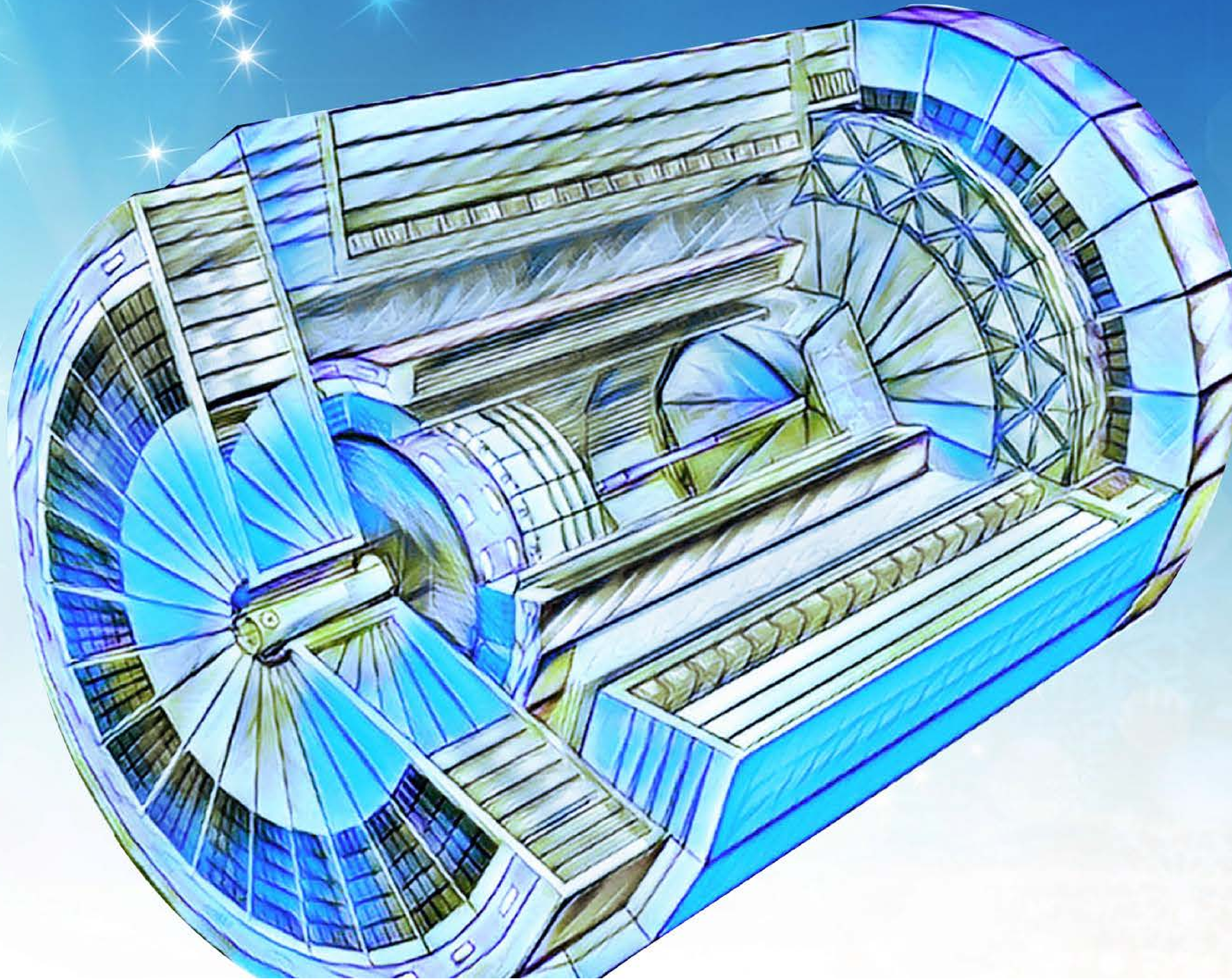
Detectors for the EIC



Thomas Ullrich

CPAD 2022

Stony Brook University

November 29, 2022

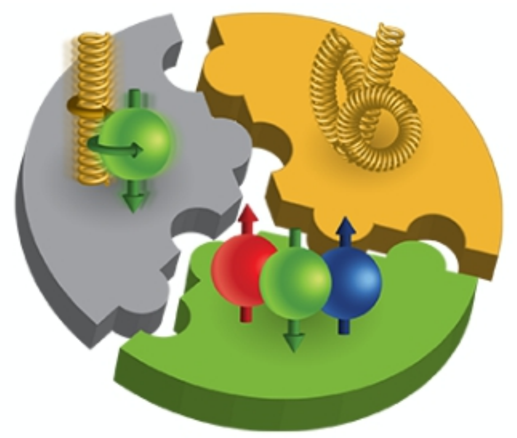
Brookhaven National Laboratory

Yale

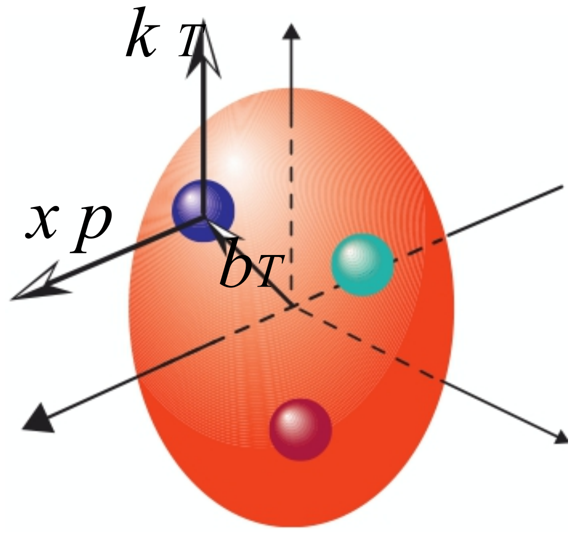
EIC Physics (= QCD Physics)

Investigate with precision the universal dynamics of gluons to understand the emergence of hadronic and nuclear matter and their properties

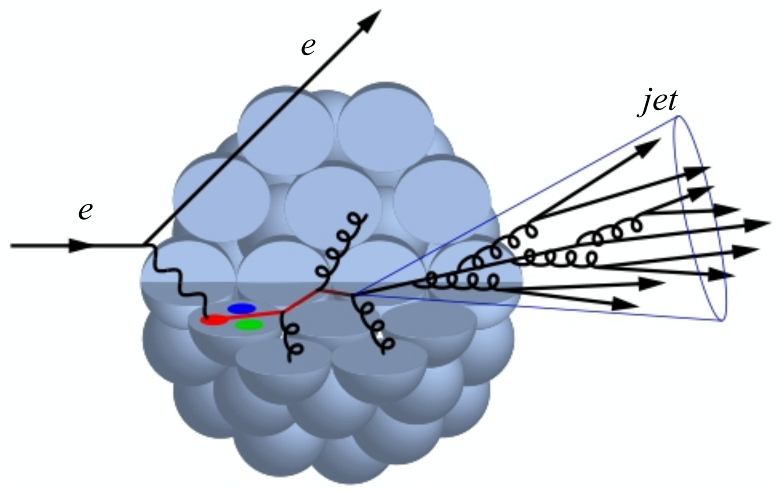
Central Questions:



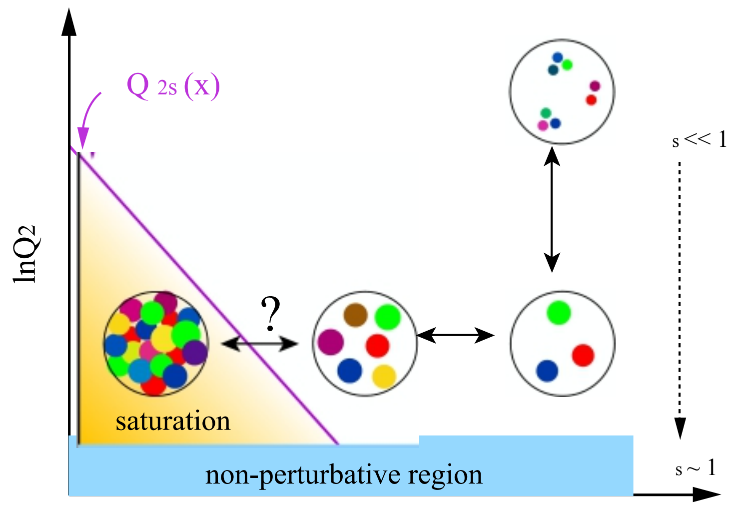
- How are sea quarks and gluons, and their spins, distributed in space and momentum inside the nucleon? How do the nucleon properties emerge from them and their interactions?



- How do color-charged quarks and gluons, and colorless jets, interact with a nuclear medium? How do confined hadronic states emerge from these quarks and gluons?

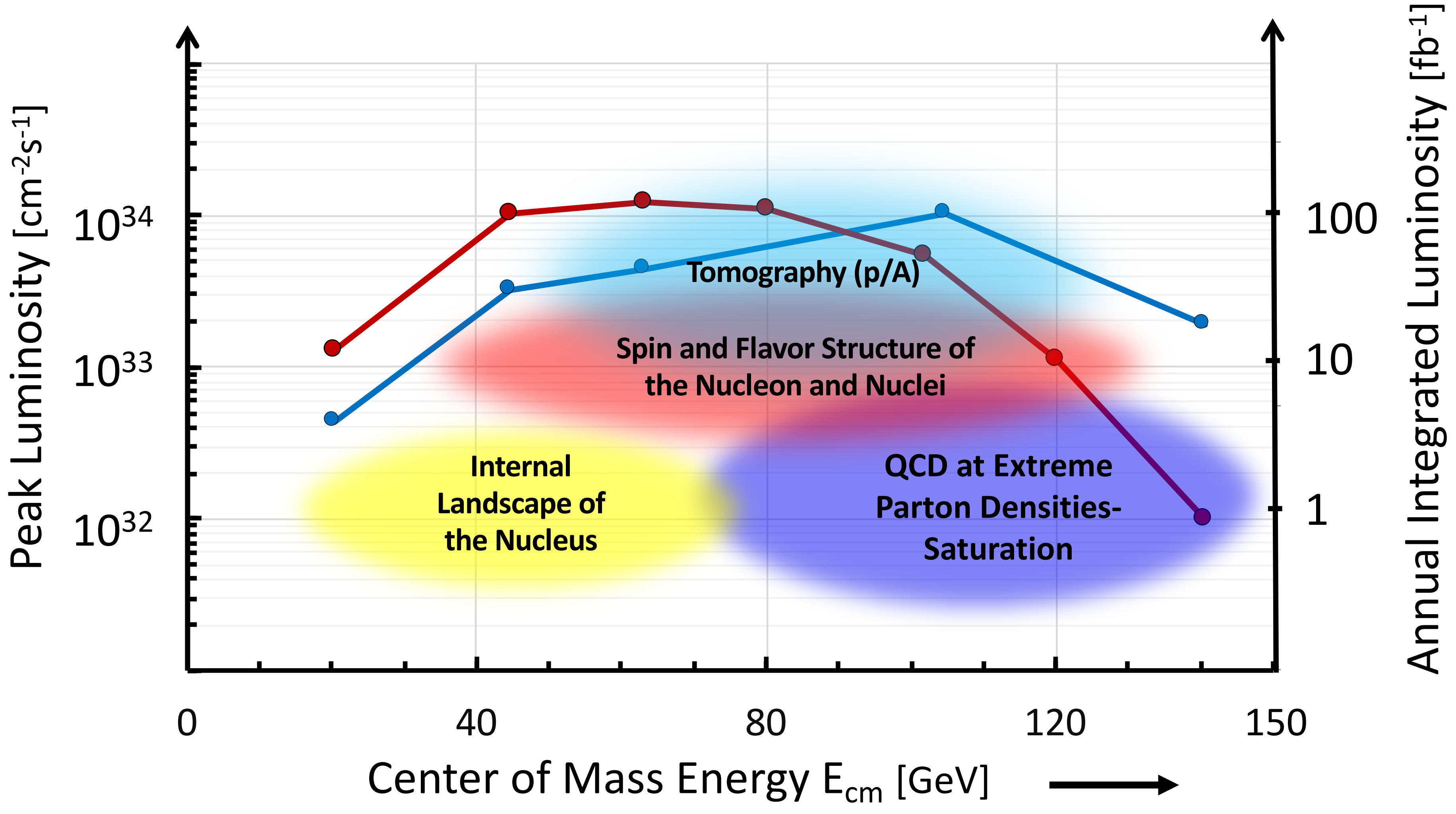


- What happens to the exploding gluon density at low-x in hadronic matter? Does it saturate at high energy, giving rise to a gluonic matter with universal properties?



Machine Requirements

- Access to gluon dominated region and wide kinematic range in x and Q^2
  - ➡ Large center-of-mass energy range $\sqrt{s}$ = 20 -140 GeV
- Access to spin structure and 3D spatial and momentum structure
  - ➡ Polarized electron and proton and light nuclear beams ≥ 70% for both
- Accessing the highest gluon densities ($Q_S^2 \sim A^{1/3}$)
  - ➡ Nuclear beams, the heavier the better (up to U)
- Studying observables as a fct. of x, Q^2, A, etc.
  - ➡ High luminosity (100x HERA): $10^{33\text{-}34}$ cm^{-2} s^{-1}



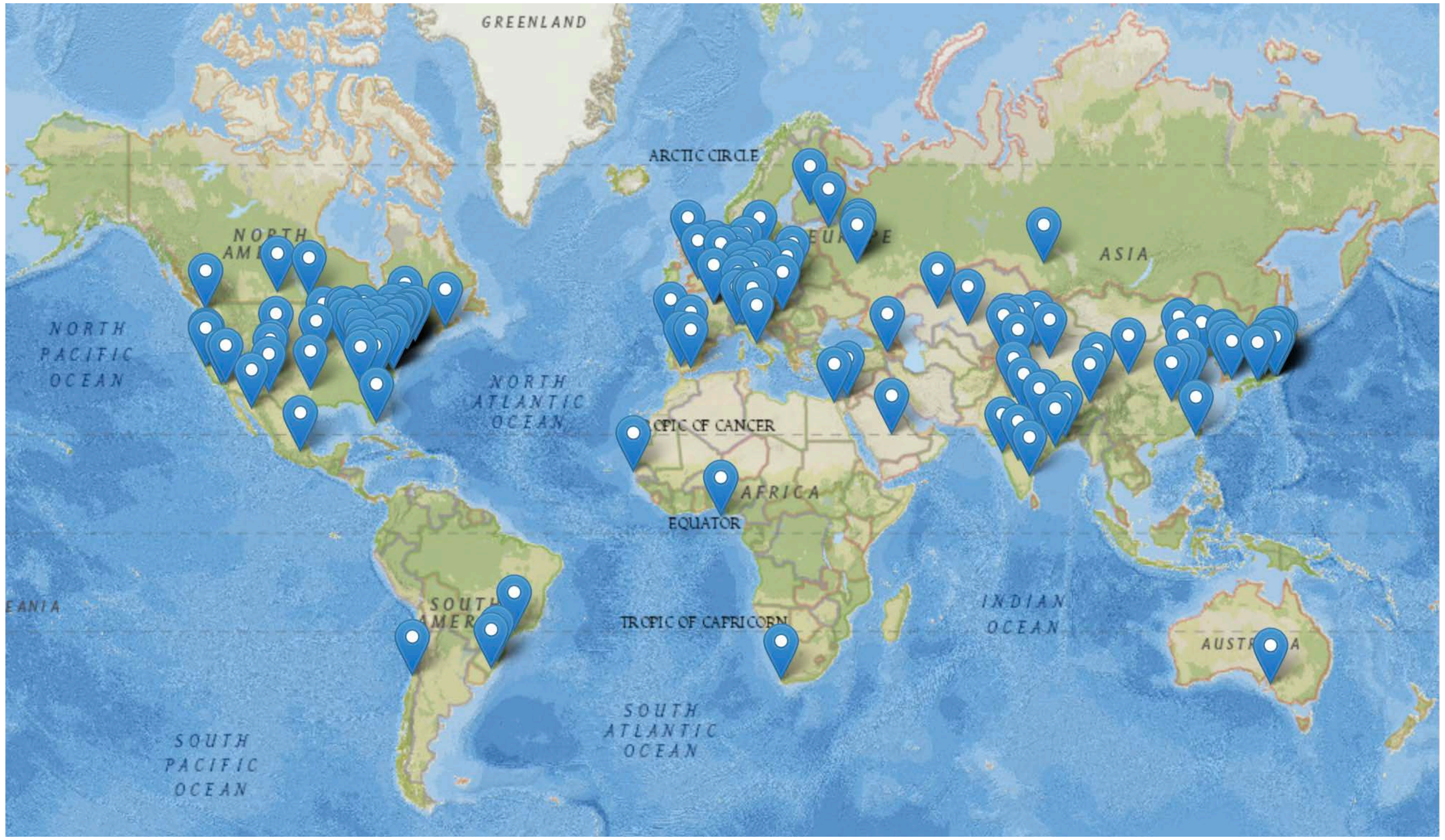
HERA@DESY

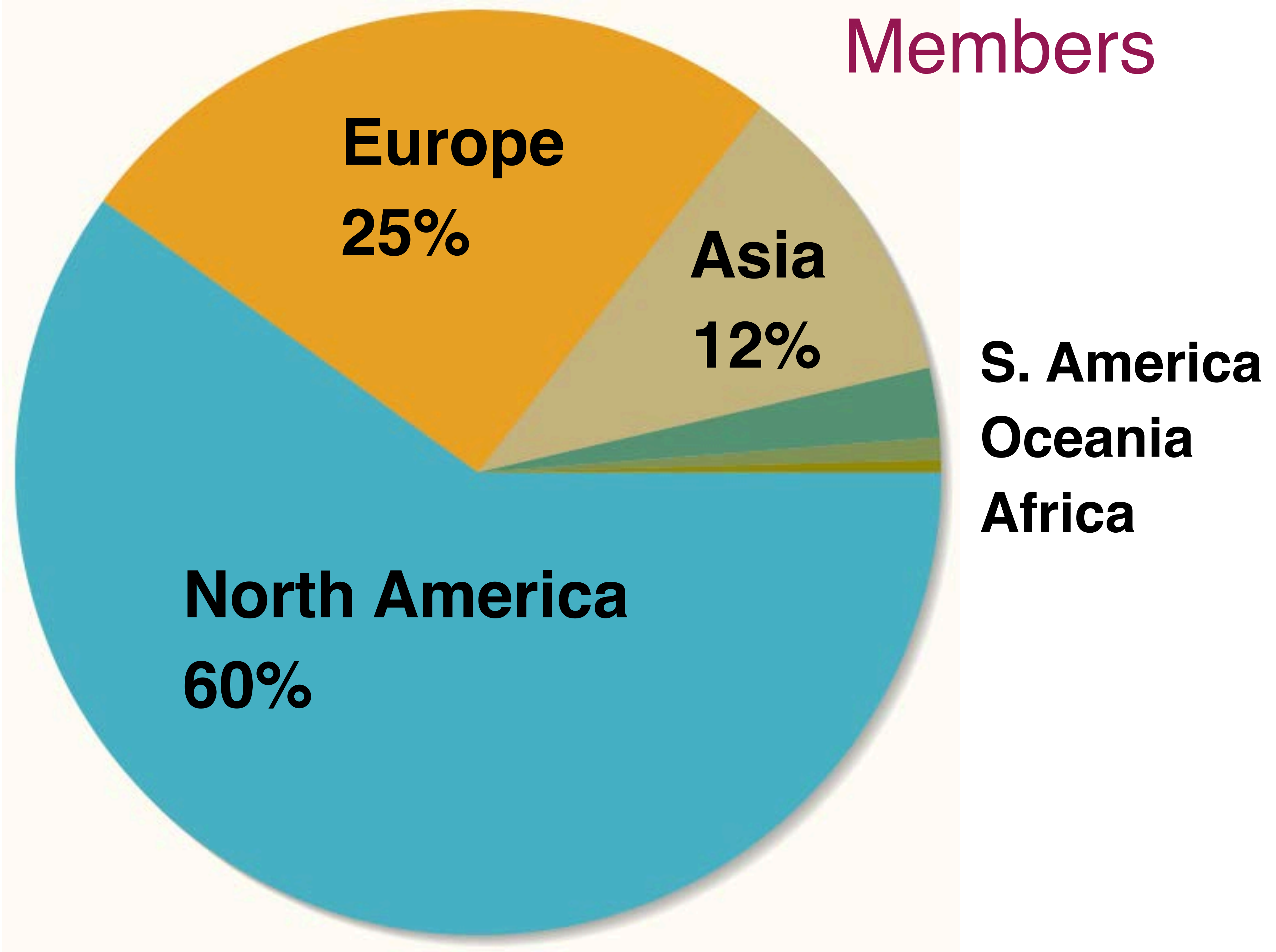
Siberian Snakes, RHIC

The Community Behind the EIC

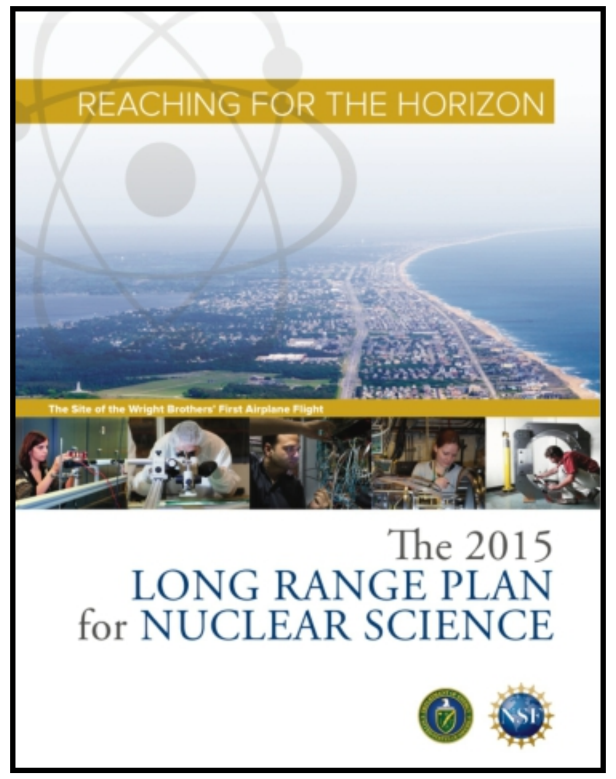
The EIC User Group: http://eicug.org

- Formation of a formal EIC User Group in 2014/2015
- 1369 members, 267 institutions, 36 countries
- EIC Science Centers at JLab (EIC²) and BNL/Stony Brook University (CFNS)
- Networks in many countries (e.g. EIC-Net in Italy)



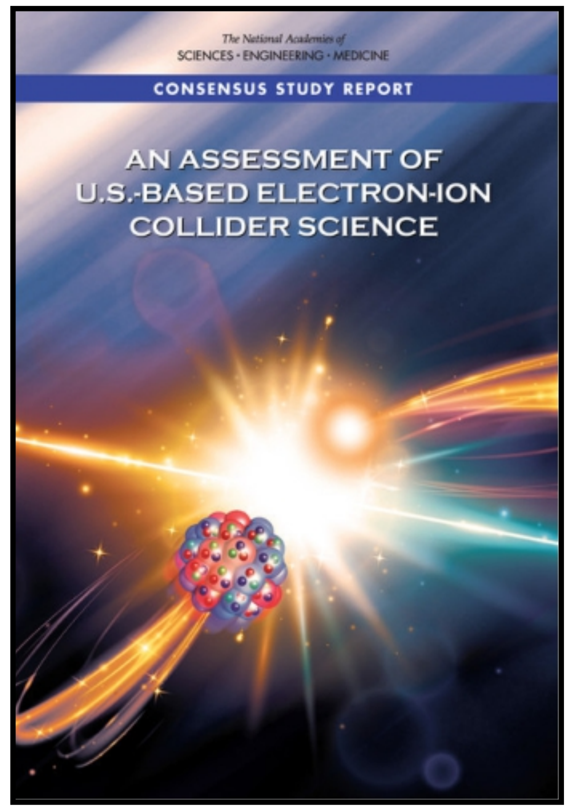


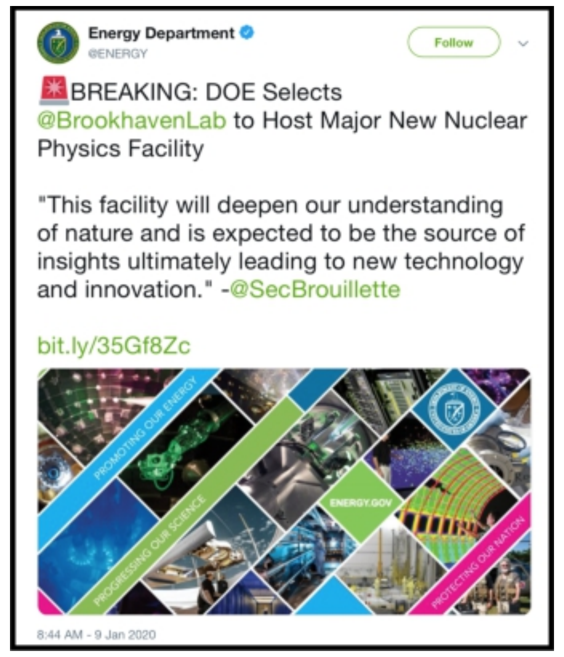
Status of US Based EIC



2015: US Nuclear Physics Long Range Plan:
"We recommend a high-energy high-luminosity polarized EIC as the highest priority for new facility construction following the completion of FRIB."

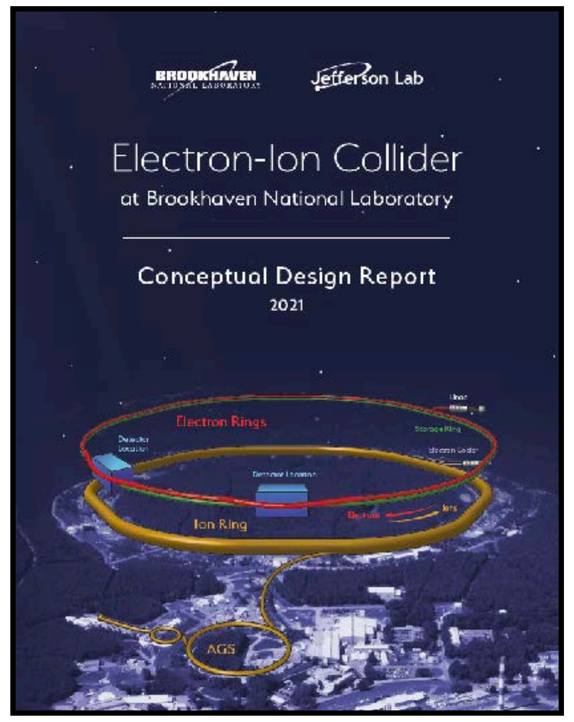
2018: National Academy EIC Review
"The committee finds that the science that can be addressed by an EIC is compelling, fundamental and timely."

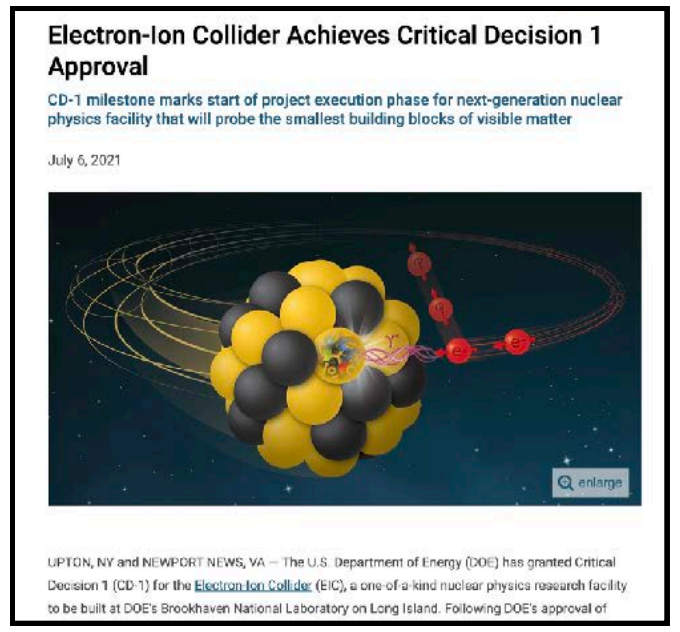




December 2019/January 2020:
After science, cost, and host review DoE gives EIC CD-0 (*Approve Mission Need*) and selects BNL as the hosting site. BNL and JLab are the hosting labs. Project management officially started 4/1/2020.

January/February 2021: Release of CDR, CD-1 Review

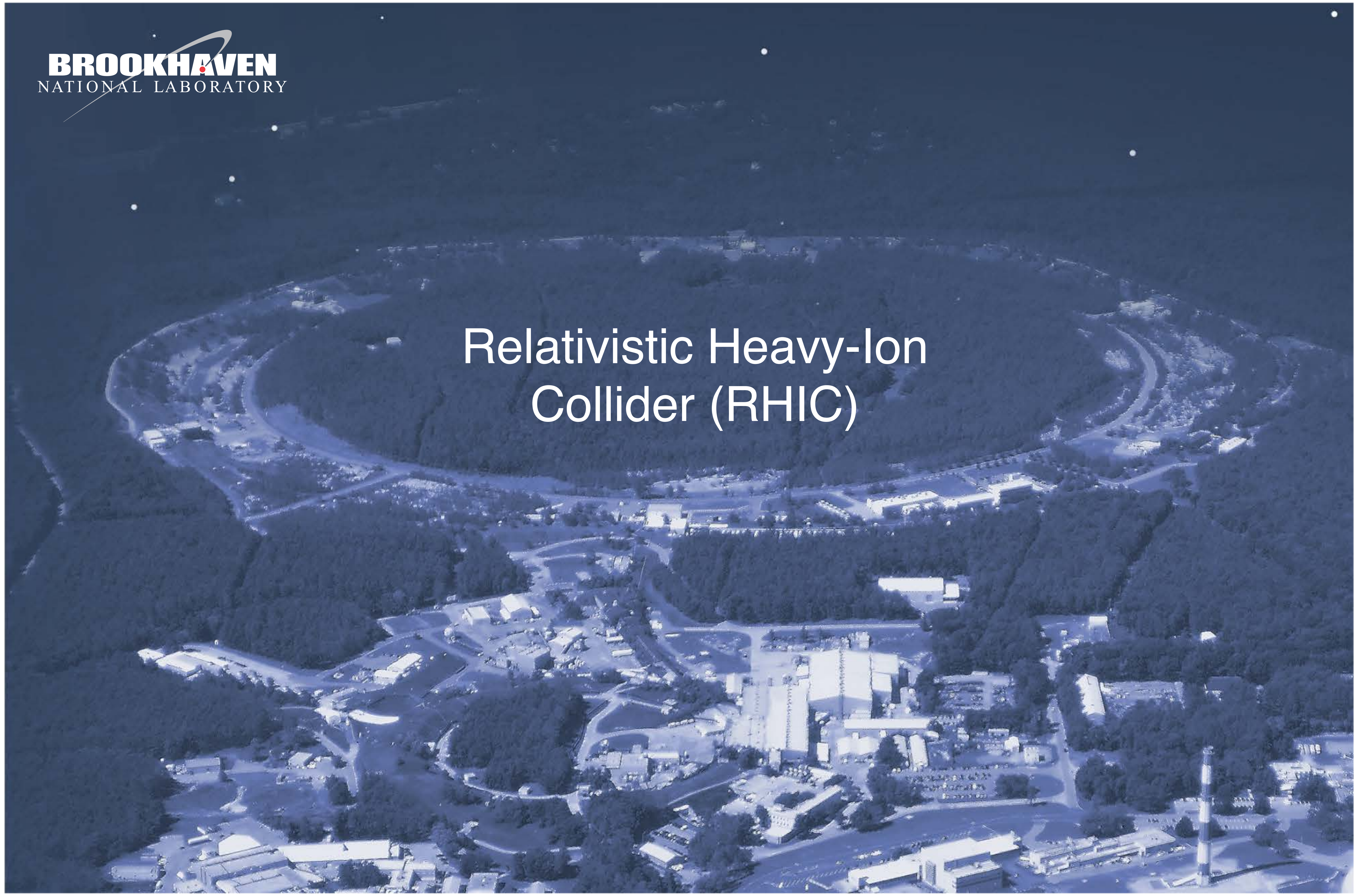




July 2021: CD-1 (*Approve Alternative Selection and Cost Range*) received.
Original cost estimate: $2 - 2.6 B
$100M from New York State towards infrastructure

EIC Machine Overview

EIC is using part of RHIC facility at BNL which is operating at its peak



EIC Machine Overview

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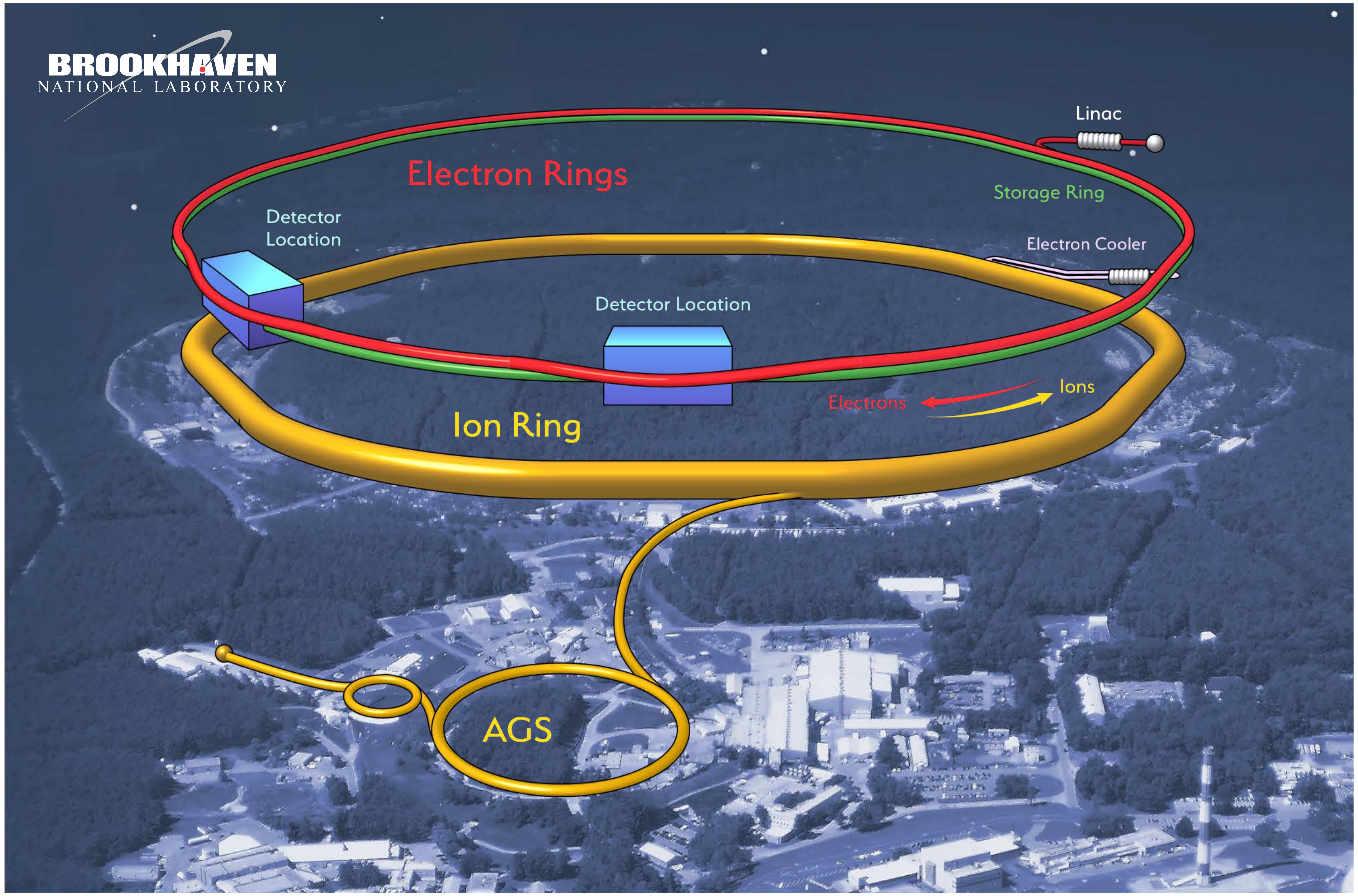
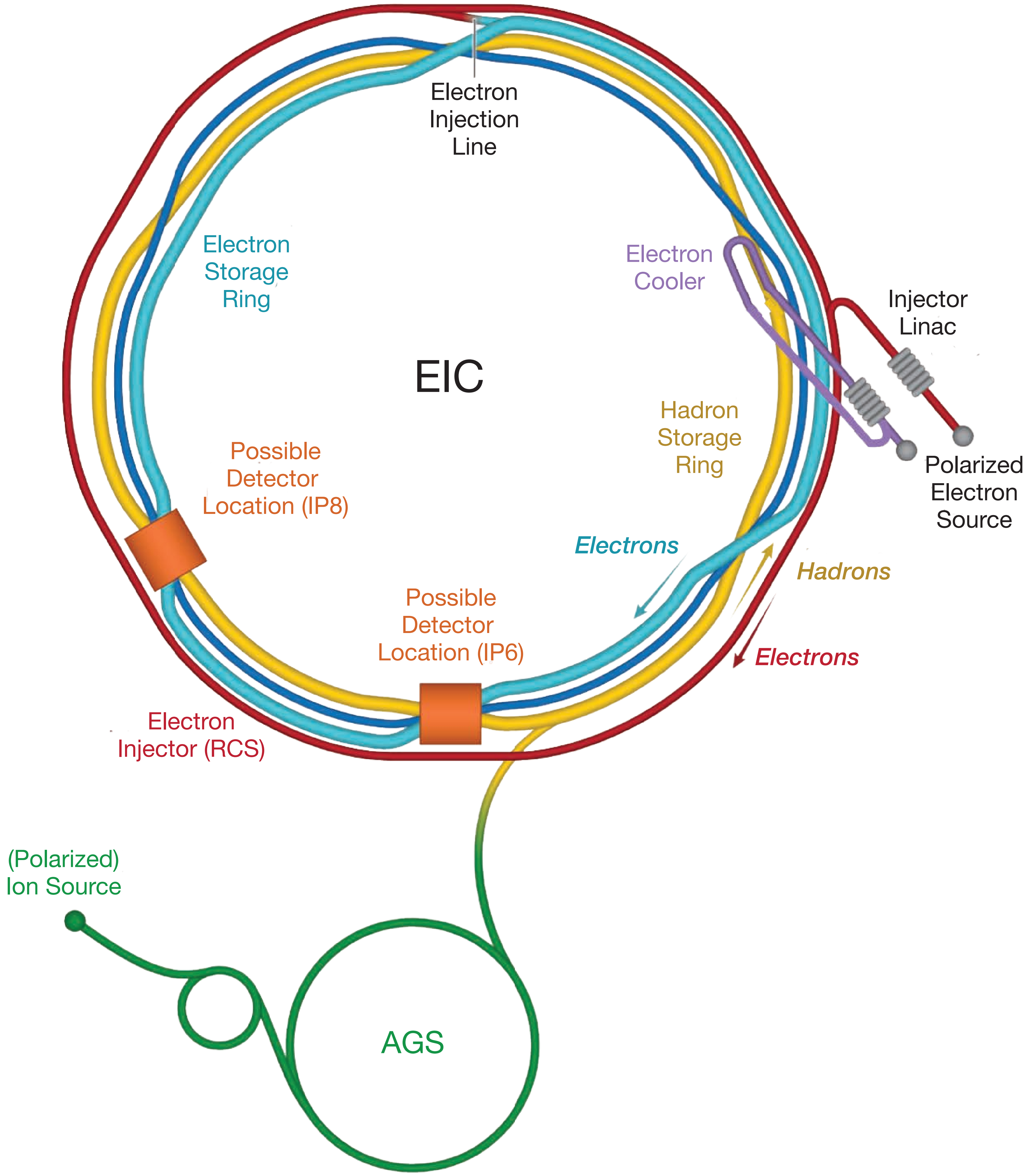


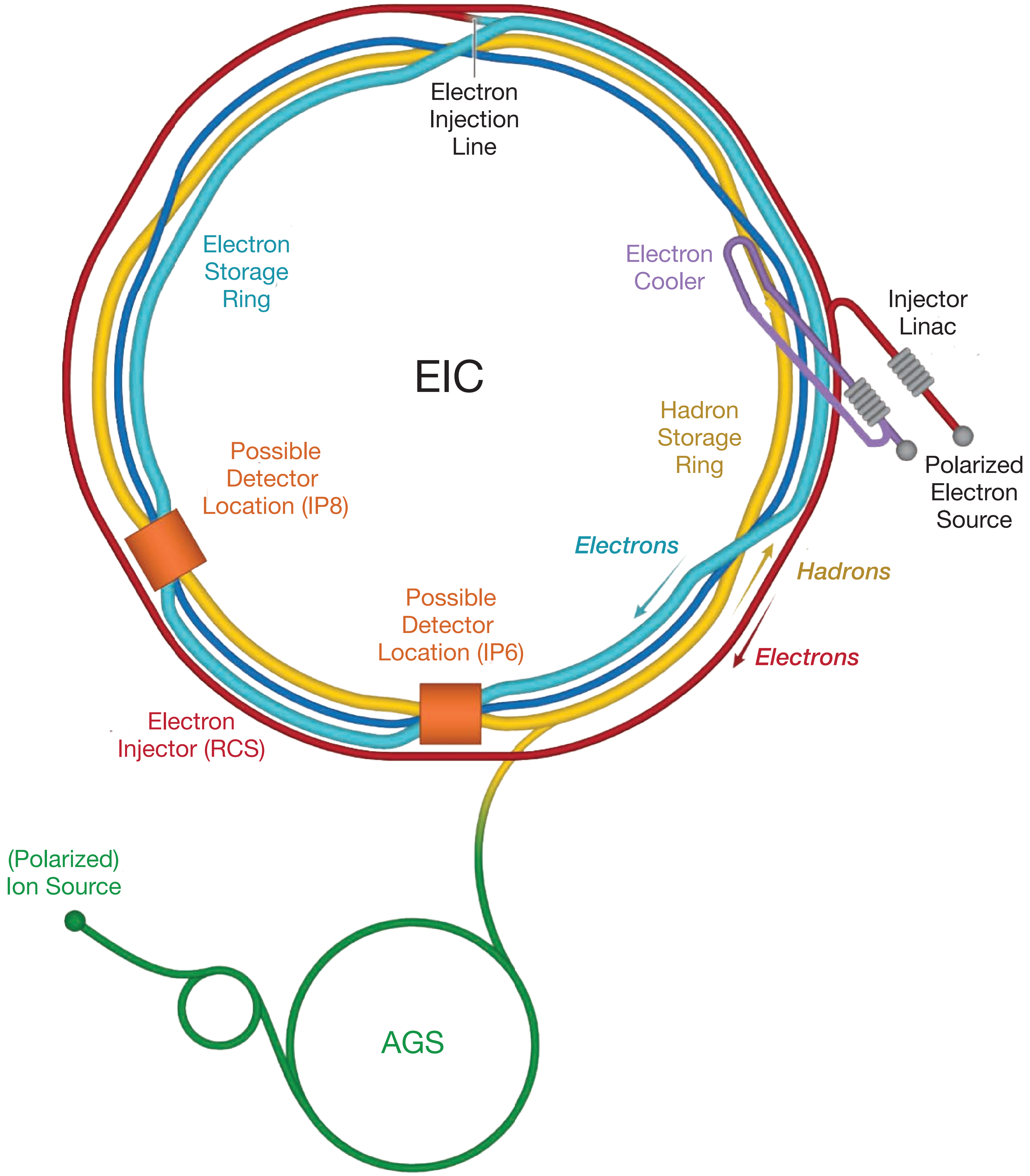


EIC Machine Overview

EIC is using part of RHIC facility at BNL which is operating at its peak

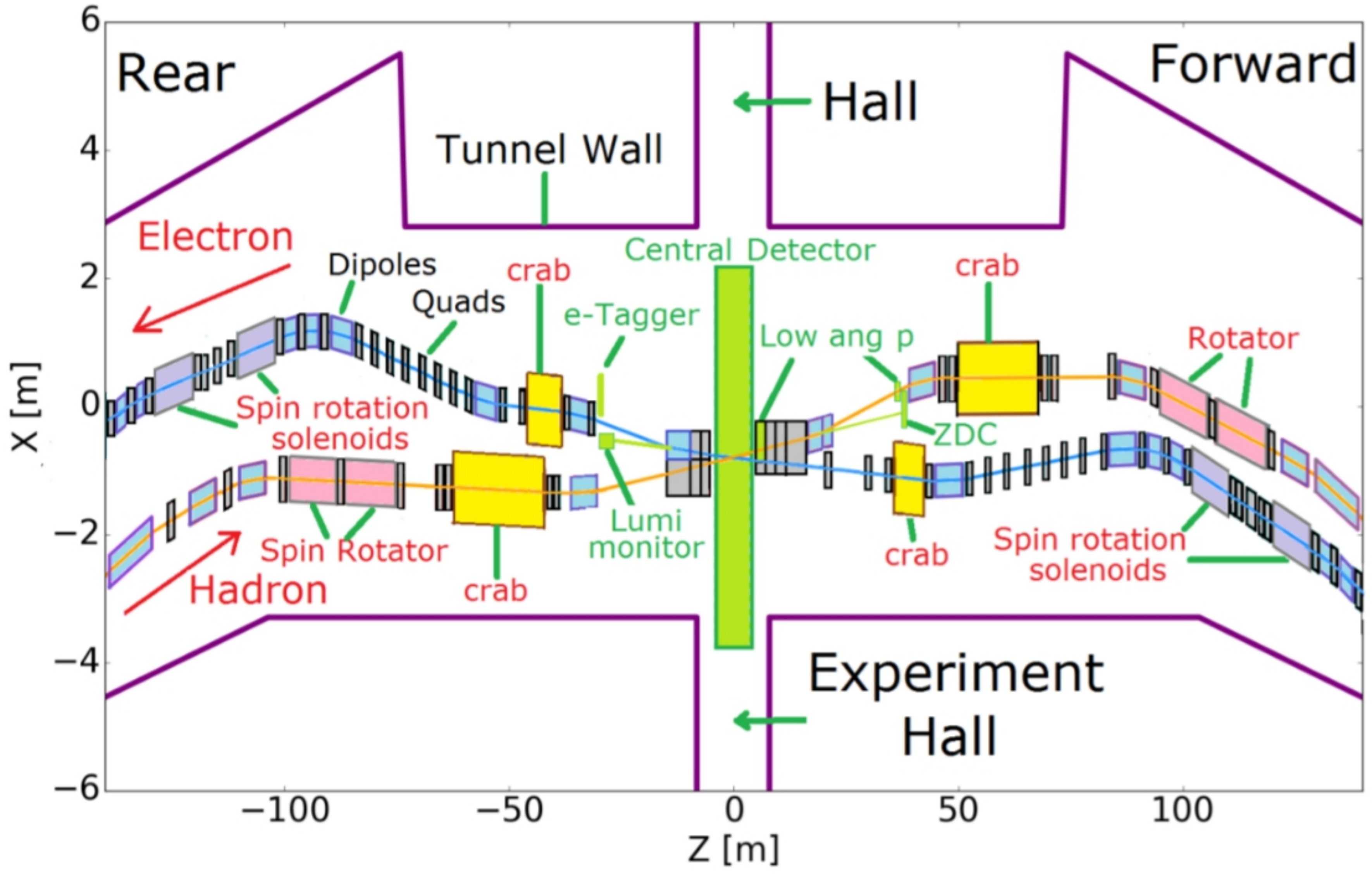
Three Ring Design

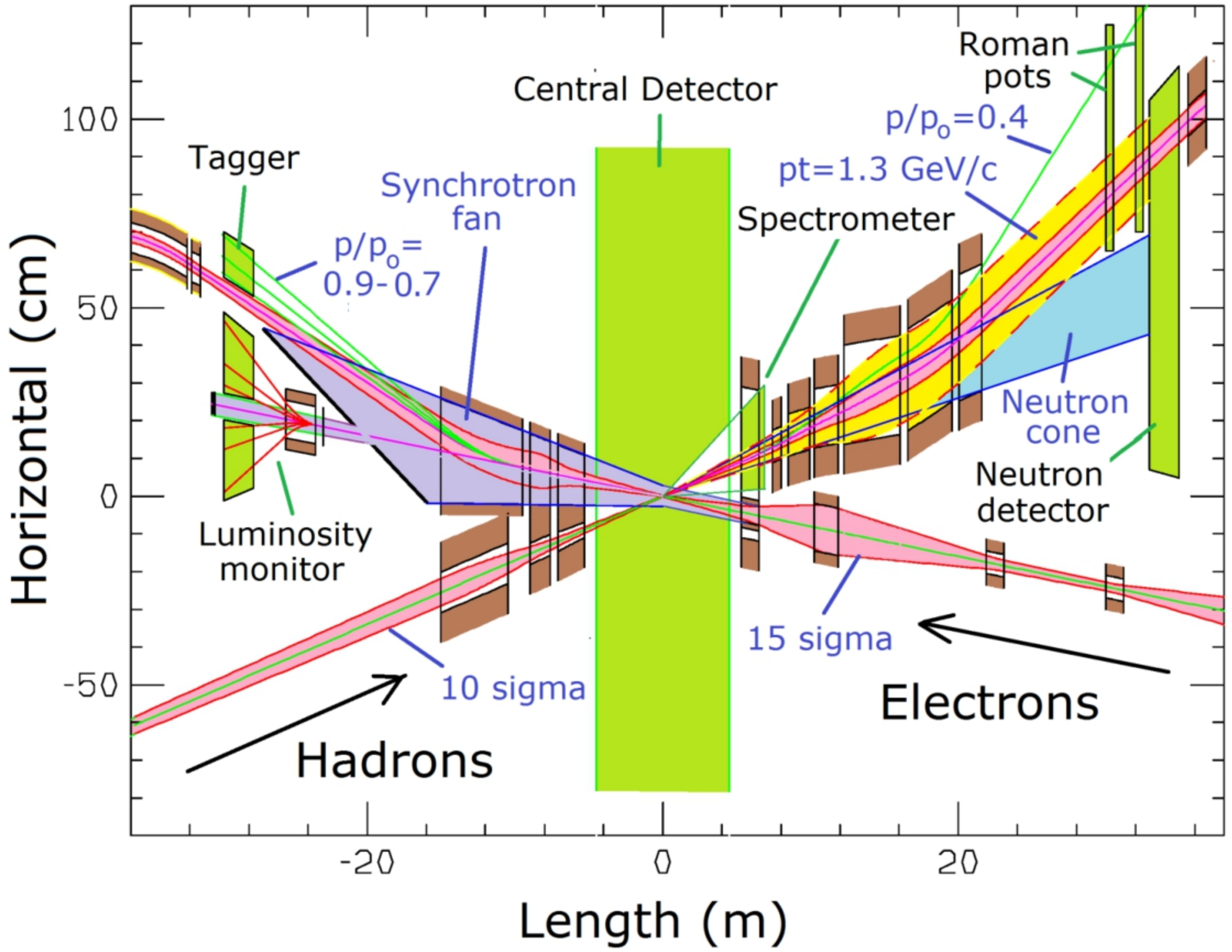
- Hadron storage ring 40-275 GeV (existing)
  - Many bunches, 1160 @ 1A beam current
  - Need strong cooling
- Electron storage ring (2.5–18 GeV, new)
  - Many bunches
  - Large beam current (2.5 A) ➔10 MW S.R. power
  - S.C. RF cavities
- Electron rapid cycling synchrotron (new)
  - 1-2 Hz
  - Spin transparent due to high periodicity
- High luminosity interaction region(s) (new)
  - $L = 10^{34} cm^{-2} s^{-1}$
  - Superconducting magnets
  - 25 mrad crossing angle with crab cavities



