Nucleon Binding Energy and Transverse Momentum Imbalance in Neutrino-Nucleus Reactions

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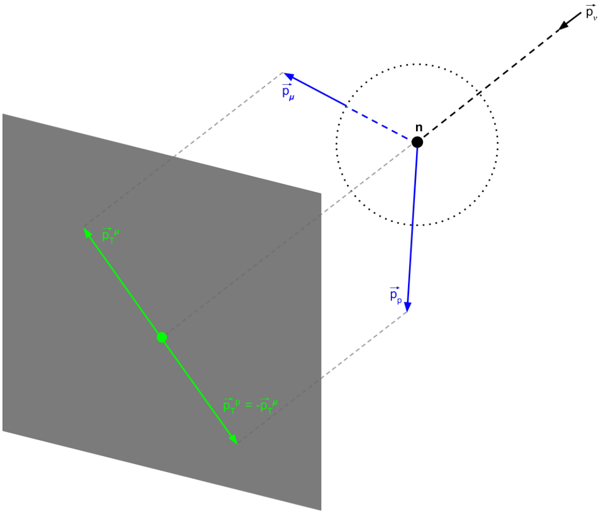
Outline

1 The Single Transverse Kinematic Imbalances

2 Measurements of Single-TKI Projections

3 Results and Sensitivities to Binding Energy

We have developed a powerful tool to diagnose FSI



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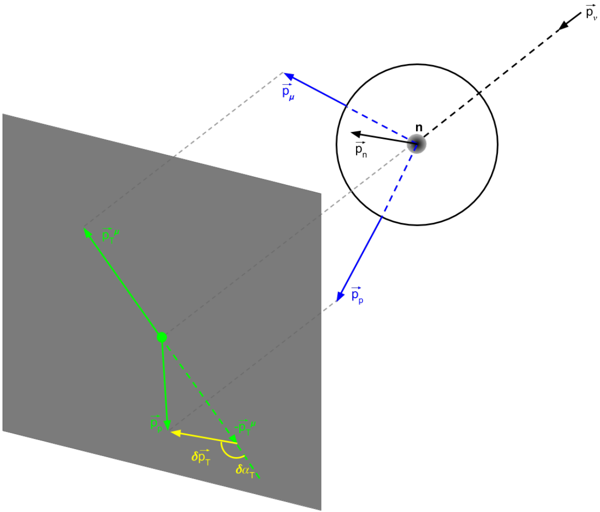
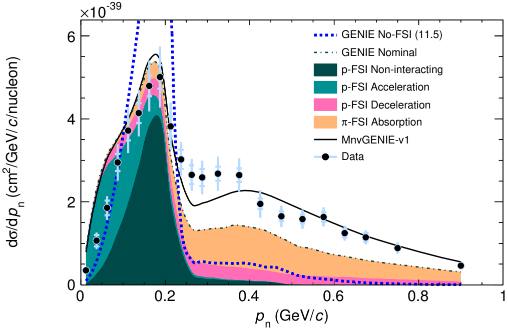


Powerful tool to diagnose FSI

MINERνA has had a fruitful journey on the transverse path:

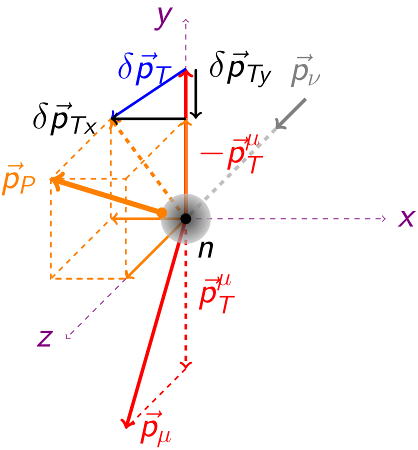


Inferred initial neutron momentum:
$p_{\mathrm{n}} = \sqrt{\delta p_{\mathrm{T}}^2 + \delta p_{\mathrm{L}}^2}$

Pile up of MC due to "accelerated" proton after going through FSI at low p_{n} bins. This turns out to be a bug.

