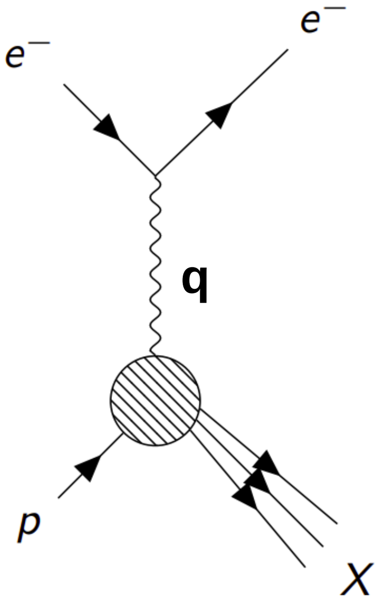
UNIVERSITY OF BIRMINGHAM | SCHOOL OF PHYSICS AND ASTRONOMY

Inclusive DIS and kinematic reconstruction at the EIC

S. Maple

Inclusive Deep Inelastic Scattering



- 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

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

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

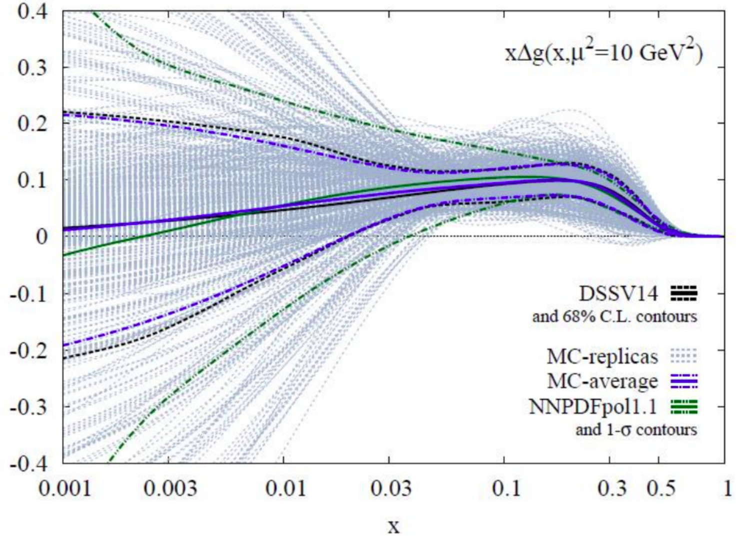
$$\sigma_r = F_2(x, Q^2) - \frac{y^2}{Y_+} F_L(x, Q^2)$$

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

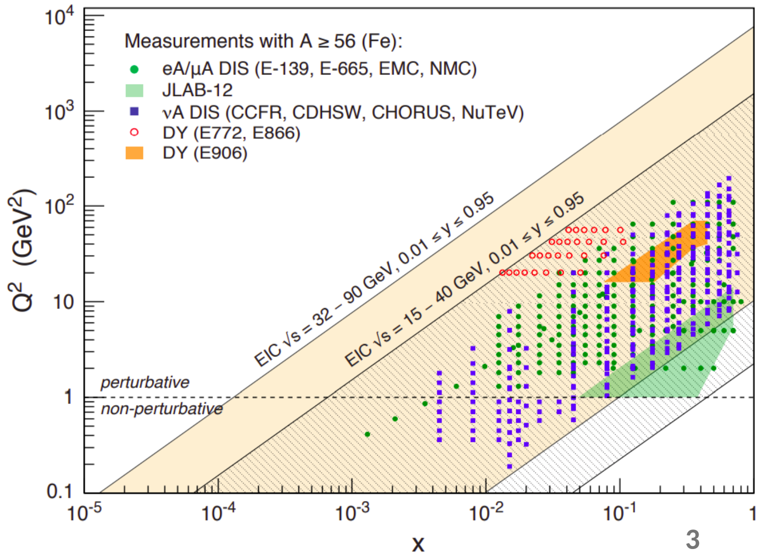
$$\frac{\Delta\sigma}{2} = \frac{1}{2}\left[\frac{d^2\sigma^{\uparrow\downarrow}}{dxdQ^2} - \frac{d^2\sigma^{\uparrow\uparrow}}{dxdQ^2}\right] \simeq \frac{4\pi\alpha^2}{Q^4} y(2-y) g_1(x, Q^2)$$

- 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)

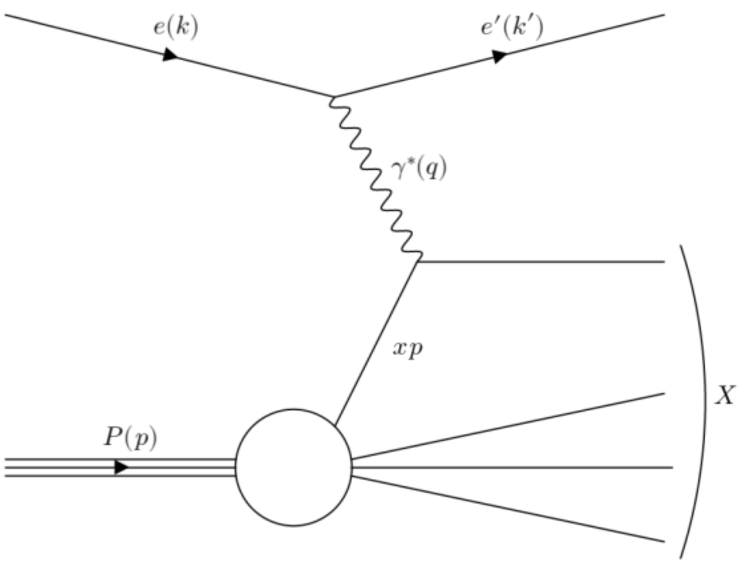


Electron-only Reconstruction

- “Inclusive” in hadronic final state → technically only need to measure scattered electron

$$Q_e^2 = 2E_0E_e(1+\cos\theta_e)$$

$$y_e = 1 - \frac{E_e(1-\cos\theta_e)}{2E_0}$$

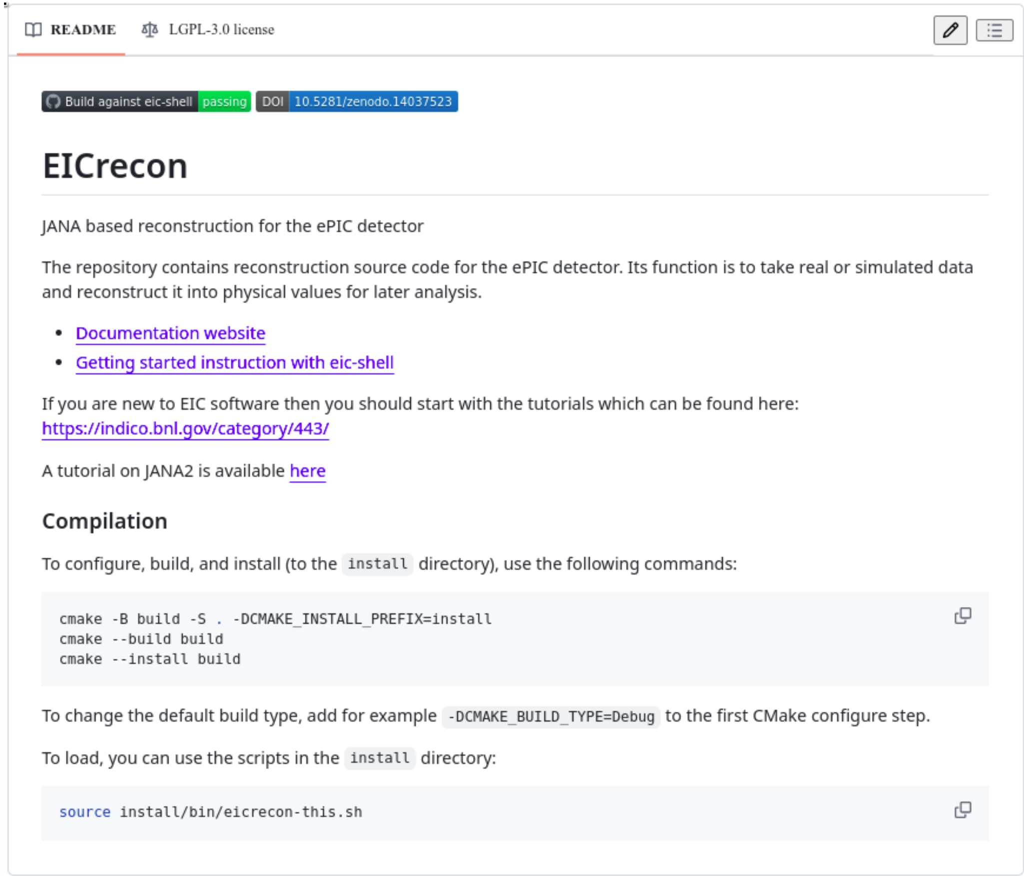


- This requires a high quality reconstruction of the scattered electrons
- Additionally require efficient electron identification and separation from backgrounds

Current status of ePIC reconstruction software

- Reconstruction handled by **EICrecon**

- Development ongoing, last year has seen:
  - **Truth-seeded → Realistic tracking**
    - Triplet seeding
    - Ambiguity resolution
  - **Truth → Realistic calorimeter clustering**
  - **Projection of tracks to calorimeter surfaces**
    - Matching tracks to ECAL cluster
  - **Realistic Electron-finding**



README LGPL-3.0 license

Build against eic-shell passing DOI 10.5281/zenodo.14037523

EICrecon

JANA based reconstruction for the ePIC detector

The repository contains reconstruction source code for the ePIC detector. Its function is to take real or simulated data and reconstruct it into physical values for later analysis.

- Documentation website
- Getting started instruction with eic-shell

If you are new to EIC software then you should start with the tutorials which can be found here: https://indico.bnl.gov/category/443/

A tutorial on JANA2 is available here

Compilation

To configure, build, and install (to the `install` directory), use the following commands:

```
cmake -B build -S . -DCMAKE_INSTALL_PREFIX=install
cmake --build build
cmake --install build
```

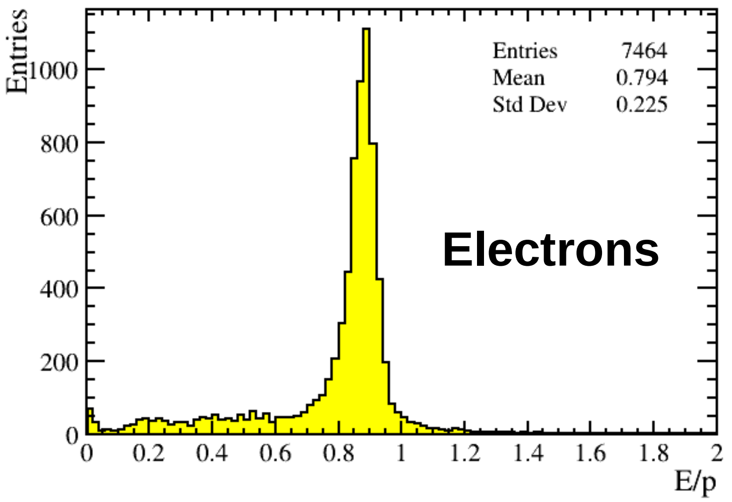
To change the default build type, add for example `-DCMAKE_BUILD_TYPE=Debug` to the first CMake configure step.

