Kaon Structure Functions

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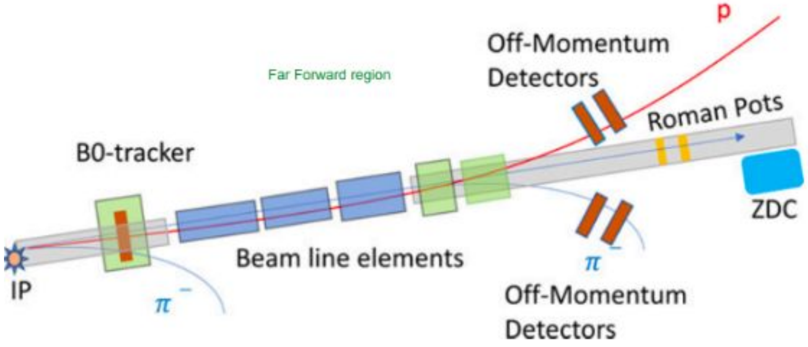
Working in conjunction with the EIC Meson SF WG



Talk Overview

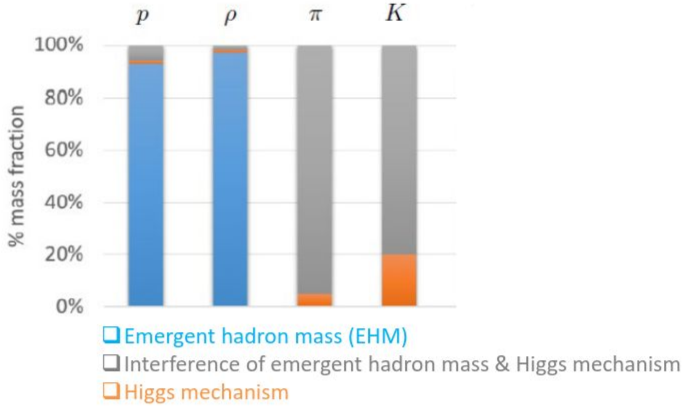
- Motivation for hadron and meson structure research
- Current meson structure experiments and data
- Theoretical predictions
- Planned future research
    - Proposed J-Lab experiments
    - Research proposed for EIC
- Current simulation campaign
- Current simulation analysis results
- Potential further work
- Summary

Understanding Hadron and Meson mass

Proton:
Quark structure: uud
Mass ≈940 MeV with majority generated by dynamics

Pion:
Quark structure: $u\bar{d}$
Mass ≈140 MeV dynamically generated mass

Kaon:
Quark structure: $u\bar{s}$
Mass ≈490 MeV boundary of Higgs and emergent mass mechanisms



Mass budget for nucleons and mesons are vastly different

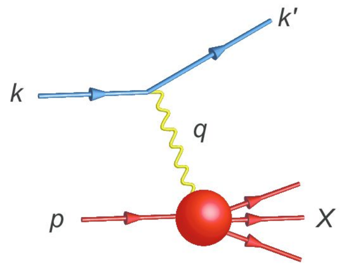
- Proton (and heavy meson) mass is large in the chiral limit – expression of Emergent hadronic mass (EHM)
- Pion/kaon: Nambu-Goldstone Boson of QCD: massless in the chiral limit
  - chiral symmetry of massless QCD dynamically broken by quark-gluon interactions and inclusion of light quark masses (DCSB, giving pion/kaon mass)
  - Without Higgs mechanism of mass generation pion/kaon would be indistinguishable

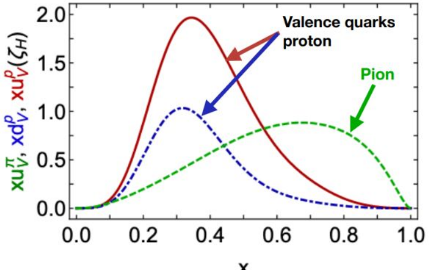
[Courtesy of Tanja Horn's talk from Workshop on Parton Distributions in the EIC Era]

Probing Meson Structure with DIS

DIS allows us to extract information about the internal parton structure of subatomic particles. Can compare the distribution of different partons that makeup particles such as pions, kaons with the proton for example

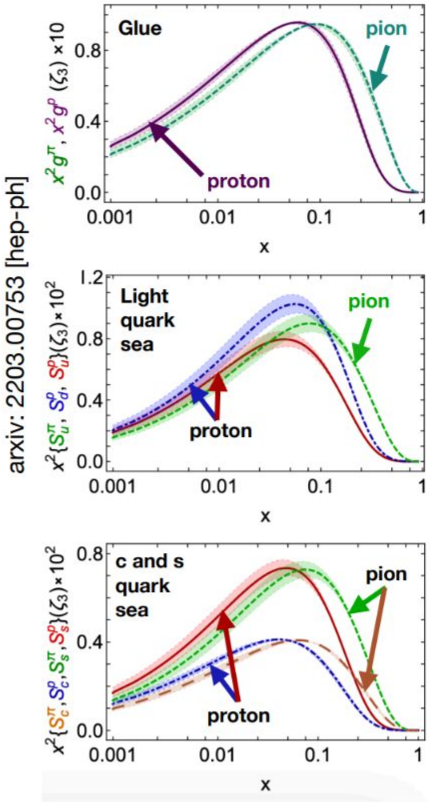
Experiments at HERA greatly developed our understanding.





Continuum Schwinger function methods (DSE)

Ya Lu, Lei Chang, Khépani Raya, Craig Roberts, José Rodriguez-Quintero, 2203.00753 [hep-ph], Phys Lett B 830 (2022) 137130/1-7

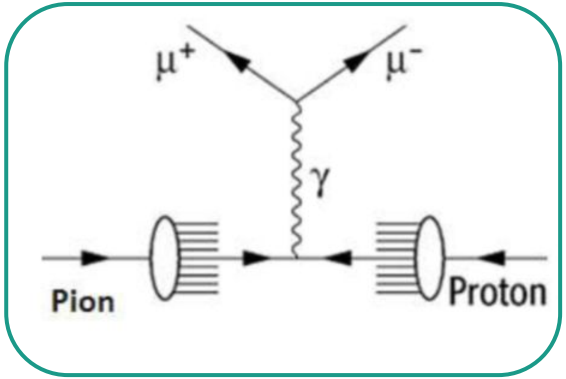


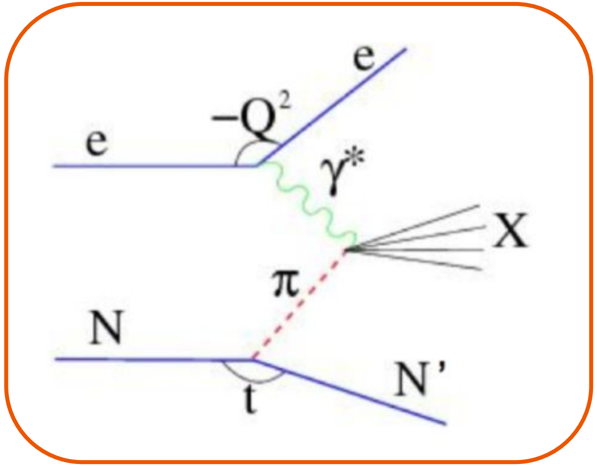
Accessing Meson Structure: Drell-Yan and the Sullivan process

Most existing data is from the Drell-Yan process where a quark and antiquark pair from a meson, such as a pion, and a proton annihilate leading to a virtual photon that decays into a lepton pair.

The Sullivan process uses an electron scattered from the meson cloud of a nucleon to infer information on the mesons structure function.

Tagged Deep Inelastic Scattering is an experimental process that refers to tagging the final state N particle, which allows reconstruction of virtual meson.





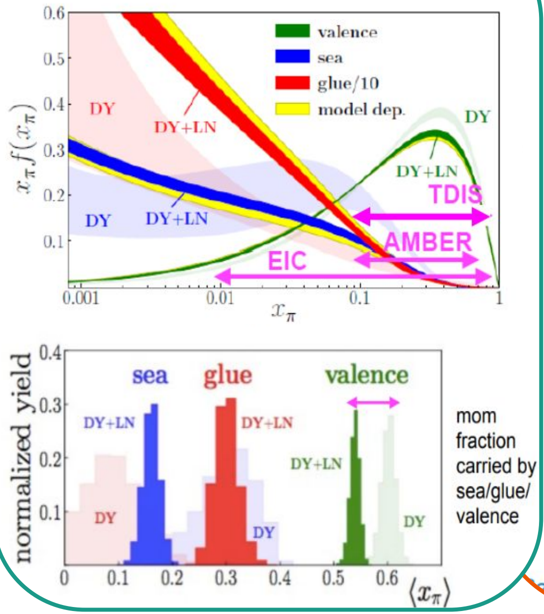
Current Theory and Data on the Pion and Kaon

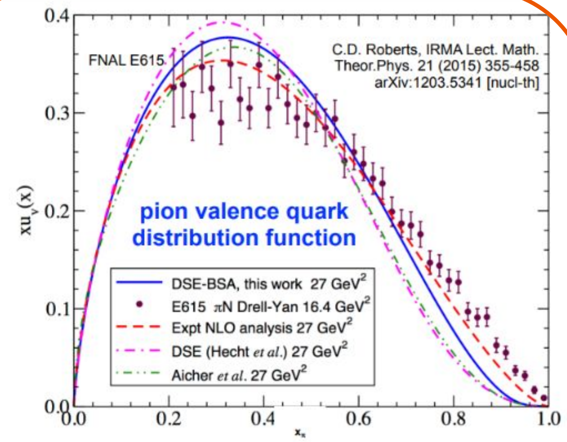
From previous experiments at CERN and Fermilab there is some understanding of distributions within pions but almost no data for kaons.

With more TDIS data can hopefully reduce PDF uncertainties.

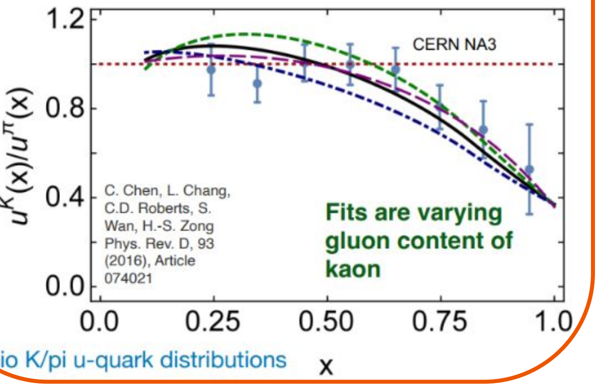
Current planned research in to meson SF with Drell-Yan at COMPASS, AMBER and via Sulliva process TDIS experiments at JLAB.
(2019 LOI arXiv:1808.00848)
(https://www.jlab.org/exp_prog/proposals/15/PR12-15-006.pdf)

P.C. Barry, N. Sato, W. Meltnichouk, Chueng-Ryon Ji (JAM Collaboration), Phys. Rev. Lett. 121, 152001 (2018)



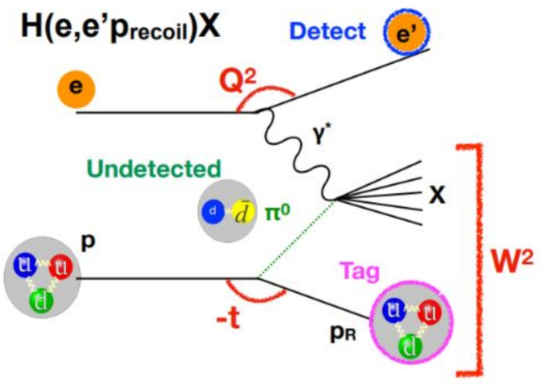


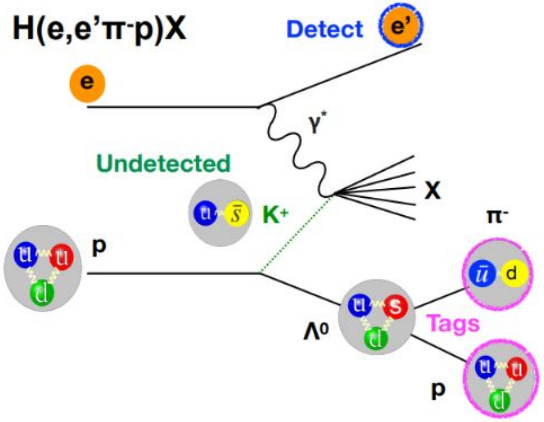
PDF (1-xπ) for x→1, pQCD expected (1-xπ)²



atio K/pi u-quark distributions

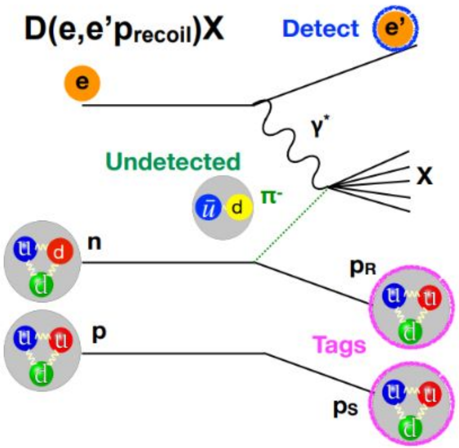
1st direct neutral pion measurement





Practically no data exists for kaon

Resolve QCD nodel tensions for charged pion



$8 < W^2 < 18$ GeV^2
$1 < Q^2 < 3$ GeV^2
$0.05 < x < 0.2$

DIS kinematic regime and event reconstruction:
x, Q^2, W^2, and M_x of recoiling system

