Measurement of nuclear effects in neutrino interactions with minimal dependence on neutrino energy

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(Dated: November 13, 2015)

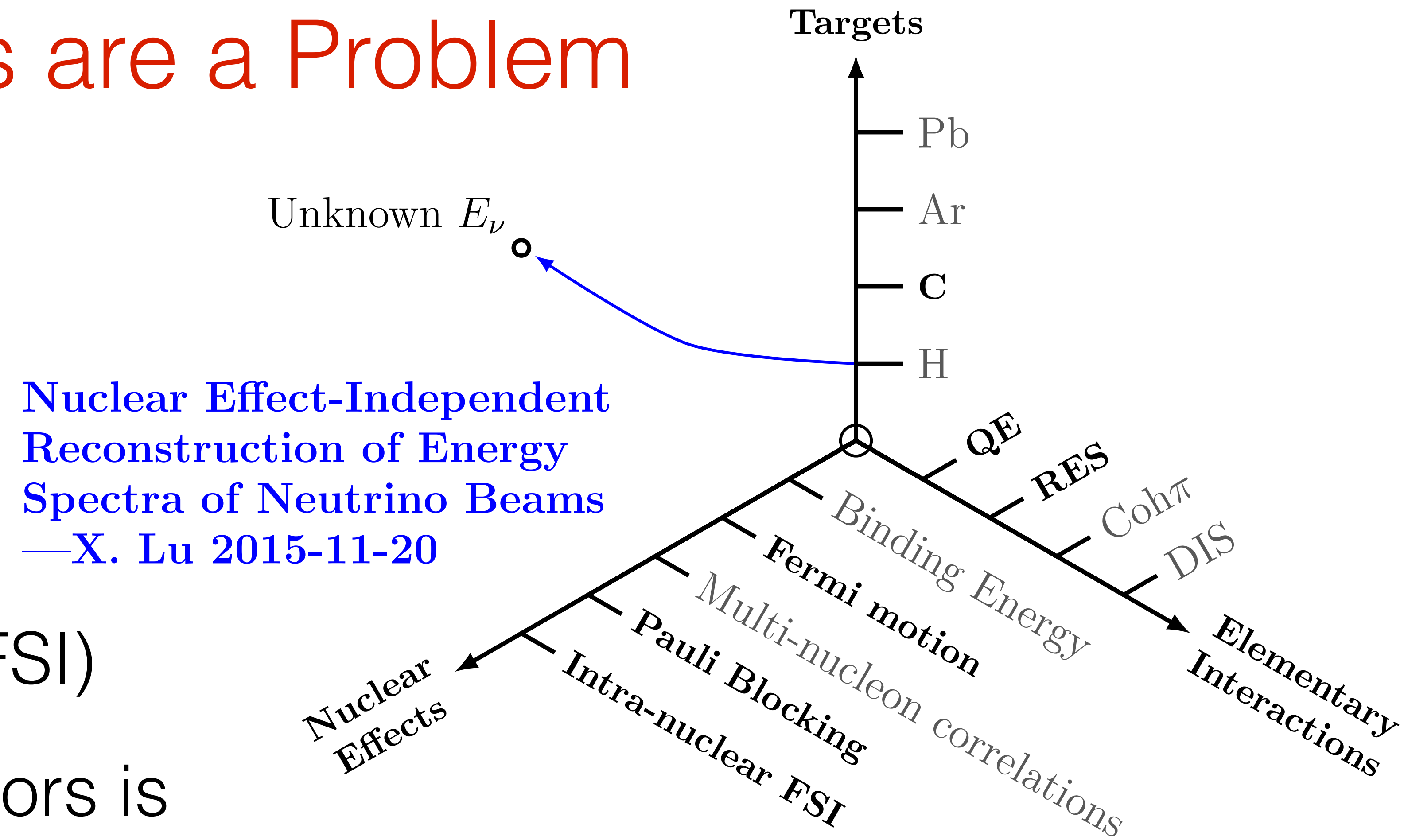
Paper in preparation.

Imperial College London

NuInt2015 Osaka
2015-11-20

Why Nuclear Effects are a Problem

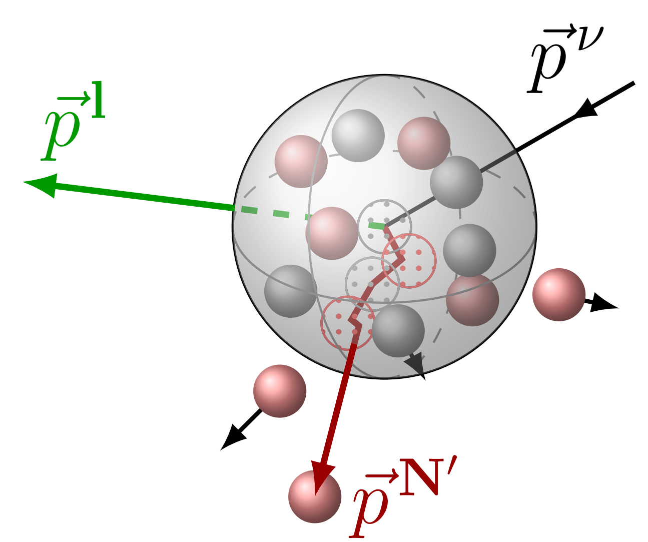
- Want to understand:
  - ➡ Event-by-event neutrino energy
  - ➡ Initial state effects
  - ➡ Final state interactions (FSI)
- What is measured in detectors is not the elementary interaction.



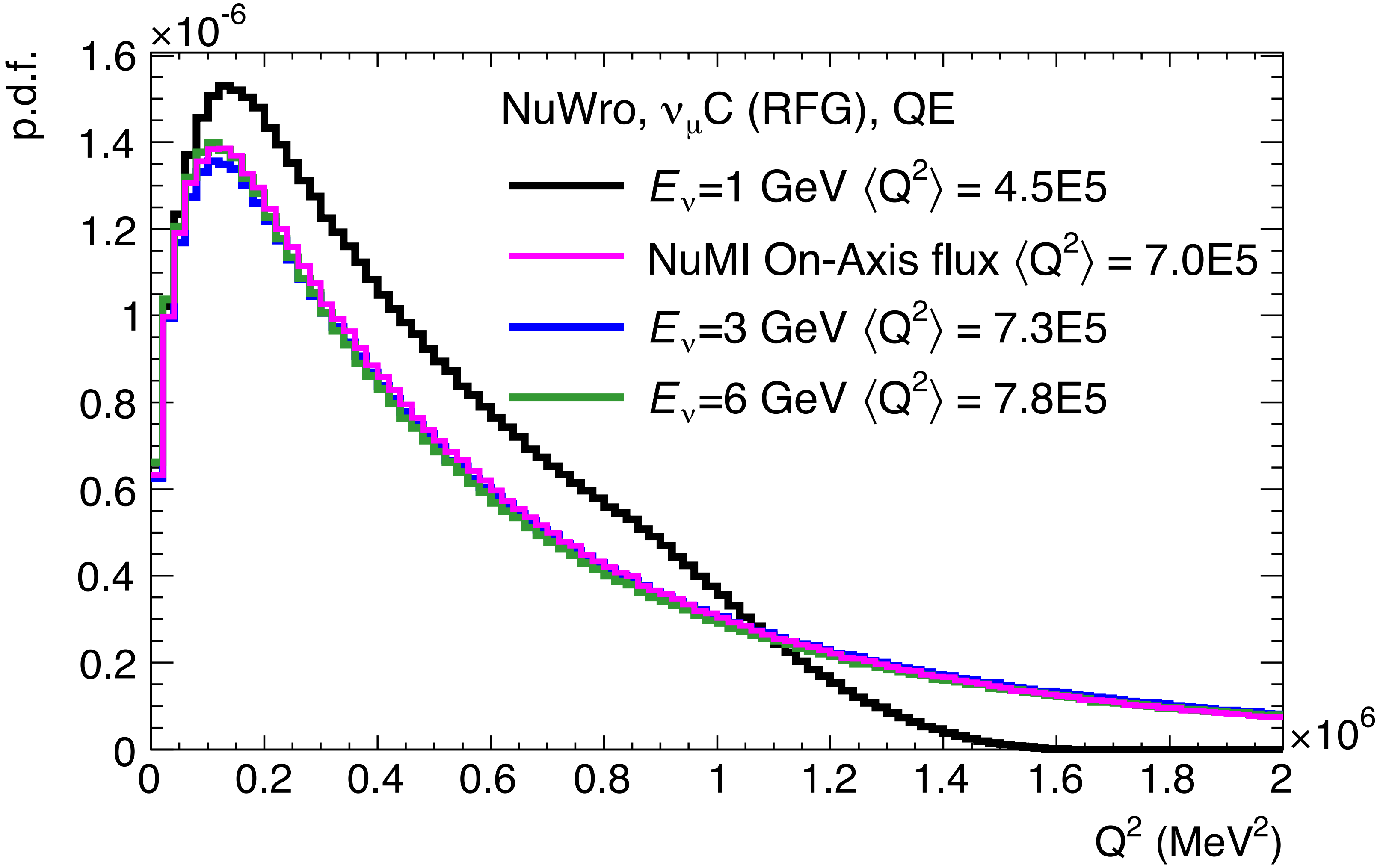
Orthogonal effects exist in all channels, on all targets

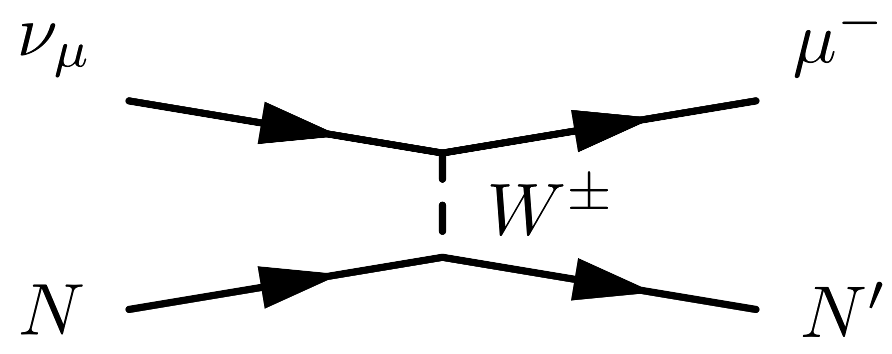
This Talk — A NuWro truth study into:

- ➡ Factorising FSI from neutrino energy.
- ➡ Transverse imbalance in QE and RES interactions.
- ➡ Transverse imbalance in anti neutrino RES interactions.



Minimal Energy dependence in the Elementary Interaction





Elementary Interaction

$$\omega \sim \frac{Q^2 + W^2 - m_{\mathrm{N}}^2}{2\sqrt{m_{\mathrm{N}}^2 + p_{\mathrm{N}}^2}},$$

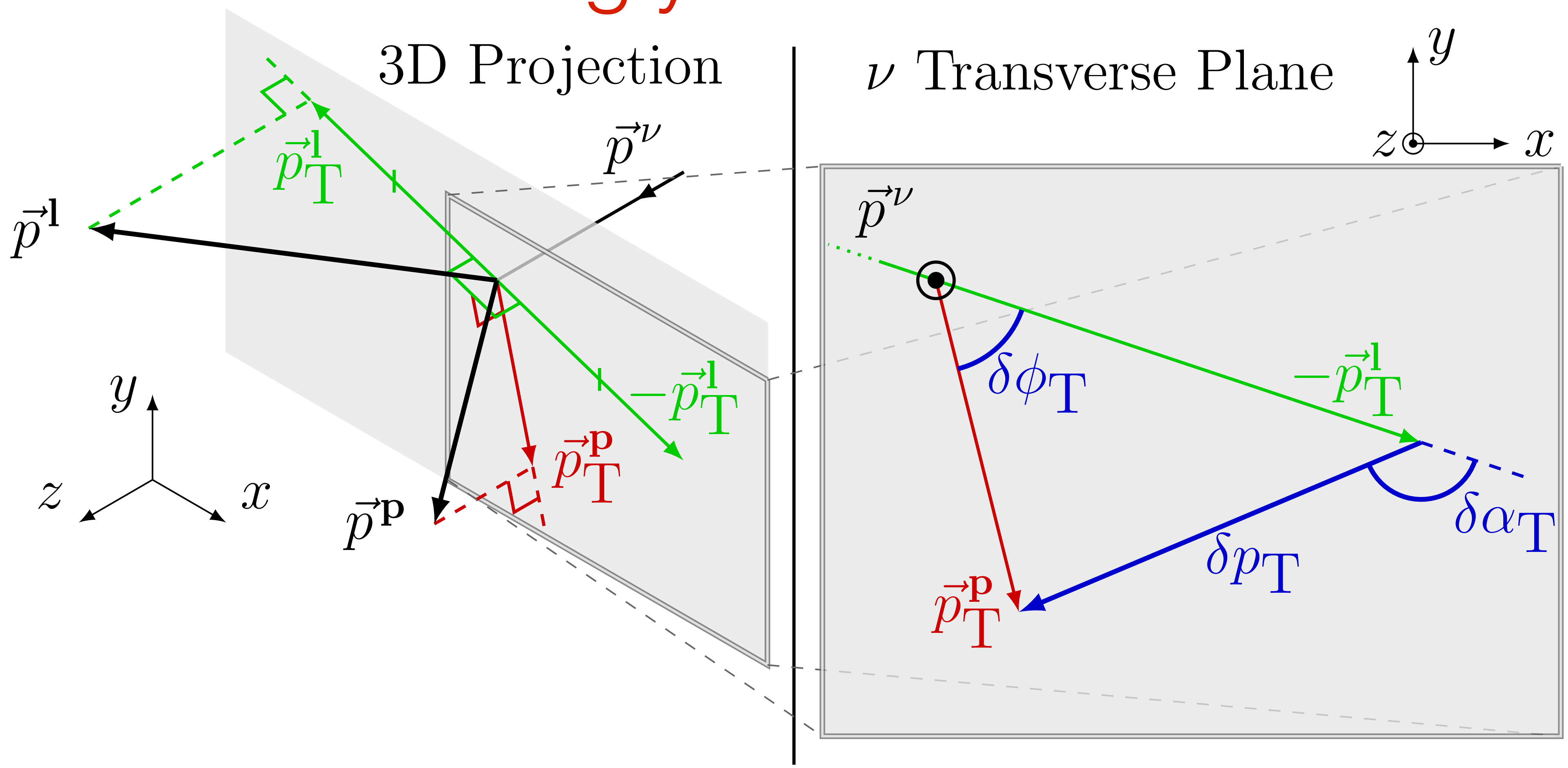
Energy transfer after averaging over p_{N} direction[2]

- For QE and RES interactions, the Q^2 phase space is bounded[1].
- Available hadronic four momentum becomes saturated at higher neutrino energy.
  - ➡ $\boldsymbol{p_{\mathrm{N}'}}$ is less neutrino energy dependent than $\boldsymbol{p_{\mu}}$.
- FSIs are determined by $\boldsymbol{p_{\mathrm{N}'}}$.

[1] C.H. Llewellyn Smith Phys.Rept. 3 (1972) 261-379

[2] Binding energy neglected.

Definition: Singly Transverse Variables



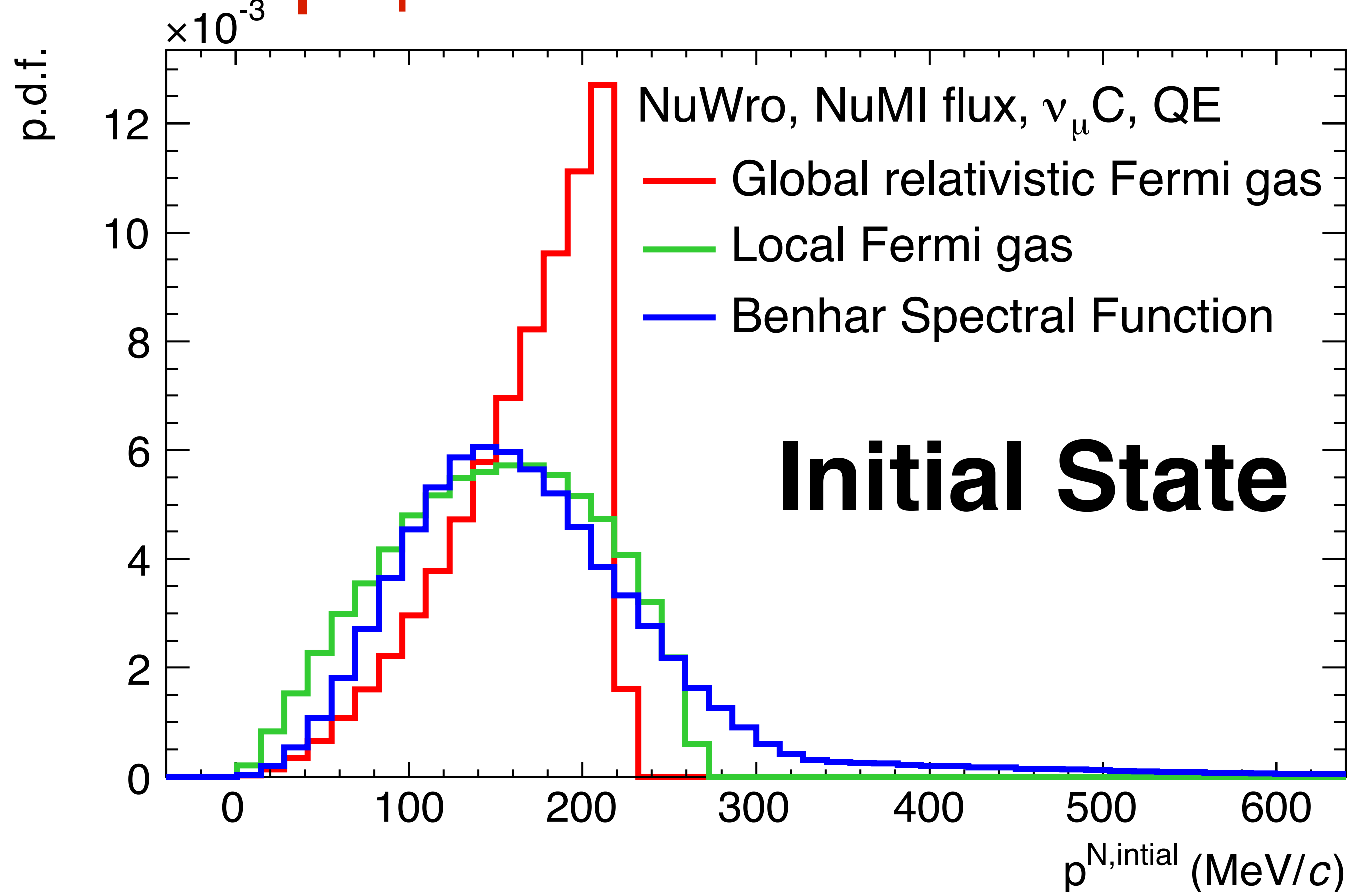
- **δp_T**: The magnitude of the overall observable transverse momentum imbalance.
- **$\delta \alpha_T$**: Characterises a processes as causing an apparent 'acceleration' ($\delta\alpha_T > 90^o$) or 'deceleration' ($\delta\alpha_T < 90^o$) on the proton along an axis defined by the lepton.
- **$\delta \phi_T$**: The angular difference from the lepton and proton being 'back-to-back' in the transverse plane.

