UNIVERSITY OF BIRMINGHAM | SCHOOL OF PHYSICS AND ASTRONOMY

Kinematic fitting for inclusive physics and tracking studies for the ePIC detector

L. Gonella, P. G. Jones, S. Maple, P. R. Newman

EIC UK Meeting

1 March 2024

Overview – Tracking Studies

- Much work has been done since the Yellow Report to converge on a tracker design ahead of the TDR
- This section showcases some of the studies which informed the geometry layout in the most recent design (craterlake)

Tracking requirements

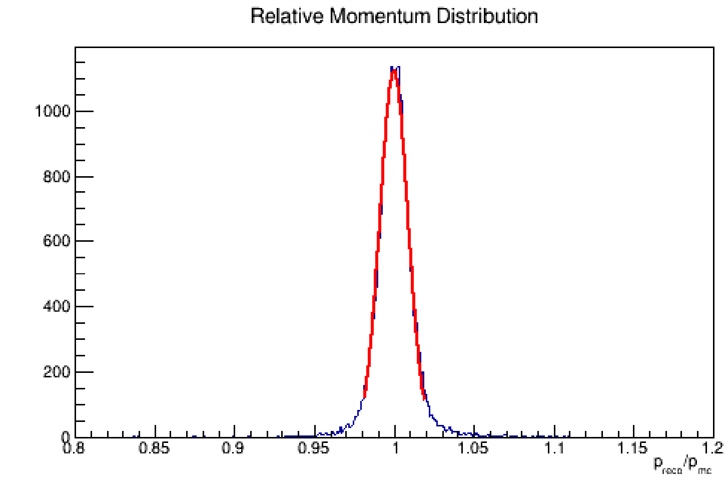
- **High precision**, **low material** tracker required for EIC physics program
  - **Precise measurement of scattered electron** (or hadrons) to reconstruct DIS kinematics
  - Momentum measurements for e.g. **invariant mass resolution, E/p** etc
  - **Jet measurements** (need tracks for particle-flow)
  - Determination of **primary vertex, secondary vertex** separation

Tracking requirements from PWGs						
			Momentum res.	Material budget	Minimum pT	Transverse pointing res.
η						
-3.5 to -3.0	Central Detector	Backward Detector	σp/p ~ 0.1%×p ⊕ 0.5%	~5% X0 or less	100-150 MeV/c	
-3.0 to -2.5					100-150 MeV/c	dca(xy) ~ 30/pT µm ⊕ 40 µm
-2.5 to -2.0			σp/p ~ 0.05%×p ⊕ 0.5%		100-150 MeV/c	dca(xy) ~ 30/pT µm ⊕ 20 µm
-2.0 to -1.5					100-150 MeV/c	
-1.5 to -1.0					100-150 MeV/c	
-1.0 to -0.5		Barrel	σp/p ~ 0.05%×p ⊕ 0.5%		100-150 MeV/c	dca(xy) ~ 20/pT µm ⊕ 5 µm
-0.5 to 0						
0 to 0.5						
0.5 to 1.0						
1.0 to 1.5		Forward Detector	σp/p ~ 0.05%×p ⊕ 1%		100-150 MeV/c	dca(xy) ~ 30/pT µm ⊕ 20 µm
1.5 to 2.0					100-150 MeV/c	
2.0 to 2.5					100-150 MeV/c	
2.5 to 3.0			σp/p ~ 0.1%×p ⊕ 2%		100-150 MeV/c	dca(xy) ~ 30/pT µm ⊕ 40 µm
3.0 to 3.5					100-150 MeV/c	dca(xy) ~ 30/pT µm ⊕ 60 µm

ePIC tracker design informed by desire to meet **momentum and $\mathbf{DCA_T}$ resolution requirements** set by physics working groups

Simulation procedure

- Negative pions generated uniformly in p_T for $0 < p_T < 10$ GeV over η range $-3.5 < \eta < 3.5$
- Propagated by Geant4 (Fun4All or EPIC-Software)
- Tracks reconstructed, momentum and DCA binned in η and p_T
- Resolution extracted from fit applied over ±2σ range to p_{rec} and DCA distributions in bins of p or p_T

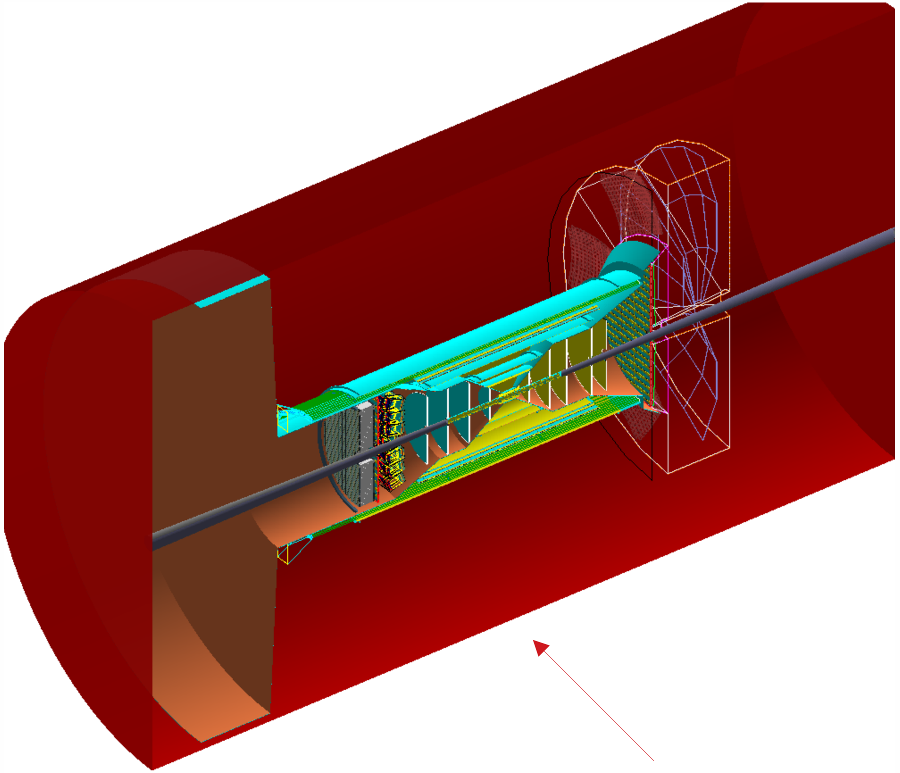


→left-hand plot represents a single momentum bin (9.5 < p < 10.5 GeV) and single η bin (0 < η < 0.5) from a Fun4All simulation of the ECCE tracker

Gaussian width taken for all p and η bins

Proposal Silicon Vertex Tracker

- From the call for proposals came a new baseline detector:
  - Barrel: **5 Si MAPS layers** with **3.3 < r < 22.68 cm** complemented by **3 µRWELL layers** at **r = 33, 51, 77 cm**
  - Endcaps: **4 Si MAPS Disks in electron going direction** with **-106 < z < -25 cm** and **5 Si MAPS Disks in hadron going direction** with **25 < z < 125 cm**



Tracker from Reference Detector

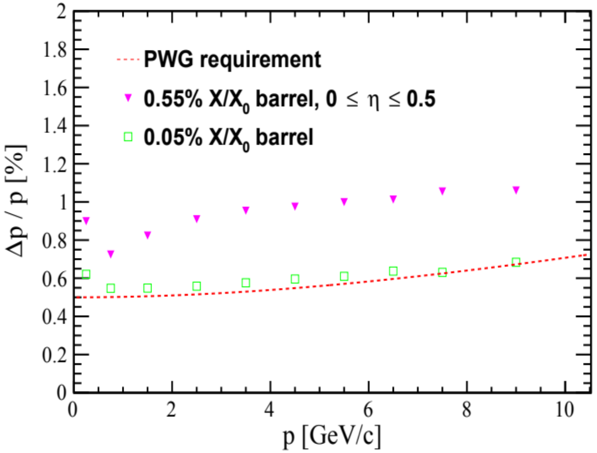
Talks describing this geometry in more detail can be found here https://indico.bnl.gov/event/15489/

