SIDIS reconstruction with ML and observables at EIC with ATHENA

Connor Pecar, on behalf of the ATHENA collaboration

XXIX International Workshop on Deep-Inelastic Scattering and Related Subjects, Santiago de Compostela

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ATHENA

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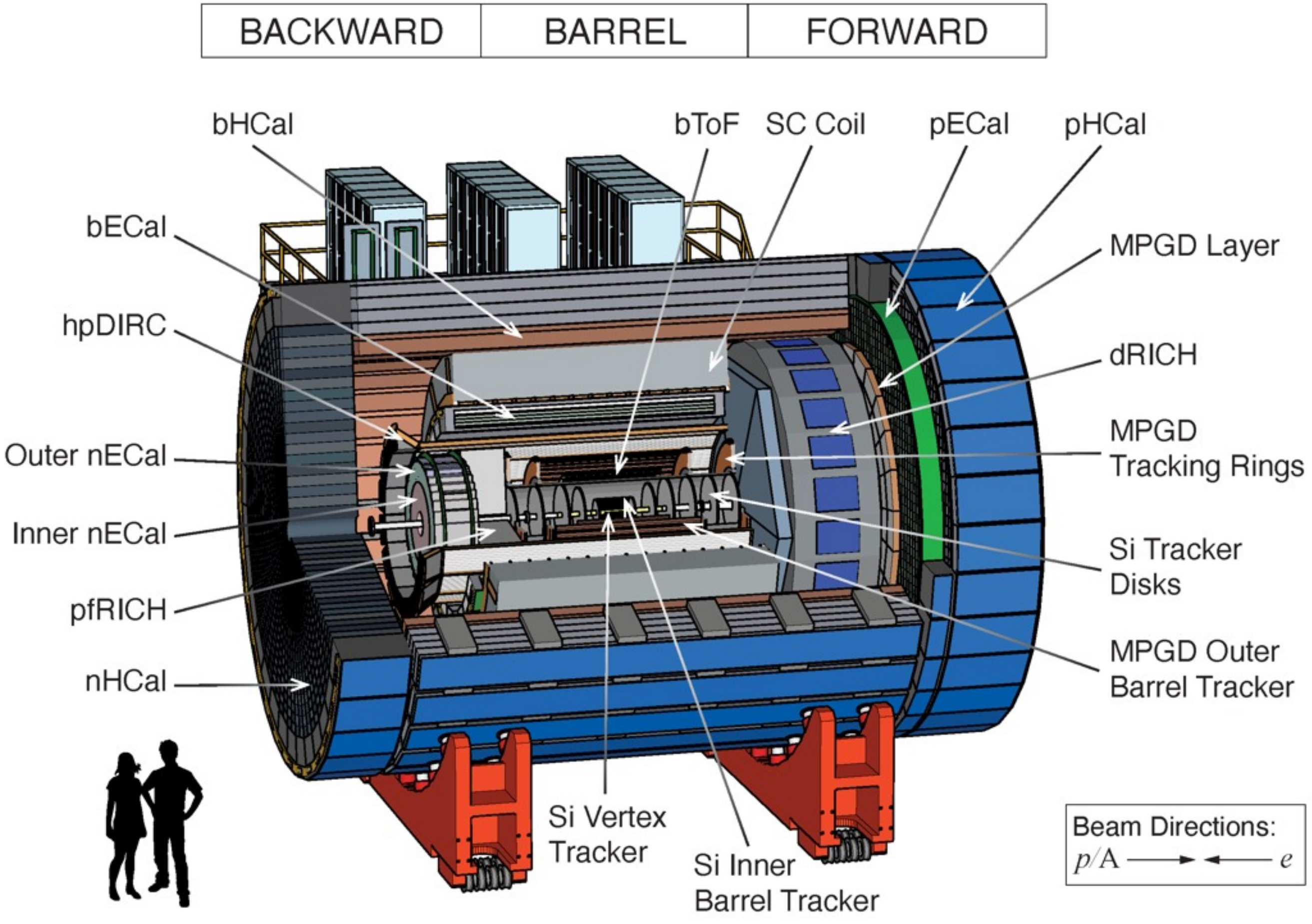
ATHENA detector

- ATHENA (A Totally Hermetic Electron Nucleon Apparatus)
- Precise tracking and PID coverage in wide momentum range – great potential for SIDIS
- ATHENA not chosen as reference detector moving forward at EIC, but these studies still applicable
  - Methods and analysis developed at reconstructed particle level will still be crucial for any EIC detector