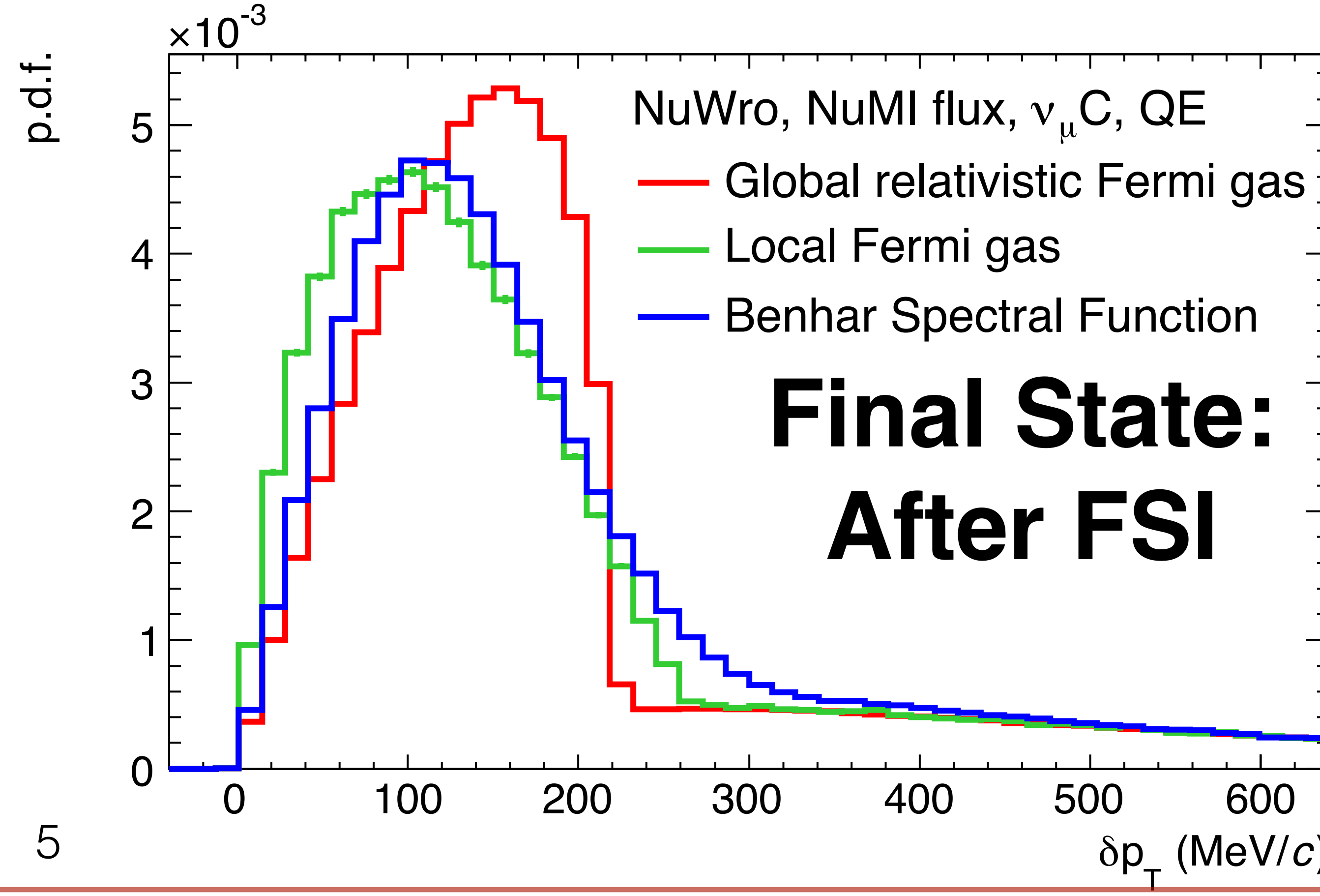
Some previous uses of transverse variables in neutrino physics:

- **MINERvA** (Phys. Rev. D 91, 071301 (2015))
- **T2K INGRID** (Phys. Rev. D. 91, 112002 (2015))
- **NOMAD** (Eur.Phys.J.C63:355-381,2009)

Initial State effect in δp_T Distribution

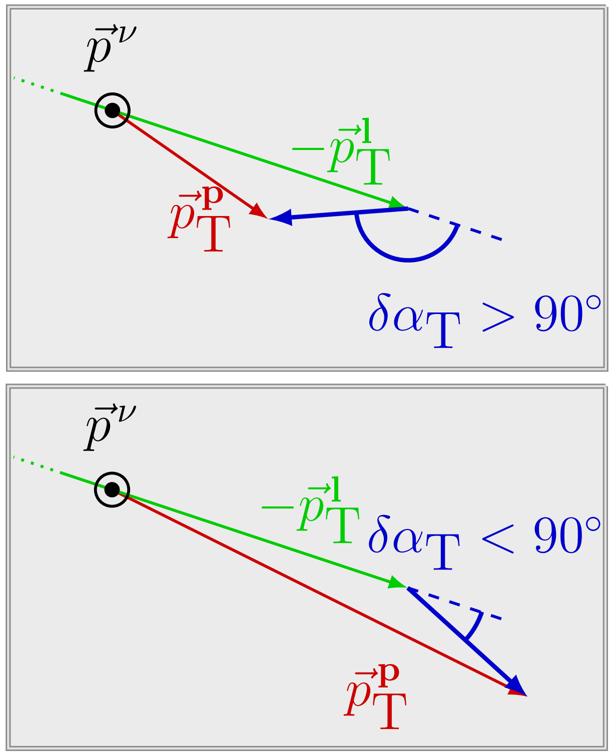
- Low δp_T characterised by weak or no FSI—reflects Fermi motion distribution.
- Peak position and width largely insensitive to the effects of FSI models because of low event-by-event FSI probability[1].
- High δp_T determined by the FSI model.



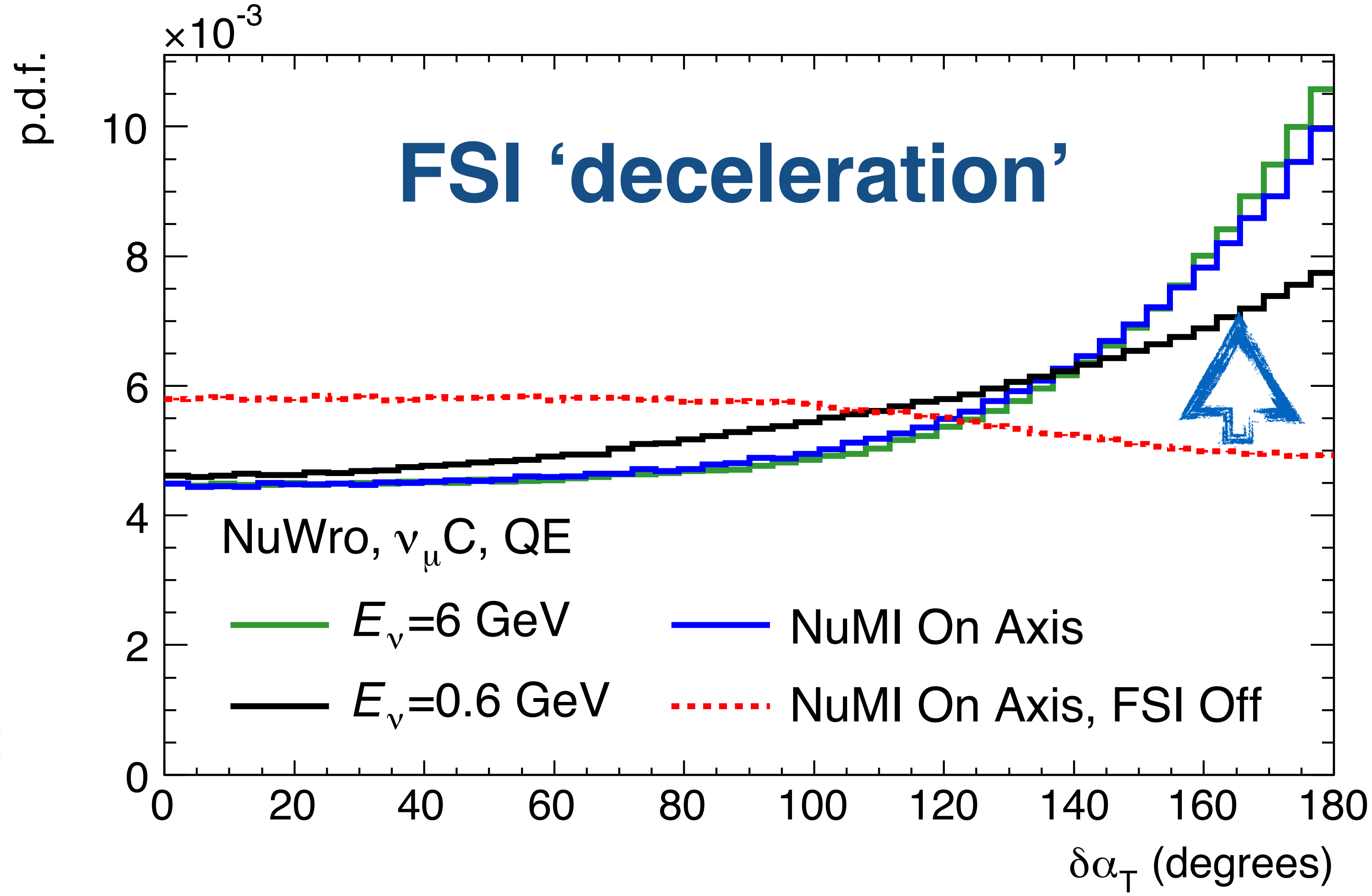


[1] Average FSI probability: NuWro RFG QE: 0.25

$\delta\alpha_T$: Accelerating or Decelerating

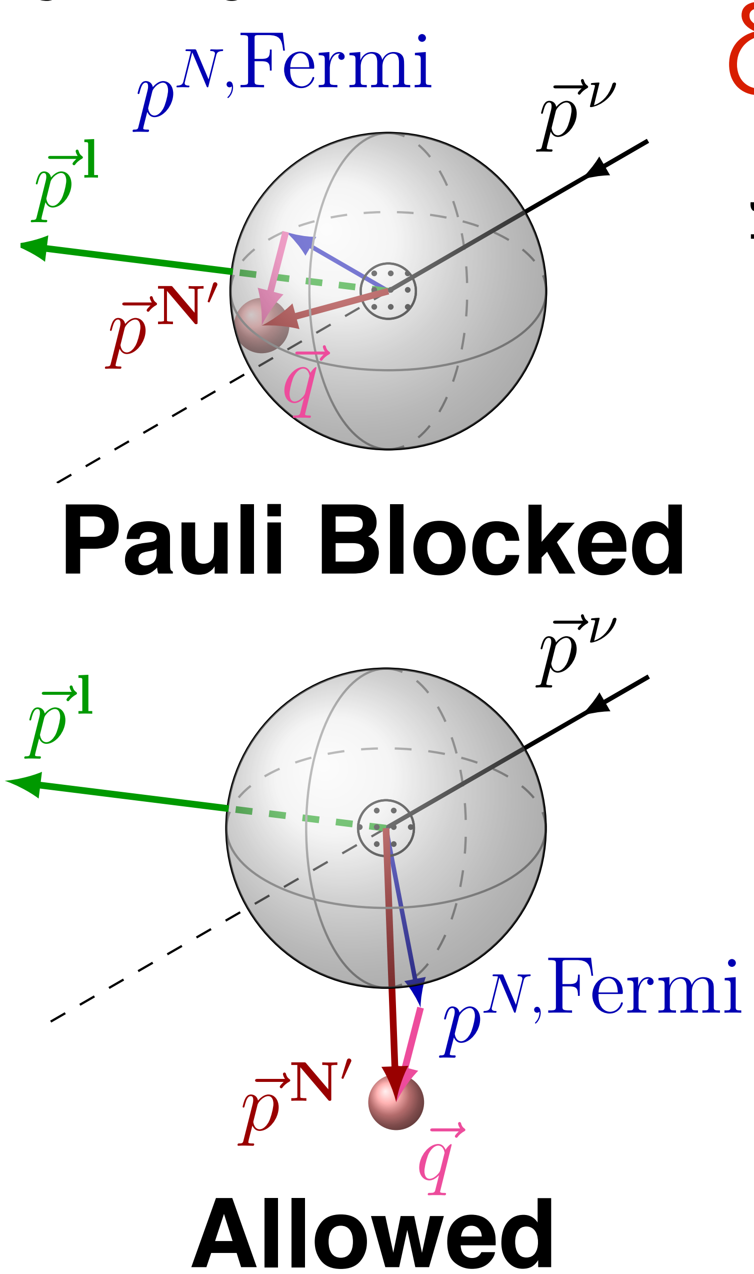


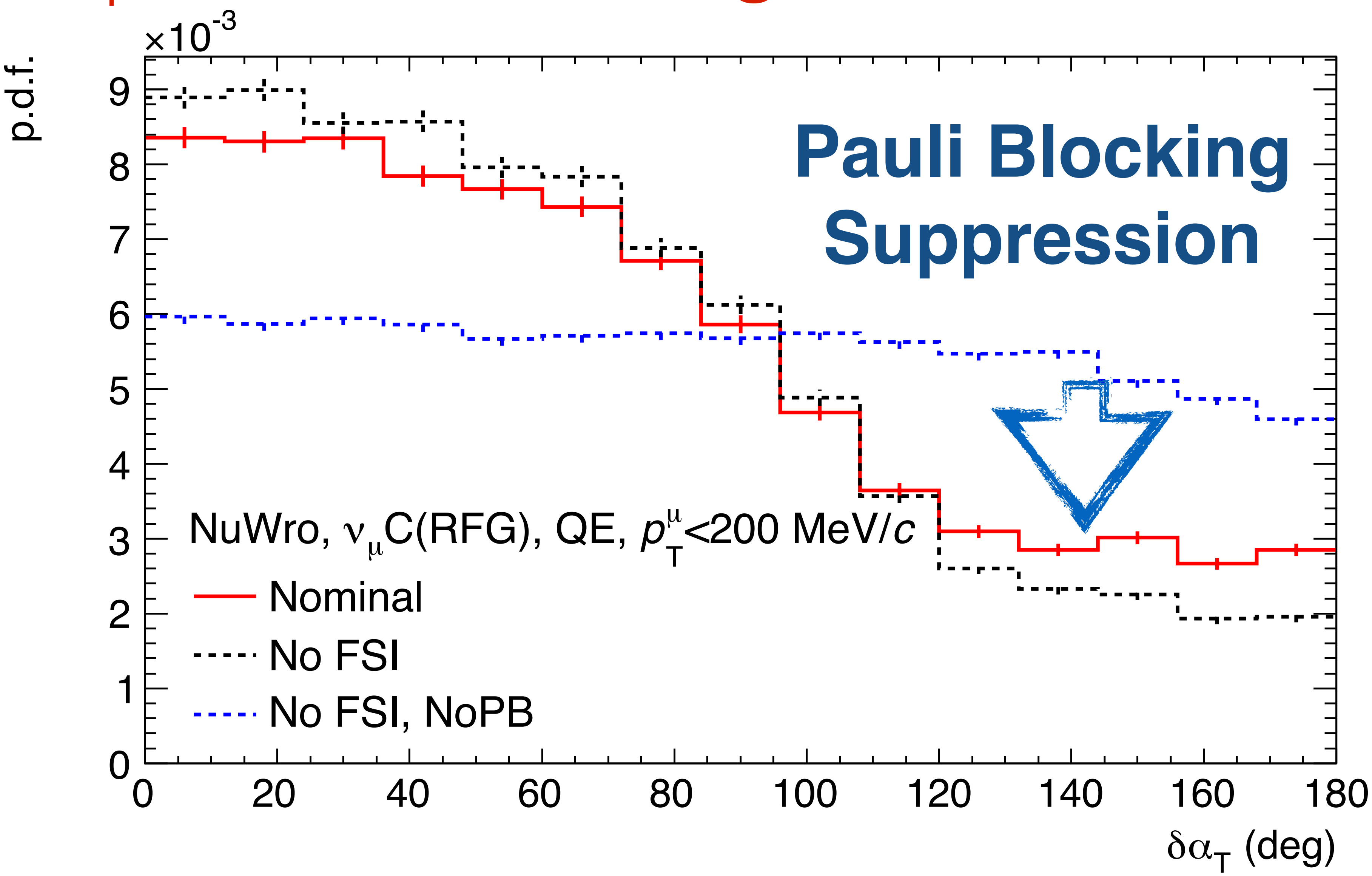
$\delta\alpha_T$ characterises apparent proton acceleration.



- Isotropy of Fermi motion boost causes flat-ish $\delta\alpha_T$.
- FSI processes generally result in momentum transfer *to* the medium.
  - ➡ FSI results in characteristic peak at the 'decelerating' end of distribution.

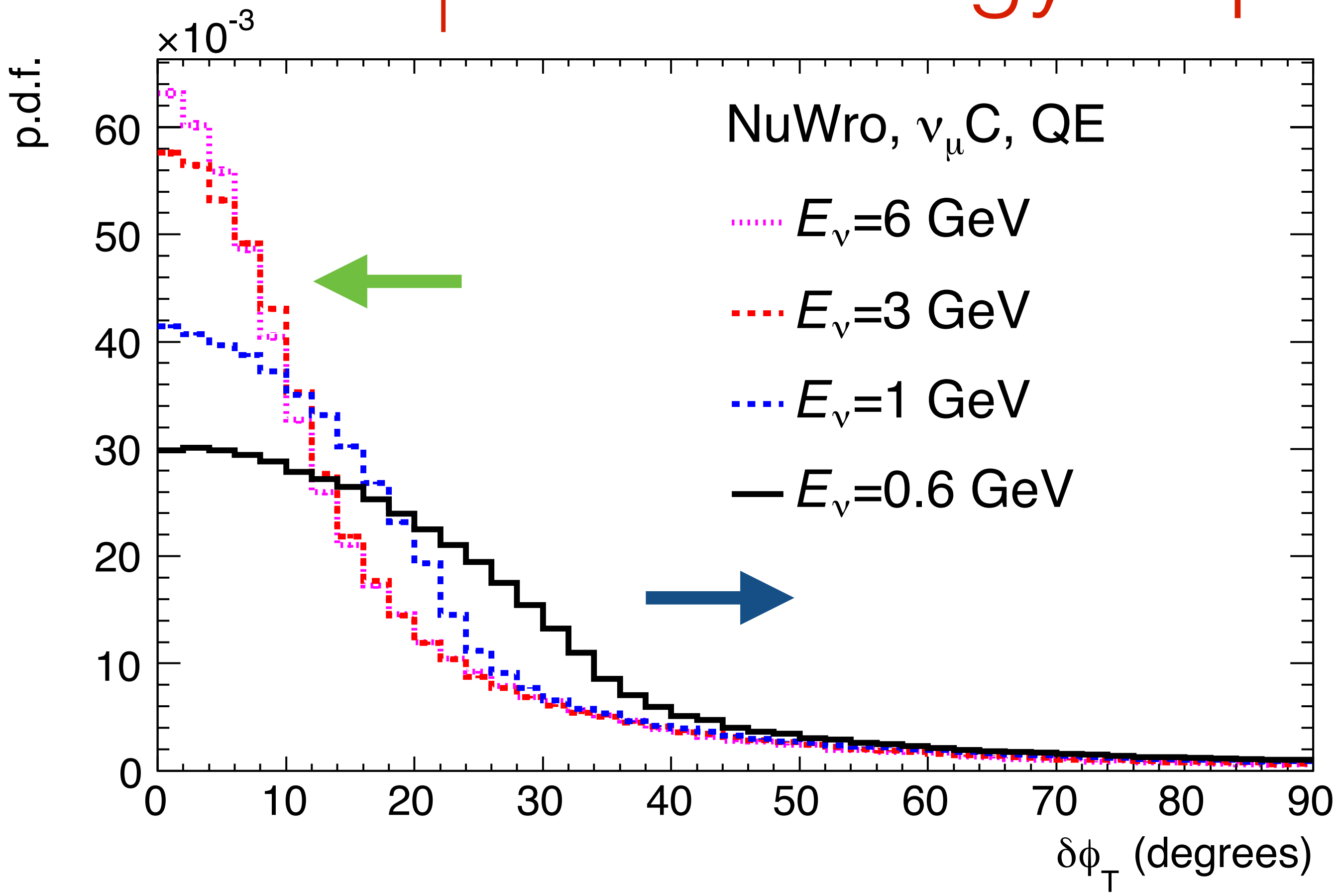
$\delta\alpha_T$: Pauli Blocking

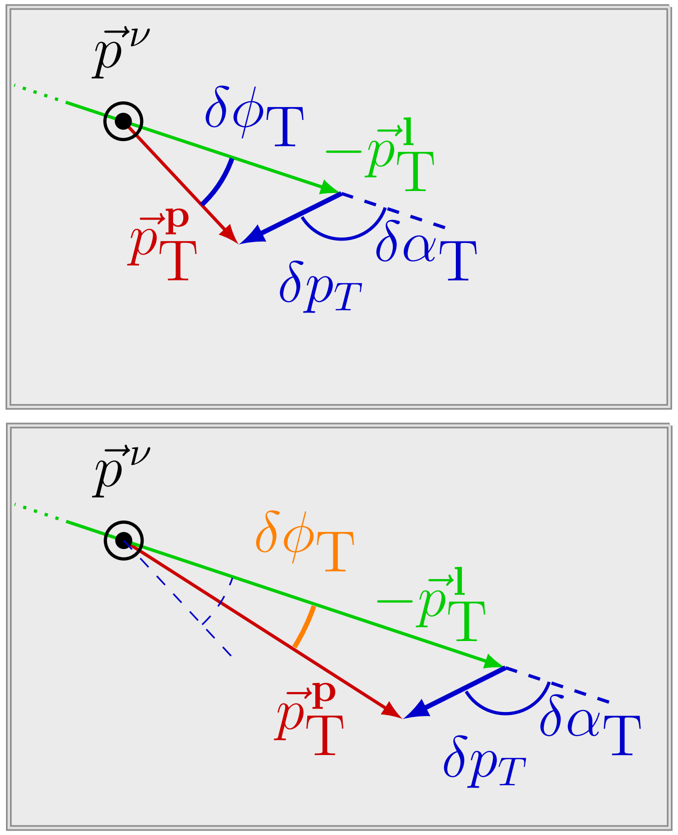




- At low p^μ_T Pauli blocking suppresses QE events with low three momentum transfer, ***q*,** when ***q*** is not aligned with the initial nucleon momentum.
  - ➡ High $\delta\alpha_T$ region is suppressed for low $\boldsymbol{q_T}$.