EIC Machine Overview

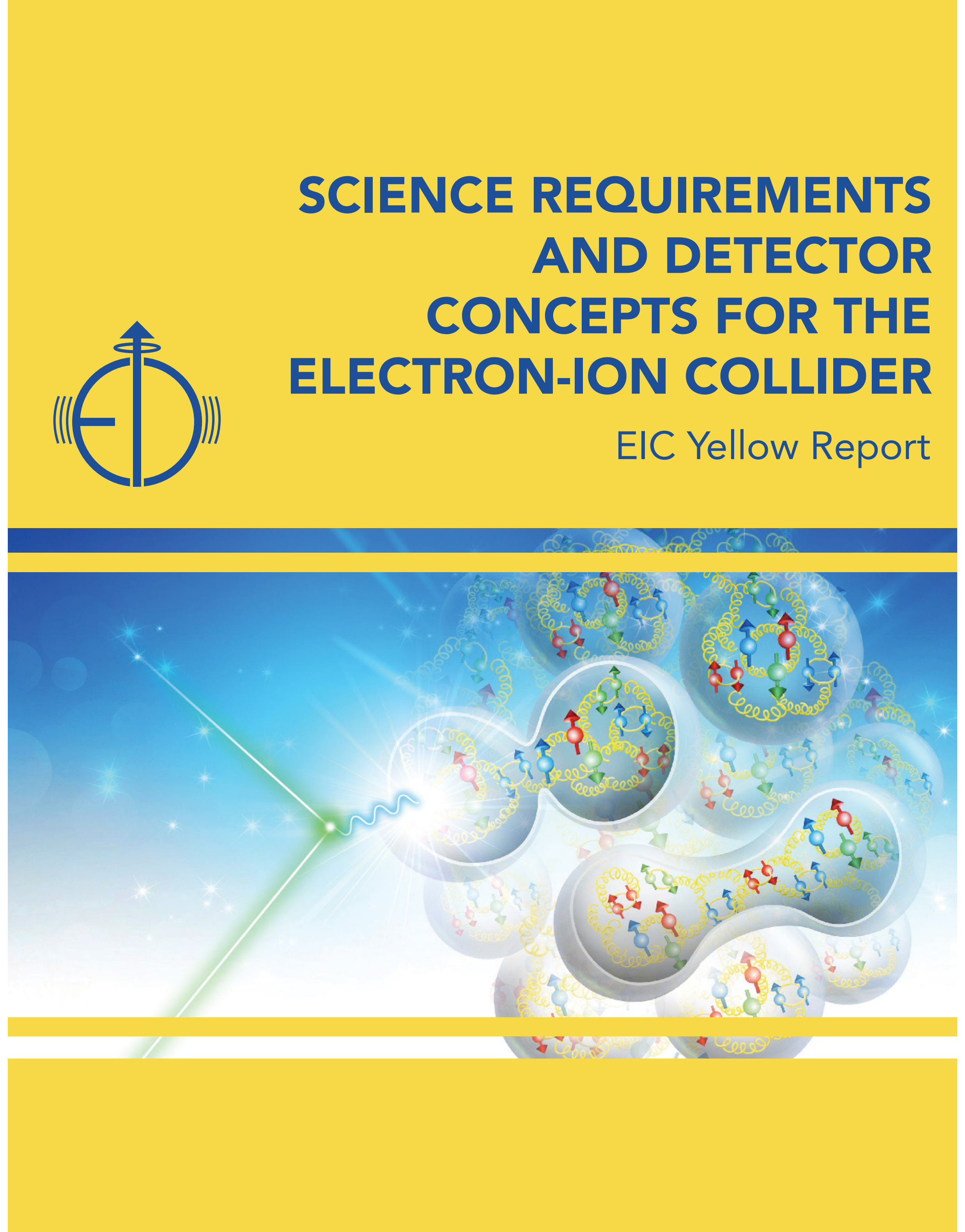
- Key parameters
  - $\sqrt{s} = 20 - 140$ GeV
  - $\mathscr{L}_{max} = 10^{34}\text{cm}^{-1}s^{-1}$
  - Polarization e & p = 70-80%
  - hadron beam A = p to U
- Requires very complex IR designed to meet physics requirements
- EIC is not your standard Collider Setup
  - asymmetric beam energies, boosted kinematics
  - crossing angle (25 mrad)
  - synchrotron backgrounds
  - machine element free region: ~9.5 m for detector
  - wide range of energies affect detector acceptance and detector technologies considerably





Detector Planning

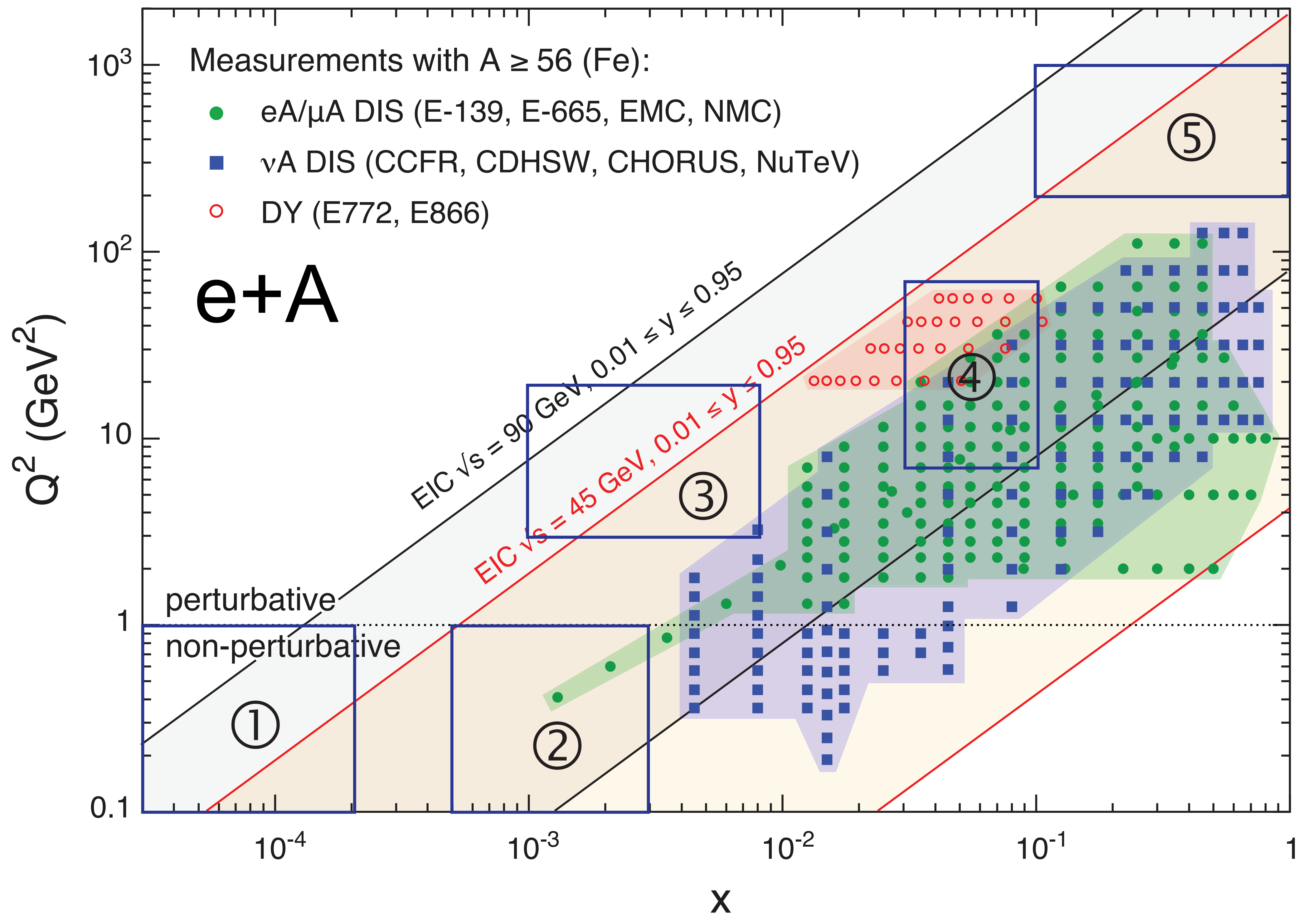
- The DOE-NP supported EIC Project includes **one** detector and **one** IR in the reference costing
- The EIC is capable of supporting a science program that includes **two** detectors and **two** interaction regions.
- The community (EIC User Group) is strongly in favor of two general purpose detectors
  - Complementarity, cross-checking, cross-calibration/reduction of systematics (see HERA), mitigating of overall risk
- **EIC User Group "Yellow Report" Effort**
  - Initiative to advance the state and detail of requirements and detector concepts in preparation for the realization of the EIC.
  - 1 year effort concluded in March 2021 with a comprehensive "Yellow" Report
  - 902 Pages, 414 authors from 121 institutions, 675 figures
  - Nucl. Phys. A 1026 (2022) 122447, arXiv:2103.05419



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

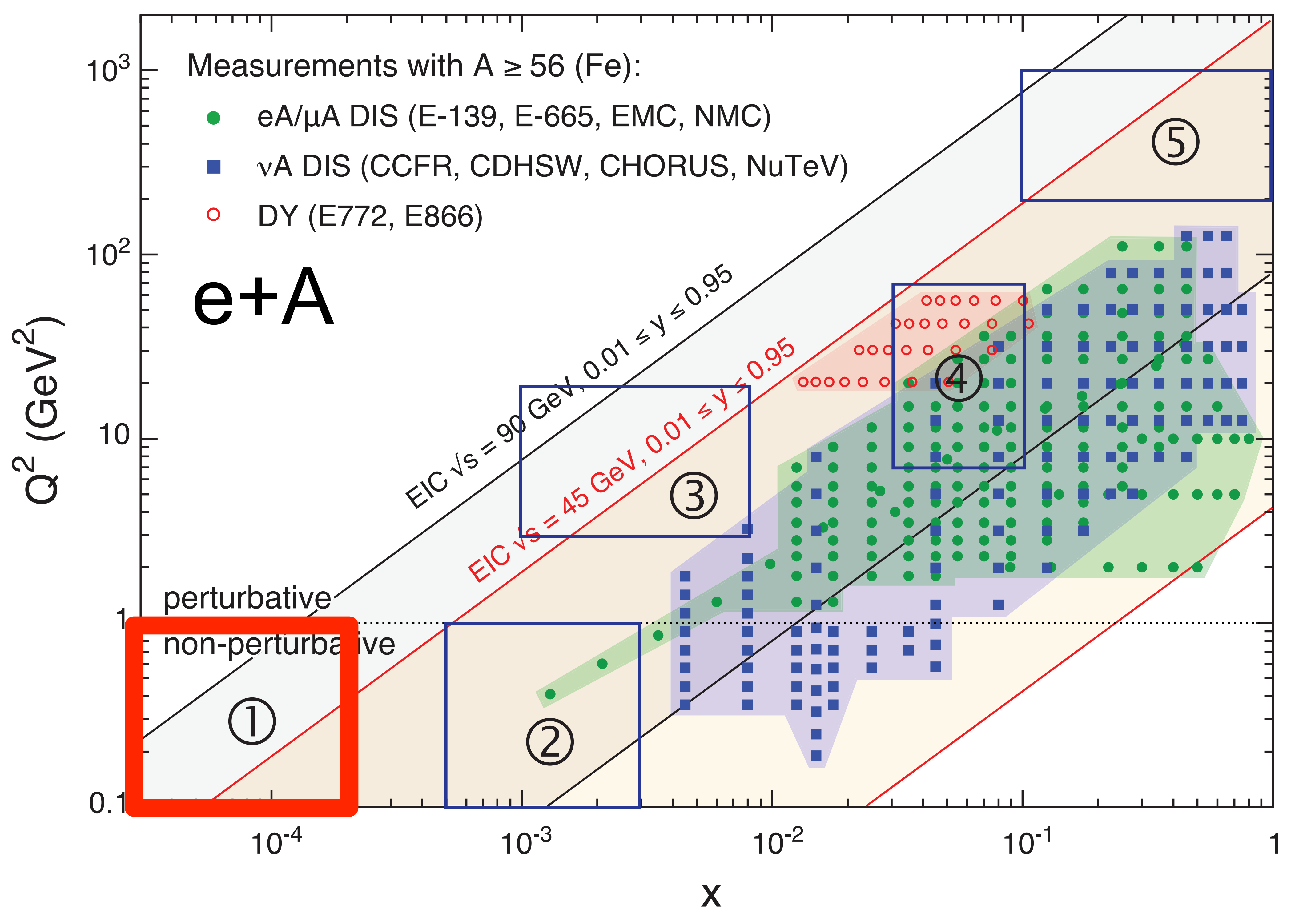
Inclusive (All): Scattered Electron Requirements

The energy and angle of scatter electron gives key variables x, y, Q^2

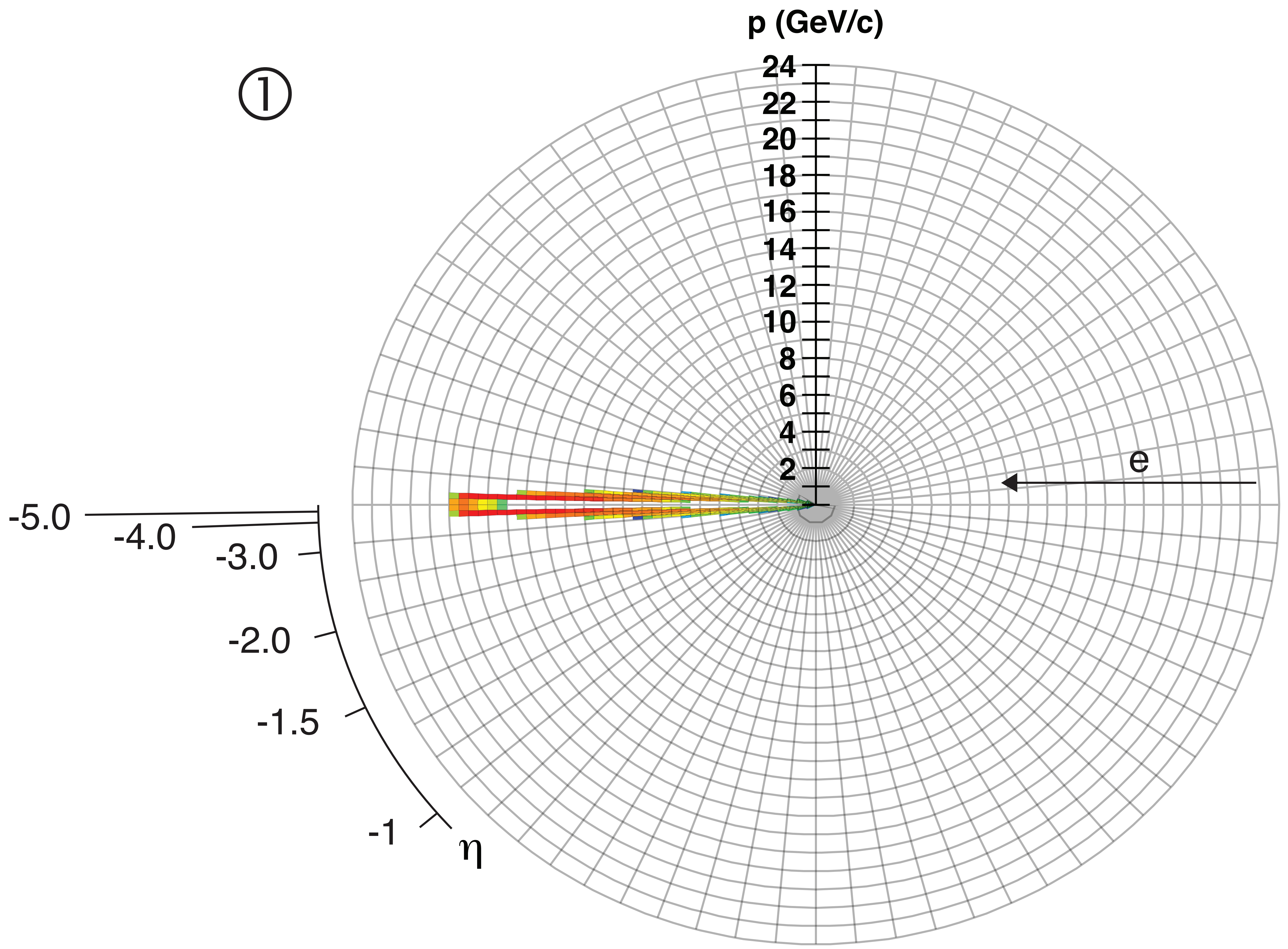


Inclusive (All): Scattered Electron Requirements

The energy and angle of scatter electron gives key variables x, y, Q^2



20 GeV on 100 GeV, $0.1 < Q^2 < 1$ GeV^2, $3\cdot10^{-5} < x < 2\cdot10^{-4}$



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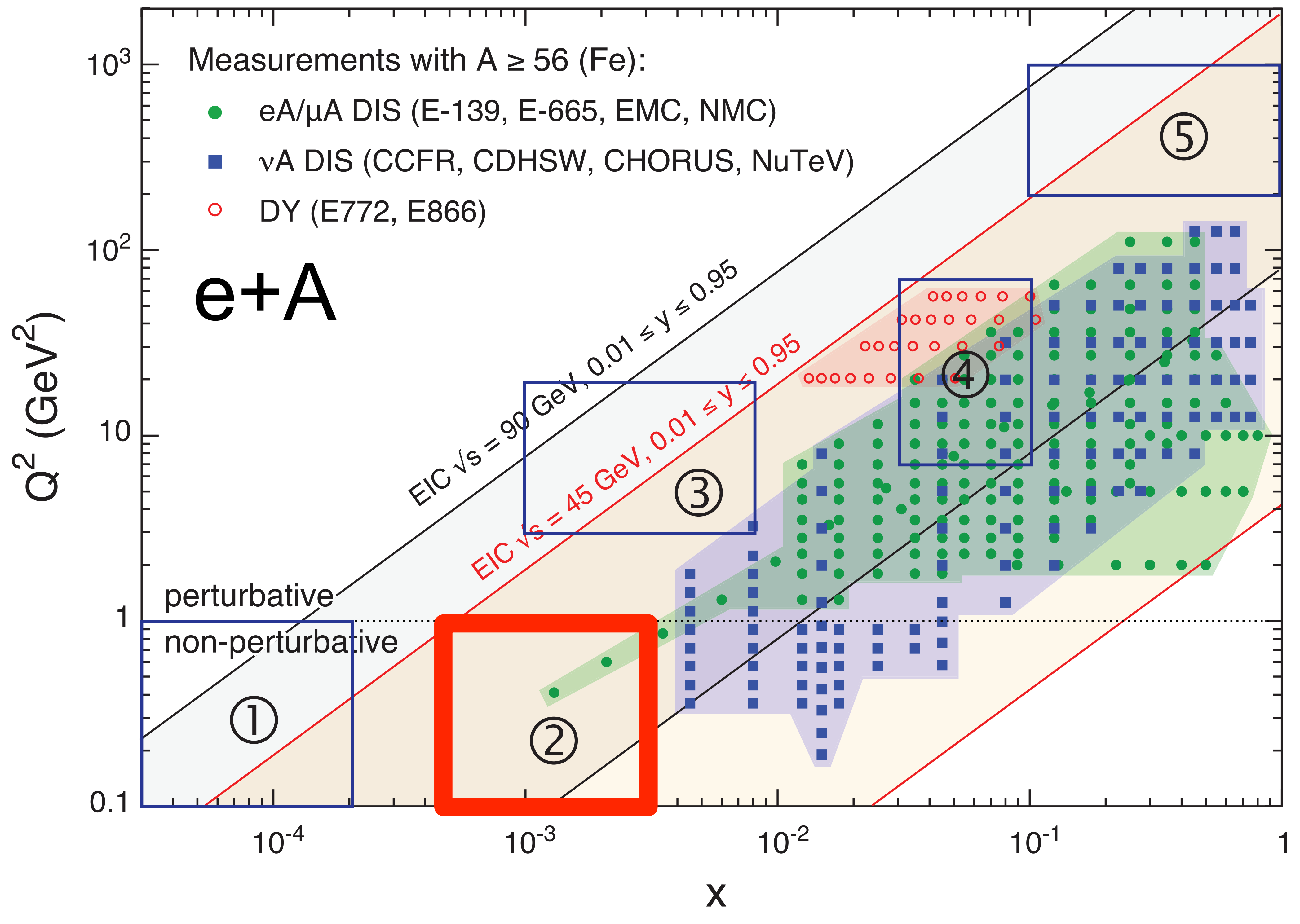
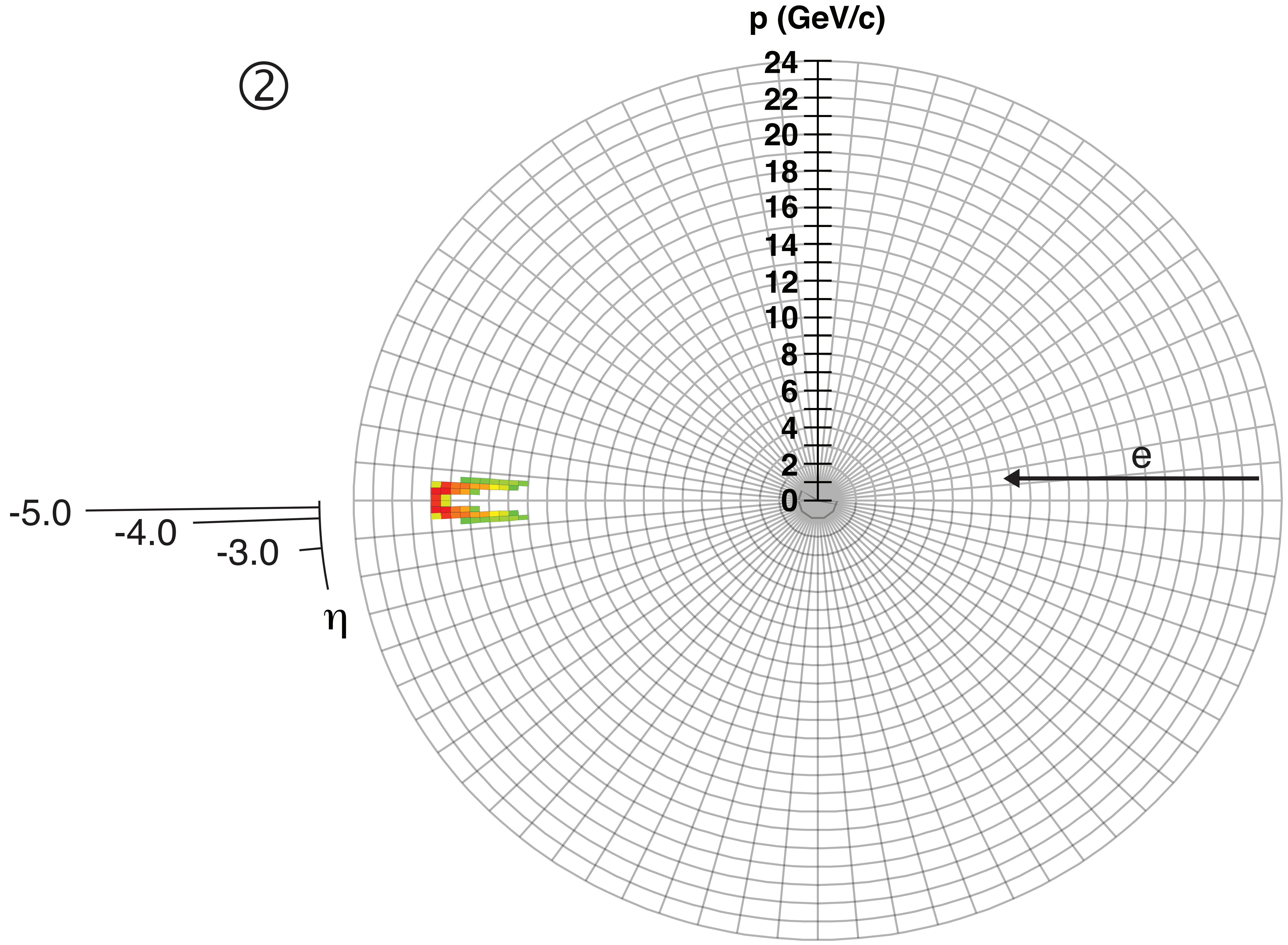
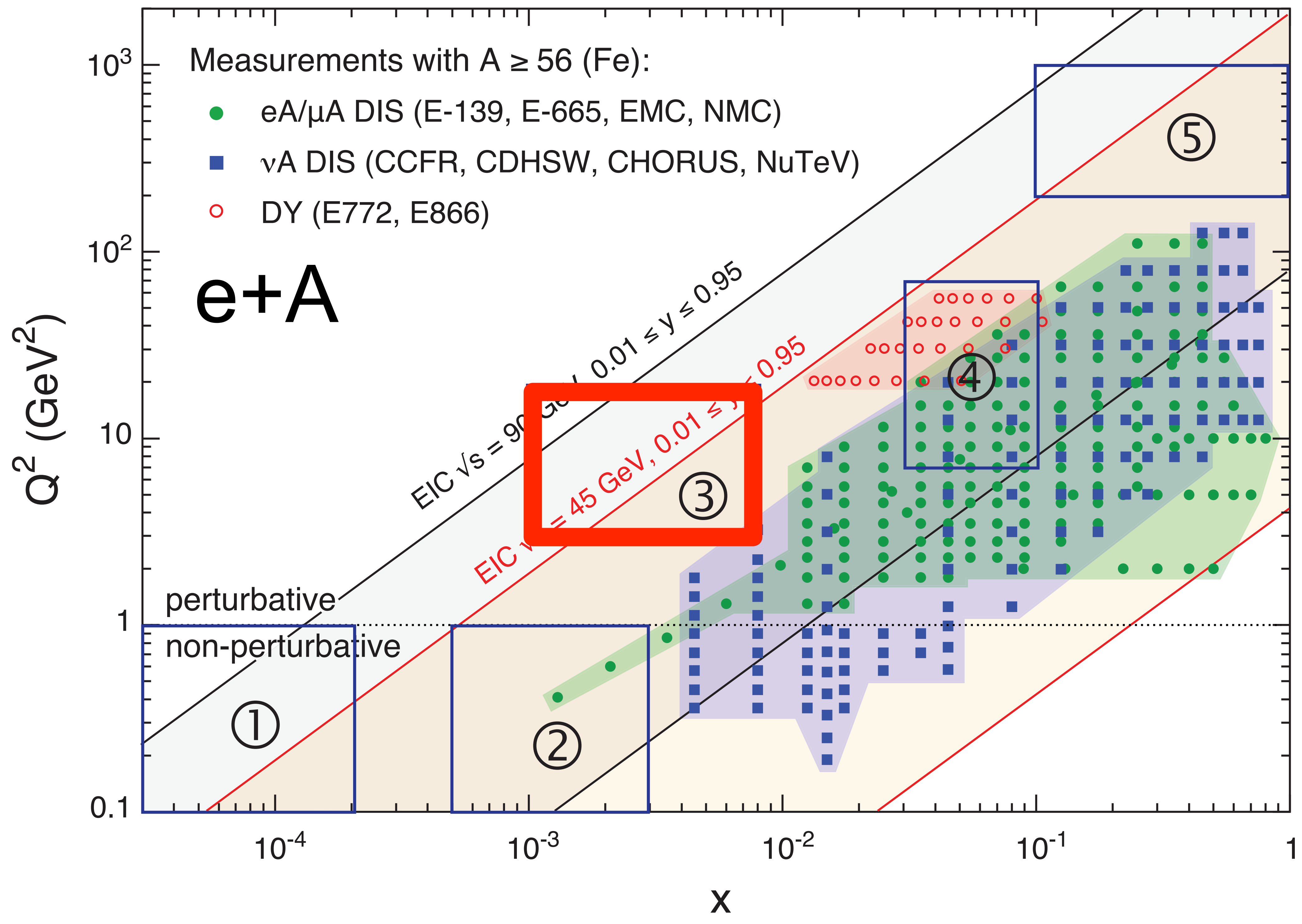


20 GeV on 100 GeV, $0.1 < Q^2 < 1$ GeV^2, $5 \cdot 10^{-4} < x < 3 \cdot 10^{-3}$

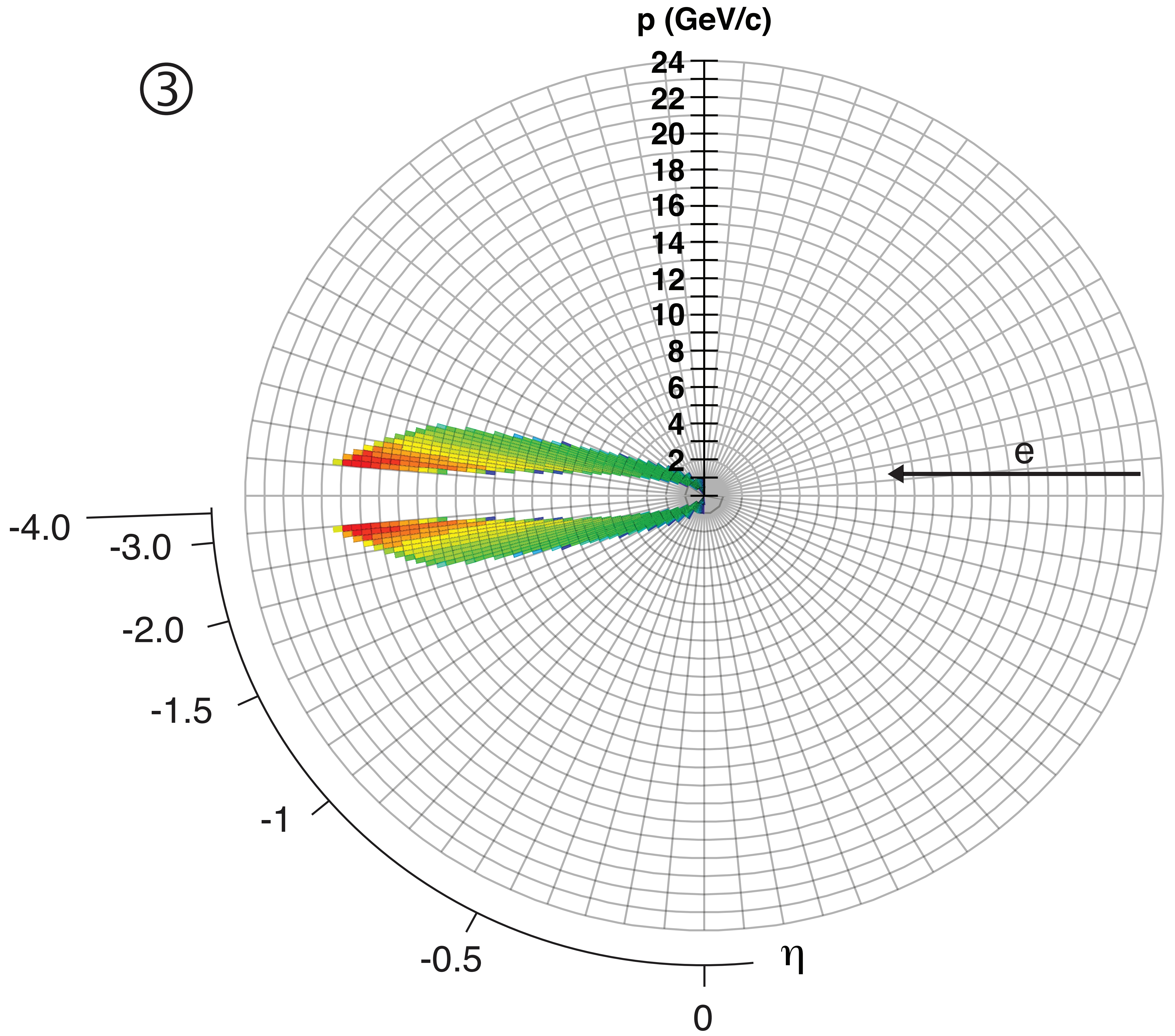


Inclusive (All): Scattered Electron Requirements

The energy and angle of scatter electron gives key variables x, y, Q^2



20 GeV on 100 GeV, $3 < Q^2 < 20$ GeV^2, $1\cdot10^{-3} < x < 8\cdot10^{-3}$



Inclusive (All): Scattered Electron Requirements

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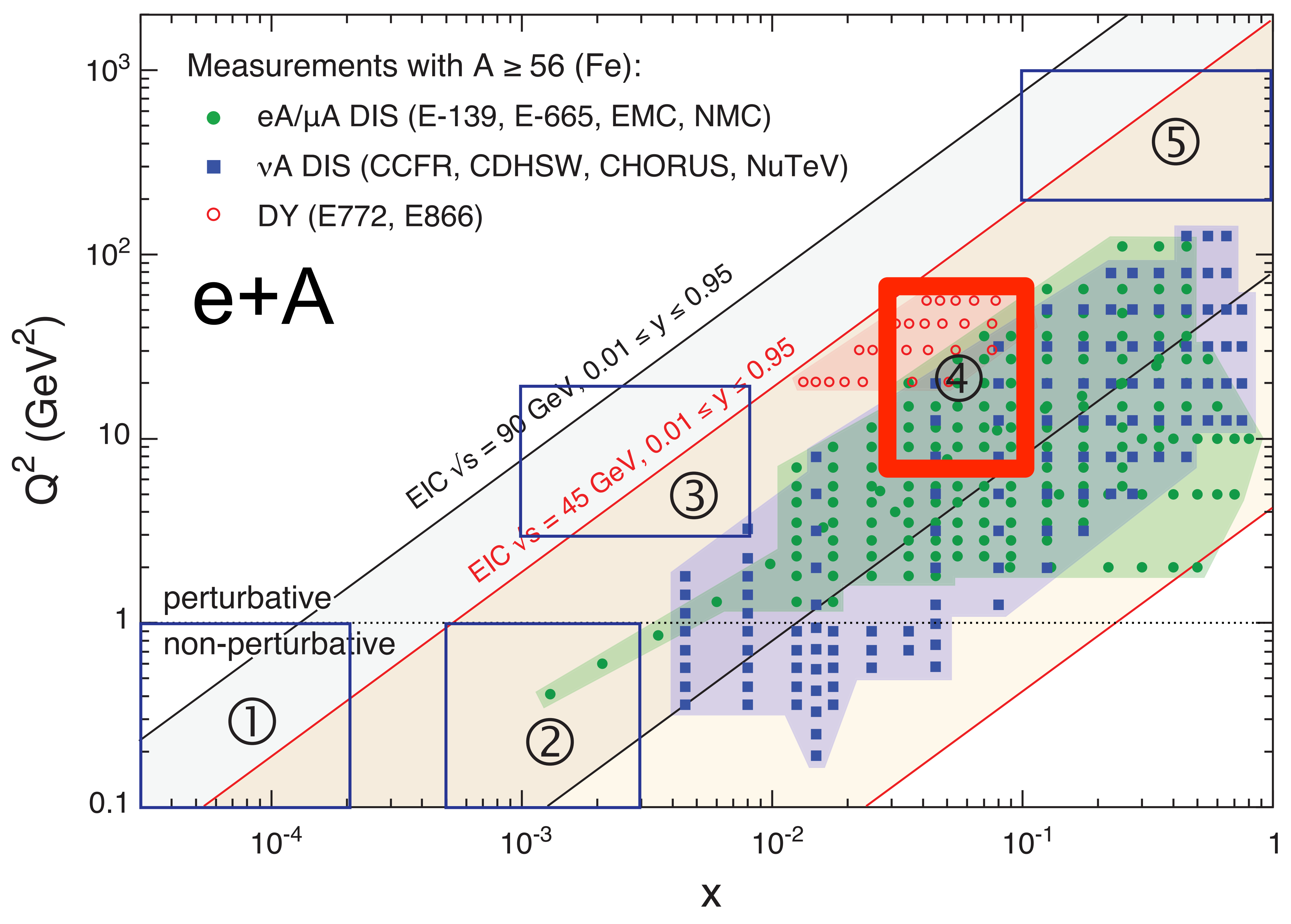
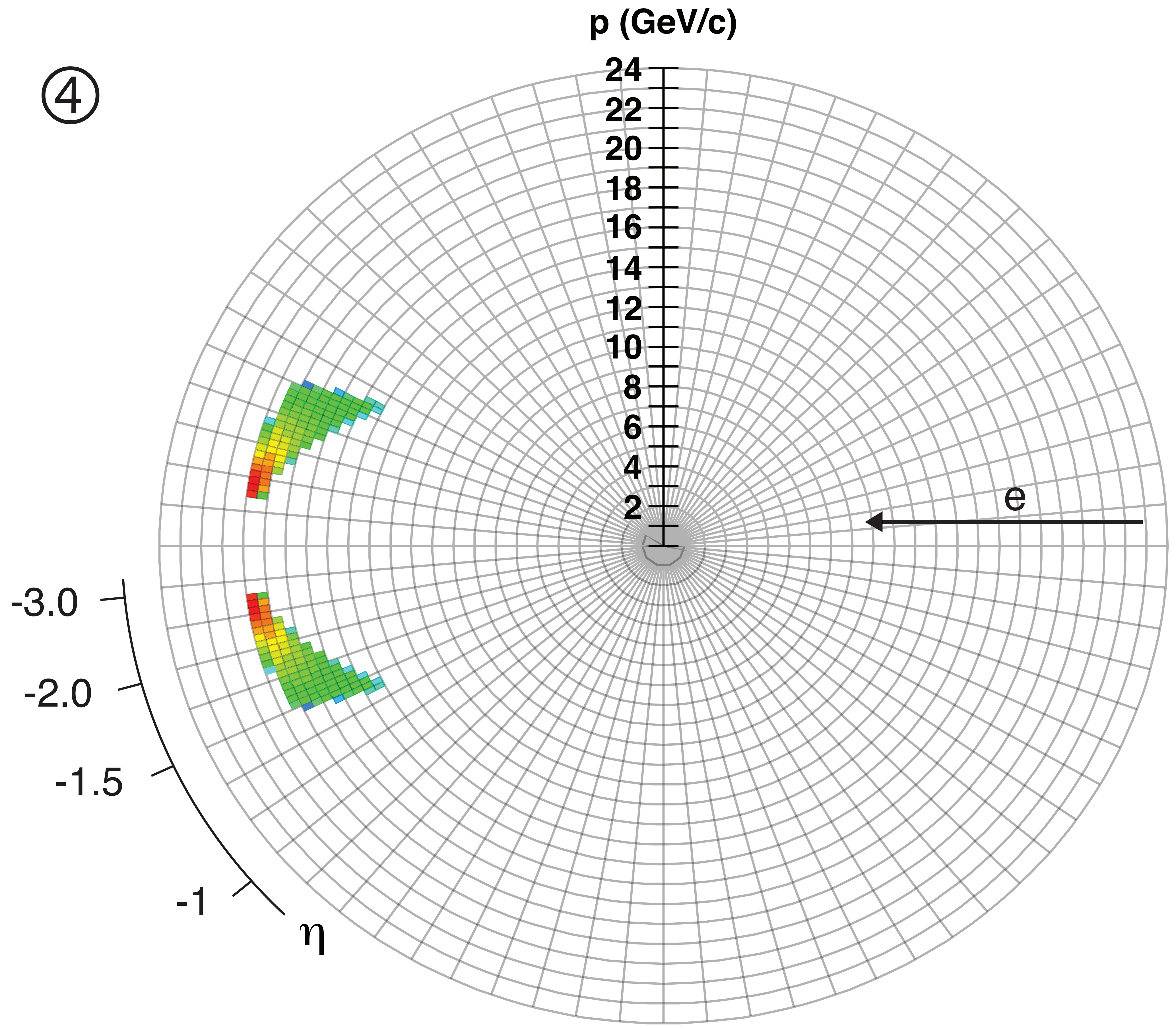


20 GeV on 100 GeV, $7 < Q^2 < 70$ GeV^2, $3{\cdot}10^{-2} < x < 1{\cdot}10^{-1}$



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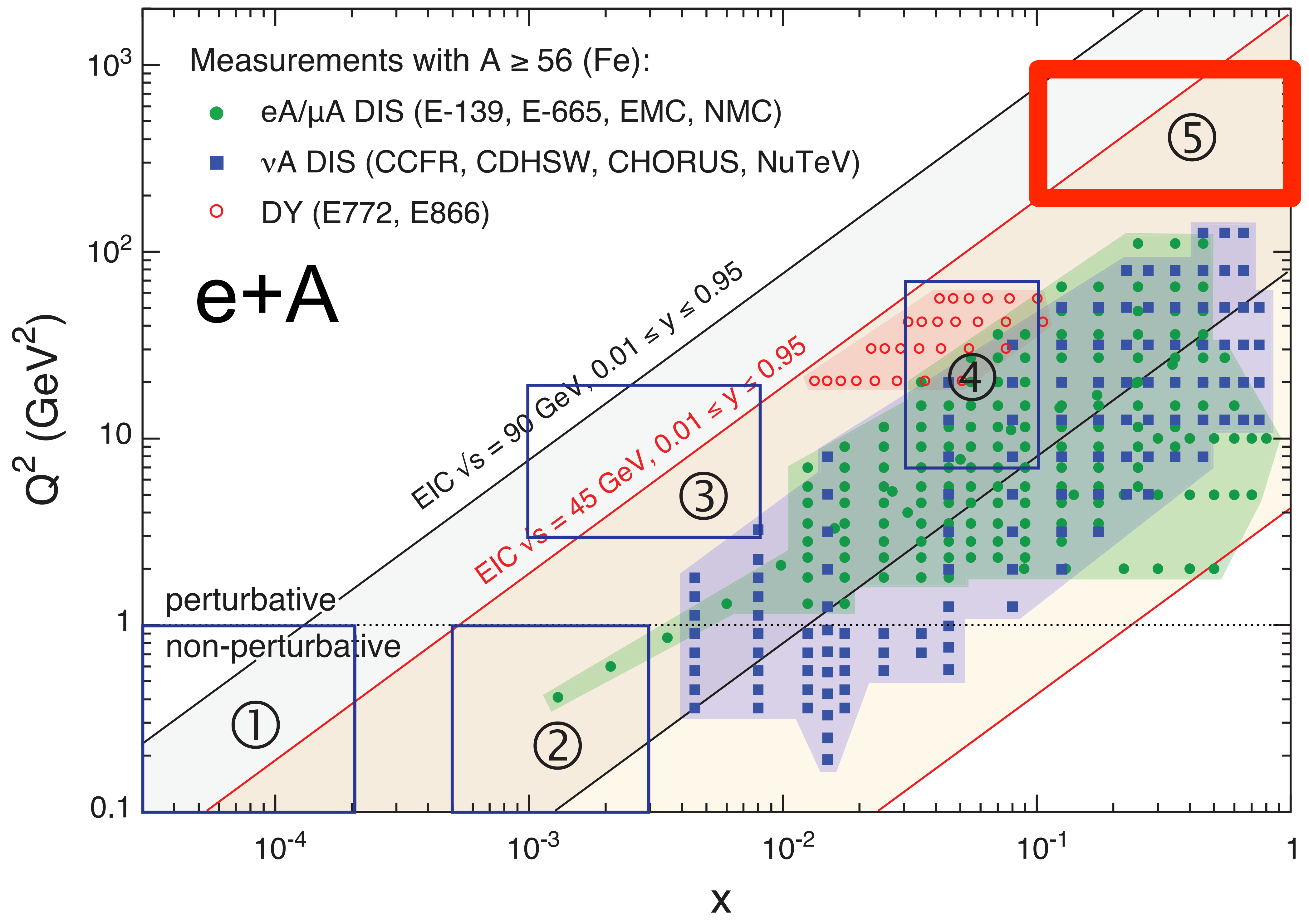
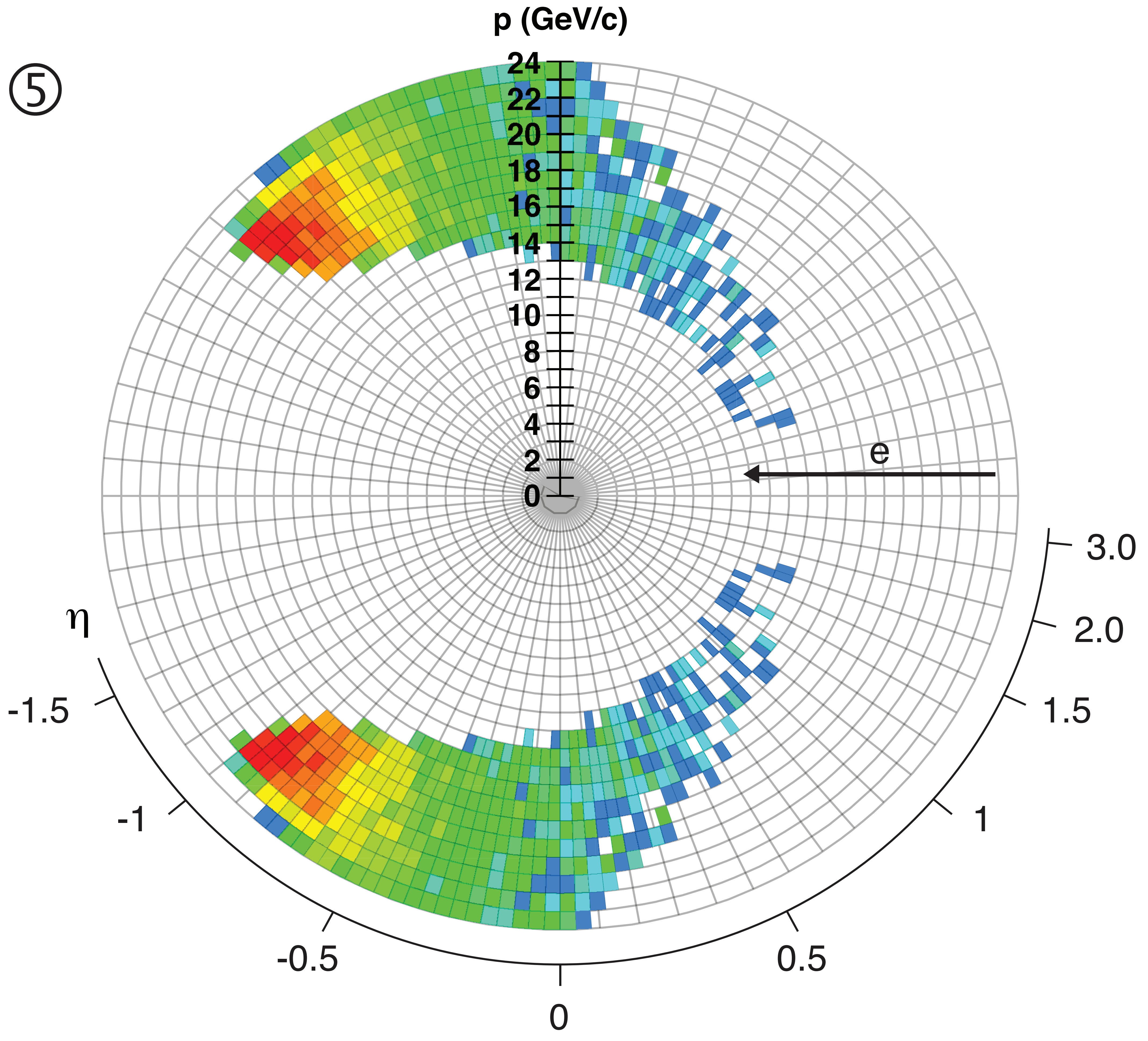


20 GeV on 100 GeV, 200 < Q² < 1000 GeV², 0.1 < x < 1

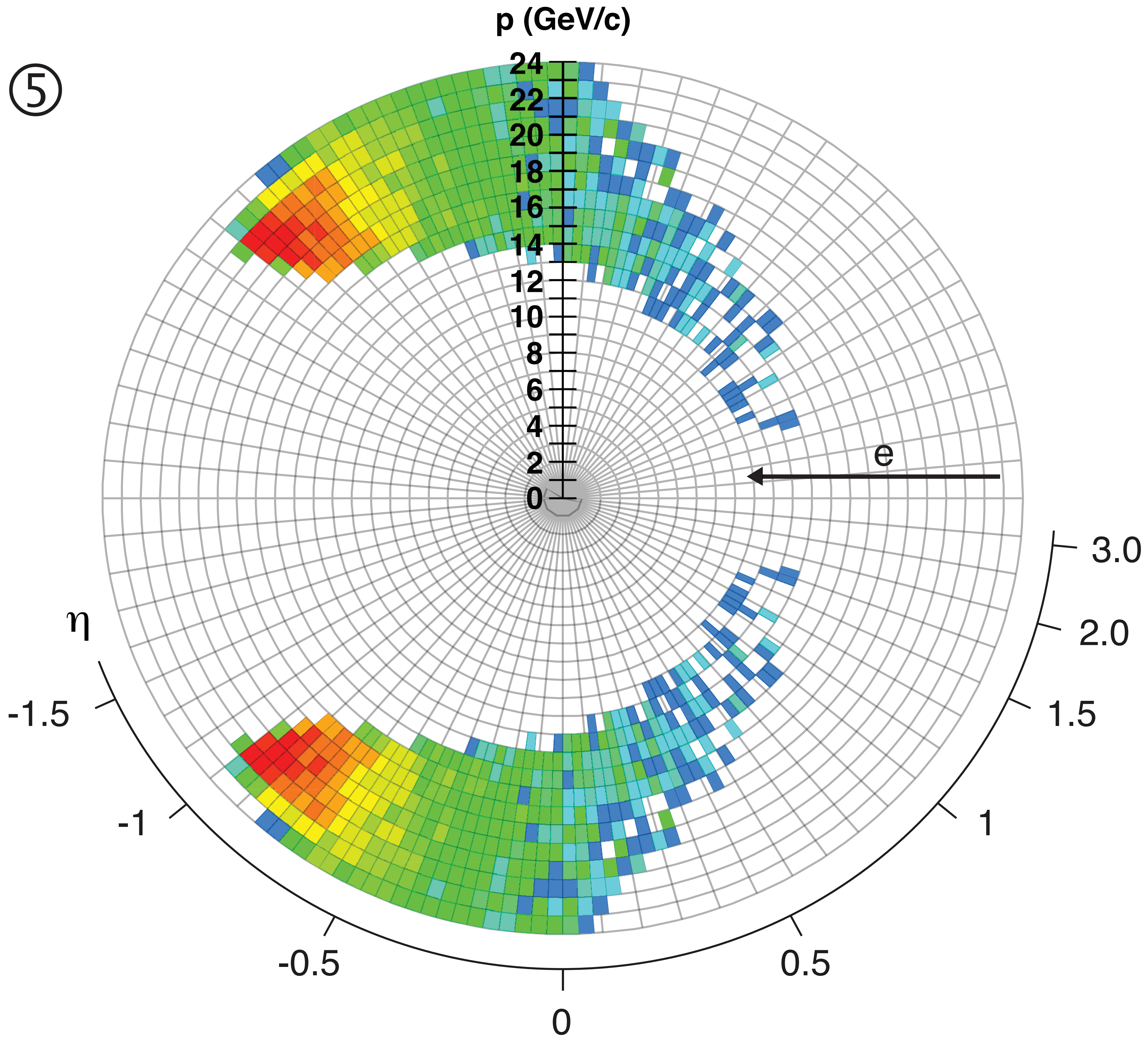


Inclusive (All): Scattered Electron Requirements

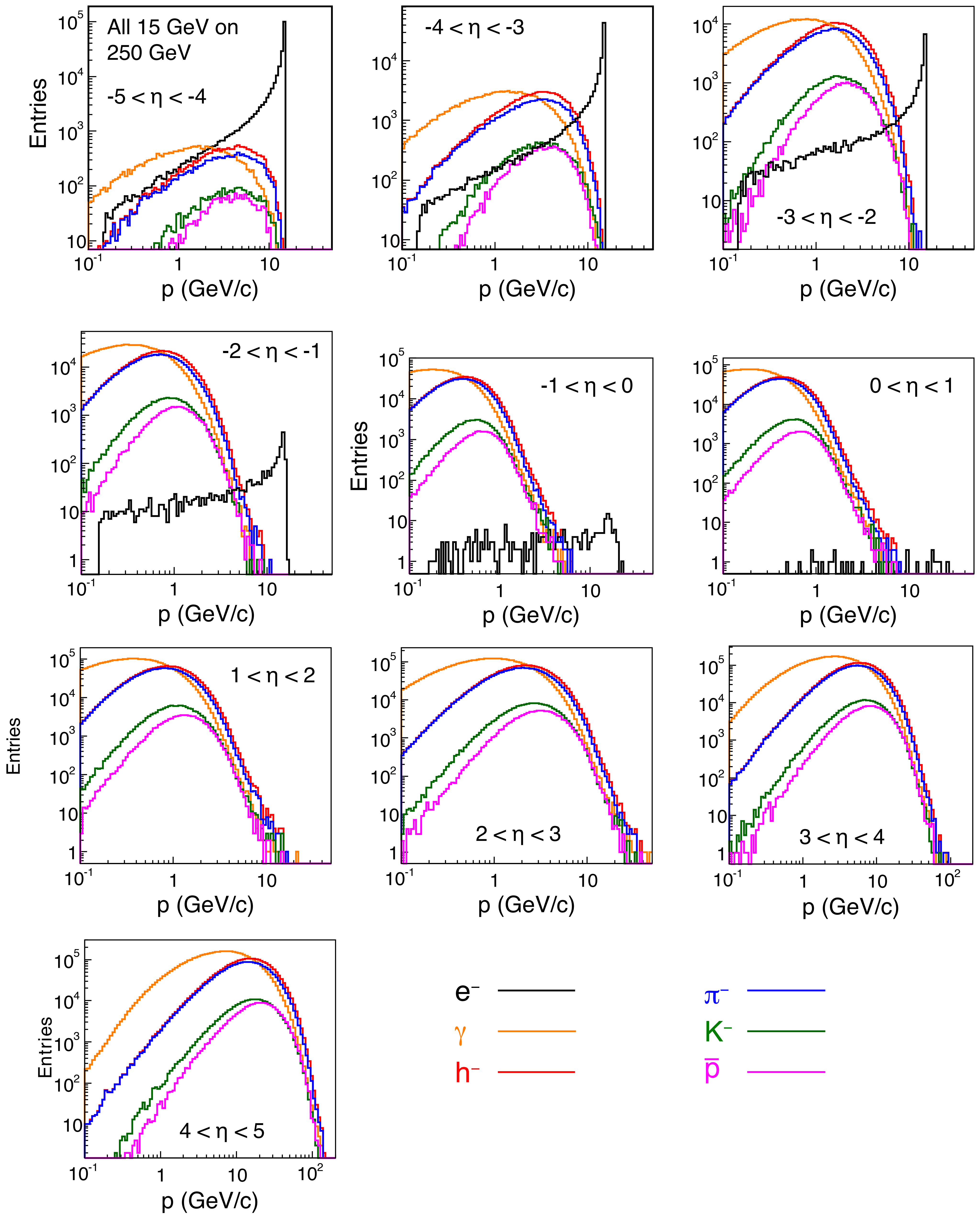
The energy and angle of scatter electron gives key variables x, y, Q^2

