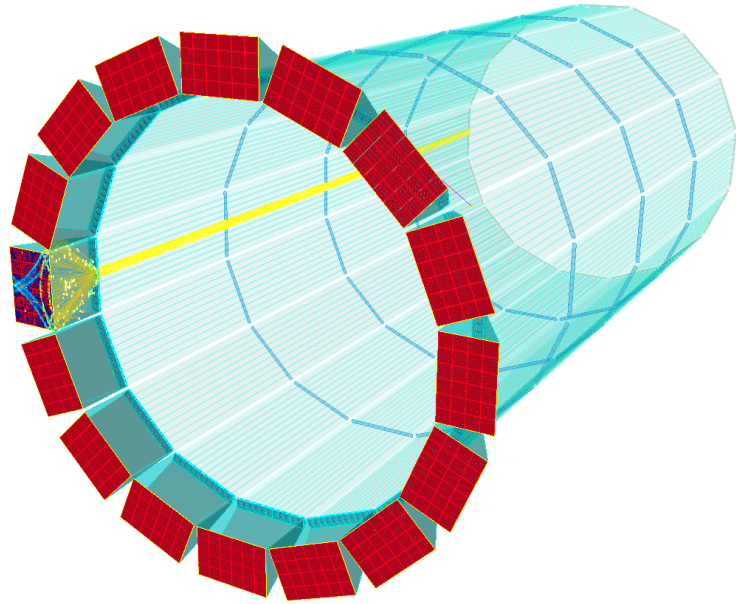
eRD103: The High-Performance DIRC

Directed R&D Proposal to Mitigate Key Risks for the ePIC Detector



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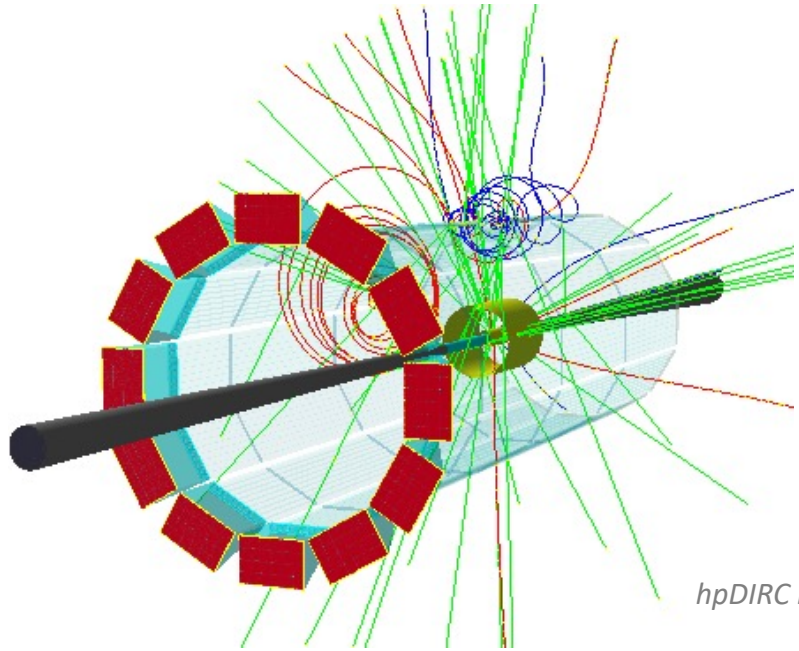
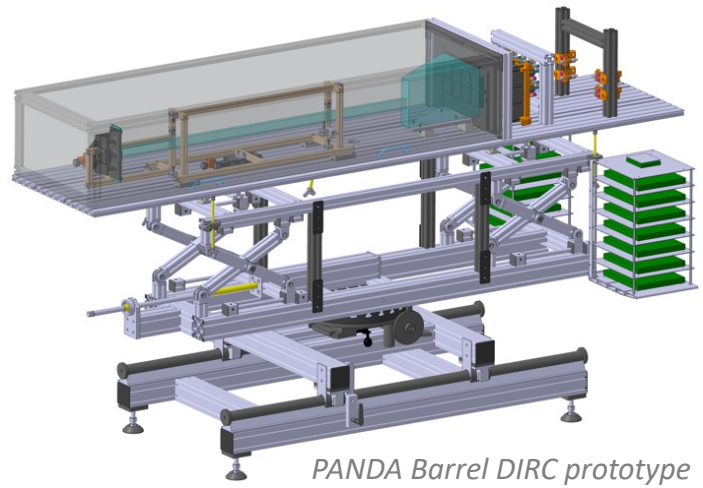
OUTLINE

- hpDIRC overview
- Roadmap towards TDR readiness
- FY22 plan, progress, and milestones
- FY23 plan, activities, and milestones
- Summary and outlook



hpDIRC in F4A simulation

BaBar DIRC radiator bars in SLAC



PANDA Barrel DIRC prototype

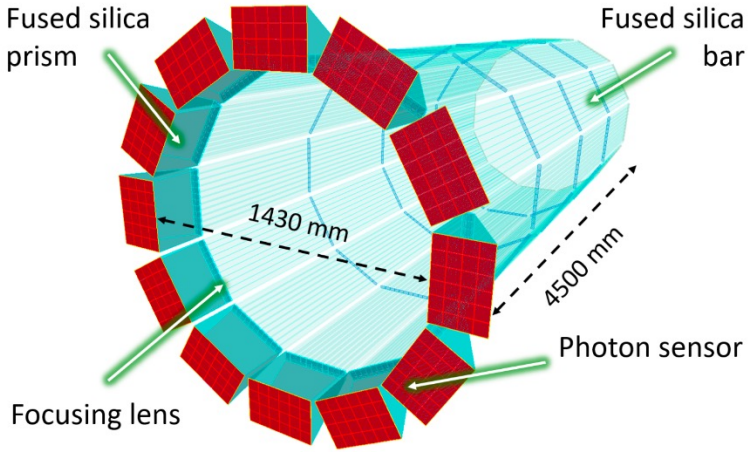
Overview

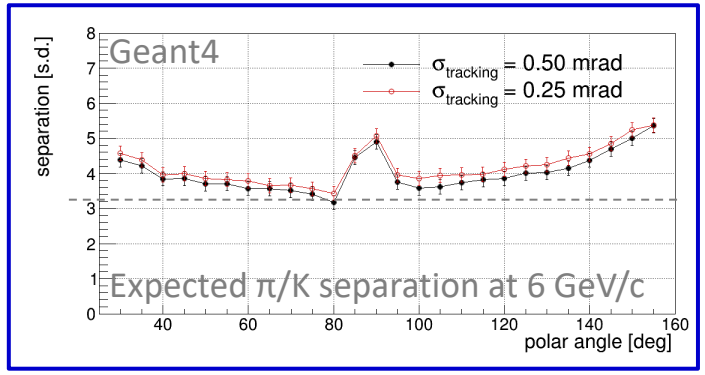
Primary eRD103 Objectives Towards TDR Readiness:

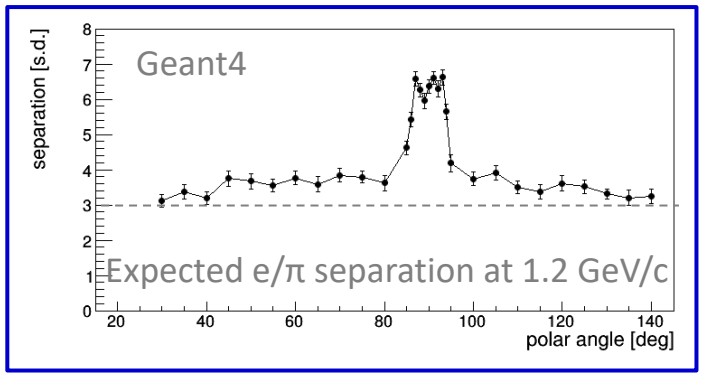
- To minimize hpDIRC risks and to realize opportunities and finalize the design
- To validate the PID performance of a cost-optimized hpDIRC design for ePIC

hpDIRC Concept:

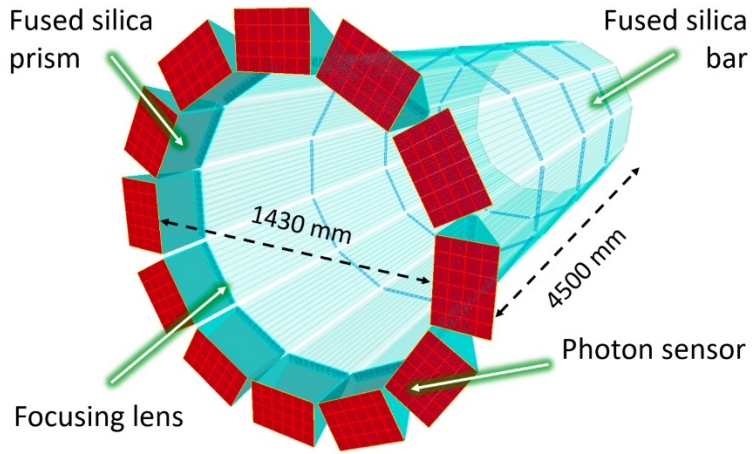
- Fast focusing DIRC, utilizing high-resolution 3D (x,y,t) reconstruction
- Design based on BaBar DIRC, R&D for SuperB FDIRC, PANDA Barrel DIRC
- Radiator/light guide: narrow fused silica bars (radius/length flexible)
- Innovative 3-layer spherical lenses
- Compact fused silica prisms as expansion volumes
- 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







