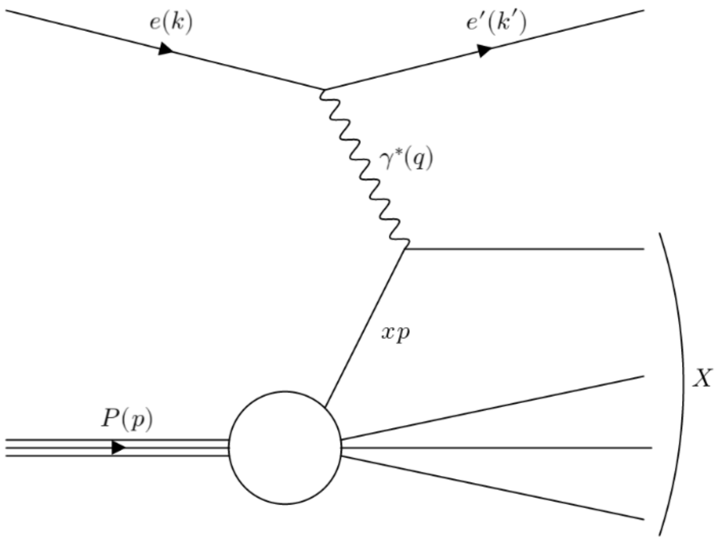
UNIVERSITY OF BIRMINGHAM | SCHOOL OF PHYSICS AND ASTRONOMY

Reconstruction of DIS kinematics

S. Maple

DIS Kinematics



- In **inclusive scattering** no constraints are placed on the hadronic final state
- At Born level we find a very simple relationship

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

"Virtuality" $Q^2 = -q^2$

CoM energy

Bjorken x

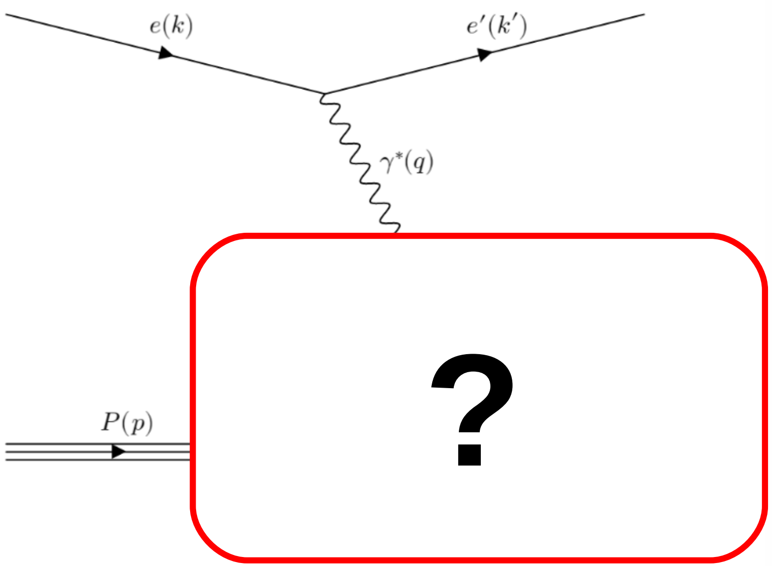
Inelasticity

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

$$x = \frac{Q^2}{2p \cdot q} \qquad W^2 \simeq sy - Q^2$$

Good reconstruction of inclusive kinematics is important beyond inclusive DIS!

DIS Kinematics beyond inclusive



- Generally, when reconstructing DIS kinematics, calculate y and Q^2, and derive x as:

$$x = \frac{Q^2}{sy}$$

- Q^2 and y have a consistent definition

- … the definition of x is not always obvious (especially in exclusive/diffractive processes) → can generally use the above relation (but I leave it to you to decide)

- I will focus on Q^2 and y reconstruction

Reconstructing the kinematics

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

- If we simply evaluate the four-momenta directly, we get the **electron method**

$$q^2 = (k - k')^2 \longrightarrow Q_e^2 = 2E_0 E_e (1 + \cos\theta_e)$$

$$p \cdot q = E_p[2E_0 - E_e(1 - \cos\theta_e)] \qquad p \cdot k = 2E_p E_0$$

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

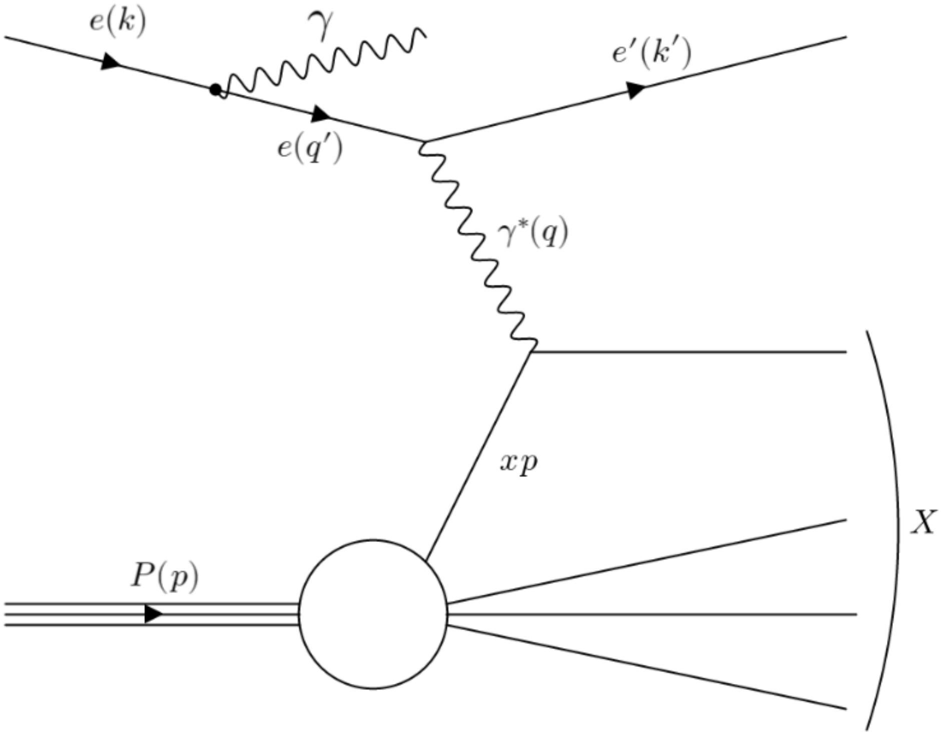
$$\frac{\delta Q^2}{Q^2} = \frac{\delta E_e}{E_e} \oplus \tan\frac{\theta_e}{2} \cdot \delta\theta_e$$

$$\frac{\delta y}{y} = \frac{1-y}{y}\left(\frac{\delta E_e}{E_e} \oplus \frac{\delta\theta_e}{\tan\frac{\theta_e}{2}}\right)$$

Problem:

- Resolution of y diverges at small y values
- Resolution of Q^2 diverges as $\theta_e \rightarrow 180$ degrees

...Some more problems



Problem:

- Beam electron may radiate a photon before interacting
  - Throws off reconstruction where beam electron energy is assumed
- Size of radiative corrections increase for increasing y

Solution:

- If this presents a problem in analysis, could include HFS information in reconstruction method