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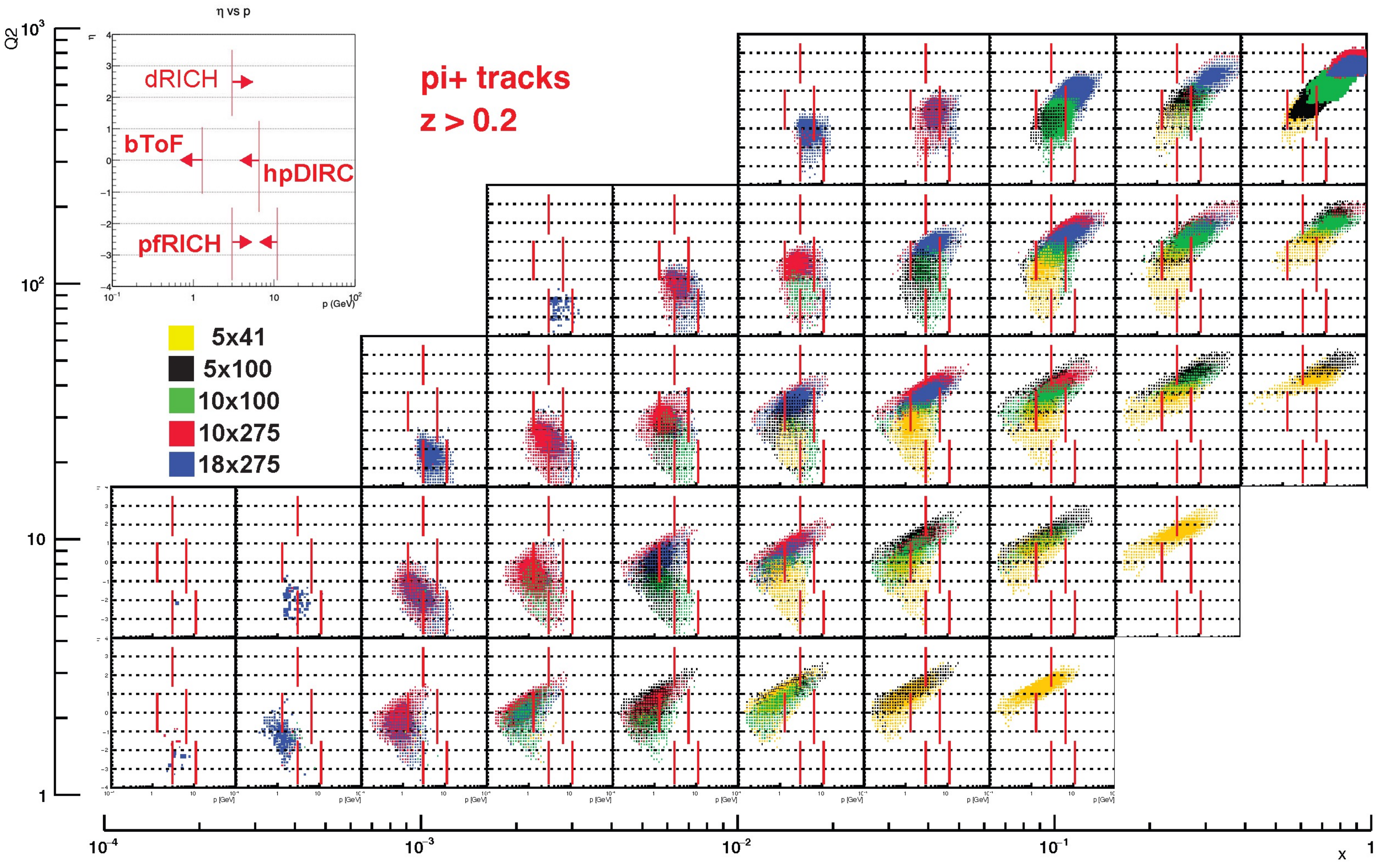
SIDIS observables with ATHENA

- Broad kinematics and PID coverage available at EIC/ATHENA
  - large lever arm for SIDIS multiplicities and asymmetries
- Many SIDIS projections made for proposal:
  - A_{LL} with kaons, gluon saturation with dihadrons, Sivers



y > 0.05

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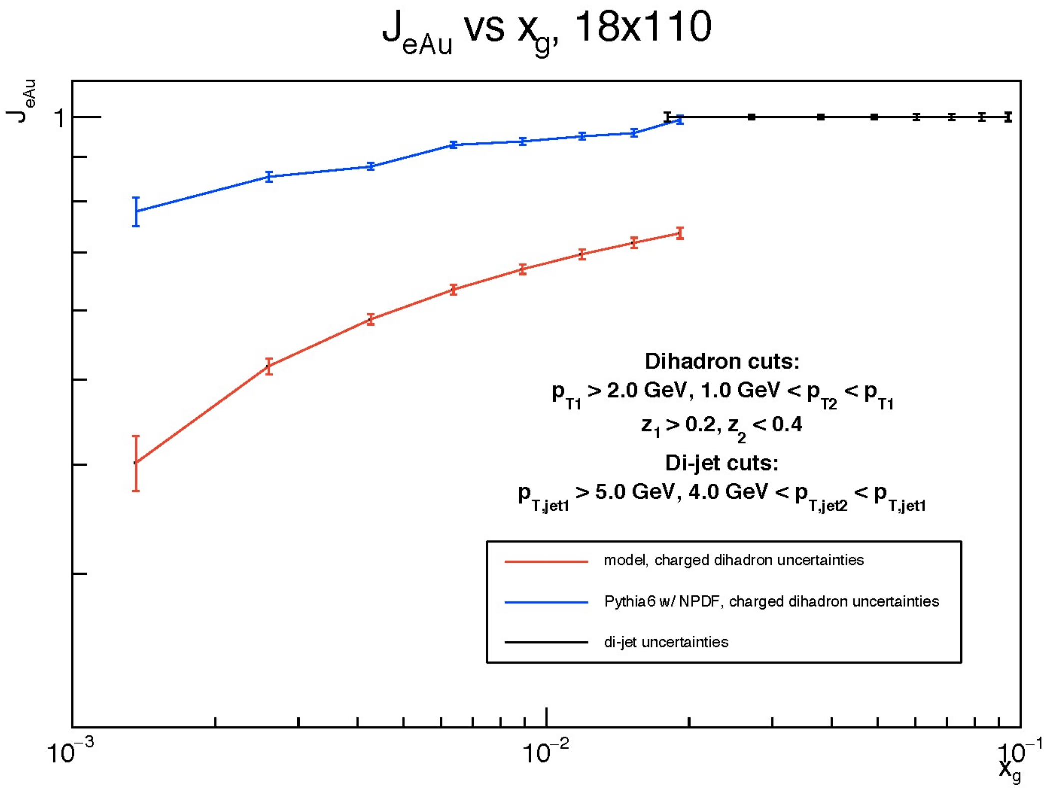
Gluon saturation with ATHENA

