Overview and Performance of the ePIC Tracker in the EIC Experiment

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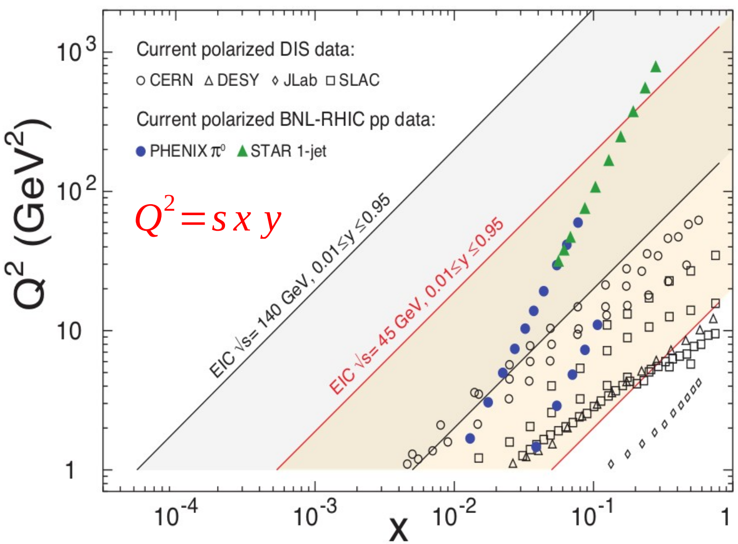
16th Pisa Meeting on Advanced Detectors,
La Biodola, Isola d'Elba, Italy

ePIC Experiment at Electron-Ion Collider

- Why ePIC Experiment ?
  - Electrons mainly interacts with electroweak interaction using Deep Inelastic Scattering (DIS): high precision
  - Polarized protons and light ions to study spin/structure physics
  - Collider to achieve wide x and Q^2 range to probe extreme gluon density regime

Wide x and Q^2 range

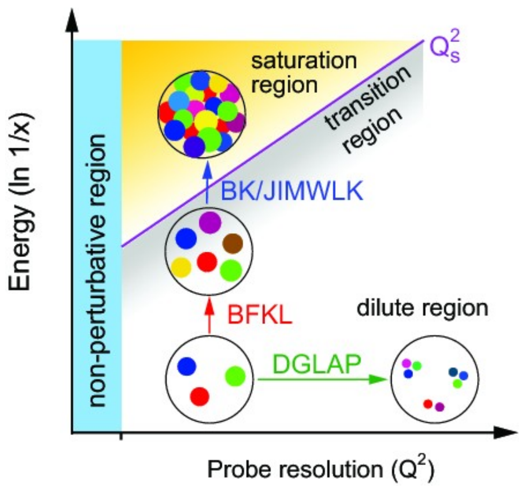


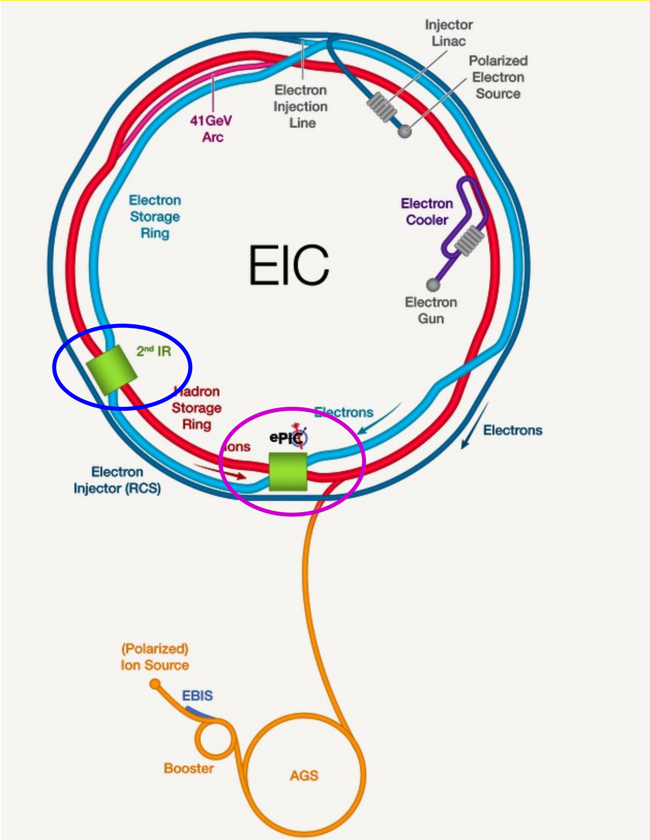
For e-N collisions at the EIC:

- ~70% polarized beams: e, p, d/^{3}He
- Electron beam (5-18 GeV)
- $\sqrt{s_{ep}}$ = 20-140 GeV (Variable)
- L_{ep} ~10^{33}-10^{34} $cm^{-2}sec^{-1}$ ~100-1000 times higher than HERA using crab cavities

For e-A collisions at the EIC:

- Wide range of nuclei
- Variable center-of-mass energy
- Luminosity per nucleon same as ep collisions





Up to two interaction regions

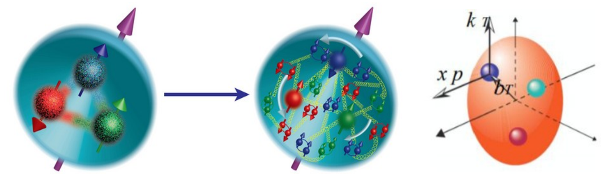
ePIC (electron-Proton/Ion Collider) experiment at Brookhaven National Laboratory (BNL), USA

Physics Goals of the ePIC Experiment

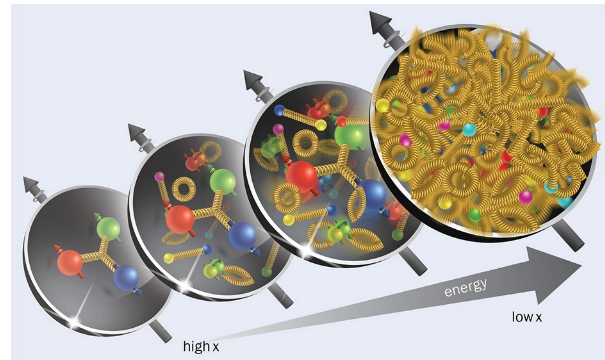
- How are sea quarks and gluons distributed inside the nucleon in both position and momentum space?
  - How do the properties (spin, mass) of nucleon emerge from constituent partons and their interactions?
- What happens to the hadronic matter at extremely high gluon density at low-x ?
  - Does it saturate at high-energy? Does this saturation give rise to a gluonic matter with universal properties in all nuclei, even proton?
- How does a dense nuclear environment affects the distribution of quarks and gluons and their interactions in nuclei?

  Energy loss and Hadronization
  - How does nuclear matter affect a fast moving color charge?
  - How do the quark-gluon interactions create nuclear binding?

Nucleon Structure



Saturation, CGC (Color Glass Condensate)



Parton Distributions in nucleons and nuclei

Inclusive DIS

$e+p/A \longrightarrow e'+X$

Spin and Flavor structure of nucleons and nuclei

Tomography Transverse Momentum Dist.

Semi-inclusive DIS

$e+p/A \longrightarrow e'+h(\pi,K,p,jet)+X$

QCD at Extreme Parton Densities - Saturation

Tomography Spatial Imaging

Exclusive DIS

$e+p/A \longrightarrow e'+p'/A'+\gamma/h(\pi,K,p,jet)$

Measure all particles in an event: Full detector coverage

DIS Kinematics

Resolution power

$$Q^2 = -q^2 = -(k_\mu - k_\mu')^2$$

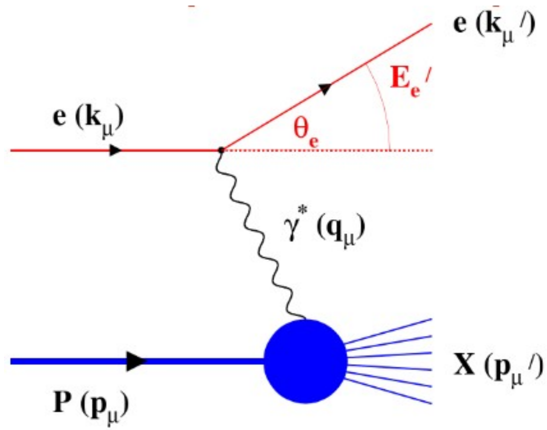
$$Q^2 = 2E_e E_e'(1 - \cos\theta_e)$$

Inelasticity

$$y = \frac{pq}{pk} = 1 - \frac{E_e'}{E_e}\cos^2\left(\frac{\theta_e}{2}\right)$$

Momentum fraction of struck quark

$$x = \frac{Q^2}{2pq} = \frac{Q^2}{sy}$$



$$s = 4E_e E_p$$

$$Q^2 = s\,x\,y$$

Measurement of a scattered electron with high resolution in the Lepton Endcap (-3.5 < η < -1.0)