- DIS with spectator tagging
  - Access to effective free targets not easily found in nature

- Small -t to maximise "true" pion content
- Very low momentum recoiling hadrons (60 - 400 MeV/c) → need novel detector

- First direct measurement of mesonic content of nucleon
- Aims to extract pion and kaon F_2 in valence regime

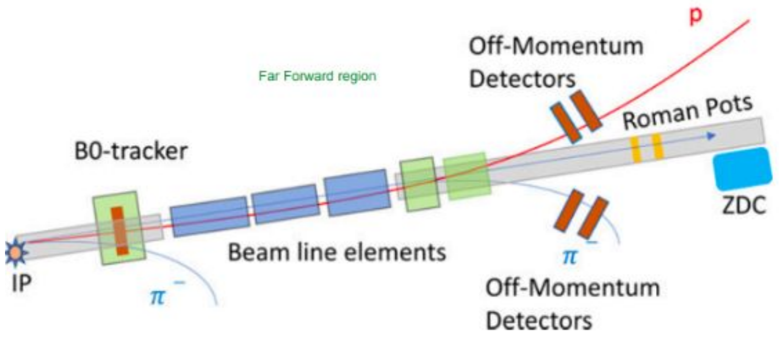
Planned J-Lab Experiments for Pion and Kaon SF [Courtesy of Rachel Montgomery]

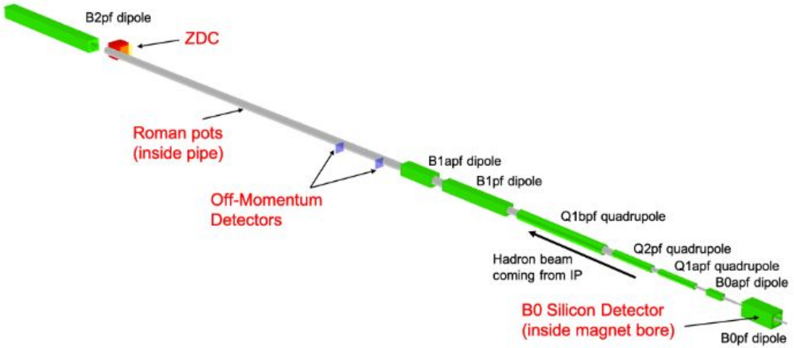
Plans for the EIC Campaign

EIC high luminosity and wide CM energy range will make a large contribution to the understanding of meson structure.

TDIS at EIC would be sullivan process reactions detached in the far forward region.

In the short term aim to simulate the the lambda decay sullivan process reactions from the ZDC FF detector, to access pion and kaon SFs using TDIS techniques, covered later.





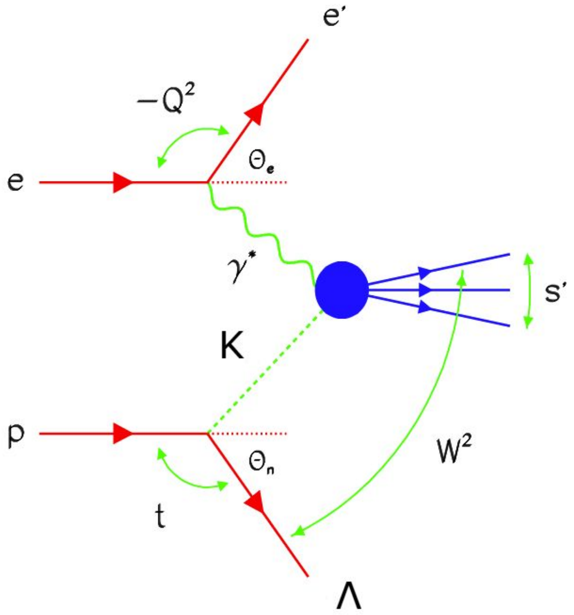
[https://arxiv.org/pdf/2103.05419]

Meson SF Data Process

Data and CSVs courtesy of Avnish Singh, CUA, and Dmitry Romanov, JLab

Meson Simulation Campaign

- Large-scale Meson SF Campaign
- Key Difference: K_Lambda System
    - Progression from pion-neutron tagging
    - Kaon SF through Sullivan Process
    - Increased decay complexity



$$\Lambda \rightarrow p + \pi^-$$

$$e + p \rightarrow e' + K^+ + \Lambda$$

$$\Lambda \rightarrow n + \pi^0$$

Preliminary Results from Meson Simulation Campaign

01 Double Angle

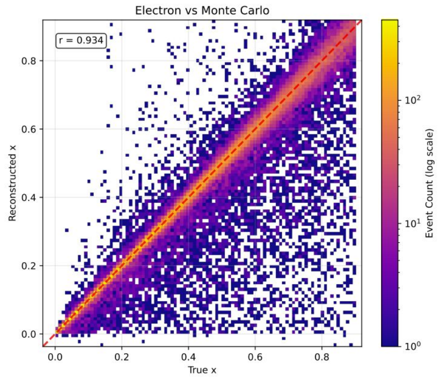
02 Electron

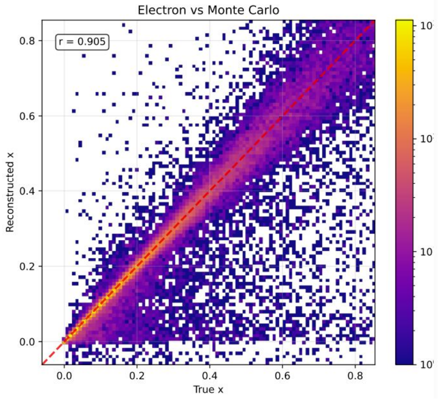
03 Jacquet-Blondel

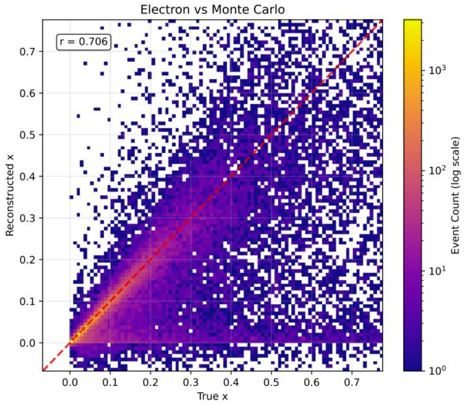
04 Machine Learning

04 Sigma

X: Bjorken X, the fraction of the hadron's momentum carried by the struck quark





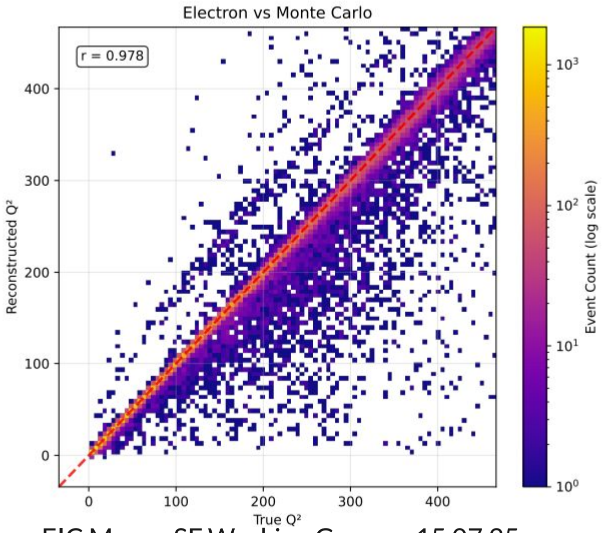


Figures: Electron Method reconstruction for x_bj. Top left of kinematics 5x41, top right has kinematics 10x100, bottom left has kinematics 18x275
(list here)

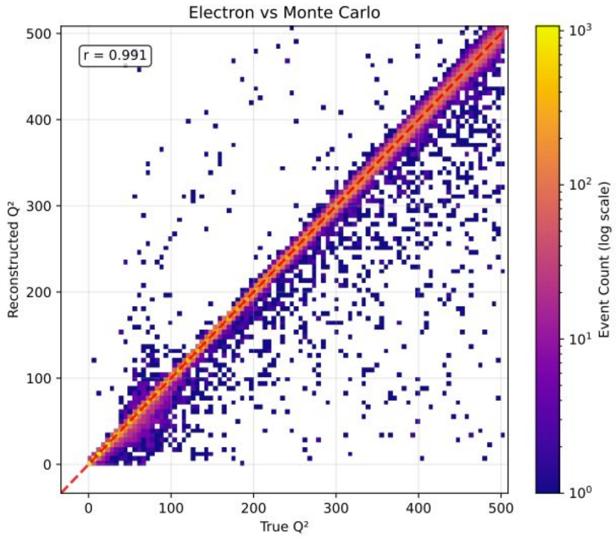
Q^2 Preliminary Results

Q^2: Four-momentum squared of lepton (electron)

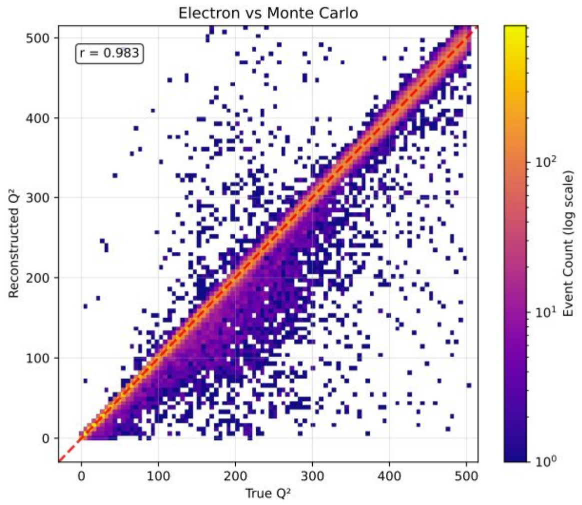
5x41:



10x100:



18x275:



Resolution Lambda

Measurement of how good the reconstructions performed compared to the MC events

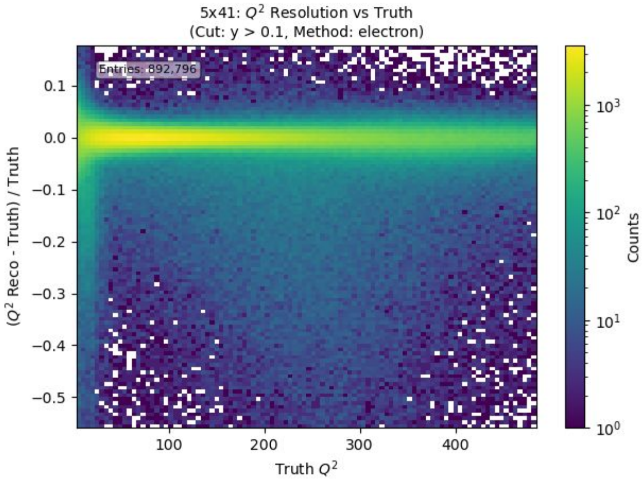
(Reconstruction-Truth)/Truth

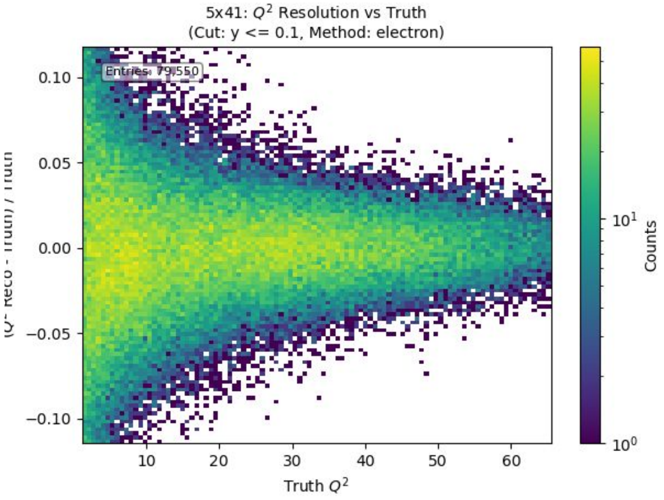
y parameter in DIS represents the fraction of the lepton's energy transfer to the hadronic system

$y > 0.1$: Higher inelasticity region

$y <= 0.1$: Lower inelasticity region

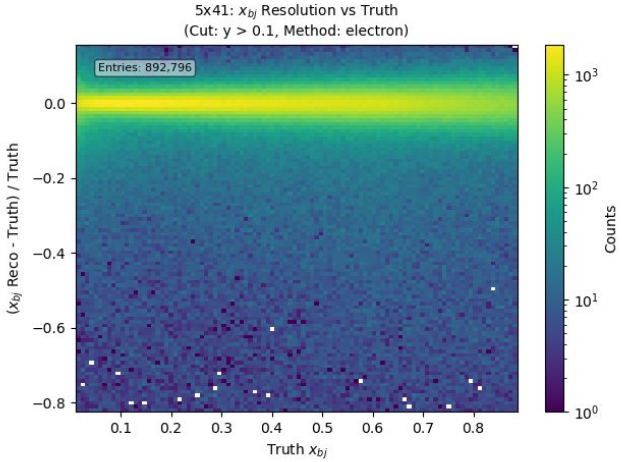
- y-cuts allow better visualization of data

