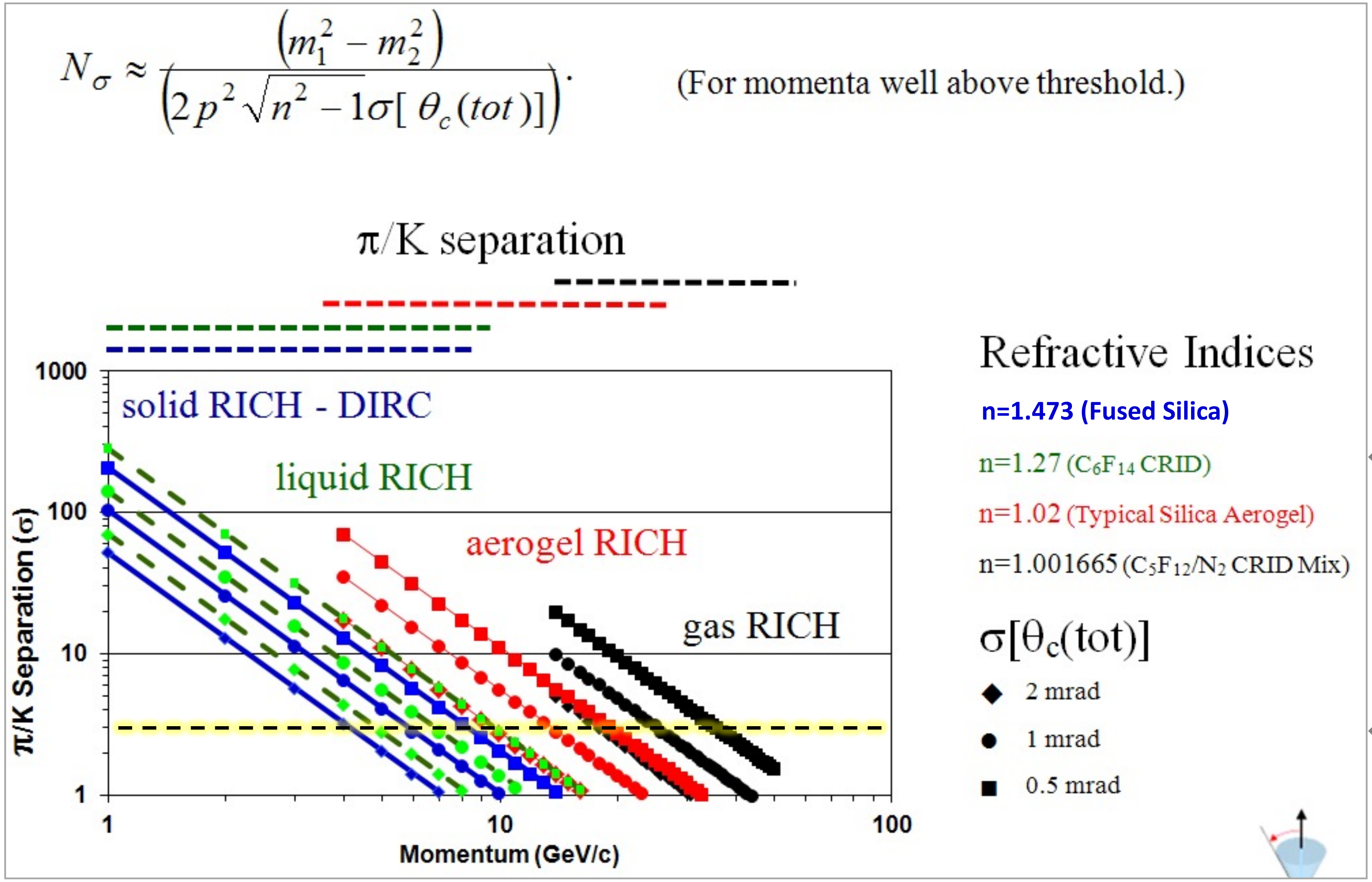


Hit pattern
BABAR DIRC



Accumulated hit pattern
PANDA Barrel DIRC

DIRC Performance Limits



colors: radiator materials

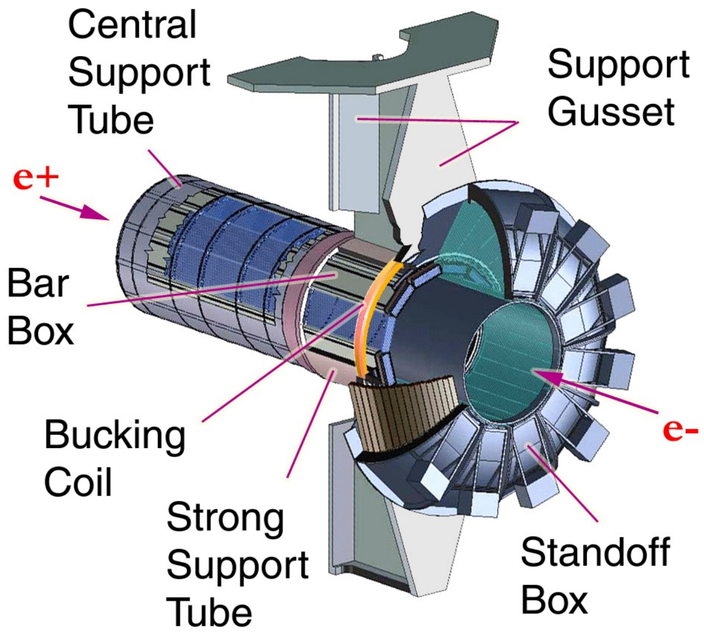
symbols: total Cherenkov angle error per particle

DIRCs can provide good π/K separation potential significantly beyond 3-4 GeV/c,

though large refractive index limits practical DIRC momentum range to below 10 GeV/c.

based on B. Ratcliff, RICH2002

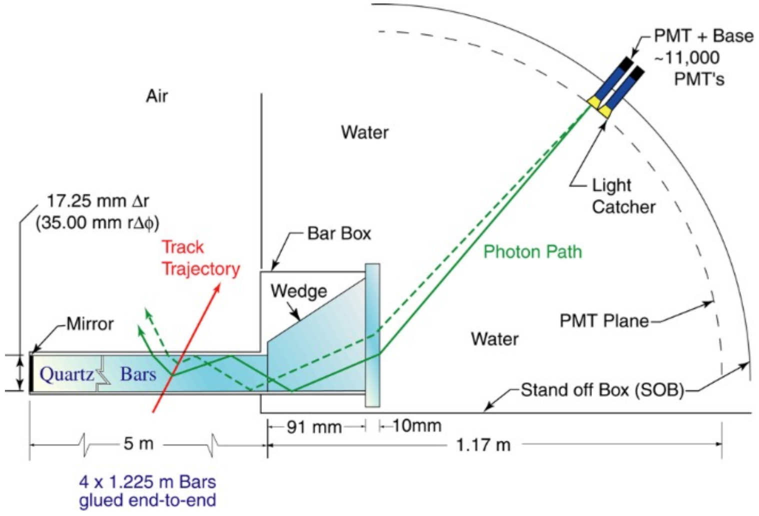
BABAR DIRC

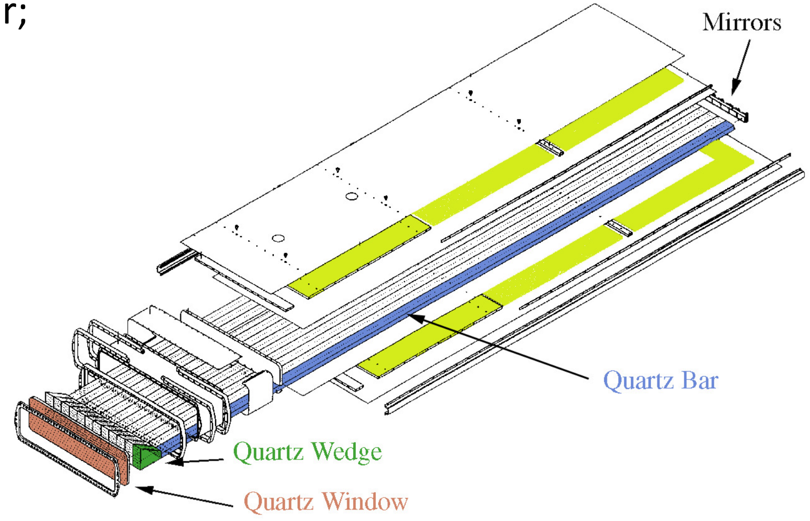

Central Support Tube
Support Gusset
e+
Bar Box
Bucking Coil
Strong Support Tube
Standoff Box
e-


CAUTION
HARD HATS
REQUIRED

BABAR DIRC

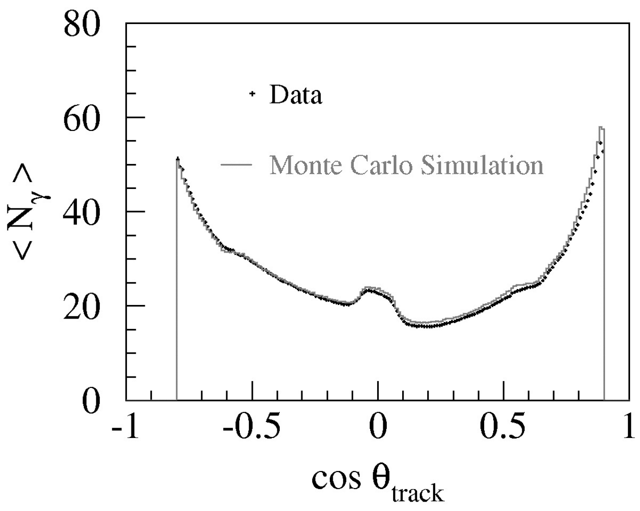
- first DIRC counter, primary hadronic PID in BABAR barrel;
- design goal 3σ π/K separation up to 4 GeV/c;
- compact, 8 cm radial thickness incl. supports;
- pinhole focusing (size of bar small compared to size of expansion volume);
- long narrow synthetic fused silica bars (17mm x 35mm x 4900mm);
- 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.

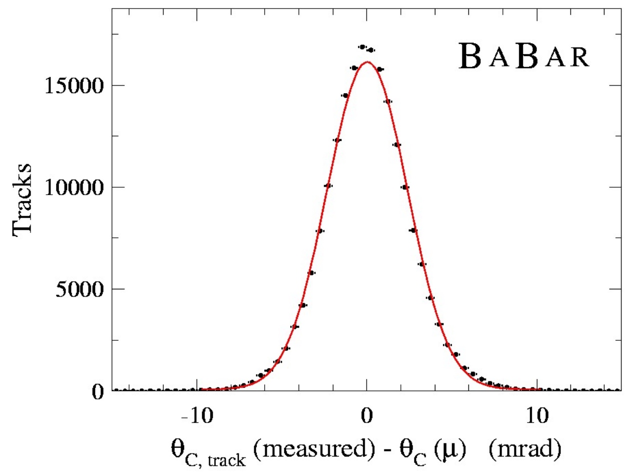


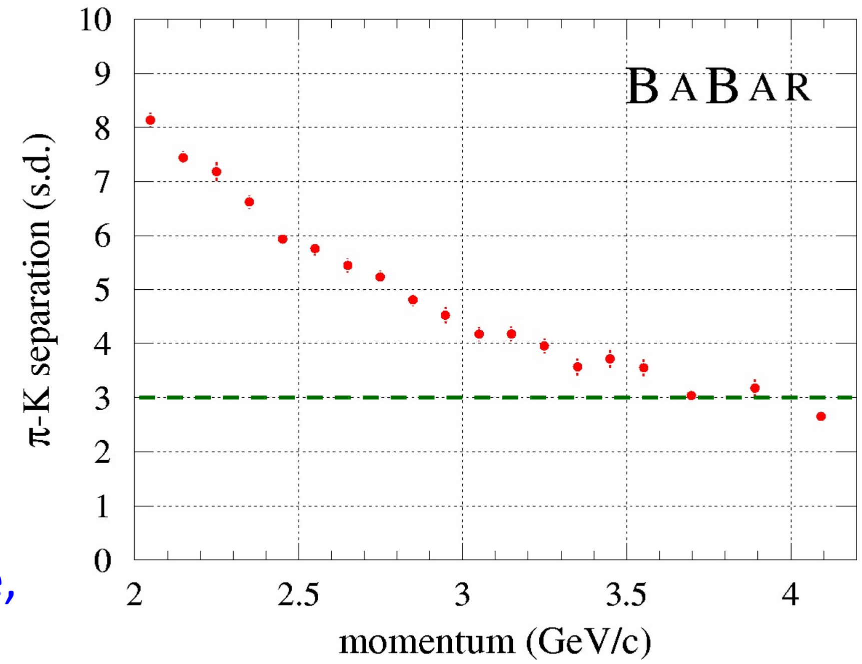


BaBar DIRC

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



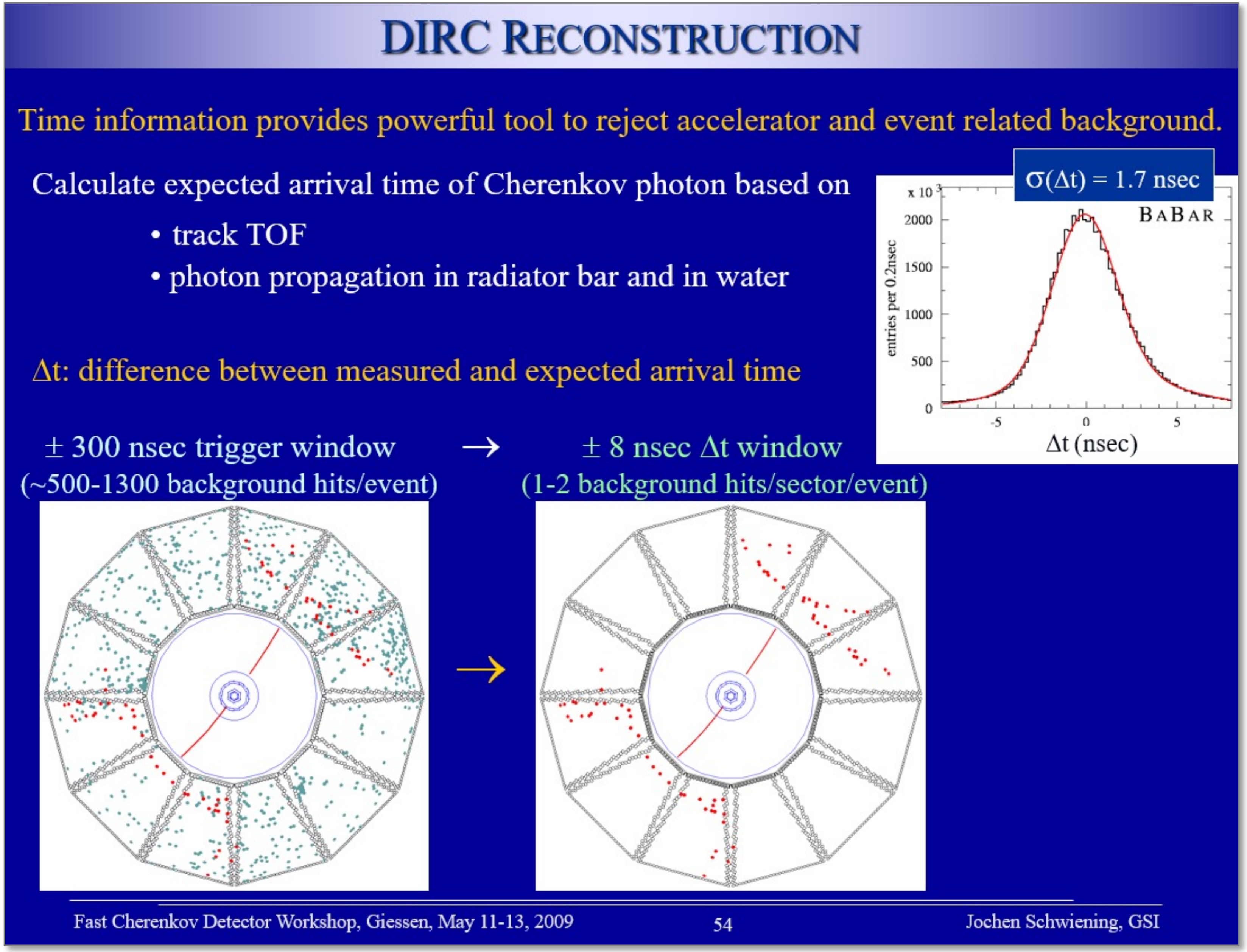




Excellent performance: very reliable, robust, easy to operate, significant contribution to almost all BABAR physics results.

Nucl.Instrum.Meth. A 538 (2005) 281

BABAR DIRC

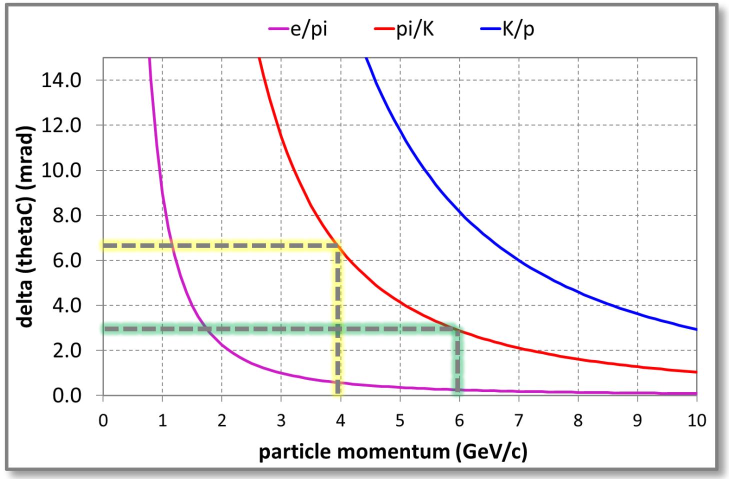


- Timing information not used for PID but crucial in dealing with accelerator-induced background
- Powerful DIRC timing variable: difference between measured and calculated photon arrival time (can provide "DIRC t_0 event time")

J.S., DIRC2009

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

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

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

$$\sigma_{\theta_c}(photon) \approx \sqrt{\sigma^2_{bar} + \sigma^2_{pix} + \sigma^2_{chrom}}$$

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

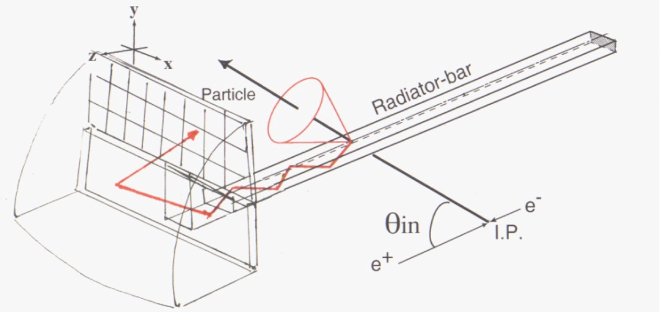
Limited in BABAR by:			Improve for future DIRCs via:
▪ size of bar image	~4.1 mrad	→	▪ focusing optics
▪ size of PMT pixel	~5.5 mrad	→	▪ smaller pixel size
▪ chromaticity (n=n(λ))	~5.4 mrad	→	▪ better time resolution
	9.6 mrad	→	5-6 mrad per photon → 1 mrad per particle (EIC goal) in reach

SuperB, Belle II, PANDA & EIC

Future DIRC Counters

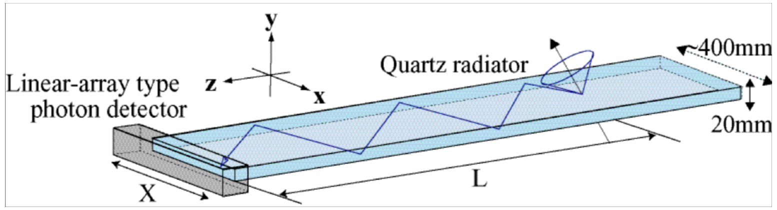
Initial next-generation DIRC R&D directions can be roughly divided into three imaging approaches using different focusing optics

- 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



Early SuperB fDIRC design

- 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



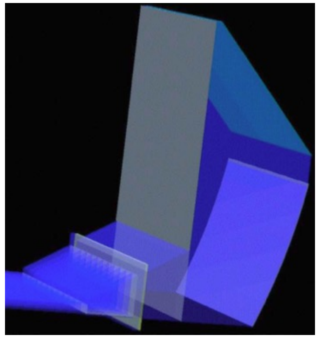
Early Belle II TOP design

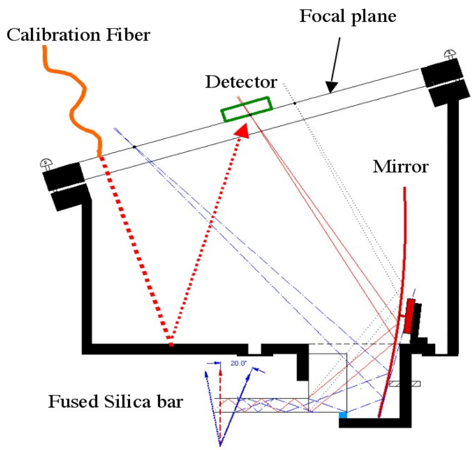
- very fast timing, very good spatial resolution
  examples: "ultimate fDIRC", EIC High-Performance DIRC
  <100 ps photon timing, large array of (~3 mm) 2D pixels → PID uses full 3D imaging

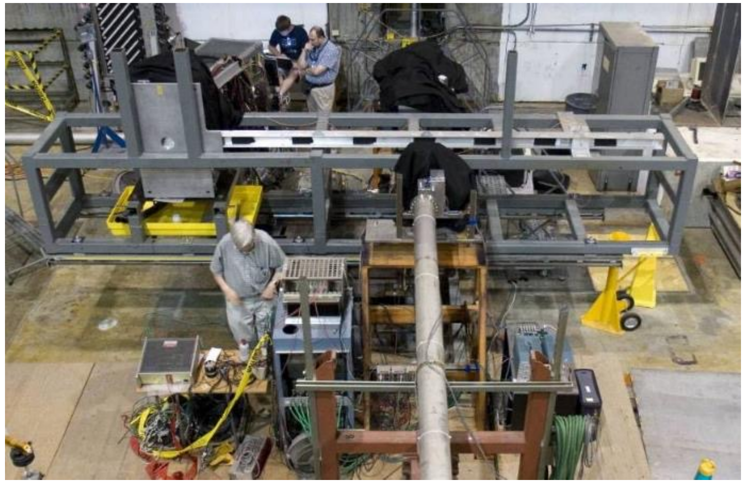
Final designs for Belle II TOP and PANDA DIRCs are hybrids derived from these initial approaches.

