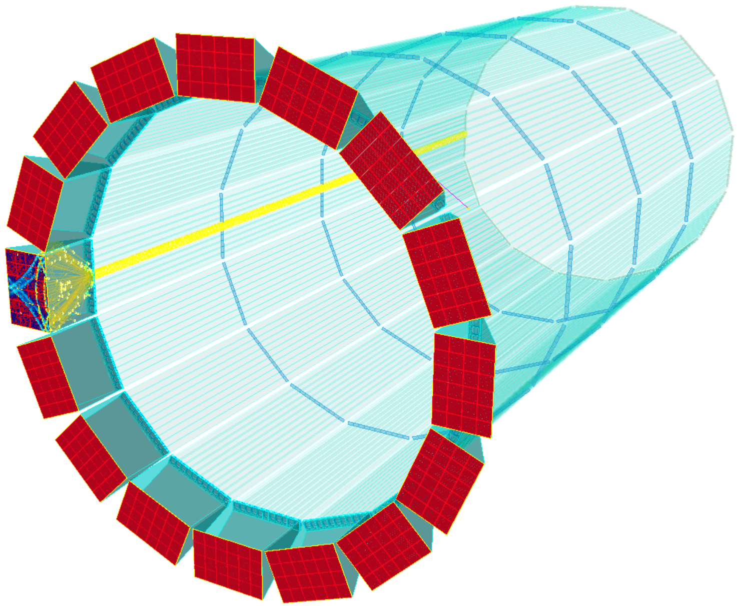
Development of a Novel Readout Concept for an EIC DIRC

Generic R&D for EIC



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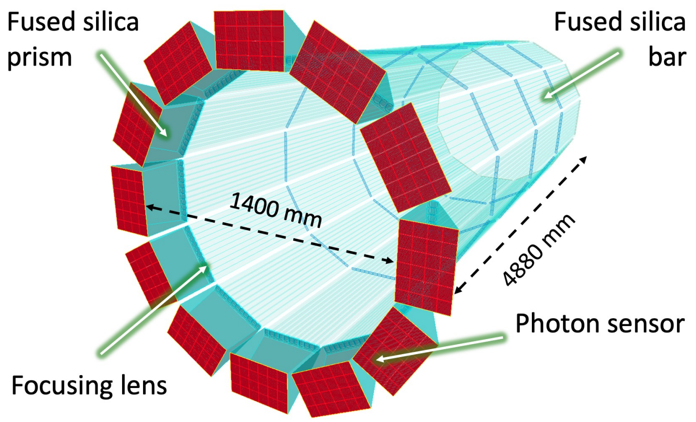
Brookhaven National Laboratory, CUA, GSI, Jefferson Lab, Old Dominion University, University of South Carolina, Stony Brook University, William & Mary

hpDIRC Concept

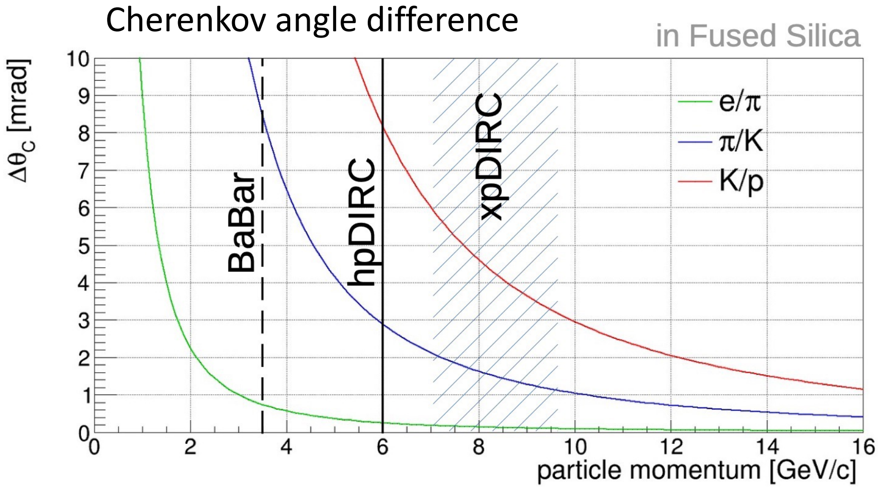
hpDIRC R&D programs

- Concept developed as part of previous Generic R&D program (eRD14)
- Validating components in CRT as part of Project R&D (eRD103)
- Developing novel optical DIRC configurations (xpDIRC) in new Generic R&D program



hpDIRC Concept:

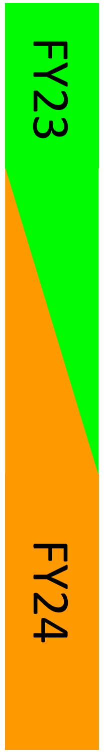
- Fast focusing DIRC, utilizing high-resolution 3D (x,y,t) reconstruction
- Design based on BaBar DIRC, R&D for SuperB FDIRC, PANDA Barrel DIRC
- Radiator/light guide: narrow fused silica bars (radius/length flexible)
- Innovative 3-layer spherical lenses
- Compact fused silica prisms as expansion volumes
- Fast photon detection: small-pixel MCP-PMTs and high-density readout electronics
- Detailed Geant4 simulation: ≥ 3 s.d. π/K separation at 6 GeV/c,
  ≥ 3 s.d. e/π separation at 1.2 GeV/c

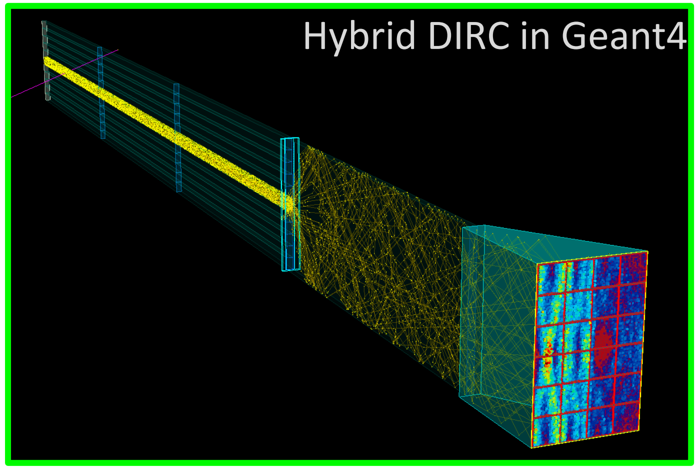


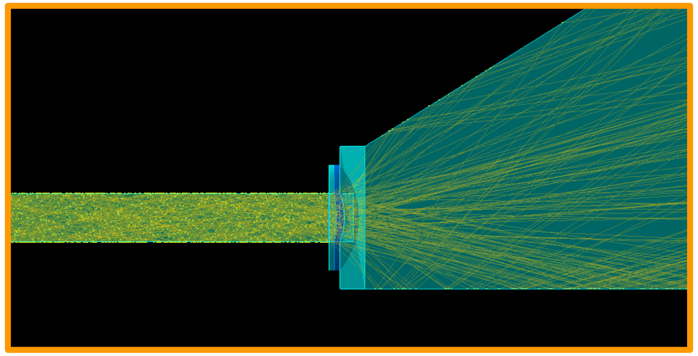
OUTLINE

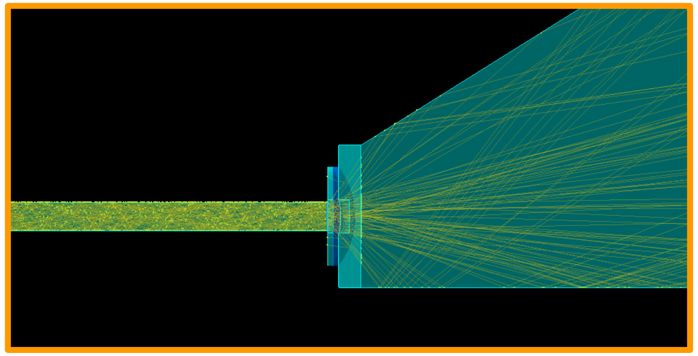
Objective: Explore innovate optical DIRC configurations to create opportunities for material budget and cost reduction, improve performance

- ➢ Investigating theoretical limits of next-generation DIRC detector performance (done)
- ➢ Initial study of novel hybrid geometry (done, optimization in FY24)
  - ➢ Cost reduction
  - ➢ Performance improvement
  - ➢ Potential use of SiPM
- ➢ Thinner bars for low-mass DIRC (very preliminary study in FY23, continuation in FY24)
  - ➢ Reduce impact of DIRC material on EMCal
  - ➢ Improve DIRC e/π performance at low momentum
- ➢ Deliverables and budget









Baseline hpDIRC Design for ePIC

- Radiator bars:
  - Size: 4580mm x 35mm x 17mm (L x W x T)
  - Barrel: 715mm radius, 12 bar boxes, 10 long bars per bar box

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

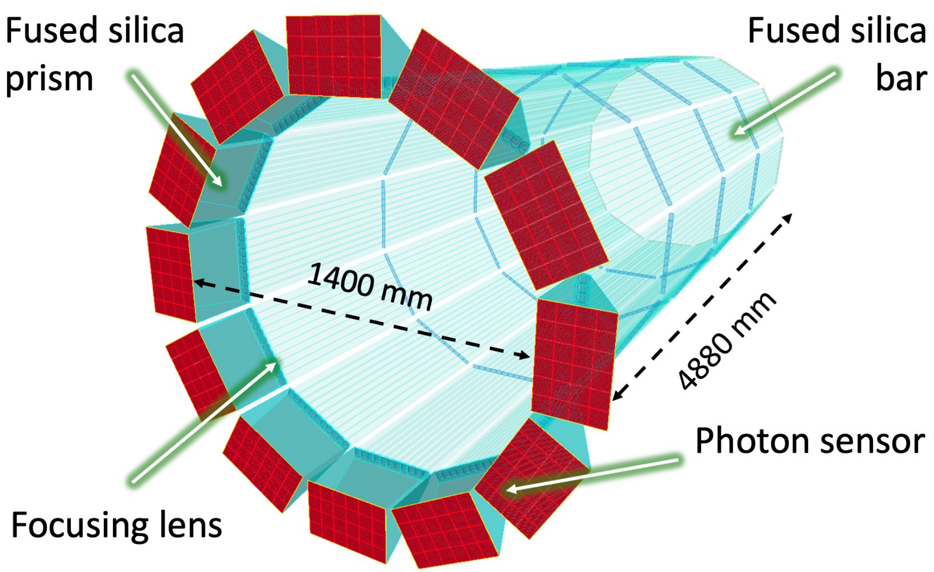
    baseline design: reuse of BaBar DIRC bars (R&D started)
- Focusing optics:

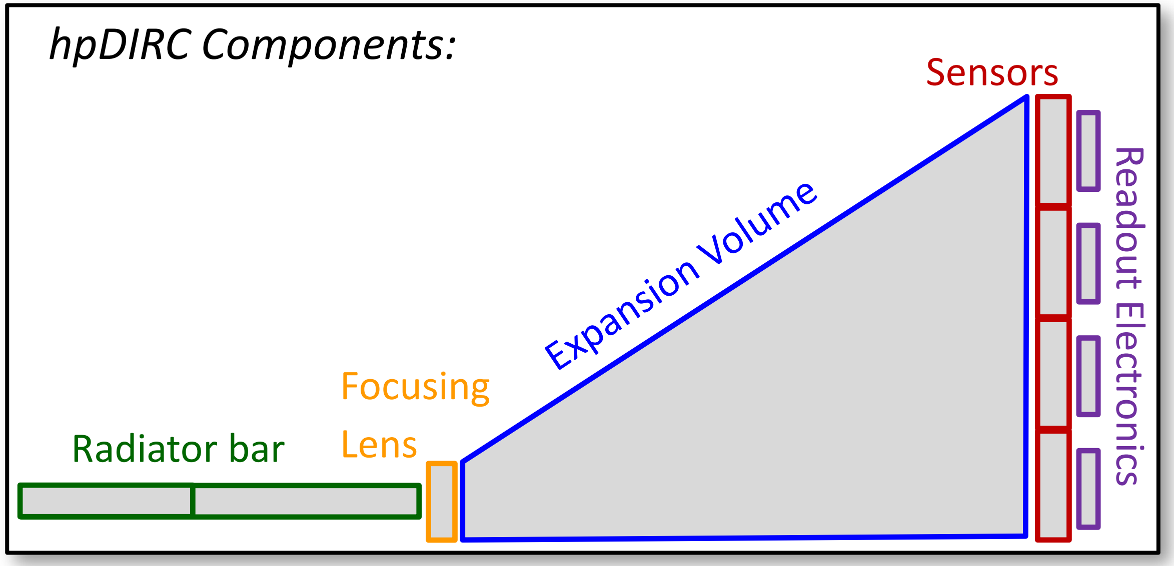
  Radiation-hard 3-layer spherical lens (sapphire)
- Expansion volume:

  Solid fused silica prism: 240 x 360 x 300 mm^3 (H x W x L)
- Readout system:

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

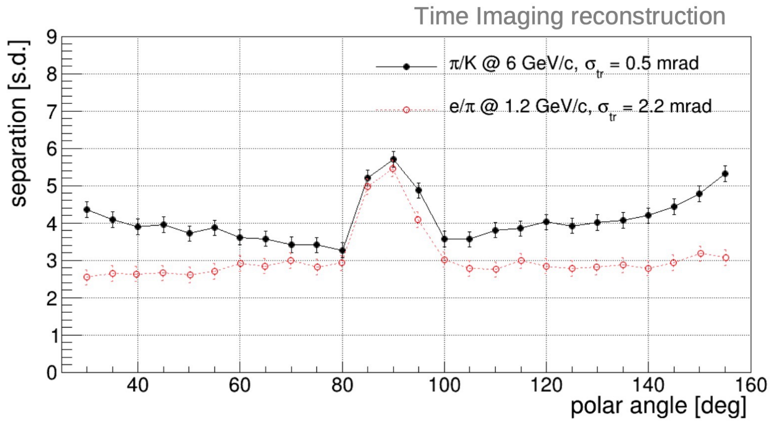
  ASIC-based Electronics (EICROC)
- Several core design aspects, as well as detailed Geant simulation, validated in PANDA Barrel DIRC beam tests (prototype tests in cosmic rays in preparation)





hpDIRC Beyond ePIC

- hpDIRC baseline design performance matches requirements for ePIC
- Reuse of BaBar DIRC bars limited some ePIC hpDIRC optics design options
- Several aspects of design and components have potential for improvement
- Performance limits and novel optical designs are explored with Geant simulation in generic R&D program (EICGENRandD12).
- Selectively disable physics processes, evaluate performance
- Isolate impact of detailed performance parameter on separation power
- Started simulation study of fundamental DIRC performance limits due to
  - multiple scattering in bar
  - chromatic dispersion of photon angle and propagation time
  - optical aberrations from focusing system
  - pixel size

