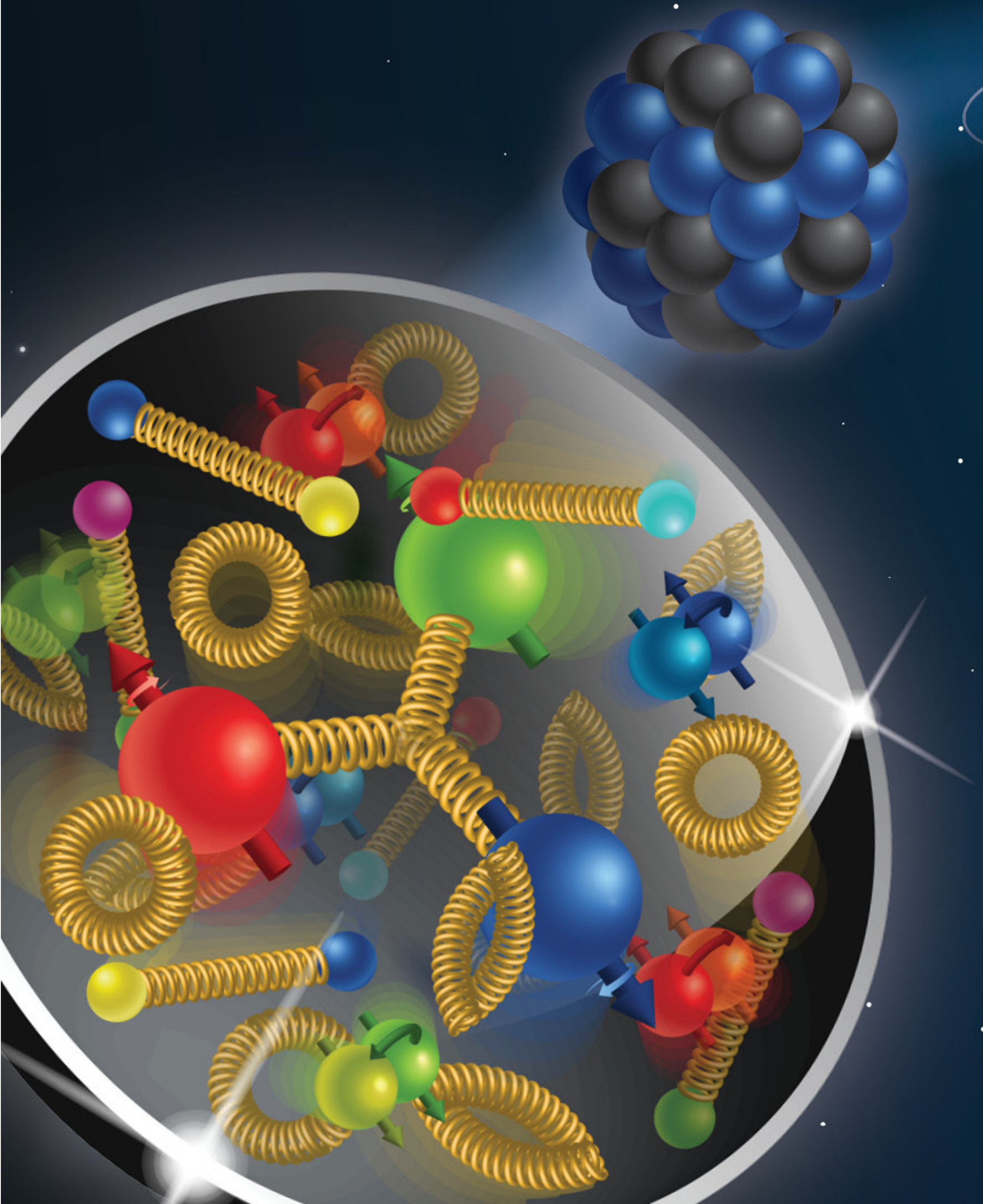


Backward region: proximity-focusing RICH

Alexander Kiselev, BNL

EIC Project Detector PID Review

July 5-6, 2023

Electron-Ion Collider

BROOKHAVEN NATIONAL LABORATORY Jefferson Lab U.S. DEPARTMENT OF ENERGY Office of Science

Outline

- Requirements
- pfRICH detector layout
- Design considerations
- Subsystem description
- Modeling results
- Detector prototyping in FY24
- pfRICH Detector Subsystem Collaboration
- Design and construction schedule
- ES&H

Electron-Ion Collider

Requirements

SCIENCE REQUIREMENTS AND DETECTOR CONCEPTS FOR THE ELECTRON-ION COLLIDER
EIC Yellow Report

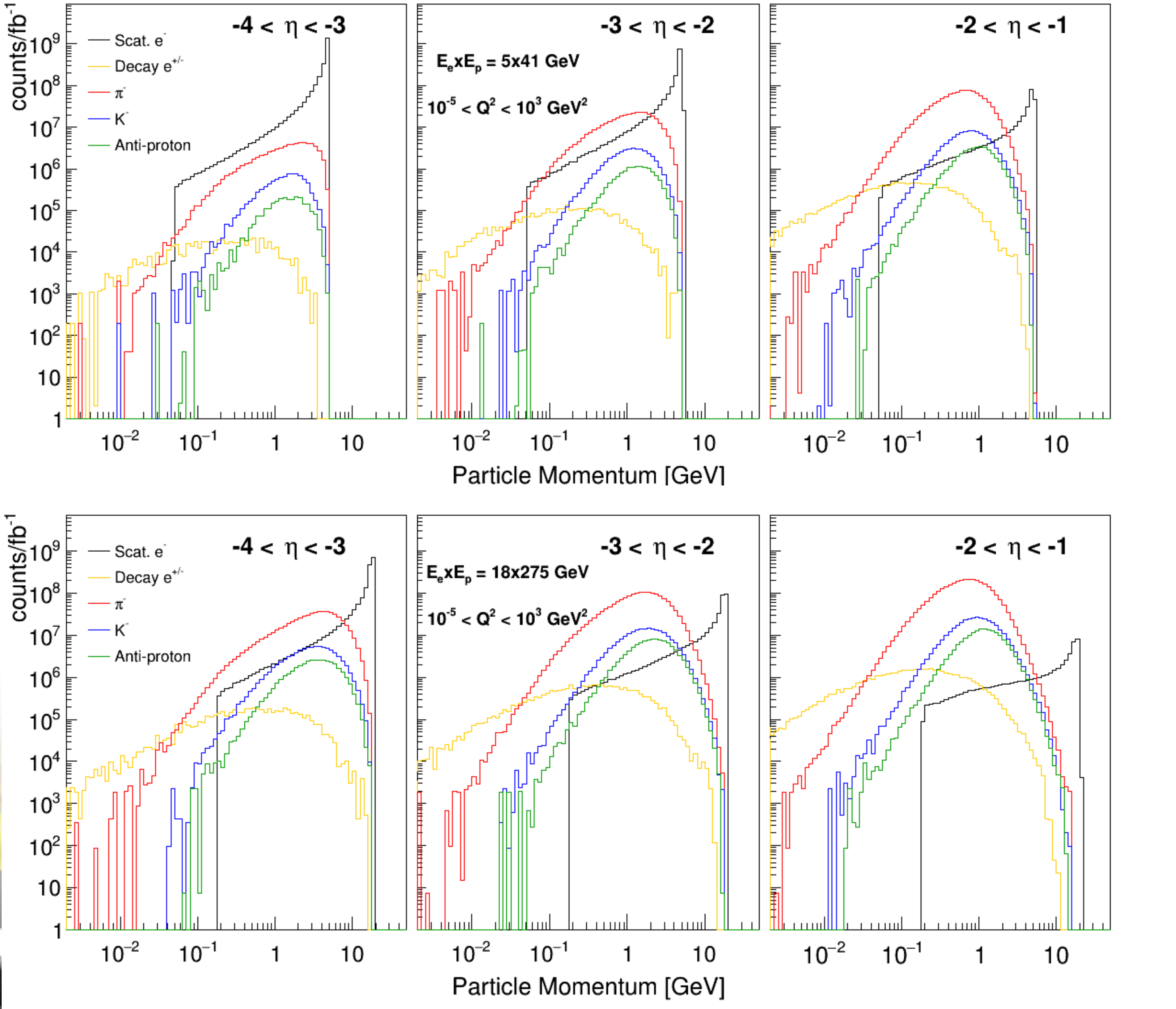
- ePIC backward RICH must provide PID coverage in the η range determined by the reach of the barrel DIRC and the acceptance of the crystal calorimeter in the e-endcap, therefore ~ -3.5 < η < ~ -1.65, at a minimum

- This part of the detector acceptance corresponds to the current fragmentation and low x physics, and is essential to support the claim of a complete hermetic coverage of the pseudorapidity range $-3.5 < \eta < 3.5$ by tracking, calorimetry and PID detectors

- Yellow report requirement: 3σ π/K separation up to 7 GeV/c

- Additional requirement: provide ~20 ps timing reference for ePIC ToF detectors

Particle momentum spectra in ePIC e-endcap

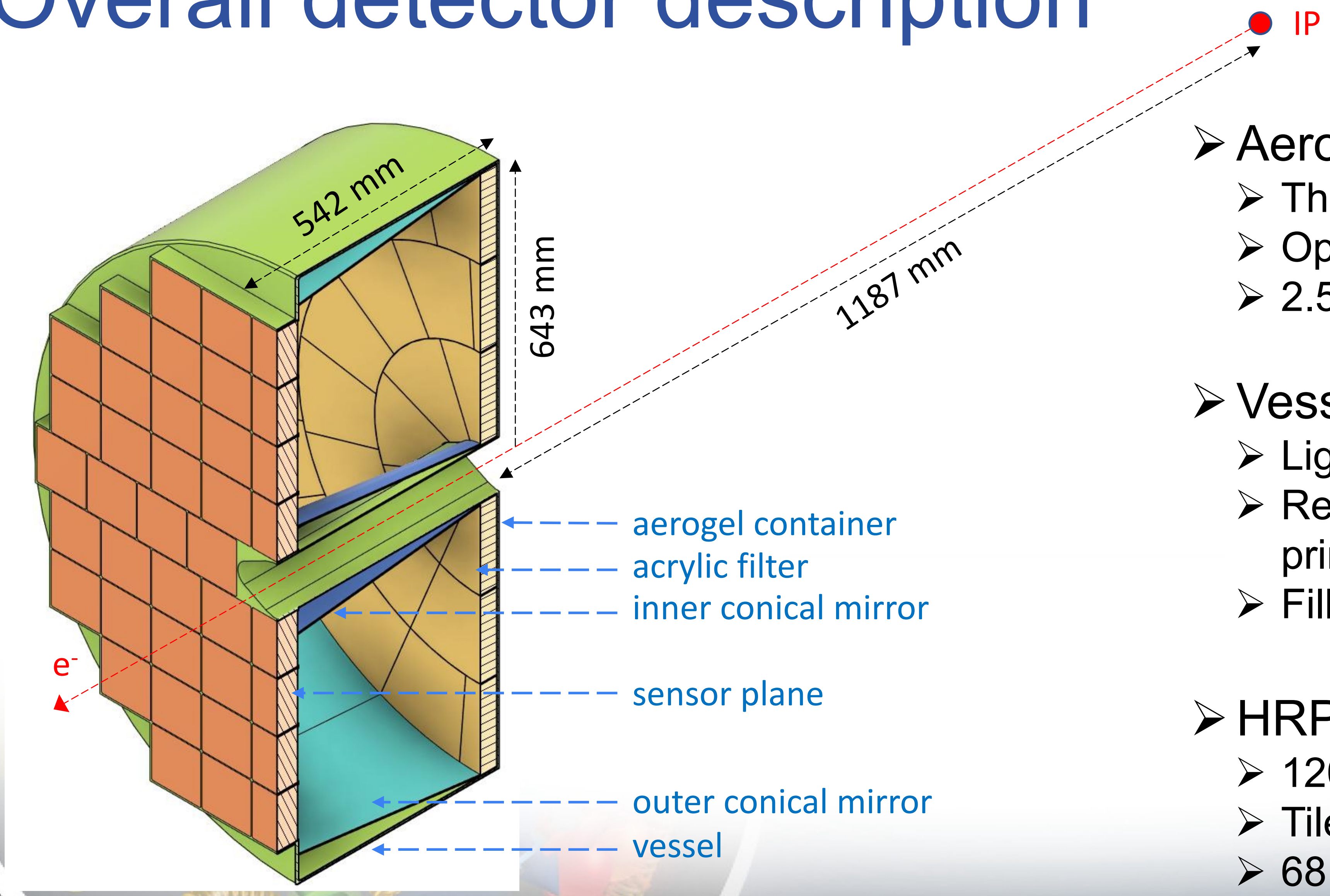


5 x 41 GeV

- Momentum dependency of π/K/p distributions is similar
  - With a π:K ratio ~3
- There is not much above ~7 GeV/c, especially at lower beam energies

