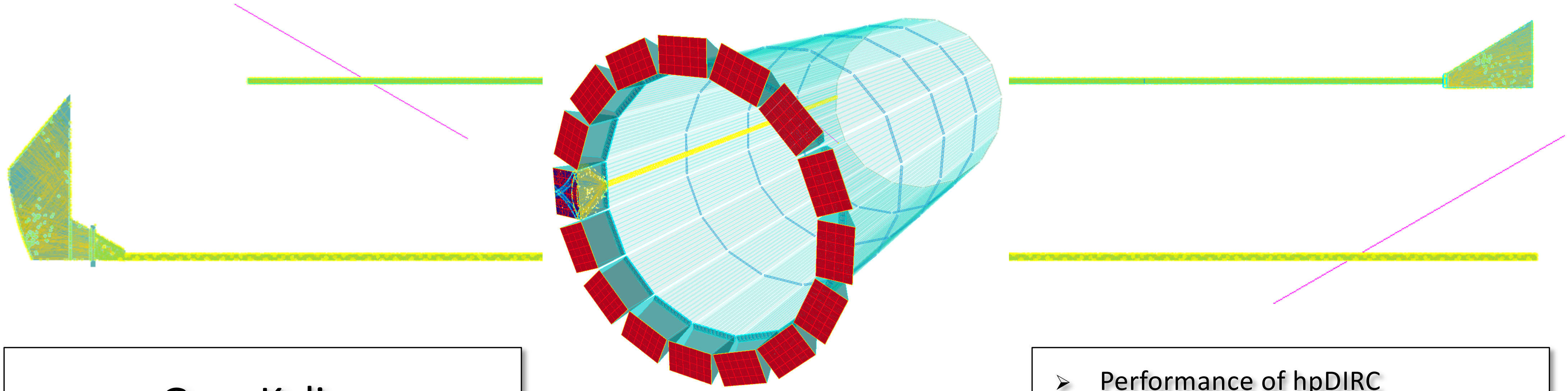
# Barrel DIRC Detectors for the EIC




Greg Kalicy

Jochen Schwiening

for the eRD14 DIRC group


- Performance of hpDIRC
- Validation of Simulation
- BaBar DIRC option
- Pro/Con of DIRC at EIC

# DIRC Resolution

*I. Adam et al., Nucl. Instr. Meth. A, 538, 2005.*

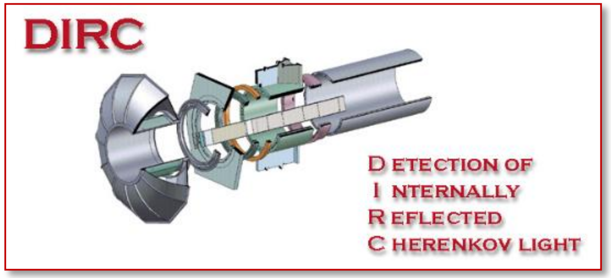
$$\sigma^2_{\theta_c}(particle) = \frac{\sigma^2_{\theta_c}(photon)}{N_\gamma} + \sigma^2_{correlated}$$

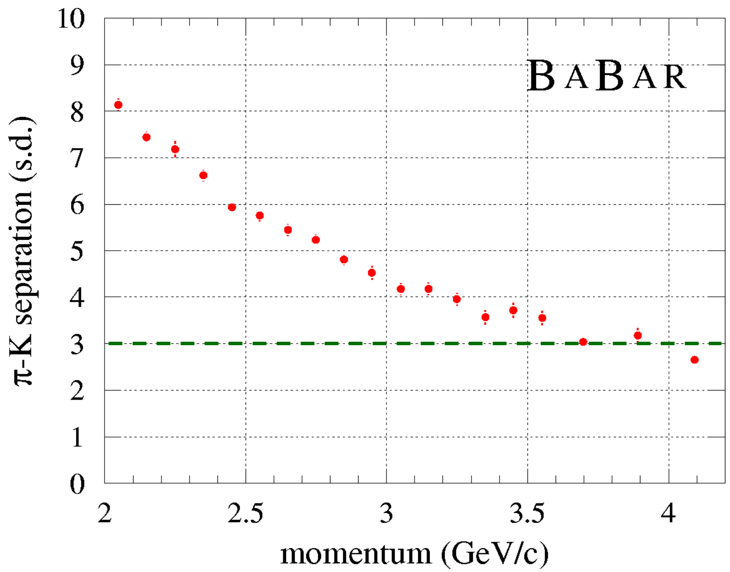
$\sigma_{\theta_c}(particle)$ Cherenkov angle resolution per particle

$\sigma_{\theta_c}(photon)$ Cherenkov angle resolution per photon
(bar size, pixel size, chromatic, bar imperfections)

$N_\gamma$ Number of detected photons per particle
(bar size, bar imperfections, Photon Detection Efficiency)

$\sigma_{correlated}$ Contribution from external sources
(tracking, multiple scattering, etc.)



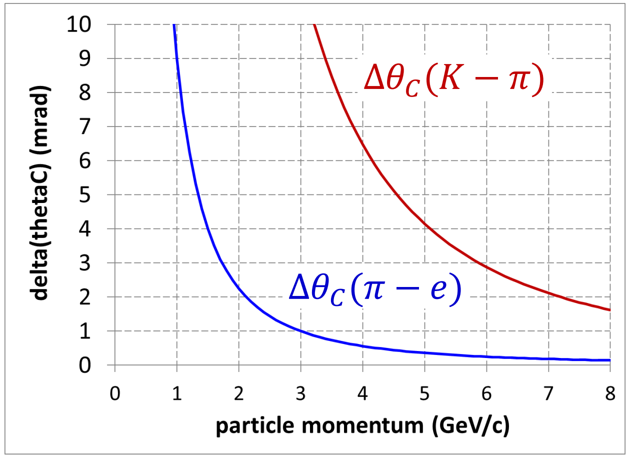




BaBar DIRC achieved 2. 4 mrad $\theta_C$ resolution at 3-4 GeV/c,

3 s.d. π/K separation at 4 GeV/c

How can we push this performance to higher momentum?

# IMPROVING ON THE BABAR DIRC




PID performance largely driven by track Cherenkov angle ($\theta_C$) resolution.

Required resolution defined by refractive index of radiator.

Example: π/K separation in synthetic fused silica <n>≈1.473

→ 2.9 mrad π/K difference in $\theta_C$ at 6 GeV/c;

→ need ~1 mrad resolution per particle for 3 s.d. separation.