SuperB fDIRC

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



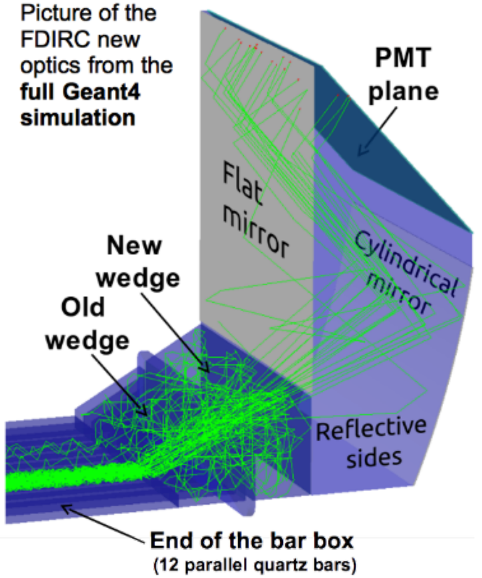




SuperB Focusing DIRC (fDIRC):

- Intended as barrel PID system for SuperB experiment in Italy (cancelled)
- 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



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

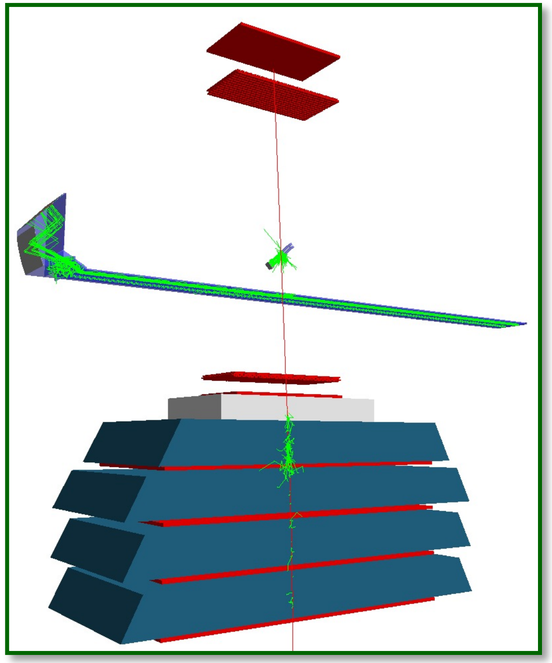
SuperB fDIRC

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.

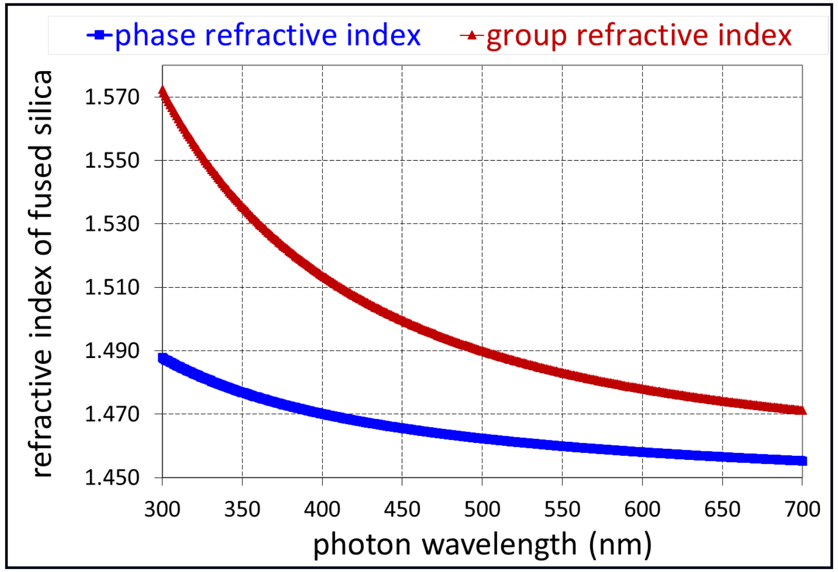
For more details on fDIRC R&D see: J. Va'vra, "Lessons learned from DIRC & FDIRC developments at SLAC", DIRC 2019 workshop, Sep. 2019.

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)

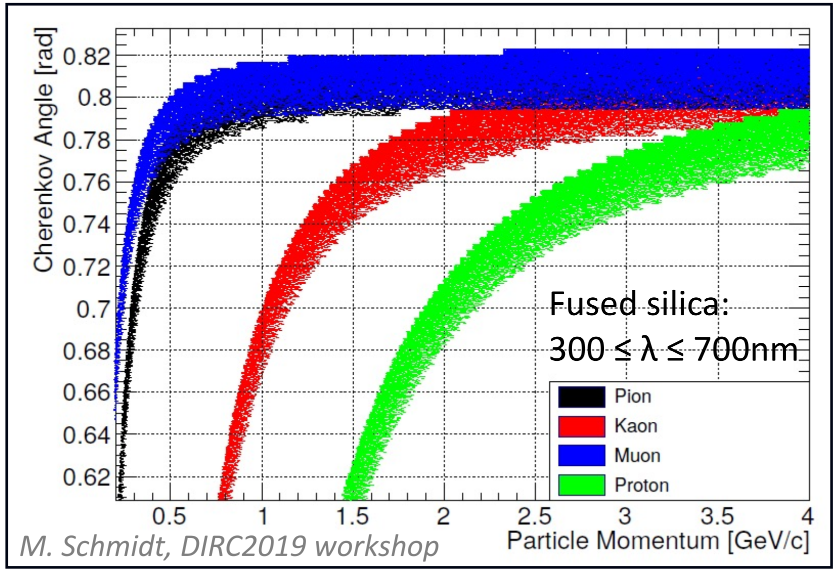
Cons:
- Production process can produce inclusions (bubbles) in bulk material or layers with optical index variations (striae)
- Dispersion of refractive index impacts angular resolution



Impact of chromatic dispersion on Cherenkov angle resolution

For $\beta=1$: $\theta_C=813...834\text{mrad}$ (for $300 \leq \lambda \leq 700$nm photons produced in FS)

→ significant contribution to Cherenkov angle resolution per photon



Several approaches to dispersion mitigation are being investigated:

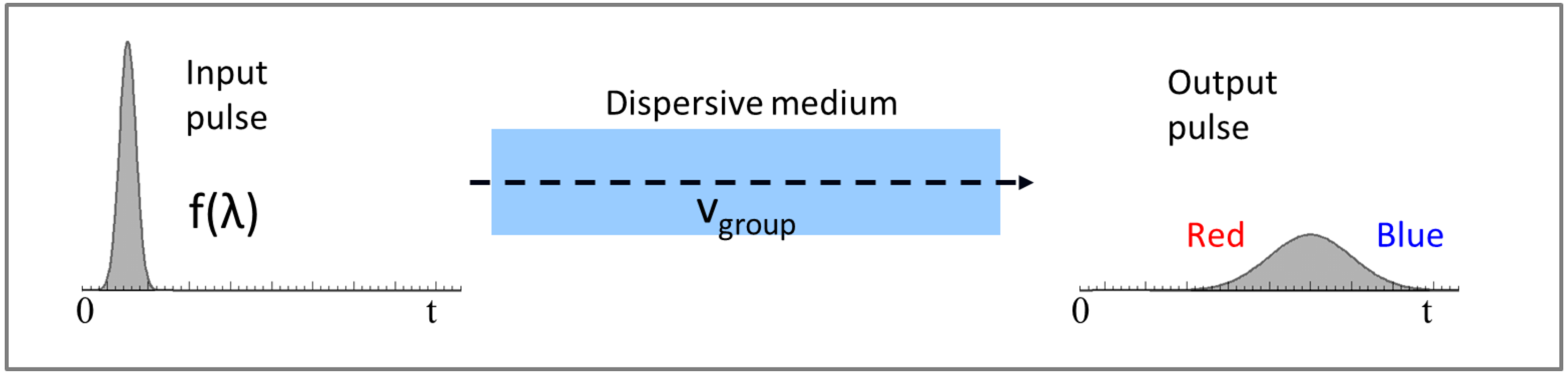
- Limit wavelength range (custom photocathode or band filter)
- Use transition to different refractive index (LiF prism)
- Use fast photon timing to tag photon wavelength using time dispersion
  → SuperB and PANDA have demonstrated feasibility of this method

Chromatic Dispersion in DIRCs

J.S., RICH 2007

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

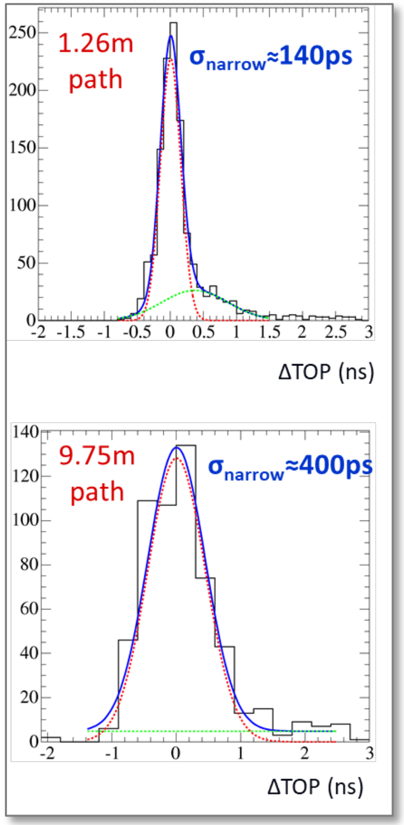
Propagation of photons controlled by n_{group} ($v_{group} = c_0/n_{group} = c_0/[n_{phase} - \lambda \cdot dn_{phase} \cdot d\lambda]$): v_{group}(red) > v_{group} (blue)



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

→ red photons arrive before blue photons

SuperB fDIRC, 1st prototype



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)

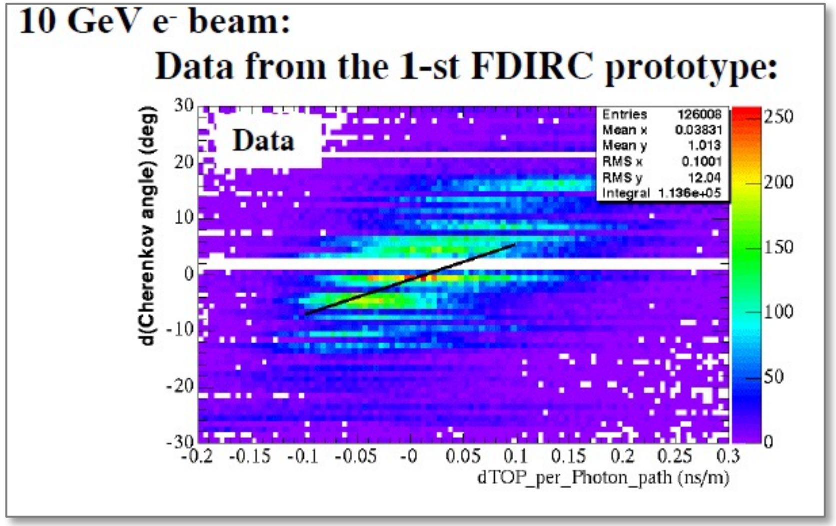
→ negative dTOP: red photons, positive dTOP: blue photons

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

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

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

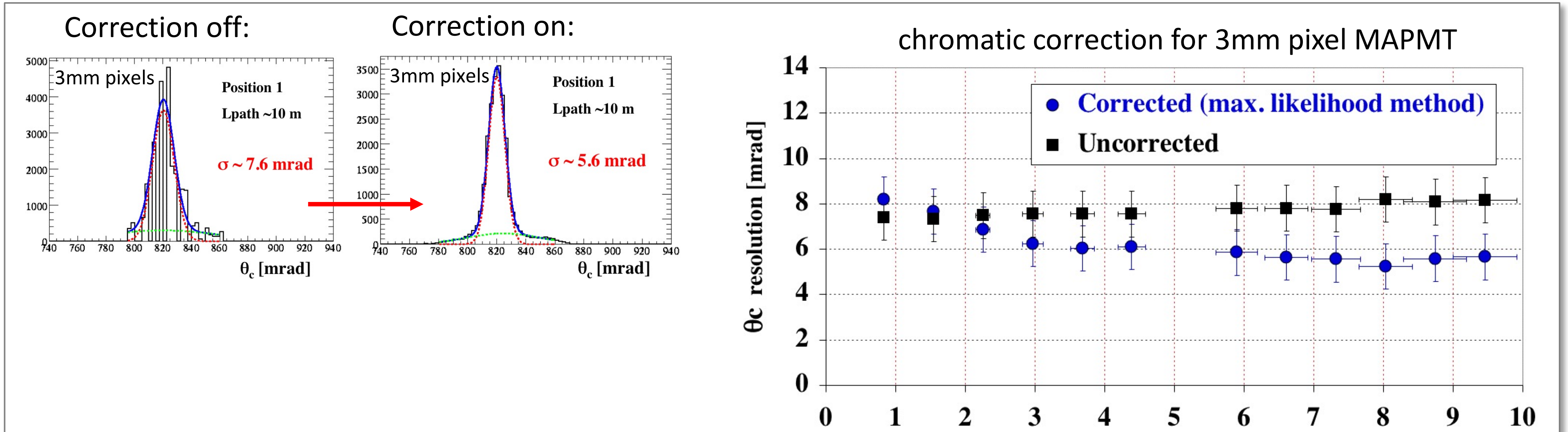
SuperB fDIRC Example



J. Va'vra, DIRC2019 workshop

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

- 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



J.S., RICH 2007

PANDA BARREL DIRC EXAMPLE

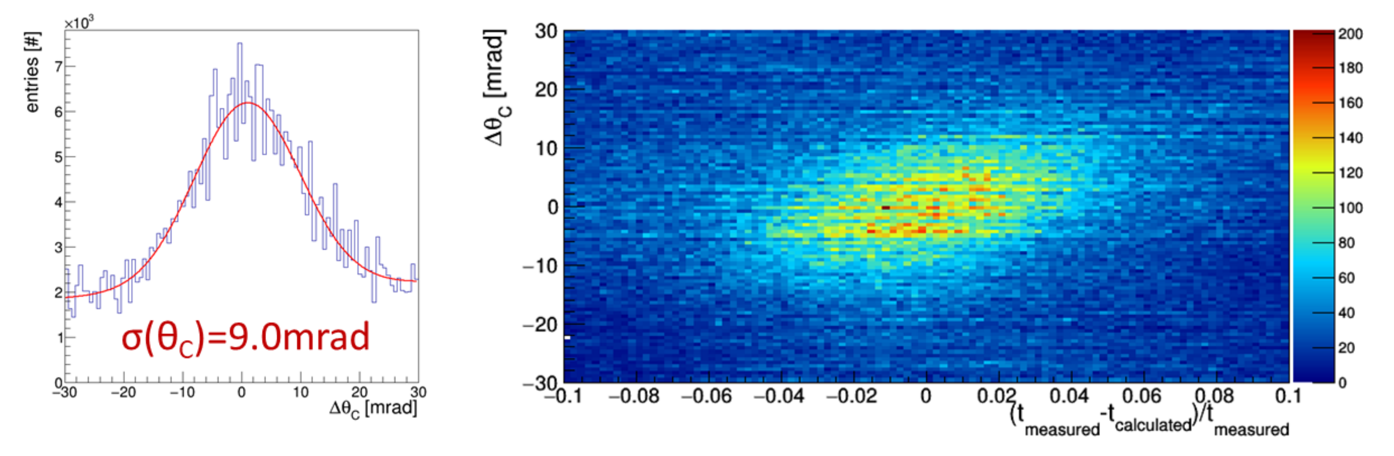
R. Dzhygadlo, April 2021, priv. comm.

Example from PANDA Barrel DIRC prototype beam test at CERN:

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 390nm)

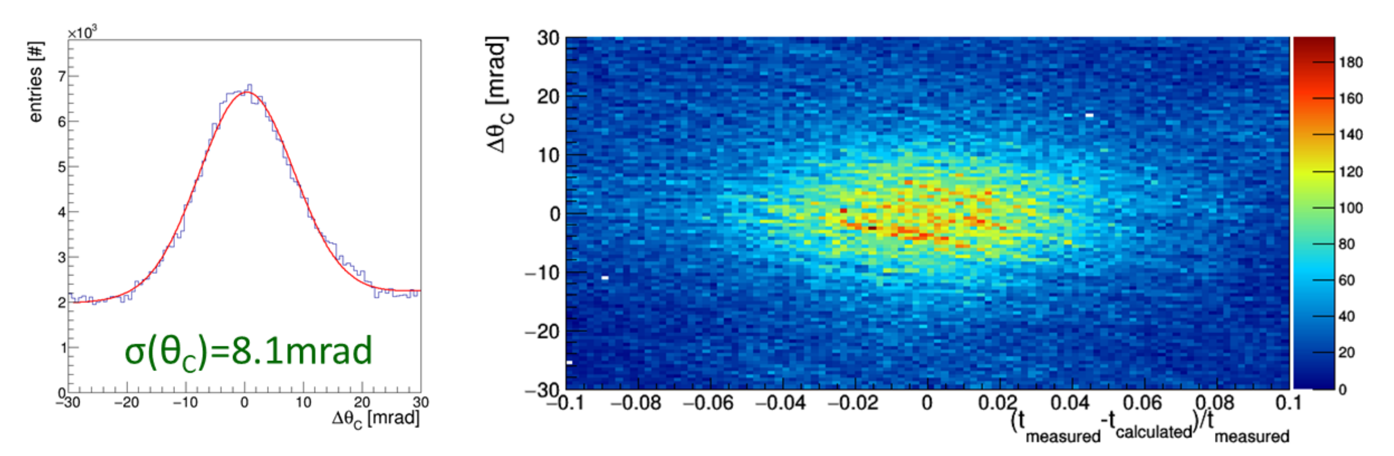
before correction



Clear improvement of Cherenkov angle resolution per photon after correction

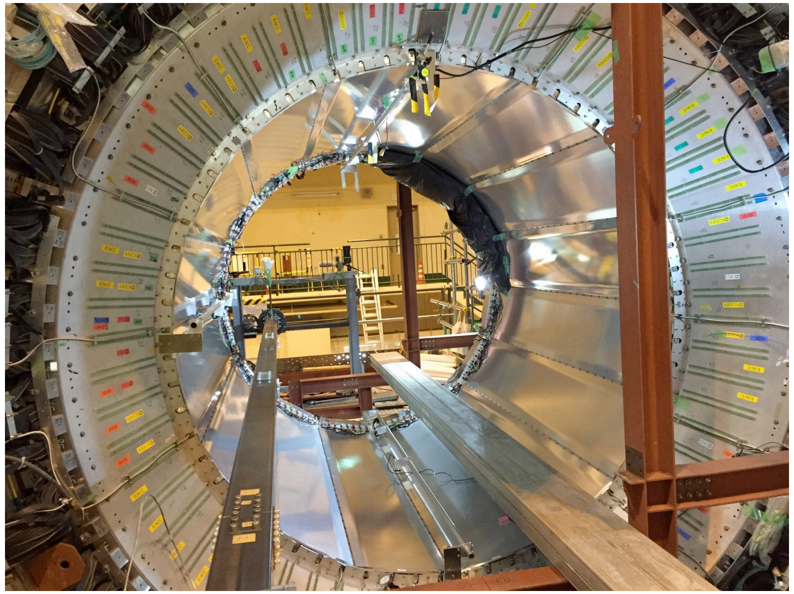
(with modest timing precision (~200ps)
and moderate photon path (1m-3.3m);
better timing, longer paths in PANDA)

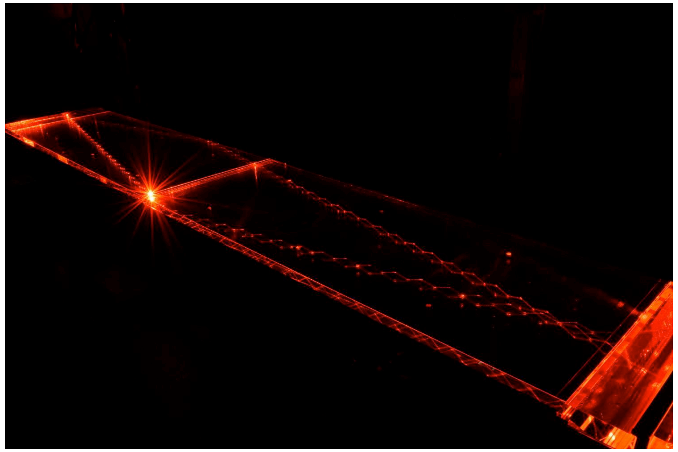
after chromatic correction by photon timing

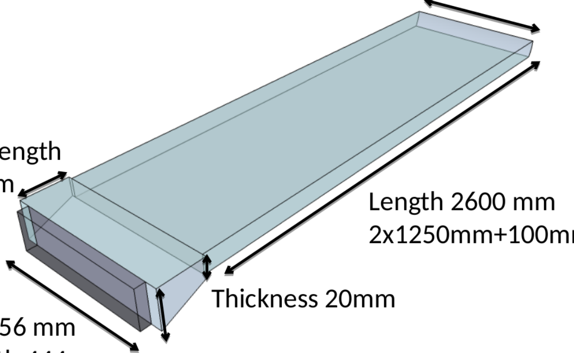


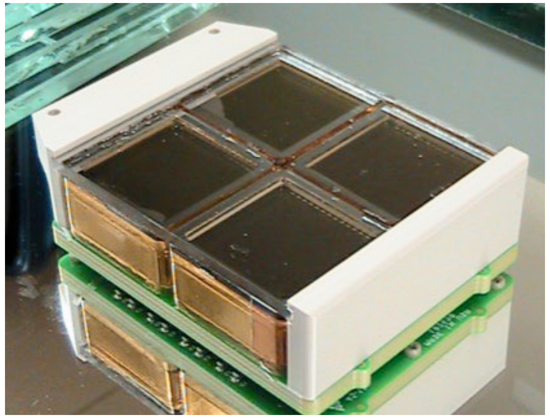
Belle II TOP

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







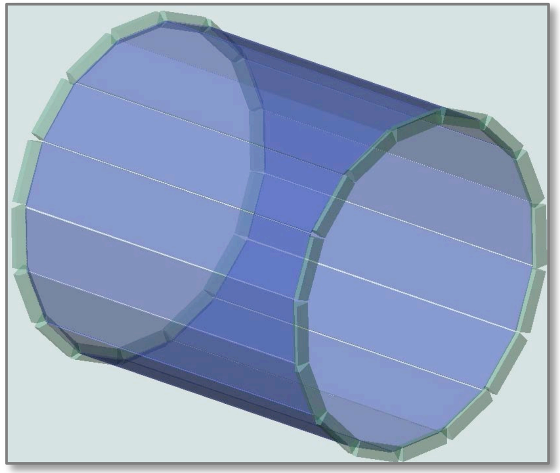


Belle II TOP

Upgrade of Belle detector for high-luminosity Belle II experiment

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

- 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.