$\delta\Phi_T$: Extra Energy Dependence



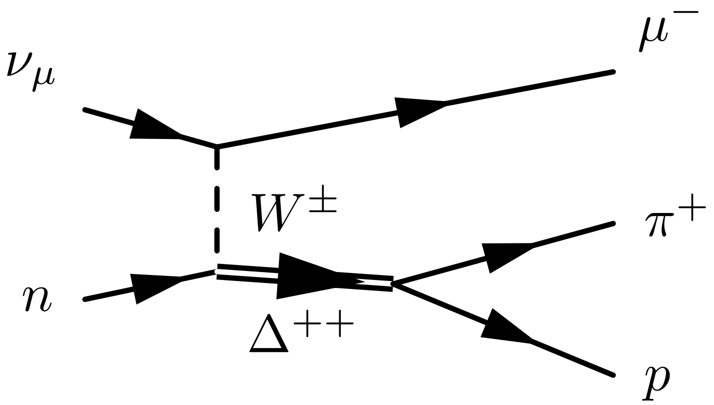


For given momentum loss (δp_T), $\delta\Phi_T$ scales inversely with muon p_T

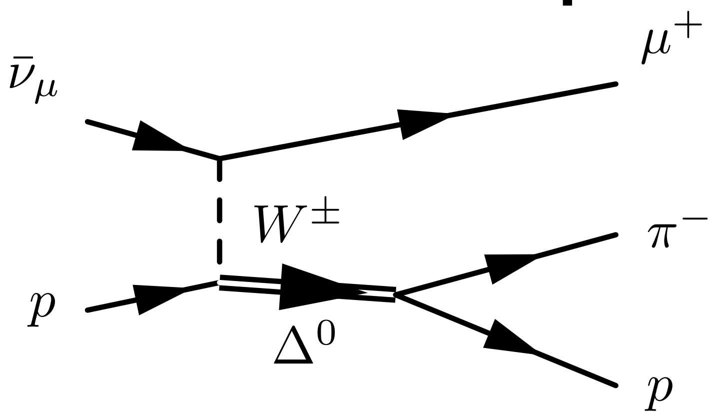
- **δp_T**, and **$\delta\alpha_T$** determined by the nucleon momentum distribution and FSIs.
  - ➡ Largely factorisable from neutrino energy.
- **$\delta\Phi_T$** includes more dependence on interaction kinematics.
  - ➡ Energy evolution below Q^2 saturation is pronounced.
- $\delta\Phi_T$ evolution for **higher energy** is opposite to evolution with **stronger FSIs**.
  - ➡ Still highly convoluted.
- Event-by-event high $\delta\Phi_T$: Low p^{μ}_T / Strong FSI ⇒ Examine in p^{μ}_T slices.

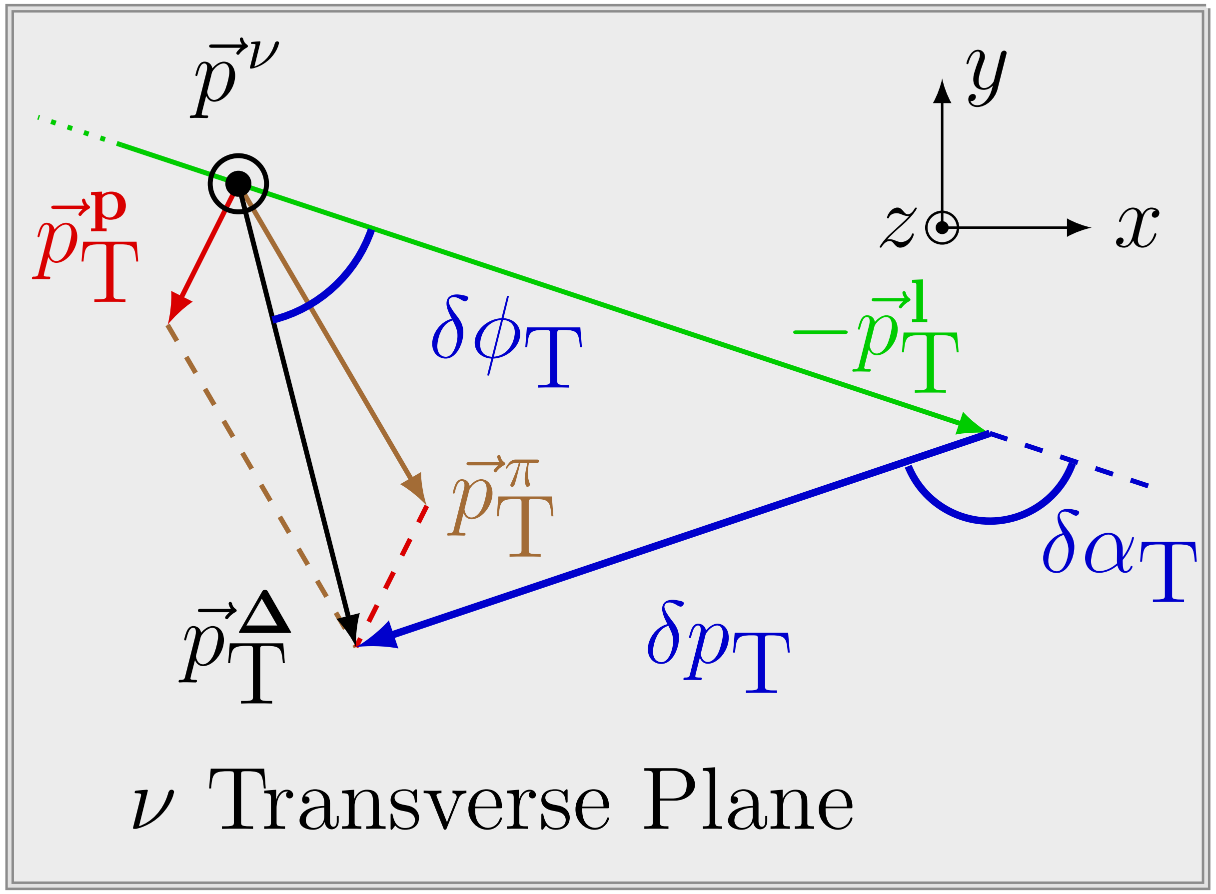
Defintion: Imbalance in Δ Production

L. Pickering



Δ Resonance charged pion production with FS proton

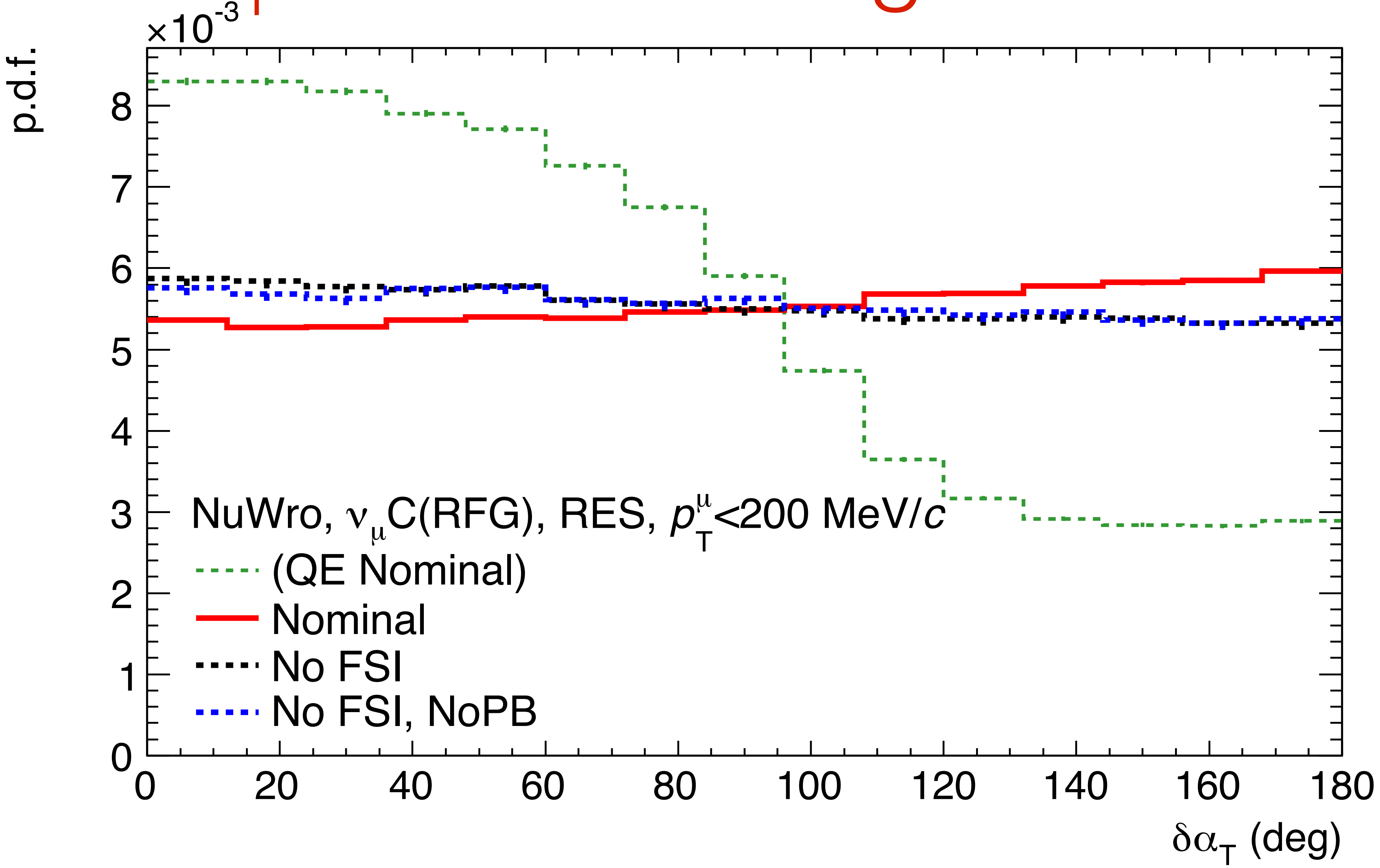




- Take imbalances in μ–p system to the next logical step.
- Examine μ–(p+$\pi^\pm$) system:
  - Expect the μ–Δ, RES, system to be balanced similarly to μ–p, QE.
- Constructible in a neutrino-mode CC1p1π^+ selection and compare to neutrino-mode CCQE-like.
- However, we can ***also*** build these in an **anti-neutrino** CC1p1π^- selection.

➡ **FSI probe in an anti-neutrino beam!**

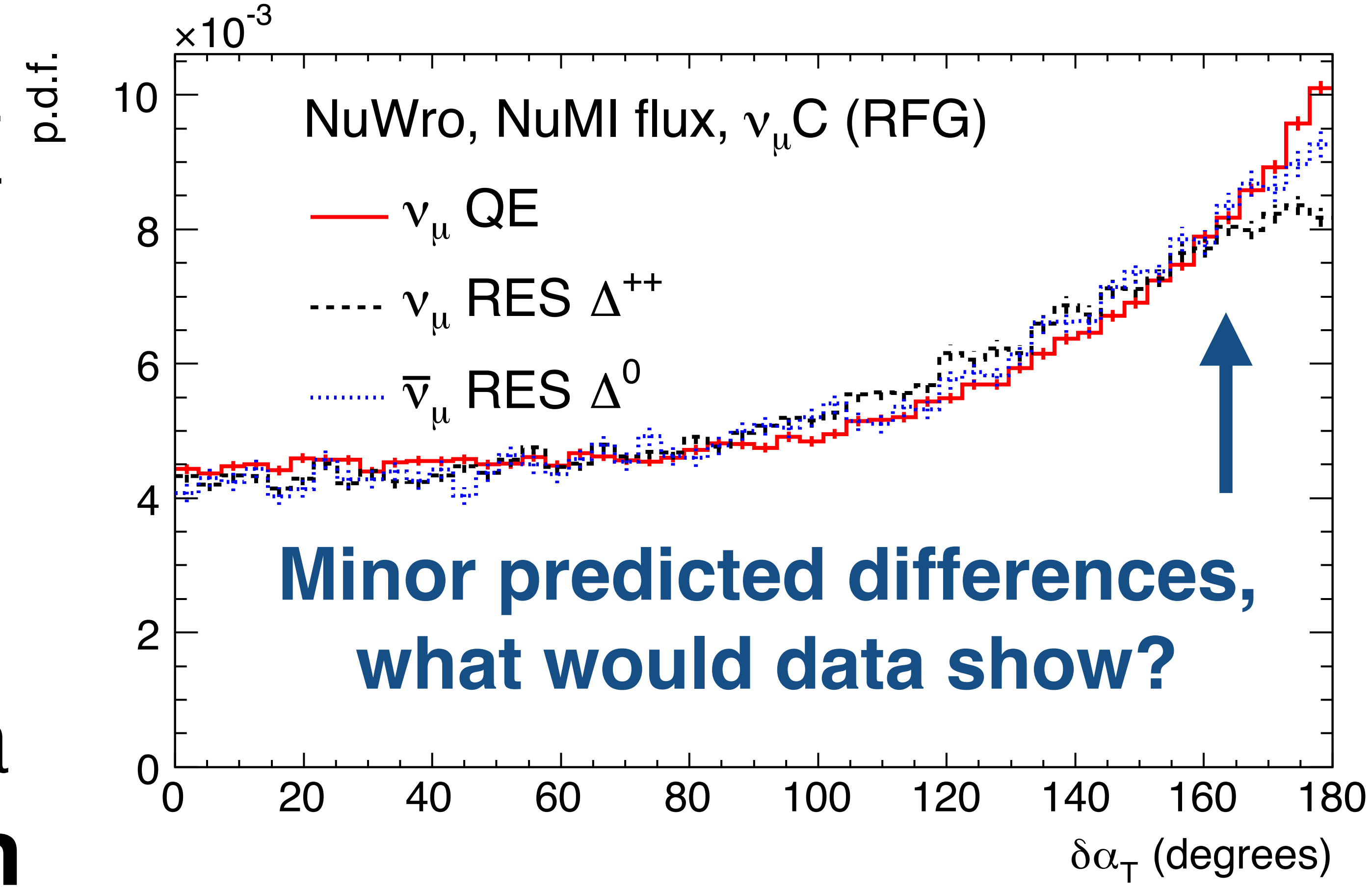
$\delta\alpha_T$: Pauli Blocking in RES

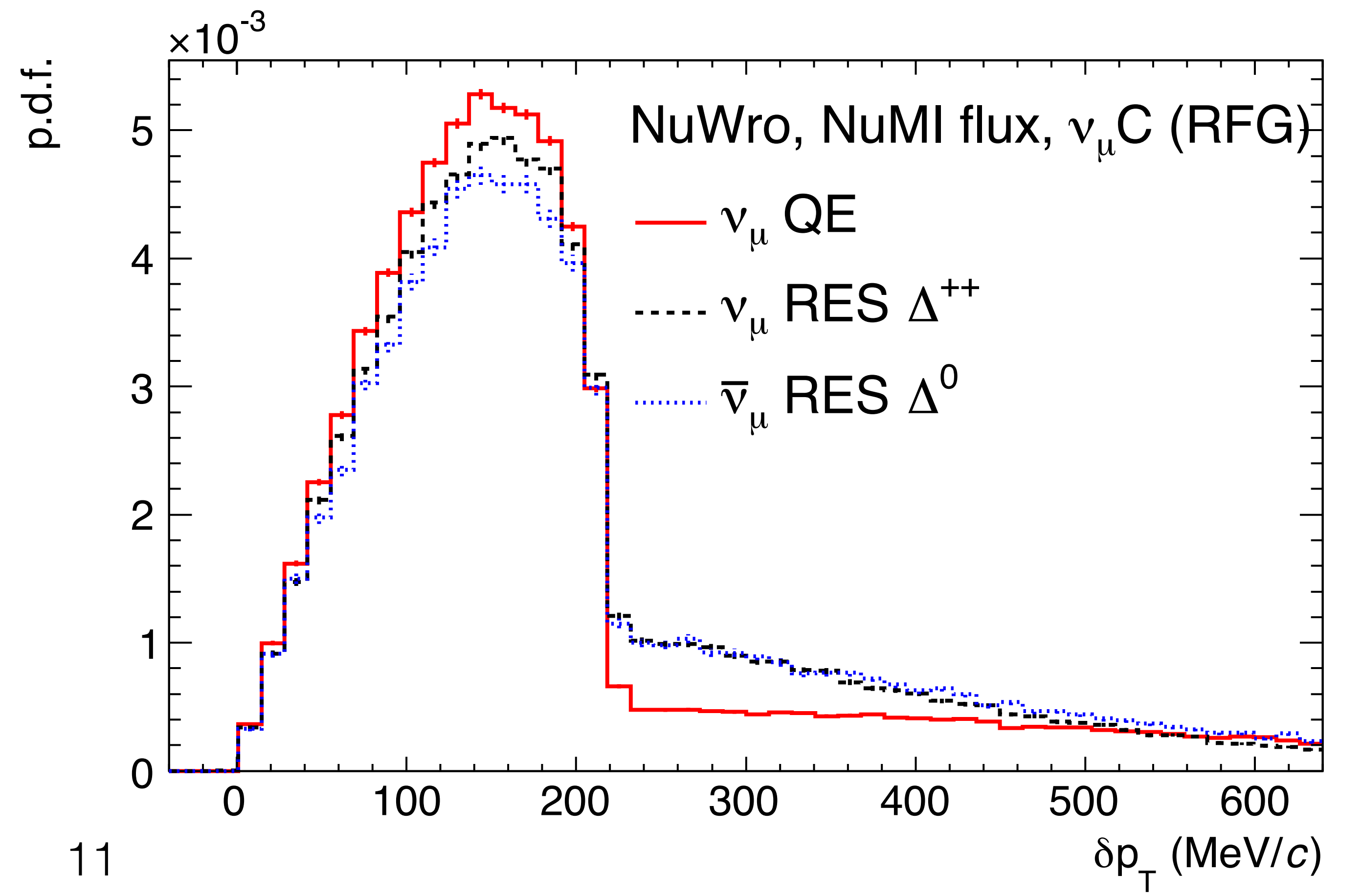


- Pauli blocking affects Δ decay: Δ → N + x.
- Naively doesn't affect Δ 'production' phase space if production/decay are decoupled.
- Will a measurement at low three-momentum transfer agree with these predictions?