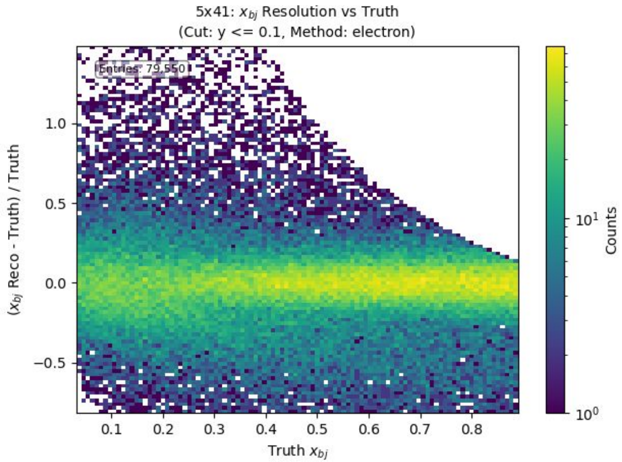


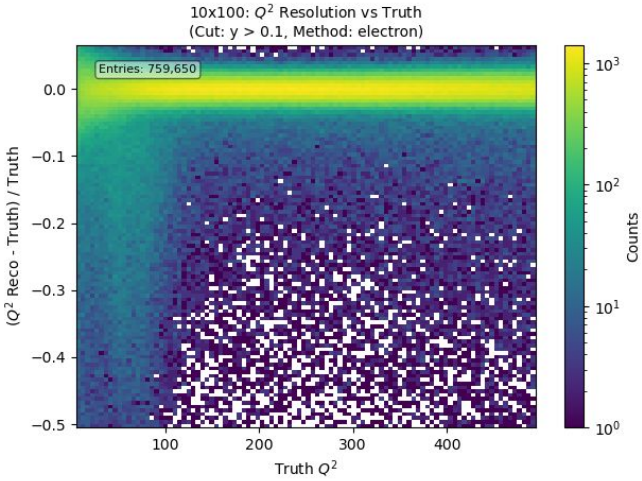


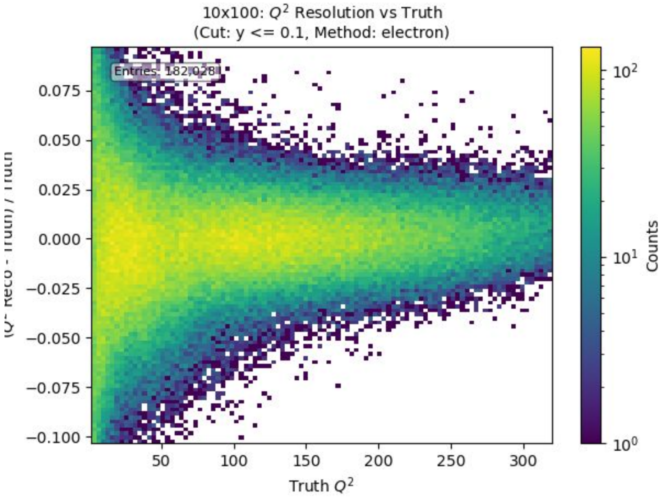
Q2: Very Tight, little scatter especially for y>0.1

X_bj: Also very good correlation with little spread



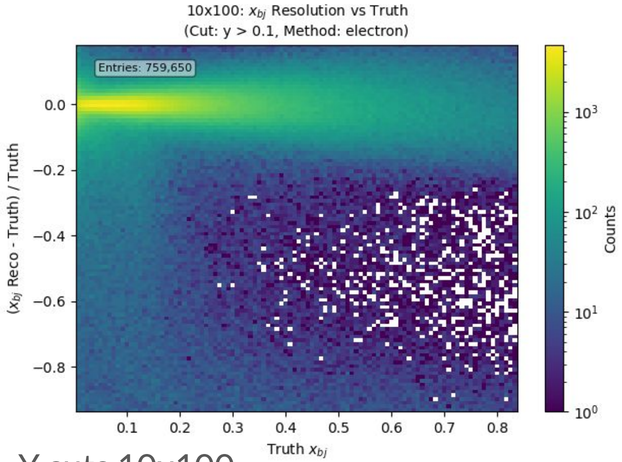


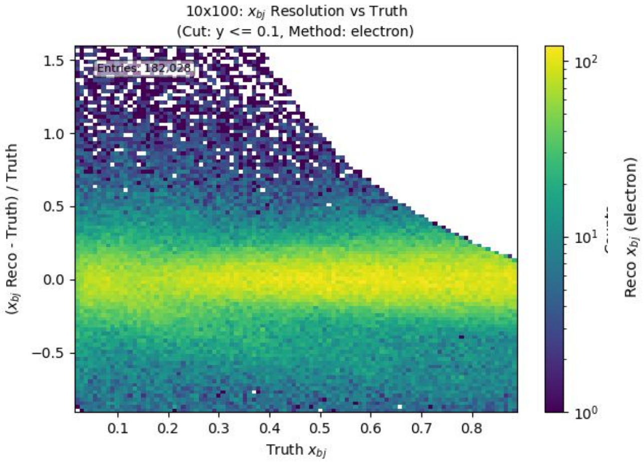


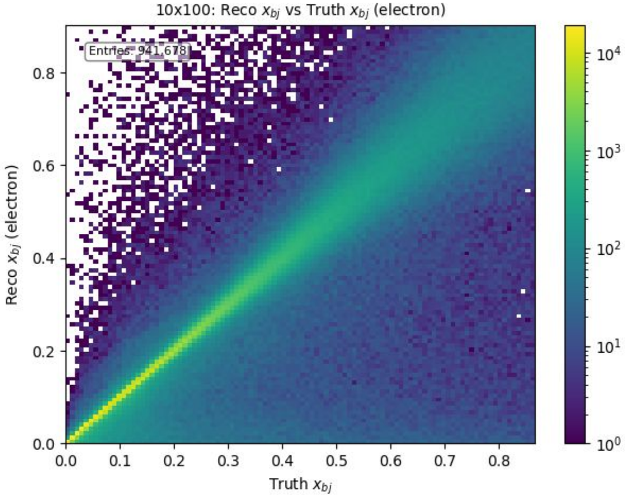


Q2: Tight correlation, slightly more scatter compared to 5x41

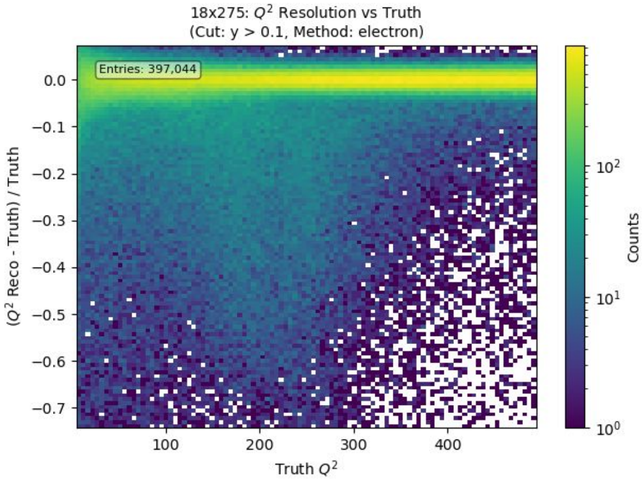
X_bj: Much more broadening. Some unphysical x_bj values, indicating some reconstruction failures, plot below

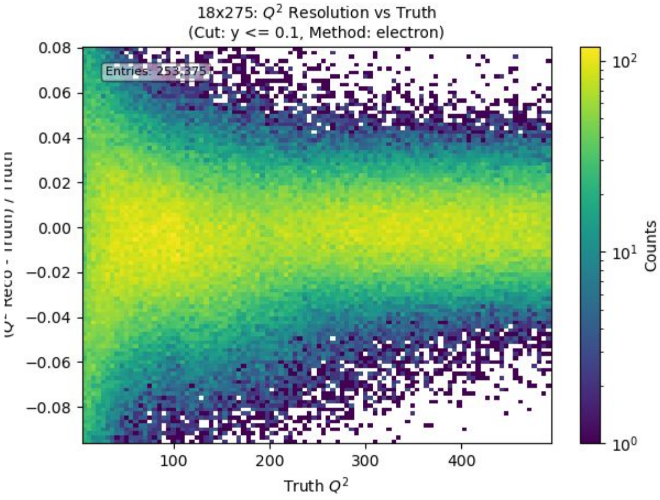






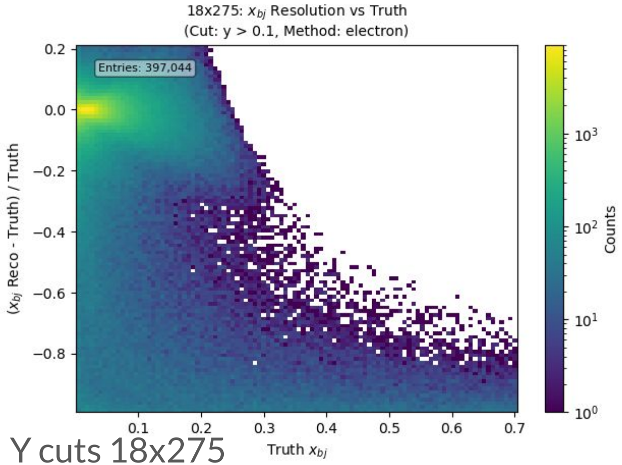
Y cuts 10x100

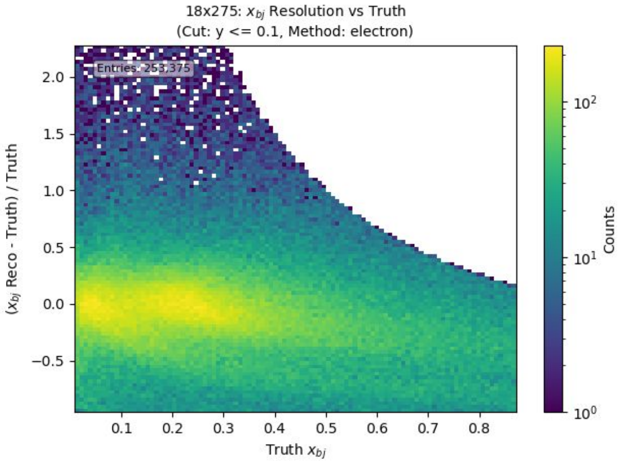


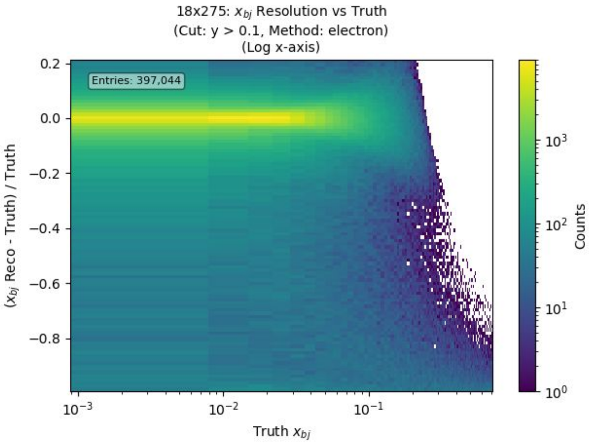


Q2: Still good correlation, but increasing scatter

X_bj: Significant broadening, more reconstruction issues at this energy. Log plot indicates resolution extends over a much larger range







Y cuts 18x275

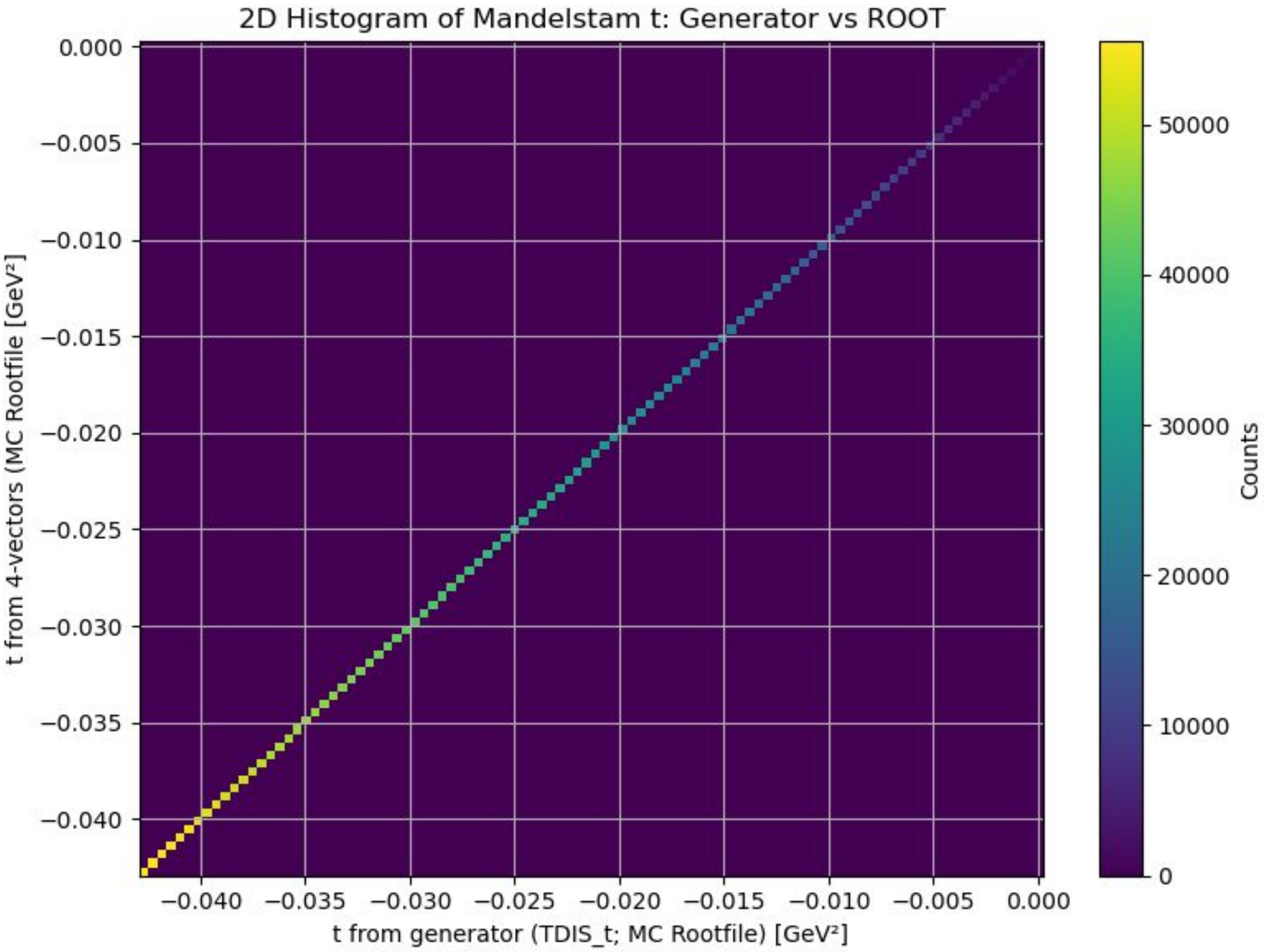


Figure courtesy of Avnish Singh. Plot shows confirmation of -t computation using 4-vectors.