Reconstruction methods in EICrecon

EICrecon / src / algorithms / reco /

FarForwardNeutronReconstructionConfig.h	Fix: Correct ZDC LYSO Sampling Fraction (#1529)
HadronicFinalState.cc	feat: particleSvc to distribute mass by PDG (#1487)
HadronicFinalState.h	feat: particleSvc to distribute mass by PDG (#1487)
InclusiveKinematicsDA.cc	feat: particleSvc to distribute mass by PDG (#1487)
InclusiveKinematicsDA.h	feat: particleSvc to distribute mass by PDG (#1487)
InclusiveKinematicsESigma.cc	InclusiveKinematicseSigma -> InclusiveKinematicsESigma (#1572)
InclusiveKinematicsESigma.h	InclusiveKinematicseSigma -> InclusiveKinematicsESigma (#1572)
InclusiveKinematicsElectron.cc	feat: particleSvc to distribute mass by PDG (#1487)
InclusiveKinematicsElectron.h	feat: particleSvc to distribute mass by PDG (#1487)
InclusiveKinematicsJB.cc	feat: particleSvc to distribute mass by PDG (#1487)
InclusiveKinematicsJB.h	feat: particleSvc to distribute mass by PDG (#1487)
InclusiveKinematicsSigma.cc	feat: particleSvc to distribute mass by PDG (#1487)
InclusiveKinematicsSigma.h	feat: particleSvc to distribute mass by PDG (#1487)
InclusiveKinematicsTruth.cc	feat: particleSvc to distribute mass by PDG (#1487)
InclusiveKinematicsTruth.h	feat: particleSvc to distribute mass by PDG (#1487)
JetReconstruction.cc	fix: convert to algorithms logger, no m_log in each algorithm class (#…
JetReconstruction.h	fix: convert to algorithms logger, no m_log in each algorithm class (#…

- Currently there are 5 reconstruction methods available in EICrecon
  - Electron method
  - Jacquet-Blondel (JB/hadron) method
  - Double-Angle (DA) method
  - Sigma method
  - E-Sigma method
- This is not a complete list of all reconstruction methods available!

JB method

- The JB method reconstructs the kinematics using only HFS information
- The inclusive HFS is all particles other than the scattered lepton
  - Including the proton/ion remnant or intact proton/ion!
- Can't guarantee that we will measure the proton remnant, so we use a choice of variables that do not require this:

$$\delta_h = \sum_h E_h - p_{z,h}$$

$$p_{t,h}^2 = \left(\sum_h p_{x,h}\right)^2 + \left(\sum_h p_{y,h}\right)^2$$

Where h runs over all HFS particles

- The polar angle of the proton remnant is ~0 so its contribution to p_T and δ_h is negligible
- From these variables, the kinematics can be reconstructed as

$$y_{JB} = \frac{\delta_h}{2E_0} \quad Q_{JB}^2 = \frac{p_{t,h}^2}{1 - y_{JB}}$$

Problem:

- The HFS may consist of many particles, some with poor resolutions
  - JB method is typically only used in CCDIS (where it is the only method)

Double-Angle method

- The DA method reconstructs the kinematics without directly using an energy measurement
  - This makes it a powerful method if you have a poor calorimeter (or track momentum) resolution

- The DA method is defined using the angles

$$\alpha_e = \tan\frac{\theta_e}{2} \qquad \alpha_h = \tan\frac{\gamma}{2} = \frac{\delta_h}{p_{t,h}}$$

as

$$y_{DA} = \frac{\alpha_h}{\alpha_e + \alpha_h} \qquad Q^2_{DA} = \frac{4E_0^2}{\alpha_e(\alpha_e + \alpha_h)}$$

- The electron energy is not used; errors associated with the HFS energy measurement largely cancel out

(e-)Sigma method

- The Sigma methods, like the DA method, use a mixture of electron and HFS information to optimise the resolution across a large region

- The Sigma method is defined as

$$y_\Sigma = \frac{\delta_h}{\delta_h + E_e(1-\cos\theta_e)} \qquad Q^2_\Sigma = \frac{E_e^2 \sin^2\theta_e}{1-y_\Sigma}$$

and the e-Sigma method instead uses

$$Q^2_{e\Sigma} = Q^2_e \qquad x_{e\Sigma} = x_\Sigma$$

- In these methods, the electron beam energy (E_0) is not used (except in Q^2 for e-Σ)
  - This makes these methods resistant to the effect of initial state QED radiation

A comment on methods not in EICrecon

Method name	Observables	y	Q^2	$x \cdot E_p$
Electron (e)	$[E_0,E,\theta]$	$1-\frac{\Sigma_e}{2E_0}$	$\frac{E^2\sin^2\theta}{1-y}$	$\frac{E(1+\cos\theta)}{2y}$
Double angle (DA) [6, 7]	$[E_0,\theta,\gamma]$	$\frac{\tan\frac{\gamma}{2}}{\tan\frac{\gamma}{2}+\tan\frac{\theta}{2}}$	$4E_0^2\cot^2\frac{\theta}{2}(1-y)$	$\frac{Q^2}{4E_0y}$
Hadron (h, JB) [4]	$[E_0,\Sigma,\gamma]$	$\frac{\Sigma}{2E_0}$	$\frac{T^2}{1-y}$	$\frac{Q^2}{2\Sigma}$
ISigma ($\mathrm{I}\Sigma$) [9]	$[E,\theta,\Sigma]$	$\frac{\Sigma}{\Sigma+\Sigma_e}$	$\frac{E^2\sin^2\theta}{1-y}$	$\frac{E(1+\cos\theta)}{2y}$
IDA [7]	$[E,\theta,\gamma]$	y_{DA}	$\frac{E^2\sin^2\theta}{1-y}$	$\frac{E(1+\cos\theta)}{2y}$
$E_0E\Sigma$	$[E_0,E,\Sigma]$	y_h	$4E_0E-4E_0^2(1-y)$	$\frac{Q^2}{2\Sigma}$
$E_0\theta\Sigma$	$[E_0,\theta,\Sigma]$	y_h	$4E_0^2\cot^2\frac{\theta}{2}(1-y)$	$\frac{Q^2}{2\Sigma}$
$\theta\Sigma\gamma$ [8]	$[\theta,\Sigma,\gamma]$	y_{DA}	$\frac{T^2}{1-y}$	$\frac{Q^2}{2\Sigma}$
Double energy (A4) [7]	$[E_0,E,E_h]$	$\frac{E-E_0}{(xE_p)-E_0}$	$4E_0y(xE_p)$	$E+E_h-E_0$
$E\Sigma T$	$[E,\Sigma,T]$	$\frac{\Sigma}{\Sigma+E\pm\sqrt{E^2+T^2}}$	$\frac{T^2}{1-y}$	$\frac{Q^2}{2\Sigma}$
E_0ET	$[E_0,E,T]$	$\frac{2E_0-E\mp\sqrt{E^2-T^2}}{2E_0}$	$\frac{T^2}{1-y}$	$\frac{Q^2}{4E_0y}$
Sigma (Σ) [9]	$[E_0,E,\Sigma,\theta]$	$y_{\mathrm{I}\Sigma}$	$Q^2_{\mathrm{I}\Sigma}$	$\frac{Q^2}{4E_0y}$
eSigma ($e\Sigma$) [9]	$[E_0,E,\Sigma,\theta]$	$\frac{2E_0\Sigma}{(\Sigma+\Sigma_e)^2}$	$2E_0E(1+\cos\theta)$	$\frac{E(1+\cos\theta)(\Sigma+\Sigma_e)}{2\Sigma}$

- A Table summarising basic methods can be found in https://arxiv.org/abs/2110.05505
- There are many ways to permute the various inputs to get a new method

A comment on methods not in EICrecon

- Ideally a method that uses the full available information optimally should give the best resolution everywhere

- Some interest has been shown in DNNs

https://arxiv.org/pdf/2110.05505

Reconstructing the Kinematics of Deep Inelastic Scattering with Deep Learning

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[b] Thomas Jefferson National Accelerator Facility, Newport News, VA 23606, USA
[c] Max-Planck-Institut für Physik, Föhringer Ring 6, 80805 München, Germany
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[e] Berkeley Institute for Data Science, University of California, Berkeley, CA 94720, USA

https://arxiv.org/pdf/2108.11638

Deeply Learning Deep Inelastic Scattering Kinematics

Markus Diefenthaler[1], Abdullah Farhat[2], Andrii Verbytskyi[3] and Yuesheng Xu[2]

