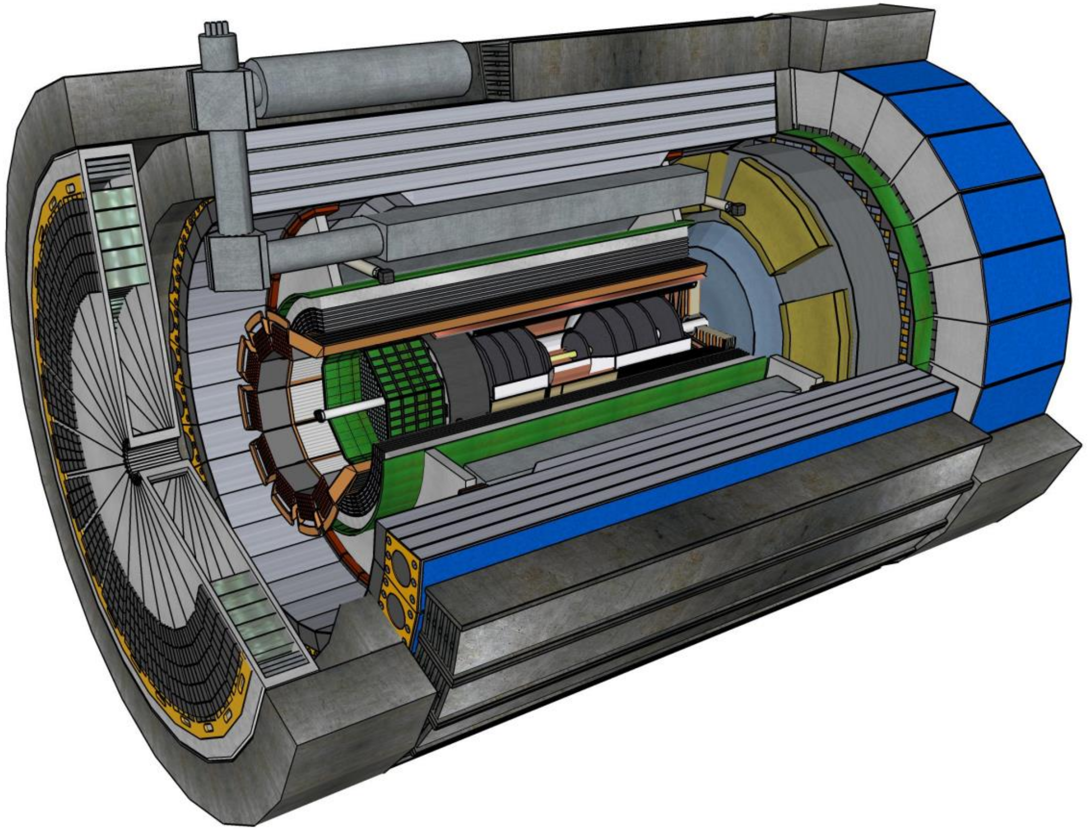
Physics of the Electron Ion Collider: *Experimental Introduction Part 2*



Rosi Reed

Lehigh University

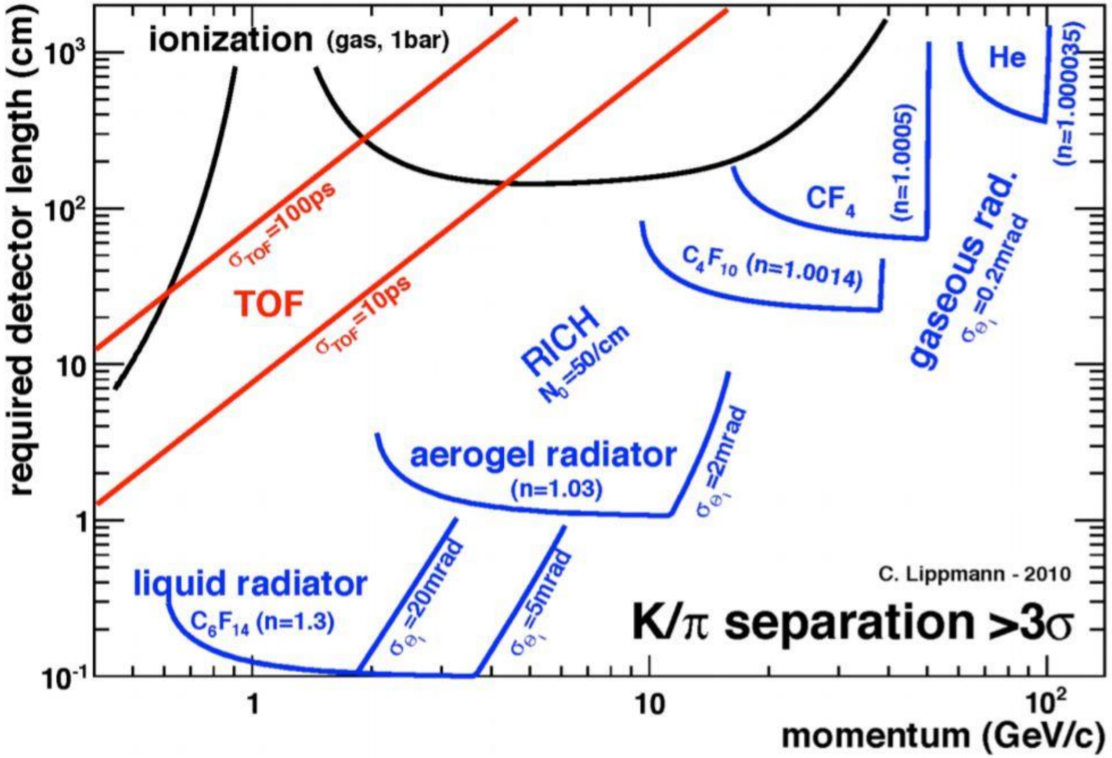
Outline of Lectures

- Lecture 1: Particle Physics Detectors and Intro to ePIC
  - Interaction of Particles with Matter
  - Detector requirements at the EIC
  - The design of the ePIC Detector
  - Tracking Detectors
- Lecture 2: ePIC Detector and the EIC Science Case
  - Calorimetry
  - Particle Identification
  - Far forward/Far backwards
  - Physics observables
  - Interaction Region Considerations

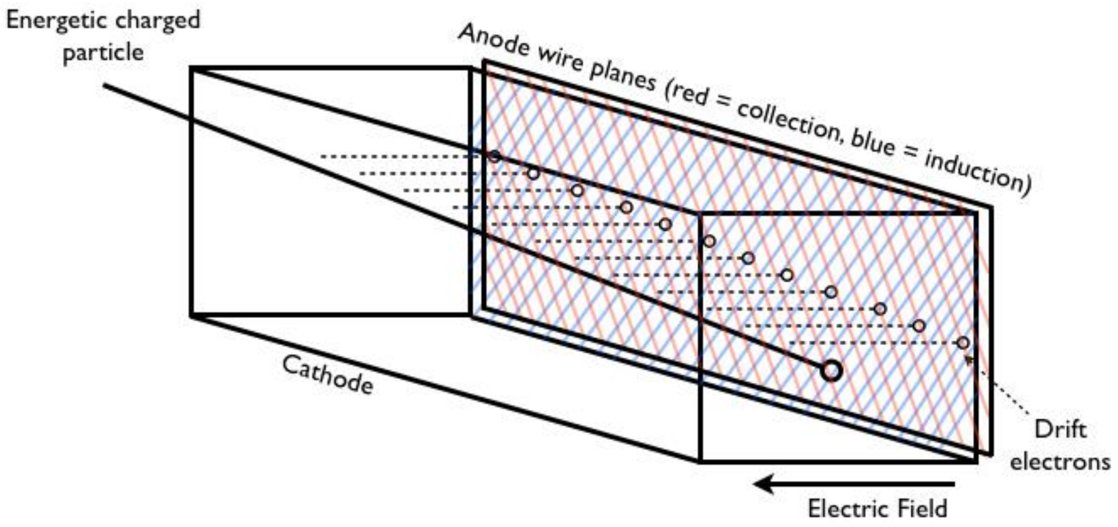
Particle Identification (PID) Detectors

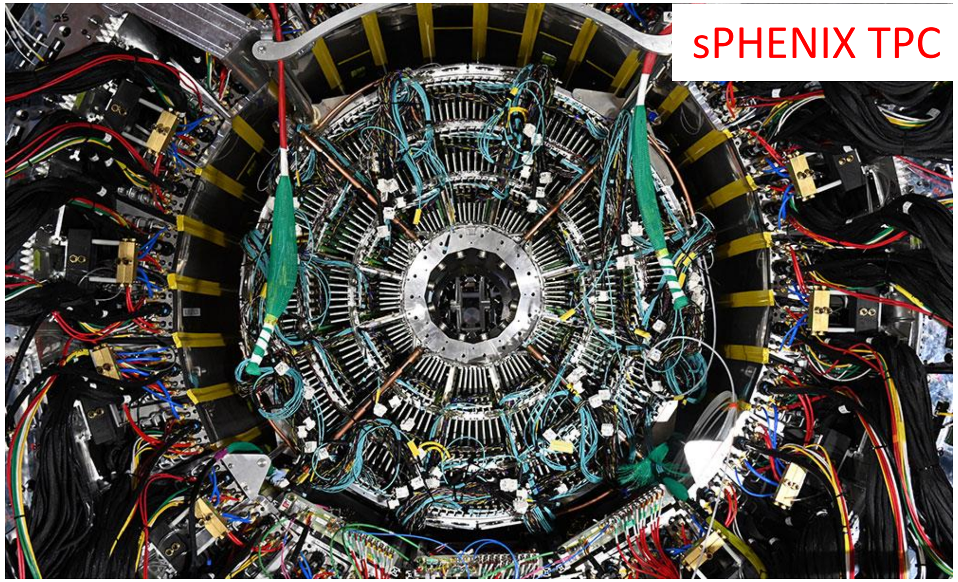
- ePIC PID detectors are: dRICH, pfRICH, hpDIRC, AC-LGAD
- Other detector technologies also exist
- There are other ways in which the ID of a particle can be obtained using detectors that are not dedicated PID detectors
  - Electron ID (eID) can use the combination of tracking and calorimetry
  - dE/dx in detectors such as Time Projection Chambers (TPCs) can also give PID along with kinematic measurements

C.Lippmann, NIMA 666 (2012) 148



Time Projection Chamber (TPC)



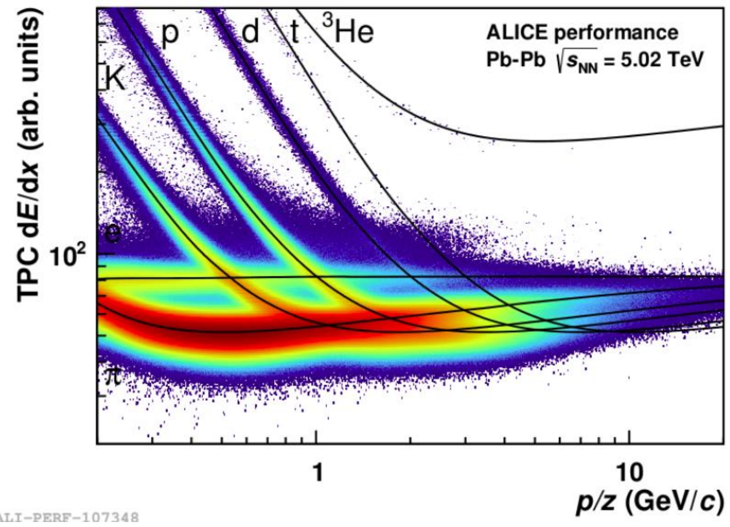


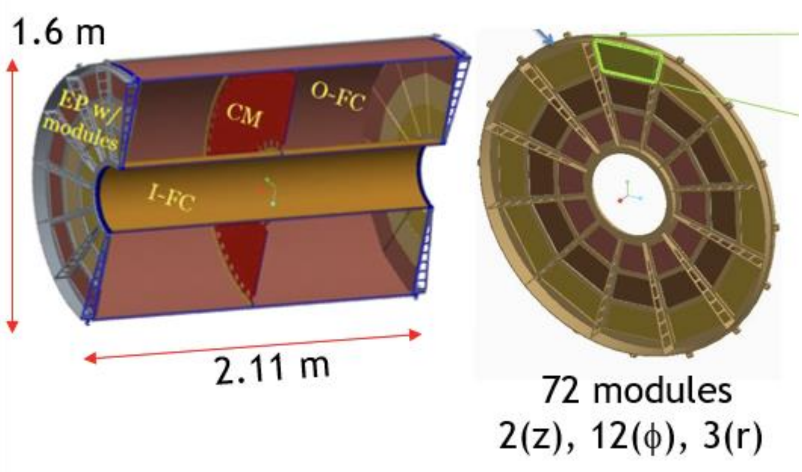
TPCS use ionization drift time to determine the 3rd coordinate of the “hit” (z = vt)

- Good for solenoidal B-fields where E||B

Readout is at the and needs to be in a configuration that suppresses ion backflow

Charge buildup in the TPC will distort particle tracks!



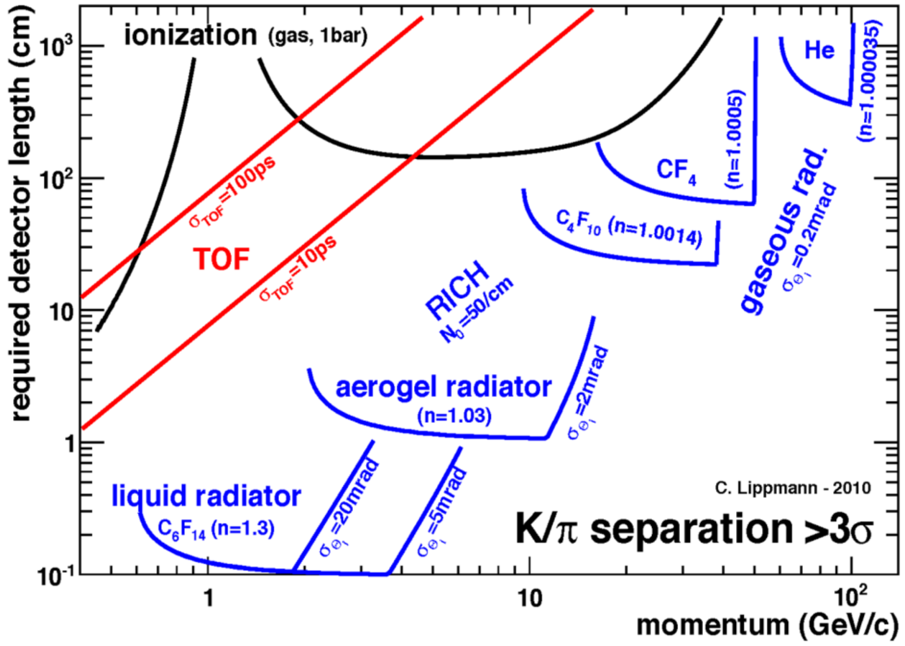


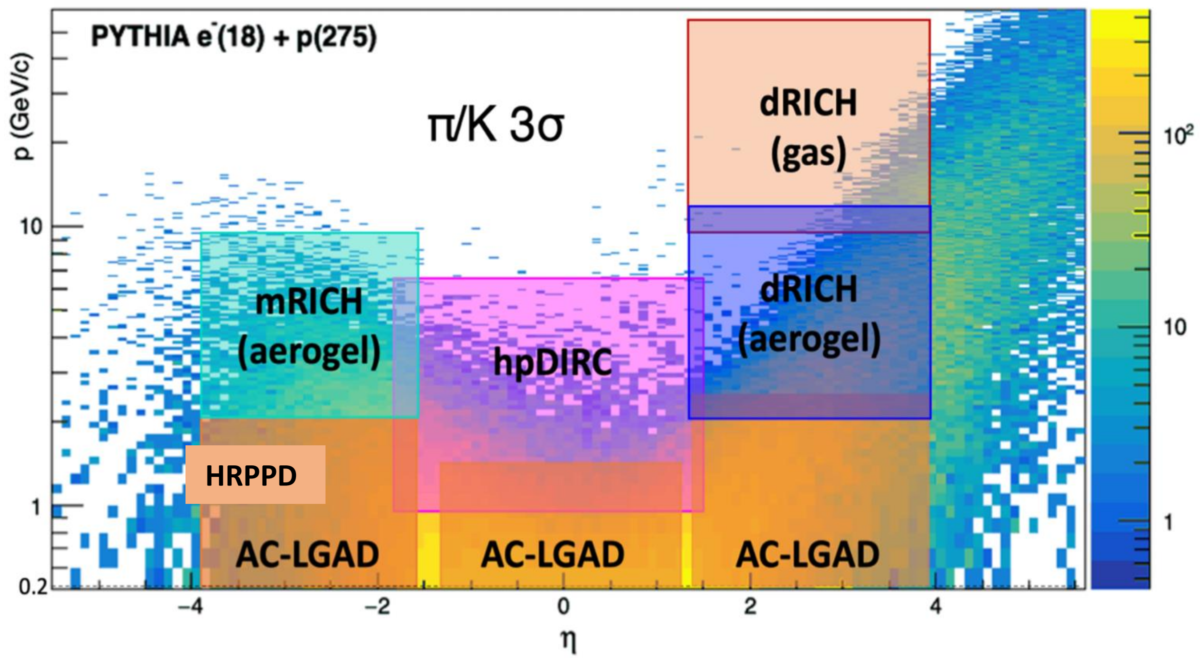
Particle ID ePIC

PID needs

- Electrons from photons ⟶ **4π coverage in tracking**
- Electrons from charged hadrons ⟶ **mostly Calorimetry+tracking**
- Charged π/K/p on track level ⟶ **Cherenkov detectors**
  - Cherenkov detectors, complemented by ToF