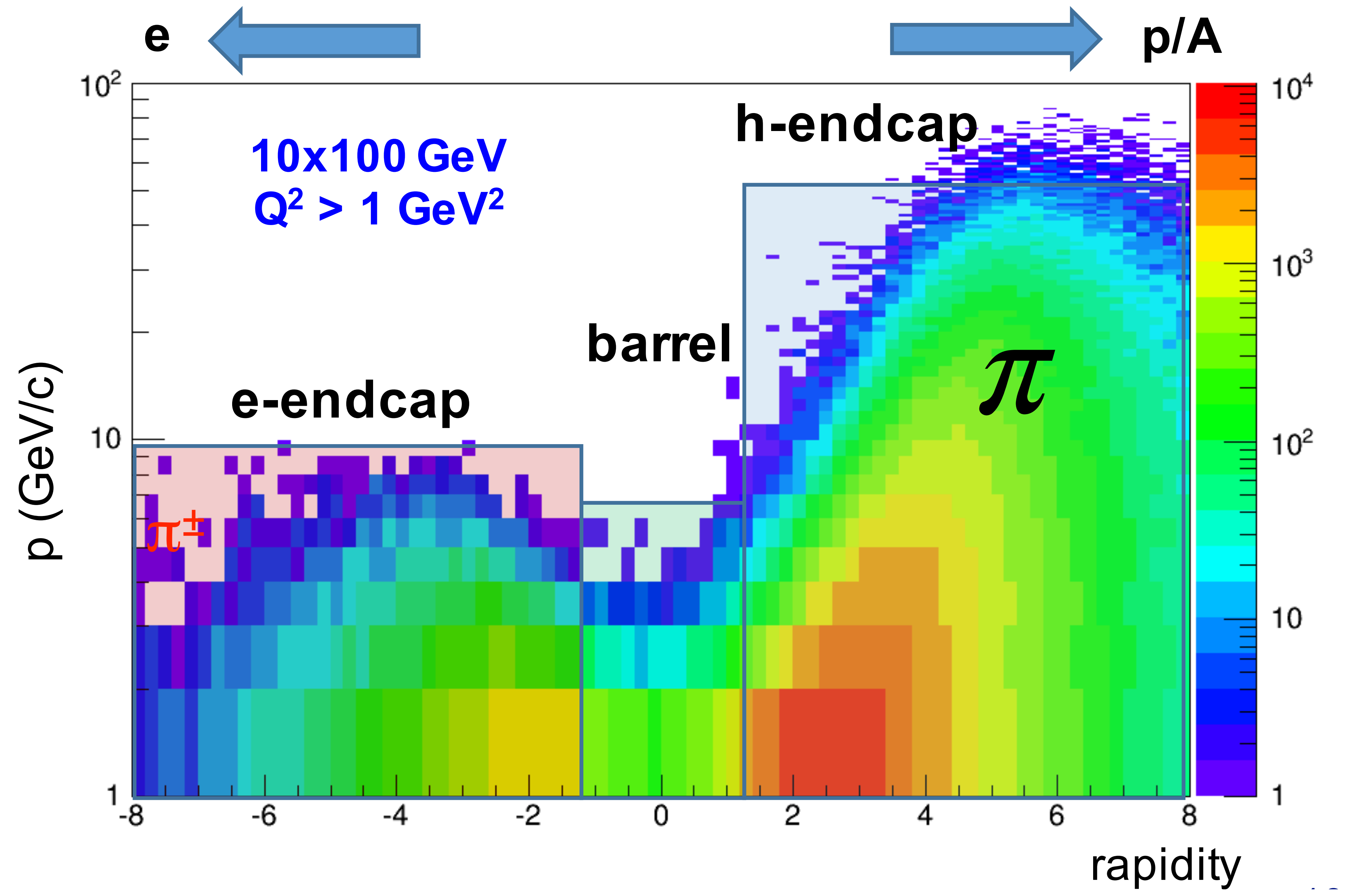
20 GeV on 100 GeV, $200 < Q^2 < 1000$ GeV^2, $0.1 < x < 1$

- e' Measurement Requires:
  - excellent electron identification (e/h)
  - equal rapidity coverage for tracking and calorimeter
  - low material budget to reduce bremsstrahlung
  - momentum/energy and angular resolution are critical



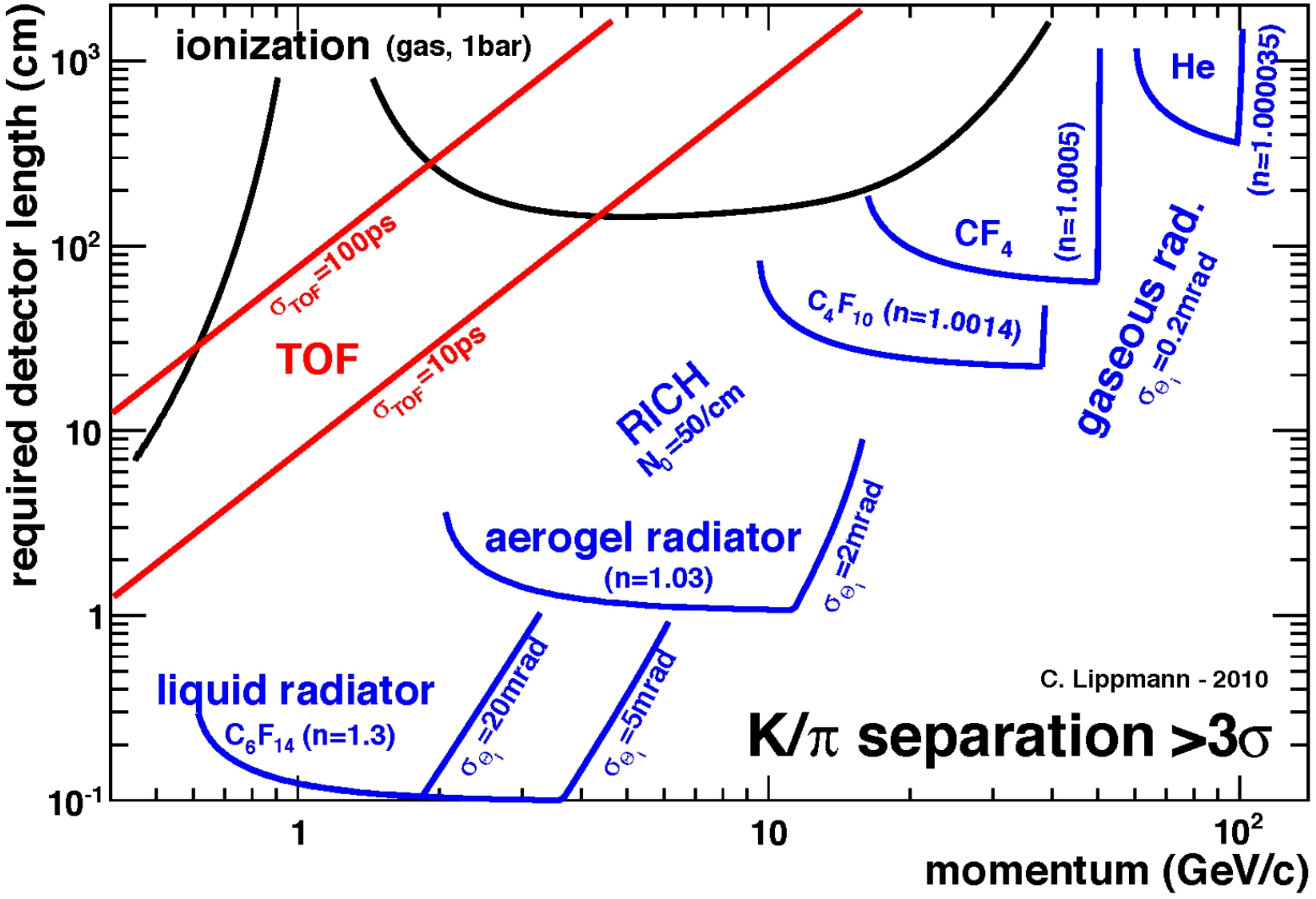
SIDIS: Hadron Identification Requirements





- Physics Requirements
  - $\pi^{\pm}, K^{\pm}, p^{\pm}$ separation over a wide range $|\eta| \leq 3.5$
- Strong Momentum–η correlation
  - -5 < η < 2: 0.2 < p < 10 GeV/c
  - 2 < η < 5: 0.2 < p < 50 GeV/c

Particle ID (PID) Techniques



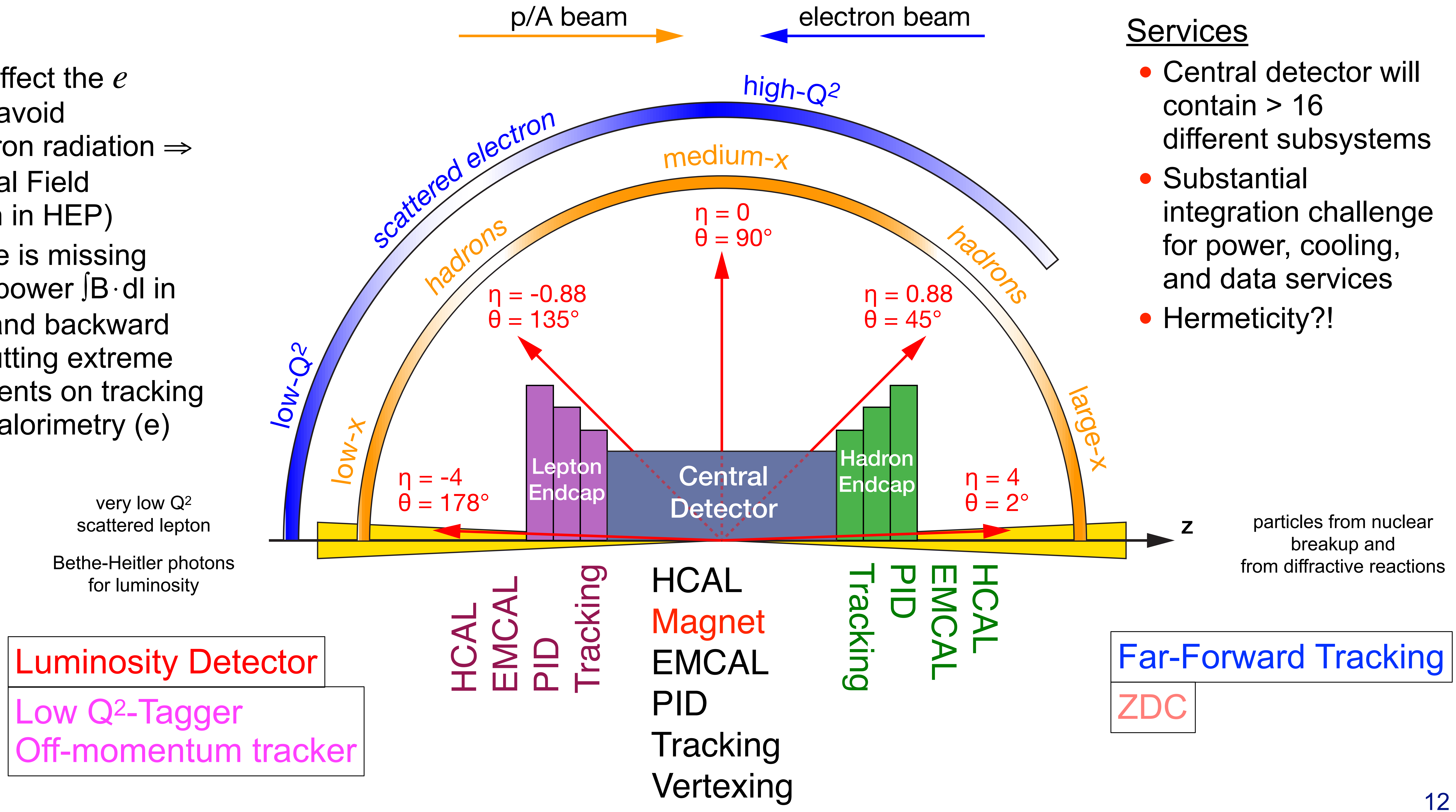
- EIC will need for most of the physics a resolution of
  - $\pi/K \sim 3-4\sigma$
  - $K/p > 1\sigma$
- Need more than one technology to cover the entire momentum ranges at different rapidities

- Need absolute particle numbers at high purity and low contamination
- EIC PID needs are more demanding then at most collider detector

EIC General Purpose Detector Concept

Magnet

- Cannot affect the e beam to avoid synchrotron radiation ⇒ Solenoidal Field (common in HEP)
- Downside is missing bending power $\int B \cdot dl$ in forward and backward region putting extreme requirements on tracking (h) and calorimetry (e)



Services

- Central detector will contain > 16 different subsystems
- Substantial integration challenge for power, cooling, and data services
- Hermeticity?!

Brief Review of Requirements (see Yellow Report)

- Hermetic detector, low mass inner tracking
- Moderate radiation hardness requirements
- Electron measurement & jets in approx. -4 < η < +4
- Good momentum resolution
  - central: $\sigma(p)/p = 0.05\,\%\,p \oplus 0.5\,\%$
  - fwd/bkd: $\sigma(p)/p = 0.1\% \oplus 0.5\,\%$
- Good impact parameter resolution:
  - $\sigma = 5 \oplus 15/p\sin^{3/2}\theta\ (\mu\mathrm{m})$
- Excellent EM resolution
  - central: $\sigma(E)/E = 10\,\%/\sqrt{E}$
  - backward: $\sigma(E)/E < 2\,\%/\sqrt{E}$
- Good hadronic energy resolution
  - forward: $\sigma(E)/E \approx 50\,\%/\sqrt{E}$
- Excellent PID π/K/p
  - forward: up to 50 GeV/c
  - central: up to 8 GeV/c
  - backward: up to 7 GeV/c
- Low pile-up, low multiplicity, data rate ~500kHz (full lumi)

Hermeticity, low mass, and PID requirements make EIC detector design challenging

Detector Proposals

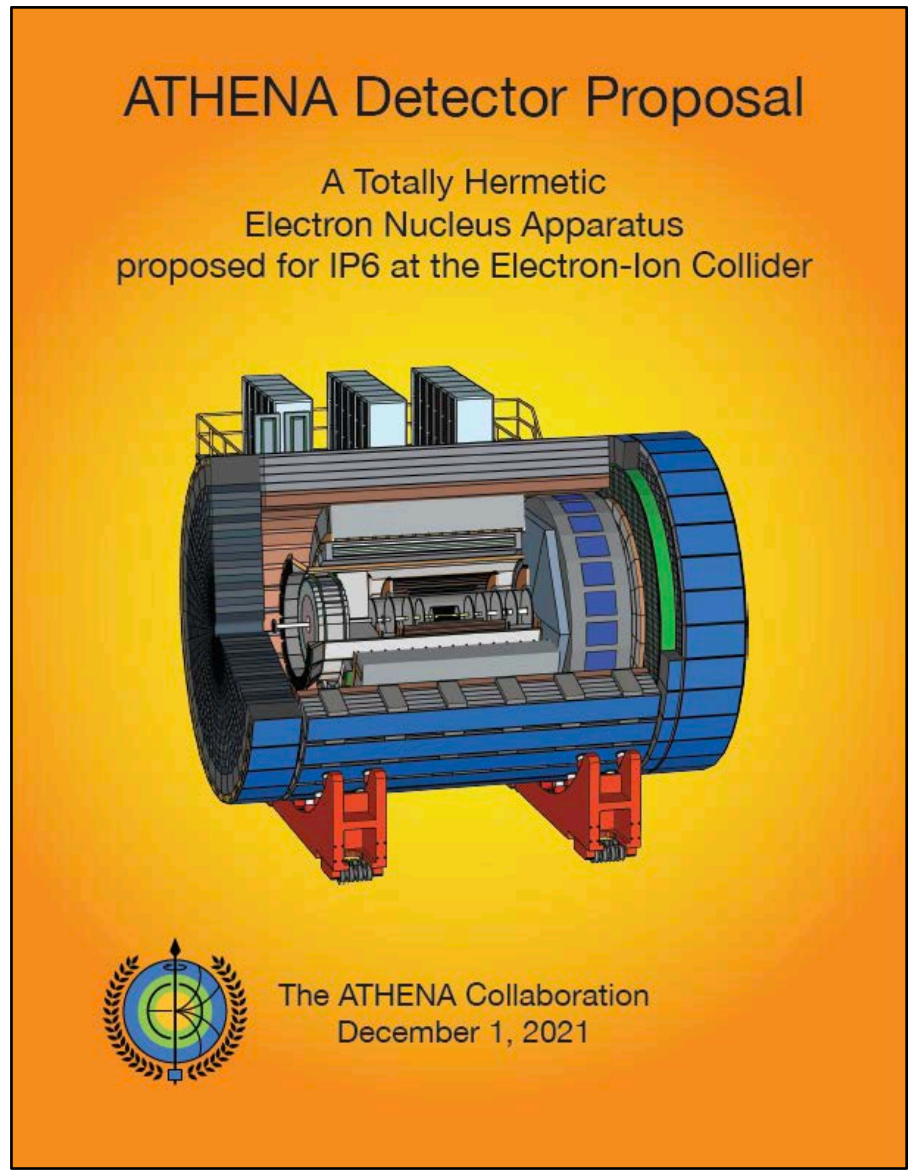
- March 6, 2021, BNL & JLab released the *Call for Collaboration Proposals for Detectors* with expected proposal submission deadline of December 1, 2021.
- Location: IP6 (in project scope), IP8
- EIC Detector Proposal Advisory Panel (DPAP) chaired by Rolf Heuer (CERN) and Patty McBride (FNAL) + 8 members
- The call was answered by 3 proto-colloborations: ATHENA, CORE, ECCE

https://www.bnl.gov/eic/cfc.php

- Review Meeting
  - Cover: Design, technology, performance, collaboration/organization, cost, schedule
  - December 13–15, 2021
  - January 19-21, 2022
- DPAP supported by EIC Detector Advisory Committee (DAC) on all technical aspects
- Report released March 1, 2022

IP6	IP8	IP6 or IP8
New large 3T magnet	New compact 2.5T magnet	Reuse 1.4T BaBar magnet

IP6



New large 3T magnet

IP8

CORE - a COmpact detectoR for the EIC

R. Alarcon,[1] M. Baker,[2] V. Baturin,[3] P. Brindza,[3] S. Bueltmann,[3] M. Bukhari,[4] R. Capobianco,[5] E. Christy,[2] S. Diehl,[5,6] M. Dugger,[1] R. Dupré,[7] R. Dzhygadlo,[8] K. Flood,[9] K. Gnanvo,[2] L. Guo,[10] T. Hayward,[5] M. Hattawy,[3] M. Hoballah,[7] M. Hohlmann,[11] C. E. Hyde [a],[3] Y. Ilieva,[12] W. W. Jacobs,[13] K. Joo,[5] G. Kalicy,[14] A. Kim,[5] V. Kubarovsky,[2] A. Lehmann,[15] W. Li,[16] D. Marchand,[7] H. Marukyan,[17] M. J. Murray,[18] H. E. Montgomery,[2] V. Morozov,[19] I. Mostafanezhad,[9] A. Movsisyan,[17] E. Munevar,[20] C. Muñoz Camacho,[7] P. Nadel-Turonski[b],[16] S. Niccolai,[7] K. Peters,[8] A. Prokudin,[2,21] J. Richards,[5] B. G. Ritchie,[1] U. Shrestha,[5] B. Schmookler,[16] G. Schnell,[22] C. Schwarz,[8] J. Schwiening,[8] P. Schweitzer,[5] P. Simmerling,[5] H. Szumila-Vance,[2] S. Tripathi,[23] N. Trotta,[5] G. Varner,[23] A. Vossen,[24] E. Voutier,[7] N. Wickramaarachchi,[14] and N. Zachariou[25]

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[5] *University of Connecticut, Storrs Connecticut 06269*
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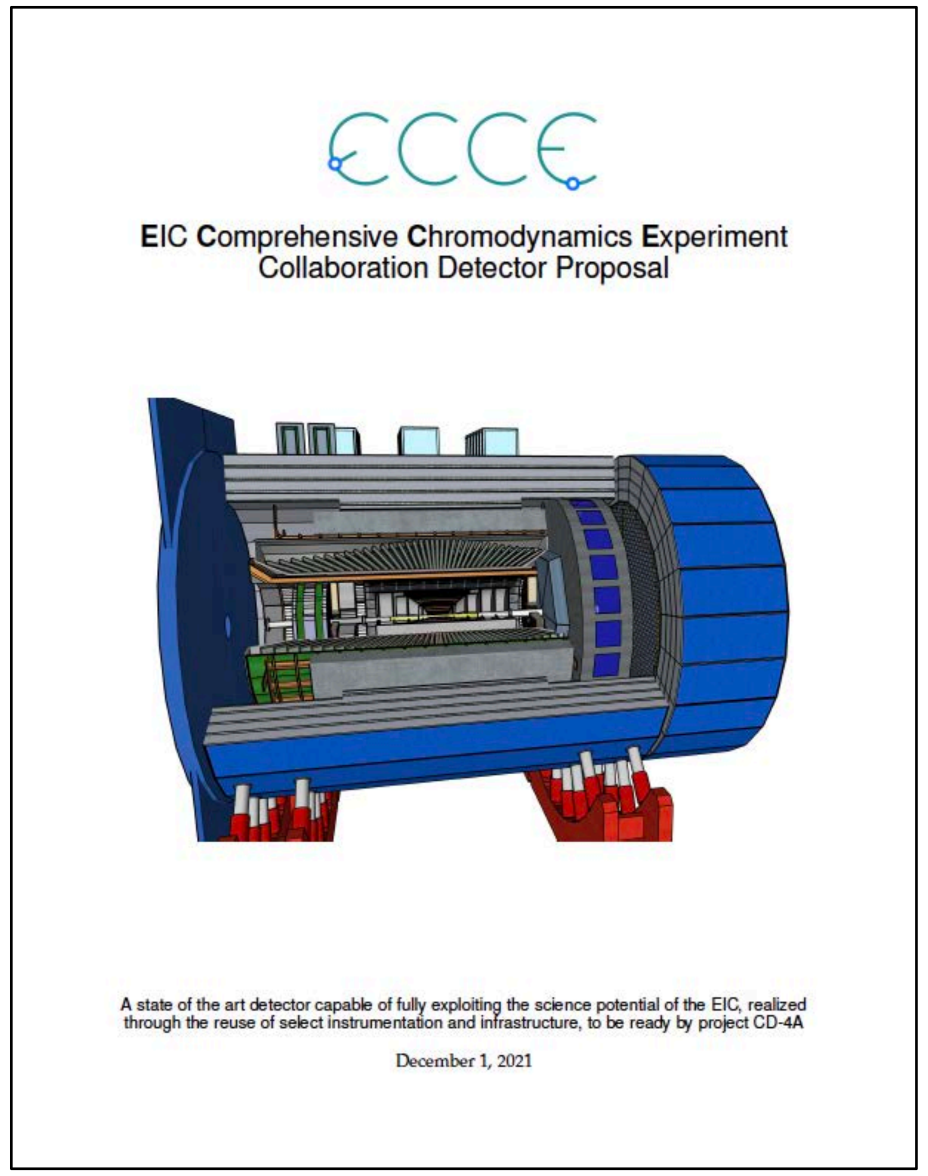
[12] *University of South Carolina, Columbia South Carolina 29208*
[13] *CEEM, Indiana University, Bloomington Indiana 47405*
[14] *Catholic University of America, Washington D.C. 20064*
[15] *Erlangen-Nuremberg University, 91058 Germany*
[16] *CFNS, Stony Brook University, Stony Brook, New York 11794*
[17] *A. Alikhanyan National Science Laboratory (Yerevan Physics Institute) Yerevan Armenia*
[18] *University of Kansas, Lawrence Kansas 66045*
[19] *Oak Ridge National Laboratory, Oak Ridge Tennessee 37830*
[20] *Universidad Distrital Francisco José de Caldas, Bogotá Colombia*
[21] *Penn State University Berks, Reading Pennsylvania 19610*
[22] *University of the Basque Country UPV/EHU & Ikerbasque, Bilbao, Spain*
[23] *University of Hawaii, Honolulu Hawaii 96822*
[24] *Duke University, Durham North Carolina 27708*
[25] *University of York, Heslington, York, YO10 5DD, UK*

(Dated: December 1, 2021)

[a] chyde@odu.edu
[b] turonski@jlab.org

New compact 2.5T magnet

IP6 or IP8



Reuse 1.4T BaBar magnet

Towards the EIC Baseline Detector (Detector 1)

DPAP:

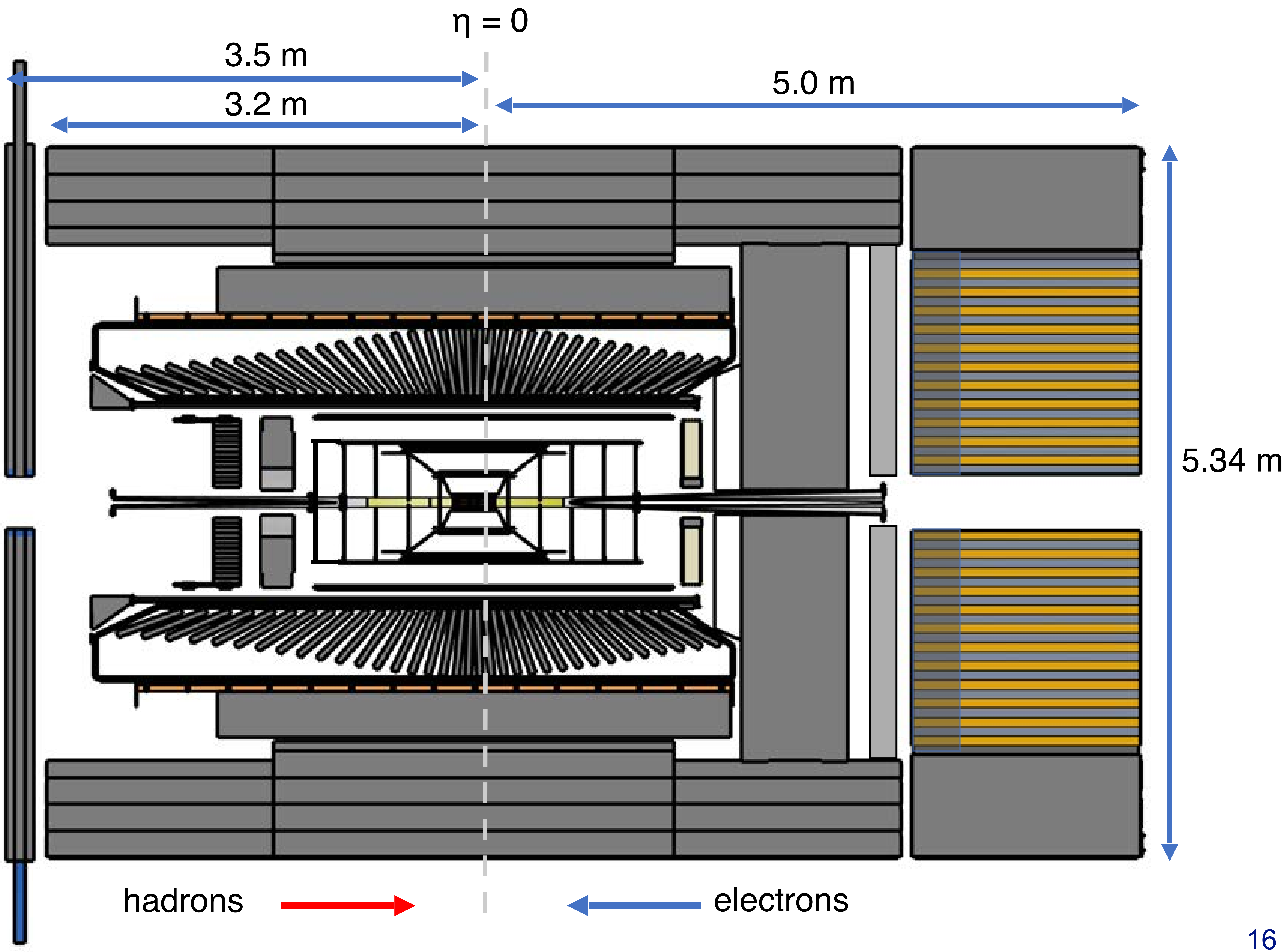
- ATHENA and ECCE satisfy the requirements to fulfill EIC's "mission need" statement
- ECCE has reduced risk and cost, and qualifies best for Detector 1
- Proto-collaborations urged to quickly consolidate its design so that the Project Detector can advance

EPIC/ePIC:

- Following the DPAP decision a new “Detector 1” collaboration was formed that is now working on the baseline design
- The collaboration names itself ‘Electron Proton and Ion Collider’ experiment, EPIC.
- However, the collaboration cannot decide if it is ePIC or EPIC. Time will tell…

EPIC - Baseline Design

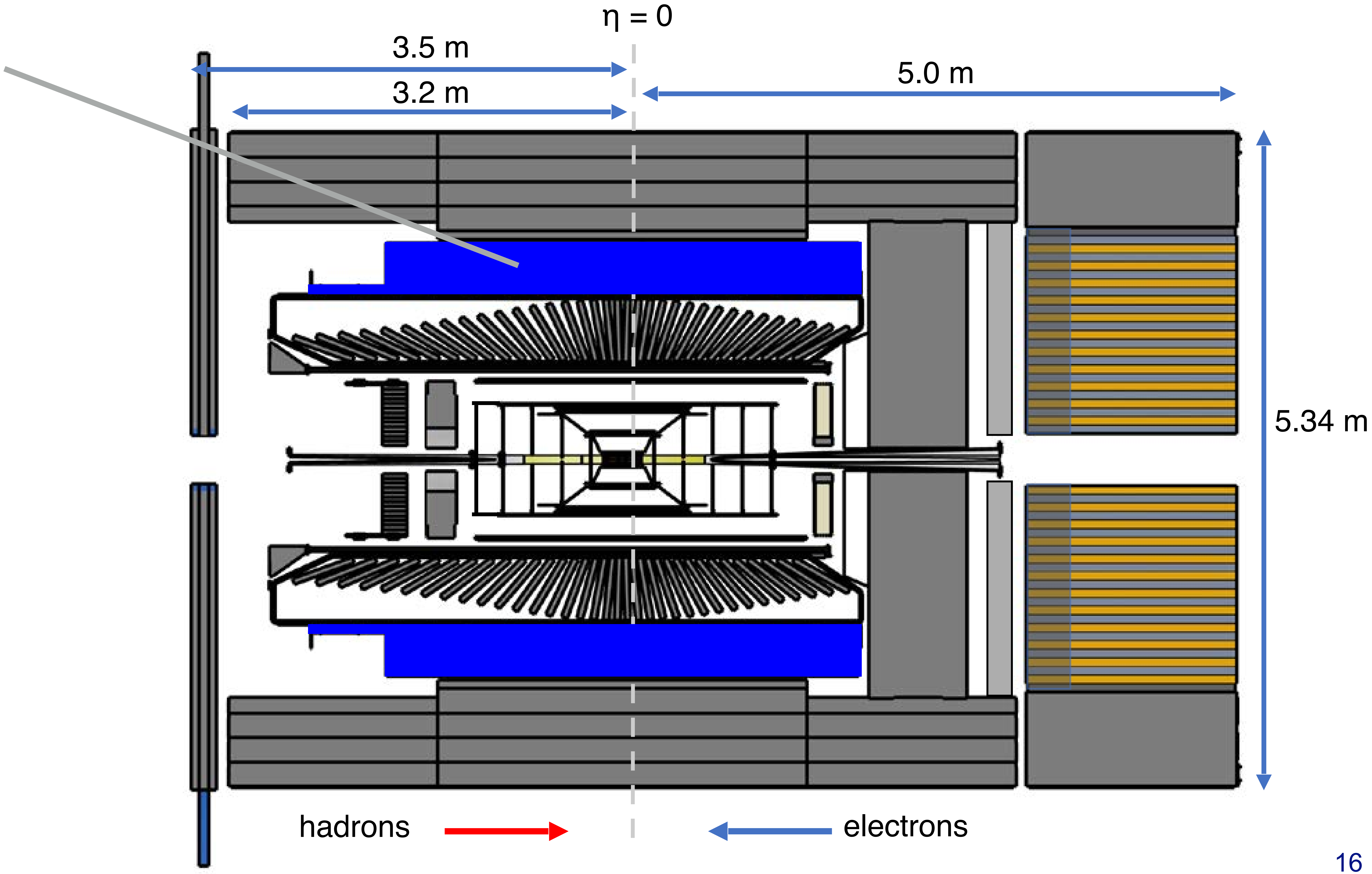
For illustration only



EPIC - Baseline Design

Magnet

- New 1.7 T SC solenoid



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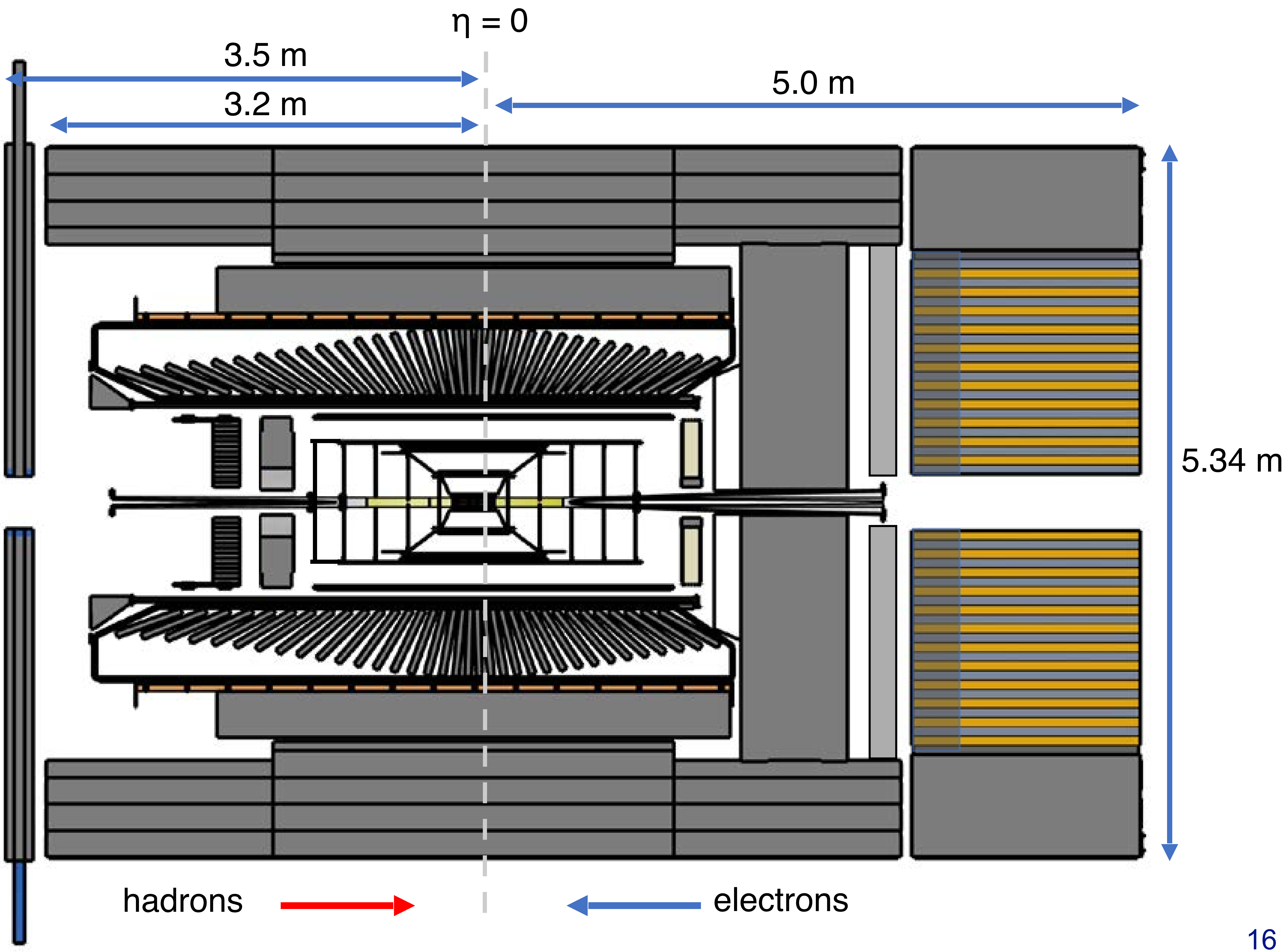
Tracking

- Si Vertex Tracker MAPS/ITS3 wafer-level stitched sensors
- Si Tracker MAPS/ITS3/EIC barrel and disks
- MPGDs (μRWELL/MMG) cylindrical and planar



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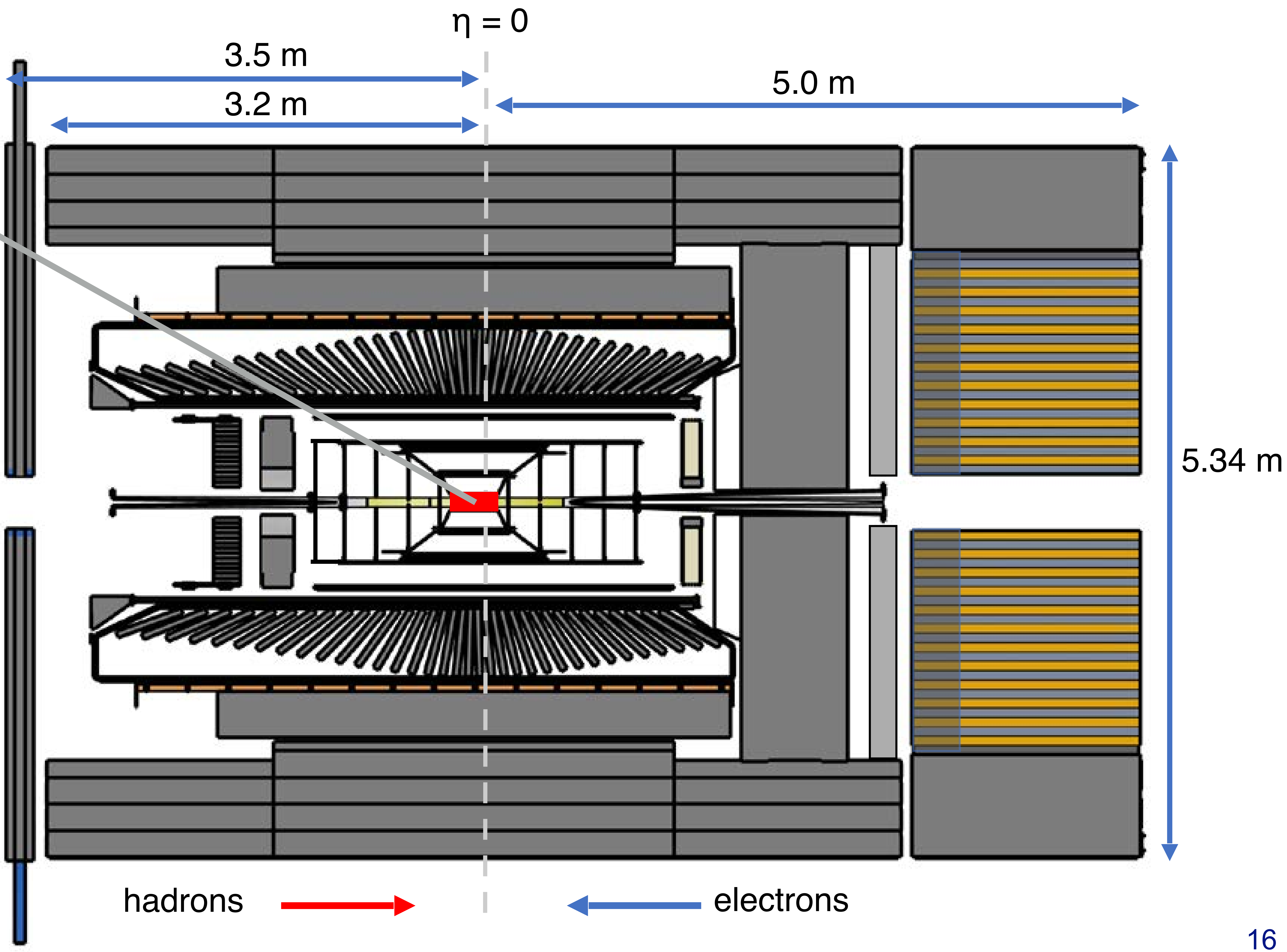

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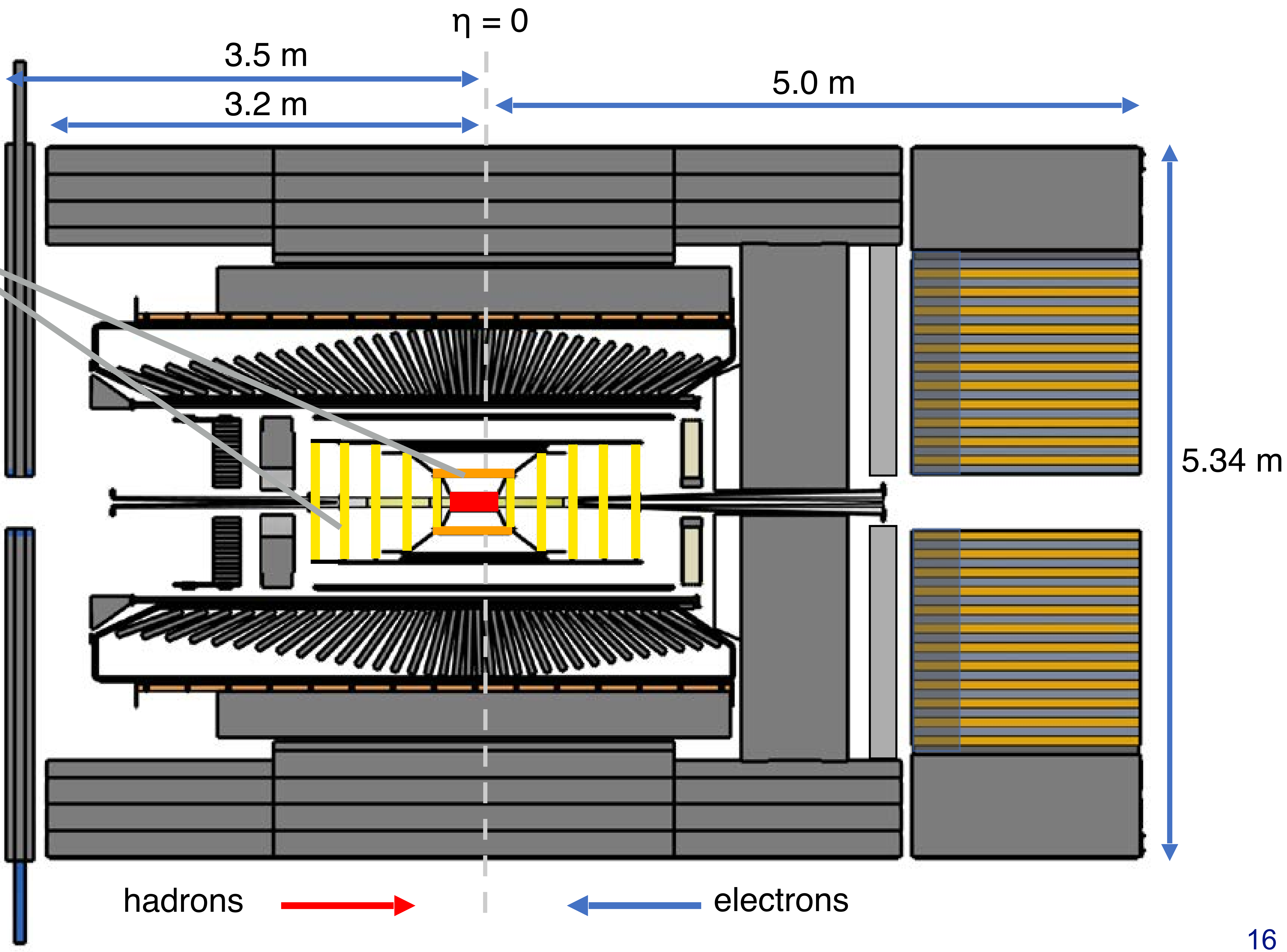

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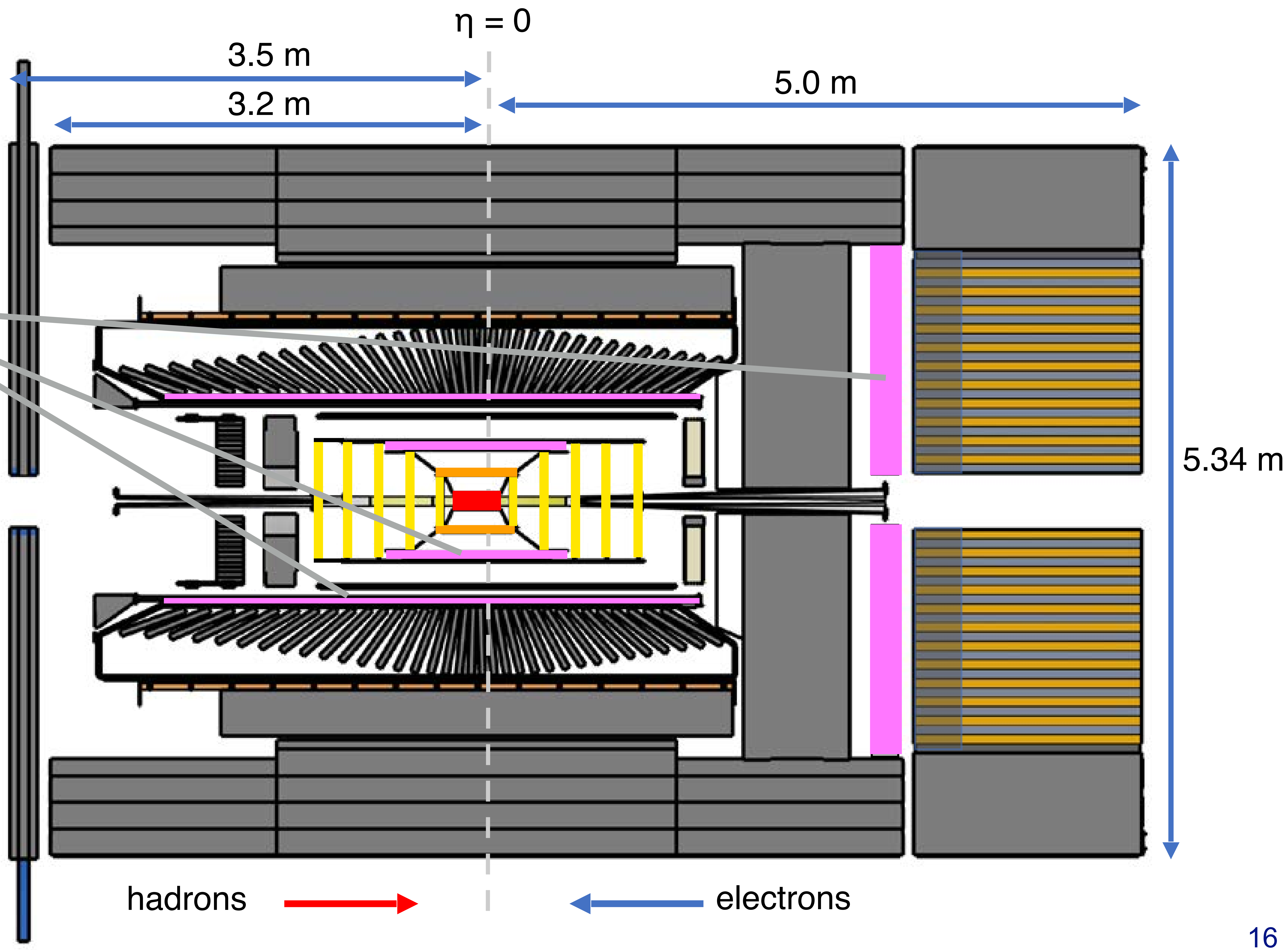