R&D Priorities

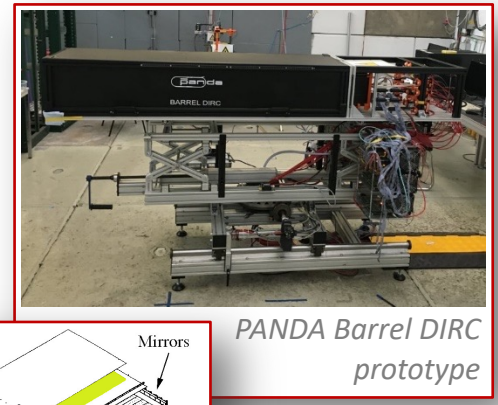


hpDIRC is the baseline hadronic barrel PID system for EPIC

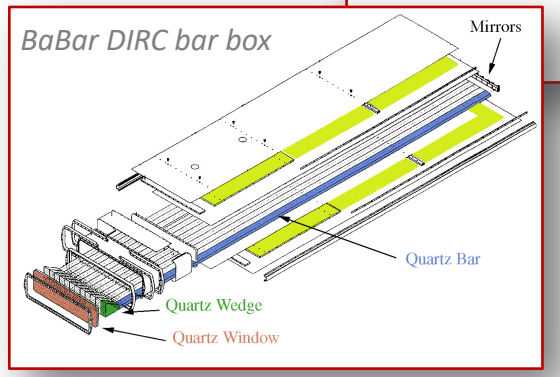
- Synergies with PANDA barrel DIRC development
- Demanding project schedule: CD-2/3A (1/2024), CD-3 (4/2025)

R&D Priorities: Minimize risks, realize opportunities

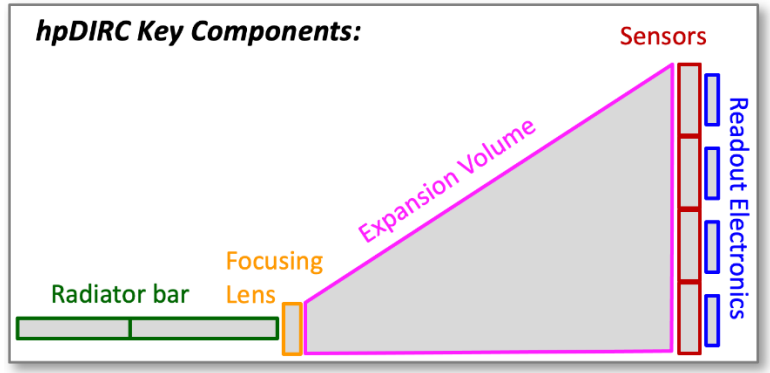
- Technical risk/opportunity: reuse of BaBar DIRC bars
- Technical risk: hpDIRC PID baseline design validation
- Opportunity: cost/performance optimization
- Technical risk: small pixel photon sensor and fast readout electronics

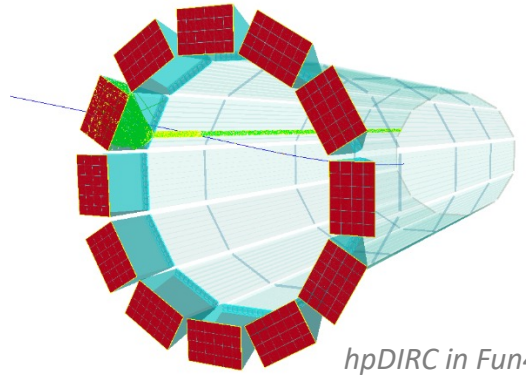


PANDA Barrel DIRC prototype



HPDIRC ROADMAP TOWARDS TDR READINESS





hpDIRC in Fun4All

Category	Subject	Comments	Program
Design in simulation	Lightguide section	Narrow bar vs. wide plate	Generic R&D program
	Cost/performance optimization	Sensor coverage	eRD103
	Expansion volume	Geometry details	eRD103
Optics	Radiator bars	Reuse of BaBar bars	JLab DSG and CUA
	Focusing optics	Radiation-hard 3-layer lens	eRD14, eRD103
Readout	Sensors	Baseline identified, alternatives being studied	eRD14, eRD110, Incom SBIR, eRD103
	Readout electronics	UH/Nalu solution based on Belle II TOP	Nalu and Incom SBIRs, eRD109, eRD103
Construction	Mechanical design	Materials and integration	Synergy with PANDA Barrel DIRC

FY22 Plan vs Reality

Initial Plan:

- hpDIRC Cost/Performance design optimization

- Incremental development of hpDIRC prototype:
  - Assembly and operation of CRT setup
  - Initial prototype with PANDA DIRC readout
  - Development of fast readout electronics
  - Procurement of sensors
- Validation of the BaBar DIRC bar reuse

FY22 Plan vs Reality

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Developments since initial FY22 proposal submission:

- JLab took over funding and committed DSG to support DIRC QA lab ⇒ Significant effort complimentary to eRD103
- Pre-TDR and TDR schedule and delay in funding for sensors + readout electronics motivated change of prototype program strategy ⇒ Reprioritized prototype program, testbeam is not realistic before planned TDR
- Delayed availability of funds for procurement at CUA and SBU delayed construction of CRT setup ⇒ Focused on simulation studies and development of components

FY22 Plan vs Reality

Initial Plan:

Action/Mitigation:

- hpDIRC Cost/Performance design optimization
  - ⇨ Finalized implementation and validation of baseline hpDIRC in ePIC simulation, studies started.
  - Moved hybrid geometry study to generic R&D proposal
- Incremental development of hpDIRC prototype:
  - Assembly and operation of CRT setup ⇨ Delayed but still planned before the end of 2022
  - Initial prototype with PANDA DIRC readout ⇨ Agreement signed, finalizing transport for end 2022
  - Development of fast readout electronics ⇨ Not selected for funding, moved to SBIRs and eRD109
  - Procurement of sensors ⇨ Not selected for eRD funding
- Validation of the BaBar DIRC bar reuse ⇨ Not selected for eRD funding, support from JLab instead

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R&D 2022 HIGHLIGHTS

Validation of the BaBar DIRC bar reuse (JLab activity):

- Build and commission QA laser setup to measure mechanical and optical quality of the bars (12/2022)
- Received BaBar DIRC reference bars from SLAC (7/2022)
- Planning of bar box transfer from SLAC to JLab (before end of 2022)

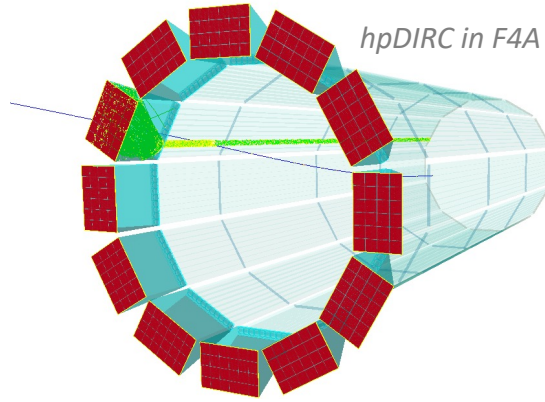
BaBar DIRC bars

Laser lab at GSI

hpDIRC studies in simulation:

- Implementation and validation of the hpDIRC in the full ePIC simulation (done)
- Initial study of the hpDIRC performance with background and magnetic field (12/2022)
- Set up study of post hpDIRC tracking layer impact on performance (continued in 2023)

hpDIRC in F4A



hpDIRC prototype:

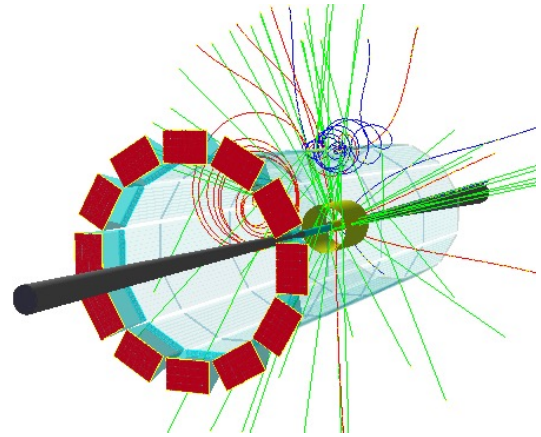
- Start of simulation studies of hpDIRC prototype with cosmic rays (done)
- Transfer of DIRC components from GSI to SBU (11-12/2022)
- Set up Cosmic Ray Telescope at SBU, start hpDIRC prototype integration (12/2022)

DIRC lab/CRT space at SBU

eRD103 R&D 2023 Plans

hpDIRC design studies in simulation:

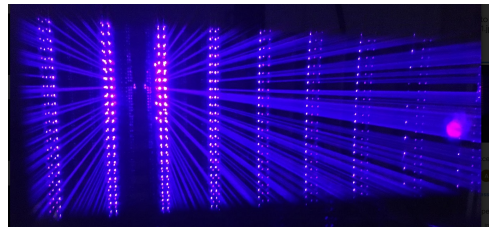
hpDIRC in F4A simulation



- Optimize hpDIRC geometry (radiator bar positioning, focusing, prism shape, MCP-PMT/HRPPD arrangement).
- Complete study of the hpDIRC performance with physical events in the full ePIC simulation
- Continue study of impact of post-DIRC tracking layer

Validation of the BaBar DIRC bar reuse (JLab activity):

DIRC bar in HeCd laser at GSI



- Measure mechanical and optical quality of the disassembled bars
- Determine impact of optical quality of the bars on hpDIRC performance

Milestones:

- Commissioning of the DIRC lab at JLab with reference bars complete (JLab/ODU, Q1/2023)
- Complete QA of bars from first disassembled BaBar DIRC bar box, decision about reusability and further disassembly strategy (JLab/CUA, Q3/2023)
- Completed evaluation of cost/performance optimized EIC DIRC design options in simulation (CUA/GSI, Q4/2023)

eRD103 R&D 2023 Plans

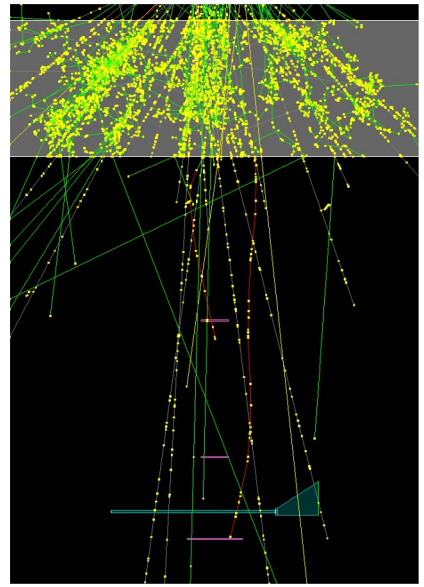
Incremental development of hpDIRC prototype:

- Complete the CRT setup with tagging, tracking, and timing detectors
- Develop DAQ, 3D tracking and event timing software for Cosmic Ray setup
- Complete the prototype simulation, evaluate the expected performance with cosmic rays
- Commission detectors, electronics, and DAQ with cosmic rays.

