Transverse Kinematic Imbalance in MINERνA: Past, Present, and Future

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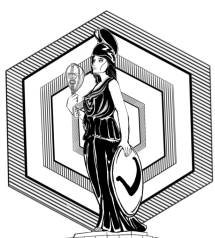
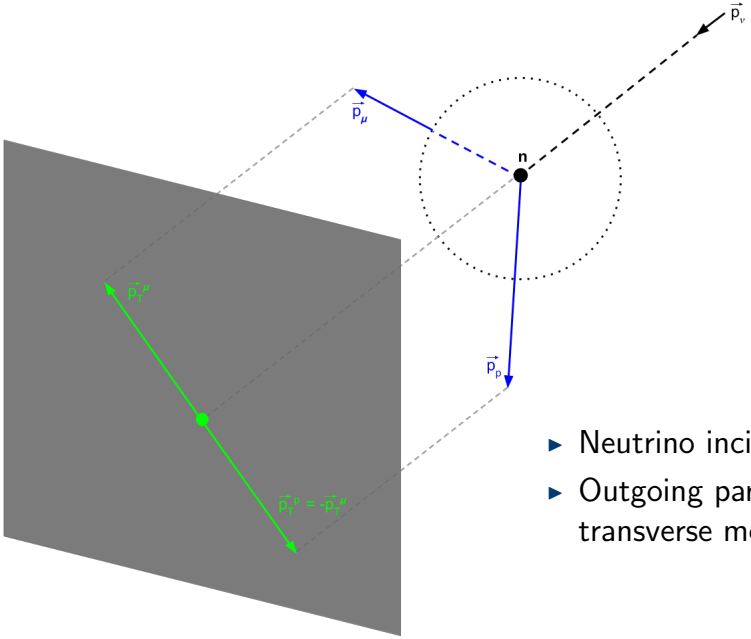


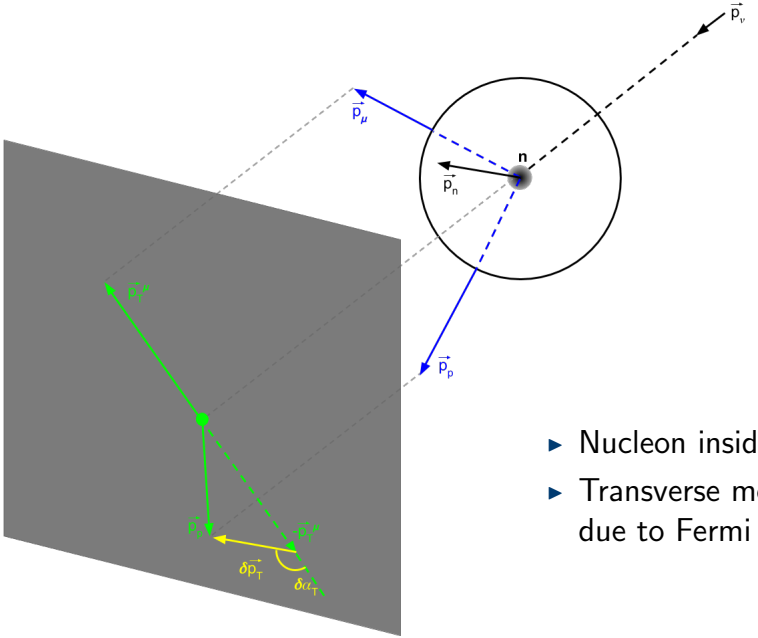
What I'm going to tell you

- Past
  - Introduction to transverse kinematic imbalance
  - MINERvA: Phys.Rev.Lett. 121 (2018) 022504
  - T2K: Phys. Rev. D 98, 032003 (2018)
  - Technique: Phys. Rev. C 94, 015503 (2016)
- Present
  - Probing GENIE's implementation of nuclear binding energy using transverse kinematic imbalance in MINERvA
  - Motivated by: https://arxiv.org/pdf/1801.07975.pdf
- Future
  - Utilizing transverse kinematic imbalance in other MINERvA analyses

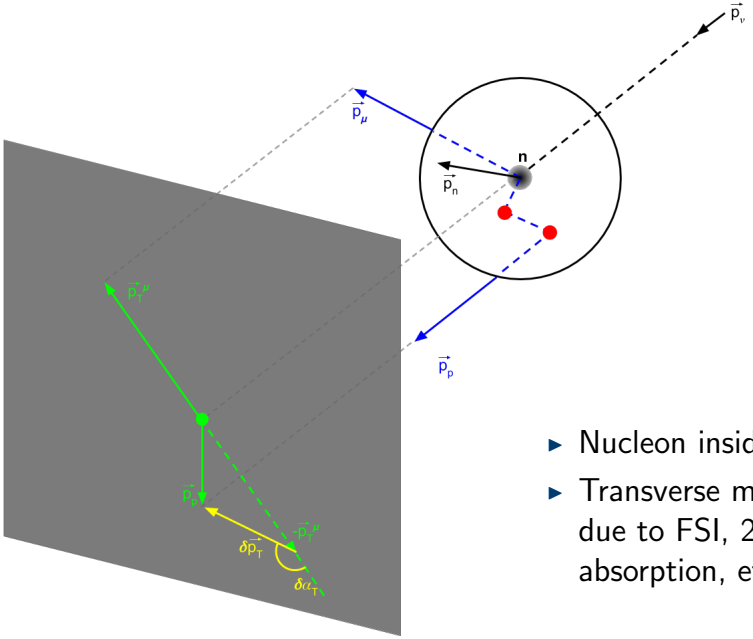
Past



- Neutrino incident on free nucleon
- Outgoing particles conserve transverse momentum

