CALORIMETRY FOR THE ePIC EXPERIMENT

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U.S. DEPARTMENT OF ENERGY
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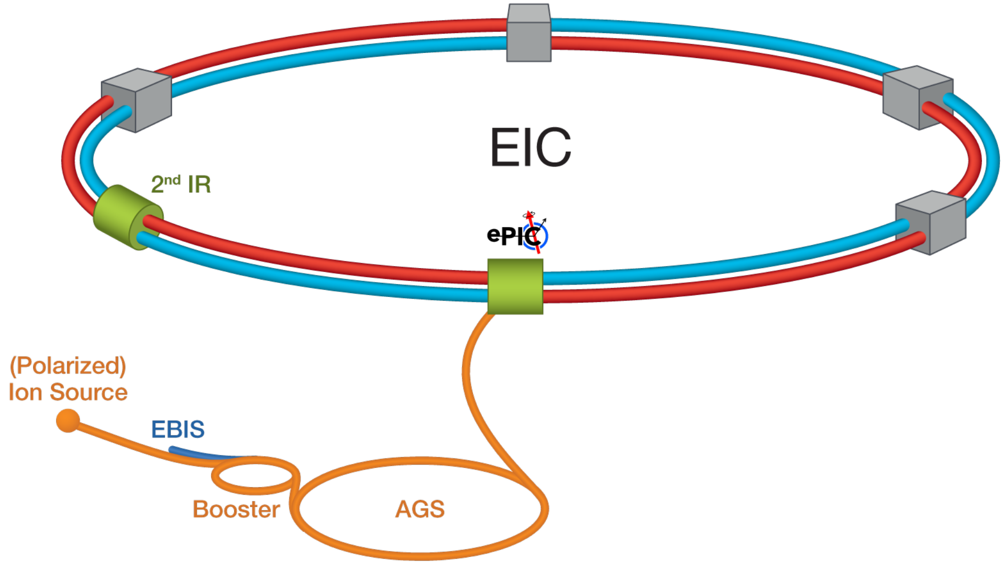
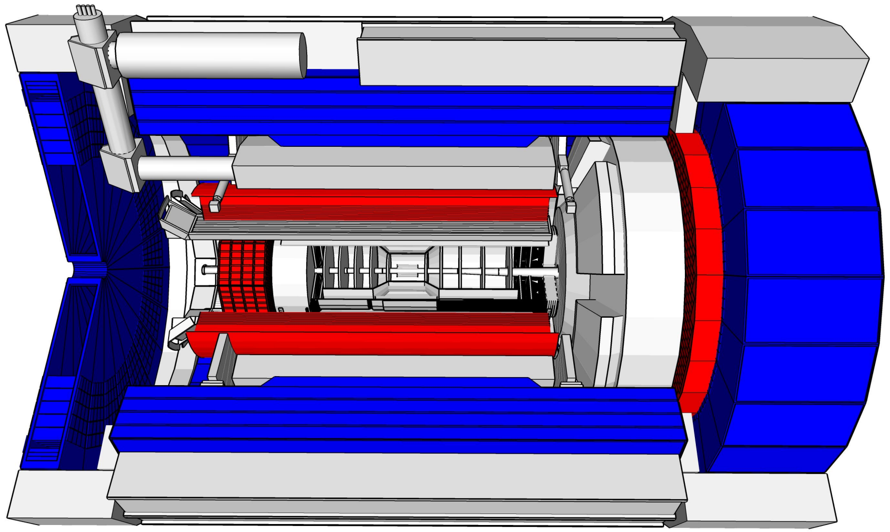
EPIC AT THE EIC

- EIC is a high luminosity machine, enabling precise measurements (Shujie's talk)
  - Much of the EIC physics lives in percent-level effects
  - Requires precision in:





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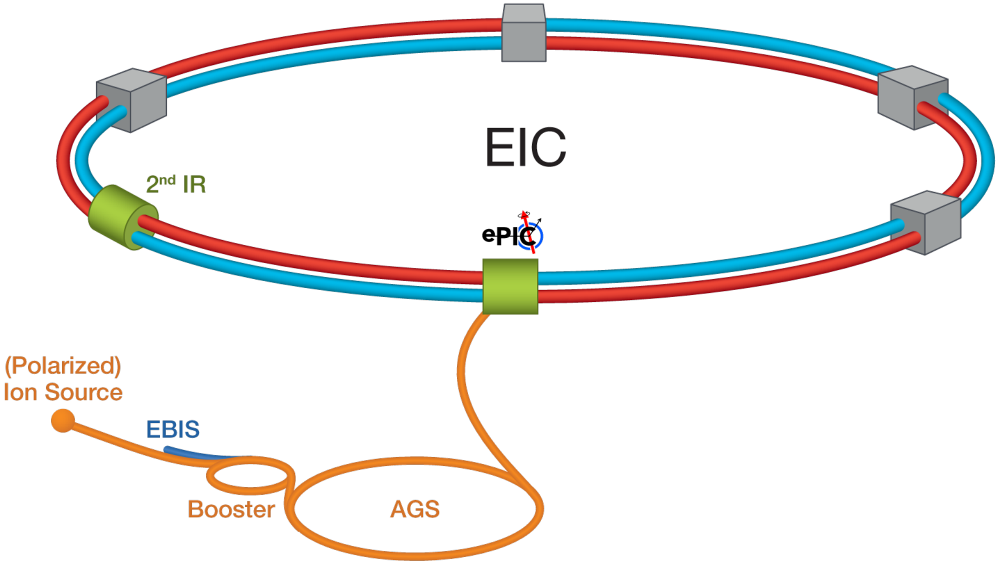

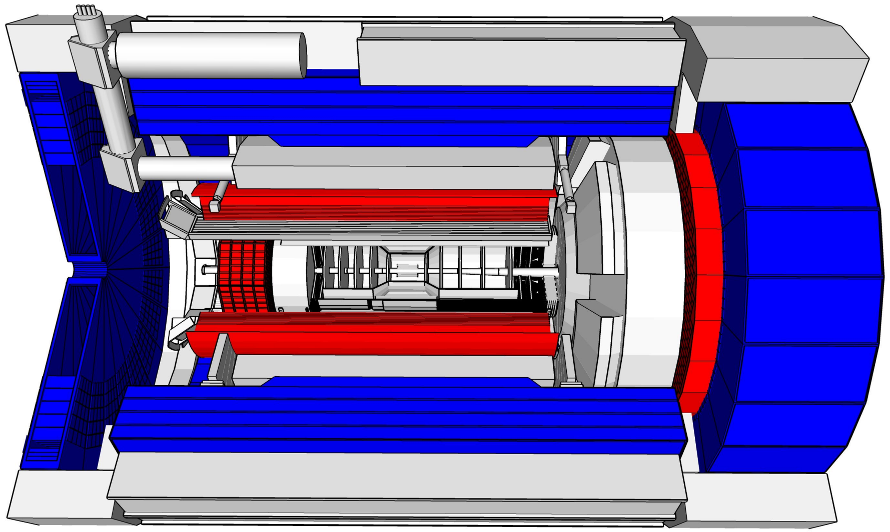

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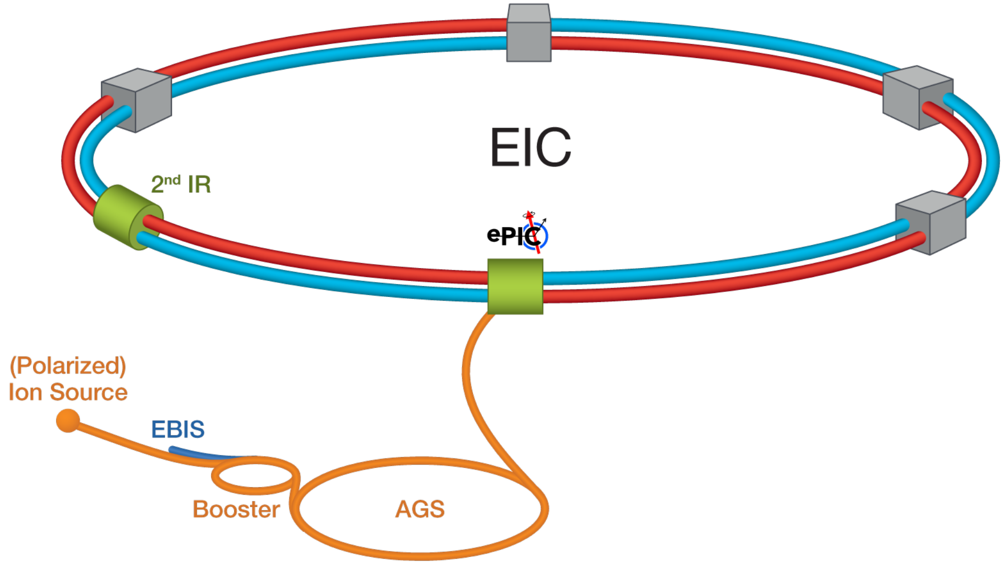

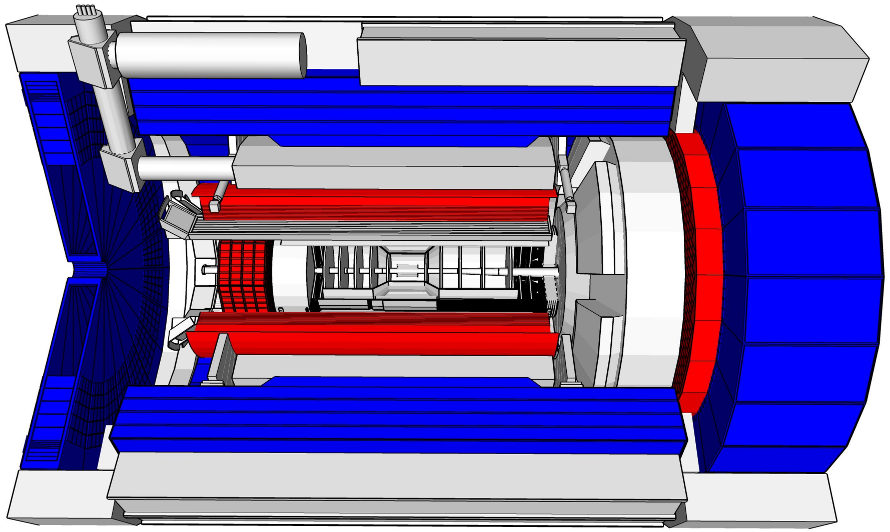

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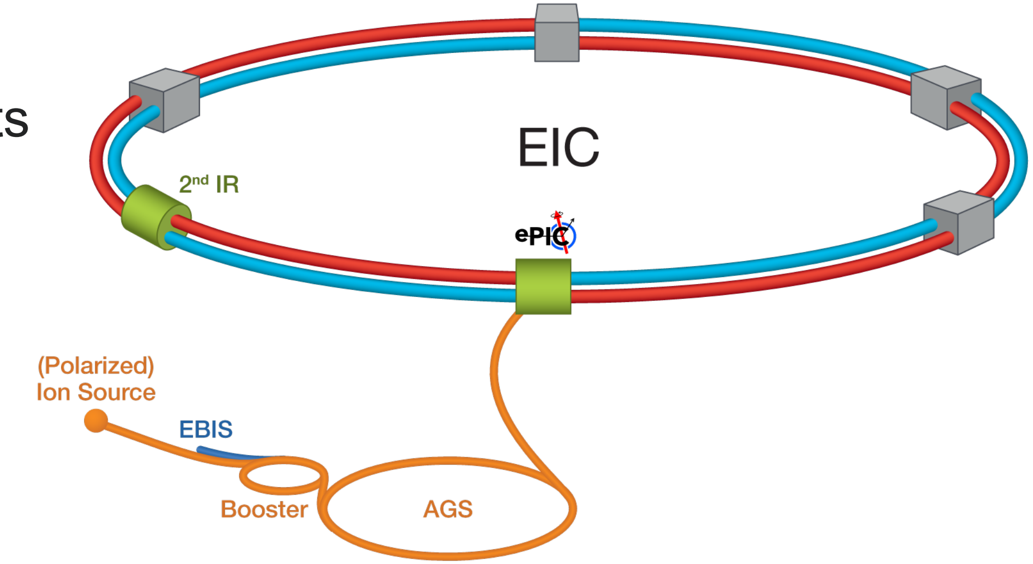

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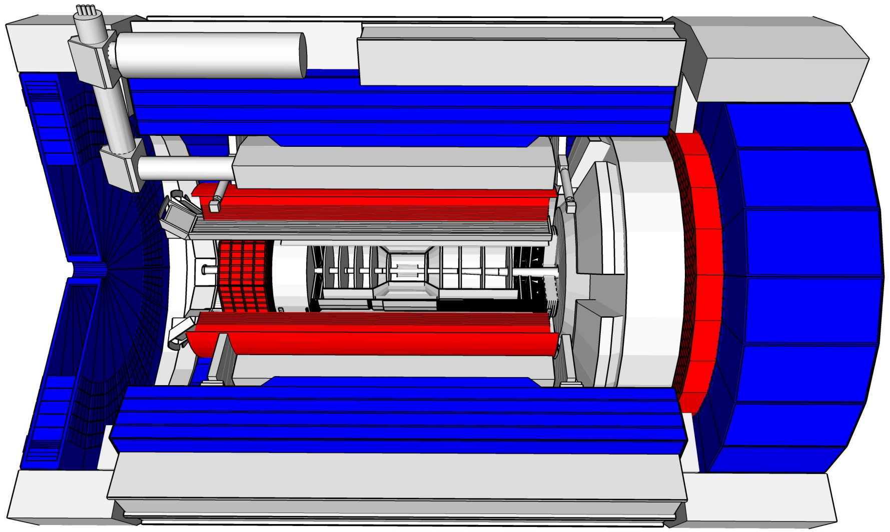
- Far-forward detectors: Michael's talk



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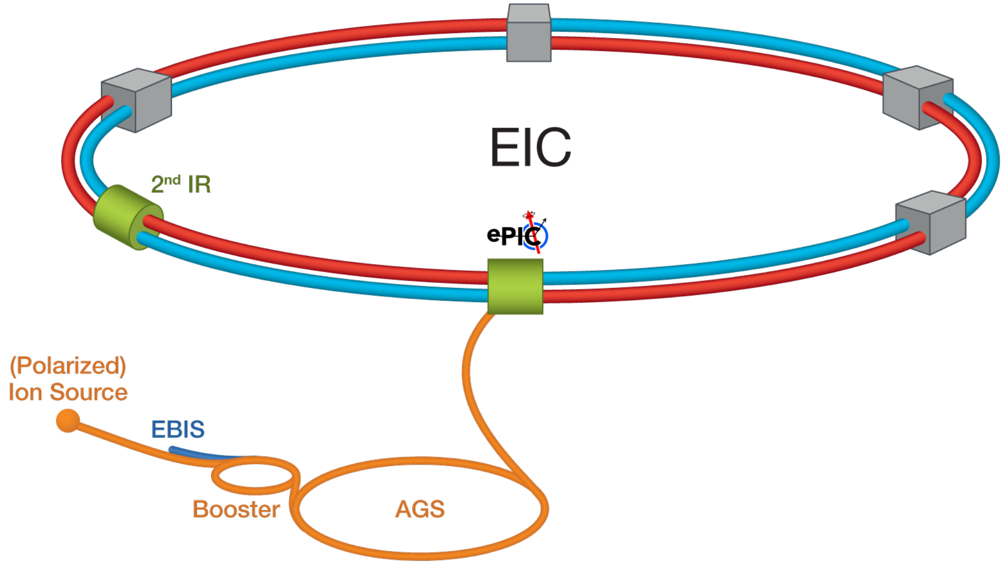

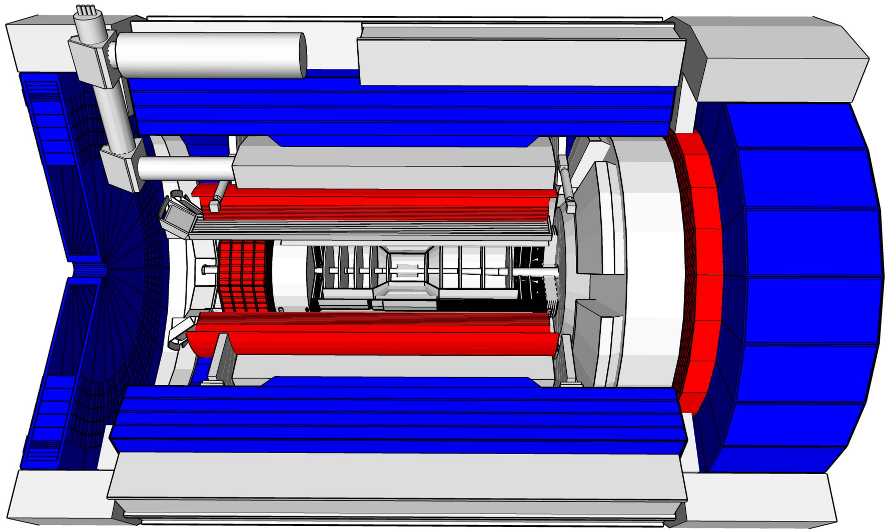

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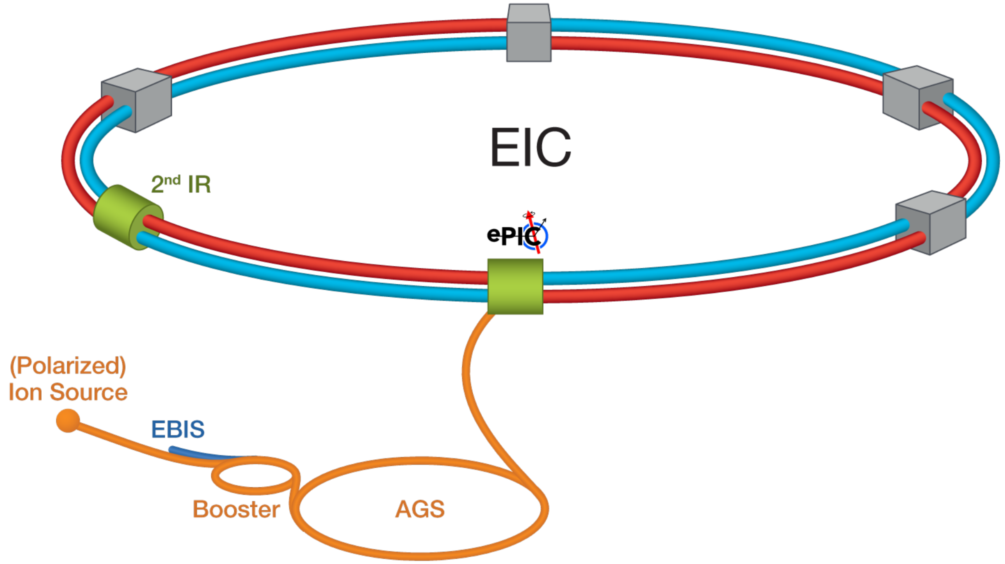
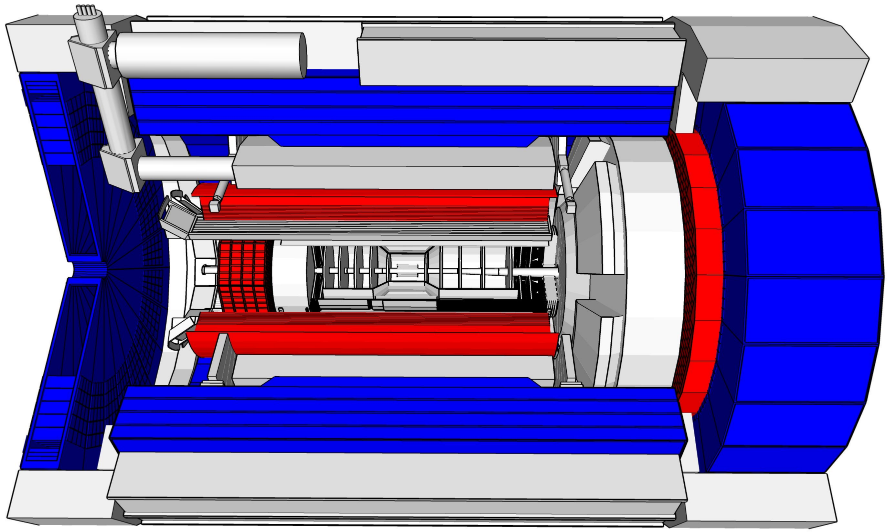
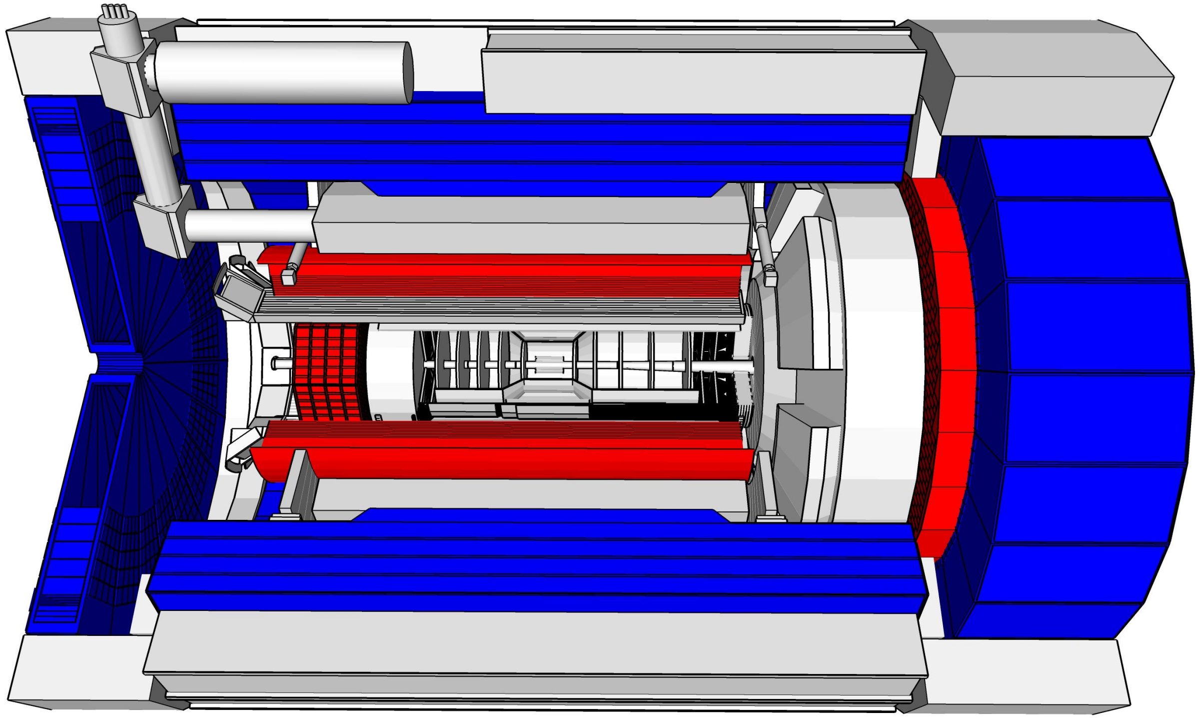
- Cross-check! – Pawel's talk