Milestones:

- Integration of hpDIRC prototype into Cosmic Ray Telescope complete (CUA/GSI/SBU, Q2/2023)
- Initial DAQ and CRT track reconstruction software ready and tested (CUA/SBU, Q3/2023)
- Commissioning of CRT setup completed (CUA/ODU/SBU, Q4/2023)

hpDIRC in CRT simulation

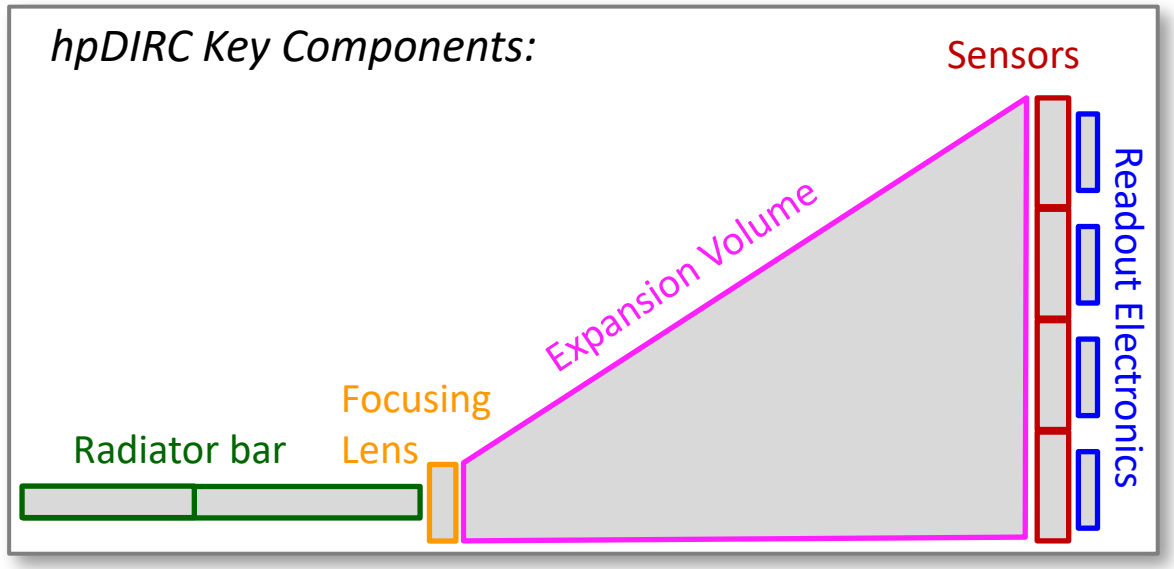


CRT space at SBU

eRD103 R&D Schedule

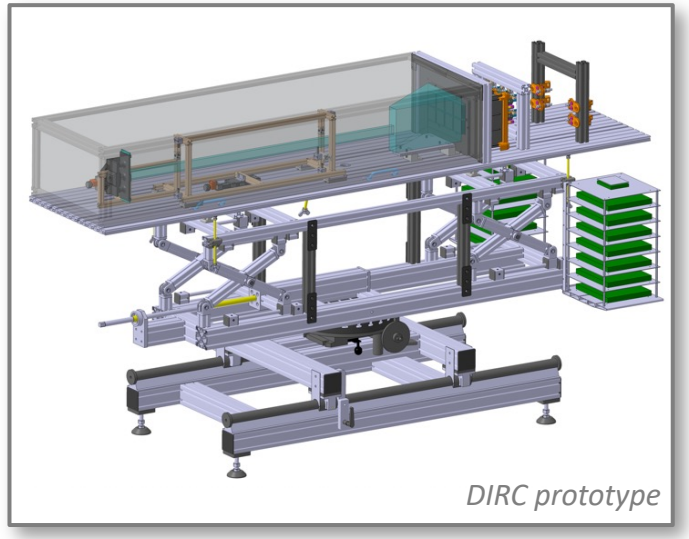
FY 22

- Preparation of the QA DIRC lab in JLab for BaBar bars
- Transfer of DIRC prototype components from GSI to SBU
- Start of CRT assembly
- hpDIRC performance studies in full ePIC Simulation



FY 23

- Validation of BaBar DIRC radiator bar reuse option
- Assembly and integration of initial prototype into CRT with tracking and timing detectors
- Development of CRT and prototype DAQ and 3D tracking code
- Cost/performance optimization of design in simulation
- Incremental upgrade of hpDIRC prototype



FY 24

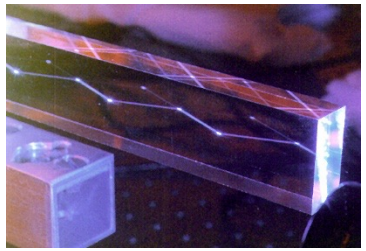
- Adaptation and evaluation of sensors and readout electronics in hpDIRC prototype
- Conclusion of prototype program with final cost/performance-optimized design
- Remaining technical, schedule, and cost risks, as well as on production readiness

BaBar DIRC Bar Box Disassembly

Technical risk/financial opportunity: reuse of BaBar DIRC bars

- BaBar DIRC disassembled in 2010, SLAC/DOE made DIRC bars available for reuse
- Potentially saves up to $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
  Four additional unmodified bar boxes already at JLab for GlueX DIRC since 2018, potentially available
  For a reasonably high yield of high-quality bars: number of bars sufficient for EIC project detector
- Advanced discussions about transfer of bar boxes to JLab, disassembly to start in early 2023
- R&D is required to finalize and validate procedure and to assess cost and technical risk
  DIRC lab at JLab built to measure quality of bar surfaces with laser system, validate disassembly method.
  Risks: deterioration after 20+ years in bar box, contamination of bar surfaces from opening of box and from heat gun disassembly.
- Lab, bar box transfer, and disassembly funded and supported by JLab; JLab DSG committed manpower to support setup and perform evaluation measurement in FY23

BaBar DIRC bar boxes at SLAC



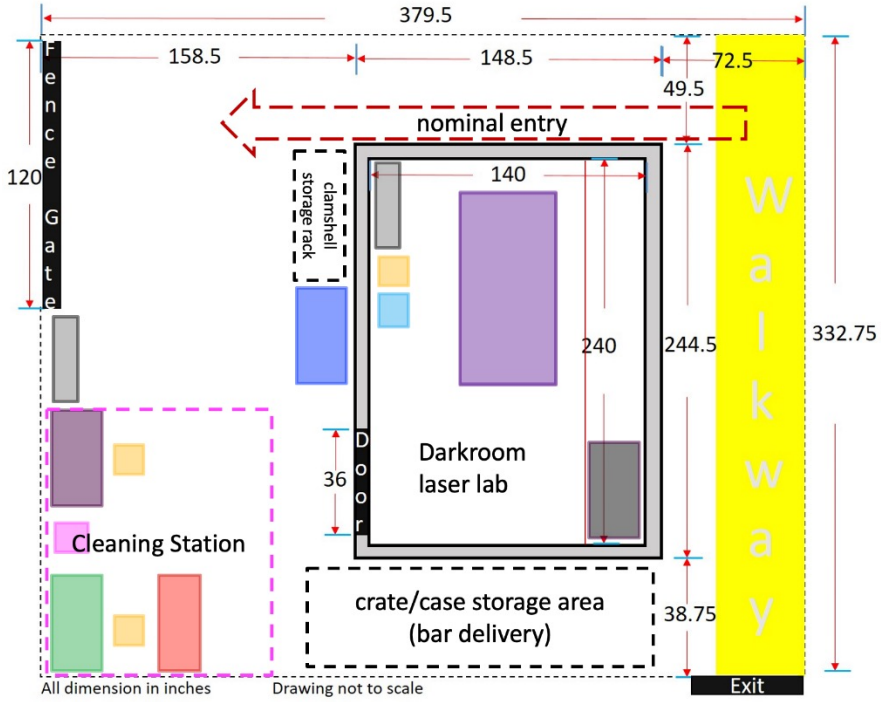
QA DIRC Lab: BaBar DIRC Bars

Construction of the DIRC QA Lab at JLab in advanced stage

- Sponsored by JLab with active help from Detector Support Group
- Most components already purchased and received
- Reference bars from SLAC received for lab commissioning
- QA Lab will consist of three parts:
  - Storage (long and short-term)
  - Cleaning/inspection station
  - Darkroom with laser setup
- Reflection coefficient measurement to evaluate surface quality
- Preparing transport of eight intact bar boxes from SLAC to JLab for disassembly at JLab, will likely use a similar method as for the successful GlueX bar box transport

DIRC QA Lab in construction at JLab

Plan of DIRC QA Lab at JLab



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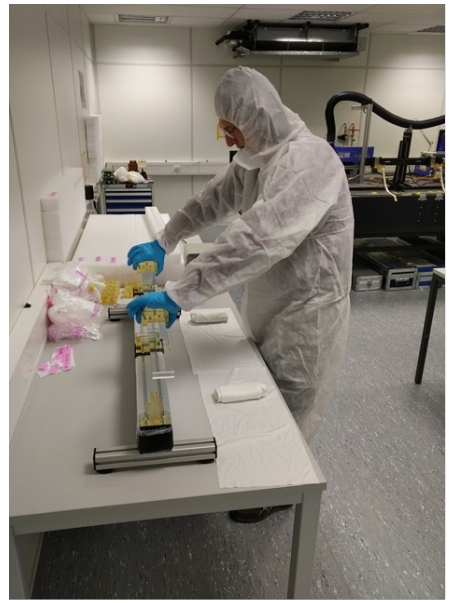
Bar cleaning station at GSI



