Particle Detectors and the ePIC Experiment
Lecture 2: EIC Detectors and ePIC

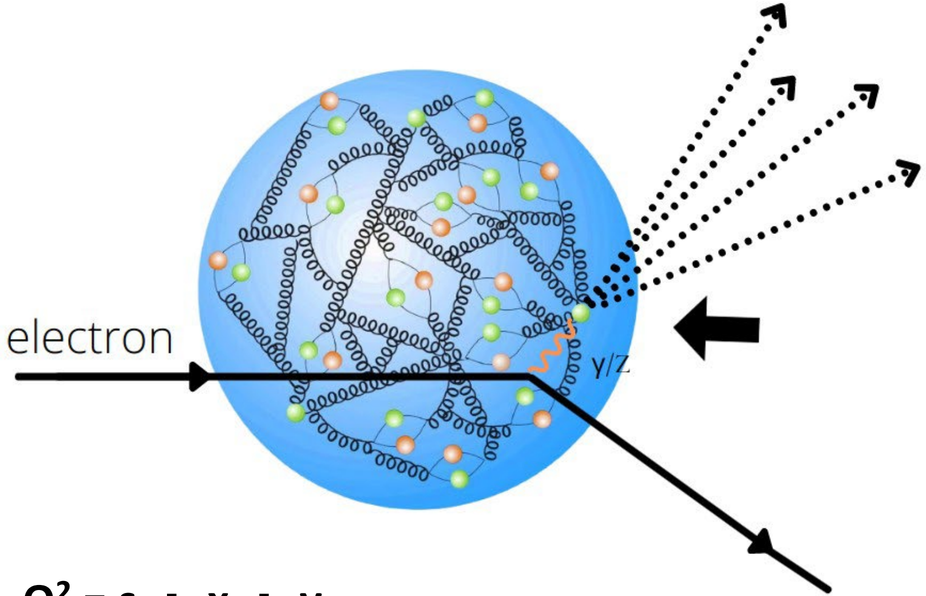
John Lajoie

2023 CFNS-CTEQ Summer School on
Physics of the Electron-Ion Collider

Outline of Lectures

- Lecture 1: Particle Physics Detectors
  - Interaction of Particles with Matter
  - Tracking Detectors
  - Calorimetry
  - Particle Identification
- Lecture 2: The ePIC Detector and the EIC
  - Detector requirements at the EIC
  - The design of the ePIC Detector
  - Interaction Region Considerations

How Do You Study the Structure of Matter?

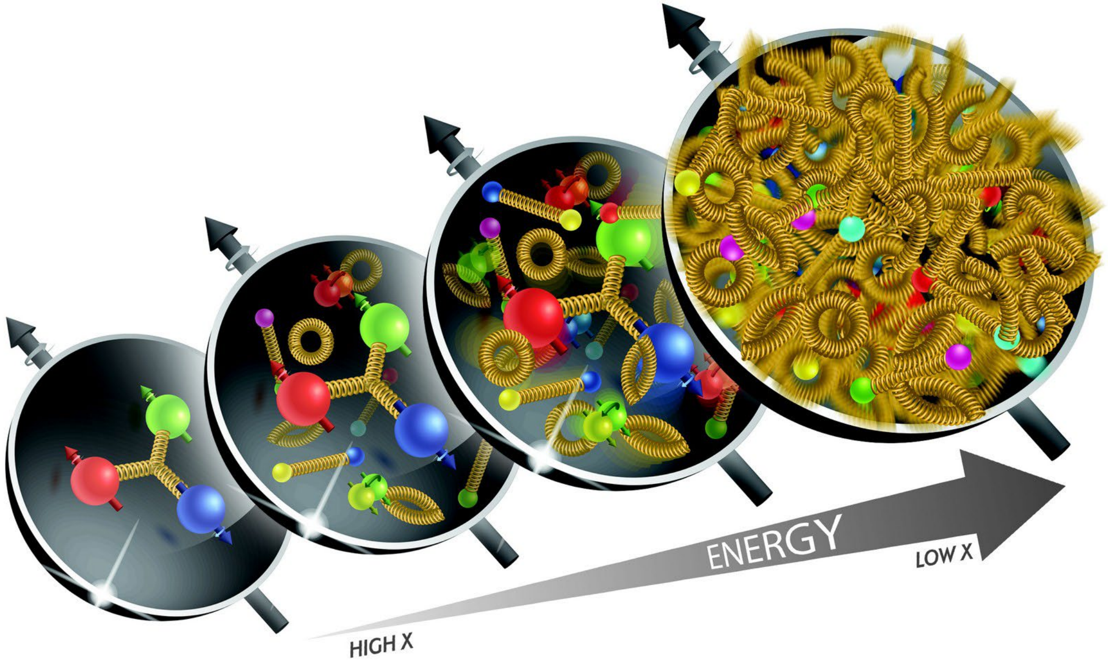


$Q^2 = s \cdot x \cdot y$

Q^2 – resolution power (virtuality of the photon)
s – center-of-mass energy squared
x - the fraction of the nucleon's momentum carried by the struck quark
y – inelasticity

Deep Inelastic Scattering: e + p → e' + X

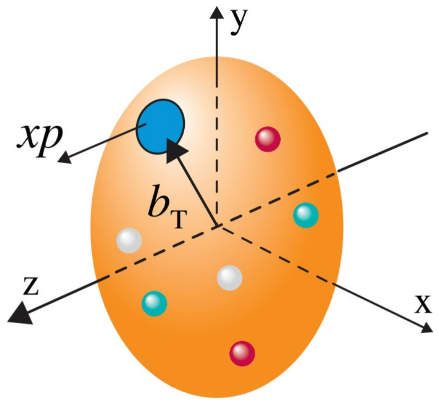
● **Golden process to probe nucleons and nuclei** with electron beams providing the unmatched precision of electromagnetic interactions



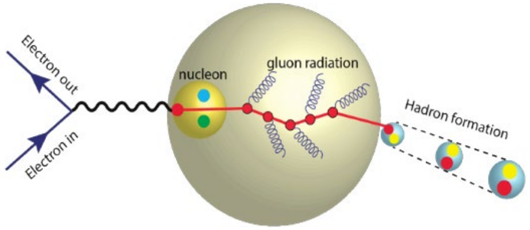
Center-of-mass energy √s: 20 – 140 GeV

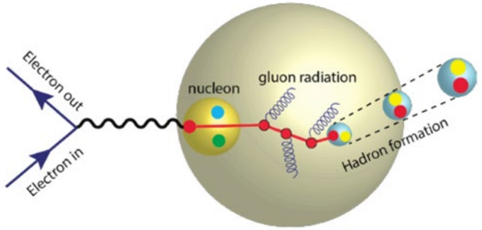
● Explore QCD landscape over large range of resolution (Q^2) and quark/gluon density (1/x)

The EIC Science Mission

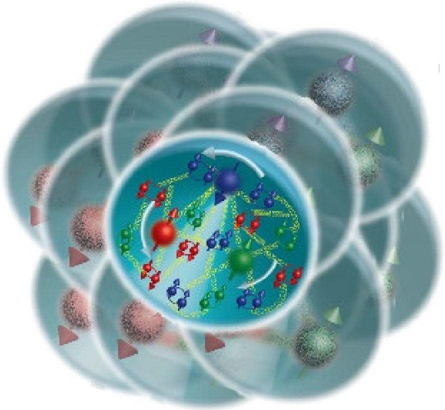


- How do the **nucleon properties like mass and spin emerge** from quarks and their interactions?
- How are the sea quarks and gluons, and their spins, distributed in space and momentum inside the nucleon?



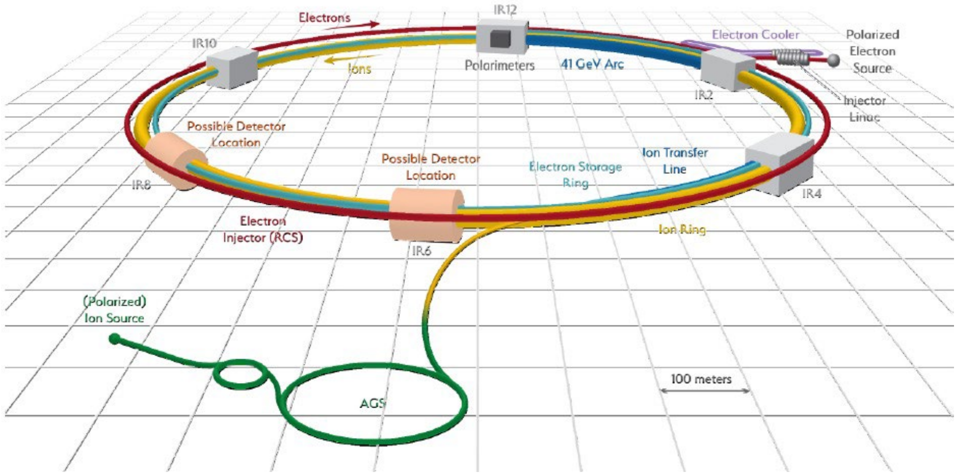


- In what manner do color-charged quarks and gluons, along with colorless jets, interact with the nuclear medium? And how do the confined hadronic states emerge from these quarks and gluons?
- What is the mechanism through which quark-gluon interactions give rise to nuclear binding?

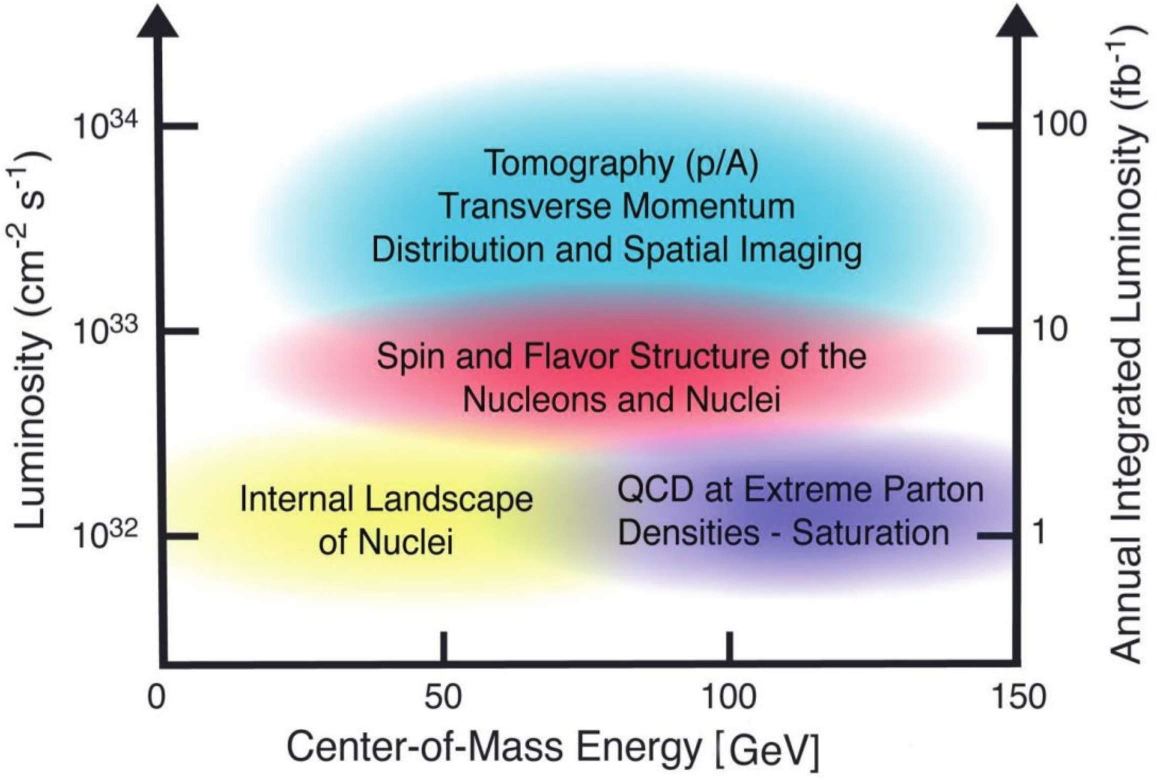


- What impact does a high-density nuclear environment have on the interactions, correlations, and behaviors of quarks and gluons?
- Is there a **saturation point** for the density of gluons in nuclei at high energies, and does this lead to the **formation of gluonic matter** with universal properties across all nuclei, including the proton?

EIC Machine Parameters

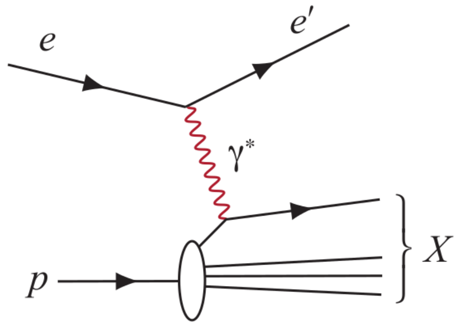


- Center of mass energy: 20 – 140 GeV
  - Electrons: 2.5 – 18 GeV
  - Protons: 40 – 275 GeV (ions: Z/A x E_{proton})
- Luminosity: 10^{34} /cm^2/sec
- Polarization: <70% (both electron and ion)
- Ion Species: proton - Uranium
- Detectors: up to 2 interaction regions with (almost) complete coverage



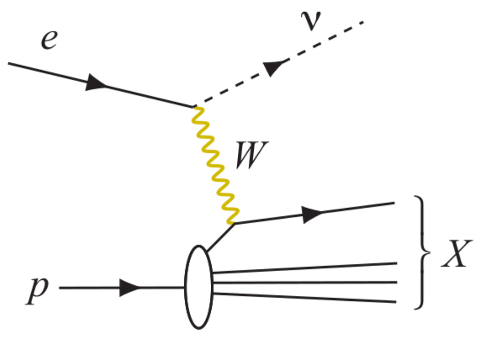
Experimental Processes to Access EIC Physics

DIS event kinematics - scattered electron or final state particles (CC DIS, low y)



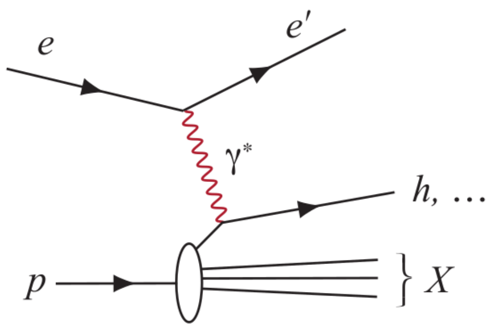
Neutral Current DIS

- Detection of scattered electron with high precision - event kinematics



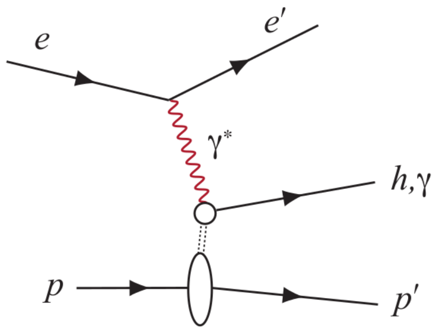
Charged Current DIS

- Event kinematics from the final state particles (Jacquet-Blondel method)



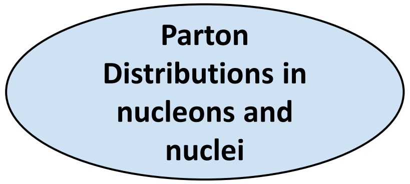
Semi-Inclusive DIS

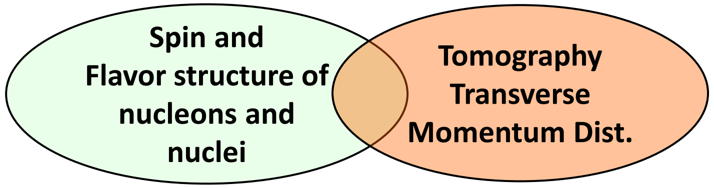
- Precise detection of scattered electron in coincidence with at least 1 hadron

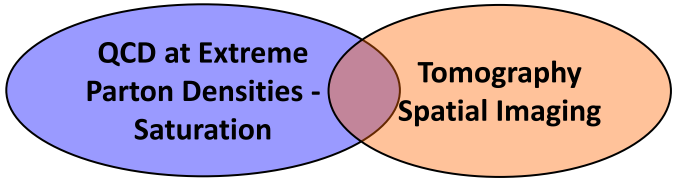


Deep Exclusive Processes

- Detection of all particles in event





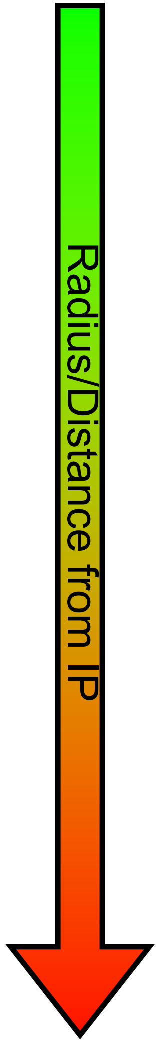


The EIC Yellow Report

The EIC yellow report was an enormous community exercise to quantify the *physics and detector requirements* to be able to purse EIC physics.

https://arxiv.org/abs/2103.05419

EIC Detector Requirements



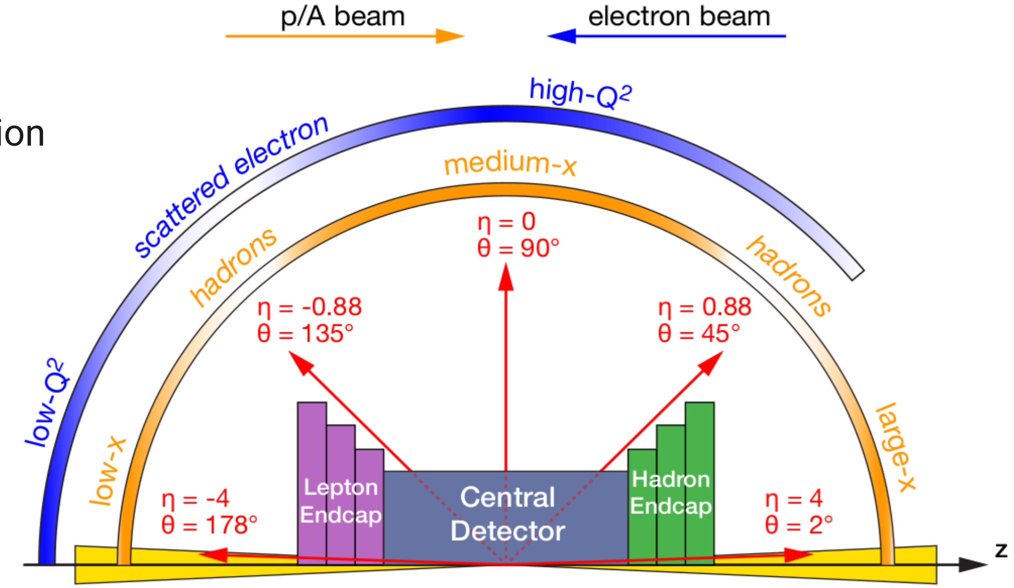
Vertex detector → Identify primary and secondary vertices,
- Low material budget: 0.05% X/X_0 per layer
- High spatial resolution: 10 mm pitch CMOS Monolithic Active Pixel Sensor

Central and Endcap tracker → High precision low mass tracking
- MAPS – tracking layers in combination with micro pattern gas detectors

Particle Identification → High performance single track PID for π, K, p separation
- RICH detectors (RICH, DIRC)
- Time-of-Flight high resolution timing detectors (LAPPDs, LGAD)
- Novel photon sensors: MCP-PMT / LAPPD

Electromagnetic calorimetry → Measure photons (E, angle), identify electrons
- $PbWO_4$ Crystals (backward), W/ScFi (forward)
- Barrel Imaging Calorimeter (Si + Pb/ScFi)

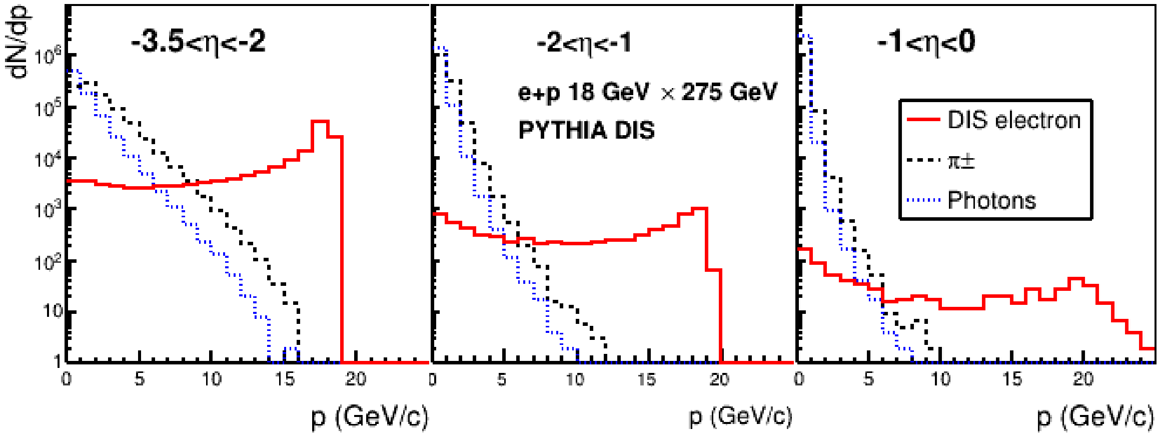
Hadron calorimetry → Measure charged hadrons, neutrons and K_L^0
- Achieve ~70%/√E + 10% for low E hadrons (~ 20 GeV)
- Fe/Sc sandwich with longitudinal segmentation



Very forward and backward detectors → Large acceptance for diffraction, tagging, neutrons from nuclear breakup
- Silicon tracking layers in lepton and hadron beam vacuum
- Zero-degree high resolution electromagnetic and hadronic calorimeters

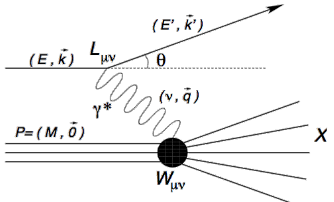
DAQ & Readout Electronics → trigger-less / streaming DAQ, Integrate AI into DAQ

Example: EM Calorimetry Requirements

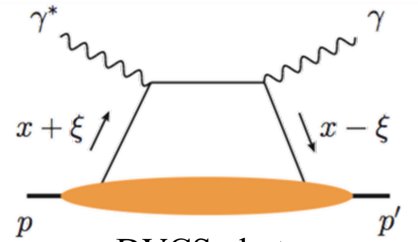


Electron/photon PID, energy, angle/position:

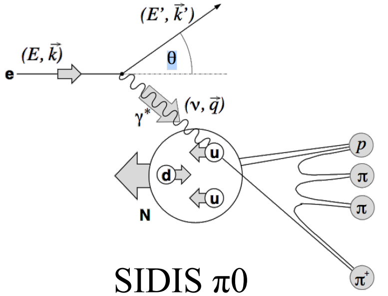
Coverage (in rapidity and energy), resolution, e/π, granularity, projectivity