18 x 275 GeV

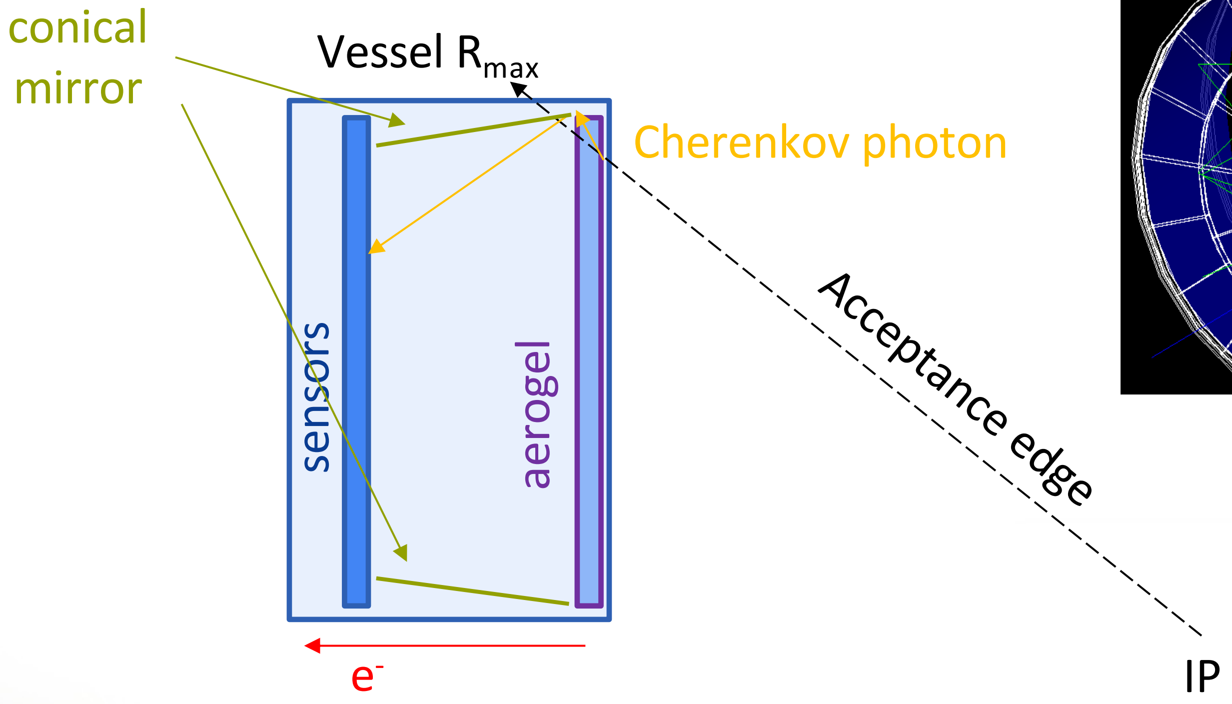
Overall detector description

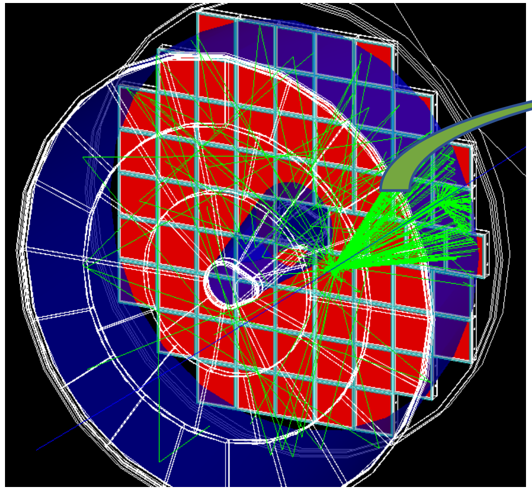


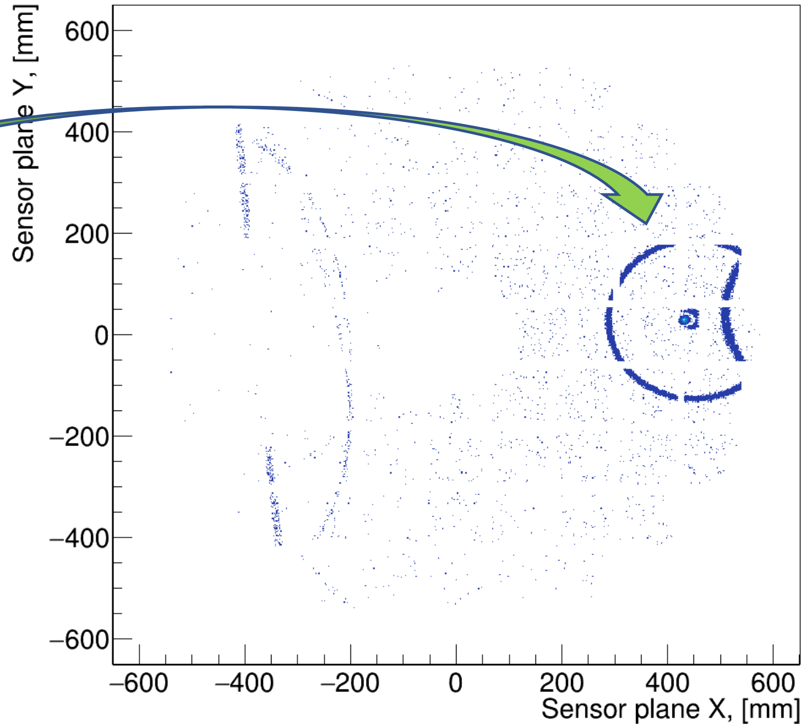
- Aerogel
  - Three radial bands
  - Opaque dividers
  - 2.5 cm thick, 42 tiles total
- Vessel
  - Lightweight structure
  - Reinforced carbon fiber and 3D printed materials
  - Filled with nitrogen
- HRPPD photosensors
  - 120 mm size
  - Tiled with a 1.5mm gap
  - 68 sensors total

Chosen as a technology baseline for ePIC in April 2023

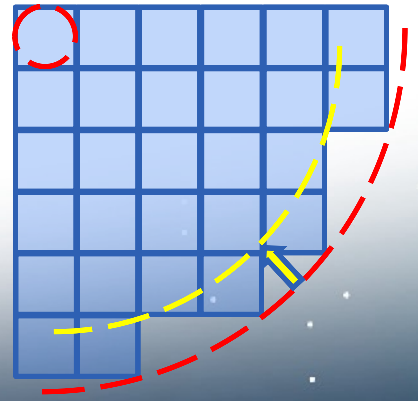
Angular acceptance optimization







- Use side wall mirrors to increase η acceptance
  - Achieve $-3.5 < \eta < -1.5$ coverage (hence overlap with the DIRC)
  - Make mirrors *conical* to avoid inefficiency on the sensor plane

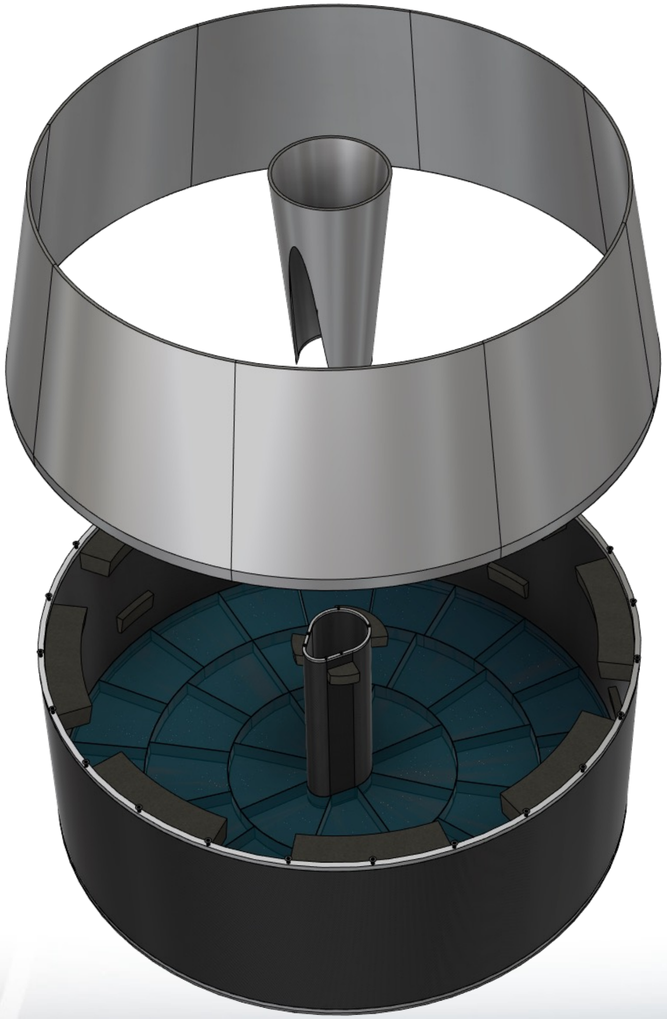


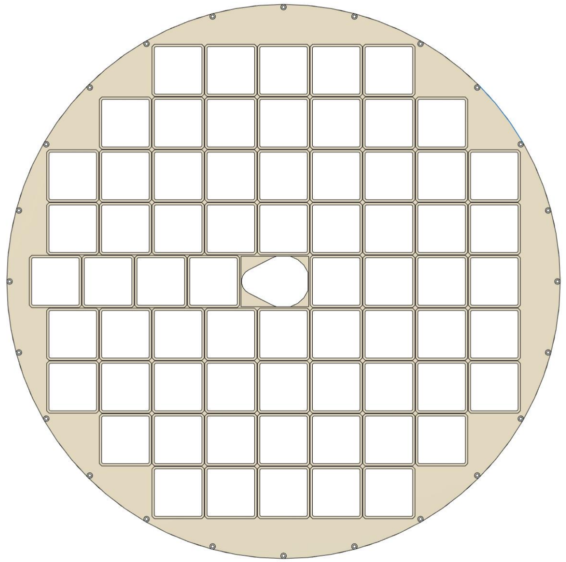
Vessel and mirrors

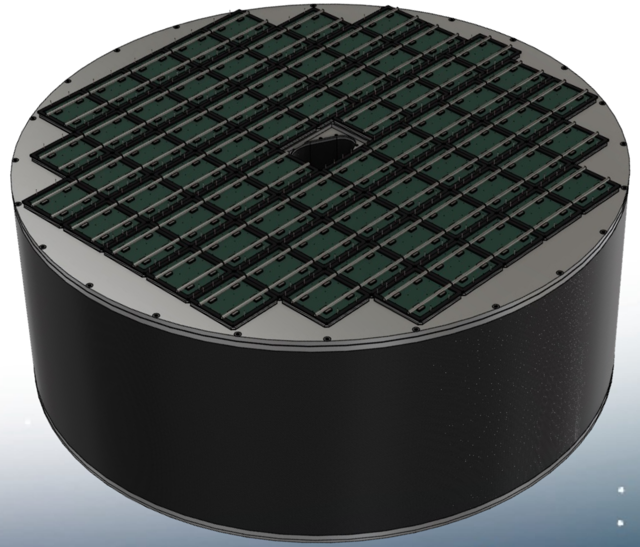
- Outer vessel shell
  - Honeycomb carbon fiber sandwich
- Inner shell
  - Molded prepreg laminate

