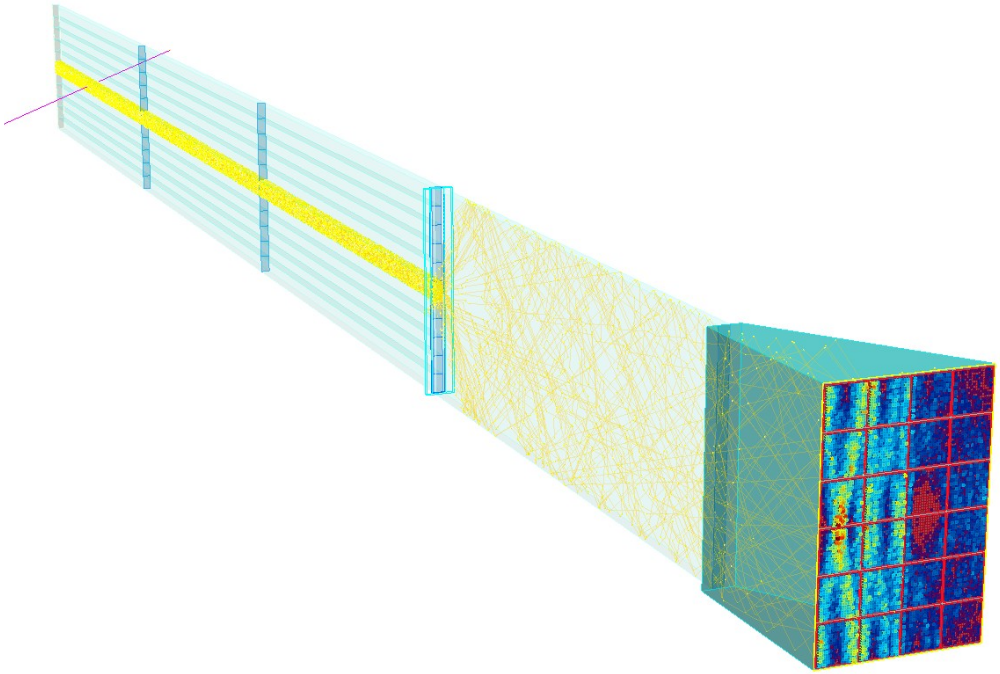
DIRC – Future Opportunities for EIC Detector-2



EICUG2023

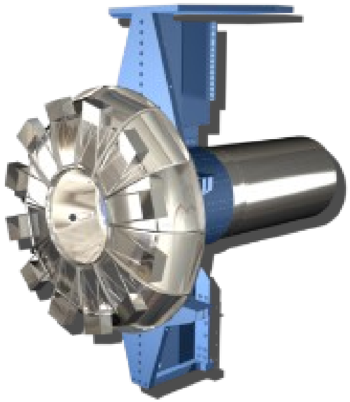
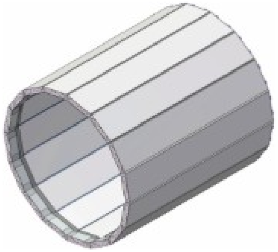
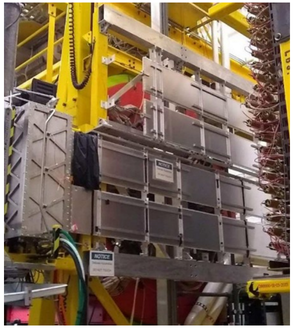
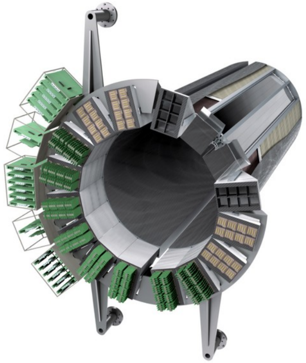
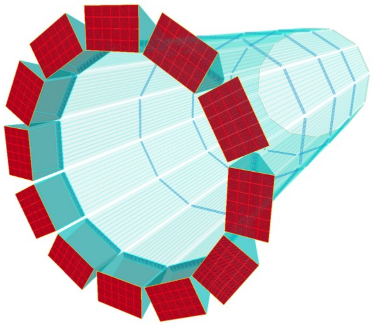
Roman Dzhygadlo GSI

- Overview
- DIRC concept / design
- Reconstruction methods
- Expected performance
- Generic R&D program

CUA GSI Stony Brook University Old Dominion University University of South Carolina Wayne State University William & Mary Jefferson Lab

DIRCs Overview

- Radially compact (few cm)
- Excellent performance
- Robust operation
- Active R&D pushing performance limits

3 s.d. π/K separation

BaBar DIRC	Belle II TOP	GlueX DIRC	PANDA Barrel DIRC	ePIC hpDIRC
3.5 GeV/c	4 GeV/c	3.7 GeV/c	3.5 GeV/c	6 GeV/c

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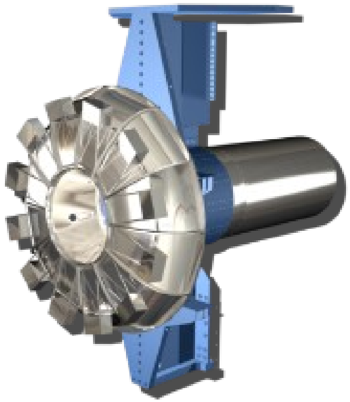
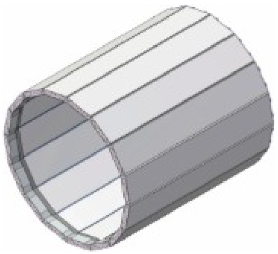
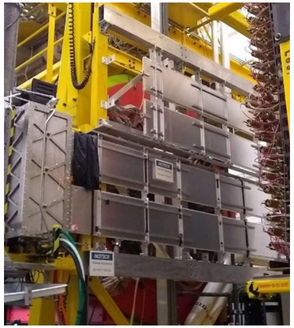
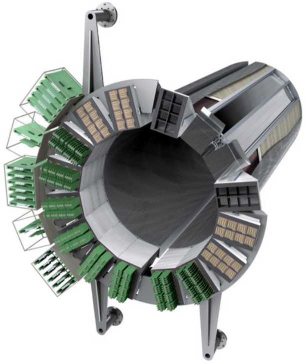
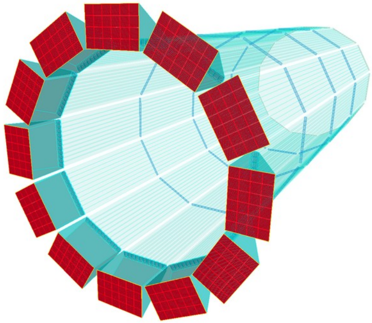
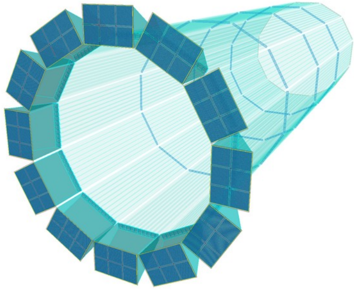







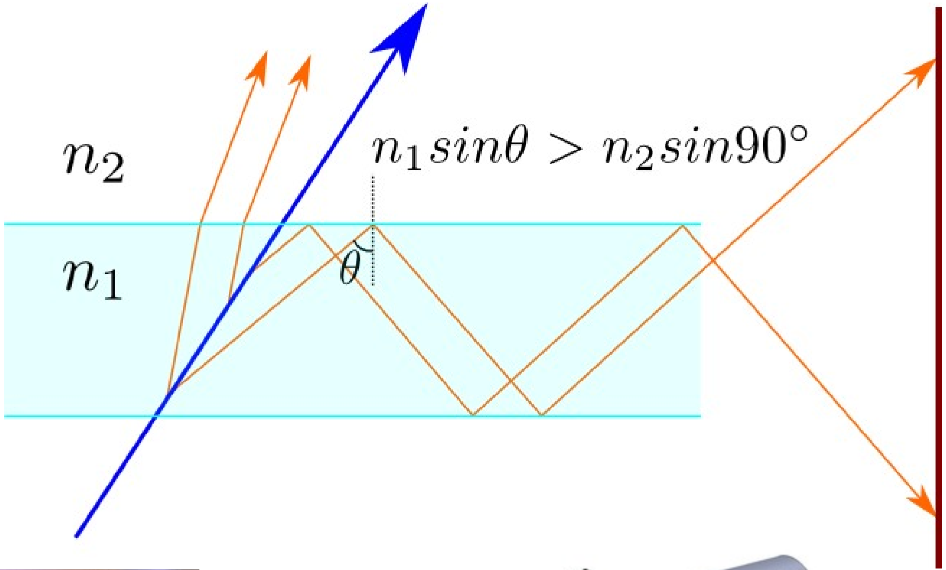
3 s.d. π/K separation

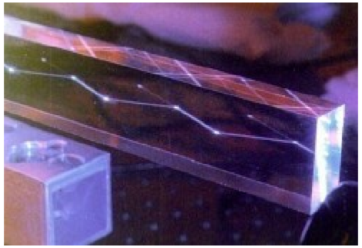
BaBar DIRC	Belle II TOP	GlueX DIRC	PANDA Barrel DIRC	ePIC hpDIRC	Det-2 xpDIRC
3.5 GeV/c	4 GeV/c	3.7 GeV/c	3.5 GeV/c	6 GeV/c	? GeV/c

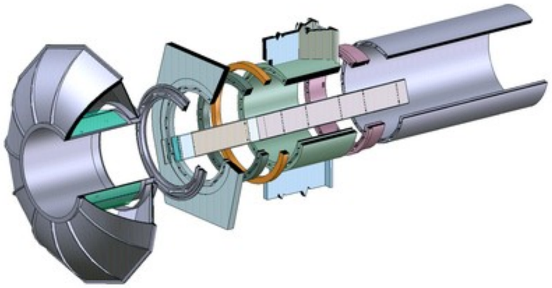
DIRC Concept

Detection of **I**nternally **R**eflected **C**herenkov Light

- Charged particle traversing radiator with refractive index ($n_1 \approx 1.47$) and $\beta = v/c > 1/n$ emits Cherenkov photons on cone with half opening angle $\cos\theta_c = 1/\beta n(\lambda)$
- Some photons are always totally internally reflected for $\beta \approx 1$ tracks
- Radiator and light guide: polished, long rectangular bar made from Synthetic Fused Silica ("Quartz")
- Proven to work (BaBar-DIRC: 3 s.d. for π/K at 3.5 GeV/c)

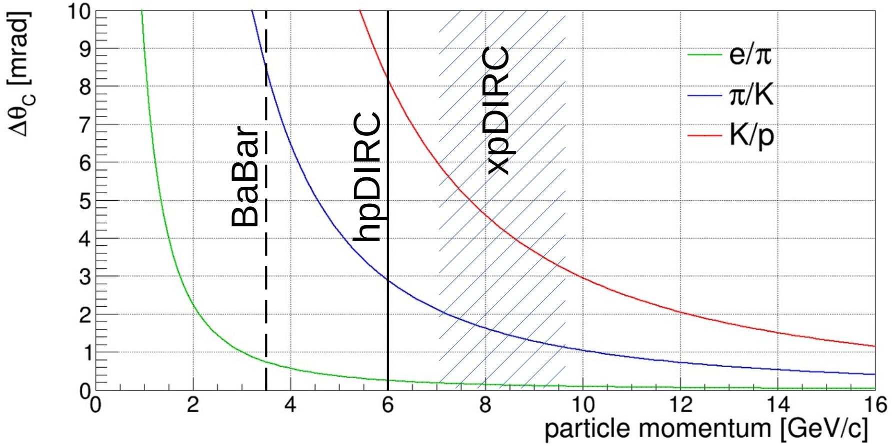






Cherenkov Angle Resolution

Cherenkov track difference:



Cherenkov track resolution:

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

improve angular resolution of tracking system, mitigate multiple scattering impact

use photon detectors better PDE, improve Cherenkov angle resolution per photon

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

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

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

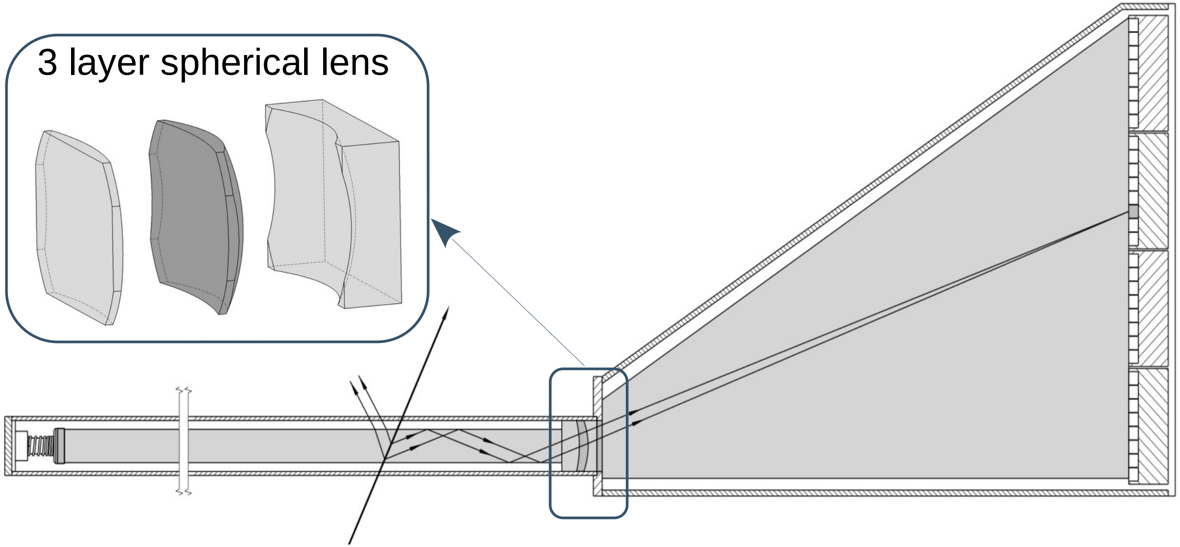
SUPERB, BELLE II, PANDA & EIC

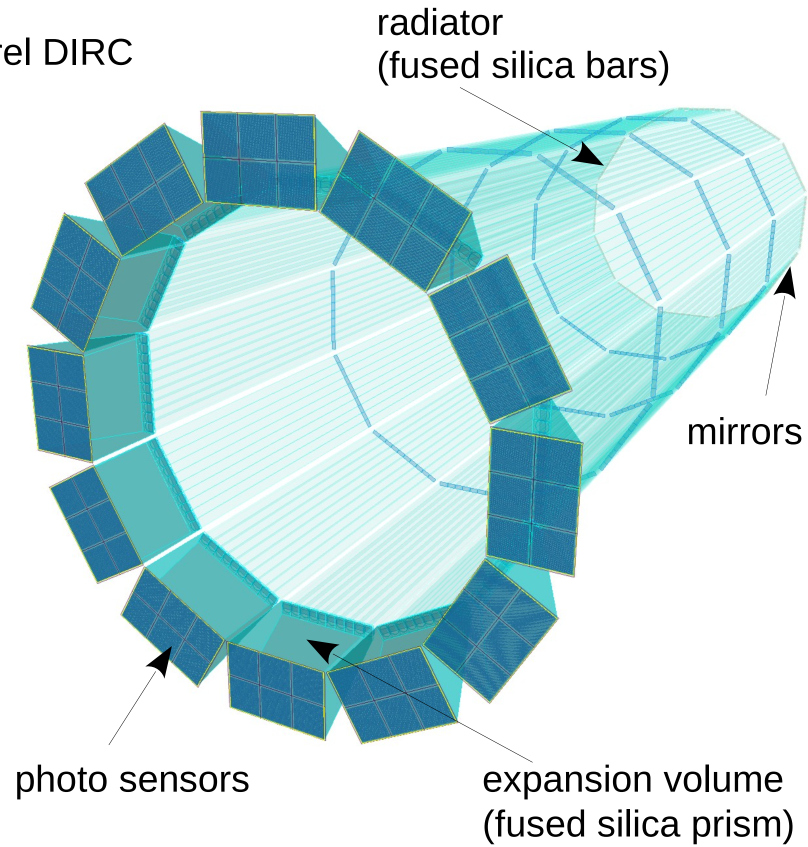
~ 1 mrad for hpDIRC

< 1 mrad for xpDIRC

Generic Design

- 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





hpDIRC Preliminary Baseline Design

Greg Kalicy: “DSC-hpDIRC” EICUG23 Fri 28/07

Radiator bars:

