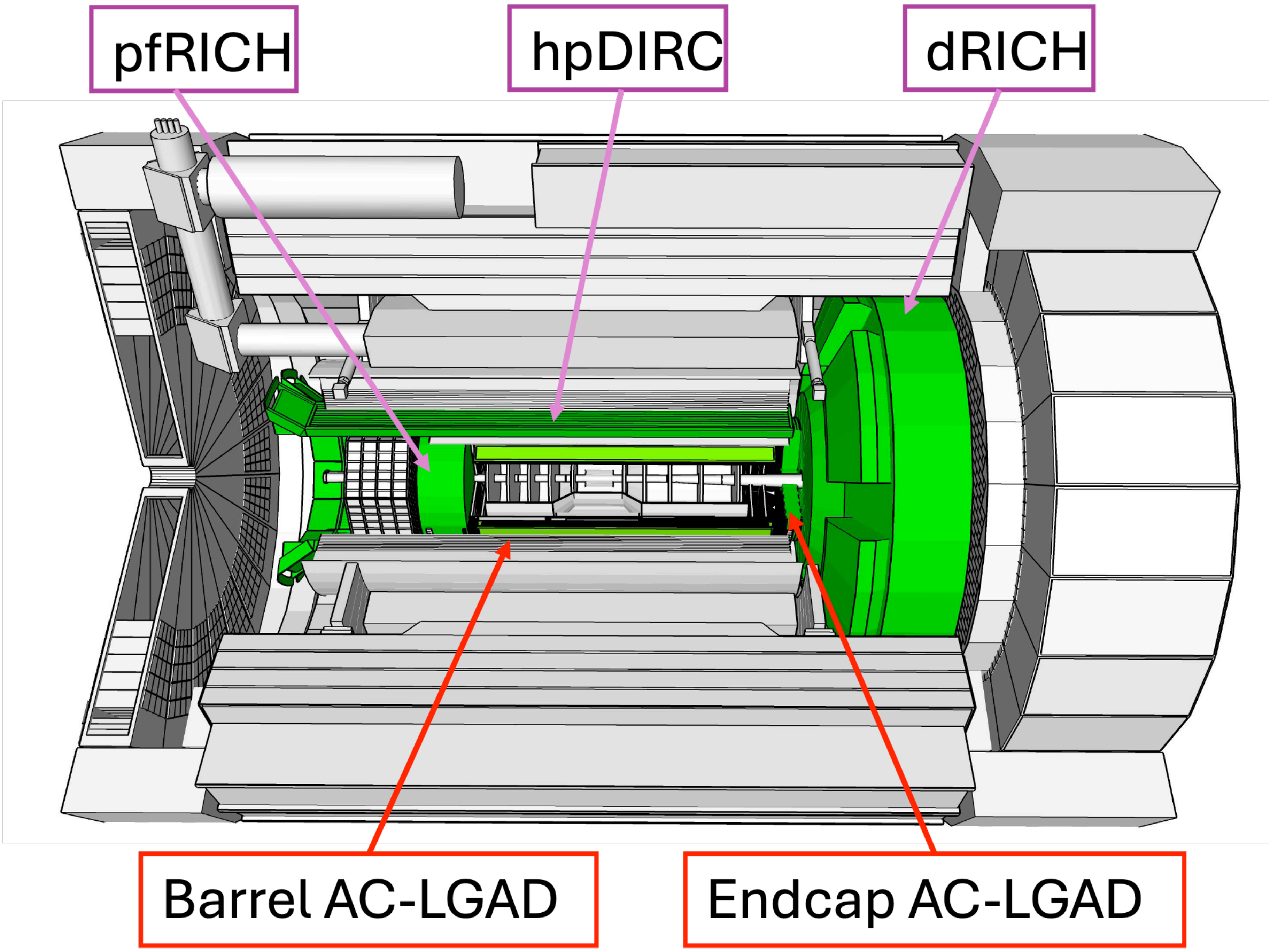
PID Technologies for the EIC



Thomas Ullrich
CFNS Summer School 2025
June 5, 2025

Brookhaven National Laboratory

Recall the Requirements

η	Nomenclature	Tracking						Electrons and Photons			$\pi/K/p$		HCAL		Muons
		Resolution	Relative Momentun	Allowed X/X_0	Minimum-p_T (MeV/c)	Transverse Pointing Res.	Longitudinal Pointing Res.	Resolution σ_E/E	PID	Min E Photon	p-Range	Separation	Resolution σ_E/E	Energy	
< -4.6	Low-Q2 tagger														
-4.6 to -4.0		Not Accessible													
-4.0 to -3.5			Reduced Performance												Muons useful for background suppression and improved resolution
-3.5 to -3.0	Backward Detector		$\sigma_p/p \sim 0.1\% \times p \oplus 2\%$	~5% or less	150-300			$1\%/E \oplus 2.5\%/\sqrt{E} \oplus 1\%$	π suppression up to 1:10^{-4}	20 MeV	≤ 10 GeV/c	≥ 3σ	$50\%/\sqrt{E} \oplus 10\%$	~500MeV	
-3.0 to -2.5															
-2.5 to -2.0			$\sigma_p/p \sim 0.02\% \times p \oplus 1\%$												
-2.0 to -1.5						dca(xy) ~ $40/p_T$ µm $\oplus$ 10 µm	dca(z) ~ $100/p_T$ µm $\oplus$ 20 µm	$2\%/E \oplus (4\text{-}8)\%/\sqrt{E} \oplus 2\%$	π suppression up to 1:(10^{-3}-10^{-2})	50 MeV					
-1.5 to -1.0															
-1.0 to -0.5	Barrel		$\sigma_p/p \sim 0.02\% \times p \oplus 5\%$		400	dca(xy) ~ $30/p_T$ µm $\oplus$ 5 µm	dca(z) ~ $30/p_T$ µm $\oplus$ 5 µm	$2\%/E \oplus (12\text{-}14)\%/\sqrt{E} \oplus (2\text{-}3)\%$	π suppression up to 1:10^{-2}	100 MeV	≤ 6 GeV/c		$100\%/\sqrt{E} \oplus 10\%$		
-0.5 to 0.0															
0.0 to 0.5															
0.5 to 1.0															
1.0 to 1.5	Forward Detectors		$\sigma_p/p \sim 0.02\% \times p \oplus 1\%$		150-300	dca(xy) ~ $40/p_T$ µm $\oplus$ 10 µm	dca(z) ~ $100/p_T$ µm $\oplus$ 20 µm	$2\%/E \oplus (4^*\text{-}12)\%/\sqrt{E} \oplus 2\%$	3σ e/π up to 15 GeV/c	50 MeV	≤ 50 GeV/c		$50\%/\sqrt{E} \oplus 10\%$		
1.5 to 2.0															
2.0 to 2.5															
2.5 to 3.0			$\sigma_p/p \sim 0.1\% \times p \oplus 2\%$												
3.0 to 3.5															
3.5 to 4.0	Instrumentation to separate charged particles from photons		Reduced Performance												
4.0 to 4.5		Not Accessible													
> 4.6	Proton Spectrometer Zero Degree Neutral Detection														

Yellow Report, arXiv:2103.05419

The YR asks for 3σ separation of $\pi/K/p$ in

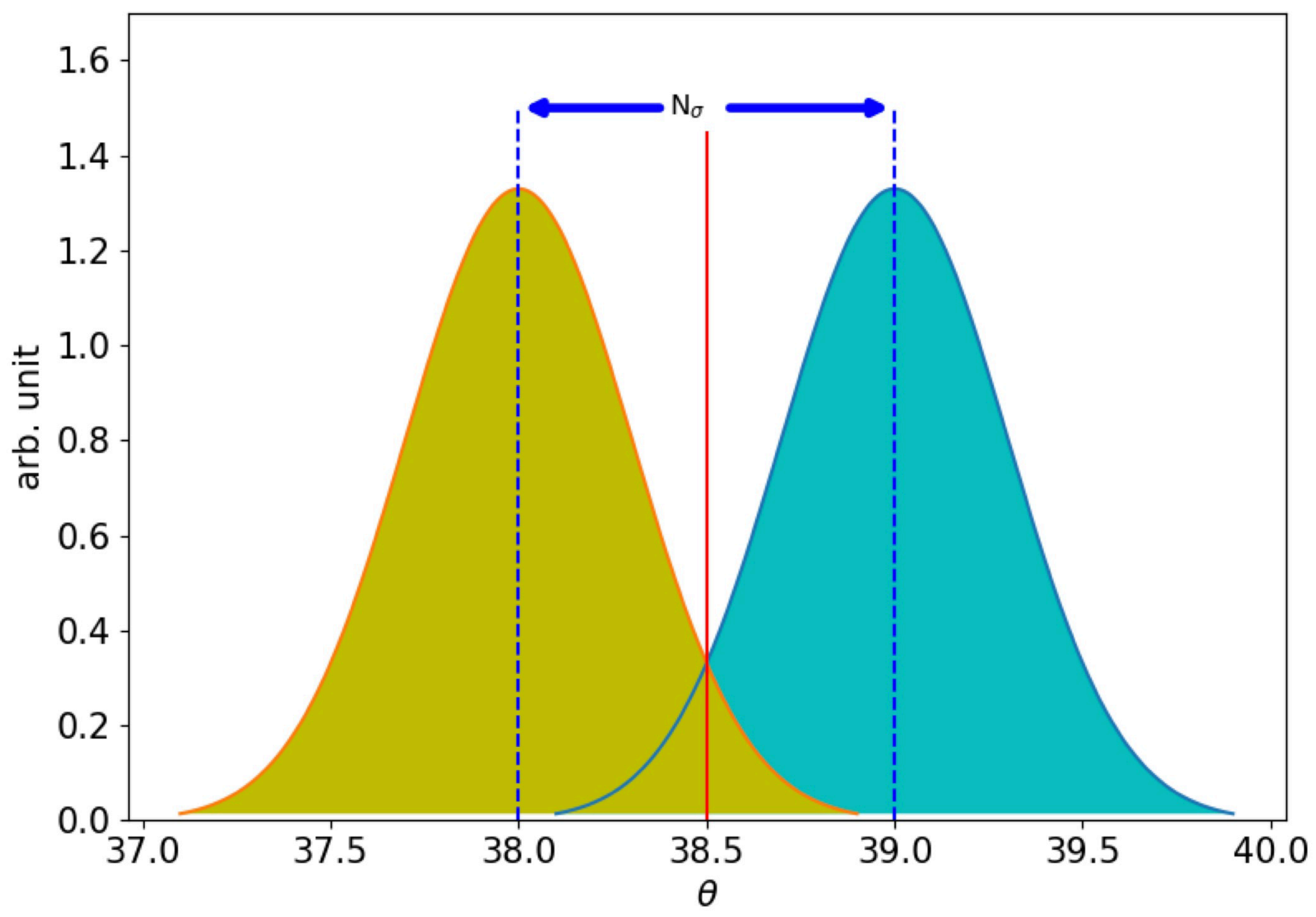
- backward (e-going): $p \leq$ 10 GeV/c
- barrel/mid-rapidity: $p \leq$ 6 GeV/c
- forward (p/A-going): $p \leq$ 50 GeV/c

Note that there was a shortcoming in not discussing the low-p requirement. This is still under discussion.

Reflection on a Definition

Say we look at the π, K separation power. We typically think of this in terms of $n\sigma$. But how is this defined?

- Many use the difference between the two Gaussians, divided by the average Gaussian σ to define the separation power

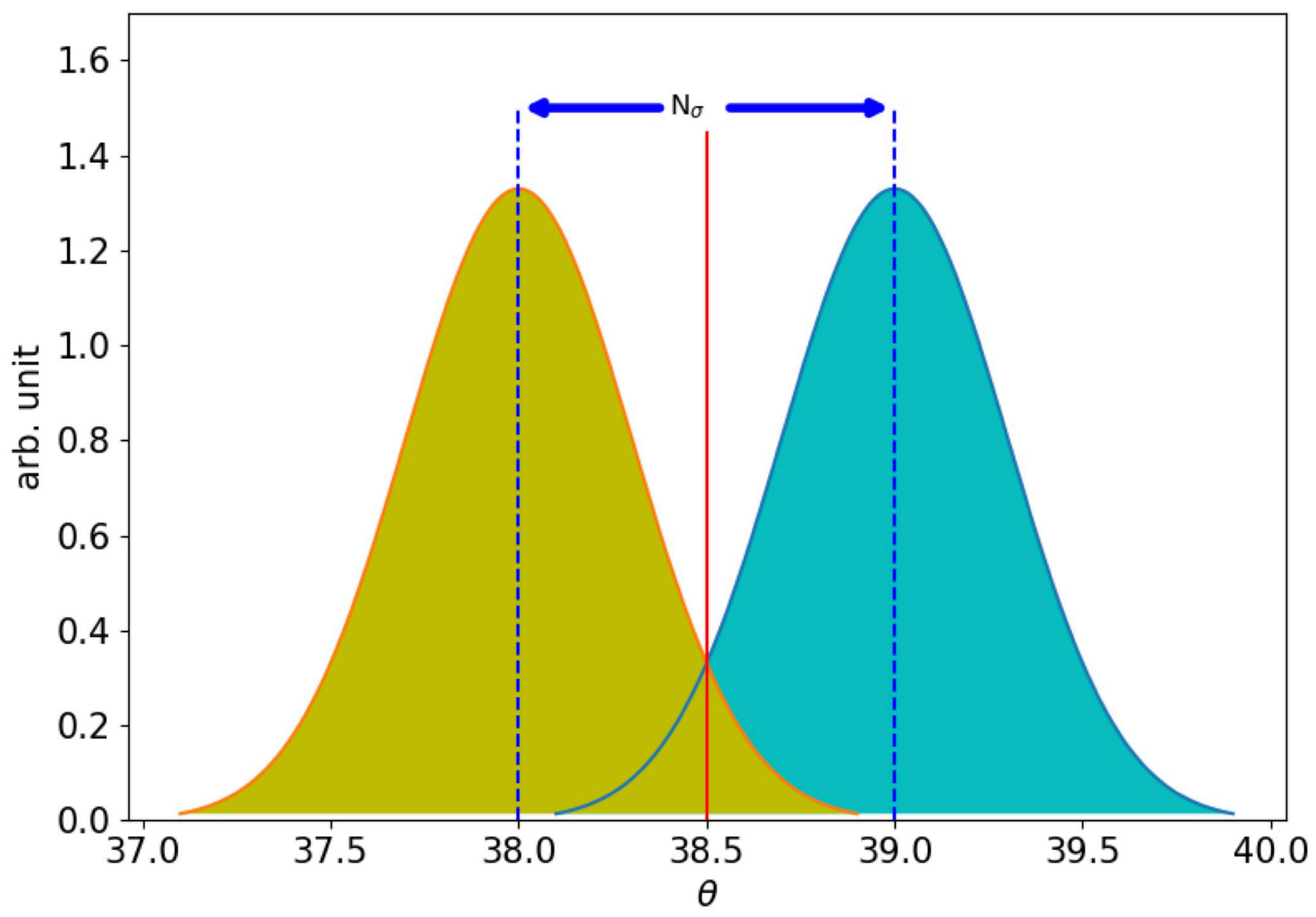


$$n\sigma = \frac{\theta_C^\pi - \theta_C^K}{(\sigma_\theta^\pi + \sigma_\theta^K)/2}$$

Reflection on a Definition

Say we look at the π, K separation power. We typically think of this in terms of $n\sigma$. But how is this defined?

- Many use the difference between the two Gaussians, divided by the average Gaussian σ to define the separation power
- However
  - this $n\sigma$ is not the quantity people are used to in statistics. The true $n\sigma$ is always smaller than the $n\sigma$ obtained from the definition we are using. This way one is overselling the performance. In short when we say 3σ, this is not the 99.73% one is used to.
  - Difference $\approx \sqrt{2}$, so 3σ is really ~2σ or 95.45%
  - OK in most cased since PID systems are too complex to be reflected by just one number.



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Recall the Requirements

<table>
<tr><th rowspan="2">η</th><th rowspan="2">Nomenclature</th><th colspan="6">Tracking</th><th colspan="3">Electrons and Photons</th><th colspan="2">$\pi/K/p$</th><th colspan="2">HCAL</th><th rowspan="2">Muons</th></tr>
<tr><th>Resolution</th><th>Relative Momentun</th><th>Allowed X/X_0</th><th>Minimum-p_T (MeV/c)</th><th>Transverse Pointing Res.</th><th>Longitudinal Pointing Res.</th><th>Resolution σ_E/E</th><th>PID</th><th>Min E Photon</th><th>p-Range</th><th>Separation</th><th>Resolution σ_E/E</th><th>Energy</th></tr>
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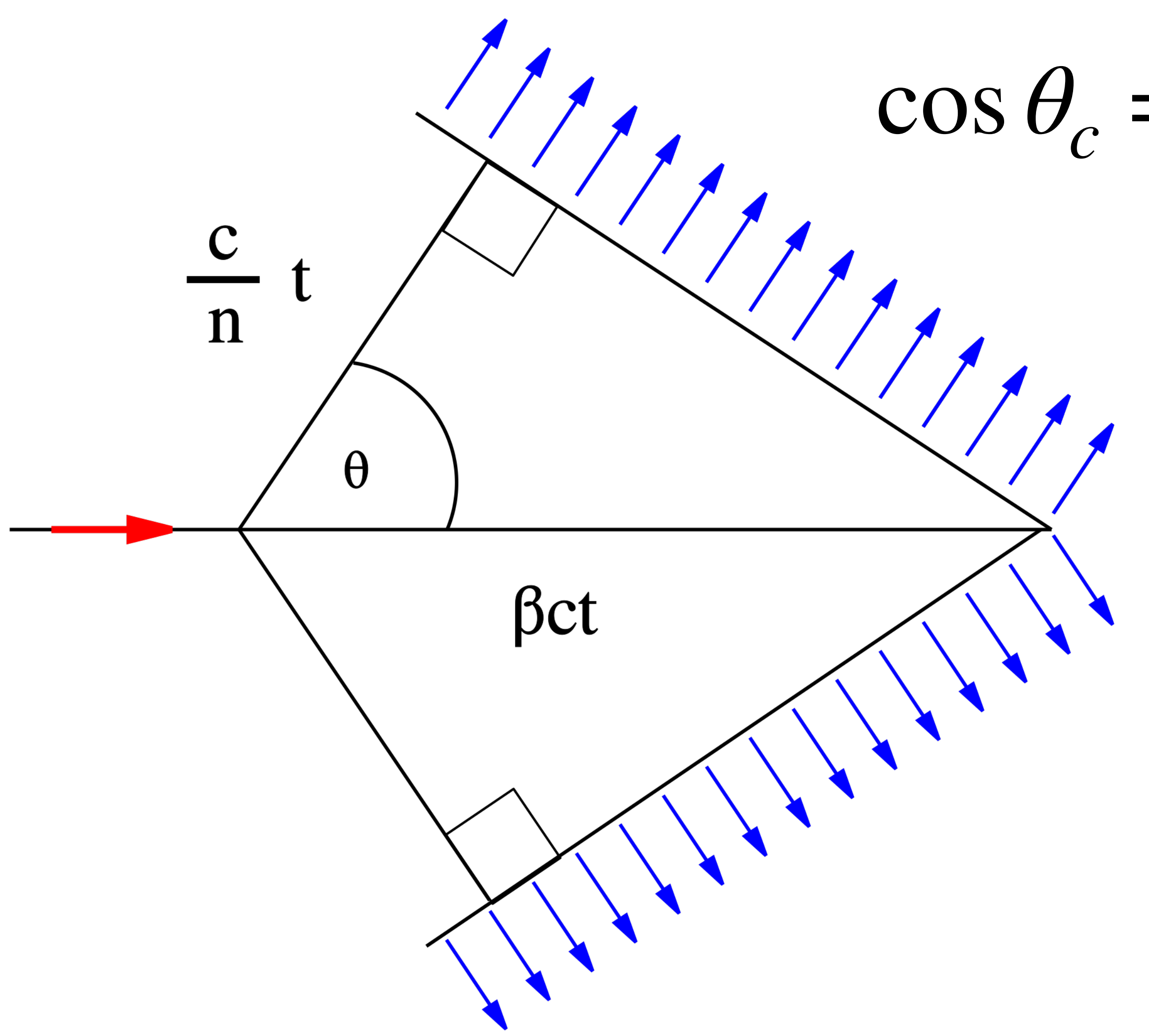
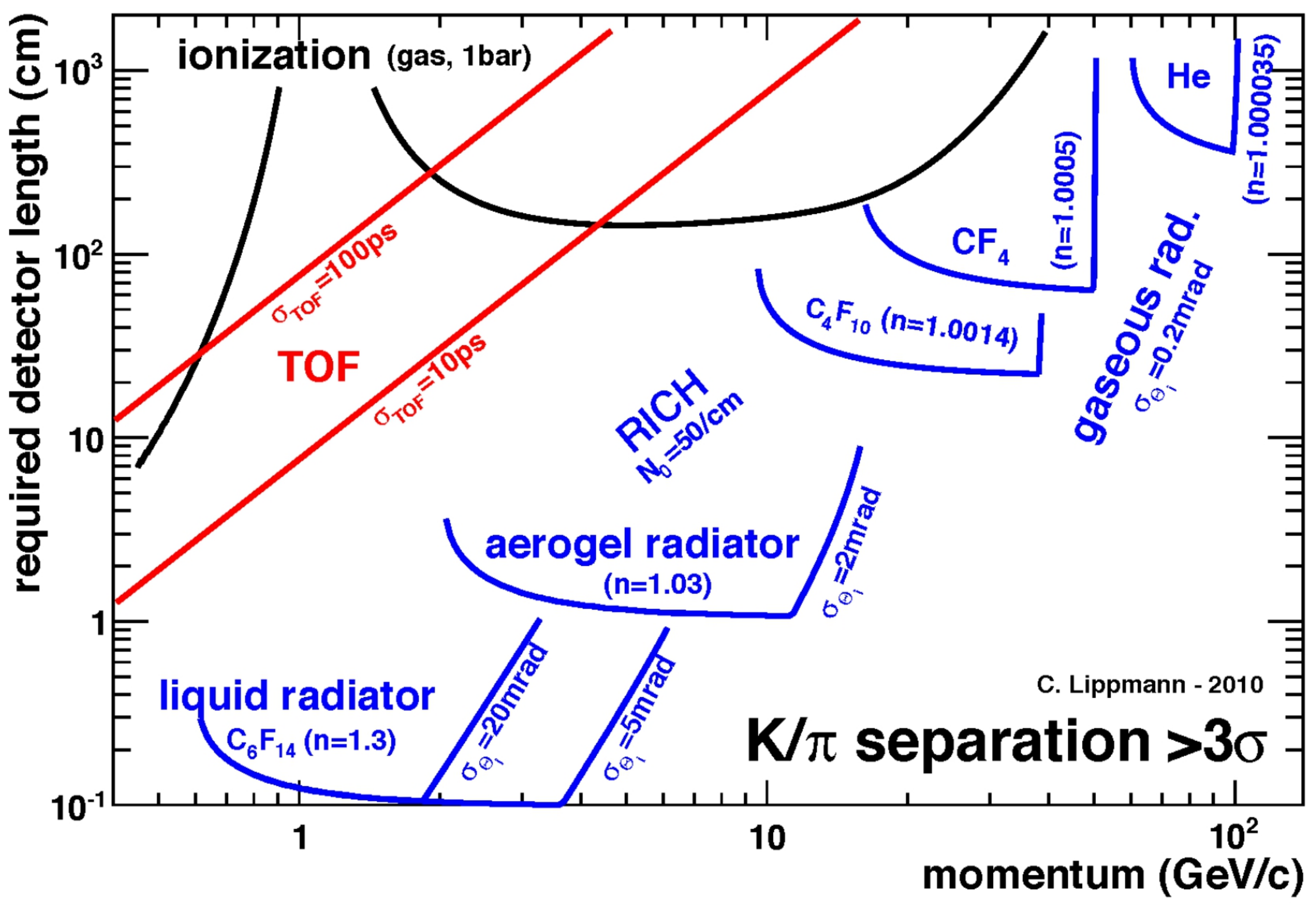
Note that there was a shortcoming in not discussing the low-p requirement. This is still under discussion.

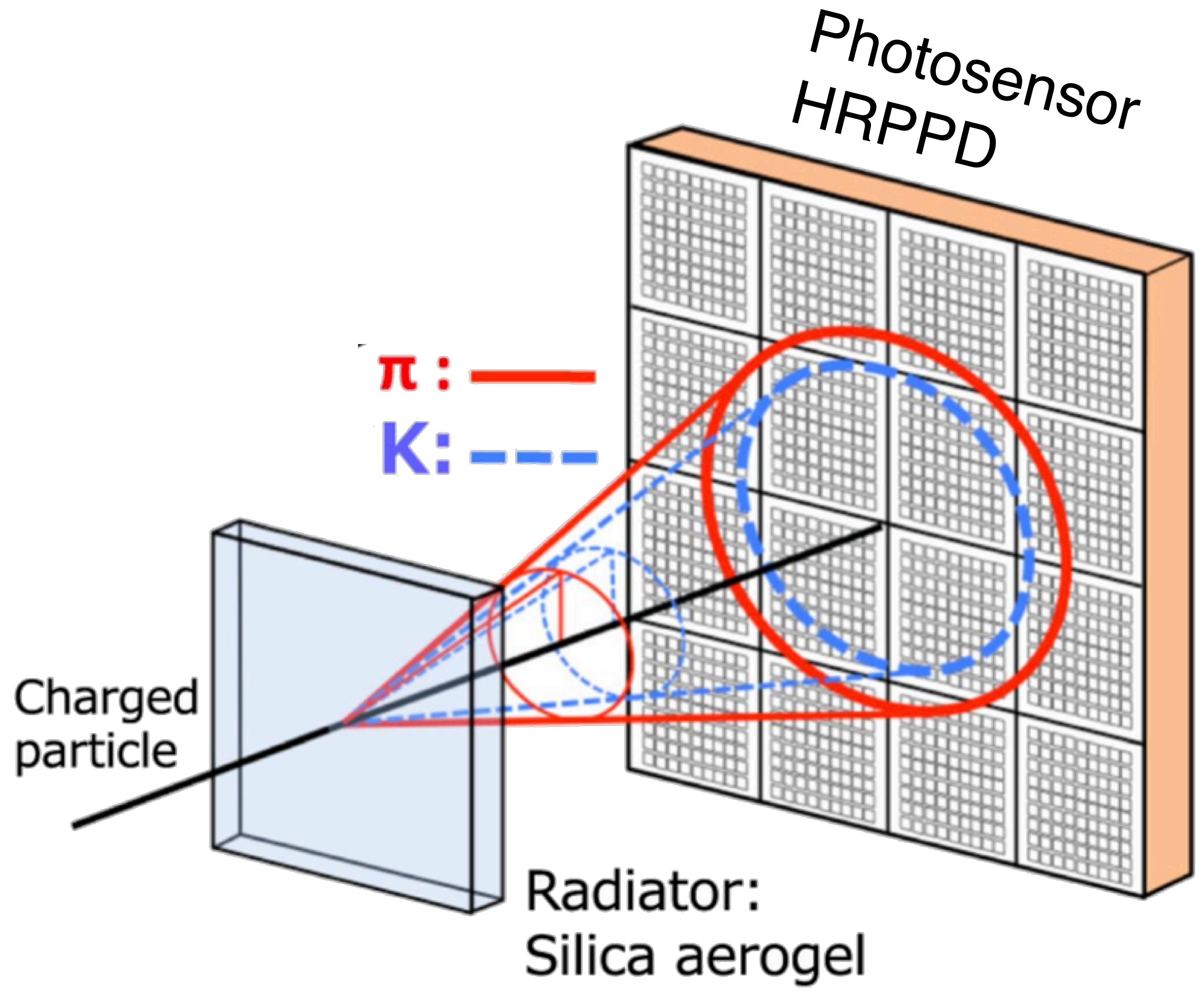
Backward Region: pfRICH

- After several iterations the solution is a proximity focusing RICH detector (aka pfRICH)
- Basic idea
  - no mirror like in “real” RICH detectors but thin radiator, here aerogel
  - aerogel sits between liquids and gases radiators providing just the right “*n*” to cover the required *p* range.



