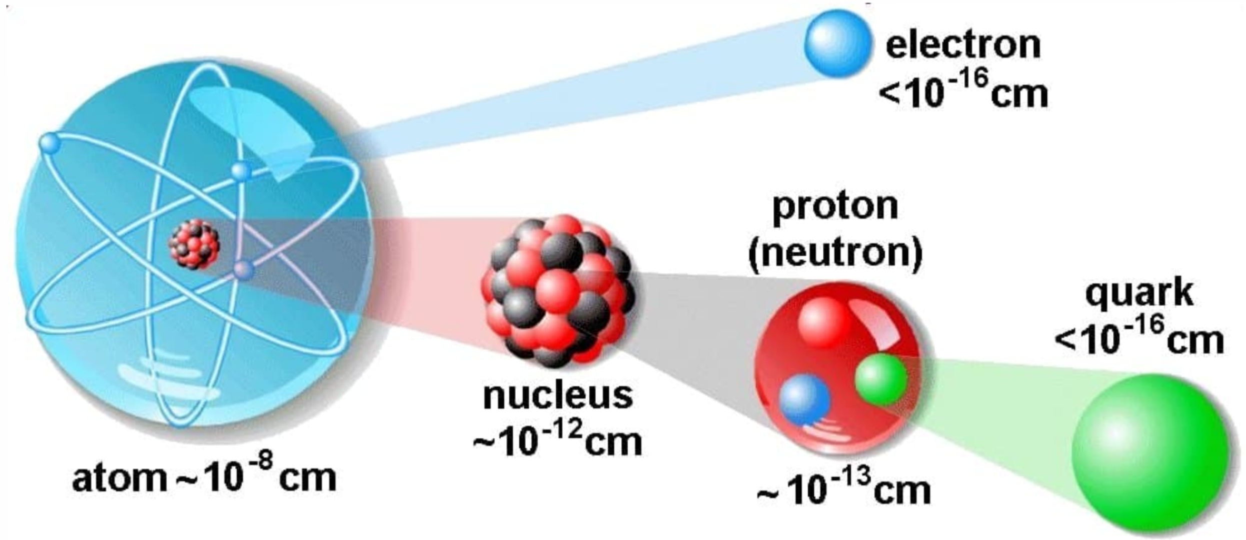
UNIVERSITY OF BIRMINGHAM | SCHOOL OF PHYSICS AND ASTRONOMY

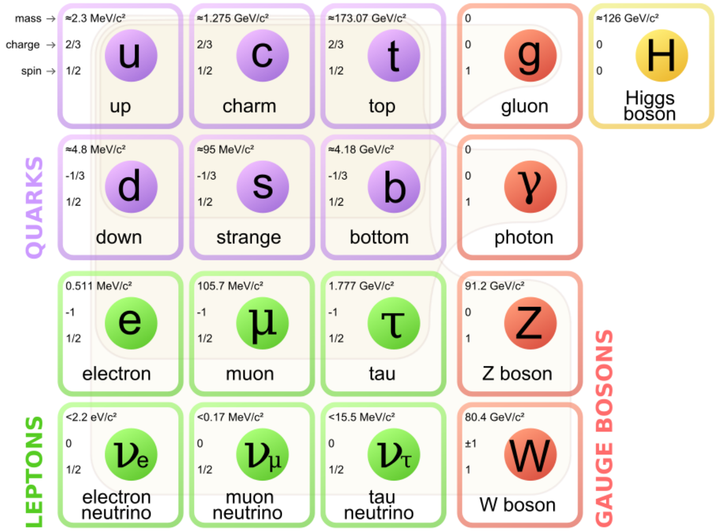
Tracking with the ePIC detector at the EIC

S. Maple

What is matter?

- Matter made up of atoms…
- Atoms are made up of protons, neutrons and electrons...
- … and protons are just 2 up quarks and a down quark?

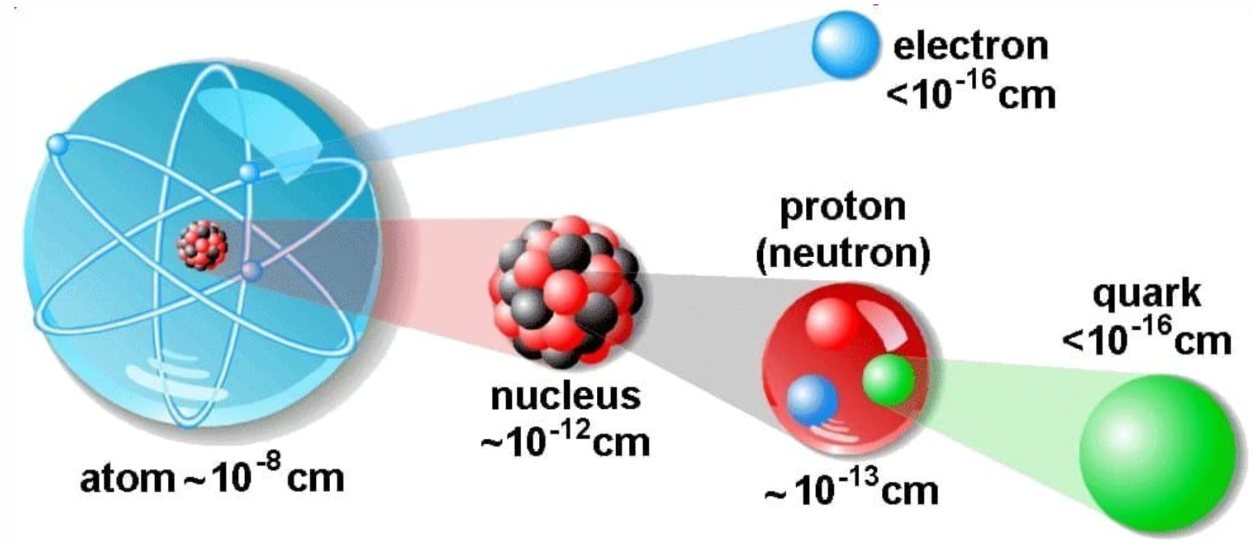


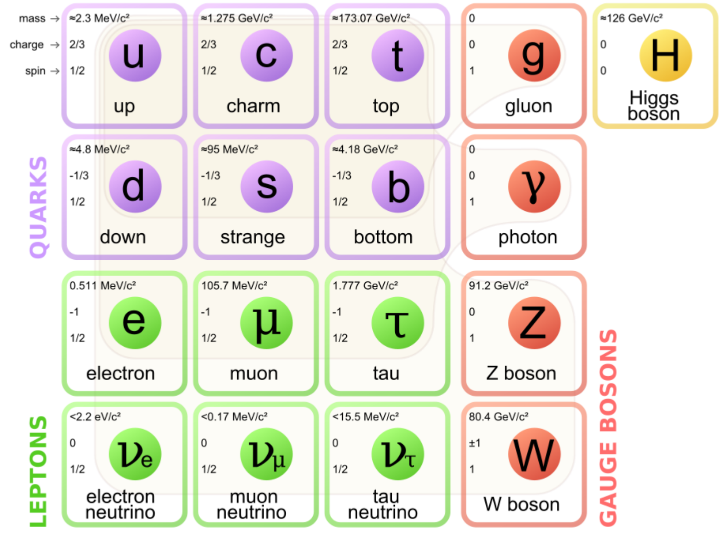


What is matter?

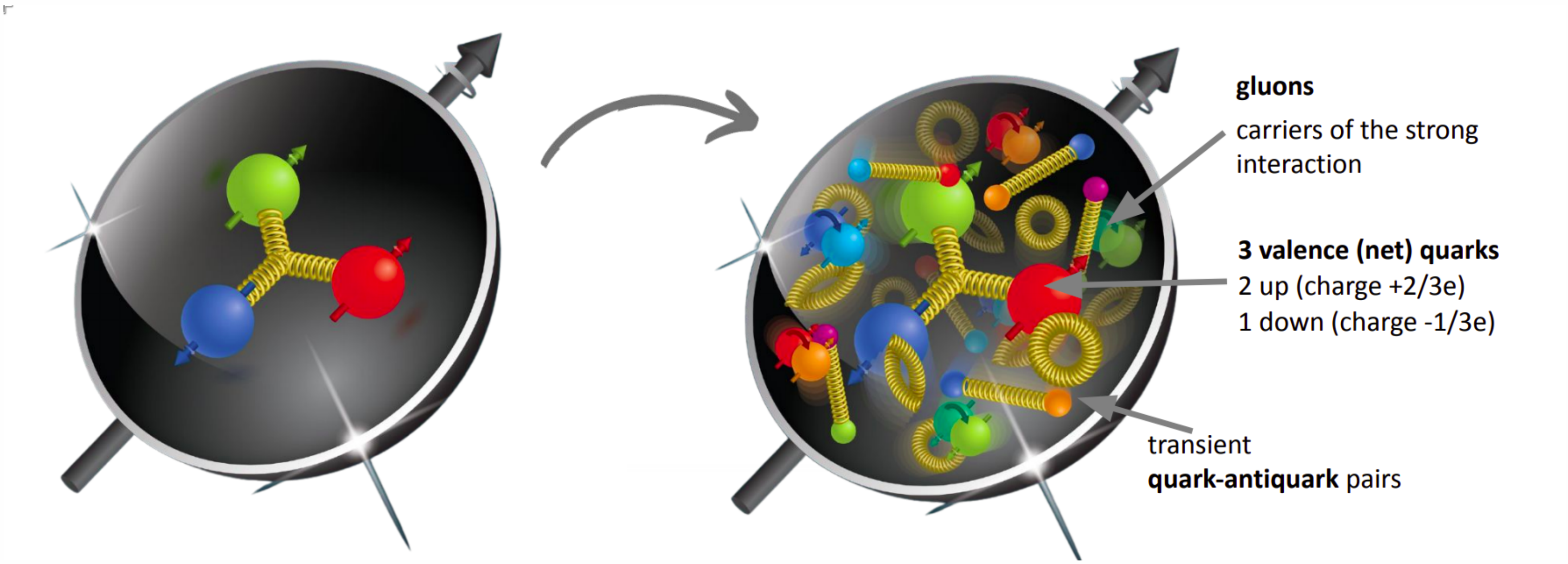
- Matter made up of atoms…
- Atoms are made up of protons, neutrons and electrons...
- … and protons are just 2 up quarks and a down quark?

- **No – they have rich structure and dynamics that are <u>partially</u> understood through years of theoretical and experimental effort!**





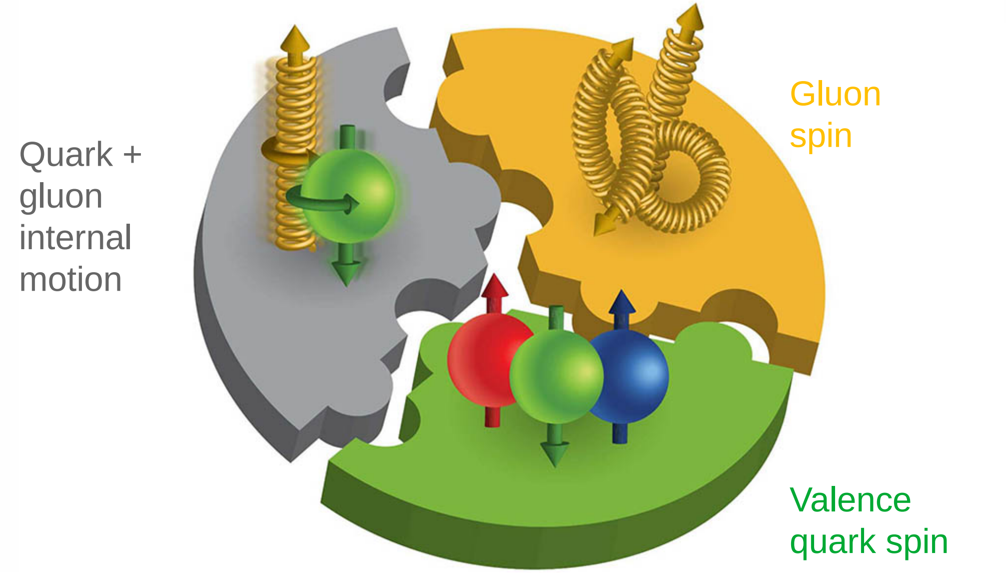
What is matter?



- The observed properties of nucleons/nuclei such as **mass** and **spin**, emerge out of a complicated system of quarks and gluons

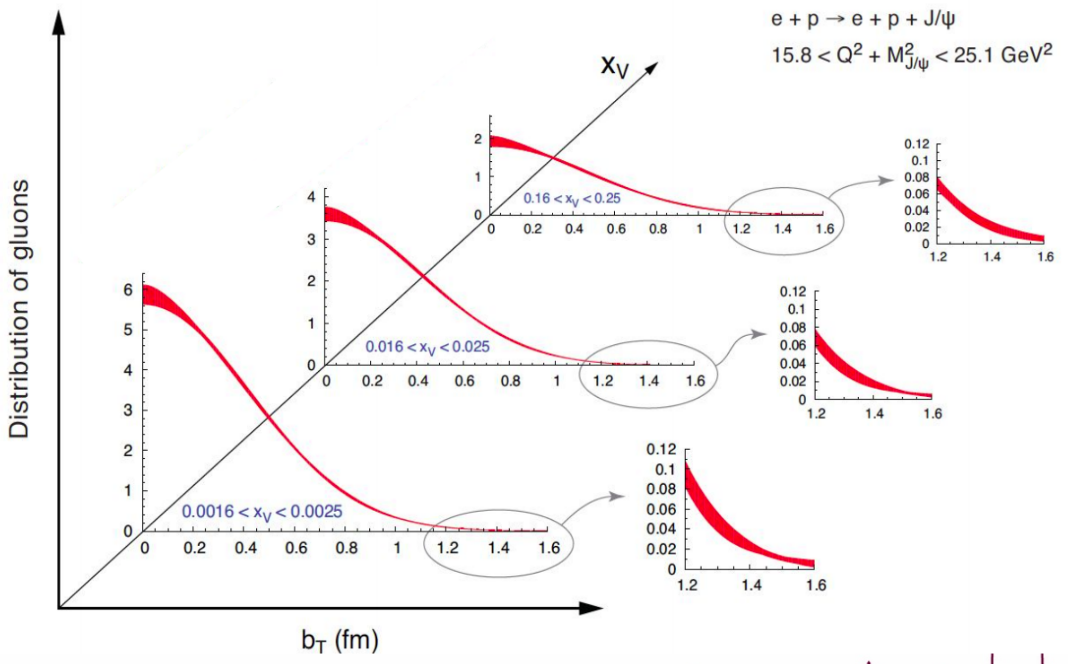
Some details are missing…

- How do the nucleonic properties such as mass and spin emerge from partons and their underlying interactions?
- How are sea quarks and gluons, and their spins, distributed in position and momentum space inside the nucleon?



$$\Delta\Sigma/2 + \Delta G + \ell_q + \ell_g = \hbar/2$$

Quark spins — Gluon spins — Quark orbital angular momentum — Gluon orbital angular momentum

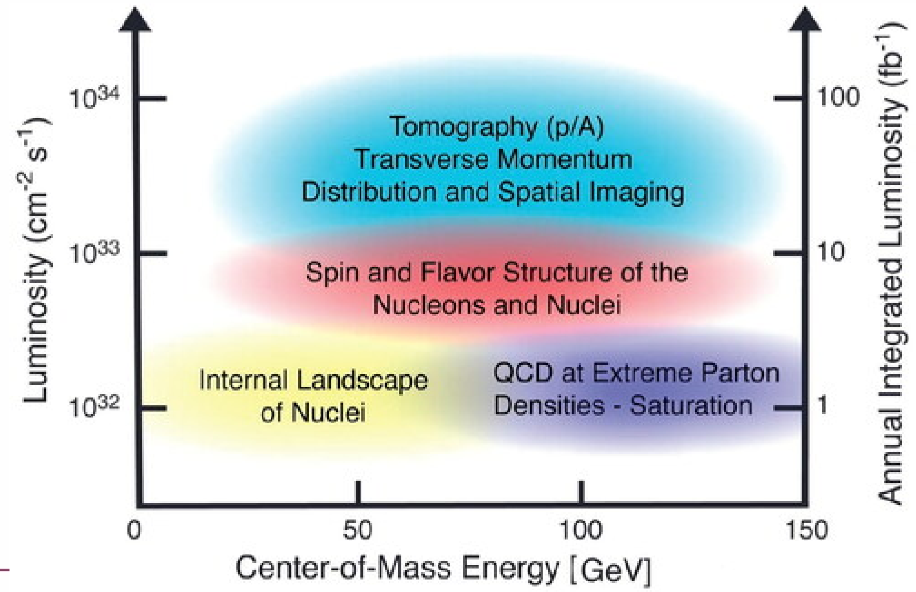


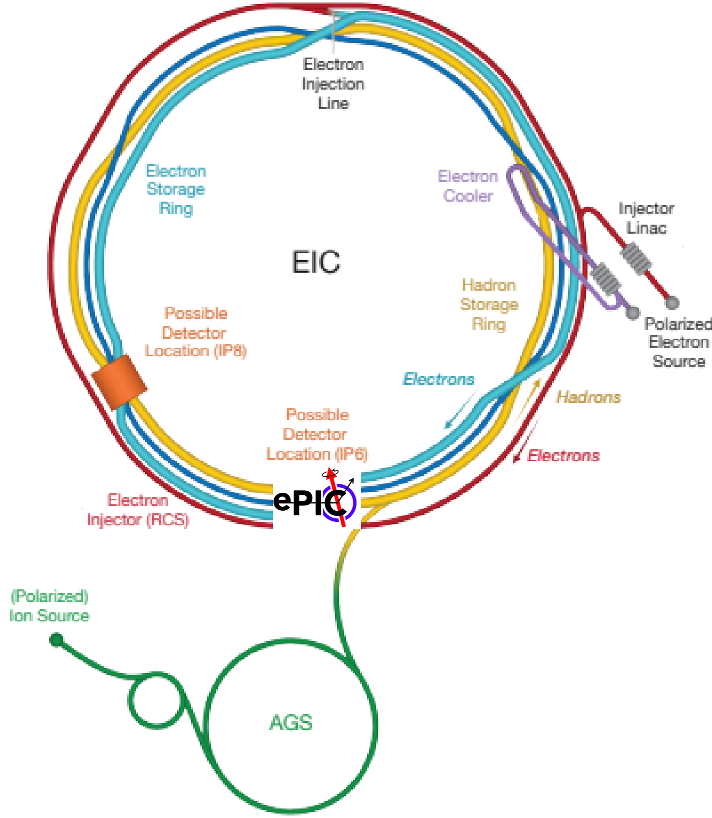
Filling in the gaps → build an EIC

Electron ring added to existing RHIC complex

- **The Electron Ion Collider (EIC) will be the world's first:**
- High luminosity ep collider: $\mathscr{L}_{max}$ = **10^{34} cm^{-2}s^{-1}**
- Polarised target collider: **~70%** (leptons and light nuclei)
- eA collider: protons/deuterons up to Uranium

and spans large c.o.m. range 28 < √s < 140 GeV for ep



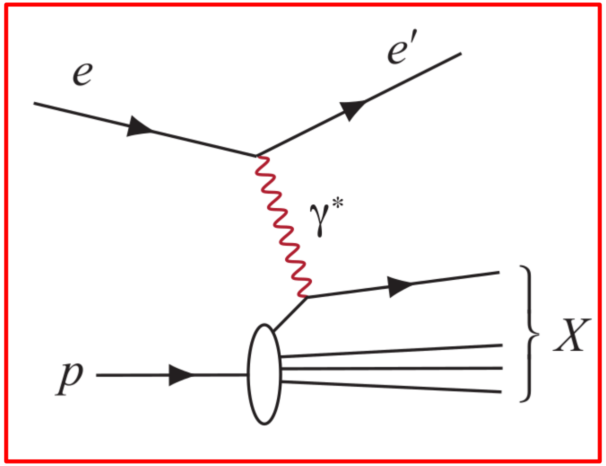


Science goals drive specifications

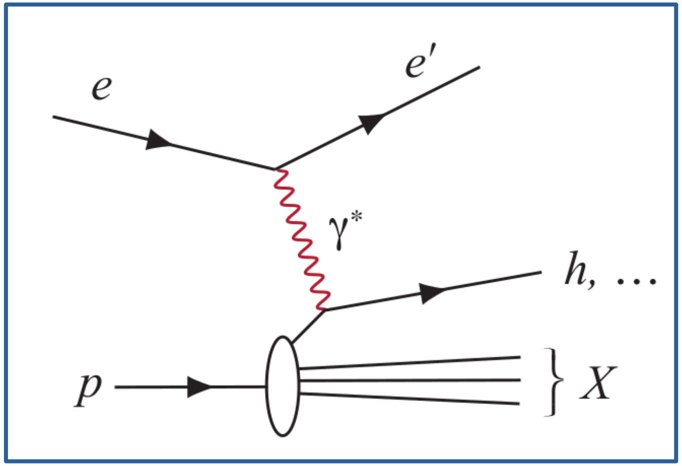
Deep Inelastic Scattering (DIS)

- **Inclusive DIS** – No constraints on hadronic final state (HFS)
  - Probes longitudinal structure of protons/nuclei
  - **Requires:** large acceptance, high quality eID, high quality reconstruction
- **Semi-Inclusive DIS** – tag 1 or more hadrons in HFS
  - Quark flavour separation, access to transverse structure
  - **Also requires:** PID, heavy flavour from vertexing
- **Exclusive/Diffractive** – all final state particles measured (proton intact)
  - 3D structure of nucleons (tomography)
  - **Requires:** proton tagging at far forward angles, high luminosity

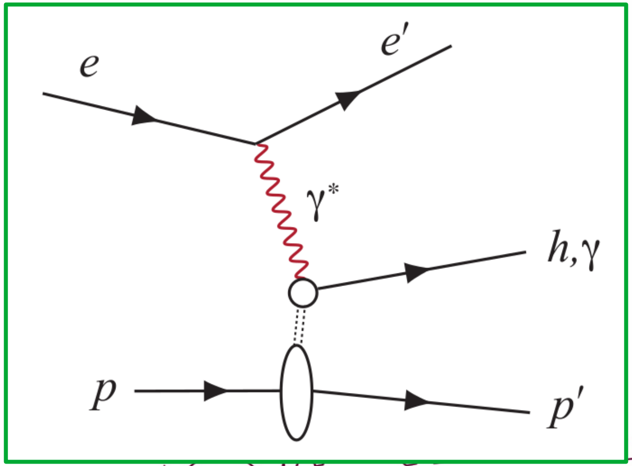
Inclusive



Semi-Inclusive

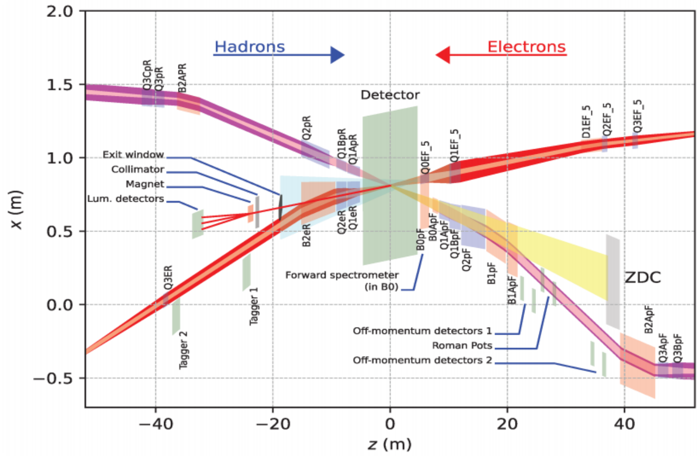


Exclusive/Diffractive



The ePIC Detector

- Asymmetric, compact central detector (|η|<4)
- Extensive beamline instrumentation
  - Roman pots, Off momentum detectors, Zero Degree Calorimeters
  - Electron tagger, luminosity monitor