- Barrel radius: 720 mm, 12 sectors
- 10 long bars per sector, 4880 mm x 35 mm x 17 mm (L x W x T)
- Long bar: 4 bars, glued end-to-end
- Short bars made from highly polished synthetic fused silica
- Flat mirror on far end

Focusing optics:

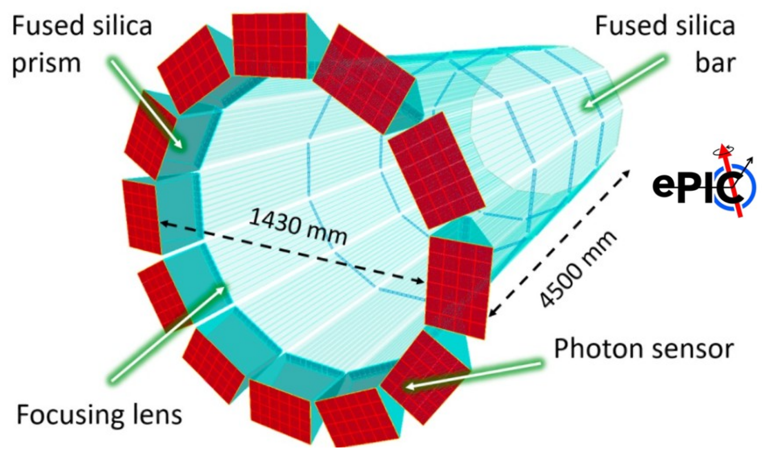
- Radiation-hard 3-layer spherical lens (sapphire or PbF2)

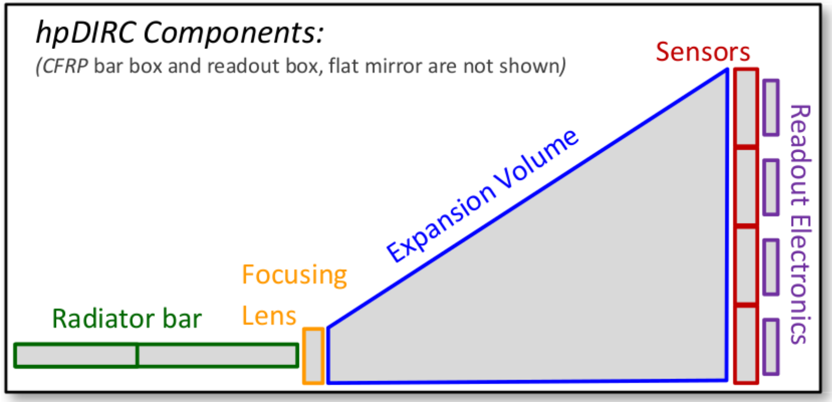
Expansion volume:

- 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. EICROC)

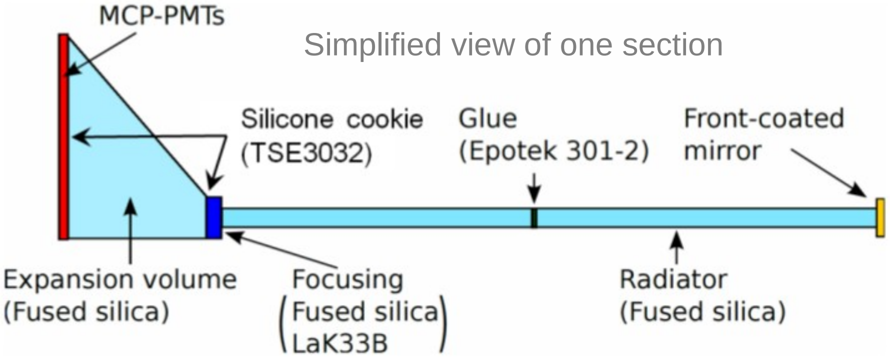


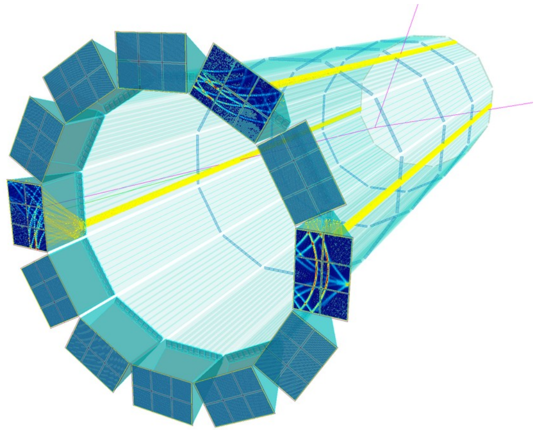


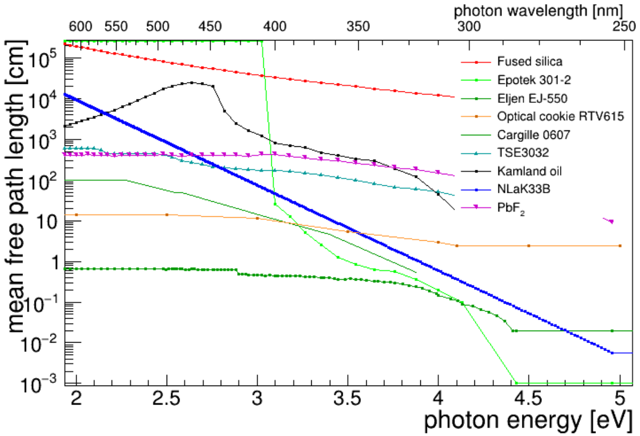
Performance Evaluation with Simulations

Geant4 simulations includes:

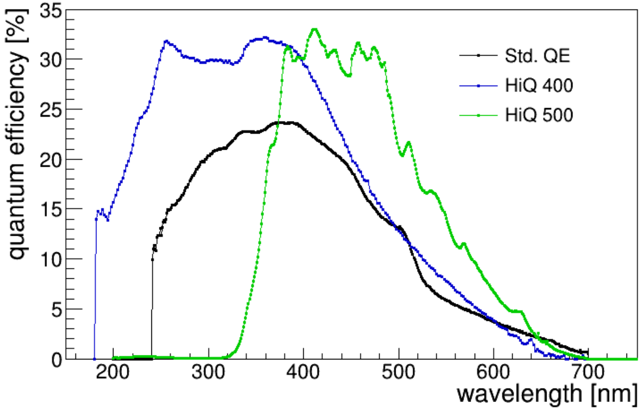
- realistic material
- wavelength dependent refraction and absorption
- mirror reflectivity
- photon transport efficiency
- wavelength dependent photon detection efficiency
- detection time precision
- tracking resolution







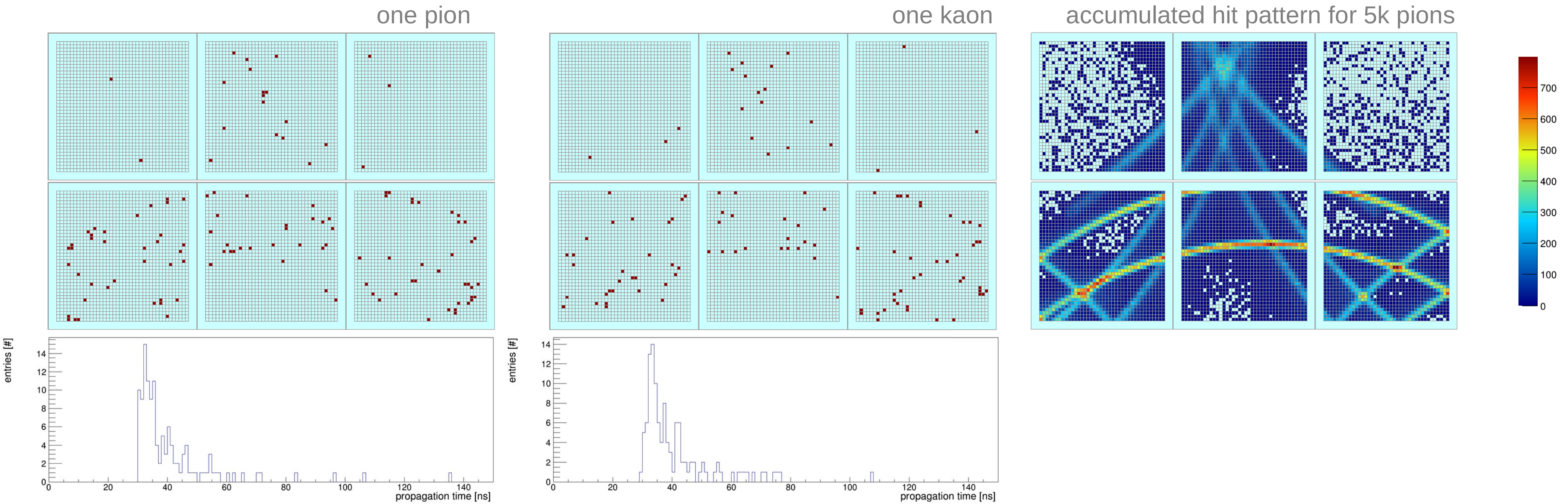
Quantum efficiency of different MCP-PMTs



Observables

- Photon yield
- Photon hit position
- Photon propagation time (~100 ps precision)

Examples for p = 6 GeV/c and θ = 30°



Reconstruction Methods

Geometrical

- BaBar-like
- uses Look-Up Tables
- delivers Cherenkov angle per particle and Single Photon Resolution (useful for calibration)
- does not depend on precise time measurement

Time Imaging

- Belle II TOP-like
- uses Probability Density Functions
- optimal use of position and time information

Neural Networks

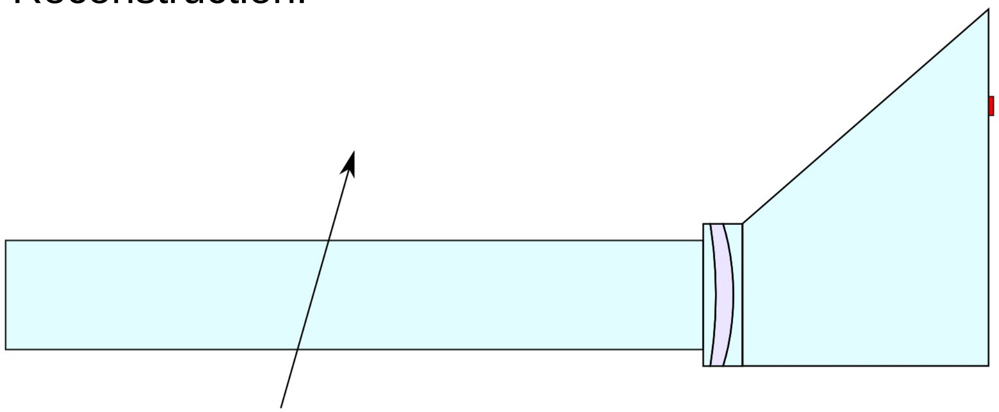
- Under development

Geometrical Reconstruction

Look Up Table generation:

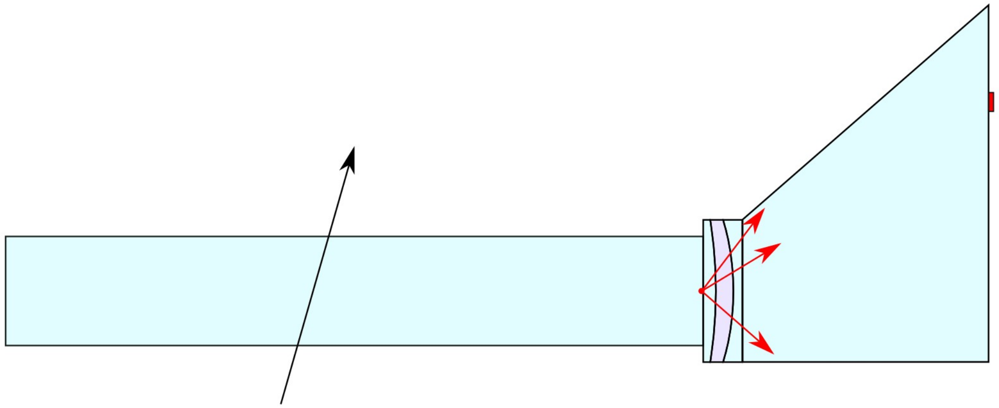
Geometrical Reconstruction

Reconstruction:



Geometrical Reconstruction

Reconstruction:



