UNIVERSITY OF BIRMINGHAM | SCHOOL OF PHYSICS AND ASTRONOMY

Kinematic Fitting for Inclusive DIS reconstruction

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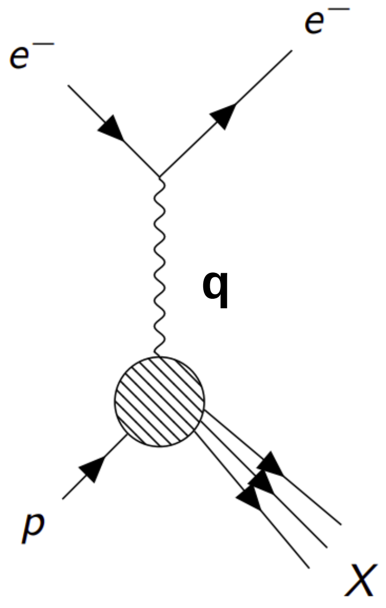
Inclusive NC DIS Kinematics

- 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



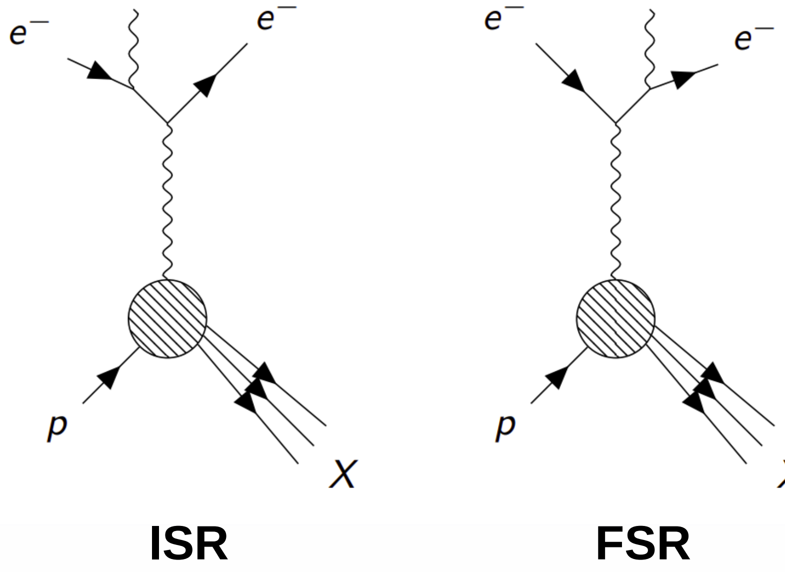
Electron method	JB method	e-Σ method	Double Angle method
$Q^2 = 2E_0 E'_e(1+\cos\theta_e)$	$y = \frac{\delta_h}{2E_0}$	$Q^2_{e\Sigma} = Q^2_e$ $\quad y_\Sigma = \frac{\delta_h}{\delta_h + \delta_e}$	$y_{DA} = \frac{\alpha_h}{\alpha_h + \alpha_e}$ $\quad \alpha_{e/h} = \tan\frac{\theta_{e/h}}{2}$
$y = 1 - \frac{E'_e}{2E_0}(1-\cos\theta_e)$	$Q^2 = \frac{p^2_{t,h}}{1-y}$	$x_{e\Sigma} = \frac{Q^2_\Sigma}{s y_\Sigma}$ $\quad Q^2_\Sigma = \frac{p^2_{t,e}}{1-y_\Sigma}$	$Q^2_{DA} = \frac{4E^2_e}{\alpha_e(\alpha_e+\alpha_h)}$

Inclusive NC DIS 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 Fitting for DIS

- Only **need** 2 quantities to obtain **x, y, Q²**

- Using measured quantities $\vec{\mathbf{D}} = \{E_e, \theta_e, \delta_h, p_{t,h}\}$ a kinematic fit can 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:

Likelihood

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

- Note: above quantities taken to be uncorrelated → Correlations between E_e, θ_e and δ_h, $p_{t,h}$ will later need to be taken into account

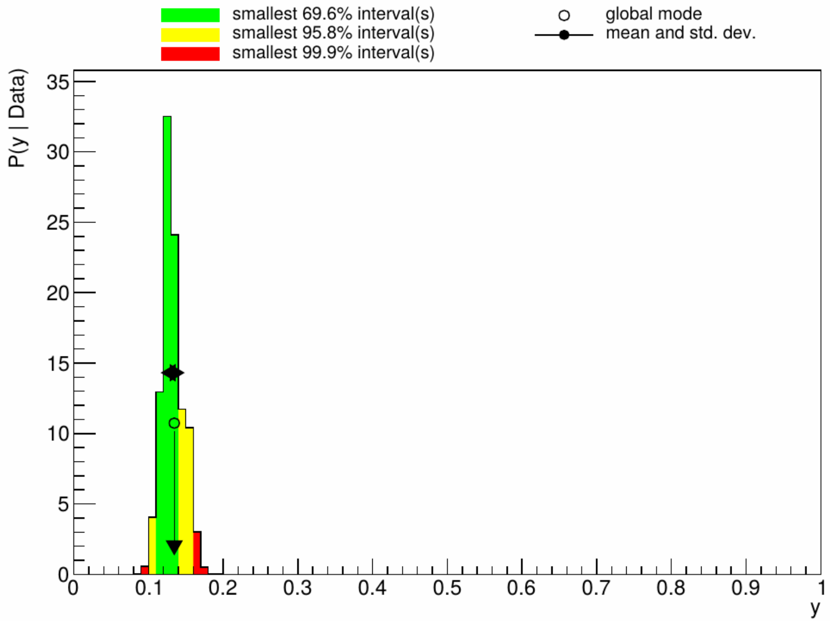
Kinematic Fitting for DIS – A Bayesian Approach

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

Prior

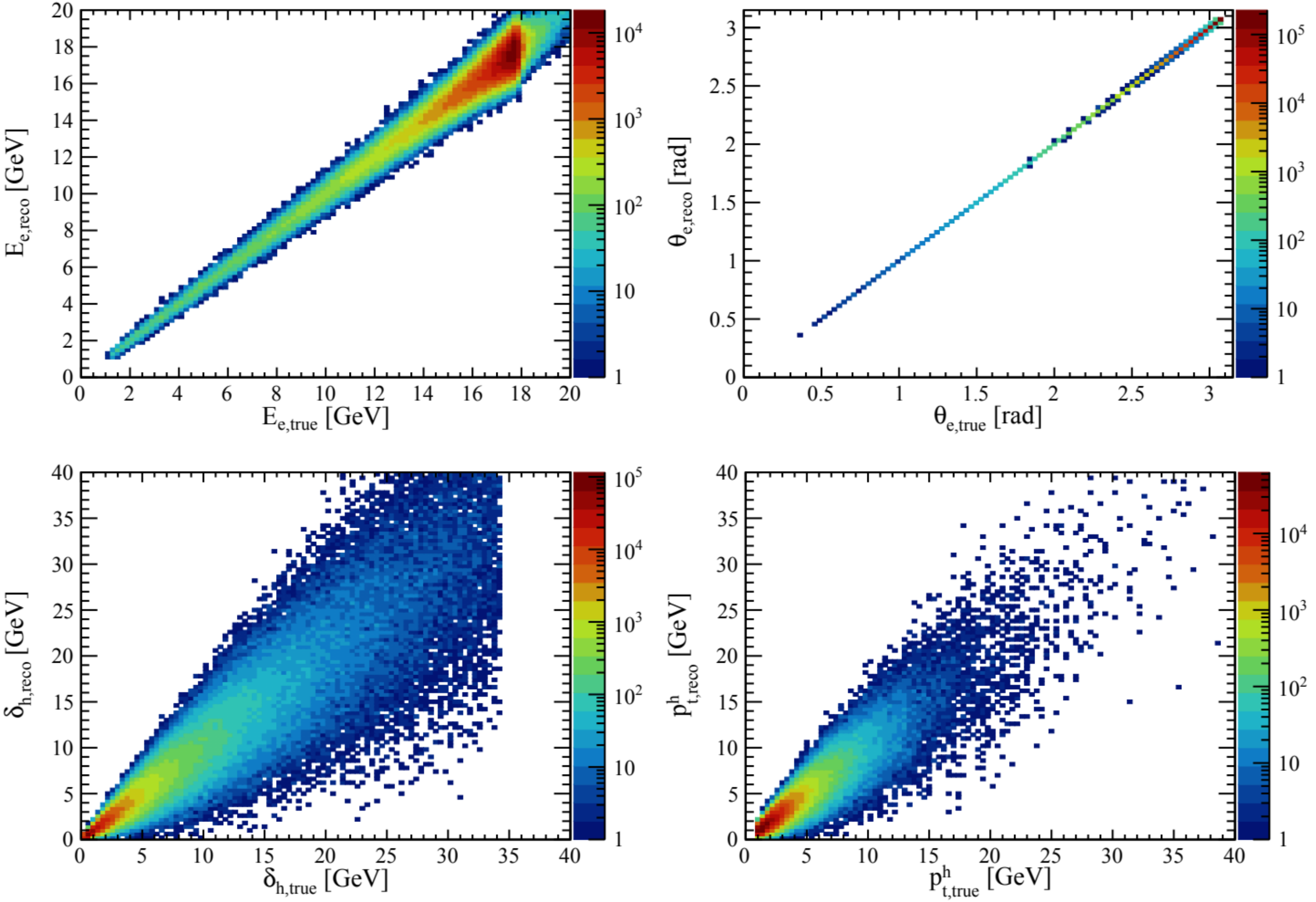
$$P_o(\overrightarrow{\lambda}) = \frac{1+(1-y)^2}{x^3y^2}\frac{[1+(1-E_\gamma/A)^2]}{E_\gamma/A}$$