Rapidity	π/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

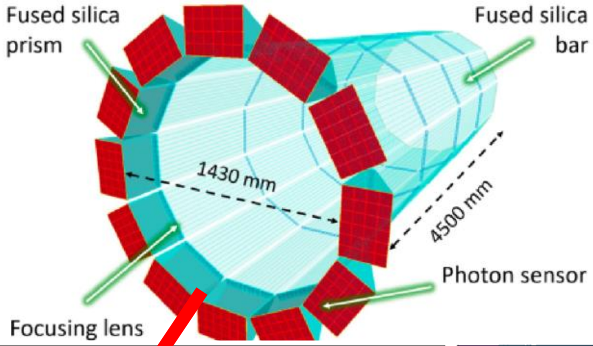




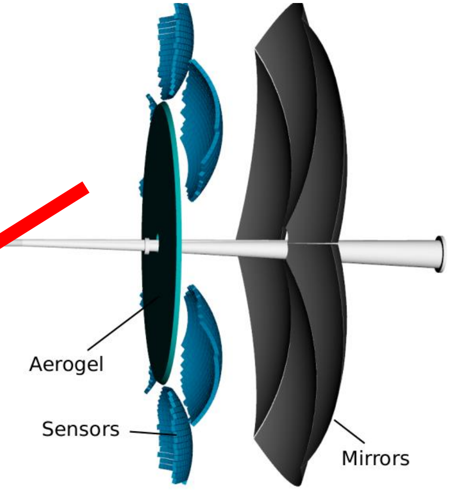
Need more than one technology to cover the entire momentum ranges at different rapidities

Particle ID ePIC

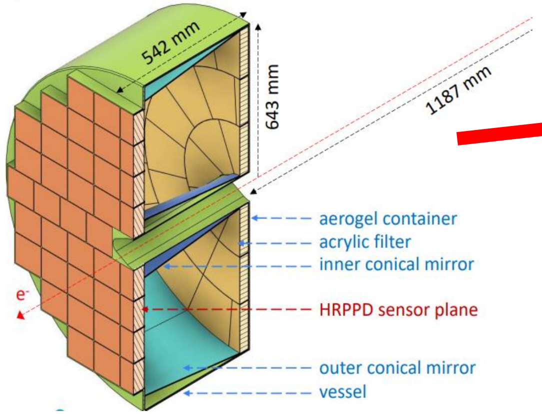
High-Performance DIRC

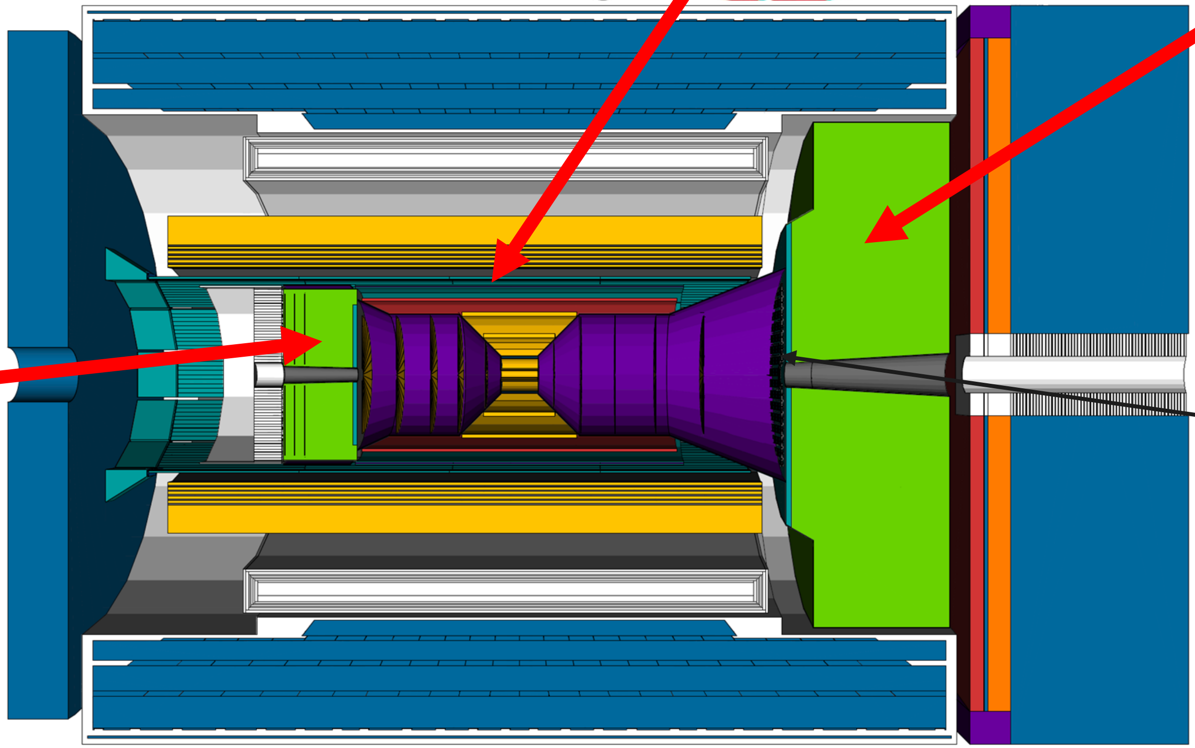


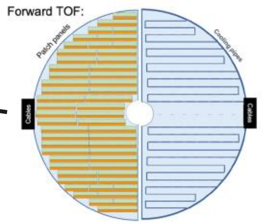
Dual-Radiator RICH(dRICH)



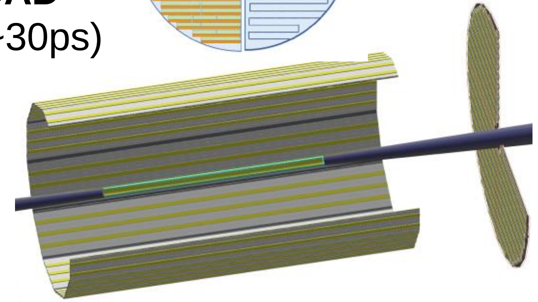
Proximity Focused (pfRICH)*





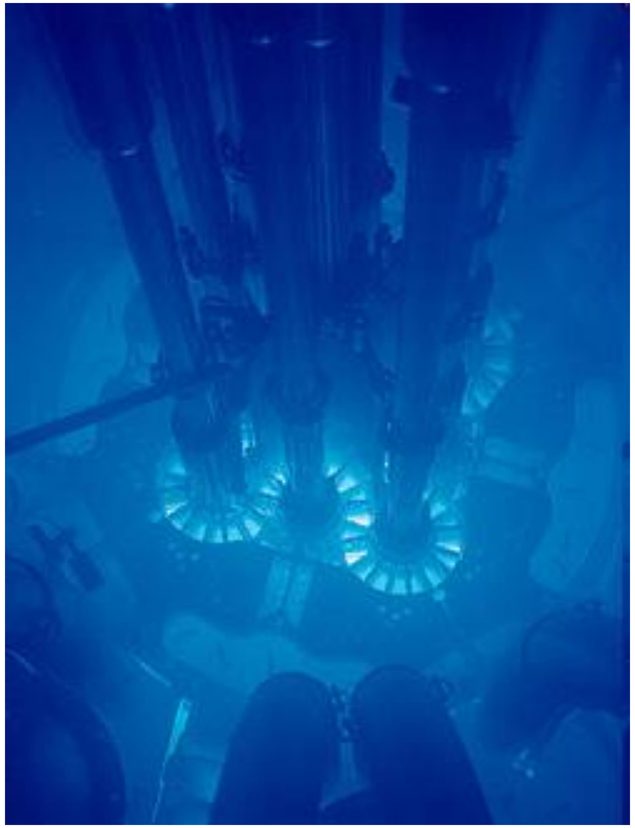


AC-LGAD TOF (~30ps)



Cerenkov Counters

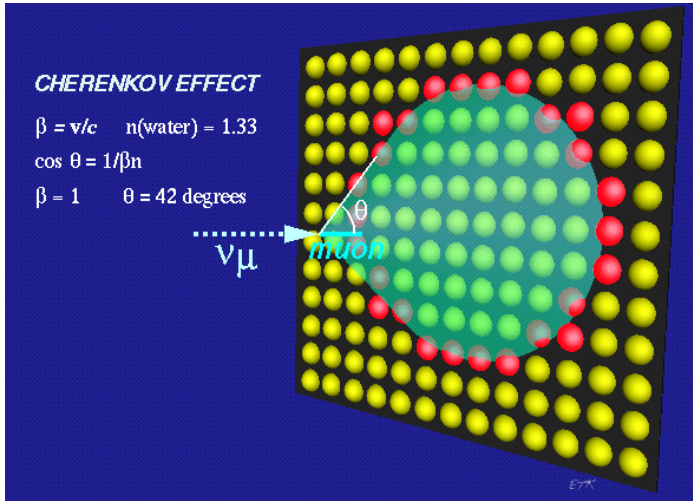
- Cerenkov light emitted when $v_{particle}$ > speed of light in a medium
  - Similar to a sonic boom (but optical)
  - Light emitted at a characteristic angle: $\cos\theta_C = \frac{1}{n\beta}$
  - Light depends on particle velocity
    - Different momentum for different masses
  - Threshold Counter:
    - 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!

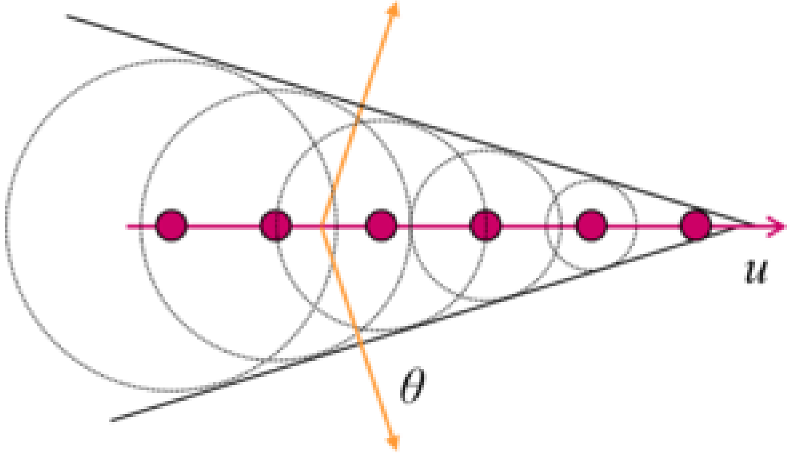


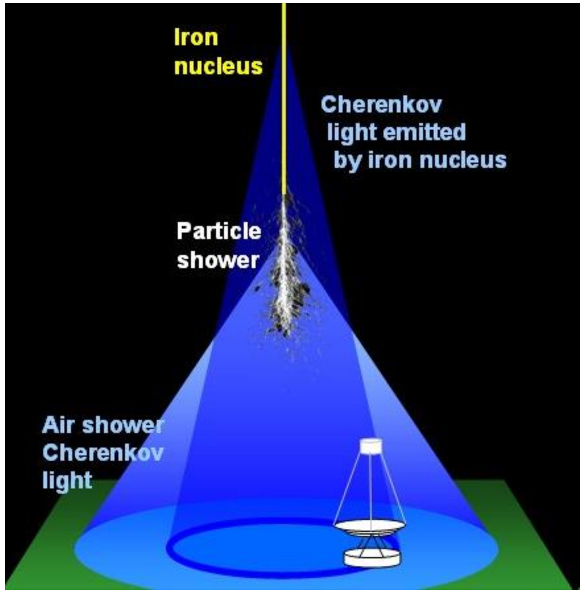
Cerenkov radiation from nuclear fission reactor core.

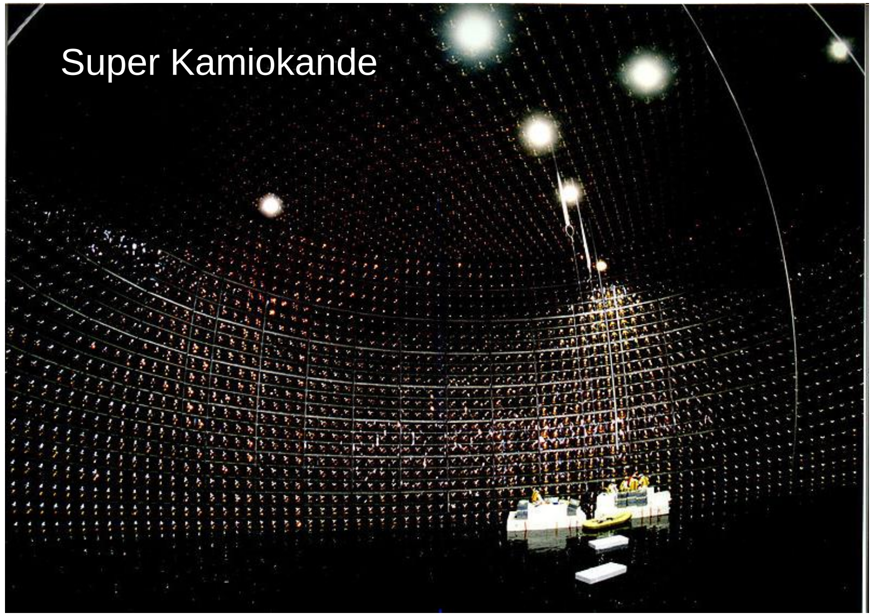
Cerenkov Counters

- Large, underground water Cerenkov counters were instrumental in demonstrating solar neutrino oscillations.
- Cerenkov light is used to detect cosmic rays in air showers



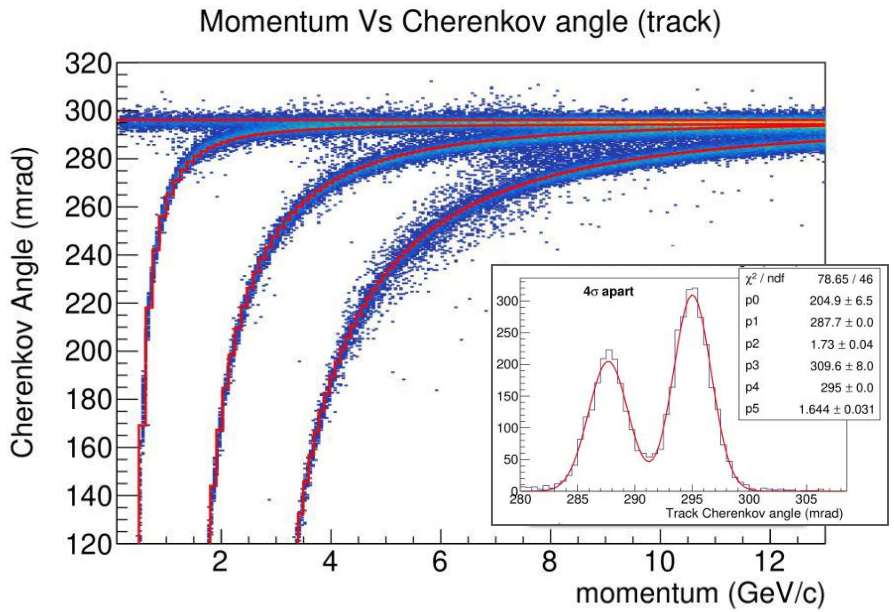




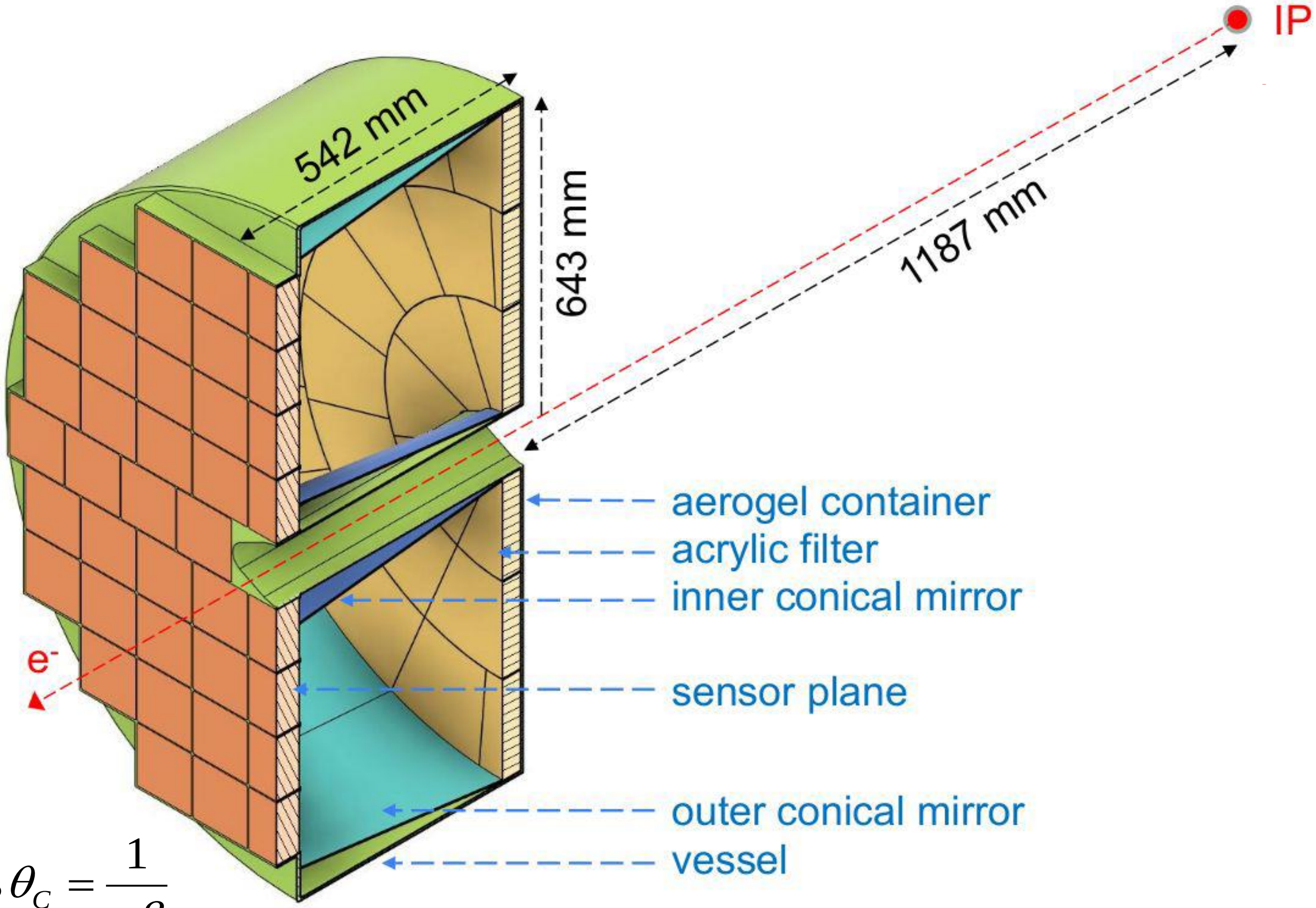


pfRICH – proximity focusing RICH

- Cherenkov radiator
  - 2.5 cm thick aerogel (n = 1.04-1.05)
  - 300 nm acrylic filter
  - $\langle N_{pe} \rangle$ ~ 11-12
  - Provide time with σ < 20 ps