t= (p-Λ)^2

Summary & Next Steps

Mesons are vital to our understanding of hadron structure, and Meson Structure Functions have the potential to improve our understanding of the boundaries of the Standard Model

Meson SF data is very sparse - and there are practically none for kaons

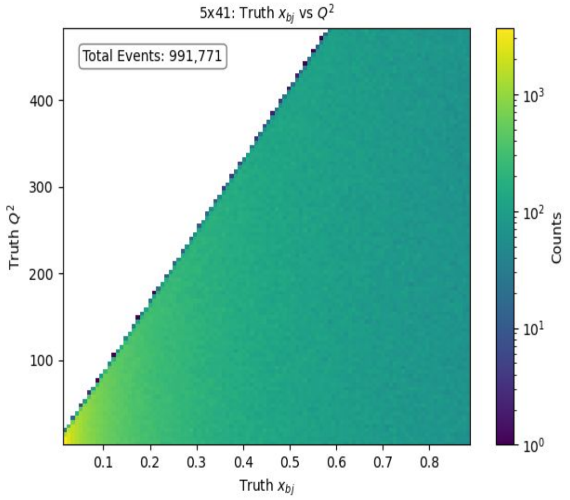
EIC/ePIC Meson Simulation Campaign has been completed with the particular focus on the kaon

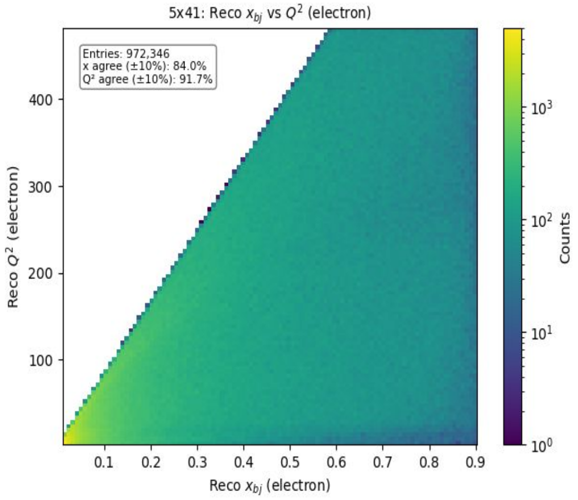
Initial results identified the suitable reconstruction method (electron) and initial t-resolution analysis

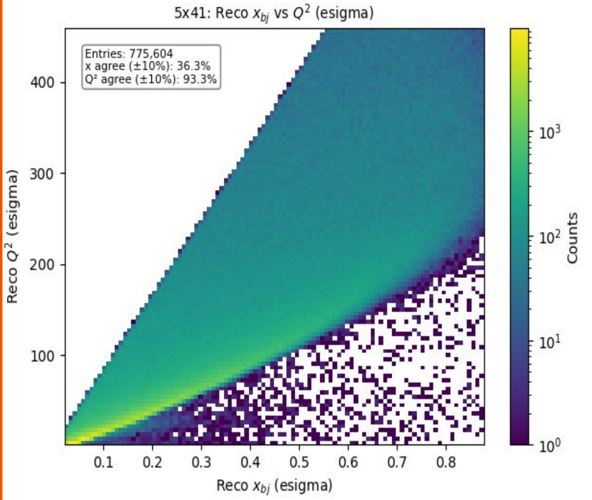
Next steps:

- Fix reconstruction resolution issues
- Find appropriate binning
- Structure Function extraction

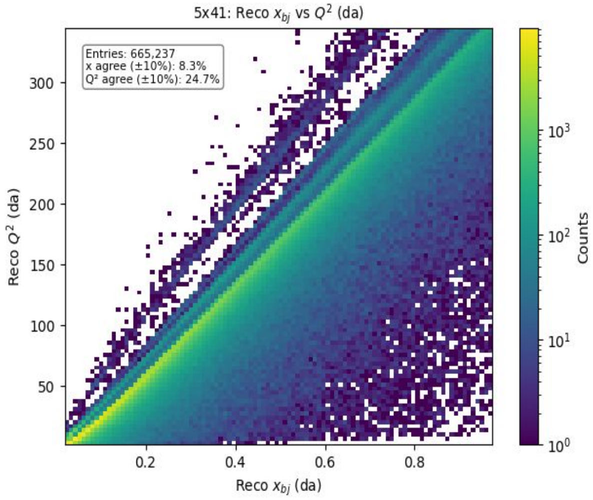
Backup Slides

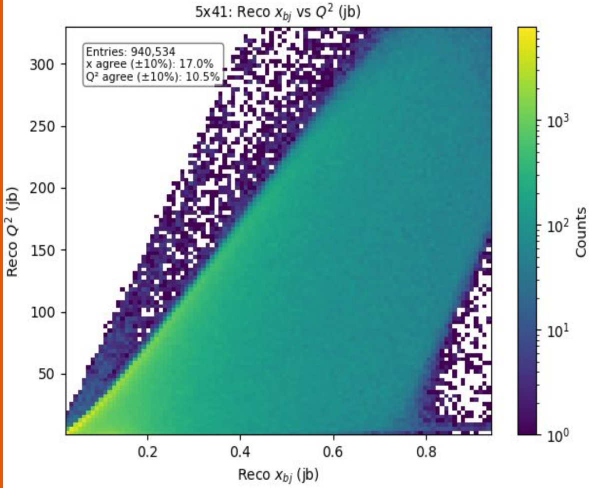


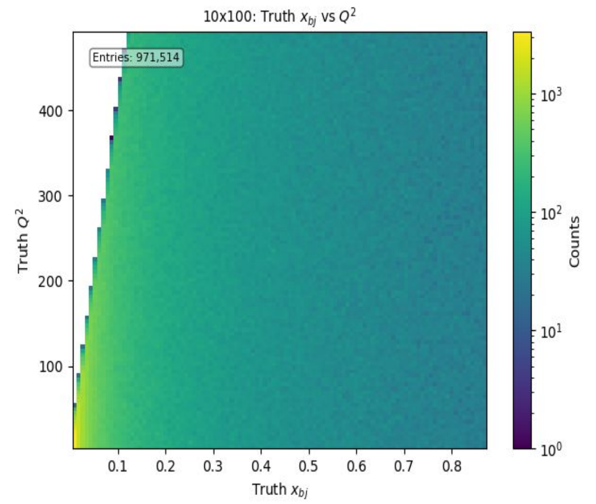


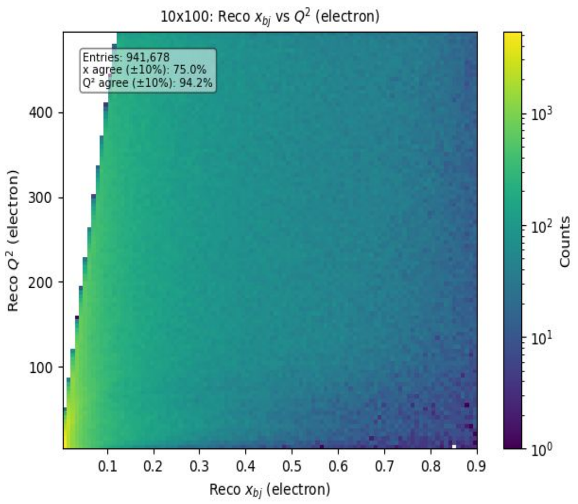


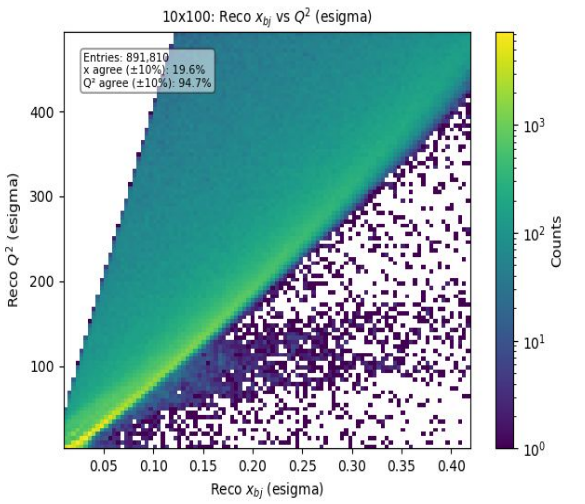
Method for 5x41	Counts	Truth +-10% Agreement
Truth	991,771	N.A
electron	972,346	84%-x, 91%-Q2
DA	665,237	8.3%-x,24.7%-Q2
esigma	775,604	36.3%-x,93.3%-Q2
J-B	940,534	17%-x,10.5%-Q2



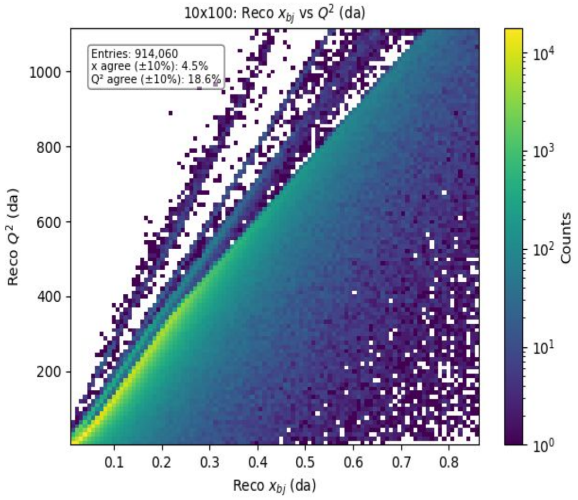


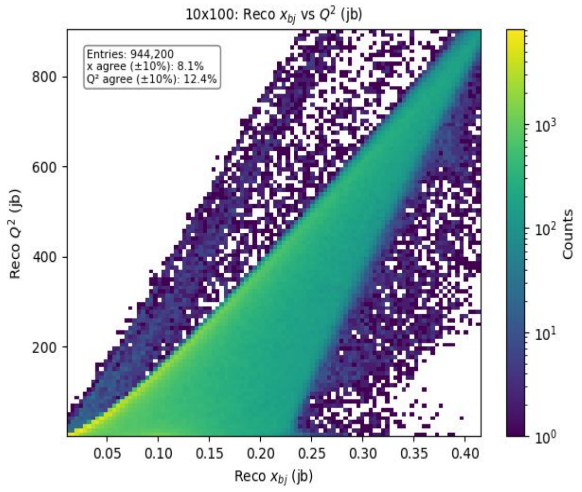


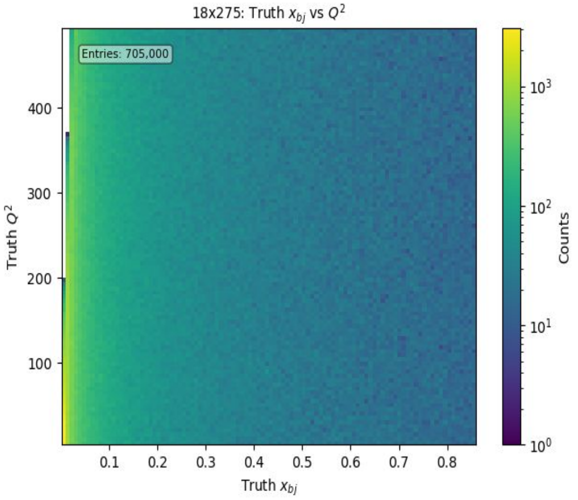


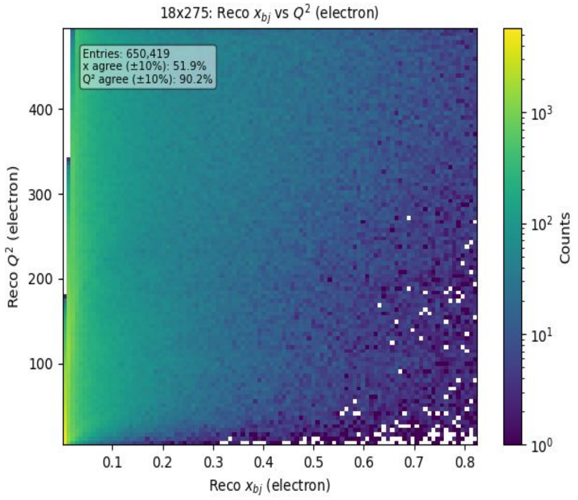


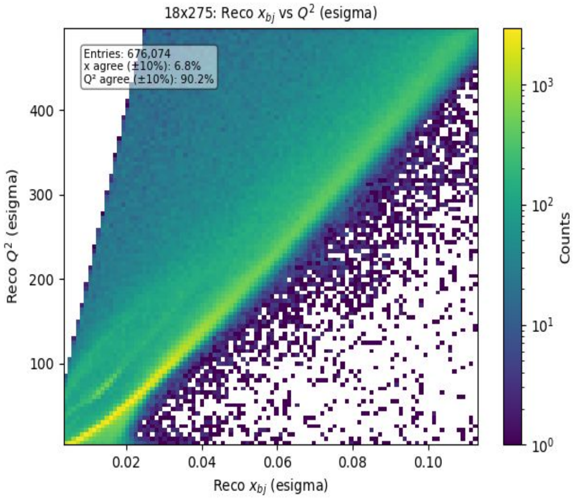
Method for 10x100	Counts	Truth +-10% Agreement
Truth	971,514	N.A
electron	941,678	75%-x, 94.2%-Q2
DA	914,060	4.5%-x,18.6%-Q2
esigma	891,810	19.6%-x,94.7%-Q2
J-B	944,200	8.1%-x,12.4%-Q2