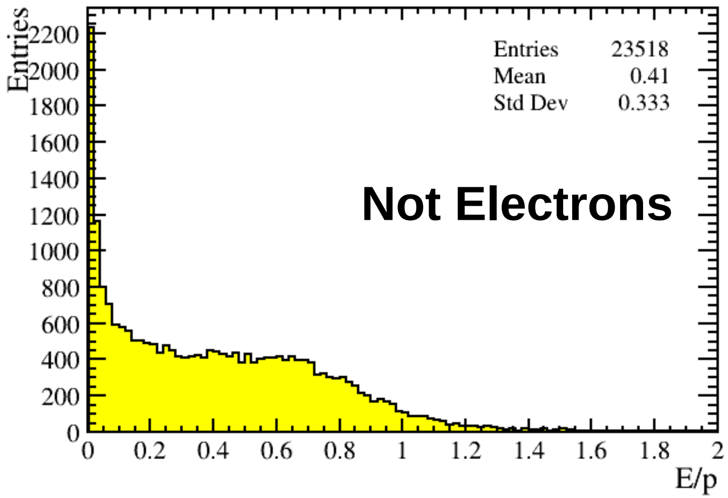
To load, you can use the scripts in the `install` directory:

```
source install/bin/eicrecon-this.sh
```

Electron finding

- Current implementation of electron finder:
  - Identifies electron candidate using an E/p cut
  - Selects highest momentum candidate
- More constraints will become available as software develops:
  - Cluster isolation
  - Ratio of energy deposited in E/HCAL
  - Cherenkov PID





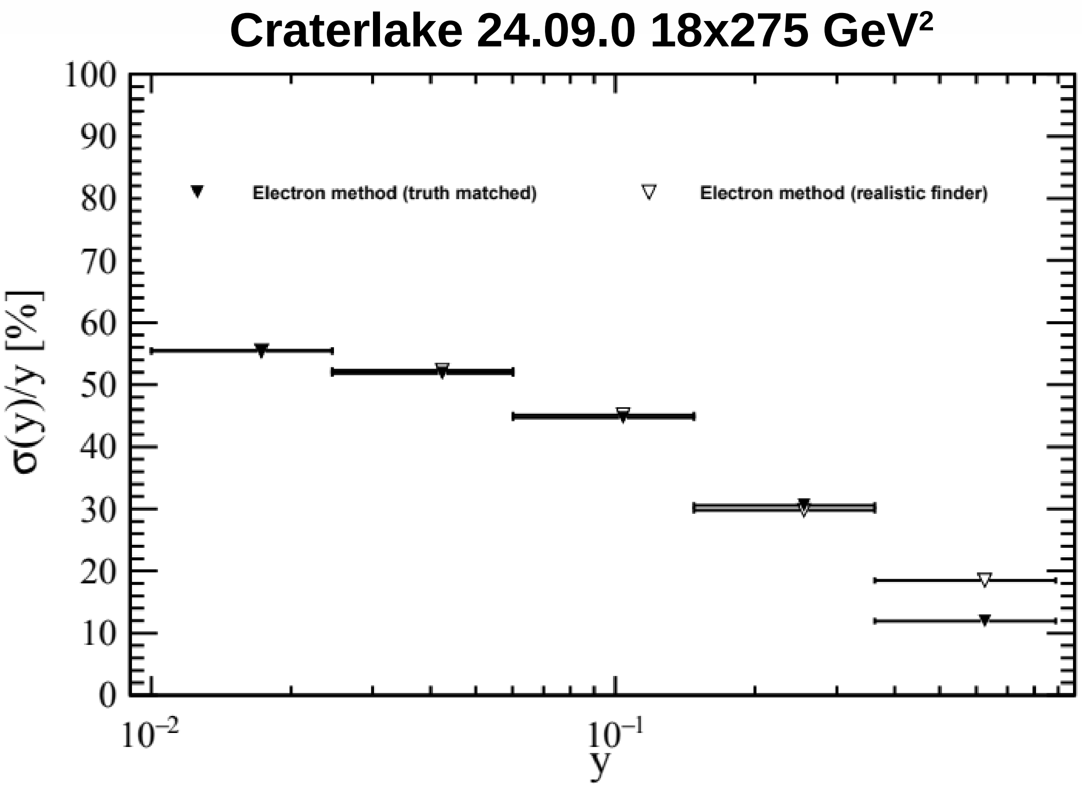
Electron finding (truth vs “realistic”)

- Resolution on inelasticity y used as performance metric
  - $\sigma(y)/y = RMS(y_{rec}/y_{true})$

- Electron-only reconstruction gives same result for truth/realistic finder

- **<u>Except</u> in highest y bin**

- High y = low scattered electron energy → selecting highest momentum candidate becomes inefficient



Electron-only reconstruction performance (tracks vs clusters)

- Reconstruct events from 18x275 GeV^2 24.10.0 campaign
  - **Realistic tracking, calorimetry, electron finding**

- Two inputs required for electron-only reconstruction
  - **E_e, θ_e**

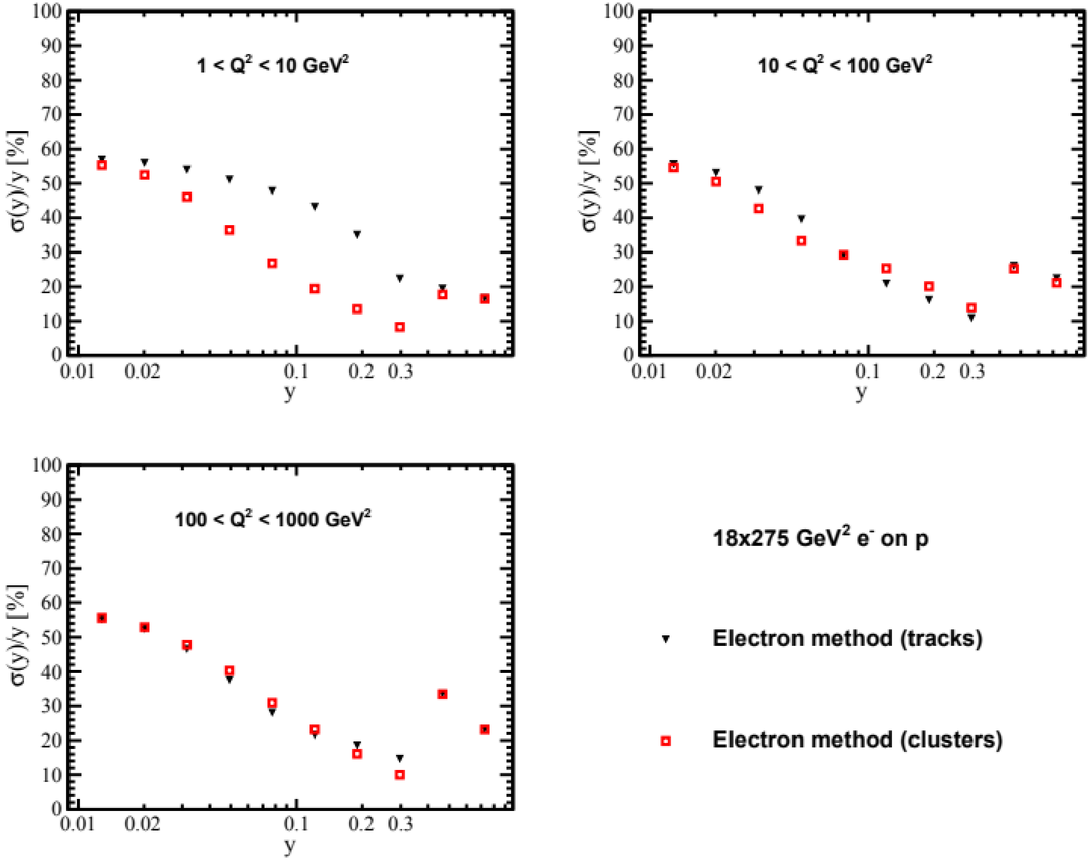
- Take θ_e from tracking
- Take E_e from either the **track momentum** or **energy of matched ECAL cluster**

Electron-only reconstruction performance (tracks vs clusters)

- **$1 < Q^2 < 10$ GeV^2**
  - Energy from clusters outperforms tracks for most of the y range
  - Highest y bins show same y reconstruction performance → misidentified electrons dominate resolution

- **$10 < Q^2 < 1000$ GeV^2**
  - Performance similar for both approaches

- **Q^2 highly correlated with θ_e → tracking poor for small angles (small B.dL)**

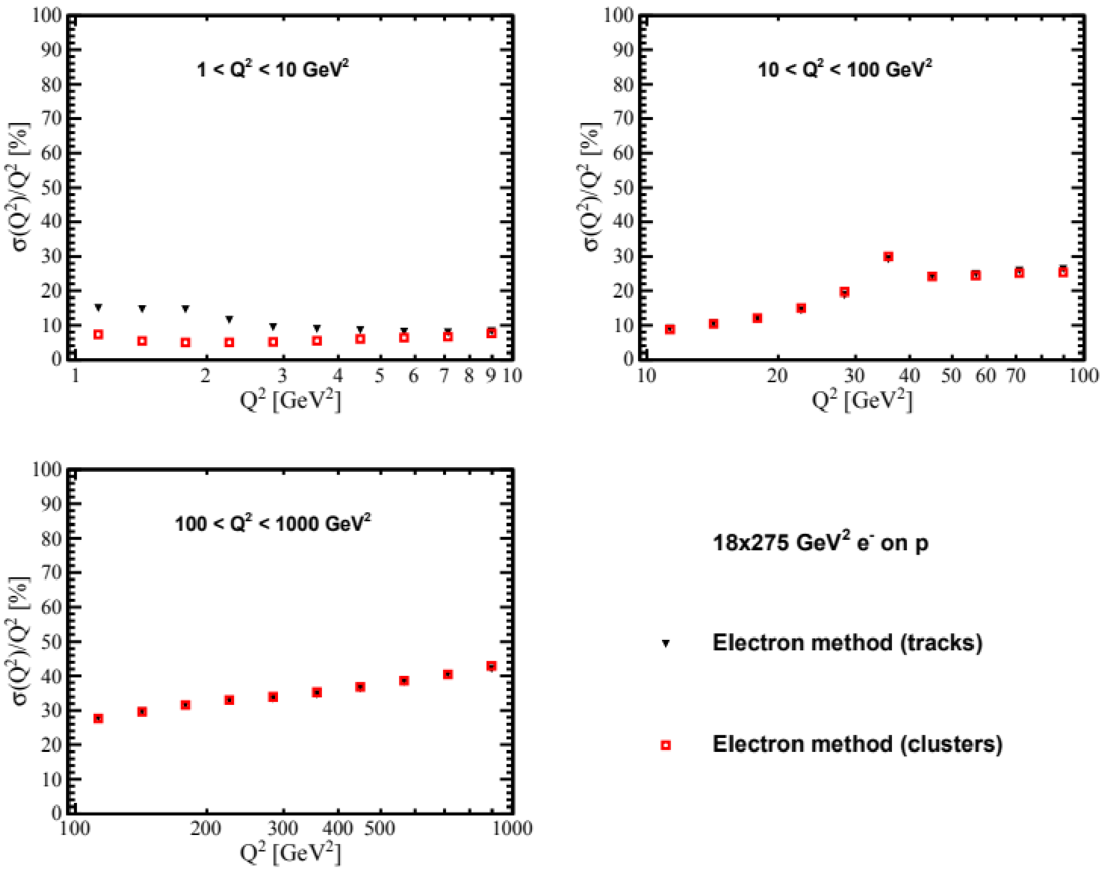


Electron-only reconstruction performance (tracks vs clusters)

- **$1 < Q^2 < 10$ GeV^2**
  - Energy from clusters outperforms tracks at low Q^2
  - As Q^2 increases, performances match → limited by θ_e resolution

- **$10 < Q^2 < 1000$ GeV^2**
  - Q^2 resolution similar for both approaches

- **Conclusion: E_e from clusters gives superior reconstruction at small θ_e (small Q^2) → doesn't matter elsewhere**



Performance with other methods

- Kinematics can be reconstructed using scattered electron alone
  - Electron method degrades at low y, and is impacted by initial/final state QED radiation
  - **Approaches using the hadronic final state (HFS) may give better reconstruction**
- Double angle method uses the ratio $p_{t,h}/\delta_h$ → uncertainties associated with HFS energy measurement cancel out
- Σ/e-Σ method do not directly use E_0 → resistant to ISR
- JB/hadron-only method (not shown) – only method available for CCDIS