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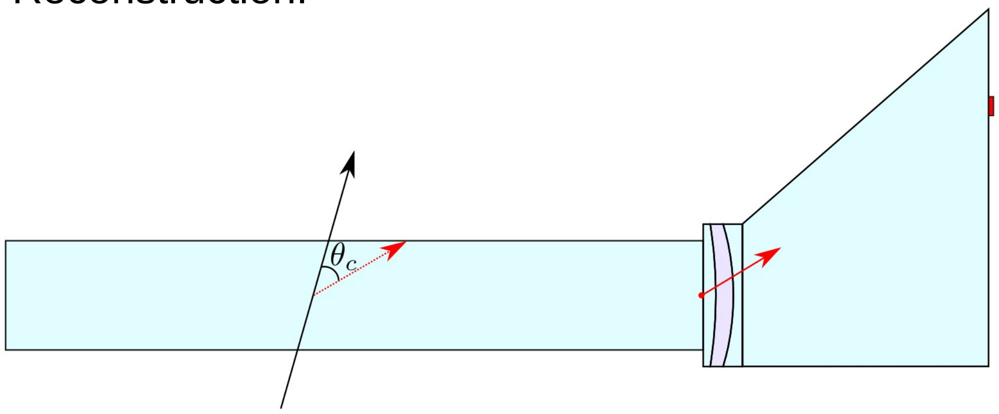

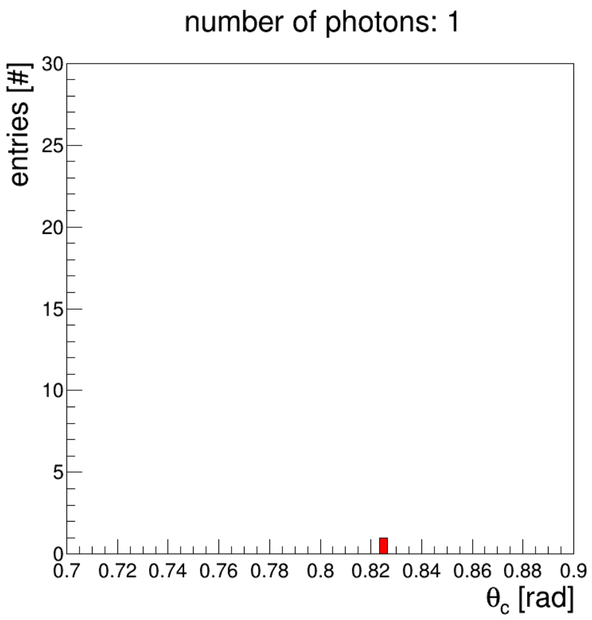

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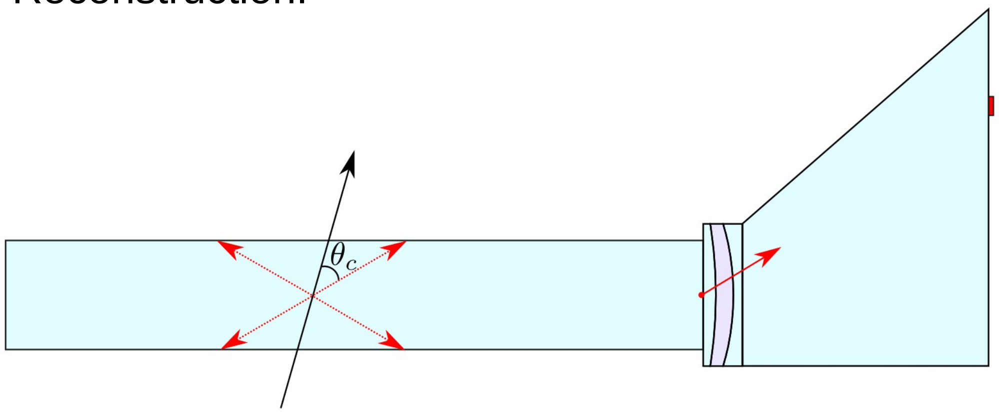

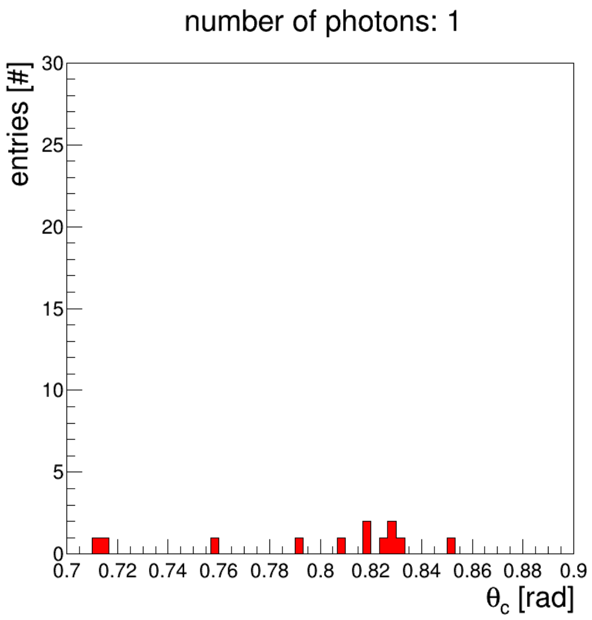

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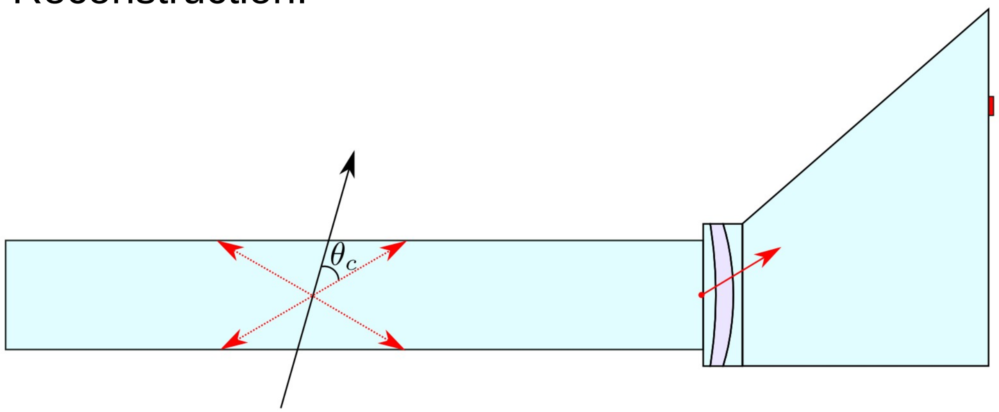

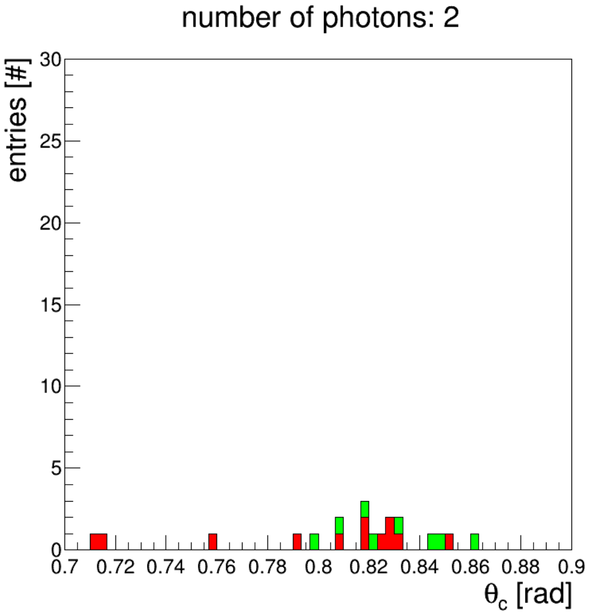

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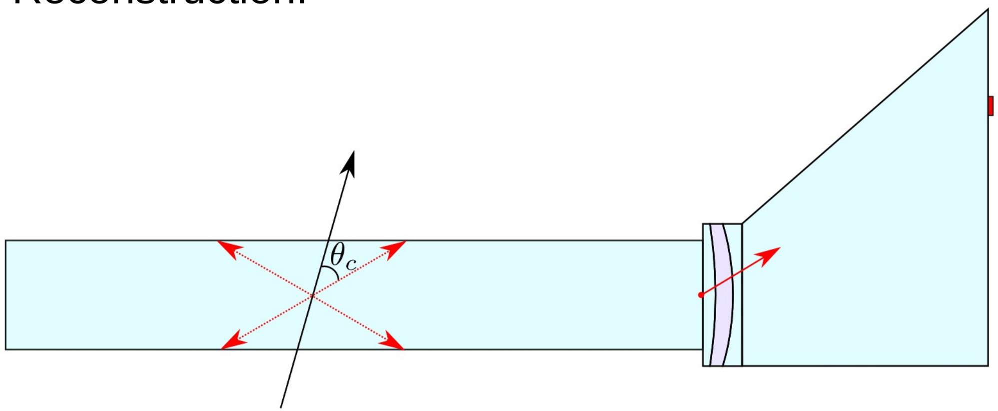

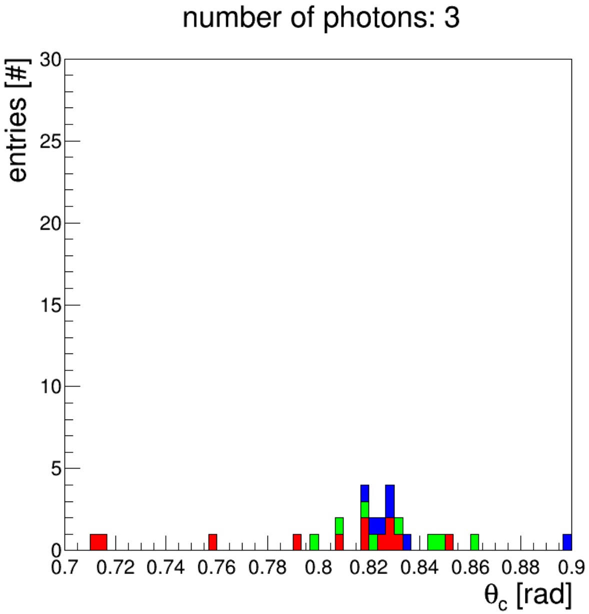

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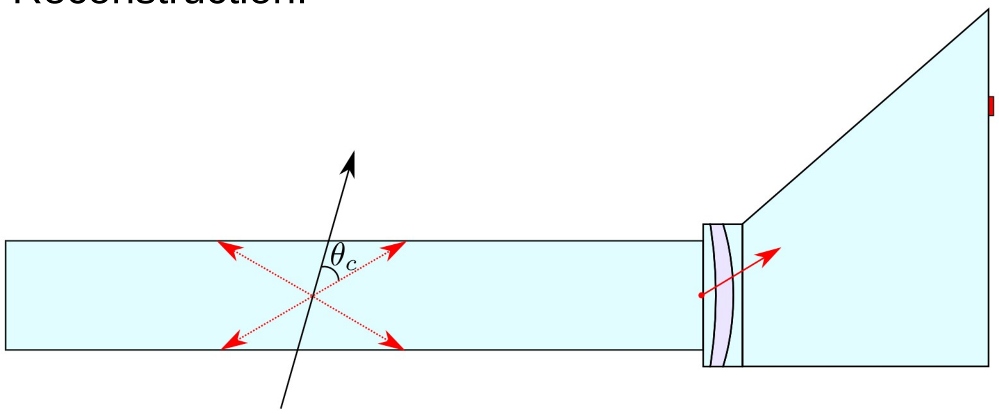

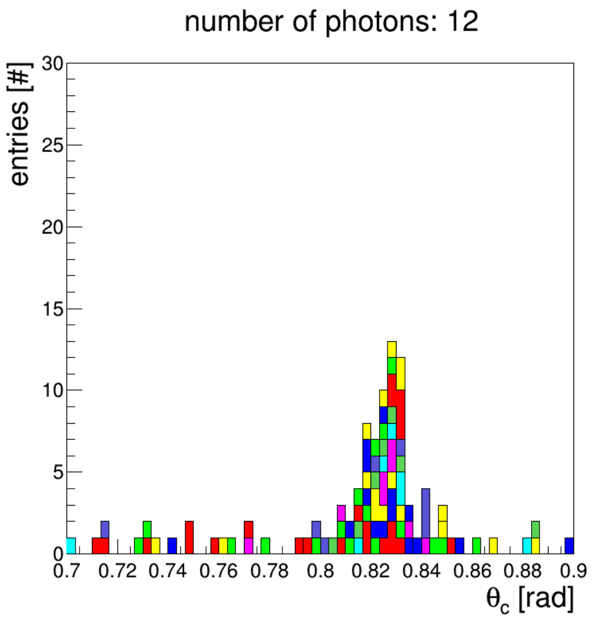

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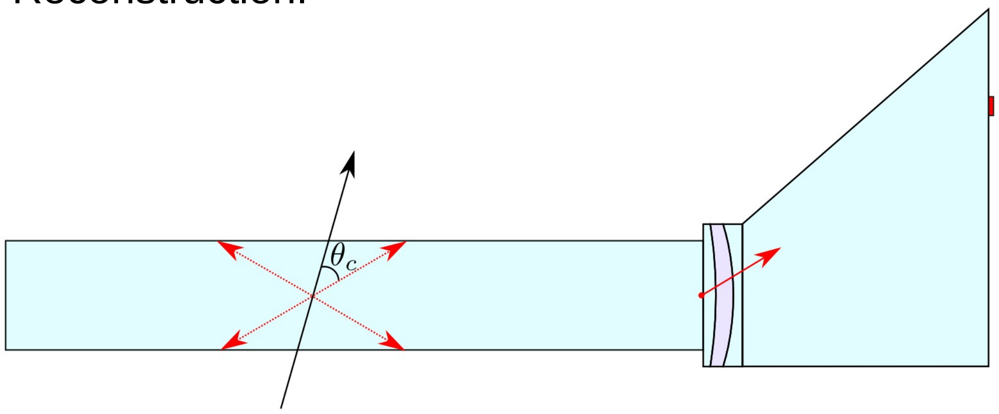

