hpDIRC - the DIRC Detector for the Future Electron Ion Collider Experiment

EPIC eRD103 eRD14

Greg Kalicy

CUA

RICH2022, Edinburgh, Sep 12-16, 2022

EXECUTIVE SUMMARY/OUTLINE

Detection of Internally Reflected Cherenkov Light

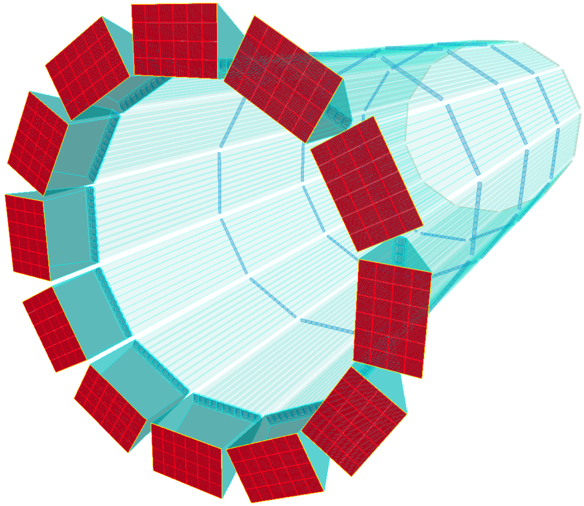
The high-performance DIRC (hpDIRC) was selected as the barrel PID system for the future electron ion collider (EIC) experiment (ePIC) at BNL

Fast focusing DIRC concept, PID goal: ≥ 3 s.d. π/K up to 6 GeV/c, ≥ 3 s.d. e/π up to ~1.2 GeV/c

Conceptual design advanced, many important performance aspects were validated in particle beams

Technical designs in progress, aiming for TDR-readiness in 2024 for CD2/3a

- PID Requirements for the EIC
- hpDIRC Design and Components
- Prototyping and Performance Validation
- Outlook

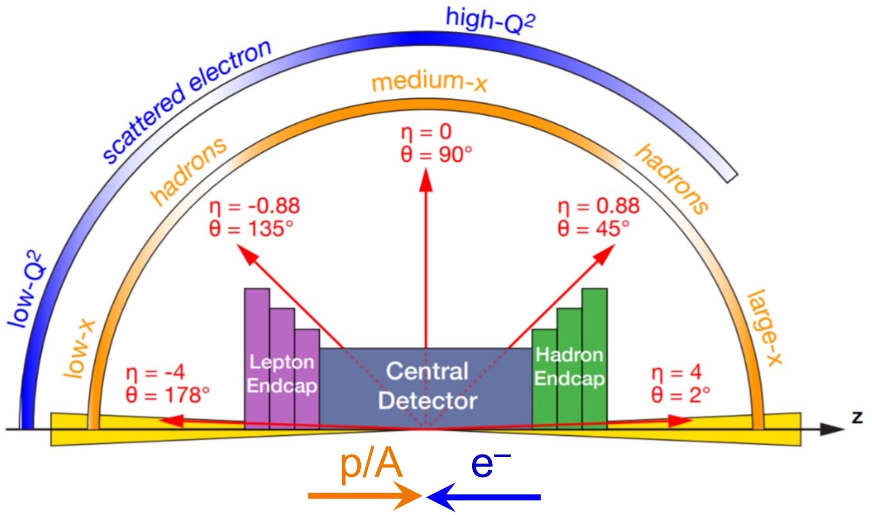


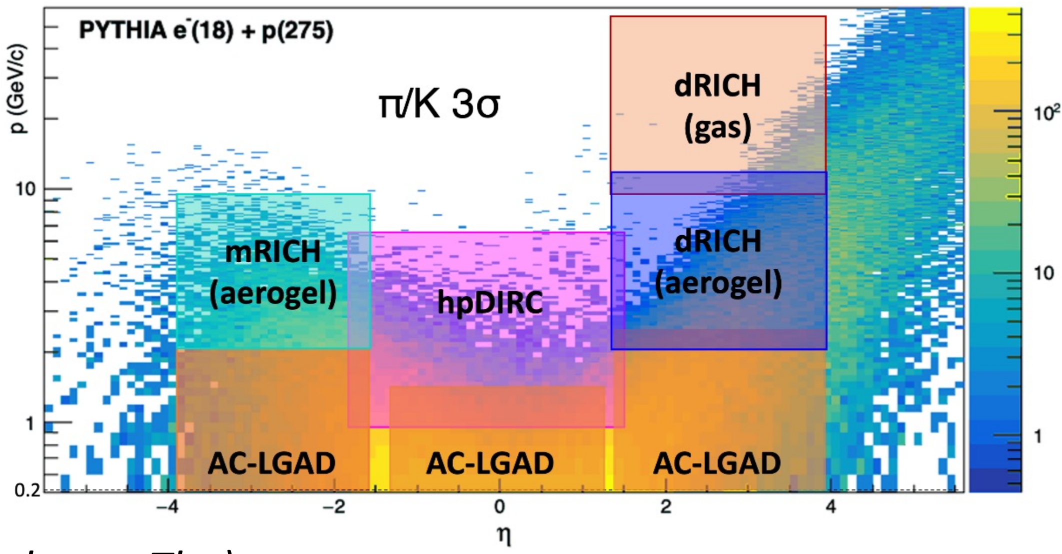
CHARGED PID AT THE EIC

EIC Yellow Report, arXiv:2103.05419

EIC physics requires clean and efficient separation of

- Electrons from photons -> 4π coverage in tracking
- Electrons from charged hadrons -> mostly provided by calorimetry
- Charged pions, kaons, and protons from each other
  - over a wide range |η| ≤ 3.5
  - with better than 3σ separation
  - contribute to pion/electron suppression
  - momentum-rapidity coverage (for π/K):
    - Hadron side: up to 50 GeV/c (dRICH)
    - Central: up to 6 GeV/c (hpDIRC)
    - Electron side: up to 10 GeV/c (mRICH)





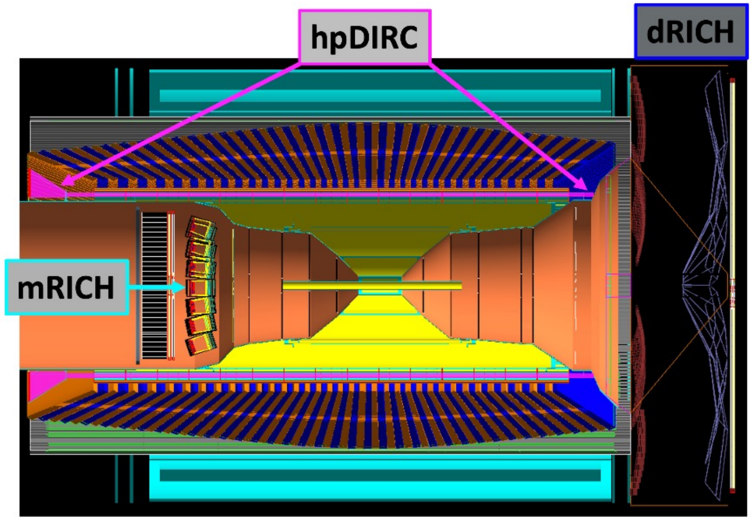
-> Suite of Cherenkov detectors (plus TOF at low momentum)

see presentations on mRICH (Xiaochun, Thu) and dRICH (Chandra, Tue; Roberto, Thu)

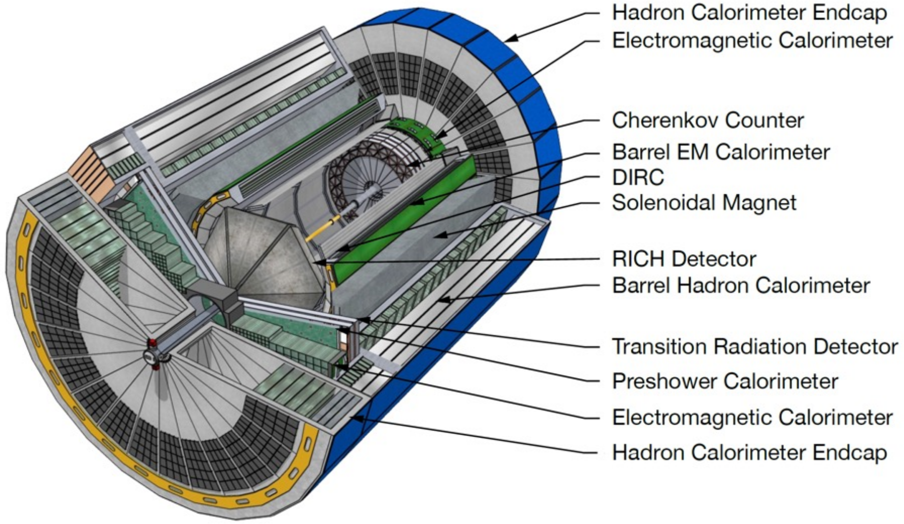
CHARGED PID AT THE EIC

EIC physics requires clean and efficient separation of

- Electrons from photons -> 4π coverage in tracking
- Electrons from charged hadrons -> mostly provided by calorimetry
- Charged pions, kaons, and protons from each other
  - over a wide range $|\eta| \leq 3.5$
  - with better than 3σ separation
  - contribute to pion/electron suppression
  - momentum-rapidity coverage (for π/K):
    - Hadron side: up to 50 GeV/c (dRICH)
    - Central: up to 6 GeV/c (hpDIRC)
    - Electron side: up to 10 GeV/c (mRICH)



Schematic view of RICH systems in EIC reference detector



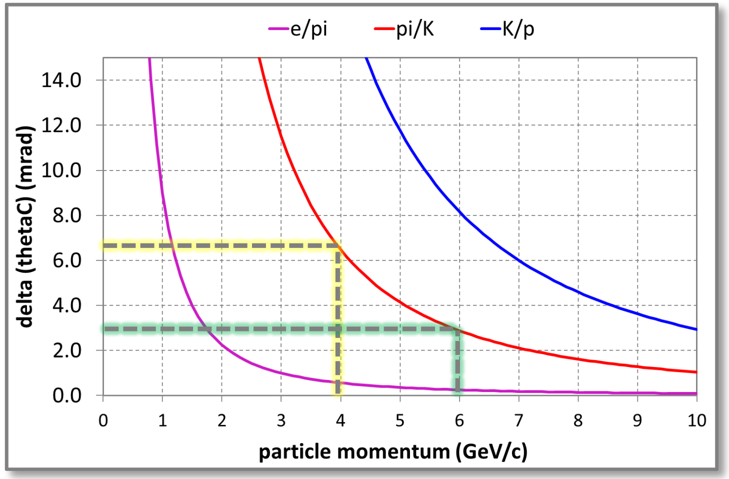
EIC requires increasing BaBar DRC π/K momentum coverage by 50%

-> R&D for a high-performance EIC DIRC started in 2011 *(BNL/DOE funding via eRD program)*

EIC Yellow Report, arXiv:2103.05419

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

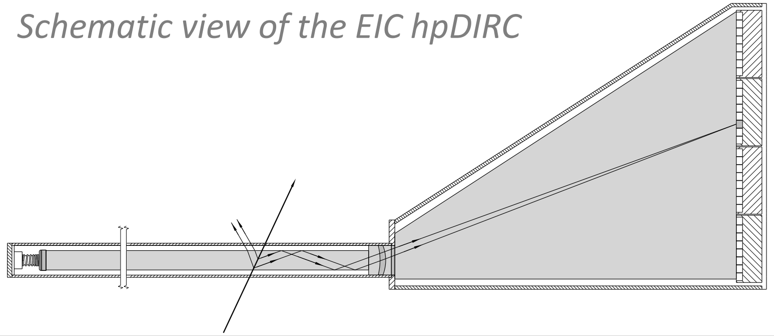
Limited in BABAR by:			Improve for future DIRCs via:
▪ size of bar image	~4.1 mrad	→	▪ focusing optics
▪ size of PMT pixel	~5.5 mrad	→	▪ smaller pixel size
▪ chromaticity (n=n(λ))	~5.4 mrad	→	▪ better time resolution
	9.6 mrad	→	5-6 mrad per photon → 1 mrad per particle (EIC goal) in reach

SUPERB, BELLE II, PANDA & EIC

A recipe for extending DIRC π/K separation coverage to 6 GeV/c

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

- Concept: fast focusing DIRC, utilizing high-resolution 3D (x,y,t) reconstruction.
- Radiation-hard 3-layer spherical lens to reduce bar image size and shape imaging plane;
- Lifetime-enhanced MCP-PMTs with fine anode segmentation to reduce pixel size;
- Fast photon timing for chromatic dispersion mitigation;
- Narrow bars for robust performance in high-multiplicity jet events (reuse BaBar DIRC bars?);
- Compact expansion volume to simplify integration into central detector.
- Benefit from additional EPIC detector improvements:
  - high-precision tracking, expect 0.5mrad polar angle resolution;
  - post-DIRC tracking layer (LGAD or MPGD) for multiple scattering mitigation.
- Predicted performance: 3σ π/K separation up to at least 6 GeV/c
  for rapidity range -1 ≤ η ≤ +1 (Cherenkov angle resolution ≤1mrad),
  supplemental e/π separation up to 1.2 GeV/c.


