Latest vertex and tracking detector developments for the future Electron-Ion Collider

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on behalf of the EIC EPIC Collaboration

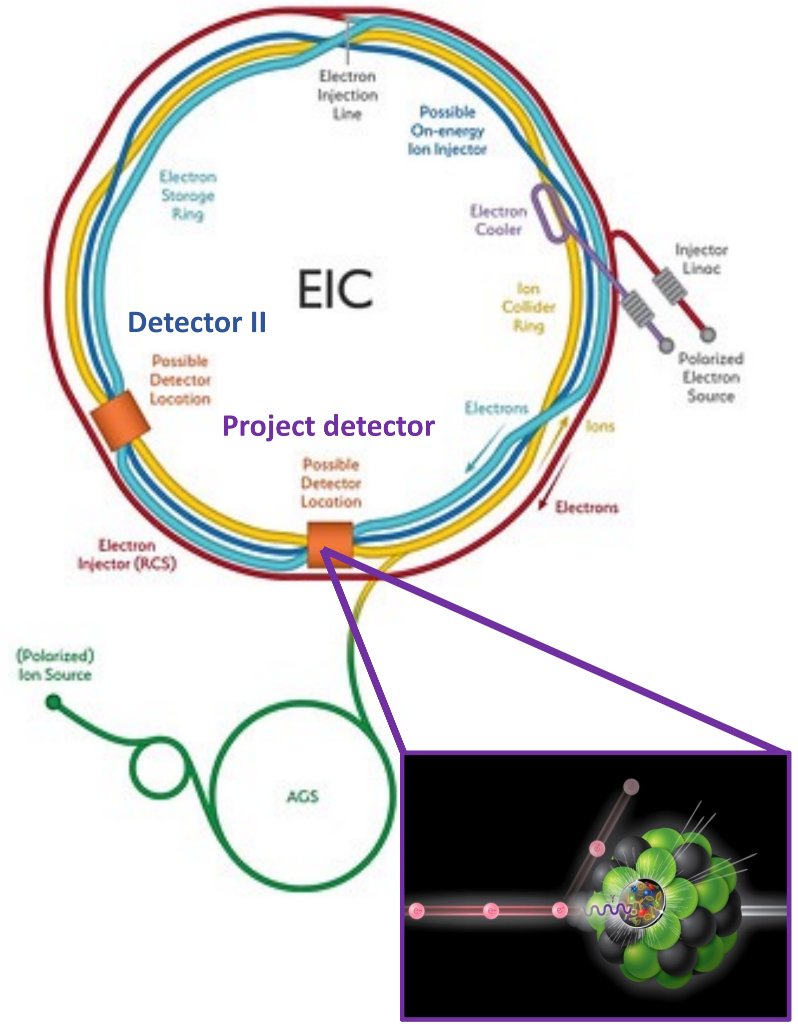
Outline

- Introduction to the Electron-Ion Collider (EIC) and the reference detector design.
- EIC project detector collaboration (EPIC) vertex and tracking detector developments:
  - Goals and work status.
  - Detector geometry optimization and performance validation.
  - Detector R&D status and progress.
- Summary and outlook

Introduction to the future Electron-Ion Collider (EIC)

- The future Electron-Ion Collider (EIC) will utilize high-luminosity high-energy e+p and e+A collisions to solve several fundamental questions in the nuclear physics field.
- This project has received CD1 approval from the US DOE in 2021 and will be built at BNL.
- The future EIC will operate:
  - (Polarized) p and nucleus (A=2-238) beams at 41, 100-275 GeV.
  - (Polarized) e beam at 5-18 GeV.
  - Instantaneous luminosity L_{int} ~ $10^{33\text{-}34}$ cm^{-2} sec^{-1}. A factor of ~1000 higher than HERA.
  - Bunch crossing rate: ~10 ns.

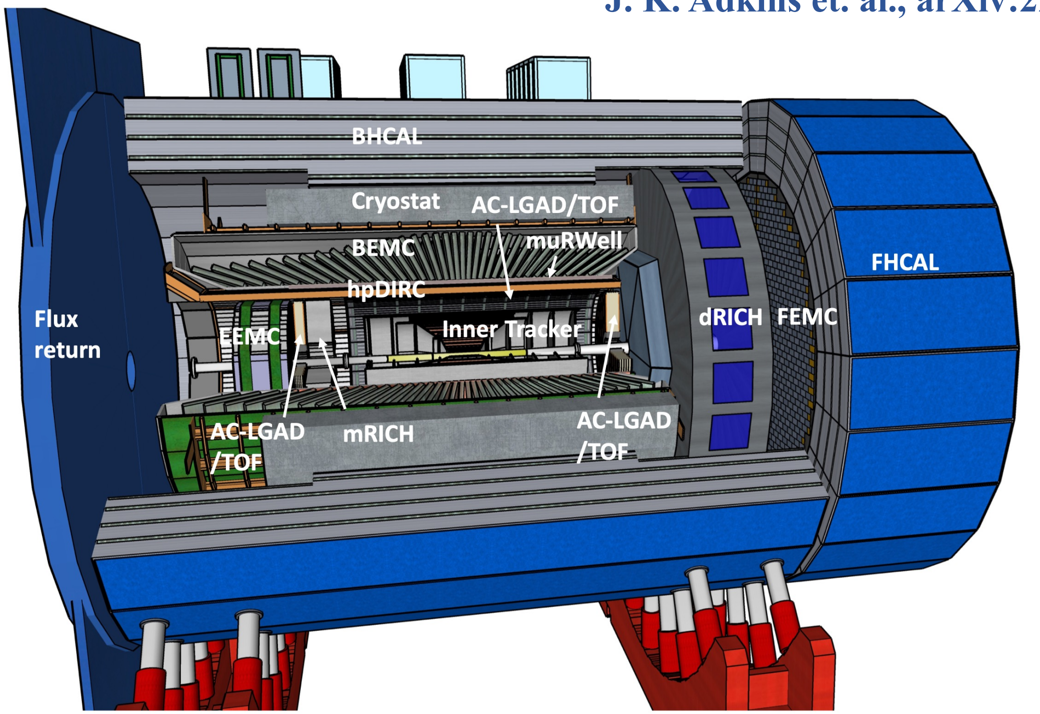
R. A. Khalek et. al., NPA 1026 (2022) 122447

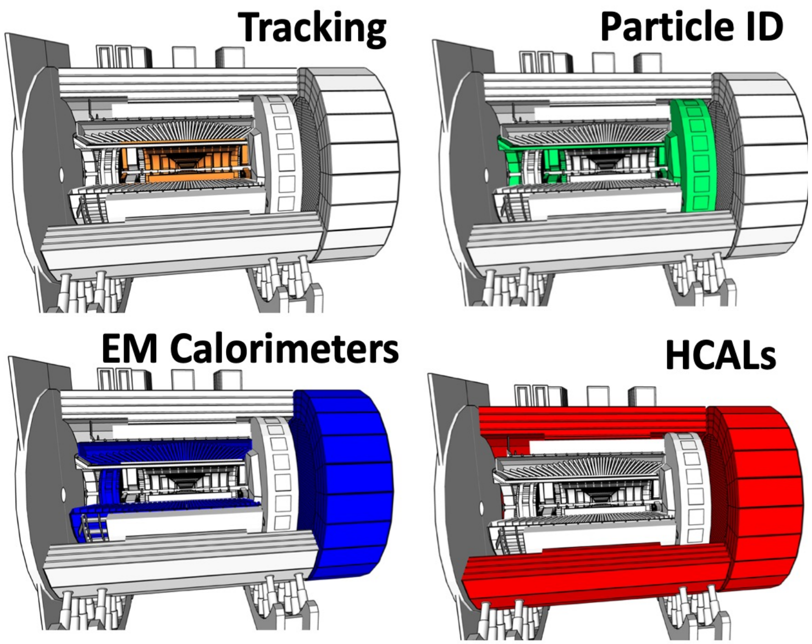


EIC reference detector selection

- The EIC project detector reference design has been selected in March 2022.
- The EIC reference detector design consists of Tracking, Particle ID, EM Calorimeter and Hadronic Calorimeter subsystems. It utilizes the existing Babar magnet (1.4T).