- Potential to probe gluon saturation with high-pT gluon dijets/dihadrons
- Away side suppression from e+p to e+A

$$J_{eA} = \frac{1}{A^{1/3}} \frac{\sigma_{eA}^{pair}/\sigma_{eA}}{\sigma_{ep}^{pair}/\sigma_{ep}}$$



EIC dijet cuts from: Phys. Rev. D 101, 072003 (2020), Page, Chu, Aschenauer

Fast simulation, scaled to 10 fb^{-1}

- Red - ATHENA projected dihadron uncertainties on model from Phys.Rev.D. 89, 074037
- Blue - JeAu using NPDF for Au and p, dihadron uncertainties
- Black - dijet uncertainties, no model calculation

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SIDIS kinematic reconstruction at EIC

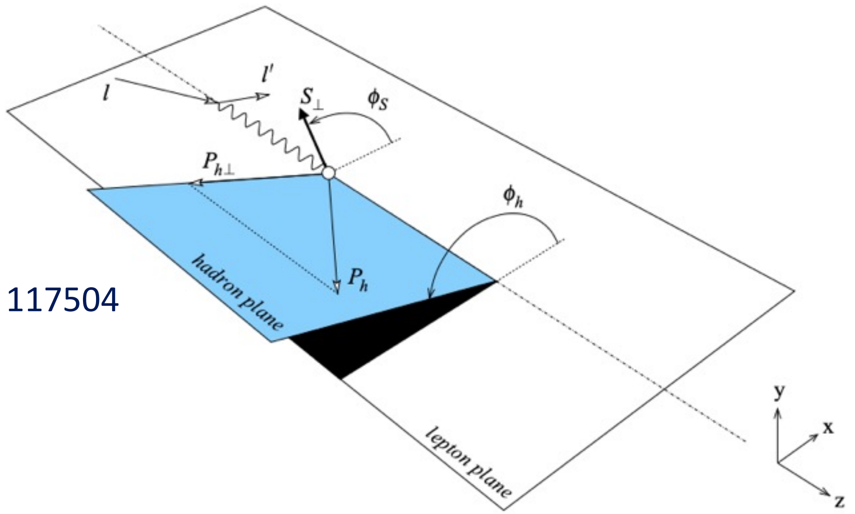
- SIDIS variables: reliant on reconstruction of virtual photon four-momentum, typically determined using

$$q = l - l'$$

- Reliable for larger y, but begins to fail for $y < \sim 0.05$

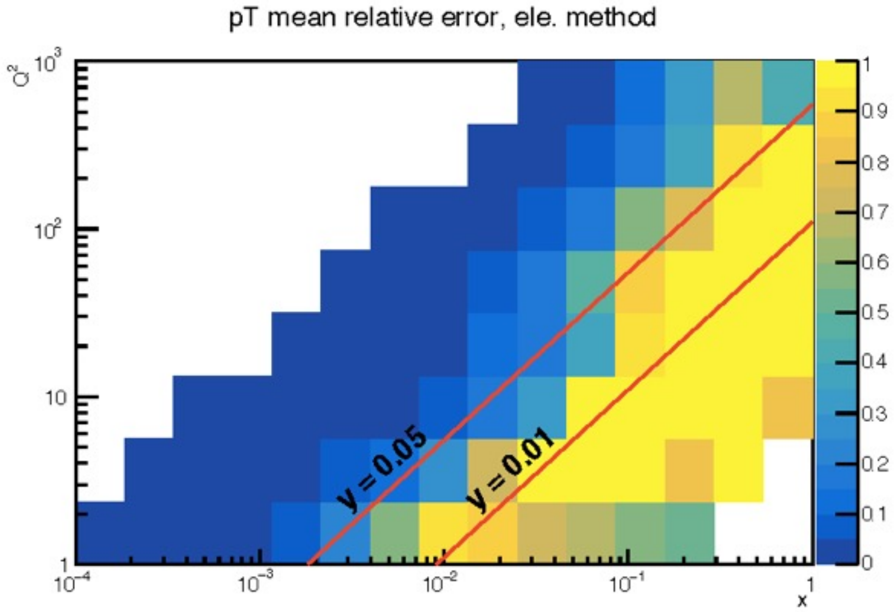
  Low-y: region of interest for TMDs, and important for evolution studies

- **To utilize full EIC kinematic reach for SIDIS studies, need improved methods to determine SIDIS variables**
- CC – would require first method without electron



Phys.Rev. D70 (2004) 117504

ATHENA full simulation:



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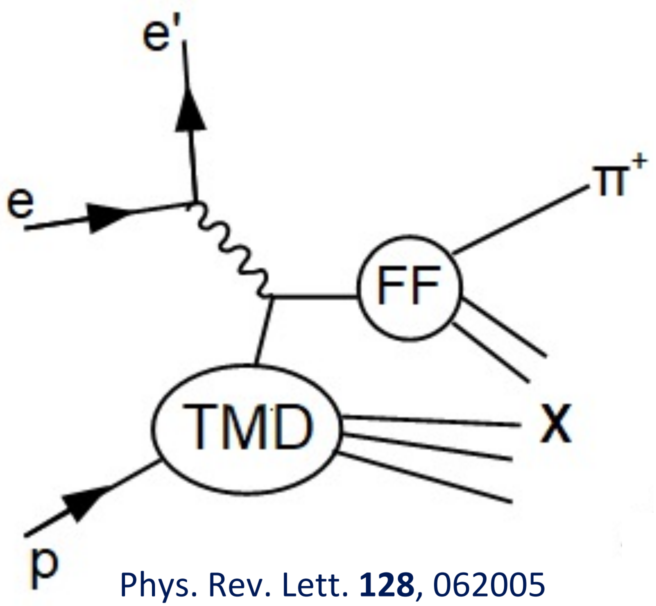
Reconstruction with hadronic final state