Schematic view of the EIC hpDIRC

Detector-1 (EPIC) hpDIRC Baseline Design

- Radiator bars:
  - Size: 4200mm x 35mm x 17mm (L x W x T)
  - Barrel: 720mm radius, 12 bar boxes, 10 long bars per bar box

    long bar: 4 bars glued end-to-end, flat mirror on far end

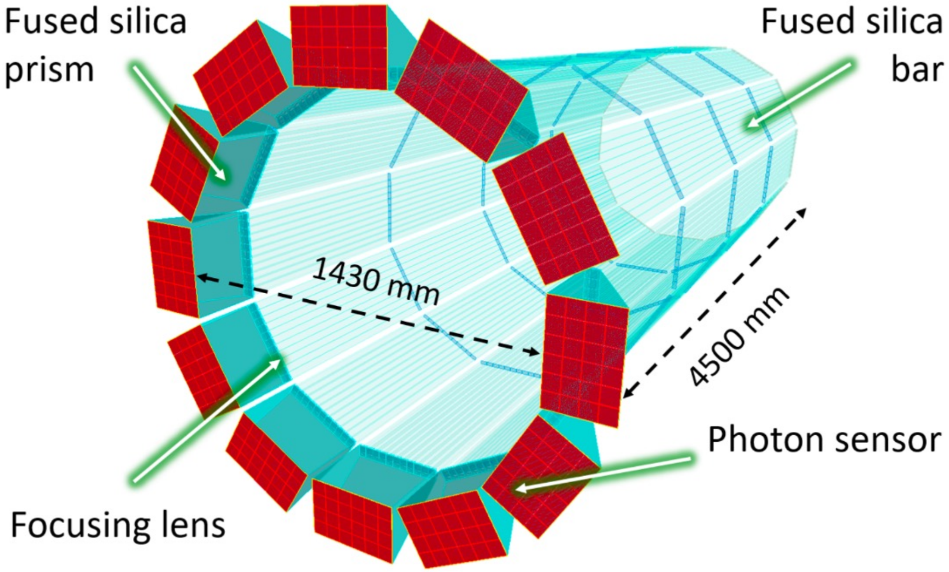
    baseline design: reuse of BaBar DIRC bars (R&D started)
- Focusing optics:

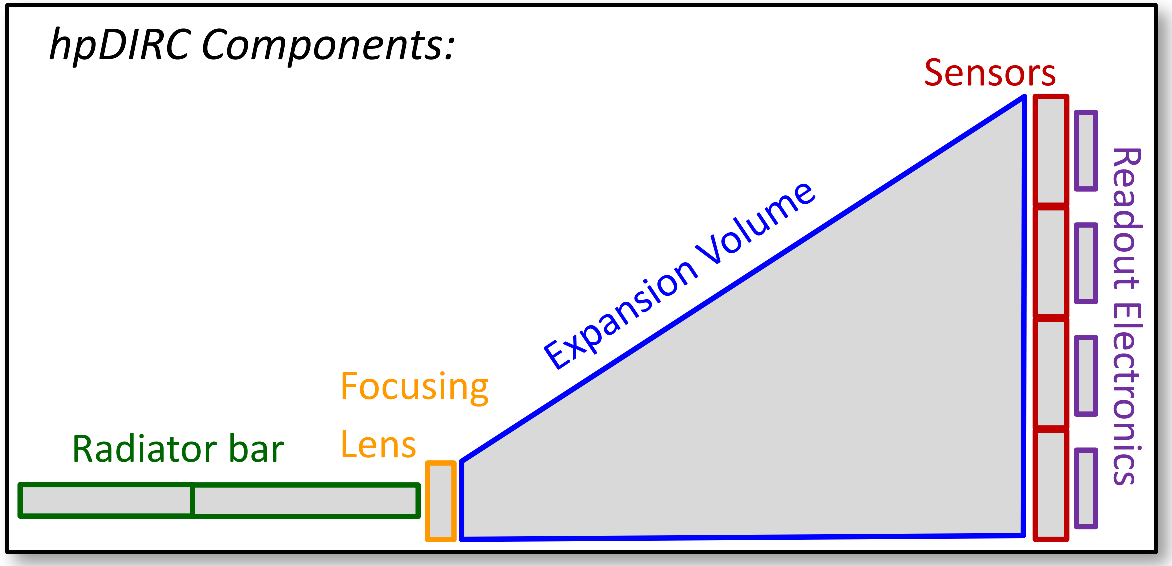
  Radiation-hard 3-layer spherical lens (sapphire or PbF_2)
- Expansion volume:

  Solid fused silica prism: 24 x 36 x 30 cm^3 (H x W x L)
- Readout system:

  MCP-PMT Sensors (e.g. Photek/Photonis/Incom)

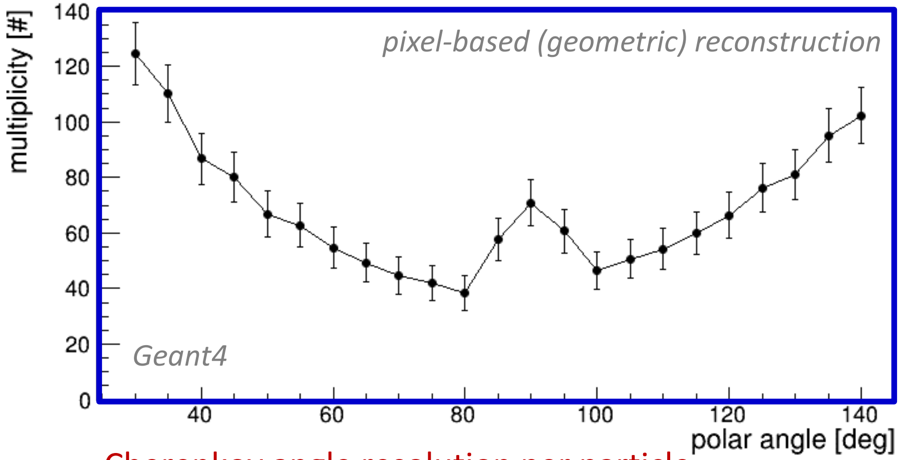
  ASIC-based Electronics (e.g UH/Nalu Scientific)
- Several core design aspects, as well as detailed Geant simulation, validated in PANDA Barrel DIRC beam tests (prototype tests in cosmic rays and test beams in preparation)



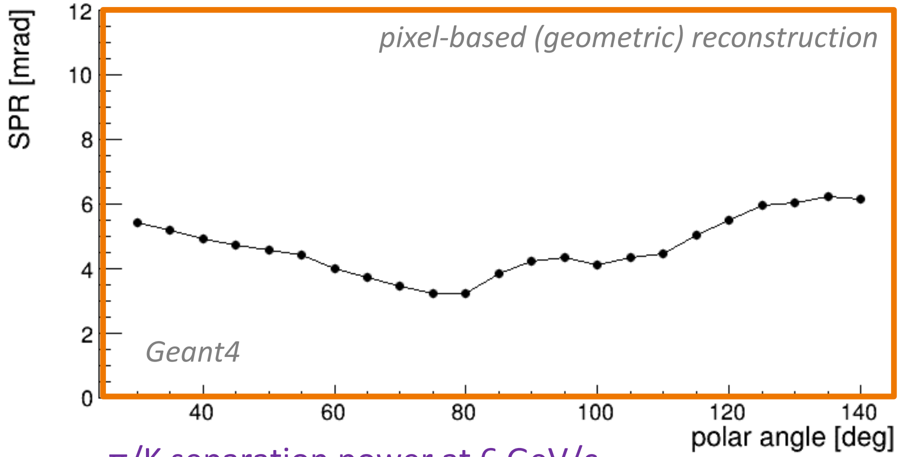


EXPECTED HPDIRC PERFORMANCE

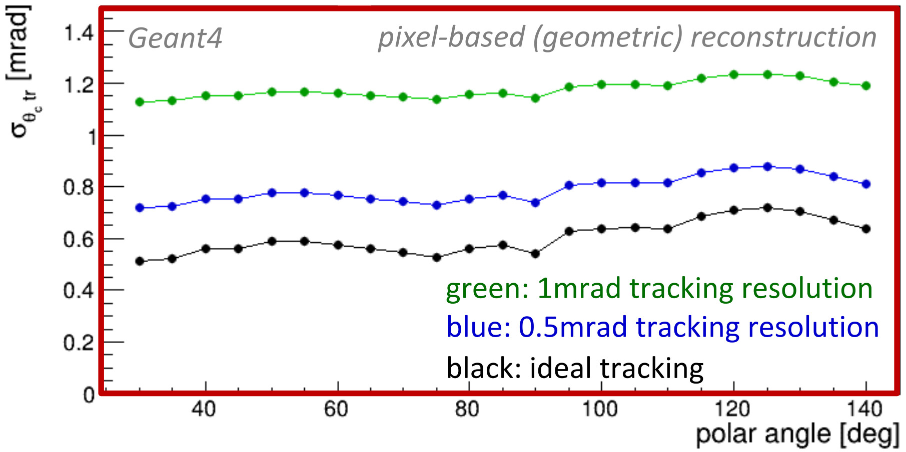
Photon yield per particle



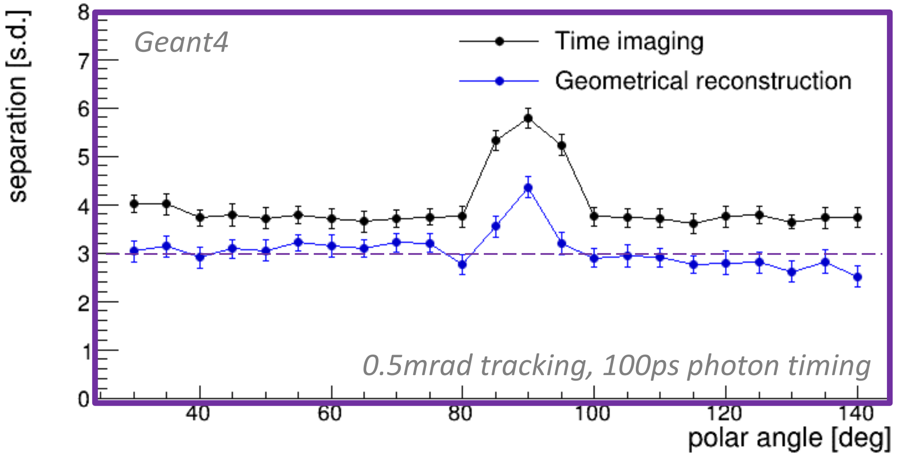
Cherenkov angle resolution per photon (SPR)



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

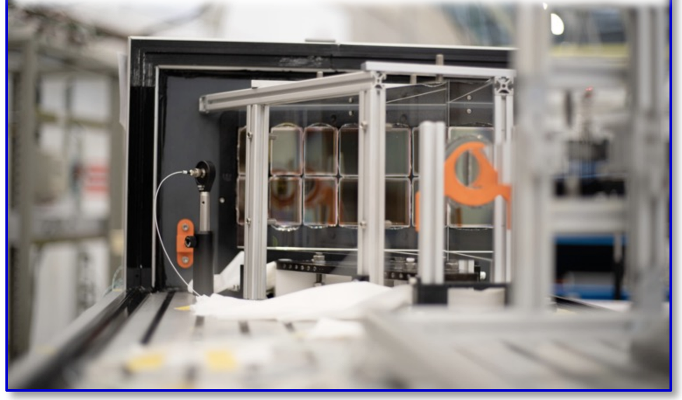
... but why should we believe the Geant prediction?

VALIDATION: PANDA BARREL DIRC SYNERGY

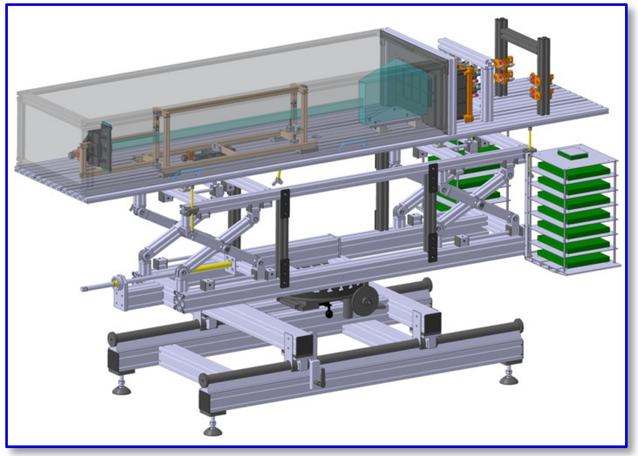
Performance validation: synergetic beam test with PANDA prototype at CERN PS in 2018

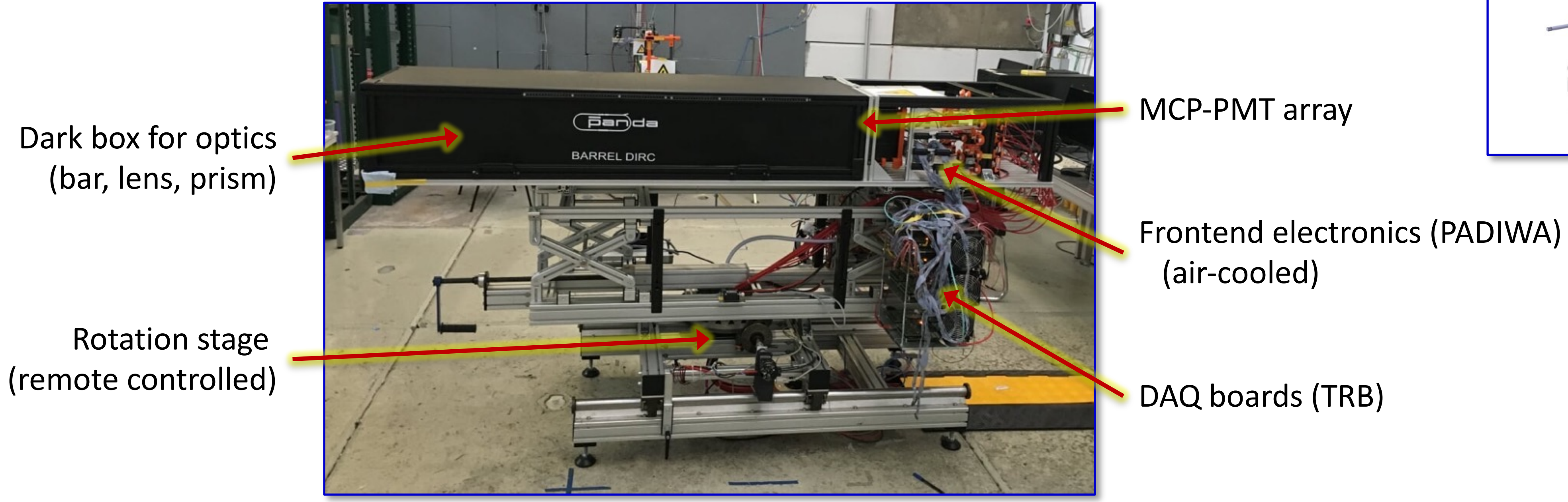
- Narrow fused silica bar, 3-layer spherical lens
- 30 cm-deep fused silica prism
- 2x4 PHOTONIS Planacon MCP-PMT array
  (larger pixels, slower readout electronics than EIC)
- PiLas picosecond laser calibration system
- 7 GeV/c π/p beam equivalent to 3.5 GeV/c π/K
- MCP-TOF system to cleanly tag π and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