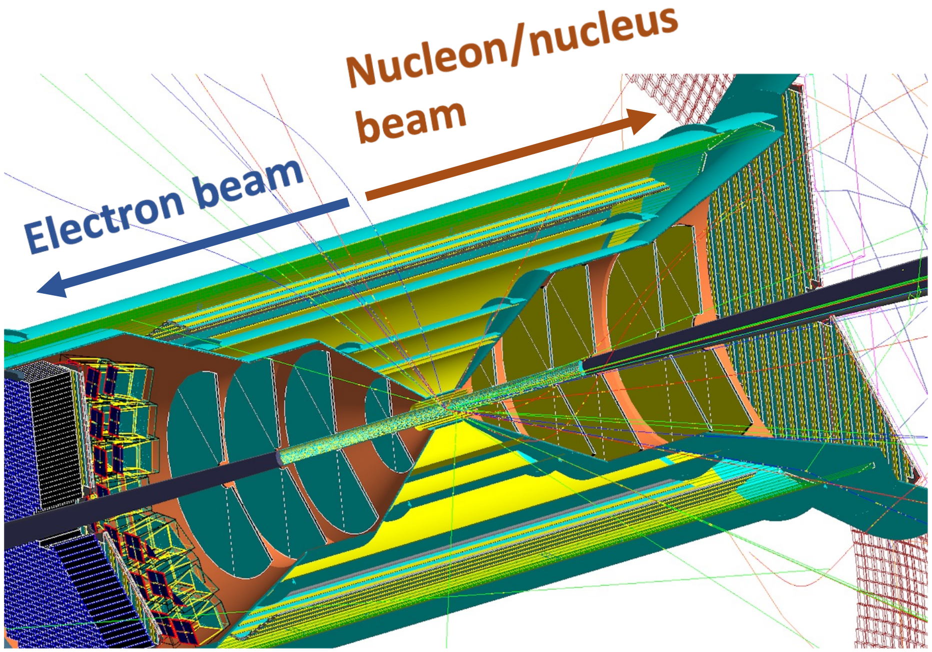
J. K. Adkins et. al., arXiv:2209.02580





EIC project detector reference design for tracking

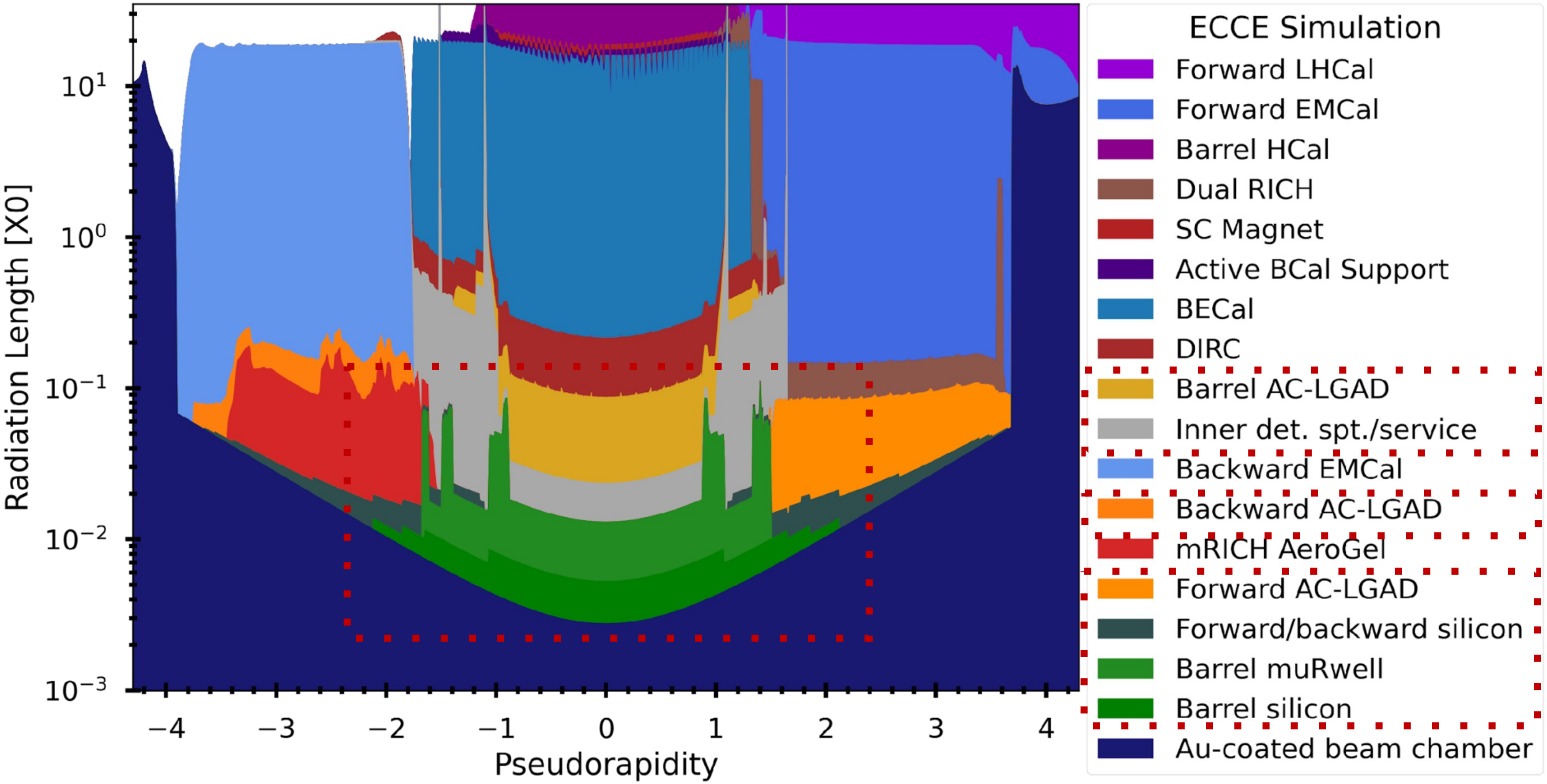
- The EIC tracking detector reference design consists of integrated MAPS, MPGD and AC-LGAD tracking subsystems with $|\eta|<3.5$. Detailed detector segmentation and service parts have been implemented in GEANT4 simulation.
- The EIC tracking detector consists of:
  - Barrel: 5 MAPS layers, 3 MPGD layers and 1 AC-LGAD layer. Inner radius: 3.3 cm, outer radius: 77 cm.
  - Hadron endcap: 5 MAPS planes and 1 AC-LGAD plane. Minimum z: 25cm, maximum z: 182cm.
  - Electron endcap: 4 MAPS planes and 1 AC-LGAD plane. Minimum z: -155.5cm, maximum z: -25cm.



EIC beam pipe is asymmetric along z axis

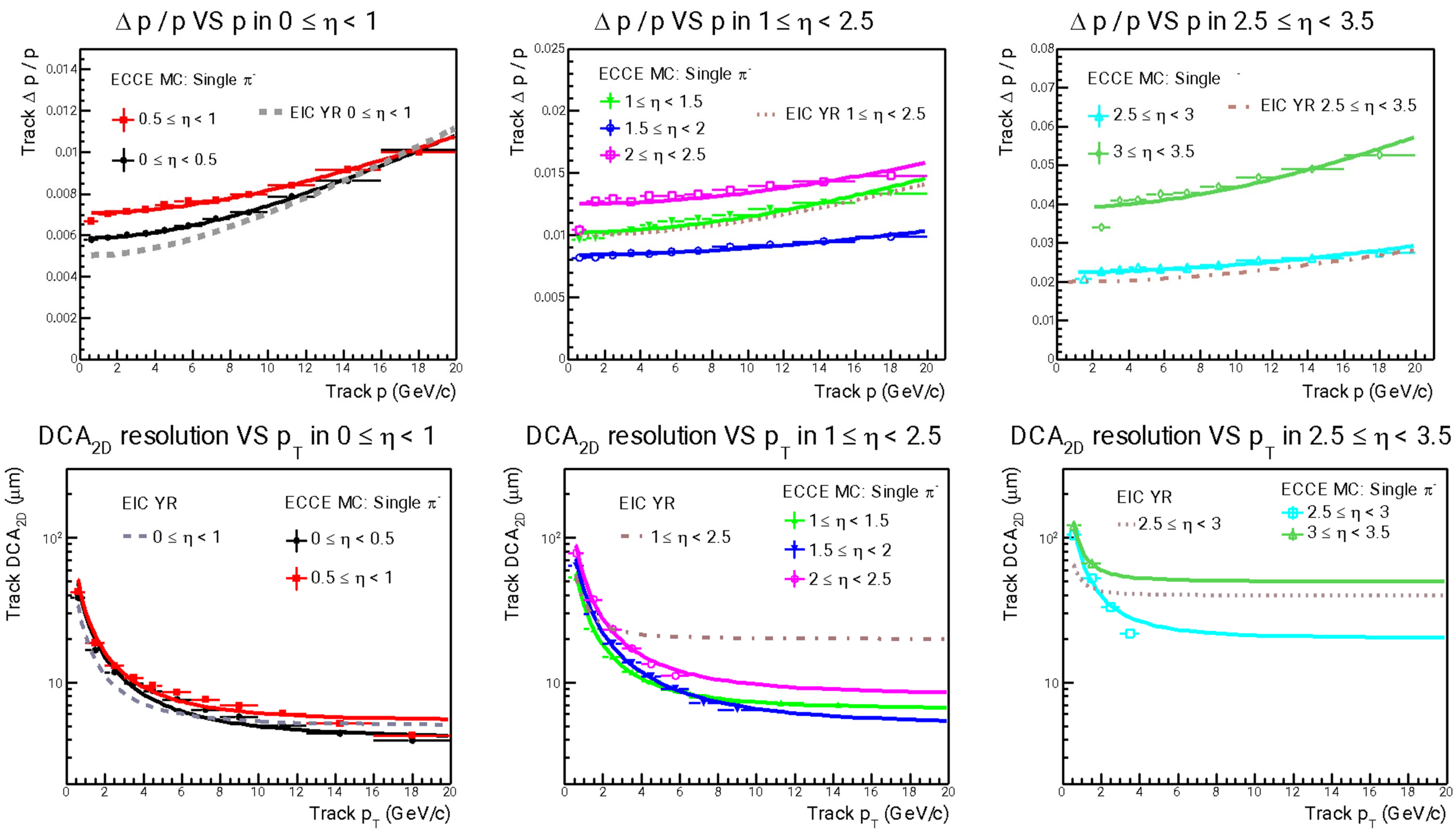
EIC reference detector material budget scan

- In the GEANT4 simulation, material budget scan of the EIC reference detector subsystems.
- The overall material budget requirement on the EIC vertex and tracking detector is <5% X/X0.



EIC reference tracking detector performance

- Track momentum dependent momentum resolution and transverse momentum dependent DCA_{2D} resolution.

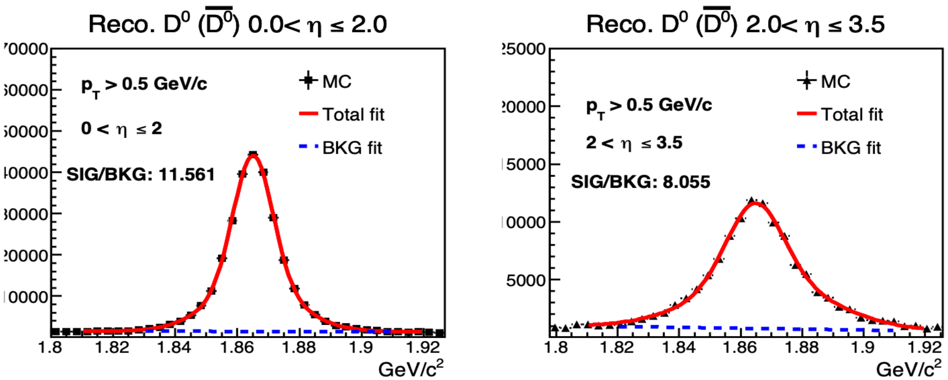


High precision heavy flavor measurements at the EIC

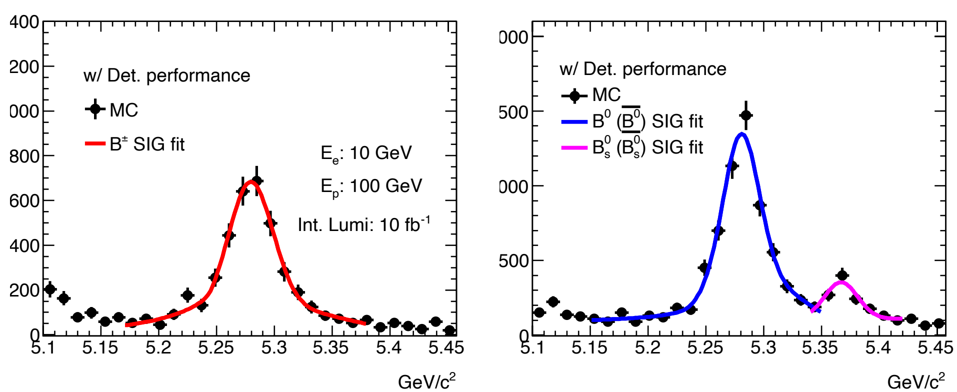
- The EIC project detector reference design can realize a series of high precision heavy flavor hadron and jet measurements to explore the EIC science portfolio.