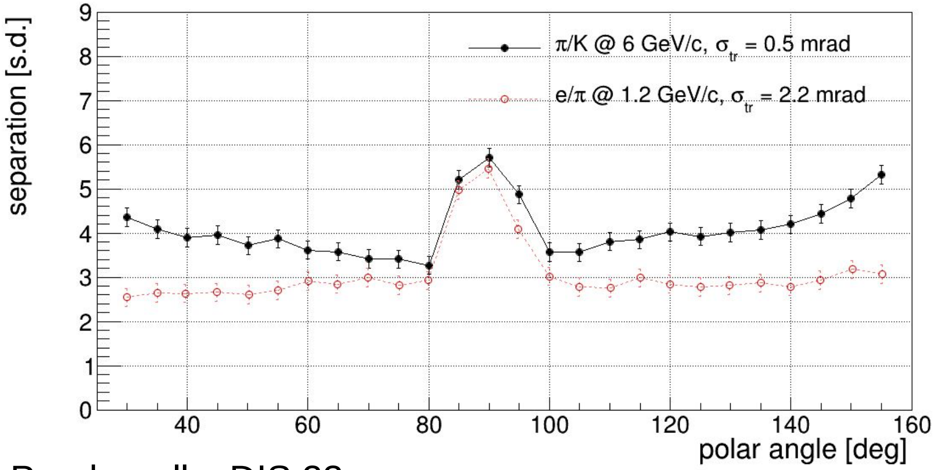


$$\cos\theta_C = \frac{1}{n\beta}$$



hpDIRC – High-Performance DIRC - ePIC

- DIRC (Detection of Internally Reflected Cherenkov light)
  - Uses total internal reflection of Cherenkov light within a solid radiator for precise particle identification
- ePIC hpDIRC components
  - 3-layer spherical lenses
  - Compact fused silica expansion volumes
  - Fast photodetection, small pixel MCP-PMT



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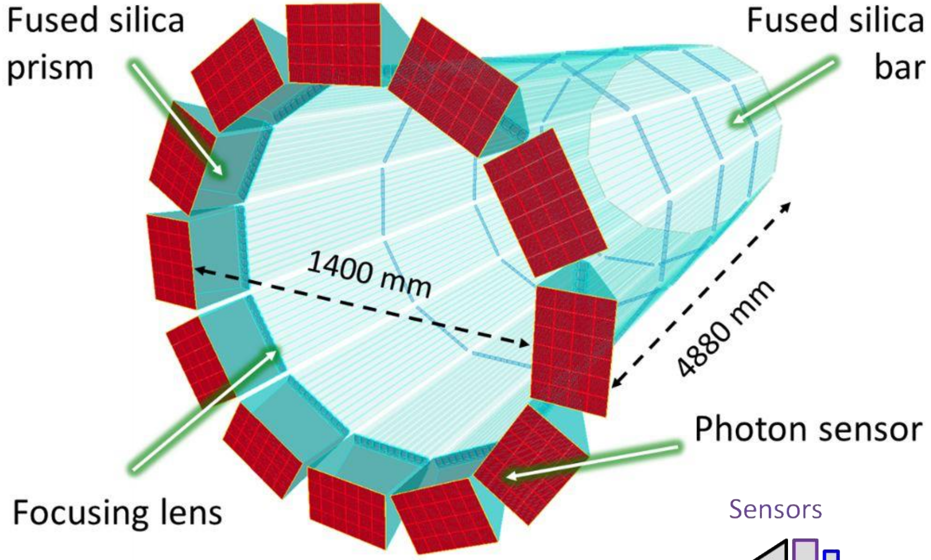
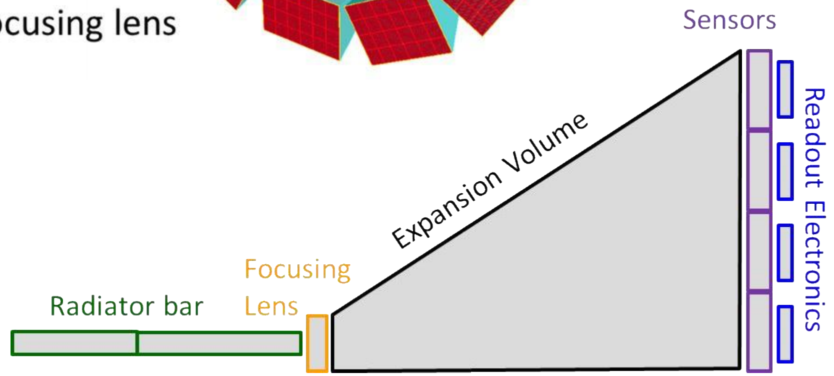
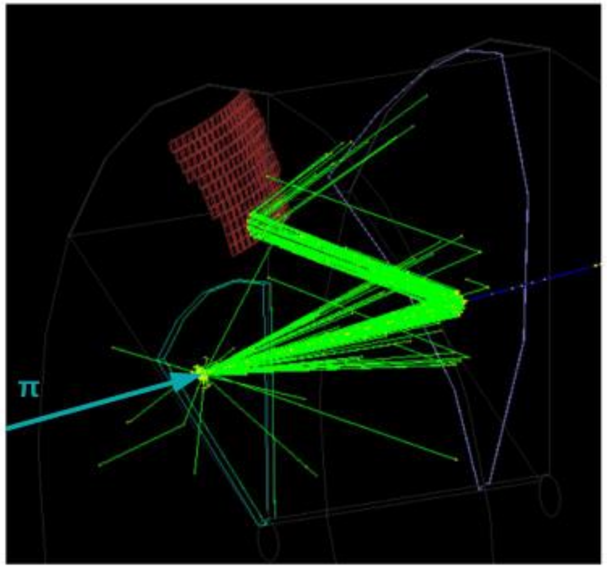
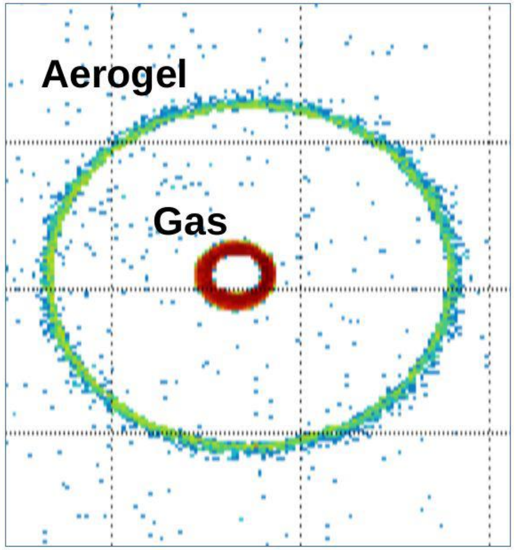




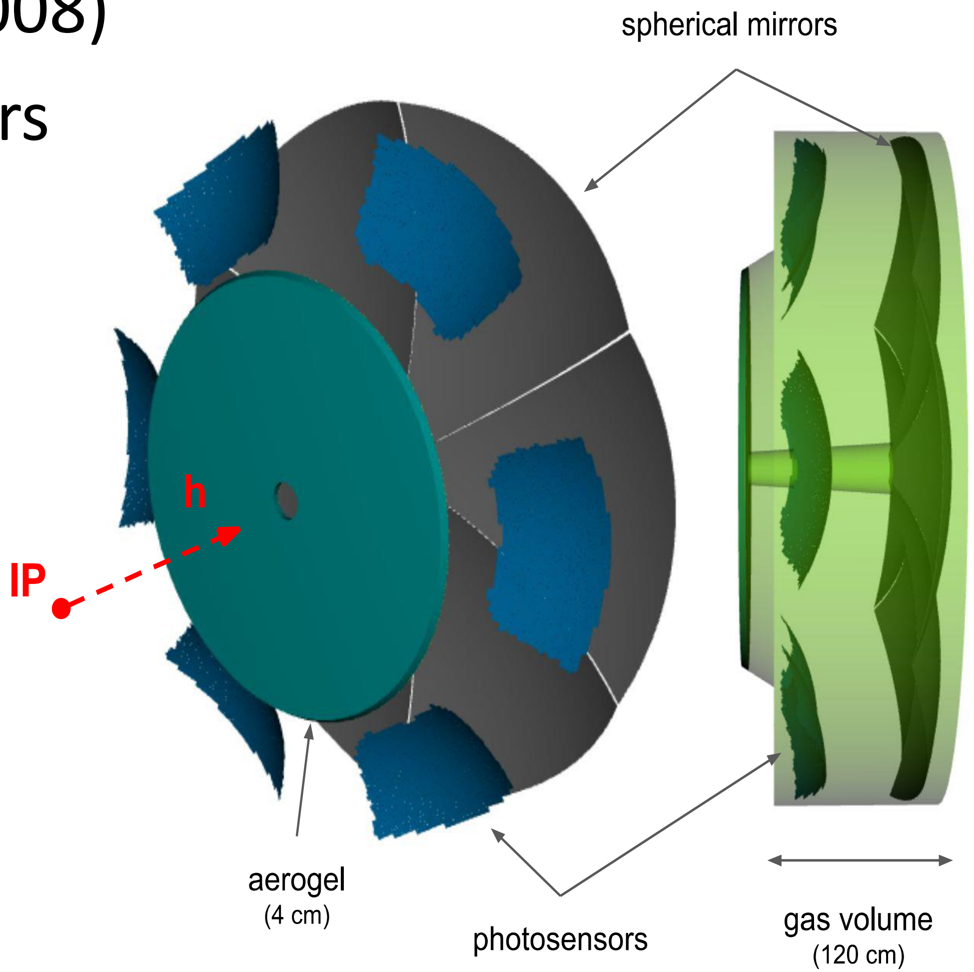
dRICH – dual-radiator RICH - ePIC

- Radiators: aerogel (n ~ 1.02) and C2F6 (n ~ 1.0008)
- Mirrors: large outward-reflecting, 6 open sectors
- Sensors: 3x3 mm^2 pixel, 0.5 m^2 / sector
  - Single-photon detection inside high B field (> 1 T)

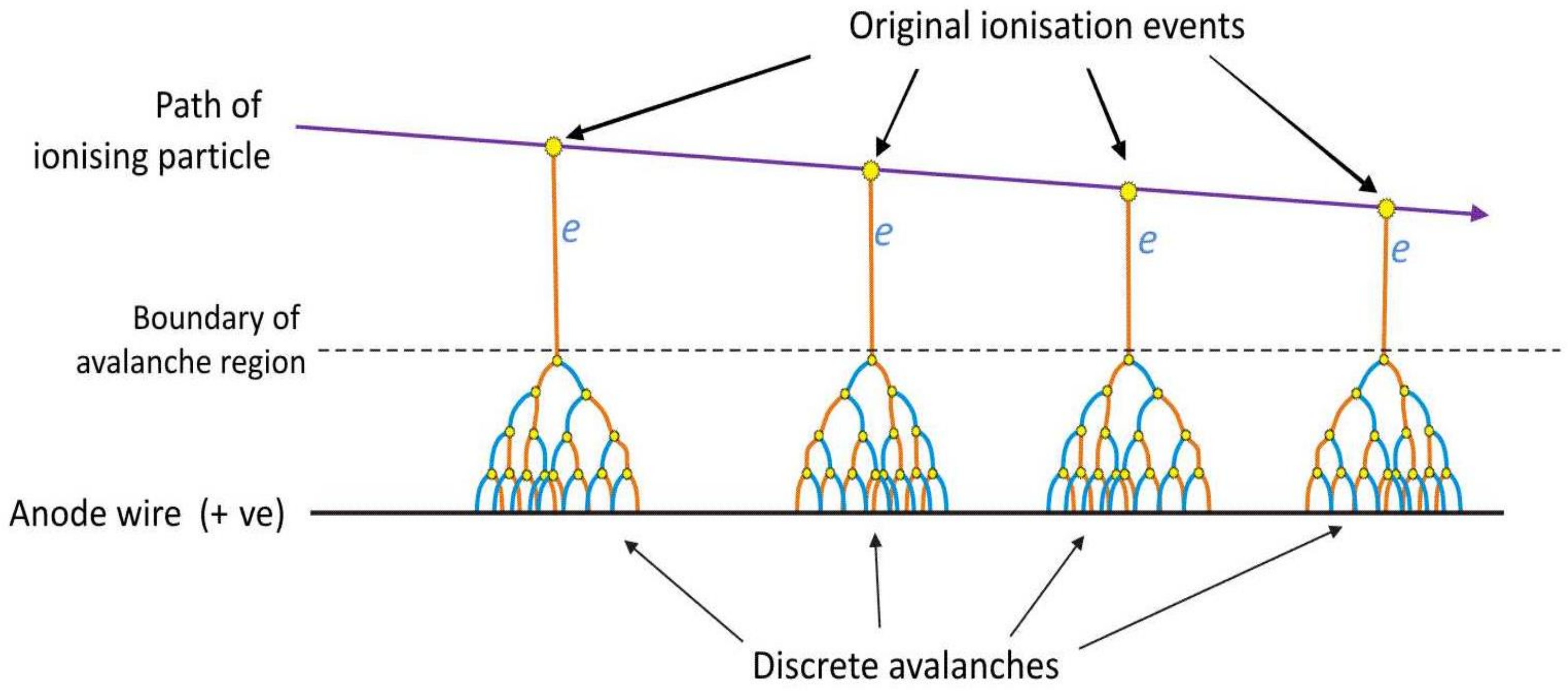




example event (accumulated hits)



Avalanche



Drift region

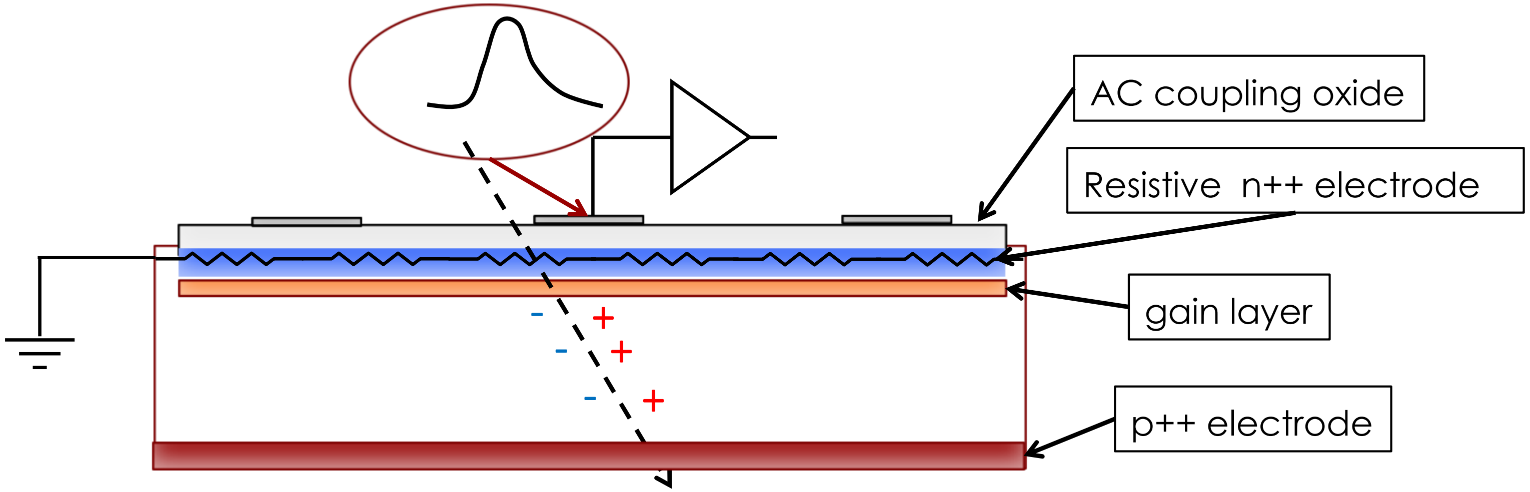
Avalanche region

M = multiplication (gain)
p = pressure
V = operating voltage
K = property of gas
ΔV_λ = change in voltage due to avalanche

$$\ln M = \frac{V}{\ln\left(\frac{b}{a}\right)} \frac{\ln 2}{\Delta V_\lambda}\left[\ln\left(\frac{V}{pa\ln(b/a)}\right) - \ln K\right]$$