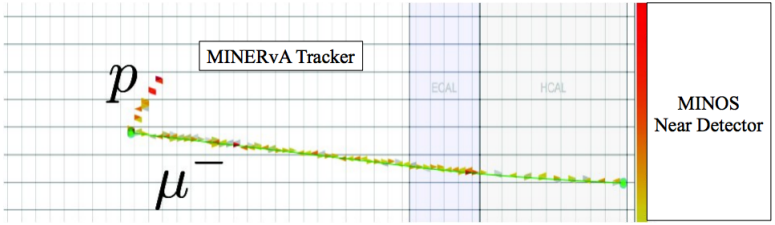


- Nucleon inside the nucleus
- Transverse momentum imbalance due to Fermi motion

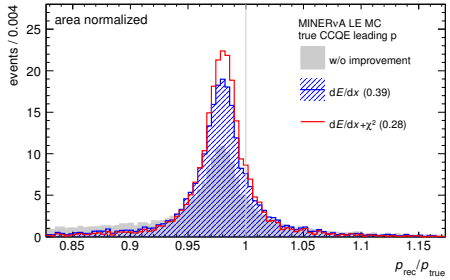


- Nucleon inside the nucleus
- Transverse momentum imbalance due to FSI, 2p2h, pion absorption, etc.

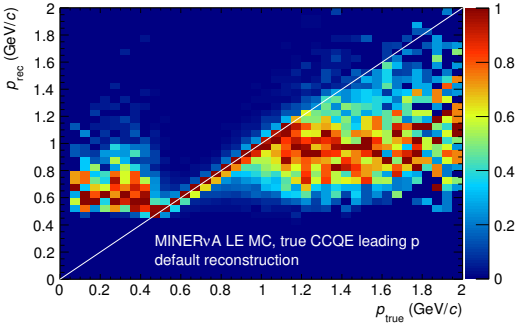
Analysis: MINERvA CC0π in 'Low Energy'

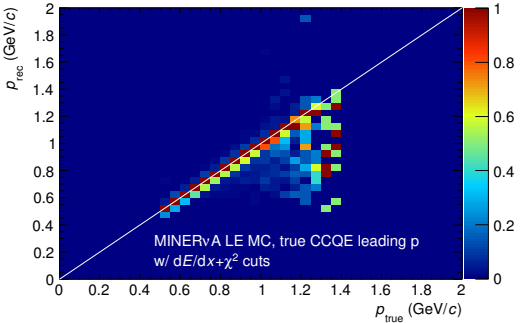


- Signal: $0\pi, 1\mu, \geq 1p$ satisfying
  - $1.5 GeV/c < p_\mu < 10.0 GeV/c, \theta_\mu < 20^\circ$
  - $0.45 GeV/c < p_p < 1.2 GeV/c, \theta_p < 70^\circ$
- 'Low Energy', FHC (ν-enhanced) configuration of NuMI: peaked at 3GeV
- Phys.Rev.Lett. 121 (2018) 022504



- Elastically Scattered Contained proton selection:
  - Cut efficiency $\sim$ 40%
  - Reconstructed momentum spread much reduced 0.7 - 1.1 GeV, resolution 3% $\sim$ 2%
  - 5-10% uncertainty in efficiency
- Clean-up cuts to improve proton and muon momentum resolution

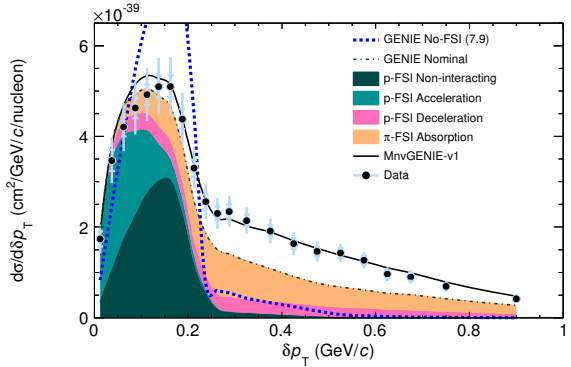


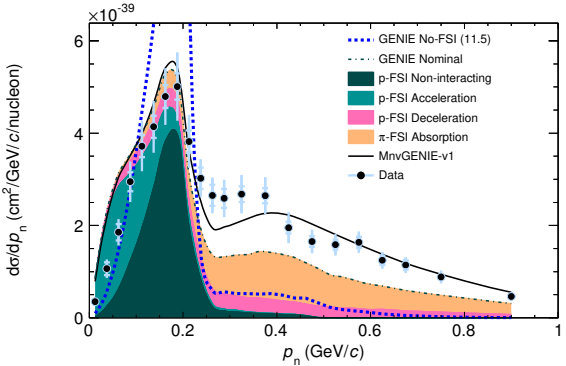


[Phys.Rev.Lett. 121 (2018) 022504]

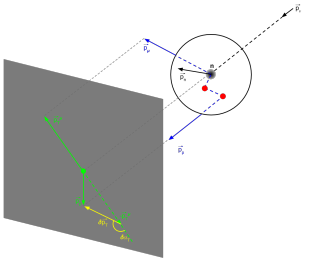
- Nominal GENIE: version 2.8.4
  - global Fermi Gas (RFG) model with Bodek-Ritchie (BR) tail [Phys. Rev. D 23, 1070 (1981)]
  - hA FSI [AIP Conf.Proc. 1405 (2011) 213-218]
- MnvGENIE-v1: GENIE MINERvA Tune (v1)
  - Added Random Phase Approximation (RPA) [Phys.Rev. C70 (2004) 055503]
  - Non-resonance pion production scaled down by 75% [Phys.Rev. D90 (2014) no.11, 112017]
  - Valencia 2p2h [Nieves et al., Phys.Lett. B707 (2012) 72-75, Phys. Rev. C 86, 015504 (2012), Phys.Rev. D88 (2013) no.11,113007, arXiv:1601.02038]
  - Tuned to MINERvA inclusive data $\rightarrow$ significant enhancement in small 4-momentum transfer region [Phys.Rev.Lett. 116 (2016) 071802]