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

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

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

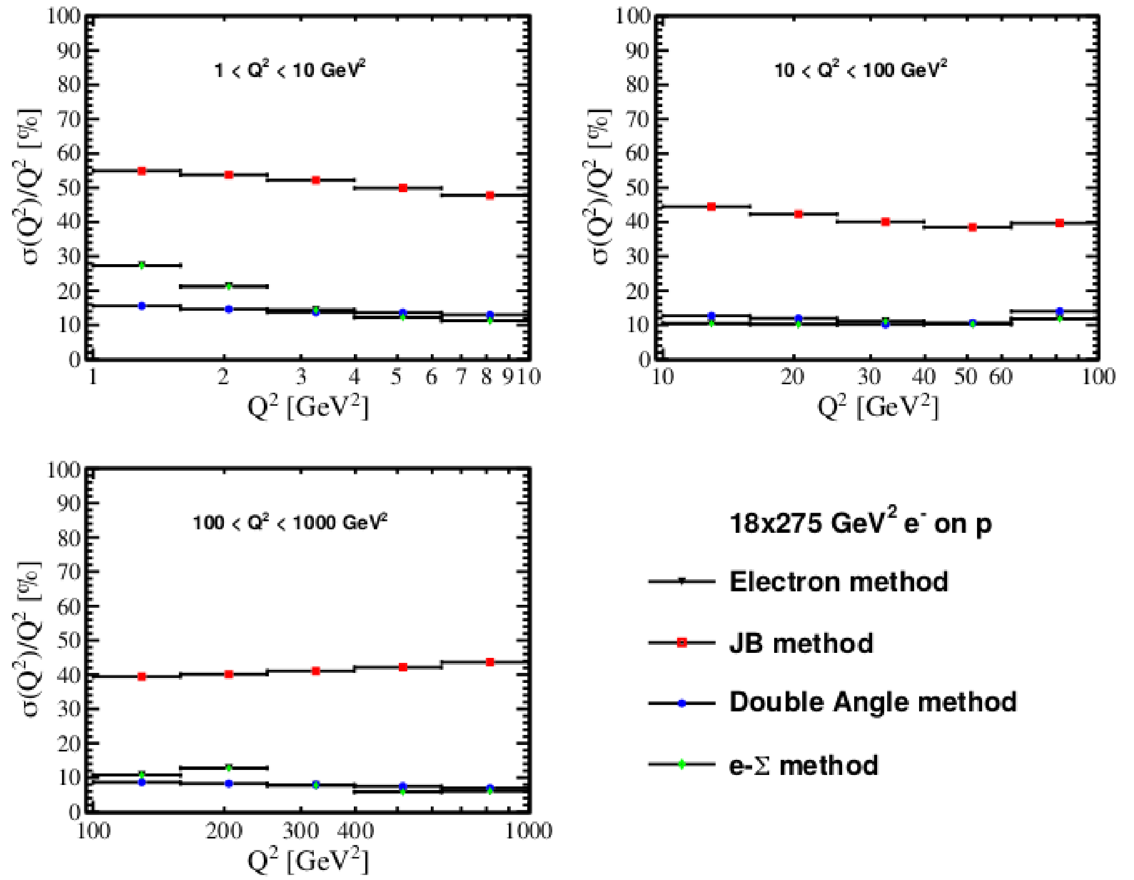
- $\vec{\mathbf{D}} = \{\mathbf{E_e}, \boldsymbol{\theta_e}, \boldsymbol{\delta_h}, \mathbf{p_{t,h}}\}$
  - Where $\boldsymbol{\delta_h}$ is $\mathbf{E - p_z}$ sum of all particles in the Hadronic Final State: $\mathbf{\Sigma\, E_i(1 - \cos\theta_i)}$
  - $\mathbf{P_{t,h}}$ is the transverse momentum of the HFS

Performance with other methods

- Evaluate performance with different reconstruction methods
  - Craterlake 23.12.0 (truth-seeding → currently inefficiency at low p_t for realistic tracking)

- Q^2 resolution for electron/mixed methods converges for $Q^2 > \sim 3GeV^2$

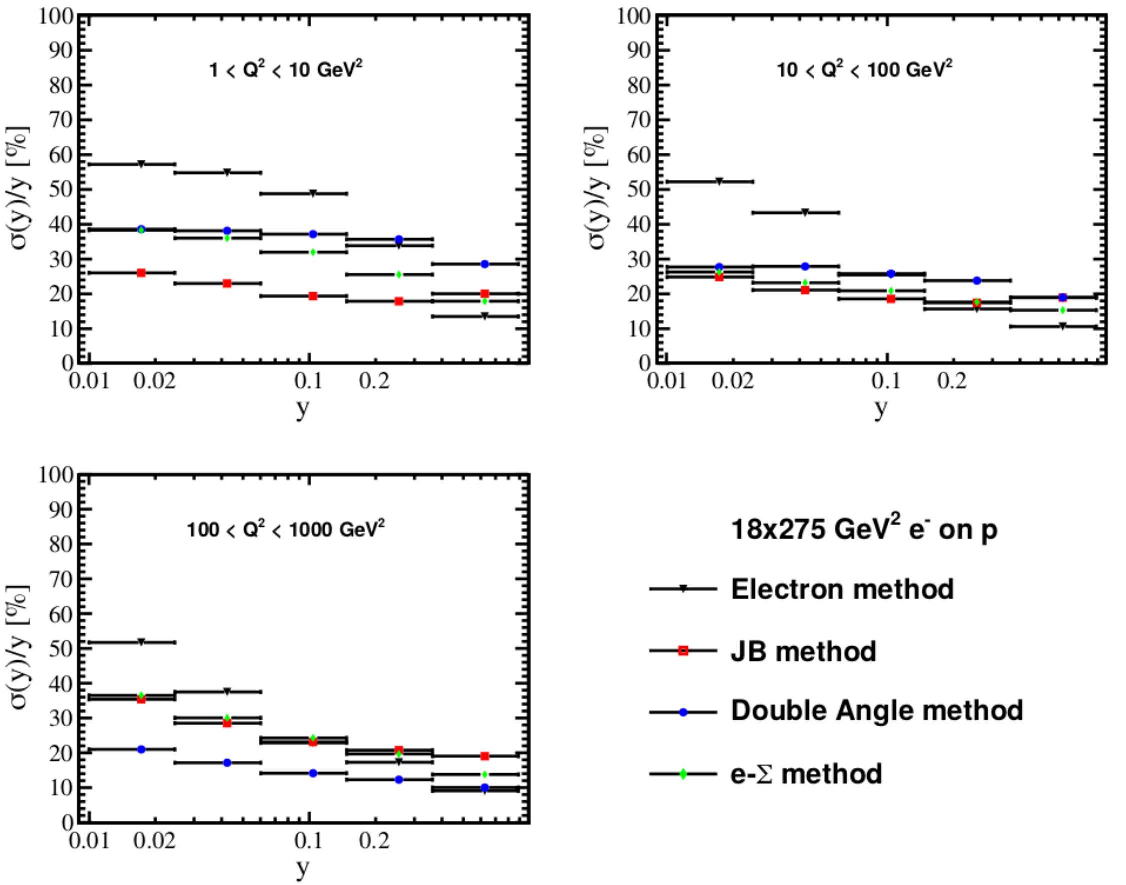
- JB method gives poor Q^2 resolution



Performance with other methods

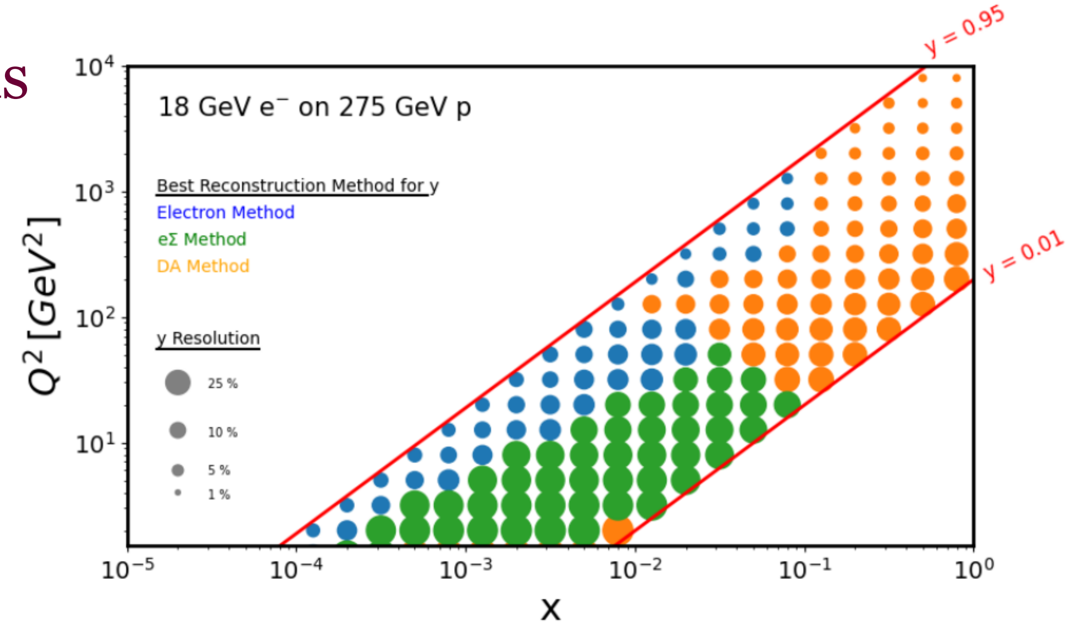
- Resolution on y is more typical performance metric than Q^2
  - Electron method wins at high y
  - DA method at low/mid y high Q^2
  - E-Σ at low/mid y, low Q^2

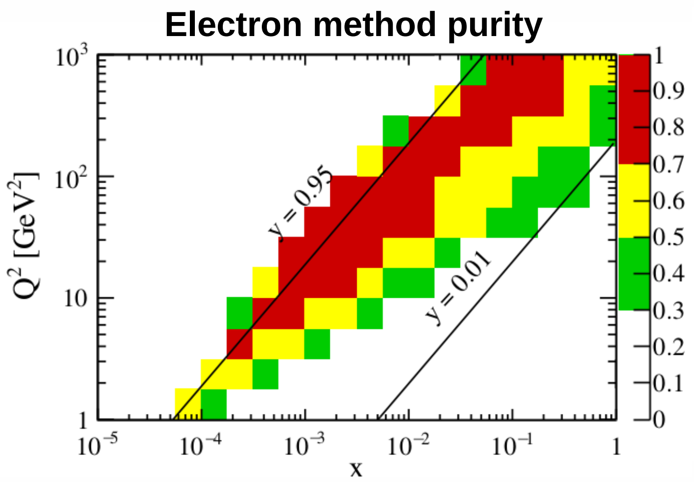
- JB method gives good y resolution, but poor Q^2 resolution limits its usefulness in reconstructing x-Q^2

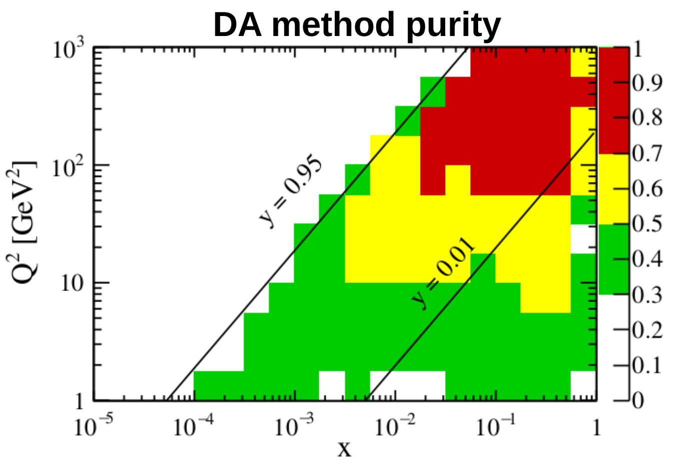


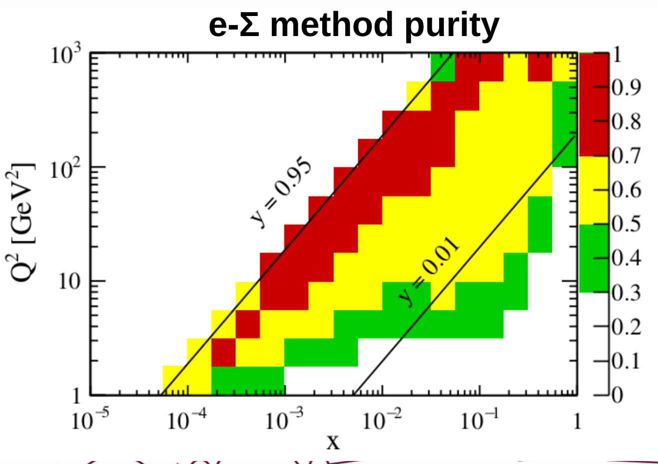
Performance with other methods

- Choosing best method allows a reasonably fine binning scheme to be chosen while maintaining sufficient bin purity



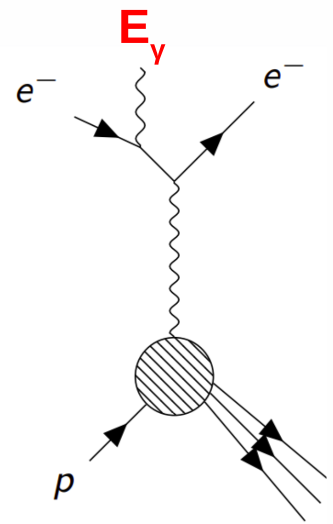






Kinematic Fitting

- Multiple methods should not be required to achieve the best reconstruction
  - If all inputs are used optimally, the best reconstruction should be achieved with a single method