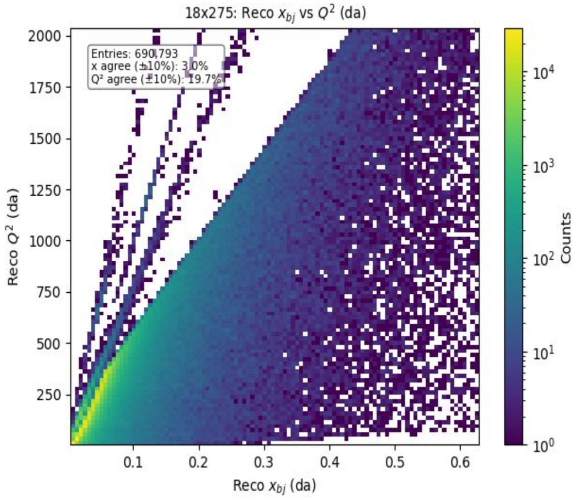


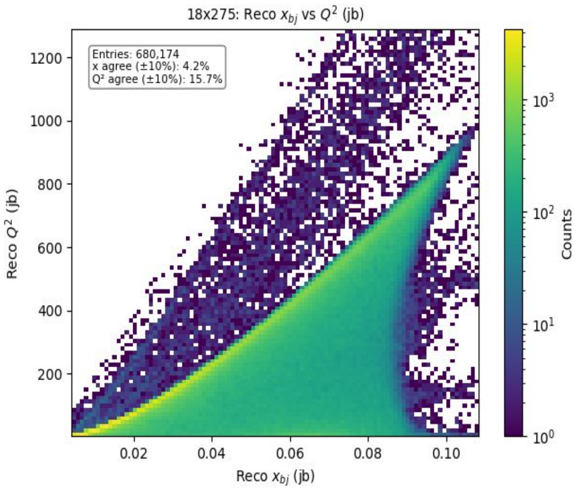


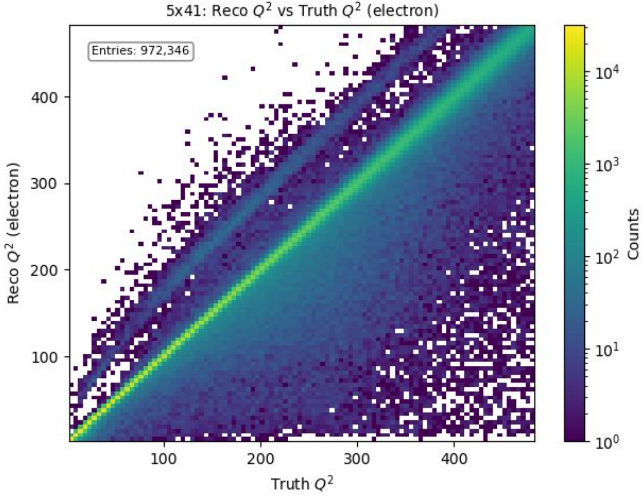


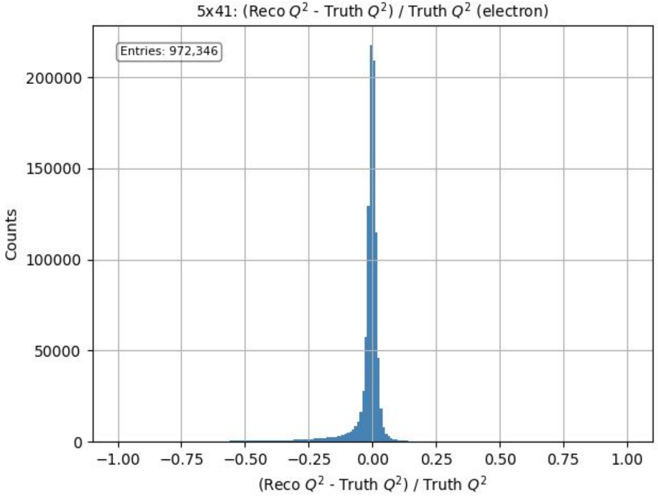


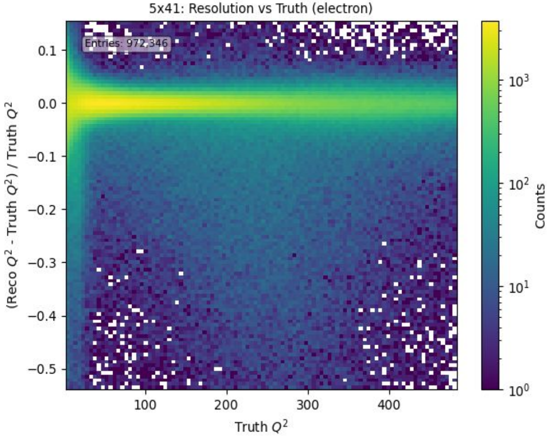
Method for 18x275	Counts	Truth +-10% Agreement
Truth	705,000	N.A
electron	650,419	51.9%-x, 90.2%-Q2
DA	690,793	3%-x,19.7%-Q2
esigma	676,074	6.8%-x,90.2%-Q2
J-B	680,174	4.2%-x,15.7%-Q2

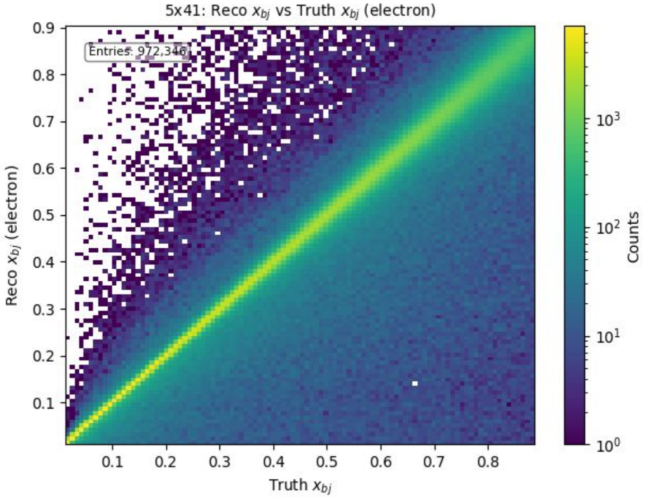


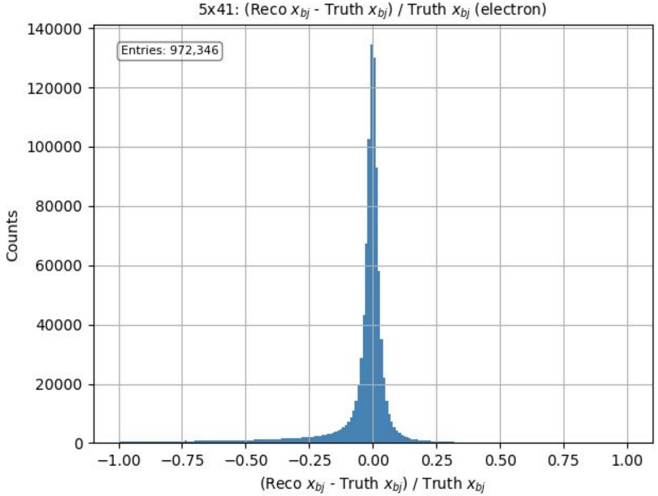


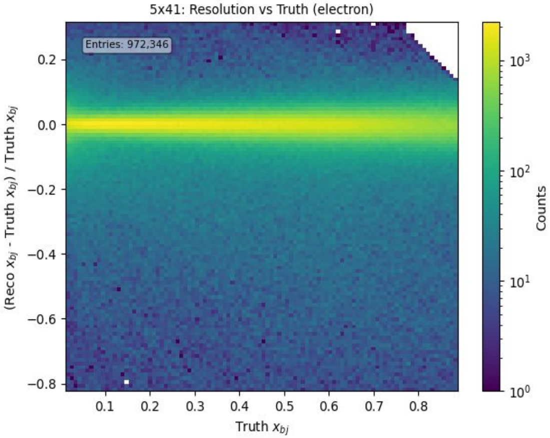

5x41: Reco Q^2 vs Truth Q^2 (electron)
Entries: 972,346
Reco Q^2 (electron)
Truth Q^2
Counts


5x41: (Reco Q^2 - Truth Q^2) / Truth Q^2 (electron)
Entries: 972,346
Counts
(Reco Q^2 - Truth Q^2) / Truth Q^2

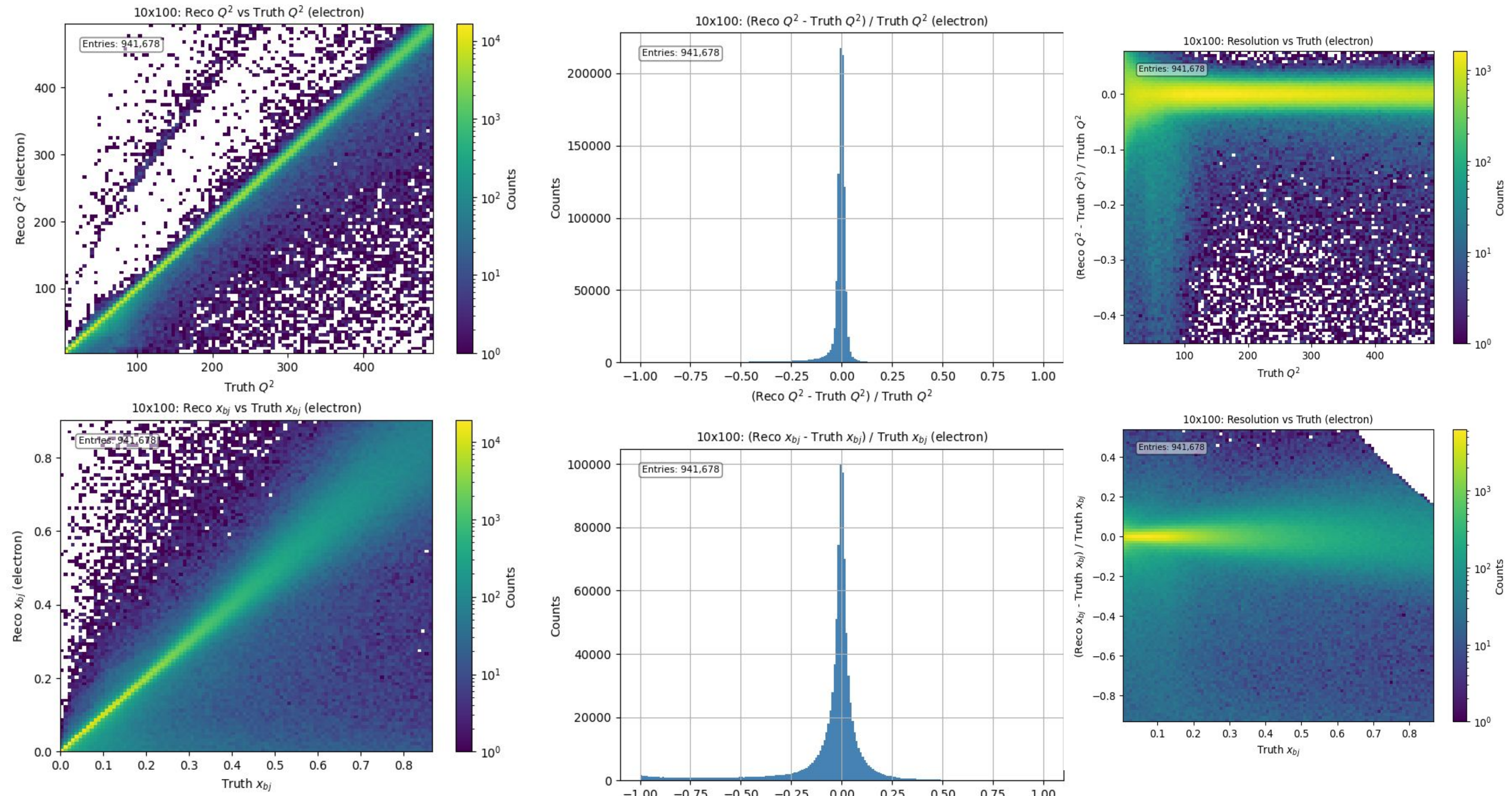

5x41: Resolution vs Truth (electron)
Entries: 972,346
(Reco Q^2 - Truth Q^2) / Truth Q^2
Truth Q^2
Counts


