UNIVERSITY OF BIRMINGHAM | SCHOOL OF PHYSICS AND ASTRONOMY

Kinematic Reconstruction

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Overview

- An initial assessment of the kinematic reconstruction performance of the EPIC detector using current simulations with EPIC software
  - Note: Still work to be done on reconstruction of hadronic final state → particle flow
- Discussion of alternative reconstruction methods that use all available information
  - Verifying reconstruction based on kinematic fit (with Bayesian method)

Kinematic Reconstruction

- The kinematics of DIS can be reconstructed from any two of the measured quantities $\vec{D} = \{E_e, \theta_e, \delta_h, p_{t,h}\}$
  - Where $\delta_h = \Sigma\, E_i(1 - \cos(\theta_i))$. E_i and θ_i are the energies and angles of deposits in the calorimeters which are not assigned to the scattered electron.
  - $P_{t,h}$ is the transverse momentum of the hadronic final state
- Resolution of conventional reconstruction methods depend on x-Q^2 of the event, detector acceptance and resolution effects, and 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

$$y = \frac{\delta_{had}}{2E_e}$$
$$Q^2 = \frac{p^2_{t\,had}}{1-y}$$

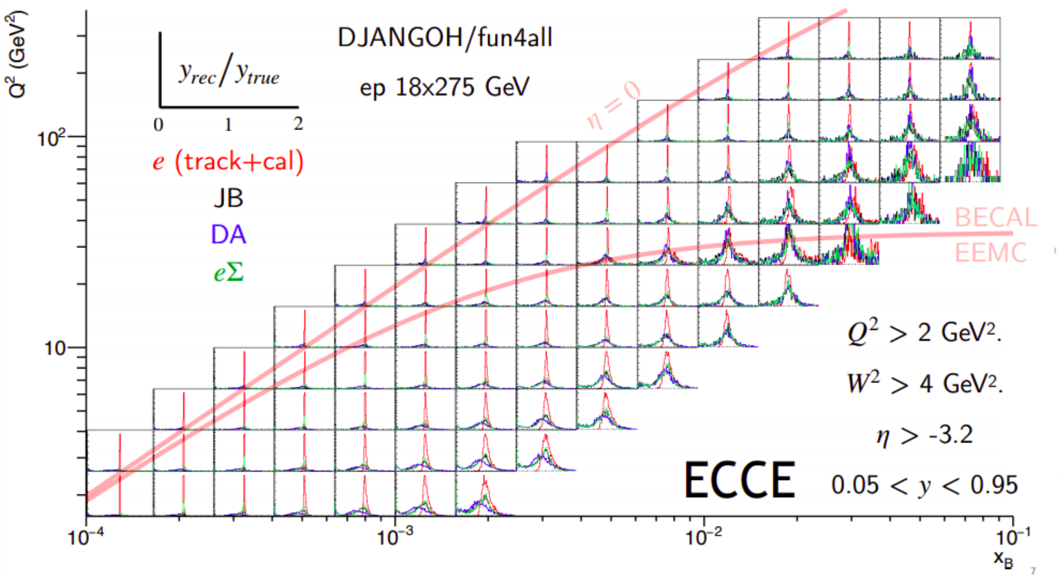
Double Angle method

$$Q^2 = 4E_e^2\frac{\sin\gamma(1+\cos\theta_e)}{\sin\gamma+\sin\theta_e-\sin(\theta_e+\gamma)}$$
$$x = \frac{E_e}{E_p}\frac{\sin\gamma+\sin\theta_e+\sin(\theta_e+\gamma)}{\sin\gamma+\sin\theta_e-\sin(\theta_e+\gamma)}$$

