Overview and Performance of the ePIC Silicon Vertex Tracker

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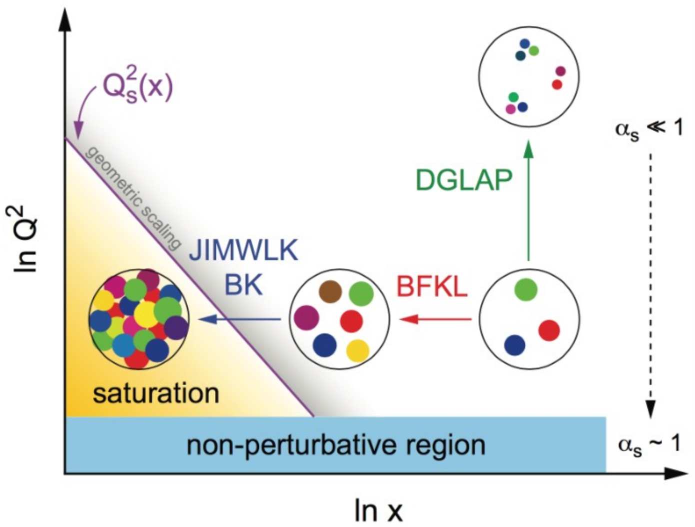
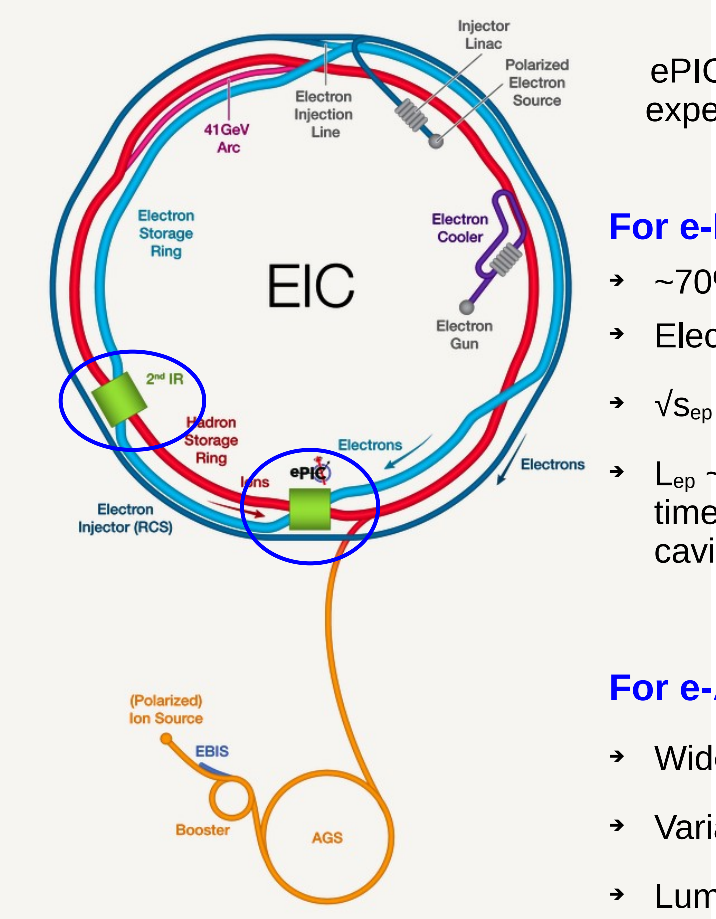
Electron-Ion Collider (EIC)

- **Why EIC ?**
  - Electrons to achieve a high precision: electro-weak interaction using Deep Inelastic Scattering (DIS)
  - Polarized protons and light ions for spin/structure physics
  - Collider to achieve wide x and Q^2 range to probe extreme gluon density regime





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

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 centre-of-mass energy
- Luminosity per nucleon same as ep collisions

More than one interaction region

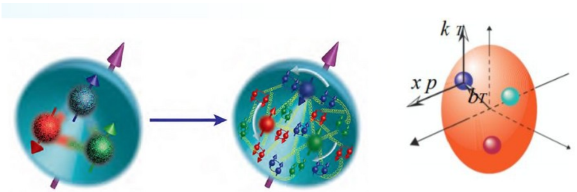
(Detector I and II (not yet scheduled in time))

Physics Goals of ePIC Experiment

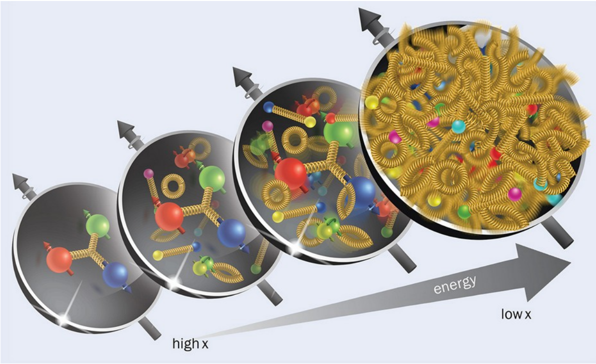
- How are partons distributed inside the nucleon in both position and momentum space? basically 3D imaging of a nucleon.
  - How do the properties (spin, mass) of nucleon emerge from constituent partons and their interactions?
- What happens to the hadronic matter at extremely high gluon density at low-x ?
  - 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 affect the quarks and gluons, their correlations and interactions?
  - How do the confined hadronic states emerge from these quarks and gluons?
  - How do the quark-gluon interactions create nuclear binding?

Energy loss and Hadronization

Nucleon Structure



Saturation, CGC (Color Glass Condensate)



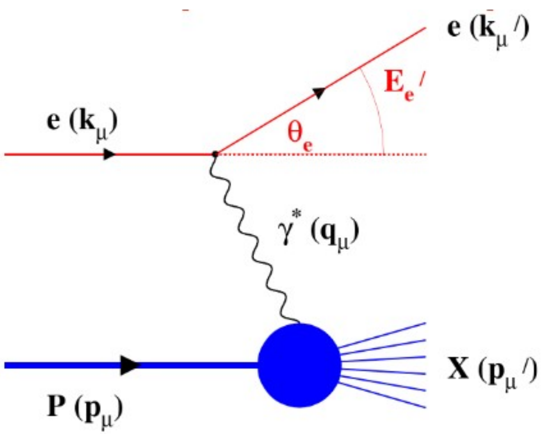
Inclusive DIS	Semi-inclusive DIS	Exclusive DIS
Parton Distributions in nucleons and nuclei	Spin and Flavor structure of nucleons and nuclei / Tomography Transverse Momentum Dist.	QCD at Extreme Parton Densities - Saturation / Tomography Spatial Imaging
e+p/A → e'+X	e+p/A → e'+h(π,K, p, jet)+X	e+p/A → e'+ p'/A'+γ/h(π,K, p, jet)

Measure all particles in a event: full detector coverage is required

Measurement of scattered electron from low Q^2 to high Q^2 region at mid and backward η

Hadron measurement from low x to high x region at all η

DIS Kinematics



$$s=4E_eE_p$$

$$Q^2=sxy$$

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

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

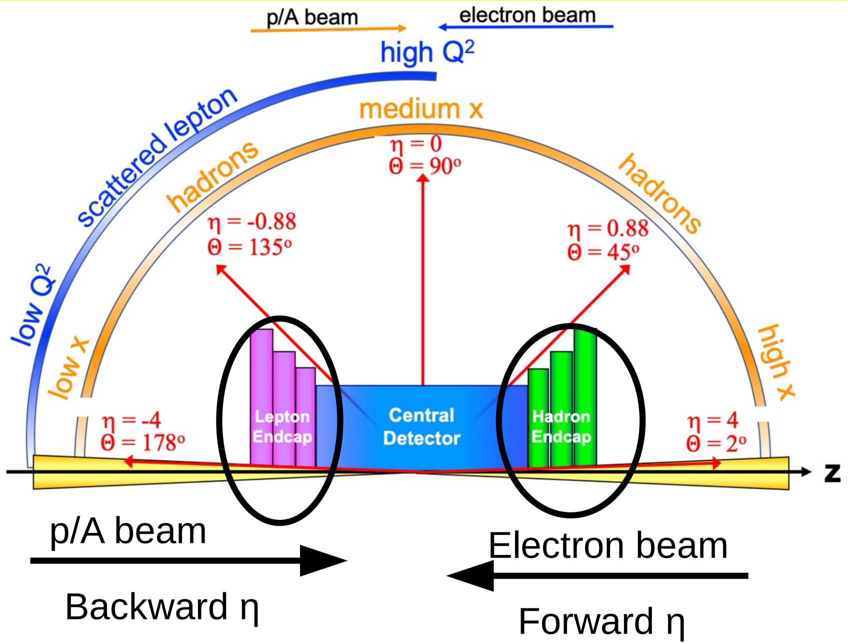
Resolution power

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

Inelasticity

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

Momentum fraction of struck quark



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

The Electron Ion Collider:Science and Status, Abhay Deshpande, Jan 2019

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

The ePIC Detector

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 (Electromagentic and Hadron)
- Solenoid magnetic field of 1.7 T (~ 2.8 m)