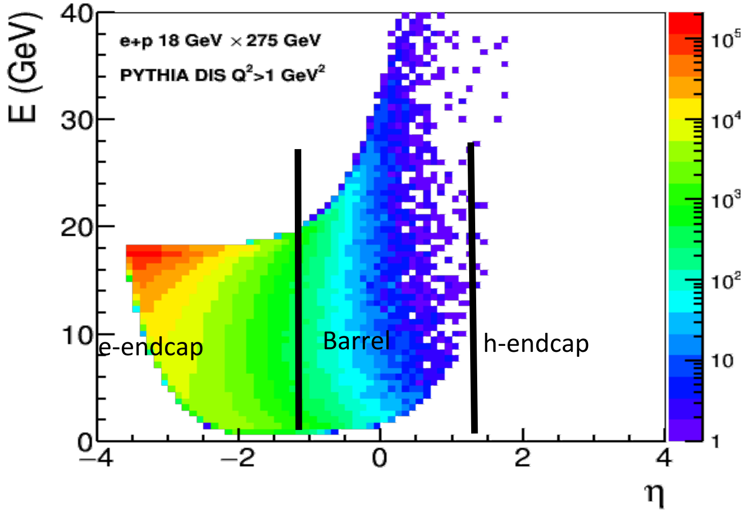
DIS e

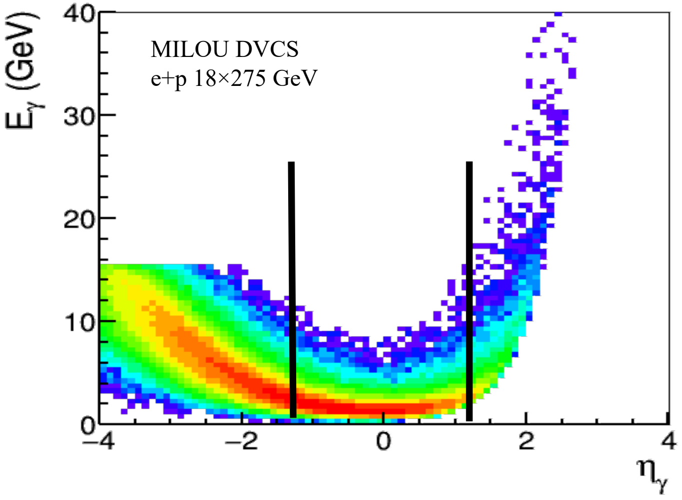


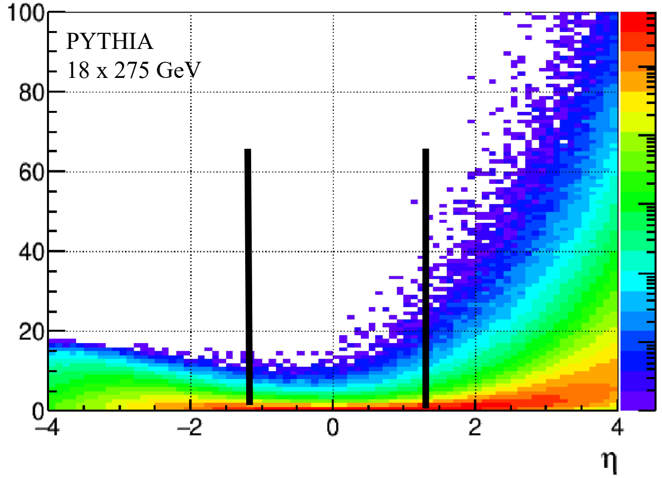
DVCS photons



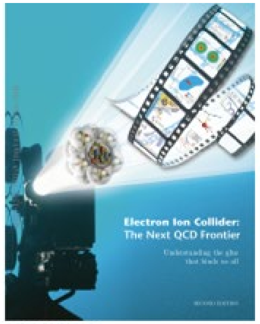
SIDIS π0



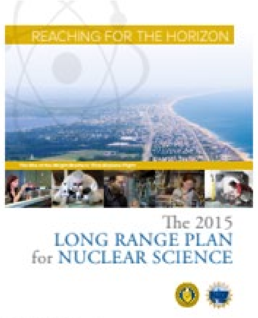




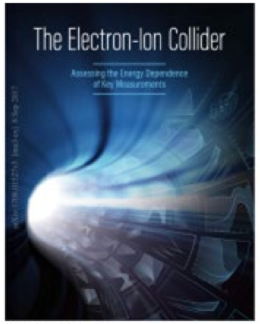
Detector Design Process Timeline



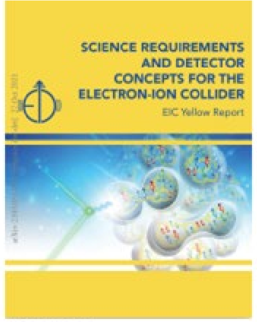
2012



2015



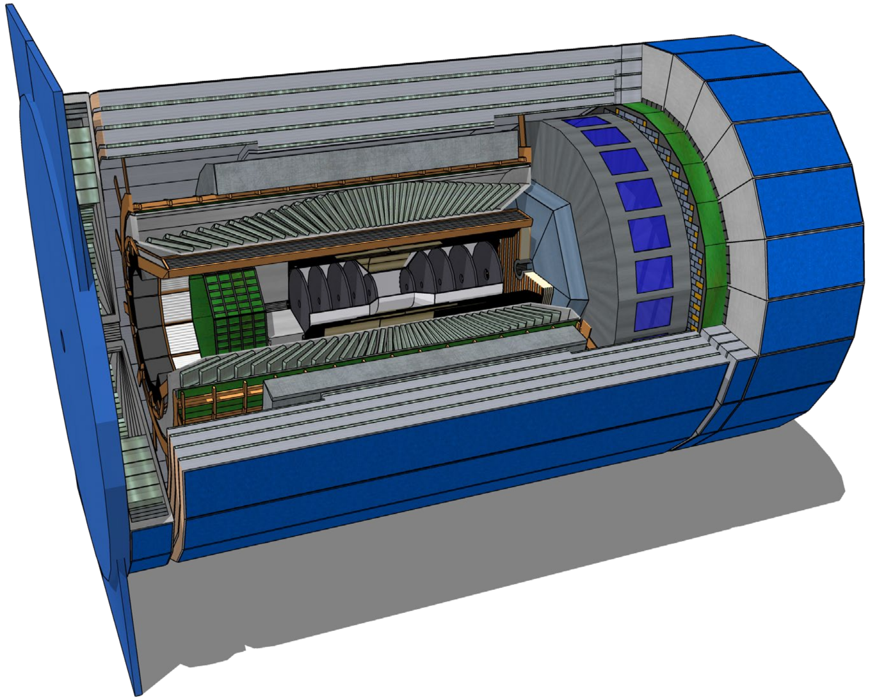
2017



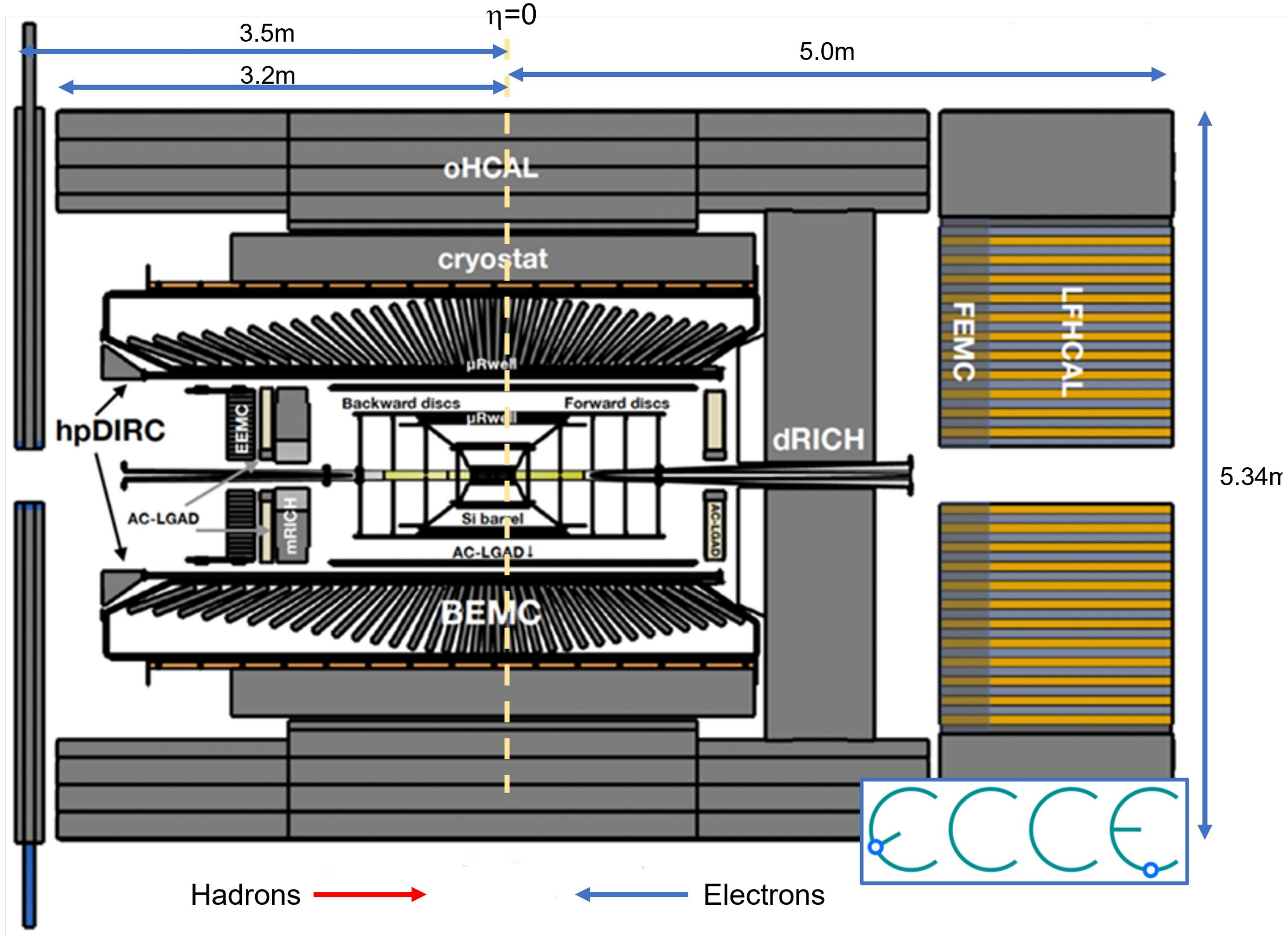
2020

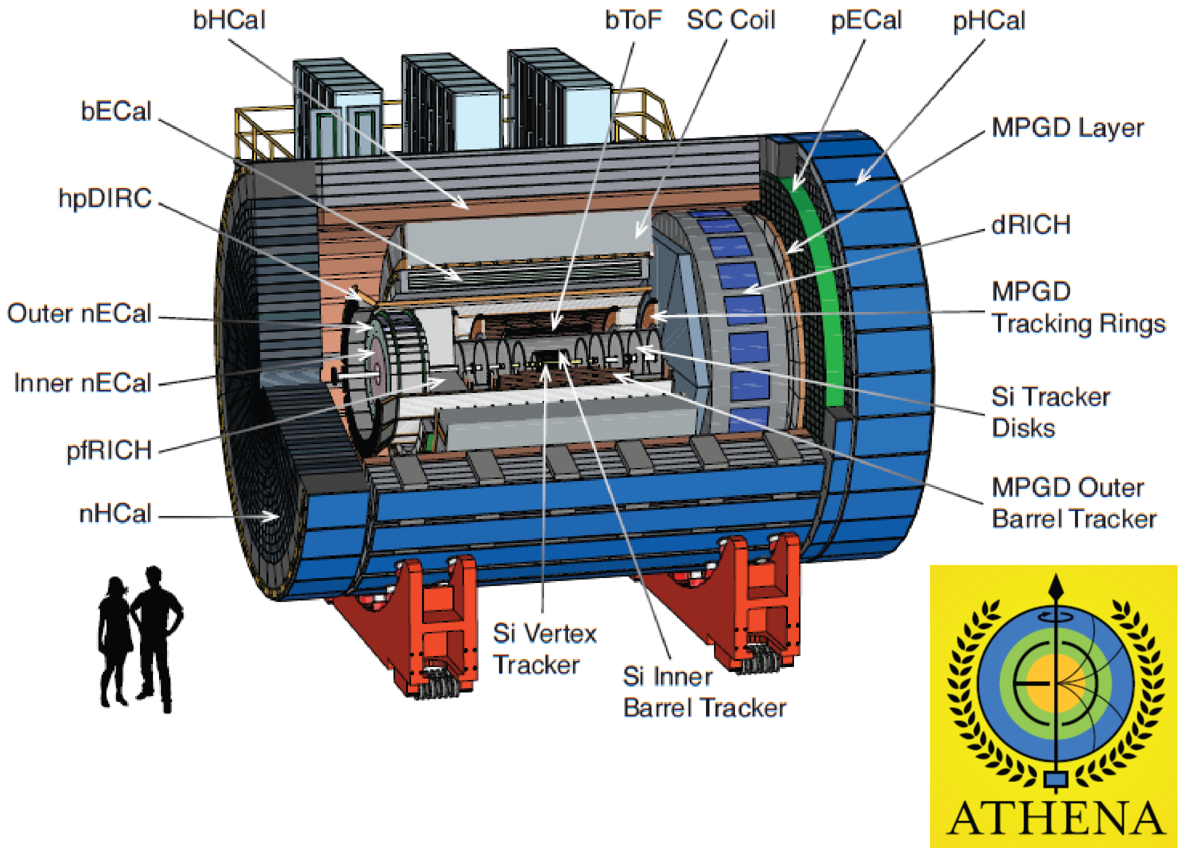
Detector and machine design parameters driven by physics objectives

- Call for proposals issued jointly by BNL and JLab in **March 2021** (Due Dec 2021)
  - ATHENA, CORE and ECCE proposals submitted
- DPAP closeout **March 2022**
  - ECCE proposal chosen as basis for first EIC detector reference design
- **Spring/Summer 2022** – ATHENA and ECCE form joint leadership team
  - Joint WG's formed and consolidation process undertaken
  - Coordination with EIC project on development of technical design
- Collaboration formation process started **July 2022**
- Charter ratified & elected ePIC Leadership Team **February 2023**
- **Working towards TDR and CD-3A and CD-2/3**



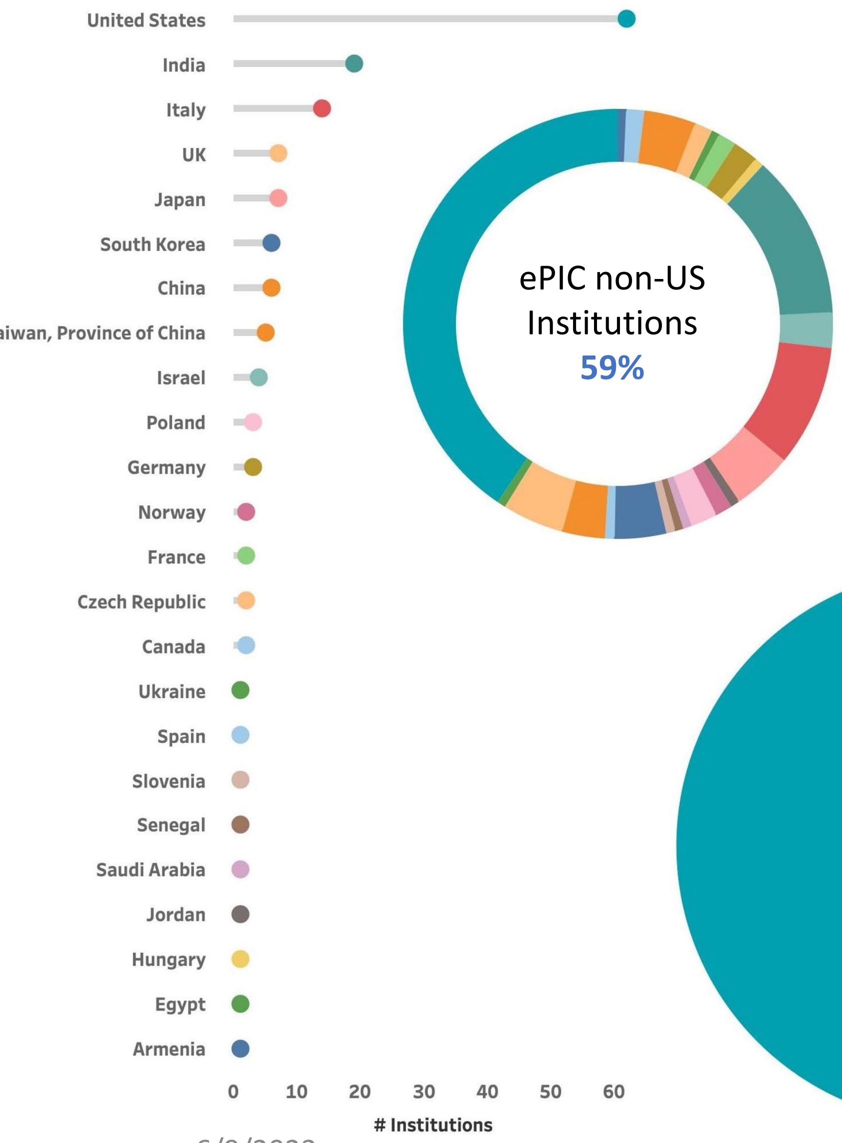
ECCE and ATHENA





Key conceptual differences – bore size and magnetic field!

The ePIC Collaboration

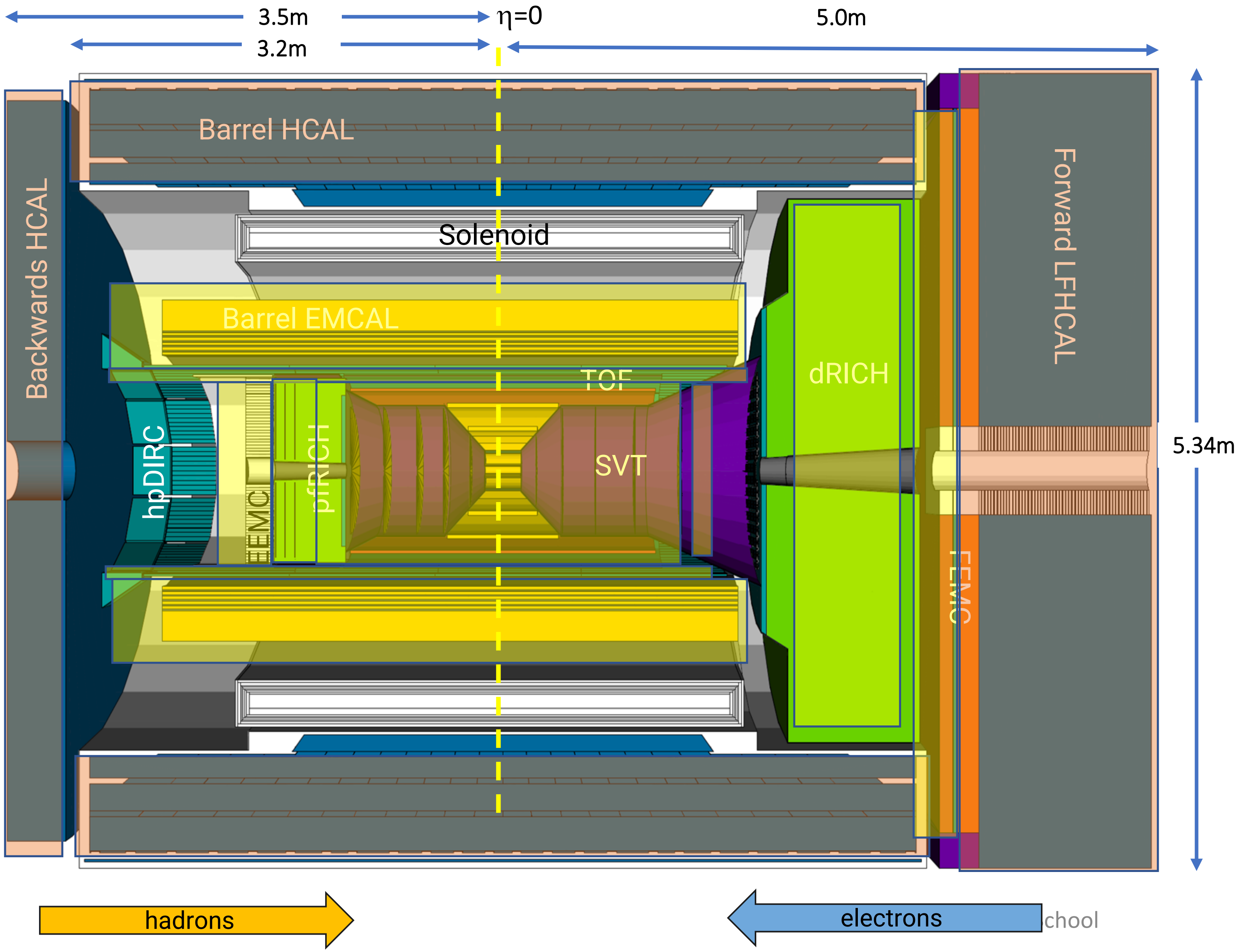


160+ institutions
24 countries

500+ participants

A truly global pursuit for a new experiment at the EIC!

ePIC Detector Design



Tracking:

- New 1.7T solenoid
- Si MAPS Tracker
- MPGDs (μRWELL/μMegas)

PID:

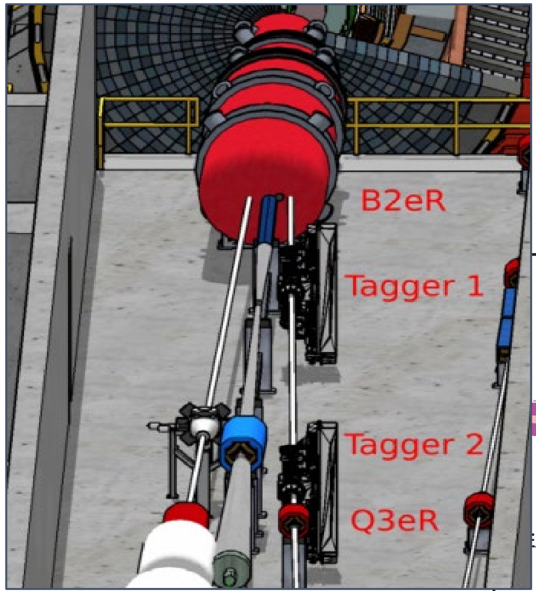
- hpDIRC
- pfRICH
- dRICH
- AC-LGAD (~30ps TOF)

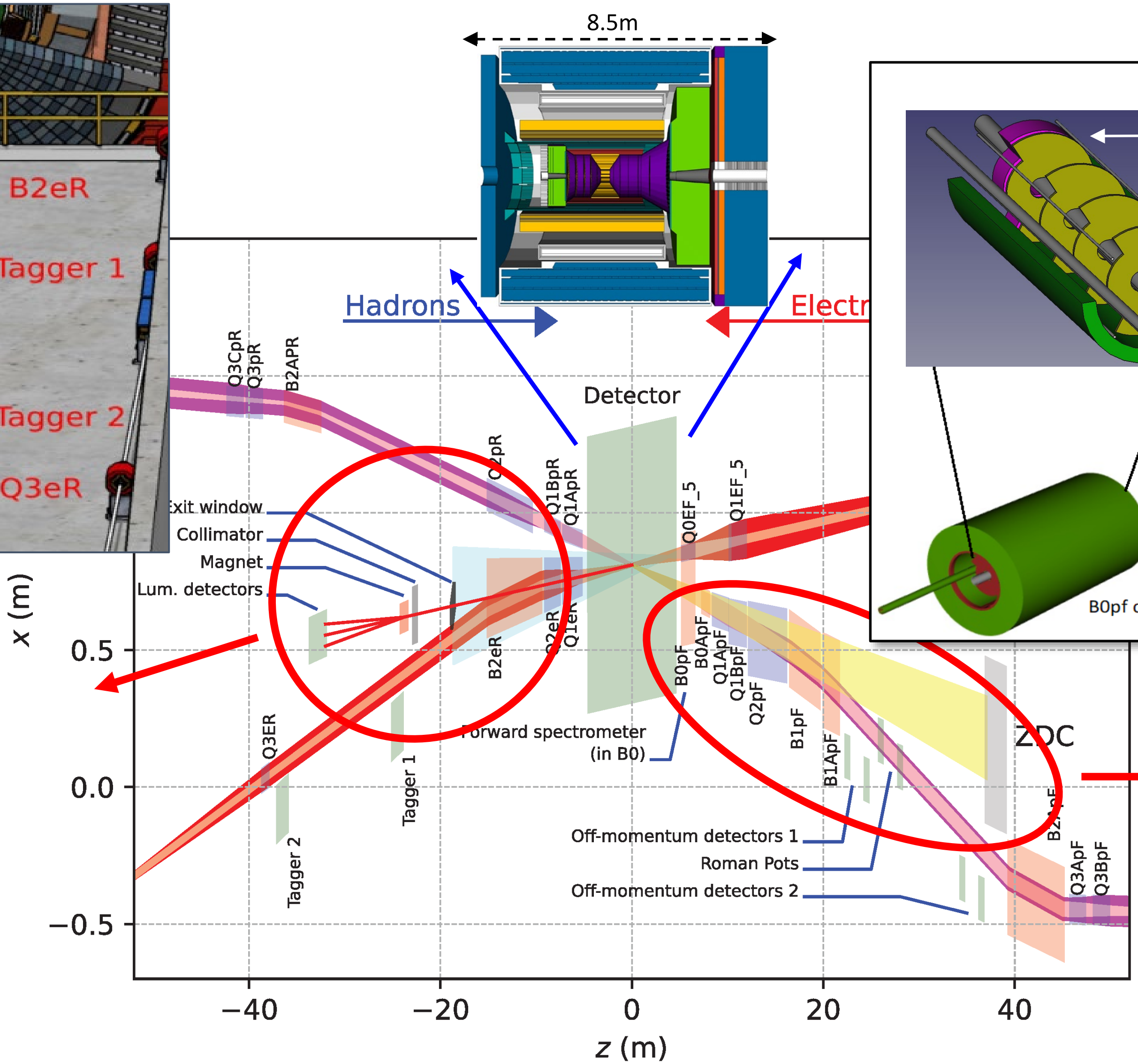
Calorimetry:

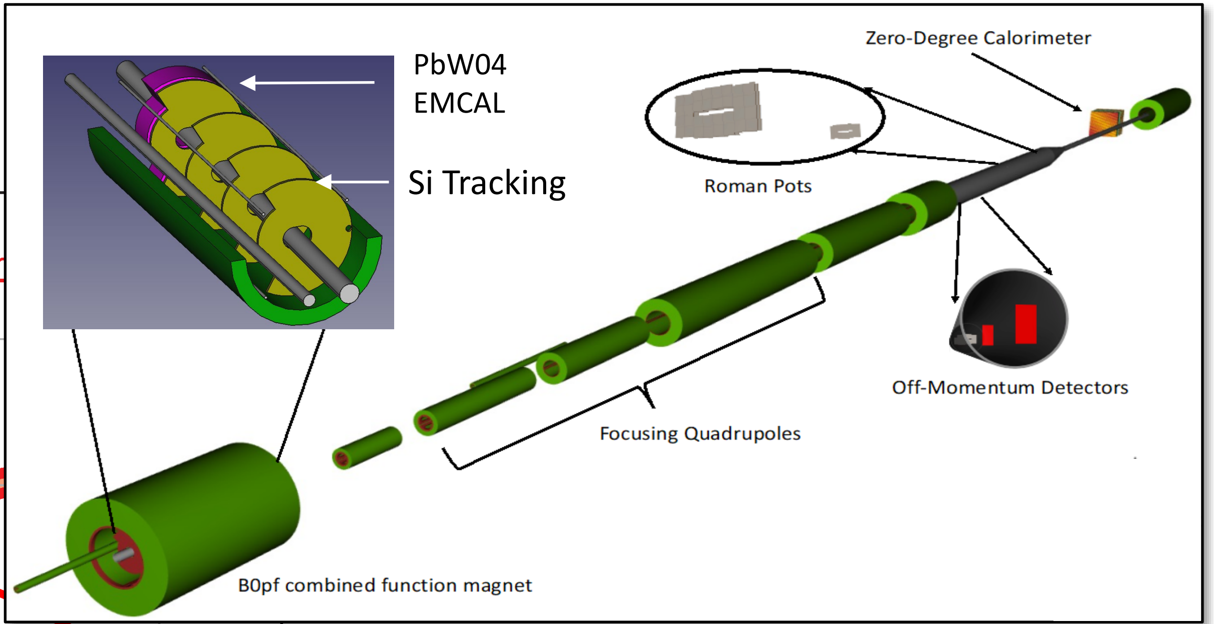
- Imaging Barrel EMCal
- PbWO4 EMCal in backward direction
- Finely segmented EMCal +HCal in forward direction
- Outer HCal (sPHENIX re-use)
- Backwards HCal (tail-catcher)

chool

Far-Forward and Far-Backward Detectors







Far-Backward Detectors

- Luminosity monitor
- Low-Q^2 Tagging Detectors

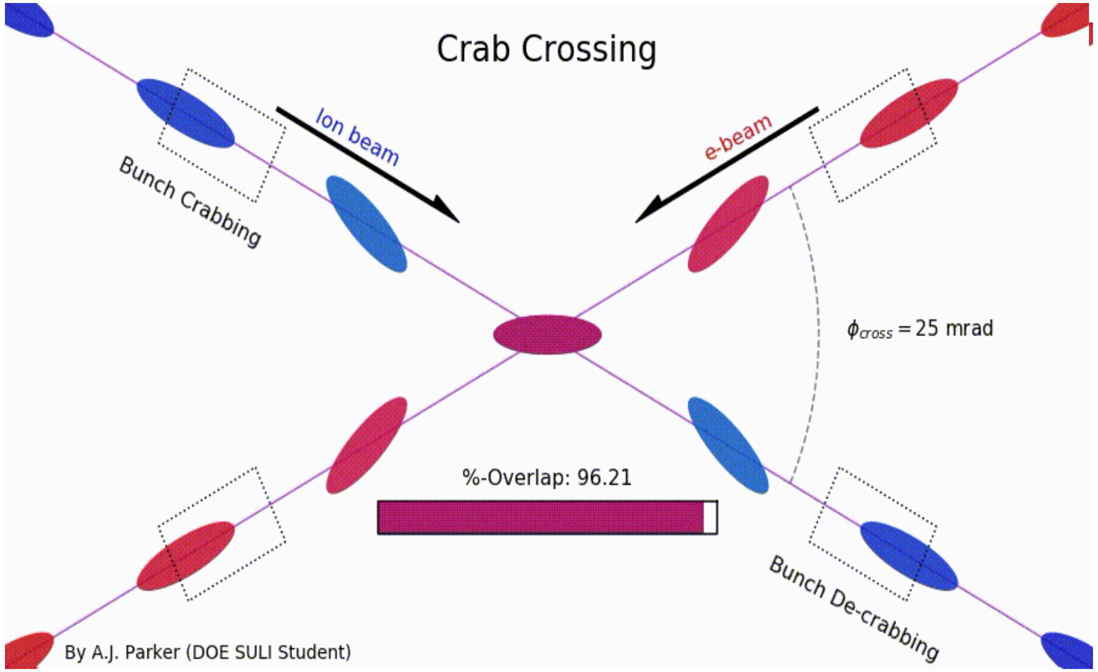
Far-Forward Detectors

- B0 Tracking and Photon Detection
- Roman Pots and Off-Momentum Detectors
- Zero-Degree Calorimeter

Why a Crossing Angle?