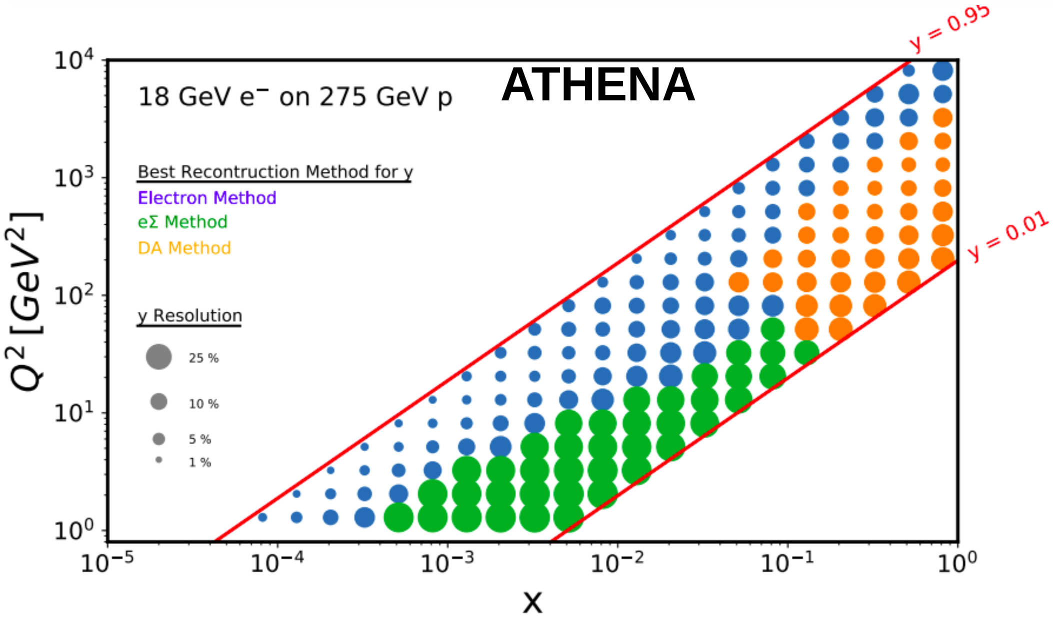
e-Σ method

$$Q^2_{e\Sigma} = Q^2_e$$
$$x_{e\Sigma} = \frac{Q^2_\Sigma}{s y_\Sigma}$$

Kinematic Resolutions – ECCE/ATHENA Proposals



- Work done during call for proposals provided first detailed assessment of relative performance of reconstruction methods for measured phase space



- Performance quantified with y_{rec}/y_{true}
  - Above plot shows distribution of y_{rec}/y_{true} for each method in each bin
  - Right hand plot shows RMS of best method for each bin

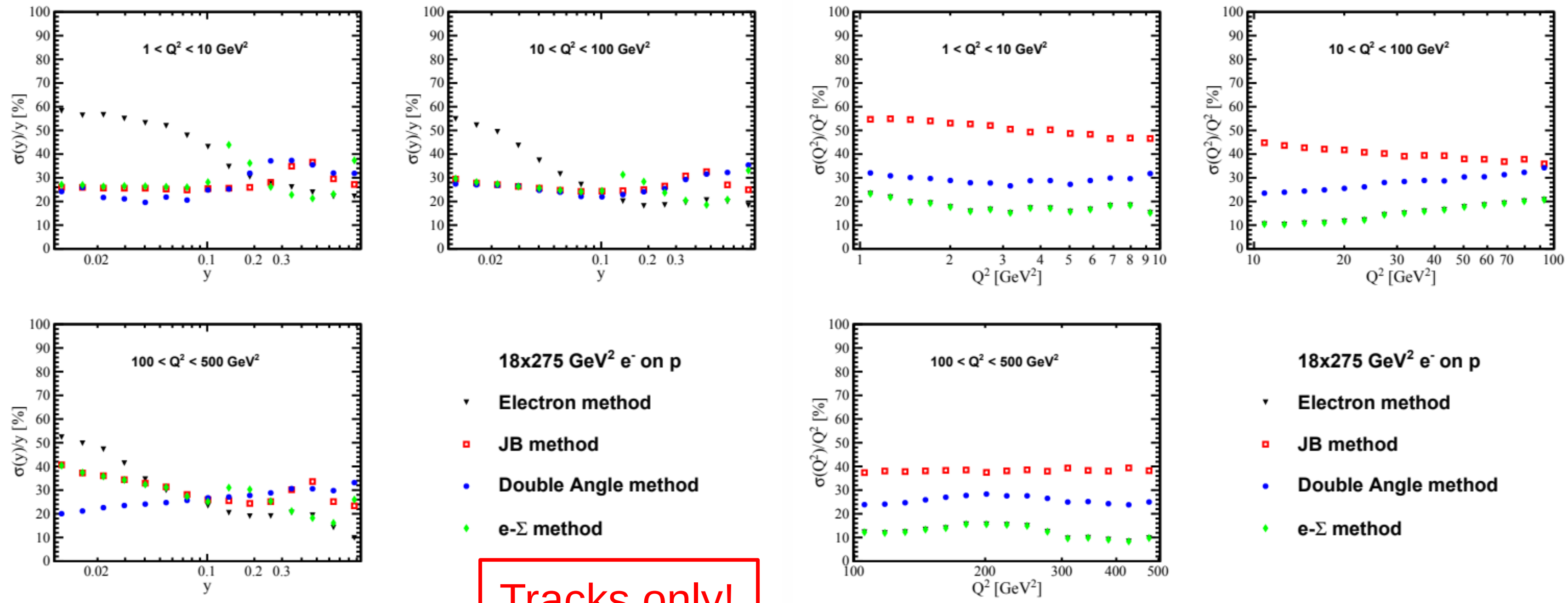
Kinematic Resolutions – EPIC

- Changes in software choice since call for proposals
  - Fun4All was the choice for ECCE, while DD4hep+Juggler was the choice for ATHENA
  - EPIC uses DD4hep+EICrecon
- Work is still required to fully reconstruct events using EPIC software
  - Calorimeter information is available, but clusters are not associated to tracks such that neutral particles can be obtained from remaining clusters (as in Juggler)
- Events are generated in Pythia8, propagated through EPIC Brycecanyon geometry (tag 22.11.2) and tracks and calorimeter clusters reconstructed

Following results are **preliminary** → much work remains to be done on reconstruction