Approach:

Smaller track angular error (better tracking detector)

Higher photon yield (modern sensors with better PDE)

Improve Cherenkov angle resolution per photon

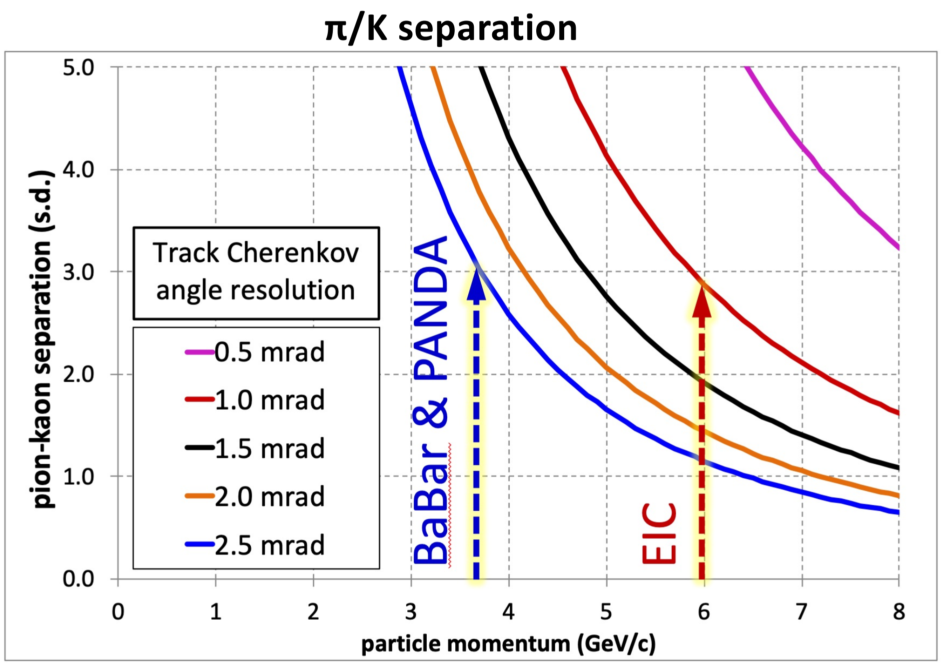
BABAR-DIRC Cherenkov angle resolution: 9.6 mrad per photon, 2.4 mrad per particle

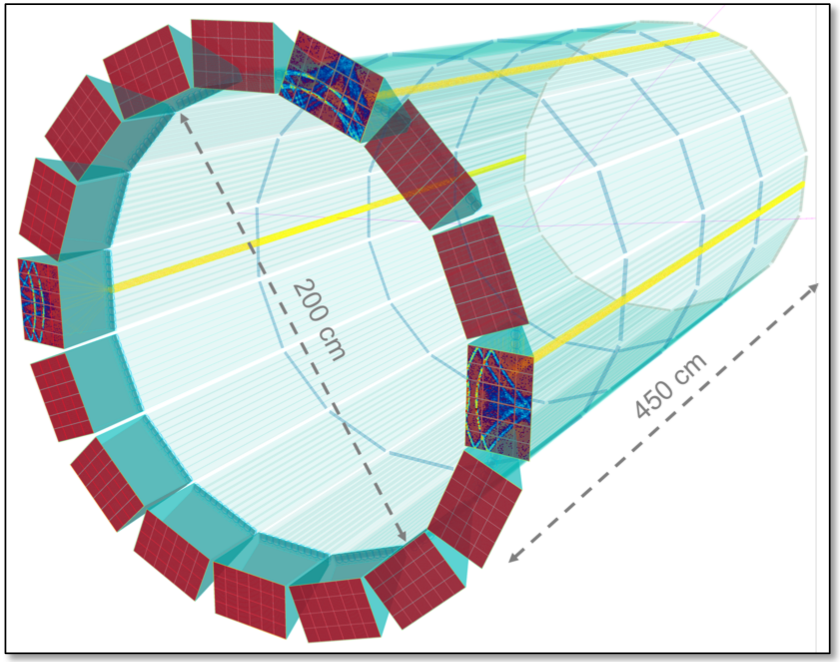
| Limited in BABAR by: | | | Improve for future DIRCs via: |
|---|---|---|---|
| ▪ size of bar image | ~4.1 mrad | → | ▪ focusing optics |
| ▪ size of PMT pixel | ~5.5 mrad | → | ▪ smaller pixel size |
| ▪ chromaticity (n=n(λ)) | ~5.4 mrad | → | ▪ better time resolution |
| | 9.6 mrad | → | 5-7 mrad per photon → 1 mrad per particle |

SUPERB, BELLE II, PANDA & EIC

# hpDIRC Performance Goal

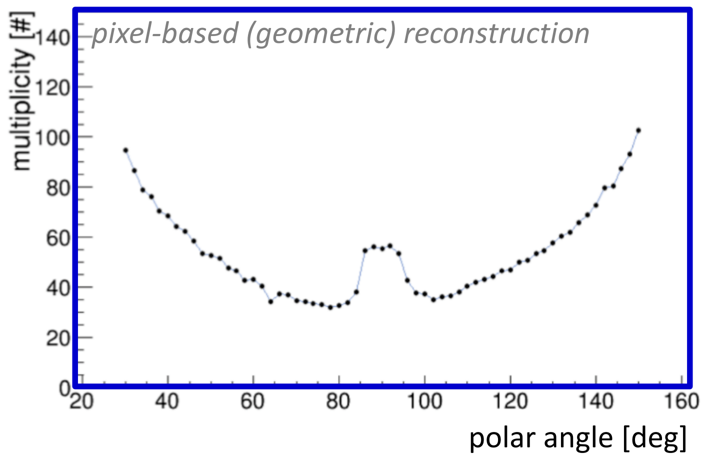
hpDIRC: a high-performance DIRC counter for radially compact hadronic PID in the barrel region of the future EIC experiments