- Front (aerogel support) wall
  - Molded prepreg laminate
- Rear (sensor support) plate
  - 3D printed using reinforced carbon

- Mirrors
  - Molded laminate substrate
  - Aluminum evaporation + coating





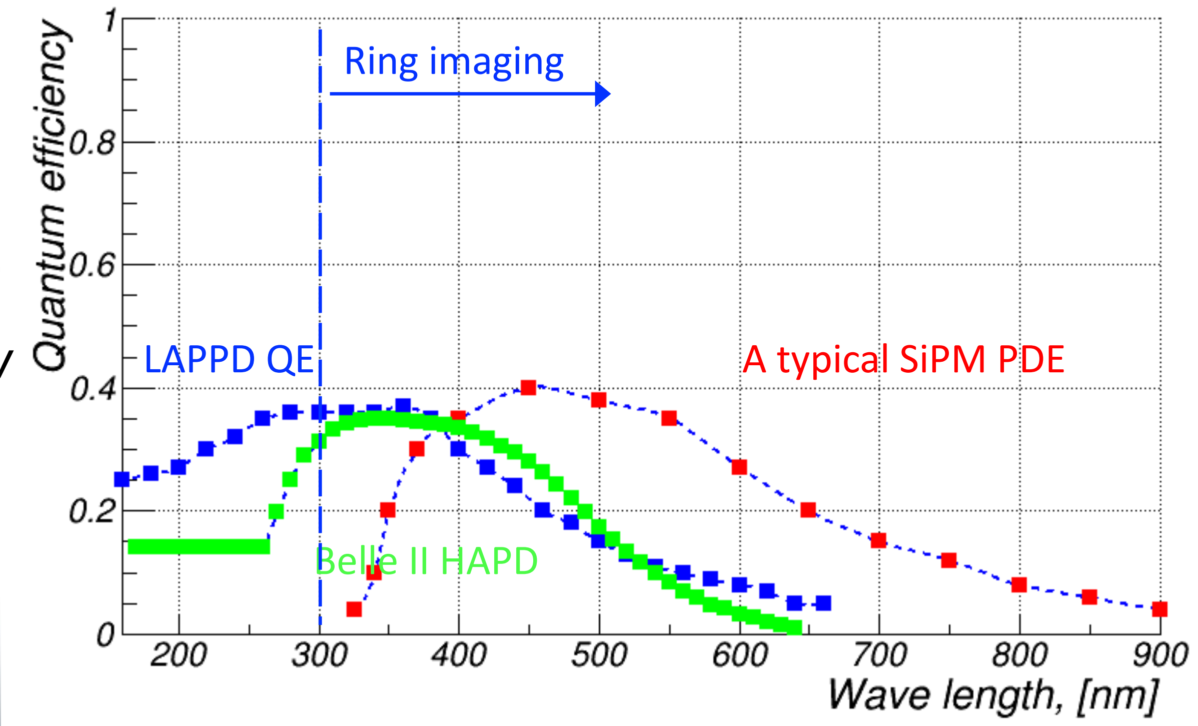


All built in-house by the pfRICH DSC member groups

Choice of aerogel

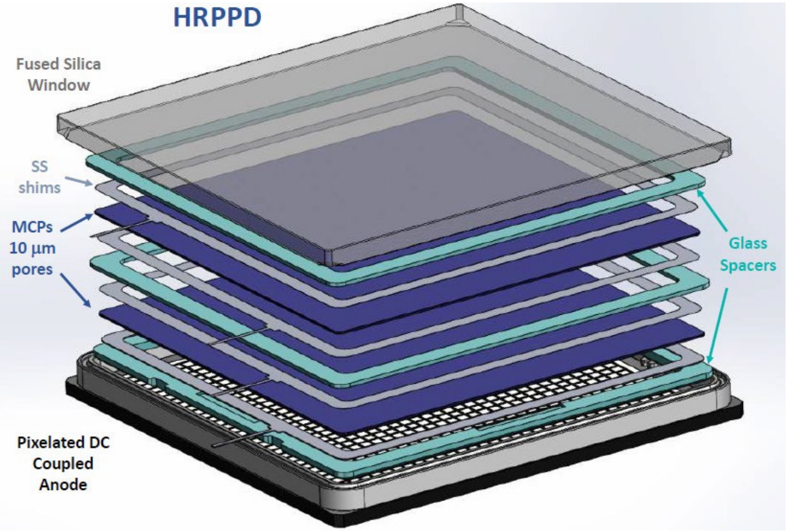
- A relatively moderate momentum reach is required for this RICH detector
- HRPPD PDE is expected to be substantially smaller than of the SiPMs
  - And peak value shifted to the UV range, where it cannot be used for ring imaging

- Consider using a high n ~ 1.040 … 1.050
  - 300 nm acrylic filter cutoff for imaging
  - $\langle N_{pe} \rangle$ ~ 11-12
  - *For ToF still make use of the UV range for abundant Cherenkov light produced in the window*
  - Natural choice for simulations: Belle II (n ~ 1.045)
  - Natural hardware reference: Chiba University aerogel recently produced for J-PARC (n = 1.040)
  - Test samples will be produced by the end of 2023



Electron-Ion Collider

Choice of photosensors and electronics



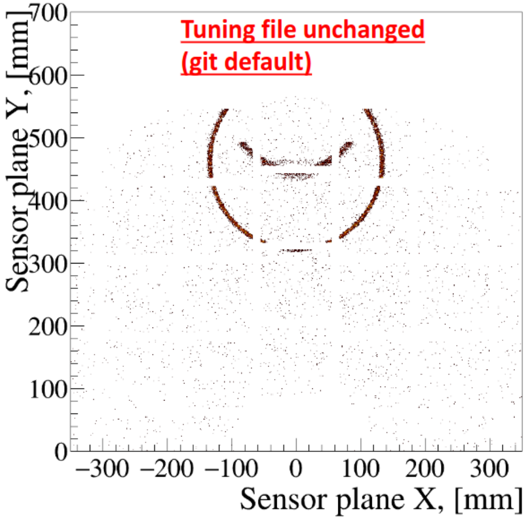
- Basic requirements:
  - Provide a timing reference better than ~20 ps for the barrel and forward ToF subsystems
  - Provide spatial resolution ~1mm
  - Have small Dark Count Rate
  - Have reasonable power dissipation in mW per channel
    - a low material budget cooling system in front of the PWO EmCal
    - as little influence on the thermal environment around the EmCal as possible
  - Allow for a compact solution to leave more space for the proximity gap

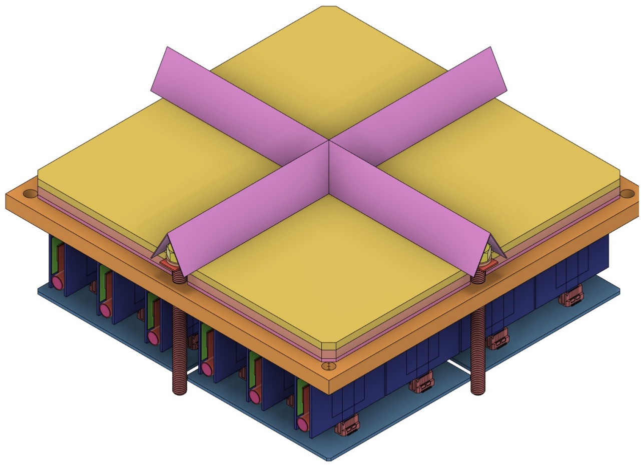
- **Photosensor: HRPPD by Incom Inc.**
  - High intrinsic SPE timing resolution
  - Low Dark Count Rate (compared to SiPMs)
  - Low cost (compared to other MCP-PMTs)
- **ASIC: EICROC by OMEGA group**
  - Meets the requirements
  - Will be available in 256+ channel configuration
  - Will be developed for ePIC AC-LGADs anyway

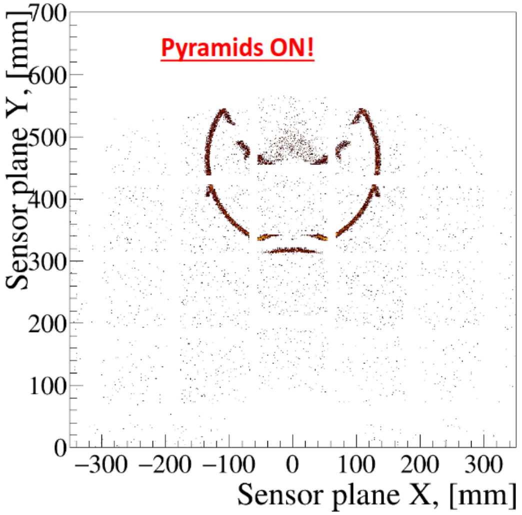
More information in the LAPPD / HRPPD and electronics talks

Performance enhancements

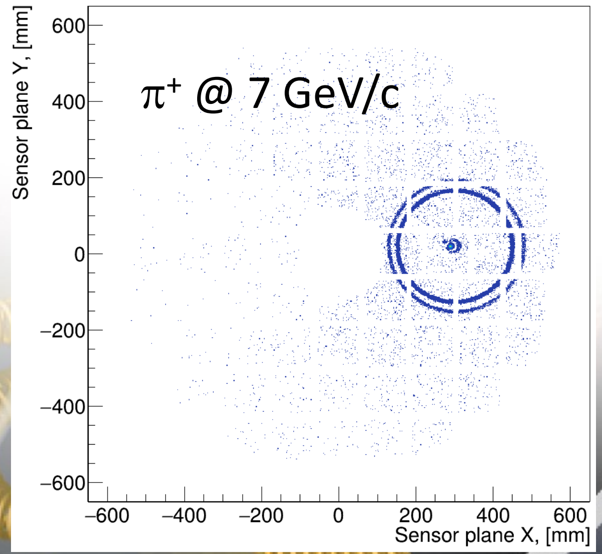
- Installation of small funneling mirrors around each sensor dead area boundaries







- Use of a dual aerogel configuration



- Both options implemented in software
- Both give a substantial increase in photon yield

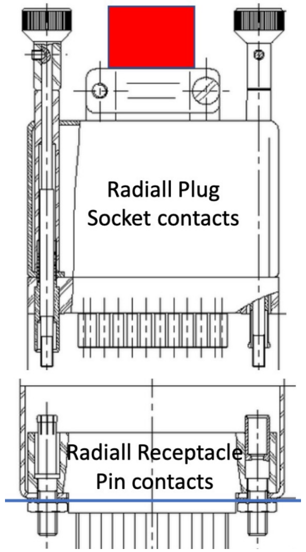
- Recently added to the baseline configuration as a consequence of a complex ePIC detector tracker optimization (pfRICH expansion volume was shortened by ~5cm)