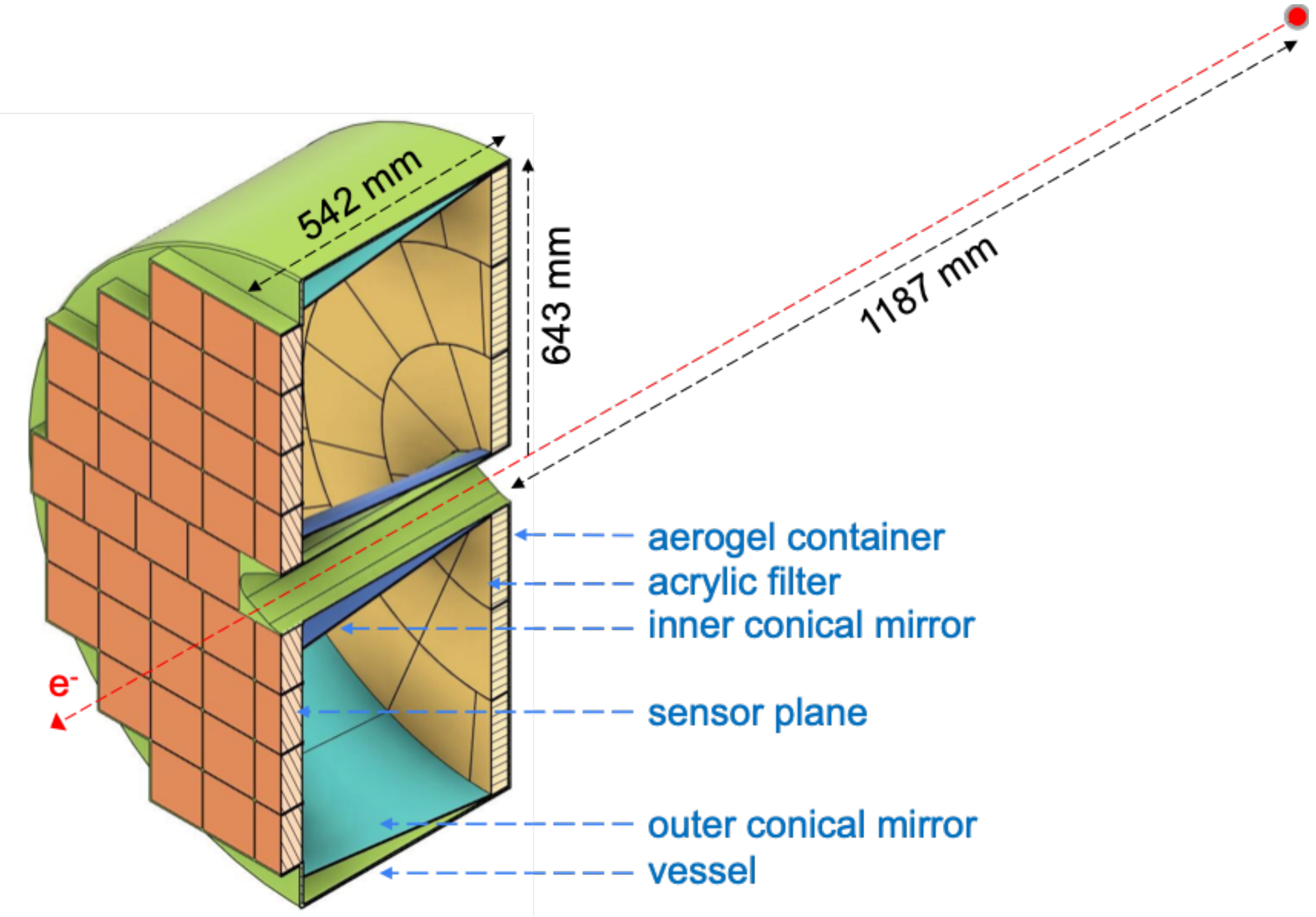
$$\cos\theta_c = \frac{1}{n\beta}$$

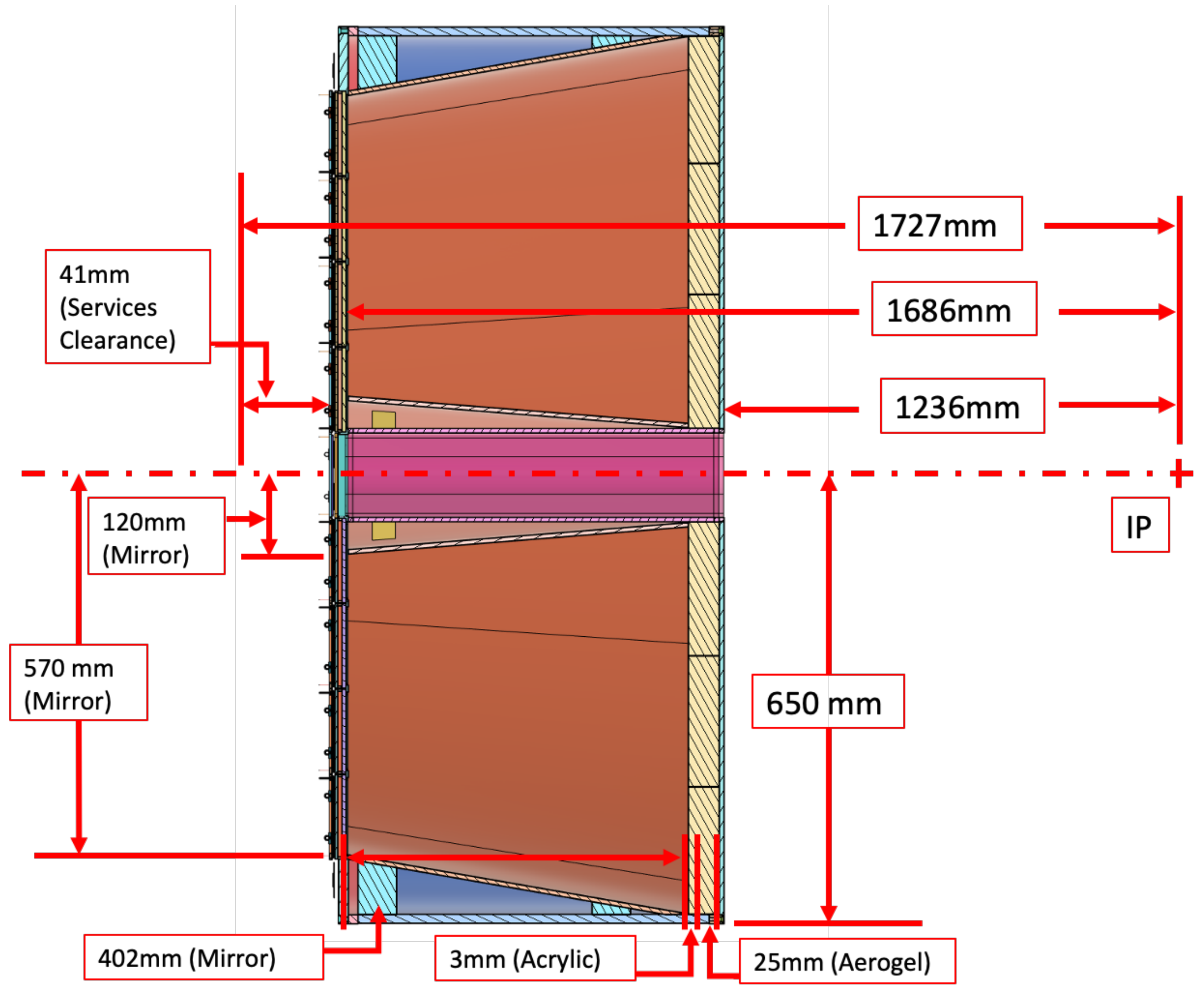


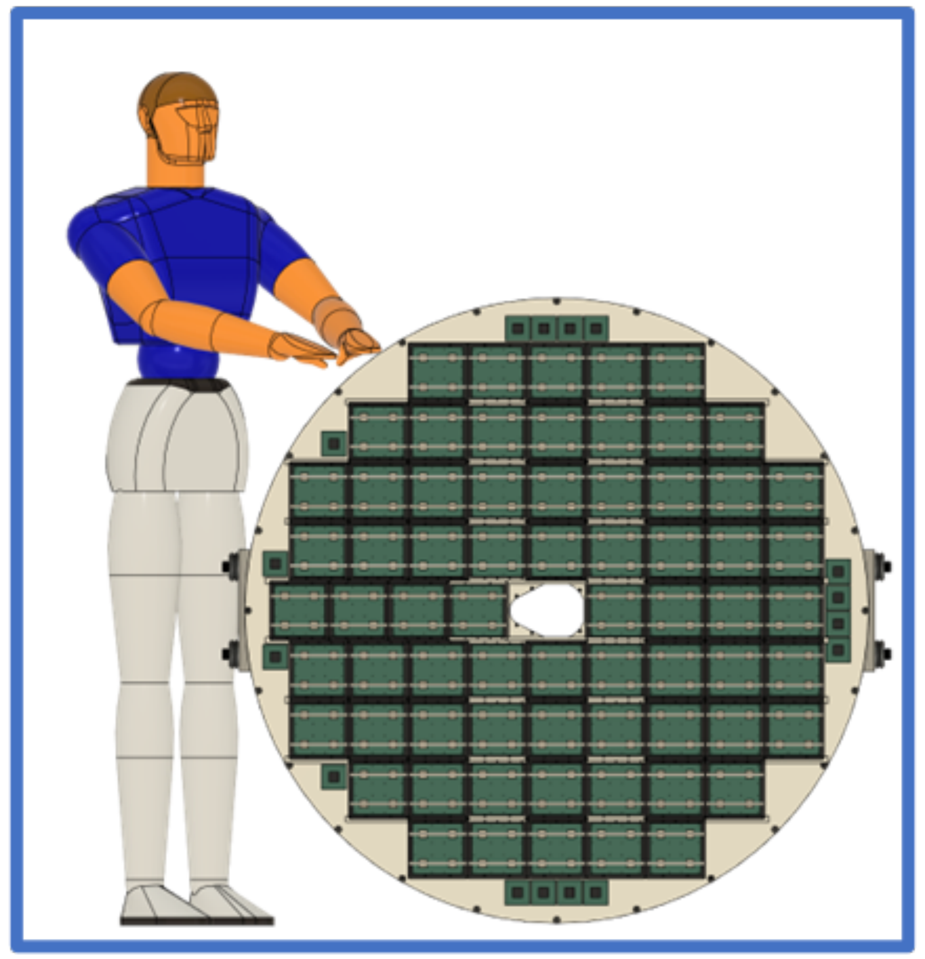


Proximity Focusing RICH (pfRICH)

- Aerogel
  - Three radial bands; Opaque dividers
  - 2.5 cm thick, 42 tiles total
- Vessel
  - Honeycomb carbon fiber sandwich
  - Filled with nitrogen
- HRPPD photosensors with timing capability
  - 12 x 12 cm size
  - 68 sensors total
  - Coverage: $-3.5 < \eta < -1.5$
  - timing resolution ~20 ps
- High reflectivity mirrors to improve the acceptance of the RICH detector



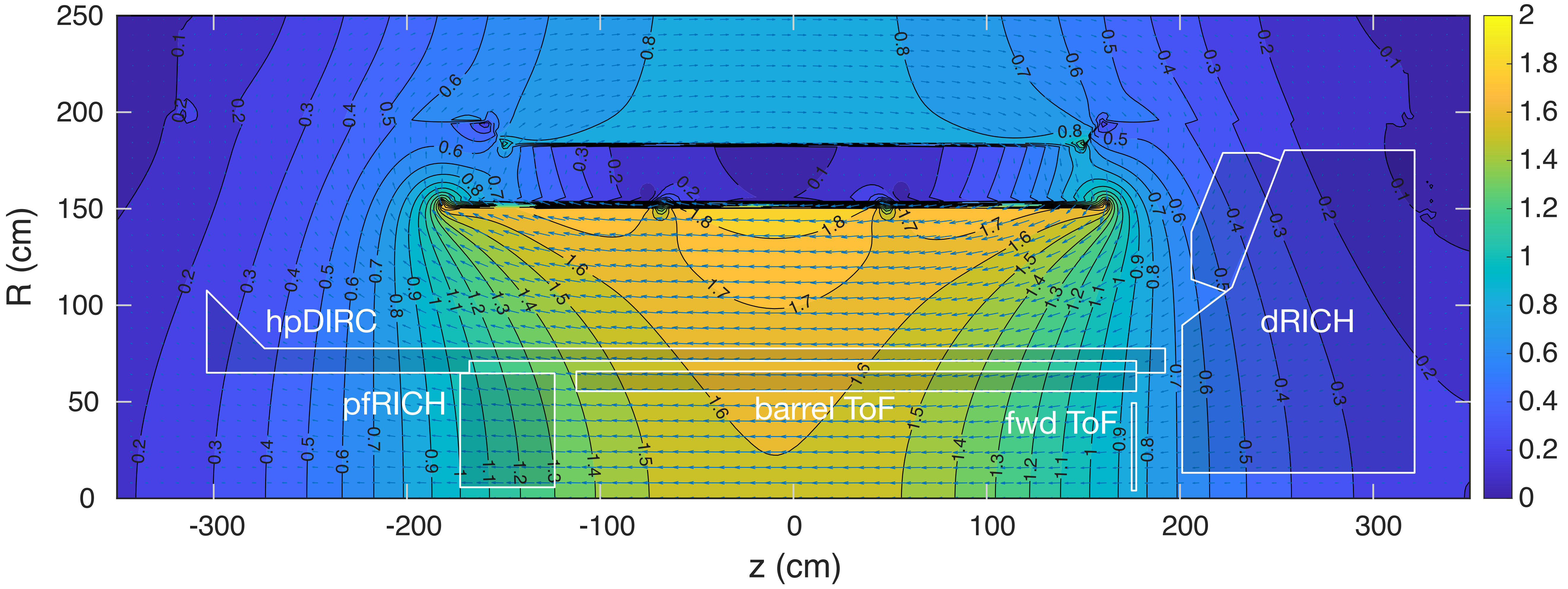


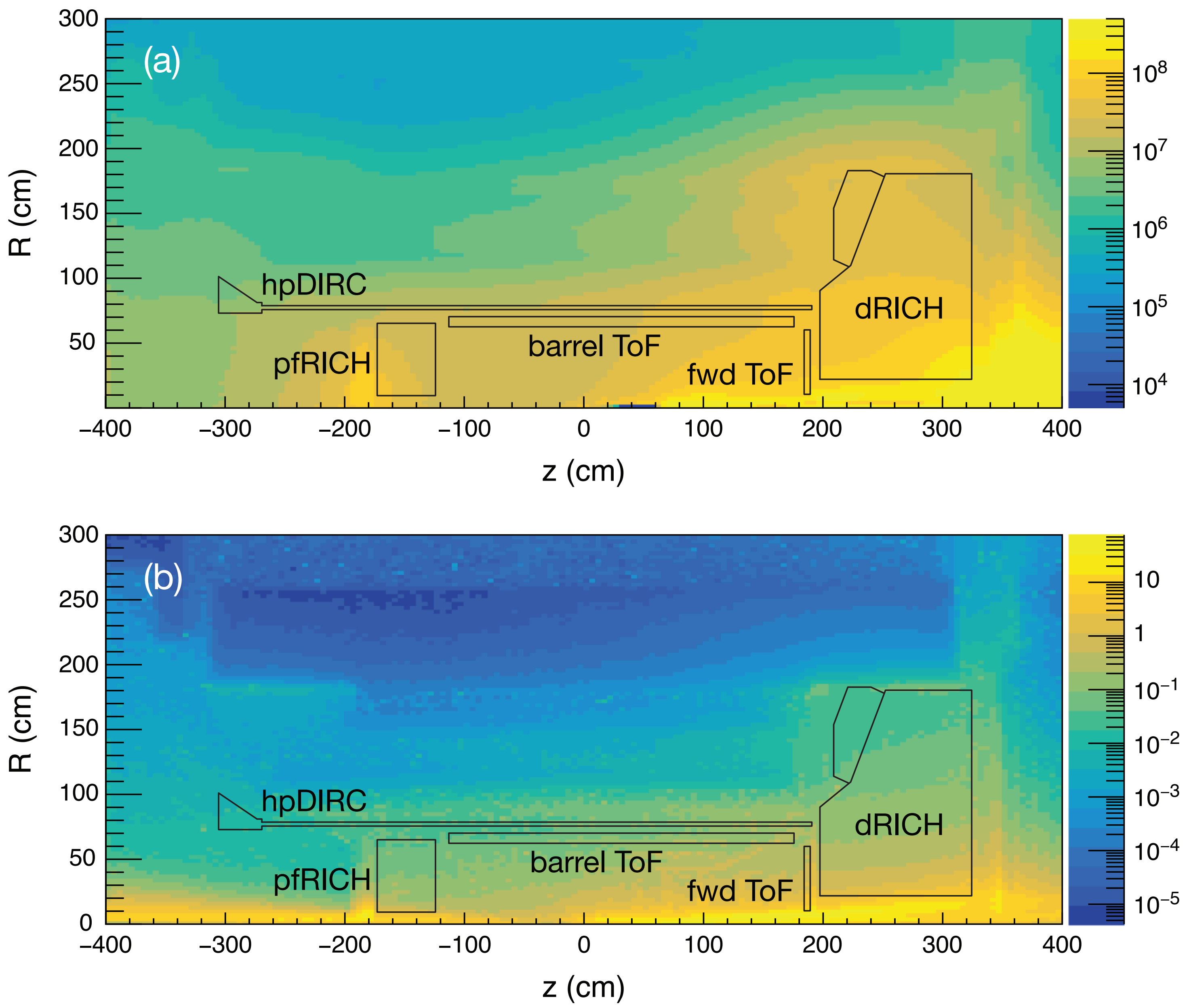


The Story with the Photosensors

- Typically the number of Cherenkov photons in RICH detectors is moderate (~10) ➟ every photon counts
- Need high efficiency in capturing the photons & high pixelization
- ePIC also need low material budget
- Huge impact: Radiation & magnetic field

- Good old photomultiplier tubes (PMT) do not work in ePIC field and are too massive
- Everything using CsI is cumbersome and not robust on long term (O_2, H_2O sensitivity, aging, maintenance)
- SiPM have issues with radiation hardness
- Way out are multichannel-plate PMTs or LAPPDs/HRPPs

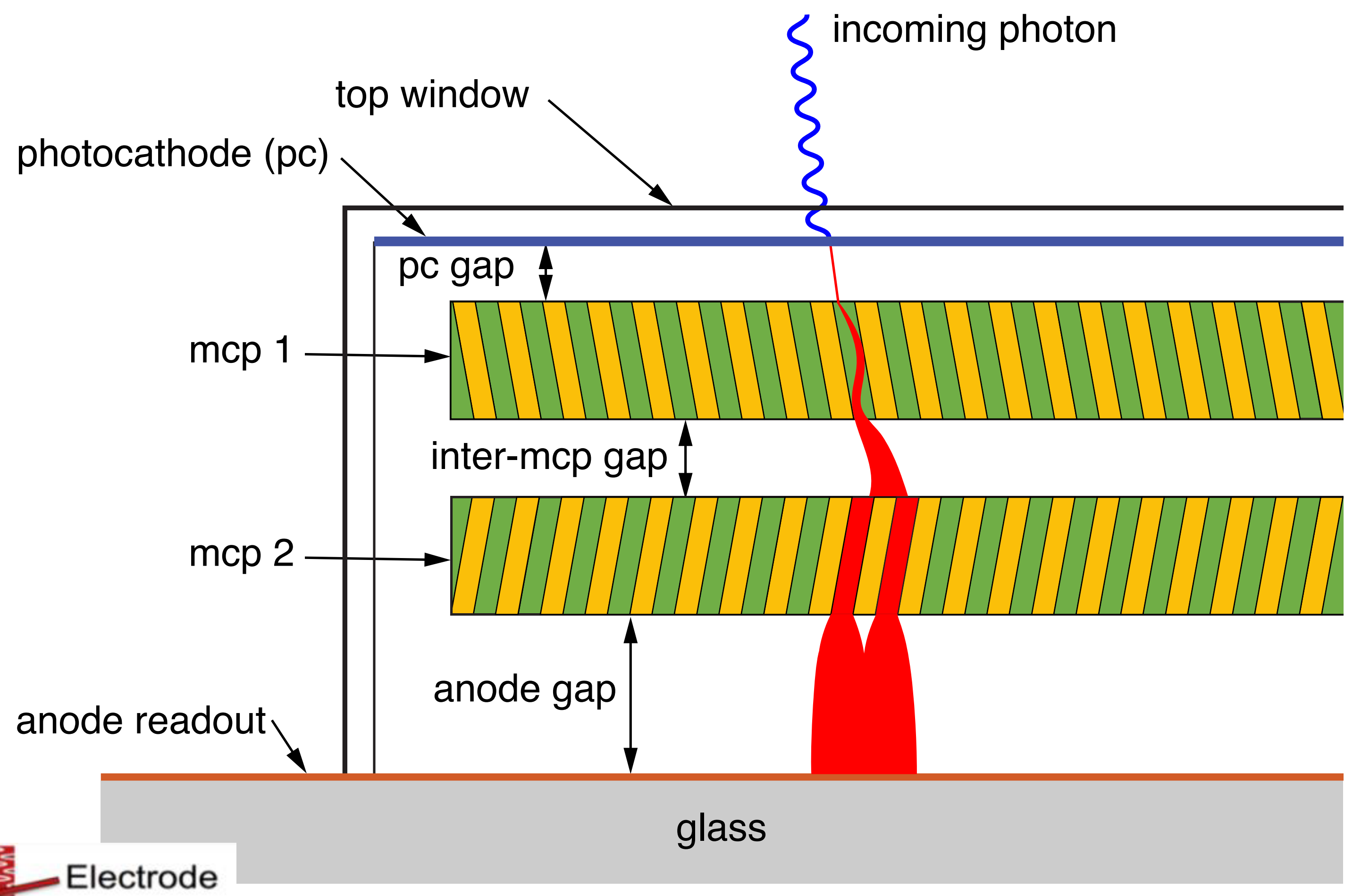




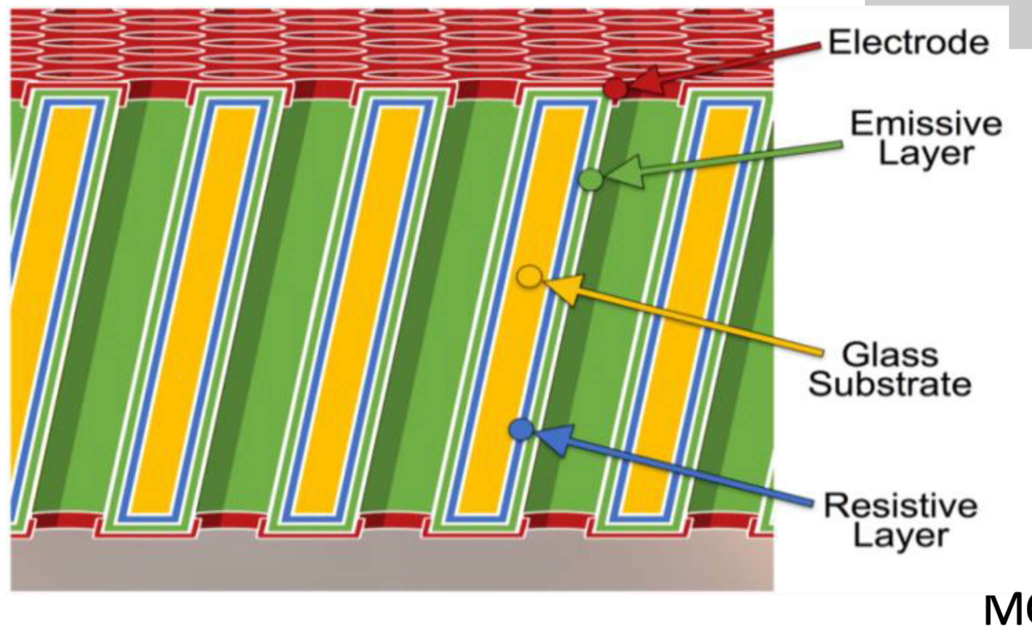
(a) Estimates of the 1-MeV neutron equivalent fluence in cm^{-2}/fb^{-1} and (b) the sum of electro-magnetic and charged-hadron doses in rads/fb^{-1} integrated in 1 fb^{-1} equivalent Pythia events for 10 x 275 GeV ep collisions.

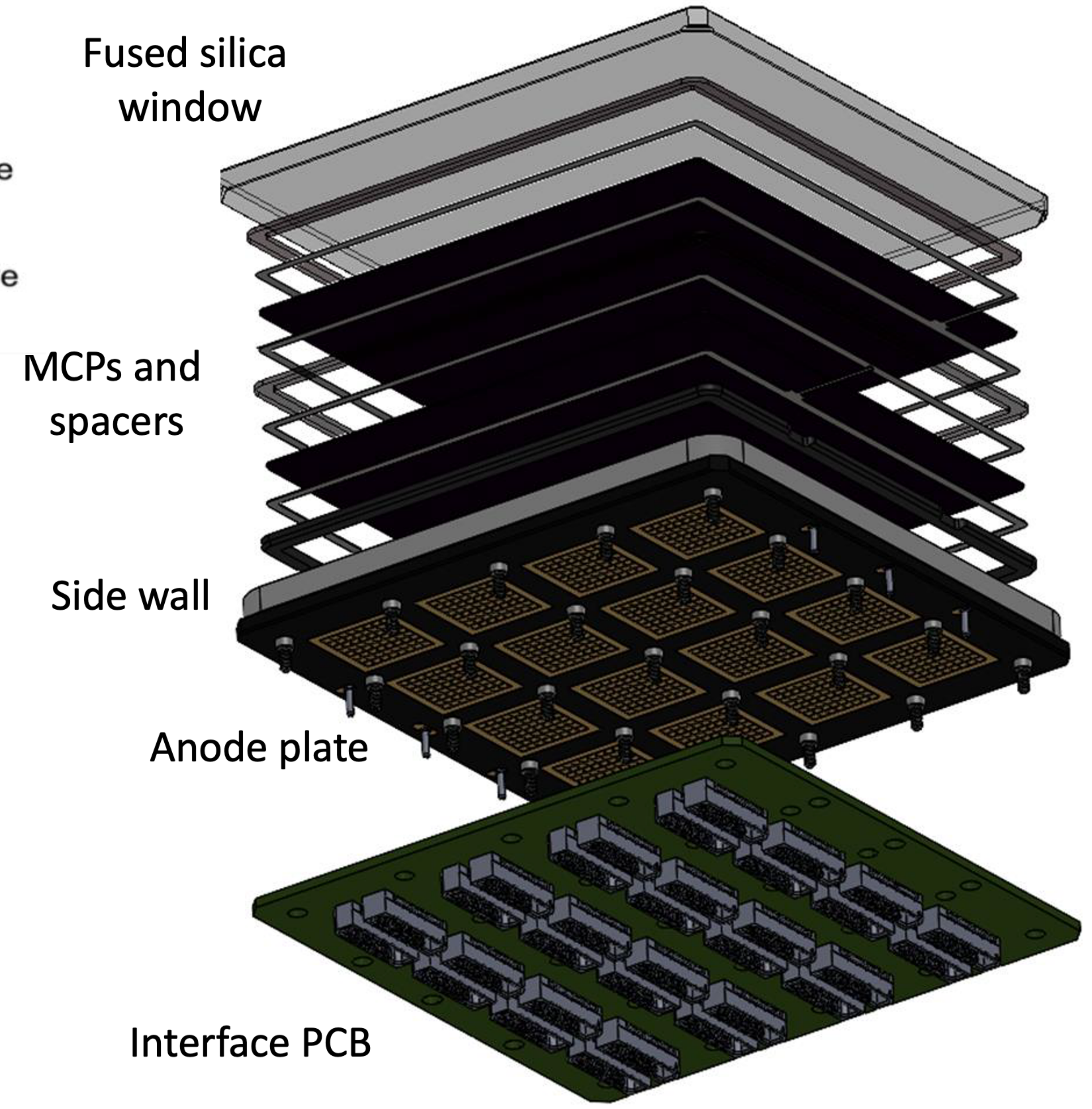
Photosensors: LAPPD & HRPPDs

- LAPPD/HRPPD potential solution for EIC
  - Photon detector + O(10) ps ToF detector at the same time
- Large-Area Picosecond PhotoDetector (LAPPD)
  - Microchannel plate (MCP) based large area picosecond photodetector (20cm x 20 cm)
- High-Resolution Picosecond PhotoDetector (HRPPD)
  - Size 10 cm x 10 cm
  - Novel multi-anode direct readout
  - Spatial resolution of ~1mm
  - Timing reference at the level of ~20 ps
  - Have reasonable power dissipation in mW per channel
  - Allow for a compact solution to leave more space for the proximity gap
  - In development by manufacturer (INCOM) with PED support by EIC project
  - Reduced gap spacing for improved timing resolution and B-Field tolerance, better tilability