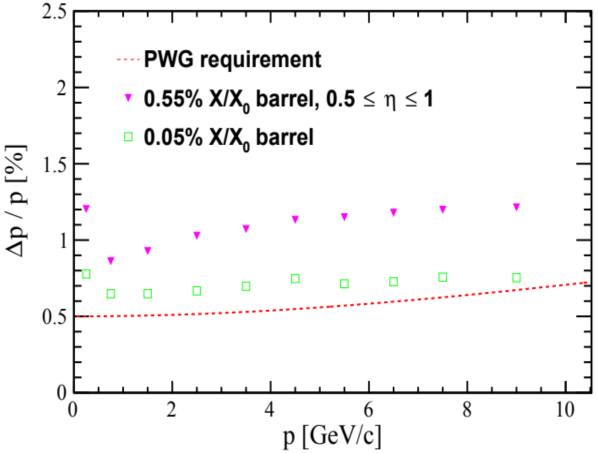
Proposal Silicon Vertex Tracker

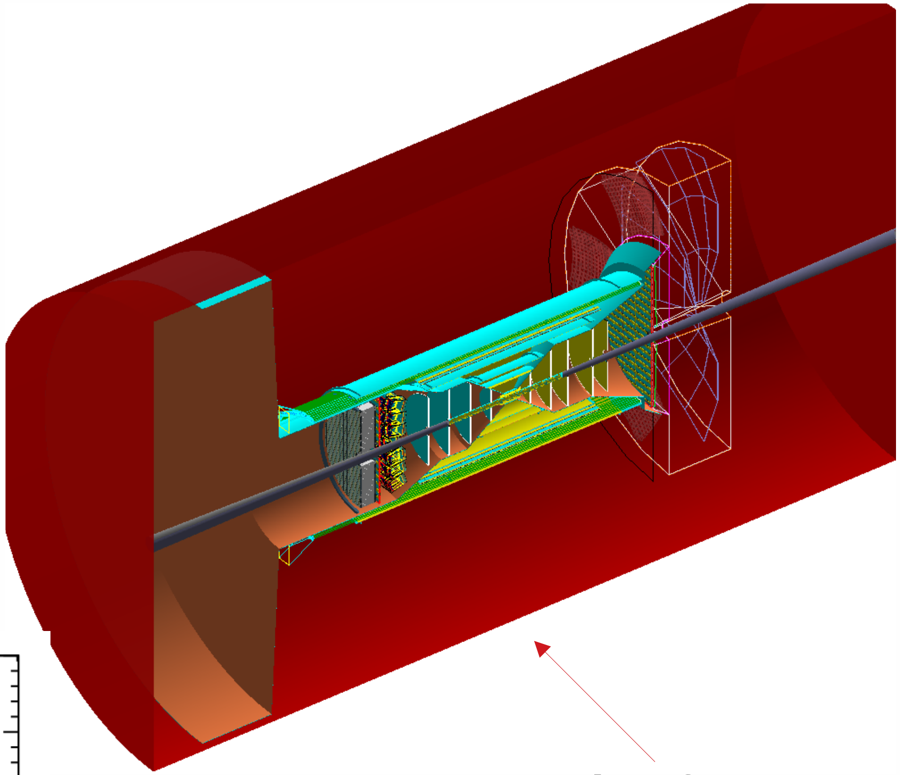
→ **Update outer barrel material estimate to include support and services**

→ **PWG momentum resolution requirement no longer met**

→ **Reconfigure barrel layout**





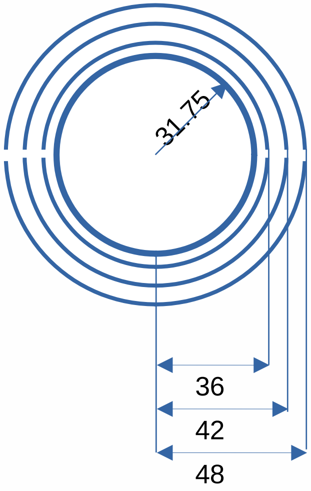


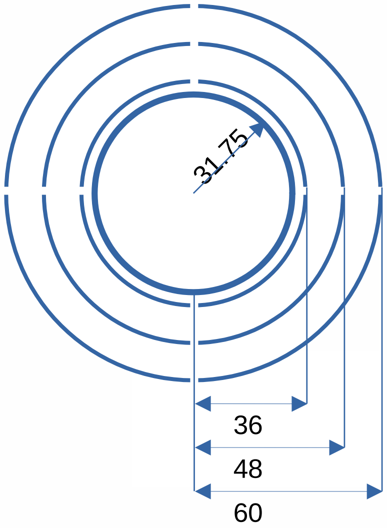
Tracker from Reference Detector

Barrel reconfiguration – Vertex layers

- **Radii of vertex layers determined by**
  - **Size of reticule**
  - **Beampipe bakeout requirements (5mm clearance)**

- Opt for 2 sensors per layer:
  - Would need to modify stitching plan
  - r = 36/42/48 mm

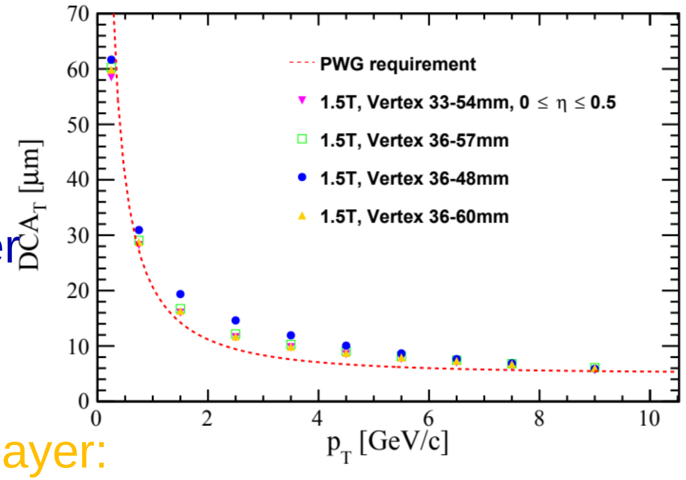


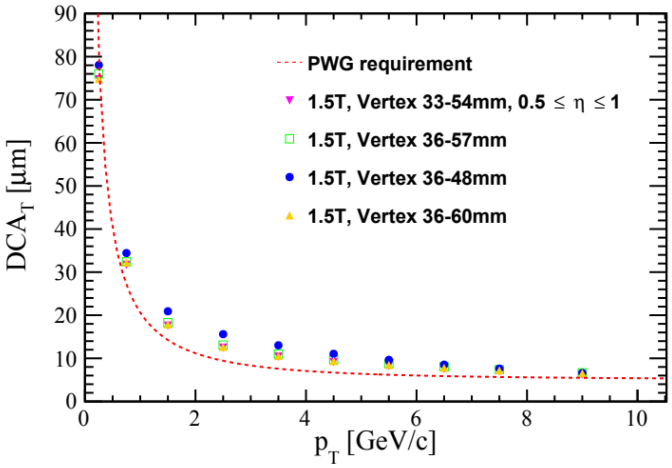


- Alternatively opt for 4 sensors per layer
  - r = 36/48/60 mm

Vertex performance comparisons

- Simulations for 4 vertex configurations:
  - Realistic reticule, 2 half layer
  - r = 36/42/48 mm
  - Active length = 24cm
  - Realistic reticule, 4 quarter layer:
  - r = 36/48/60 mm
  - Active length = 27cm