View from inside the Barrel DIRC dark box

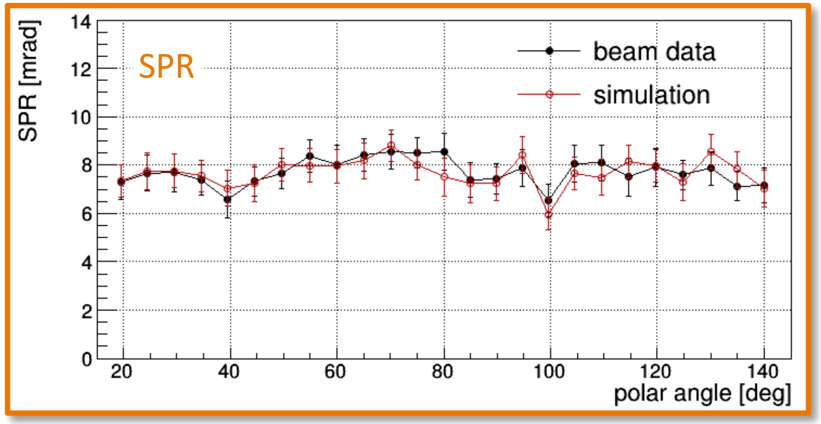


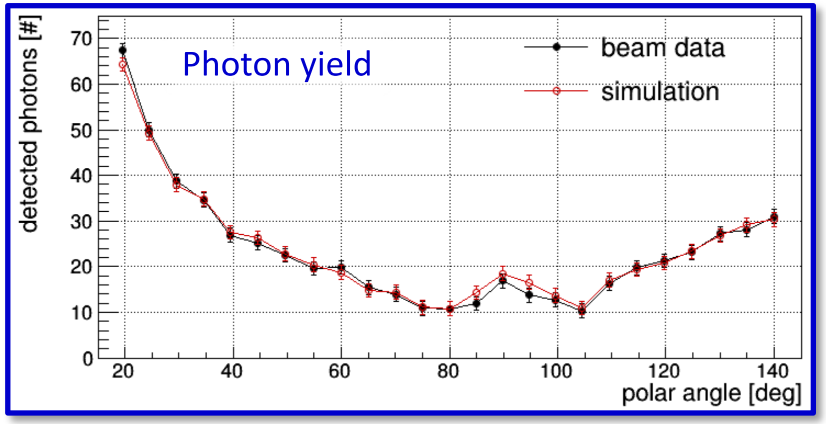
Schematic view of 2018 prototype



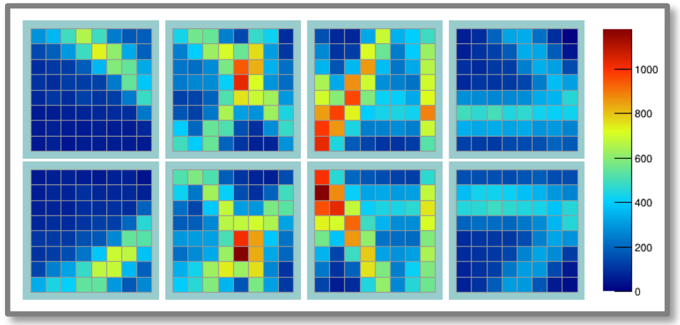


Performance validation: 2018 prototype at CERN PS

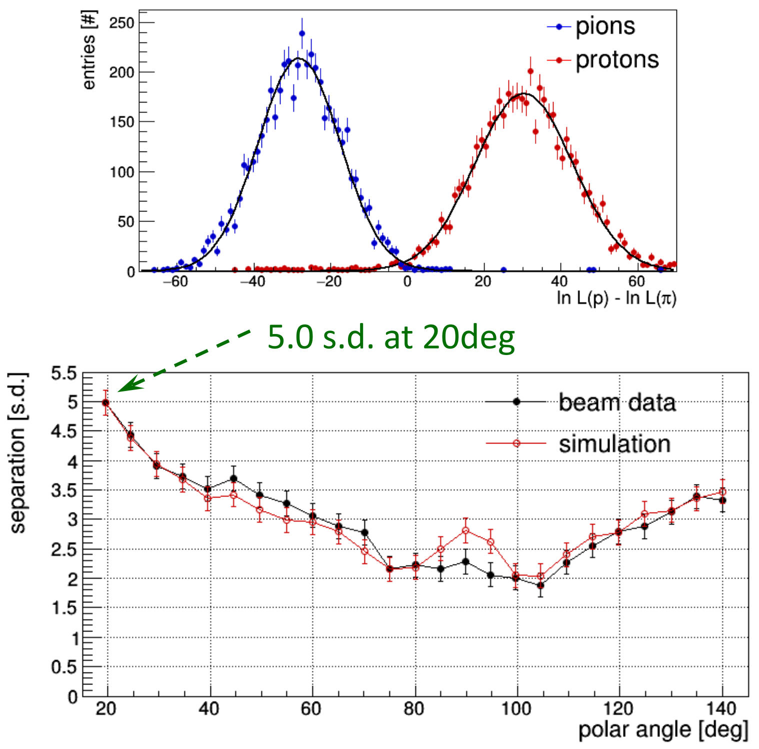




observed hit pattern at polar angle 20°



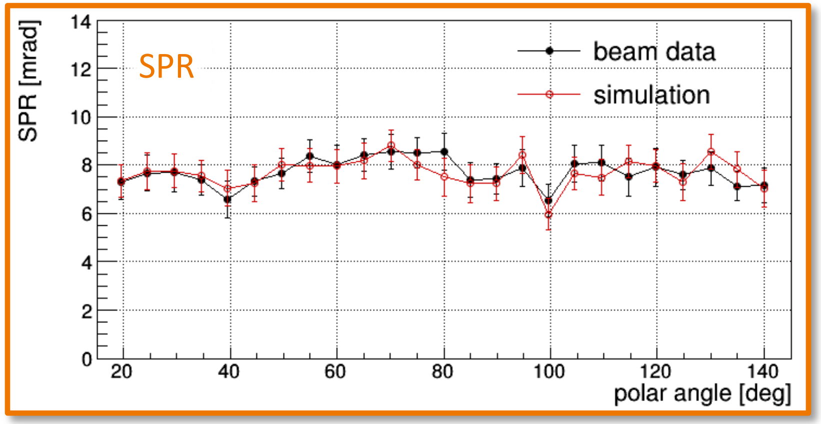
π/p separation power @ 7 GeV/c

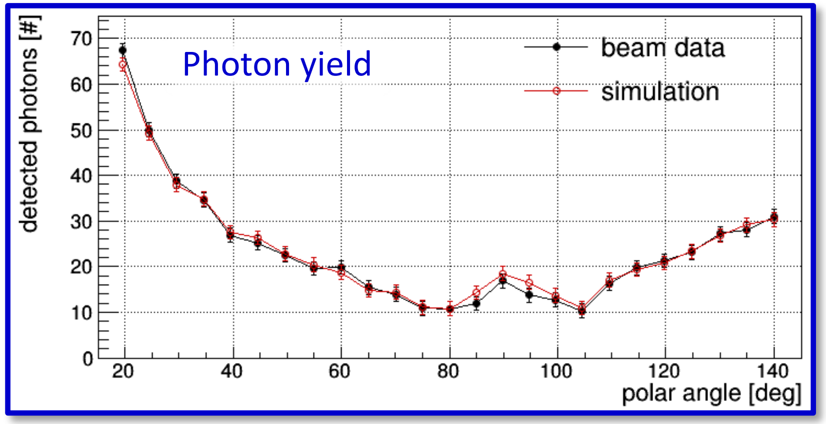


- Measured Cherenkov angle resolution per photon (SPR), photon yield, and π/K separation in excellent agreement with expectation and Geant4 simulation
- Achieved π/K separation power of N_{sep}=5.0 s.d. with time imaging reconstruction for PANDA configuration, will improve with smaller pixels, better PDE and timing
- Same simulation/reconstruction code used for EIC high-performance DIRC -> good degree of confidence in Geant prediction for hpDIRC performance

(see also Roman's talk on Monday)

Performance validation: 2018 prototype at CERN PS

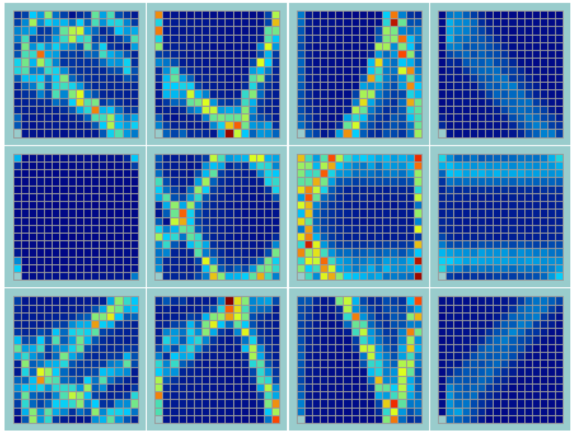




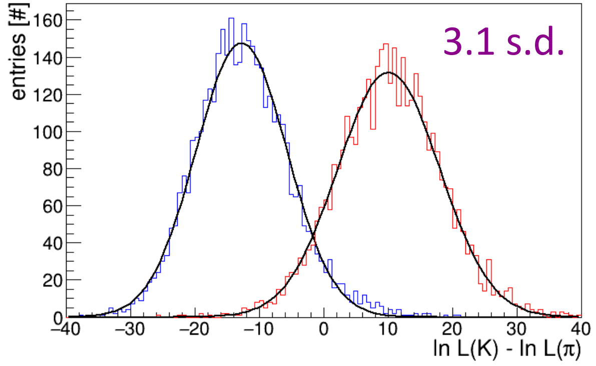
- Measured Cherenkov angle resolution per photon (SPR), photon yield, and π/K separation in excellent agreement with expectation and Geant4 simulation
- Achieved π/K separation power of N_{sep}=5.0 s.d. with time imaging reconstruction for PANDA configuration, will improve with smaller pixels, better PDE and timing
- Same simulation/reconstruction code used for EIC high-performance DIRC
  -> good degree of confidence in Geant prediction for hpDIRC performance
- Expected π/K separation of future prototype at 6 GeV/c at 20°: 3.1 s.d.
  (assuming new MCP-PMTs with smaller pixels and electronics, 100ps single p.e. timing)
- Transfer of PANDA Barrel DIRC prototype to US for hpDIRC tests in fall 2022

Geant simulation of hpDIRC prototype

Accumulated hit pattern



Expected π/K separation at 6 GeV/c at 20°

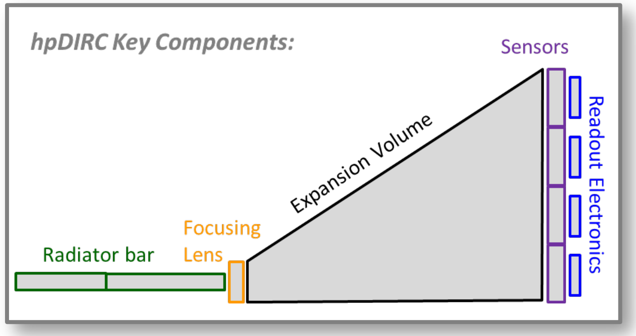


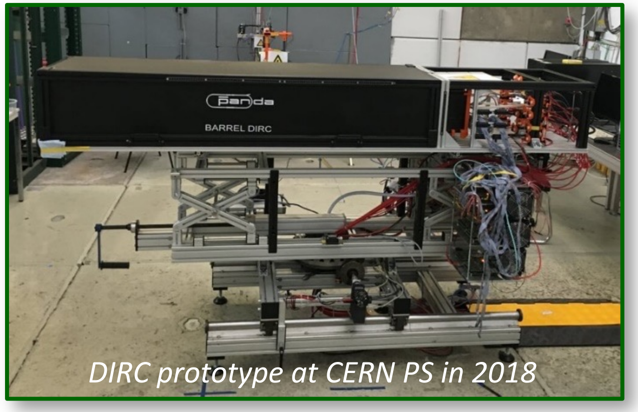
hpDIRC: Remaining R&D

Main objective: To validate the PID performance of a cost-optimized hpDIRC design for with a vertical-slice prototype by FY24

- Currently evaluating components and prototypes in DIRC labs (ODU, JLab, GSI, BNL)
- Cosmic ray telescope (SBU) will be used for incremental hpDIRC prototype assembly, readout integration, and preparation for possible particle beam test in Fermilab
- Key prototype components transferred from PANDA Barrel DIRC will be used to save cost and time
- Primary R&D focus on bars, lenses, MCP-PMTs, readout electronics

Prototype readout stack at UH/Nalu

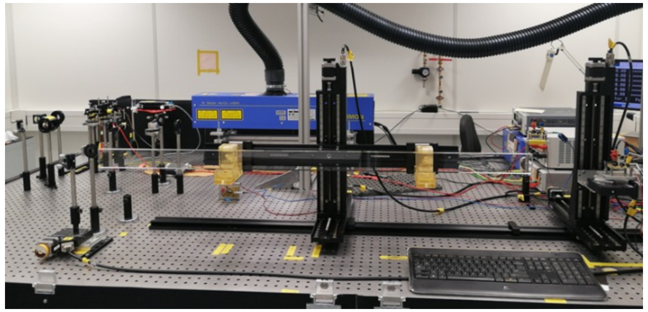


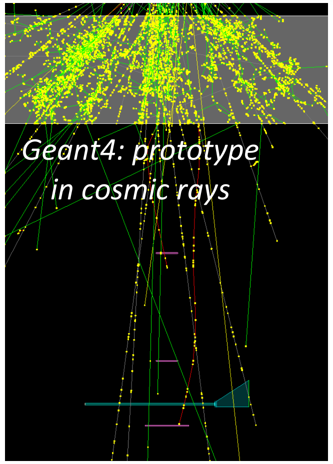


DIRC prototype at CERN PS in 2018

DIRC lab @ ODU

DIRC lab @ GSI

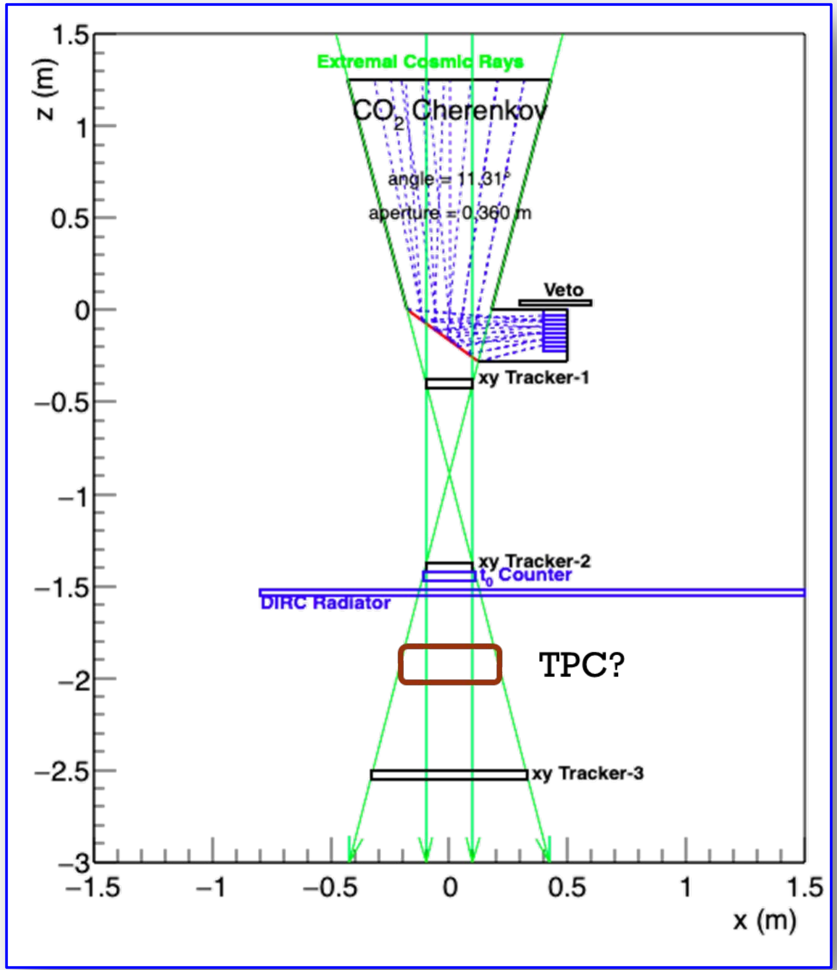



Geant4: prototype in cosmic rays

Prototype Plans

Opportunity: Tests of DIRC Prototype with Cosmic Rays

- Crowded beam test schedules – validate hpDIRC with cosmic muons
- Work on mechanical and readout aspects of hpDIRC prototype
- Collaboration of CUA – GSI – ODU – SBU to develop cosmic ray telescope (CRT) design and measurement plan