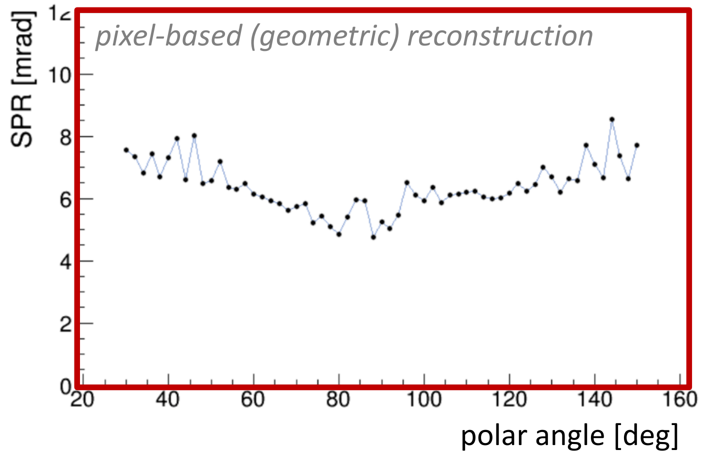



# HPDIRC PERFORMANCE IN GEANT4

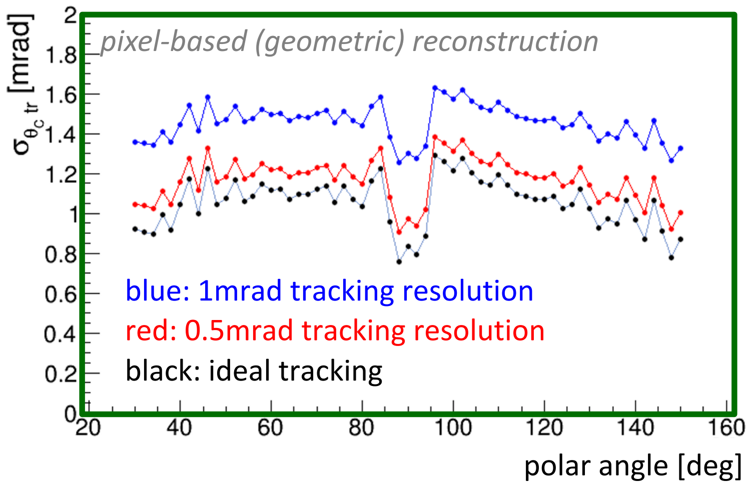
Photon yield per particle



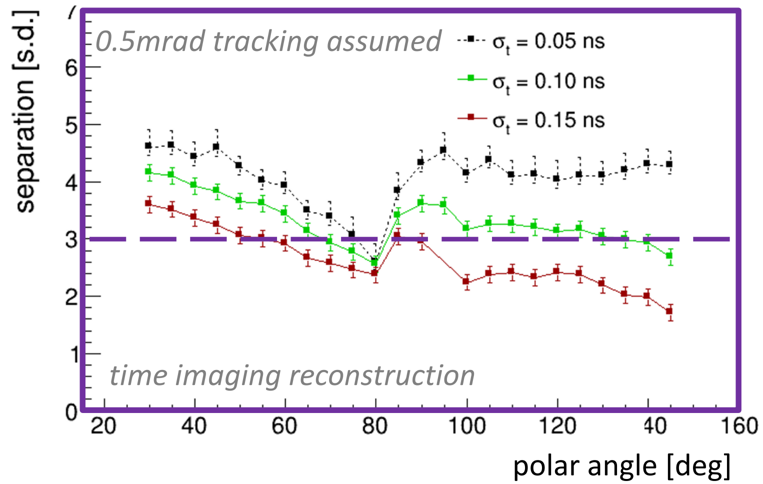

Cherenkov angle resolution per photon (SPR)




Cherenkov angle resolution angle per particle




π/K separation power at 6 GeV/c



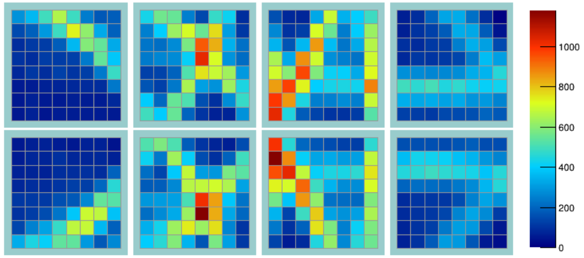
# VALIDATION OF HPDIRC SIMULATION

**PANDA Barrel DIRC prototype at CERN PS in July/Aug 2018** (reduced number of MCP-PMTs)

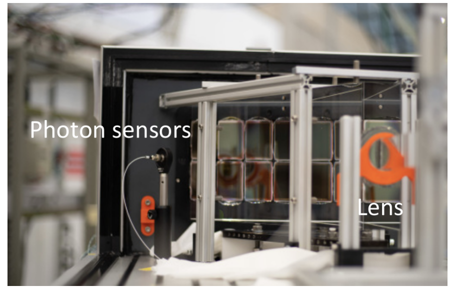
*PANDA Cherenkov Group,*
*Il Nuovo Cimento C 42 02-03*
*and JINST 15 C03055.*

- Caveat: larger sensor pixels, slower electronics than EIC DIRC
  prototype designed for PANDA goal: 3σ π/K separation @ 3.5 GeV/c
- Optics similar to EIC DIRC design:
  narrow bar, fused silica prism, 3-layer spherical lens
- Measured key quantities: **photon yield, Cherenkov angle resolution per photon and per particle, and π/K separation power – all in very good agreement with simulation** (same simulation used for EIC DIRC)