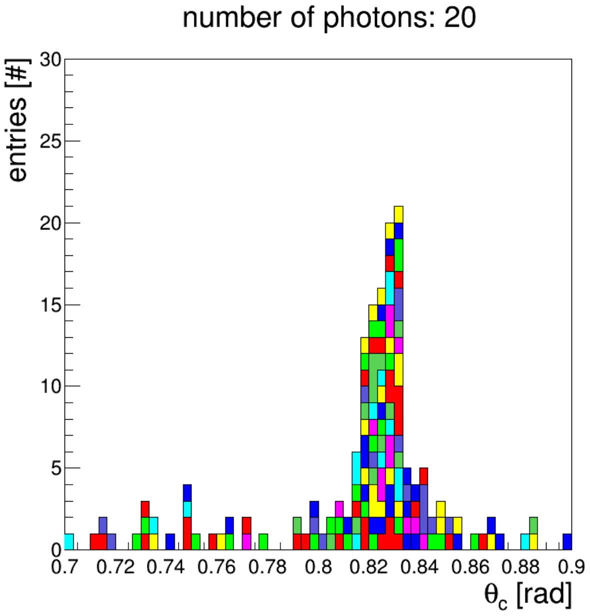

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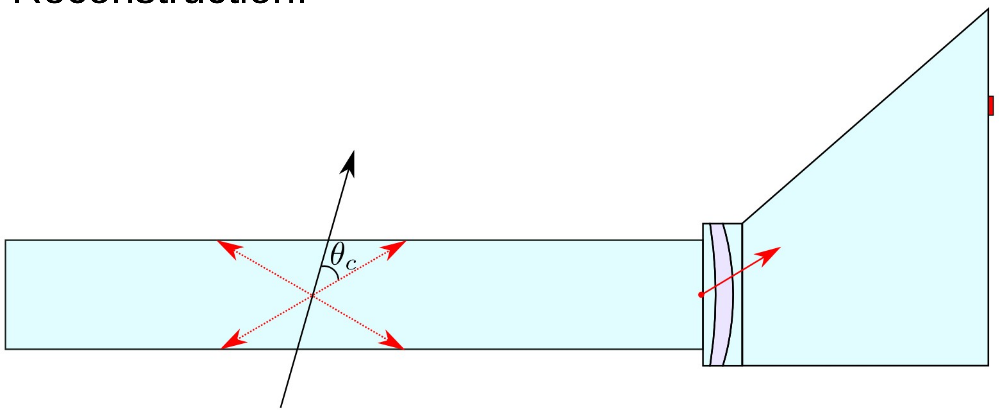

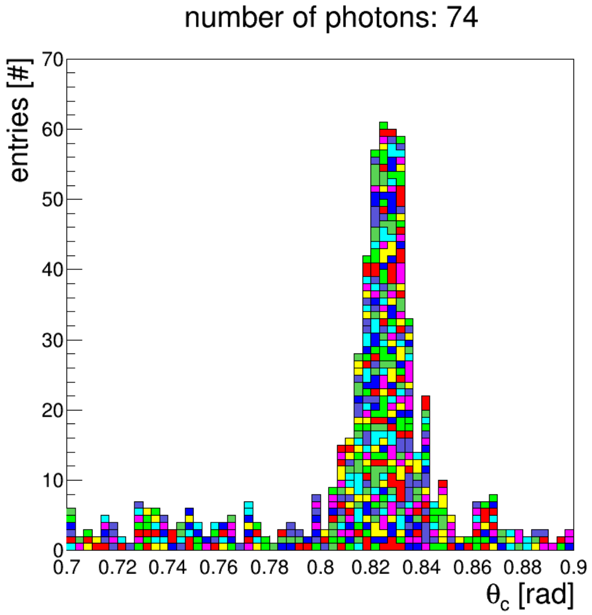

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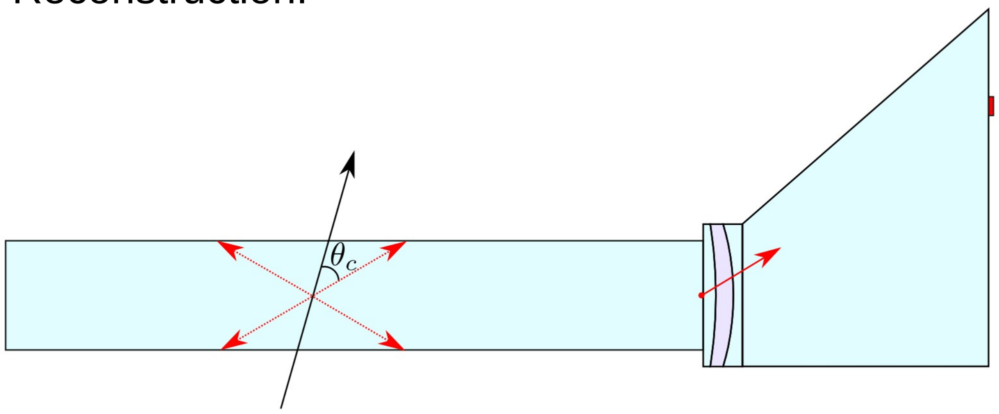

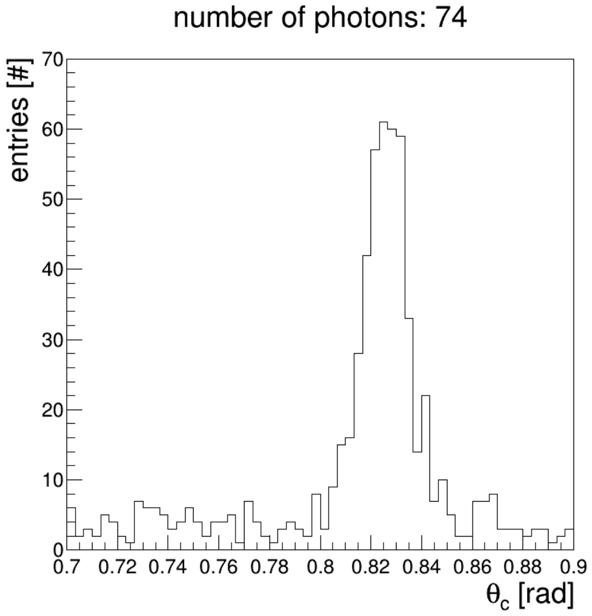

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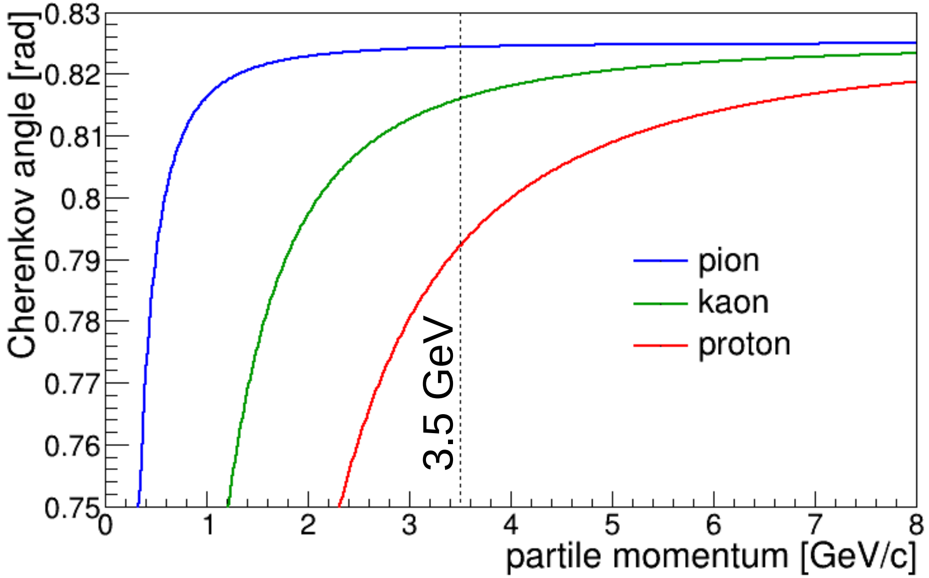
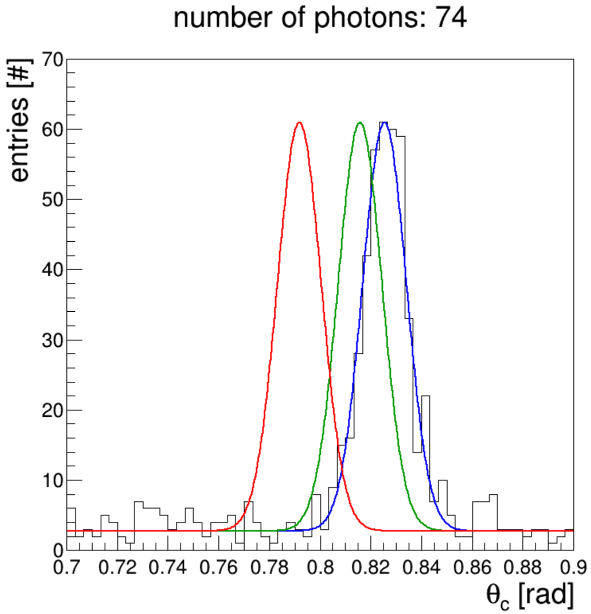




Likelihood calculation:

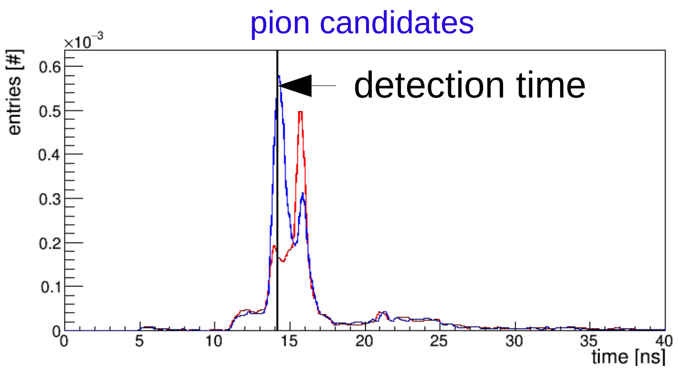
$$\log\mathcal{L}_h = \sum_{i=1}^{N} \log(S_h(c_i) + B_h(c_i)) + \log P_h(N)$$

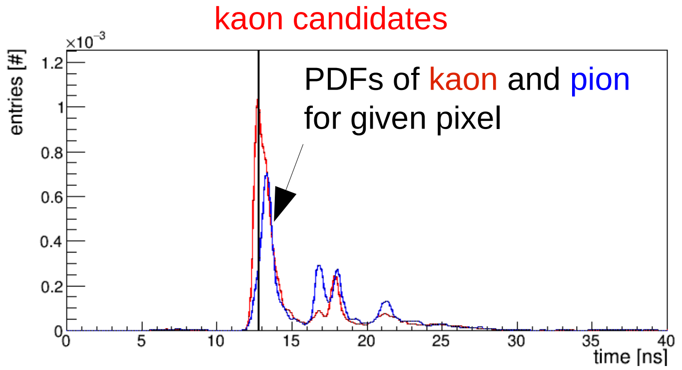
signal — combinatorial background

Time Imaging

TI likelihood:

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





Probability density functions

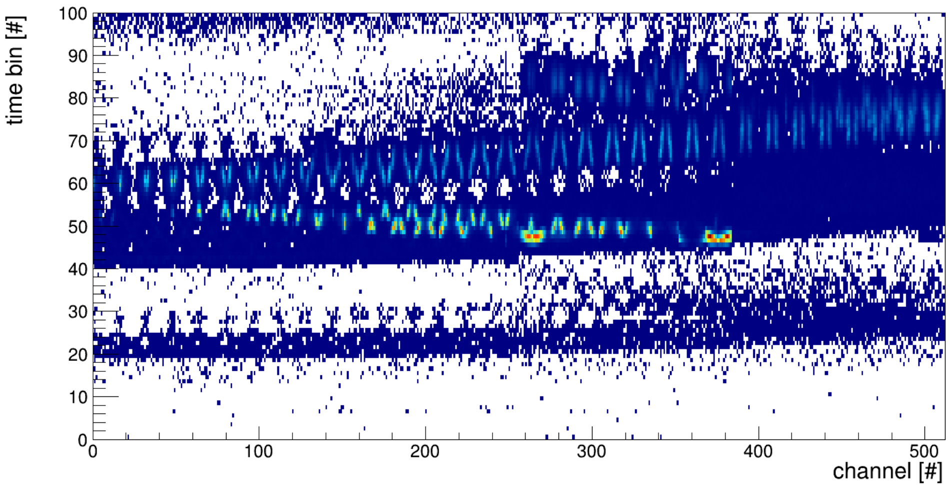
- from data: best PID, requires a large amount of data in whole angular and momentum acceptance
- simulated: full Geant4 simulation of every possible particle type direction and momentum
- analytical: fast, low memory footprint
  - initially developed for Belle II TOP (M. Staric, et al., Nucl. Inst. and Meth. A 595 (2008) 252)
  - modified to account for spherical lens focusing (PDFs using LUT)

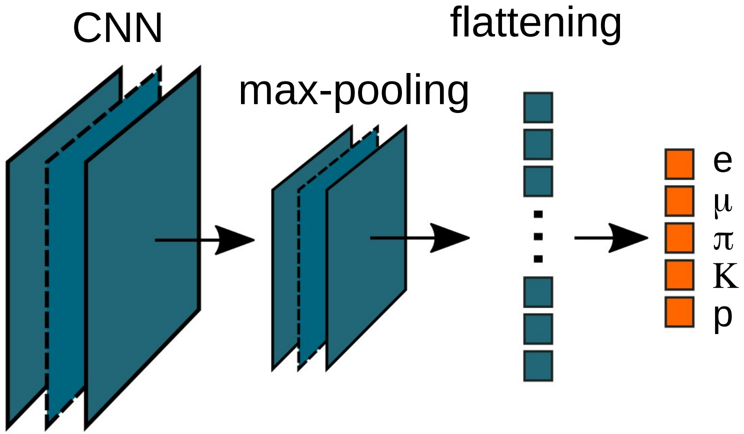
(R. Dzhygadlo et al. 2020 JINST 15 C09050, arXiv:2009.09927)

Neural Network Reconstruction

- directly using binned time and channel id to provide PID
- training relatively fast (for specific angles)
- performance comparable with Time Imaging (for specific angles)

