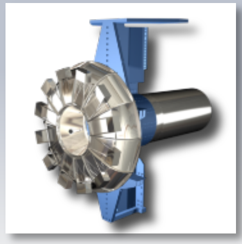
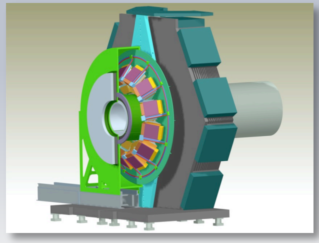
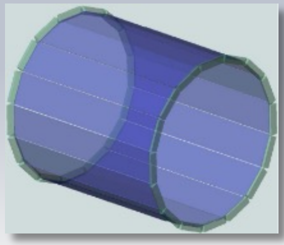
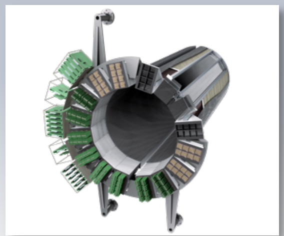
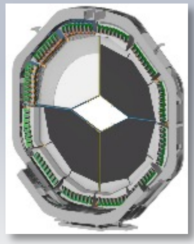
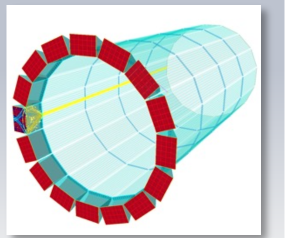




EIC

DIRC DETECTORS

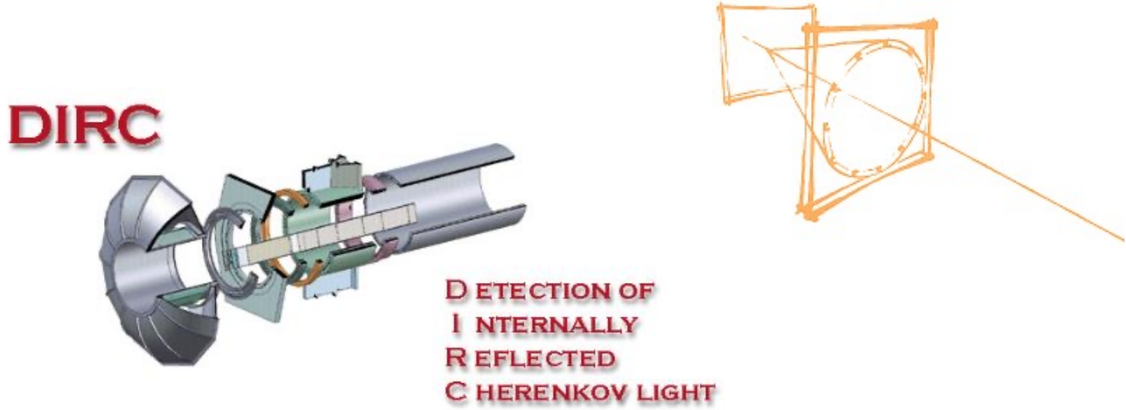
FROM BABAR TO PANDA AND BEYOND

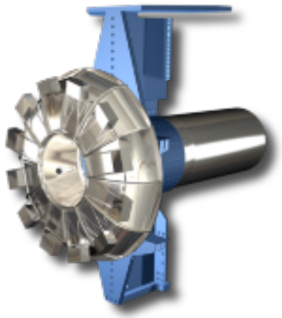
Particle Physics Seminar
PI Bonn
June 24, 2021

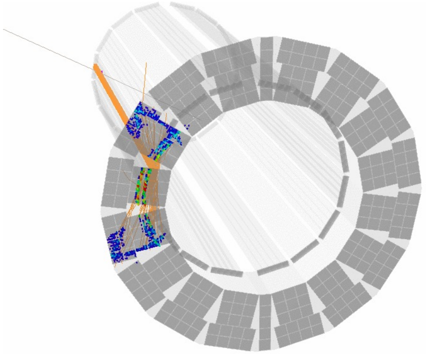
Jochen Schwiening

GSI Helmholtzzentrum für Schwerionenforschung GmbH

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

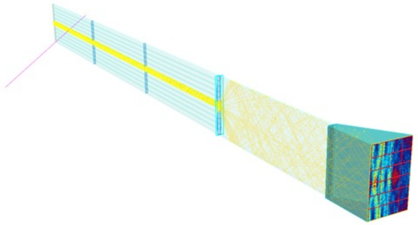






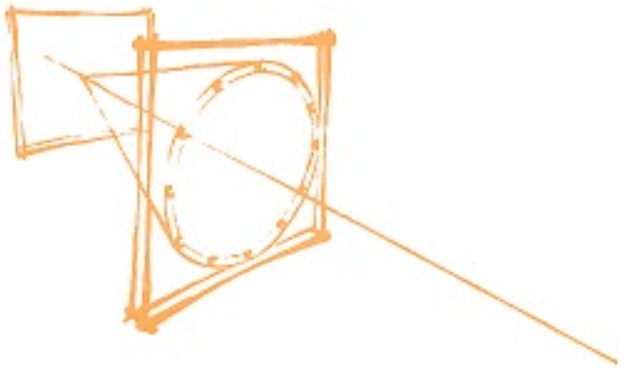
30 years of detector research with many interesting results,
too much even for a 45-minute seminar – for more details see:

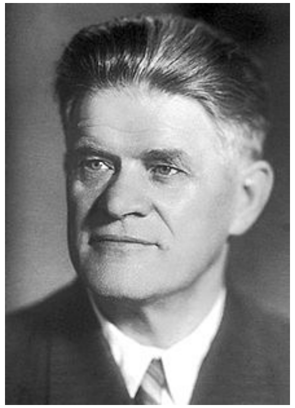
- *Recent review: B. Ratcliff and J. Va'vra, Nucl.Instrum.Meth. A 970 (2020) 163442*
- *RICH workshop series (most recent: RICH2018, Moscow)*
- *DIRC workshop series (most recent: DIRC2019, Rauischholzhausen)*

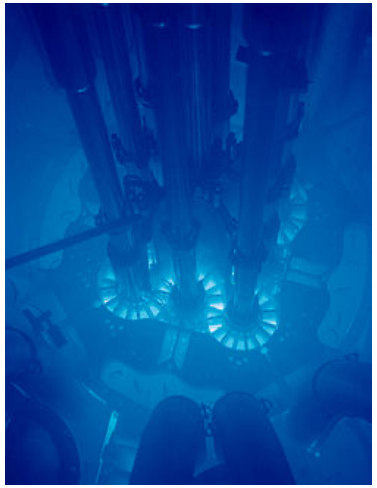


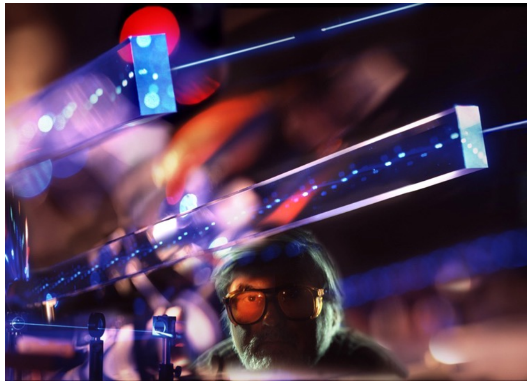
Thanks to my colleagues in the DIRC community who provided information and material.

CHERENKOV FUNDAMENTALS



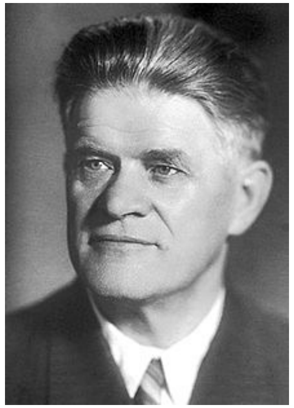






A charged particle passing through an optically transparent medium with a velocity greater than the phase velocity of light in that medium emits prompt photons, called Cherenkov radiation

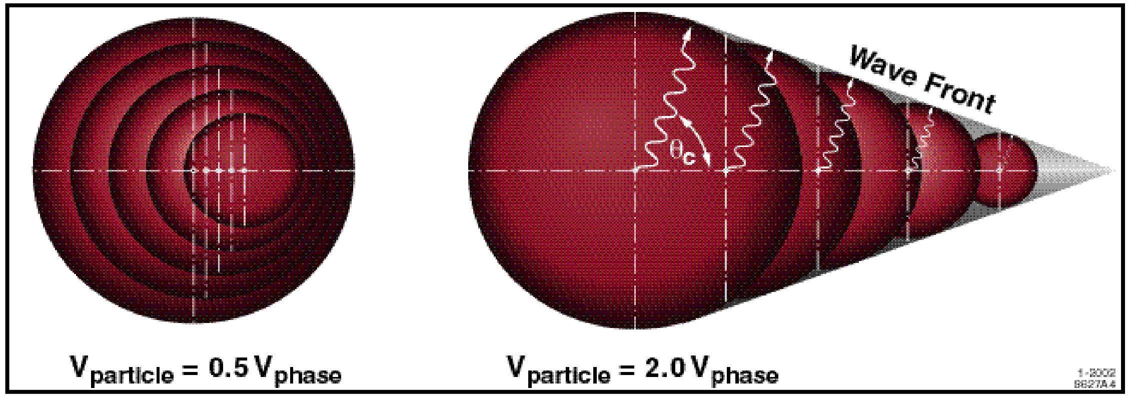
- Named after the Russian scientist Pavel Cherenkov who was the first to study the effect in depth in the 1930s (Nobel Prize in 1958).
- Theory of Relativity: nothing can go faster than the speed of light *c* (in vacuum).
- However, due to the refractive index n_p of a material, a particle *can* go faster than the *local* speed of light in the medium $c_p = c/n_p$.
- Analogous to the bow wave of a boat travelling over water or the sonic boom of an airplane travelling faster than the speed of sound.

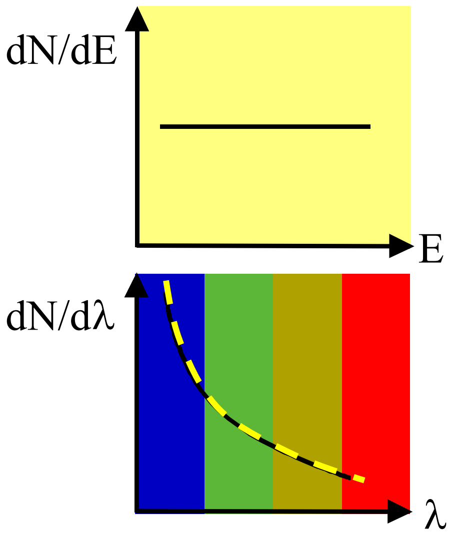


Павел Алексеевич Черенков

This and some of the following slides thanks to Roger Forty's lectures at 2010 ICFA Instrumentation School, Bariloche
http://particulas.cnea.gov.ar/workshops/icfa/wiki/index.php/Particle_Identification

Cherenkov Radiation





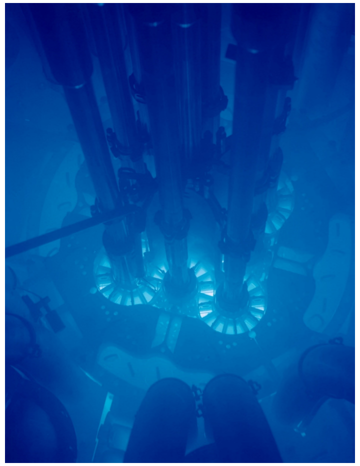
Threshold: $$\beta_{\text{thresh}} = \frac{v_{\text{thresh}}}{c} = \frac{1}{\mathrm{n}(\lambda)}$$

Production angle: $$\cos\theta_c = \frac{1}{\beta\,\mathrm{n}(\lambda)}$$

Number of photons: $$\mathrm{N}_{\text{photons}} = L\frac{\alpha^2 z^2}{r_e m_e c^2}\int \sin^2\theta_c(E)\,dE$$

Light produced equally distributed over photon energies, proportional $1/\lambda^2$

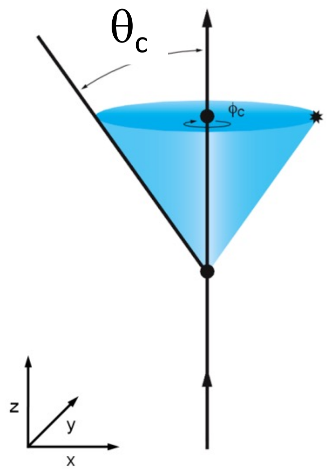
→ *eery blue light seen in nuclear reactors*



Advanced Test Reactor at ANL

Cherenkov radiation: attractive properties for particle detectors

- Existence of a threshold velocity;
- Number of photons related to particle velocity;
- Emission angle related to particle velocity;
- Angle and photon yield depend on particle charge Z.



Main Cherenkov detector concepts in particle physics:

Threshold Counter

Select material with refractive index n_1: particle type A produces Cherenkov light, particle type B does not

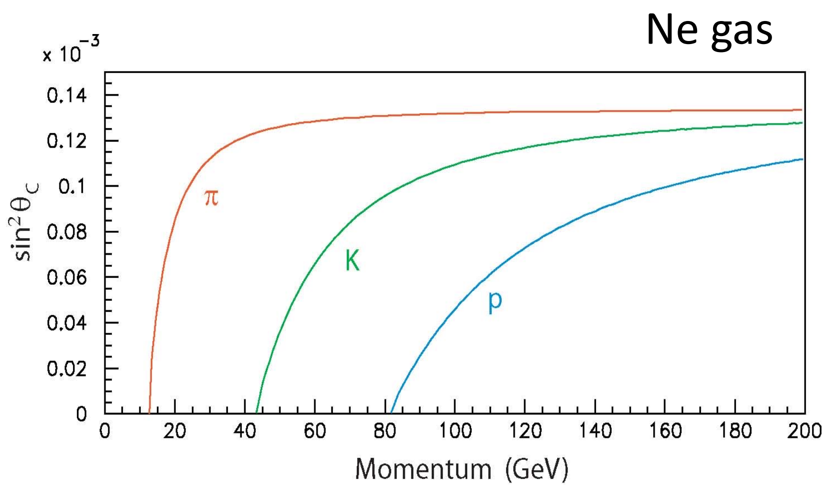
Ring Imaging Cherenkov Counter (RICH)

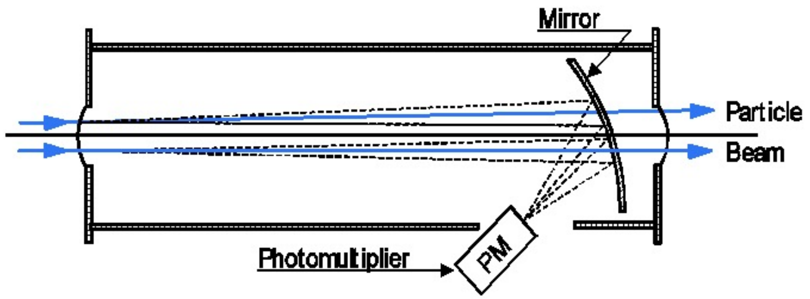
Select material with refractive index n_2: multiple Cherenkov photons are detected for most particle species, image Cherenkov rings, precisely measure Cherenkov angles

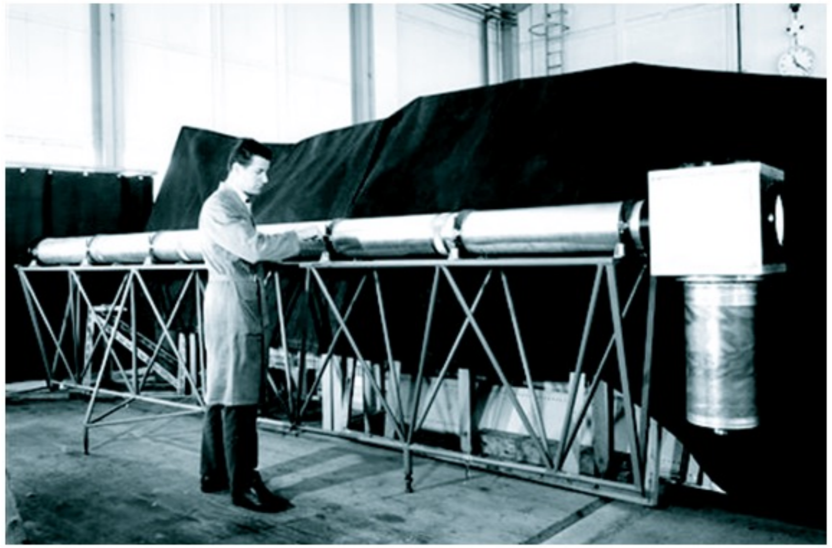
PID: Compare ring image with expected image for e/μ/π/K/p (likelihood test) or calculate mass from track β

Reconstruction uses independent momentum measurement (B field, tracking).

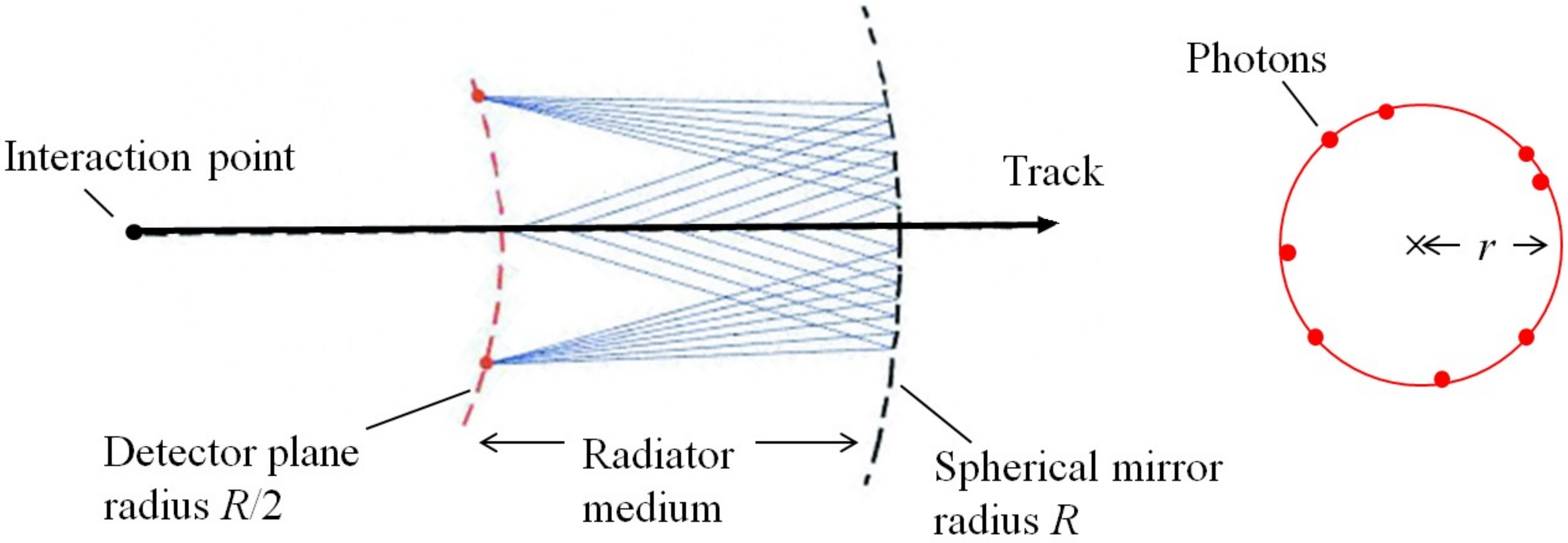
- Well-defined, tunable value of $\beta_{thr} = 1/n$ in threshold Cherenkov detectors.
- Select n based on application.
  Example: identify particles in a beam line with a 50 GeV π^+ beam with some proton contamination
- By choosing a medium with a suitable refractive index (in this case Neon), it can be arranged that the π will produce light, but the protons will not.







- Threshold counters mostly give a yes/no answer, less useful when the tracks have a wide momentum range even though some are used in modern experiments (for example Belle ACC).
- However, more information can be extracted from the Cherenkov angle (*"threshold mode" still in play as well*) → the Cherenkov cone can be imaged into a ring with multiple photons.

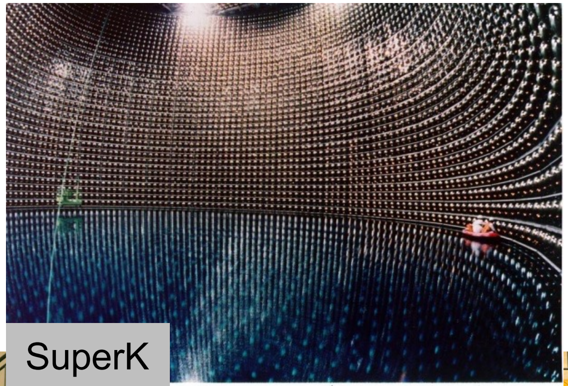


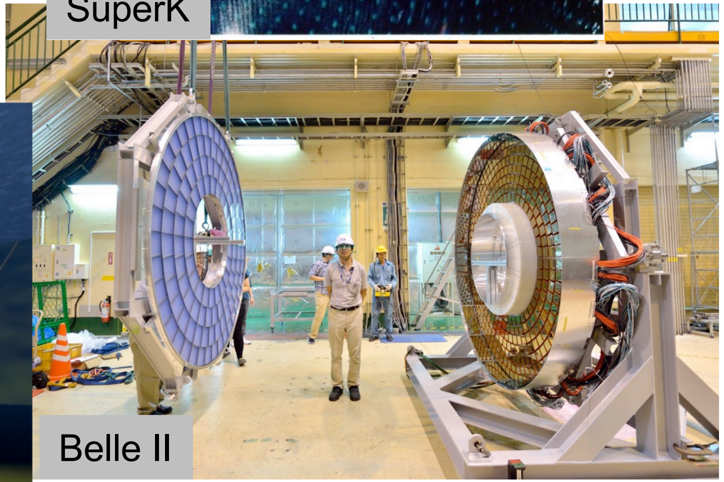
- Measuring the "ring radius" *r* allows the Cherenkov angle θ_C to be determined directly each photon provides measurement of θ_C, combining N photons

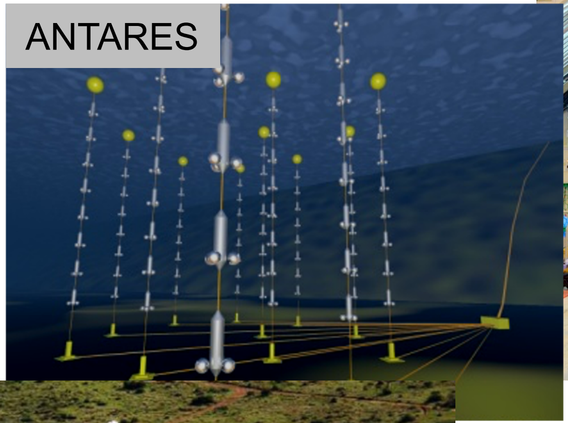
→ θ_C error proportional to $\frac{1}{\sqrt{N}}$ → powerful principle behind Ring Imaging Cherenkov (RICH) detectors

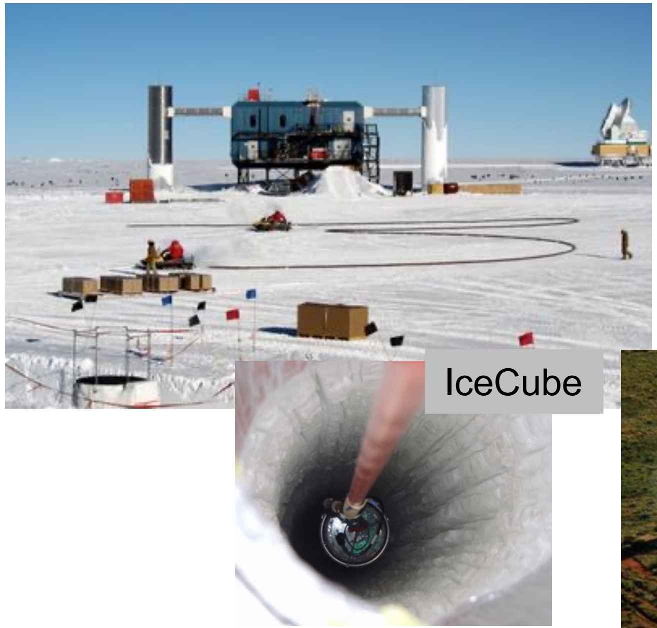
RICH detectors come in many shapes and sizes in particle physics, nuclear physics, and particle astrophysics.

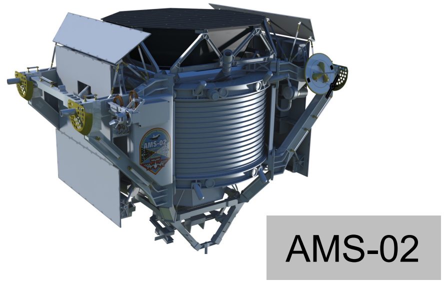
- Large neutrino observatories underground or in ice/deep sea (SuperK, KM3net, IceCube, etc)
- Imaging Air Cherenkov Telescopes (HESS, etc)
- Space experiments (AMS, CREAM, etc)
- High-energy physics (BABAR, Belle II, LHCb, PANDA, CBM, etc)

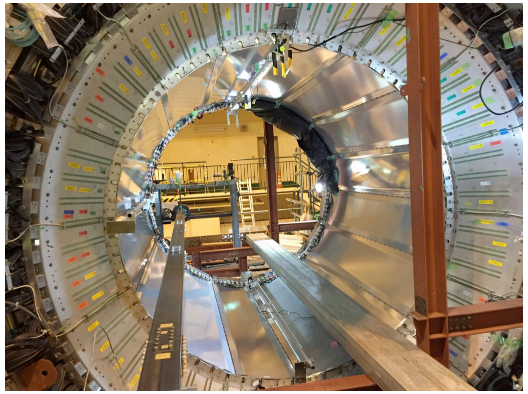




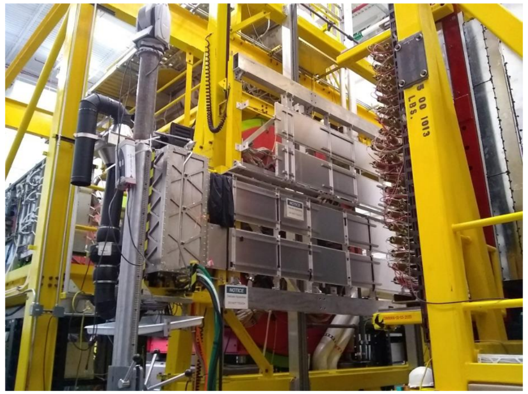


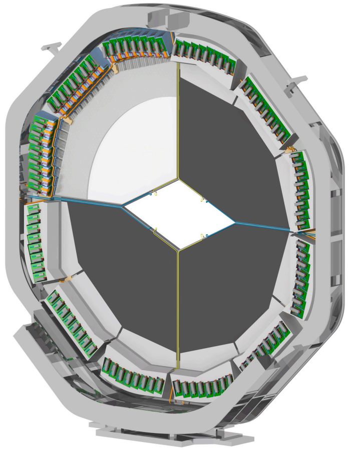


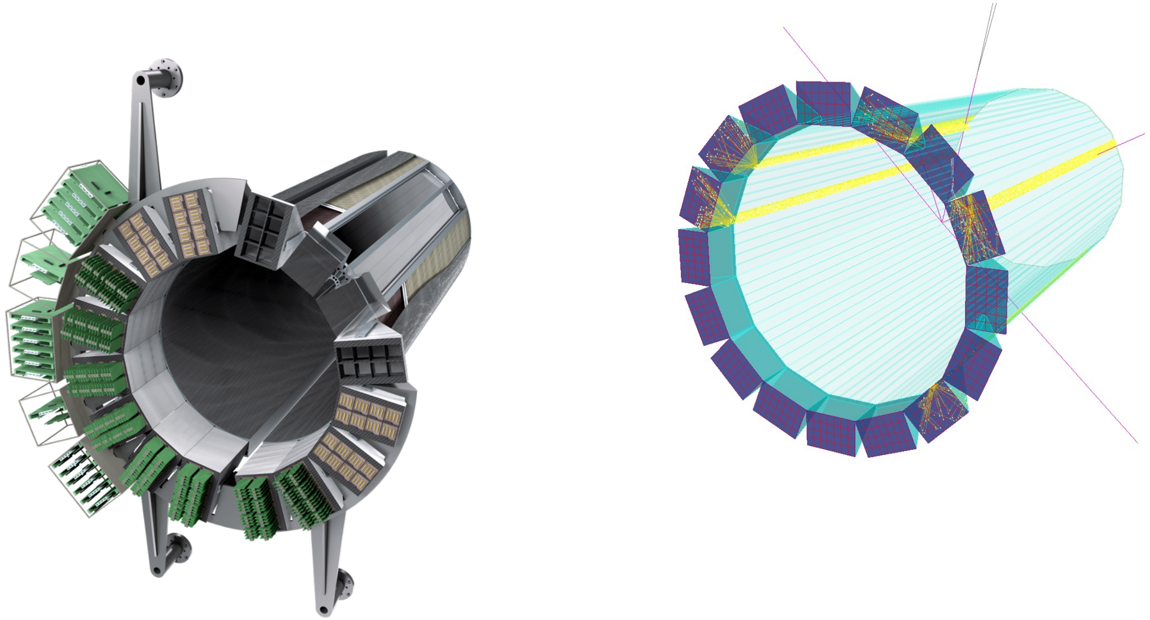




DIRC DETECTORS

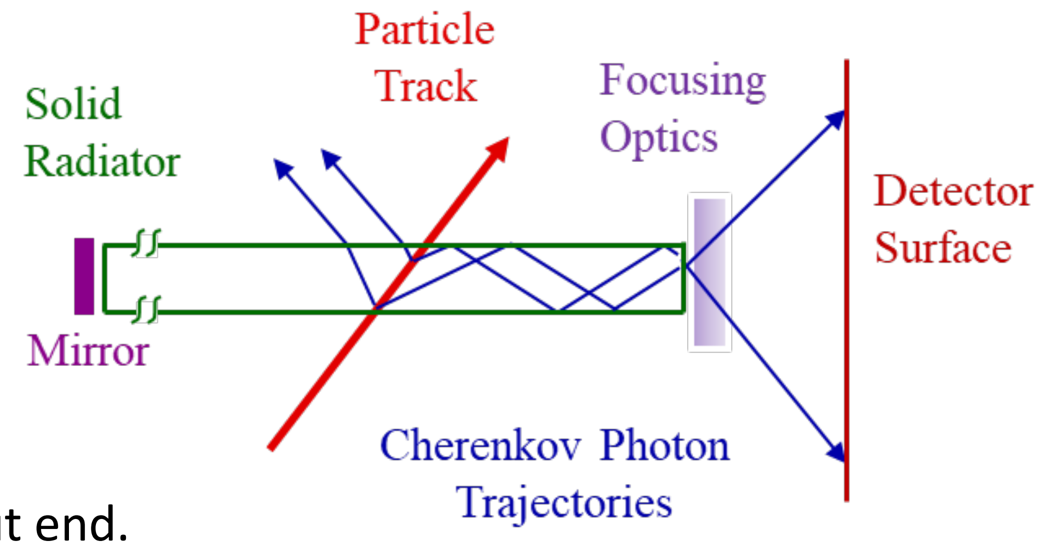


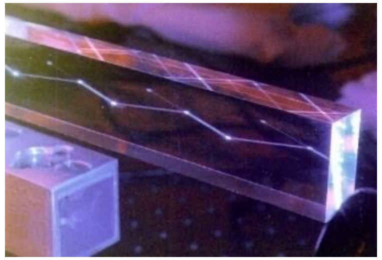




Detection of Internally Reflected Cherenkov Light

- DIRC: Compact subtype of 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.
- Photons exit radiator via optional focusing optics into expansion region,
  detected on photon detector array.

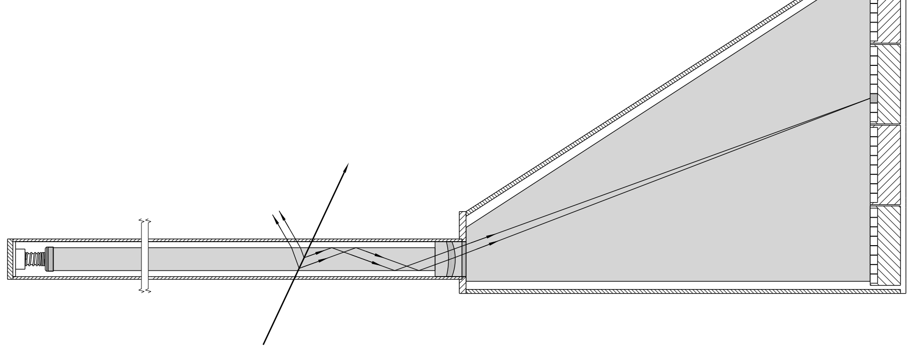




DIRC Concept

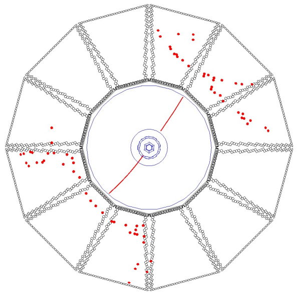
- Magnitude of Cherenkov angle conserved during many internal reflections
  (provided optical surfaces are square, parallel, highly polished)
- Quartz bar/plate/disk both radiator and light guide,
  transporting photons away from crowded central detector
  to suitable sensor location
- DIRC is intrinsically 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

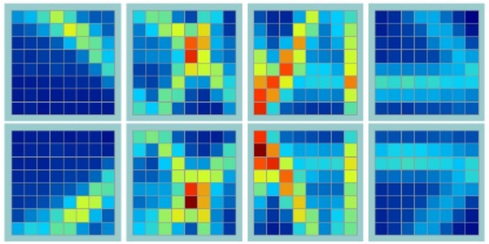


DIRC hit patterns are not typical Cherenkov rings.