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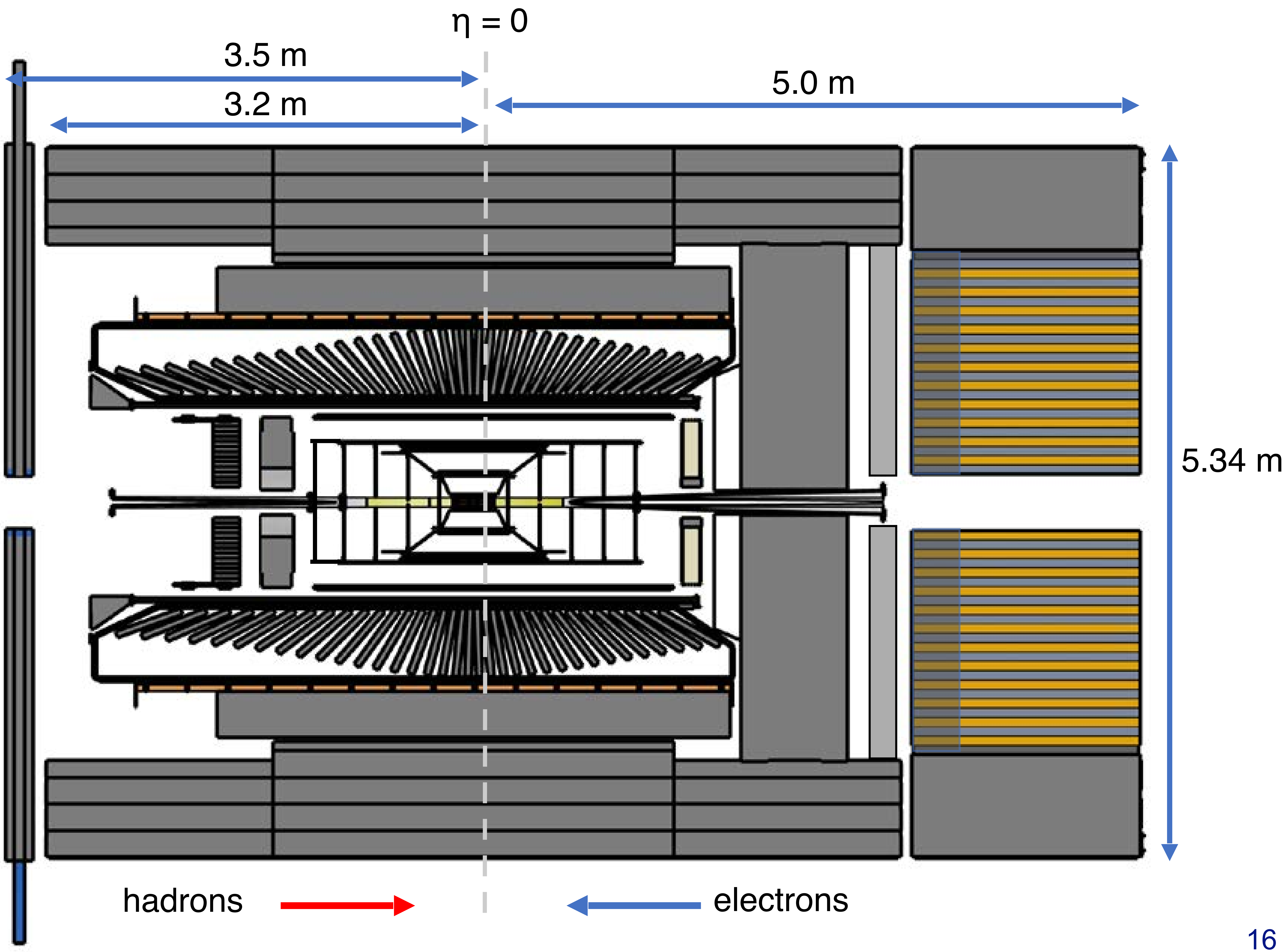
- high performance DIRC (hpDIRC)
- dual RICH (aerogel + gaseous)
- aerogel RICH/modular w/ Fresnel **or** proximity focussing RICH
- ToF using AC-LGAD



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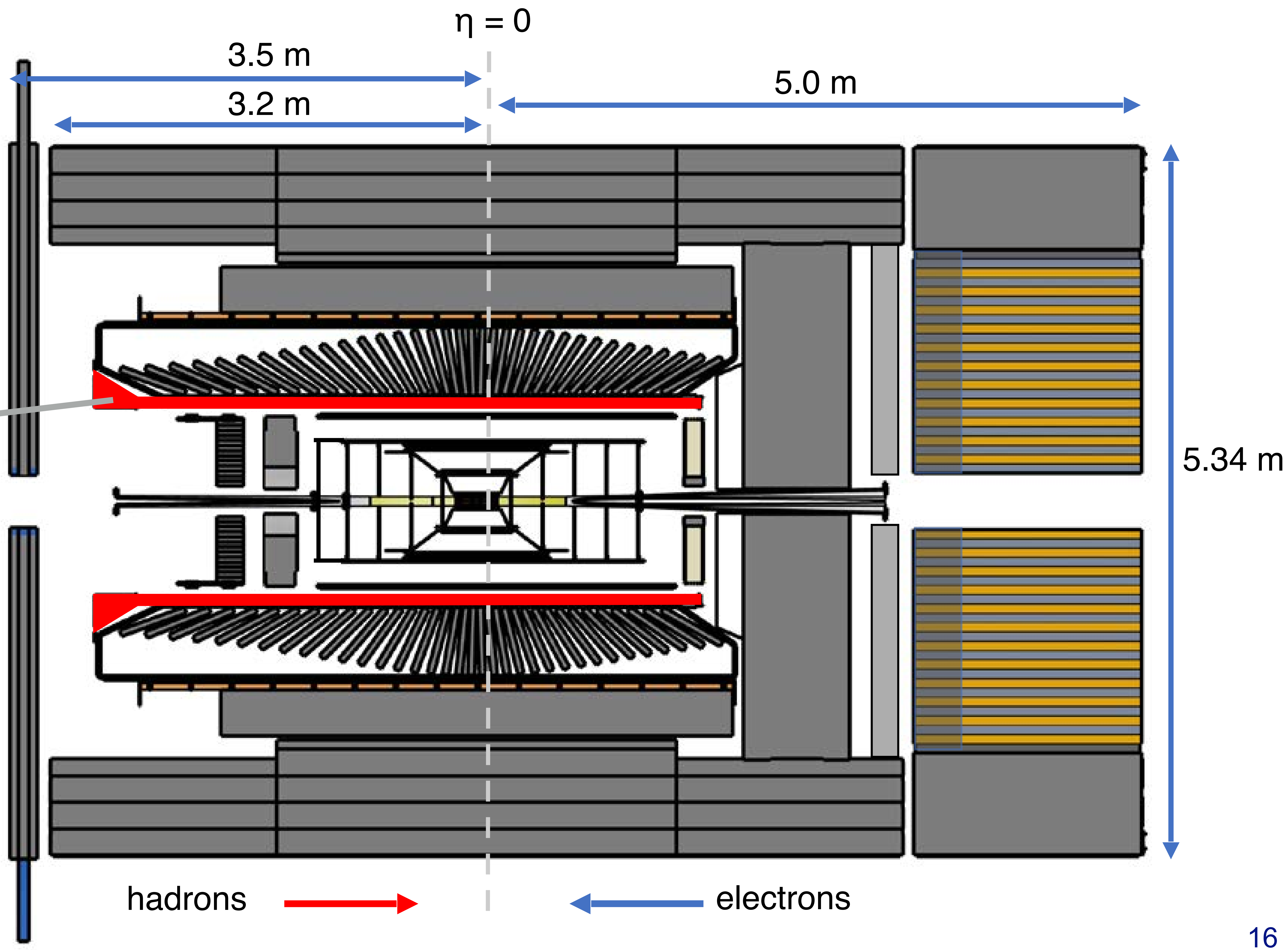

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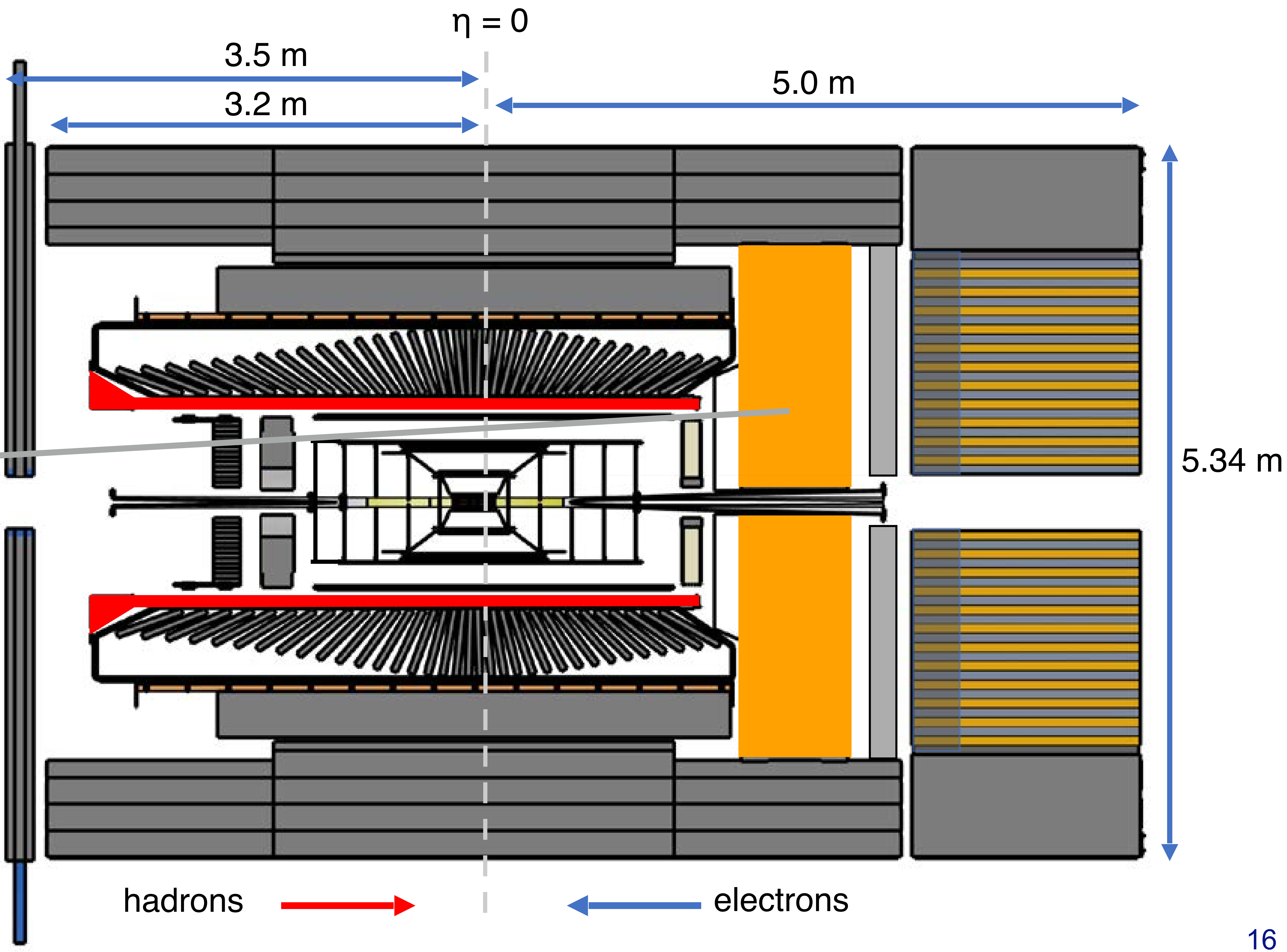

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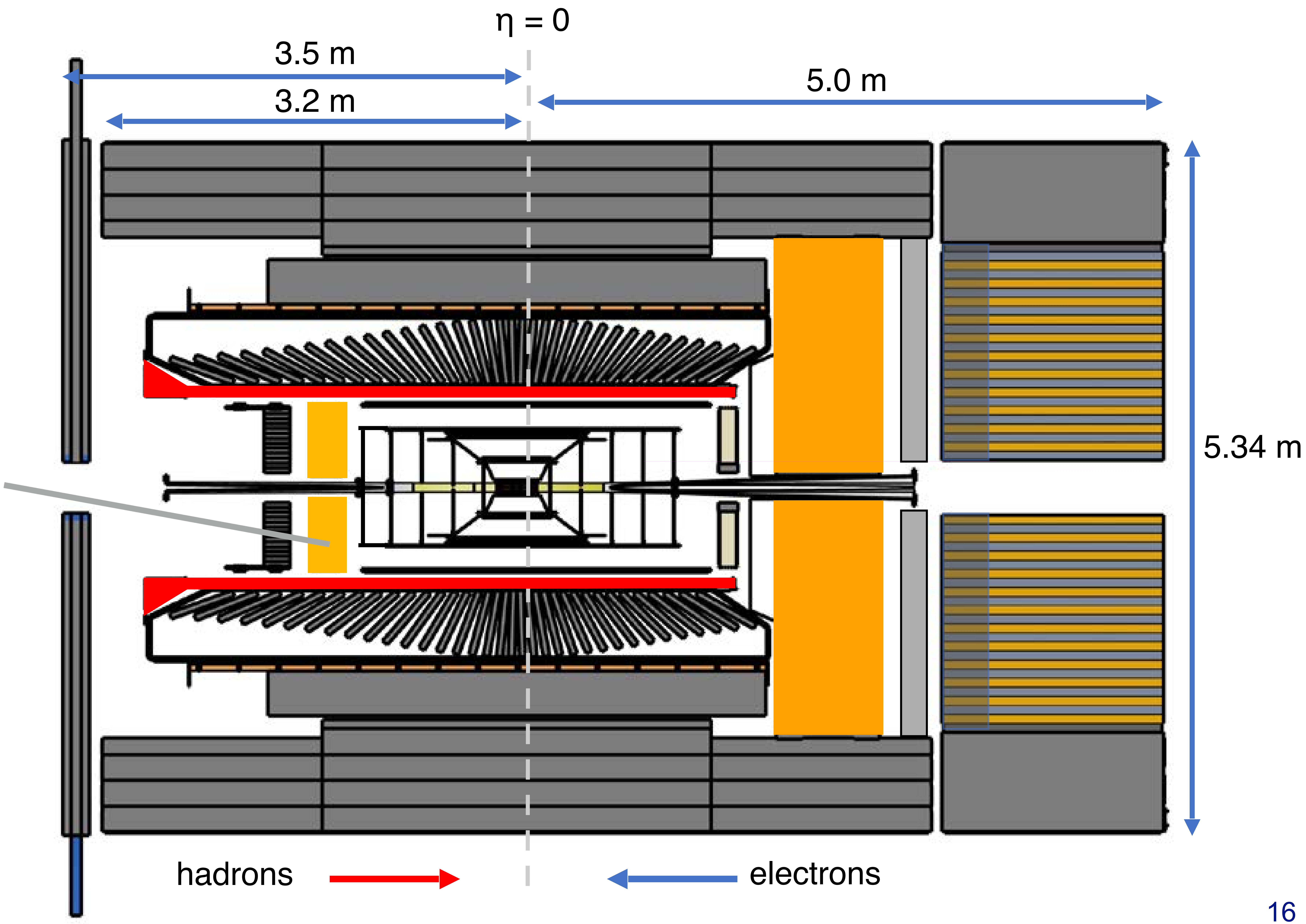

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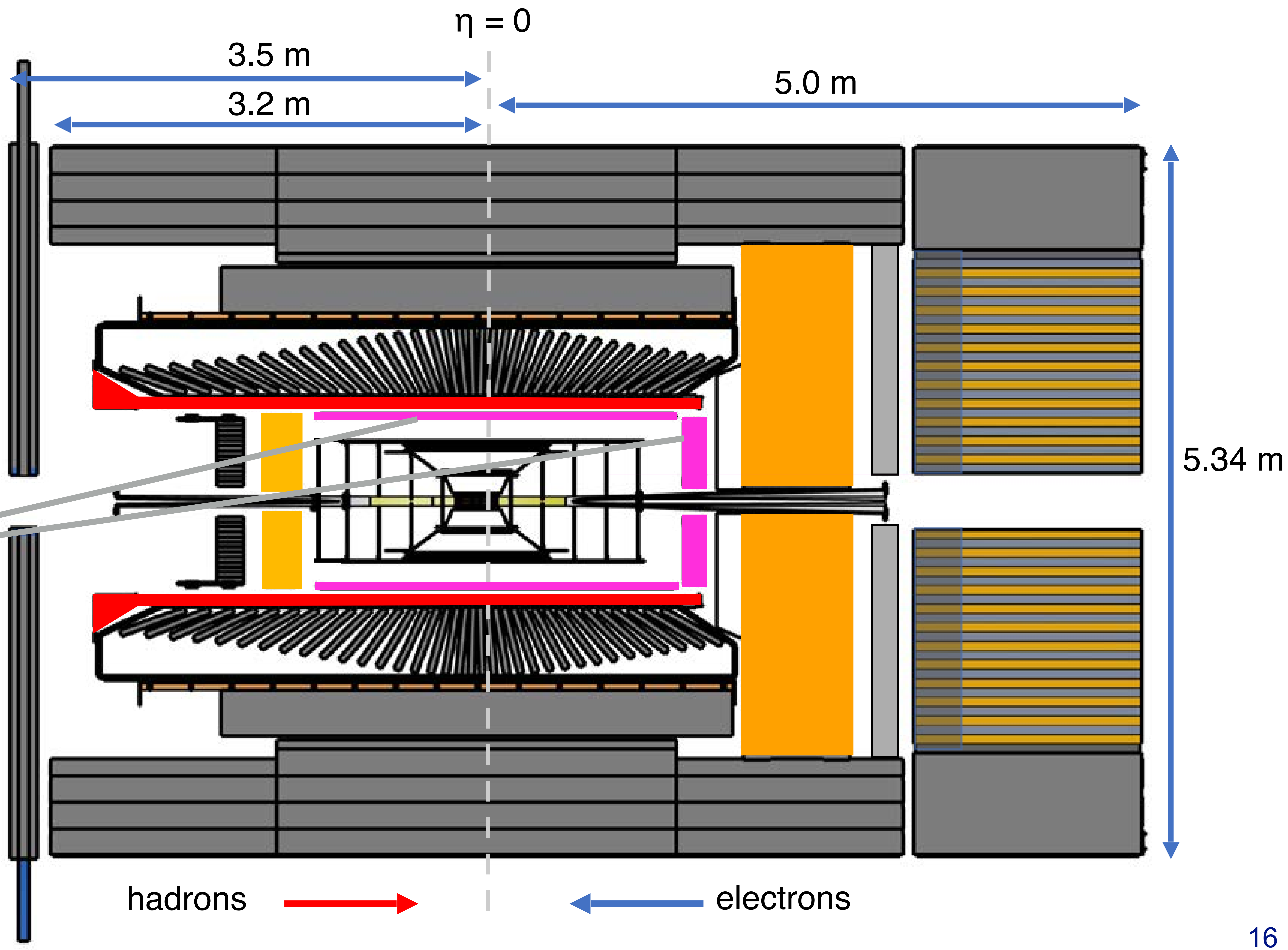

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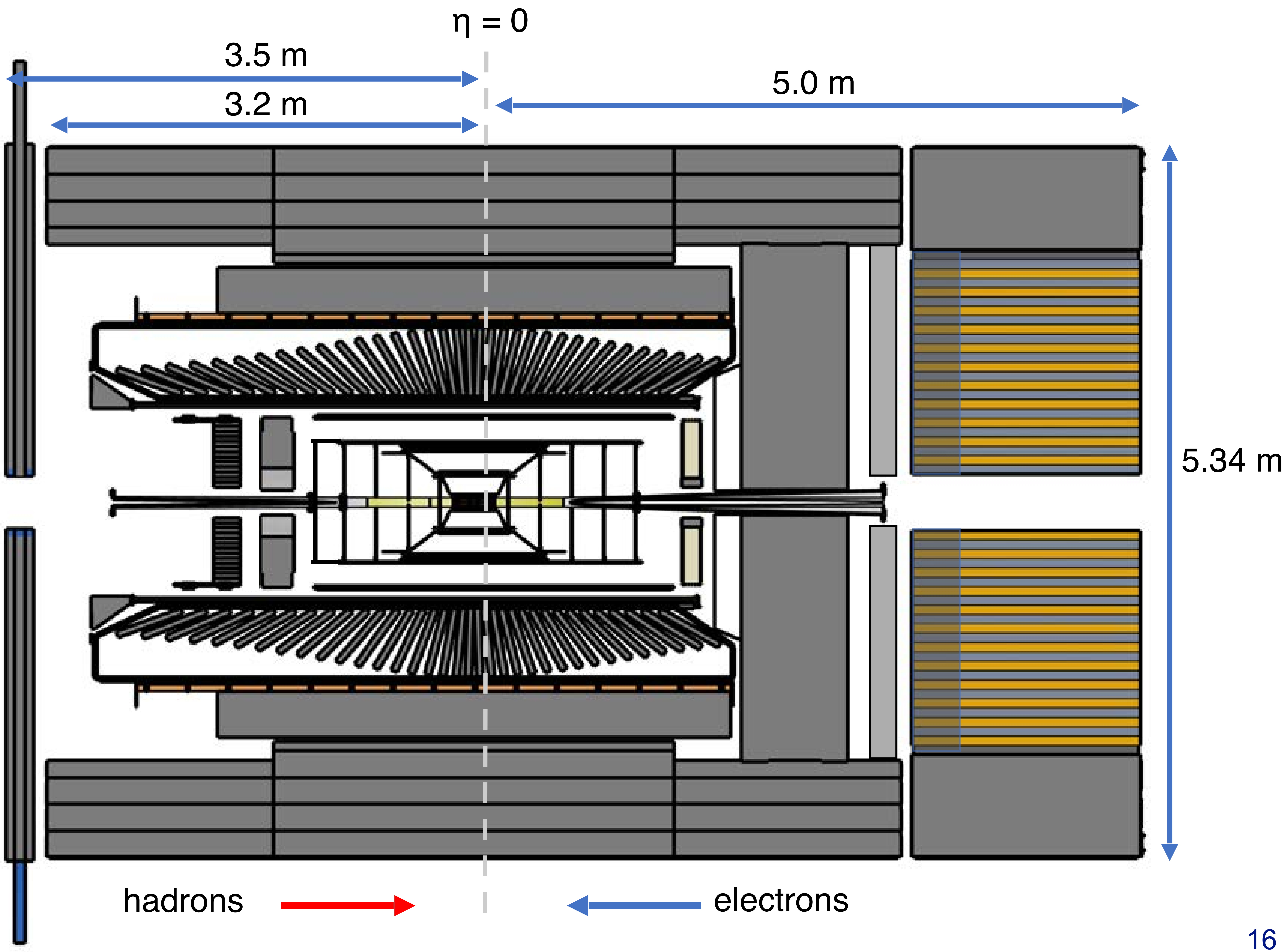
- finely segmented W/SciFi EMCal
- $PbWO_4$ EMCal



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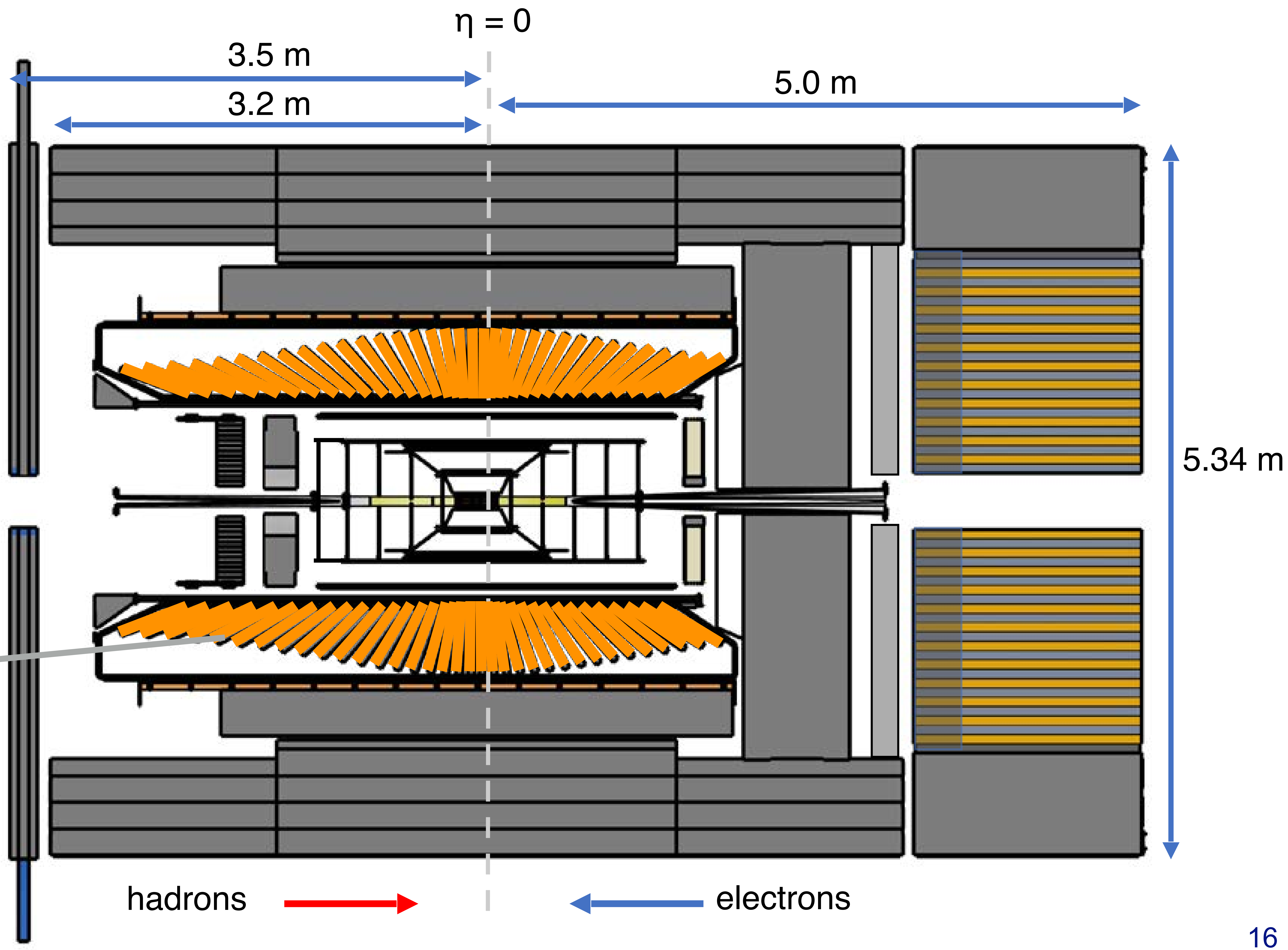

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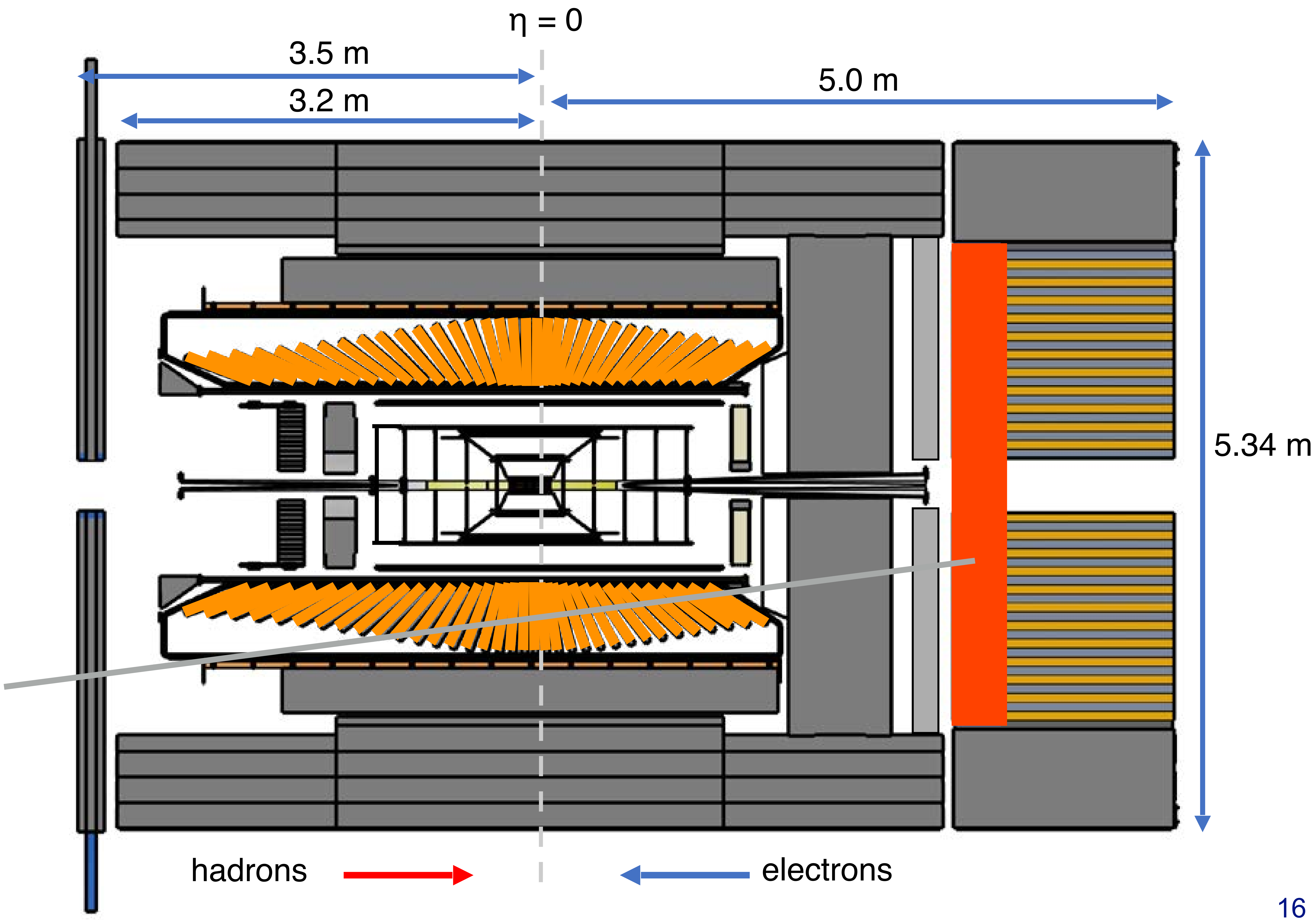

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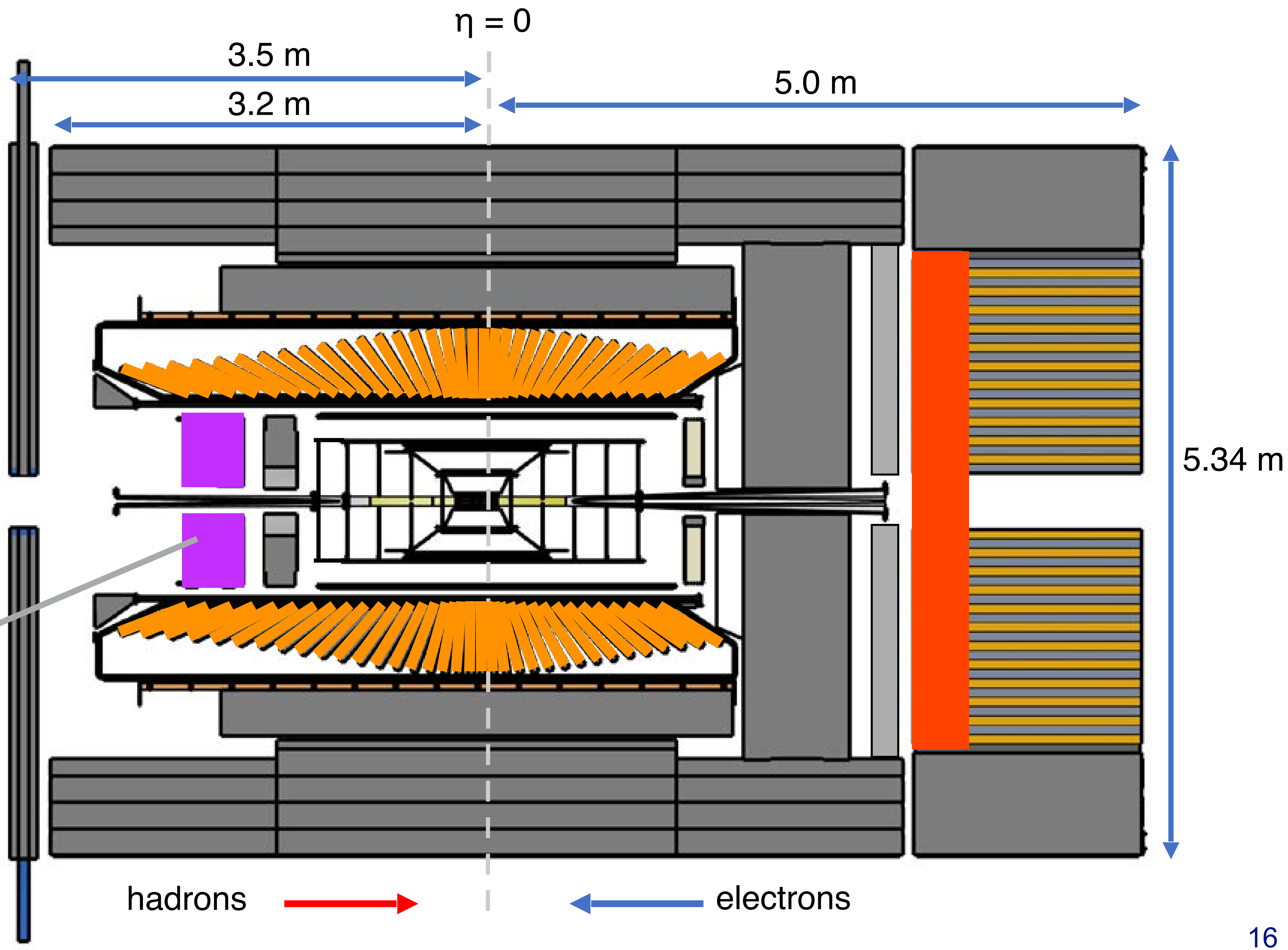

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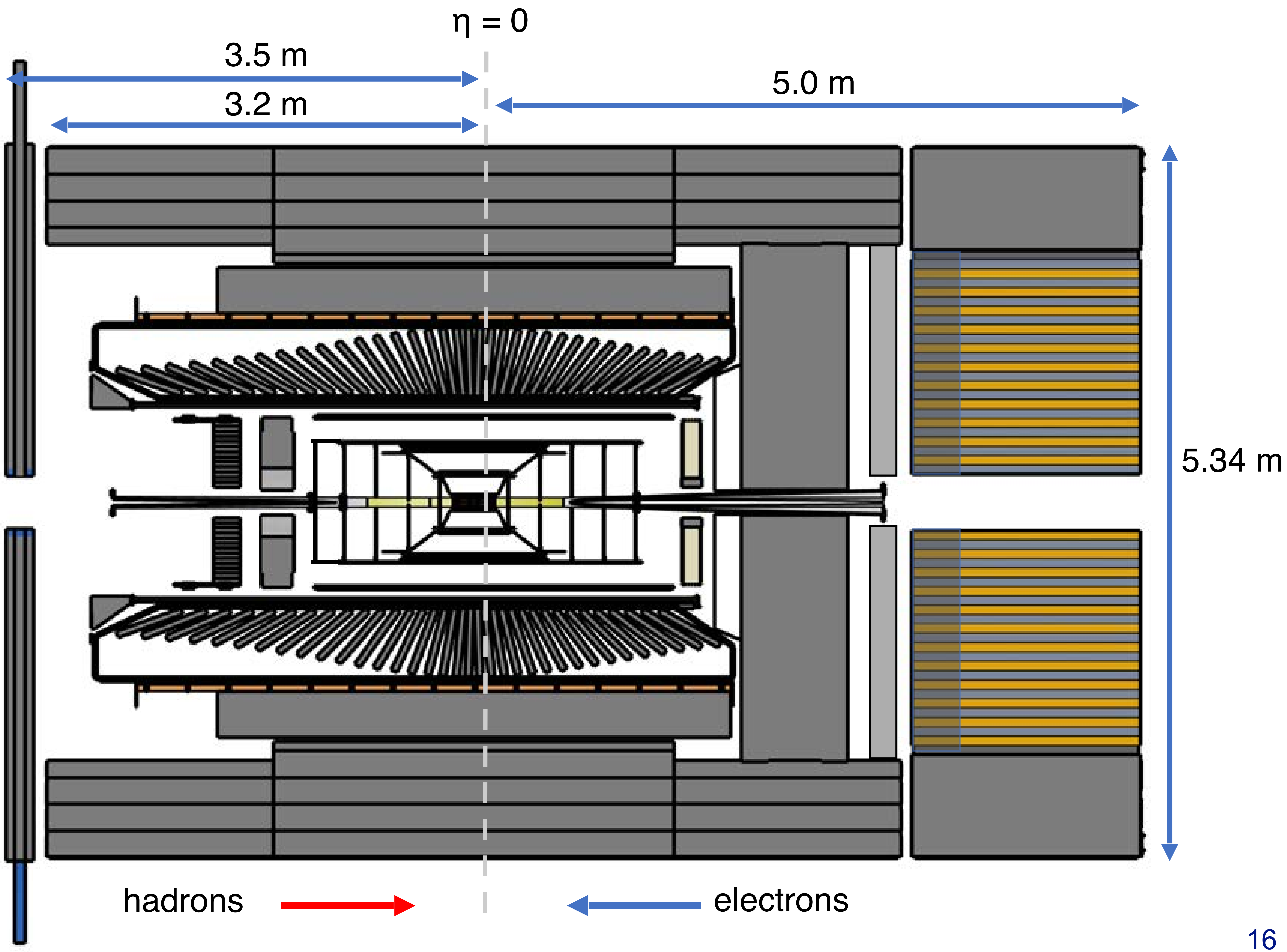
- long. separated Fe-W-Sc calorimeter w/ high-η insert



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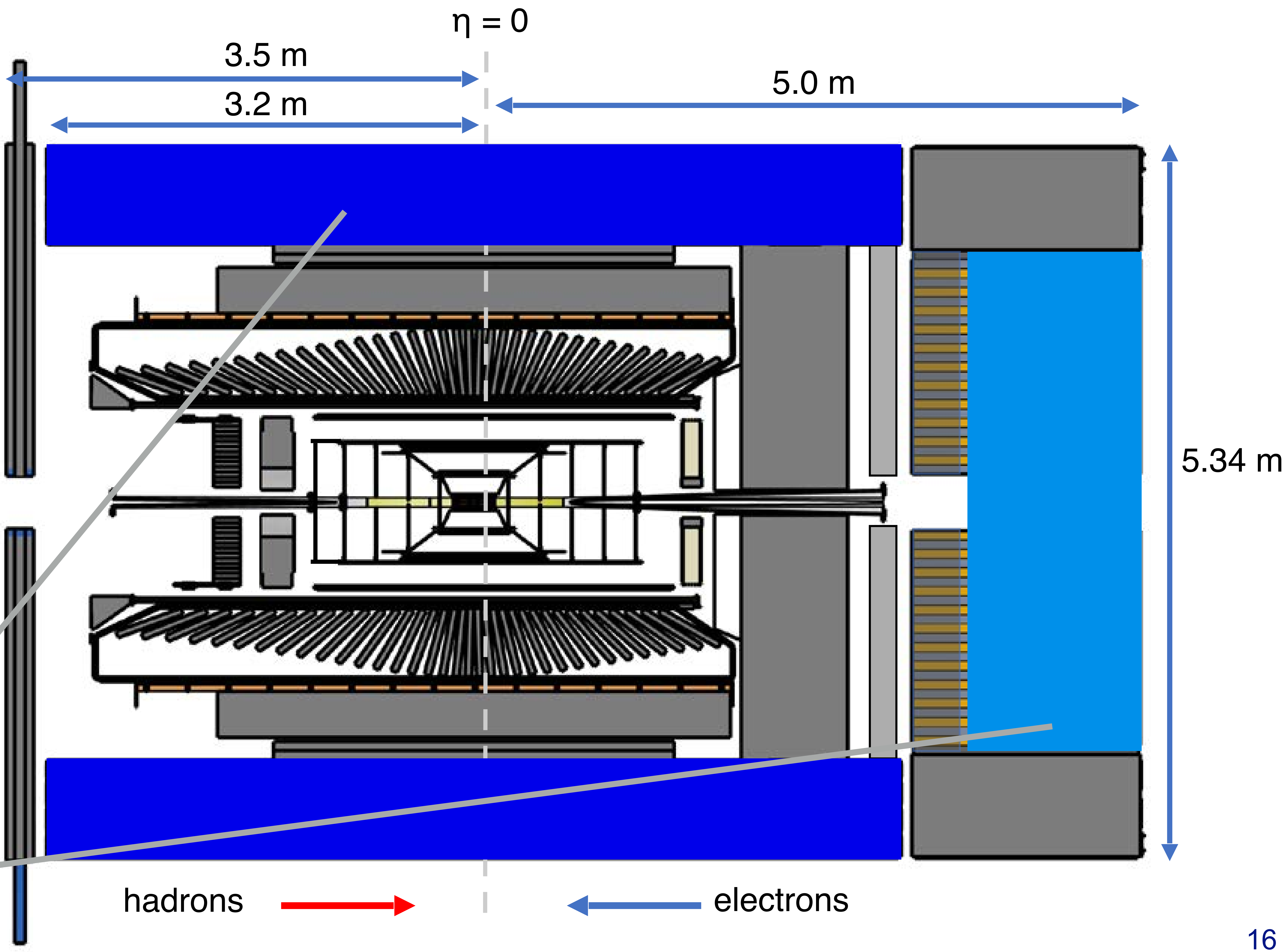

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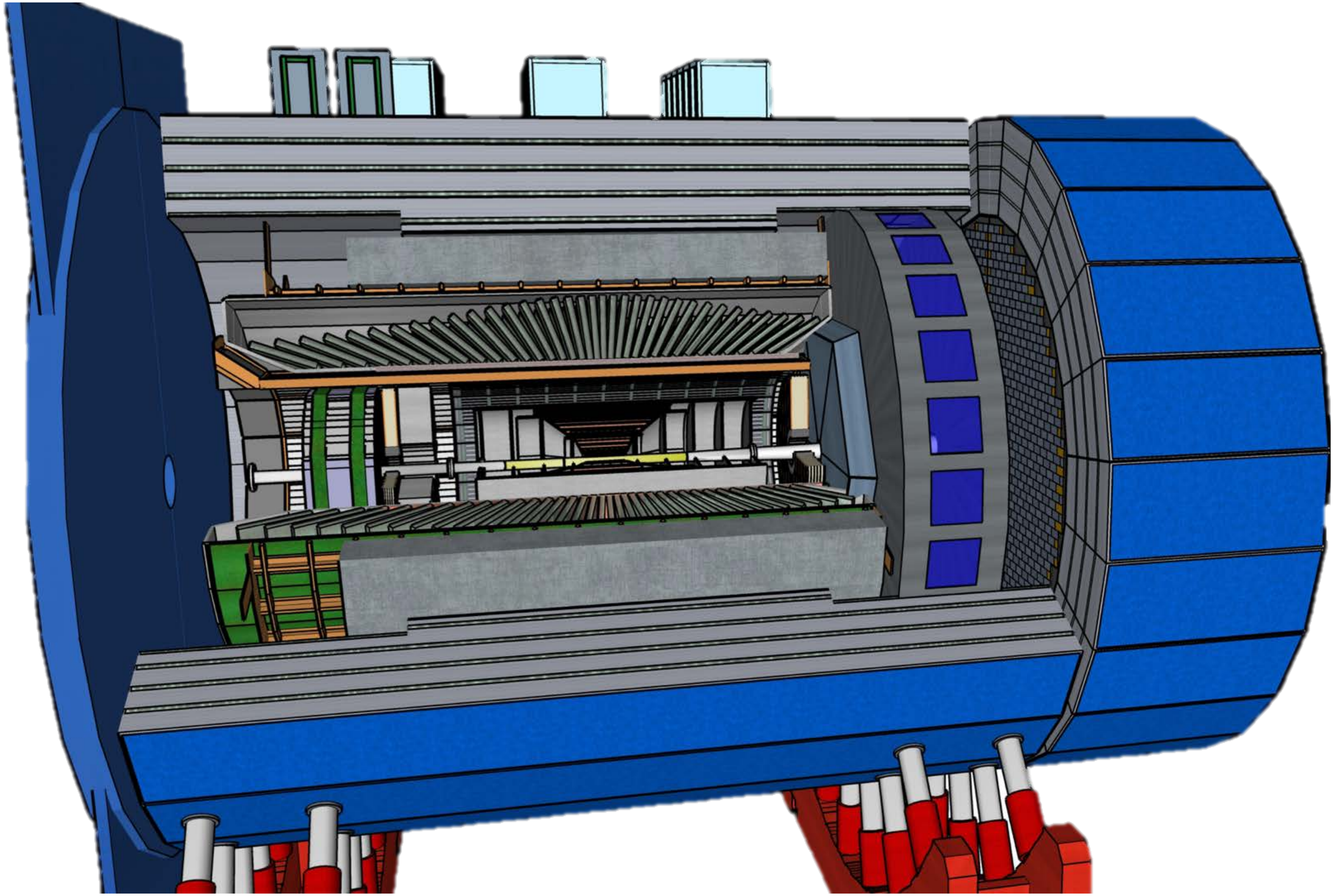
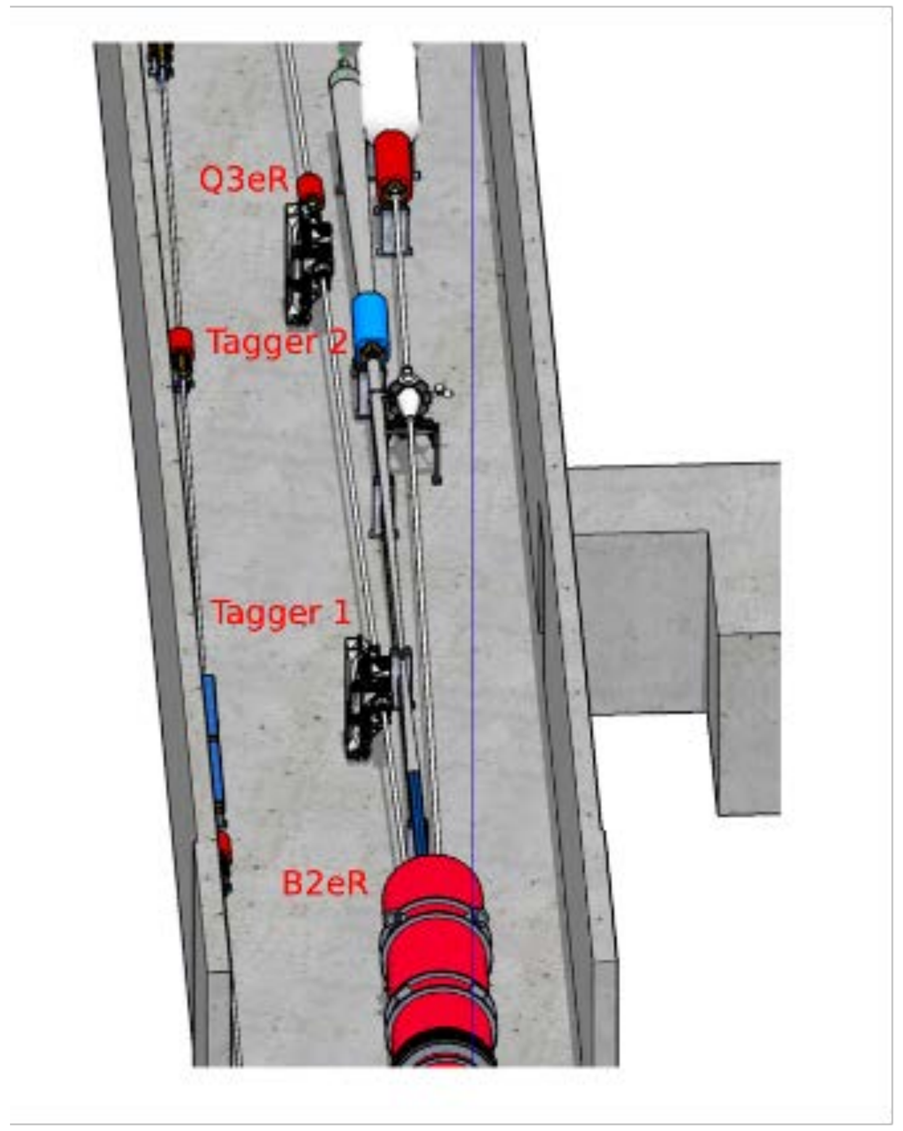
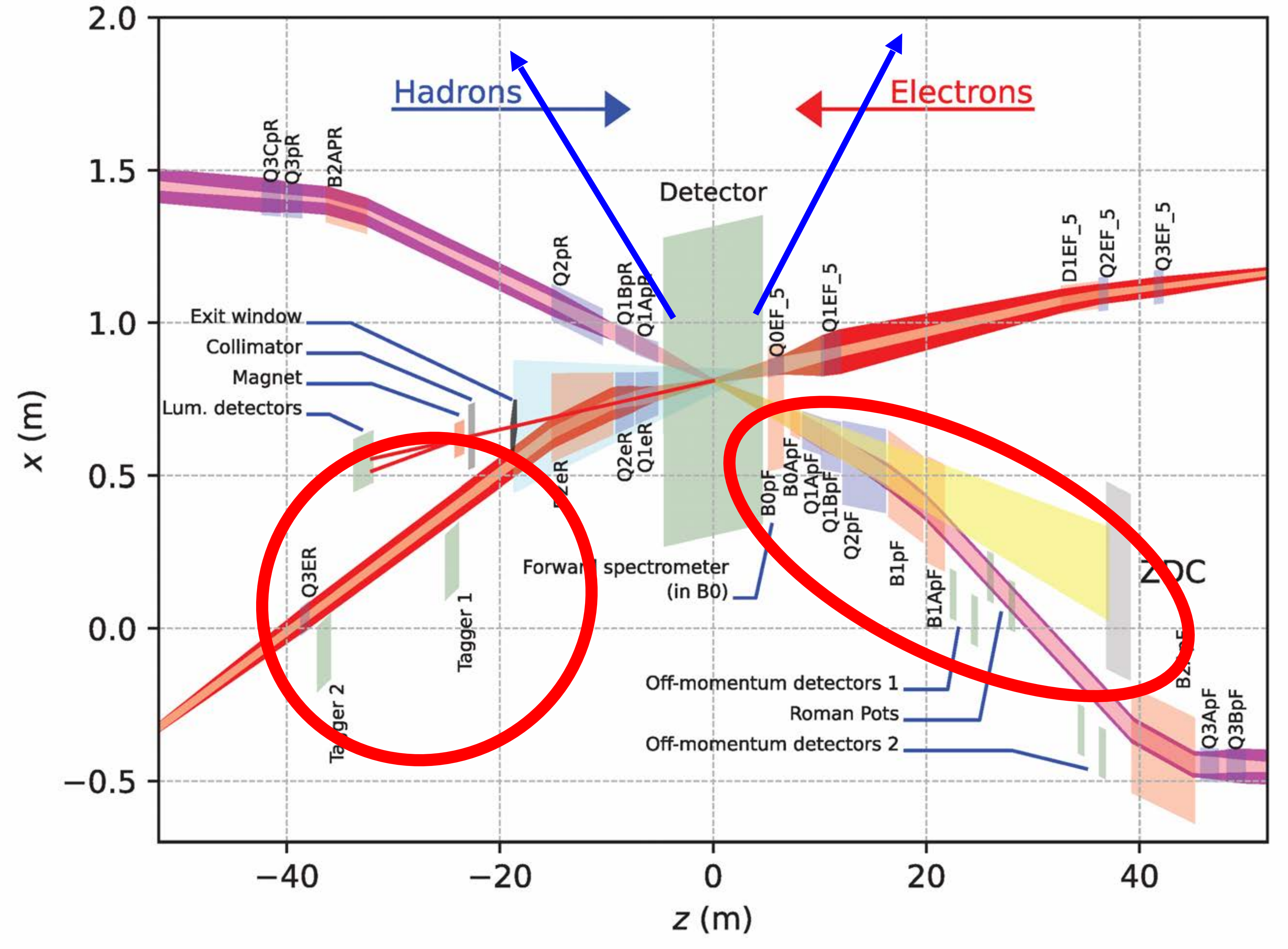
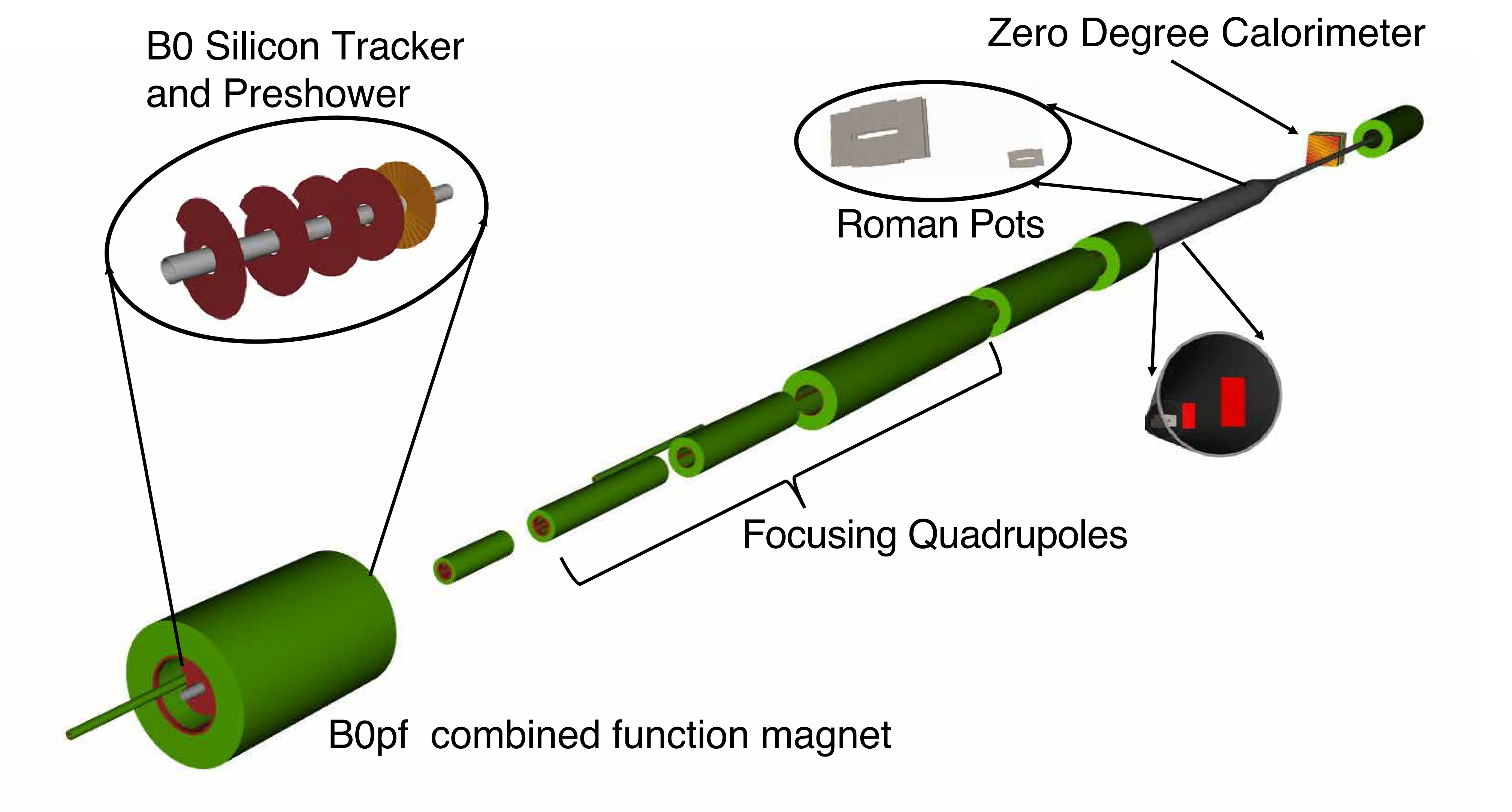


EPIC Baseline - Along the Beamline







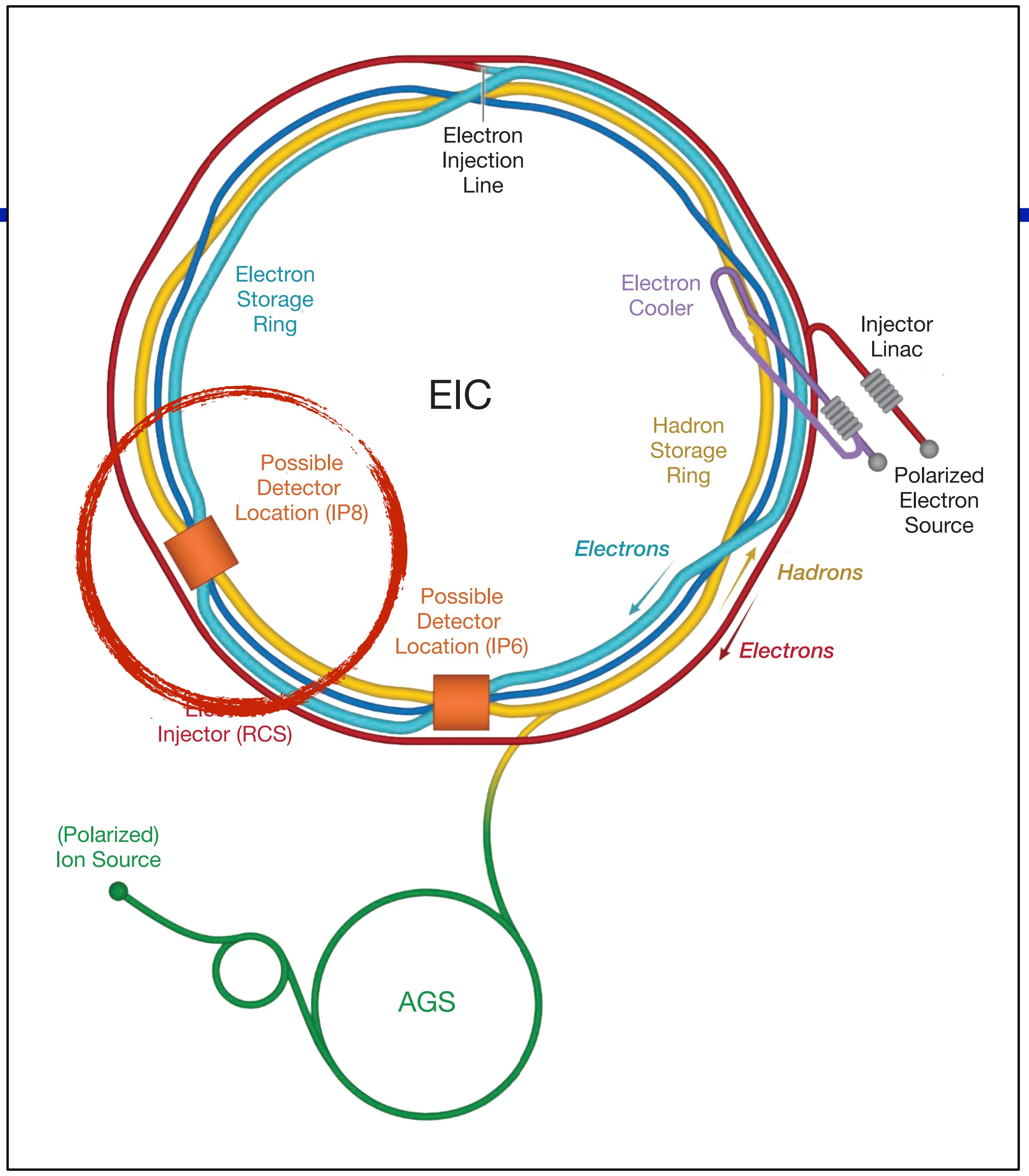
EIC physics includes final-states particles at $|\eta| > 4.5$.