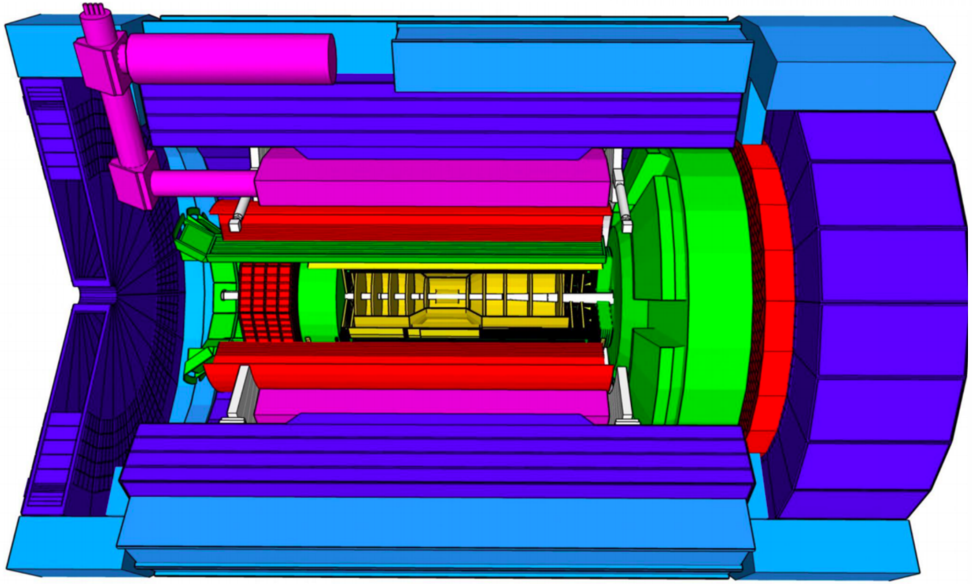
Magnet
- New 1.7 T SC solenoid, 2.8 m bore diameter

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)



Proton/Ion beam

Electron beam

Physics Derived Tracking Requirements

- High precision primary vertexing
- Secondary vertex separation
- Low material budget
- Good momentum resolution
- Low p_T tracking
- Large Acceptance
- Well Integrated

→ **Dedicated physics studies performed to set limits on resolutions (YR 2020)**

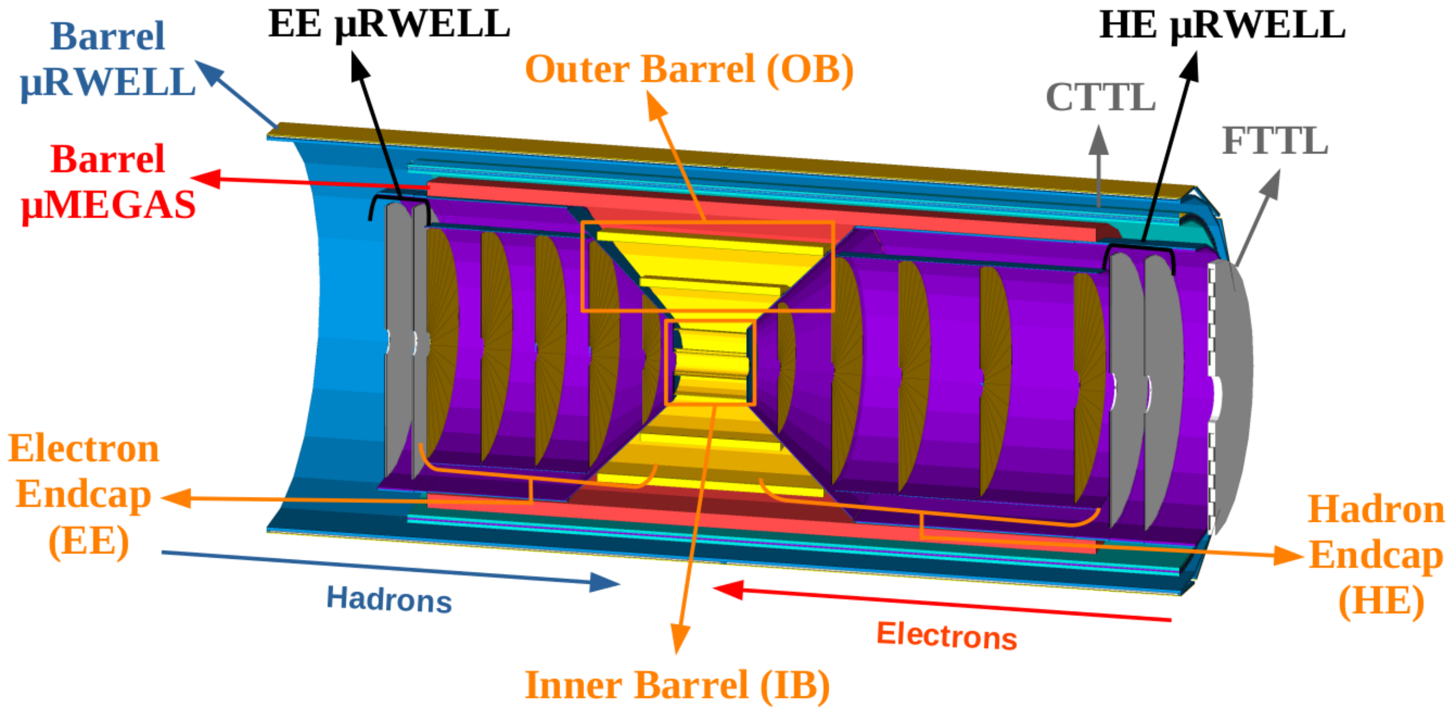
Tracking requirements from PWGs

η			Momentum res.	Material budget	Minimum pT	Transverse pointing res.
-3.5 to -3.0		Backward Detector	$\sigma p/p \sim 0.1\% \times p \oplus 0.5\%$	~5% X0 or less	100-150 MeV/c	
-3.0 to -2.5					100-150 MeV/c	$dca(xy) \sim 30/pT\ \mu m \oplus 40\ \mu m$
-2.5 to -2.0			$\sigma p/p \sim 0.05\% \times p \oplus 0.5\%$		100-150 MeV/c	$dca(xy) \sim 30/pT\ \mu m \oplus 20\ \mu m$
-2.0 to -1.5					100-150 MeV/c	
-1.5 to -1.0					100-150 MeV/c	
-1.0 to -0.5		Barrel	$\sigma p/p \sim 0.05\% \times p \oplus 0.5\%$		100-150 MeV/c	$dca(xy) \sim 20/pT\ \mu m \oplus 5\ \mu m$
-0.5 to 0	Central Detector					
0 to 0.5						
0.5 to 1.0						
1.0 to 1.5		Forward Detector	$\sigma p/p \sim 0.05\% \times p \oplus 1\%$		100-150 MeV/c	$dca(xy) \sim 30/pT\ \mu m \oplus 20\ \mu m$
1.5 to 2.0					100-150 MeV/c	
2.0 to 2.5					100-150 MeV/c	
2.5 to 3.0			$\sigma p/p \sim 0.1\% \times p \oplus 2\%$		100-150 MeV/c	$dca(xy) \sim 30/pT\ \mu m \oplus 40\ \mu m$
3.0 to 3.5					100-150 MeV/c	$dca(xy) \sim 30/pT\ \mu m \oplus 60\ \mu m$

EIC YR Table 11.2

Tracking System

- **Silicon tracker** occupies a volume of **r~43 cm** and **-105 < z < 135 cm**
- **MPGD+AC-LGAD** detectors fill remaining tracking volume: **r~80 cm** and **-120 < z < 174 cm**



SVT

3 Inner Barrel layers
- stitched wafer-scale sensors
- 0.05% X/X_0 per layer (sim)

2 Outer Barrel layers
- stitched but not wafer-scale
- 0.25% + 0.55% X/X_0 (sim)

5 Disks per side
- stitched but not wafer-scale
- 0.25% X/X_0 per disk (sim)

Silicon Sensor Technology - MAPS

- **Monolithic Active Pixel Sensors (MAPS) chosen for the Silicon Vertex Tracker (SVT)**
  - "Monolithic" – Sensor and electronic contained in same silicon substrate
  - Small pixel pitch (< 30μm) → needed for vertexing
  - Low power consumption → low mass
  - Moderate Radiation Hardness

- **ALICE ITS3 project aims at developing an extremely low mass MAPS sensor for HL-LHC**
  - Detector specifications and timeline are very compatible with the EIC

→ Sensor being developed through partnership of ITS3 and ePIC-SVT groups

Table 2.1: ITS3 general parameters.

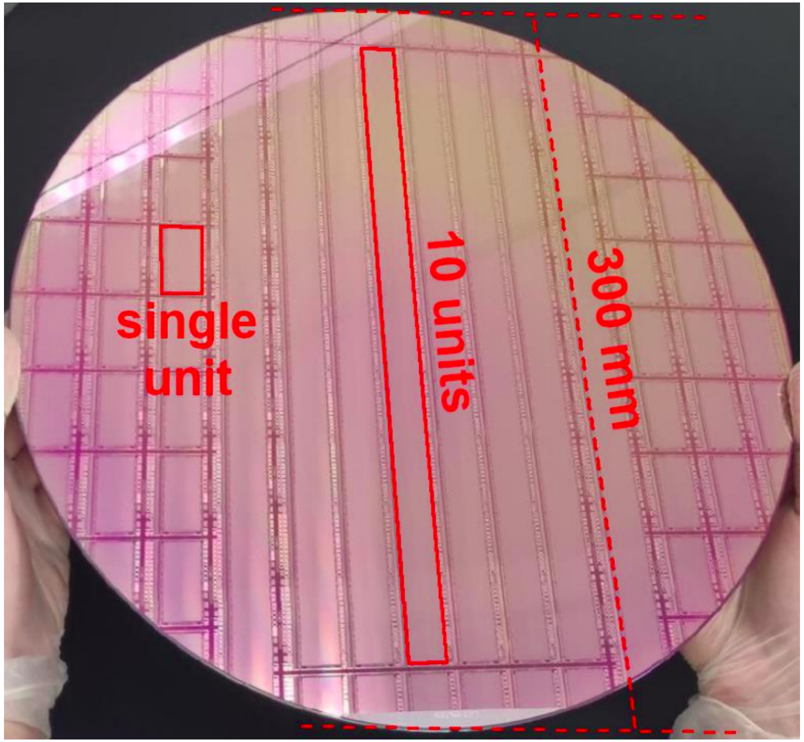
Beampipe inner/outer radius (mm)		16.0/16.5	
IB Layer parameters	Layer 0	Layer 1	Layer 2
Radial position (mm)	19.0	25.2	31.5
Length (sensitive area) (mm)	260	260	260
Pseudo-rapidity coverage[a]	±2.5	±2.3	±2.0
Active area (cm^2)	305	407	507
Pixel sensors dimensions (mm^2)	266×58.7	266×78.3	266×97.8
Number of pixel sensors / layer		2	
Material budget ($\%X_0$ / layer)		0.07	
Silicon thickness (μm / layer)		≤ 50	
Pixel size (μm^2)		$O(20 \times 22.5)$	
Power density (mW/cm^2)		40	
NIEL (1 MeV n_{eq} cm^{-2})		10^{13}	
TID (kGray)		10	

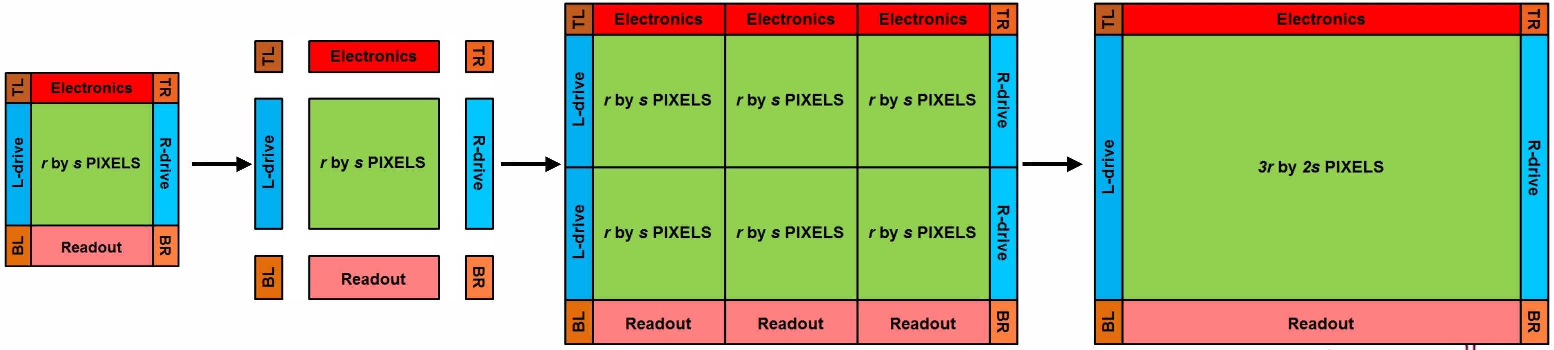
[a] The pseudorapidity coverage of the detector layers refers to tracks originating from a collision at the nominal interaction point ($z = 0$).

Stitched MAPS

- **Normal fabrication** – light shone through mask with size ~3x3cm (reticle) to pattern circuits on wafer
  - **Limited to size of mask**

- In **"stitching"** the mask is subdivided and different sections are repeated across the wafer
  - **Can achieve devices larger than the mask → up to wafer-scale**
  - Only need connections at extreme ends





Silicon Tracker Barrel

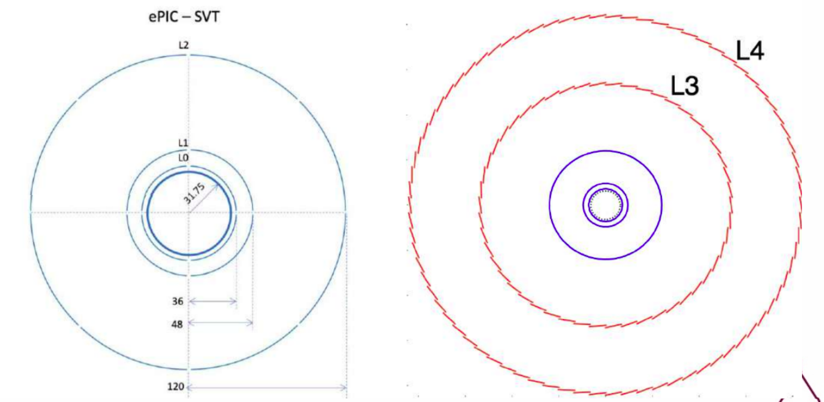
Layer	Radius (mm)	Length (mm)	Sensors
L0	36	270	4
L1	48	270	4
L2	120	270	8

Layer	Radius (mm)	Length (mm)	X/X0%
L3	270	540	0.25
L4	420	840	0.55

- **Barrel uses stitched MAPS**
  - 65nm CMOS imaging process
  - Low power
  - High precision ~20μm pitch

- **Inner Barrel**
  - Directly use ITS3 wafer-scale sensor

- **Outer Barrel**
  - “Traditional” stave design
  - Use **EIC Large Area Sensor (EIC-LAS)**
    → Stitched but not wafer-scale modification of ITS3 sensor

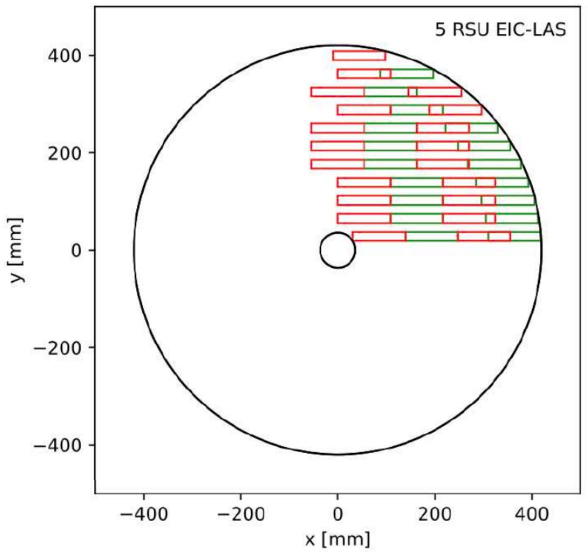


Silicon Tracker Disks

Disk	Technology	z (mm)	r_{in} (mm)	r_{out} (mm)
ED0	MAPS	-250	36.76	230
ED1	MAPS	-450	36.76	430
ED2	MAPS	-650	36.76	430
ED3	MAPS	-850	40.06	430
ED4	MAPS	-1050	46.35	430
Bwd MPGD 1	μRWELL	-1100	46.53	500
Bwd MPGD 2	μRWELL	-1200	46.35	500

Disk	Technology	z (mm)	r_{in} (mm)	r_{out} (mm)
HD0	MAPS	250	36.76	230
HD1	MAPS	450	36.76	430
HD2	MAPS	700	38.42	430
HD3	MAPS	1000	54.43	430
HD4	MAPS	1350	70.14	430
Fwd MPGD 1	μRWELL	1480	70.14	500
Fwd MPGD 2	μRWELL	1610	70.14	500
FTTL	AC-LGAD	1740	80.00	500

- **Disks uses stitched MAPS**
  - 65nm CMOS imaging process
  - Low power
  - High precision ~20μm pitch
- **Tiled EIC-LAS**
  - Front and back of disk

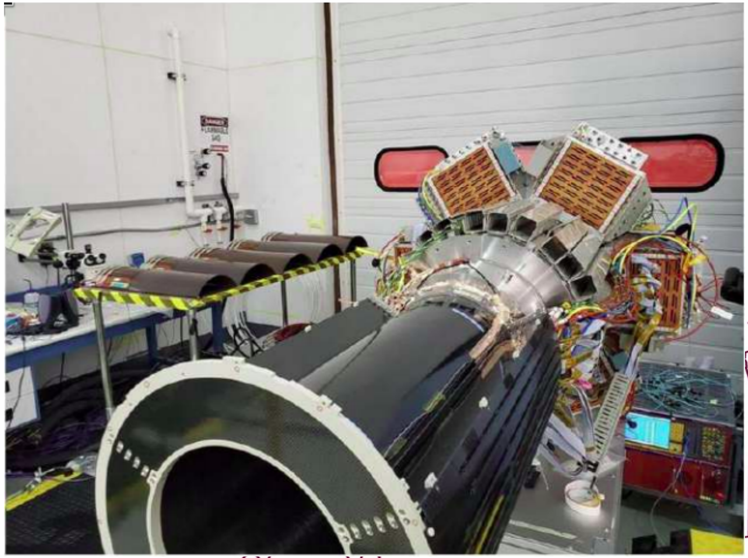


Gaseous Tracker Technology - MPGDs

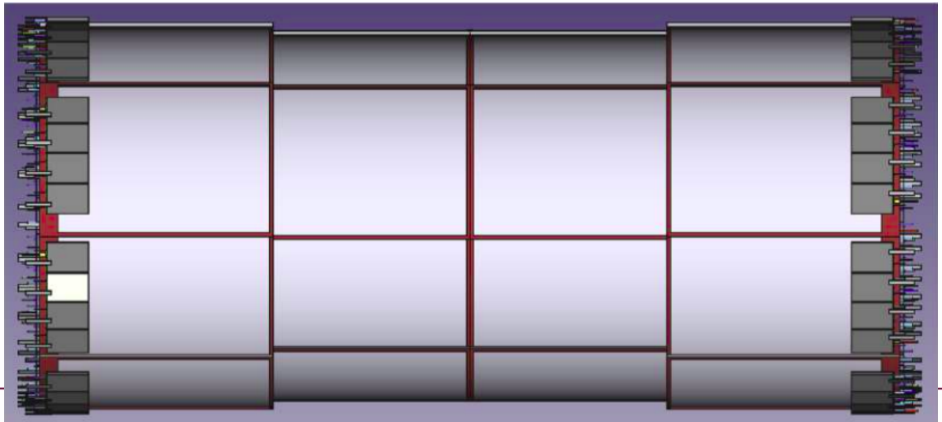
- **Two types of MPGD used: µRWELL and Micromegas**

- **Barrel Micromegas: CyMBaL**
  - Cylindrical Micromegas technology developed for CLAS12 BMT
  - Material ~0.5% X/X_0 in active areas
  - Spatial resolution ~150µm
  - Timing resolution ~10ns

CLAS12 BMT



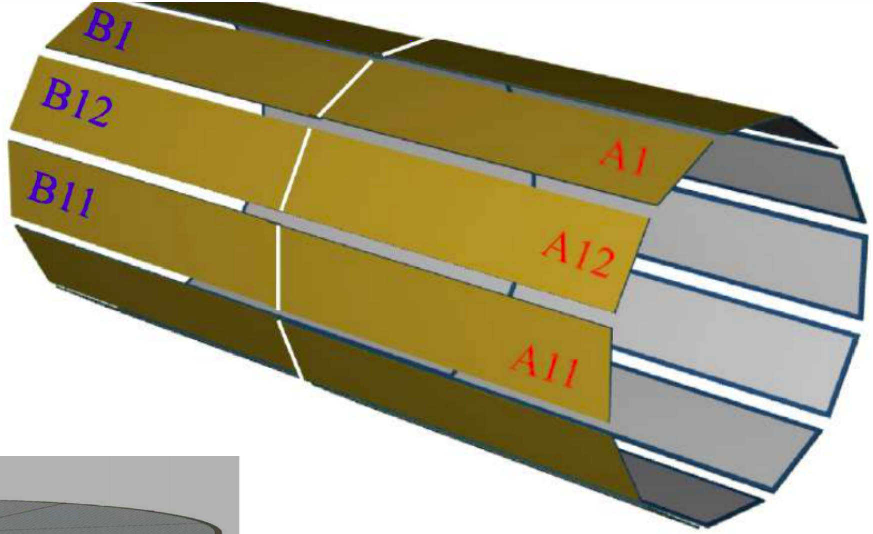
CyMBaL



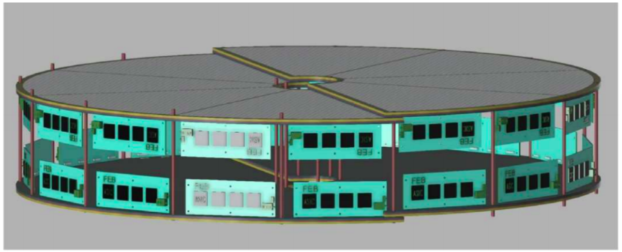
Gaseous Tracker Technology - MPGDs

- **Two types of MPGD used: µRWELL and Micromegas**

- **Barrel µRWELL: µRWELL-BOT (Barrel Outer Tracker)**
  - Provides seed point for DIRC
  - Material <2% X/X_0 in active area
  - Spatial Resolution ~150µm
  - Timing resolution ~10ns



