UNIVERSITY OF BIRMINGHAM | SCHOOL OF PHYSICS AND ASTRONOMY

Kinematic Fitting for the reconstruction of ISR in Neutral Current DIS

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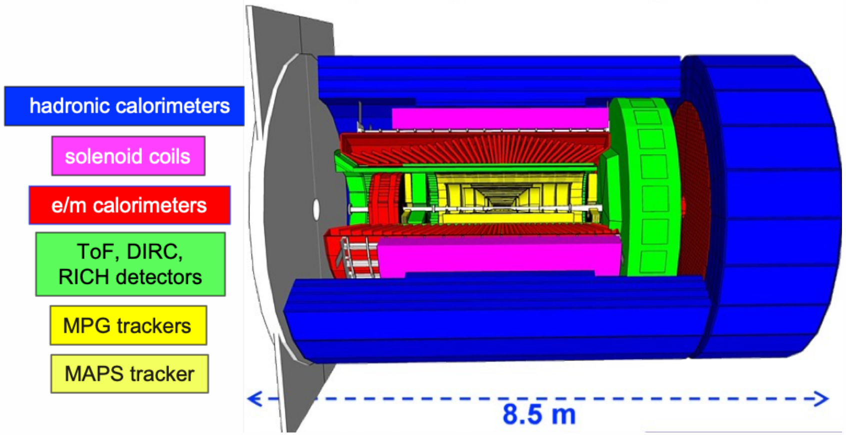
Detectors for DIS

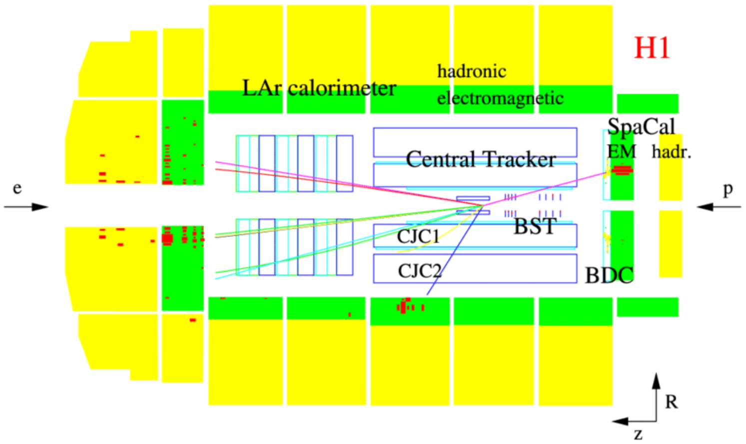
Two detectors considered in following studies

ePIC @ EIC: Simulations
→ Performance benchmarks



- To be located at EIC (BNL Upton NY)
  → Data taking from early 2030s
  - High luminosity: $\mathscr{L}_{max}$ **= 10^{34} cm^{-2}s^{-1}**
  - Variable $\sqrt{s}_{ep}$: ranging from **28 to 140 GeV**
  - High polarisation: **~70%** for e, light nucleon
  - Ion beams: Proton to Uranium

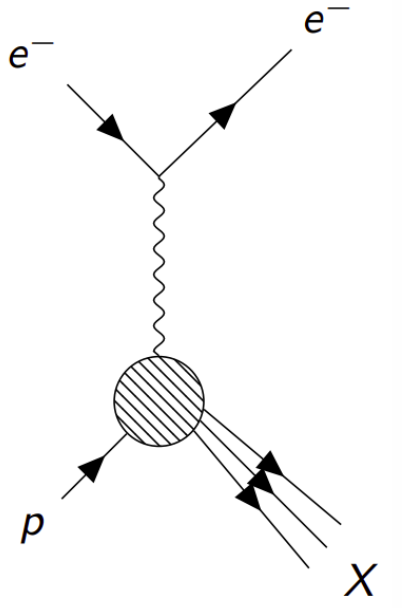
H1 @ HERA: Simulations + Data
→ ISR Benchmarks + Validation



- Located at HERA (DESY Hamburg)
  → Data taking from 1992-2007
  - Peak luminosity: $\mathscr{L}_{max}$ **> ~4 x 10^{31} cm^{-2}s^{-1}**
  - $\sqrt{s}_{ep}$: **~300-320 GeV**