- Need sub-systems integrated within and alongside the accelerator beam line
- **Far-Backward**
  - Luminosity monitor
  - Low-Q^2 tagging detectors $\Rightarrow$ scattered electron at small angles

- **Far-Forward**
  - B0 spectrometer $\Rightarrow$ silicon tracking system and photon EM calorimetry
  - Off-Momentum Detector (OMD) $\Rightarrow$ for particles from nuclear breakup
  - Roman Pots (RP) $\Rightarrow$ for tagging and reconstruction of protons
  - Zero-Degree Calorimeter (ZDC) $\Rightarrow$ for photons and neutrons

A Second EIC Detector

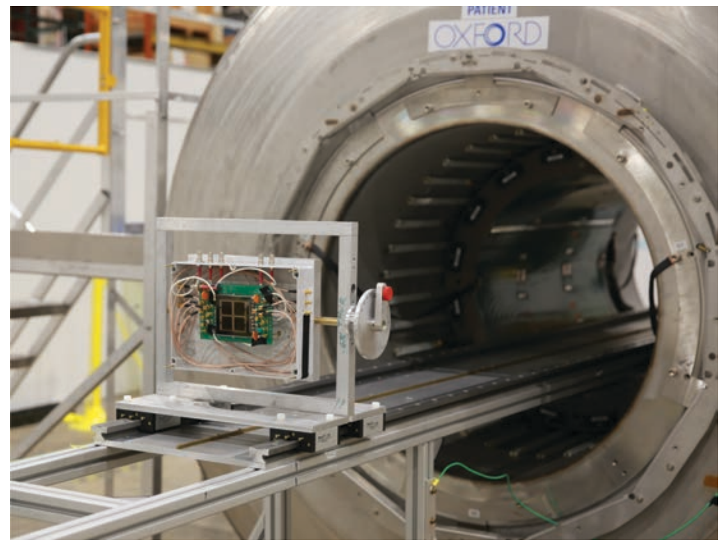
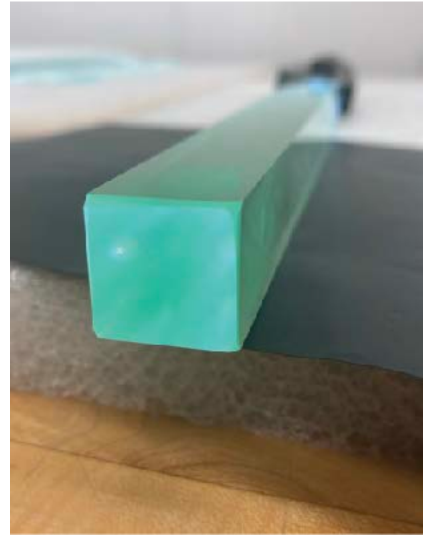
- Activities
  - EICUG Working Group, PR efforts, push for recommendation/initiative in NSAC Long Range Plan 2023
- Potentially realized with a 3-5 year delay to EPIC
- Opportunities:
  - new technologies that are not mature enough or too risky for the 1st detector can be considered to provide full complementarity
  - this needs a well-thought-out R&D program that will be guided and inspired by efforts on Detector-II
  - making full use of the reinstated generic EIC detector program

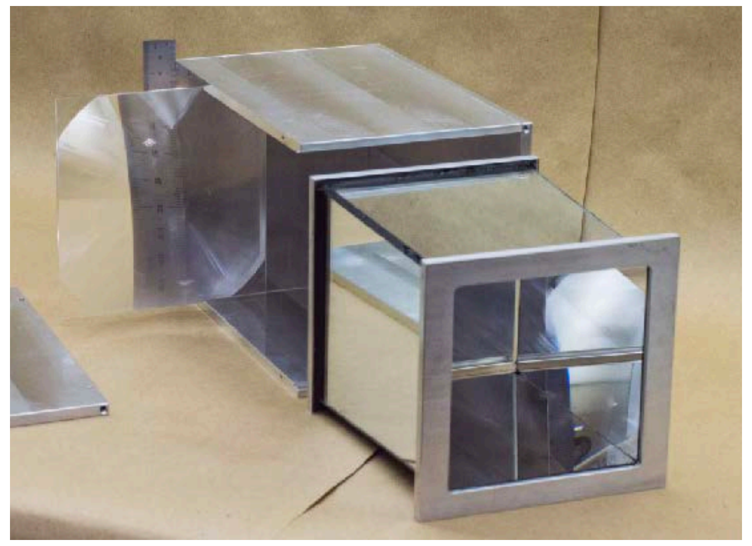
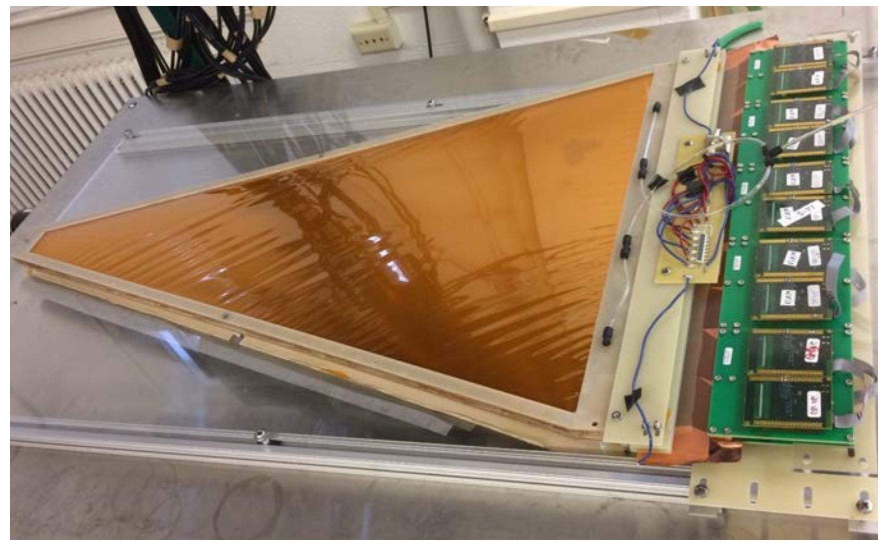


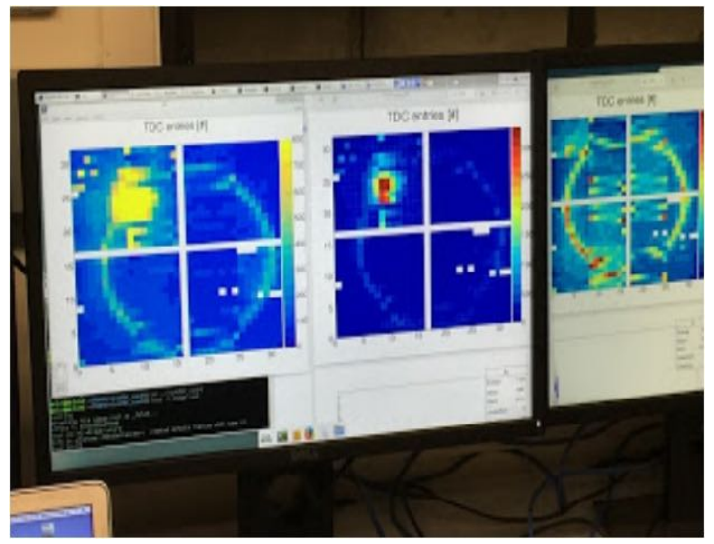
Complementarity:
- secondary focus in IP8
  - enhances the low-p_T and low-x (large-x_L) acceptance of recoiling target system
- enhanced PID acceptance and reach in areas of phase space
- more emphasize on μ detection
- stonger B field

From Concept to Reality - R&D

- Generic R&D Program 2011-2021
  - Operated by BNL and supported through funds by the DOE Office of Nuclear Physics
  - FY21: 281 participants from 75 institutions (37 non-US)
  - Many of the subsystems in EPIC were developed and matured in this program and and EPIC detector working group/consortia member were part of the program
  - https://wiki.bnl.gov/conferences/index.php/EIC_R%25D
- Project R&D
  - Aims at achieving the maturity required to carry out final design and construction
  - Support **only** projects that perform R&D on technologies used in EPIC
  - https://wiki.bnl.gov/conferences/index.php?title=General_Info



Generic R&D Projects 2014-2021

Project	Topic
eRD1	EIC Calorimeter Development
eRD2	A Compact Magnetic Field Cloaking Device
eRD3	Design and assembly of fast and lightweight forward tracking prototype systems
eRD6	Tracking and PID detector R&D towards an EIC detector
eRD10	(Sub) 10 Picosecond Timing Detectors at the EIC
eRD11	RICH detector for the EIC's forward region particle identification - Simulations
eRD12	Polarimeter, Luminosity Monitor and Low Q2-Tagger for Electron Beam
eRD14	An integrated program for particle identification (PID)
eRD15	R&D for a Compton Electron Detector
eRD16	Forward/Backward Tracking at EIC using MAPS Detectors
eRD17	BeAGLE: A Tool to Refine Detector Requirements for eA Collisions in the Nuclear Shadowing/Saturation Regime
eRD18	Precision Central Silicon Tracking & Vertexing
eRD19	Detailed Simulations of Machine Background Sources and the Impact to Detector Operations
eRD20	Developing Simulation and Analysis Tools for the EIC
eRD21	EIC Background Studies and the Impact on the IR and Detector design
eRD22	GEM based Transition Radiation Tracker R&D
eRD23	Streaming Readout for EIC Detectors
eRD24	Silicon Detectors with high Position and Timing Resolution as Roman Pots at EIC
eRD25	Si-Tracking
eRD26	Pulsed Laser System for Compton Polarimetry
eRD27	High Resolution ZDC
eRD28	Superconducting Nanowire Detectors
eRD29	Precision Timing Silicon Detectors for combined PID and Tracking System

Tracking | PID | Calorimetry | Software/Simulations | Other

Project R&D Projects 2022+

Project	Topic
eRD101	mRICH / aerogel RICH
eRD102	dRICH
eRD103	hpDIRC
eRD104	Service reduction
eRD105	SciGlass
eRD106	Forward EMCAL
eRD107	Forward HCAL
eRD108	Cylindrical & Planar MPGD
eRD109	ASICs/Electronics
eRD110	Photosensors
eRD111	Si-Tracker (no sensors)
eRD112	ToF with AC-LGAD
eRD113	ITS3/EIC MAPS development

Tracking | PID | Calorimetry | Sensors | Electronics

Project R&D Projects 2022+

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onics

- **Need for Generic R&D**
  - Recall: NP has no general detector R&D subprogram
  - Continue developing technologies that are not ready for day-1 (CD-4a timeline) but that would offer superior technologies down the road
  - R&D for complementary technologies that could be used in a 2nd EIC detector and for future EPIC upgrades keeping the EIC on cutting-edge
  - Bring benefit for other programs in NP, HEP, medical application (e.g. PET w/ ToF), and more environmental-friendly technologies

New Generic R&D Program 2022+

- After lots of efforts: Generic program reconstituted starting this year
  - funded by DOE, coordinated by JLab
  - `https://www.jlab.org/research/eic_rd_prgm`
  - total of 30 proposals were received on July 25, 2022

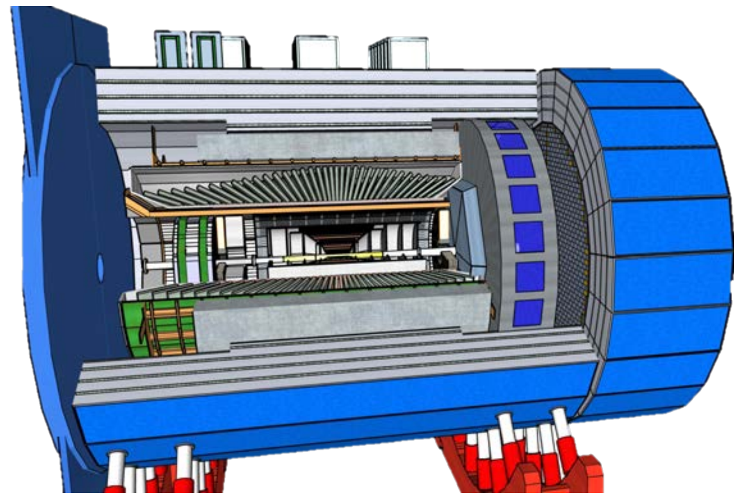
Topic
CSGlass for hadron calorimetry at the EIC
A proposal for MPGD-based transition radiation detector/tracker
Continued Development and Evaluation of a Low-Power High-Density High Timing Precision Readout ASIC for AC-LGADs (HPSoC)
A new radiation tolerant low power Phase-Locked Loop IP block in a 65 nm technology for precision clocking in the EIC frontend electronics
Refined Methods for Transfer Matrix Reconstruction Using Beamline Silicon Detectors for Exclusive Processes at the EIC
Development of a Novel Readout Concept for an EIC DIRC
Tracking and PID with a GridPIX Detector

Particle identification and tracking in real time using Machine Learning on FPGA
Superconducting Nanowire Detectors for the EIC
EIC KLM R&D Proposal
Development of Thin Gap MPGDs for EIC Trackers
Simplified LGAD structure with fine pixelation
Imaging Calorimetry for the Electron-Ion Collider
Silicon Tracking and Vertexing Consortium, Section 1: Embedded Monolithic Active Pixel Sensor R&D
Silicon Tracking and Vertexing Consortium, Section 2: Aluminum Flexible Circuit Manufacturing Capability

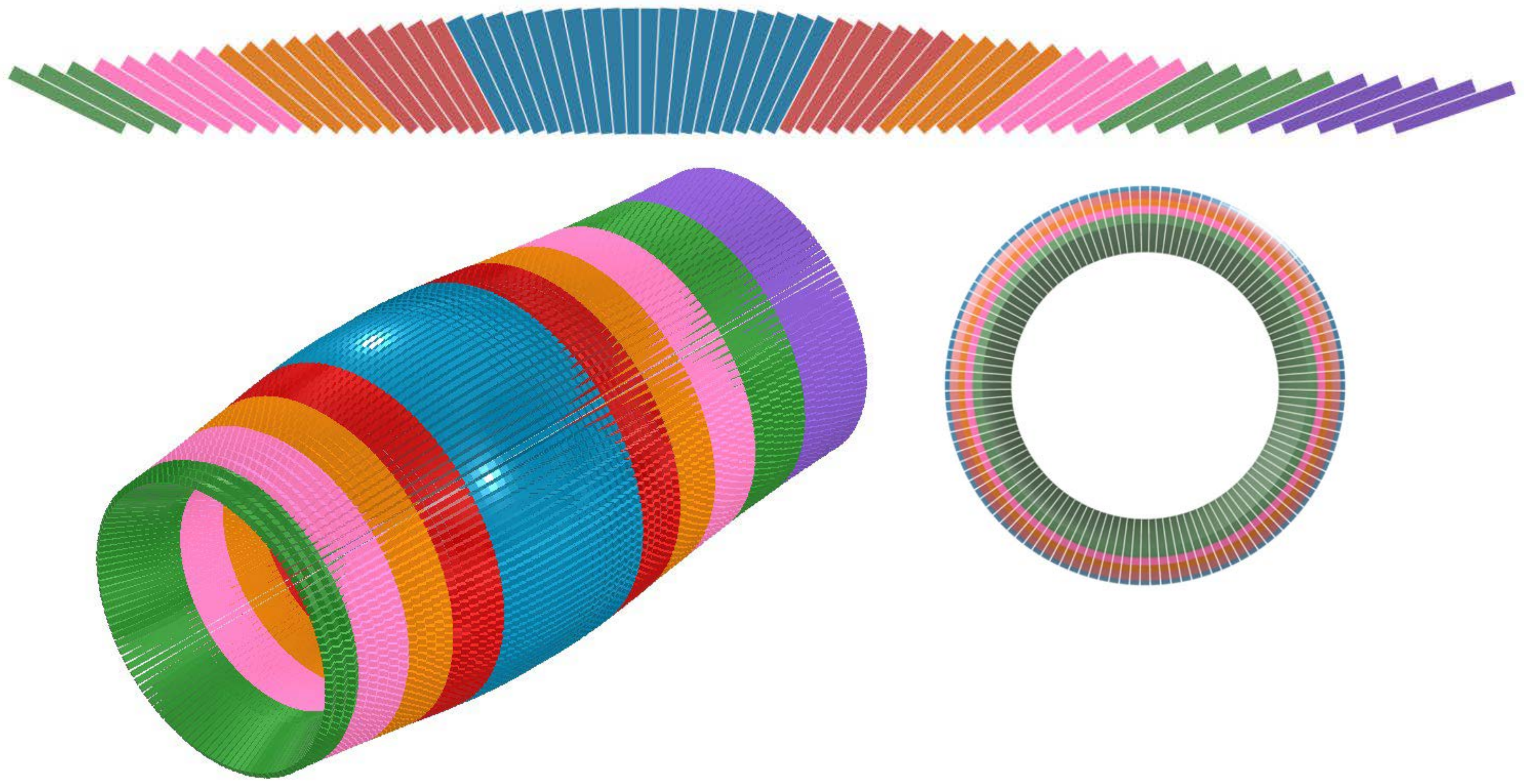
Tracking | PID | Calorimetry | Software/AI | ASICs/FEE

Example: Crystals and Glasses (eRD1 & eRD105)

- EIC barrel needs high quality EM calorimetry
- Typically requires Lead Tungstate (PbWO4) crystals
- Crystals are expensive, few vendors (SICCAS, CRYTUR)
  - Quality and QA issues
  - Moderate production capacity, raw material shortage
  - EPIC: used in backward EMCAL (need $2\%/\sqrt{E}$)



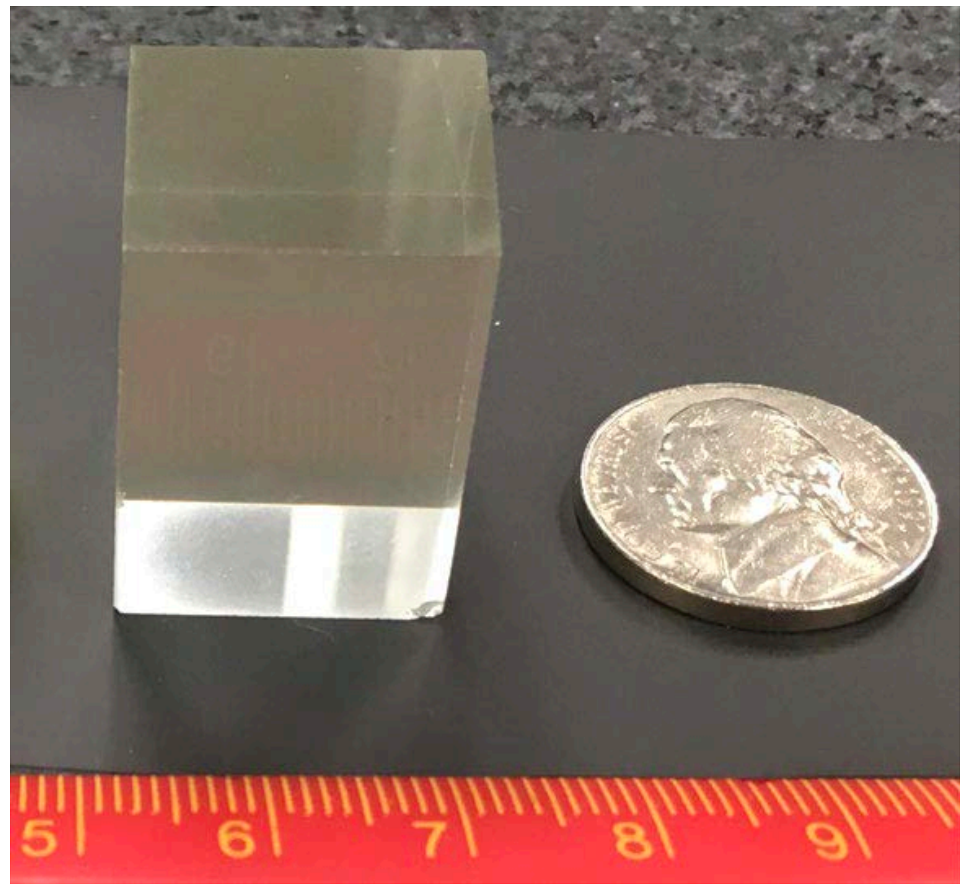
EPIC
barrel EMCal



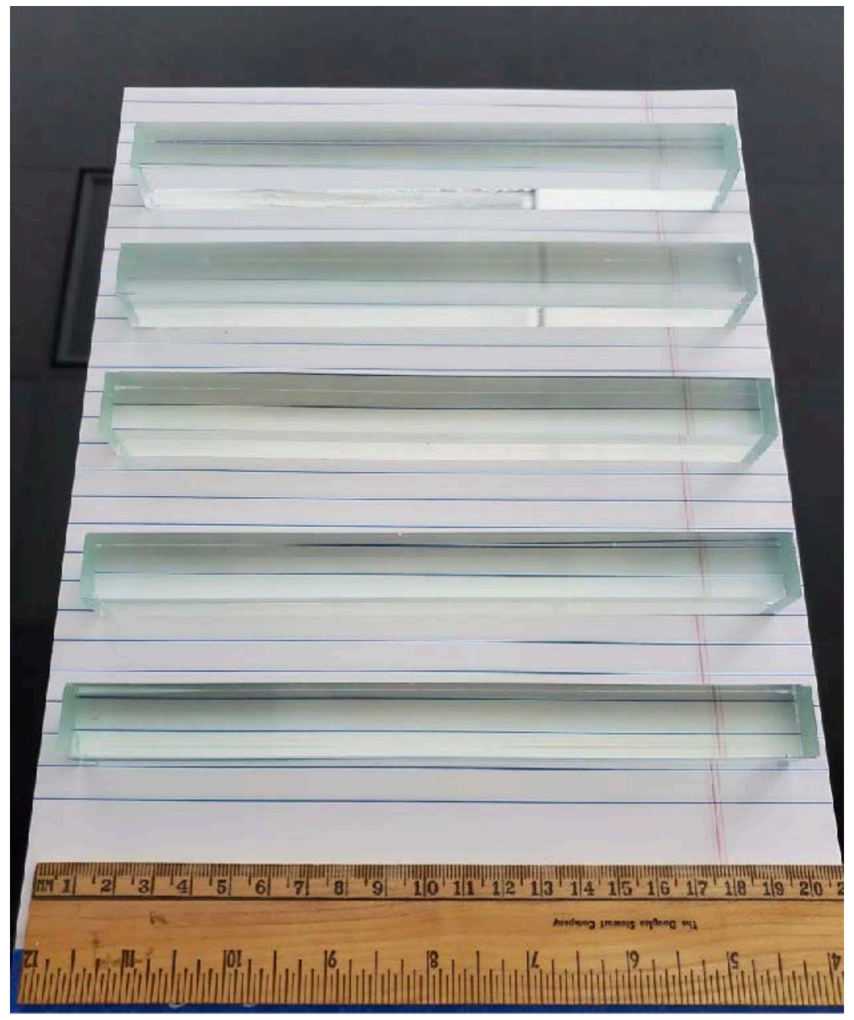
- New effort R&D: Scintillating glasses (CUA/ Vitreous State Laboratory: Scintilex)
  - Similar to lead glass in many properties but exhibit >30× the light yield per GeV
  - Nano-sized particles of $BaSi_2O_5$
  - Allows doping: Gd, Yb, Ce, …
  - Efforts combined in EEEMCAL consortium

Example: Crystals and Glasses (cont.)

Steady progress due to R&D program and Small Business Innovation Research (SBIR) funding

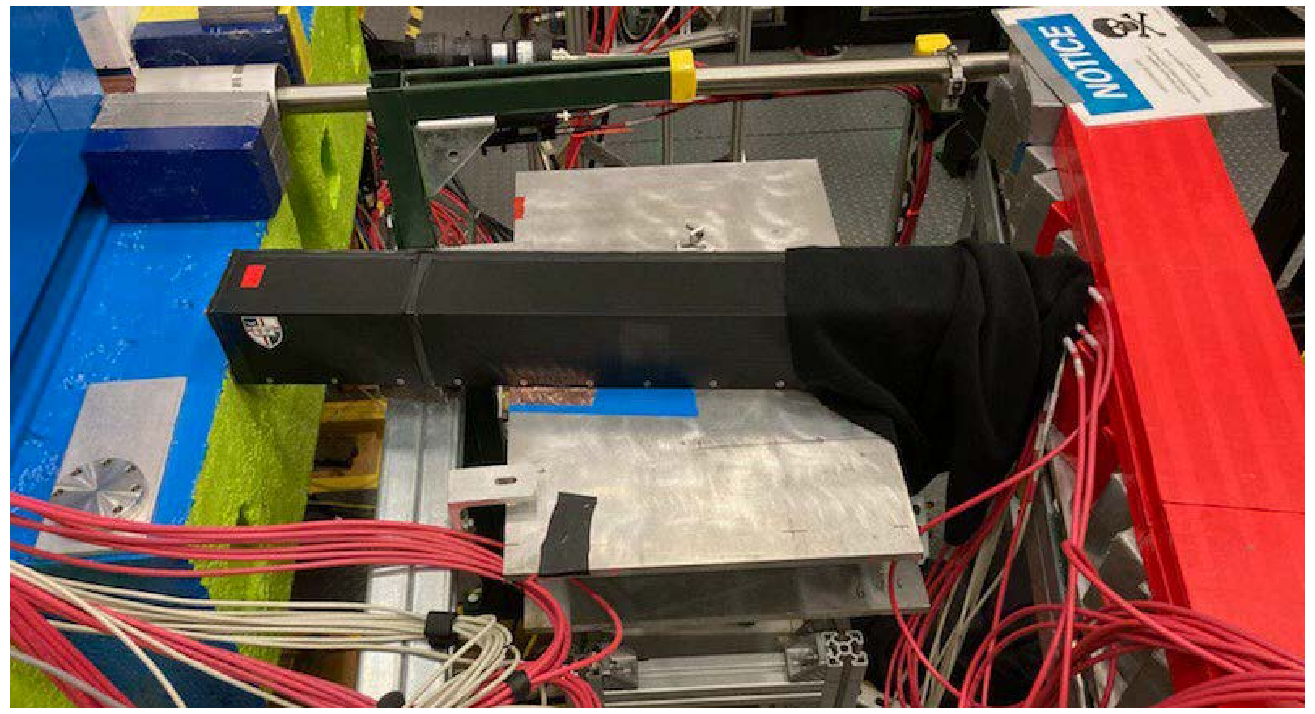


2019: 2cm x 2cm x 4cm



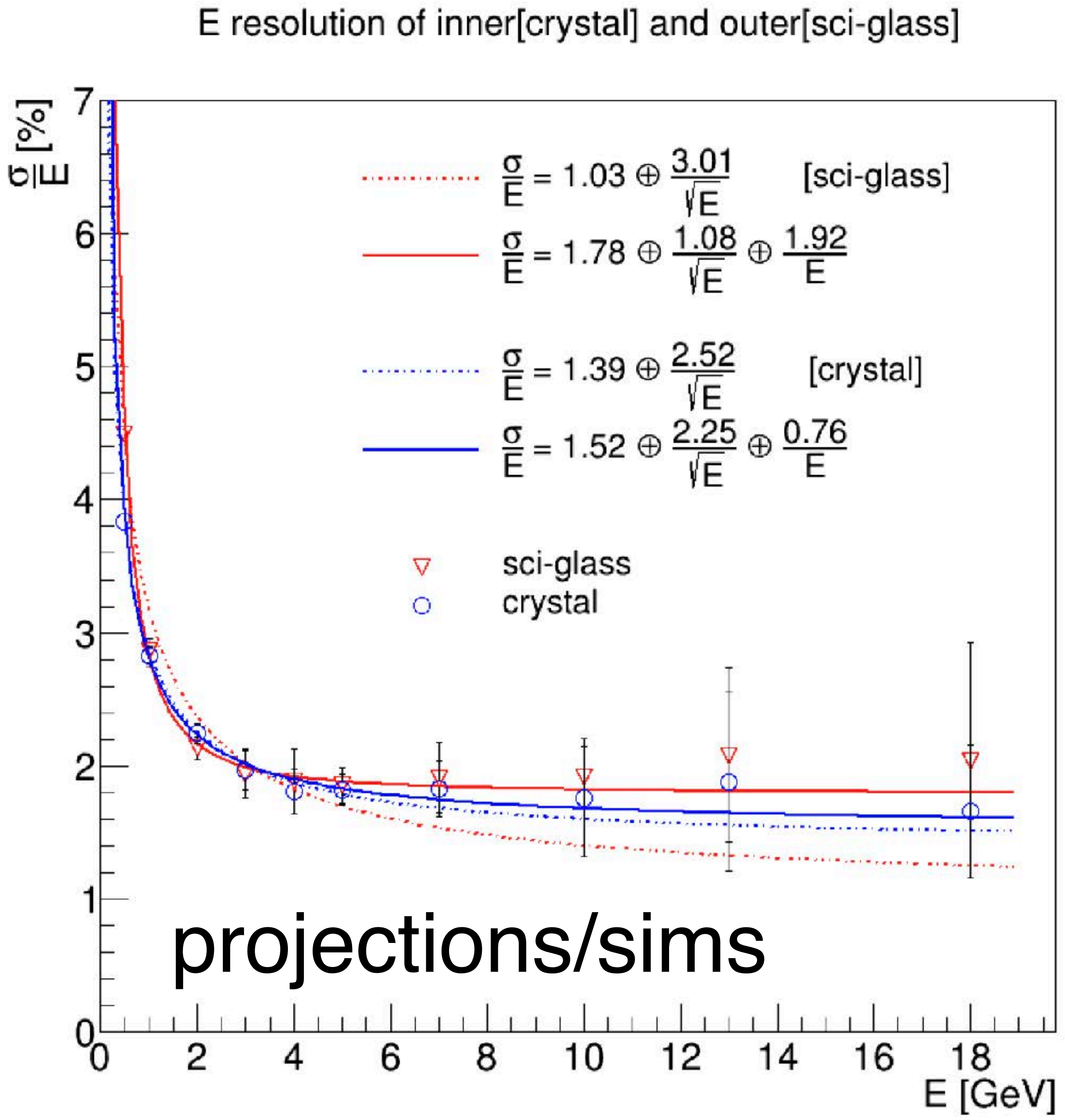
2020: 2cm x 2cm x 20cm (7 X_0)

2021: 2cm x 2cm x 40cm (10-20 X_0)



Test beam w/ prototype test 40 cm

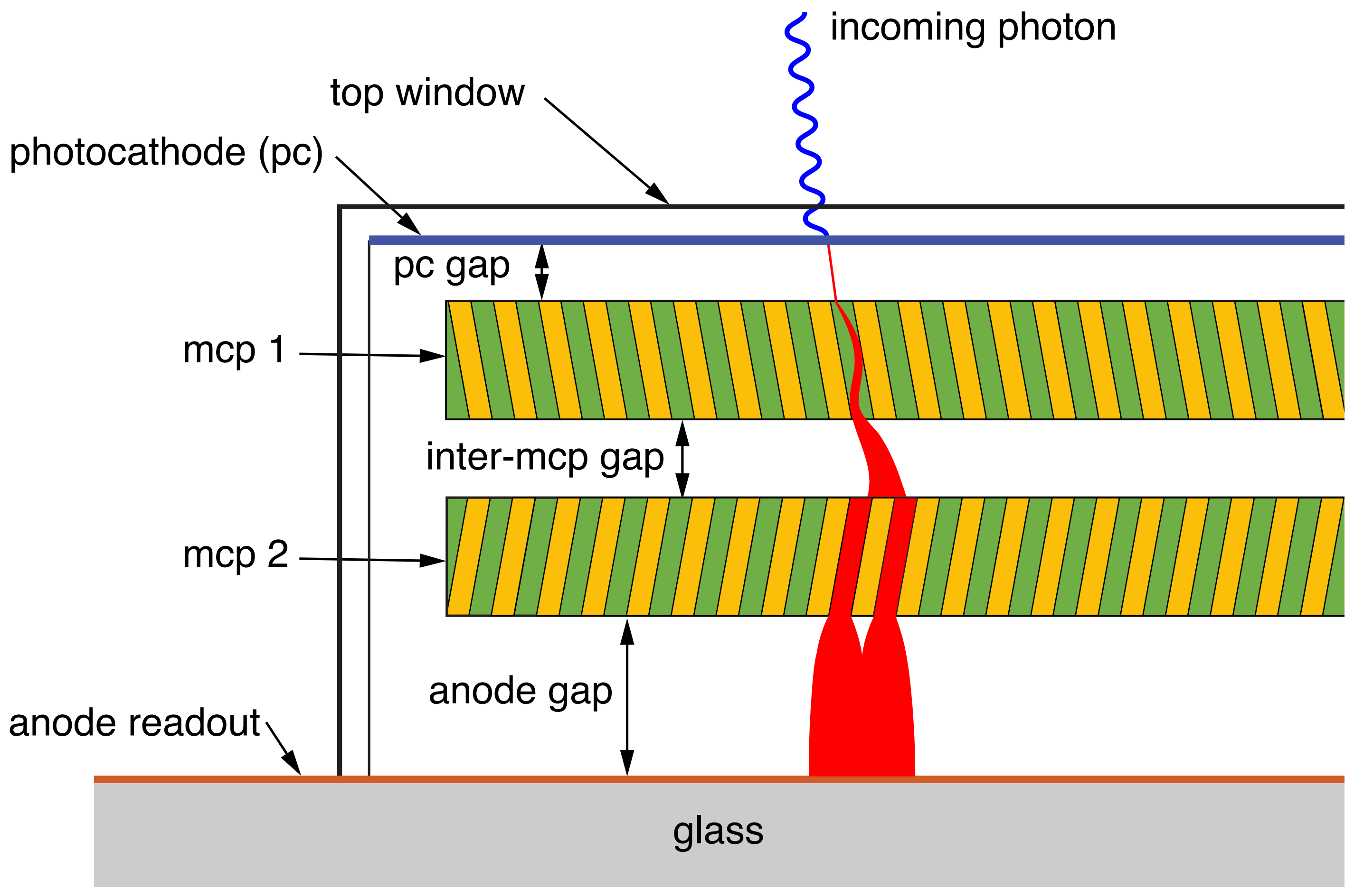
- 40cm long bars will match $PbWO_4$ resolution required & achieved
- Radiation test very positive
- SBIR phase-II to start large-scale production (40+ cm, rectangular and projective shapes)
- Test beams with 40 cm prototype underway
- Path to inexpensive high resolution EM calorimeters



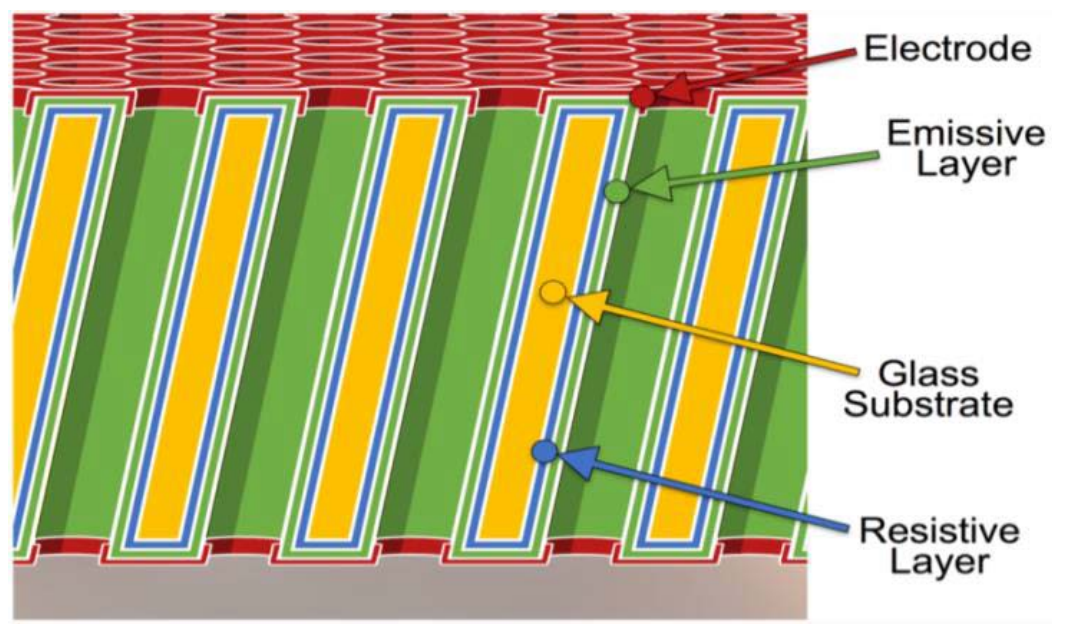
Example: Photosensors/LAPPDs (eRD14 & eRD110)

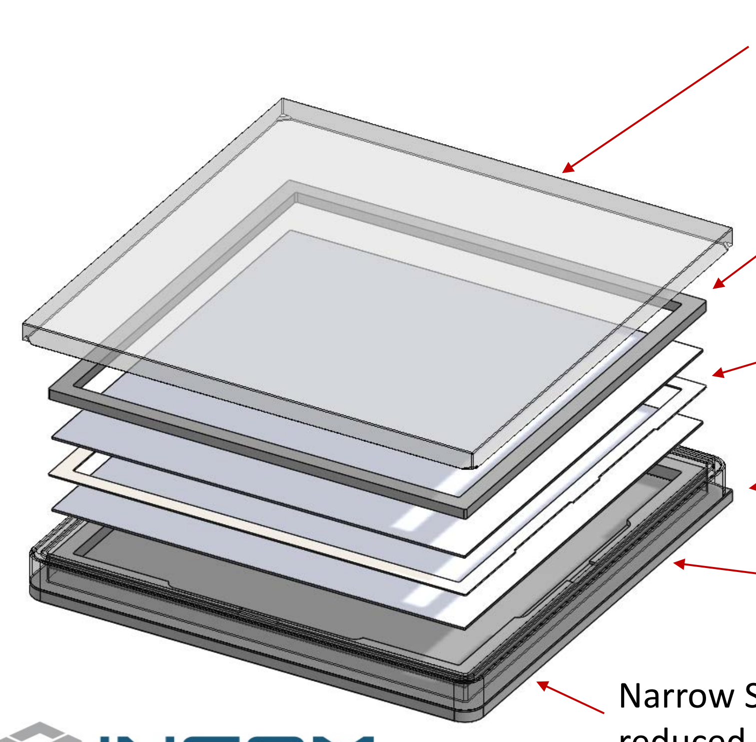
EIC requires highly-pixilated photodetectors working at 1.7-2 T. This problem is most critical for RICH detectors and is not fully solved yet

- SiPM: dark count rates ➟ Cooling ($T < -30^{\circ}$) & annealing cycles ($T > 120^{\circ}$)
- MCP-PMT (expensive, not tolerant to strong magnetic fields)
- Large-Area Picosecond PhotoDetector (LAPPD) potential solution Photon detector **+** ~20 ps ToF detector at the same time
  - Microchannel plate (MCP) based large area photodetector
  - Original LAPPD-Collaboration (HEP), now INCOM (Gen-II)
  - Cost efficient in mass production
  - High enough quantum efficiency and uniform high gain up to ~10^7
  - Promising but still not fully applicable for EIC needs
    - pixelization (DC-coupled strips or 2D pixellation)
    - field resilience
    - tilability/form-factor
- High-Resolution Picosecond PhotoDetector (HRPPD)
  - Novel multi-anode direct readout
  - Reduced gap spacing for improved timing resolution and B-Field tolerance