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.

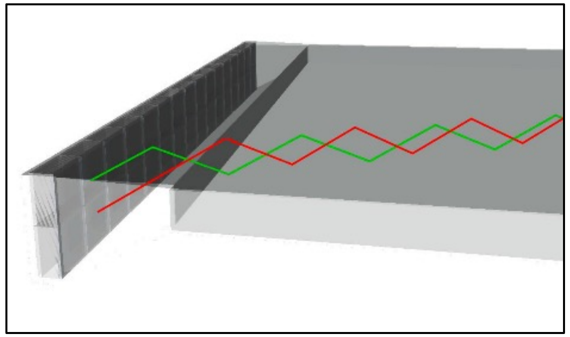
BELLE II TOP

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

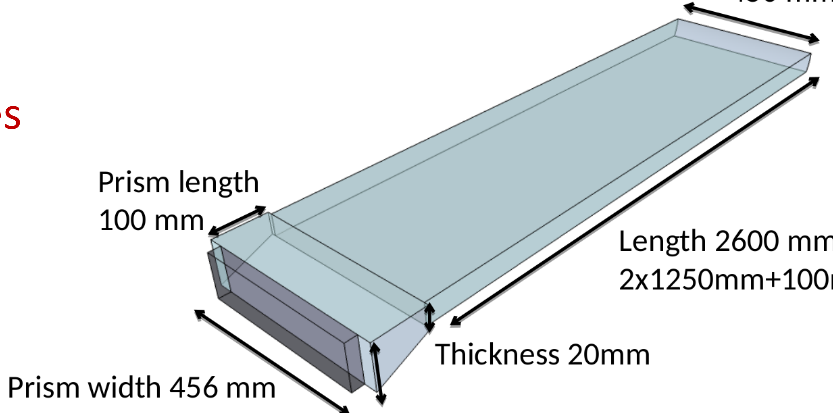
Photon detector: array of 2x16 Hamamatsu SL-10 MCP-PMTs per sector (4x4 pixels each);

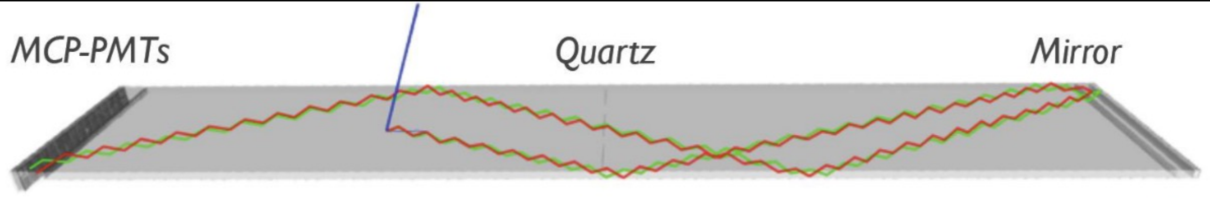
MCP-PMT lifetime issues will require replacement of (most) MCP-PMTs, starting in 2022.

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

Belle II TOP

Y. Arita, QFPU 2013

Early TOP concept: 2-D readout,

x-position (5mm pixels) and time ($\sigma_t \approx 40$ps)

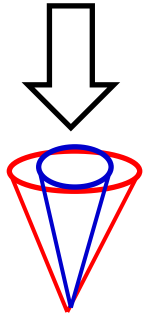
Hit pattern: position vs. time

Ring image animation

Ring image has high sensitivity to incident position and angles of particles.

Ring image of TOP counter

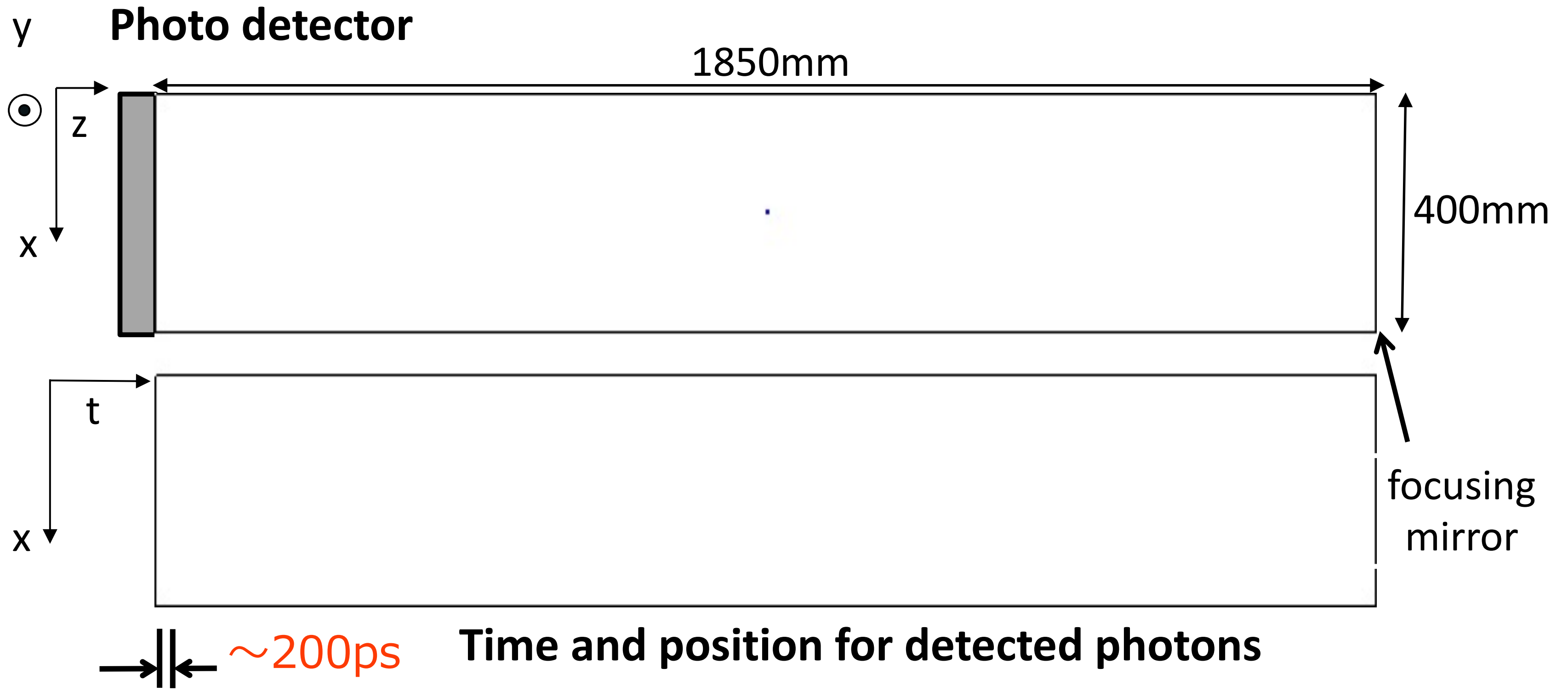
Top view



π/K

→ β are different

$$cos\theta_c = \frac{1}{n\beta}$$



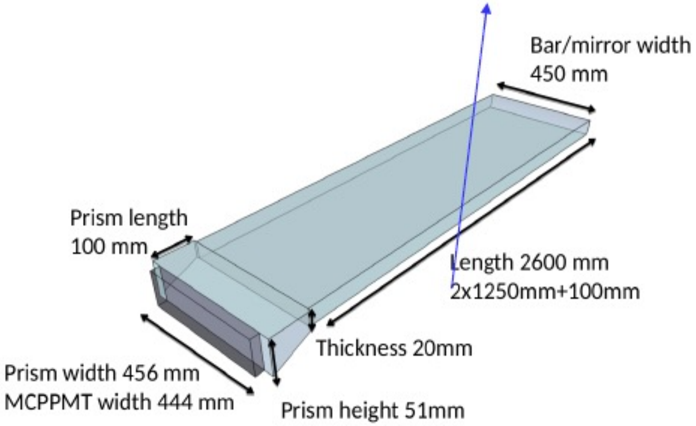
Time and position for detected photons

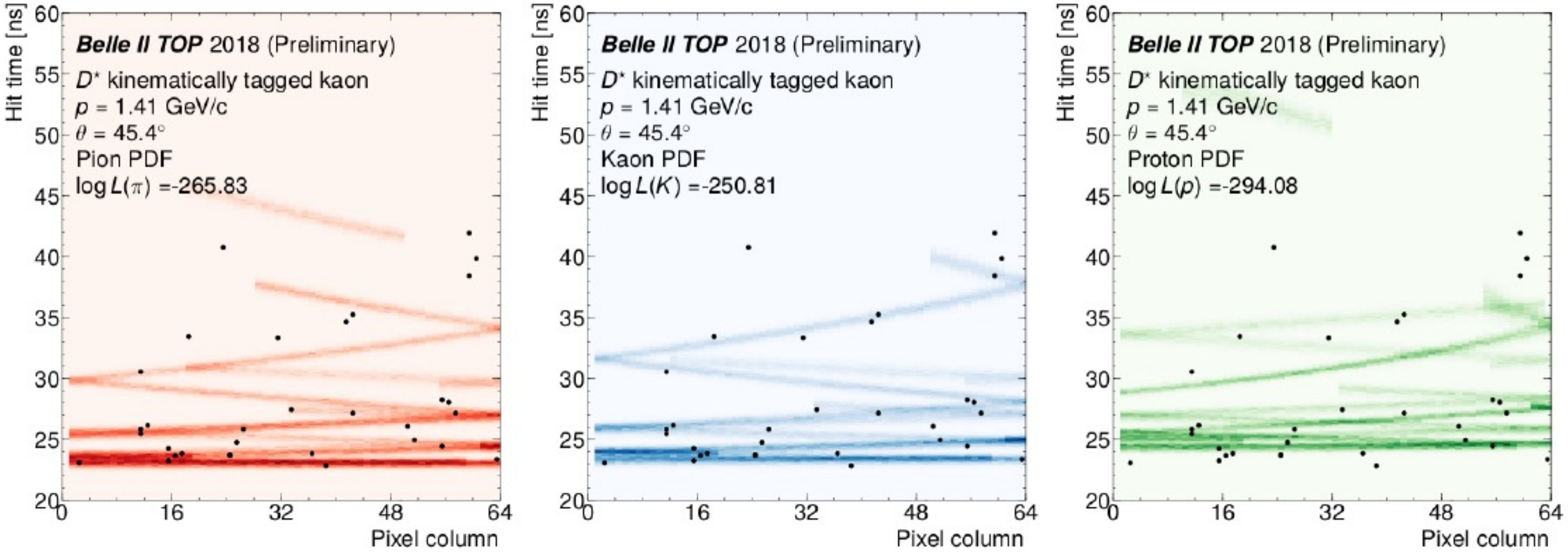
Belle II TOP

G. Varner, DIRC2019

TOP "Cherenkov Rings" II

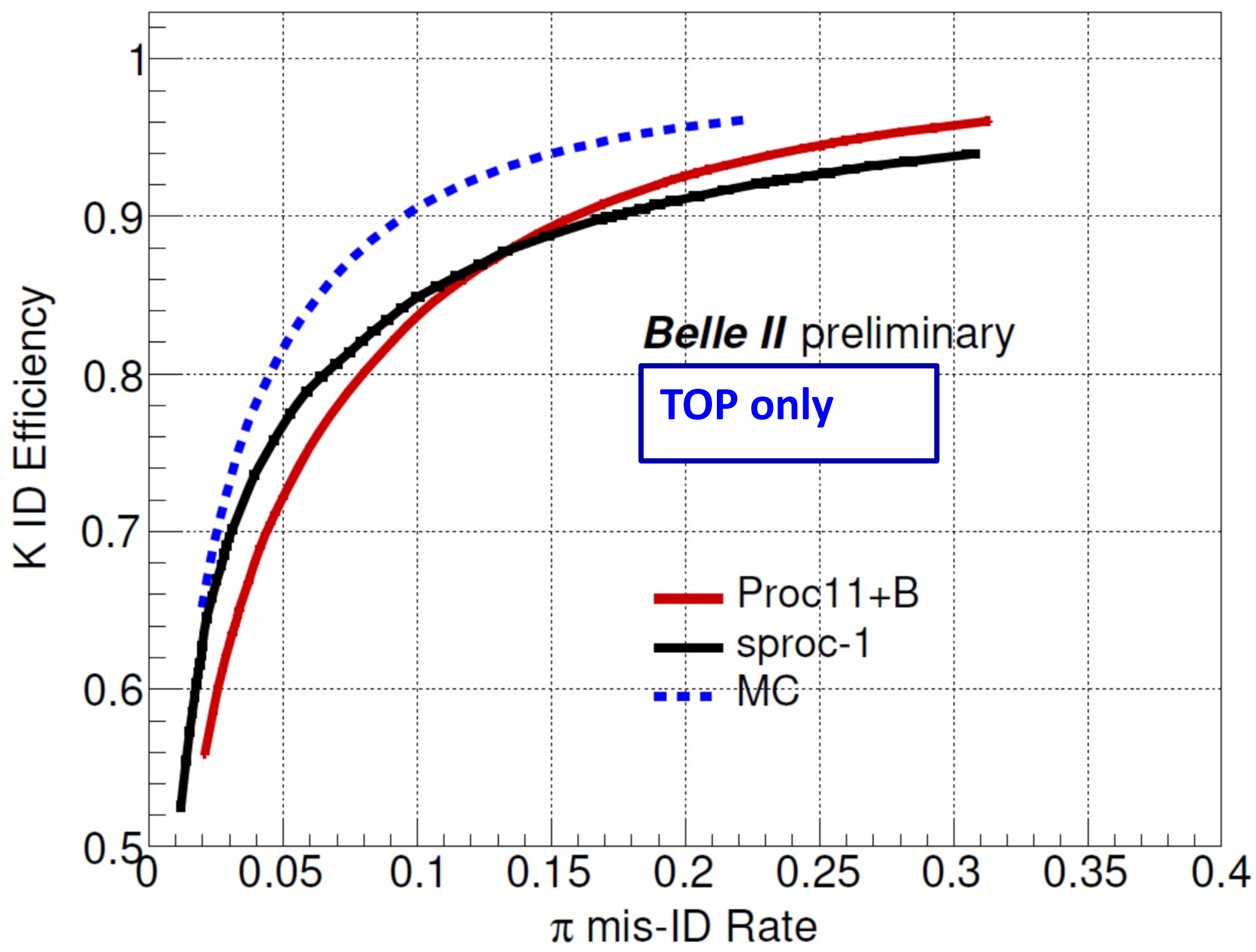
- $D^{*+} \to D^0 \pi_s^+ ; D^0 \to K^- \pi^+$
- Kaon facing mirror-side of TOP bar
  - PDF differences dominated by shape
  - Though for proton, also timing



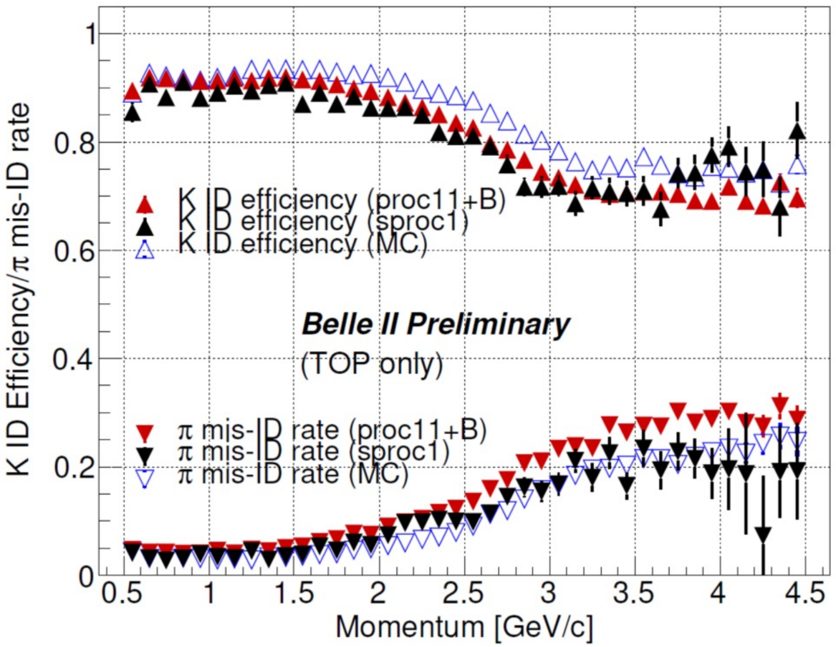


Belle II TOP

G. Varner, May 2021, priv. comm.



- Efficiencies and mis-ID rates measured for kinematically identified pions and kaons approaching simulation expectation



DIRC Reconstruction/PID in Belle II

M. Staric, RICH2010
M. Staric et al. NIMA 639 (2011) 252

Belle II TOP developed innovative time-based imaging concept.

Extended likelihood probability density functions (PDF):

photon time of propagation in plate, mirror, and prism

for every pixel

derived either from simulation (for prototype tests)

or analytically (required for experiment).

For each pixel with hit, compare hit time with PDF for each particle type.