Kinematic Resolutions – EPIC

- Reconstructed 18x275 GeV^2 NC-DIS events using conventional reconstruction methods
  - Only charged particles (from tracks) used in reconstruction
  - Reasonable behaviour → y resolution for **electron** method deteriorates at low y, **DA** method good at low y high Q^2, **JB** and **e-Σ** remain fairly constant



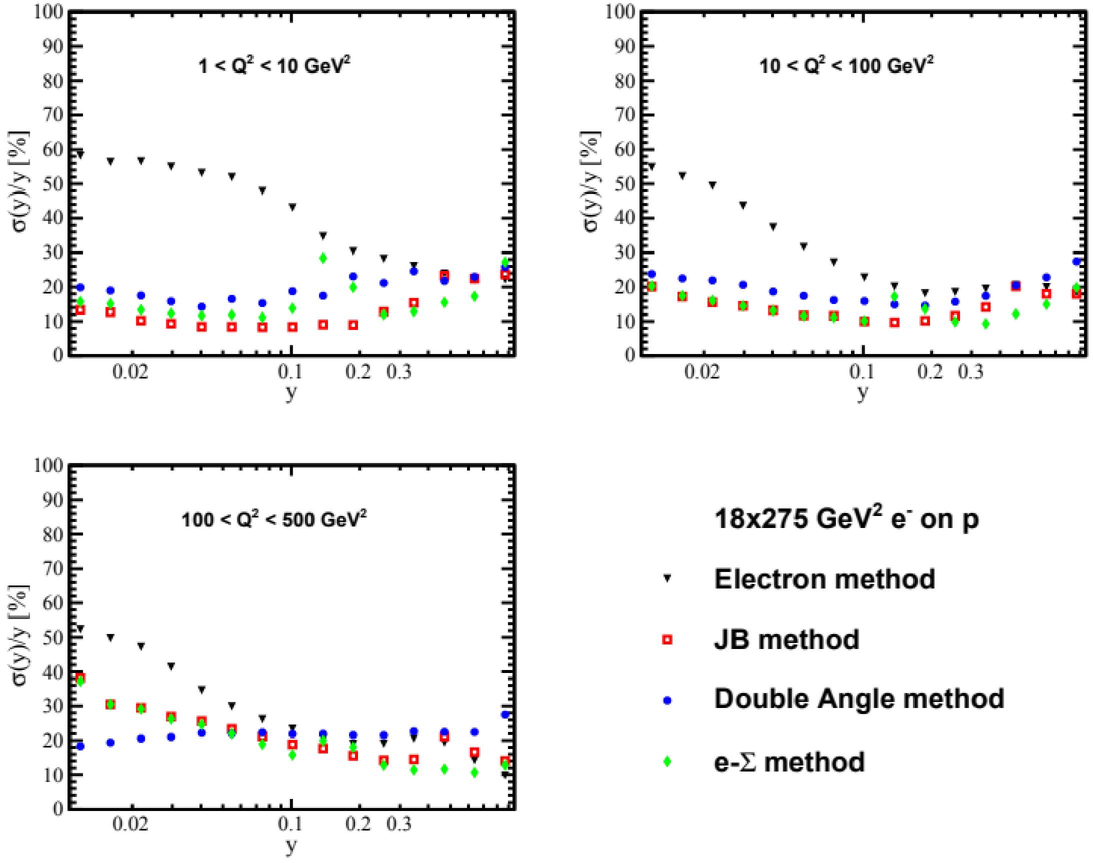
Tracks only!

Kinematic Resolutions – EPIC

Tracks and smeared EM neutrals

- An improved reconstruction for events relying on HFS information can be obtained by including neutral hadrons
- Inclusion of neutral hadrons from calorimeters is non-trivial, so for a first approximation, we include truth neutrals (from MC) with energy smeared according to calorimeter resolutions (table for smearing parameters in backup)
  - First we include π^0 and γ smeared by ECAL resolution