HV system

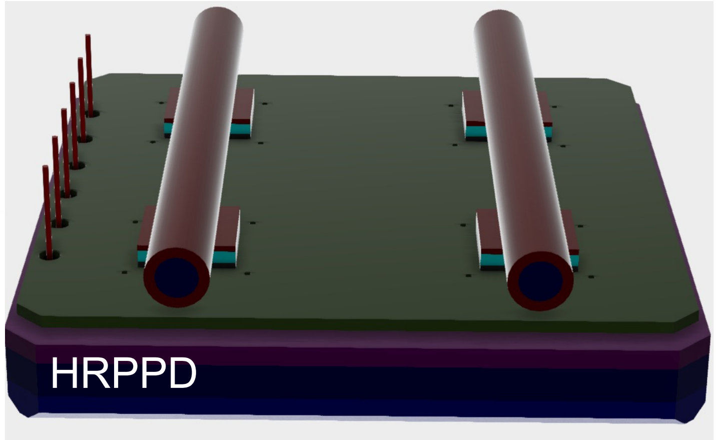
- CAEN HV mainframes and *stackable* HV modules
- CERN-approved Radiall connectors

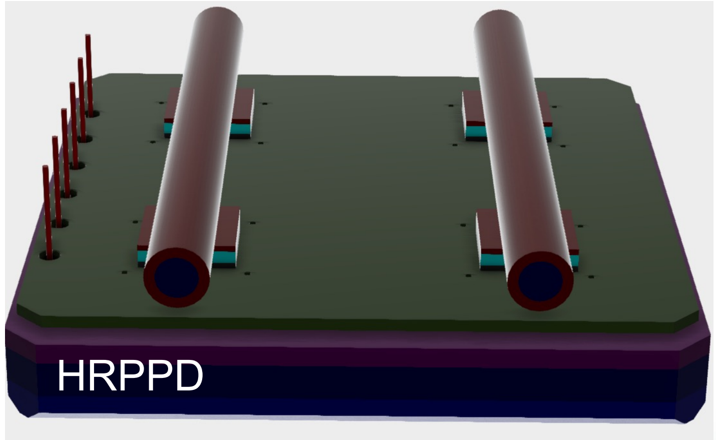
23x A1515BV's

From PSUs
56 wires HV cable



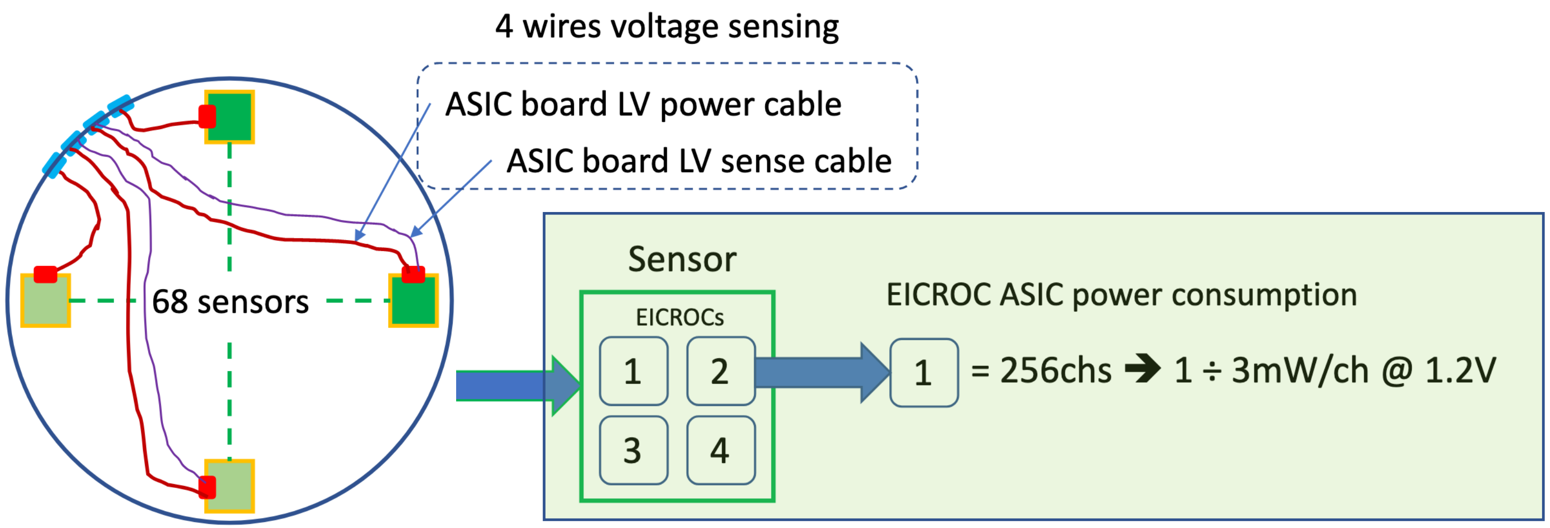
On-detector part





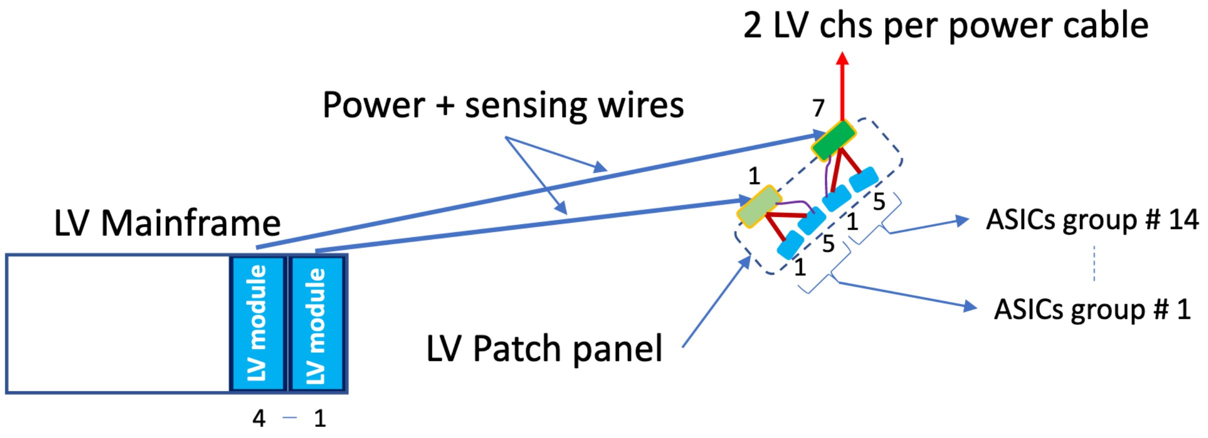
six Teflon coated wires per HRPPD

LV system



Wiener LV mainframe and modules

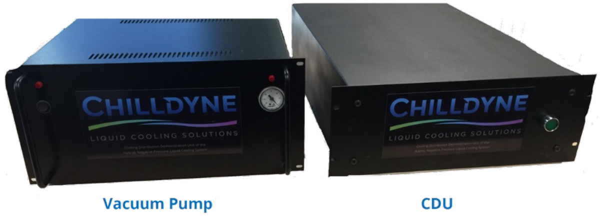
- Each Sensor
  - 4EICROCs x 256chs = 1024chs/sensor ➔ @3mW/ch ➔ ~3W/se
- Whole detector
  - 68sensors x 2.5A ➔ 170A@1.2V ➔ 204W
  - Add 20% extra current for the ancillary electronic components
    - 170A + 20% = 204A@1.2V ➔ 245W
  - Add 20% extra current for safety margin
    - 204A + 20% = **245A@1.2V** ➔ **294W**



Cooling system

Off Detector

- Chilldyne Circulator
  - 8 lpm
  - -10 psi
  - 5°C to 40°C



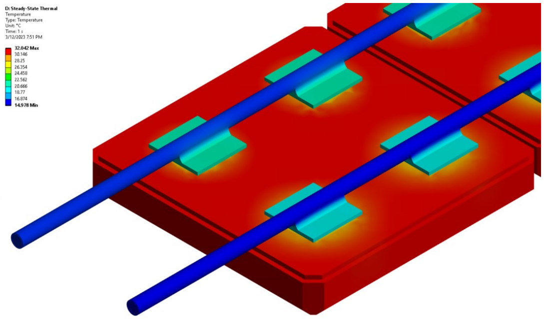
- Polyscience Chiller
  - 9.8 l/min @ 43.4 psi
  - -20°C to 40°C ±0.1°C
  - 800 W @ 10°C

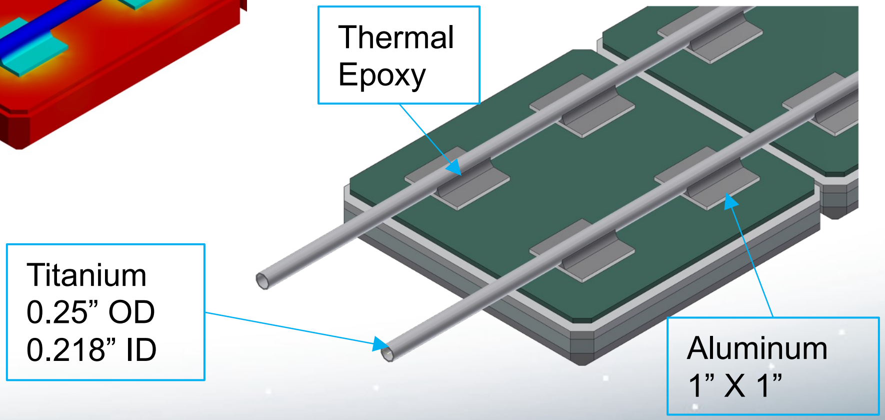
- Distribution Panel
  - Flowmeters
  - Flow Transmitters

On Detector

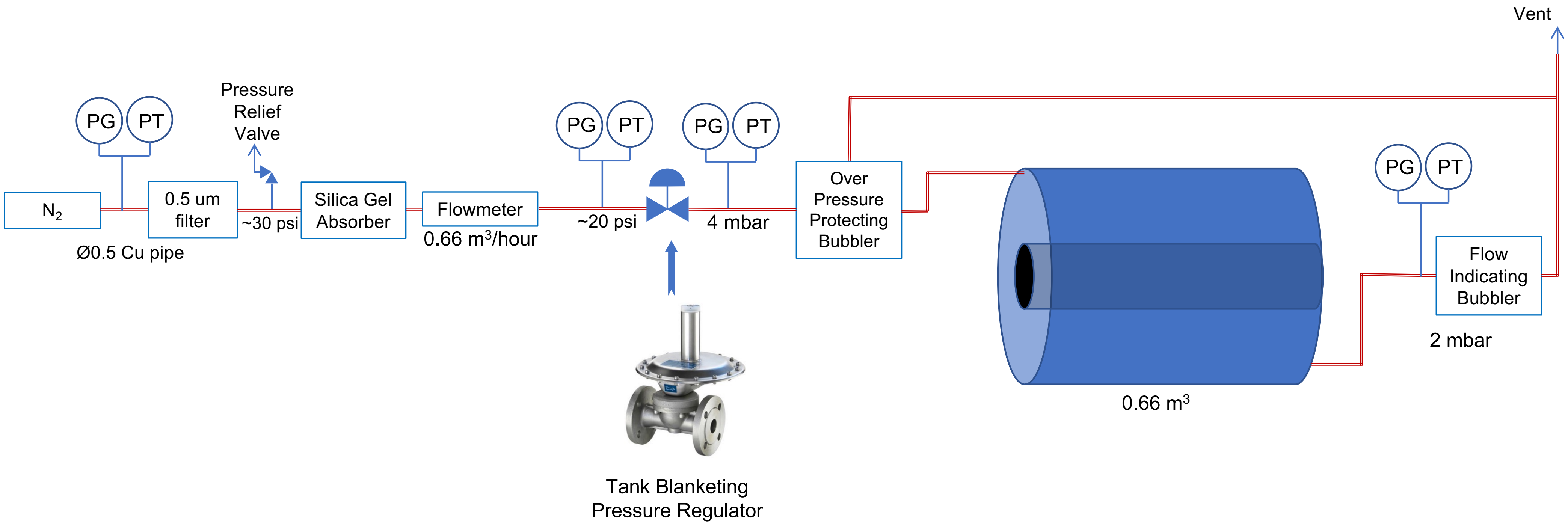
- Heat dissipation: 400W
- Tube @ Δ2°C: ~3 lpm
- ΔP ~0.25 psi