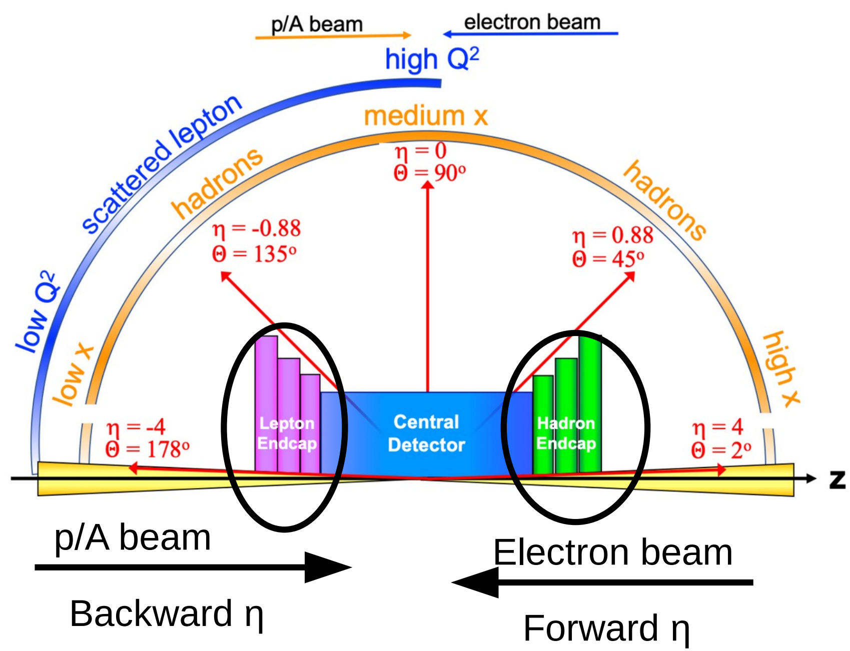
Determines electron kinematics

Particle energy: ~ 0.02-18 GeV

Scattered electron: **low Q^2 to high Q^2 region** at mid and backward η

Hadrons: **low x to high x region at all η**

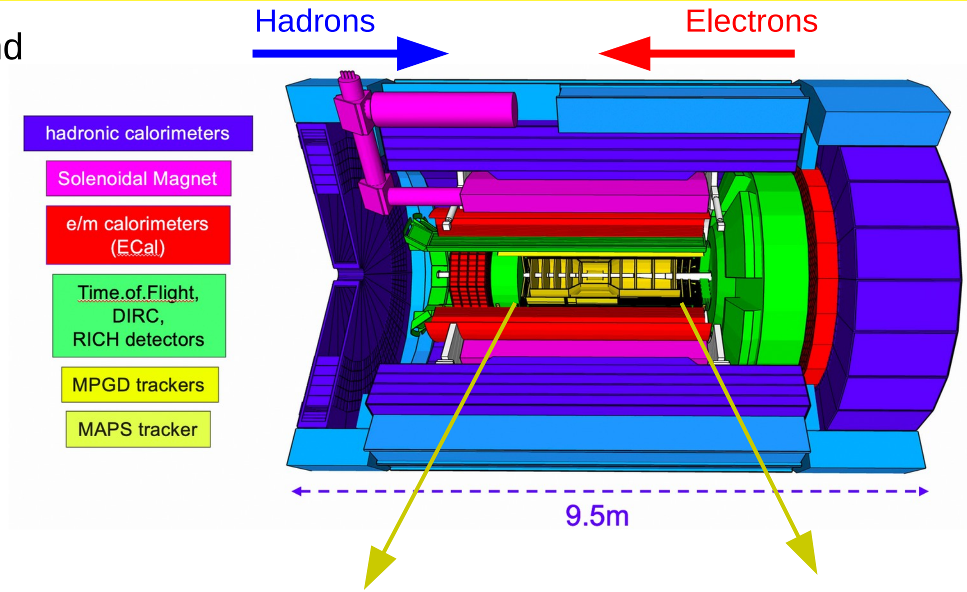
High granularity and low material budget in Central, Far-Forward and Far-Backward play a very crucial role to met the physics requirements



Central Detector, Far-Forward, Far-Backward detectors, and Streaming Readout

Central Detector

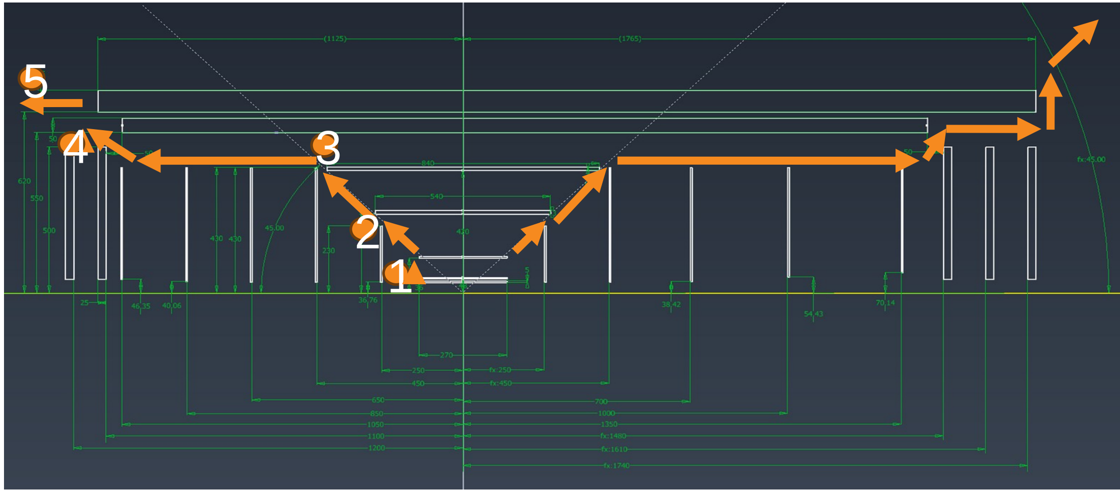
- Tracking and vertexing detectors
- Particle identification detectors (time-of-flight, DIRC, dRICH), and calorimeters (Electromagnetic and Hadron)
- Solenoid magnetic field of 1.7 T (~ 2.8 m)



Far-Forward detectors

- To measure the neutral and charged particles at very large forward η close to the beamline

ePIC Central Tracking Detectors



Far-Backward detectors

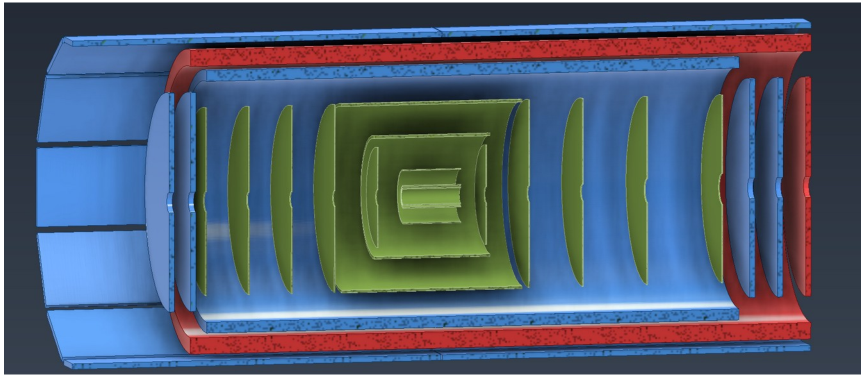
- To measure the luminosity and low-Q^2 events

Streaming Readout

Services

The ePIC Central Tracking Detector

The ePIC tracking system (|η| < 3.5) is a hybrid detector based on both silicon and gaseous technologies



Barrel Region:

- **Silicon Vertex Tracker (SVT):**
  - SVT Inner Barrel (IB) L_0, L_1, L_2 and Outer Barrel (OB) L_3, L_4
  - Monolithic Active Pixel Sensors (MAPS) based on 65 nm CMOS technology being developed by ALICE
  - High granularity and low material budget are the key features to achieve a good momentum and pointing resolution
- **MPGD (Micro-Pattern Gas Detectors)** **Poster by Kondo Gnanvo**
  - Gaseous detectors to cover a large outer tracking volume
  - Provides a good timing performance (Provide ~ 10 − 30 ns timing resolution) for pattern recognition
- **AC-LGAD Sensors**
  - Excellent time resolution for the particle identification by time-of-fight method
  - Provides an extra hit for pattern recognition and tracking

SVT IB, OB and Disks (MAPS)

MPGD Barrels and Disks

AC-LGAD TOF

SVT to achieve a precise tracking and vertexing capability

(pitch ~ 20 μm)

Forward region: Five MAPS silicon disks followed by two MPGD (Micro-Pattern Gas Detectors) layers and a TOF layer