CALORIMETRY AT THE EIC

- Calorimetry at the EIC has some unique challenges:
  - Wide variety in CM energy, 5 GeV e^- x 41 GeV p/A to 18 GeV e^- x 275 GeV p
- EIC physics lives at all scales!
  - Large dynamic range required, hundreds of GeV to tens of MeV
  - Most challenging constraint is not always simply measuring energy
- Electron identification
  - Very stringent requirements on e/h separation to identify DIS events from the much larger photoproduction background
  - 1-in-10000 rejection of pions in the few GeV range!
- Streaming readout
- Integration with PID & tracking detectors



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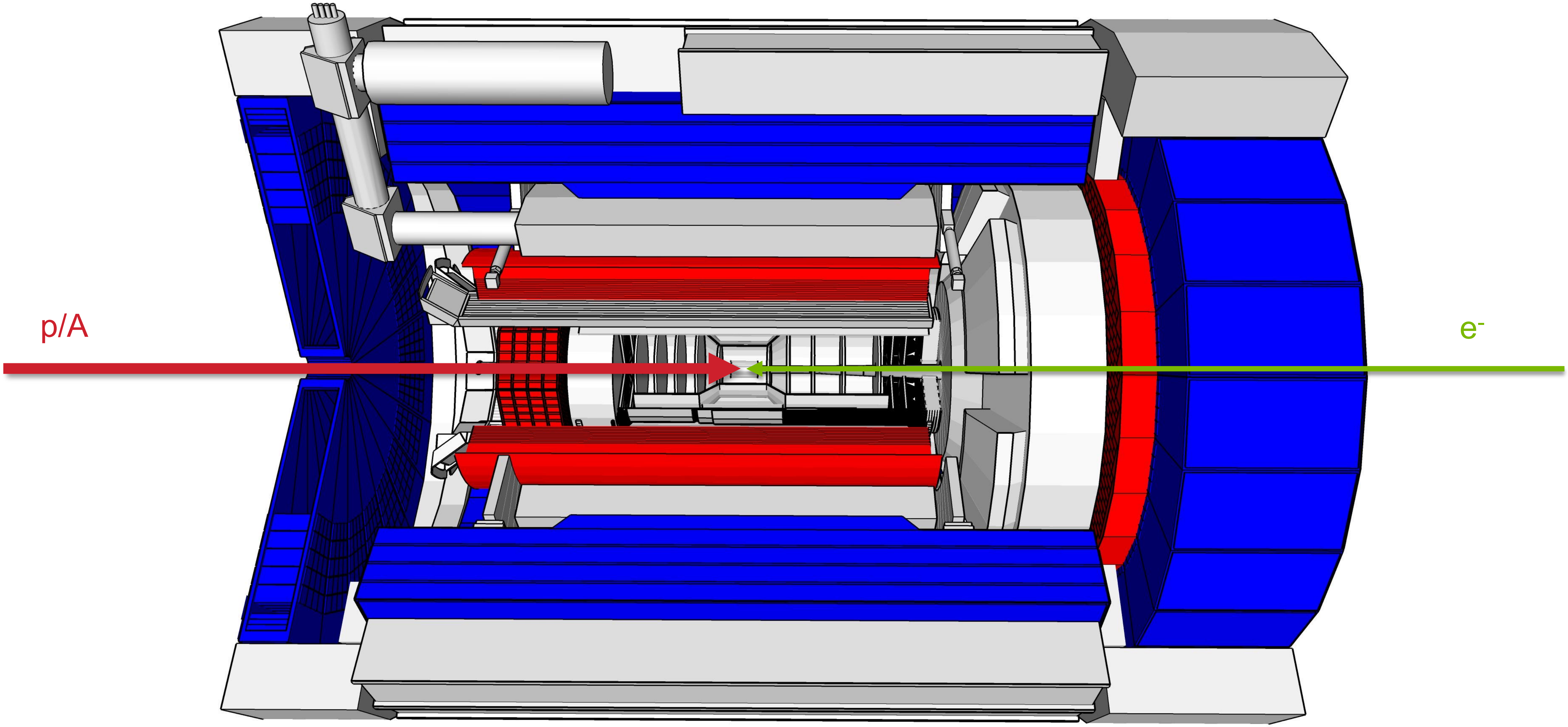

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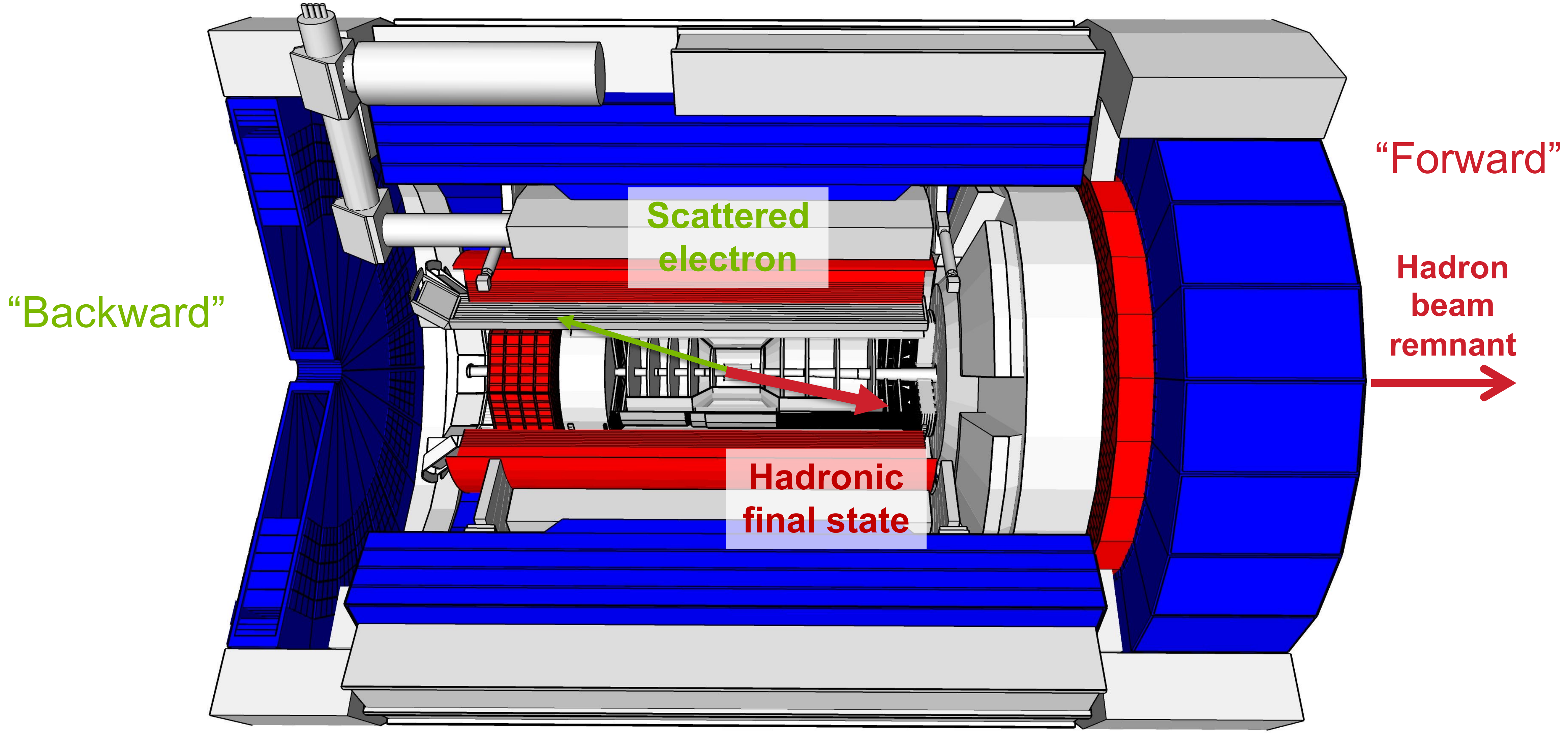


BACKWARD CALORIMETERS

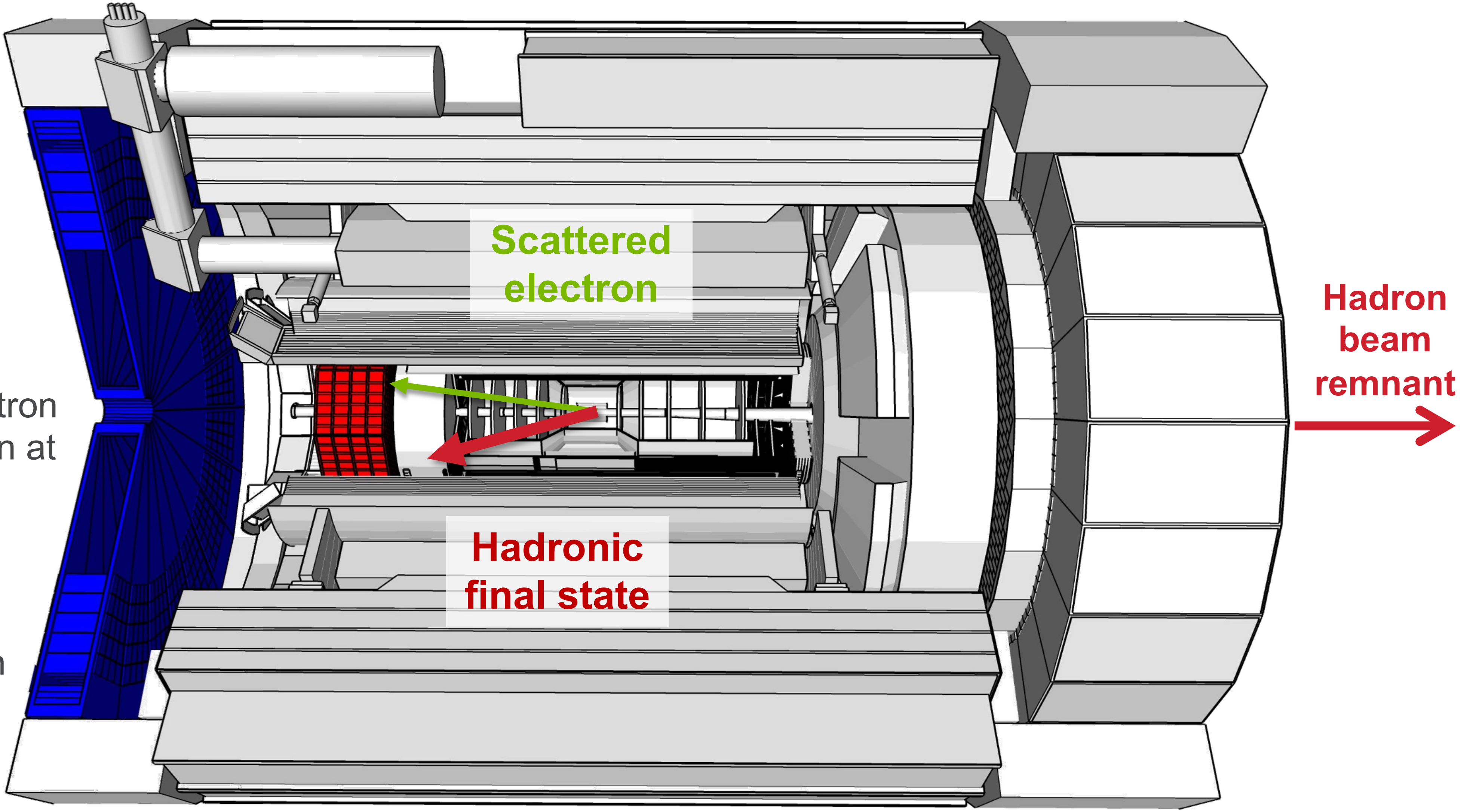
$-3.6 < \eta < -1.7$

Low Q^2, low x

Physics:
gluon saturation, nuclear terra incognita

Challenge:
Measure the electron with high precision at small scattering angles

Separate the scattered electron from the nearby hadrons



BACKWARD CALORIMETERS

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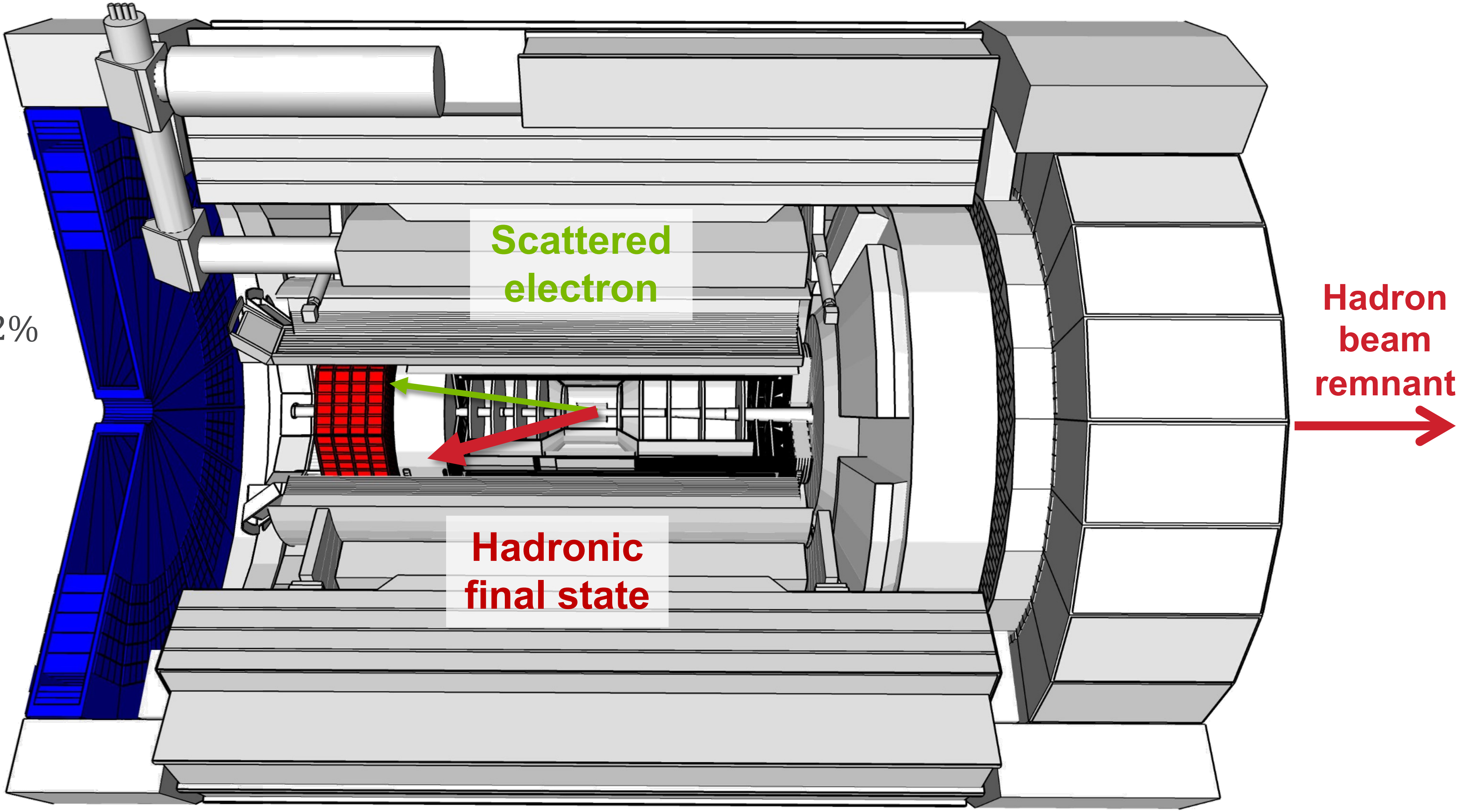
Low Q^2, low x

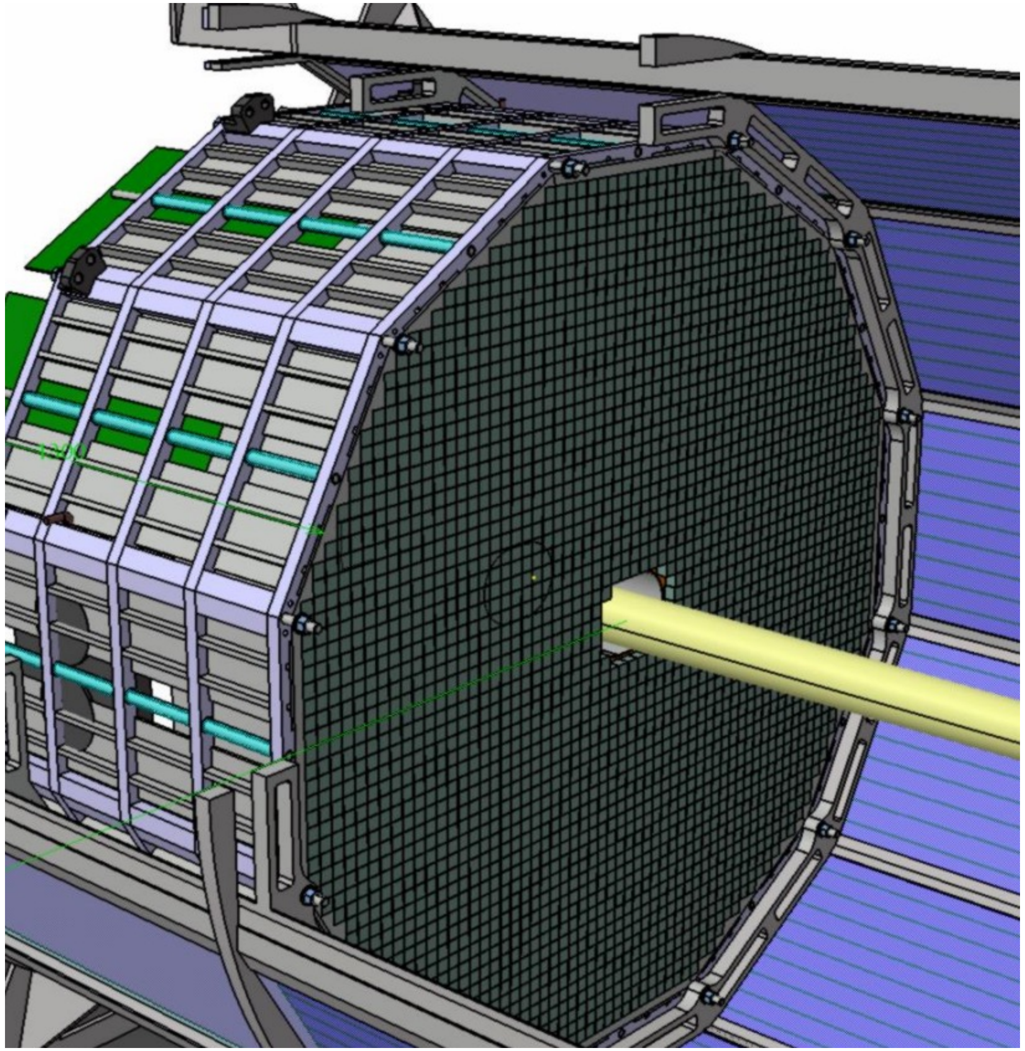
Resolution requirements:

EMCal:
$\frac{\sigma_E}{E} \sim \frac{2-3\%}{\sqrt{E}} \oplus 1-2\%$

HCal:
$\frac{\sigma_E}{E} \sim \frac{100\%}{\sqrt{E}} \oplus 10\%$

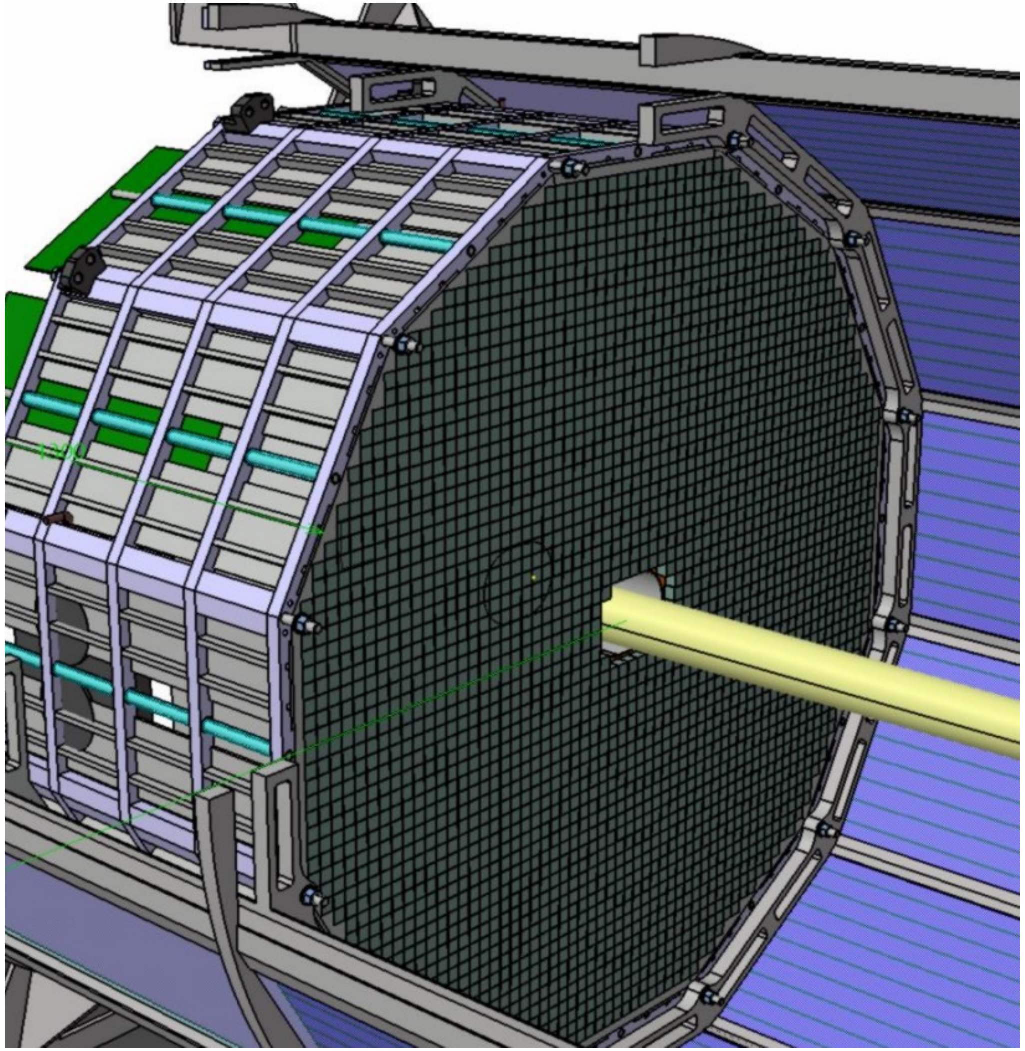


BACKWARD ELECTROMAGNETIC CALORIMETER

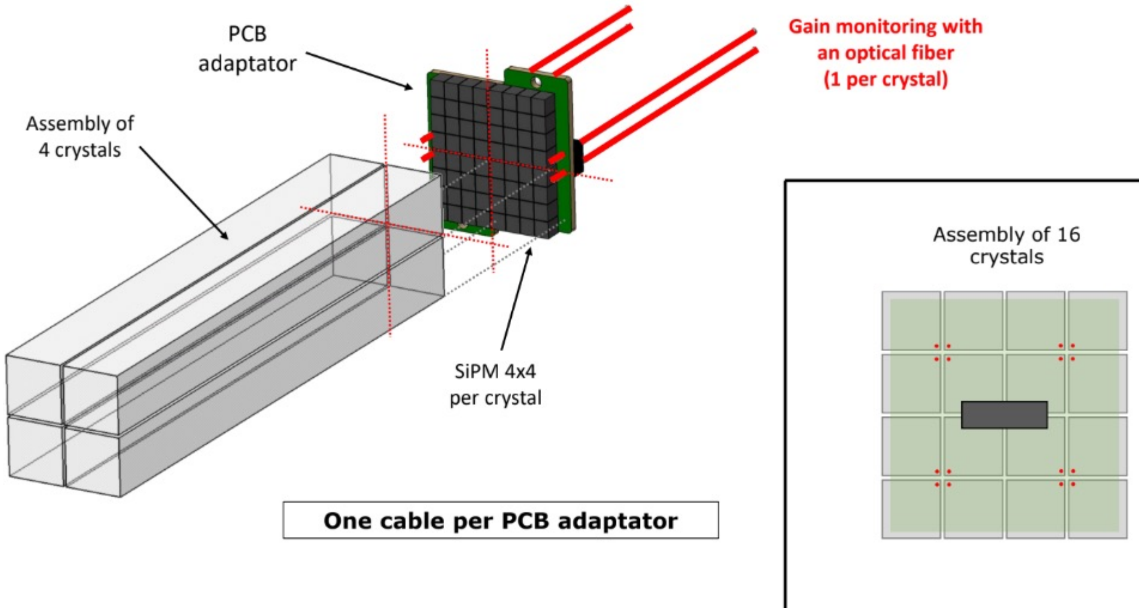


- Largest cross section for small electron scattering angles
  - Captures vast majority of scattered electrons
  - Often better resolution than tracker in this region
- Required energy resolution of $\frac{2\%}{\sqrt{E}} \otimes 1 - 3\%$
  - For most electrons, dominated by constant term
  - Need precise mechanical construction & calibration techniques
- 1 in 10^4 pion suppression
- Detection of photons above 50 MeV
- Radiation hardness

BACKWARD ELECTROMAGNETIC CALORIMETER



- Only realistic option to meet all of these requirements is $PbWO_4$
  - High density (small Molière radius), high scintillation light yield, fast scintillation, rad hard
  - Readout via HPK S14160-3010PS SiPMs



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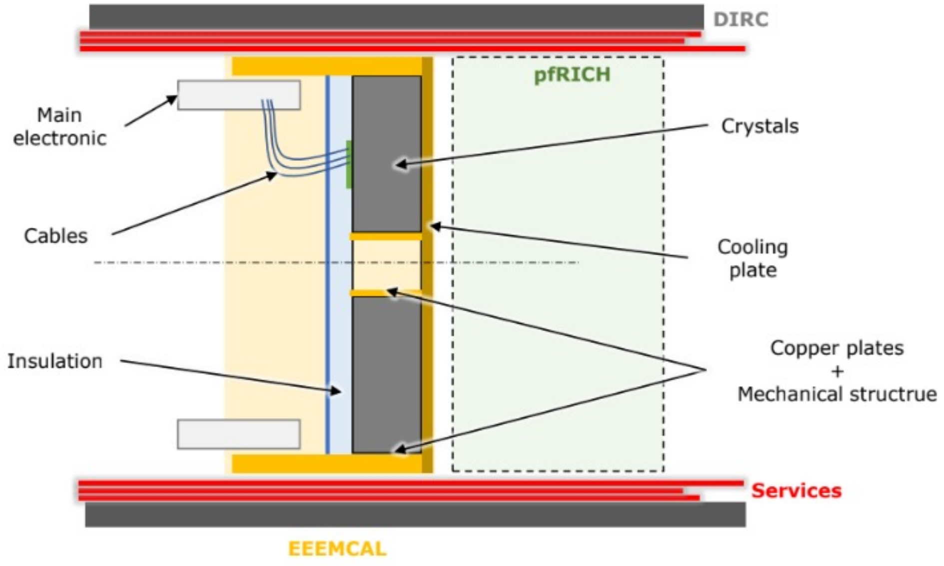
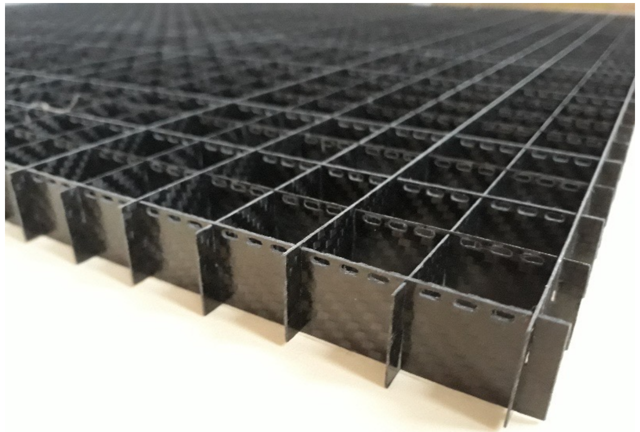
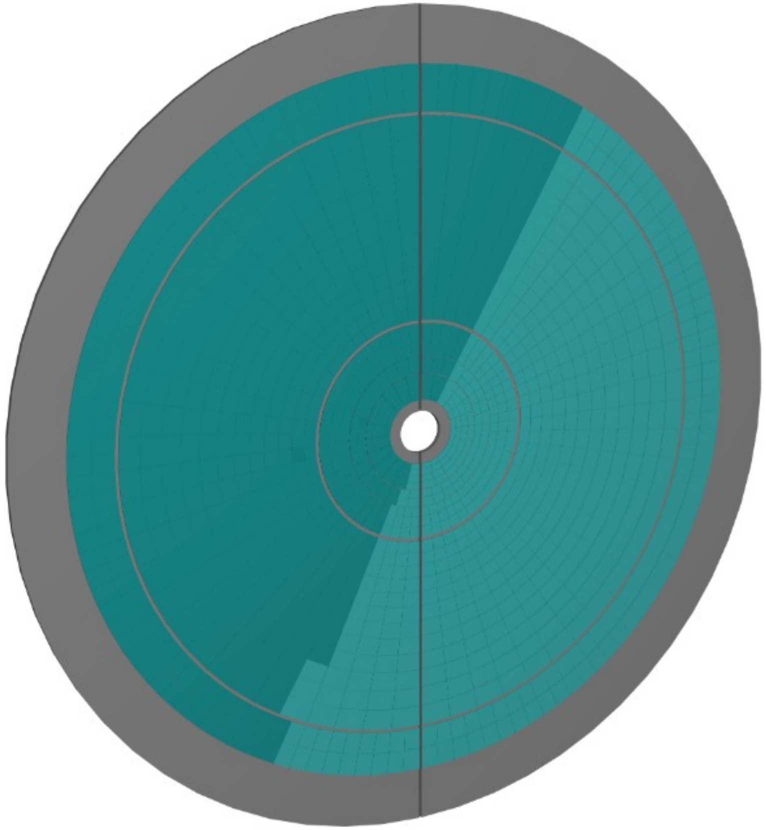




- $PbWO_4$ light yield is a strong function of temperature, ~2% per C°
  - Big integration challenge, pfRICH electronics sits nearby
  - Needs temperature stability & monitoring to reach resolution goals
- Non-trivial interplay between achieving temperature stability and reducing dead material between the crystals
  - Crystals held by two 0.5 mm thick carbon fiber frames
  - One in front 2 cm of a block, one in back 2 cm
  - Air gap in-between

BACKWARD HADRONIC CALORIMETER

ePIC



- Experience from H1 & ZEUS, backward HCal useful for improving e/h separation at low-x
  - Electron & hadrons go in the same direction, substantial overlap in the EMCal
- Low-x hadronic final state important for studying gluon saturation, typically backward-going
- Hadron energies are low, serves in part as a tail-catcher for the EMCal
  - Energy resolution requirements not stringent
  - Position resolution should be good enough to match Hcal clusters to energy deposits in Emcal
- Exact design still in progress, some combination of steel + large scintillator tiles & SiPM readout
  - Similar to BELLE KLM

BARREL CALORIMETERS

$-1.7 < \eta < 1.4$

High Q^2, Mid x

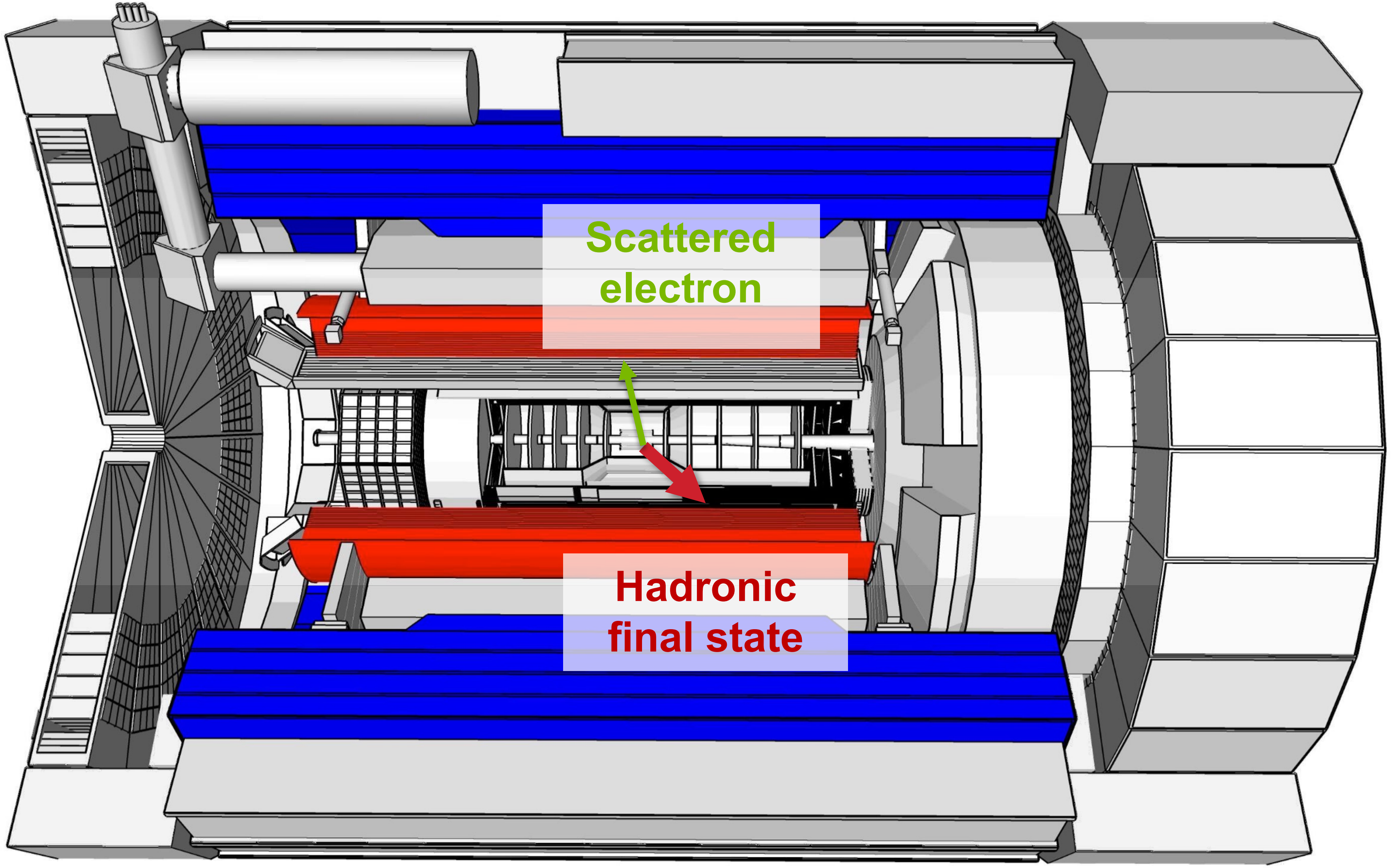
Example Physics:
DVCS, DVMP

Challenges:
Identify components of hadronic final state, e.g. separate π^0 from γ

Identify low energy e^- from high *y* DIS

Contain 30+ GeV energy e^- from high Q^2

Measure low energy γ



BARREL CALORIMETERS

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High Q², **Mid x**

Resolution requirements:

EMCal:
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HCal:
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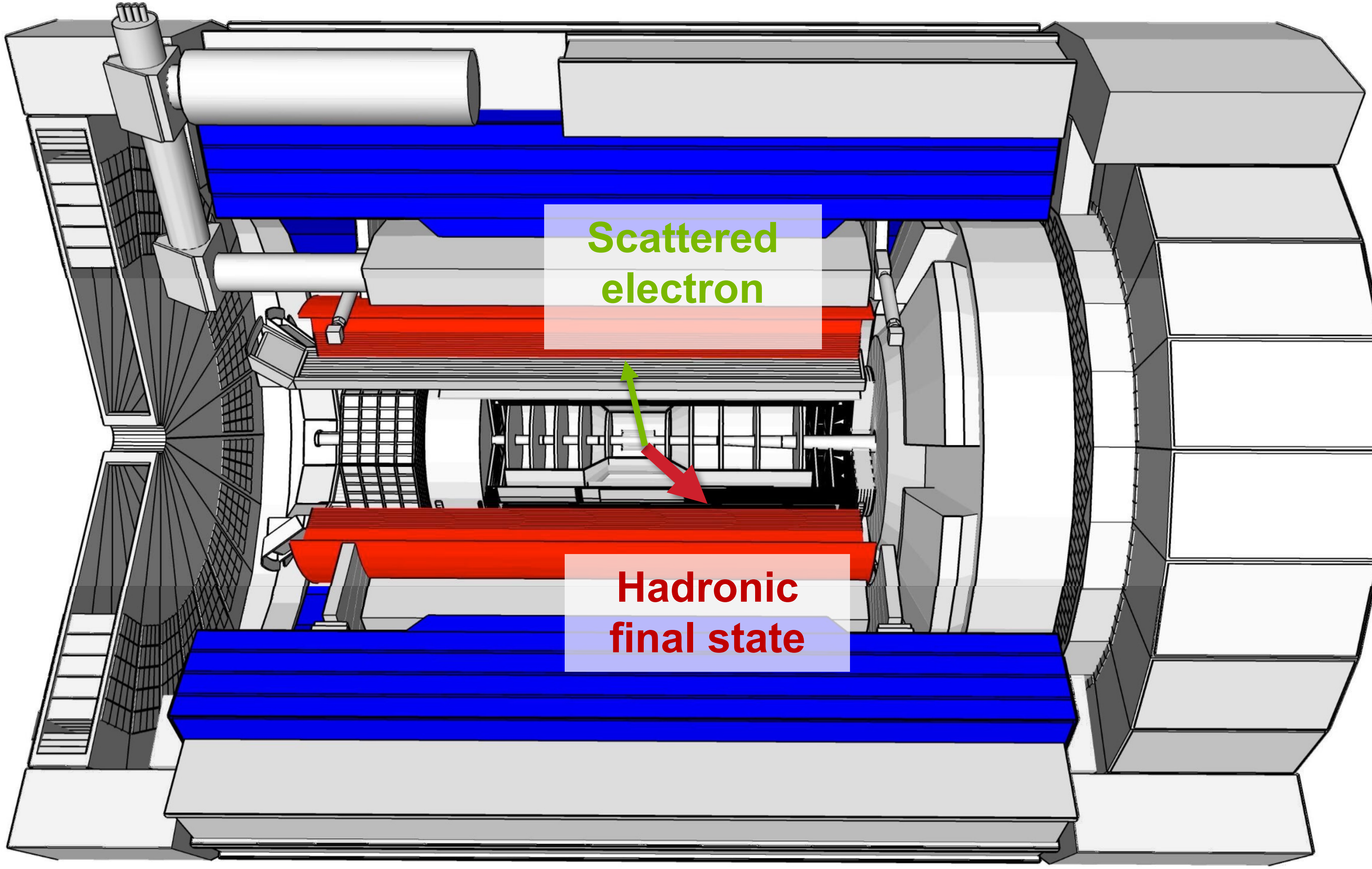
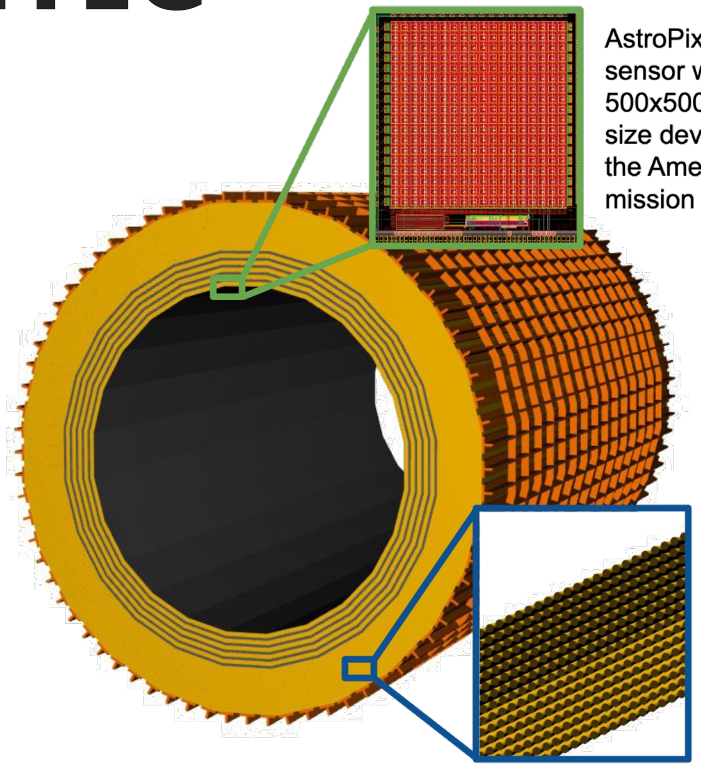