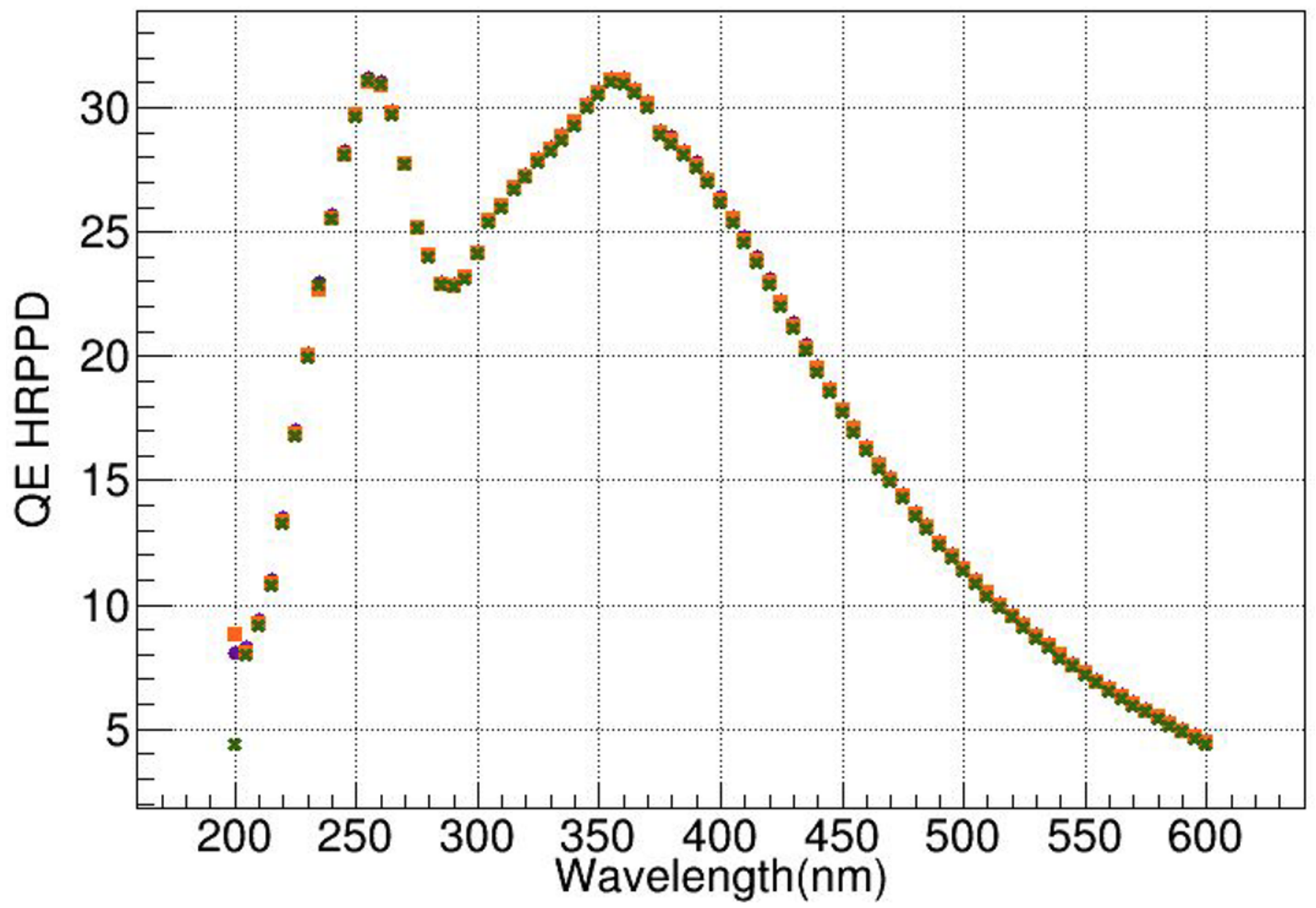
ALD+ glass substrate MCP: cross section



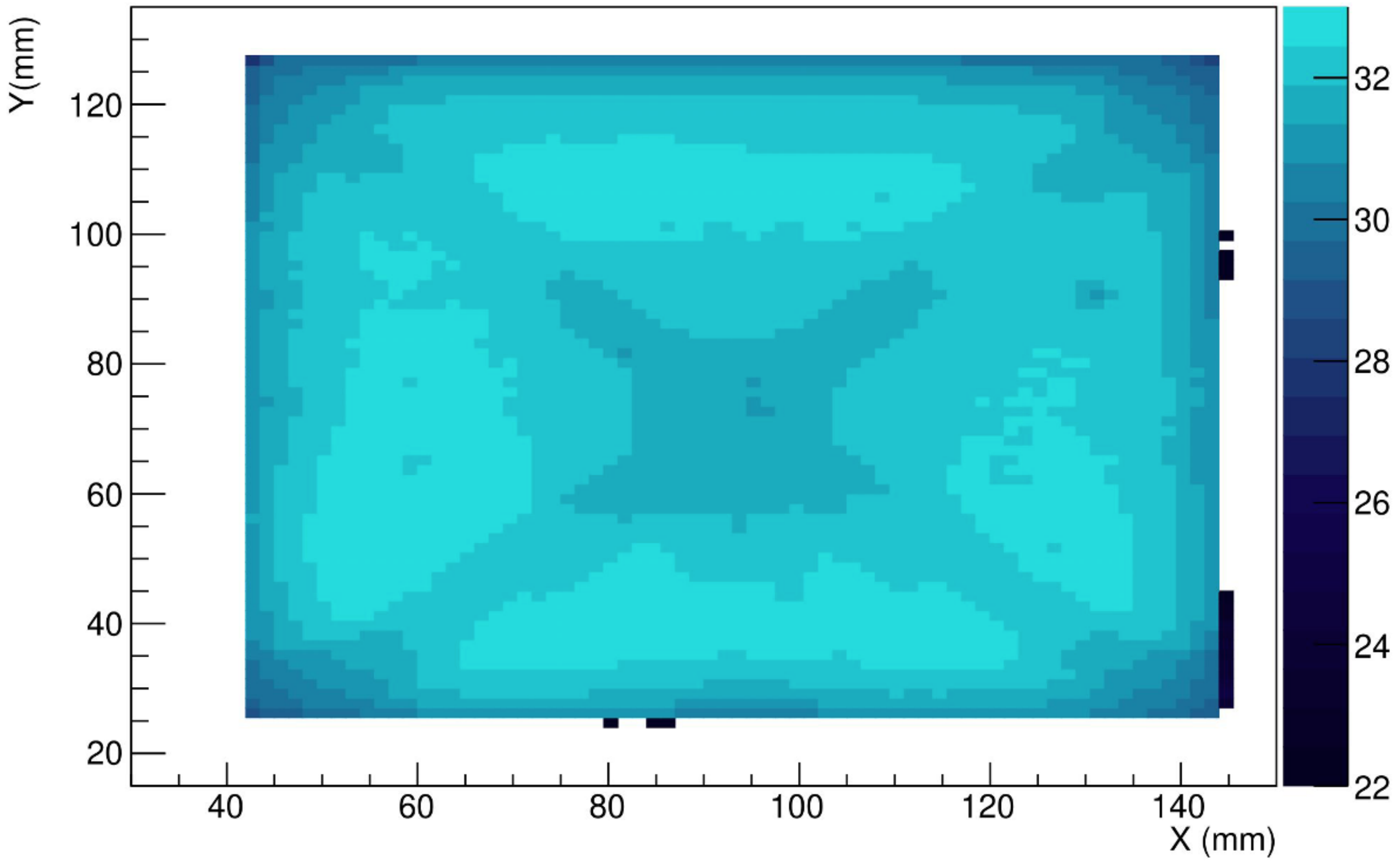


pfRICH - Looking Good

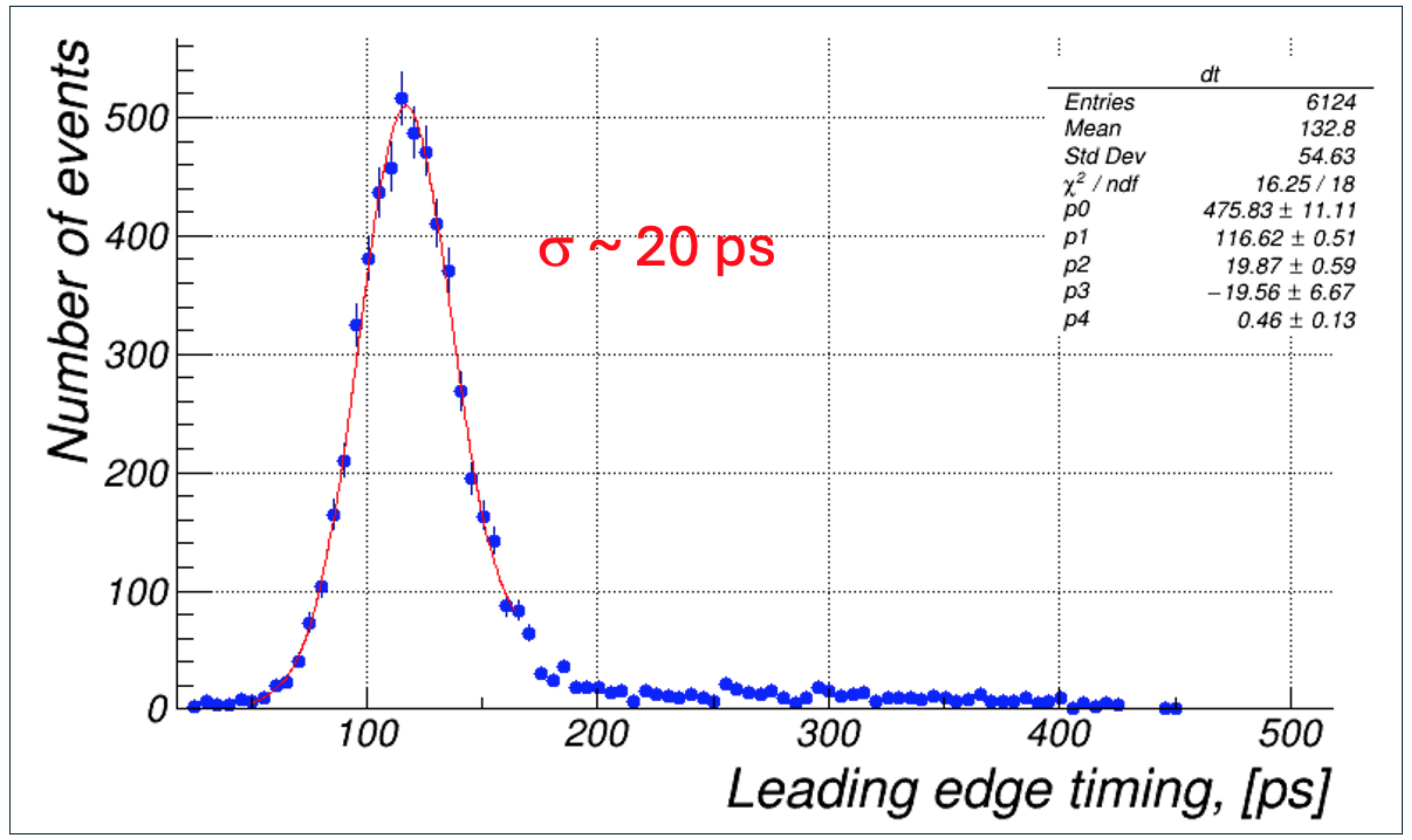
EIC HRPPD QE as a function of wavelength

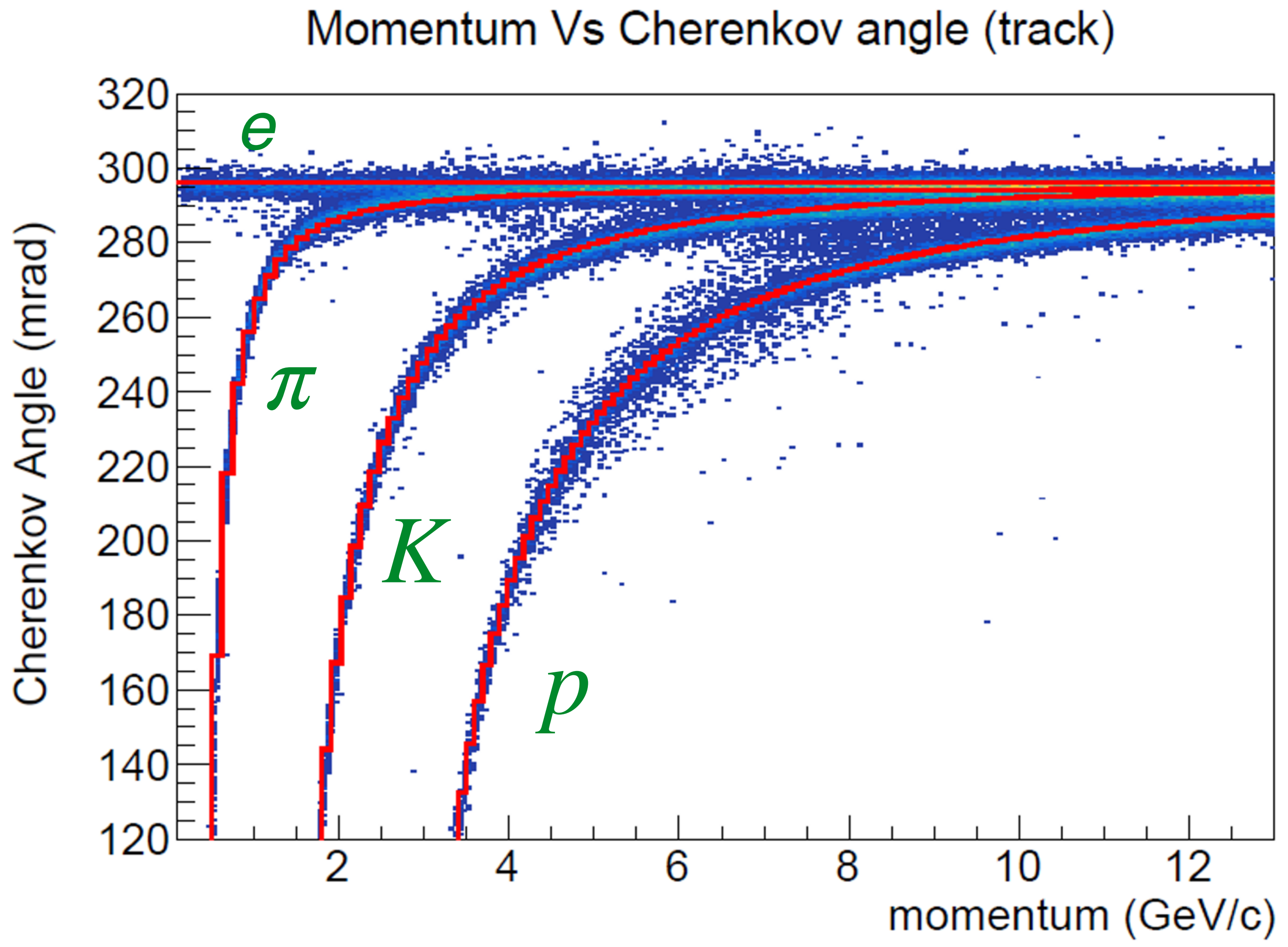


QE map in the full active area at a wavelength of 365 nm

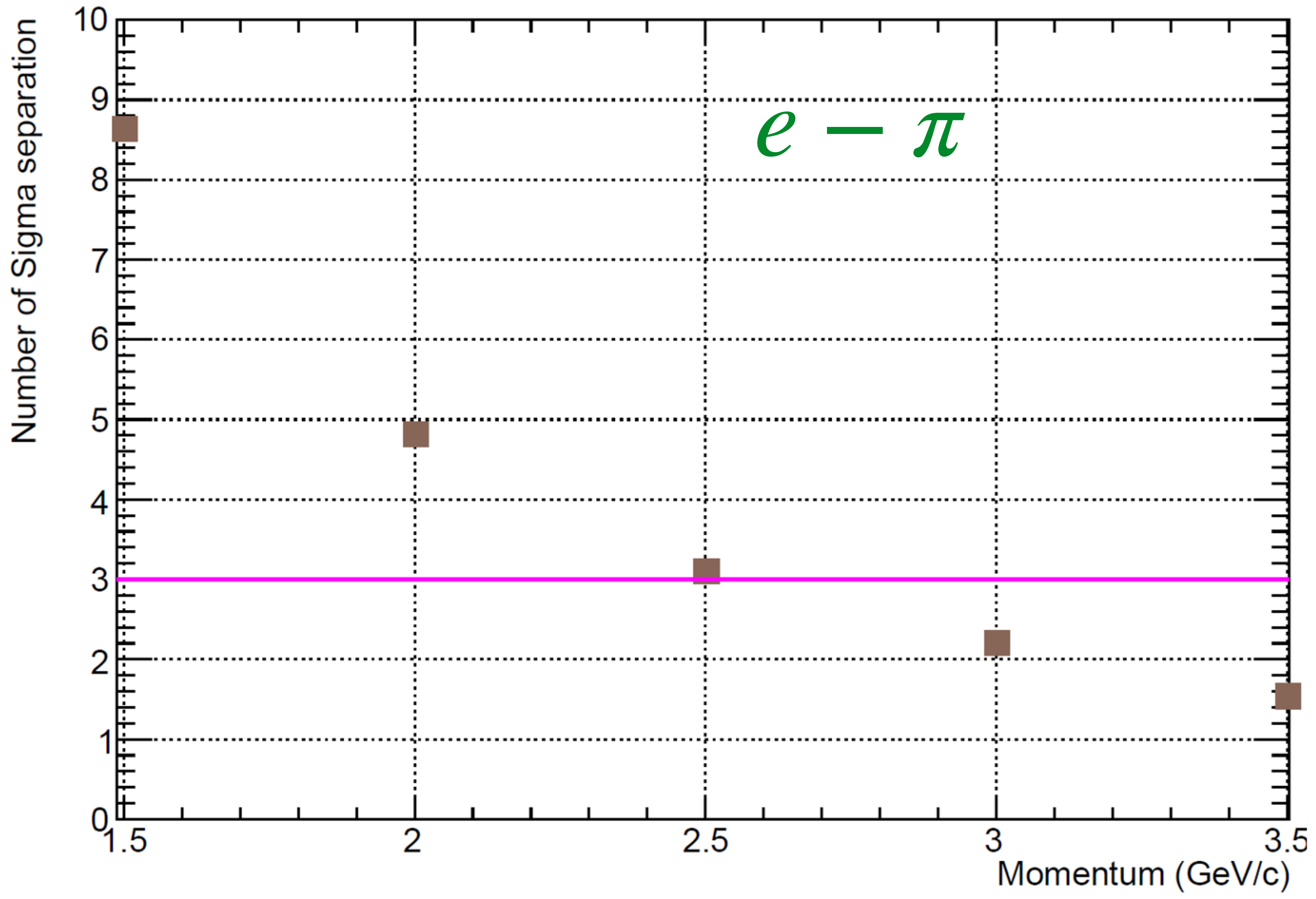


Single photon timing resolution measured using femtosecond laser





-2.8 < η < -1.9



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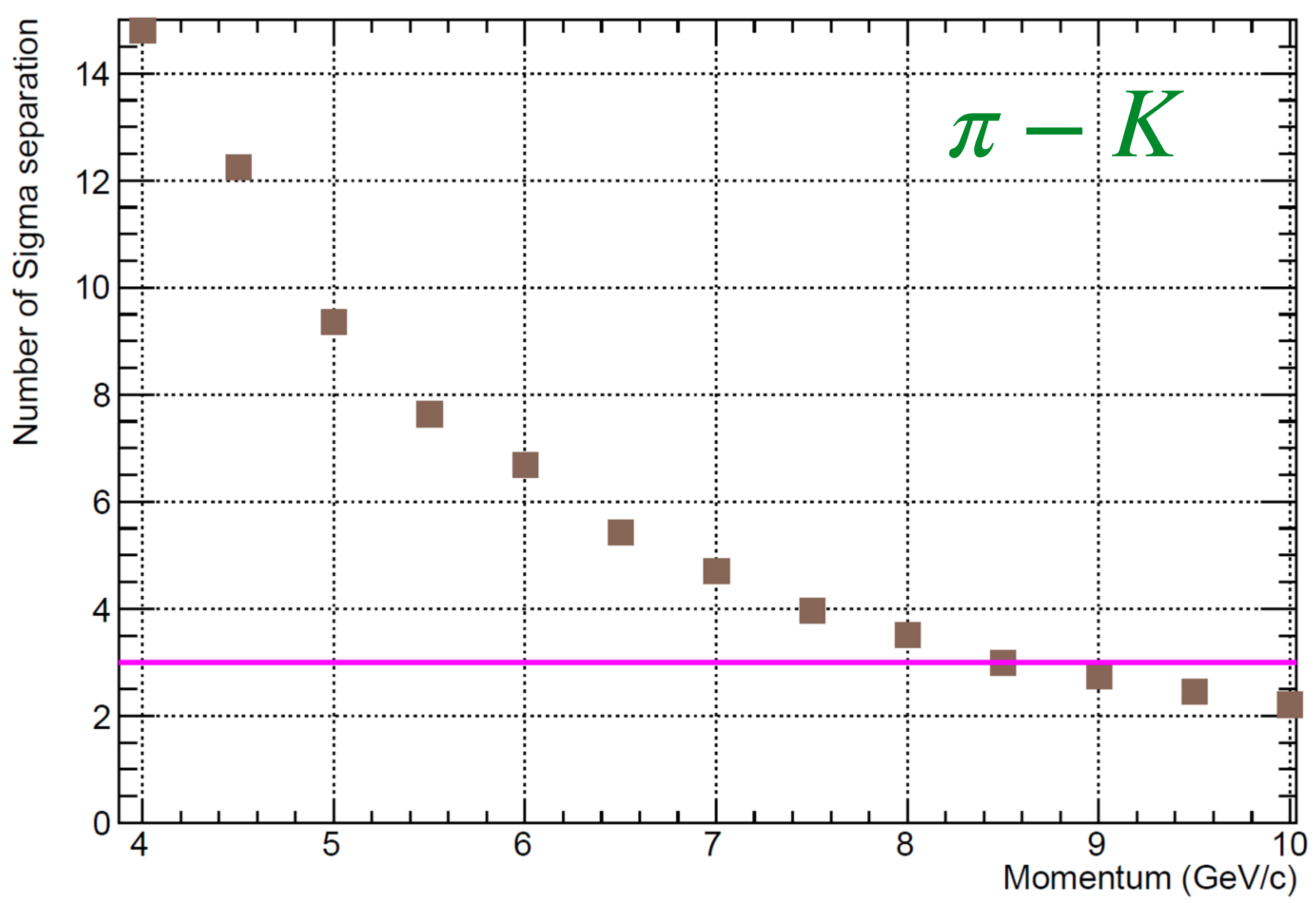
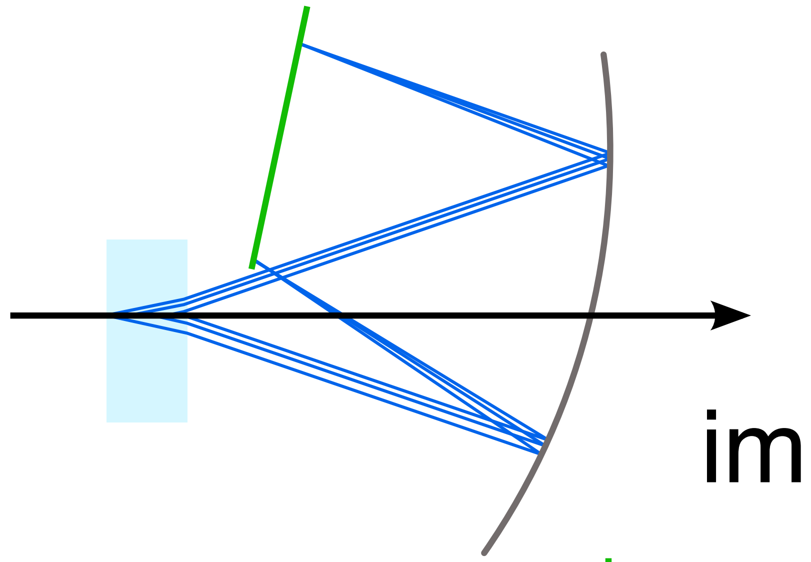
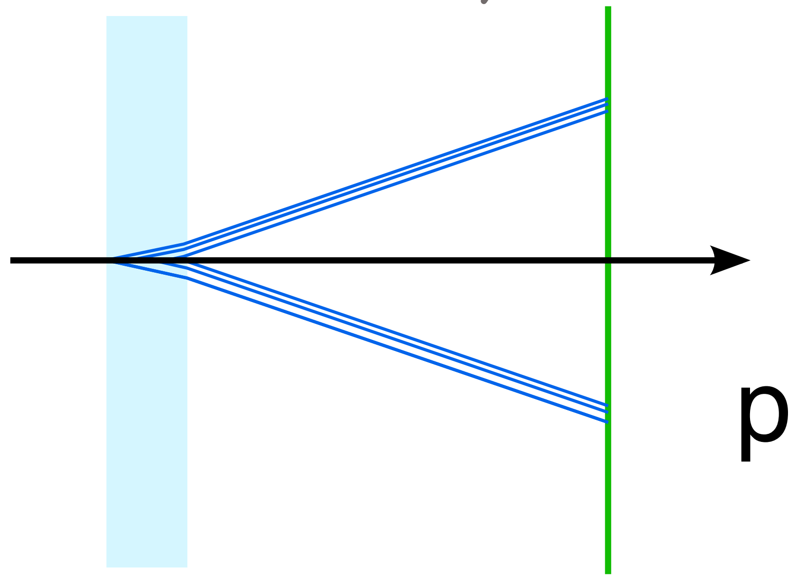
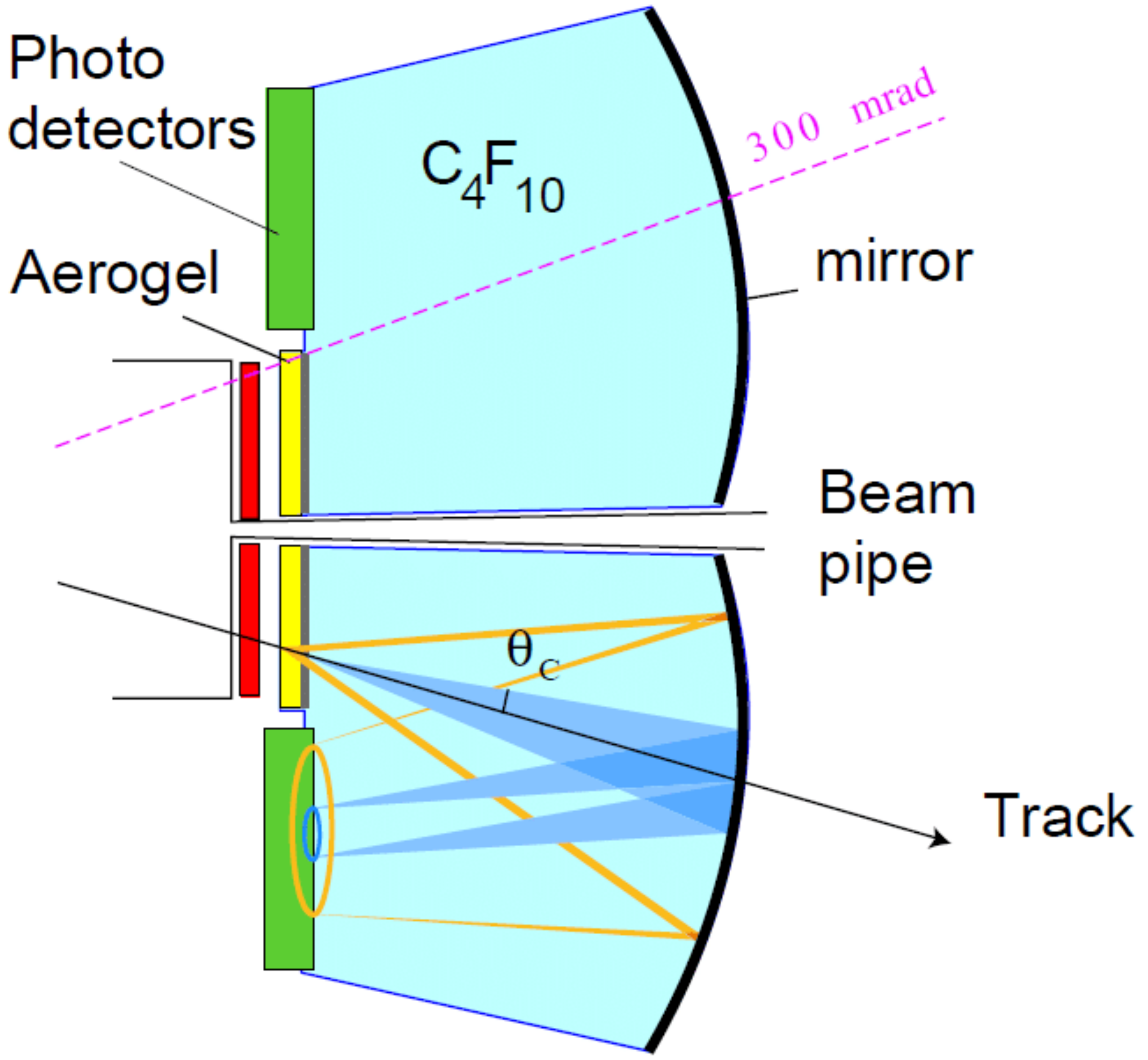


Forward Region: dualRICH (dRICH)

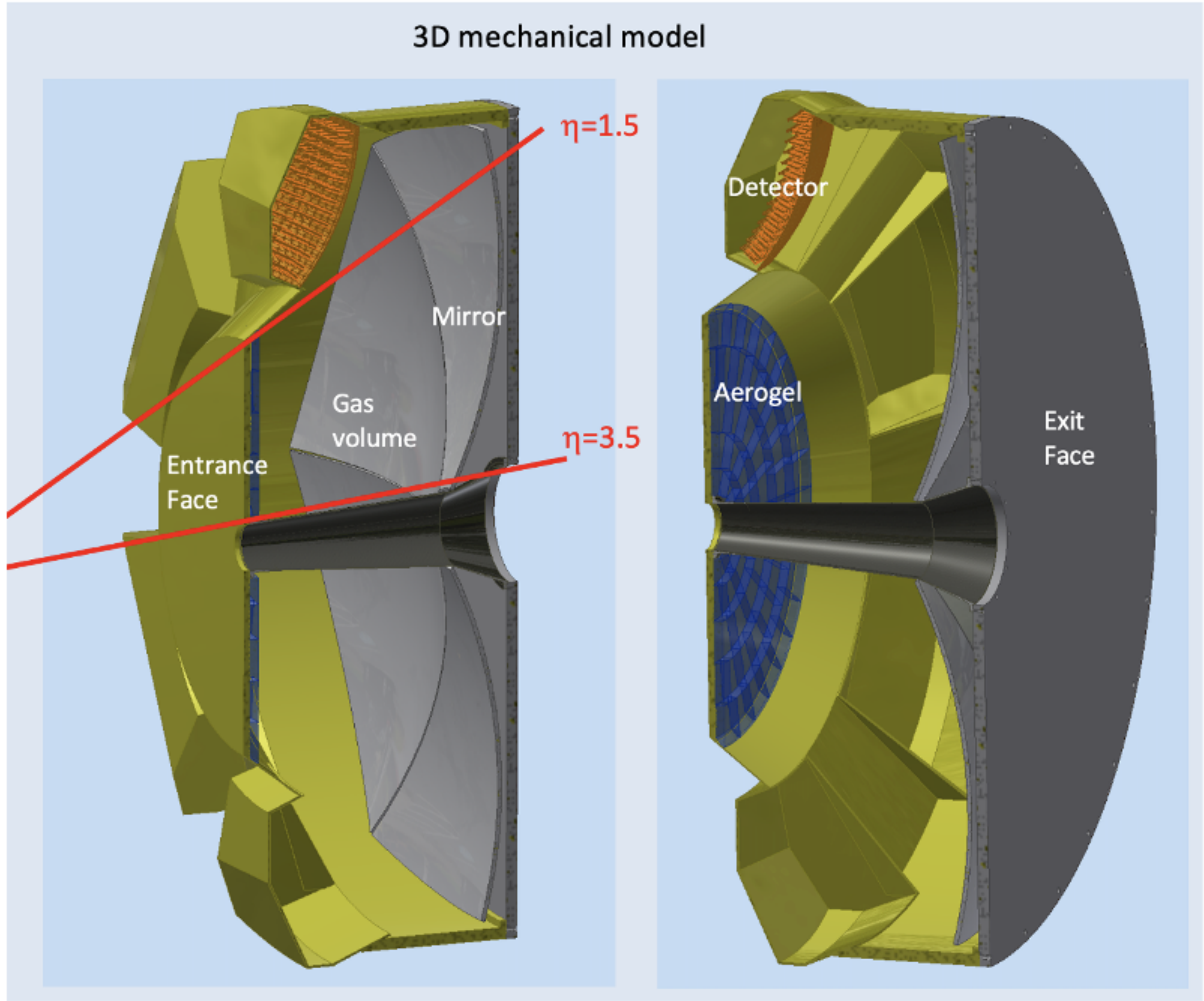
- Forward region has the most challenging requirements
  - Provide **continuous** hadron identification from~3 GeV/c to~50 GeV/c, ➠ dual radiator
  - Supplement electron and positron identification from a few hundred MeV/c up to about 15 GeV/c. ➠ dual radiator
  - Work in a high B field ~ 0.5T (field lines!) ➠ SiPM photosensors
  - Fit in limited space (for a gas RICH) ➠ curved detector