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



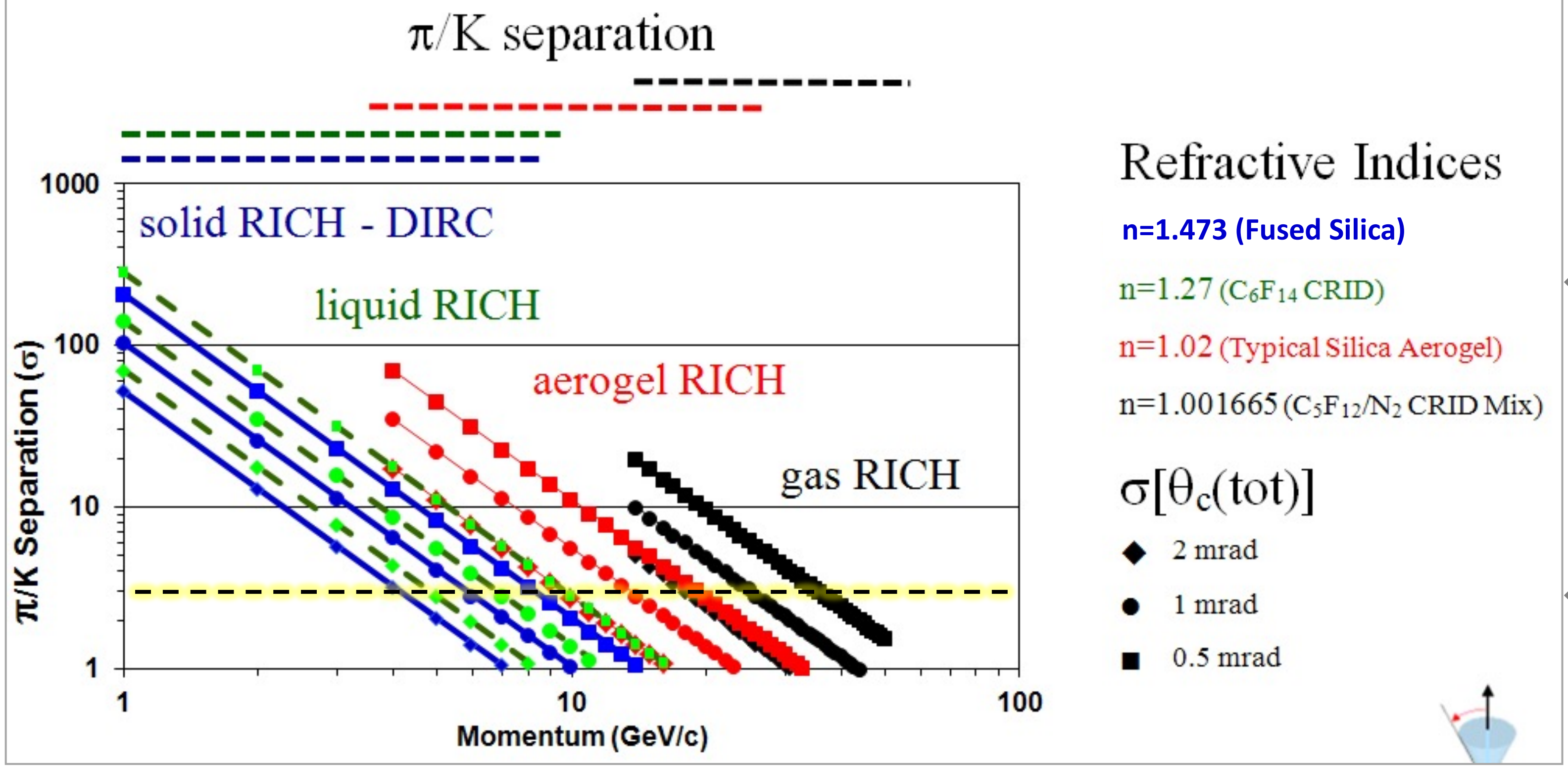
Accumulated hit pattern PANDA Barrel DIRC

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

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

$$N_\sigma \approx \frac{(m_1^2 - m_2^2)}{(2p^2\sqrt{n^2-1}\,\sigma[\theta_c(tot)])}.$$

(For momenta well above threshold.)



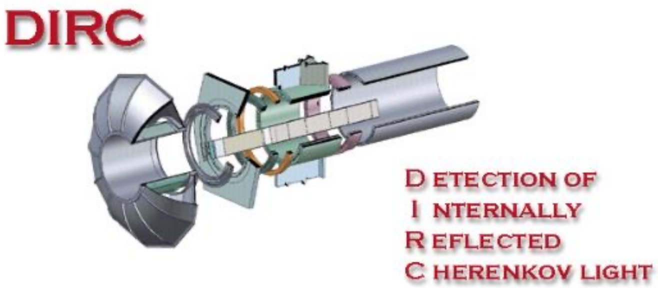
colors: radiator materials

symbols: total Cherenkov angle error per particle

based on B. Ratcliff, RICH2002

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.

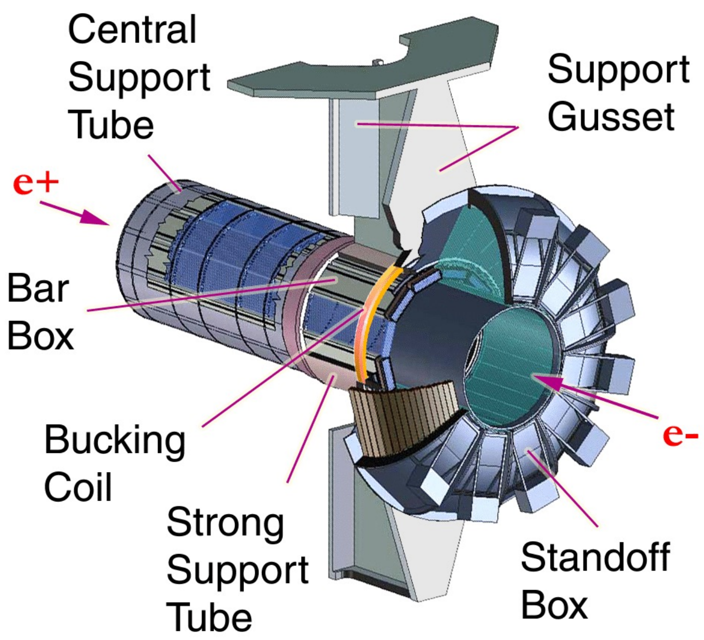


- 1991: first description of DIRC concept; 1992: first DIRC publication§
- 1993-1996: progression of prototypes and DIRC R&D
- Nov 1994: decision in favor of DIRC for hadronic PID for BABAR
- Nov 1998: installed part of DIRC; start of cosmic ray run, commissioning run
- April 1999: BABAR moves into beam line, added 4 more bar boxes
- Nov 1999: all 12 bar boxes installed, start of first physics run
- early 2000s: 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

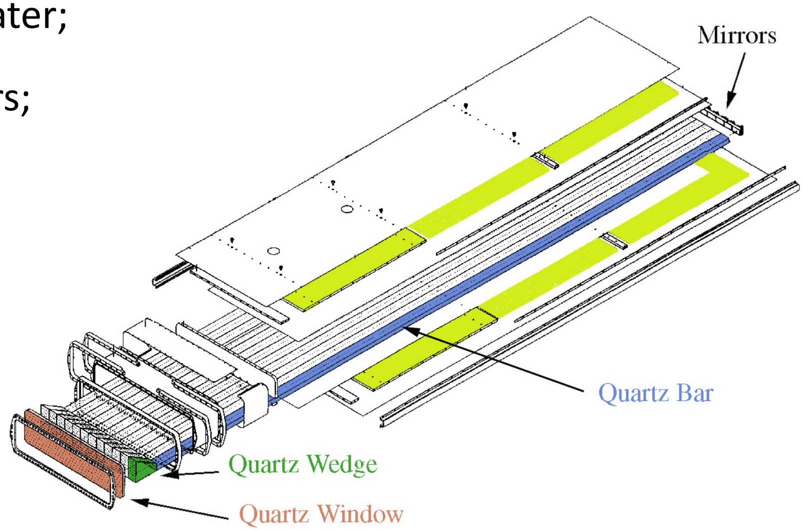
- large expansion volume
- pinhole focusing
- 1'' PMTs
- moderate photon timing
- first DIRC



BABAR DIRC

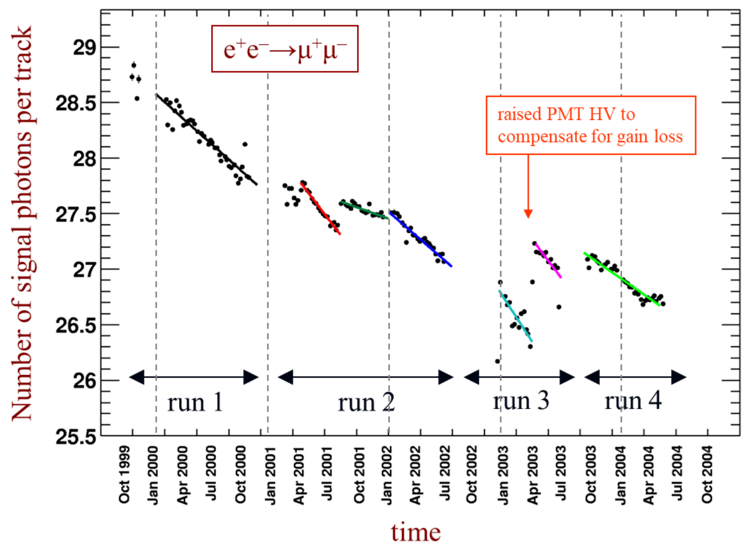
- first DIRC counter, primary hadronic PID in BABAR barrel;
- design goal 3σ π/K separation up to 4 GeV/c;
- compact, 8 cm radial thickness incl. supports;
- pinhole focusing (size of bar small compared to size of expansion volume);
- long narrow synthetic fused silica bars (17mm x 35mm x 4900mm);
-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



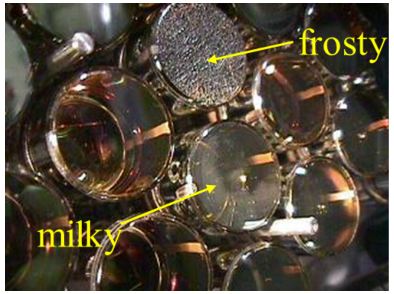
DIRC Operations were Stable and Robust

- Calibration constants stable to typically *rms* < 0.1ns per year.
- No problems with water or gas systems.
- No evidence for deterioration of bar surfaces or glue joints.

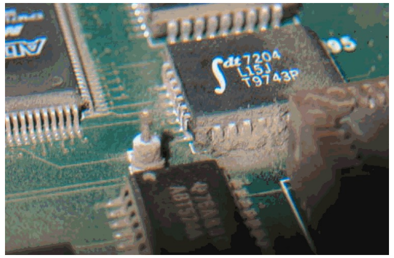


The three most significant operational issues:

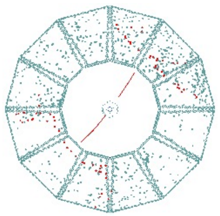
- Concerns about PMT longevity due to PMT window degradation;
  → photon loss a few % level, no problem for PID performance.



- Some damage to electronics due to dust/dirt from civil engineering near experiment;
  → solved by cleaning and application of conformal coating.

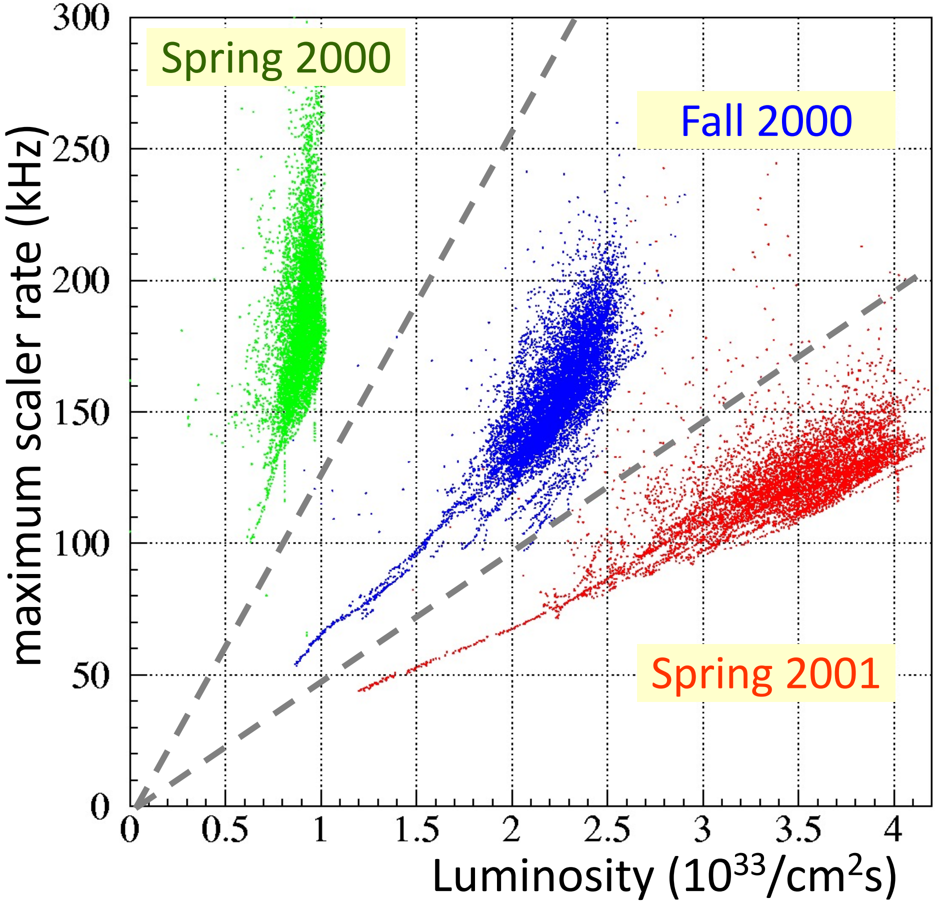


- Sensitivity of the DIRC to machine background interacting in the water of the expansion region (primarily DAQ issue);
  → solved by adding lead shielding between beam line and DIRC inner radius and by upgrading TDCs.



Succession of lead shielding installed in 2000 and 2001.

Thanks to shielding, PMT rates acceptable even at 4 × design luminosity.



DIRC TDC1: ~5% inefficiency at 250 kHz

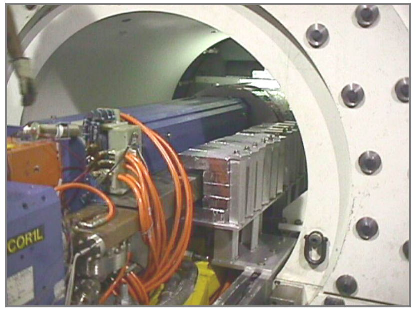
PMT Rate vs. Luminosity shows that lead shielding essential in protecting DIRC from few MeV photon accelerator induced background (radiative Bhabhas etc).

New TDC chips were installed during shutdown Fall 2002.

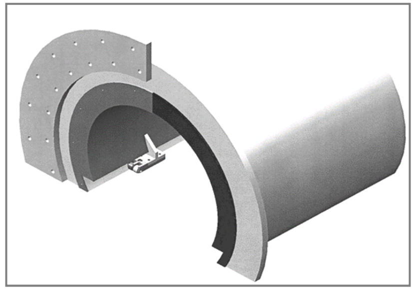
DIRC TDC2: <5% deadtime at 2.5MHz

Final TDC and shielding configuration were "background safe" at highest lumi.

2000: lead brick shielding



2001: engineered lead shield

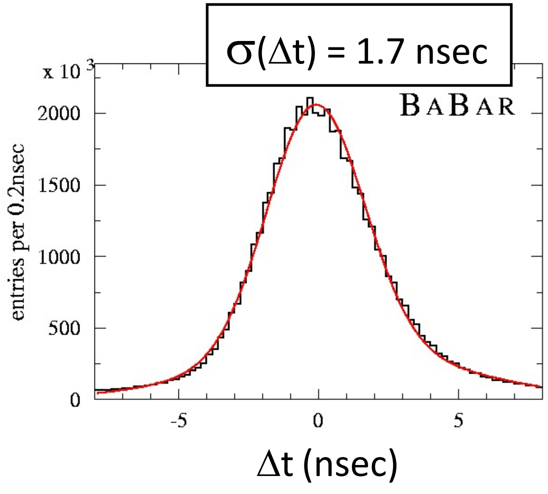


Timing information not used for PID but crucial in dealing with accelerator-induced background

Calculate expected arrival time of Cherenkov photon based on

- track TOF
- photon propagation in radiator bar and in water

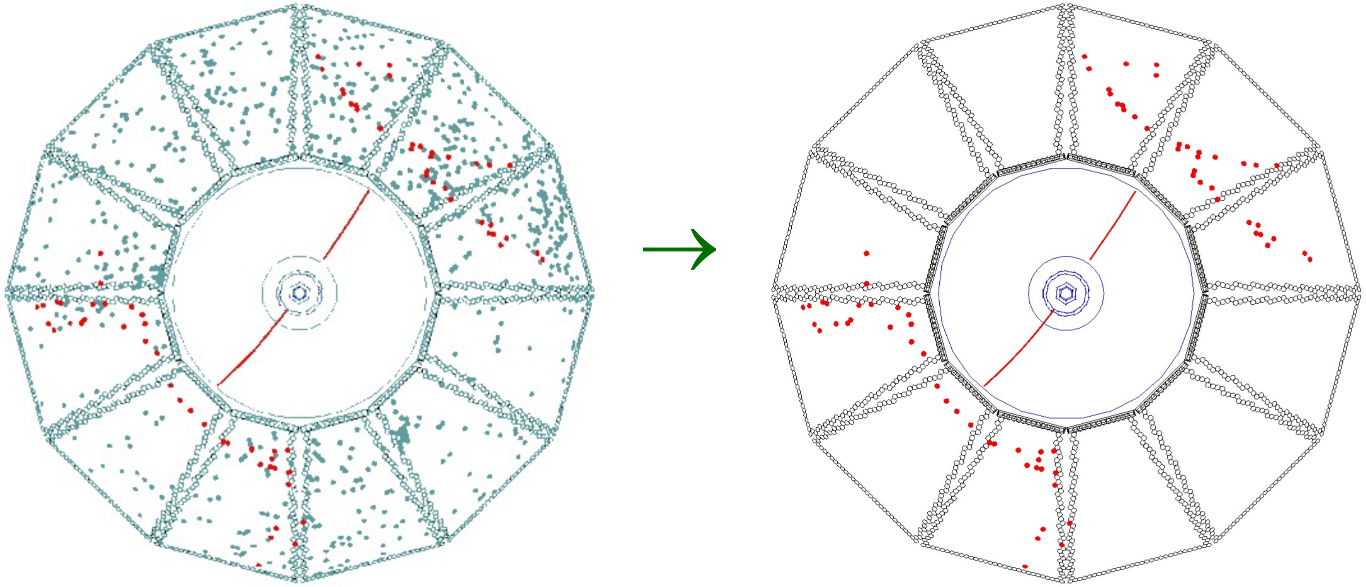
Δt: difference between measured and expected arrival time



(Δt can provide "DIRC t_0 event time")

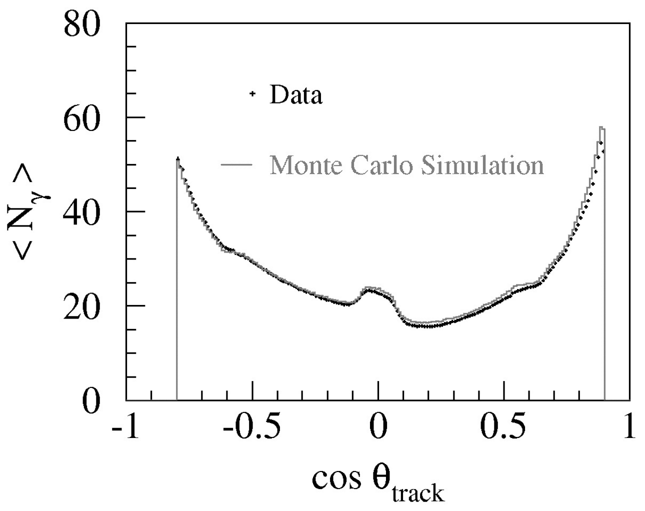
$\pm$ 300 nsec trigger window → $\pm$ 8 nsec Δt window

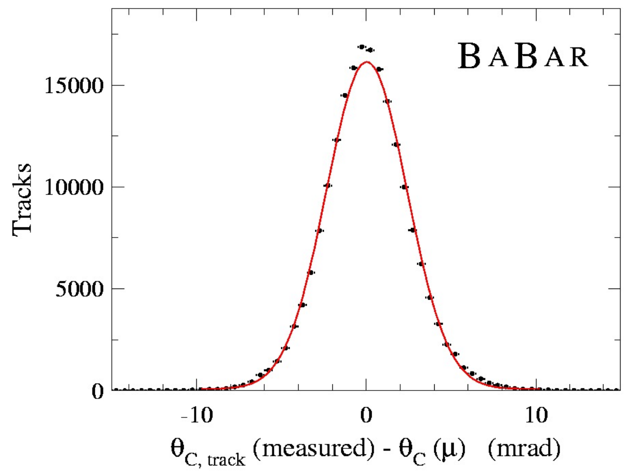
(~500-1300 background hits/event) (1-2 background hits/sector/event)

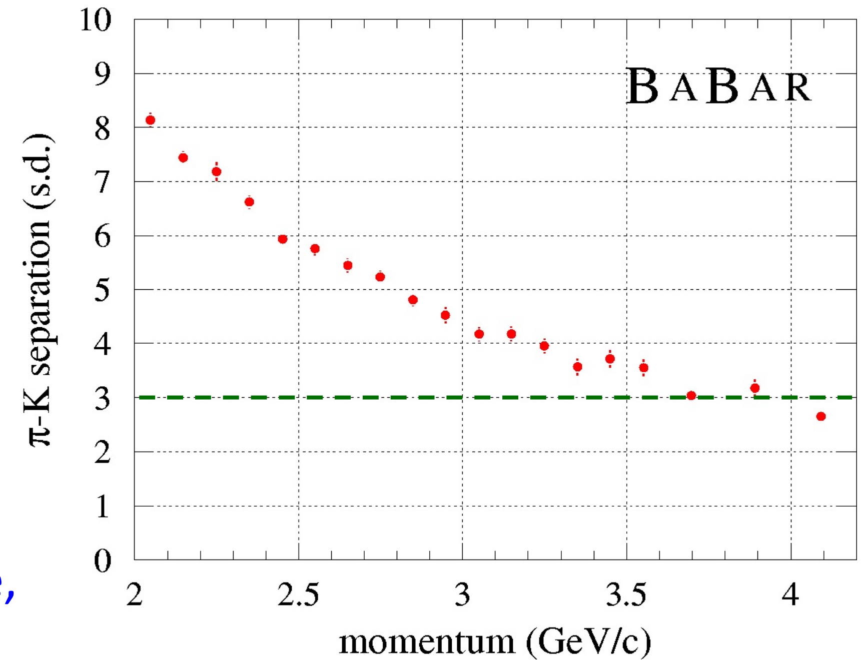


BABAR DIRC

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





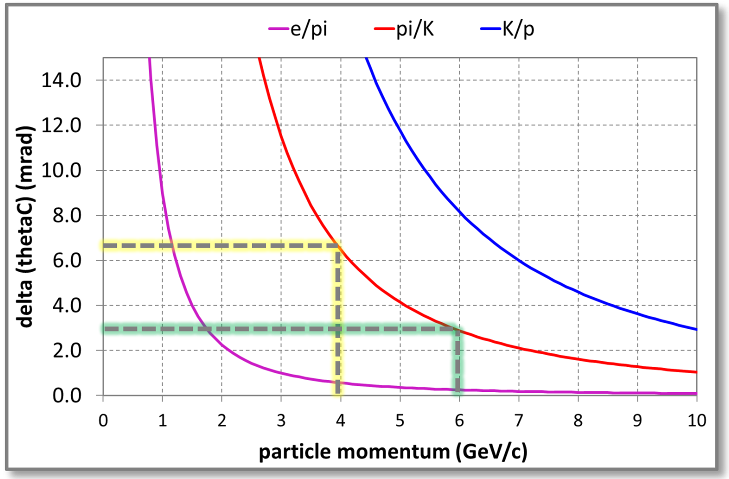


Excellent performance: very reliable, robust, easy to operate, significant contribution to almost all BABAR physics results.

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

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 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 $\sigma_{\theta_c}(photon) = 9.6$ 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

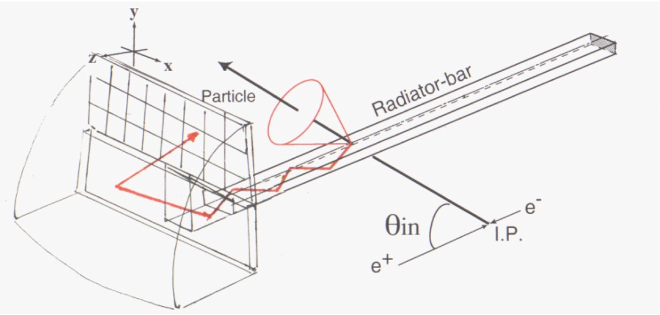
SUPERB, BELLE II, PANDA & EIC

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

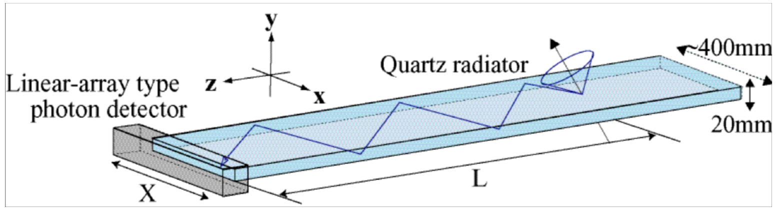


Early SuperB fDIRC design

- 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

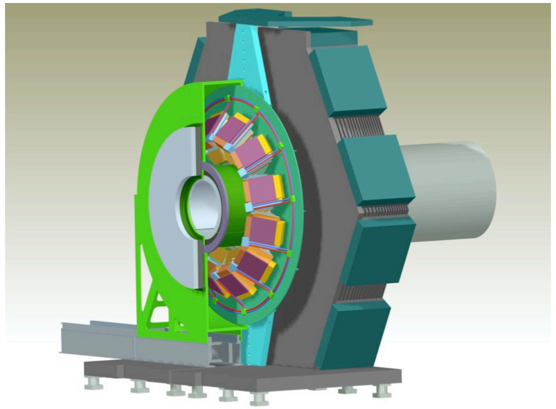
  examples: "ultimate fDIRC", EIC High-Performance DIRC

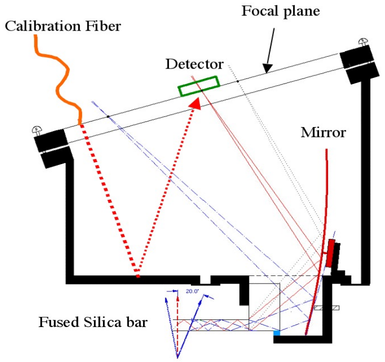
  <100 ps photon timing, large array of (~3 mm) 2D pixels → PID uses full 3D imaging

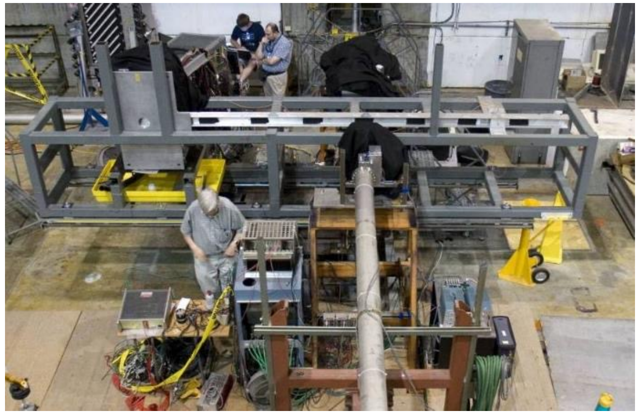
Final designs for Belle II TOP and PANDA DIRCs are hybrids derived from these initial approaches.

SuperB fDIRC

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



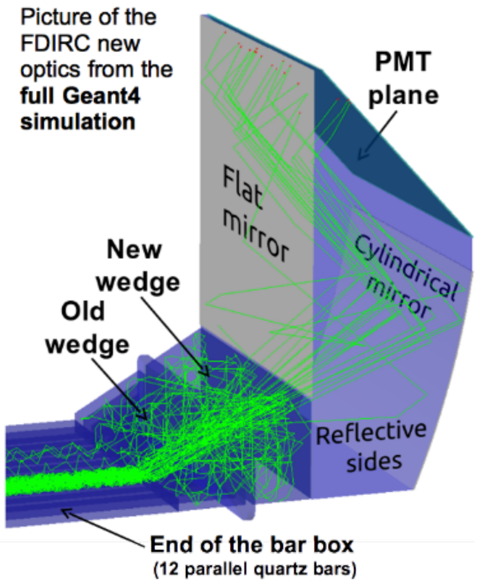




SuperB Focusing DIRC (fDIRC):

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

- 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



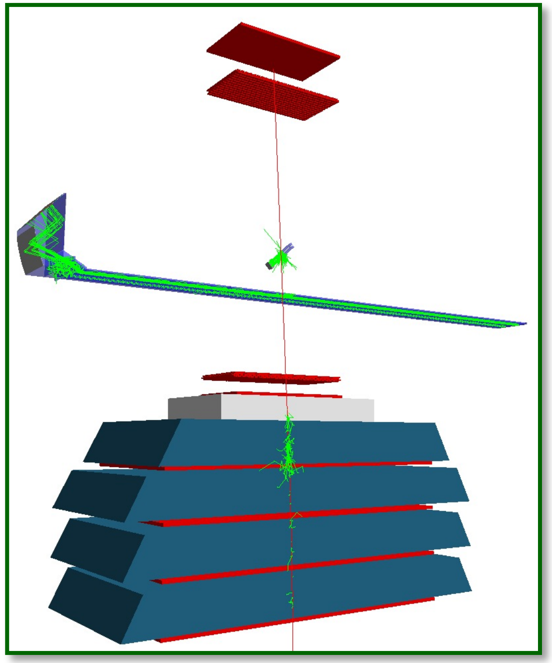
D.A. Roberts et al., RICH 2016
Nucl.Instrum.Meth. A 766 (2014) 114

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.

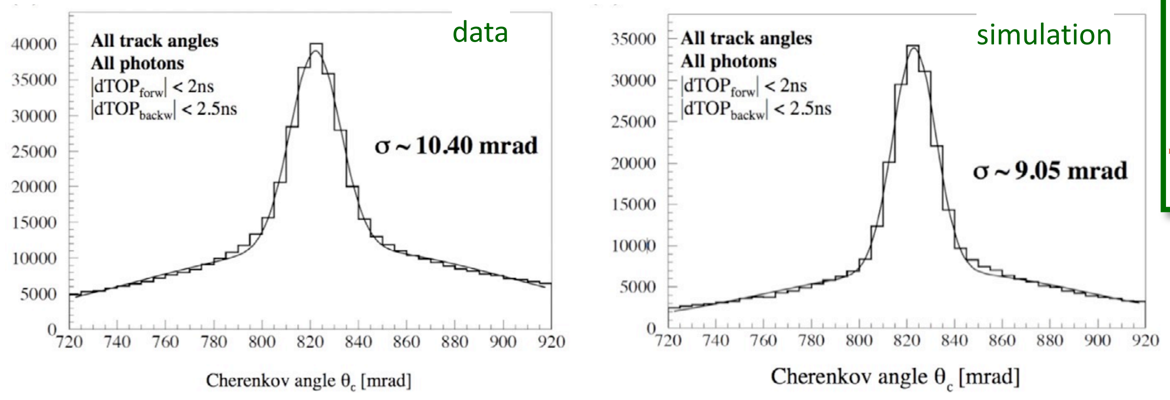
Clearly demonstrated resolution improvement

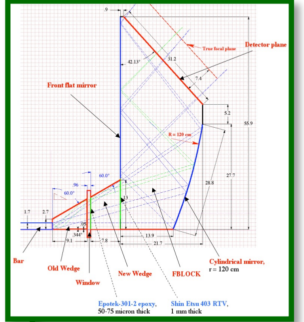
from chromatic dispersion correction with fast timing.