Phys.Rev.Lett. 121 (2018) no.2, 022504

Single-TKI Transverse projections



We can project δp_{T} into components parallel:

$$\hat{y} = -\hat{p}_T^\mu$$

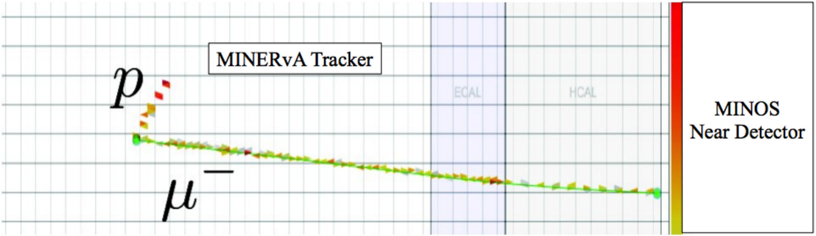
and perpendicula:

$$\hat{x} = \frac{\vec{p}_\nu \times \vec{p}_\mu}{|\vec{p}_\nu \times \vec{p}_\mu|}$$

to the muon transverse momentum $\vec{p}_{\mathrm{T}}^\mu$

Signal Definition

The new variables are natural extensions of the Single-TKI measurements in Phys.Rev.Lett. 121 (2018) no.2, 022504.



- *CCQELike*: 1 muon, 0 mesons and at least 1 proton
- Muon and proton kinematic requirements to avoid regions that MINERνA has no acceptance:
  $1.5~\mathrm{GeV}/c < p_\mu < 10~\mathrm{GeV}/c, \theta_\mu < 20^\circ$
  $0.45~\mathrm{GeV}/c < p_P < 1.2~\mathrm{GeV}/c, \theta_p < 70^\circ$

MC Setup

Cross section extracted with GENIE 2.8.4 and MnvGENIE-v1:

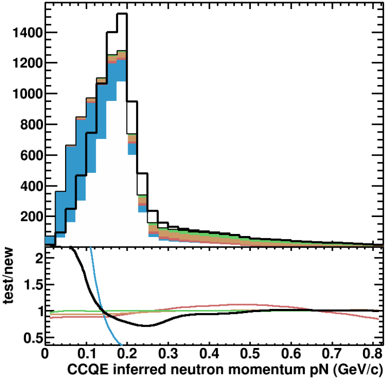
Expert level information for record only

- FMBodekRitchie Fermi gas model, Rein-Seghal RES model, Bodek-Yang DIS parametrization and GENIE hA FSI model.
- Valencia 2p2h model with MINERνA tune
- RPA modification to QE
- Non-resonant pion reduction to 43% of nominal

And finally, MnvGENIE-v1.0.1 removes the elastic FSI in GENIE to correct the GENIE FSI bug:

- removes elastic FSI,
- increases no-FSI by 50%,
- shown to effectively account for the GENIE FSI bug.

A GENIE FSI Fix

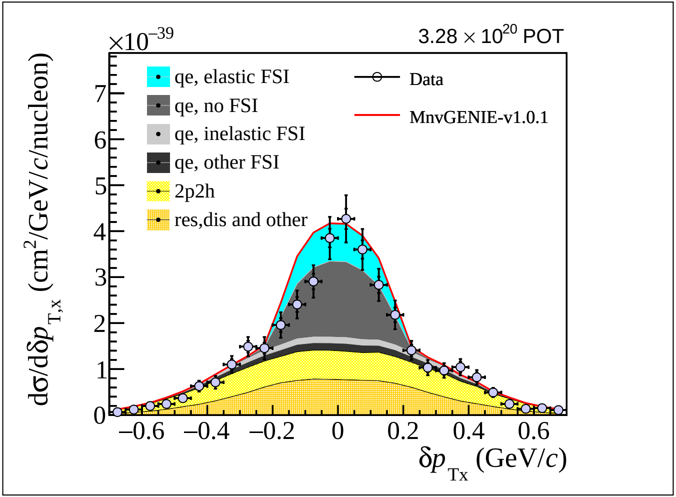


Elastic hadron-nucleus scattering in neutrino-nucleus reactions and transverse kinematics measurements (arXiv 1906.10576)

Black: a distribution with corrected elastic FSI
Blue: the bugged version of elastic FSI in GENIE