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

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

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

JB method

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

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

e-Σ method

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

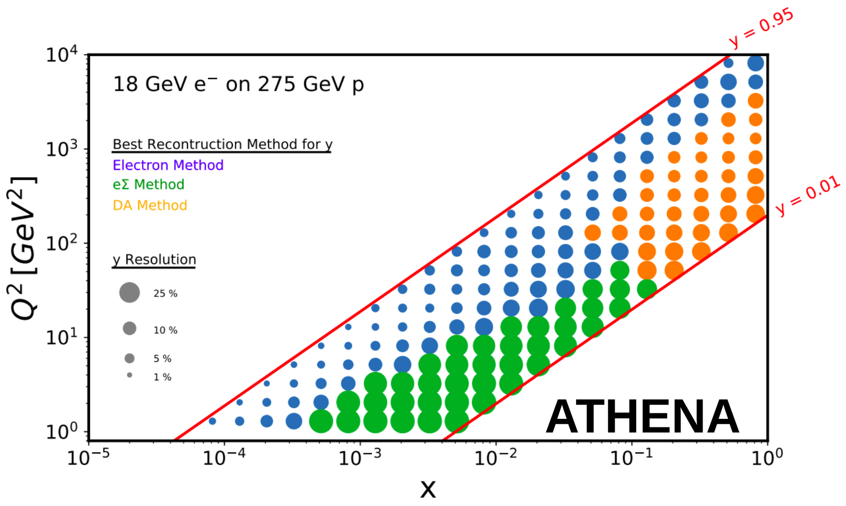
$$x_{e\Sigma} = \frac{Q^2_\Sigma}{s y_\Sigma} \qquad Q^2_\Sigma = \frac{p^2_{t,e}}{1-y_\Sigma}$$

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 achieved using all measured quantities simultaneously
  - This has been done for kinematic reconstruction using Neural Networks [1][2]
  - Can alternatively perform a kinematic fit of measured quantities [3] → this is the focus of this work.

Kinematic Fit (KF) Reconstruction

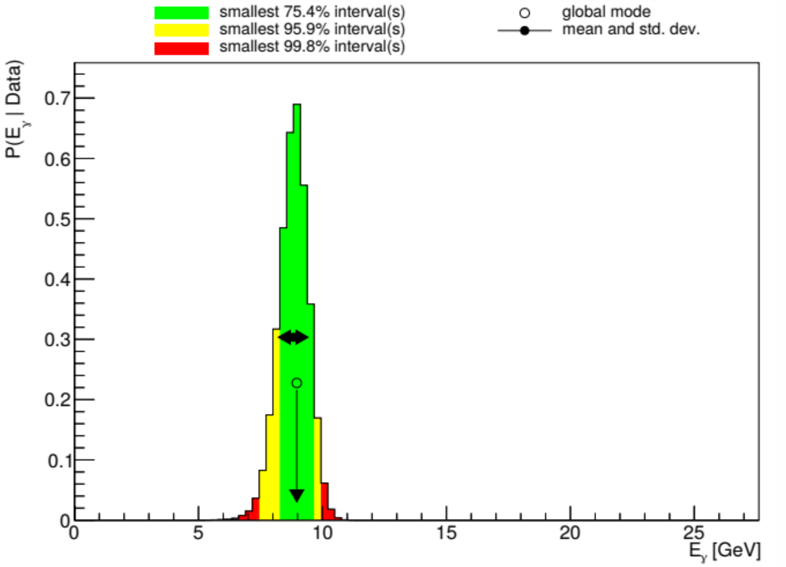
- Kinematic fit of **all 4** measured quantities:
  - Extract DIS kinematics, and energy of a possible ISR photon: $\vec{\boldsymbol{\lambda}} = \{\mathbf{x}, \mathbf{y}, \mathbf{E_\gamma}\}$