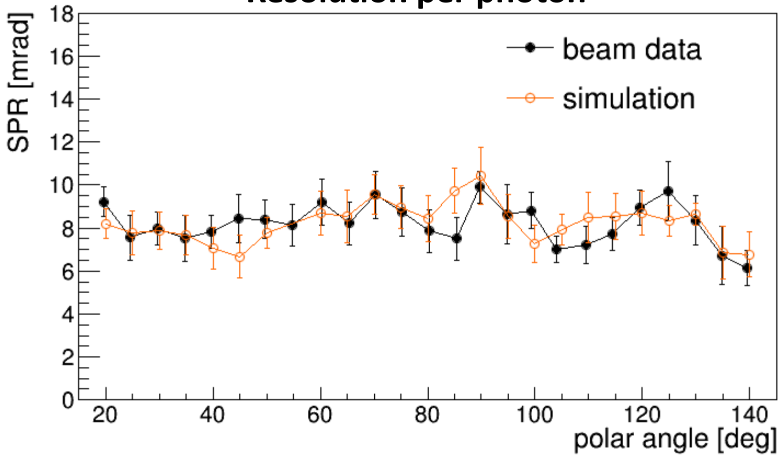
**Example of hit pattern**



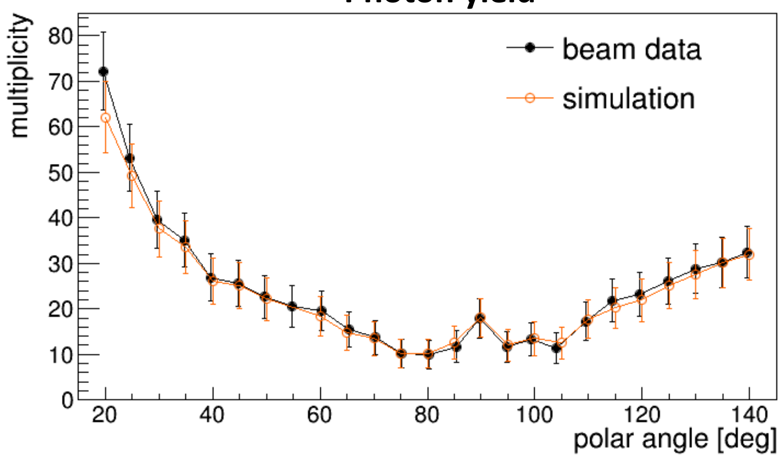

**PANDA Barrel DIRC Prototype**




**Resolution per photon**




**Photon yield**



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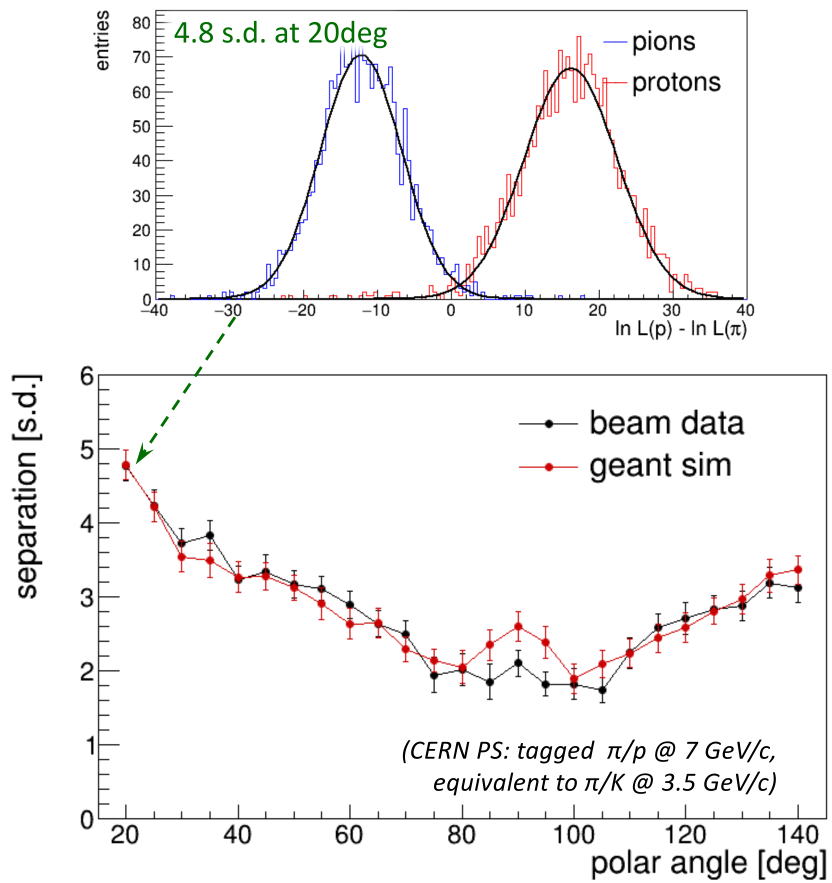
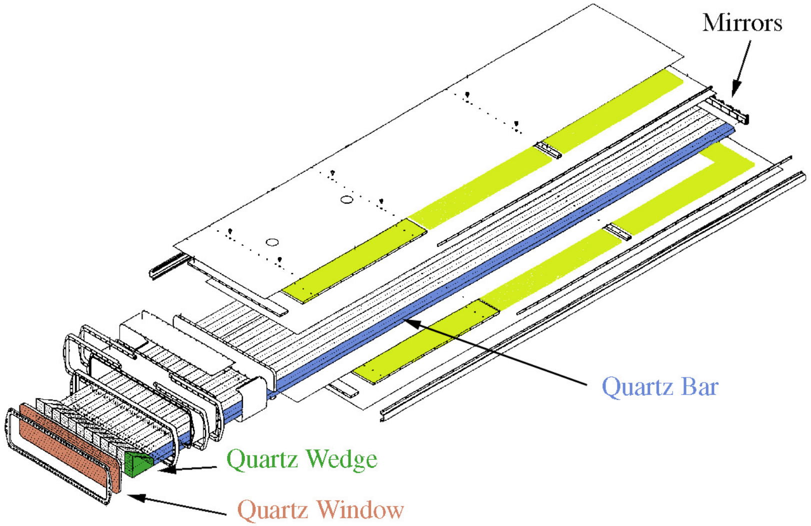
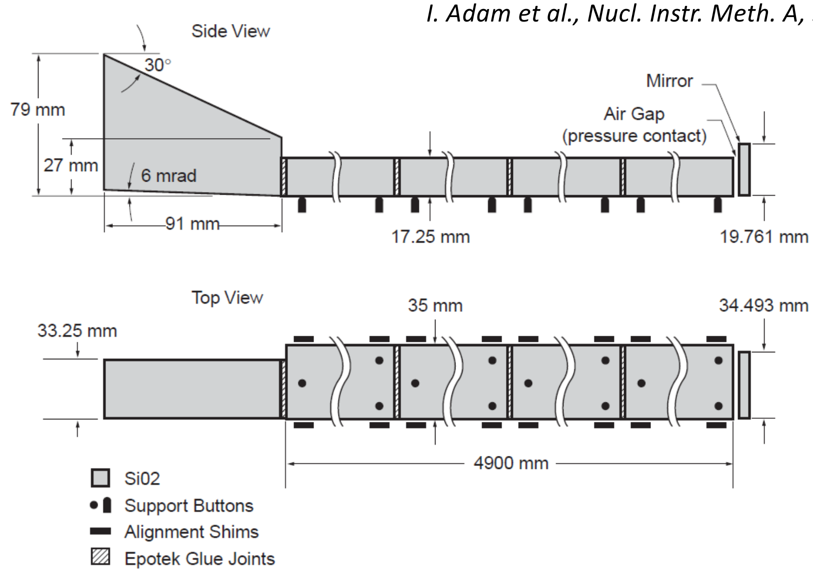
**Separation Power**



# BaBar DIRC Bar Boxes




*I. Adam et al., Nucl. Instr. Meth. A, 538, 2005.*




BaBar DIRC bars:

- 144 long bars, made of 576 short bars
- Synthetic fused silica (Spectrosil)
- 5Å *rms* polish, square, sharp corners

12 bar boxes:

- Twelve long (4.9m) bars per box
  Four short (1.225m) bars glued end-to-end
- 150µm air gap between bars
- Dry nitrogen flow

Optics:

- Mirror on forward end
- Fused silica wedge on readout end
- Fused silica window closes box on readout end
- Pinhole focusing on PMT plane

Wedge has 6 mrad angle on bottom surface,
optimized for use in BaBar,
not ideal for reuse in future experiments

*D.A. Roberts et al., "Results from the FDIRC prototype", RICH 2016 and Nucl. Instr. Meth. A, 766, 2014.*

## Focusing DIRC (FDIRC):

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

Important constraint:

Reuse of unmodified BABAR DIRC bar boxes,

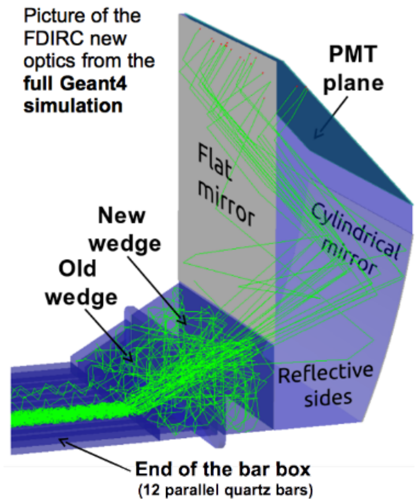
readout outside magnetic field, high accelerator backgrounds

Design based on R&D at SLAC;

new optics (replace large tank) and electronics

Complete redesign of the photon camera (SLAC-PUB-14282)

- True 3D imaging using:
  - 25× smaller volume of the photon camera
  - 10× better timing resolution to detect single photons
- Optical design based entirely on solid fused silica to avoid water or oil as optical medium
- Array of MaPMTs (H8500) for photon detection.




# BaBar DIRC option for EIC

B. Dey et al., *"Design and performance of the focusing DIRC detector", Nucl. Instr. Meth. A, 775, 2016.*

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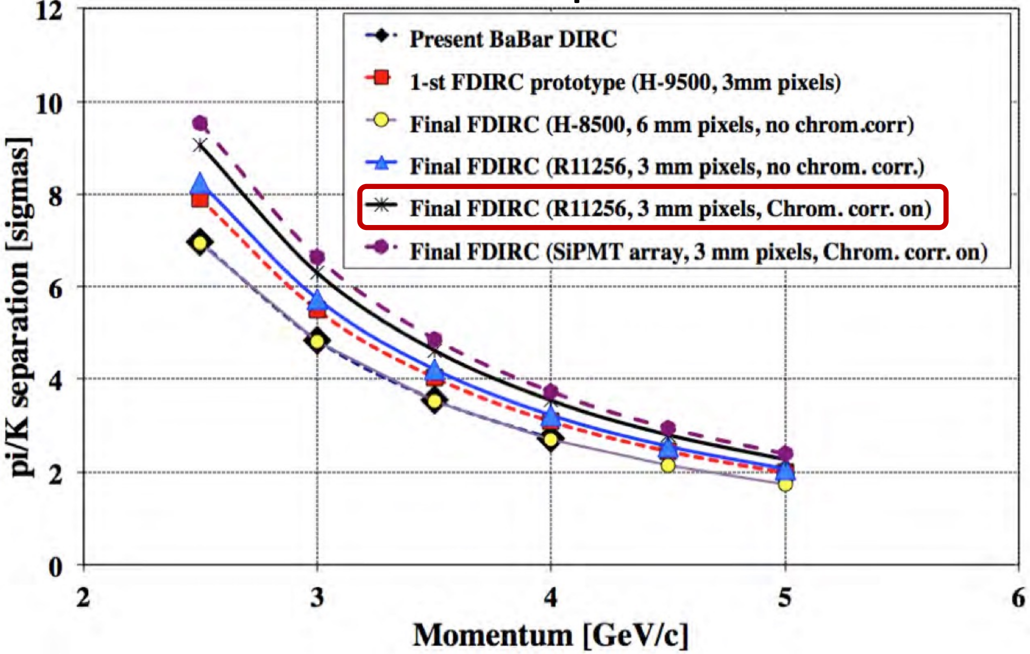
- Optical design based entirely on solid fused silica to avoid water or oil as optical medium
- Array of MaPMTs (H8500) for photon detection.