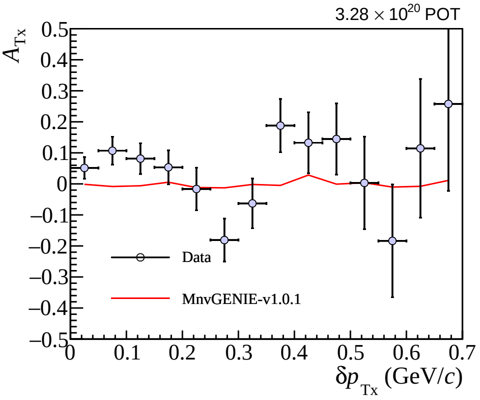
Replacing elastic FSI with no-FSI effectively reproduces the corrected distribution without having to reprocess the large number of existing MC.

δp_{Tx}



The distribution has hints of asymmetry and there are small structures at -0.3 and 0.35

δp_{Tx} asymmetry



We calculate the asymmetry in each δp_{Tx} bin:

$$A_{Tx} = \frac{\sigma_+ - \sigma_-}{\sigma_+ + \sigma_-},$$
$$\text{for } \delta p_{\mathrm{Tx}} > 0.$$

And calculated 1.3σ effect.

Figment of imagination or something real?

Some old single-pion production results

Asymmetries in Δ events exits. We have an irreducible pion absorption background.

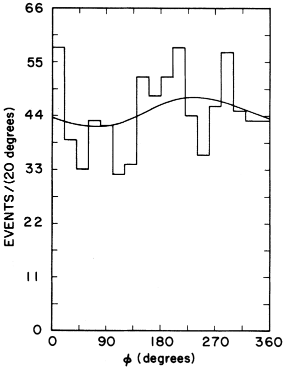
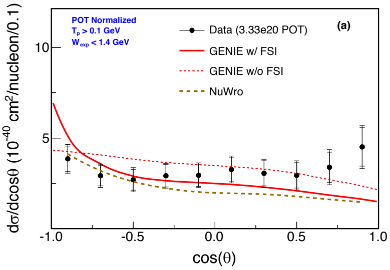


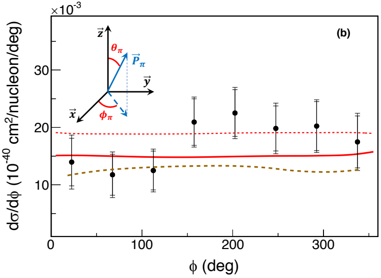
FIG. 16. Distribution of events in the pion azimuthal angle ϕ for the final state $\mu^- p \pi^+$, with $M(p\pi^+) < 1.4$ GeV. The curve is the area-normalized prediction of the Adler model.

Study of single-pion production by weak charged currents in low-energy νd interactions (Phys. Rev. D 26, 3297 (1982))

MINERνA's very own π^0 production results

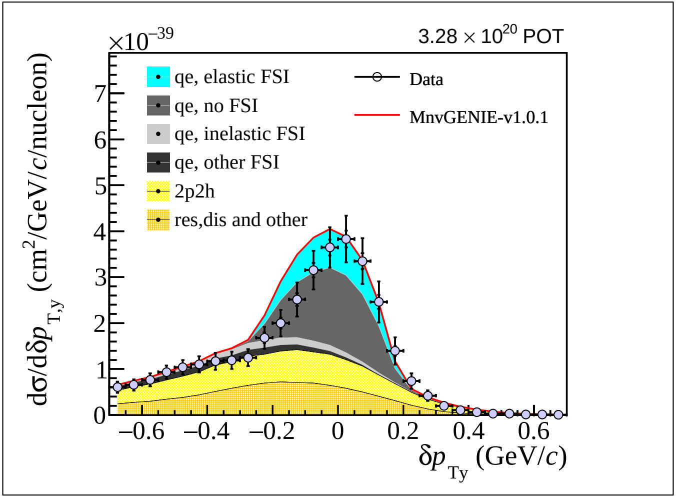
Measurement of ν_μ charged-current single π^0 production on hydrocarbon in the few-GeV region using MINERνA (Phys.Rev. D96 (2017) no.7, 072003)





Future high-statistics Single-TKI measurements in the Medium Energy (ME) will shed light on the significance of the asymmetry.
It might be possible to constrain the faction of pion absorption events with this asymmetry (arXiv:1907.11212)

δp_{Ty}



A clear peak shift. δp_{Ty} is sensitive to the binding energy implementation of the models.