Backward region: Five MAPS silicon disks followed by two MPGD layers

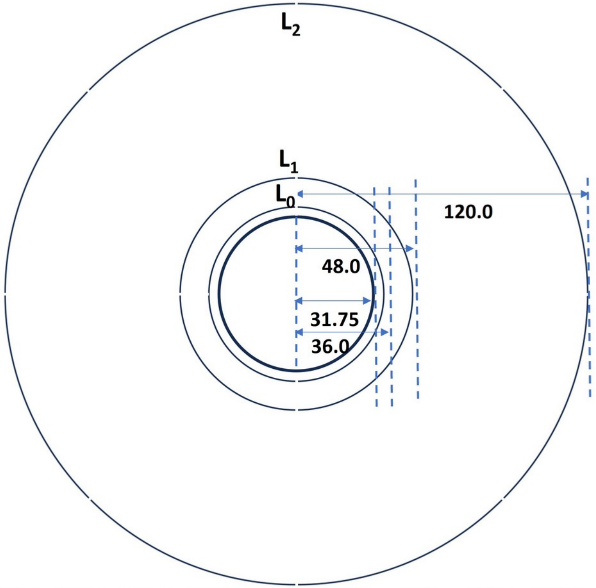
ePIC SVT is based on MAPS 65 nm CMOS Imaging Technology

SVT IB (L_0, L_1, L_2) :

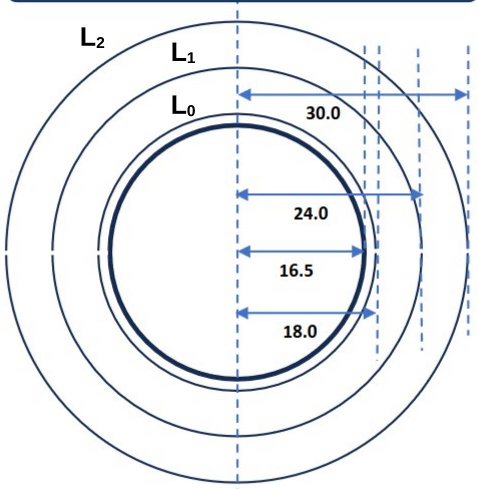
- Transverse pointing resolution can be improved by reducing X/X_0
- Three innermost layers (IB) are bent wafer-size sensors with ultra-low material budget (0.05 % X/X_0 per layer) similar to ALICE ITS3
- Radius: Two times larger for the L_0, L_1 and four times for L_2 than ITS3
- Relying on air cooling (~ 8 m/s air speed) but challenging due to the presence of the disks
- Minimal mechanical support and no services in active area

CERN-LHCC-2024-003 ; ALICE-TDR-021

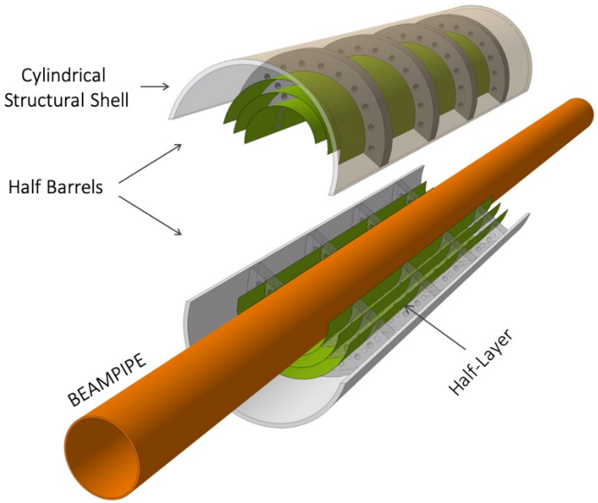
ePIC-SVT

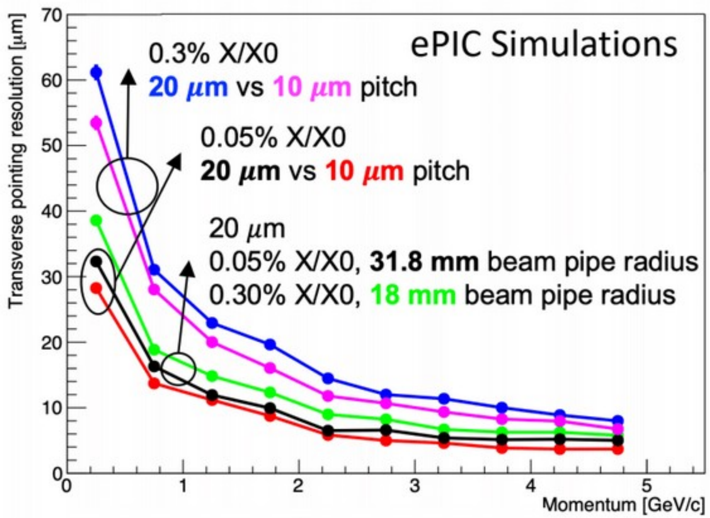


ITS3 ALICE



Layout of ALICE ITS3 detector



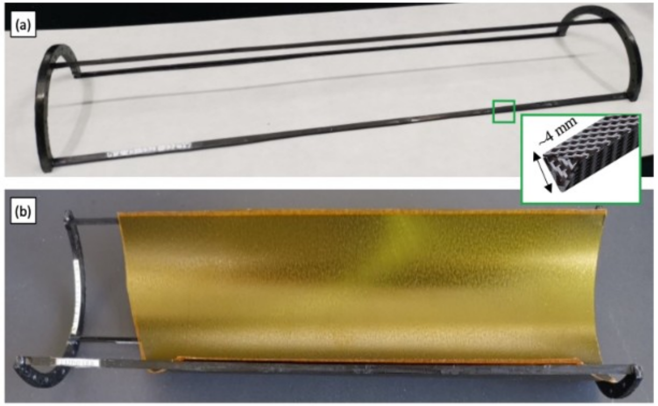


ePIC SVT Inner Barrel (IB) Support Structure

CERN-LHCC-2024-003 ; ALICE-TDR-021

ITS3 Alternative design

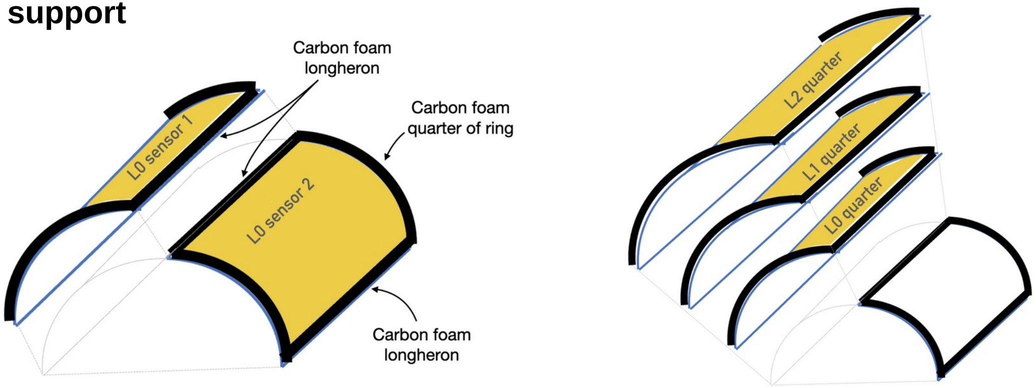
G. Feofilov et al., **ITS3 WP4** 10 October 2023



First design and printing of a light support (carbon foam) structure includes glueing of 2 half-rings and 3 longerons

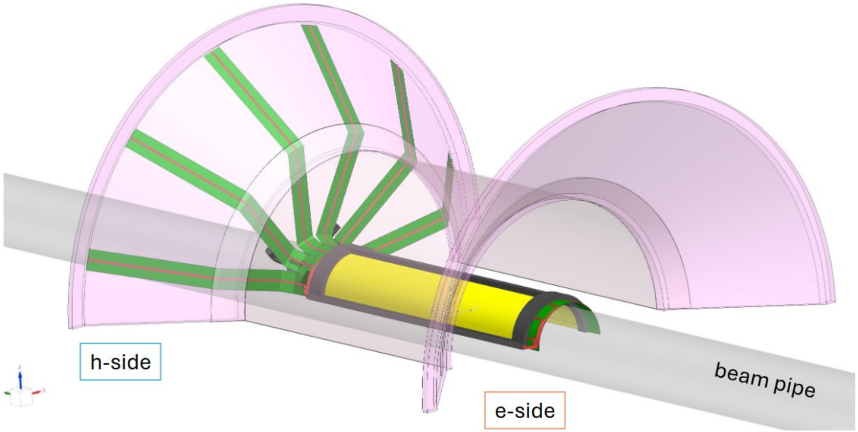
Inspired by ITS3 R&D: ePIC SVT IB (L_0, L_1, L_2)

Local support



FPC on hadron side (h-side)