ALD+ glass substrate MCP: cross section

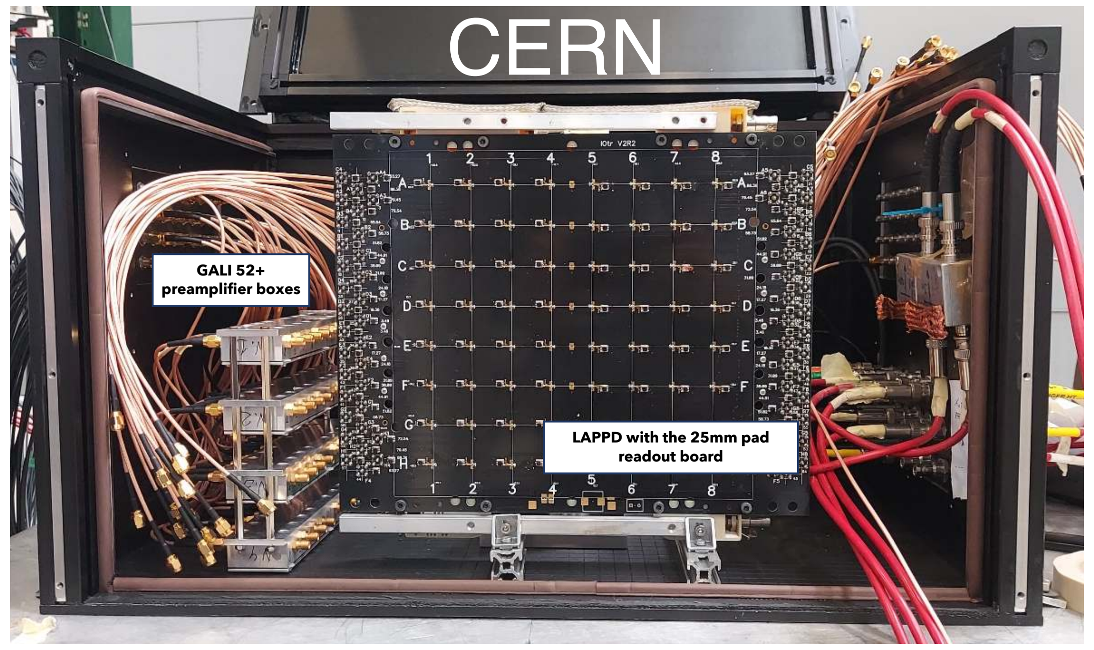


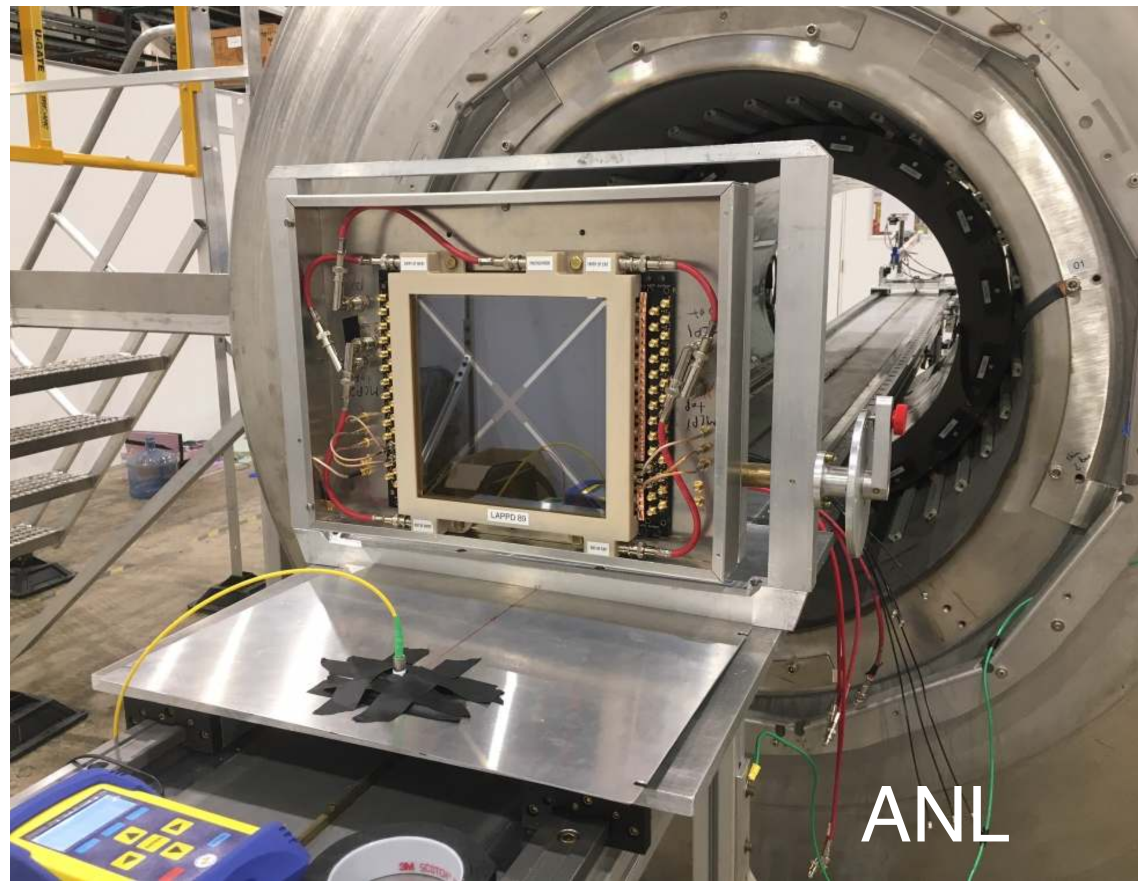


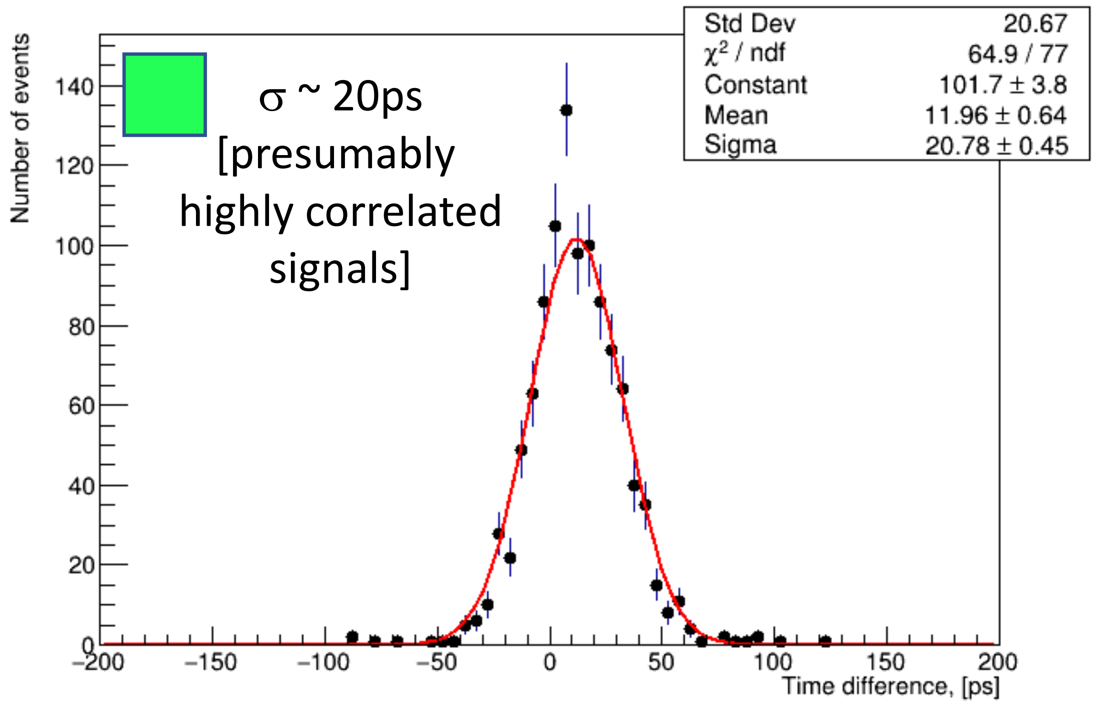
INCOM BRIGHT IDEAS

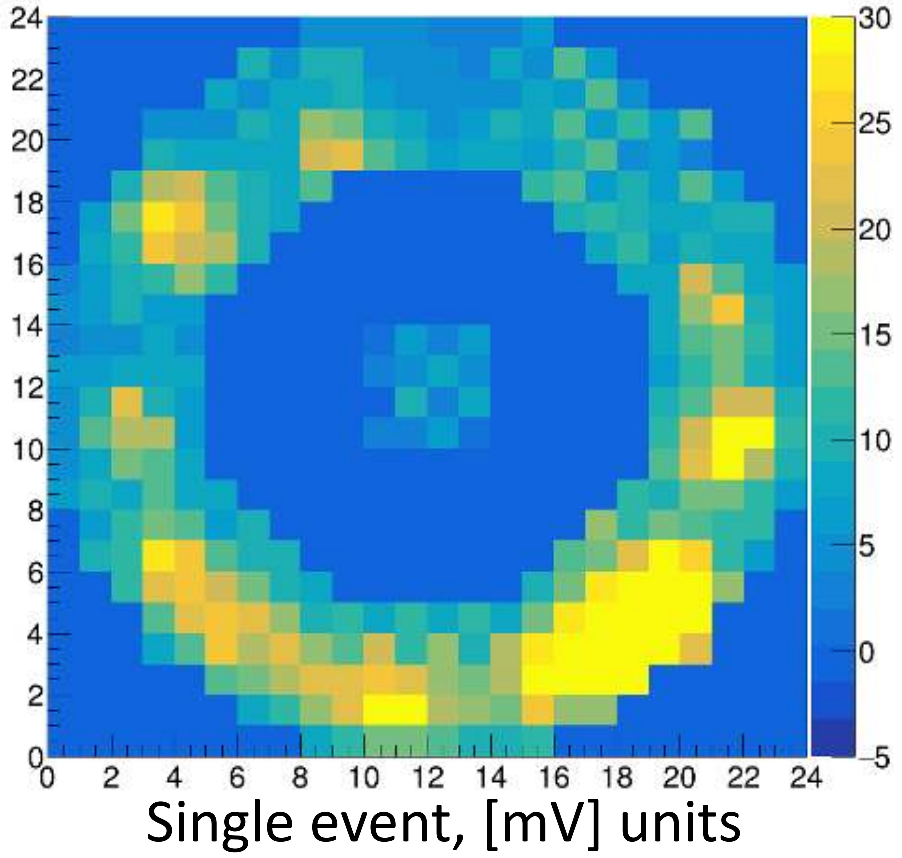
Example: LAPPDs Efforts

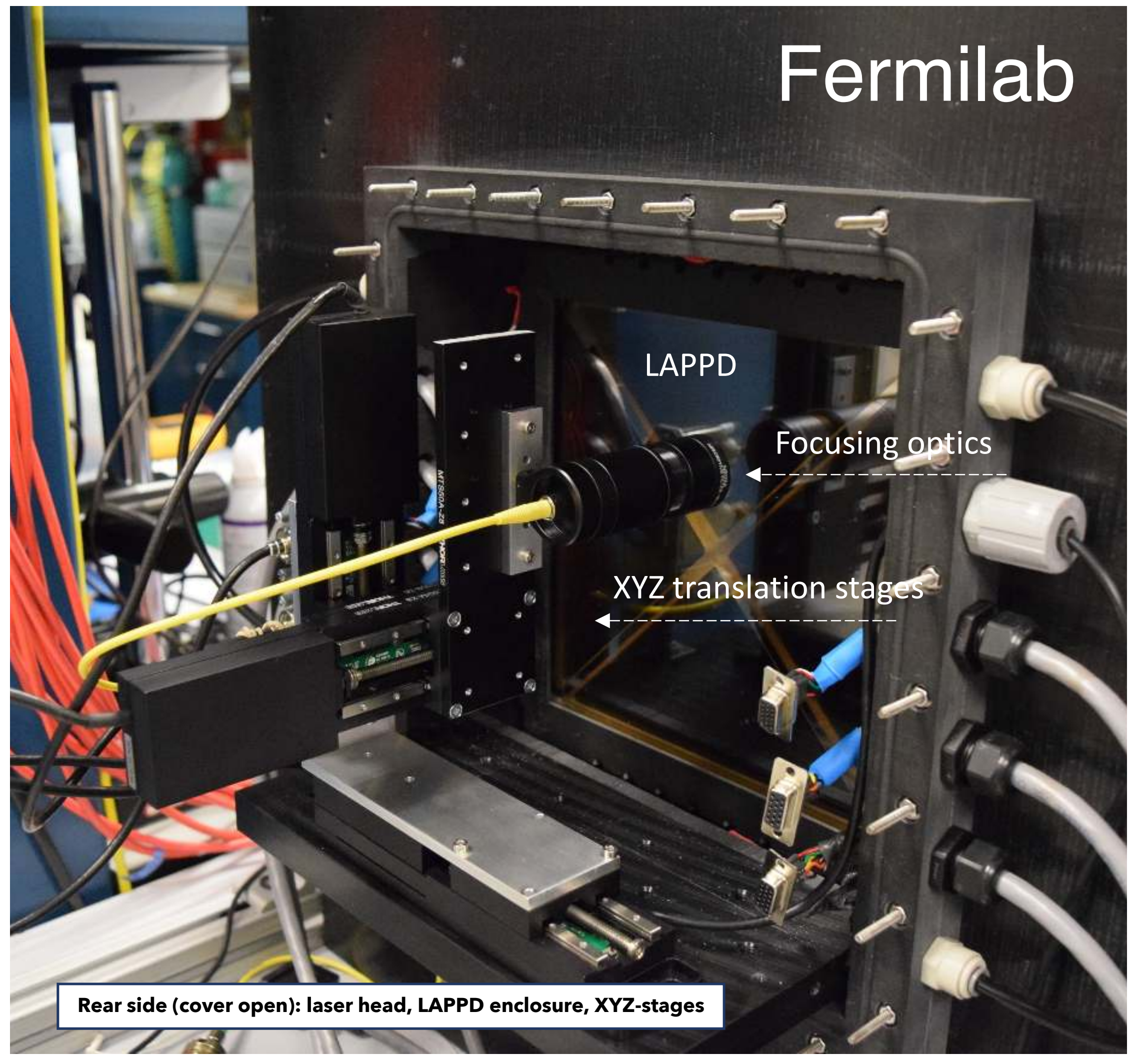
- LAPPD characterization in magnetic field (ANL)
- Beam tests (with a focus on LAPPD timing resolution)
  - Fermilab: June 2022
  - CERN: October 2022
  - also Glasgow, Ljubljana
- DC-coupled HRPPD interfacing
- Work in a (very) close contact with the manufacturer
  - Participation in SBIR proposals
  - Beam tests and other measurements with Incom experts present
- Organization of open LAPPD workshops
- Synergistic activities in the field of medical imaging
- DOE SBIR support



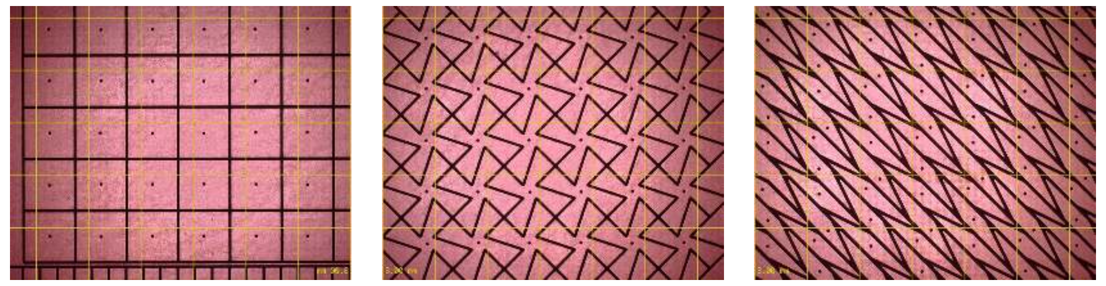








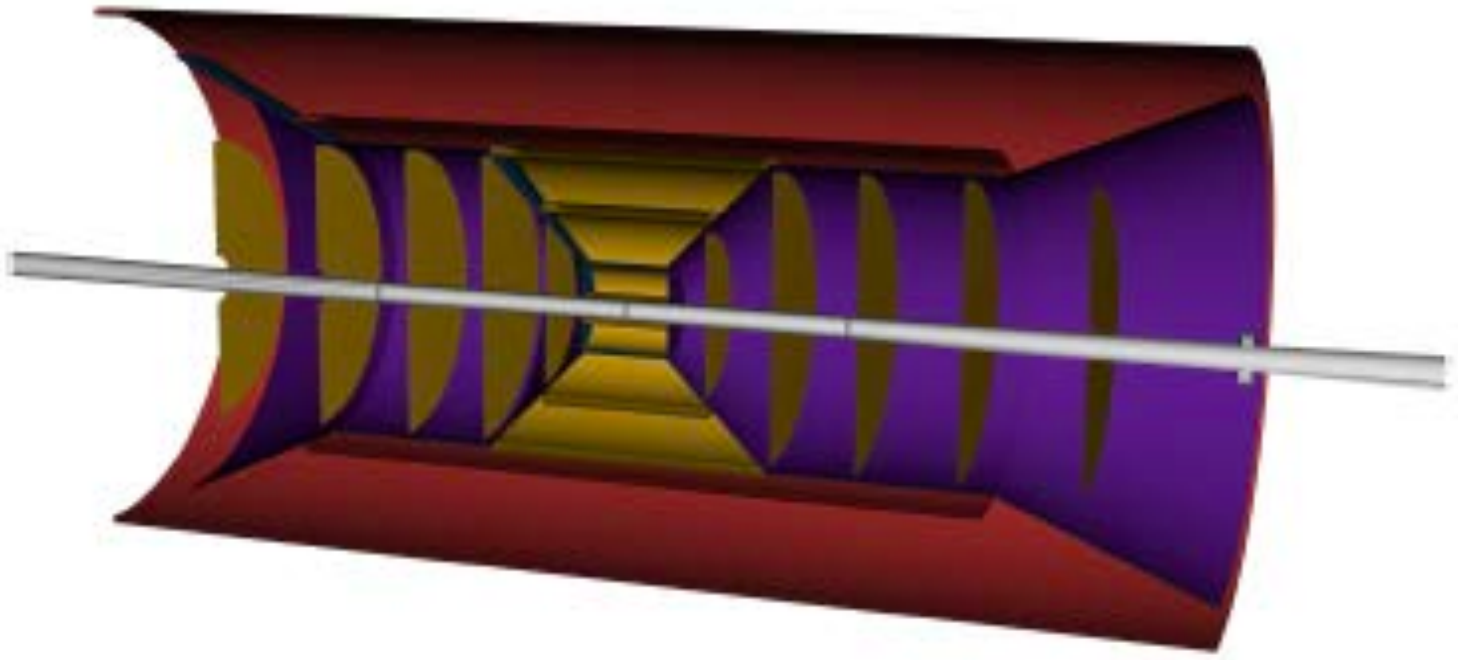
A variety of finely pixelated readout boards



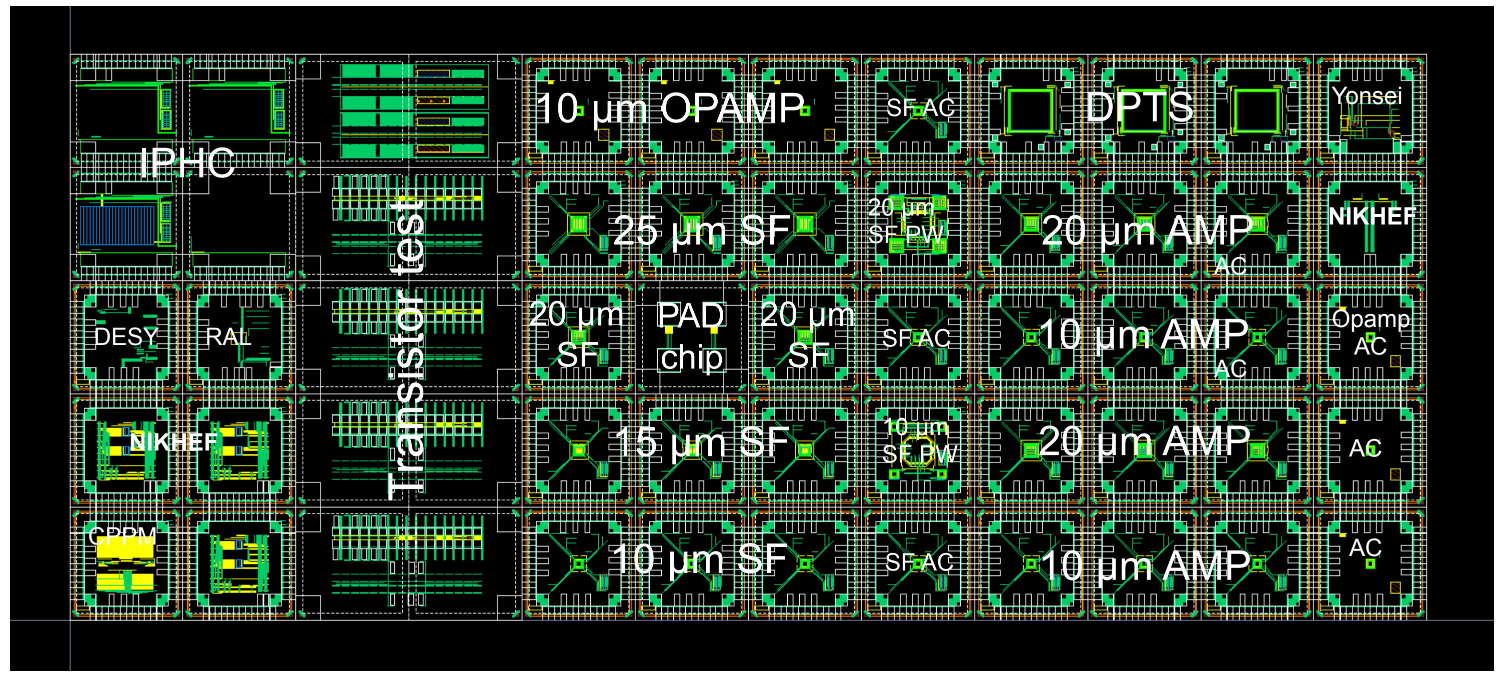
Example: ITS3 MAPS Sensors (eRD25, eRD113)

Parameter	ALPIDE (existing)	Wafer-scale sensor (this proposal)
Technology node	180 nm	65 nm
Silicon thickness	50 µm	20-40 µm
Pixel size	27 x 29 µm	O(10 x 10 µm)
Chip dimensions	1.5 x 3.0 cm	scalable up to 28 x 10 cm
Front-end pulse duration	~ 5 µs	~ 200 ns
Time resolution	~ 1 µs	< 100 ns (option: <10ns)
Max particle fluence	100 MHz/cm^2	100 MHz/cm^2
Max particle readout rate	10 MHz/cm^2	100 MHz/cm^2
Power Consumption	40 mW/cm^2	< 20 mW/cm^2 (pixel matrix)
Detection efficiency	> 99%	> 99%
Fake hit rate	< 10^{-7} event/pixel	< 10^{-7} event/pixel
NIEL radiation tolerance	~3 x 10^{13} 1 MeV n_{eq}/cm^2	10^{14} 1 MeV n_{eq}/cm^2
TID radiation tolerance	3 MRad	10 MRad

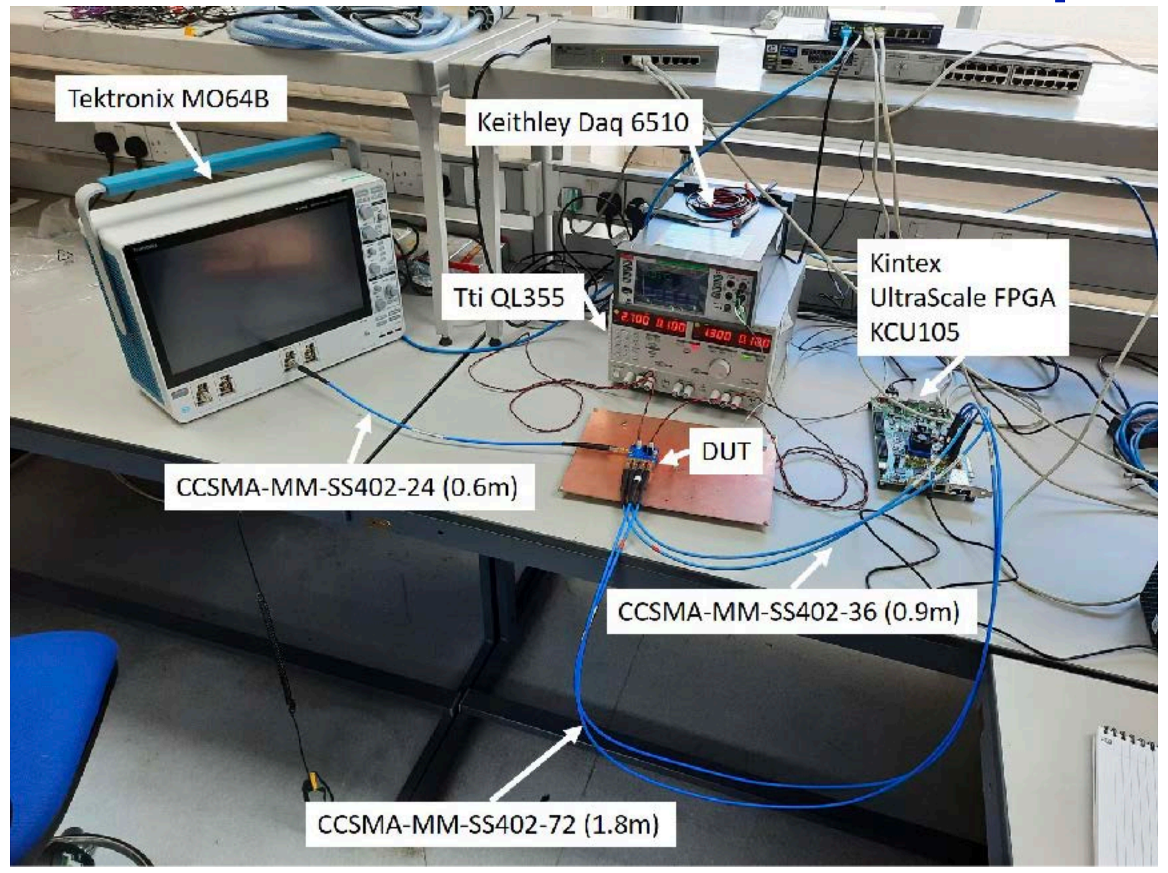
EPIC Tracker



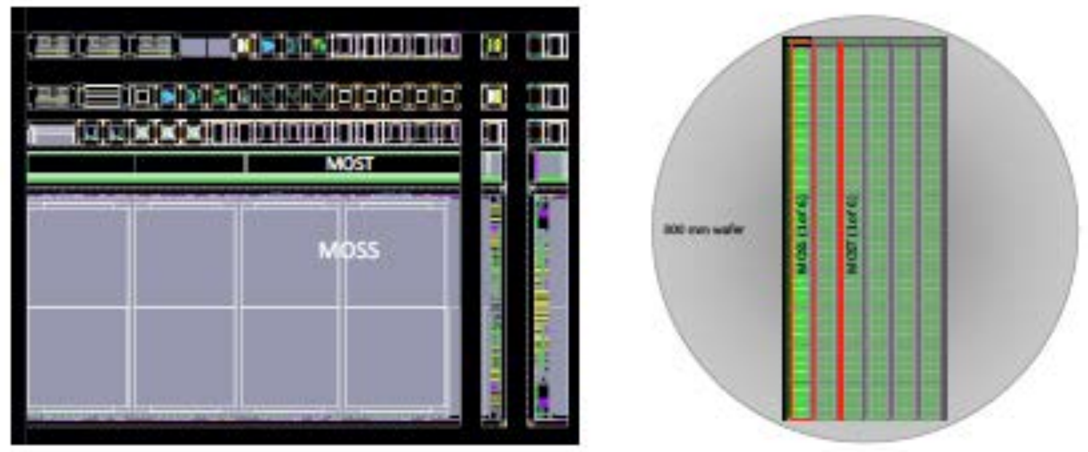
Successful MLR1 submission/performance



Characterization EIC UK Groups



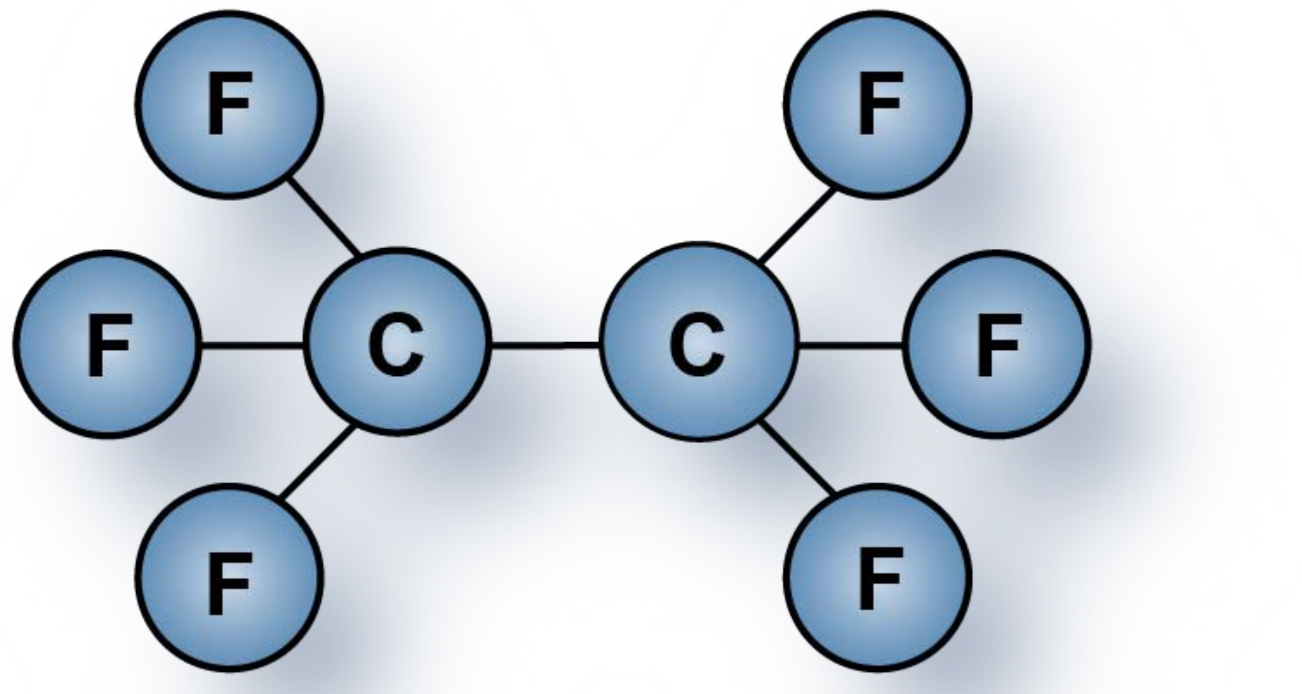
First Engineering Run Q4 2022



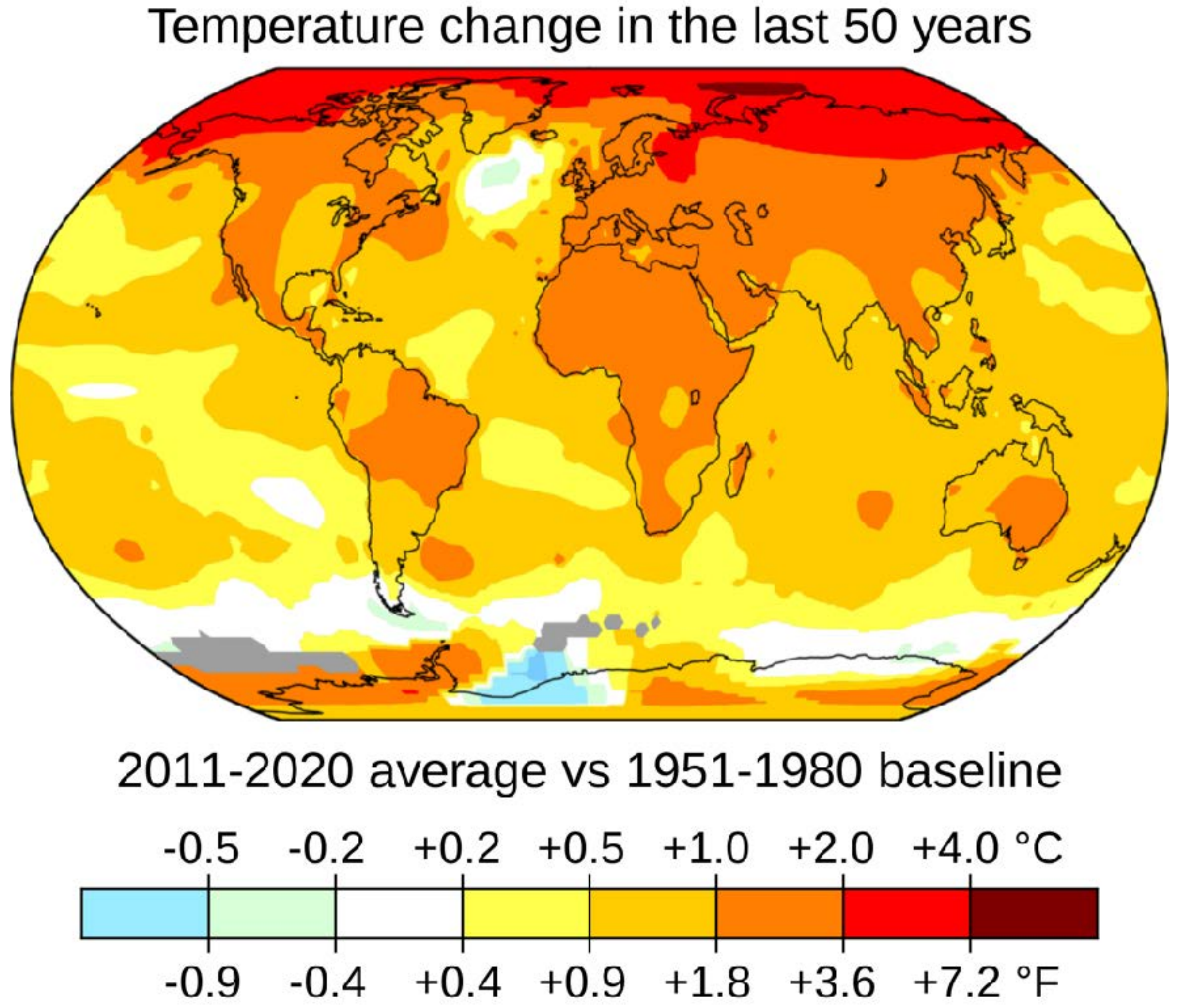
- EIC Vertex & Tracking Requirements:
  - Spatial resolution: ~5 µm, material budget < 0.3% X/X_0 per layer, integration time ~2 µs, low power consumption (air cooling)
  - Consensus that technology of choice is MAPS but none of the existing MAPS sensors meets all of the requirements
- **EIC MAPS**
  - EIC Si Consortium joined forces with ALICE/ITS3 collaboration developing novel MAPS sensor
  - Goal is to develop Large-area, wafer-scale, stitched sensors bent around beam pipe using latest 65 nm MAPS technology
  - EIC sensor development needs to fork-off later to develop an ITS3-derived sensor for outer layers (non stitched wafer-scale sensors)

Example: Radiator Gases

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



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



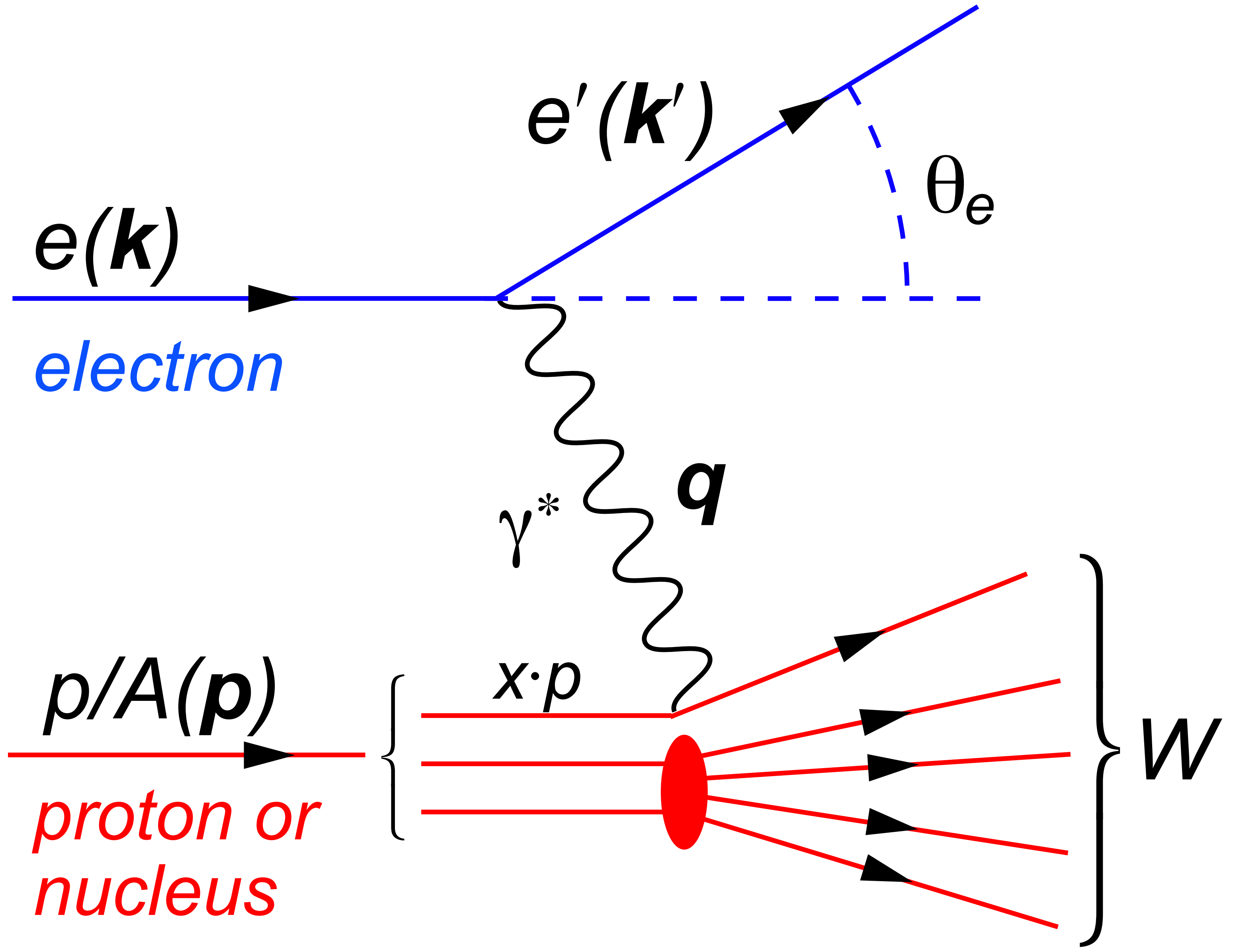
Take Away Message

- An Electron-Ion Collider will contribute profoundly to the understanding of matter and be an important component in our suite of tools to revolutionize our knowledge in the next decades
- Detector requirements are established in Yellow Report (arXiv:2103.05419)
- EIC Detectors are unique and challenging to realize
  - Hermiticity, PID, high precision, low material, complex IR
- EPIC Collaboration formed
  - Ongoing efforts focused on consolidation and developing EPIC technical design for CD-2/3A
  - 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
- Instrumentation challenges: Photodetectors, high resolution EM calorimetry, wafer-scale stitched sensors MAPS, μRWell, replacement of global warming gases
- Sound generic R&D program from 2011-2021, new project R&D program in place to reduce remaining risks and strong new generic R&D program starting in 2022!

EIC Talks at CPAD '22: MPGD (M. Posik), AC-LGAD (O. Hartbrich), SiPM/dRICH (P. Antonioli), Calorimetry (C. Woody), Imaging Calorimeter (J. Kim), Fwd EMCal (Z. Ji), LFHCAL (N. Novitzky), Insert Cal (M. Arratia), LAPPD (J. Xie), LAPPD (A. Kiselev)

Backup Slides

Deep Inelastic Scattering (DIS)



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

Q^2: resolution power, virtuality

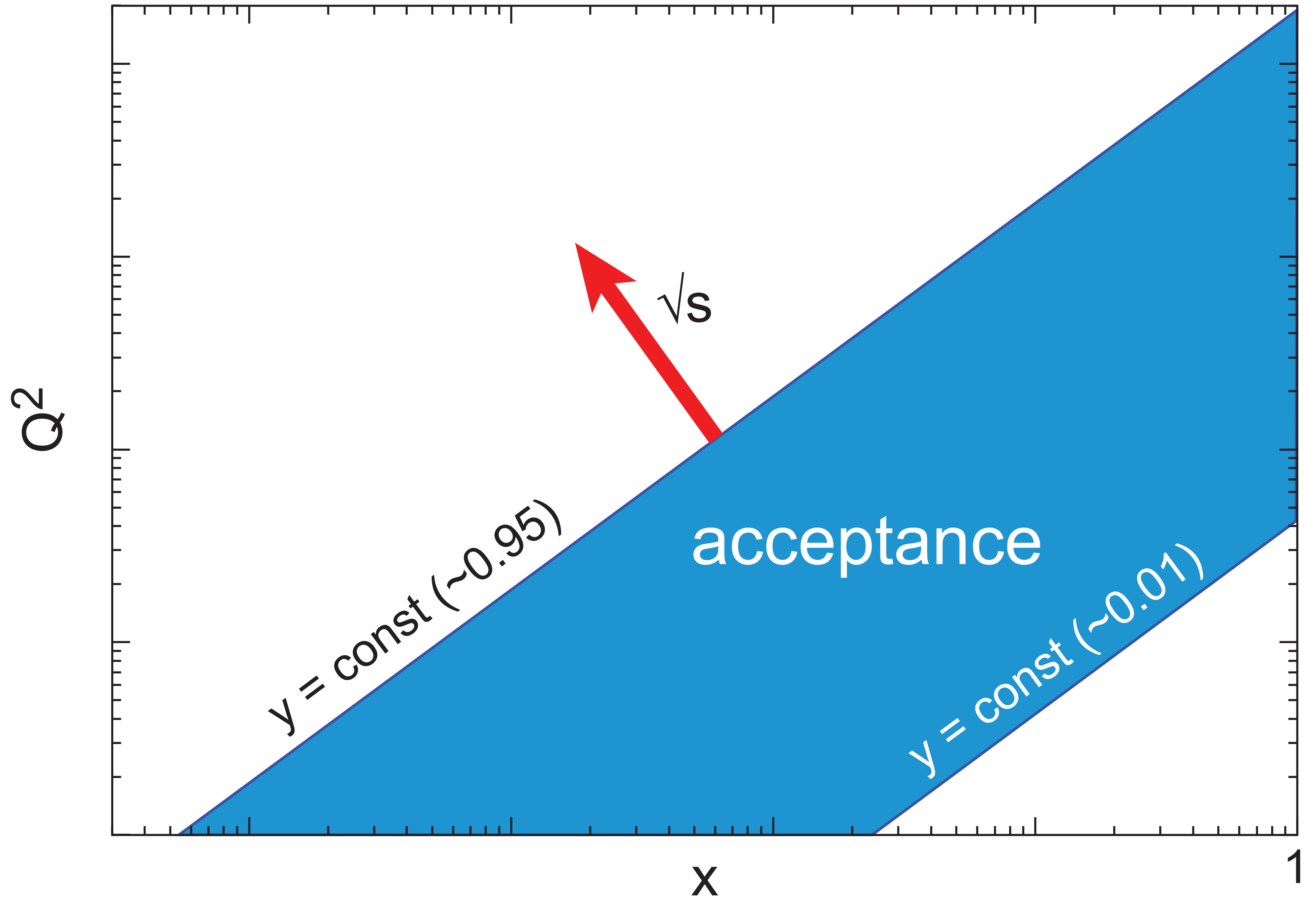
s: center-of-mass energy squared

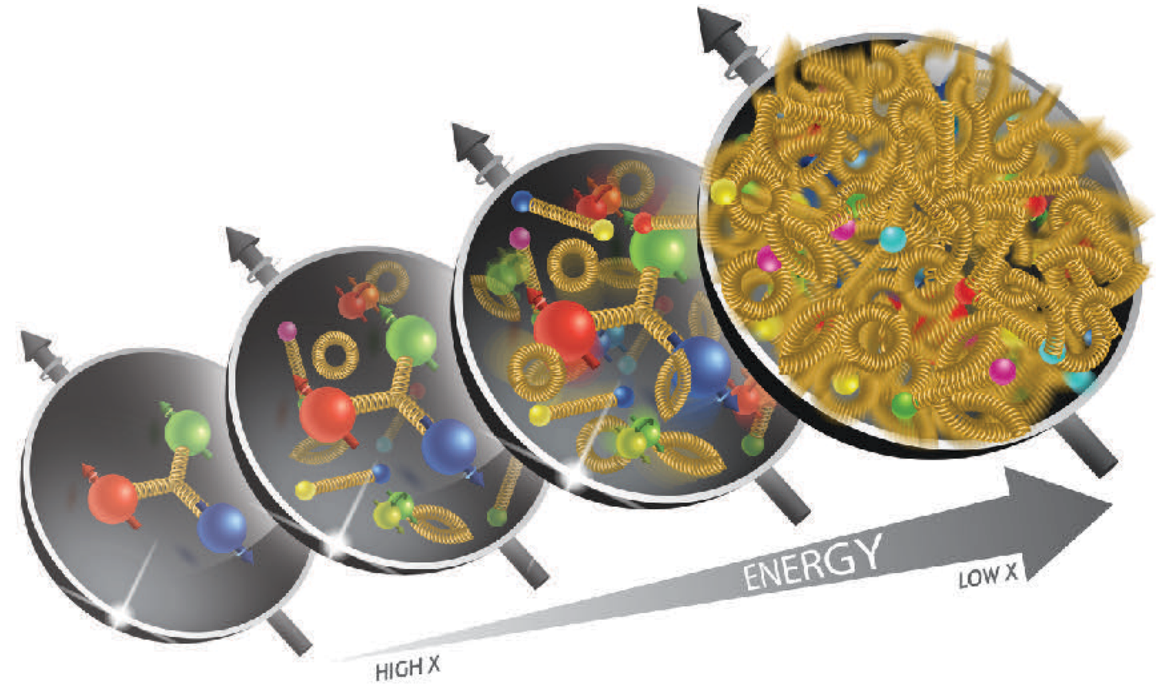
x: momentum fraction of nucleon's momentum carried by parton (0 < x < 1)

y: inelasticity (0 < y < 1)

DIS:

- As a probe, electron beams provide unmatched precision of the e.m. interaction
- Direct, model independent, determination of kinematics of physics processes



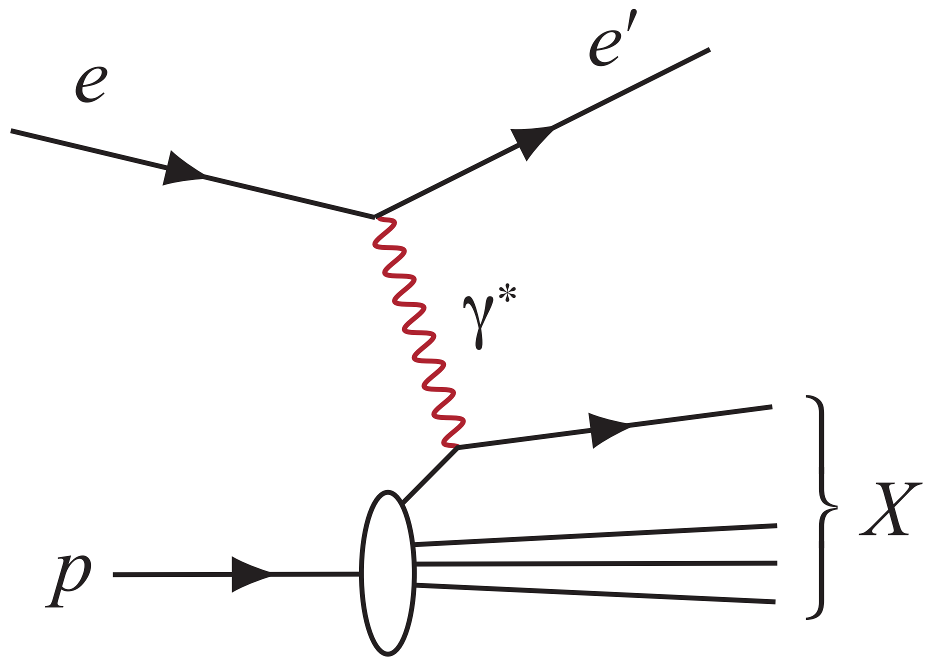


Gluons dominate matter for $x < 0.1$

Category of Processes to Study

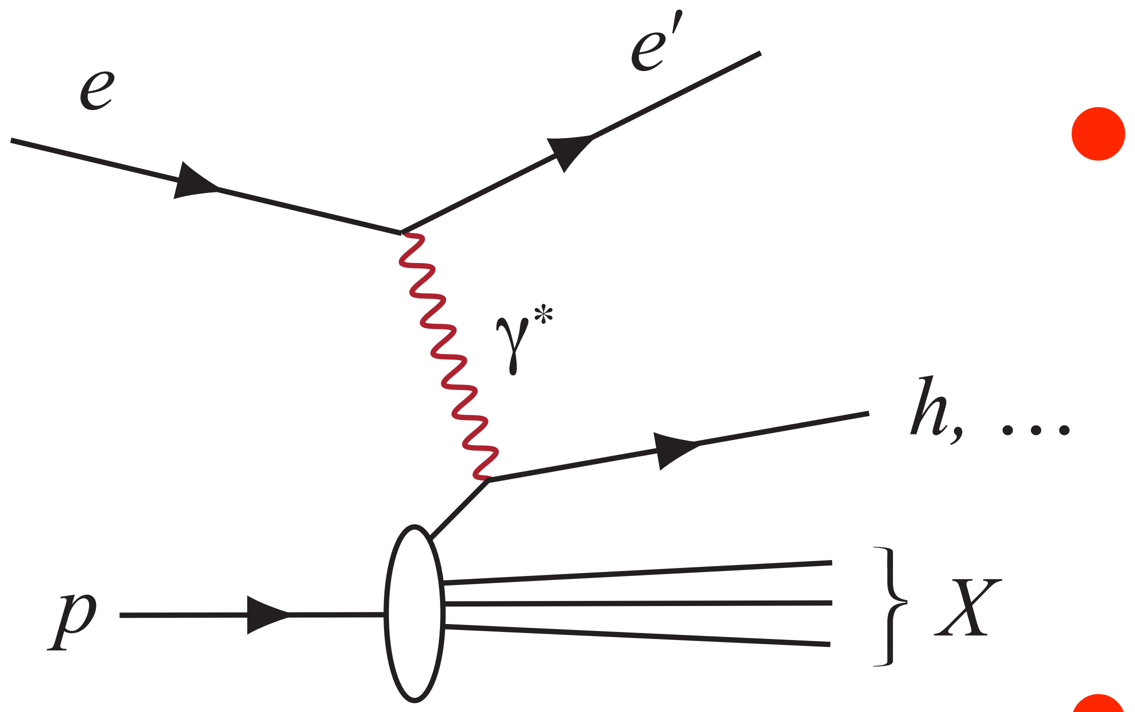
Measurement categories to address EIC physics:

$\int \mathscr{L} dt$



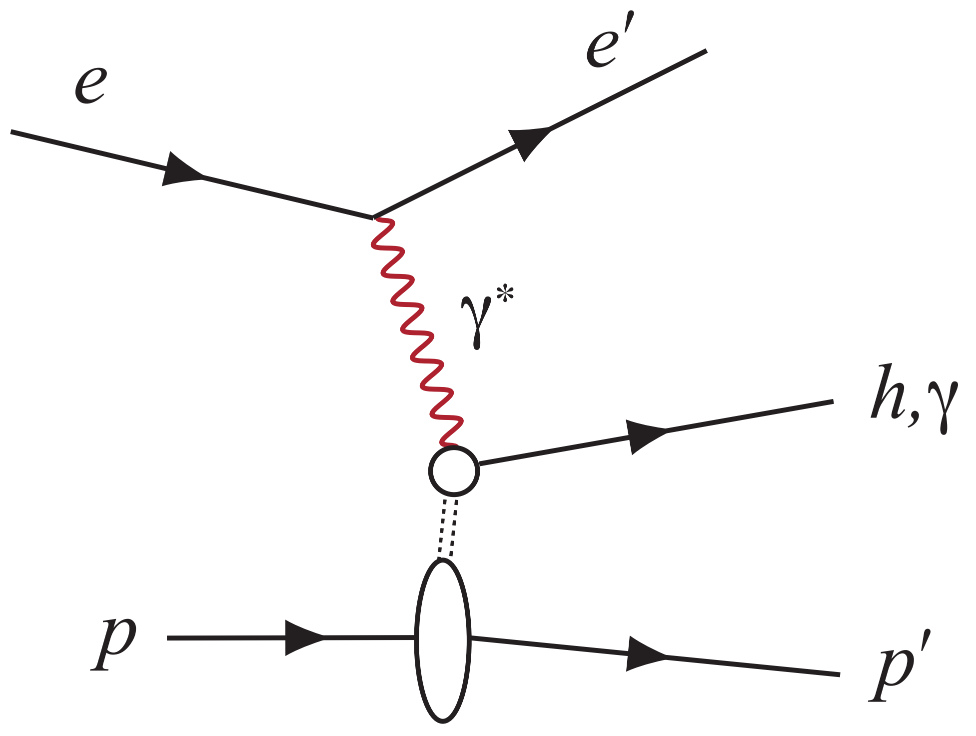
- Inclusive DIS (e')
  - fine multi-dimensional binning in x, Q^2

1 fb^{-1}



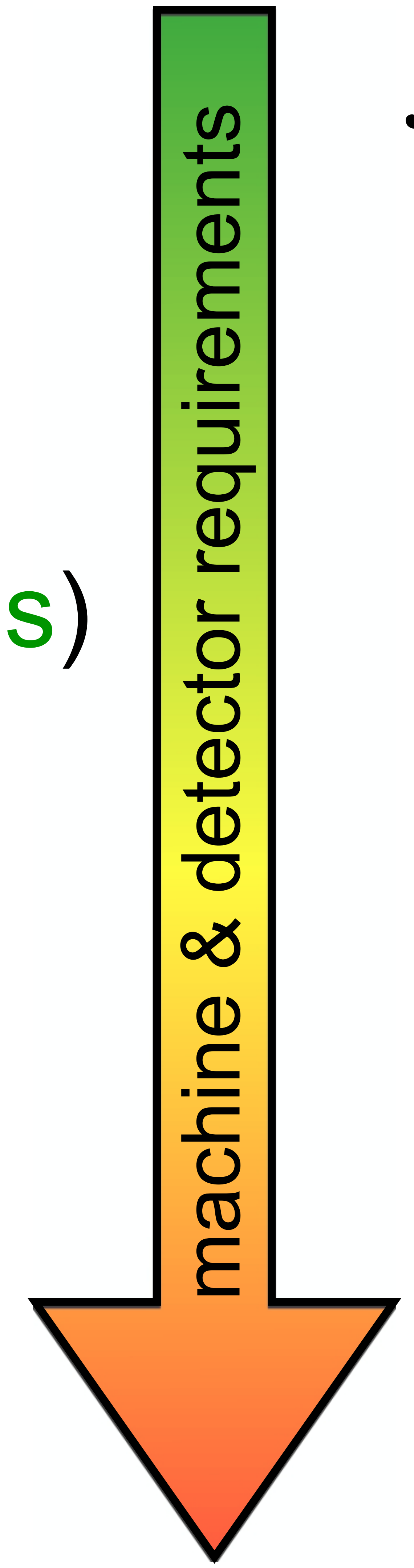
- Semi-inclusive DIS / SIDIS (fwd hadrons)
  - 5-dimensional binning in x, Q^2, z, p_T, θ

10 fb^{-1}



- Exclusive processes (hermeticity)
  - 4-dimensional binning in x, Q^2, t, θ to reach |t| > 1 GeV2