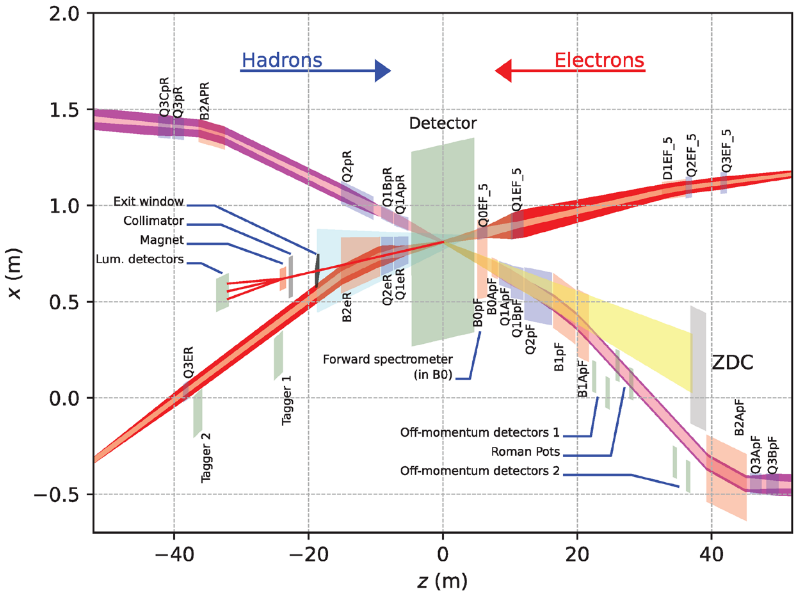
- Brings focusing magnets close to IP
  → high luminosity
- Beam separation without separation dipoles
  → reduced synchrotron radiation background

But significant loss of luminosity!

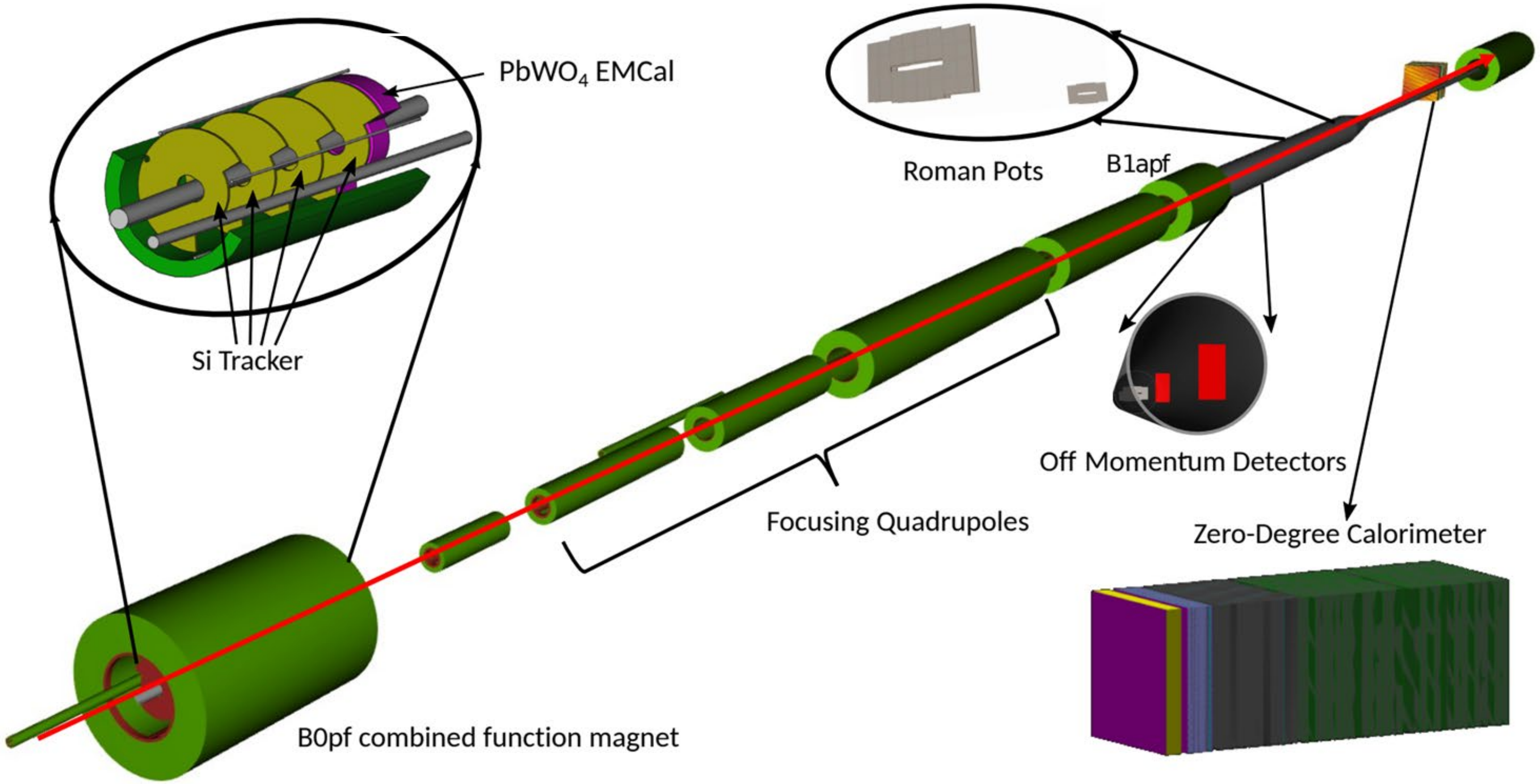


Solution: Crab crossing

- Head-on collision geometry is restored by rotating the bunches before colliding ("crab crossing")
- Bunch rotation ("crabbing") is accomplished by transversely deflecting RF resonators ("crab cavities")
- Actual collision point moves laterally during bunch interaction



Far-Forward Detectors

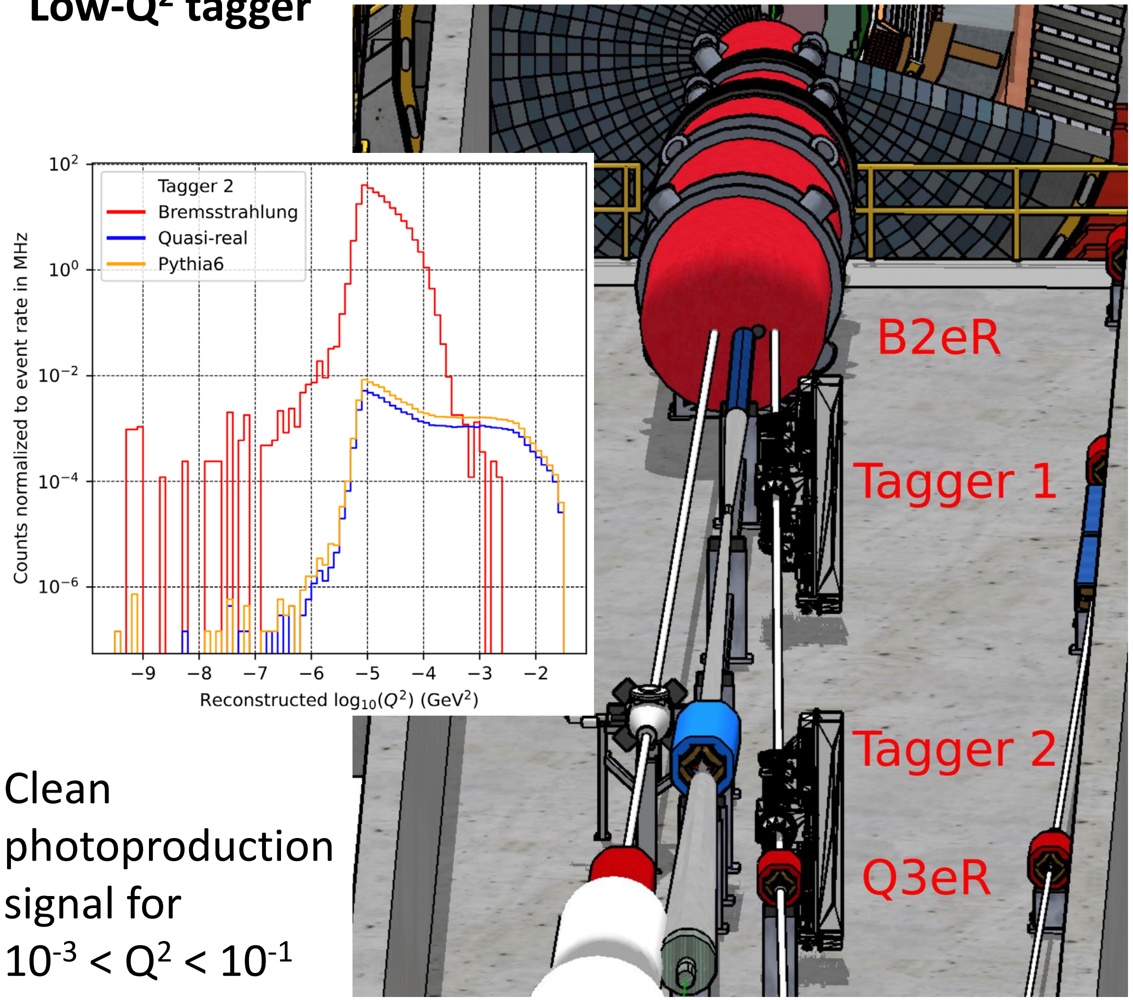


- **B0 system:** Measures charged particles in the forward direction and tags neutral particles
- **Off-momentum detectors:** Measure charged particles resulting from, e.g., decays and fission
- **Roman pot detectors:** Measure charged particles near the beam
- **Zero-degree calorimeter:** Measures neutral particles at small angles

Detector	Acceptance
Zero-Degree Calorimeter (ZDC)	θ < 5.5 mrad (η > 6)
Roman Pots (2 stations)	0.0 < θ < 5.0 mrad (η > 6)
Off-Momentum Detectors (2 stations)	θ < 5.0 mrad (η > 6)
B0 Detector	5.5 < θ < 20.0 mrad (4.6 < η < 5.9)

Far Backwards Detectors

Low-Q^2 tagger

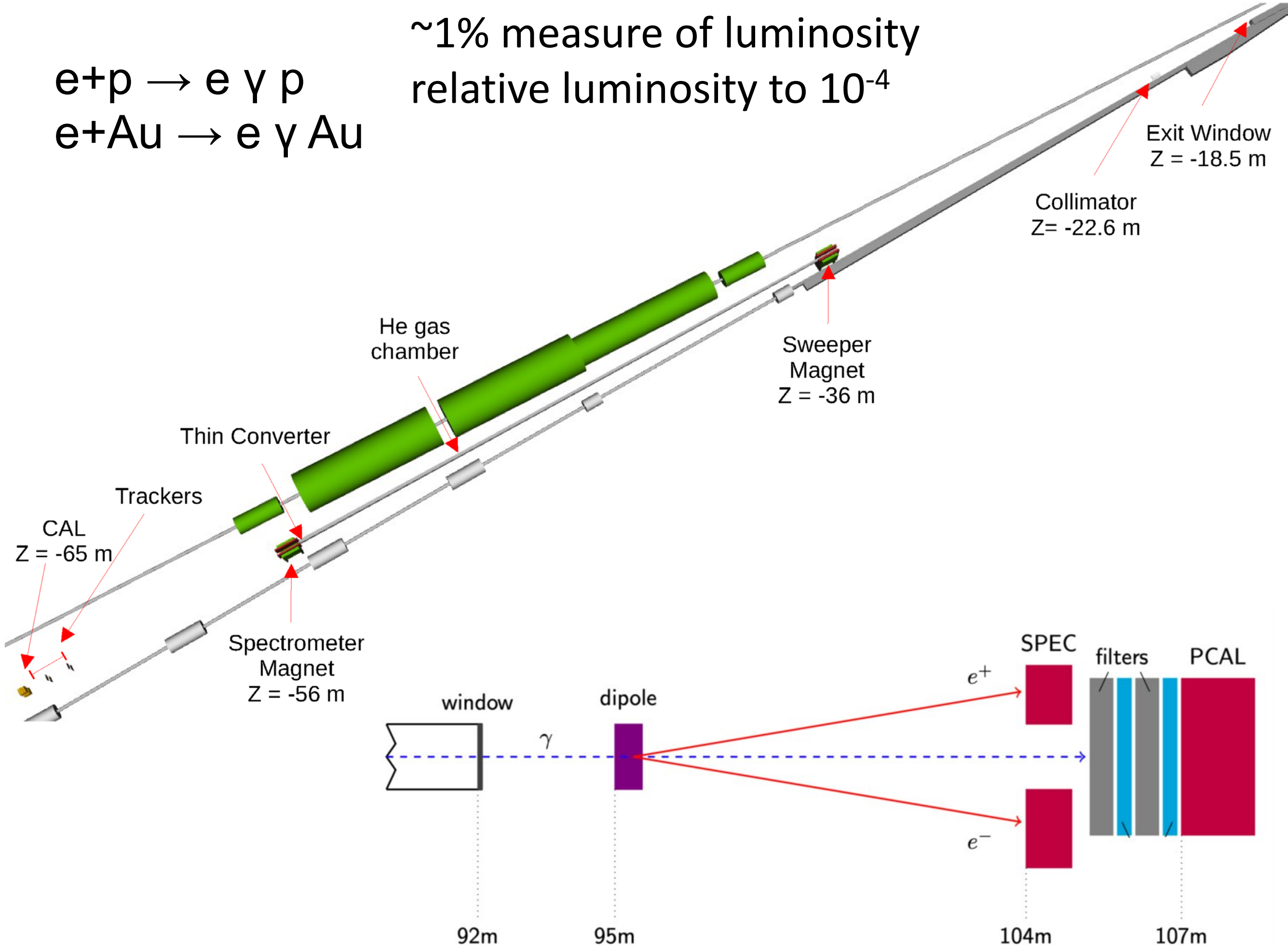


Clean photoproduction signal for $10^{-3} < Q^2 < 10^{-1}$

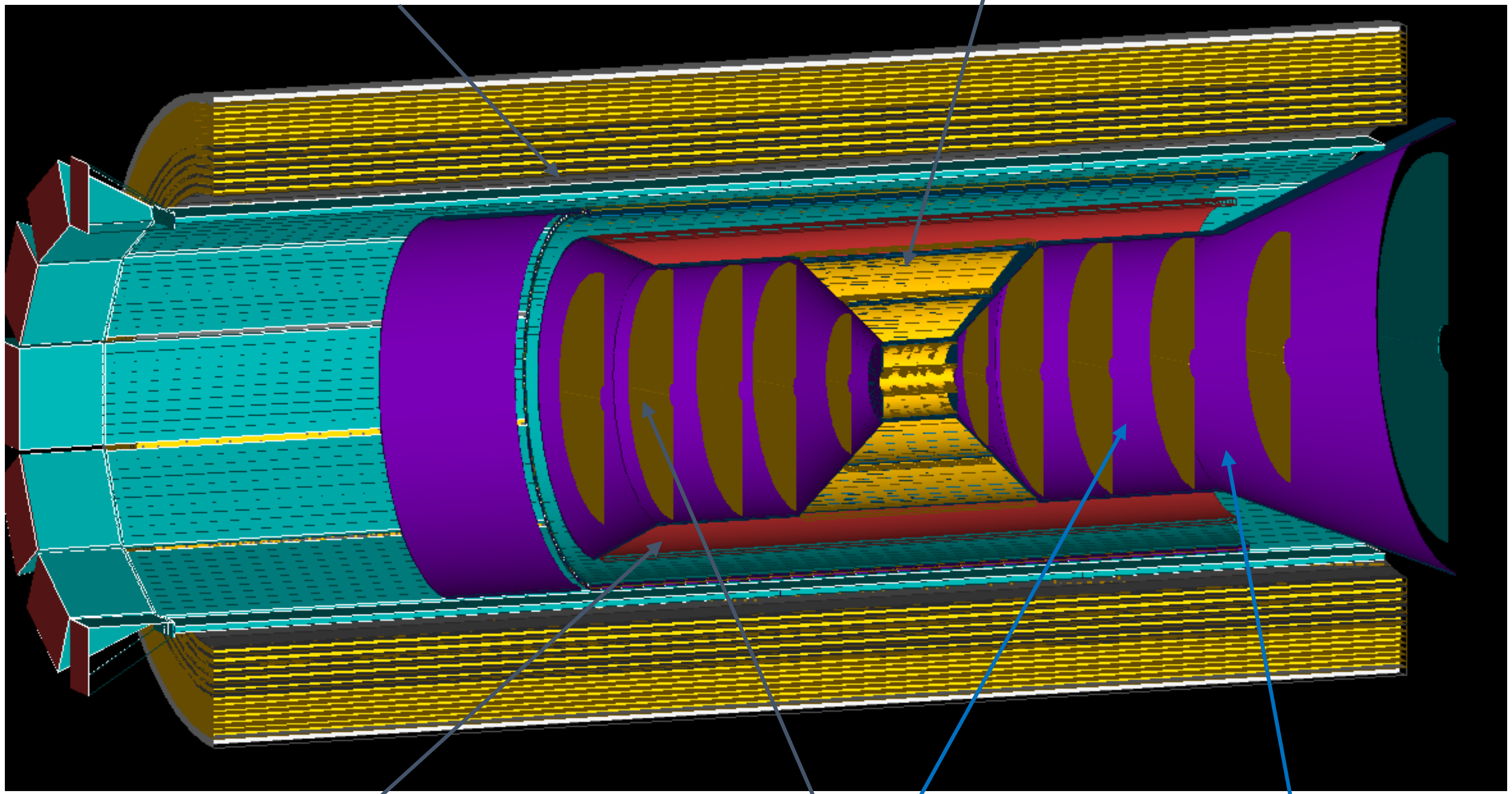
Luminosity Spectrometer

$e+p \rightarrow e\,\gamma\,p$
$e+Au \rightarrow e\,\gamma\,Au$

~1% measure of luminosity
relative luminosity to 10^{-4}



Tracking



- **Inner two vertex layers** optimized for beam pipe bakeout and ITS-3 sensor size
- Third layer dual-purpose (vertex + sagitta) - **5 layers total**
- **Five discs in forward/backwards** direction (ITS-3 based large area sensor design EIC LAS)
- **Cylindrical μMega** provide pattern recognition redundancy
- **1st AstroPix layer of Barrel ECal** provides ring seed direction, space point for pattern recognition

Tracking

Technology

ITS3 MAPS based Si-detectors:

- O(10μm) pitch, $X/X^0 \sim 0.05 – 0.55\%$/ layer

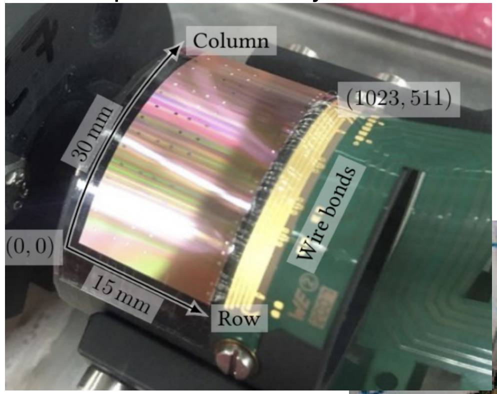
Gaseous tracker:

- $\sigma = 55$ μm, $X/X_0 \sim 0.2\%$/layer

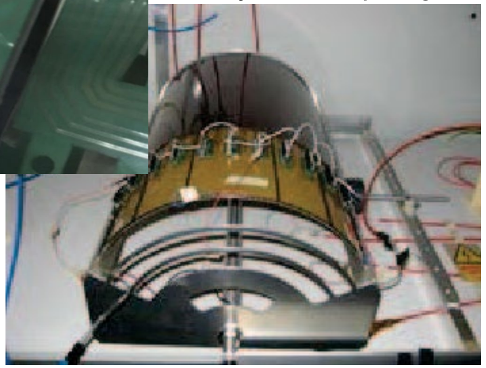
AstroPix outer tracker layer:

- 500μm pixel pitch ($\sigma = 144$ μm)

First "μITS3" assembly at CERN

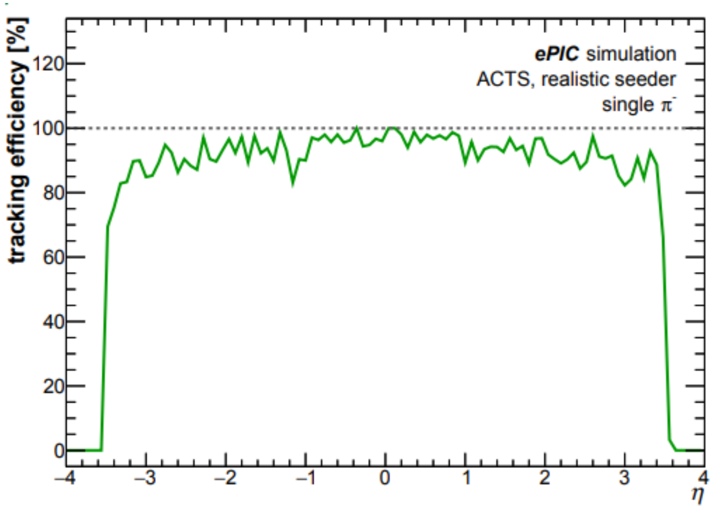


Cylindrical μMega

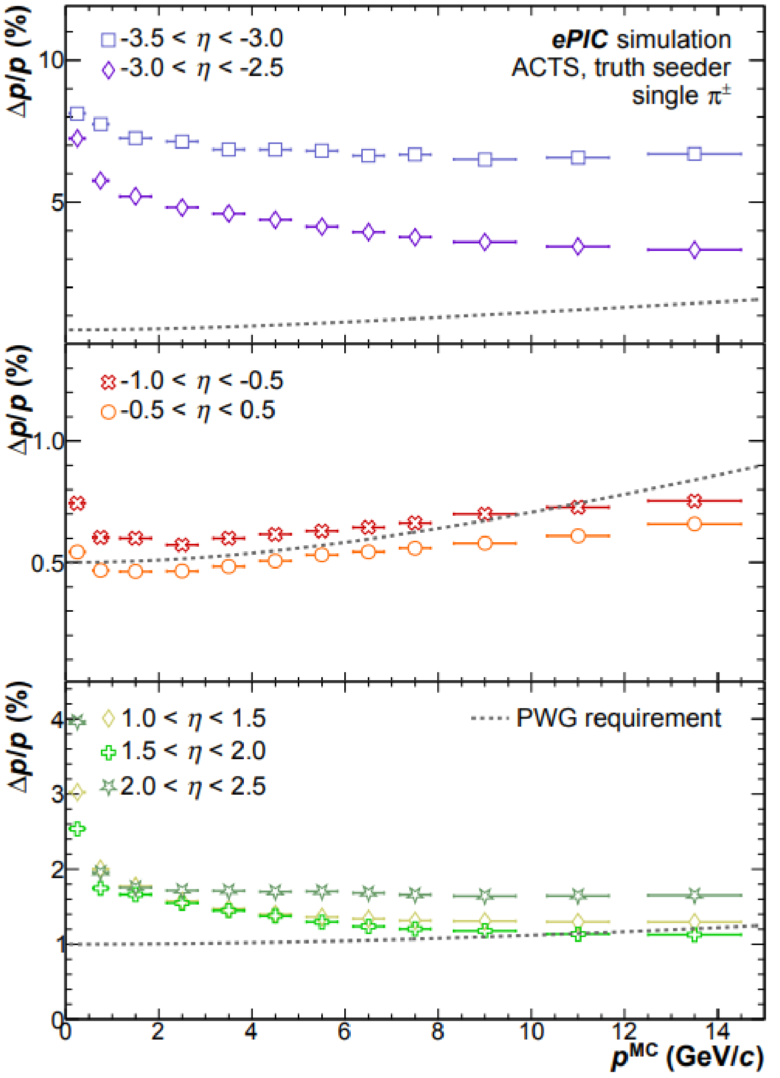


Simulated performance

F. Bock, Hard Probes 2023



F. Bock, Hard Probes 2023



E. Yeats, R. Cruz-Torres, N. Schmidt, S. Maple

- Meets EICUG Yellow Report design requirements
- Backward momentum resolution complemented by calorimetric resolution