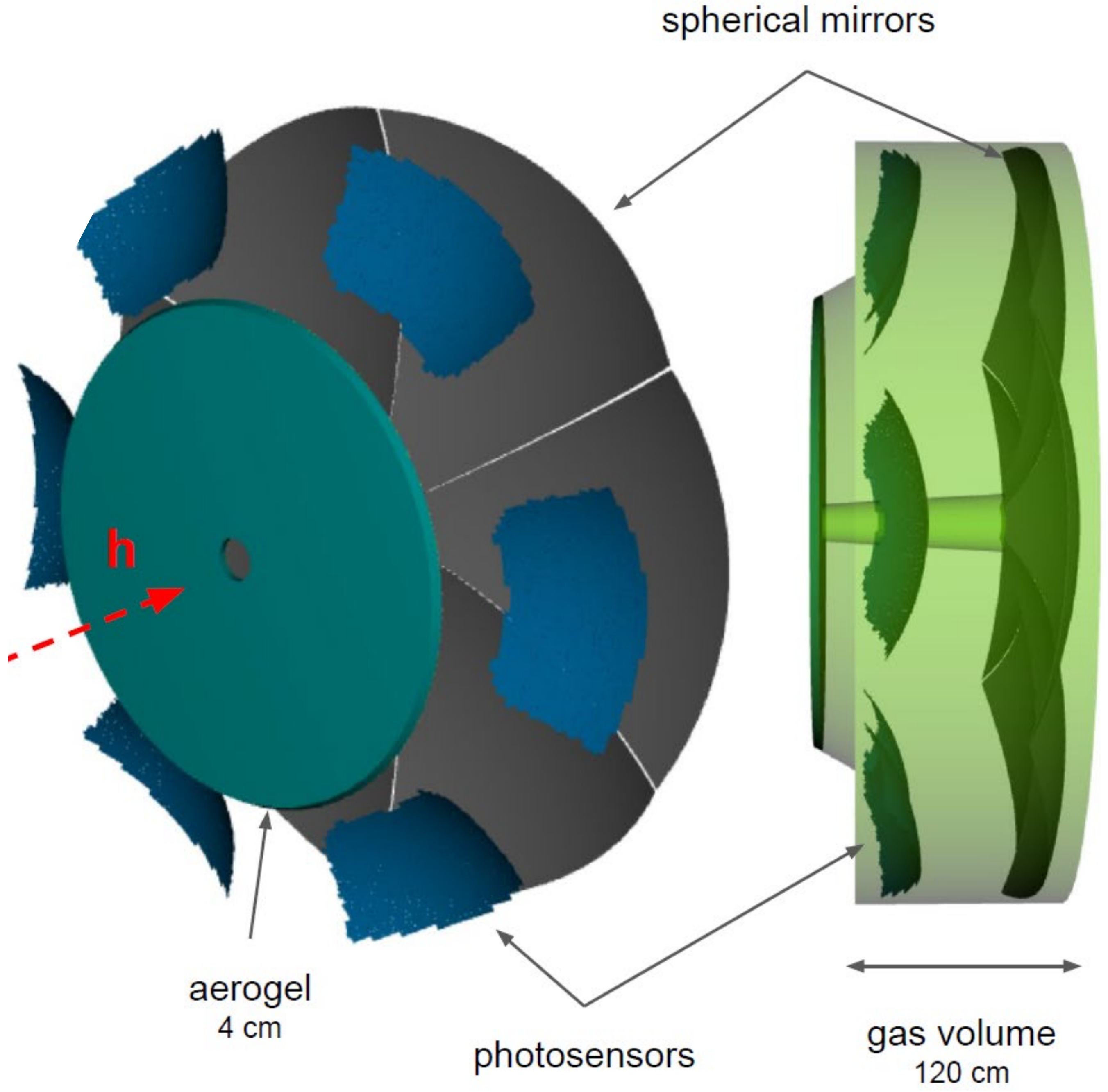

imaging with mirror

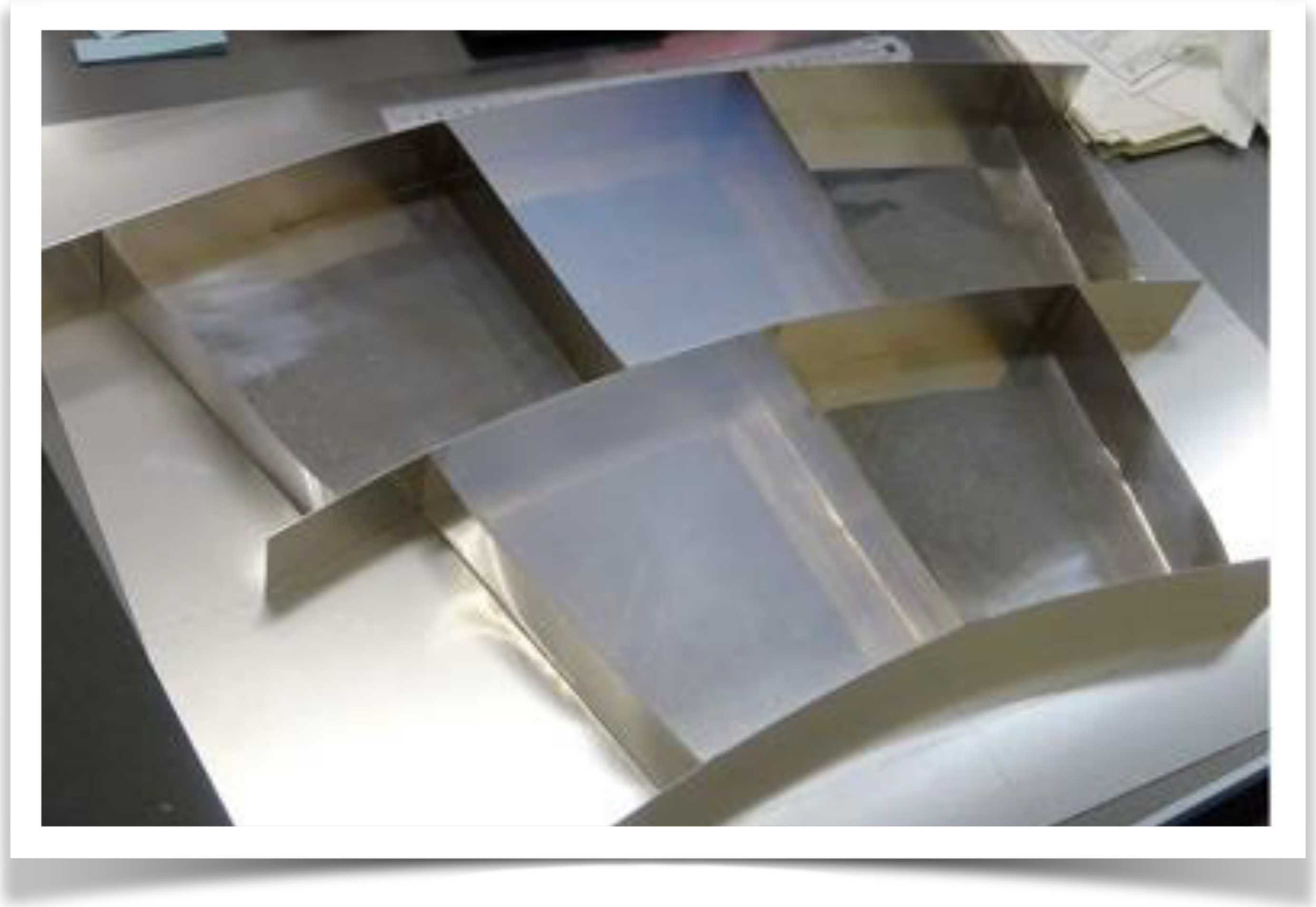

proximity focusing



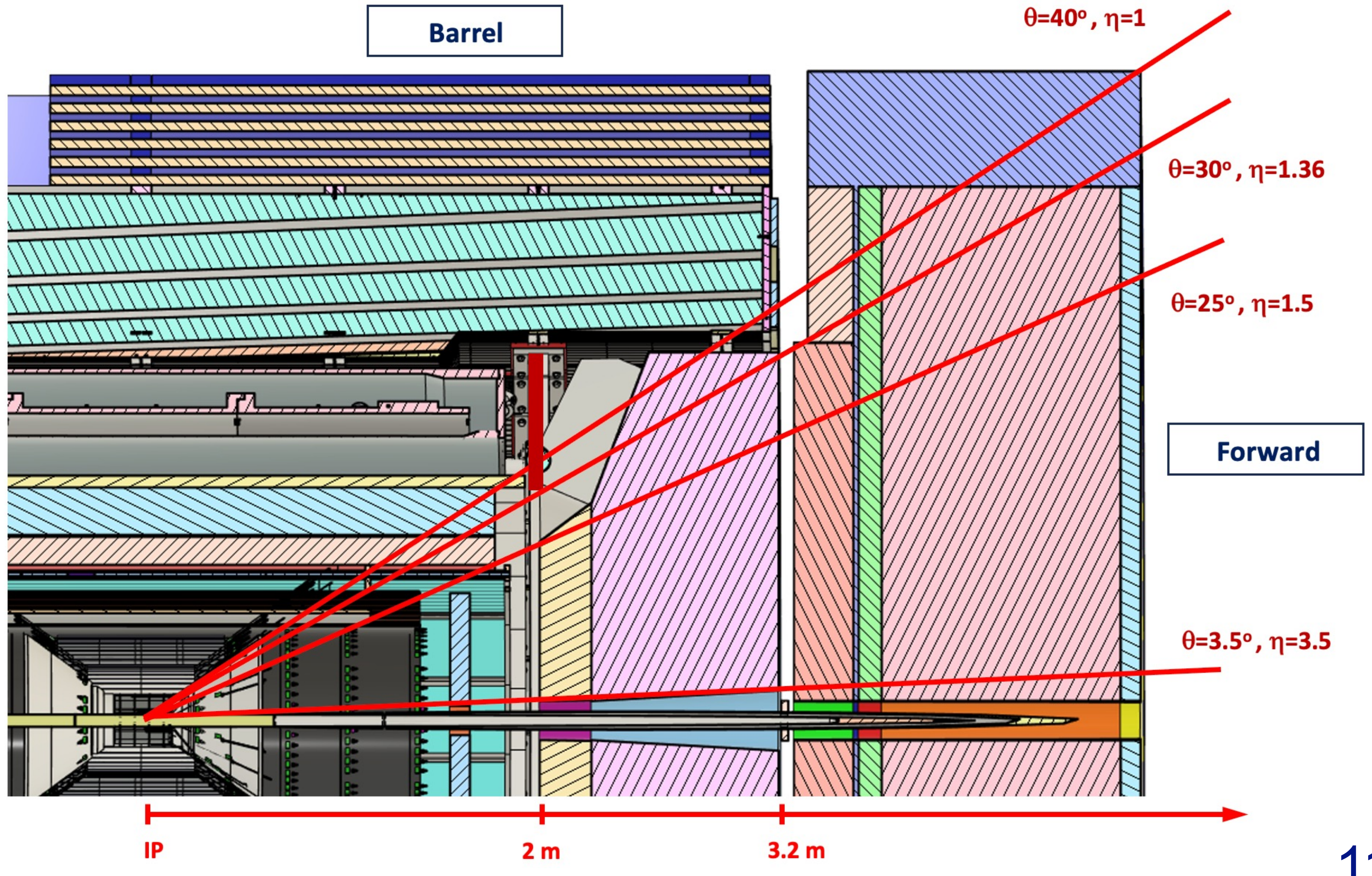
dRICH Overview





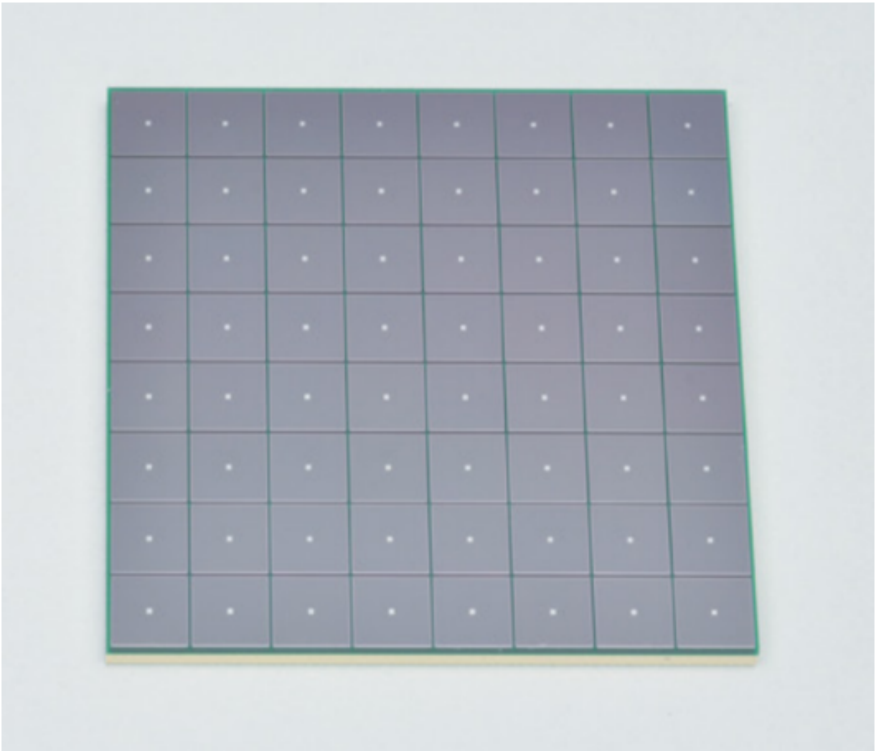


- Aerogel n ~ 1.026
- Gas C_2F_6 (hexafluoroethane) n=1.0008
- Spherical mirror with R ~ 220 cm
- Build with Carbon Fiber Reinforced Polymer (CFRP). It's a composite material made by combining carbon fibers + polymer resin (like epoxy).



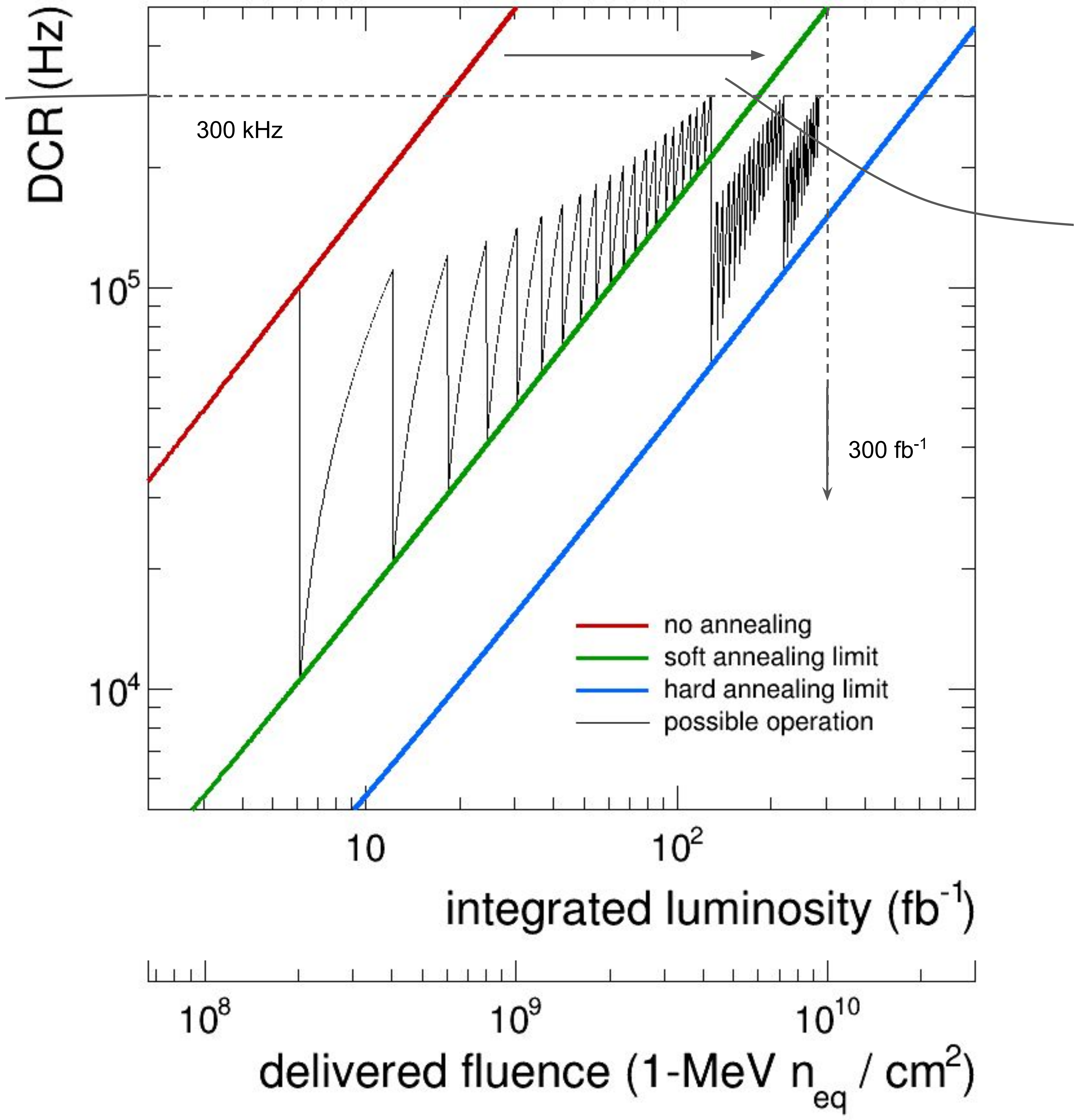
The Challenge: SiPM Sensors

- Need to cover 3 m^2
- 3x3 mm^2 pixel
- Pros
  - single photon detection
  - high efficiency
  - excellent timing resolution
  - insensitive to magnetic fields
- Cons
  - not radiation tolerant
  - large dark current rate ~50kHz/mm2 @ T = 24˚C



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

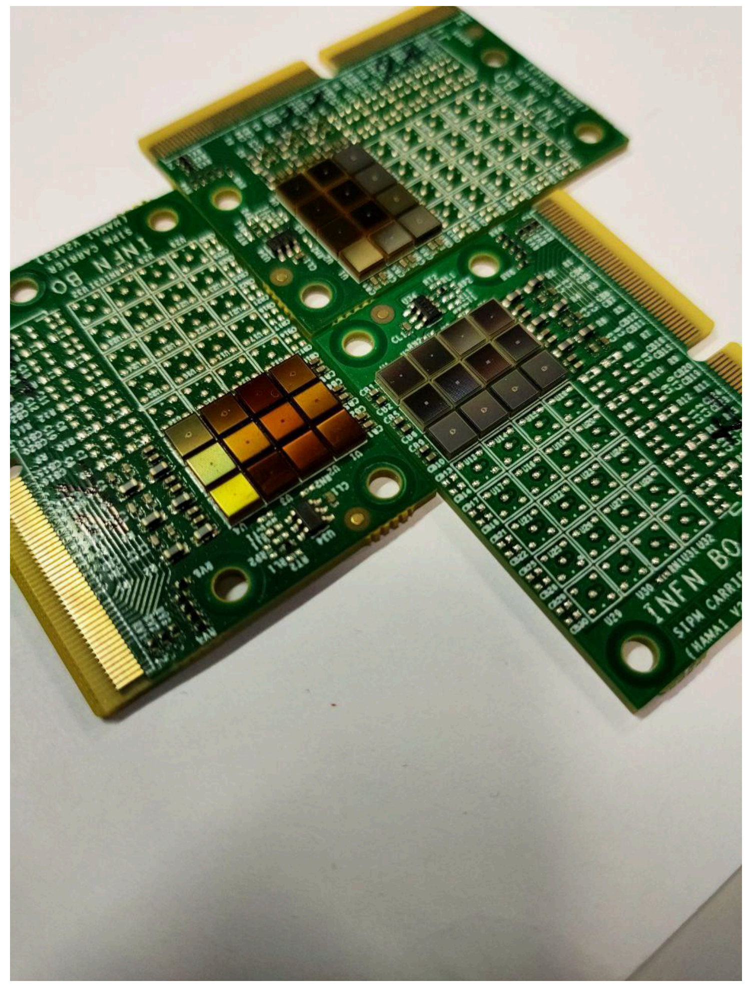
max acceptable DCR for Physics performance
~ 10 noise hits / sector within 500 ps

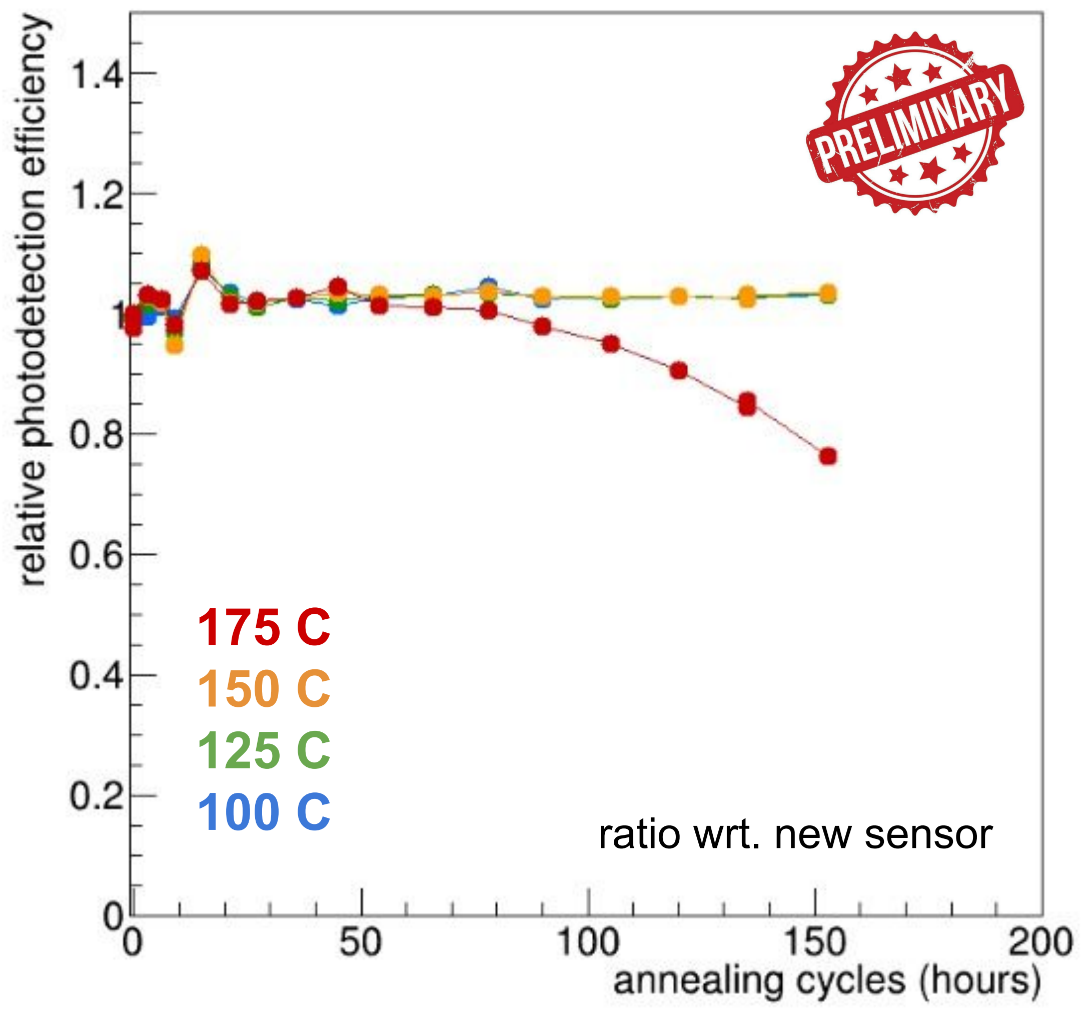


A Tour de Force - SiPM in dRICH

Mitigation Strategies

- reduce DCR at low T
  - operation at T = -30˚C
- recover radiation damage
  - in-situ high-T annealing
- exploit timing capabilities with ALCOR front end chip
- Test shows it works but T ~ 150˚C seems limit (see yellow chip)





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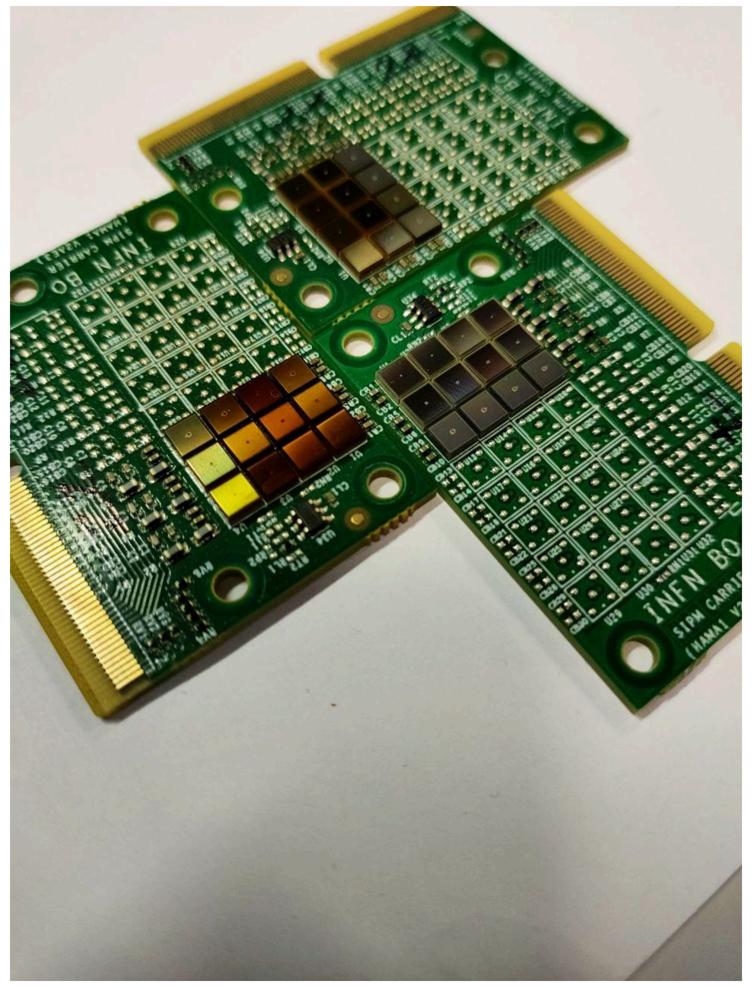
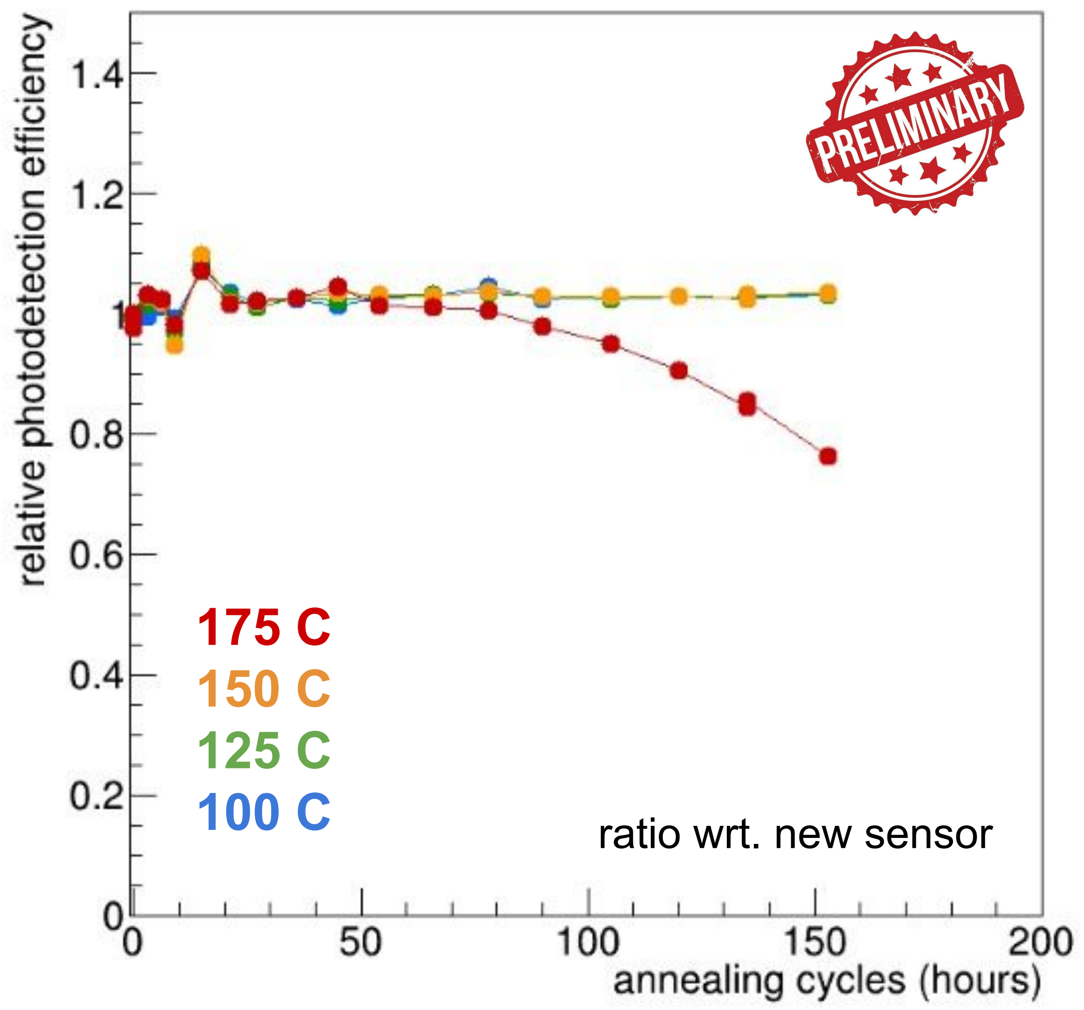
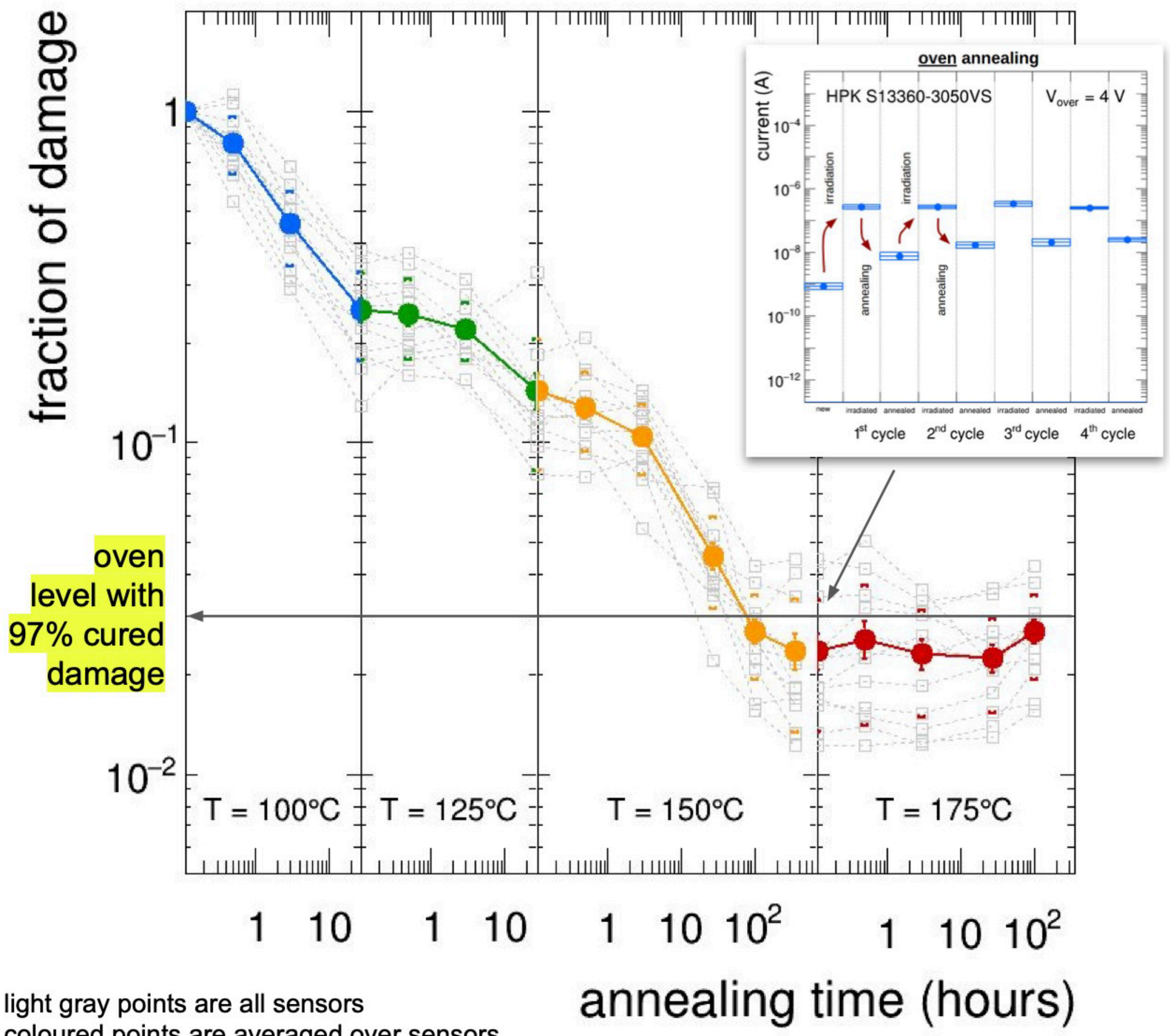