AC-LGAD
Time of Flight (TOF) Detector

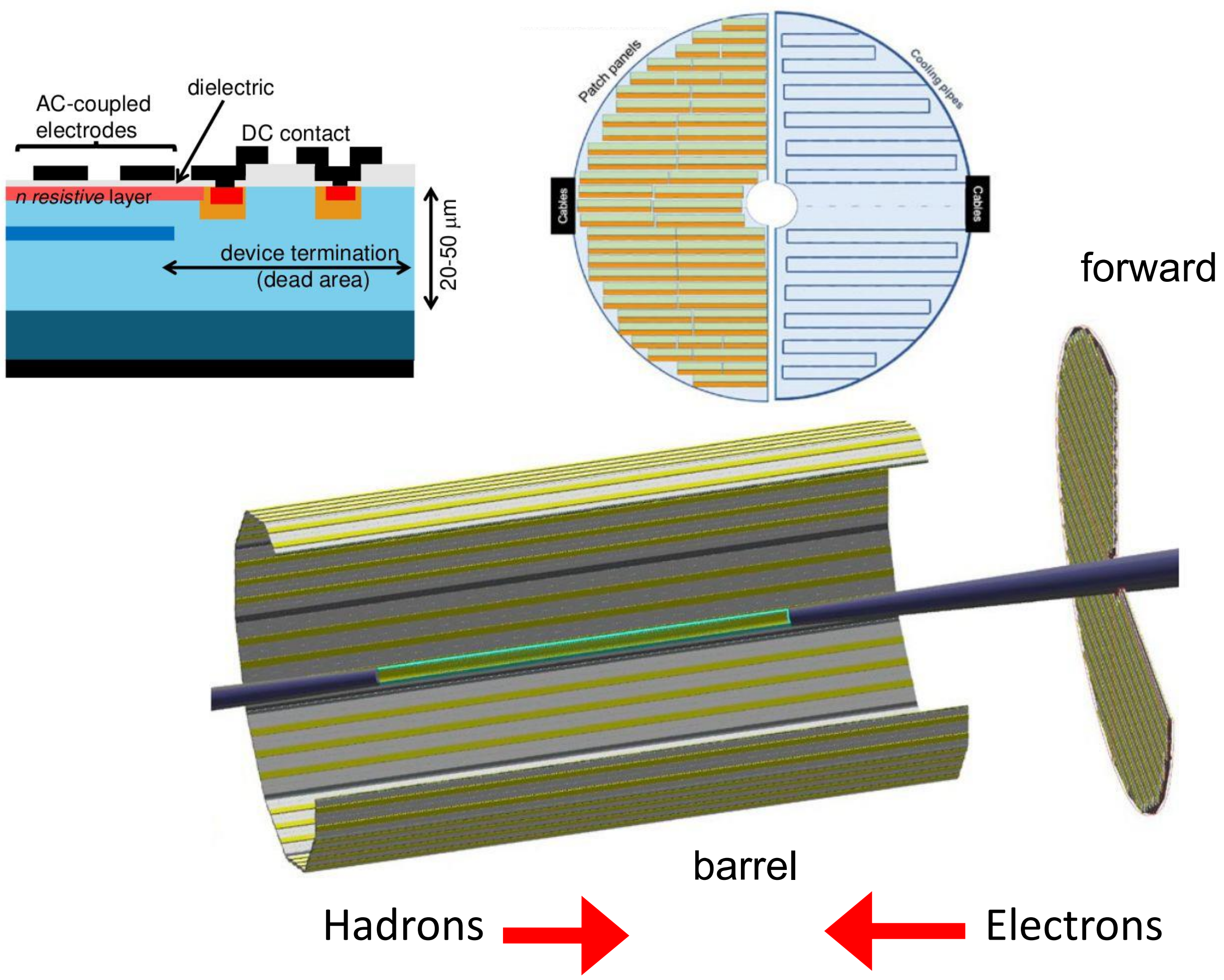
- Low-gain avalanche diodes (LGADs)
- AC-LGAD - gain layer is not segmented, signal is read-out via AC coupling
  - Capacitive coupling → no direct electrical connection between the detector and the readout electronics, the signal is transferred through a thin insulating layer
- Charged particle generates electron-hole pairs
- High E-field in the LGAD layer amplifies signal (avalanche)
- Induces signal on the AC-coupled electrodes



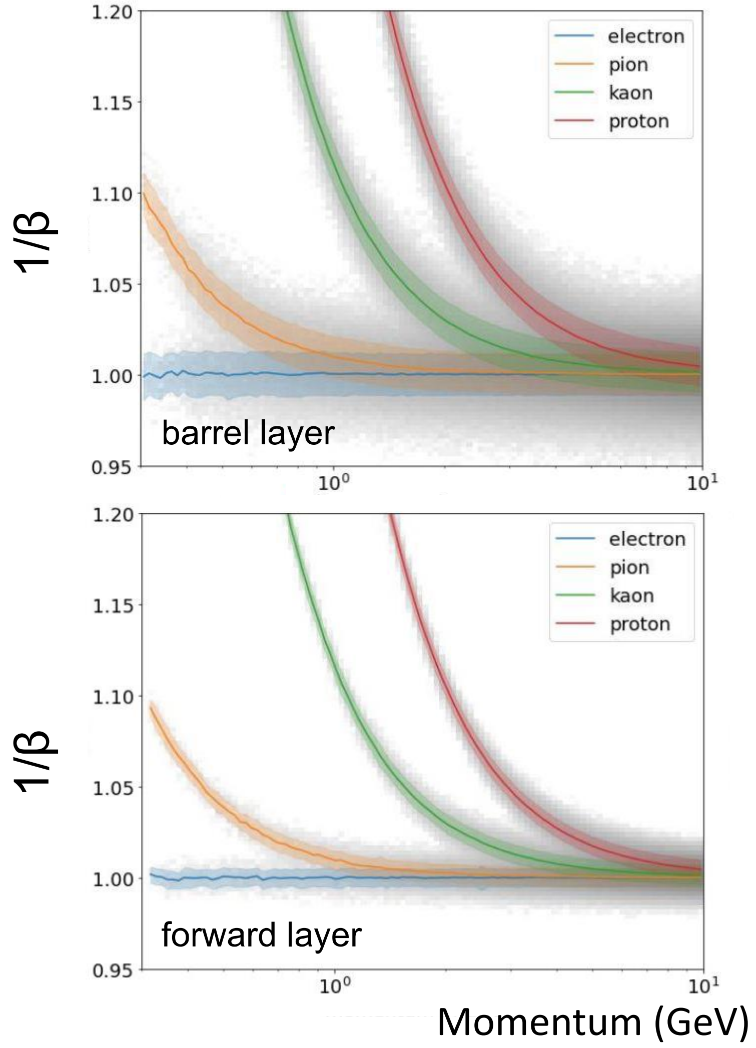
https://doi.org/10.1016/j.nima.2020.163479

AC-LGAD ePIC

- Two AC-LGAD layers
  - Barrel, $|\eta| < 1.4$
  - Forward, $1.5 < \eta < 3.5$
- Barrel
  - 500 µm x 1 cm strips
  - 1% X_0
- Forward
  - 500 µm x 500 µm pixels
  - 8% X0
- Performance
  - Spatial resolution: 30 µm
  - Time resolution: $\sigma \sim 25$ ps

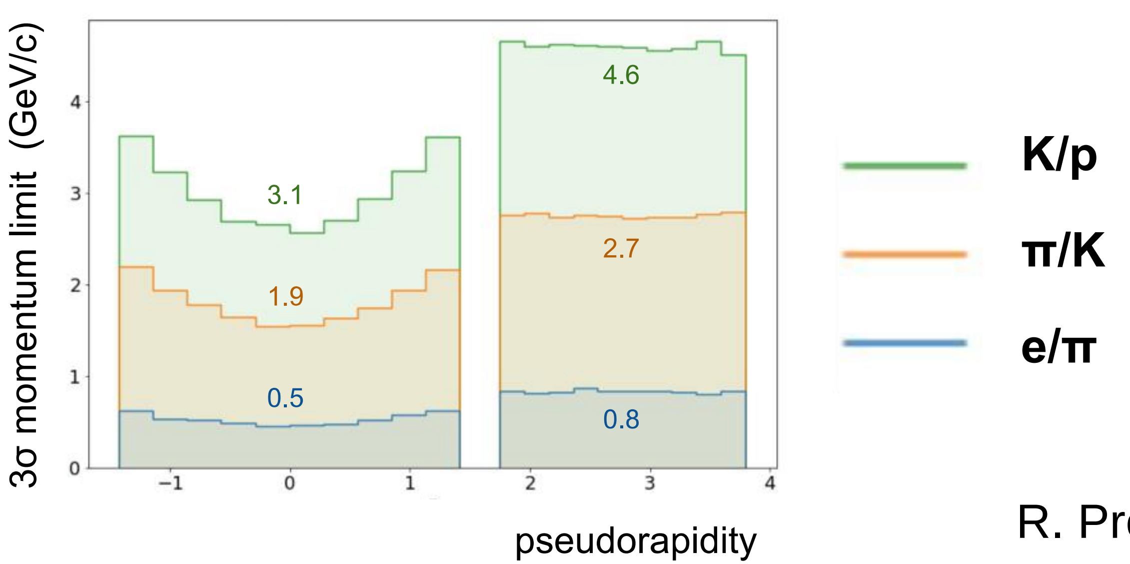


AC-LGAD ePIC



Barrel Layer
- e/π up to 0.5 GeV
- π/K up to 1.9 GeV
- K/p up to 3.1 GeV

Forward Layer
- e/π up to 0.8 GeV
- π/K up to 2.7 GeV
- K/p up to 4.6 GeV



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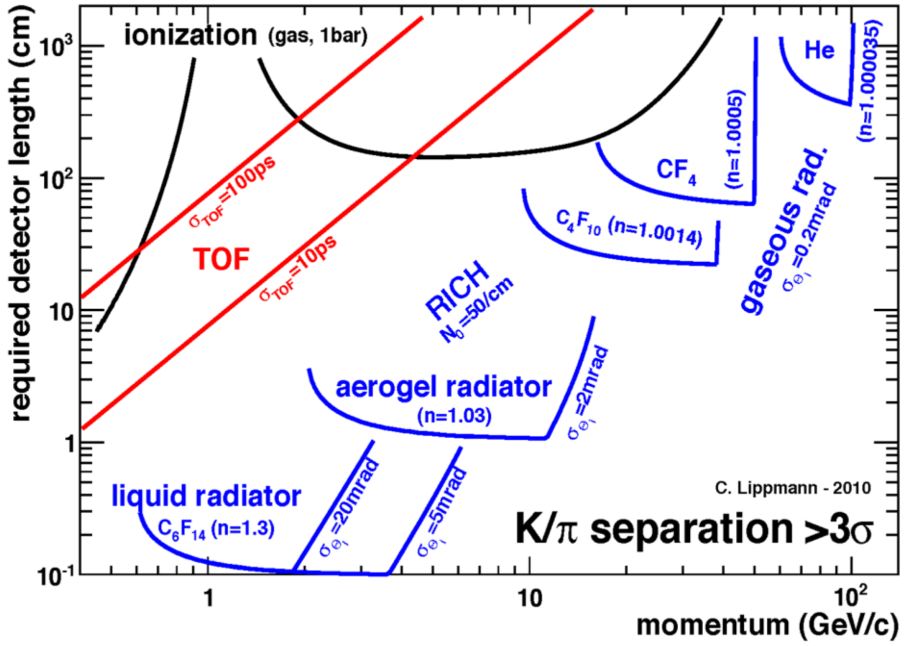
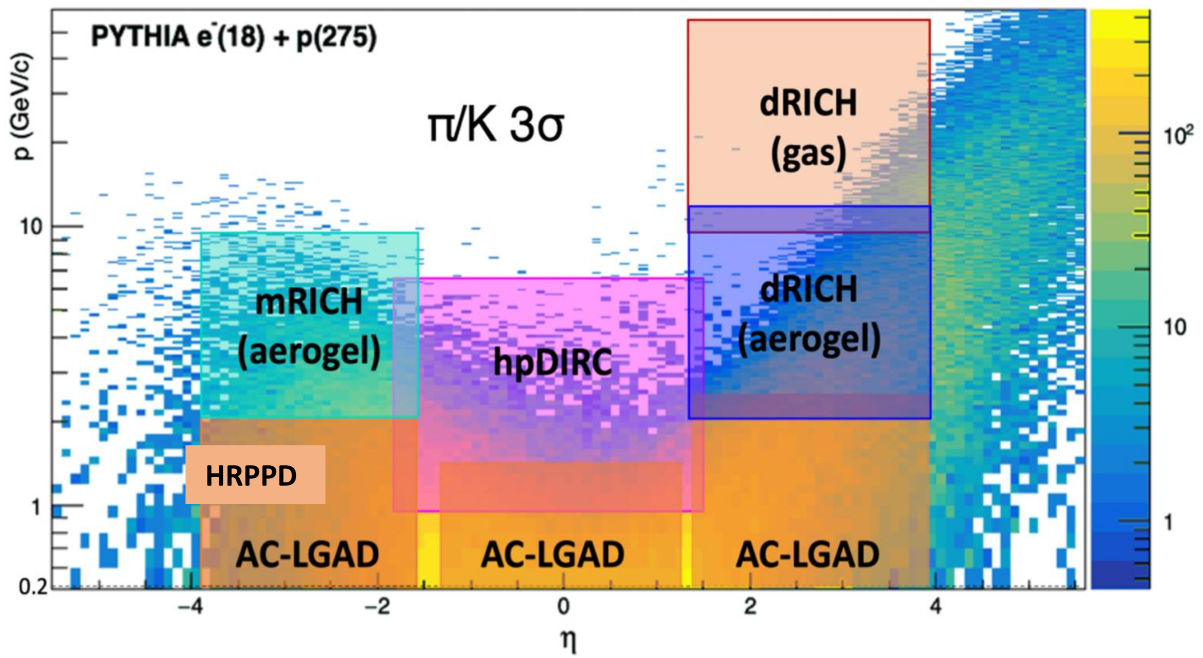




Need more than one technology to cover the entire momentum ranges at different rapidities

Scintillation Counters

- Basic idea is to convert the ionization to light, then collect the light
  - Has the advantage of a high efficiency even at low energies
- Organic Scintillators are typically a plastic (or oil) doped
  with a fluorescing chemical.
  - Passage of ionizing radiation excites the molecules and sets them into motion (vibration)
  - Excited state spacings are of order ~eV, vibrational spacings around 1/10 eV
  - Excited states decay to the vibrational ground state quickly (~ps), then later to the electronic ground state (~10ns)
  - As a result, the material is essentially transparent to its own radiation!
    - Since most molecules are in the ground only one of many possible transition photons is likely to be absorbed.
    - The doping elements shift the UV light to visible

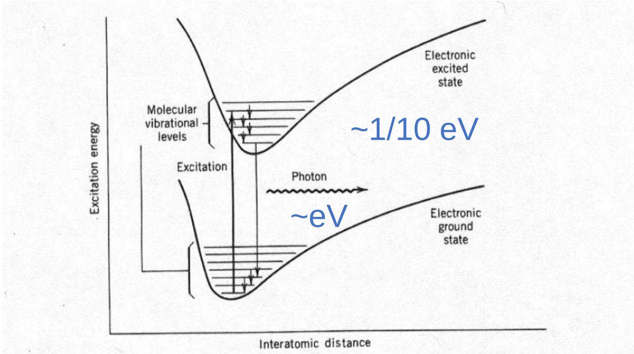


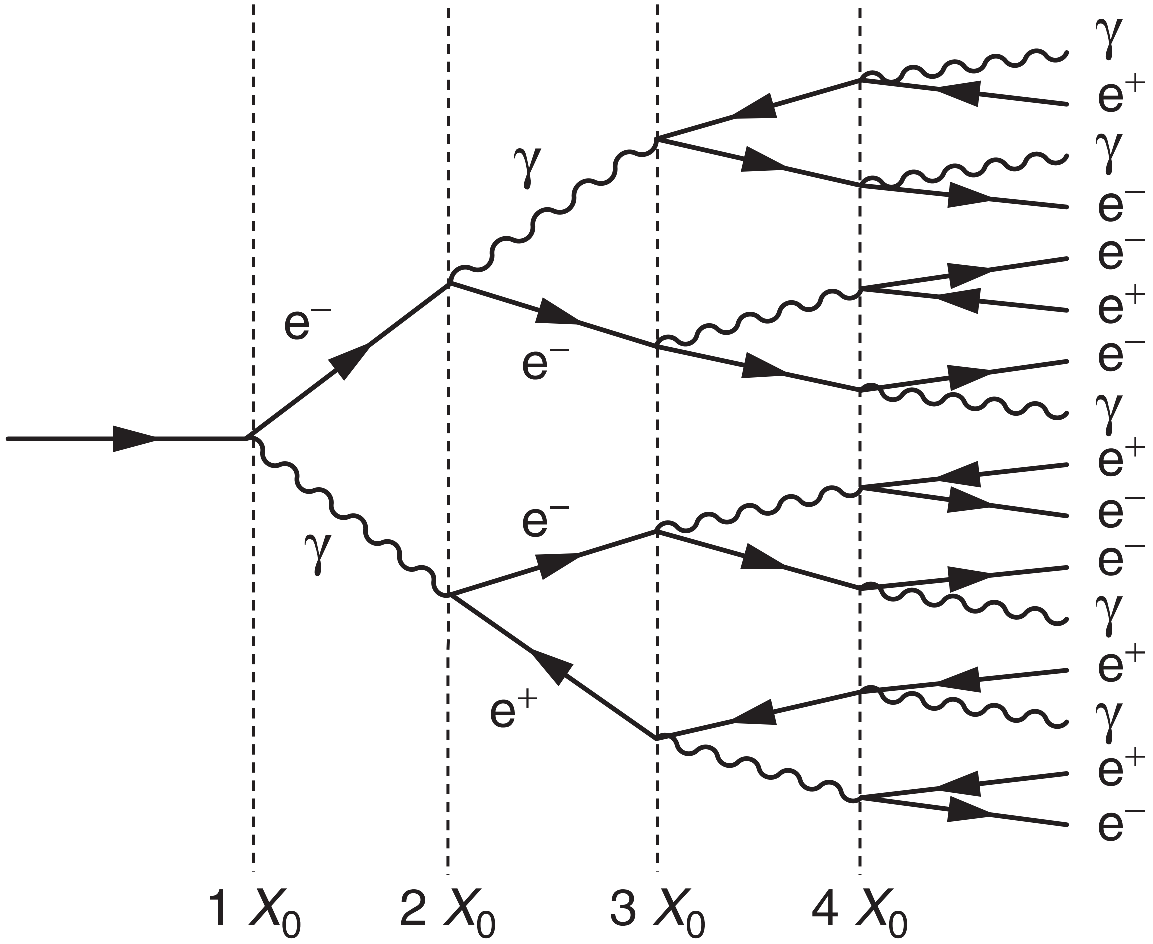
Figure 7.15 Electronic structure in an organic scintillator. The electronic states are represented as a potential minimum, resulting from the combined effects of the molecular attraction that keeps us from separating the atoms to greater distances and the repulsion that keeps us from forcing the atoms closer together (because the Pauli principle does not let the atomic wave functions overlap). Inside the electronic potential minimum is a sequence of levels that result from the atoms of the molecule vibrating against one another.