Investigating FSIs in Δ Resonance Production

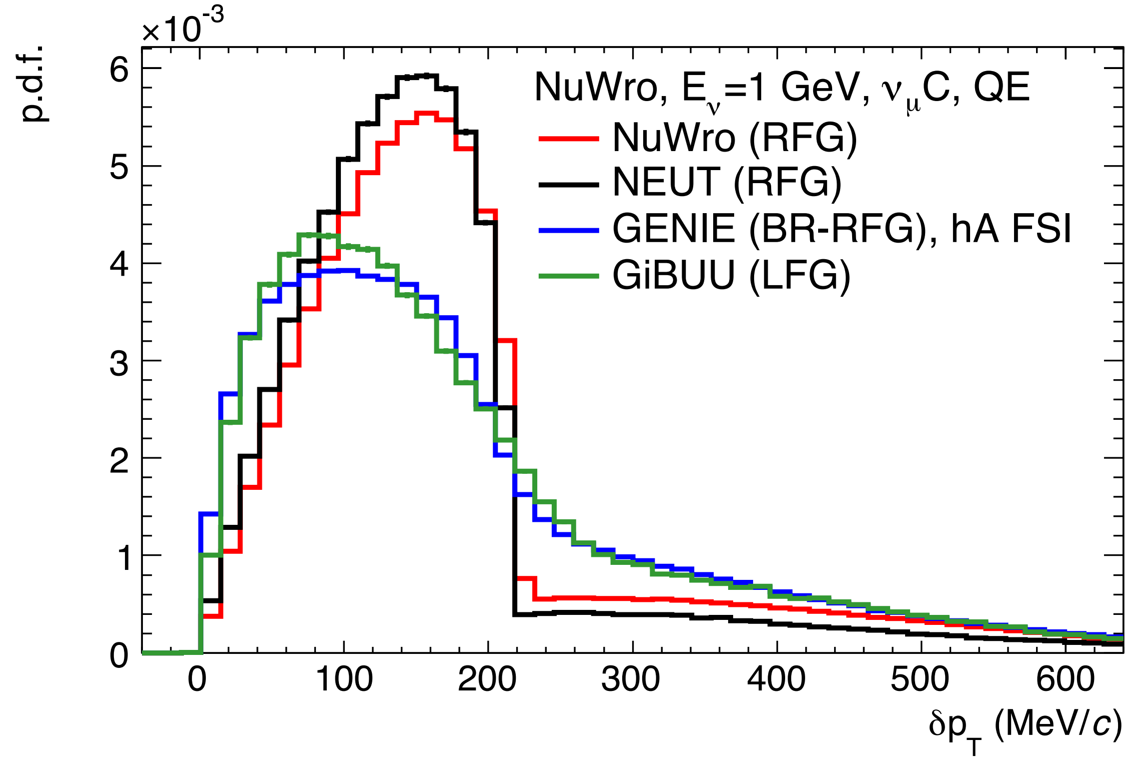
- Comparisons between QE and Δ^{++} and Δ^{0} highlight differences in proton, π^{+}, and π^{-} FSI.
- Measuring these distributions would allow a probe of FSI effects **within neutrino-nuclear scattering**.
- Often nucleon-nucleus, π-nucleus data is used. Intra- and extra-nuclear forces may be different.

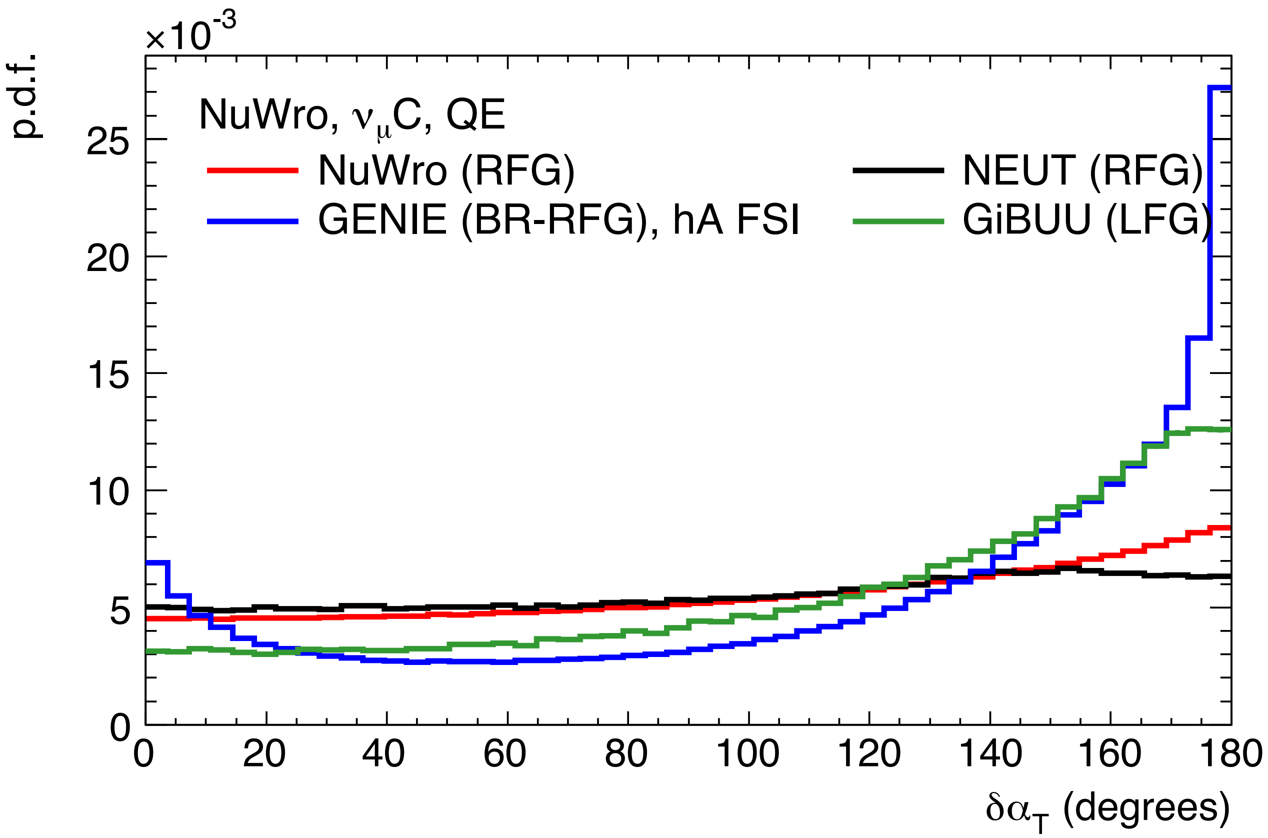


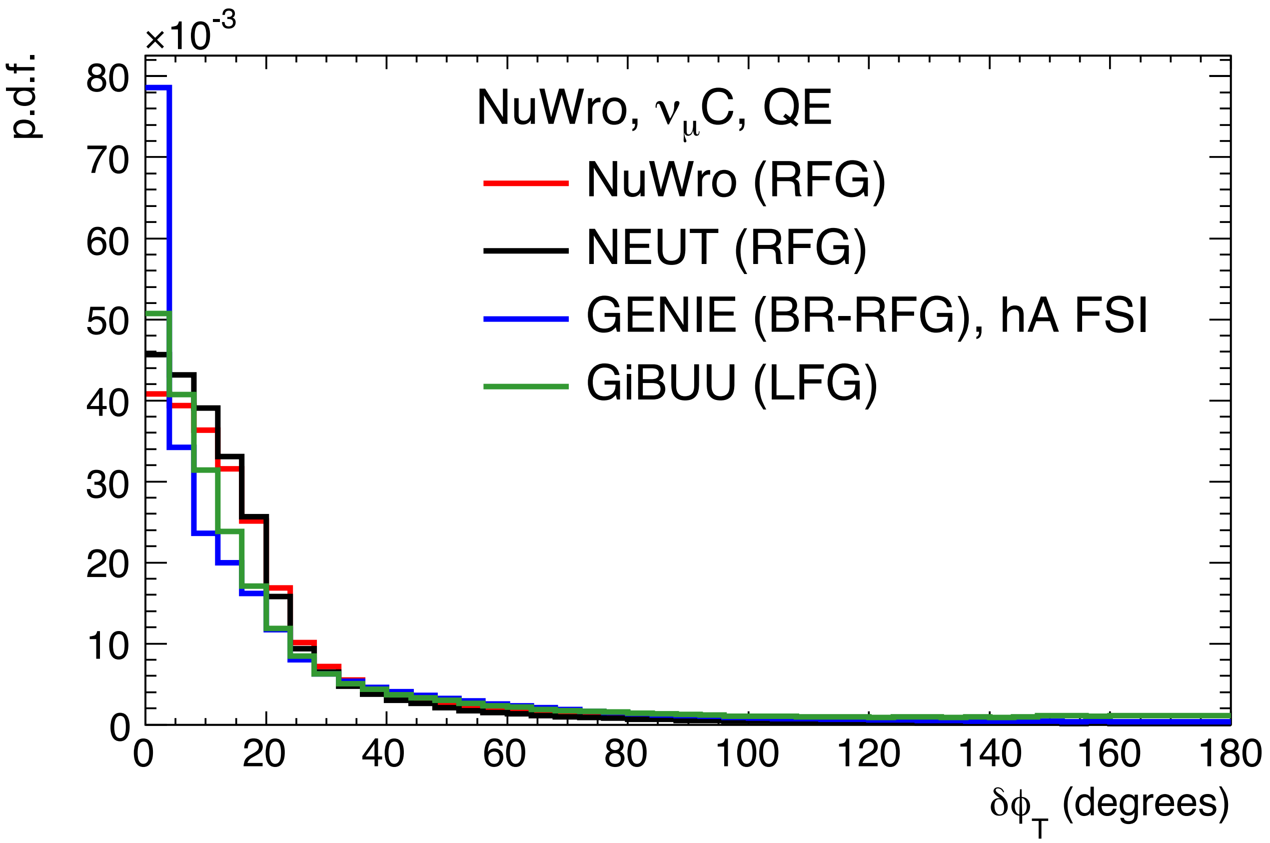


L. Pickering

1 GeV Generator Comparisons







Concluding Remarks

- Through a NuWro MC truth study we have shown that single transverse imbalance is a powerful way to isolate a number of nuclear effects.
  - ➡ Can be measured in neutrino-nucleus scattering—a complementary approach to hadron beams on thin-target.
  - ➡ Can probe nuclear effects in an anti-neutrino beam.
- **In future**: Compare to more generators and models to show that transverse imbalance is a powerful way to discriminate between models.
- Which experiment is going to provide the first measurement of transverse imbalance in (anti)neutrino Δ production?

Thank you for listening

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[3] *Department of Physics, Oxford University, Oxford, Oxfordshire, United Kingdom*
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(Dated: November 13, 2015)

We present a phenomenological study of nuclear effects, especially of final-state interactions (FSIs), in neutrino charged-current interactions. Transverse kinematic imbalance in an exclusive measurement is a direct probe of nuclear effects. Novel observables with minimal dependence on the neutrino energy are proposed to constrain nuclear effects in the neutrino quasielastic scattering, and especially in the resonant production.

Paper in Preparation

The authors express their gratitude to the NuWro group, K. Duffy, K. McFarland, R. Shah, J. Sobczyk, T. Stewart, and C. Wilkinson for helpful discussions.

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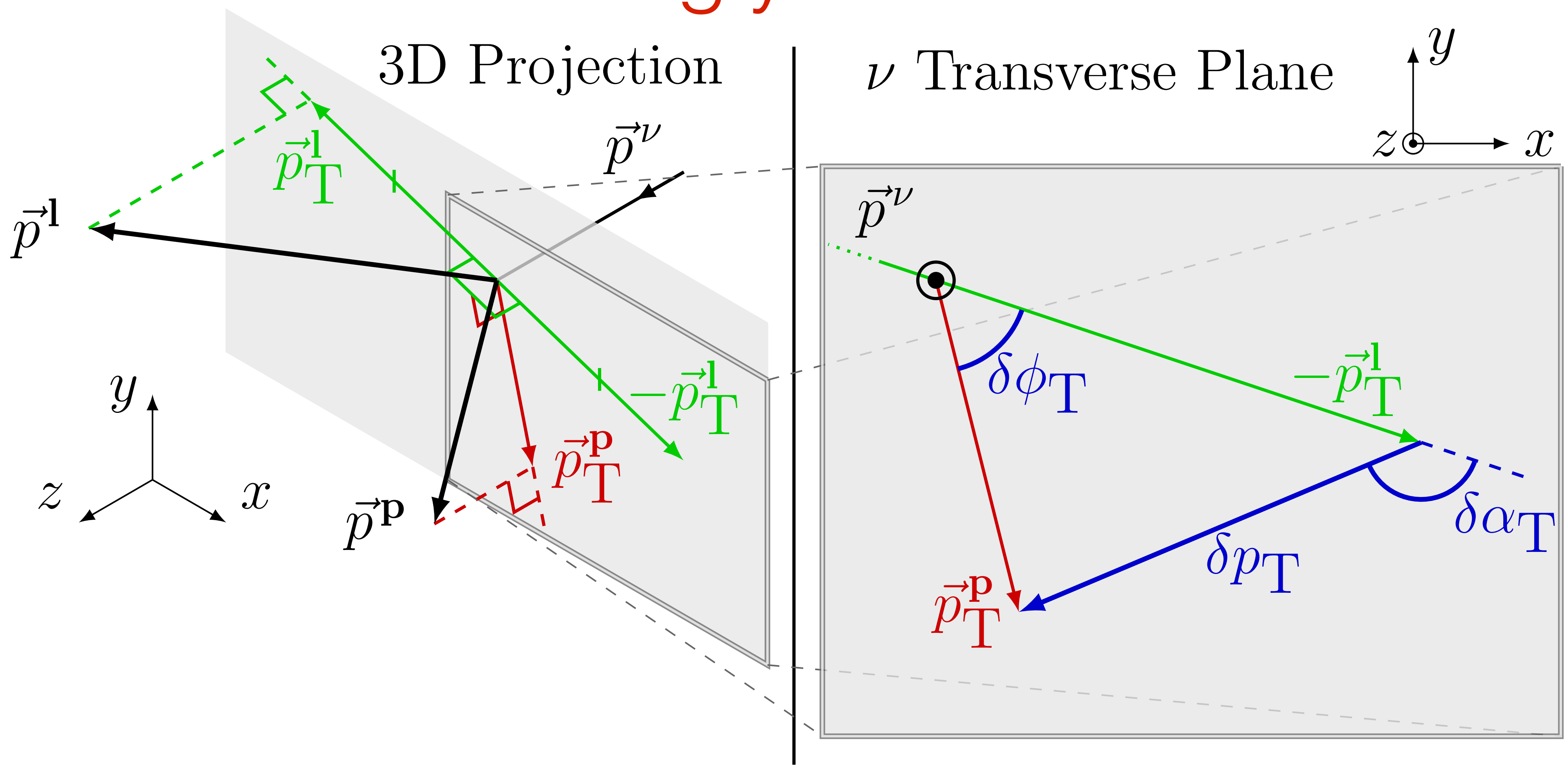
Previous Uses: Singly Transverse Variables



Previous use of transverse variables in neutrino physics:

- **MINERvA** (Phys. Rev. D 91, 071301 (2015))
  - ➡Measured: φ = 180 - $\delta\Phi_T$ in **CC0Pi.**
- **T2K INGRID** (Phys. Rev. D. 91, 112002 (2015))
  - ➡Use: (180 - $\delta\Phi_T$) for selection purity in **CCQE.**
- **NOMAD** (Eur.Phys.J.C63:355-381,2009)
  - ➡Use: (α = 180 - $\delta\Phi_T$), δp_T as selection likelihood inputs in **CCQE.**

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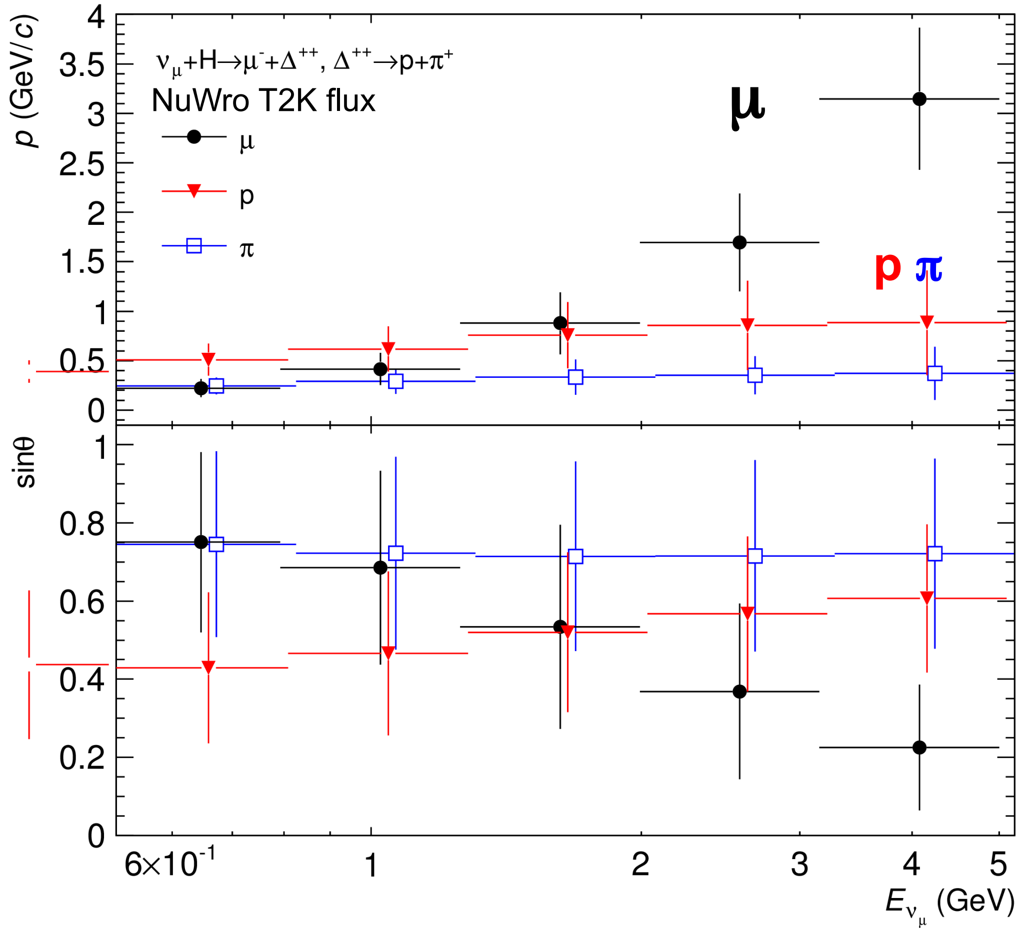
Energy Transfer Saturation

Minimal energy dependence with final-state hadronic kinematics

$$\nu + \mathrm{N} \rightarrow l' + \mathrm{N}'$$

N: nucleon
N': nucleon' or resonance
4-momentum transfer from lepton: $(\omega, \vec{q})$
Virtuality: Q^2
Invariant mass of N': W
Ignoring binding energy, so that $E_{\mathrm{N}}^2 = p_{\mathrm{N}}^2 + m_{\mathrm{N}}^2$



$$\omega E_{\mathrm{N}} = \frac{Q^2 + W^2 - m_{\mathrm{N}}^2}{2} + \vec{q} \cdot \vec{p_{\mathrm{N}}}$$

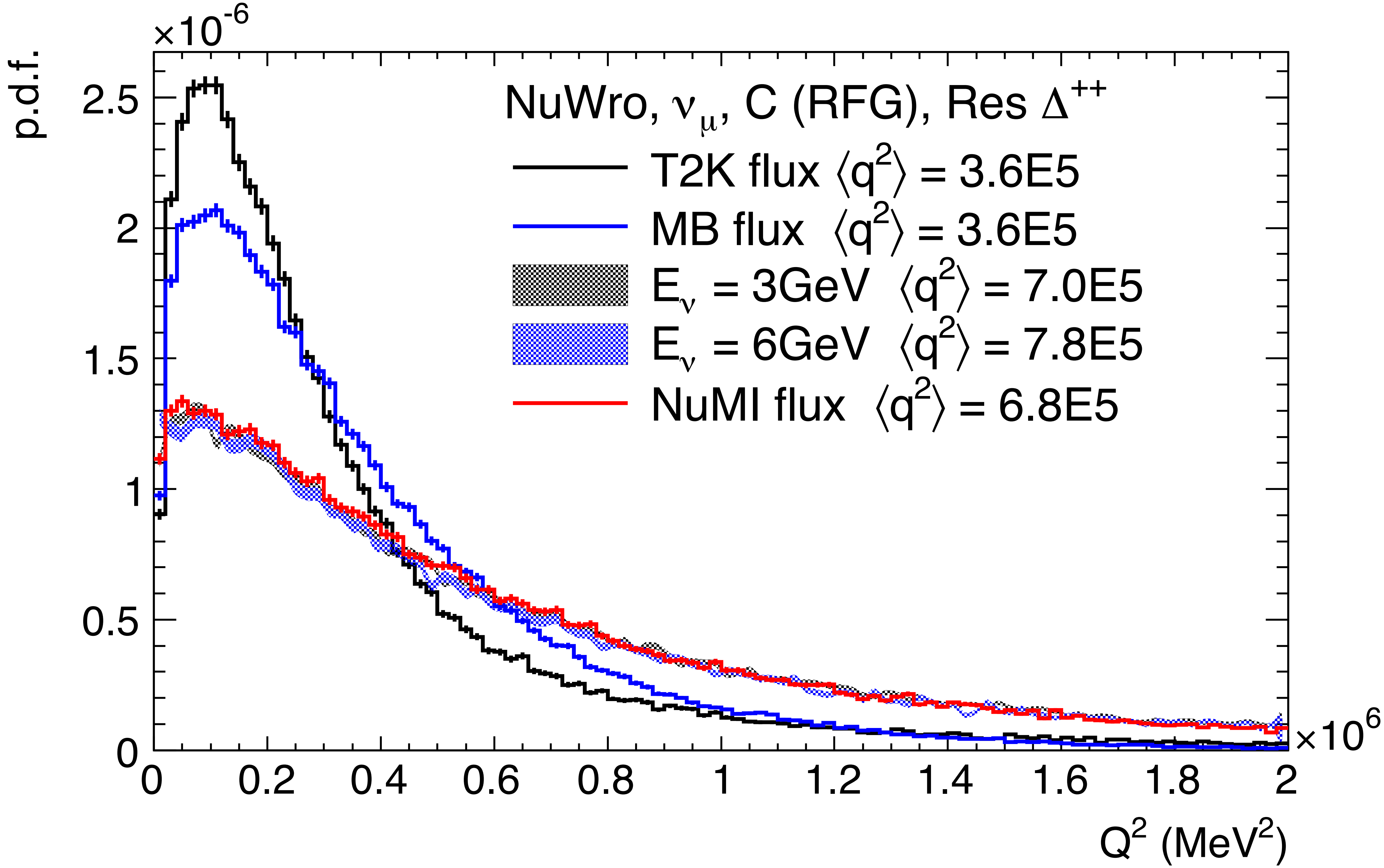
Fermi motion isotropic, ~ 0 on average

$$\omega \sim \frac{Q^2 + W^2 - m_{\mathrm{N}}^2}{2\sqrt{m_{\mathrm{N}}^2 + p_{\mathrm{N}}^2}}$$