Bar storage at SLAC

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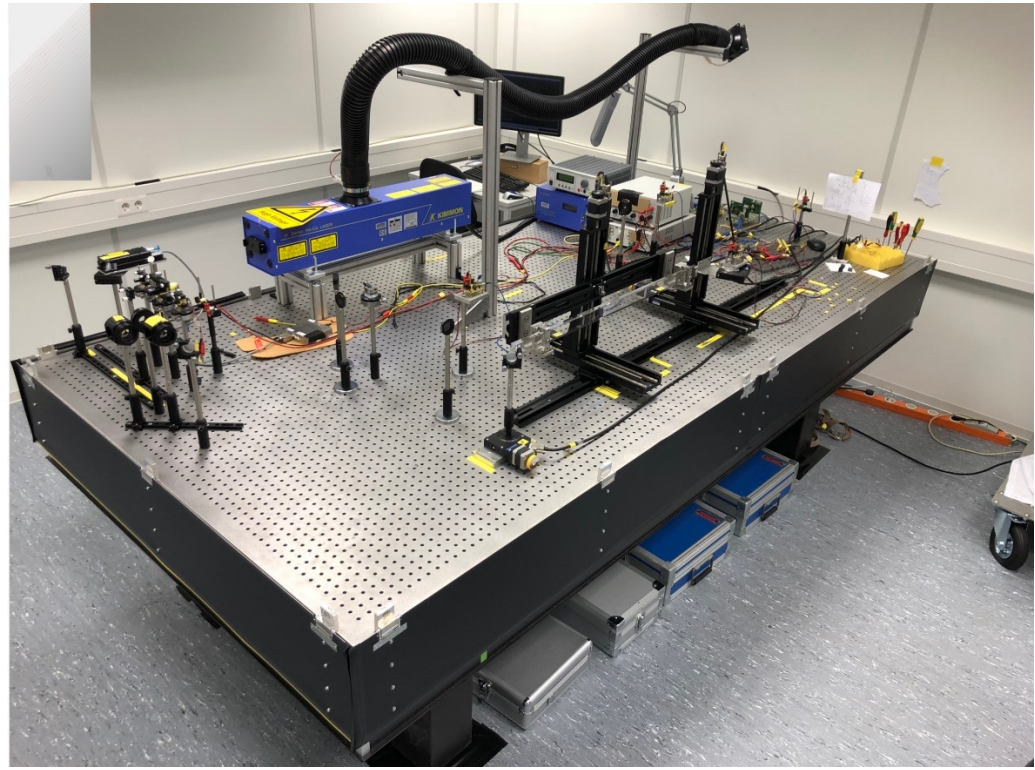
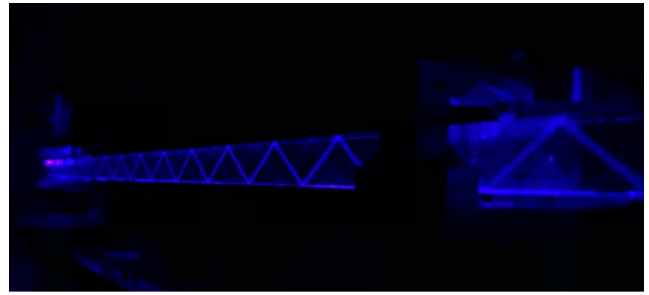
DIRC laser lab at GSI



DIRC bar in laser lab



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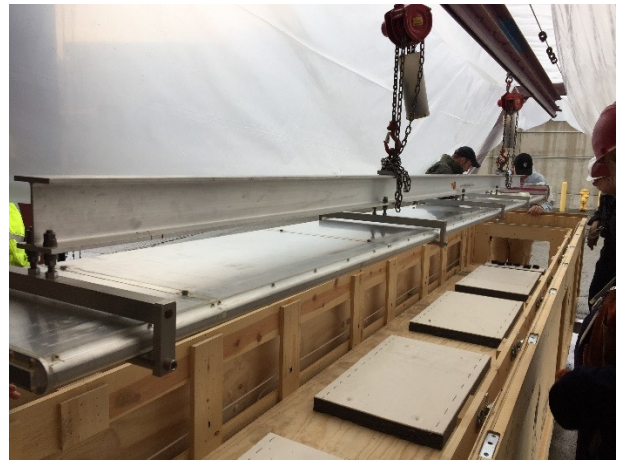
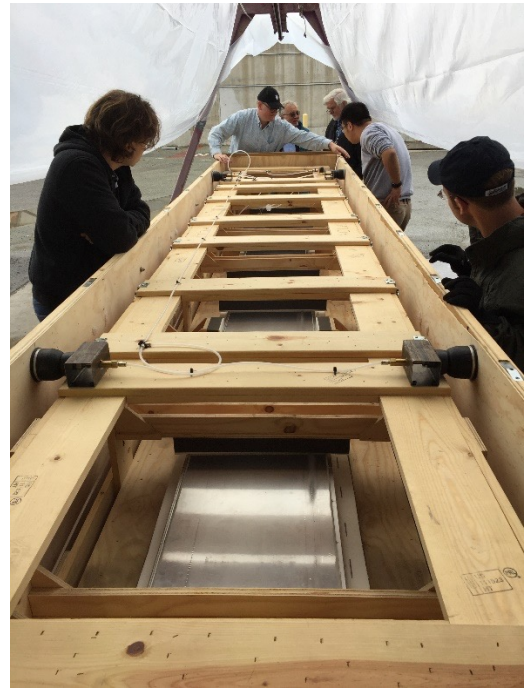
BaBar DIRC bar box transportation for GlueX





SENSORS

MCP-PMT is the leading hpDIRC sensor candidate

Different maturity of small-pixel MCP-PMT sensor development:

- Established: PHOTONIS XP85122-S
- More recently developed: Photek MAPMT 253
- Under development: INCOM Gen III HRPPD

Small-pore MCP-PMTs shown to work well in ePIC magnetic field

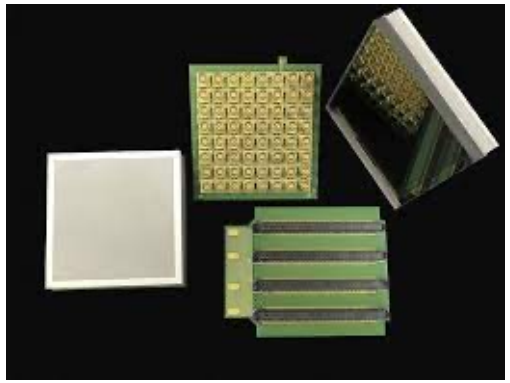
(see overview of MCP-PMT performance in high B-fields from A. Lehmann at RICH2022)

SiPMs as potential alternative (part of hpDIRC generic R&D proposal)

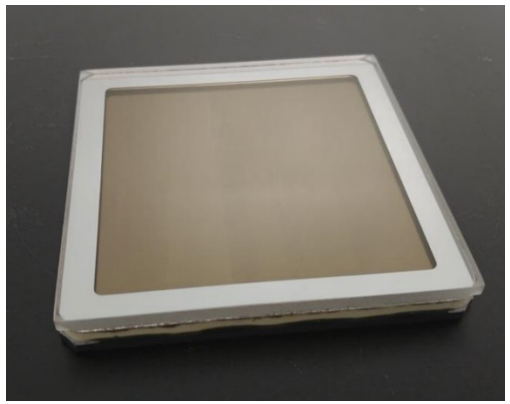
(dark noise, radiation damage, cooling, annealing, integration issues)

PHOTONIS XP85122-S

Photek MAPMT 253



INCOM Gen III HRPPD

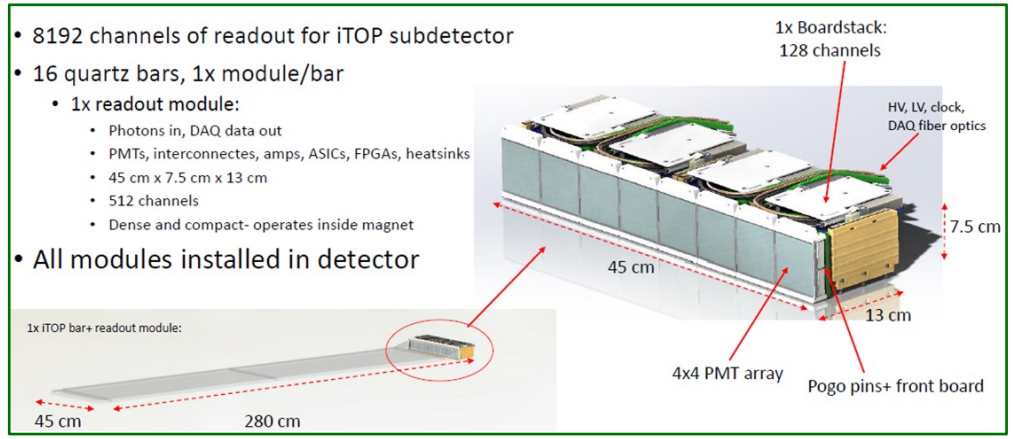


READOUT ELECTRONICS

hpDIRC unique readout requirements:

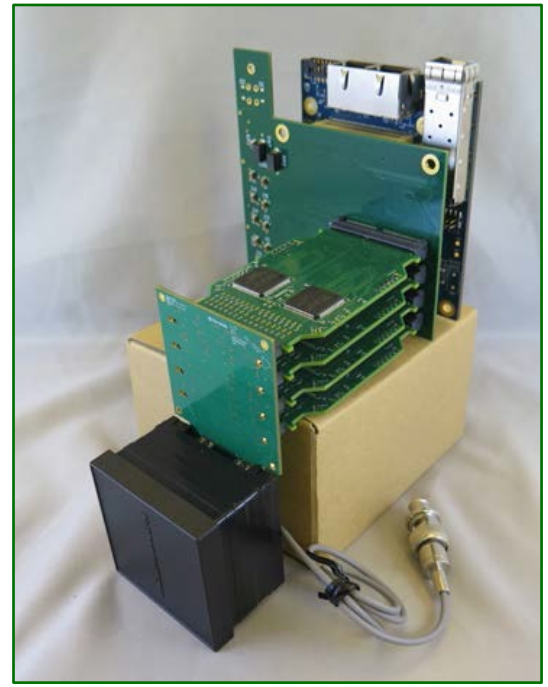
- Large number of small sensor pixels
- Fast single photon timing in high B field
- High photon rates and sensor occupancies

