ACTS in ePIC at the future EIC

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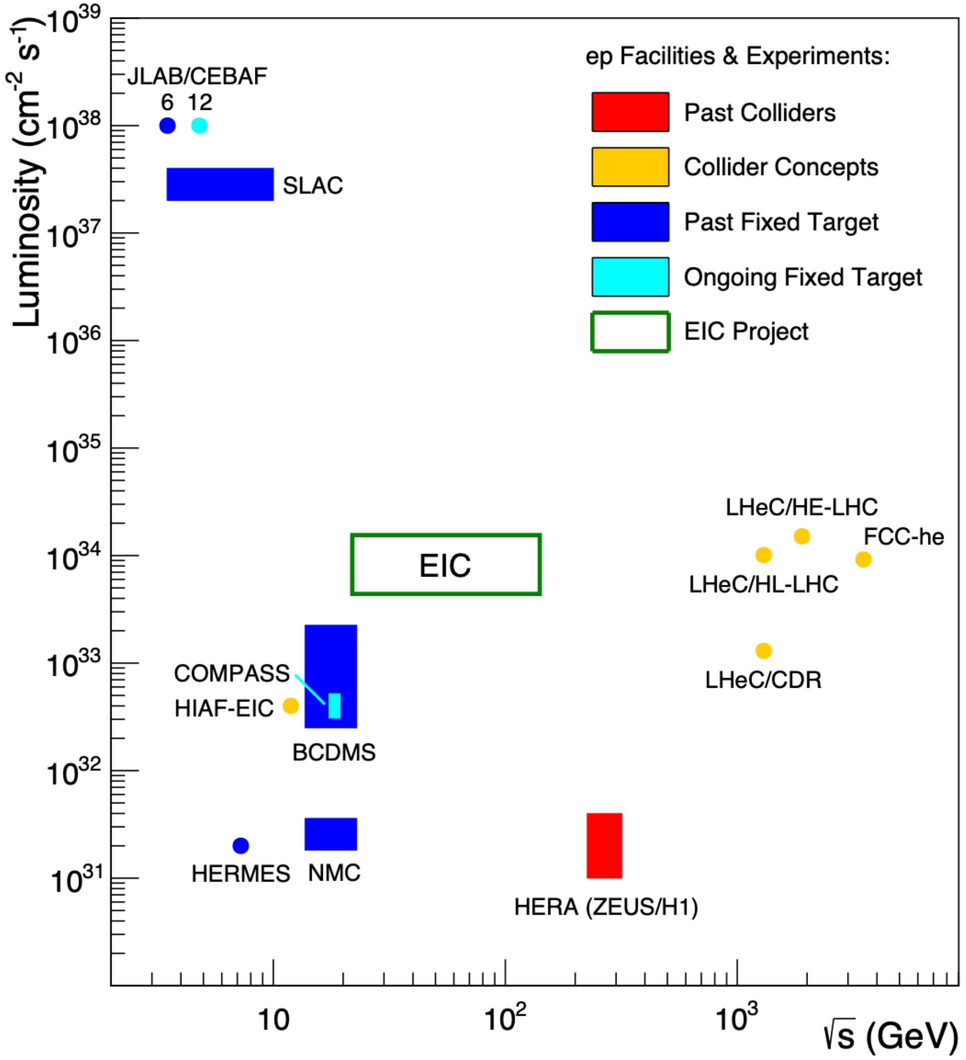
On behalf of the tracking and vertexing working group

The Electron-Ion Collider (EIC)



The EIC will be the first

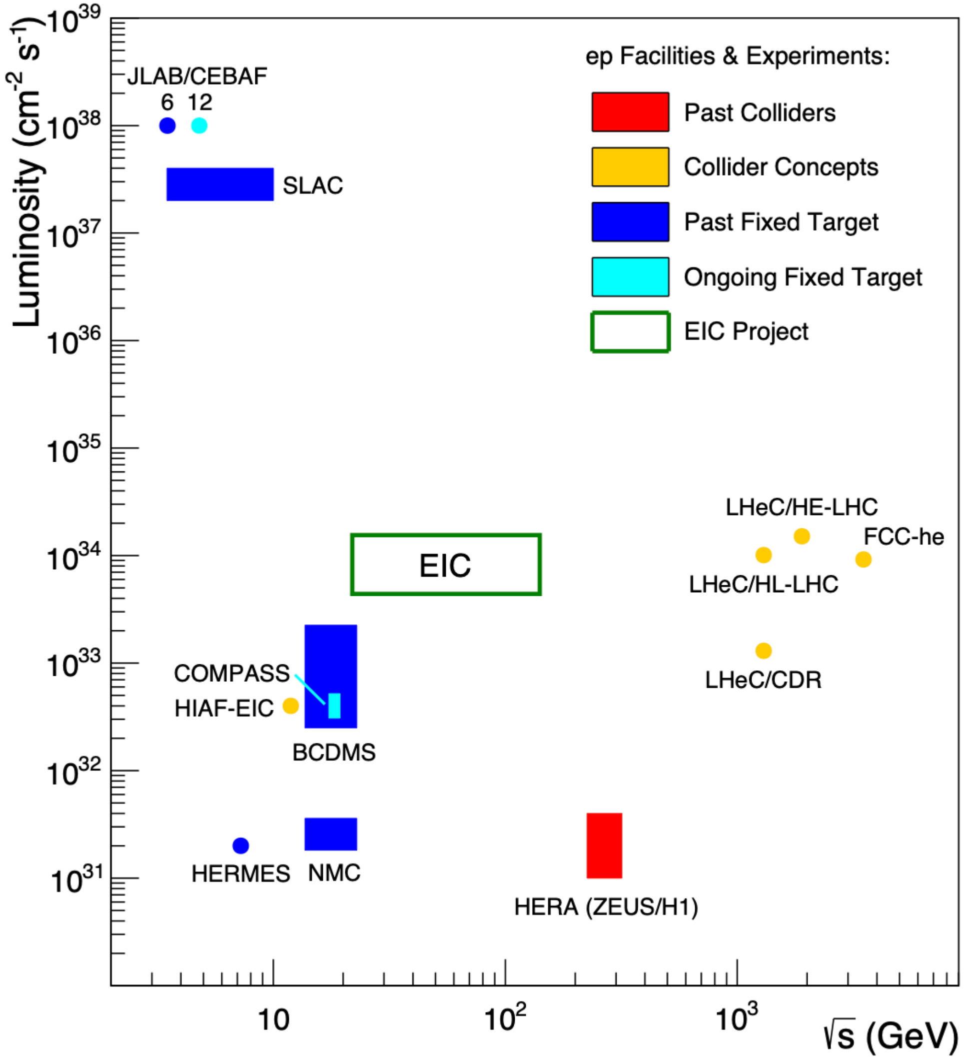
- High-luminosity e-p collider
- Polarized target collider
- Electron-nucleus collider

EIC energy range: $20 < \sqrt{s} < 141\ GeV$

<u>Main physics topics to be explored at the EIC</u>

- Nucleon structure – full three-dimensional momentum and spatial structure, as well as spin structure
- Origin of nucleon (hadron) mass – how is the nucleon's mass generated by the underlying internal partonic interactions
- Dense partonic systems in nuclei
- Science beyond the 2018 National Academies of Science (NAS) report

The Electron-Ion Collider (EIC)