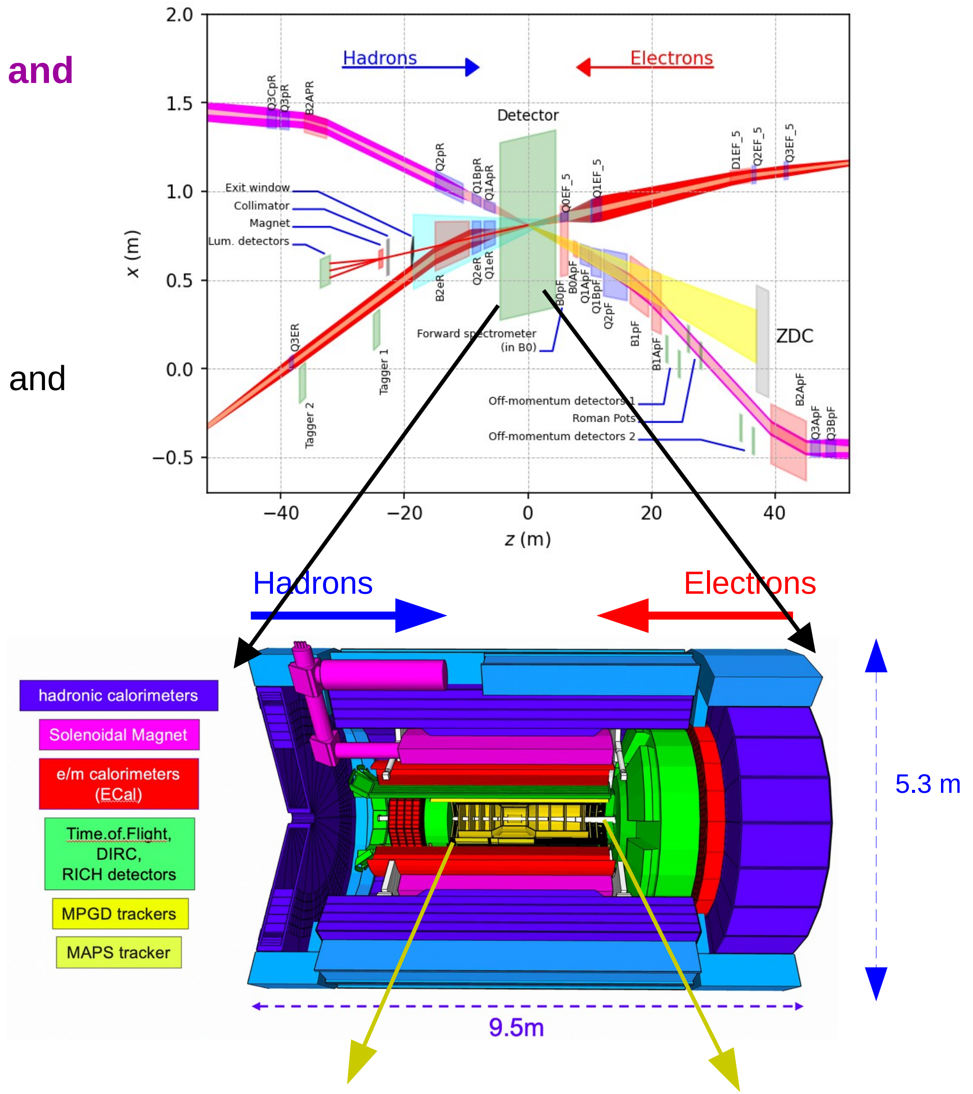
Far Forward detectors

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

Far Backward detectors

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

Streaming Readout

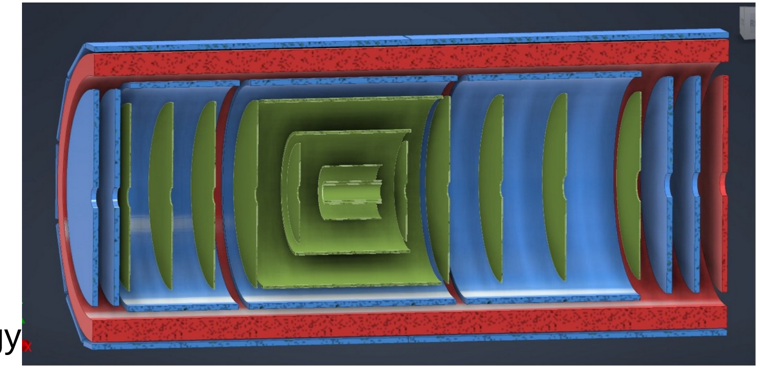


ePIC Central Tracking Detectors

The ePIC Central Tracking Detector Layout

The ePIC tracking system is a hybrid detector based on both silicon and gaseous technologies

$|\eta| < 3.5$



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
  - High granularity and low material budget are the key features to achieve a good momentum and pointing resolution
- **MPGD (Micro-Pattern Gas Detectors)**
  - Gasesous 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
  - Provide an extra hit for pattern recognition and tracking

SVT achieve a precise tracking and vertexing capability

(pitch ~ 20 µm)

IB: Inner Barrel

OB: Outer Barrel

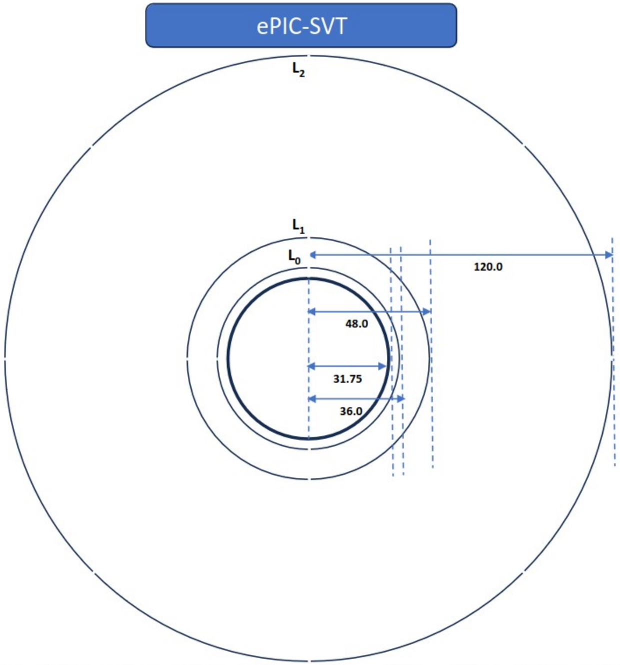
Forward region: Five MAPS silicon disks followed by two MPGD (Micro-Pattern Gas Detectors) layers and a TOF layer

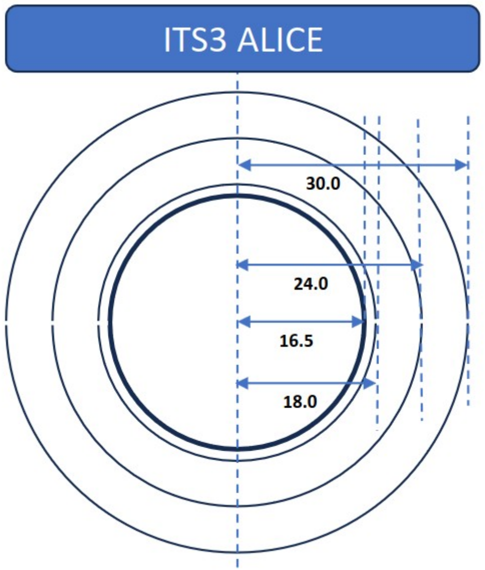
Backward region: Five MAPS silicon disks followed by two MPGD layers

ePIC SVT is based on MAPS 65 nm CMOS Imaging Technology

SVT IB:

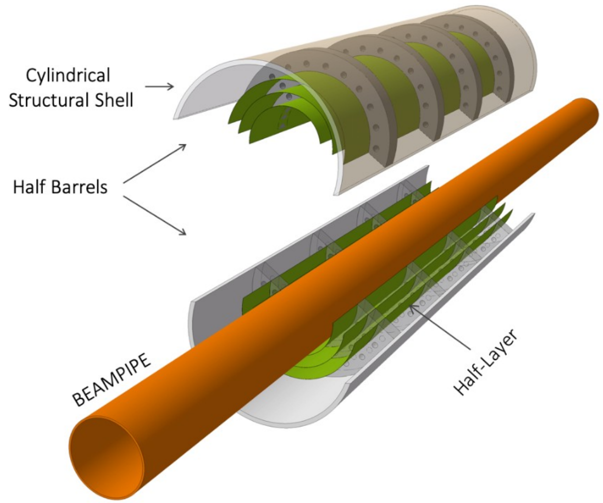
- Transverse pointing resolution can be improved by reducing X/X_0
- Three innermost layers (IB) are bent wafer-size sensors with ultra-low material budget (0.05 % X/X_0 per layer) similar to ALICE ITS3
- Radius: Two times larger for the L_0, L_1 and four times for L_2 than ITS3
- Relying on air cooling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

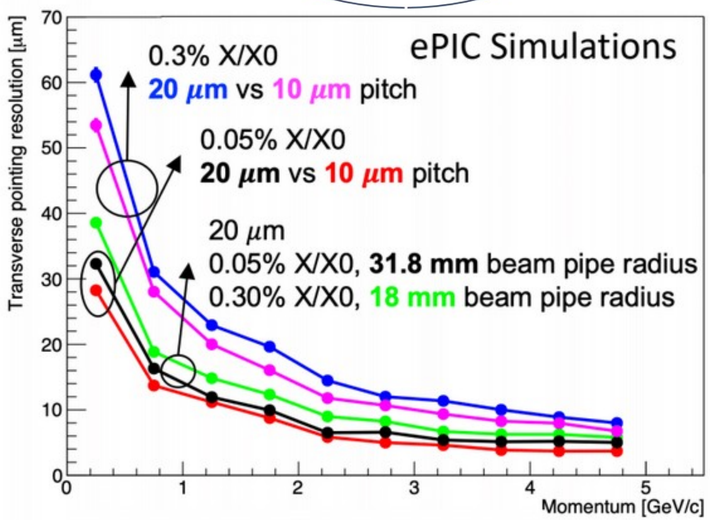




https://cds.cern.ch/record/2703140/

Layout of ALICE ITS3 detector





ePIC SVT Outer Barrel (OB) and Disks

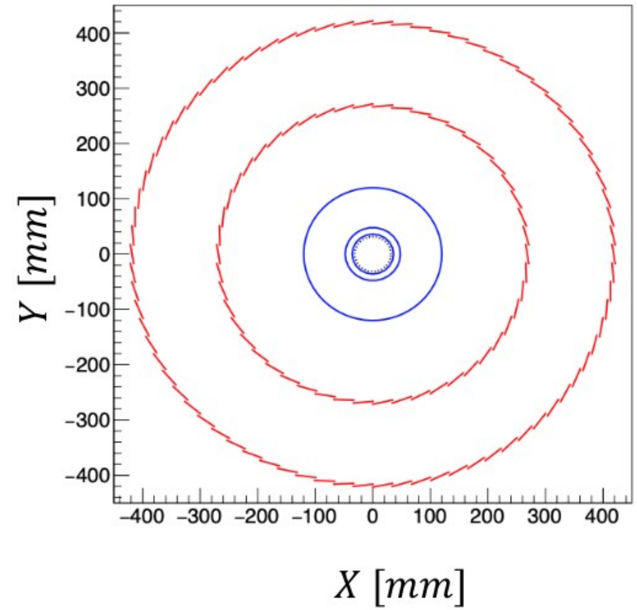
ePIC SVT is based on MAPS 65 nm CMOS Imaging Technology