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



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

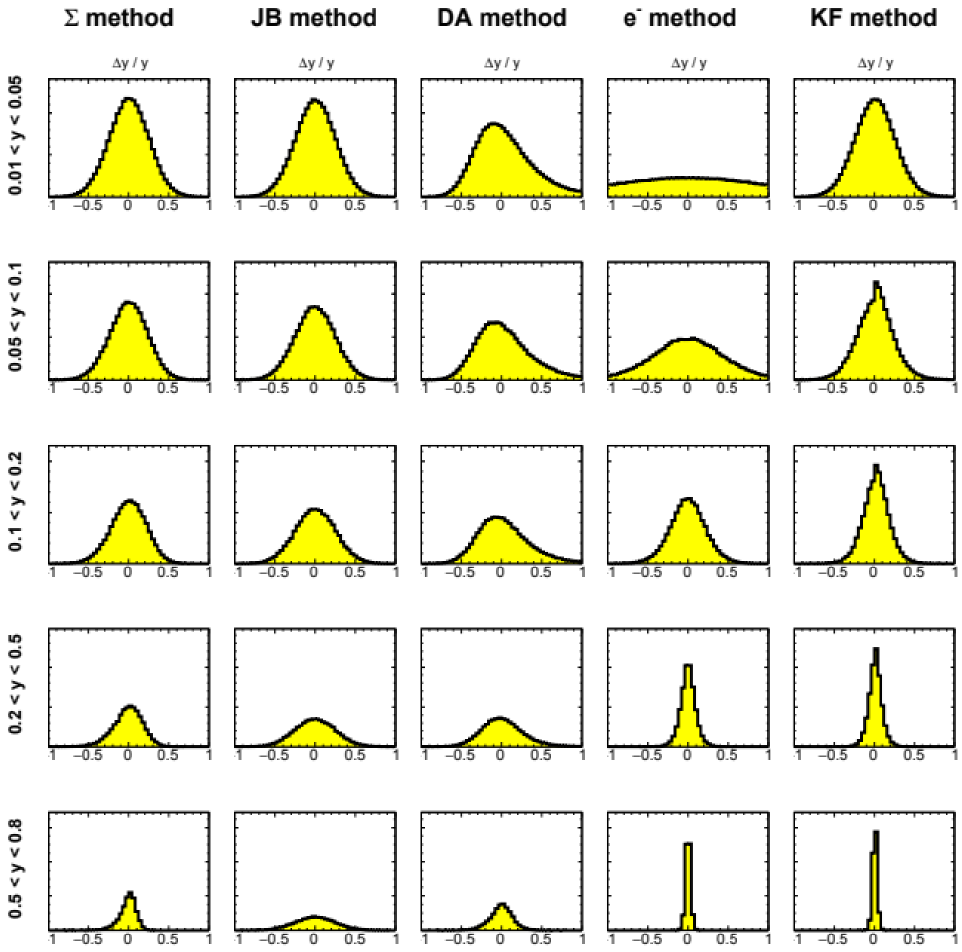
Smeared EIC pseudodata



- 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%
- $\sigma(\delta_h) / \delta_h$ = 25%
- $\sigma(p_{T,h}) / p_{T,h}$ = 25%

Smeared EIC pseudodata (No ISR)



- Smearing resolutions used as input for KF

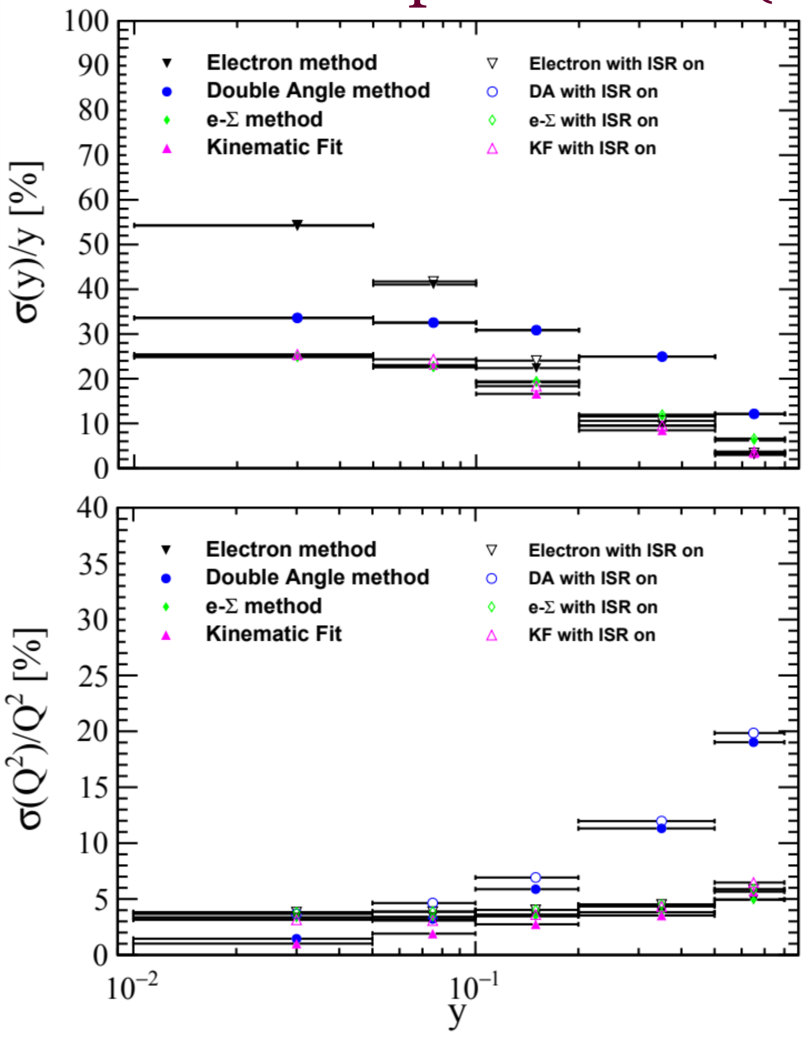
$$P(\vec{D}|\vec{\lambda}) = \frac{1}{\sqrt{2\pi}\sigma_E} \exp -\frac{(E_e - E_e^\lambda)^2}{2\sigma_E^2} \times \frac{1}{\sqrt{2\pi}\sigma_\theta} \exp -\frac{(\theta_e - \theta_e^\lambda)^2}{2\sigma_\theta^2} \times \frac{1}{\sqrt{2\pi}\sigma_{\delta_h}} \exp -\frac{(\delta_h - \delta_h^\lambda)^2}{2\sigma_{\delta_h}^2}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