GENIE implementation and corrections

In order to investigate if the peak shift originate from mishandling of binding energy, we considered two adhock corrections: **Correction common to both**:

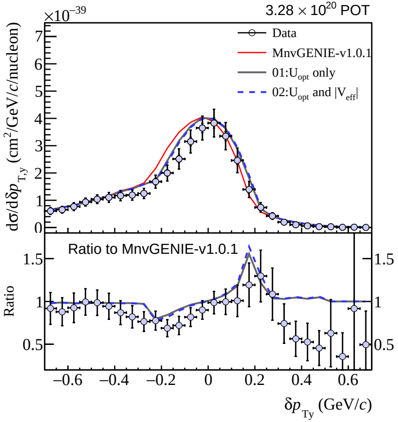
- Add 25 MeV to outgoing proton. This is the removal energy arbitrarily subtracted from final state proton in Carbon.
- Subtract 10.1 MeV from the muon to account for the lack of excitation energy in particle generation.

Then we have:

1. U_{opt}: Subtract $|U_{\mathrm{opt}}|$ from the proton and add to the muon
2. U_{opt} and V_{eff}: Also add $|V_{\mathrm{eff}}^{\mathrm{P}}|$ to the proton and subtract $|V_{\mathrm{eff}}|$ from the muon

U_{opt} was a fit obtained from *Eur.Phys.J. C79 (2019) no.4, 293* and averages to be 2.3 MeV due to proton minimum momentum cuts.
$V_{\mathrm{eff}} = V_{\mathrm{eff}}^{\mathrm{P}} = 3.1\ \mathrm{MeV}$

Comparing GENIE corrections



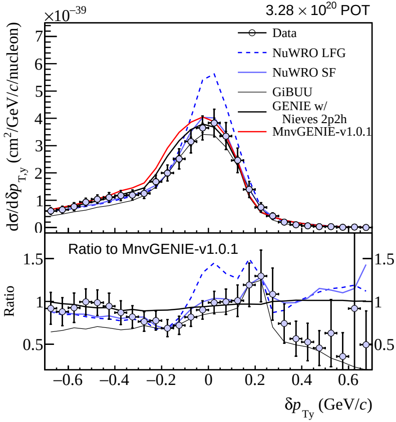
Generator peaks better conform to data.

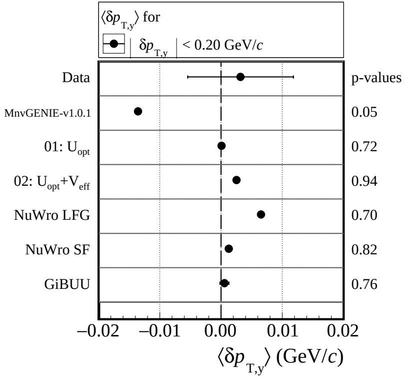
U_{opt} and V_{eff} have small effects.

Undo the 25 MeV removal energy while simulate E_x is by far the most significant.

The take home message:
the adhoc corrections produce more sensible peak positions. We need more careful treatment of the GENIE binding energy.

Model comparisons





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Conclusion

- Extended the Single-TKI measurements to δp_{Tx} and δp_{Ty}.
- Applied corrections to GENIE FSI model.
- Hints of asymmetry in δp_{Tx} not modelled by current generators.
- δp_{Ty} implies binding energy needs better treatment.

The Single-TKI variables can be measured for other elements such as Argon, providing constraints on nuclear effects such as the binding energy for current and future experiments.

Future MINERνA measurements of the Single-TKI variables in the high-statistics ME samples will further our understanding of nuclear effects and aid in precise nuclear modelling.