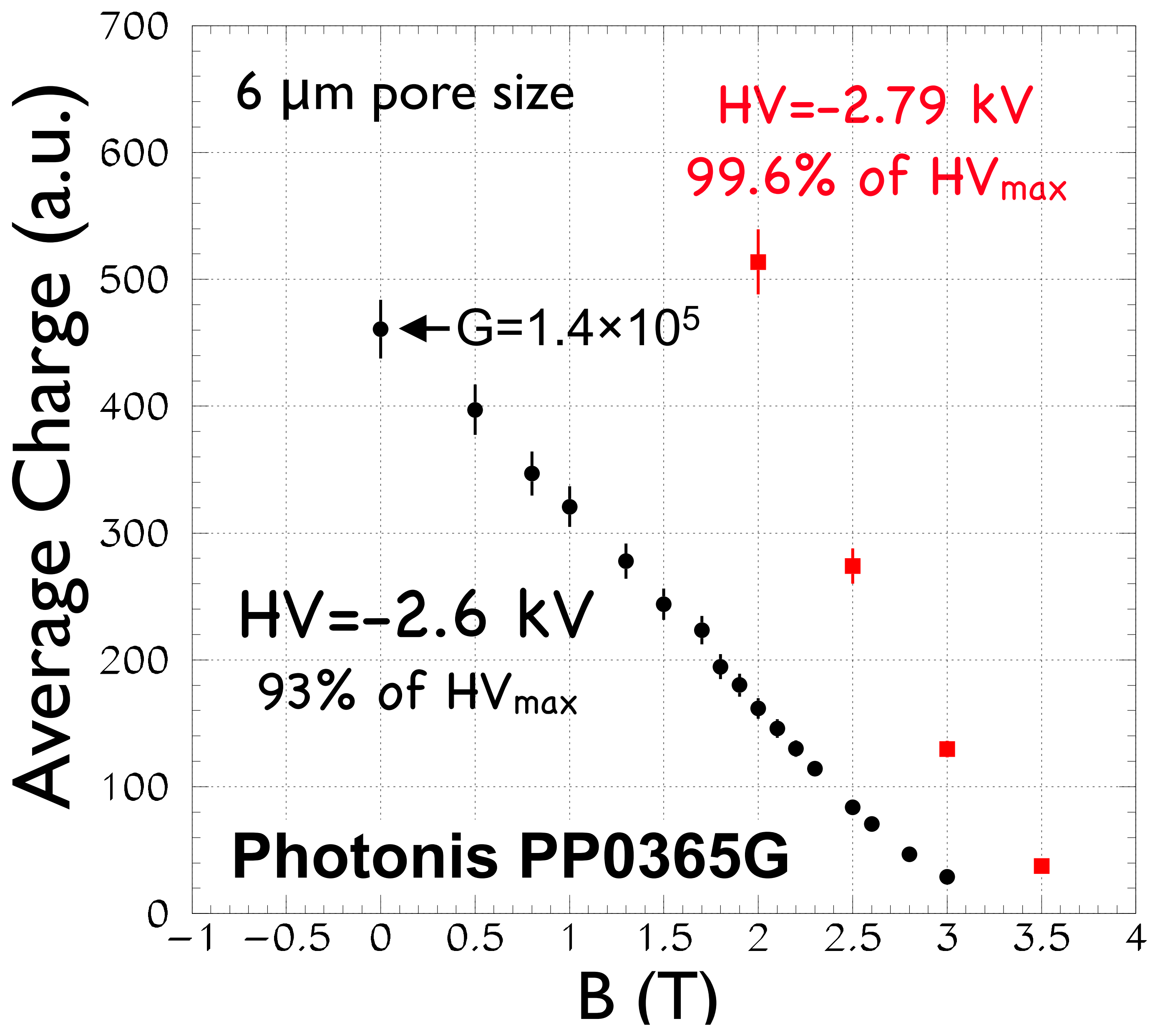
10-100 fb^{-1}

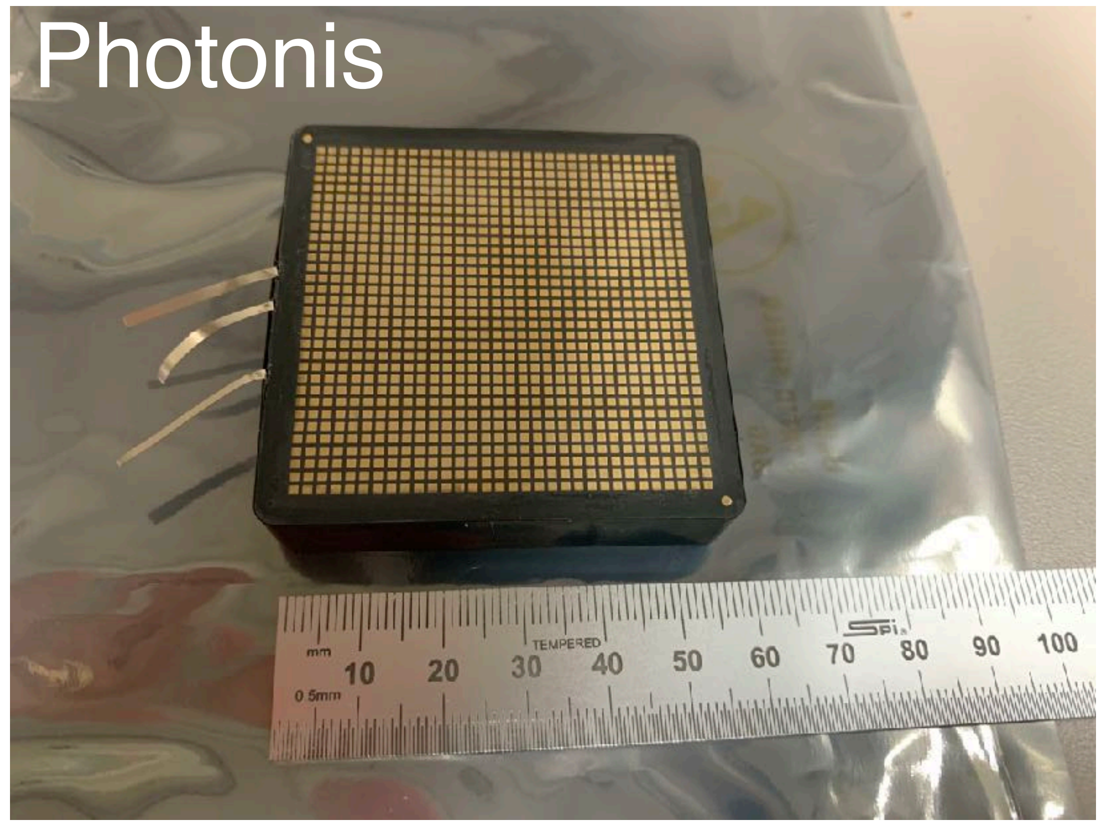


Example: Photosensors (eRD14 & eRD110)

- EIC requires highly-pixilated photodetectors working at 1.5-3 T. This problem is most critical for RICH detectors and is not fully solved yet.
- Currently
  - Calorimetry ➟ SiPM (~OK)
  - RICH detectors ➟ SiPM (noise, mitigation strategies)
  - hpDIRC ➟ MCP PMT (~OK but expensive, field resistance on edge)

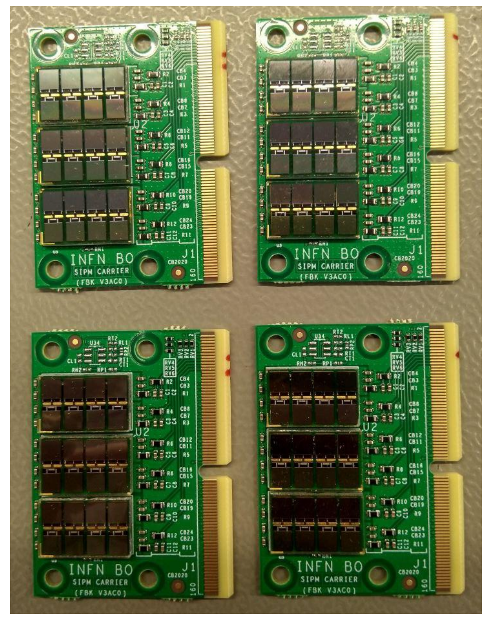
- <u>MCP-PMTs</u>
  - On market: Photonis/Photek
  - Characterization of performance in eRD14
  - Not tolerant to magnetic fields (angle!)
  - OK for hpDIRC (readout in low B region)
  - No collaboration with vendor



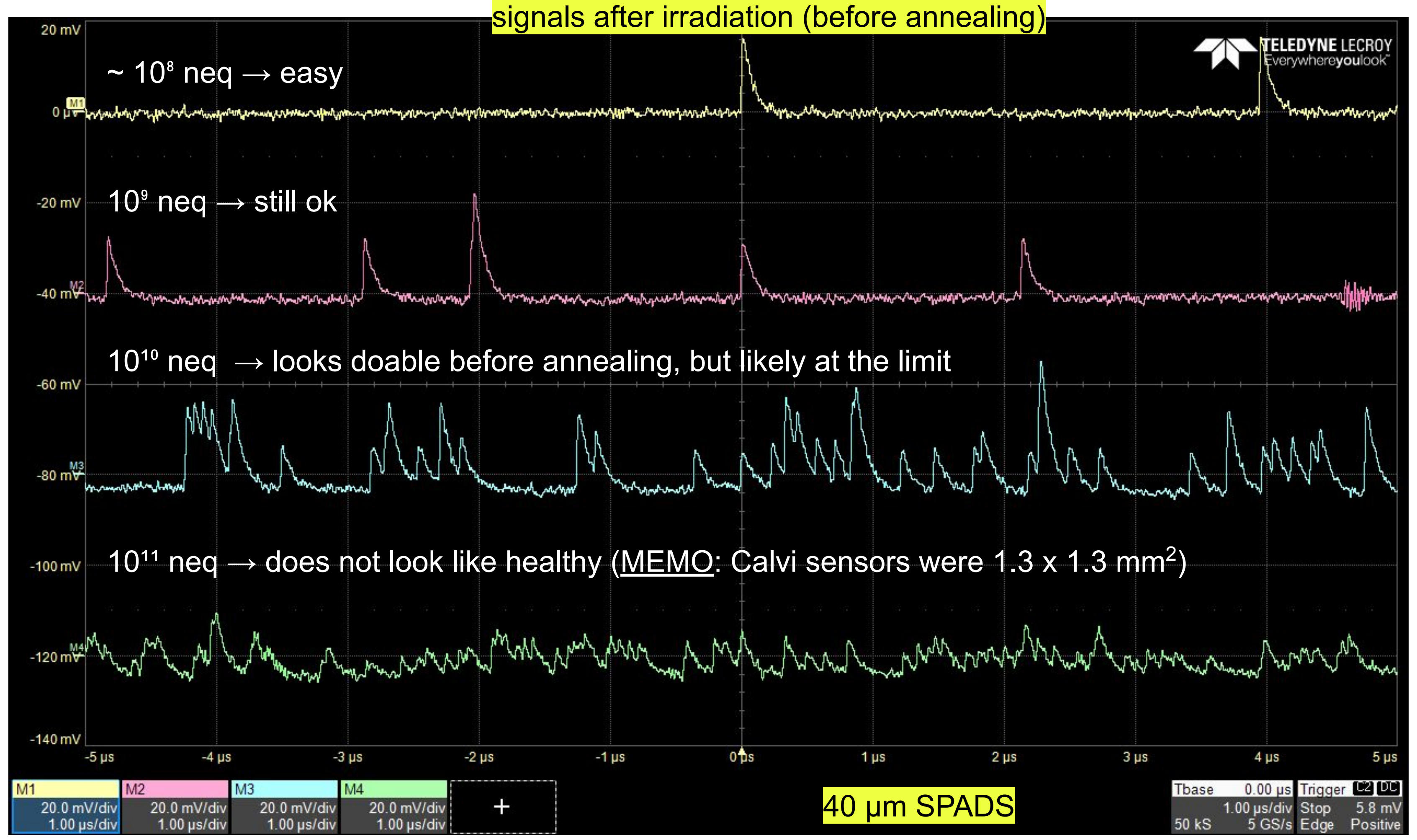


Example: Photosensors (cont.)

- SiPM
  - Pros: high photon efficiency, good time resolution, insensitive to magnetic field
  - Cons: large dark count rates (data rate!), not radiation tolerant
  - 10^{11} (1-MeV) neq/cm at dRICH sensor location reached after 10 years



Courtesy R. Preghenella



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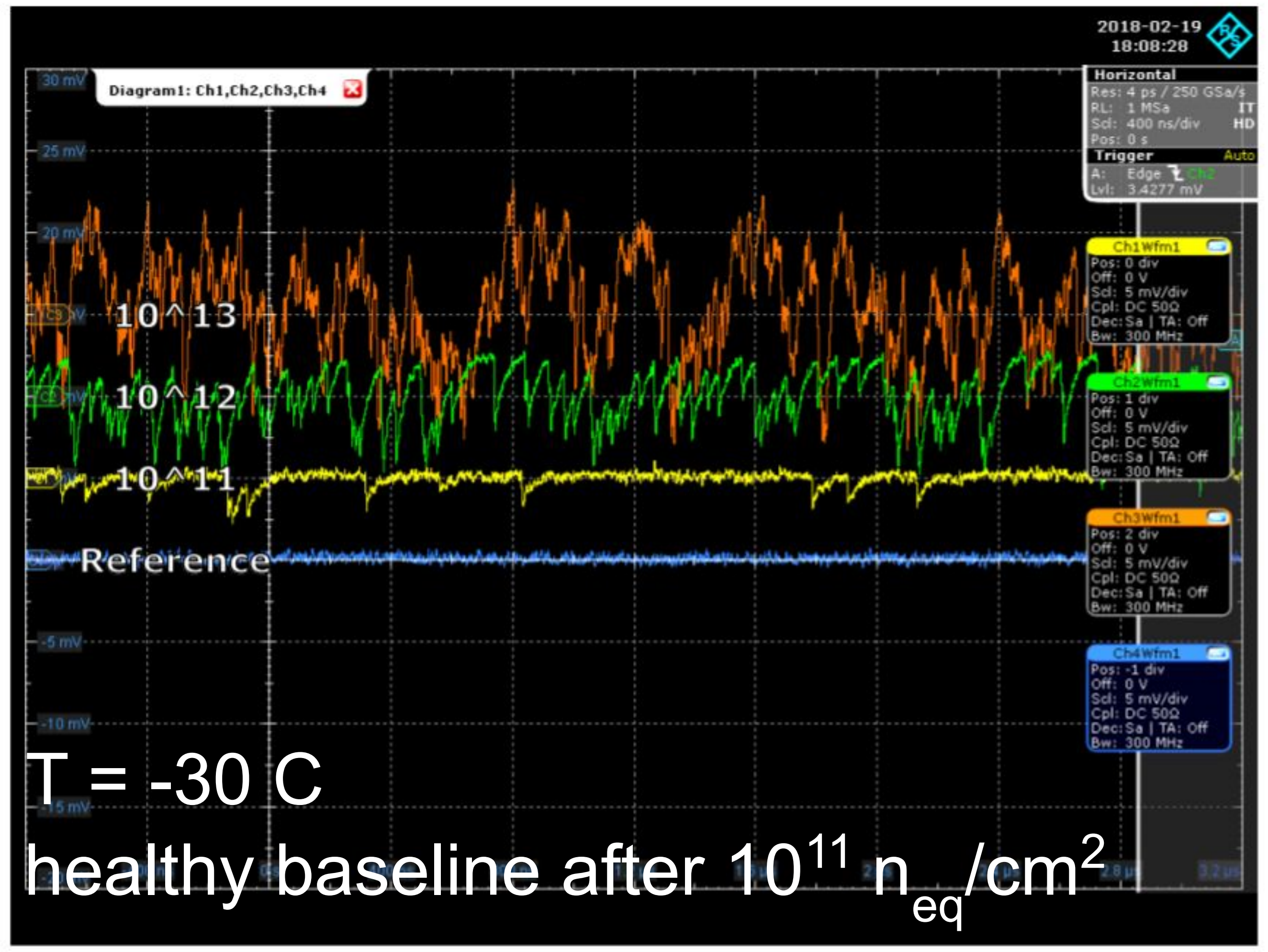
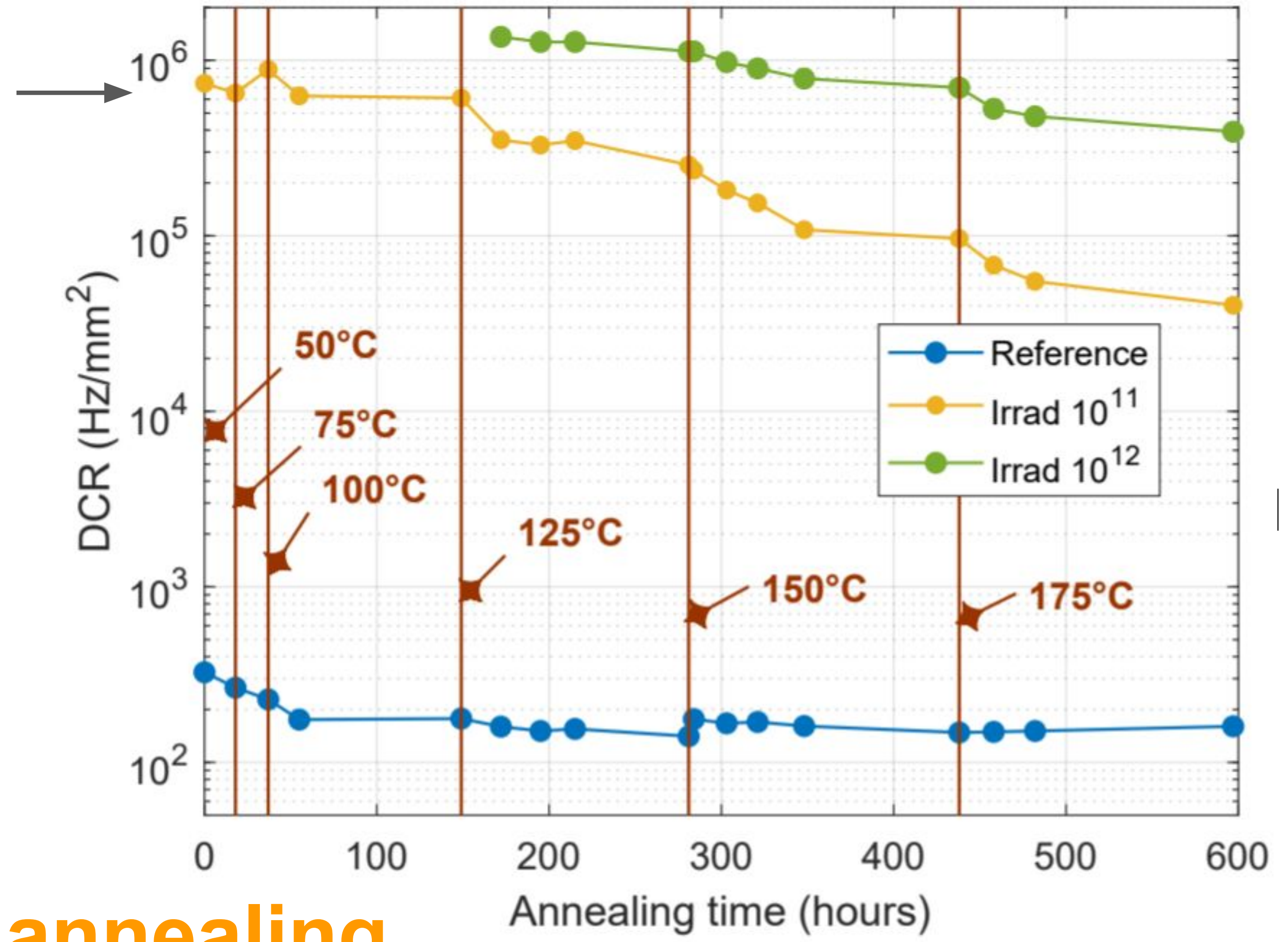


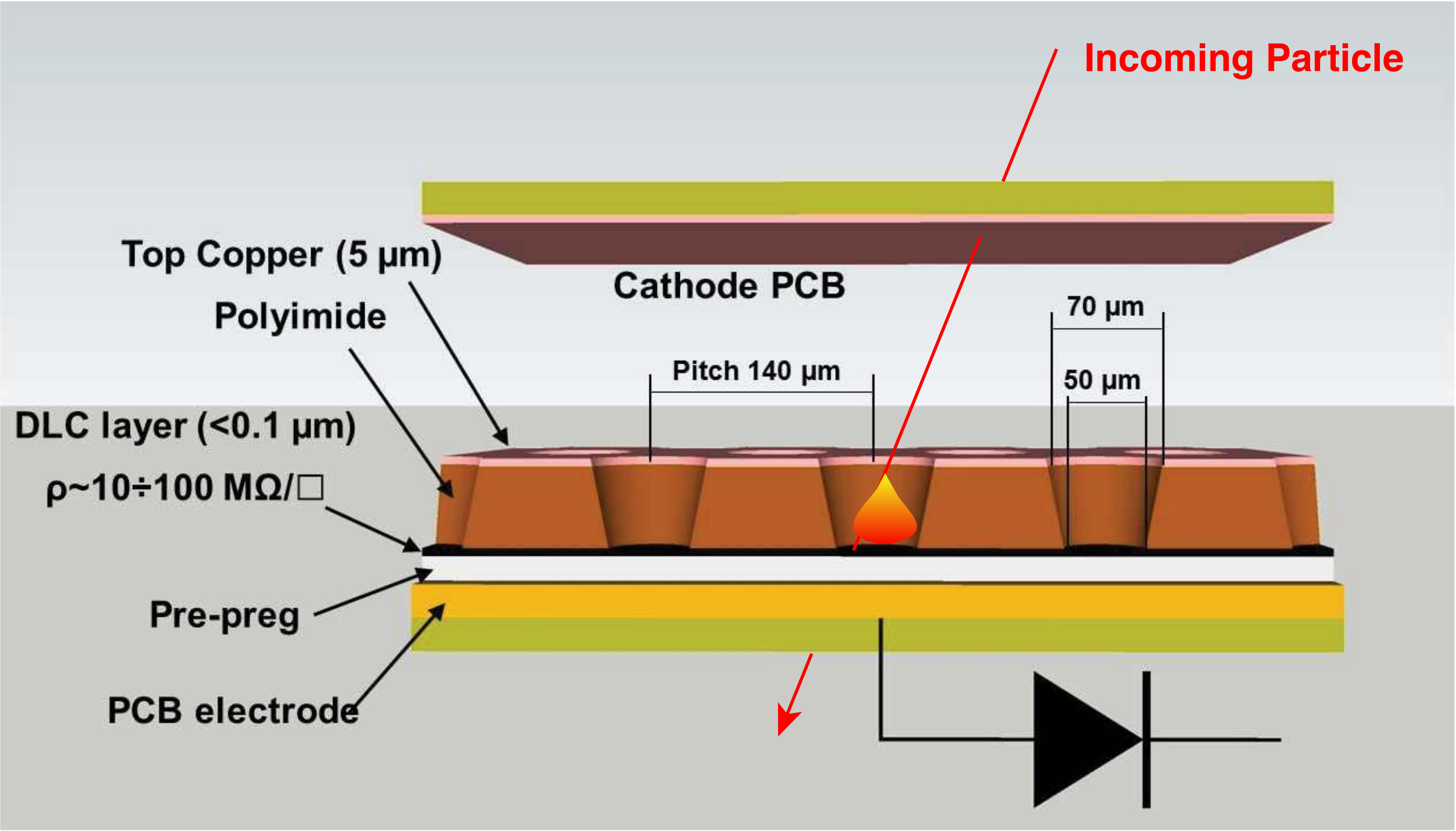


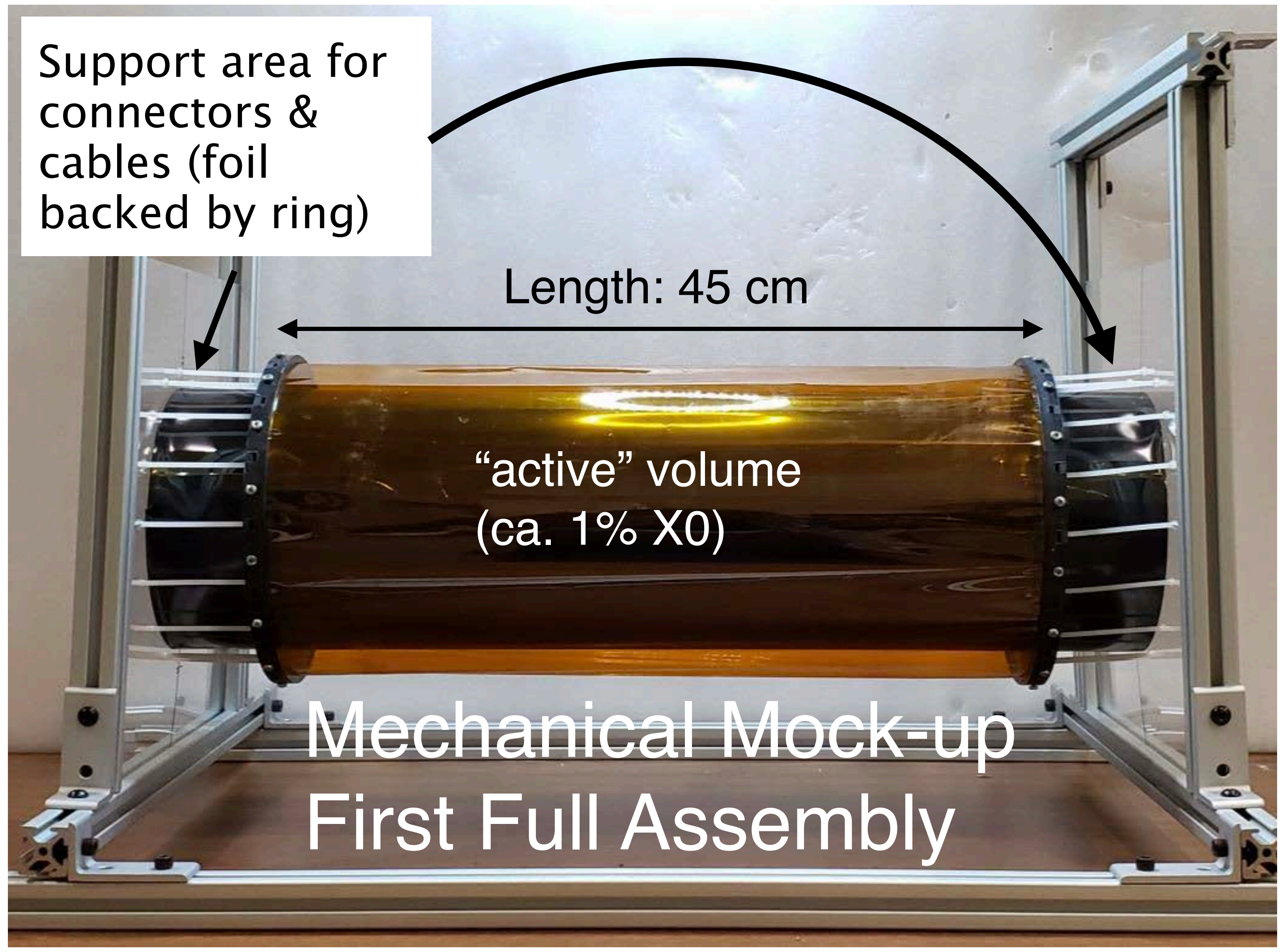
annealing

- Mitigation:
  - Cooling ($T < -30°$) & annealing cycles ($T > 120°$), anneal-in-place needed
  - Variations in devices from different providers ➟ detailed characterization
  - Lots of synergy with efforts in Italy (INFN) & collaboration with FBK
  - Unclear how to modify SiPM design to achieve better radiation hardness (S13360-3050US stands out!)

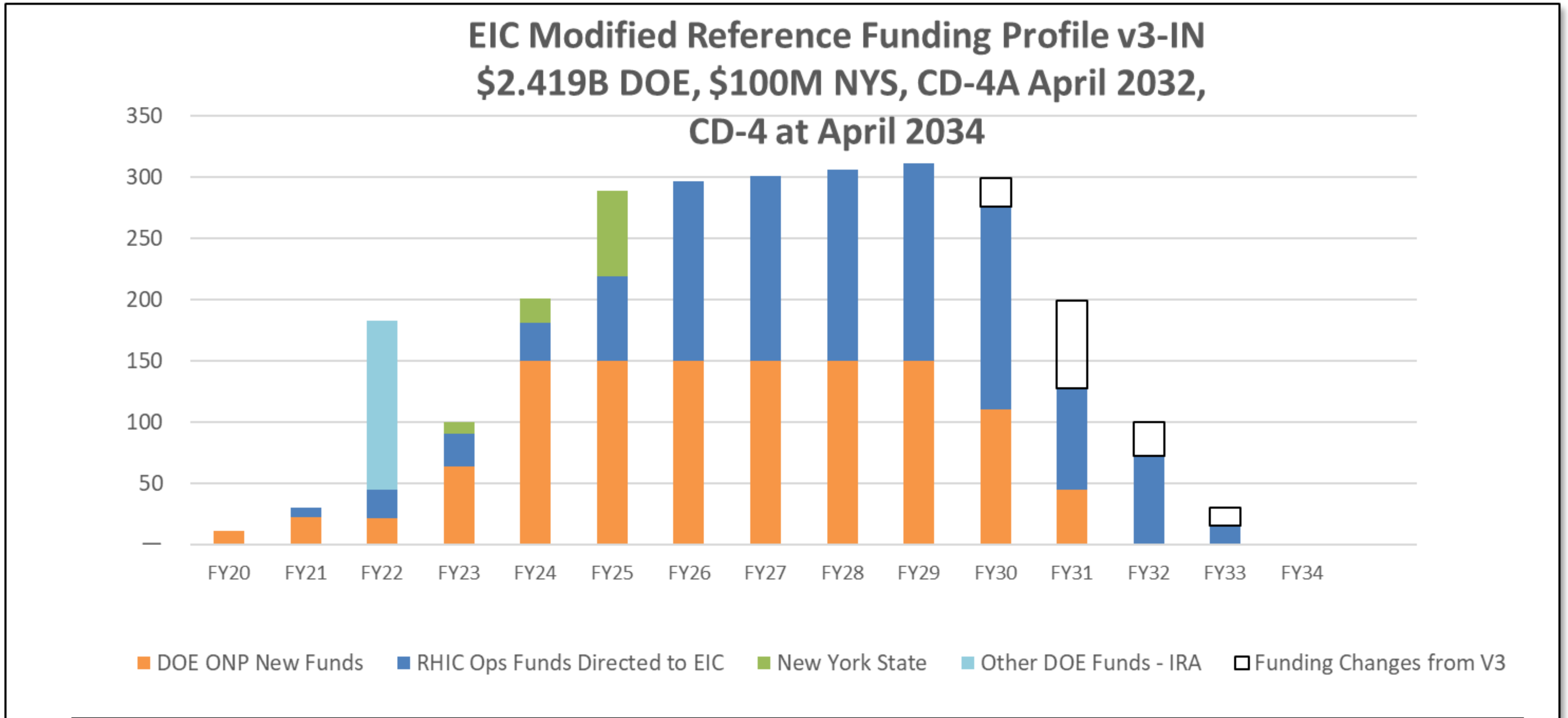
Example: Cylindrical and Planar μRWell (eRD6, eRD108)

- Barrel (cyl.) and endcap (planar) tracking using MPGDs
- μRWell technology is recent development
- Use instead GEMs or Micromegas
  - combines the advantages of GEM and Micromegas
  - easier detector construction, no stretching as for GEMS
  - lower material budget
  - save around 25% in material cost
- Envision capacitive-sharing pad readout: Vertical stack of pads layers → transfer of initial charge from MPGD by capacitive coupling
- Has not yet been adopted in any experiment



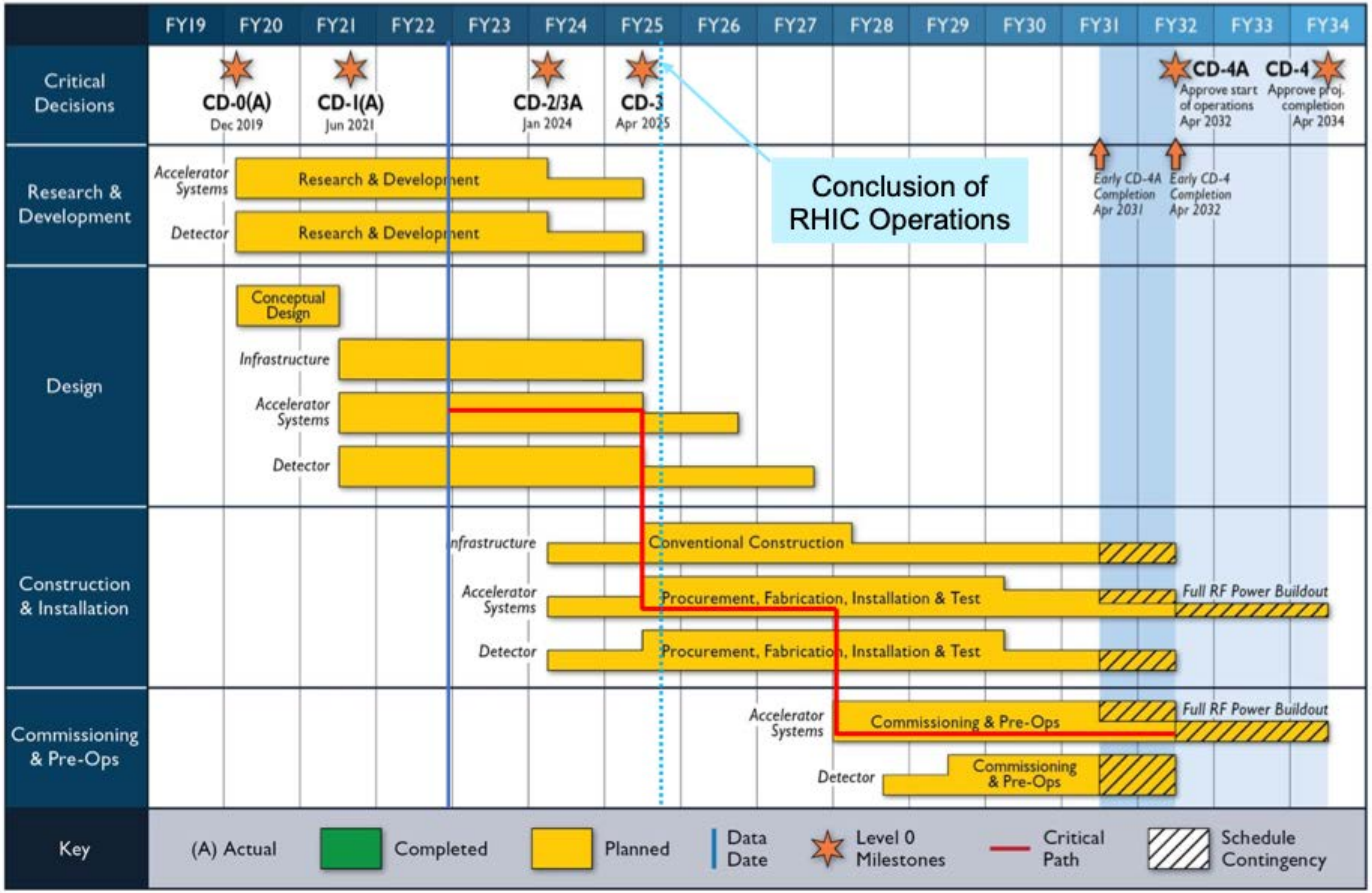


DOE Funding Plan

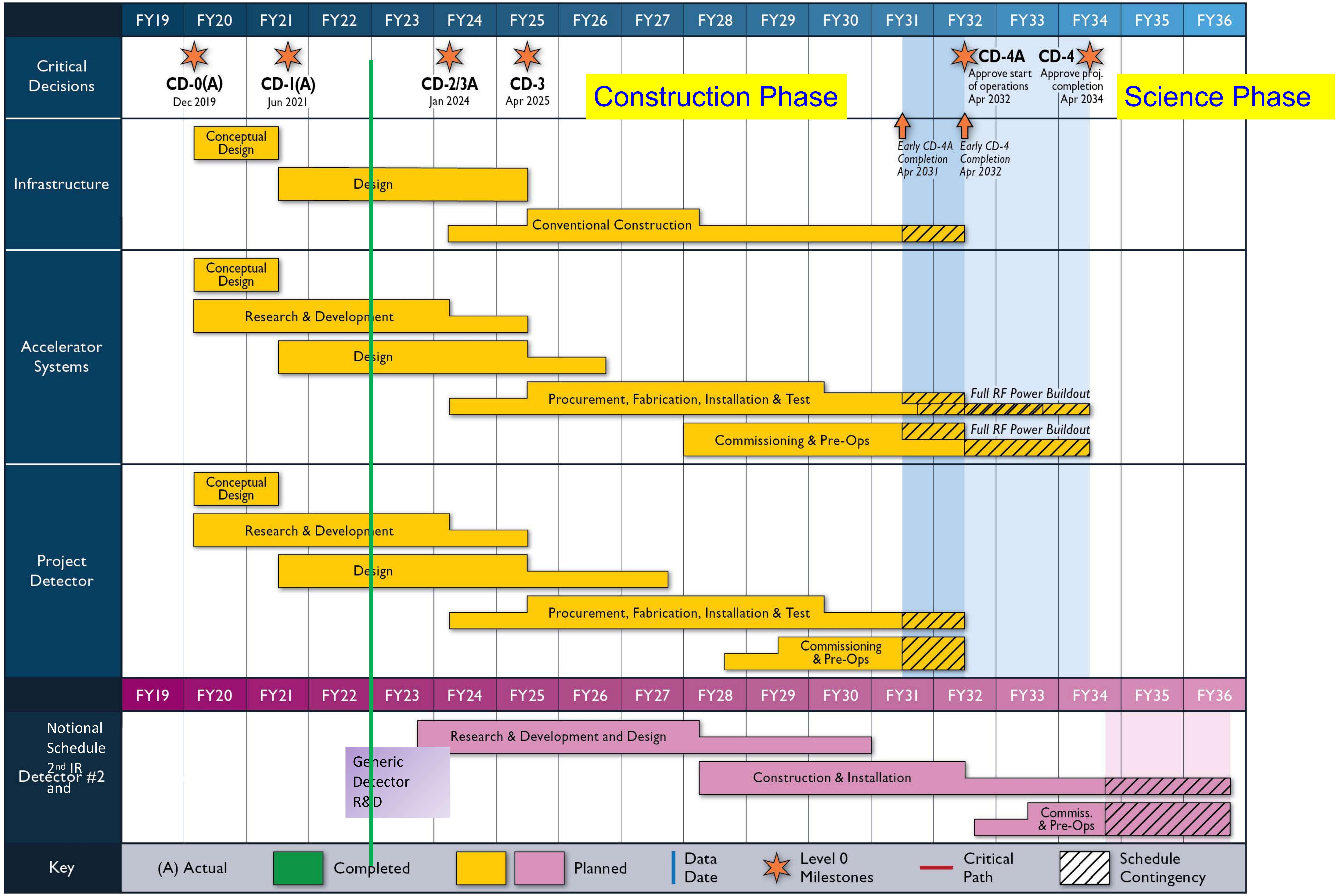


- **Inflation Reduction Act funding of $138.24M** is a game changer and mitigates risk of slower than optimum ramp of new funding to the $150M/year needed.
- Possibility of significant package of long lead procurement items (CD-3A) helping to mitigate risks including procurement, supply chain, inflation and schedule.

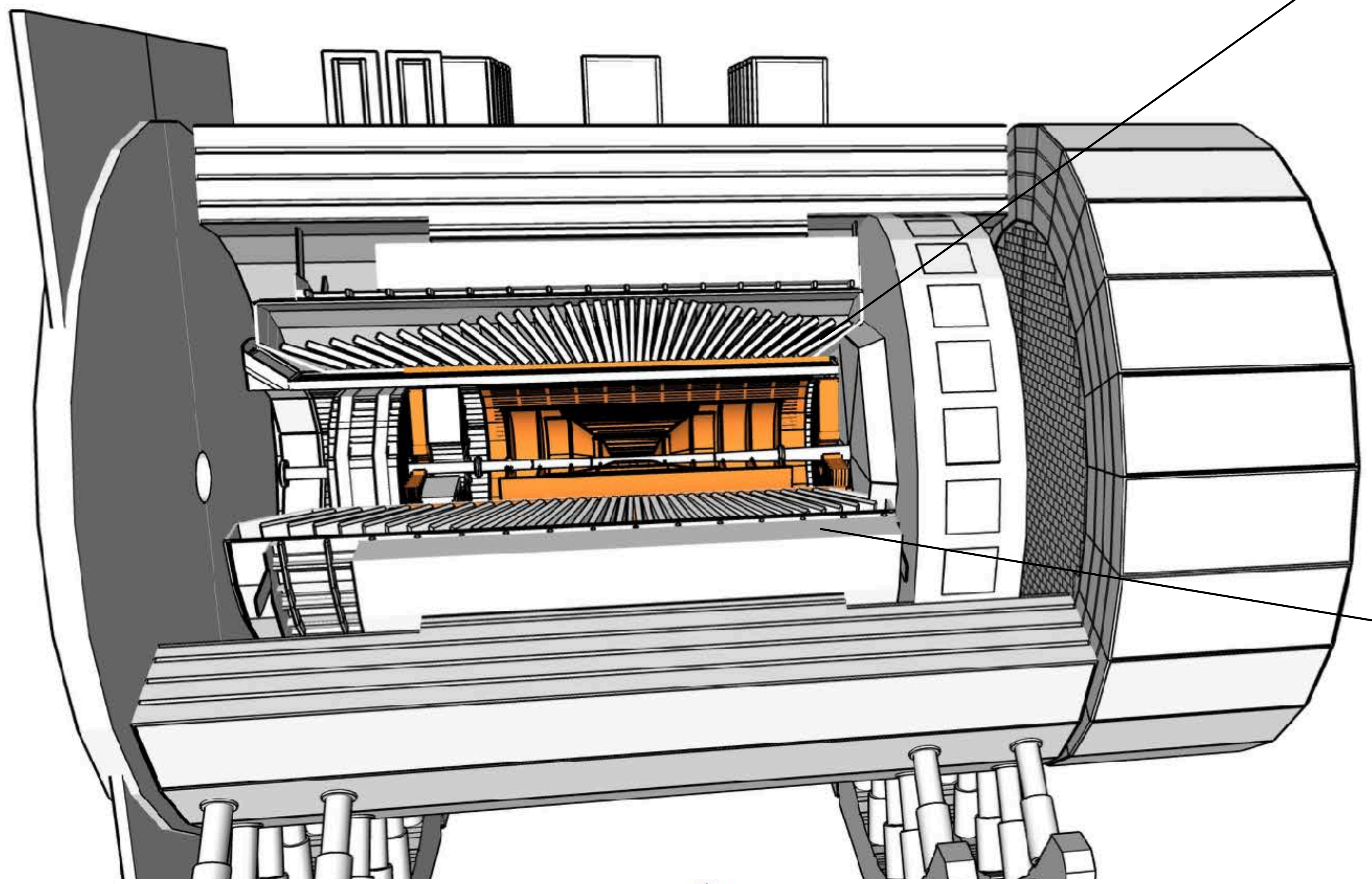
EIC Reference Schedule - V3

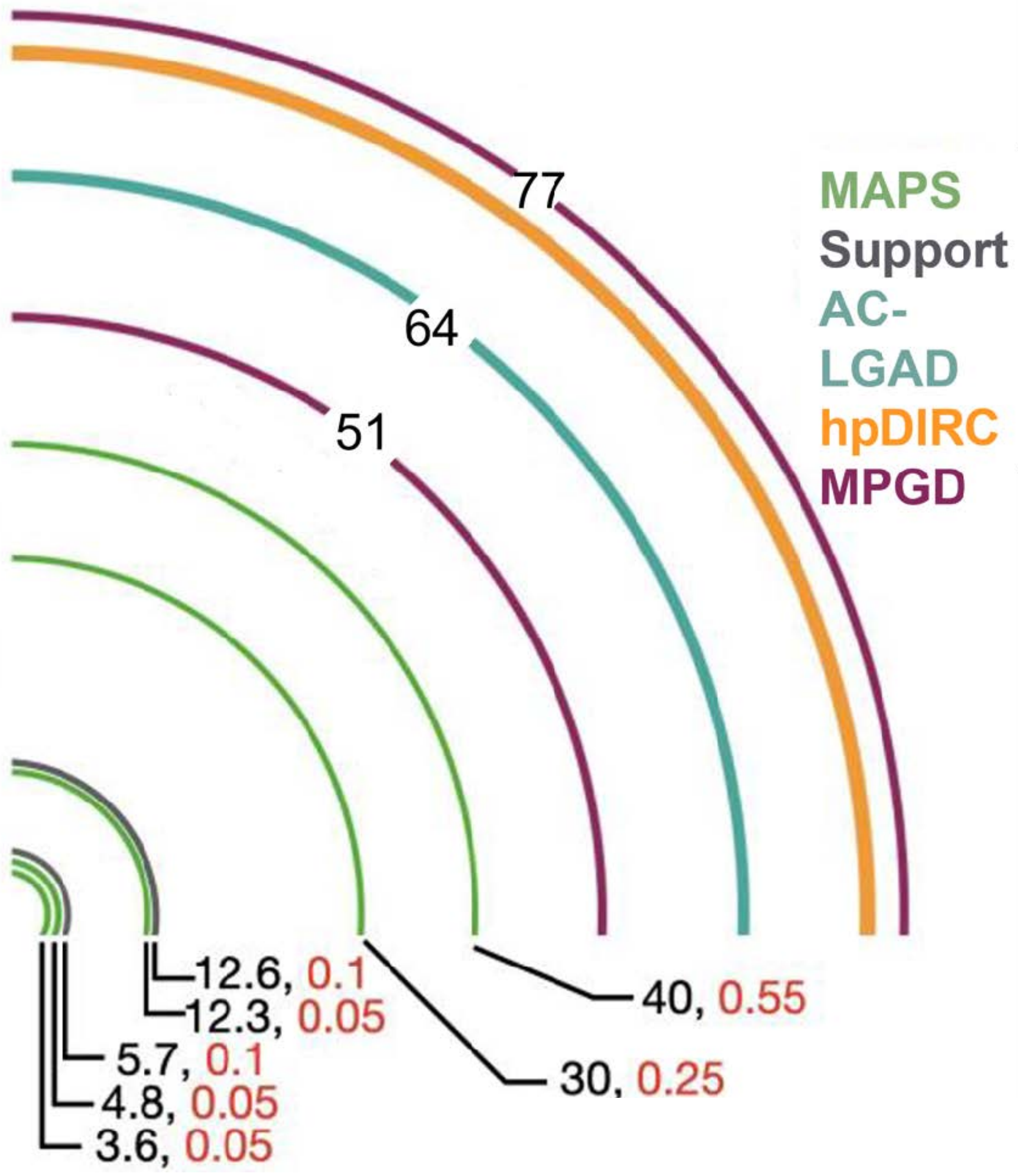


Reference Schedule for 2nd IR and Detector



Tracking





Black numbers are radii in cm

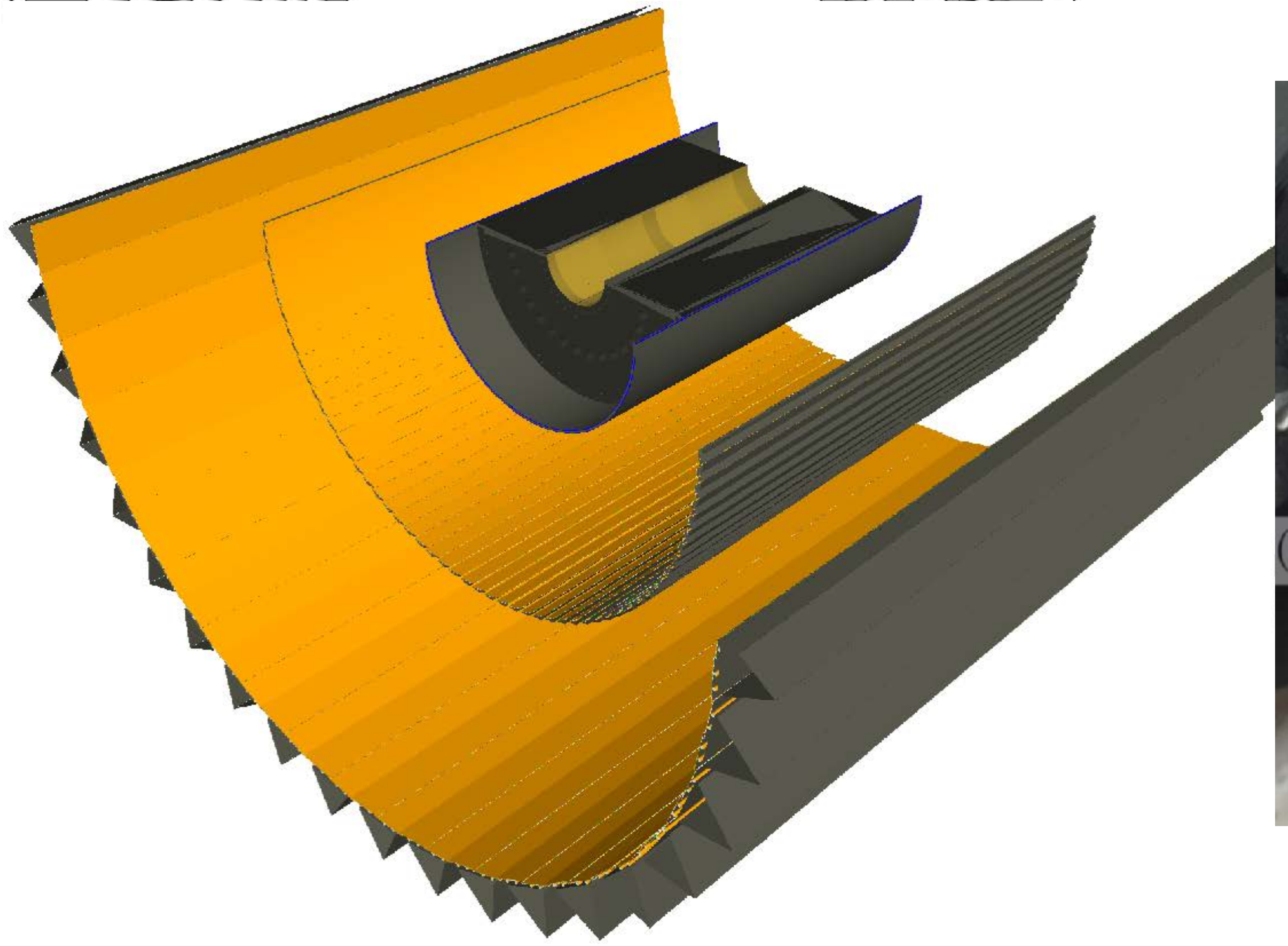
Red numbers are material in % X0

Si Tracker based on ALICE ITS3 65nm MAPS sensors.

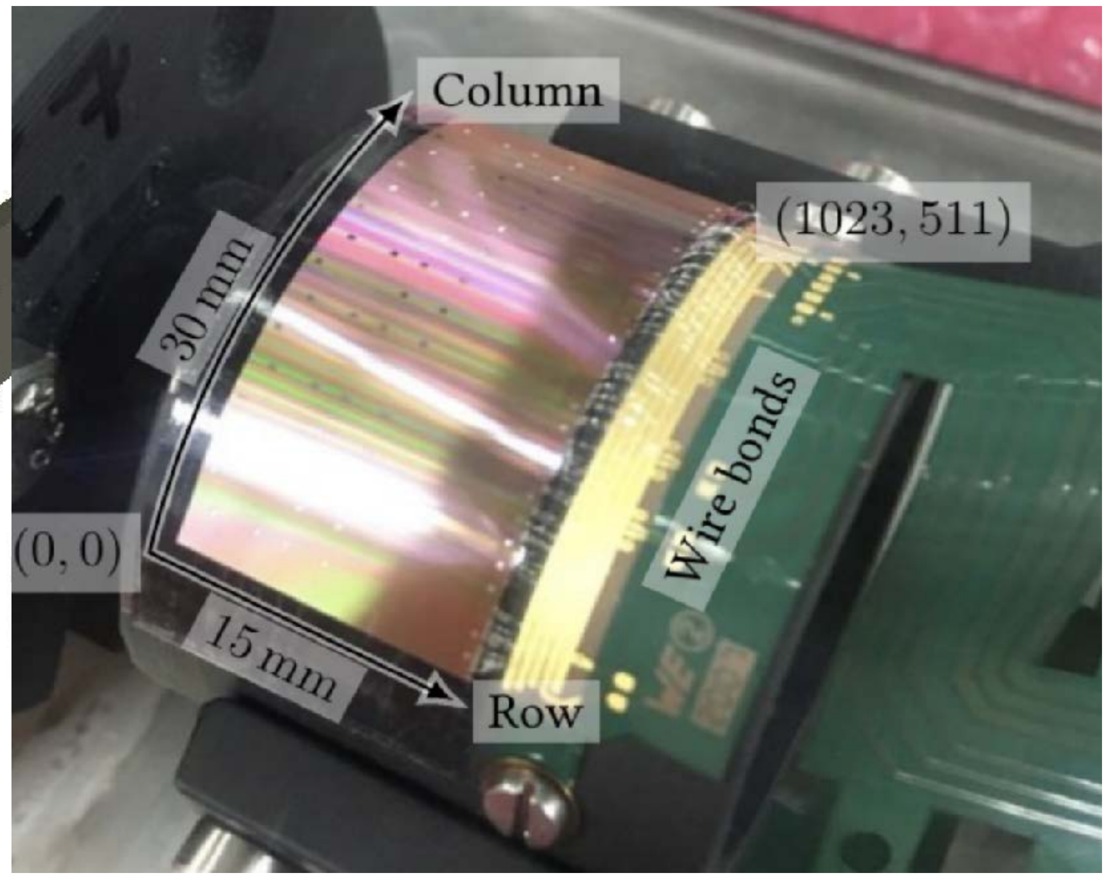
Five layers in barrel, supplemented by MPGDs for pattern recognition.