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

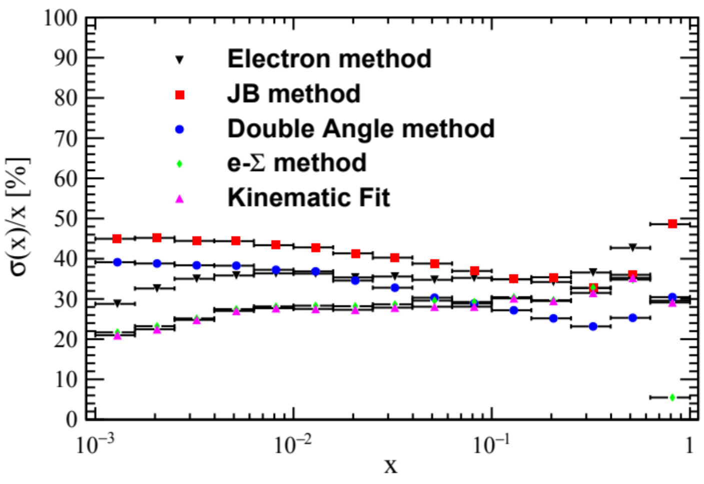
2. Prior $$P_o(\vec{\lambda}) = \frac{1 + (1-y)^2}{x^3 y^2} \frac{[1 + (1 - E_\gamma/A)^2]}{E_\gamma/A}$$

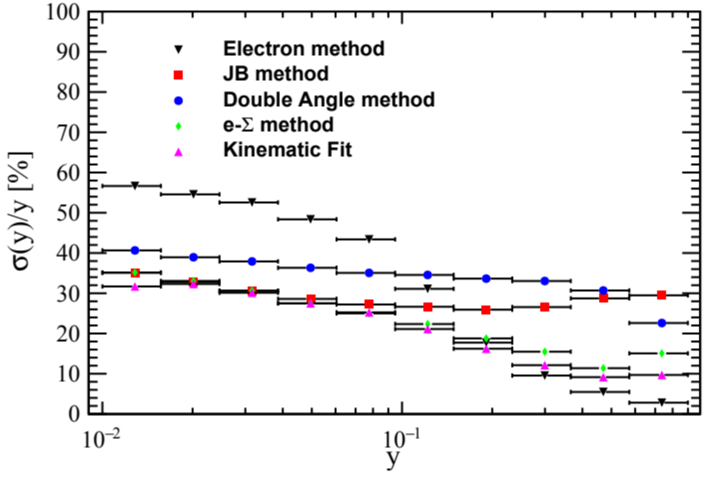
3. Posterior $$P(\vec{\lambda}|\vec{D}) \propto P(\vec{D}|\vec{\lambda}) P_o(\vec{\lambda}).$$

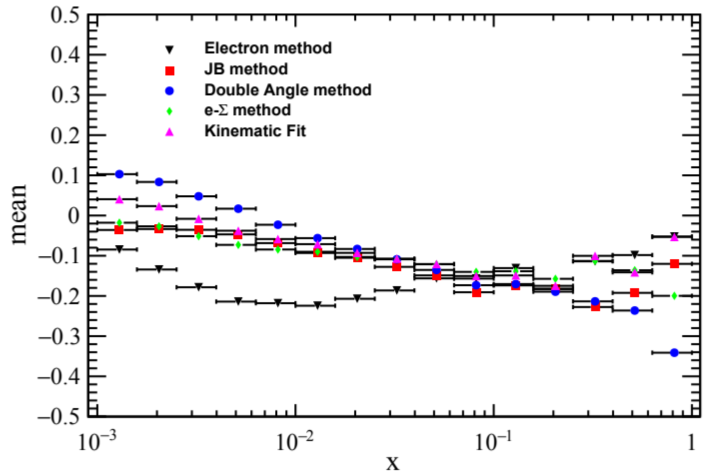
- **Posterior extracted** using Metropolis-Hastings algorithm:
  - → Fitted values of **x, y, E$_\gamma$** taken from global mode of the posterior