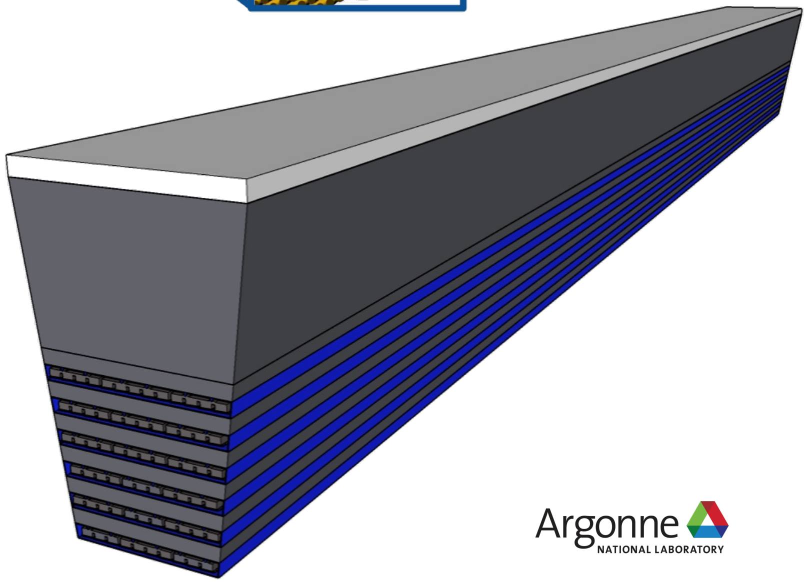
BARREL ELECTROMAGNETIC CALORIMETER

- Hybrid sampling Pb/SciFi + Silicon pixel sensor

- 4.4 m long scintillating fibers, SiPM readout on both ends
    - Longitudinally segmented
    - Similar to KLOE & GlueX
    - “Time-Projection” calorimeter - $\Delta t \rightarrow z$
    - HGCROC for front-end electronics

- Interleaved with layers of AstroPix MAPS silicon pixel sensors
    - Very low power consumption (few mW/cm^2)
    - 500 µm “cube” pixels
    - Good resolution (~7%) on energy deposited in pixel





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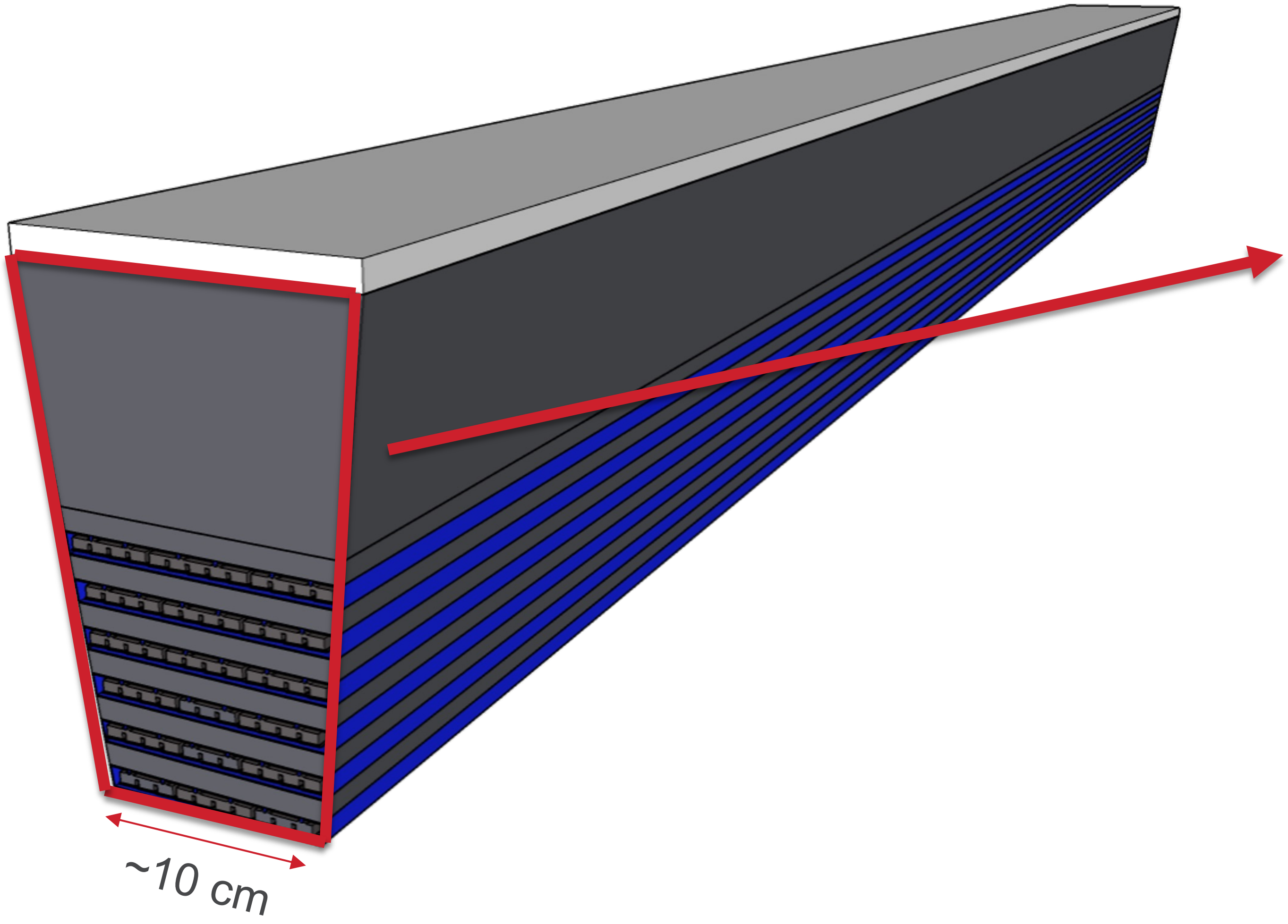
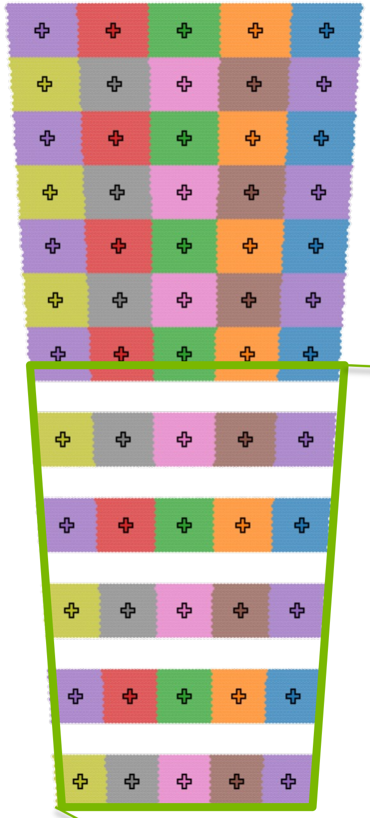
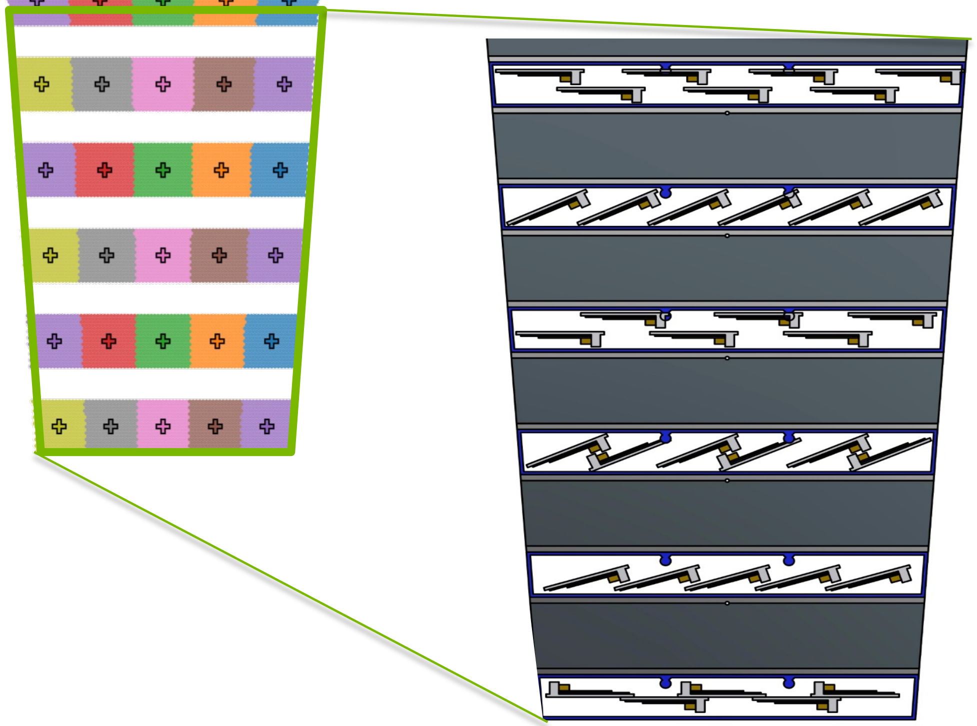
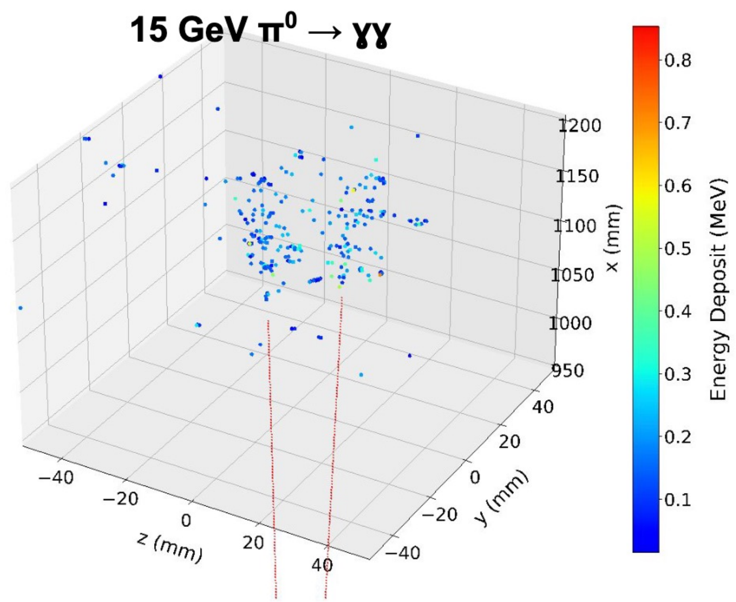


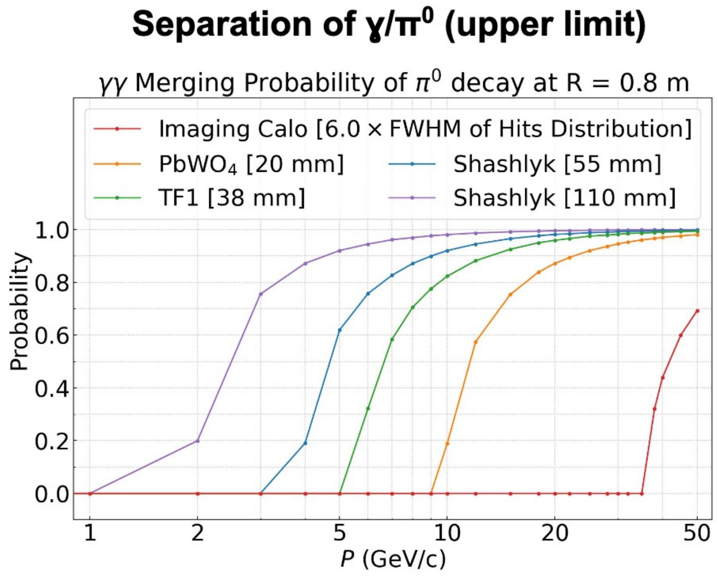
SiPM Readout Scheme
Light guides to 1.2x1.2 cm SiPMs

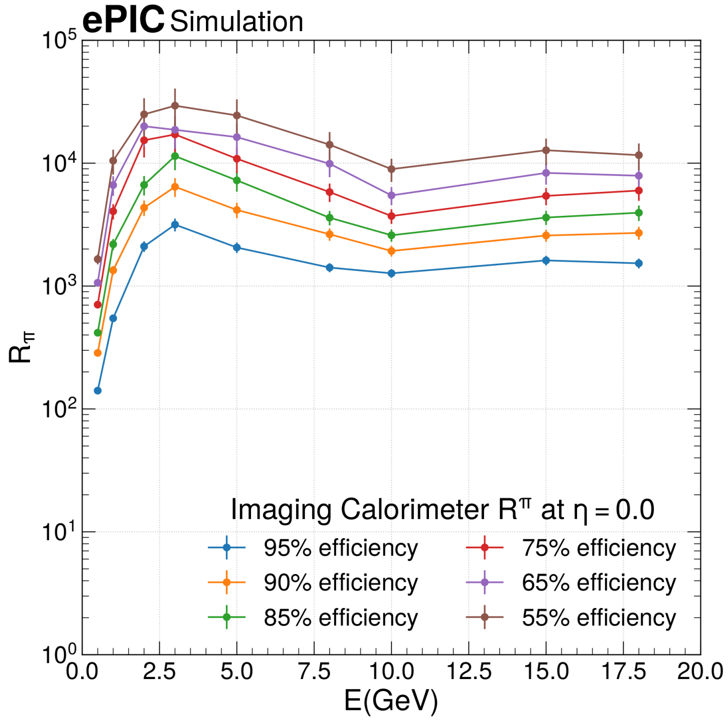


AstroPix Tiling Options



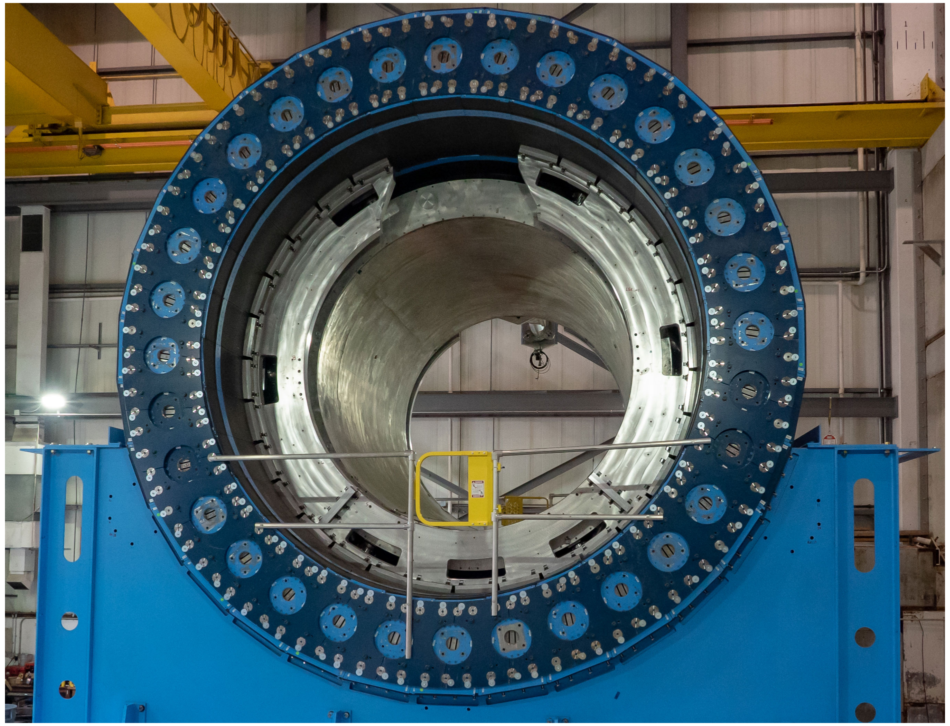




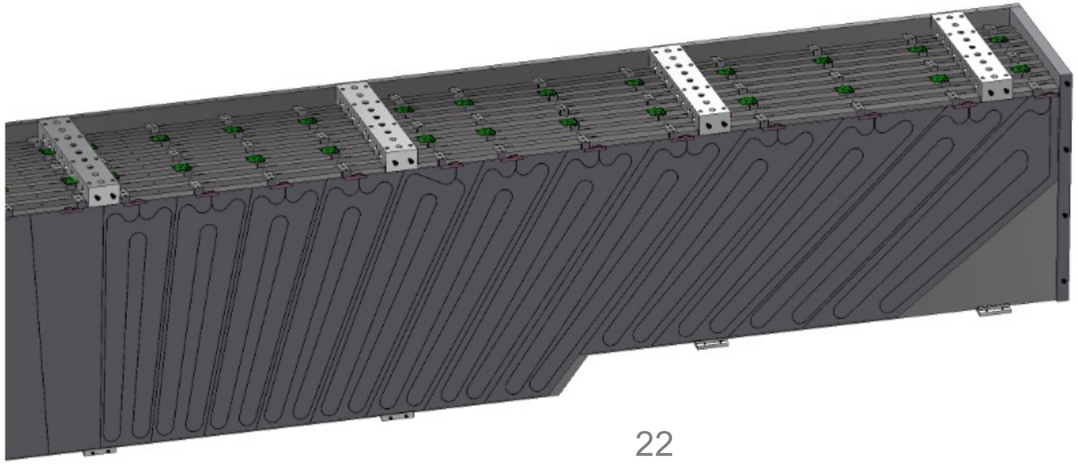


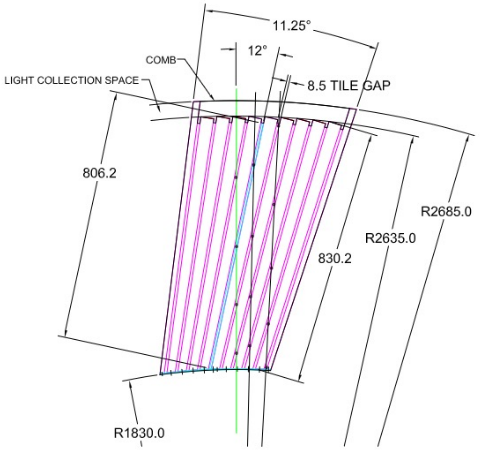
- Interleaving of AstroPix sensors allow for excellent position resolution
  - Angular resolution on the order of 0.1 degree
  - Separate π^0 from ɣ beyond 30 GeV
  - Can do vertexing on photons!
- Very effective separation of electrons from hadrons based on shower shape discrimination
  - Still quite effective at ~1 GeV & below

BARREL HADRONIC CALORIMETER



- Modest requirements on energy resolution
  - ~ $100\%/\sqrt{E}$
  - Hadrons in barrel typically low energy (<5 GeV), better measured by tracking
  - Tag jets with large neutral hadron component
- Measure muons from e.g. $J/\psi \rightarrow \mu\mu$
- Reuse from sPHENIX