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

SuperB fDIRC

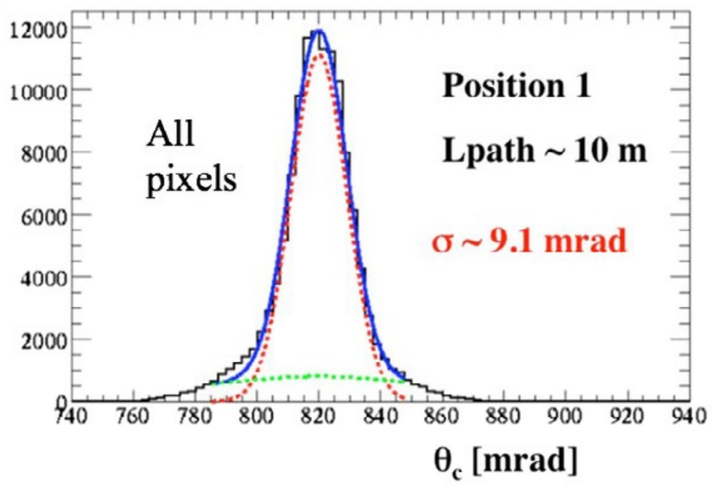
Cherenkov angle resolution per photon for the second prototype in cosmic rays



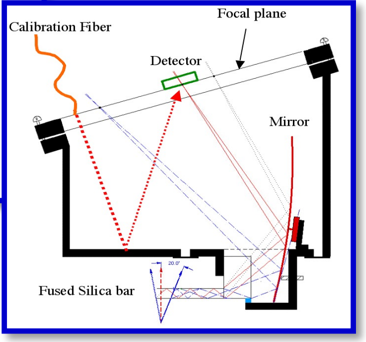


focusing block

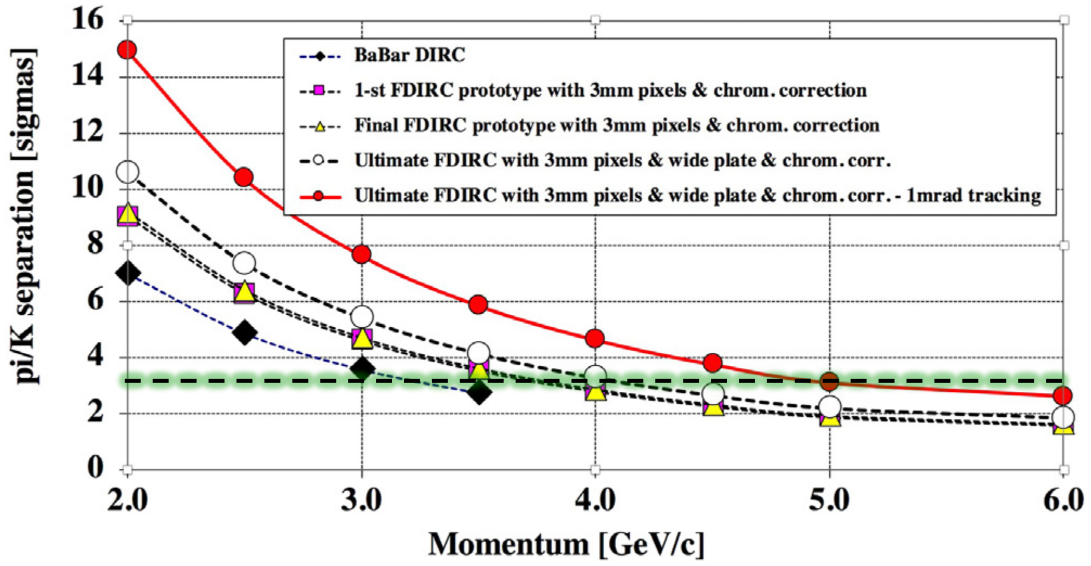
Cherenkov angle resolution per photon for the first prototype in electron beam



oil tank



Comparison of BABAR/fDIRC expected performance



B. Ratcliff and J. Va'vra, Nucl.Instrum.Meth. A 970 (2020) 163442

Technical challenge: properties of synthetic fused silica (FS)

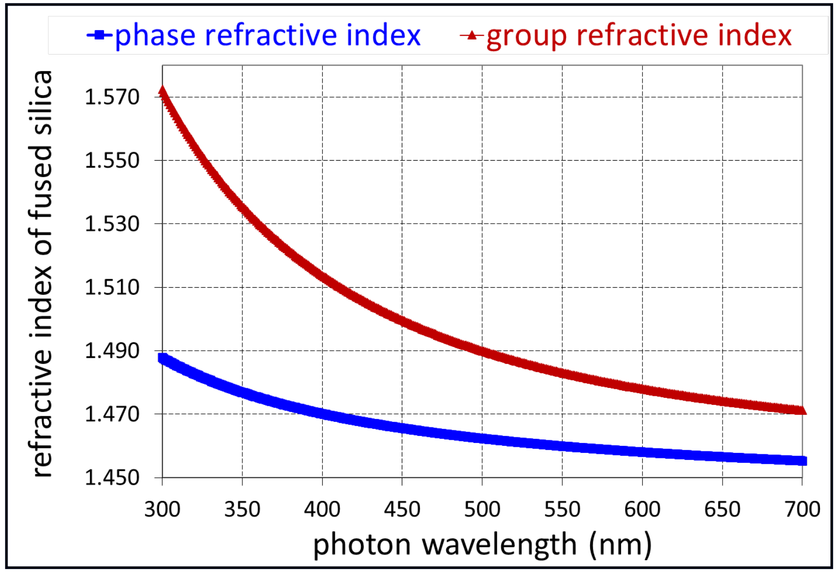
Pros: Optically transparent over wide wavelength range

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)

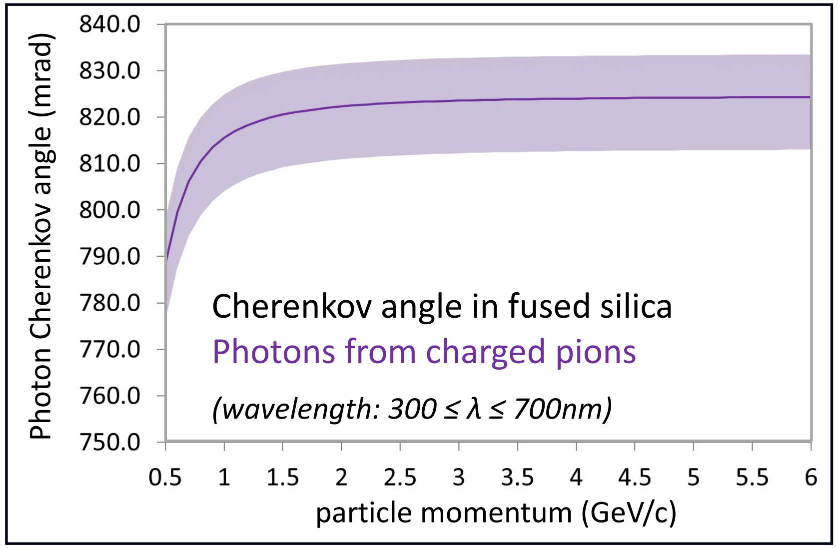
Dispersion of refractive index impacts angular resolution



Impact of chromatic dispersion on Cherenkov angle resolution

For $\beta=1$: $\theta_C=813 \ldots 834$mrad (for $300 \le \lambda \le 700$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

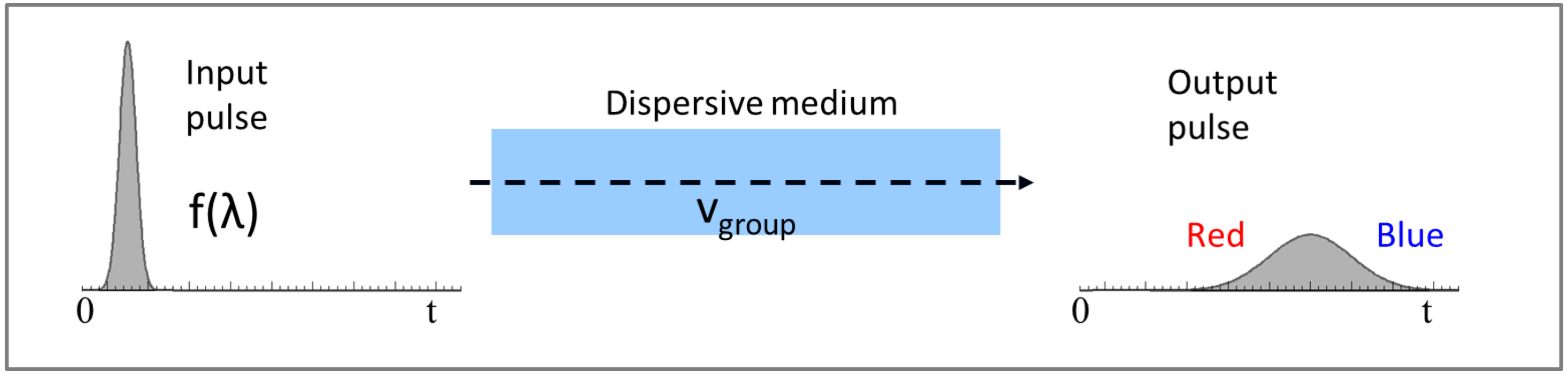
→ SuperB fDIRC first to demonstrate feasibility of this method

CHROMATIC DISPERSION IN DIRCs

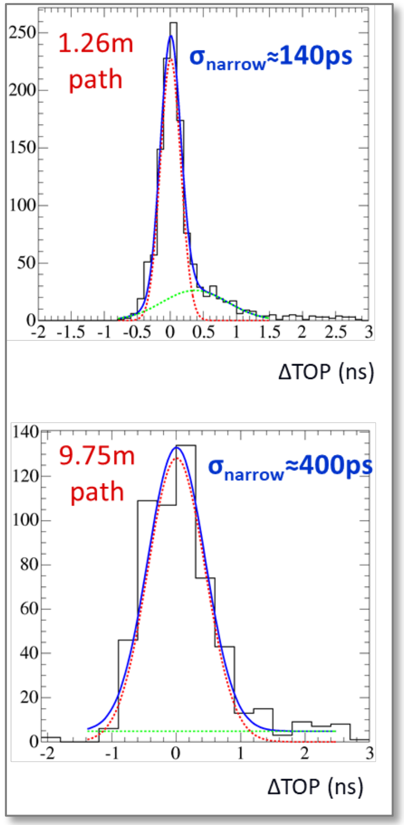
JS, RICH 2007

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

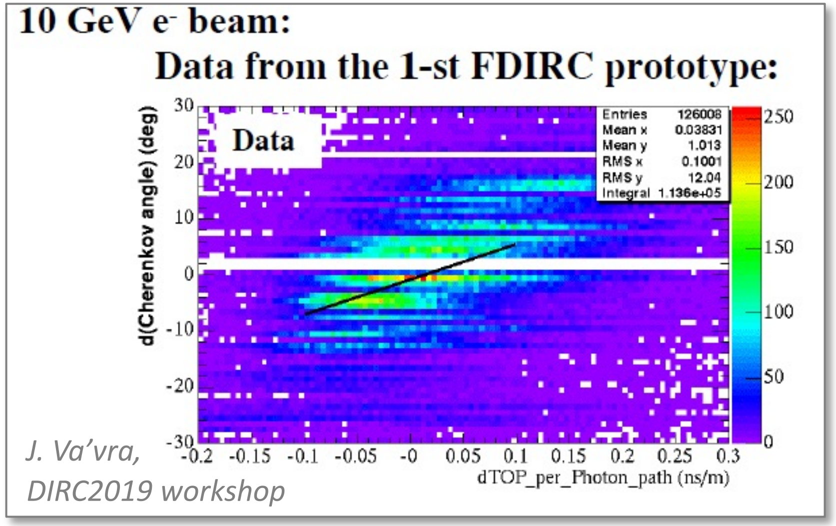
Photon color tag dTOP: time difference between the measured propagation time of a photon and the expected propagation time (calculated for photon with the average wavelength)

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

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

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

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

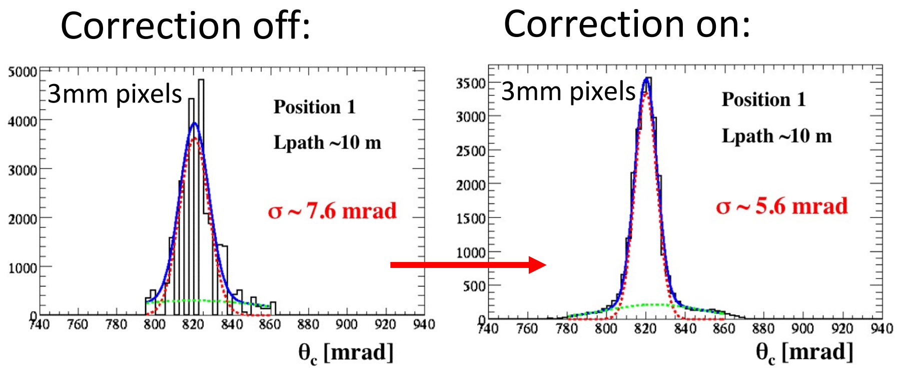


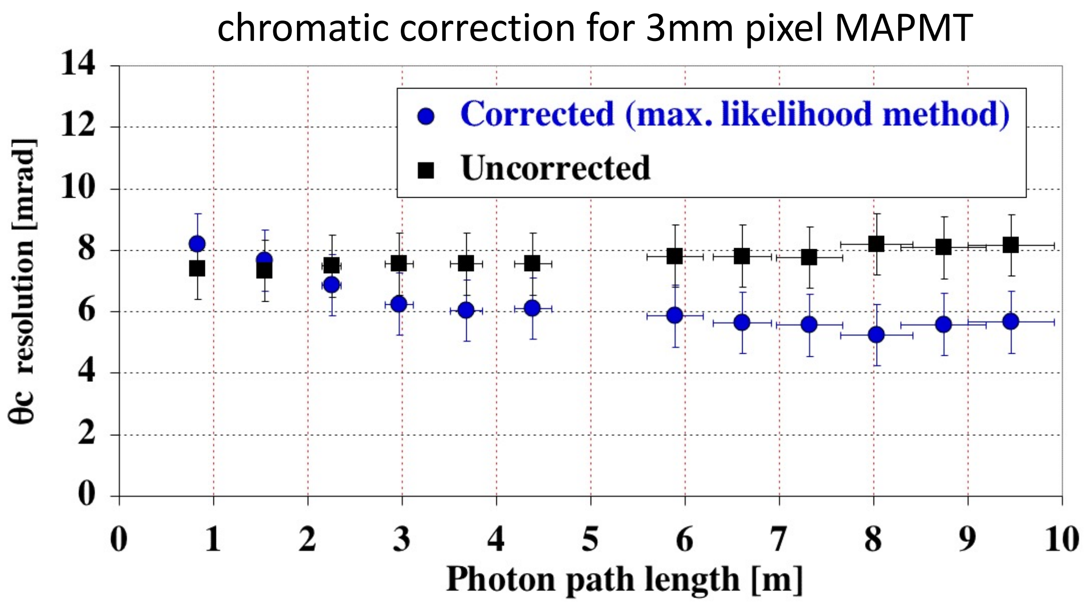
J. Va'vra, DIRC2019 workshop

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





JS, RICH 2007

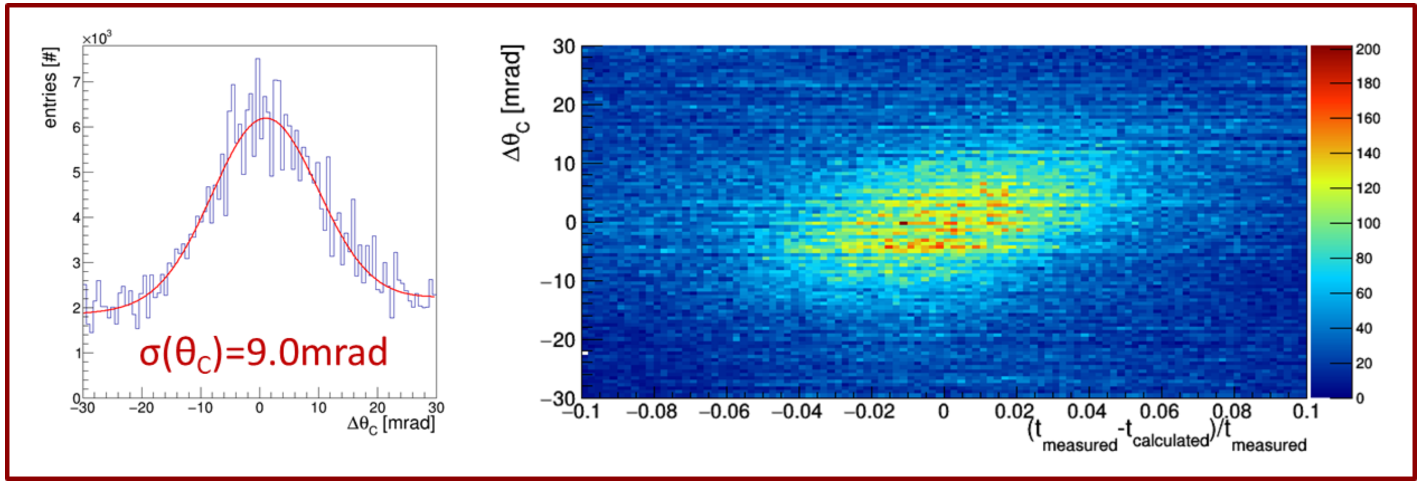
R. Dzhygadlo, April 2021, priv. comm.

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

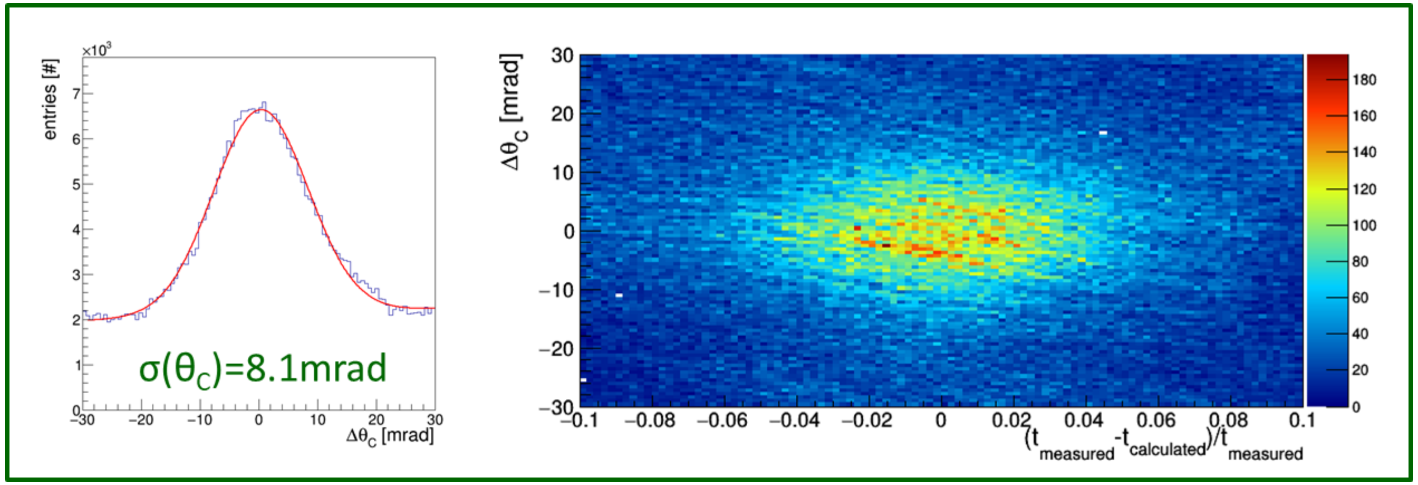
PANDA Barrel DIRC prototype at CERN PS,
7 GeV/c, mixed hadron beam, 90° polar angle

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



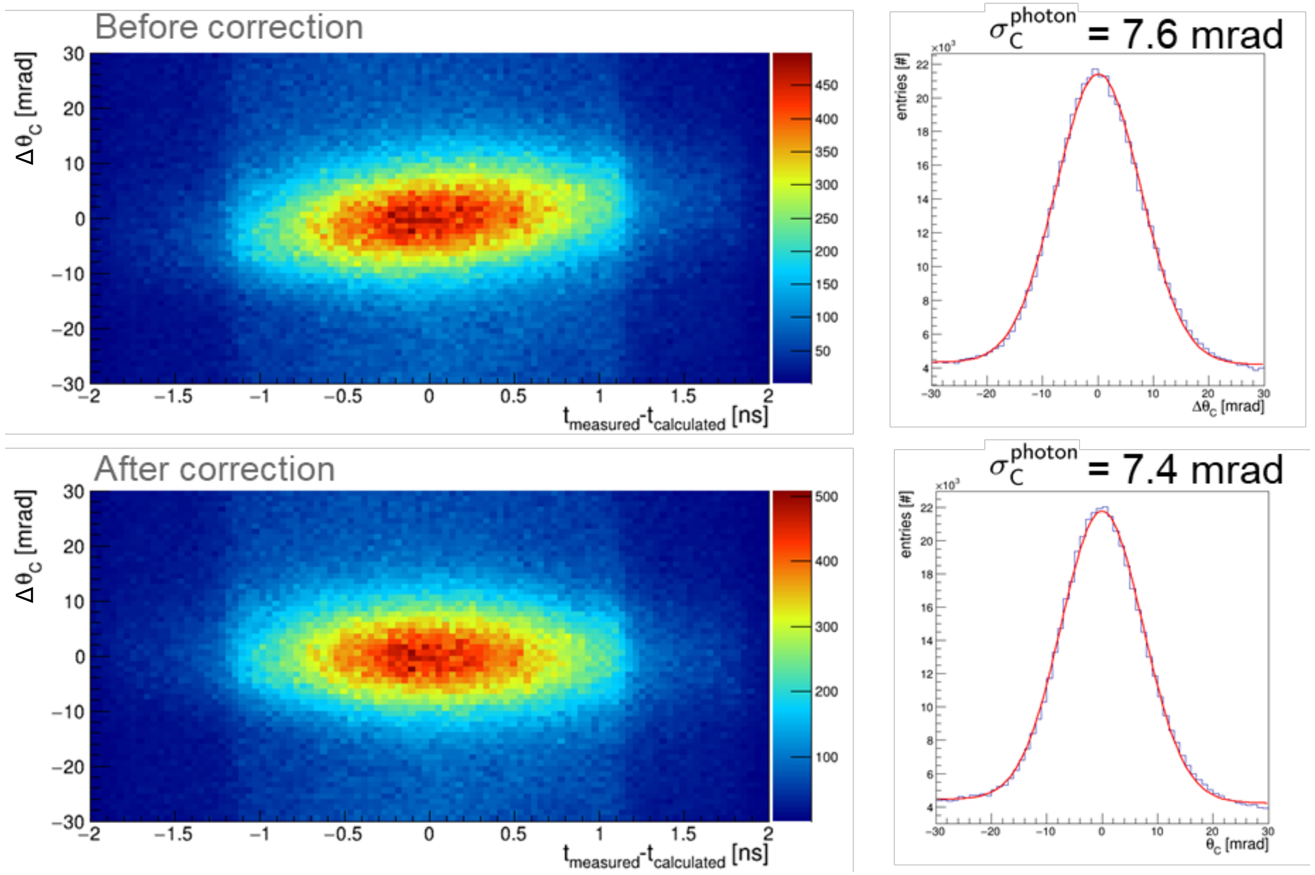
Clear improvement of Cherenkov angle resolution per photon after correction

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

Example from GlueX DIRC:

GlueX-II physics run 2020

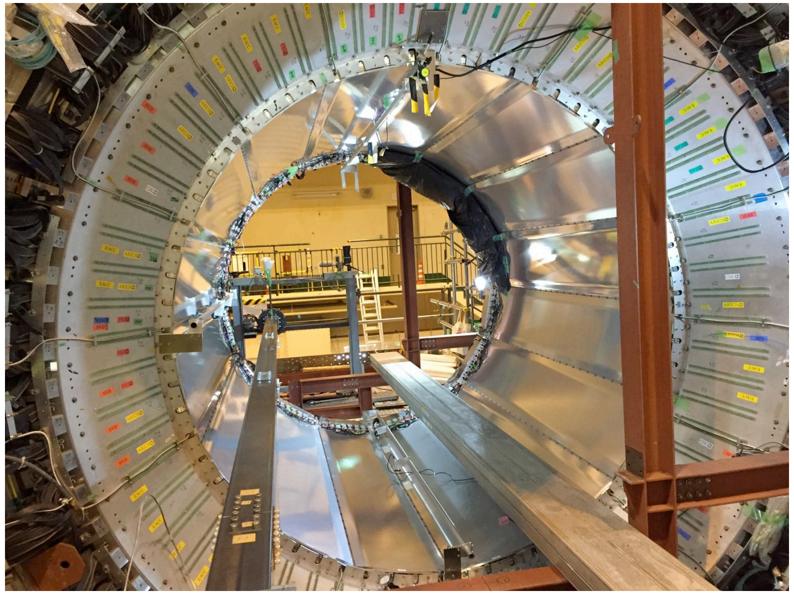
Cherenkov angle corrected by photon propagation time difference
(calculated using average wavelength of 370nm)



Modest improvement of Cherenkov angle resolution per photon after correction

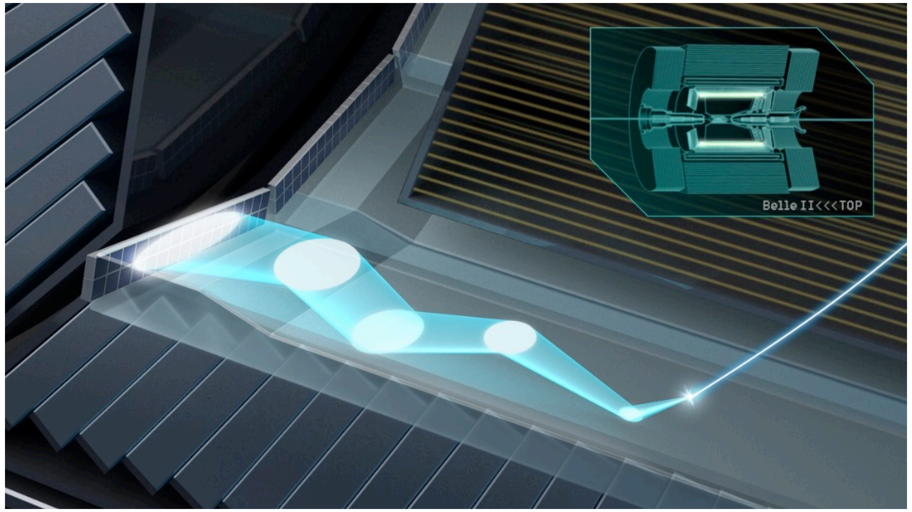
(poor timing precision (0.8-1ns) but long photon paths (5-10m))

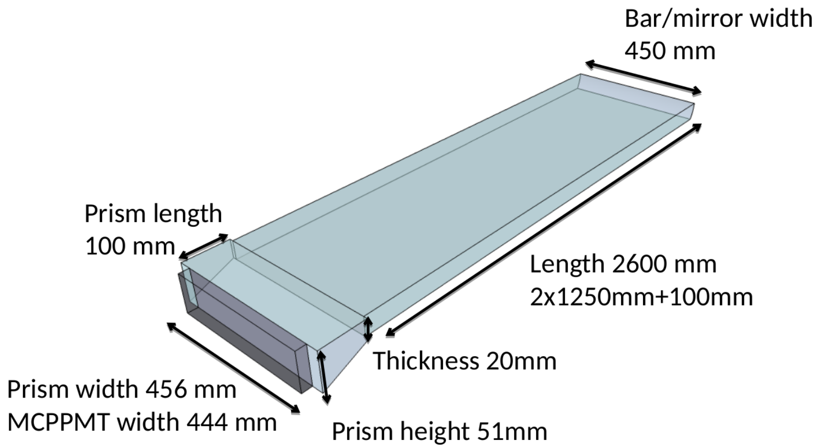
R. Dzhygadlo, TIPP2021 May 2021

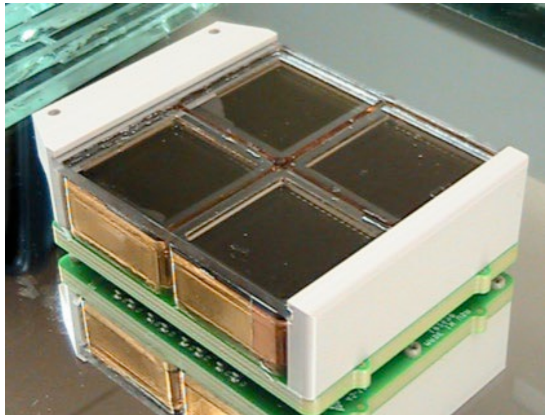


Belle II TOP

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



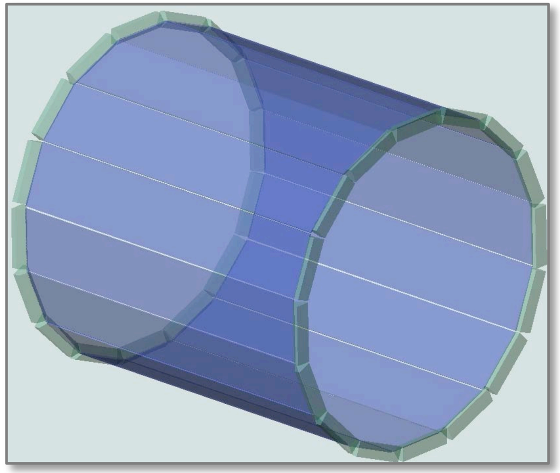




Upgrade of Belle detector for high-luminosity Belle II experiment

- 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)

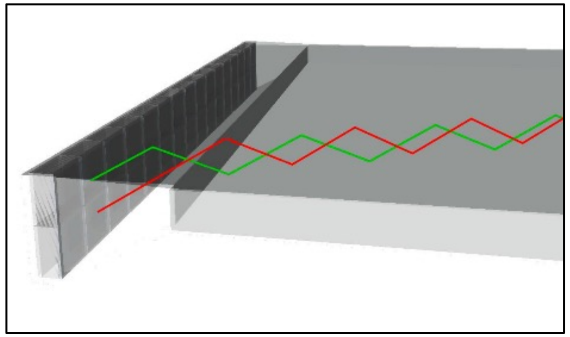
– ultimately rejected due to chromatic dispersion issues and sensitivity to backgrounds.

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

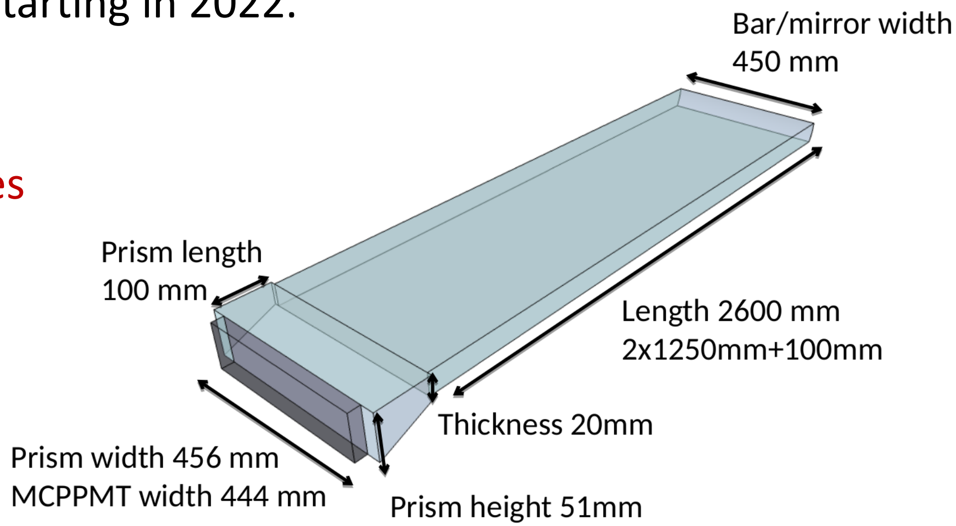
Photon detector: array of 2x16 Hamamatsu SL-10 MCP-PMTs per sector (4x4 pixels each);

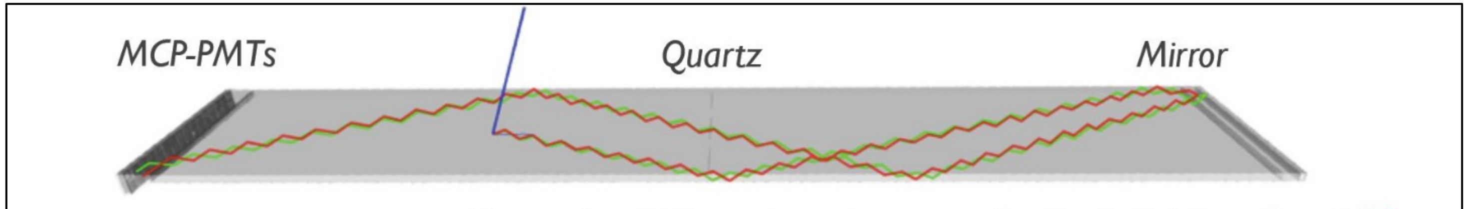
MCP-PMT lifetime issues will require replacement of (most) MCP-PMTs, starting in 2022.