Full likelihood:

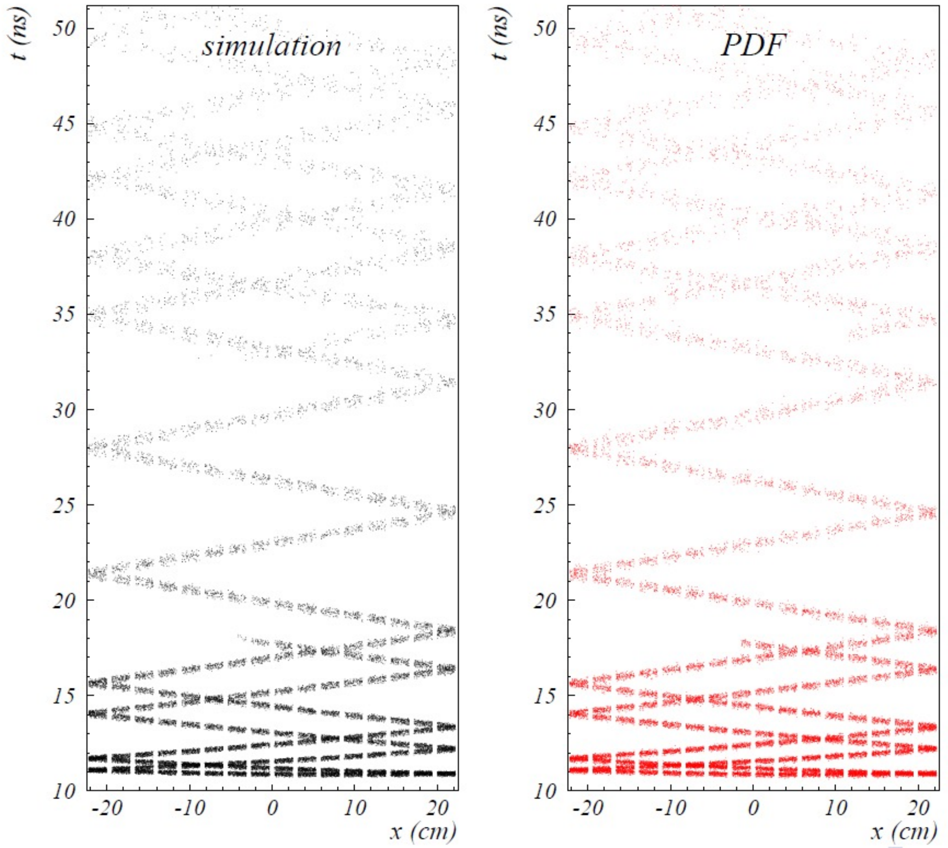
$$L_H = \prod_N \mathrm{pdf}(x_i, y_i, t_i; H) \times P_{N_0}(N)$$

Describes complex features of the hit pattern very well.

Prism and focusing optics add additional complication for analytical method.

(Detailed performance studies underway for Belle II and PANDA.)

pure TOP counter: comparison of PDFs simulation vs. analytical calculation

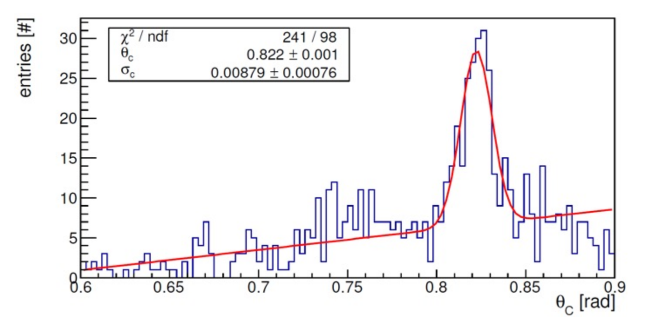


DIRC RECONSTRUCTION/PID IN PANDA

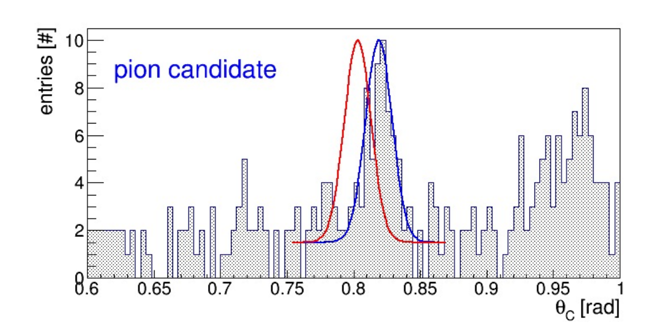
R. Dzhygadlo, CHEP2019

Examples of reconstruction/PID methods from PANDA Barrel DIRC

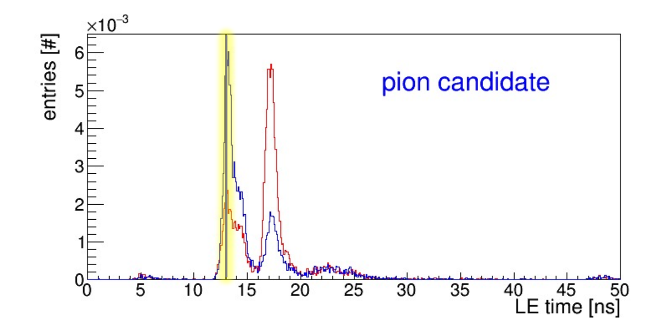
- track-by-track fit of single photon Cherenkov angle distribution based on look-up tables to extract track Cherenkov angle ("BABAR-like")



- 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)



- first attempts using advanced AI/ML techniques underway

ECFA European Committee for Future Accelerators

DIRC RECONSTRUCTION/PID IN PANDA

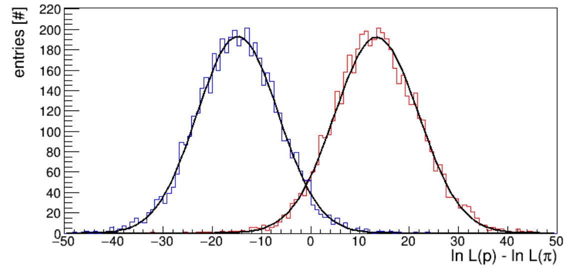
PANDA Barrel DIRC prototype, CERN 2018, 20° polar angle
7 GeV/c π/p beam, equiv. to 3.5 GeV/c π/K

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)
- first attempts using advanced AI/ML techniques underway

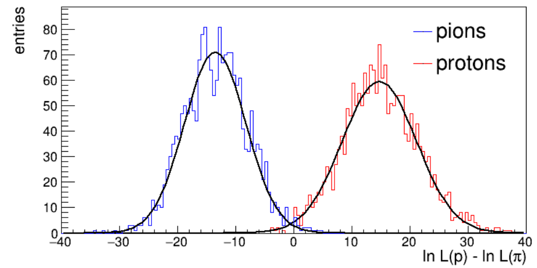
geometrical reconstruction

π/K separation: 3.5 s.d.

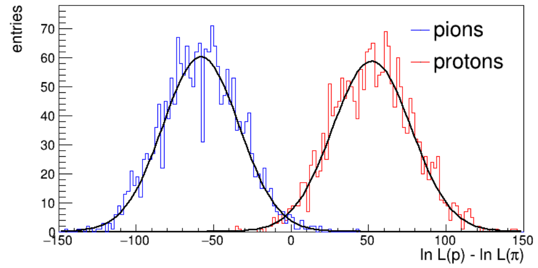


time imaging

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

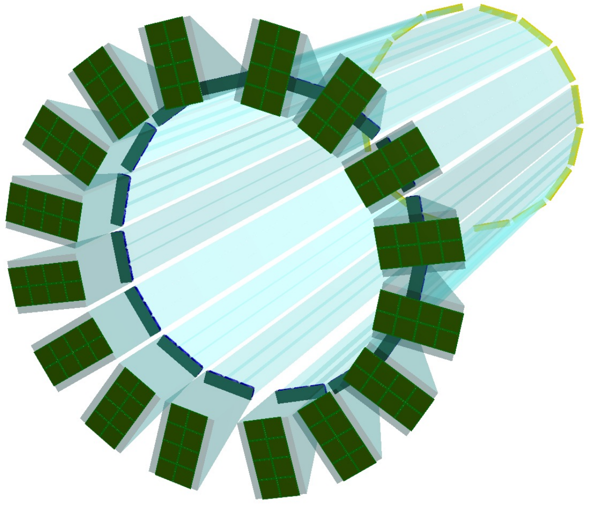


beam data PDF: π/K separation: 4.8 s.d

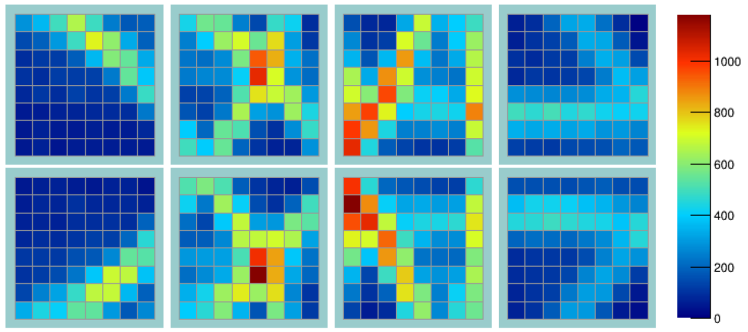


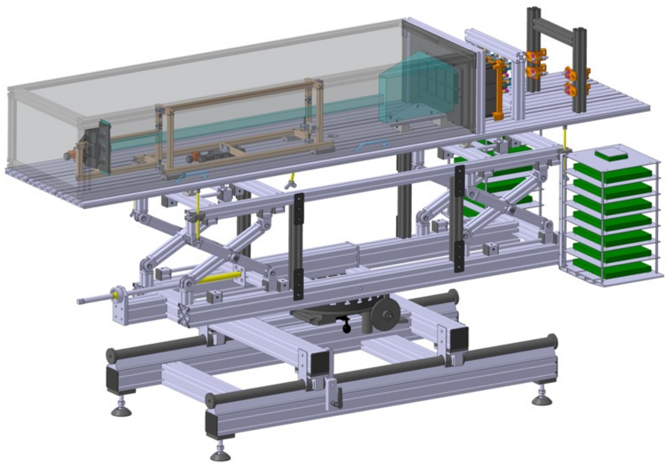
R. Dzhygadlo, CHEP2019

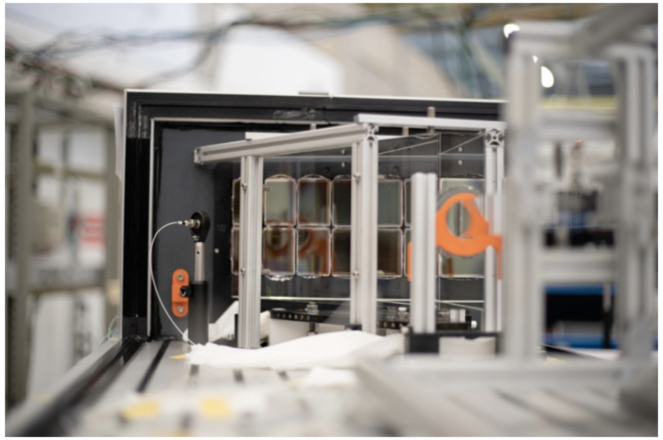
- [x] compact photon camera
- [x] spherical lens focusing
- [x] small pixels (MCP-PMT)
- [x] fast photon timing
- [x] dispersion mitigation



PANDA Barrel DIRC



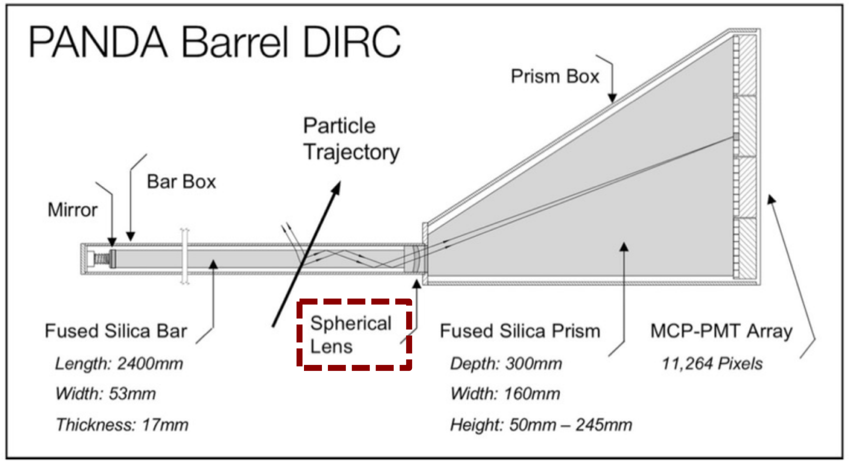




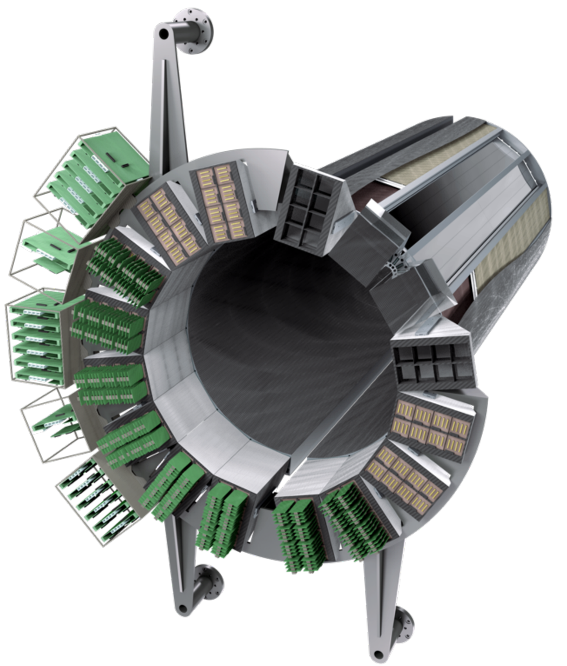
PANDA Barrel DIRC

- 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, Cham., 2020

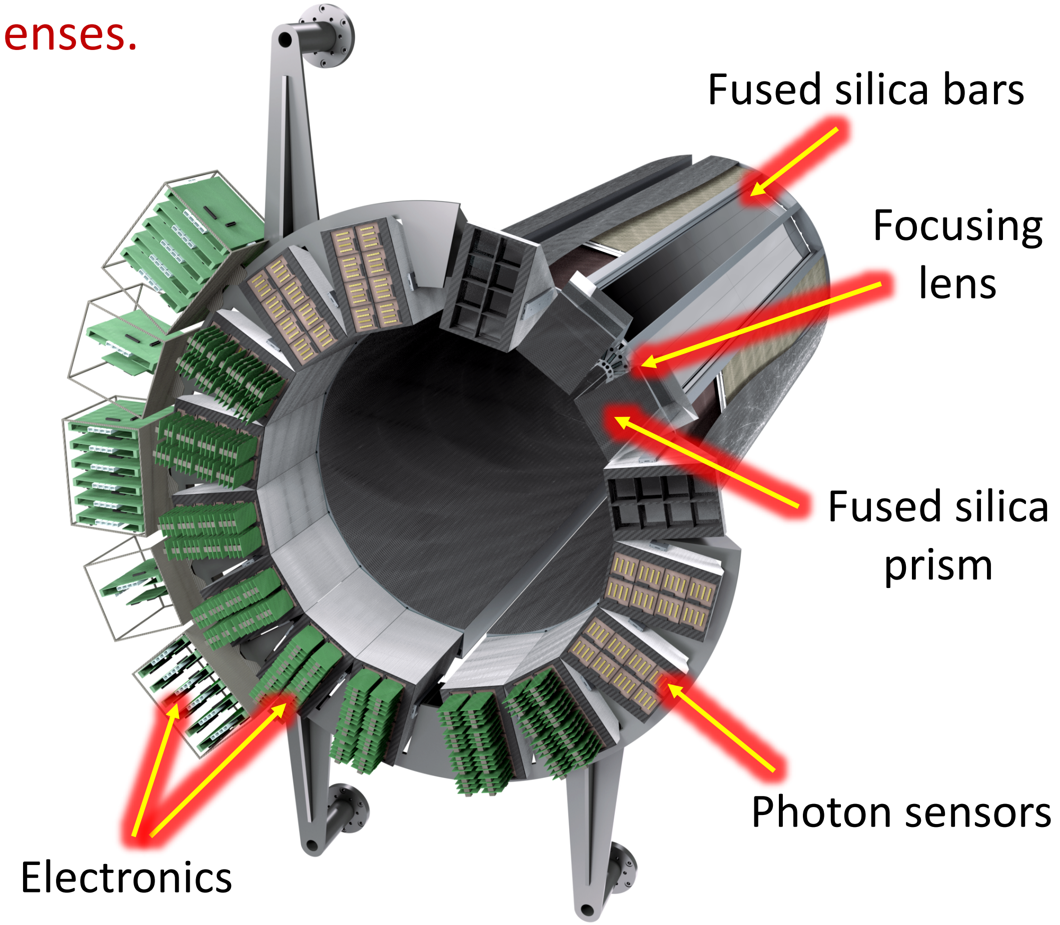


PANDA Barrel DIRC TDR
J. Phys. G: Nucl. Part. Phys. 46 045001
arXiv:1710.00684

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

Expected performance from detailed Geant4 simulation:

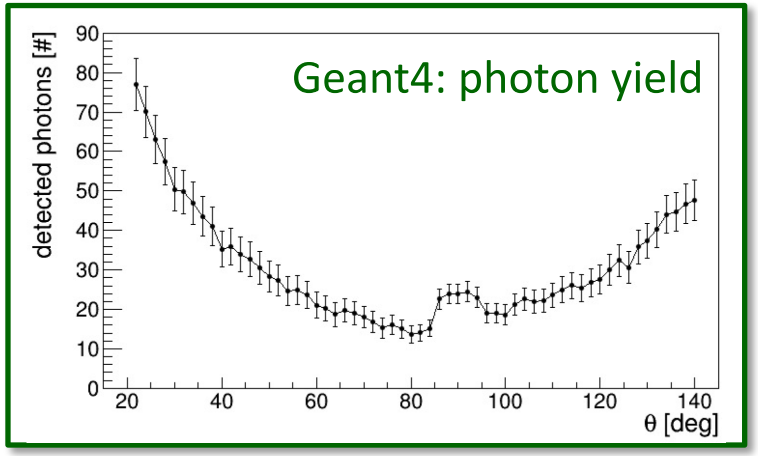
Used geometrical reconstruction (BABAR-like) to determine

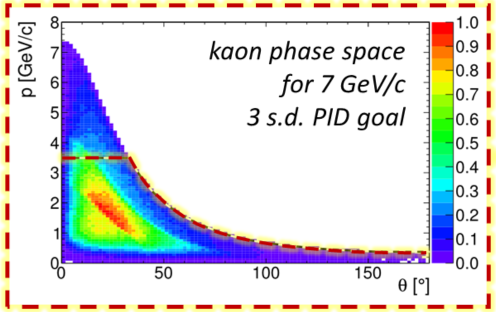
photon yield and single photon Cherenkov angle resolution (SPR).

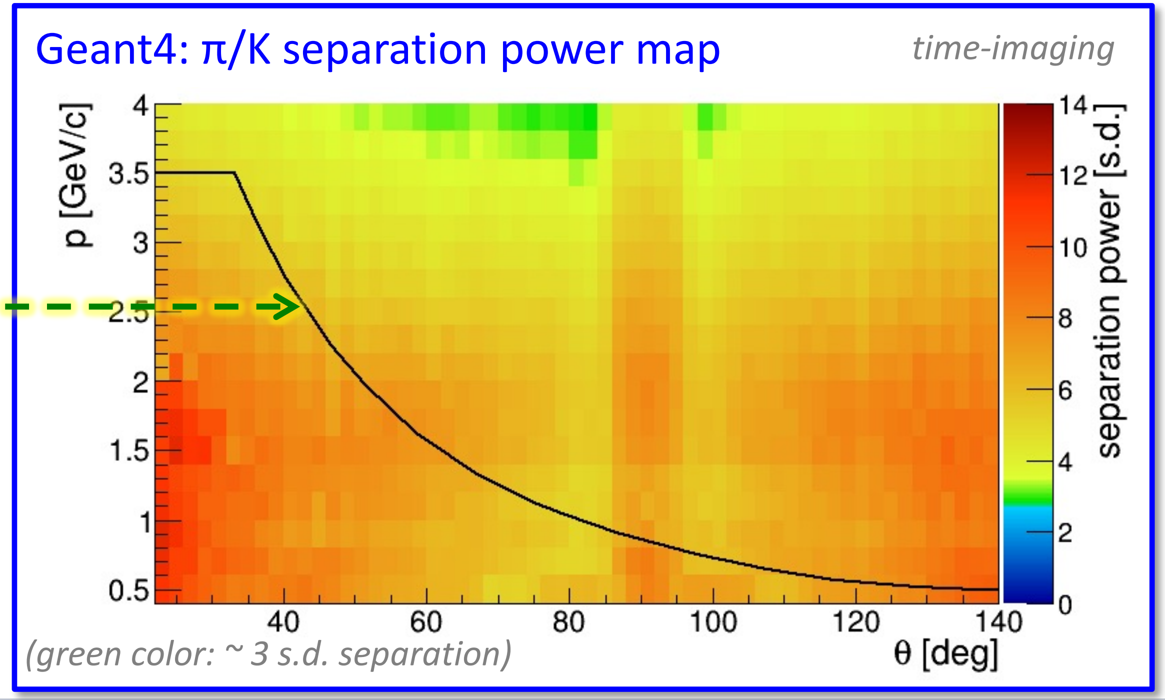
Latest generation of MCP-PMTs will further increase photon yield by up to 50%.