- 9 Modules:
  - ~50W,
  - ~Δ17°C
  - Water ~Δ1.2°C





Gas system

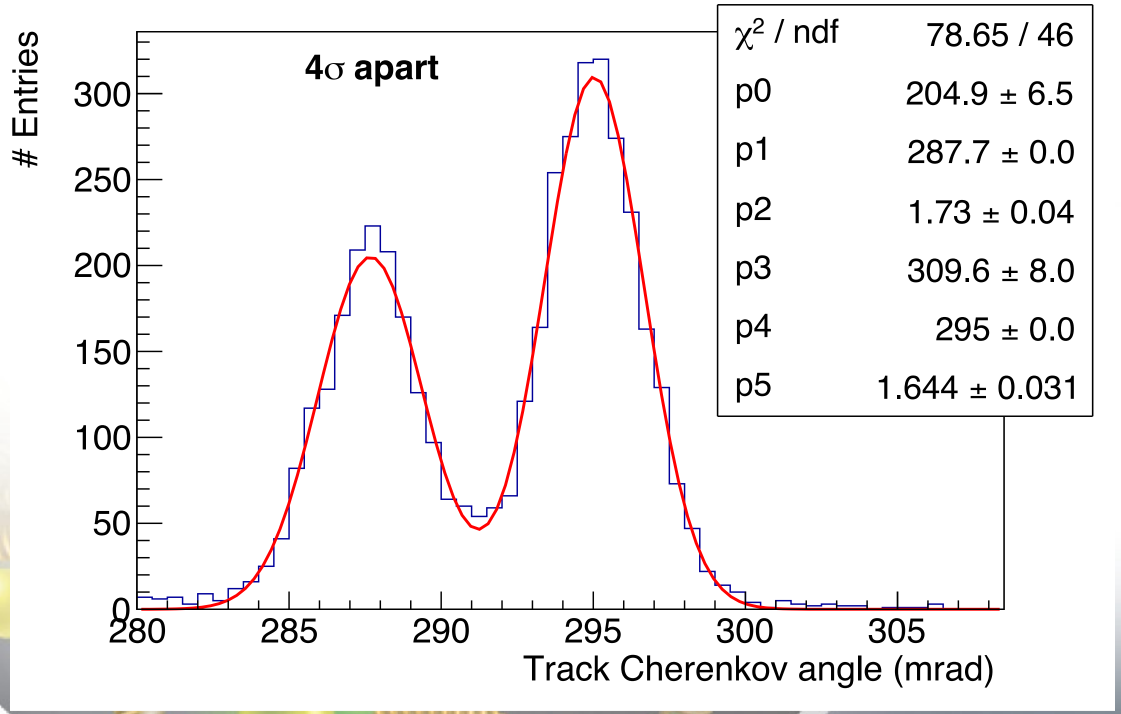


- Assume nitrogen only configuration
- One volume exchange per hour at a pressure 2-4 mbar
- Gas quality (industrial, ultra-pure,…) needs to be finalized

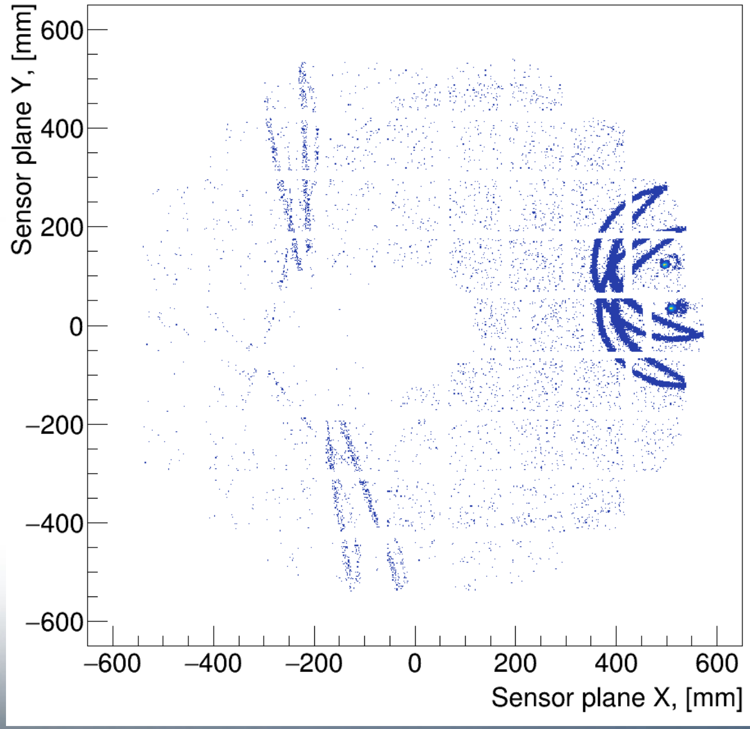
Monte-Carlo simulations: performance highlights

- Standalone GEANT4 code with a particle gun or HEPMC3 import
- Simulation with (almost) all known optical effects included
- Event-level digitization / reconstruction chain
  - χ^2 based algorithm with a full combinatorial hit-to-track ambiguity resolution

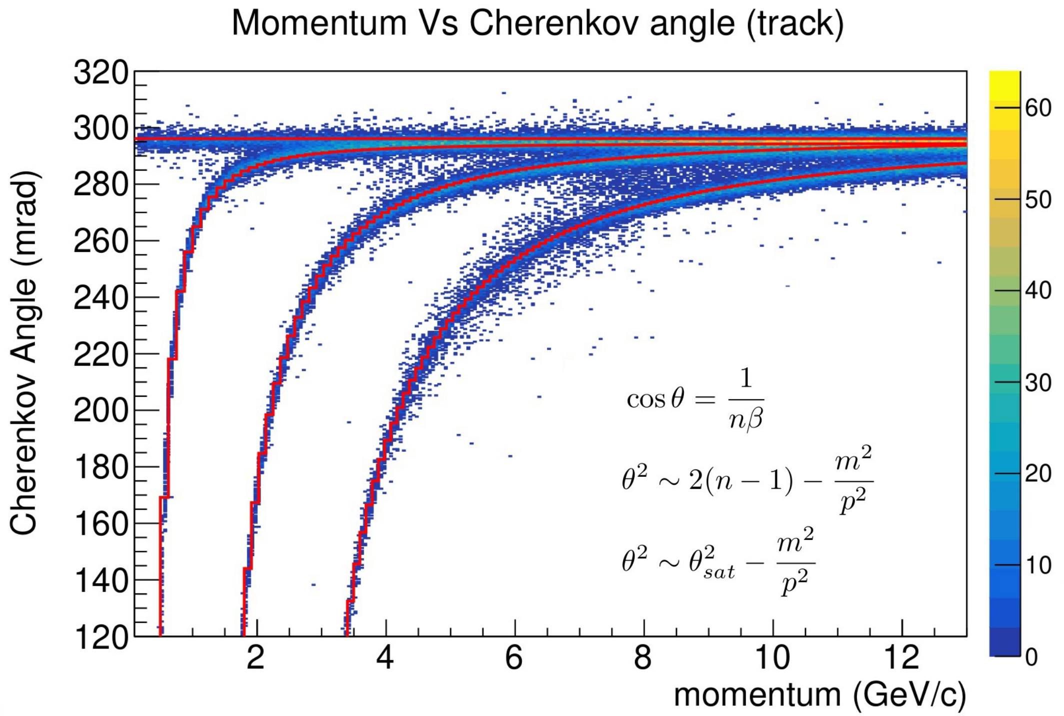
π and K @ 7.25 GeV/c: >4 σ separation

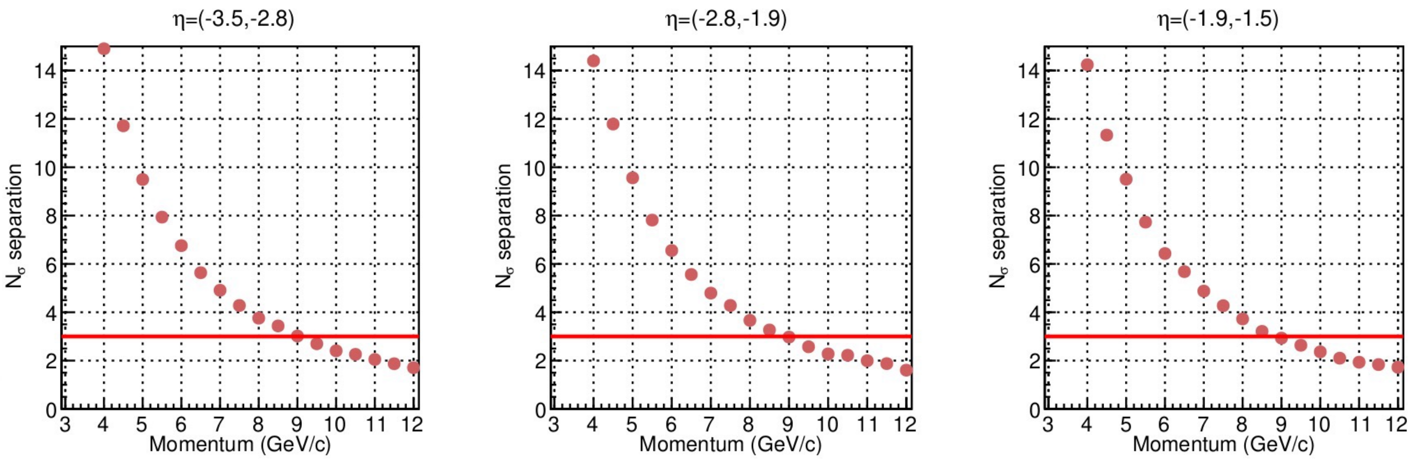


7 GeV/c π and K @ η = -1.9: <5% misidentification rate
(plot accumulated over 1000 two-track events)



e/π/K/p separation





e/π/K/p response integrated over the whole η acceptance

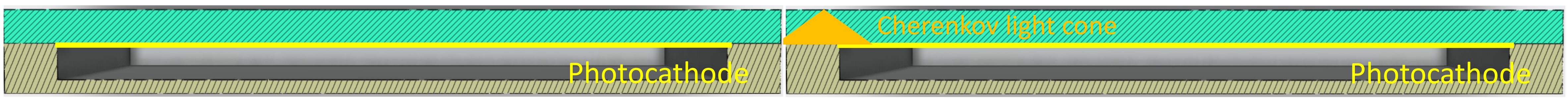
π/K N_σ separation in η bins

- Comfortably reach 7+ GeV/c momentum range with a higher than 3σ π/K separation level

Geometric efficiency for timing purposes

High energy charged particle produces dozens of p.e.'s in the HRPPD window

charged particle (missing the "active" area)