- Through conservation of momentum and energy, **hadronic final state (HFS) should also contain enough information to constrain q**
  - To our knowledge, first done by A. Vossen for EIC YR
- Methods utilizing hadronic final state could be more robust with respect to radiative corrections
  - Impact of radiative effects expected to be large at EIC, studies ongoing



Phys. Rev. Lett. **128**, 062005

Reconstruction with hadronic final state

- Method used in EIC YR and ATHENA proposal to reconstruct virtual photon using hadronic final state (HFS)
  - x and y components - summed HFS momentum
  - z and t components - solved for algebraically using

$$y = \frac{p.q}{p.l} \qquad Q^2 = -q^2$$

and DIS variables from any DIS reconstruction method

i)	*Leptonic variables*	$q \equiv q_l = k_2 - k_1, \quad y_l = p_1.(k_1 - k_2)/p_1.k_1$
ii)	*Hadronic variables* [81]	$q \equiv q_h = p_2 - p_1, \quad y_l = p_1.(p_2 - p_1)/p_1.k_1$
iii)	*Jacquet-Blondel variables* [82]	$Q^2_{JB} = (\vec{p}_{2,\perp})^2/(1 - y_{JB}), \quad y_{JB} = \Sigma/(2E(k_1))$ $\Sigma = \sum_h (E_h - p_{h,z})$
iv)	*Mixed variables* [81]	$q = q_l, y_m = y_{JB}$
v)	*Double angle method* [83]	$Q^2_{DA} = \frac{4E(k_2)^2 \cos^2(\theta(k_2)/2)}{\sin^2(\theta(k_2)/2) + \sin(\theta(k_2)/2)\cos(\theta(k_2)/2)\tan(\theta(p_2)/2)},$ $y_{DA} = 1 - \frac{\sin(\theta(k_2)/2)}{\sin(\theta(k_2)/2) + \cos(\theta(k_2)/2)\tan(\theta(p_2)/2)},$

Prog. Part. Nucl. Phys. 2013, Blümlein

- \+ solution in quadratic equation found to always be closer to MC truth
- Resolution improved if this is carried out in head-on frame, then transformed to lab frame
  - Large crossing angle needed for EIC

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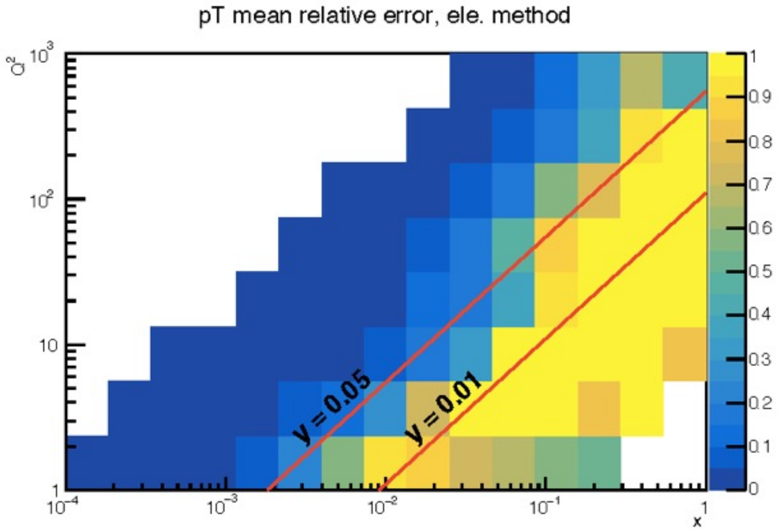
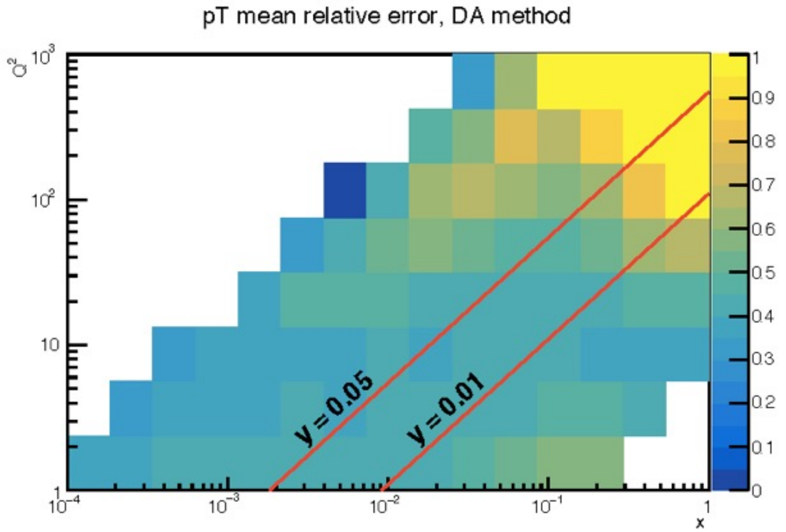
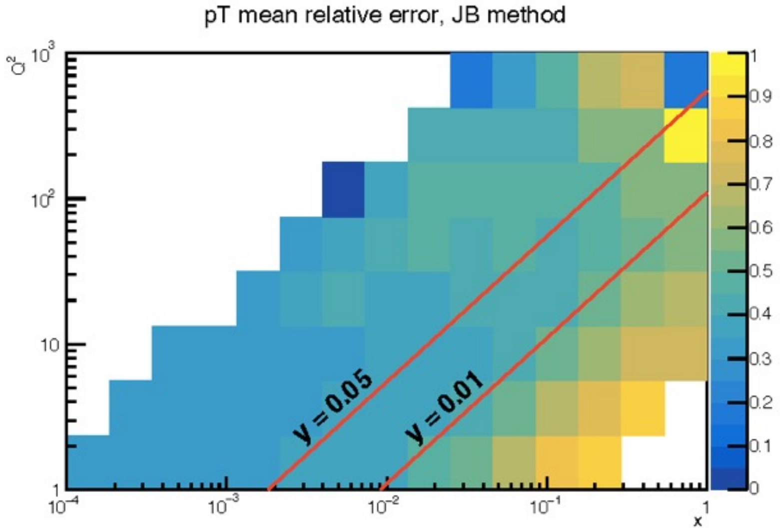
ATHENA full simulation SIDIS resolution, p_T