- Using measured quantities $\vec{\mathbf{D}} = \{E_e, \theta_e, \delta_h, p_{t,h}\}$ an event-by-event kinematic fit can provide the best reconstruction and extract additional information: $\vec{\boldsymbol{\lambda}} = \{x, y, E_\gamma\}$

E_γ is energy of an ISR photon

- For kinematic fit, can use a **likelihood** function based on knowledge
  of the detector resolutions:

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

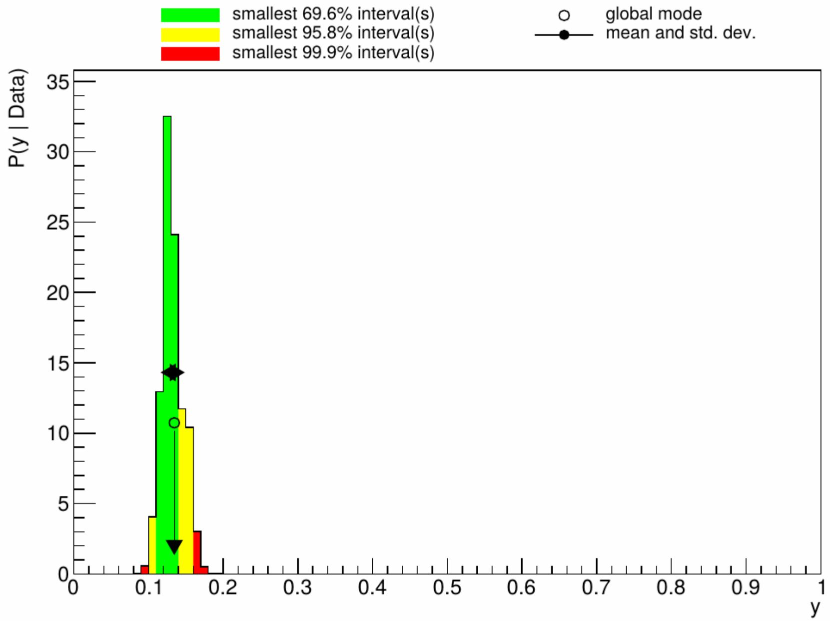
Kinematic Fitting – A Bayesian Approach

- A Bayesian method can be applied in which basic features of the DIS cross section are encoded as a **prior**:

Prior

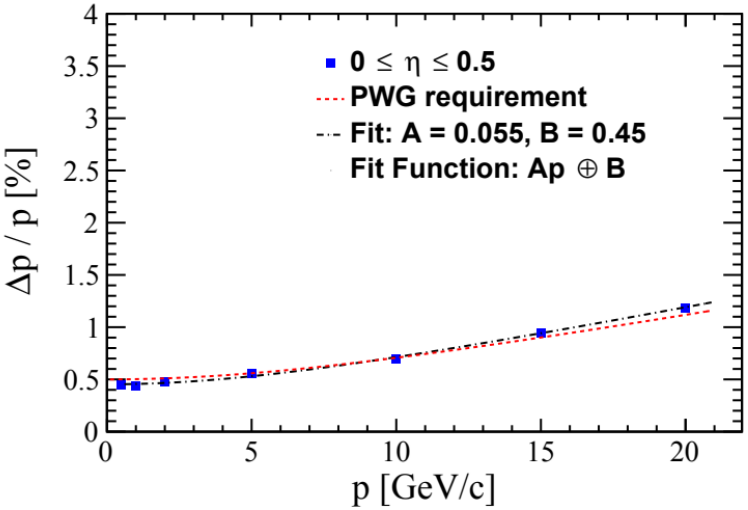
$$P_o(\vec{\lambda}) = \frac{1+(1-y)^2}{x^3y^2}\,\frac{[1+(1-E_\gamma/A)^2]}{E_\gamma/A}$$

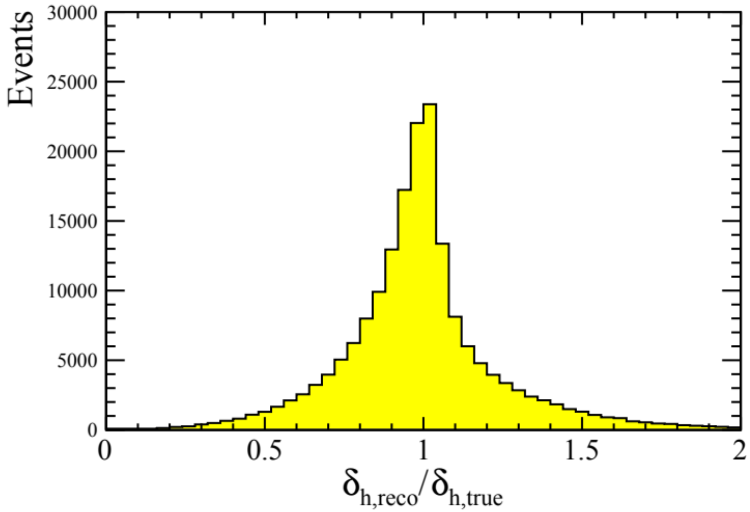
- Use "Bayesian analysis toolkit" to calculate most probable values of set $\vec{\lambda}$ given measured quantities $\vec{D}$
  - Values for **x, y, E_γ** taken from global mode

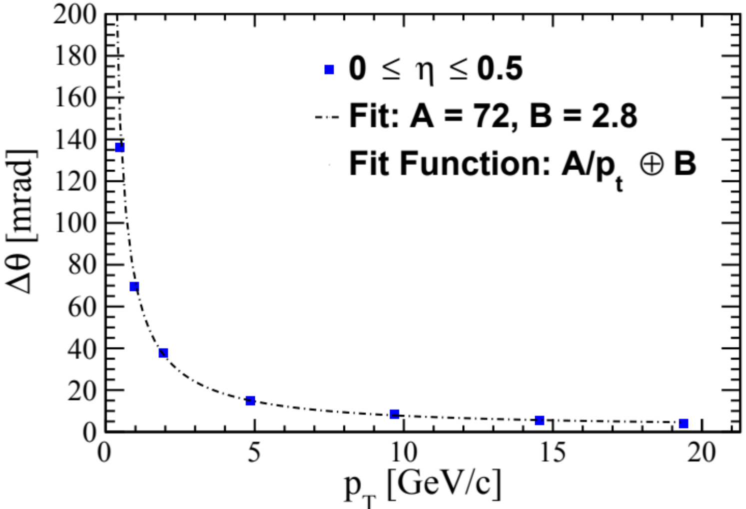


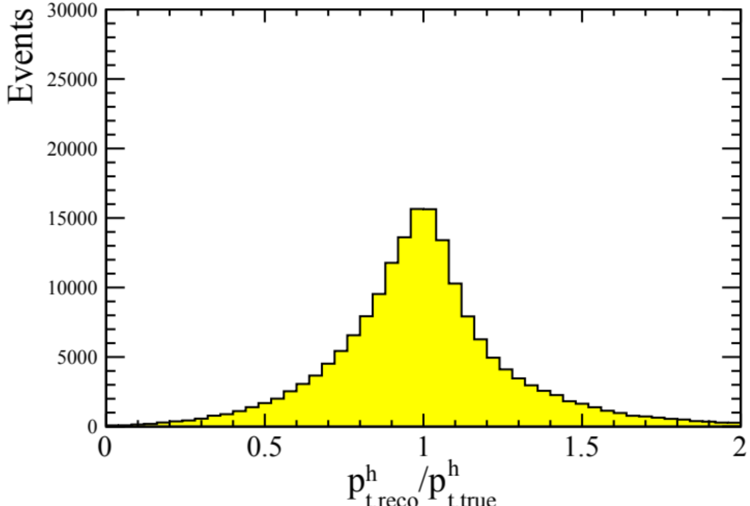
Marginalised **y** distribution for a single DIS event

Fully Simulated ePIC pseudodata (No ISR)









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

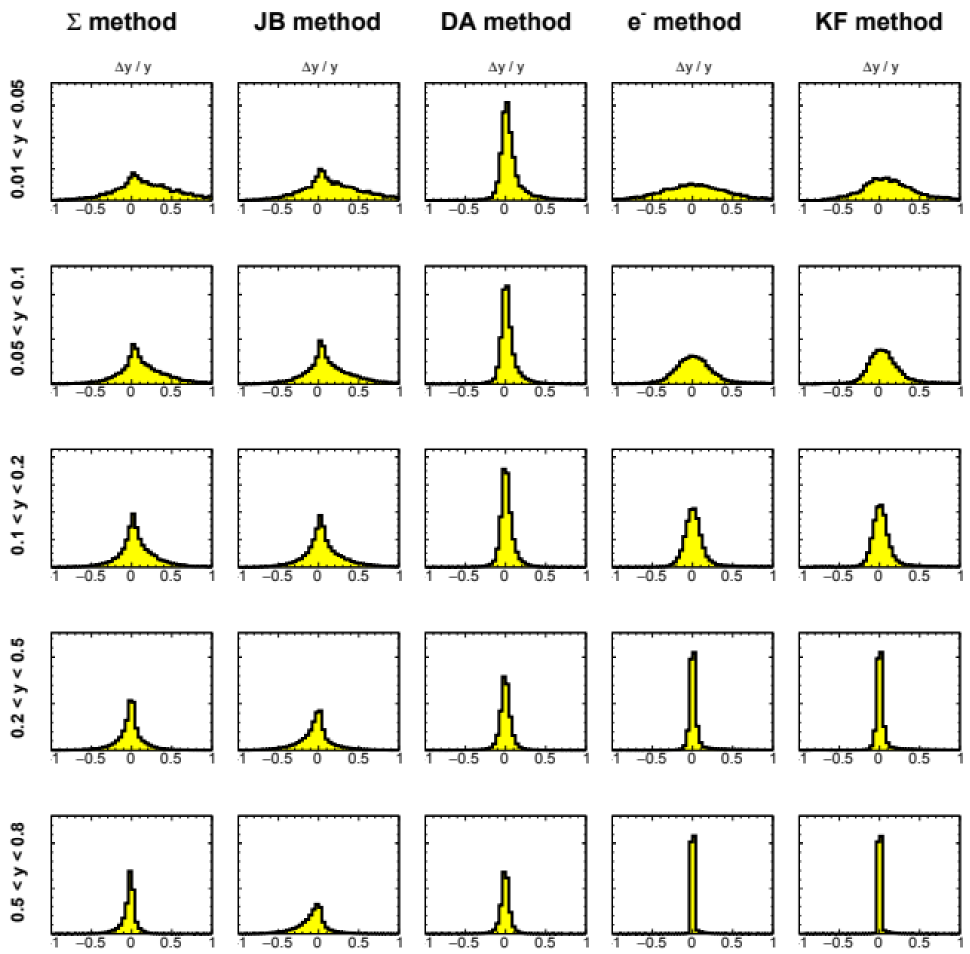
$$\sigma_\theta = 72/p_t \oplus 2.8 \text{ in mrad}$$

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

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

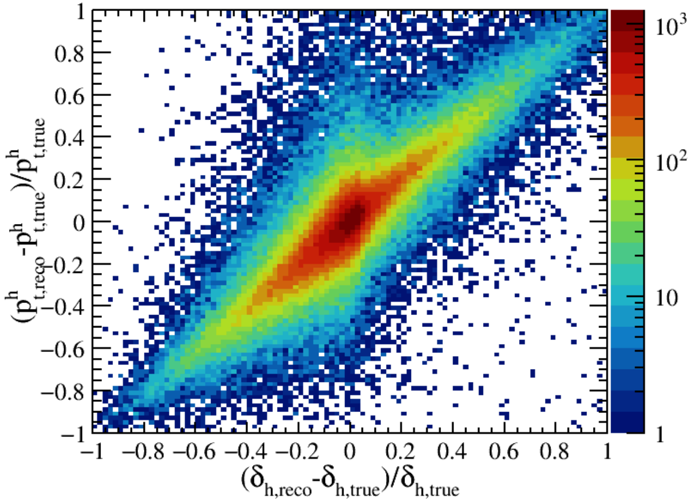
- Parametrised ePIC full sim resolutions
  - Pythia8 NCDIS
  - Craterlake 23.12.0
  - $Q^2 > 100$ GeV^2
  - Ele from tracking

Fully Simulated ePIC pseudodata (No ISR)