See X. Lu's talk for complete details of MINERvA tune

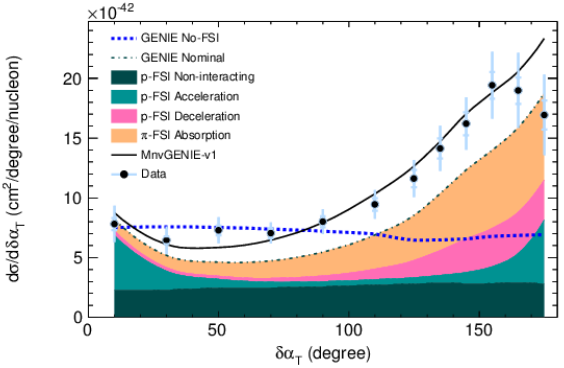




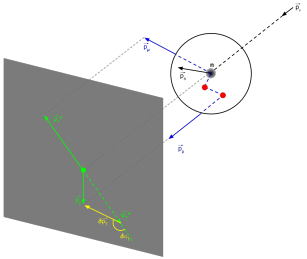
- $p_n \equiv \sqrt{\delta p_T^2 + \delta p_L^2}$
- Both effectively probe different sources of Final State Interactions
- Discrepancies with simulation are evident



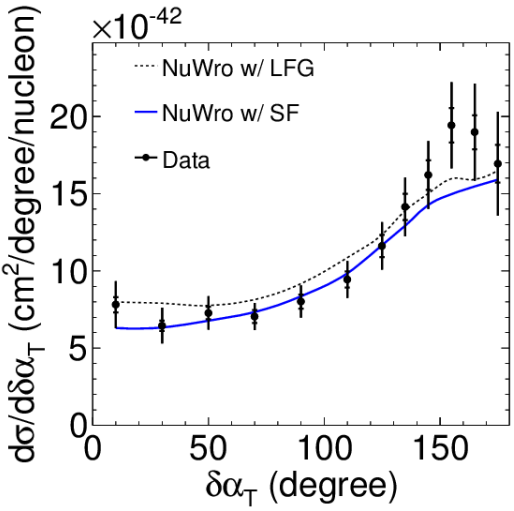
[Phys.Rev.Lett. 121 (2018) 022504]

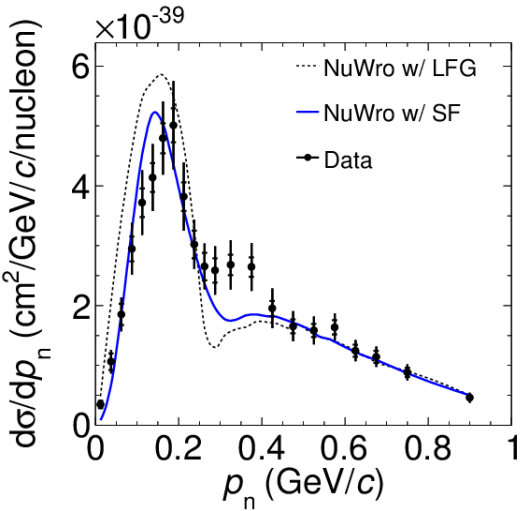


- The effect of Fermi motion has no shape as a function of $\delta\alpha_T$
- Shape reveals the effect of FSI, 2p2h, pion absorption, etc.



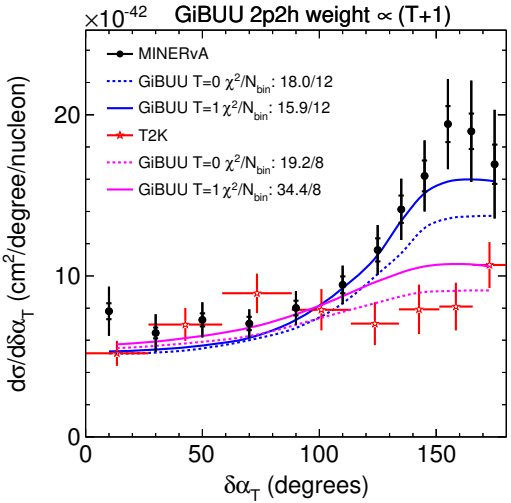
[Phys.Rev.Lett. 121 (2018) 022504]





- Data prefer NuWro's Spectral function over its local Fermi gas model
- Lacking strength in the resonant, 2p2h region

[Phys.Rev.Lett. 121 (2018) 022504]

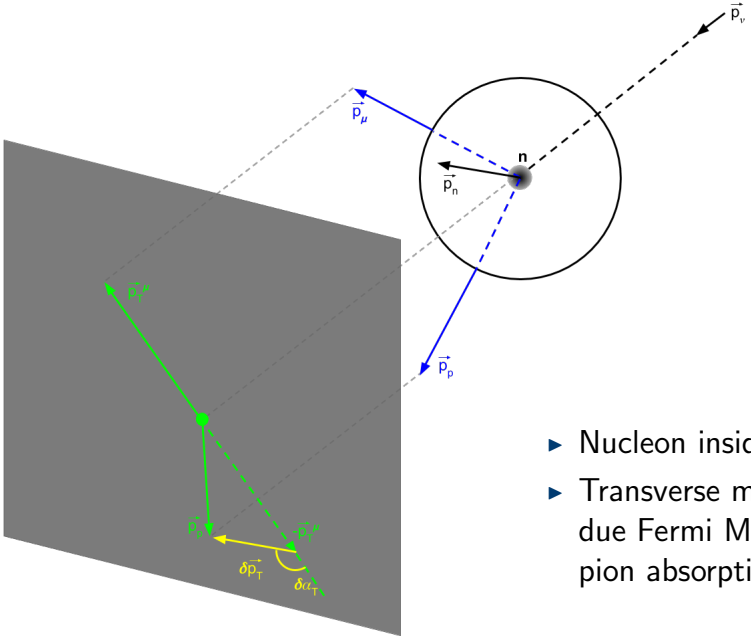


- T parameterizes 2p2h in GiBUU; T=0 is the proper theory because carbon is isoscalar
- T=1 has twice the 2p2h contribution as T=0; the difference between the curves is comparable for MINERvA and T2K predictions
- π production is more significant at MINERvA energies ($E_\nu \sim 3GeV$) than at T2K energies ($E_\nu \sim 0.6GeV$)
- For $T = 0$ to describe both data, GiBUU resonance at MINERvA must be even stronger