5x41: Reco x_{bj} vs Truth x_{bj} (electron)
Entries: 972,346
Reco x_{bj} (electron)
Truth x_{bj}
Counts

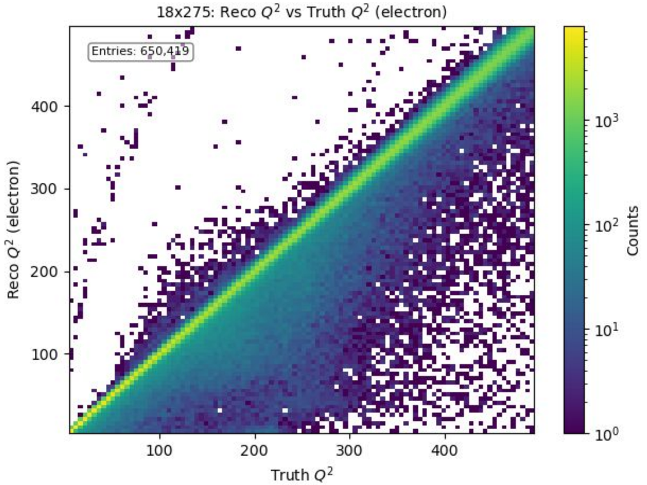

5x41: (Reco x_{bj} - Truth x_{bj}) / Truth x_{bj} (electron)
Entries: 972,346
Counts
(Reco x_{bj} - Truth x_{bj}) / Truth x_{bj}

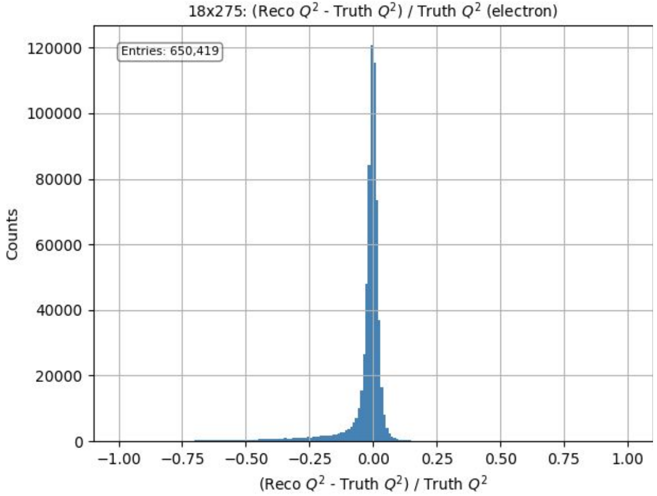

5x41: Resolution vs Truth (electron)
Entries: 972,346
(Reco x_{bj} - Truth x_{bj}) / Truth x_{bj}
Truth x_{bj}
Counts

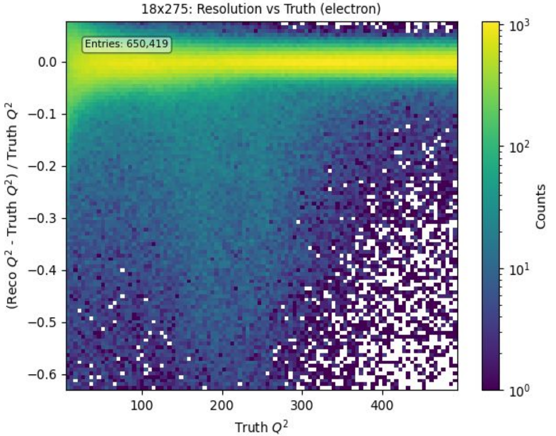
5x41

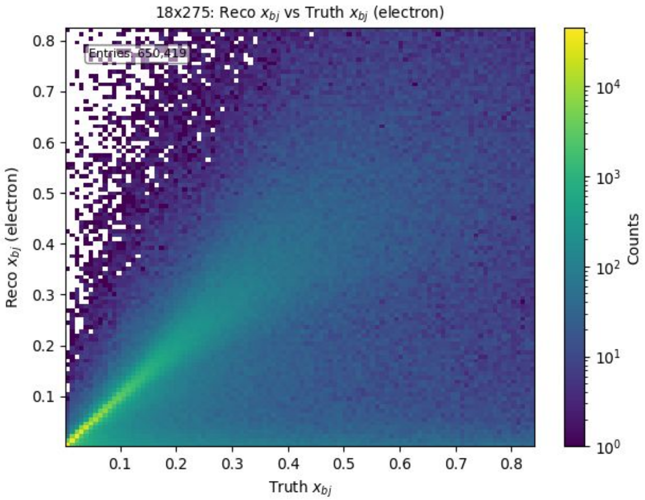


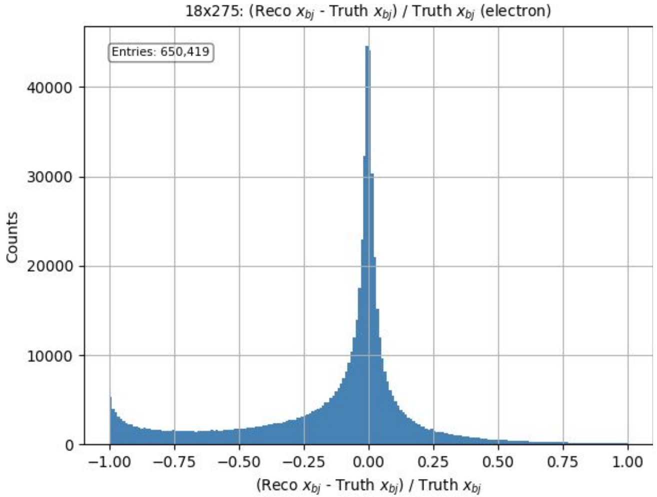
10x100 - noticed some negative x_bj for higher energies

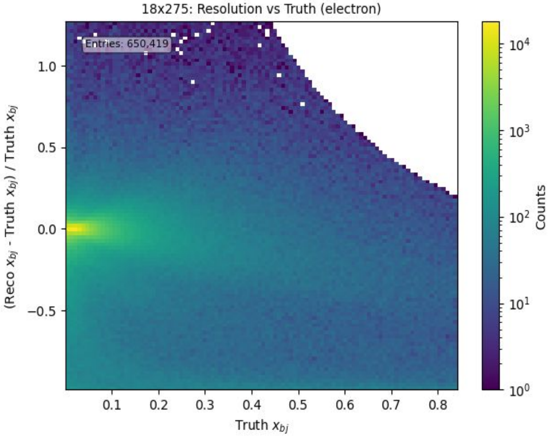

18x275: Reco Q^2 vs Truth Q^2 (electron)
Entries: 650,419
Reco Q^2 (electron)
Truth Q^2
Counts


18x275: (Reco Q^2 - Truth Q^2) / Truth Q^2 (electron)
Entries: 650,419
Counts
(Reco Q^2 - Truth Q^2) / Truth Q^2


18x275: Resolution vs Truth (electron)
Entries: 650,419
(Reco Q^2 - Truth Q^2) / Truth Q^2
Truth Q^2
Counts

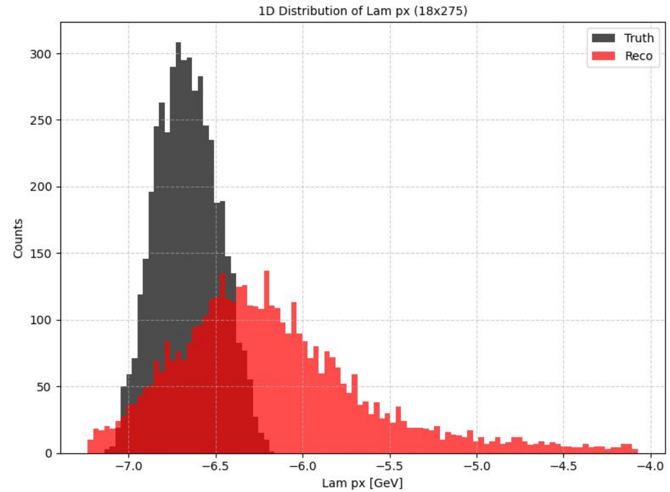

18x275: Reco x_{bj} vs Truth x_{bj} (electron)
Entries: 650,419
Reco x_{bj} (electron)
Truth x_{bj}
Counts

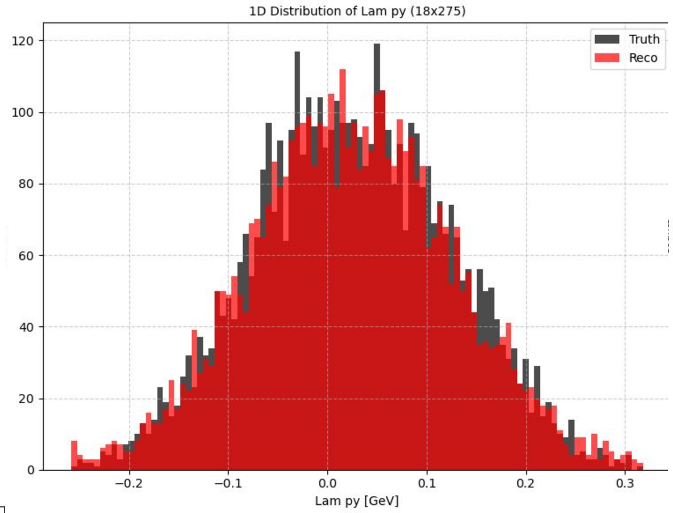

18x275: (Reco x_{bj} - Truth x_{bj}) / Truth x_{bj} (electron)
Entries: 650,419
Counts
(Reco x_{bj} - Truth x_{bj}) / Truth x_{bj}

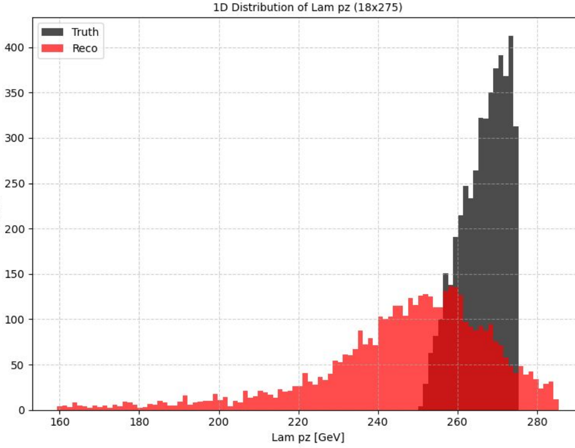

18x275: Resolution vs Truth (electron)
Entries: 650,419
(Reco x_{bj} - Truth x_{bj}) / Truth x_{bj}
Truth x_{bj}
Counts