Reminder: Electromagnet Showers

Resolution of EM Calorimeters

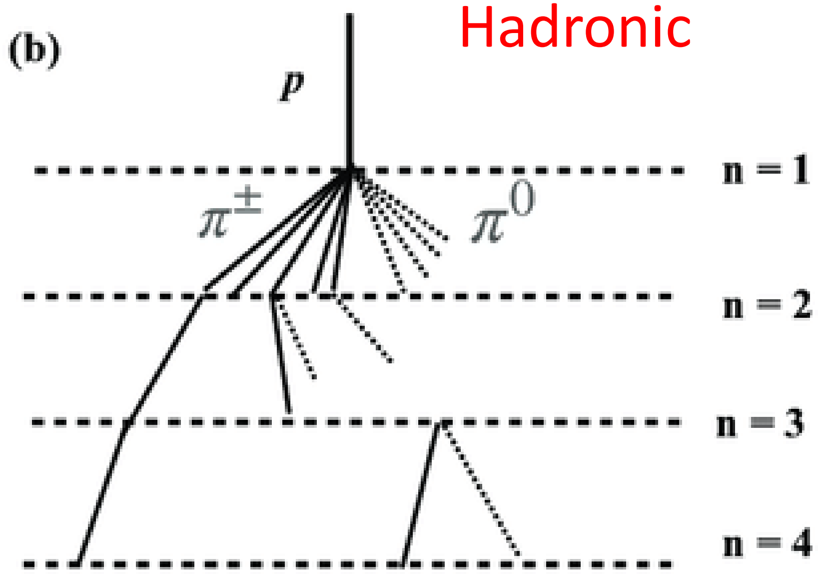
$$\frac{\sigma_E}{E} \sim \frac{3\% - 10\%}{\sqrt{E/\mathrm{GeV}}}.$$

- Number of EM particles essentially doubles every radiation length
- Light is collected to determine energy
- Shower develops until E_{ave} falls below the critical energy E_c
    - Electrons and positrons then lose energy by ionization

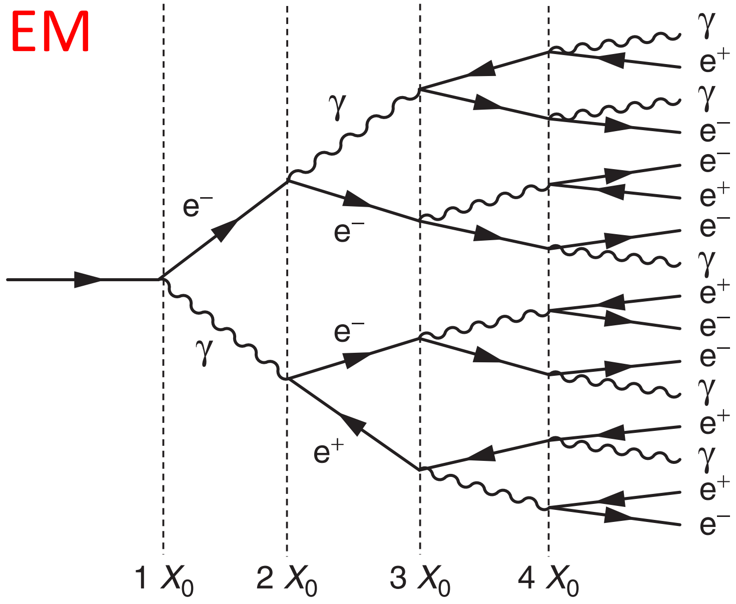


Reminder: Hadronic Showers

Hadronic



EM



- Hadronic showers are messier and larger than EM showers
- Electromagnetic component due to $\pi^0 \rightarrow \gamma\gamma$
- Nuclear interaction interaction length $\lambda_n \rightarrow$ mean distance between hadronic interactions
  - Much larger than radiation length!

Resolution of Hadronic Calorimeters

$$\frac{\sigma_E}{E} \gtrsim \frac{50\%}{\sqrt{E/\mathrm{GeV}}}$$

material	X_0 (g/cm^2)	λ_n (g/cm^2)
H_2	63	52.4
Al	24	106
Fe	13.8	132
Pb	6.3	193

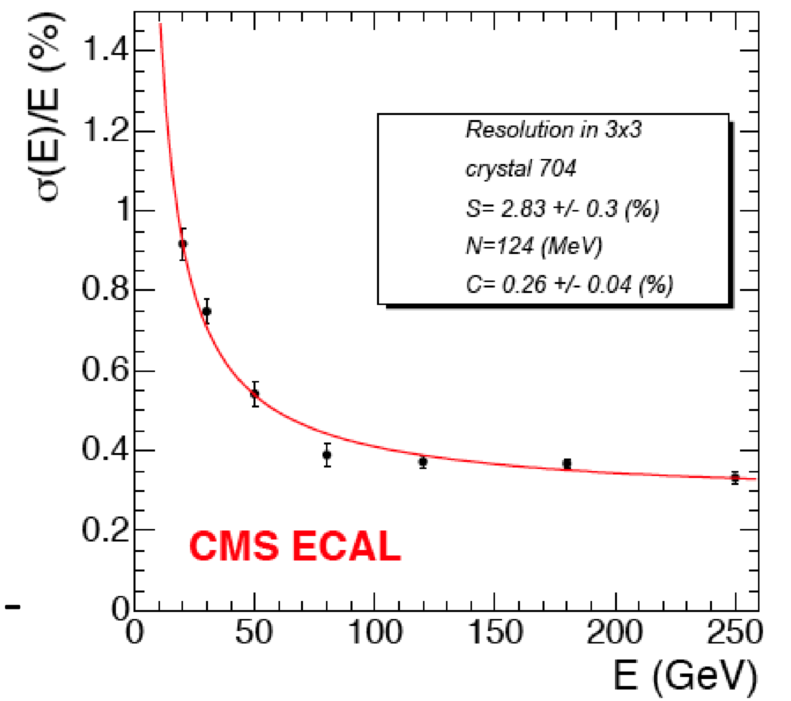
Energy Resolution in Calorimetry

$$\frac{\sigma}{E} = \frac{a}{\sqrt{E}} \oplus \frac{b}{E} \oplus c$$

Stochastic term (a): Fluctuations in the number of signal generating processes, for example the number of electrons that are detected as signals

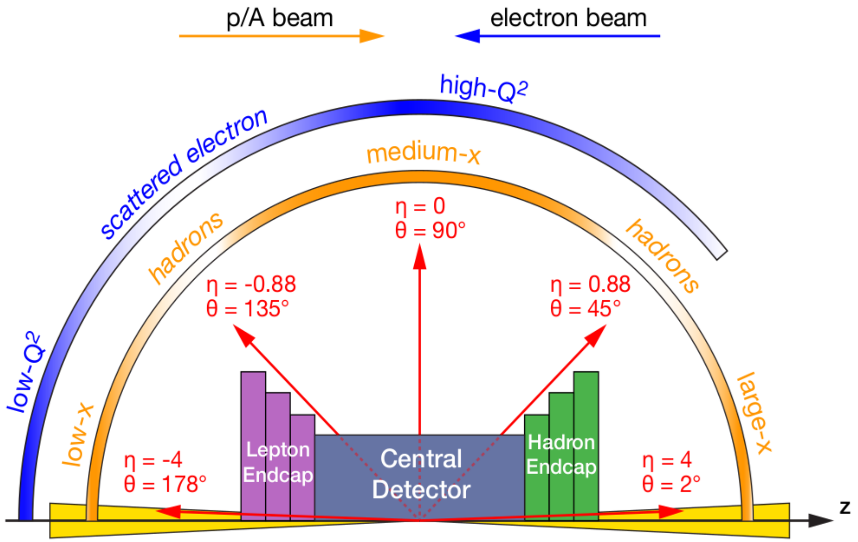
Noise term (b): Noise in readout electronics, ‘pile up’ from other collision events close in time, etc.

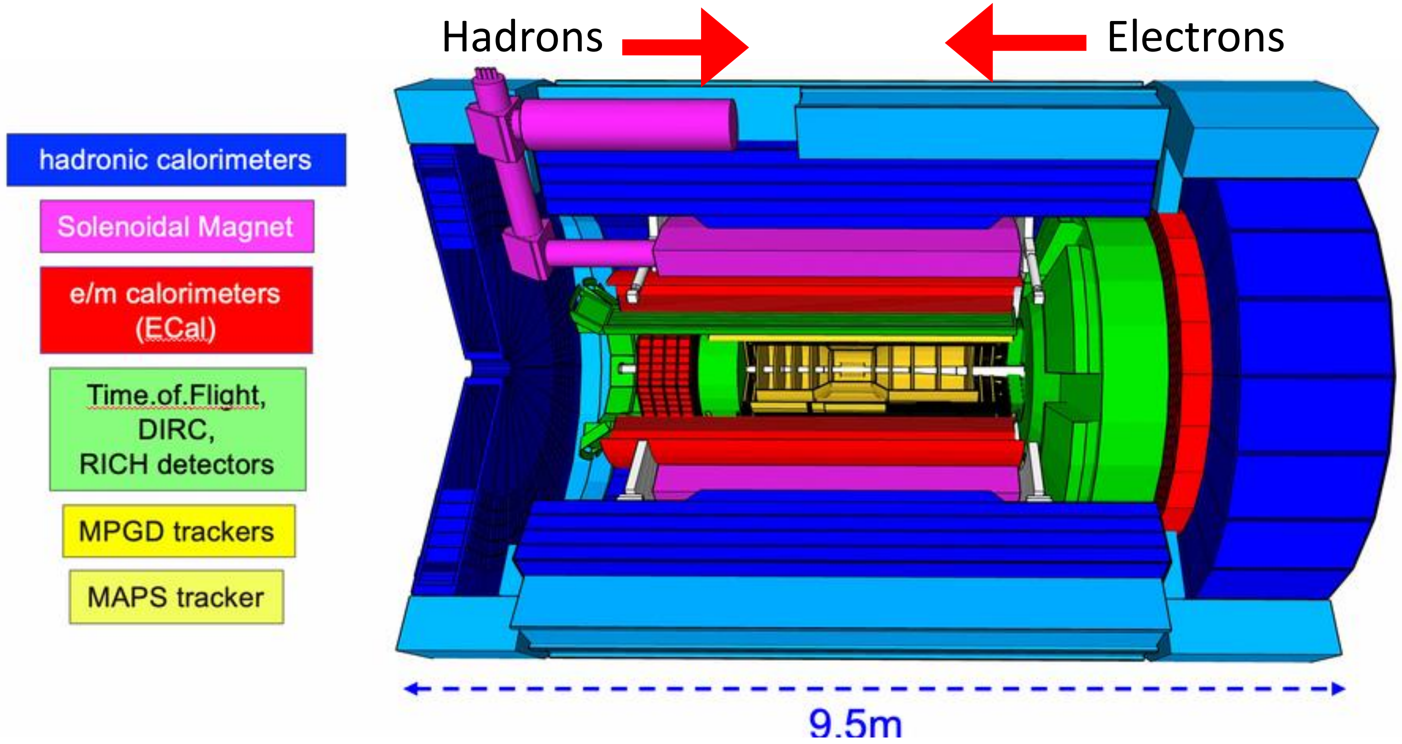
Constant term (c): Imperfections in calorimeter construction, non-uniform response, calibration errors, energy lost in dead material (before or in detector)



A small constant term is crucial for good energy resolution at the highest particle energies.

ePIC Detector → EMCal





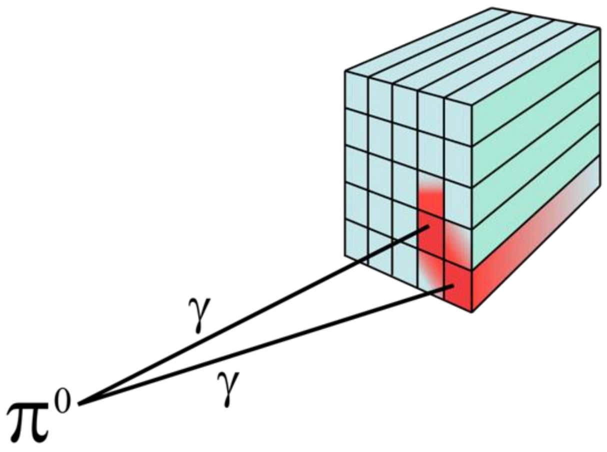
EIC Detector Requirements EMCal

Electromagnetic calorimetry → Measure photons (E, angle), identify electrons

- $PbWO_4$ Crystals (backward), W/ScFi (forward)
- Barrel Imaging Calorimeter (Si + Pb/ScFi)

Detailed EMCal Requirements

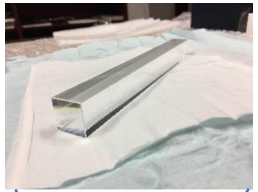
	Electron endcap (Backward)	Barrel	Hadron endcap (Forward)
Energy Resolution	$\frac{(2-3)\%}{\sqrt{E}} \oplus 1\%$	$\frac{(10-12)\%}{\sqrt{E}} \oplus 2\%$	$\frac{(10-12)\%}{\sqrt{E}} \oplus 2\%$
Shower Energy range	0.1−18 GeV	0.1−50 GeV	0.1−100 GeV
$\pi\pm$ suppression (helped by other subsystems)	Up to 10^4		
$\pi^0/\boldsymbol{\gamma}$ discrimination	Up to 18 GeV/c	Up to 10 GeV/c	Up to 50 GeV/c
Rad dose (includes background) at 10^{34} sm^{-2} sec^{-1}	<3 krad/year	<0.1 krad/year	<4 krad/year
Max hit rate per tower (includes background)	50 kHz	5 kHz	20 kHz
Neutron flux, at 10^{34} sm^{-2} sec^{-1}	10^{10} /cm^2/year	10^{10} /cm^2/year	10^{11} /cm^2/year
Limited space	Compact (small X_0)		
Material on the way	Minimized		

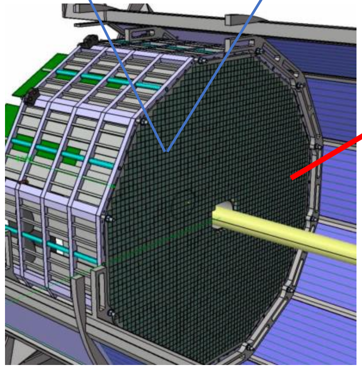


Distinguishing between π^0 and γ is complicated for high momentum π^0s due to cluster merging

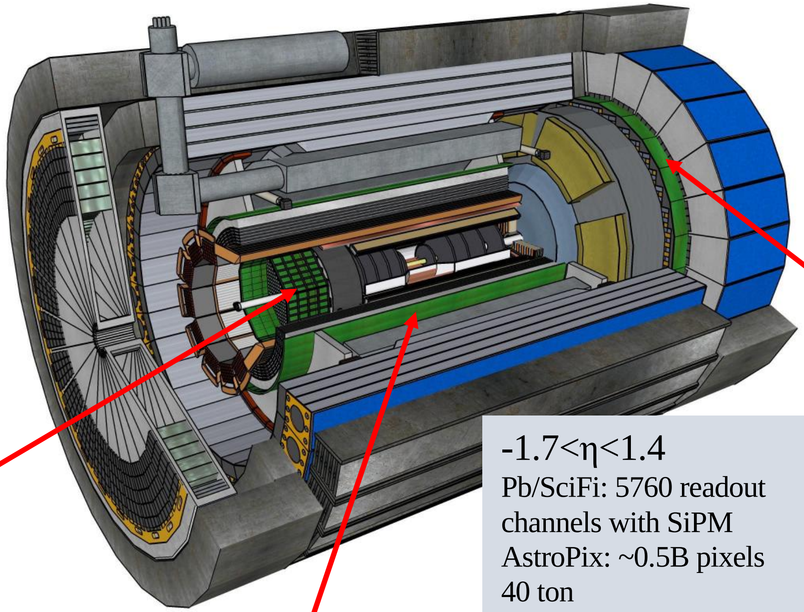
ePIC Electromagnetic Calorimetry

PbWO4

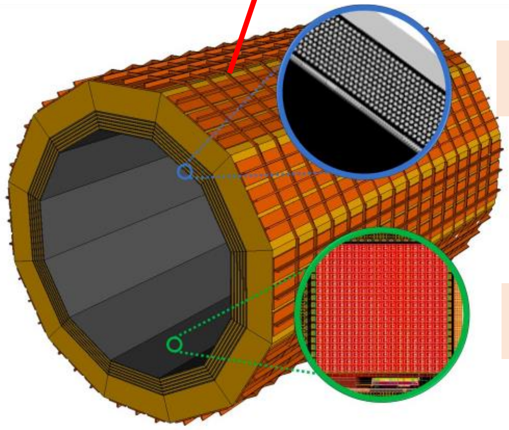




-3.5<η<-1.7
~3k crystals
R_{outer}=64cm
SiPM readout
2 ton



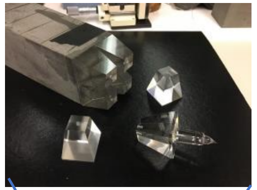
-1.7<η<1.4
Pb/SciFi: 5760 readout channels with SiPM
AstroPix: ~0.5B pixels
40 ton