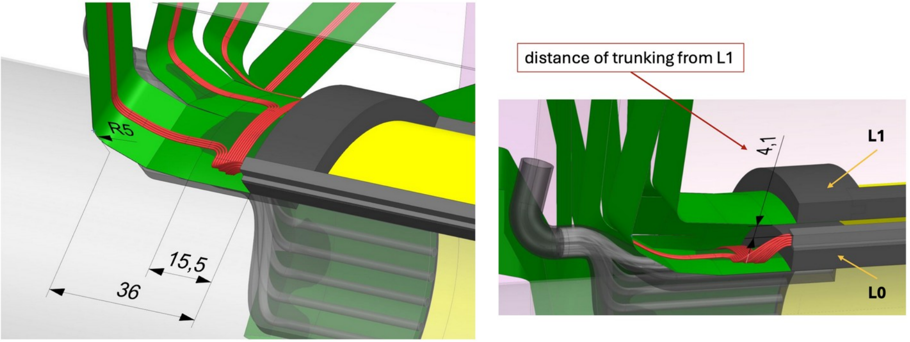
Global support



Bending/assembly on a half vs quarter-of-layer/barrel bases currently being considered

h-side view - 1

- fpc bending radius 5 mm
- overall extension from support edge: 36 mm

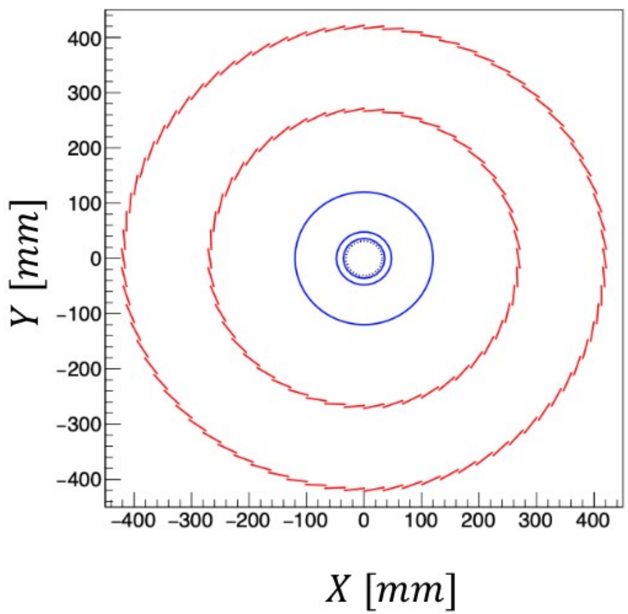


ePIC SVT is based on MAPS 65 nm CMOS Imaging Technology

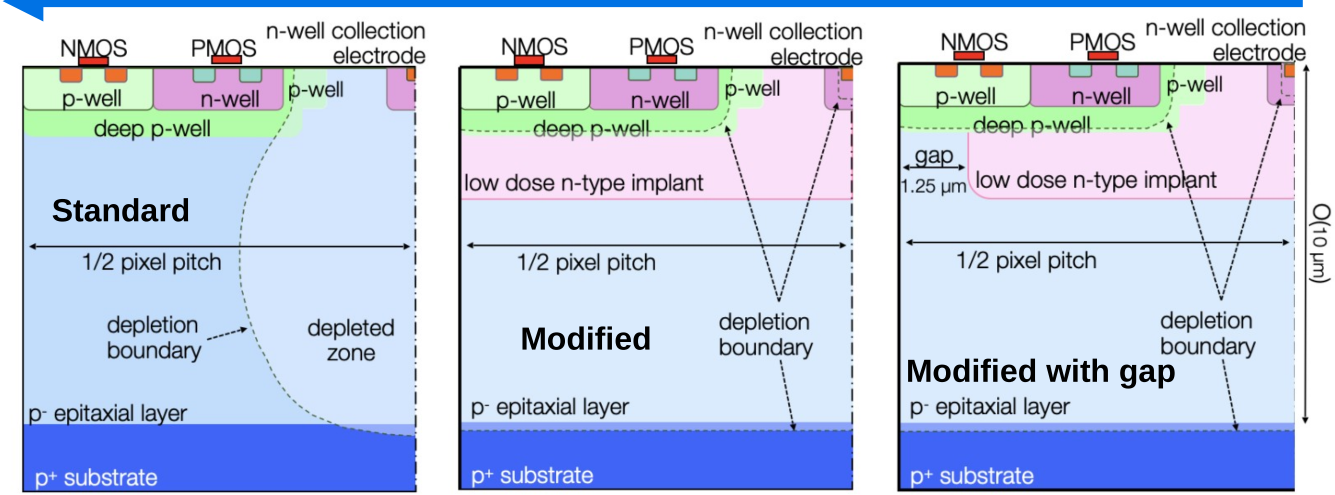
SVT OB and Disks (L_3 and L_4):

- Increase the acceptance in η
- "FLAT" Large Area Sensors (LASs) derived from ITS3 optimized for high yield, low cost, large area coverage
- Stitched sensors based on the modification of ITS3 sensors but not wafer scale
- Staved structure, Carbon fiber support, and integrated cooling liquid or air
- Large lever-arm together with a good spatial resolution improves momentum resolution
- Disks inner radius are constraint by the beam-pipe

Outer Barrel (OB)



Charge sharing

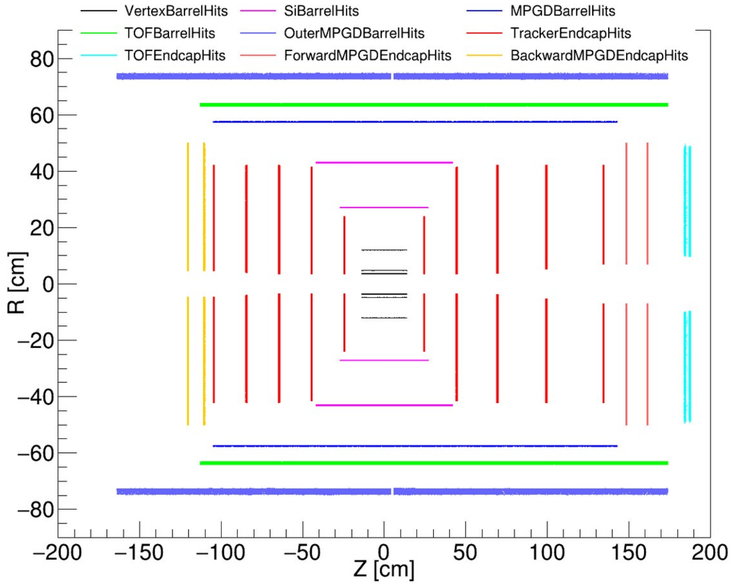


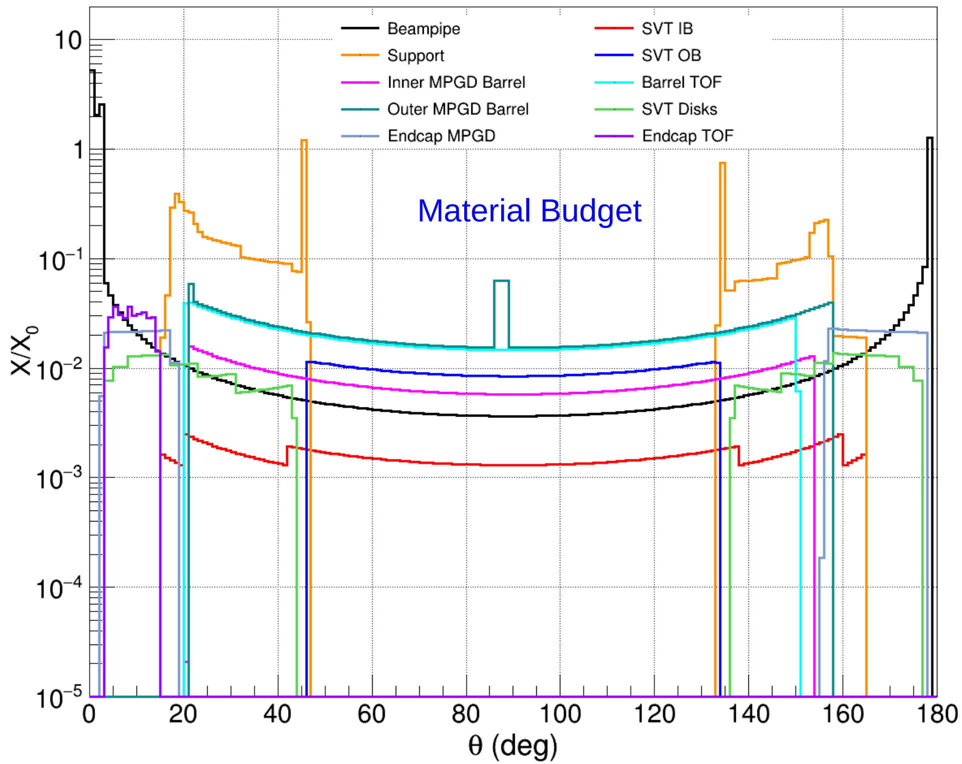
https://doi.org/10.1016/j.nima.2017.07.046