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

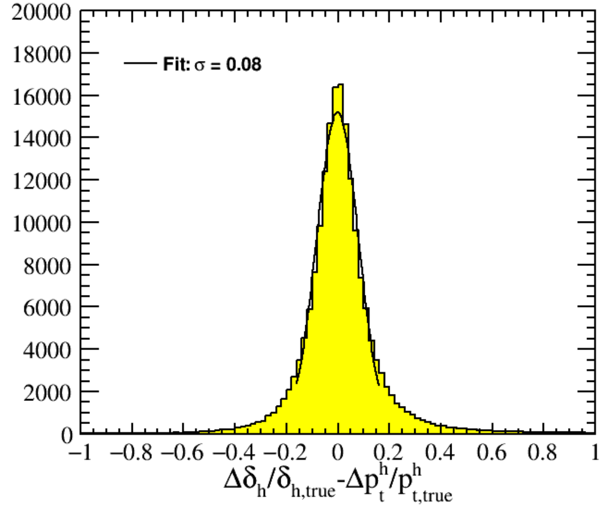
HFS Correlations



- 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:

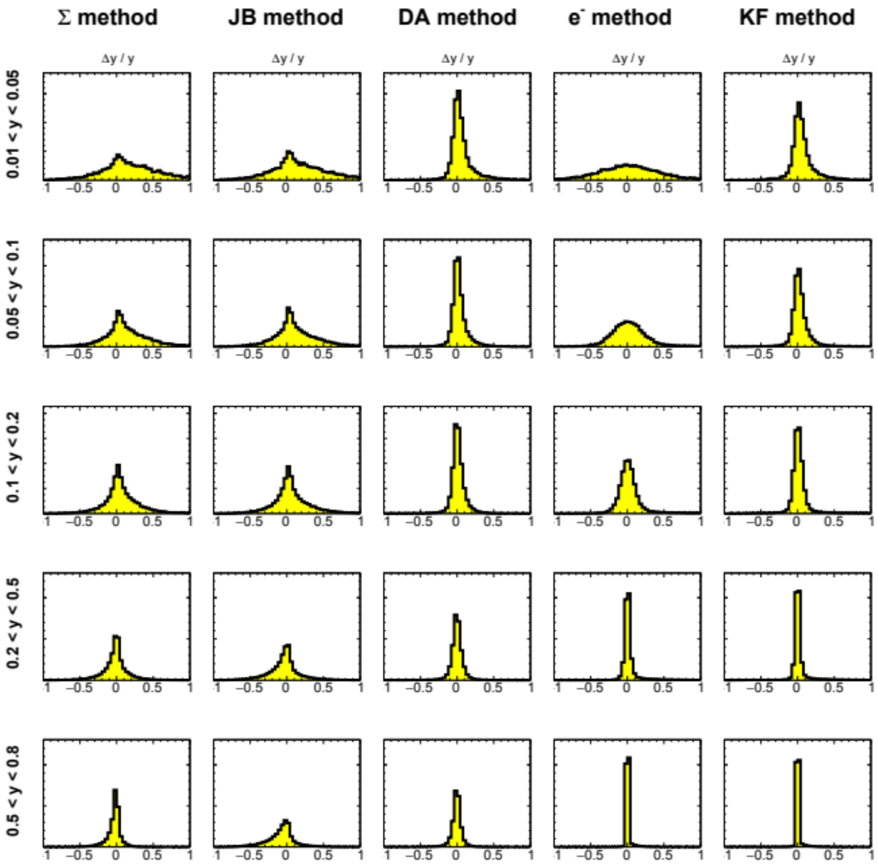
$$P(\vec{D}|\vec{\lambda})_{corr} = P(\vec{D}|\vec{\lambda})_{uncorr}\frac{1}{\sqrt{2\pi}\sigma_{corr}} \cdot \exp -\frac{(c-c^{\lambda})^2}{2\sigma^2_{corr}}$$

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



Correlation width σ_{corr}~8%

Fully Simulated ePIC pseudodata (No ISR) – HFS Correlation



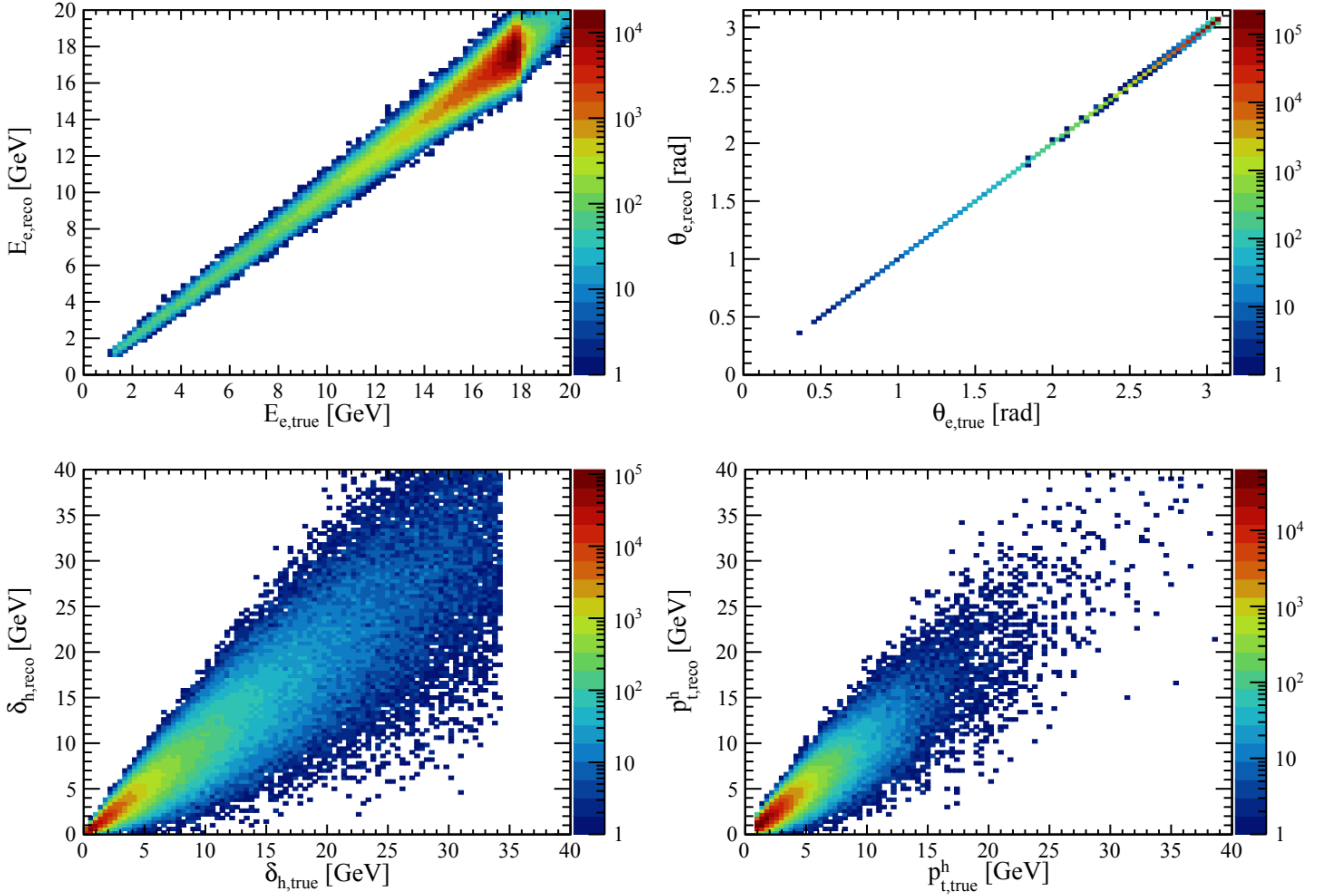
- **Performance of KF recovered at low y!**
  - Not yet perfect → but performance comparable to DA method achieved at low y, while maintaining electron method performance at high y
- Further improvements in likelihood possible for HFS resolutions and correlation parametrisations

Summary

- **Wealth of opportunities for inclusive physics at the EIC**
- **Software for ePIC rapidly developing**
  - Early version of electron-finder working well for low/mid y
  - To be updated as software progresses
- **Inputs to kinematic reconstruction methods important for optimising reconstruction**
  - Electron energy should be taken from calorimeters at low Q^2, at higher Q^2 tracker is also viable
- **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

Backup

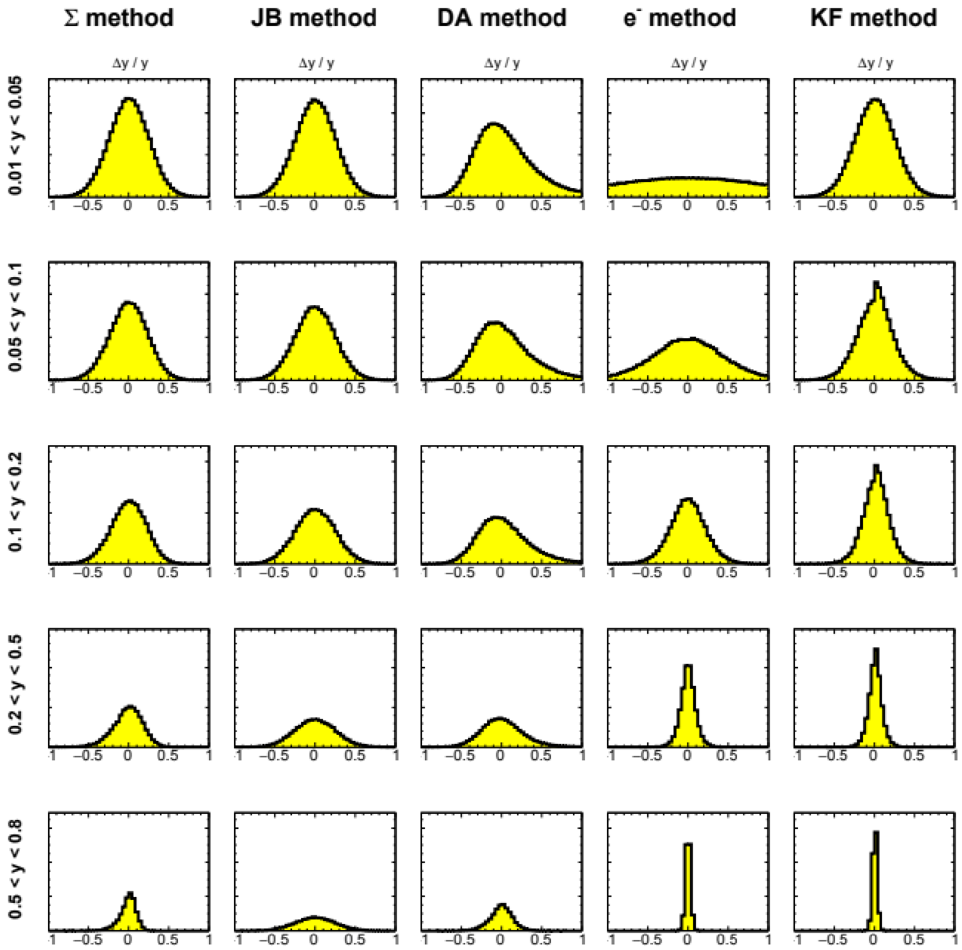
Smeared EIC pseudodata



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

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

Smeared EIC pseudodata (No ISR)