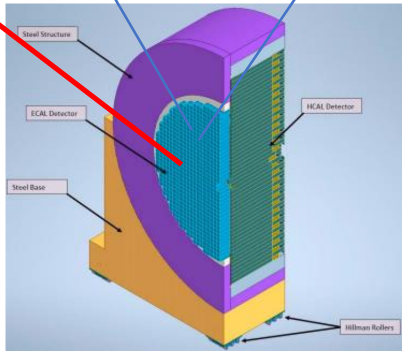


Pb/SciFi

AstroPix

W/SciFi

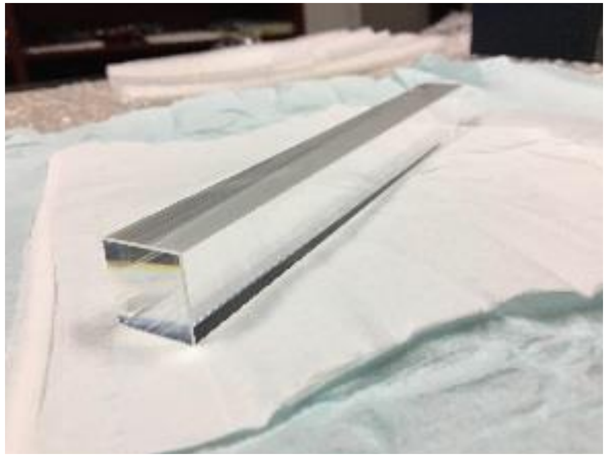




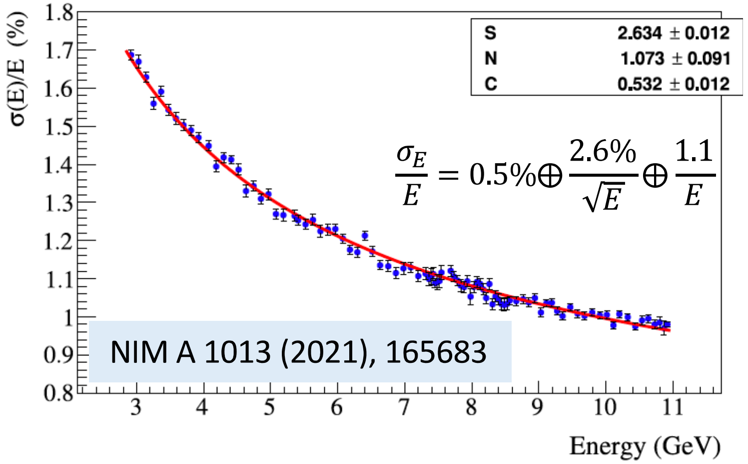
1.4<η<3.7
~19k towers
R_{outer}=190cm
SiPM readout
20 ton

EEEMCal

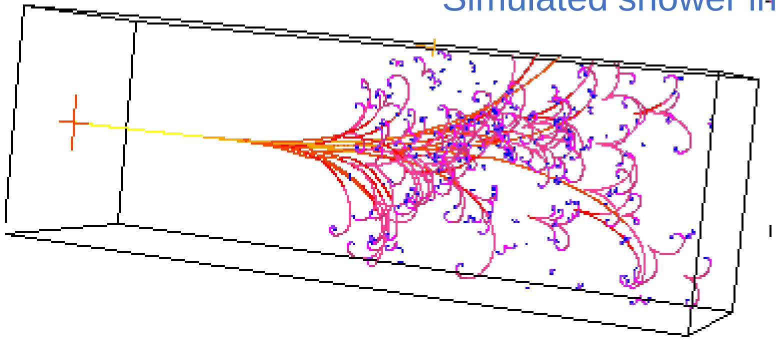
- Electron Endcap: $PbWO_4$
  - Key for finding DIS electron → Defines DIS kinematics
  - High resolution, particularly at small angles
  - Strong hadron background suppression
  - Radiated γ measurements down to 100 MeV
  - DVCS photons (Deeply Virtual Compton Scattering)
  - Also decay photons (π^0/γ) and decay e



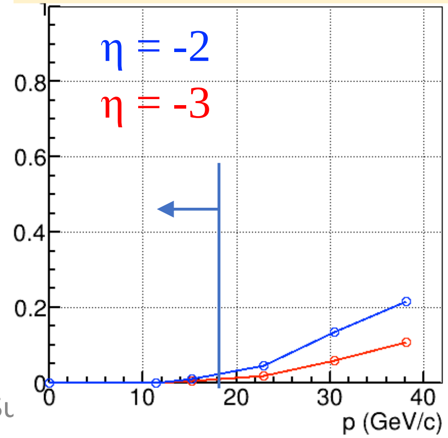
Jlab-PrimEx eta/NPS PWO EMCal prototype



Simulated shower in a PbW crystal.



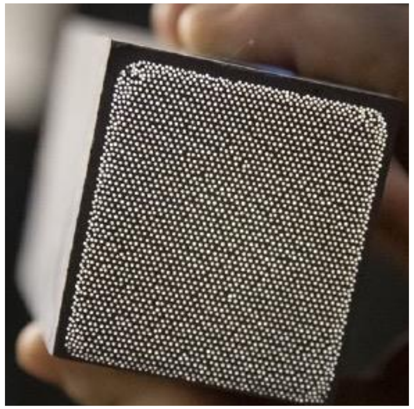
! 0 merging prob
(after shower profile analysis)



Hadron Endcap

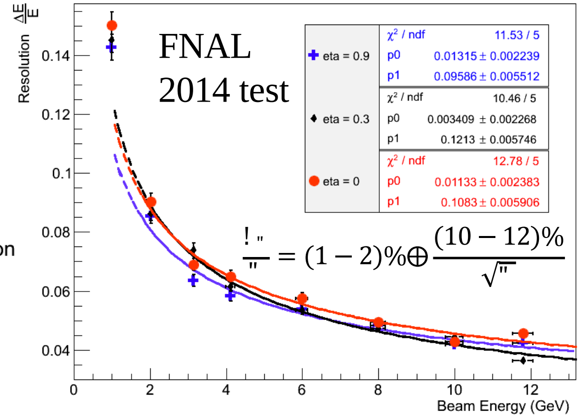
W + SciFi SPACAL Design
sPHENIX EMCal: 25k towers

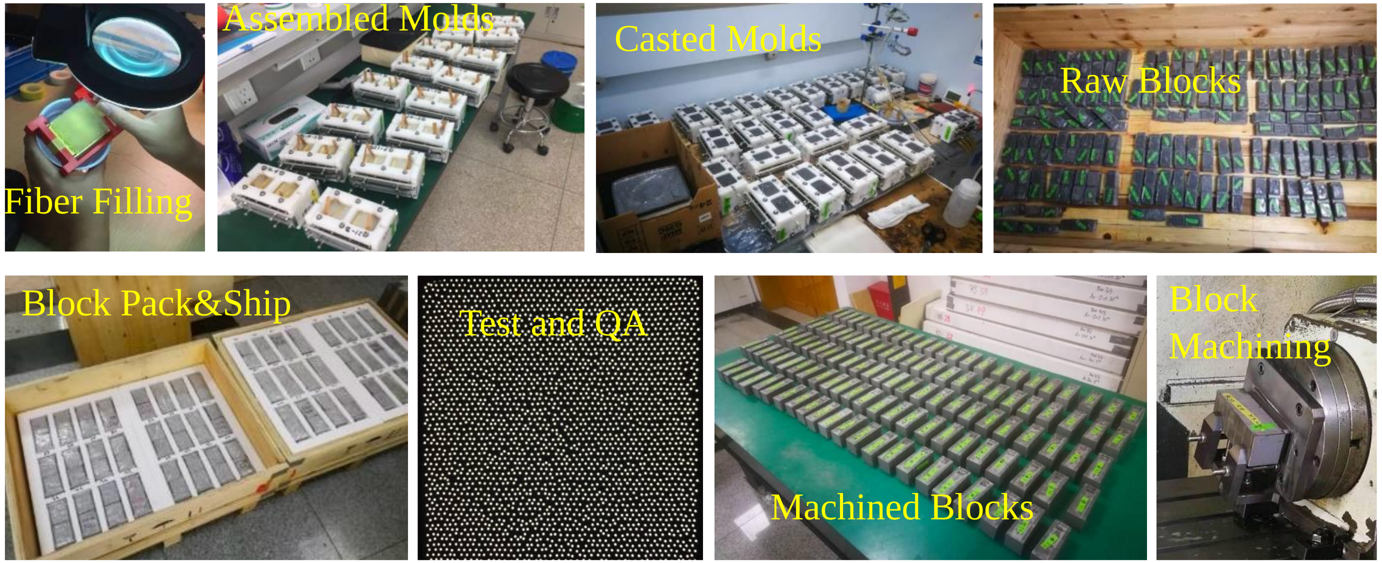
- Compact: X_0 = 0.7cm
- High granularity: Rm = 2cm
- Sampling fraction: ~2.3%
- Good resolution
- Jets up to energies ~100 GeV
- $\pi 0/\gamma$ discrimination to 50 GeV
- Decay electrons



Energy Resolution

EIC BEMC at eta=0.9, 0.3, 0, Energy Resolution

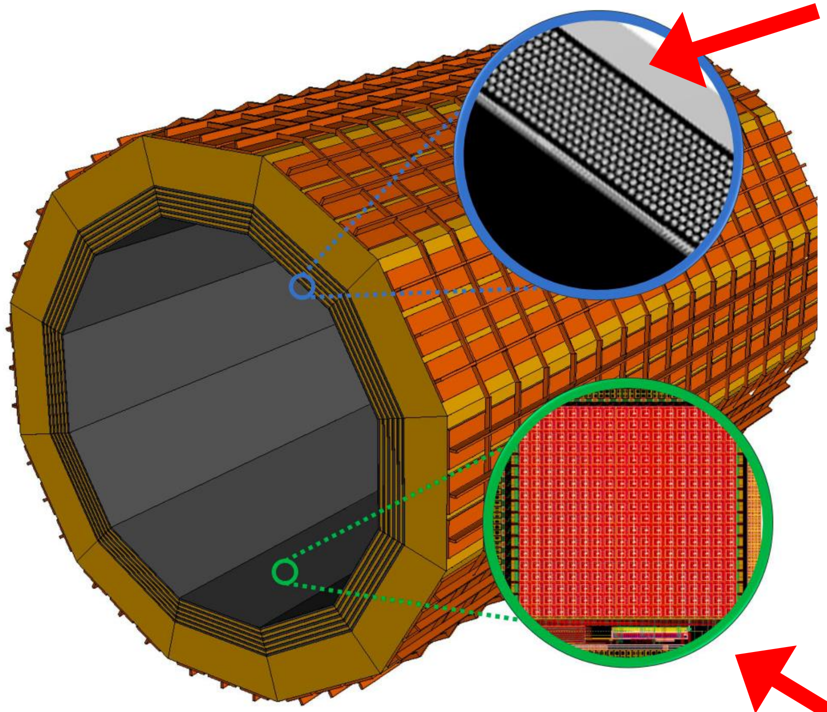


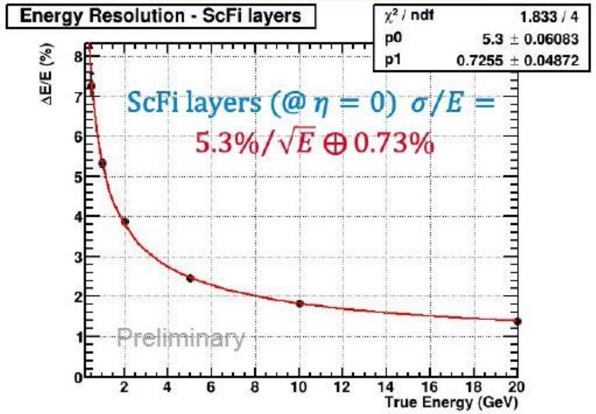


Barrel: Pb/SciFi + Imaging

Hybrid Concept:

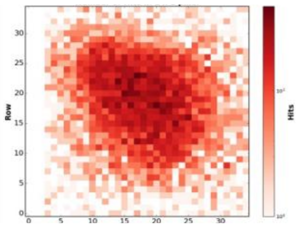
- 6 imaging Si layers (4 layers in baseline)
- Interleaved w/5 Pb/SciFi layers
- Followed by a thick Pb/SciFi layer ($17X_0$ total)
- Pb/SciFi → Scintillating fibers embedded in Pb (Similar to GlueX barrel EMCal)
- Imaging: Monolithic silicon sensor AstroPix (NASA's AMEGO-X mission)



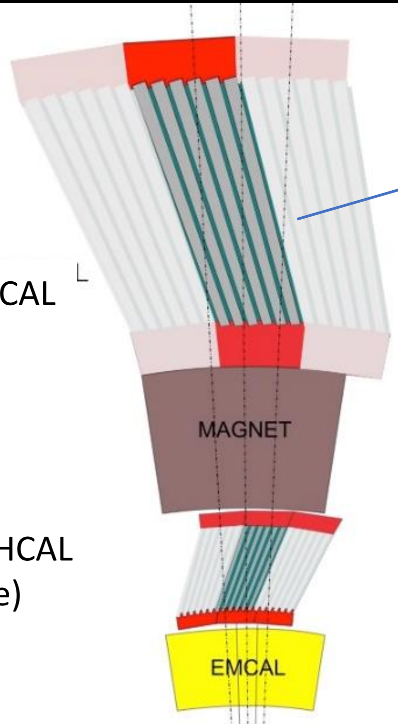


Test Beam: $\sigma/E \sim 5.2\%/\sqrt{E} \oplus 2\%$

FY23 tests (FNAL):
Performs well in much harsher conditions than EIC



Hadronic Calorimetry (sPHENIX→ ePIC)



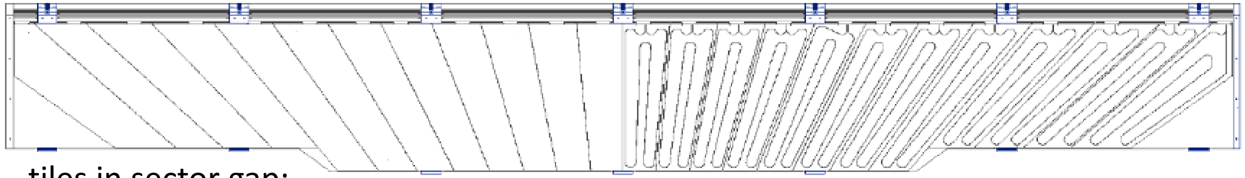
- HCAL steel and scintillating tiles with wavelength shifting fiber
  - **Outer HCal (outside the solenoid)**
  - **$\Delta\eta \times \Delta\phi \approx 0.1 \times 0.1$**
  - **1,536 readout channels**
- SiPM Readout

- Outer HCAL $\approx 3.5\lambda_I$
- Magnet $\approx 1.4X_0$
- (Frame $\approx 0.25\lambda_I$) (sPHENIX)
- (EMCAL $\approx 18X_0 \approx 0.7\lambda_I$) (sPHENIX)

HCAL performance requirements driven by jet physics in HI collisions

- Uniform fiducial acceptance $-1<\eta<1$ and $0<\phi<2\pi$
  - Extended coverage $-1.1<\eta<1.1$ to account for jet cone
- **(sPHENIX)** Absorb >95% of energy from a 30 GeV jet
  - Requires ~4.9 nuclear interaction length depth
- **(sPHENIX)** Hadronic energy resolution of *combined* calorimetry:
  - UPP: $\frac{\sigma}{E} < \frac{150\%}{\sqrt{E}}$ (in central Au+Au collisions)
  - Gaussian response (limited tails)
- HCAL created by instrumenting barrel magnetic flux return

Outer HCAL Design



tiles in sector gap:

32 assembled and tested sectors - 1.9m inner radius, 2.6m outer radius

10 rows of 8mm scint. tiles (24 tiles per row), 12^{o} tilt angle

Tapered 1020 steel plates ~26.1mm - ~42.4mm

Completed sector is 6.3m long, 13.5 tons

Cabling is fun!