SVT OB and Disks:

- 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

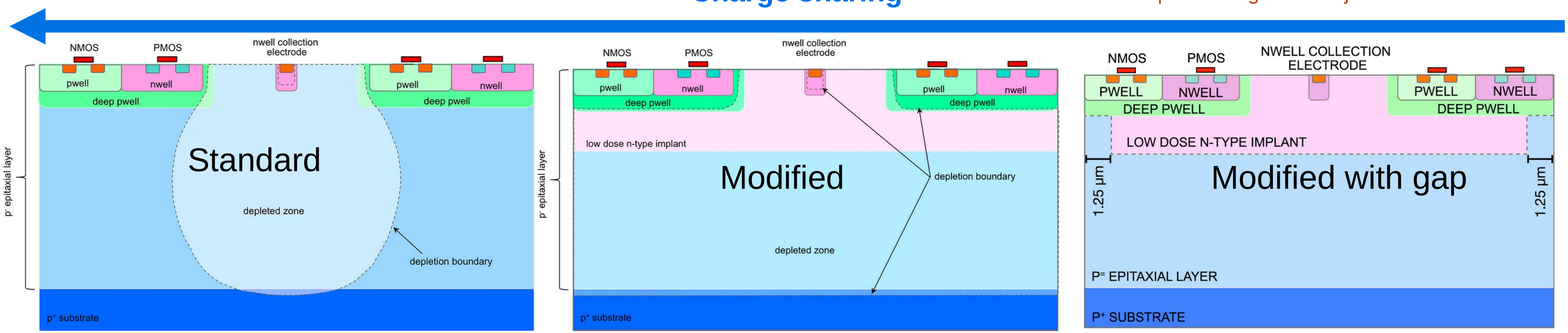
Stronger requirements for ePIC in terms of integration time!

Outer Barrel (OB)

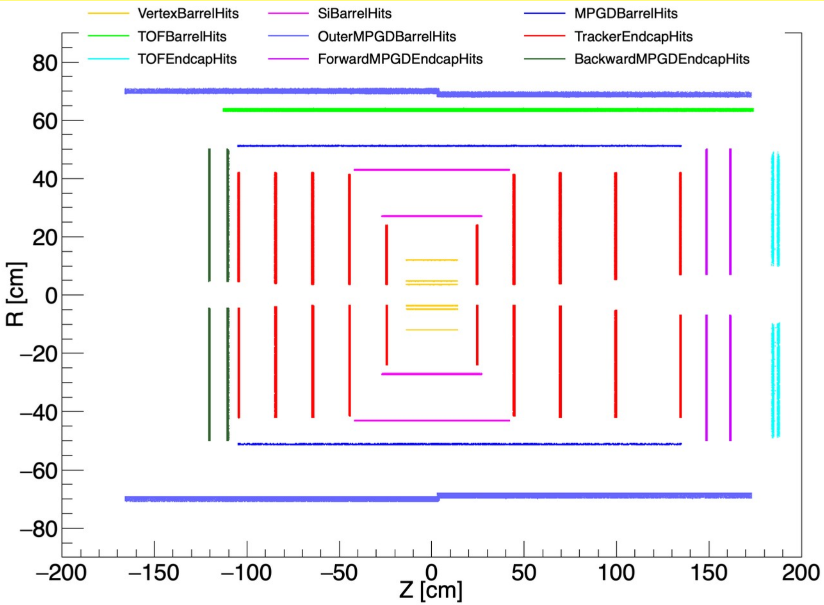


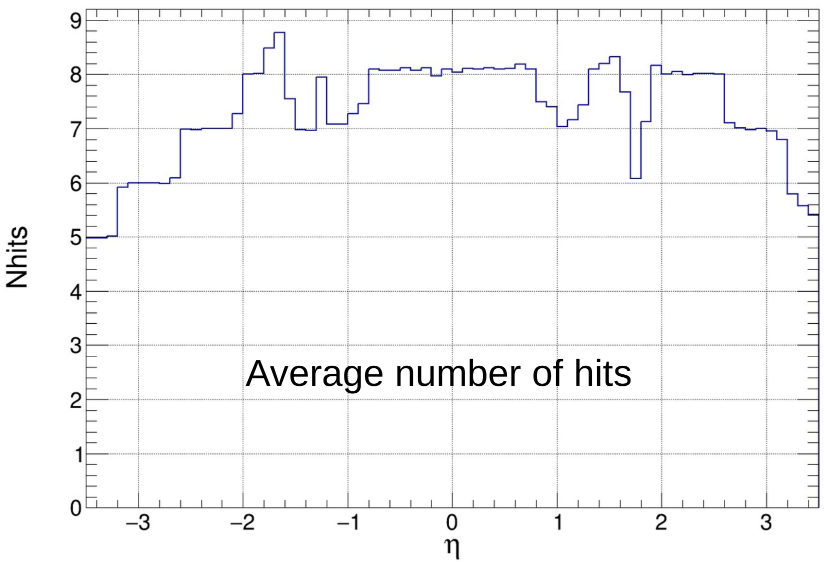
https://doi.org/10.1016/j.nima.2017.07.046
https://doi.org/10.1016/j.nima.2023.168589

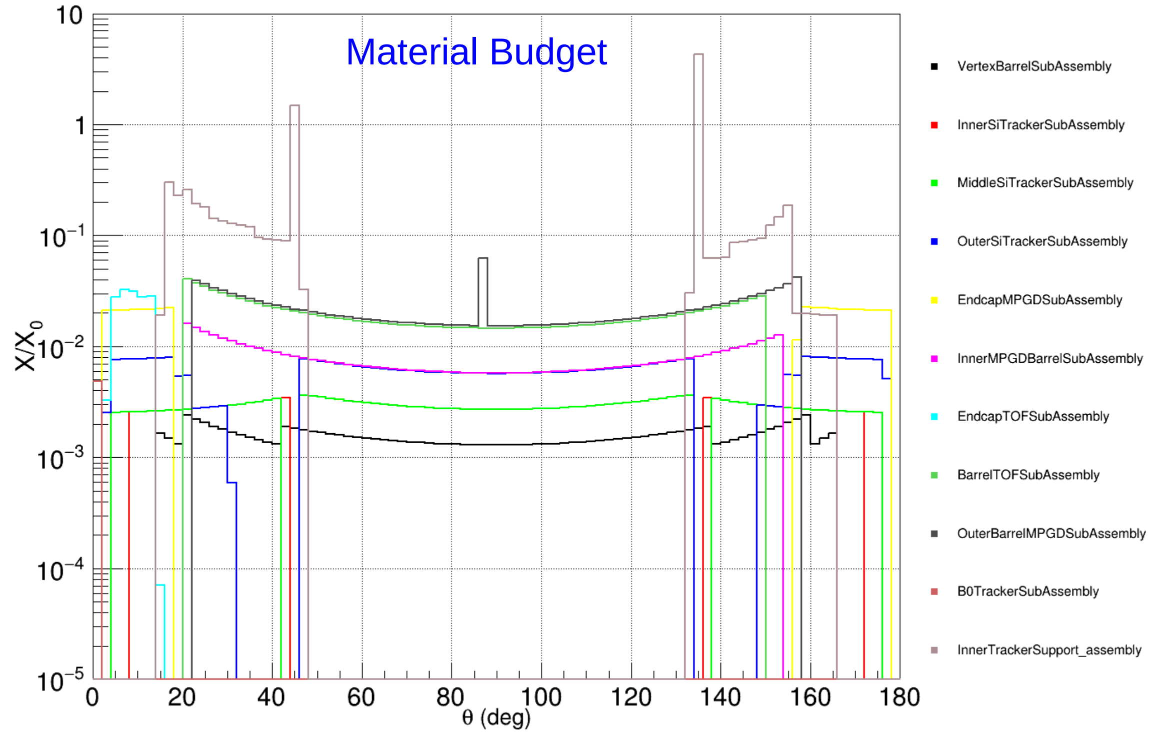
Charge sharing



The ePIC Tracker Hit map and Material Budget







Two main features of Material Budget:

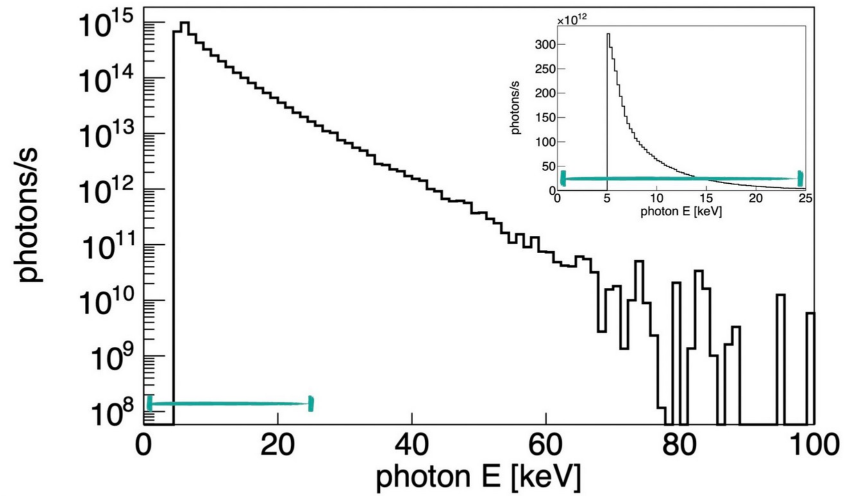
- Minimal material in the active areas of the SVT IB and OB
- ~10% service material