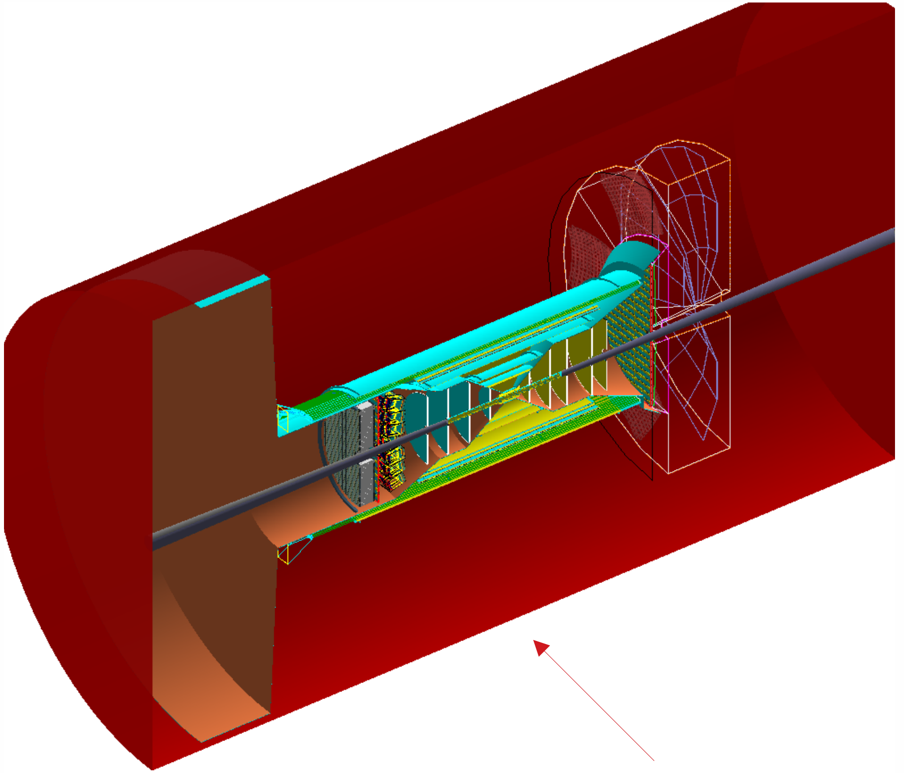
- **Endcap µRWELLs: µRWELL-ECT**
  - Comparable to above



A brief history…

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

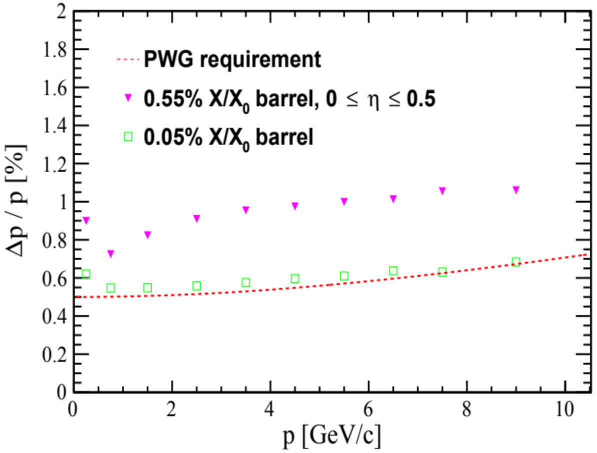
Talks describing this geometry in more detail can be found here https://indico.bnl.gov/event/15489/

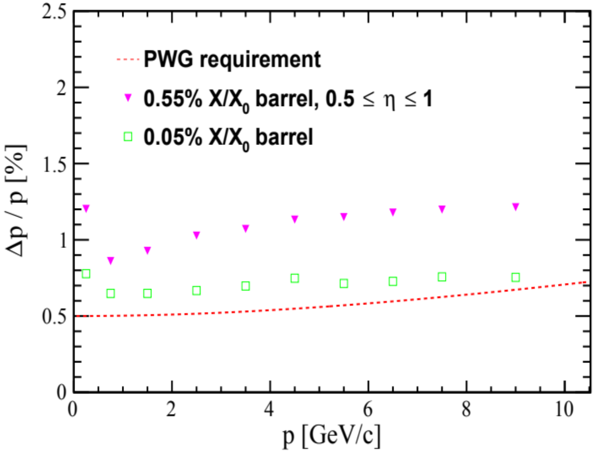
Proposal Silicon Vertex Tracker

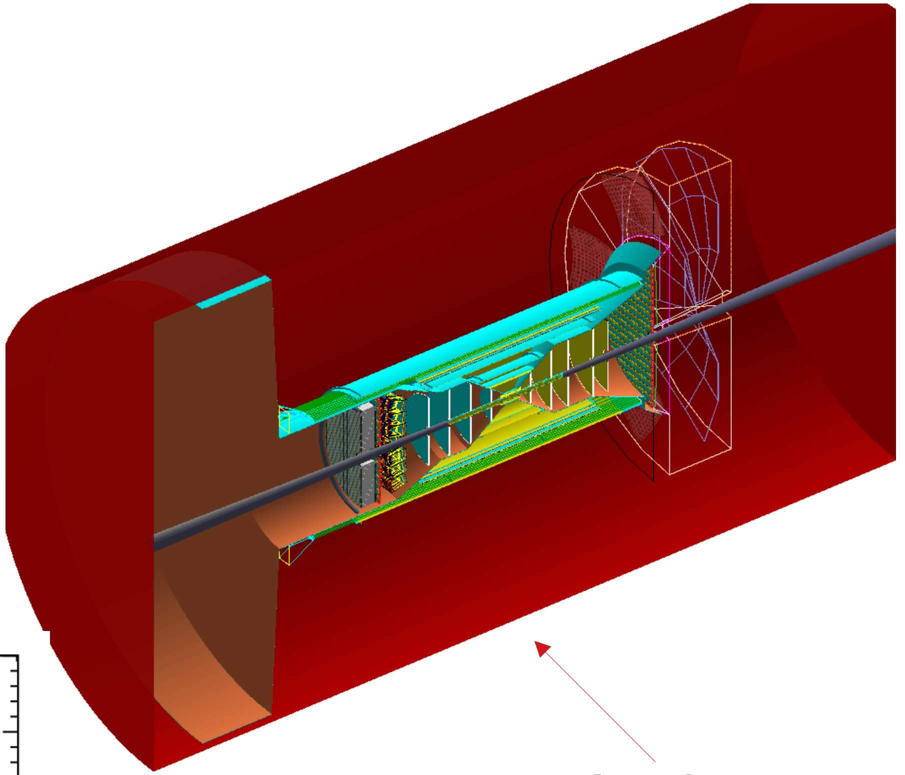
→ **Update outer barrel material estimate to include support and services**

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

→ **Reconfigure barrel layout**





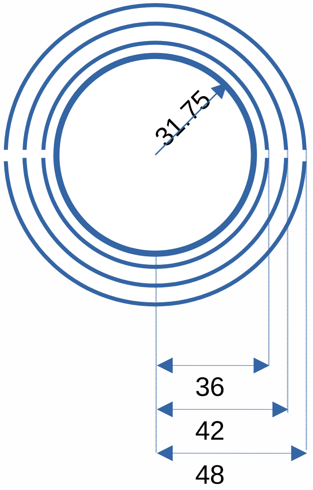


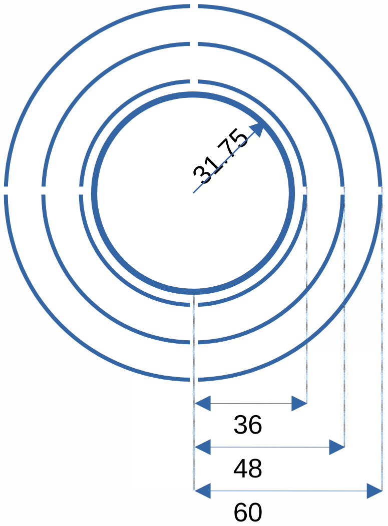
Tracker from Reference Detector

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

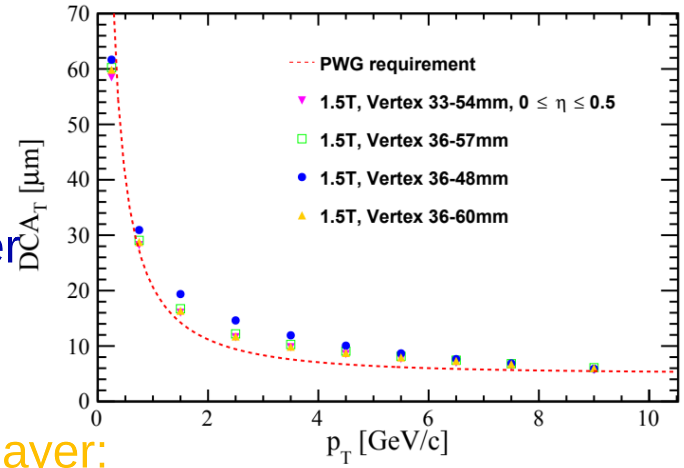


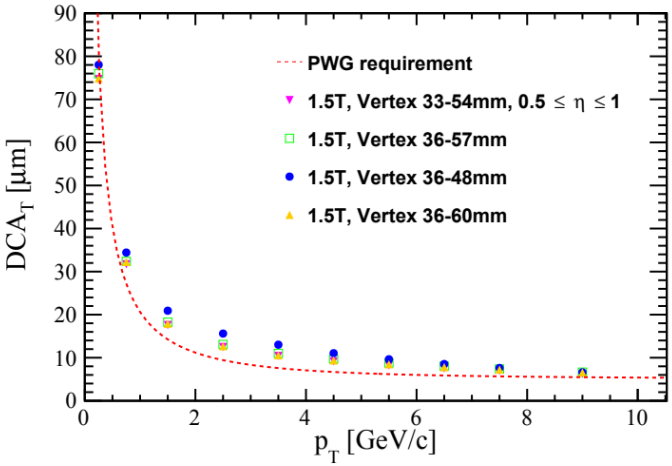


- Alternatively opt for 4 sensors per layer
  - r = 36/48/60 mm

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



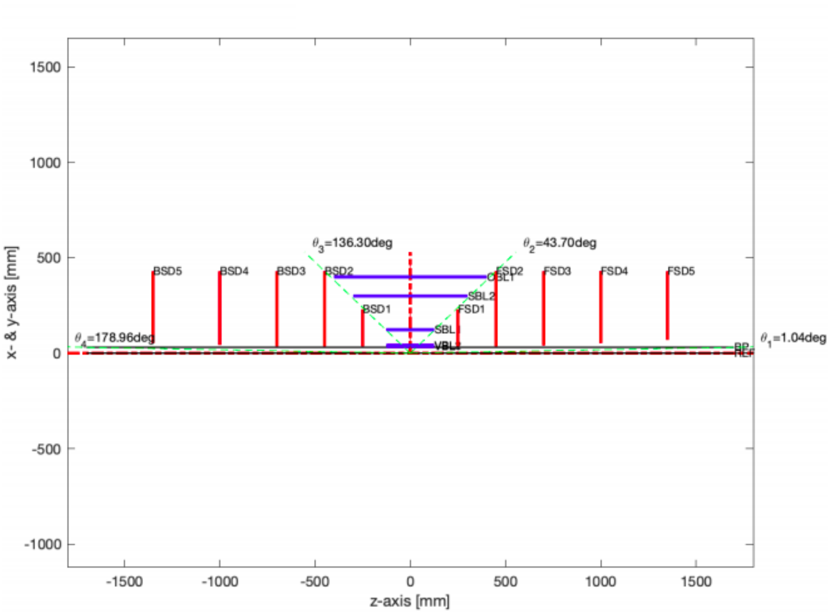


Some difference in DCA_T
→ **depends distance between r_1 and r_2**
→ **$(r_2 – r_1)$ is an important parameter**

- 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 ~ 0.25%
- Outer (third) vertex barrel layer with increased radius to r = 120 mm while preserving its length,

Notes:

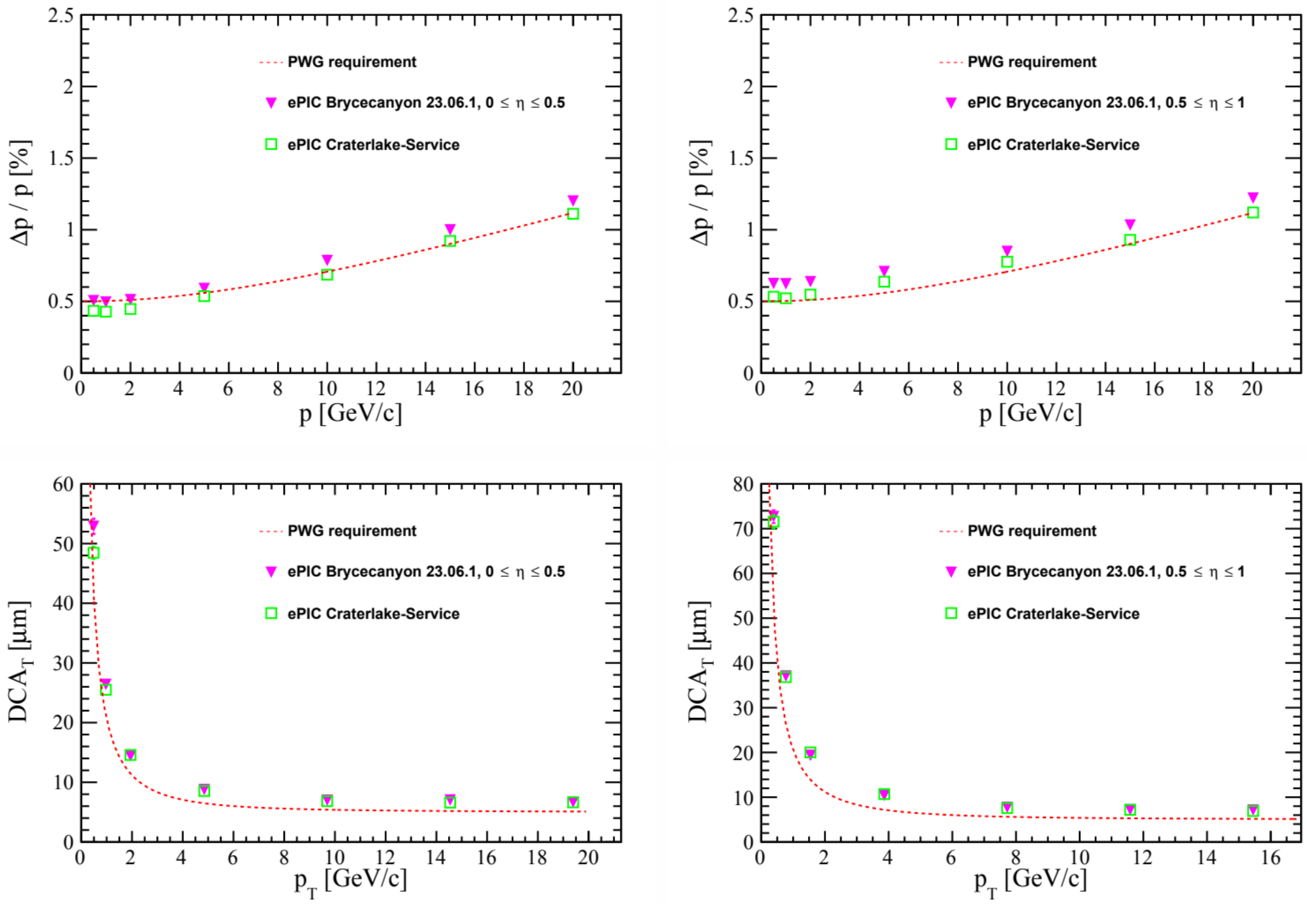
The lengths assume reticle lengths of 30 mm.

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



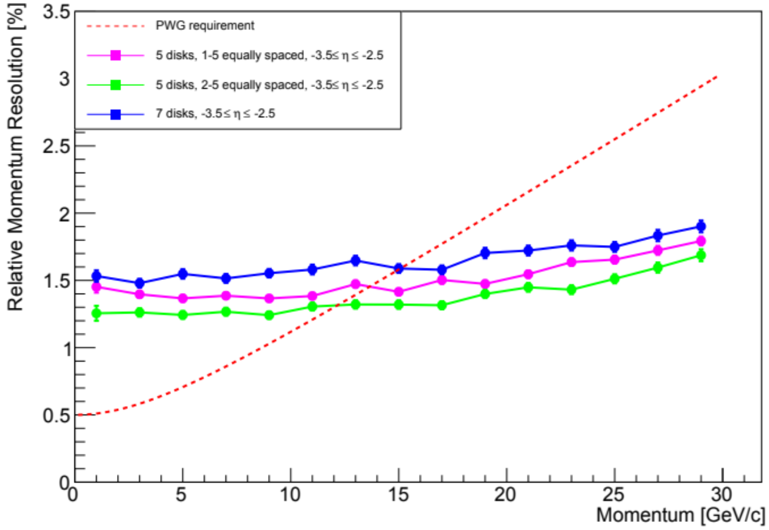
BARREL	r [mm]	l [mm]	X/X0 %
L0	36	270	0.05
L1	48	270	0.05
L2	**120**	270	**0.05**
L3	**270**	540	**0.25**
L4	**420**	840	0.55
Cyl.Micromegas layer	550	2300	0.5
AC-LGAD layer	640	2400	1.0
μRWELL behind DIRC	**730**	3420	~1.0%

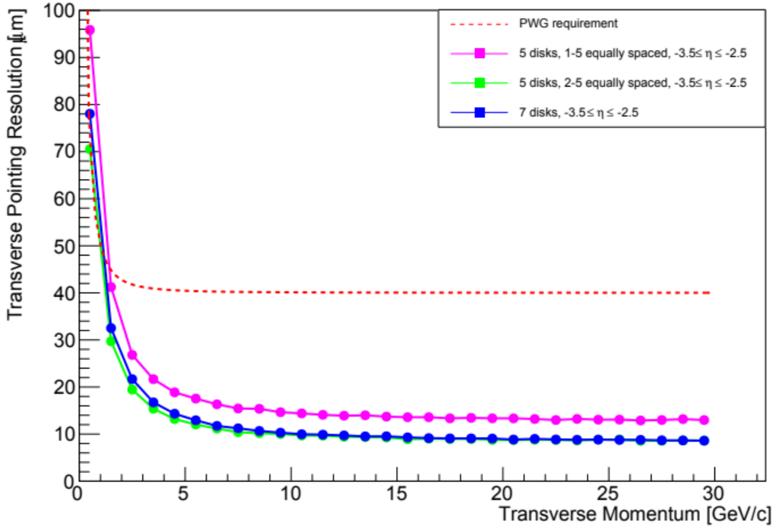
Barrel performance recovered!

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)

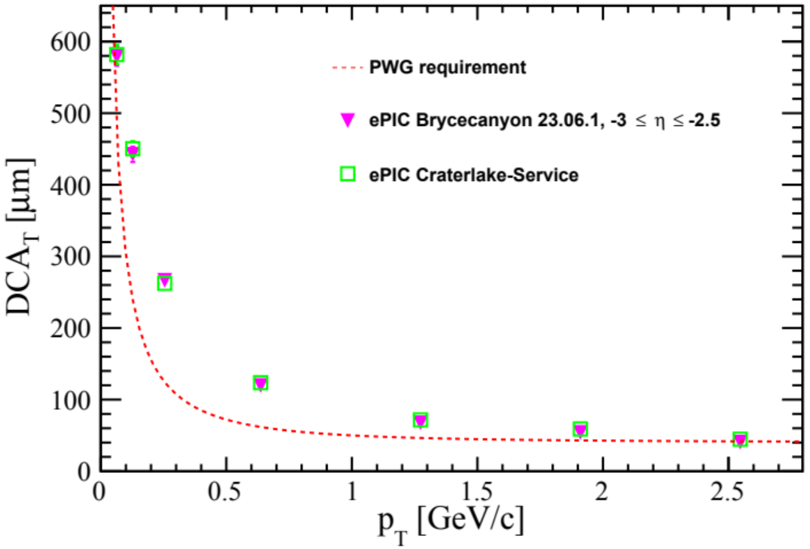


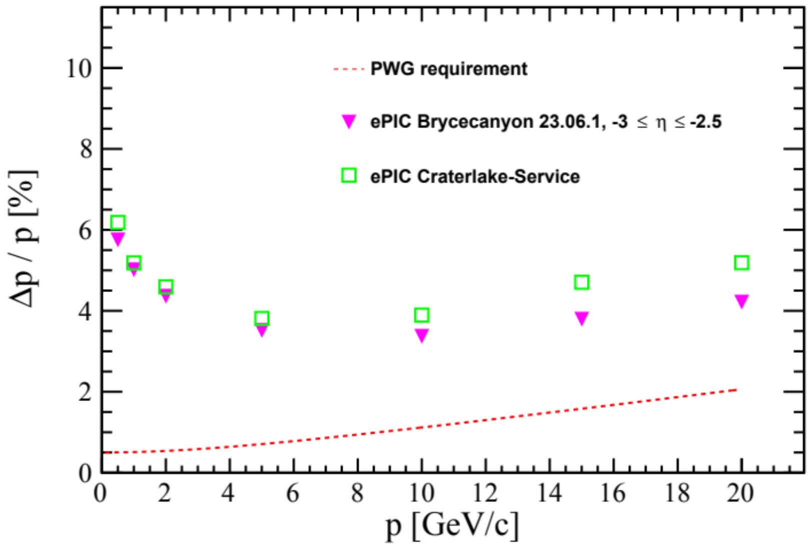


Craterlake Disks Performance

- **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





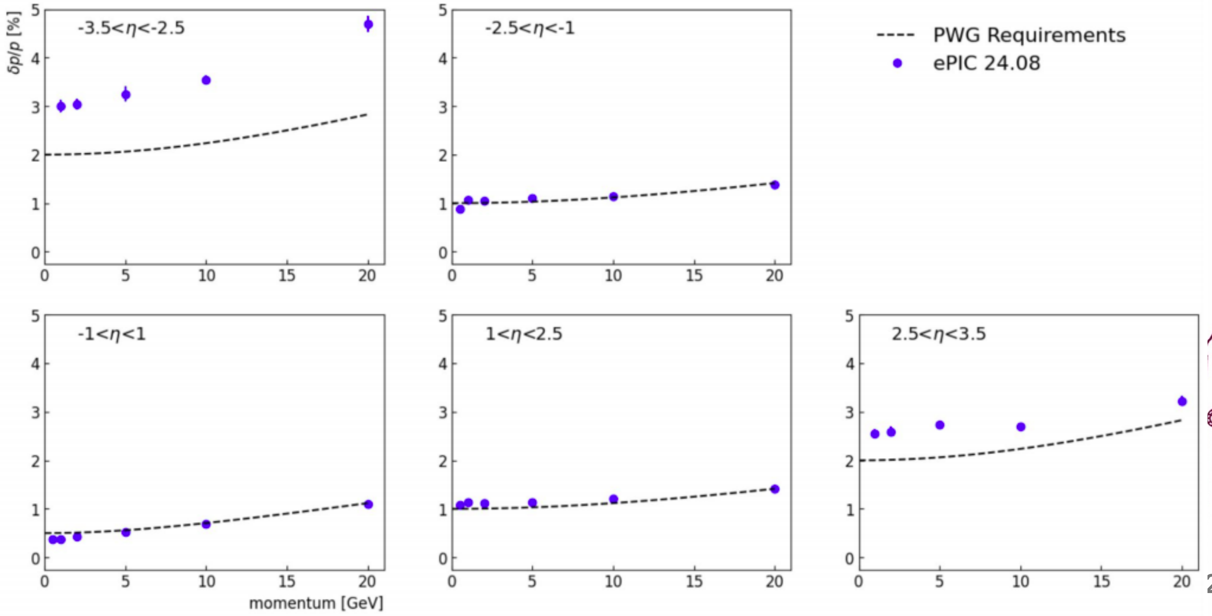
Now the current version

Tracking Performance – Momentum Resolution

- Requirements on relative momentum resolution **met in central and most of forward region**
- Backward requirement **still challenging to meet**
  - High resolution electromagnetic calorimetry in this region → may provide better reconstruction