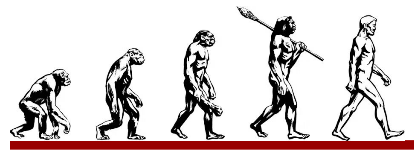


online self-annealing with forward bias

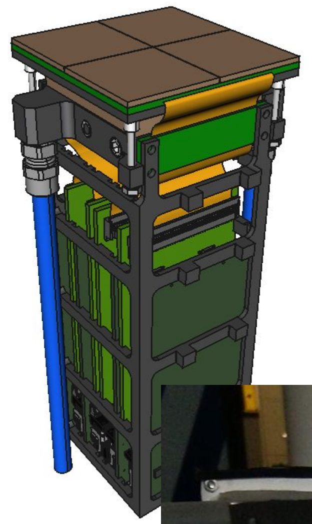


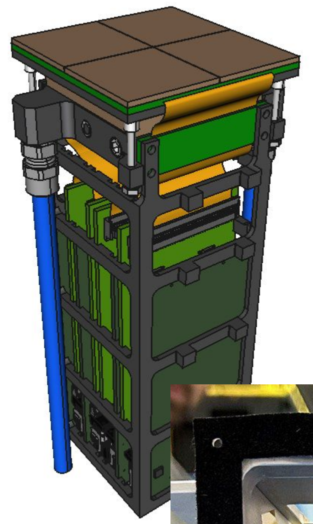
light gray points are all sensors
coloured points are averaged over sensors
coloured brackets is the RMS

dRICH Evolution

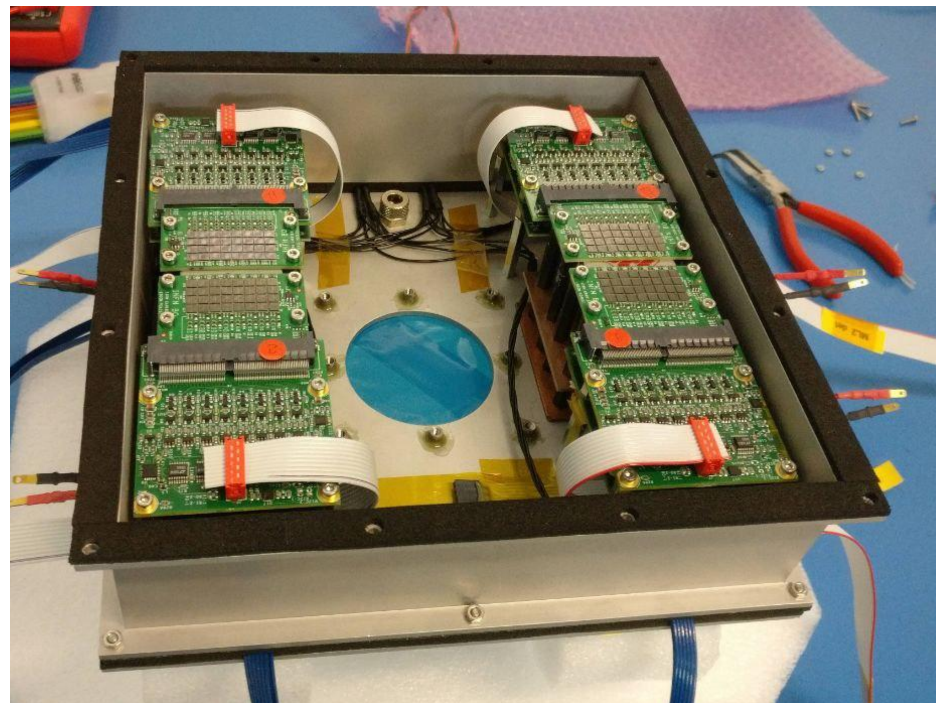


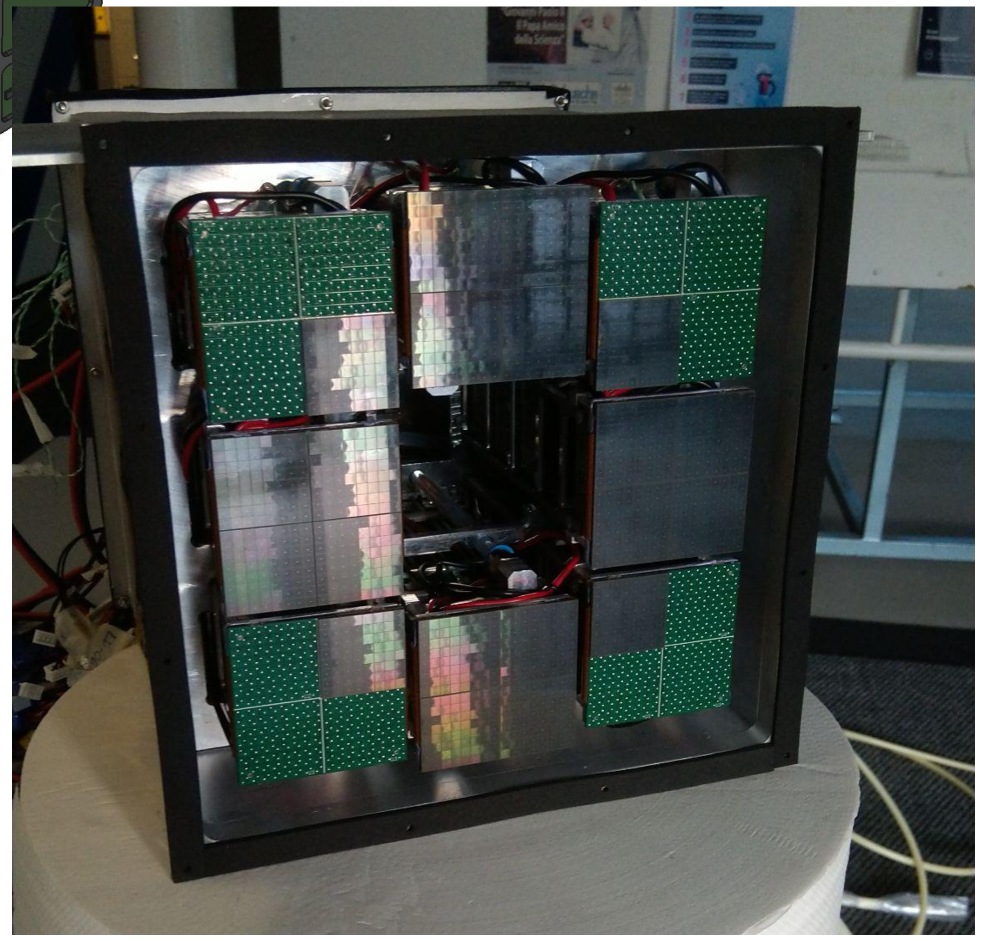
towards construction

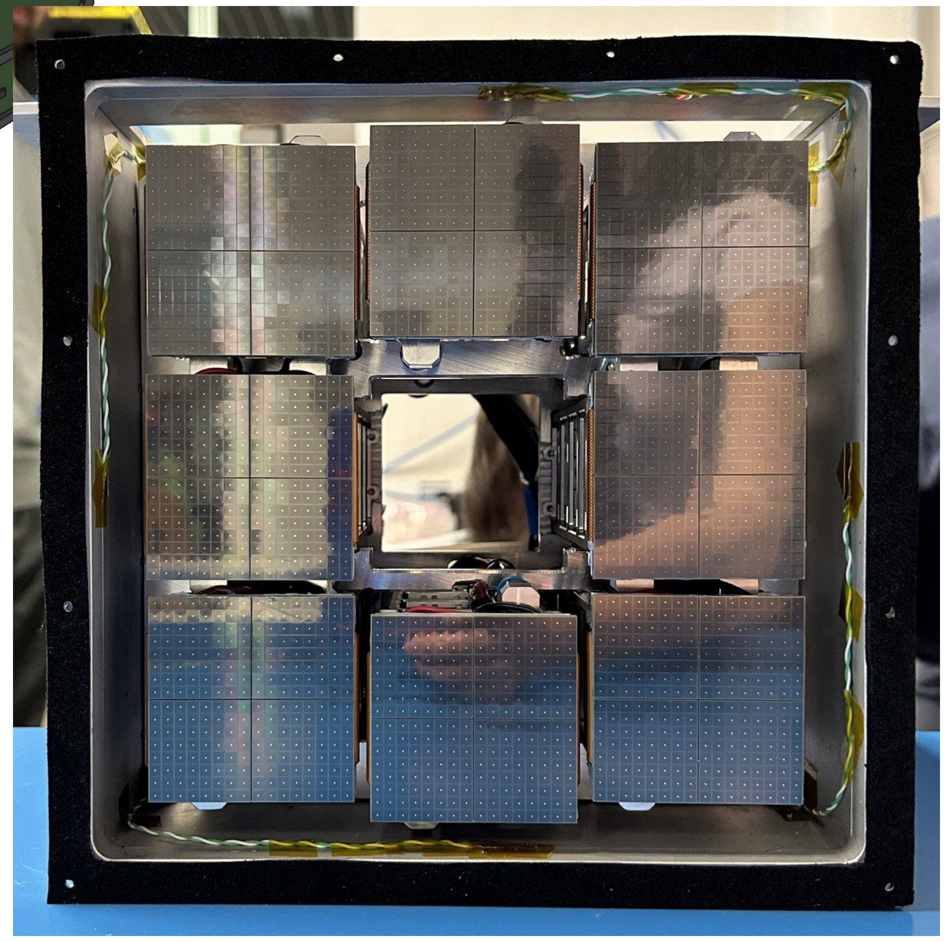


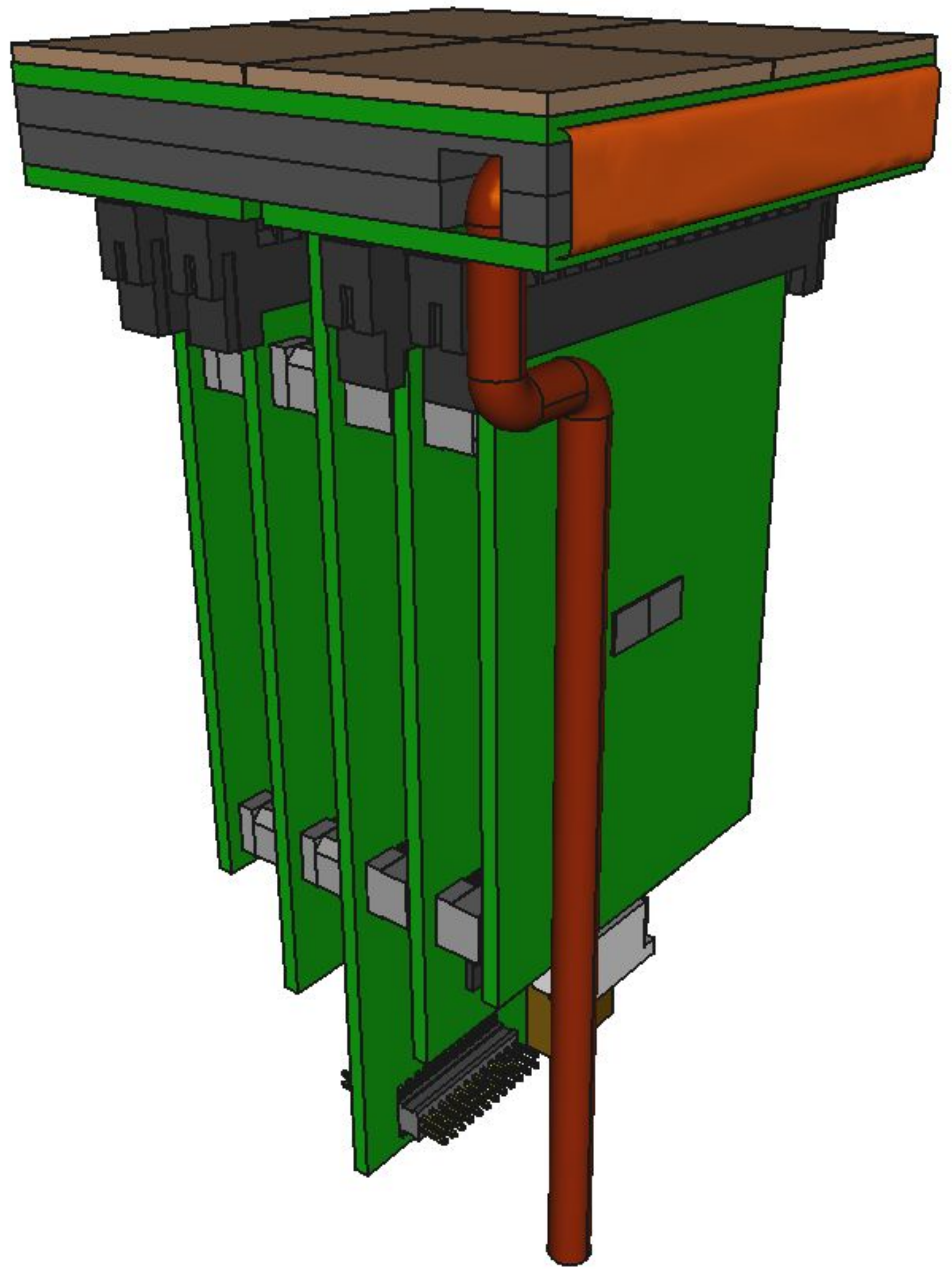


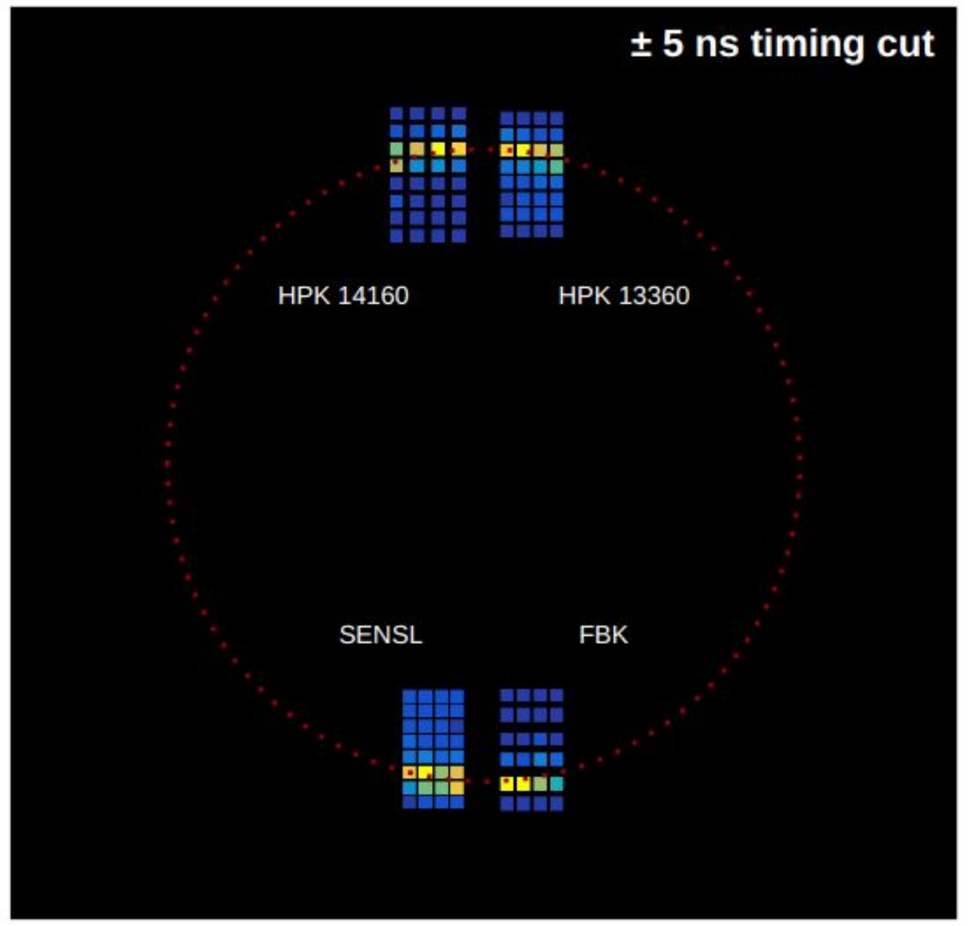
2022	2023	2024	2025
electronics v1	electronics v2	electronics v2.1	electronics v3 final prototype