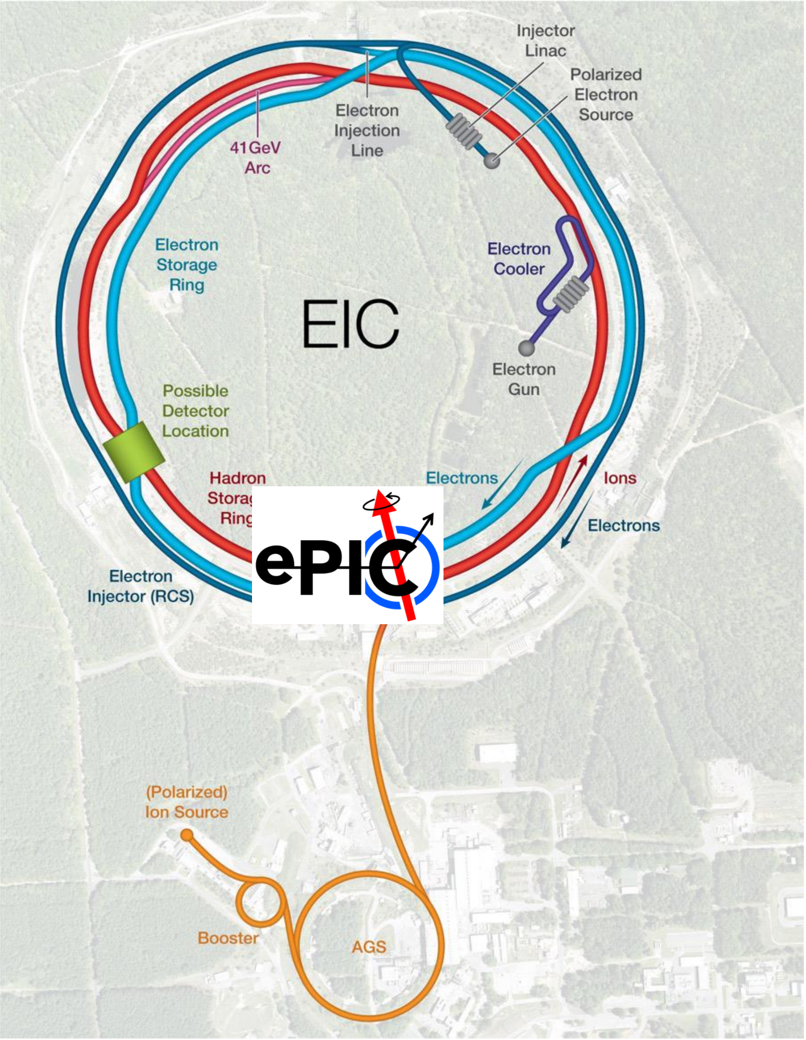


Start of science program:

Early-Mid. 2030s

Location:

BNL



ePIC central detector design

Magnet

- New 1.7 T SC solenoid, 2.8 m bore diameter

Tracking

- Si Vertex Tracker MAPS wafer-level stitched sensors (ALICE ITS3)
- Si Tracker MAPS barrel and disks
- Gaseous tracker: MPGDs (μRWELL, MMG) cylindrical and planar

PID

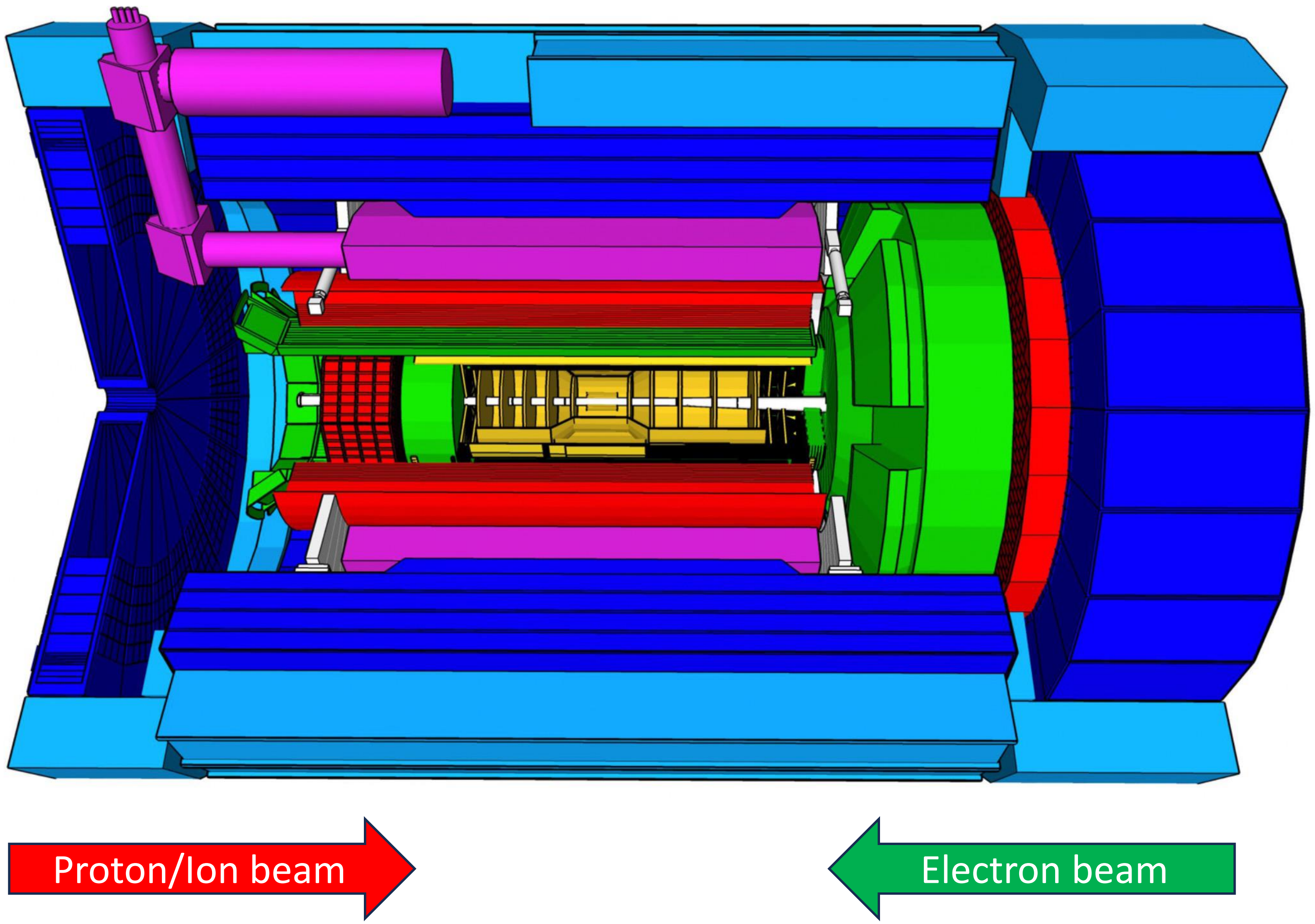
- high performance DIRC (hpDIRC)
- dual RICH (aerogel + gas) (forward)
- proximity focussing RICH (backward)
- ToF using AC-LGAD (barrel+forward)

EM Calorimetry

- imaging EMCal (barrel)
- W-powder/SciFi (forward)
- $PbWO_4$ crystals (backward)

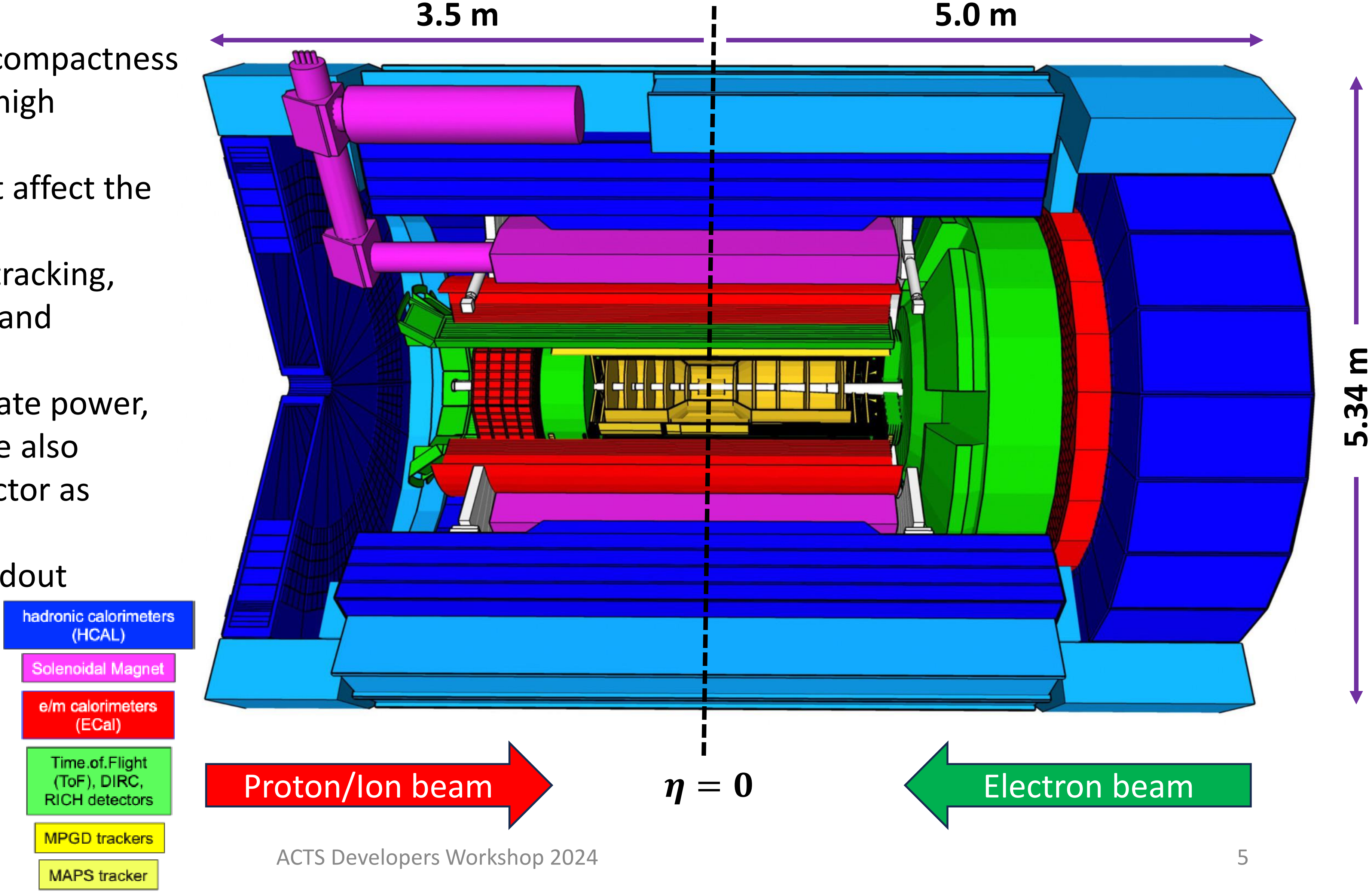
Hadron calorimetry

- FeSc (barrel, re-used from sPHENIX)
- Steel/Scint – W/Scint (backward/forward)