Expected performance (in SuperB): 3 s.d. π/K separation up to 4.5 GeV/c

**π/K performance of the FDIRC for various choices of sensors and pixel sizes**



# BaBar DIRC option for EIC

## GlueX DIRC:

- After cancellation of SuperB project, BaBar DIRC bars became available to other experiments, 4 boxes awarded to GlueX
- PID upgrade for GlueX experiment in Hall D at Jefferson Lab to extend physics reach.
- GlueX PID requirements similar to proven fDIRC/BaBar DIRC performance goal: **π/K separation with 3 s.d. up to ~4 GeV/c**
- Reuse unmodified bar boxes, new simplified FDIRC expansion volume design (to reduce cost)

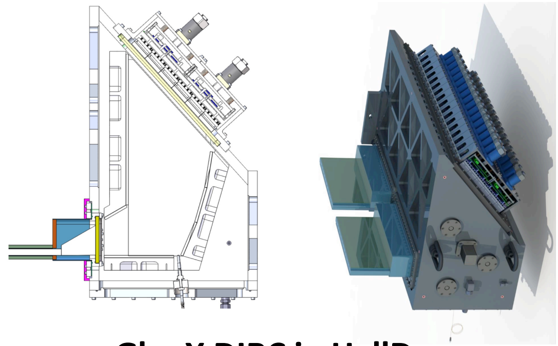
In 2017 solved major technological challenge:

how do you safely transport ~20 yr old, fragile bar boxes from SLAC to JLab without risking damage to edges or glue joints?

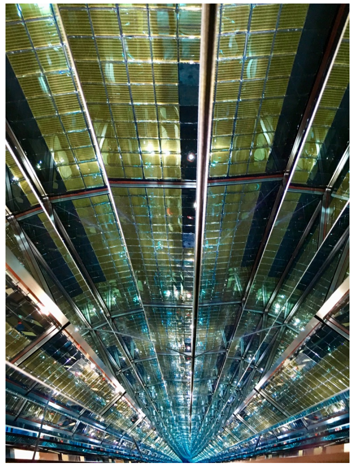
GlueX DIRC installed in late 2018, commissioned in 2019,

successfully operating in GlueX Phase-II

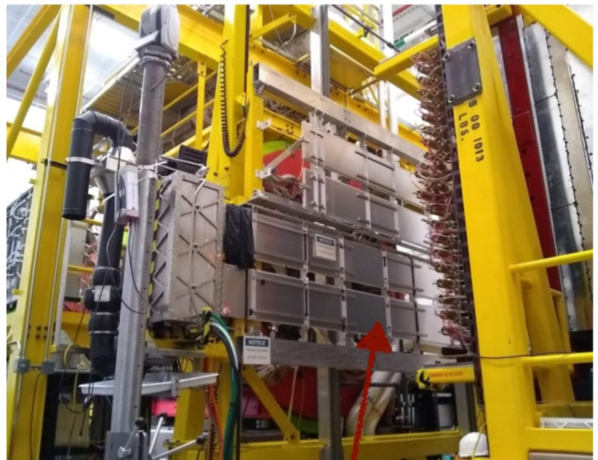
**Water-filled readout box**



**Inside readout box**



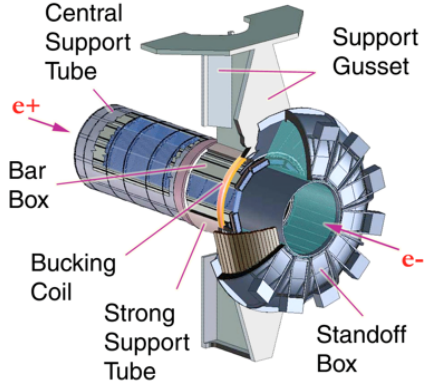
**GlueX DIRC in HallD**



**48 fused silica radiator bars installed, covering θ < 11°**

# DIRC Barbox Transportation (SLAC to JLab)

**BaBar DIRC Detector**




⇒

**DIRC Bar Box Storage at SLAC**

⇒

**On the Road in New Mexico**


⇓


**A long and very, very careful drive**

⇐

**3000 miles later at JLab**

⇐

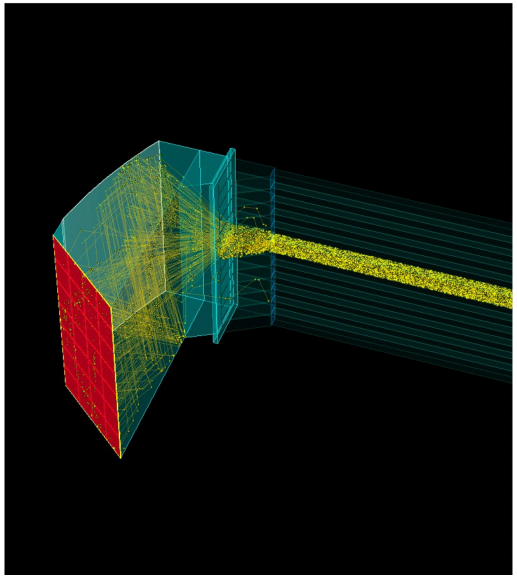
**DIRC Bar Box in Hall D**

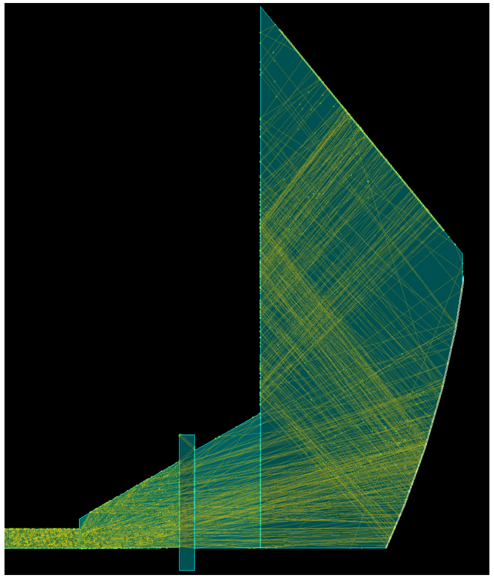
W. Li & J. Schwiening | GlueX DIRC | INSTR'20, Novosibirsk | Feb. 27, 2020 6