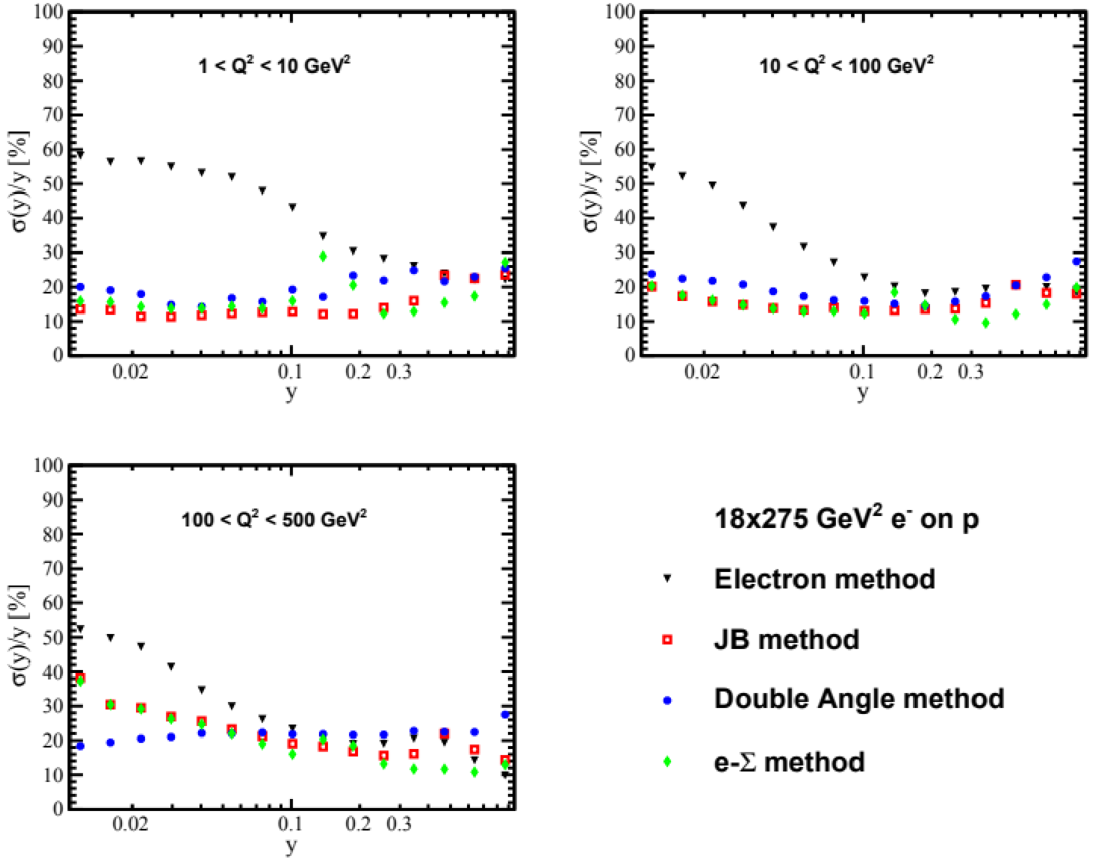
    → large improvement in resolutions for **JB** and **e-Σ**



Kinematic Resolutions – EPIC

Tracks and smeared neutrals

- All other neutral hadrons smeared according to HCAL resolution
  - Difference in y-resolution is minimal
    → ECAL does most of the work



What if we use all available information?

- Conventional reconstruction methods tend to use 2 of the 4 available pieces of information (E_e, θ_e, δ_h, $p_{t,h}$)
- Other approaches that use all information are also available
  - The use of Deep Neural Networks to reconstruct DIS kinematics has been explored in the context of HERA and the EIC and demonstrates excellent performance when reconstructing DIS kinematics and handling initial state radiation (ISR)
  - An alternative that use a kinematic fit of the observables based on knowledge of detector resolutions has also been explored and is covered in the following slides

Reconstructing the Kinematics of Deep Inelastic Scattering with Deep Learning

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ABSTRACT: We introduce a method to reconstruct the kinematics of neutral-current deep inelastic scattering (DIS) using a deep neural network (DNN). Unlike traditional methods, it exploits the full kinematic information of both the scattered electron and the hadronic-final state, and it accounts for QED radiation by identifying events with radiated photons and event-level momentum imbalance. The method is studied with simulated events at HERA and the future Electron-Ion Collider (EIC). We show that the DNN method outperforms all the traditional methods over the full phase space, improving resolution and reducing bias. Our method has the potential to extend the kinematic reach of future experiments at the EIC, and thus their discovery potential in polarized and nuclear DIS.

https://arxiv.org/abs/2110.05505

*Corresponding author.

See also:
https://arxiv.org/abs/2108.11638
https://arxiv.org/abs/2206.04897

Reconstruction with a Kinematic Fit

- Reconstruction is overconstrained: only need 2 quantities to obtain x, y, Q^2
- From the measured quantities $\vec{D} = \{E_e, \theta_e, \delta_h, p_{t,h}\}$ we can use a kinematic fit to reconstruct an additional piece of information: $\vec{\lambda} = \{x, y, \mathbf{E_\gamma}\}$

E_γ is energy of an ISR photon

- For a kinematic fit, all we need is a **likelihood** function based on our knowledge of the detector resolutions:

Likelihood

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

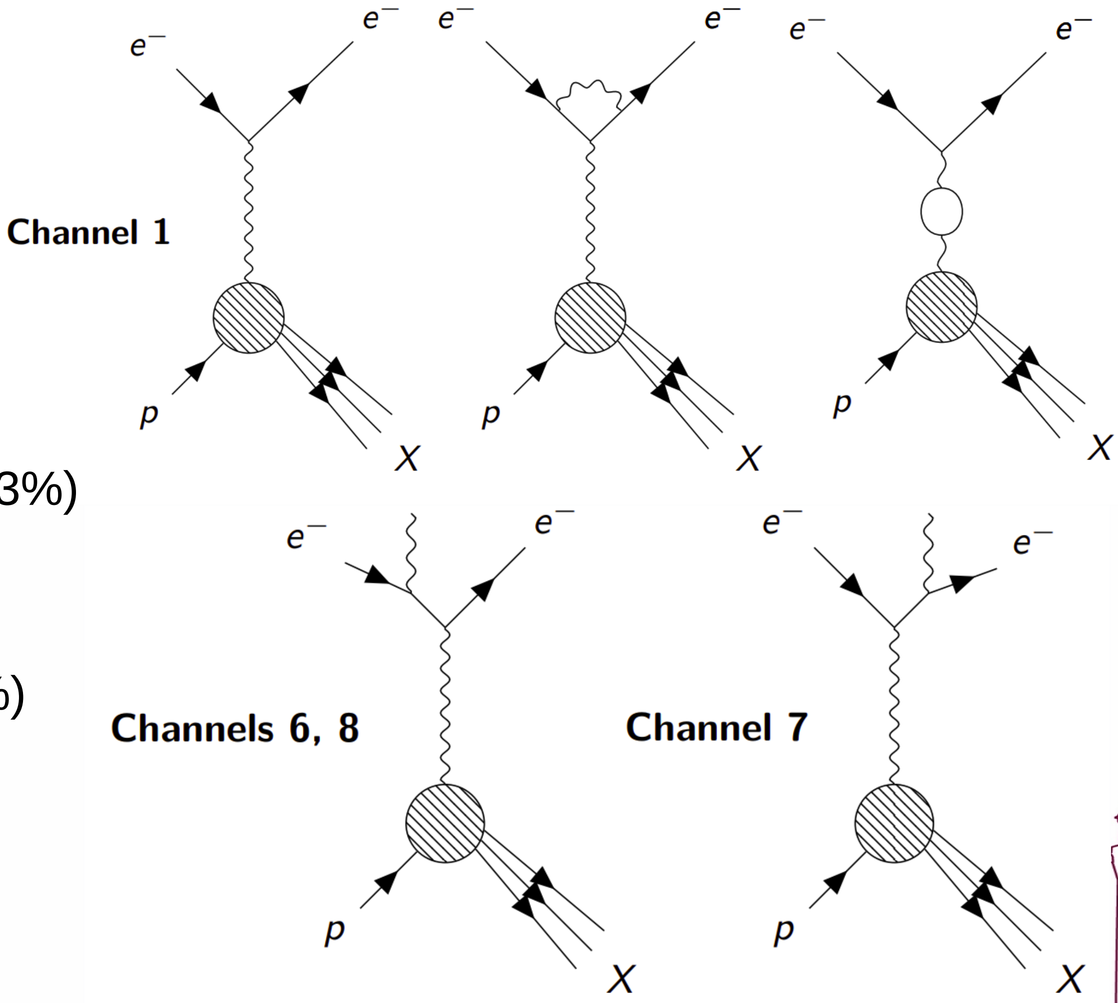
- A Bayesian method can also be applied in which information from our knowledge of the cross sections is encoded as a **prior**:

Prior

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

Event generation

- Djangoh 4.6.10 used to generate 18x275 GeV^2 e-p events
  - ISR/FSR=ON
  - $Q^2>100GeV^2$
  - W>2GeV
- Channel 1: Non Radiative NC (~53%)
- Channel 6: ISR (~28%)
- Channel 7: FSR (~18%)
- Channel 8: “Compton event” (~1%)



Reconstruction with Kinematic Fit (Bayesian Analysis Toolkit) [1]

- Input smeared (or reconstructed) variables $\vec{D} = \{E_e, \theta_e, \delta_h, p_{t,h}\}$
- Define prior distribution and likelihood

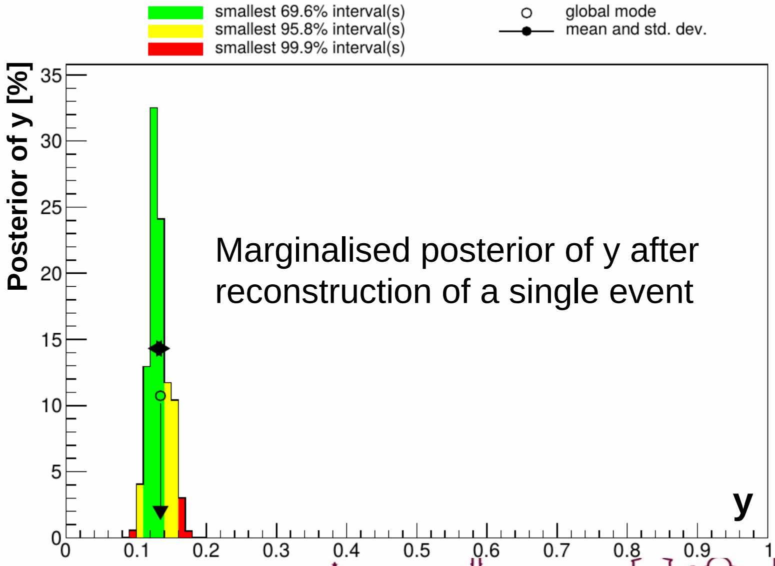
$$P(\vec{D}|\vec{\lambda}) \propto \frac{1}{\sqrt{2\pi}\sigma_E} e^{-\frac{(E_e - E_e^{\lambda})^2}{2\sigma_E^2}} \frac{1}{\sqrt{2\pi}\sigma_\theta} e^{-\frac{(\theta_e - \theta_e^{\lambda})^2}{2\sigma_\theta^2}} \frac{1}{\sqrt{2\pi}\sigma_{\delta_h}} e^{-\frac{(\delta_h - \delta_h^{\lambda})^2}{2\sigma_{\delta_h}^2}}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