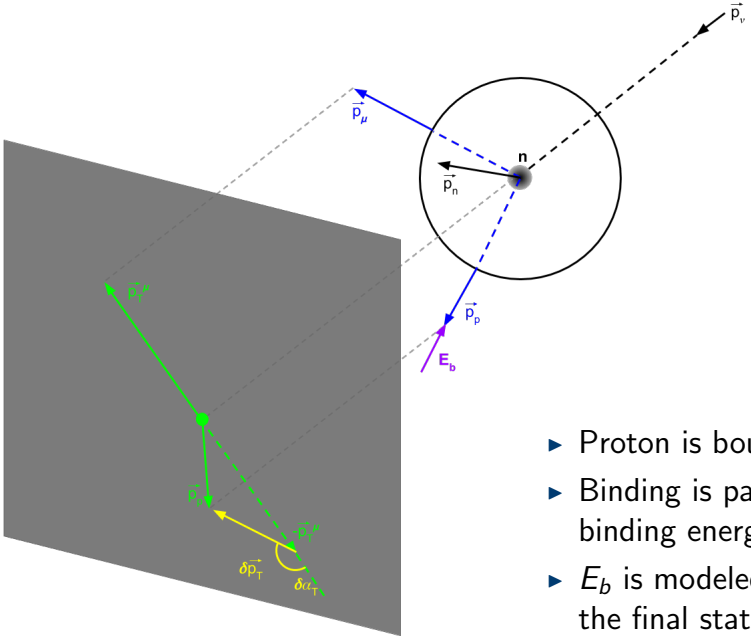
[Phys.Rev.Lett. 121 (2018) 022504, Phys. Rev. D 98, 032003 (2018), see also S. Dolan et al. arXiv:1804.09488]

Present: Binding Energy

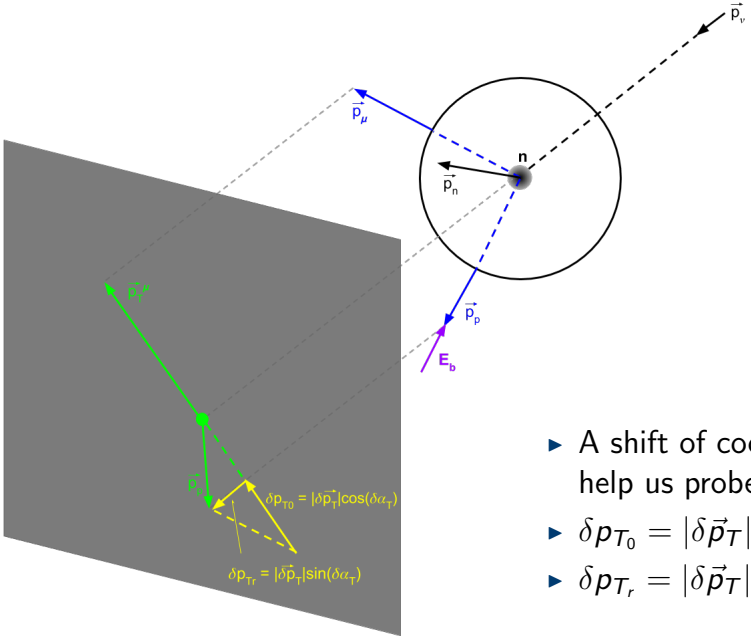
- Prediction from Arie Bodek that GENIE mis-models the nuclear binding energy [arXiv:1801.07975]
- Specifically, the separation energy is double-counted
- This analysis recommends E_b for C of 10.1 MeV, and 10.0 MeV, for ν, and $\bar{\nu}$, respectively (table 8 of paper)
- Are we sensitive to a potential mis-modeling of the binding energy?
- We investigate using transverse kinematic imbalance



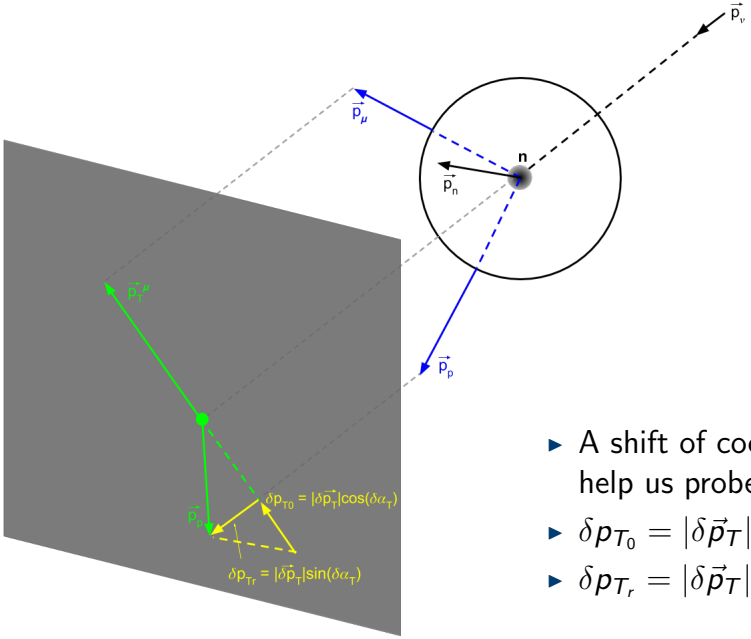
- Nucleon inside the nucleus
- Transverse momentum imbalance due Fermi Motion, FSI, 2p2h, pion absorption, etc.