Current design:

- Momentum selection: new CO_2 Cherenkov threshold tagger (> ~3.5 GeV/c)
- 3D tracking: two GEM tracker stations (from sPHENIX) above and below DIRC bar, potentially combined with TPC prototype
- Shower rejection: scintillator plates as veto counters
- T_0 start counter: MCP-PMT/LAPPD or PICOSEC-Micromegas counter
- Mechanical design progressing, prototype polar angle rotation foreseen
- Geant simulation package in preparation

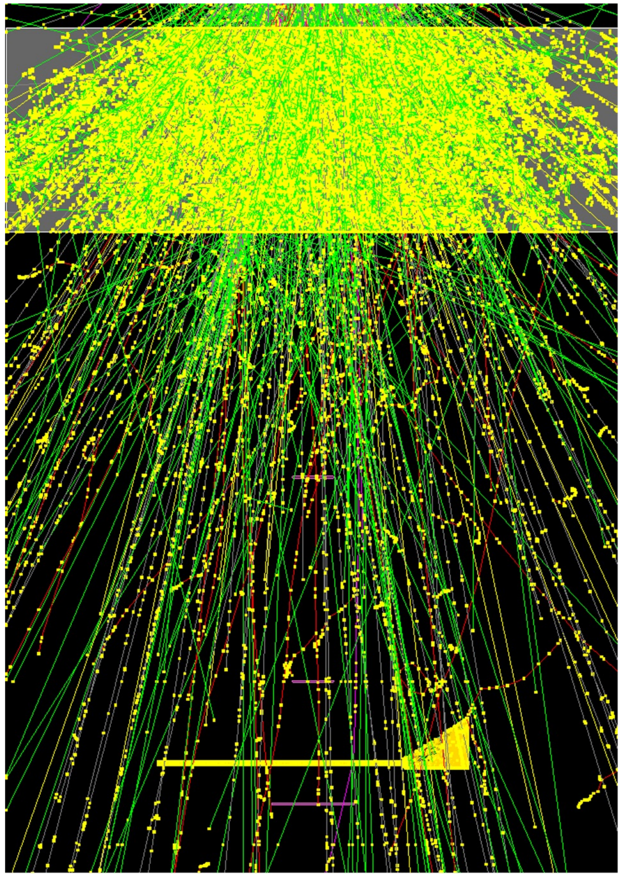
Opportunity: Tests of DIRC Prototype with Cosmic Rays

- Crowded beam test schedules – validate hpDIRC with cosmic muons
- Work on mechanical and readout aspects of hpDIRC prototype
- Collaboration of CUA – GSI – ODU – SBU to develop cosmic ray telescope (CRT) design and measurement plan

Current design:

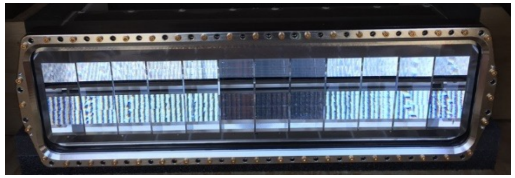
- Momentum selection: new CO_2 Cherenkov threshold tagger (> ~3.5 GeV/c)
- 3D tracking: two GEM tracker stations (from sPHENIX) above and below DIRC bar, potentially combined with TPC prototype
- Shower rejection: scintillator plates as veto counters
- T_0 start counter: MCP-PMT/LAPPD or PICOSEC-Micromegas counter
- Mechanical design progressing, prototype polar angle rotation foreseen
- Geant simulation package in preparation

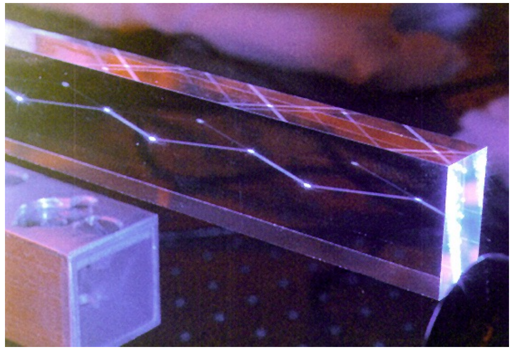
Geant: ~10 seconds of real time



Opportunity and technical challenge: Reuse of BaBar DIRC bars

- DIRC bars notoriously expensive and difficult to produce – BaBar DIRC bars available for reuse
- Bar width and thickness fully compatible with latest hpDIRC design
- Reuse potentially saves approximately $5M in cost, reduces technical and schedule risk
- Full-size bar boxes are too long, do not fit into EIC central detector, wedges deteriorate resolution: need to disassemble bar boxes for reuse
- Eight bar boxes located at SLAC, awarded to JLab for potential use in EIC
  For reasonably high yield of high-quality bars: number of bars sufficient for EPIC hpDIRC
- Detailed plan developed with SLAC DIRC experts to open bar boxes and decouple long bars into short bars in SLAC DIRC lab using heat gun (Matt McCulloch and Jerry Va'vra involved)
- Bars will be shipped to new QA DIRC lab at JLab to measure quality of bar surfaces with laser system, validate disassembly method using HeCd laser scans (reflection coefficient).
  (Risks: deterioration after 20+ years in bar box, contamination of bar surfaces from opening of box and from heat gun disassembly)





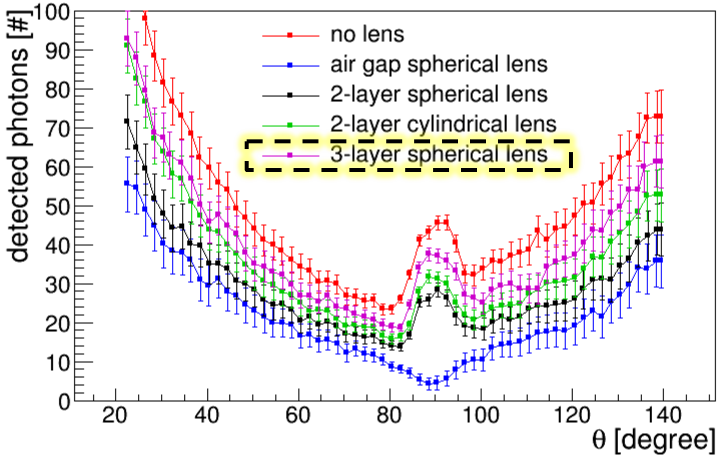
Technical challenge: lens focusing

Barrel DIRC counters (PANDA, EIC) 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

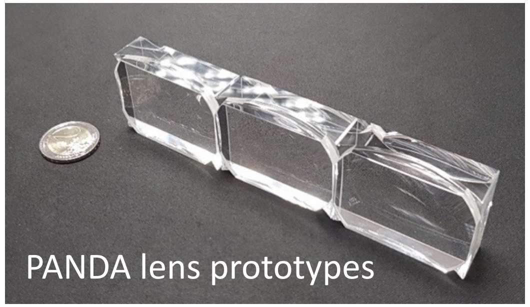
Geant4 simulation: photon yield



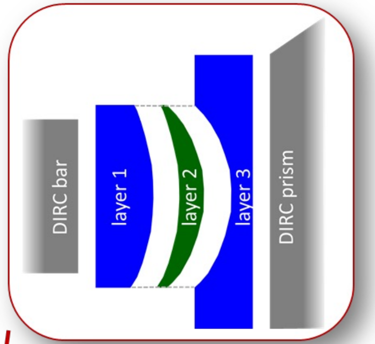
Innovative solution:

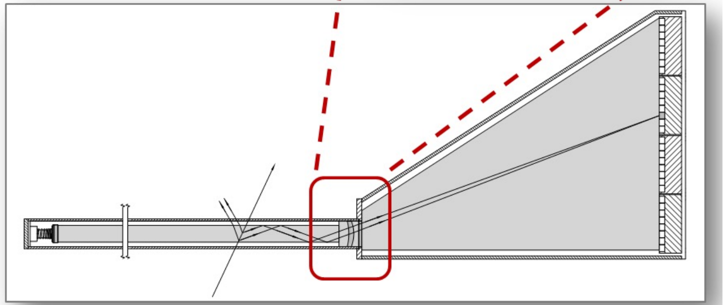
- 3-layer compound lens (without air gap):

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



PANDA lens prototypes



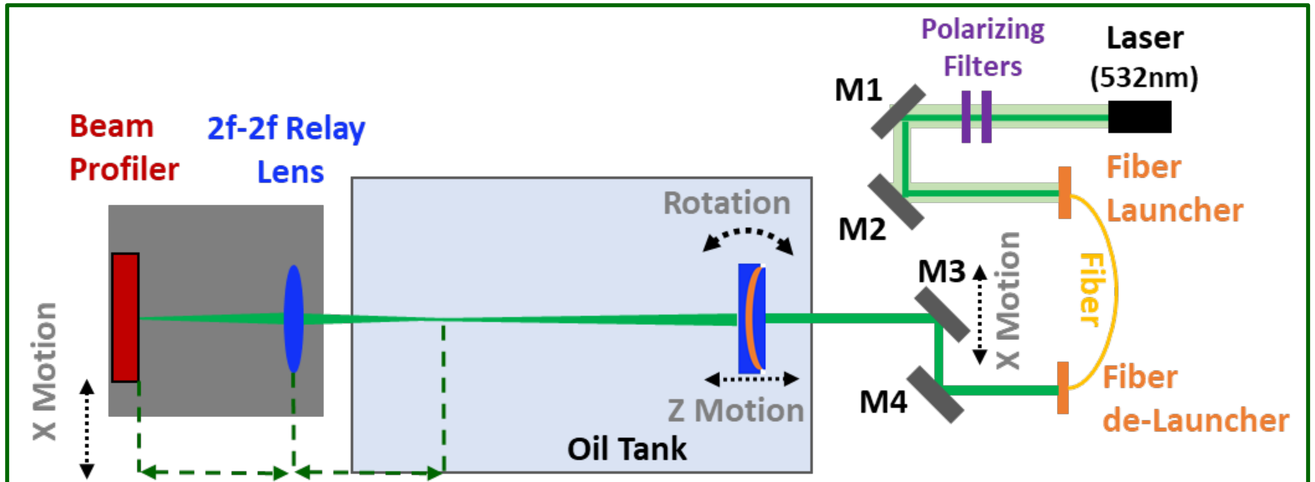


- Creates flat focal plane – matched to fused silica prism shape
- Avoids photon loss and barrel PID gap
- Detailed radiation-hardness studies performed with ^{60}Co source, neutron irradiation next
- Lanthanum crown glass (LaK33B) for PANDA, rad-hard sapphire or PbF_2 for EIC
- Performance of spherical 3-layer lenses validated with PANDA Barrel DIRC prototype

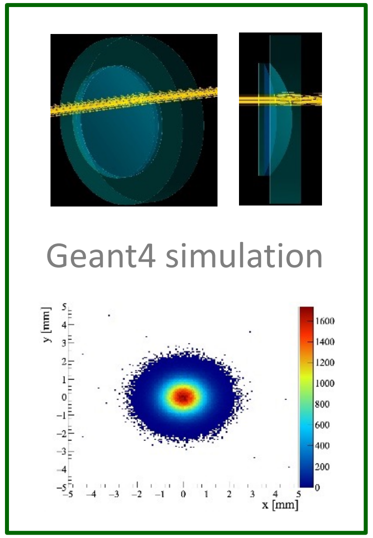
(see also Roman's talk on Monday)

HPDIRC LENS FOCUSING

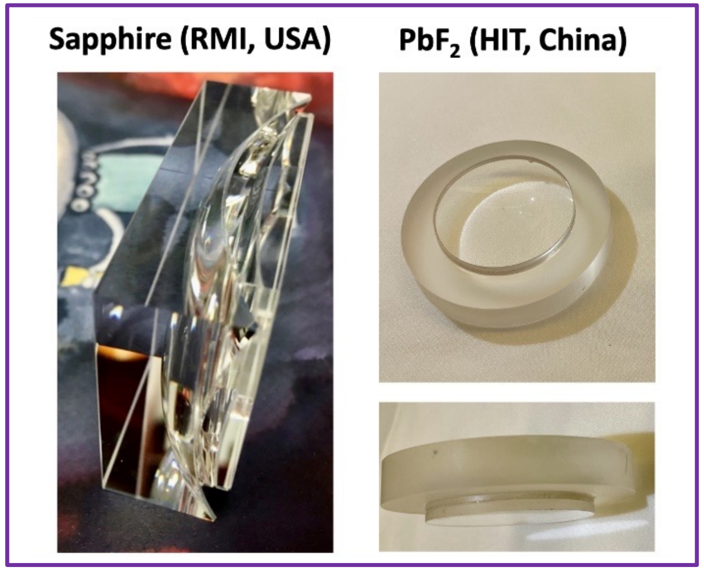
- ➢ Detailed scans of lens focusing properties with laser in optical lab at ODU