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

Background Sources:

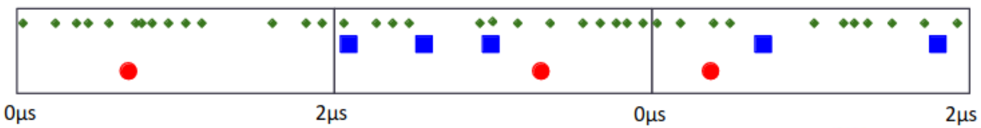
- Synchrotron Radiation: 1.8M photons (5-100 KeV) from Synrad Software
- electron+gas, hadron+gas modelled as "Fixed target" events
- NB: No "MB events" background for now

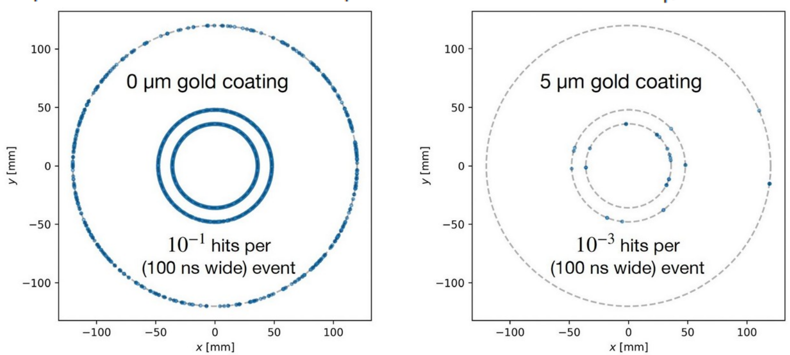
https://wiki.bnl.gov/EPIC/index.php?title=Background



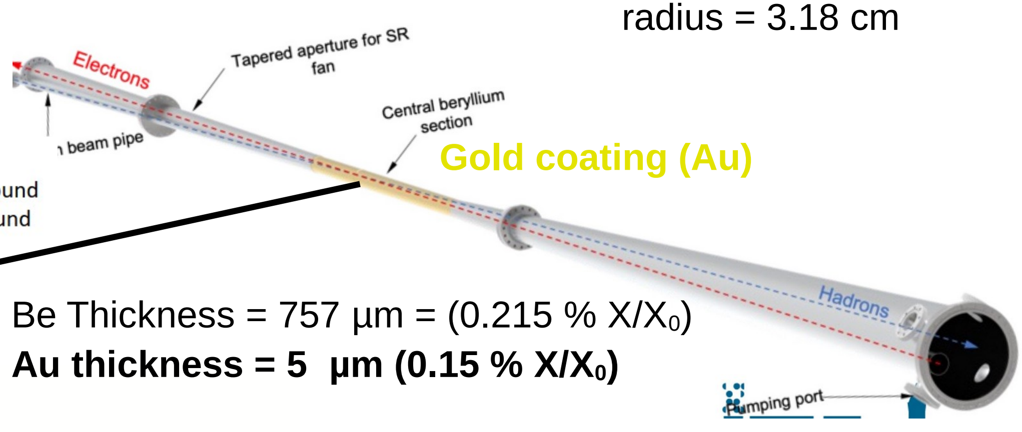
Merge with signal events (DIS, particle gun):

1. Considering a time slice of 2 μs as the MAPS integration time
2. Select how many background events to add from Poisson distribution
3. Draw random events and SR photons from weighted distribution and place uniformly at random times
4. Put the signal event(s) at random point(s) in the slice and create hepmc file





Beam pipe (0.365 % X/X_0)
radius = 3.18 cm

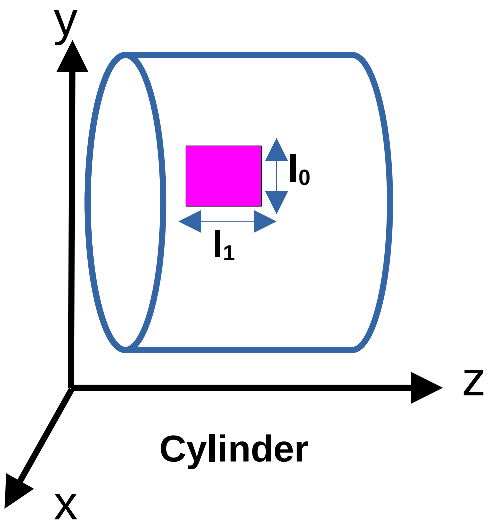


Be Thickness = 757 μm = (0.215 % X/X_0)

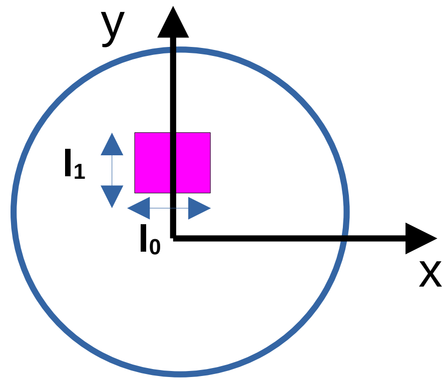
Au thickness = 5 μm (0.15 % X/X_0)

Reduction by about 2 orders of magnitude in Synchrotron Radiation

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



Cylinder



Disks

Tracking is done in EICRecon framework based on **ACTs (A Common Tracking Software)**

Tracking: Track finding and fitting using combinatorial Kalman Filter (CKF)

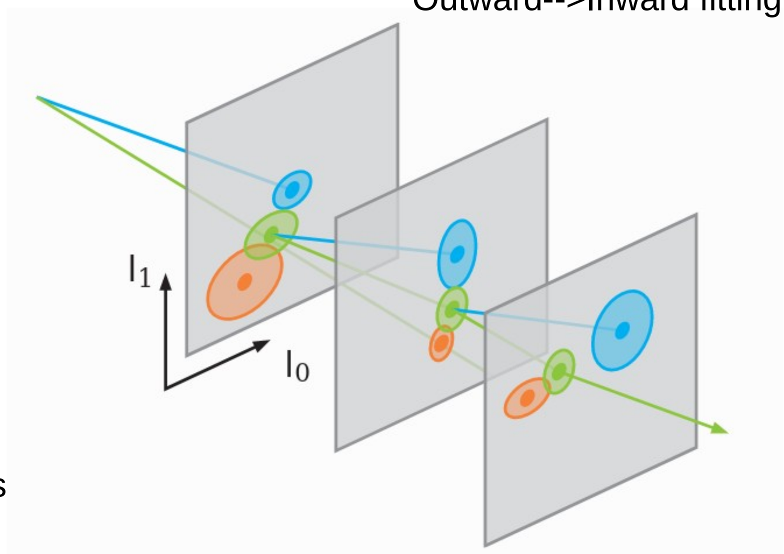
Three Steps (Kalman Filter):

1. Extrapolation
2. Filtering
3. Smoothing

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

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)**



Parameter Covariance (Symmetric Matrix) = 6(6+1)/2 = 18 independent entries

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)

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

arXiv:1805.12014 [physics.ins-det]