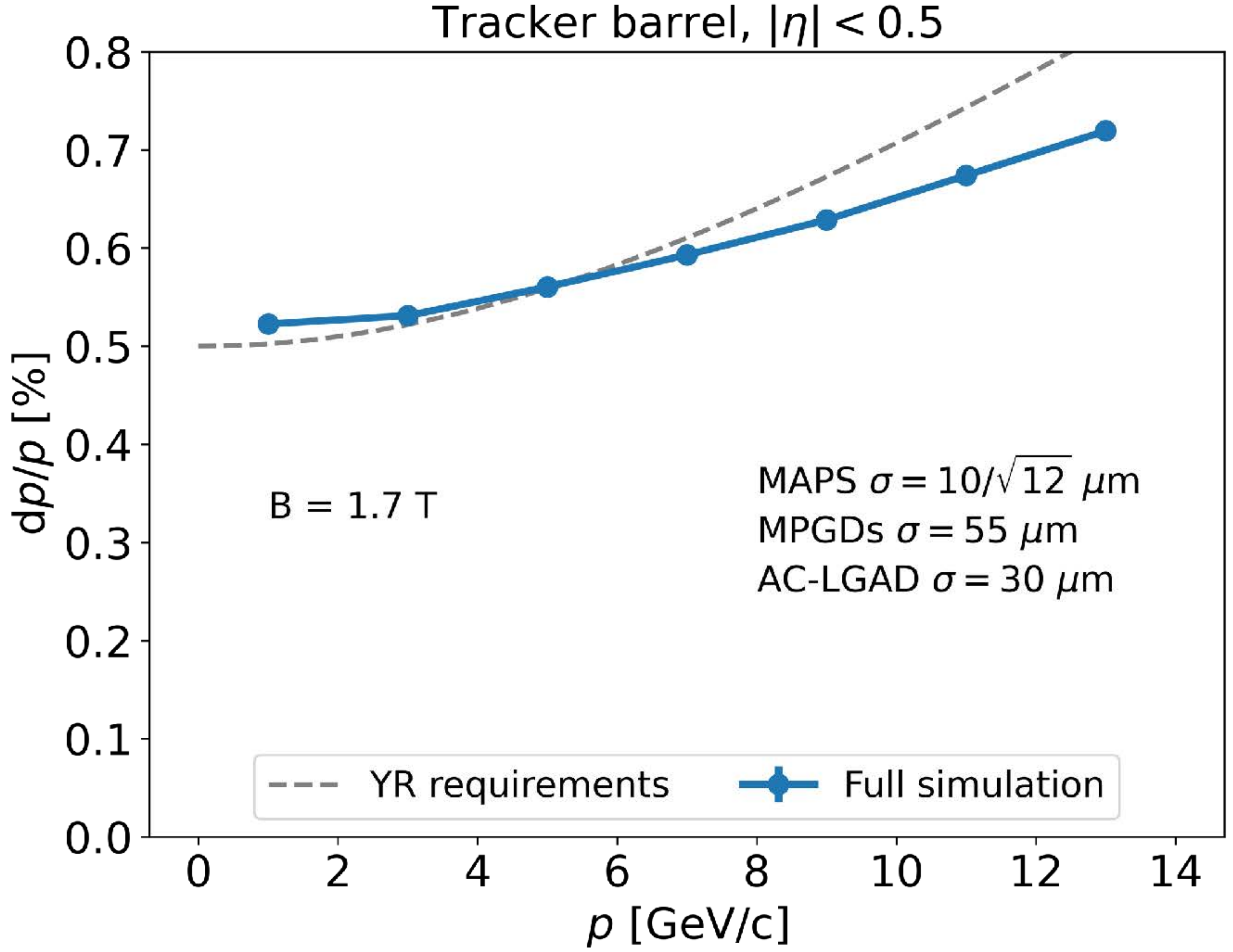
Five discs in forward/backward directions (+MPGD in forward)

Meets EICUG Yellow Report design requirements.



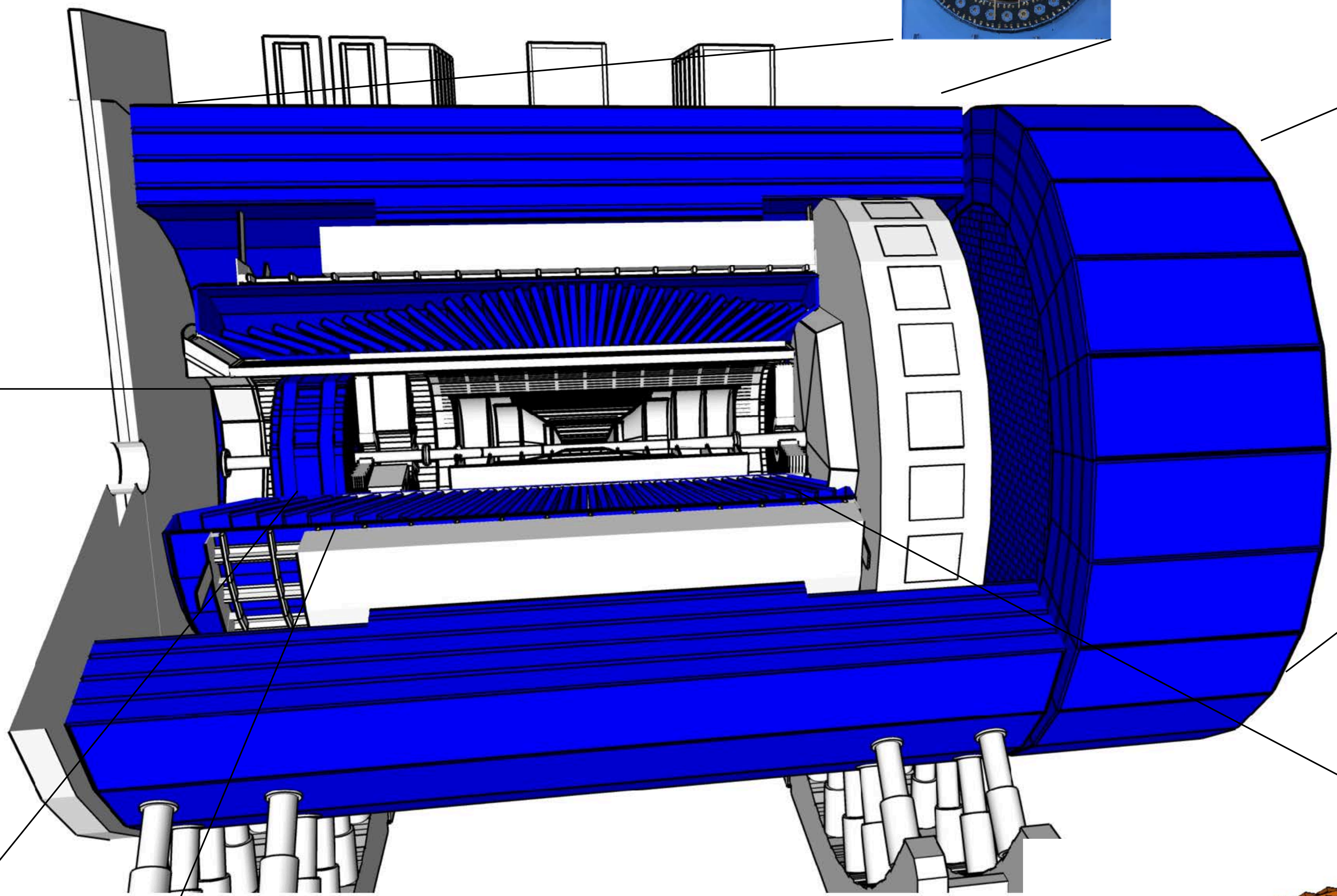
First “μITS3” assembly at CERN



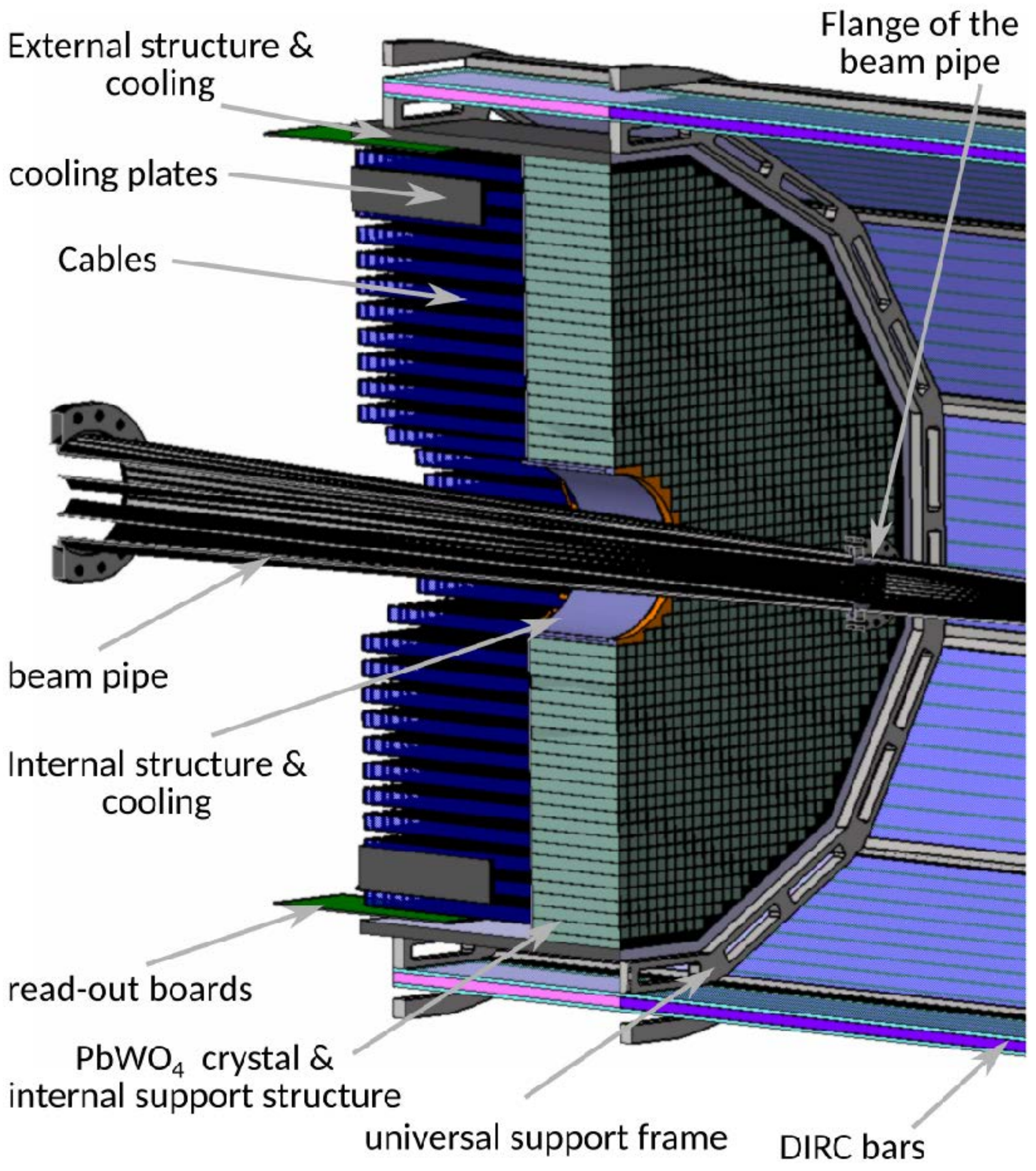


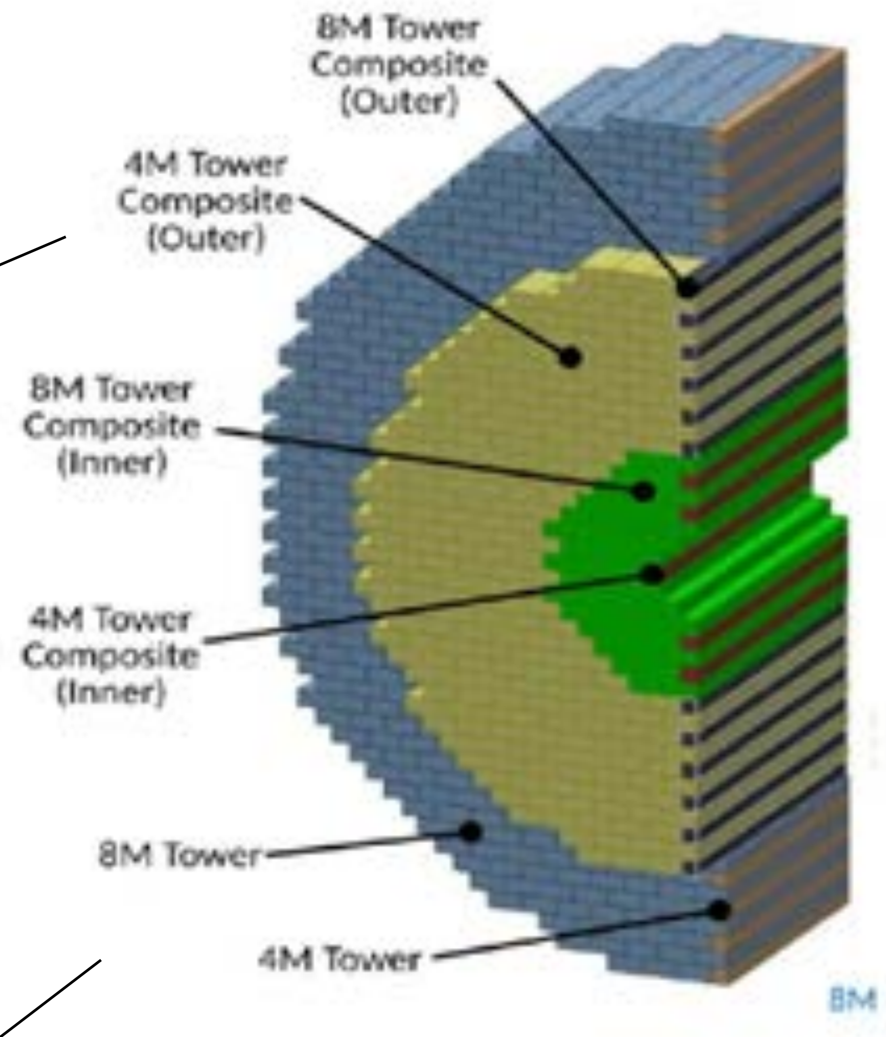
Calorimetry

Barrel HCAL (sPHENIX re-use)

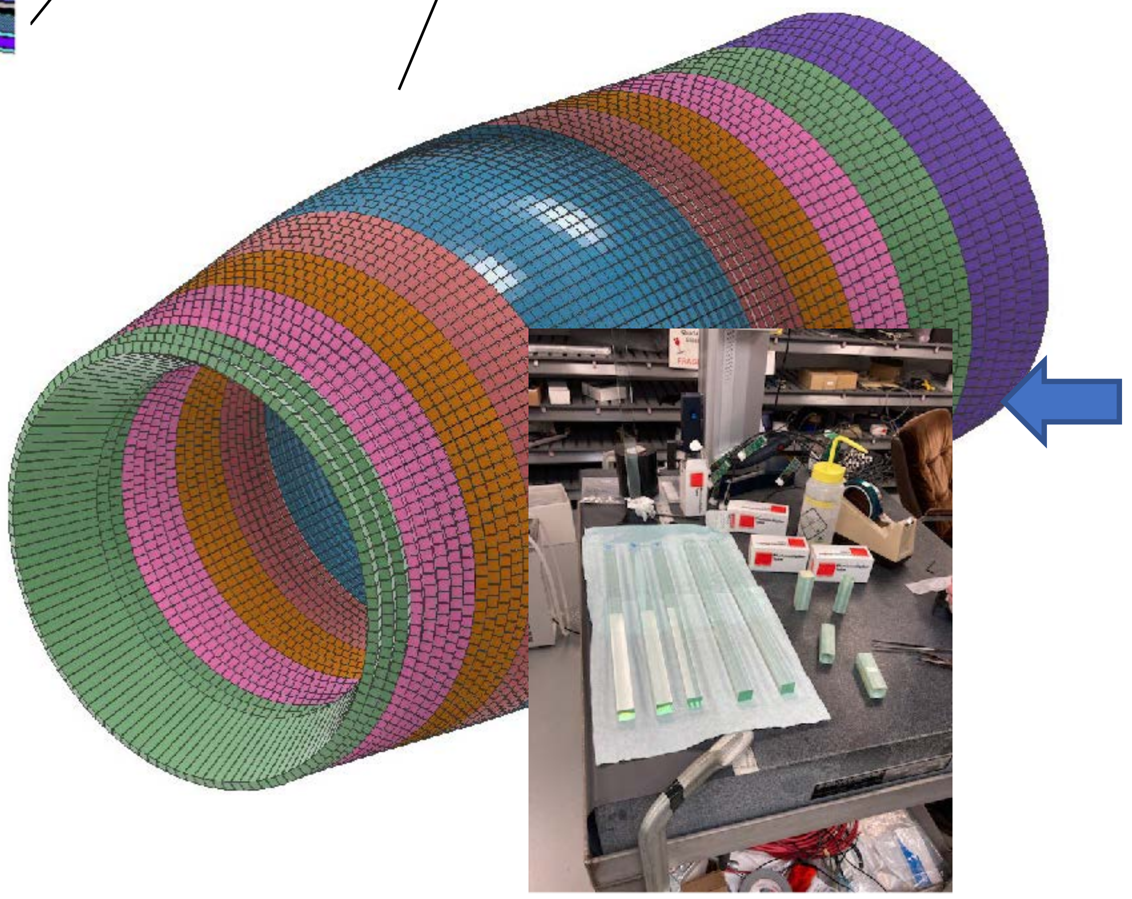


Backwards EMCal PbW04 crystals

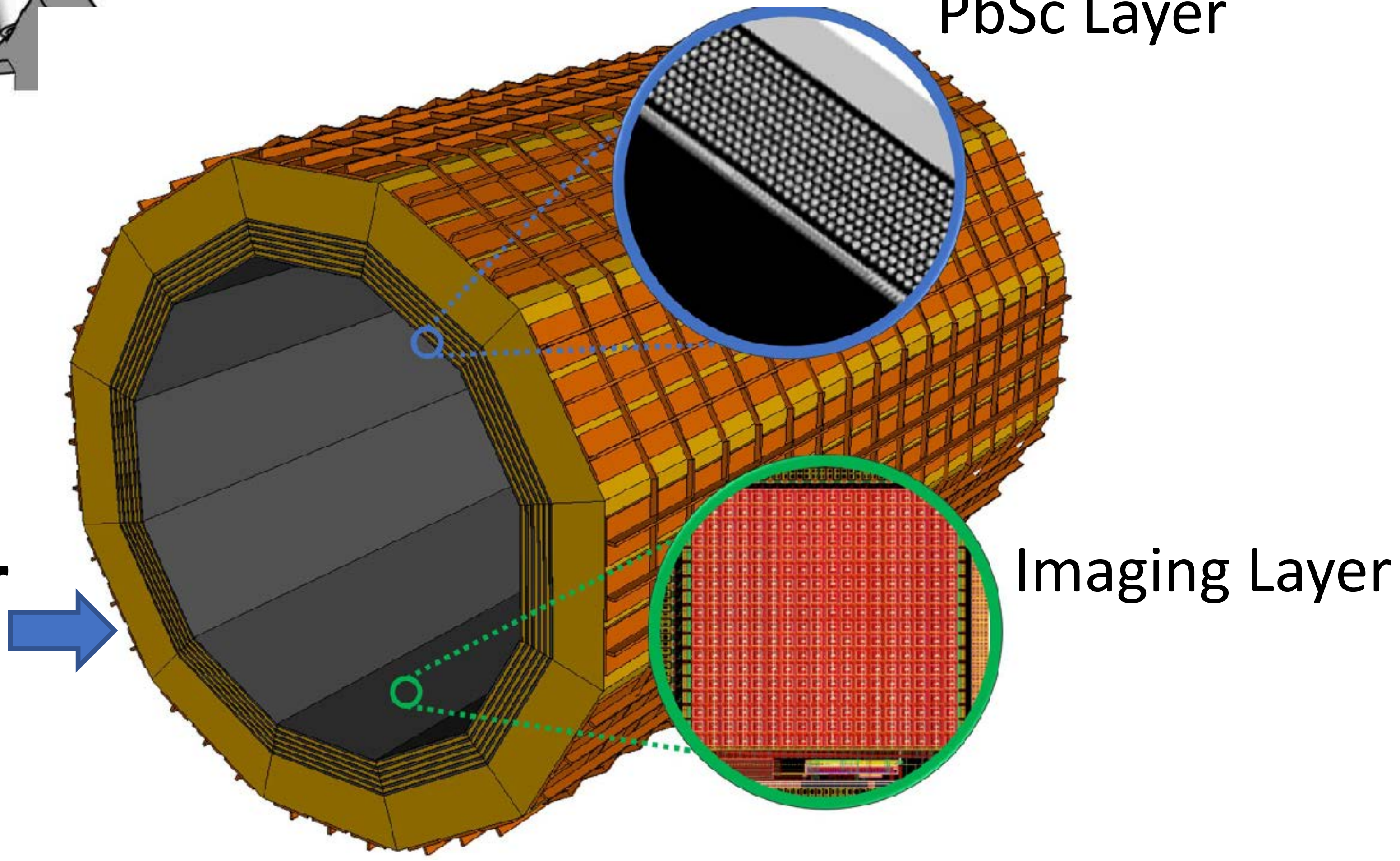




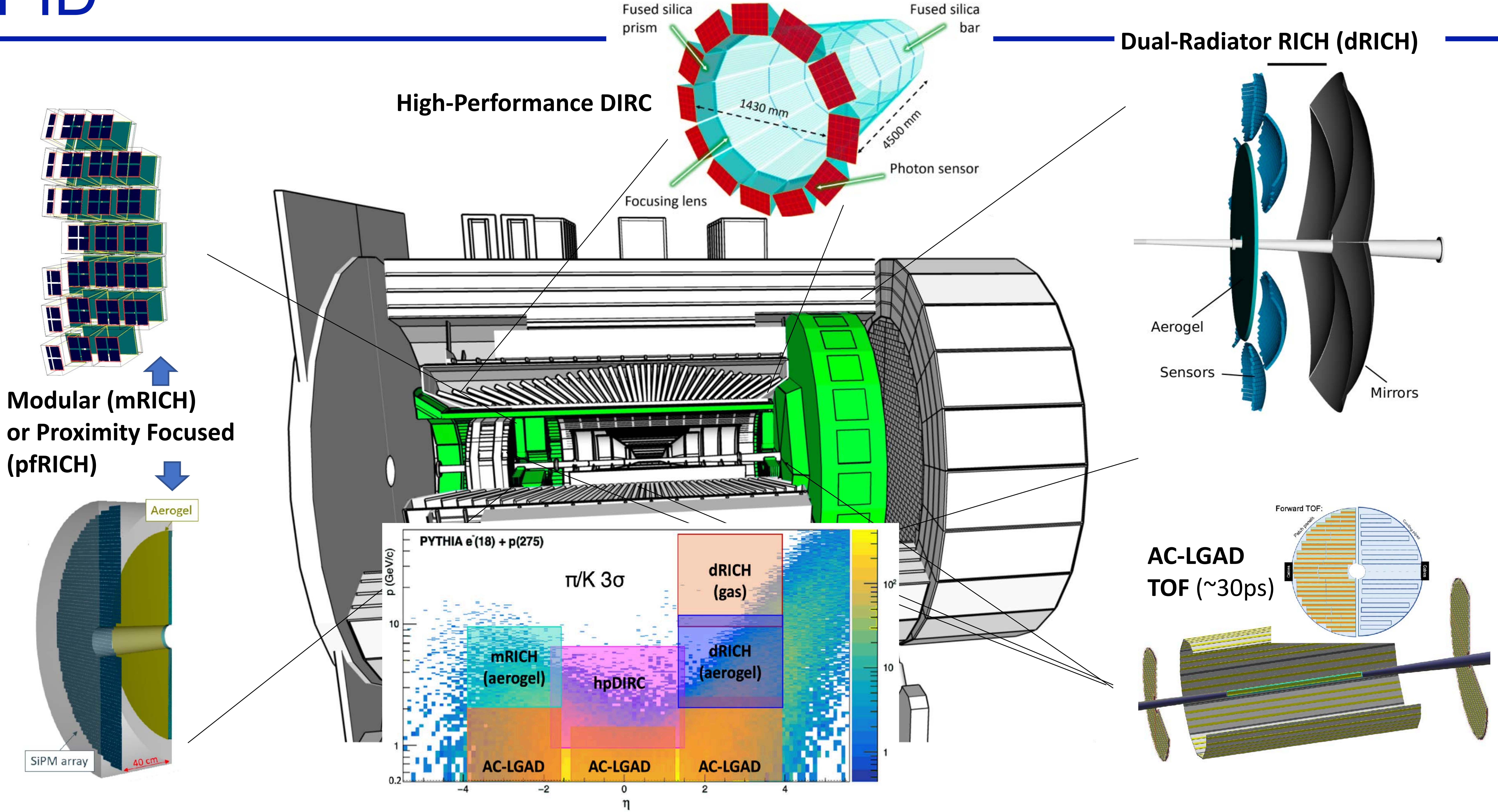
High granularity W/SciFi EMCal Longitudinally separated HCAL with high-η insert



Complementary options for BECAL: SciGlass or Imaging Calorimeter

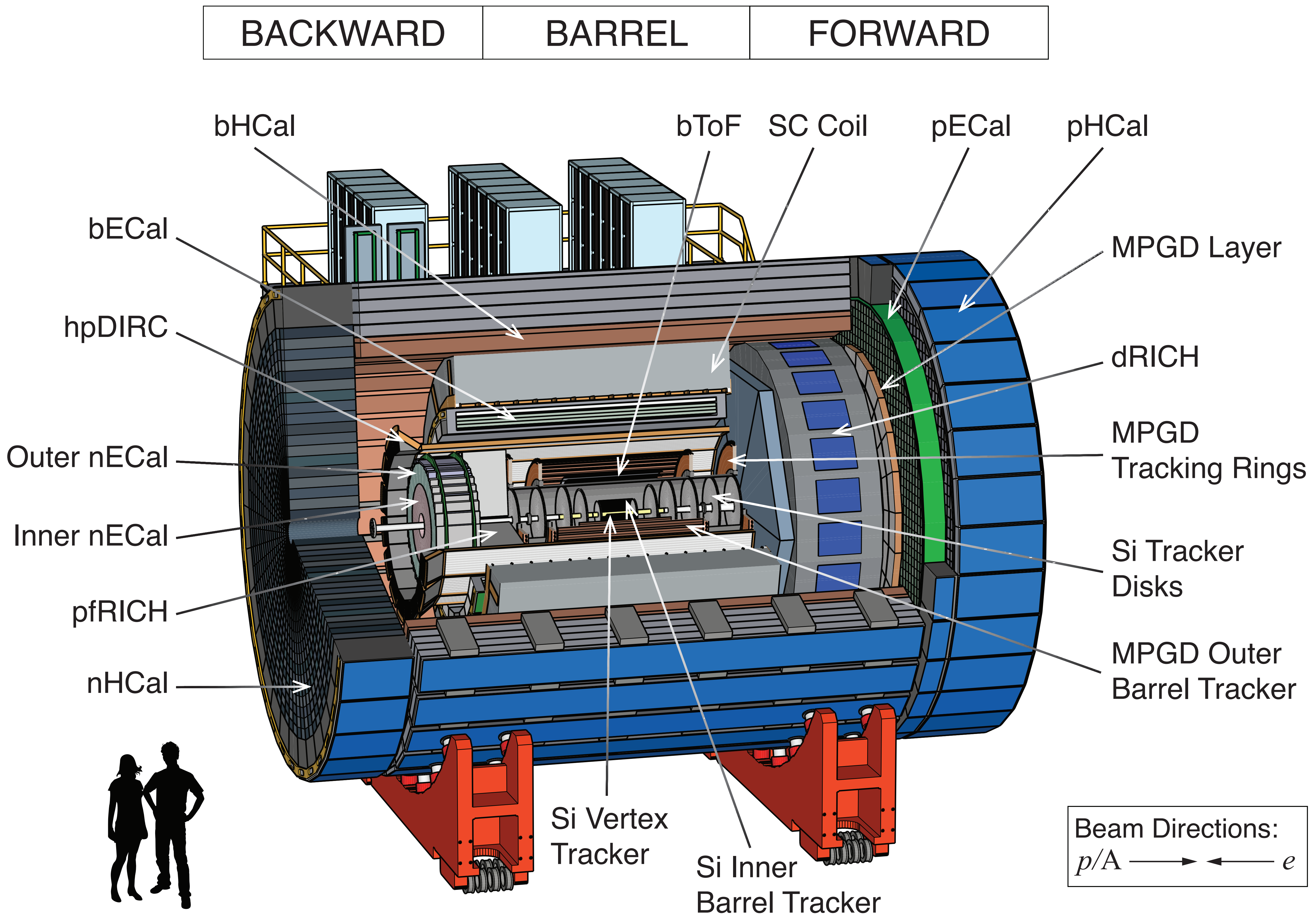


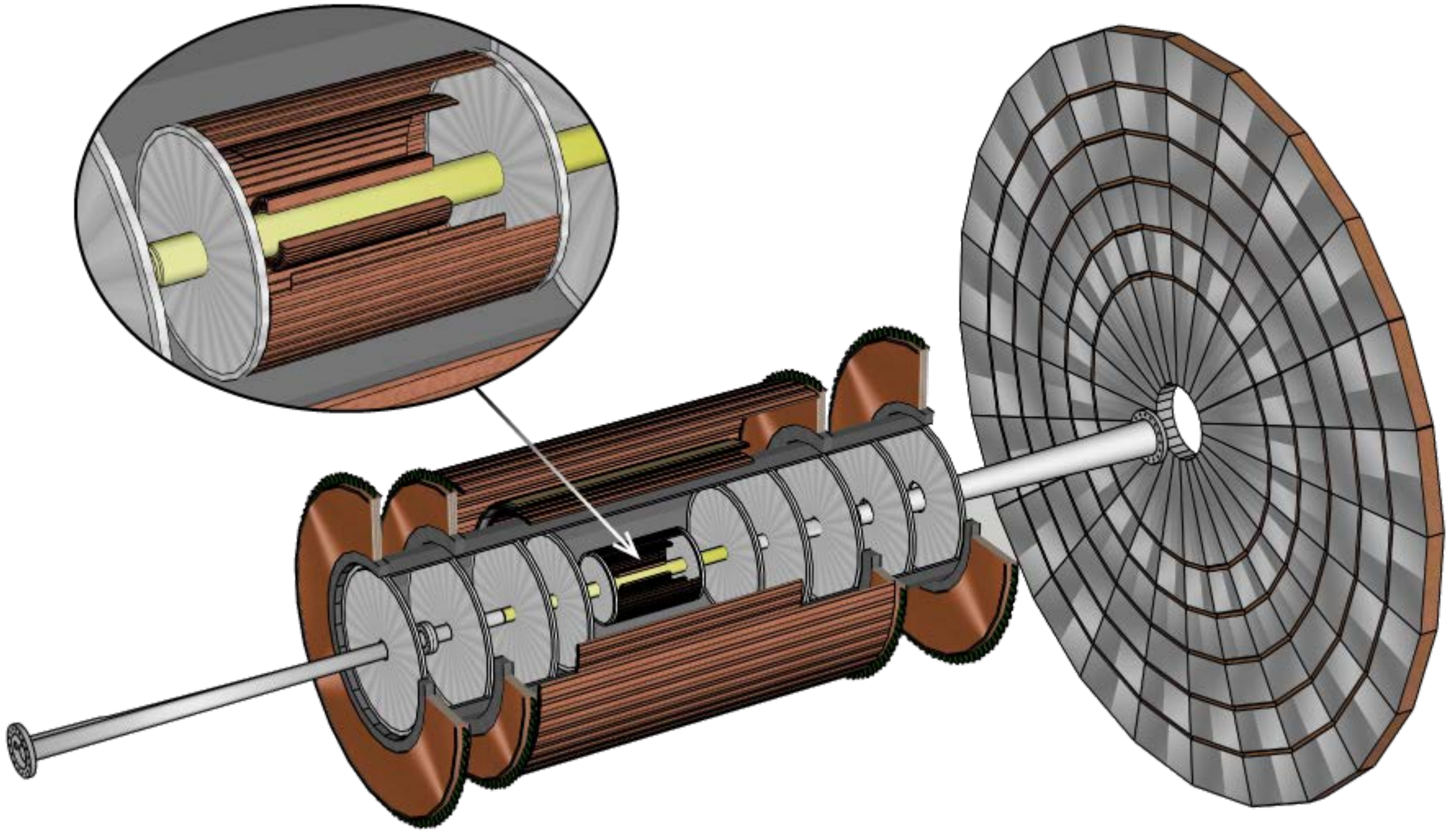
PID



High-Performance DIRC
Fused silica prism
Fused silica bar
1430 mm
4500 mm
Photon sensor
Focusing lens
Dual-Radiator RICH (dRICH)
Aerogel
Sensors
Mirrors
Modular (mRICH)
or Proximity Focused
(pfRICH)
Aerogel
SiPM array
40 cm
AC-LGAD
TOF (~30ps)
Forward TOF:
PYTHIA e(18) + p(275)
π/K 3σ
dRICH (gas)
mRICH (aerogel)
hpDIRC
dRICH (aerogel)
AC-LGAD
AC-LGAD
AC-LGAD
p (GeV/c)
η

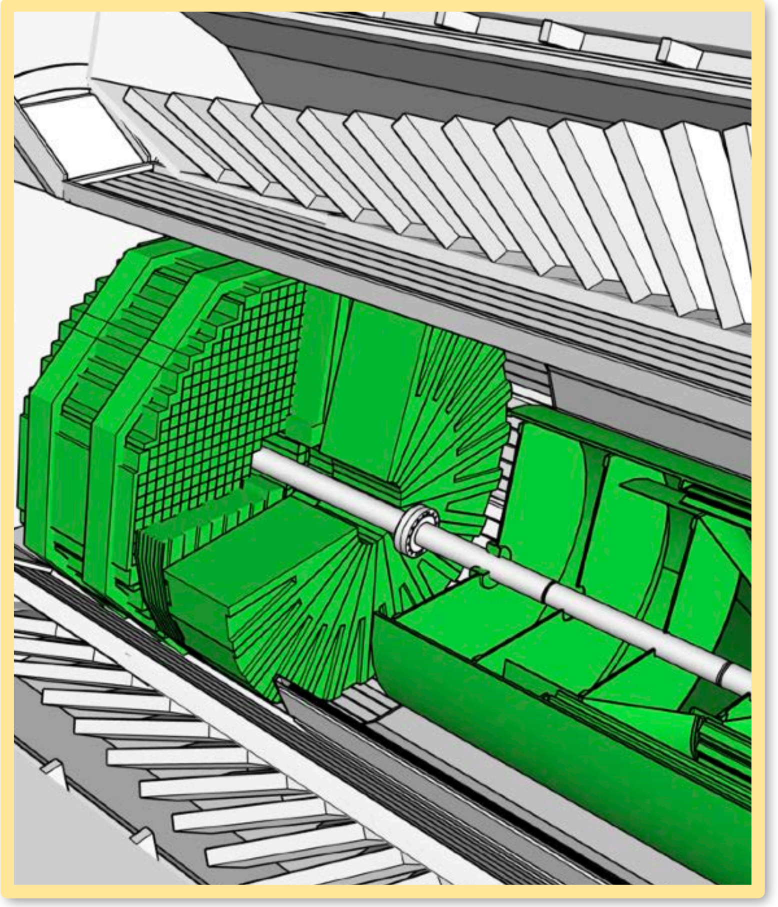
ATHENA - A Totally Hermetic Electron Nucleus Apparatus





https://athena-eic.org

ECCE - EIC Comprehensive Chromodynamics Experiment



Backward Endcap

Tracking:
- ITS3 MAPS Si discs (x4)
- AC-LGAD

PID:
- mRICH
- AC-LGAD TOF
- $PbWO_4$ EM Calorimeter (EEMC)

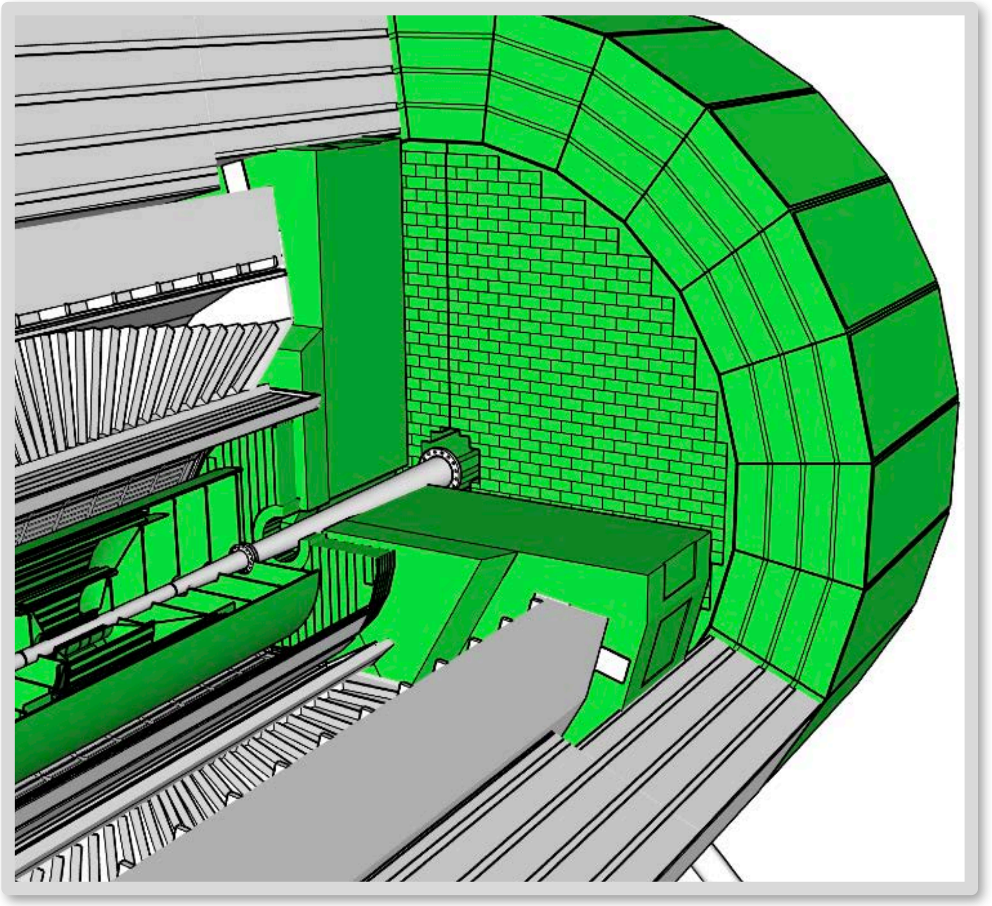
Barrel

Tracking:
- ITS3 MAPS Si (vertex x3; sagitta x2)
- μRWell outer layer (x2)
- AC-LGAD (before hpDIRC)
- μRWell (after hpDIRC)

h-PID:
- AC-LGAD TOF
- hpDIRC

Electron ID:
- SciGlass EM Cal (BEMC)

Hadron calorimetry:
- Outer Fe/Sc Calorimeter (oHCAL)
- Instrumented frame (iHCAL)

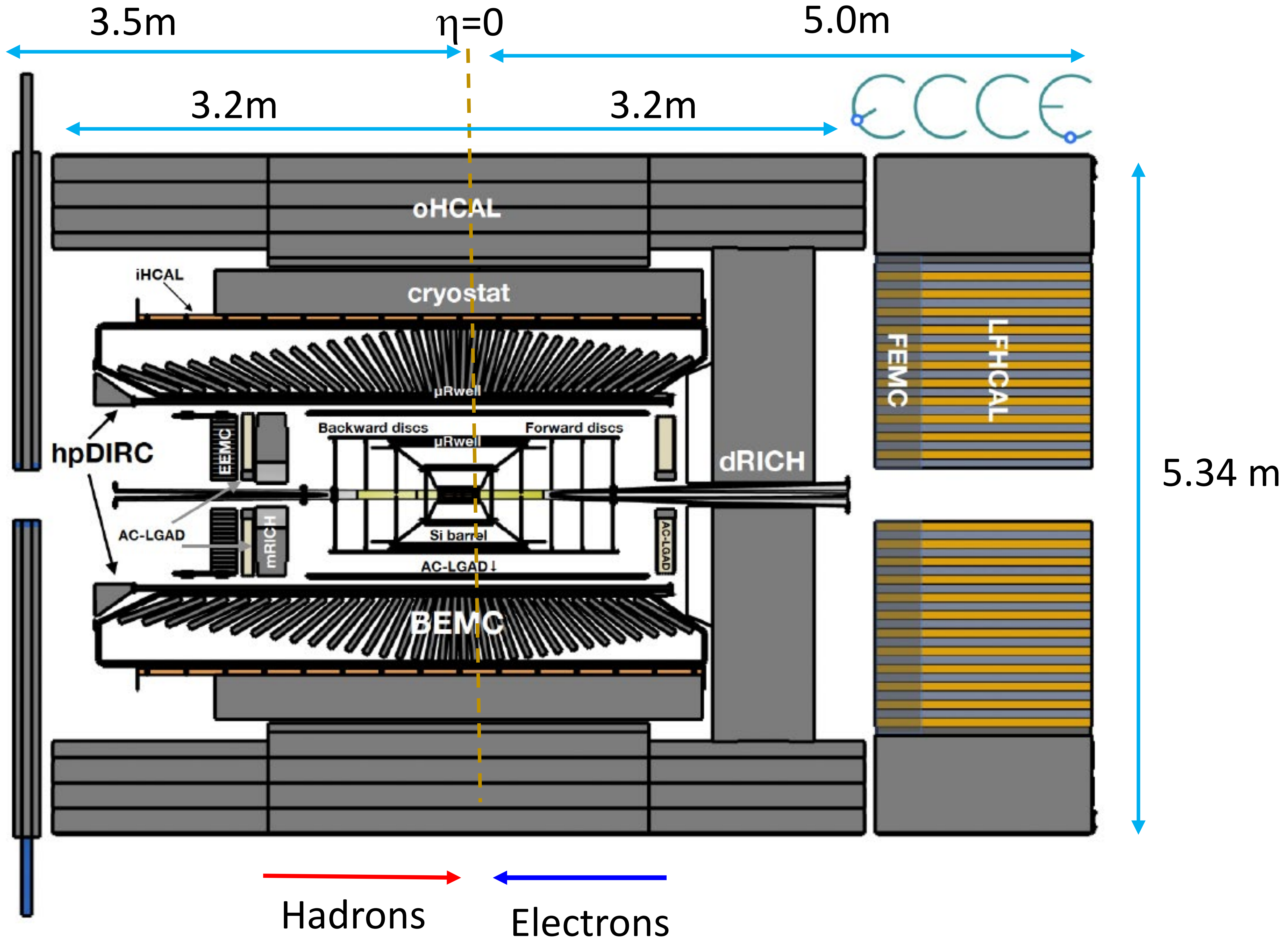


Forward Endcap

Tracking:
- ITS3 MAPS Si discs (x5)
- AC-LGAD

PID:
- dRICH
- AC-LGAD TOF

Calorimetry:
- Pb/ScFi shashlik (FEMC)
- Longitudinally separated hadronic calorimeter (LHFCAL)



https://www.ecce-eic.org

CORE: a COmpact detectoR for the EIC

Neutral hadron and muon ID detector (KLM)

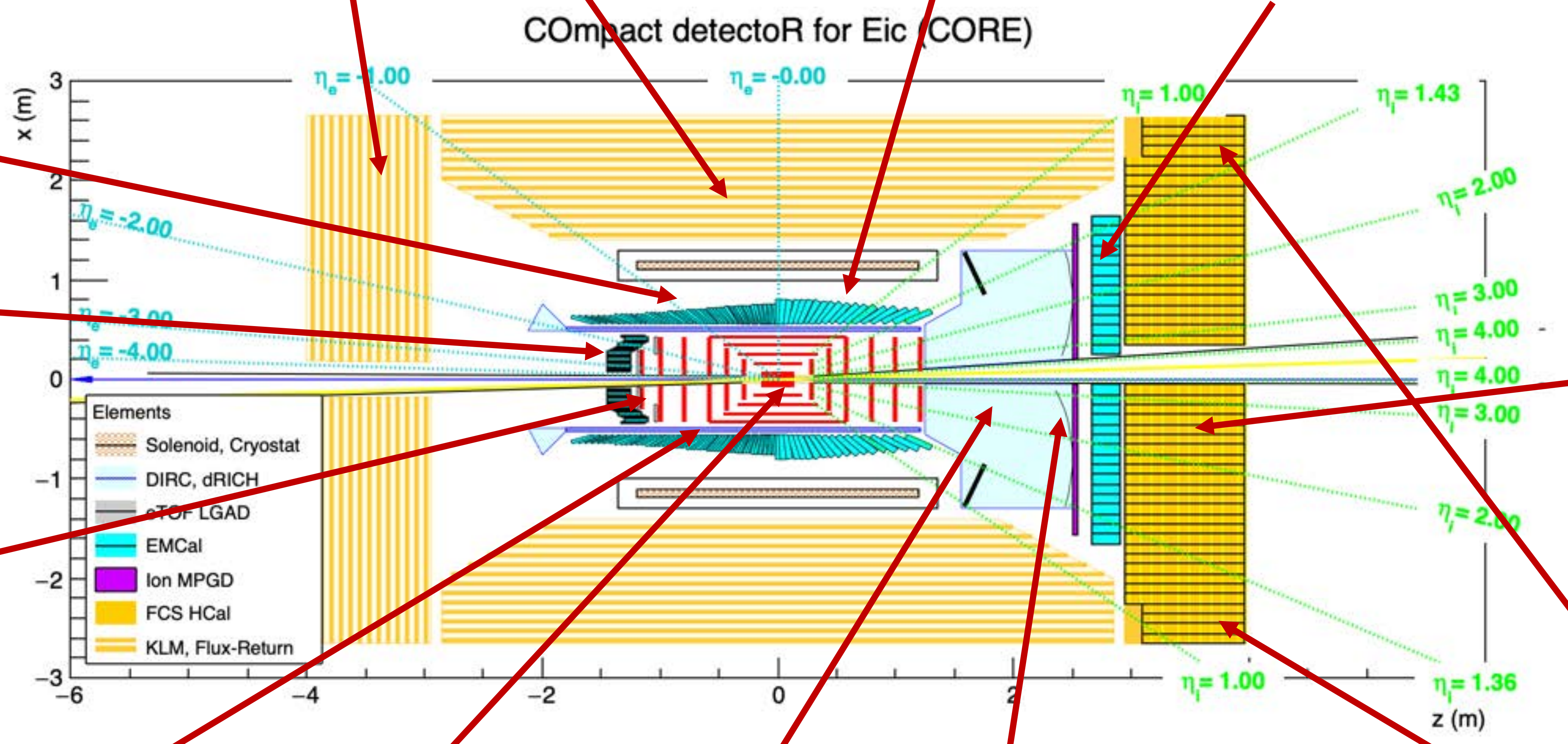
Projective W-shaslik EMcal

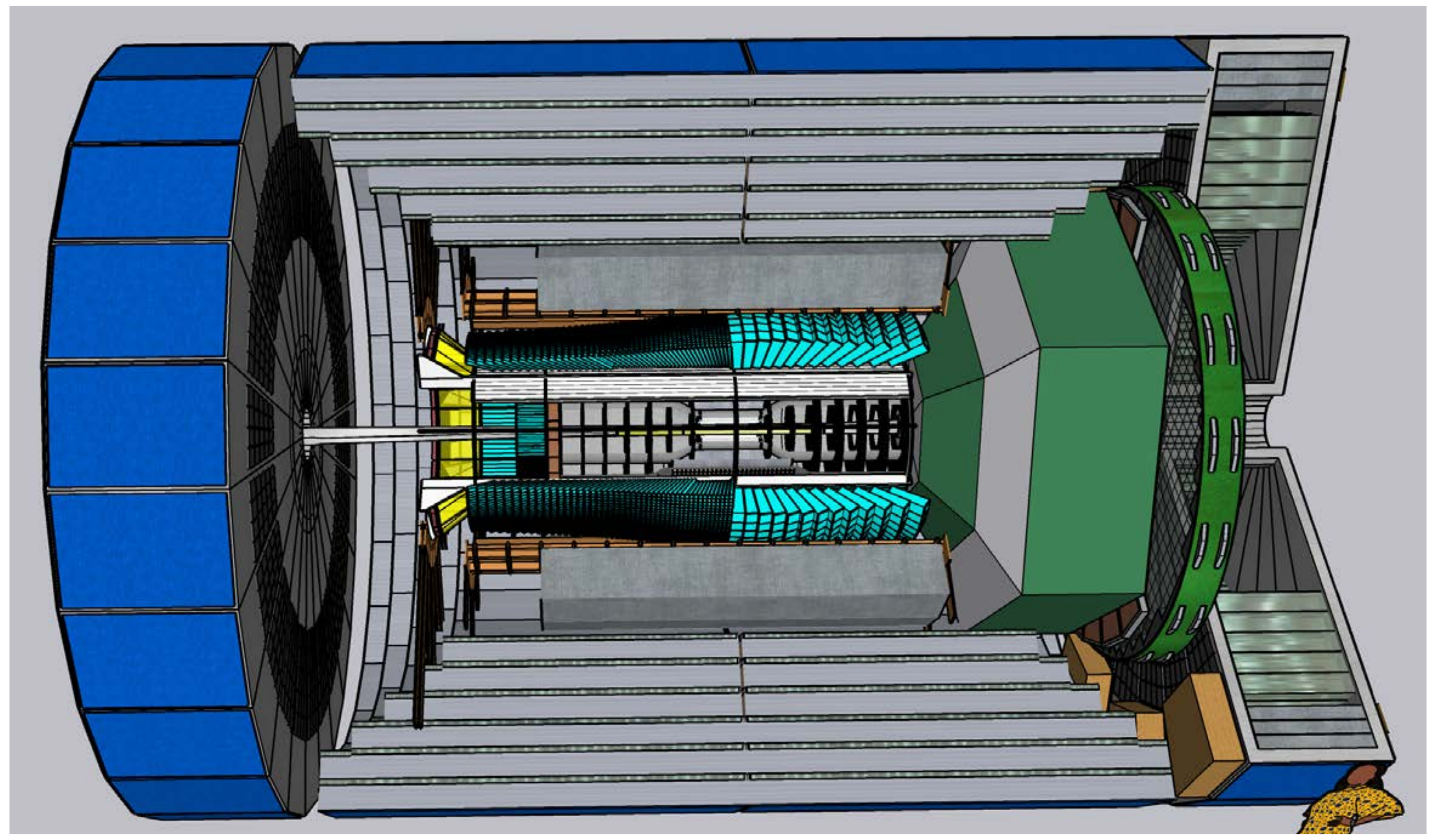
Non-projective W-shaslik EMcal

Projective $PbWO_4$ EMcal

Non-projective $PbWO_4$ EMcal

LGAD TOF





Hcal, new Fe/Sci modules (44 layers)

Hcal, outer rings: re-used STAR FCS modules (36 layers)

Silicon tracker

MPGD tracker

DIRC

Dual-radiator RICH

https://eic.jlab.org/core/