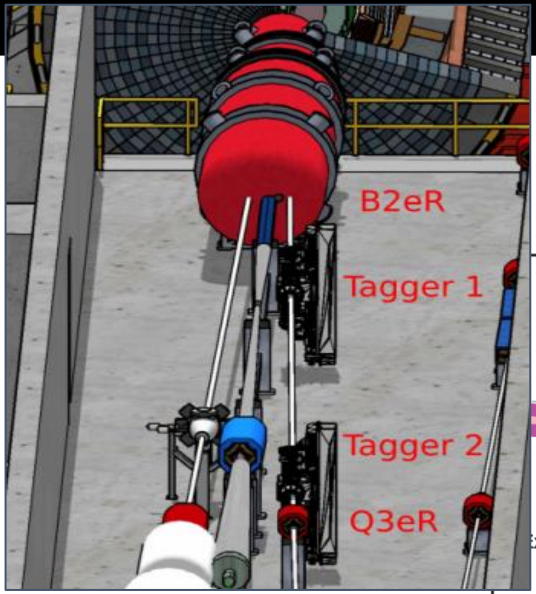
Assembly Detail:
5 scintillators/tower
48 towers per sector
32 sectors;
1536 channels (7680 SiPMs)

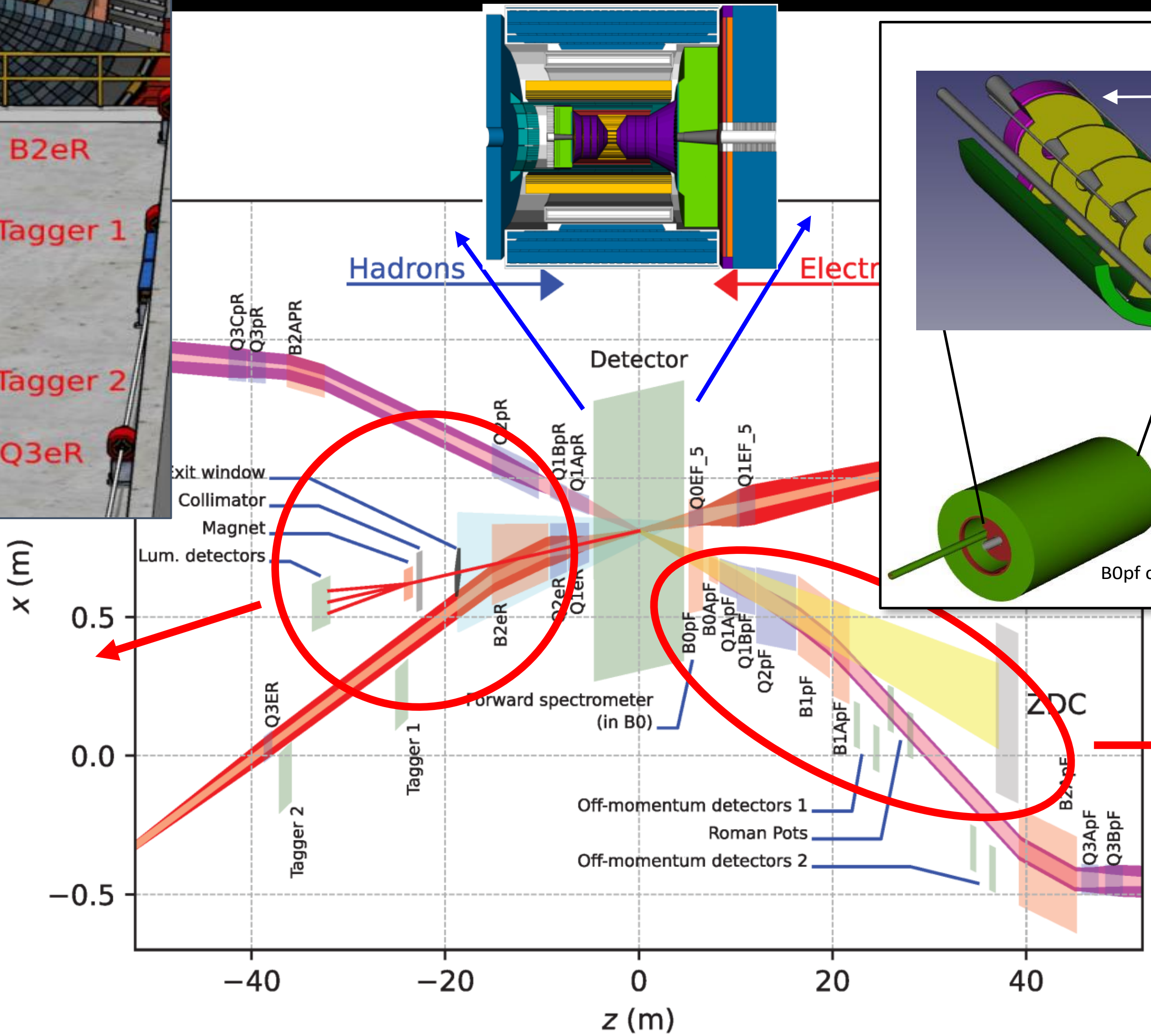
Tower preamplifiers

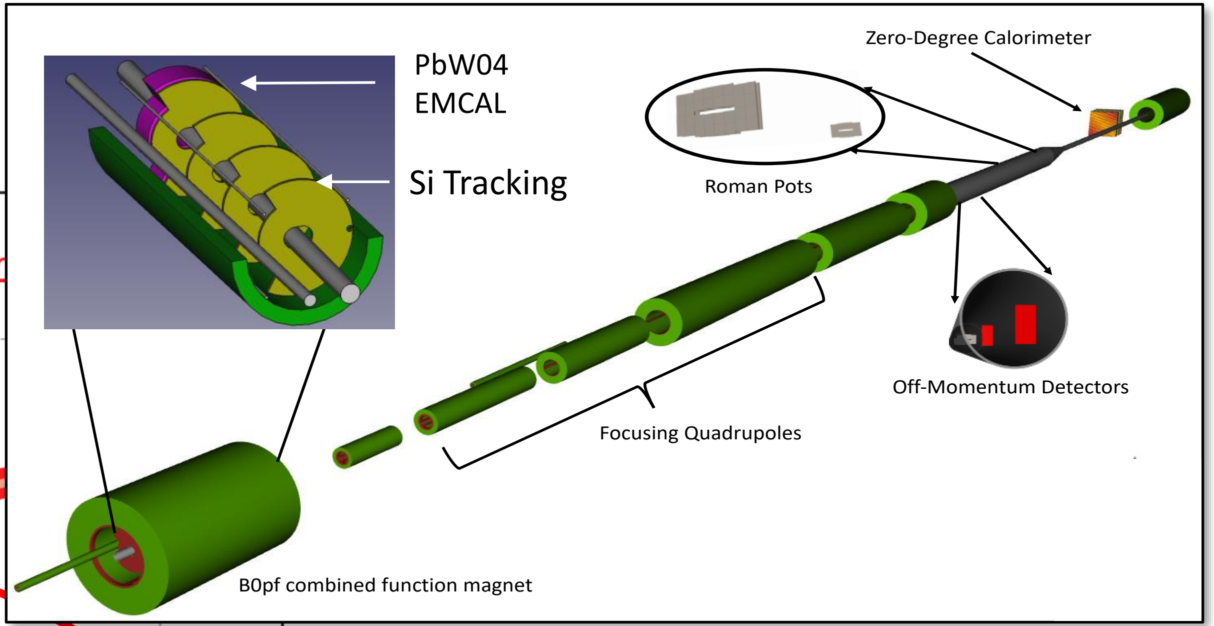
LV/Bias and slow controls.

Tower signals cabled out to digitizers

Far-Forward and Far-Backward Detectors







Far-Backward Detectors

- Luminosity monitor
- Low-Q^2 Tagging Detectors

Far-Forward Detectors

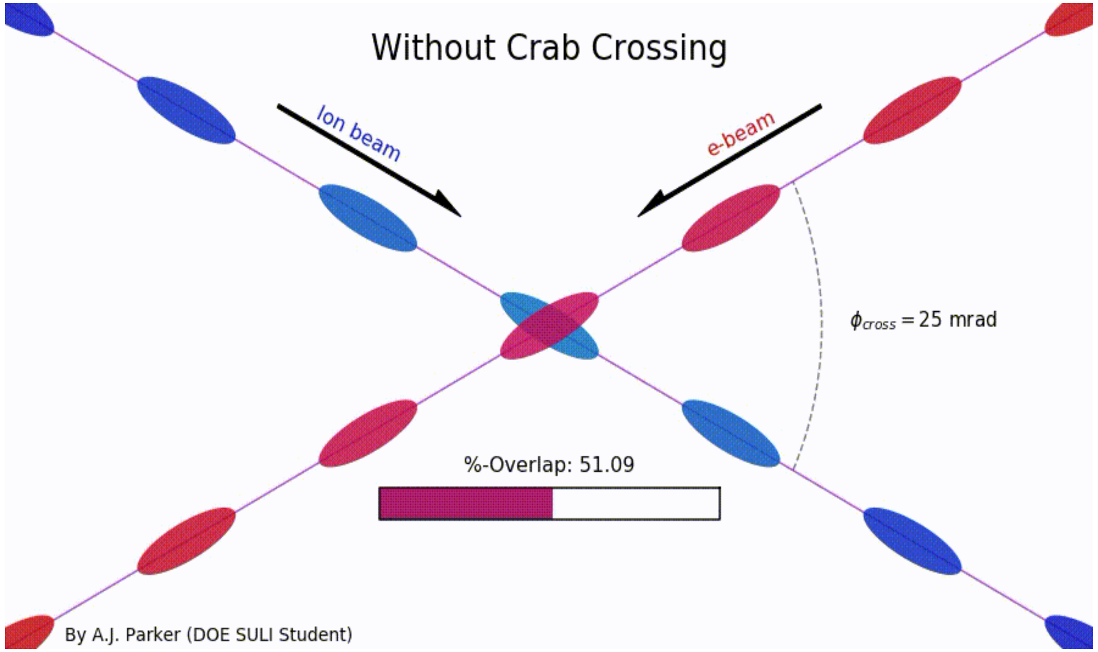
- B0 Tracking and Photon Detection
- Roman Pots and Off-Momentum Detectors
- Zero-Degree Calorimeter

A Few Other Experimental Concerns

Why a Crossing Angle?

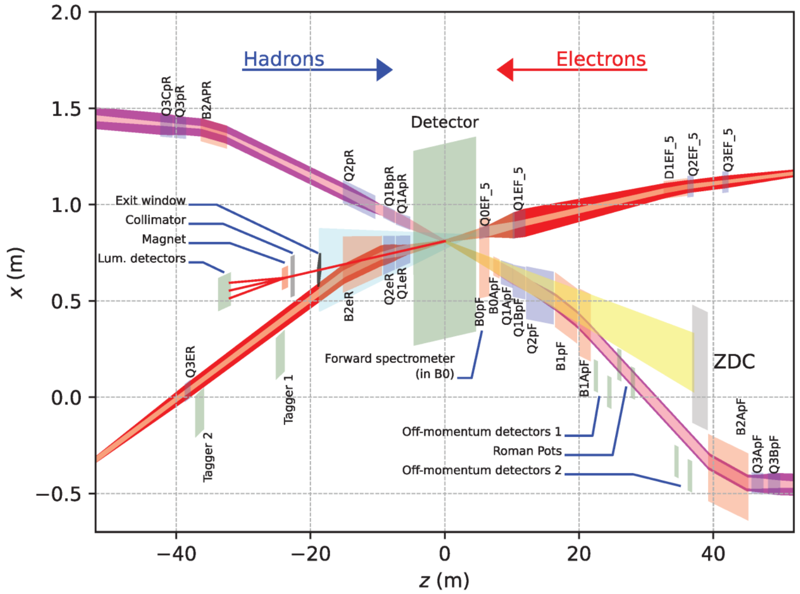
- Brings focusing magnets close to IP
  → high luminosity
- Beam separation without separation dipoles
  → reduced synchrotron radiation background

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



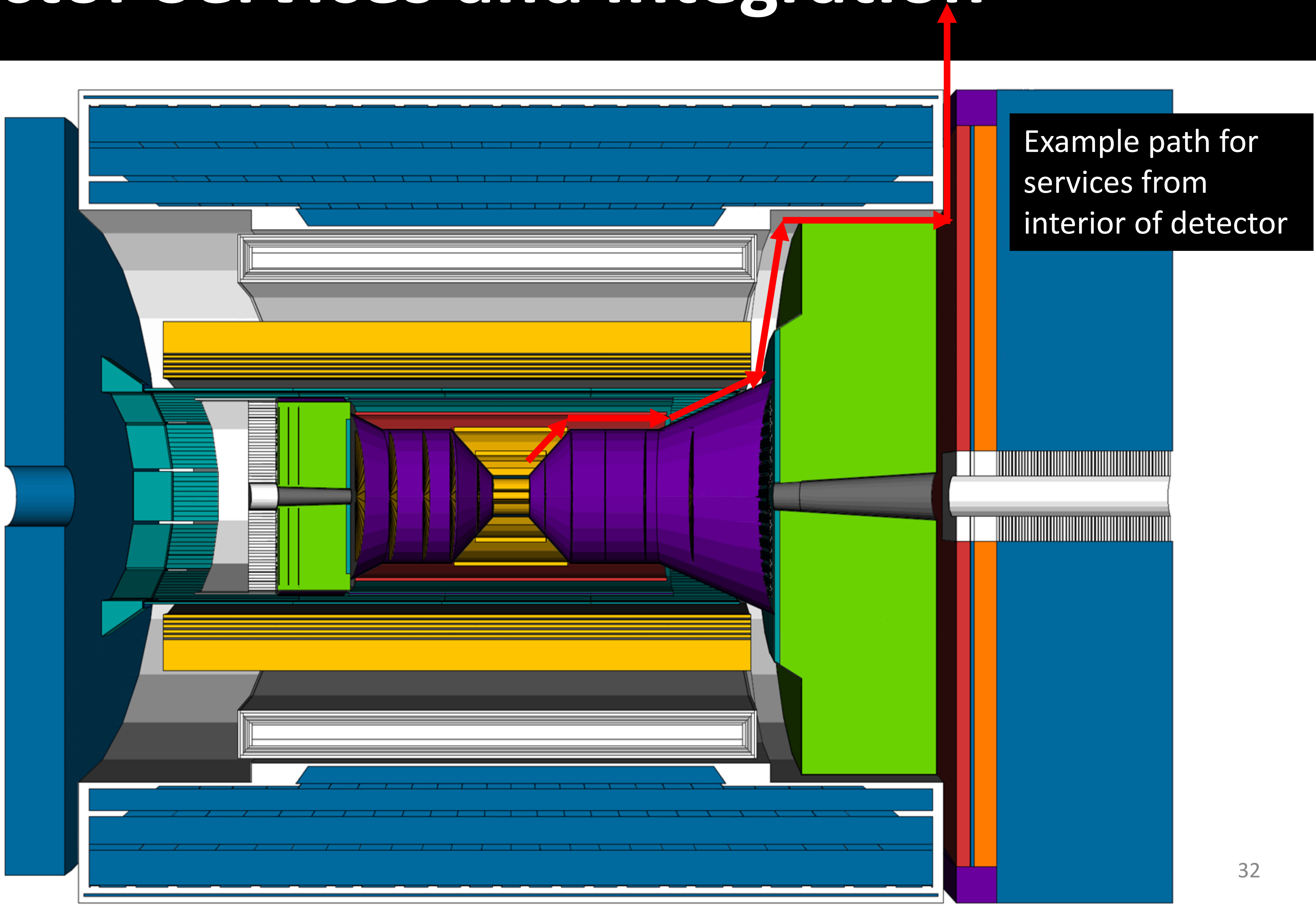
Detector Services and Integration

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.



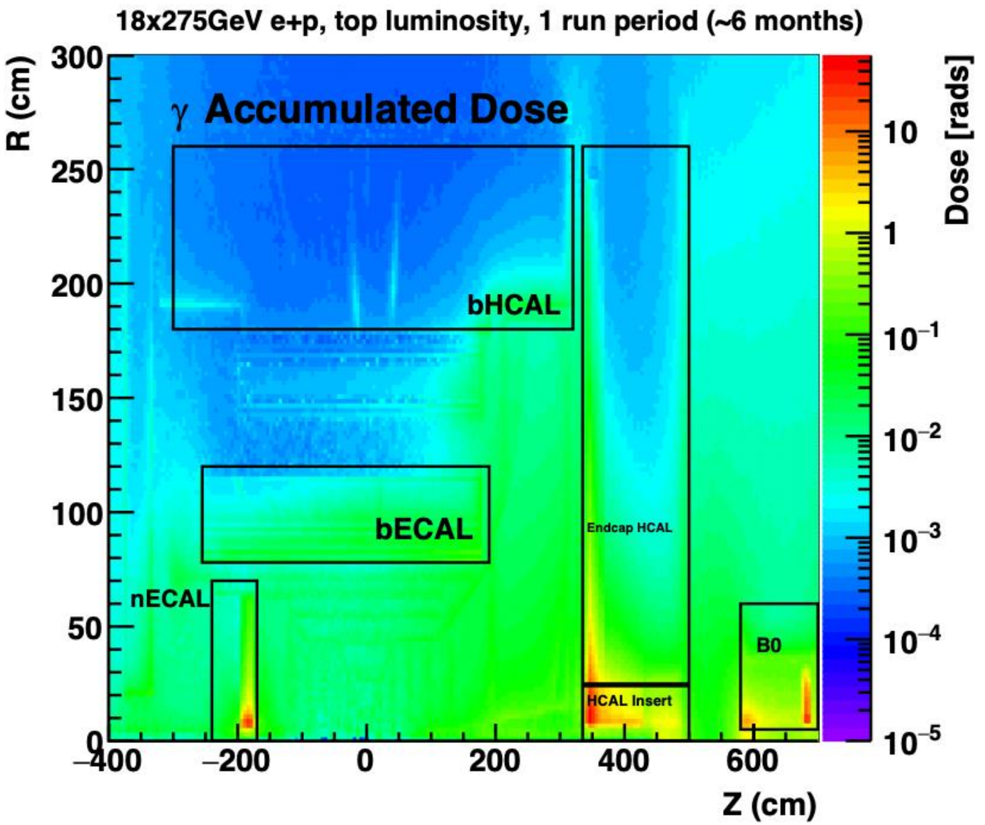
Detector Backgrounds/Radiation

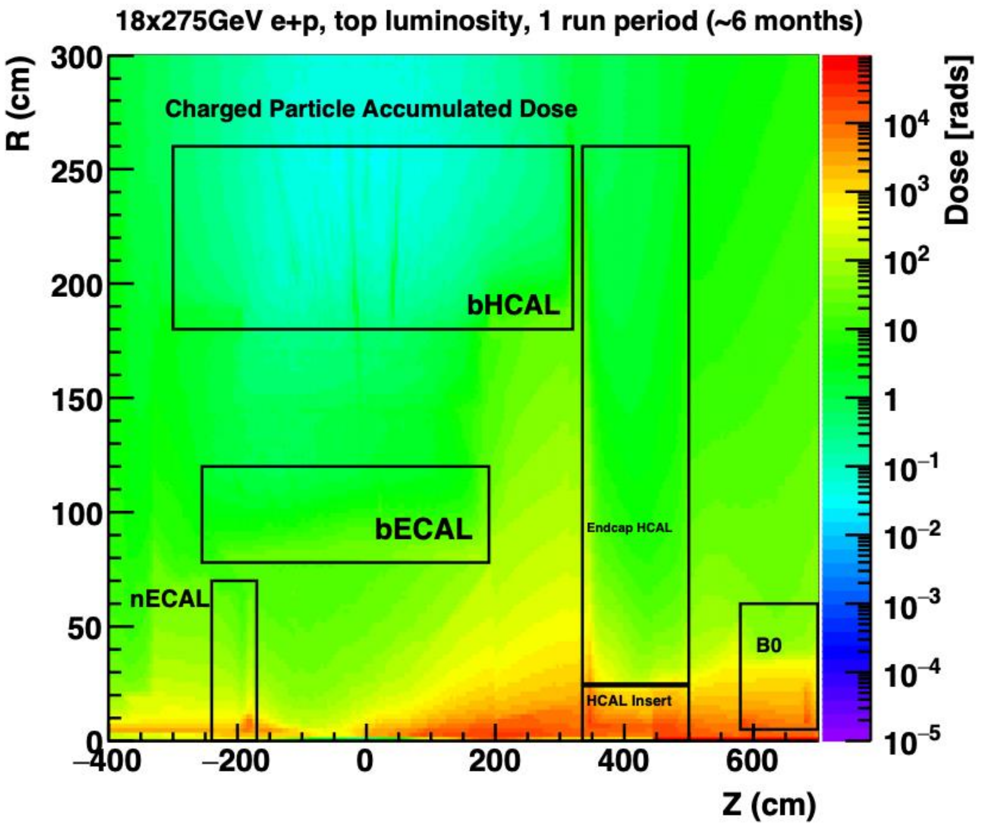
- Three types of background/radiation sources we need to worry about:
  - Primary collisions
  - Synchrotron radiation
  - Beam-gas induced
- All of these couple with the beam parameters
  - Divergence, energy spread, crossing angle, bunch length