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

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

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

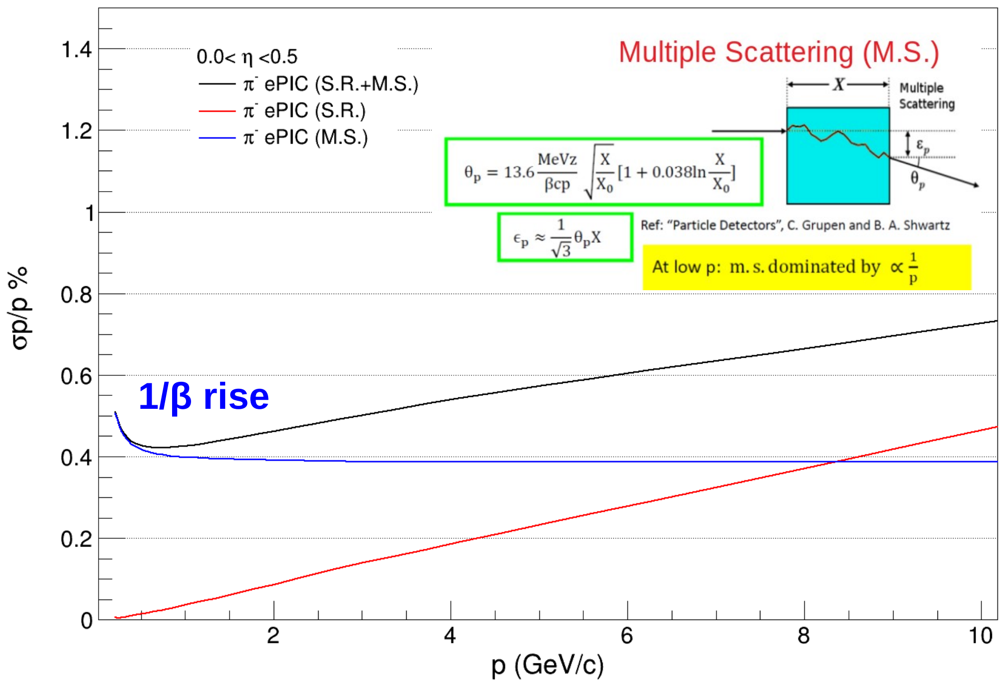
Curvature

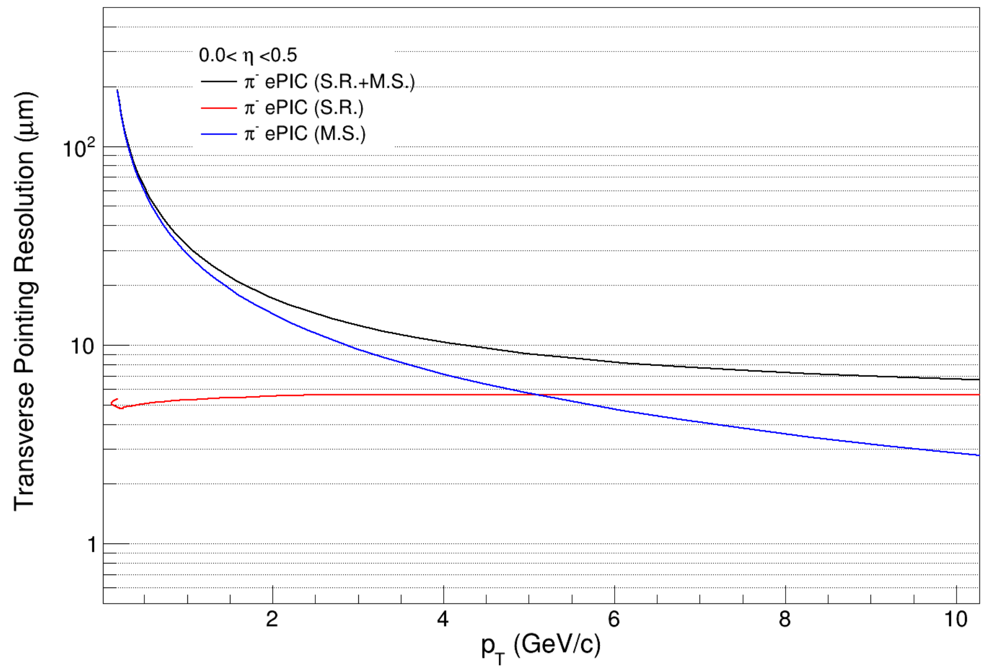
$$\frac{\sigma_{p_T}}{p_T}(MS) \propto \frac{1}{\beta p} \qquad p = \frac{Const}{\beta}$$

Curvature

Momentum and mass Hypothesis

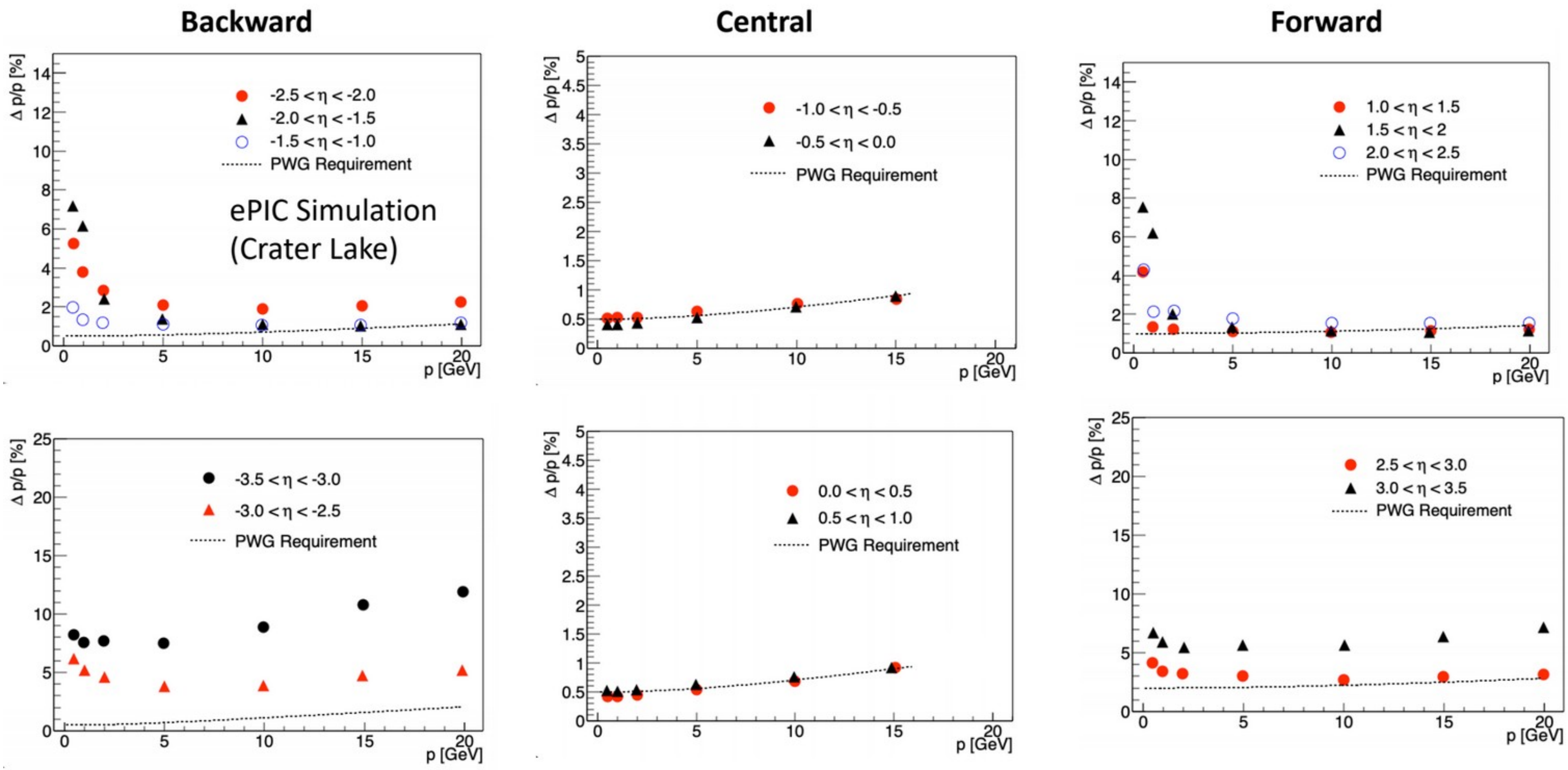
$$\Delta d_0|_{m.s.} \approx \frac{0.0136\,\mathrm{GeV/c}}{\beta p_T} r_0 \sqrt{\frac{d}{X_0 \sin\theta}} \sqrt{1 + \frac{1}{2}\left(\frac{r_0}{L_0}\right) + \frac{N}{4}\left(\frac{r_0}{L_0}\right)^2}$$