- Smearing resolutions used as input for KF

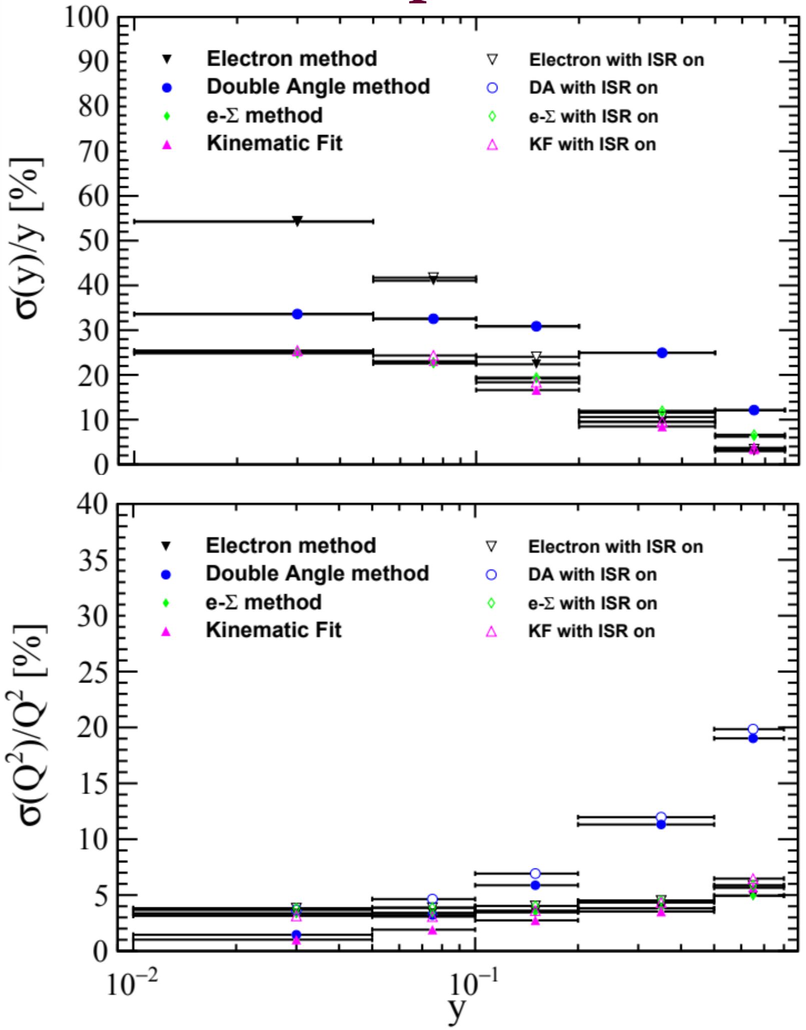
$$P(\vec{D}|\vec{\lambda}) = \frac{1}{\sqrt{2\pi}\sigma_E} \exp -\frac{(E_e - E_e^{\lambda})^2}{2\sigma_E^2} \times \frac{1}{\sqrt{2\pi}\sigma_\theta} \exp -\frac{(\theta_e - \theta_e^{\lambda})^2}{2\sigma_\theta^2} \times \frac{1}{\sqrt{2\pi}\sigma_{\delta_h}} \exp -\frac{(\delta_h - \delta_h^{\lambda})^2}{2\sigma_{\delta_h}^2}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

- Stick to using prior 1 from https://arxiv.org/abs/2206.04897

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

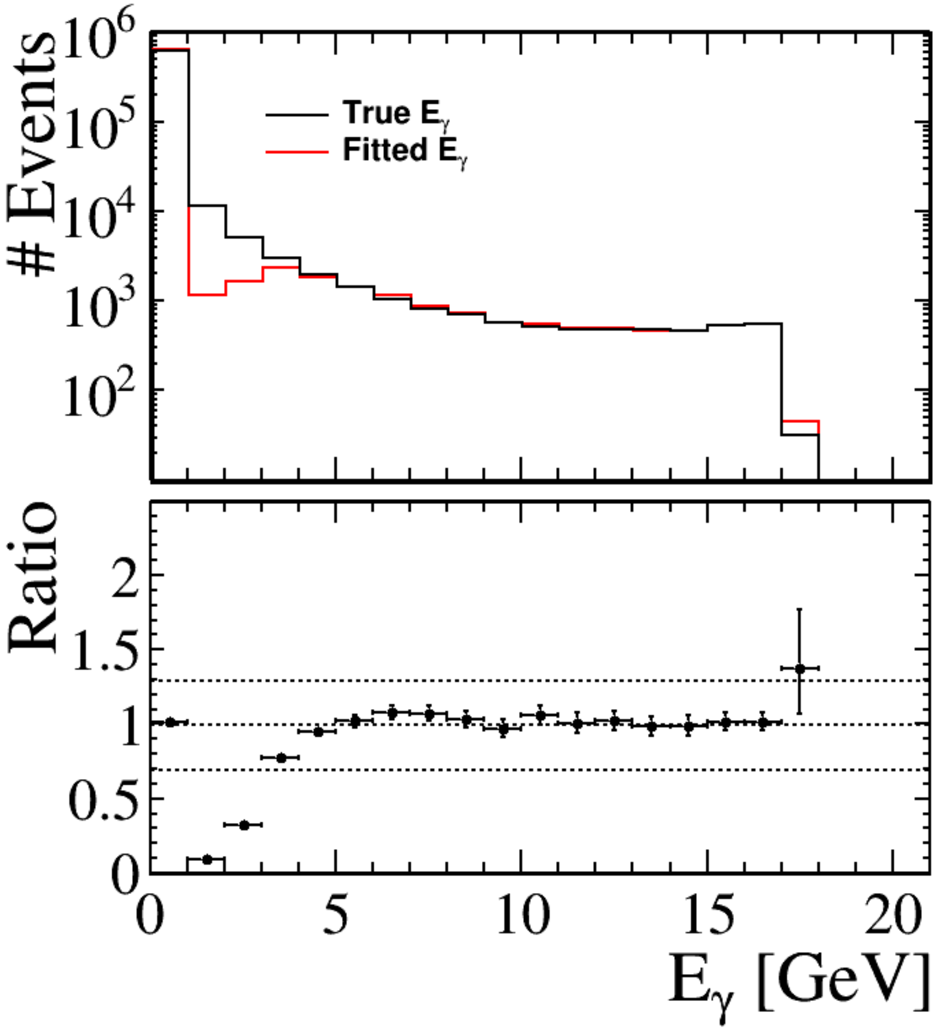
- Compare y resolutions:
  - KF method meets or exceeds conventional

Smeared EIC pseudodata (W/ ISR)

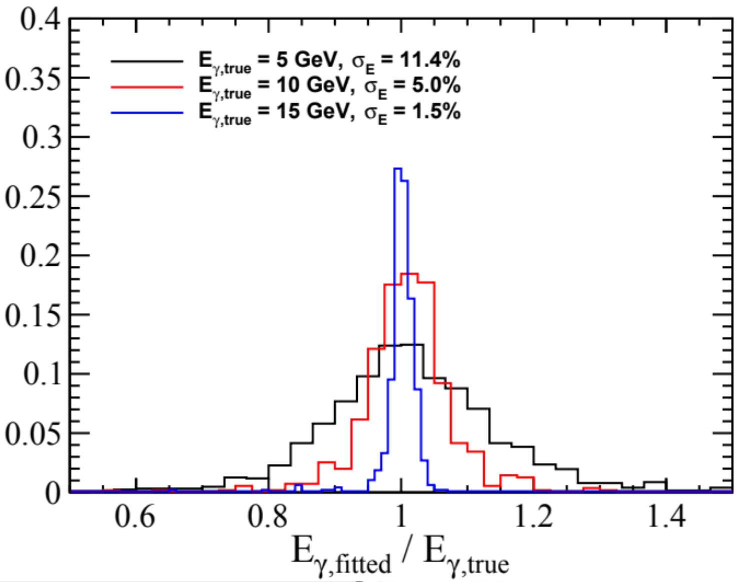


- Compare resolutions: no ISR to with ISR on
  - "Realistic" Σ_{tot} cut of 31 GeV applied to remove high energy ISR
- Some, but not big, difference between observed resolutions
  - Even for the electron method!

Smeared EIC pseudodata (W/ ISR)

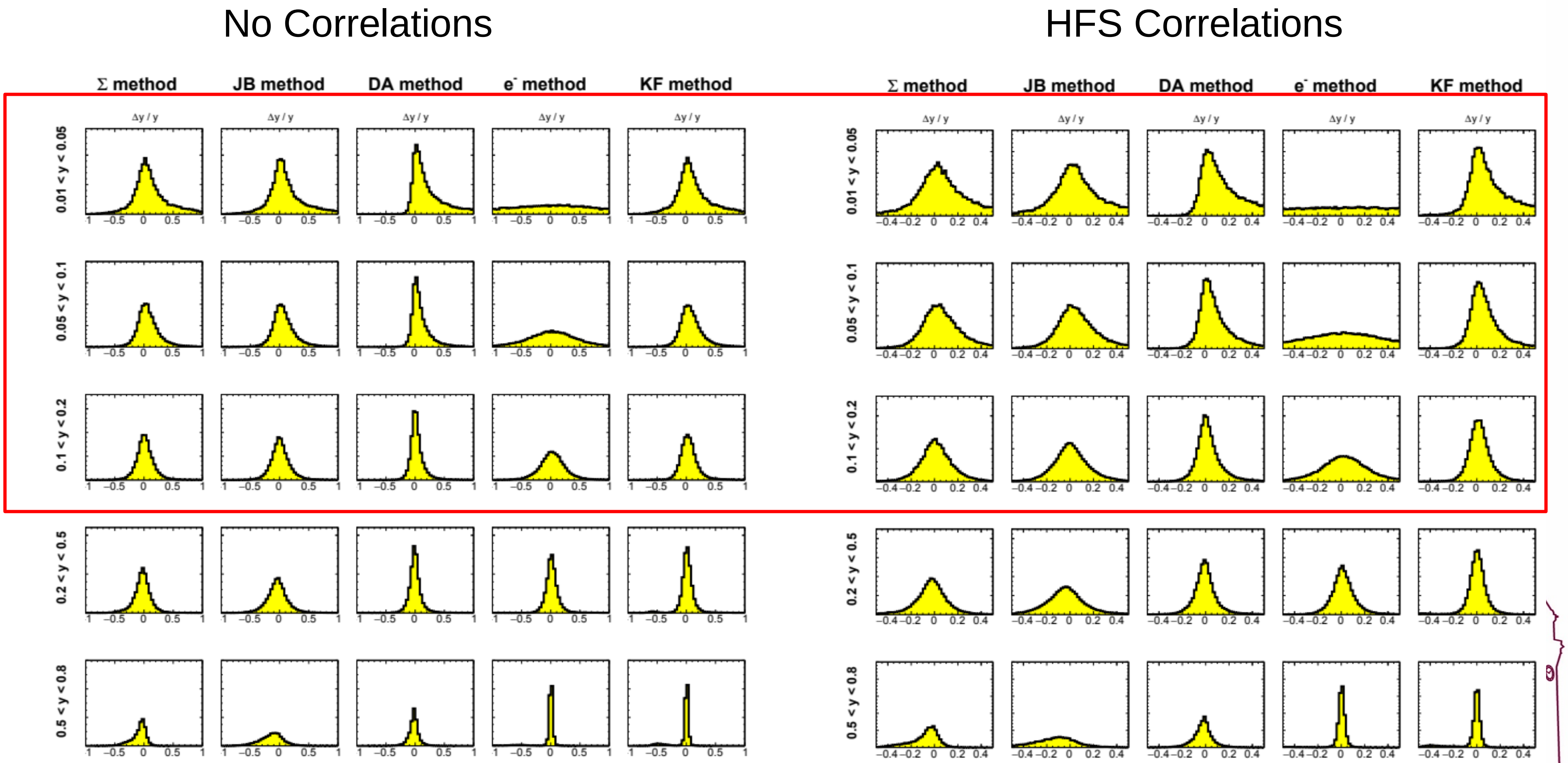


- Compare true and measured ISR energy distributions
  - Distribution well reproduced for higher E_γ
  - Ratio within 30% for E_γ > 3 GeV
  - Within 10% for E_γ > 4 GeV
- Reasonable resolution