Requirement

η			Momentum res.
-3.5 to -3.0	Central Detector	Backward Detector	σp/p ~ 0.1%×p ⊕ 2%
-3.0 to -2.5			
-2.5 to -2.0			σp/p ~ 0.05%×p ⊕ 1%
-2.0 to -1.5			
-1.5 to -1.0			
-1.0 to -0.5		Barrel	σp/p ~ 0.05%×p ⊕ 0.5%
-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%
1.5 to 2.0			
2.0 to 2.5			
2.5 to 3.0			σp/p ~ 0.1%×p ⊕ 2%
3.0 to 3.5			

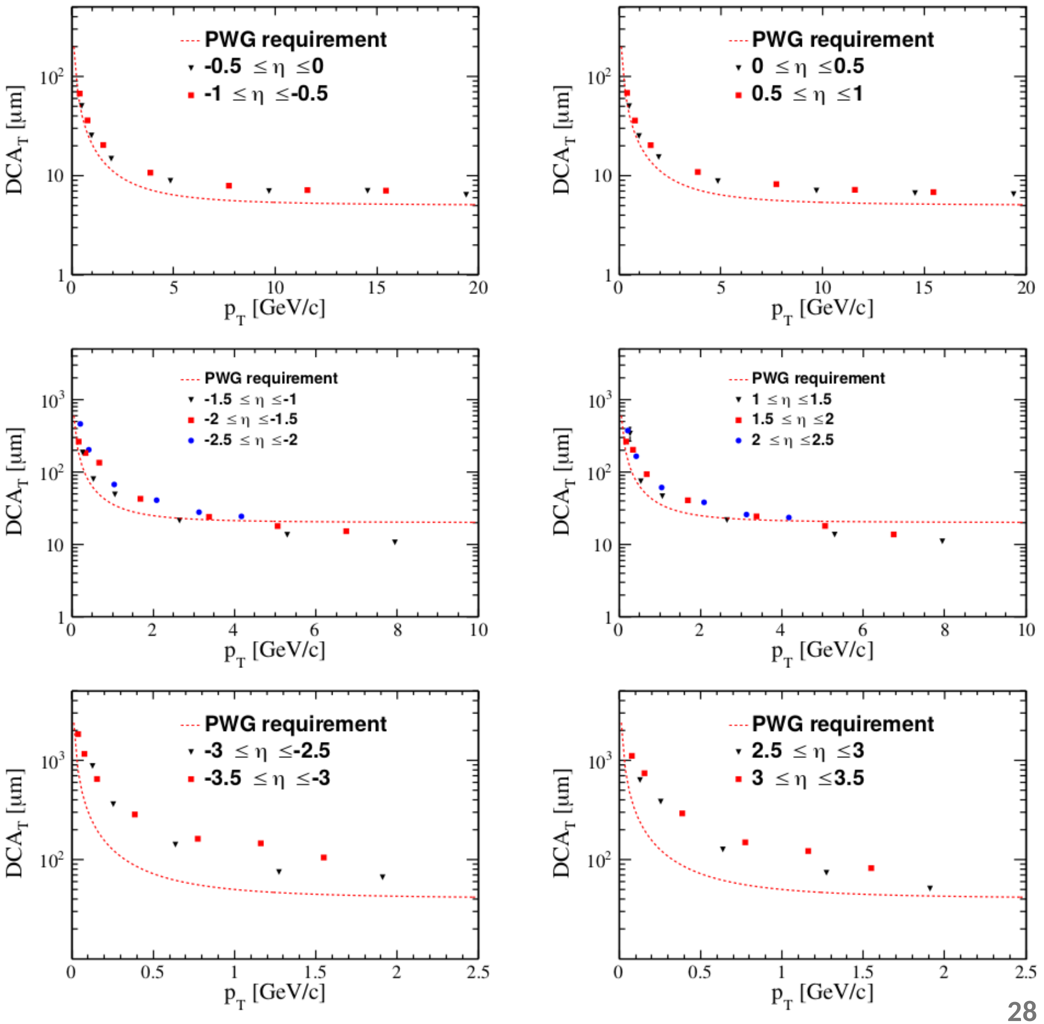


Tracking Performance – Transverse Pointing Resolution

- Performance consistent with requirement line for all but largest pseudorapidities
  - Next step for ePIC → Understand how this impacts the physics

Requirement

η			Transverse pointing res.
-3.5 to -3.0	Central Detector	Backward Detector	
-3.0 to -2.5			dca(xy) ~ 30/pT μm ⊕ 40 μm
-2.5 to -2.0			dca(xy) ~ 30/pT μm ⊕ 20 μm
-2.0 to -1.5			
-1.5 to -1.0			
-1.0 to -0.5		Barrel	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	dca(xy) ~ 30/pT μm ⊕ 20 μm
1.5 to 2.0			
2.0 to 2.5			
2.5 to 3.0			dca(xy) ~ 30/pT μm ⊕ 40 μm
3.0 to 3.5			dca(xy) ~ 30/pT μm ⊕ 60 μm



Particle Rates

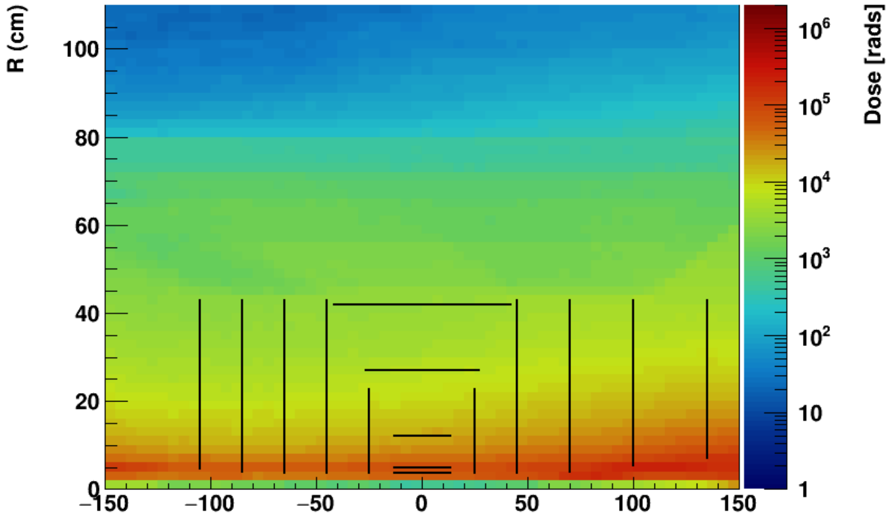
- EIC bunch crossing frequency: **98.5 MHz (roughly every 10ns)**

- Interaction frequency is orders of magnitude lower:
  - **Physics (DIS) events up to 500 kHz**
  - Also background processes: **interactions of beams with residual gas** in the beampipe
    → Vacuum improves with run time, **beam-gas** rate decreases
  - **Synchrotron radiation** reduced by 5μm gold coating applied to beampipe

Rate (kHz)	5×41	5×100	10×100	10×275	18×275	Vacuum
DIS ep	12.5	129	184	500	83	-
p beam-gas	12.2	22.0	31.9	32.6	22.5	10 000 A h
p beam-gas	131.1	236.4	342.8	350.3	241.8	100 A h
e beam-gas	2181.97	2826.38	3177.25	3177.25	316.94	10 000 A h

Radiation levels

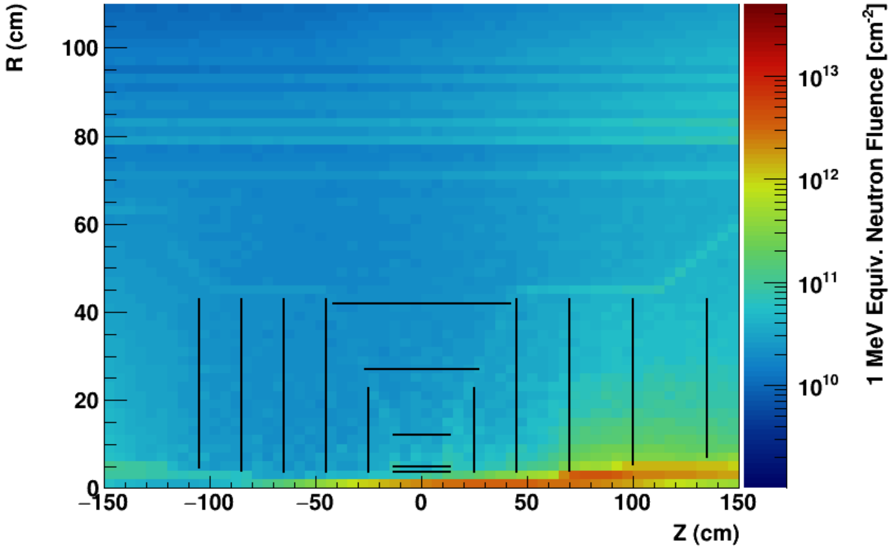
- Example study:
  - Assume 10 years of running at top luminosity
    → 100% run time for 6 months per year running
  - 10 GeV e^- on 275 GeV p DIS events
  - 10 GeV e^- and 275 GeV p beam-gas interaction



<u>**Total Dose and Fluence over SVT Envelope**</u>

- Total Ionising Dose <u>**below 1Mrad**</u>
  - Maximal in the beampipe
    → **10-100krad or lower in tracking layers**

- **Fluence ≲ $5\text{x}10^{13}$ n_{eq}/cm^2**
  - Also maximal in the beampipe
    → **typically <10^{11}-10^{12} in tracking layers**



<u>**Within current ITS3 specifications**</u>

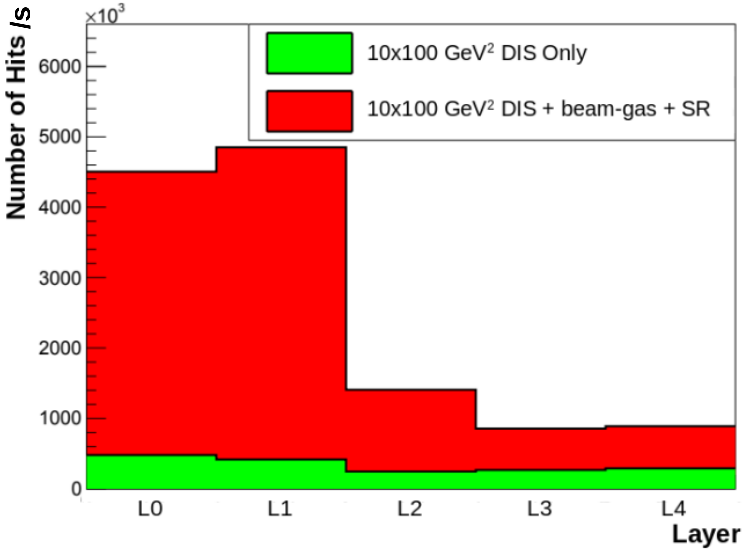
Hit Rates in the SVT

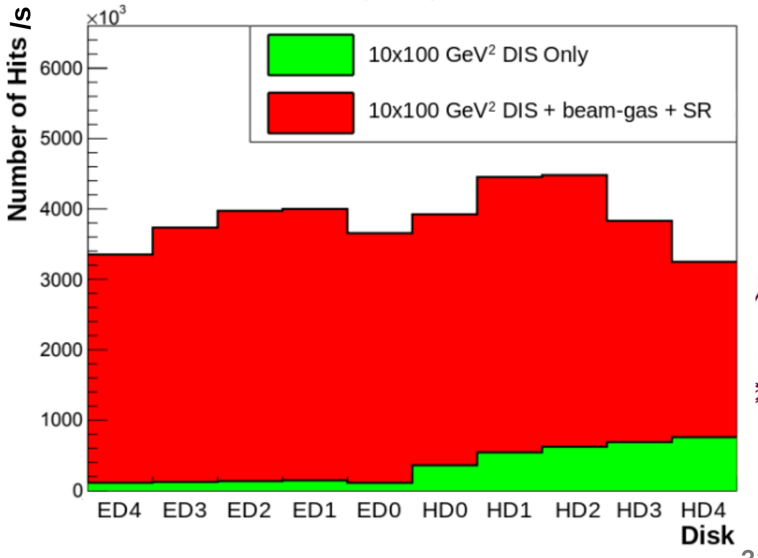
- Example study:
  - 10 GeV e^- on 100 GeV p DIS events
  - 10 GeV e^- and 100 GeV p beam-gas interactions
  - SR from 10 GeV e^-

- **Background events dominate hit rates in SVT**
  - 3-5 MHz in IB and disks
  - <1 MHz in OB

- For 2μs frame rate and 20.8x22.8μm^2 pixels → maximum hit occupancy **~10^{-7} per pixel per frame**
  - **Not a challenge for sensor + readout electronics**

	Hits/pixel/frame		Hits/pixel/frame		Hits/pixel/frame
L0	7.00E-08	**ED0**	1.96E-08	**HD0**	2.11E-08
L1	5.65E-08	**ED1**	7.07E-09	**HD1**	7.87E-09
L2	6.56E-09	**ED2**	6.81E-09	**HD2**	7.68E-09
L3	8.85E-10	**ED3**	6.40E-09	**HD3**	6.59E-09
L4	3.80E-10	**ED4**	5.76E-09	**HD4**	5.62E-09

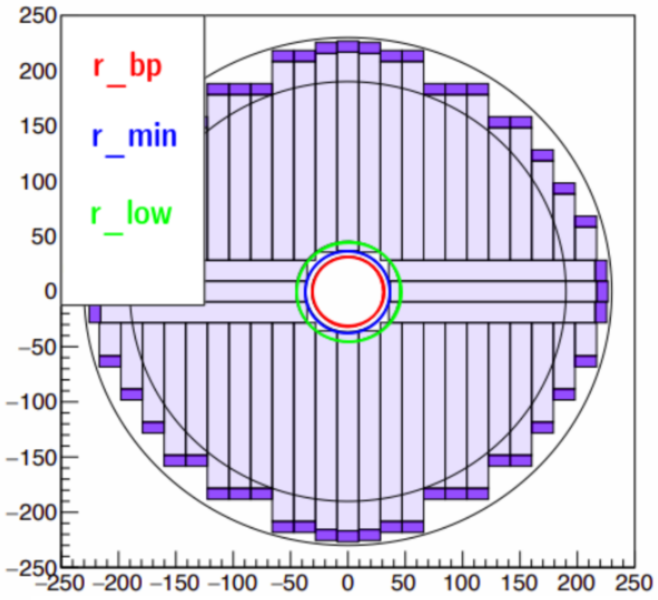


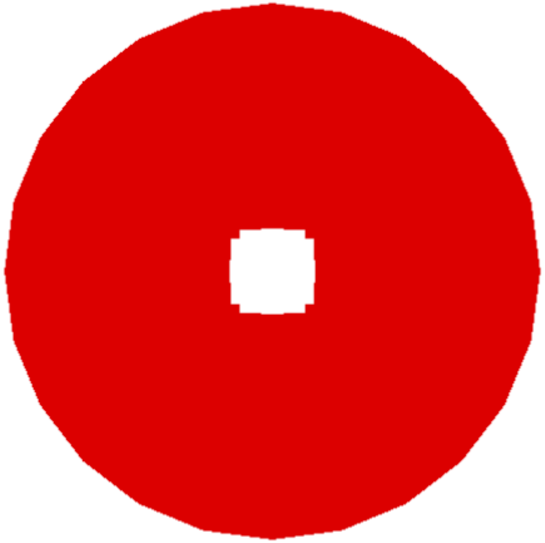


SVT Acceptance at large |η|

- Disk inner openings are **not circular**
  - Constructed from **tiles of rectangular sensors**
    → inner opening is square-ish
  - Beams collide with **25mrad crossing angle**
    → **inner opening shifted** to accommodate
    → Offset is **larger for disks further from the IP**

- Disks provide full acceptance for $\mathbf{r > r_{low}}$
- Partial acceptance for $\mathbf{r_{min} < r < r_{low}}$
- No acceptance for $\mathbf{r < r_{min}}$



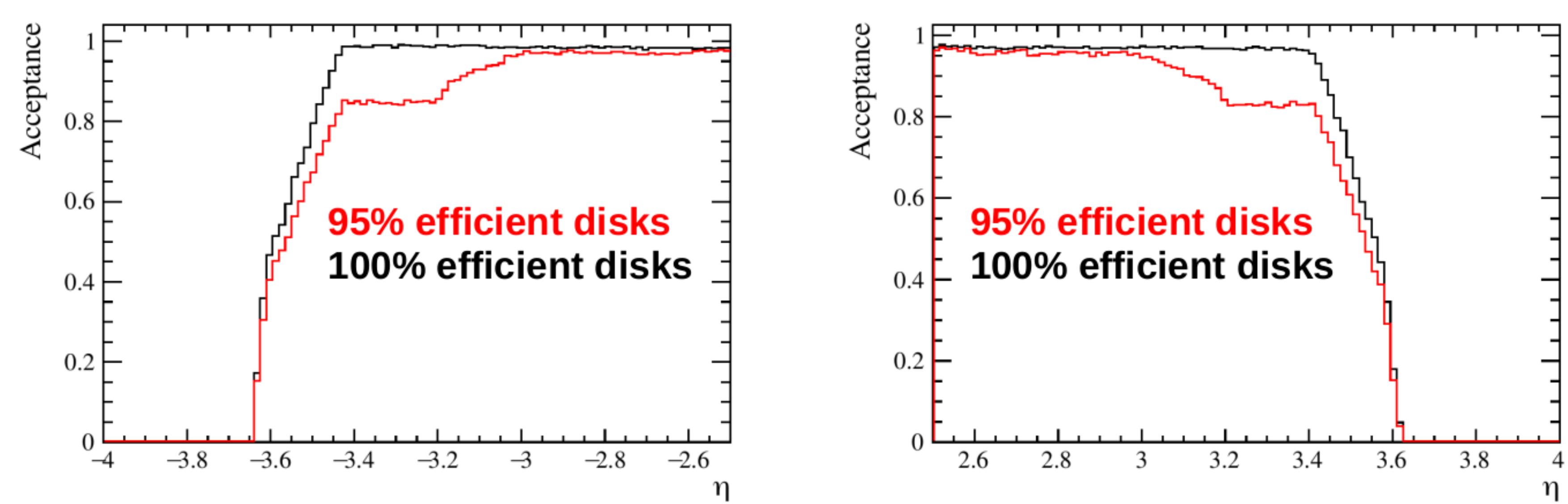


SVT Acceptance at large |η|

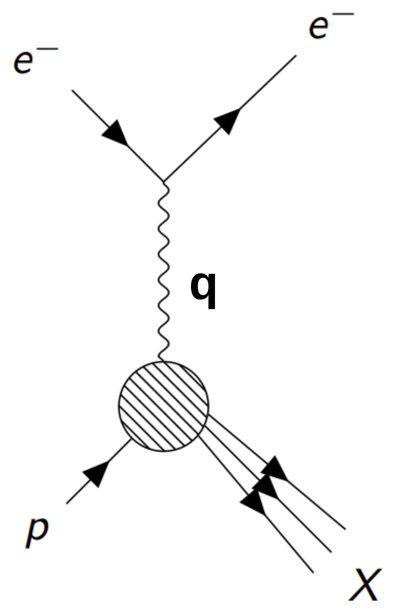
- Require 3 or more hits to reconstruct a track
  - Simulate single e^- ($\eta<0$) and π^- ($\eta>0$)
  - "Reconstructed" if >2 hits

Only 3 Si disks for |η|>3.3
→ **Efficiency becomes important**
→ **Maximise active area around opening**

$$\text{Acceptance} = \frac{\text{Number of events with 3 or more hits}}{\text{Total number of events}}.$$



Brief Interlude – DIS Kinematics



- In **inclusive scattering** no constraints are placed on the hadronic final state
- Events described using three **related** kinematic variables:

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

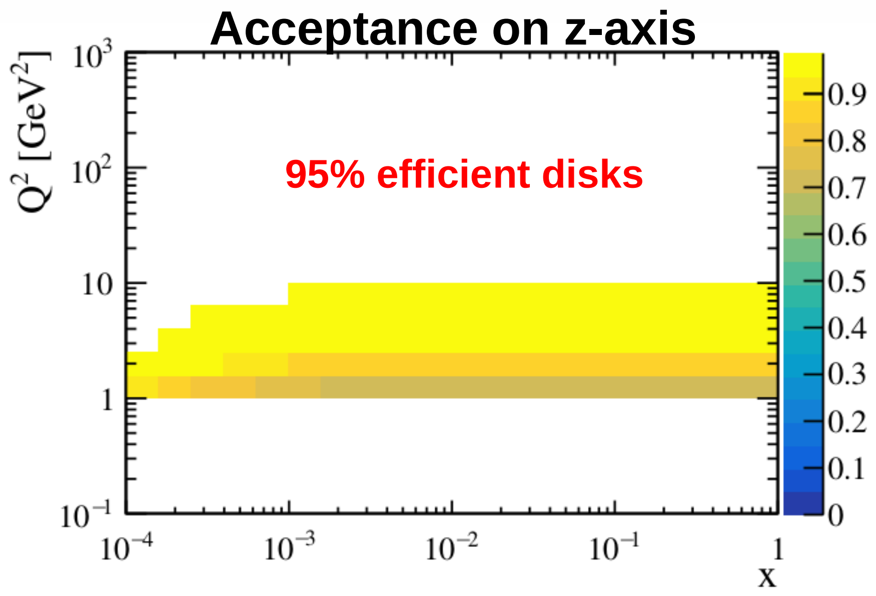
- **"Virtuality"** $Q^2 = -q^2$
- **CoM energy**
- **Bjorken x**
- **Inelasticity**

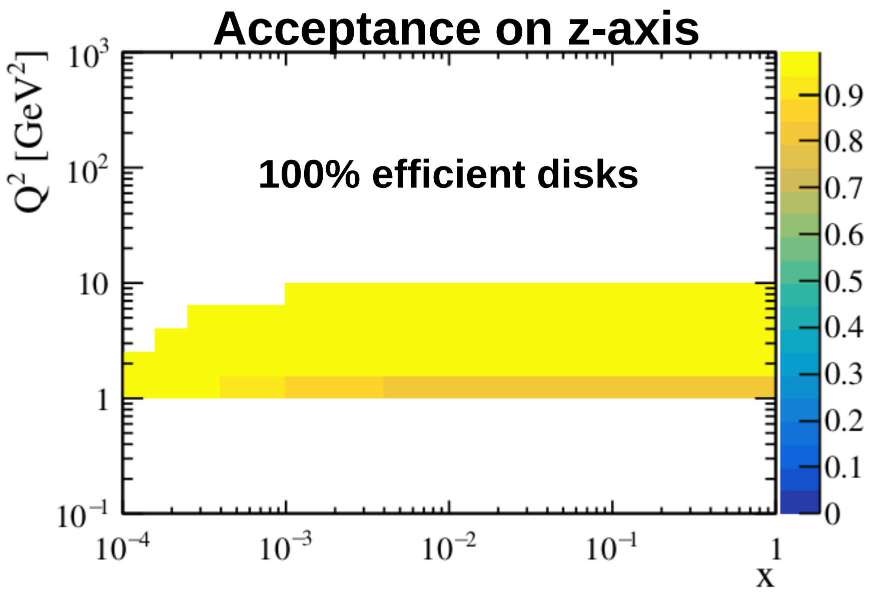
$$Q^2 = -(q \cdot q) \qquad x = \frac{Q^2}{2p \cdot q} \qquad y = \frac{p \cdot q}{p \cdot k}.$$

A good reconstruction of these quantities is essential for EIC physics!