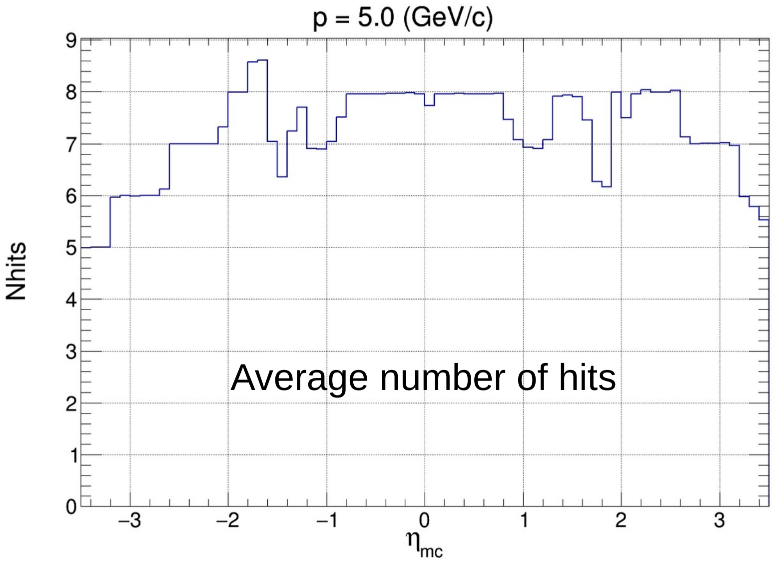
arXiv:2403.08952 [physics.ins-det]

Stronger requirements for ePIC in terms of integration time!

The ePIC Tracker Hit Map and Material Budget







Minimal amount of material in the SVT IB and OB

- ~10 % support material for services in conical shape

Average number of hits ≥ 5 for |η| < 3.5

Radiation Environment in ePIC

Simulation for 10 GeV electron and 275 GeV proton DIS interactions at ~ 500 kHz (Luminosity = 10^{34} cm^{-2} s^{-1})

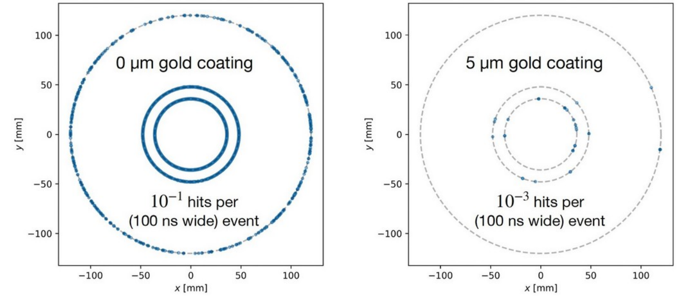
10 half-year running periods, 100% up-time

Hit occupancy: Low, O(10^{-7}) per pixel assuming O(µs) readout frame

Background Sources:

- electron+gas, hadron+gas modeled as "fixed target" pythia events (10 kAhr)
- Synchrotron Radiation: not considered

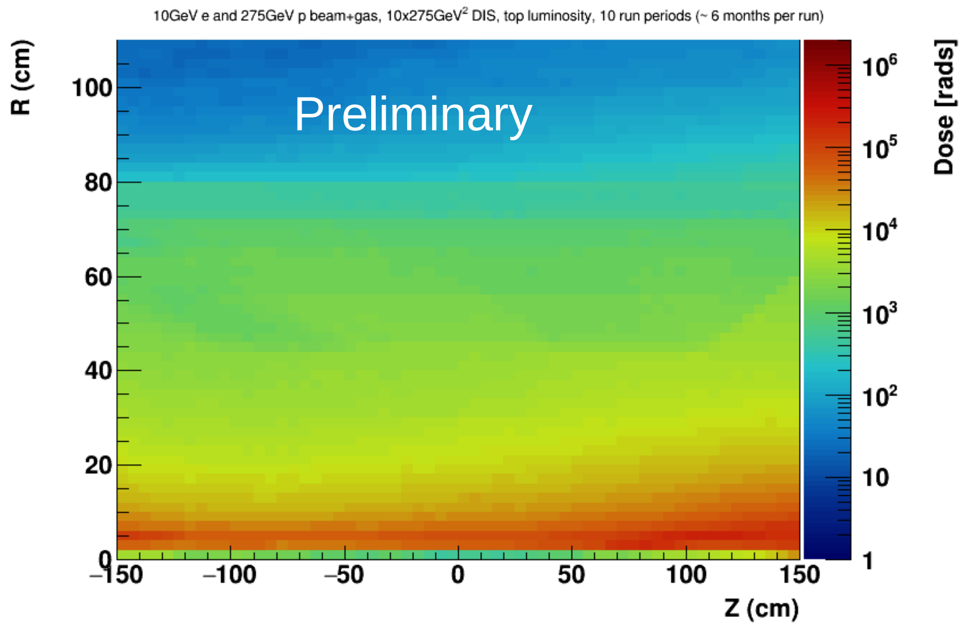
Reduction by about 2 orders of magnitude in Synchrotron Radiation

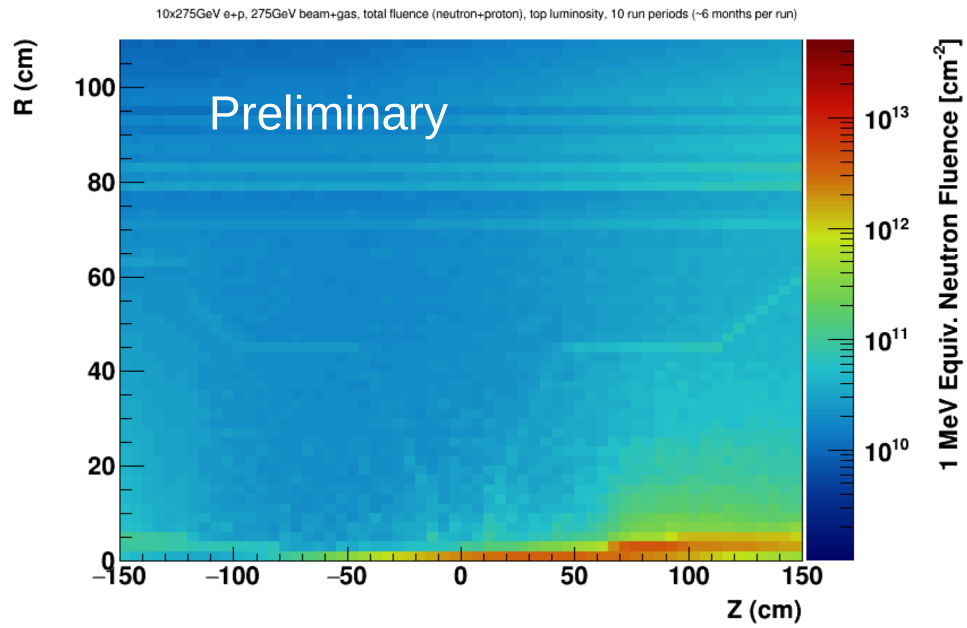


Total Ionizing Dose (TID): A few 100 kRad close to the beampipe and below 10 kRad in most of the SVT projected

Non-Ionizing Energy Loss (NIEL): Fluence up to few 10^{12} n_{eq} /cm^2 for the inner region of the the hadron endcap, otherwise 10^{11} n_{eq}/cm^2 or less

https://wiki.bnl.gov/EPIC/index.php?title=Background





Tracking in the ePIC Experiment

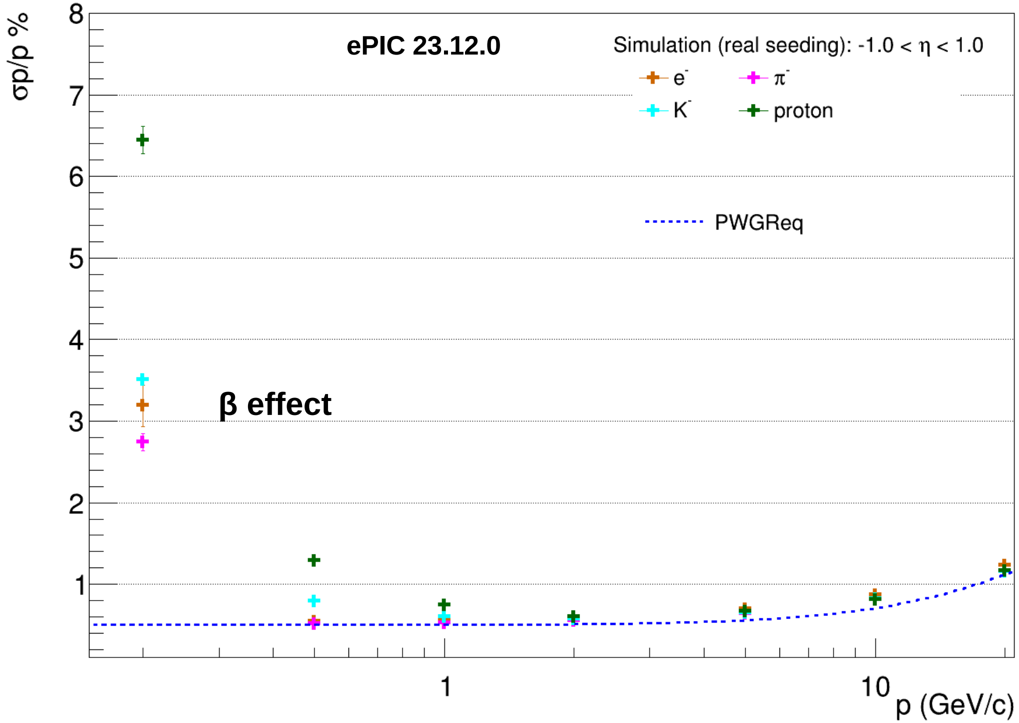
Reconstruction of particle trajectory (in presence of magnetic field, material effect, background hits)-**4D tracking**