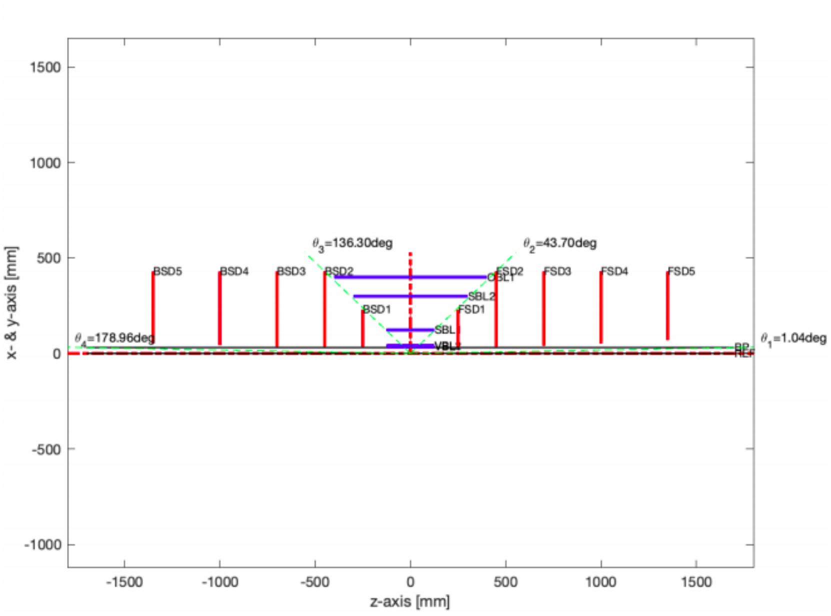


Some difference in DCA_T
→ **depends distance between r_1 and r_2**
→ **$(r_2 – r_1)$ is an important parameter**

- Proposal config:
- r = 33/43.5/54 mm
- Proposal config moved at 5 mm from beam pipe
- r = 36/46.5/57 mm

Barrel Reconfiguration

Is the YR mid-rapidity performance recoverable in 1.4T?



Following the previous steps, consider:

- Outer barrel layer at r = 420 mm,
- ~45 degree cone,
- Single sagitta layer with r <= 270 mm, $X/X_0 \sim 0.25\%$
- Outer (third) vertex barrel layer with increased radius to r = 120 mm while preserving its length,

Notes:

The lengths assume reticle lengths of 30 mm.

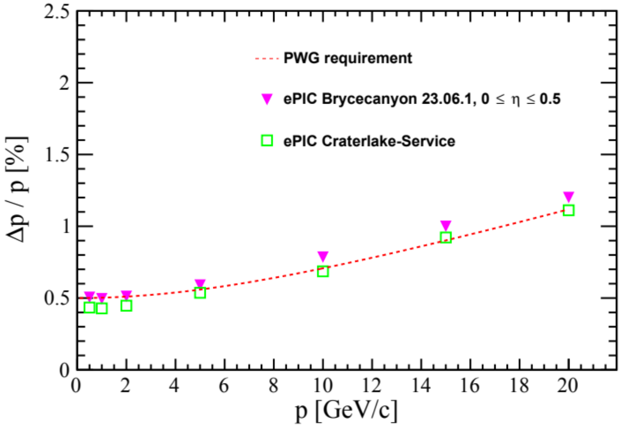
Services and service routing will need further attention; it is not for today, but I have concerns over the “double-cone” and otherwise consider a single projection angle determined by the DIRC length impractically shallow. Not for today.

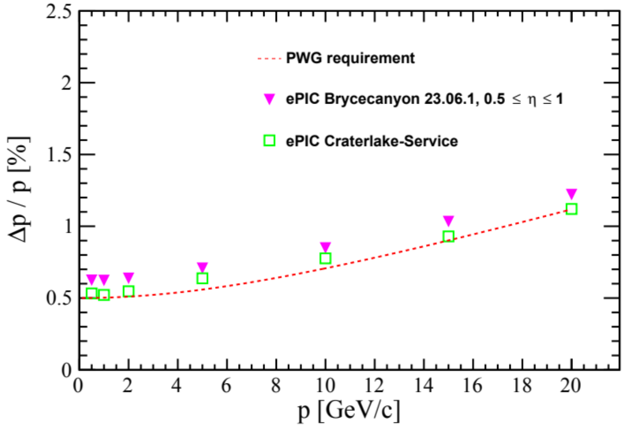
Key points:

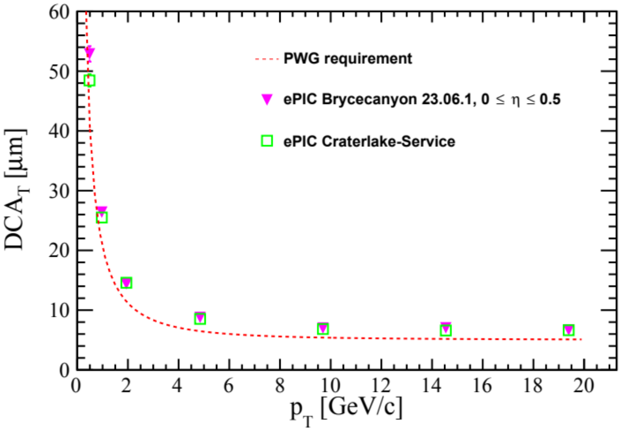
- Keep first 2 vertex layers at **36,48mm**
- **Drive out radius of 3rd vertex layer to 12cm** to contribute to sagitta measurement
- Drive out Si outer layers from r~20cm to **r=27,42cm for larger lever arm** of high precision, low material MAPS layers

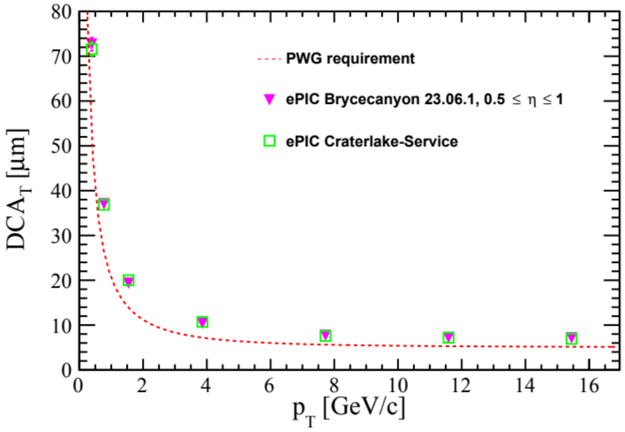
Slide from E. Sichtermann https://indico.bnl.gov/event/16261/

Craterlake Barrel Performance









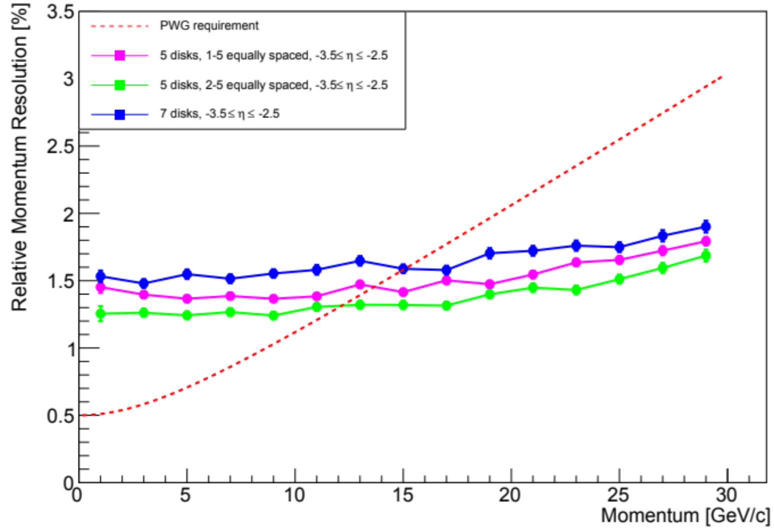
BARREL	r [mm]	l [mm]	X/X0 %
L0	36	270	0.05
L1	48	270	0.05
L2	**120**	270	**0.05**
L3	**270**	540	**0.25**
L4	**420**	840	0.55
Cyl.Micromegas layer	550	2300	0.5
AC-LGAD layer	640	2400	1.0
μRWELL behind DIRC	**730**	3420	~1.0%