Transverse momentum (w.r.t. q), 10x275, pi+, z > 0.2:





DA, hybrid method -> pT resolution more acceptable at low y



<- JB, HFS only Potential for CC

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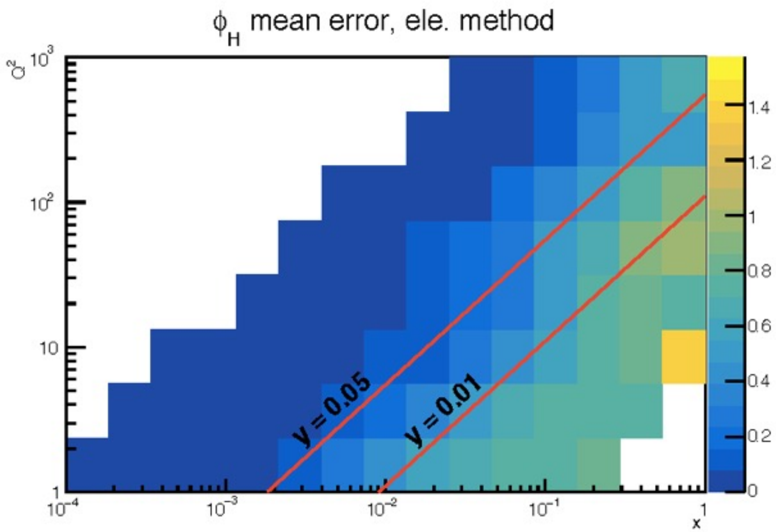
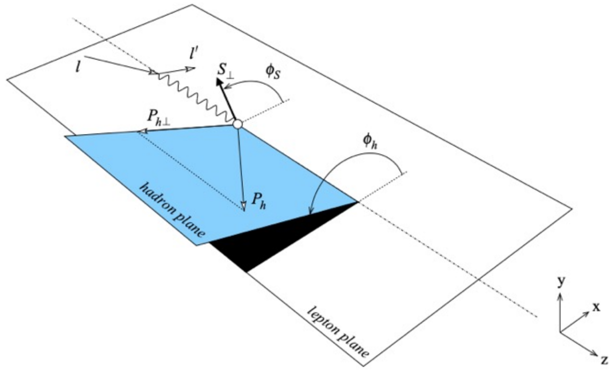
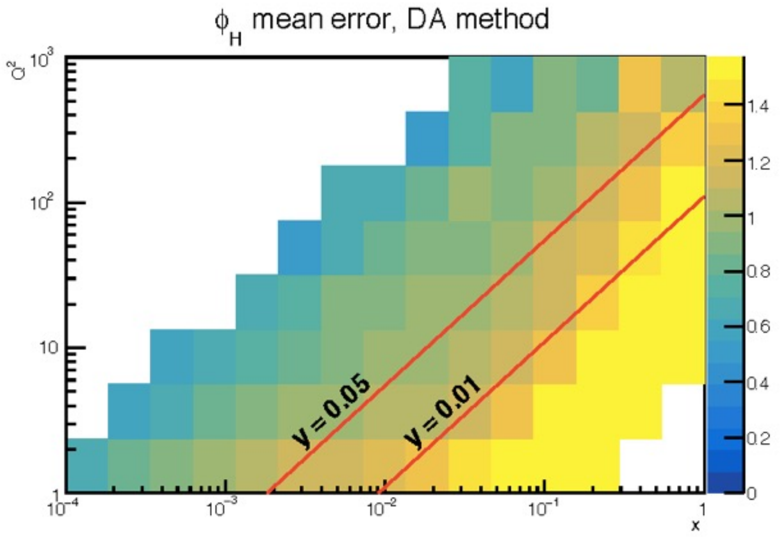
ATHENA full simulation SIDIS resolution, ϕ_h

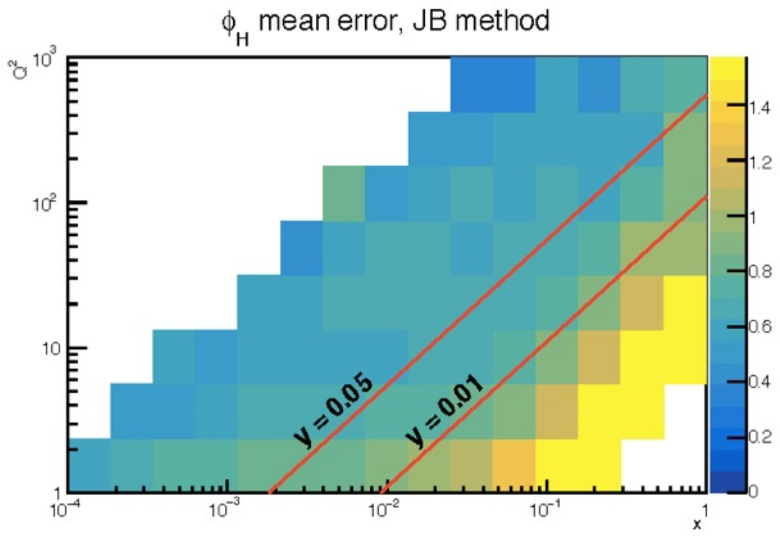
ATHENA full simulation, 10x275,
pi+, z > 0.2