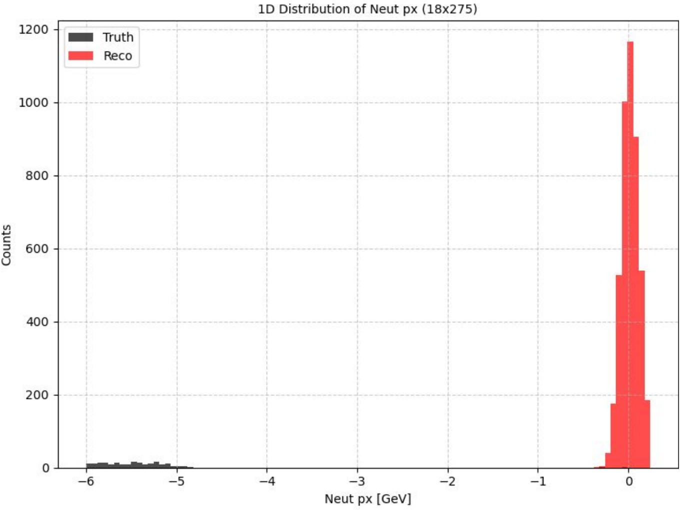
18x275

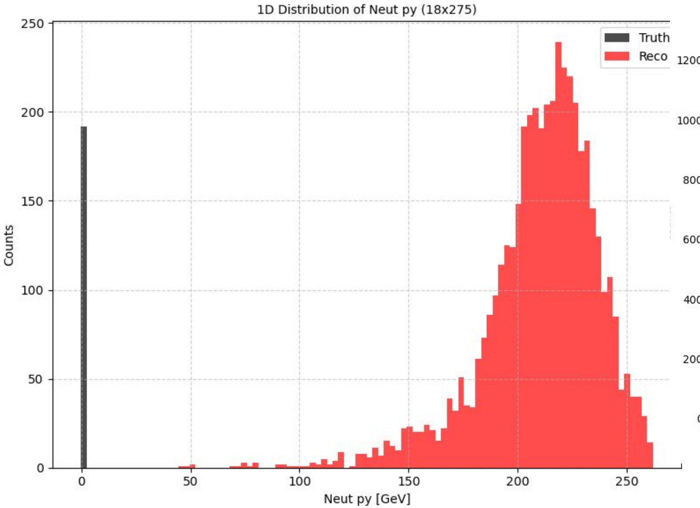
Reconstruction Method Details

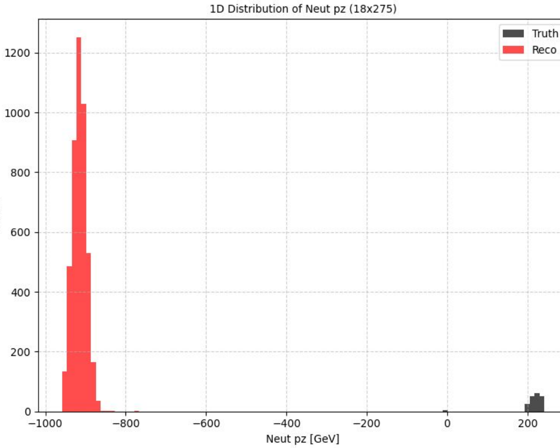




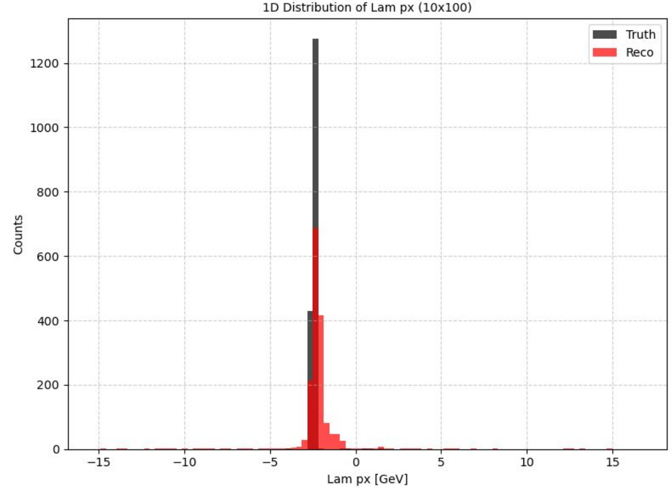


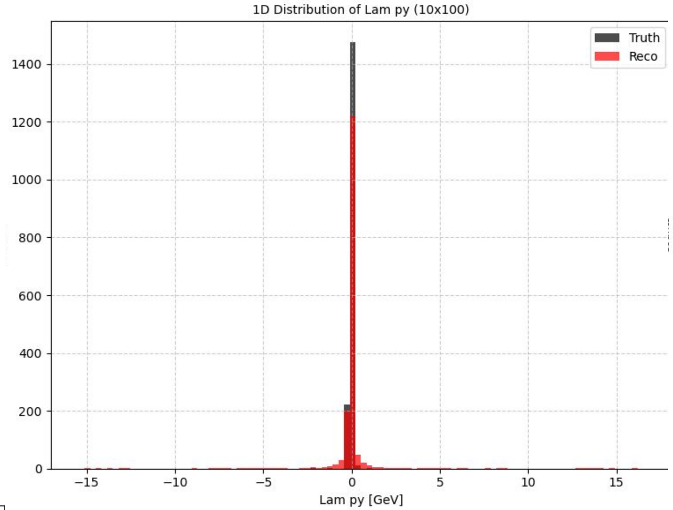


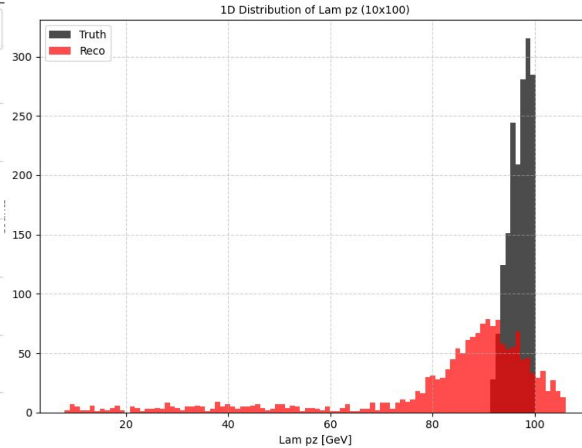


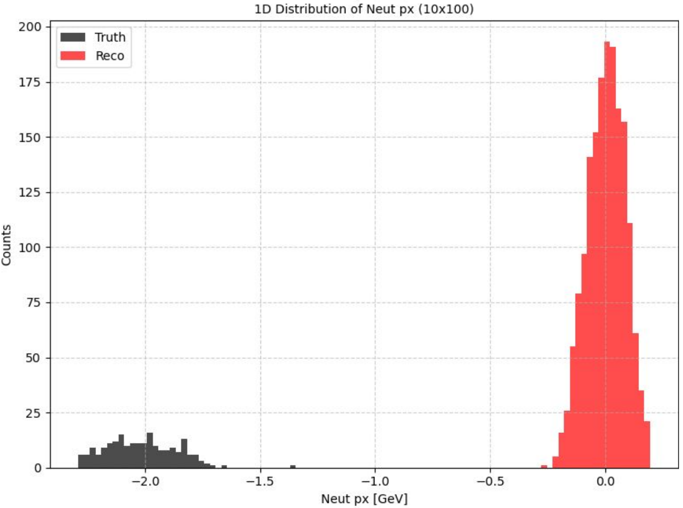


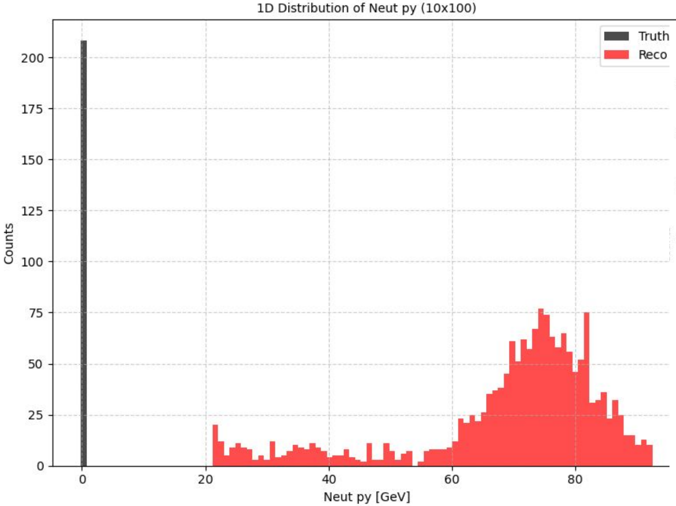
18x275 momdistro

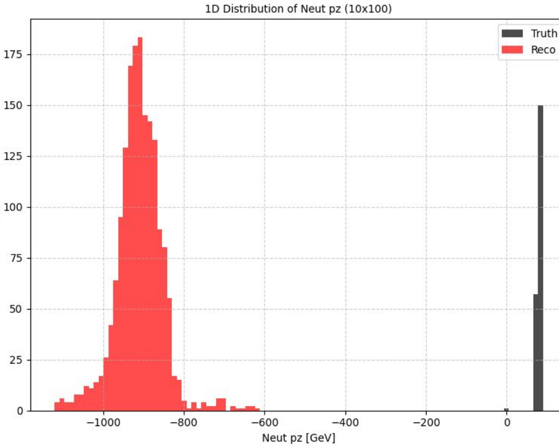




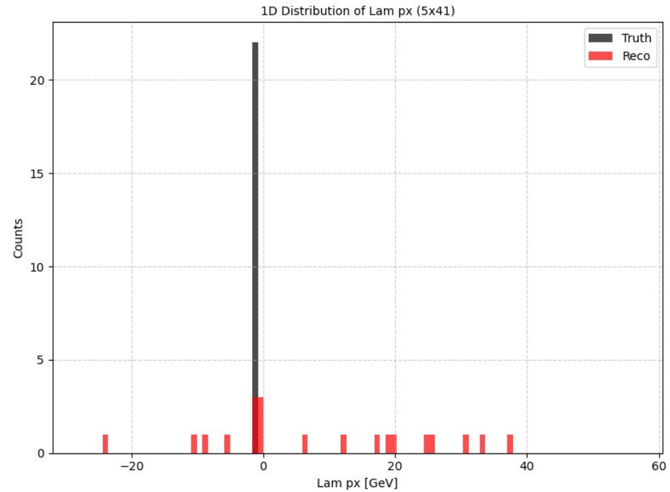


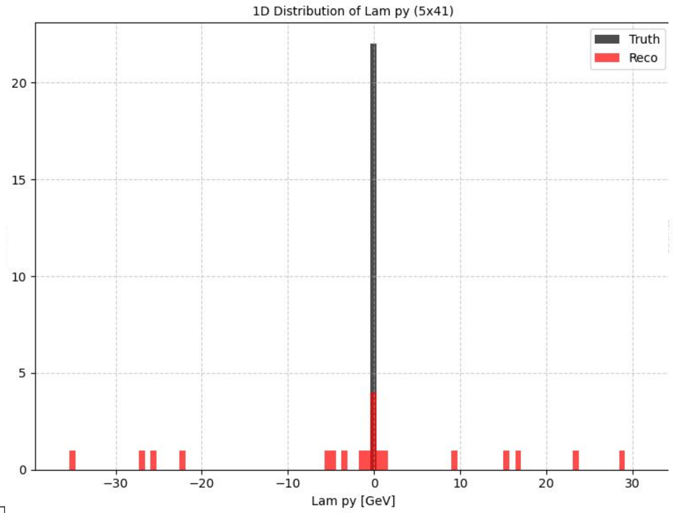


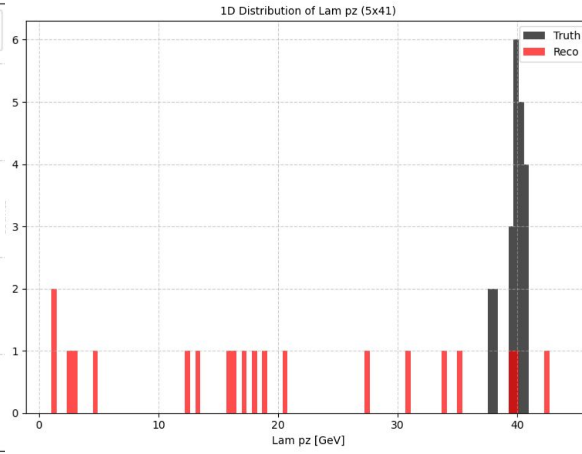


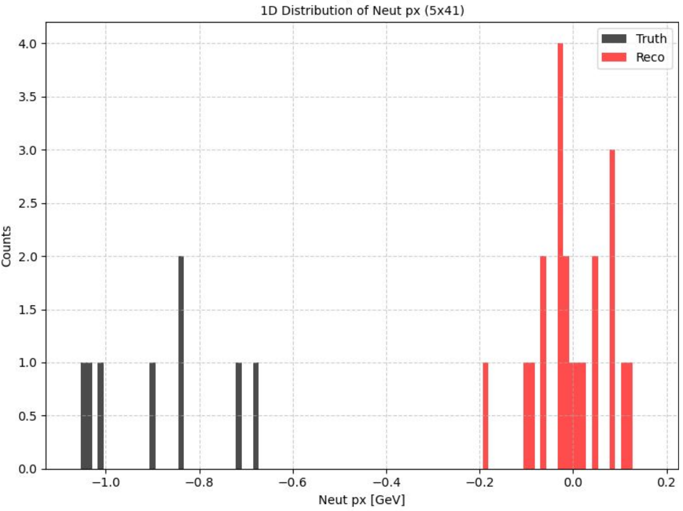


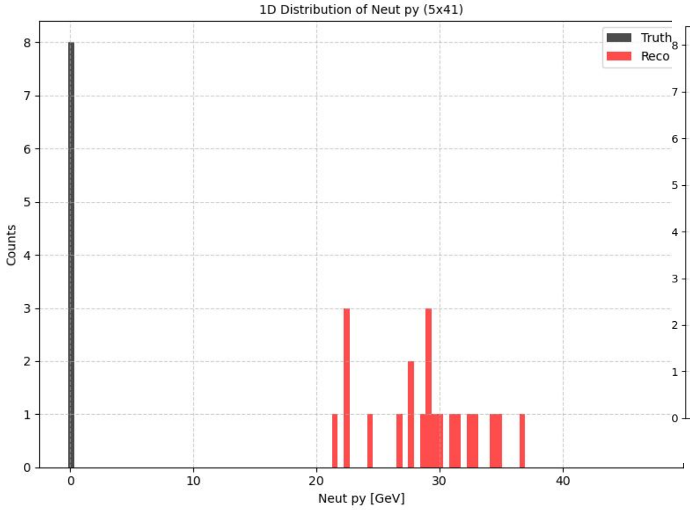