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

Y. Arita, QFPU 2013

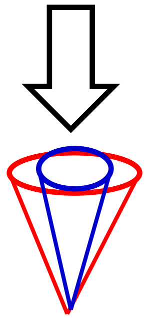
Early TOP concept: 2-D readout,

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

Hit pattern: position vs. time

Ring image of TOP counter

Top view



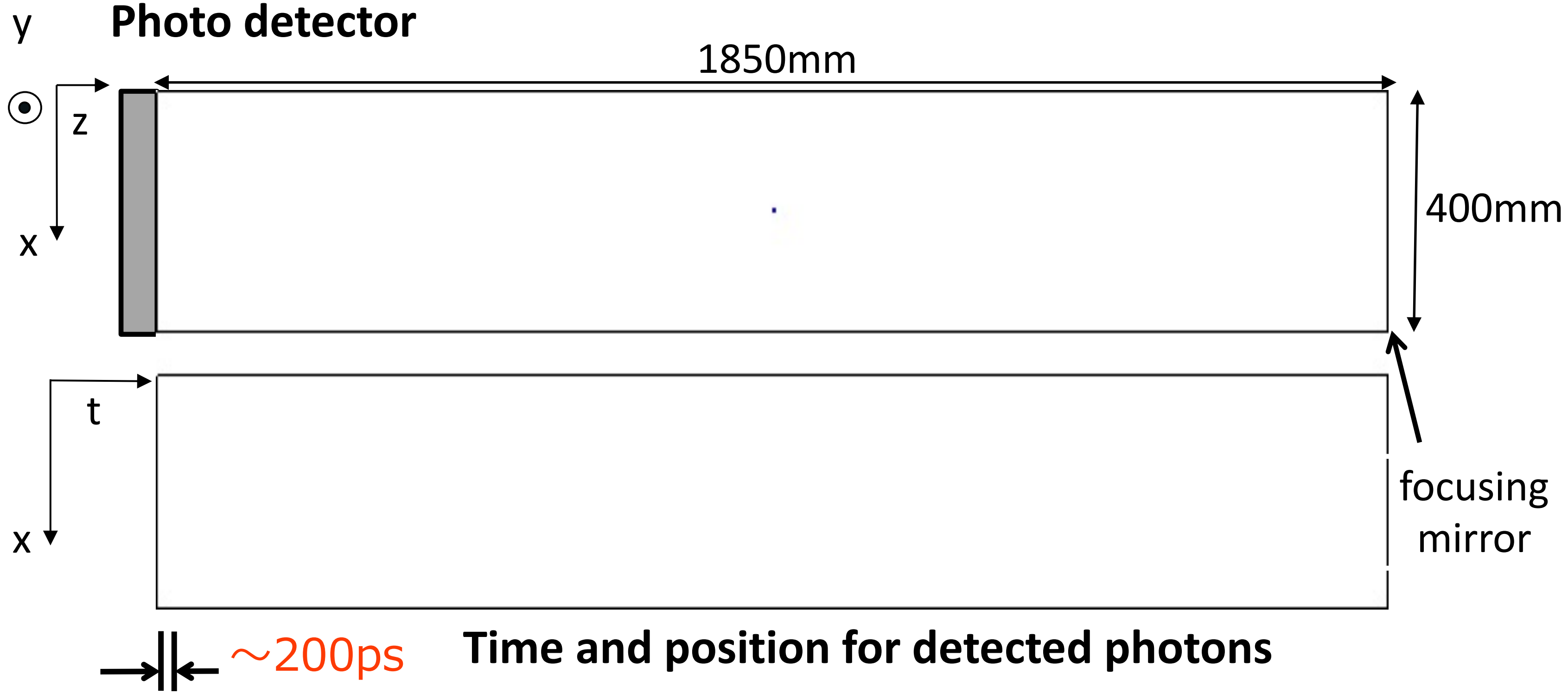
π/K

→ β are different

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

Ring image animation

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



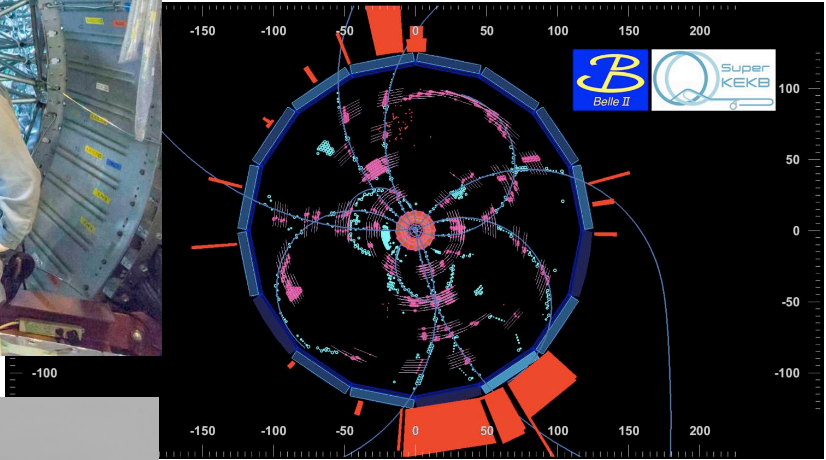
Time and position for detected photons

Belle II TOP

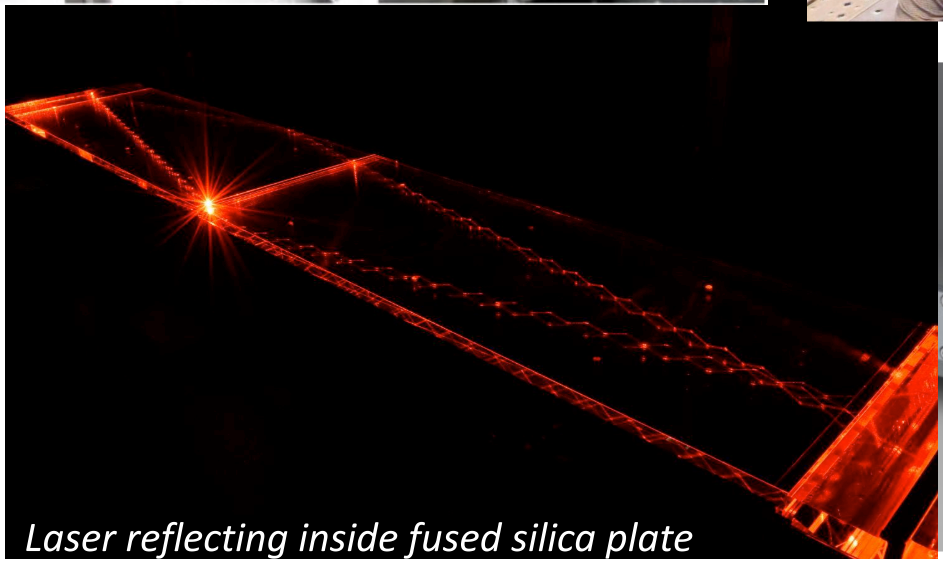
K. Inami, DIRC2017
G. Varner, DIRC2019

Optics on gluing stage

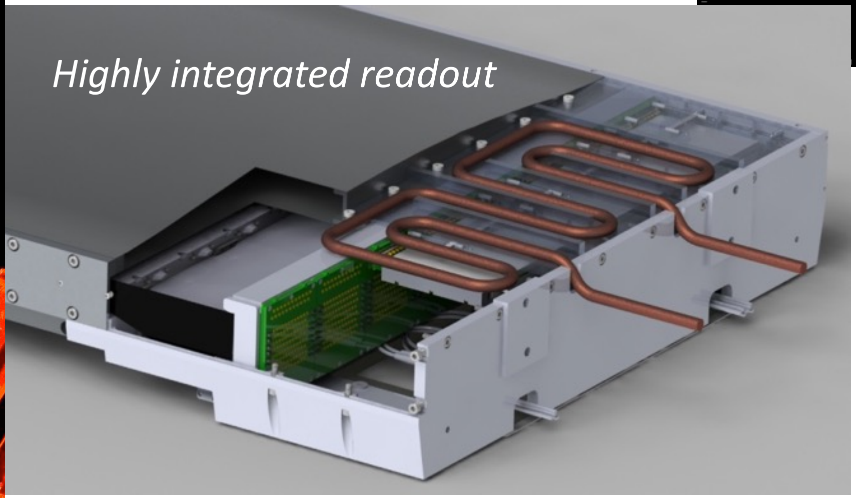
Successful installation in 2016



First collision in physics run, March 2017



Laser reflecting inside fused silica plate

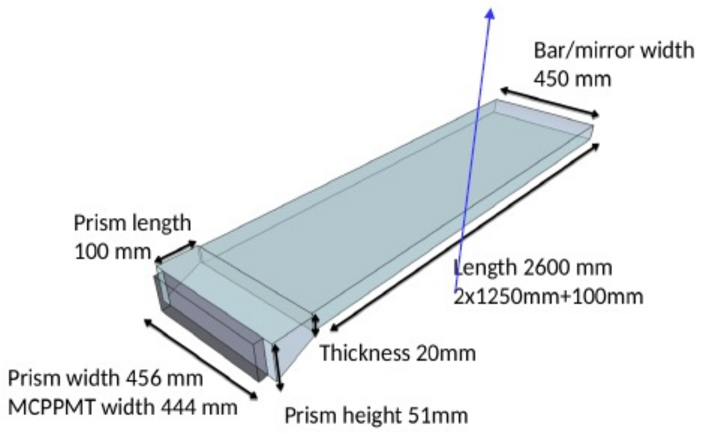


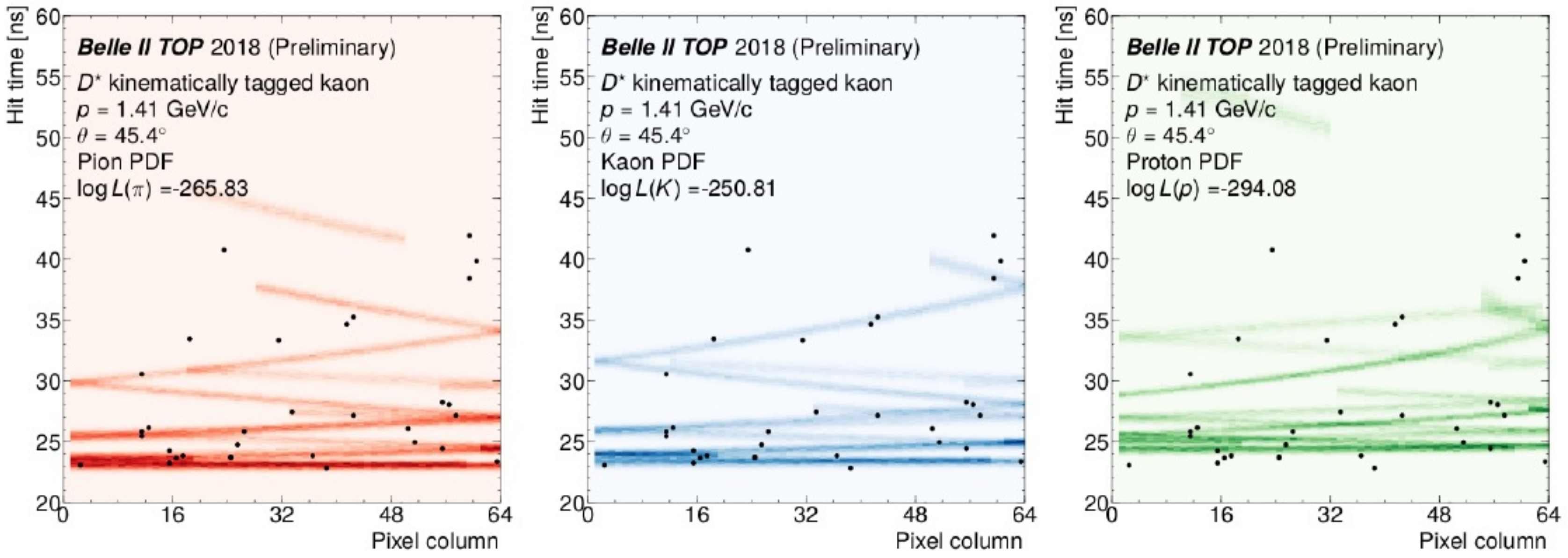
Highly integrated readout

G. Varner, DIRC2019

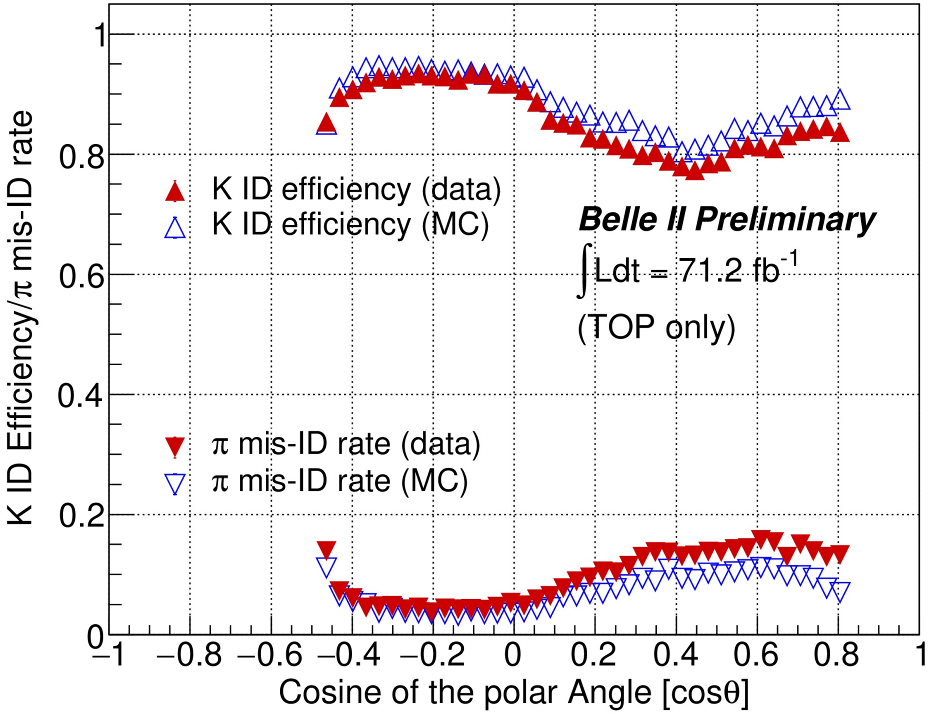
TOP "Cherenkov Rings" II

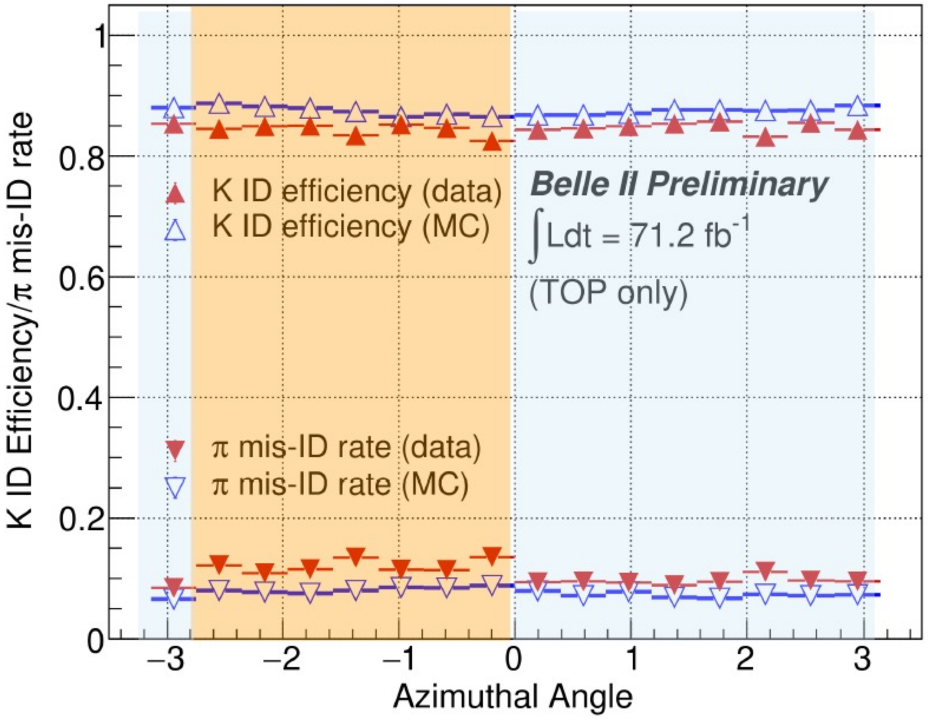
- $D^{*+} \to D^0 \pi_s^+ ; D^0 \to K^- \pi^+$
- Kaon facing mirror-side of TOP bar
  - PDF differences dominated by shape
  - Though for proton, also timing

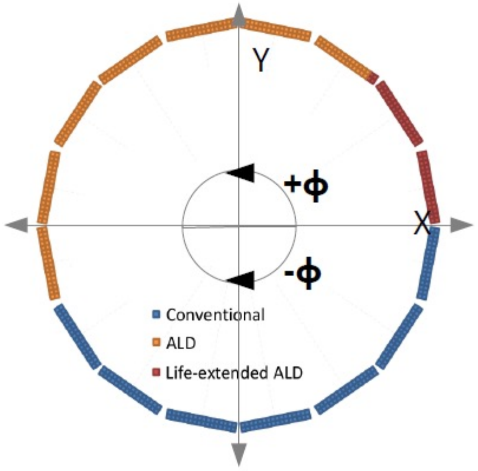




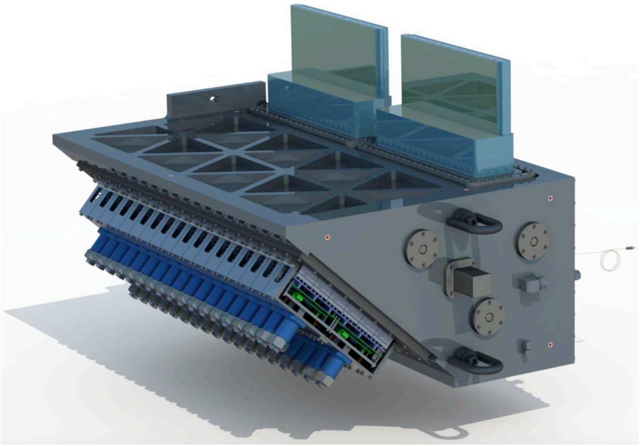
- Efficiencies and mis-ID rates measured for kinematically identified pions and kaons approaching simulation expectation





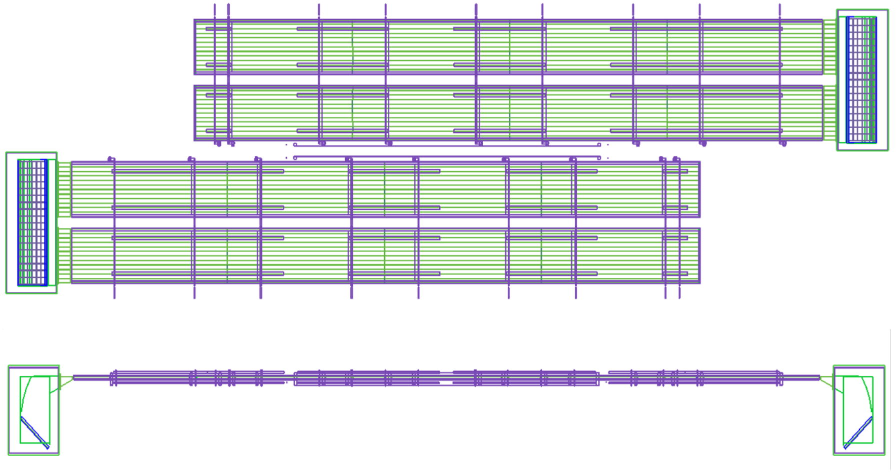


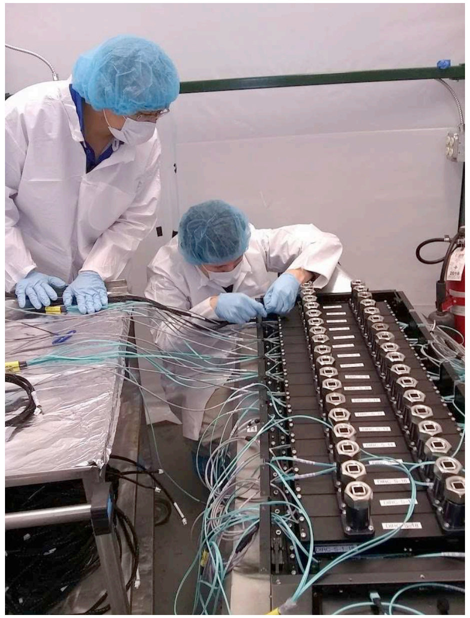
S. Sandilya, TIPP21, May 2021

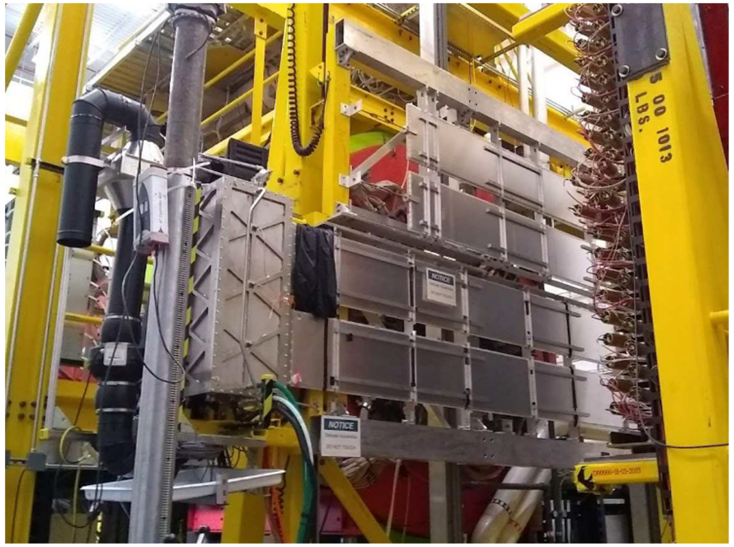


GlueX DIRC

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







GlueX DIRC

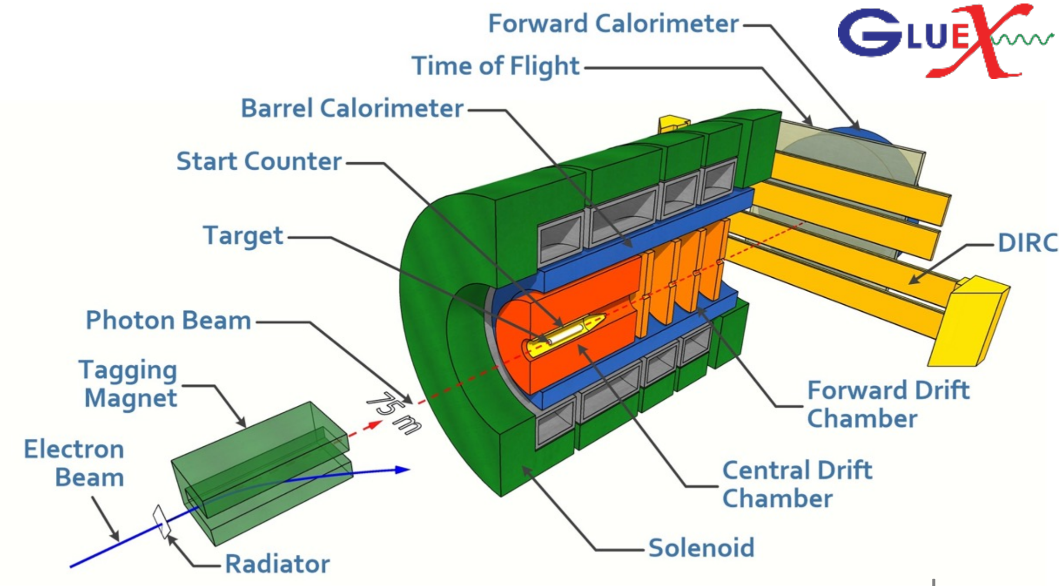
- compact photon camera
- approx. cyl. mirror focusing
- small pixels (MCP-PMT)
- moderate photon timing
- dispersion mitigation*
- legacy components

- 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 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;
- opportunity to evaluate PANDA Barrel DIRC simulation and reconstruction/PID algorithms (“FAIR Phase-0”).

BABAR DIRC bar boxes

← in storage at SLAC

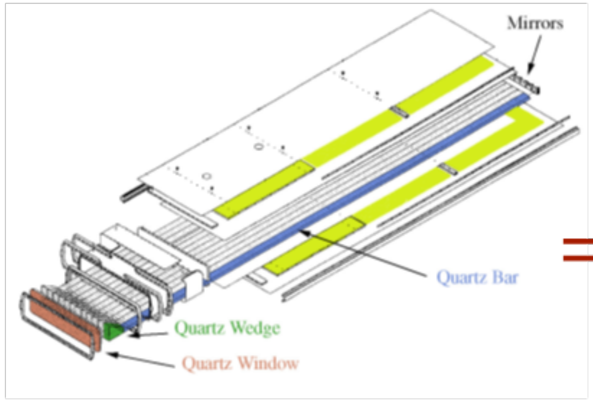
installed at JLab →



gluex.org

- Transportation of the bar boxes from SLAC to JLab in 2017/2018 after thorough planning
- Bar boxes in crate, with oil/air shocks inside another crate, acceleration monitoring, continuous visual monitoring of bars

BaBar DIRC Bar Box



⇒

DIRC Bar Box Storage at SLAC

⇒

On the Road in New Mexico

⇓

A long and very, very careful drive

⇐

3000 miles later at JLab

⇐

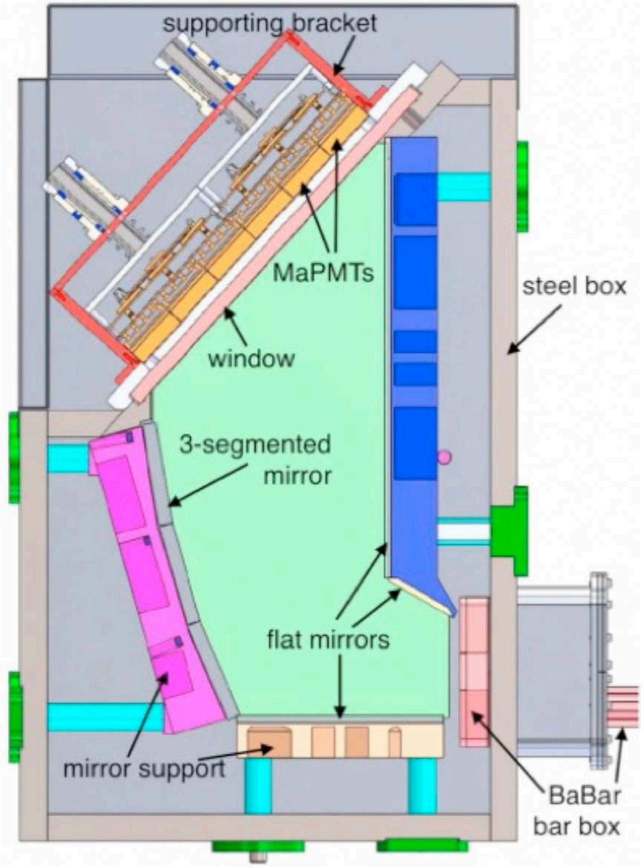
DIRC Bar Box in Hall D

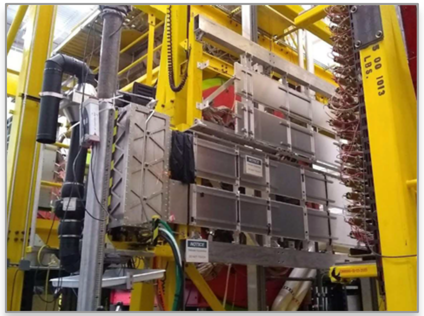
W. Li, JS, INSTR'20, Feb 2020

GlueX DIRC

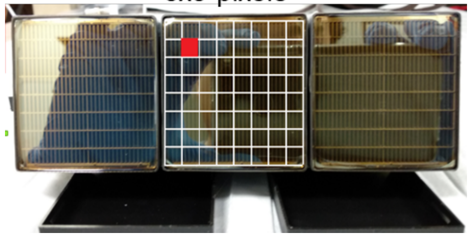
- Forward DIRC wall, reusing four BABAR DIRC bar boxes;
- Optics design based on SuperB fDIRC;
- Significant design simplification and cost reduction by replacing fused silica block with DI water and cylindrical mirror with set of three flat mirrors;
- Two “optical boxes” coupled to two bar boxes each, 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.

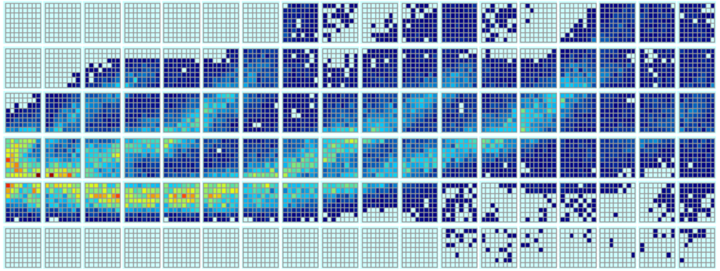
GlueX optical box





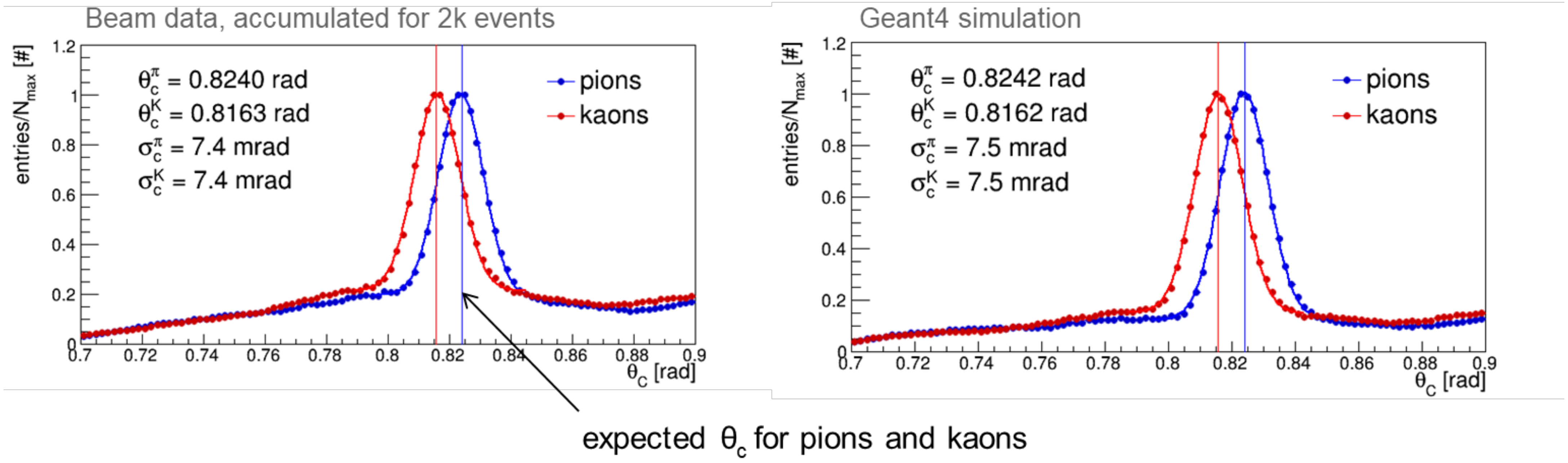
Hamamatsu H12700 MaPMT
8x8 pixels





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

Cherenkov angle resolution per photon (SPR)



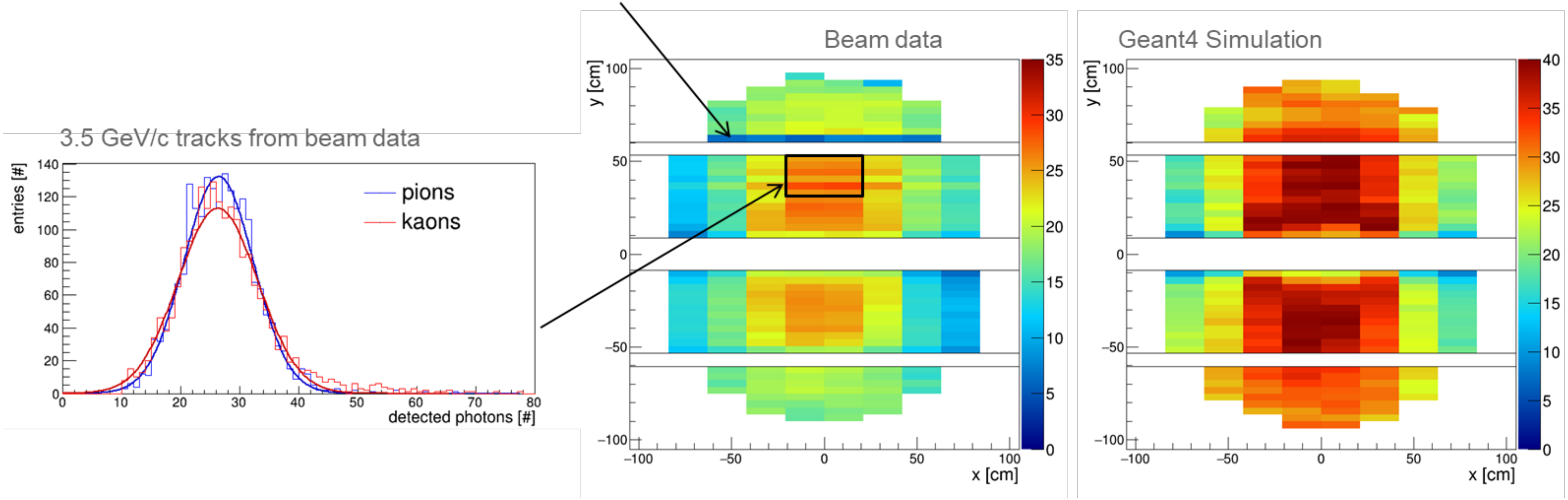
- Good Cherenkov angle resolution per photon, 25% improvement compared to BABAR
- Good agreement between beam data and simulation for hit pattern and SPR

R. Dzhygadlo, TIPP2021 May 2021

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

Cherenkov photon yield

Lower yield from bar #11
(matches BABAR observation)



- Simulation overestimates photon yield by ~35%

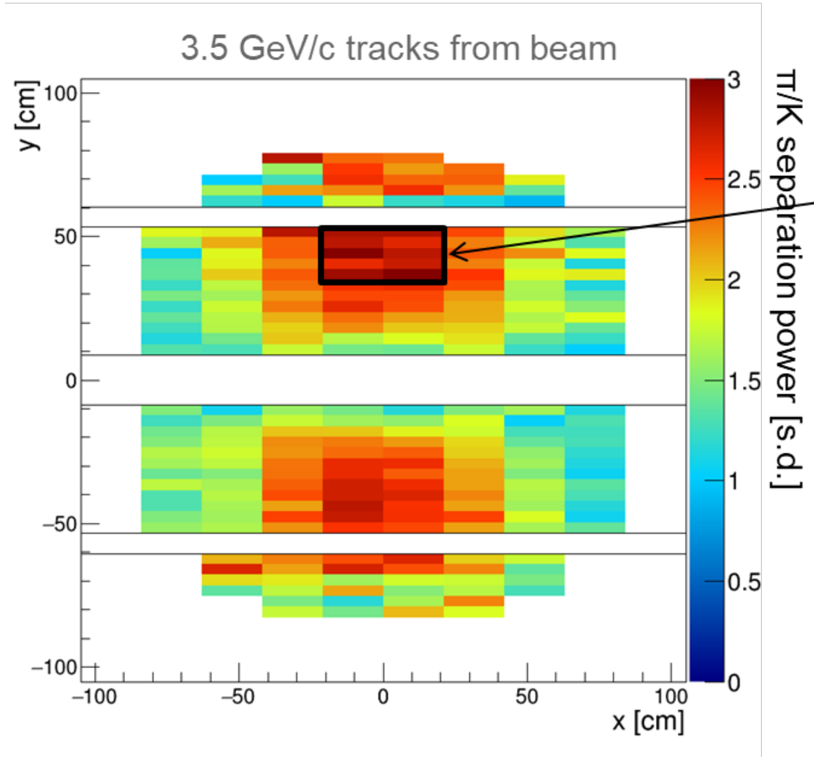
  Likely cause: degradation of mirror surfaces due to corrosion in water in 2019/2020

  Mirrors will be replaced this summer and protected by window for next GlueX II run

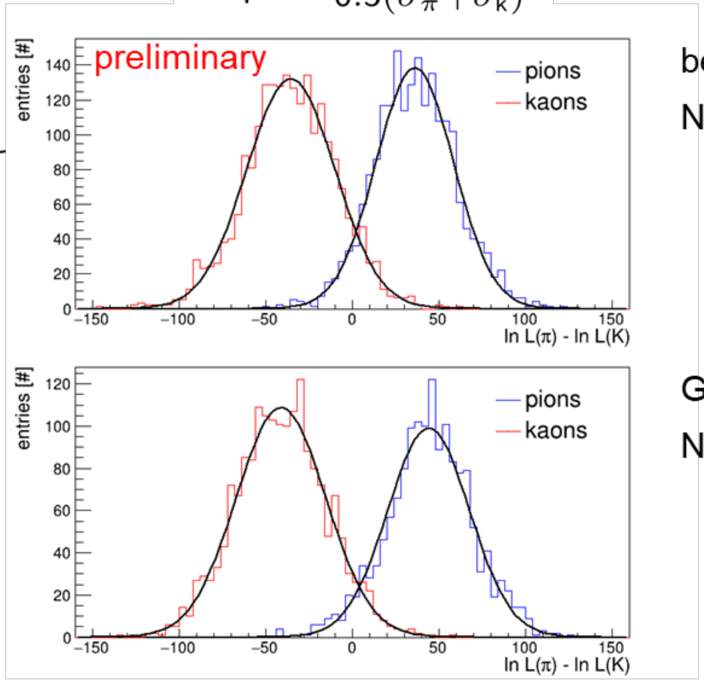
R. Dzhygadlo, TIPP2021 May 2021

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

π/K separation power



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



beam data:

N_{sep} = 3.0 ± 0.1 s.d.

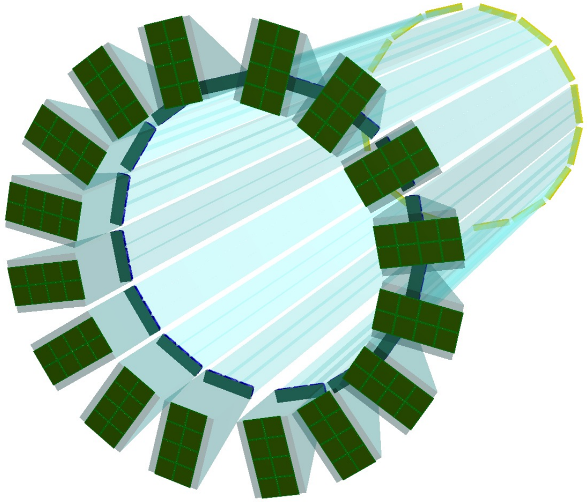
Geant4 simulation:

N_{sep} = 3.4 ± 0.1 s.d.

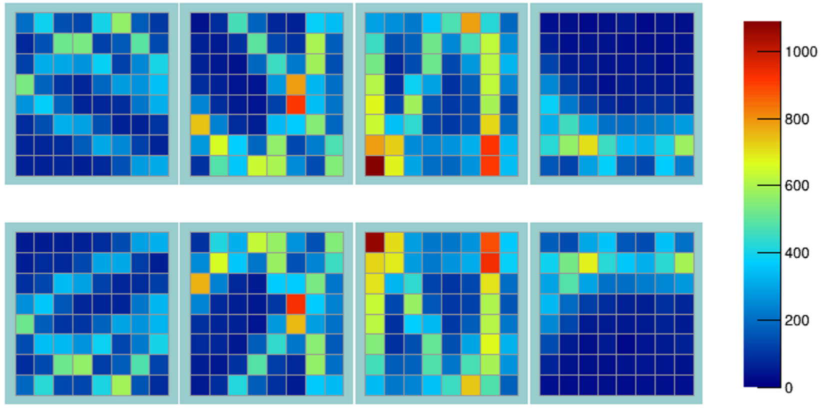
- π/K separation power already close to goal
- Yield-corrected simulation overestimates separation power by 10-15%
- Performance expected to further improve with better understanding of calibration and alignment and more data – current statistics prevent use of time imaging method *(algorithm with best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

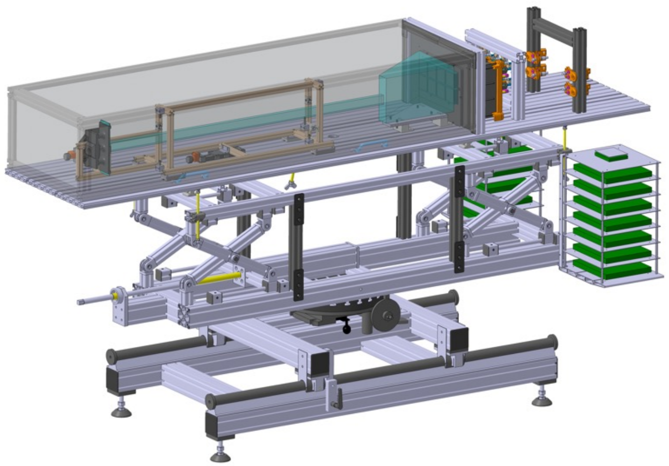
R. Dzhygadlo, TIPP2021 May 2021

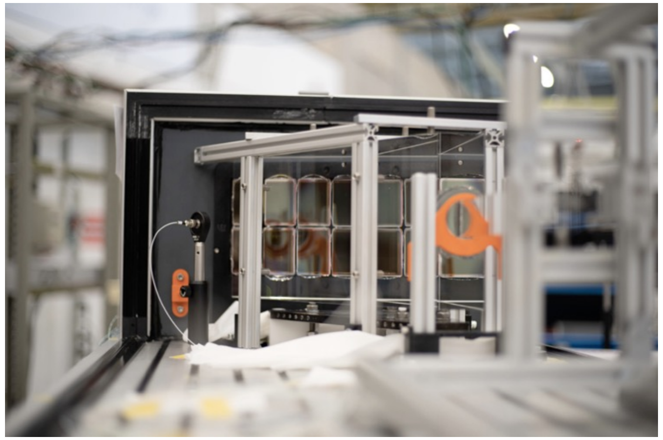
- compact photon camera
- spherical lens focusing
- small pixels (MCP-PMT)
- fast photon timing
- dispersion mitigation



PANDA Barrel DIRC



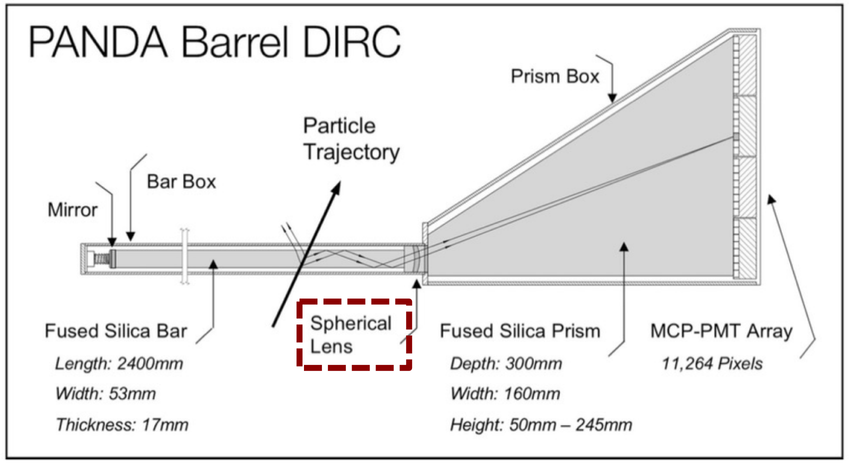




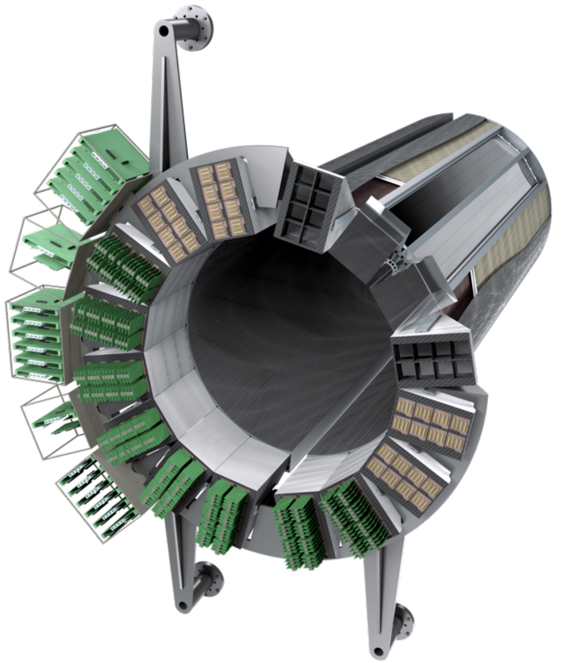
PANDA Barrel DIRC

- 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.