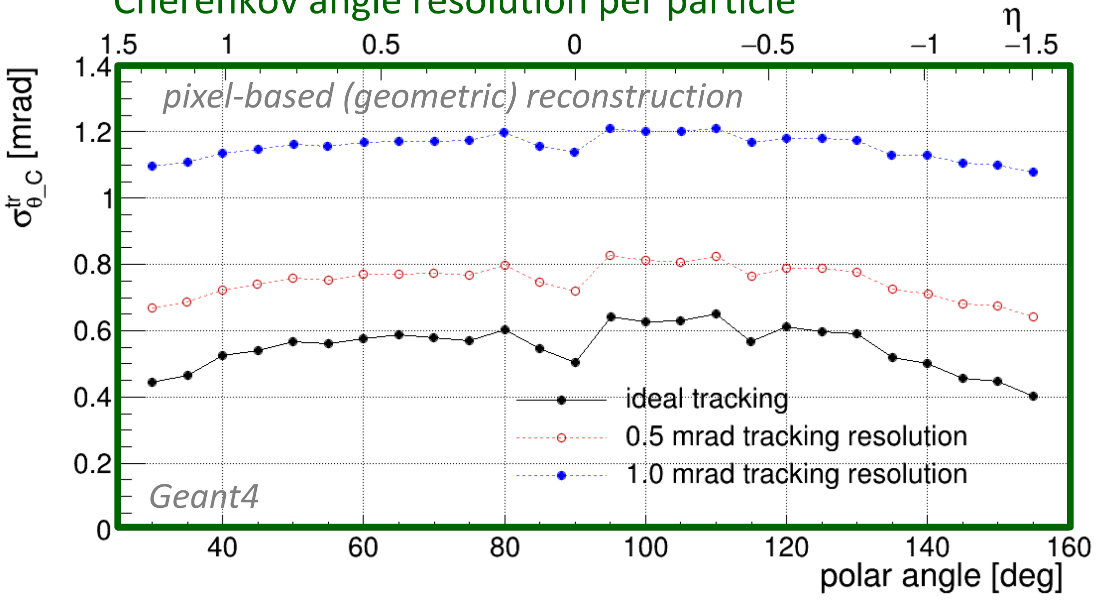


- compact photon camera
- spherical lens focusing
- small pixels (MCP-PMT)
- fast photon timing
- dispersion mitigation
- precision tracking
- mult. scattering mitigation

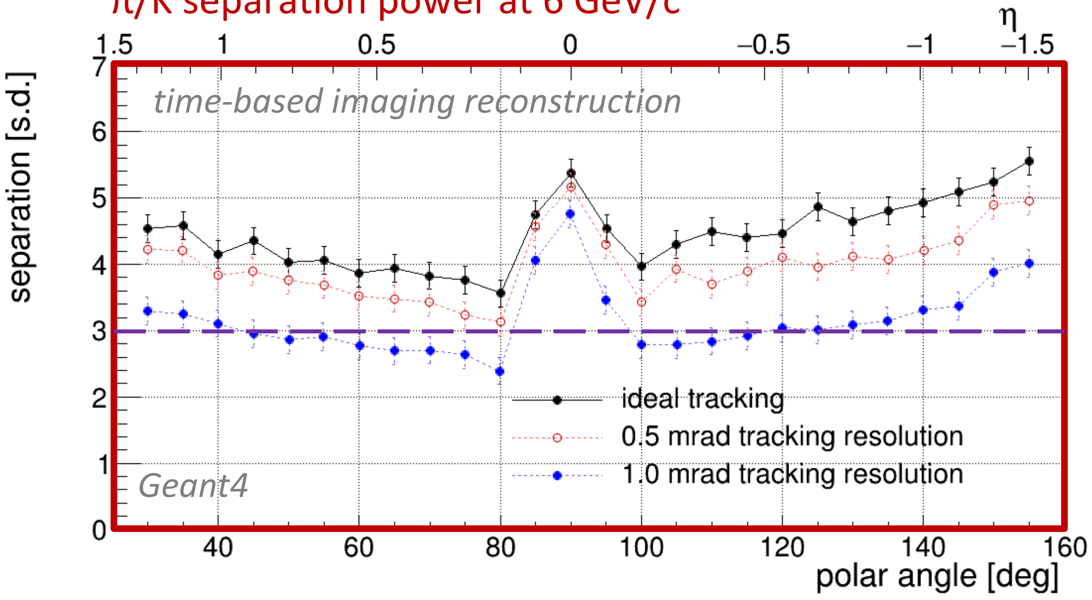
hpDIRC Performance vs. Tracking

Impact of tracking angular resolution on hpDIRC performance

Cherenkov angle resolution per particle



π/K separation power at 6 GeV/c



Note:

- *π/K Cherenkov angle difference at 6 GeV/c: $\Delta\Theta_c \approx 3$ mrad, at 10 GeV/c: $\Delta\Theta_c \approx 1$ mrad*
- *Yellow Report tracking requirement: 0.5 mrad resolution at 6 GeV/c*

Simulation studies performed with

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

→ High-precision angular resolution crucial for reaching required hpDIRC performance

FY23 Results: DIRC Performance Limits

Main effects limiting future DIRC performance

- Multiple scattering (MS) inside the bar

  dominates at lower momentum

  → possible mitigation: thinner bar, post-DIRC tracking

- Chromatic dispersion (CD) of angle and time

  dominates at higher momentum

  → possible mitigation: limit spectral acceptance

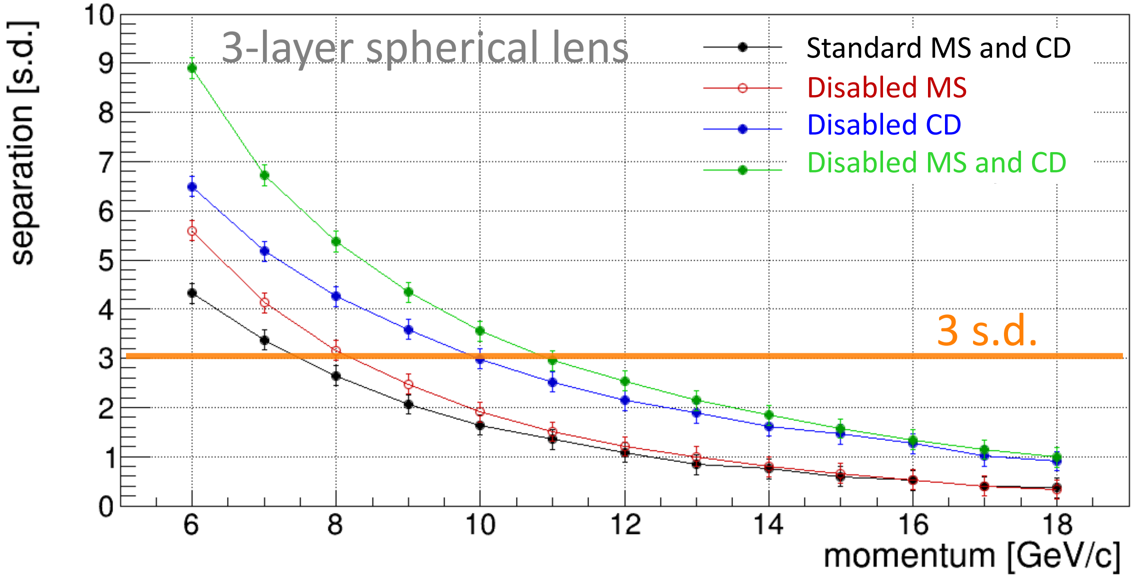
- Optical aberrations from focusing system

  → possible mitigation: hybrid optics, aspherical lenses

- Pixel size

  → possible mitigation: MCP-PMTs and SiPM with small pixels (~1.5mm) commercially available, very active field

π/K separation of ePIC hpDIRC – impact of physics processes



Simulation studies performed with

- Stand-alone Geant4 simulation
- Single particles from particle gun
- 30^{o} polar angle
- No magnetic field, no other ePIC subsystems

FY23 Results: π/K separation of ePIC hpDIRC – focusing

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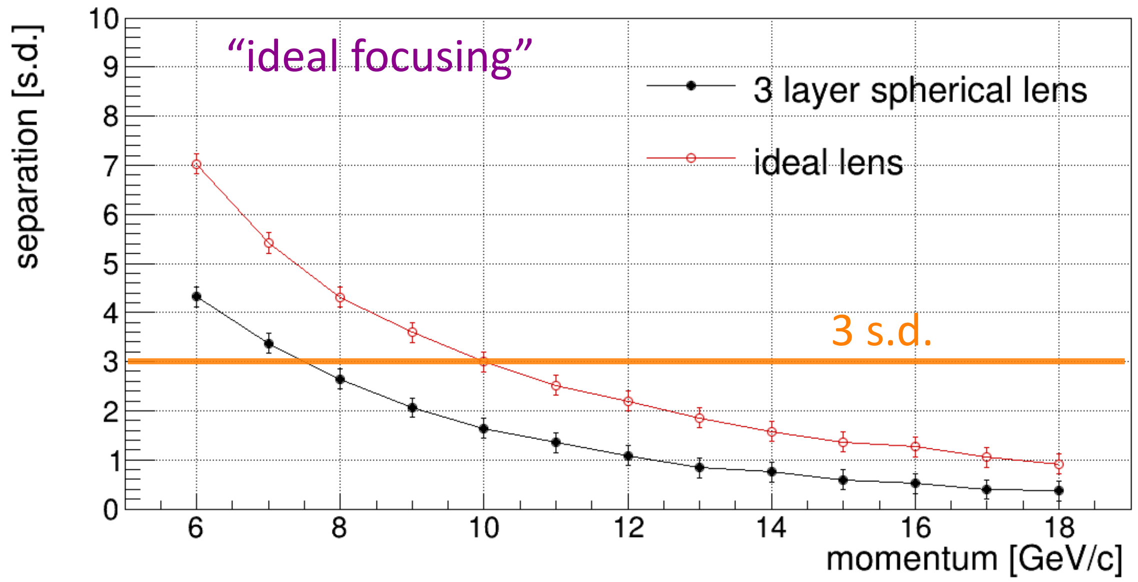
π/K separation of ePIC hpDIRC – with theoretical "ideal focussing"



FY23 RESULTS: π/K SEPARATION OF EPIC HPDIRC – FOCUSING

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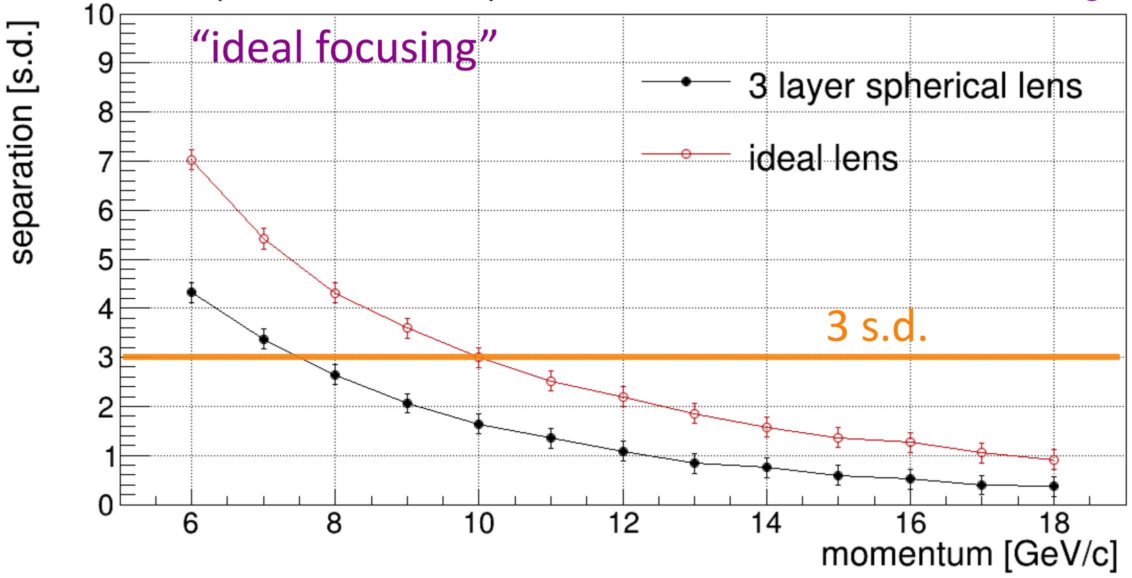

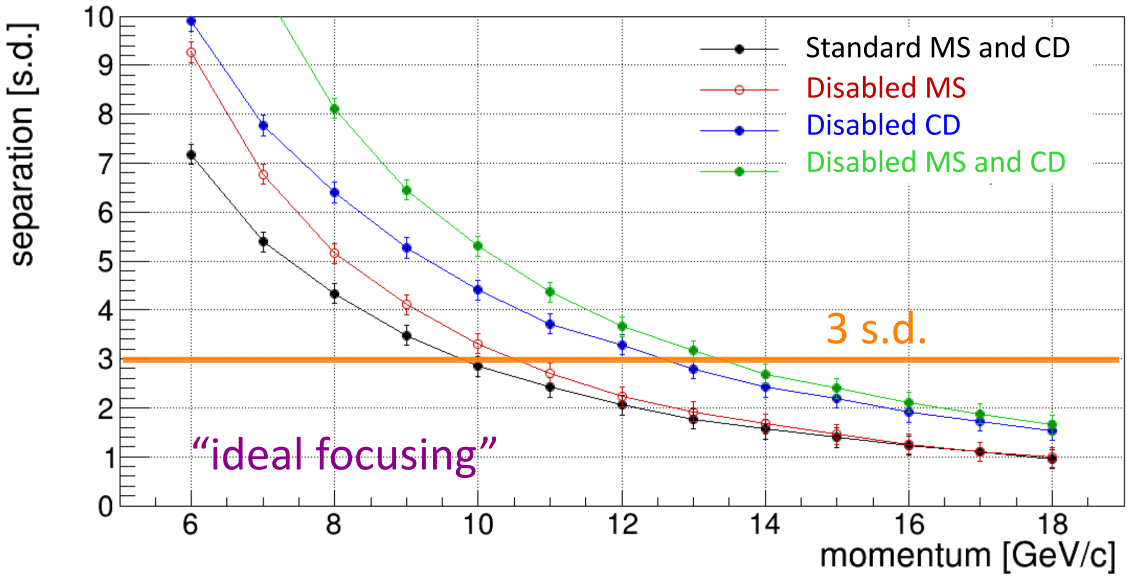

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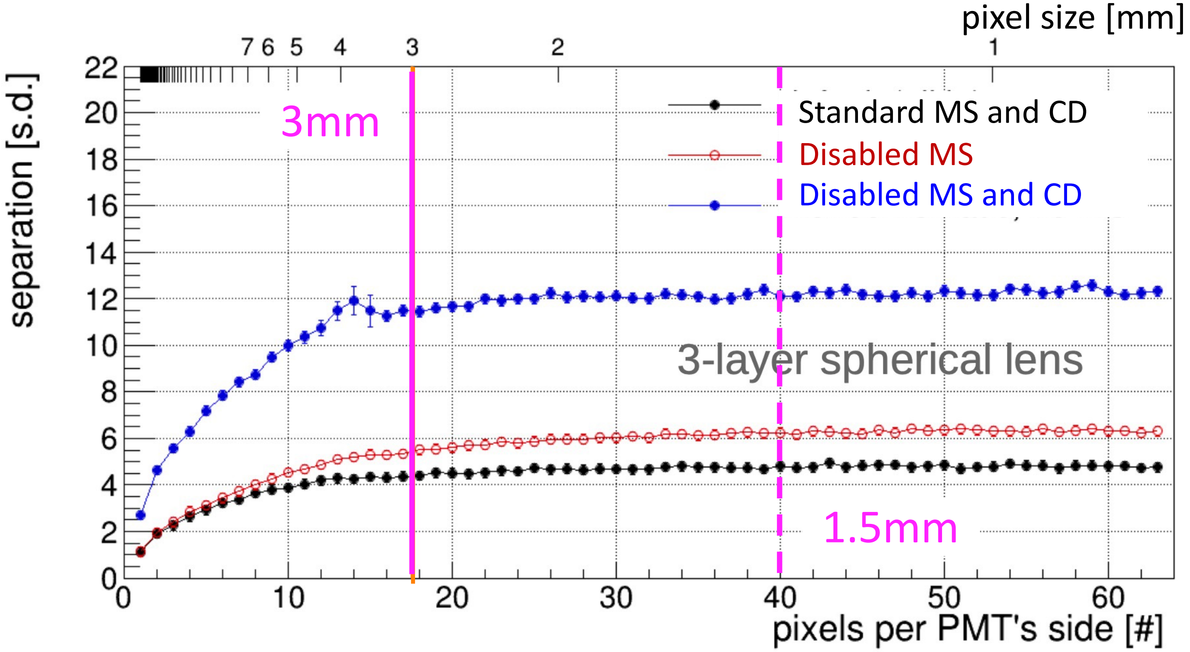
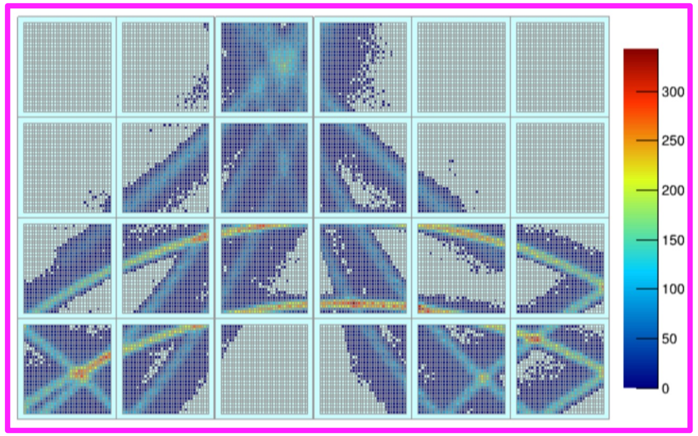
π/K separation of ePIC hpDIRC at 6 GeV/c – pixel size effect



32x32 pixels (1.6 mm) per 2'' MCP-PMT



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→ Optical aberrations, multiple scattering, pixel size are promising areas;
start with hybrid optics, initial exploration of thin bar and small-pixel sensors.