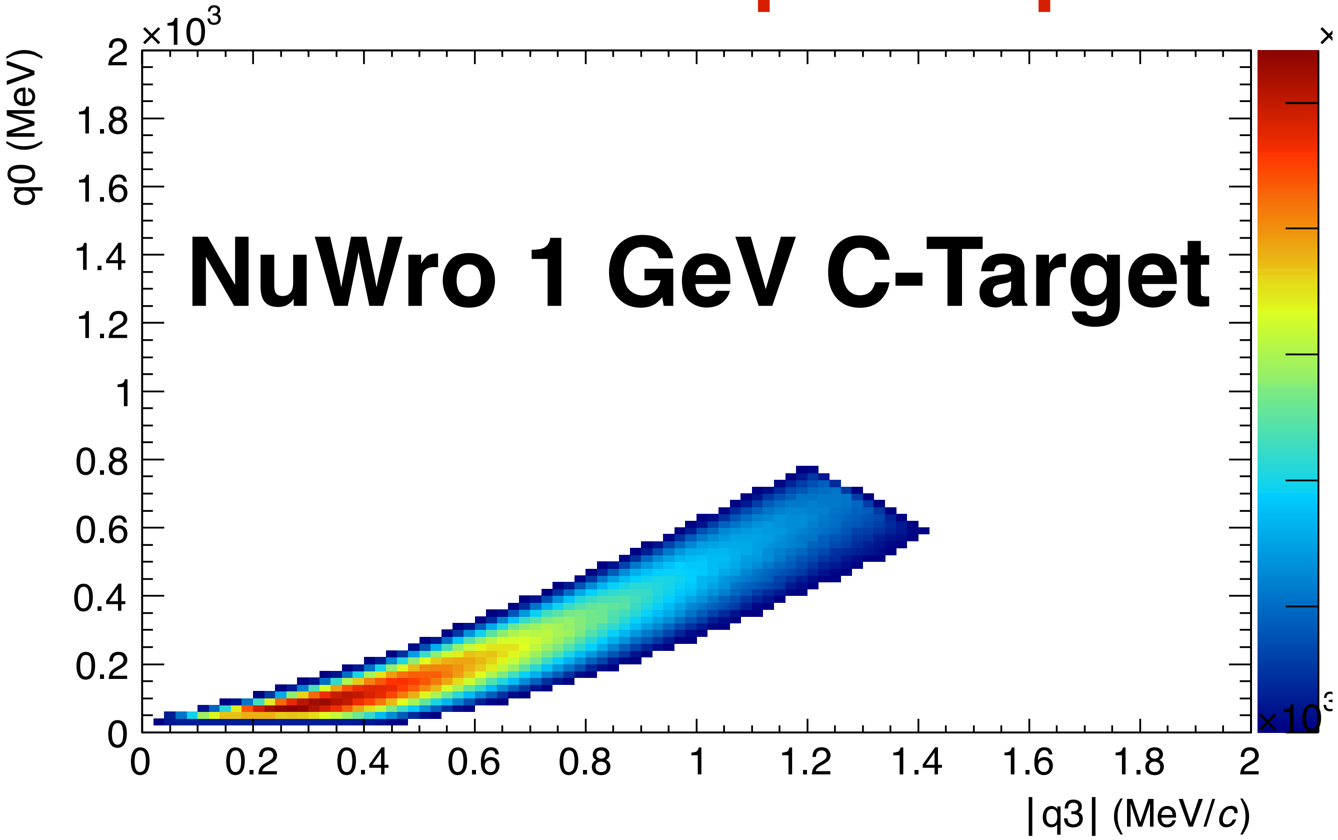
$p_{\mathrm{N}}^2/2m_{\mathrm{N}}^2 \simeq 2\%$ effect

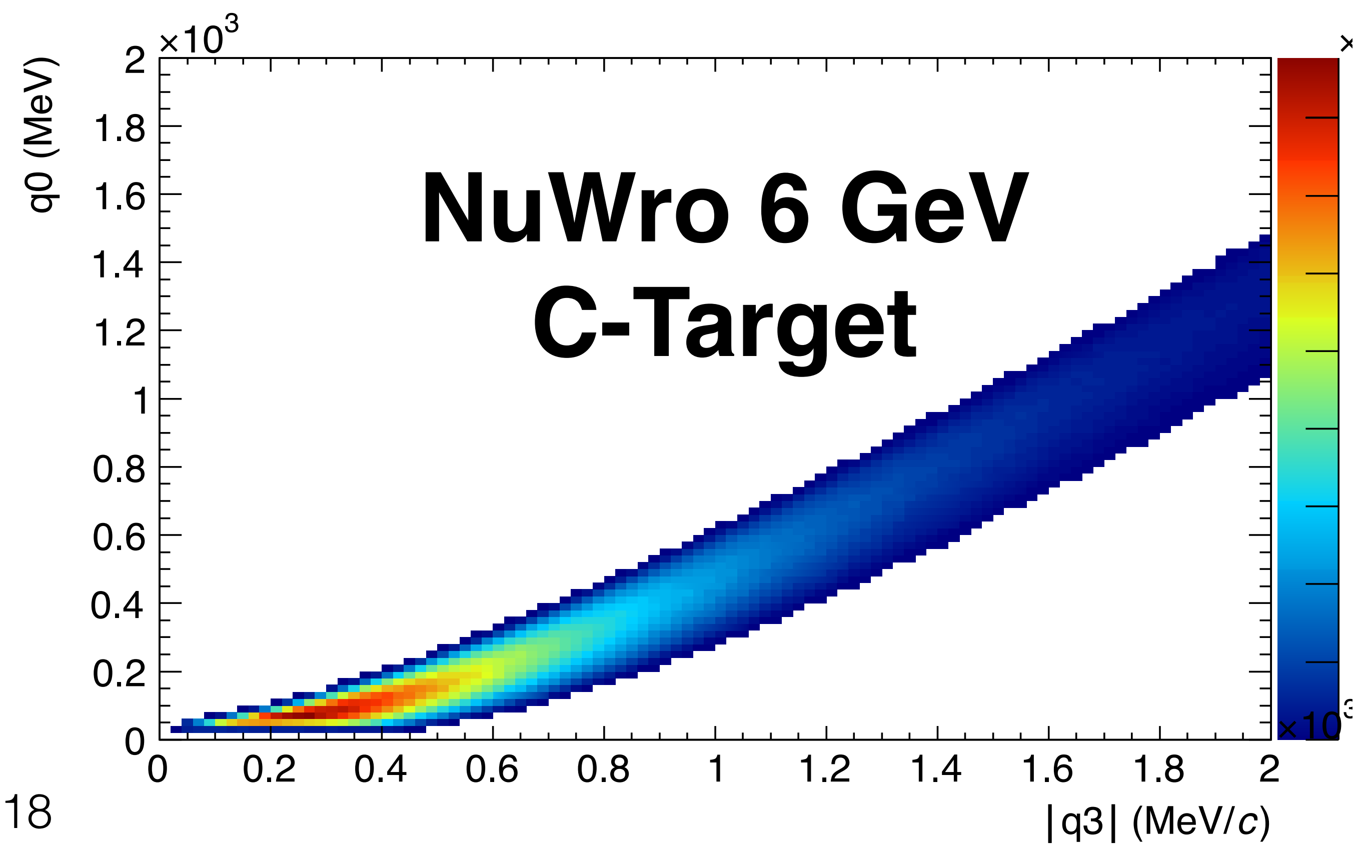
For QE and RES, $Q^2 \ll m_{\mathrm{N}}^2$ (interaction length)
W is nucleon or resonance mass.
ω "saturates" when $E_\nu > \omega(Q^2 = m_{\mathrm{N}}^2) \sim m_{\mathrm{N}}/2$
Hadronic kinematics much less E_ν-dependent than leptonic ones

RES Q^2, Δ++ Saturation.

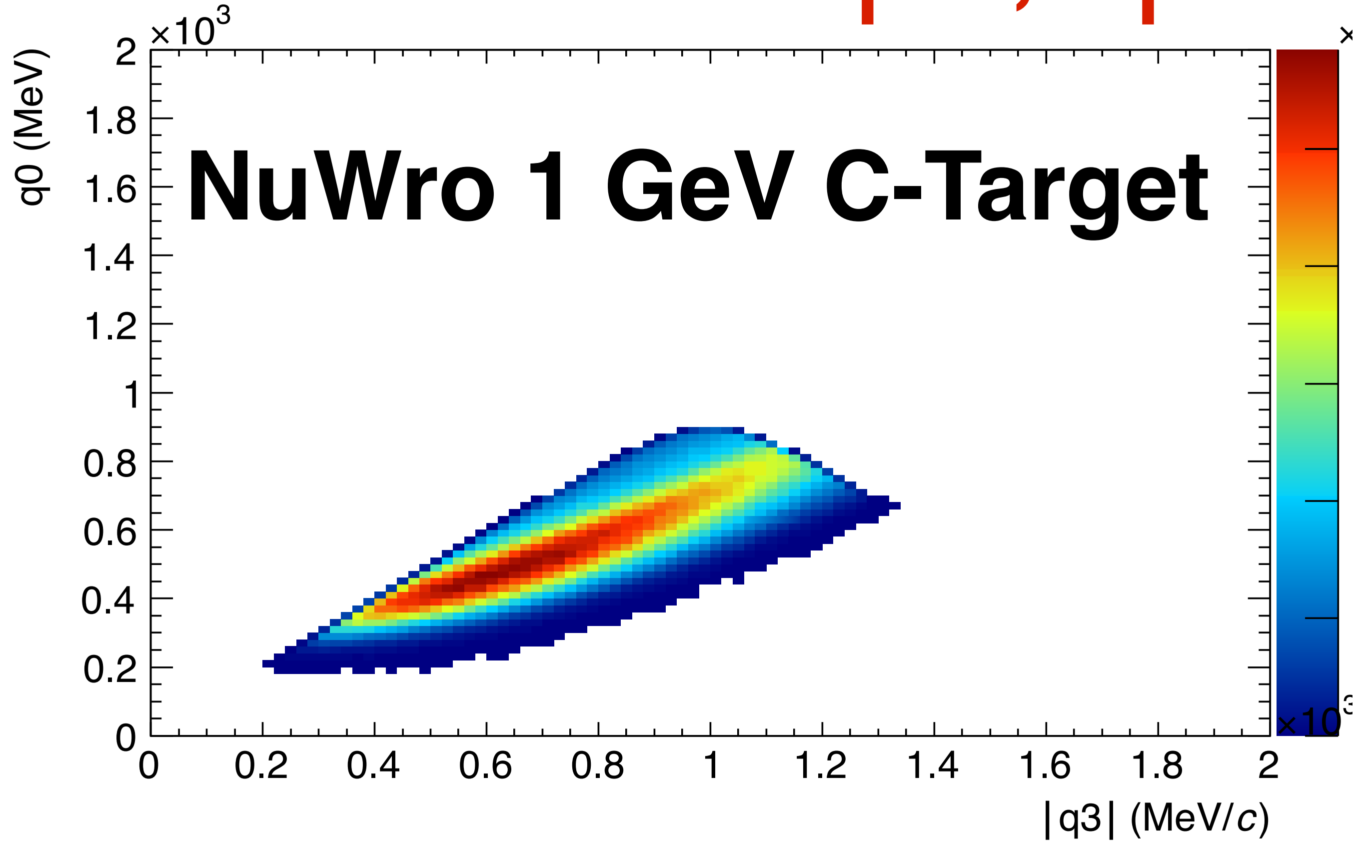


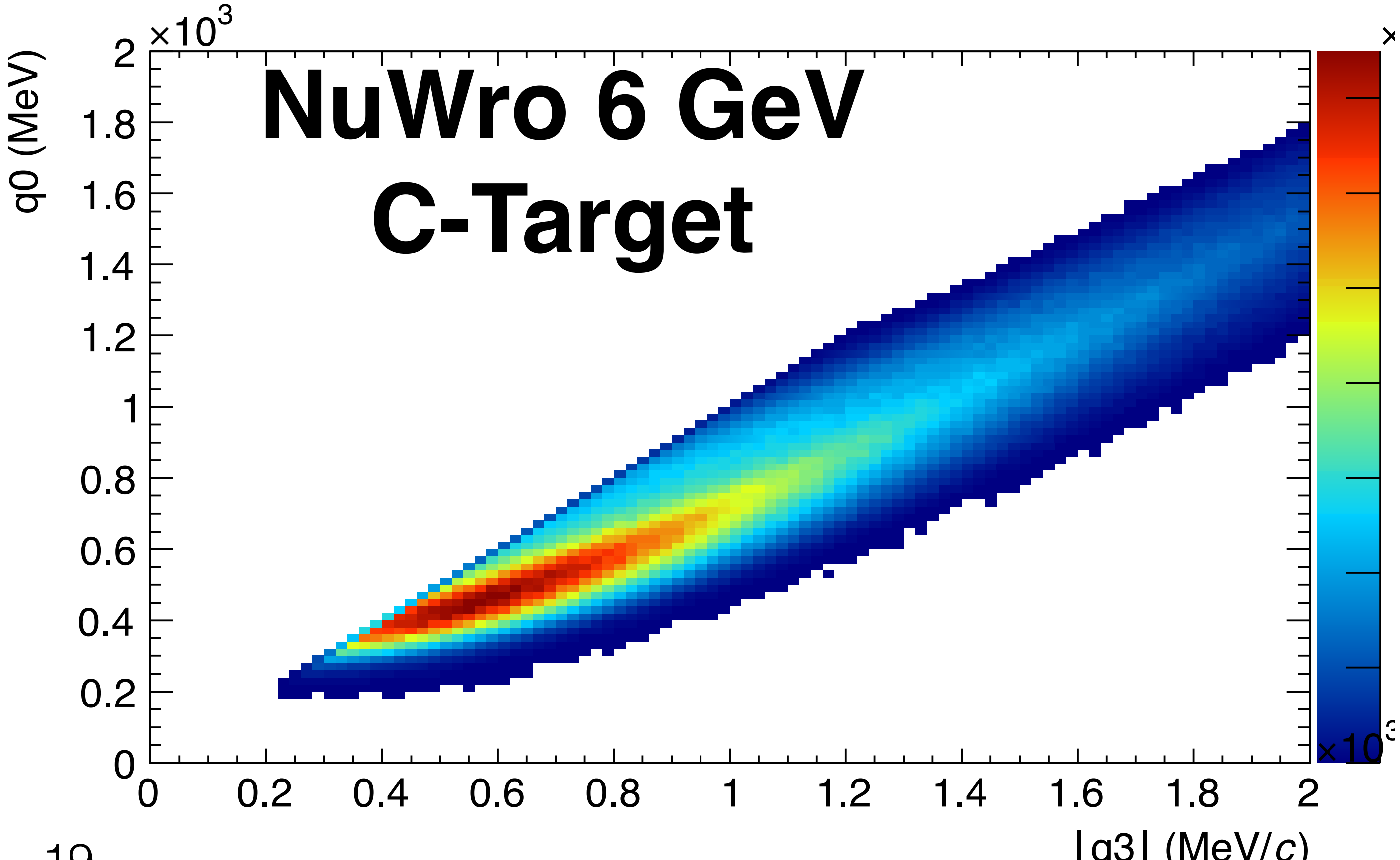
QE q0,q3 Saturation.



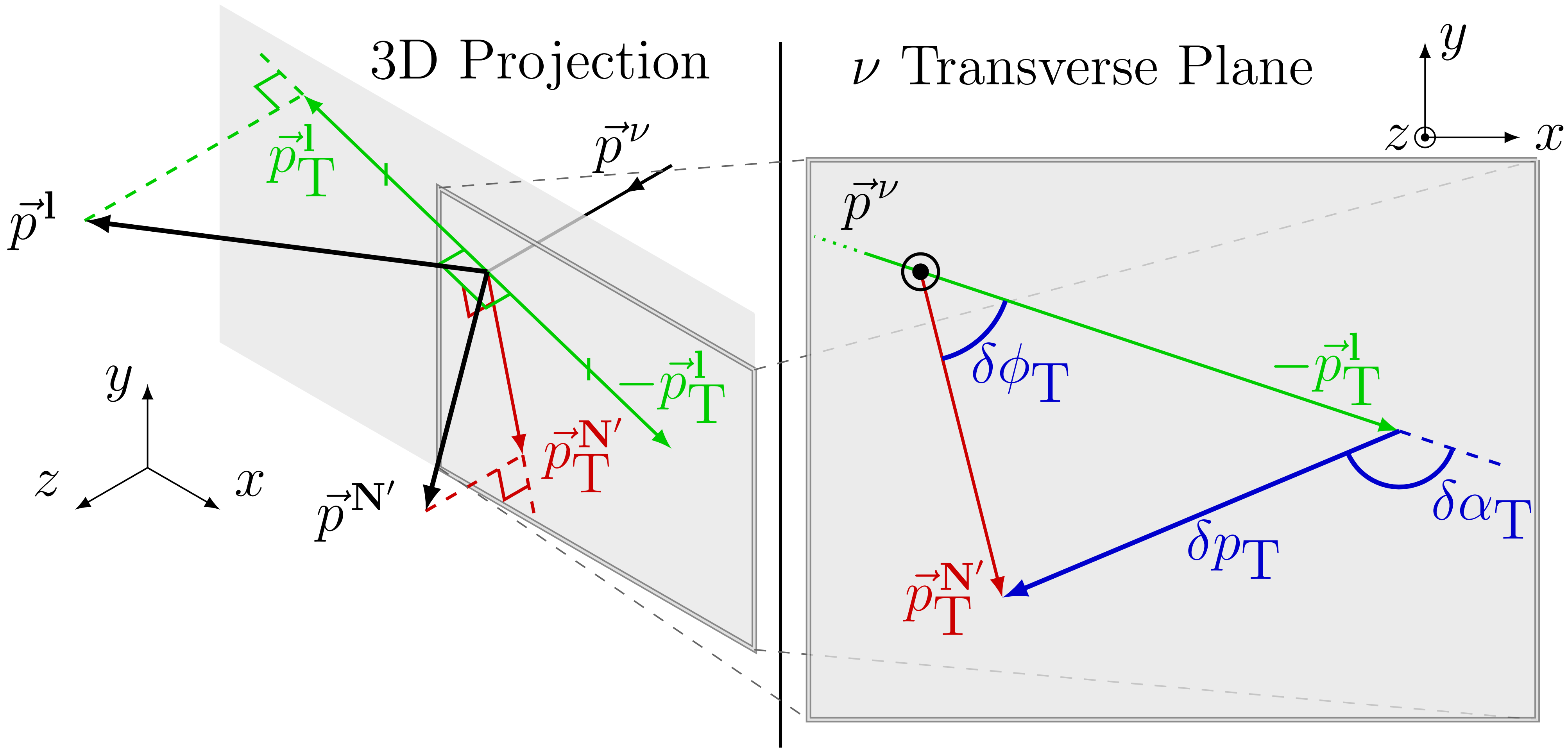


RES q0,q3 Saturation.