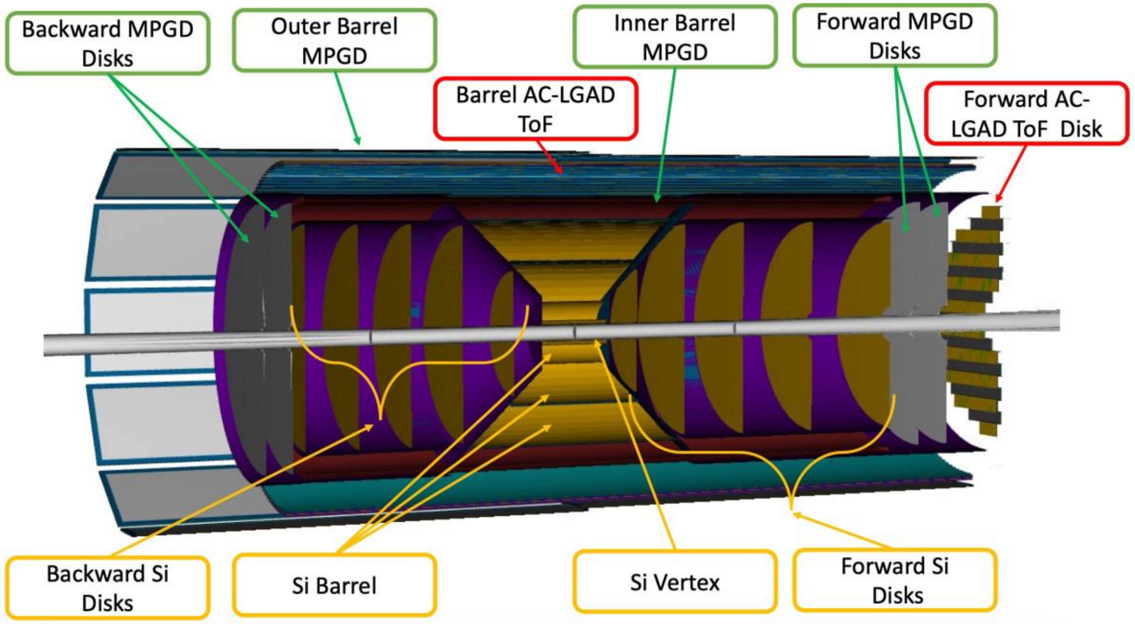
ePIC central detector design

- Central detector is ~9m long – compactness comes from IR design allowing high luminosity
- Solenoidal field – magnet won’t affect the electron beam
- Combines > 16 subsystems for tracking, vertexing, PID, EM calorimetry, and hadronic calorimetry
- Substantial challenges to integrate power, cooling, and data services, while also maintaining as hermetic a detector as possible
- Detector will use streaming-readout approach



ePIC central detector design – tracking

Full tracking system: Silicon Vertex Tracker (SVT) + MPGDs + AC-LGAD TOFs detectors

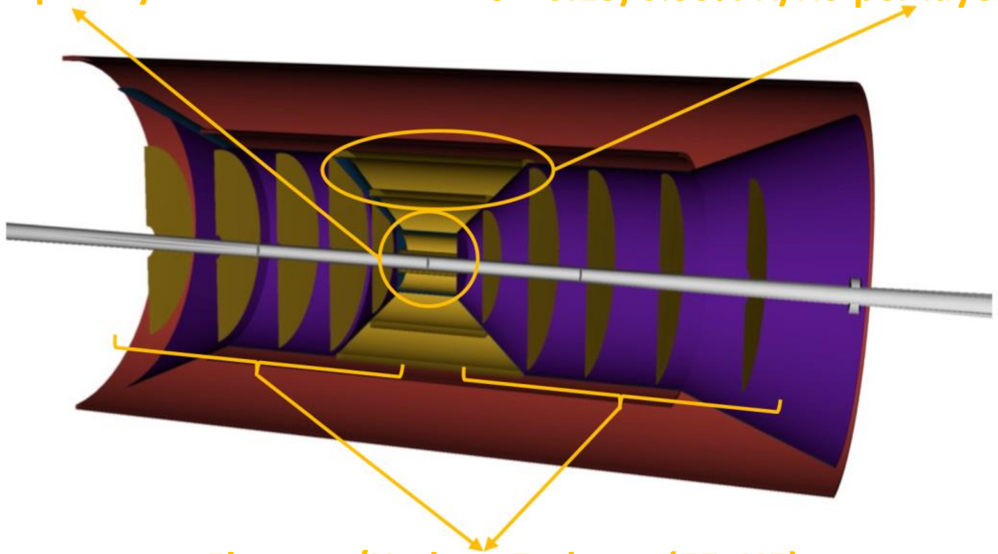


MPGDs and **AC-LGADs** provide
- additional hit points for track reconstruction
- fast timing hits for background rejection (~10-20 ns)

SVT

Inner Barrel (IB)
- **Two curved silicon vertex layers**
- **One curved dual-purpose layer**
- **0.05% X/X0 per layer**

Outer Barrel (OB)
- **One stave-based sagitta layer**
- **One stave-based outer layer**
- **0.25/0.55% X/X0 per layer**



Electron/Hadron Endcaps (EE, HE)
- **Five disks on either side of the Interaction Region**
- **0.25% X/X0 per layer**

65 nm MAPS technology (ALICE ITS3)
O(20x20 μm^2) pixel size
Total active area of 8.5 m^2

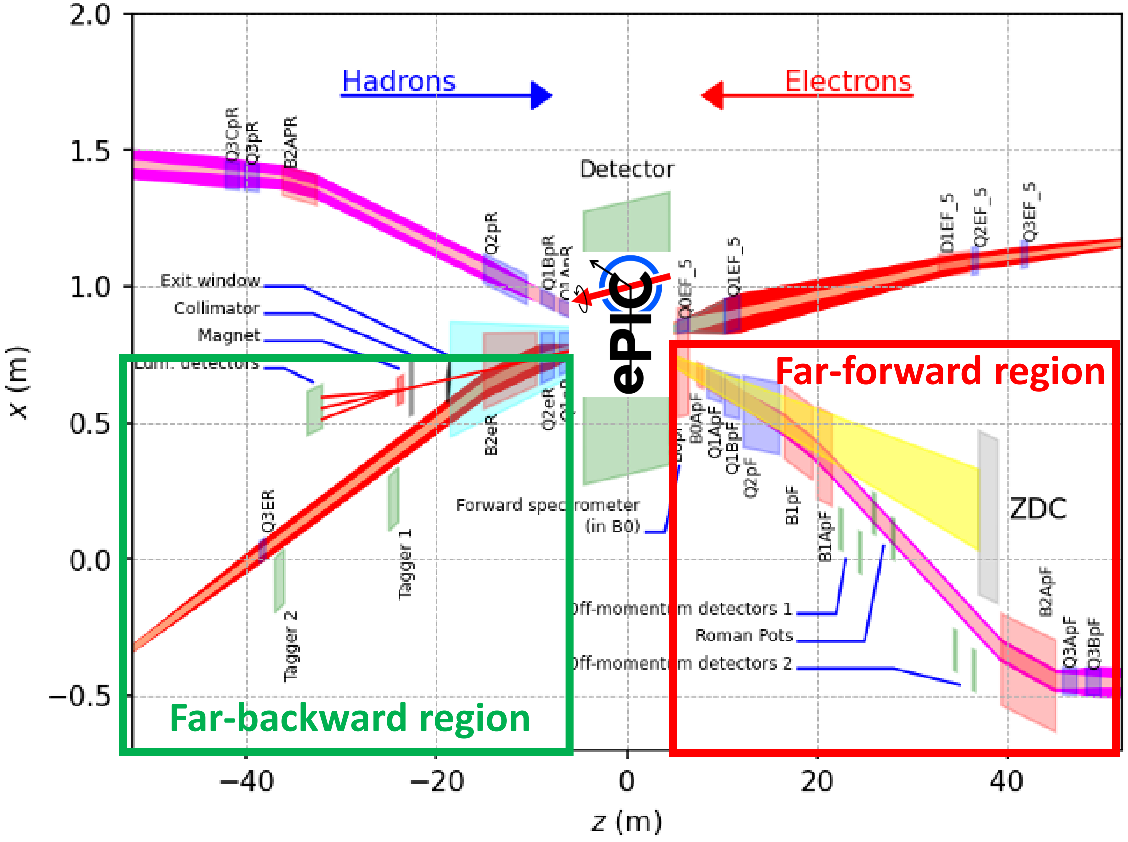
ePIC detector design – some unique features

- The full detector design is integrated over the entire 90m long EIC interaction region.