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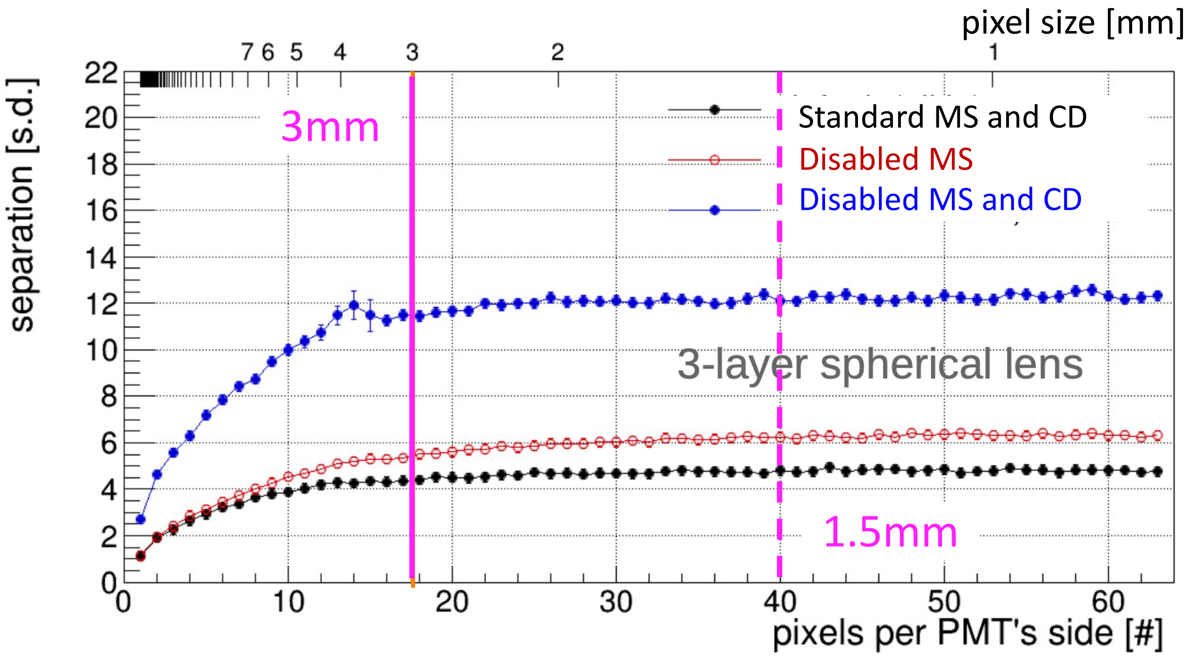

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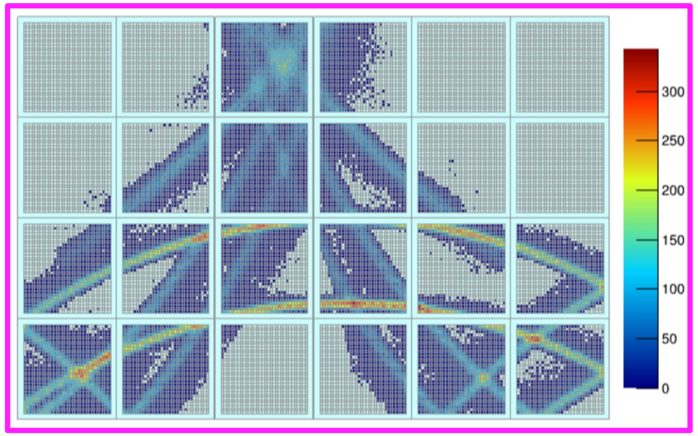
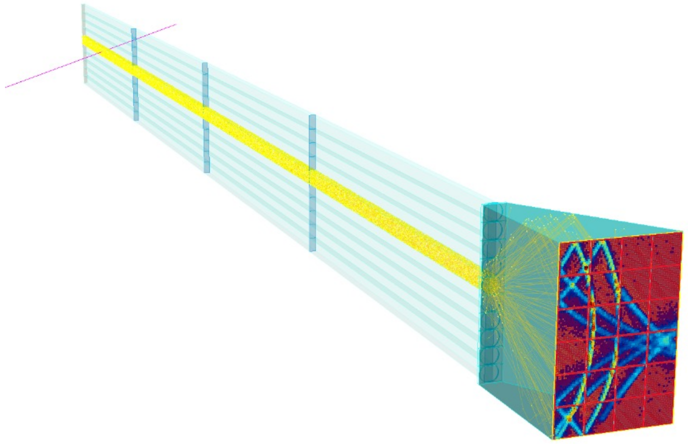
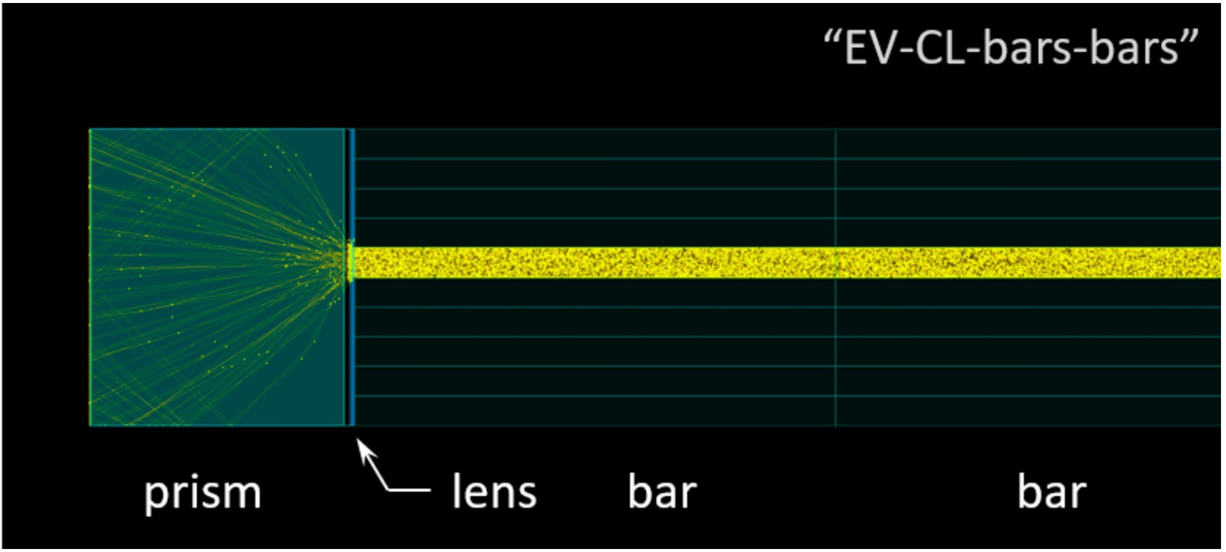


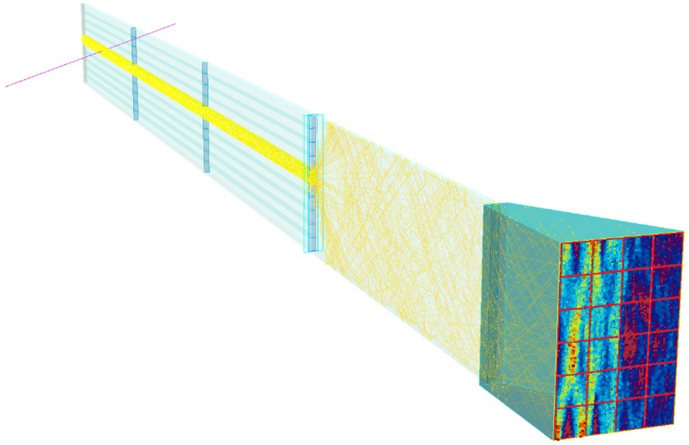
FY23 Results: Alternative Design

- ePIC detector barrel length requires additional “light guide” section to connect BaBar DIRC bars to prism
- Alternative to baseline (narrow bars) is one single short wide plate

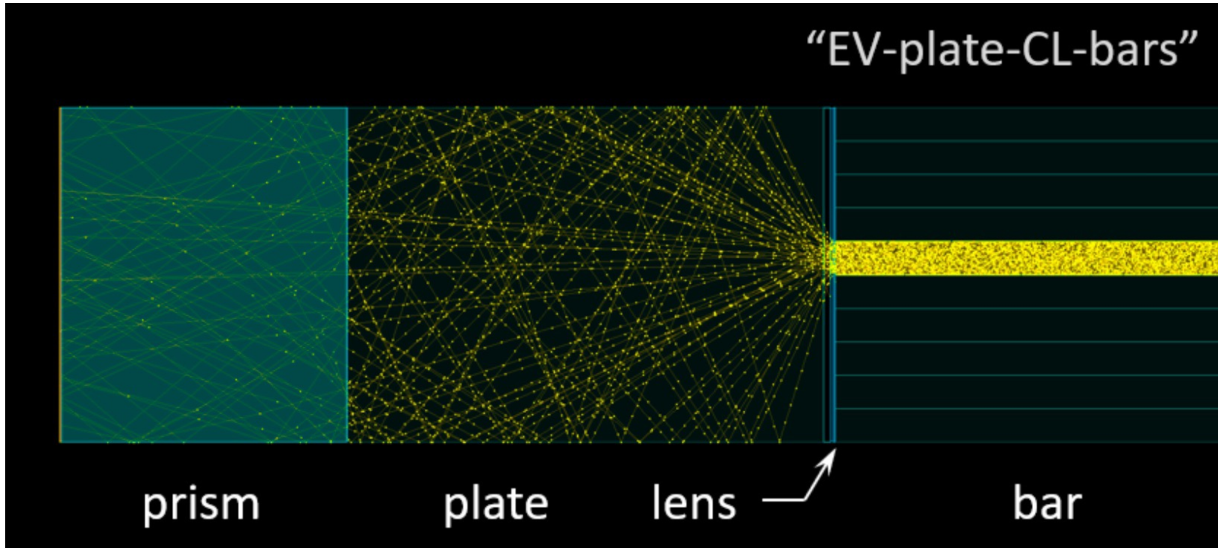


Only narrow bars in each sector





Hybrid of bars and plate in each sector



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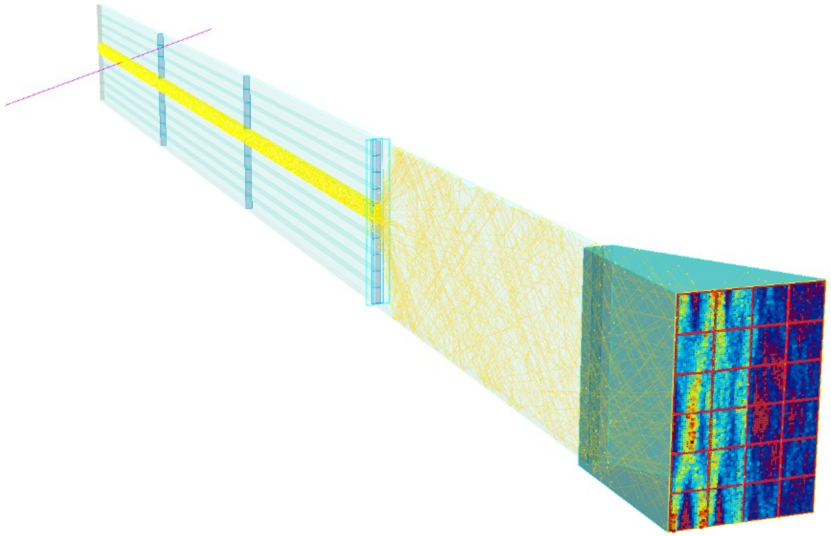
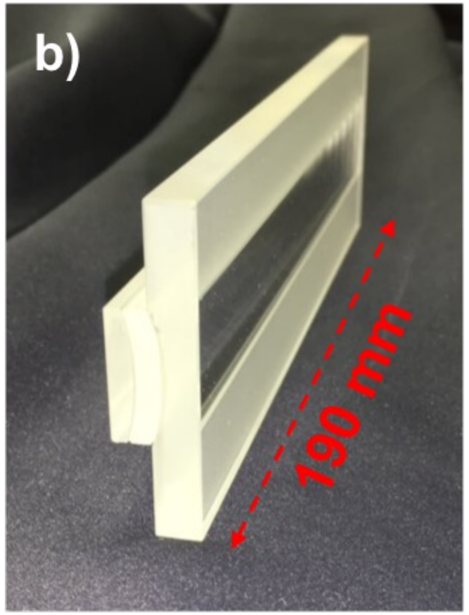
- Expansion volume effectively starts at end of narrow bar, improving angular resolution, possible use of cylindrical lens





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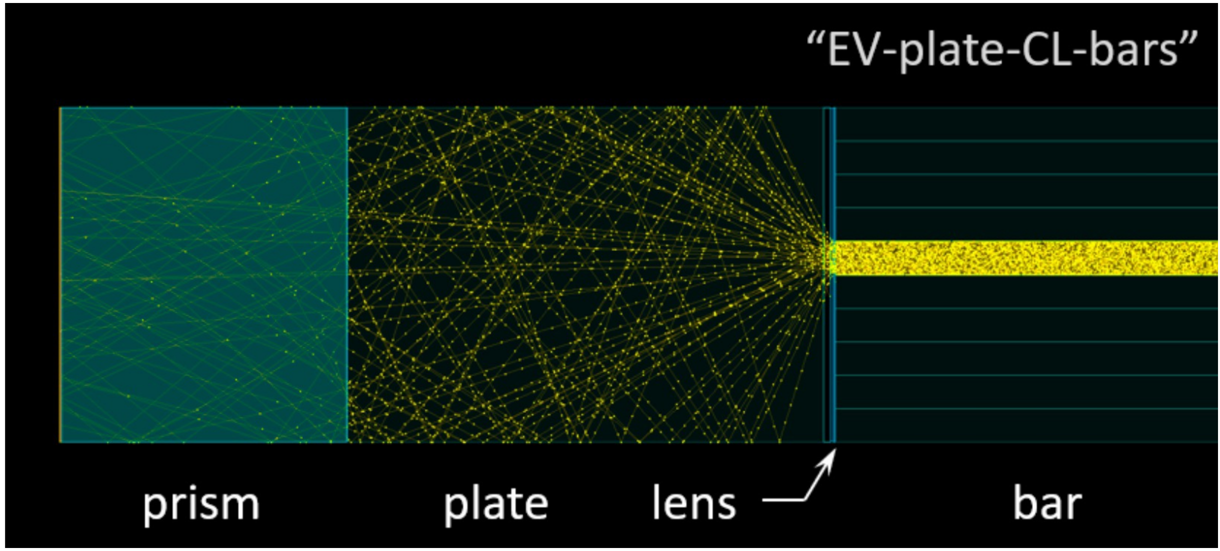