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

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

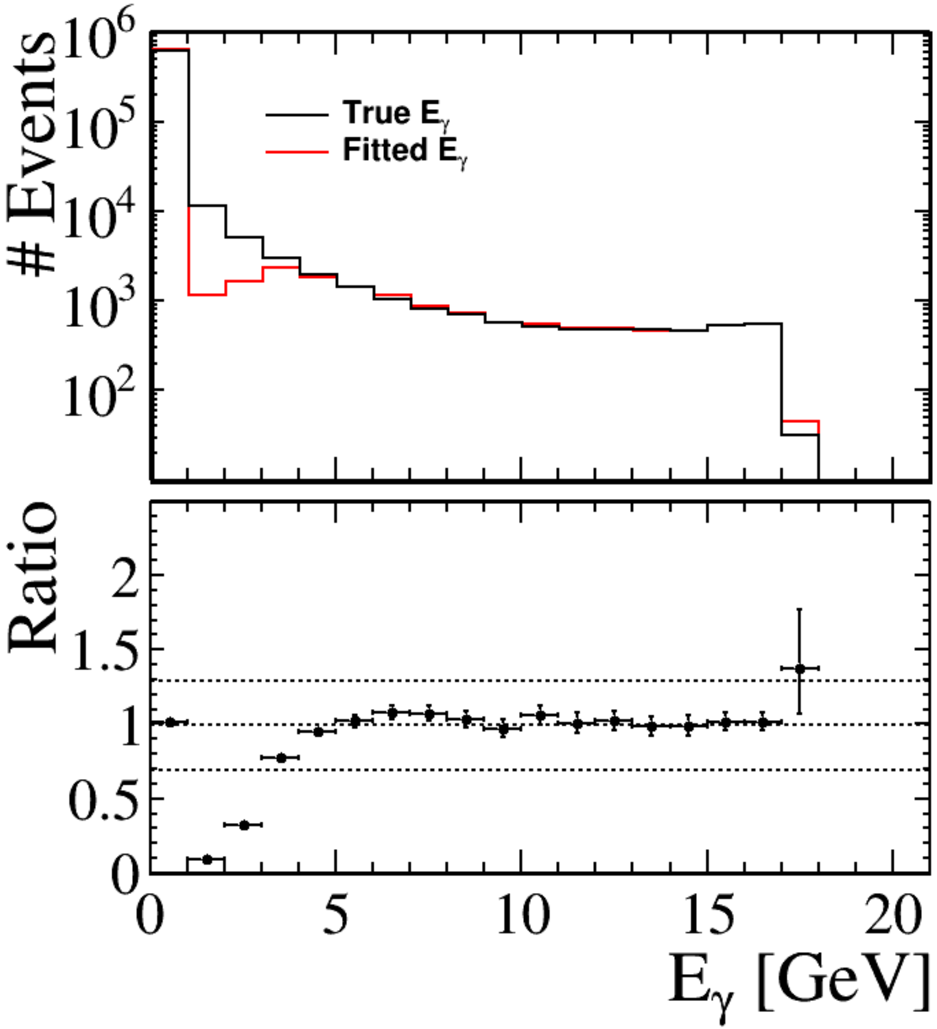
- Compare y resolutions:
  - KF method meets or exceeds conventional

Smeared EIC pseudodata (W/ ISR)

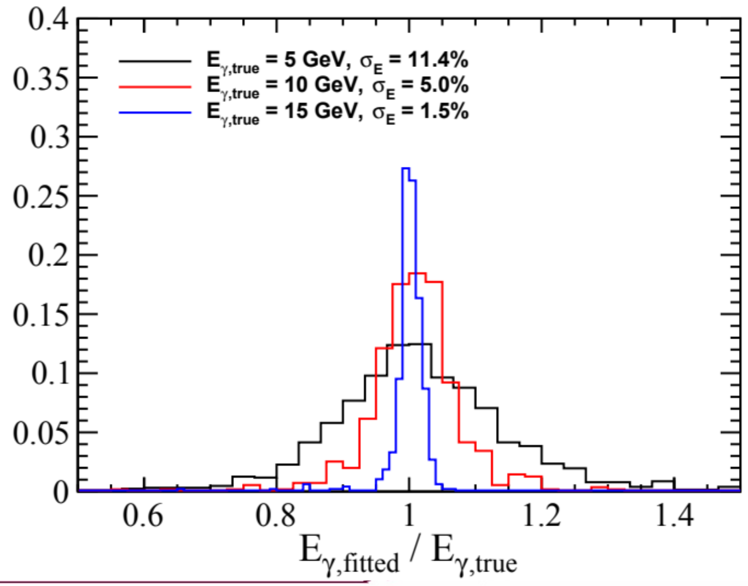


- Compare resolutions: no ISR to with ISR on
  - “Realistic” Σ_{tot} cut of 31 GeV applied to remove high energy ISR
- Some, but not big, difference between observed resolutions
  - Even for the electron method!

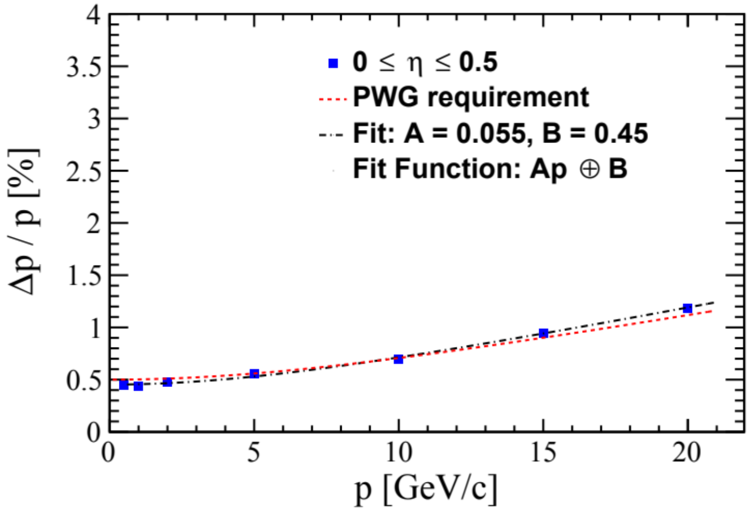
Smeared EIC pseudodata (W/ ISR)

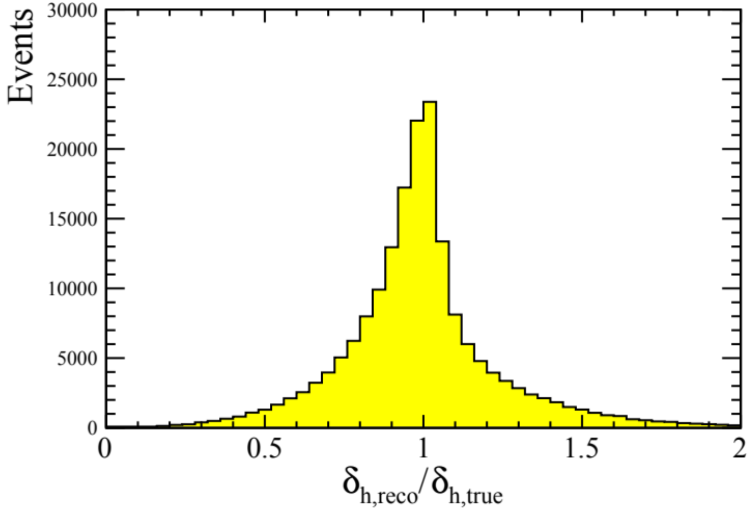


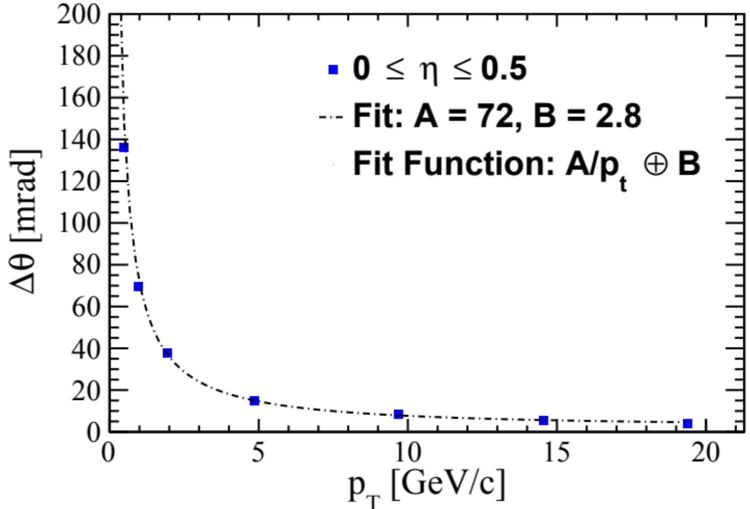
- Compare true and measured ISR energy distributions
  - Distribution well reproduced for higher E_γ
  - Ratio within 30% for E_γ > 3 GeV
  - Within 10% for E_γ > 4 GeV
- Reasonable resolution