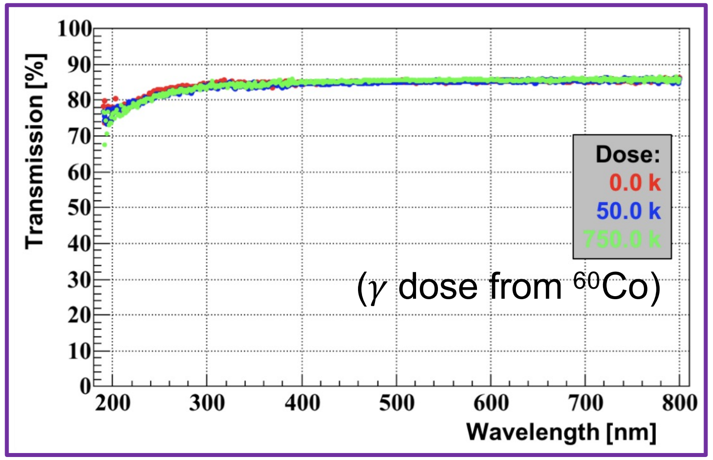
Close collaboration with Prof. Charles I. Sukenik (ODU)



Radiation-hard 3-layer lens prototypes

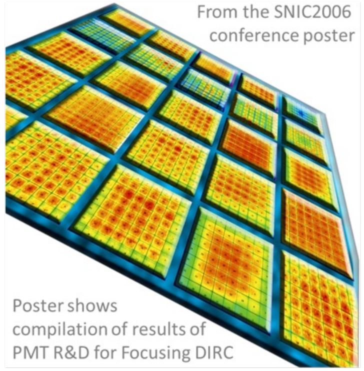


Radiation hardness of sapphire



DIRC Sensor Requirements

Sensor development has been crucial to DIRC progress

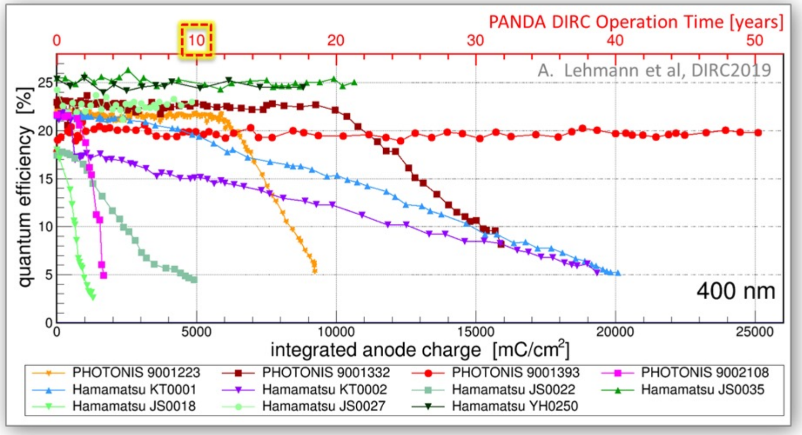


Main hpDIRC development directions: Smaller pixels and faster single photon timing

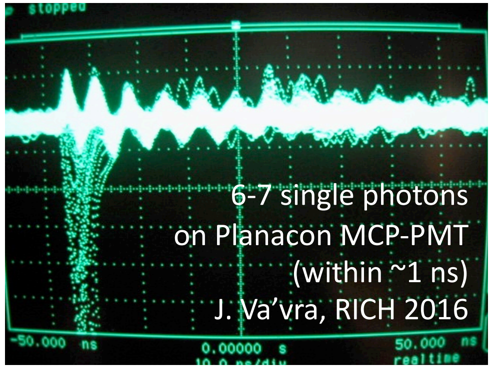
- reduces sensitivity to backgrounds
- improves Cherenkov angle resolution per photon
- allows chromatic dispersion mitigation

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?)



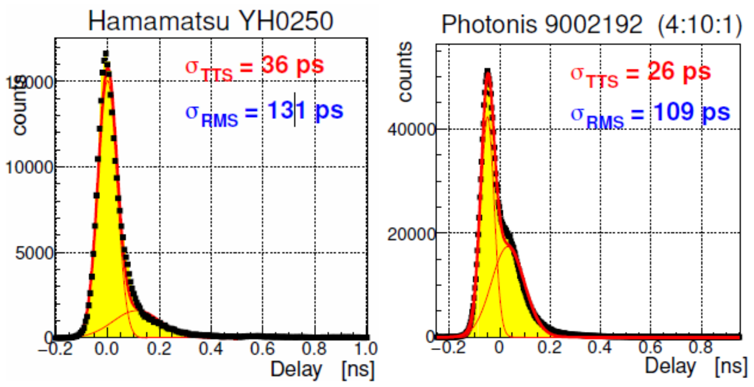
(see also Steffen talk tomorrow)



Sensor development has been crucial to DIRC progress

Single photon detection

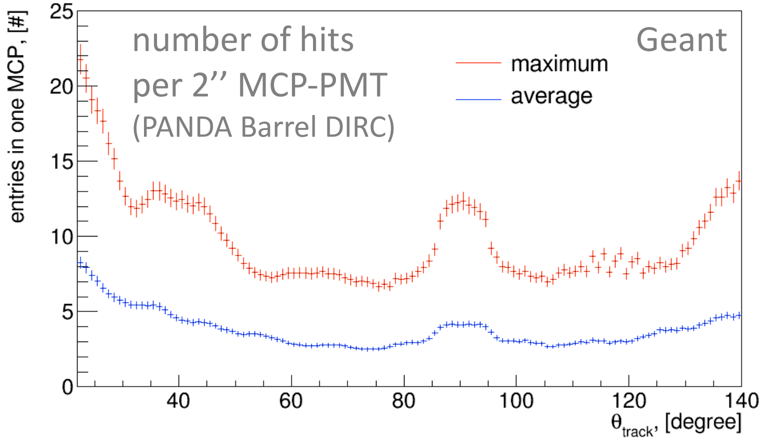
- excellent rms timing precision, more important than simple TTS
- reduce tails in timing distribution by increasing PC-MCP voltage



A. Lehmann
TIPP2021 (updates tomorrow)

High photon yield (up to 120 photoelectrons per particle, multiple particles per sector)

- need long lifetime (often >10-20 C/cm^2)
- need highly pixelated readout, likely DC-coupled
  (capacitive coupling could be difficult due to ambiguities)
- need tolerance for high occupancy per sensor
  (concern about coherent oscillations)



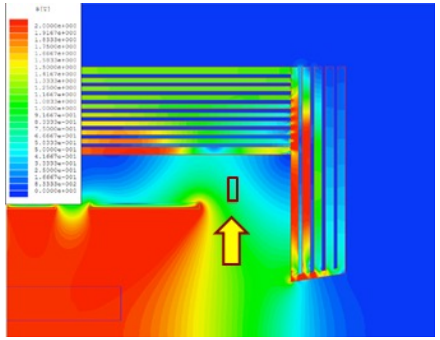
JS
ANL MCP-PMT Workshop 2014

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

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

Challenge: single photon detection with 100ps precision in high B fields

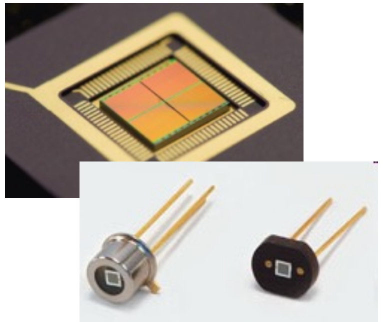
DIRC sensor location in PANDA, B~1T



- Multi-anode Photomultipliers (MaPMTs)

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

  cost-efficient but do not work in magnetic fields, serious challenge for DIRC integration



- Geiger-mode Avalanche Photo Diodes (SiPMs)

  high dark count rate problematic for reconstruction (DIRCs need large time window)

  radiation hardness a serious issue → cryogenic operation and annealing?

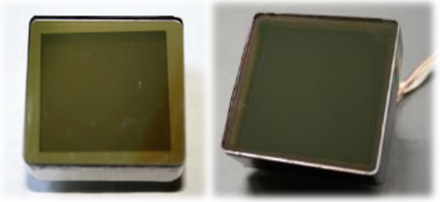
  cost-efficient, could be a good candidate in the future, needs further R&D

- Micro-channel Plate Photomultipliers (MCP-PMTs)

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

  previous issues with rate capability and aging resolved in recent years

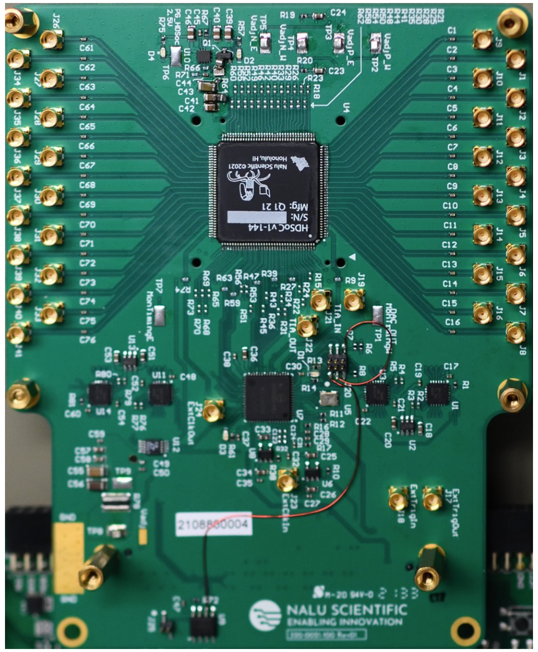
  multiple vendors available Hamamatsu, Photek, Photonis (, and LAPPD)



(see also Albert's talk tomorrow)

- hpDIRC unique readout requirements:
  - Sensors (Large number of small pixels; Fast single photon timing; Relatively high photon rates and sensor occupancies)
  - Performance requirements (fast timing, triggerless streaming, data reduction, bandwidth, latency and throughput)
  - Critical factors (e.g. power consumption, integration issues at the detector front end)
- The close collaboration between Nalu and UH was established several years ago in the design, fabrication and deployment of the Belle II DIRC TOP detector (below left), which shares many similarities to the hpDIRC.
- High Density digitizer System on a Chip (HDSoC):New front-end readout system based on the waveform sampling low-power, higher-performance SiREAD ASICs.
  - ASICs integrated on boards directly matching the footprint of the sensor
  - Readout cards are arranged as a board stack, placed behind the photosensor, permitting seamless abutting of the sensor array
  - A simple and standard power and serial interface allows groups of 256- anode devices to be collected into a single ethernet acquisition node

32-chnl test HDSoC ASIC



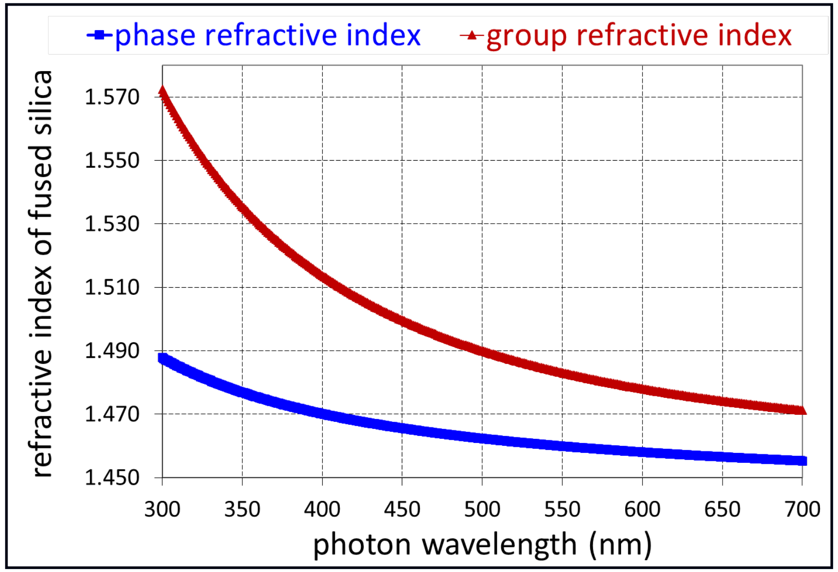
HDSoC ASIC parameters:

HDSoC Parameter	Specifications
Channels	64
Sampling rate	1-2 GSa/s
Storage samples/ch	4096
Analog Bandwidth	0.7-1.1 GHz
RMS Voltage Noise	<1mV
Dynamic Range	10-11 bits
Signal Voltage range	2.1 V
ADC on Chip	12-bits
Feature extraction	on chip
Readout	Serial LVDS
Power Consumption	20-40 mW/ch

Technical challenge: properties of synthetic fused silica

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

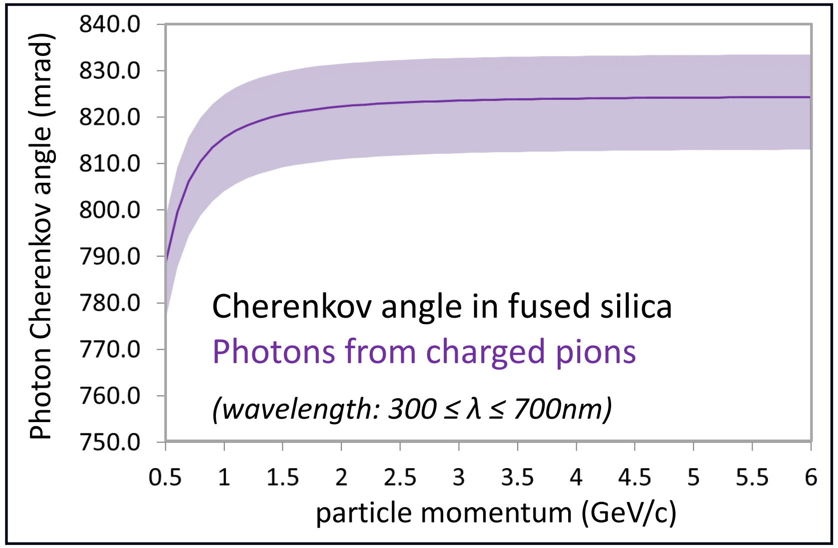
Cons:
- Production process can produce inclusions (bubbles) in bulk material or layers with optical index variations (striae)
- Dispersion of refractive index impacts angular resolution



Impact of chromatic dispersion on Cherenkov angle resolution

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

→ significant contribution to Cherenkov angle resolution per photon



Several approaches to dispersion mitigation are being investigated:

- Limit wavelength range (custom photocathode or band filter)
- Use transition to different refractive index (LiF prism)
- Use fast photon timing to tag photon wavelength using time dispersion
  - → SuperB fDIRC first to demonstrate feasibility of this method *(JS, RICH2007)*