SVT Acceptance vs x-Q^2

- Inclusive kinematics can be fully calculated from the energy and angle of the scattered electron
  - Generate DIS events (Pythia8 18x275 GeV^2, $1<Q^2<10$ GeV^2)
  - Mapping between electron scattering angle and acceptance vs η
- Evaluate **disk acceptance** in x-Q^2 bins → **see where it impacts measurement plane**

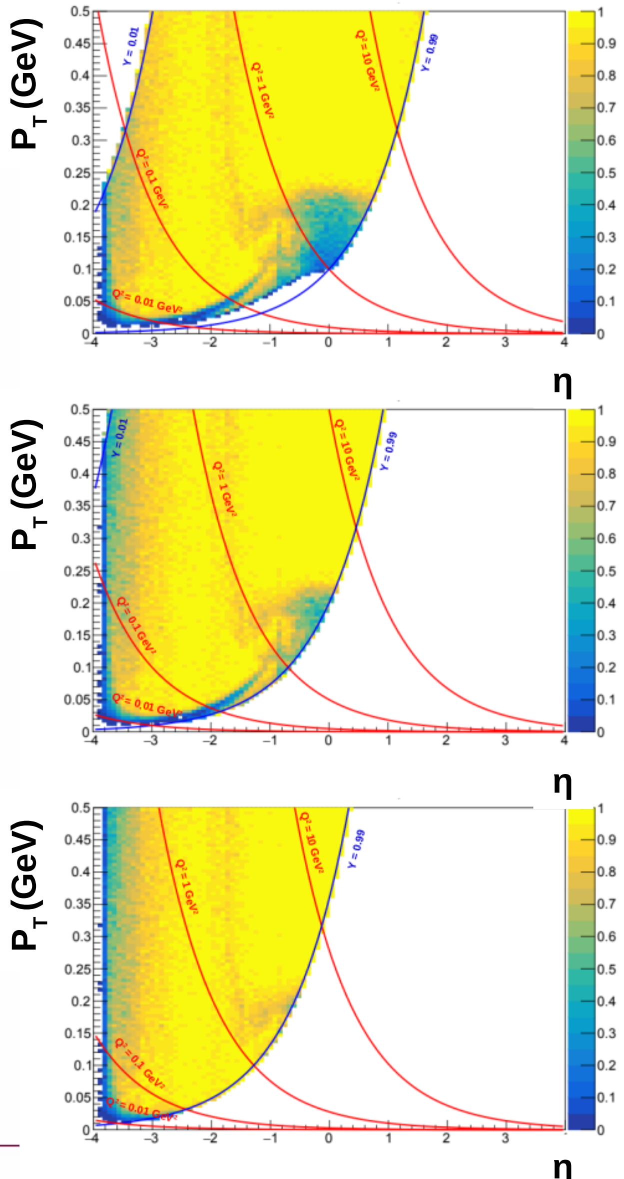




Increasing Realism…

- **Full detector is involved in reconstructing DIS electrons**
- Track reconstruction has to be able to reconstruct the track → **<u>some events lost along the way</u>**
- Typical requirement to find electron is a matched cluster in the electromagnetic calorimeter

- Simulate single electrons in full detector
  - Require: reconstructed track, 1+ ECAL clusters
- Isolines are drawn for y=0.01, 0.99 (blue) and Q^2=0.01, 0.1, 1, 10 GeV^2 (red)
- **Acceptance losses at:**
  - **Low η (edge of disk acceptance)**
  - **Low p/p_T (track reconstruction fails or electron doesn't reach ECAL)**



<u>e⁻ Energy</u>

5 GeV

10 GeV

18 GeV

Summary of Tracking Studies

- **The Tracking System for ePIC is required to be low mass and high precision**
  - Achieved using a hybrid tracking system of MAPS complemented by MPGDs

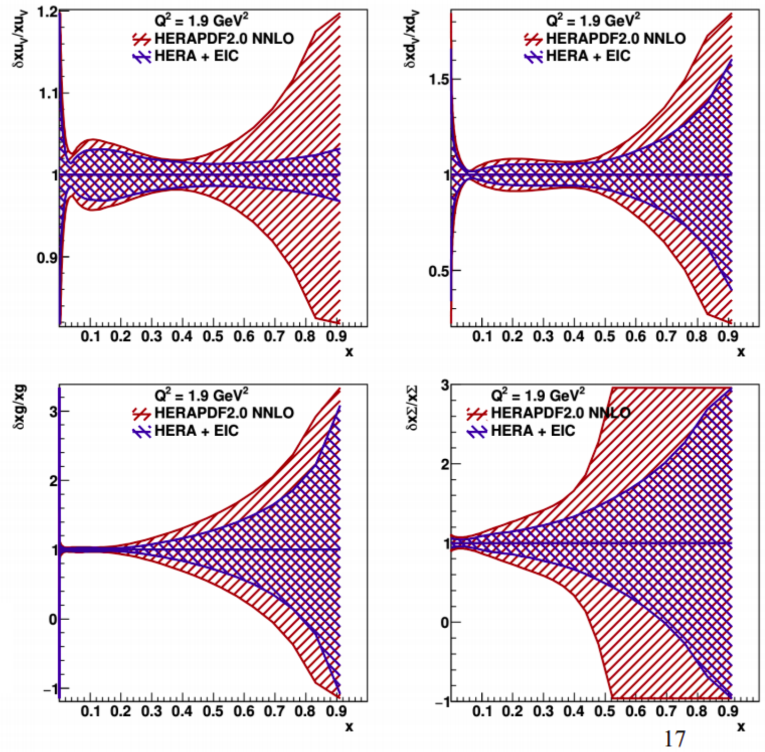
- **Tracking performance (momentum and pointing resolution) is within reach of Yellow Report targets for most of the range**
  - Dedicated physics studies required to evaluate if these requirements are sufficient

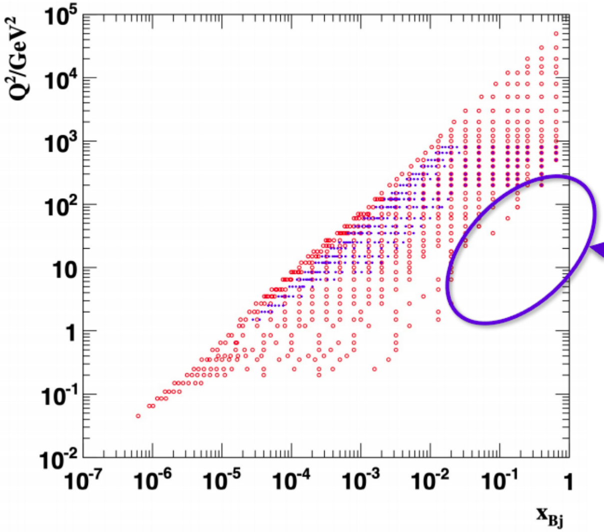
- **The EIC will be subject to beam related backgrounds of Synchrotron Radiation and beam-gas interactions**
  - Average pixel hit rate in the SVT layers: 10^{-7} per pixel per frame → does not pose a challenge for the sensor + readout electronics
  - Radiation load is manageable: Dose ~100krad and Fluence ~10^{12} n_{eq}/cm^2 in tracker

- **Large acceptance for DIS electrons across kinematic plane**

Inclusive DIS at the EIC

- Inclusive DIS provides access to collinear parton density functions
  - Even for unpolarised ep, the EIC will have a huge impact!





HERA data have limited high x sensitivity due to kinematic correlation between x and Q^2 and $1/Q^4$ factor in cross section

8

Inclusive DIS at the EIC

- The EIC provides a unique environment for the study of nucleons/nuclei with an Inclusive Physics programme:
  - **High luminosity ep collider**
  - **Polarised proton/light nucleus collider**
  - **eA collider**

- For **unpolarised** p/A – measure F_2, F_L

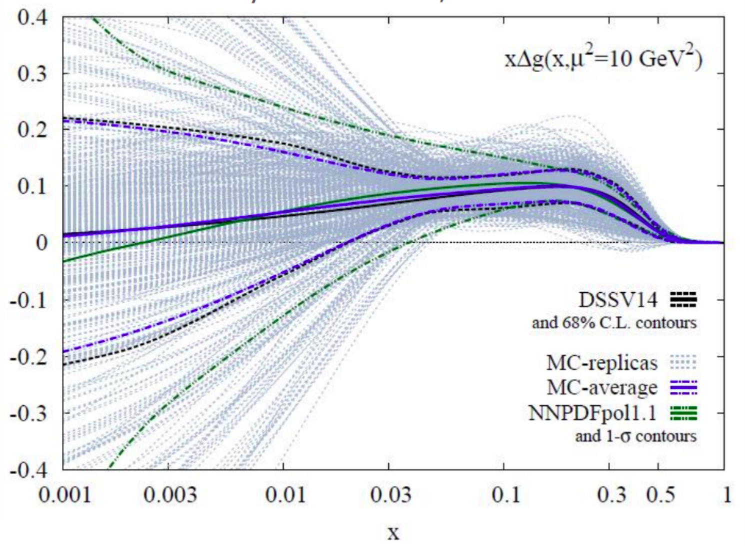
$$\sigma_r = F_2(x,Q^2) - \frac{y^2}{Y_+} F_L(x,Q^2)$$

- For **polarised** p/^{3}He – extract g_1

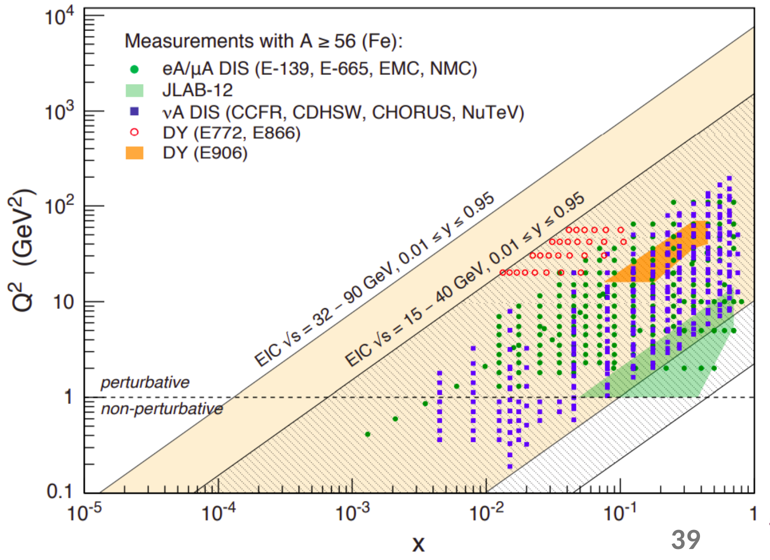
$$\frac{\Delta\sigma}{2} = \frac{1}{2}\left[\frac{d^2\sigma^{\uparrow\downarrow}}{dxdQ^2} - \frac{d^2\sigma^{\uparrow\uparrow}}{dxdQ^2}\right] \simeq \frac{4\pi\alpha^2}{Q^4} y(2-y) g_1(x,Q^2)$$

- **Vary c.o.m. energy/polarisation → measure cross section vs x-Q^2**
- **High precision x-Q^2 reconstruction required!**

Phys. Rev. D **100**, 114027



Aschenauer et al. PRD **96**, 114005 (2017)



Reconstructing Inclusive Kinematics

- Inclusive DIS kinematics can be reconstructed from **two measured quantities**
  → $\vec{D} = \{E_e, \theta_e, \delta_h, p_{t,h}\}$
  - 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

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

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

JB method

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

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

Σ method

$$y_\Sigma = \frac{\delta_h}{\delta_h + \delta_e}$$

$$Q^2_\Sigma = \frac{p_{t,e}^2}{1-y_\Sigma}$$

Double Angle method

$$y_{DA} = \frac{\alpha_h}{\alpha_h + \alpha_e}$$

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

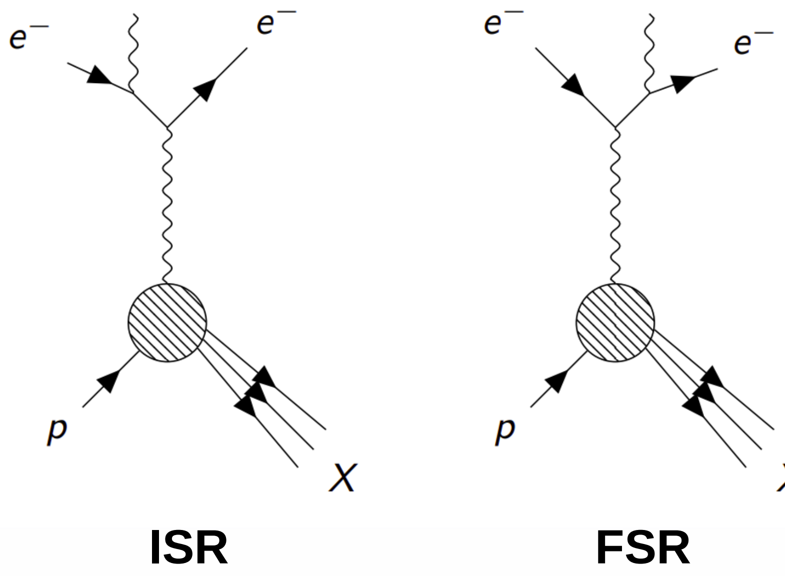
$$\alpha_{e/h} = \tan\frac{\theta_{e/h}}{2}$$

Reconstructing Inclusive Kinematics with QED radiation

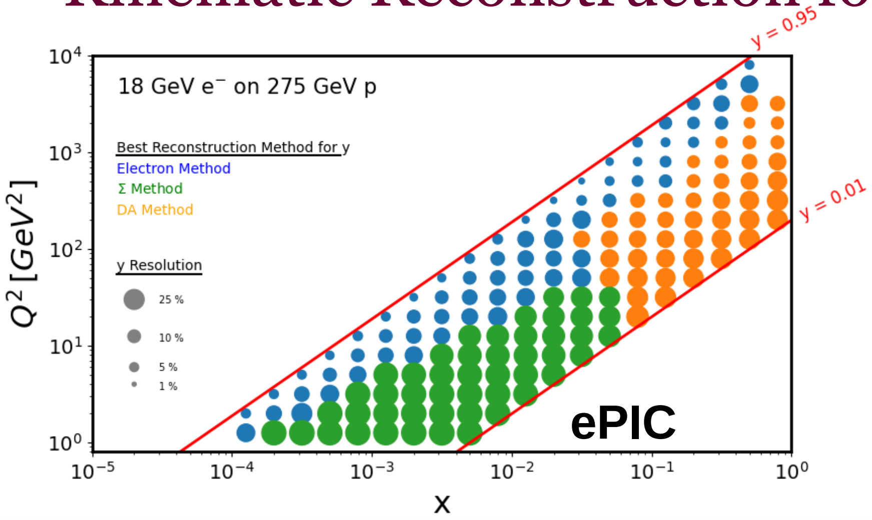
- Presence of **QED radiation changes event kinematics** → Errors in reconstruction when only using two measured quantities

- **FSR not too problematic**: typically collinear to scattered electron → measured together in ECAL

- **ISR more difficult to account for**: reduces electron beam energy, radiated photon typically disappears down beampipe



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
  - Some have proposed using Neural Networks https://arxiv.org/abs/2110.05505
  - Can alternatively perform a **kinematic fit of measured quantities.**

Kinematic Fit (KF) Reconstruction

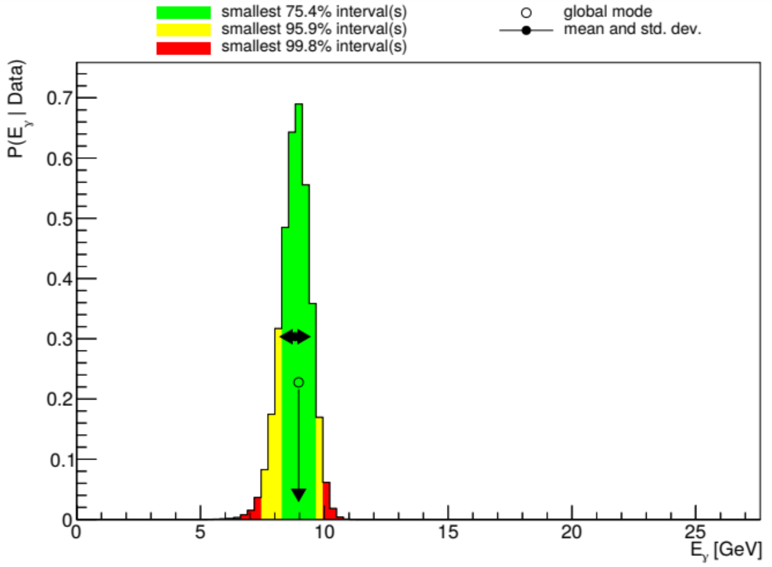
- Kinematic fit of **all 4** measured quantities:
  - Extract DIS kinematics, and energy of a possible ISR photon: $\vec{\lambda}$ = {x, y, E_γ}

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

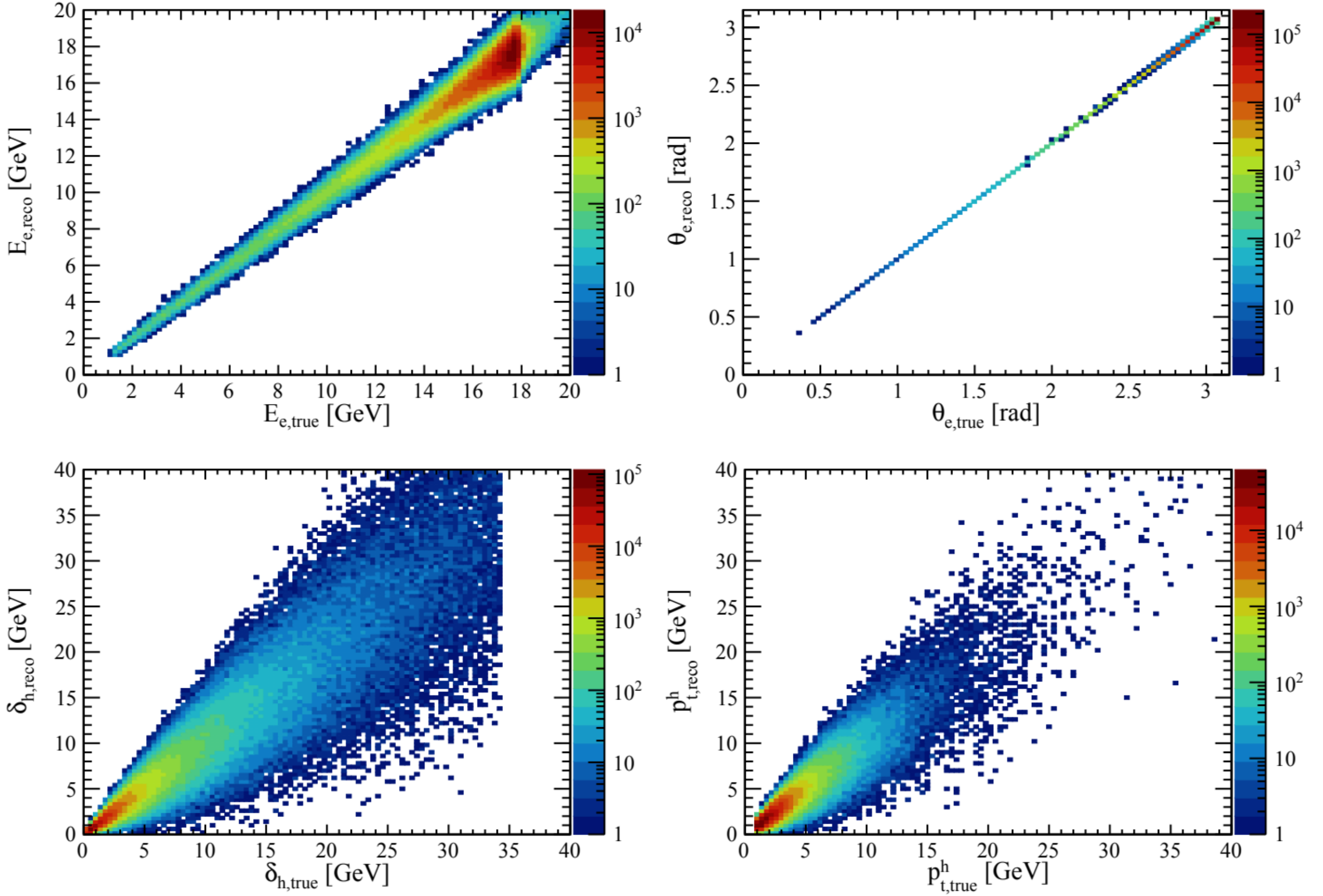
3. Posterior $$P(\vec{\lambda}|\vec{D}) \propto P(\vec{D}|\vec{\lambda}) P_o(\vec{\lambda}).$$

- **Posterior extracted** using Metropolis-Hastings algorithm:
  - → Fitted values of **x, y, E_γ** taken from global mode of the posterior



Marginalised E_γ posterior distribution for a single DIS event

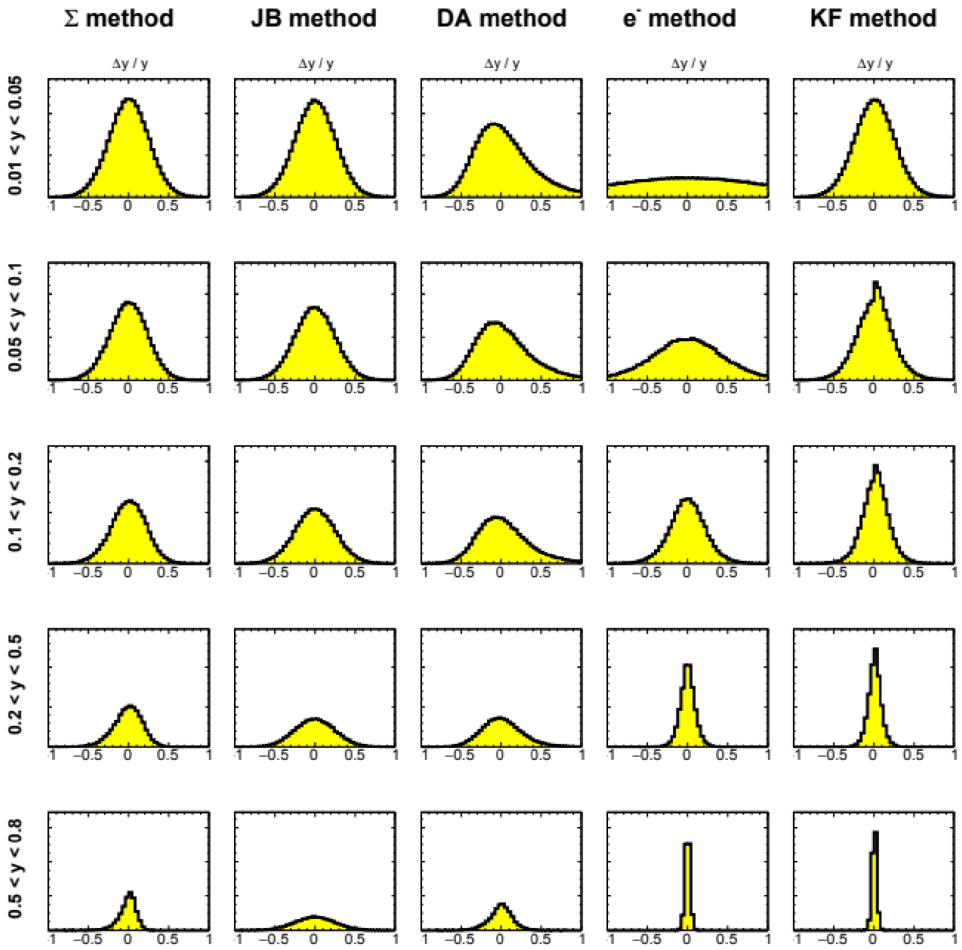
Smeared EIC pseudodata



- EIC DIS events generated with Djangoh
  - 18x275, Q^2>1 GeV^2
- Smear by estimated resolutions