Belle II TOP readout solution



- High-density readout must be tileable, match sensor form factor, limited space behind sensor plane
- Demanding environment: triggerless streaming, data reduction, bandwidth, latency and throughput, power consumption, integration issues, etc
- No solution on the market that meets hpDIRC requirements and scales well

Early prototype of readout stack

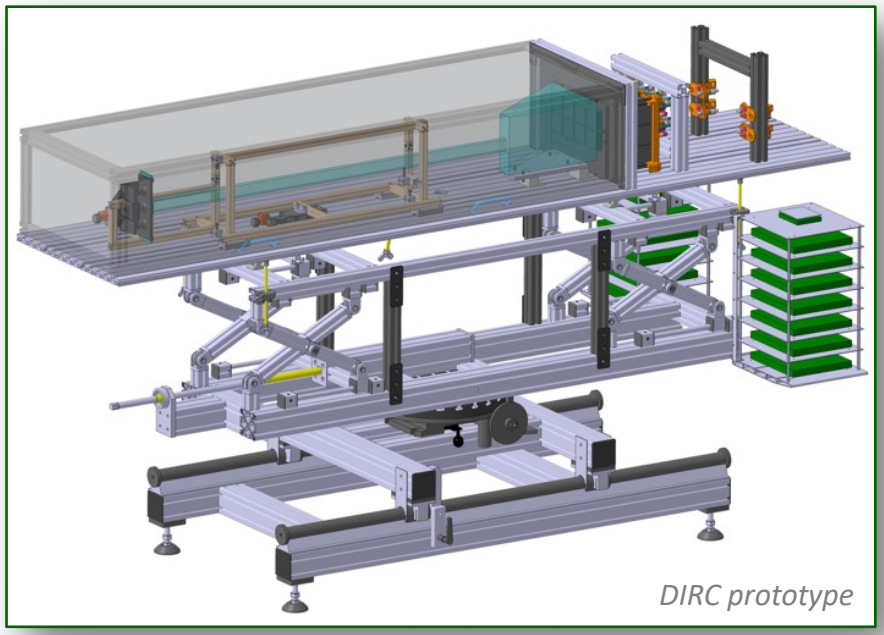


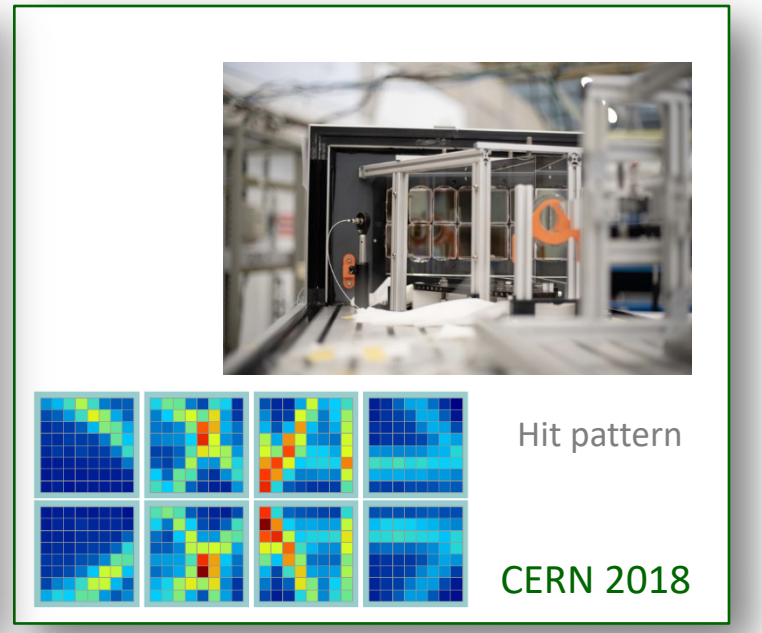
- Close collaboration between Nalu and UH, successful design, fabrication and deployment of Belle II TOP readout (shares many similarities with the hpDIRC)
- Observing Nalu SBIR proposals and considering submitting eRD109 proposal for FY24

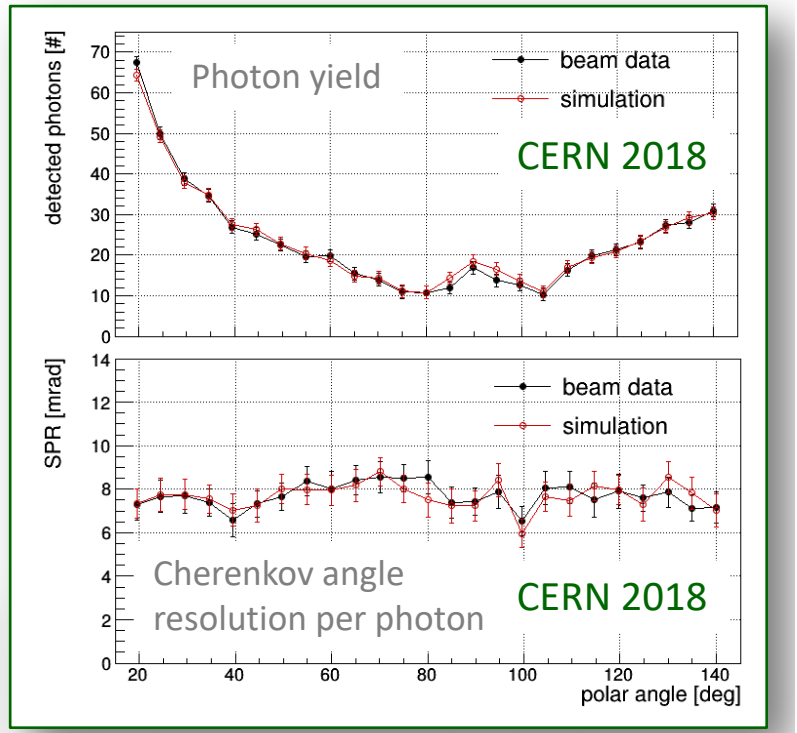
HPDIRC PROTOTYPE: DEVELOPMENT

Technical risk: hpDIRC PID design validation

- Many aspects of hpDIRC already validated in particle beams
- PANDA Barrel DIRC prototype tested with particle beams at CERN (2015-18)
  (included 3-layer spherical lens – but older MCP-PMTs, larger pixels, slower electronics)
- Up to 5 s.d. p/π separation at 7 GeV/c (equivalent to 5.2 s.d. π/K at 3.5 GeV/c)
- Excellent agreement with simulation (same simulation used for hpDIRC)







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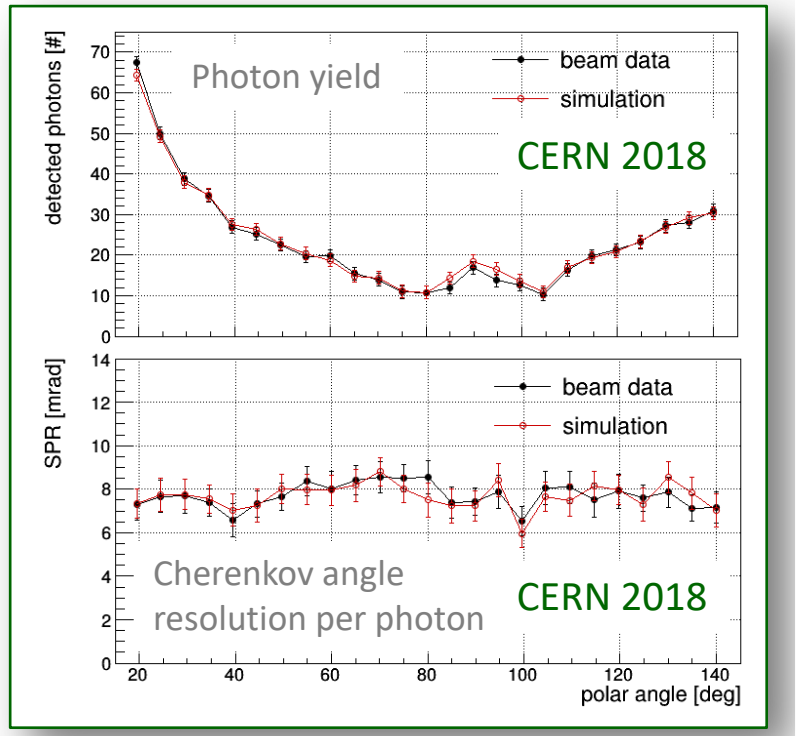
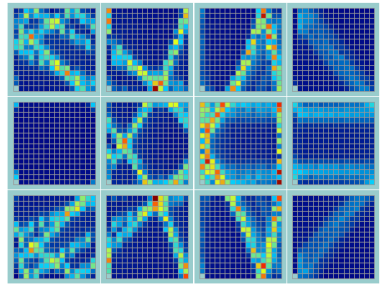
- Up to 5 s.d. p/π separation at 7 GeV/c (equivalent to 5.2 s.d. π/K at 3.5 GeV/c)
- Excellent agreement with simulation (same simulation used for hpDIRC)



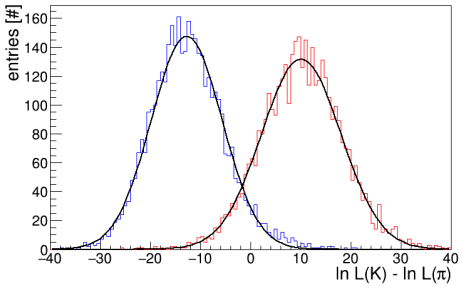
- Used this simulation to predict PID performance of upgraded hpDIRC prototype
  (new MCP-PMTs and electronics, 3mm pixels, improved PDE, 100ps timing)
- Expected π/K separation at 6 GeV/c at 20°: 3.1 s.d.
- Upgraded PANDA Barrel DIRC prototype (new sensors, new electronics) capable of hpDIRC PID performance validation in particle beams