Angular resolution still poor at low-y with all methods





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Machine learning reconstruction

- Based on hybrid HFS-electron SIDIS reconstruction, using ML to combine information from both to reconstruct q
  - Potential to correct overall HFS momentum and to more accurately reconstruct z and t components than exact formula
  - ML models used for DIS reconstruction have been shown to be able to naturally account for radiative effects
    - (arXiv:2108.11638 and talk in WG6 by A. Farhat on Wednesday, as well as J.NIM.A, Arratia, Britzger, Long, Nachman, 2021 with talk in WG1 on Wednesday)
- Currently utilizing graph-like neural network architectures designed for jet reconstruction
  - Treating DIS HFS at EIC similar to a jet

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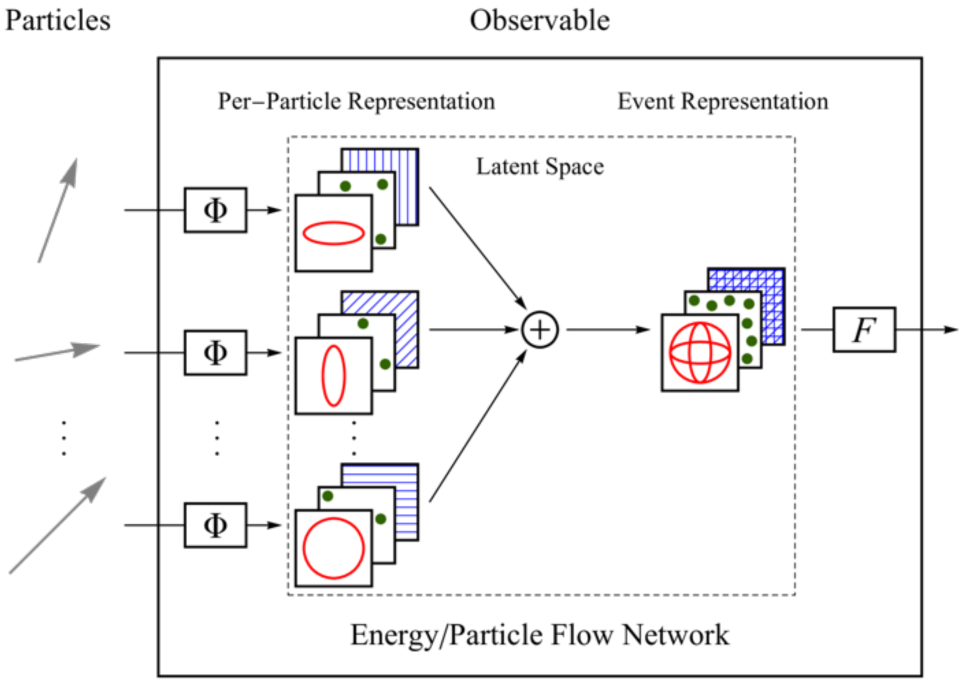
Particle flow networks

- Particle flow networks (PFN) developed by Komiske et al., (JHEP 01 (2019) 121, Komiske, Metodiev, Thaler)
  - Accepts unordered set of particles
  - Particles -> input to layers Φ
    - Summed over to created latent space of ℓ variables
  - Global features of event concatenated with latent space variables
  - Latent space variables and global features fed to layers F, produce final output
- Designed to be general purpose, universal approximator on sets of particles



JHEP 01 (2019) 121

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ML SIDIS model and training

- Model combining electron and HFS:
  - Particle features for PFN: momentum, energy, η, φ in lab frame
  - Event-wide features: electron four momentum, DIS variables from JB, DA, electron methods
    - DIS variables will eventually be replaced with final reconstructed Q2 and x (see talks on DIS reconstruction), but in this study statistics for training were limited
  - Target: MC virtual photon four-momentum in lab frame
- Training sample: ATHENA full simulation
  - HFS at the level of reconstructed particles
  - Version of dd4hep ATHENA full sim. used for detector proposal
    - Still some features missing, e.g. proper scattered electron ID
  - 10 GeV electron beam, 275 GeV proton beam, crossing angle -25 mrad
  - Trained on 3 million events with $Q^2 > 1$ GeV^2, 2 million with $Q^2 > 10$ GeV^2
  - 1 million $Q^2 > 1$ GeV^2 events for validation