- $\sigma(\theta_e)$ = 0.1mrad
- $\sigma(E_e)$ / E = 11% /sqrt(E) ⊕ 2%
- $\sigma(\delta_h) / \delta_h$ = 25%
- $\sigma(p_{T,h}) / p_{T,h}$ = 25%

Smeared EIC pseudodata (No ISR)



- **Smearing resolutions used as input for KF**

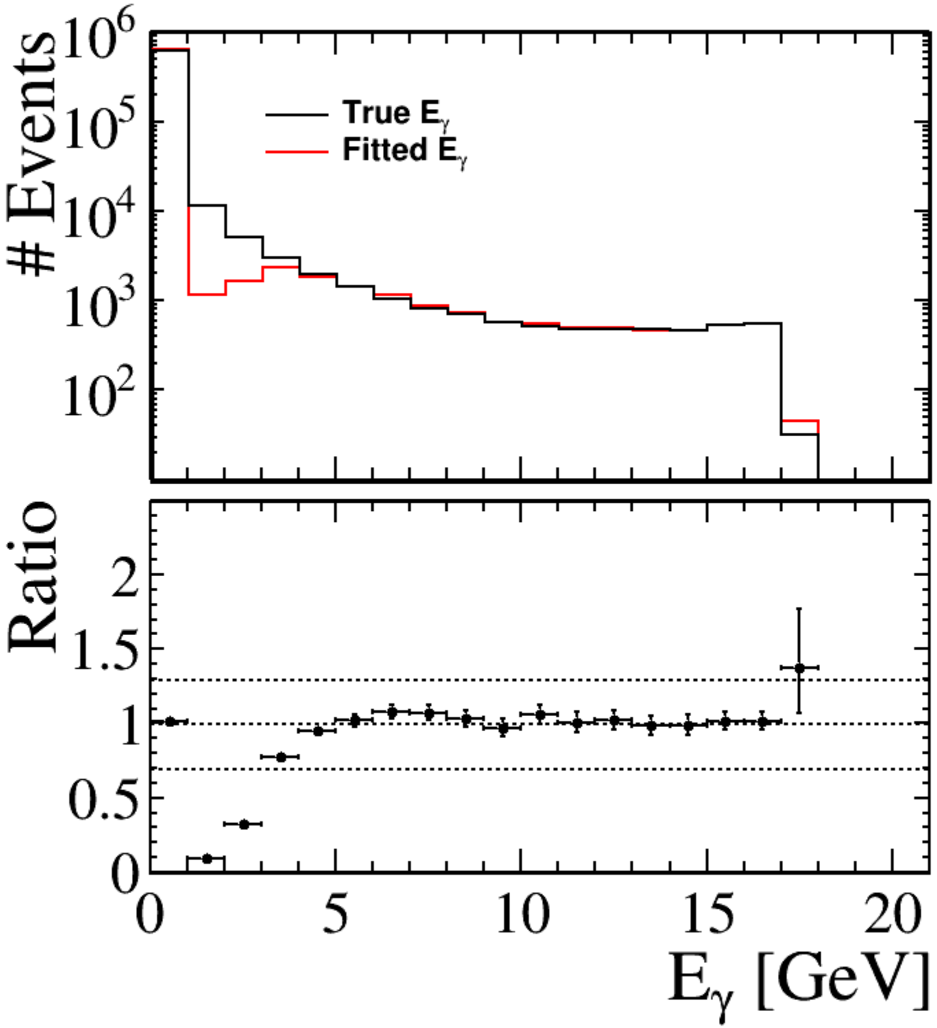
$$P(\vec{D}|\vec{\lambda}) = \frac{1}{\sqrt{2\pi}\sigma_E} \exp - \frac{(E_e - E_e^{\lambda})^2}{2\sigma_E^2} \times \frac{1}{\sqrt{2\pi}\sigma_\theta} \exp - \frac{(\theta_e - \theta_e^{\lambda})^2}{2\sigma_\theta^2} \times \frac{1}{\sqrt{2\pi}\sigma_{\delta_h}} \exp - \frac{(\delta_h - \delta_h^{\lambda})^2}{2\sigma_{\delta_h}^2} \times \frac{1}{\sqrt{2\pi}\sigma_{p_t^h}} \exp - \frac{(p_t^h - p_t^{h\lambda})^2}{2\sigma_{p_t^h}^2}.$$

- **Prior as before:**

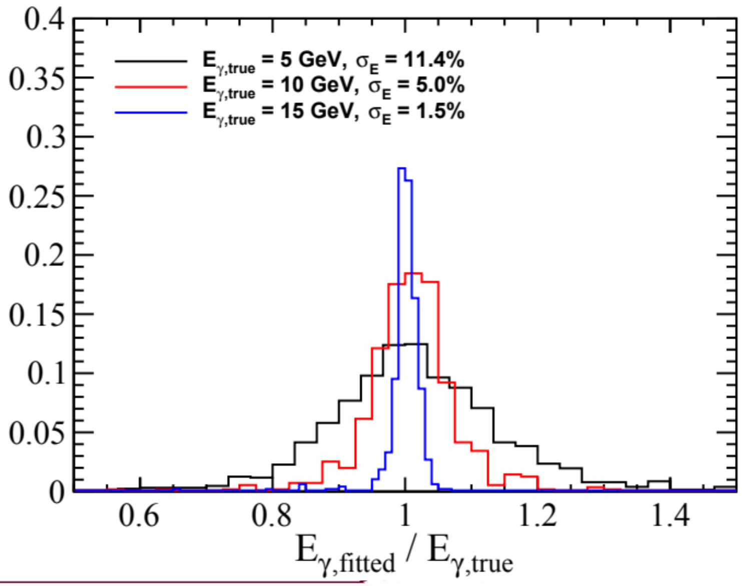
$$P_0(\vec{\lambda}) = \frac{1 + (1-y)^2}{x^3 y^2} \frac{1 + (1 - E_\gamma/E_0)^2}{E_\gamma/E_0}$$

- **Compare y resolutions**:
  - KF method meets or exceeds conventional

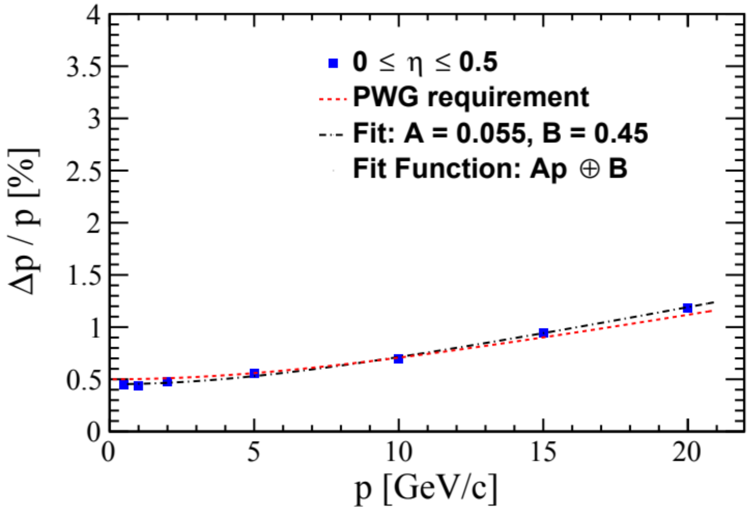
Smeared EIC pseudodata (W/ ISR)

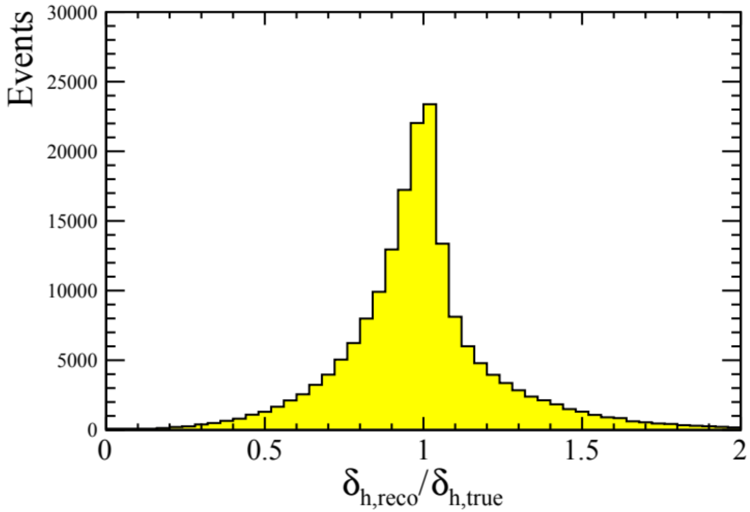


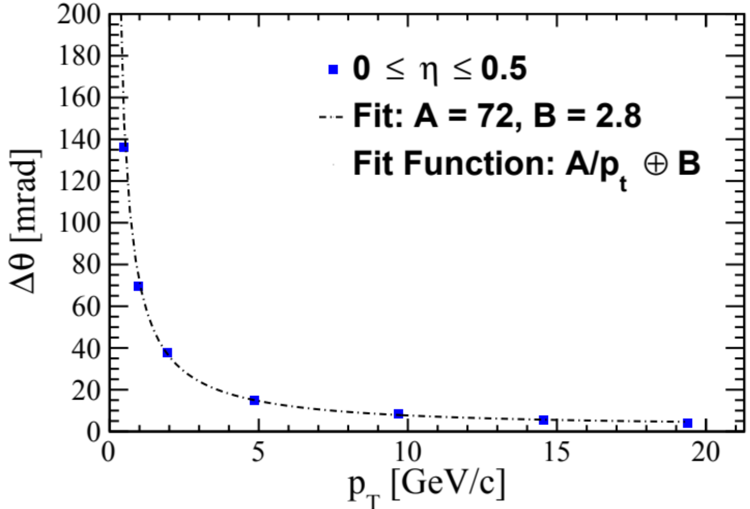
- **Compare true and measured ISR energy distributions**
  - Distribution **well reproduced for higher E_γ**
  - Ratio within **30% for E_γ > 3 GeV**
  - Within **10% for E_γ > 4 GeV**
- **Reasonable energy resolution**

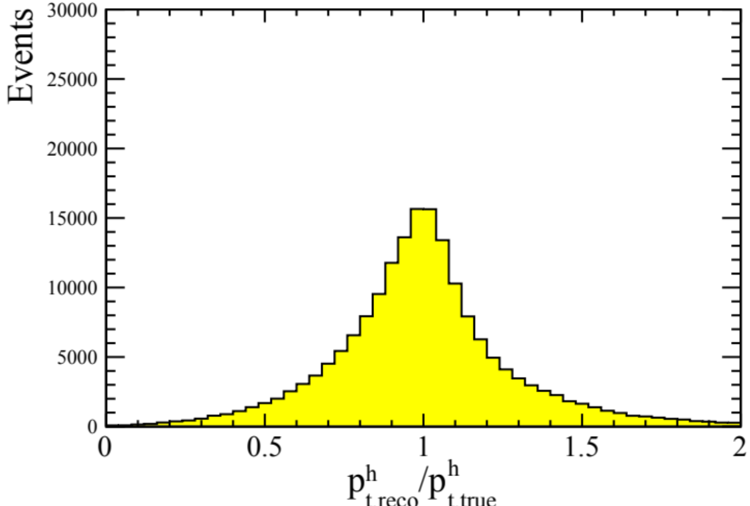


Fully Simulated ePIC pseudodata (No ISR)









$$\sigma_E = 0.055 \cdot p \oplus 0.45 \text{ in GeV}$$

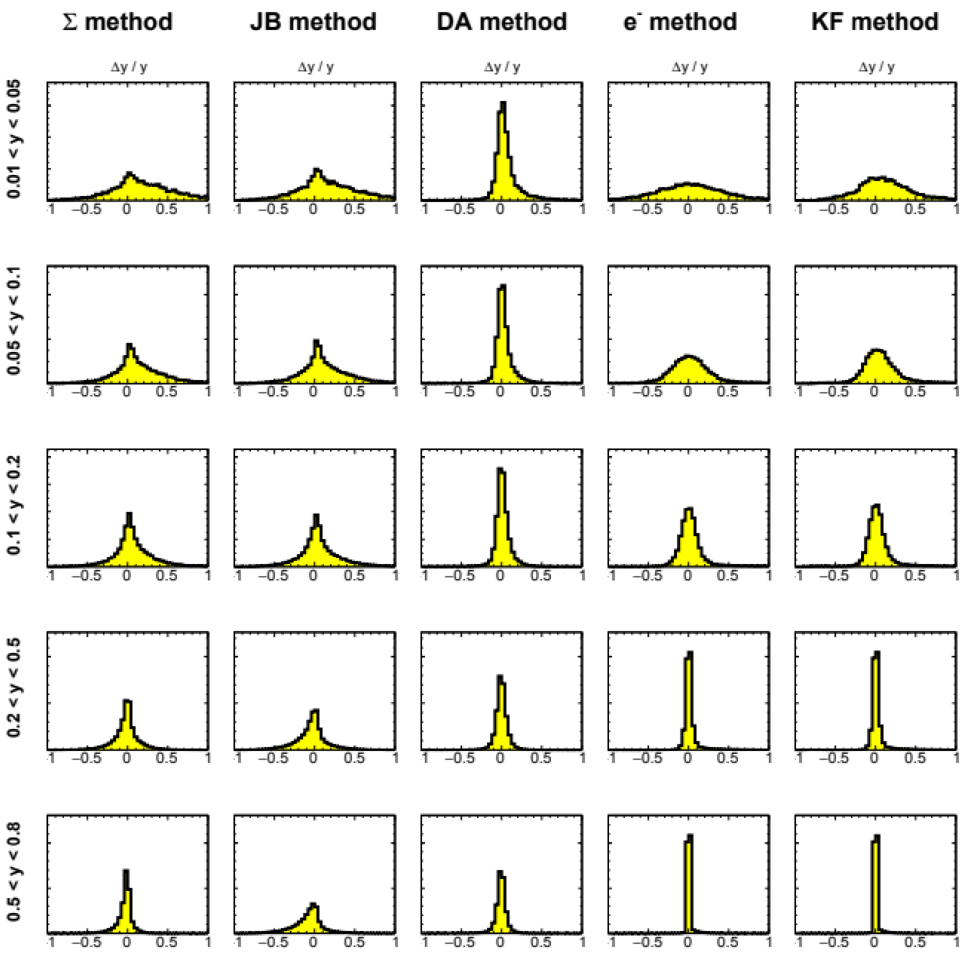
$$\sigma_\theta = 72/p_t \oplus 2.8 \text{ in mrad}$$

$$\sigma_{\delta_h} = 0.25 \cdot \delta_h \text{ in GeV}$$

$$\sigma_{p_t^h} = 0.25 \cdot p_t^h \text{ in GeV.}$$

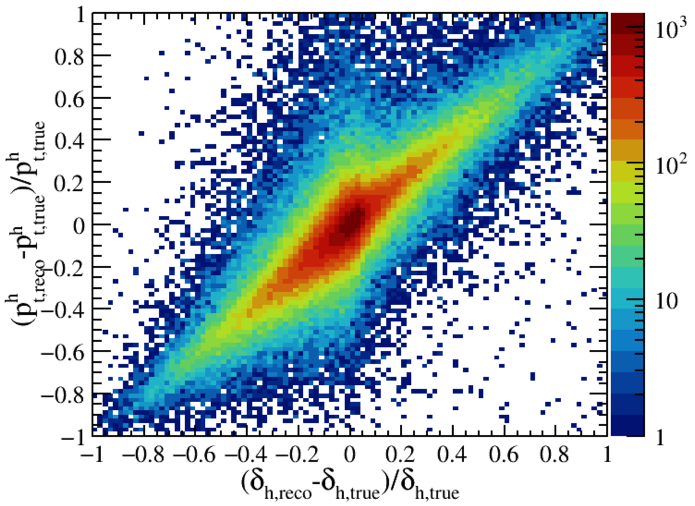
- Parametrised ePIC full sim resolutions
  - Pythia8 NCDIS
  - Craterlake 23.12.0
  - $Q^2 > 100$ GeV^2
  - Ele from tracking

Fully Simulated ePIC pseudodata (No ISR)



- KF gives **comparable y resolution to electron method** at high y
- **Loses at low y to DA method**

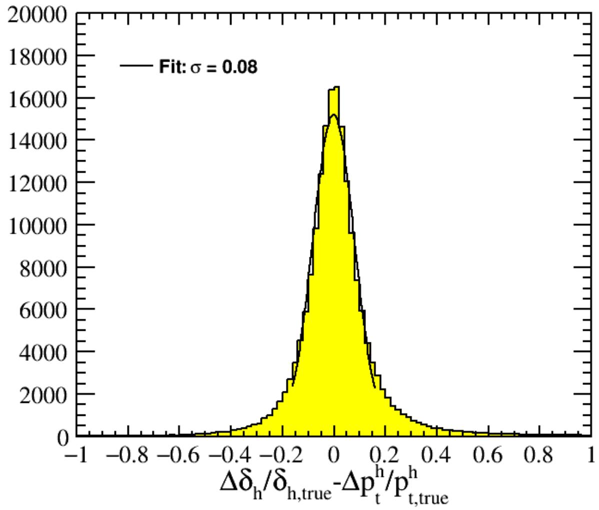
HFS Correlations



- Correlations in HFS variables mostly due to energy fluctuations in calorimeters
  - Introduce extra term that reduces likelihood if p_t is overestimated and δ underestimated or vice versa:

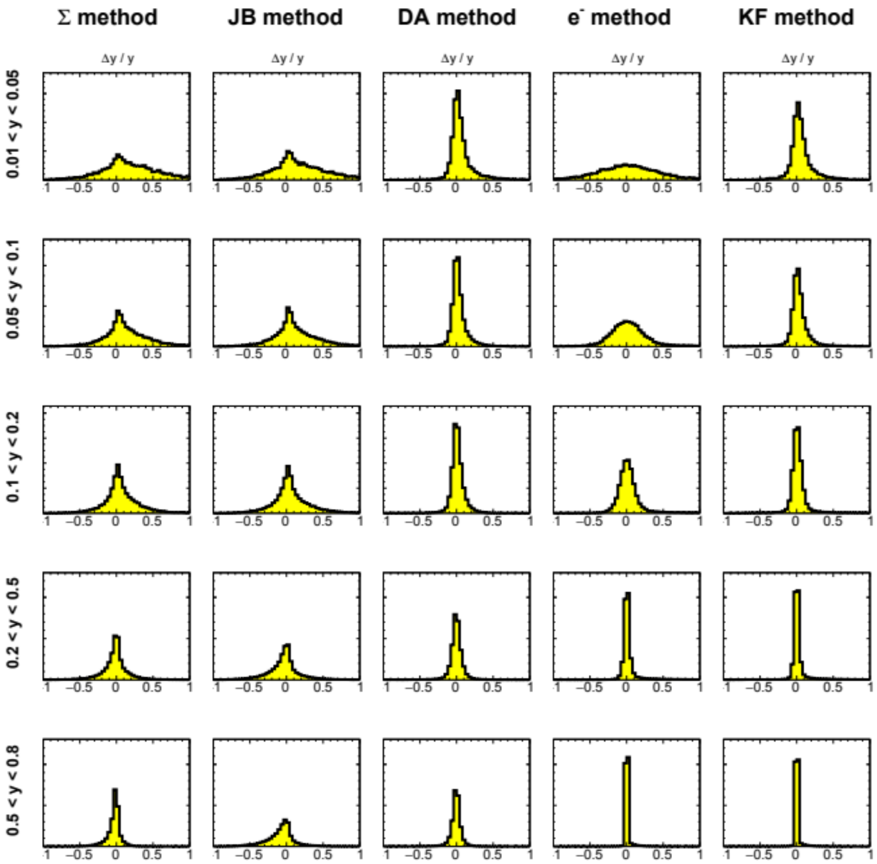
$$P(\vec{D}|\vec{\lambda})_{corr} = P(\vec{D}|\vec{\lambda})_{uncorr} \frac{1}{\sqrt{2\pi}\sigma_{corr}} \cdot \exp - \frac{(c - c^{\lambda})^2}{2\sigma_{corr}^2}$$

$$c = \frac{\delta_{h,reco} - \delta_{h,true}}{\delta_{h,true}} - \frac{p^h_{t,reco} - p^h_{t,true}}{p^h_{t,true}}$$



Correlation width σ_{corr}~8%

Fully Simulated ePIC pseudodata (No ISR) – HFS Correlation



- **Performance of KF recovered at low y!**
  - Not perfect here → but performance comparable to DA method achieved at low y, while maintaining electron method performance at high y
- **Further improvements in likelihood possible**
  → HFS resolutions and correlation parametrisations

What about ISR?