Geant simulation of upgraded prototype

Accumulated hit pattern



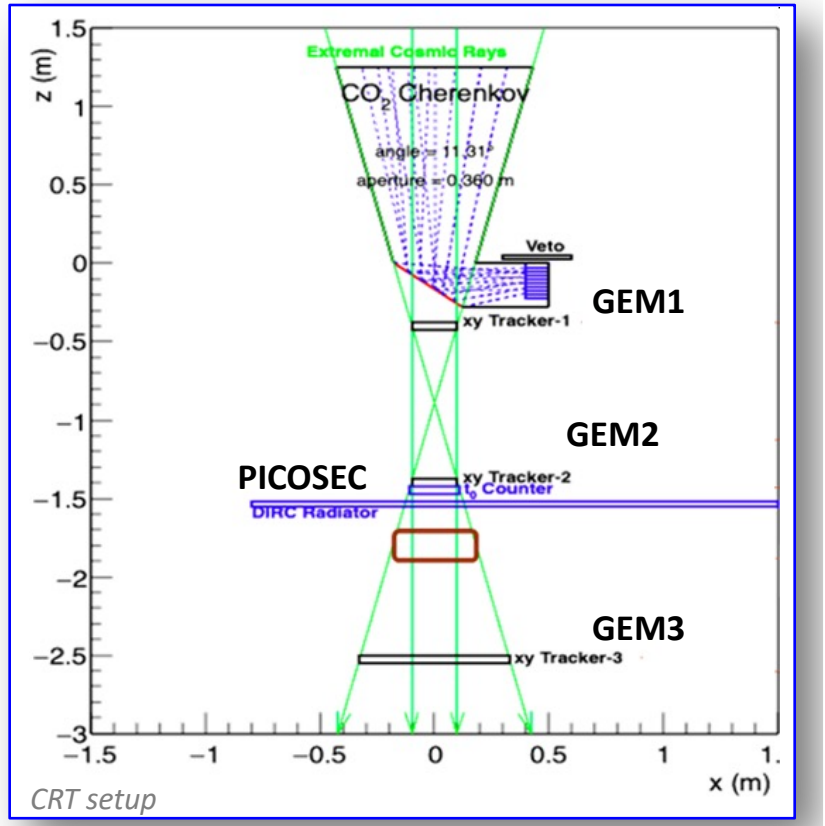
π/K separation at 6 GeV/c at 20°



HPDIRC PROTOTYPE: DEVELOPMENT AND VALIDATION

Opportunity: Preparation of Tests of DIRC Prototype with Cosmic Rays

- Crowded beam test schedules – validate hpDIRC with cosmic muons
- Collaboration of CUA – GSI – ODU – SBU to develop cosmic ray telescope (CRT) design and measurement plan
- Work on mechanical and readout aspects of hpDIRC
- Future facility for validating completed hpDIRC bar boxes with cosmics



CRT setup

Current design:

- Momentum selection: new CO_2 Cherenkov threshold tagger ($p \geq 3.5$ GeV/c)
- 3D tracking: 3 GEM tracker stations above and below DIRC bar
- Shower rejection: scintillator plates as veto counters
- T_0 start counter: PICOSEC module (eRD51 collaboration)
- Mechanical design progressing, includes polar angle rotation and X/Y movement of bar

HPDIRC PROTOTYPE: DIRC LAB AT SBU

New hpDIRC lab at SBU

- Space for hpDIRC Lab at SBU used until recently for construction of sPHENIX TPC detector
- Now empty and ready for CRT and hpDIRC components
- Cleanroom environment well-suited for DIRC prototype and future bar box assembly
- SBU group committed to take the lead on future bar gluing

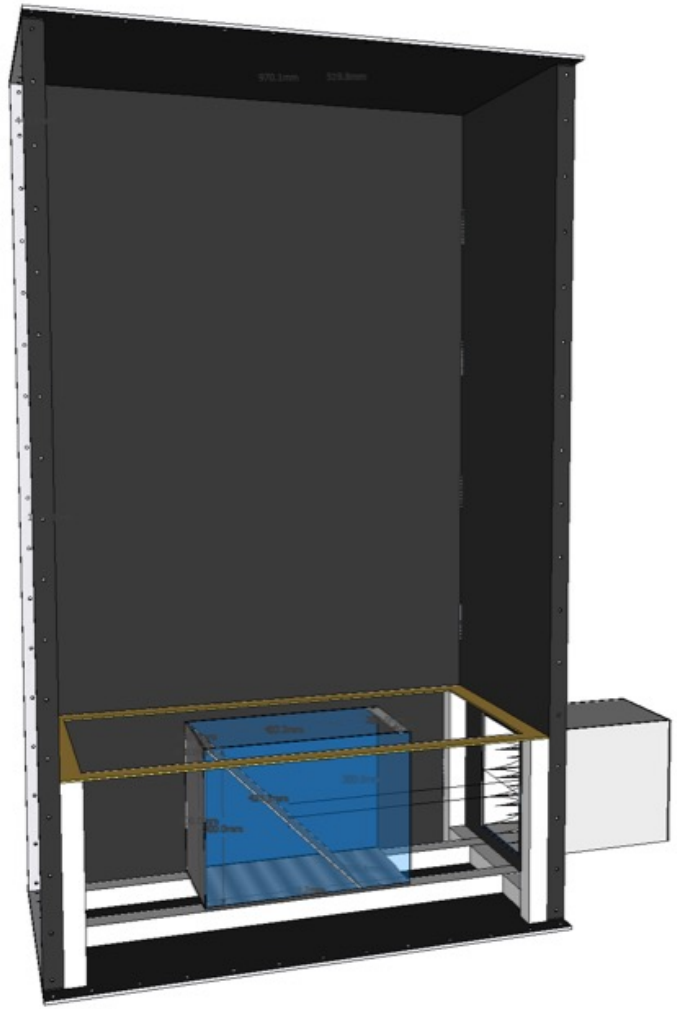
Space for CRT at SBU

CRT Development: Cherenkov Tagger

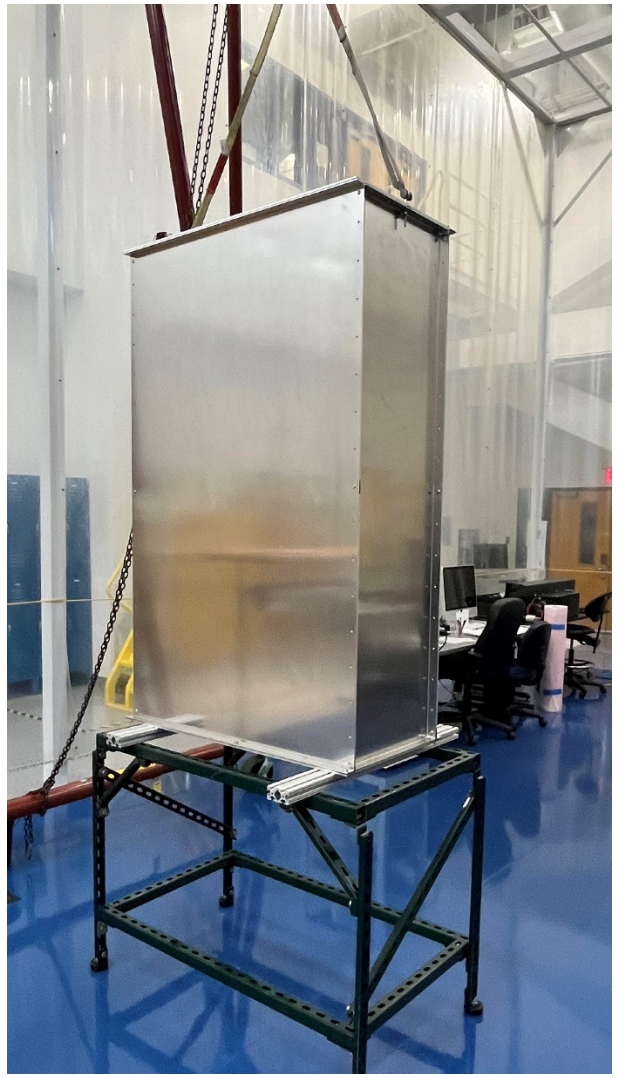
CRT Cherenkov tagger is being developed and constructed at ODU

- Mirror and light catcher will be coated at SBU to improve reflectivity
- Transport to SBU and installation in CRT planned for early 2023