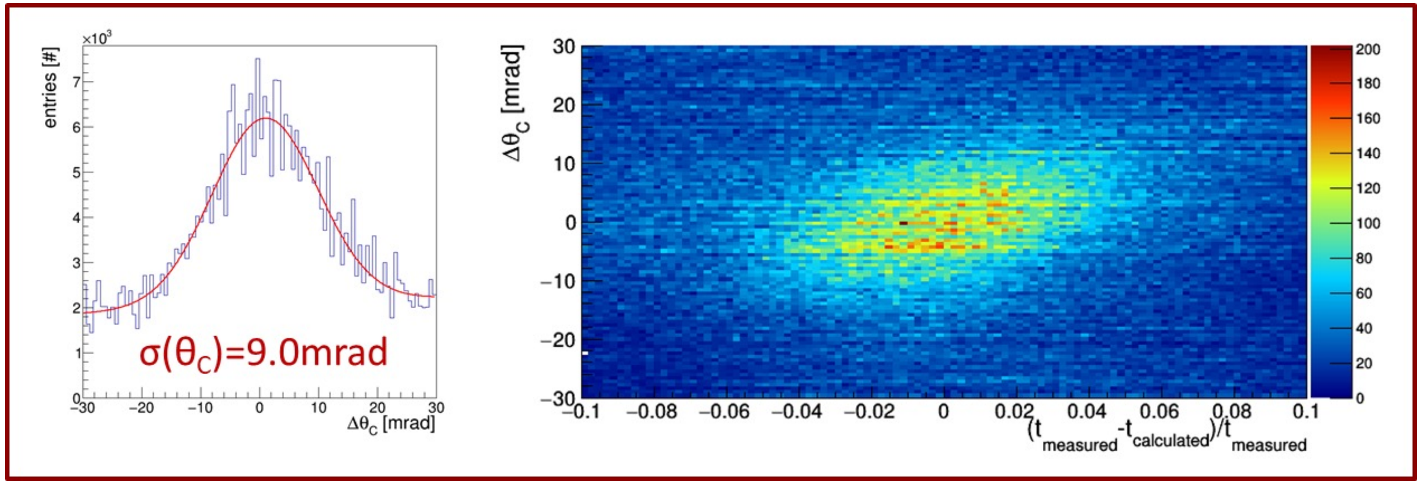
(see also Roman's talk on Monday)

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

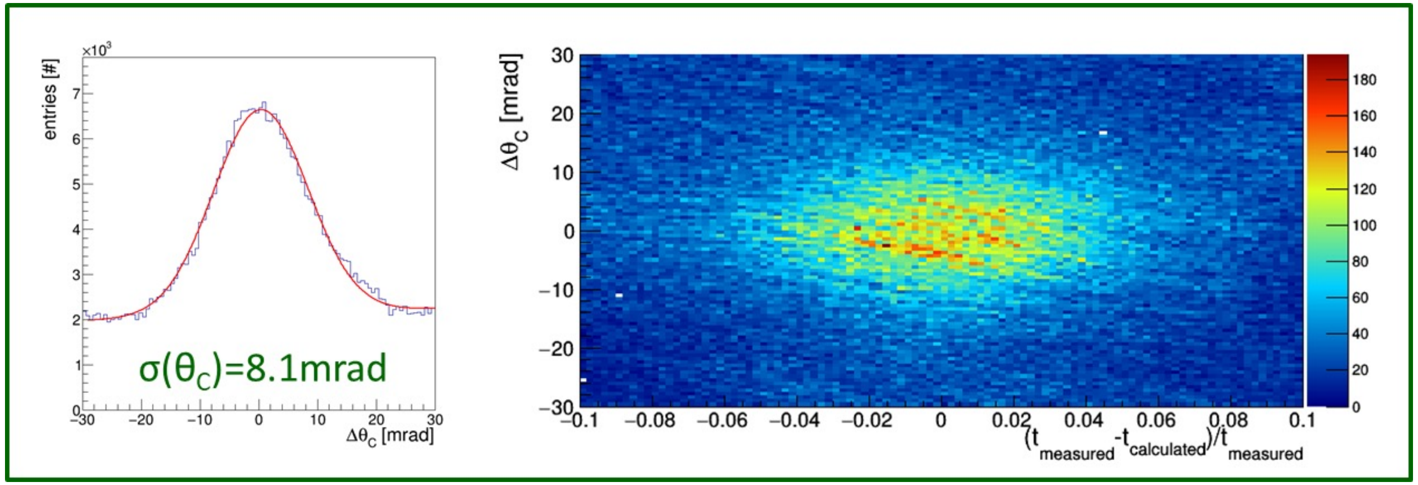
PANDA Barrel DIRC prototype at CERN PS,
7 GeV/c, mixed hadron beam, 90° polar angle

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

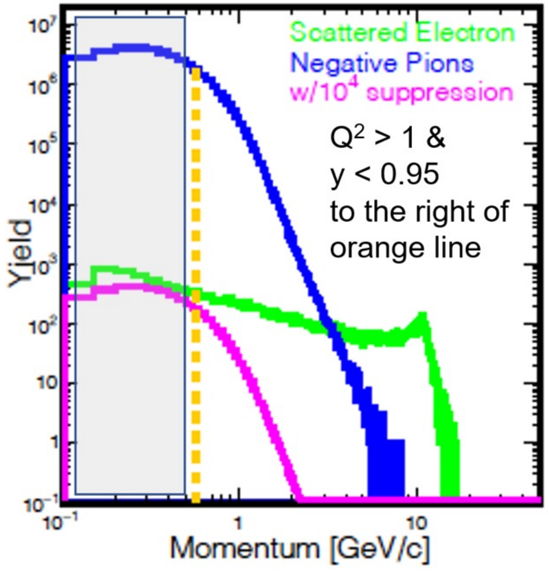
(beam test with modest timing precision (~200ps) and moderate photon path (1m-3.3m);
expect better timing, longer paths, larger correction effect for EIC hpDIRC)

EXPECTED HPDIRC PERFORMANCE

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 $\mathcal{O}(10^4)$ 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)

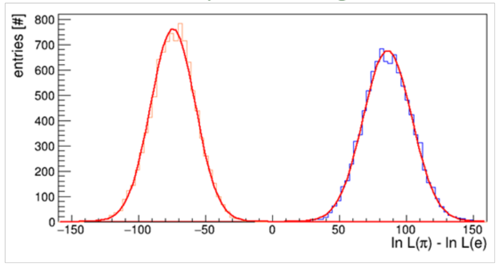
-1.0 < η < 0.0 (half of DIRC Barrel)



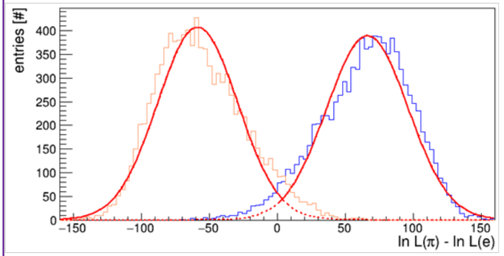
CORE simulation, B. Schmookler

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

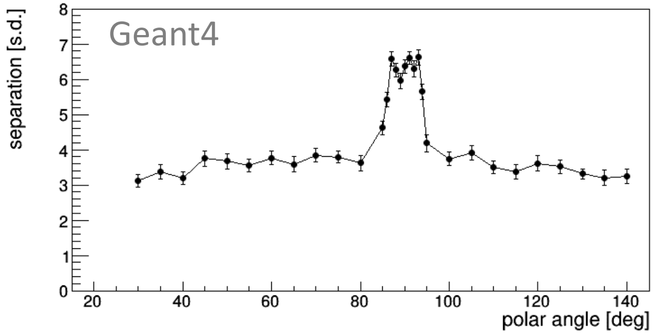
without multiple scattering: ~9 s.d.



with multiple scattering: ~4 s.d.



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



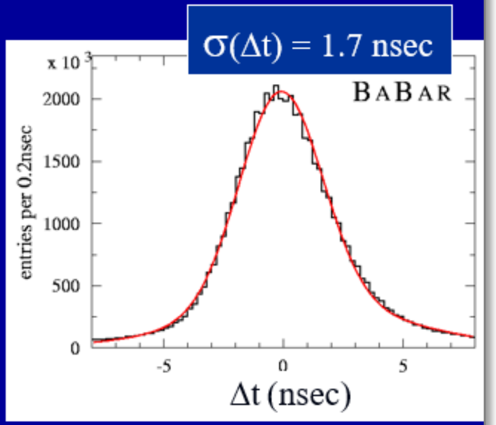
DIRC RECONSTRUCTION

Time information provides powerful tool to reject accelerator and event related background.

Calculate expected arrival time of Cherenkov photon based on

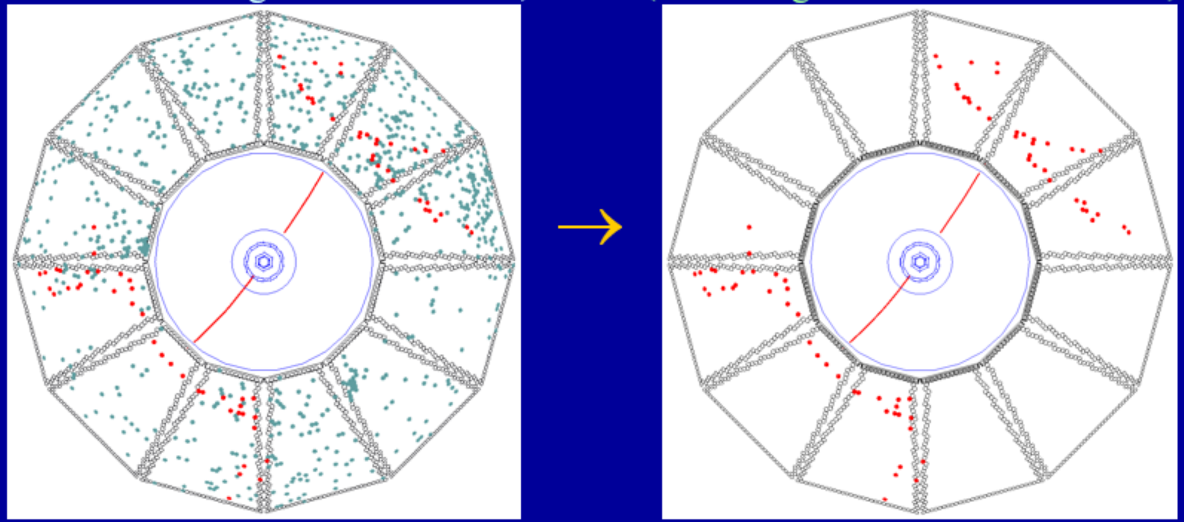
- track TOF
- photon propagation in radiator bar and in water

Δt: difference between measured and expected arrival time



± 300 nsec trigger window → ± 8 nsec Δt window

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



Fast Cherenkov Detector Workshop, Giessen, May 11-13, 2009 54 Jochen Schwiening, GSI

- Timing information not used for PID but crucial in dealing with accelerator-induced background
- Powerful DIRC timing variable: difference between measured and calculated photon arrival time
- Backgrounds from other tracks can be efficiently suppressed
- hpDIRC sensor timing factor >10 better than BaBar

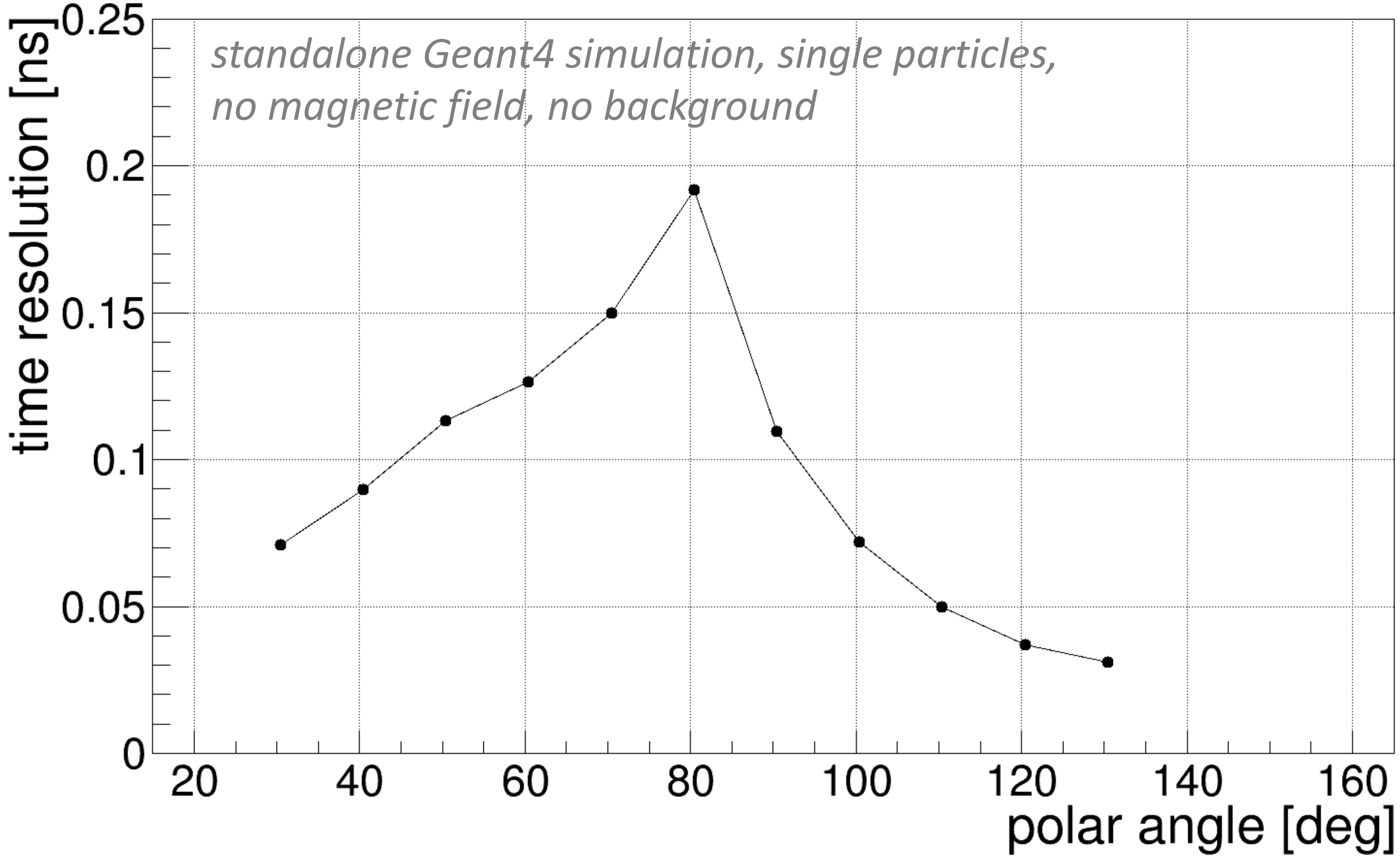
J.S., DIRC2009

HPDIRC TRACK TIME RESOLUTION

Calculate average time of Cherenkov light emission per particle

from difference between measured and calculated arrival time for each detected photon