# SIMULATION OF THE BABAR DIRC OPTION

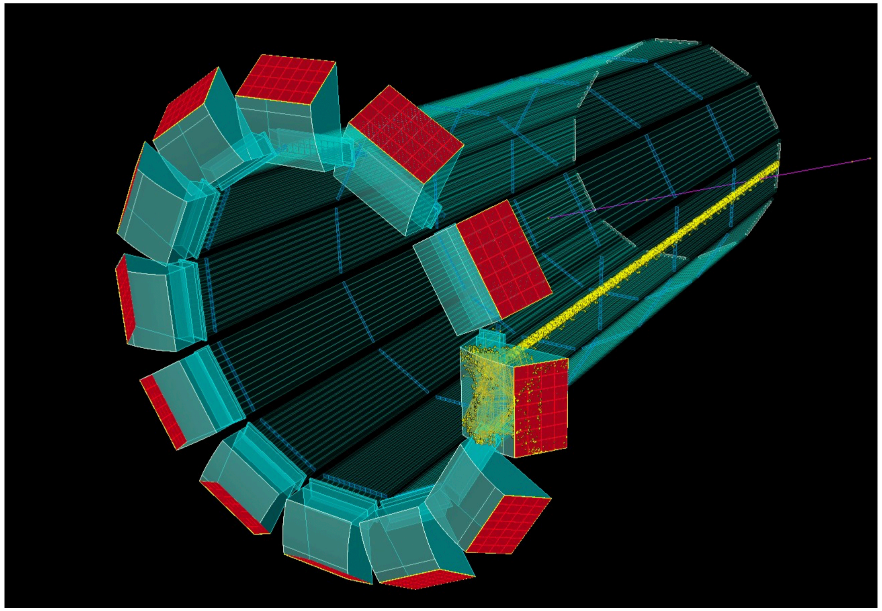
- Implemented BaBar DIRC bar box geometry and SLAC FDIRC focusing block in standalone Geant4
- Modification of reconstruction algorithm required (to deal with reflections in focusing block and impact of wedge angle)
- Expect PID performance estimate this summer

**Bar box + readout section**

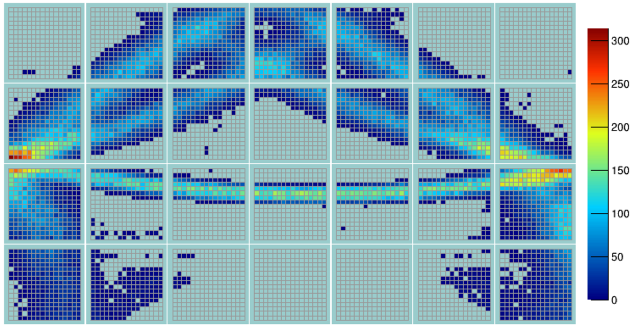




**BaBar DIRC bar boxes for EIC in Geant4**

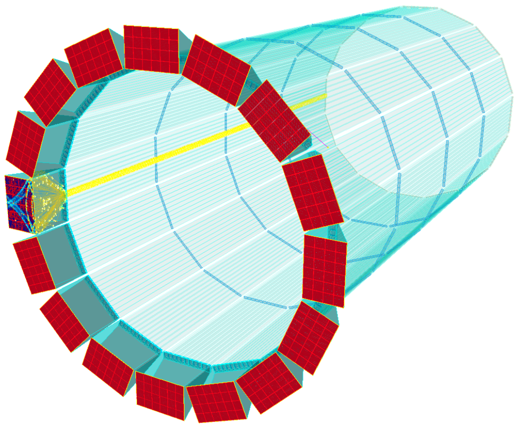


**Example of accumulated hit pattern**

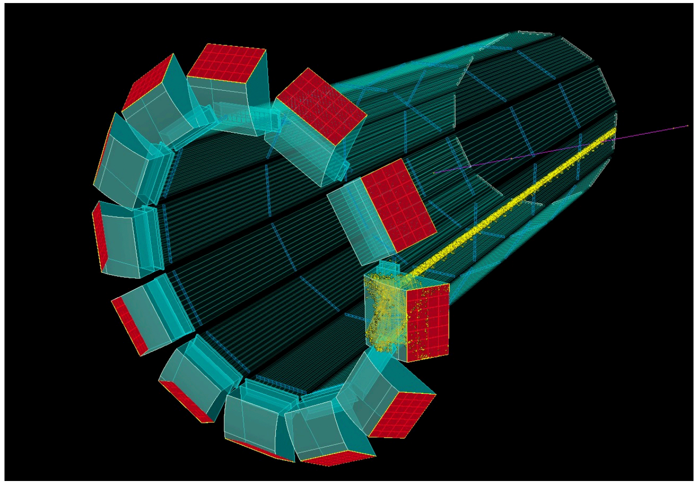


# EIC DIRC OPTIONS

**High-performance EIC DIRC**



**EIC FDIRC: reuse BaBar DIRC bar boxes**



Focusing by spherical lens

Compact prism as expansion volume

Length of bar box (3-4.8 m, 3 or 4 bars) and size of prism can be optimized for detector integration

Expect 3 s.d. π/K separation up to 6 GeV/c

Focusing by cylindrical mirror

Focusing block as expansion volume

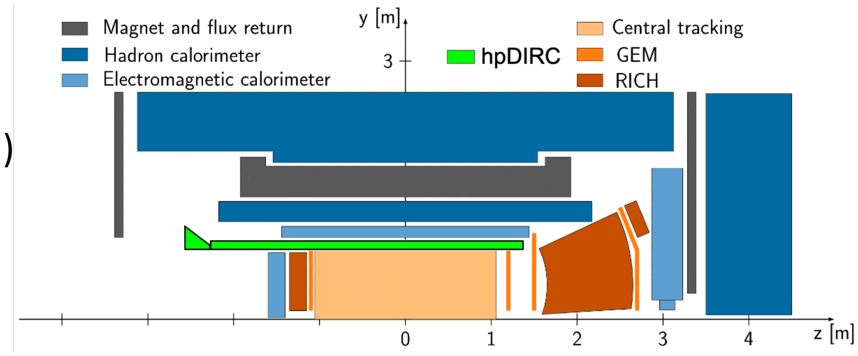
Length of bar box fixed (4.9 m, 4 bars, modification of bar box considered an unacceptable risk)

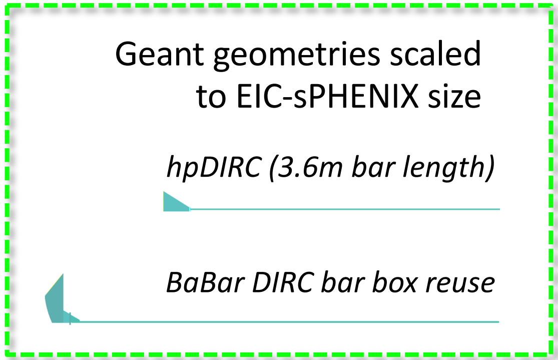
SuperB FDIRC: expect 3 s.d. π/K separation up to 4.5 GeV/c

EIC FDIRC: PID performance evaluation ongoing

# HPDIRC

- Pros:
  - **Radially compact** (impact on cost of post-DIRC systems)
  - **Flexible design** (to deal with sensor in B-field and detector integration)
  - **Low demand on detector infrastructure** (no cryogenic cooling, no flammable gases)
  - **Excellent performance over wide angular range** (≥ 3 s.d. π/K up to 6 GeV/c, contribution to low momentum e/π
  - **Supplemental time-of-flight measurement**
  - **R&D at advanced stage** (PID performance estimate based on test beam results, excellent agreement between simulation and prototype data)