Si Detector Readout

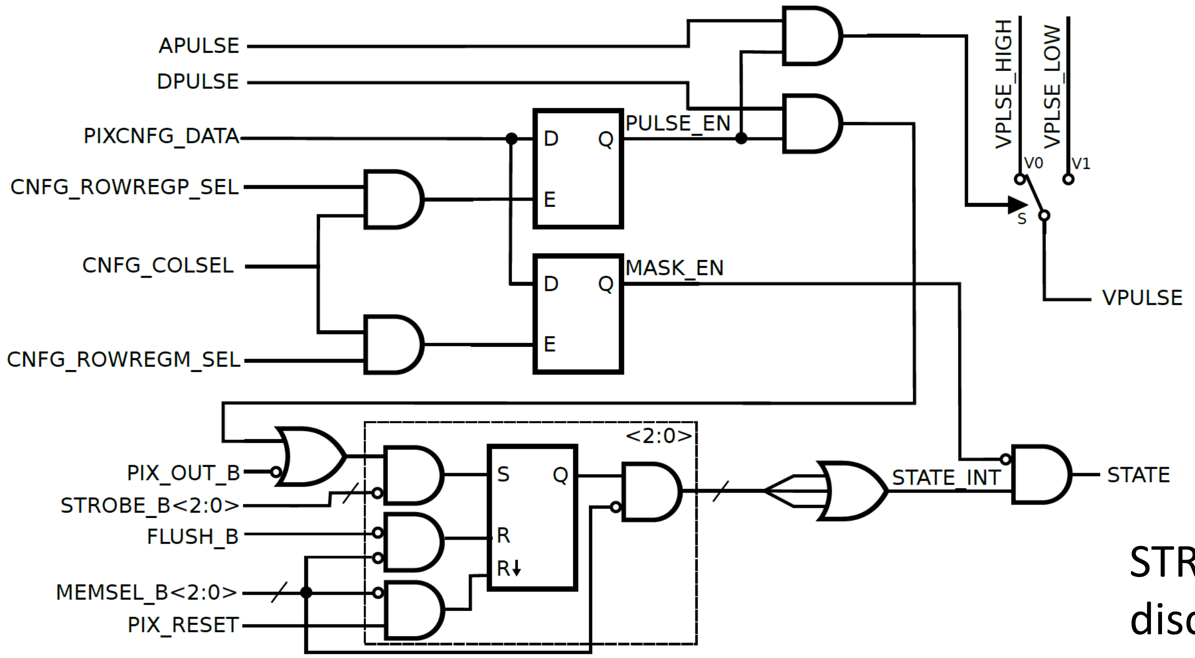
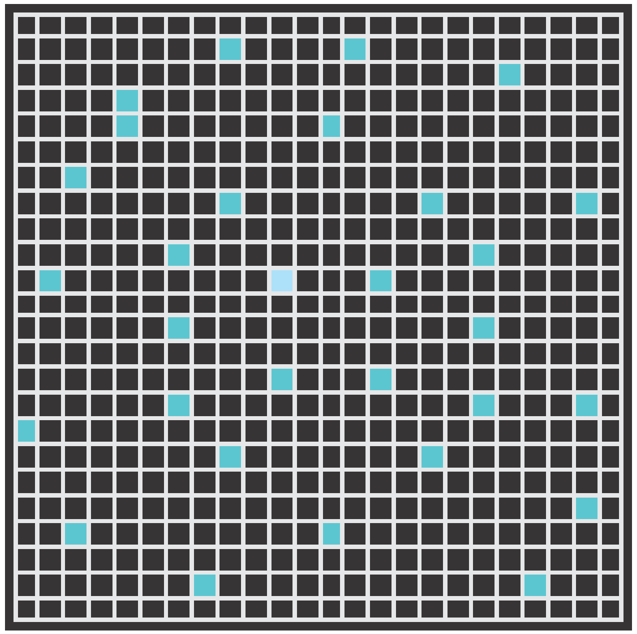


Figure 4.2: Functional diagram of the pixel logic



STROBE selects 1 out of 3 latches to store state of discriminator; then MEMSEL allow reading out 1 out of 3 latches through priority encoder.

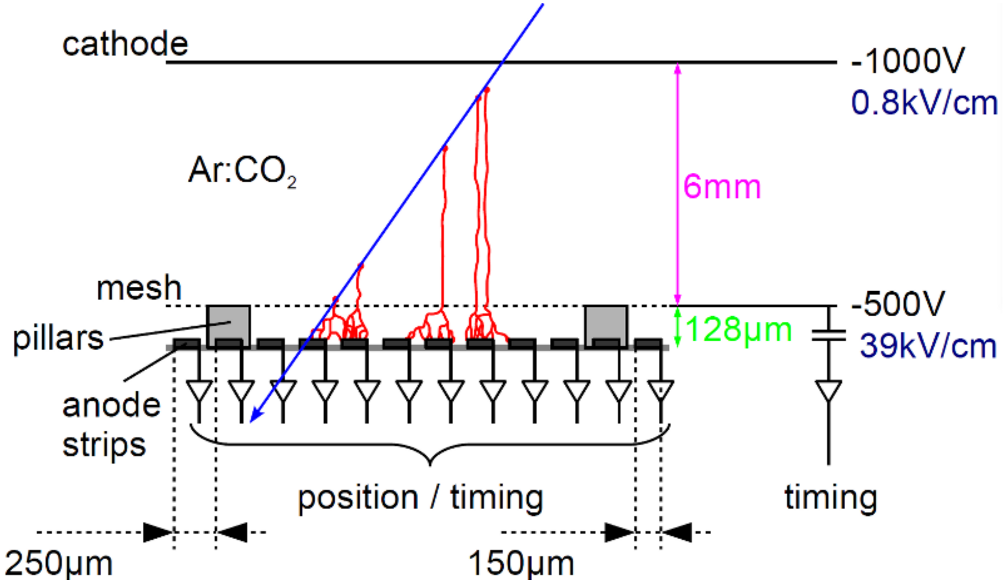
The precision of time measurement of ALPIDE/ALICE-ITS3 cannot be better than time between STROBES; but if STROBES are sent too often, same hits will be reported multiple times.

The ITS3 STROBE time is expected to be about 2μs – this will integrate over 200 bunch crossings! Need a fast detector to sort ambiguities!

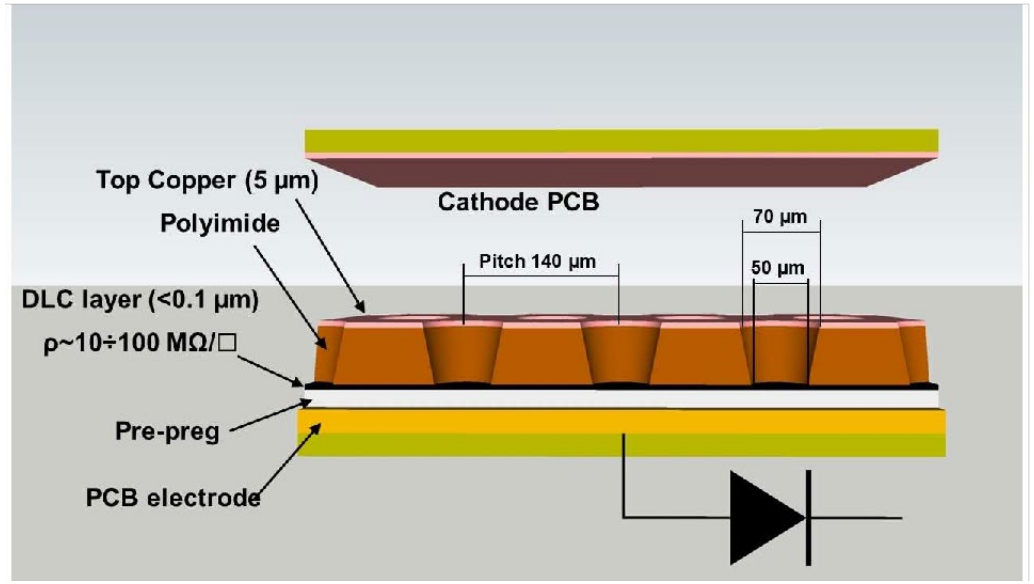
Micro Pattern Gas Detectors

Both types of detectors have good spatial resolution of order ~150μm with a fast time response (<10ns). mMega detectors have been demonstrated in a cylindrical geometry.

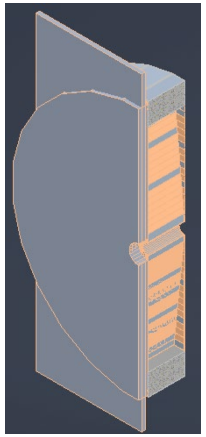
μMega Detector



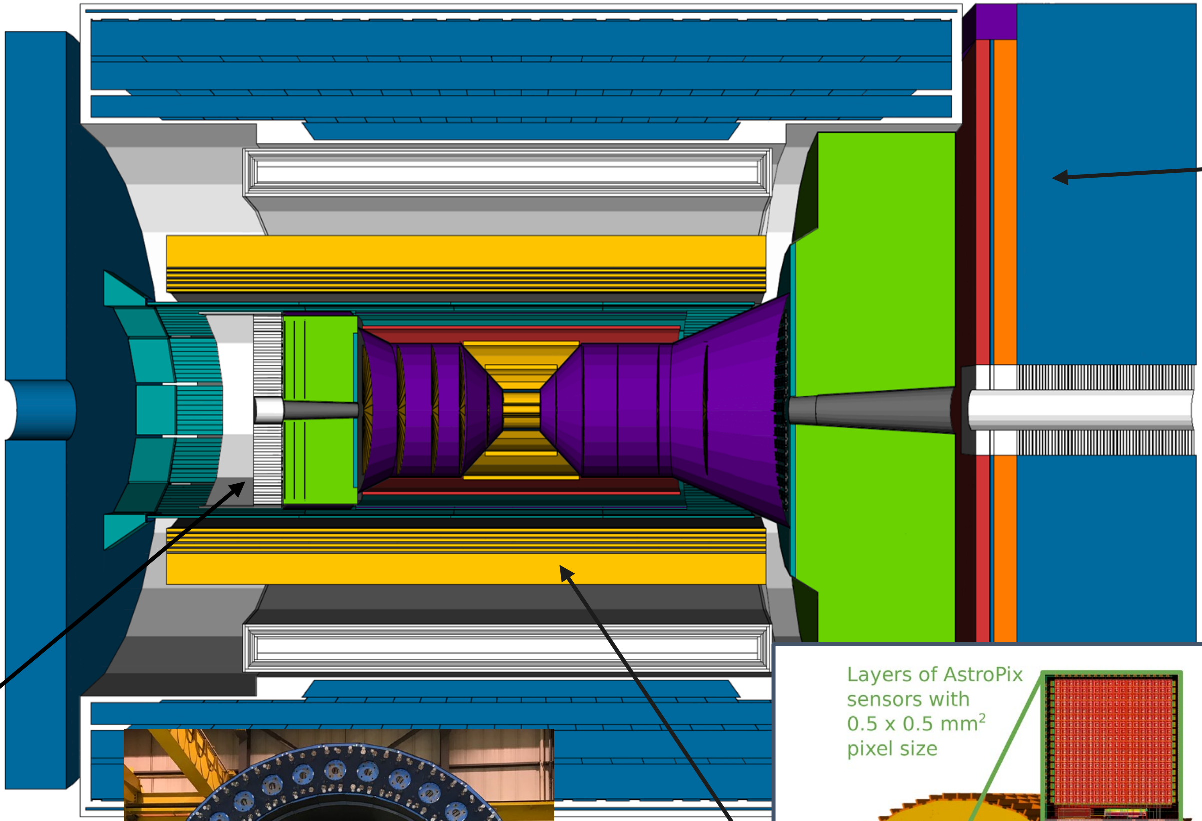
μRWell Detector

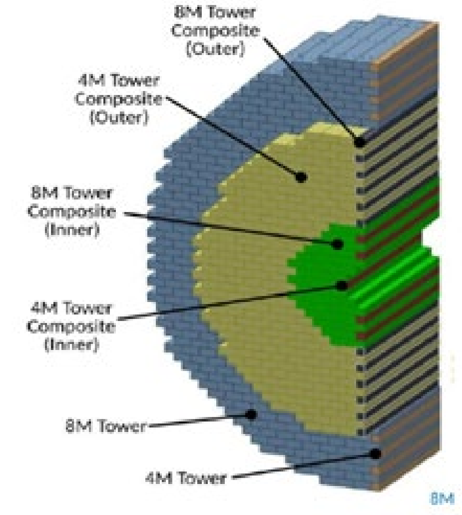


Calorimetry

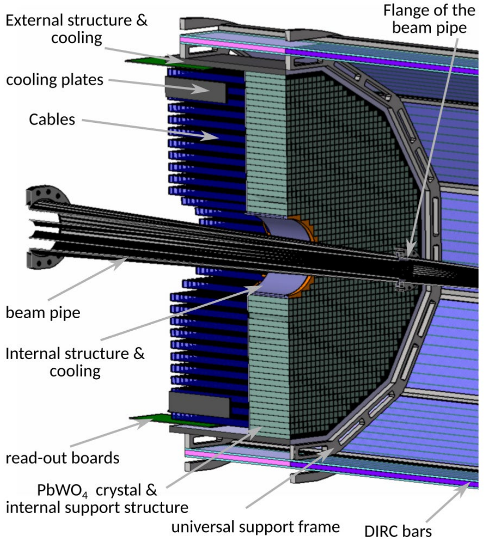


Backwards HCal Steel/Sc Sandwich tail catcher



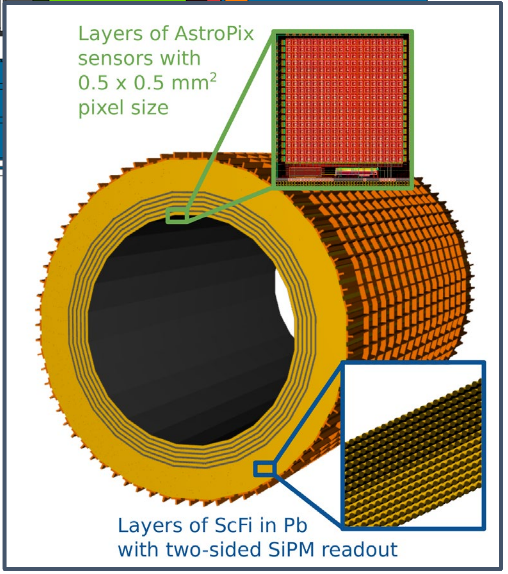


High granularity W/SciFi EMCal Longitudinally separated HCAL with high-η insert



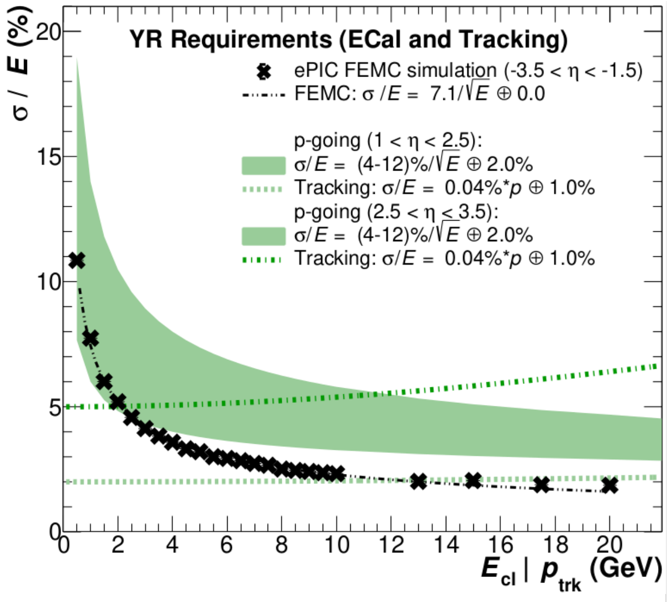
Backwards EMCal PbW04 crystals

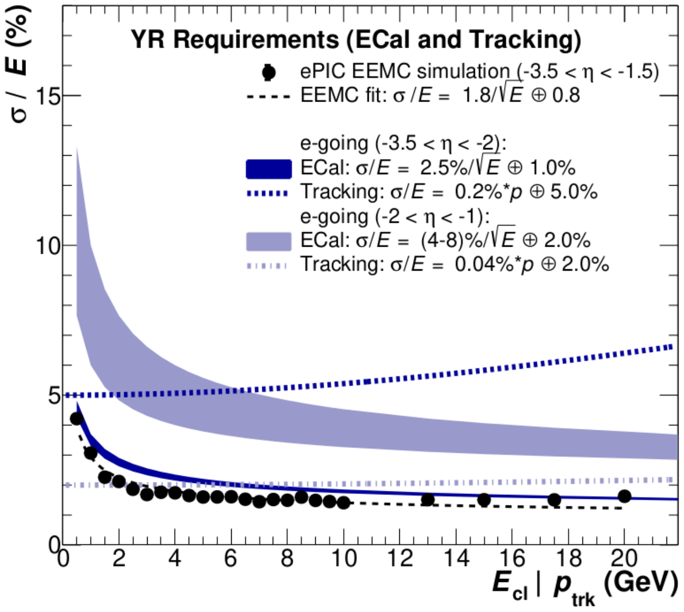
Barrel HCAL (sPHENIX re-use)

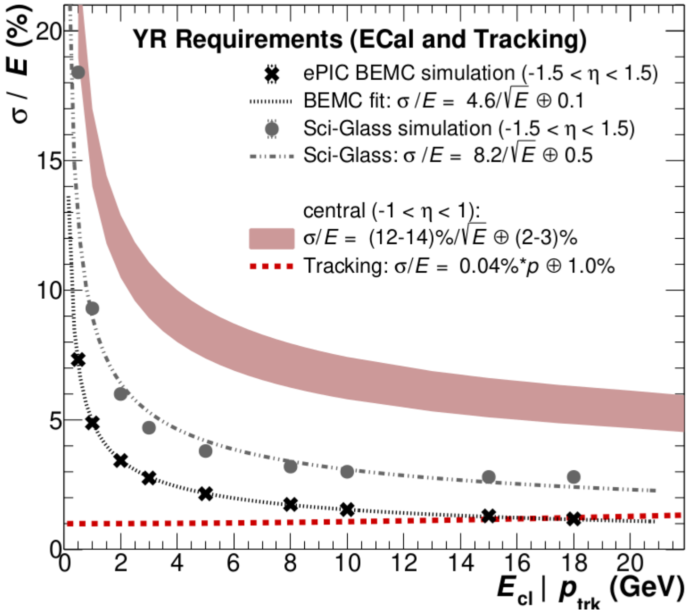


Calorimetry Performance

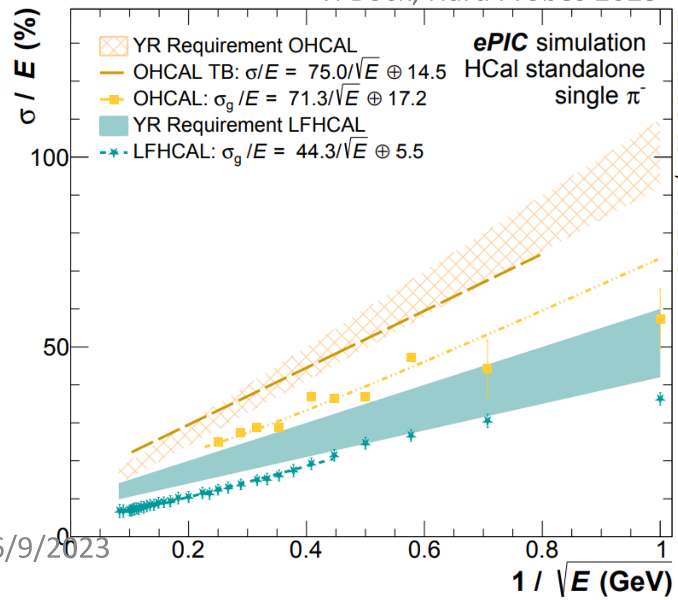
plots by N. Schmidt







F. Bock, Hard Probes 2023



D. Anderson, F. Bock

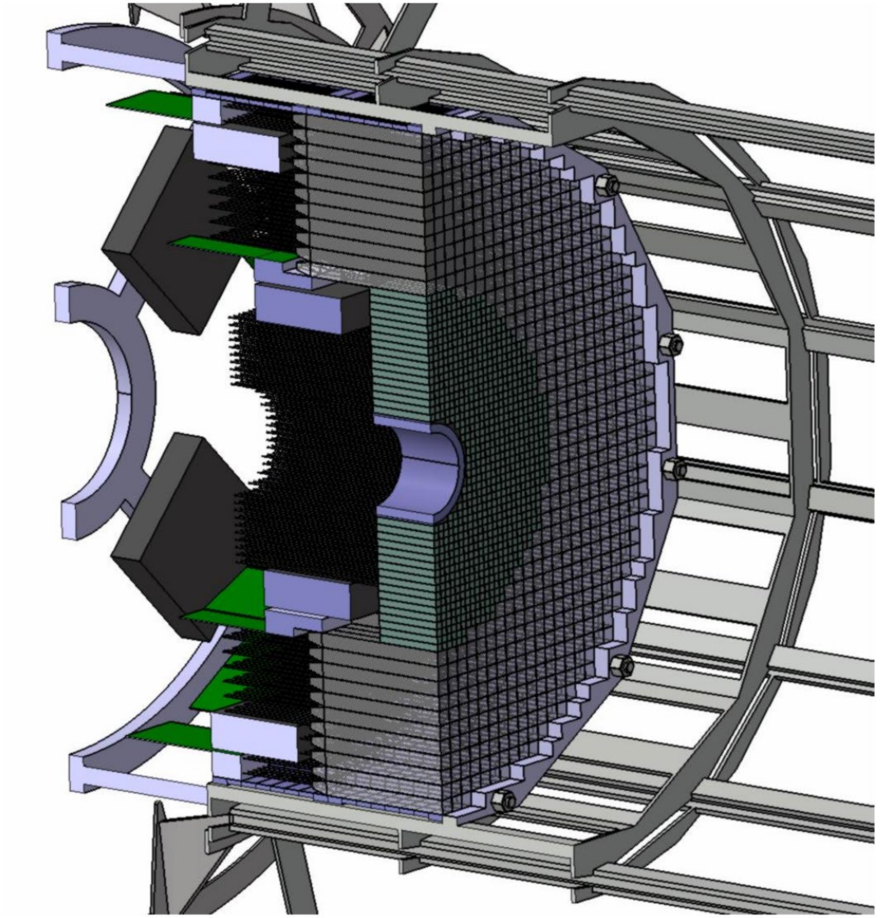
Performance on energy resolution and matching

- Technologies fulfill YR requirements on energy resolution
- Ongoing simulation studies related to overlaps between different η regions for calorimetry and reconstruction algorithms

Ongoing work on Monte-Carlo validation

- Validation for high Z absorbers

Backward Calorimetry



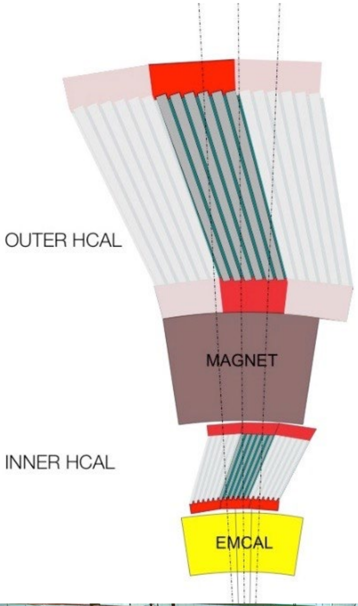
Backward EMCAL

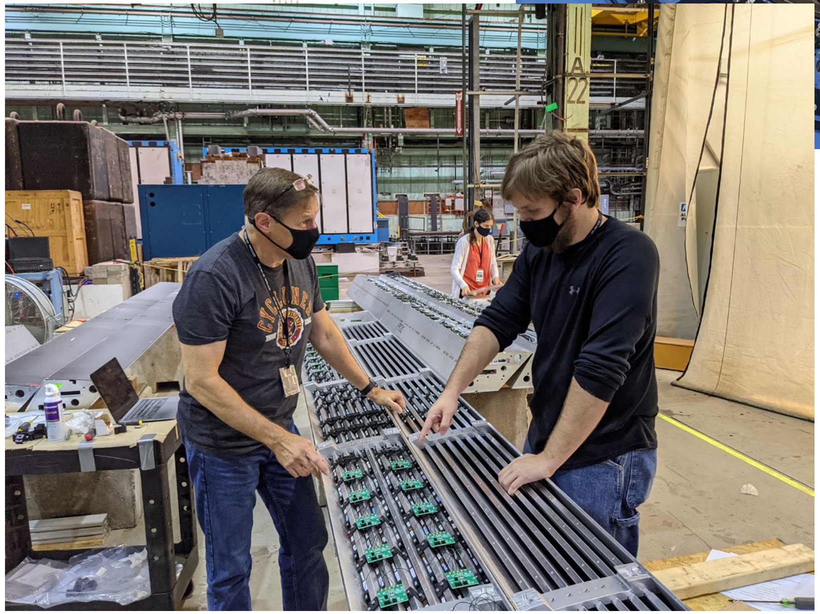
- Non-projective **$PbWO_4$ calorimeter** (EEEMC-Consortium)
  - $2 \times 2 \times 20$ cm^3 crystals
  - Length ~$20X/X_0$, transverse size ~Molière radius
  - Located inside the inner DIRC frame
  - Preferred readout: SiPMs of pixel size 10µm or 15µm
  - Cooling to keep temperature stable within ± 0.1 °C
- Ongoing efforts advancing the design to increase coverage in η ($-3.7 < \eta < -1.5$) with inlay around beampipe