- Proton is bound in the nucleus
- Binding is parameterized by binding energy, E_b
- E_b is modeled as a subtraction of the final state proton momentum



- A shift of coordinate system can help us probe E_b
- $\delta p_{T_0} = |\delta\vec{p}_T| sin(\delta\alpha_T)$
- $\delta p_{T_r} = |\delta\vec{p}_T| cos(\delta\alpha_T)$



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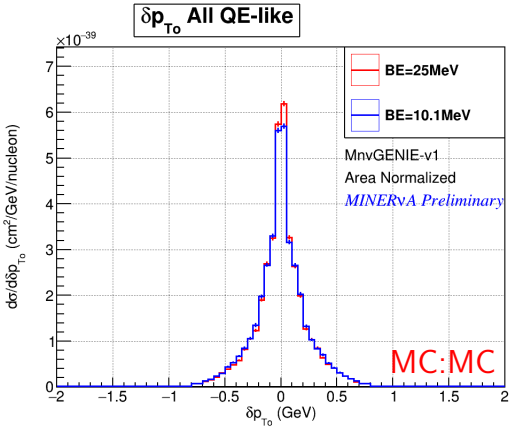
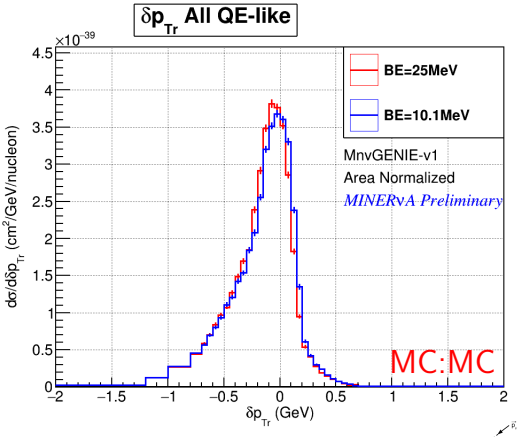
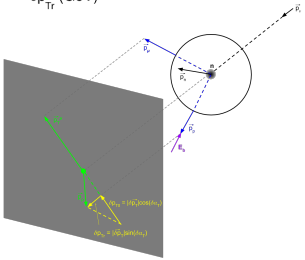
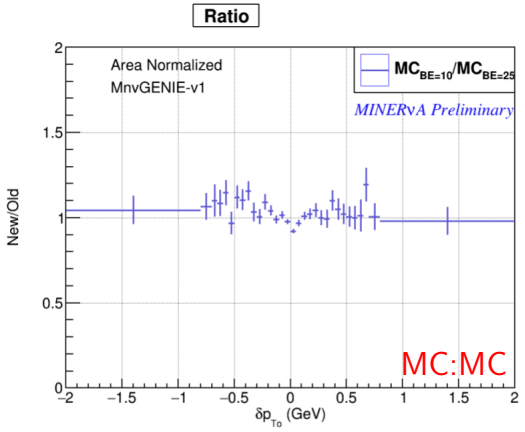
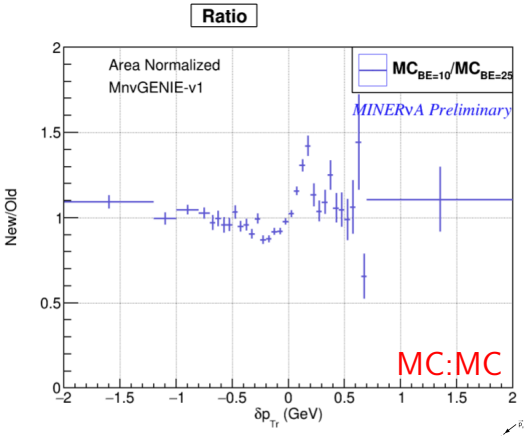




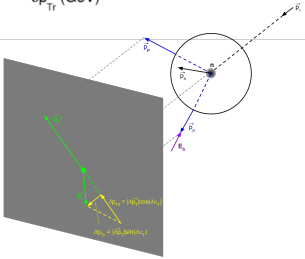
- δp_{T_0} and δp_{T_r} are sensitive to changes of E_b in GENIE
- GENIE uses $E_b = 25$ MeV by default