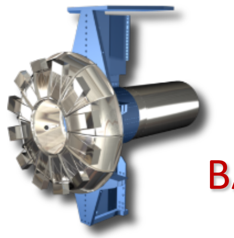


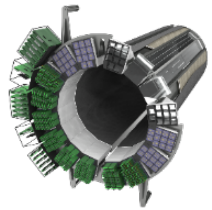



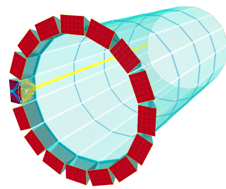

- Cons:
  - Potential challenge of integrating expansion volume, in particular for BaBar DIRC design (focusing block and sensors outside flux return?)
  - No currently proven sensor solution for 3 T magnetic field option

# EXTRA SLIDES

# Barrel DIRC Counters



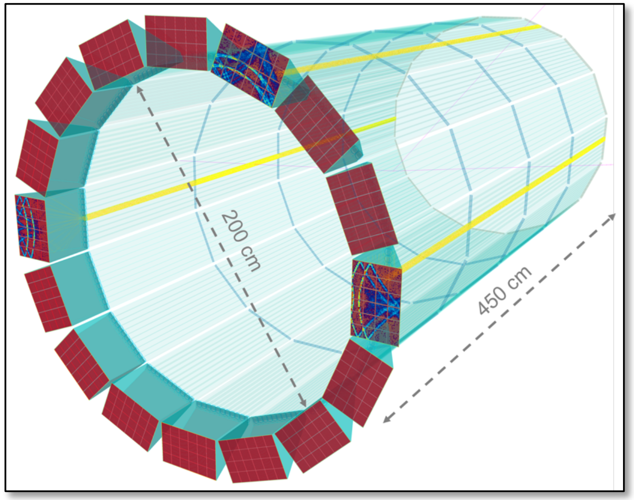




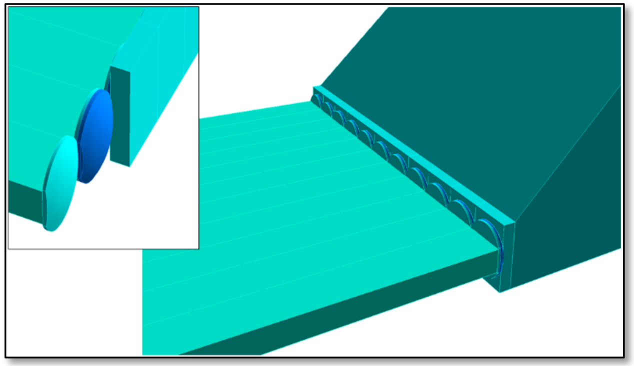
| | BaBar DIRC | PANDA Barrel DIRC | EIC hpDIRC |
|---|---|---|---|
| Radiator geometry | Narrow bars *(35mm)* | Narrow bars *(53mm)* | Narrow bars *(32mm)* |
| Barrel radius | 85cm | 48cm | 100cm |
| Bar length | 490cm *(4×122.5cm)* | 240cm *(2×120cm)* | 420cm *(4×105cm)* |
| Number of long bars | 144 *(12×12 bars)* | 48 *(16×3 bars)* | 176 *(16×11 bars)* |
| Expansion volume | 110cm, ultrapure water | 30cm, fused silica | 30cm, fused silica |
| Focusing | None (pinhole) | Spherical lens system | Spherical lens system |
| Photodetector | ~11k PMTs | ~11k MCP-PMT pixels | ~100k MCP-PMT pixels |
| Timing resolution | ~1.5ns | ~0.1ns | ~0.1ns |
| Pixel size | 25mm diameter | 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 3.5 GeV/c | 3 s.d. π/K to 6 GeV/c |
| Timeline | 1999 - 2008 | Installation 2023/24 | TDR-ready in 2023 |

## Concept: fast focusing DIRC

Inspired by design elements from BaBar, SuperB, Belle II, and PANDA




- Generic reference design: 1m barrel radius, 16 sectors
- 176 radiator bars (11 per sector), synthetic fused silica,
  17mm (T) × 32mm (W) × 4200mm (L)
- Focusing optics: innovative radiation-hard 3-layer spherical lens
- Compact photon camera:
  30cm-deep solid fused silica prisms as expansion volumes
  Lifetime-enhanced MCP-PMTs with 3x3mm$^2$ pixels
  Fast readout electronics (~100,000 channels , <100ps single photon timing)
- Expected performance (Geant4 simulation):
  30-100 detected photons per particle,
  ≥ 3 s.d. π/K separation at 6 GeV/c

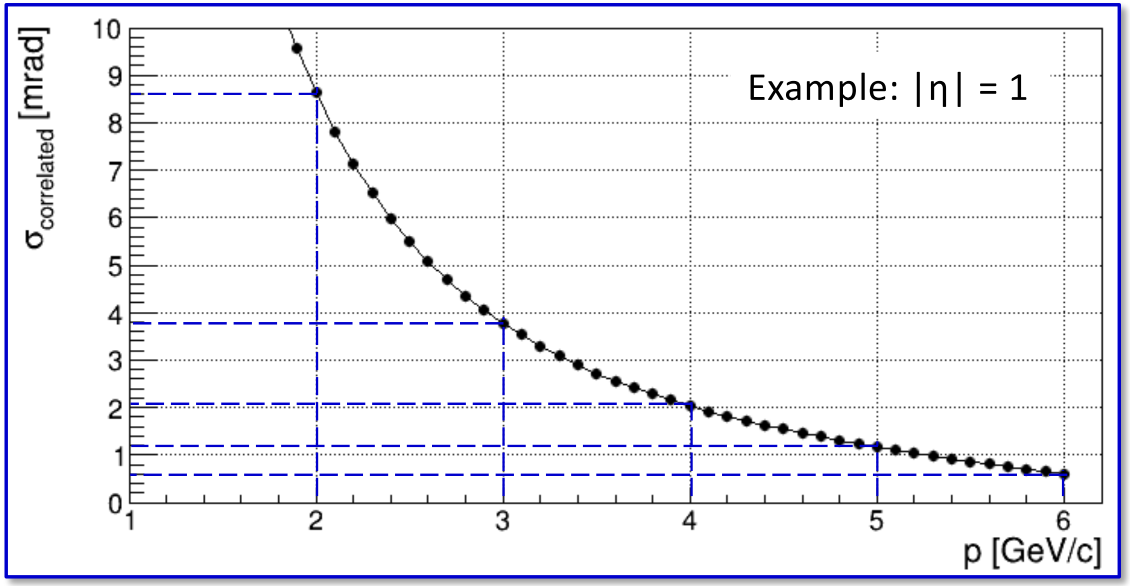


# hpDIRC Resolution – External Requirements

$$\sigma_{\theta_c}^2(particle) = \sigma_{\theta_c}^2(photon) / N_\gamma + \sigma_{correlated}^2$$

| | |
|---|---|
| $\sigma_{\theta_c}(particle)$ | Cherenkov angle resolution per particle |
| $\sigma_{\theta_c}(photon)$ | Cherenkov angle resolution per photon |
| $N_\gamma$ | Number of detected photons per particle |
| $\sigma_{correlated}$ | Contribution from external sources (tracking, multiple scattering, etc.) |

*Maximum allowed contribution from correlated term while keeping hpDIRC π/K separation power at 3 s.d.*