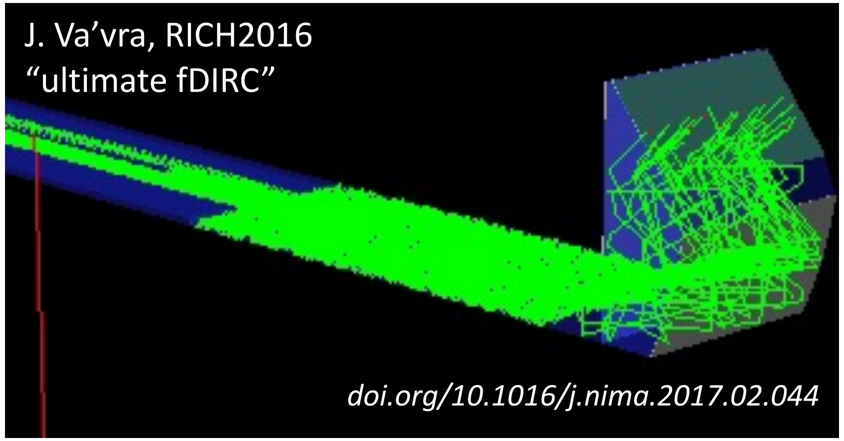
Good precision for large number of photoelectrons, can be useful as TOF "stop time" if event T_0 is known

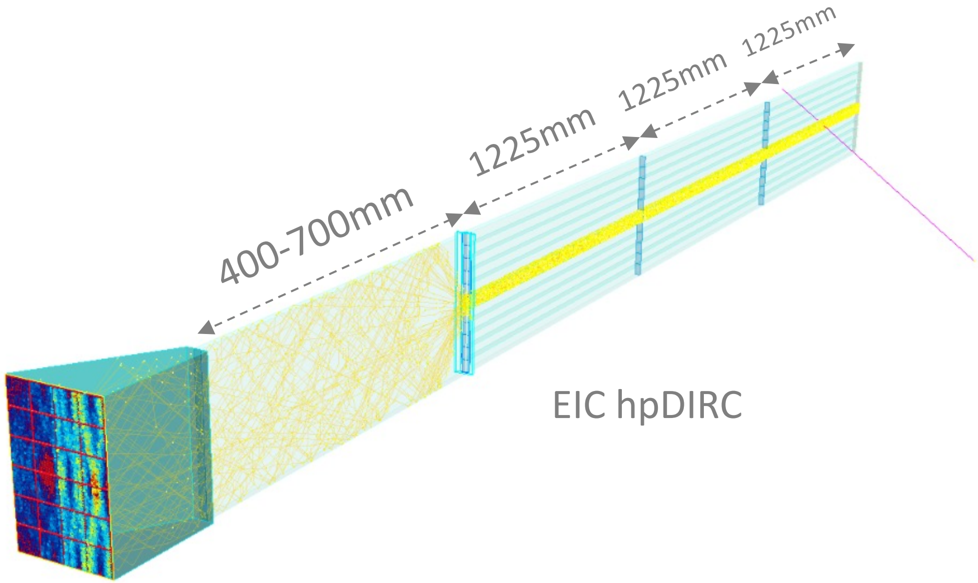


Opportunity: Cost saving and performance improvement

- EIC detector barrel length requires additional fused silica bars or plate to connect BaBar DIRC bars to prism
- Narrow bars could be obtained by cutting and repolishing BaBar DIRC bars or by ordering new bars from industry
- At RICH 2016 J. Va'vra showed the "ultimate fDIRC" concept for SuperB with then best-in-class predicted DIRC performance

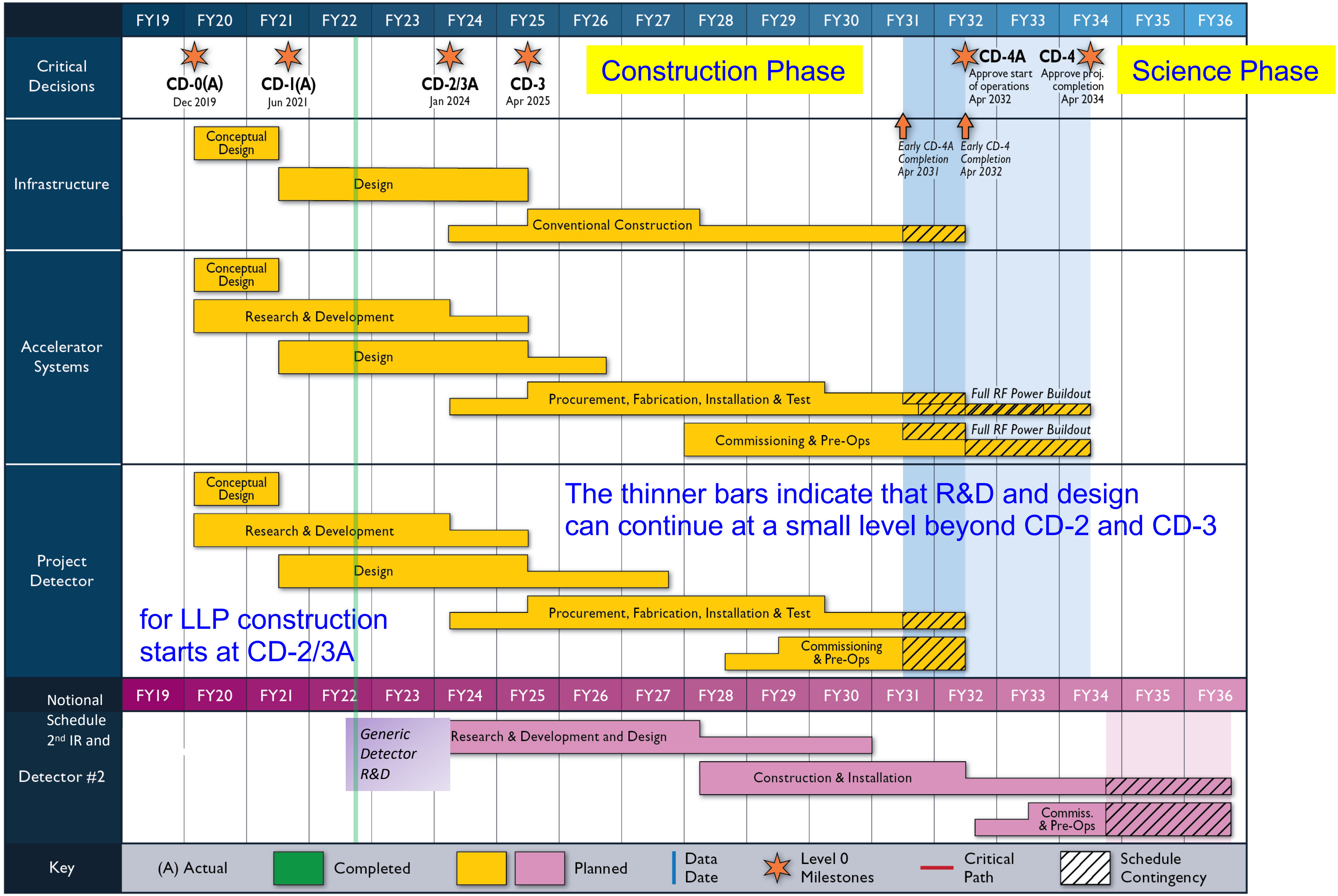
  Concept: use single short wide plate as transition light guide between BaBar DIRC bars and expansion volume
- For EIC hpDIRC design: use plate as lightguide between BaBar DIRC bars and prism, combine with lens focusing
- Would significantly reduce cost compared to new narrow bars and potentially improve hpDIRC performance



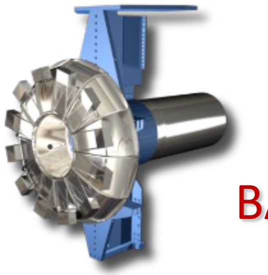


GEANT4 visualization of hybrid of bars and plate in each sector

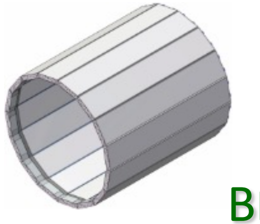
EIC Reference Schedule



BARREL DIRC OVERVIEW

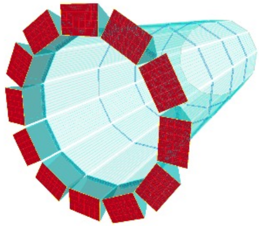


BABAR DIRC



BELLE II TOP

PANDA BARREL DIRC



EPIC HPDIRC*

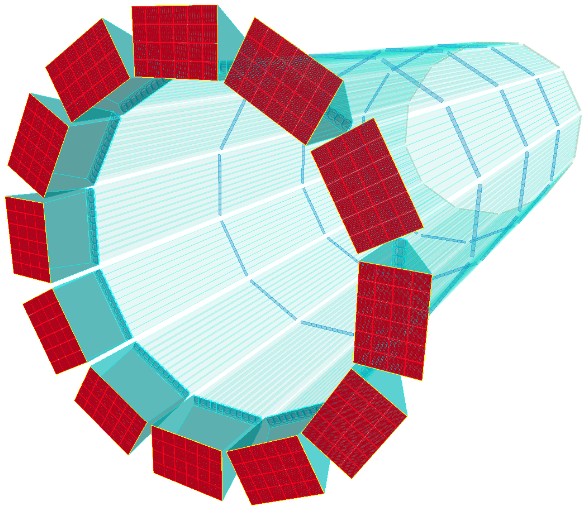
Radiator geometry	Narrow bars *(35mm)*	Wide plates *(450mm)*	Narrow bars *(53mm)*	Narrow bars *(35mm)*
Barrel radius	85cm	115cm	48cm	72cm
Bar length	490cm *(4×122.5)*	250cm *(2×125)*	240cm *(2×120)*	420cm *(3×122.5 + 1x52.5)*
Number of long bars	144 *(12×12 bars)*	16 *(16×1 plates)*	48 *(16×3 bars)*	120 *(12×10 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	~74k 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	Running (installed 2016)	Installation ~2025	TDR-ready in 2024

Preliminary design

SUMMARY & OUTLOOK

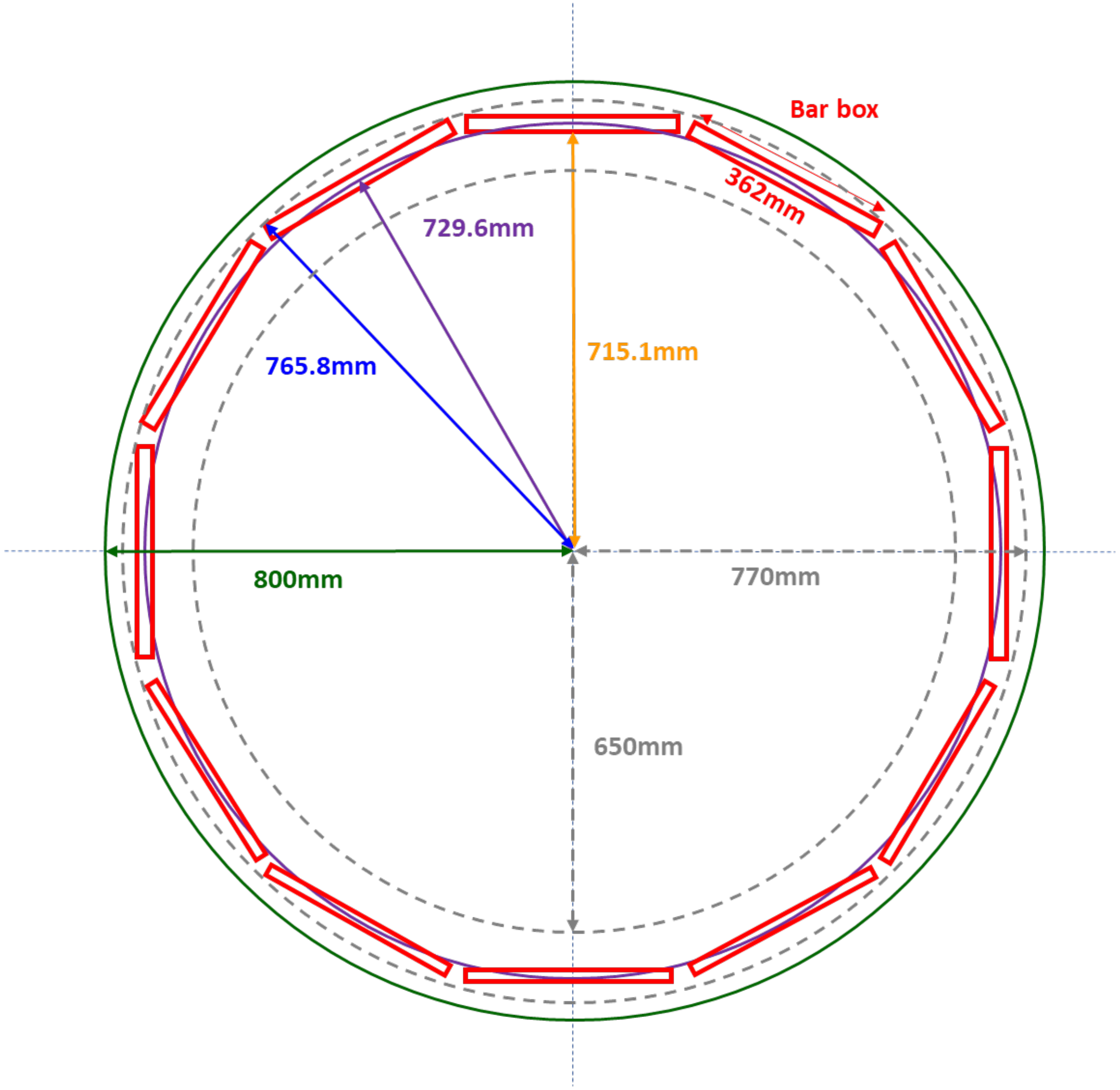
- The Electron Ion Collider is being developed on an aggressive schedule to become the next major facility for nuclear physics in the USA
- The hpDIRC was selected for the barrel PID of the EIC Detector-1 (EPIC)
- Fast focusing DIRC concept, improving on BaBar, Belle-II, PANDA, etc
- Expected PID: ≥ 3 s.d. π/K up to 6 GeV/c, ≥ 3 s.d. e/π up to ~1.2 GeV/c
- Conceptual design well-advanced (simulation and lenses validated in particle beams)
- Key elements of the hpDIRC are the novel radiation-hard, multi-layer spherical lens, small-pixel photosensors, and fast readout electronic.
- Next steps towards a TDR in 2024: design optimization, full system prototype, investigating possibility of reusing BaBar DIRC radiator bars.