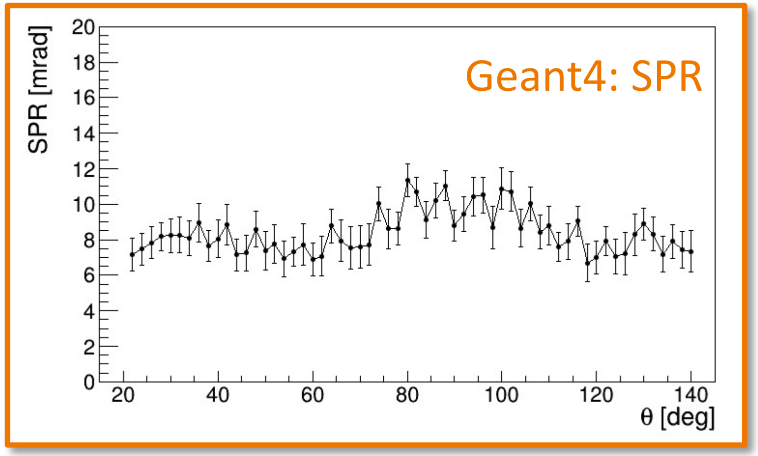
Time-imaging delivers best performance for π/K separation power map,

PANDA PID performance goal exceeded for entire phase space









R. Dzhygadlo, priv. comm.

Lens Focusing

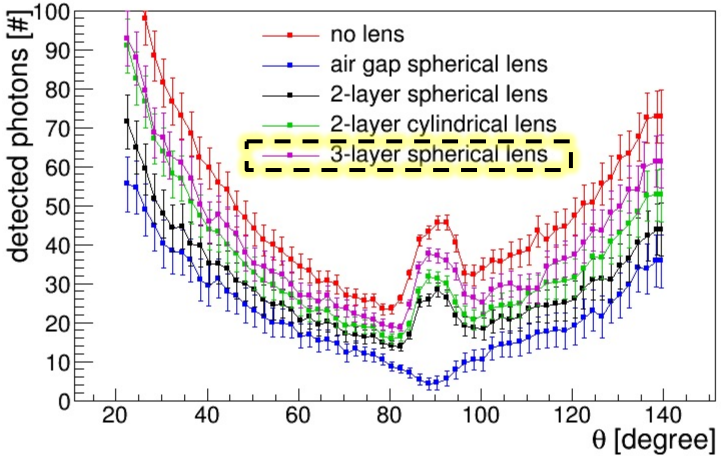
Technical challenge: lens focusing

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

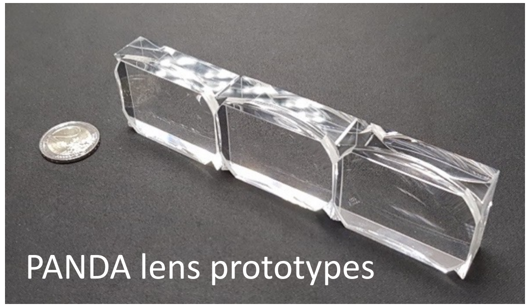
Geant4 simulation: photon yield

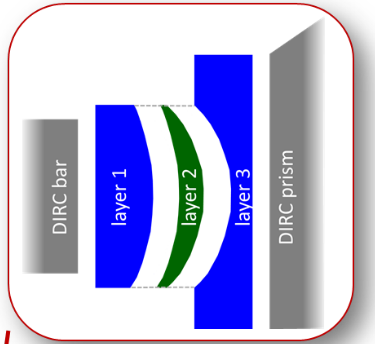


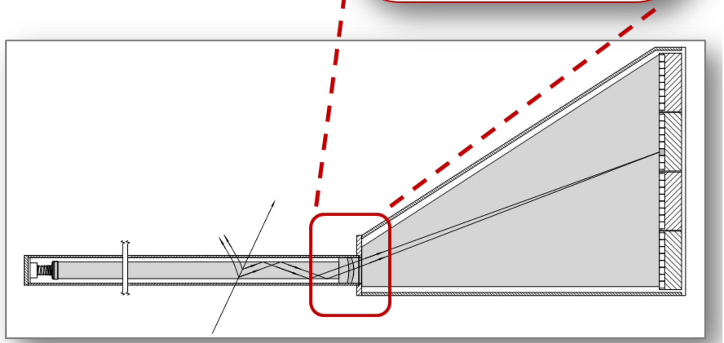
Innovative solution:

- 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





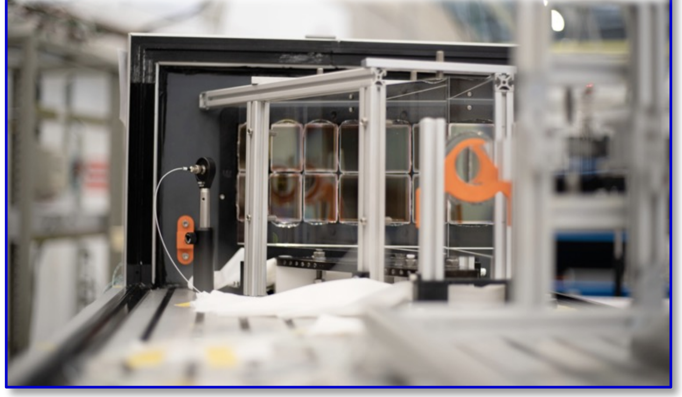
- Creates flat focal plane – matched to fused silica prism shape
- Avoids photon loss and barrel PID gap
- Lanthanum crown glass (LaK33B) for PANDA, rad-hard sapphire or PbF_2 for EIC
- Currently using standard spherical shapes – study aspherical shapes for future DIRCs to minimize aberrations?

see also G. Kalicy, DIRC2019

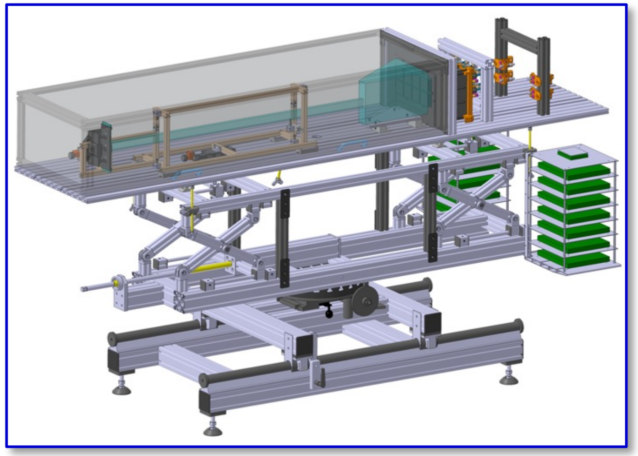
Performance validation: 2018 prototype at CERN PS

- Narrow fused silica bar, 3-layer spherical lens
- 30 cm-deep fused silica prism
- 2x4 PHOTONIS Planacon MCP-PMT array
- PiLas picosecond laser calibration system
- 7 GeV/c π/p beam equivalent to 3.5 GeV/c π/K
- MCP-TOF system to cleanly tag π and p events

View from inside the Barrel DIRC dark box

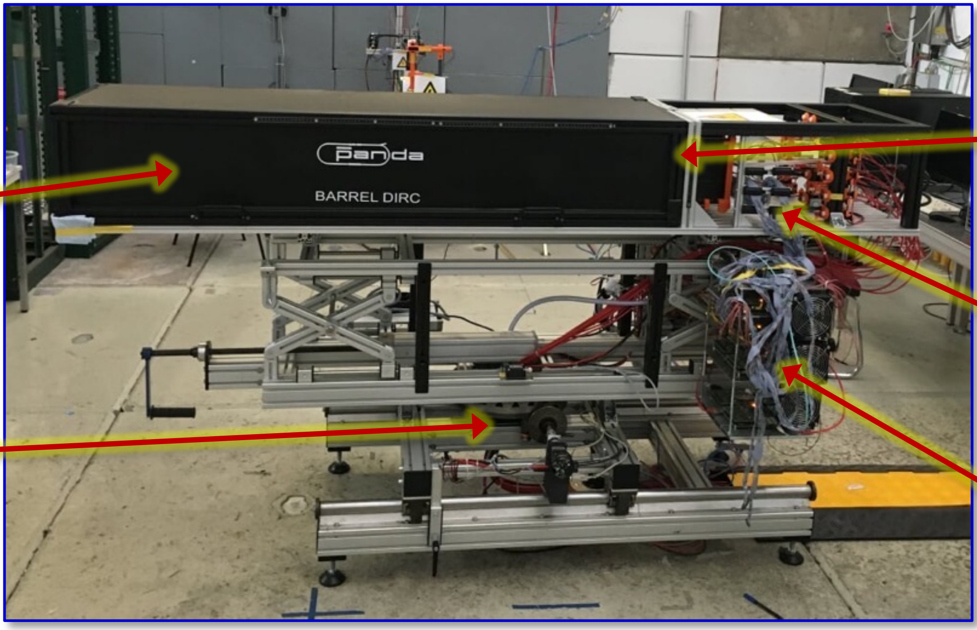


Schematic view of 2018 prototype



Dark box for optics (bar, lens, prism)

Rotation stage (remote controlled)

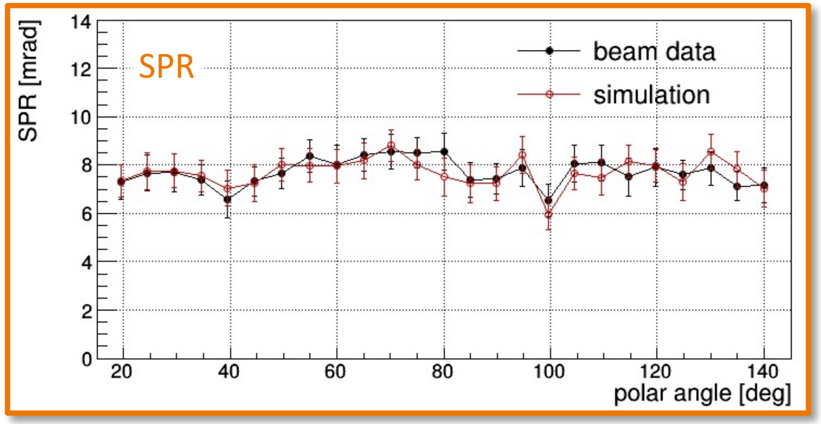


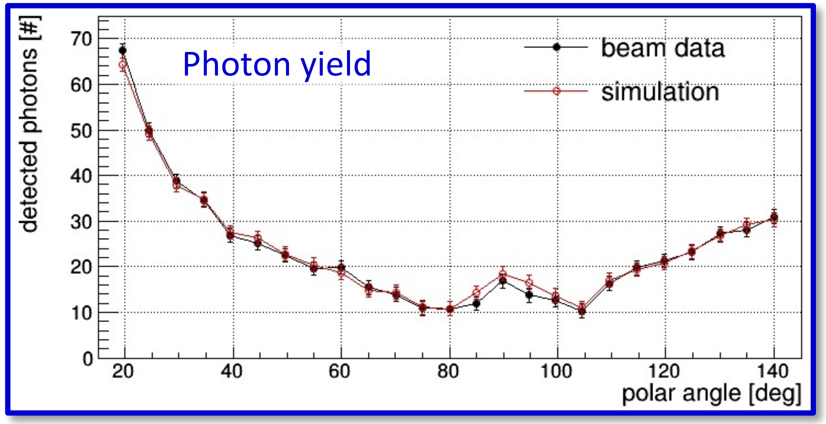
MCP-PMT array

Frontend electronics (PADIWA) (air-cooled)

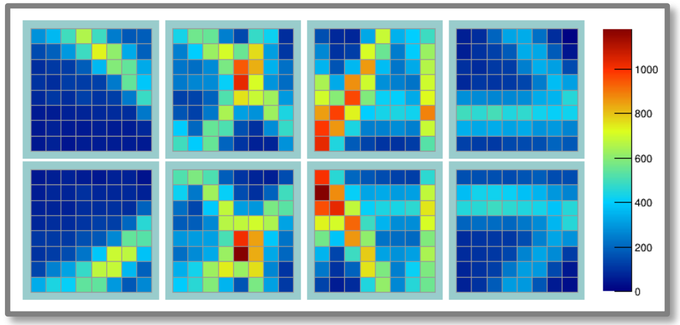
DAQ boards (TRB)

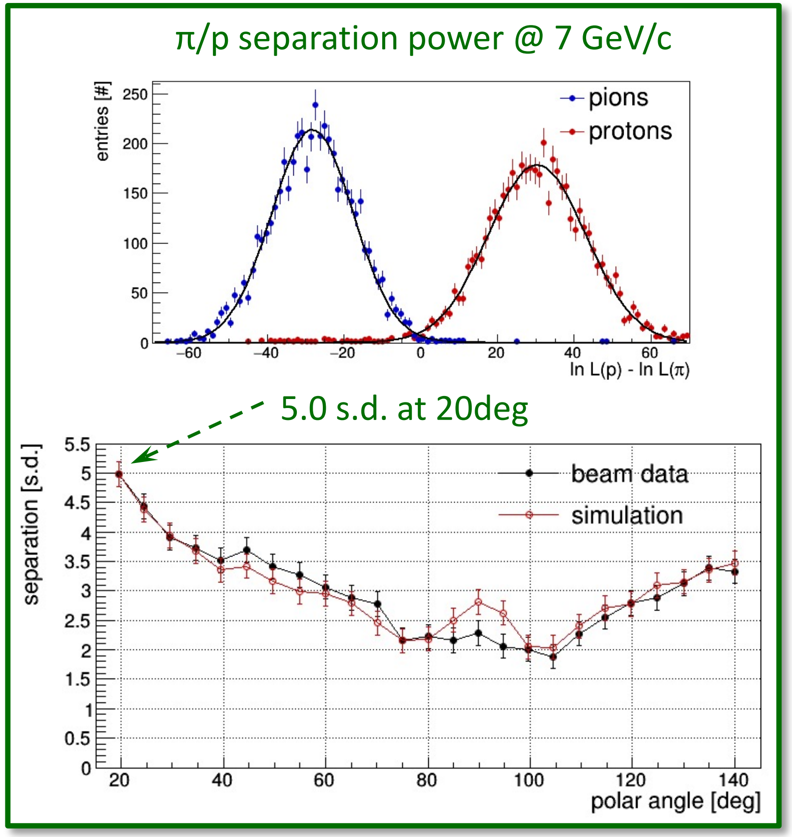
Performance validation: 2018 prototype at CERN PS





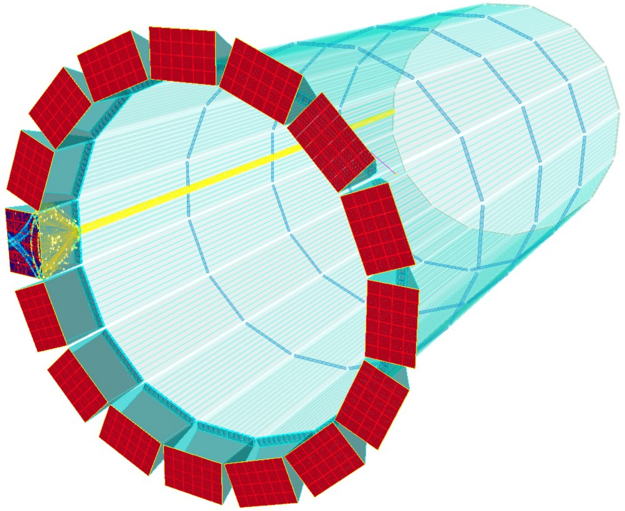
observed hit pattern at polar angle 20°





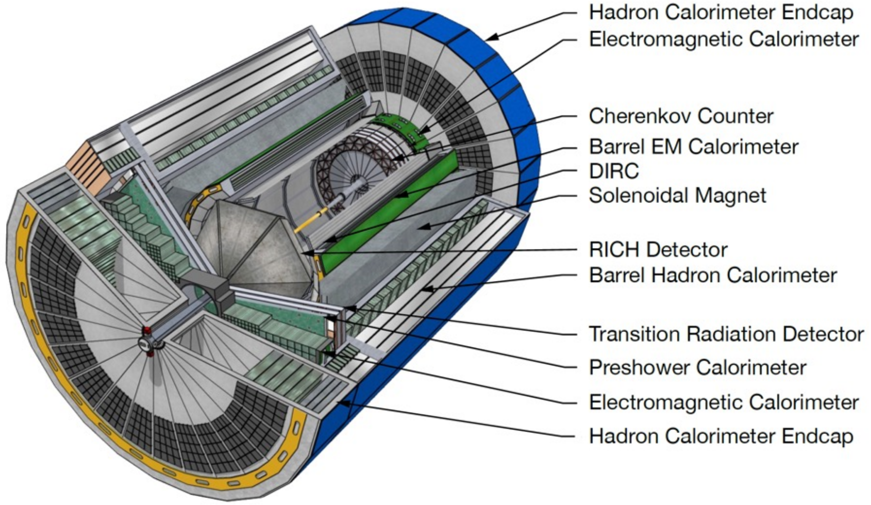
- Scans of beam incident angle and position for different momenta
- Measured Cherenkov angle resolution per photon (SPR), photon yield, and π/K separation in excellent agreement with expectation and Geant4 simulation
- Achieved π/K separation power of N_{sep}=5.0 s.d. with time imaging reconstruction 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 high-performance DIRC

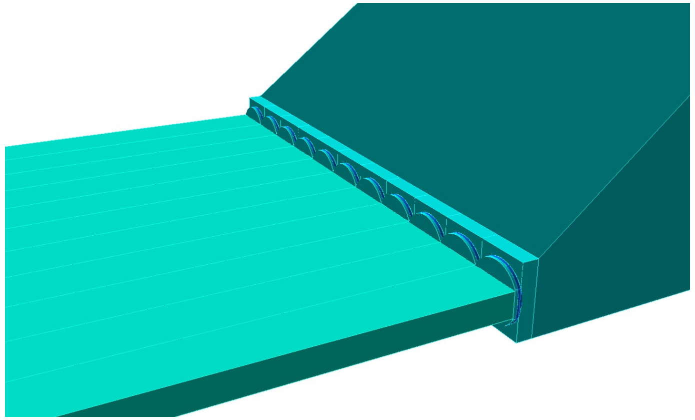
R. Dzhygadlo, priv. comm.



EIC High-Performance DIRC

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



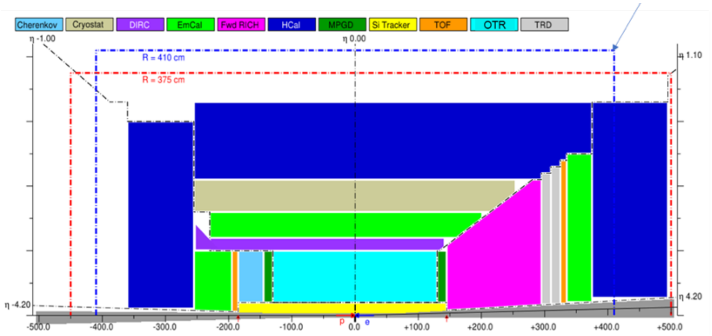


EIC Yellow Report, arXiv:2103.05419

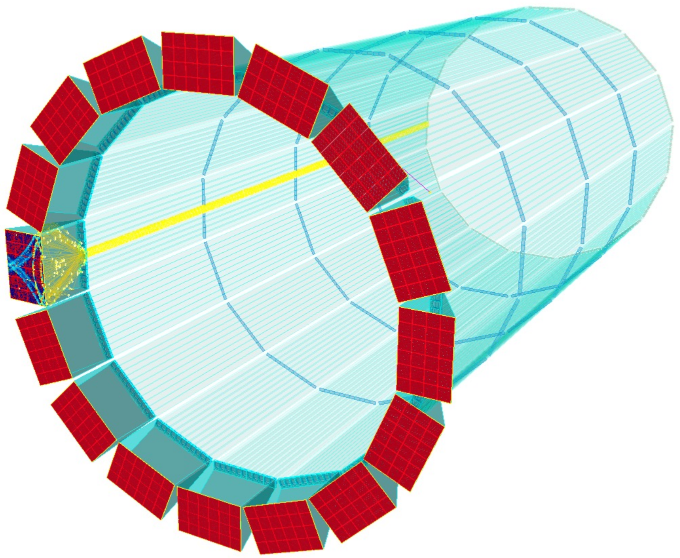
EIC High-Performance DIRC (hpDIRC)

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

- being developed by the EIC PID consortium (eRD14), EIC generic detector R&D program;
- 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 ≤ η≤ +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;
- radiation-hard 3-layer spherical lens;
- high-precision tracking, expect 0.5mrad polar angle resolution;
- post-DIRC tracking layer (MPGD) for multiple scattering mitigation;
- selected as baseline hadron PID system for EIC detector barrel (reference detector).