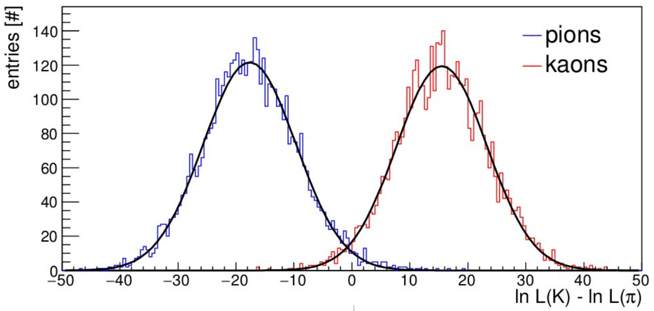
input to the neural network





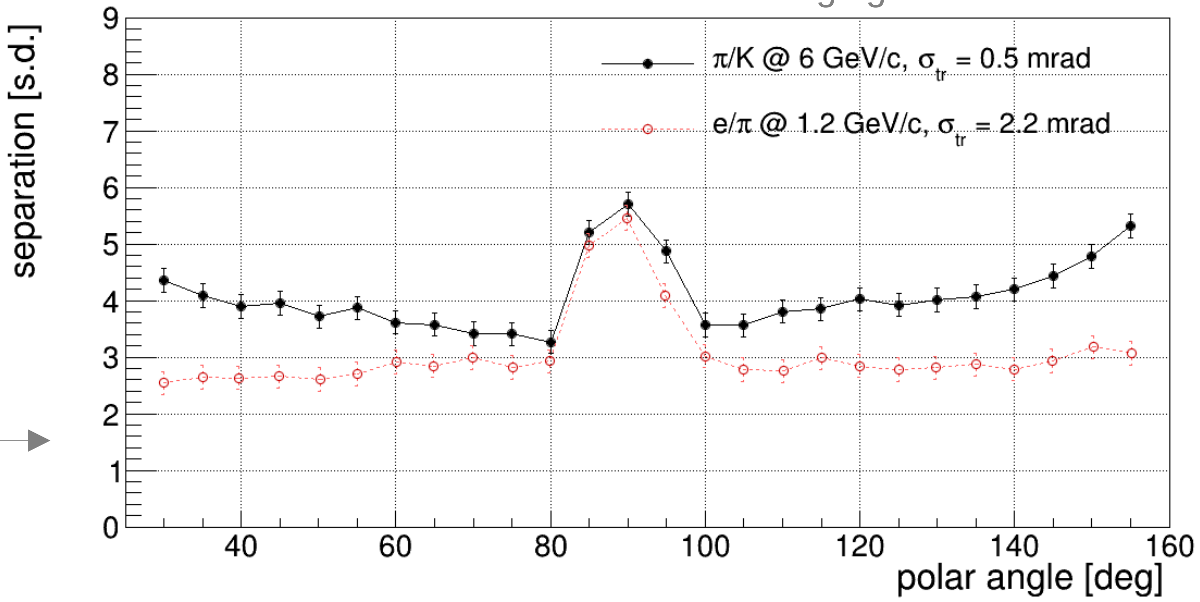
Expected Performance for hpDIRC design

track-by-track max. likelihood fit



$$N_{\mathrm{sep}} = \frac{|\mu_1 - \mu_2|}{0.5(\sigma_1 + \sigma_2)}$$

Time Imaging reconstruction



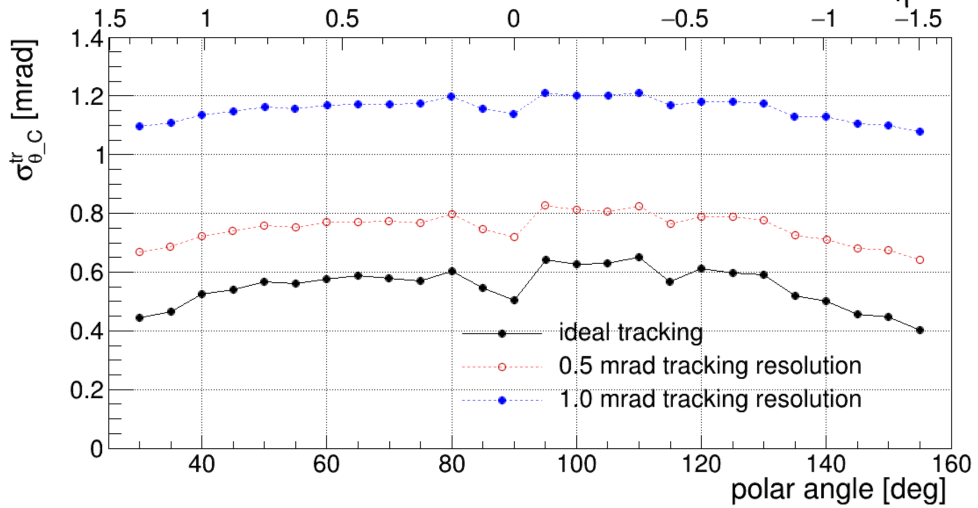
Performance vs Tracking Resolution

$$\sigma_{\theta_C}^{\text{track}} = \sqrt{\left(\frac{\sigma_{\theta_C}^{\text{photon}}}{\sqrt{N_{\text{photons}}}}\right)^2 + \left(\sigma^{\text{correlated}}\right)^2}$$

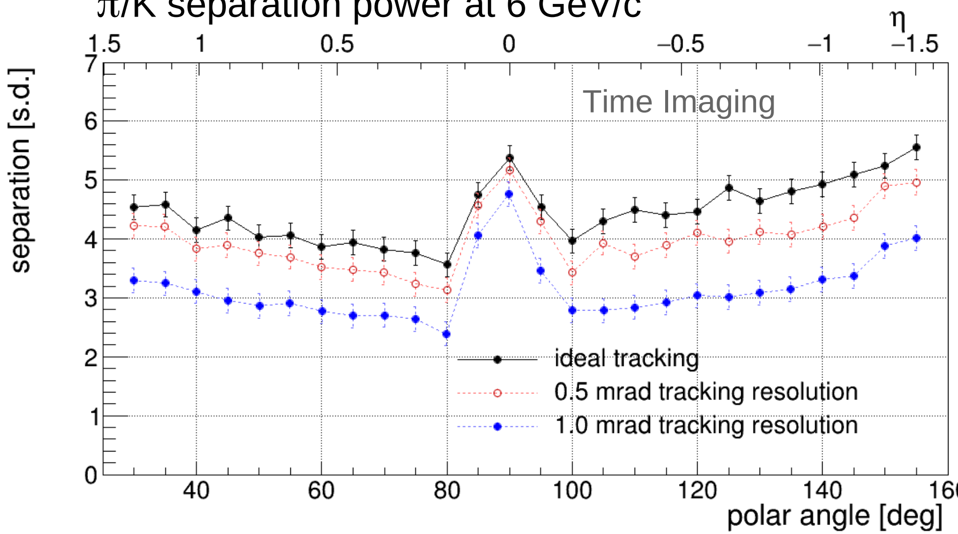
what we need from the tracking:

- magnitude
- direction (~0.5 mrad)
- impact position in the radiator (~mm)

Cherenkov angle resolution per particle



π/K separation power at 6 GeV/c

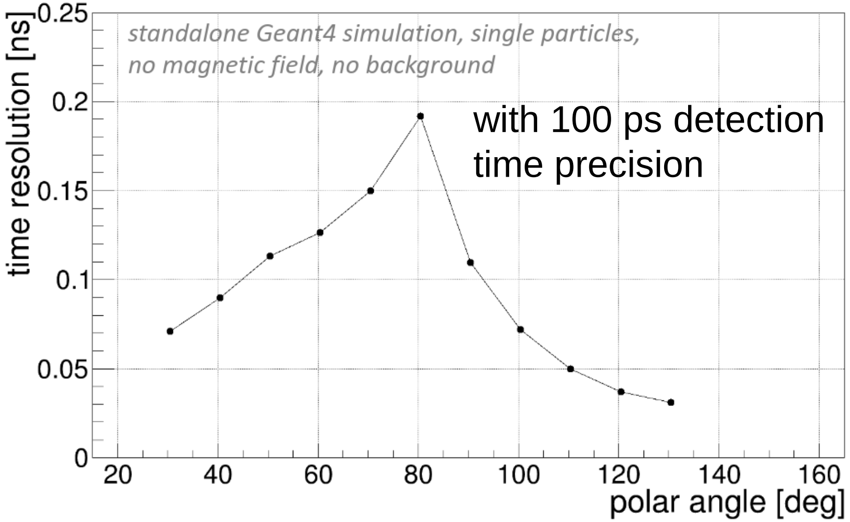


→ high-precision tracking resolution is crucial for reaching best performance

Start Time

- average time of Cherenkov light emission per particle can be obtained from difference between measured and calculated arrival time for each detected photon

resolution of the determined start time:



- good precision for large number of photoelectrons and steep angles
- can be useful as TOF "stop time" if event T_0 is known

Generic R&D for EIC Detector-2

EICGENRandD22

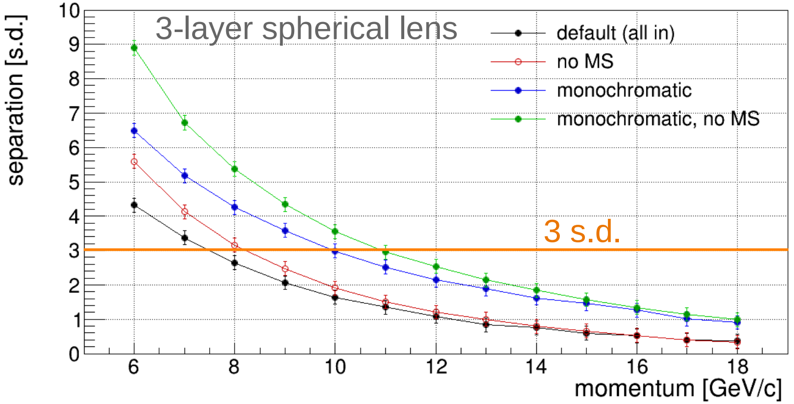
- Performance of hpDIRC baseline design good match to ePIC PID requirements but planned reuse of BaBar DIRC bars limits some design options
- xpDIRC for Detector-2 has no such constrains
- EICGENRandD22 is aimed to investigate ways to improve on the ePIC hpDIRC design for Det-2
  - extending the π/K limit to higher momenta
  - reducing the material budget

Generic R&D for EIC Detector-2

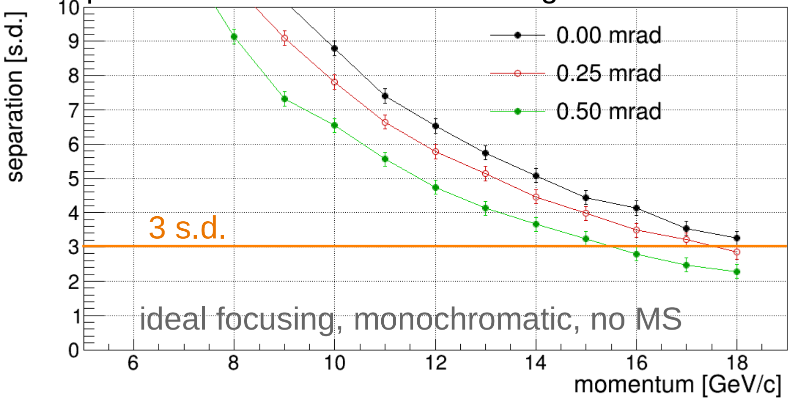
Factors constraining performance:

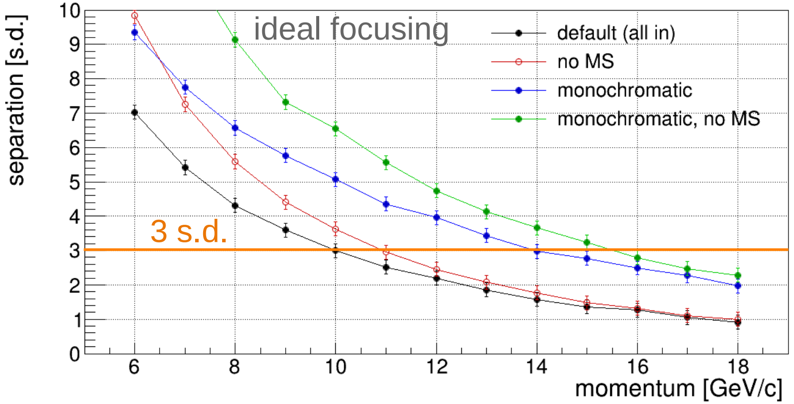
- multiple scattering (MS) inside the bar (dominates at lower momentum)
- chromatic dispersion of angle and time
- aberrations of focusing system
- time precision
- photo-sensor's pixel dimensions

π/K @ 30°, 100 ps time precision,
1.7 mm pixel size, 0.5 mrad tracking



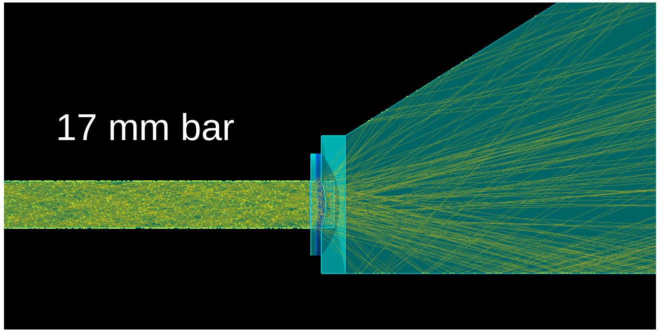
performance for different tracking resolution