Tracking: Track finding and fitting using combinatorial Kalman Filter (CKF): **ACTs (A Common Tracking Software)**

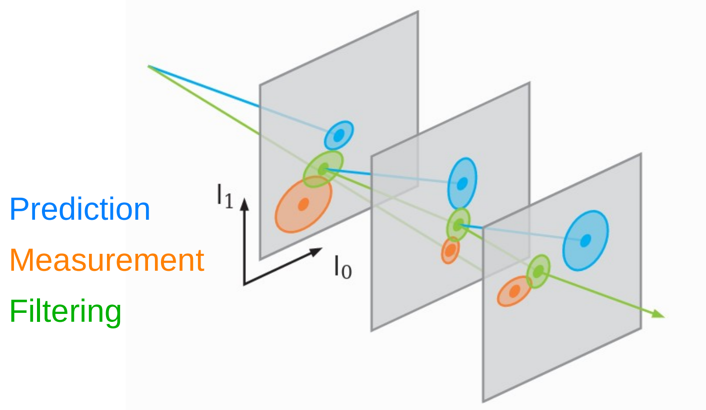
Track Parameters: $(l_0, \ l_1 \ , \ \phi, \ \theta, \ 1/p, \ t)$

- l_0 ,l_1: local parameters describing the sensor surface
- ϕ: Azimuthal angle in global coordinates
- θ: angle w.r.t. z axis in global coordinates
- p: Momentum of the track
- **t: time of hit (important due to background)**

Momentum Resolution



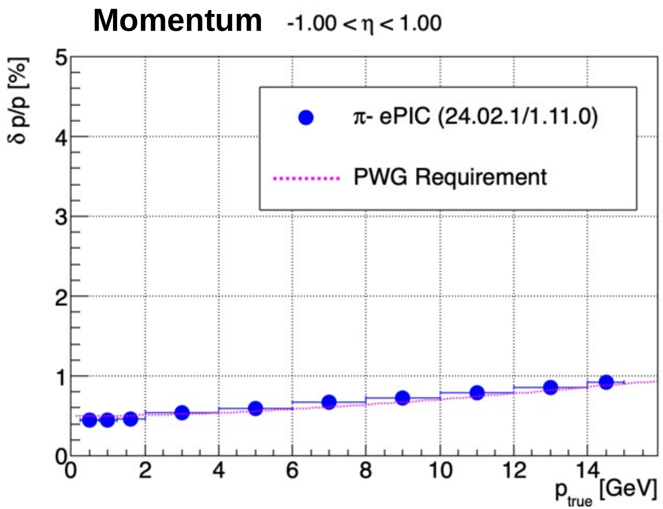
Inward--> Outward fitting
Outward-->Inward fitting

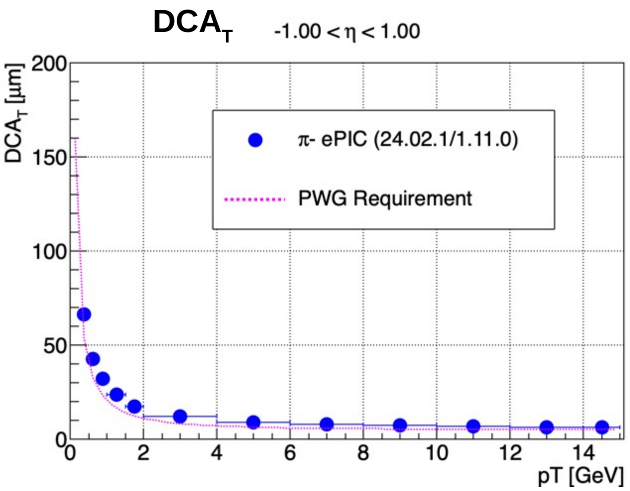


Three Steps (Kalman Filter)

1. Extrapolation
2. Filtering
3. Smoothing

Preliminary Performances

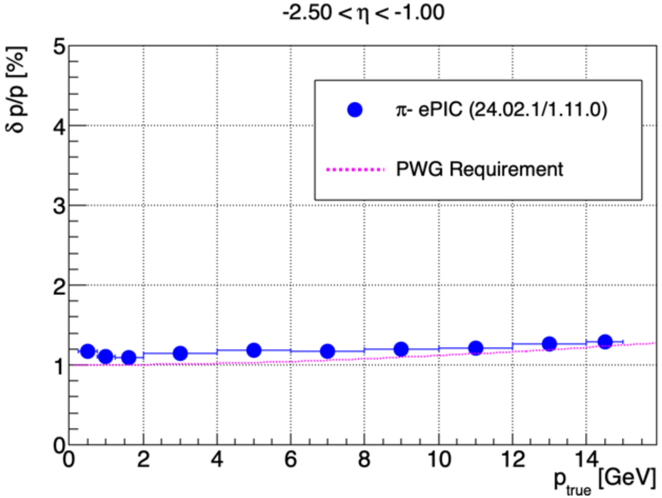


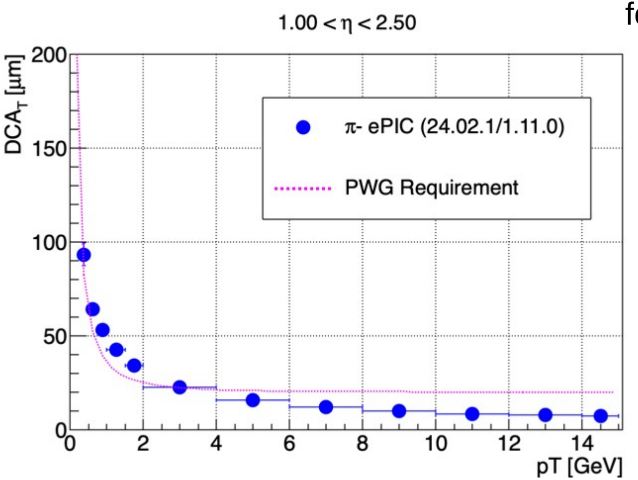


Momentum and Distance of Closest Approach (DCA_T) Resolutions

Requirements are met in the central region

Requirements are substantially met in the forward/hadron and backward/electron region





Physics objectives in the far backward/ electron region will need to be met by means of using precise tracking and electron calorimetry

Theta/Phi Resolutions at DIRC Layer

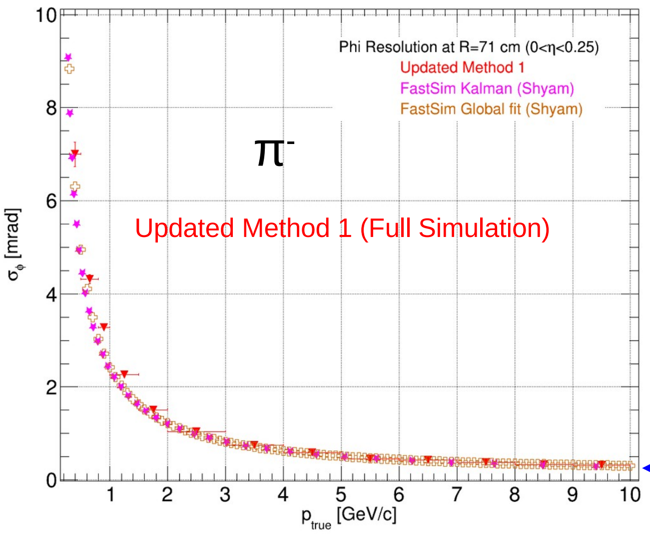
Important for Cherenkov Particle Identification