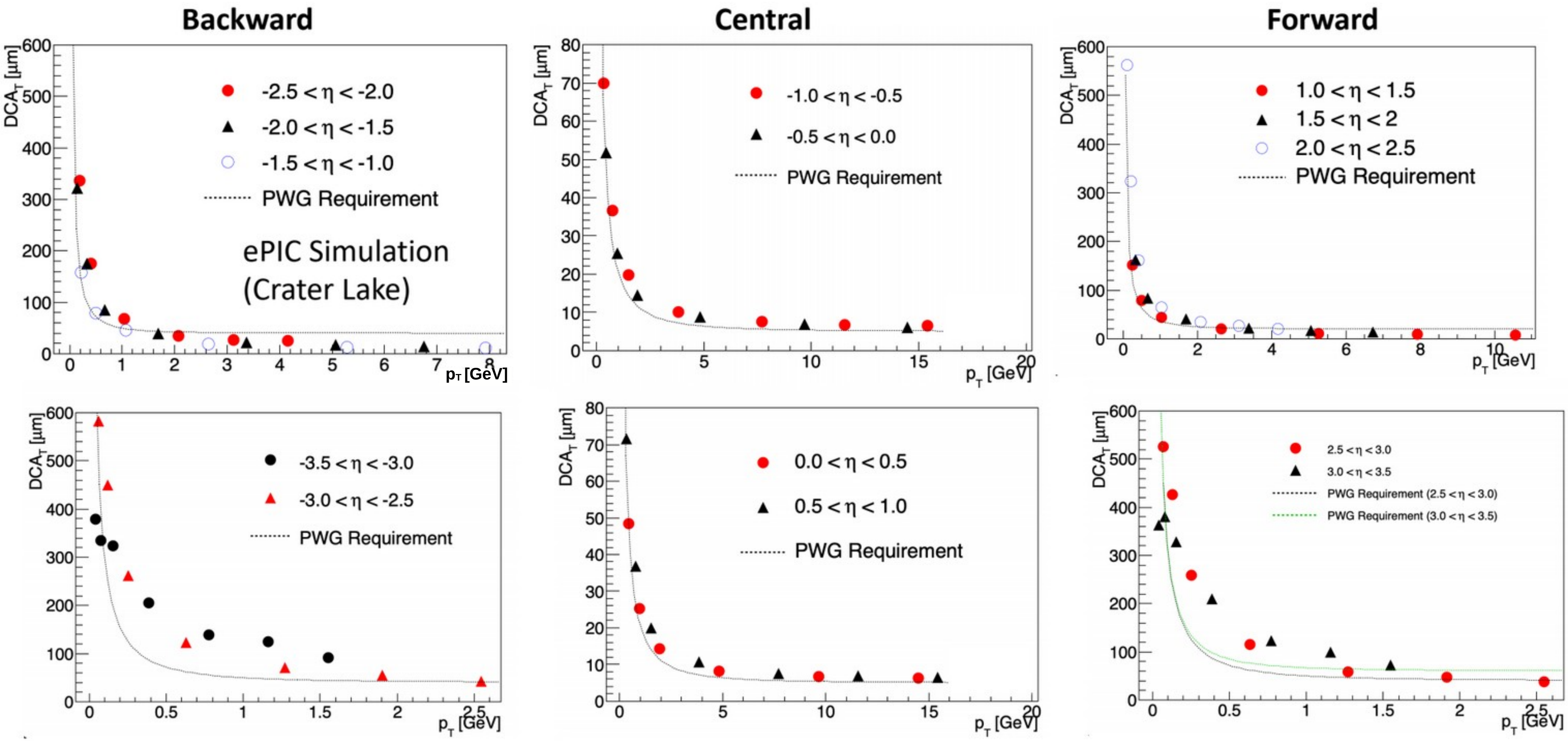


Tracking Performances: Momentum Resolution

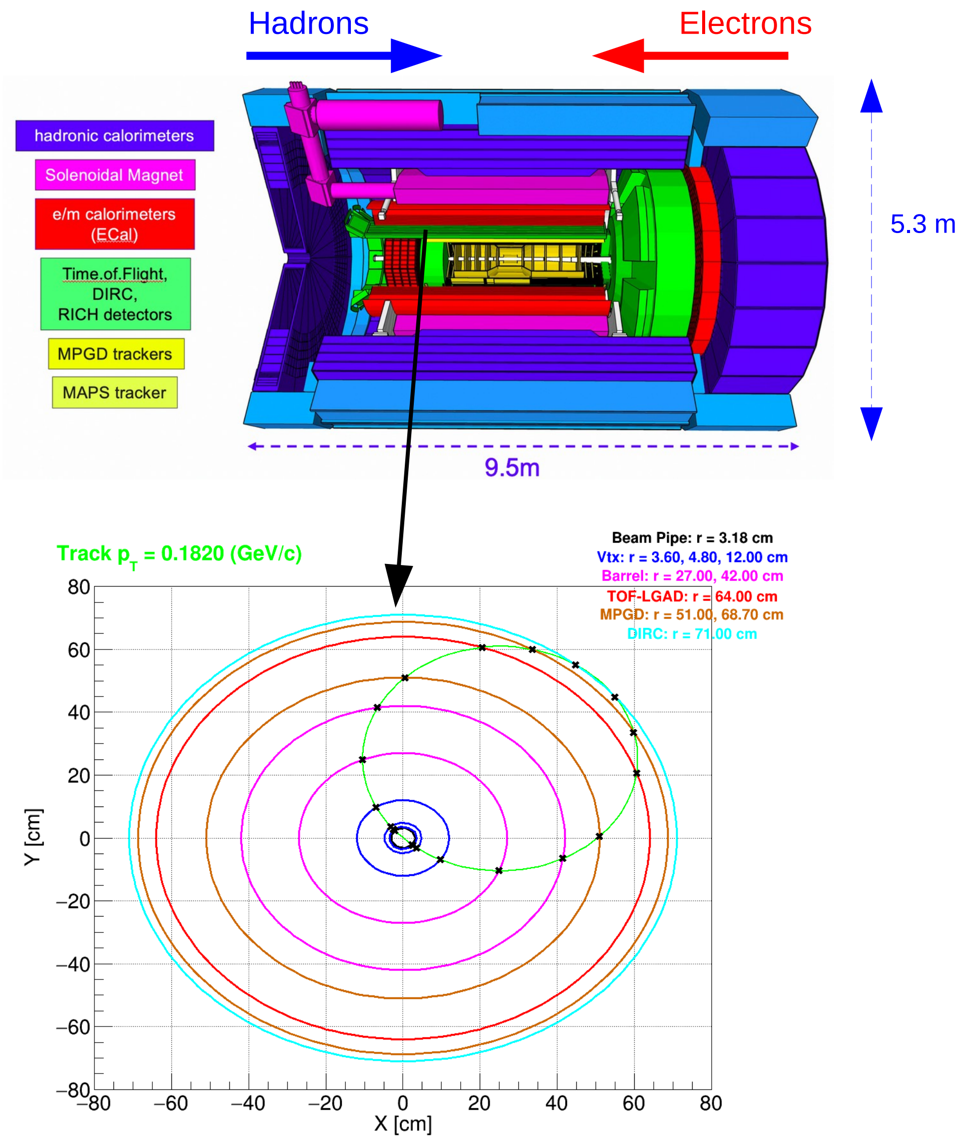
Simulated performance: Truth Seeding (ePICSimulation, Crater Lake)-Pions



Simulated performance: Truth Seeding (ePICSimulation, Crater Lake)-Pions



Theta/Phi Resolutions at the DIRC Layer



Important for Cherenkov Particle Identification

$$p_T(GeV/c) = 0.3\,B[T]\,R_{track}[m]$$

Extrapolation of track at DIRC R = 71 cm

At η = 0

$$R_{track} = \frac{R_{OutMPGD}}{2} = 0.3435\,m$$

$$p_{Tmin} = 0.3 * 1.7 * 0.3435 = 0.1752\,GeV/c$$

Fast Simulation based on **Global fit** and the **Kalman filter**

Estimation of Theta/Phi resolutions at DIRC (71 cm)

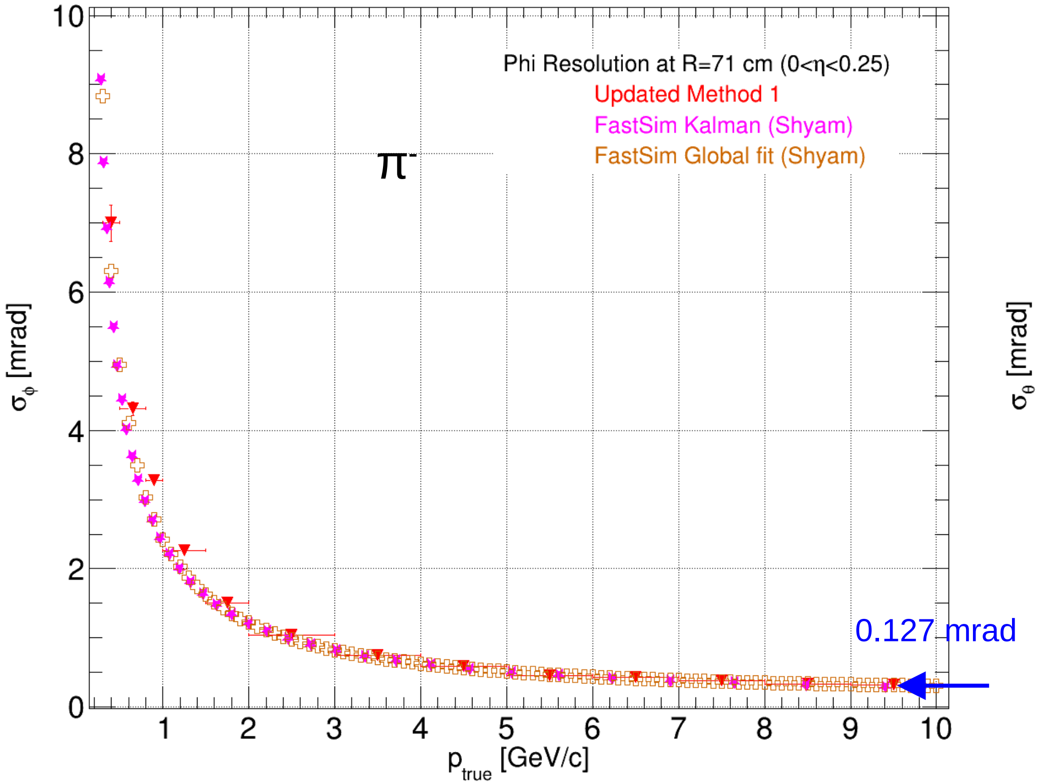
DIRC: Disk Imaging Ring Cherenkov

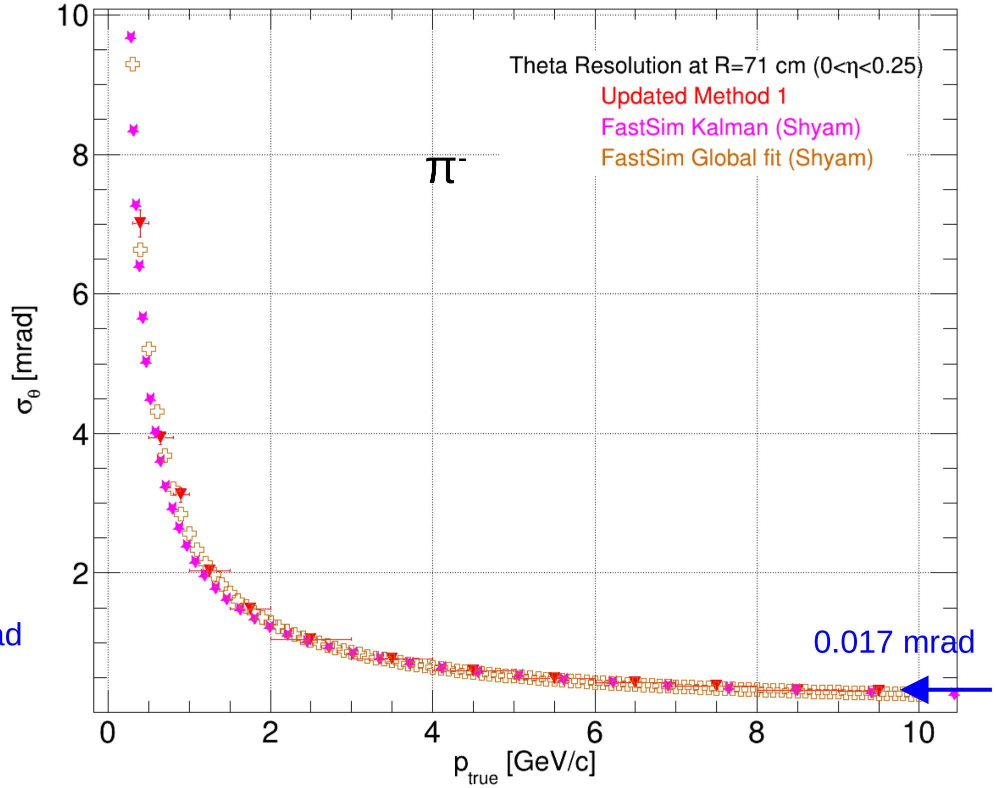
Theta/Phi Resolutions at DIRC Layer

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)