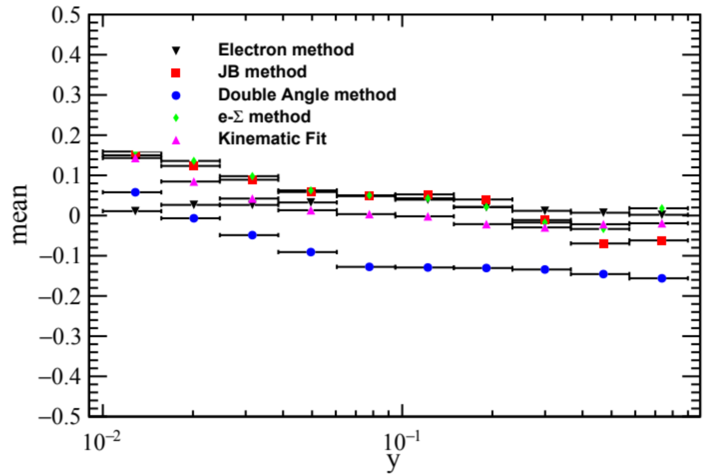


Impact on Kinematic Resolutions at ePIC









- 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 *

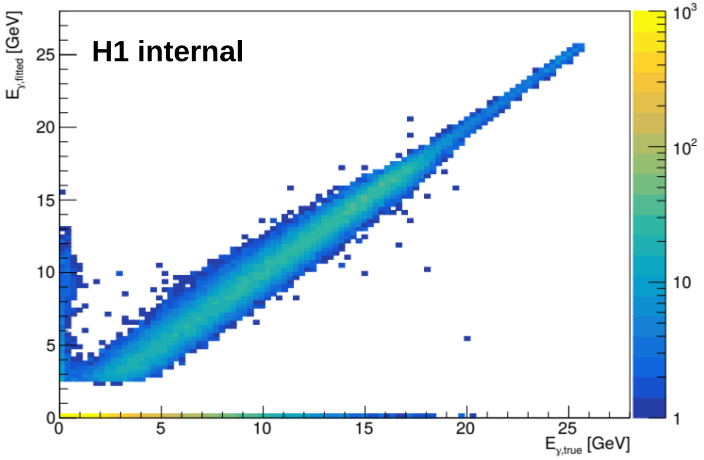
Mean

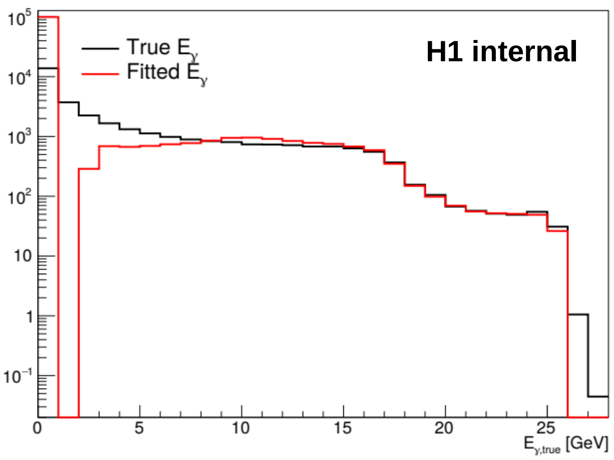
- KF shows low bias

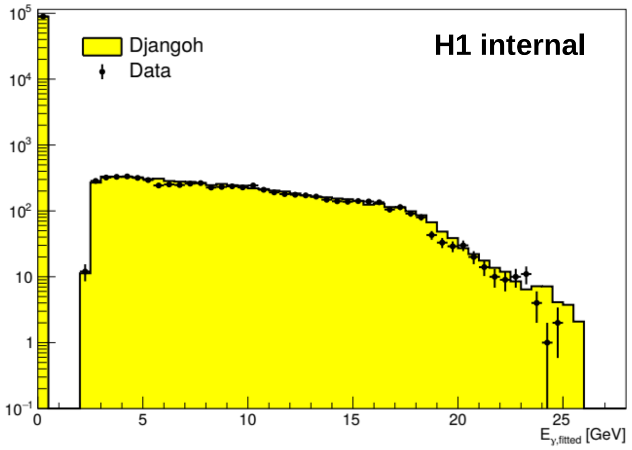
ISR Reconstruction at H1

H1 provides mature simulations that are extremely useful to validate the KF method

- Perform kinematic fit on H1 e^+p 03/04 MC+Data (ISR present)
  - Require $E_e > 11$ GeV in LAr Calorimeter
  - Additional cuts on $0.01 < y_{e\Sigma} < 0.6$ and $Q^2 > 200$ GeV^2