- The central (tracking) detector has an asymmetric design, due to the larger hadron beam energy relative to the electron beam energy.
- The beams have a large (25 mRad) crossing angle, which leads to an asymmetry in the horizontal direction.
- The ePIC detector will use a streaming readout mode (time slices). The time component for tracking and vertexing will be important.

- ACTS track finding and fitting is being used in the central and far-forward (B0 detector) regions. For the B0 detector, thank you to the ACTS developers for adding geometry support for an off-axis detector.
- Focus of this presentation will be on tracking and vertexing in the central detector region.

Interaction region (IR) design



Software for the realization of the ePIC experiment

Our software design is based on **lessons learned in the worldwide NP and HEP community** and a **decision-making process** involving the whole community. We will continue to work with the worldwide NP and HEP community.

Modular Simulation, Reconstruction, and Analysis Toolkit using tools from the NP-HEP community

MC Event Generators

Detector Simulations in Geant4

Readout Simulation (Digitization)

Reconstruction in JANA2

Physics Analyses

EDM4eic data model based on EDM4hep and podio.
Geometry Description and Detector Interface using DD4hep.

Continuous Integration for Detector and Physics Benchmarks and Reproducibility

We are providing a production-ready software stack throughout the development:

- **Milestone**: Software enabled first large-scale simulation campaign for ePIC.

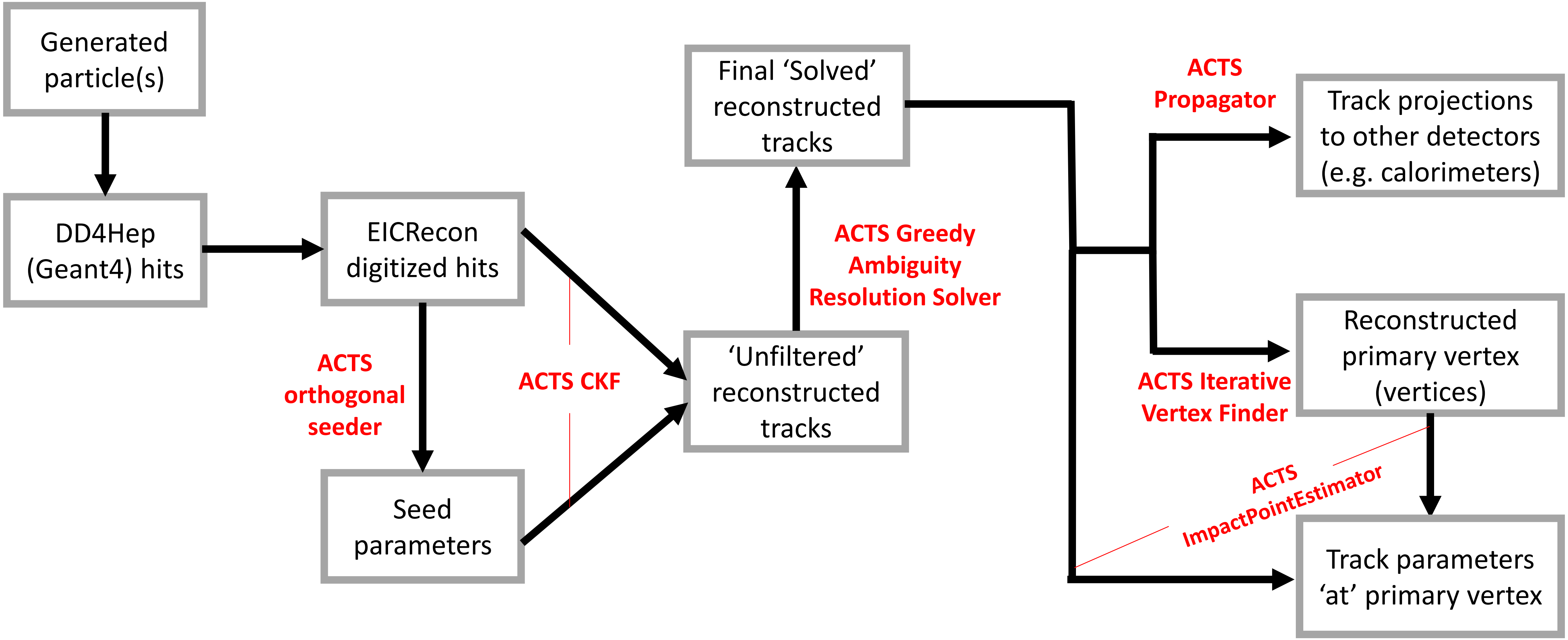
We have a good foundation to meet the near-term and long-term software needs for ePIC.

Accomplishments over the last year

- Implementation of curved DD4Hep geometries in the barrel region and integration with ACTS.
- Development of path for continuous upgrades of ACTS versions in our software framework.
  - Currently using ACTS v33
  - Creation of a set of benchmark plots to inform us about the impact of any given update
- Implementation of ACTS *Greedy Ambiguity Resolution Solver*
  - Removal of tracks arising from ‘duplicate’ seeds
  - Selection of best track if multiple ‘trackTips’ exist for a given seed
  - Removal of tracks with too-few measurement hits when running idealistic (i.e. truth-seeded) tracking mode
- Primary vertex finding, using *ZScanVertexFinder* for seeding followed by *IterativeVertexFinder.* Primary vertex fitting then uses *FullBilloirVertexFitter.*
  - Creation of data structures to store primary vertex information and list of tracks used in the vertex fit.
  - Development of analysis codes that use *ImpactPointEstimator* to project reconstructed tracks – originally reconstructed at beamline PoCA – to 3D DCA point with respect to primary vertex.
  - Ongoing efforts to use ACTS tools for secondary vertex finding and fitting
- Ongoing studies of effects of electronic noise and beam-induced backgrounds on track efficiency and purity.

Tracking workflow

An idealistic tracking mode that uses MC information also exists for testing/comparison.