Singly Transverse Imbalances: Math



$$\delta\phi_{\mathrm{T}} \equiv \arccos \frac{-\vec{p}_{\mathrm{T}}^{\,l'} \cdot \vec{p}_{\mathrm{T}}^{\,\mathrm{N}'}}{\left|\vec{p}_{\mathrm{T}}^{\,l'} \cdot \vec{p}_{\mathrm{T}}^{\,\mathrm{N}'}\right|},$$

$$\delta\vec{p}_{\mathrm{T}} \equiv \vec{p}_{\mathrm{T}}^{\,l'} + \vec{p}_{\mathrm{T}}^{\,\mathrm{N}'},$$

$$\delta\alpha_{\mathrm{T}} \equiv \arccos \frac{-\vec{p}_{\mathrm{T}}^{\,l'} \cdot \delta\vec{p}_{\mathrm{T}}}{\left|\vec{p}_{\mathrm{T}}^{\,l'} \cdot \delta\vec{p}_{\mathrm{T}}\right|},$$

A Study of Nuclear Effects

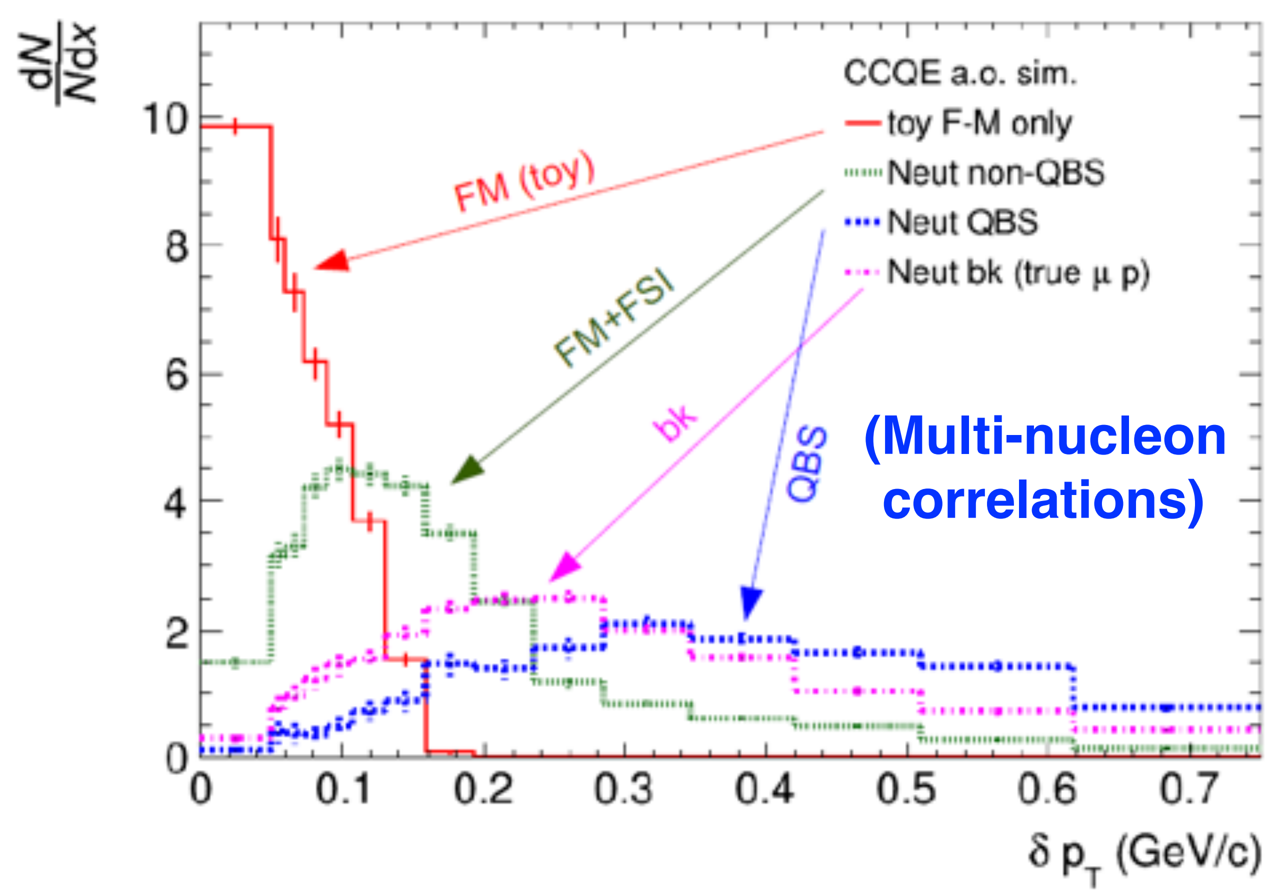
Non-stacked histograms.
"5%-binning": each bin has ~5% stat. error.
Points: reconstruction
Lines: simulation
Not corrected for efficiency or acceptance, only affecting normalization →
Normalized as probability density function

Observations for δp_T:

1) Before washed out by other effects, pF distribution preserved

2) Landau-like distribution from FSI (note at $\delta p_T \to 0$ and inf)

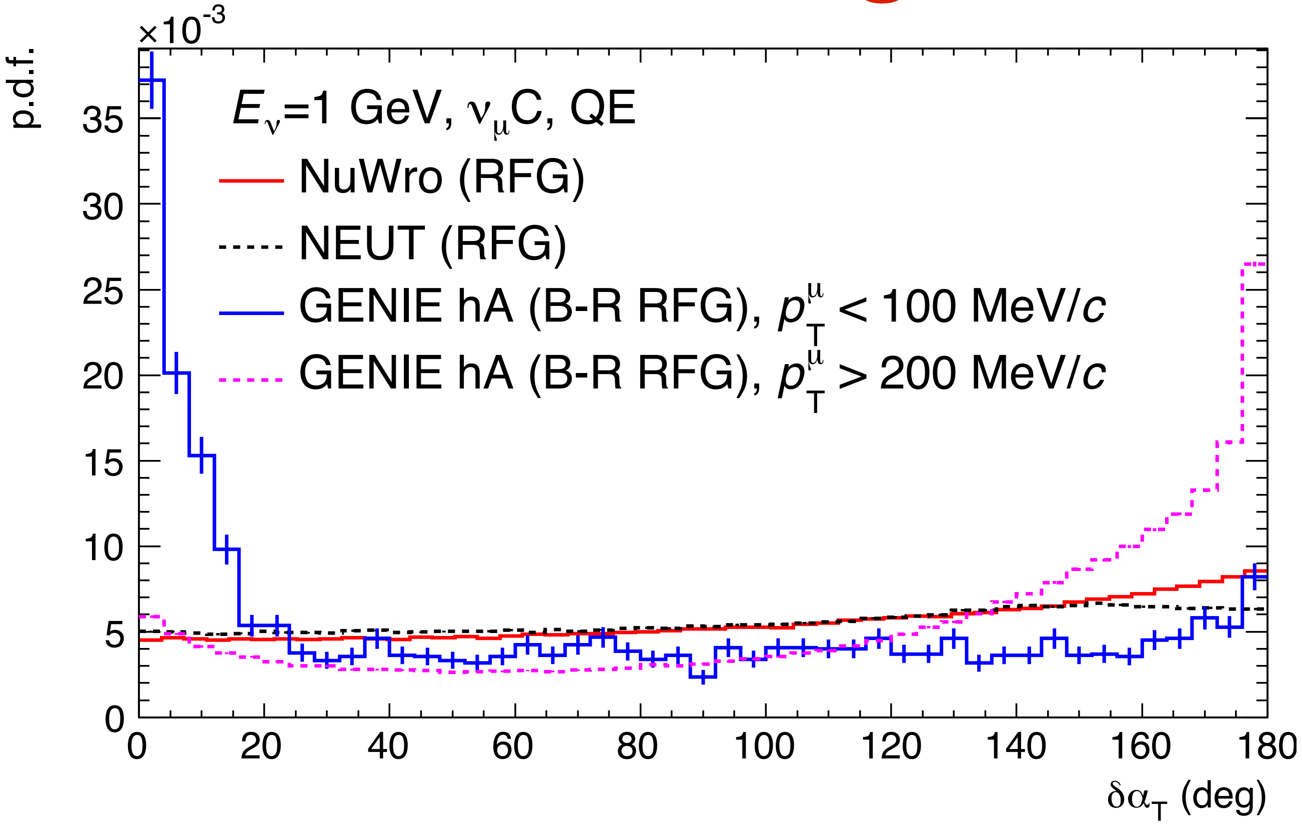
3) Red-shift due to mass split. Compared to QBS, all background channels are low mass states.

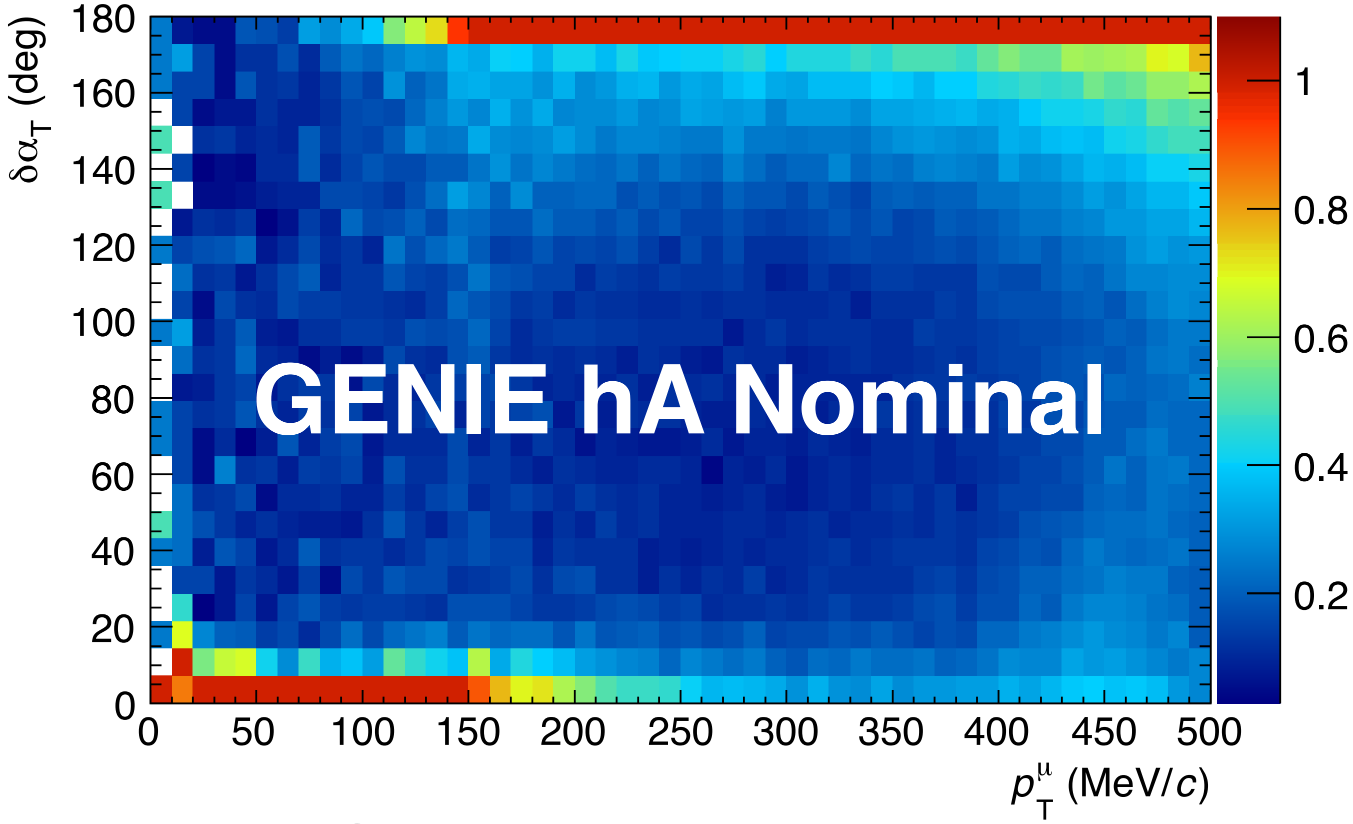


2-Feb-2015 X.-G. Lu, Oxford 9

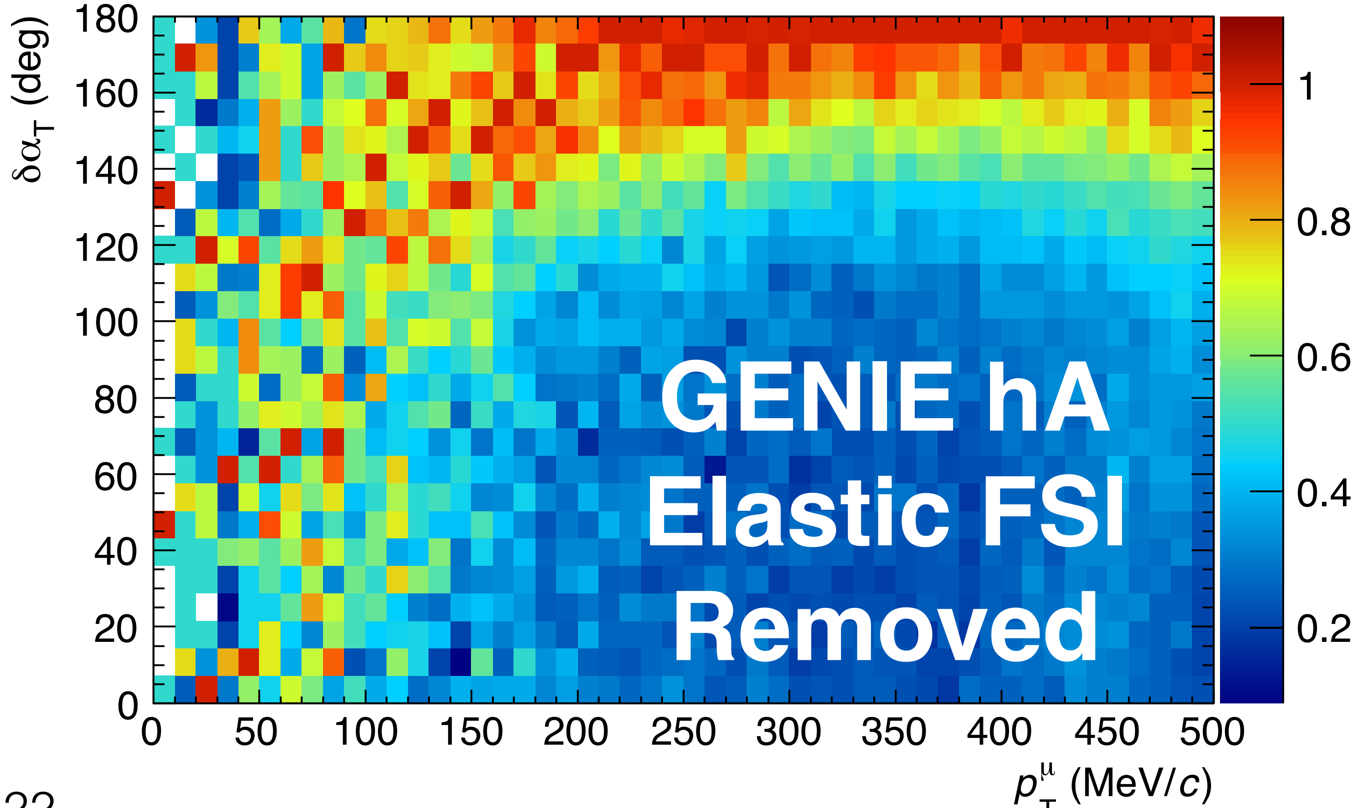
T2K Internal: http://www.t2k.org/asg/xsec/meetings/2015/niwg-022015-premeeting/xluTAB/view

Accelerating FSI in GENIE hA Prediction





Y Slice Normalised.



- New distributions are a good test of generator predictions—untuned.
- GENIE hA appears to cause an excess of accelerating FSI to bring proton and muon more back-to-back.
- Removing events with elastic FSIs removes this effect.