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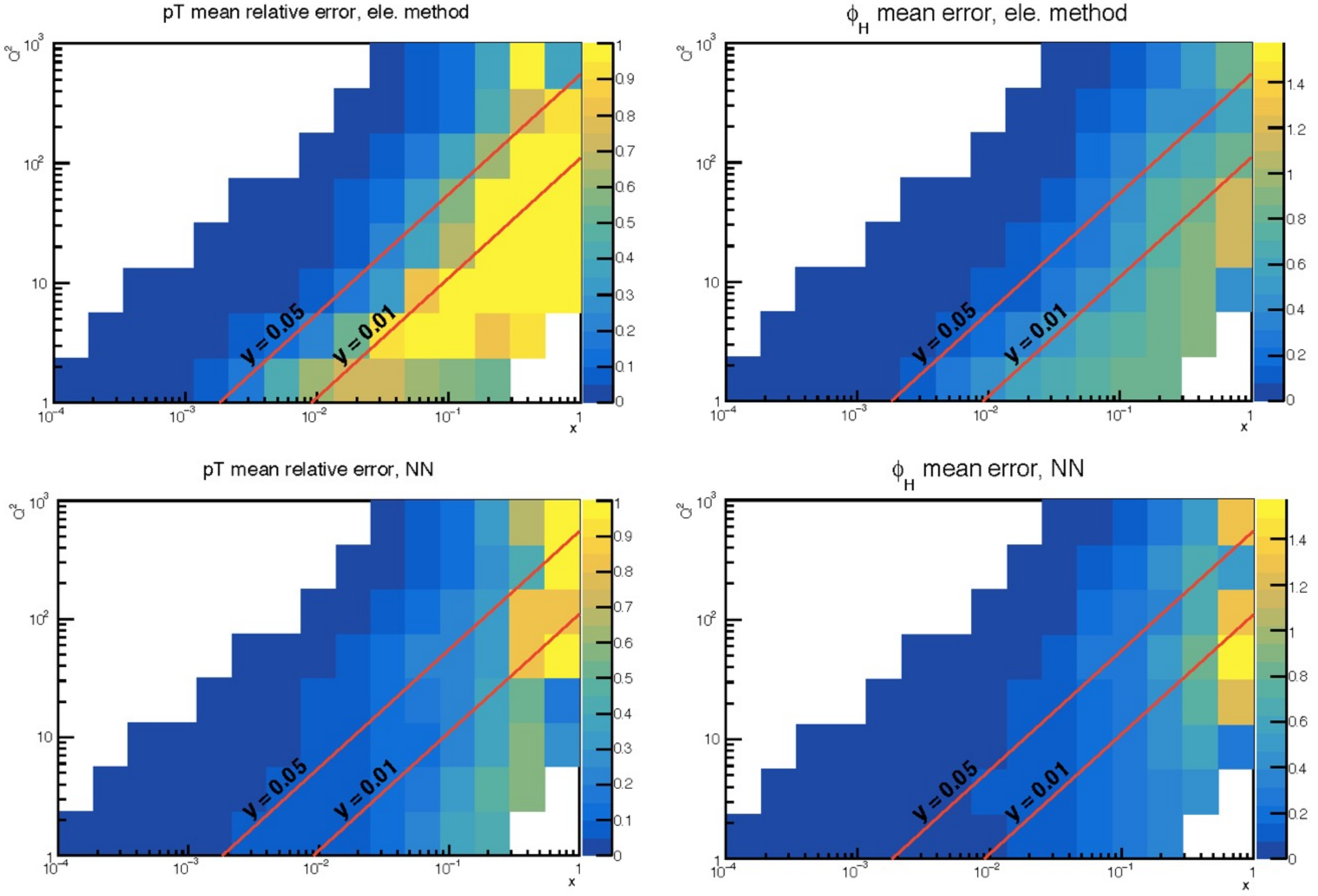
ATHENA full simulation, 10x275, pi+, z > 0.2

$$\frac{p_T - p_{T,true}}{p_{T,true}}$$

$$\phi_H - \phi_{H,true}$$

Electron method

Neural network



PFN able to correct electron method in almost all of x-Q2

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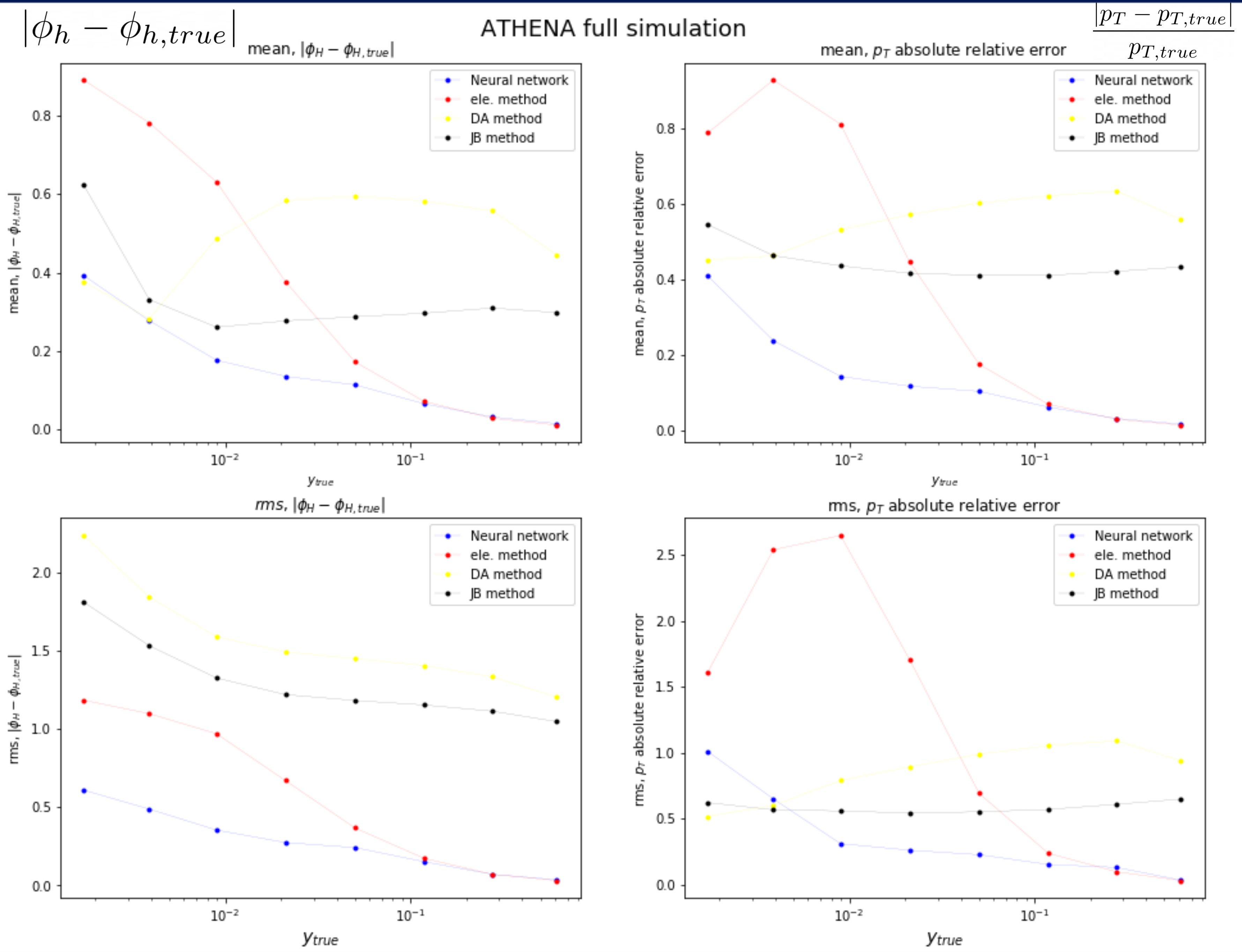
ATHENA full simulation, 10x275, pi+, z > 0.2