Reco. $D^0(\overline{D^0})$ in e+p collisions

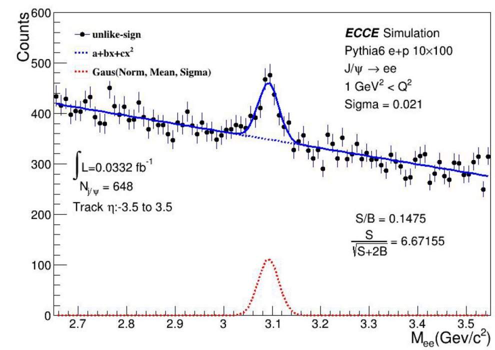
X. Li et. al., arXiv: 2207.10632



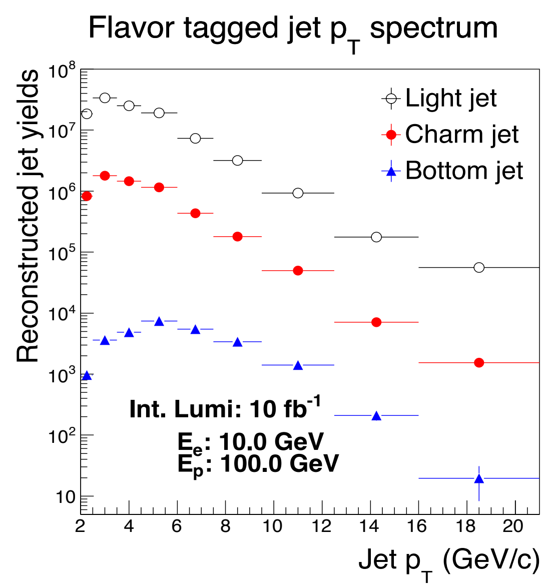
Reco. $B^{\pm}, B^0(\overline{B^0}), B_s^0(\overline{B_s^0})$ in e+p collisions



X. Li et. al., arXiv: 2207.10356



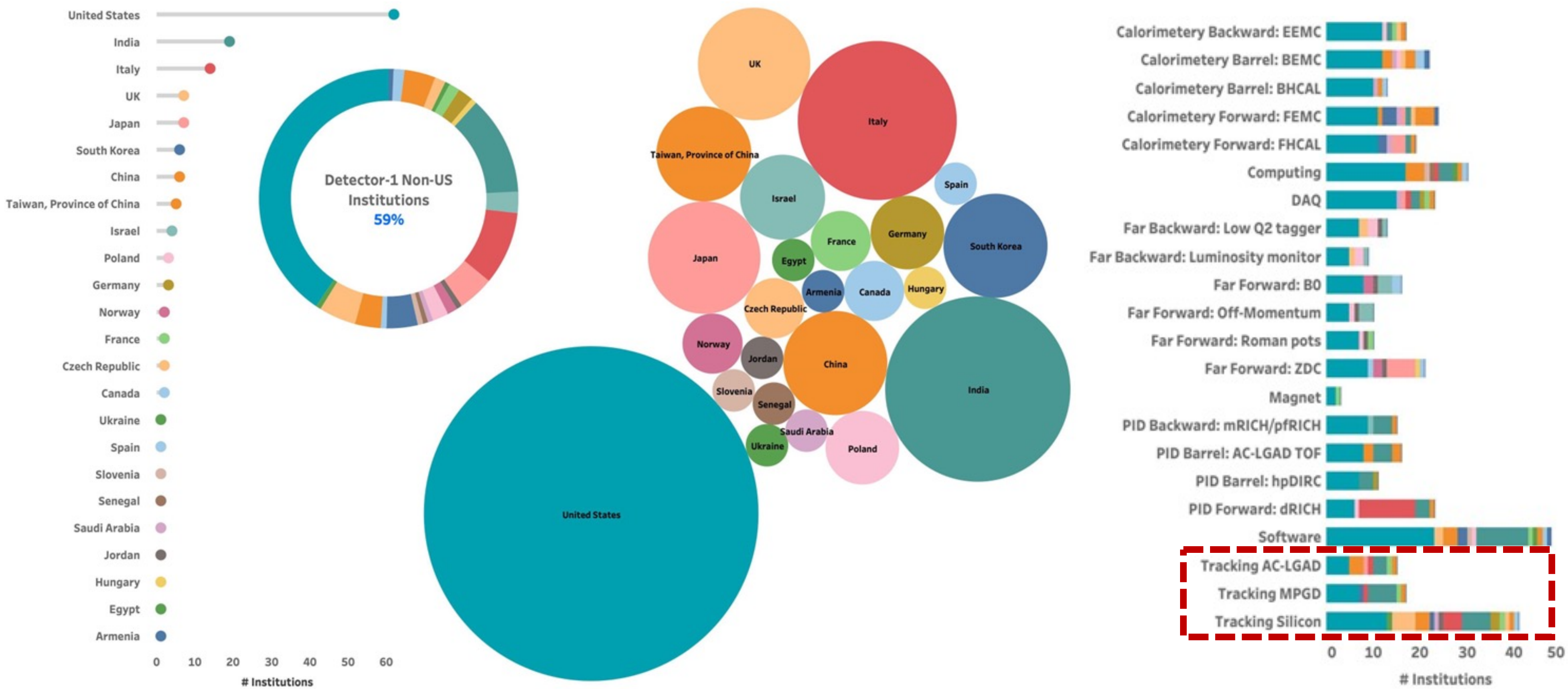
Reco. J/ψ



Reco. c-jet b-jet

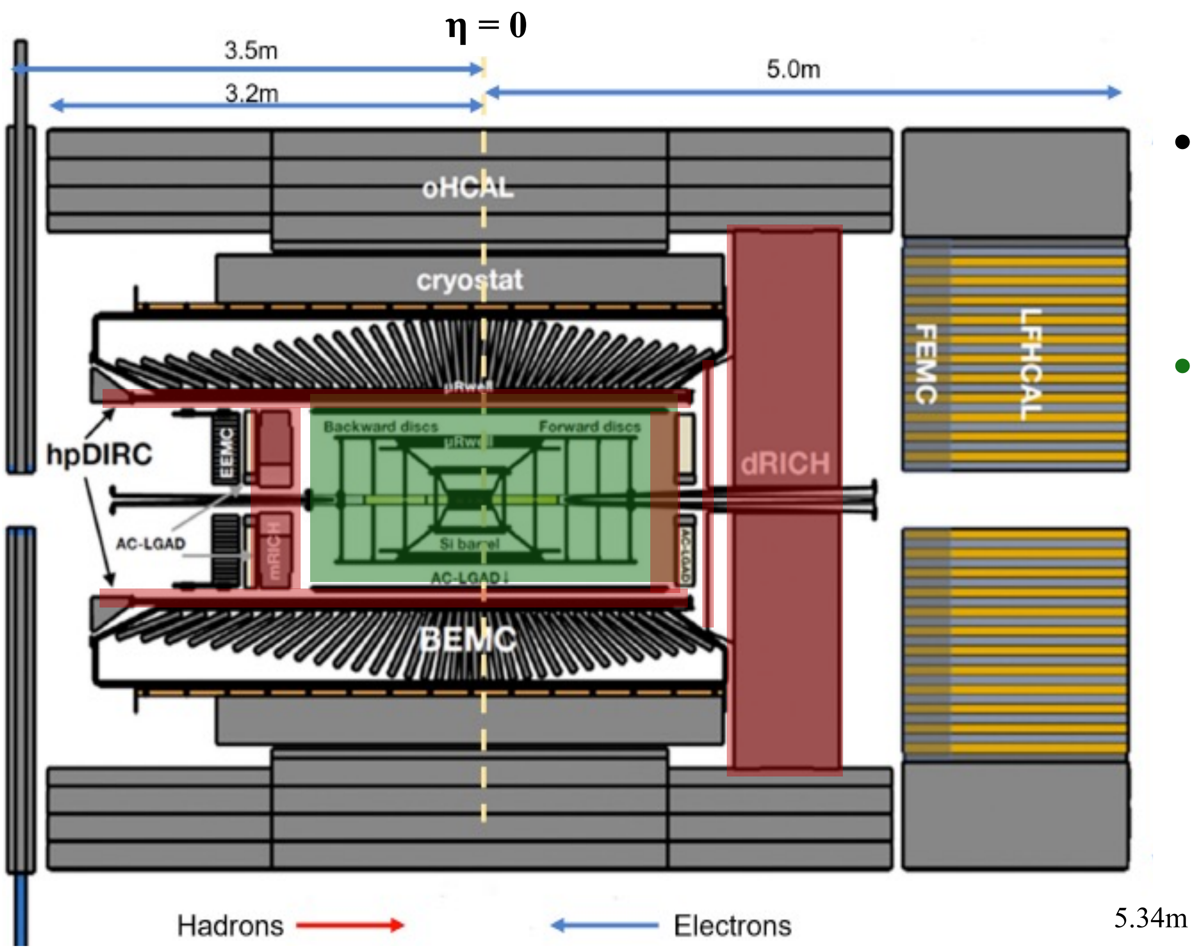
EPIC collaboration and detector developments

- New EIC collaboration: EPIC has been formed in July 2022 to work on the project detector design optimization.
- The EPIC collaboration consists of 500+ participants from 160+ institutions in nearly 30 countries.



EPIC collaboration and detector developments

- New EIC collaboration: EPIC has been formed in July 2022 to work on the project detector design optimization.
- Current EPIC detector design:

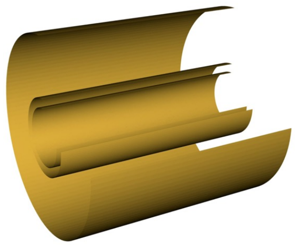


- The EPIC detector will utilize the new 1.7 T magnet.
- The EPIC detector design consists of optimized tracking, PID and calorimeter subsystems.
- The EPIC tracking detector includes the Si MAPS tracker and the MPGD (μRWELL or μMegas) tracker in the barrel, hadron endcap and electron endcap regions. AC-LGAD layer/plane serves as the outer tracker.