Updated Method 1 (Full Simulation) matches with Fast Simulation method





DIRC: Disk Imaging Ring Chrerenkov

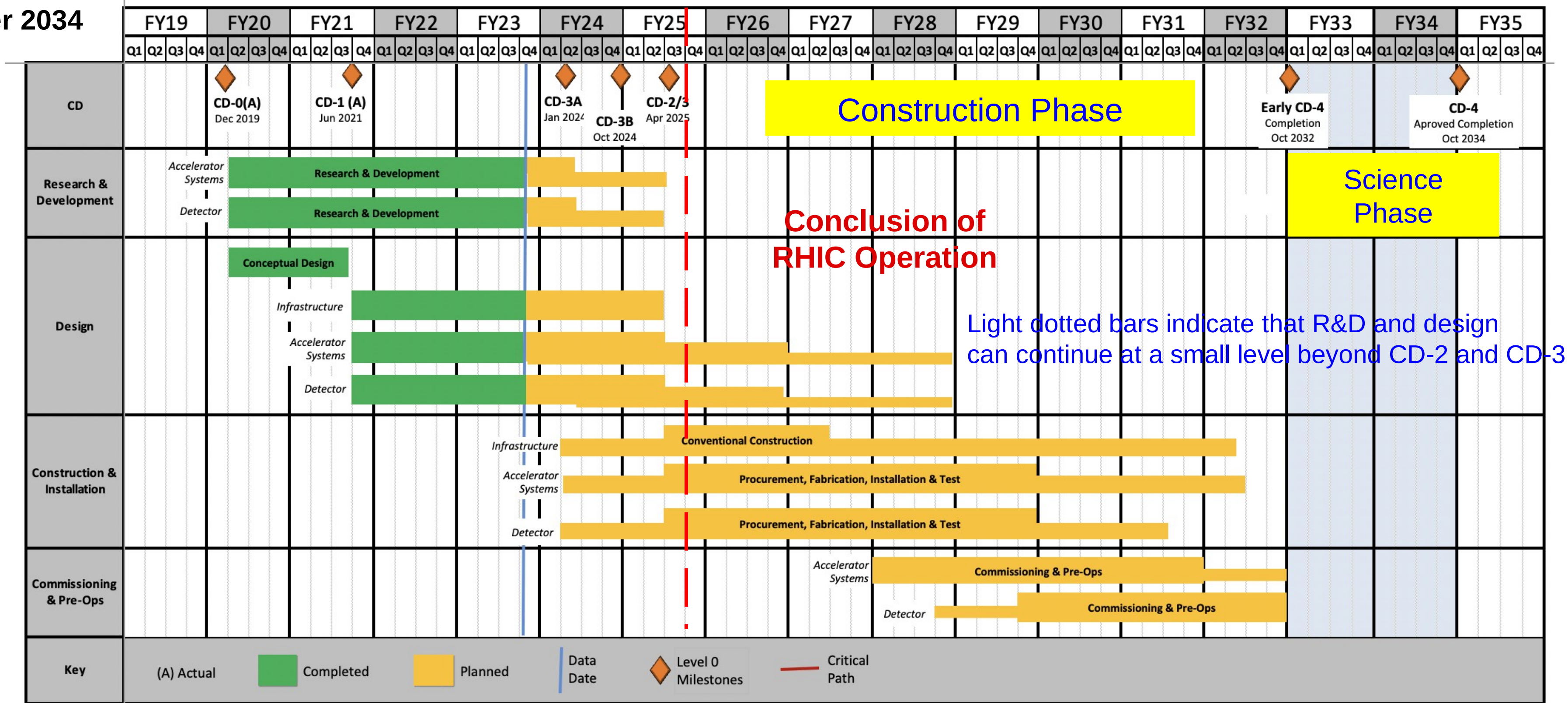
https://indico.bnl.gov/event/20473/contributions/85332/attachments/51915/89153/Fast_Simulation_ePIC_Collaboration_Meeting_Shyam_Kumar.pdf

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

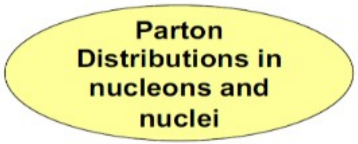
- ePIC tracker consists of both state-of-the-art silicon and gaseous detector technologies
- ePIC SVT will help to achieve a good momentum resolution as well as pointing resolution because of a good spatial resolution and limited material budget
- MPGD layers provide good space point and timing resolution over a large area and will also help in pattern recognition
- Beam pipe coated with the Gold layer plays an important role in the reduction of synchrotron radiation
- ePIC tracker performance matches the physics requirements set by the EIC LoI

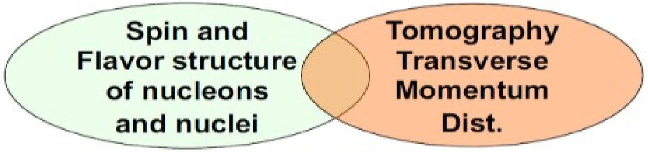
THANK YOU !!!

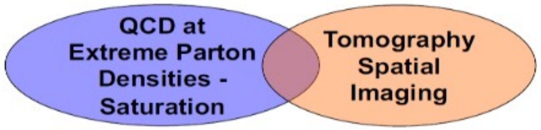
Ref: Science Requirements and Detector Concepts for the Electron-Ion Collider: EIC Yellow Report arXiv:2103.05419 [physics.ins-det]

Measurement of the Physics Processes

Understanding hadron physics measurements with electroweak reactions (EIC experiment)

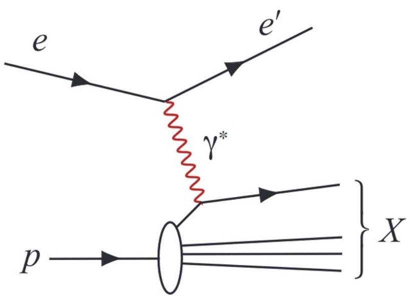






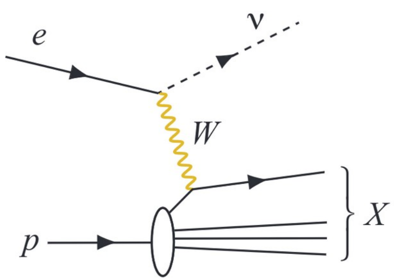
Neutral-current Inclusive DIS

e+p/A → e'+X



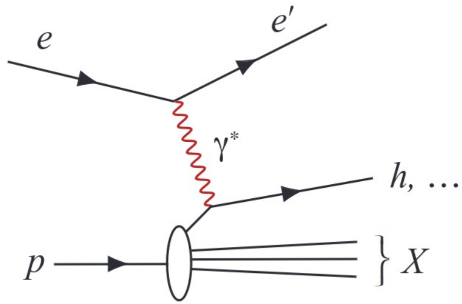
Charged-current Inclusive DIS

e+p/A → ν+X



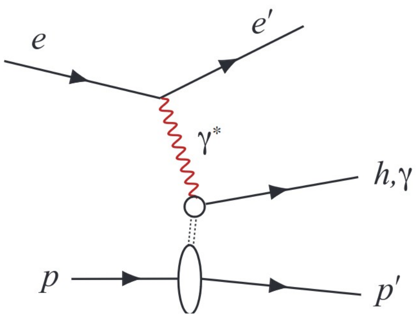
Semi-inclusive DIS

e+p/A → e'+h(π,K, p, jet)+X



Exclusive DIS

e+p/A → e'+ p'/A'+γ/h(π,K, p, jet)



Neutral-current DIS:

- Detection of scattered electron (e') with high precision is critical for all processes to determine the event kinematics

Charged-current DIS:

- At high momentum transfer Q^2, the interaction is mediated by W+- gauge boson instead of virtual photon
- Event kinematics need to be reconstructed from final state particles

Semi-inclusive DIS:

- Measurement of at least one identified hadron in coincidence with the scattered electron
- Tracking and hadronic calorimetry
- Heavy flavor identification via vertexing
- Light flavor identification from PID detectors

Exclusive DIS:

- Measure all particles in a event
- Efficient proton tagging
- Full acceptance coverage

EIC Kinematic Coverage

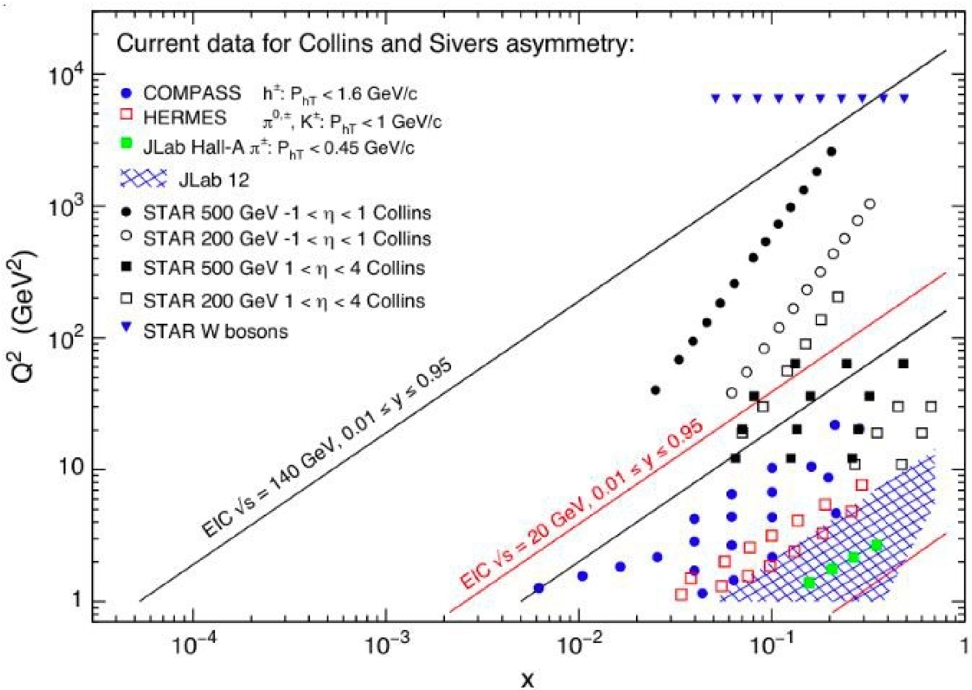
$$x=\frac{Q^2}{2\,p\,q}=\frac{Q^2}{sy} \;\rightarrow\; Q^2=s\,x\,y$$