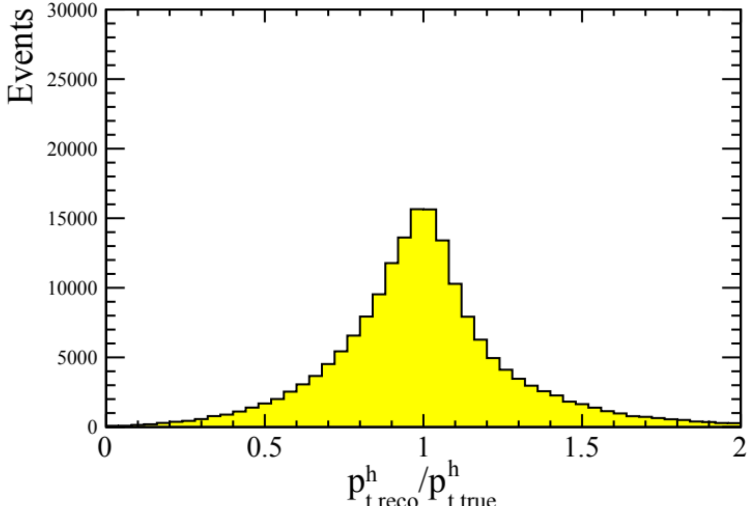


Fully Simulated ePIC pseudodata (No ISR)









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

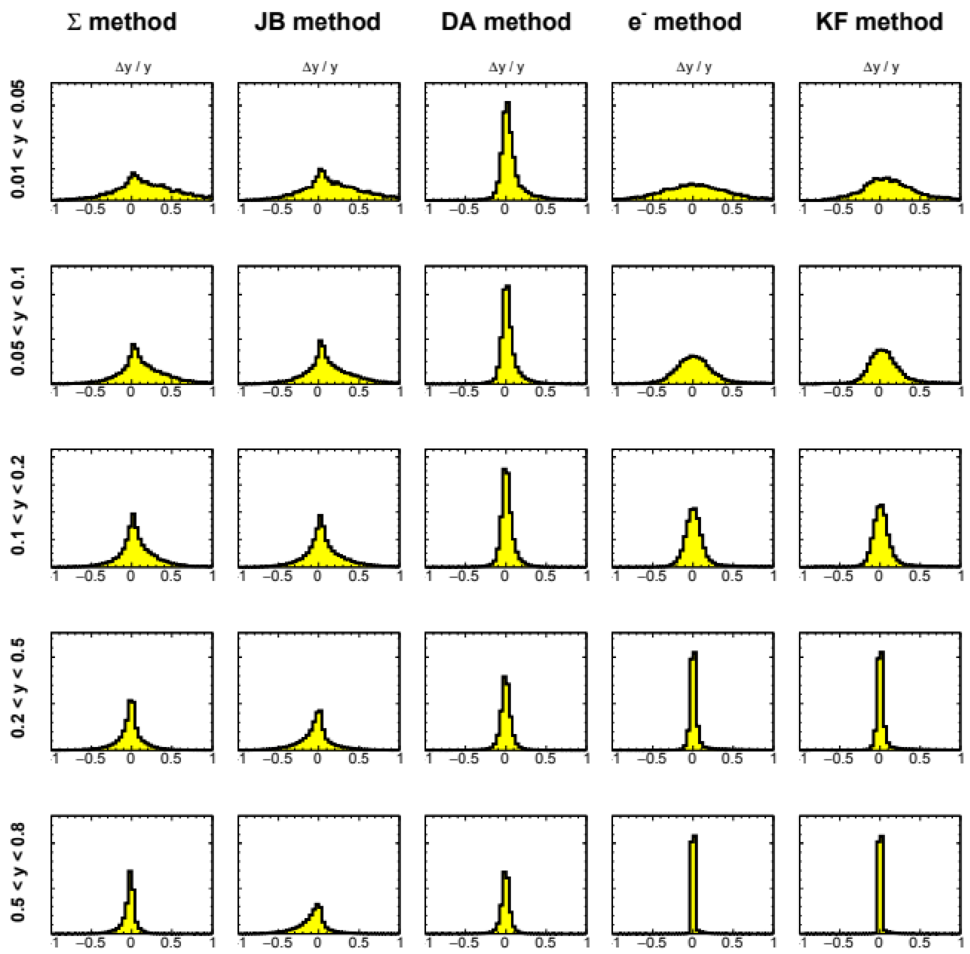
$$\sigma_\theta = 72/p_t \oplus 2.8 \text{ in mrad}$$

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

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

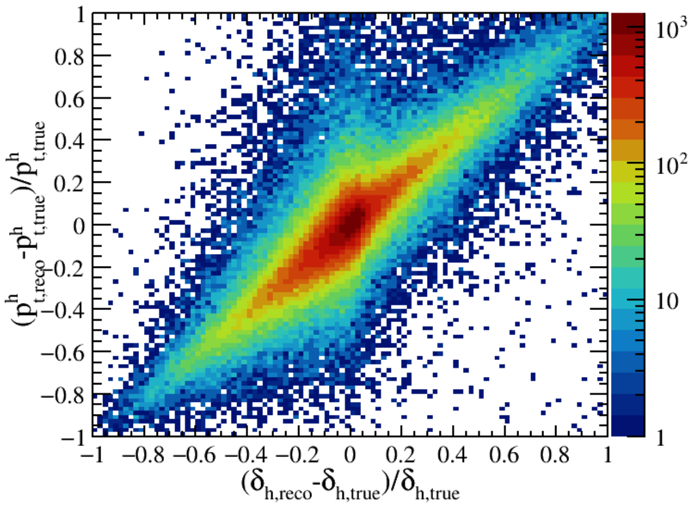
- Parametrised ePIC full sim resolutions
  - Pythia8 NCDIS
  - Craterlake 23.12.0
  - $Q^2 > 100$ GeV^2
  - Ele from tracking

Fully Simulated ePIC pseudodata (No ISR)



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

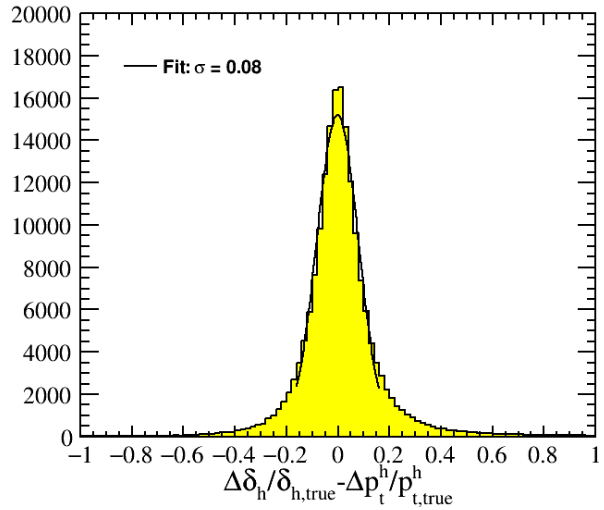
HFS Correlations



- 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:

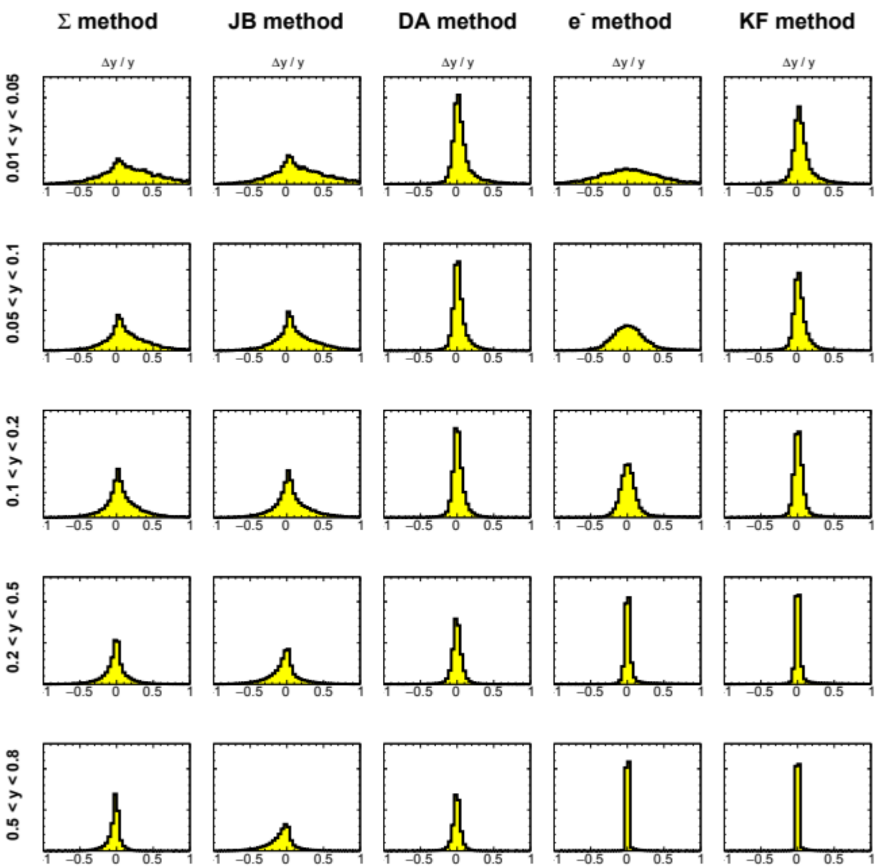
$$P(\vec{D}|\vec{\lambda})_{corr} = P(\vec{D}|\vec{\lambda})_{uncorr} \frac{1}{\sqrt{2\pi}\sigma_{corr}} \cdot \exp - \frac{(c - c^{\lambda})^2}{2\sigma^2_{corr}}$$