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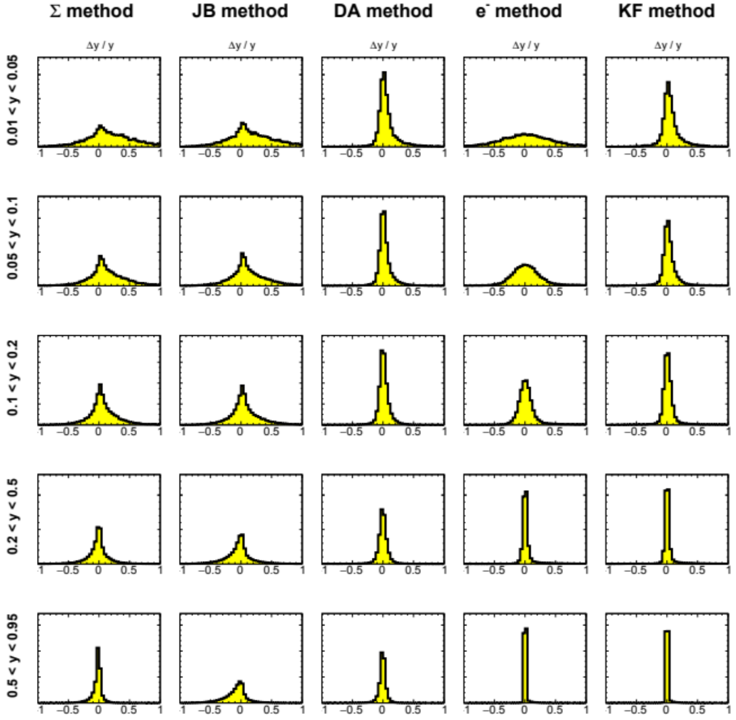
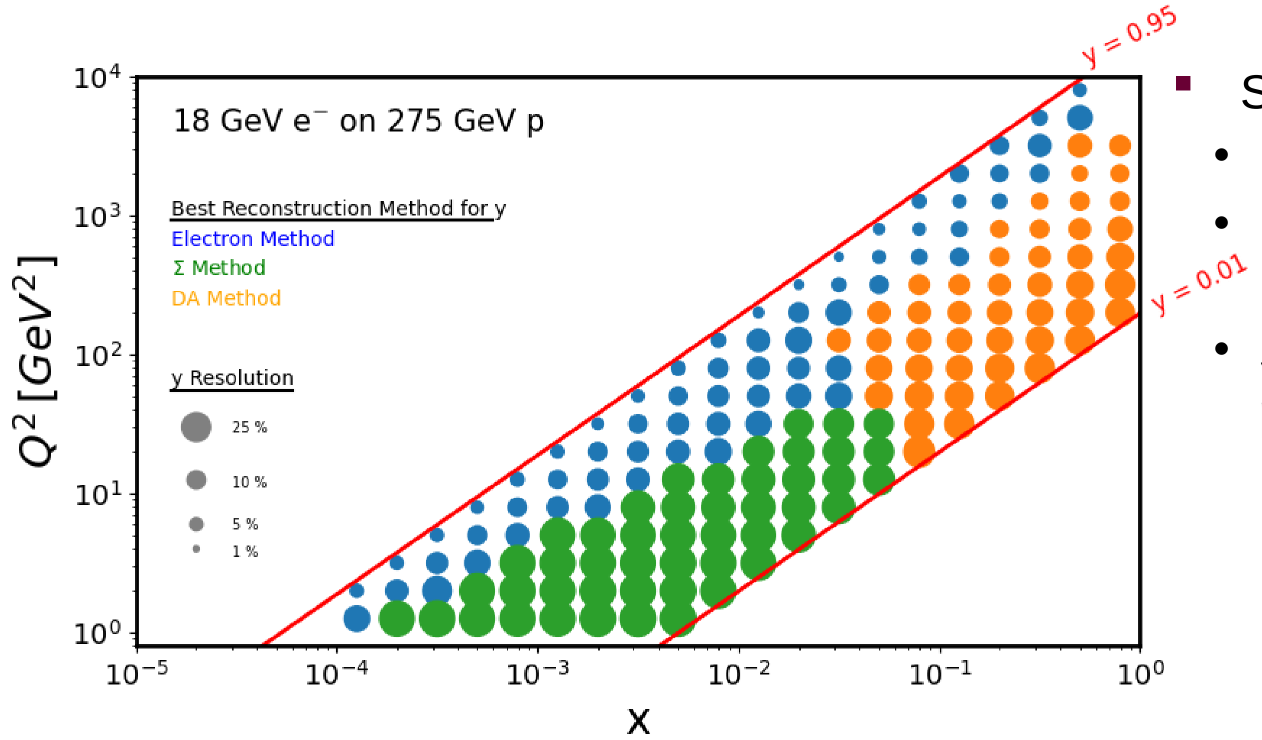
[3] Max-Planck-Institut für Physik, D-80805 Munich, Germany

- …And I've been looking into kinematic fitting



Which method should I use?

- The obvious choice is the method that gives the best resolution for your analysis
  - Here's what that might look like for inclusive DIS:

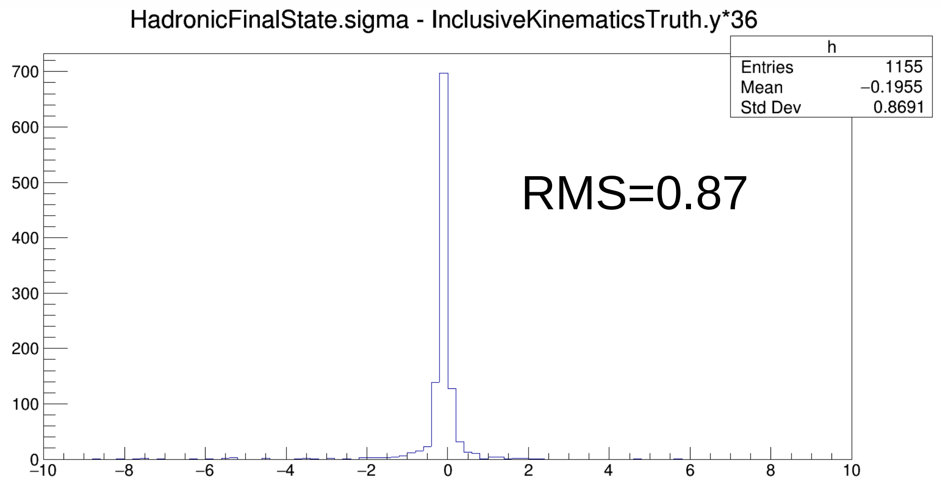


- Some general features are seen:
  - Electron method best at large y
  - DA method at high x and Q2 → large angles for e⁻ and HFS
  - Sigma method fills the remaining phase space

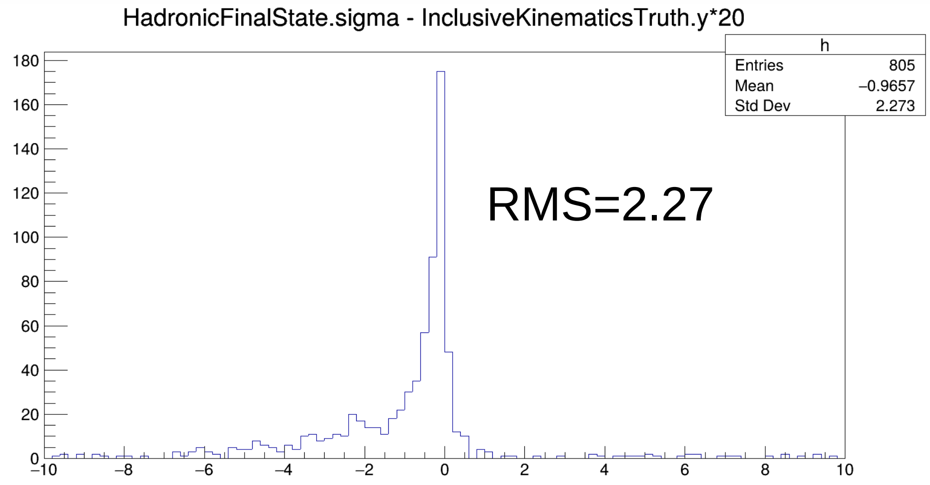
Which method should I use?