Backward HCAL in consideration

- Possible upgrade path

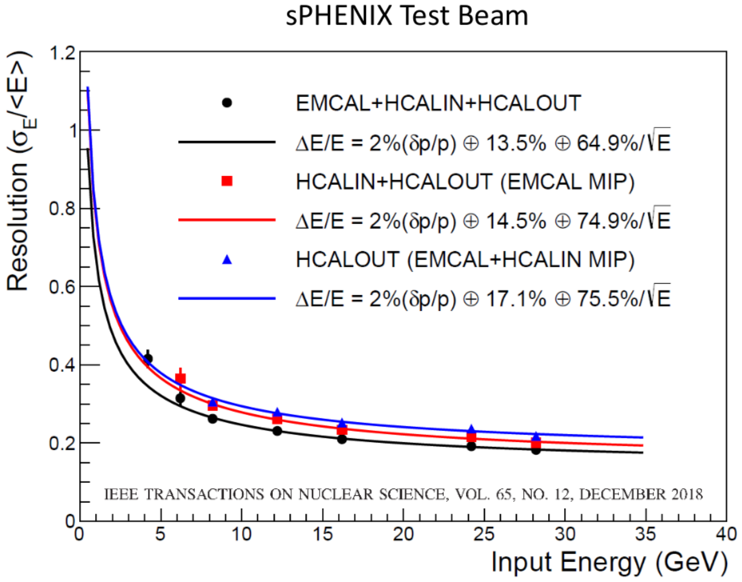
Barrel Hadronic Calorimetry





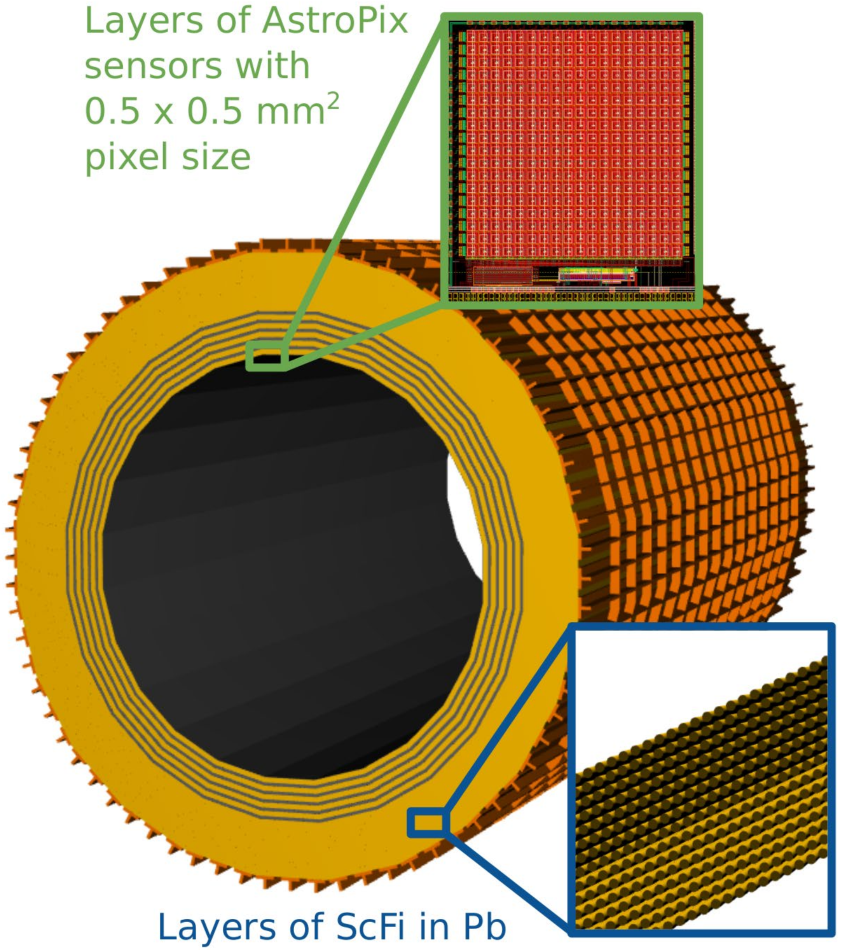
Reuse of sPHENIX outer (outside of the Solenoid) HCal ≈ 3.5λ_I

- Steel and scintillating tiles with wavelength shifting fiber
- $\Delta\eta \times \Delta\phi \approx 0.1 \times 0.1$ (1,536 readout channels, SiPMs)



Barrel EM Calorimetry

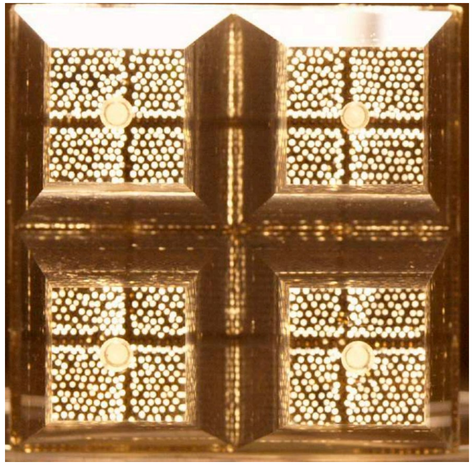
- **Hybrid concept**
  - Imaging calorimetry based on monolithic silicon sensors AstroPix (NASA's AMEGO-X mission) - 500 µm x 500 µm pixels Nuclear Inst. and Methods in Physics Research, A 1019 (2021) 165795
  - Scintillating fibers in Pb (Similar to GlueX Barrel ECal, 2-side readout w/ SiPMs) Nuclear Inst. and Methods in Physics Research, A 896 (2018) 24-42
- 6 layers of imaging Si sensors interleaved with 5 Pb/ScFi layers and followed by a large chunk of Pb/ScFi section (can be extended to inner HCAL)
- Total radiation thickness for EMCAL of ~20 X_0
- Detector coverage: $-1.7 < \eta < 1.3$ which overlaps with "electron-going" side endcap

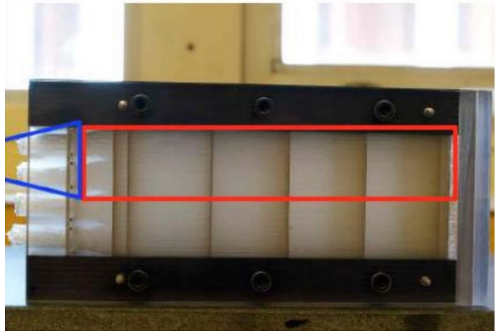


Energy resolution - SciFi/Pb Layers: $5.3\% / \sqrt{E} \oplus 1.0\%$

Position resolution - Imaging Layers (+ 2-side SciFi readout): with 1st layer hit information ~ pixel size

Forward EM Calorimetry





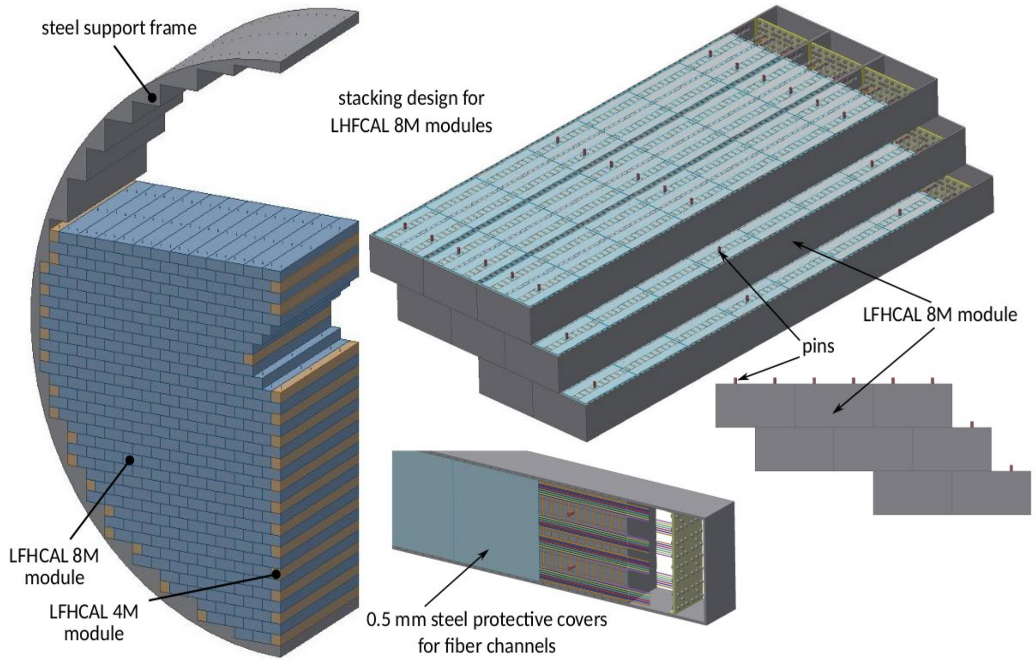
- W/SciFi: scintillating fibers embedded in W/epoxy mix
  - Similar to sPHENIX W/SciFi
  - X/X_0 = 23 (17 cm + 10 cm readout), 2.5 x 2.5 cm towers (R_M=~2.3 cm)
  - Easier construction for WSciFi calorimeter
  - Compactness and higher EM-shower containment

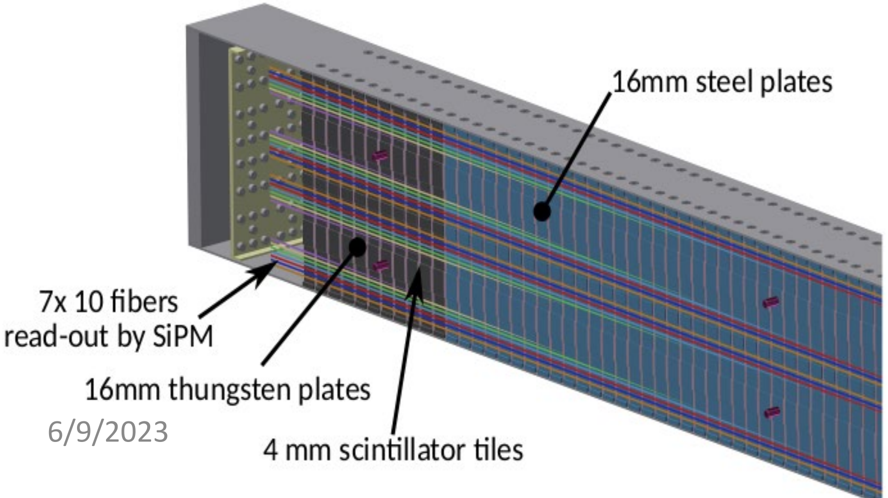
R&D: Improvement of light collection eff. and uniformity

Simulations:

- Expected E resolution ~ $11\%/\sqrt{E} \oplus 2\%$
- Can effectively separate γ/π^0 (z = 3.5 m) with ML methods

Forward Hadronic Calorimetry





Design based on longitudinally separated steel and scintillator tiles (ORNL)

- Inspired by Projectile Spectator Detector (CBM)
  - 60 layers of steel-sci plates + 10 layers of W-Sci plates (5 x 5 cm towers)
  - 7 signals per tower (from 10 plates)
  - λ/λ_0 = 6.9 (HCAL only, larger shower containment)

- Ongoing efforts to explore granular inlay around beampipe

Particle Identification

- Sometimes it's just not enough to know that a particle passed by (and maybe it's charge). Some physics requires that we *identify* the particle as an electron, muon, proton, pion, kaon, etc.

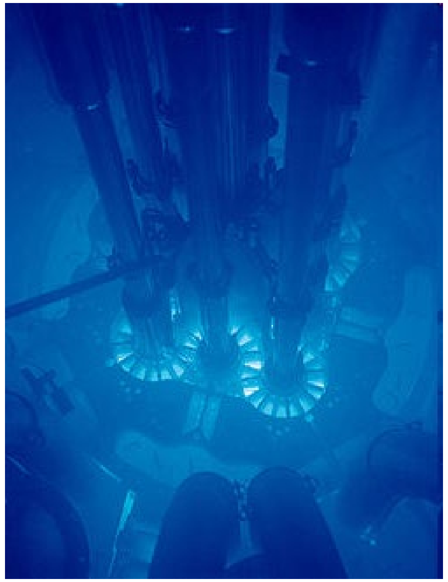
- Many techniques:
  - Electrons: match momentum (tracking) and calorimetry (energy)
  - Reconstruct a decay (calculate invariant mass)
  - Penetration depth (muons)
  - Time of Flight (sensitive to velocity)
  - Cerenkov radiation (sensitive to velocity)
  - …

Cerenkov Counters

- Cerenkov light is emitted when a particle travels faster than the speed of light in a medium
  - Similar to a sonic boom (but optical)
  - Light emitted at a characteristic angle:

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

  - Light depends on particle velocity
    - Different momentum for different masses
  - Threshold Counter:
    - Just detect the light
  - Ring Imaging Cerenkov (RICH):
    - Image the ring, measure the angle
    - Can be used to identify different particle types
    - Typically, only a few photons, measurements are delicate!



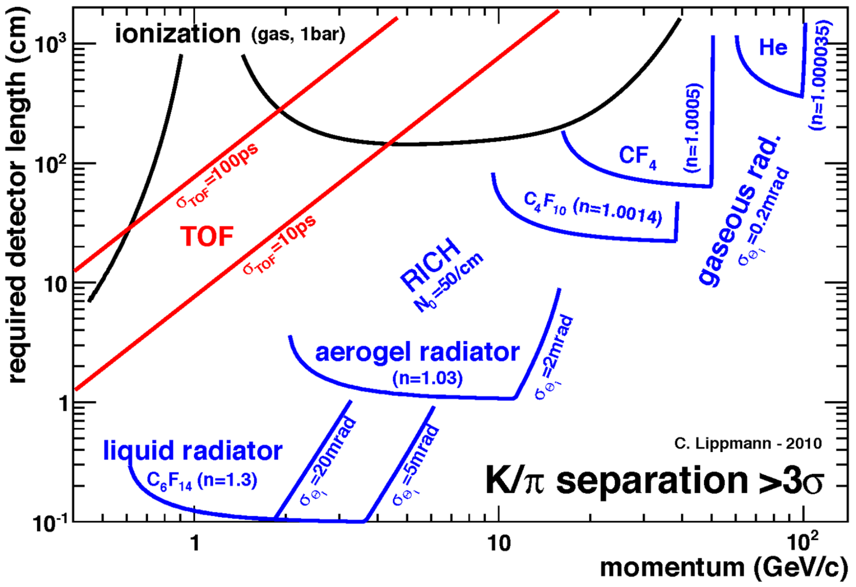
Cerenkov radiation from nuclear fission reactor core.

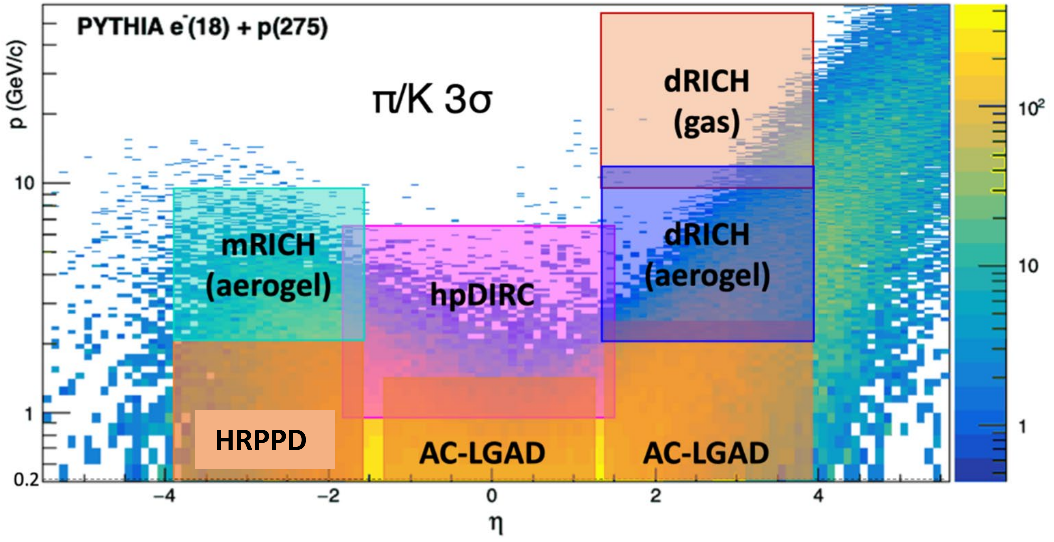
Particle ID

Particle IDentification needs

- Electrons from photons ⟶ **4π coverage in tracking**
- Electrons from charged hadrons ⟶ **mostly provided by calorimetry and tracking**
- Charged pions, kaons and protons from each other on track level ⟶ **Cherenkov detectors**
    - Cherenkov detectors, complemented by ToF

Rapidity	$\pi/K/p$ and π^0/γ	e/h	Min p_T (E)
-3.5 – -1.0	7 GeV/c	18 GeV/c	100 MeV/c
-1.0 – 1.0	8-10 GeV/c	8 GeV/c	100 MeV/c
1.0 – 3.5	50 GeV/c	20 GeV/c	100 MeV/c



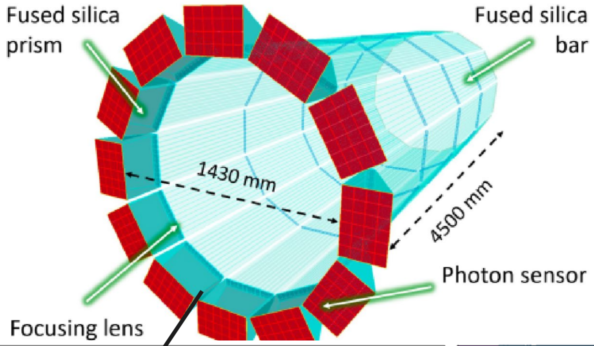


Need more than one technology to cover the entire momentum ranges at different rapidities

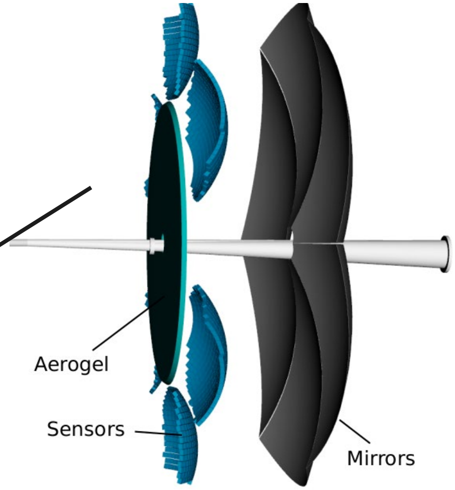
Particle ID

High-Performance DIRC

- Quartz bar radiator (BaBAR bars)
- light detection with MCP-PMTs
- Fully focused
- π/K 3σ separation at 6 GeV/c



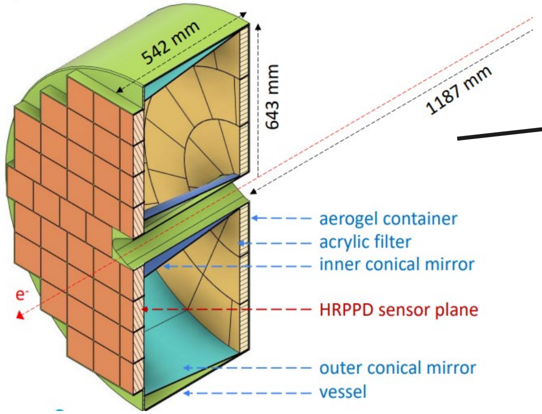
Dual-Radiator RICH(dRICH)

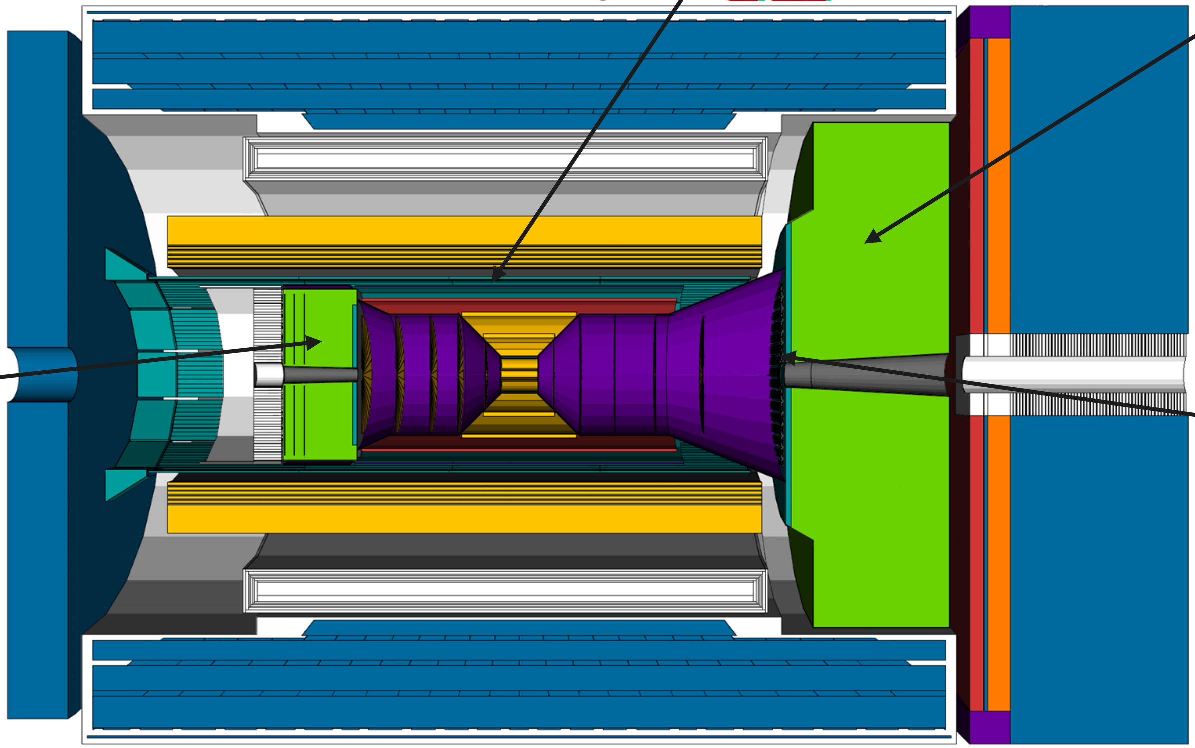


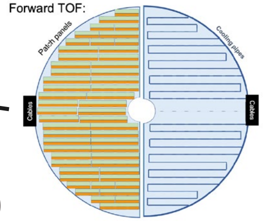
- C_2F_6 Gas Volume and Aerogel
- Sensors tiled on spheres (SiPMs)
- π/K 3σ sep. at 50 GeV/c

Proximity Focused (pfRICH)*

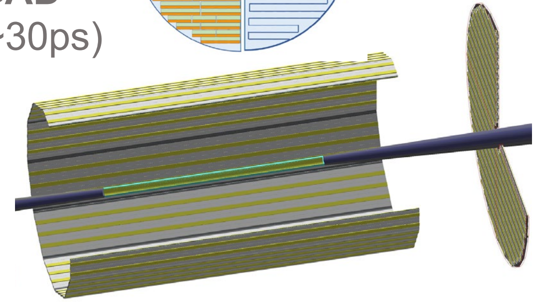
- Long proximity gap (~40 cm)
- Sensor: LAPPDs
- up to 9 GeV/c 3σ π/K sep.