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



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

- Conventional reconstruction methods do not fully exploit information measured in NC events → methods such as kinematic fitting (or DNNs) use all measured quantities simultaneously to give a best estimate of the kinematics

- Kinematic fitting method explored using an informative prior based on features of DIS and bremsstrahlung cross sections:
  - In ideal case (smeared uncorrelated) the KF method matches or exceeds the performance of conventional methods
  - If correlations between HFS quantities are included, as in full ePIC detector simulations, the DA method may exceed the basic (uncorrelated) KF

- Extending the KF method to account for correlations in the HFS recovers this performance → delivers y resolution comparable to best method for each y bin

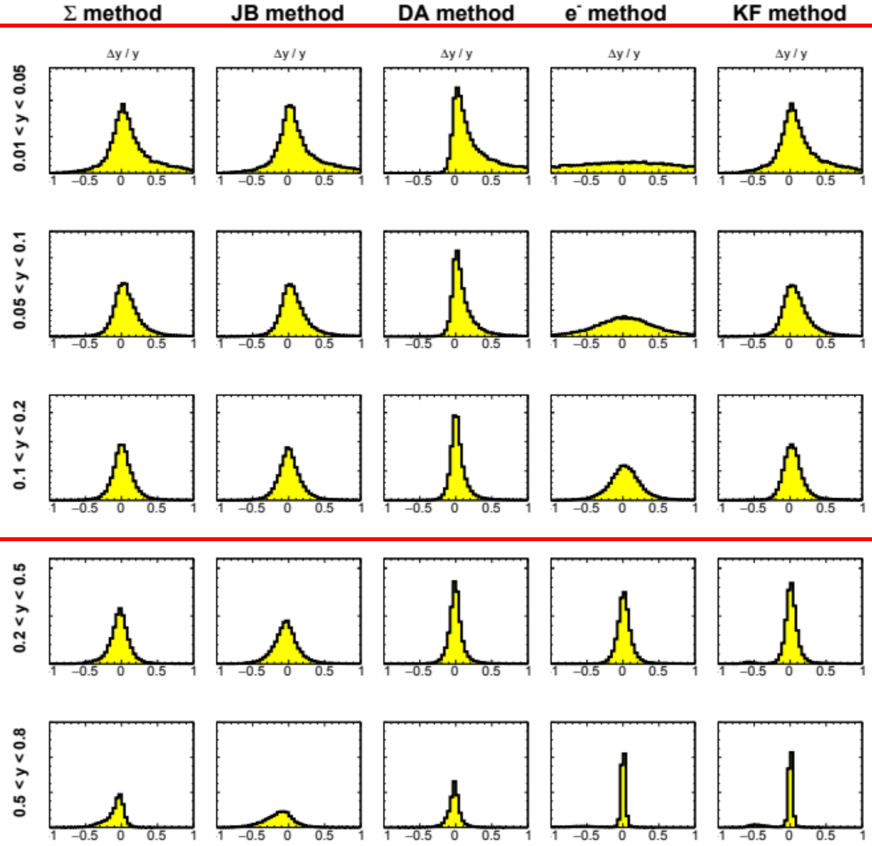
- Can identify ISR with good efficiency and resolution for E_γ greater than a few GeV
  - Possibility to extend measurements down to lower Q^2, or add to an F_L extraction