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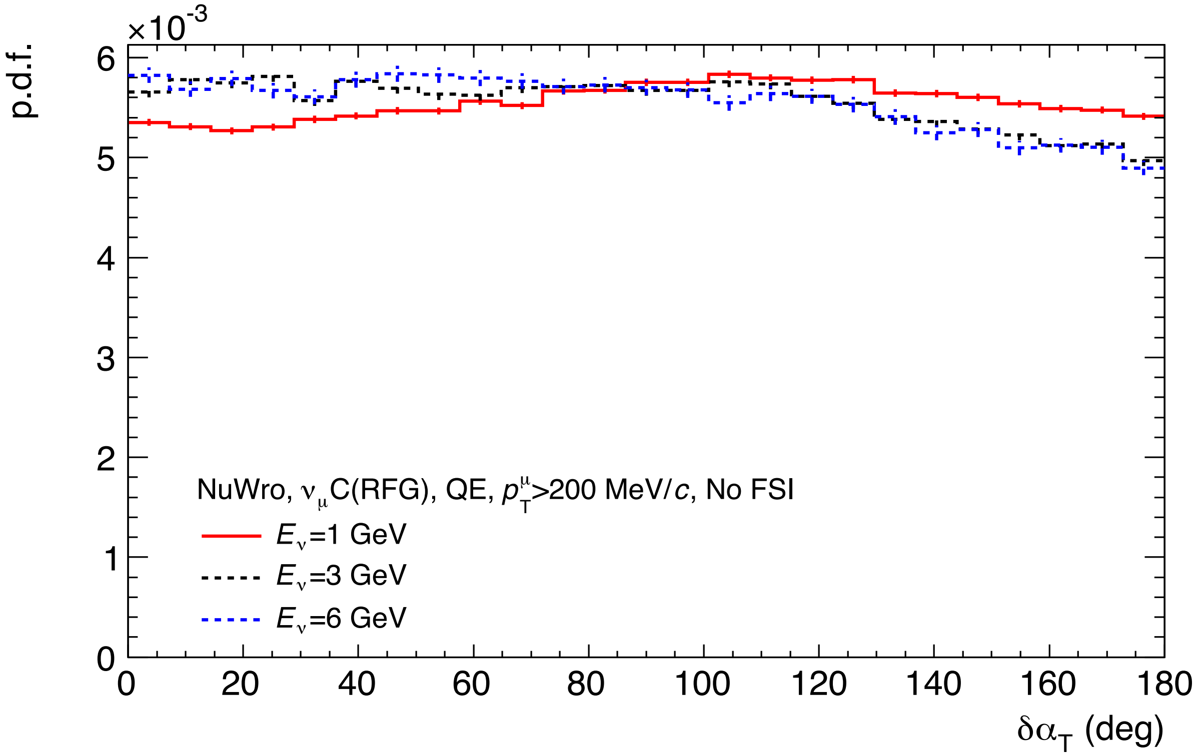
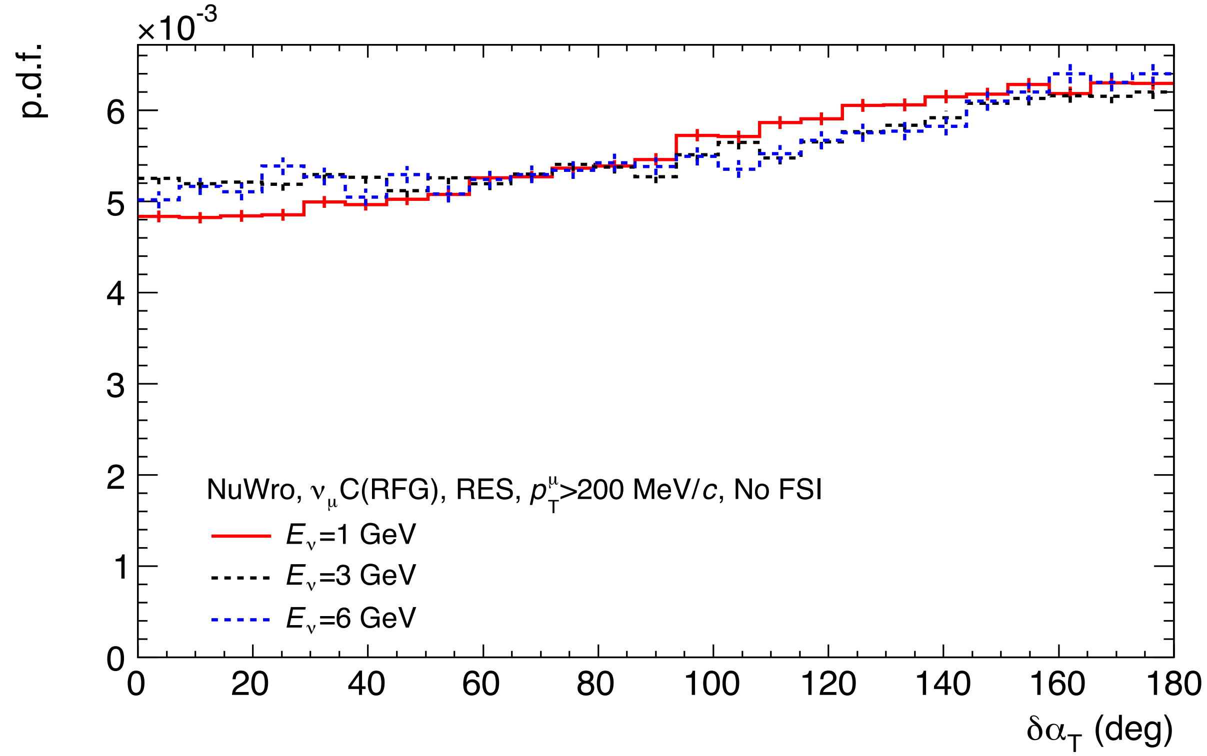
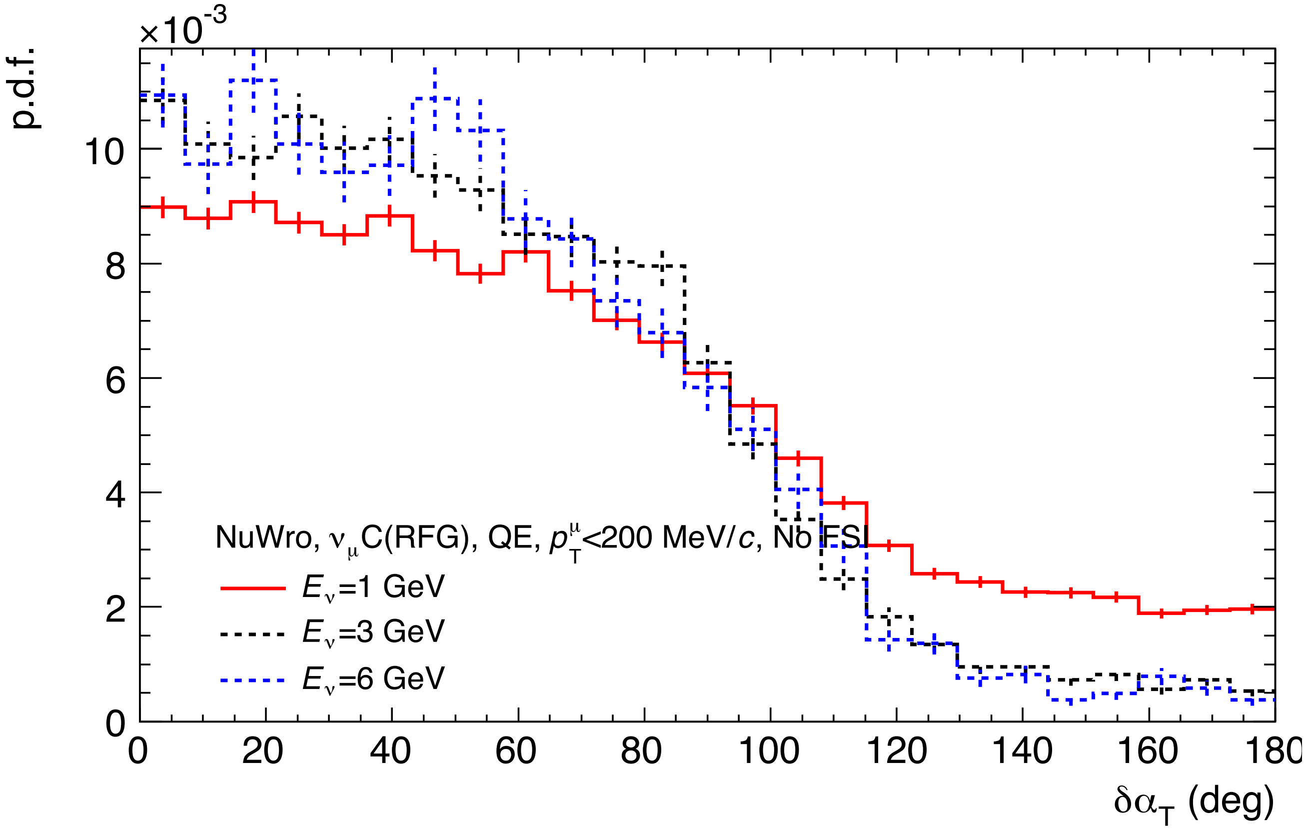
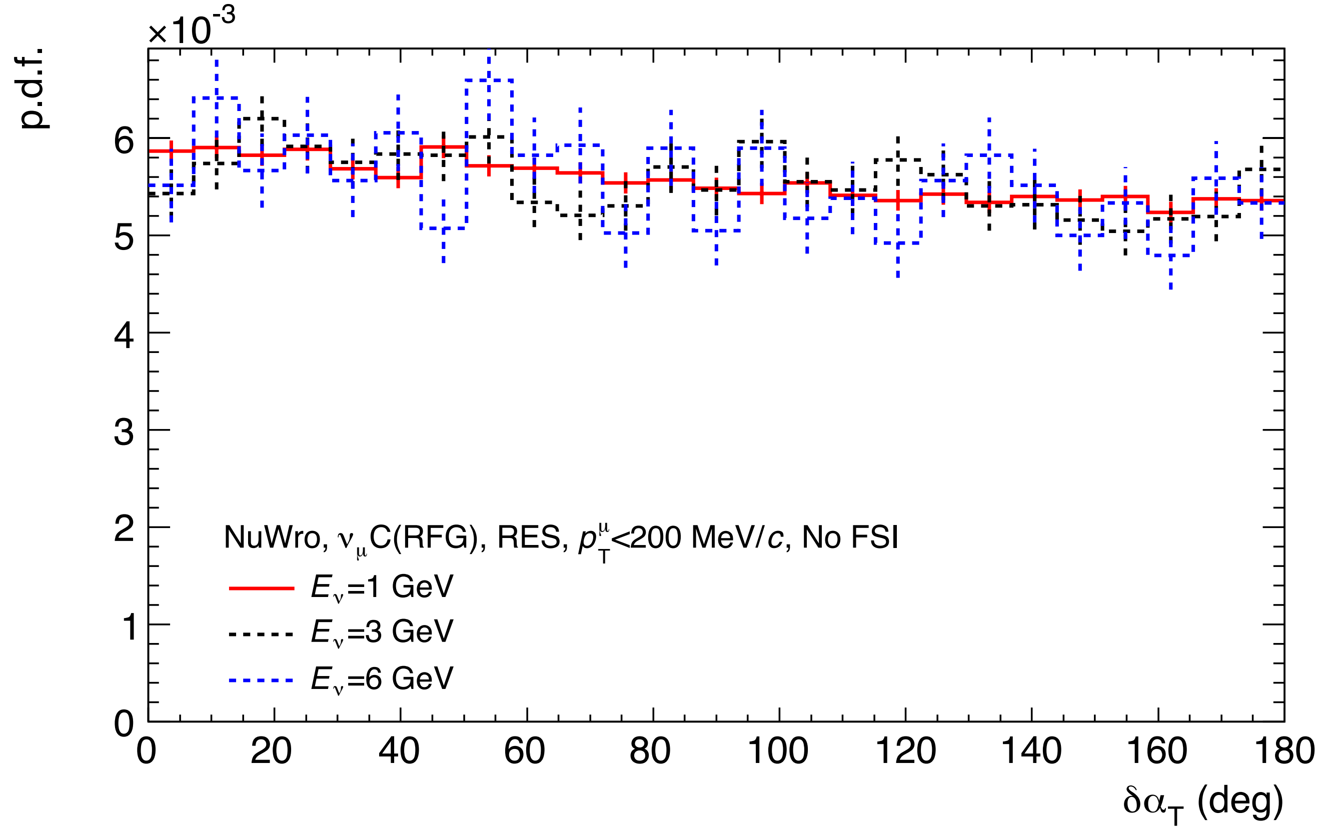
NuWro: Energy effects

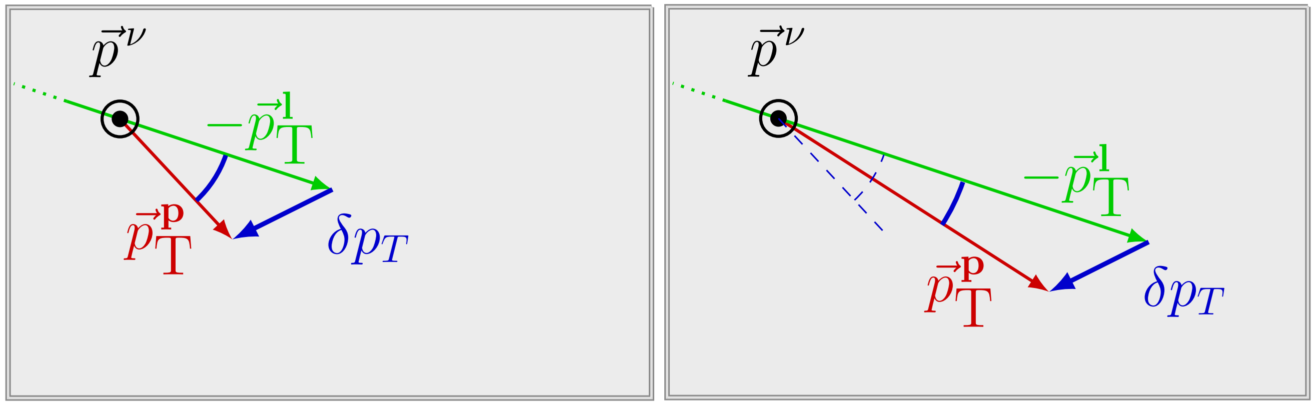




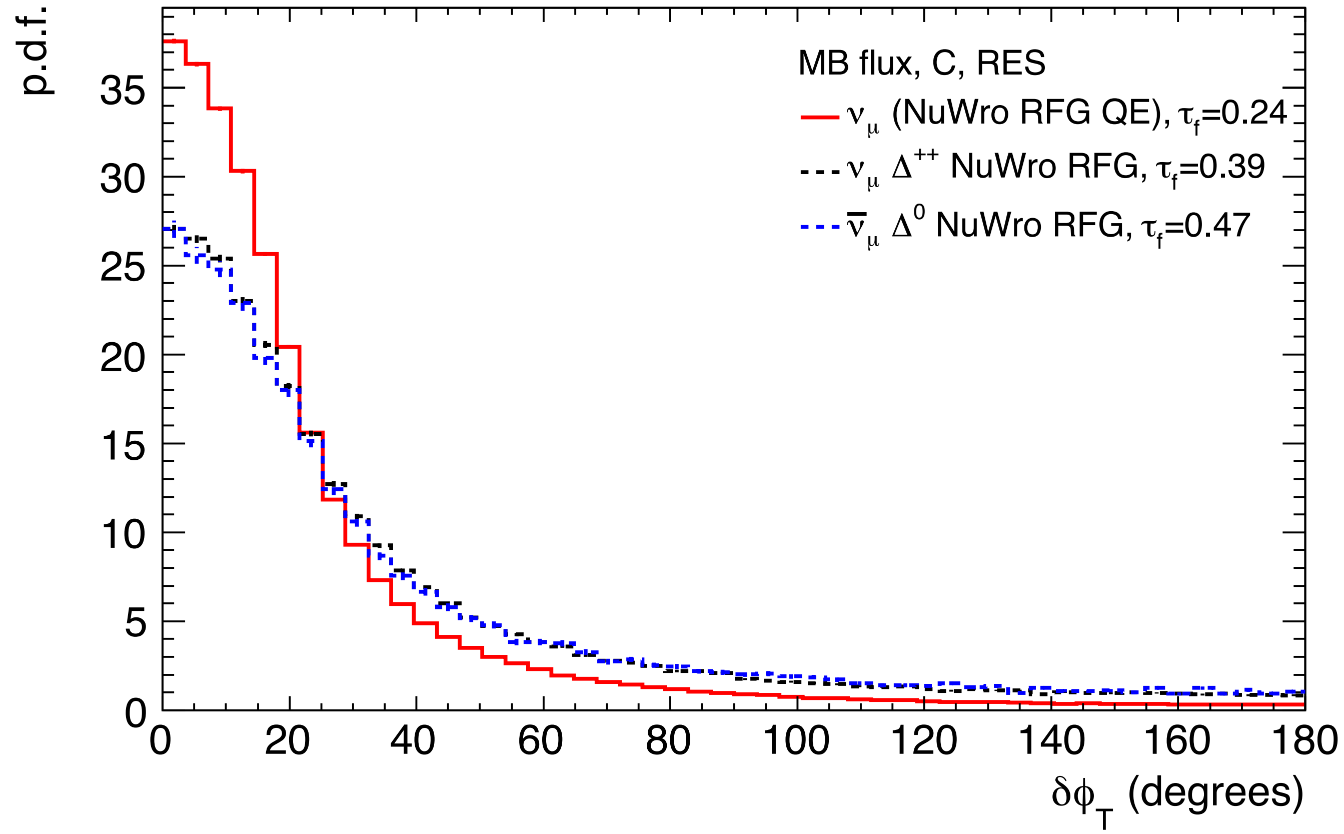




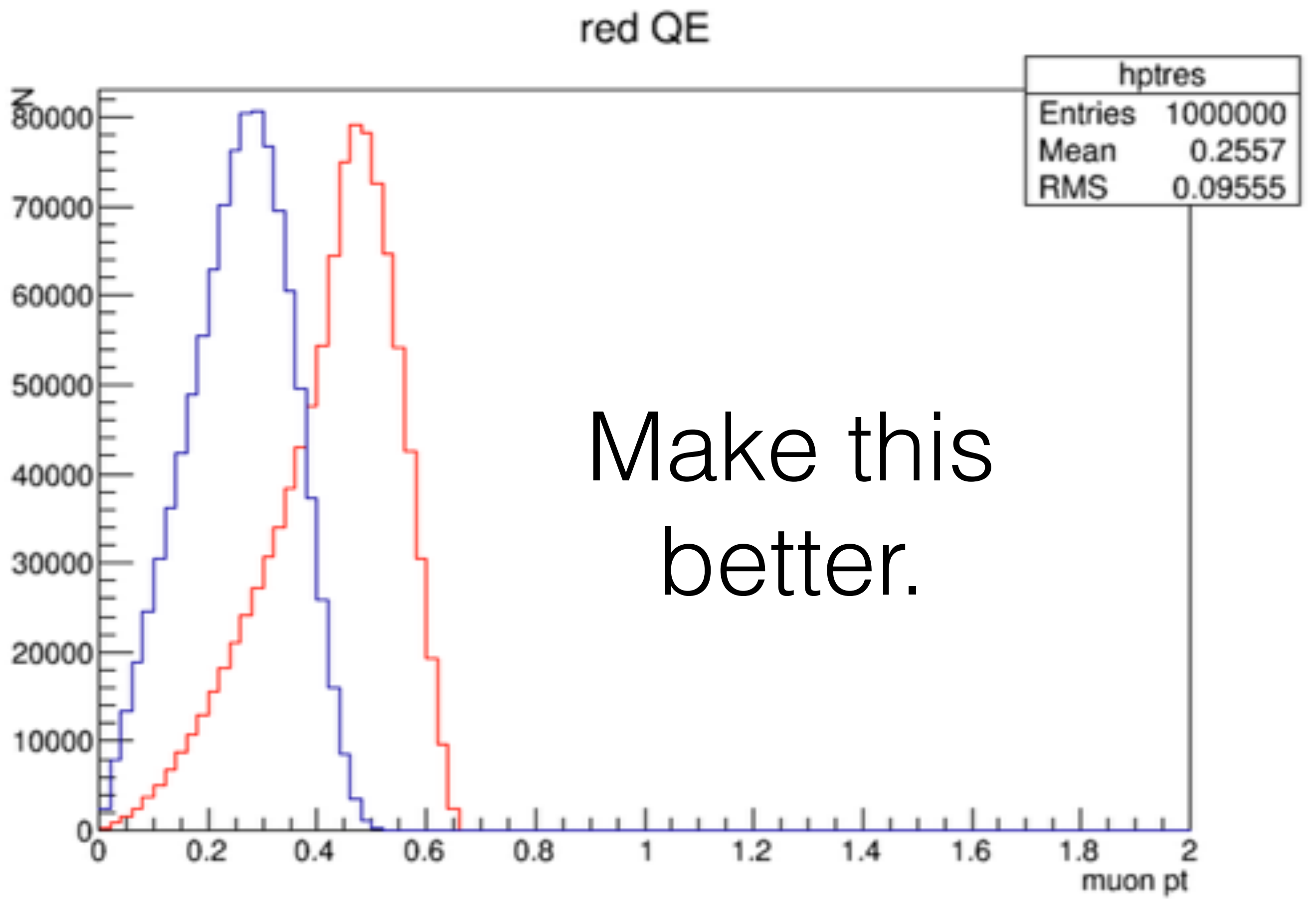
Single Transverse Imbalance in Δ Production



For given δp_T, $\delta\Phi_T$ scales with muon p_T

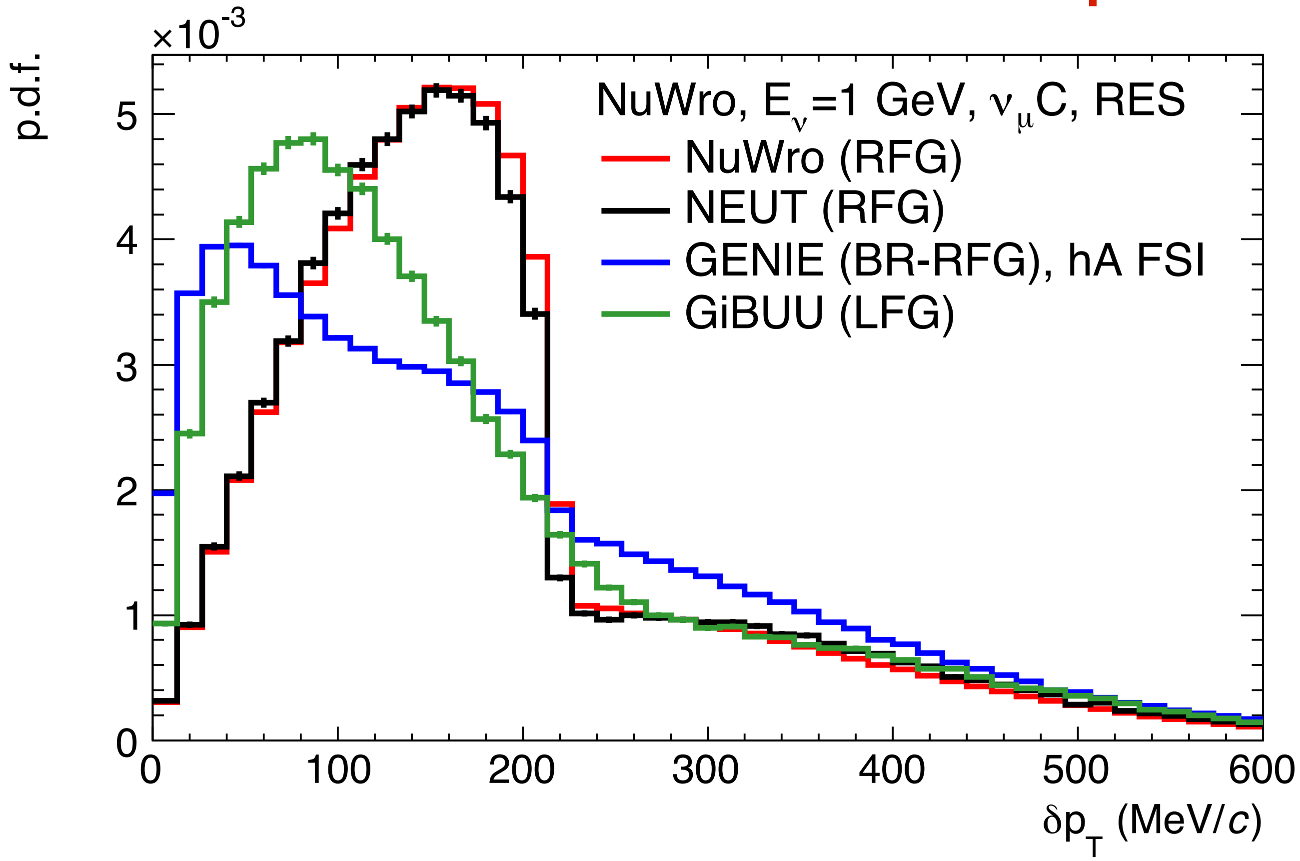


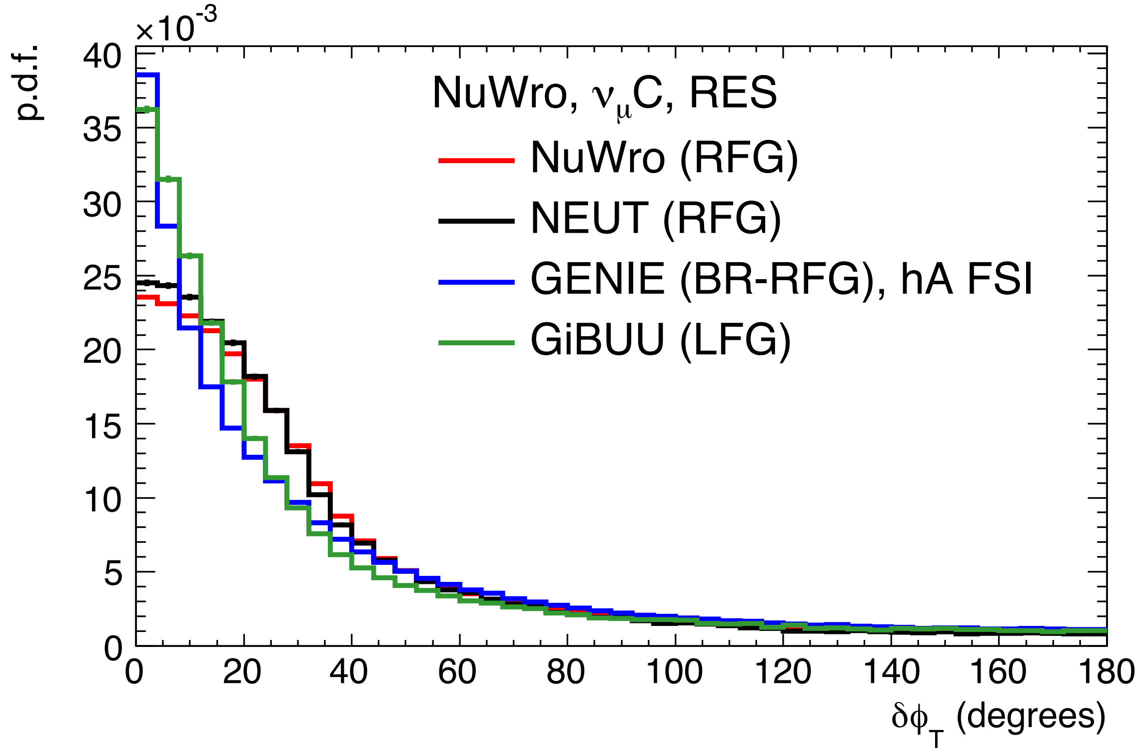
- $\delta\Phi_T$ becomes challenging to use in direct QE–RES comparisons due to larger dependence on the interaction kinematics.
- Can examine in p^{μ}_{T} slices.