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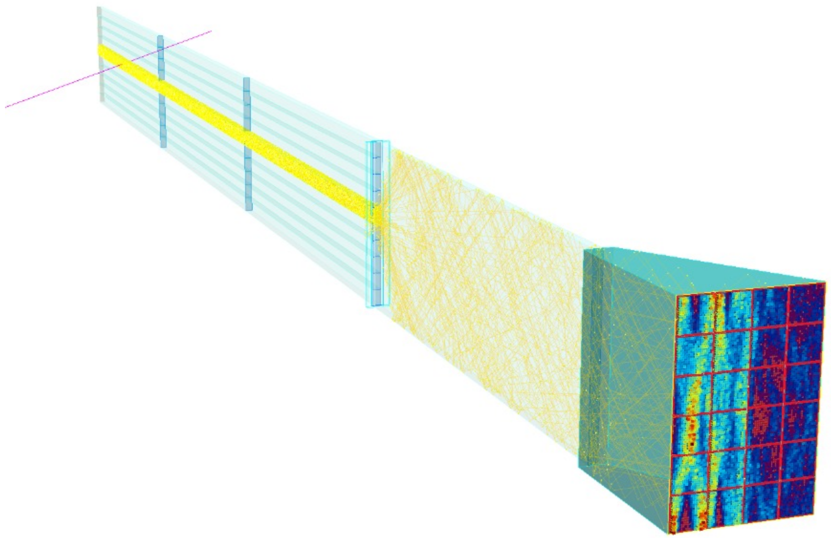
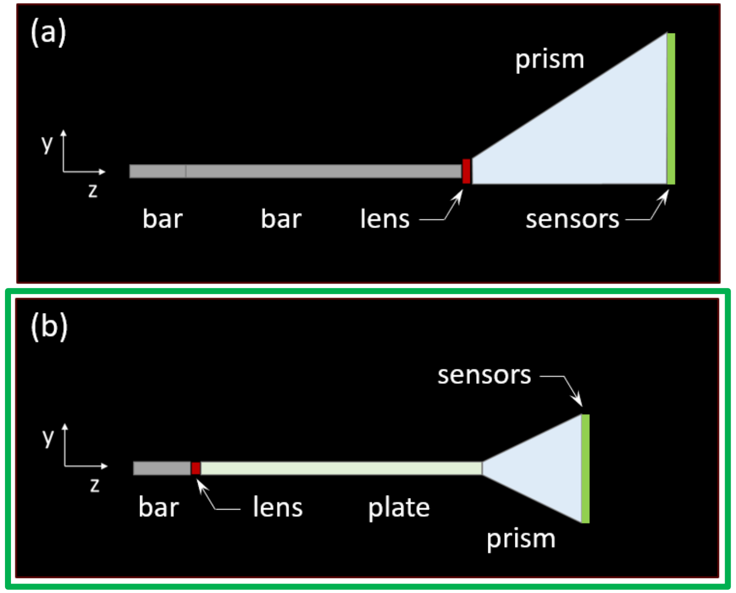
- Longer expansion in plate in plate could make shorter prism possible, with smaller sensor area, possibly enabling use of SiPM





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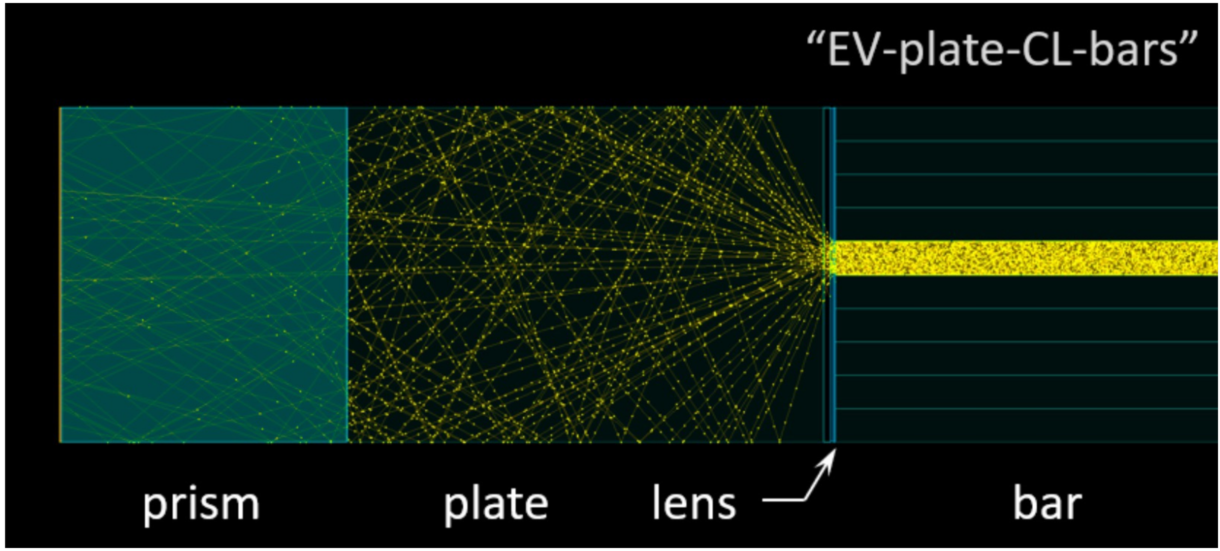


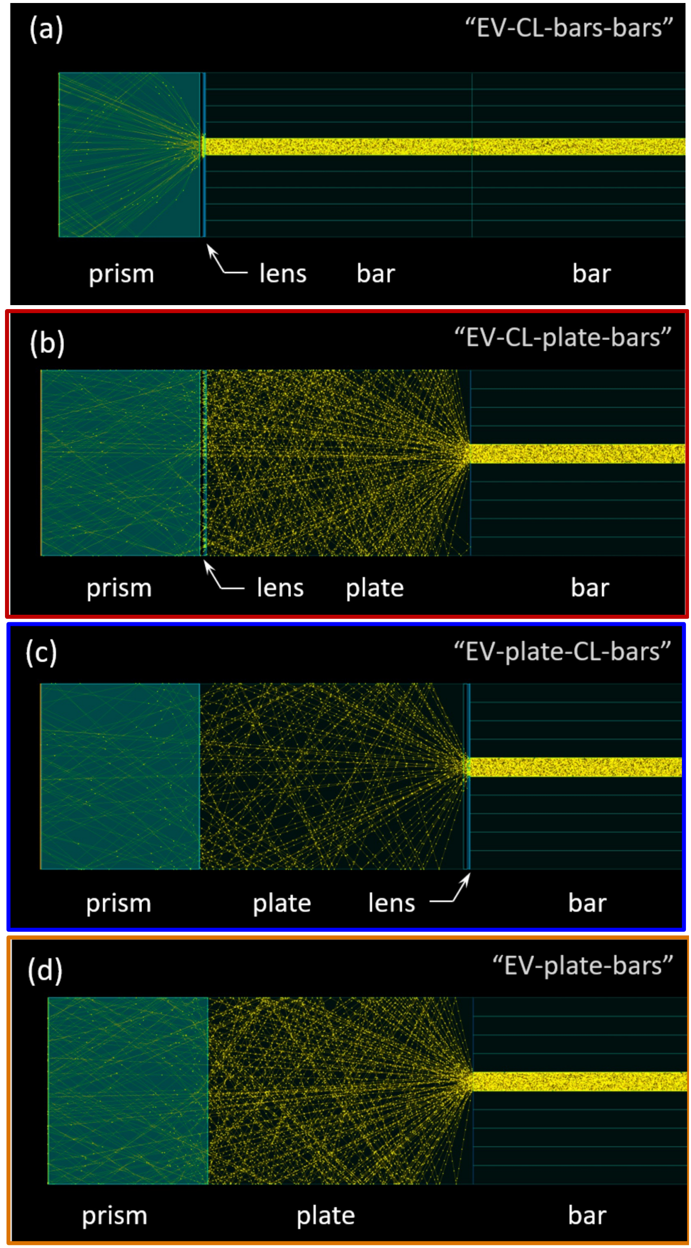
FY23 Results: Alternative Design

(a) hpDIRC design with narrow bars used for both the active area and the light guide section, and cylindrical lens (CL) placed between the bars and the prism (EV)

(b) conservative xpDIRC hybrid design with narrow bars coupled to a wide plate as light guide via a cylindrical lens

(c) novel xpDIRC hybrid design with the cylindrical lens placed between the narrow bars and the wide plate

(d) simplified design without focusing, with narrow bars coupled to the wide plate



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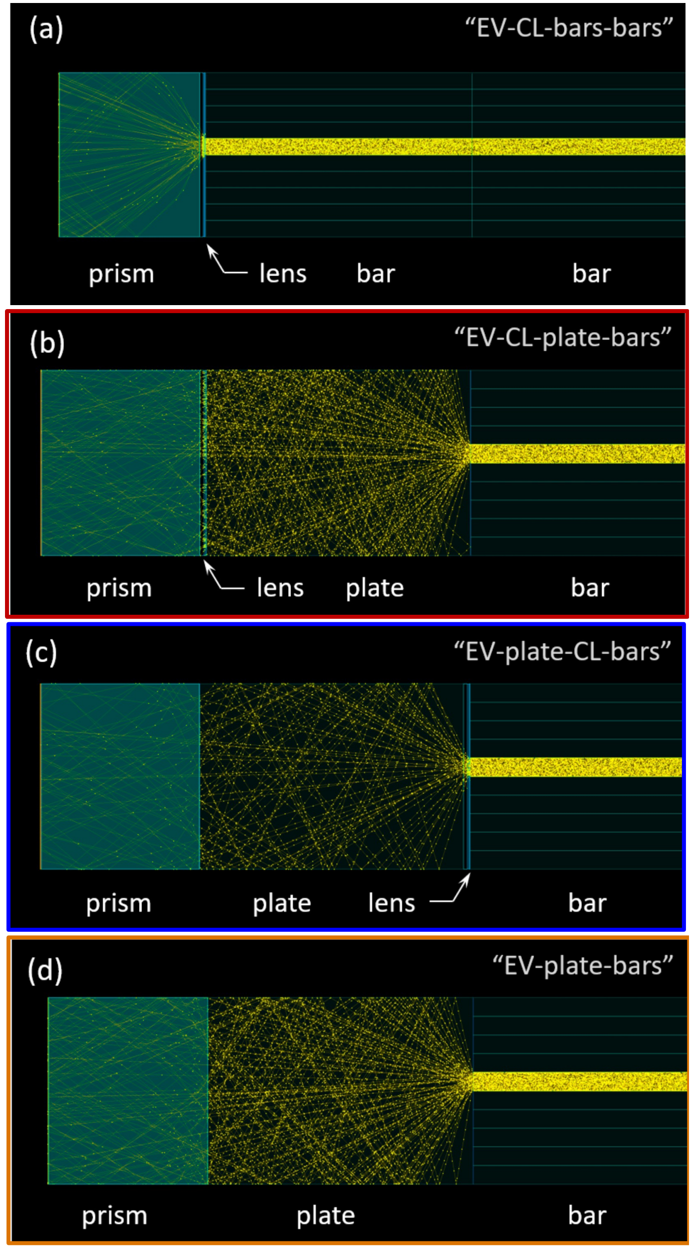
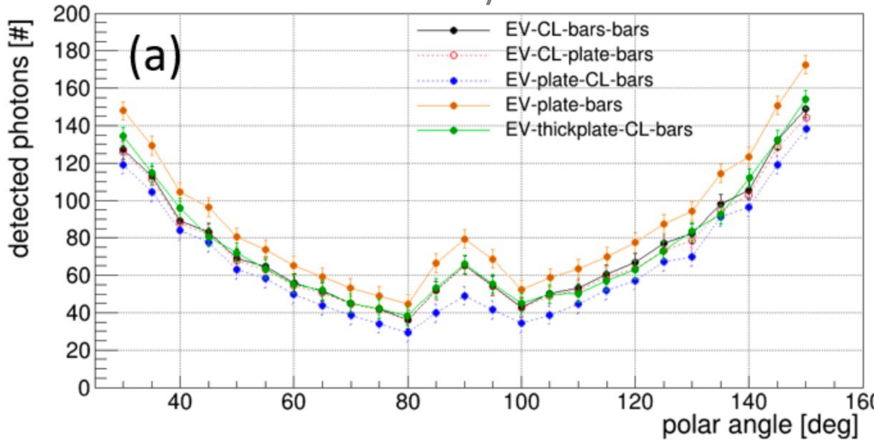
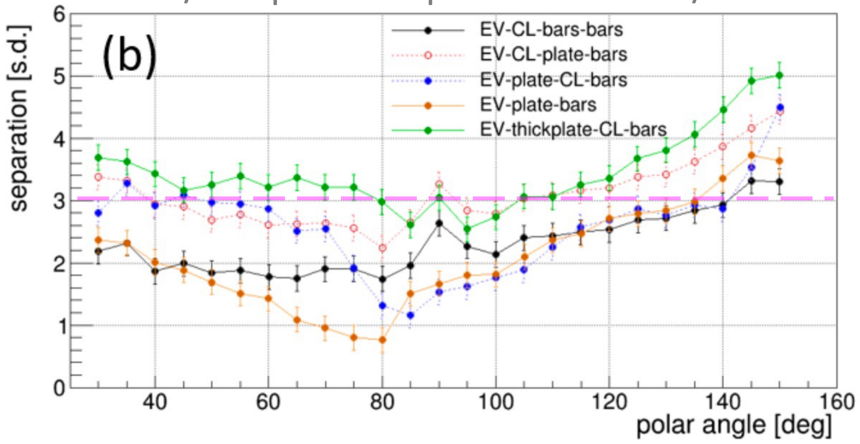


Photon yield



π/K separation power at 6 GeV/c



FY23 RESULTS: ALTERNATIVE DESIGN

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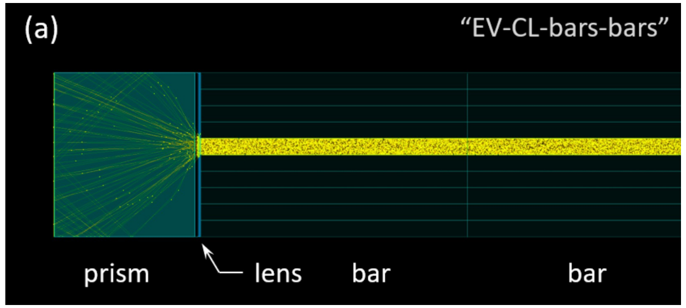
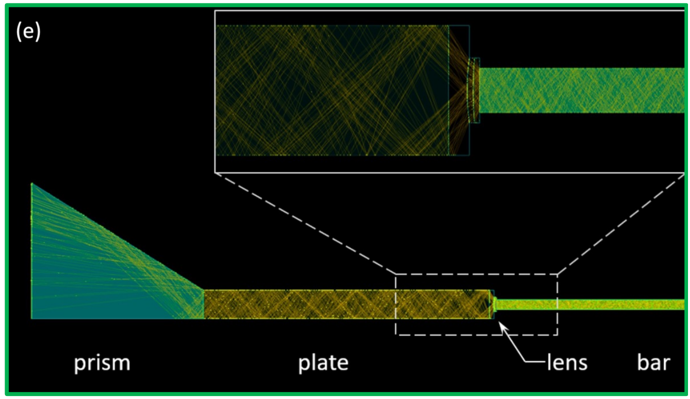
(c) novel xpDIRC hybrid design with the cylindrical lens placed between the narrow bars and the wide plate