- Exclusive final states may have far fewer "HFS" particles – and may not have any neutral component
  - HFS may be quite well measured → improved performance of mixed (and JB) methods

Diffractive phi 18x110 (e-Au)
$\delta_{h,reco} - \delta_{h,true}$



NCDIS 10x100 (e-p)
$\delta_{h,reco} - \delta_{h,true}$



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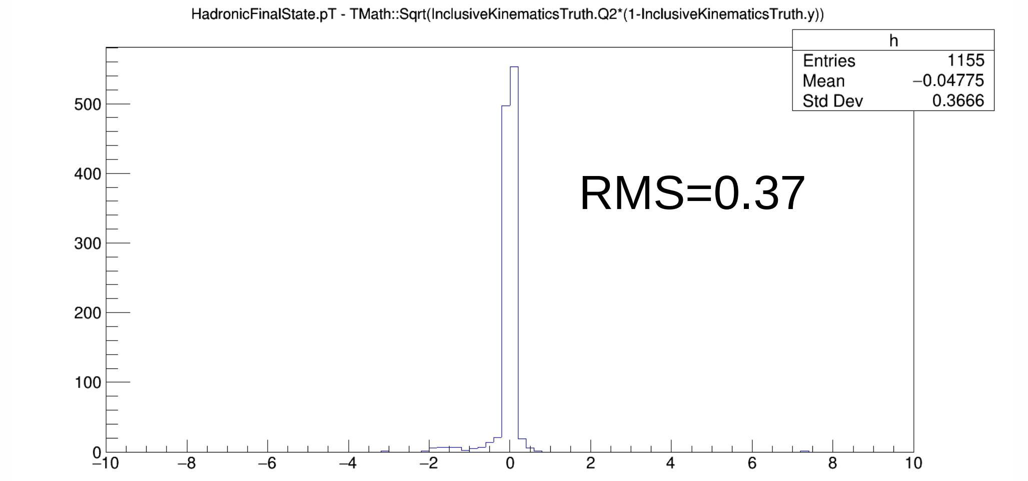
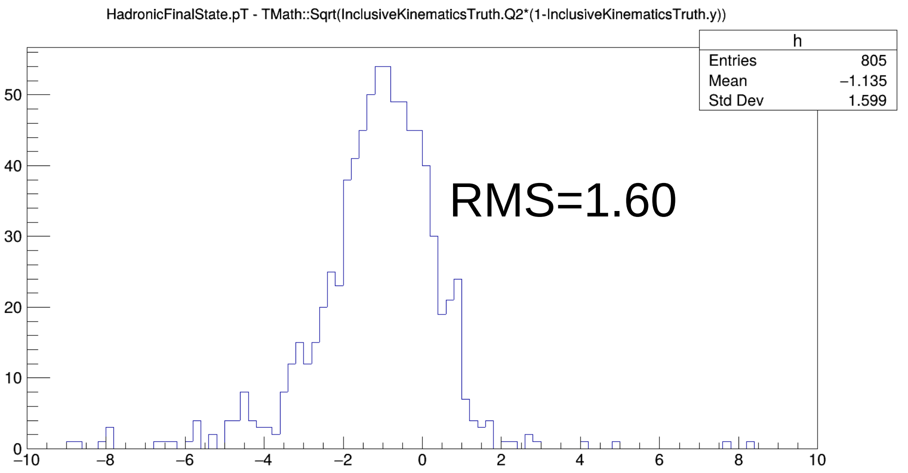
Diffractive phi 18x110 (e-Au)
$pT_{h,reco} - pT_{h,true}$



NCDIS 10x100 (e-p)
$pT_{h,reco} - pT_{h,true}$



Impact of HFS measurement on reconstruction methods

- Four inputs to the reconstruction methods measured by the detector: **$(E_e, \theta_e, p_{t,h}, \delta_h)$**
- The resolutions of these variables are responsible for the performance of the methods
- Consider an example event with x=0.01, y=0.2, for 10x100 beam configuration