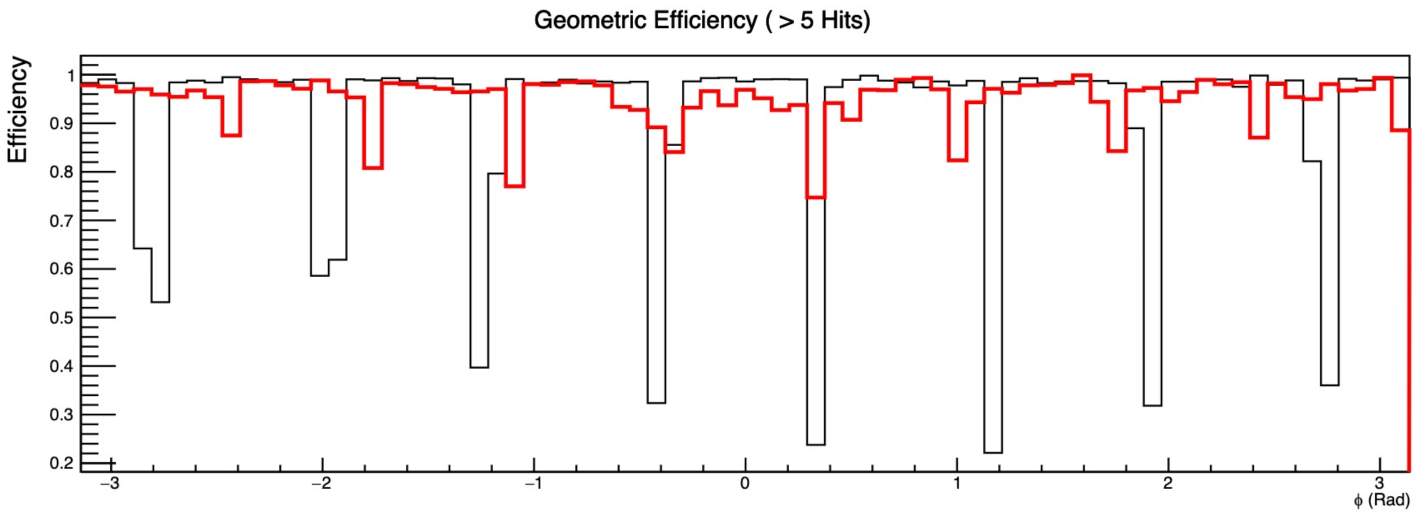
- Cherenkov light cone produced in the window creates a ~12mm spot on the photocathode

- Tiling HRPPDs as a "flat wall" with minimal gaps provides >90% geometric efficiency …
- … and it is complemented by timing from ring imaging photoelectrons to achieve ~100%

Geometric efficiency for timing purposes

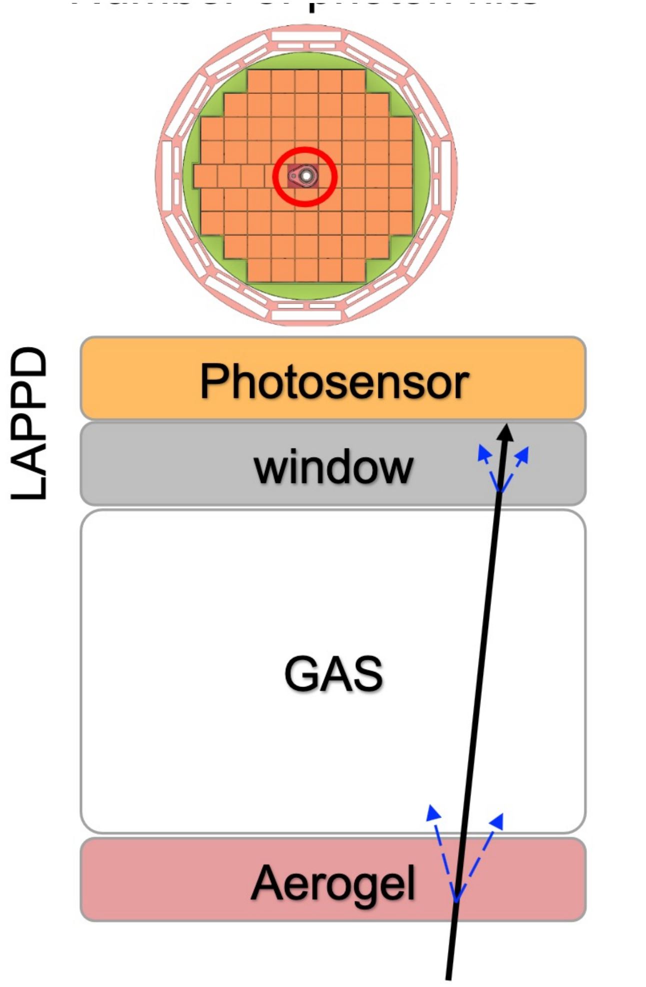
- Timing provided by both aerogel (<N_{pe}> ~12) and HRPPD window photons (<N_{pe}> above 80)
  - Their combined geometric acceptance will be ~100%

- **ToF** meas. ← # photon hits created by particles
  - pfRICH receives photon hits from aerogel, acrylic filter, gas in expansion volume, and **LAPPD window**
- **Efficiency** (η, ϕ): prob. of particle creating N_{pe} > 5.
  - **20 ps t_0 resolution** by having 6 photons, assuming 50 ps single photon time resolution (timing resolution **20ps = 50ps /** $\sqrt{6}$).



Red dips → ribs from Aerogel wall

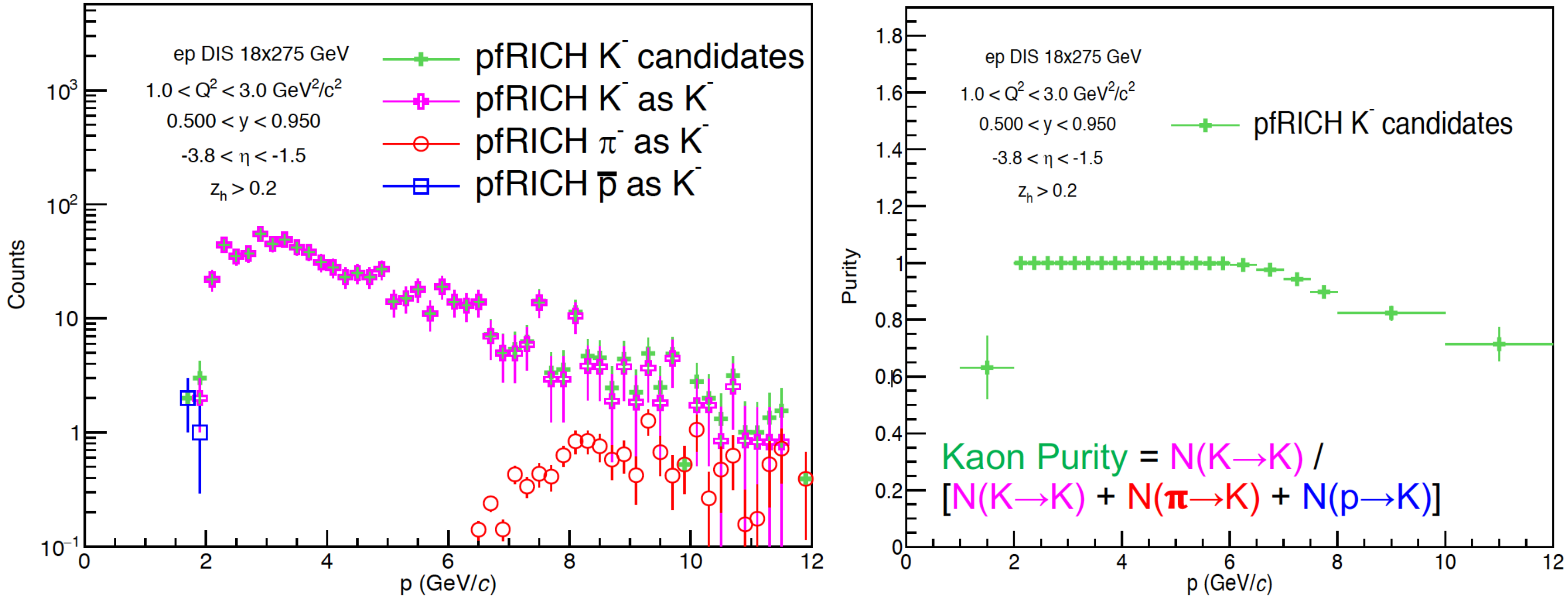
Black dips → ribs from window ceramic boundary



Single Particles fired at $\eta = -3$

SIDIS modeling results

- PYTHIA 18 x 275 GeV simulation
- Parameterized pfRICH hadron PID response, assuming 100% kaon detection efficiency



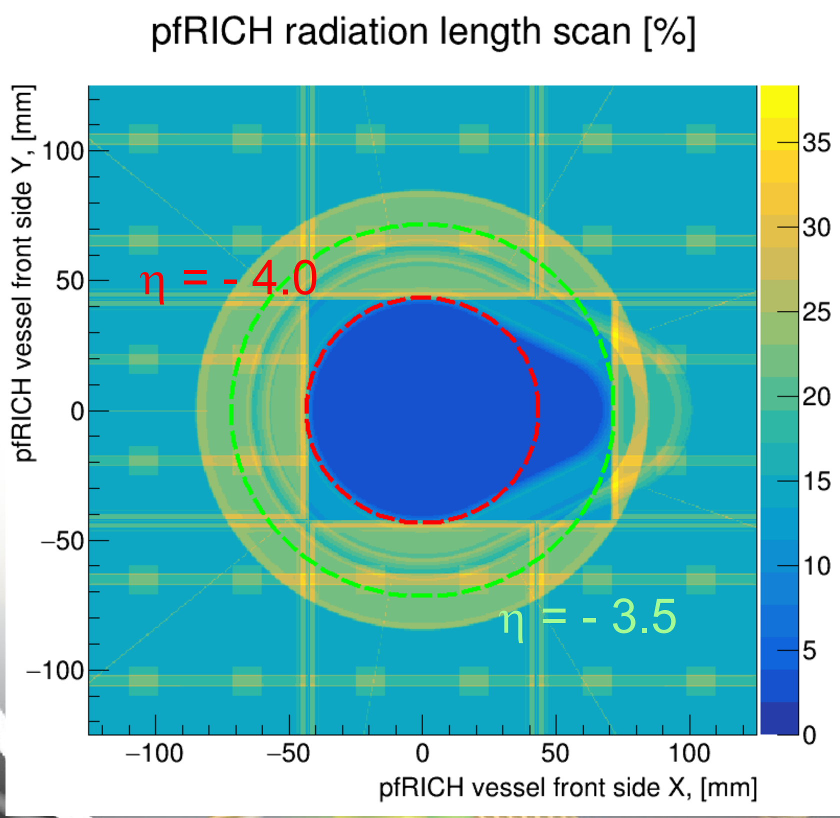
High Kaon Purity ~ 95% at 7 GeV/c

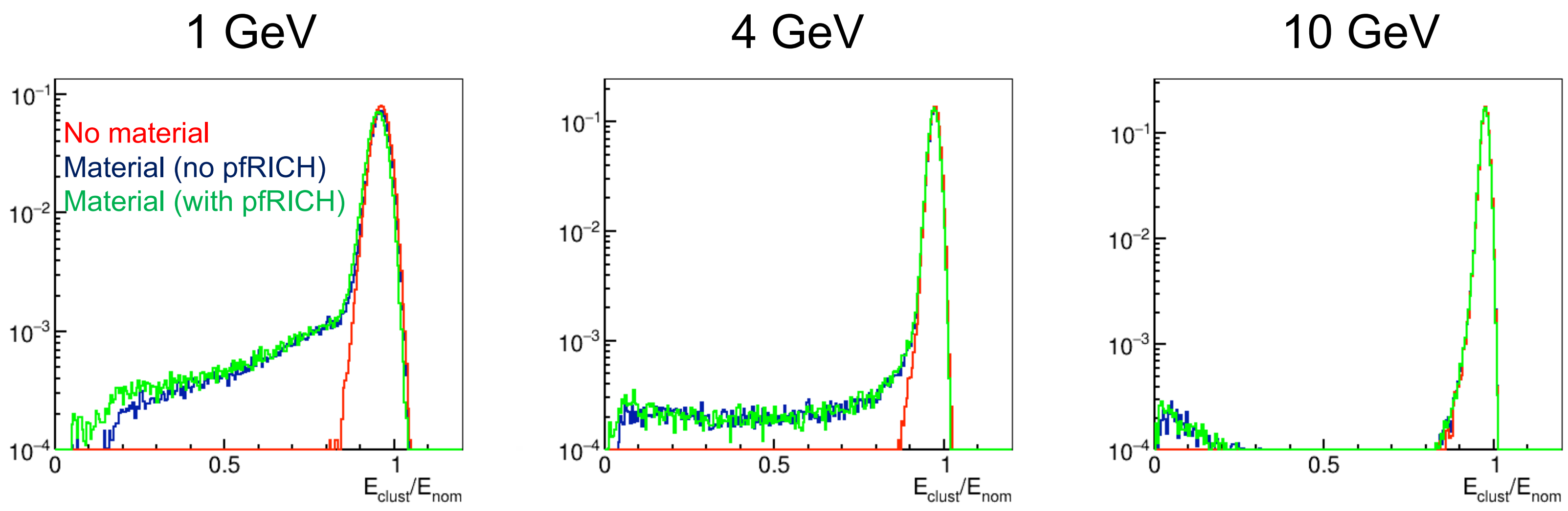
→ this **goes beyond** the requirement of SIDIS physics in the YR

pfRICH material effect on the backward EmCal

- pfRICH GEANT implementation imported in ePIC framework as a GDML file
  - Material implemented to the best of our knowledge (vessel, HRPPDs, cooling system, etc)