(d) simplified design without focusing, with narrow bars coupled to the wide plate

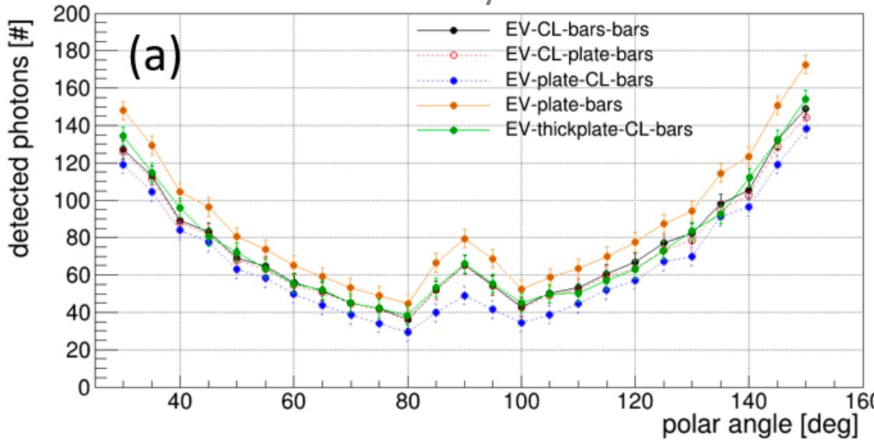
(e) xpDIRC "thick plate" hybrid design with cylindrical lens placed between the narrow bars and 50 mm-thick* wide plate → best performance, warrants further studies





(*50 mm-thickness *ad hoc* choice based on current lens and prism, can be reduced, to be studied)

Photon yield



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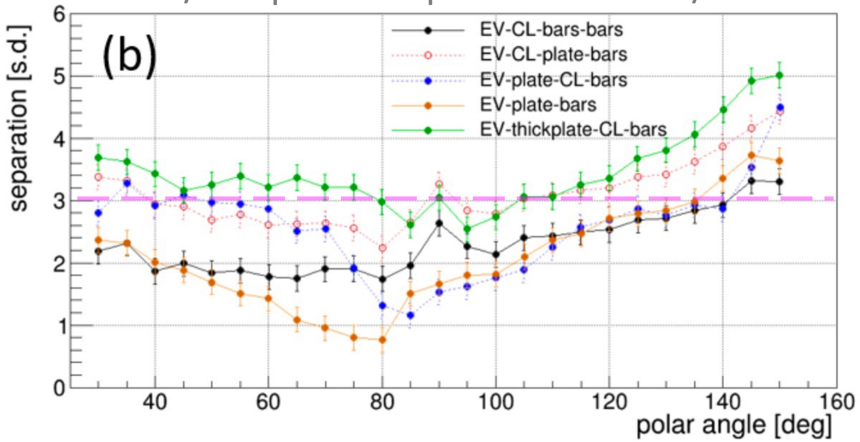
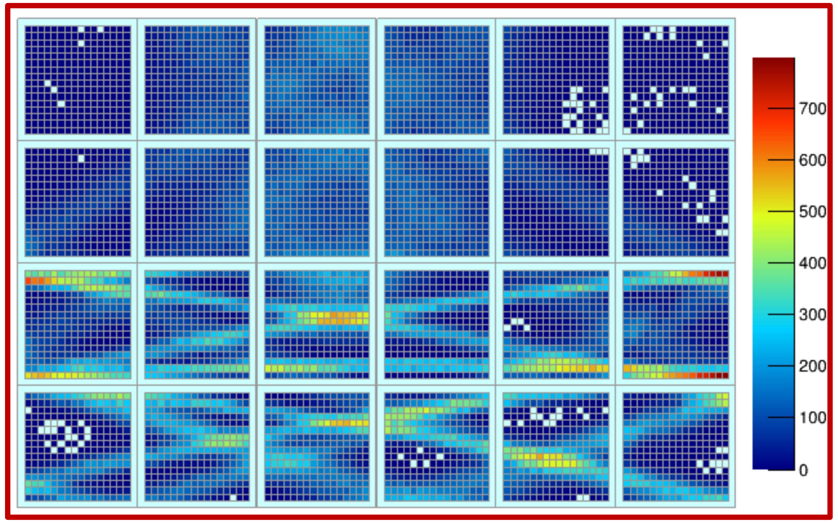


FY23 Conclusions and Outlook

- Configuration where the cylindrical lens is positioned between the wide plate and the expansion volume comes close to achieving the desired 3 s.d. separation power at 6 GeV/c
- Alternative cylindrical lens positions require additional optimization to determine if their performance can be enhanced
- Configuration with thicker plate to mitigate photon loss has a lot of potential, especially with thinner radiator bar option
- Combination of optimized spherical lenses with wide plate will be investigated

narrow bars - wide plate - cylindrical lens



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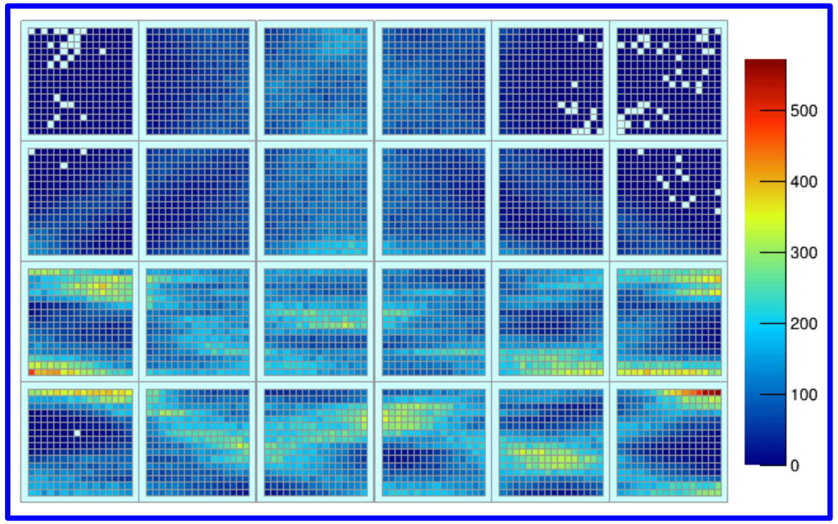

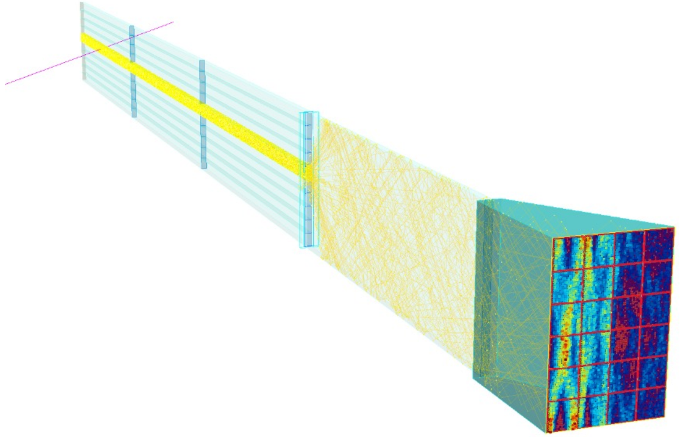

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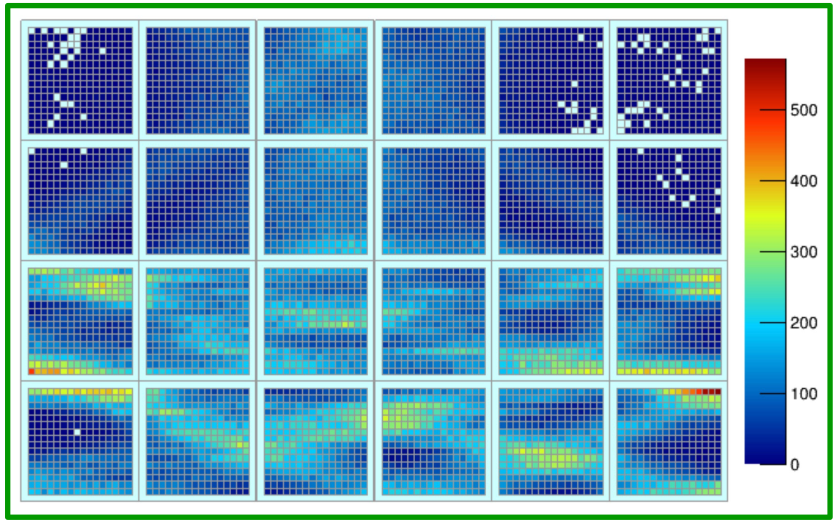
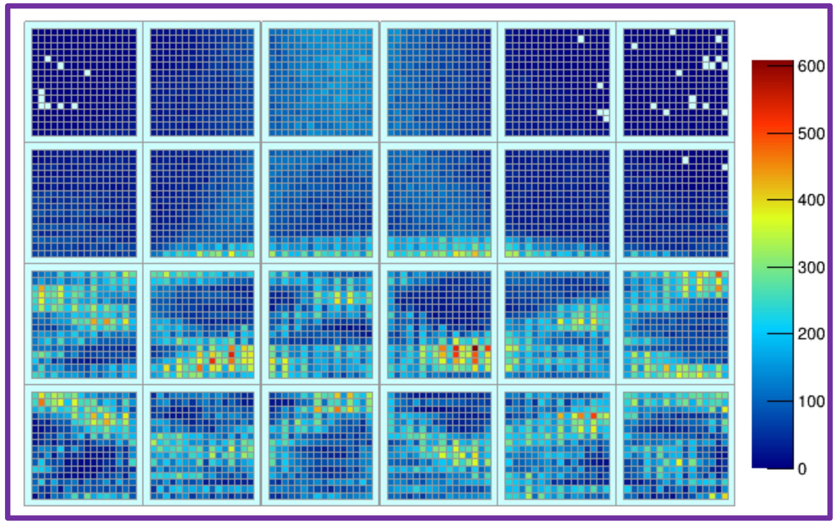
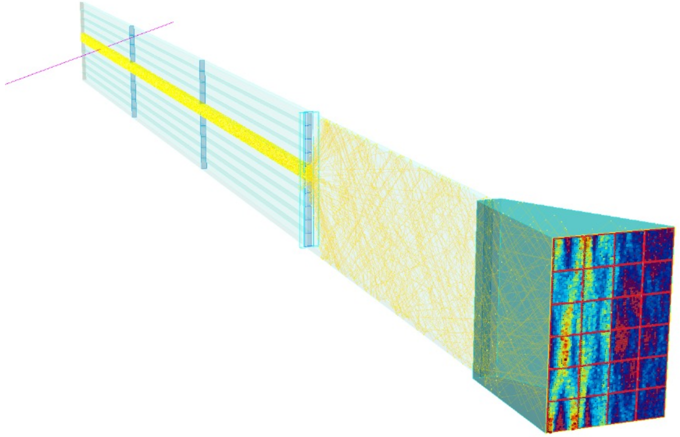
narrow bars - cylindrical lens – thick wide plate



narrow bars - spherical lenses - wide plate





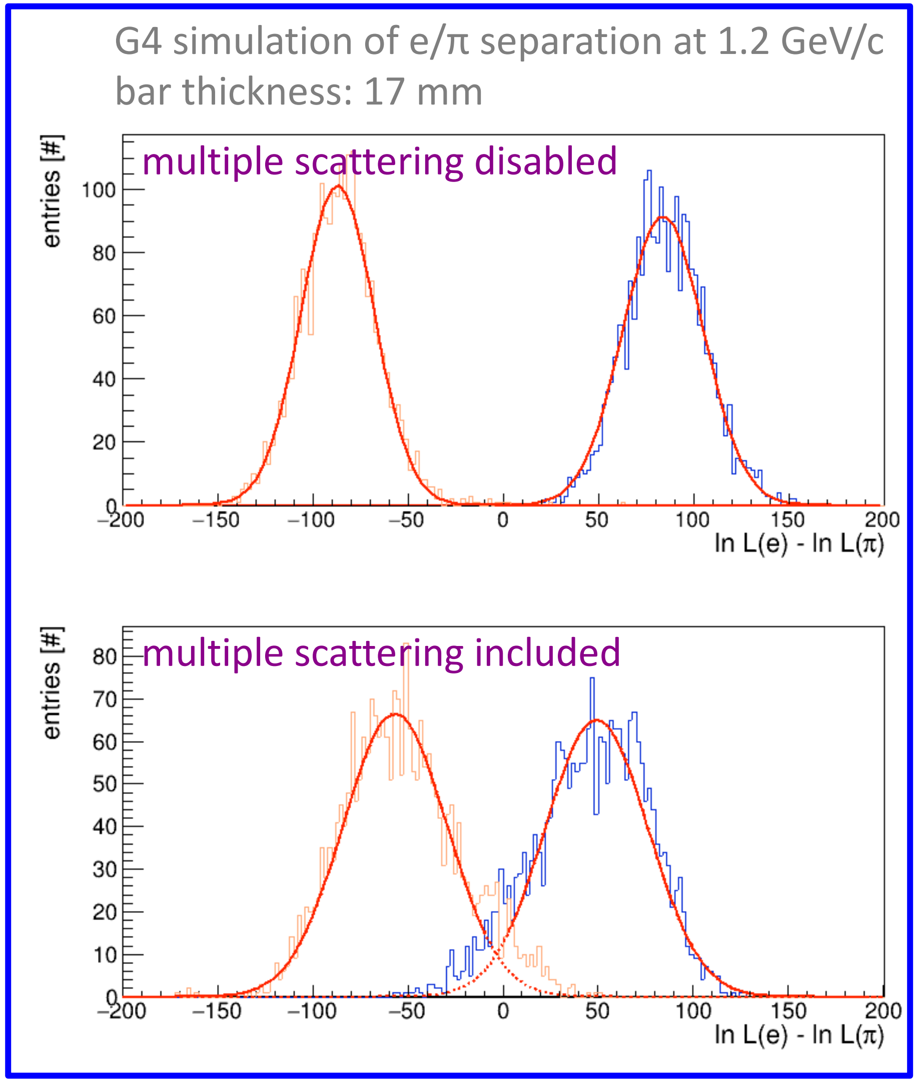
PRE-FY24 STUDIES: LOW-MASS THIN XPDIRC

Key advantages of low-mass thin xpDIRC *(10mm example):*

- 41% reduction in mass benefits the EMCal performance
- Multiple scattering in the DIRC bar limiting factor for hpDIRC performance at lower momentum and at high momentum
- Potential for significant e/π ID improvement around 1 GeV/c, without significantly affecting π/K ID above 4 GeV/c
- Smaller bar thickness simplifies focusing lens design/performance

Challenges:

- Lower photon yield
- More complicated fabrication – but production of large 10 mm-thin fused silica radiator bars/plate by industry feasible (1250 x 660 x 10 mm^3 prototype plate produced by Nikon for LHCb TORCH DIRC)