Backup

A simple case without FSI

For a bound nucleon scattering without FSI:

$$\begin{pmatrix} E_\nu \\ 0 \\ 0 \\ p_\nu \end{pmatrix} + \begin{pmatrix} M_N - \epsilon^N \\ k_x \\ k_y \\ k_z \end{pmatrix} = \begin{pmatrix} E_{l'} \\ 0 \\ p_{l'y} \\ p_{l'z} \end{pmatrix} + \begin{pmatrix} E_p \\ p_{px} \\ p_{py} \\ p_{pz} \end{pmatrix} \tag{1}$$

and rearranging:

$$\begin{pmatrix} \nu \\ 0 \\ q_T \\ q_l \end{pmatrix} + \begin{pmatrix} M_N - \epsilon^N \\ k_x \\ k_y \\ k_z \end{pmatrix} = \begin{pmatrix} E_p \\ p_{px} = \delta p_{Tx} \\ q_T + \delta p_{Ty} \\ p_{pz} \end{pmatrix} \tag{2}$$

δp_{Tx} is precisely the measure of Fermi motion, while the effects of ϵ occurs in y and z axis only.

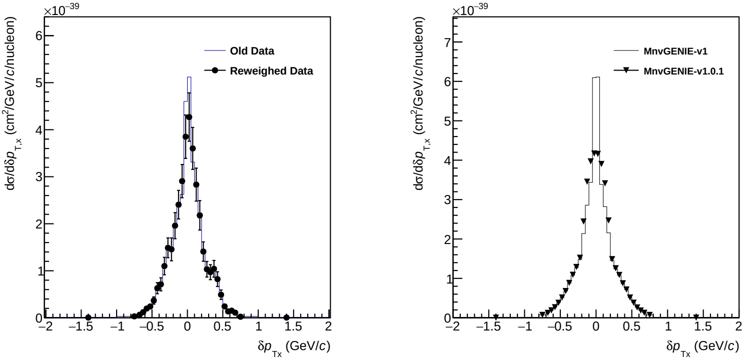


Figure: δp_{Tx}, data on the left, MC on the right. Elastic FSI preferentially produce nucleons close to the reaction plane, therefore producing an unphysical peak near 0. The updated MC does not experience the bug and therefore produces a smoother distribution. There is a corresponding reduction in the peak in data as a result of increased MC efficiencies at the peak