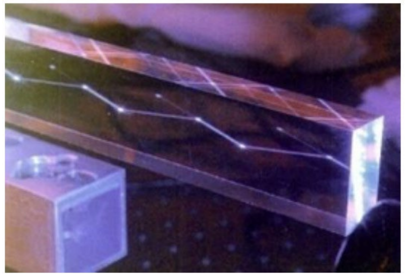


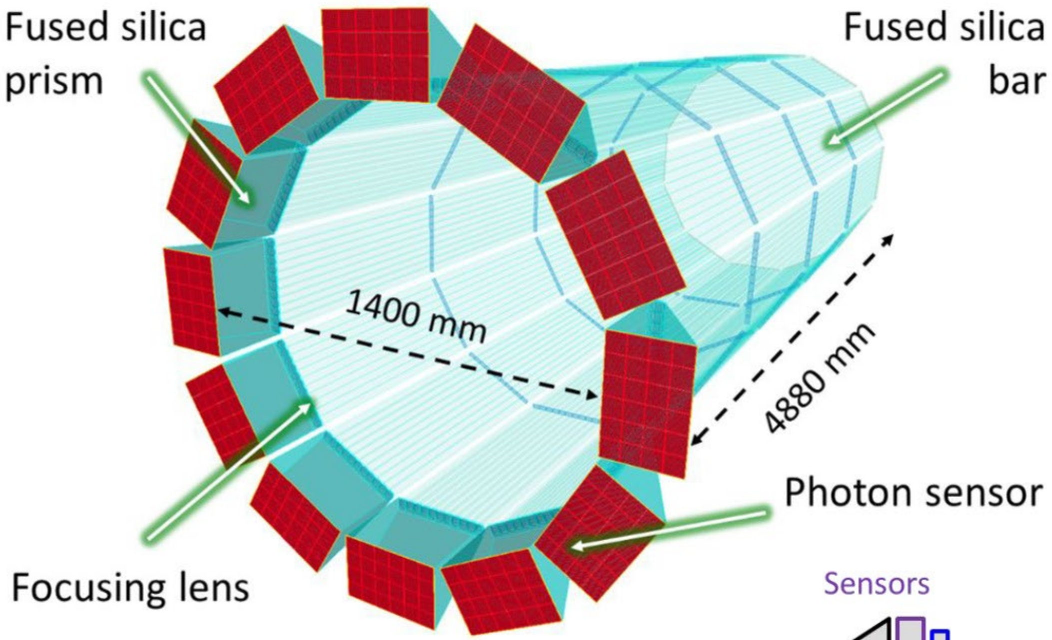
AC-LGAD TOF (~30ps)

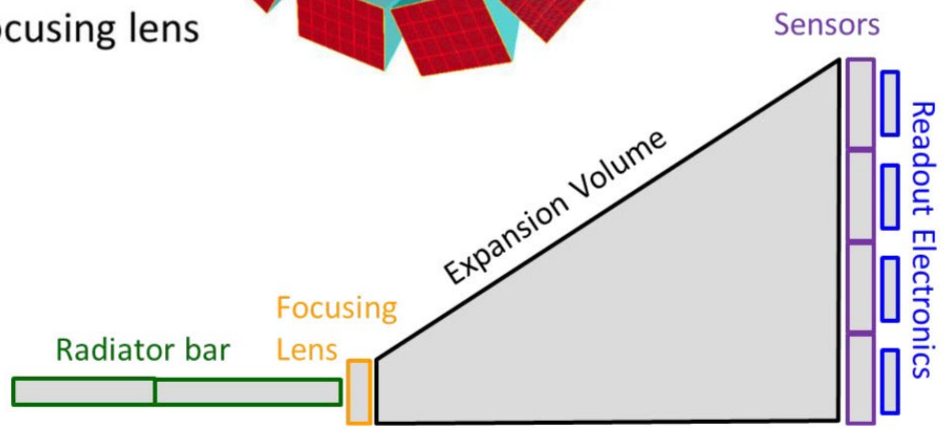


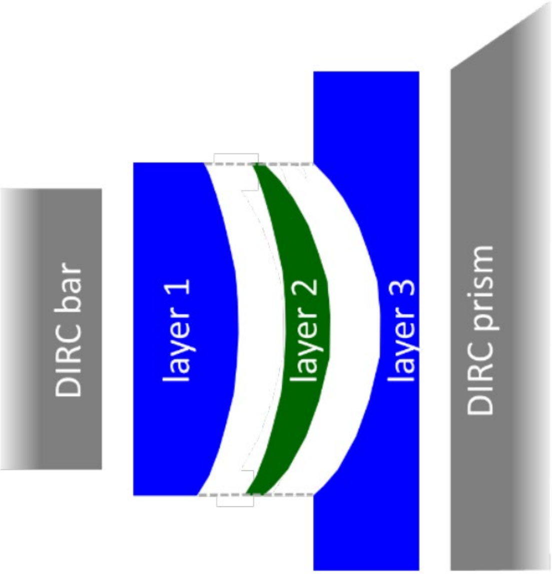
- Accurate space point for tracking
- forward disk and central barrel

hp-DIRC

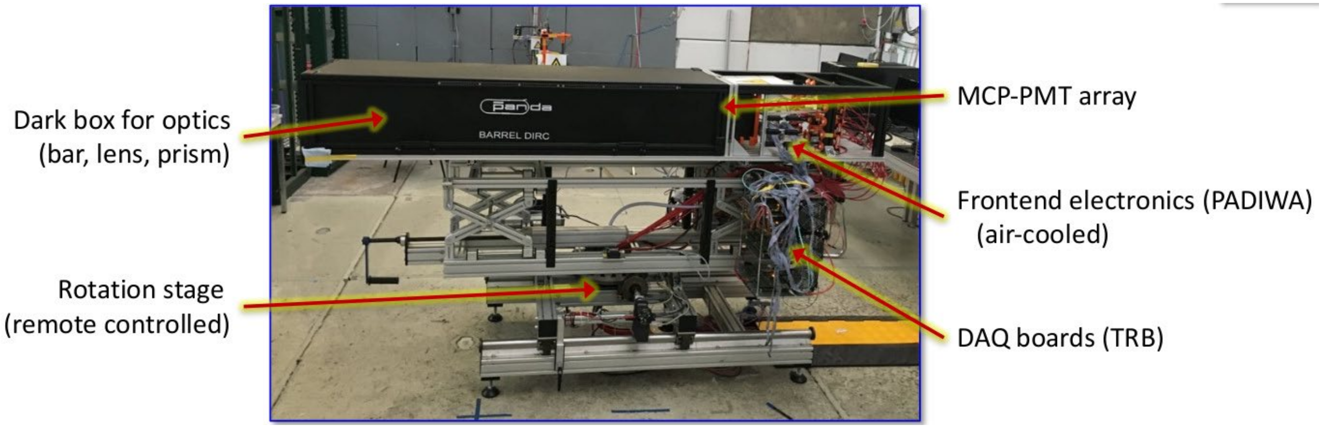




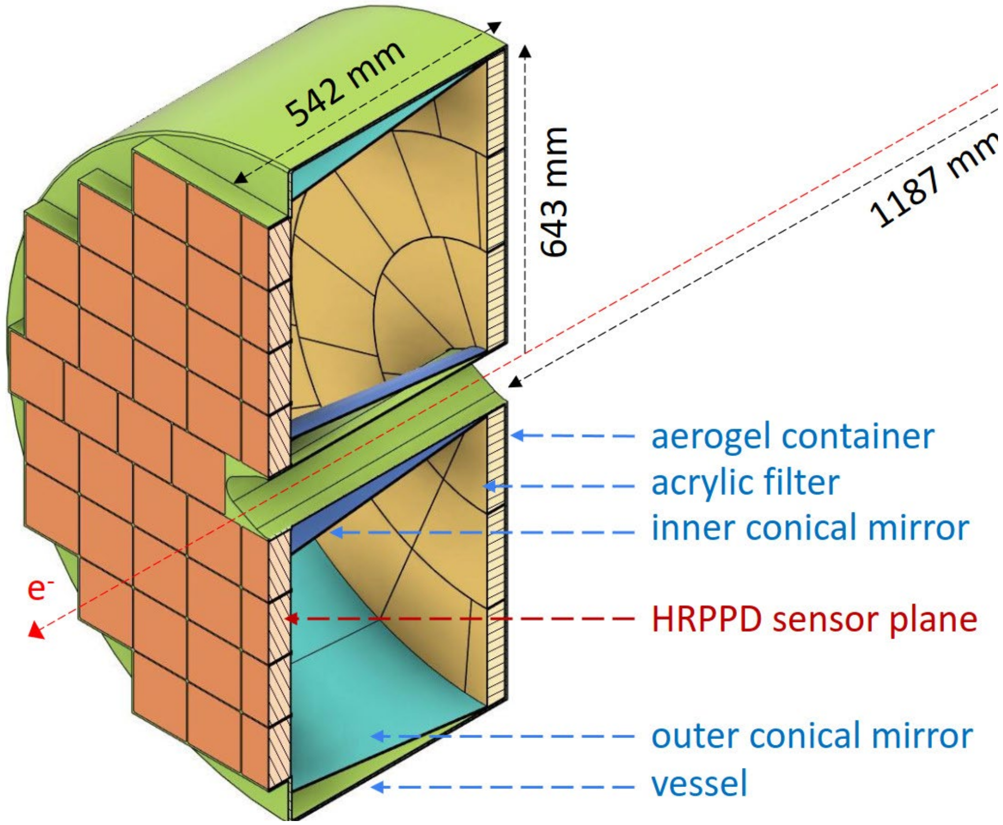




- Improved resolution.
- Key components:
  - Innovative focusing lens
  - Compact fused silica expansion.
  - Fast photon detection.

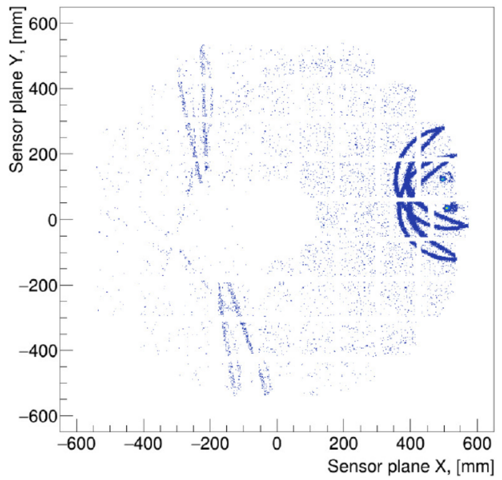


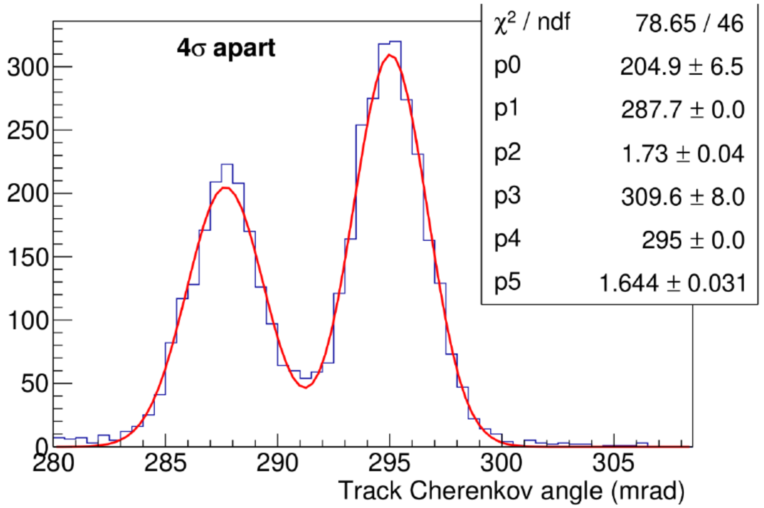
Proximity Focusing RICH



e-endcap RICH for ePIC detector

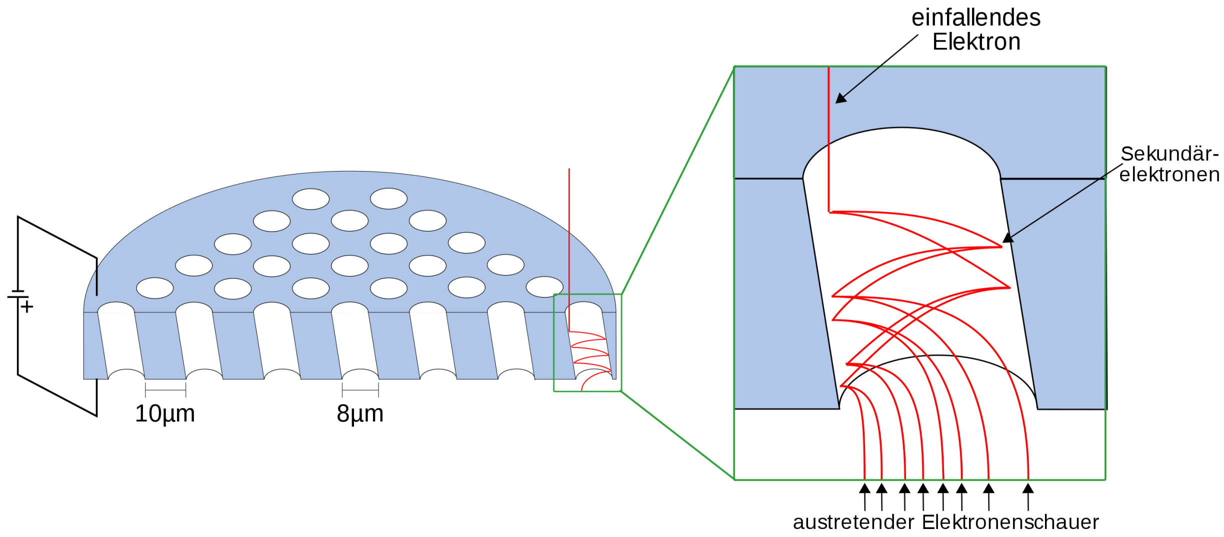
- A classical proximity focusing RICH
- Pseudorapidity coverage: $-3.5 < \eta < -1.5$
- Uniform performance in the whole $\{\eta,\phi\}$ range
- π/K separation above 3σ up to ~ 9.0 GeV/c and ~10-20ps t_0 reference with a ~100% geometric efficiency in one detector





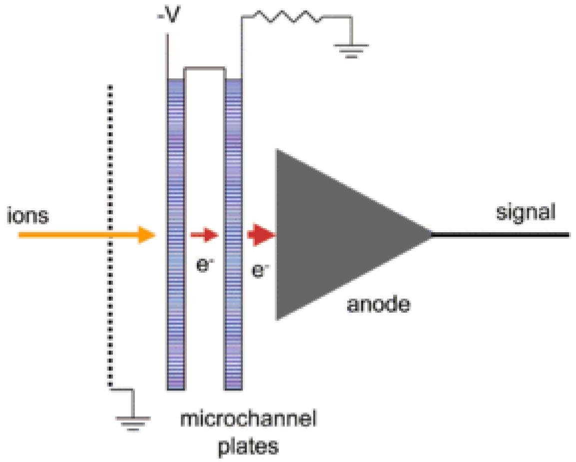
Sophisticated chi-squared analysis capable of performing efficient pid with complicated event topologies.

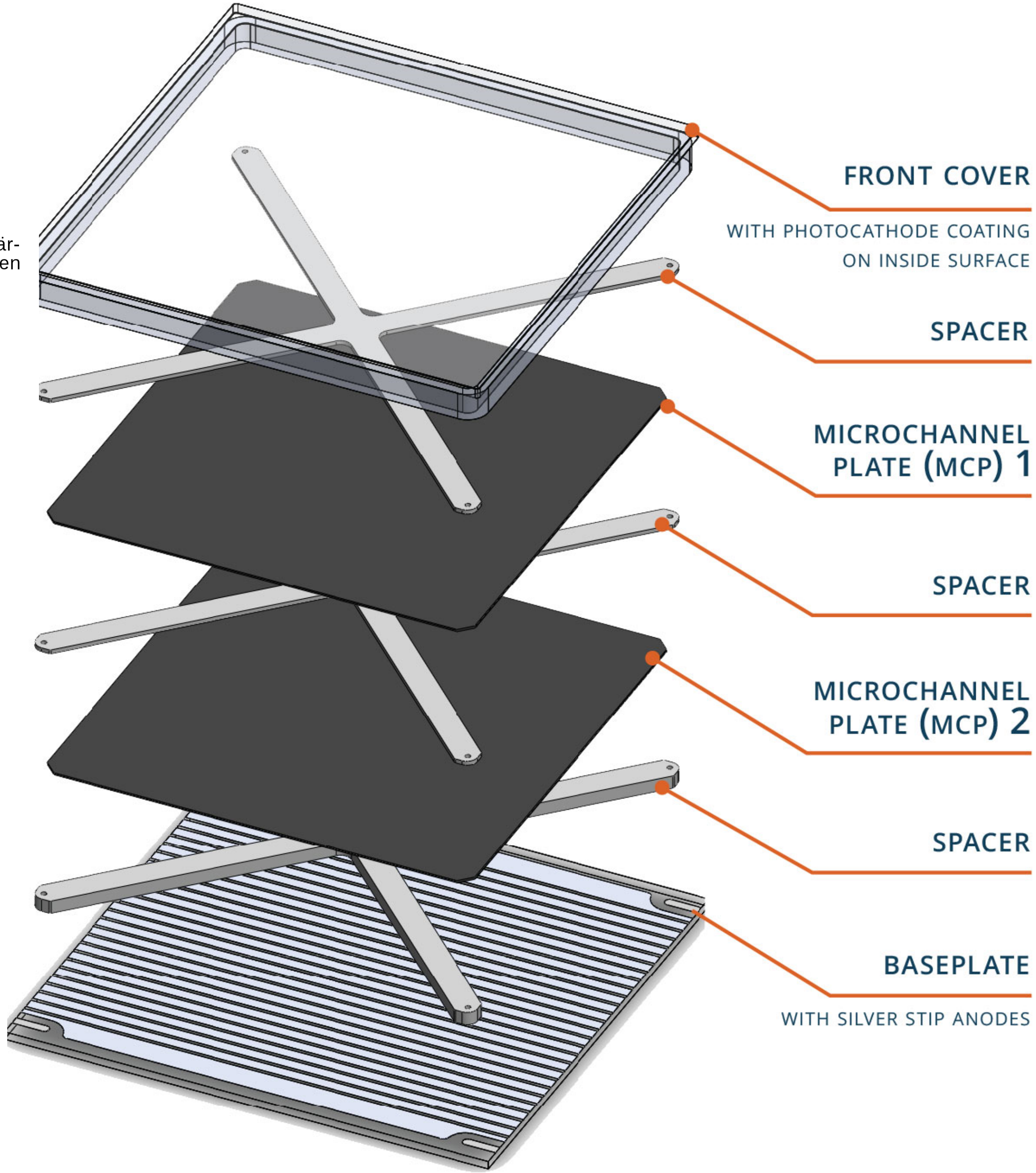
LAPPD/HRPPD's



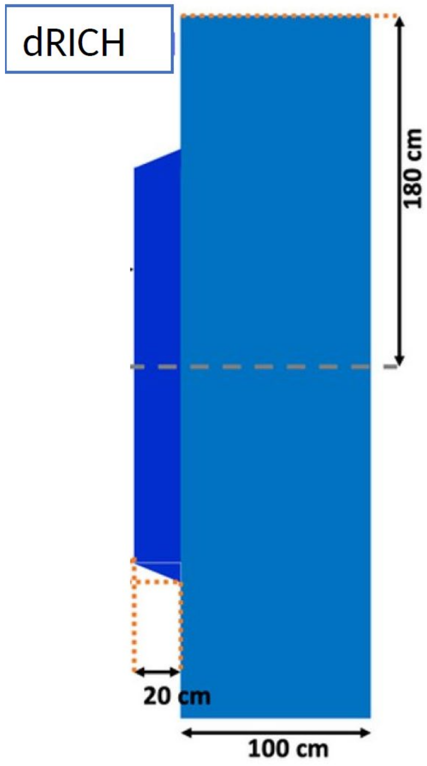
LAPPD's offer good gain, excellent timing and large area coverage with a configurable readout structure.

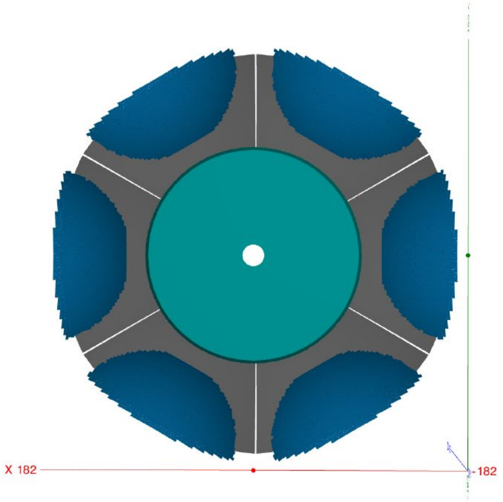
In the ePIC pfRICH they can be used both to detect Cerenkov photons from the aerogel as well as the passage of the primary particle.





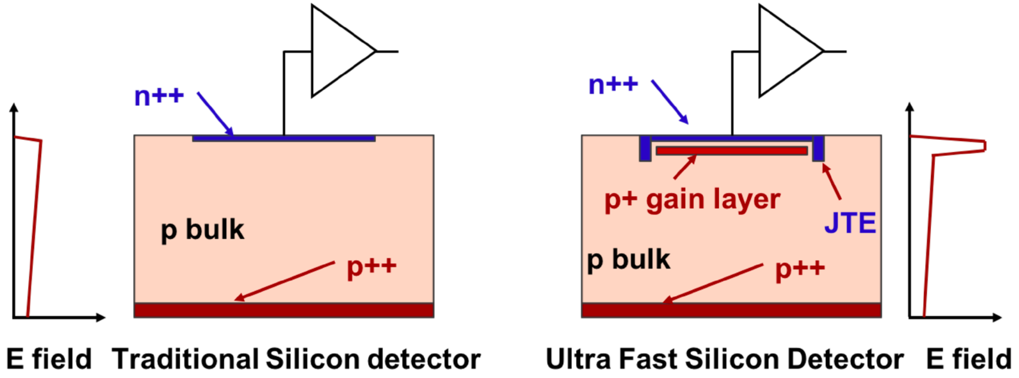
Dual Radiator RICH

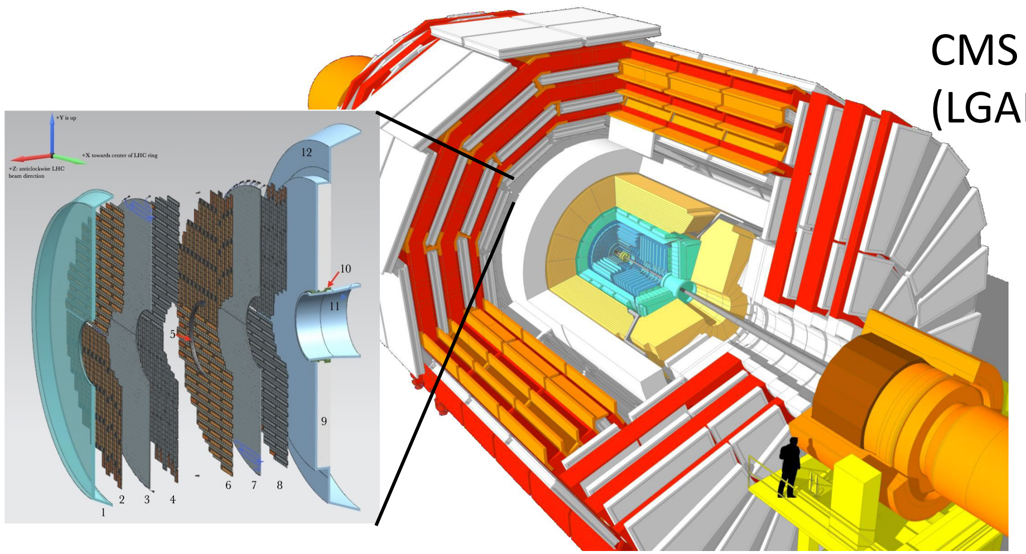




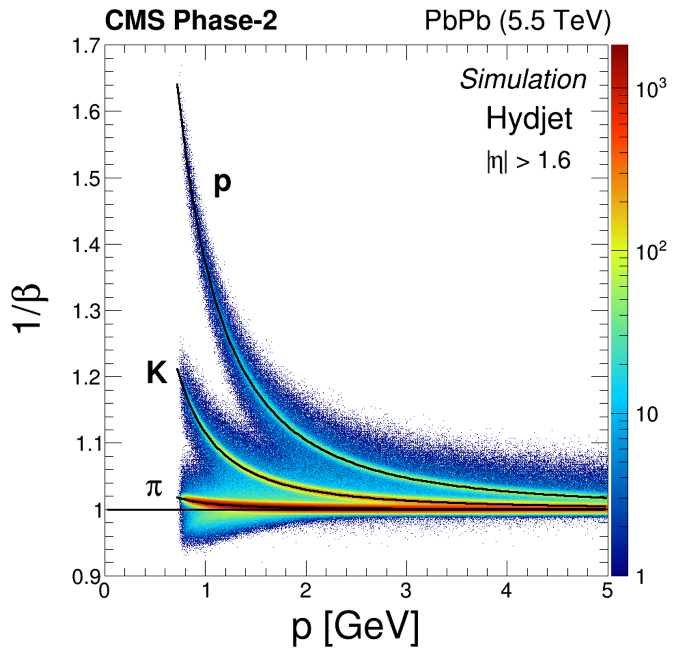
- Requirements:
  - Wide acceptance (+- 300 mrad/ $1.5<\eta\leq3.5$)
  - High momentum coverage up to 50GeV/c pi-K
    - Dual radiator (aerogel (n ~1.02)+ C_2F_6 gas (n~1.0008))
- Short radiator space available
  - Smaller number of detected photons → Critical optical tuning and control over background hits.
- Large sensor surface to be covered in magnetic field.
  - Limited choice of photon-sensor(SiPM as a cheap solution)
- Simulation contains: 6 identical sectors composing.
  - Spherical mirror with radius 220 cm
  - SiPM sensors with realistic PDE and additional 70% safety factor.

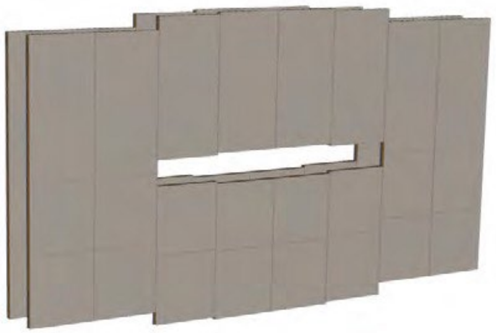
AC-LGAD TOF



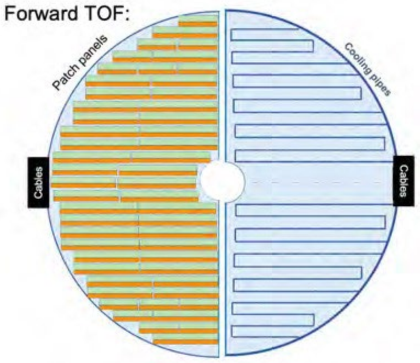


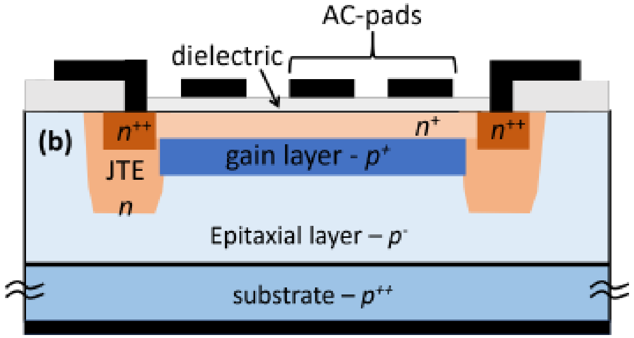
AC-LGAD detectors add an AC-coupled readout to provide both *fast timing response* and *excellent spatial resolution* (4D).