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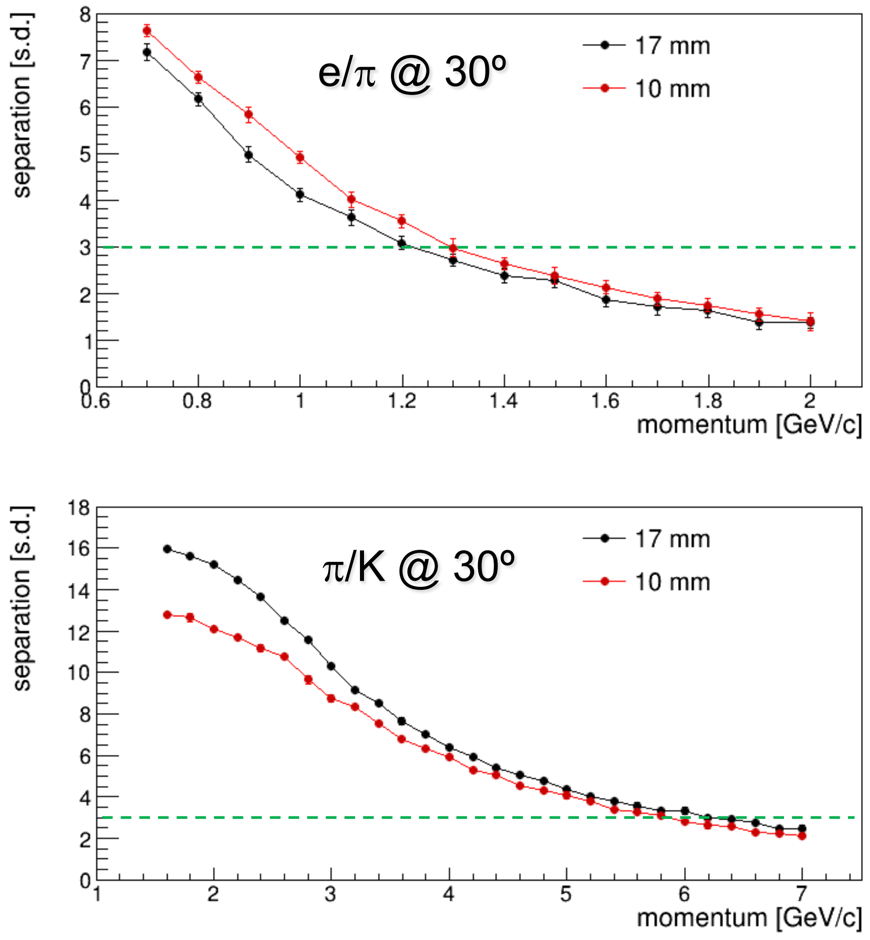
- Potential for significant e/π ID improvement around 1 GeV/c, without significantly affecting π/K ID above 4 GeV/c
- Smaller bar thickness simplifies focusing lens design/performance

Challenges:

- Lower photon yield
- More complicated fabrication – but production of large 10 mm-thin fused silica radiator bars/plate by industry feasible (1250 x 660 x 10 mm^3 prototype plate produced by Nikon for LHCb TORCH DIRC

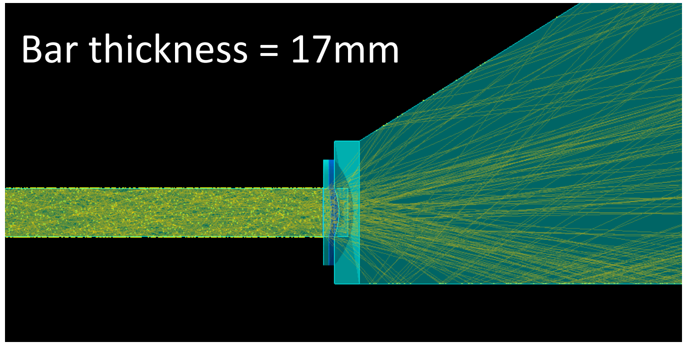
G4 simulation performance of 10mm and 17mm options of hpDIRC (CORE scenario)

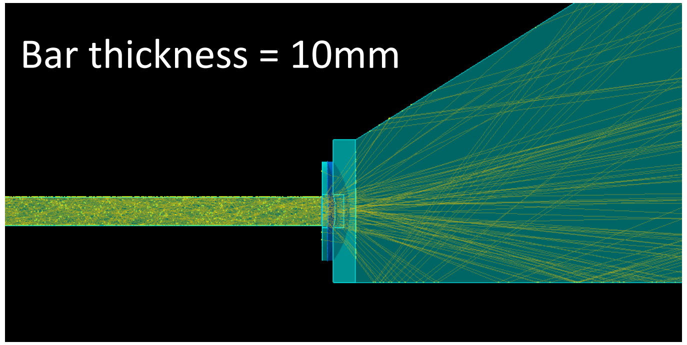


PRE-FY24 STUDIES: LOW-MASS THIN XPDIRC

Key advantages of low-mass thin xpDIRC *(10mm example):*

- 41% reduction in mass benefits the EMCal performance
- Multiple scattering in the DIRC bar limiting factor for hpDIRC performance at lower momentum and at high momentum
- Potential for significant e/π ID improvement around 1 GeV/c, without significantly affecting π/K ID above 4 GeV/c
- Smaller bar thickness simplifies focusing lens design/performance





Challenges:

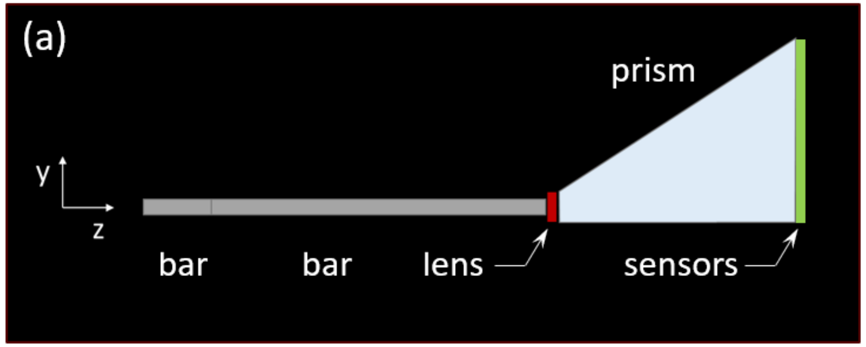
- Lower photon yield
- More complicated fabrication – but production of large 10 mm-thin fused silica radiator bars/plate by industry feasible (1250 x 660 x 10 mm^3 prototype plate produced by Nikon for LHCb TORCH DIRC

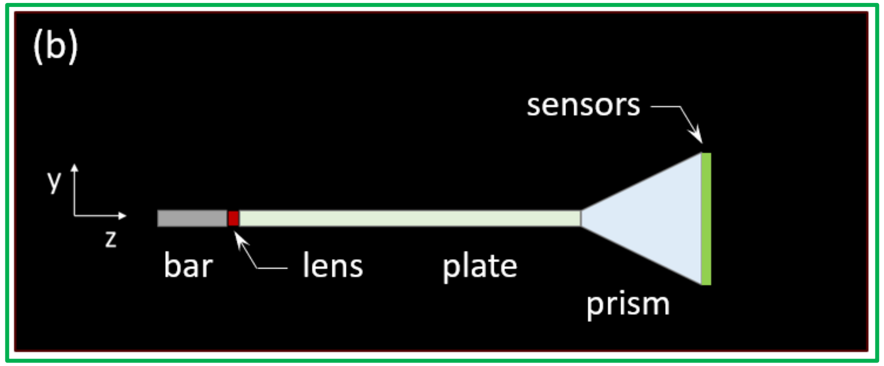
10 mm–thick LHCb TORCH prototype

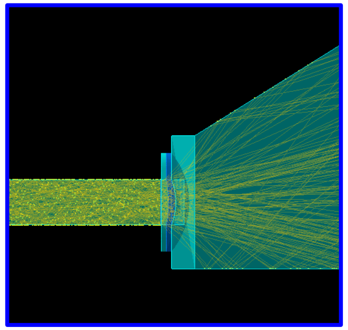
FY24 PLANS

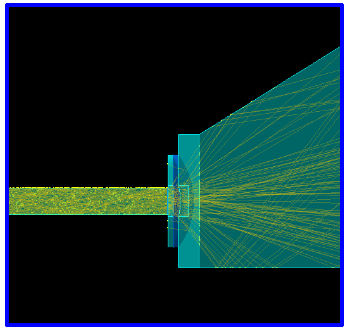
Activity focus:

- Hybrid optics (mitigate focusing errors and reduce cost)
  - Study of plate configuration with spherical lenses
  - Optimize lens properties for longer expansion in plate
  - Study shorter prism, two half-width prisms, possibly with SiPM readout (cost reduction, reduce sensor area of prism by factor 3-4)
  - Optimize "Thick plate" hybrid design (avoids photon loss in the lens)
- Thinner bars (mitigate multiple scattering effects in DIRC bars)
  - Study potential combination with "Thick plate" hybrid design









Deliverables:

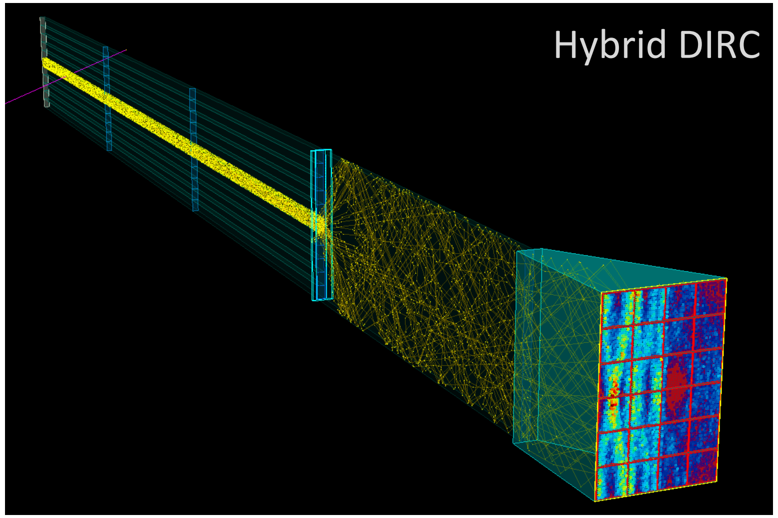
Evaluation of the DIRC performance with

- thinner bars, including the xpDIRC hybrid optics option with spherical lenses
- xpDIRC geometry with a small and/or narrow expansion volume
- SiPM readout based on current state-of- the-art sensors

xpDIRC R&D Activities

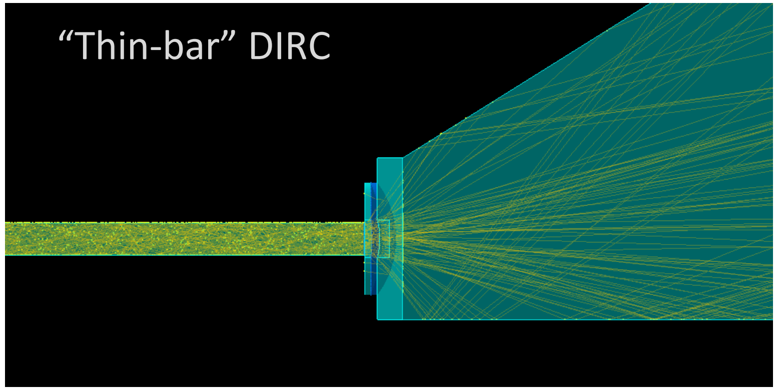
FY 23

- Evaluation of the performance of the hpDIRC/xpDIRC hybrid geometry
  - Narrow bars with wide plate, impact on light-guide section decision for Detector-1
  - Narrow bars with wide plate and new focusing optics, impact on design of xpDIRC for Detector-2



FY 24

- Complete studies of the xpDIRC geometry
- Evaluation of the DIRC performance with thinner bars
- Evaluation of the performance of the xpDIRC geometry with a small and/or narrow expansion volume, with MCP-PMT/SiPM readout



FY 25

- Requirements of SiPM performance parameters (dark noise and after-pulsing) for xpDIRC with SiPM readout
- Experimental validation of xpDIRC geometry aspects (eRD103 synergy) using available lenses/prisms (or procuring new components)

FY24 Budget Request

2024 Requests:

- Top priorities:
  - Continue support for CUA graduate student Md. Imran Hossain
  - Provide travel support for collaborative in-person meetings
- Strengthen team, accelerate progress by adding support for new 50% CUA PostDoc (fallback option: add support for new CUA undergraduate student)

	100%	80%	60%
Graduate student, CUA, 100%	$50k	$50k	$50k
Postdoc, CUA, 50%	$60k	0	0
Undergraduate student, CUA, 100%	0	$15k	0k
Travel, CUA/GSI	$15k	$15k	$15k
Total	$125k	$80k	$65k

Committee Question

For the size of focal plane you envision, can you show from a simple calculation that SiPMs are actually a realistic option?

(For noise levels, assume new SiPMs and a realistic low temperature.)

Sensor area of current ePIC hpDIRC prism 85750 mm^2, ~9000 pixels (3 mm x 3 mm)

- Simplest scenario: no cooling, no annealing, initial SiPM Dark Count Rate (DCR) 100 kHz/mm^2 at room temperature
  - At start of experiment: total raw DCR hit rate 110 GHz, 900 DCR hits per prism in 100 ns time window used in DIRC reco *(compared to 30-200 signal hits)* *[Impact of cooling: approx. factor 2 DCR reduction per 10° C]*
  - At 10^9 1-MeV n_{eq}/cm^2: 10 000 DCR hits/prism in 100 ns time window
- More advanced "dRICH" scenario (HPK S13360-3050, cooling to -30° C plus annealing, keeping DCR below 100 kHz/pixel)
  - 10 DCR hits/prism in 100 ns window at start of experiment, up to 100 hits/prism at 10^9 1-MeV n_{eq}/cm^2

DIRC PID performance may be OK in dRICH scenario (beam test with laser pulser added: ~10% separation power loss for 50 extra hits)

However, implementation of cooling to -30° C and annealing for DIRC not trivial, possible impact on fused silica optics

Proposed EICGen studies: shorter prism and/or split prism → could reduce sensor area per prism by up to factor 4, possibly reduce cooling requirements (-10° C enough?) or remove need for annealing

Ageing model

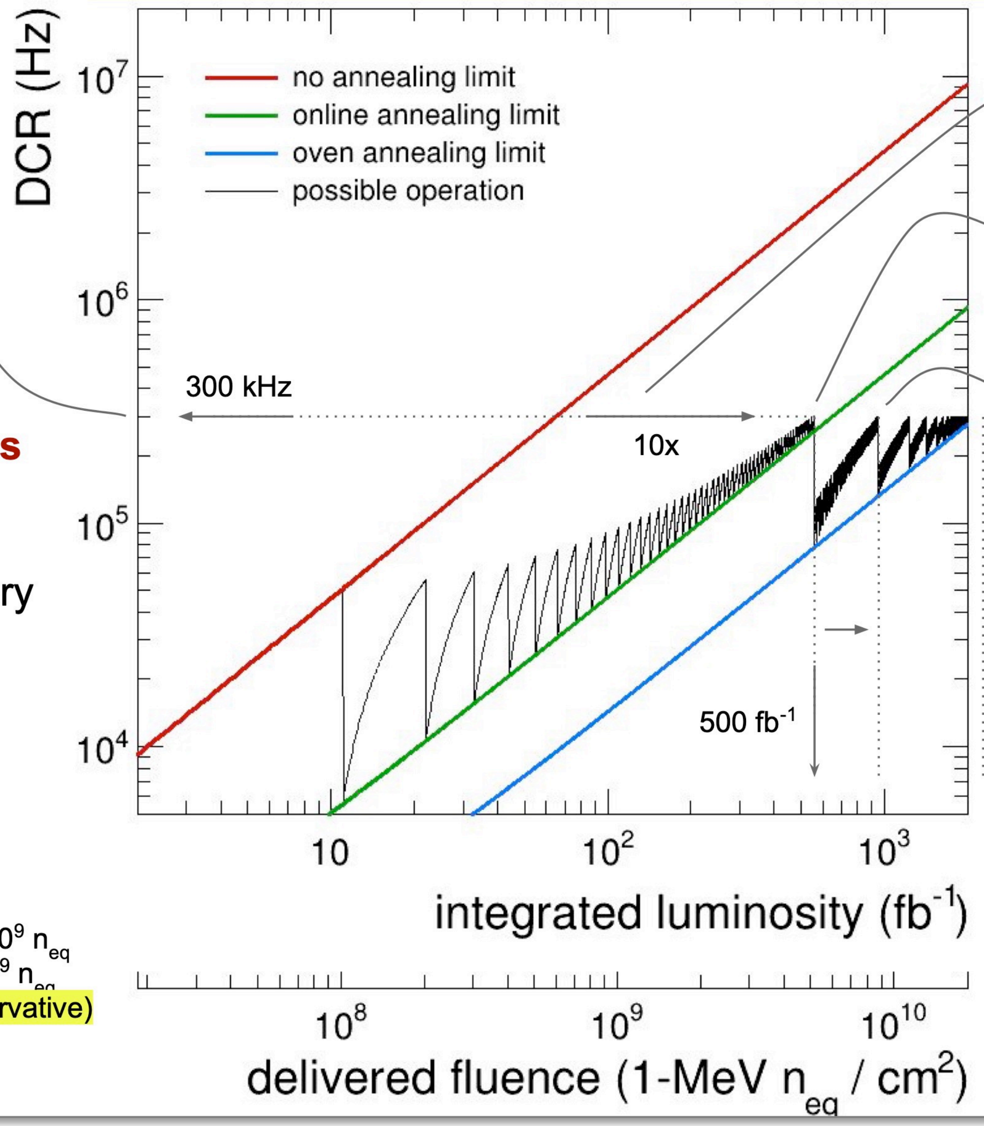
Hamamatsu S13360-3050 @ Vover = 4 V, T = -30 C

max acceptable DCR for Physics performance

~ 10 noise hits / sector within 500 ps

to keep dRICH performance throughout the years the sensors must fulfill requirements on