Likelihood

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

Prior

- Uniformly distribute parameters x, y, E_γ until initial parameters with valid probability are found
- Run Metropolis algorithm (MCMC) to find posterior distribution (Bayes' theorem)
- Output values of x, y, E_γ at mode of posterior

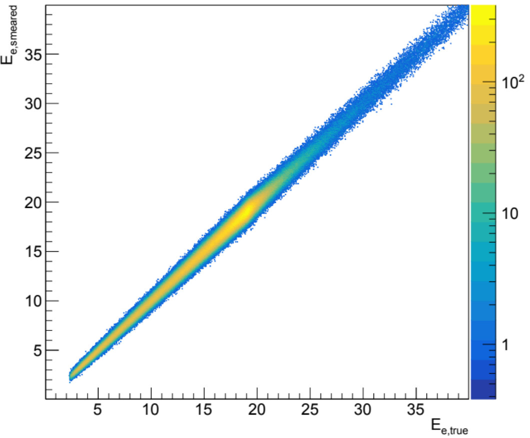


[1] https://arxiv.org/abs/0808.2552

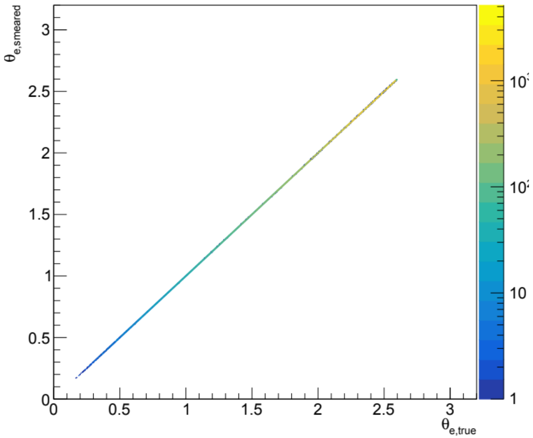
Smearing

- "True" quantities from event generator smeared according to YR detector requirement matrix:
  - Use central/forward ECAL resolution requirement for electron smearing (for Q^2>100GeV^2 most electrons scattered into barrel)
  - Angular resolution requirement not present in detector requirement matrix → estimate 1mrad

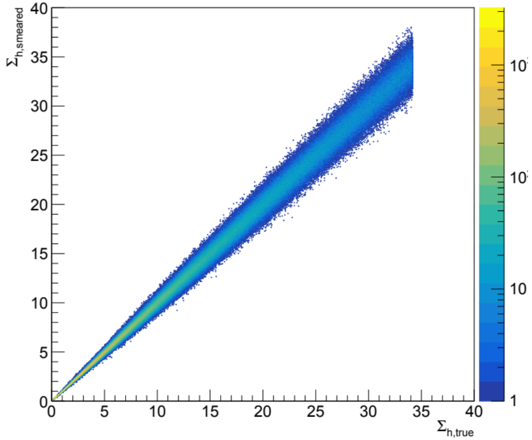
$E_{e,smeared}$ vs $E_{e,true}$



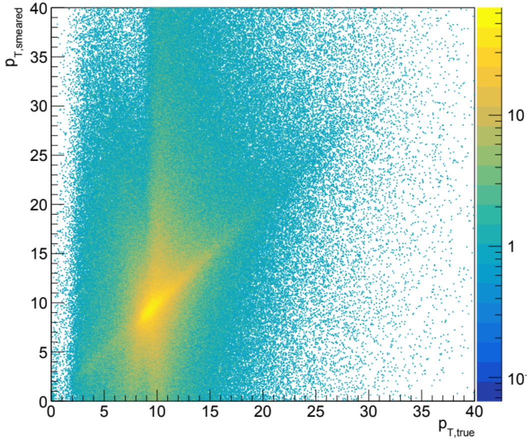
$\theta_{e,smeared}$ vs $\theta_{e,true}$