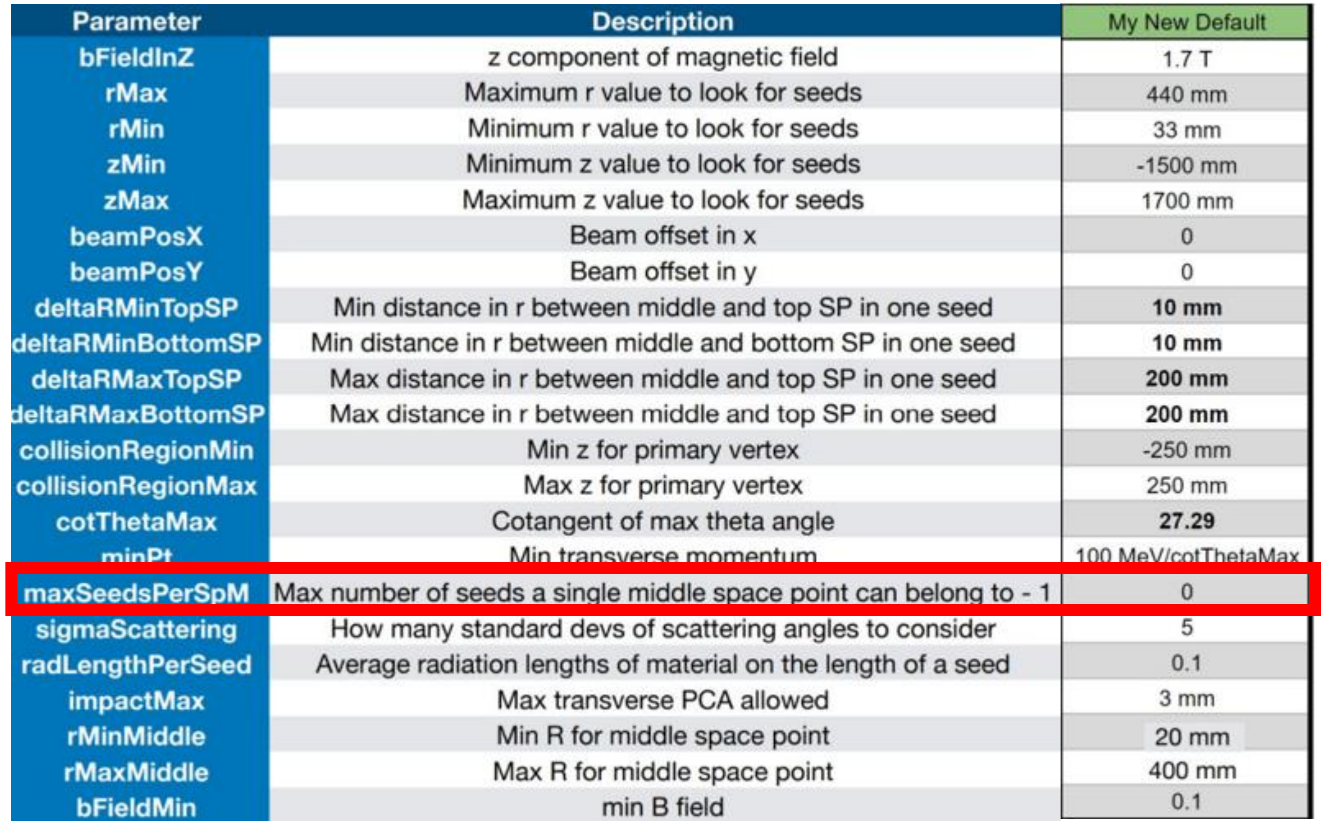


Seed duplicates – particles have multiple seeds

If we have a particle at mid-rapidity which hits layers L0, L1, L2, L3, and L4, then we can make the following combinations:

1. L0,L1,L2
2. L0,L2,L3
3. L0,L3,L4
4. ✖ L0,L1,L3
5. ✖ L0,L1,L4
6. ✖ L0,L2,L4
7. ✖ L1,L2,L3
8. ✖ L1,L2,L4
9. ✖ L1,L3,L4
10. ✖ L2,L3,L4

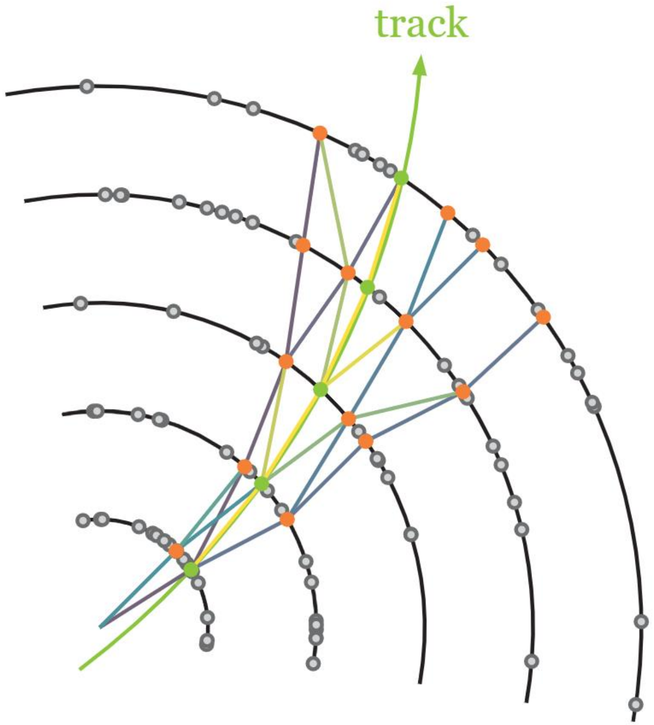
ACTS seed finder and filter parameters



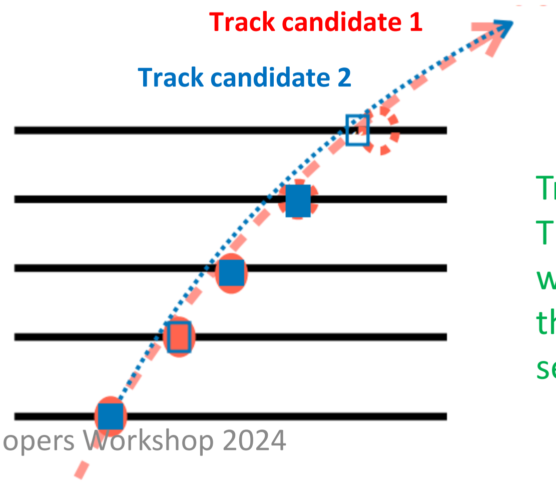
Parameter	Description	My New Default
bFieldInZ	z component of magnetic field	1.7 T
rMax	Maximum r value to look for seeds	440 mm
rMin	Minimum r value to look for seeds	33 mm
zMin	Minimum z value to look for seeds	-1500 mm
zMax	Maximum z value to look for seeds	1700 mm
beamPosX	Beam offset in x	0
beamPosY	Beam offset in y	0
deltaRMinTopSP	Min distance in r between middle and top SP in one seed	**10 mm**
deltaRMinBottomSP	Min distance in r between middle and bottom SP in one seed	**10 mm**
deltaRMaxTopSP	Max distance in r between middle and top SP in one seed	**200 mm**
deltaRMaxBottomSP	Max distance in r between middle and top SP in one seed	**200 mm**
collisionRegionMin	Min z for primary vertex	-250 mm
collisionRegionMax	Max z for primary vertex	250 mm
cotThetaMax	Cotangent of max theta angle	**27.29**
minPt	Min transverse momentum	100 MeV/cotThetaMax
maxSeedsPerSpM	Max number of seeds a single middle space point can belong to - 1	0
sigmaScattering	How many standard devs of scattering angles to consider	5
radLengthPerSeed	Average radiation lengths of material on the length of a seed	0.1
impactMax	Max transverse PCA allowed	3 mm
rMinMiddle	Min R for middle space point	20 mm
rMaxMiddle	Max R for middle space point	400 mm
bFieldMin	min B field	0.1

ACTS Greedy Ambiguity Resolution Solver

- The *ACTS Greedy Ambiguity Resolution Solver* has been implemented into the standard ePIC track reconstruction framework. The solved tracks produced by this algorithm are now the default tracking output for track performance studies and downstream algorithms (e.g. vertexing).
- The *ACTS Greedy Ambiguity Resolution Solver* takes as input all track candidates (*trackTips*) from the CKF and filters them to produce a set of solved tracks.
- These solved tracks combine input track candidates which contain a minimum number of shared hits. This is important for removing duplicate seeds.
- In addition, the input track candidates are required to have a minimum of number of track fit measurements to be considered a solved track.



All track candidates – including multiple candidates associated with a given track seed – are passed as input into the *ACTS Greedy Ambiguity Resolution Solver.*