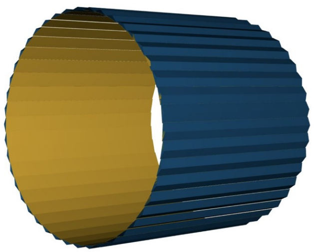
A. Tricoli talk on Oct. 27

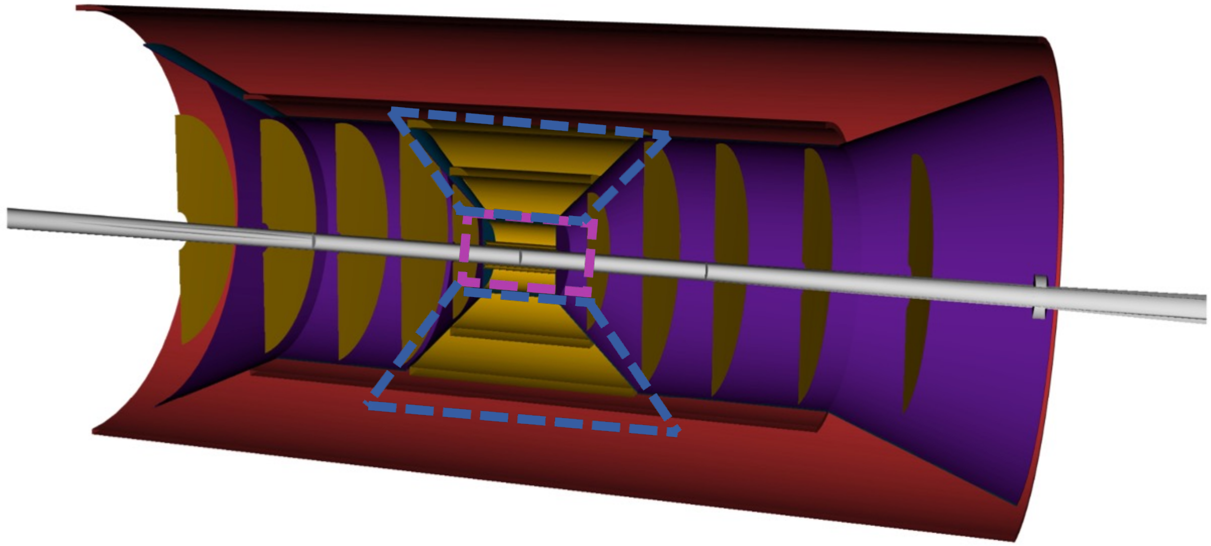
EPIC MAPS tracker geometry optimization (Barrel)

- Silicon vertex barrel layer geometry:
  - Updated geometry due to beam pipe (radius at 3.18cm) bakeout requirements and constraints from ITS3 type sensor size (pixel pitch at 10μm). Vertex layer 1 radius at 3.6cm, vertex layer 2 radius at 4.8cm and the vertex layer 3 radius at 12cm. 0.35 m^2 active area, ~3.5B channels.



- Silicon tracking barrel layer geometry:
  - Move the 4th silicon layer to 27cm radius, 5th silicon layer to 42cm radius to improve tracking performance. Pixel pitch at 10μm, 3.13 m^2 active area, ~31.3B channels.

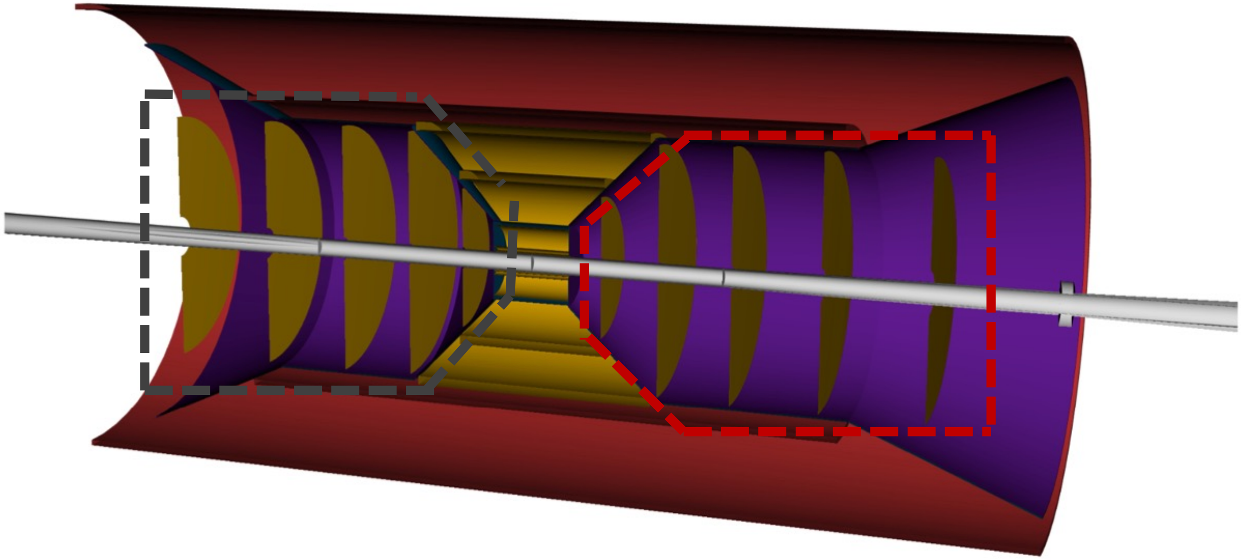




EPIC MAPS tracker geometry

EPIC MAPS tracker geometry optimization (Endcap)

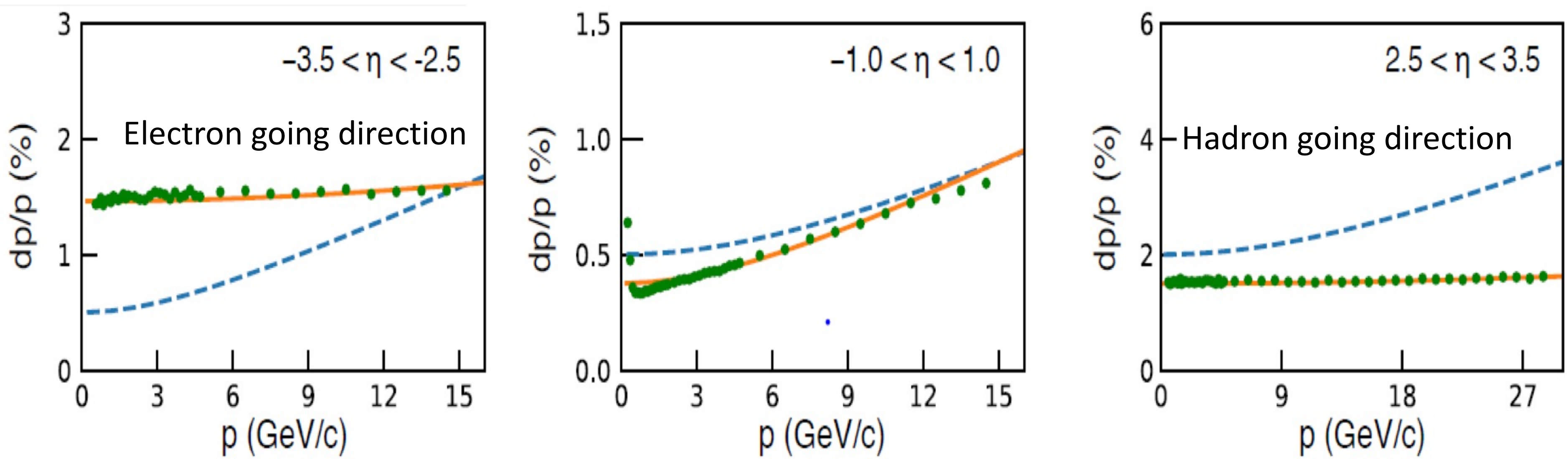
- Silicon hadron endcap geometry:
  - 5 MAPS (pixel pitch at 10μm) based disks with the z locations at 25cm, 45cm, 70cm, 100cm and 135cm. Inner radius varies from 3.6cm to 6.5 cm and outer radius varies from 19cm to 43cm.
- Silicon electron endcap geometry:
  - 5 MAPS (pixel pitch at 10μm) based disks with the z locations at -25cm, -45cm, -65cm, -90cm and -115cm due to detector integration requirements. Inner radius varies from 3.6cm to 5.6cm and outer radius varies from 19cm to 43cm.
- Around 4.8 m^2 active area, ~48B channels.



EPIC MAPS tracker geometry

Tracking performance of EPIC detector design (I)

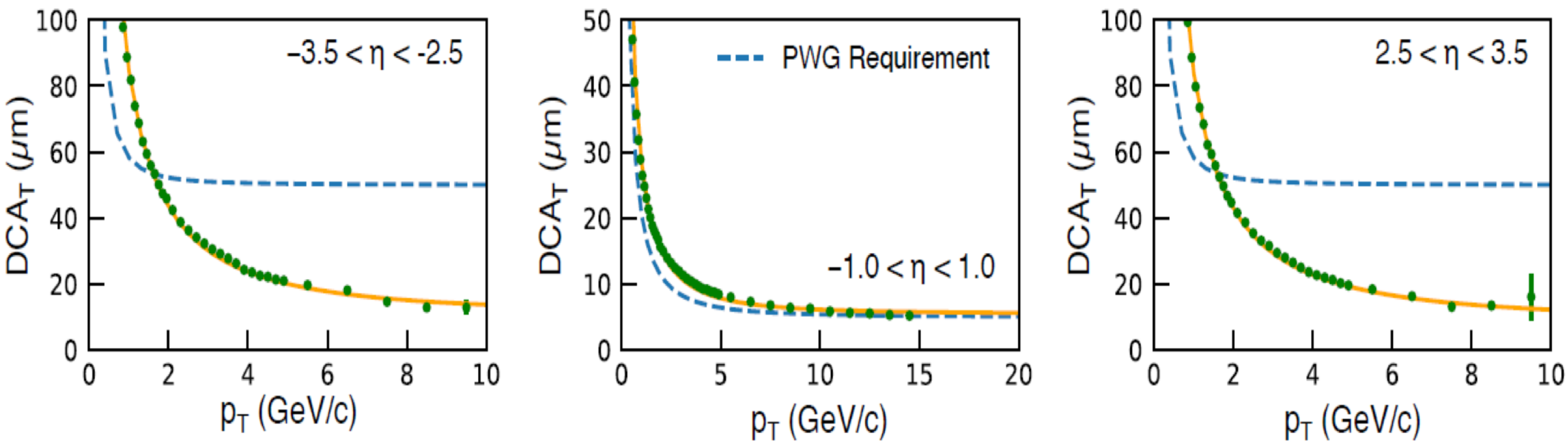
- Tracking momentum resolution of the EPIC tracking detector in the -1.0<η<3.5 meets the EIC yellow report requirements.
- Material budget reduction in the electron going direction (η <-1.0) and joint tracking and calorimeter measurements are under study to improve the tracking resolution.



- The optimized EPIC tracker design provides better tracking momentum resolutions than the EIC reference design in most pseudorapidity regions.

Tracking performance of EPIC detector design (II)

- Transverse momentum dependent transverse Distance of Closest Approach (DCA_T) resolution in most pseudorapidity regions also meets the EIC yellow report requirements.

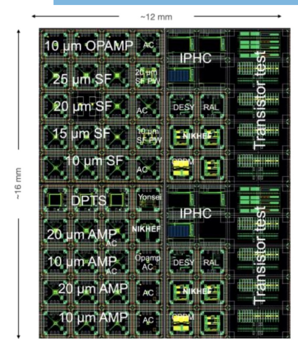


- Detector geometry optimization with cable and service routine implementation is ongoing.
- Will update tracking performance (e.g., efficiency) with the EIC backgrounds (beam gas, synchrotron radiation).