- effects of radiation damage
- capability of annealing recovery
- excellent time resolution



online annealing extends SiPM lifetime by ~ 10x

more aggressive annealing needed here

might need to unmount SiPM (oven)

up to 1000 fb^{-1} with only one oven annealing cycle

optimisation of online annealing protocol could reach beyond that

model input from R&D measurements

- DCR increase: 500 kHz/10^9 n_{eq}
- residual DCR (online annealing): 50 kHz/10^9 n_{eq}
- residual DCR (oven annealing): 15 kHz/10^9 n_{eq}

1-MeV neq fluence from background group (conservative)

- 9 10^6 n_{eq} / fb^{-1}
- includes 10x safety factor

these predictions are according to present knowledge / tested solutions

there are more handles to further mitigate DCR

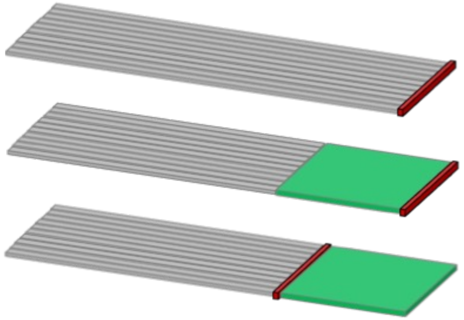
lower Vover, 3V

lover T operation -40 C or below

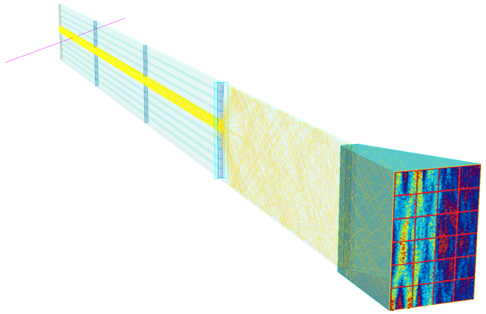
9

Thanks to Marco Contalbrigo et al., ePIC dRICH studies

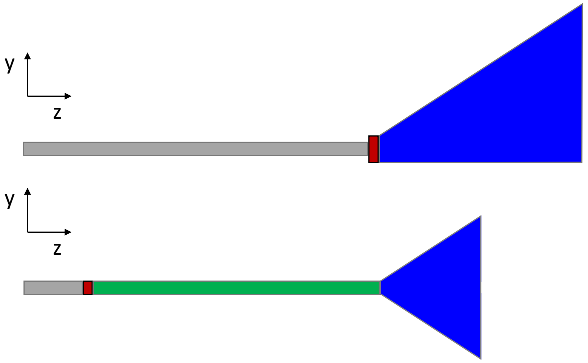
SUMMARY AND OUTLOOK



- Performance of hpDIRC baseline design good match to ePIC PID requirements
  but planned reuse of BaBar DIRC bars limits ePIC hpDIRC design options
- Generic DIRC R&D explores innovative optical DIRC configurations
  to create opportunities for cost reduction, performance improvement, and complementarity
- Narrow bar/wide plate hybrid could reduce cost of light guides and improve the performance
- Novel hybrid lens configurations (xpDIRC) may enable designs with more compact prisms,
  reducing the material budget, potentially making SiPM a viable option for the xpDIRC
- Thinner bars reduce the DIRC material budget, lowering the impact on the EMCal;
  reduction of multiple scattering inside the bar could improve the DIRC e/π separation



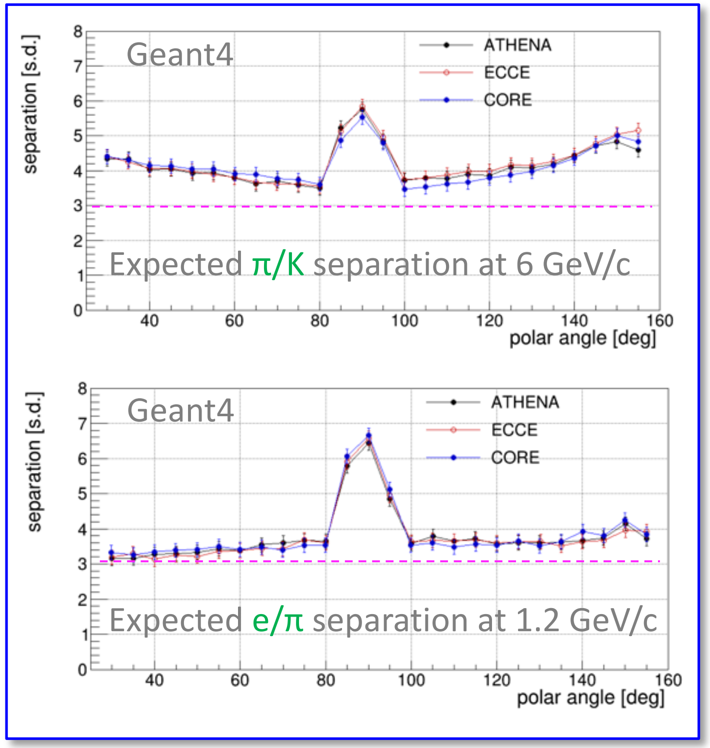
Thank you all for your attention

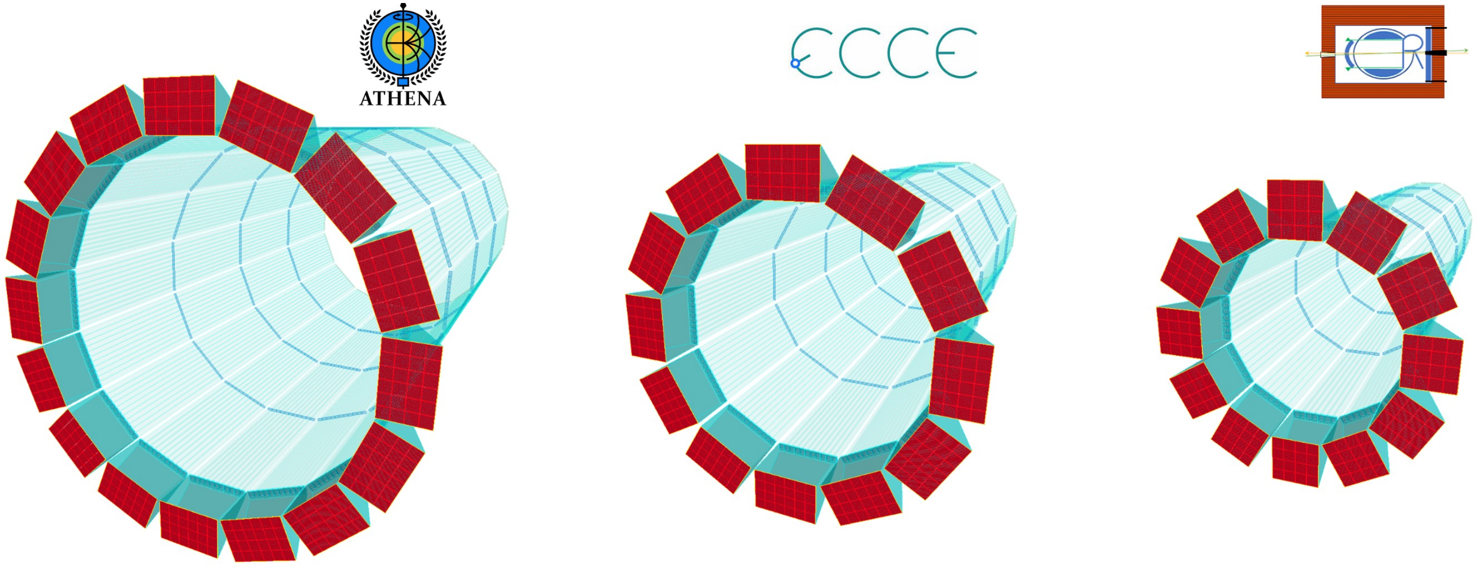


Extra Material

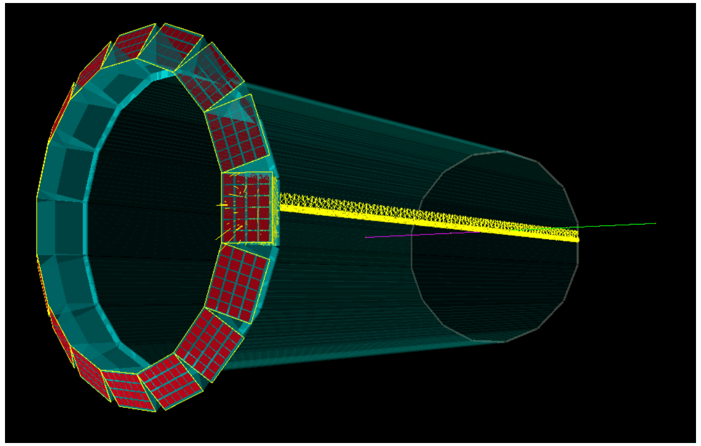
FLEXIBILITY OF HPDIRC DESIGN

- hpDIRC PID performance largely independent of number of sectors, barrel radius, and bar length – design can be optimized for integration
- Expansion volume shape can be optimized for MCP-PMT magnetic field performance (tilted sensor plane)

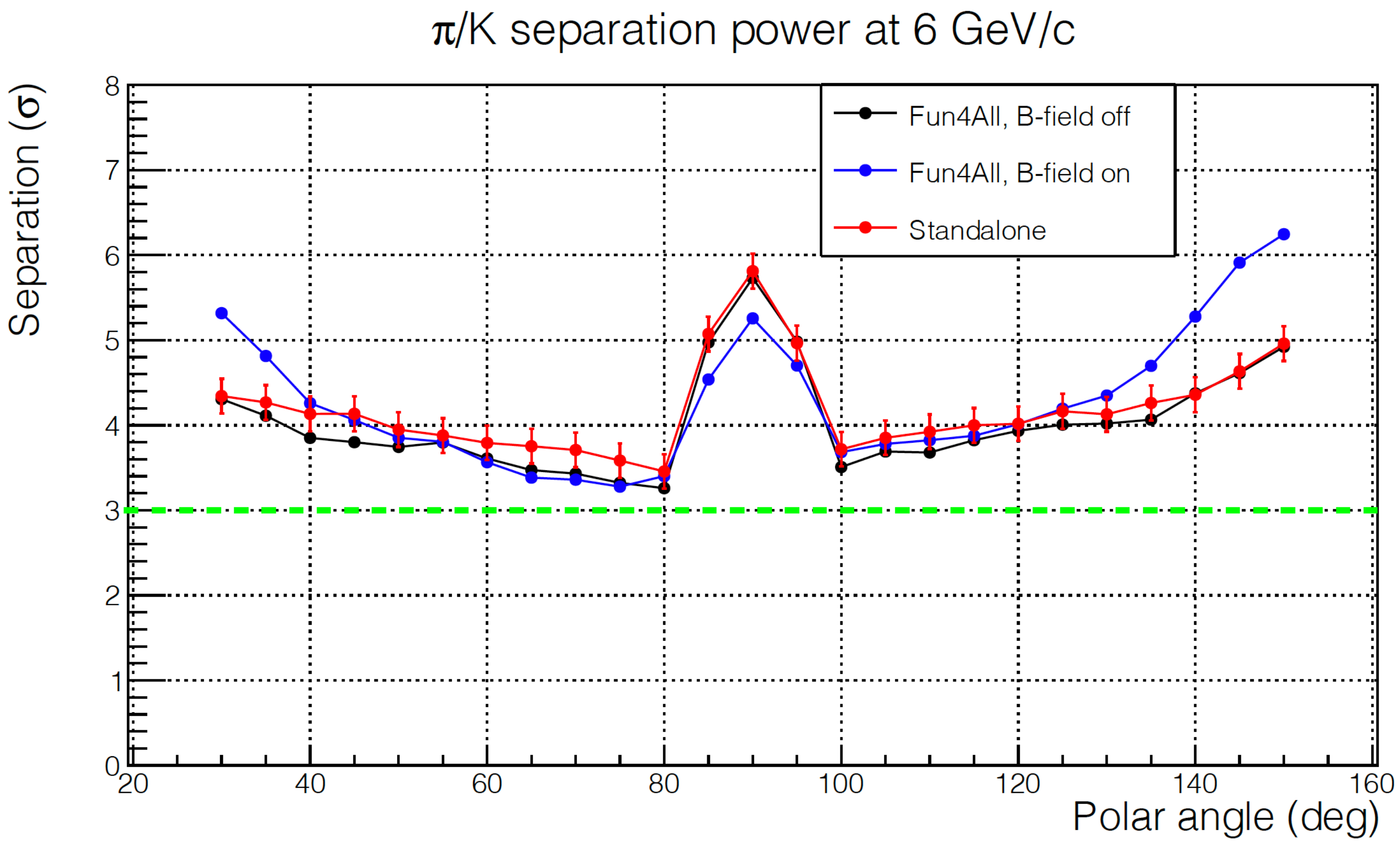




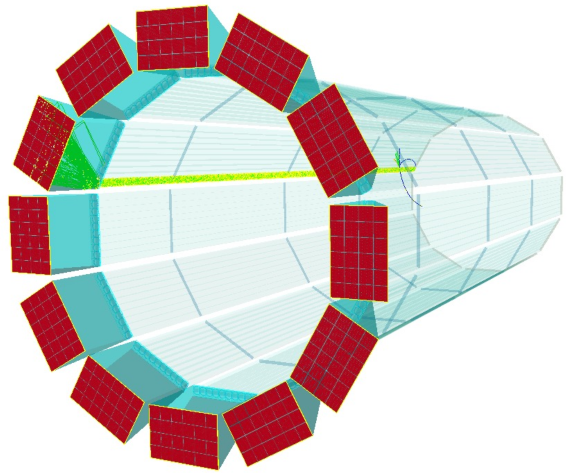
Geant4: hpDIRC designs to scale



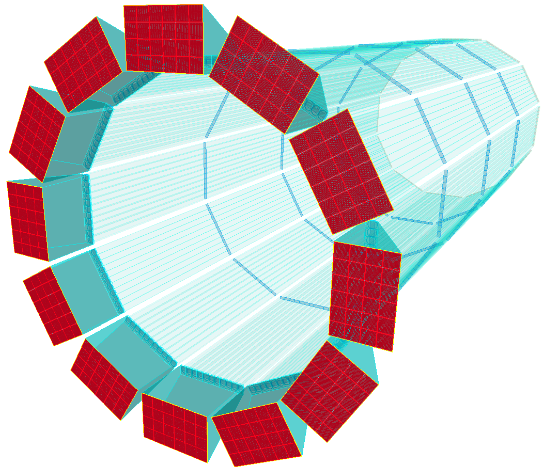
hpDIRC Simulated Performance



hpDIRC single track simulation in Fun4All



hpDIRC geometry in standalone Geant4



Comparison of hpDIRC performance in standalone G4 simulation and Fun4All

Small differences result of different physics lists

(hadronic processes absent in our standalone G4)