Backup

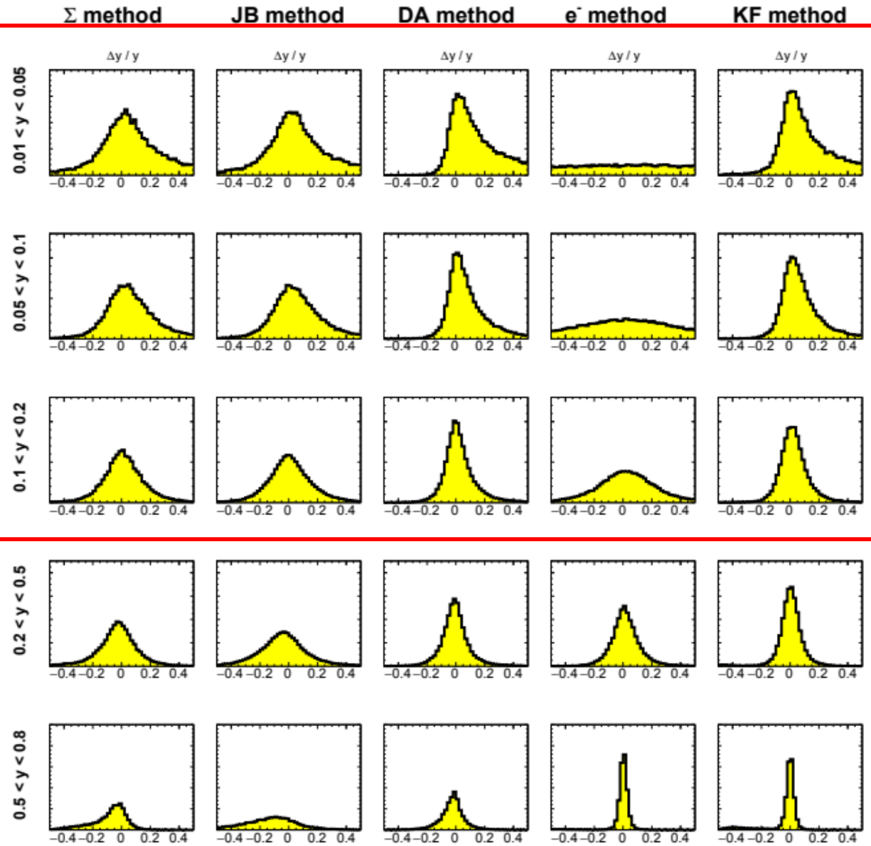
*Note different x scale

H1 Resolution on y

No Correlations



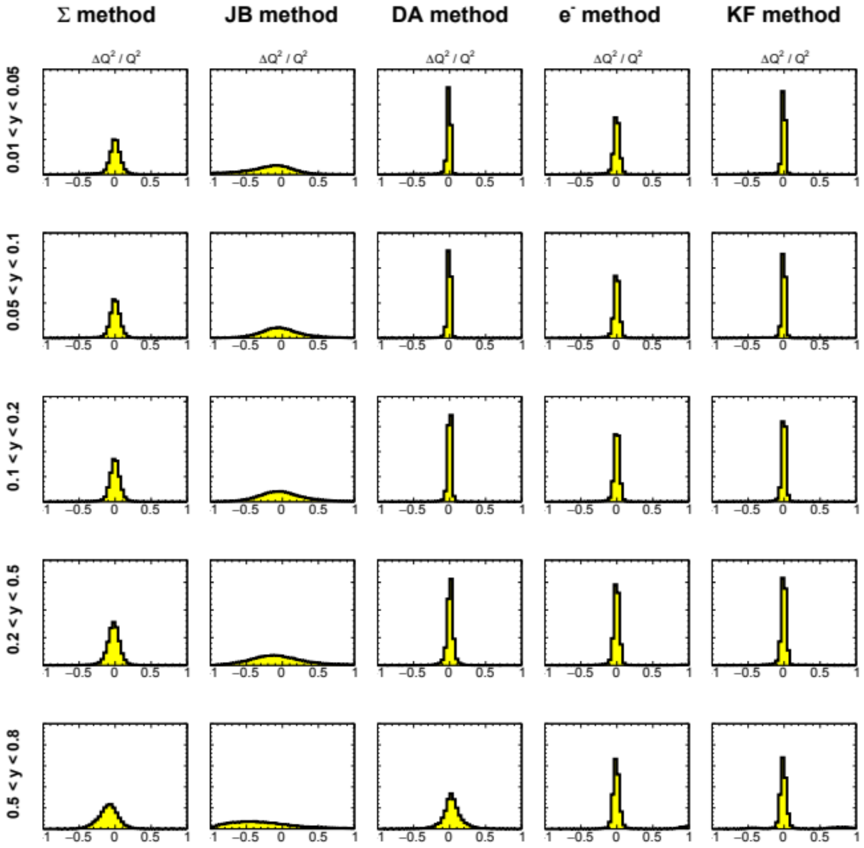
HFS Correlations



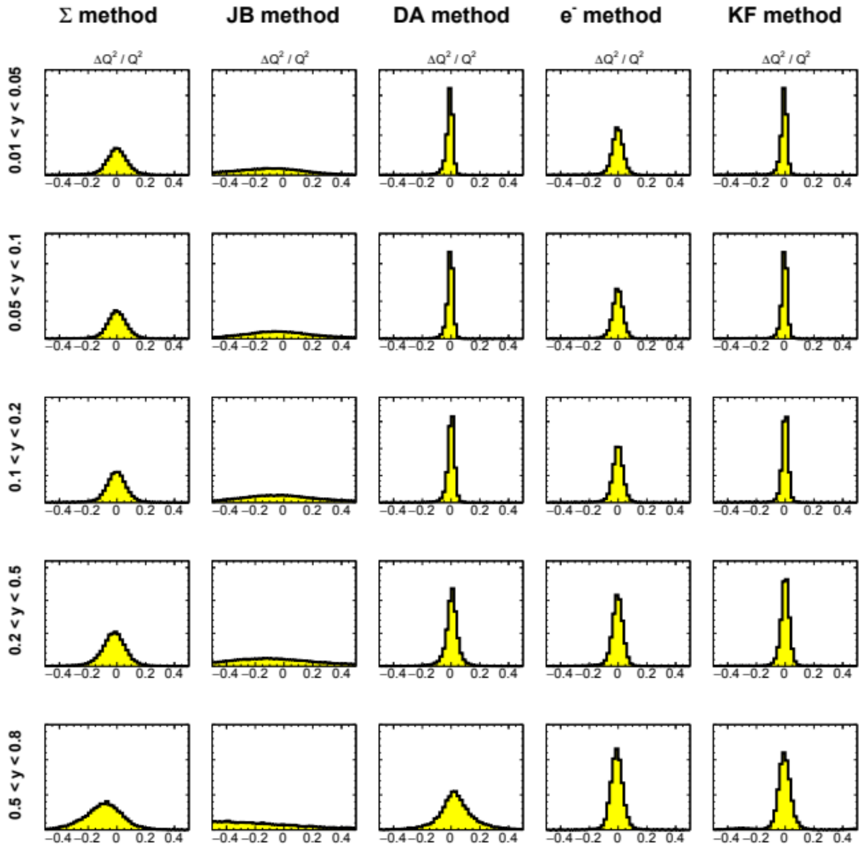
*Note different x scale

H1 Resolution on Q²

No Correlations

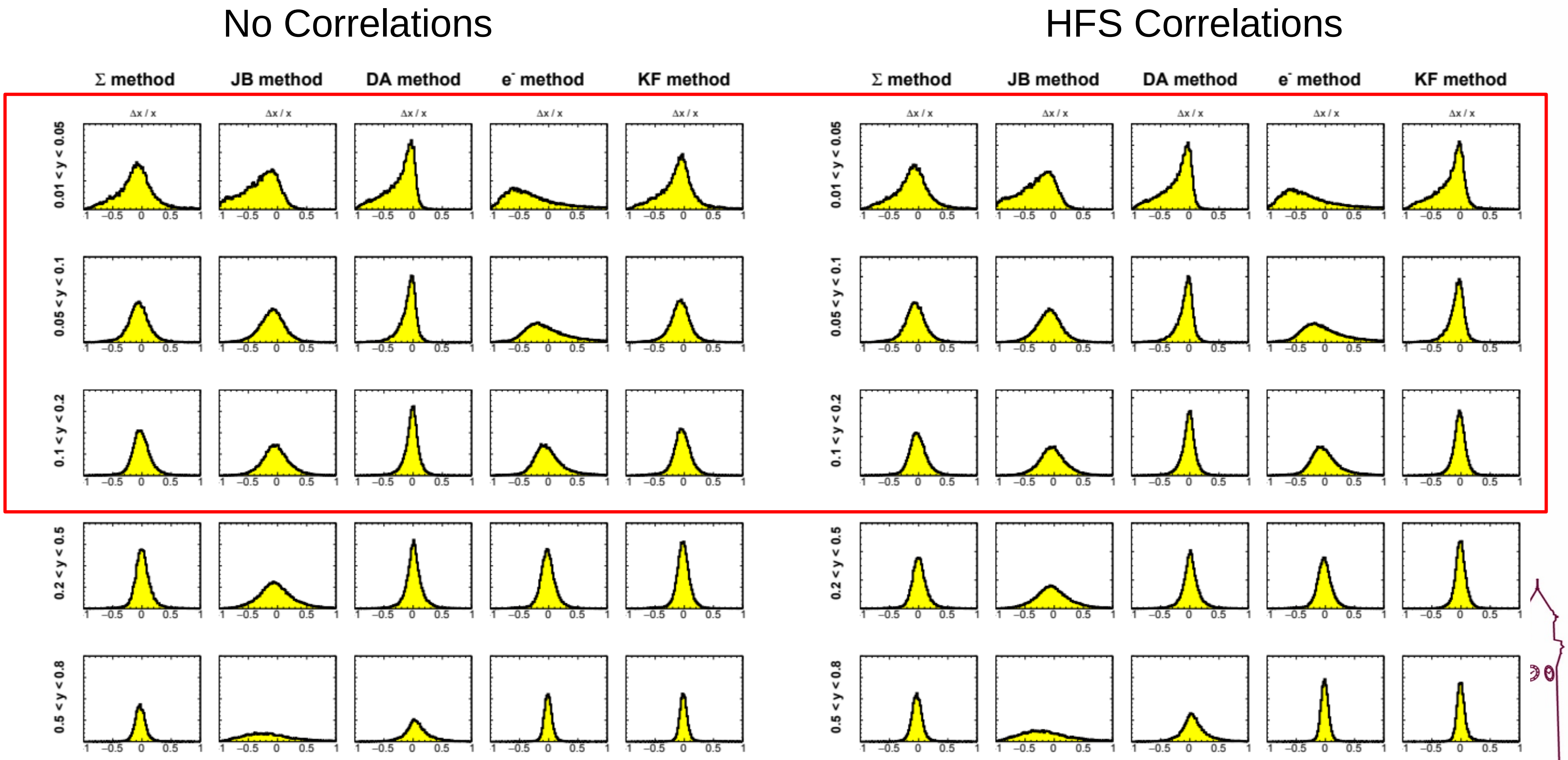