- Comparison with other HFS/hybrid methods vs y_{true}
- NN by far best performance for azimuthal angle, and at least equaling electron method for large y

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$$|\phi_h - \phi_{h,true}|$$

ATHENA full simulation

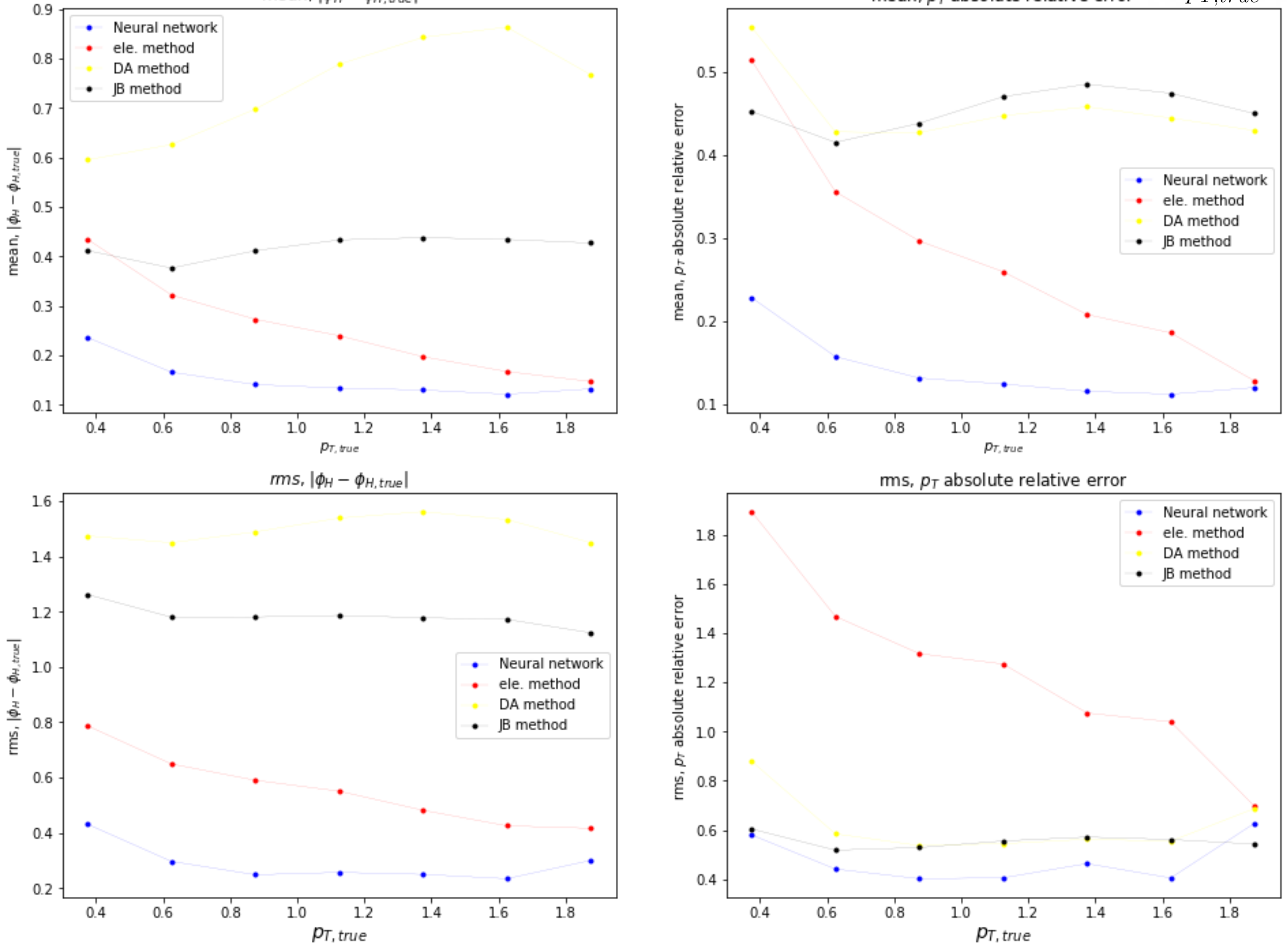
$$\frac{|p_T - p_{T,true}|}{p_{T,true}}$$

ATHENA full simulation, 10x275, pi+, z > 0.2

Mean:

RMS:

- Comparison with other HFS methods vs true pT
- NN again clearly outperforming other methods for all pT



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Summary

- Projections with the ATHENA detector demonstrate the exciting capabilities and kinematic coverage of the EIC for SIDIS measurements
- The EIC has the potential for a conclusive measurement of gluon saturation
- The electron method fails for $y < 0.05$, but can be improved using the hadronic final state and DIS variables to reconstruct virtual photon axis
- We demonstrate a machine learning approach combining the hadronic final state and scattered electron which surpasses existing methods for all of x-Q2 and p_T
- Next steps in reconstruction:
  - Currently working on replacing the particle flow network with an architecture which can learn correlations between HFS particles (such as a GNN)
  - Method will need to be tested with better implementation of radiative effects

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