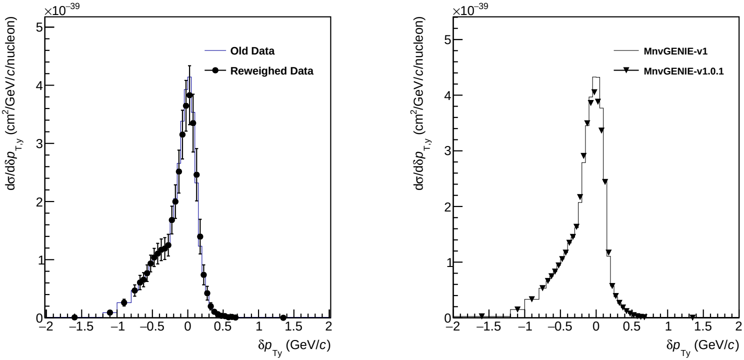


Figure: δp_{Ty}

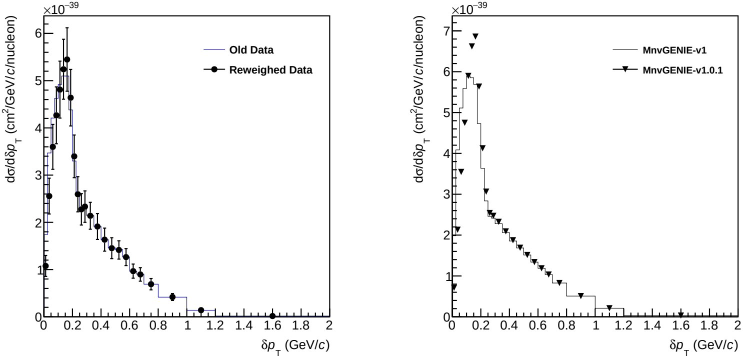


Figure: δp_{T}

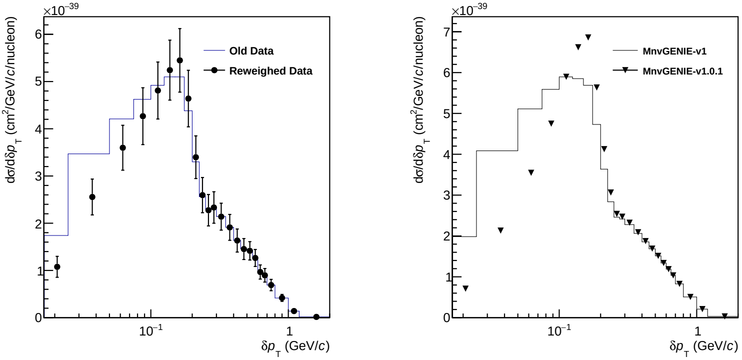


Figure: δp_{T}

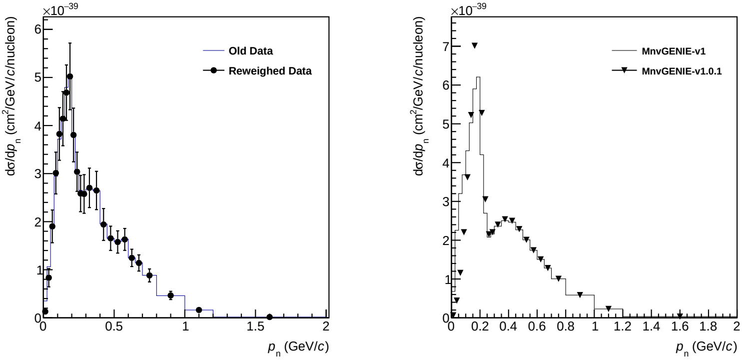
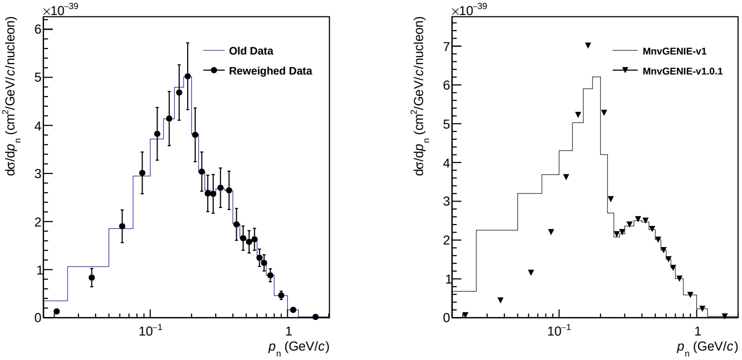


Figure: p_{n}



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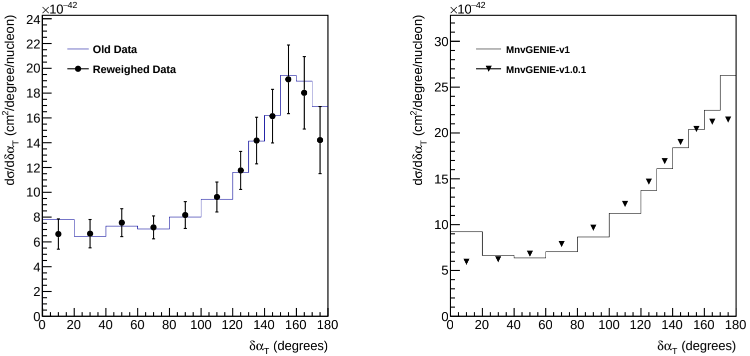