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



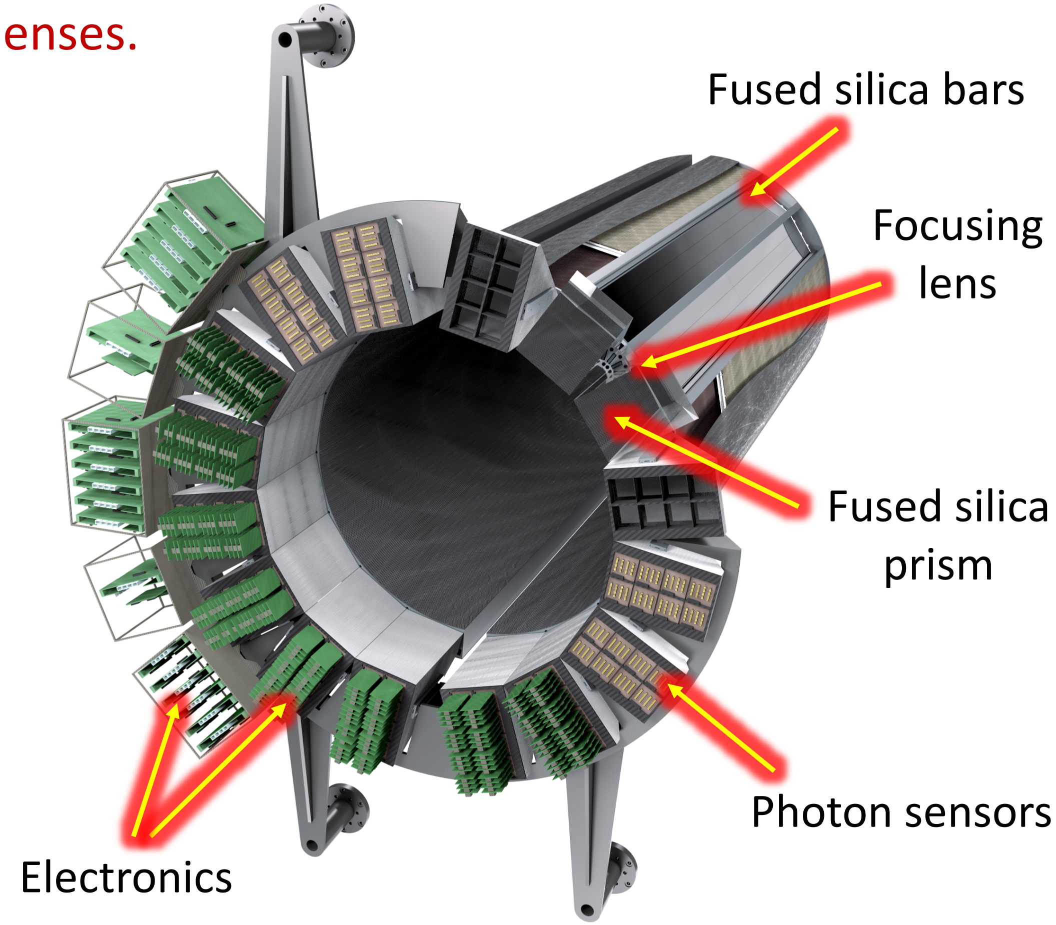
Handbook of Particle Detection and Imaging, Springer, Cham., 2020



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

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:

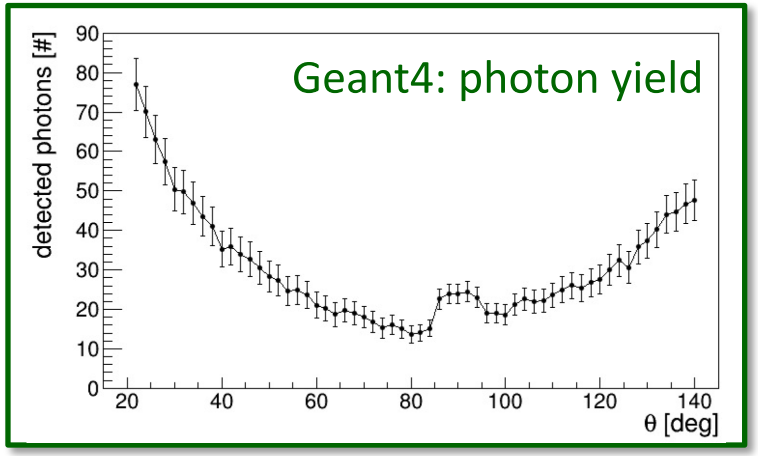
Used geometrical reconstruction (BABAR-like) to determine

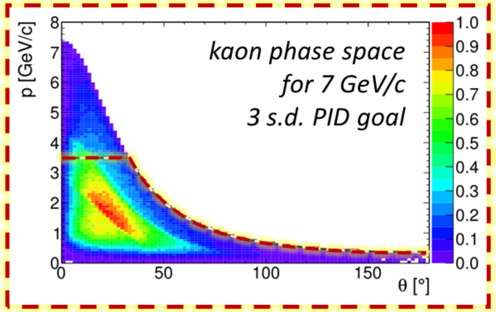
photon yield and single photon Cherenkov angle resolution (SPR).

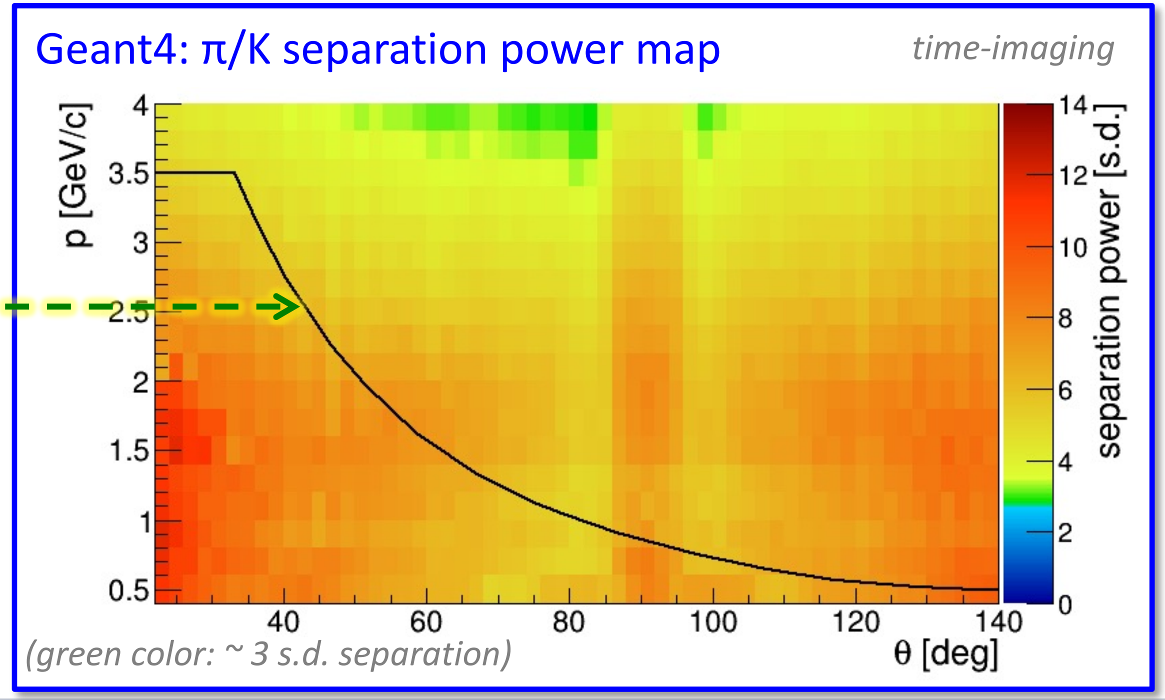
Latest generation of MCP-PMTs will further increase photon yield by up to 50%.

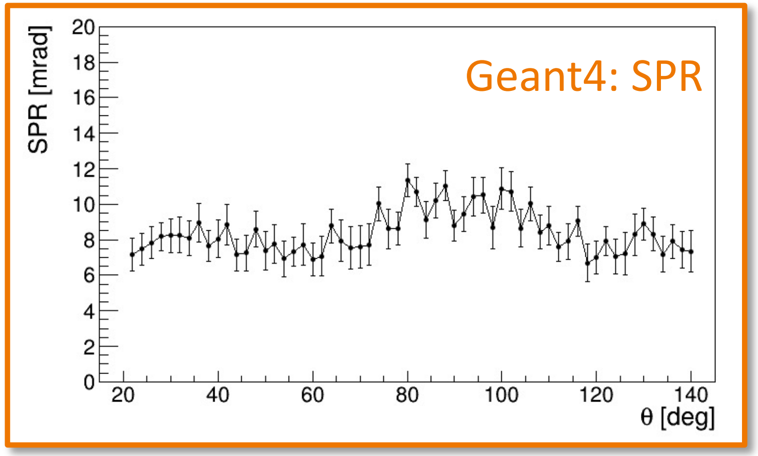
Time-imaging delivers best performance for π/K separation power map,

PANDA PID performance goal exceeded for entire phase space









R. Dzhygadlo, priv. comm.

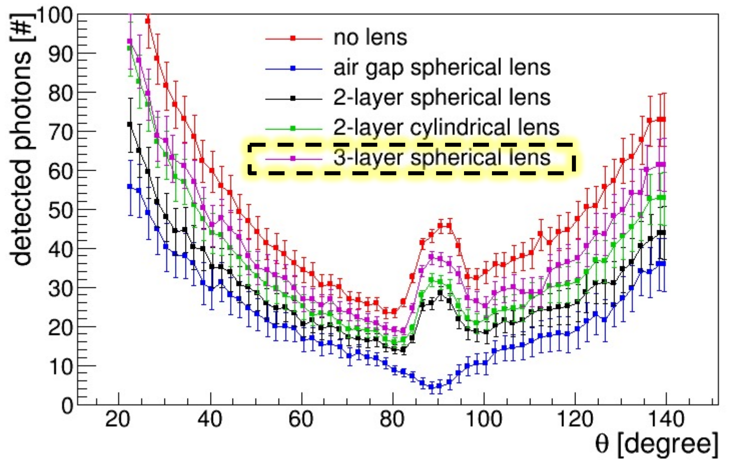
Technical challenge: lens focusing

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

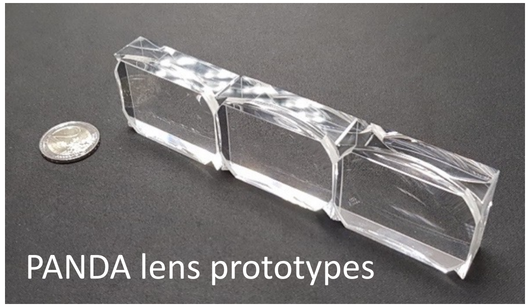
Geant4 simulation: photon yield



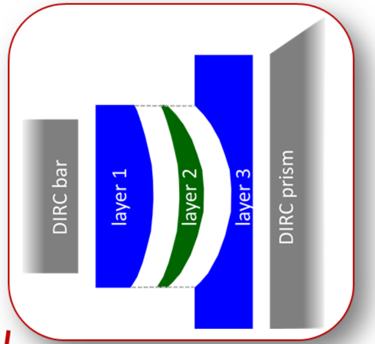
Innovative solution:

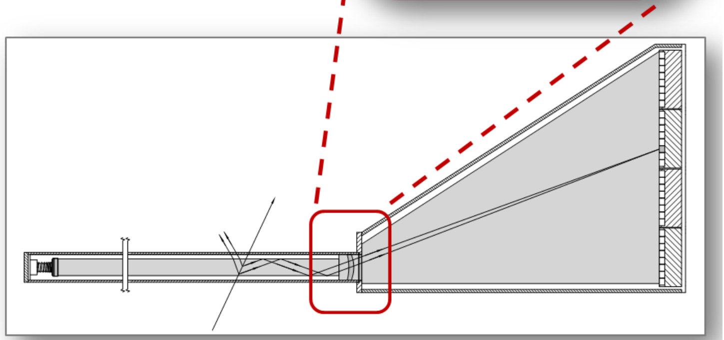
- 3-layer compound lens (without air gap):

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



PANDA lens prototypes





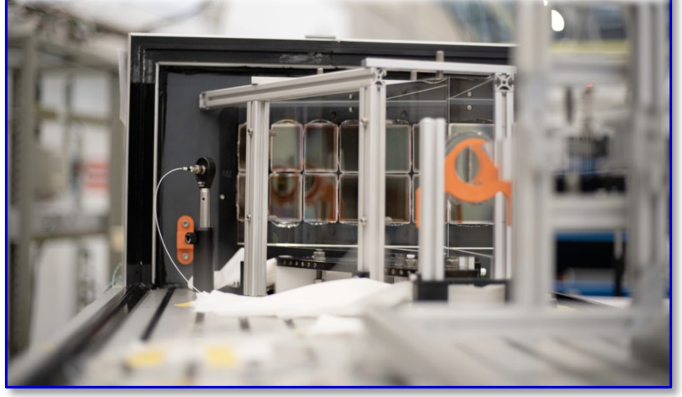
- Creates flat focal plane – matched to fused silica prism shape
- Avoids photon loss and barrel PID gap
- Lanthanum crown glass (LaK33B) for PANDA, rad-hard sapphire or PbF_2 for EIC
- Currently using standard spherical shapes – study aspherical shapes for future DIRCs to minimize aberrations?

see also G. Kalicy, DIRC2019

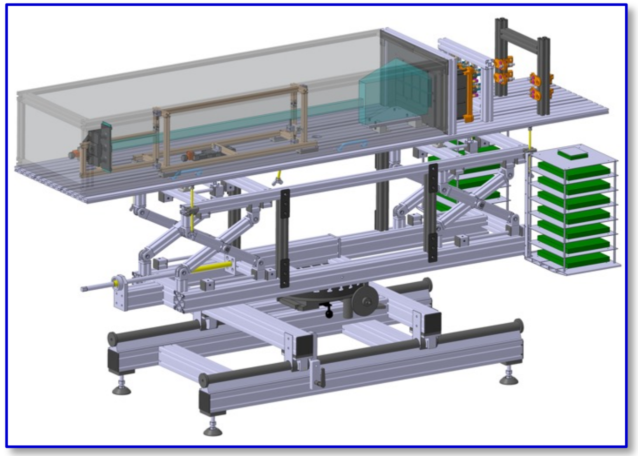
Performance validation: 2018 prototype at CERN PS

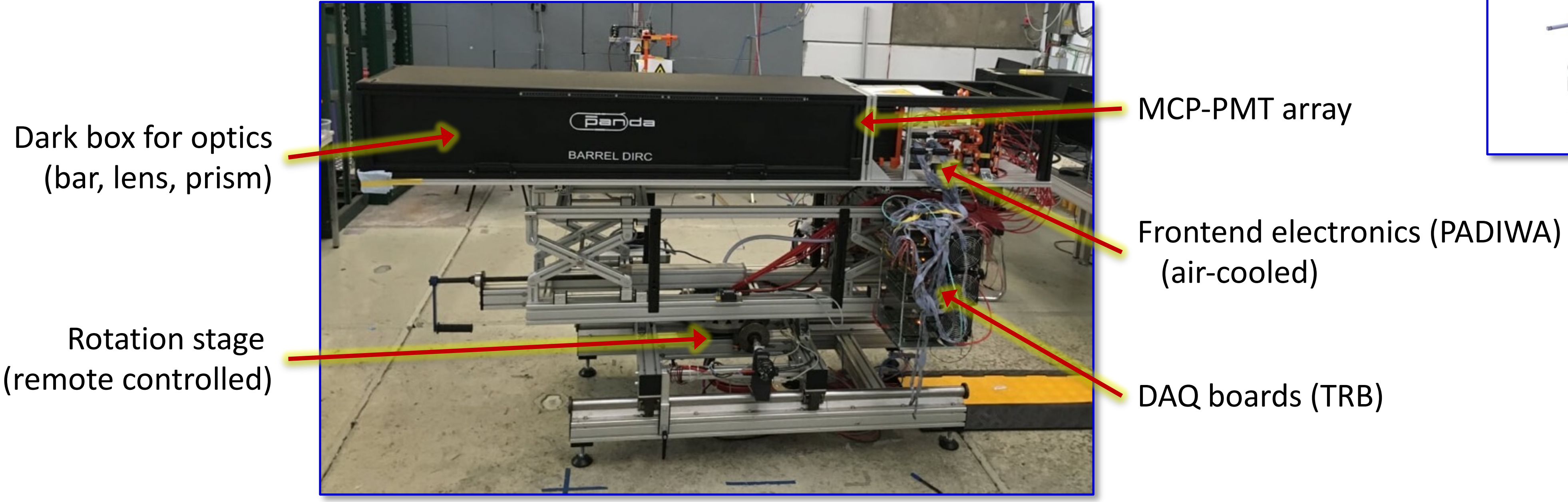
- Narrow fused silica bar, 3-layer spherical lens
- 30 cm-deep fused silica prism
- 2x4 PHOTONIS Planacon MCP-PMT array
- PiLas picosecond laser calibration system
- 7 GeV/c π/p beam equivalent to 3.5 GeV/c π/K
- MCP-TOF system to cleanly tag π and p events

View from inside the Barrel DIRC dark box

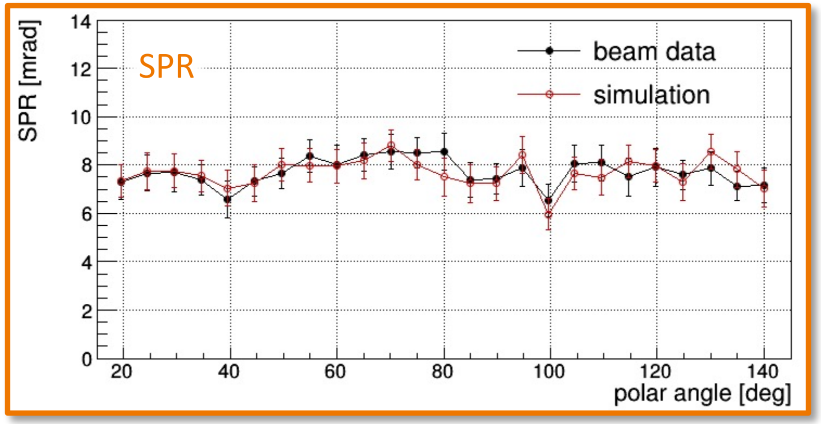


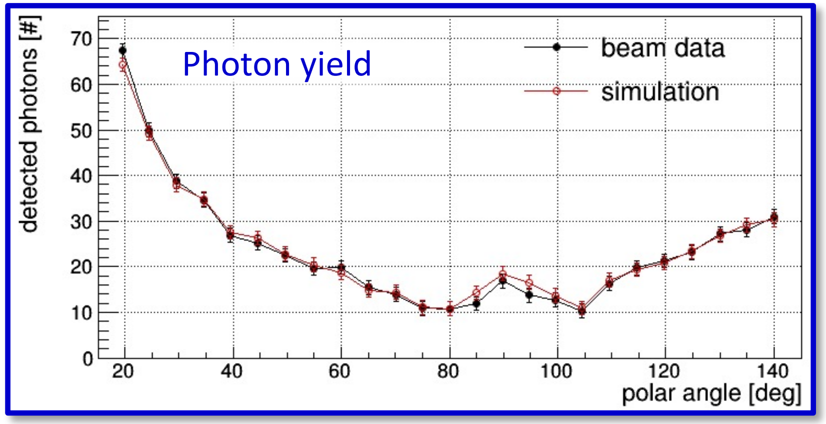
Schematic view of 2018 prototype



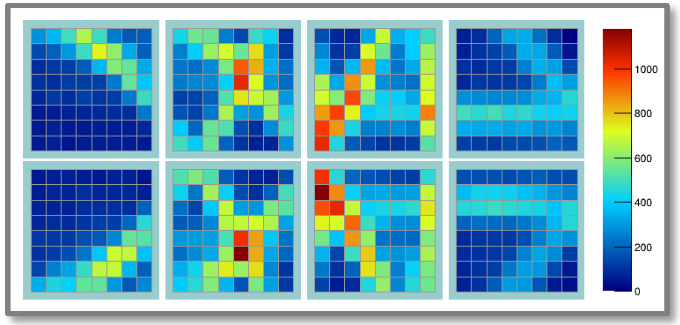


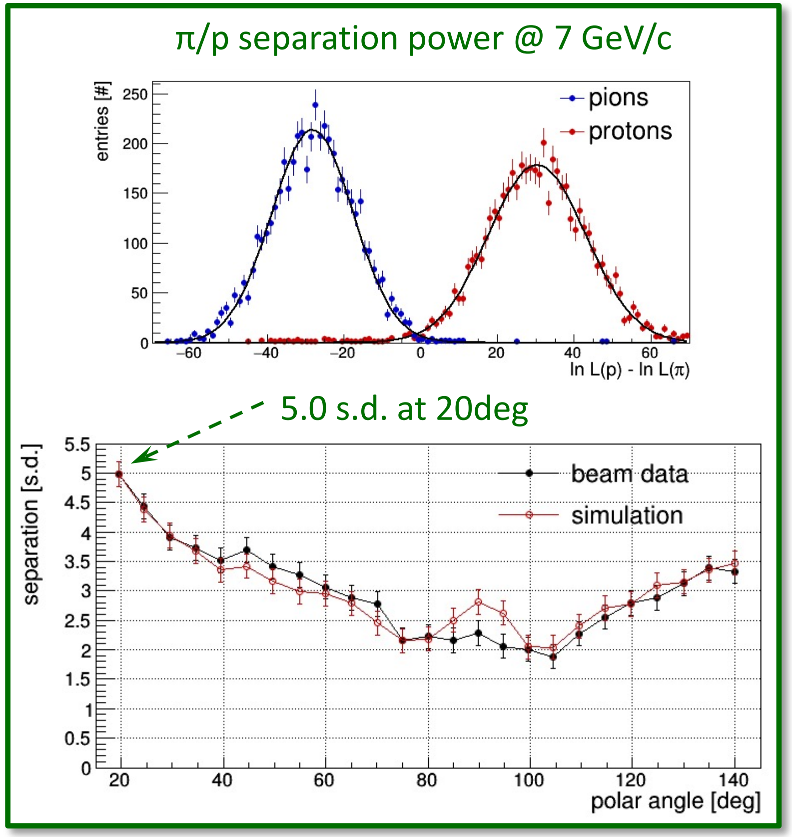
Performance validation: 2018 prototype at CERN PS





observed hit pattern at polar angle 20°





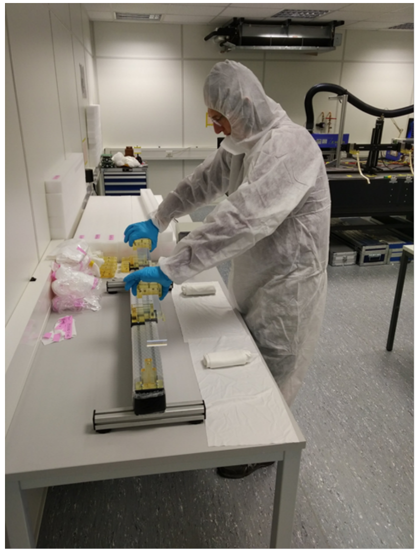
- Scans of beam incident angle and position for different momenta
- Measured Cherenkov angle resolution per photon (SPR), photon yield, and π/K separation in excellent agreement with expectation and Geant4 simulation
- Achieved π/K separation power of N_{sep}=5.0 s.d. with time imaging reconstruction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

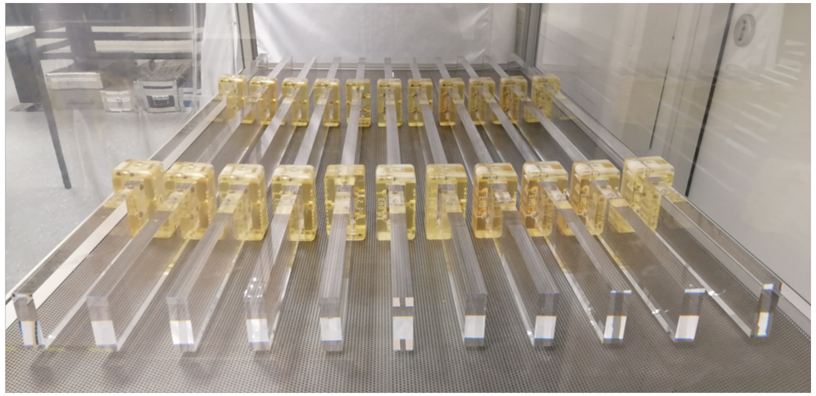
R. Dzhygadlo, priv. comm.

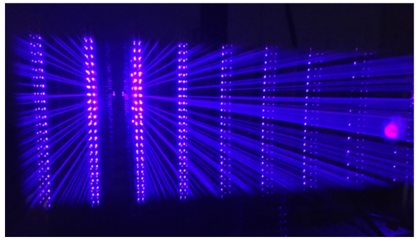
PANDA Barrel DIRC

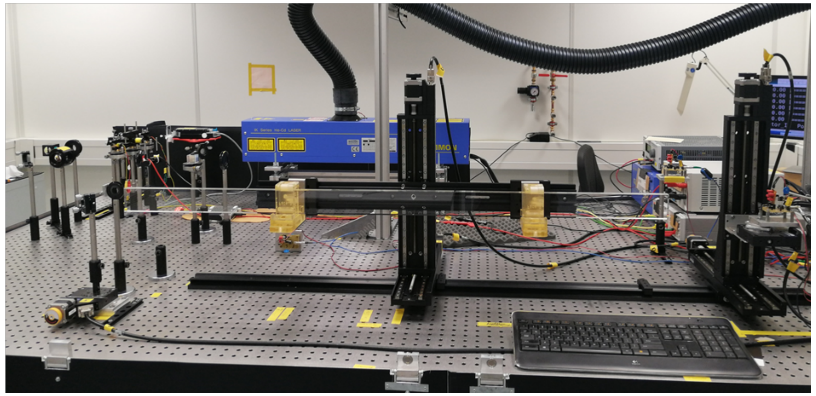
- series production of components started in 2019
- first call for tenders: fused silica bars
  contract awarded to Nikon Corp, Japan in Sep 2019
- 112 DIRC bars delivered by Feb 2021, ahead of schedule
- all bars meet or exceed specifications
  (e.g., 2-5 Å surface roughness)
- measuring quality of internal bar surfaces at GSI
  (laser scanning system, internal reflection coefficient)
- second call for tenders: MCP-PMTs
  contract awarded to Photonis Netherlands in Dec 2021
- Planacon XP85112 production ramping up, first units expected in July
- next up: spherical lenses, prisms, bar boxes in 2022/23, electronics in 2023/24
- installation in PANDA planned for summer 2025

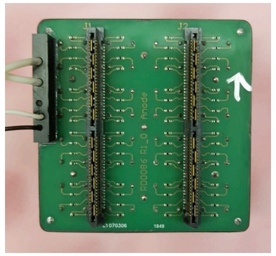
Nikon bars in DIRC lab at GSI



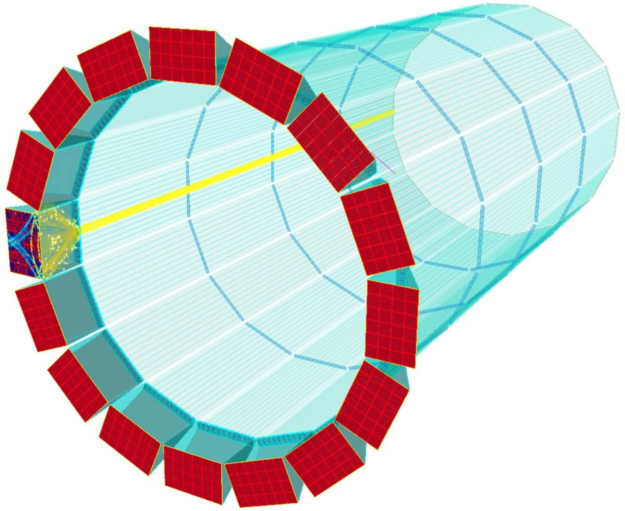






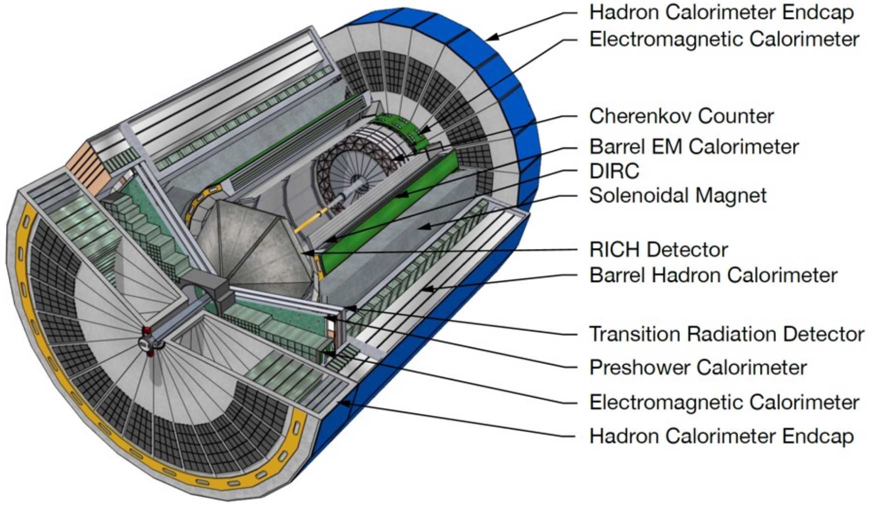


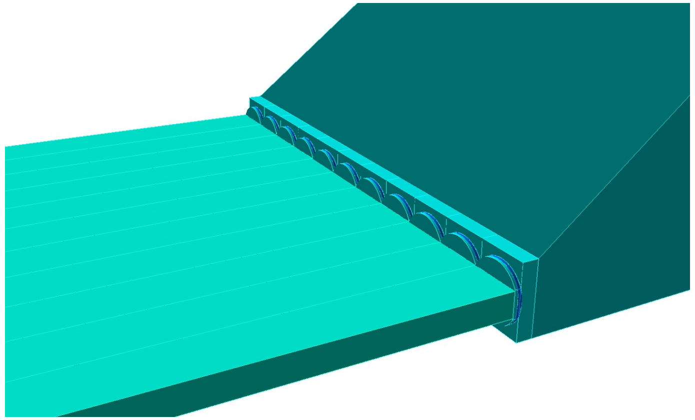
Planacon XP85112 (A. Lehmann, TIPP2021)



EIC 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 (?)



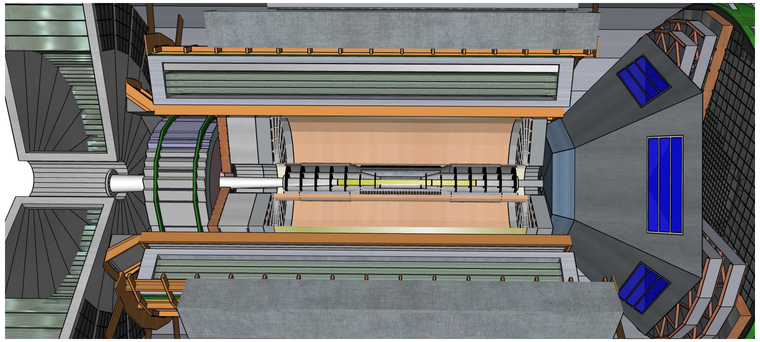


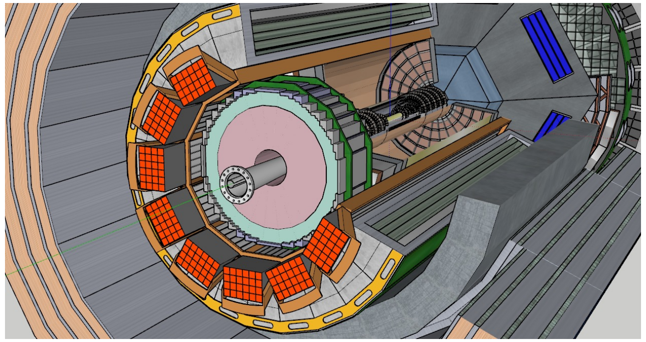
EIC Yellow Report, arXiv:2103.05419

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
- legacy components (?)

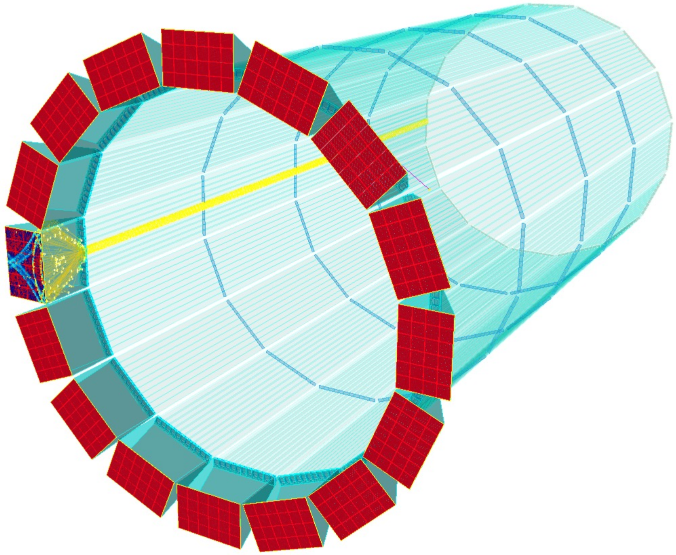
- being developed by the EIC PID consortium (eRD14), EIC generic detector R&D program;
- push DIRC performance significantly past state-of-the-art, increase π/K range by 50%:
- 3σ π/K separation up to at least 6 GeV/c for rapidity range $-1 \leq \eta \leq +1$ (Cherenkov angle resolution ≤1mrad), add supplemental e/π separation up to 1.2 GeV/c;
- narrow bars for robust performance in high-multiplicity jet events;
- radiation-hard 3-layer spherical lens;
- high-precision tracking, expect 0.5mrad polar angle resolution;
- post-DIRC tracking layer (LGAD or MPGD) for multiple scattering mitigation;
- selected as baseline hadron PID system for EIC detector barrel (reference detector).