- **Track extrapolation uncertainty at DIRC layer: Estimation of Theta/Phi resolutions at DIRC (at 71 cm)**
- Chromatic uncertainty due to emission of photons of different energy (refractive index n = n(E))
- Measurement uncertainty in the position reconstruction of photons due to pixel size

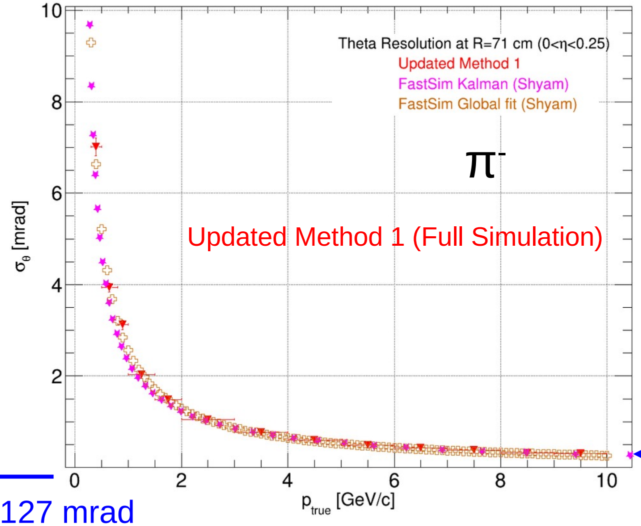
Fast Simulation (Kalman) uses Inward to Outward fitting algorithm considering multiple scattering at the Outer MPGD layer

Global fit also take care of multiple scattering at Outer MPGD layer (parameters are global)

Good compatibilty among different methods

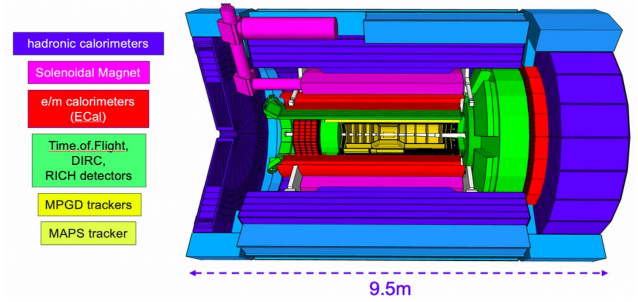


0.127 mrad



0.017 mrad

DIRC: Disk Imaging Ring Cherenkov



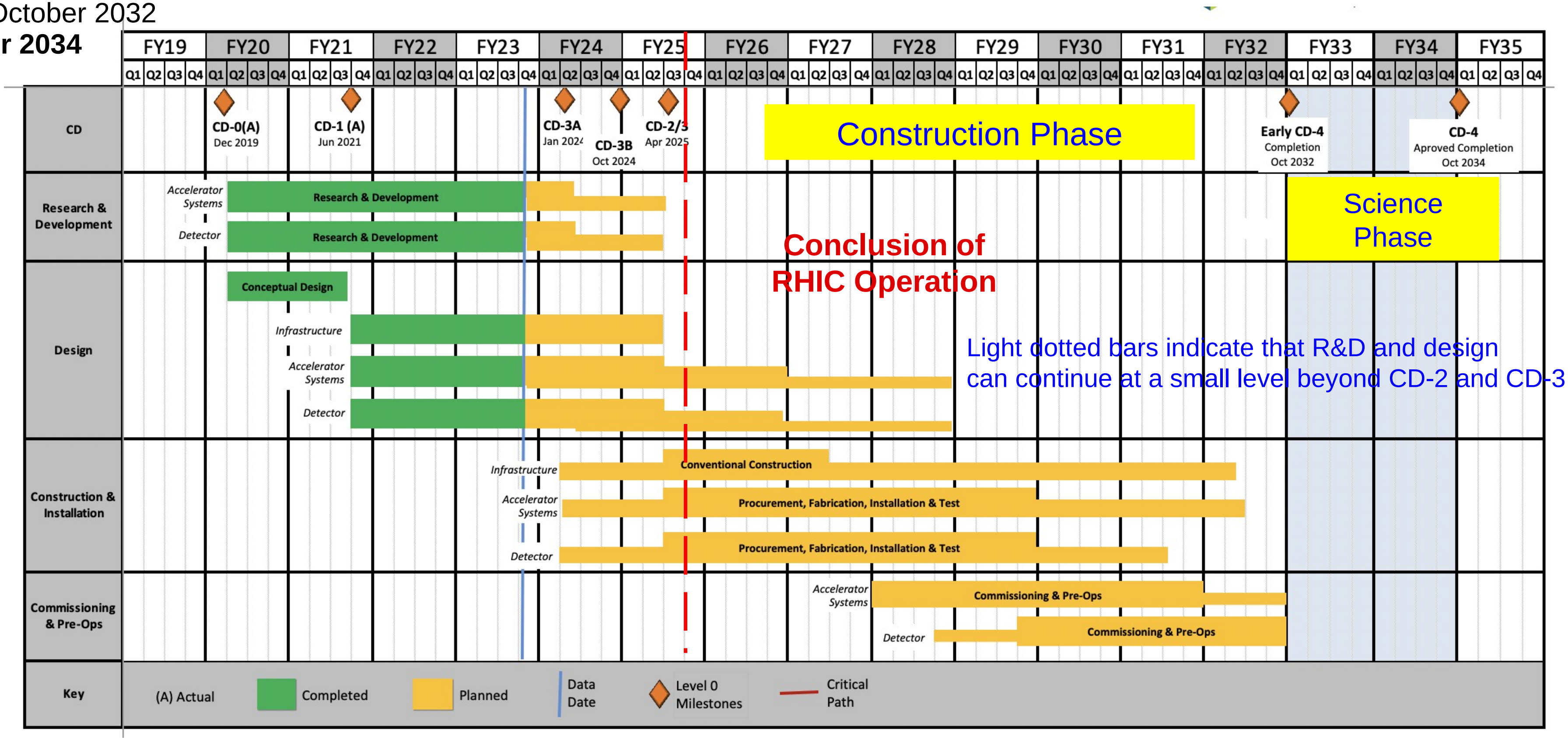
https://indico.bnl.gov/event/20473/contributions/85332/attachments/51915/89153/Fast_Simulation_ePIC_Collaboration_Meeting_Shyam_Kumar.pdf

ePIC Experiment/EIC Timeline

EIC Critical Decision Plan
CD-0/Site Selection December 2019 ✓
CD-1 Alternate Selection and Cost, Range Approved June 2021 ✓
CD-3A Long Lead Procurement Approval, January 2024
CD-3B October 2024
CD-2/3 April 2025
early CD-4 October 2032
CD-4 October 2034

CD-2:
Approve preliminary design for all subdetectors
Design Maturity: >60%
Need "pre-"TDR
Baseline project in scope, cost, schedule

CD-3:
Approve final design for all subdetectors
Design Maturity: ~90%
Need full TDR



Summary

- ePIC tracker consists of both state-of-the-art silicon and gaseous detector technologies
- ePIC SVT IB and OB will help to achieve required momentum resolution and DCA performance
- Coating beampipe with gold layer (high density) helps in the reduction of synchrotron radiation
- MPGD layers will also help in pattern recognition as they provide space point with a good timing information over a large area
- The ePIC tracker is optimized in terms of technology and layout to achieve the required physics performance set by the EIC LoI

THANK YOU !!!

Ref: Science Requirements and Detector Concepts for the Electron-Ion Collider: EIC Yellow Report arXiv:2103.05419 [physics.ins-det]

Spatial Resolution (SR): Uncertainty associated with pixel size ($\sigma_{r\varphi}$)

Multiple Scattering (MS): Uncertainty associated with material thickness (x/X_0)

Extension of Gluckstern formulas

arXiv:1805.12014 [physics.ins-det]

Momentum Resolution:

$$\frac{\Delta p_T}{p_T}\Big|_{res.} = \frac{\sigma_{r\phi}\, p_T}{0.3\, B_0 L_0^2}\sqrt{\frac{720N^3}{(N-1)(N+1)(N+2)(N+3)}} \approx \frac{12\,\sigma_{r\phi}\, p_T}{0.3\, B_0 L_0^2}\sqrt{\frac{5}{N+5}}$$

$$\frac{\Delta p_T}{p_T}\Big|_{m.s.} = \frac{N}{\sqrt{(N+1)(N-1)}}\,\frac{0.0136\,\mathrm{GeV/c}}{0.3\beta\, B_0 L_0}\sqrt{\frac{d_{tot}}{X_0\,\sin\theta}}\left(1+0.038\ln\frac{d}{X_0\,\sin\theta}\right)$$

SR → MS →

$$\frac{\sigma_{p_T}}{p_T} = \sqrt{\left(\frac{\sigma_{p_T}}{p_T}\right)^2_{SR} + \left(\frac{\sigma_{p_T}}{p_T}\right)^2_{MS}}$$