EIC Yellow Report, arXiv:2103.05419

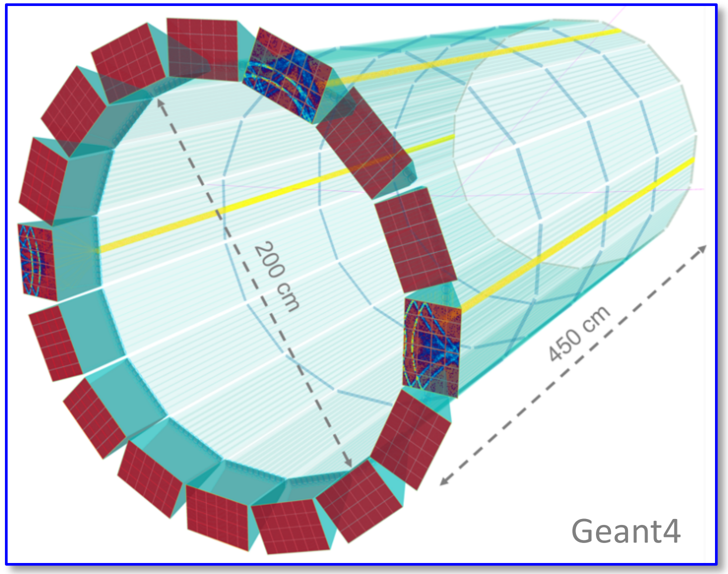


EIC High-Performance DIRC

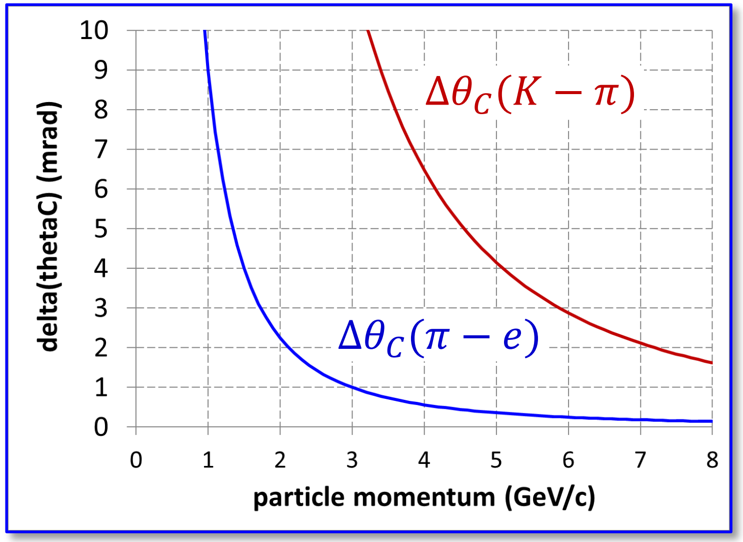
Initial generic design

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

- Details of bar width and length, number of sectors, will depend on specific design of EIC experiment proposal (working with CORE, ECCE, EIC@IP6)
- Focusing optics: innovative radiation-hard 3-layer spherical lens
- Compact expansion volume: 30cm-deep solid fused silica prisms
- Sensors and fast high-density electronics being studied within the same eRD14 EIC PID consortium
- Leading contender for sensor: lifetime-enhanced MCP-PMTs with small pixels (3mmx3mm), else SiPM if magnetic field is too high
- Leading contender for readout electronics: waveform-sampling electronics, next-gen version of Belle II TOP readout
- Full Geant4 simulation based on validated PANDA Barrel DIRC code
- Validation with prototype in cosmic muons and particle in preparation

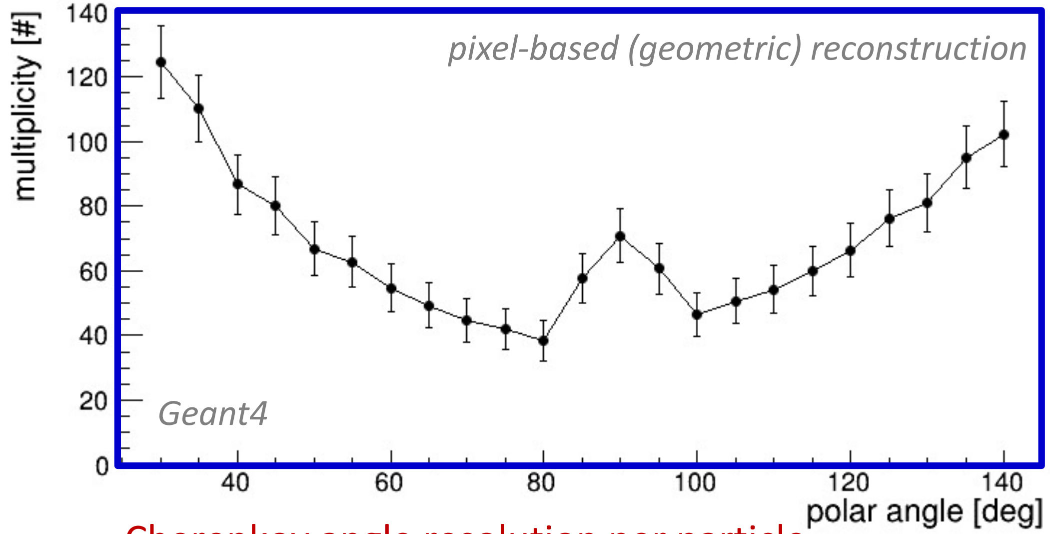


DIRC π/K, e/π Cherenkov angle difference

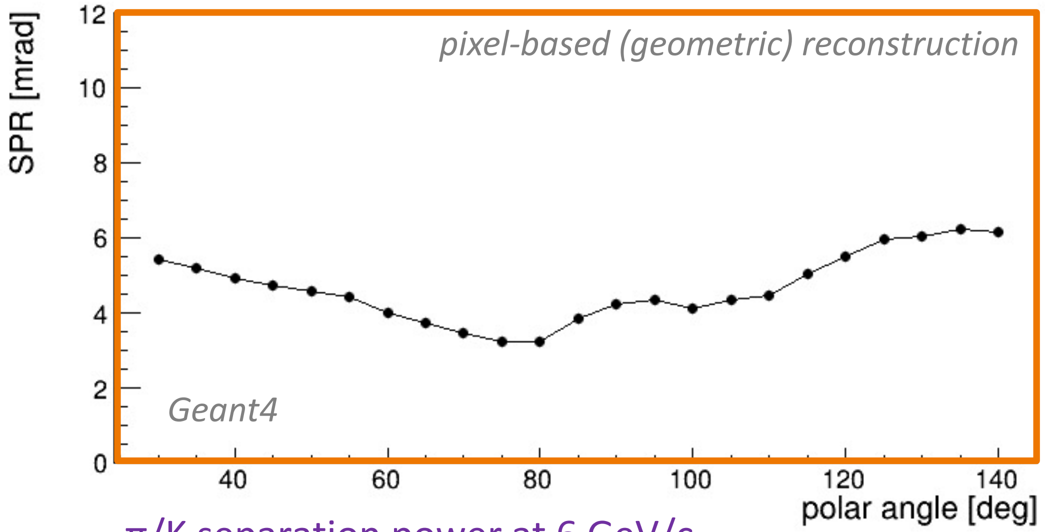


EIC High-Performance DIRC

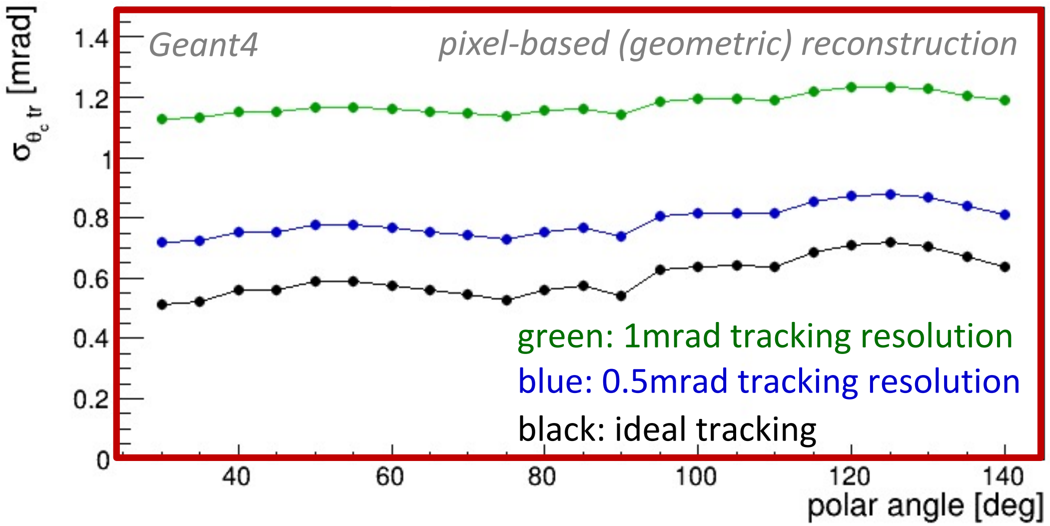
Photon yield per particle



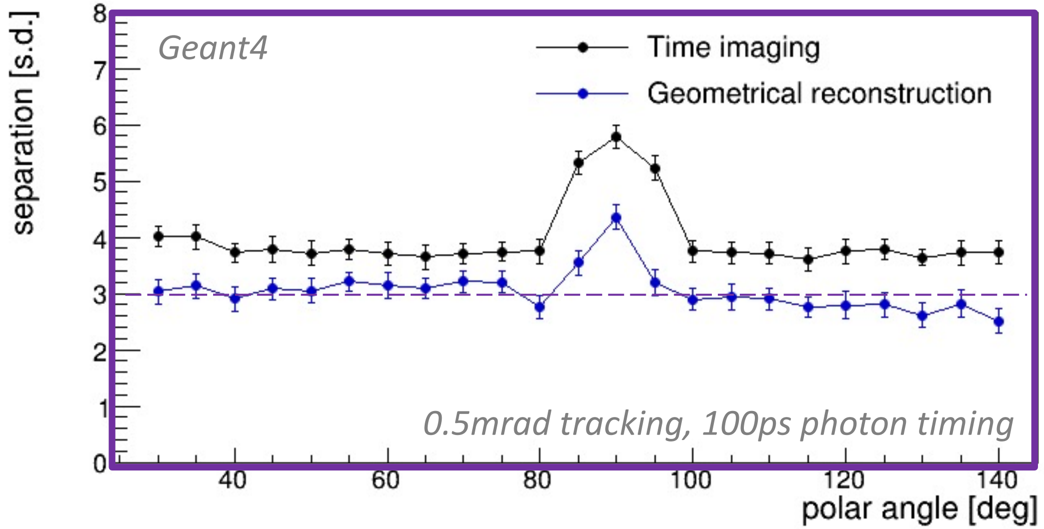
Cherenkov angle resolution per photon (SPR)



Cherenkov angle resolution per particle



π/K separation power at 6 GeV/c



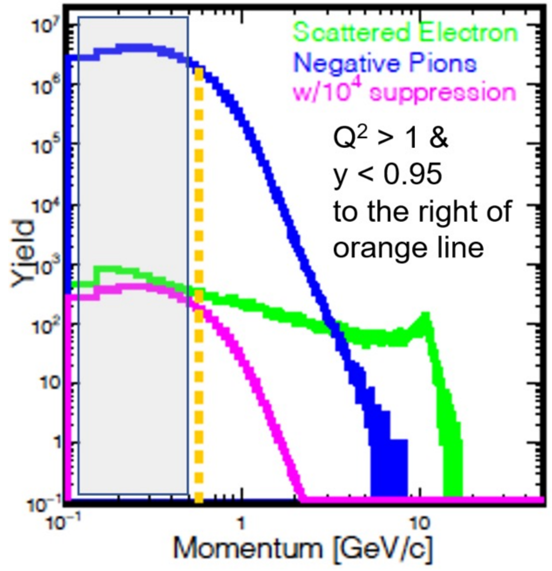
→ 3 s.d. π/K separation at 6 GeV/c and 1 mrad Cherenkov angle resolution seems to be in reach

JS, eRD14 report, BNL, Mar 2021

Challenge: e/π separation at low momentum

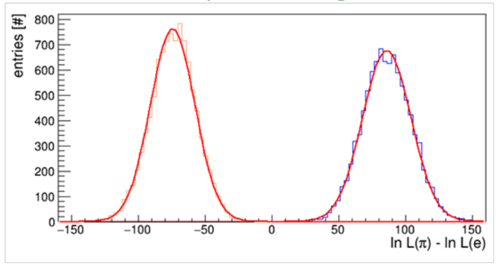
- Yellow report effort identified need for supplemental e/π suppression from PID systems to support EM calorimeter at lower momentum
- Simulation shows that ID of scattered electron requires $O(10^4)$ suppression of large pionic background
- hpDIRC e/π performance at low momentum very different from high-momentum domain, dominated by multiple scattering (MS) and EM showers in DIRC bars
- 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 additional MPGD tracking layer outside DIRC radius starting (also expected to further improve high-momentum π/K separation)

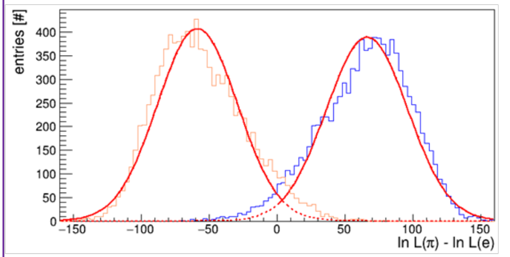
-1.0 < η < 0.0 (half of DIRC Barrel)



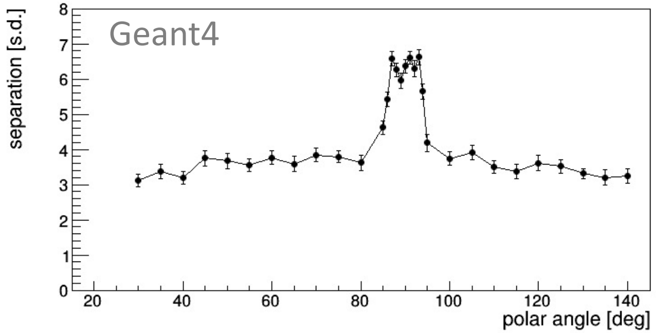
CORE simulation, B. Schmookler

Example from Geant4
e/π log-likelihood difference
1 GeV/c momentum,
30° polar angle,
0.8mrad tracking resolution

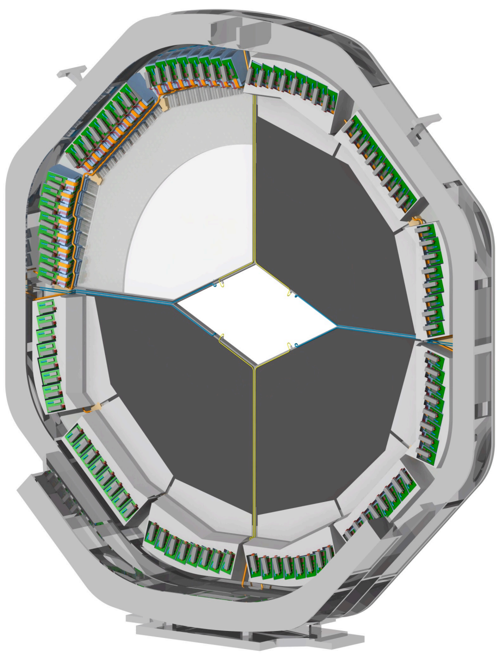




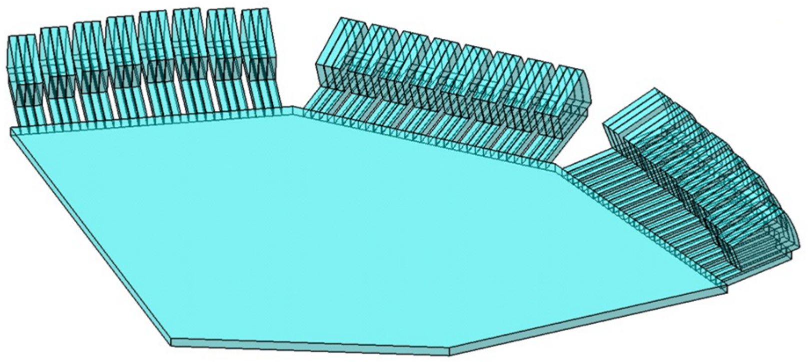
hpDIRC e/π separation at 1.2 GeV/c without MS mitigation

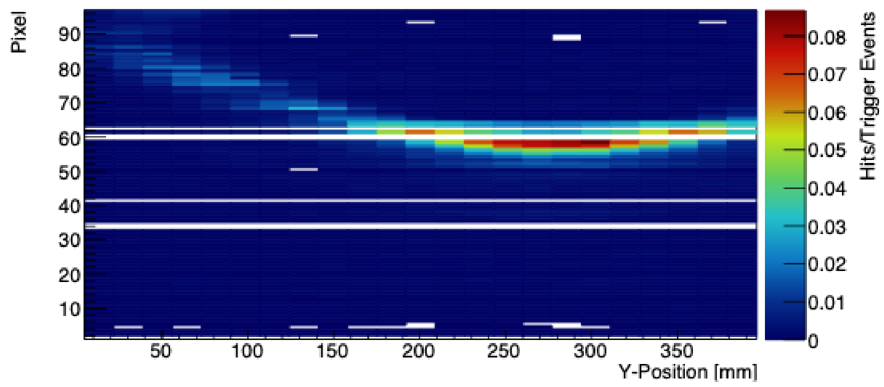


- compact photon camera
- cylindrical mirror focusing
- small pixels (MCP-PMT)
- fast photon timing
- endcap geometry



PANDA Endcap Disc DIRC

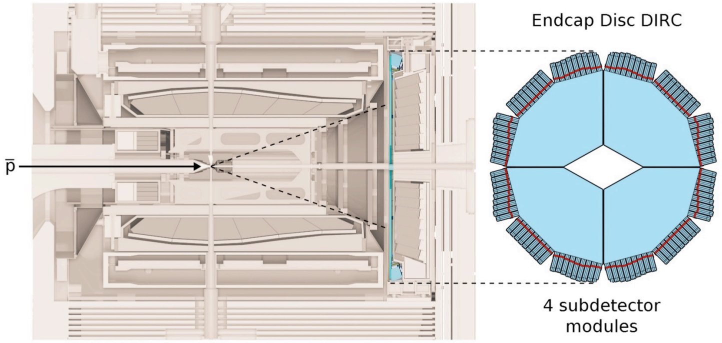


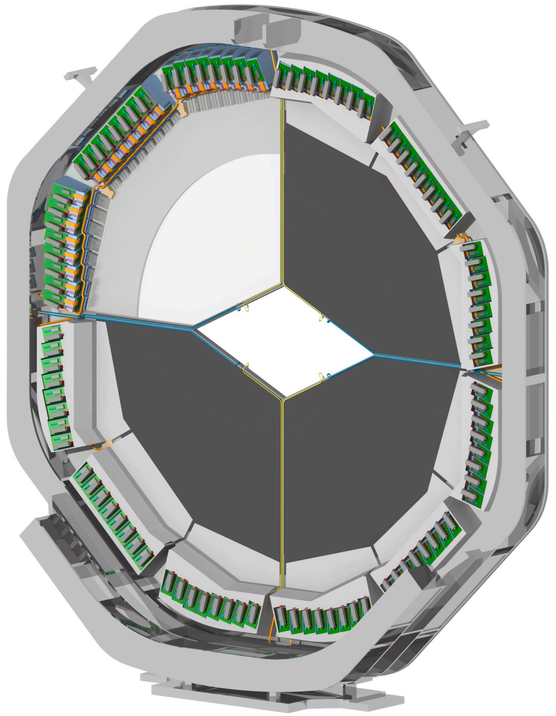


PANDA Endcap Disc DIRC (EDD)

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

- 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

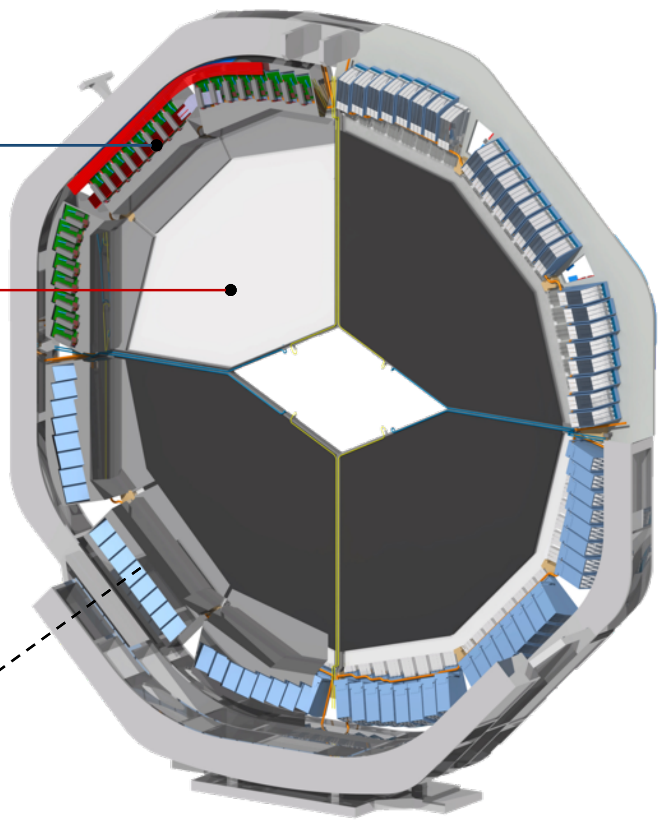
Optics made of synthetic fused silica

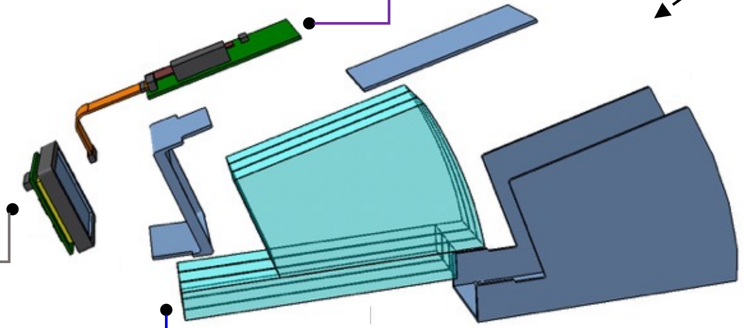
4 independent quadrants

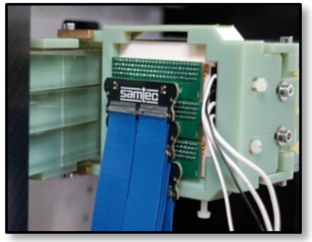
Focusing elements convert angle to position information

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

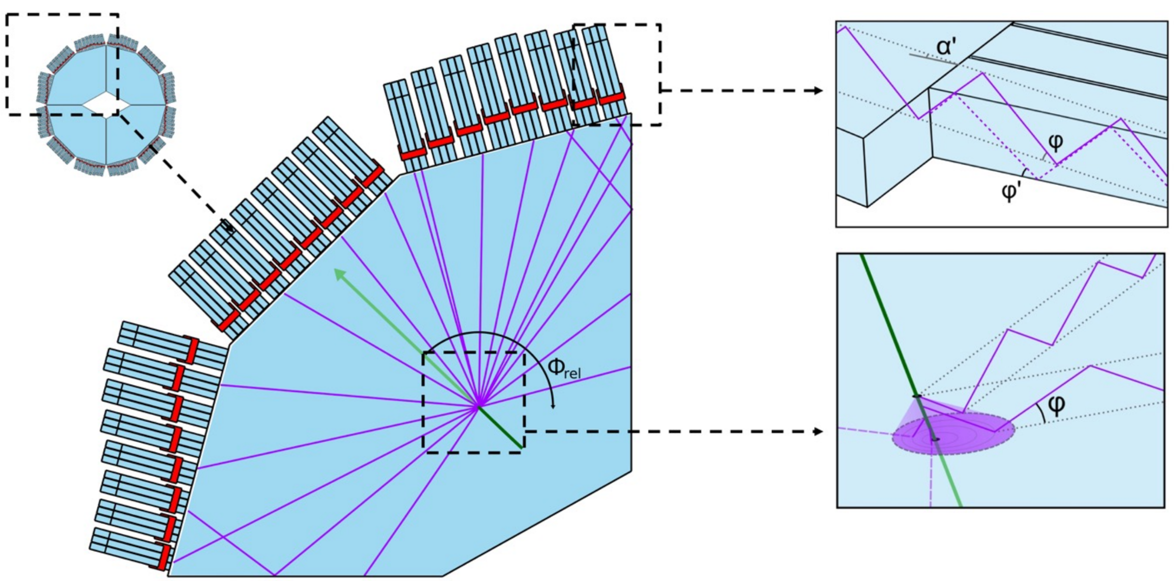
Novel design, validated with particle beams since 2016.