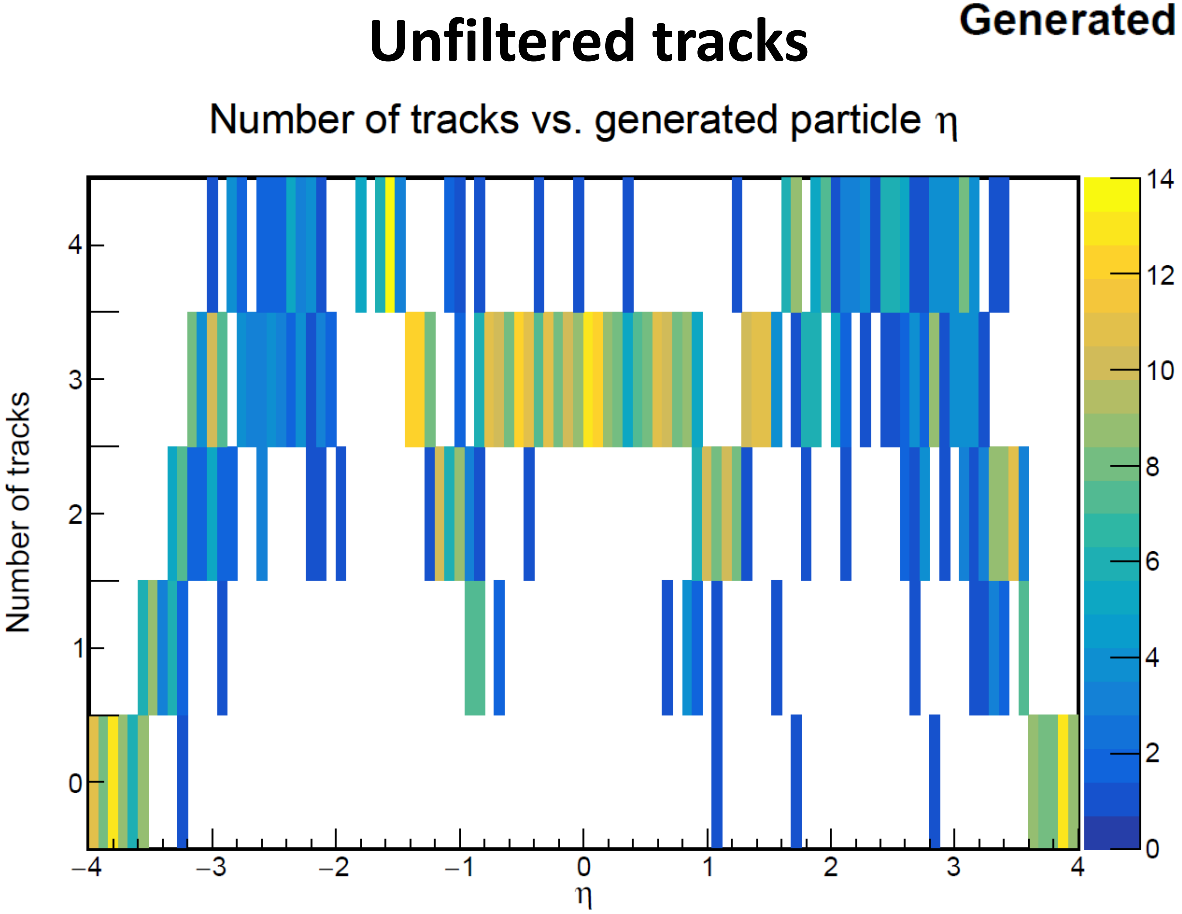
Tracks with shared hits are filtered. This combines track candidates with multiple seed triplets from the same particle (duplicate seeds).

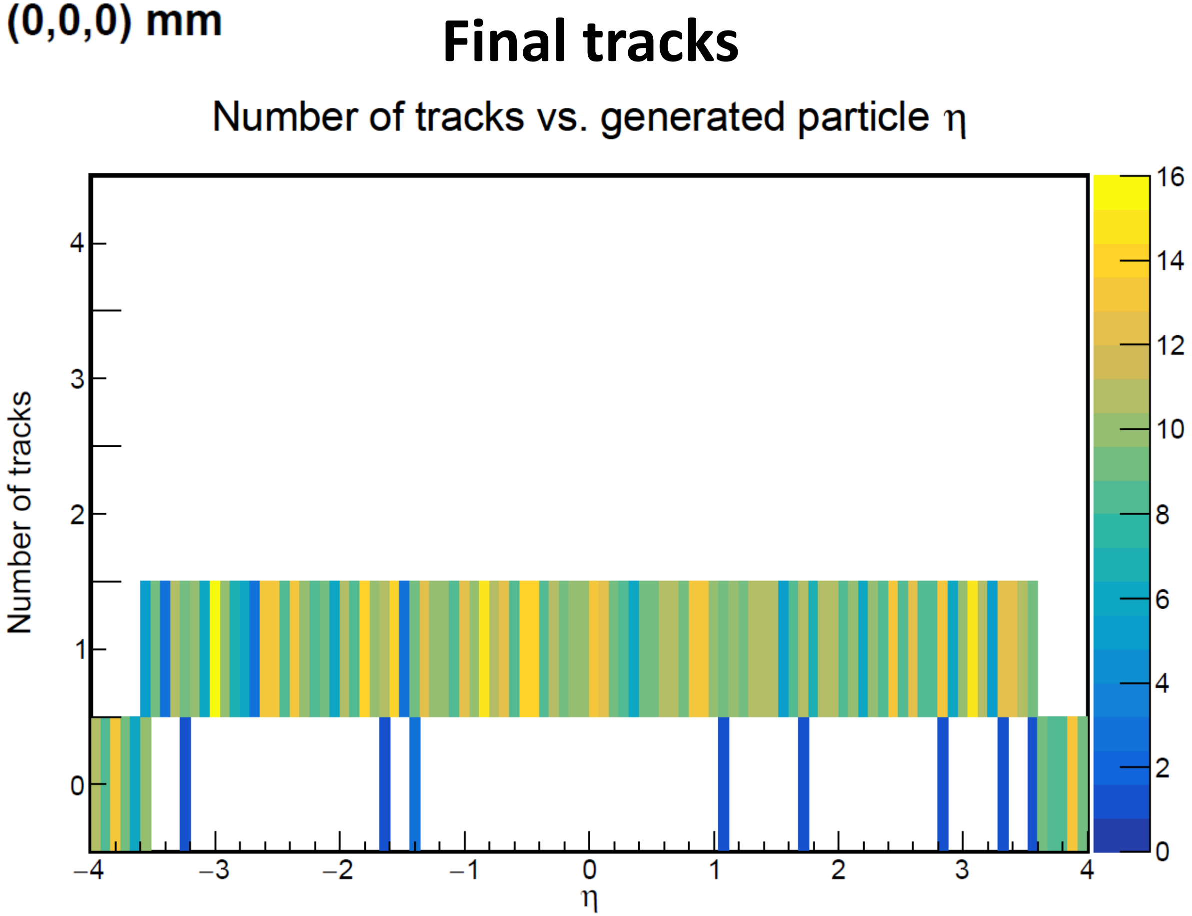
Reconstruction multiplicity/efficiency: single-particle simulation

Single μ^- generated:

0.5 GeV/c < P < 20 GeV/c
$-4 < \eta < 4$

Generated vertex: (0,0,0) mm

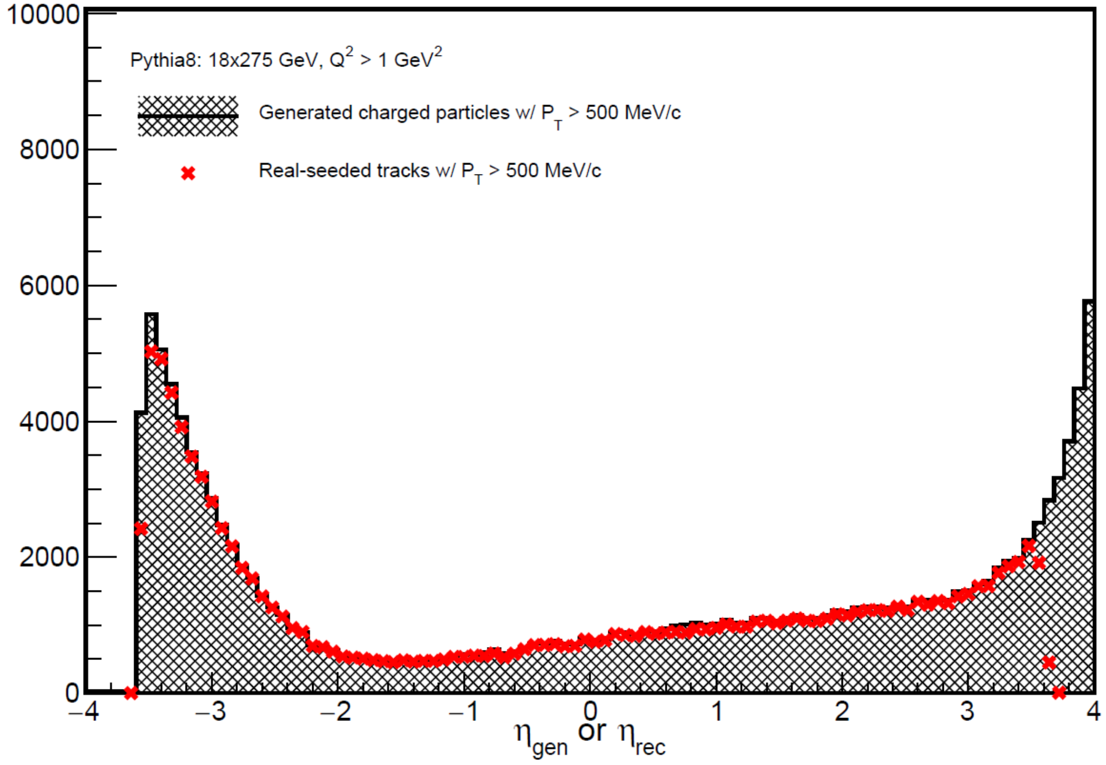




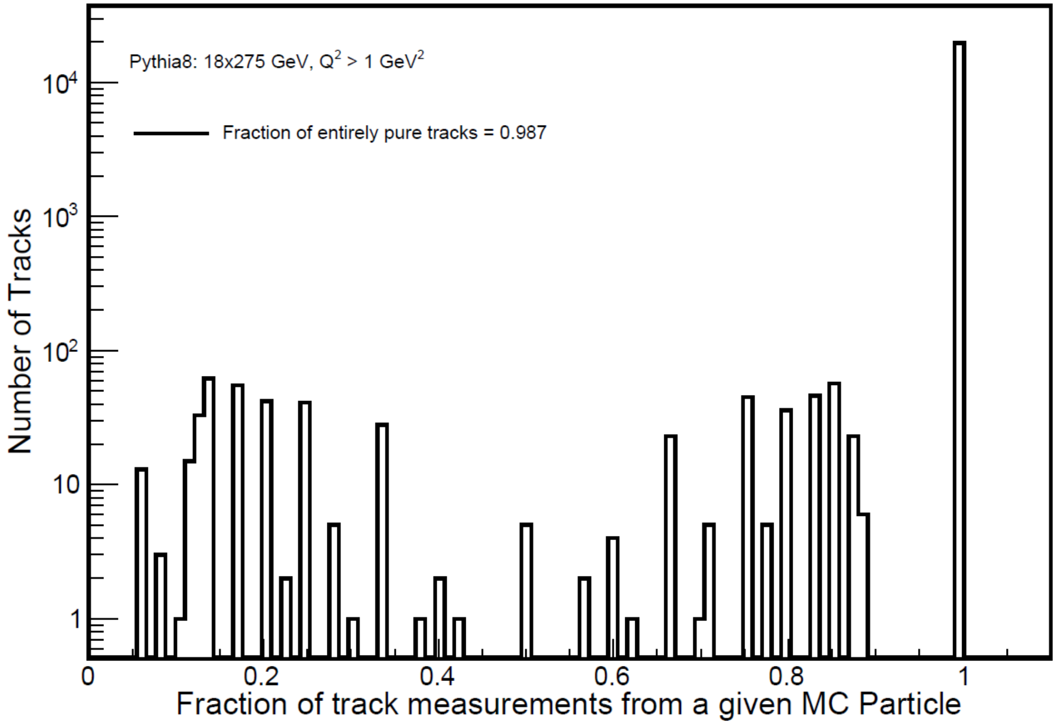
Tracking performance for simulated DIS events

Simulation of electron-proton scattering in *Pythia8* with $Q^2 > 1$ GeV^2 at the 18x275 GeV beam energy setting. A realistic beam spot and beam-smearing effects are included in the event generation.

Generated and reconstructed pseudo-rapidity distribution



Track purity



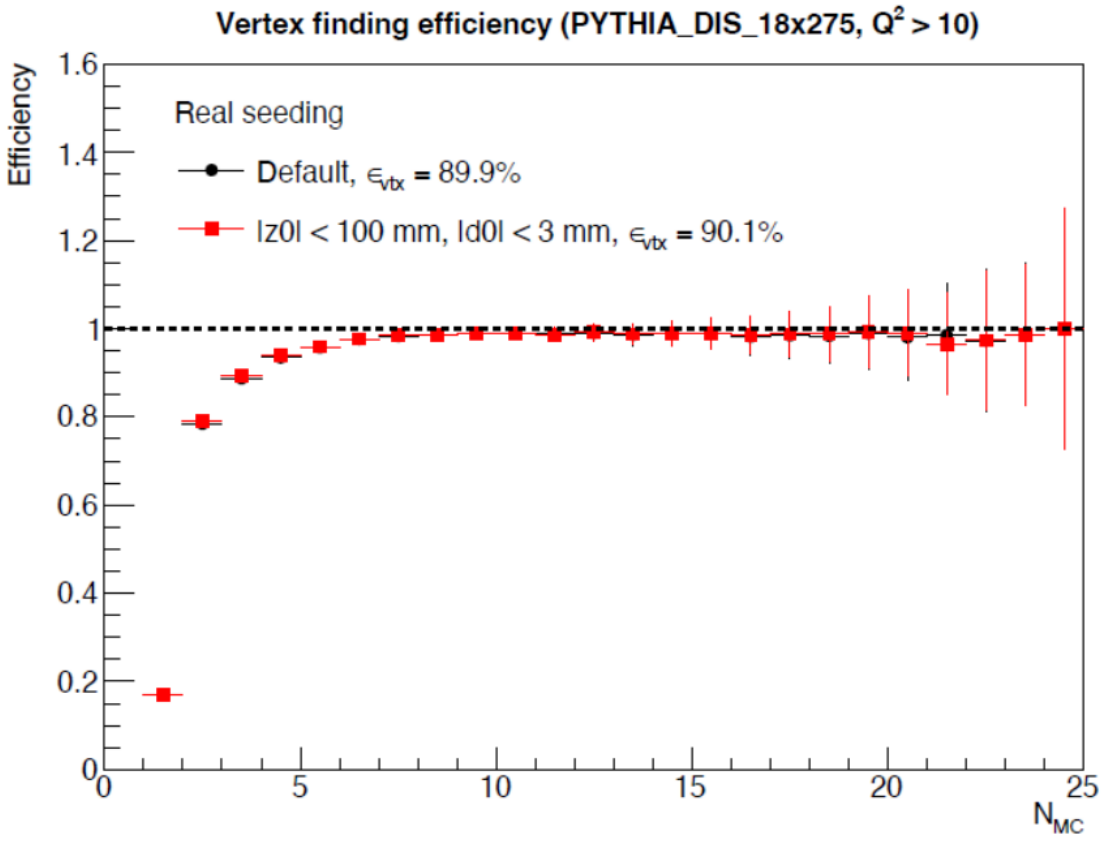
Seeding inefficiencies at low momentum

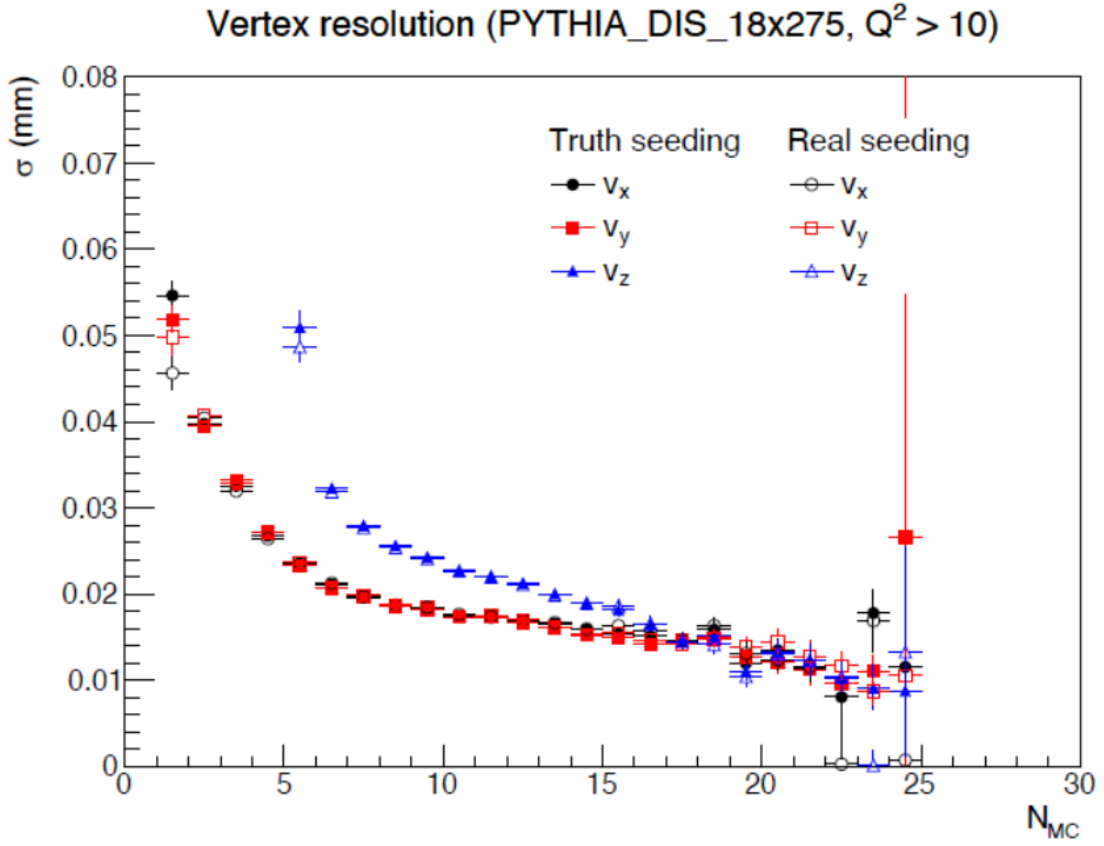
- The ACTS Orthogonal seeder gives very good performance for particles with transverse momentum greater than 400-500 MeV/c.
- We found eta-dependent inefficiencies for particles with lower transverse momenta. This occurred for particles which leave the tracking volume (without curling) and fulfill all the criteria mentioned on the ACTS seeding documentation page for space-point doublets and triplets.
- After some investigation of the ACTS Orthogonal seeder code, we found the cause of this was the *deltaPhiMax* parameter, which limits how far apart the middle/top and middle/bottom space points can be in the azimuthal direction.
- **Request from our side**: can the seeding documentation be updated to include a comprehensive list and description of tunable parameters for the (Orthogonal) seed finder and the seed filter?