-3.3 < η < -1.9



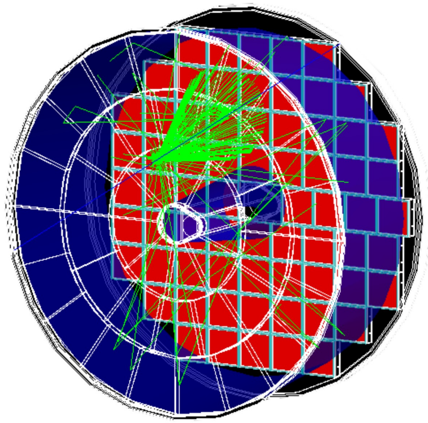


- No effect on (~gaussian) peak width
- Lower energy tails (the largest at 1 GeV)
- No effect for high energy electrons (10 GeV)
- Minimal effect from pfRICH overall

pfRICH Detector Subsystem Collaboration (DSC)

Institution	Main focus	Comments
Brookhaven Lab	HRPPD integration, ASIC interface, detector and physic modeling, engineering support	
Chiba University	Aerogel production	No institutional commitment
Duke University	Software support	
INFN Genova	HRPPD evaluation, modeling	Synergetic activities with
INFN Trieste	HRPPD evaluation, modeling	dRICH (aerogel, software)
Jefferson Lab	Engineering support, test beam data analysis	
Ljubljana University		Participating as experts
Purdue University	Vessel & mirror design and construction	
Stony Brook University	Vessel & mirror design and construction	
Temple University	Aerogel QA station	
University of Glasgow	HRPPD & MCP-PMT evaluation	
Yale University	HRPPD QA station	

A Proximity-Focusing RICH for the ePIC Experiment
– Conceptual Design Report –
(Draft 1.1)



Babak Azmoun[1], Deb Sankar Bhattacharya[2], Daniel Cacace[1], Helen Caines[3], Chandradoy Chatterjee[2], Jaydeep Datta[4], Abhay Deshpande[4], Christopher Dilks[5,6], James Dunlop[1], Alex Eslinger[6], Prakhar Garg[4,3], Tom Hemmick[4], Alexander Jentsch[*,1], Alexander Kiselev[*,1], Henry Klest[4], Samo Korpar[7], Peter Križan[7], Jeffery Landgraf[1], Saverio Minutoli[8], Charles-Joseph Naïm[4], Mikhail Osipenko[8], Brian Page[*,1], Sanghwa Park[9], Matt Posik[10], Rok Pestotnik[7], Andrej Seljak[7], Prashanth Shanmuganathan[1], Nikolai Smirnov[3], Bernd Surrow[10], Makoto Tabata[11], Silvia Dalla Torre[2], Zhoudunming Tu[*,1], Thomas Ullrich[*,1,3], Jan Vanek[1], Anselm Vossen[5,6], Craig Woody[1], and Zhengqiao Zhang[1]

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[11]Chiba University, Chiba, Japan¶

Electron-Ion Collider

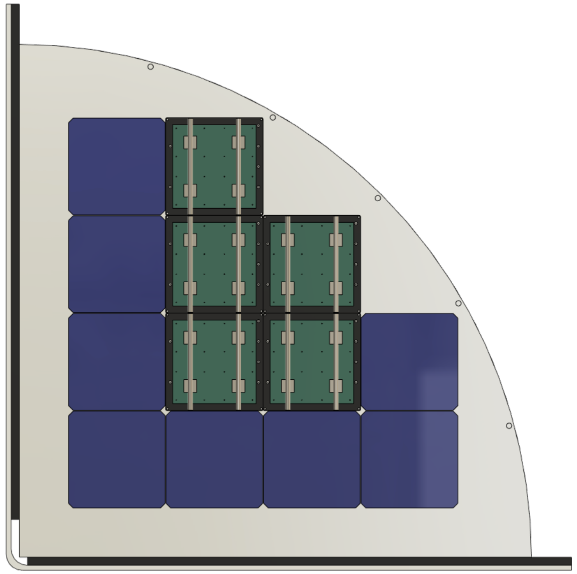
Detector prototype tests in FY24

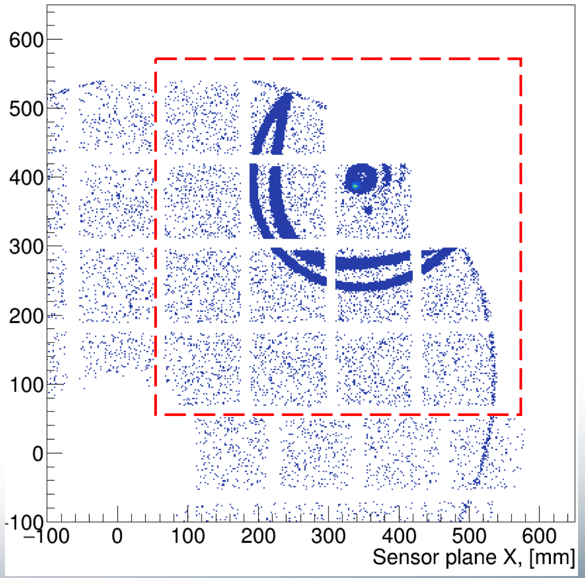
- Build a full chain pfRICH quadrant prototype and quantify its π/K separation performance and timing resolution at the Fermilab Test Beam Facility

  - Verify composite and 3D printed materials usage in a vessel design
  - Evaluate Chiba Aerogel Factory tiles for pfRICH usage
  - Make use of the first five HRPPDs produced by Incom, in a fully integrated on-board ASIC configuration
  - Evaluate conical mirror performance

  - Check detector component integration

  - Evaluate elements of the HV, LV, cooling and gas systems
  - Use collected data with various particle species to tune reconstruction algorithms