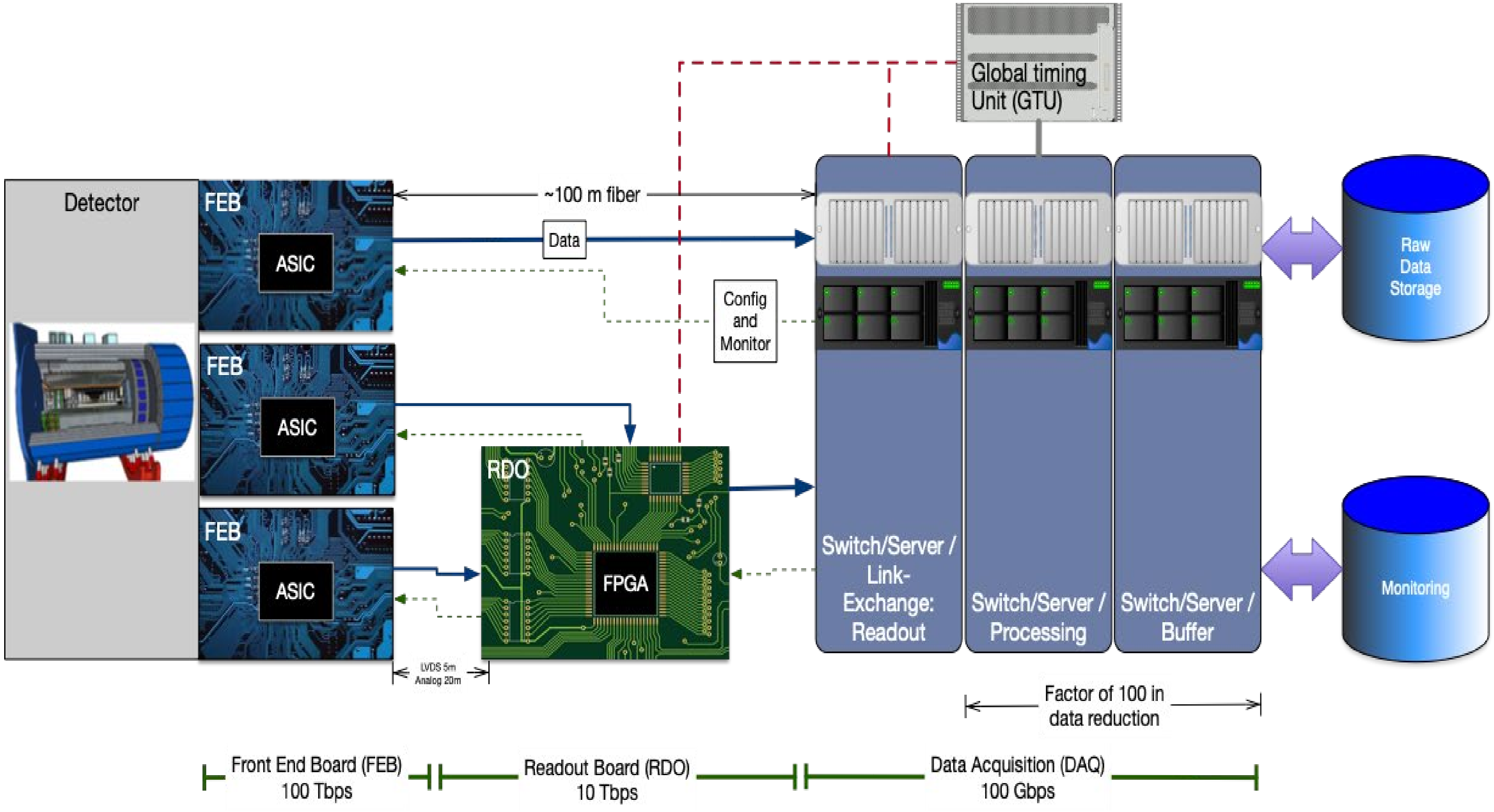


Roman pot arrays





ePIC Streaming DAQ

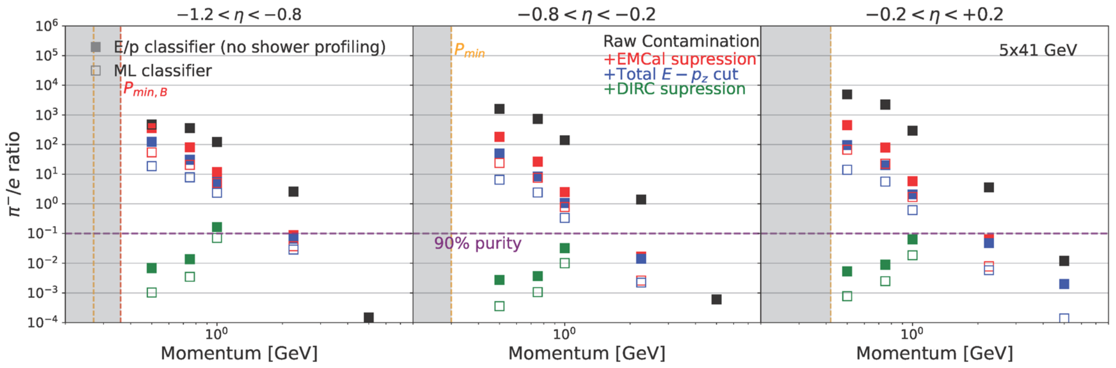


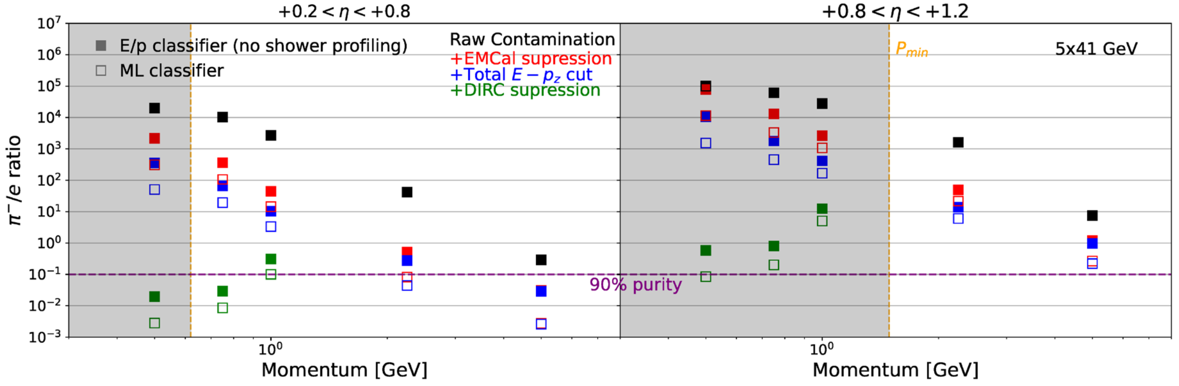
- No External trigger
- All collision data digitized but aggressively zero suppressed at FEB
- Low / zero deadtime
- Event selection can be based upon full data from all detectors (in real time, or later)
- Collision data flow is independent and unidirectional-> no global latency requirements
- Avoiding hardware trigger avoids complex custom hardware and firmware
- Data volume is reduced as much as possible at each stage

5 x 41 GeV

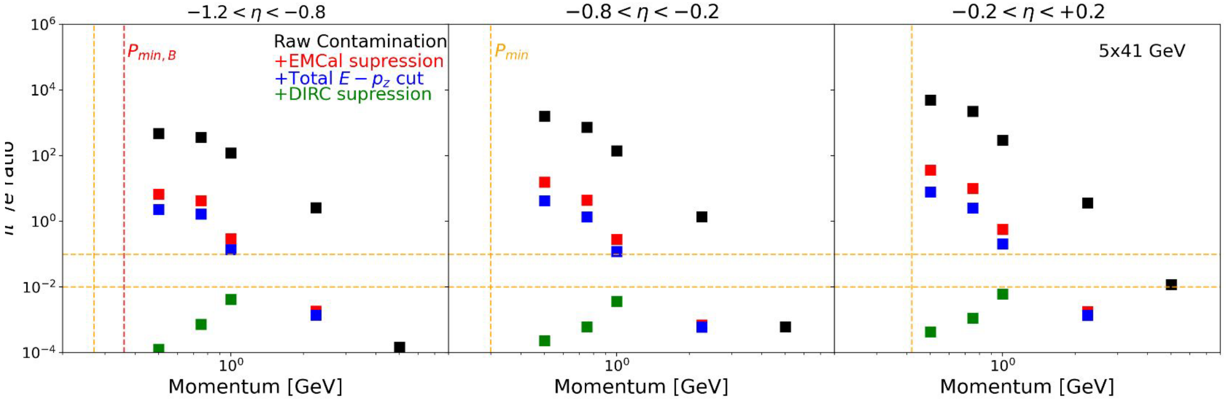
Note that the 5x41 GeV plots do not take advantage of the extended hpDIRC coverage

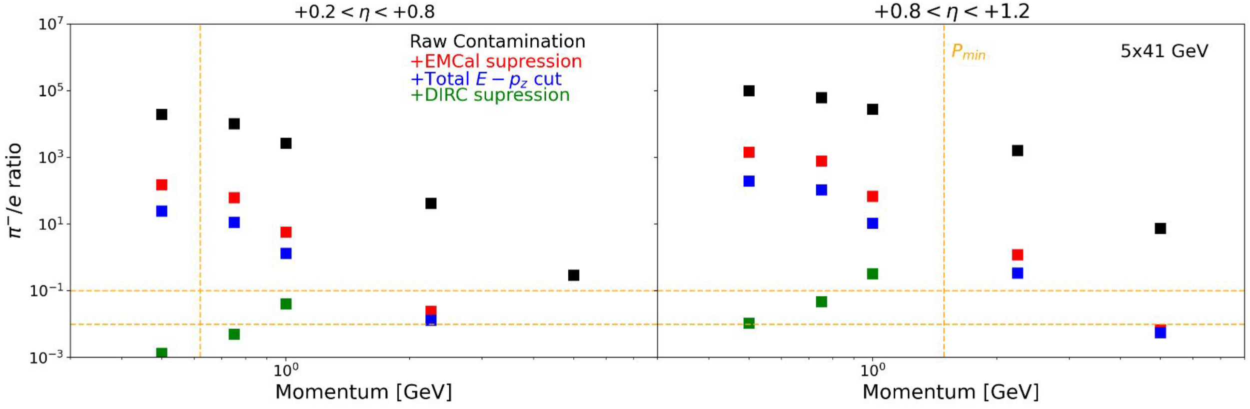
SciGlass EMCal Results
(from D. Kalinkin, 4/3/2023)





Imaging EMCal Results
(from M. Zurek, 4/6/2023)





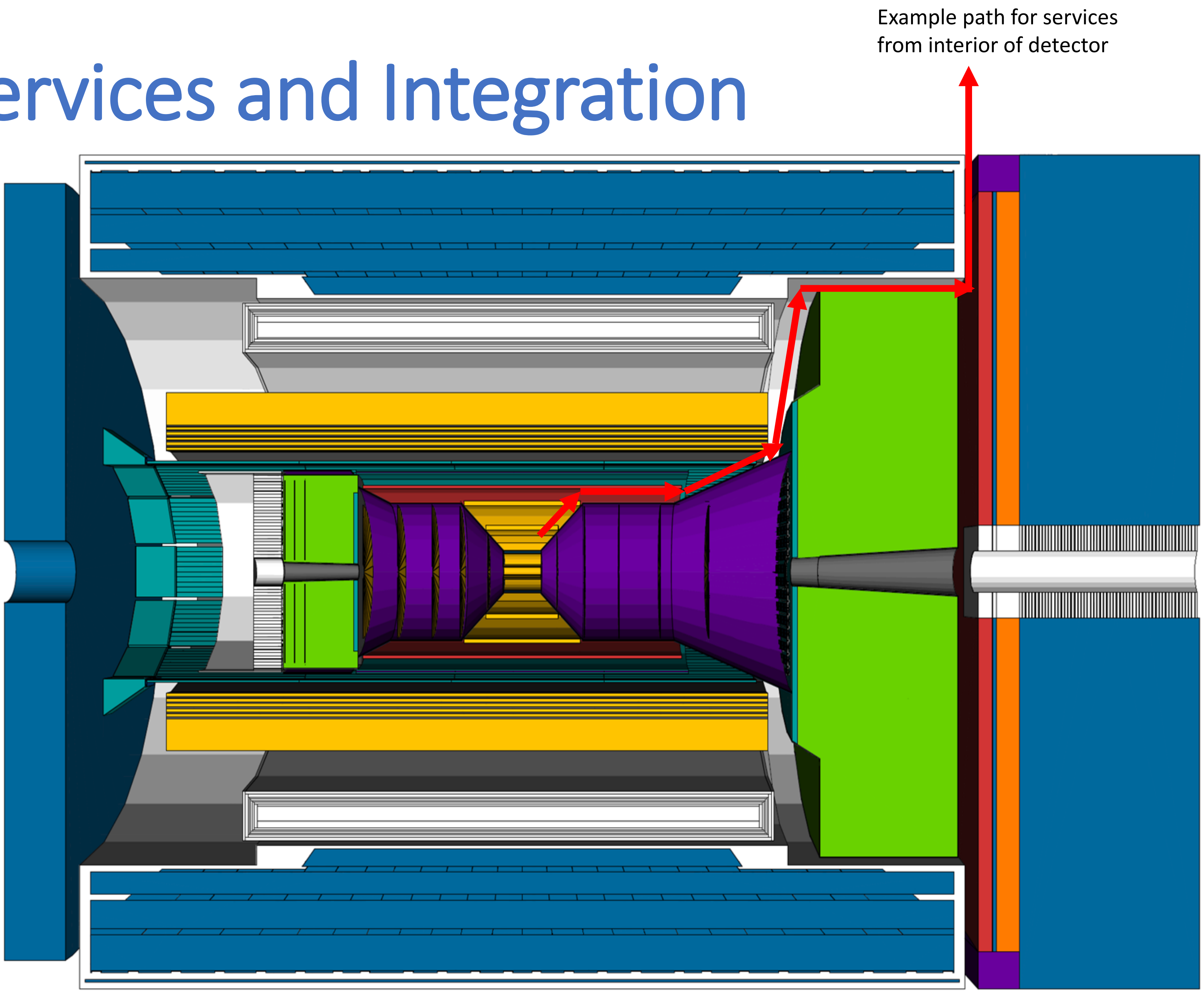
Detector Services and Integration

Detectors require:

- Support frames
- Power
- Cooling
- Signals out
- …

All of this represents dead, un-instrumented material in the path of the particles you are trying to detect!

Clever engineering and integration is required to minimize to optimize the capabilities of the combined detector.



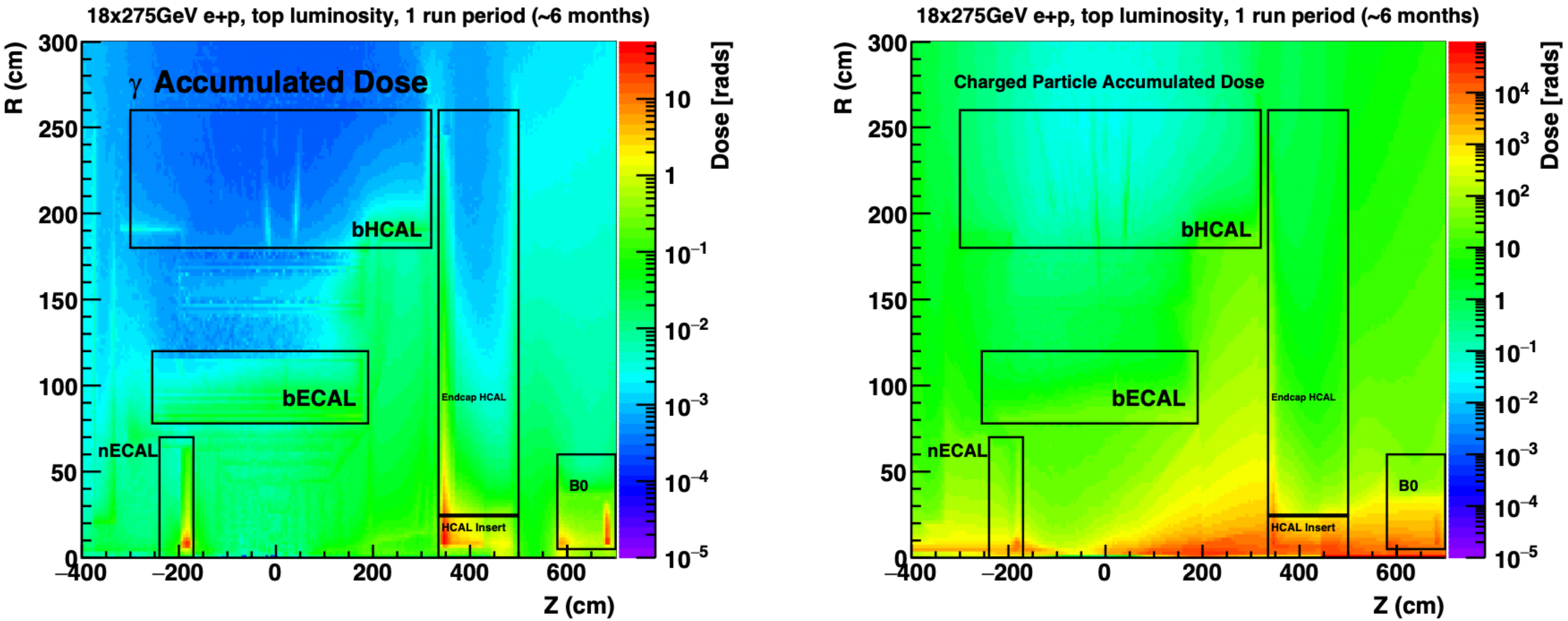
Detector Backgrounds/Radiation

- Three types of background/radiation sources we need to worry about:
  - Primary collisions
  - Synchrotron radiation
  - Beam-gas induced
- All of these couple with the beam parameters
  - Divergence, energy spread, crossing angle, bunch length

- Why are these “bad”?
  - Detector occupancy
    - Additional hits in detectors (especially for the tracker vertexing layers)
    - Affects PID detectors due to scattering and secondary interactions
  - Detector lifetime (radiation damage)

Primary Collisions (photons and charged)

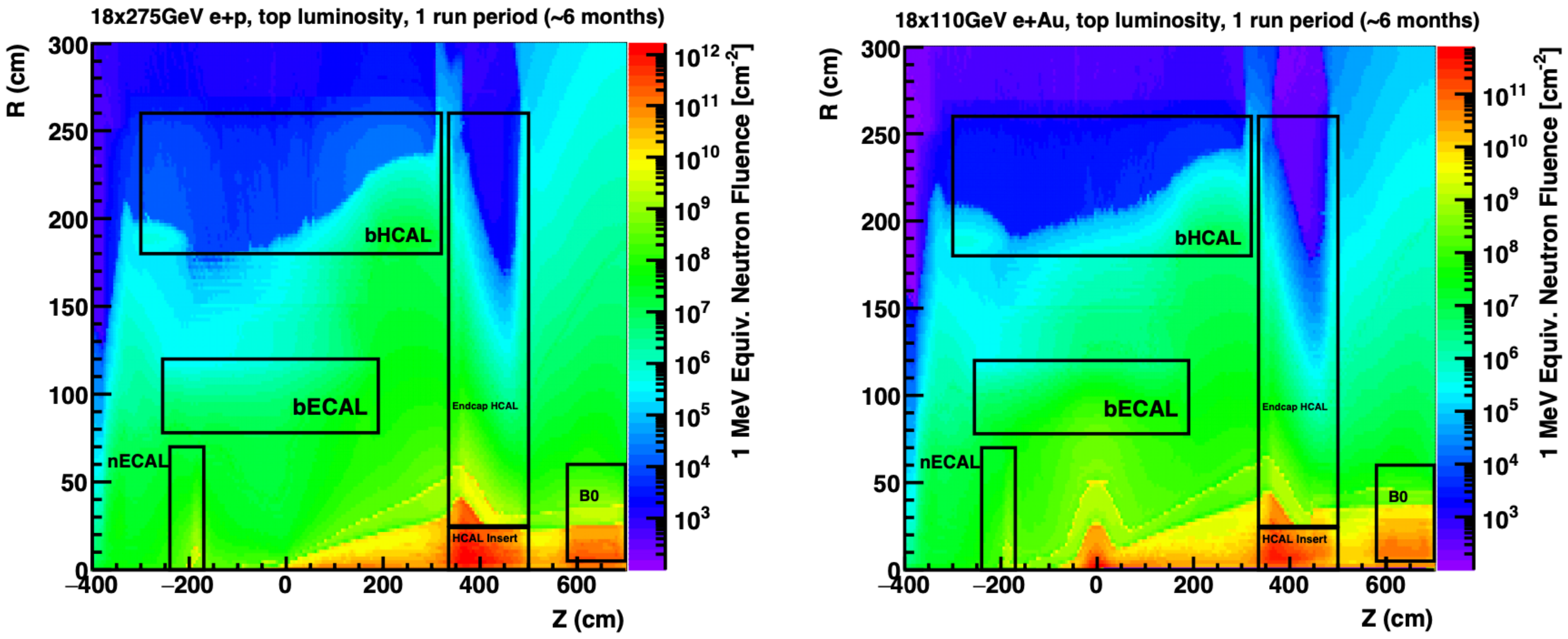
- Primary source of *ionizing radiation* and *low energy neutrons*



Radiation doses from gamma and charged particles fairly low across most of ePIC.
Regions of highest dose near the beam line - can reach ~ 100 kRad.

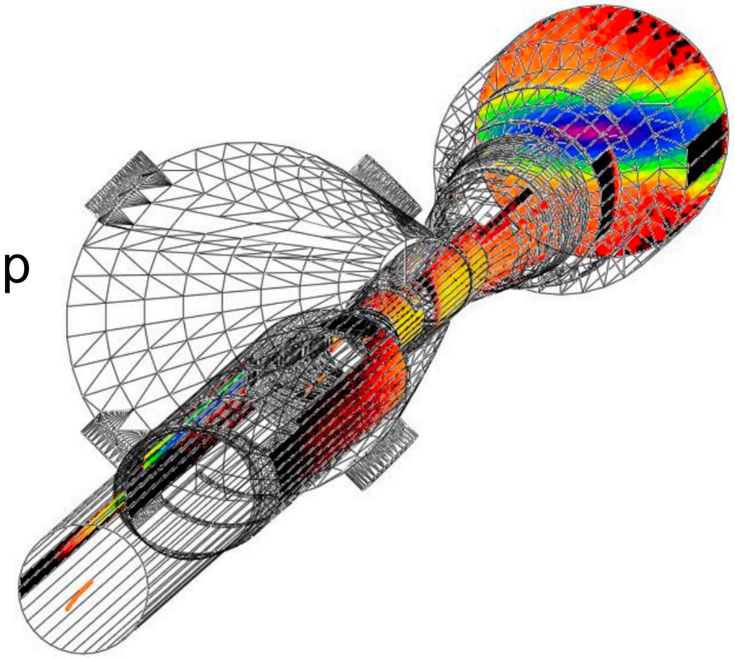
Primary Collisions (neutrons)