EIC silicon detector R&D status – MAPS I

- Propose to use the 65nm Monolithic Active Pixel Sensor (MAPS) technology for the EIC silicon vertex/tracking detector construction. We welcome new collaborators to join us and provide alternative technical options as well.
- Technology candidate for EPIC silicon vertex layers: ITS3-like MAPS sensor with
  - pixel size around $10\mu m$,
  - 0.05% X/X0 radiation length per layer,
  - Time resolution at O(100ns),
  - Fake-hit rate $<10^{-7}$,
  - radiation tolerance at around 10^{15} 1MeV n_{eq}/cm^2 at 20 °C.
- Prototype sensors (APTS, CE65, DPTS) are under characterization.

F. Carnesecchi talk on Oct. 25

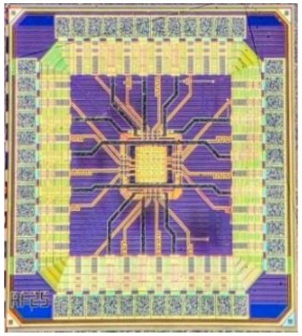


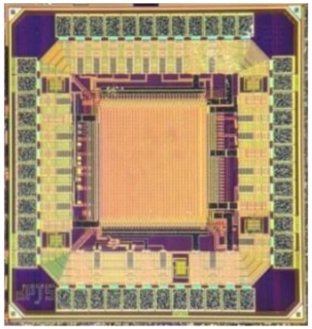
ALICE

ALICE ITS3 sensor design MLR1

Analogue Pixel Test Structure (APTS)

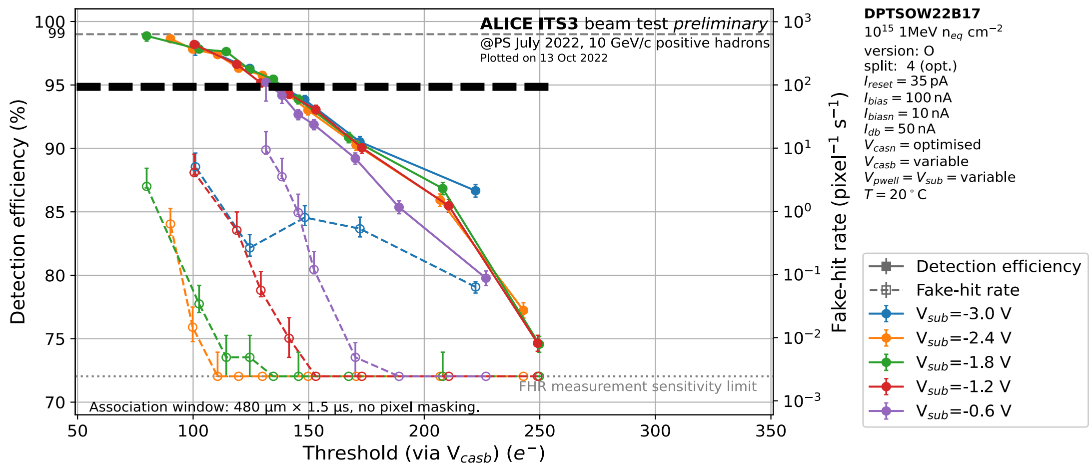
Digital Pixel Test Structure (DPTS)





EIC silicon detector R&D status – MAPS II

- Technology candidates for the middle sagitta layers and endcap disks: flat MAPS sensors with similar features of the ALICE ITS3 technology and the detector will consist of stitched sensor staves.

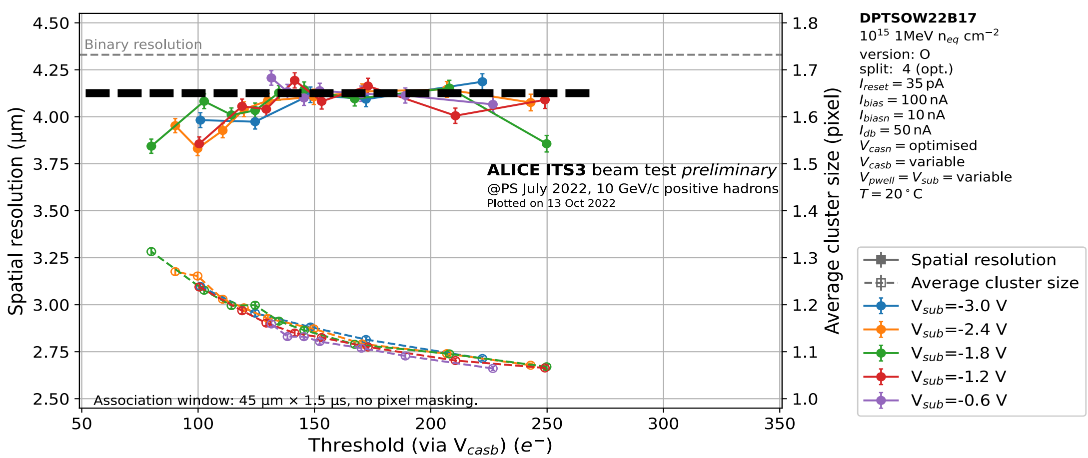


P. Becht talk on Oct. 25

L. Lautner talk on Oct. 25

Efficiency and fake hit rate of ALICE DPTS in DESY beam tests with irradiation dose at 10^{15} 1MeV n_{eq} cm^{-2}

ALICE

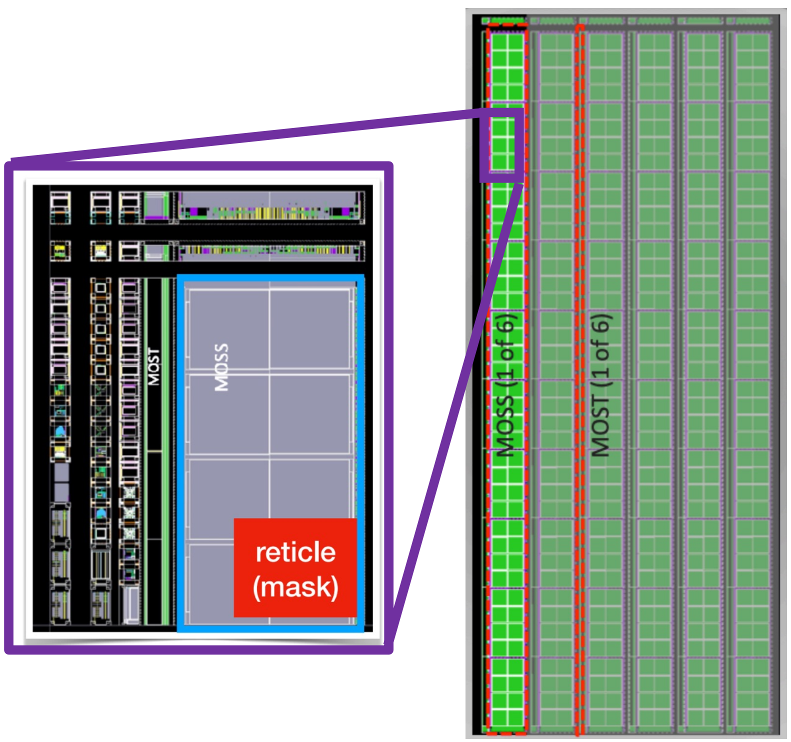


Spatial resolution of ALICE DPTS in DESY beam tests with irradiation dose at 10^{15} 1MeV n_{eq} cm^{-2}

EIC silicon detector R&D status – MAPS III

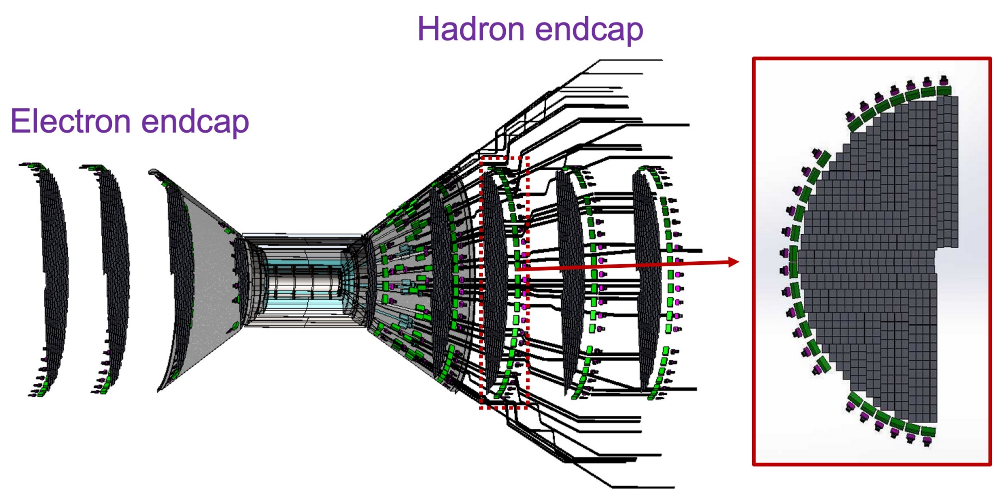
- Other components such as sensor design for the sagitta layers and disks, readout architecture, detector mechanical structure, powering, cooling and integration are under developments.

ALICE ITS3 ER1 design



ALICE ITS3 vertex layer feasibility assembly

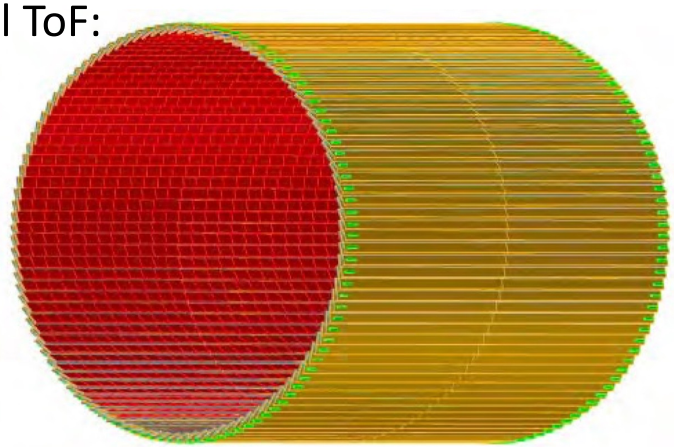
EIC silicon tracker conceptual mechanical design

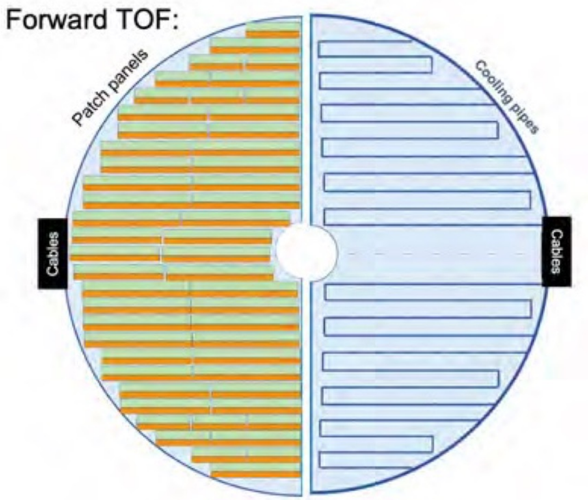


EIC silicon detector R&D status – AC-LGAD I

- Detailed detector geometry of the barrel and hadron endcap AC-LGAD tracker (ToF) has been developed.