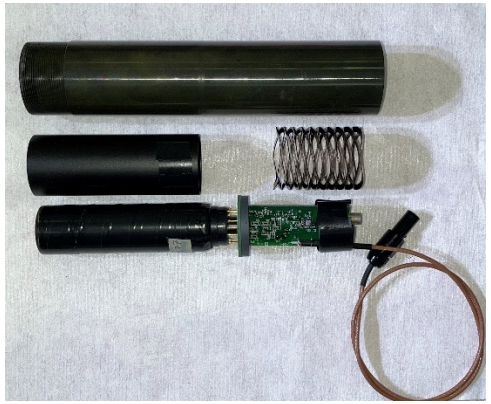
CAD drawing of Cherenkov tagger



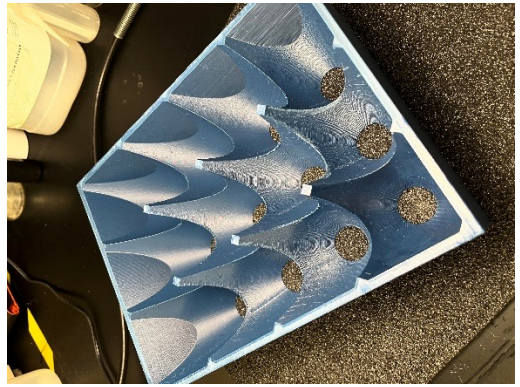
Cherenkov tagger in construction at ODU



Tagger PMT



3D-printed Winston cones

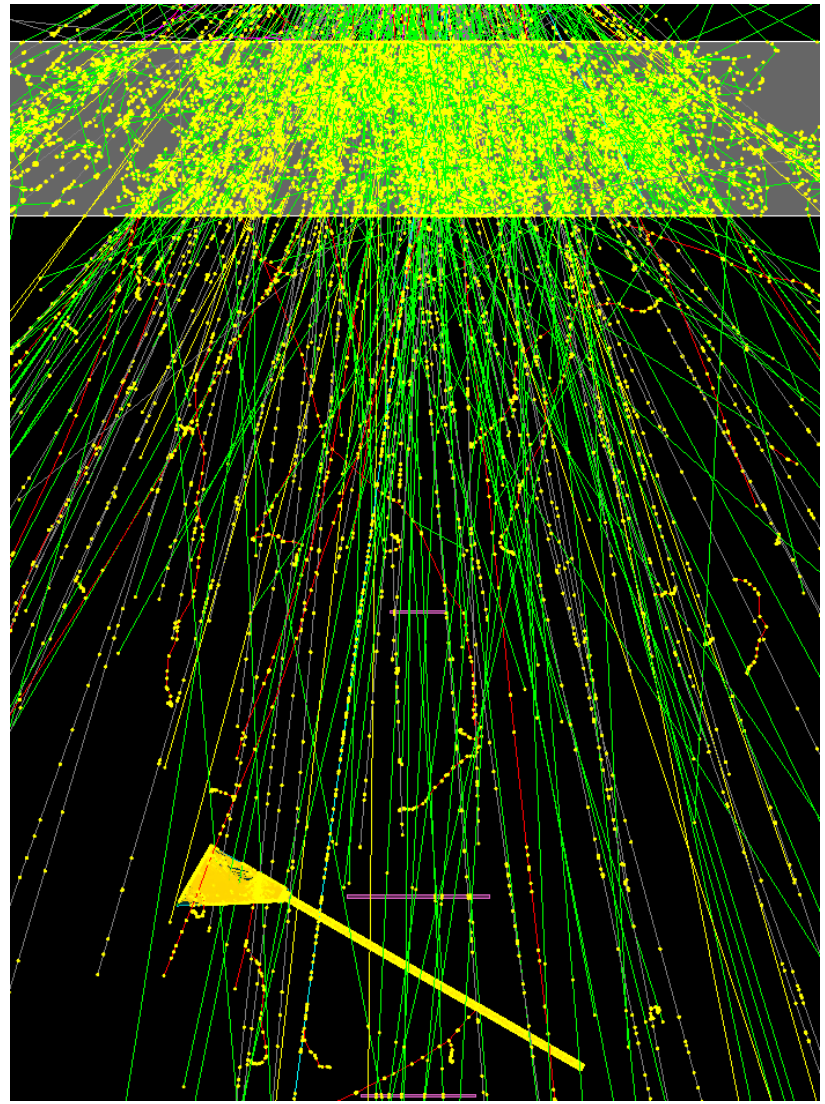


HPDIRC PROTOTYPE: SIMULATION STUDIES

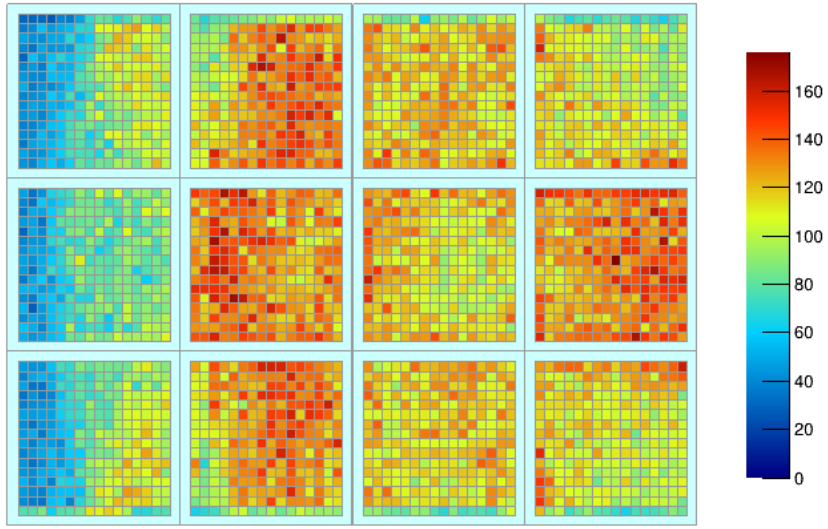
hpDIRC prototype implemented in Geant4 (CRY generator)

- Implemented tracking detectors and material budget above CRT
  - Example: prototype is in 60° polar angle
  - Track momentum above 3.5 GeV/c
  - Will require at least 150 hours of data taking per configuration

10 sec of hpDIRC in CRT simulation



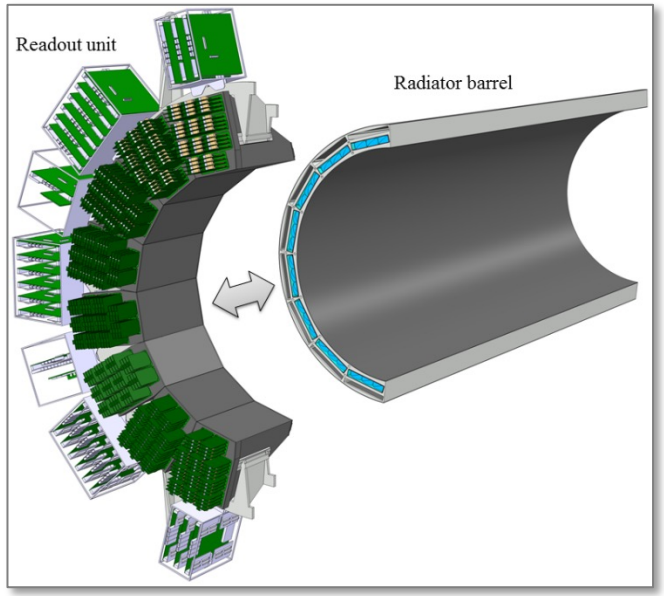
Hit pattern accumulated over 240h

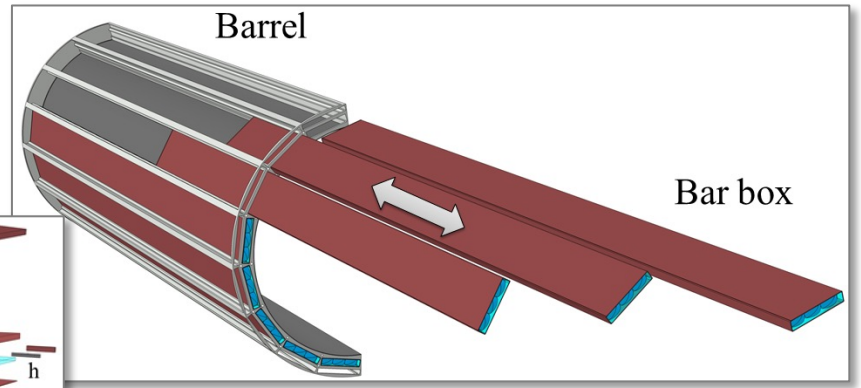


Mechanical Design: Bar Boxes

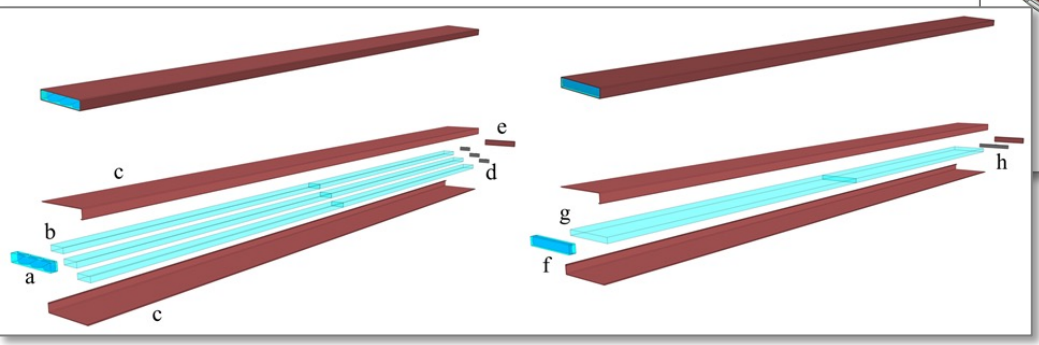
Synergy with PANDA Barrel DIRC will help to tackle many questions

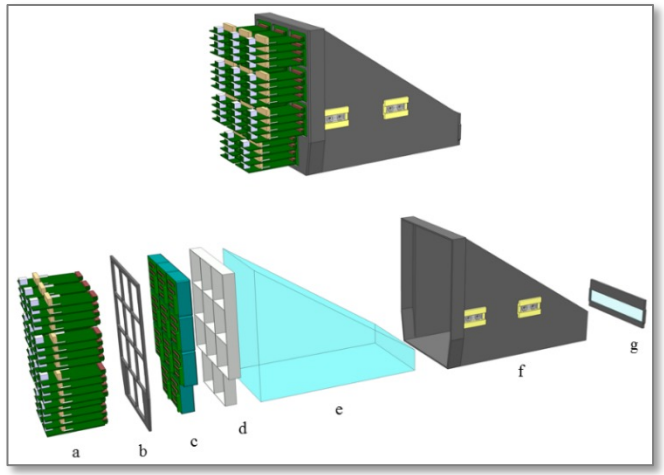
- Integration into ePIC detector support structure, cooling, nitrogen flow
- Material used for bar boxes:
  - CFRP being studied in terms of stiffness, mechanical properties, and in terms of outgassing and the potential long-term impact of material outgassing on the bar surfaces
  - BaBar-like aluminium/hexcel panel approach as backup solution