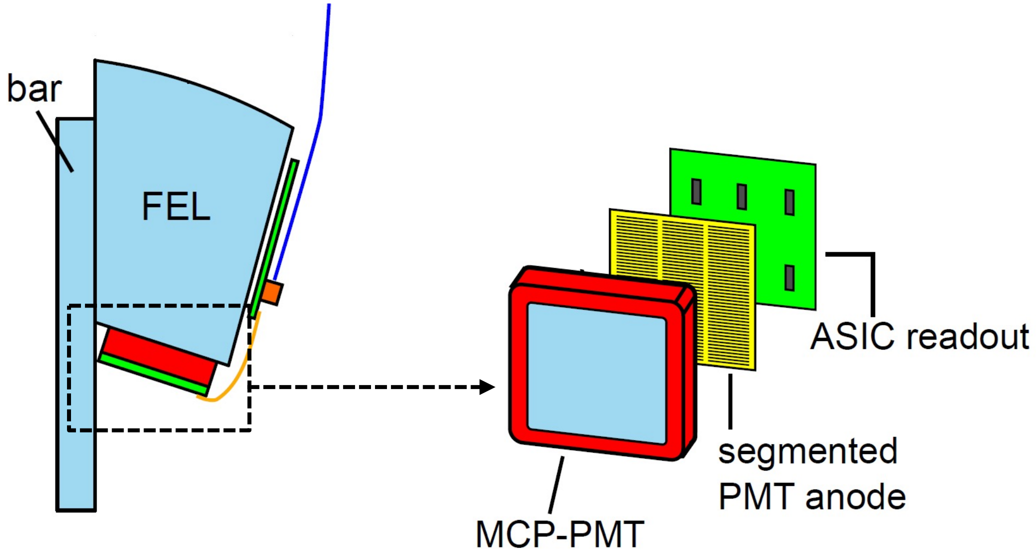
goal: first-of-series quadrant in 2025

TDR available at arXiv:1912.12638

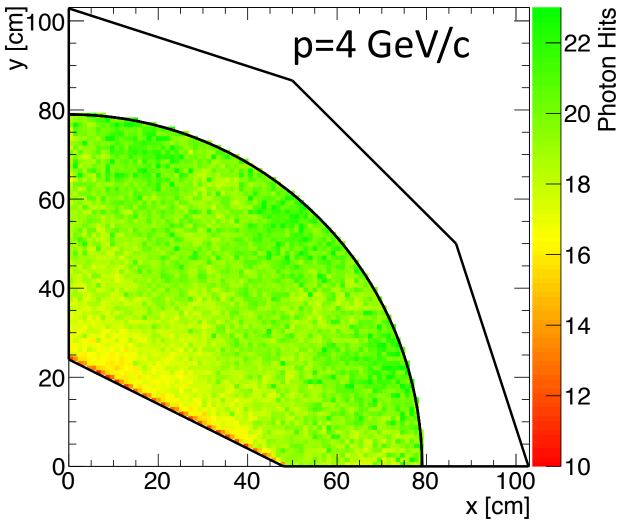
J.S. RICH2018

PANDA ENDCAP DISC DIRC

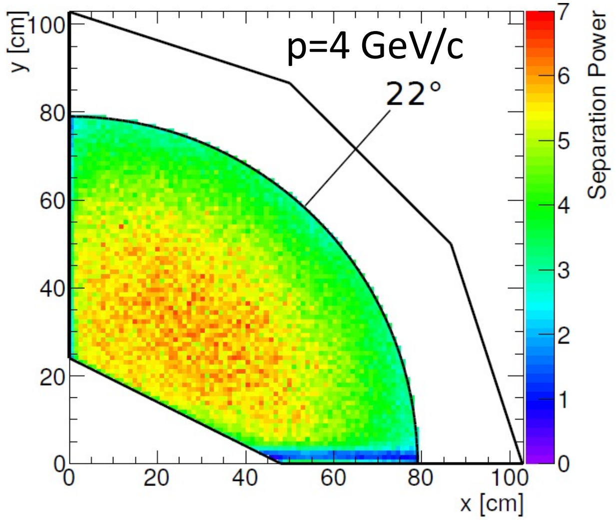




Photon yield (Geant)



π/K separation power (Geant)



- Analytical reconstruction

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

- Simulation expects about 20 detected photons per charged particle
- Expect to except 3 s.d. separation power goal for almost the entire active area

Additional information, including prototype test beam results, see C. Schwarz, INSTR20

DIRC Sensor Requirements

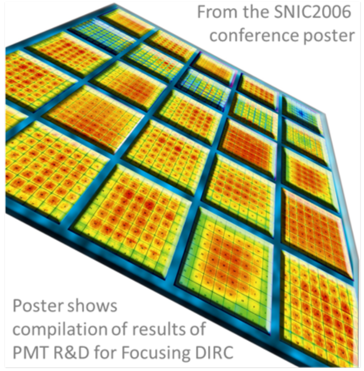
Sensor development has been crucial to DIRC progress

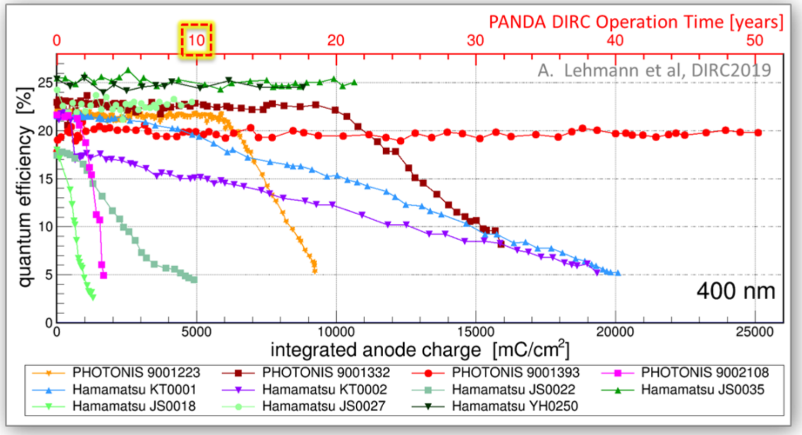
Main development goals: Smaller pixels and faster single photon timing

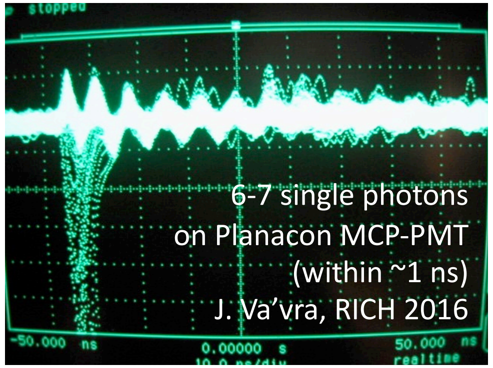
- reduces sensitivity to backgrounds
- improves Cherenkov angle resolution per photon
- allows chromatic dispersion mitigation
- anode design needs to match required angular resolution
  (required pitch may be asymmetric – see PANDA EDD)

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?)







DIRC Sensor Requirements

Sensor development has been crucial to DIRC progress

Single photon detection

- excellent rms timing precision more important than TTS
- reduce tails in timing distribution

High photon yield (up to 100 photoelectrons per particle)

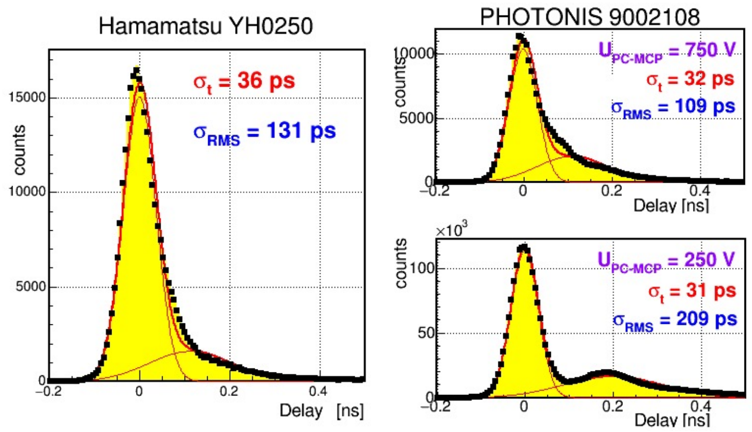
- need pixelated readout to determine position without ambiguities
- need tolerance for high occupancy per sensor

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

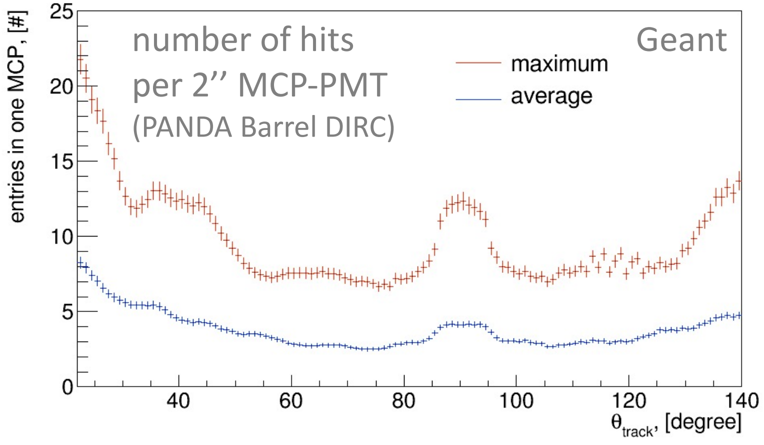
- need low noise rates (coincidence timing very difficult/impossible to use)

Leading candidates: MCP-PMT and SiPM

- see detailed discussion of both sensors types later today



A. Lehmann
RICH2018



J.S.
ANL MCP-PMT Workshop 2014

DIRC Design Ideas

What about a design based on the "best of..." of DIRC design 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.

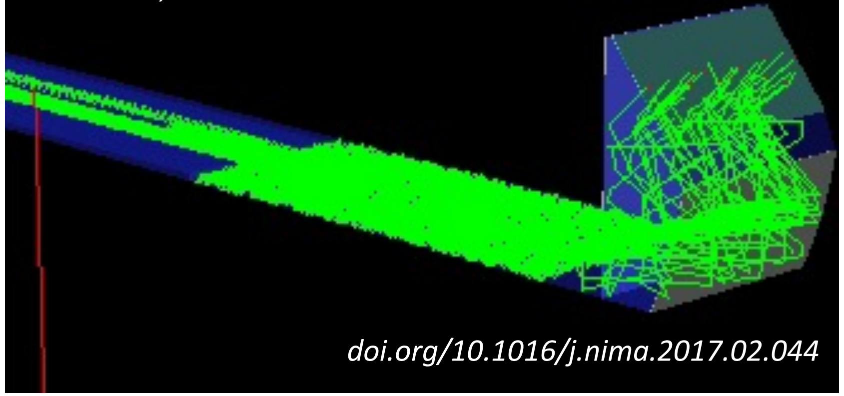
Best of both worlds:

- 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 so far

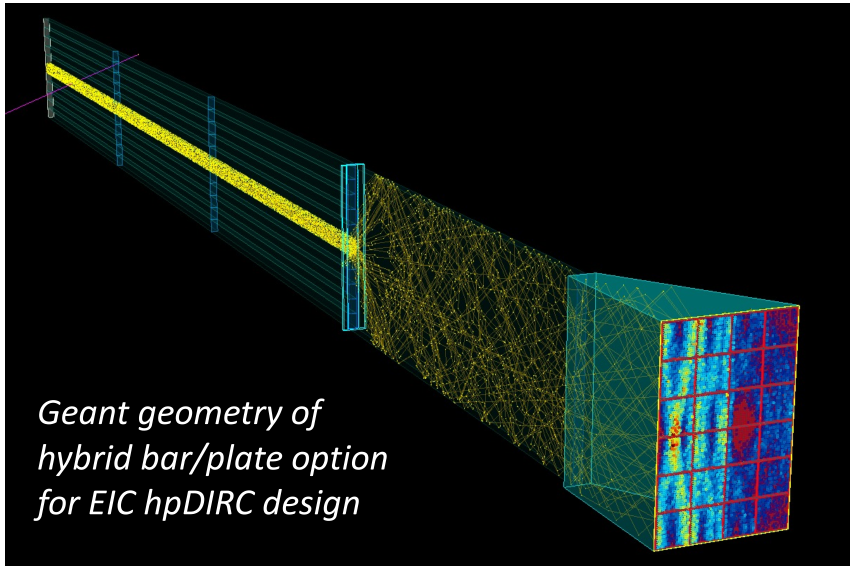
Combining this hybrid design with time-based imaging with faster photon timing and better tracking should lead to further improvement

Simulation study as possible option for EIC hpDIRC is underway (eRD14).

J. Va'vra, RICH2016



doi.org/10.1016/j.nima.2017.02.044



Geant geometry of hybrid bar/plate option for EIC hpDIRC design

SUMMARY

DIRC counters have become a popular solution for compact 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, GlueX, 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);

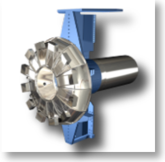
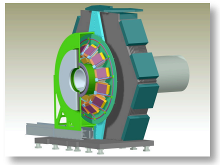
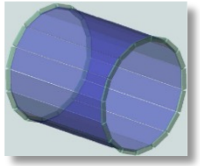
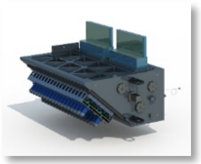
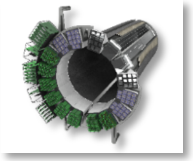
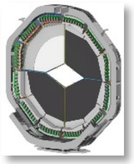
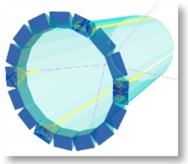
(b) focusing design emphasizing high-precision photon timing (Belle II);

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

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

EIC hpDIRC design extends BABAR π/K range by 50%, adds useful e/π separation at low momentum.

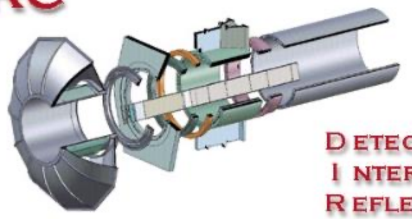
Even after 20 years, R&D still very active, pushing the DIRC performance limits further.

EXTRA MATERIAL

DIRC TIMELINE

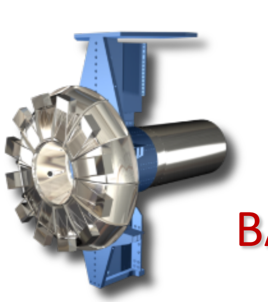
DIRC used for the first time in BABAR as primary hadronic particle ID system, flavor tagging, primary goal: π/K ID to 4 GeV/c.



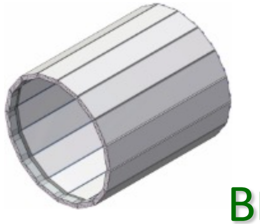
- 1992: first publication of DIRC concept§.
- 1993-1996: progression of prototypes and DIRC R&D.
- Nov 1994: decision in favor of DIRC for hadronic PID for BABAR.
- Nov 1998: installed part of DIRC; start of cosmic ray run, commissioning run.
- April 1999: BABAR moves into beam line, added 4 more bar boxes.
- Nov 1999: all 12 bar boxes installed, start of first physics run.
- early 2000s: 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)
- Oct 2013: call for proposals for reuse of BABAR DIRC radiator bars (ultimately awarded to JLab: GlueX, EIC).
- 2016: installation of TOP counter into Belle II.
- 2018: installation of DIRC counter into GlueX.

§B. Ratcliff, SLAC-PUB-6047 (Jan. 1993)

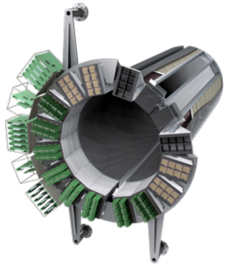
BARREL DIRC OVERVIEW



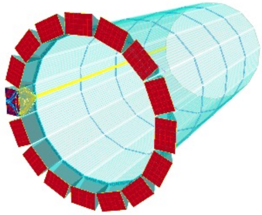
BABAR DIRC



BELLE II TOP



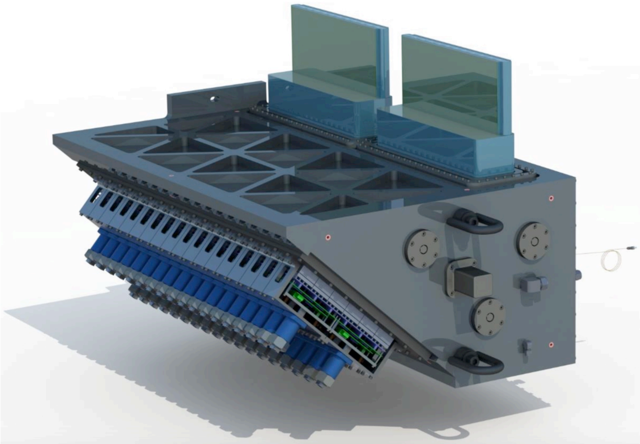
PANDA BARREL DIRC



EIC HPDIRC*

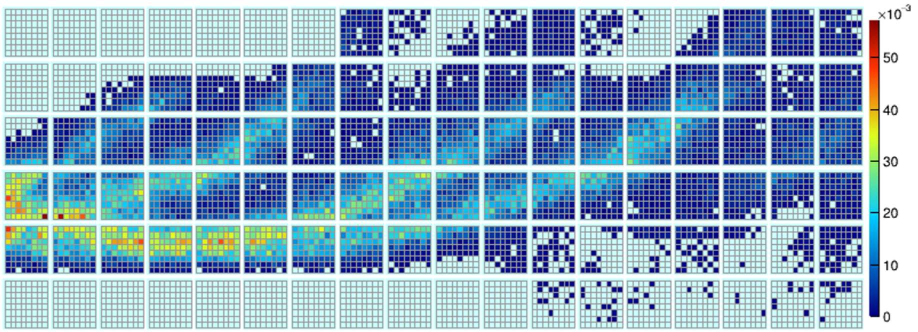
	BABAR DIRC	BELLE II TOP	PANDA BARREL DIRC	EIC HPDIRC*
Radiator geometry	Narrow bars *(35mm)*	Wide plates *(450mm)*	Narrow bars *(53mm)*	Narrow bars *(35mm)*
Barrel radius	85cm	115cm	48cm	100cm
Bar length	490cm *(4×122.5cm)*	250cm *(2×125cm)*	240cm *(2×120cm)*	420cm *(4×105cm)*
Number of long bars	144 *(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	~8k 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 2024/25	TDR-ready in 2024