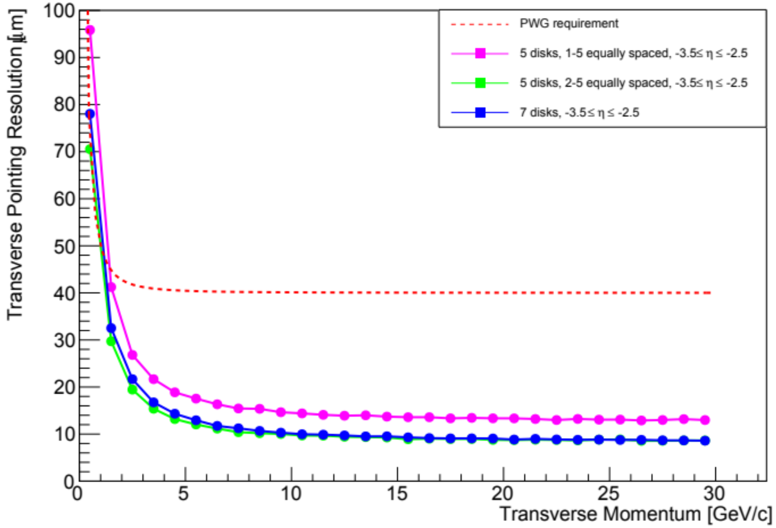
Barrel performance recovered!

Disks Optimisation

- Disks spread over **largest lever arm** available
- # of Disks is **compromise between resolution and redundancy**
- Many studies performed throughout yellow report and call for proposals
- **More disks increase material**, giving **worse resolution**, but **increasing redundancy**
- **Larger lever arm** between 1st and 2nd disk **improves DCA_T resolution**
- <5 disks gives **insufficient η coverage**

Old studies (not ePIC)

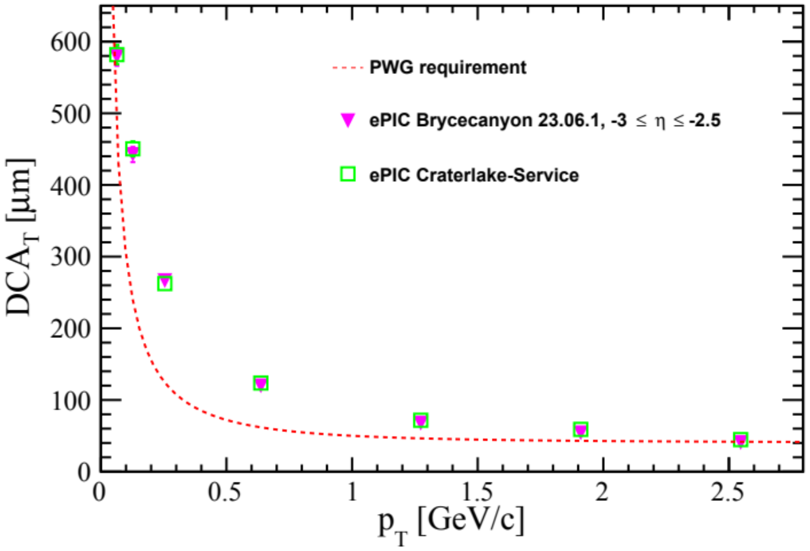


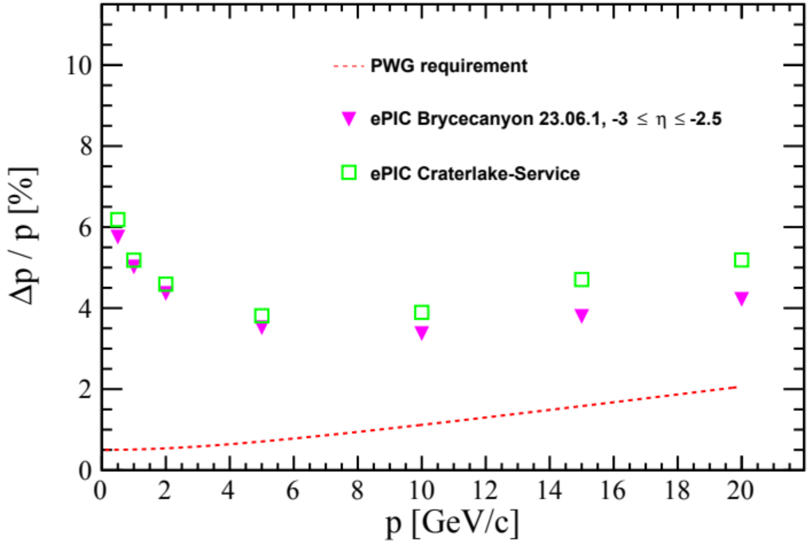


Craterlake Disks Performance

- **5 Disks per side**
- Occupy **full available lever arm**
- **Challenging requirements** in backwards region with 1.7T field

DISKS	+z [mm]	-z [mm]	X/X0 %
E/HD0	250	-250	0.24
E/HD1	450	-450	0.24
E/HD2	700	-650	0.24
E/HD3	1000	-900	0.24
E/HD4	**1350**	**-1150**	0.24





Summary – Tracking Studies

- Simulation studies showed that optimisation of proposal tracking config was required
- Barrel region reconfigured → central resolution requirements met
- Disk layout chosen to optimise resolutions → still challenging to meet requirements in these regions with 1.7T field
- Passive material has notable effect on momentum and DCA_T resolution → simulations must be kept up to date with R&D progress on low material solutions

Overview – Kinematic Fitting for inclusive DIS

- **Future e-p colliders coming** → can use this time to make sure we get the most out of them.

- Event by event **kinematic fit makes full use of all information** to reconstruct inclusive kinematics with high precision.
  - This has been looked at in the context of ZEUS using smeared MC (see paper from R. Aggarwal and A. Caldwell https://arxiv.org/abs/2206.04897)
    → **The work shown here demonstrates feasibility with full simulations of ePIC and H1**

- Overconstraint allows us to **reconstruct energy of possible ISR photon** → effectively lowers electron beam energy, extending kinematic reach.

Inclusive NC DIS Kinematics

- Inclusive DIS kinematics can be reconstructed from **two measured quantities**
  → $\vec{\mathbf{D}} = \{E_e, \theta_e, \delta_h, p_{t,h}\}$
  - Where δ_h is $E - p_z$ sum of all particles in the Hadronic Final State: $\Sigma\, E_i(1 - \cos\theta_i)$
  - $P_{t,h}$ is the transverse momentum of the HFS
- Resolution of conventional reconstruction methods depend on:
  - Event x-Q^2
  - Detector acceptance and resolution effects
  - Size of radiative processes