PANDA Barrel DIRC example of DIRC mechanical design



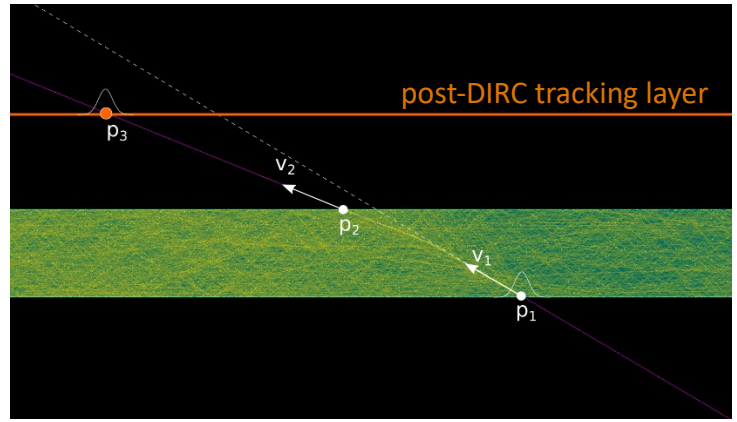


HPDIRC SIMULATION: POST-DIRC TRACKING

hpDIRC resolution at lower momenta dominated by multiple scattering

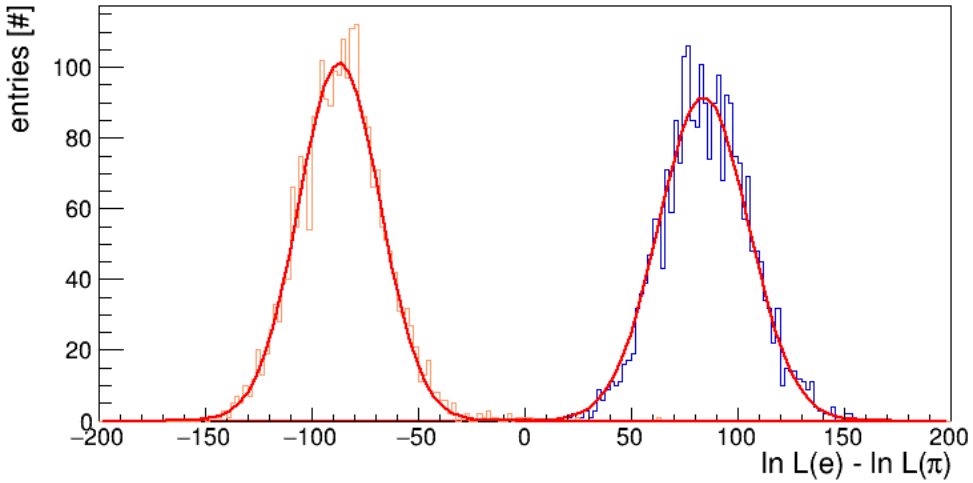
- Additional layer of tracking behind hpDIRC could mitigate impact on performance (non-Gaussian tails → efficiency, mis-ID)
- Initial studies in stand alone simulations performed
- Input from tracking working group needed to move forward

G4 simulation of hpDIRC

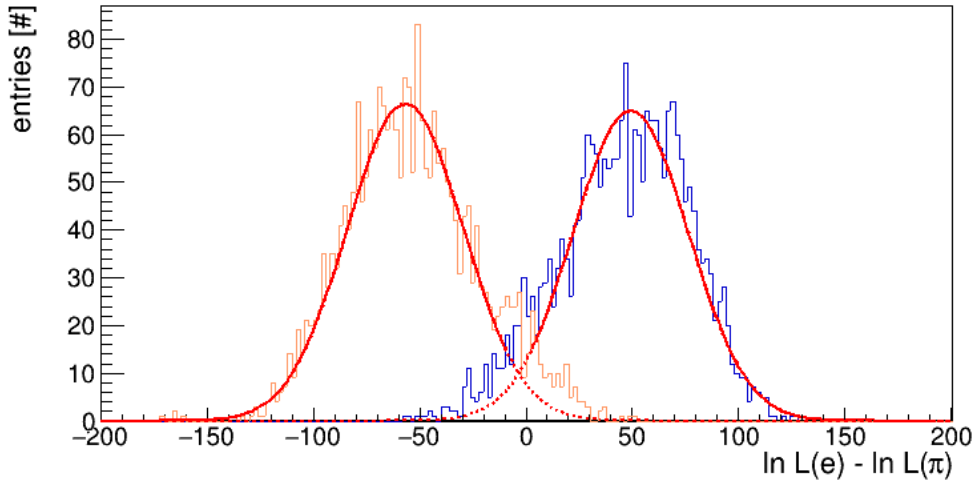


Example from Geant4
e/π log-likelihood difference
1.2 GeV/c momentum,
30° polar angle,
2.2 mrad tracking resolution

Geant without multiple scattering: ~9 s.d.



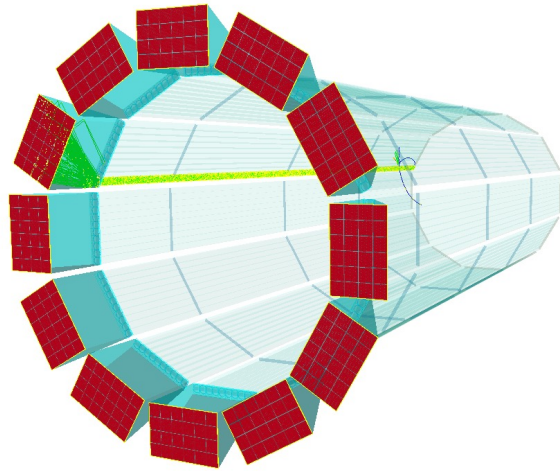
Geant with multiple scattering: ~4 s.d.



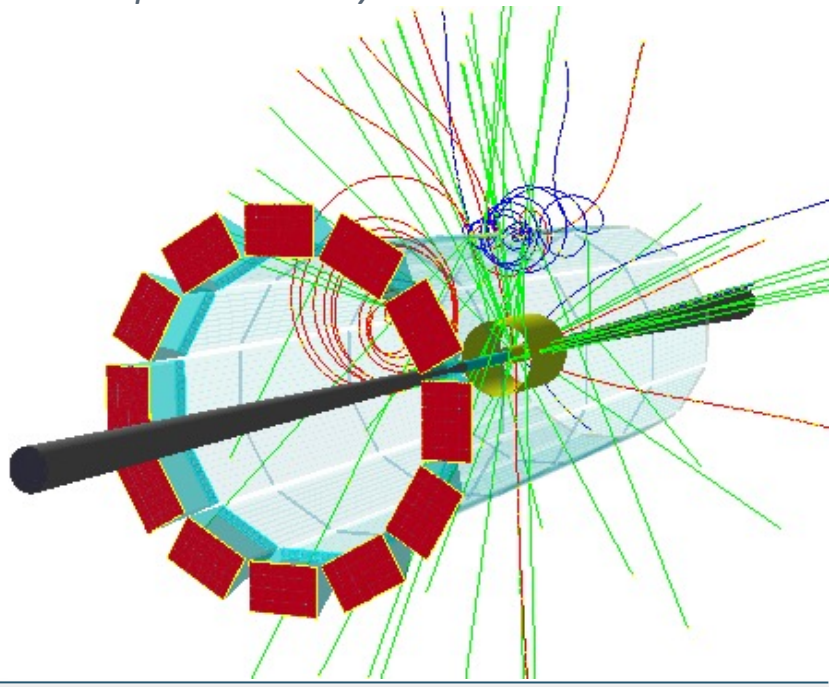
HPDIRC SIMULATION: FULL SYSTEM STUDIES

- Standalone G4 hpDIRC simulation (validated in CERN beam tests) implemented into ePIC detector simulation (Fun4All)
- Includes realistic geometry and wavelength-dependent material properties, based on prototypes, processes with all relevant resolution terms
- Enables important studies of impact of magnetic field, nearby tracks in same bar box or same bar, beam background, particle flux, etc
- hpDIRC performance in ePIC Detector simulation matches standalone simulation results
- Impact of magnetic field on performance study underway
- Started studies with Pythia events to tackle more realistic performance, multiplicity of tracks per bar, impact of backgrounds

hpDIRC single track simulation in F4A



hpDIRC with Pythia event in F4A



FY23 Budget Request

FY 23 Plan:

- hpDIRC Cost/Performance design optimization
- hpDIRC prototype in CRT:
  - Assembly and operation of CRT setup
  - Commissioning of tagging, tracking, and timing detectors
  - Initial prototype with PANDA DIRC readout
- Validation of the BaBar DIRC bar reuse

Budget request:

- ⇨ Extend CUA PostDoc contract
- ⇨ Travel for CUA, materials for SBU and CUA
- ⇨ Graduate student for SBU
- ⇨ Materials and travel for CUA, GSI
- ⇨ No eRD funding requested

Notes

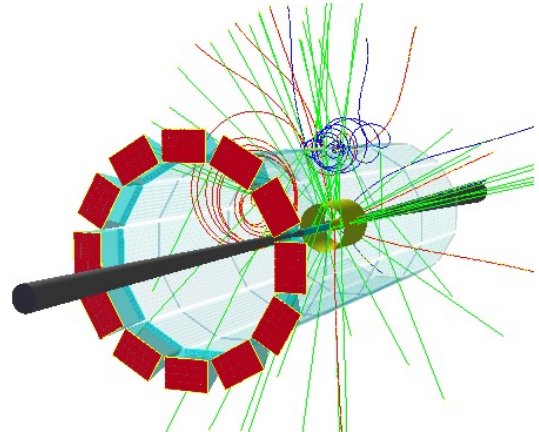
- JLab DSG committed to support QA lab and bar measurement
- Request for financial support for ODU technician withdrawn from proposal

Item	Institution	Requested
Postdoc (50%) hpDIRC software	CUA	$80k
Prototype Equipment	CUA	$20k
Travel to DIRC lab at SBU	CUA/GSI	$30k
CRT Graduate student	SBU	$61.5k
CRT VMM-SRS system	SBU	$23.5k
CRT materials	SBU	$15k
Total		$230k

SUMMARY/OUTLOOK

- Important eRD103 progress in 2022, close to meeting declared milestones for 2022
- Delayed start of eRD programs and helpful committee feedback to FY22 proposal prompted adjustments to eRD103 R&D plan
- Modified eRD103 proposal incorporates hpDIRC multi-program R&D effort with clearly defined roadmap towards TDR readiness in time for CD-3
- Continuation of program in 2023 with focus on Cosmic ray telescope (CRT), validation of BaBar bars reuse option, and completion of cost optimized hpDIRC design
- Preparing the way for potential future incremental upgrade of the hpDIRC prototype when bars, sensors, and readout electronics become available
- A vertical-slice prototype in a particle beam remains an option for 2024

hpDIRC in F4A simulation



CRT space at SBU

Thank you all for your attention