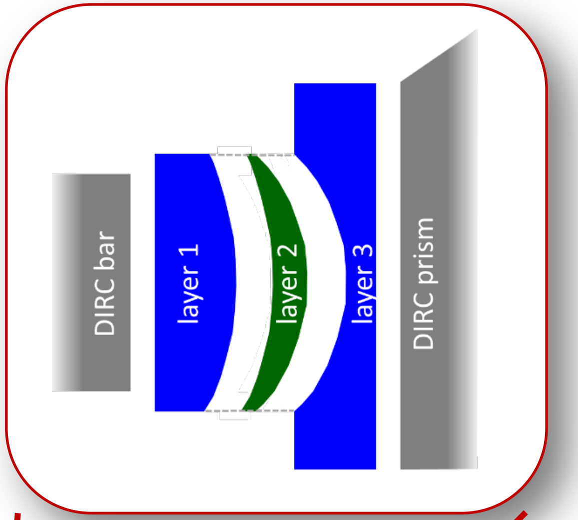
HPDIRC COMPONENTS: 3-LAYER LENS

Technical risk: hpDIRC PID design validation

- Radiation hardness and focusing performance of 3-layer lens

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

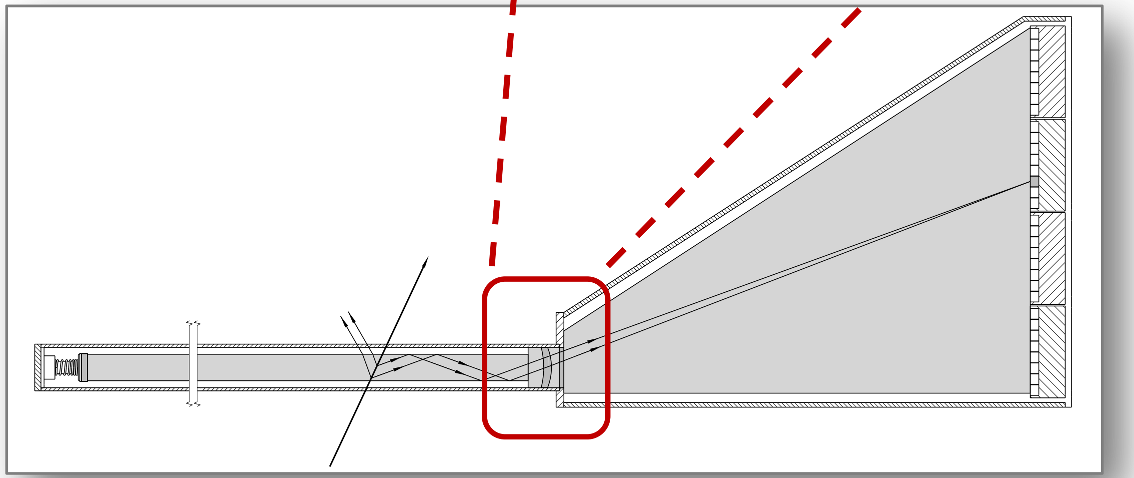


Key element of hpDIRC design:

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

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

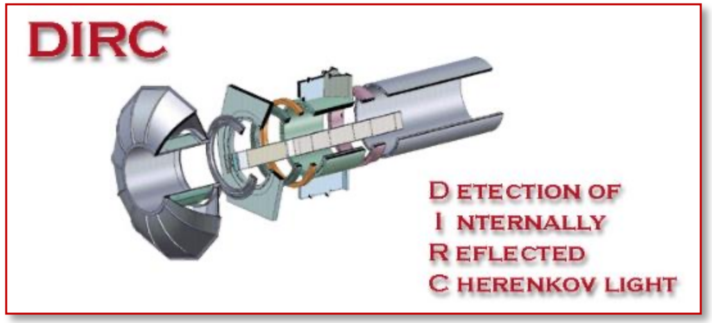
- Creates flat focal plane – matched to fused silica prism shape
- Avoids photon loss and barrel PID gap
- Successfully produced prototype lenses and validated performance in PANDA Barrel DIRC prototype with particle beams at CERN and GSI



DIRC Resolution

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

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

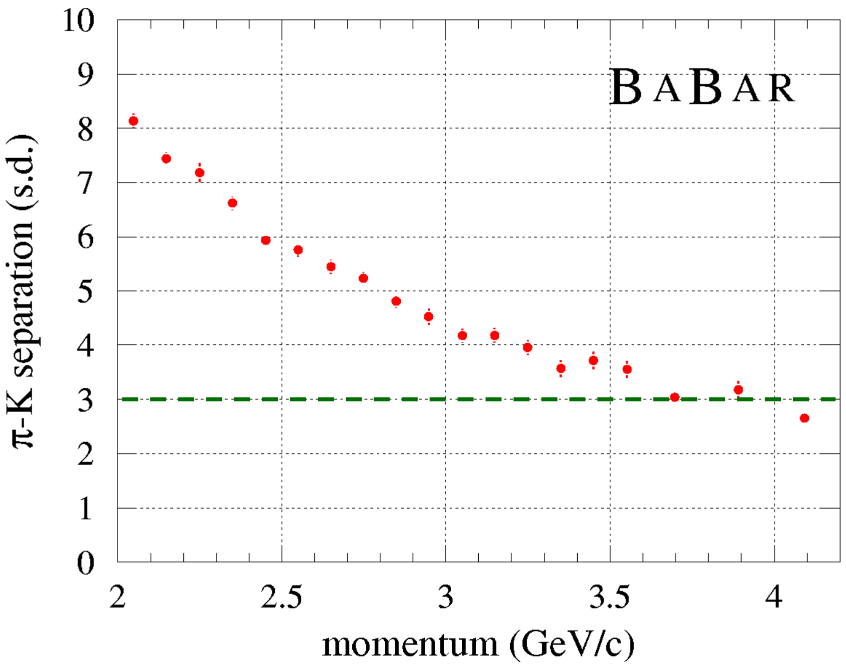


$\sigma_{\theta_c}(particle)$ Cherenkov angle resolution per particle

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

N_γ Number of detected photons per particle
(bar size, bar imperfections, Photon Detection Efficiency)

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

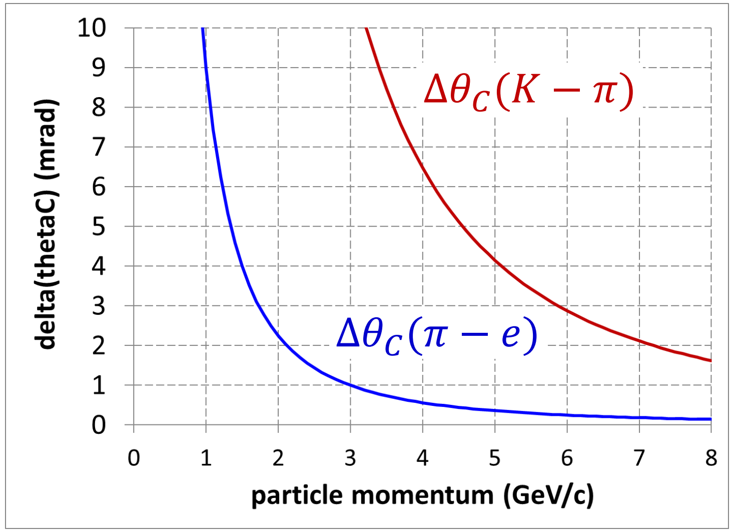


BaBar DIRC achieved 2. 4 mrad θ_C resolution at 3-4 GeV/c,

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 (θ_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 θ_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

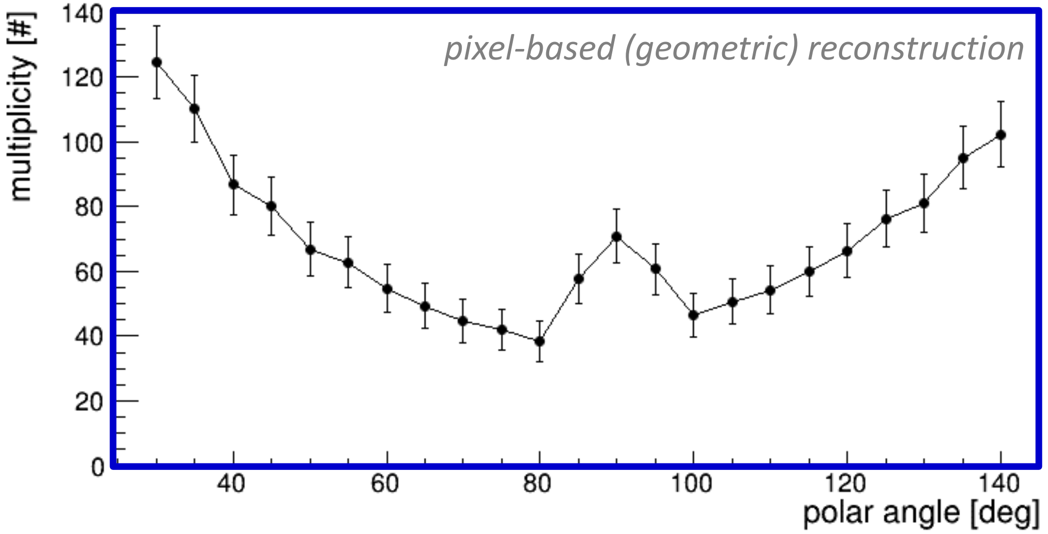
BABAR-DIRC Cherenkov angle resolution: 9.6 mrad per photon, 2.4 mrad per particle

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

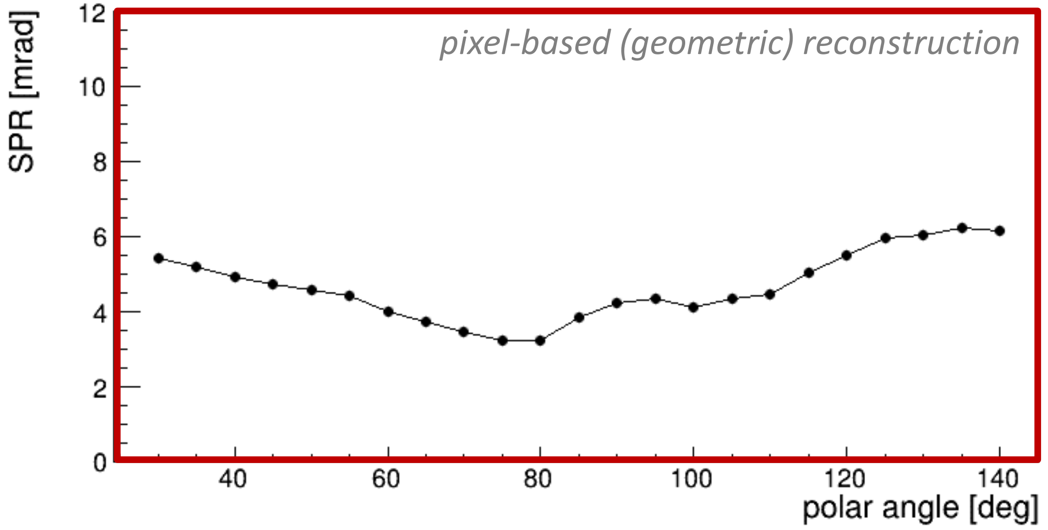
SUPERB, BELLE II, PANDA & EIC

hpDIRC Performance in Geant4

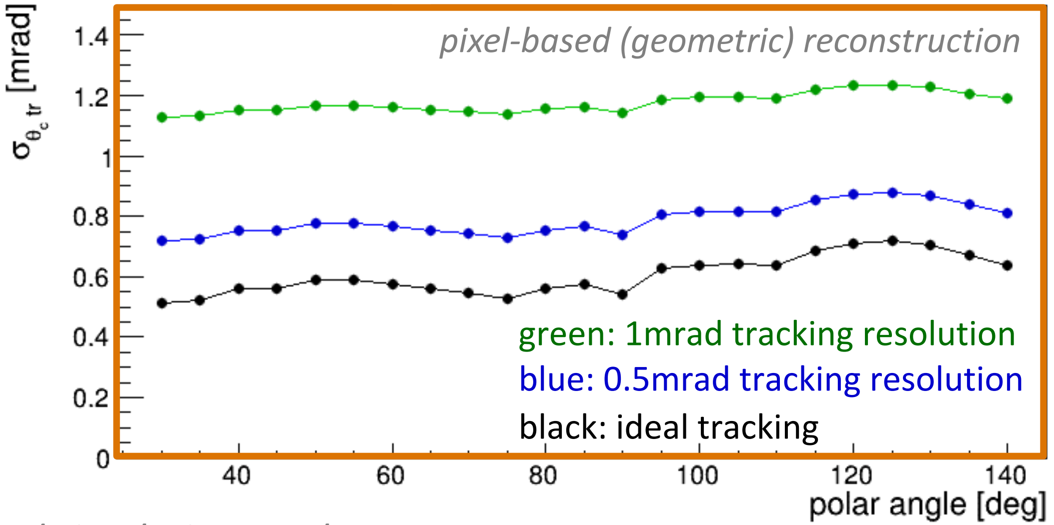
Photon yield per particle



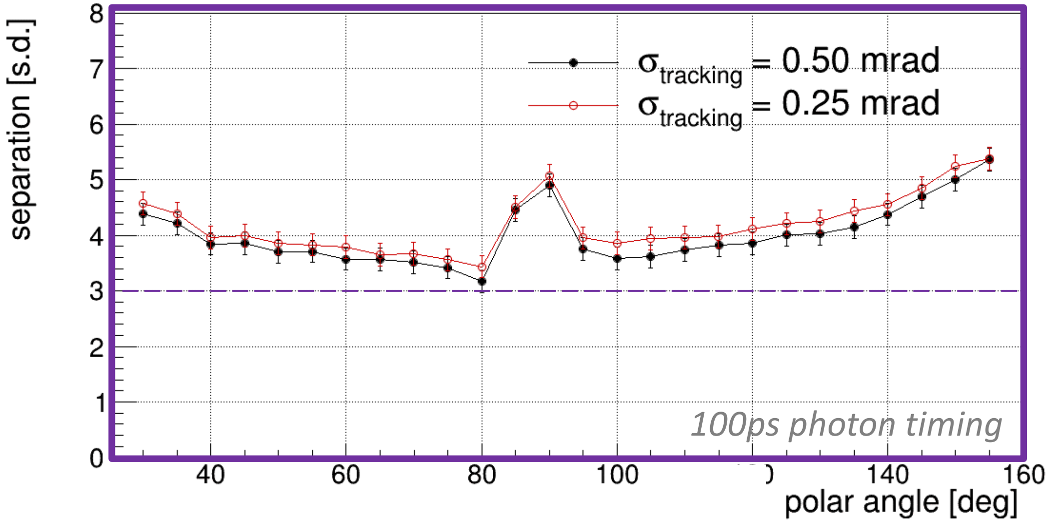
Cherenkov angle resolution per photon (SPR)



Cherenkov angle resolution angle per particle



π/K separation power at 6 GeV/c



updated simulation results, summer 2020