$\sigma(E_e)$ = 0.1 GeV

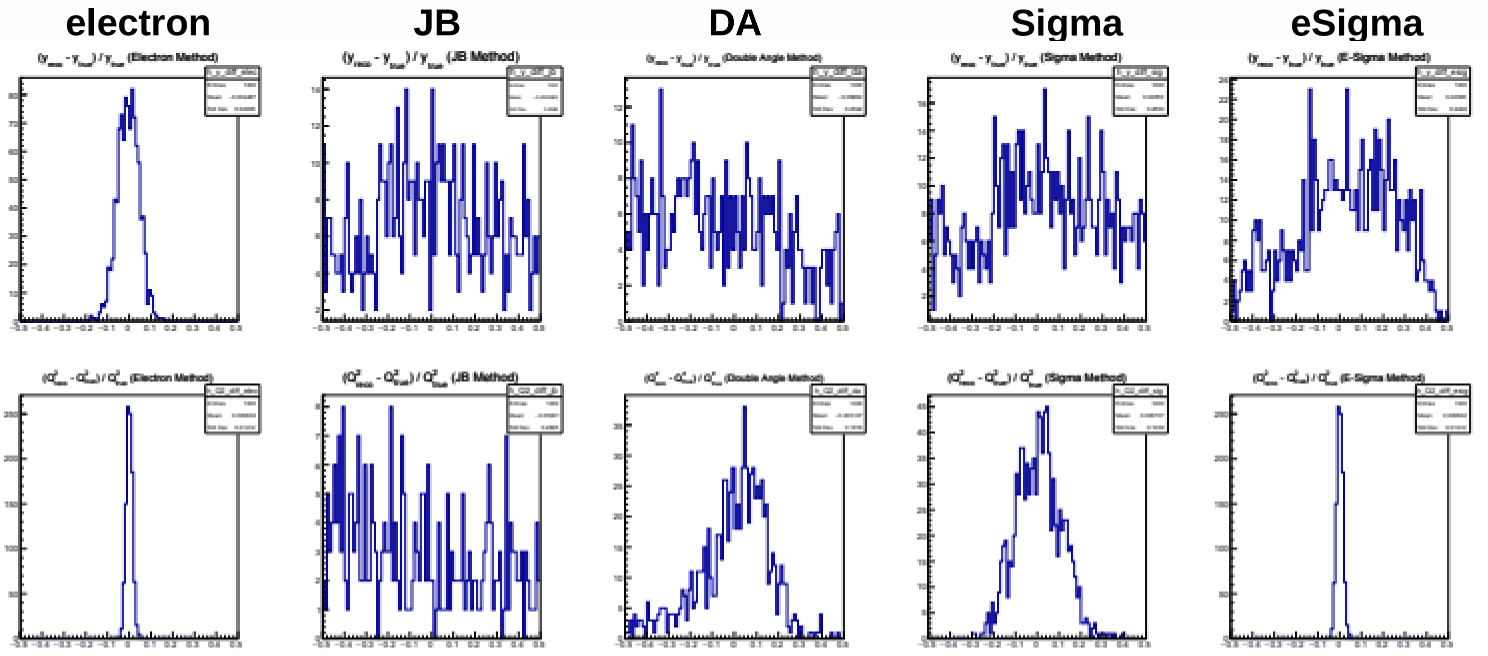
$\sigma(\theta_e)$ = 1 mrad

$\sigma(p_{t,h})$ = 2 GeV

$\sigma(\delta_h)$ = 2 GeV

$(y_{reco}-y_{true})/y_{true}$

$(Q^2_{reco}-Q^2_{true})/Q^2_{true}$



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$\sigma(E_e)$ = 0.1 GeV

$\sigma(\theta_e)$ = 1 mrad

$\sigma(p_{t,h})$ = 1.5 GeV

$\sigma(\delta_h)$ = 1.5 GeV

$(y_{reco}-y_{true})/y_{true}$

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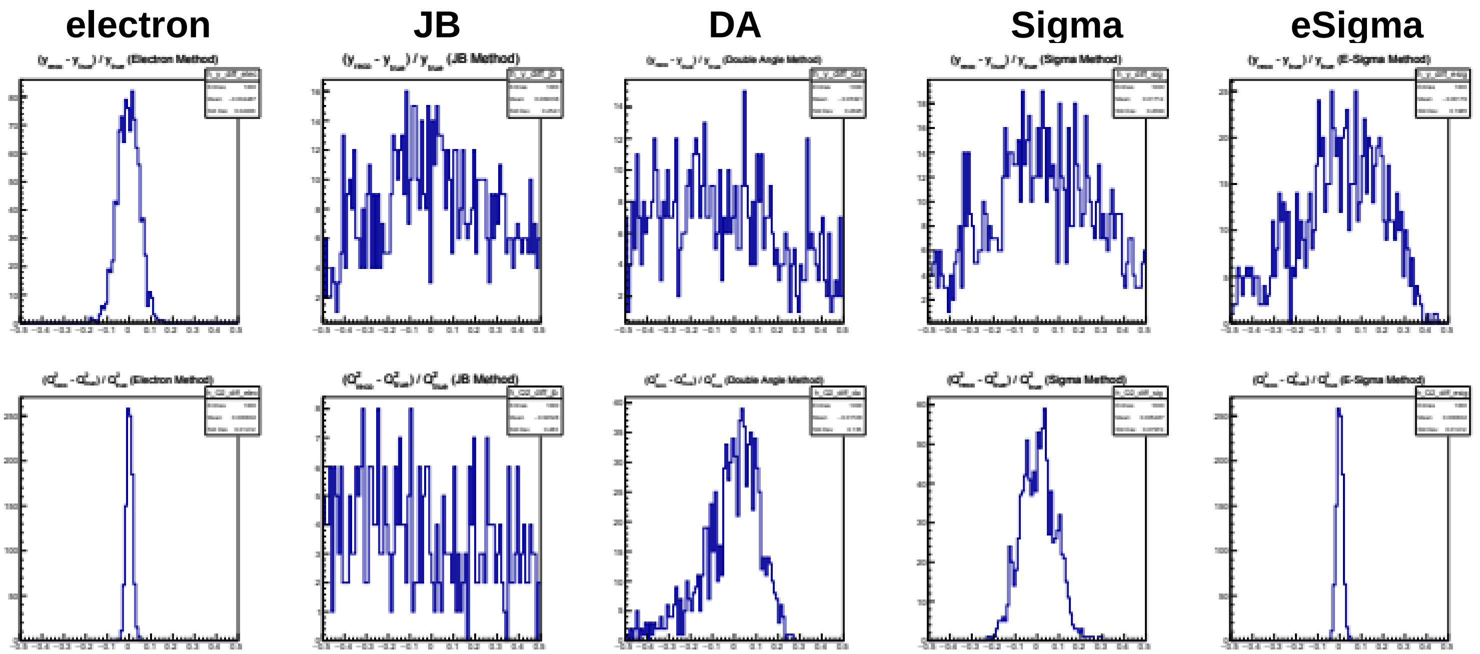

Impact of HFS measurement on reconstruction methods

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$\sigma(\delta_h)$ = 1 GeV

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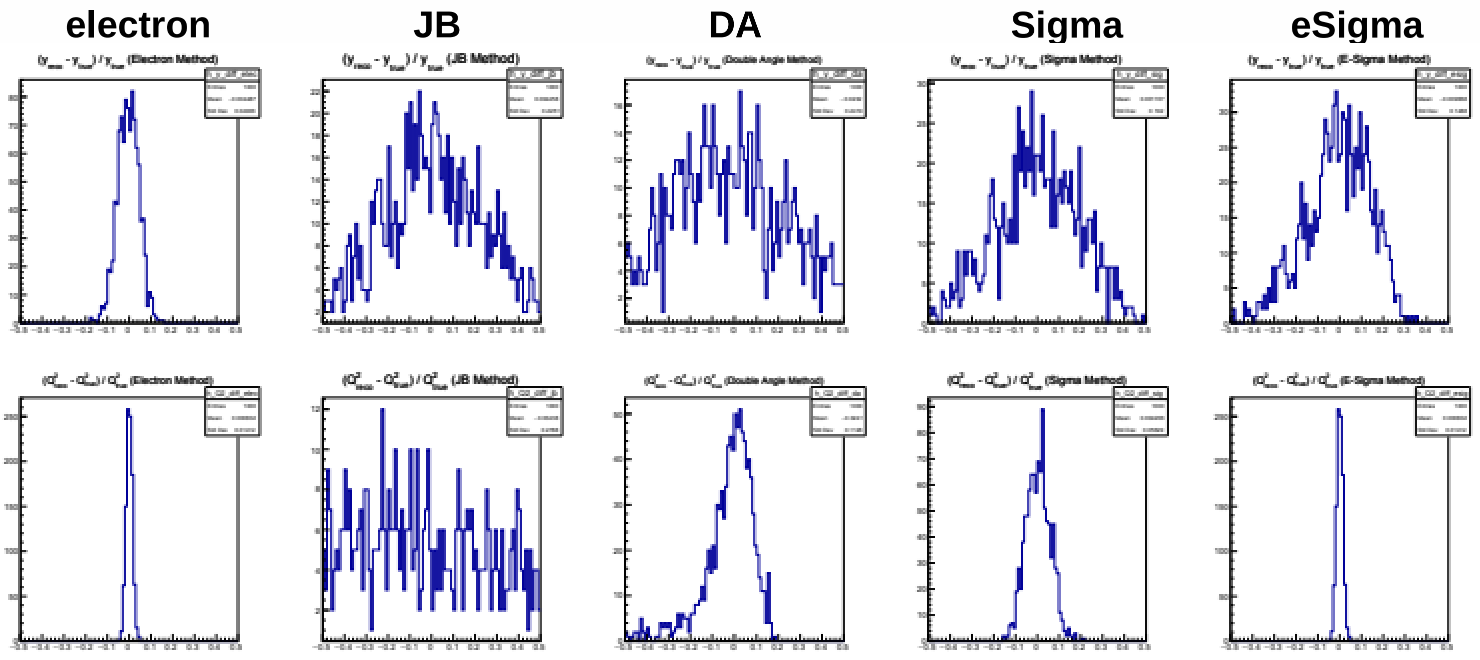
$(Q^2_{reco}-Q^2_{true})/Q^2_{true}$