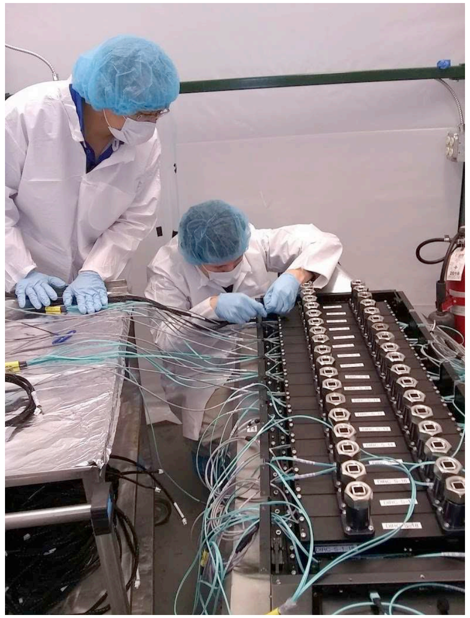
**Initial generic design*

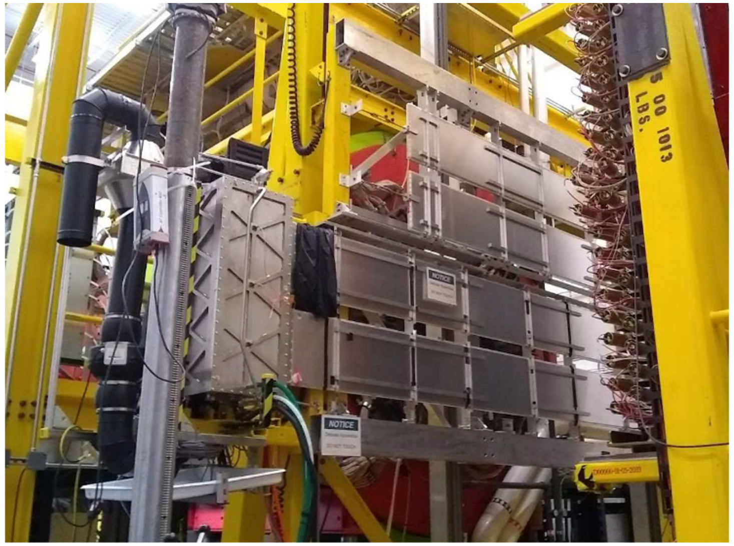


GlueX DIRC

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







GlueX DIRC

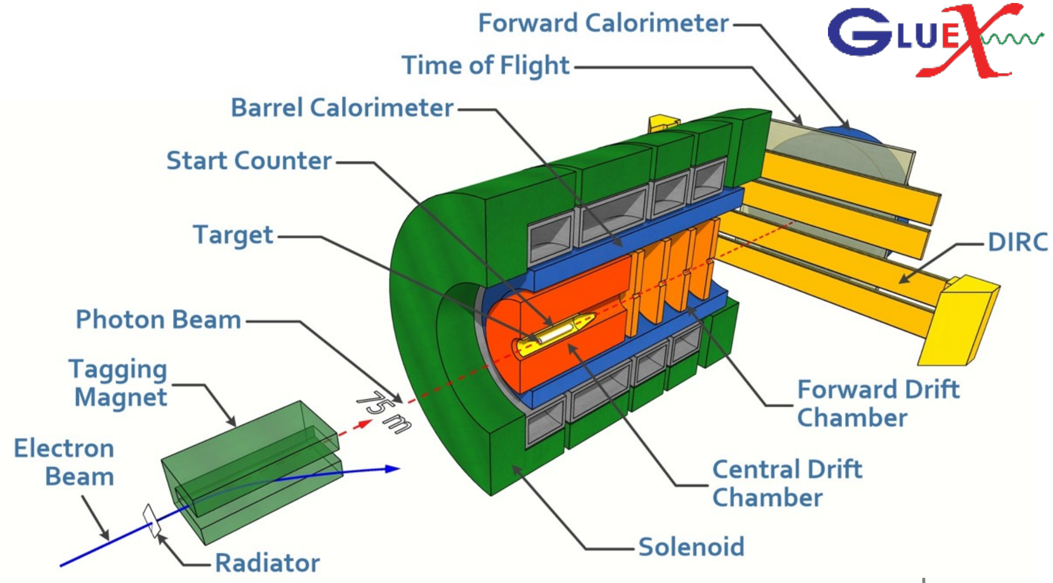
- forward PID upgrade for GlueX-II;
- extend GlueX physics reach by improving π/K separation from 2 GeV/c (TOF) to 3σ π/K separation at 3.6 GeV/c ;
- cost savings by reusing legacy BABAR DIRC bar boxes with new optics and readout;
- four bar boxes transported from SLAC to JLab in 2017/2018;
- installation into GlueX in 2018, commissioning in 2019;
- successfully operating in GlueX II run in 2020.

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

BABAR DIRC bar boxes

← in storage at SLAC

installed at JLab →

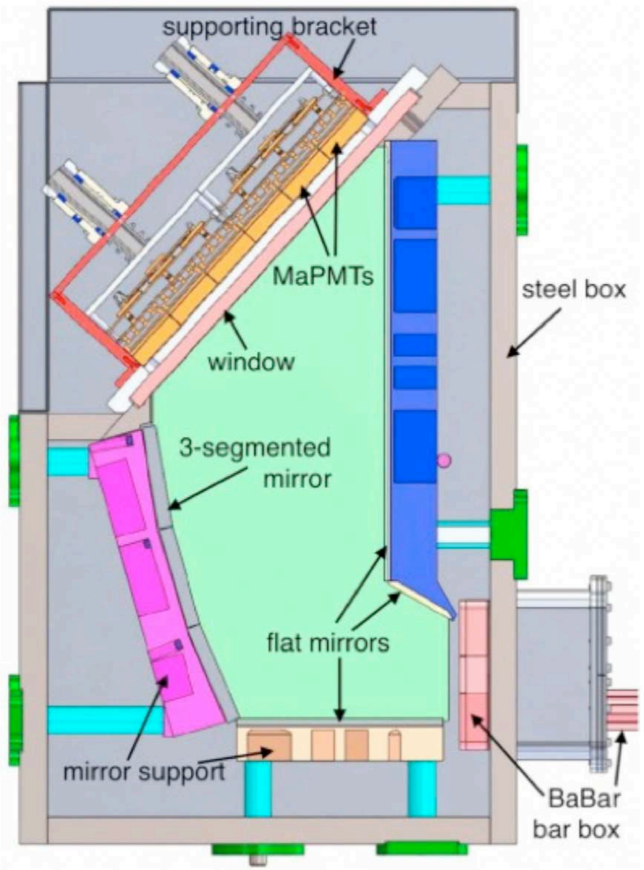


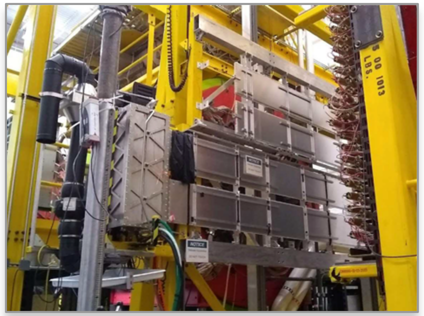
gluex.org

GlueX DIRC

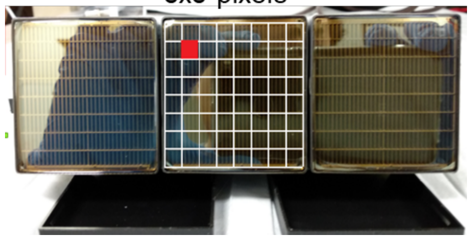
- Forward DIRC wall, reusing four BABAR DIRC bar boxes;
- Optics design based on SuperB fDIRC;
- Significant design simplification and cost reduction by replacing fused silica block with DI water and cylindrical mirror with set of three flat mirrors;
- Two "optical boxes" coupled to two bar boxes each, above and below the beam;
- Array of 90 H12700 MaPMTs in each optical box;
- 11520 MAROC readout channels for leading edge time and ToT (CLAS 12 RICH design);
- Adopted PANDA Barrel DIRC geometric reconstruction algorithm;
- Modest photon timing (0.8-1ns precision) for partial chromatic dispersion mitigation.

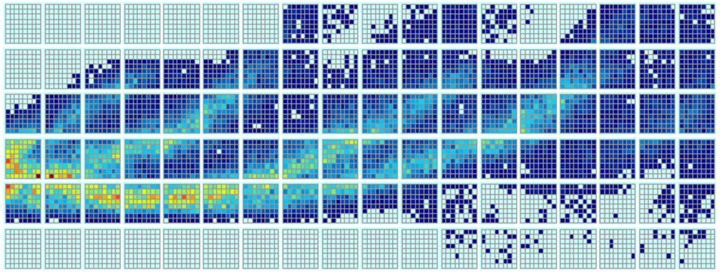
GlueX optical box





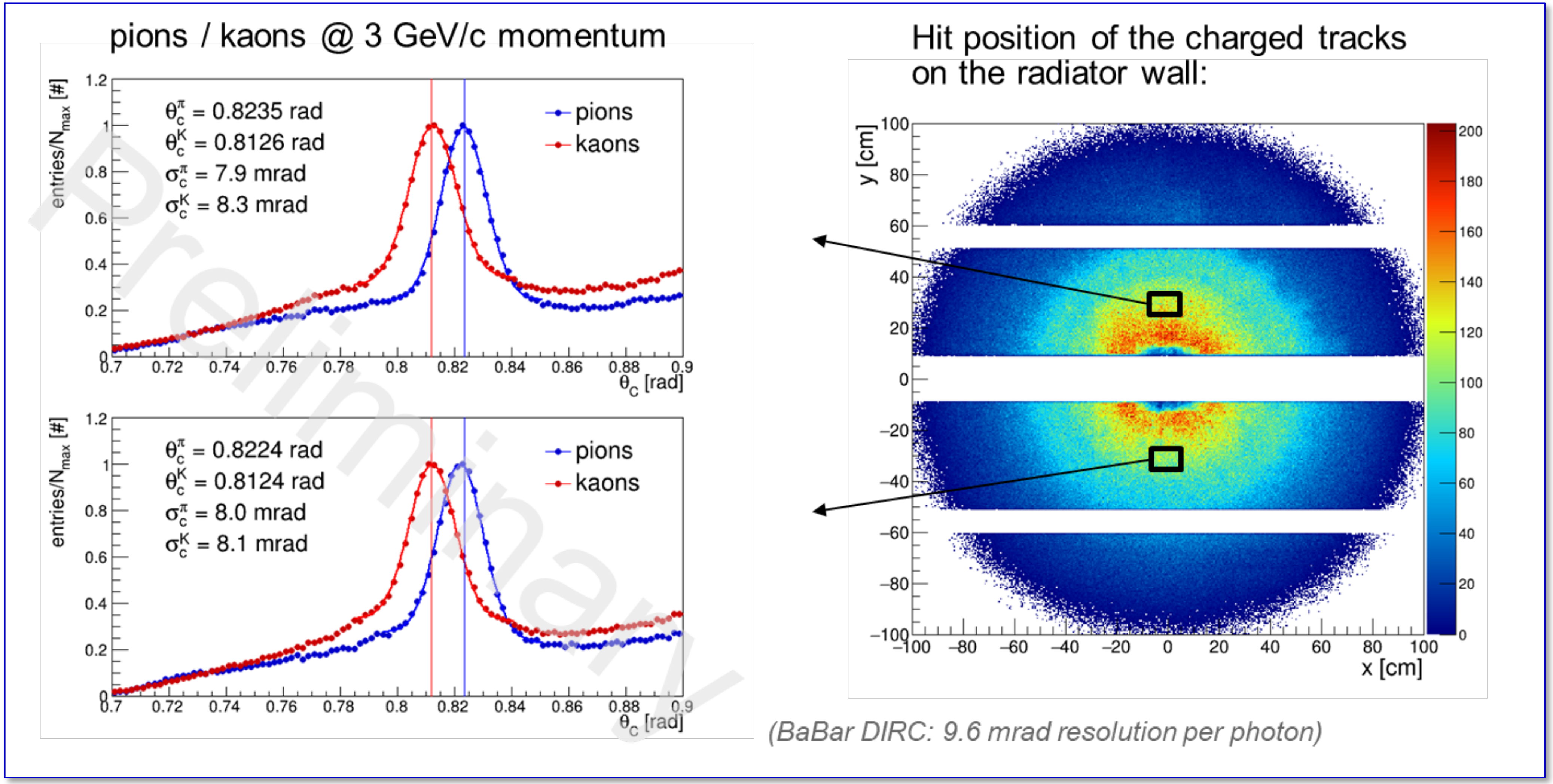
Hamamatsu H12700 MaPMT
8x8 pixels





GlueX DIRC

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



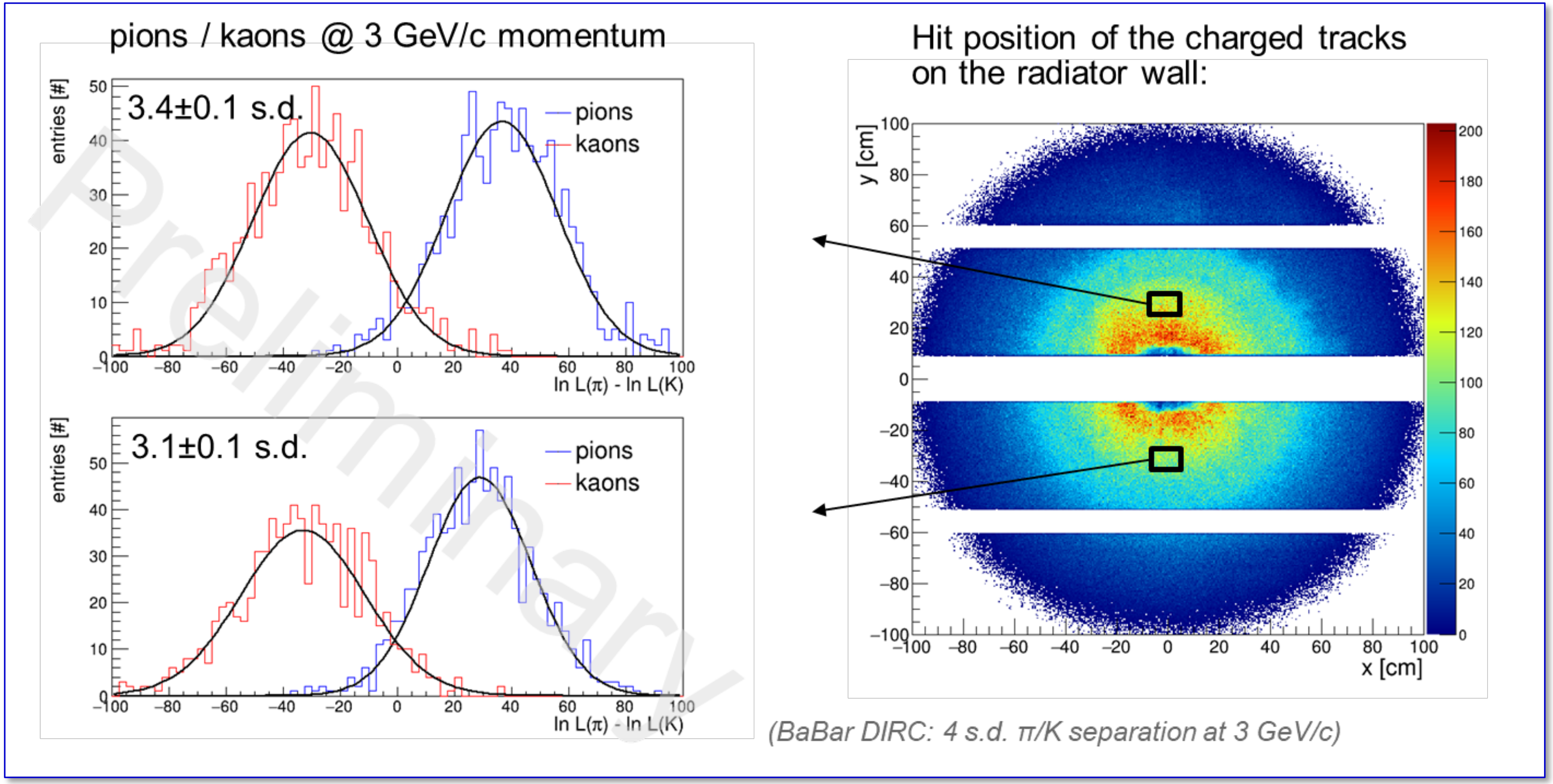
(BaBar DIRC: 9.6 mrad resolution per photon)

➢ Measured Cherenkov angle resolution per photon agrees with design and simulation

J.S., W. Li, INSTR'20, Feb 2020

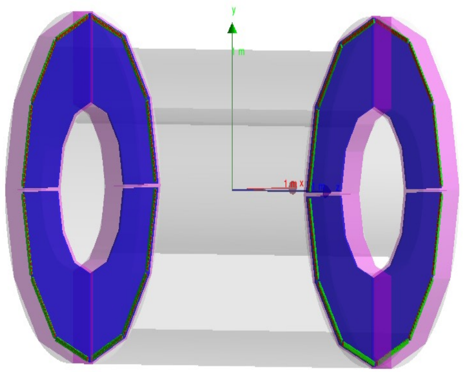
GLUEX DIRC

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



- ➢ Initial π/K separation: 3 s.d. at 3 GeV/c (very preliminary, alignment and calibration to be improved)

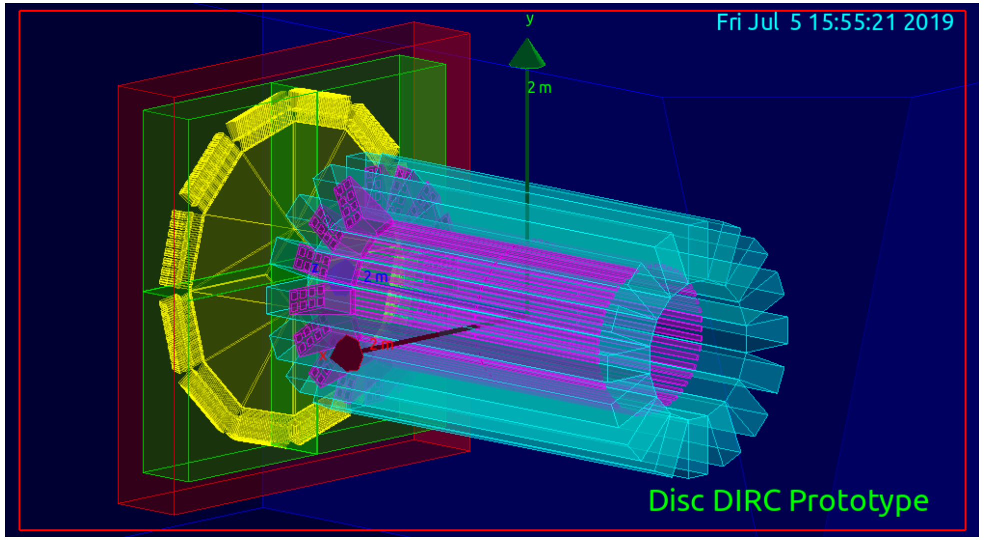
J.S., W. Li, INSTR'20, Feb 2020

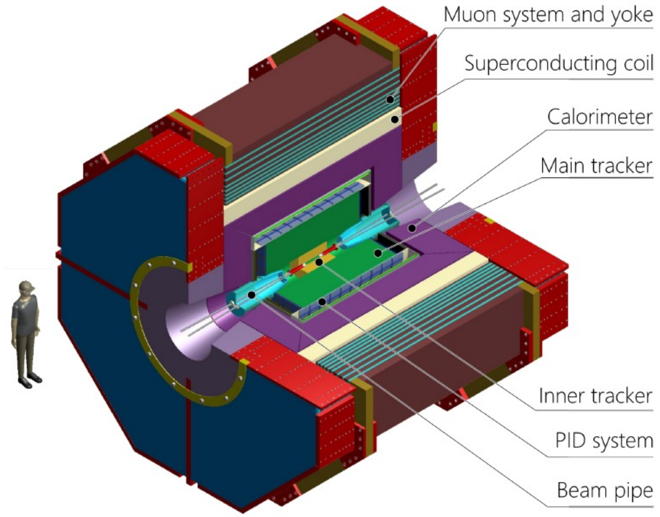


Qian LIU, STCF workshop 2020

Super Charm Tau DIRCs

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



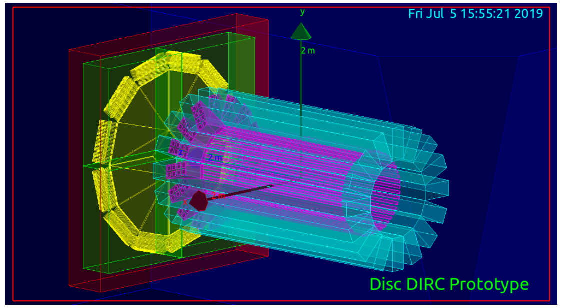


M. Schmidt, DIRC2019

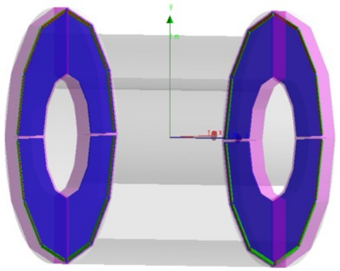
SCTF DIRCs

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

- barrel and/or endcap PID for the planned Super Charm-Tau/Super Tau-Charm Facility
- 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 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).



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



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