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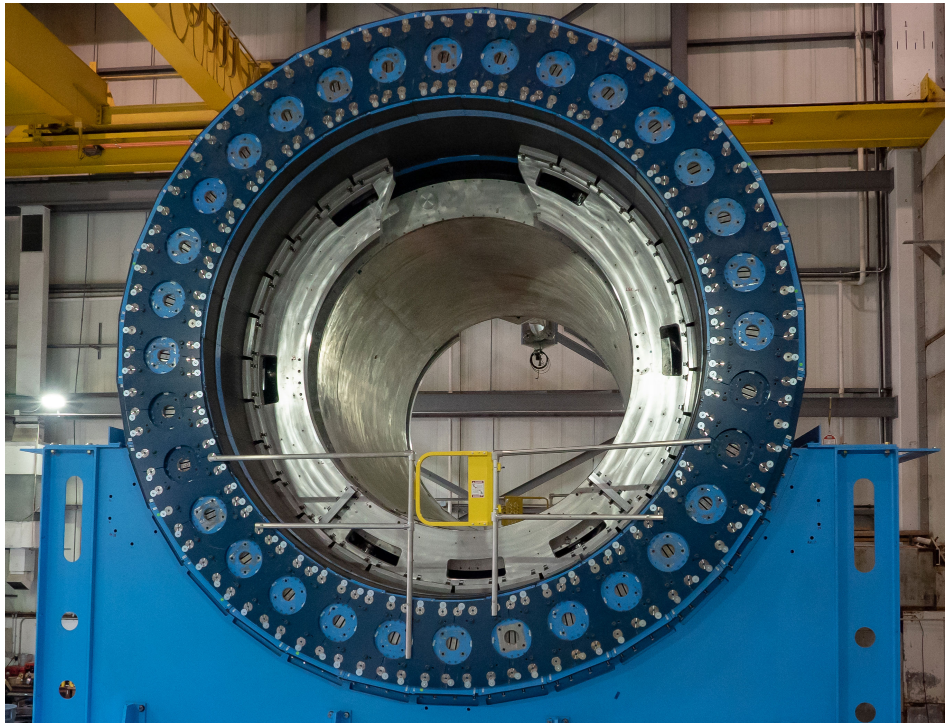
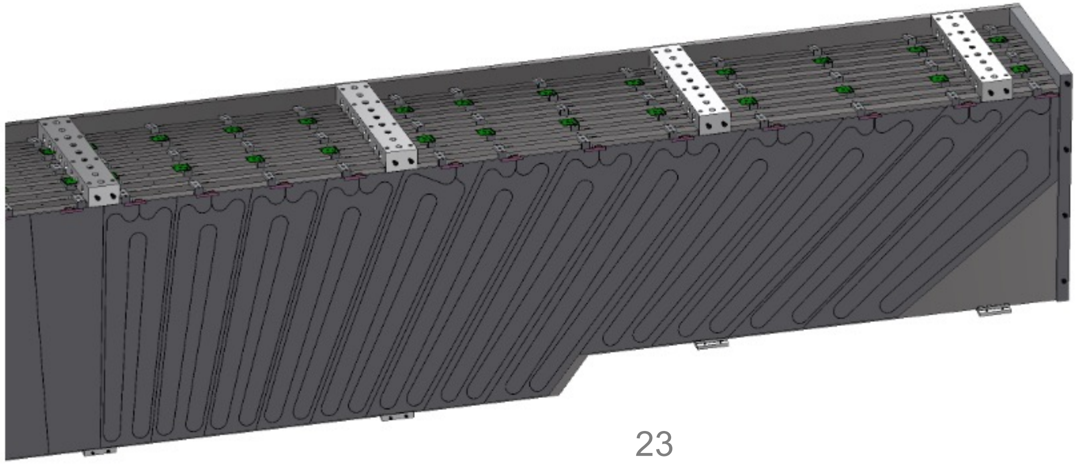
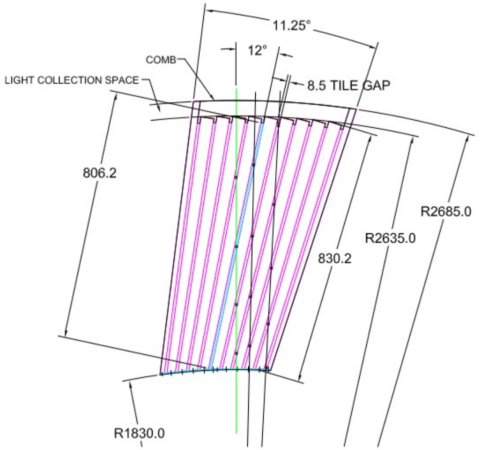


- Steel/Scintillator design
  - Steel plates tiled at an angle to prevent channeling
  - Straight tracks have a sizable path length through scintillator, good for MIP detection
  - Readout via HPK S12572 series SiPMs
- Refurbish for EIC
  - Expect minor radiation damage from sPHENIX, can replace SiPMs with HPK S14 series
  - Upgrade electronics to HGCROC
  - Increase segmentation by reading out each tile individually





FORWARD CALORIMETERS

$1.4 < \eta < 4$

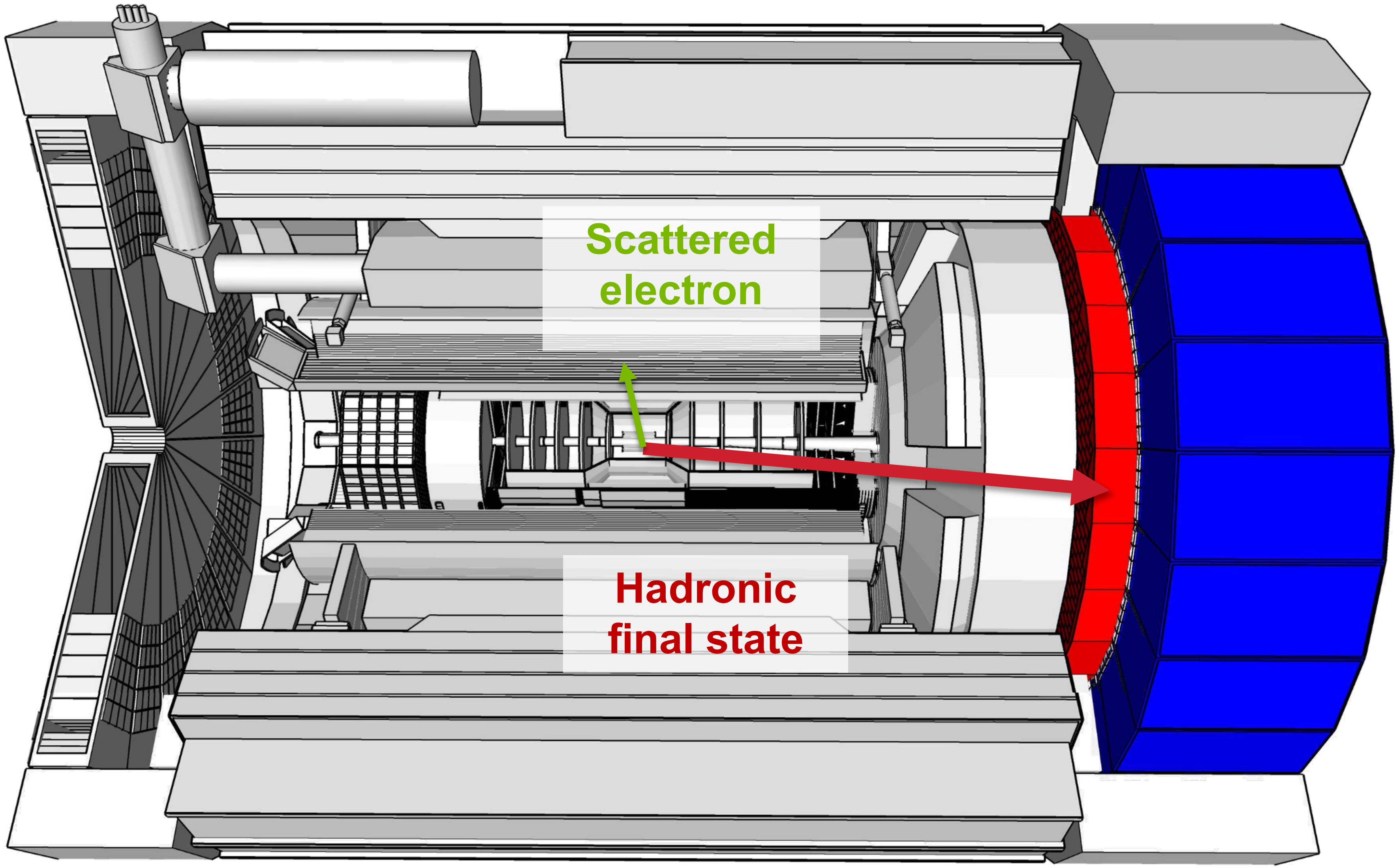
High Q^2, High x

Example Physics:
TMDs, Jets, SIDIS

Challenges:
Contain the highly energetic hadronic final state

Separate clusters in a dense hadronic environment

Highest radiation load near hadron beam



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Resolution requirements:

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HCal:

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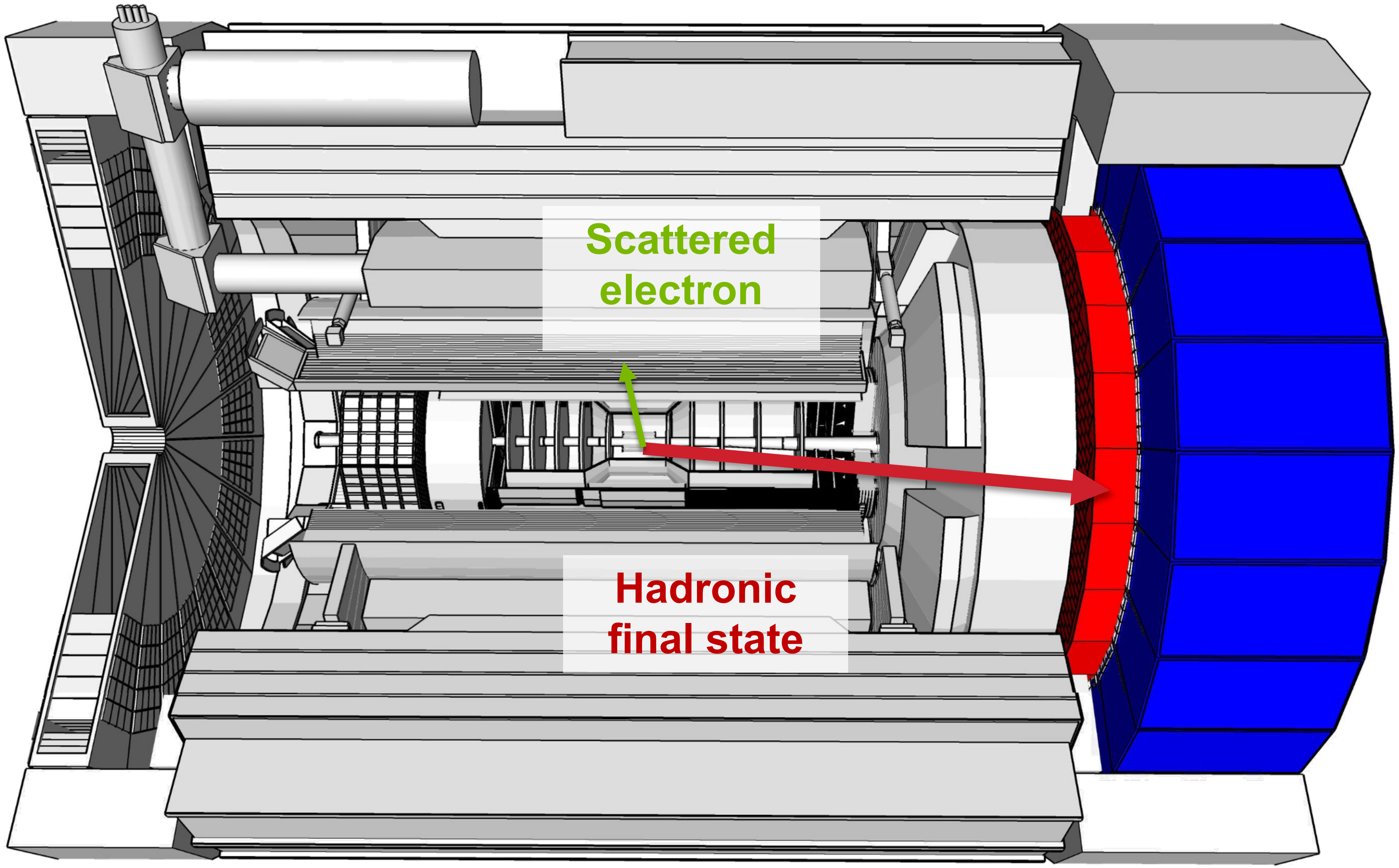
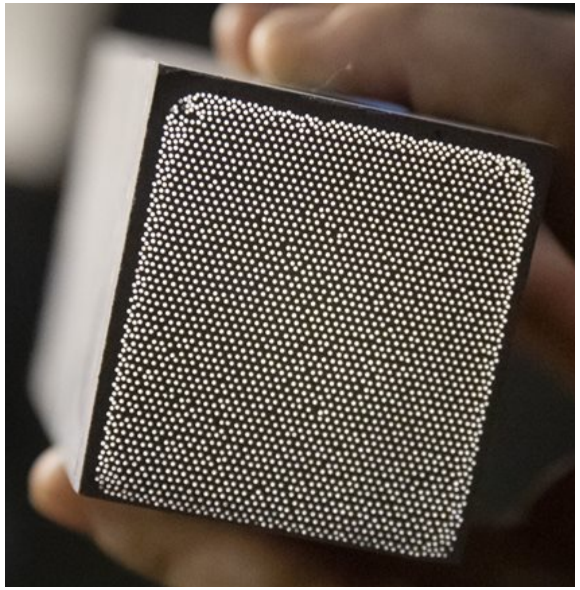
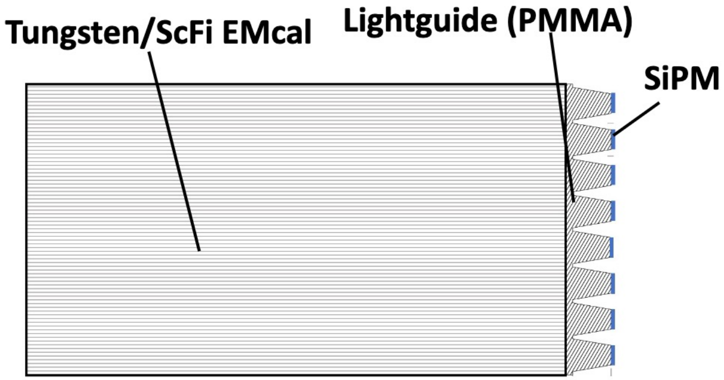


FORWARD ELECTROMAGNETIC CALORIMETER

- Tungsten + SciFi SPACAL design
  - Developed through EIC R&D and applied successfully in sPHENIX EMCal
  - Tungsten powder mixed with epoxy
- Position resolution vital to separate π^0 from γ at high energy
  - Dense absorber (~10 g/cm^3)
  - Readout with many SiPMs to create a small tower size
- Uniformity of construction important to reduce constant term
  - Dominates at high energy
  - Powder + epoxy enables fine control over spatial distribution of scintillator





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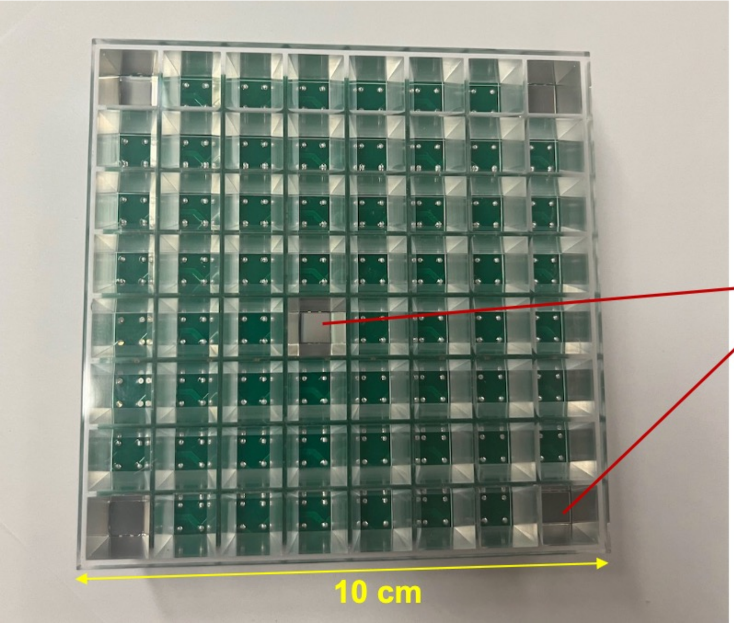
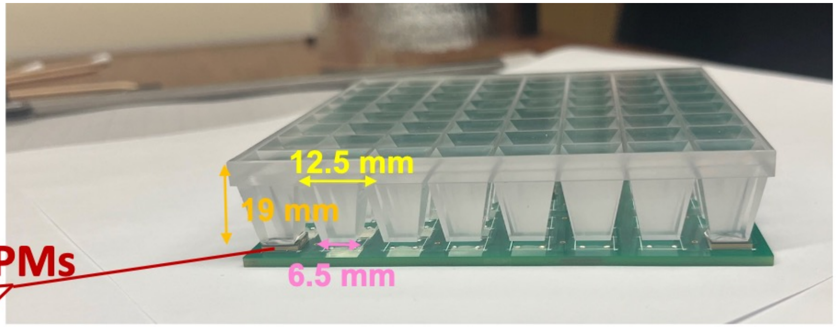
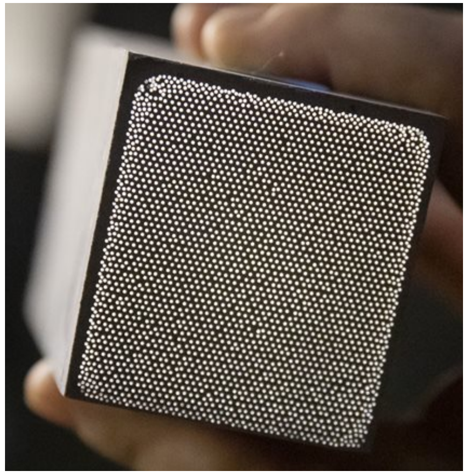
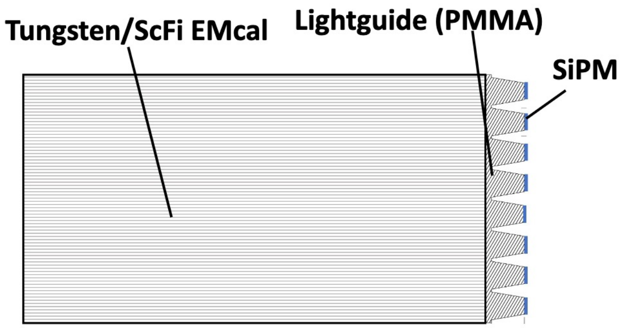




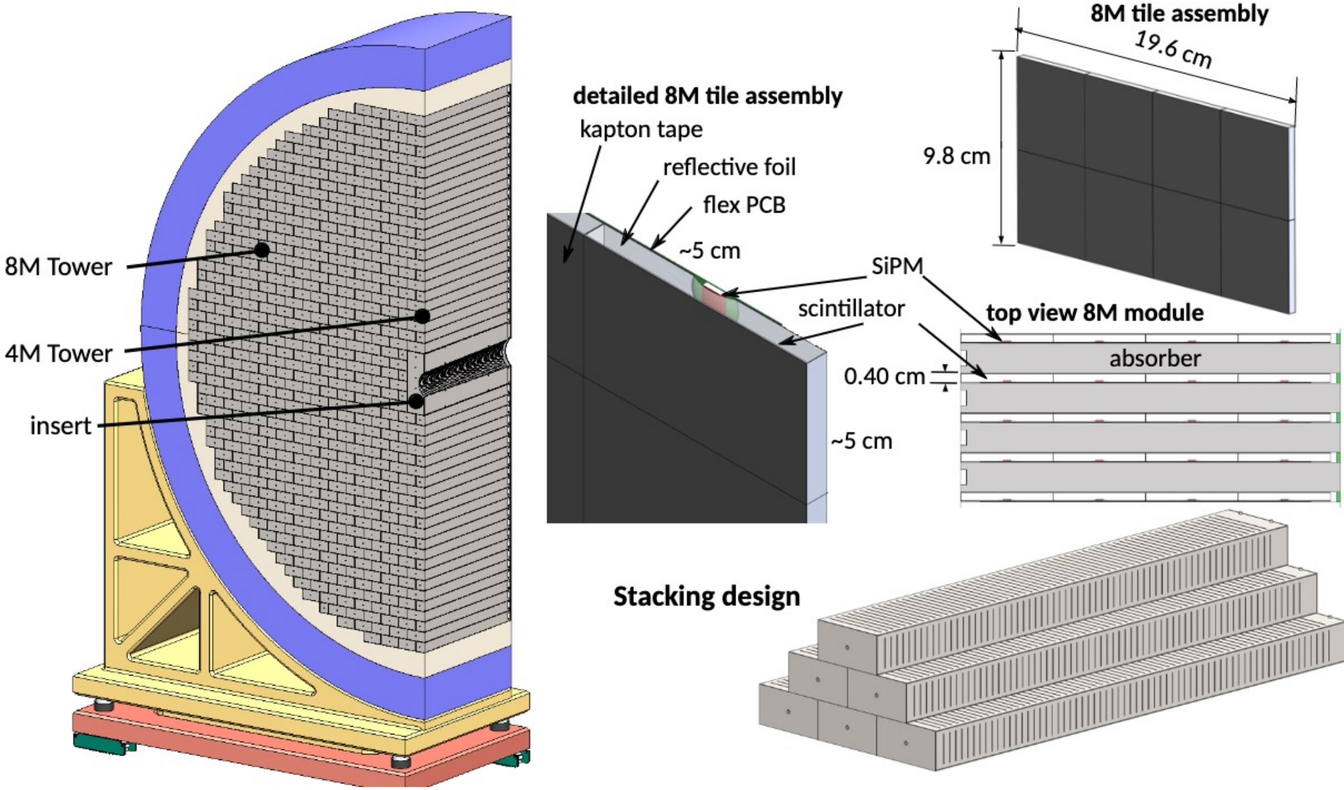




- 5 cm x 5 cm x 17 cm blocks of absorber + fibers
  - Four independent towers per block
- Each 2.5 x 2.5 cm tower is readout by four 6x6mm HPK S14 series SiPMs
- Expected energy resolution ~ $\frac{10\%}{\sqrt{E}} \oplus 1 - 3\%$