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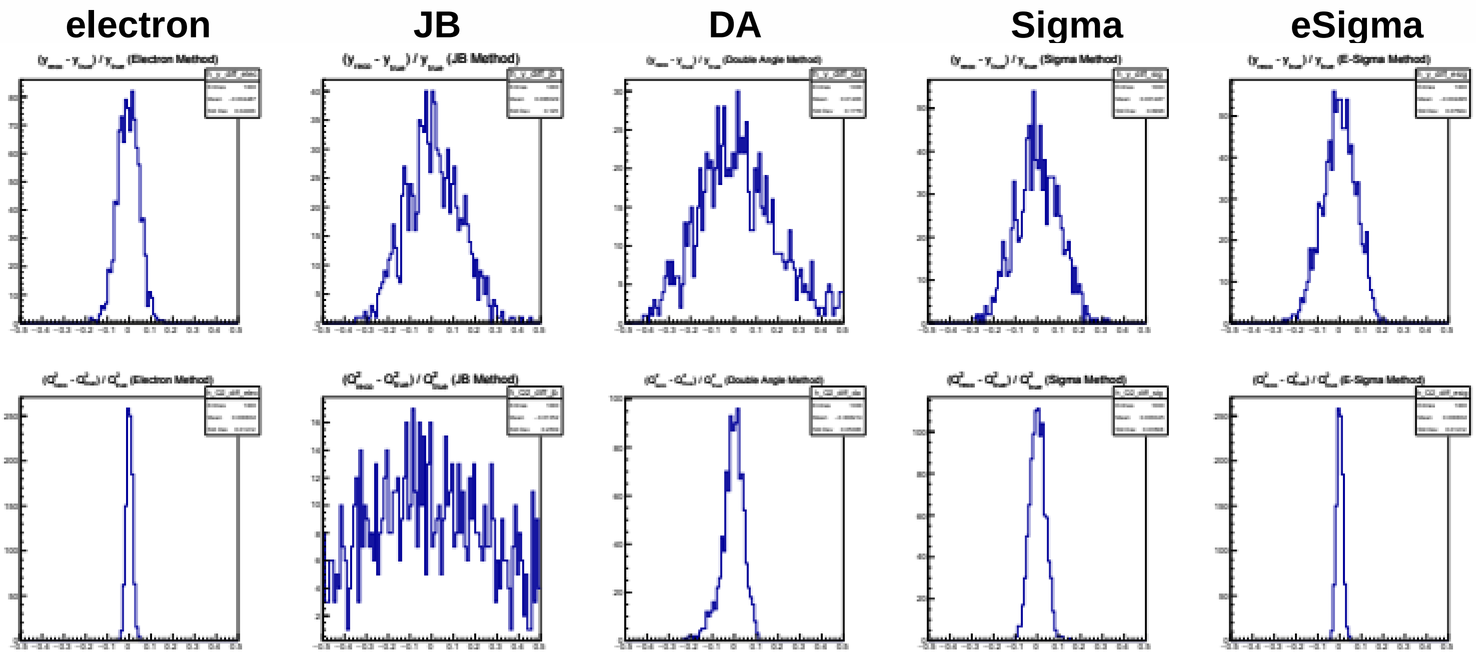
$(y_{reco}-y_{true})/y_{true}$

$(Q^2_{reco}-Q^2_{true})/Q^2_{true}$



Impact of E_e measurement on reconstruction methods

- Four inputs to the reconstruction methods measured by the detector: **(E_e, θ_e, $p_{t,h}$, δ_h)**
- The resolutions of these variables are responsible for the performance of the methods
- Consider an example event with x=0.01, y=0.2, for 10x100 beam configuration

$\sigma(E_e)$ = 0.2 GeV

$\sigma(\theta_e)$ = 1 mrad

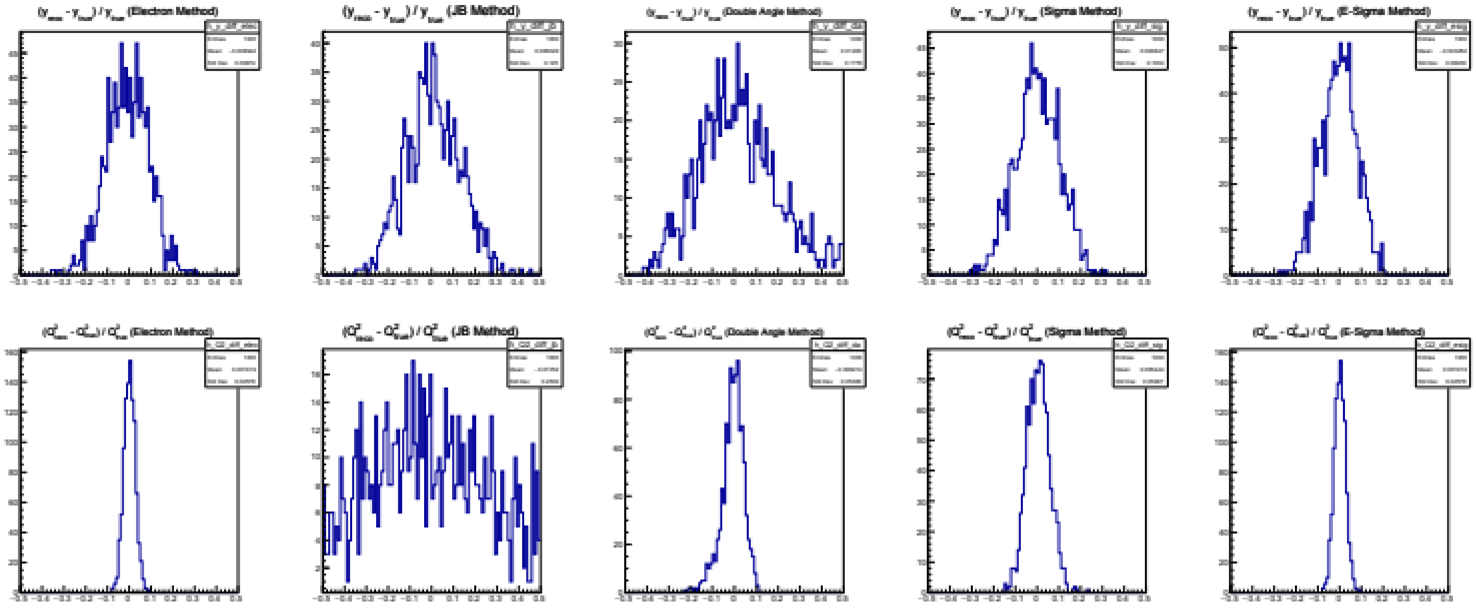
$\sigma(p_{t,h})$ = 0.5 GeV

$\sigma(\delta_h)$ = 0.5 GeV

$(y_{reco}-y_{true})/y_{true}$

$(Q^2_{reco}-Q^2_{true})/Q^2_{true}$

electron | **JB** | **DA** | **Sigma** | **eSigma**



Impact of E_e measurement on reconstruction methods

- Four inputs to the reconstruction methods measured by the detector: **(E_e, θ_e, $p_{t,h}$, δ_h)**
- The resolutions of these variables are responsible for the performance of the methods
- Consider an example event with x=0.01, y=0.2, for 10x100 beam configuration