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



Thank you all for your attention.

Extra Slides



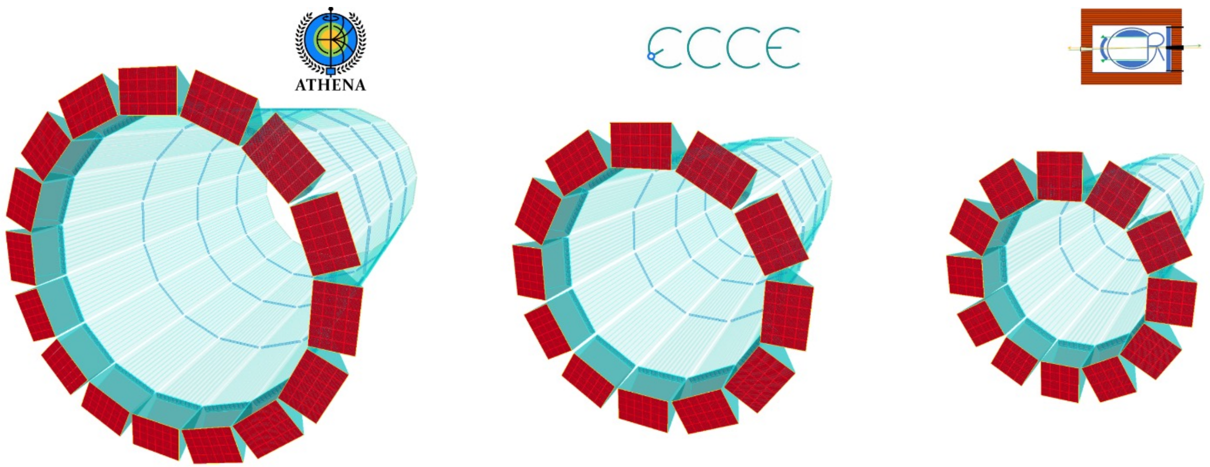
ECCE proposal hpDIRC configuration

- 10 bars side by side per bar box
- 12 bar boxes
- 20mm rib width between bar boxes
- Barbox width: 362mm
- Barbox thickness: 29mm

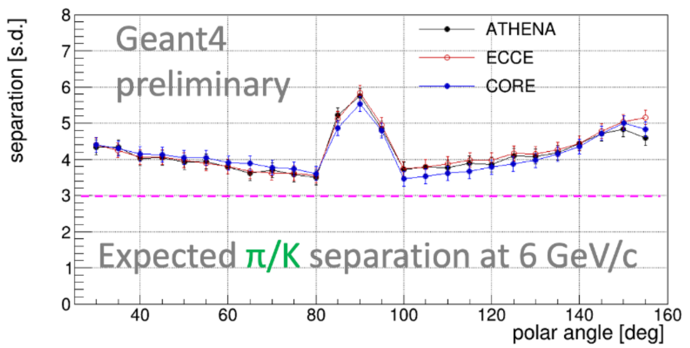
- Middle hpDIRC radius: 729.6mm
- Minimum hpDIRC radius: 715.1mm
- Maximum hpDIRC radius: 765.8mm
- hpDIRC total radial thickness 50.7mm
- Azimuthal coverage 91.6%

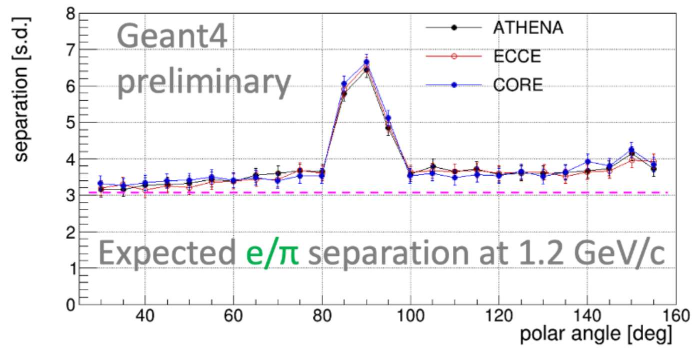
hpDIRC Simulation

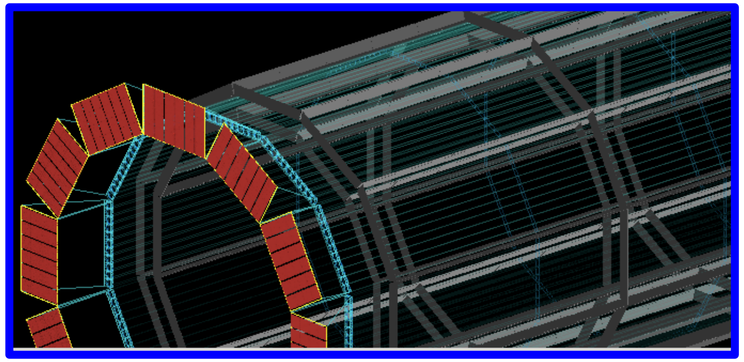
- Realistic geometry and material properties based on prototypes, with wavelength-dependent material properties and processes with all relevant resolution terms
- Performance in EIC Reference Detector simulation matches standalone simulation results
- Standalone simulation validated with test beam data results
- Performance largely independent of number of sectors, barrel radius, and bar length!



Geant4: hpDIRC designs to scale







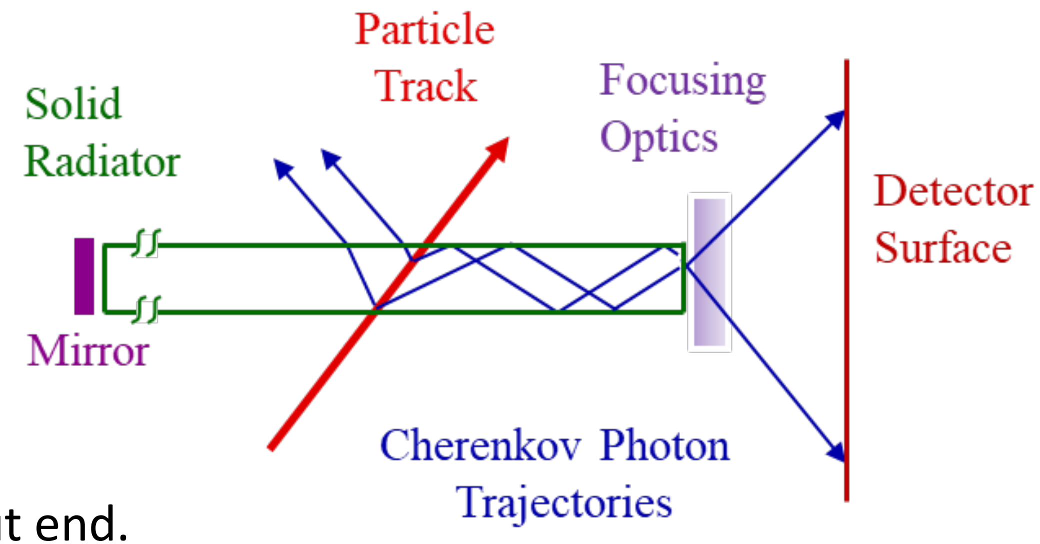
Detection of Internally Reflected Cherenkov Light

- 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

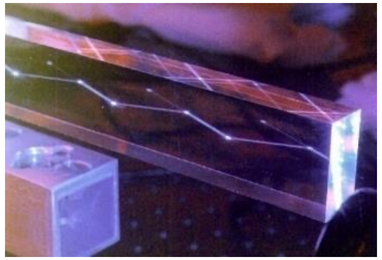
- For n>√2 some photons are always
  totally internally reflected for $\beta \approx 1$ tracks

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



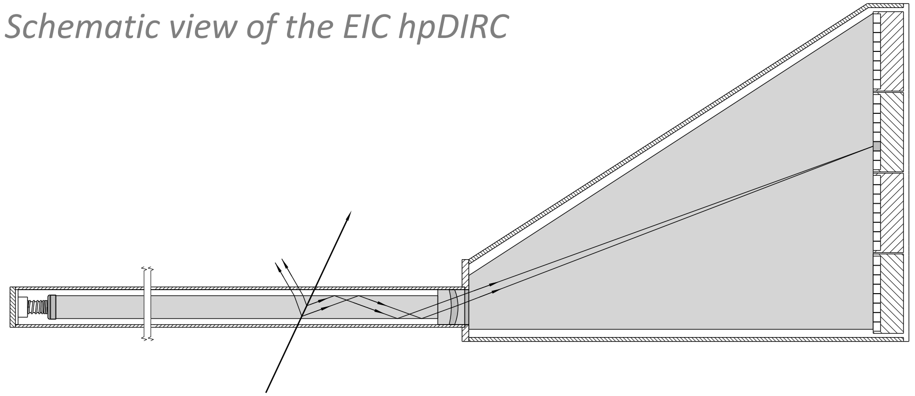
- Mirror attached to one bar end, reflects photon back to readout end.

- Photons exit radiator via optional focusing optics into expansion region,
  detected on photon detector array.



DIRC Concept

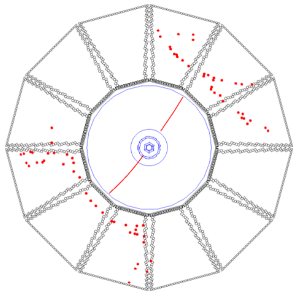
- Magnitude of Cherenkov angle conserved during many internal reflections
  (provided optical surfaces are square, parallel, highly polished)
- Quartz bar/plate/disk both radiator and light guide,
  transporting photons away from crowded central detector
  to suitable sensor location
- DIRC is intrinsically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



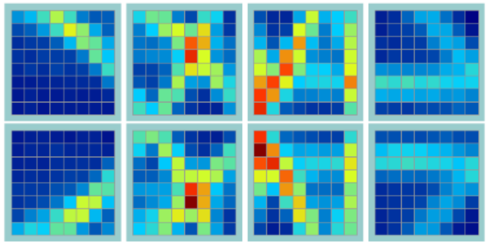
Schematic view of the EIC hpDIRC

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.



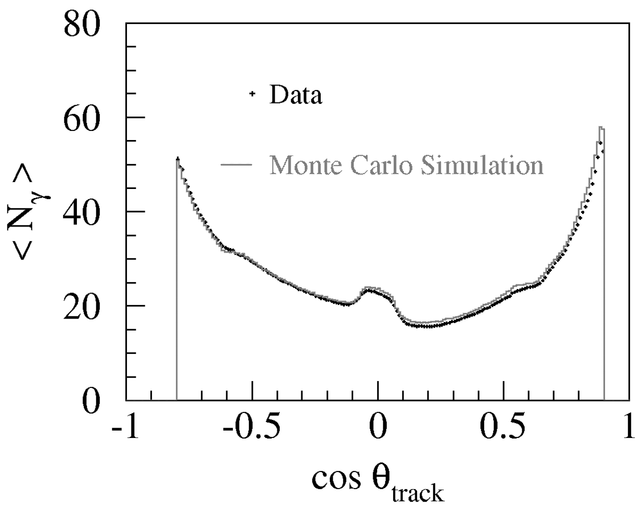
Hit pattern BABAR DIRC

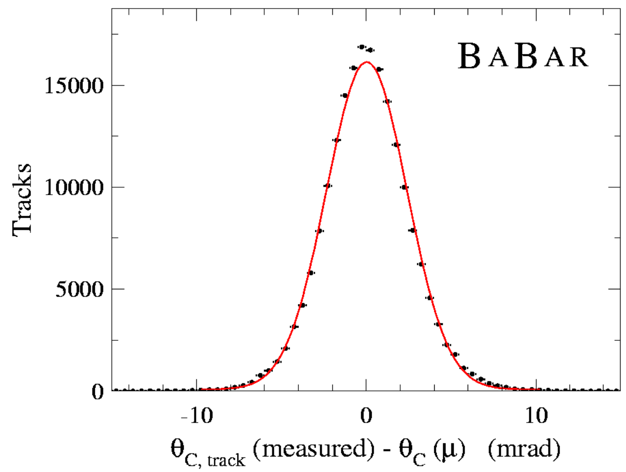


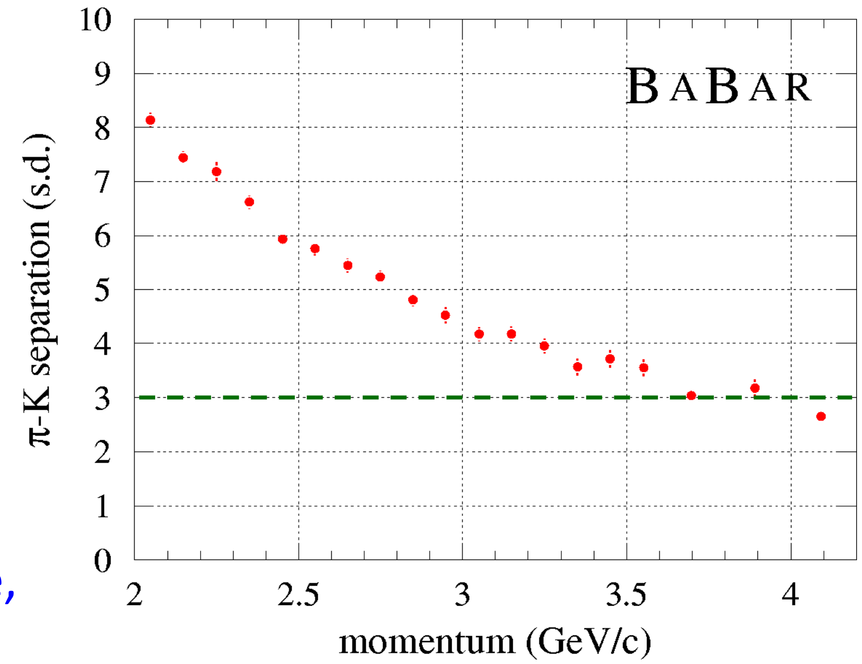
Accumulated hit pattern PANDA Barrel DIRC

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