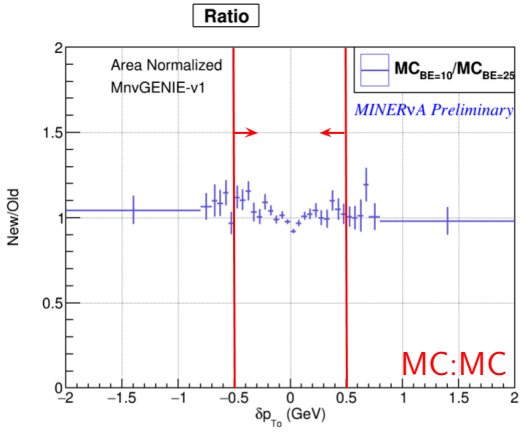


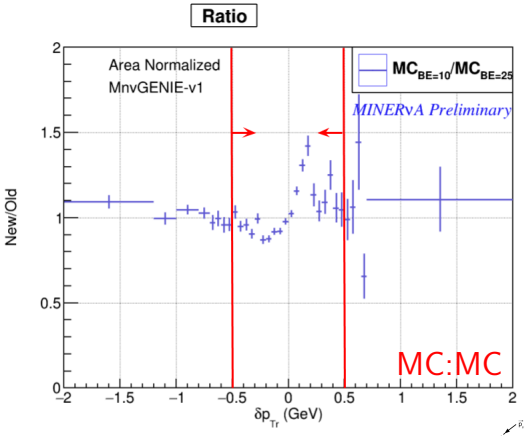




- δp_{T_r} probes changes to E_b with good resolution
- δp_{T_0} not so much







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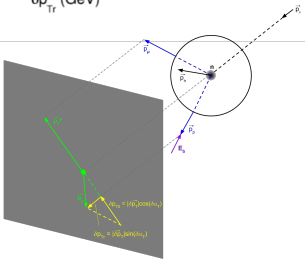
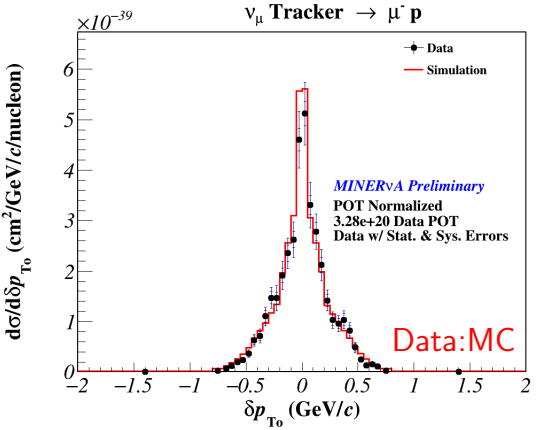
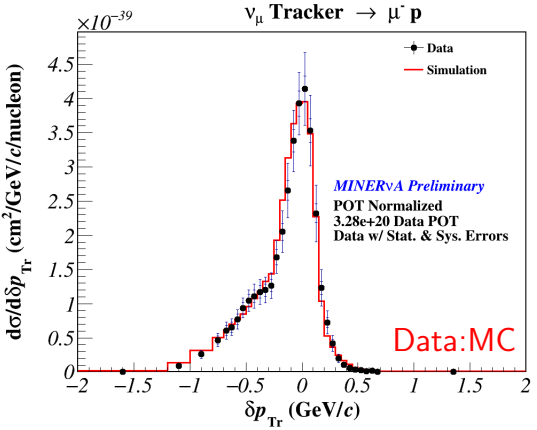
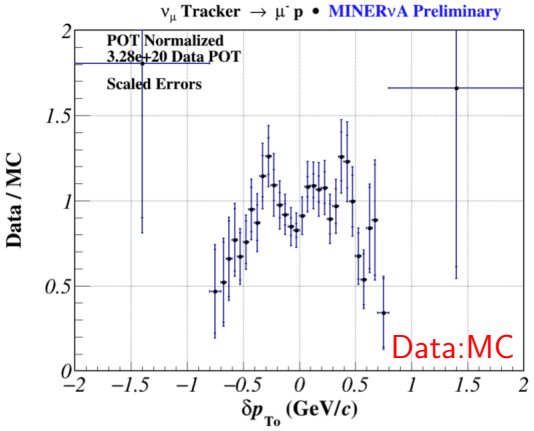
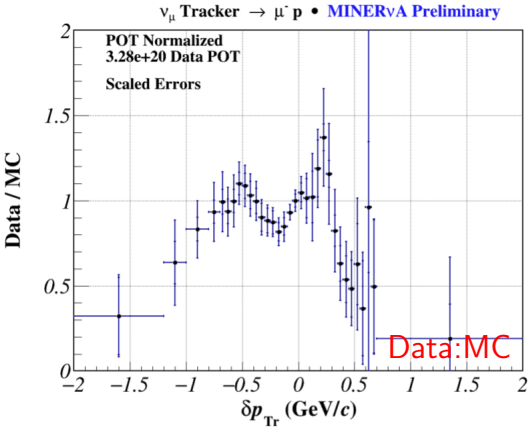




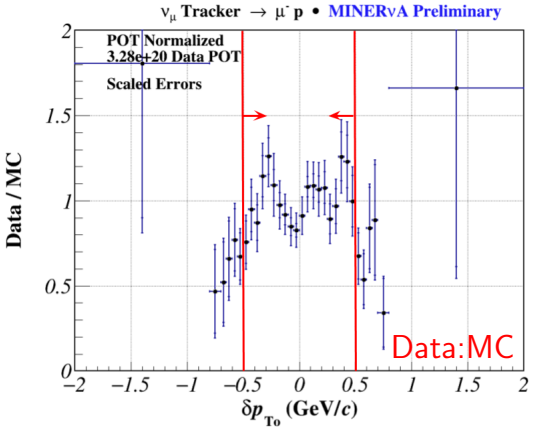


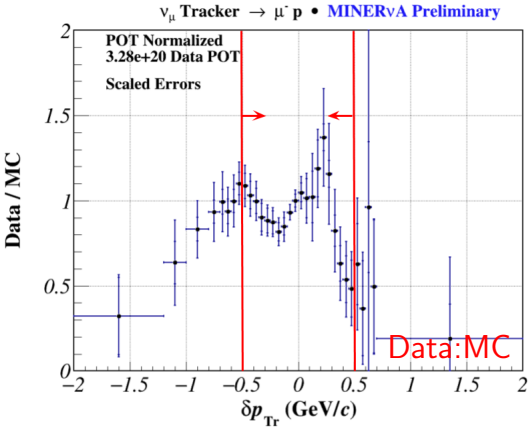
- We refactor the existing analysis using δp_{T_0} and δp_{T_r}
- Is there evidence that E_b is mis-modeled?