$\sigma(E_e)$ = 0.3 GeV

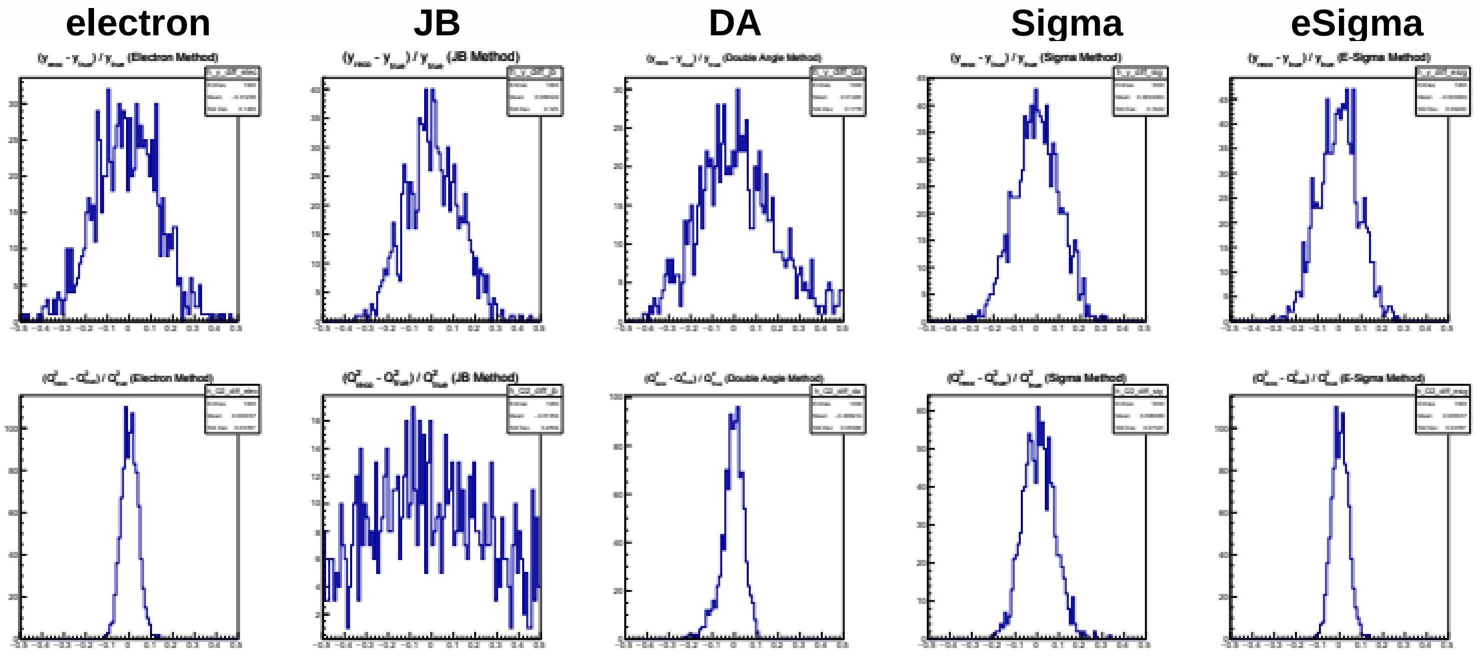
$\sigma(\theta_e)$ = 1 mrad

$\sigma(p_{t,h})$ = 0.5 GeV

$\sigma(\delta_h)$ = 0.5 GeV

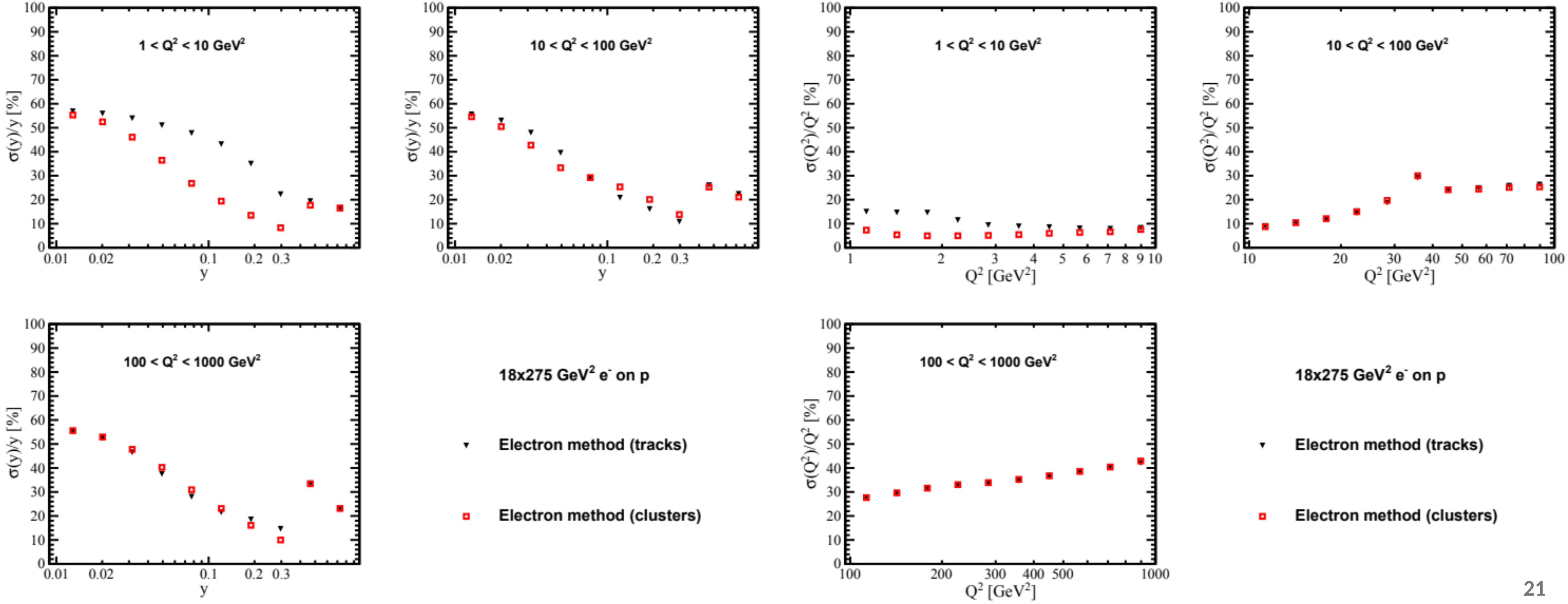
$(y_{reco}-y_{true})/y_{true}$

$(Q^2_{reco}-Q^2_{true})/Q^2_{true}$



E_e from Calorimeter vs Tracker

- ECAL provides better electron reconstruction than tracker at low Q^2 (below ~5 GeV^2)
  - Note: 18 GeV e^- beam here, may change for 5, 10 GeV beams
  - Note 2: Realistic eID here, needs further investigation

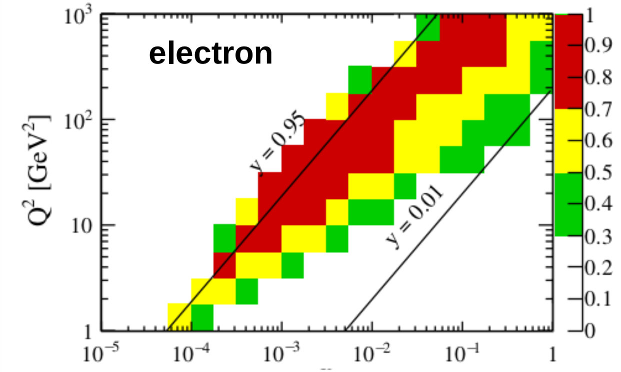


Considerations for optimising exclusive analyses

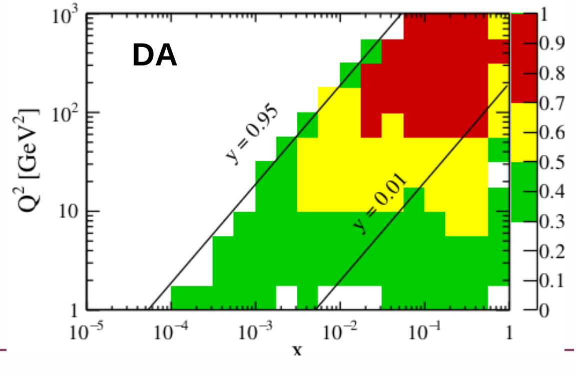
- What kinematic variables are you cutting on/plotting in: y, Q^2, x, W?

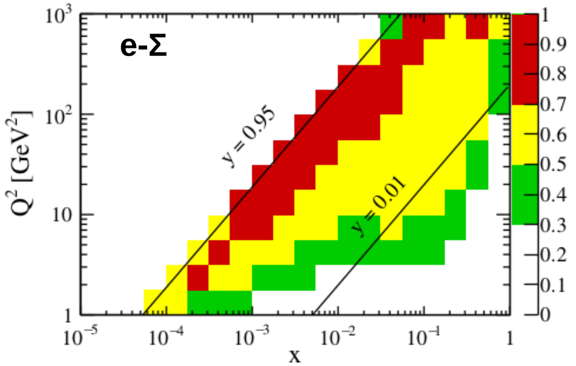
- Is the aim to optimise a binning scheme?