Electron method

$$Q^2 = 2E_e E'_e(1+\cos\theta_e)$$

$$y = 1 - \frac{E'_e}{2E_e}(1-\cos\theta_e)$$

JB method

$$y = \frac{\delta_h}{2E_e}$$

$$Q^2 = \frac{p_{t,h}^2}{1-y}$$

e-Σ method

$$Q^2_{e\Sigma} = Q^2_e \qquad y_\Sigma = \frac{\delta_h}{\delta_h + \delta_e}$$

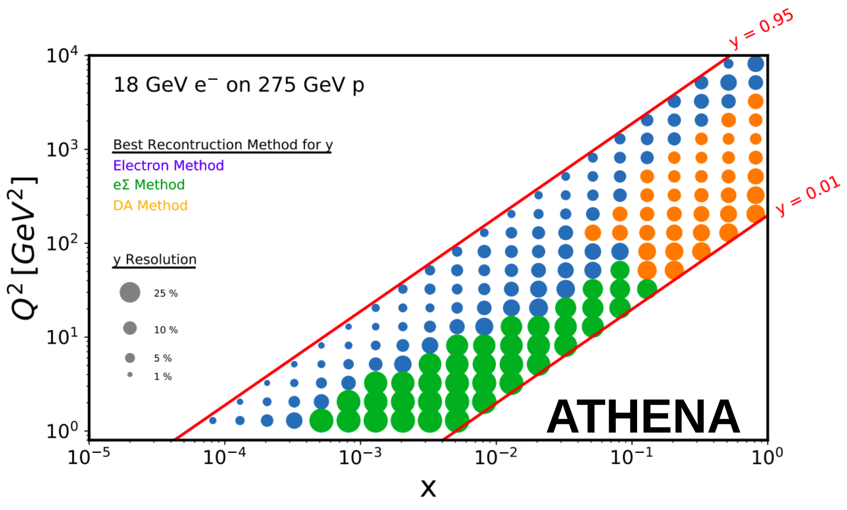
$$x_{e\Sigma} = \frac{Q^2_\Sigma}{s y_\Sigma} \qquad Q^2_\Sigma = \frac{p^2_{t,e}}{1 - y_\Sigma}$$

Double Angle method

$$y_{DA} = \frac{\alpha_h}{\alpha_h + \alpha_e} \qquad \alpha_{e/h} = \tan\frac{\theta_{e/h}}{2}$$

$$Q^2_{DA} = \frac{4E_e^2}{\alpha_e(\alpha_e + \alpha_h)}$$

Kinematic Reconstruction for EIC – A Brief History



No single method wins everywhere!

- Detailed simulations performed, reconstruction methods chosen to optimise resolutions throughout phase space
  → Resolution throughout phase space allowing 5 (log) bins per decade in x and Q^2
- Coverage driven by acceptance:
  - $0.01 < y < 0.95$, $Q^2 > 1$ GeV^2
- Lower y accessible → however it's easier to rely on overlap between data at different √s

What if we use all available information?

- Best reconstruction should be possible using all measured quantities simultaneously
  - One approach is to use a Neural Network https://arxiv.org/abs/2110.05505
  - Can alternatively perform a kinematic fit of measured quantities.

Kinematic Fit (KF) Reconstruction

- Kinematic fit of **all 4** measured quantities:
  - Extract DIS kinematics, and energy of a possible ISR photon: $\vec{\lambda} = \{x, y, E_\gamma\}$

1. Likelihood

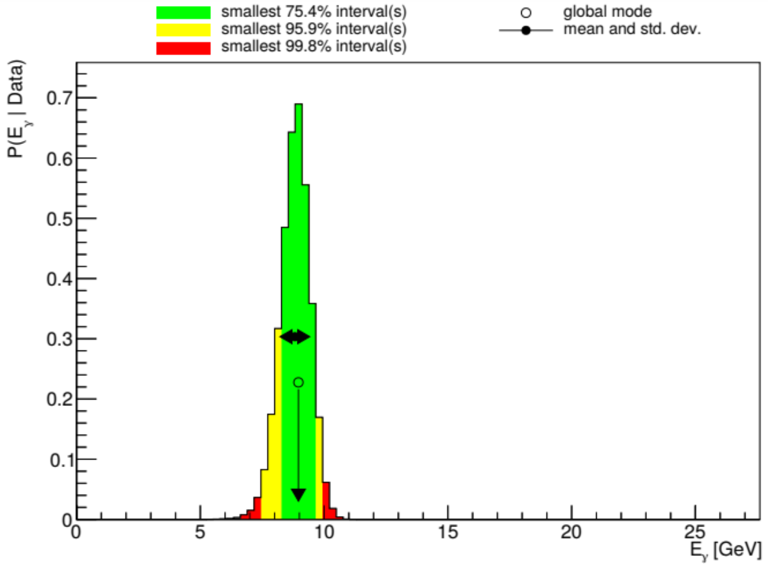
$$P(\vec{D}|\vec{\lambda}) \propto \frac{1}{\sqrt{2\pi}\sigma_E} e^{-\frac{(E_e-E_e^\lambda)^2}{2\sigma_E^2}} \frac{1}{\sqrt{2\pi}\sigma_\theta} e^{-\frac{(\theta_e-\theta_e^\lambda)^2}{2\sigma_\theta^2}} \frac{1}{\sqrt{2\pi}\sigma_{\delta_h}} e^{-\frac{(\delta_h-\delta_h^\lambda)^2}{2\sigma_{\delta_h}^2}} \frac{1}{\sqrt{2\pi}\sigma_{P_{T,h}}} e^{-\frac{(P_{T,h}-P_{T,h}^\lambda)^2}{2\sigma_{P_{T,h}}^2}}$$

2. Prior

$$P_o(\vec{\lambda}) = \frac{1+(1-y)^2}{x^3y^2}\,\frac{[1+(1-E_\gamma/A)^2]}{E_\gamma/A}$$

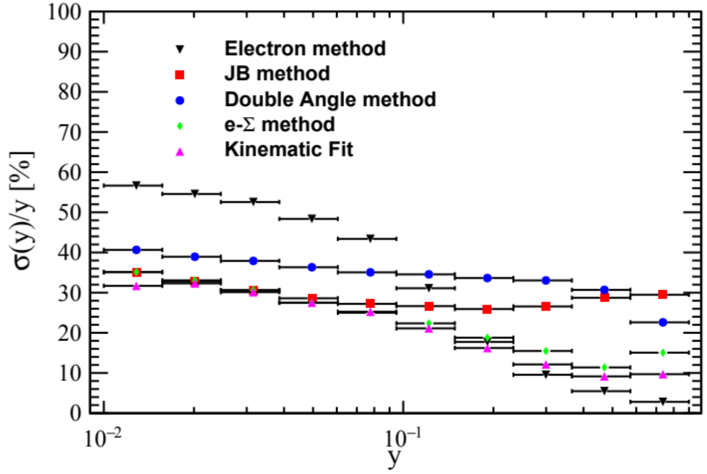
3. Posterior

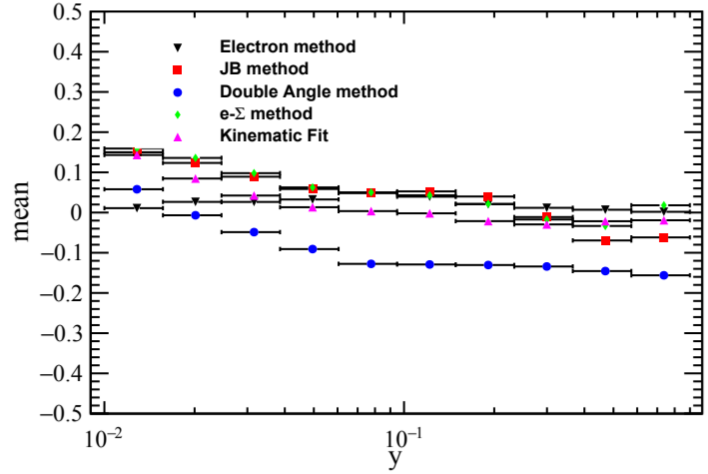
$$P(\vec{\lambda}|\vec{D}) \propto P(\vec{D}|\vec{\lambda})P_o(\vec{\lambda}).$$



- **Posterior extracted** using Metropolis-Hastings algorithm:
  - → Fitted values of **x, y, E$_\gamma$** taken from global mode of the posterior

Kinematic Resolutions at ePIC (EIC Project Detector)





- Simulations in ePIC software:
  - 18x275 GeV^2 ep
  - $Q^2 > 1\ GeV^2$
  - No QED Rad