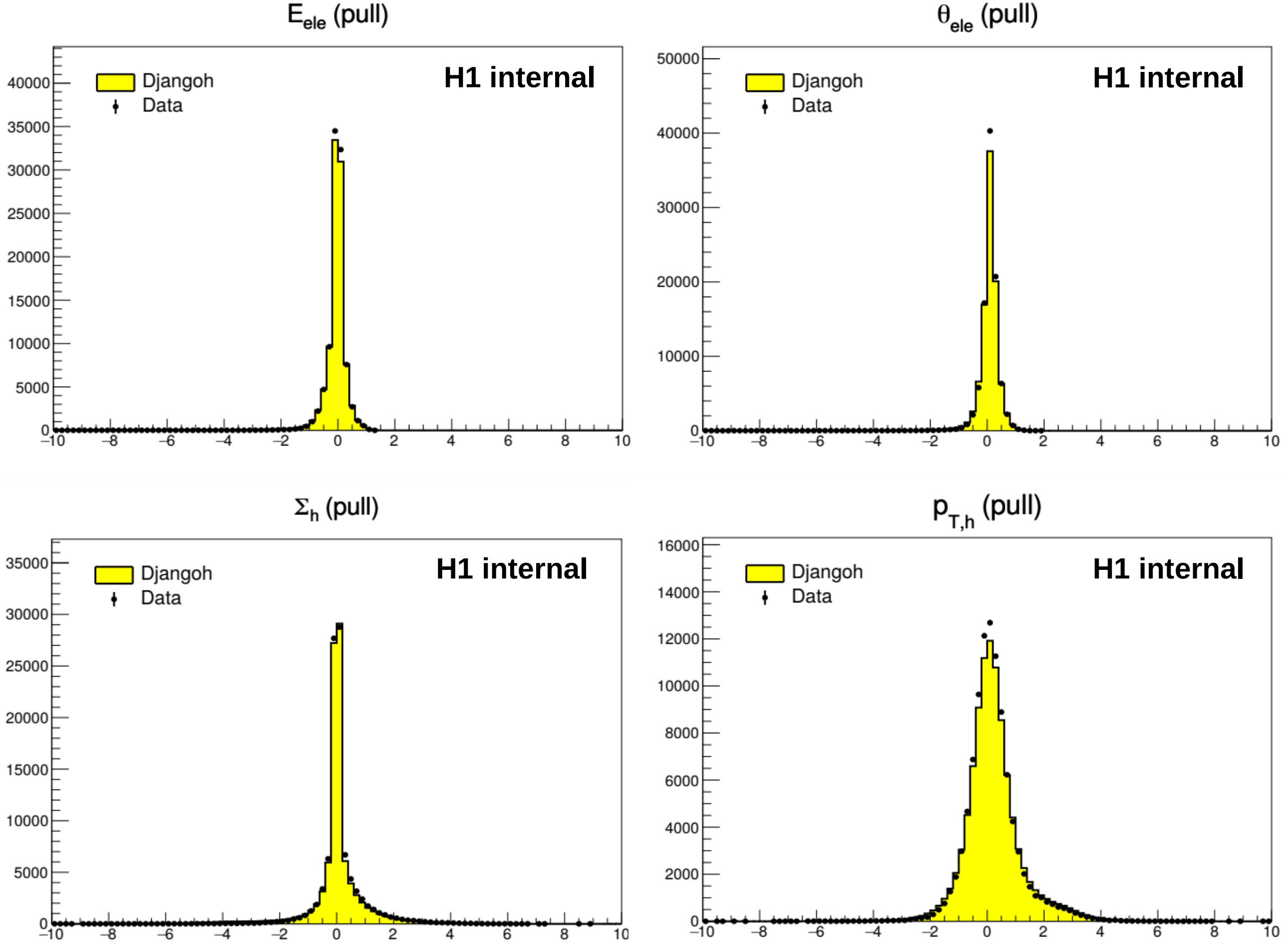




- ISR reconstructed with good resolution and efficiency for $E_\gamma > \sim 7$GeV in MC
- Good match between data and MC $E_{\gamma,\mathrm{fitted}}$ distributions