Barrel ToF:



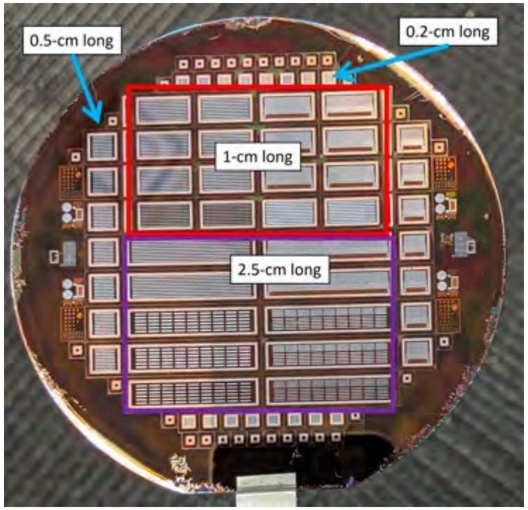


- Barrel AC-LGAD tracker (ToF):
  - Pixel size 0.5mm by 1.0mm.
  - 10.9 m^2 active area with 2.4M channels.
  - Spatial resolution 30μm in rφ.
  - Timing resolution 30ps.
- Hadron endcap AC-LGAD tracker (ToF):
  - Pixel size 0.5mm by 0.5mm.
  - 2.22 m^2 active area with 8.8M channels.
  - Spatial resolution 30μm in xy.
  - Timing resolution 25ps.

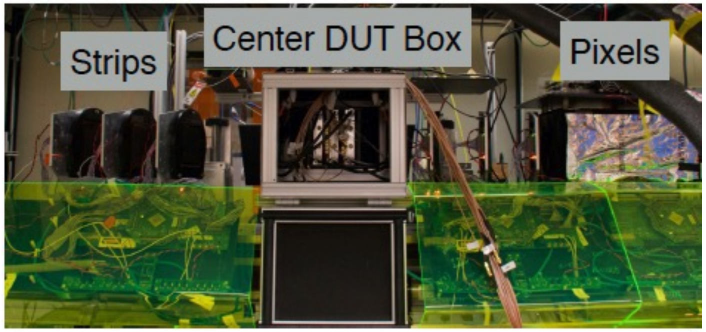
EIC silicon detector R&D status – AC-LGAD II

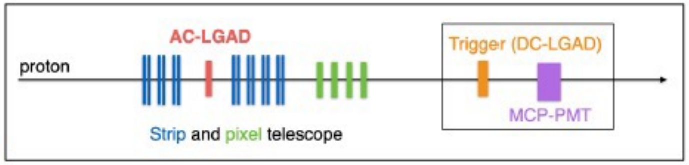
- New prototype sensors have been produced at BNL and HPK.
- New AC-LGAD strip design prototype sensor have been characterized with beam tests at FNAL. Around 30μm spatial resolution and better than 30ps timing resolution per hit can be achieved.
- Irradiation tests ($10^{13\text{-}16}$ n_{eq} cm^{-2}) have been carried out with 500MeV proton beam at LANL LANSCE for new AC-LGAD protype sensors. Will evaluate the radiation impacts.

AC-LGAD prototype sensor

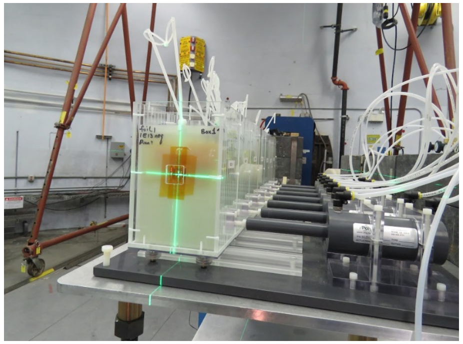


AC-LGAD FNAL beam test setup



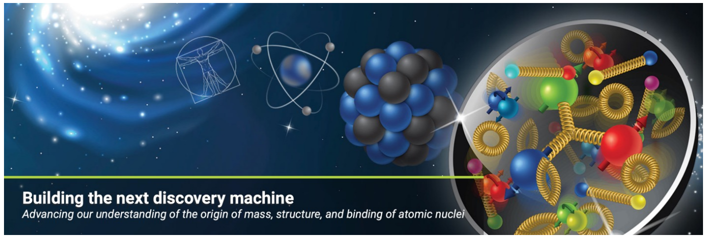


Irradiation tests at LANSCE



EIC project detector R&D status

- A series of EIC project detector R&D projects have been setup by the newly formed EIC center (hosted by BNL&JLab).
  - eRD104: Silicon vertex/tracking detector service part material budget reduction.
  - eRD111: Silicon vertex/tracking detector mechanical design.
  - eRD113: MAPS silicon sensor R&D for the EIC silicon vertex/tracking detector.
  - eRD112: AC-LGAD detector R&D.
  - …



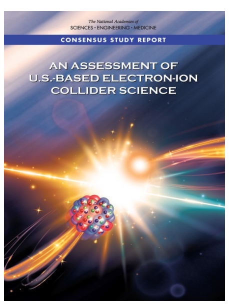
- Further contributions are very welcome!

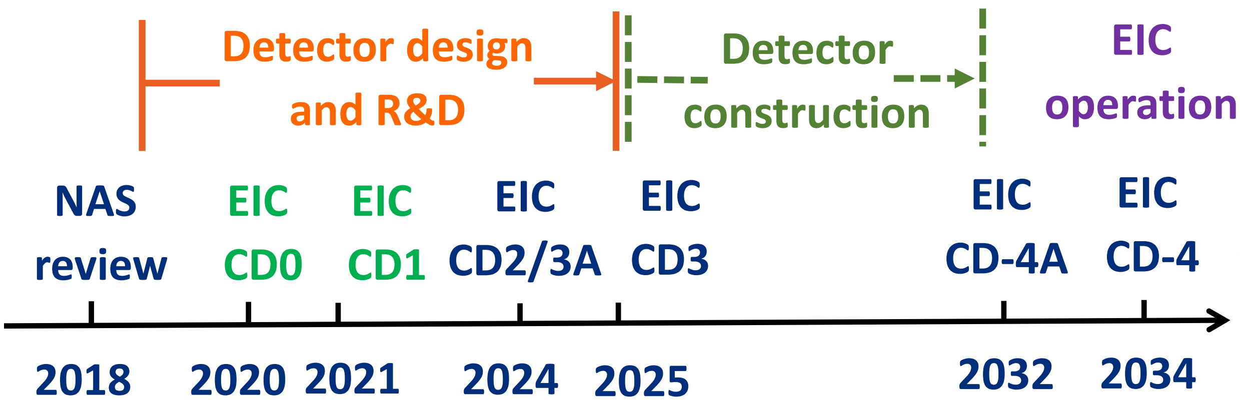
EPIC tracking development remaining tasks and requests

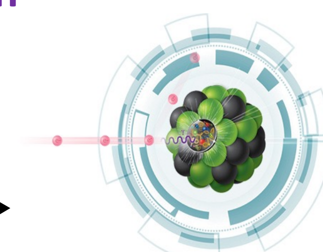
- Simulation developments
  - Background implementation for tracking performance studies.
  - Further optimization in the endcap disk layout, detector redundancy studies.
  - Alternative technologies to be included in the simulation production.
- Technology readiness
  - R&D plan, status and results.
  - Cost, risk and schedule updates.
- Detector integration
  - Integration with other detector subsystems for the detector geometry optimization and technology down selection.
- Physics WG inputs

Summary and Outlook

- Good progresses have been achieved for the EIC project detector (EPIC) design optimization and related R&D.
- Current EPIC silicon vertex and tracking detector optimized design can achieve better tracking performance and meet most of the EIC yellow report requirements.
- The ongoing EIC silicon detector R&D aligns well with several parallel projects (e.g., LHC upgrades) and we welcome new collaborators to join us for the EIC detector realization!







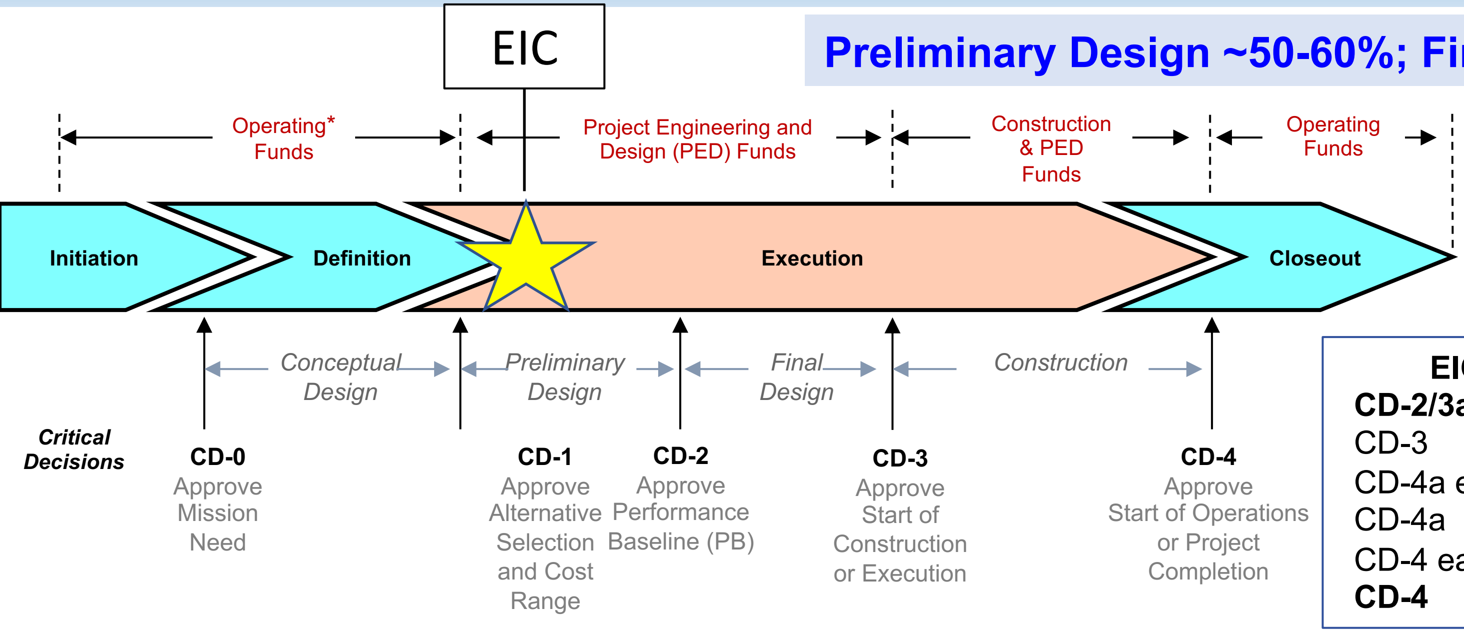
Workshop Announcement

- The CPAD 2022 workshop will be organized at Stony Brook University, USA from November 29 to December 2, 2022, with the **extended abstract submission deadline to October 30, 2022**. We look forward to see you there!
- Conference link: https://www.stonybrook.edu/cfns/cpad2022/index.html
- Registration link: https://indico.bnl.gov/event/17072/page/461-registration

Backup

DOE Project Decision Process

Preliminary Design ~50-60%; Final Design ≥ 85%



EIC Critical Decision Plan

CD-2/3a	**January 2024**
CD-3	April 2025
CD-4a early finish	April 2031
CD-4a	April 2032
CD-4 early finish	April 2032
CD-4	**April 2034**

CD-2 – Approve Performance Baseline: CD-2 is an approval of the preliminary design of the project and the baseline scope, cost, and schedule. What is most relevant is that CD-2 means there is now a definitive plan that the project will be measured against in cost, schedule and technical performance.