Resolution

- **KF matches or beats conventional recon methods** except e-method at high y *

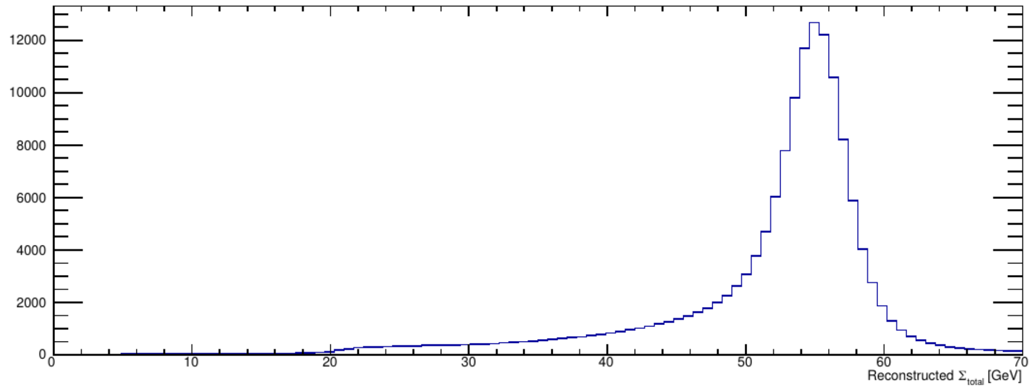
Mean

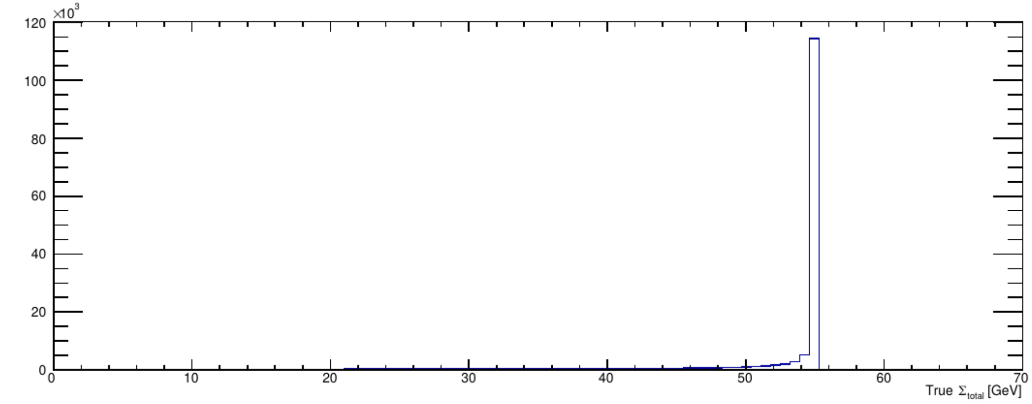
- **KF shows low bias**

Kinematic Fitting at H1

- Simulations are one thing – but will it work with real data?
- Perform kinematic fit reconstruction on H1 e^+p 03/04 MC+Data
- Use a standard H1 high Q^2 event selection
  - E_e > 11 GeV in Lar Calorimeter
  - $(E-p_z)_{total}$ cuts removed so **still have ISR**
  - For plotting, require $0.01 < y_{e\Sigma} < 0.6$ and $Q^2 > 200$ GeV^2

ISR from Kinematic Fitting at H1





- ISR energy estimate based purely on event kinematics can be found:

$$E_\gamma = E_{e,beam} - \tfrac{1}{2}\Sigma_{total}$$

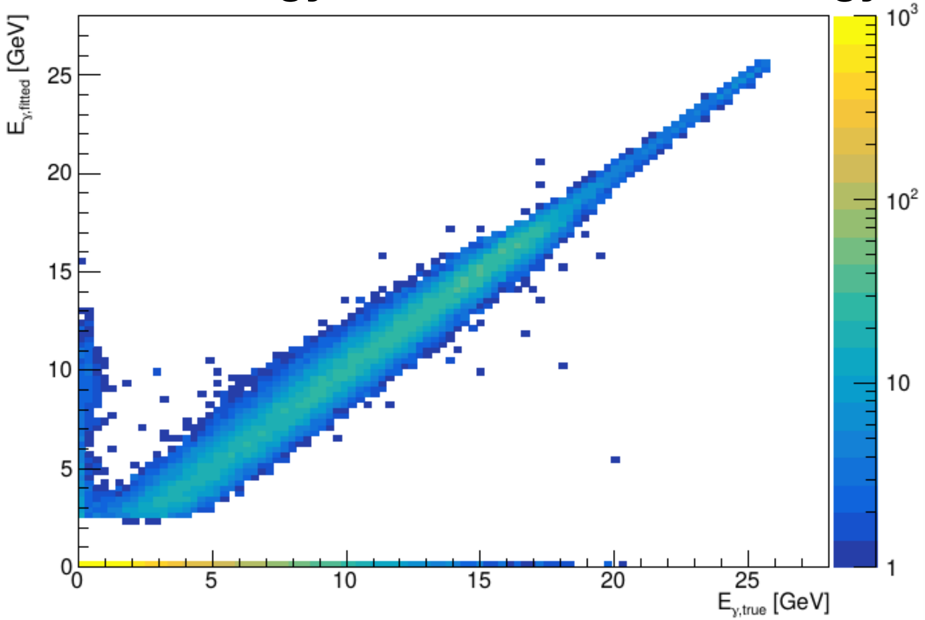
  - Where Σ_{total} is E-p_z sum of all particles in event (~$2E_e$ if no ISR)

- Peak in reconstructed Σ_{total} is broad → need to be careful not to attribute to ISR that which could be caused by a resolution effect