Validate KF Method with Pulls (H1)

- Draw pull distributions to look for biases
  - Pull of z is defined as $(z_{\text{fitted}}-z_{\text{reco}})\,/\,\mathrm{RMS}(z_{\text{fitted}}-z_{\text{reco}})_{\text{MC}}$

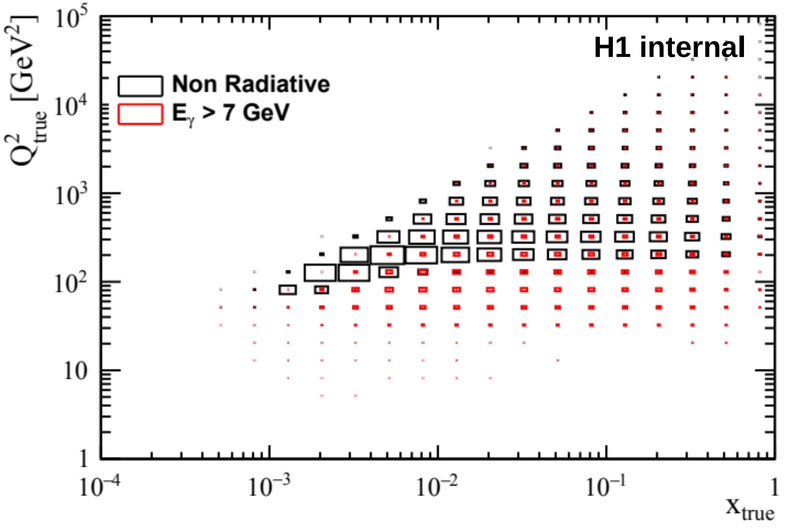


Why identify ISR?

- 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 is extended

What does this mean?

- Use to measure F_2 in an extended (low Q^2) kinematic range at EIC
- Possible F_L measurement at EIC in future, and maybe H1 now...



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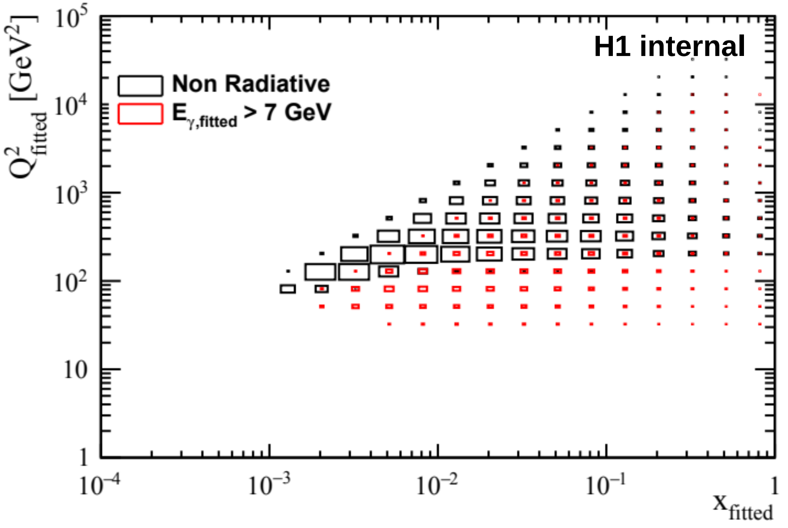

H1 Data

Summary

- A kinematic fit based method is presented for reconstruction of inclusive DIS variables, and energy of a possible ISR photon
- Resolution of inclusive DIS variables studied using simulations in the ePIC software framework for 18x275 GeV^2 DIS events → KF performs well
- ISR reconstruction using KF validated using H1 MC/Data
  - Hard ISR (>~7GeV) identified with good resolution and efficiency
  - Application of KF to Data and MC shows good agreement
  - Identifying ISR extends kinematic range that is accessible → exciting future measurements!