HFS Correlations

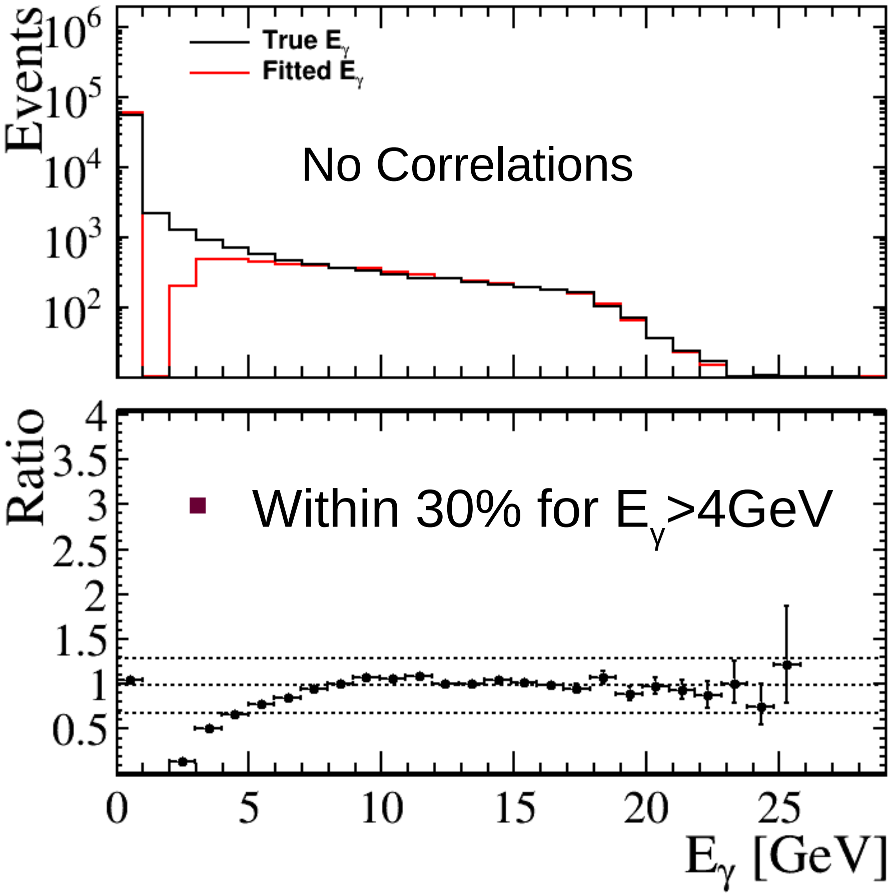


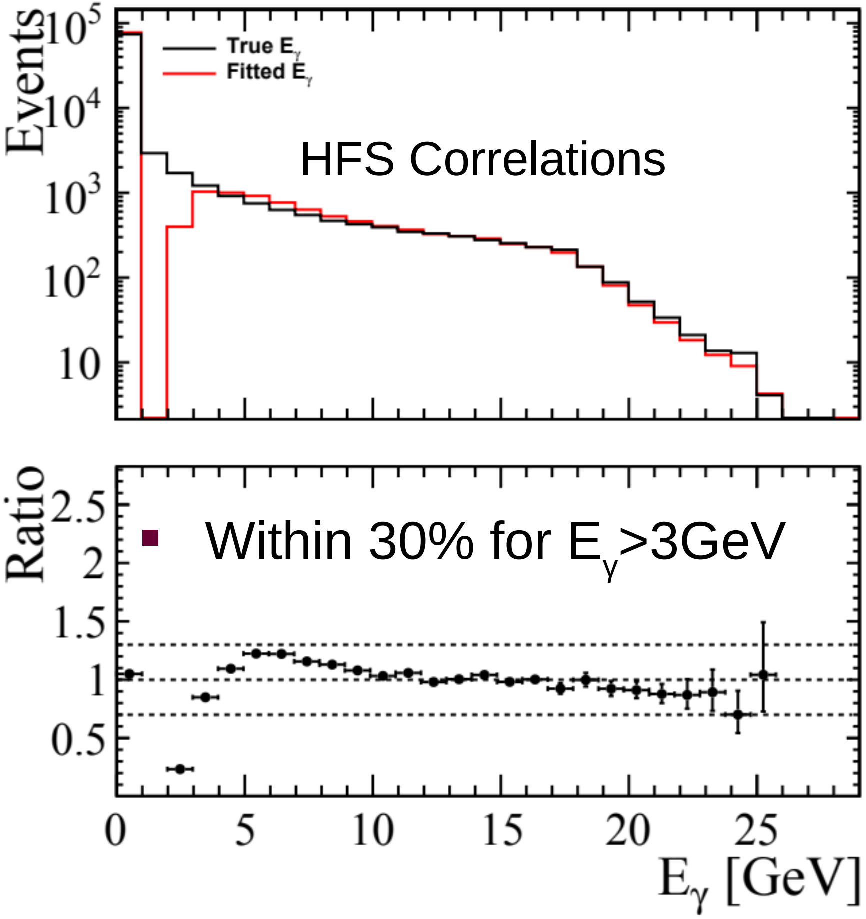
Minimal difference for Q²

H1 Resolution on x

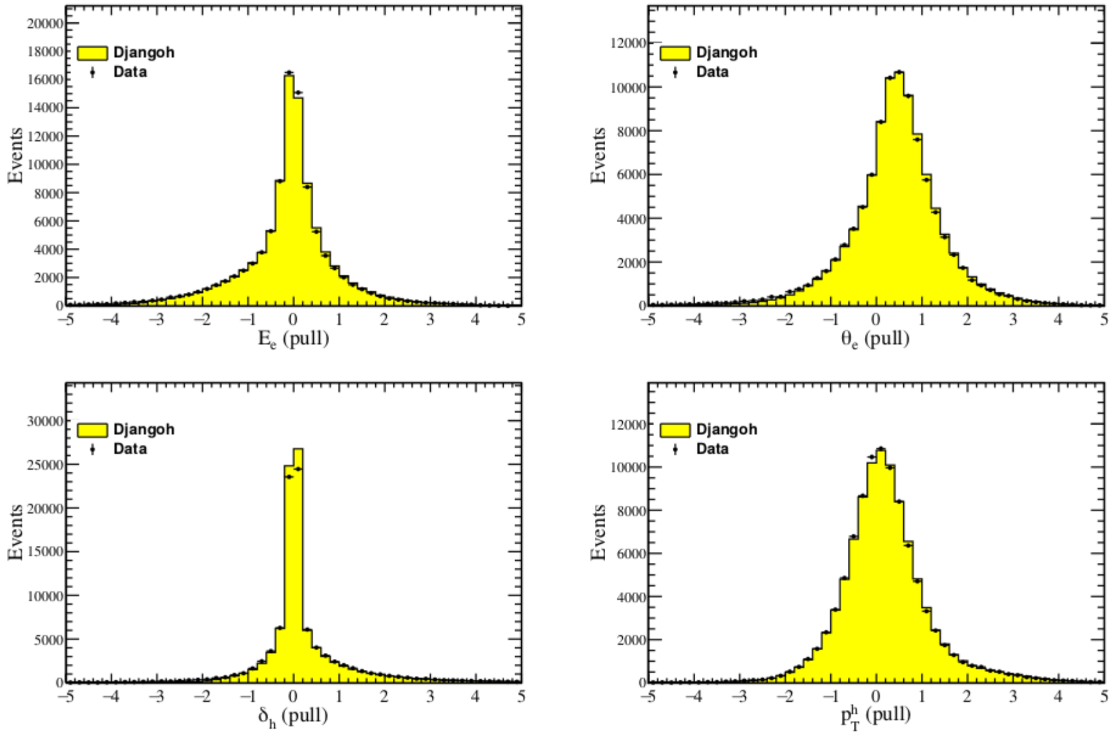


H1 ISR reconstruction





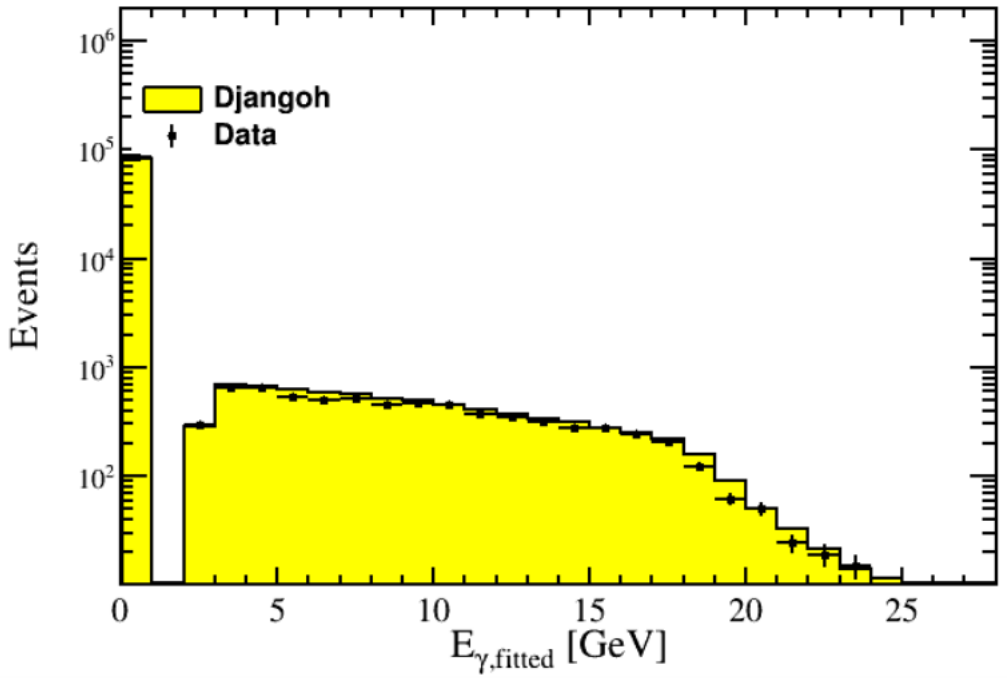
H1 Data and MC (ISR On)