- Primary source of *ionizing radiation* and *low energy neutrons*

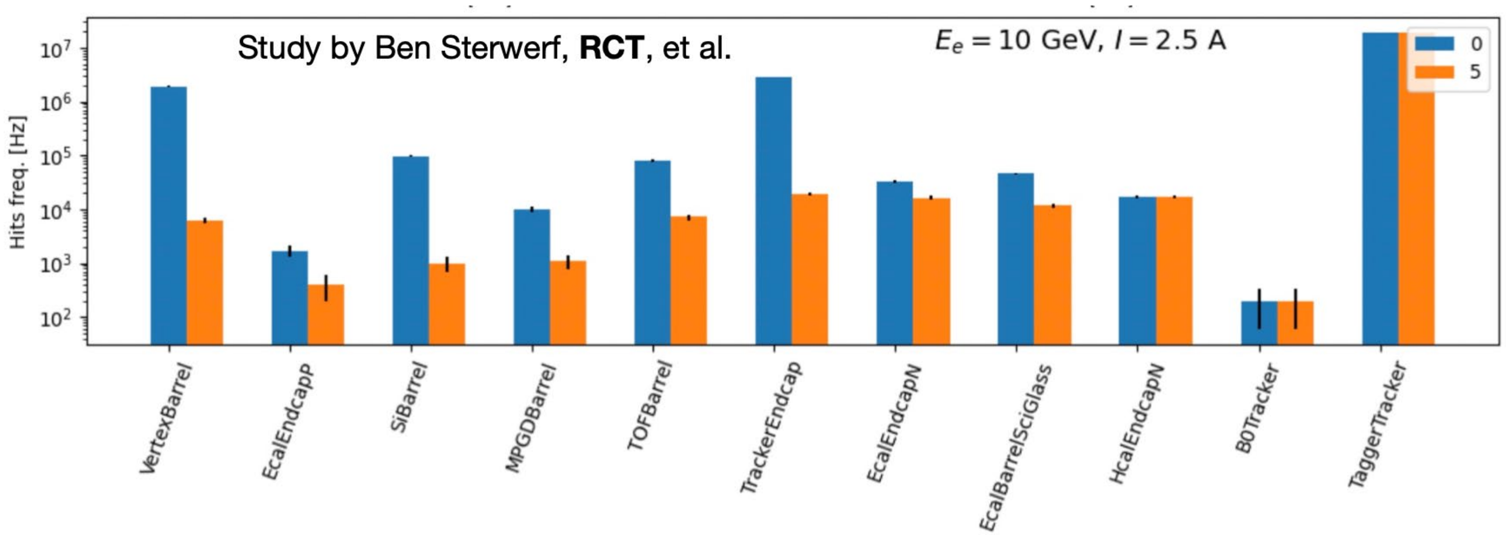


1 MeV equivalent neutron fluence highest near the beamline -> implications for SiPMs.

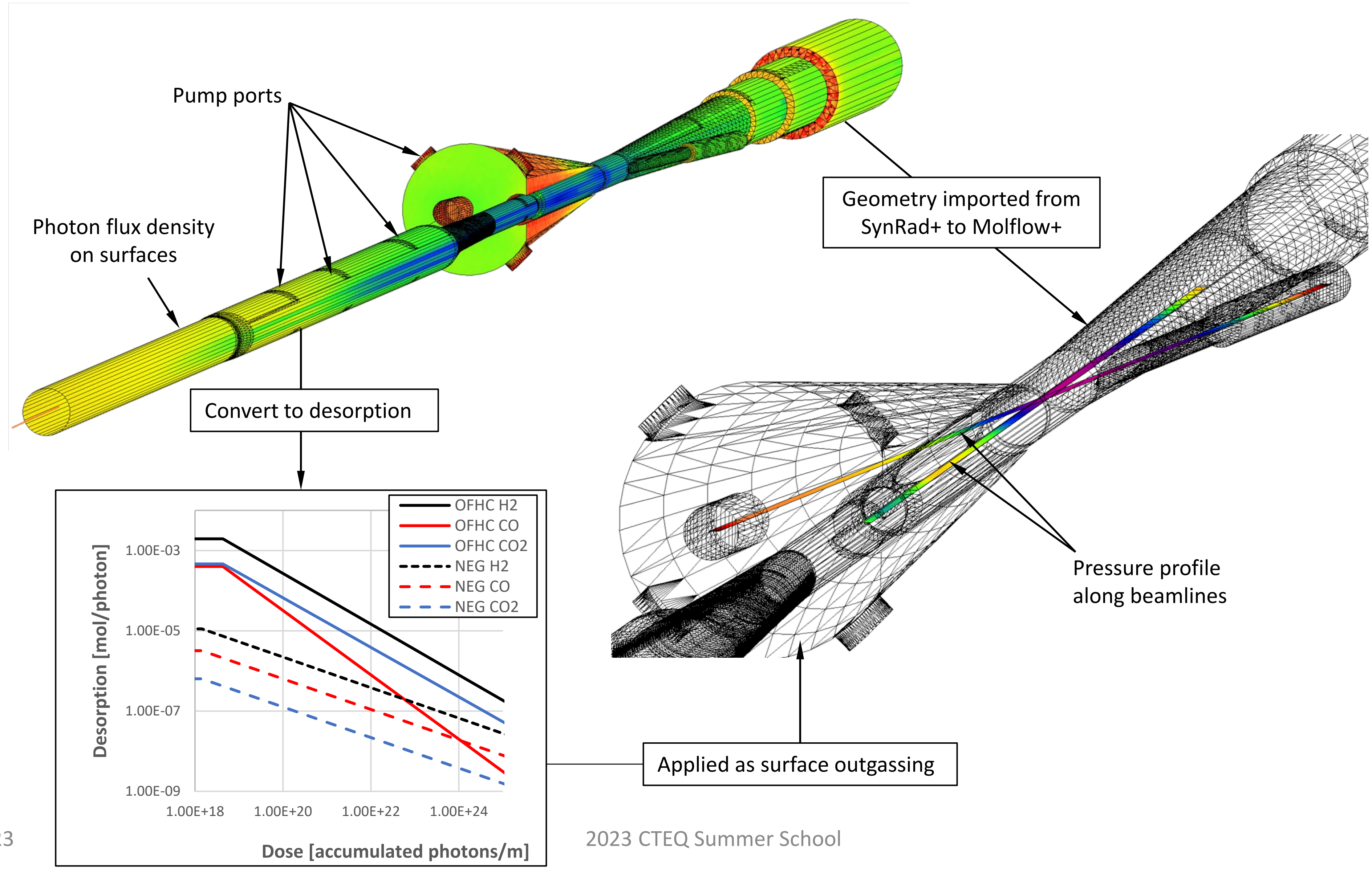
Synchrotron Radiation



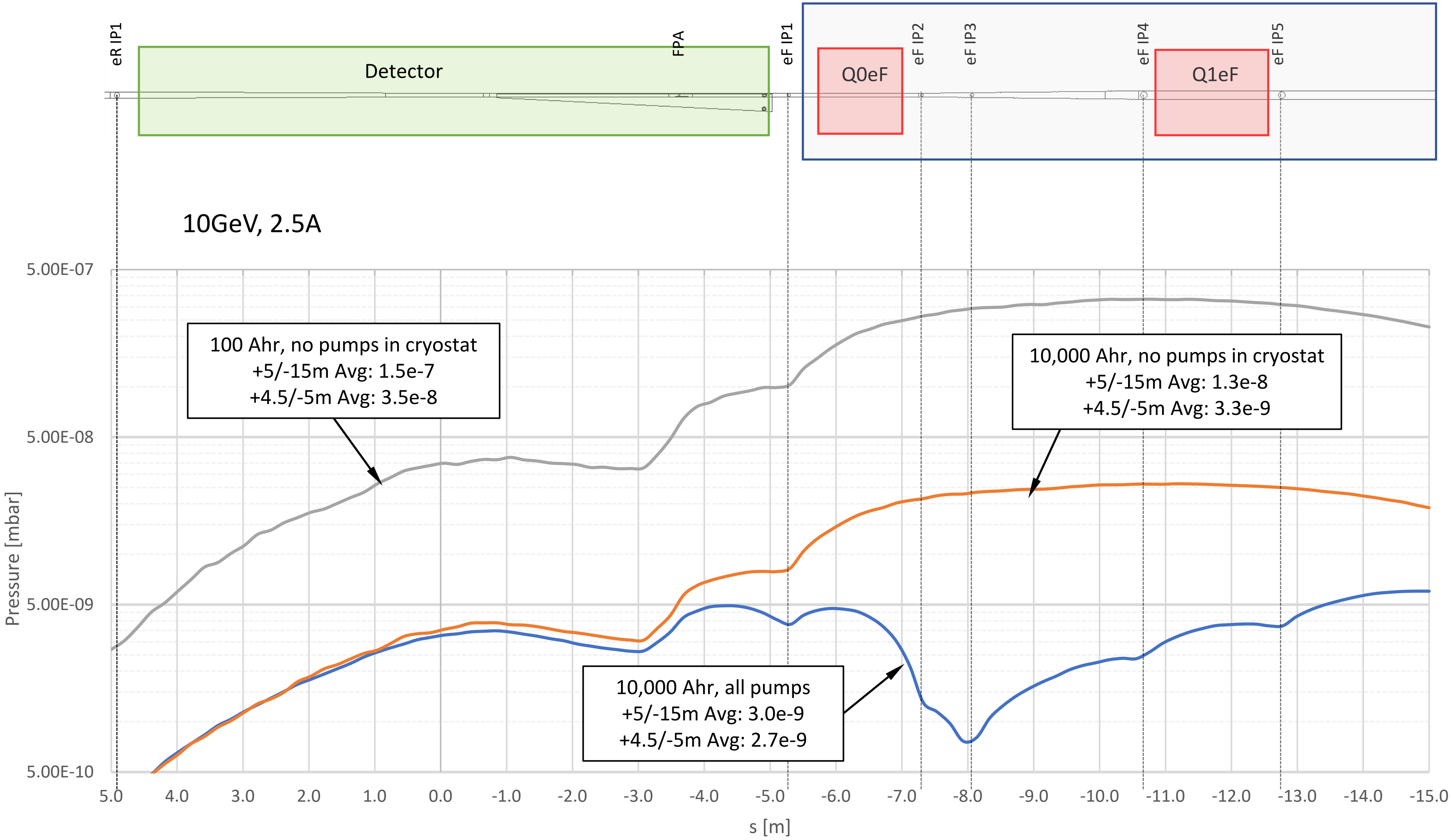
- Extensive simulations by of SR by accelerator background WG group
  - SynRad+ modeling software
  - Input:
    - 3D model of beampipe
    - Beam emittance, current Magnet locations and fields
  - Output:
    - Synchrotron Radiation – Position, Flux, Energy, Direction
- Synchrotron Radiation Mitigation
  - Photon absorber configuration:
  - Wider beam pipe for
    - 13.5 σ clearance in x
    - 23 σ clearance in y
  - Beampipe material/structure
    - 2-5 μm Au coating
    - Sawtooth/ridge texture for photon absorption



Synchrotron Radiation and Desorption



Pressure in Forward Cryostat

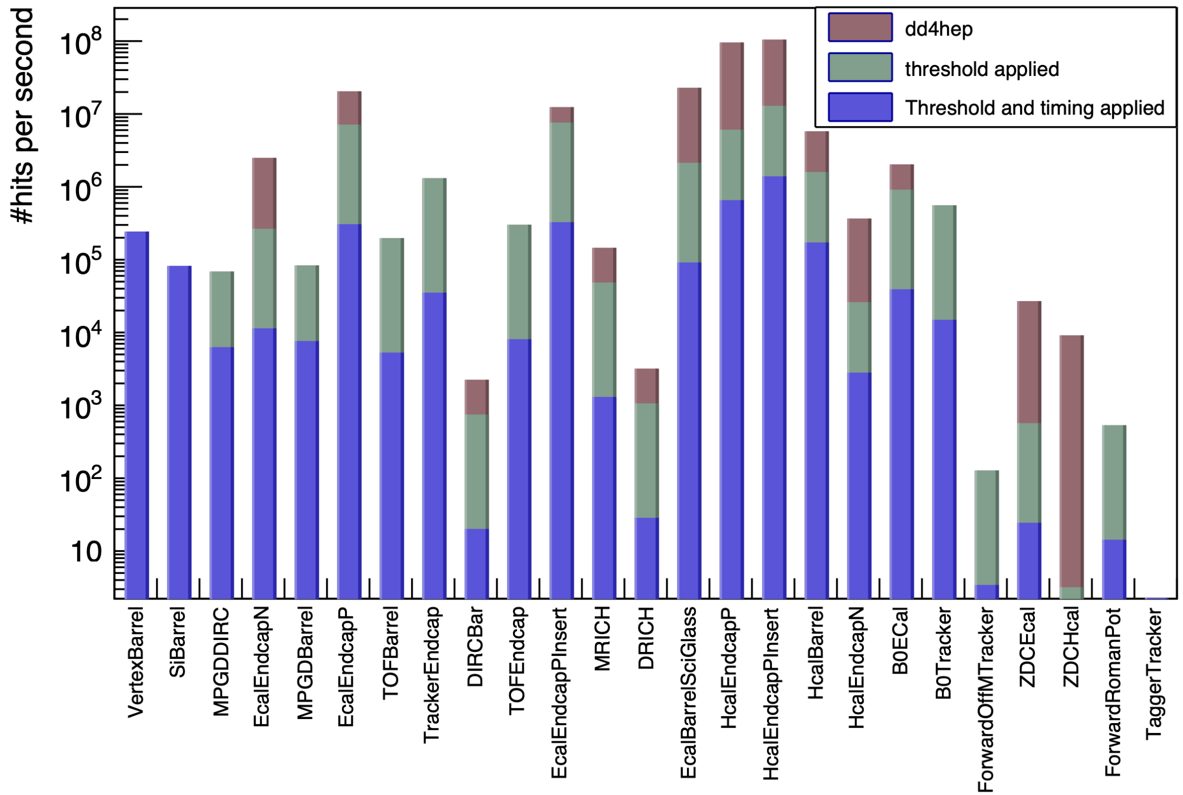


Beam-Gas Consequences

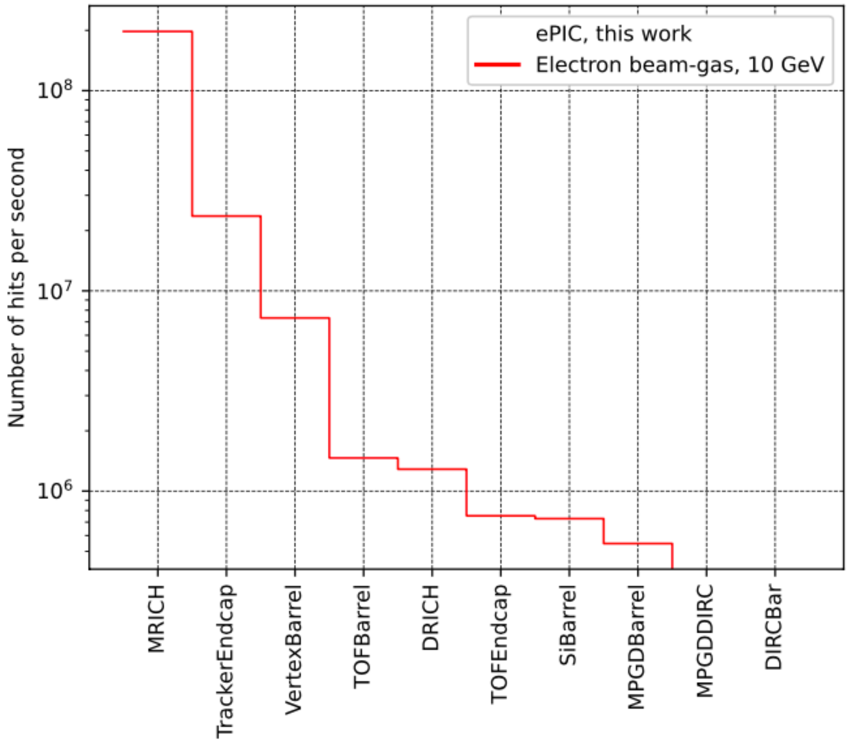
rates in kHz	5x41 GeV	5x100 GeV	10x100 GeV	10x275 GeV	18x275 GeV
DIS ep	12.5 kHz	129 kHz	184 kHz	500 kHz	83 kHz
hadron beam gas	12.2kHz	22.0kHz	31.9kHz	32.6kHz	22.5kHz
electron beam gas	2181.97 kHz	2826.38 kHz	3177.25 kHz	3177.25 kHz	316.94 kHz

Proton Beam: $\mathrm{p/A} + H^2 \rightarrow stuff$

(also a significant contribution to low-energy neutrons in detector hall)

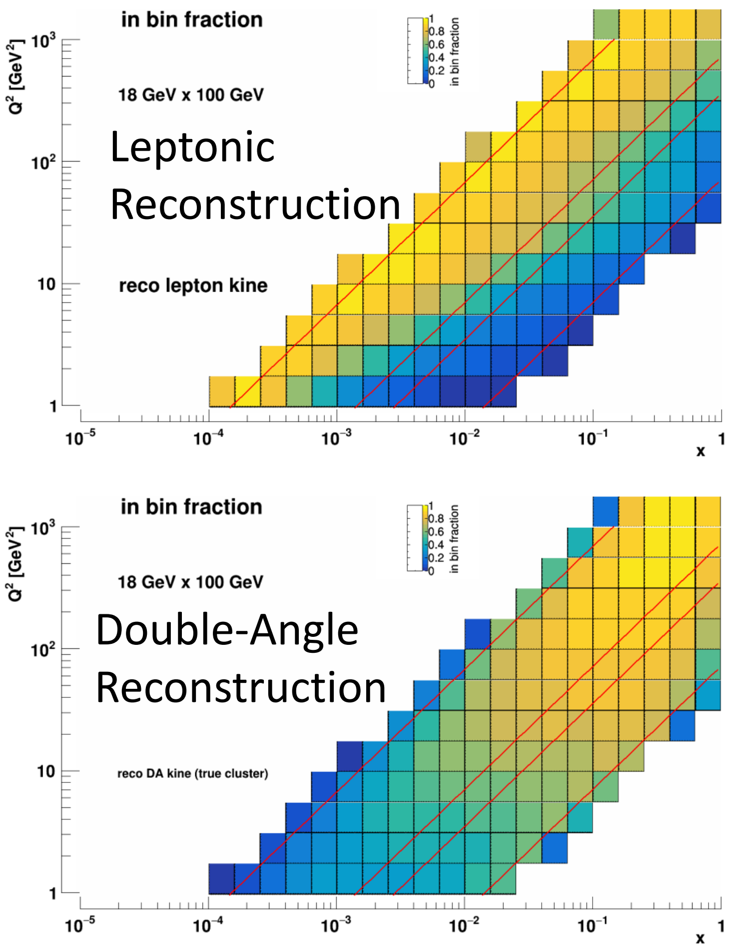


Electron Beam: $\mathrm{e} + H^2 \rightarrow e' + \gamma + H^2$



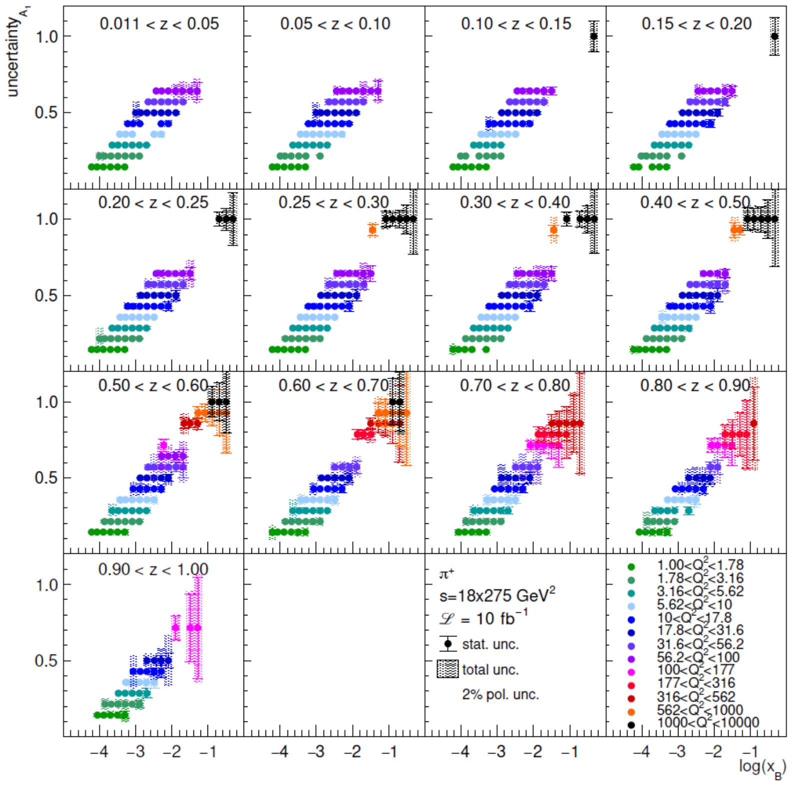
ePIC Physics Studies

First large-scale simulation campaign completed
Regular simulation campaigns every month

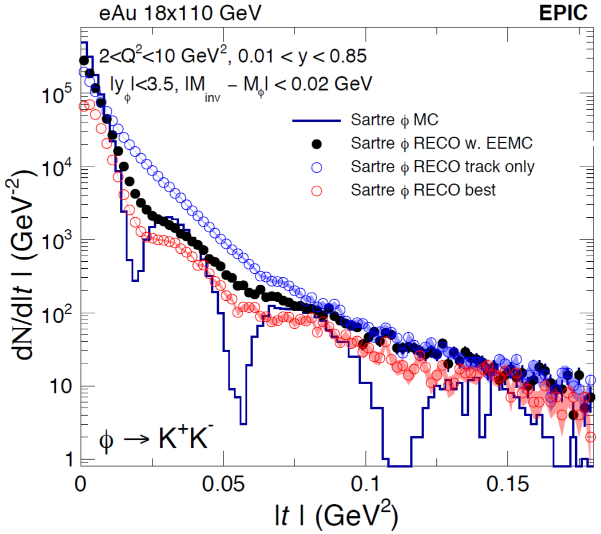


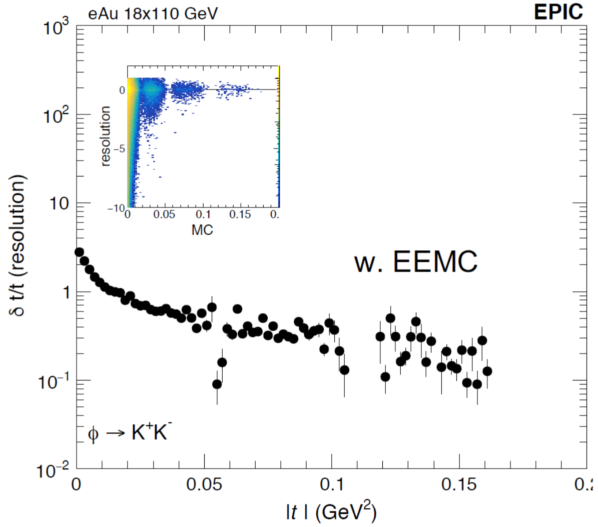
Ralf Seidl

Projected A_1 Uncertainties



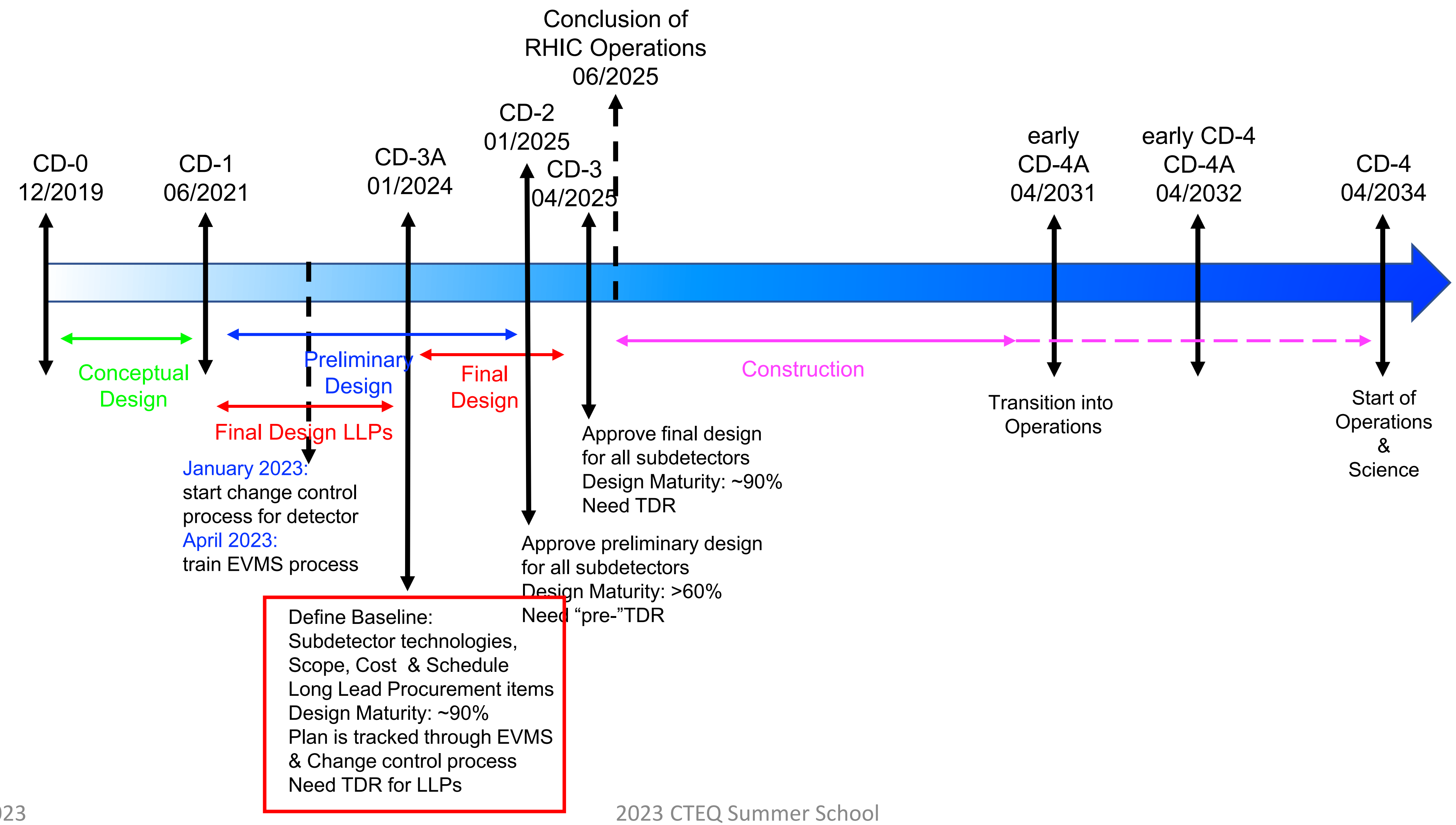
Charlotte Van Hulse





Kong Tu

EIC Project Schedule



Conclusions

- Modern particle physics detectors subsystems are a marvel of advanced science, engineering, and humility.
  - There is some beautiful physics in particle detection
  - Each technology has its advantages and disadvantages
  - There is constant development to improve and refine these technologies

- The ePIC Detector is maturing into a detailed technical design to pursue the EIC science program.
  - The key to a successful EIC detector is a combination of technologies that work together to meet the scientific requirements
  - EIC detectors are an enormous undertaking that will require participation and expertise from both the RHIC and JLab communities, as well as key international contributions!


"New directions in science are launched by new tools much more often than by new concepts."
Freeman Dyson


BACK UP

Lecture 1 Seed Question #1 : Neutrons (I)

- Neutrons have no charge, so no EM interaction
- Must have a strong interaction with nuclei in material
- Reactions like (n,p), (n,α), $(n,2n)$ are possible
- For interactions with charged final states our previous discussion takes over:
  - You can now either detect the α or the photon shower

$$^{10}B + n \rightarrow {}^{7}Li^{*} + \alpha$$

- For low (thermal) energies the primary process is neutron capture (n,γ)
- Neutrons will lose energy through (strong) elastic scattering in the material

Lecture 1 Seed Question #1 : Neutrons (II)

- For a neutron scattering off a nucleus A:

$$\frac{E'}{E} = \frac{A^2 + 1 + 2A\cos\theta}{(A+1)^2}$$

E = incident neutron energy
E' = final neutron energy

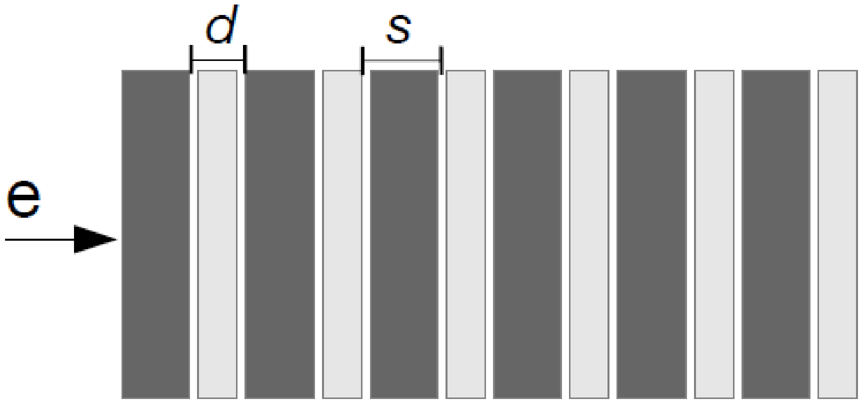
- For θ=180^o (head-on collision):

$$\left.\left(\frac{E'}{E}\right)\right|_{\min} = \left(\frac{A-1}{A+1}\right)^2$$

  - Heavy nuclei can slow neutrons down a lot
  - For hydrogen this value is 0 – the neutron “knocks out” a proton
  - This is important for calorimeters based on scintillator!

Lecture 1 Seed Question #2: Sampling Fraction

f_{sampl} is: $$\frac{d \cdot dE/dx^{active}_{MIP}}{d \cdot dE/dx^{active}_{MIP} + s \cdot dE/dx^{absorber}_{MIP}}$$



Lecture 2 Seed Question #1 :

- Here's a simple thought exercise that requires a bit of schitzophrenia:
- Start by imagining the perfect EIC experiment. Sketch out on a piece of paper a diagram of the experiment, including not just the central barrel but the far-forward detectors. Use what you have learned in the past week to guess where you want calorimetry, PID, tracking, etc. This doesn't need to be perfect, just take what you have learned and pull it all together. Think about what detector systems need to work together.

- Now, take a step back and for each detector system consider:
  - What sort of services does this detector need? Power, gas, cooling, etc? How will you hold it up? How will you take it apart to service it between runs?
  - Take a wild guess at what each detector will cost. Include not just the detector but the labor, engineering, etc. Again, just use some "physicist intuition" to estimate a number.