ECCE proposal concept drawings

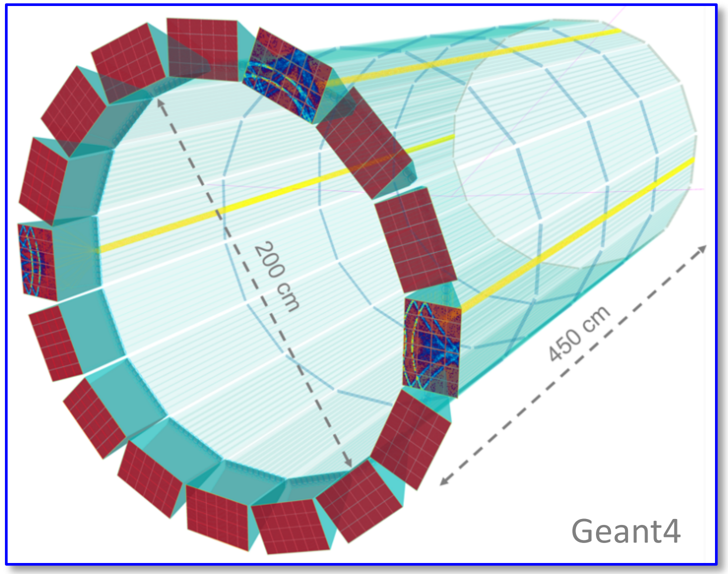
ECCE meeting, June 2021



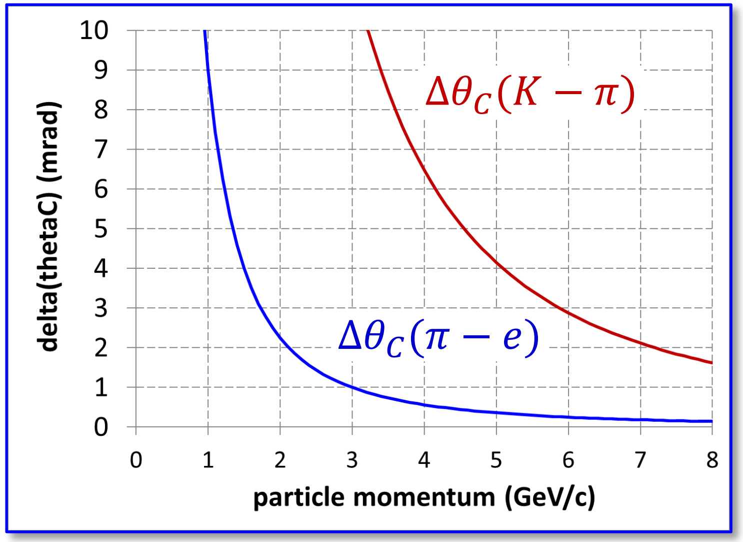
Initial generic design

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

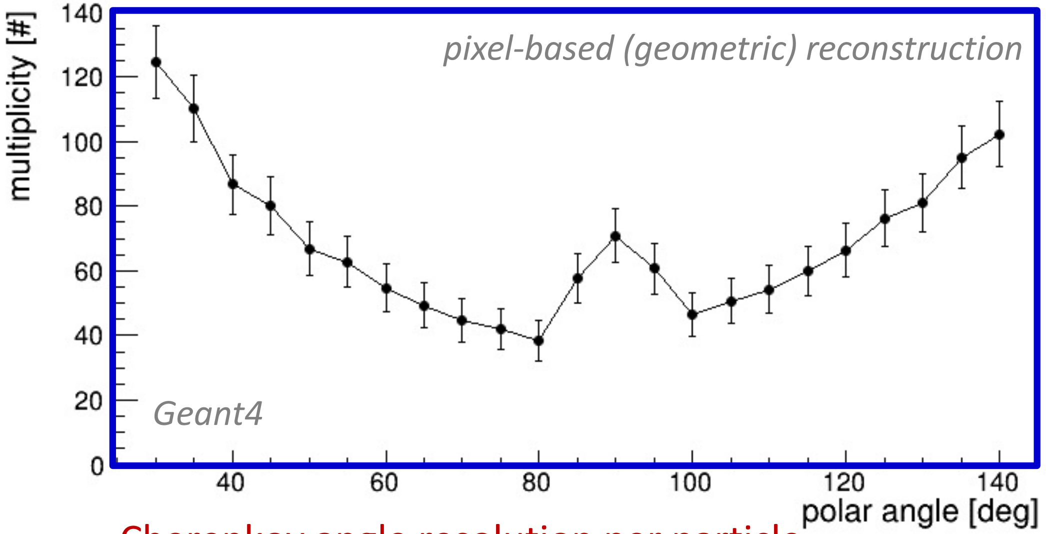
- Details of radius, bar width and length, number of sectors, will depend on specific design of EIC experiment proposal (ATHENA, CORE, ECCE)
- Focusing optics: innovative radiation-hard 3-layer spherical lens
- Compact expansion volume: 30cm-deep solid fused silica prisms
- Sensors and fast high-density 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



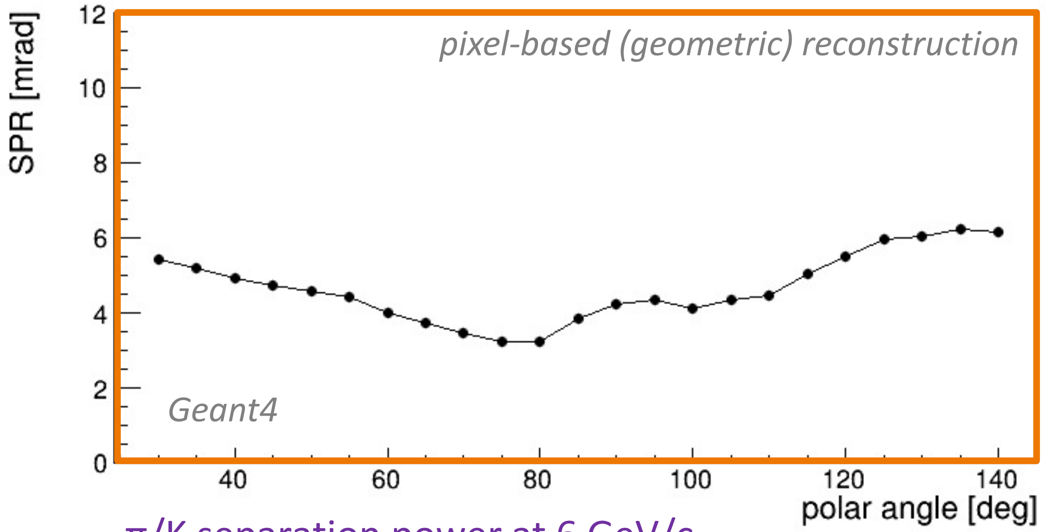
DIRC π/K, e/π Cherenkov angle difference



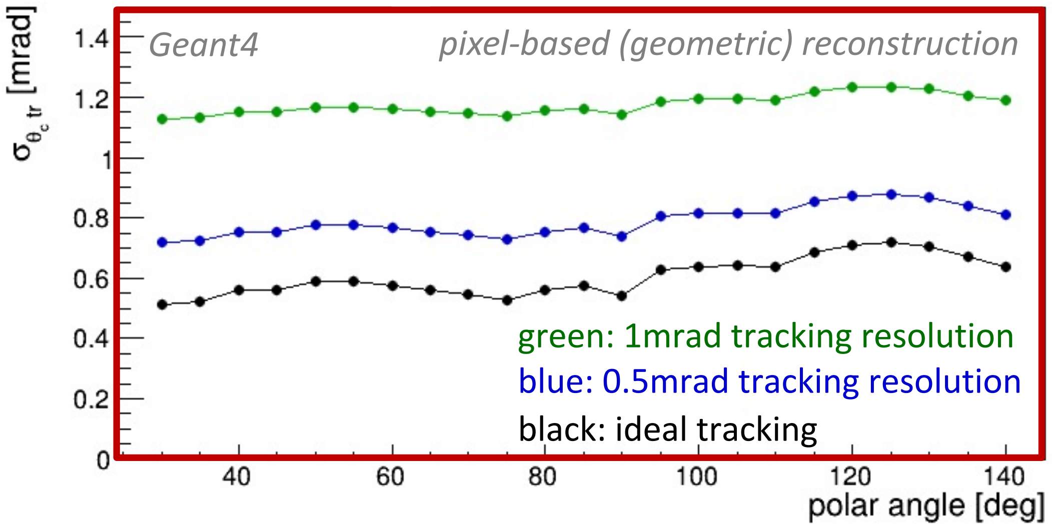
Photon yield per particle



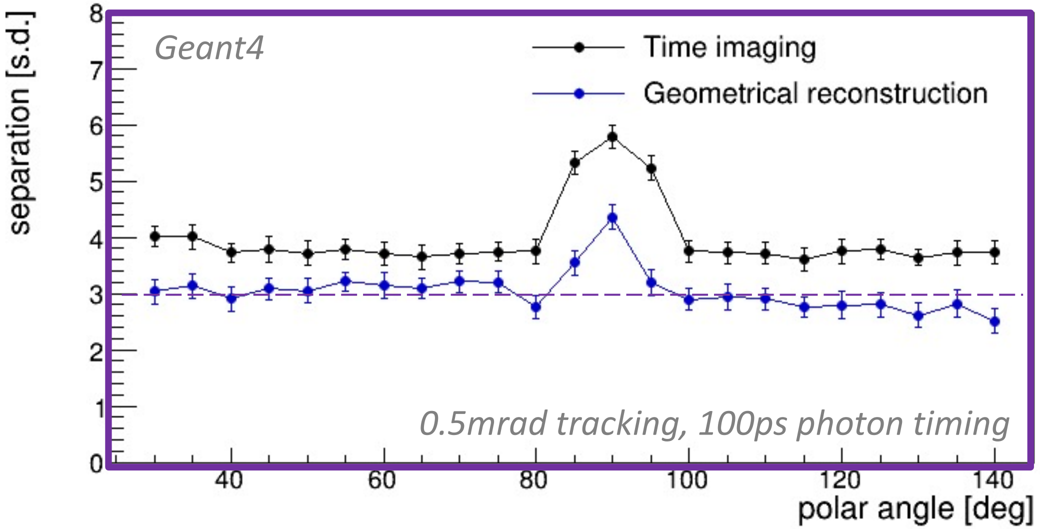
Cherenkov angle resolution per photon (SPR)



Cherenkov angle resolution per particle



π/K separation power at 6 GeV/c



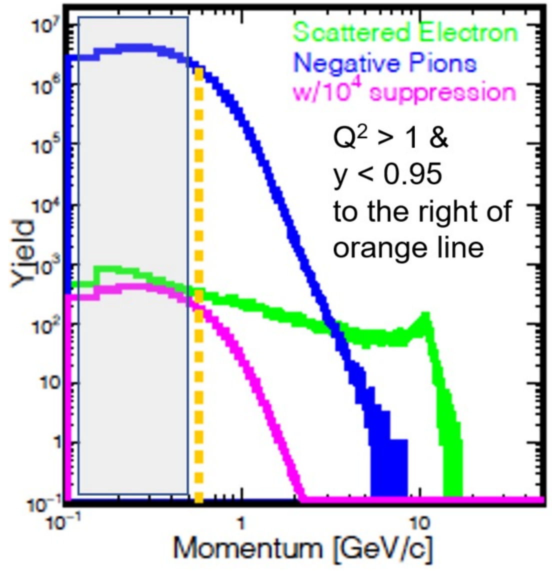
→ 3 s.d. π/K separation at 6 GeV/c and 1 mrad Cherenkov angle resolution seems to be in reach

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)

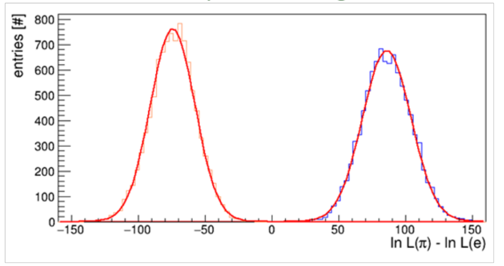
-1.0 < η < 0.0 (half of DIRC Barrel)



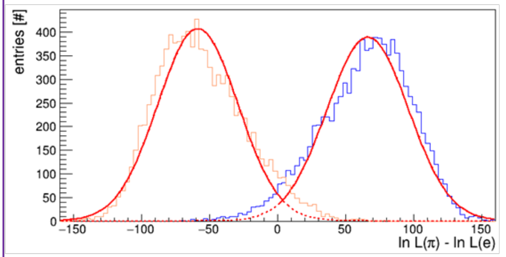
CORE simulation, B. Schmookler

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

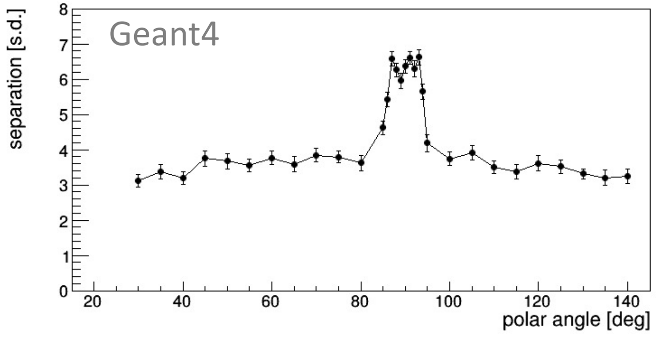
without multiple scattering: ~9 s.d.



with multiple scattering: ~4 s.d.

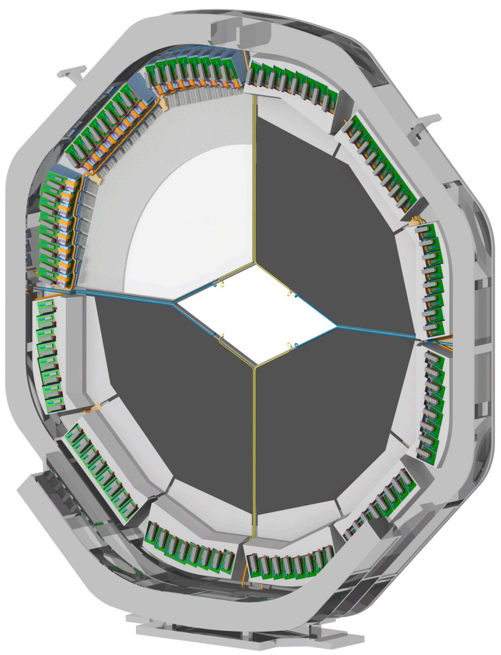


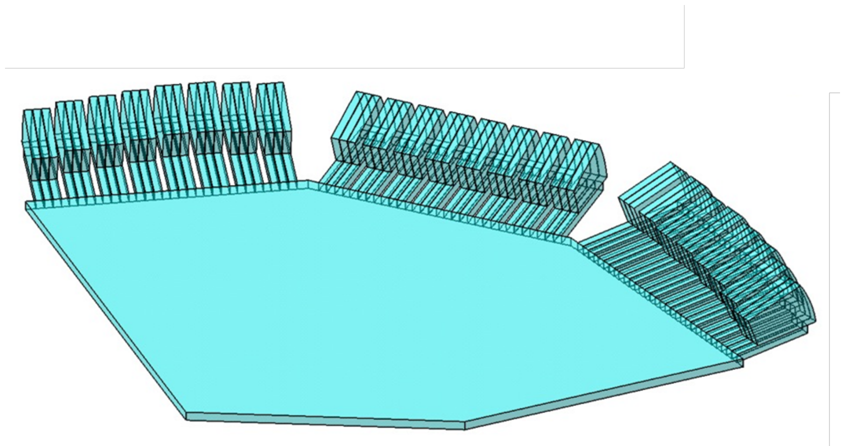
hpDIRC e/π separation at 1.2 GeV/c
without MS mitigation

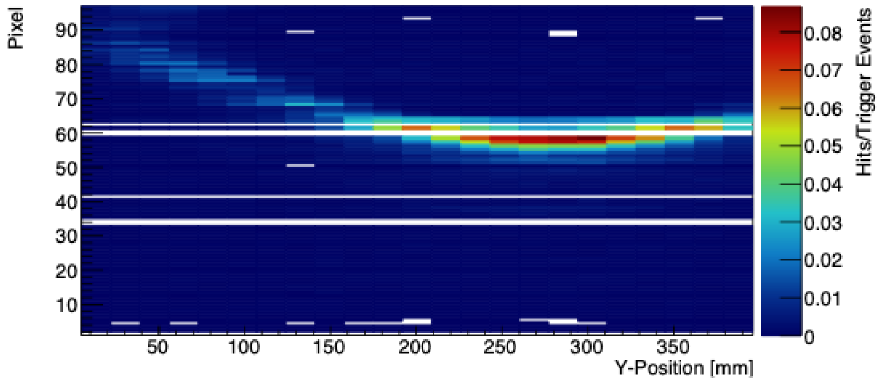


- compact photon camera
- cylindrical mirror focusing
- small pixels (MCP-PMT)
- fast photon timing
- endcap geometry

PANDA Endcap Disc DIRC



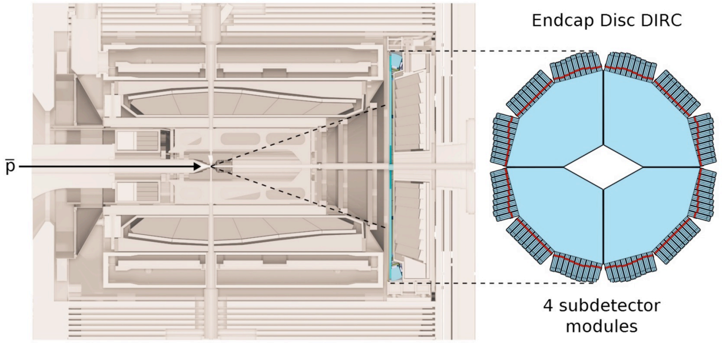


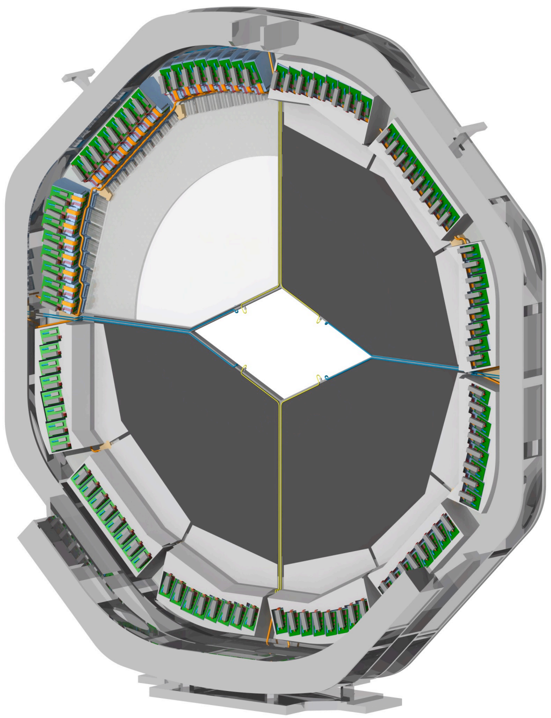


PANDA Endcap Disc DIRC (EDD)

- 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

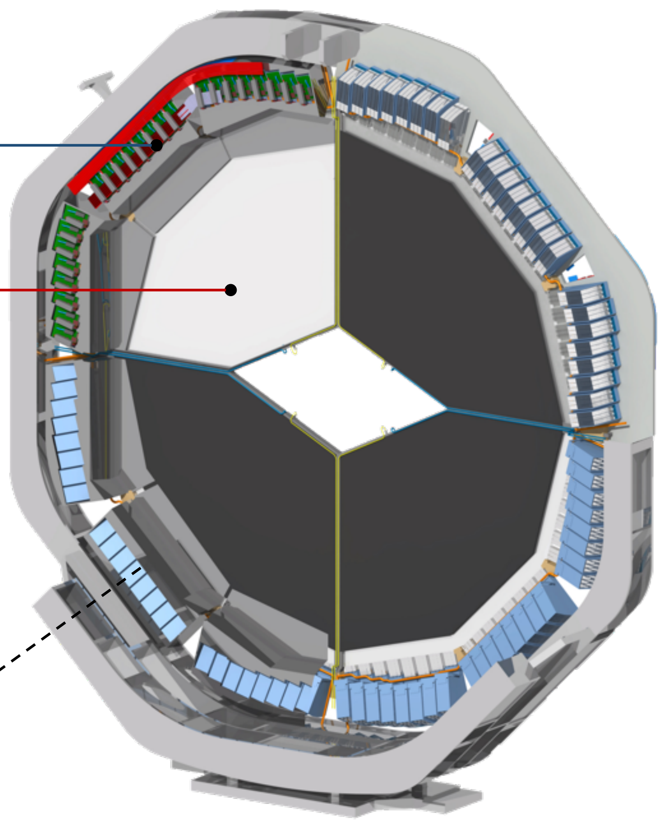
Optics made of synthetic fused silica

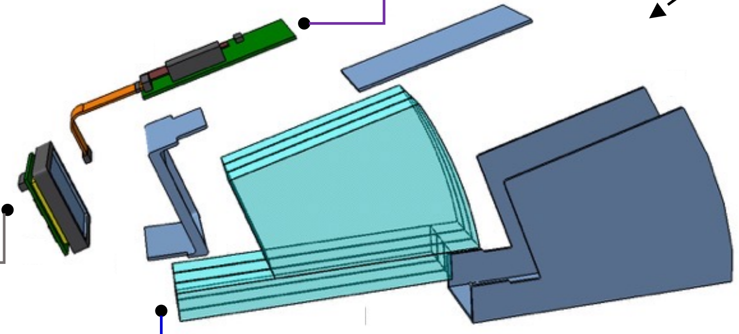
4 independent quadrants

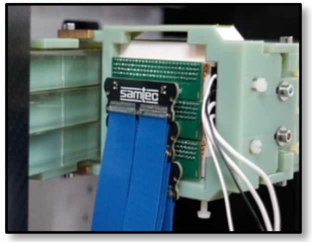
Focusing elements convert angle to position information

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

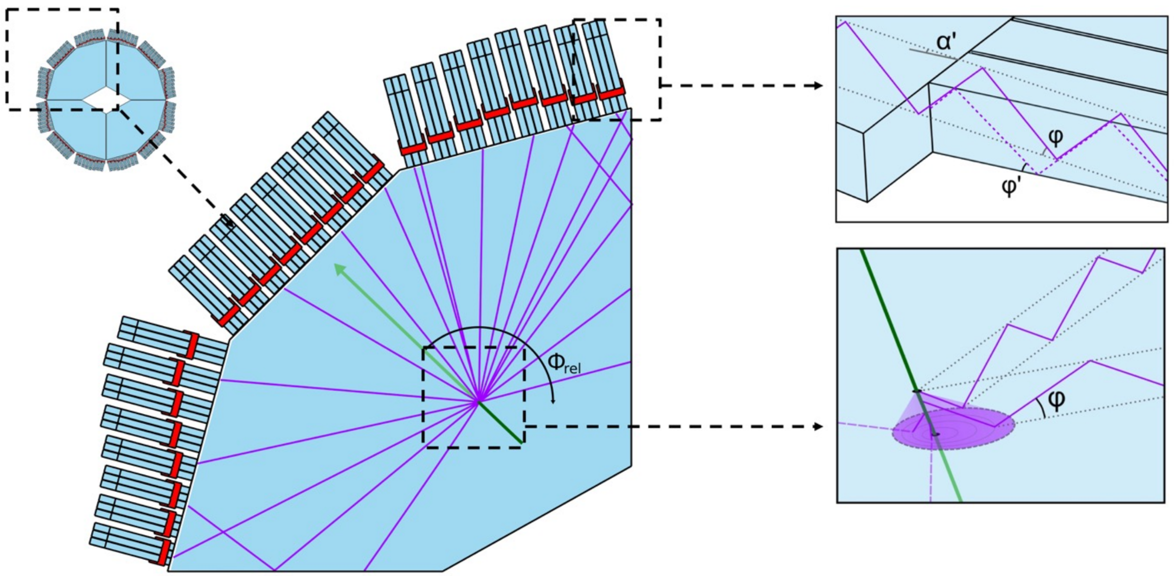
~29k channels

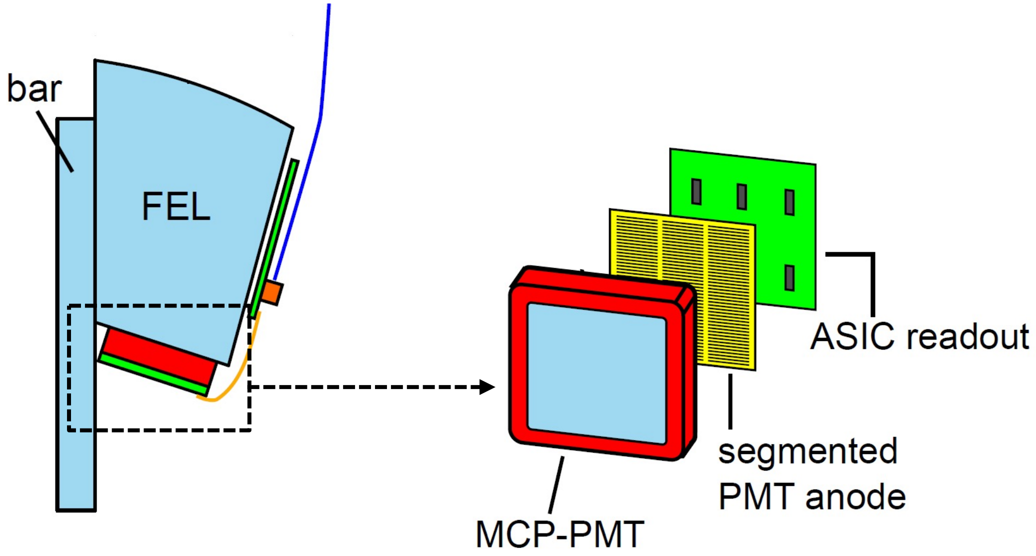
Novel design, validated with particle beams since 2016.

goal: first-of-series quadrant in 2025

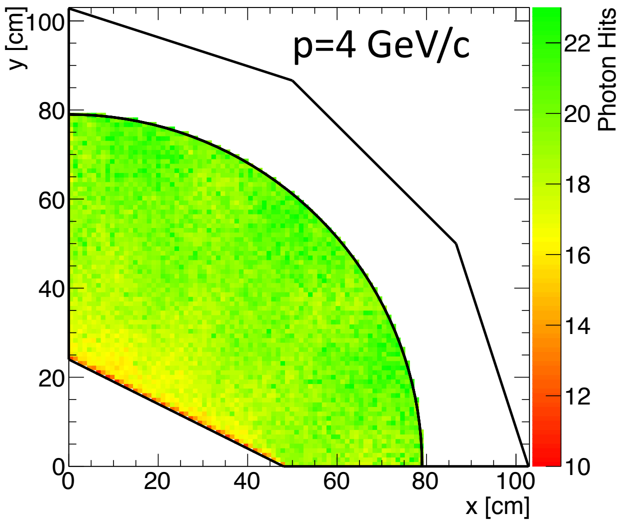
TDR available at arXiv:1912.12638

JS RICH2018

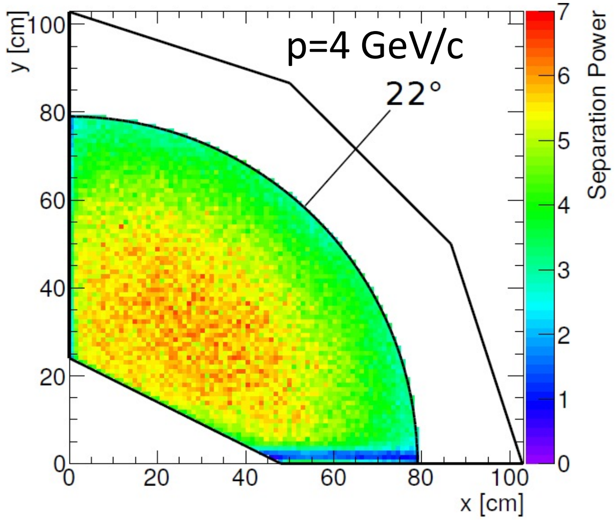




Photon yield (Geant)



π/K separation power (Geant)

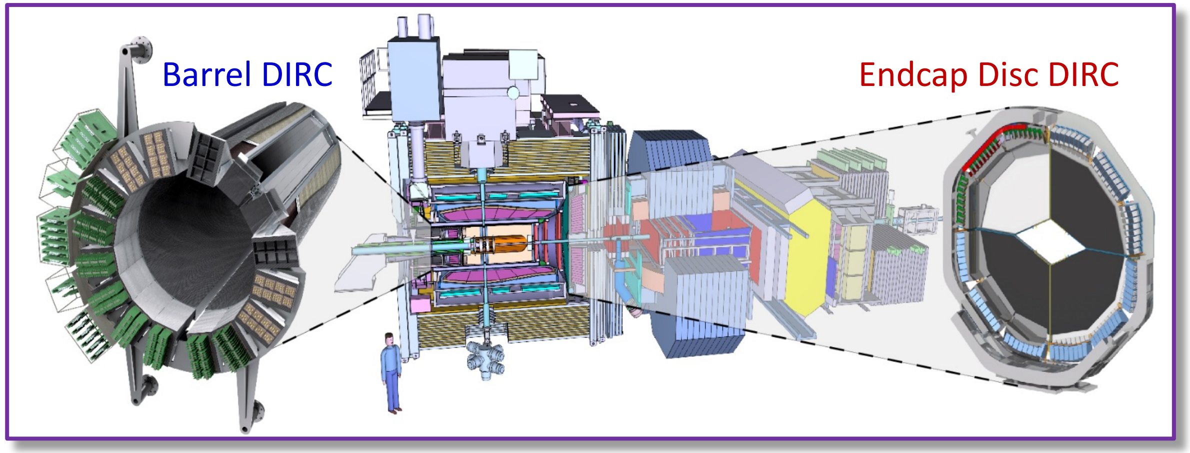


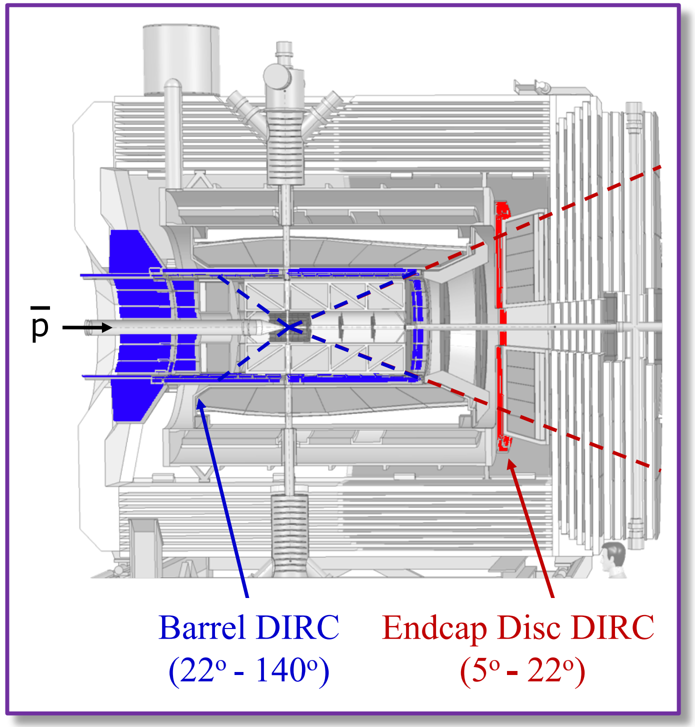
- Analytical reconstruction

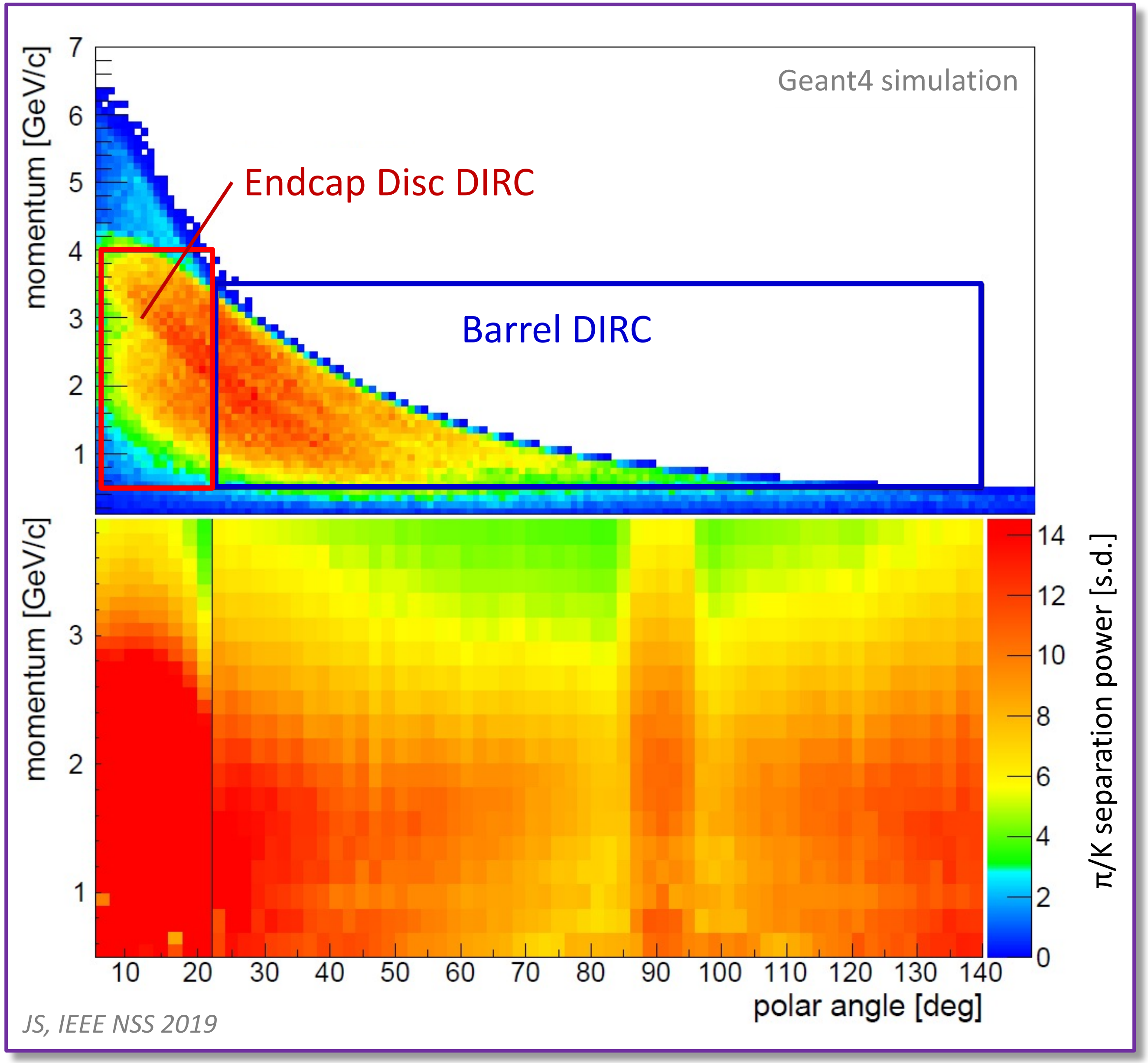
$$\theta_c = \arccos\left(\sin\theta_p \cos\phi_{\mathrm{rel}} \cos\varphi + \cos\theta_p \sin\varphi\right)$$