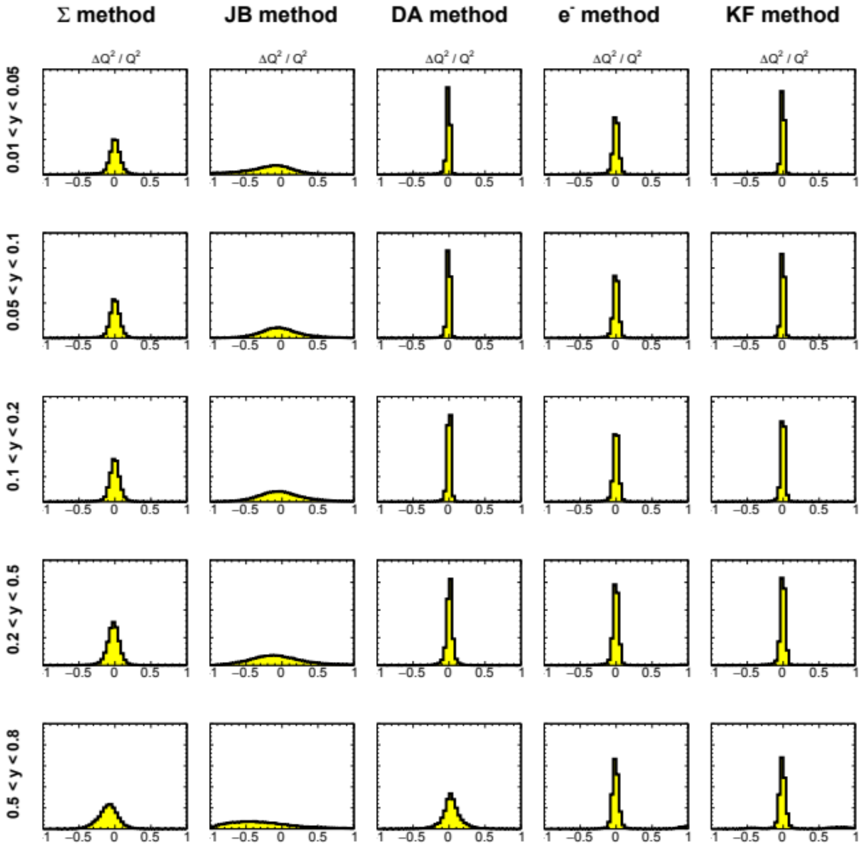
*Note different x scale

H1 Resolution on y

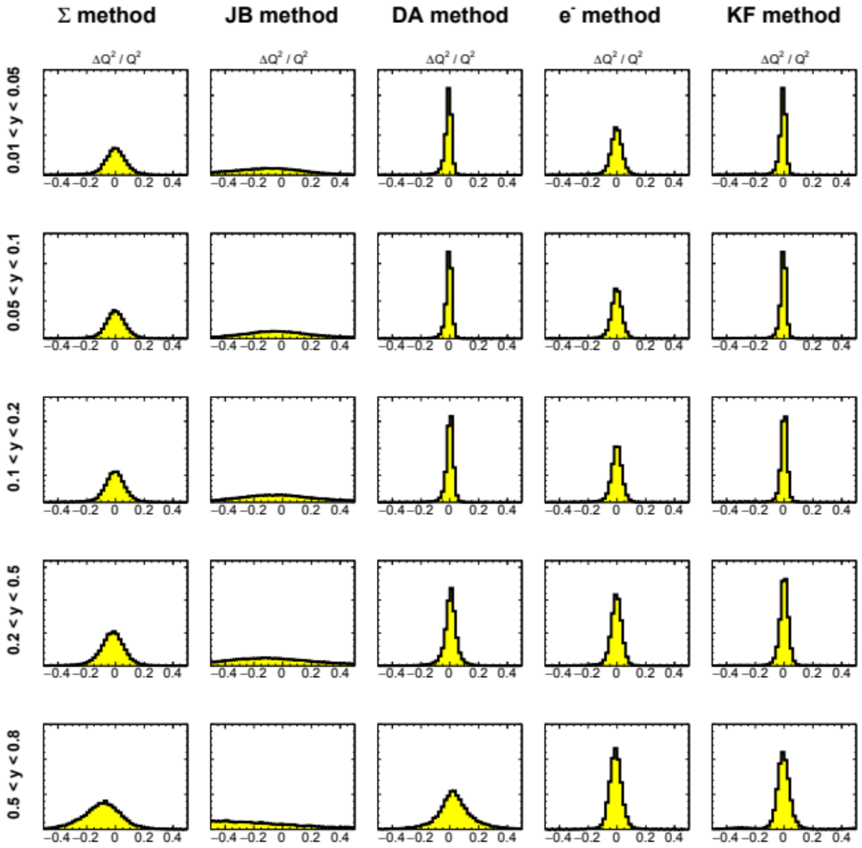


H1 Resolution on Q²

No Correlations

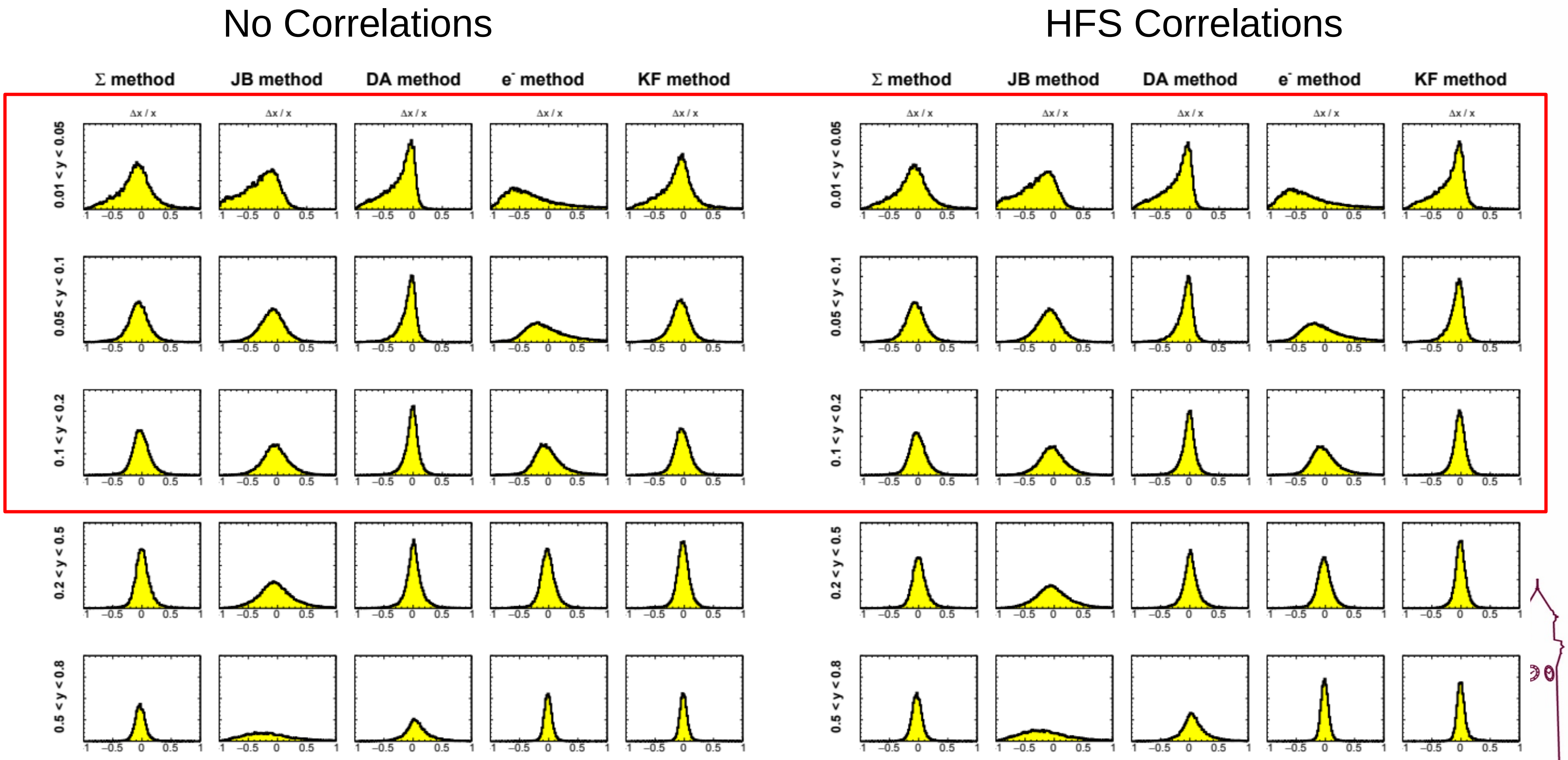


HFS Correlations

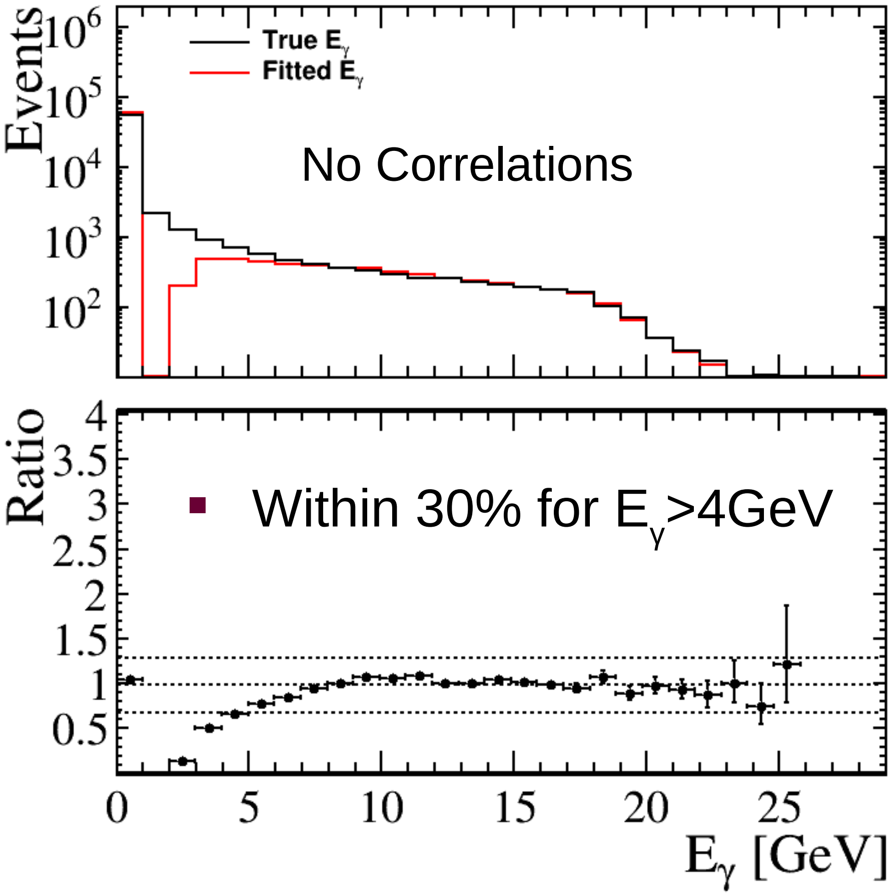


Minimal difference for Q²

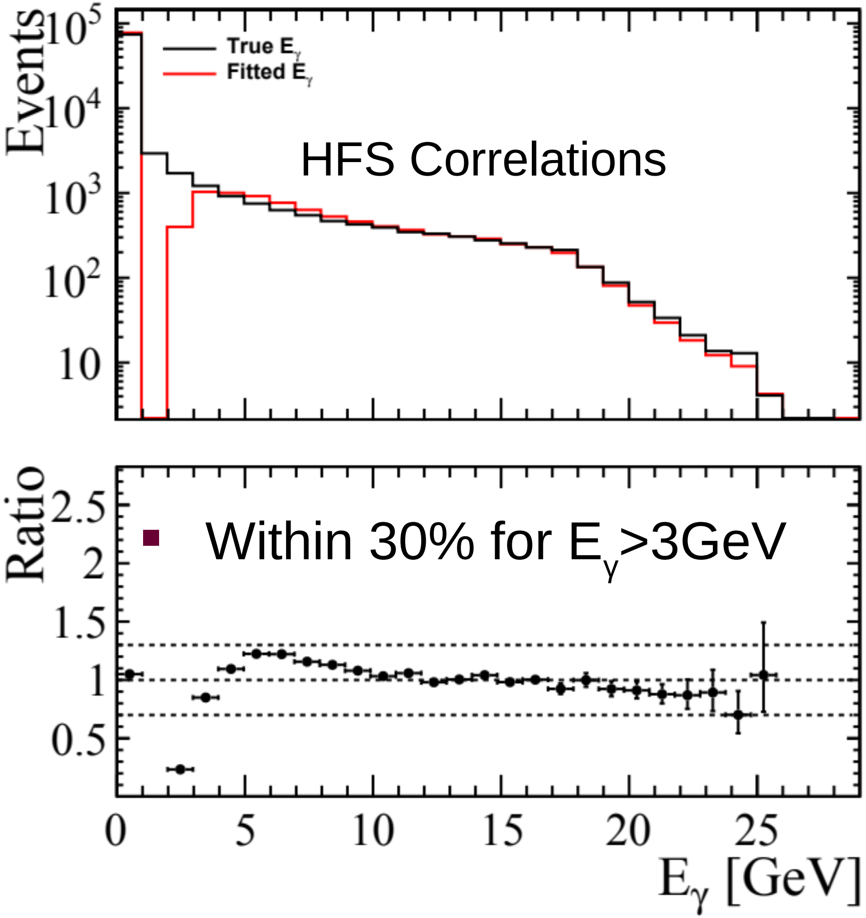
H1 Resolution on x



H1 ISR reconstruction

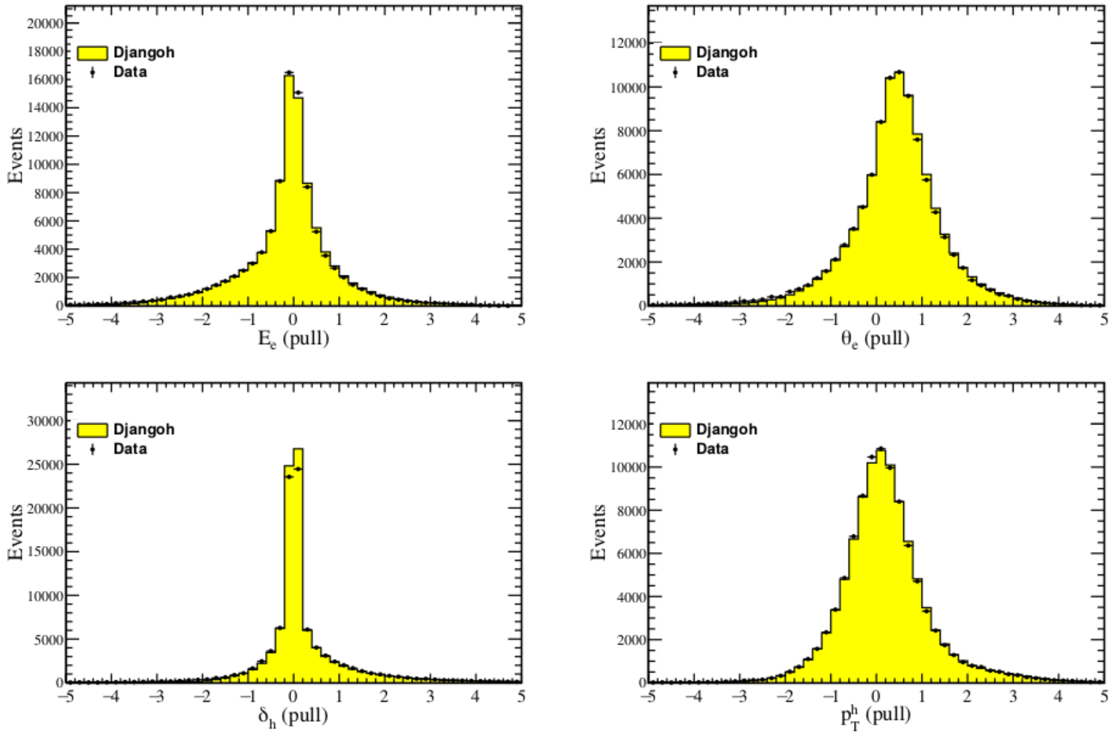


- Within 30% for E_γ>4GeV



- Within 30% for E_γ>3GeV

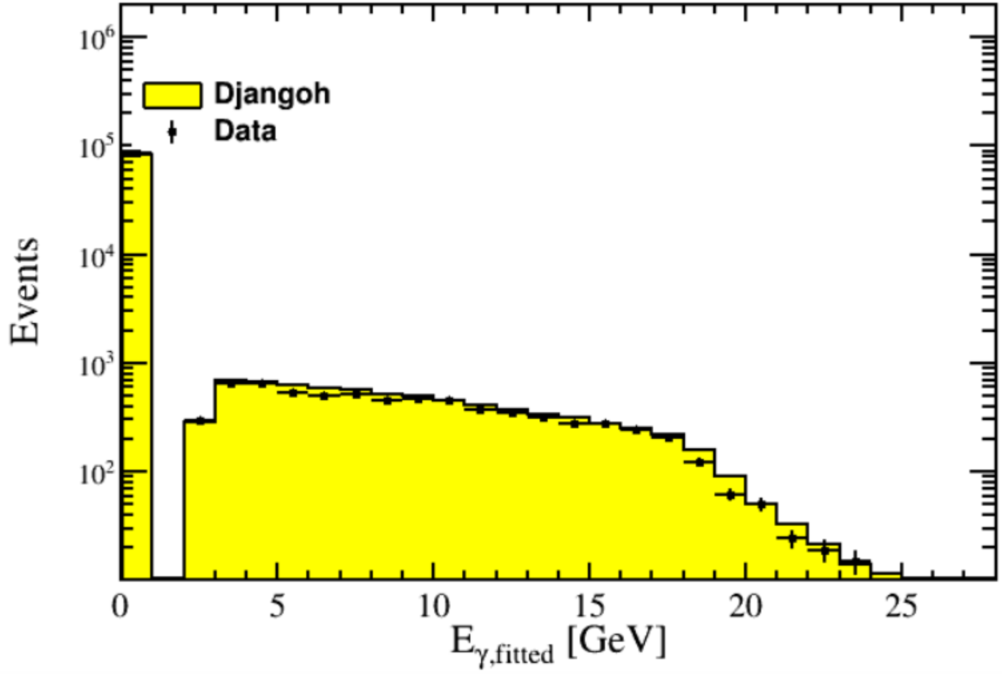
H1 Data and MC (ISR On)



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