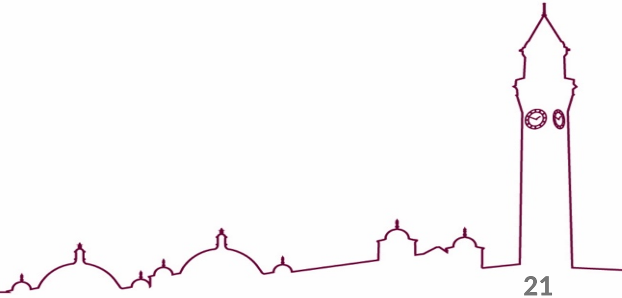
- KF reconstruction is applied with a likelihood function constructed from the following resolutions:
  - $\sigma(\theta_e)$ = 4mrad
  - $\sigma(E_e)$ / E = 11% /sqrt(E) ⊕ 1%
  - $\sigma(\delta_h)$ / δ_h = 13.5%
  - $\sigma(p_{T,h})$ / $p_{T,h}$ = 54% /sqrt($p_{T,h}$) ⊕ 4%
- No correlation term included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

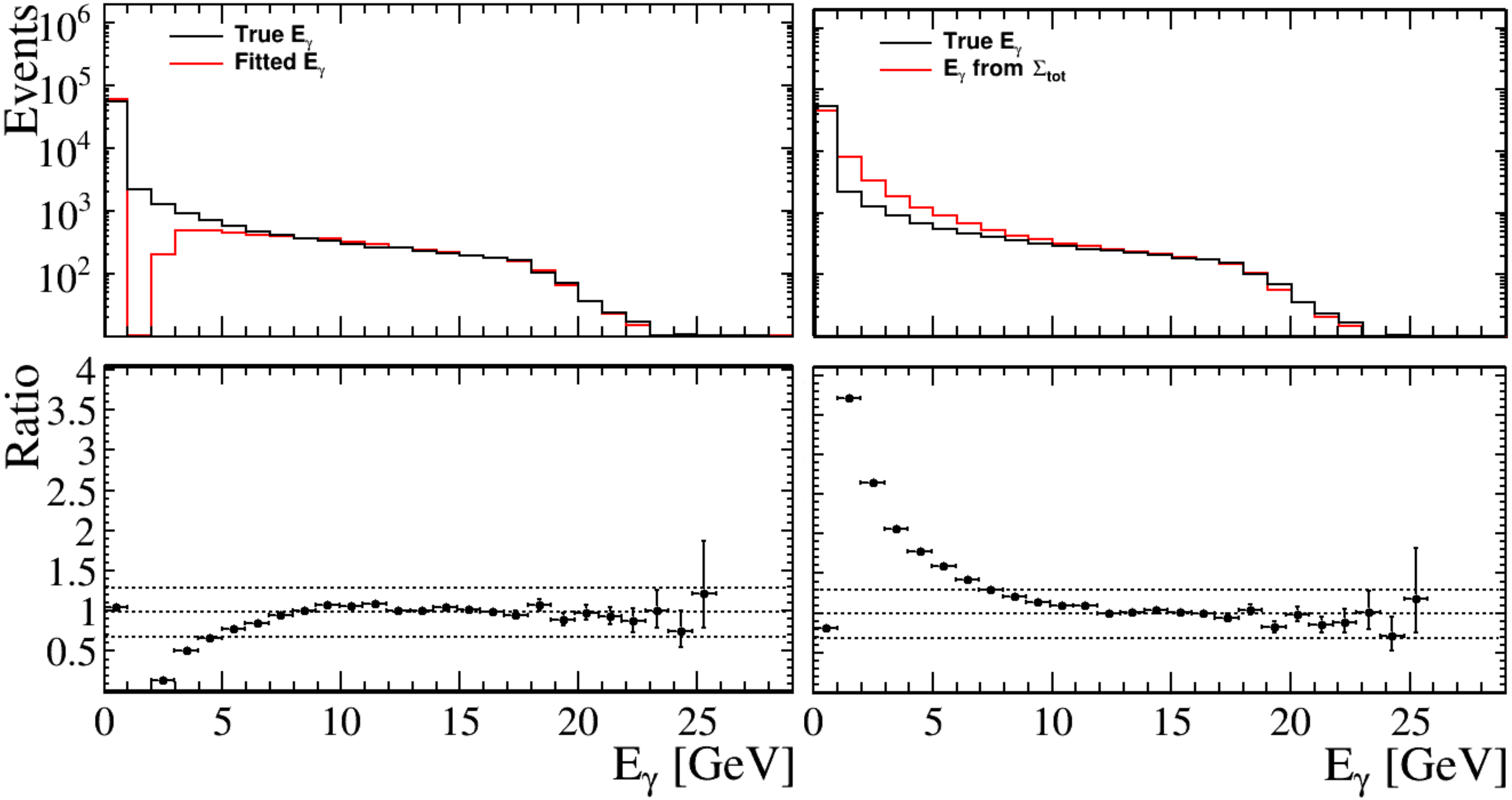


- Good agreement for E_γ prediction by data and MC (Djangoh)



H1 Data and MC (ISR On)

KF prediction | Σ prediction



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

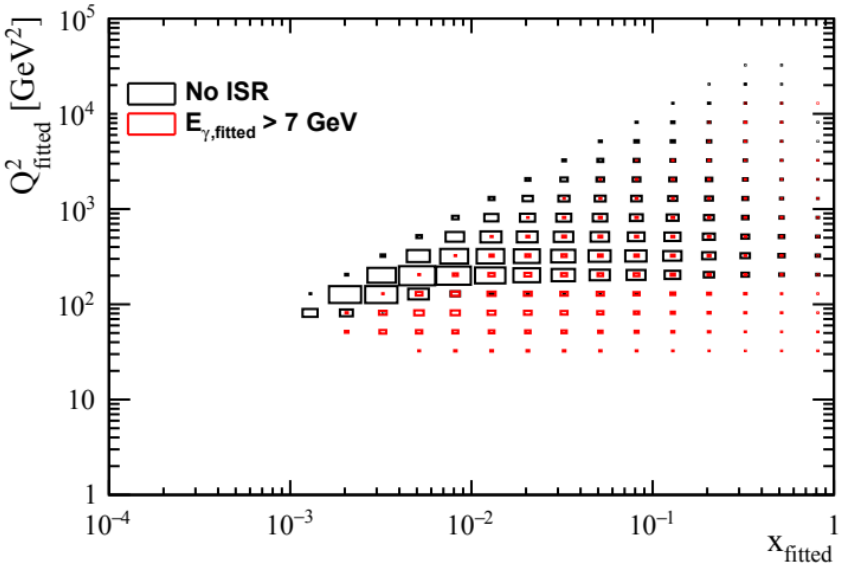
Σ approach does not miss ISR events, but overestimates

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

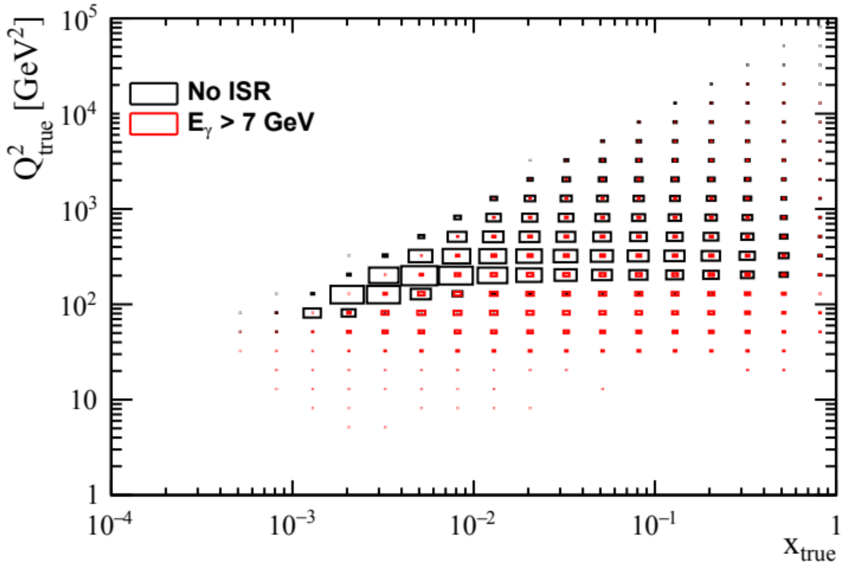
Why identify ISR?

- 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