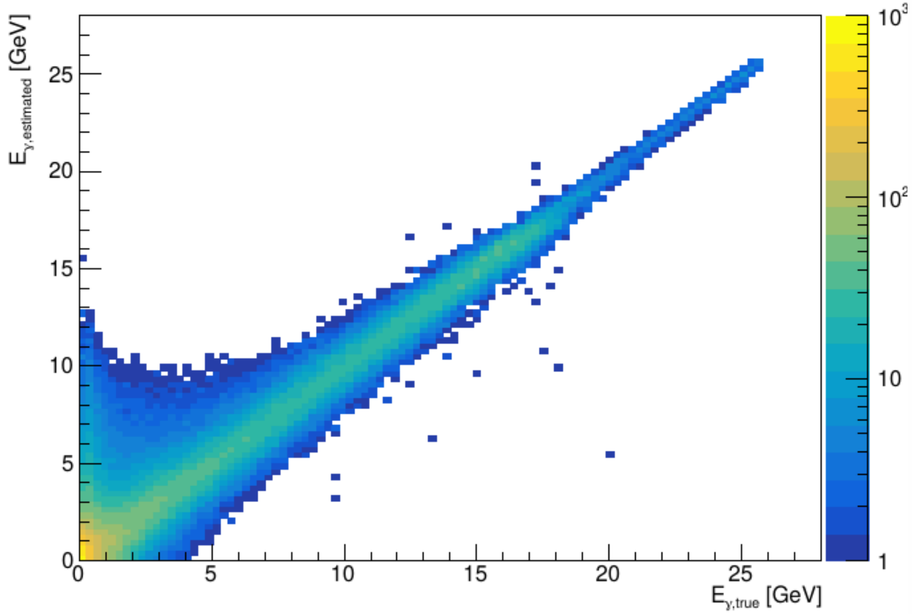
- Prior for E_γ in KF helps avoid this

ISR from Kinematic Fitting at H1

ISR Energy from KF vs True Energy



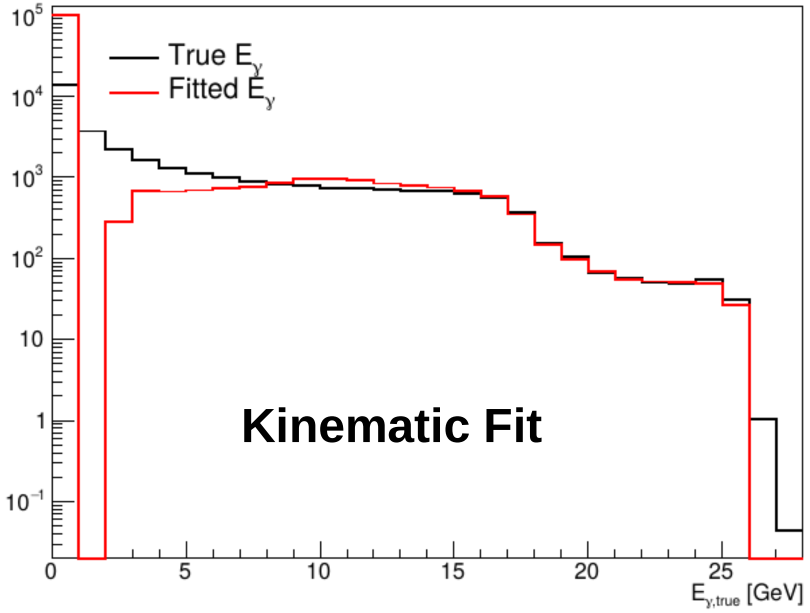
Estimate from Σ_{total} constraint vs True Energy

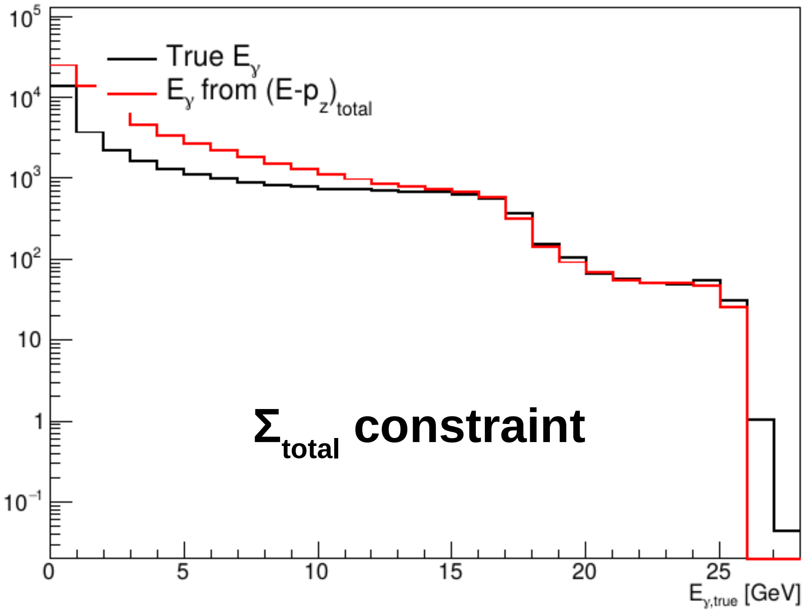


Note logarithmic z scale

- E_{γ} resolution similar for both approaches at high $E_{\gamma,true}$
- KF misses some ISR events but gives clear picture, Σ_{total} approach doesn't miss events but drastically overestimates amount ISR

ISR from Kinematic Fitting at H1

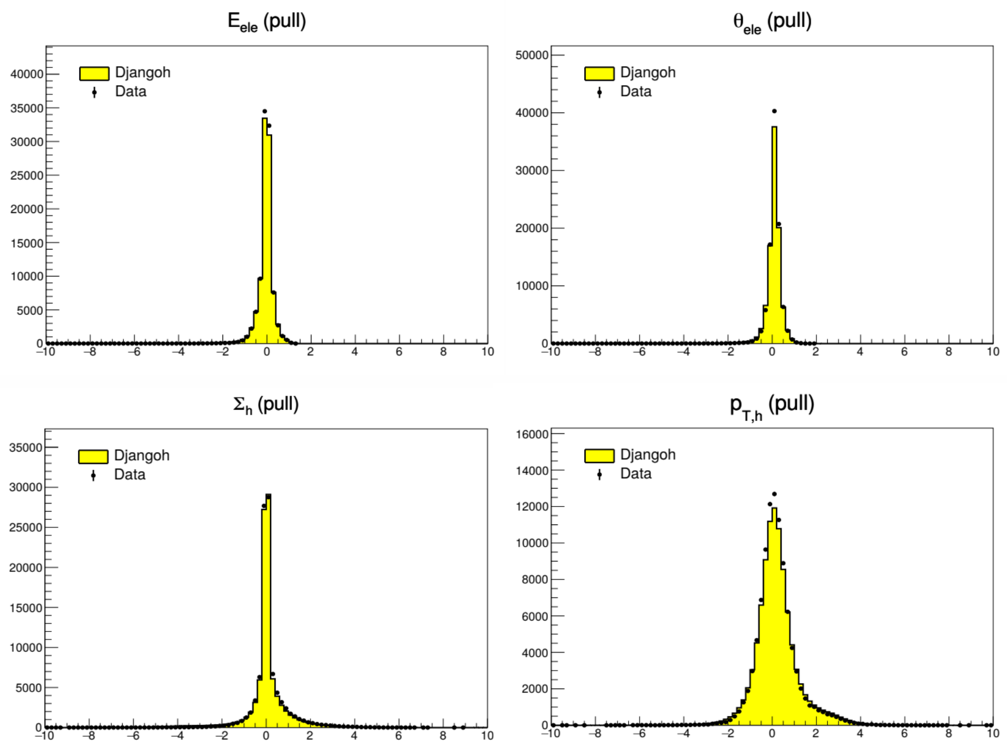




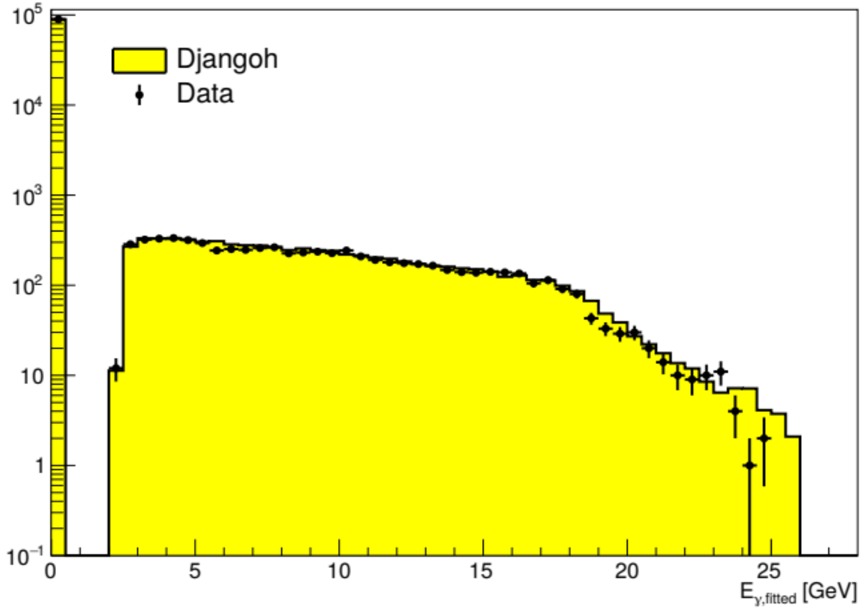
- Amount of ISR predicted by KF matches quite well for $E_{\gamma,true}$ > ~7 GeV
- Σ_{total} constraint approach overestimates until $E_{\gamma,true}$ > ~12 GeV

Some sanity checks…

- Use pulls to look for bias between data/MC
  - Pull of z defined as $(z_{fitted}-z_{reco})$ / $RMS(z_{fitted}-z_{reco})_{MC}$