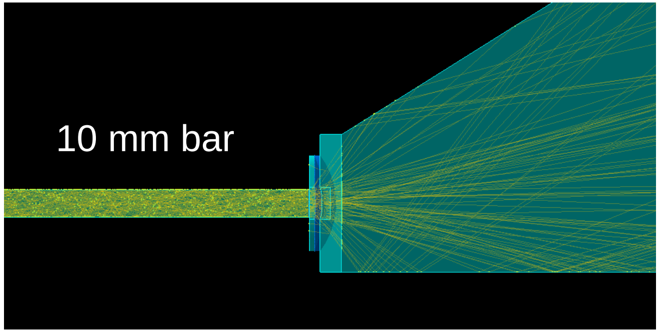


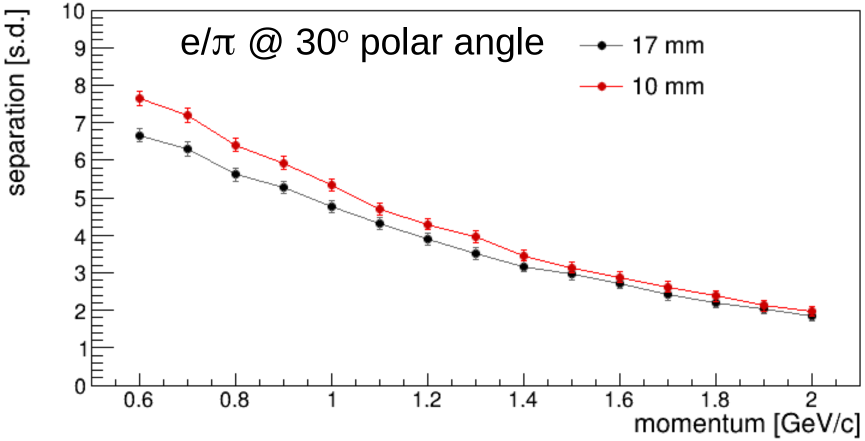


Multiple Scattering Mitigation

- thinner radiator



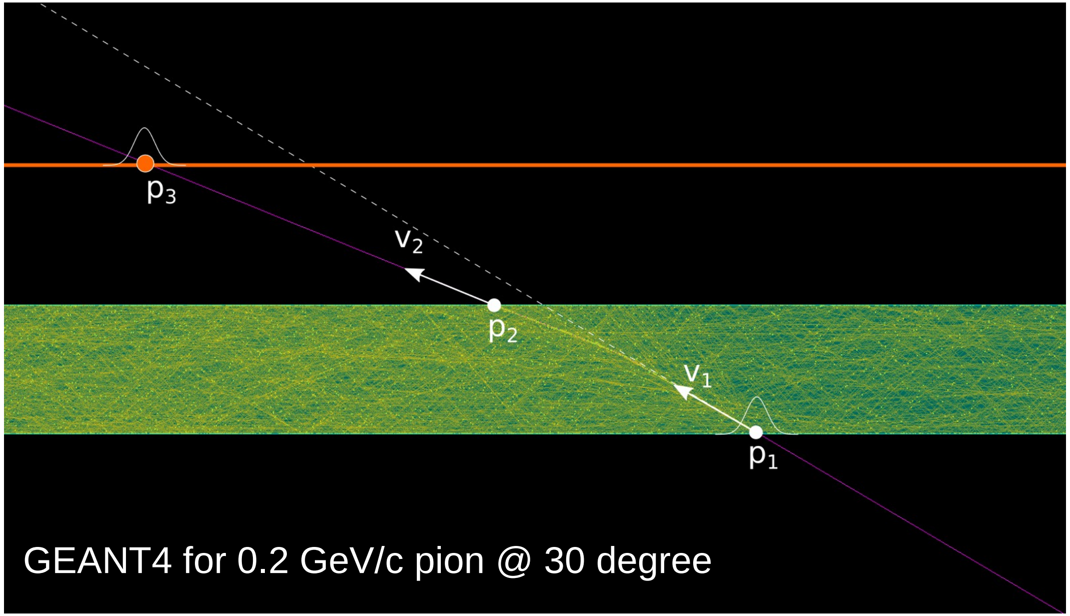




- performance gain at low momentum, especially for e/π
- make focusing less demanding
- reduce impact on EMCal performance

Multiple Scattering Mitigation

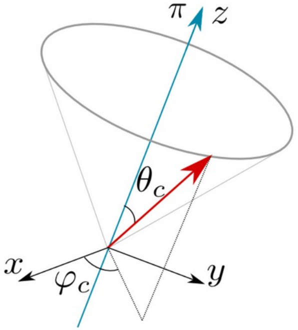
- thinner radiator
- post-DIRC tracking

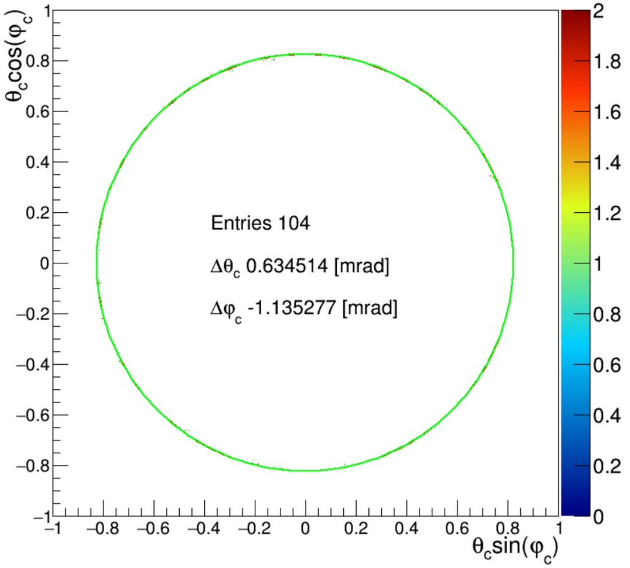


Multiple Scattering Mitigation

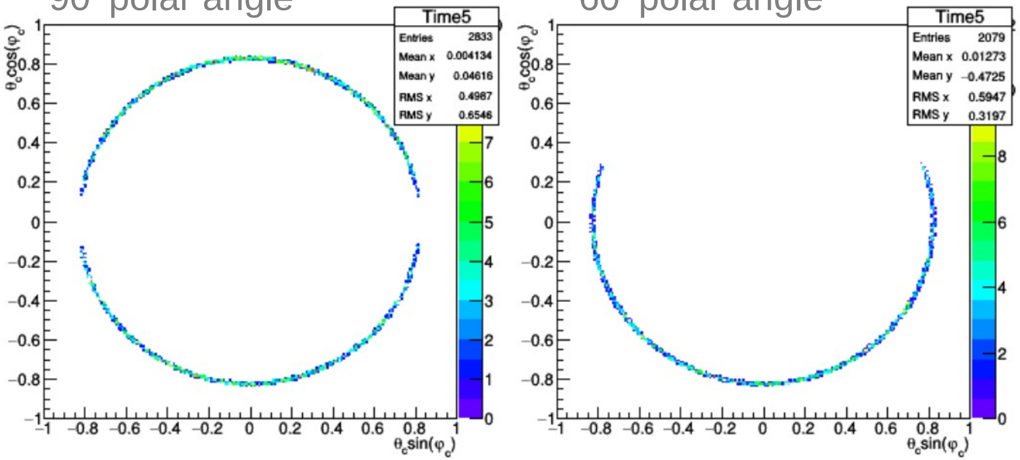
- thinner radiator
- post-DIRC tracking
- Cherenkov ring fit (corrects the direction of the charged track)

Cherenkov photons are distributed on a ring:





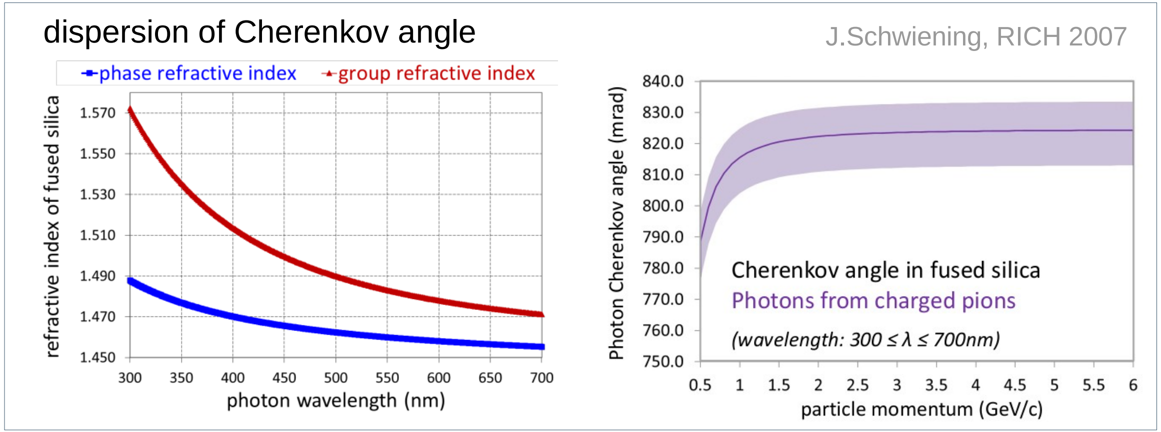
Accumulated pattern for 100 pions @ 6 GeV/c:

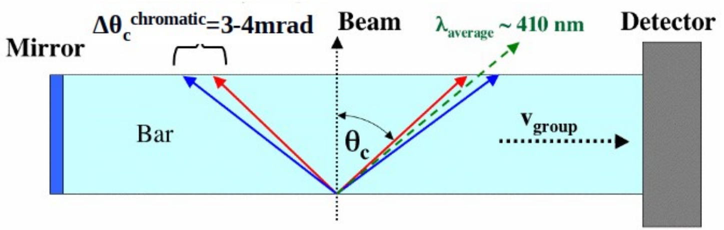


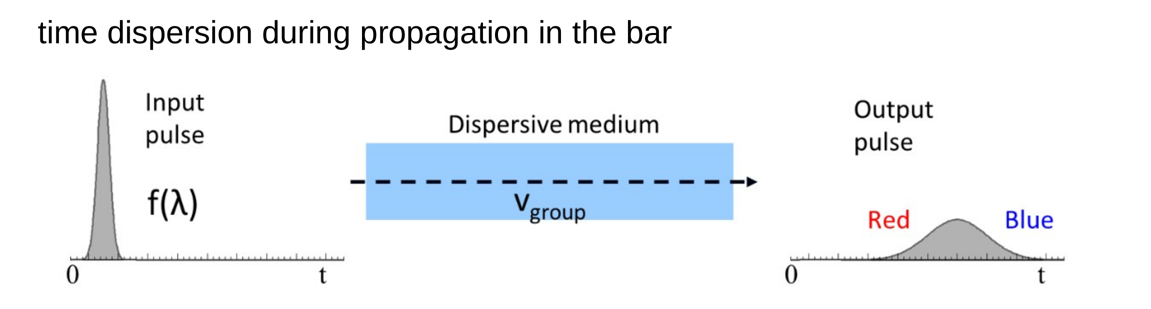
→ works well for polar angles around 90^o

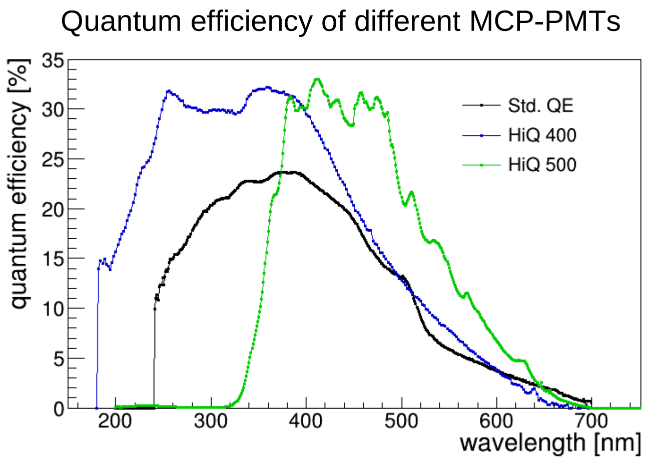
Chromatic Dispersion Mitigation

- Applying wavelength cut (choosing PMT photocathode, inserting band filter)









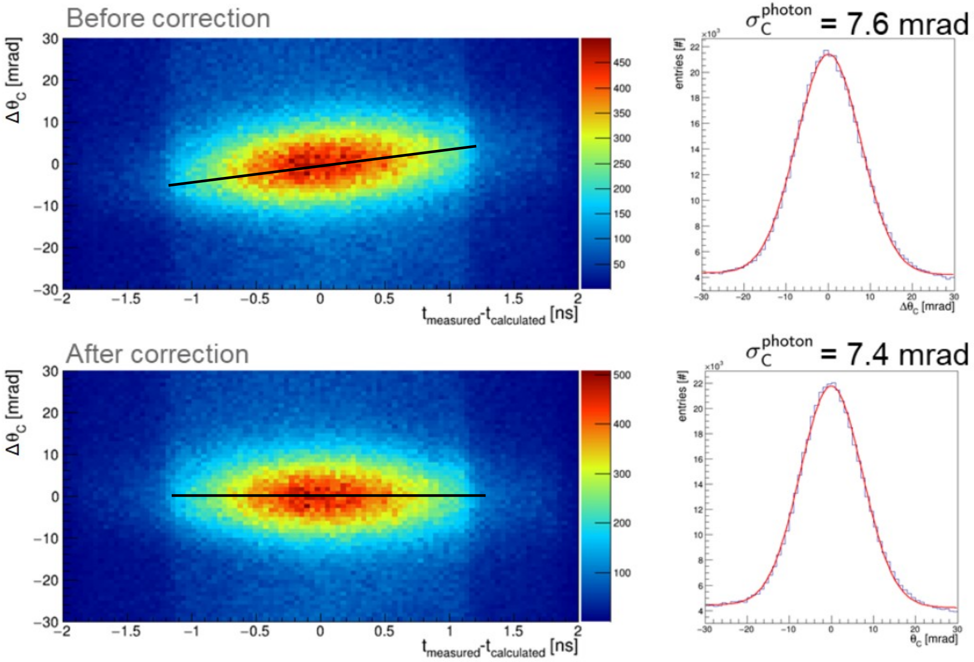
Chromatic Dispersion Mitigation

- Applying wavelength cut (choosing PMT, inserting band filter)
- Chromatic Dispersion Correction (using geometrical reconstruction)

Example from GlueX DIRC data (timing precision ~0.8 ns)

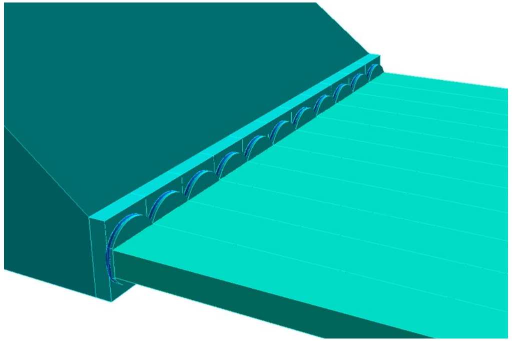
Correlation between emission angle and propagation time:

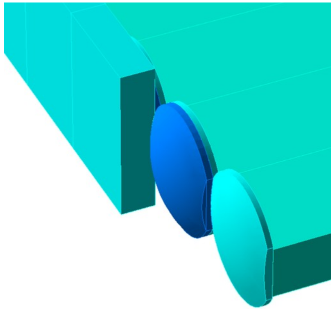
(calculated using average wavelength of 370 nm)