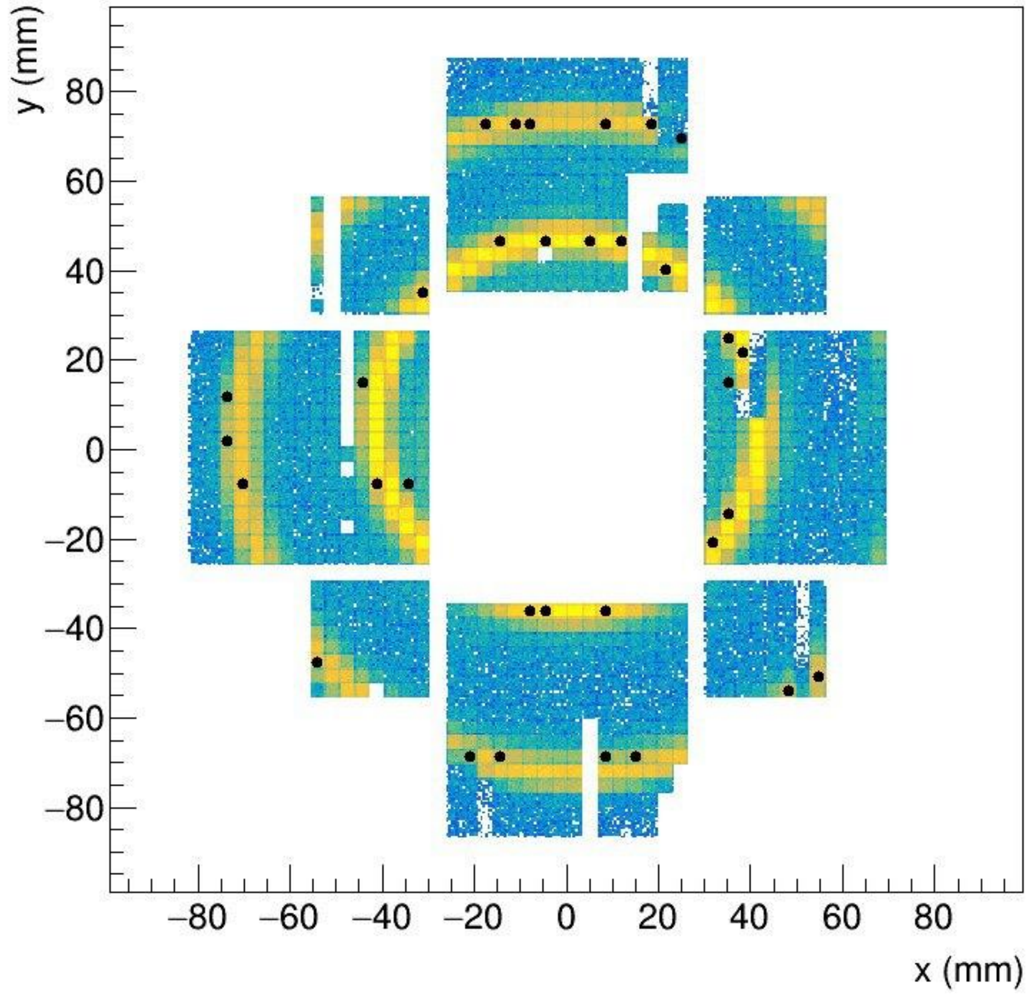


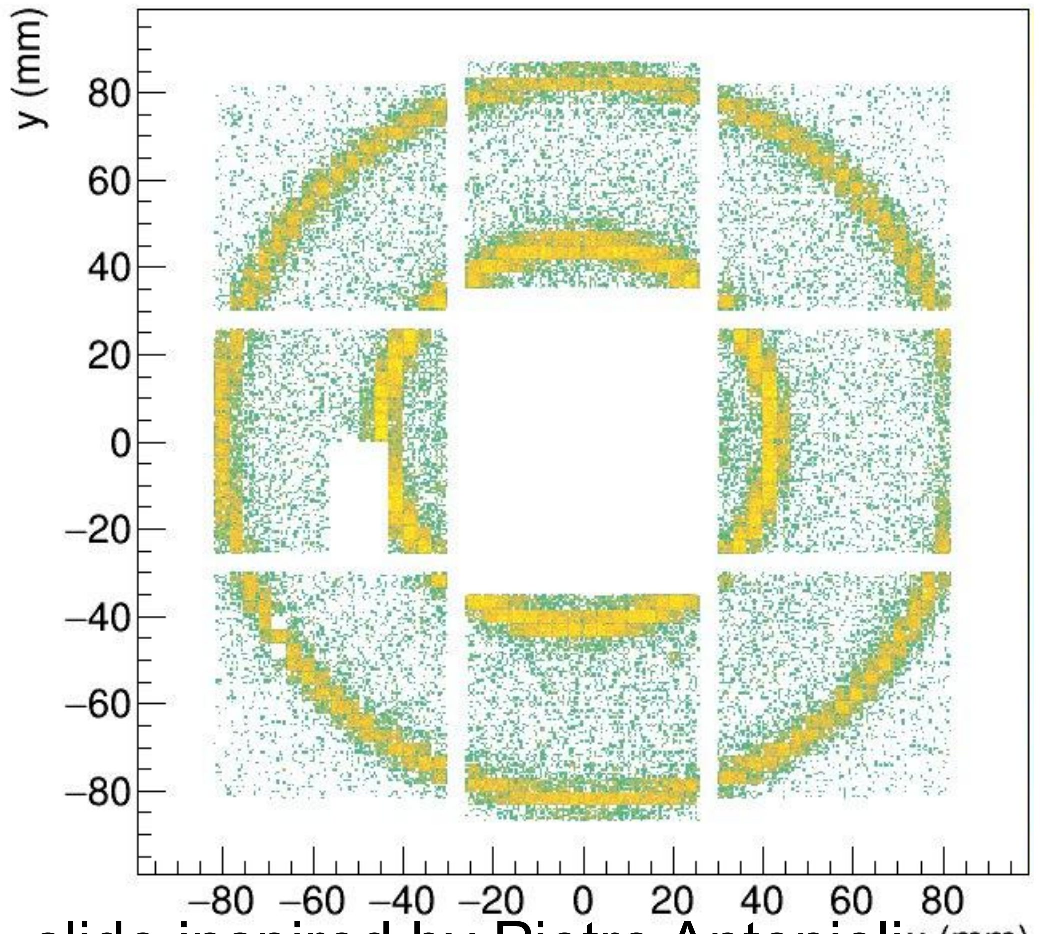






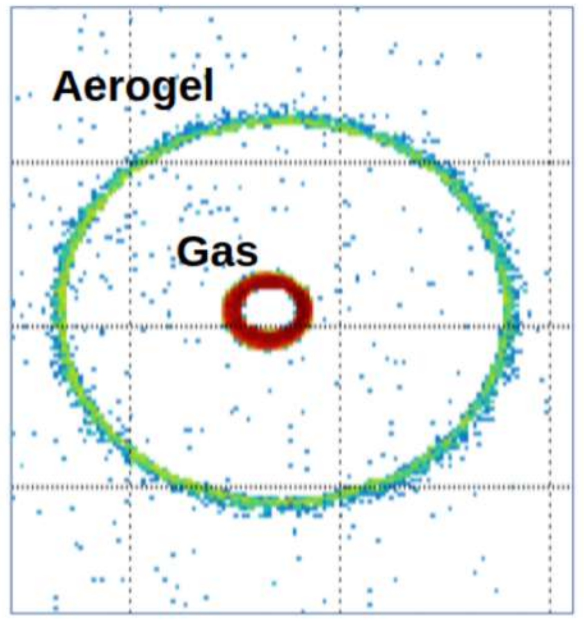


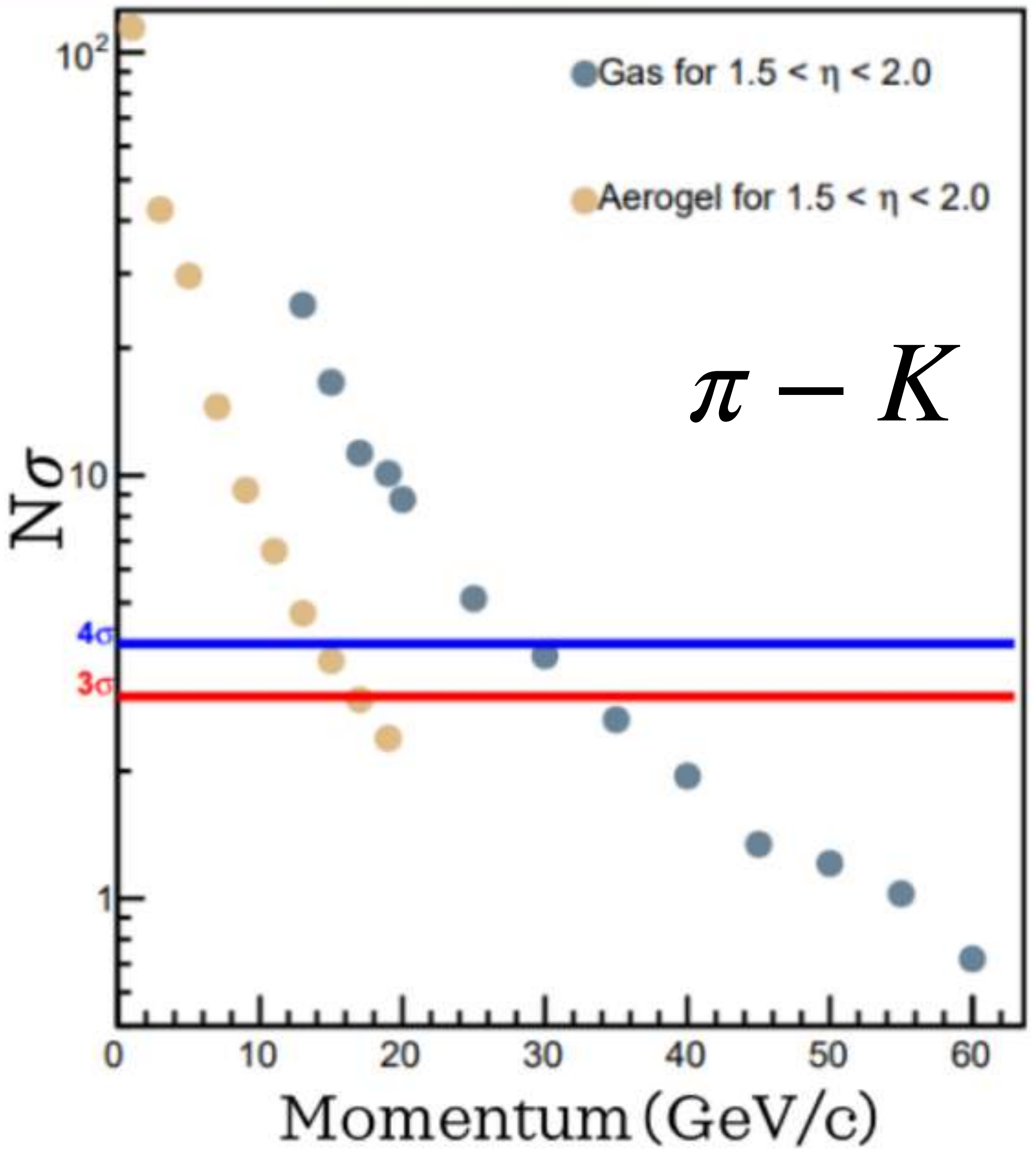


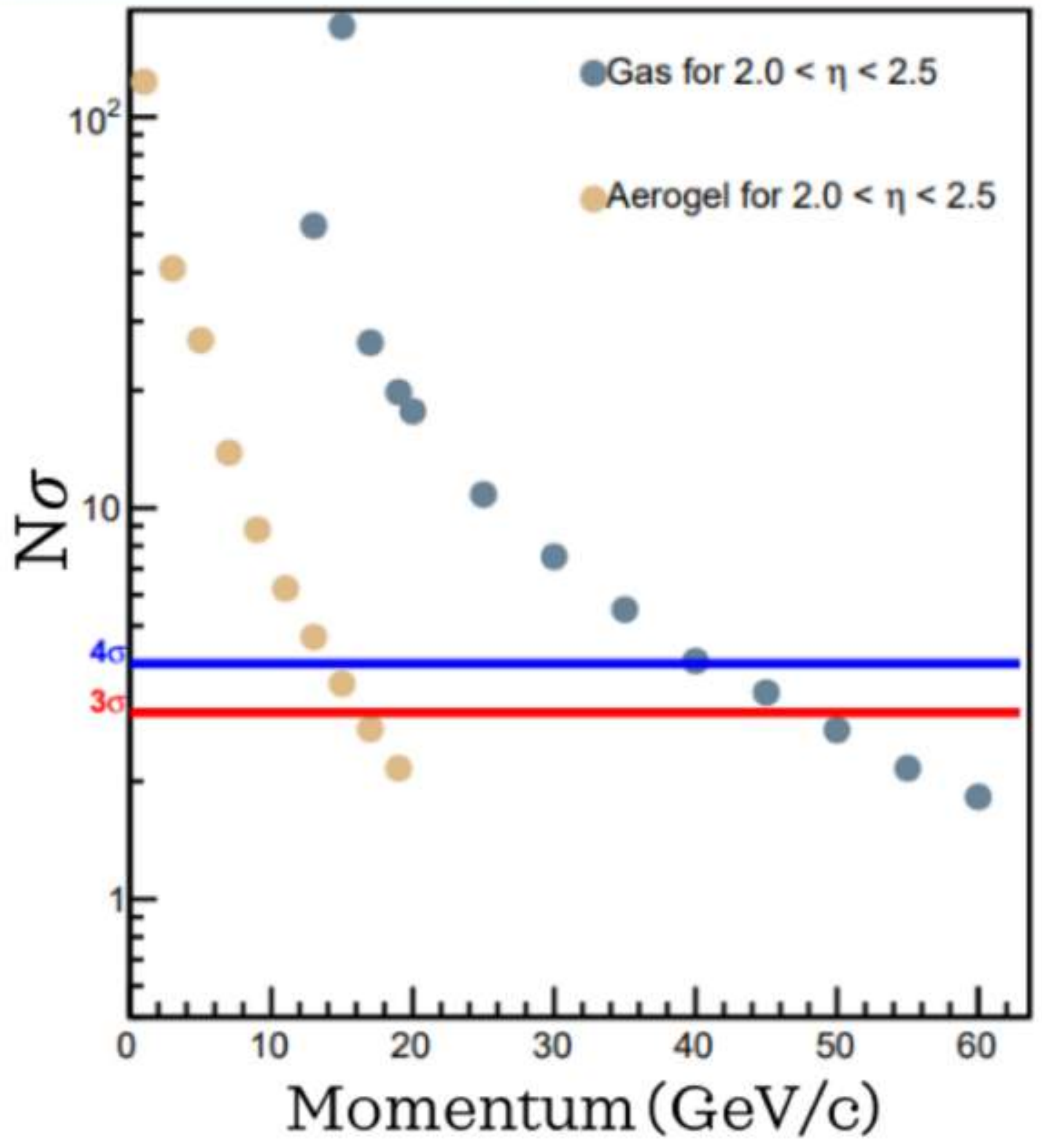


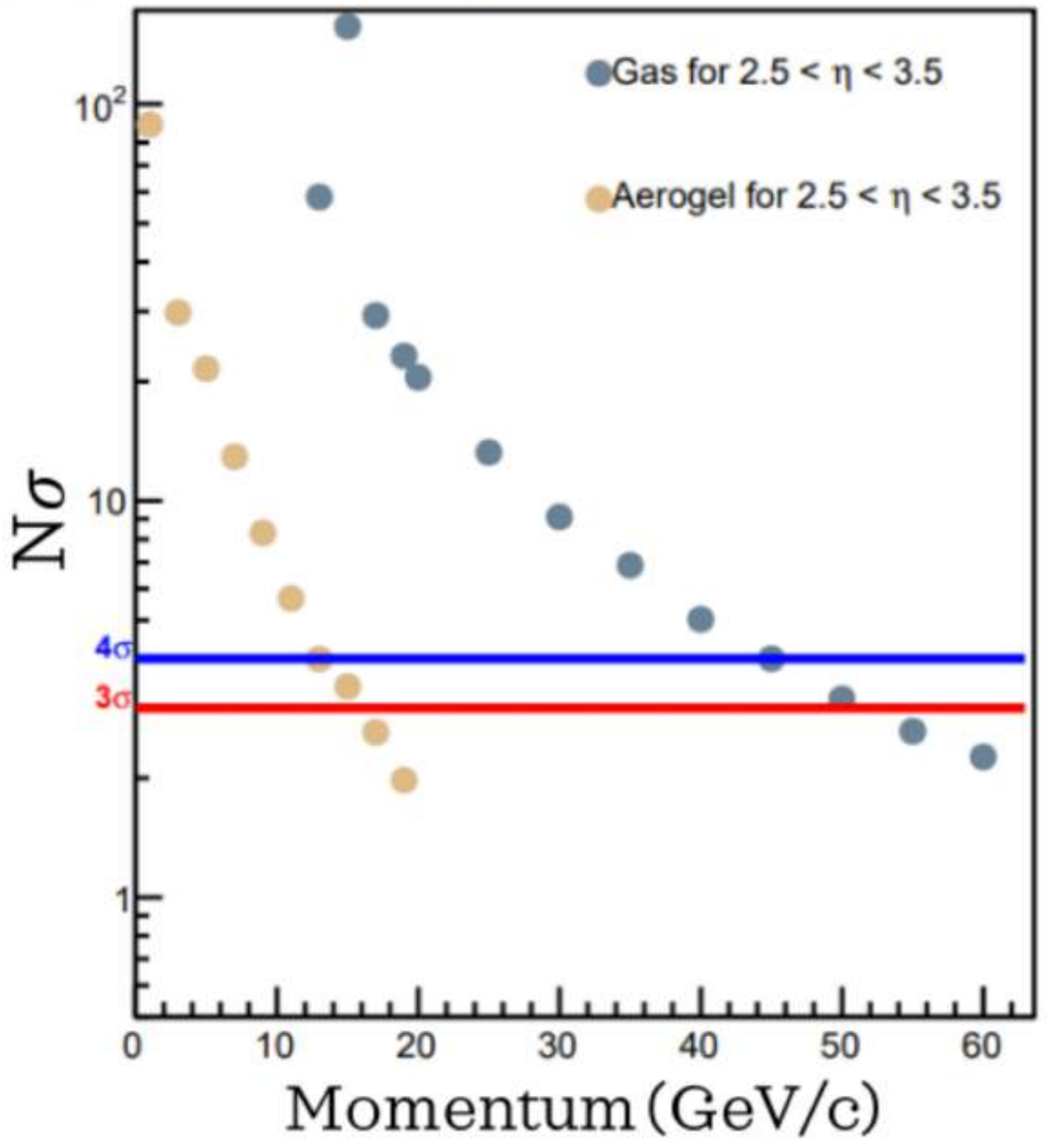
slide inspired by Pietro Antonioli

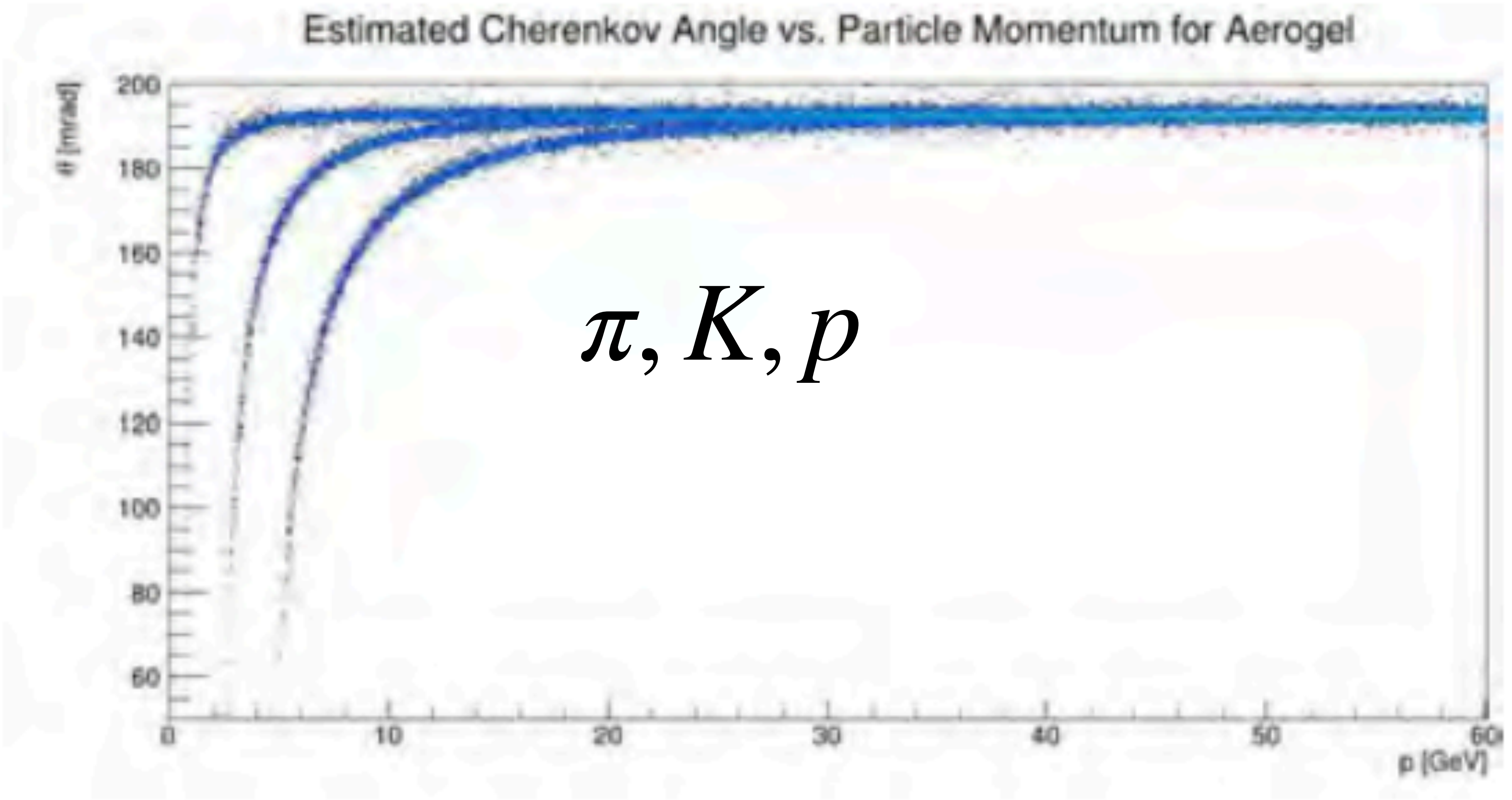
dRICH Performance

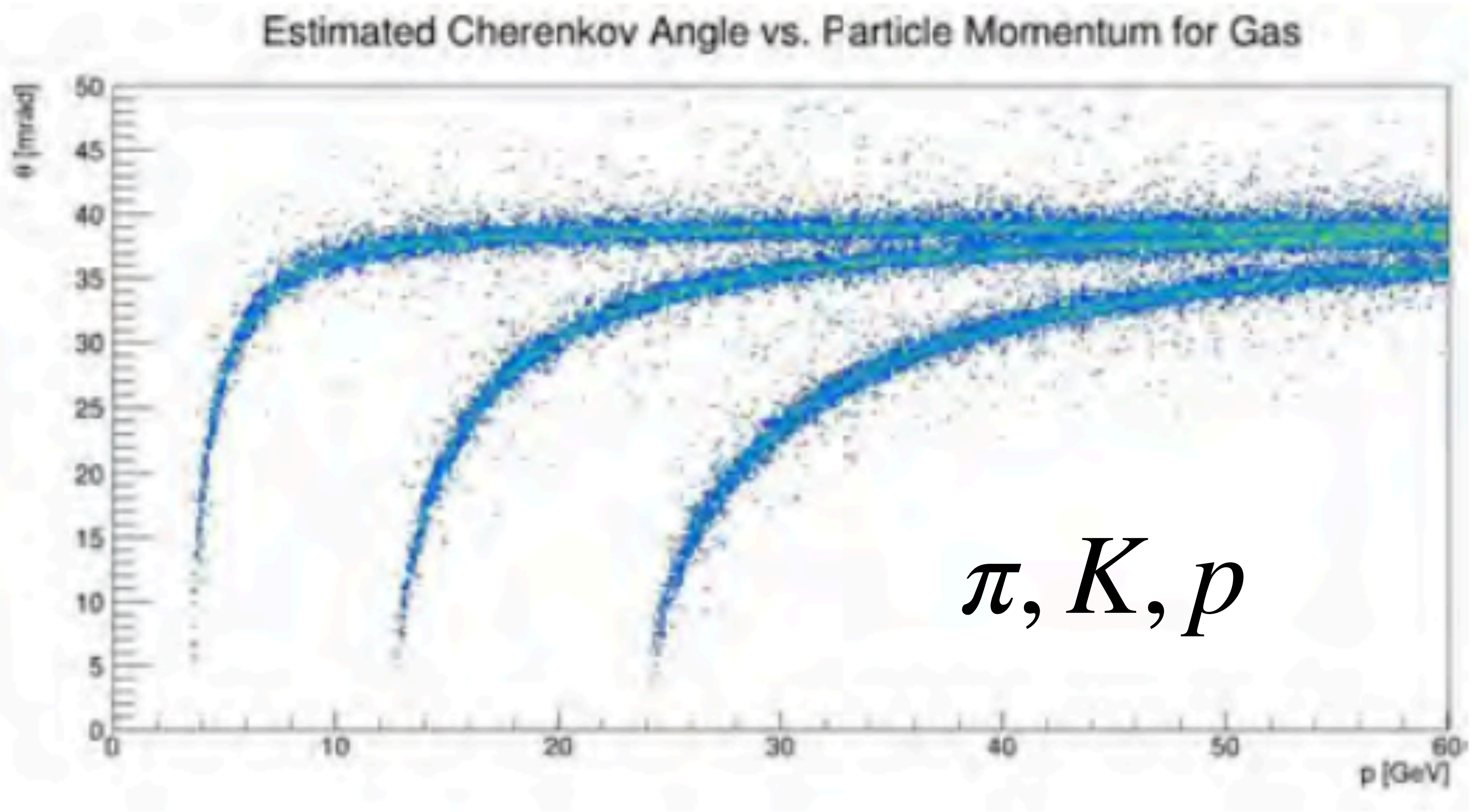








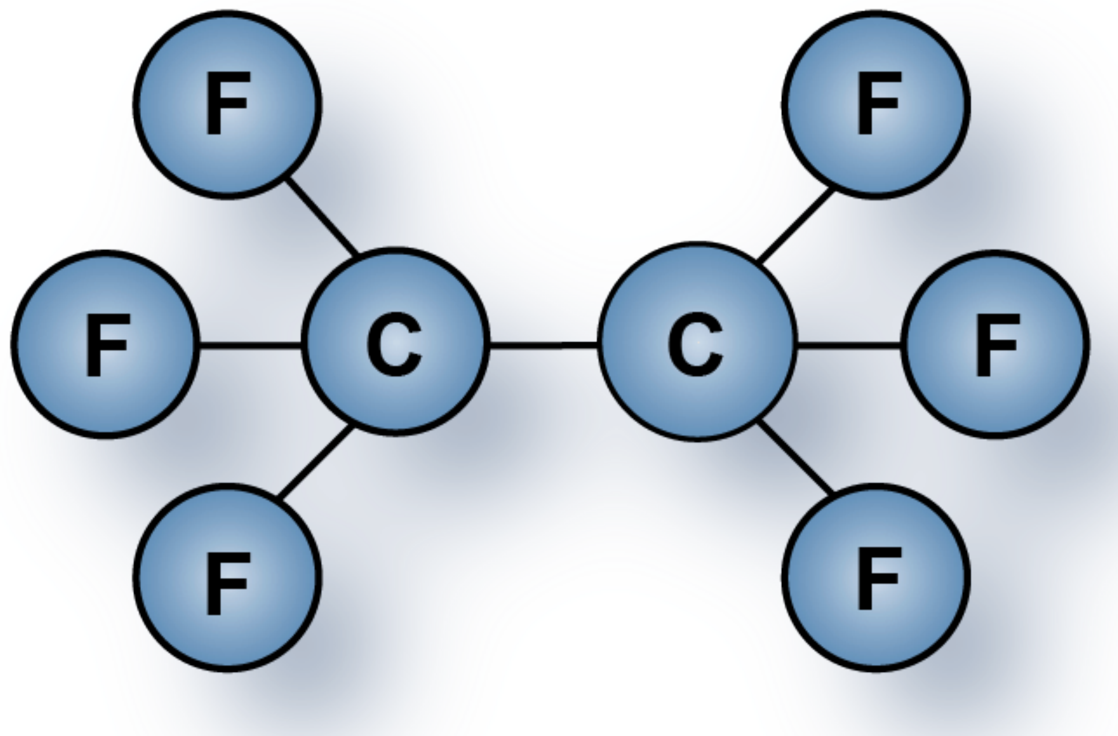




Simulations of performance is looking good!

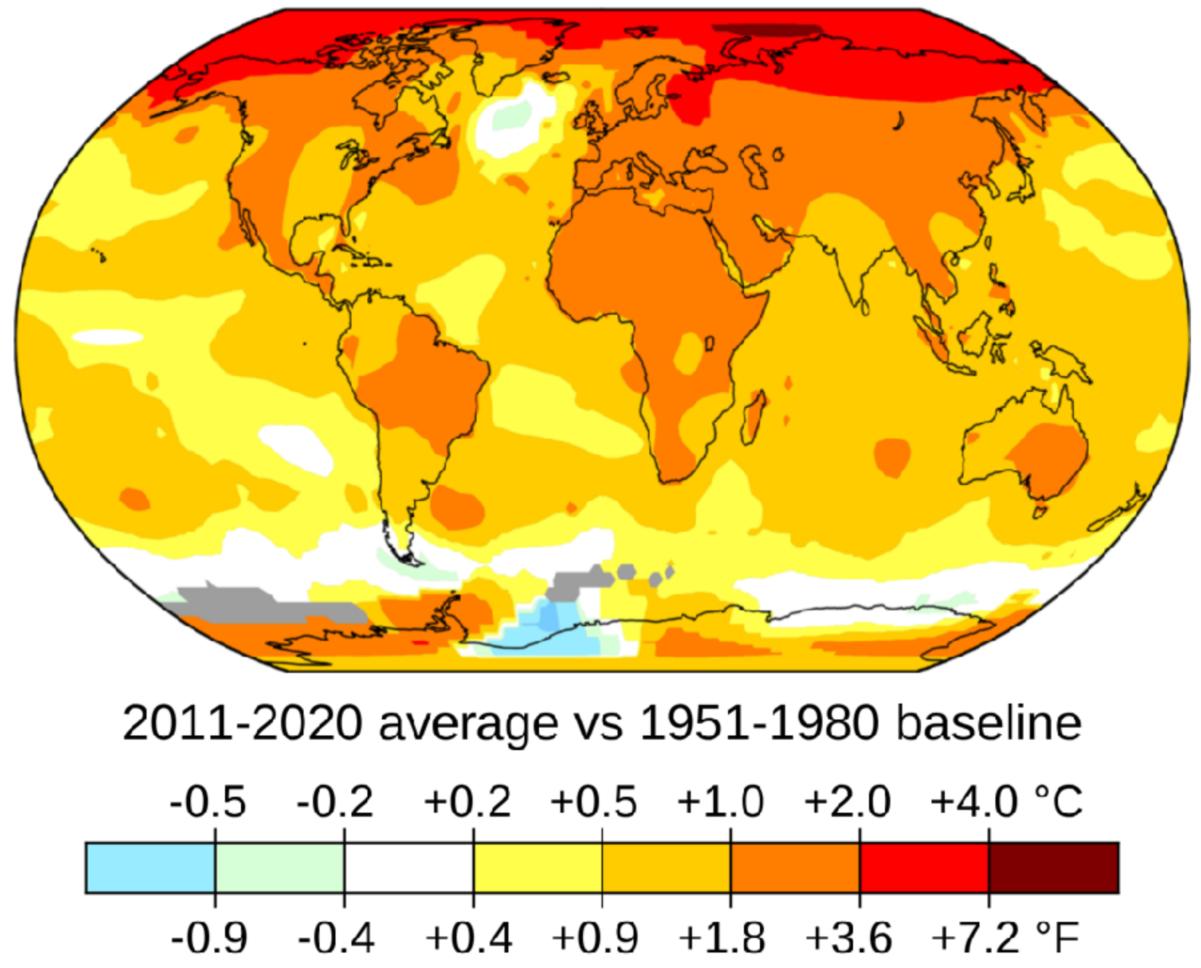
dRICH & Global Warming

- Radiator gases for EIC RICH detectors are fluorocarbons that exhibit extremely high Global Warming Power: GWP(C_2F_6) ~$\mathcal{O}$(10k), GWP(CO_2) = 1
- Increasingly prohibited across the world
- Where used
  - complex and expensive close circulation systems needed
  - increasing procurement issues expected
- RICH performance is preserved when fluorocarbons at atmospheric pressure are replaced with argon pressurized at a few bar
- The challenge is to design vessel that allows
  - safe high-pressure operation
  - minimizing its impact on the overall detector material budget.
  - engineering in progress - R&D ongoing



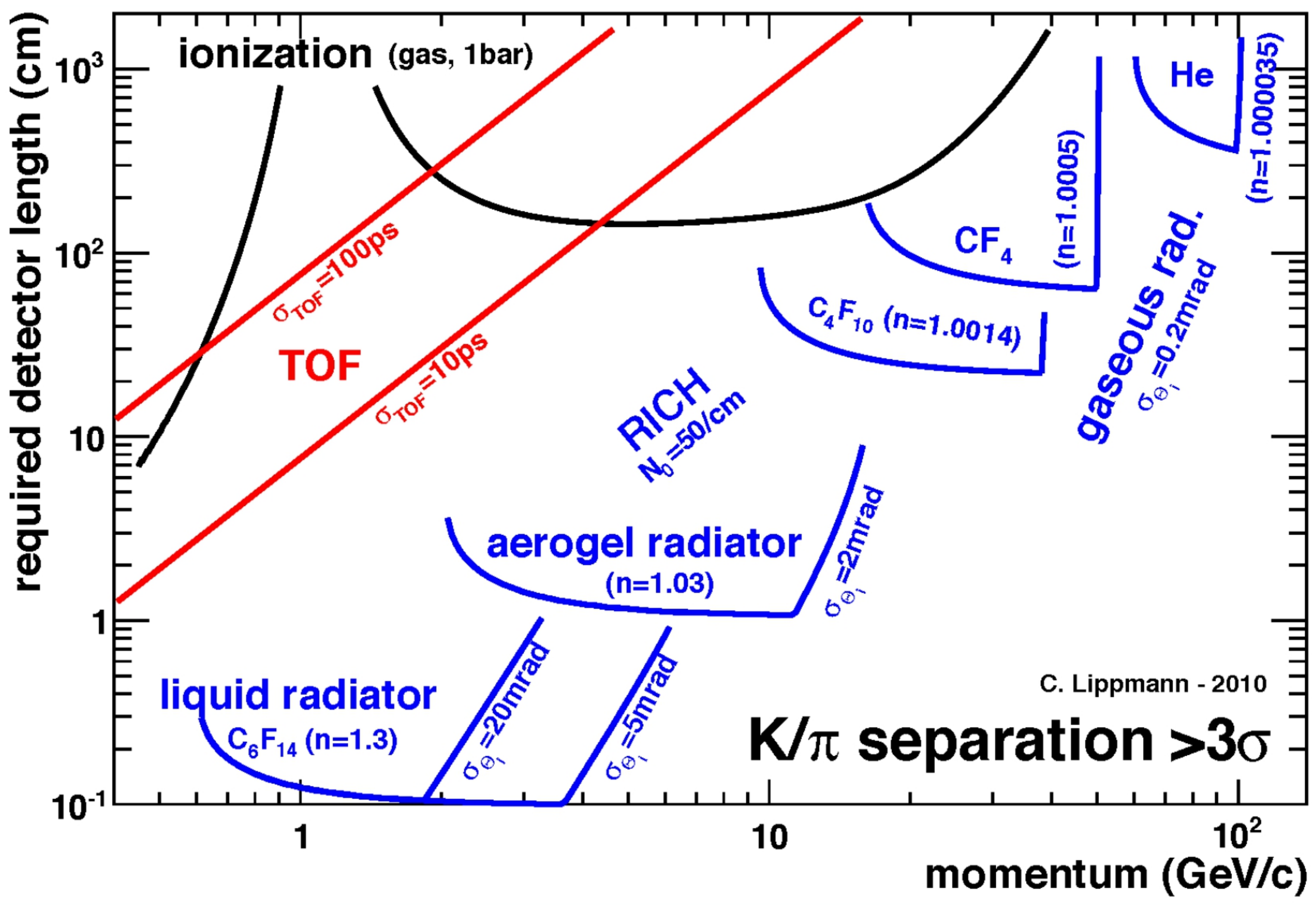
Formula	Name	Lifetime years	Global Warming Potential (GWP) 100-yr horizon	100-yr horizon	500-year horizon
			(SAR[a])	(AR4[b])	(AR4)
CF_4	PFC-14	50 000	6500	7390	11 200
C_2F_6	PFC-116	10 000	9200	12 200	18 200
C_3F_8	PFC-218	2600	7000	8830	12 500

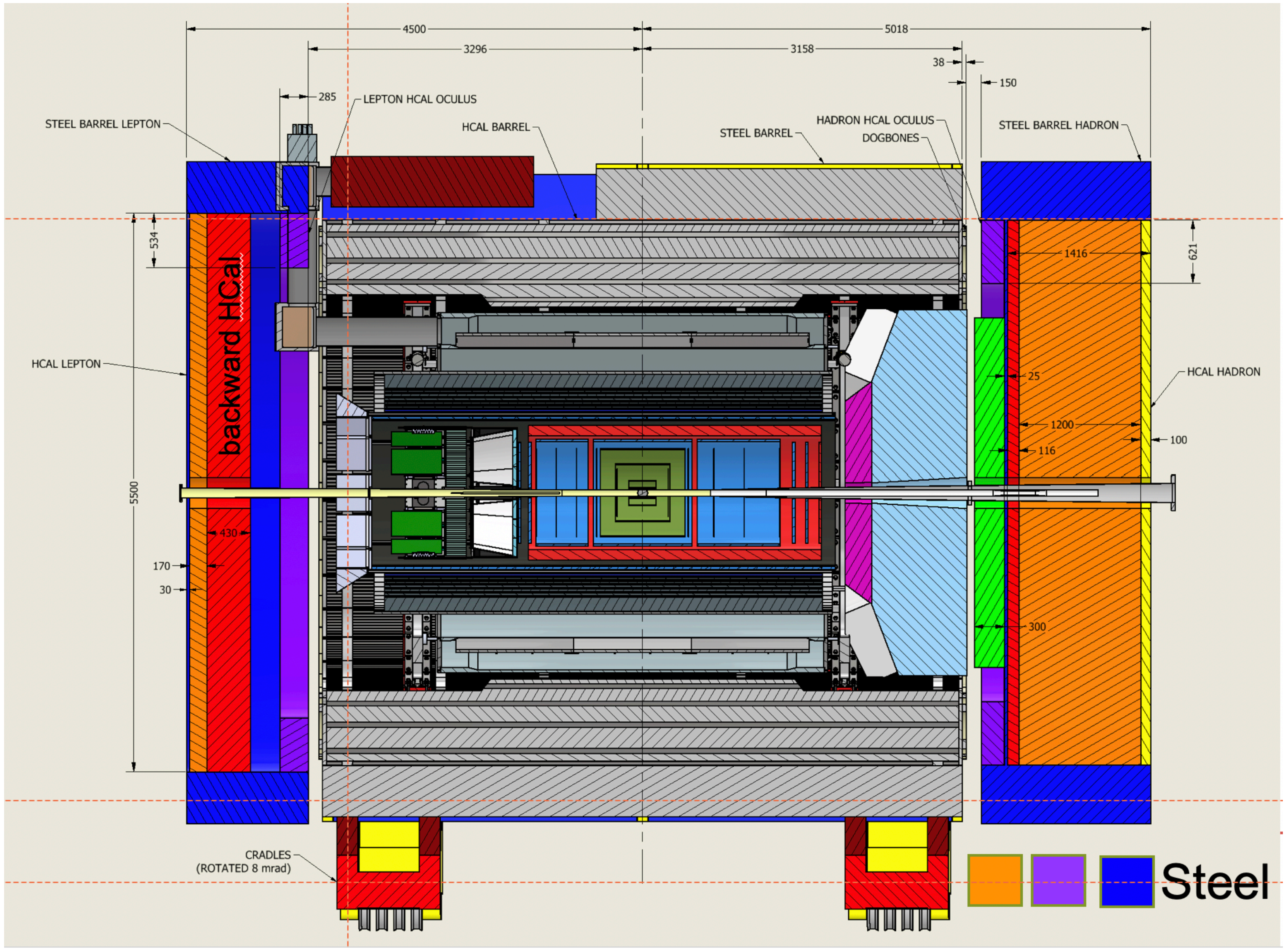
Temperature change in the last 50 years



Barrel-Region: high performance DIRC

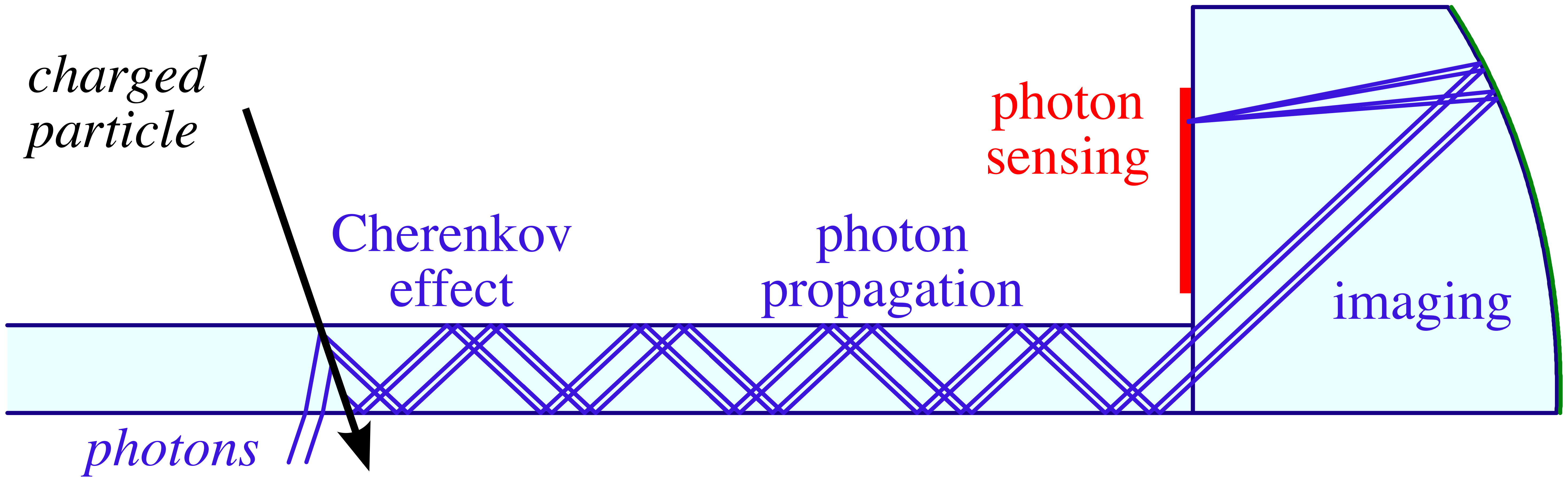
- There is not much room in the barrel for PID between the tracking layers and the EM calorimeter
- Need to cover up to *p* = 6 GeV/c
- There's no way around RICH detectors but need a short radiator plus readout?