- **<u>ISR energy can be determined due to energy/momentum conservation</u>**
  - If electron beam is -z and hadron beam is +z then **sum of the E-p_z value of all particles** in the event → $\boldsymbol{\Sigma_{total} = 2E_{e,beam}}$
  - If the energy of the electron beam is reduced by the emission of an ISR photon then

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

  - This relation is used implicitly in the Σ-method, where $2E_{e,beam}$ is replaced by $(\delta_e+\delta_h)$

$$y_\Sigma = \frac{\delta_h}{\delta_h + \delta_e}$$

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

$\boldsymbol{\delta_h}$ is $\boldsymbol{E - p_z}$ sum of all particles in the HFS
$\boldsymbol{\delta_e}$ is $\boldsymbol{E - p_z}$ of electron

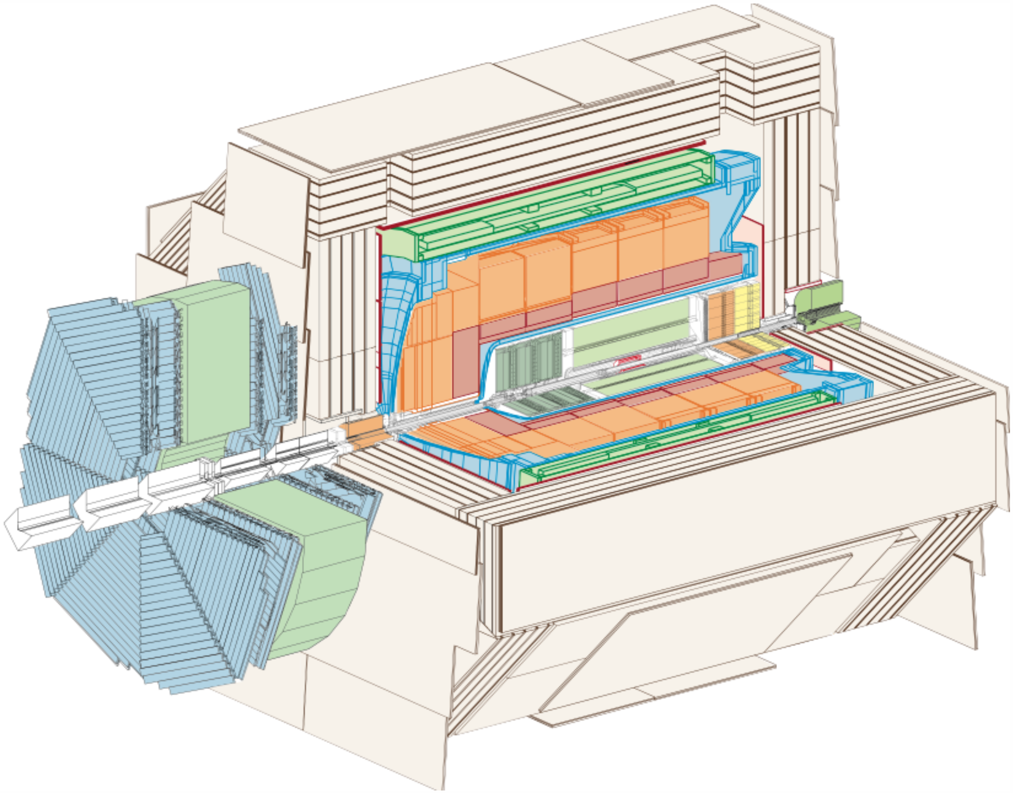
- The **resolution on reconstructed Σ_{total} is poor** → need to be careful not to attribute to ISR that which could be caused by a resolution effect
  - **<u>Prior for E_{γ} in Kinematic Fit helps avoid this</u>**

Kinematic Fitting at H1

- **Simulations are one thing but…**
  - Need full simulations with ISR?
  - Will method work with real data?

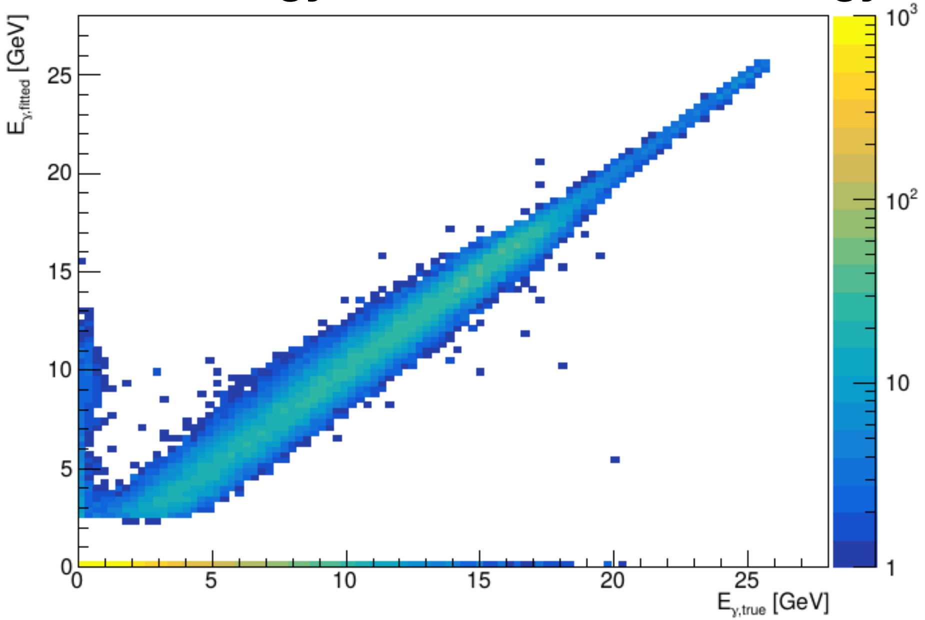
- **Previous ep collider: HERA** (@ DESY)
  - H1 was one of 2 general purpose detectors
- **Perform kinematic fit reconstruction on H1 $e^{+}p$ 2003/2004 MC+Data**

- 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

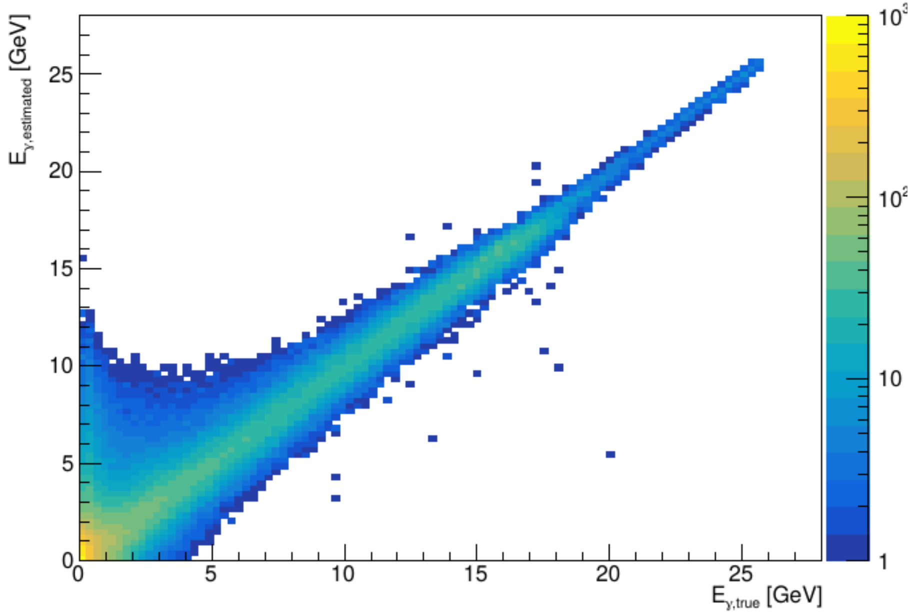


ISR from Kinematic Fitting at H1

ISR Energy from KF vs True Energy



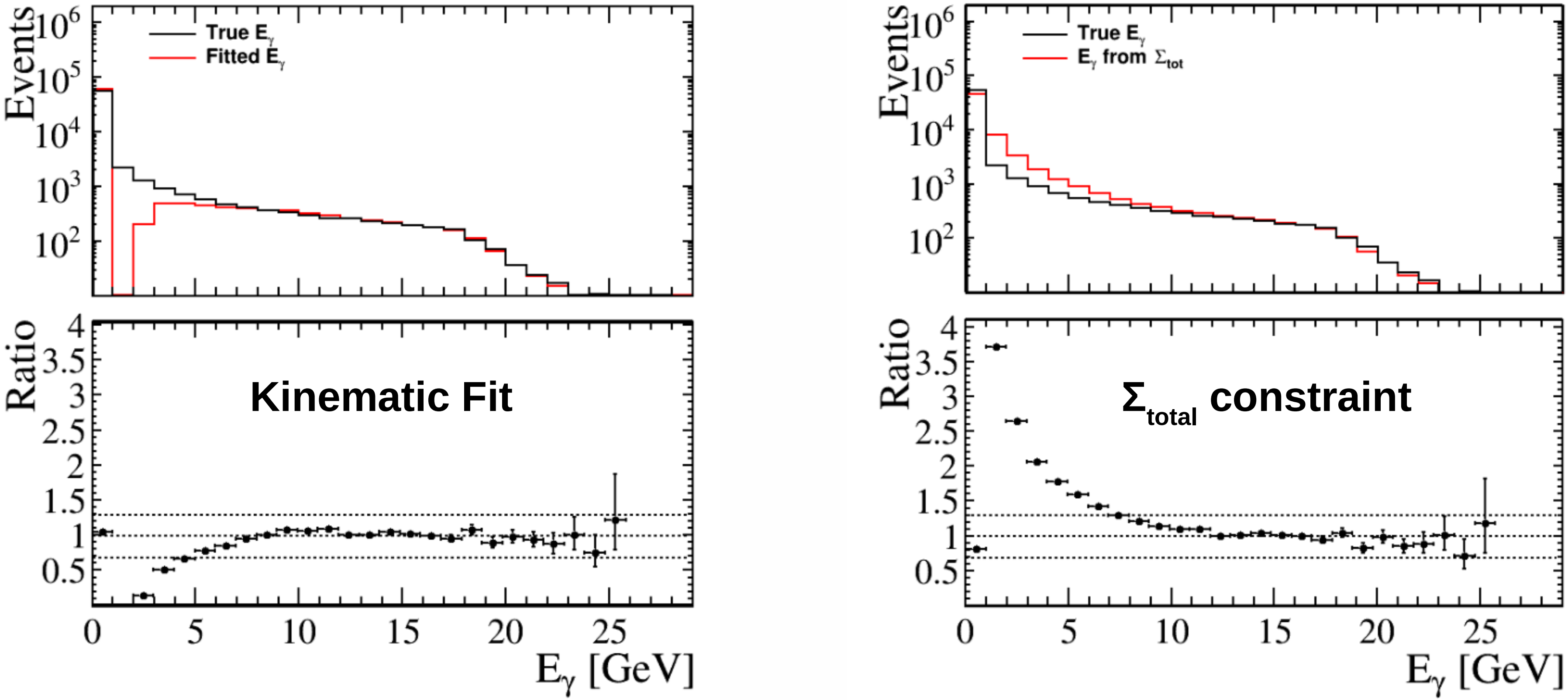
Estimate from Σ_{total} constraint vs True Energy



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

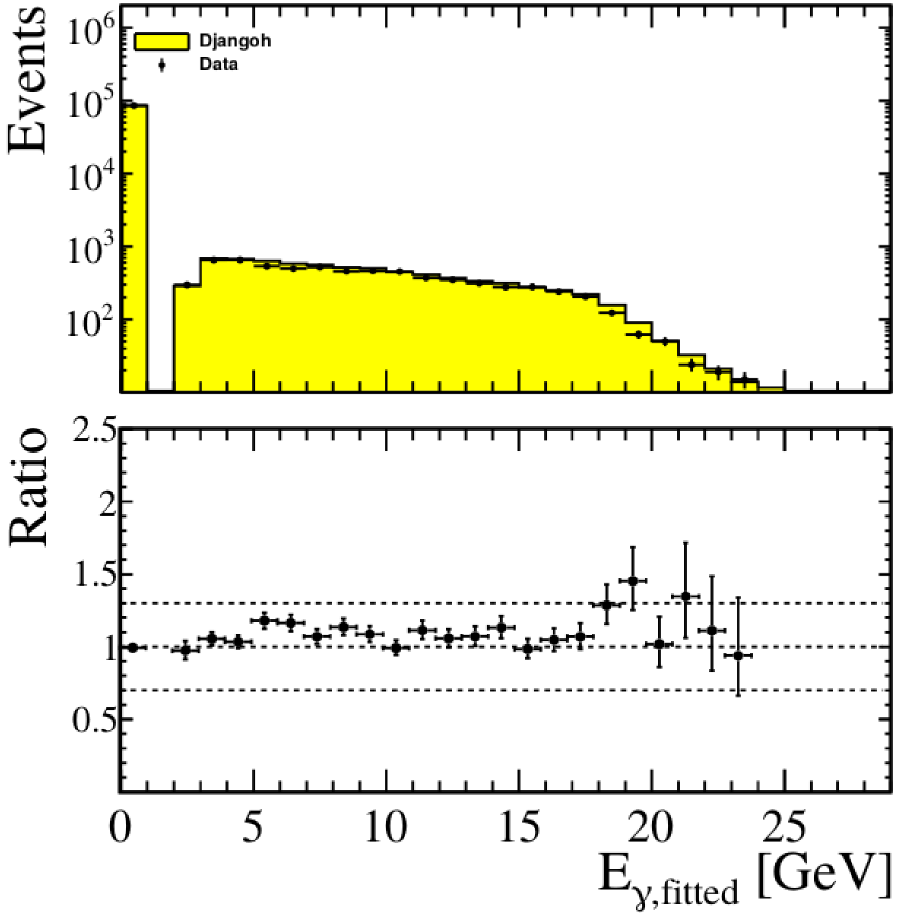
ISR from Kinematic Fitting at H1



- Amount of ISR predicted by KF matches quite well for $E_{\gamma,true}$ > ~4 GeV
- Σ_{total} constraint approach overestimates until $E_{\gamma,true}$ > ~8 GeV

Comparison to Data

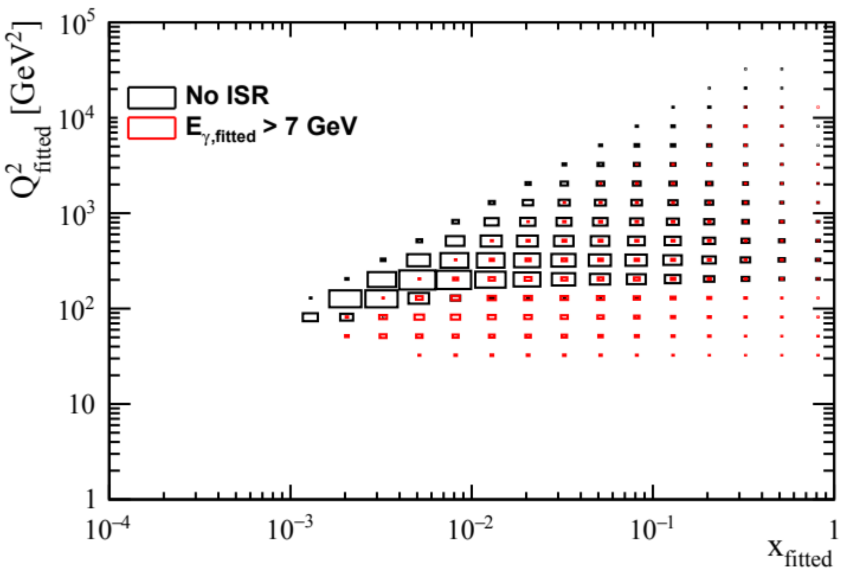
- **Good agreement between number of events predicted by KF for data+MC!**



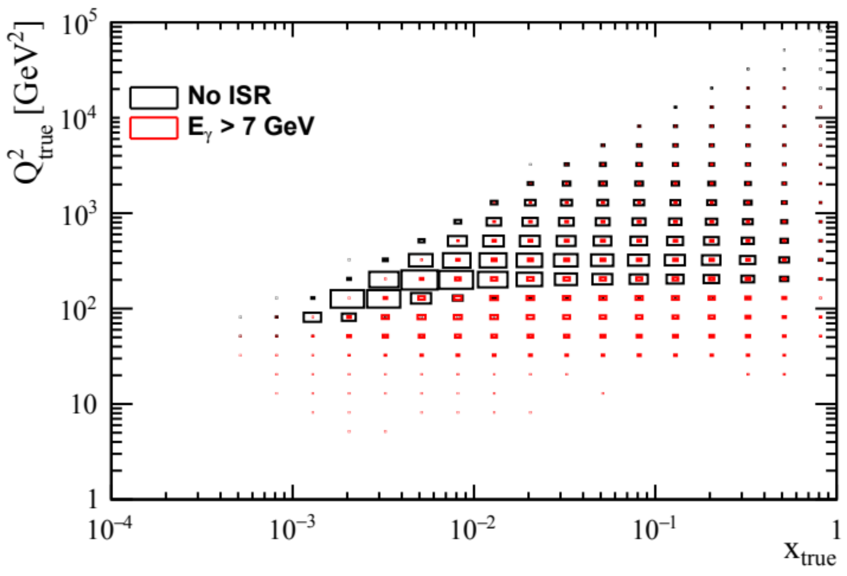
Why identify ISR?

- ISR lowers the electron beam energy
  - **Scattered electrons in low Q^2 events don't enter main detector**
    → lower energy electrons scattered at larger angles → 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 of Kinematic Reconstruction

- **Wealth of opportunities for inclusive physics at the EIC**

- **Methods using HFS information can improve resolution depending on conditions**
  - Can achieve good resolutions if best method is chosen for each x-Q^2 bin

- **Kinematic fitting method explored:**
  - The DA method may outperform the basic (uncorrelated) KF at low y
  - Extending KF method to account for correlations in the HFS recovers this performance → delivers y resolution comparable to best method for each y bin
  - ISR reconstruction improved on in KF method compared to Σ-like methods
  - KF method works for realistic detector conditions

Summary

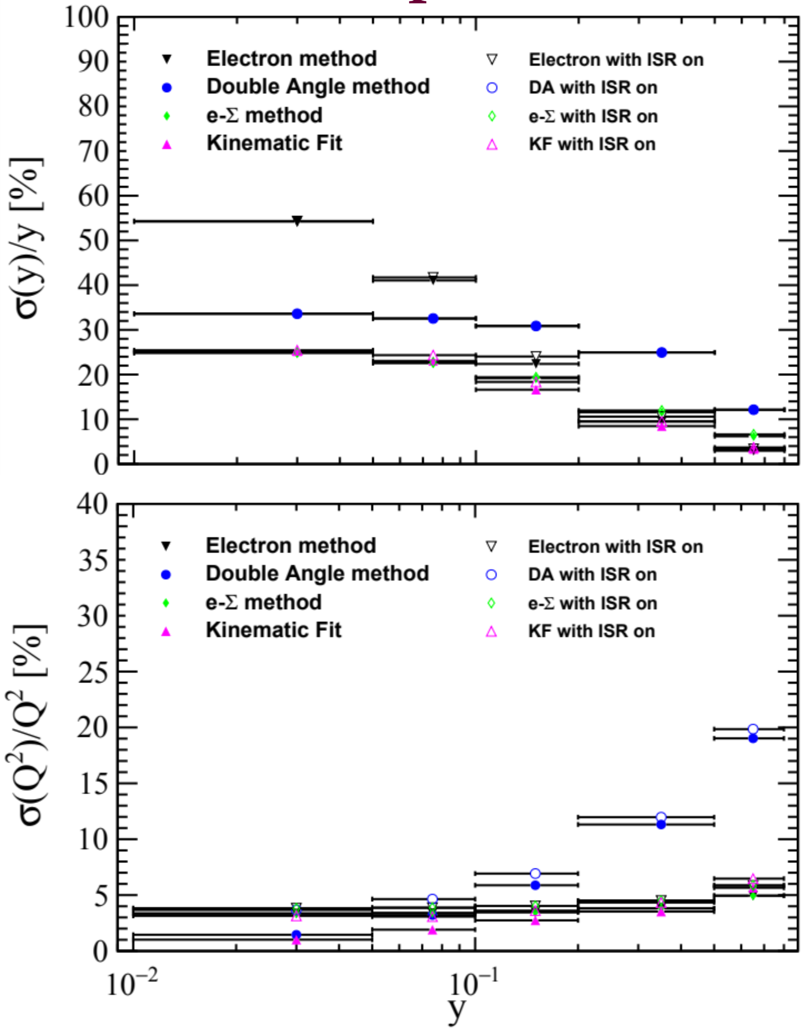
- **The EIC will greatly improve our understanding of nucleon/nuclear structure**

- **The EIC Physics Programme sets stringent requirements on the design and performance of the tracking detector**
  - The chosen technologies should be able to deliver the physics, and operate well in the conditions of the EIC

- **Inclusive DIS measurements require an accurate reconstruction of the kinematics**
  - This can be achieved through the optimal use of the measured quantities
  - An event-by-event kinematic fit may provide a single method that gives an optimal reconstruction and extends the accessible phase space

Backup

Smeared EIC pseudodata (W/ ISR)



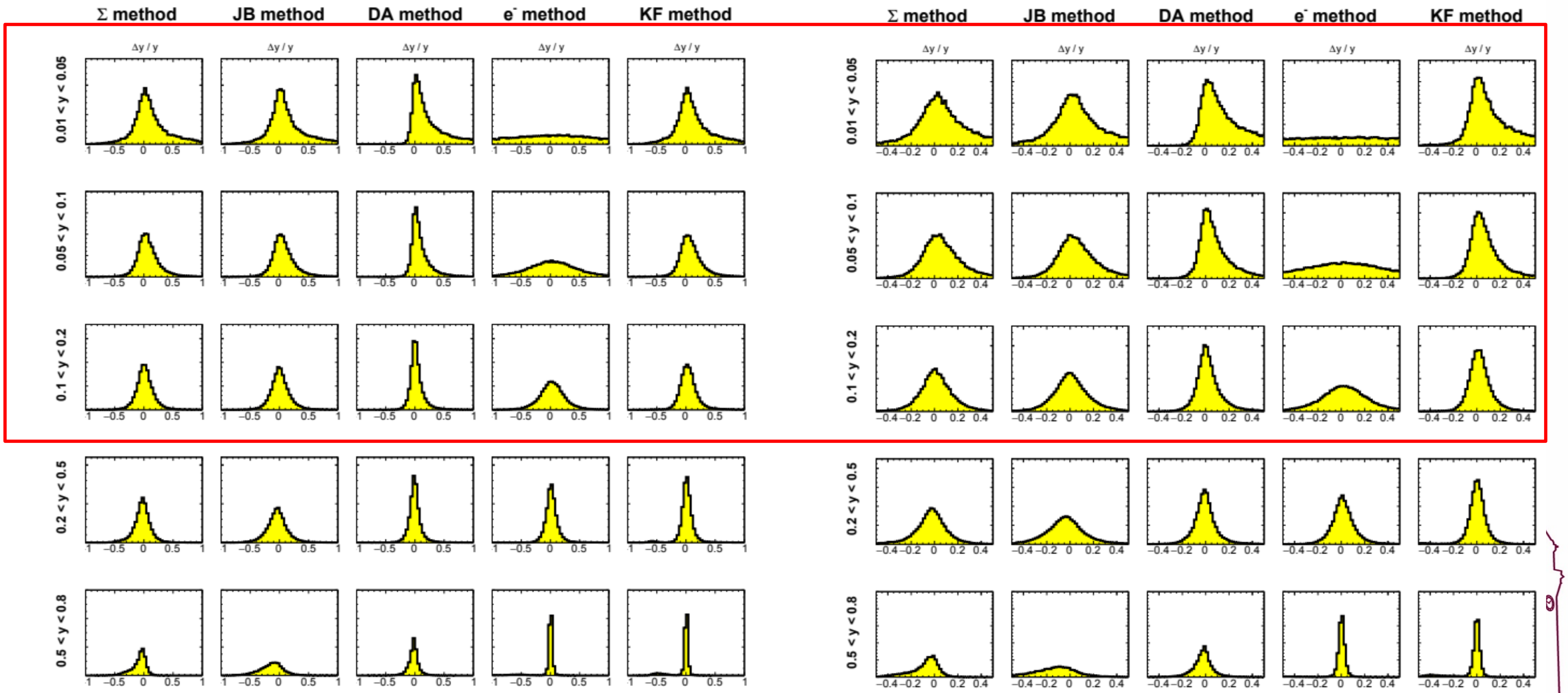
- Compare resolutions: no ISR to with ISR on
  - "Realistic" Σ_{tot} cut of 31 GeV applied to remove high energy ISR
- Some, but not big, difference between observed resolutions
  - Even for the electron method!