10x100 momdistro

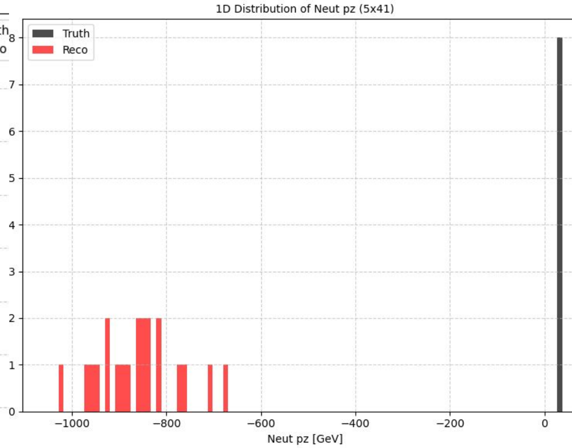




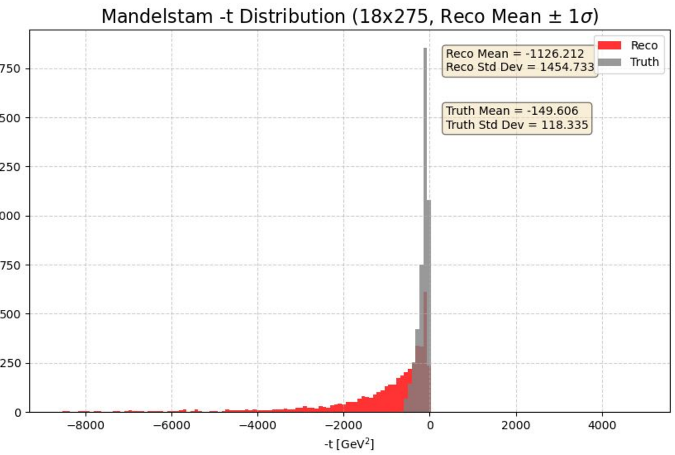


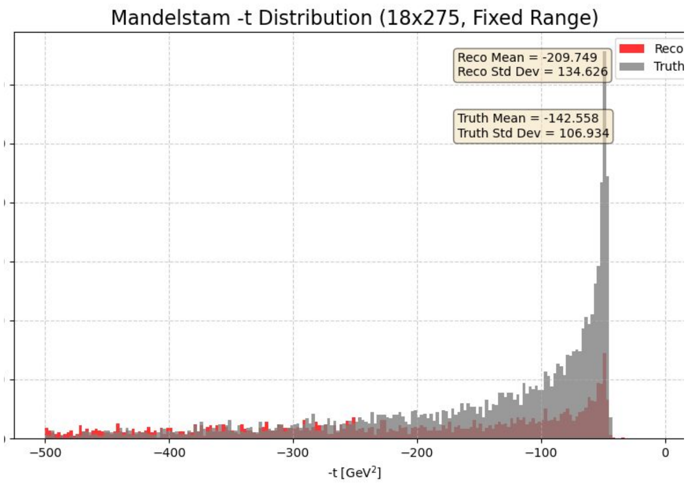


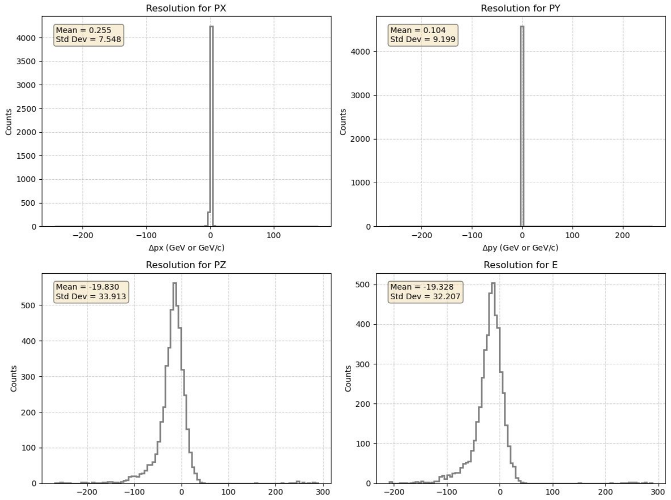


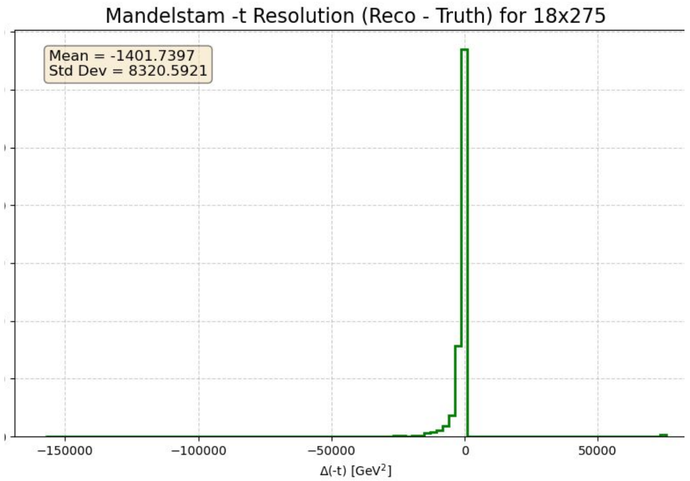


5x41 momdistro

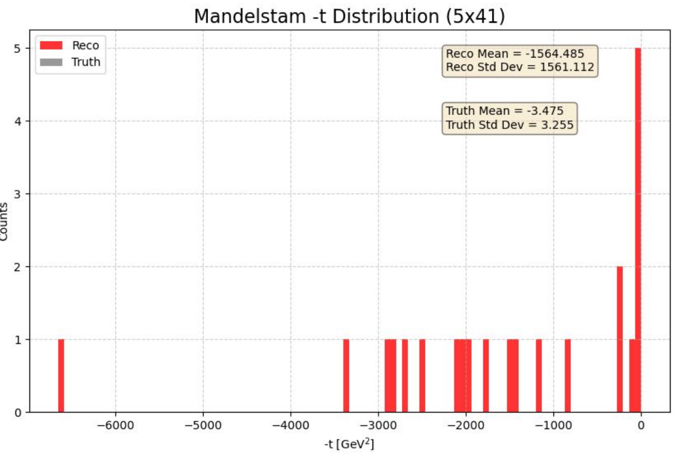


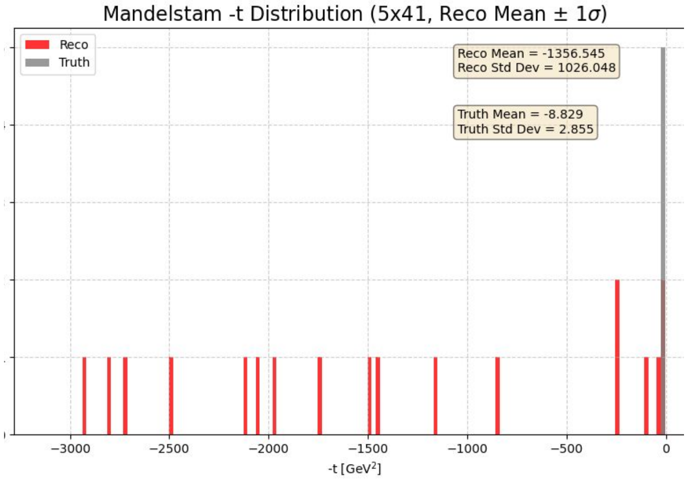


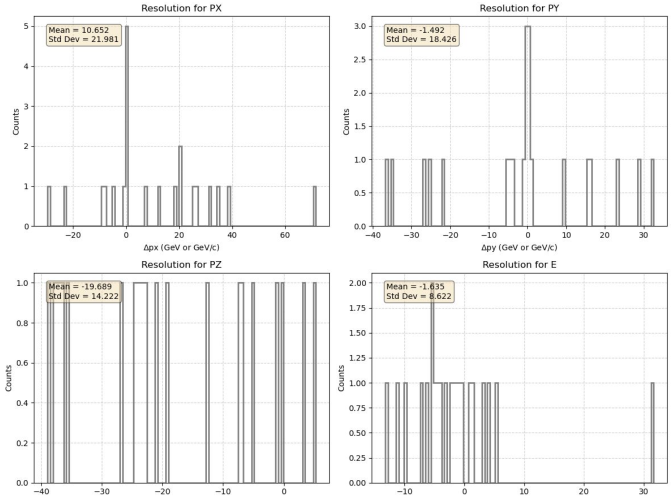


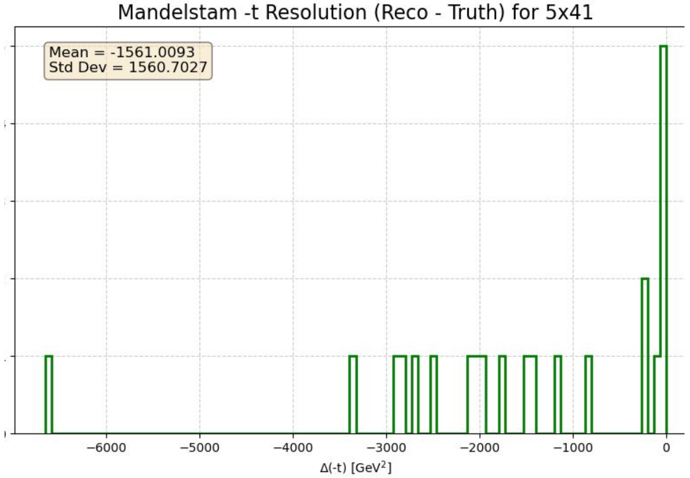


18x275 t distro

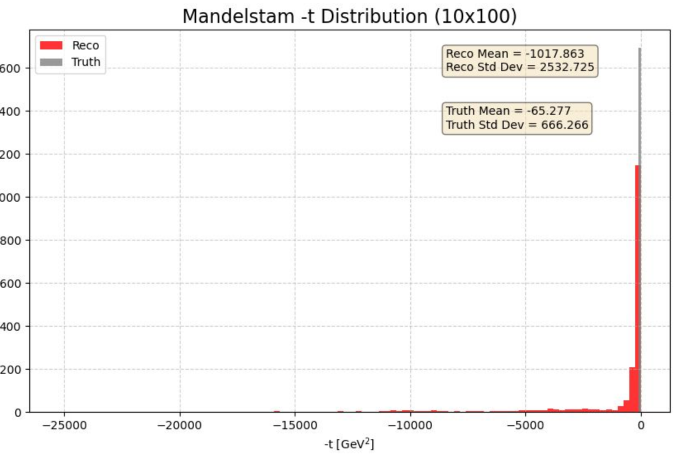


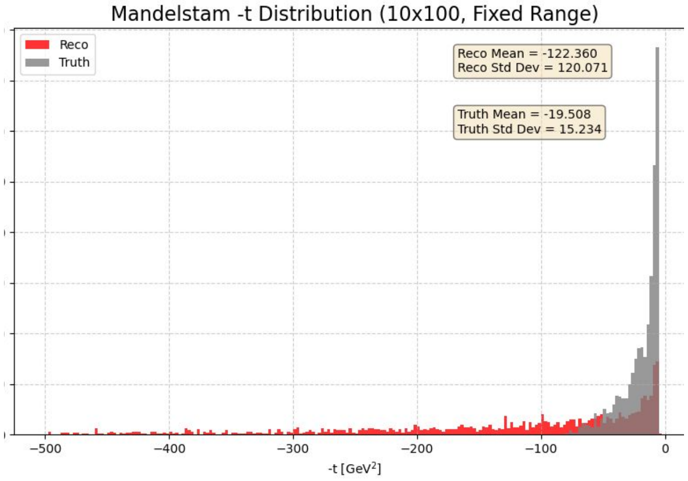


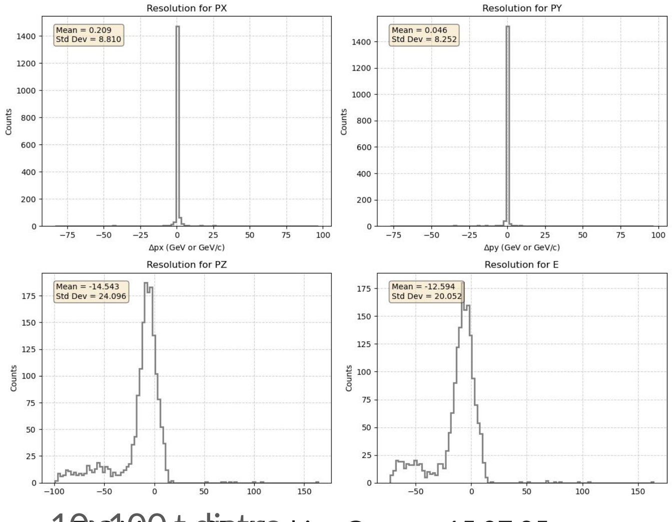


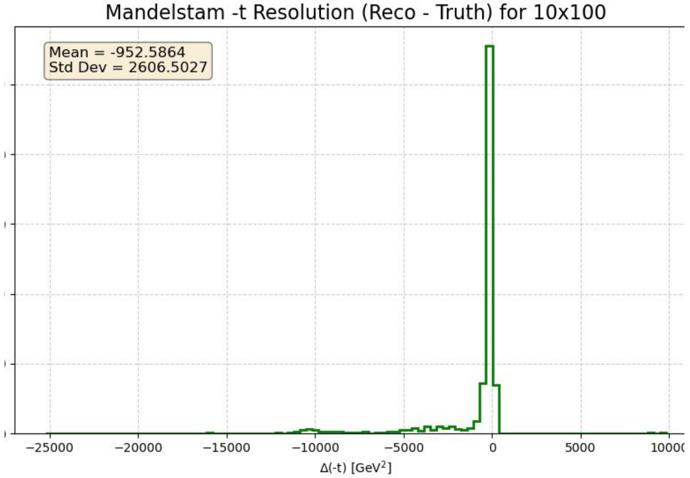


5x41 t distro









10x100 t distro