- 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

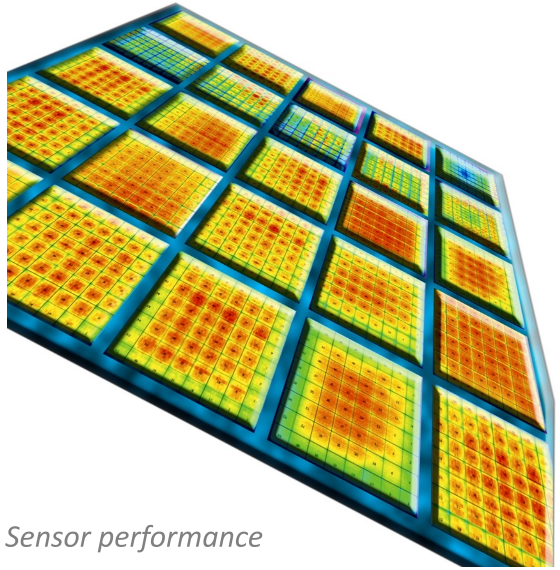

Barrel DIRC
Endcap Disc DIRC


p̄
Barrel DIRC
(22° - 140°)
Endcap Disc DIRC
(5° - 22°)

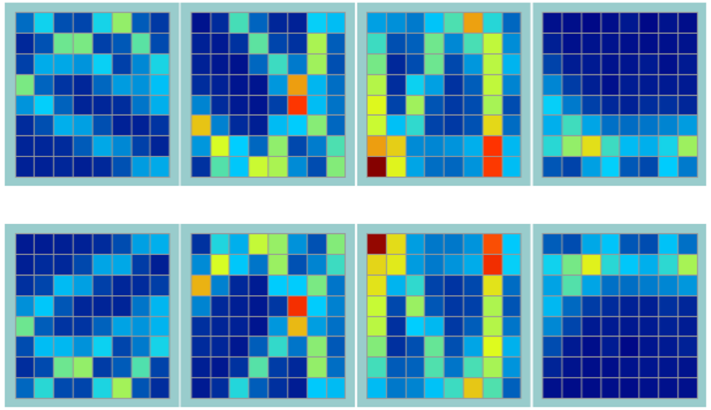

Geant4 simulation
Endcap Disc DIRC
Barrel DIRC
momentum [GeV/c]
π/K separation power [s.d.]
polar angle [deg]
JS, IEEE NSS 2019

Progress of Key Technologies

Bar/plate fabrication



Sensor performance



Reconstruction/PID algorithms

DIRC RADIATOR PRODUCTION

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

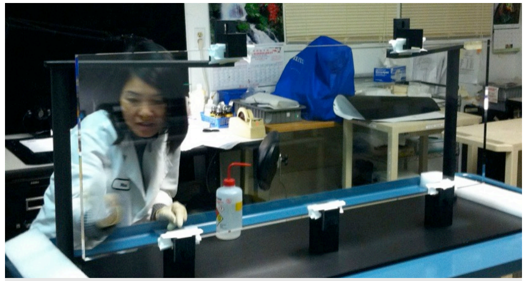
Extensive PANDA Barrel DIRC R&D prototype program with eight optical companies

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

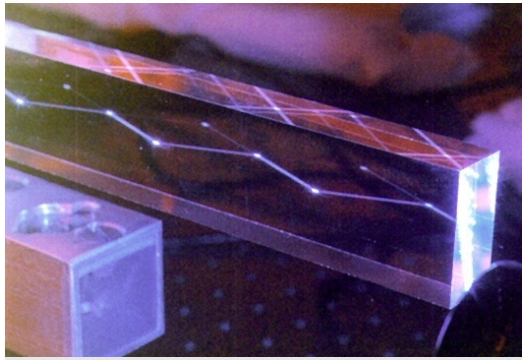
Tested new synthetic fused silica materials (Corning, Heraeus, Nikon), all suitable for PANDA

Successful series production with Nikon encouraging for future DIRC projects

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

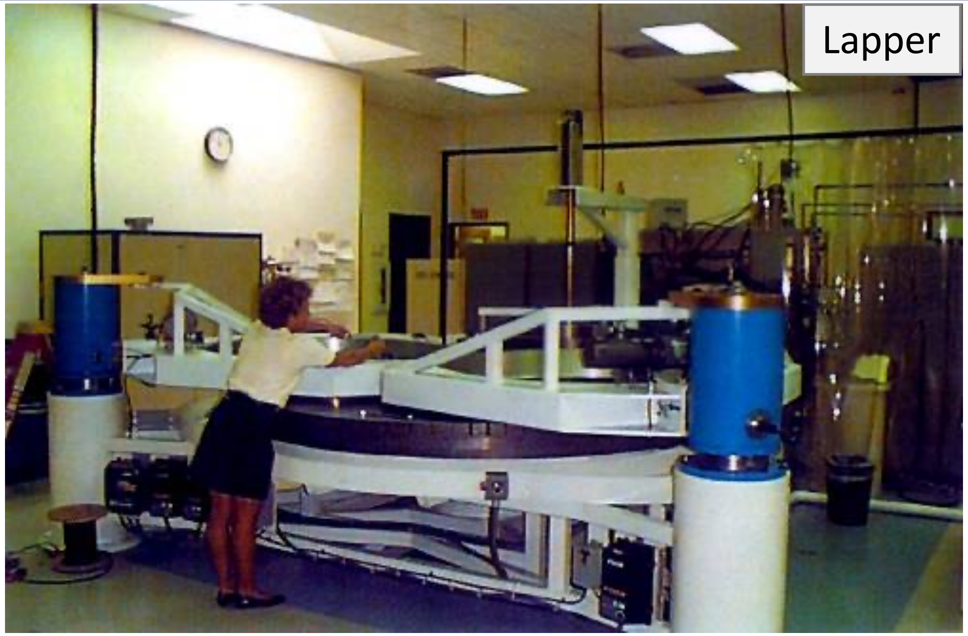


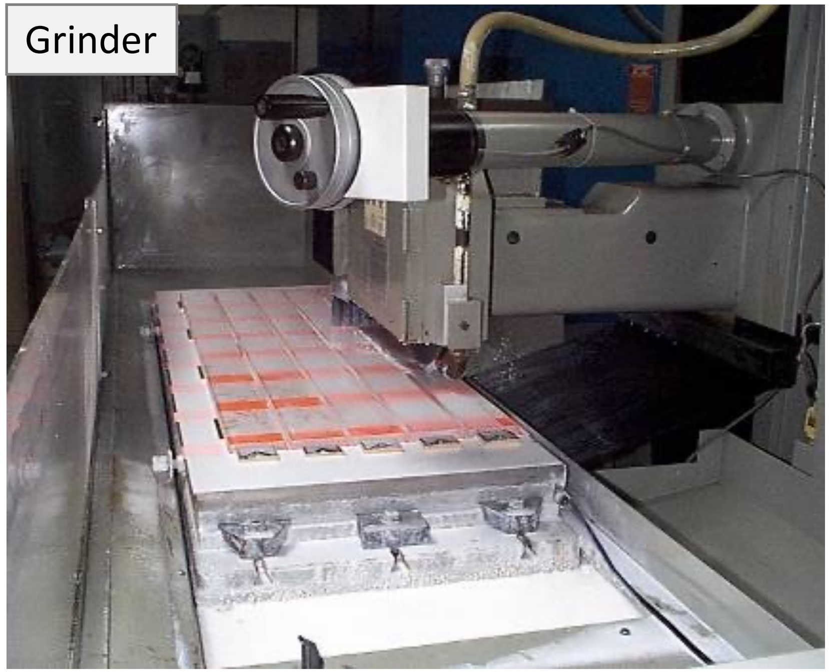
Cleaning of Belle II TOP plate (Zygo)



BABAR DIRC bar in laser beam

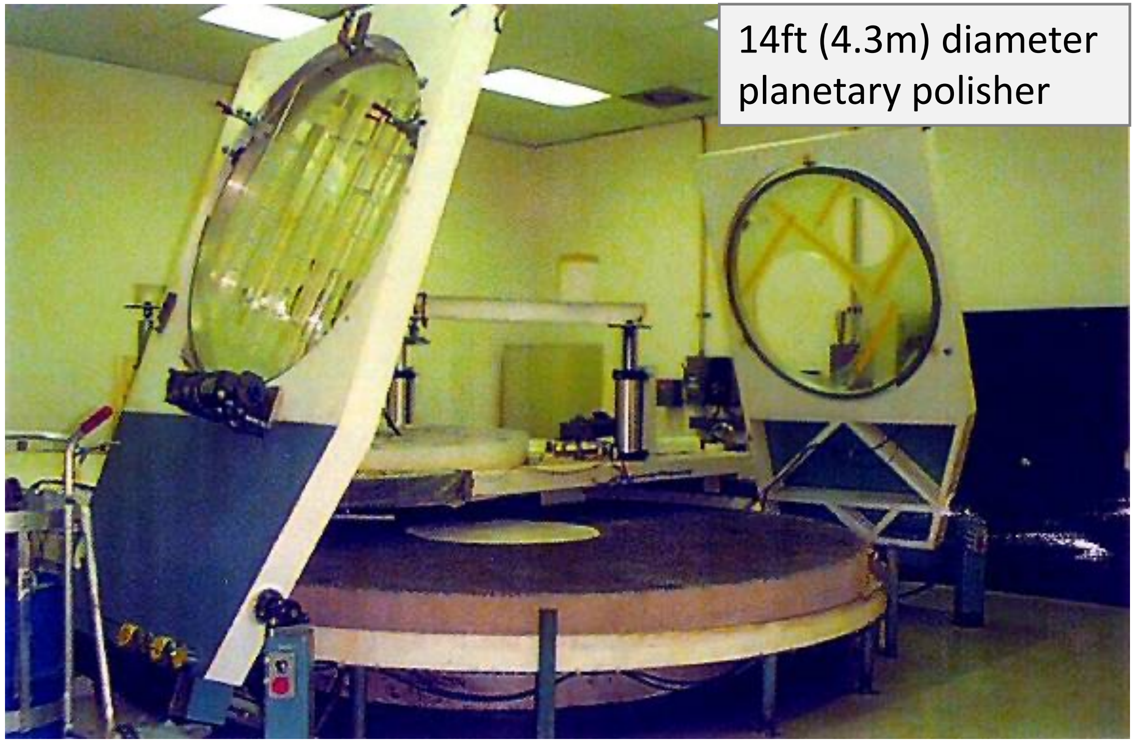
BABAR DIRC Bar Production





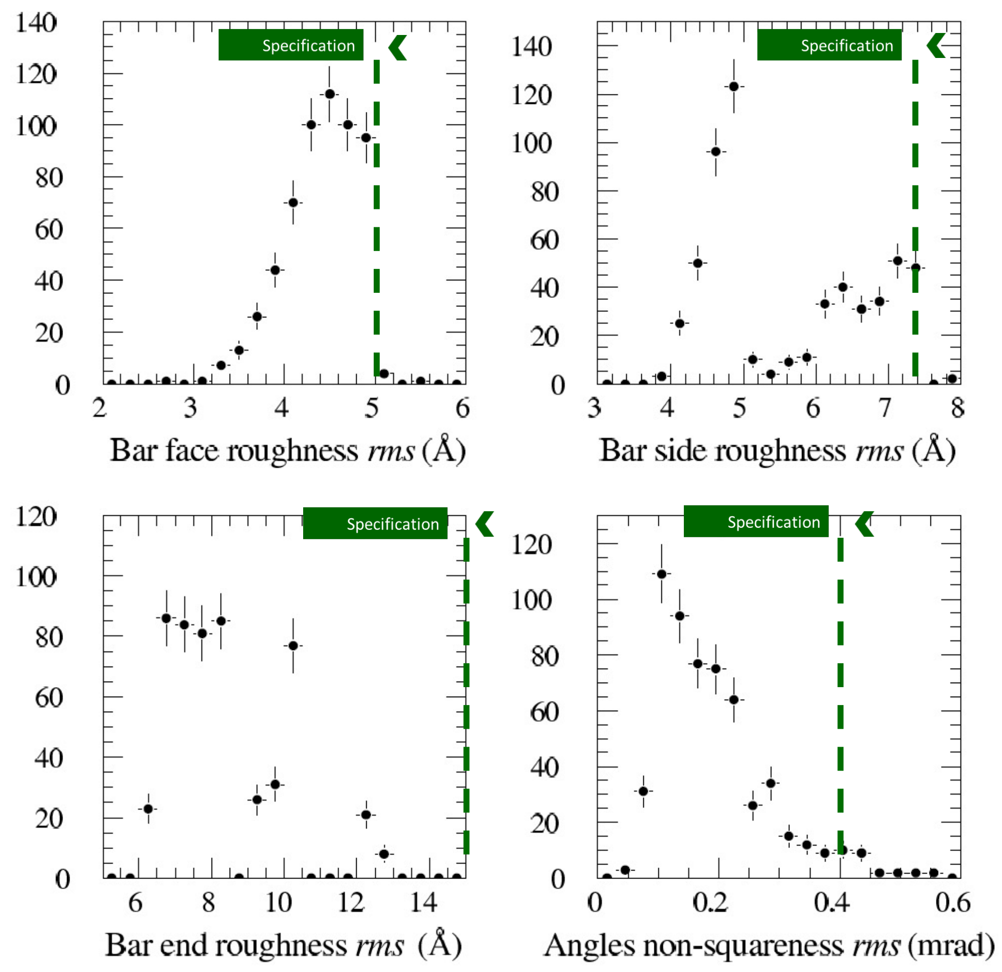
JS, DIRC2009 workshop

BABAR DIRC BAR PRODUCTION



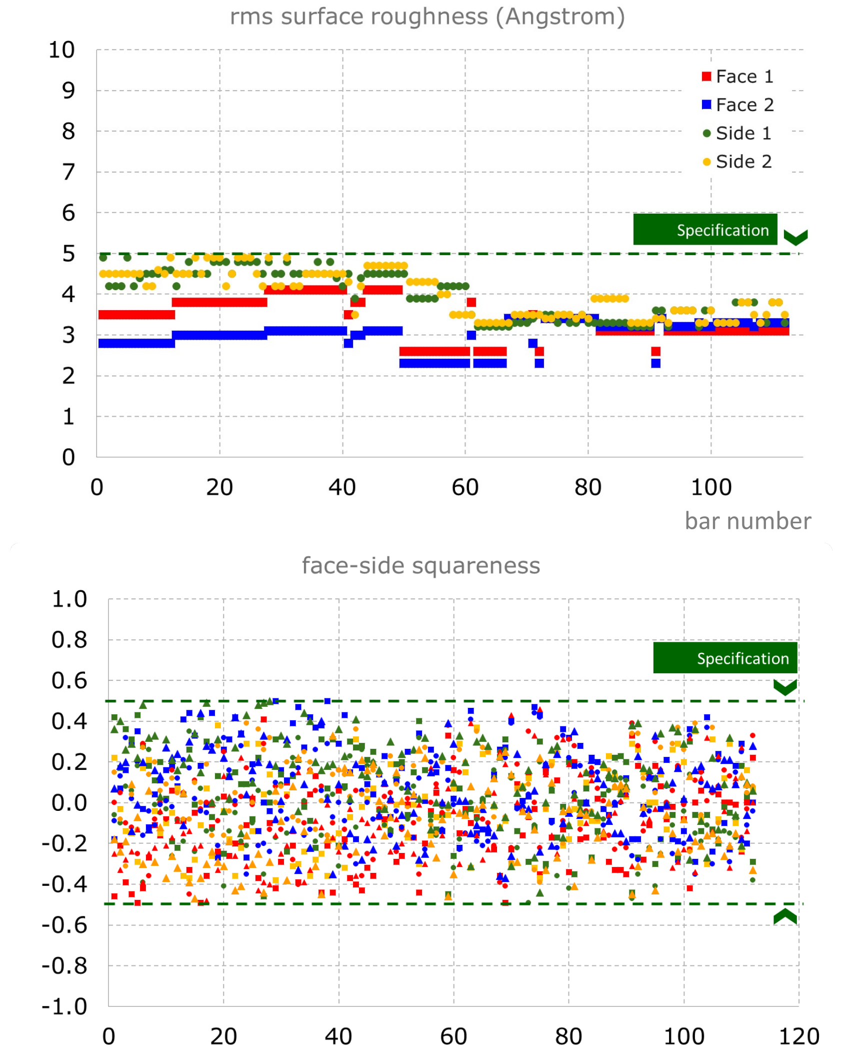
JS, DIRC2009 workshop

BABAR DIRC QA results for polish and angles



JS, DIRC2009 workshop

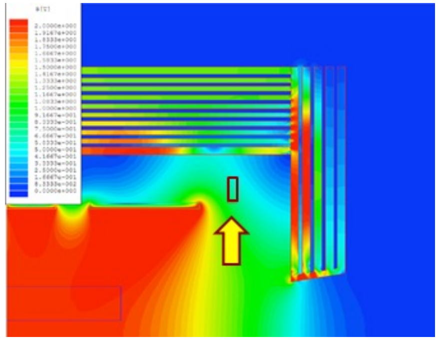
PANDA Barrel DIRC QA results for polish and angles



G. Schepers, TIPP2021

DIRC SENSOR OPTIONS

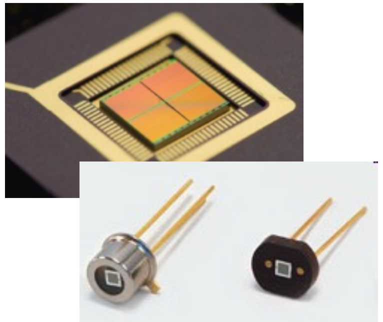
DIRC sensor location in PANDA, B~1T



- 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

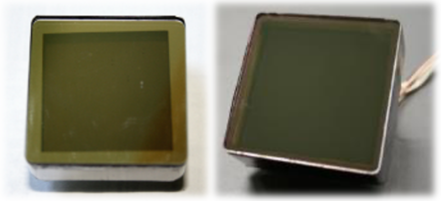


- Geiger-mode Avalanche Photo Diodes (SiPMs)

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

  radiation hardness a serious issue → cryogenic operation and annealing?

  could be a good candidate in the future, needs further R&D

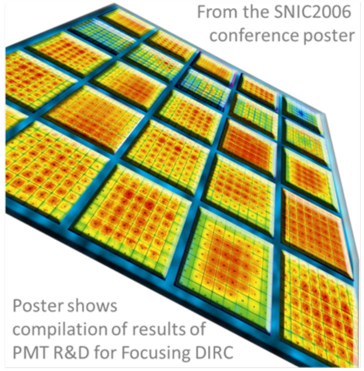


- Micro-channel Plate Photomultipliers (MCP-PMTs)

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

  issues with rate capability and aging resolved in recent years

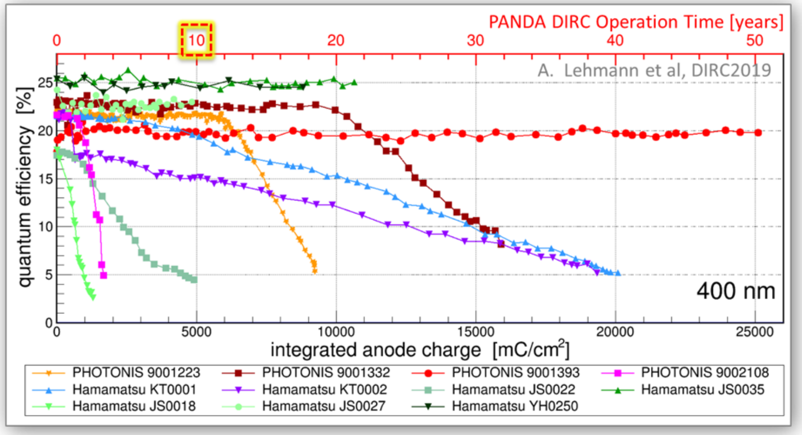
  multiple vendors available Hamamatsu, Photek, Photonis (, and LAPPD)


From the SNIC2006 conference poster
Poster shows compilation of results of PMT R&D for Focusing DIRC

Sensor development has been crucial to DIRC progress

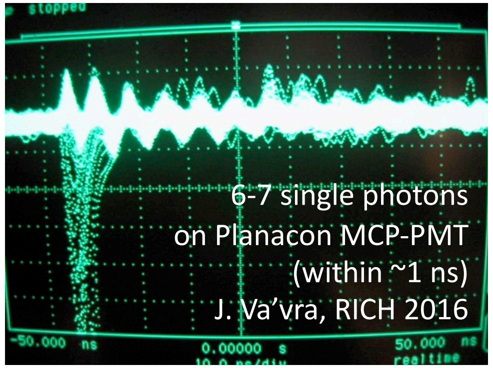
Main DIRC development directions: Smaller pixels and faster single photon timing

- 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)



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?)


6-7 single photons on Planacon MCP-PMT (within ~1 ns)
J. Va'vra, RICH 2016

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)

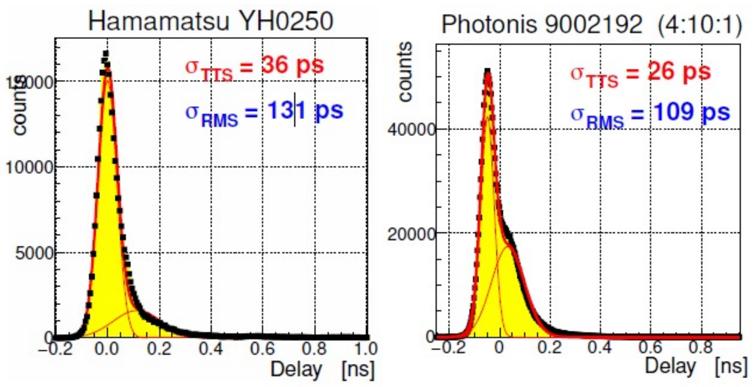
- need pixelated readout to determine position without ambiguities
- need tolerance for high occupancy per sensor

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

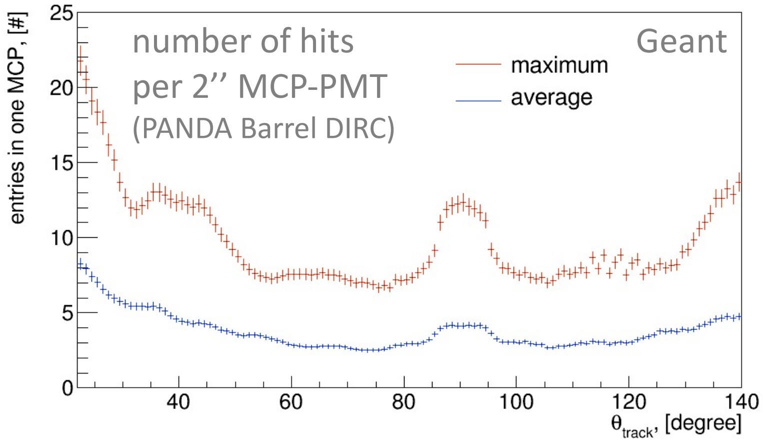
- need low noise rates (coincidence timing very difficult/impossible to use)
- High dark count rate and radiation damage currently showstoppers for SiPM

Leading candidate for DIRCs: MCP-PMT

- Commercial MCP-PMTs baseline solution for PANDA DIRCs and LHCb TORCH
- Hoping for significant cost reduction in future due to LAPPD™ effort



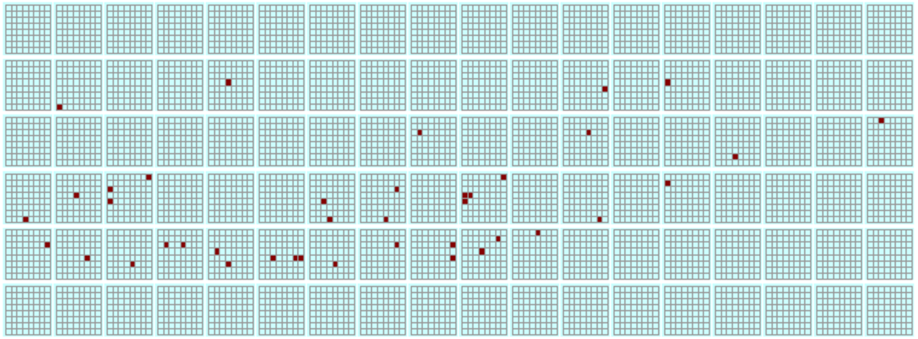
A. Lehmann
TIPP2021

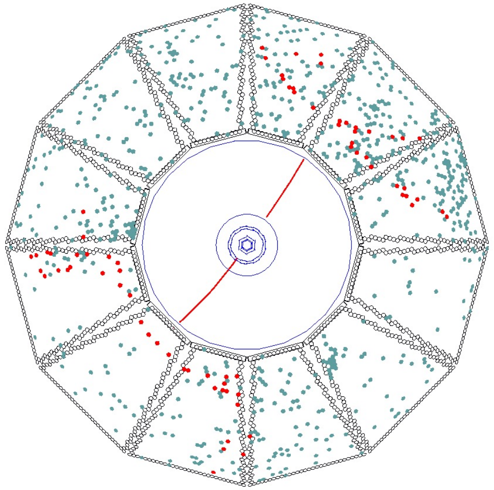


JS
ANL MCP-PMT Workshop 2014

DIRC Reconstruction/PID

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





Single dimuon event, BABAR beam data

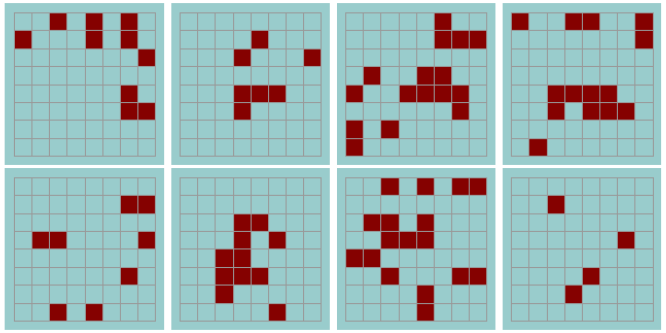
DIRC hit patterns do not look like your typical RICH “rings”

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

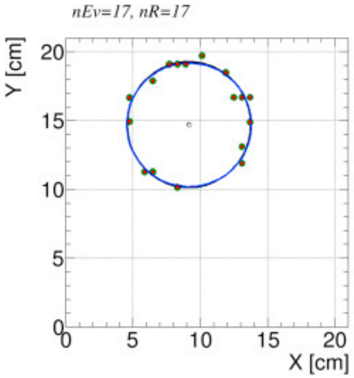
Detector space is often not the best space for DIRC reconstruction, no simple ring fits

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



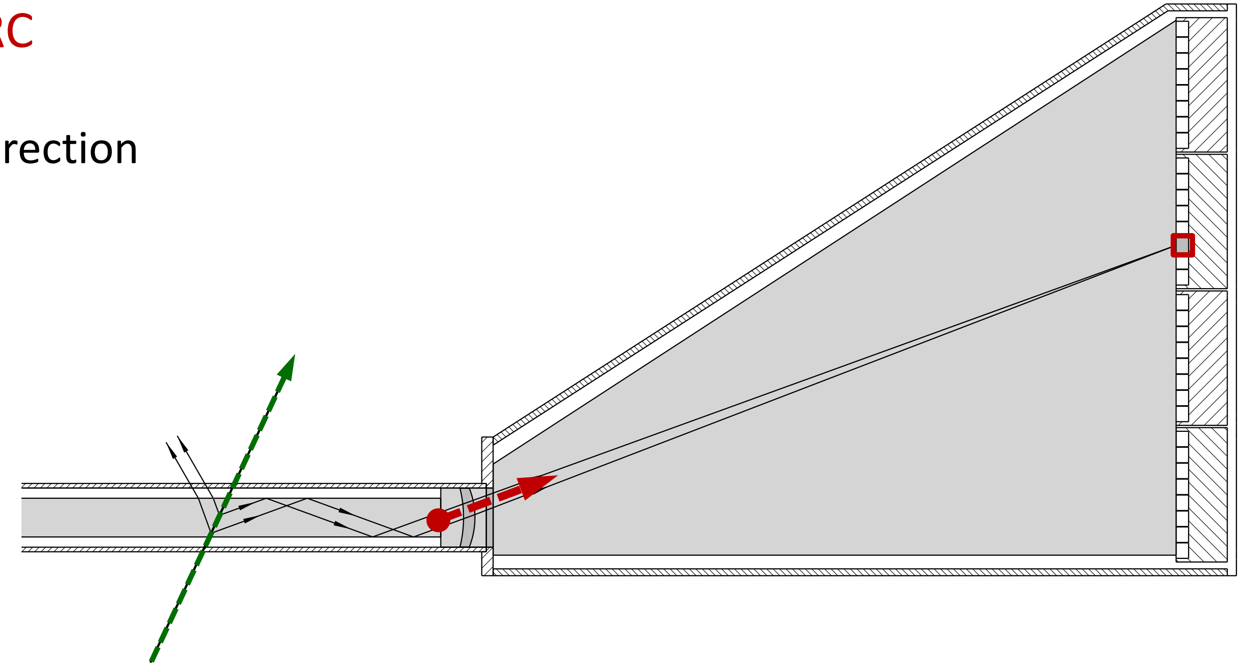
For comparison: Single event in CMB RICH (CO_2) prototype

Geometric reconstruction, example for PANDA Barrel DIRC

Developed for BABAR DIRC, approximates Cherenkov photon direction

as 3D vector from center of end of bar to center of pixel

(allowing for reflections)

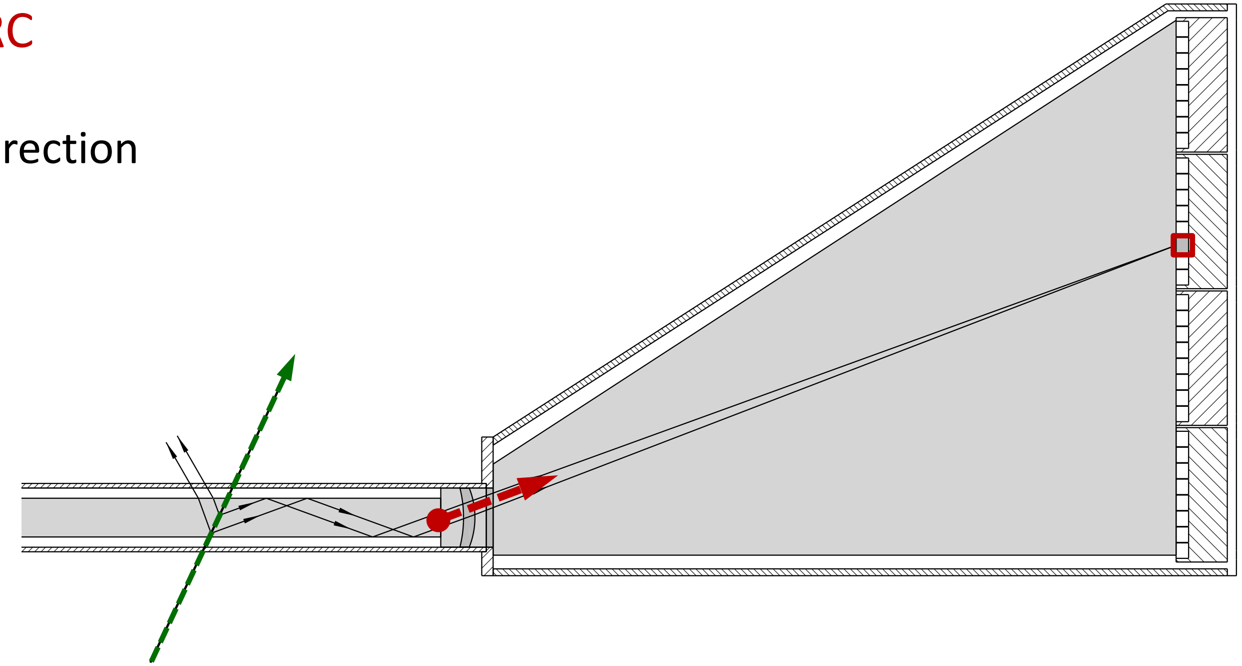


Geometric reconstruction, example for PANDA Barrel DIRC

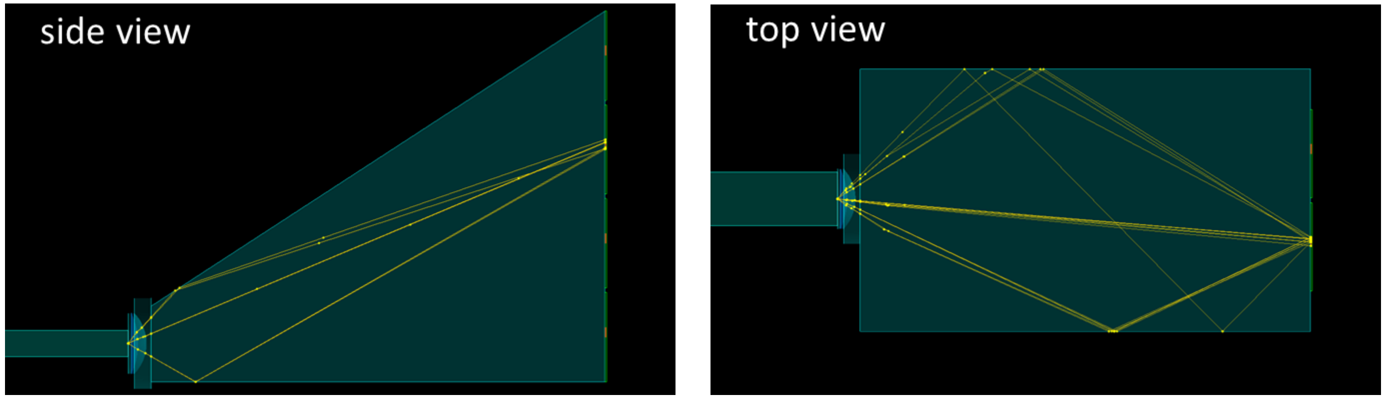
Developed for BABAR DIRC, approximates Cherenkov photon direction
as 3D vector from center of end of bar to center of pixel
(allowing for reflections)

Use photon gun in simulation to create look-up tables (LUT)
of photon vectors for every pixel/bar combination