- 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*

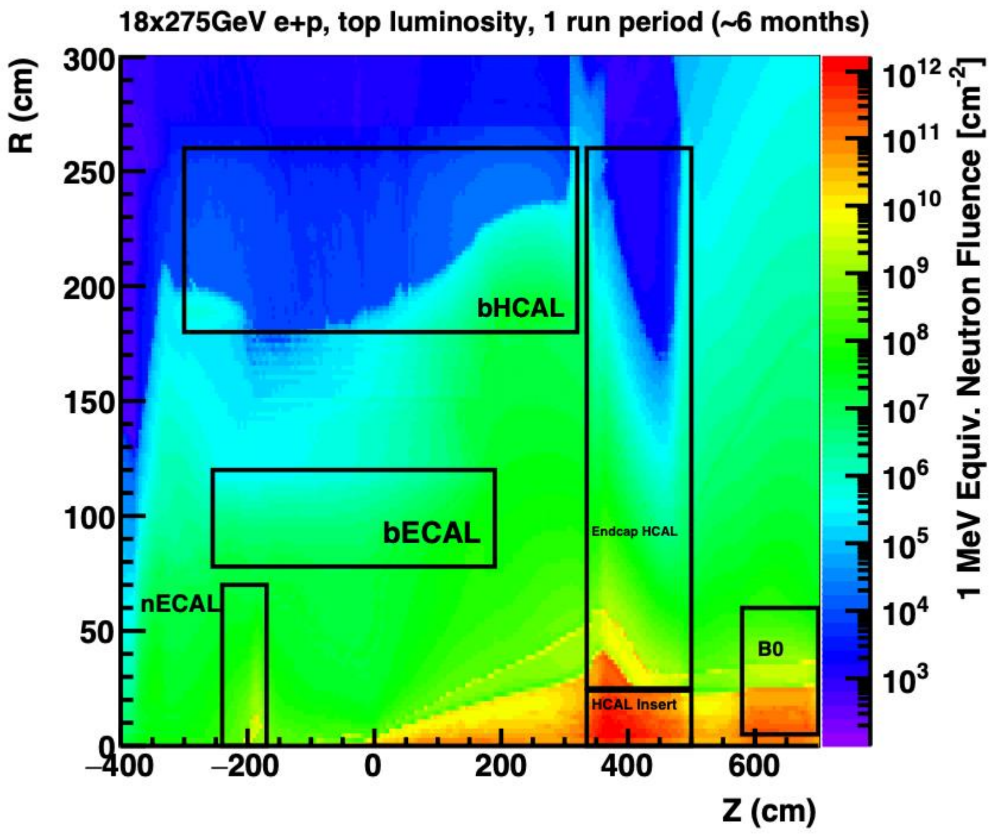


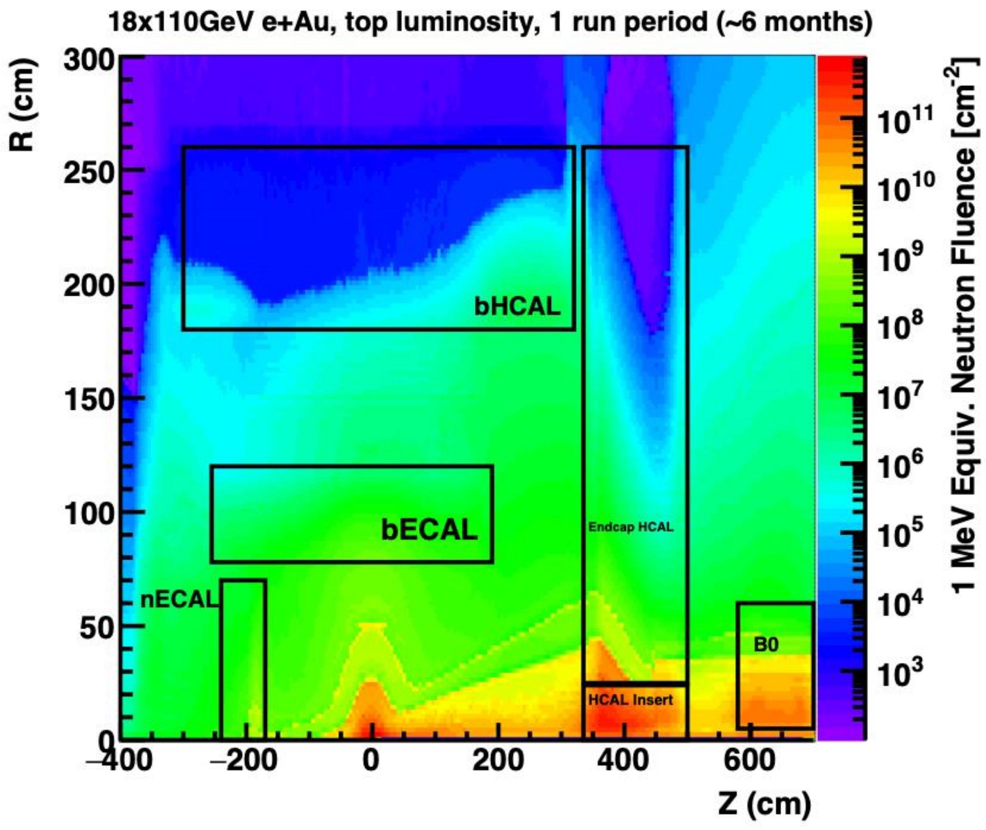


Radiation doses from gamma and charged particles fairly low across most of ePIC.
Regions of highest dose near the beam line - can reach ~ 100 kRad.

Primary Collisions (neutrons)

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

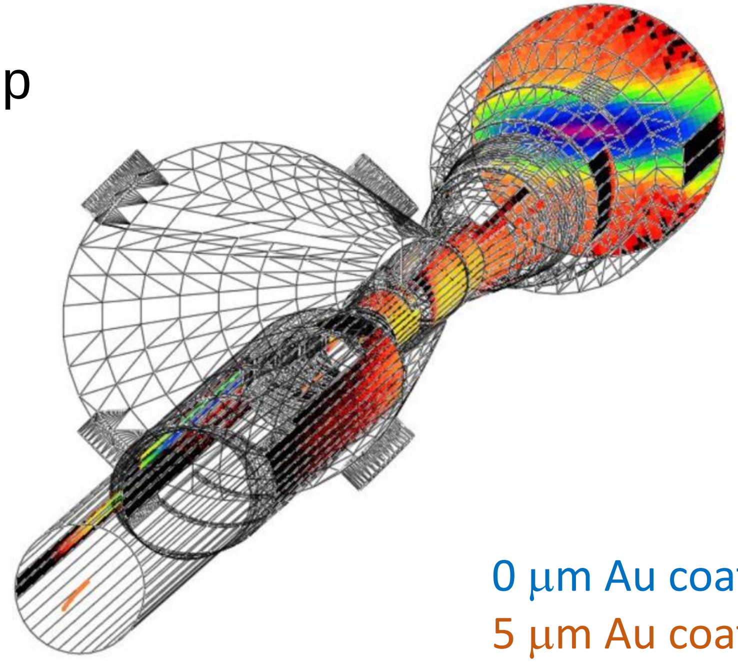




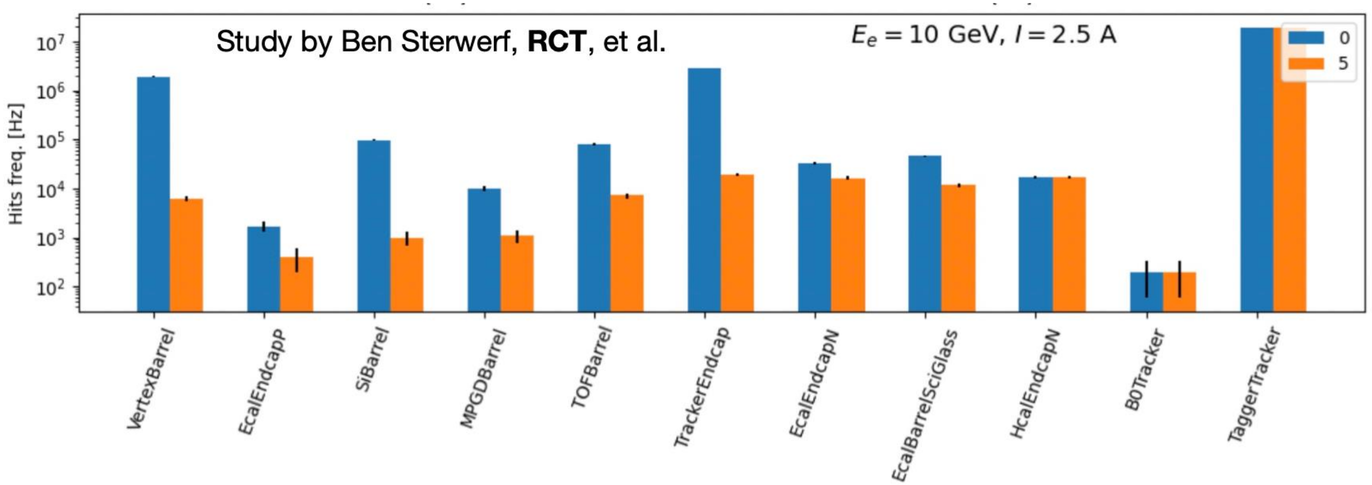
1 MeV equivalent neutron fluence highest near the beamline -> implications for SiPMs.

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



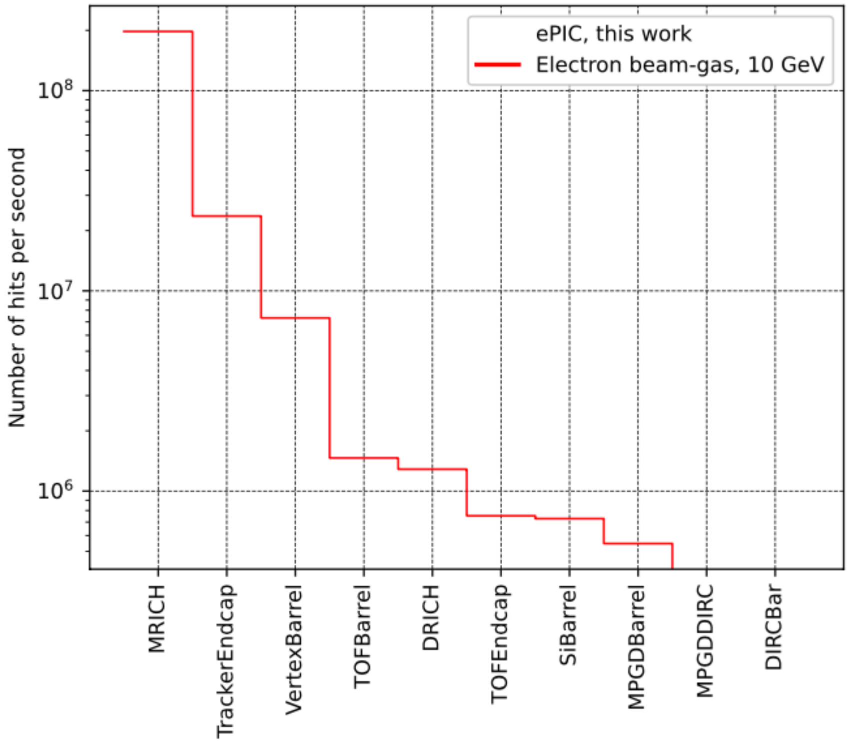
0 μm Au coating
5 μm Au coating



Beam-Gas Consequences

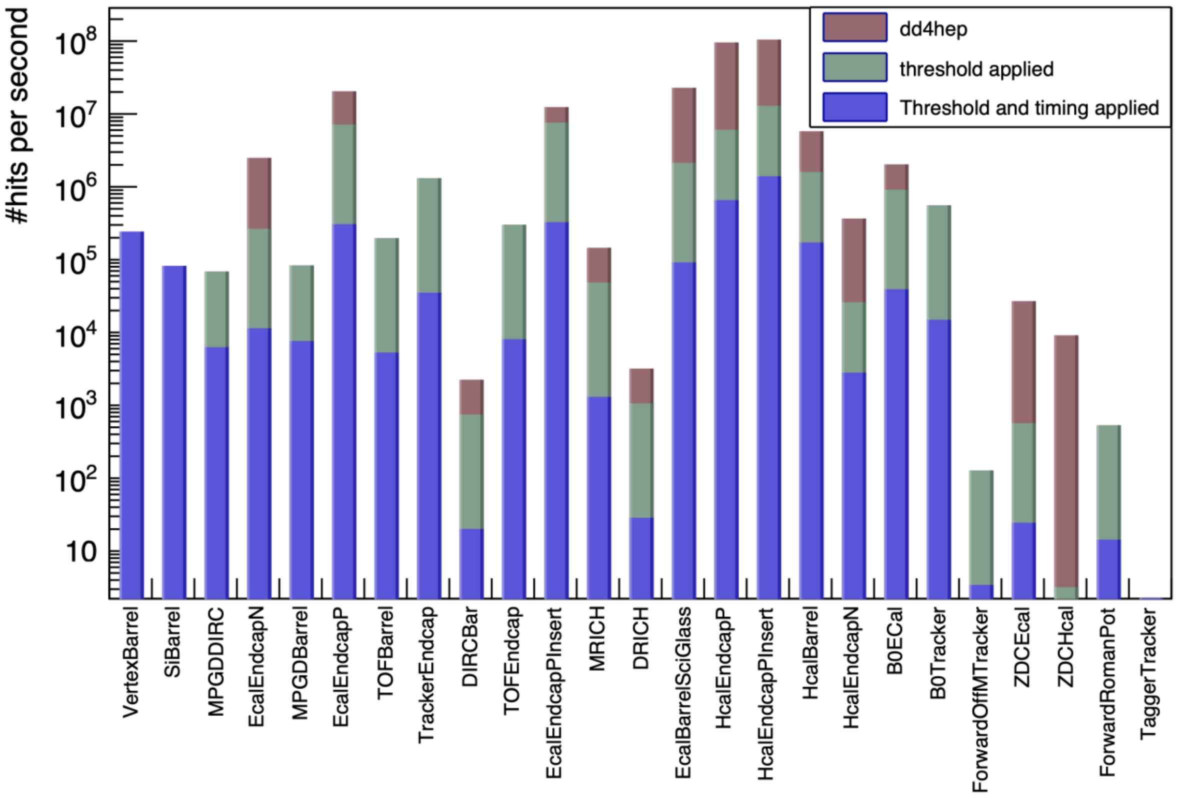
rates in kHz	5x41 GeV	5x100 GeV	10x100 GeV	10x275 GeV	18x275 GeV
DIS ep	12.5 kHz	129 kHz	184 kHz	500 kHz	83 kHz
hadron beam gas	12.2kHz	22.0kHz	31.9kHz	32.6kHz	22.5kHz
electron beam gas	2181.97 kHz	2826.38 kHz	3177.25 kHz	3177.25 kHz	316.94 kHz

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



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

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



Final Thoughts

- In order to determine the answers to the fundamental structure of nuclear matter we need to understand the kinematics and flavor of all particles from our electron-ion collisions
- A large-scale optimization regarding cost, speed, resolution, robustness, technology interplay
- Pieces of ePIC already exist and are working well!
- Beam tests are ongoing → Simulation is good but not sufficient
- Detector subsystems are essentially separate projects

Things I didn't cover

- Read-out electronics
- Data Acquisition (DAQ), Streaming Read-Out
- Calorimeter Clustering Routines, Tracking algorithms, Jet Finding
- Algorithms that combine information from a variety of detectors (Particle Flow is an example)
- Far forward/far backward regions
- Unfolding and other corrections for efficiency and resolution
- And probably a lot else… Many years of working on detectors…