$\delta_{h,smeared}$ vs $\delta_{h,true}$

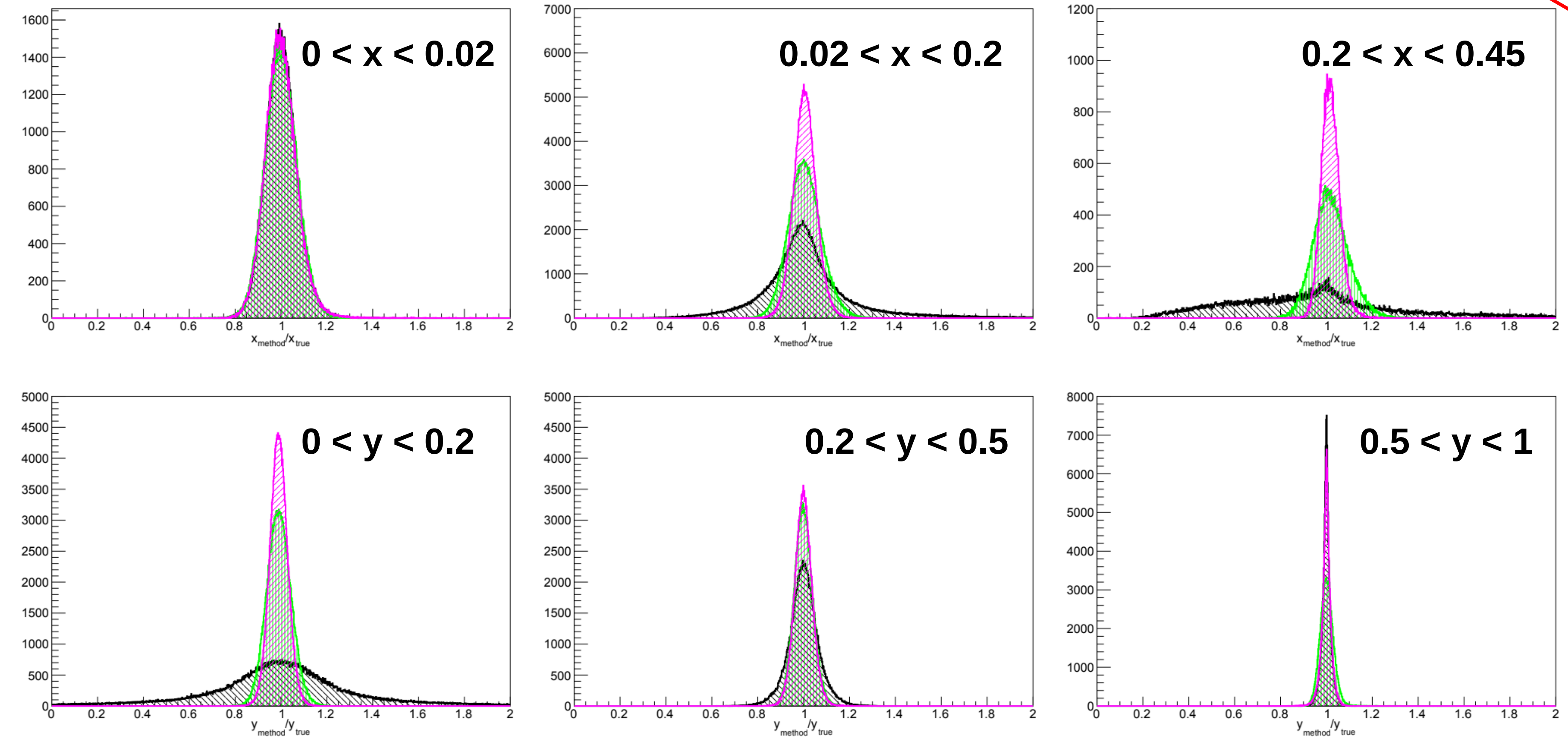


$p_{T,smeared}$ vs $p_{T,true}$



Comparison to to conventional methods – Channel 1 only

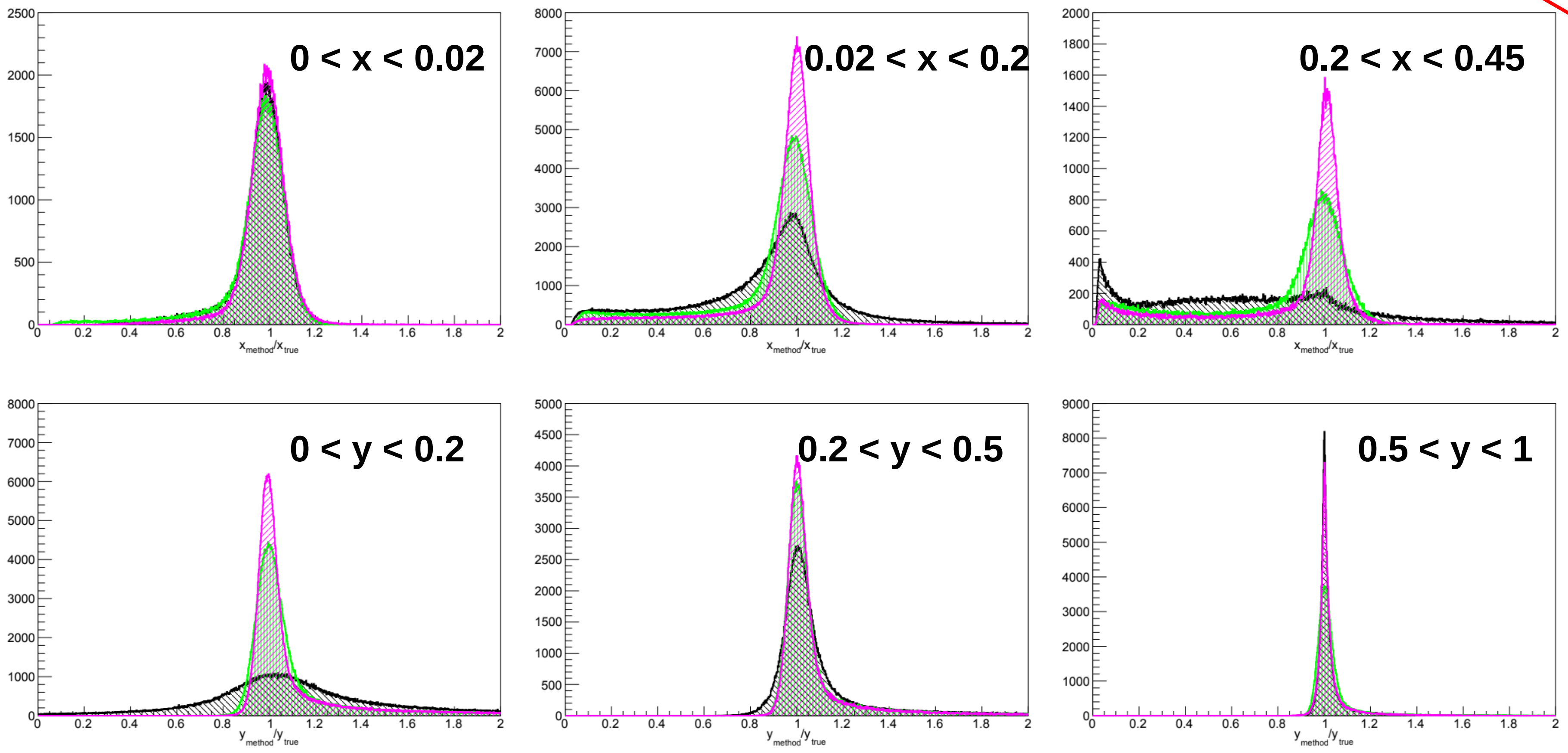
No ISR present!