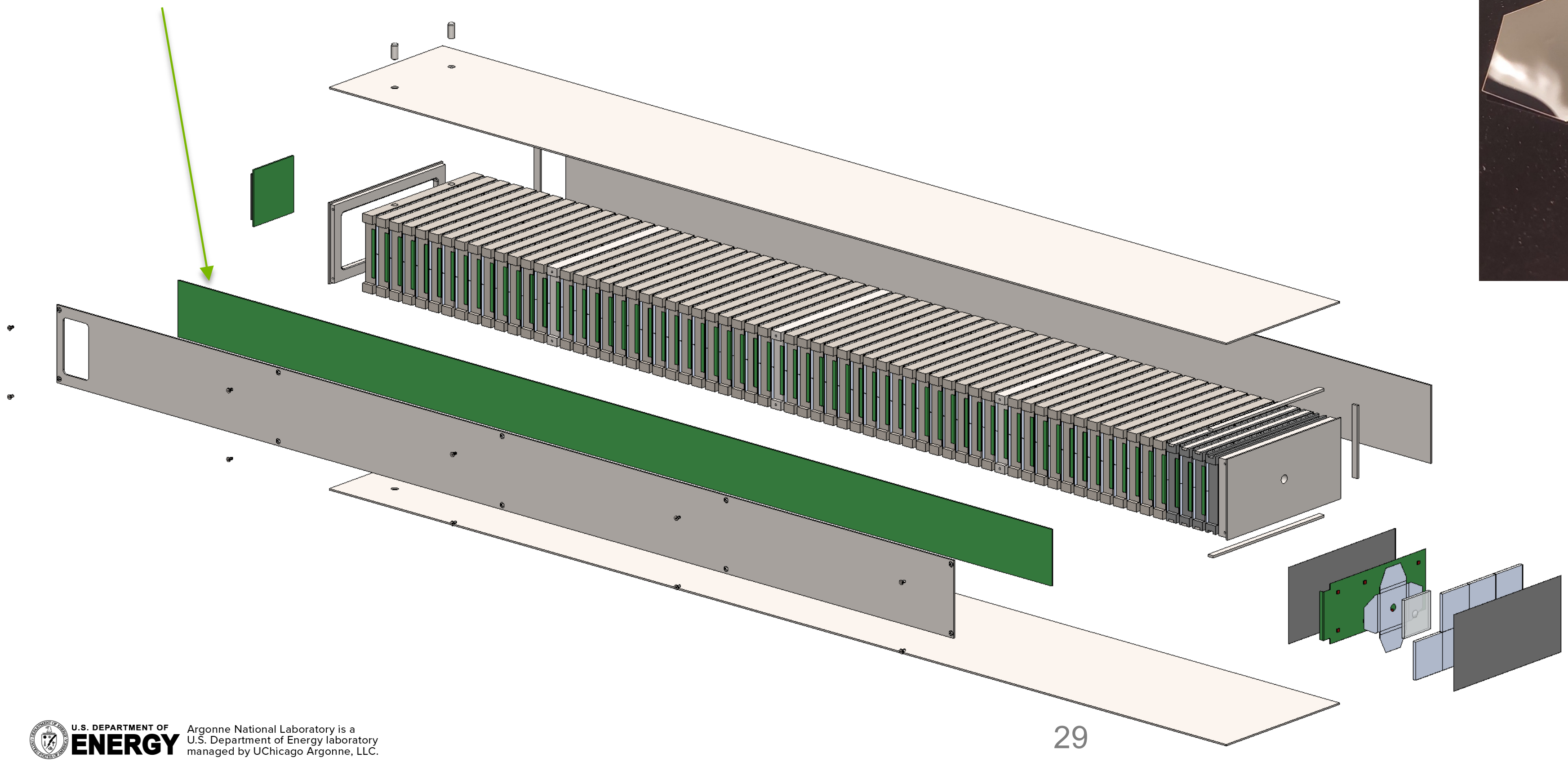
FORWARD HADRONIC CALORIMETER

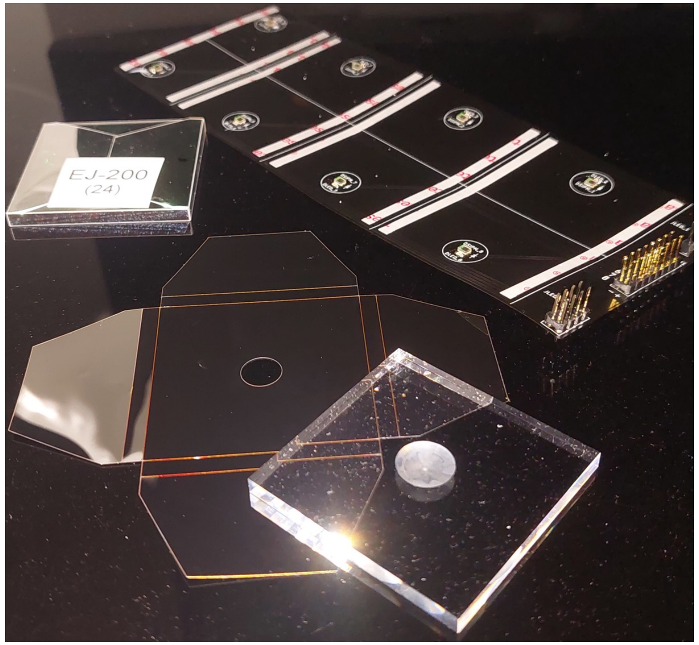
- Steel + Scintillator SiPM-on-tile
  - Pioneered by CALICE analog HCal
  - Ideal for particle-flow measurements!
- Highly segmented longitudinally, 65 layers per tower
  - 565,760 SiPMs
  - 65 layers ganged into 7 readout channels
- Stackable for “easy” construction
  - Steel as absorber significantly simplifies design, improves material uniformity
  - Achieves ~6.5 λ_0
- Expected resolution ~ $\frac{45\%}{\sqrt{E}} \oplus 5\%$
  - Exceeds requirements defined by Yellow Report!



FORWARD HADRONIC CALORIMETER

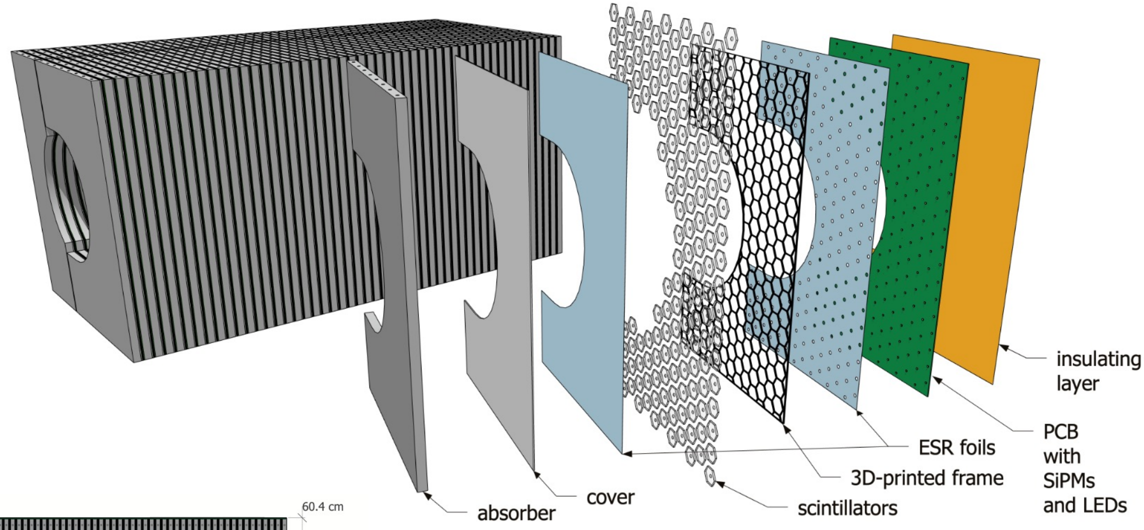
- SiPMs mounted to thin flex PCBs
  - Signals routed along PCB to periphery
- Signals brought to HGCROC at back by a thin flex PCB that runs longitudinally alongside the tower

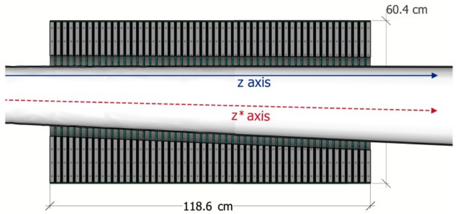


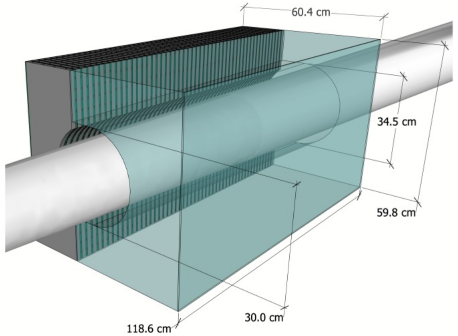


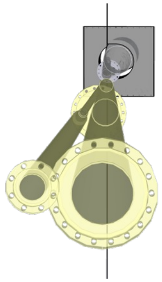
FORWARD INSERT CALORIMETER

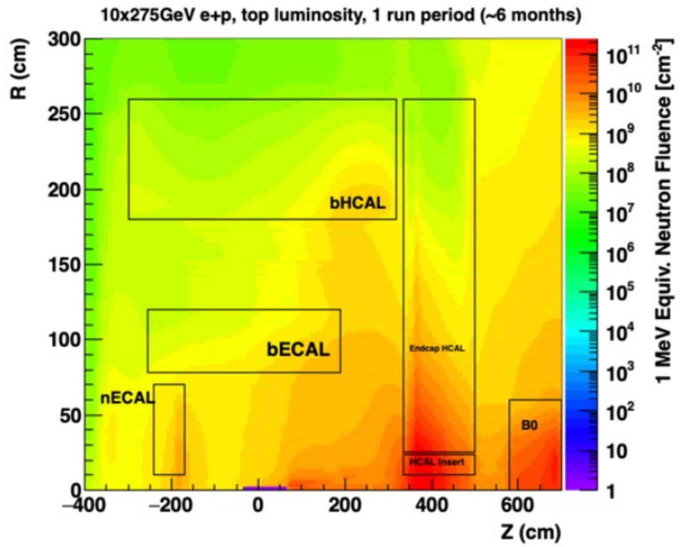
- Insert to extend central detector acceptance as much as possible in the forward direction
  - Crucial for containment of hadronic final state for inclusive kinematic reconstruction and rapidity gap diffractive measurements
  - $3.2 < \eta < 4$
  - Needs to accommodate complex beam pipe geometry
- Small hexagonal scintillator tiles for better spatial uniformity & increased light yield
- High radiation load
  - SiPMs will be serviceable
  - ~10^{12} neq/cm^2/year



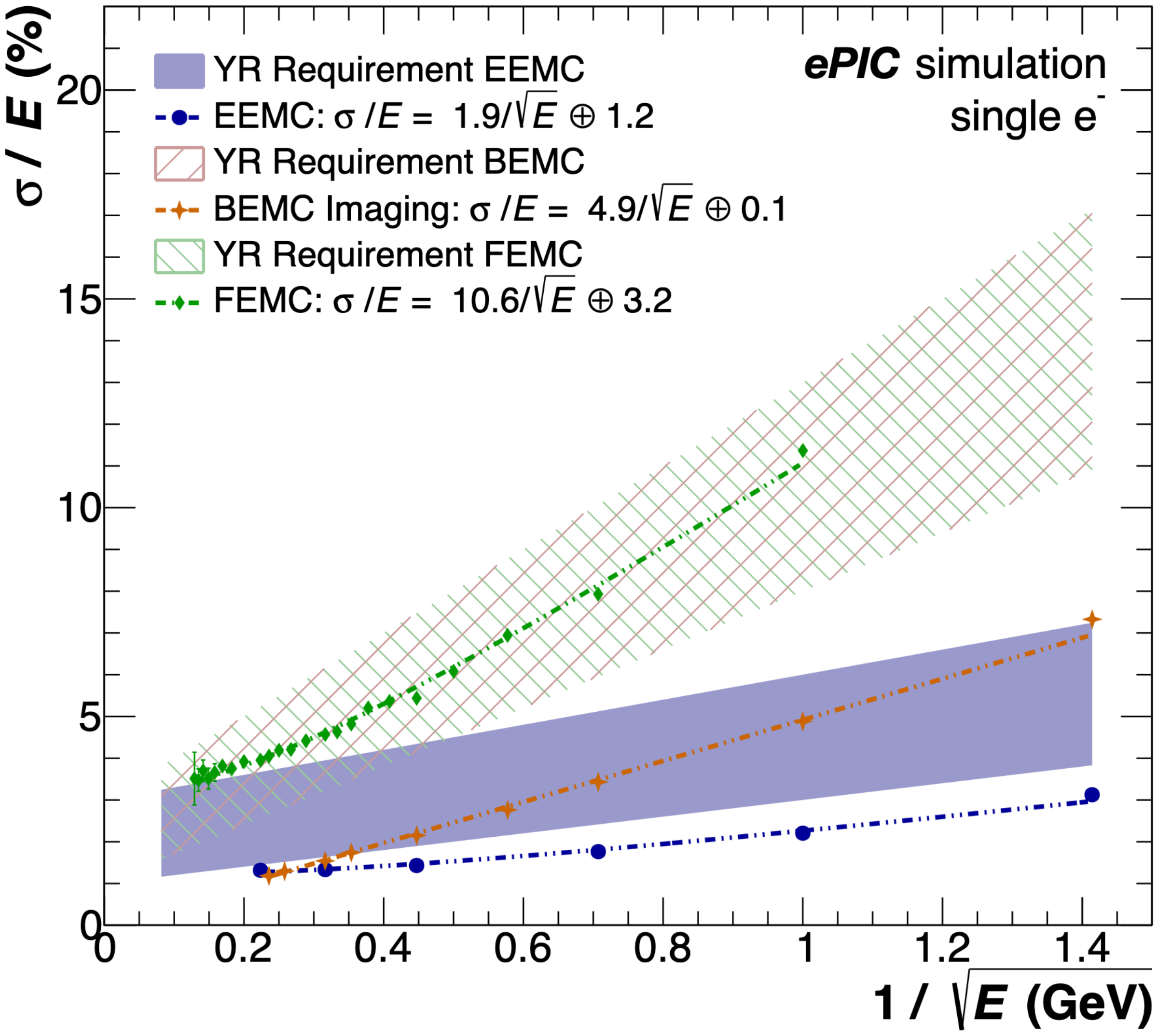


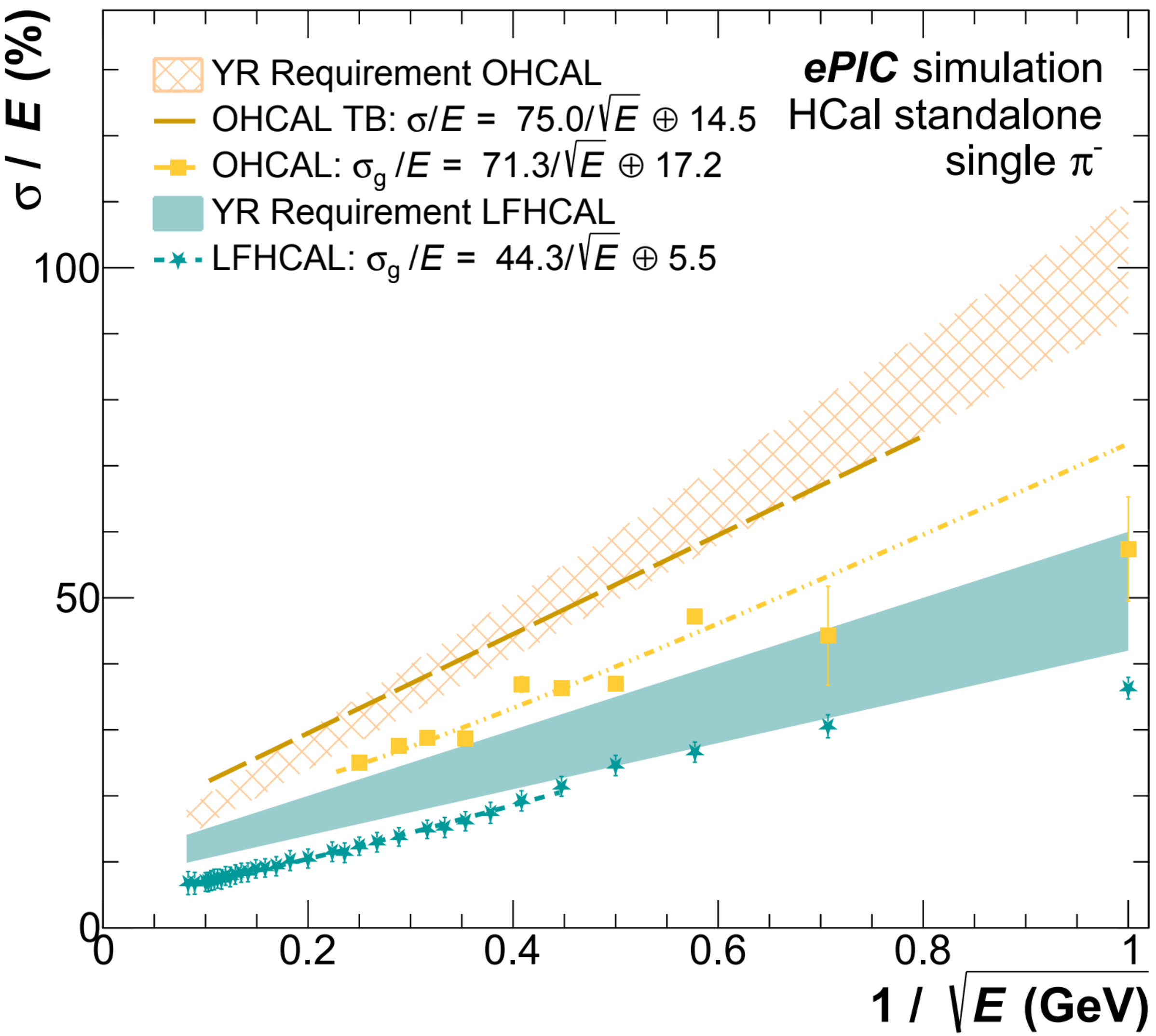






PERFORMANCE PROJECTIONS

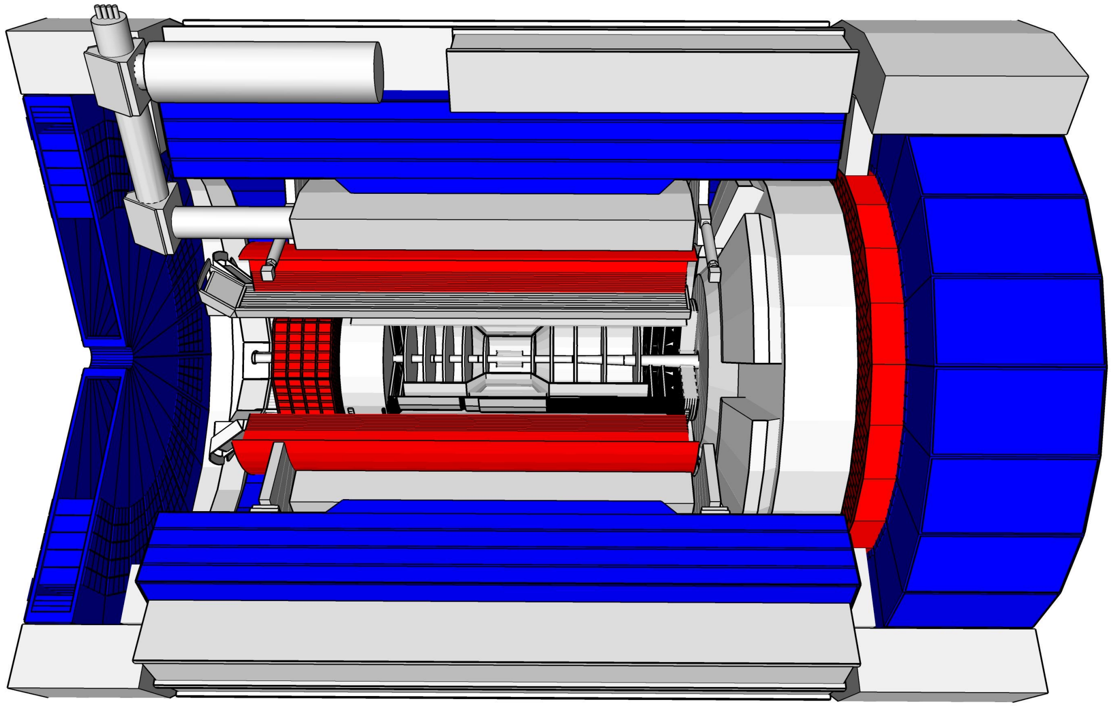




CONCLUSION

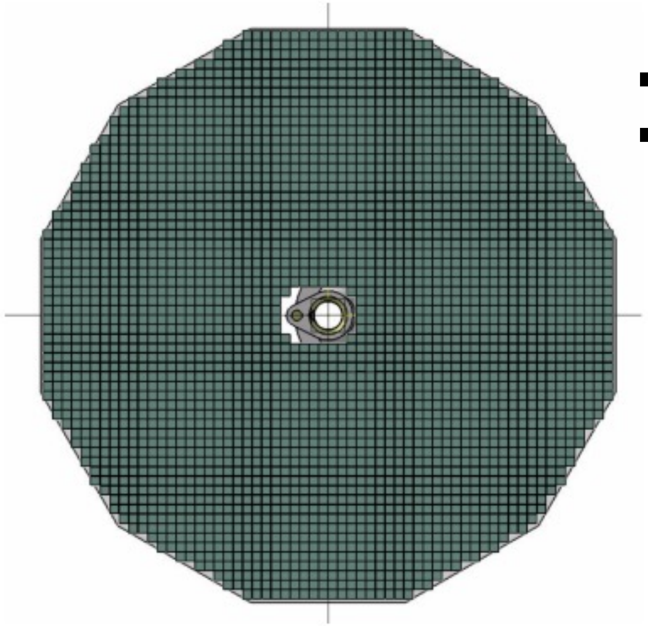
- Calorimetry is a vital component of the EIC detector package
- ePIC employs unique calorimetry designs to meet the varied demands of the different detector regions
  - Designed to meet the multifarious challenges & physics of the EIC!
- The ePIC calorimeter designs meet or exceed their performance requirements!
- EIC is scheduled to begin running in 2032
  - CD3 & Construction to begin in earnest in 2025
- **ePIC TDR coming soon, stay tuned!**

Thanks to everyone who provided the information for this talk!