- The effect of modifying E_b is concentrated in the region $-0.5 \lesssim \delta p_{T_r}, \delta p_{T_0} \lesssim 0.5$
- It seems like we're on the right track





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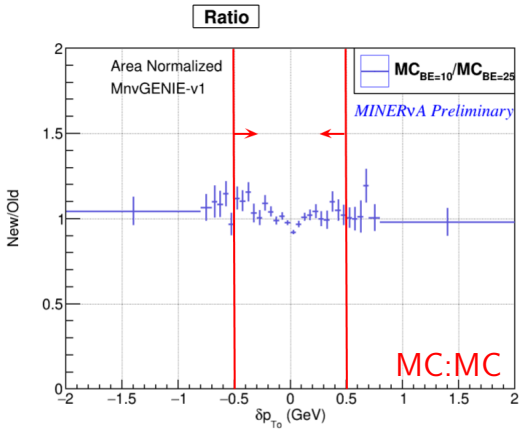
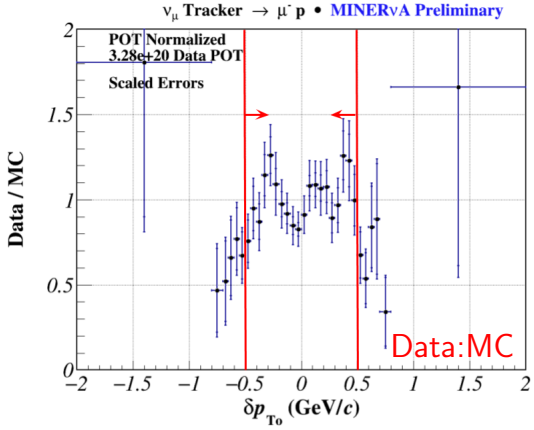
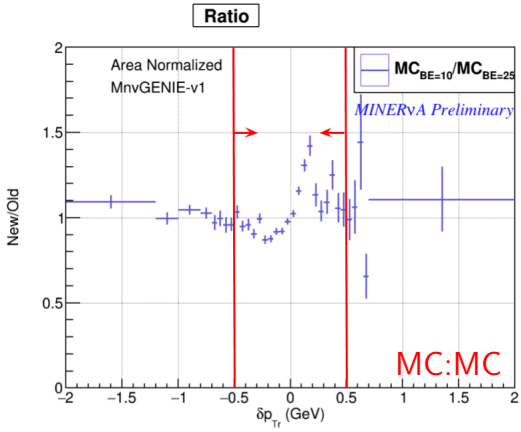
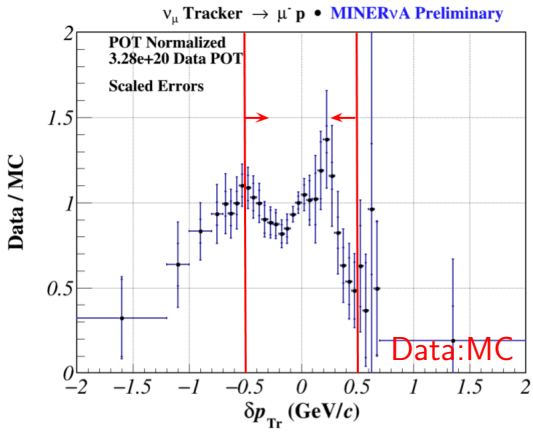




- Remember, this is the *insensitive* variable

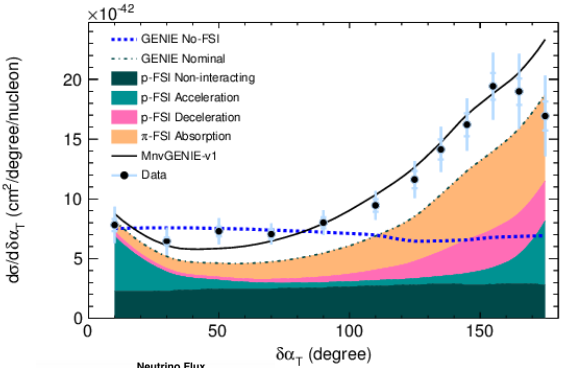




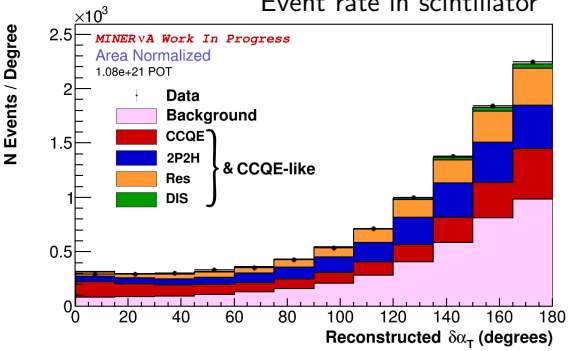
- Similar shift in peak position; same order of magnitude
- Investigation is ongoing

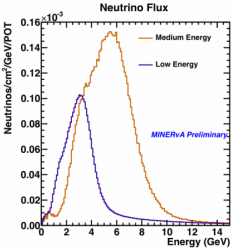
Future

Analysis: MINERvA CC0π in 'Medium Energy'