Primary vertex finding and fitting

The primary vertex finding algorithm rarely finds more than a single vertex for a given DIS event.

At the EIC, in-bunch pile up will be very small, with minimum bias collisions happening about once every 200 bunch crossings.





Ongoing vertexing-related efforts

- We use the *ImpactPointEstimator* to calculate the track parameters at the DCA to the primary vertex for our set of reconstructed tracks. This allows us to study the ability of DCA_{xy} and DCA_{z} cuts to separate primary and secondary tracks
- **Request from our side**: the *ImpactPointEstimator* class has several methods – the estimate3DImpactParameters method calculates the track parameters at the 3D DCA point w.r.t a vertex, while the *getImpactParameters* seems to define a Perigee surface at the vertex and calculate local coordinates on that surface. Additional documentation would be useful here, since we had to read though the code to understand what these various functions were doing.
- Initial studies have been done on secondary vertexing using two tracks as input. These efforts make use of either the *FullBilloirVertexFitter* or the *AdaptiveMultiVertexFinder*.

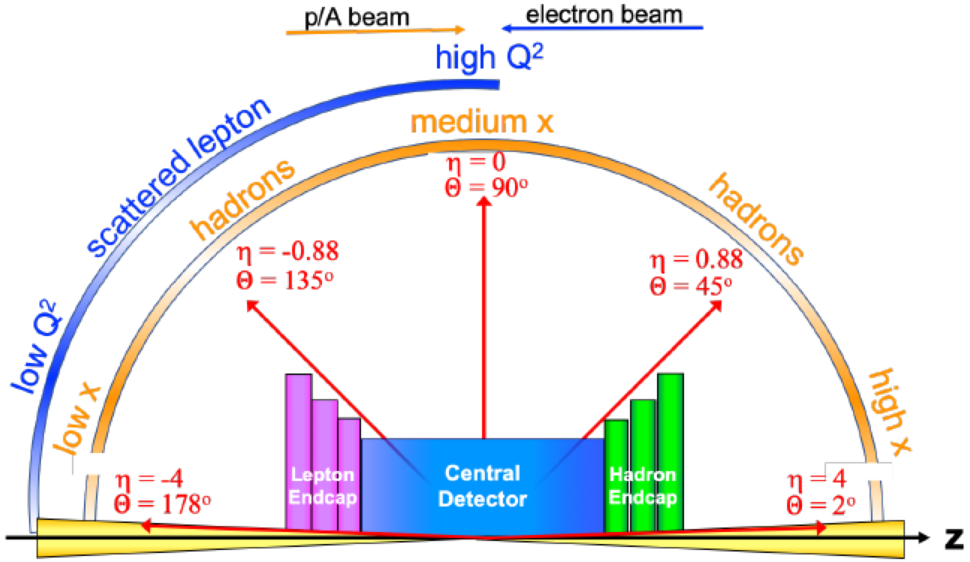
Summary and longer-term goals

- The EIC project is proceeding. ePIC is the collaboration formed to build the first EIC detector.
- We have developed a mature track and vertex reconstruction framework based on ACTS. A big thanks to the ACTS developers for all the ongoing support!
- We continue to add more realism into the simulation:
  - We plan to add more-realistic digitization/clustering; electronic noise; and beam-induced backgrounds.
  - We plan to incorporate the time information from the fast-tracking layers into the reconstruction alongside realistic time frames. This will allow us to create ‘physics’ events within each time frame. If we have multiple fast-timing hits for a given track, we can try to incorporate the timing information into the track chi2 calculation.
- This will allow to truly study the capabilities of ePIC to fully realize the science goals of the EIC.

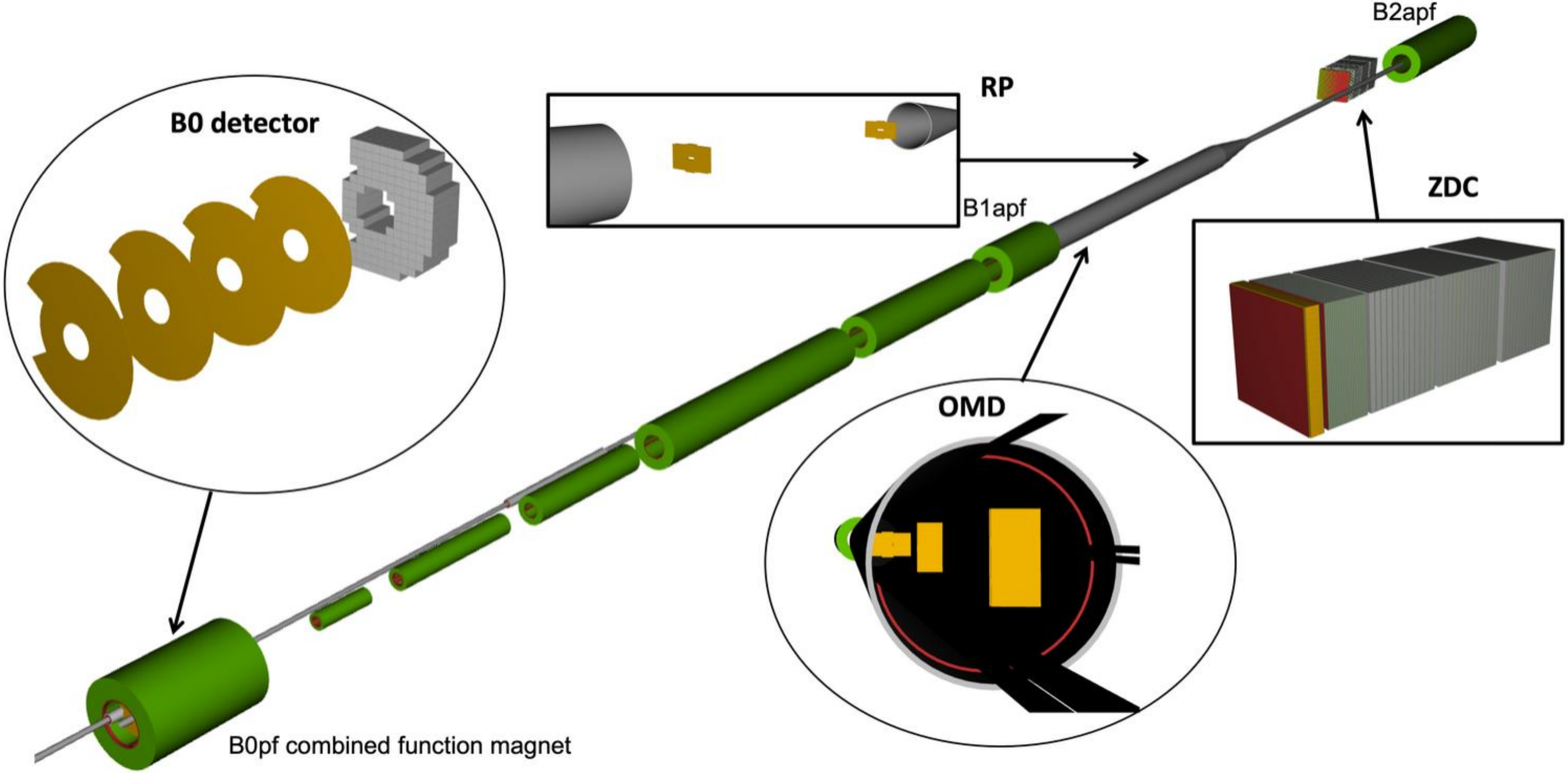
Backup

General EIC detector requirements

Detector requirement	Associated challenge
Hermetic coverage for the scattered electron	Leave no gaps in EMcal coverage while also incorporating PID readout
Good momentum resolution over the entire detector acceptance, including for the endcap regions	Design trackers to optimize momentum resolution when the particle has a large component parallel to the solenoid field
High scattered electron purity in the backwards direction and barrel	Require high-precision EMcals and additional detectors for low momentum
PID for π/K/p separation down to very low momenta	Combine multiple technologies to obtain continuous coverage from high to low momentum
Good forward calorimetry and PID	Need good energy resolution for hadronic final state; space is constrained for PID detector placement



Far-forward region



The ePIC Collaboration

ePIC

171 institutions
24 countries

500+ participants

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