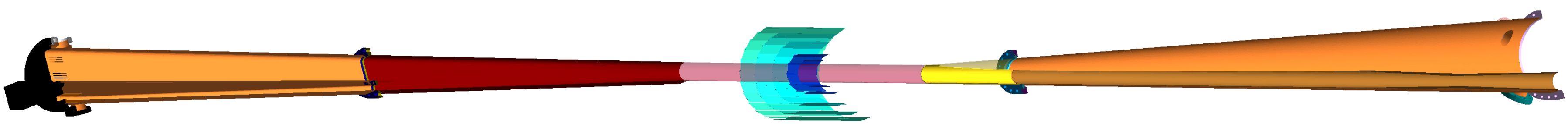
→ pre-TDR is required for CD-2 (pre-TDR = preliminary version of TDR)

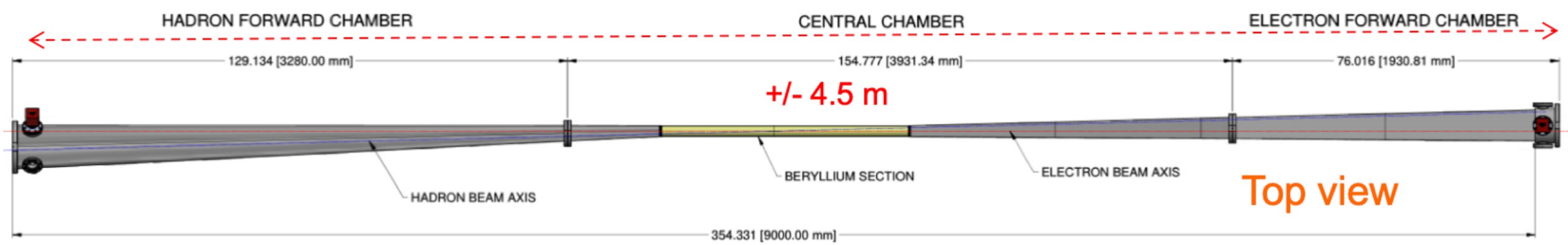
CD-3 – Approve Start of Construction: CD-3 is an approval of the project's final design and authorizes release of funds for construction. What is most relevant is that projects can now proceed with construction related procurements and activities. CD-3 is sometimes split in CD-3A in a tailored approach to approve start construction for long-lead procurements.

→ TDR is required for CD-3

EIC beam pipe design

- The EIC project detector beam crossing angle is 25 mrad.
- The EIC beam pile is asymmetric along z axis and has a shift along x axis.

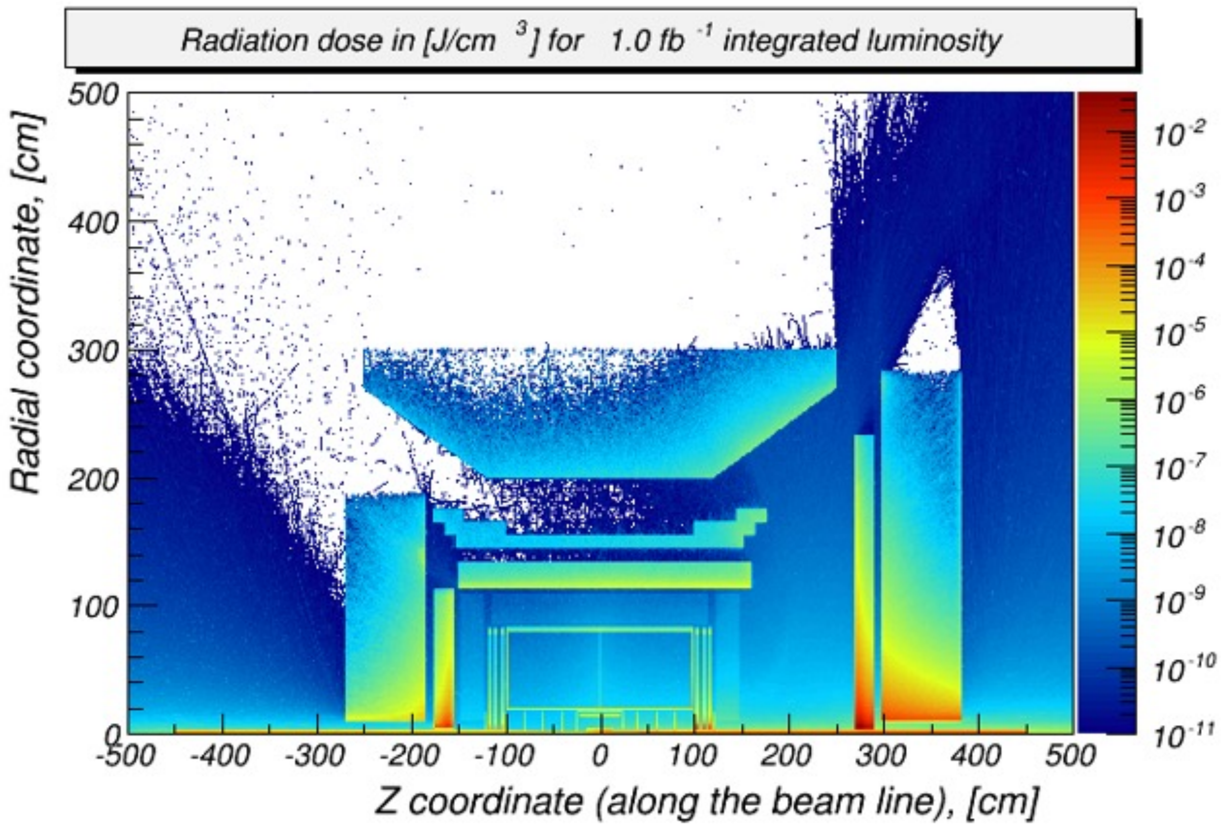




EIC background study

- The EIC backgrounds consist of neutron flux, nucleon/electron beam gas and synchrotron radiation.

R. A. Khalek et. al., NPA 1026 (2022) 122447



- Neutron flux: $6x10^{10}$ n_{eq}/yr at 10^{34} $cm^{-2}s^{-1}$ instantaneous luminosity.
- Beam gas: ~10 kHz inelastic beam gas interaction rate.
- Synchrotron radiation: under study.

EIC reference silicon vertex/tracking detector geometry

- The ECCE tracking detector geometries have been archived in the Fun4All ECCE associated repositories.

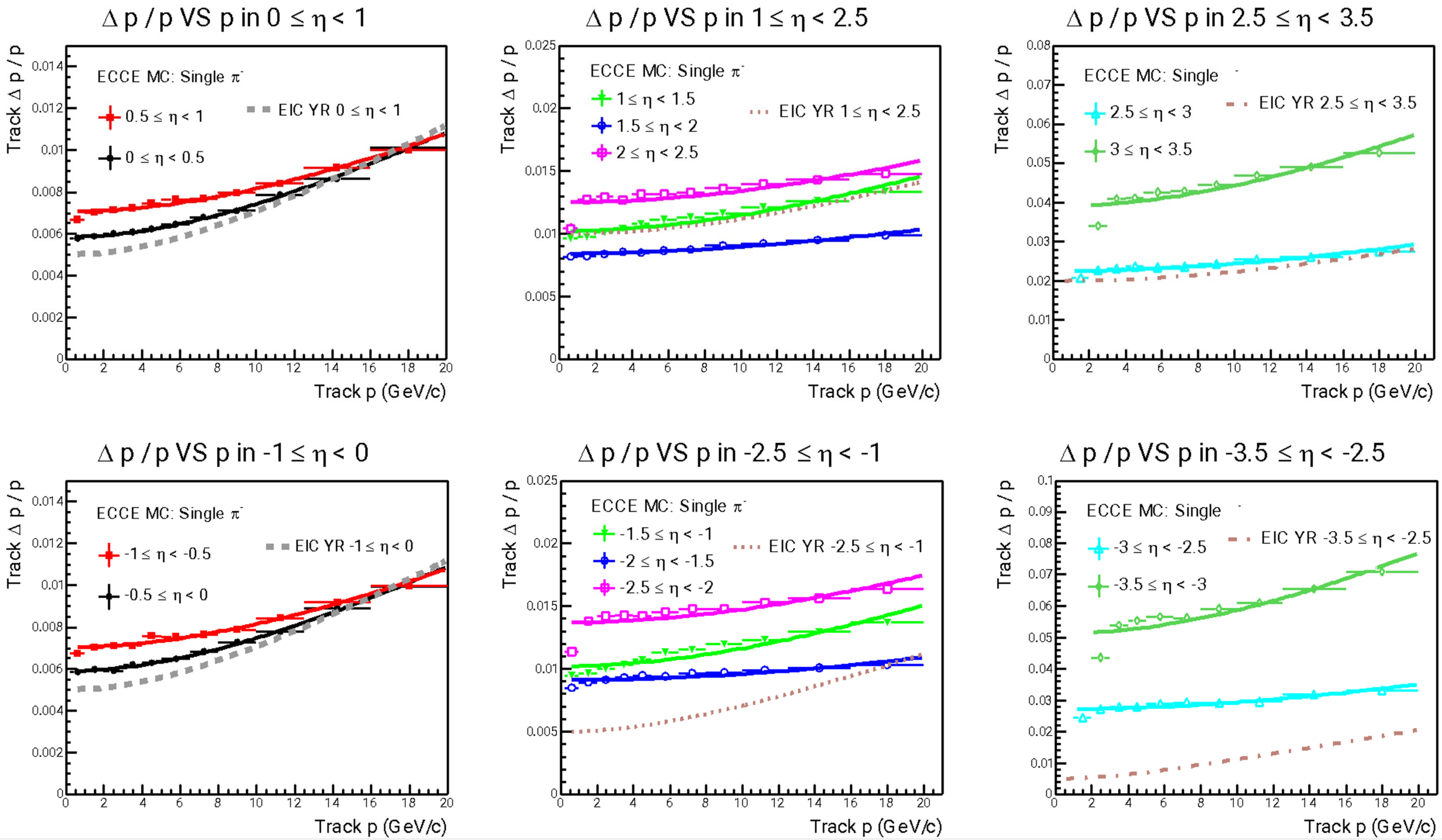
Barrel index	R (cm)	z_{min} (cm)	z_{max} (cm)
1	3.3	-13.5	13.5
2	4.35	-13.5	13.5
3	5.4	-13.5	13.5
4	21.0	-27	27
5	22.68	-30	30