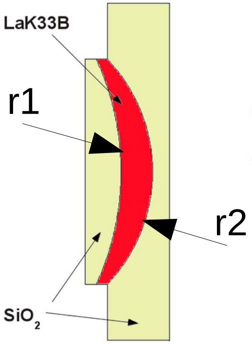


Improving the Focusing System

- fine-tuning radii of 3-layer spherical lens
- aspherical lenses

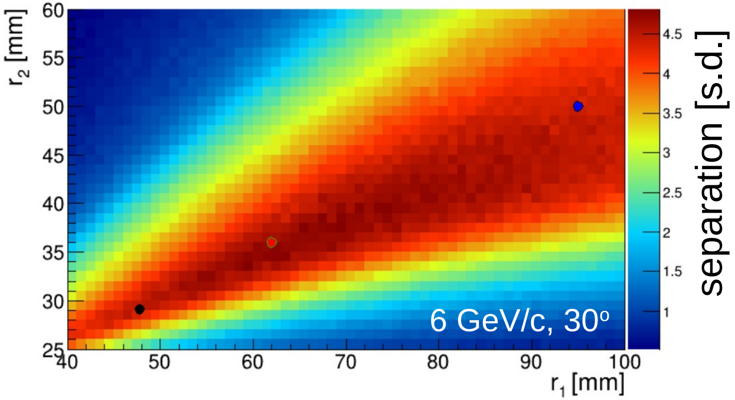






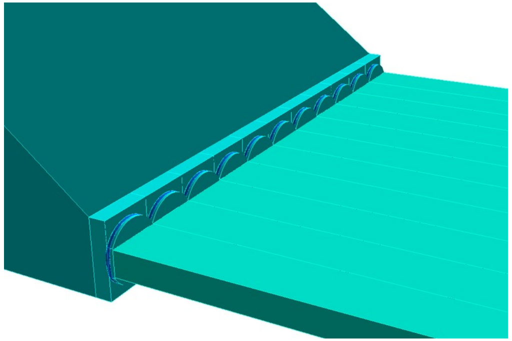
lens prototype

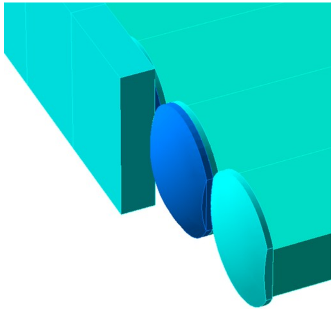
π/K separation power for different radii

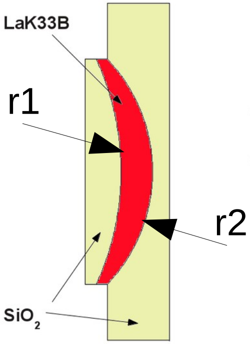


Improving the Focusing System

- fine-tuning radii of 3-layer spherical lens
- aspherical lenses
- alternative focusing systems (Focusing DIRC NIMP A 876 (2017) 141–144)







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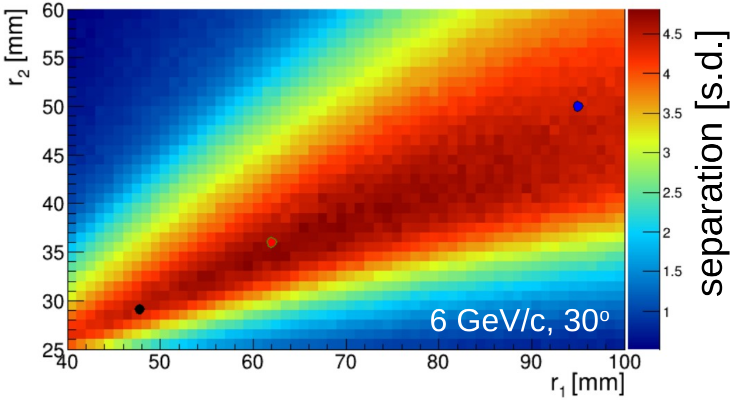
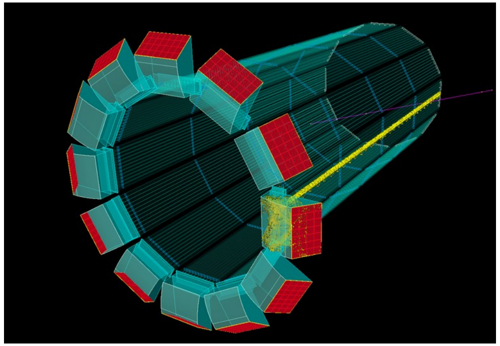




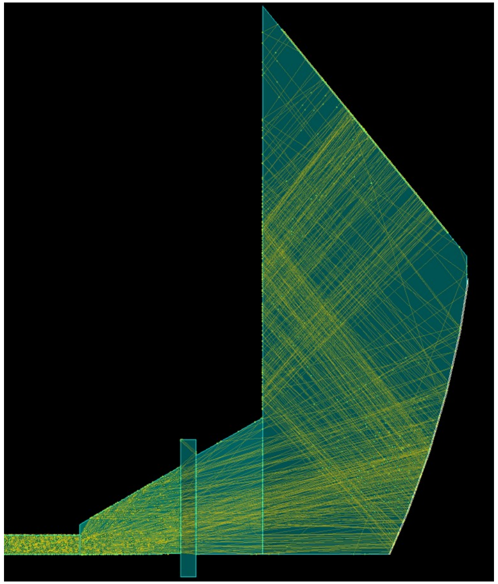
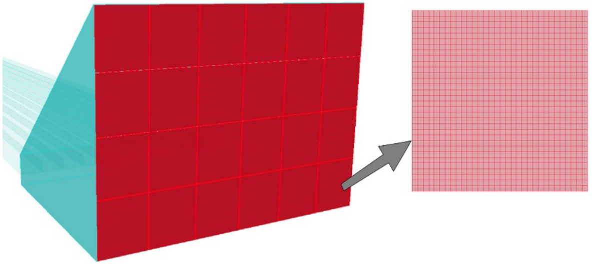


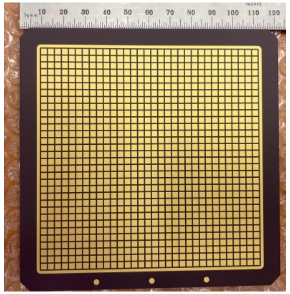
Photo-sensor's Pixel Dimensions

- Limited benefit from smaller pixel size

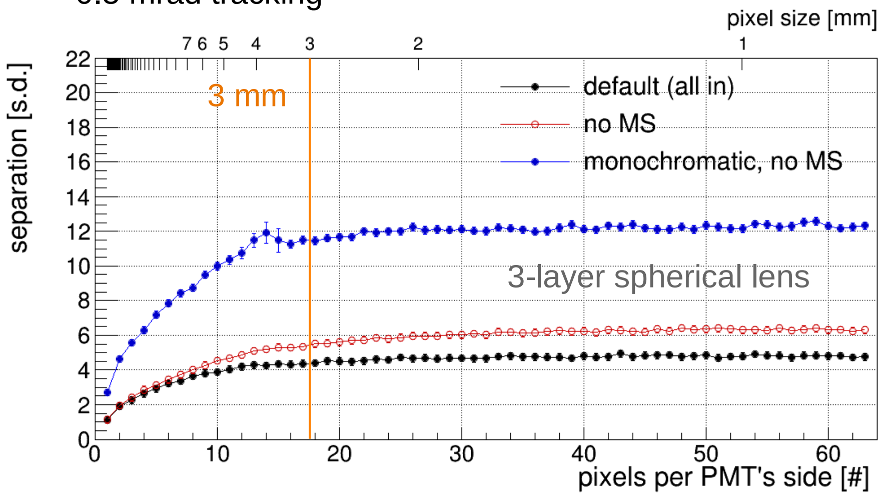
  2-inch MCP-PMTs with 1.6 mm pixel size and small SiPM are already commercially available

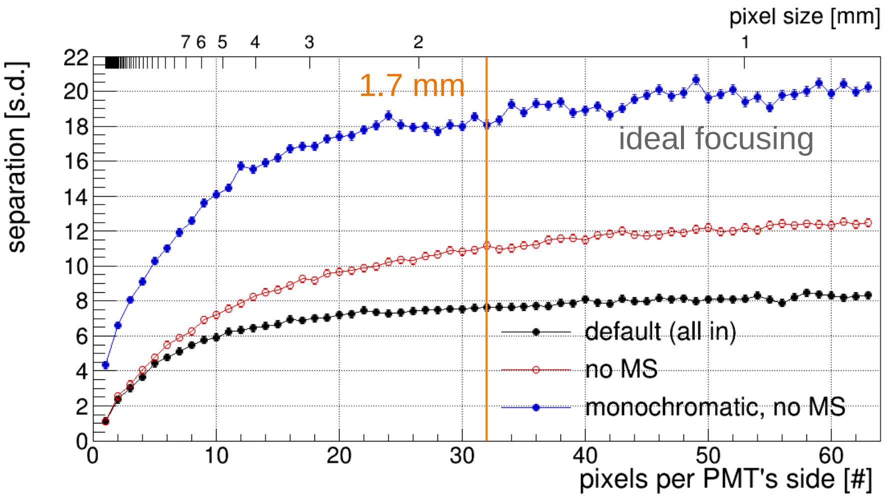


INCOM Gen III HRPPD prototype



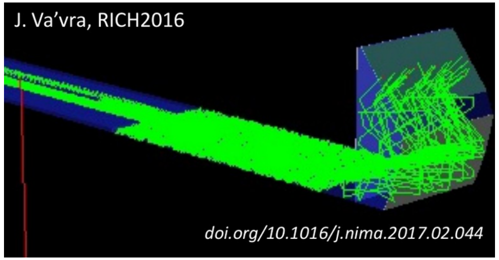
π/K @ 6 GeV/c@ 30°, 100 ps time precision, 0.5 mrad tracking

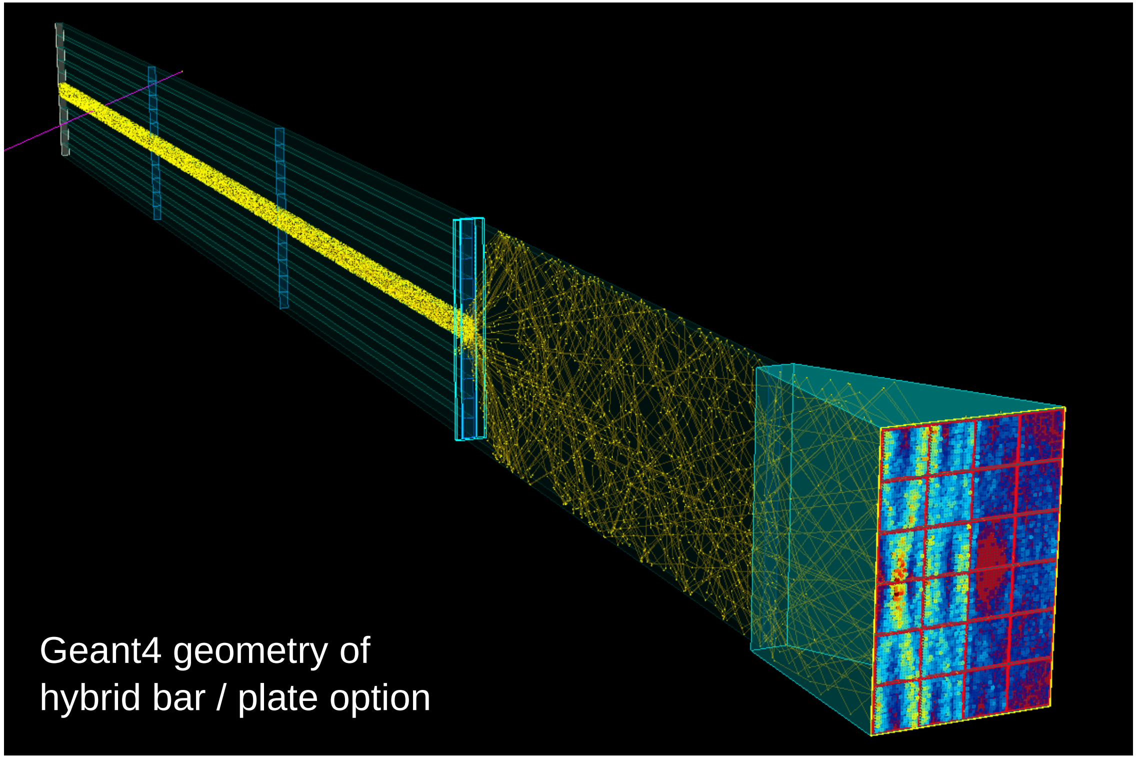




Alternative Designs

- At RICH 2016 J. Va'vra showed the "ultimate fDIRC" concept
- narrow bars in "active area" ensure robust performance in multi-track events
- plate as a part of the expansion volume provides better angular resolution

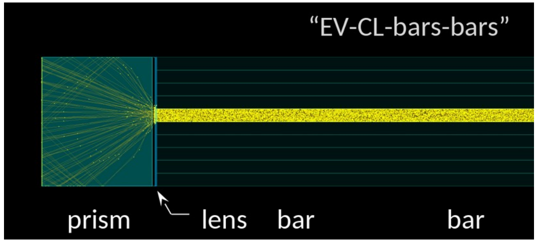


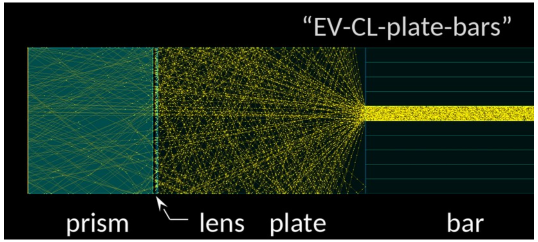


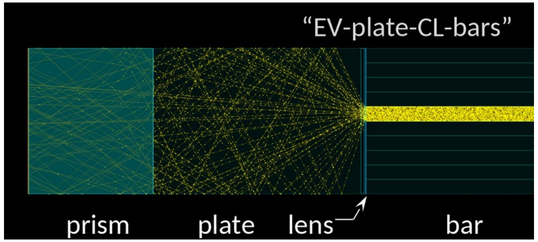
Alternative Designs

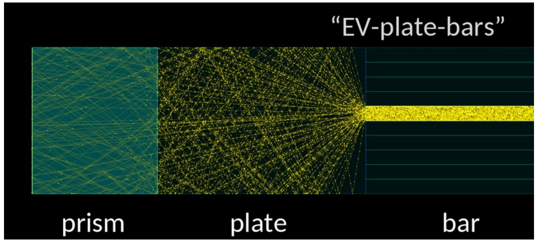
- cylindrical lenses with a plate as expansion volume

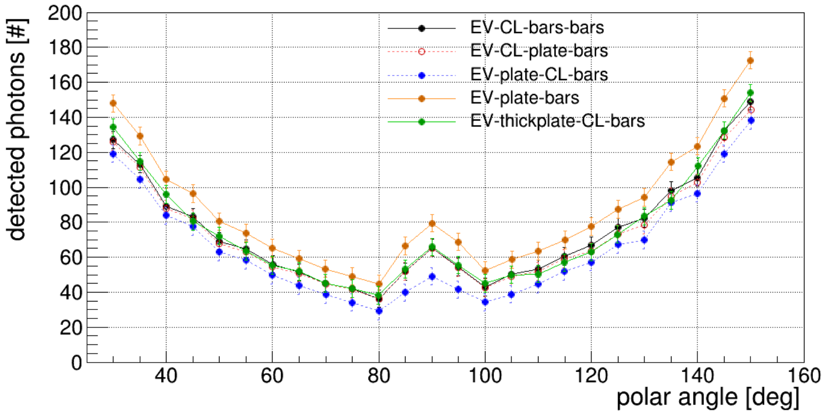
π/K @ 6 GeV/c, 100 ps time precision, 0.5 mrad tracking