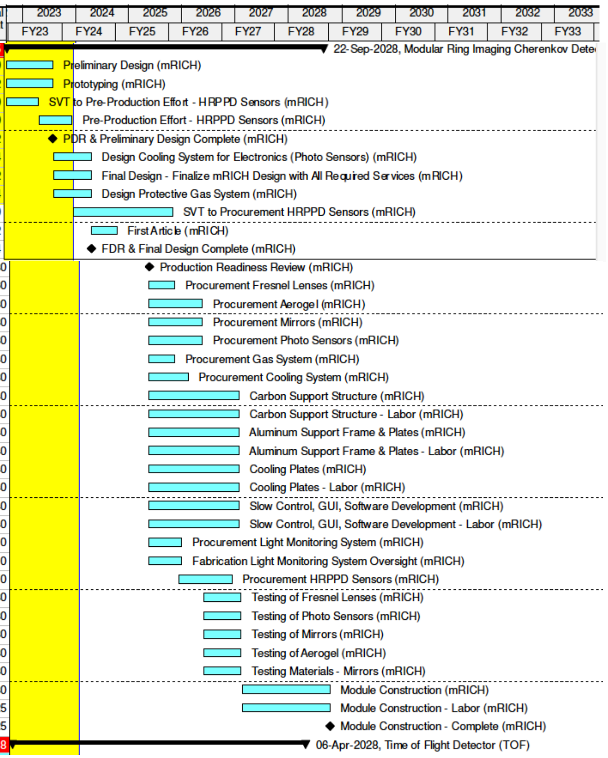




One of the considered five-sensor configurations

Cost and Schedule

Activity ID	BNL_Estir	BNL_PM Rep	Activity Name	Original Duration	Predecessors	Successors	Start	Finish	Budgeted Labor Units	Budgeted Labor Cost	Budgeted Nonlabor Units	Budgeted Nonlabor Cost	Budgeted Total Cost	Total Float
Modular Ring Imaging Cherenkov Detector (mRICH)/Proximity Focusing Ring Imaging Cherenkov (pfRICH)				1494			03-Oct-2022	22-Sep-2028	9400	$968,912.43	2932000	$3,292,597.96	$4,261,510.39	625
E1004_30000	bzihlma	ewoolsx	Preliminary Design (mRICH)	220	L2_0180, L3_6010, EIPMPF _L_FY22	E1004_30060, E1004_30010, E1004_30020	03-Oct-2022	18-Aug-2023	1500	$135,744.60	0	$0.00	$135,744.60	470
E1004_30010	bzihlma	ewoolsx	Prototyping (mRICH)	220	E1004_30000	E1004_30060	03-Oct-2022	18-Aug-2023	0	$0.00	100000	$110,772.90	$110,772.90	552
E1004_30020	bzihlma	ewoolsx	SVT to Pre-Production Effort - HRPPD Sensors (mRICH)	152	E1004_30000	E1004_30030	03-Oct-2022	12-May-2023	0	$0.00	0	$0.00	$0.00	470
E1004_30030	bzihlma	ewoolsx	Pre-Production Effort - HRPPD Sensors (mRICH)	157	E1004_30020	E1004_30040	15-May-2023	29-Dec-2023	0	$0.00	230000	$247,356.95	$247,356.95	470
E1004_30060	bzihlma	ewoolsx	PDR & Preliminary Design Complete (mRICH)	0	E1004_30000, E1004_30010	E1004_30070, PM_0101_3090		18-Aug-2023	0	$0.00	0	$0.00	$0.00	552
E1004_30090	bzihlma	ewoolsx	Design Cooling System for Electronics (Photo Sensors) (mRICH)	180	E1004_30070	L2_0960, E1004_30110	21-Aug-2023	09-May-2024	800	$94,445.75	0	$0.00	$94,445.75	674
E1004_30070	bzihlma	ewoolsx	Final Design - Finalize mRICH Design with All Required Services (mRICH)	180	E1004_30060	E1004_30080, E1004_30120, E1004_30140, E1004_30130,	21-Aug-2023	09-May-2024	1000	$88,727.74	0	$0.00	$88,727.74	552
E1004_30100	bzihlma	ewoolsx	Design Protective Gas System (mRICH)	180	E1004_30070	L2_0960, E1004_30110	21-Aug-2023	09-May-2024	0	$0.00	0	$0.00	$0.00	674
E1004_30040	bzihlma	ewoolsx	SVT to Procurement HRPPD Sensors (mRICH)	475	E1004_30030	E1004_30050	02-Jan-2024	20-Nov-2025	0	$0.00	0	$0.00	$0.00	470
E1004_30080	bzihlma	ewoolsx	First Article (mRICH)	123	E1004_30070	E1004_30120	09-May-2024	01-Nov-2024	0	$0.00	40000	$45,894.46	$45,894.46	552
E1004_30110	bzihlma	ewoolsx	FDR & Final Design Complete (mRICH)	0	E1004_30070, E1004_30100, E1004_30090	E1004_30120, PM_0101_5100		09-May-2024	0	$0.00	0	$0.00	$0.00	674
E1004_30120	bzihlma	ewoolsx	Production Readiness Review (mRICH)	0	E1004_30070, E1004_30110, L2_0400, E1004_30080	E1004_30140, E1004_30130, E1004_30170, E1004_30200,		01-May-2025	0	$0.00	0	$0.00	$0.00	430
E1004_30130	bzihlma	ewoolsx	Procurement Fresnel Lenses (mRICH)	120	E1004_30120, E1004_30070	E1004_30160, E1004_30340	02-May-2025	22-Oct-2025	0	$0.00	6400	$7,549.42	$7,549.42	560
E1004_30140	bzihlma	ewoolsx	Procurement Aerogel (mRICH)	250	E1004_30120, E1004_30070	E1004_30150, E1004_30340	02-May-2025	01-May-2026	0	$0.00	307200	$341,526.70	$341,526.70	430
E1004_30170	bzihlma	ewoolsx	Procurement Mirrors (mRICH)	250	E1004_30120, E1004_30070	E1004_30180, E1004_30340	02-May-2025	01-May-2026	0	$0.00	25600	$30,608.33	$30,608.33	430
E1004_30200	bzihlma	ewoolsx	Procurement Photo Sensors (mRICH)	250	E1004_30120, E1004_30070	E1004_30210, E1004_30340	02-May-2025	01-May-2026	0	$0.00	1493000	$1,659,828.66	$1,659,828.66	430
E1004_30220	bzihlma	ewoolsx	Procurement Gas System (mRICH)	120	E1004_30120, E1004_30070	E1004_30340	02-May-2025	22-Oct-2025	0	$0.00	50000	$58,979.84	$58,979.84	740
E1004_30230	bzihlma	ewoolsx	Procurement Cooling System (mRICH)	180	E1004_30120, E1004_30070	E1004_30340, L2_0960	02-May-2025	22-Jan-2026	0	$0.00	200000	$237,975.92	$237,975.92	680
E1004_30240	bzihlma	ewoolsx	Carbon Support Structure (mRICH)	420	E1004_30120	E1004_30250	02-May-2025	07-Jan-2027	0	$0.00	50000	$60,362.56	$60,362.56	440
E1004_30250	bzihlma	ewoolsx	Carbon Support Structure - Labor (mRICH)	420	E1004_30240	E1004_30340	02-May-2025	07-Jan-2027	200	$18,865.10	0	$0.00	$18,865.10	440
E1004_30260	bzihlma	ewoolsx	Aluminum Support Frame & Plates (mRICH)	420	E1004_30120	E1004_30270	02-May-2025	07-Jan-2027	0	$0.00	15000	$18,108.77	$18,108.77	440
E1004_30270	bzihlma	ewoolsx	Aluminum Support Frame & Plates - Labor (mRICH)	420	E1004_30260	E1004_30340	02-May-2025	07-Jan-2027	200	$18,865.10	0	$0.00	$18,865.10	440
E1004_30280	bzihlma	ewoolsx	Cooling Plates (mRICH)	420	E1004_30120	E1004_30290	02-May-2025	07-Jan-2027	0	$0.00	20000	$24,145.03	$24,145.03	440
E1004_30290	bzihlma	ewoolsx	Cooling Plates - Labor (mRICH)	420	E1004_30280	E1004_30340	02-May-2025	07-Jan-2027	200	$18,865.10	0	$0.00	$18,865.10	440
E1004_30300	bzihlma	ewoolsx	Slow Control, GUI, Software Development (mRICH)	420	E1004_30120	E1004_30310	02-May-2025	07-Jan-2027	0	$0.00	50000	$60,362.56	$60,362.56	440
E1004_30310	bzihlma	ewoolsx	Slow Control, GUI, Software Development - Labor (mRICH)	420	E1004_30300	E1004_30340	02-May-2025	07-Jan-2027	800	$125,348.11	0	$0.00	$125,348.11	440
E1004_30320	bzihlma	ewoolsx	Procurement Light Monitoring System (mRICH)	150	E1004_30070, L2_0400	E1004_30330	02-May-2025	08-Dec-2025	0	$0.00	100000	$118,576.65	$118,576.65	710
E1004_30330	bzihlma	ewoolsx	Fabrication Light Monitoring System Oversight (mRICH)	150	E1004_30320	E1004_30340	02-May-2025	08-Dec-2025	800	$84,257.14	0	$0.00	$84,257.14	710
E1004_30050	bzihlma	ewoolsx	Procurement HRPPD Sensors (mRICH)	250	E1004_30040	E1004_30340	21-Nov-2025	20-Nov-2026	0	$0.00	200000	$215,093.00	$215,093.00	470
E1004_30160	bzihlma	ewoolsx	Testing of Fresnel Lenses (mRICH)	180	E1004_30130, E1004_30150	E1004_30340	04-May-2026	22-Jan-2027	100	$15,906.34	0	$0.00	$15,906.34	430
E1004_30210	bzihlma	ewoolsx	Testing of Photo Sensors (mRICH)	180	E1004_30200	E1004_30340	04-May-2026	22-Jan-2027	400	$63,625.37	0	$0.00	$63,625.37	430
E1004_30180	bzihlma	ewoolsx	Testing of Mirrors (mRICH)	180	E1004_30170	E1004_30190	04-May-2026	22-Jan-2027	400	$38,302.90	0	$0.00	$38,302.90	430
E1004_30150	bzihlma	ewoolsx	Testing of Aerogel (mRICH)	180	E1004_30140	E1004_30160	04-May-2026	22-Jan-2027	500	$18,166.60	0	$0.00	$18,166.60	430
E1004_30190	bzihlma	ewoolsx	Testing Materials - Mirrors (mRICH)	180	E1004_30180	E1004_30340	04-May-2026	22-Jan-2027	0	$0.00	32000	$39,218.43	$39,218.43	430
E1004_30340	bzihlma	ewoolsx	Module Construction (mRICH)	420	E1004_30140, E1004_30130, E1004_30170, E1004_30:	E1004_30350, L2_0960, L2_0960, E1000_4350, E1004_303	25-Jan-2027	22-Sep-2028	0	$0.00	12800	$16,237.78	$16,237.78	430
E1004_30350	bzihlma	ewoolsx	Module Construction - Labor (mRICH)	420	E1004_30340	E1004_30360	25-Jan-2027	22-Sep-2028	2500	$247,792.57	0	$0.00	$247,792.57	625
E1004_30360	bzihlma	ewoolsx	Module Construction - Complete (mRICH)	0	E1004_30340, E1004_30350	L2_0600		22-Sep-2028	0	$0.00	0	$0.00	$0.00	625
Time of Flight Detector (TOF)				1376			03-Oct-2022	06-Apr-2028	54658	$4,561,591.80	6293192	$7,208,402.81	$11,769,994.61	618



- pfRICH is not yet incorporated in P6 (change control process)
  - Expecting this process to converge on a time scale of a month
- Its cost is consistent with the current P6 estimate
  - A detailed costing sheet was produced for the collaboration review in March 2023
- Construction schedule needs to be adjusted

Electron-Ion Collider

ES&H and QA

- Avoid flammable gases as a Cherenkov radiator
- Use off the shelf high voltage system proven to work for CMS
- Develop safe assembly and installation procedures

- Aerogel QA test station will be built at Temple University
- HRPPD QA test station (replica of Incom's one) will be built at BNL

Summary

- pfRICH technical performance parameters are taken from the EIC community Yellow Report, adjusted via subsequent studies by the ePIC collaboration
- Proposed pfRICH detector performance goes beyond the established requirements
- Integration plans and procedures are defined
- Fabrication and assembly plans are consistent with the overall project schedule
- Design is mature enough to be ready for the Final Design Review in Fall 2024
- All subsystems fully costed, mostly using budgetary quotes and / or vendor feedback

pfRICH performance parameters

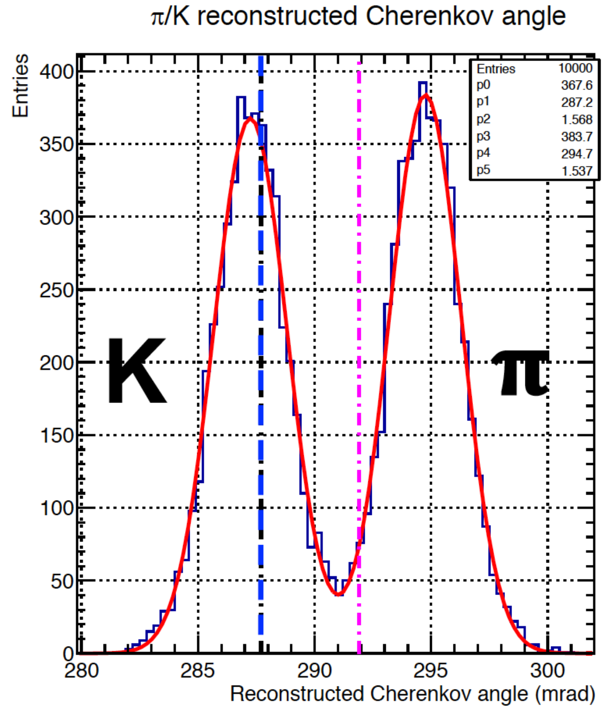
- Pseudorapidity coverage: $-3.5 < \eta < -1.5$
- Uniform performance in this $\{\eta,\phi\}$ range

- $>3\sigma$ π/K separation up to ~ 9.0 GeV/c
- <20ps t_0 reference for the ToF subsystems with a ~100% geometric efficiency

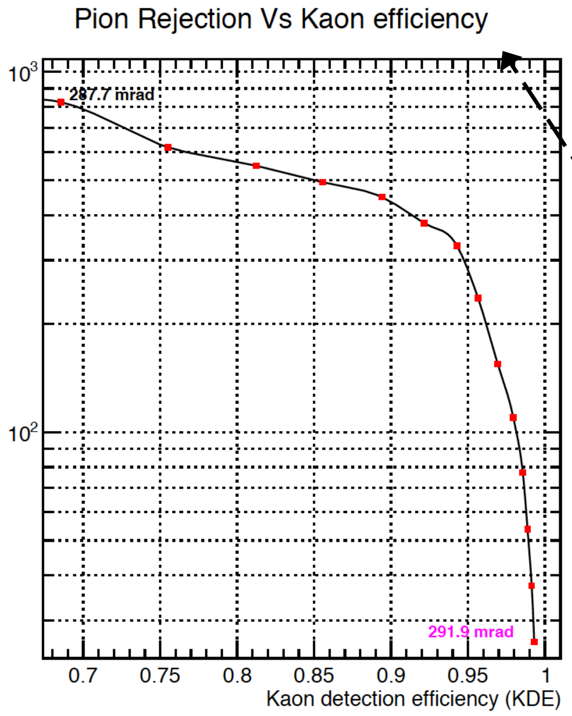
Backup

Detection efficiency vs rejection factor

- Reconstructed Cherenkov photon emission angle is available on a track-by-track basis
  - in a real experiment as well
- A cut on this quantity can be used as a trade off between KDE and PRF



High purity High efficiency



For 7 GeV/c pions and kaons:

- Pion Rejection Factor (PRF) as a function of Kaon detection efficiency (KDE) is computed.
- The tunable theta cut is varied from Kaon Cherenkov angle (~287 mrad) to the overlap region (292 mrad).
- PRF > 250 is at 95% KDE.