*Note different x scale

H1 Resolution on y

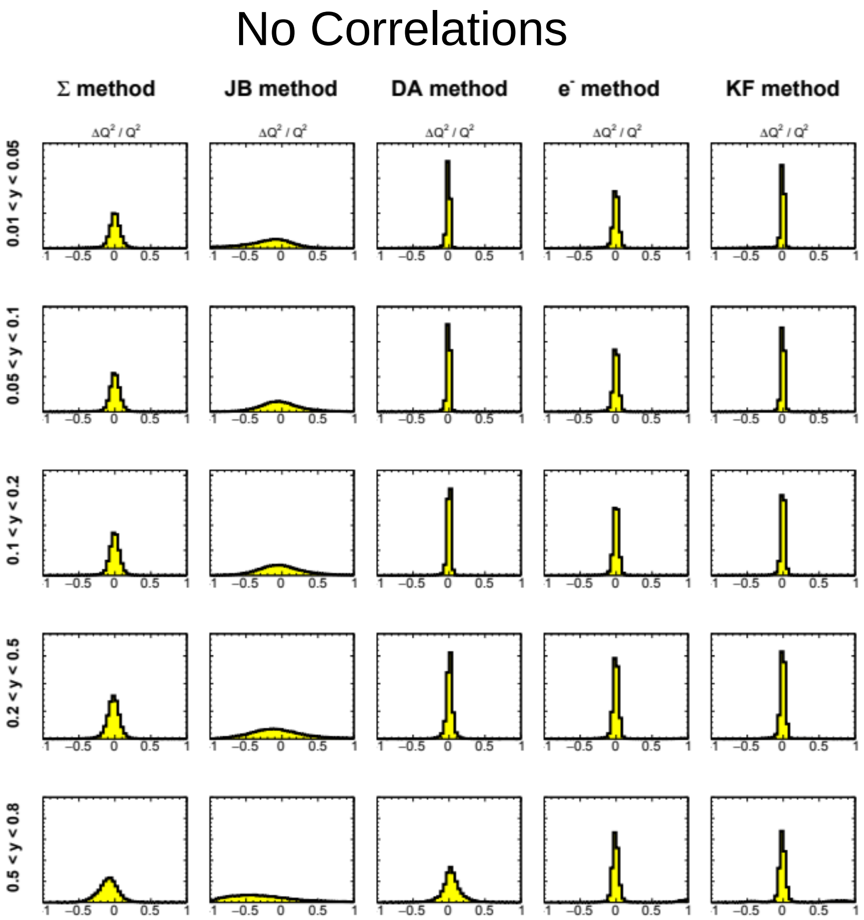
No Correlations

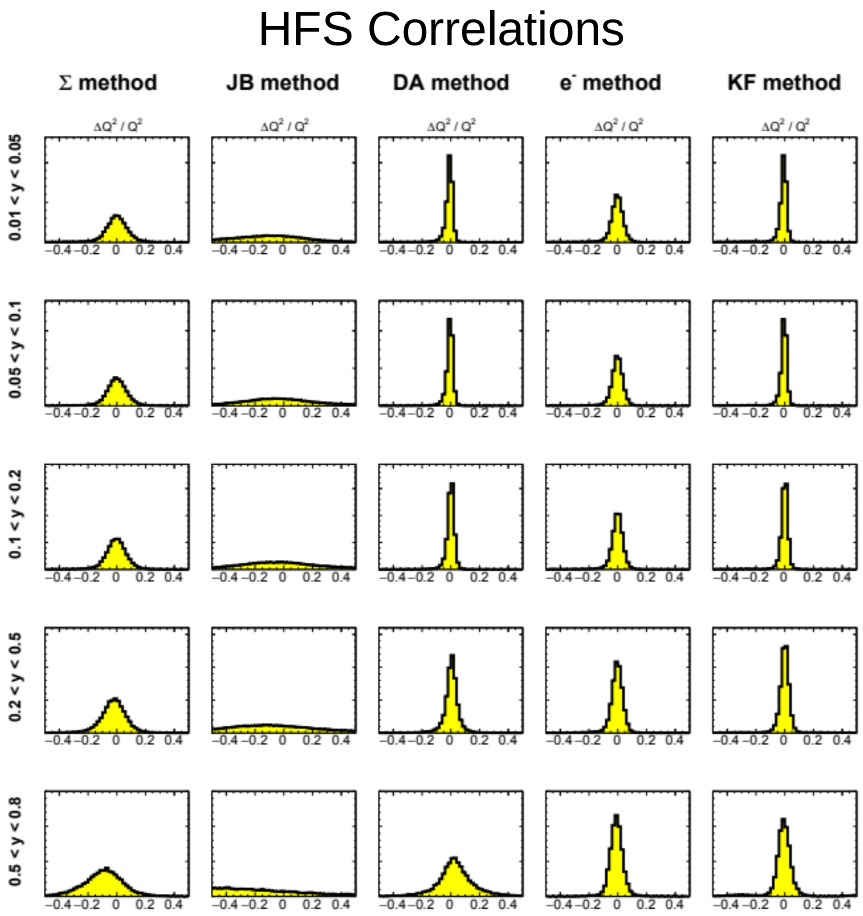
HFS Correlations



*Note different x scale

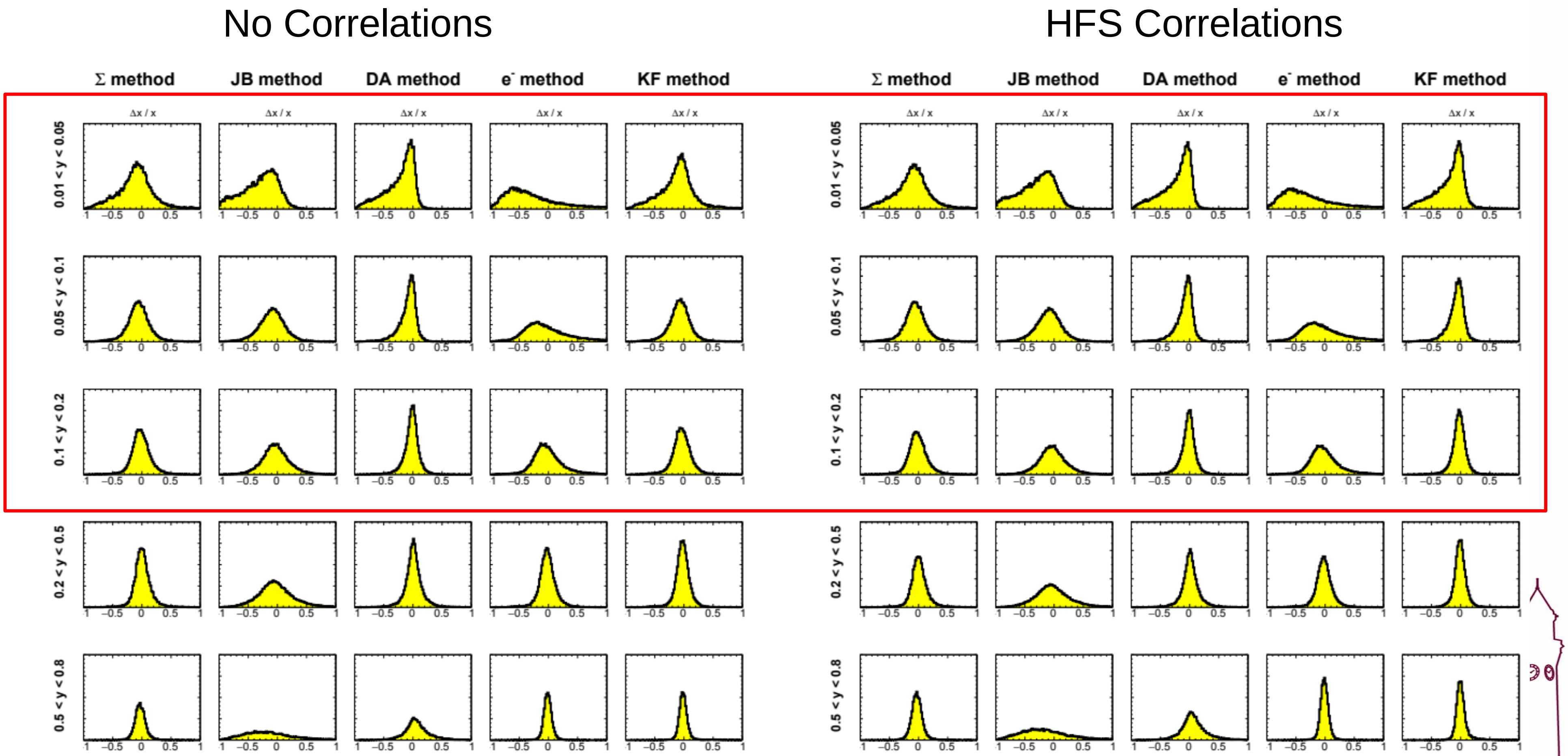
H1 Resolution on Q^2



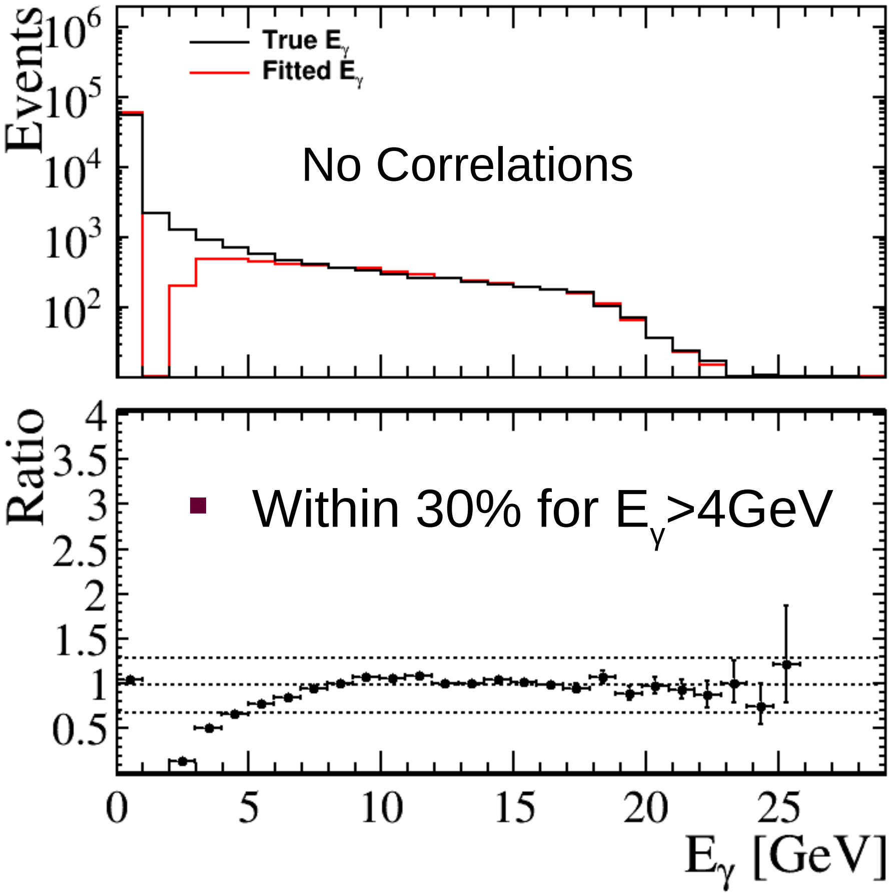


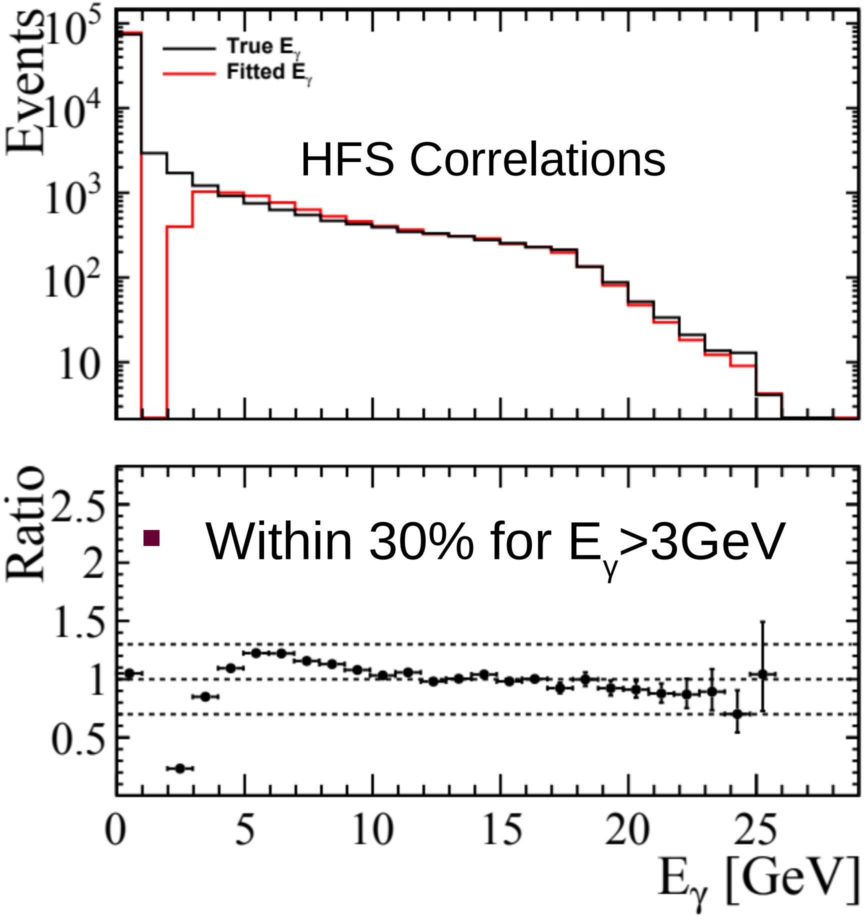
Minimal difference for Q^2

H1 Resolution on x

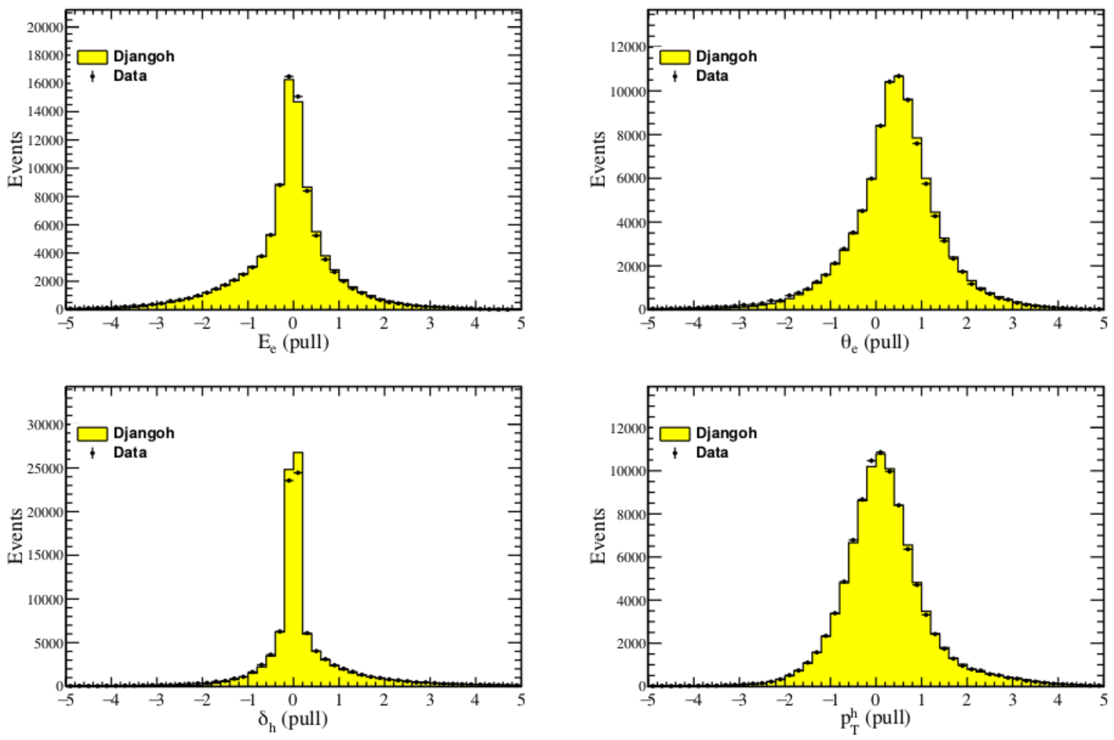


H1 ISR reconstruction





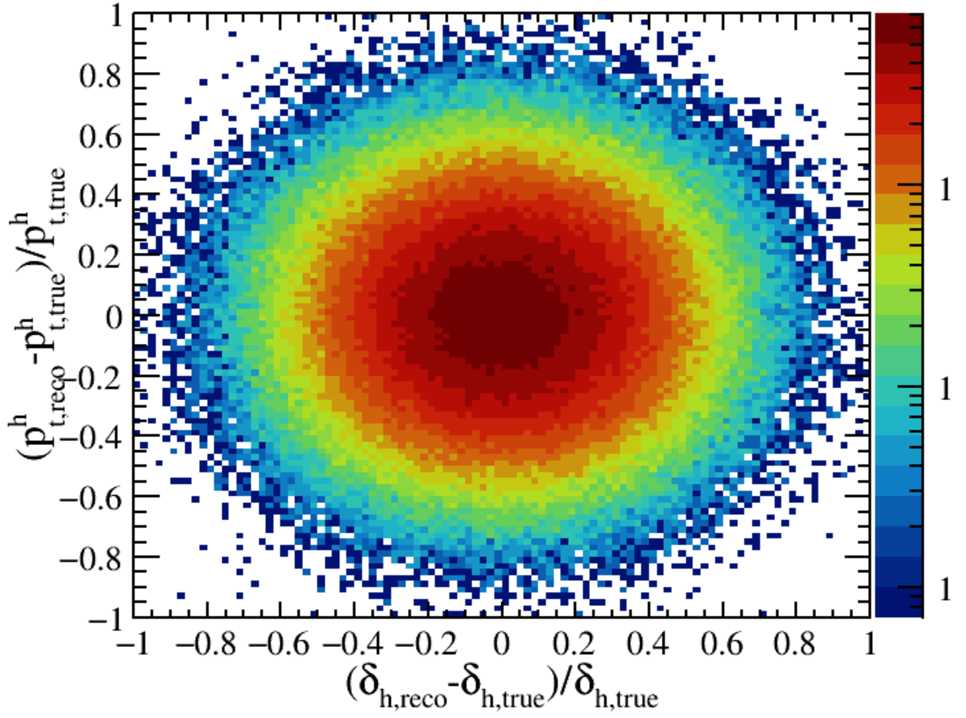
H1 Data and MC (ISR On)

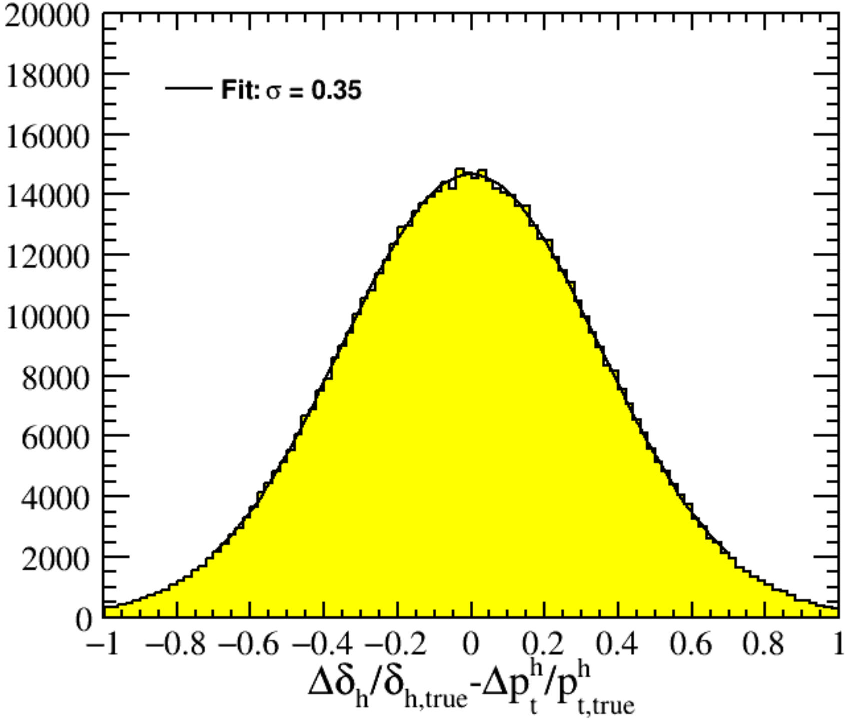


- KF reconstruction is applied with a likelihood function constructed from the following resolutions:
  - $\sigma(\theta_e)$ = 4mrad
  - $\sigma(E_e)$ / E = 11% /sqrt(E) $\oplus$ 1%
  - $\sigma(\delta_h)$ / δ_h = 13.5%
  - $\sigma(p_{T,h})$ / $p_{T,h}$ = 54% /sqrt($p_{T,h}$) $\oplus$ 4%
- No correlation term included for H1 studies
- Good agreement for pulls from data and Djangoh

$$g = \frac{D_{i,fitted} - D_{i,reco}}{RMS_{MC}}$$

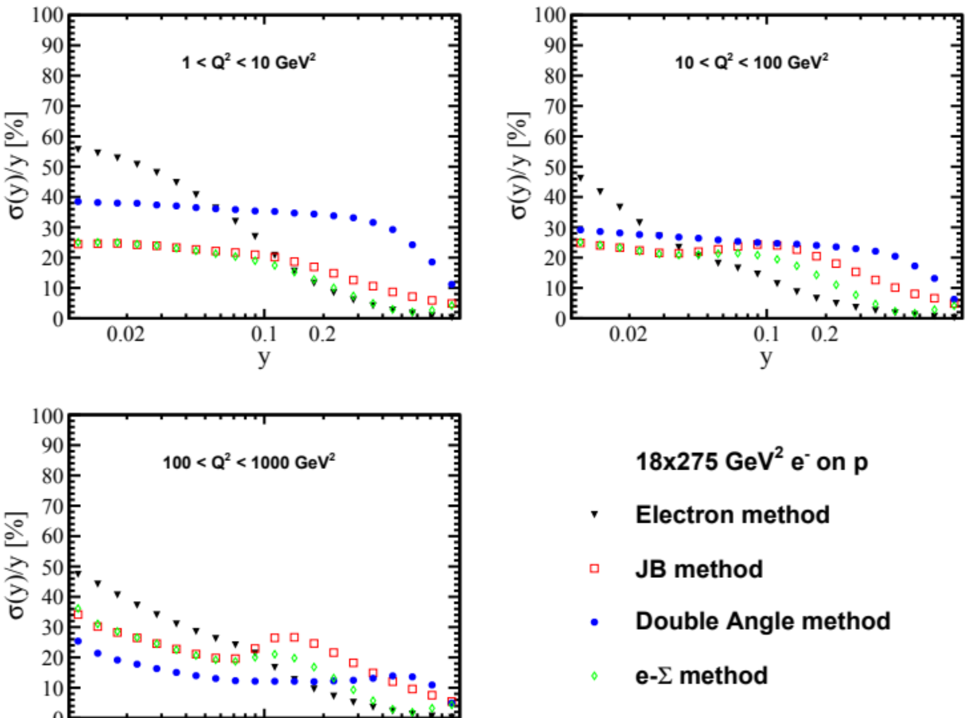
Truth Smearing correlations





Kinematic Reconstruction for EIC – A Brief History

- Assessment of **relative performance of reconstruction methods** for measured phase space in ECCE and ATHENA proposals (2021)



ATHENA