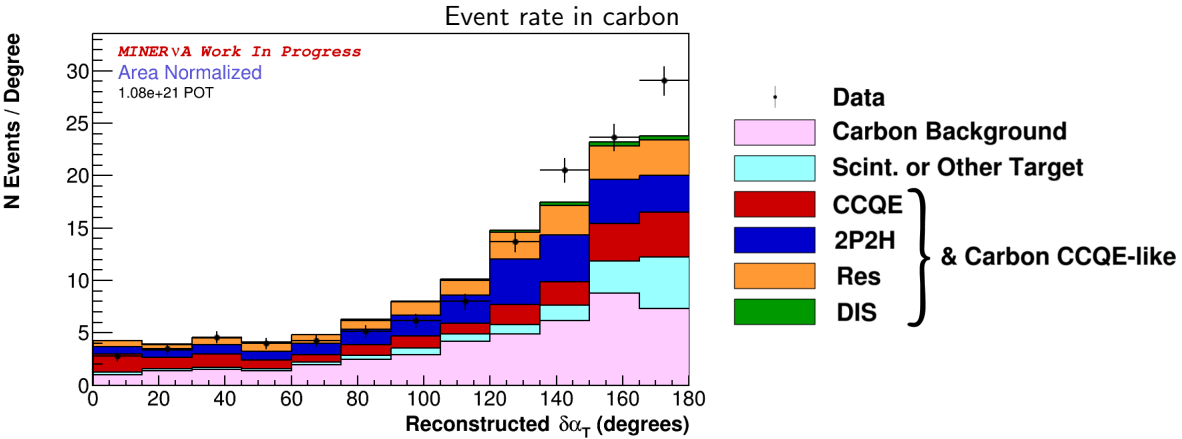


Event rate in scintillator

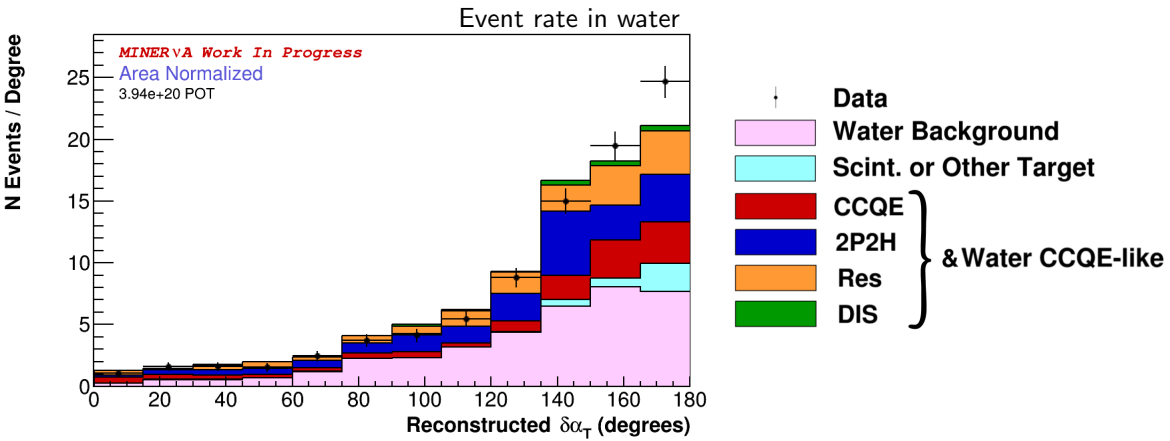




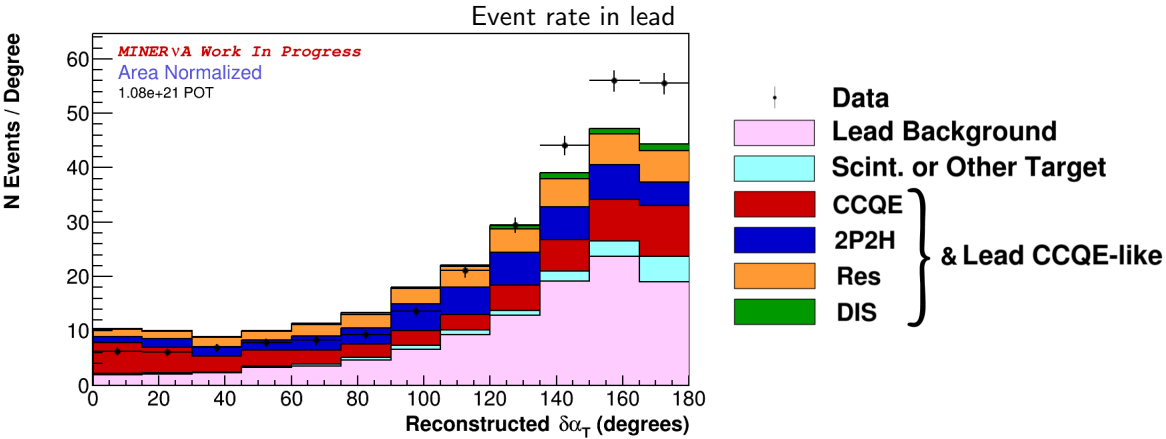
- 'Medium Energy' beam has higher peak $E\nu$
- Reconstruction of transverse kinematic imbalance convolutes detector effects and nuclear effects
- Modified proton cuts to better correspond to detector acceptance to reduce model dependance



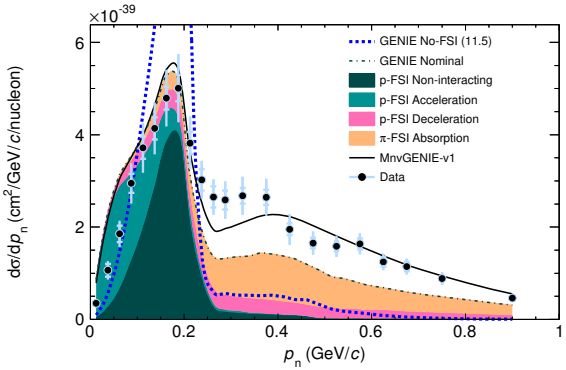
- 'Carbon background' = non-CCQE-like interactions on carbon



- This selection now requires a proton, and therefore has a higher average Q^2, which corresponds to increased background contamination



- See J. Kleykamp's presentation for details of this analysis



- p_n can be interpreted as the initial state neutron momentum, but also as the final state nuclear remnant
- This interpretation can be further explored using our low recoil analysis
- Stay tuned to hear more about this from Xianguo...

Conclusions

- Past
  - We've developed the infrastructure to probe nuclear effects using transverse kinematic imbalance
  - Documented in: Phys.Rev.Lett. 121 (2018) 022504
- Present
  - The current investigation into using this method to probe nuclear binding energy is promising
  - Motivated by: https://arxiv.org/pdf/1801.07975.pdf
- Future
  - We'll continue to leverage the power of this method in other MINERvA analyses

This material is based upon work supported by U.S. Department of Energy award DE-SC-0008475

THANK YOU