Figure: $\delta\alpha_{\mathrm{T}}$

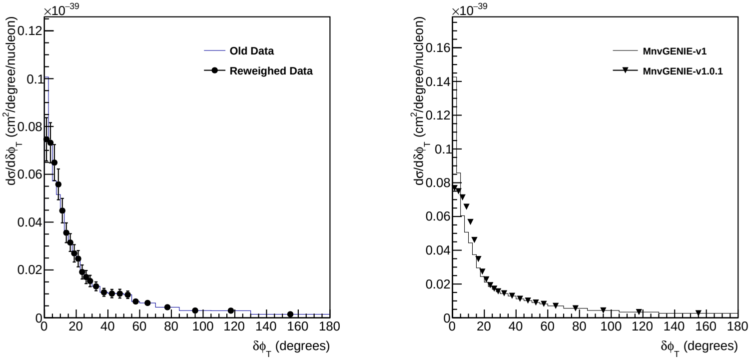


Figure: $\delta\phi_{\mathrm{T}}$

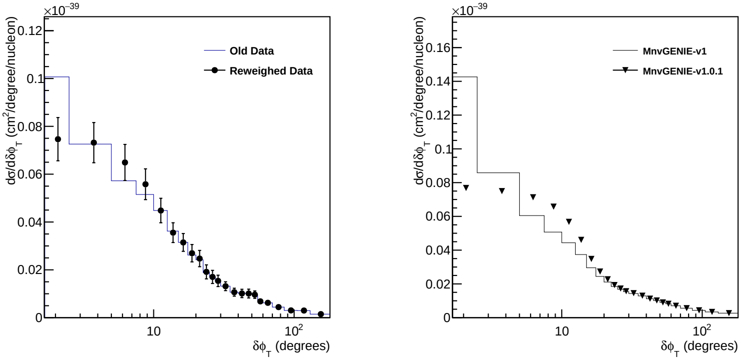
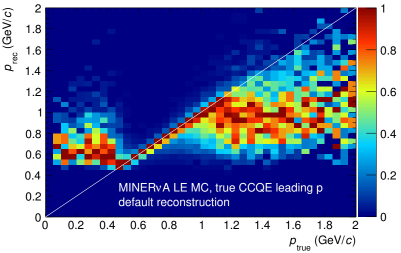
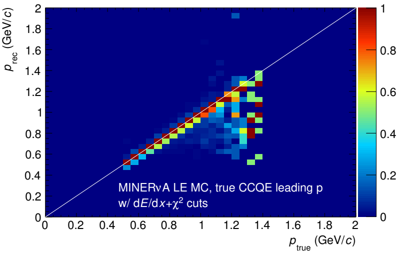
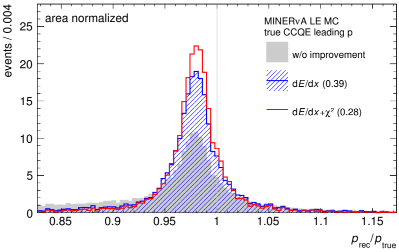


Figure: $\delta\phi_{\mathrm{T}}$

Event Selection







- Low Energy Neutrino datasets, 3.28×10^{20} proton on target.
- Proton dE/dX and χ^2 cuts performed to select protons with well reconstructed momentum

Correction to GENIE

GENIE:

$$\nu_{GENIE} = \sqrt{M_p^2 + (\boldsymbol{k} + \boldsymbol{q})^2} + \frac{\boldsymbol{k}^2}{2M_{A-1}} - M_p + S^p \tag{3}$$

The corrected:

$$\nu_{corr} = \sqrt{M_p^2 + (\boldsymbol{k} + \boldsymbol{q})^2} - |U_{\mathrm{opt}}| + \frac{\boldsymbol{k}^2}{2M_{A-1}^*} - M_p + S^p + E_x \tag{4}$$

We have:

$$\nu_{corr} = \nu_{GENIE} - |U_{\mathrm{opt}}| + E_x \tag{5}$$

$$E_\mu^{GENIE} = E_\mu^{corr} - |U_{\mathrm{opt}}| + E_x \tag{6}$$

$$E_\mu^{corr} = E_\mu^{GENIE} + |U_{\mathrm{opt}}| - E_x \tag{7}$$

Correction to GENIE

Hadronic Side:

$$E_p^{GENIE} = E\prime_p^{GENIE} - \Delta(25) \tag{8}$$

$$E\prime_p^{GENIE} = \sqrt{M_p^2 + (\boldsymbol{k} + \boldsymbol{q})^2} \tag{9}$$

$$E_p^{corr} = E\prime_p^{GENIE} - |U_{\mathrm{opt}}| = E_p^{GENIE} + \Delta - |U_{\mathrm{opt}}| \tag{10}$$

In the case of GENIE we need to put $\Delta = 25$ to the generated proton.