Detection of Internally Reflected Cherenkov Light

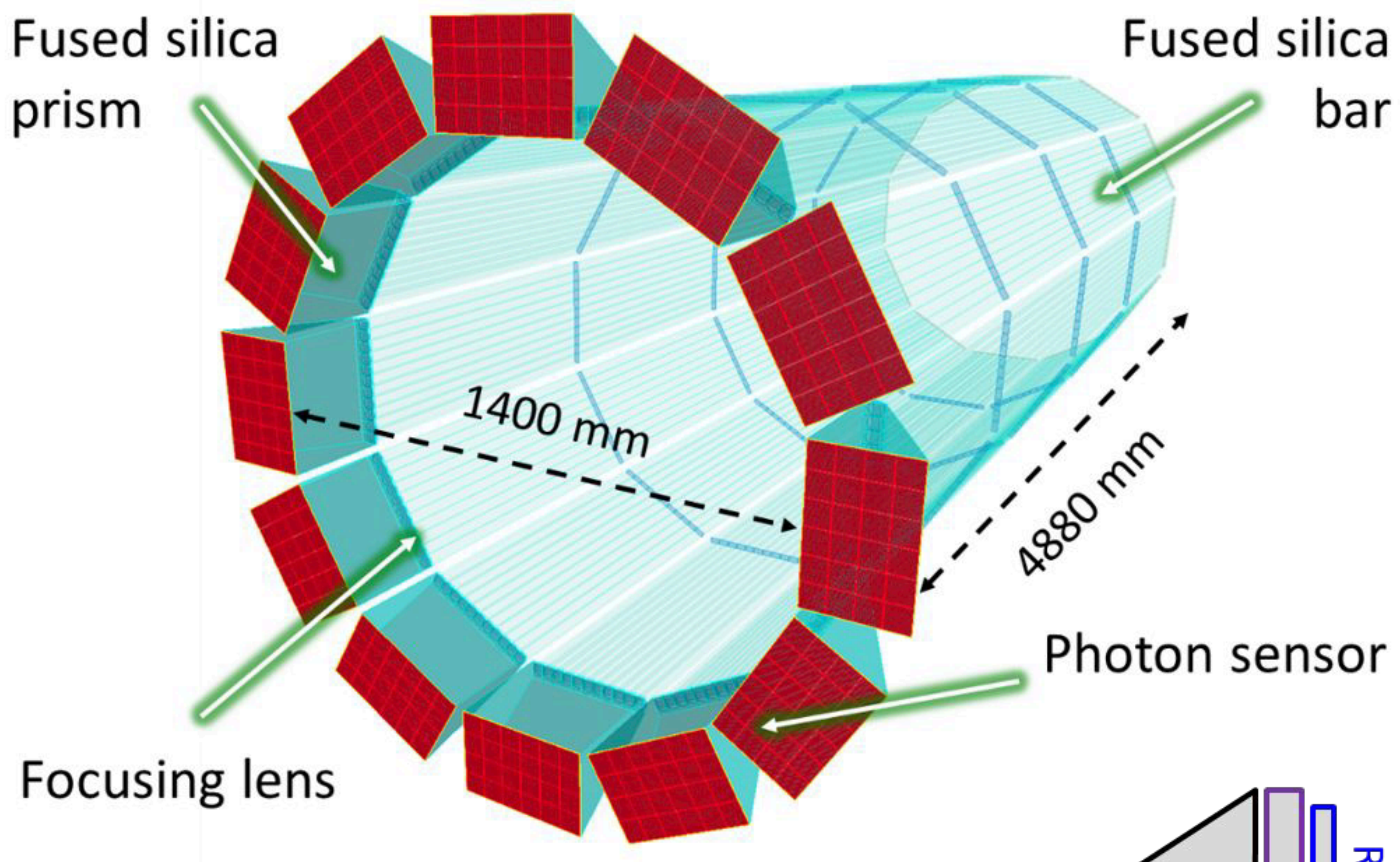
Concept:

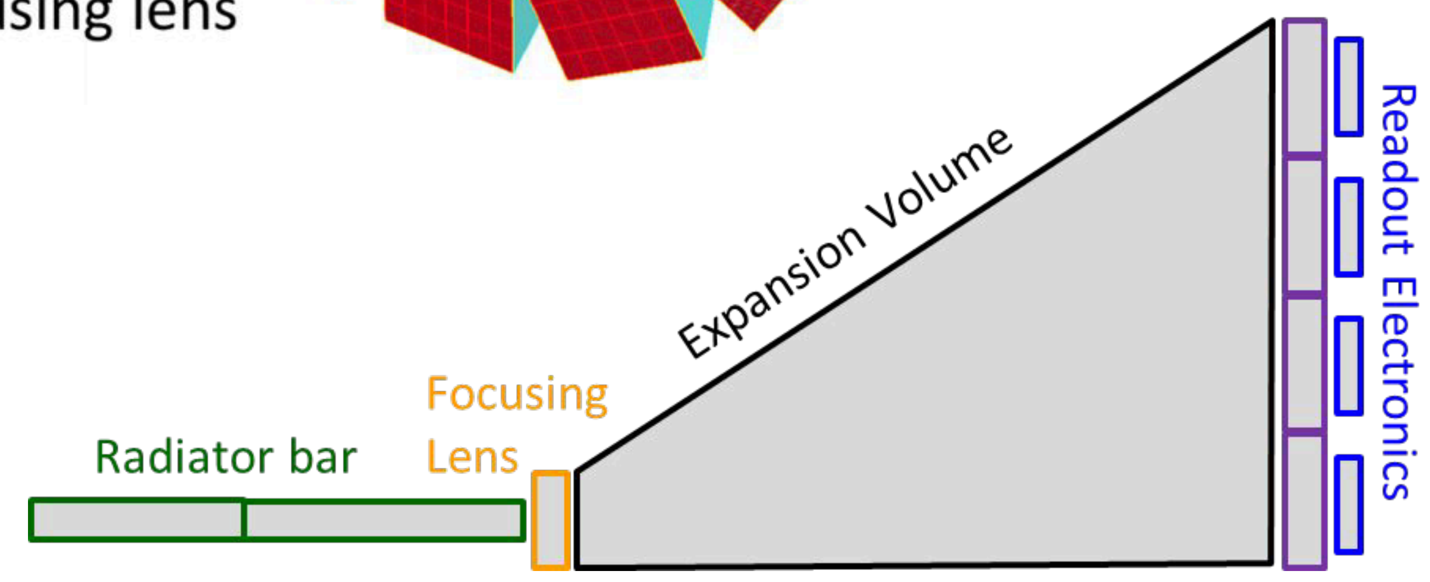


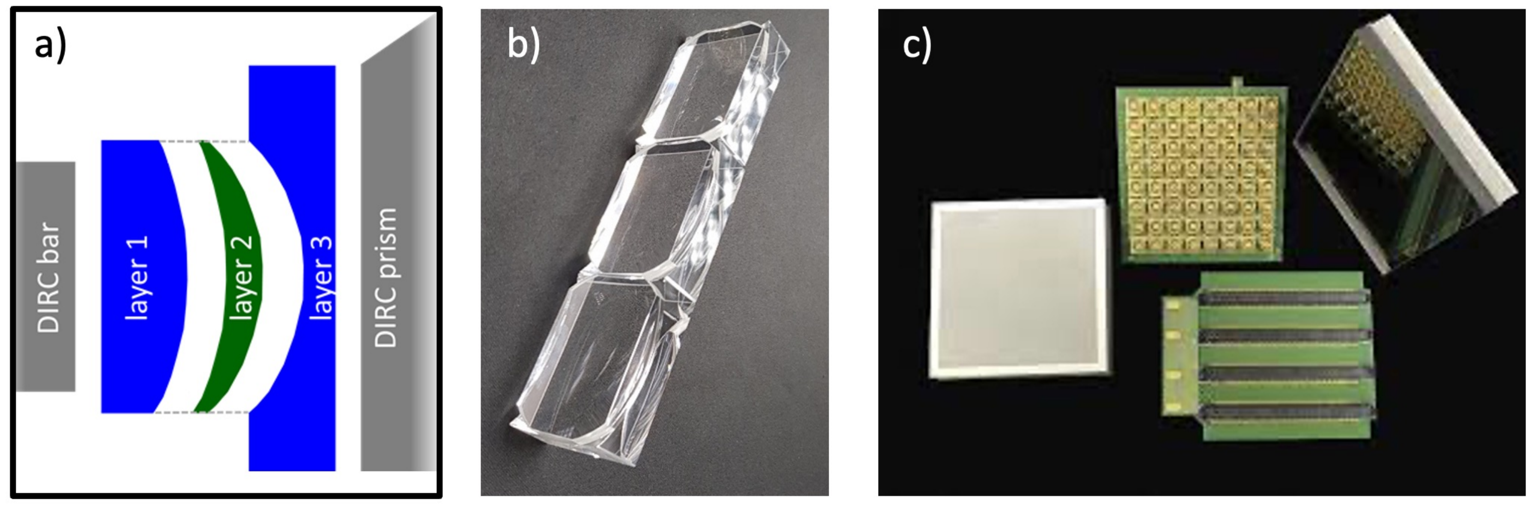
- Light is captured by total internal reflection inside the solid radiator
- With glass/quartz there are many $\mathcal{O}(100)$ photons even for thin bars
- Reaches the light sensors at the detector perimeter
- Precise rectangular cross section of the radiator preserving the angular information of the Cherenkov light cone.
- One example is the DIRC of the BaBar experiment at SLAC

hpDIRC Overview

- **Bars:**
  - Barrel radius: 762 mm, 12 sectors, 10 long bars per sector
  - Reuse bars from decommissioned BABAR DIRC, supplemented by new bars/plates
- **Lenses:**
  - Novel 3-layer spherical focusing lens essential for achieving the PID performance ePIC requires.
  - Lens design avoids the dramatic photon loss caused by air gap transitions in standard lens systems.
- **Prisms:**
  - Prism expansion volume is made of synthetic fused silica. D
  - Detector plane of each prism is covered by an array of 24 sensors
- **Sensors:**
  - In the baseline design of the hpDIRC, commercial microchannel plate photomultiplier tubes (MCP-PMTs) with a pore size of 10 μm or smaller were assumed with pixel size of 3.2 mm
  - HRPPDs (pfRICH) are an alternative

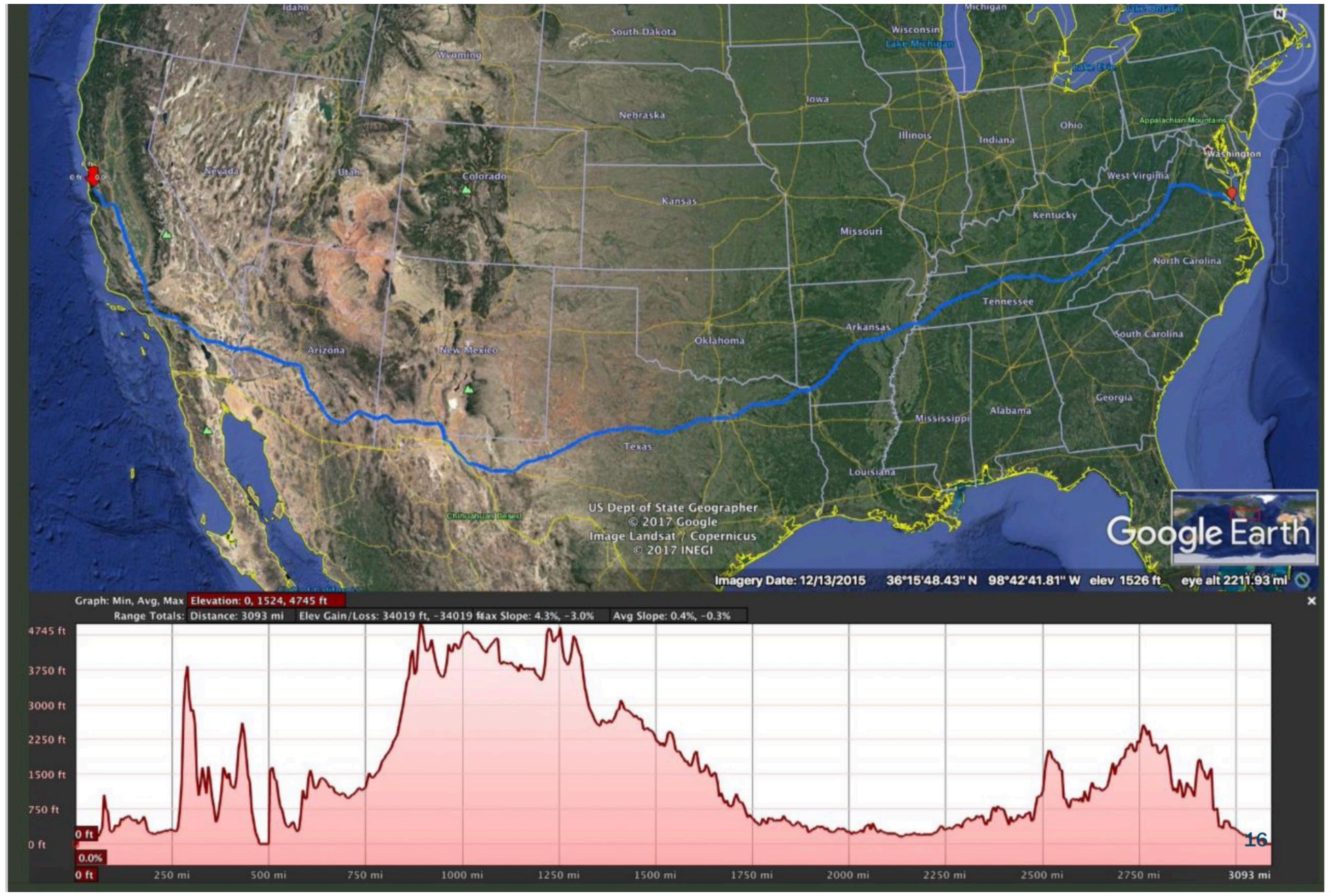


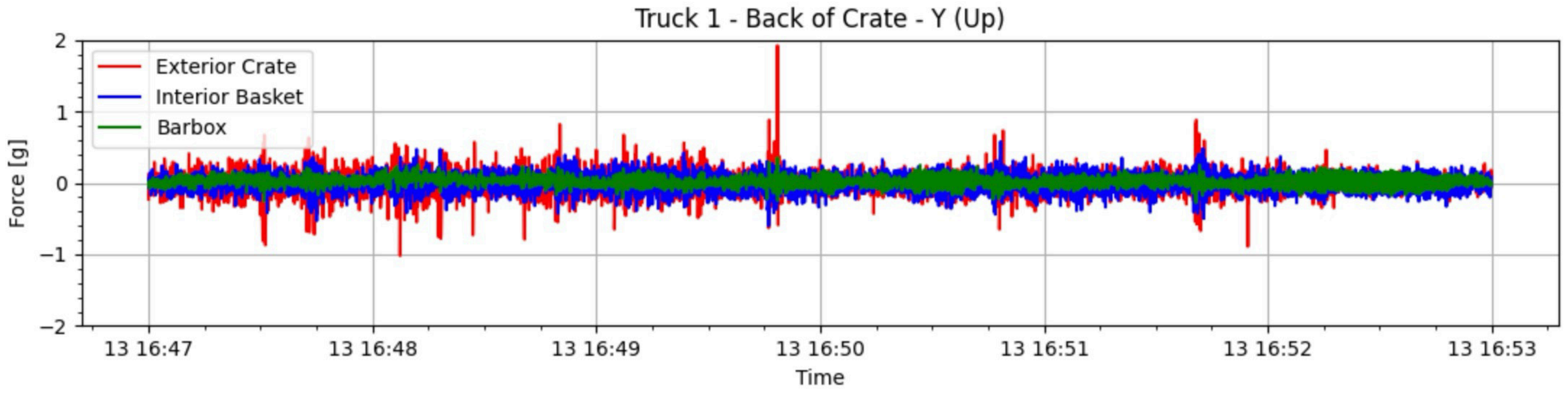


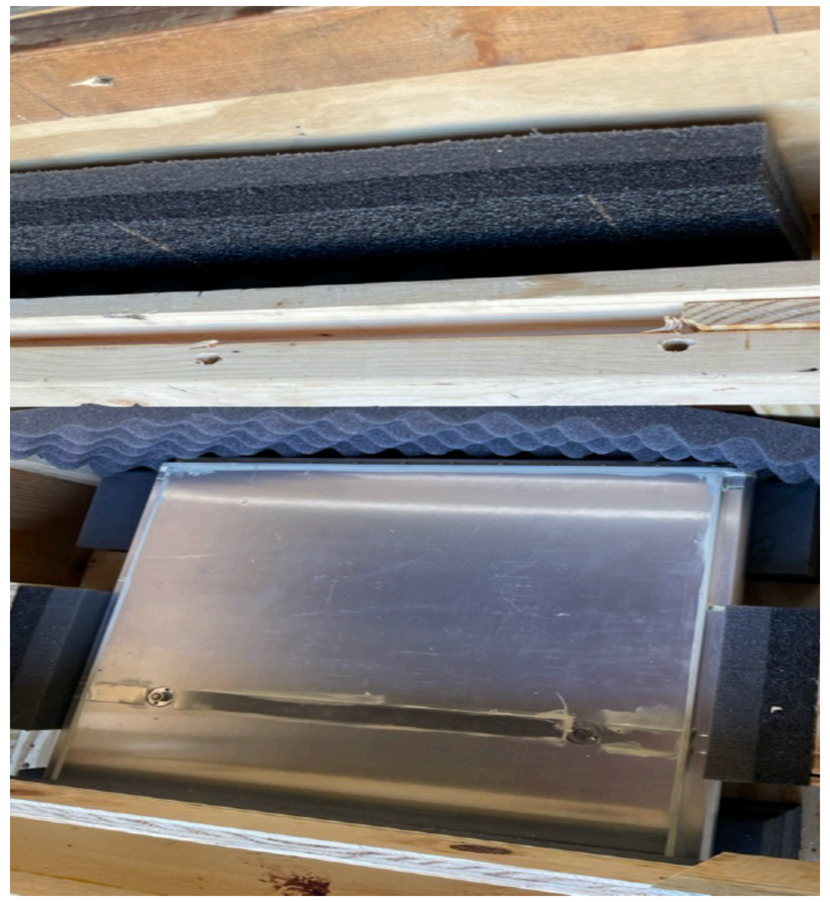


BaBar DIRC Bar Reuse

- Successful transport of 8 DIRC bar boxes in April 2024
  - Low attitude road from SLAC, CA to JLab, VA
  - Shocks absorbing foam
  - Hydraulic shocks
  - Air shocks
  - Shock absorbing donuts
  - Air-ride, temperature control trucks
  - Goal: Keep shocks on Bar box below 1g







Bars are Safe (Sigh!)

- Bar boxes disassembled into individual bars at JLab
  - Aluminum covers will need to be ” opened”, glue joints between bars decoupled
- Optical quality of bars after disassembly will be evaluated in QA DIRC lab
- QA Lab will consist of:
- Cleaning/inspection station
- Darkroom with laser setup to measure quality of DIRC bars
- Storage (long and short-term)
- Reflection coefficient measurement to evaluate surface quality

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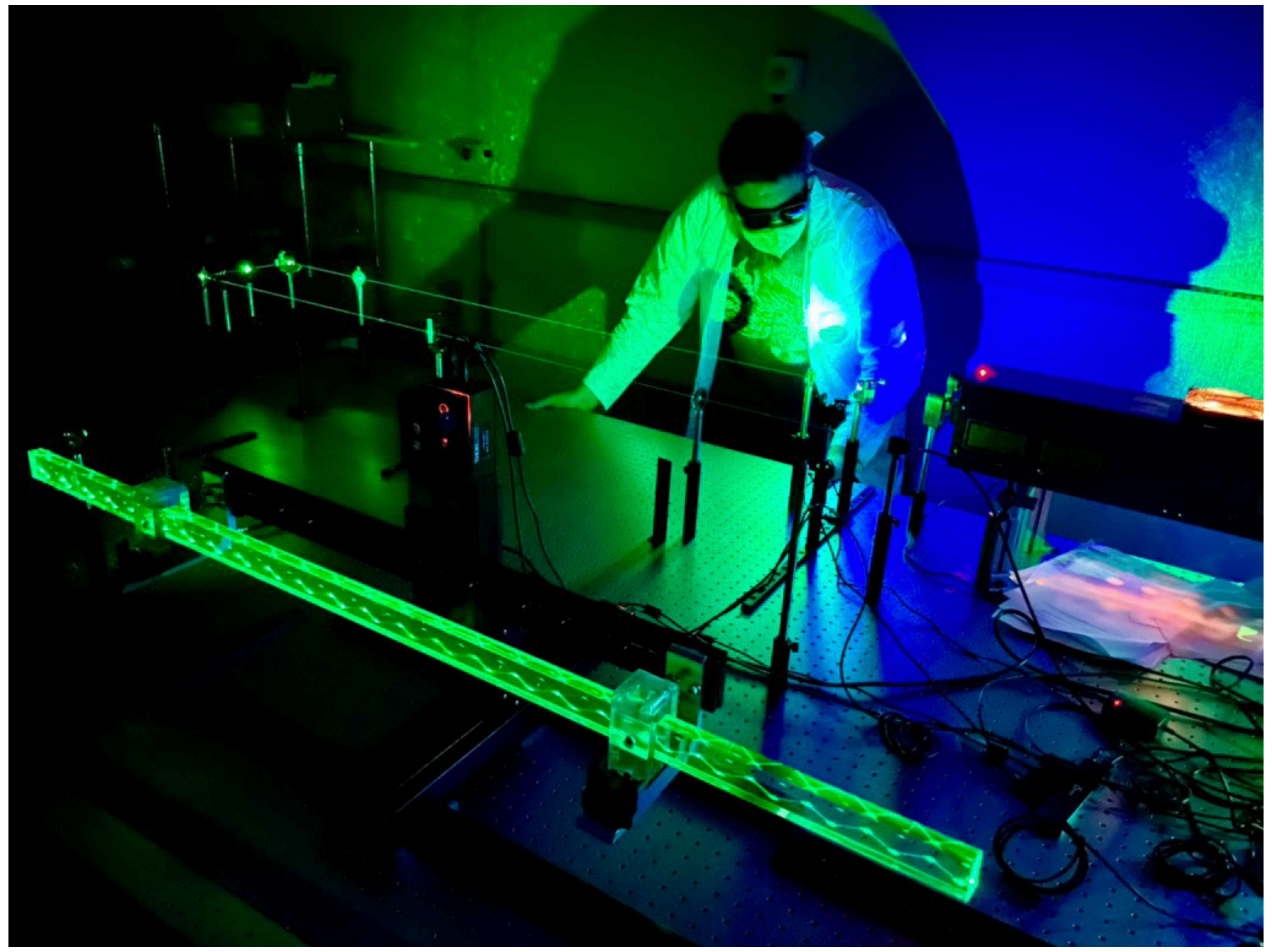

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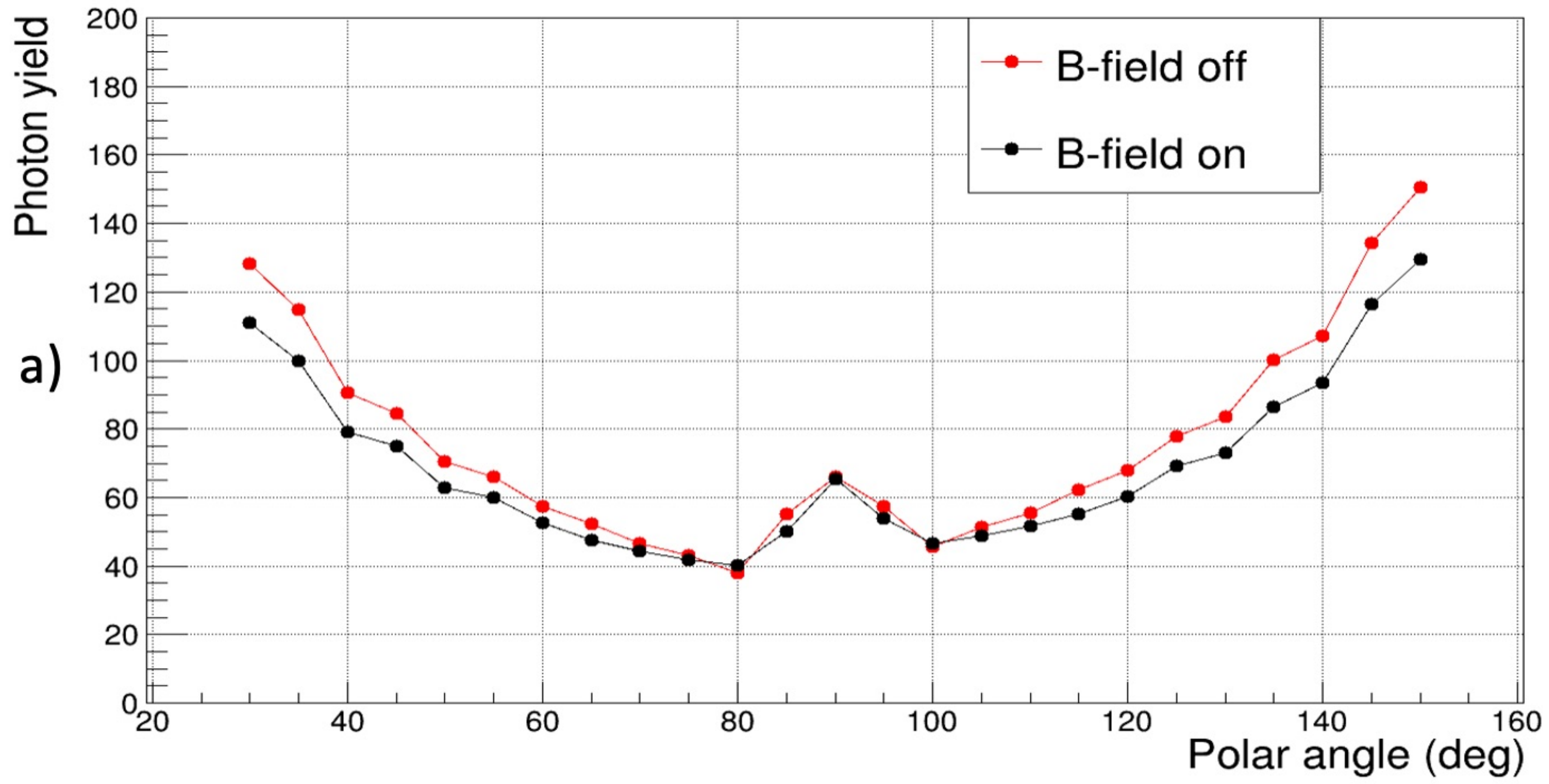
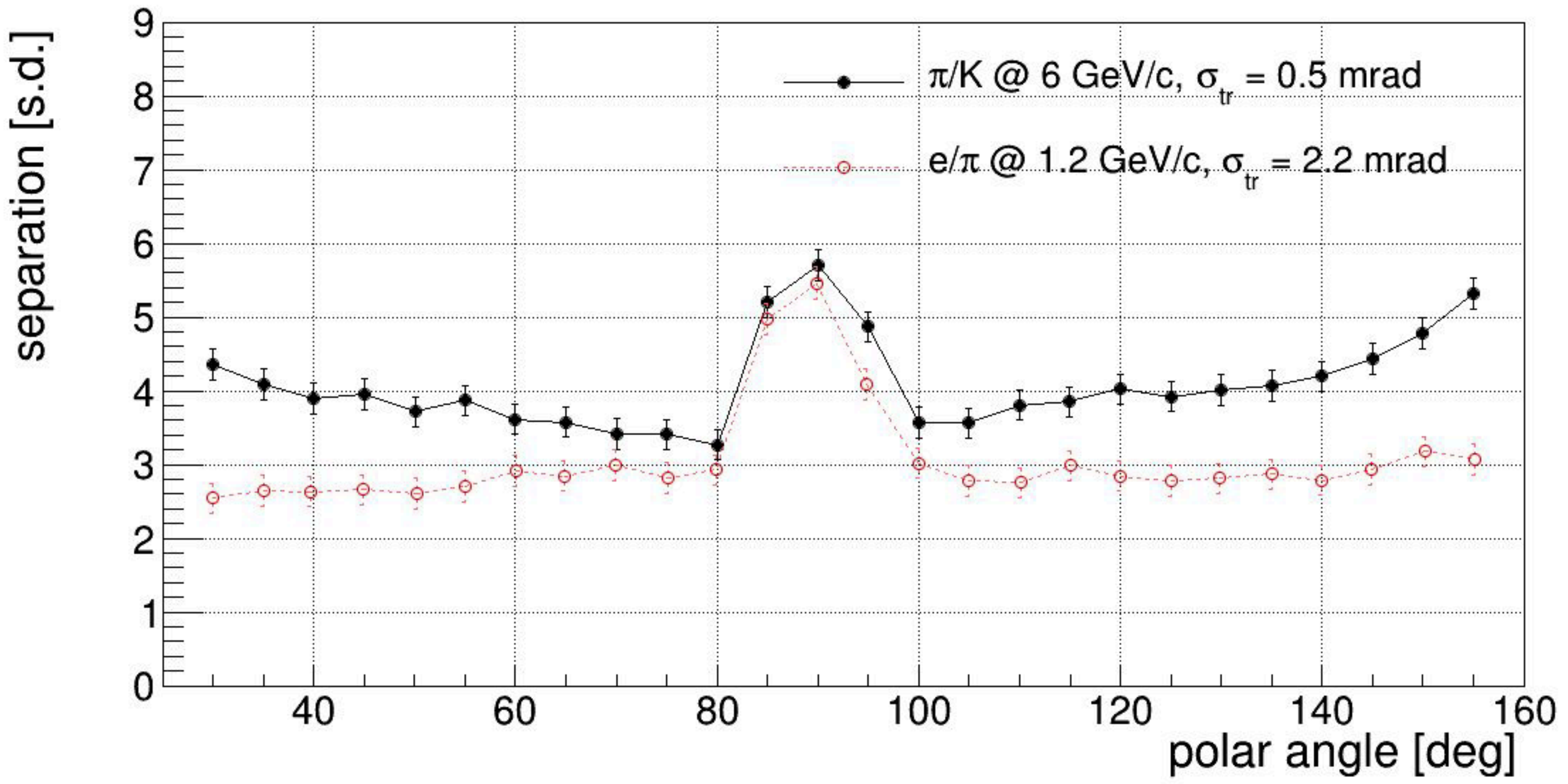
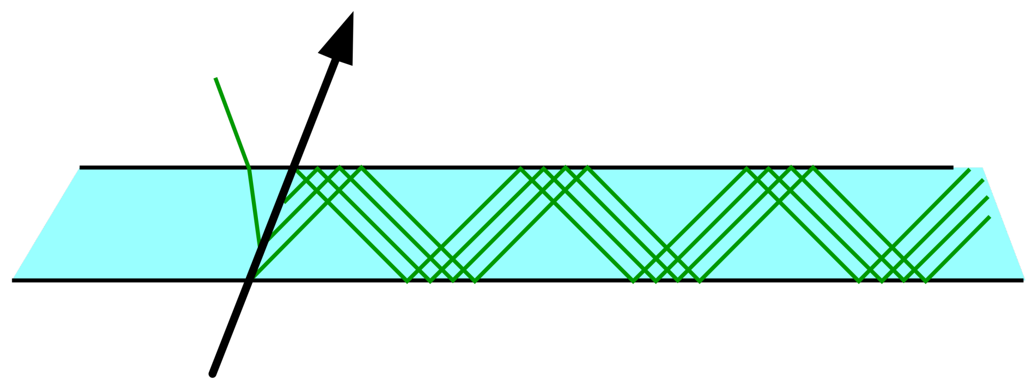
hpDIRC Performance



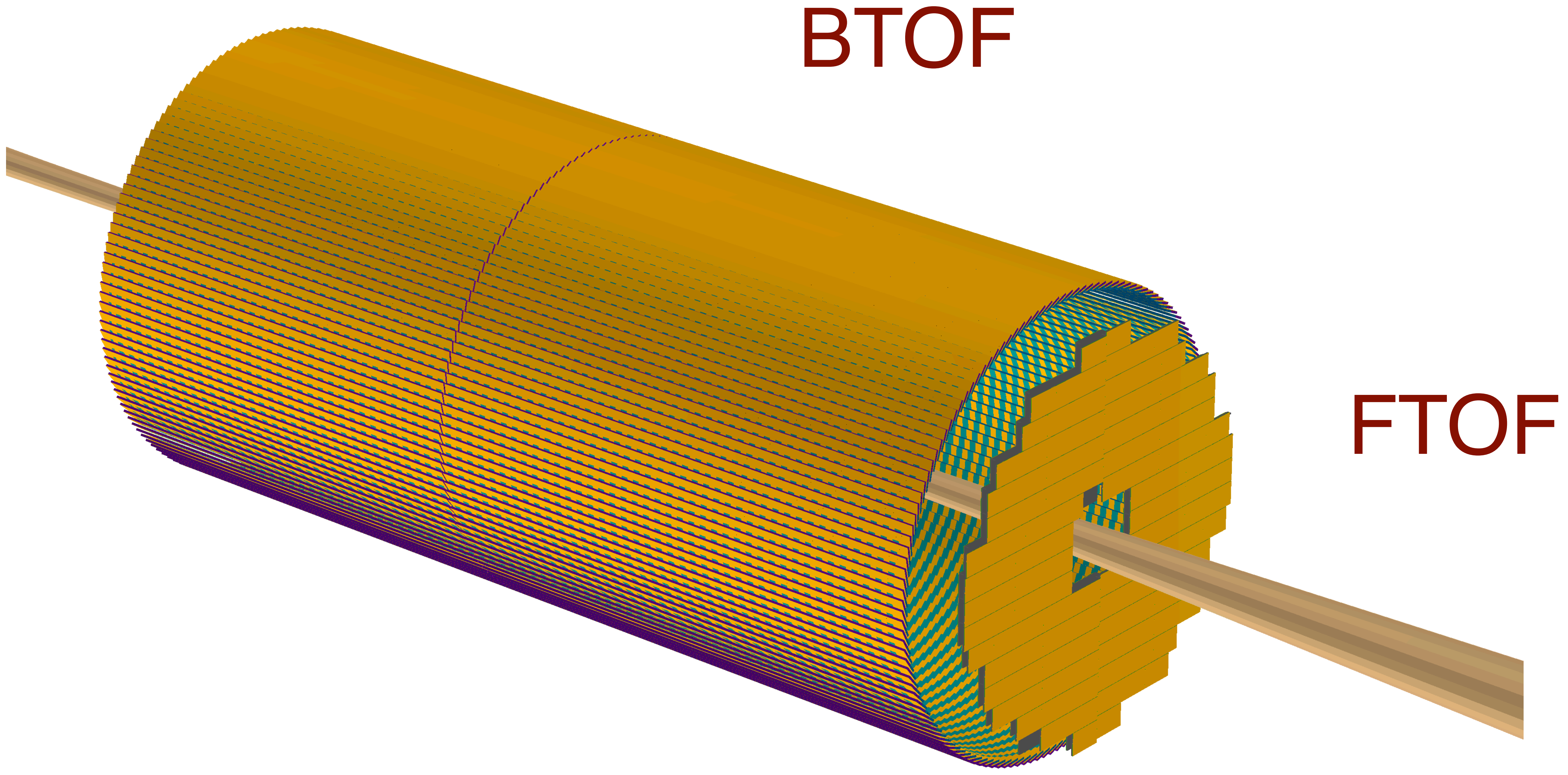


- Simulations show promising performances.
- Critical at the end is the quality of the pointing accuracy of the track into the bar which is needed to reconstruct the crossing and PID



Time-of-Flight - What, Where, When?