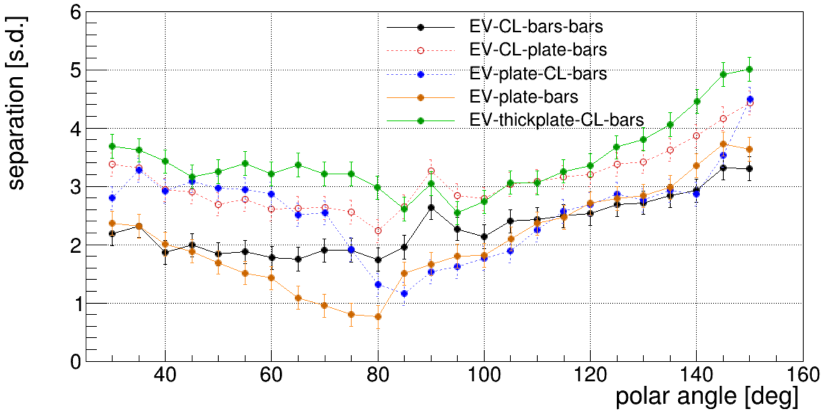






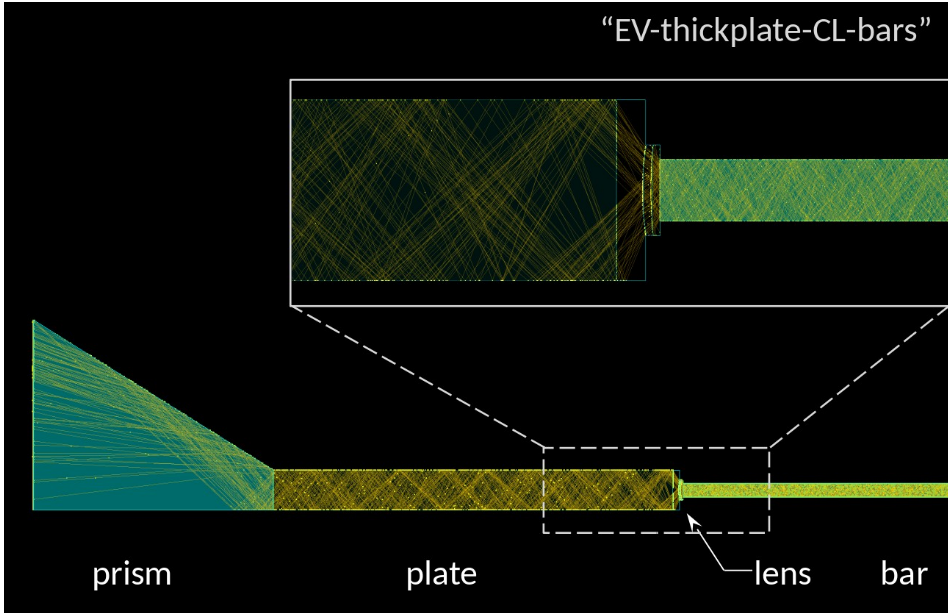






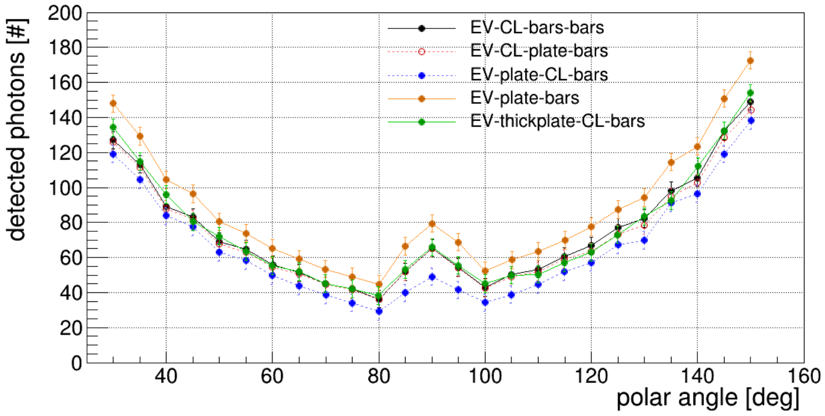
Alternative Designs

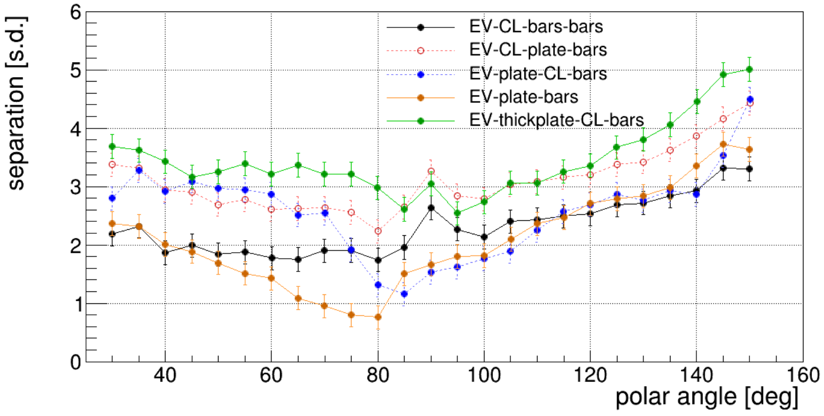
- cylindrical lenses with a plate as expansion volume



➡ best performance achieved for a hybrid design with the cylindrical lens placed between the narrow bars and a wide plate (50 mm thickness, can be optimized)

π/K @ 6 GeV/c, 100 ps time precision, 0.5 mrad tracking





Alternative Designs

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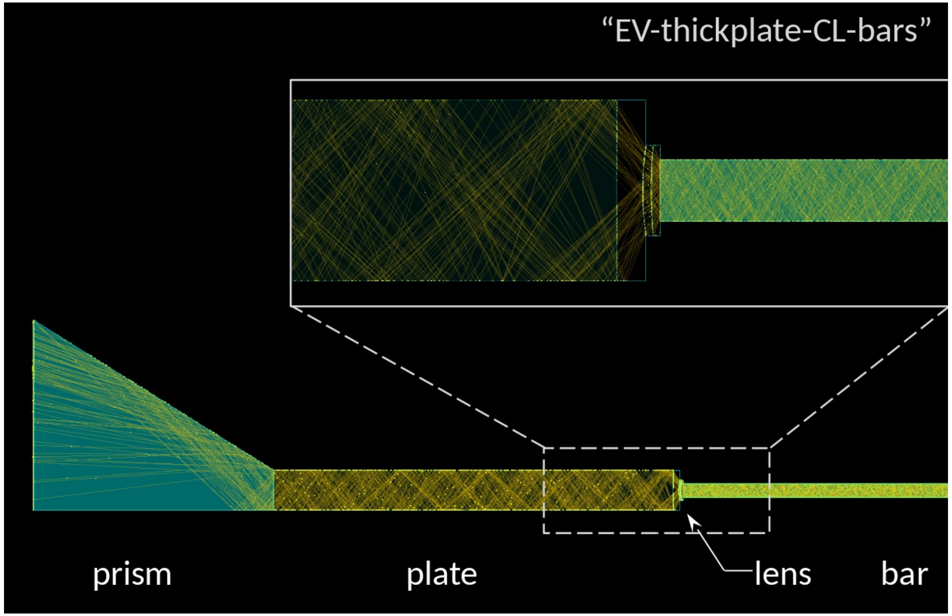
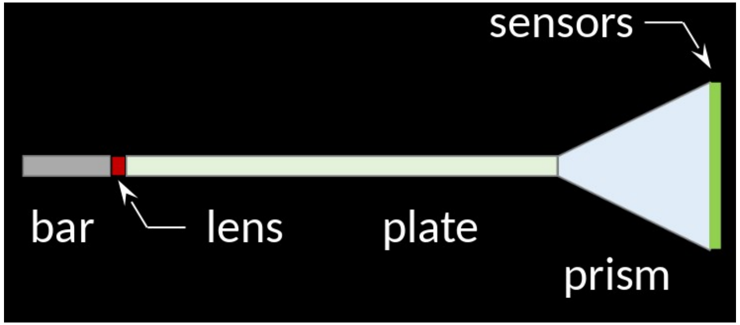


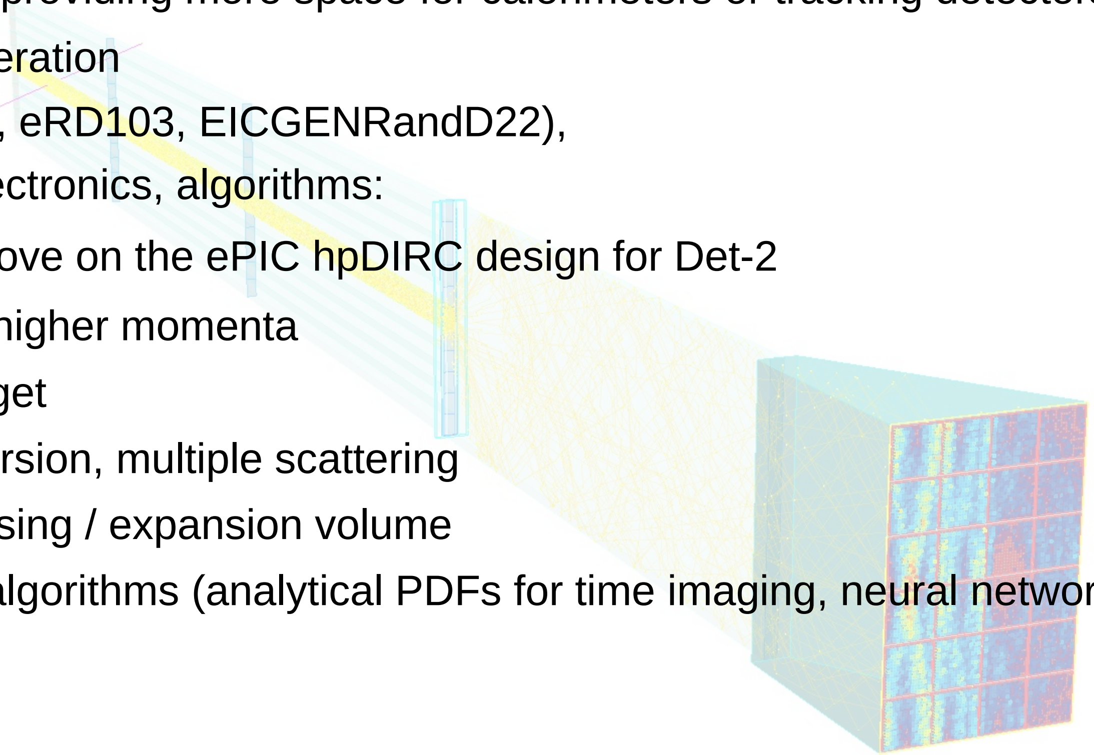
- spherical lenses with a plate as expansion volume and a smaller prism

  (easier integration, smaller photo detector area → SiPM)



Summary

- DIRCs are radially very compact, providing more space for calorimeters or tracking detectors
- Excellent performance, robust operation
- Active and complex R&D (eRD14, eRD103, EICGENRandD22), applying advances in sensors, electronics, algorithms:
    - investigating ways to improve on the ePIC hpDIRC design for Det-2
    - extending the π/K limit to higher momenta
    - reducing the material budget
    - mitigating chromatic dispersion, multiple scattering
    - alternative design for focusing / expansion volume
    - improving reconstruction algorithms (analytical PDFs for time imaging, neural networks)



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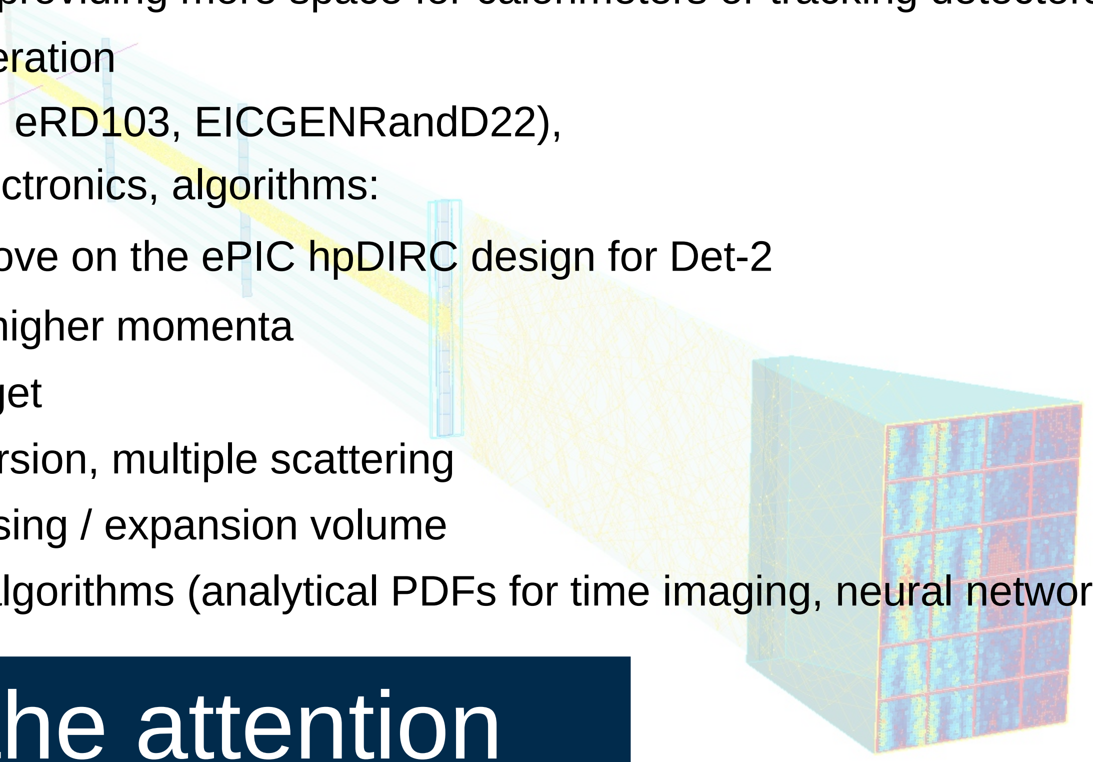

Thank you for the attention