H-endcap index	z (cm)	r_{in} (cm)	r_{out} (cm)
1	25	3.5	18.5
2	49	3.5	36.5
3	73	4.5	40.5
4	106	5.5	41.5
5	125	7.5	43.5

e-endcap index	z (cm)	r_{in} (cm)	r_{out} (cm)
1	-25	3.5	18.5
2	-52	3.5	36.5
3	-79	4.5	40.5
4	-106	5.5	41.5

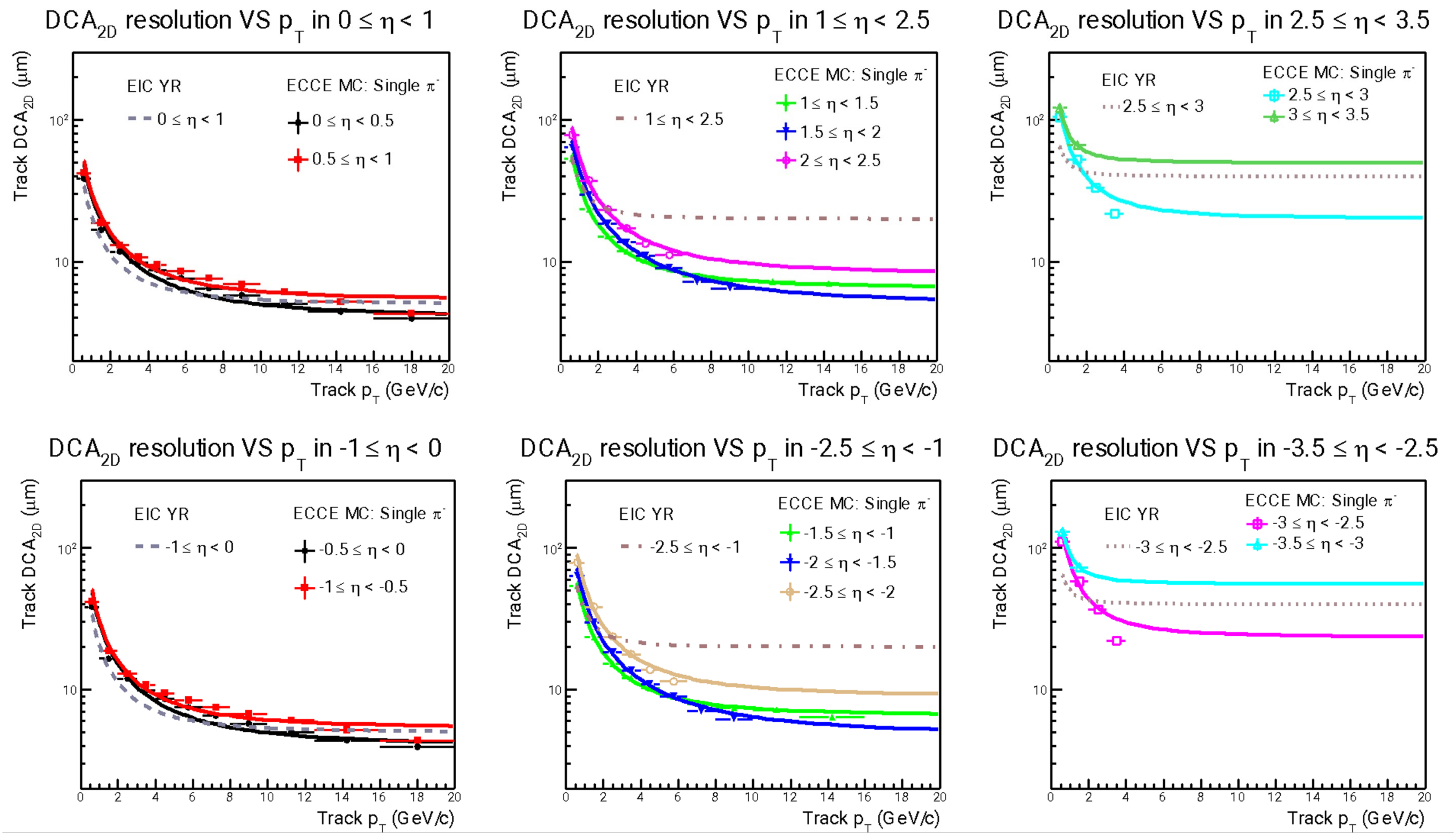
EIC reference tracking detector momentum resolution

- Track momentum dependent momentum resolution.



EIC reference tracking detector DCA_{2D} resolution

- Track p_T dependent DCA_{2D} resolution.



EPIC tracking detector working plan and goals

- Simulation:
  - Simulation task break down and priority list summarized in the EPIC WIKI page: https://wiki.bnl.gov/EPIC/index.php?title=Tracking
  - Reevaluate the tracking performance with the new 1.7T B-field with the produced simulation samples using the EPIC common software.
- Technology review:
  - Complete review of the choice of tracking technologies.
  - Identify risks & fallback solutions for each technology.
  - Close coordination with the detector consortia (EIC Silicon consortium, MPGD consortium).
- EIC Tracking Detector configuration:
  - Develop a technical design of the integrated tracking detector, which can meet the proposed EIC physics requirements towards the EIC CD2/3A review scheduled in 2023.
- Validate the tracking performance based on inputs from the physics WGs:
  - List of key tracking requirements such as momentum resolution, vertex and projection spatial resolutions.

EPIC Tracking Detector Working Group Information

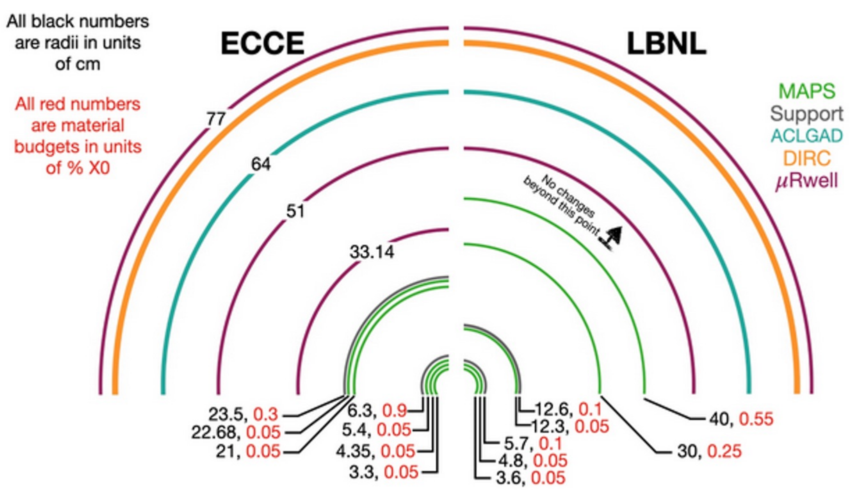
- Move towards the EIC detector technical design by the EPIC collaboration.
- About the EIC EPIC tracking working group:
  - Conveners: Xuan Li (xuanli@lanl.gov), Kondo Gnanvo (kagnanvo@jlab.org), Laura Gonella (laura.gonella@cern.ch), Francesco Bossu (francesco.bossu@cea.fr)
  - Email mailing list: eic-projdet-tracking-l@lists.bnl.gov
  - We have weekly meetings scheduled at 11:00AM US eastern time every Thursday and the meeting indico link: https://indico.bnl.gov/category/404/
  - Mattermost channel: https://eic.cloud.mattermost.com/main/channels/tracking
  - WIKI page: https://wiki.bnl.gov/EPIC/index.php?title=Tracking
- Welcome new collaborators to join us and send us your tracking performance requirements!

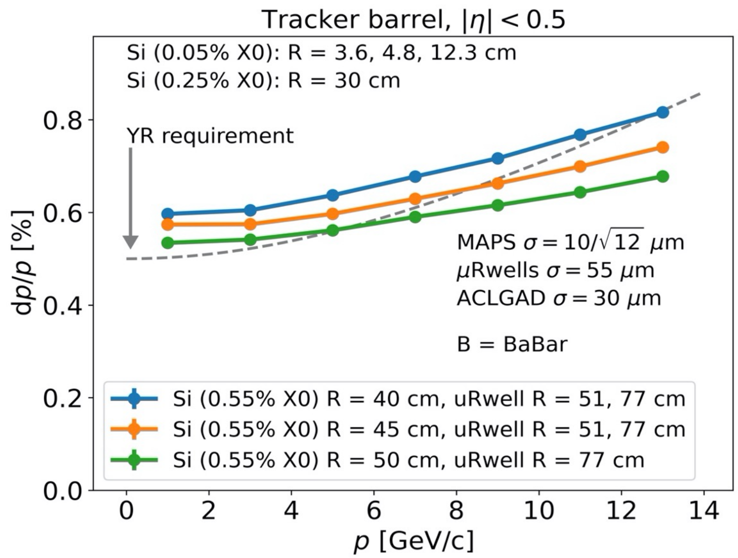
Barrel silicon vertex/tracking optimization

- Silicon vertex and sagitta layer optimization:

Updated Silicon barrel geometry in simulation:

	r (cm)	length (cm)	X/X0
1	3.6	27	0.05%
2	4.8	27	0.05%
Support	5.7	15.4	0.1%
3	12.3	27	0.05%
Support	12.6	30.6	0.1%
4	30	77	0.25%
5	40	104	0.55%





- Reconfiguration of vertex and sagitta layers position and material budgets implemented in MC.
- Moving out the 3rd vertex layer and the sagitta layers can help improve the tracking momentum resolutions to get close the EIC YR requirements.

Track reconstruction with the EPIC MAPS tracker

- Reconstructed tracks in the EPIC MAPS vertex and tracking detector in GEANT4 simulation.