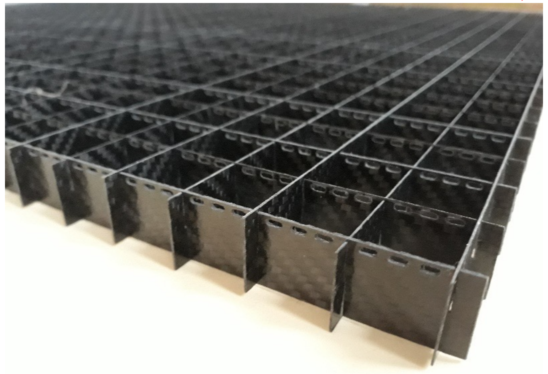


Thank you!

BACKUP

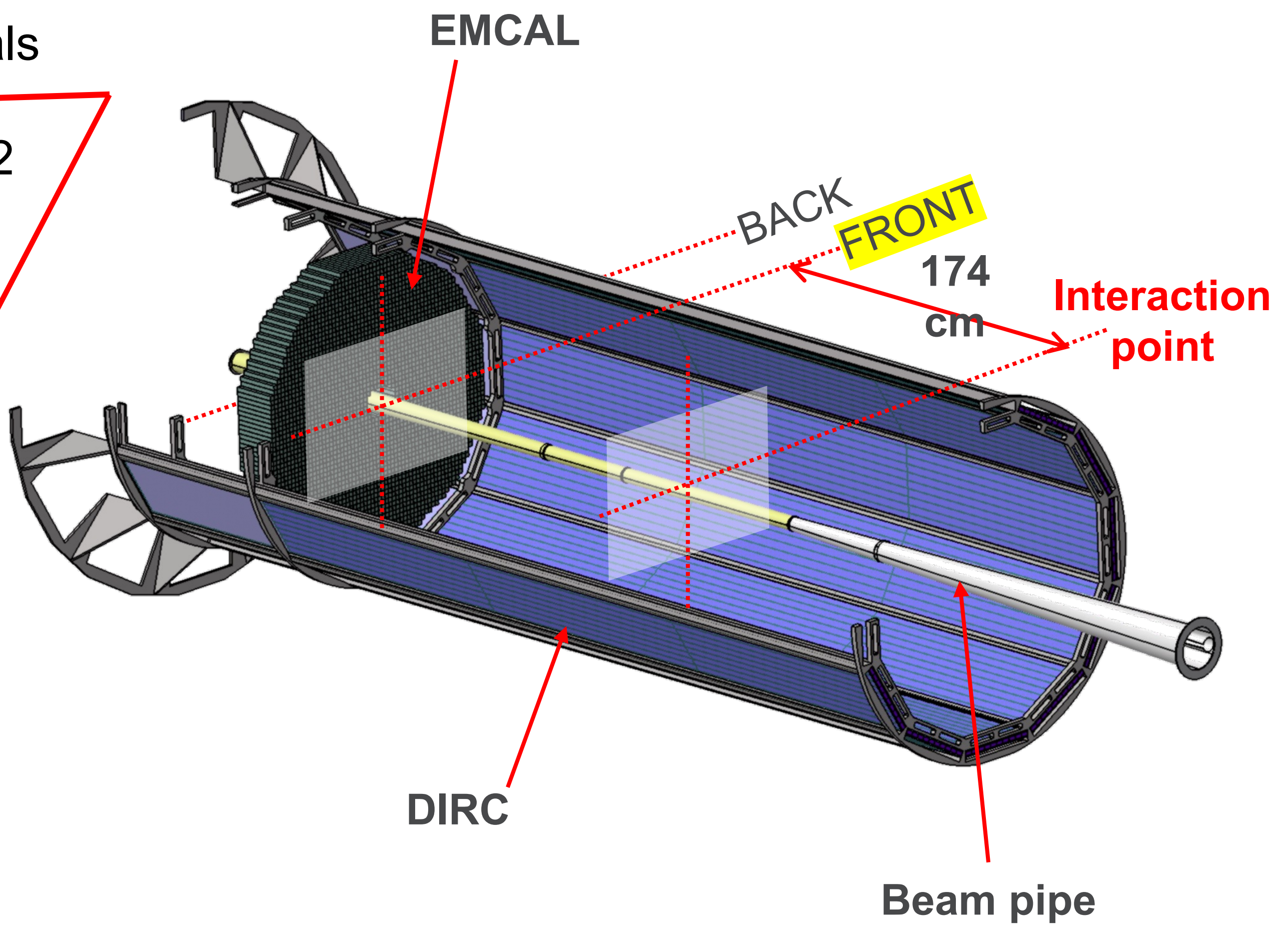


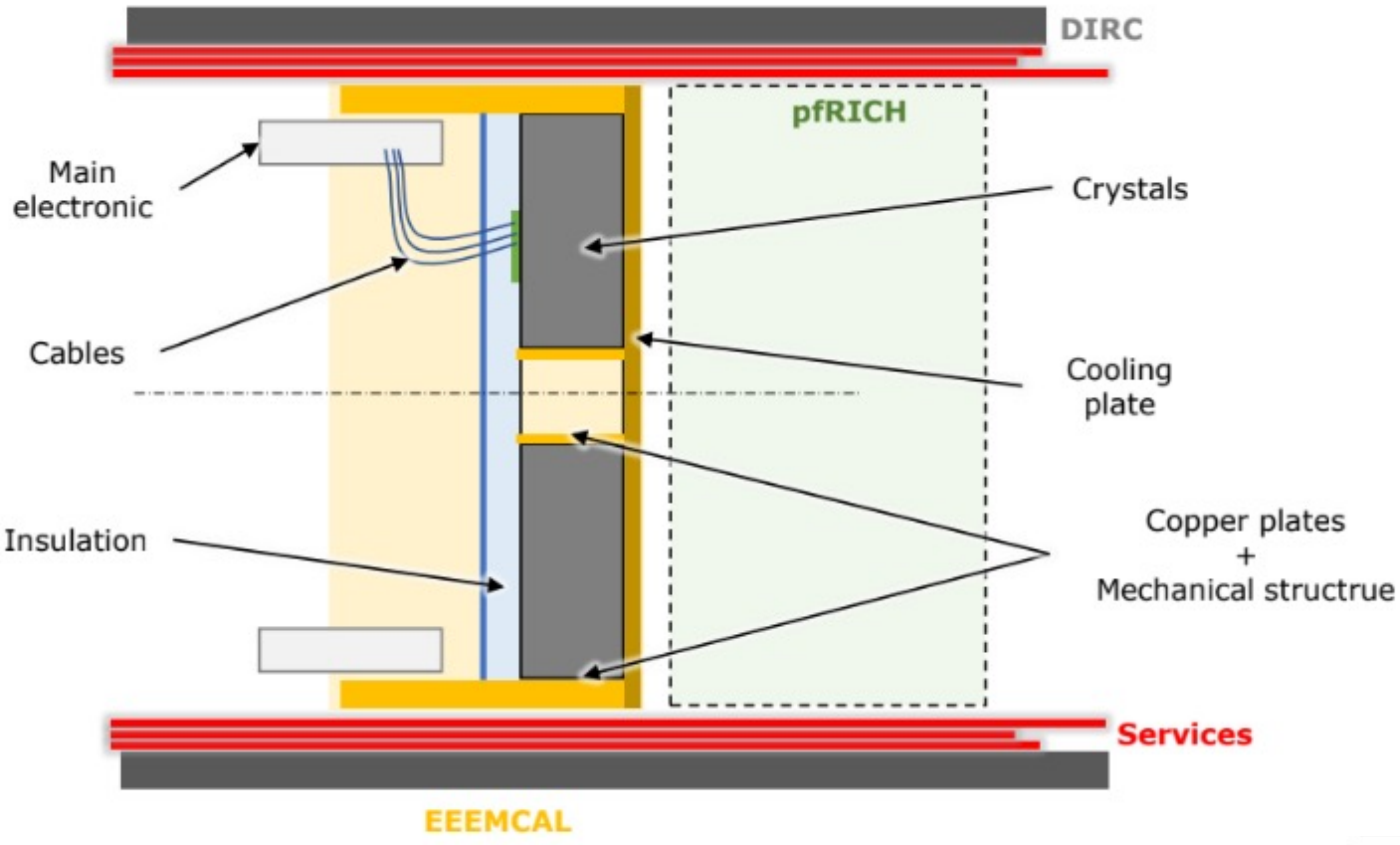
- 2x2x20 cm^3 PWO crystals
- 0.5-mm-thick C-fiber between crystals along 2 cm in the front & back; 0.5 mm of air elsewhere

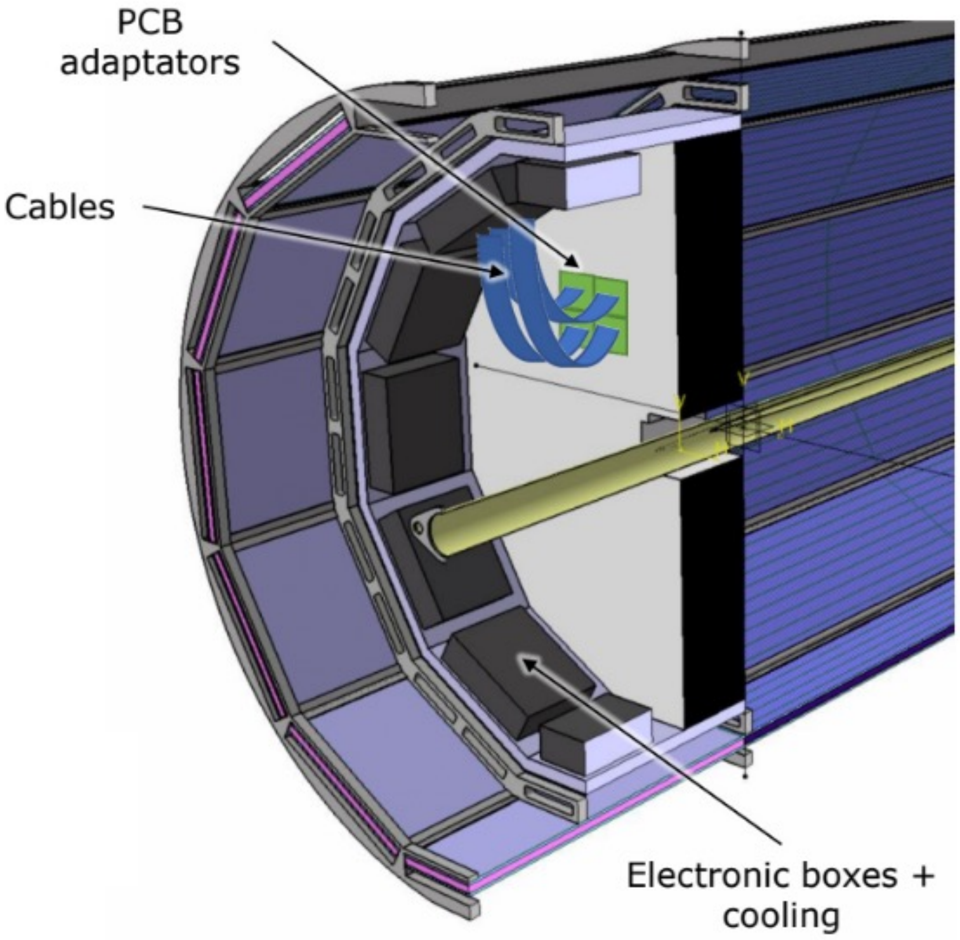


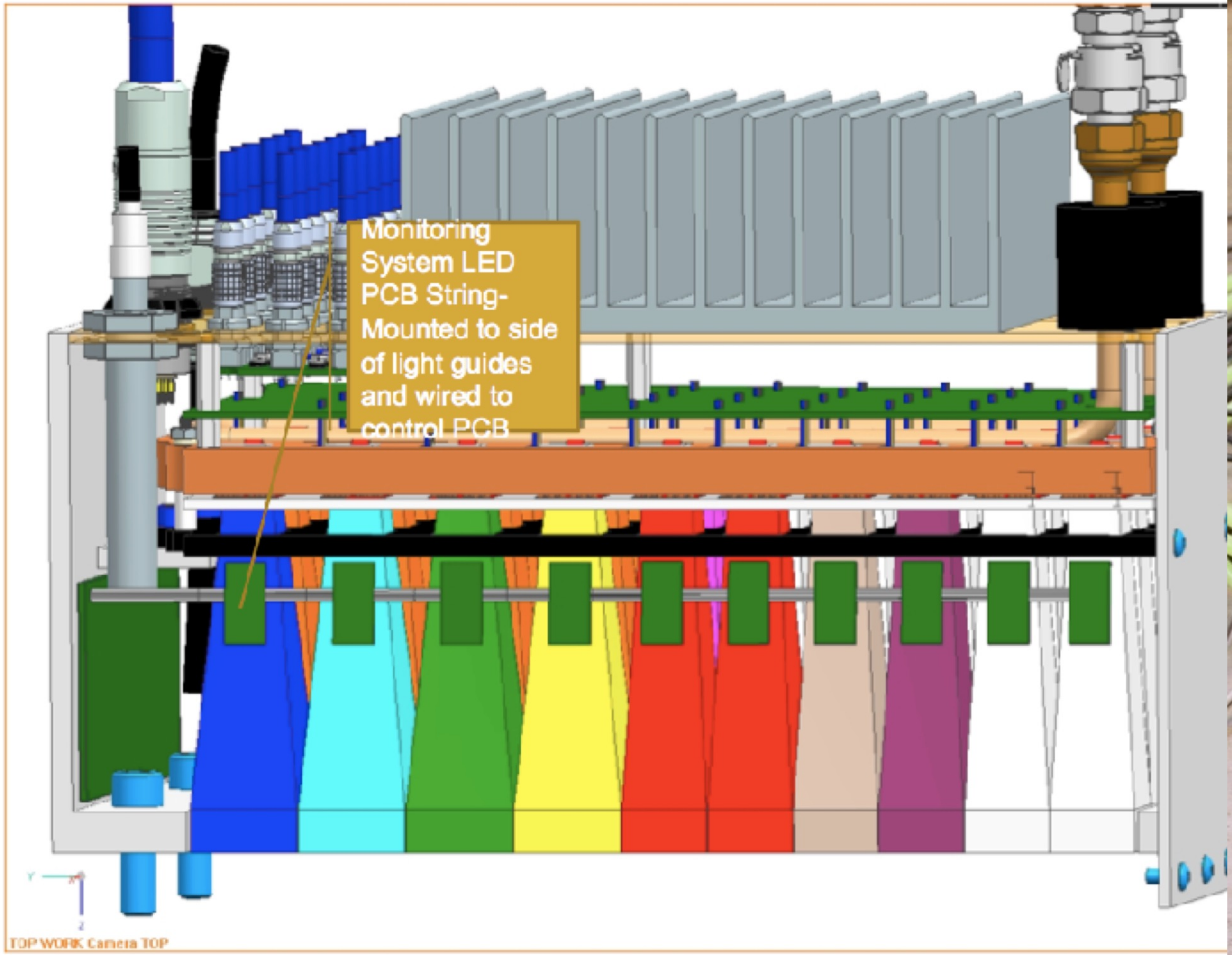
Specifications:

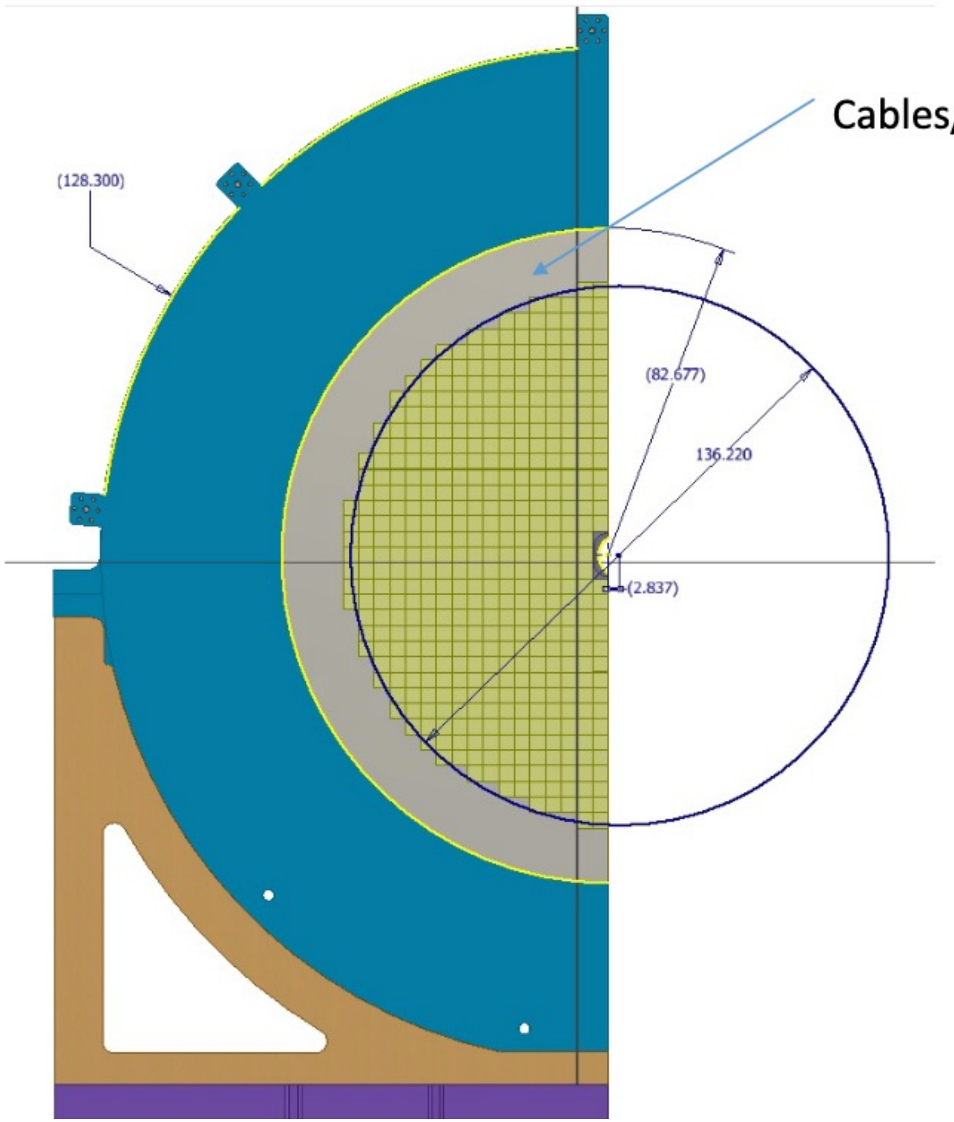
PWO:	8,28g/cm3
Dimension:	20x20x200 mm
Mass:	0,662 Kg
Nb:	≈ 2850 crystals
Total mass:	≈ 1900 Kg
External diameter:	≈ 123 cm
Space max:	0,5 mm (carbon plate)




DIRC
pfRICH
Main electronic
Crystals
Cables
Cooling plate
Insulation
Copper plates + Mechanical structrue
Services
EEEMCAL


PCB adaptators
Cables
Electronic boxes + cooling


Monitoring System LED PCB String-Mounted to side of light guides and wired to control PCB
TOP WORK Camera TOP


(128.300)
Cables/cooling Envelope
(82.677)
136.220
(2.837)

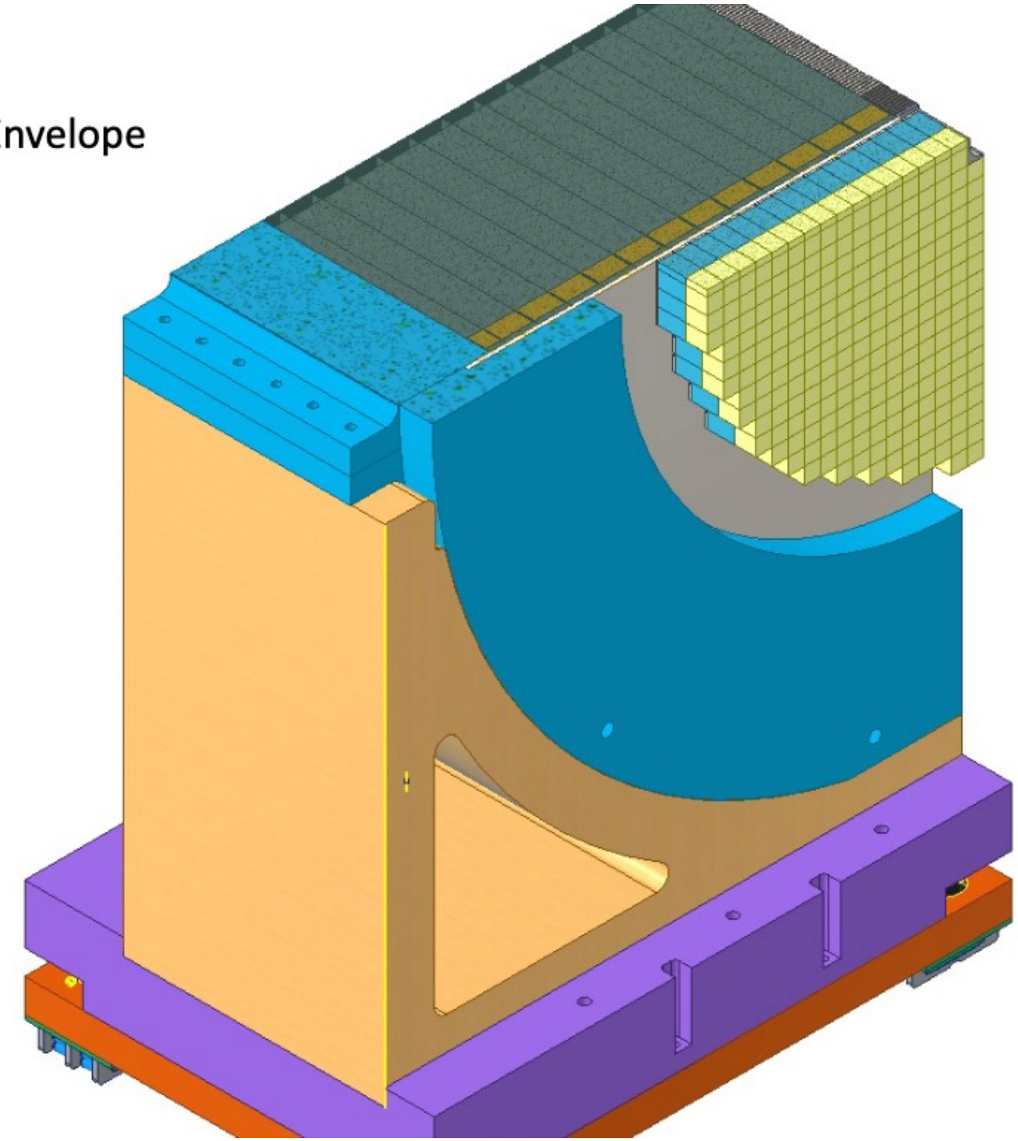


Table 3.5: EIC beam parameters for e-Au operation for different center-of-mass energies $\sqrt{s}$, with strong hadron cooling.