Fast method, one LUT for all particle tracks



Geant4 photon paths for example pixel



Geometric reconstruction, example for PANDA Barrel DIRC

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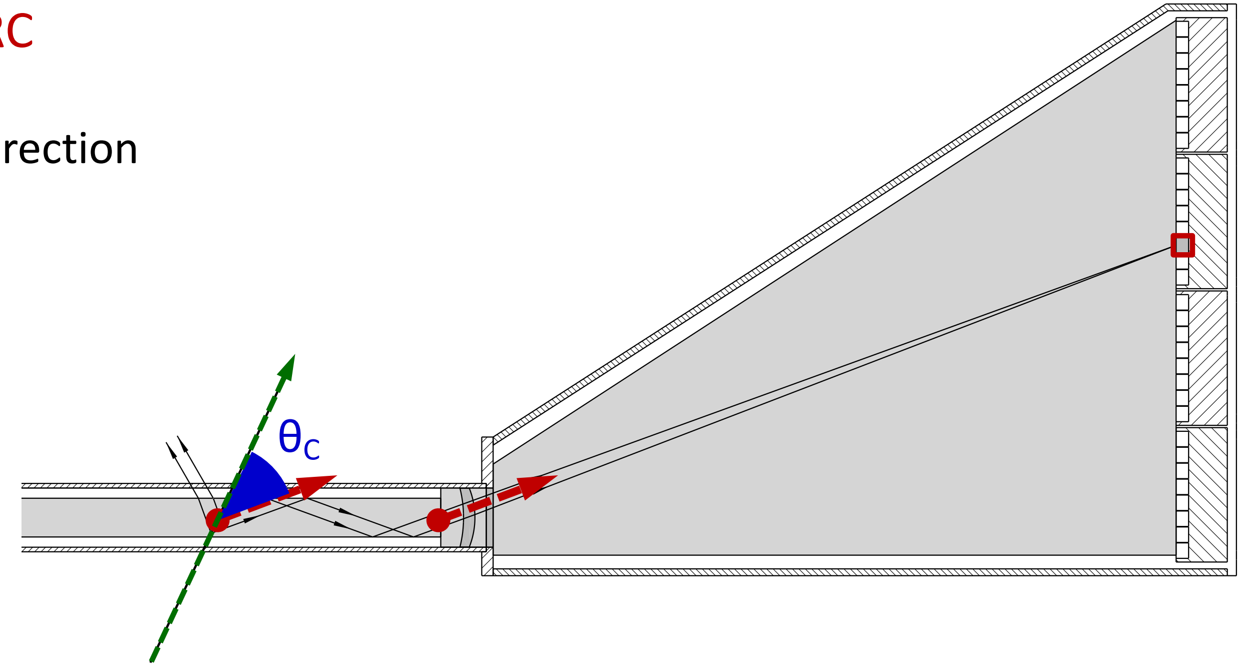


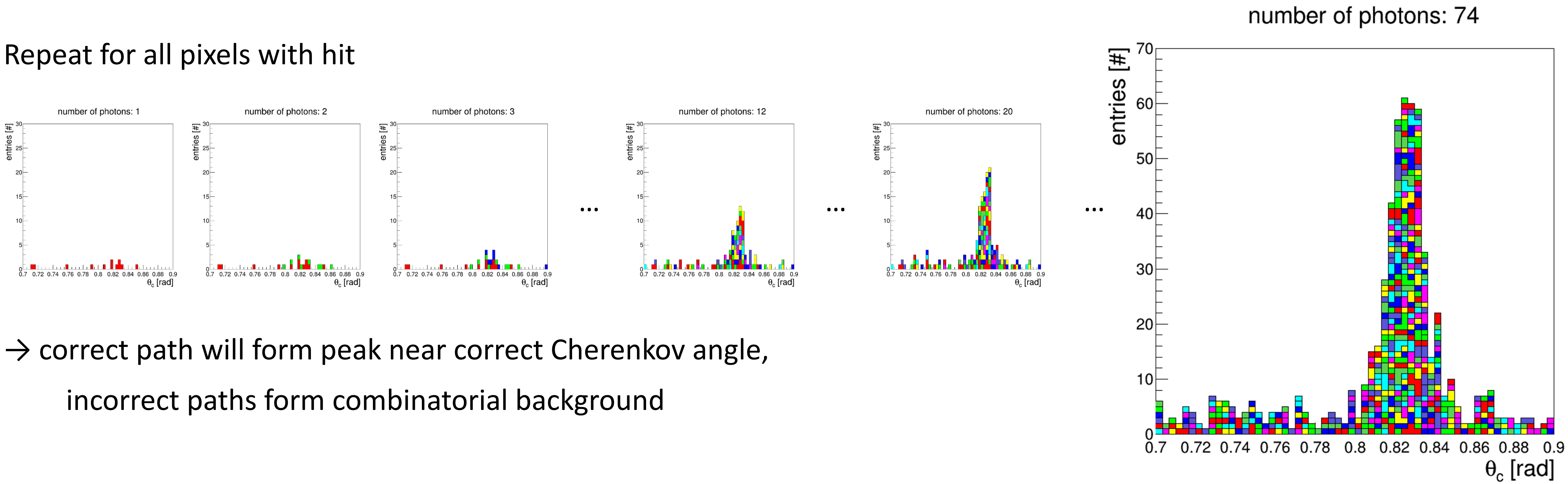
Pixel with hit → retrieve 3D direction vector collection from LUT

Combine each direction vector with particle direction vector from tracker → obtain Cherenkov angle per photon (θ_C ,ϕ_C)

Consider all possible reflections in bar (up/down, left/right, forward/backward) and in prism as ambiguities

Geometric reconstruction, example for PANDA Barrel DIRC

Repeat for all pixels with hit

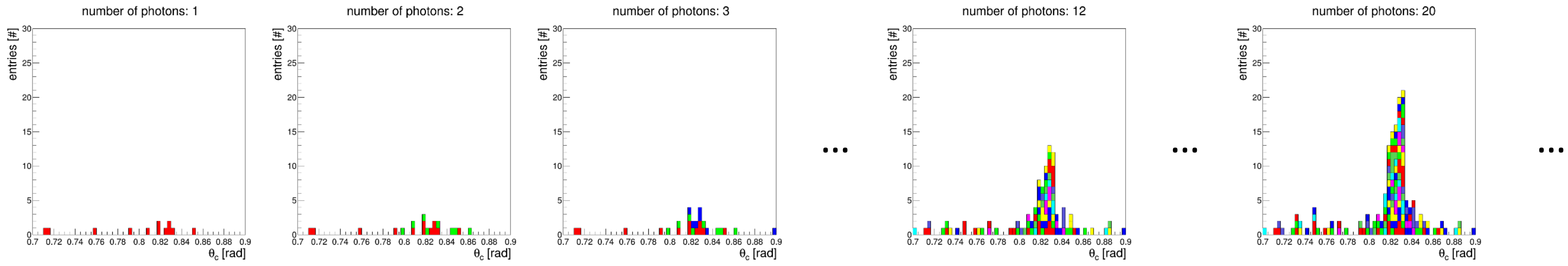


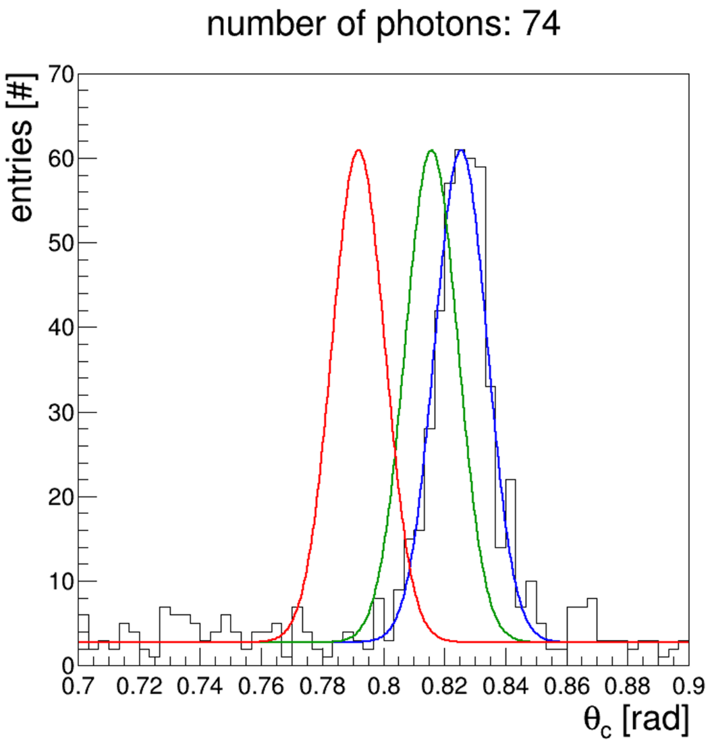
→ correct path will form peak near correct Cherenkov angle,

incorrect paths form combinatorial background

Geometric reconstruction, example for PANDA Barrel DIRC

Repeat for all pixels with hit





→ correct path will form peak near correct Cherenkov angle,

incorrect paths form combinatorial background

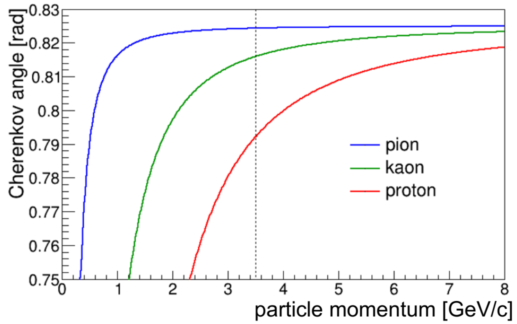
Use unbinned log-likelihood hypothesis test to extract PID info from distribution

→ extract mean of Gaussian (plus linear background) for each hypothesis

Likelihood calculation:

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

signal — combinatorial background



Obtain log-likelihood differences → select particle

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:

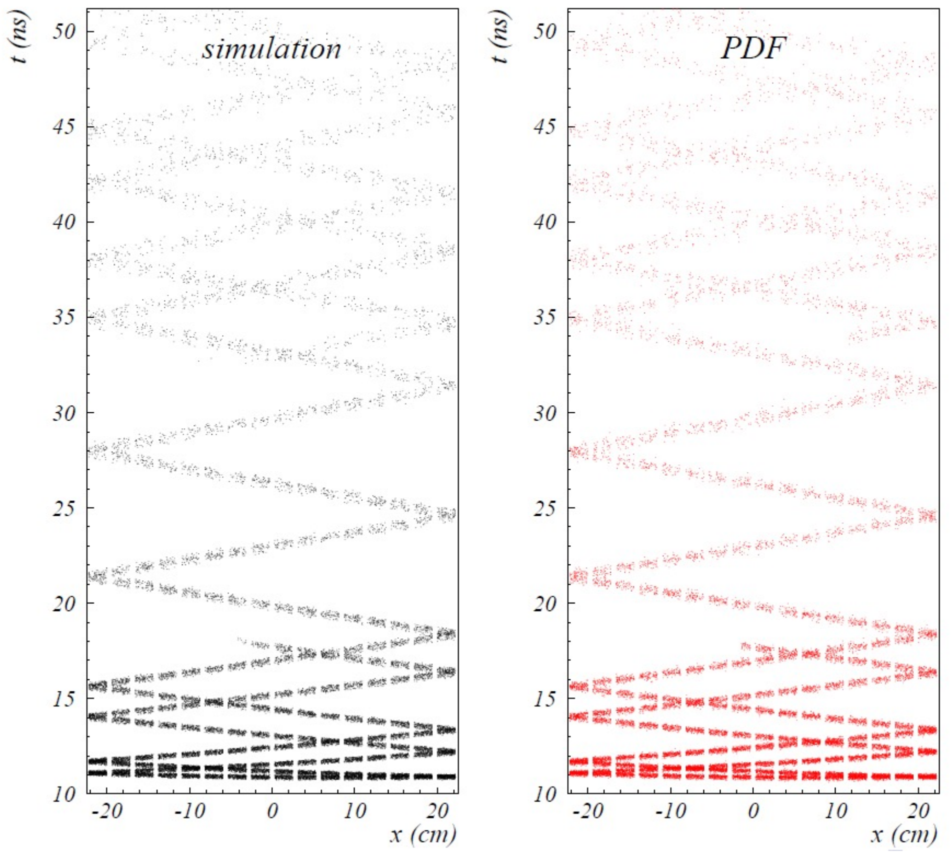
$$L_H = \prod_N \mathrm{pdf}(x_i, y_i, t_i; H) \times P_{N_0}(N)$$

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.)

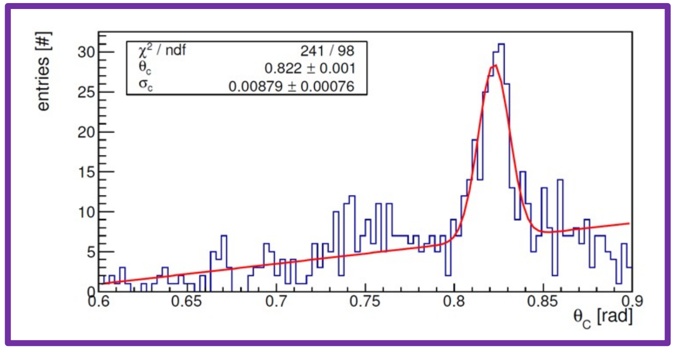
pure TOP counter: comparison of PDFs simulation vs. analytical calculation



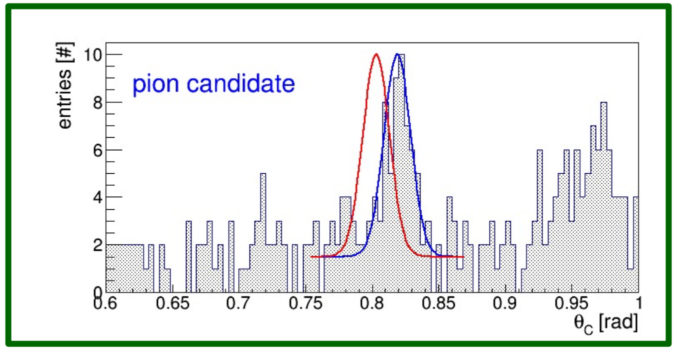
R. Dzhygadlo, CHEP2019

Examples of reconstruction/PID methods from PANDA Barrel DIRC

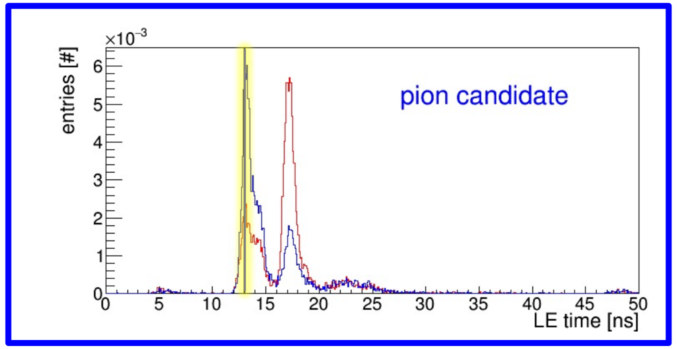
- track-by-track fit of single photon Cherenkov angle distribution based on look-up tables to extract track Cherenkov angle ("BABAR-like") →



- 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) →



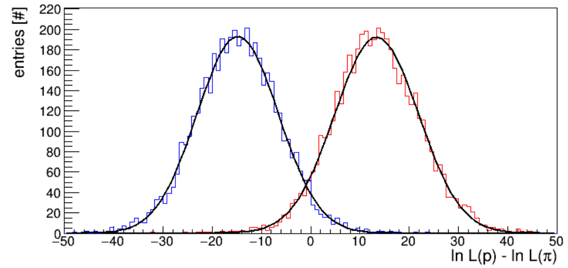
PANDA Barrel DIRC prototype, CERN 2018, 20° polar angle
7 GeV/c π/p beam, equiv. to 3.5 GeV/c π/K

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

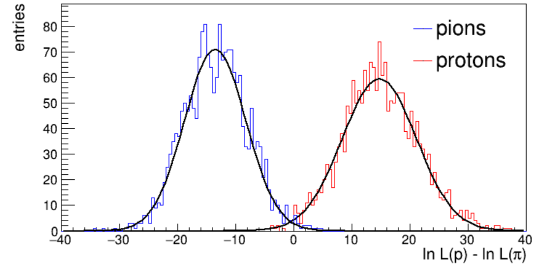
geometrical reconstruction

π/K separation: 3.5 s.d.

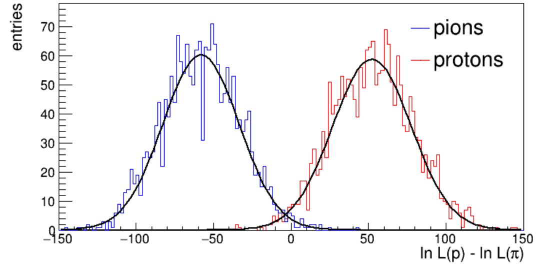


time imaging

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



beam data PDF: π/K separation: 4.8 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:

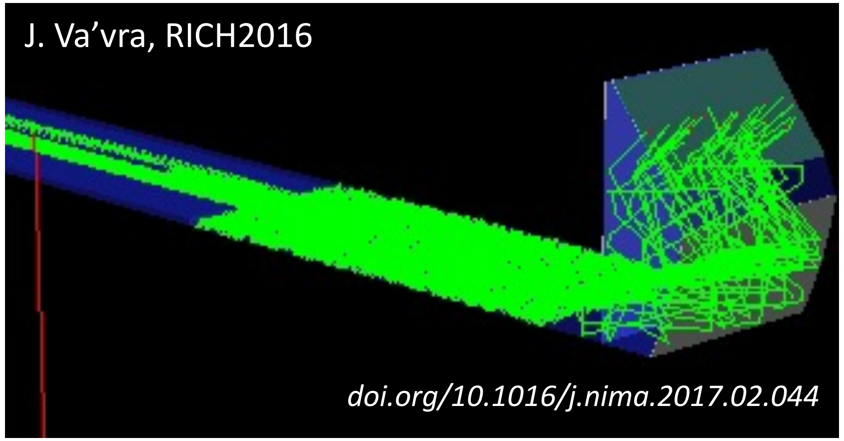
- smaller fused silica block, cylindrical mirror, sensors with 3mm pixel pitch;
- disassemble BABAR DIRC bar boxes, remove wedges;
- replace last bar with one common plate for all 12 bars in box.

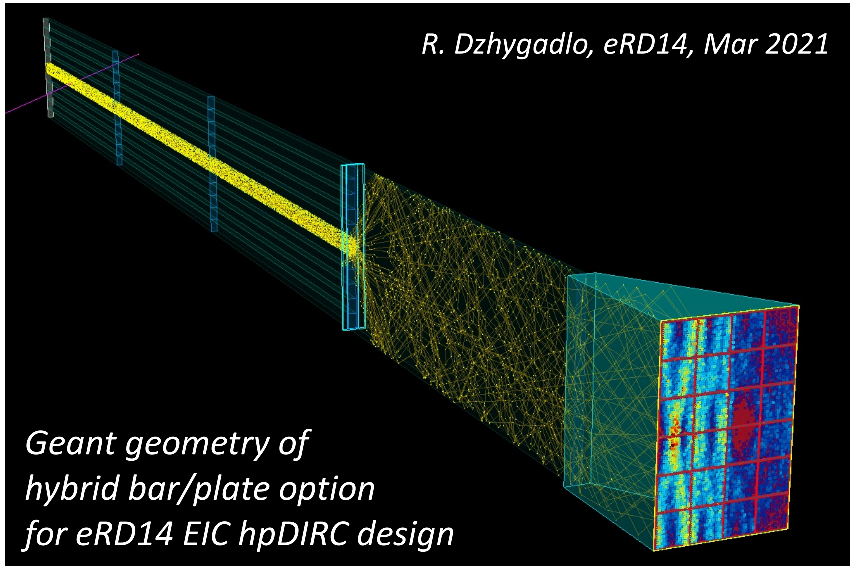
Best of both worlds:

- 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 so far

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

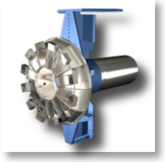
Simulation study as possible option for EIC hpDIRC is underway (eRD14).



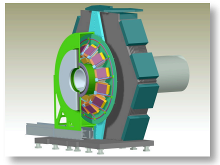


Geant geometry of hybrid bar/plate option for eRD14 EIC hpDIRC design

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

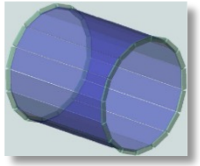


DIRCs are radially very compact, providing more space for calorimeters or tracking detectors.



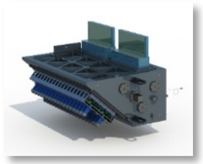
BABAR DIRC was the first DIRC, PID for barrel region, very successful, π/K up to ~4 GeV/c (1999-2008).

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



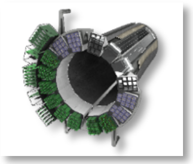
R&D to make DIRC readout more compact, expand momentum reach, use for endcap.

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



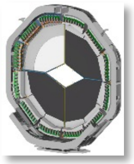
Main R&D directions *(with significant overlap/synergy)*:

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



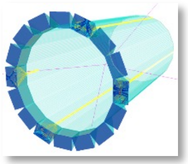
(b) focusing design emphasizing high-precision photon timing (Belle II);

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



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

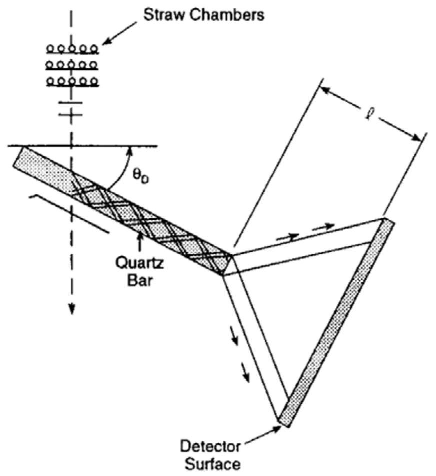
EIC hpDIRC design extends BABAR π/K range by 50%, adds useful e/π separation at low momentum.

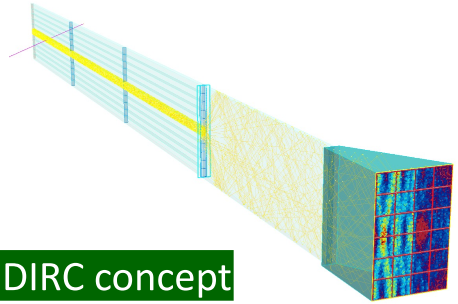


Even after 20 years, R&D still very active, pushing the DIRC performance limits further.

Summary

1994: Conceptual BABAR DIRC prototype





2021: EIC ultimate DIRC concept

Time Flies…

1994: Bonn Seminar

PHYSIKALISCHES SEMINAR

J. Schwiening

Bose-Einstein-Korrelationen im Boson-Antiboson-System?
Neue Messungen zur Produktion und Korrelation neutraler Kaonen
mit dem OPAL-Detektor

Montag, 13. Juni 1994, 18 Uhr c. t.

HS I (PIB)

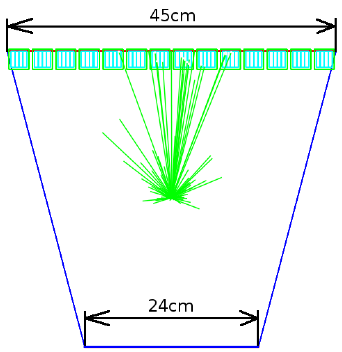
24.06.2021 (Thu)	10:15-11:30	TS: "DIRC Detectors - from BaBar to PANDA and Beyond"	Jochen Schwiening	Online

2021: Bonn Seminar

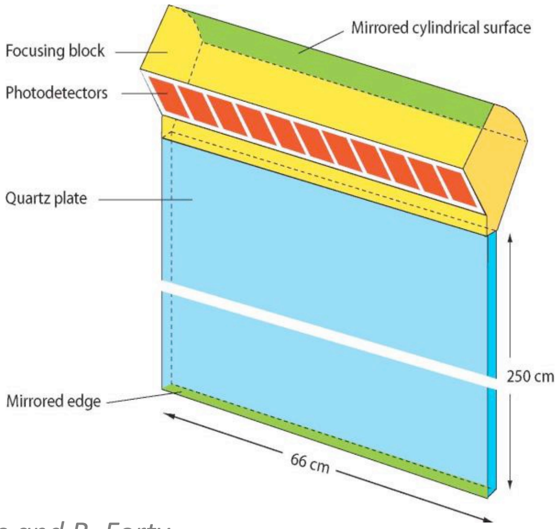
Thank You For Your Attention

EXTRA MATERIAL

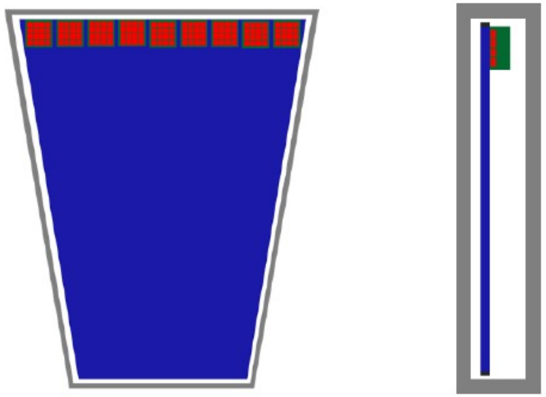
DIRC-Based Time-of-Flight



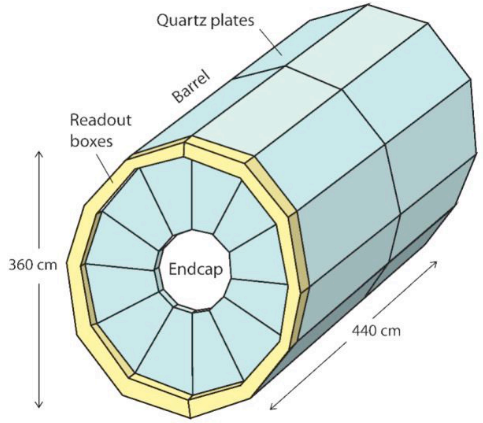
SuperB FTOF concept
N. Arnaud et al, NIMA 718 (2013) 557



TORCH
M. Charles and R. Forty,
Nucl.Instrum.Meth.A639:173-176 (2011)



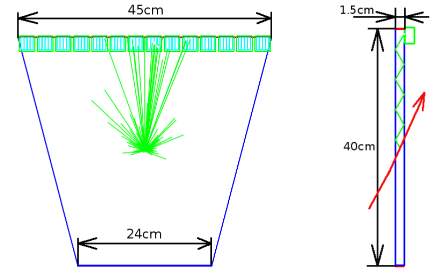
STCF DTOF concept
B. Qi et al, arXiv 2104.05297



TORCH-like concept
for FCC-ee

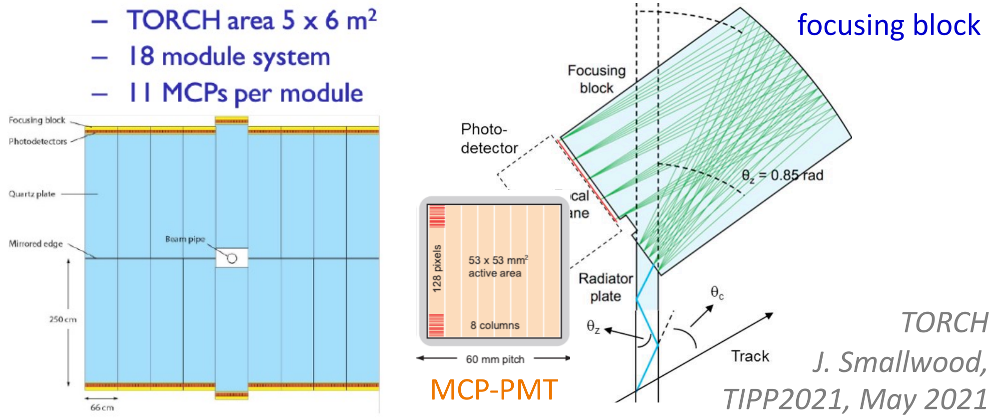
- Generate Cherenkov light in DIRC bar or plate, image photons, reconstruct 3D photon propagation path, calculate time of particle crossing DIRC

- 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



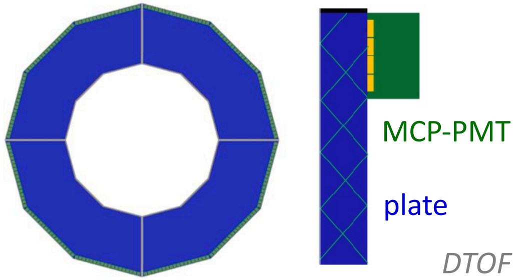
FTOF
L. Burmistrov
Acta Phys. Pol. B Proc. Suppl. 4, 91 (2011)

- 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

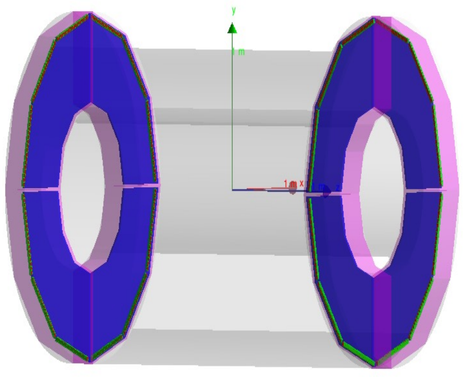


TORCH
J. Smallwood,
TIPP2021, May 2021

- 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

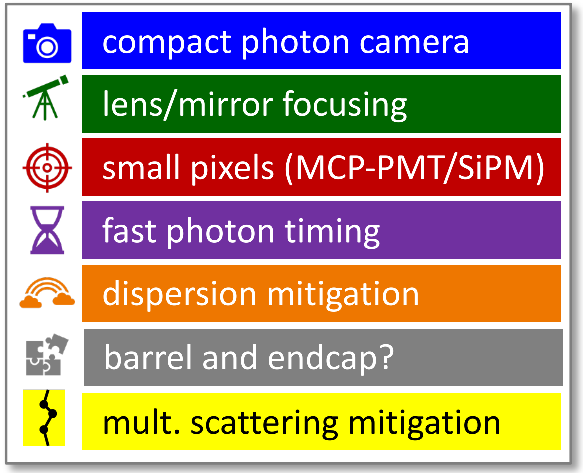


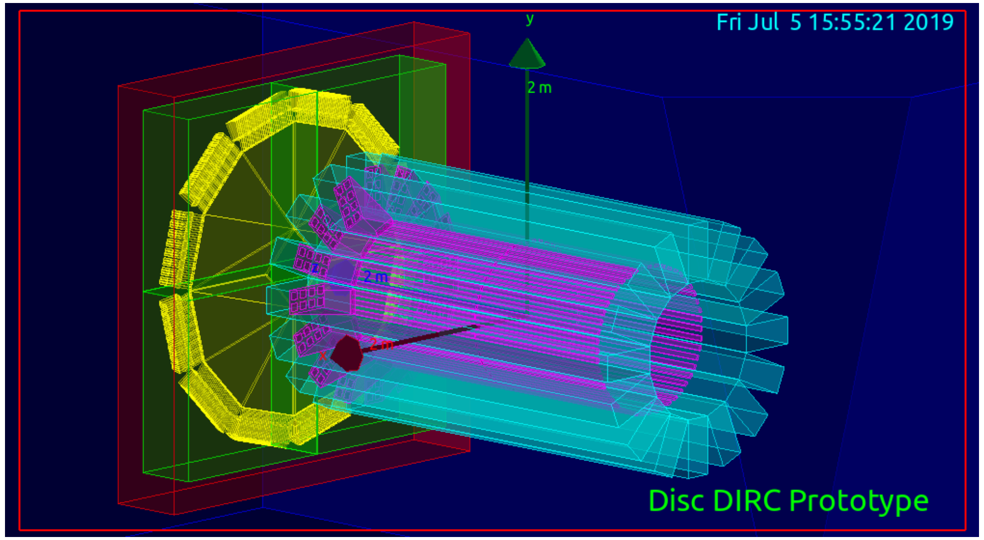
DTOF
B. Qi et al, arXiv 2104.05297



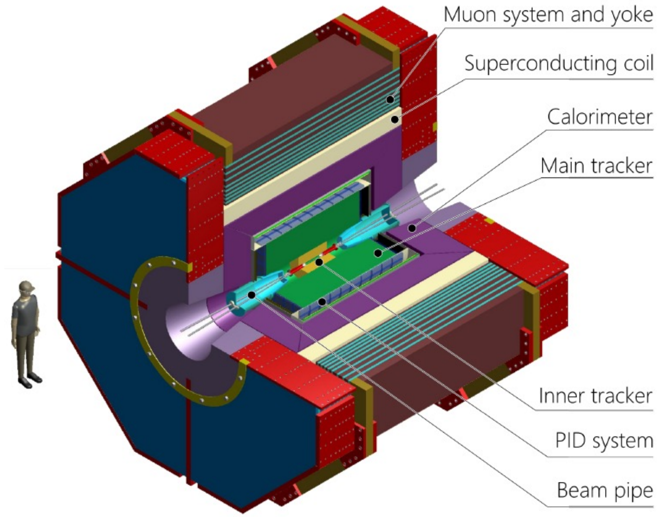
Qian LIU, STCF workshop 2020

Super Charm Tau DIRCs





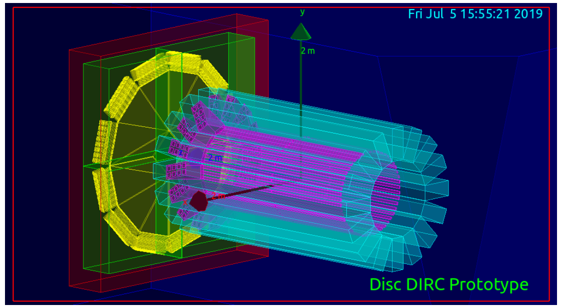
M. Schmidt, DIRC2019



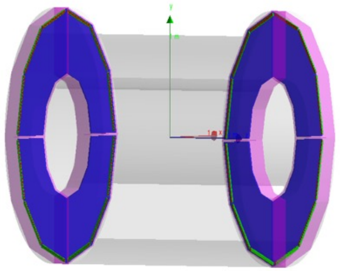
SCTF DIRCs

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

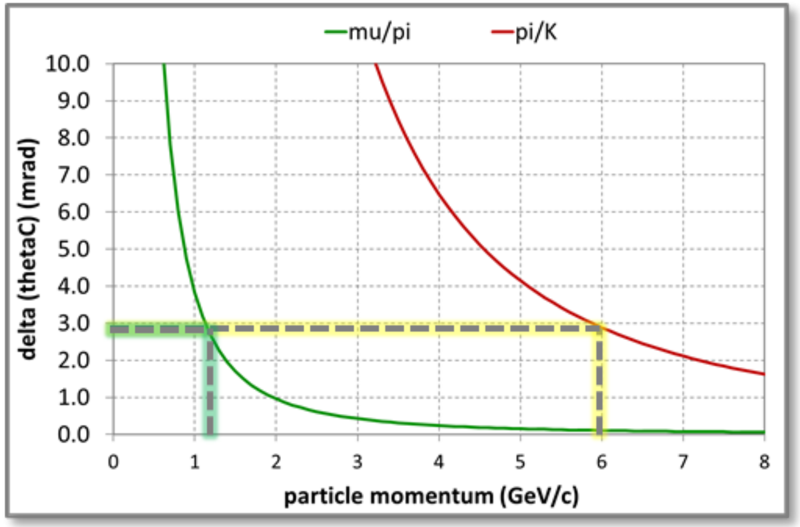
- barrel and/or endcap PID for the planned Super Charm-Tau/Super Tau-Charm Facility
- unique and challenging task for DIRCs: 3σ μ/π separation up to 1.2 GeV/c
- μ/π separation at 1.2 GeV/c close to π/K separation at 6 GeV/c,
  ~1mrad Cherenkov angle resolution per particle required for 3σ separation
- 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).



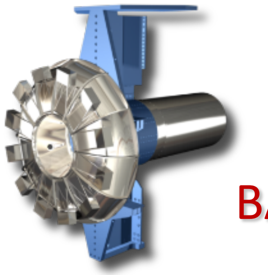
Barrel/endcap disc DIRC option, M. Schmidt, DIRC2019



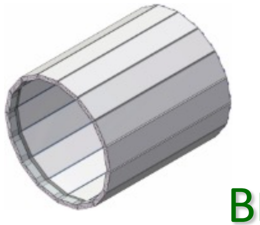
Endcap DIRC/TOF option, Qian LIU
Future charm-tau factory workshop, Nov 2020



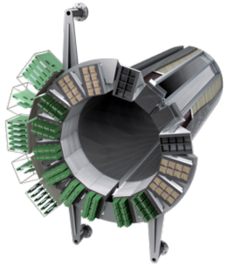
BARREL DIRC OVERVIEW



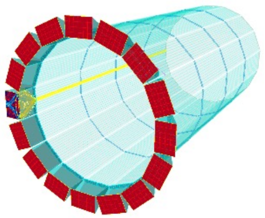
BABAR DIRC



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*