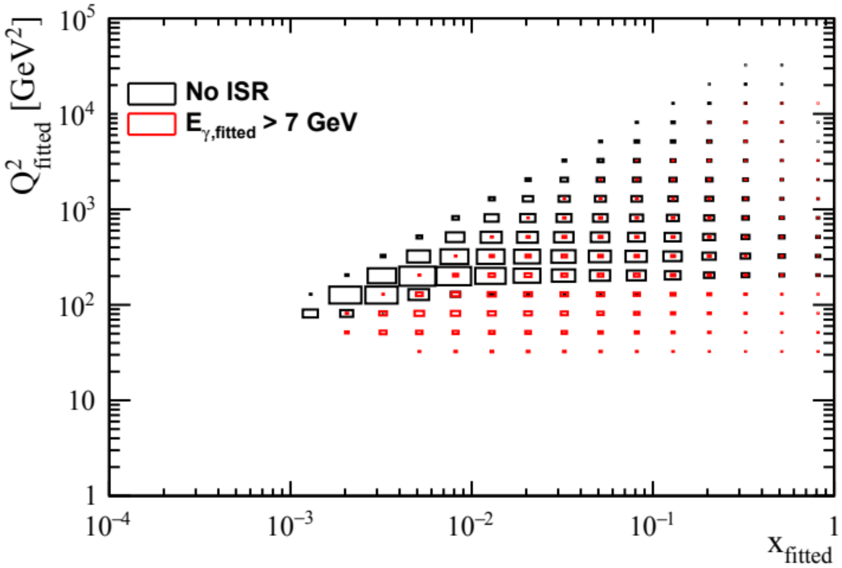
- ISR prediction by KF shows good agreement between data and MC



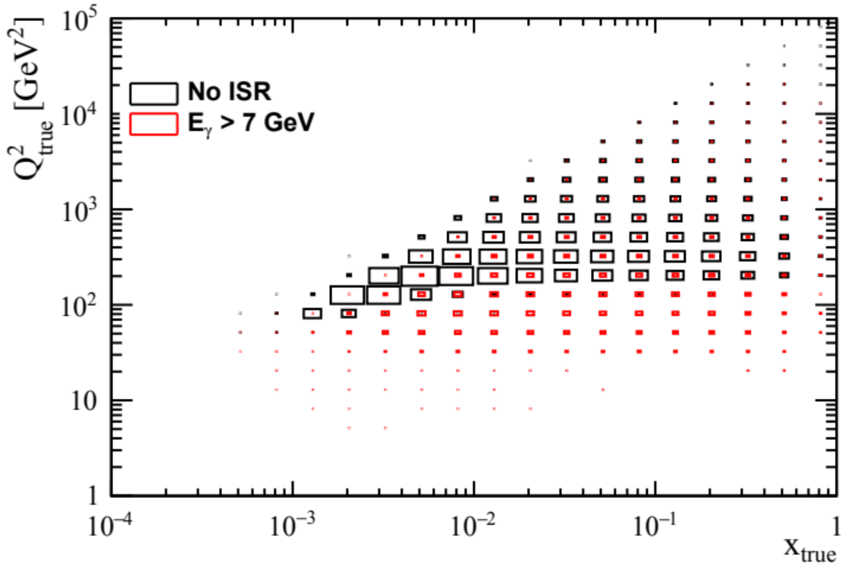
Why identify ISR?

- ISR lowers the electron beam energy
  - Scattered electrons in low Q^2 events don't enter main detector
    → lower energy electrons are scattered at larger angles that may be within the detector acceptance
    → kinematic reach extended

#events vs x_{kf}-Q^2_{kf} with data



#events vs x_{true}-Q^2_{true} with Djangoh



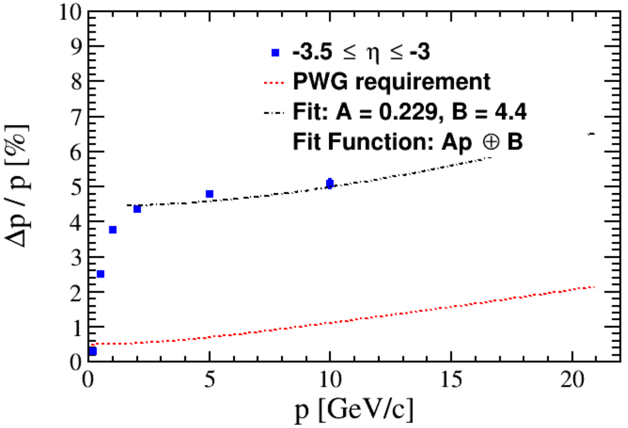
Note x-Q^2 binning here is arbitrary (not an official H1 binning)

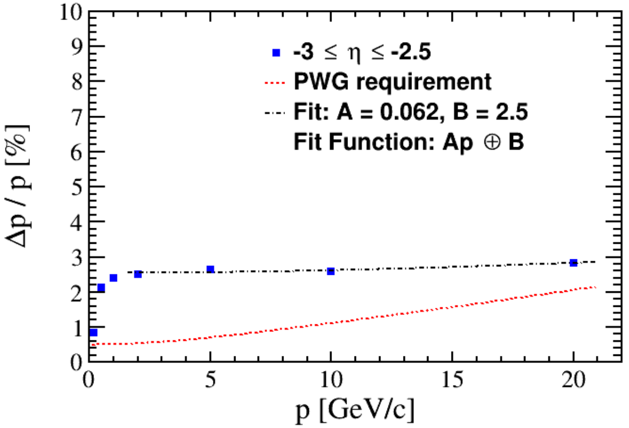
Summary – Kinematic Fitting for inclusive DIS

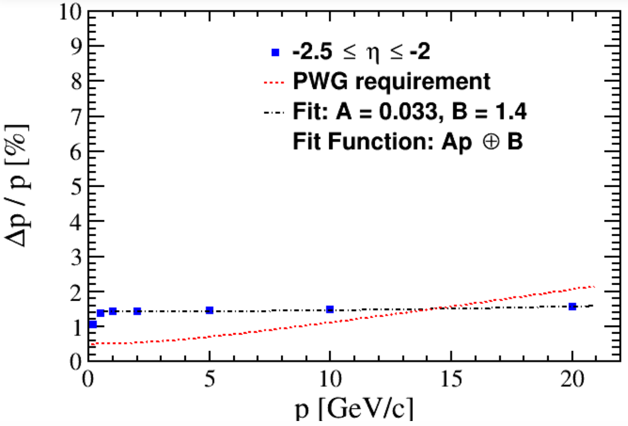
- Best possible reconstruction should be achieved by using all available information together: KF method is one way → shows good resolution with ePIC simulation
- KF helps identify ISR → offers improvement compared to approach using Σ_{total} constraint
- Keeping events with hard ISR increases kinematic reach → applications

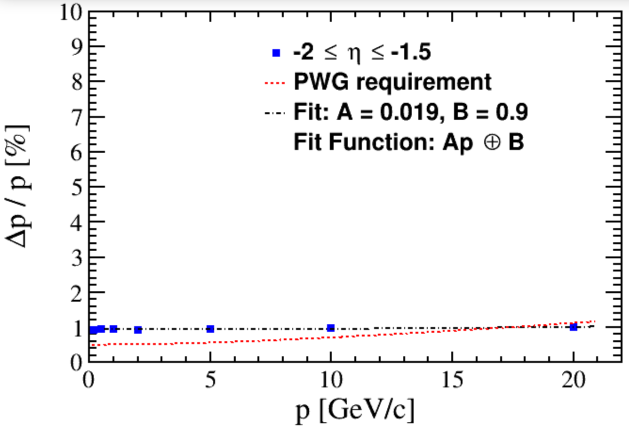
Backup

Extending to lower Q^2









- Previously restricted events to high Q^2 events with electrons scattered into barrel
  - Extended to events with Q^2>1GeV^2 → Requires parametrisation of dE/E and dθ in pseudorapidity bins

A couple of caveats:

- At low p_T an issue with truth track seeding in simulations at the time results sees dp/p improve at low p → unphysical ("fixed" in eicrecon)
- Electron "finding" as largest pT electron → bad approximation at high y