Resolution power (Q^2)

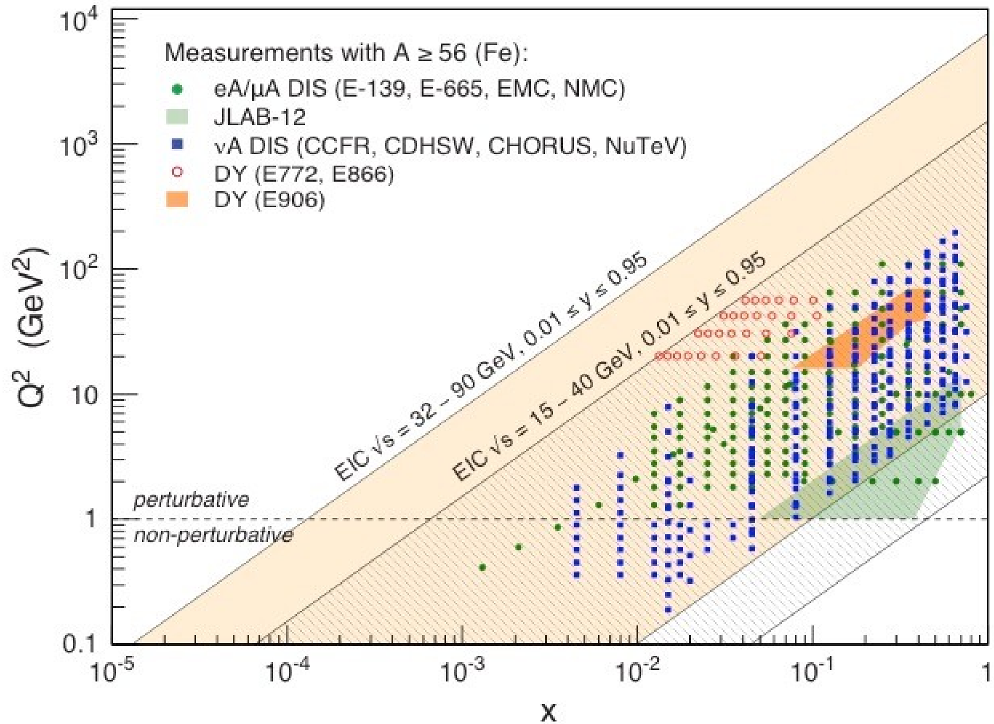
Inelasticity (y)

Momentum fraction of struck quark (x)

EIC Yellow Report: kin. reach for Sivers and Collins (wide x, Q2 range)



e-N collisions



e-A collisions

Momentum and Transverse Pointing Resolution

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

Momentum Resolution:

arXiv:1805.12014 [physics.ins-det]

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

$$\approx \frac{12\,\sigma_{r\phi}\, p_T}{0.3\, B_0 L_0^2}\sqrt{\frac{5}{N+5}}$$

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

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

Radiation Levels in ePIC Experiment

- Bunch Cross frequency 98.5 MHz but Interaction frequency much lower
- DIS events rate for ep collisions up to ~500 kHz, $L = 10 \times 10^{33}\, cm^{-2}\, sec^{-1}$
- Much lower than those seen at LHC
- Example study: 10x275 GeV DIS ep events + beam gas backgrounds
- Upper bound estimate: top luminosity, 10 run period of six months at 100% run time

Total Ionizing Dose < 1 Mrad

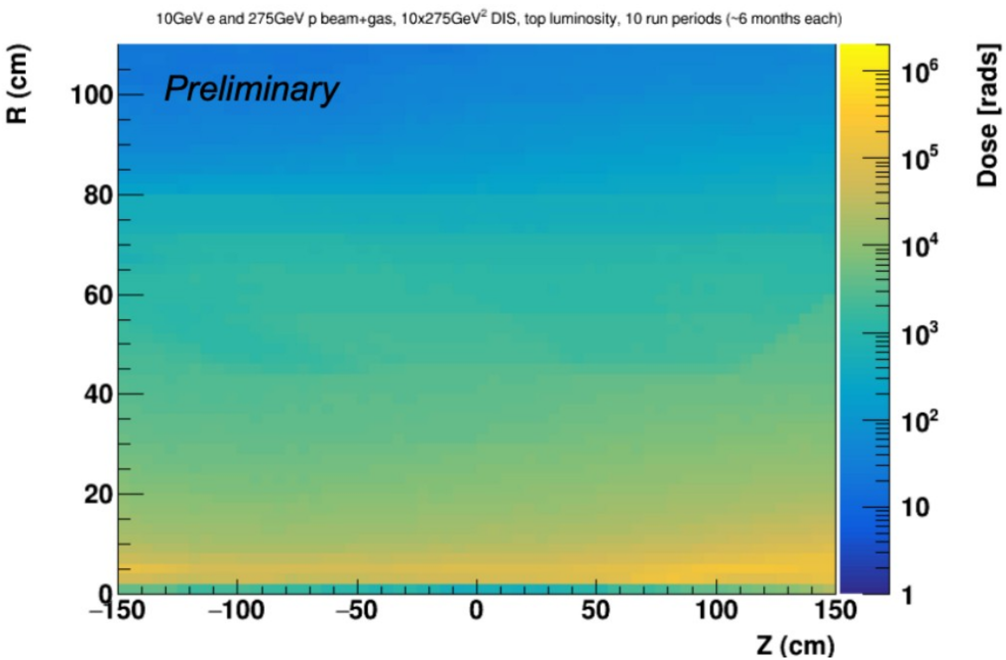
Fluence below 5×10^{13} n_{eq}/cm^2

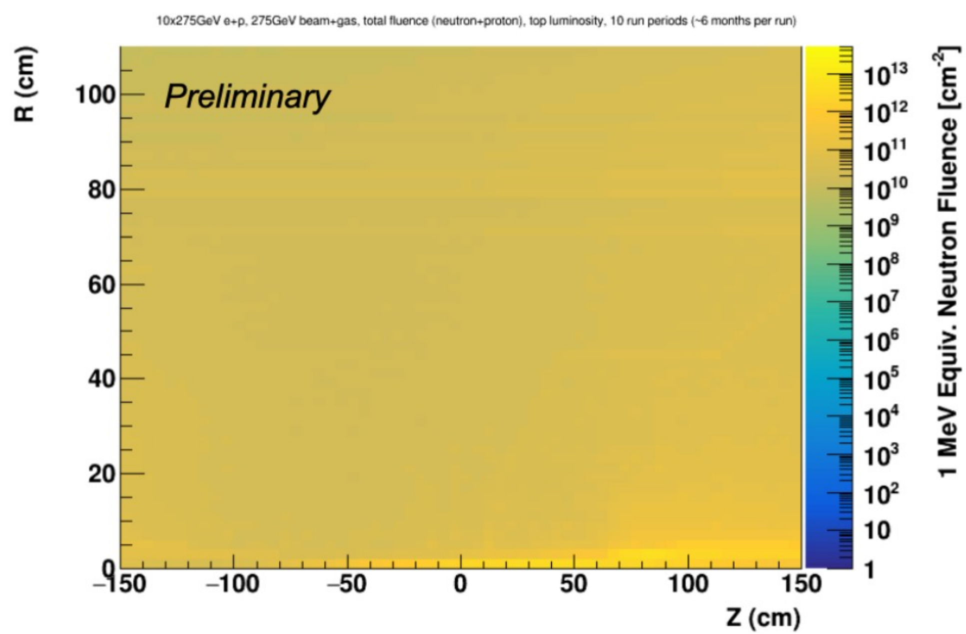
Wafer-scale sensor ePIC

NIEL radiation tolerence = 10^{14} n_{eq}/cm^2

TID radiation tolerence = 10 Mrad

Radiation map over the silicon tracker envelope

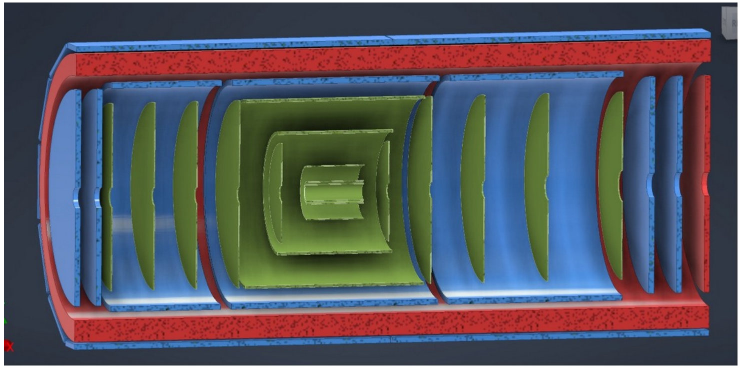




The ePIC Central Tracking Detector Layout

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

|η| < 3.5



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

MPGD Barrels and Disks

AC-LGAD TOF

SVT IB, OB and Disks (MAPS)

SVT achieve a precise tracking and vertexing capability

(pitch ~ 20 µm)

IB: Inner Barrel

OB: Outer Barrel