- Early detectors had no ToF systems included
- The Yellow Report did not investigate the relevance of low-p
- Potential use:
  - Extending measurement of $\rho \to \pi^+\pi^-$, $\phi \to K^+K^-$, $\Lambda_c^+ \to pK^-\pi^+$
- Originally ToF was proposed in 4π but had to eliminated in the backward (e-going direction) since to's heat dissipation and material thickness would have jeopardized the high precision EM calorimeter.
- Now forward (h-going) and in barrel



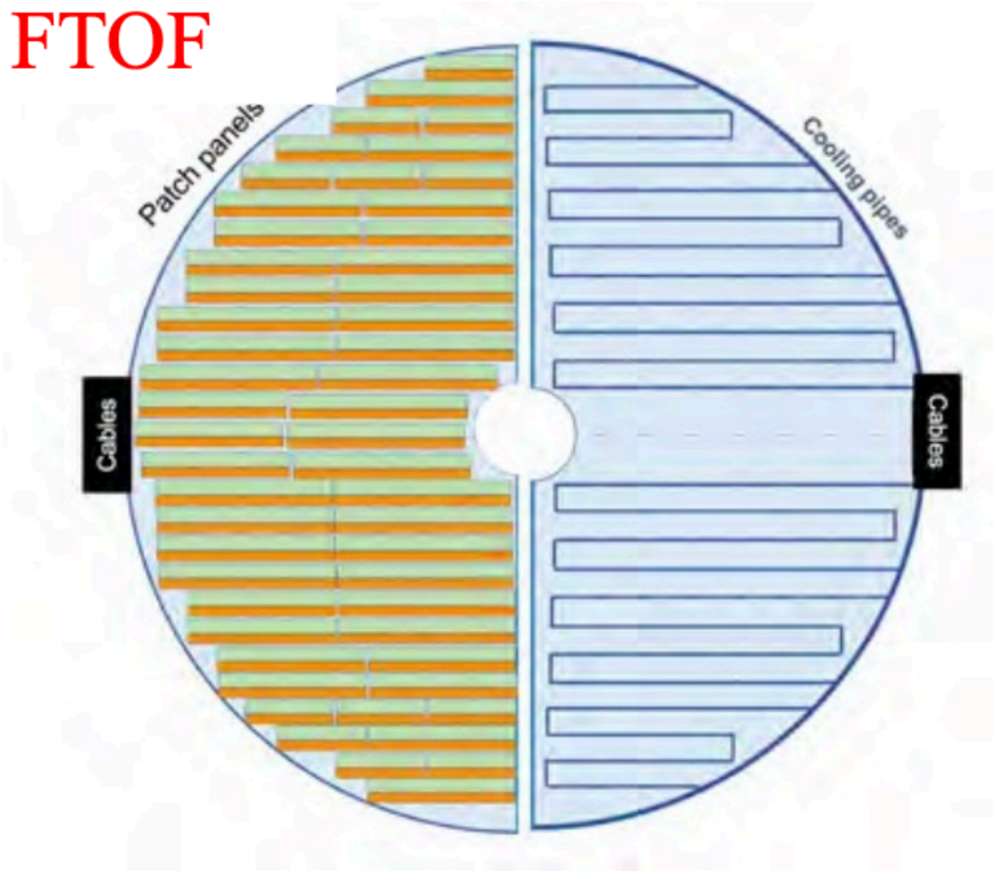
ToF Overview

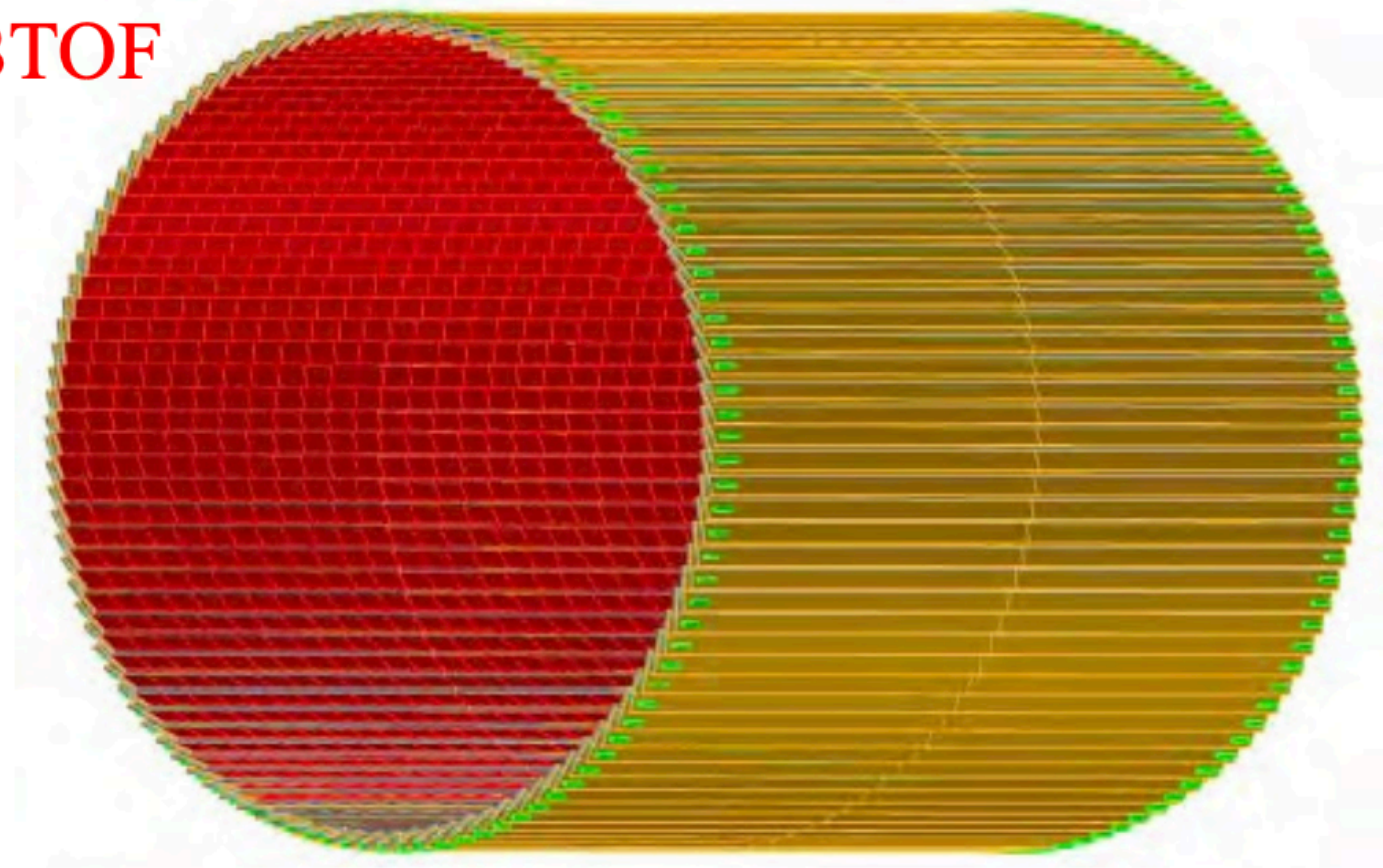
BTOF

- covers mid-rapidity $-1.33 < \eta < 1.74$
- Strip-type AC-LGAD sensors are used
  - reduces material (less cooling needed)
- Placed at R = 64 cm

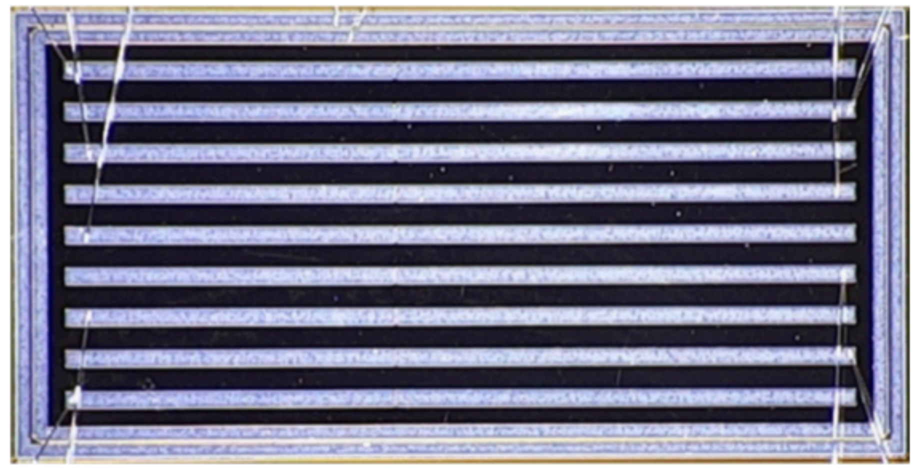
FTOF

- covers $1.84 < \eta < 3.61$
- Strip-type AC-LGAD sensors are used

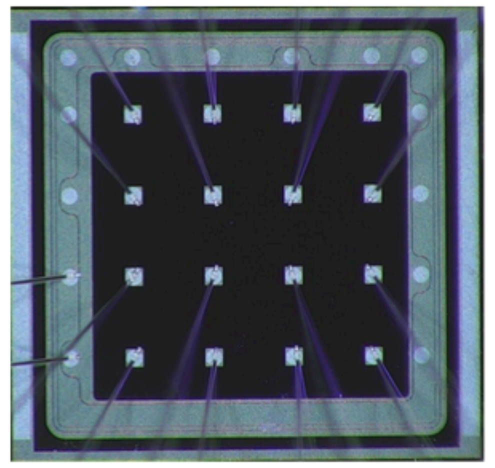




HPK Strip Sensor (4.5x10 mm^2)



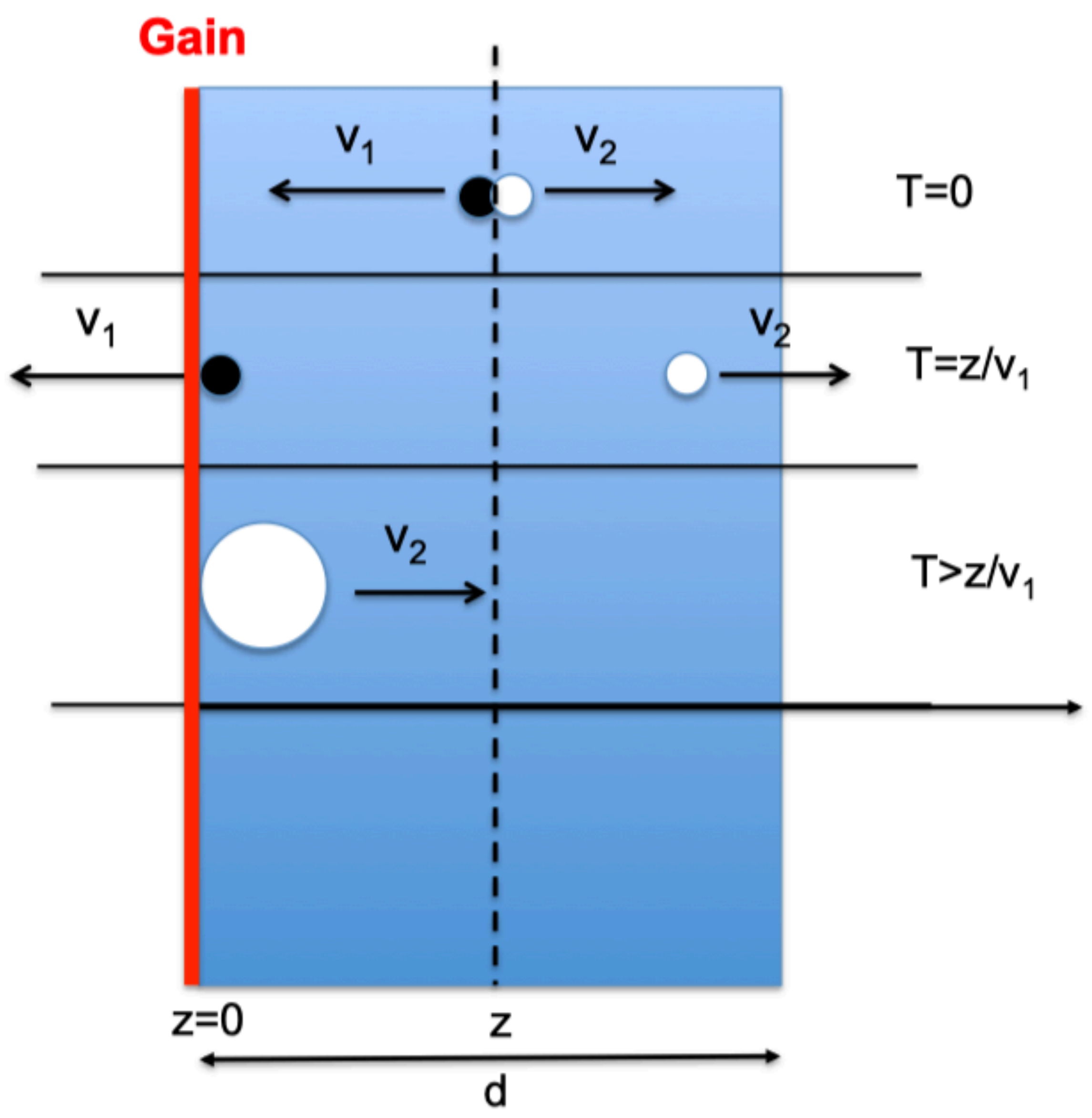
HPK Pixel Sensor (2x2 mm^2)



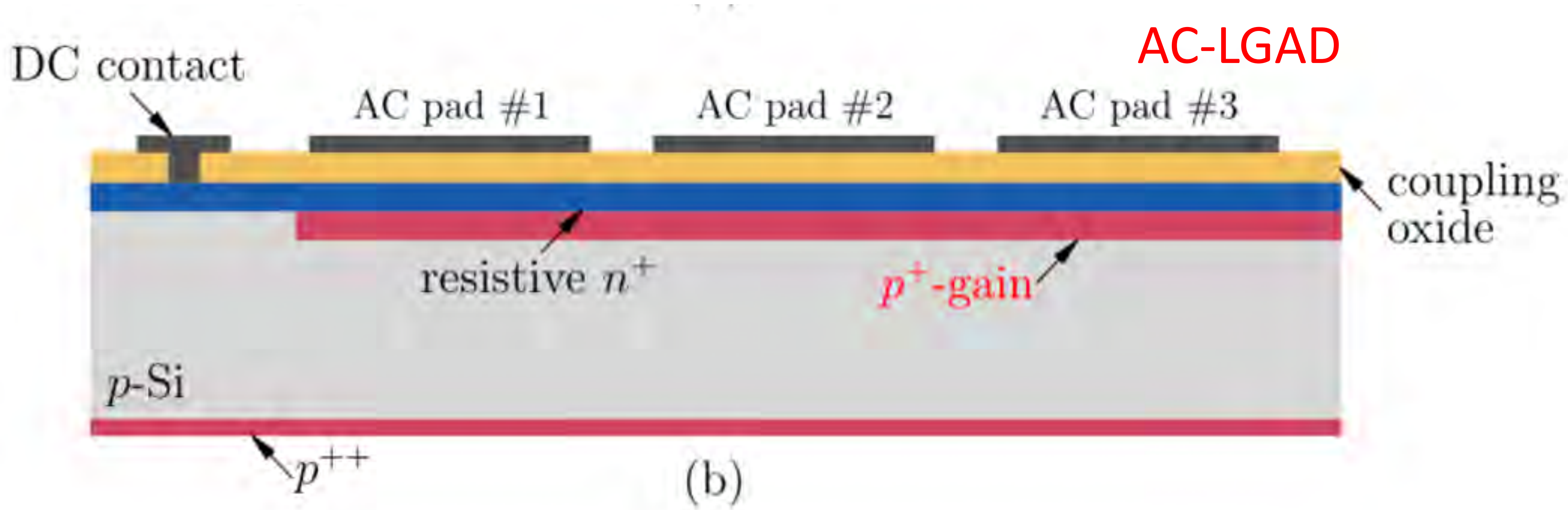
Subsystem	Area (m^2)	dimension (mm^2)	channel count	timing σ_t (ps)	spatial σ_x (μm)	material budget (X/X_0)
Barrel TOF	12	0.5*10	2.4M	35	30 ($r \cdot \phi$)	3%
Forward TOF	1.1	0.5*0.5	3.2M	25	30 (x, y)	5%

ToF with Si Sensors: LGAD

- Low Gain Avalanche Diode Sensor (Hybrid)
  - Issues: fill factor, heat



- How it works:
  - An e-h pair is produced at position z
  - The electron arrives at z=0 at time $T=z/v_1$
  - The electron multiplies in high field in layer at z=0
  - The holes move back to z=d inducing the dominant part of the signal

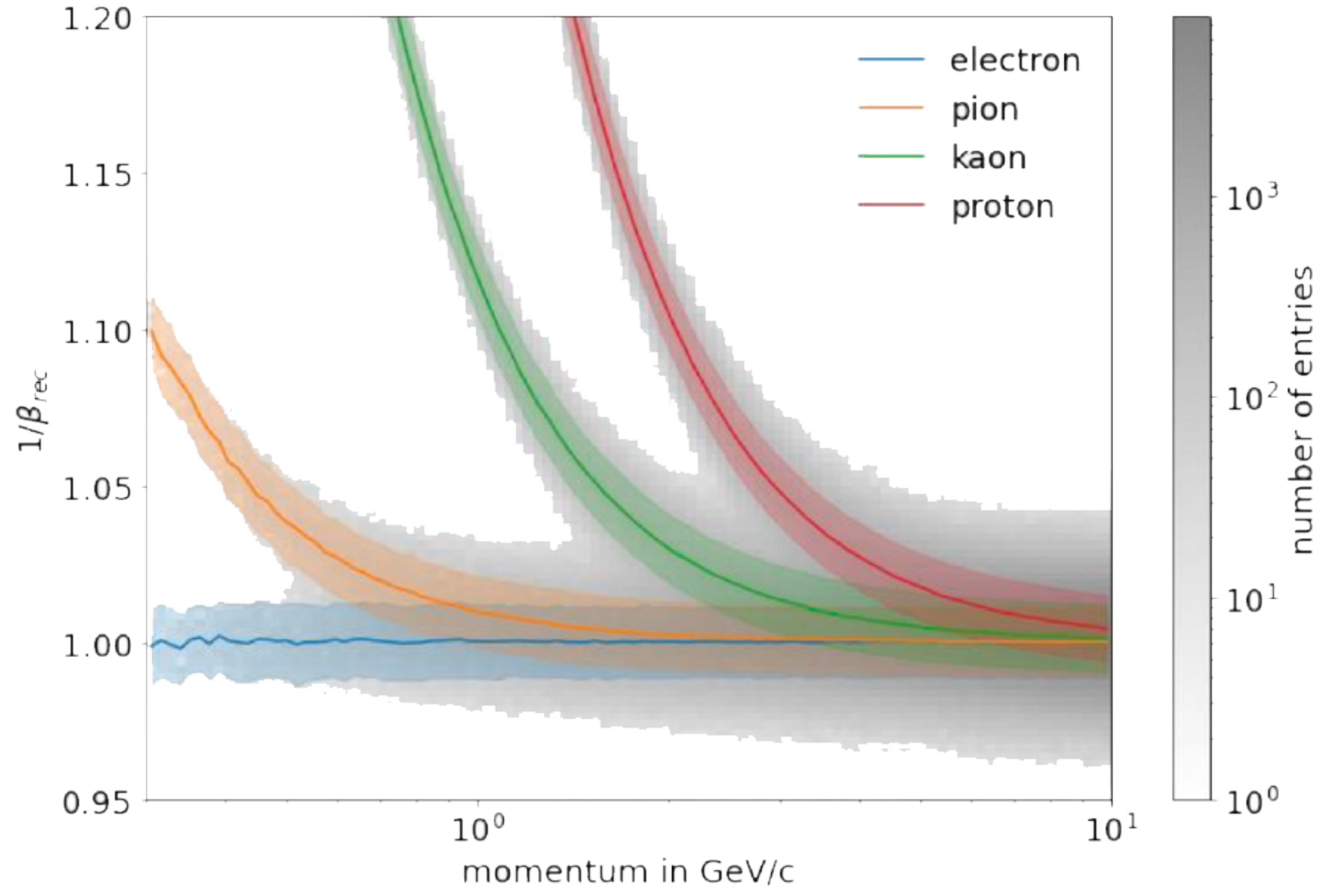


Time ?

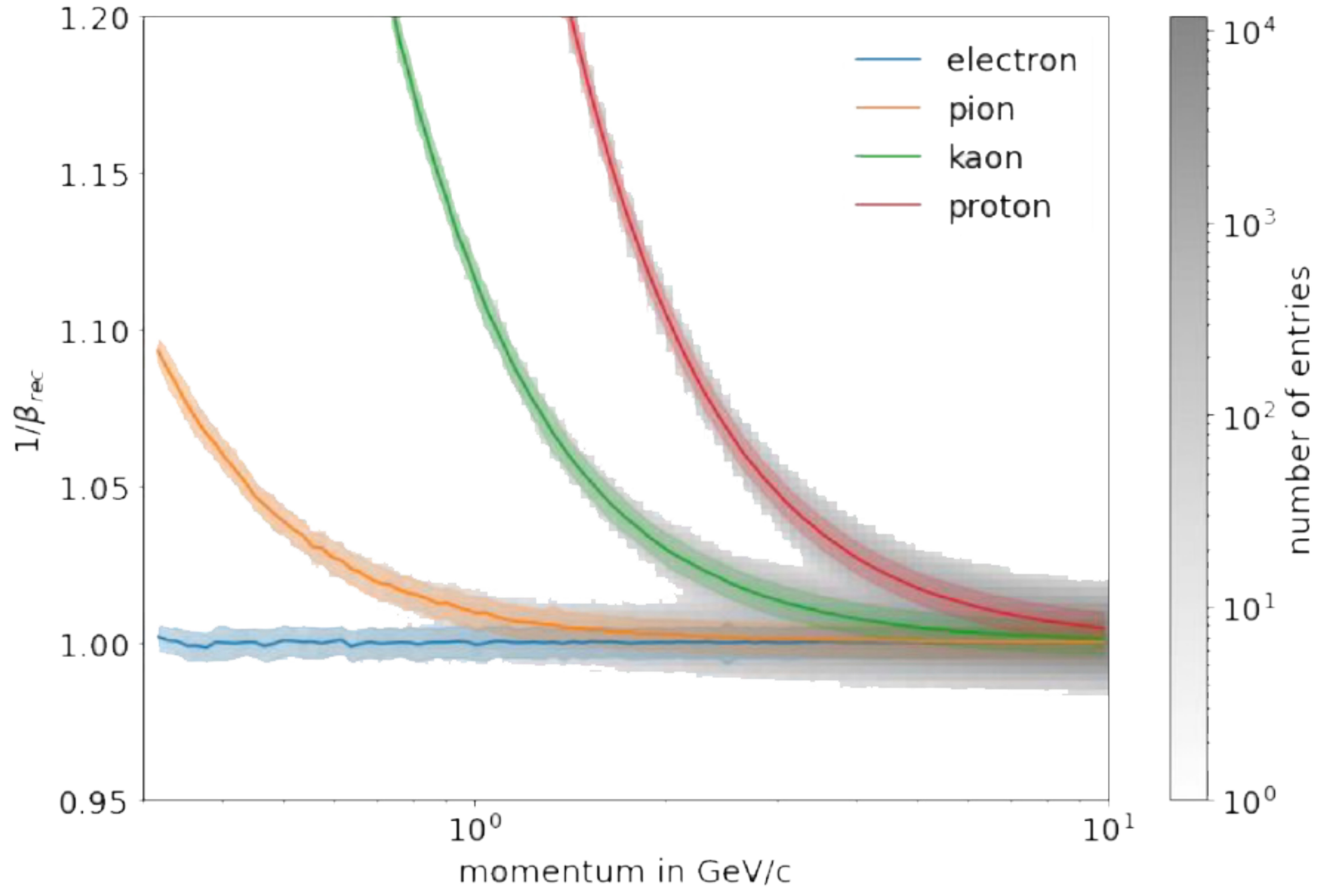
- Sensor measures some time t_{measured} with good precision ~30ps
- To determine the time of flight we need also a start time t_0
- Time of flight is $\Delta t = t_{\text{measured}} - t_0$
- How to get t_0?
  - Bootstrapping when 4π coverage (think about how?)
    - works in ePIC HRPPDs in pfRICH provide excellent t_{measured} as well
  - Use identified scattered electron (v = c plus path length)
    - works for dominant e' regions (barrel/ToF and backward/HRPPD)
  - use beam crossing (clock, beam info, crab crossing) - tricky
    - works in simulations - real life?
- Best precision t_{measured} doesn't help if t_0 resolution is not great.
  - Expect at best δt_0 ~ 20ps

TOF Performance

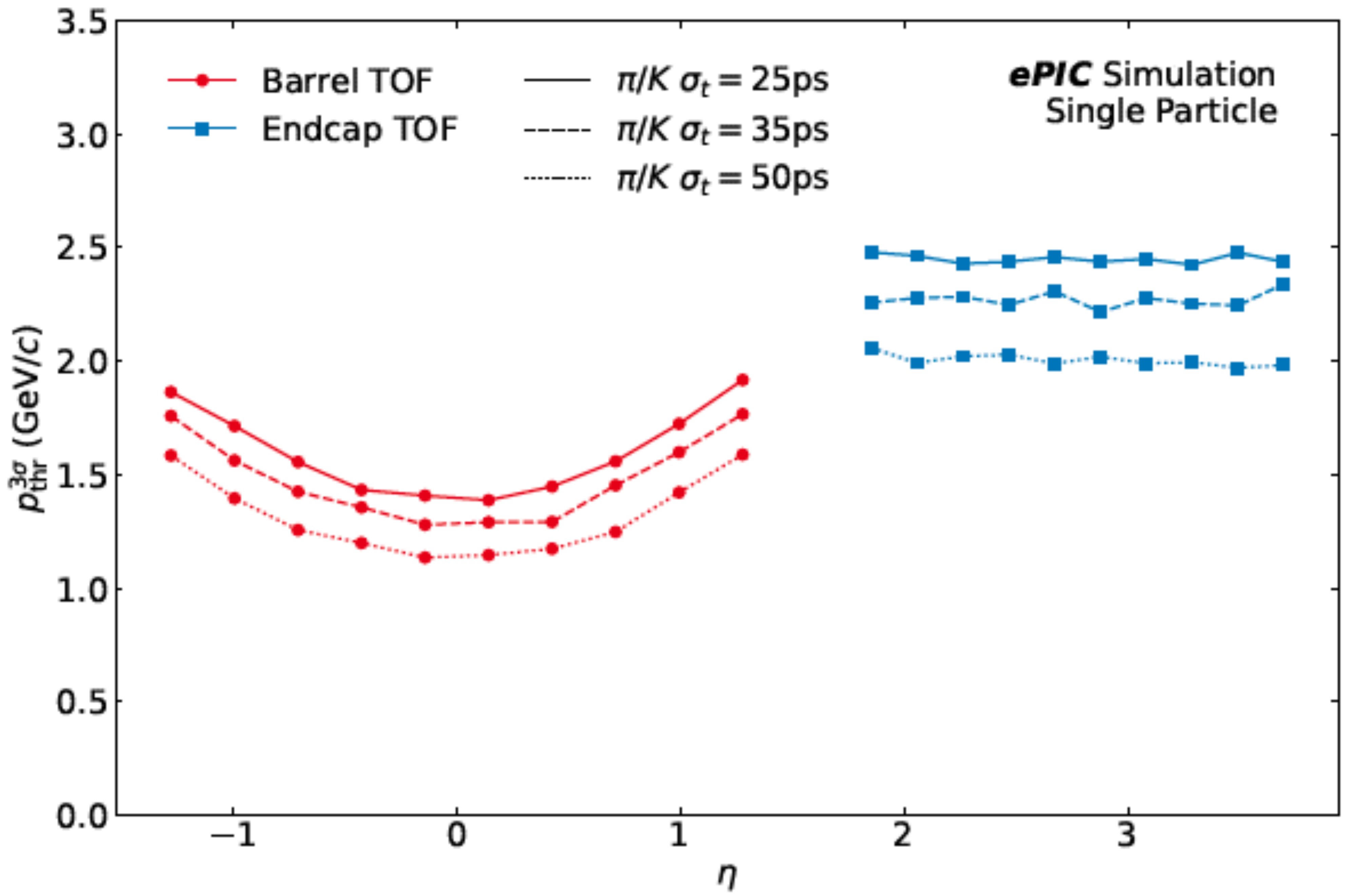
- Barrel Region
  - e/pi up to 0.5 GeV/c
  - pi/K up to 1.9 GeV/c
  - K/p up to 3.1 GeV/c



- Endcap Region
  - e/pi up to 0.8 GeV/c
  - pi/K up to 2.7 GeV/c
  - K/p up to 4.6 GeV/c



- Simulations show promising performances at low-p
- Goof overlap with other PID systems



Summary

If you only carry 3 lessons back home with you I succeeded:

- ePIC covers an impressive range ($-3.5 < \eta < 3.5$) with PID detectors more than any collider experiment past or present
- Dominant technology are Cherenkov detectors (pfRICH, dRICH, hpDIRC) using gas, aerogel, and glass.
- They are augmented by fast Si sensors (AC-LGAD) in ToF detectors for low-p PID
- They all provide key contribution to the EIC physics program