Acknowledgements

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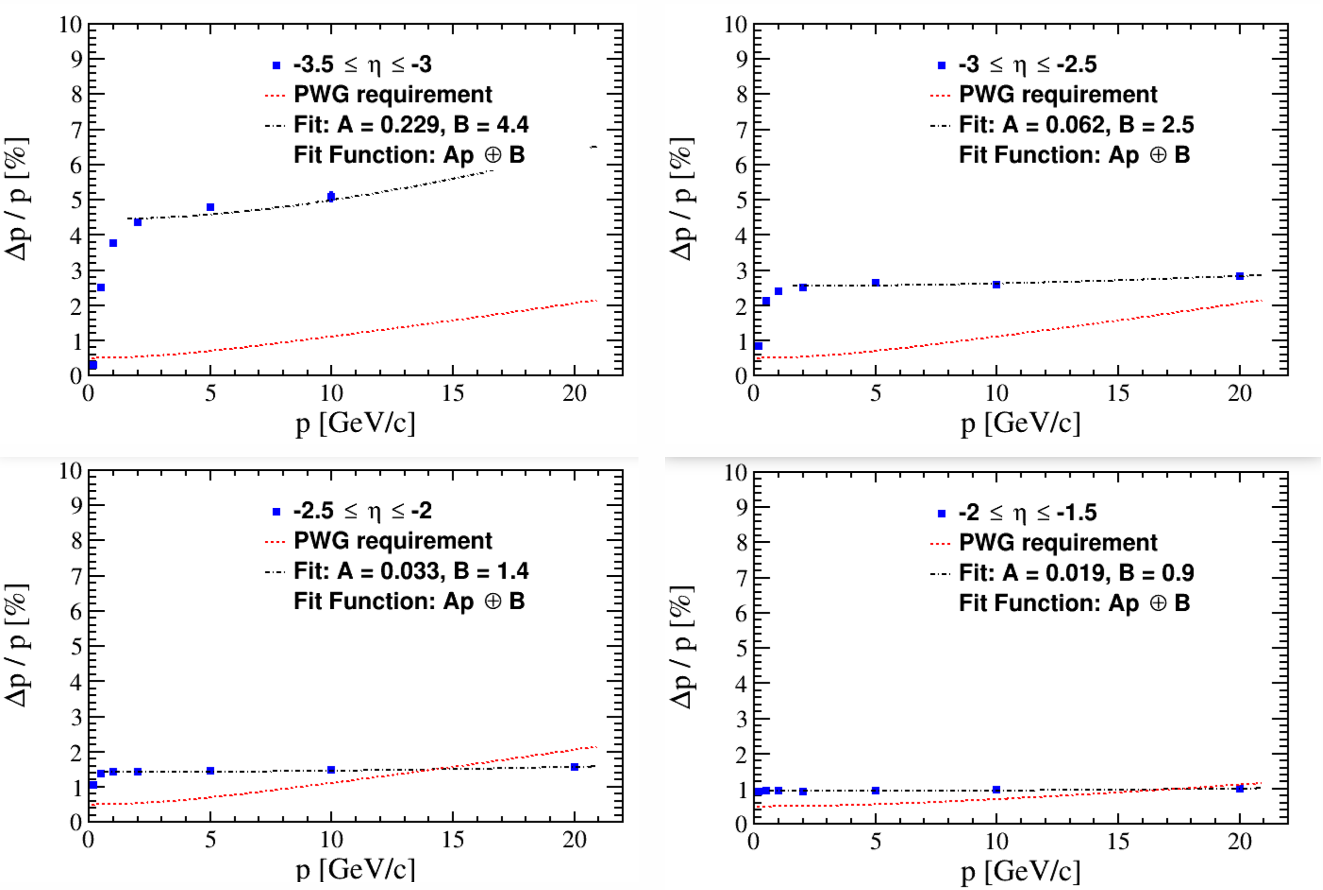
References

1) M. Arratia, D. Britzger, O. Long, B. Nachman, Reconstructing the Kinematics of Deep Inelastic Scattering with Deep Learning, Nuclear Inst. and Methods in Physics Research, A 1025 (2022) 166164
2) M. Diefenthaler, A. Farhat, A. Verbytskyi, Y. Xu, Deeply Learning Deep Inelastic ScatteringKinematics (Aug 2021). arXiv:2108.11638.
3) R. Aggarwal and A. Caldwell, “Kinematic fitting of neutral current events in deep inelastic ep collisions.,” JINST, vol. 17, no. 09, p. P09035, 2022.

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