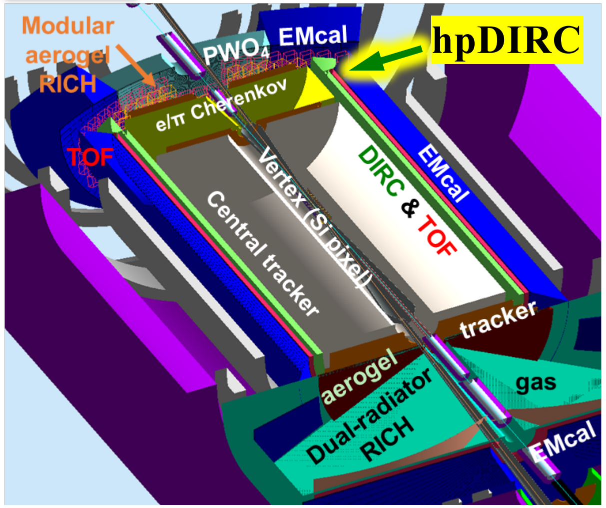
# DIRC External Requirements

| | |
|---|---|
| **Tracking** | |
| *Angular resolution (at DIRC radius)* | σ = 0.5 mrad at high momentum (for hpDIRC) |
| *Position resolution (at DIRC radius)* | Few mm |
| *Momentum resolution (at DIRC radius)* | Not very sensitive, post-DIRC track point(s) beneficial (non-Gaussian tails) |
| **Magnetic Field** | No specific B-field value assumed in simulation/reconstruction<br>Favor 1.5 T solenoid field to match currently available MCP-PMTs |
| **Space Requirement** | *(Note: generic simulation, not matched to any particular detector yet)* |
| *Radius* | 100 cm (hpDIRC, standalone Geant4 simulation)<br>83.65 cm (BaBar DIRC bar box reuse) |
| *Radial thickness (in active region)* | 7-8 cm, including mechanical support |
| *Total length*<br>*(bars plus expansion volume)* | 330-450 cm (hpDIRC, depending on detector framework)<br>530 cm (BaBar DIRC bar box reuse) |
| *Material budget (in active region)* | ~16-18% of a radiation length at normal incidence |
| *Expansion volume size* | 24 x 36 x 30 $cm^3$ (H x W x L) fused silica prism (hpDIRC)<br>56 x 42 x 22 $cm^3$ (H x W x L) fused silica block (FDIRC, to be optimized) |

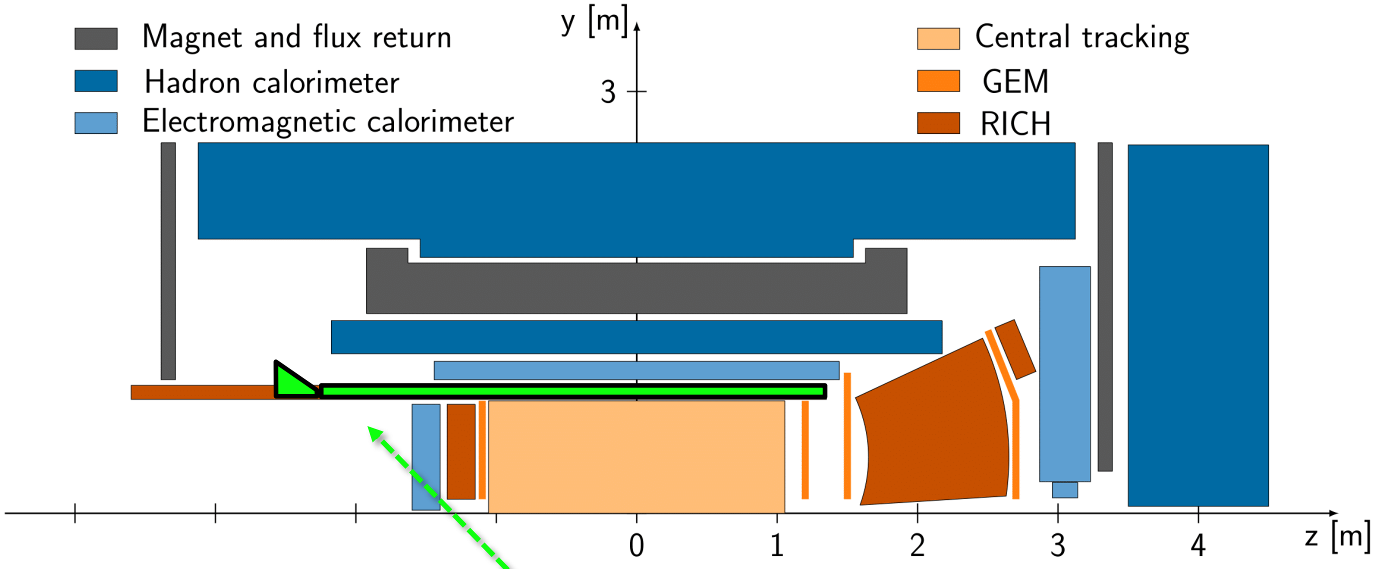
# DIRC Integration

Potential DIRC integration examples

JLEIC

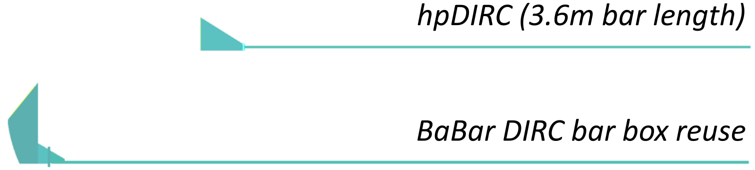



Day-one detector based on sPHENIX, 2018 LoI layout




DIRC expansion volume (prism or focusing block and sensors) can be located outside EM calorimeter barrel acceptance *(depending on bar length)*

Geant geometries scaled to EIC-sPHENIX drawing



# DIRC Simulation Assumptions

| | |
|---|---|
| **Bar Material** | Synthetic fused silica, polished to 0.5 nm *rms* surface roughness, transmission and reflection coefficient based on PANDA DIRC bar measurements |
| **Bar Dimension** | Current simulation uses 1.7 x 3.2 $cm^2$ bar cross-section (to be optimized) for hpDIRC and 1.7 x 3.5 $cm^2$ for the BaBar DIRC bar box reuse<br>(Plate and hybrid geometry options to be studied for hpDIRC.) |
| **Focusing System** | 3-layer spherical lens (hpDIRC), optical properties based on tested prototypes |
| **Mirror** | Front-coated mirror, reflectivity based on BaBar DIRC mirror measurement |
| **Glue** | Epotek 301-2, transmission based on BaBar DIRC measurements |
| **Optical Cookies** | RTV, transmission based on GlueX DIRC measurements |
| **Sensors** | MCP-PMTs, 3 x 3 $mm^2$ pixel size, CE/QE/PDE based on PANDA DIRC measurements |
| **Mechanical System** | All DIRC components made from aluminum alloy or CFRP (PANDA DIRC) |
| **Readout Electronics** | Assume 100 ps timing precision per photon (sensor, electronics, synchronization)<br>Readout boards and cables not included in Geant simulation |
| **Background** | Random dark noise background, based on PANDA DIRC measurements |
| **Tracking** | 0.5 mrad polar angle resolution, no post-DIRC tracking assumed |
| **Particle Generation** | Standalone Geant4, single tracks, no magnetic field |