Transverse Pointing Resolution:

$$\Delta d_0|_{res} \approx \frac{3\sigma_{r\phi}}{\sqrt{N+5}}\sqrt{1+\frac{8r_0}{L_0}+\frac{28r_0^2}{L_0^2}+\frac{40r_0^3}{L_0^3}+\frac{20r_0^4}{L_0^4}}$$

$$\Delta d_0|_{m.s.} \approx \frac{0.0136\,\mathrm{GeV/c}}{\beta p_T} r_0 \sqrt{\frac{d}{X_0\sin\theta}}\sqrt{1+\frac{1}{2}\left(\frac{r_0}{L_0}\right)+\frac{N}{4}\left(\frac{r_0}{L_0}\right)^2}$$

SR → MS →

$$\sigma_{d_0} = \sqrt{\sigma_{d_0 SR}^2 + \sigma_{d_0 MS}^2}$$

Formulas are valid for equal spacing, equal detector resolutions of each layer, and equal thickness

Tracking Performances (Fast Simulation)

Spatial Resolution (SR): Uncertainty associated with pixel size ($\sigma_{r\varphi}$)
Multiple Scattering (MS): Uncertainty associated with material thickness (x/X_0)

$$\sigma_{d_0} = \sqrt{\sigma_{d_0 SR}{}^2 + \sigma_{d_0 MS}{}^2}$$

$$\frac{\sigma_{p_T}}{p_T} = \sqrt{\left(\frac{\sigma_{p_T}}{p_T}\right)_{SR}^2 + \left(\frac{\sigma_{p_T}}{p_T}\right)_{MS}^2}$$

arXiv:1805.12014 [physics.ins-det]

$$\Delta d_0|_{res} \approx \frac{3\sigma_{r\phi}}{\sqrt{N+5}}\sqrt{1 + \frac{8r_0}{L_0} + \frac{28r_0^2}{L_0^2} + \frac{40r_0^3}{L_0^3} + \frac{20r_0^4}{L_0^4}}$$

$$\frac{\sigma_{p_T}}{p_T}(SR) \propto \sigma_{r\phi}\, p$$

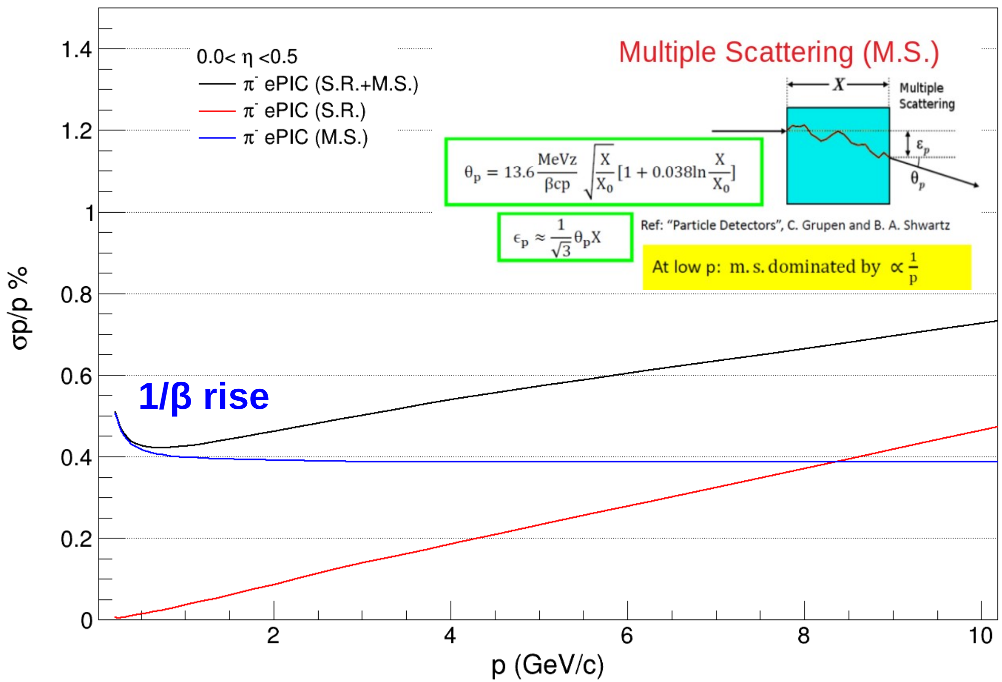
Curvature

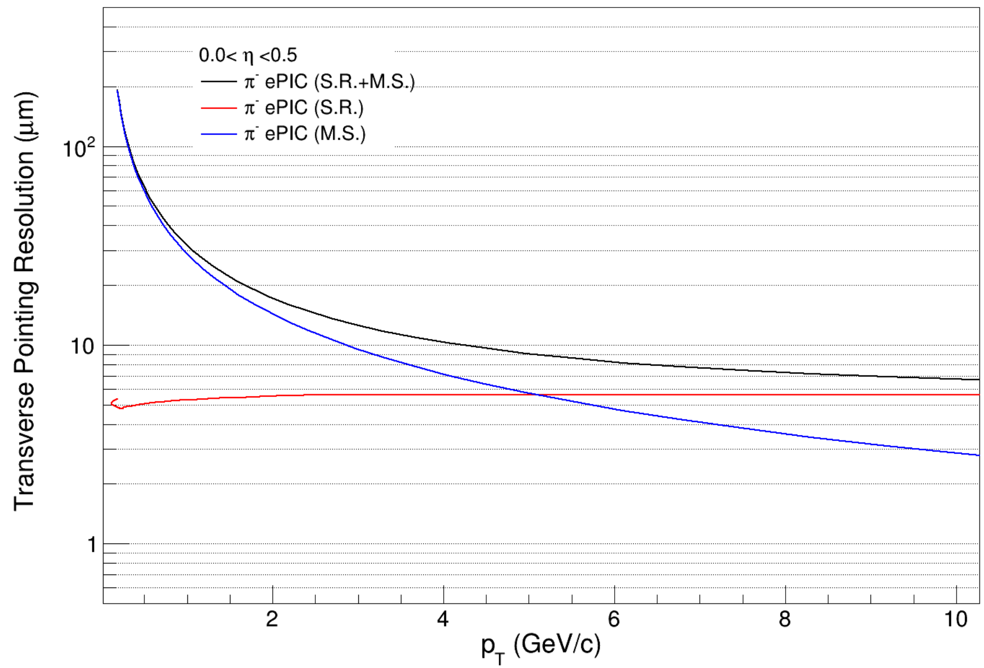
$$\frac{\sigma_{p_T}}{p_T}(MS) \propto \frac{1}{\beta p} \qquad p = \frac{Const}{\beta}$$

Curvature

Momentum and mass Hypothesis

$$\Delta d_0|_{m.s.} \approx \frac{0.0136\ \mathrm{GeV/c}}{\beta p_T} r_0 \sqrt{\frac{d}{X_0 \sin\theta}} \sqrt{1 + \frac{1}{2}\left(\frac{r_0}{L_0}\right) + \frac{N}{4}\left(\frac{r_0}{L_0}\right)^2}$$

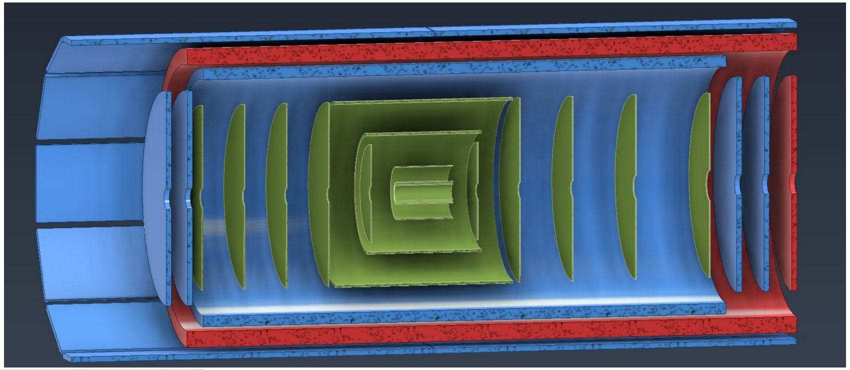




The ePIC Central Tracking Detector Layout

ePIC tracking system consist of silicon detector as well as gaseous detectors

|η| < 3.5



SVT IB, OB and Disks (MAPS)

MPGD Barrels and Disks

AC-LGAD TOF

Barrel region

Component	Radius (cm)	$\sigma_{r\phi}$ (µm)	σ_z (µm)	X/X_0 %
Beam pipe	3.18			0.36
SVT IB L_0	3.6	5.77	5.77	0.05
SVT IB L_1	4.8	5.77	5.77	0.05
SVT IB L_2	12.0	5.77	5.77	0.05
SVT OB L_3	27.0	5.77	5.77	0.25
SVT OB L_4	42.0	5.77	5.77	0.55
Inner MPGD	51.0	150	150	0.5
TOF	64.0	30	3000	1.0
Outer MPGD	68.7	150	150	1.5