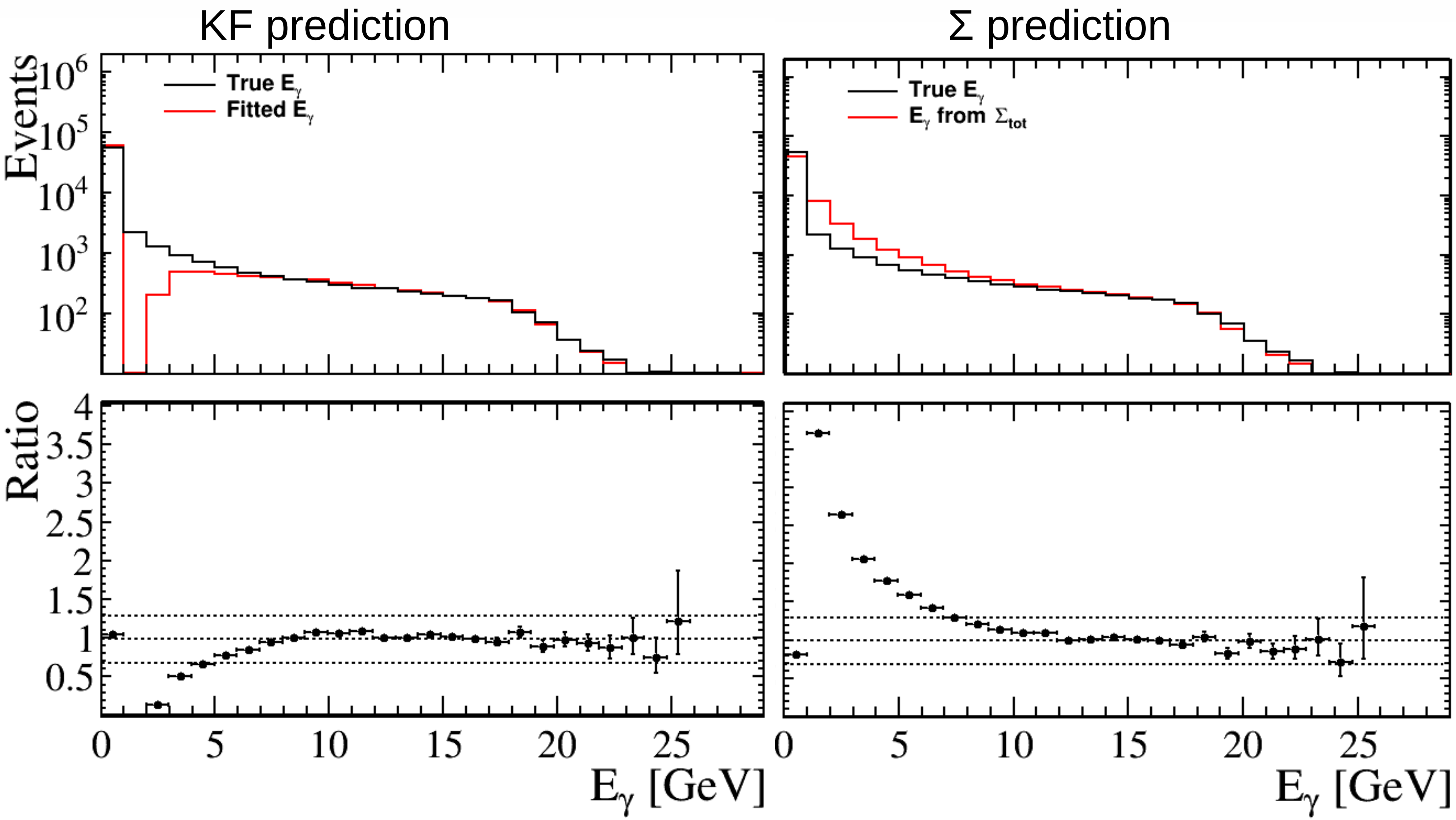
$$g = \frac{D_{i,fitted} - D_{i,reco}}{RMS_{MC}}$$

H1 Data and MC (ISR On)



- Good agreement for E_γ prediction by data and MC (Djangoh)

H1 Data and MC (ISR On)



KF (w/ prior 1) doesn't typically predict presence of ISR that could be equally explained by a resolution effect

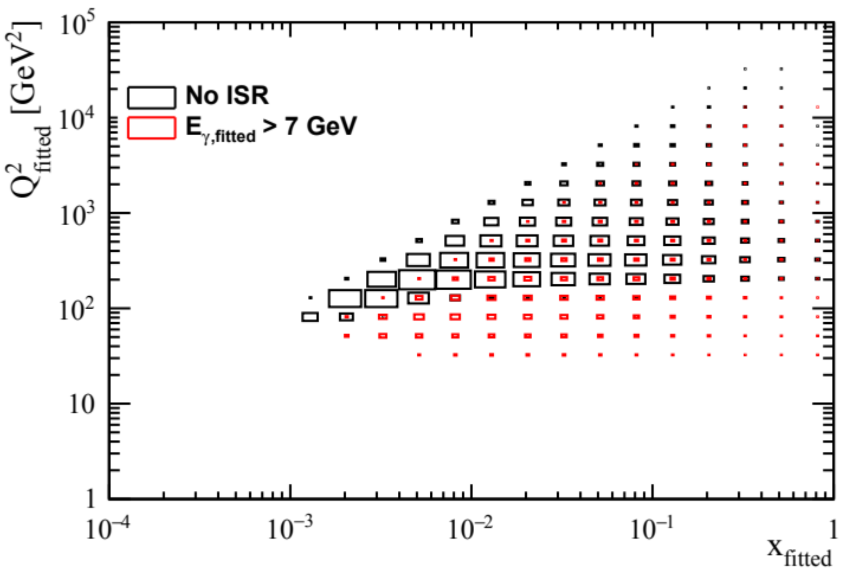
Σ approach does not miss ISR events, but overestimates

Ratio within 30% of unity for E_γ>4GeV (KF) and E_γ>7GeV (Σ)

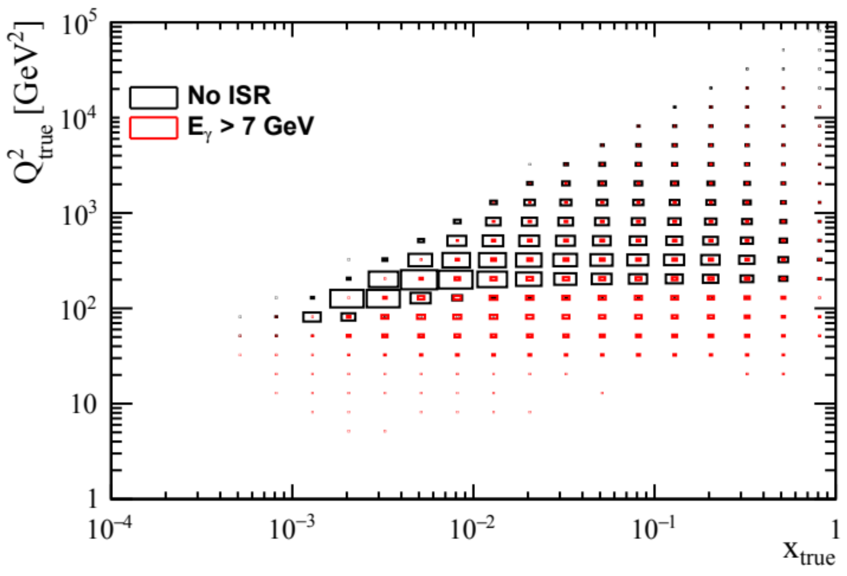
Why identify ISR?

- 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)

Truth Smearing correlations