Species	Au ion	electron	Au ion	electron	Au ion	electron	Au ion	electron
Energy [GeV]	110	18	110	10	110	5	41	5
CM energy [GeV]	89.0		66.3		46.9		28.6	
Bunch intensity [10^{10}]	0.08	6.2	0.05	17.2	0.05	17.2	0.036	17.2
No. of bunches	290		1160		1160		1160	
Beam current [A]	0.23	0.227	0.57	2.50	0.57	2.50	0.41	2.50
RMS norm. emit., h/v [μm]	5.1/0.7	705/20	5.0/0.4	391/20	5.0/0.4	196/20	3.0/0.3	196/20
RMS emittance, h/v [nm]	43.2/5.8	20.0/0.6	42.3/3.0	20.0/1.0	42.3/3.0	20.0/2.0	68.1/5.7	20.0/2.0
β^*, h/v [cm]]	91/4	196/41	91/4	193/12	91/4	193/6	90/4	307/11
IP RMS beam size, h/v [μm]	198/15		196/11		197/11		248/15	
K_x	0.077		0.057		0.056		0.061	
RMS $\Delta\theta$, h/v [μrad]	218/379	101/37	216/274	102/92	215/275	102/185	275/377	81/136
BB parameter, h/v [10^{-3}]	1/1	37/100	3/3	43/47	3/2	86/47	5/4	61/37
RMS long. emittance [10^{-3}, eV·s]	16		16		16		16	
RMS bunch length [cm]	7	0.9	7	0.7	7	0.7	11.6	0.7
RMS $\Delta p/p$ [10^{-4}]	6.2	10.9	6.2	5.8	6.2	6.8	10	6.8
Max. space charge	0.007	neglig.	0.008	neglig.	0.008	neglig.	0.038	neglig.
Piwinski angle [rad]	4.4	1.1	4.5	1.2	4.5	1.5	5.8	1.2
Long. IBS time [h]	0.33		0.36		0.36		0.85	
Transv. IBS time [h]	0.81		0.89		0.89		0.16	
Hourglass factor H	0.85		0.85		0.85		0.71	
Luminosity [10^{33}cm^{-2}s^{-1}]	0.52		4.76		4.77		1.67	

Table 3.3: EIC beam parameters for different center-of-mass energies $\sqrt{s}$, with strong hadron cooling. High divergence configuration.

Species	proton	electron	proton	electron	proton	electron	proton	electron	proton	electron
Energy [GeV]	275	18	275	10	100	10	100	5	41	5
CM energy [GeV]	140.7		104.9		63.2		44.7		28.6	
Bunch intensity [10^{10}]	19.1	6.2	6.9	17.2	6.9	17.2	4.8	17.2	2.6	13.3
No. of bunches	290		1160		1160		1160		1160	
Beam current [A]	0.69	0.227	1	2.5	1	2.5	0.69	2.5	0.38	1.93
RMS norm. emit., h/v [μm]	5.2/0.47	845/71	3.3/0.3	391/26	3.2/0.29	391/26	2.7/0.25	196/18	1.9/0.45	196/34
RMS emittance, h/v [nm]	18/1.6	24/2.0	11.3/1.0	20/1.3	30/2.7	20/1.3	26/2.3	20/1.8	44/10	20/3.5
β^*, h/v [cm]]	80/7.1	59/5.7	80/7.2	45/5.6	63/5.7	96/12	61/5.5	78/7.1	90/7.1	196/21.0
IP RMS beam size, h/v [μm]	119/11		95/8.5		138/12		125/11		198/27	
K_x	11.1		11.1		11.1		11.1		7.3	
RMS $\Delta\theta$, h/v [μrad]	150/150	202/187	119/119	211/152	220/220	145/105	206/206	160/160	220/380	101/129
BB parameter, h/v [10^{-3}]	3/3	93/100	12/12	72/100	12/12	72/100	14/14	100/100	15/9	53/42
RMS long. emittance [10^{-3}, eV·s]	36		36		21		21		11	
RMS bunch length [cm]	6	0.9	6	0.7	7	0.7	7	0.7	7.5	0.7
RMS $\Delta p/p$ [10^{-4}]	6.8	10.9	6.8	5.8	9.7	5.8	9.7	6.8	10.3	6.8
Max. space charge	0.007	neglig.	0.004	neglig.	0.026	neglig.	0.021	neglig.	0.05	neglig.
Piwinski angle [rad]	6.3	2.1	7.9	2.4	6.3	1.8	7.0	2.0	4.2	1.1
Long. IBS time [h]	2.0		2.9		2.5		3.1		3.8	
Transv. IBS time [h]	2.0		2		2.0/4.0		2.0/4.0		3.4/2.1	
Hourglass factor H	0.91		0.94		0.90		0.88		0.93	
Luminosity [$10^{33}\text{cm}^{-2}\text{s}^{-1}$]	1.54		10.00		4.48		3.68		0.44	

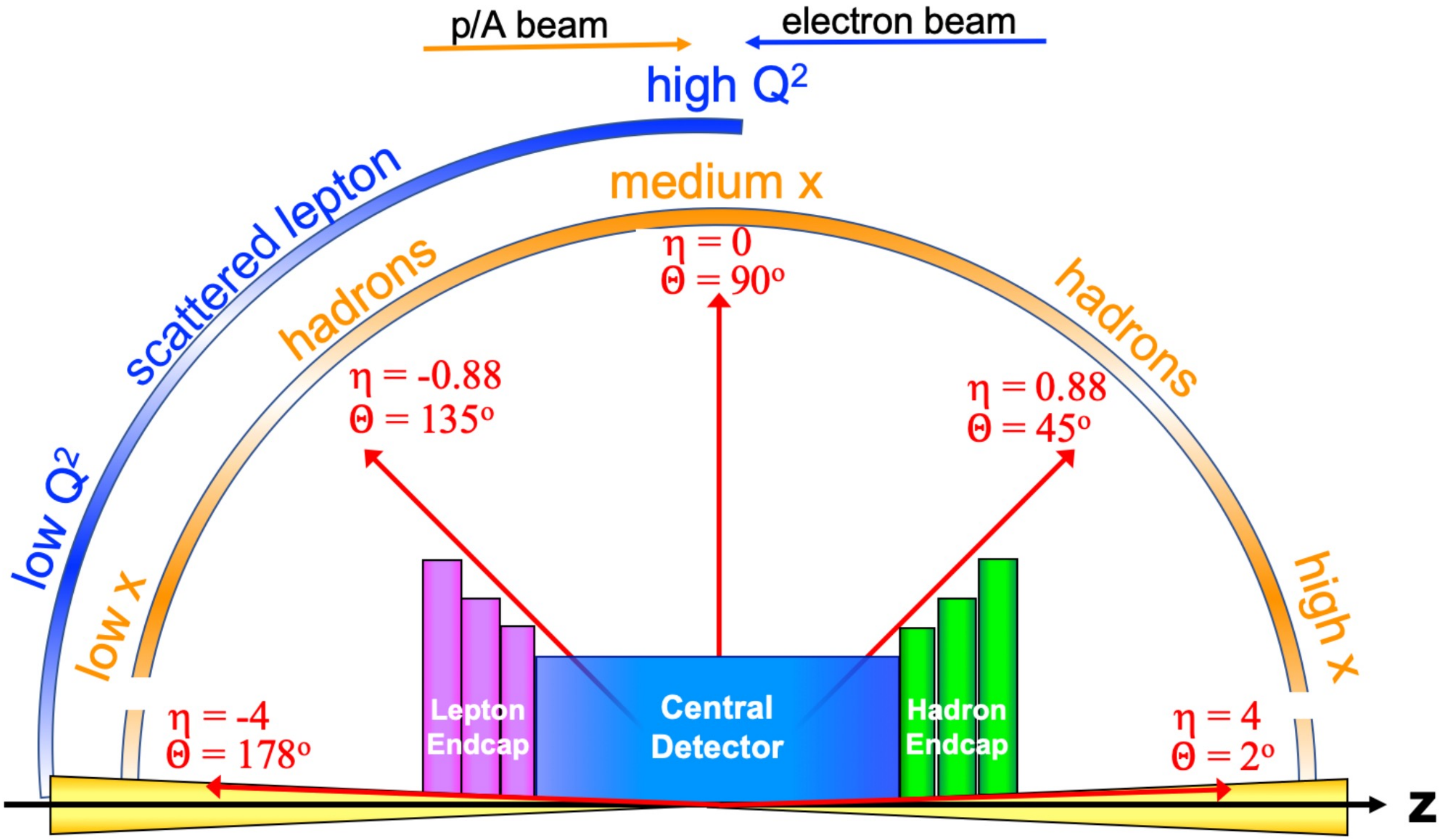
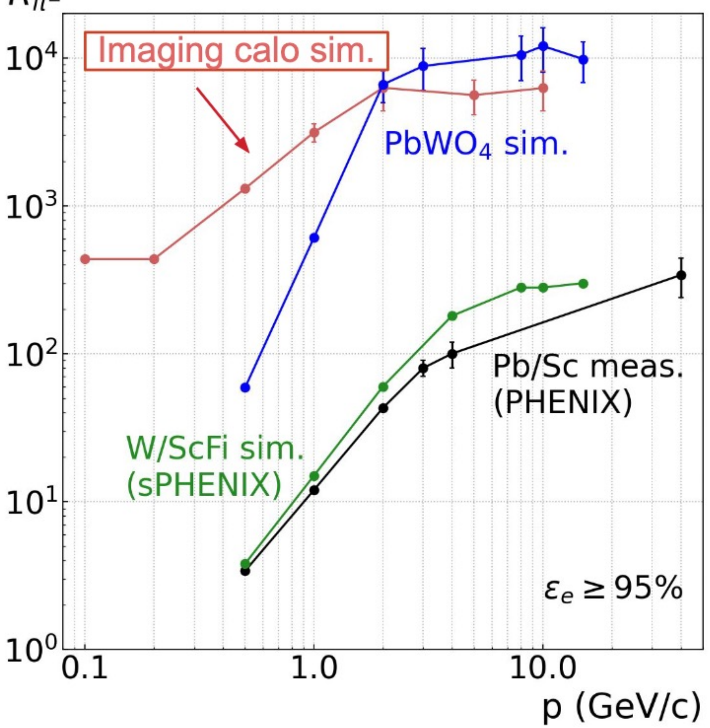


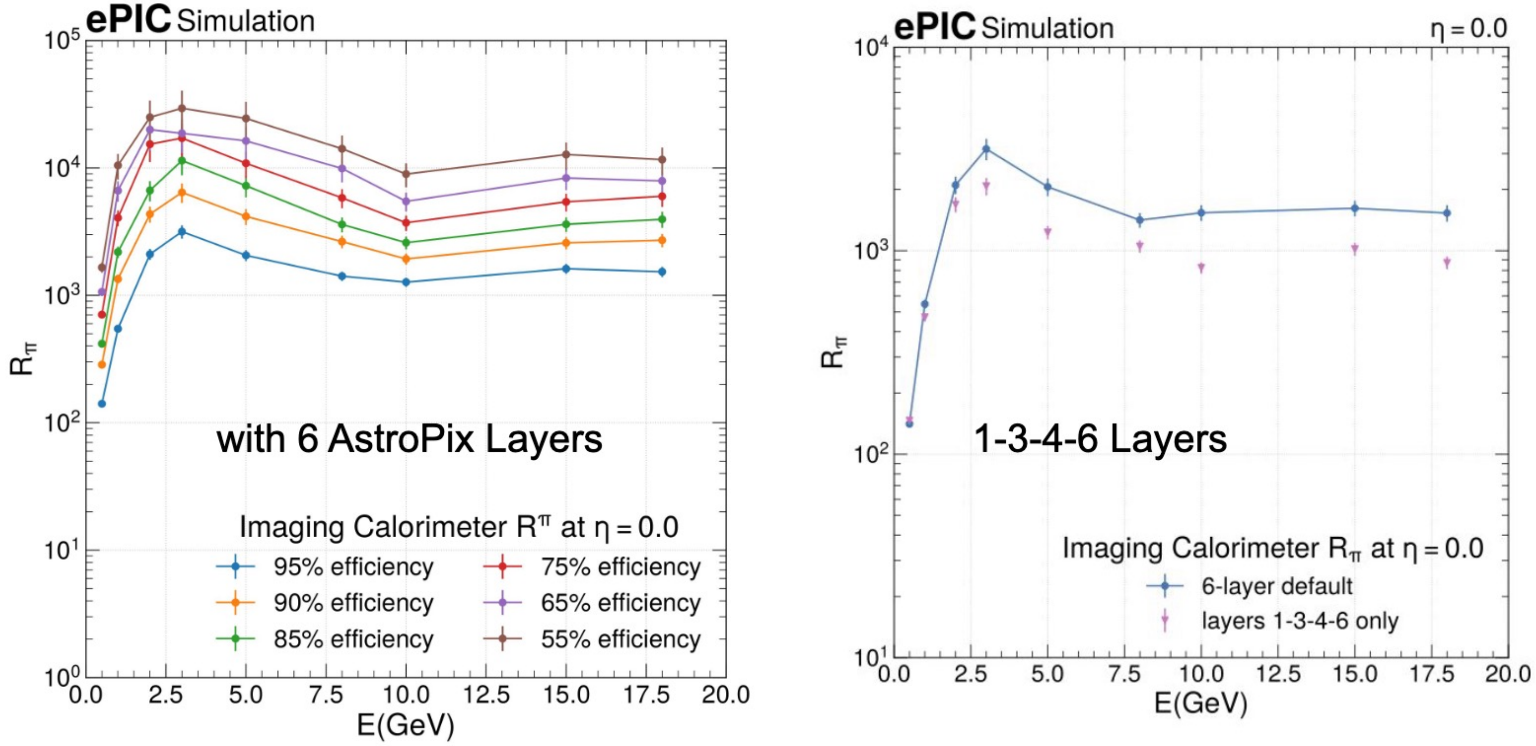
Figure 8.1: A schematic showing how hadrons and the scattered lepton for different $x - Q^2$ are distributed over the detector rapidity coverage.

Electron Identification

Standalone simulation

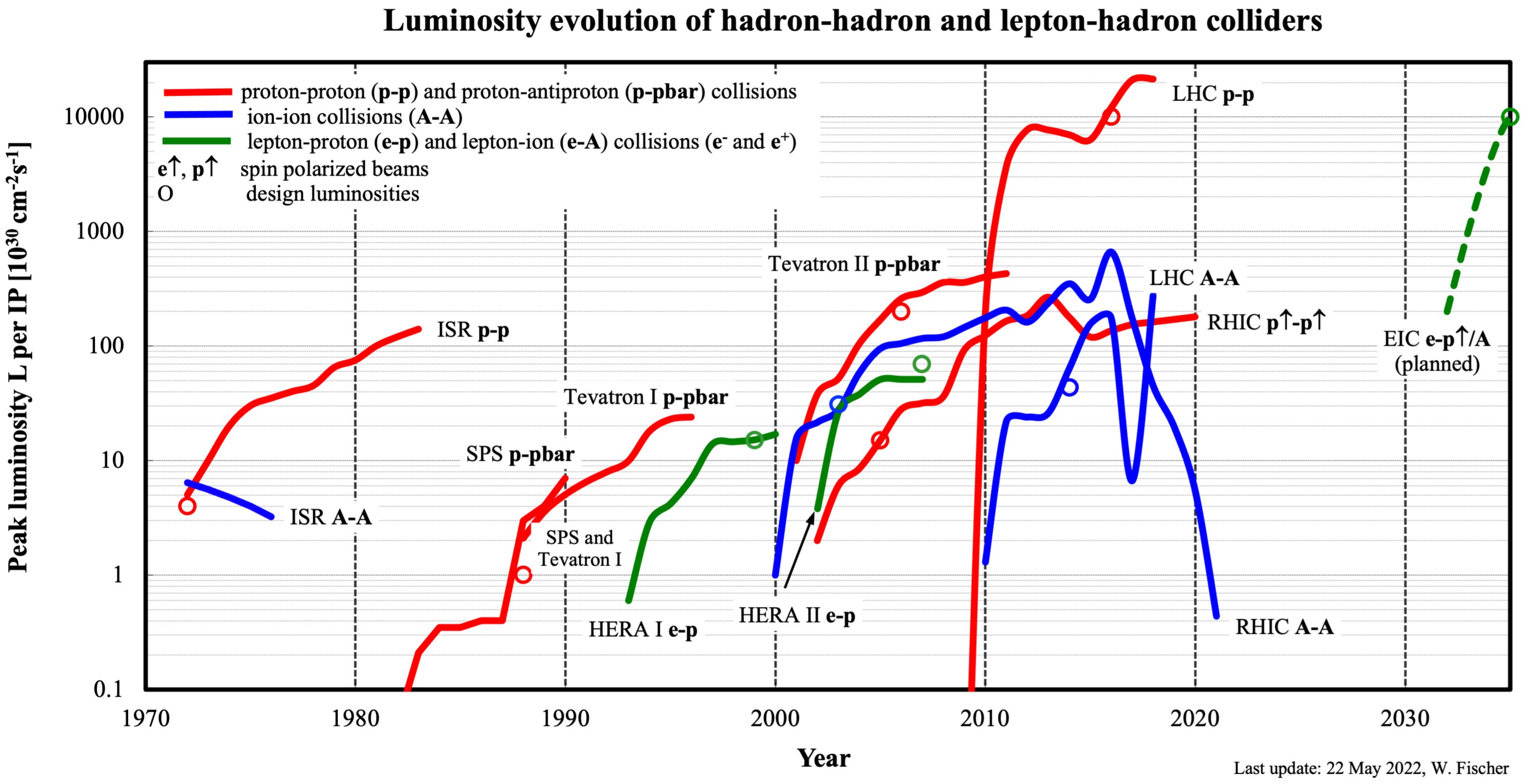


Realistic ePIC simulation



- **Goal:** Separation of electrons from background in Deep Inelastic Scattering (DIS) processes
- Method: **E/p cut (Pb/ScFi) + Neural Network** using 3D position and energy info from imaging layers

- e-π separation exceeds **10^3** in pion suppression at **95% efficiency** above 1 GeV in realistic


Luminosity evolution of hadron-hadron and lepton-hadron colliders
proton-proton (p-p) and proton-antiproton (p-pbar) collisions
ion-ion collisions (A-A)
lepton-proton (e-p) and lepton-ion (e-A) collisions (e- and e+)
e↑, p↑ spin polarized beams
O design luminosities
Peak luminosity L per IP [10^30 cm^-2 s^-1]
10000
1000
100
10
1
0.1
1970
1980
1990
2000
2010
2020
2030
Year
ISR p-p
ISR A-A
SPS p-pbar
SPS and Tevatron I
Tevatron I p-pbar
HERA I e-p
HERA II e-p
Tevatron II p-pbar
LHC p-p
LHC A-A
RHIC p↑-p↑
RHIC A-A
EIC e-p↑/A (planned)
Last update: 22 May 2022, W. Fischer