Electron method **e-Σ method** **Kinematic Fit**

Comparison to to conventional methods – All Channels

ISR present!



Electron method **e-Σ method** **Kinematic Fit**

Summary

- An initial evaluation of y reconstruction performance of conventional reconstruction methods from EPIC Brycecanyon (22.11.2) simulations in EPIC software is shown
  - Reasonable performance using tracking information only
  - Inclusion of truth neutrals (smeared by calorimeter resolutions) noticeably improves performance of methods relying on HFS
- A reconstruction method based on a kinematic fit of all information is presented for an 18x275 GeV^2 e on p Djangoh sample including radiative effects
  - With perfect knowledge of detector resolutions, the kinematic fit based method outperforms conventional methods with and without ISR present

Next Steps

- Include neutral information directly from calorimeter clusters in full simulations, benchmark detector resolutions and apply kinematic fit to fully reconstructed events

Backup

Neutral Hadron Smearing Parameters

Table 6: Specifications and properties for the electromagnetic and hadronic calorimeters from the Geant simulation. Note that d_{act} does not include readout. The acceptance of the EEMC can be achieved with a small inner calorimeter as discussed in the text. The energy resolutions for EEMC, BEMC and OHCAL are those expected from prototype tests or experiments [2, 30, 31, 32]. Further details can be found in the [5].

	EEMC	BEMC	FEMC	IHCAL	OHCAL	LFHCAL
tower size	2x2x20 cm^3	4x4x45.5 cm^3 projective projective	in: 1x1x37.5 cm^3 out: 1.6x1.6x37.5 cm^3 out: 1.6x1.6x37.5 cm^3	$\Delta\eta \sim 0.1$ $\Delta\varphi \sim 0.1$ $l \sim 4.5$ cm	$\Delta\eta \sim 0.1$ $\Delta\varphi \sim 0.1$ $l \sim 88$ cm	5x5x140 cm^3
material	$PbWO_4$	SciGlass	Pb/Scintillator	Steel/ Scintillator	Steel/ Scintillator	Steel/W/ Scintillator
d_{abs}	-	-	1.6 mm	13 mm	in: 10.2 mm out: 14.7 mm	16 mm
d_{act}	20 cm	45.5 cm	4 mm	7 mm	7 mm	4 mm
N_{layers}	1	1	66	4	5	70
$N_{towers(channel)}$	2876	8960	19200/34416	1728	1536	9040(63280)
X/X_O	~ 20	~ 16	~ 19	~ 2	$36-48$	$65-72$
R_M	2.73 cm	3.58 cm	5.18 cm	2.48 cm	14.40 cm	21.11cm
f_{sampl}	0.914	0.970	0.220	0.059	0.035	0.040
λ/λ_0	~ 0.9	~ 1.6	~ 0.9	~ 0.2	$\sim 4-5$	$7.6-8.2$
η acceptance	$-3.7 < \eta < -1.8$	$-1.7 < \eta < 1.3$	$1.3 < \eta < 4$	$1.1 < \eta < 1.1$	$1.1 < \eta < 1.1$	$1.1 < \eta < 4$
resolution						
- energy	$2/\sqrt{E} \oplus 1$	$2.5/\sqrt{E} \oplus 1.6$	$7.1/\sqrt{E} \oplus 0.3$		$75/\sqrt{E} \oplus 14.5$	$33.2/\sqrt{E} \oplus 1.4$
- φ	~ 0.03	~ 0.05	~ 0.04		~ 0.1	~ 0.25
- η	~ 0.015	~ 0.018	~ 0.02		~ 0.06	~ 0.08