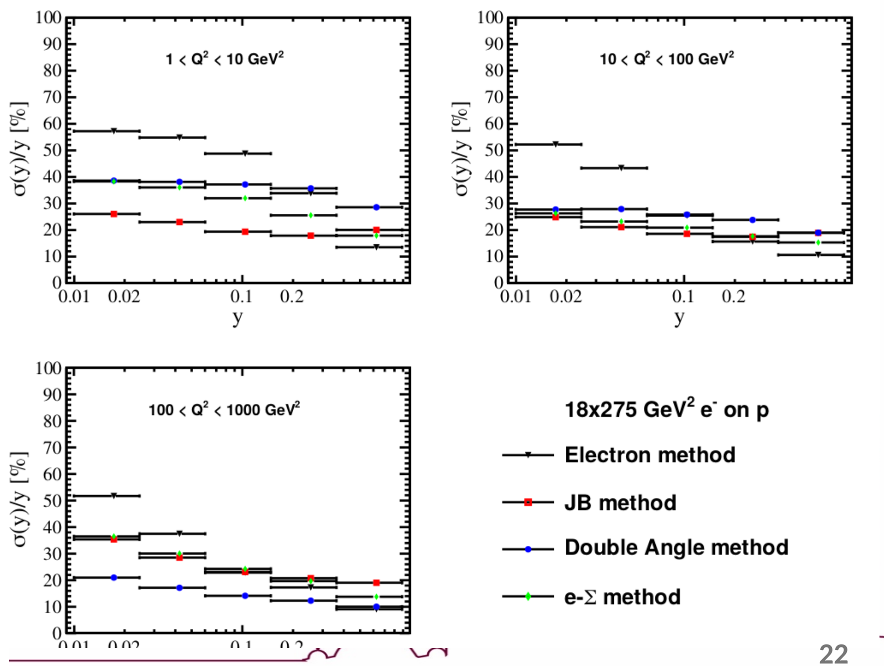
- Just want the best resolution? → in what variable?



Purity of x-Q^2 bins



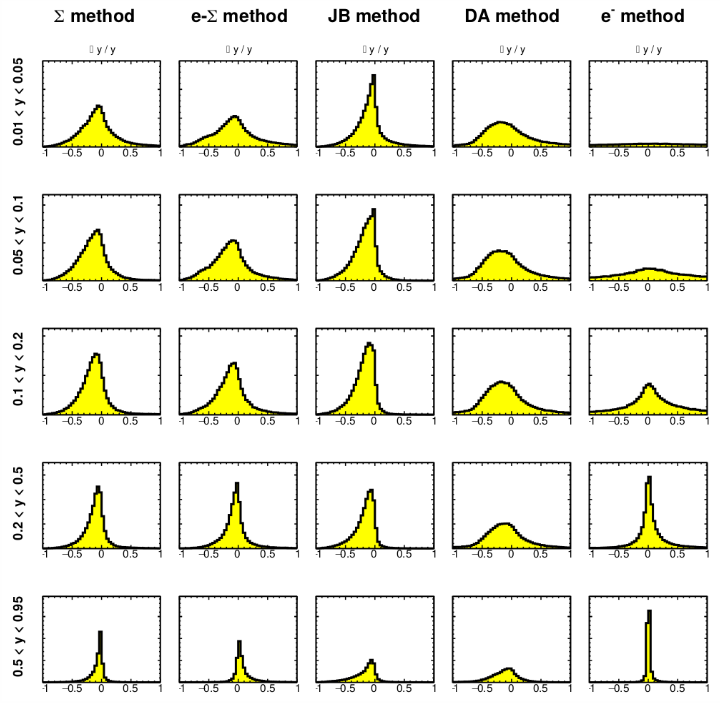




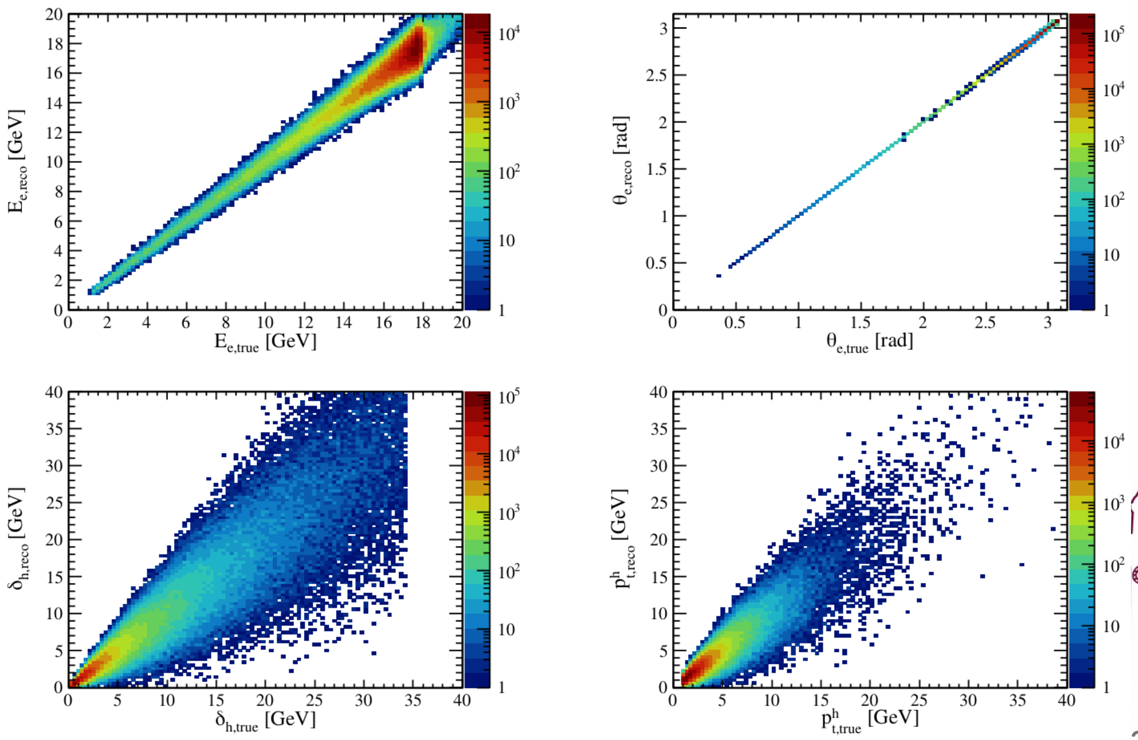
Considerations for optimising exclusive analyses

- What are the benchmark plots to check that everything is working?

dy/y, dx/x, dQ2/Q2?



E_e, θ_e, δ_h, $p_{t,h}$ reco vs true? Q^2, x, y reco vs true?



Conclusion

My thoughts

- A good reconstruction of the inclusive kinematics is needed for many processes
- The optimal reconstruction method should be found through dedicated studies by the analysers for a given process
  - Exclusive analysers may benefit greatly from mixed reconstruction methods

Discussion topics

- Q: What are the QA plots to know that my reconstructed kinematics are correct?
  - SM: I like x, y, Q^2 (reco – true)/true distributions → if it's not centred at ~1 then something is likely wrong → other suggestions?
- Q: What plot do I make to decide the best method for my analysis?
  - SM: Depends what your final plot is meant to be → if you are plotting e.g. differential xSec vs Q^2, could compare the Q^2 resolution vs Q^2 in your area of the phase space and choose the method that is best over the largest range
- Any other topics?