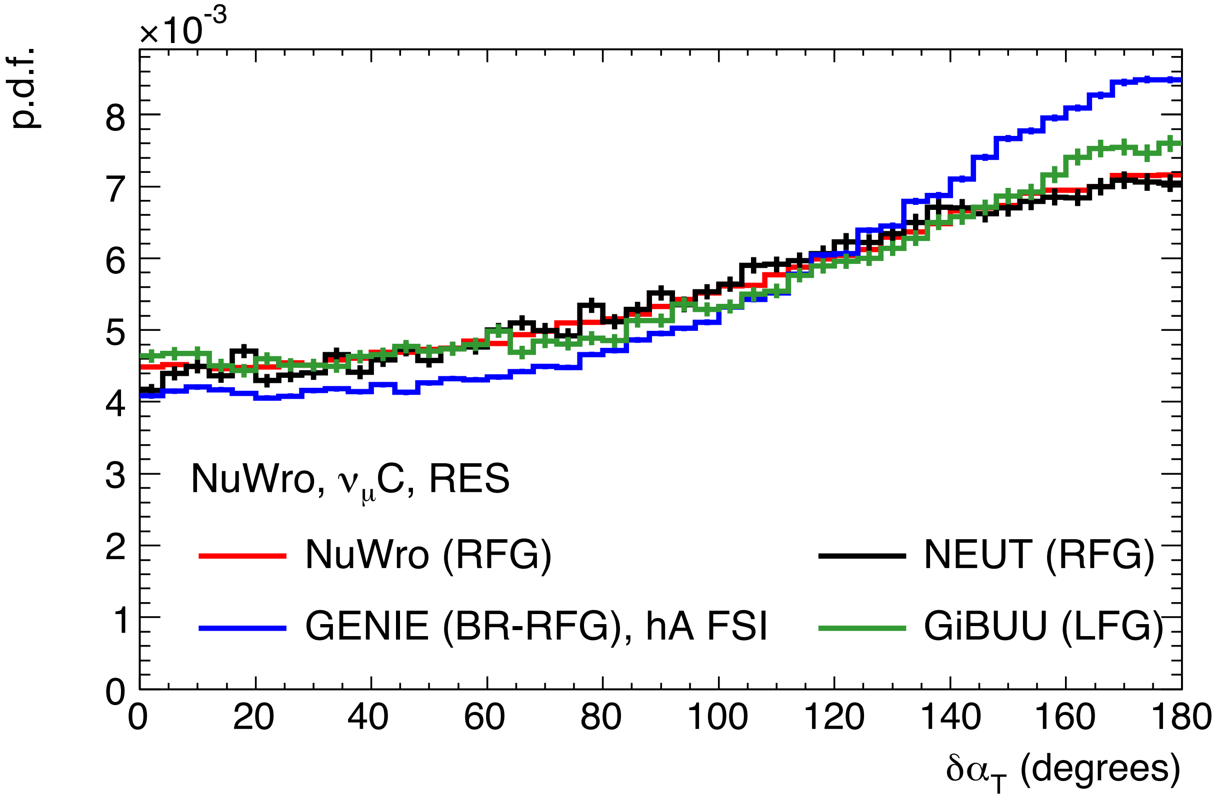


Make this better.

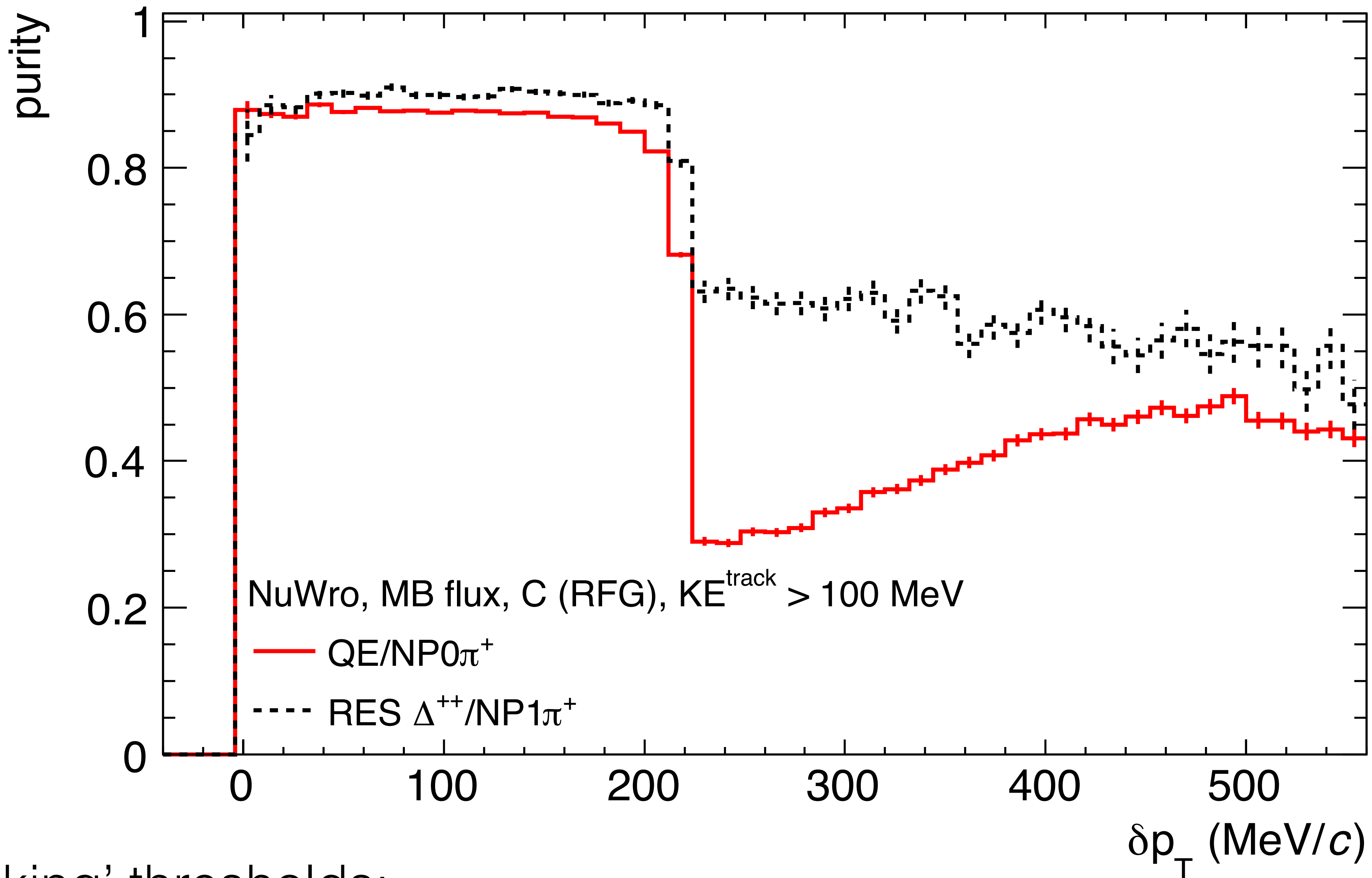
1 GeV Generator Comparisons





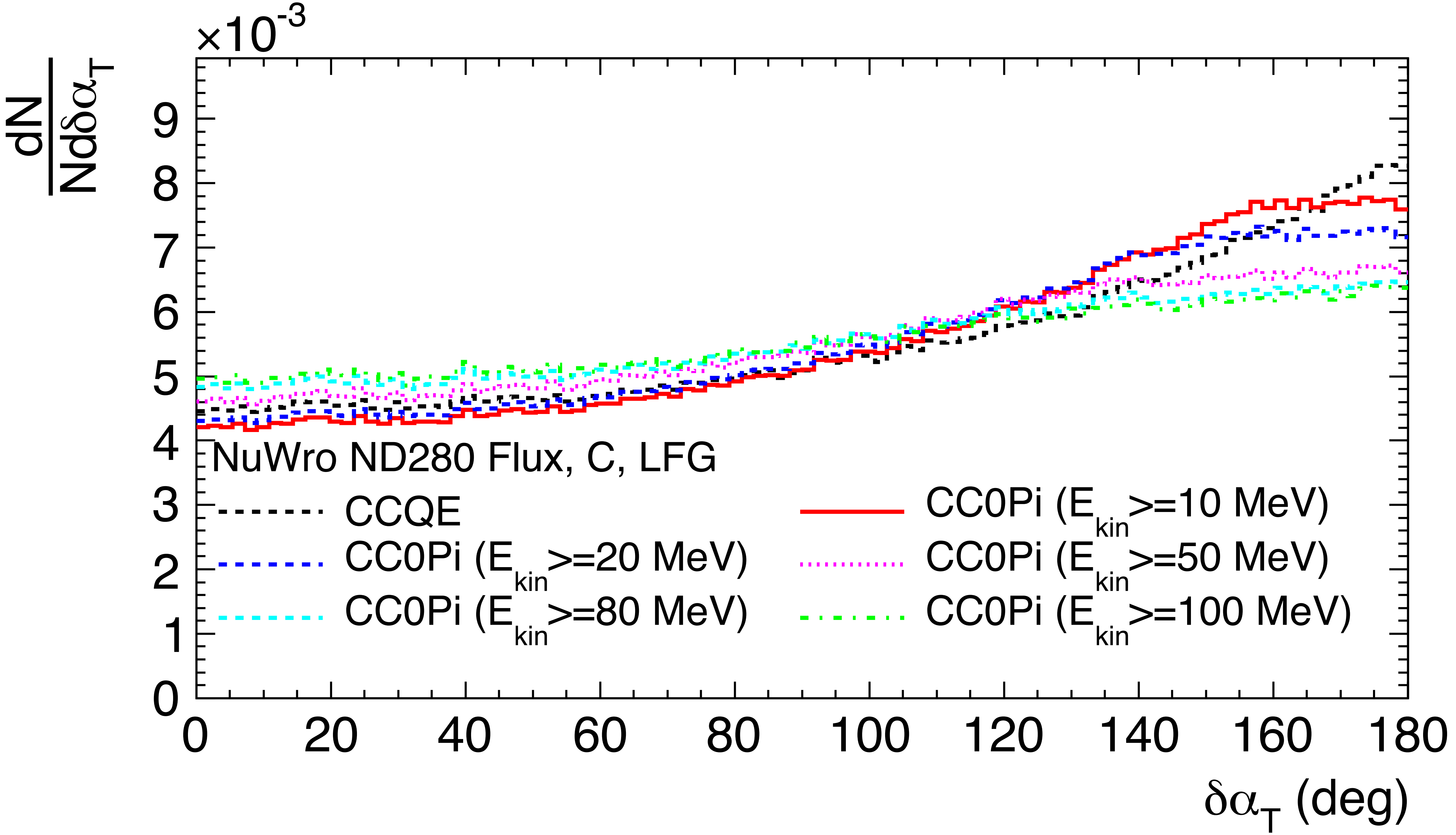


Imbalance as a Selection Variable



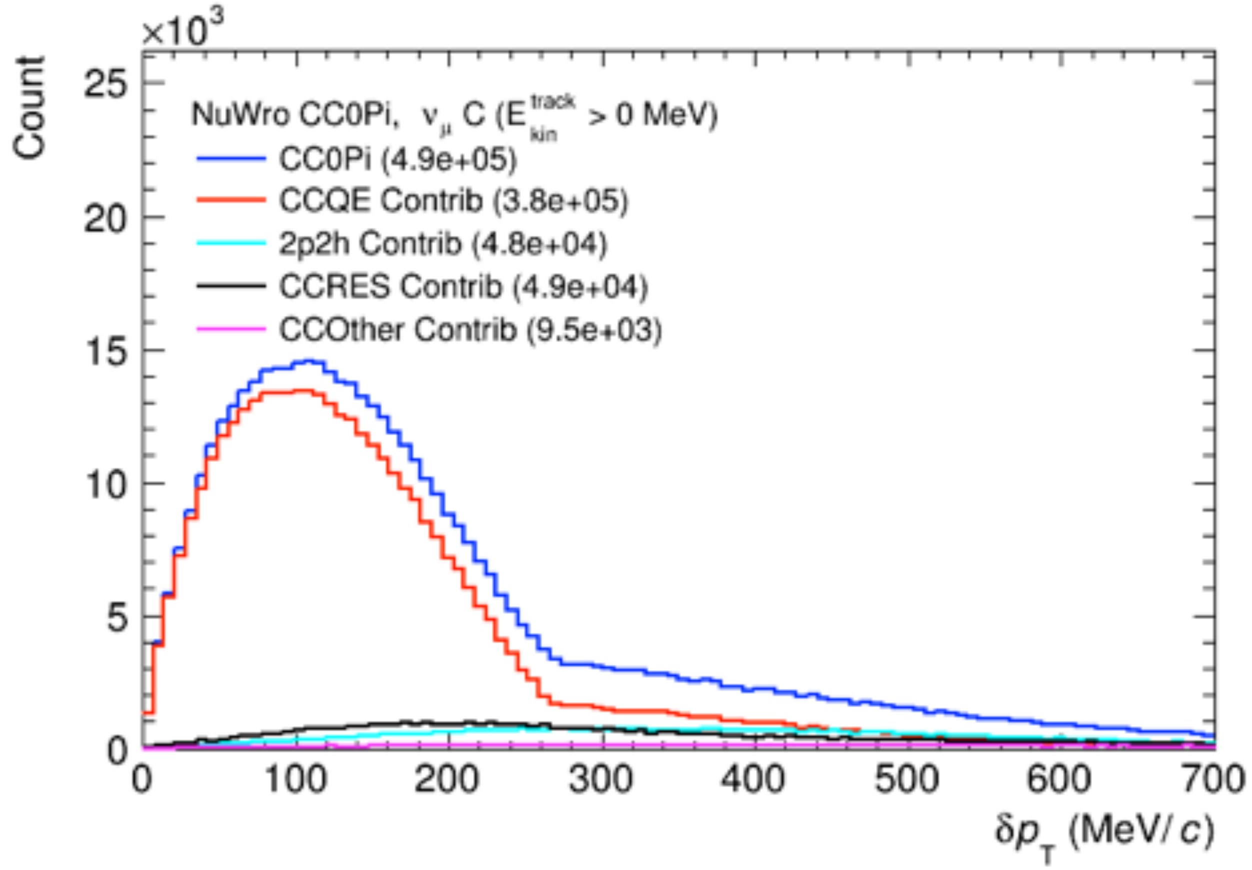
- Apply 'tracking' thresholds:
  - ➡ p, $\pi^{\pm}$: KE^{Track} > 100 MeV.
  - ➡ neutrals undetected.
  - ➡ lepton$^{\pm}$ required.
- Use CCnp0Pi and CCnp1Pi+ to select QE and RES Δ events.
- Data measurements of distributions including hadronic kinematics are important.

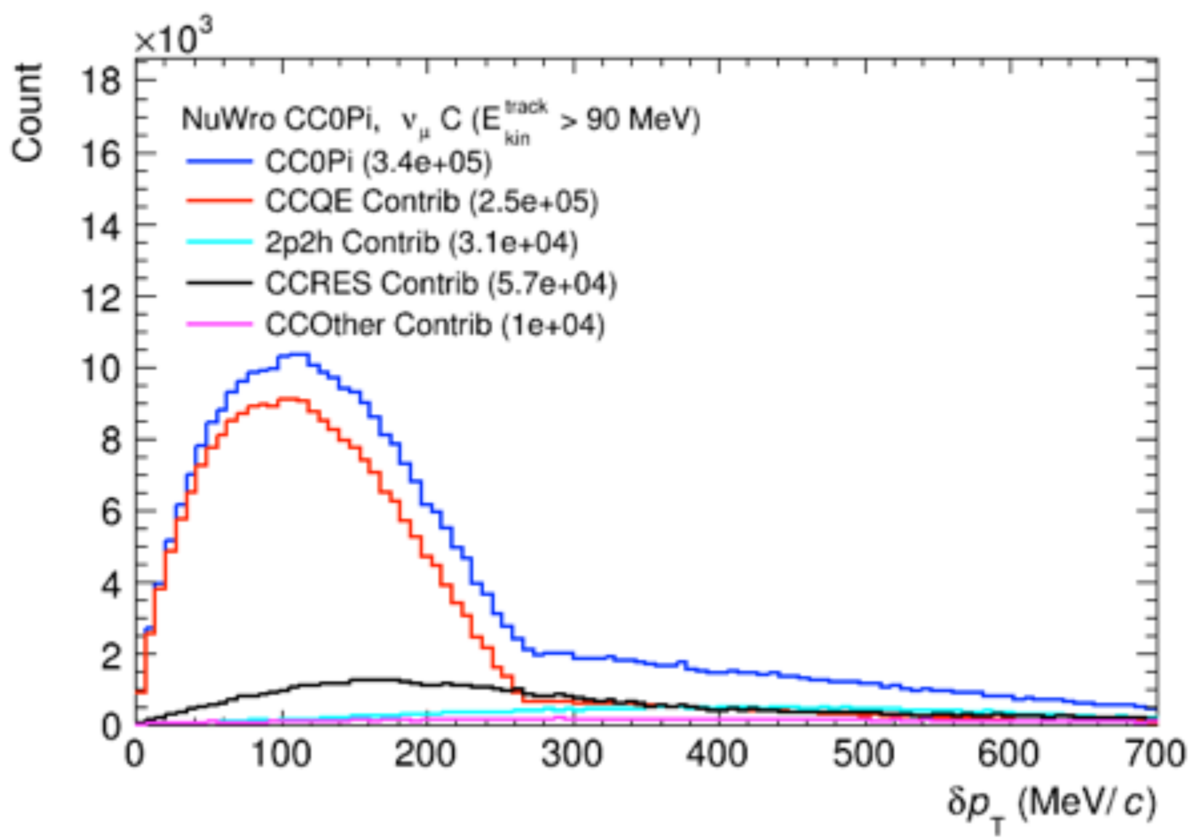
Imbalance as a Selection Variable



Imperial College London

Imbalance as a Selection Variable





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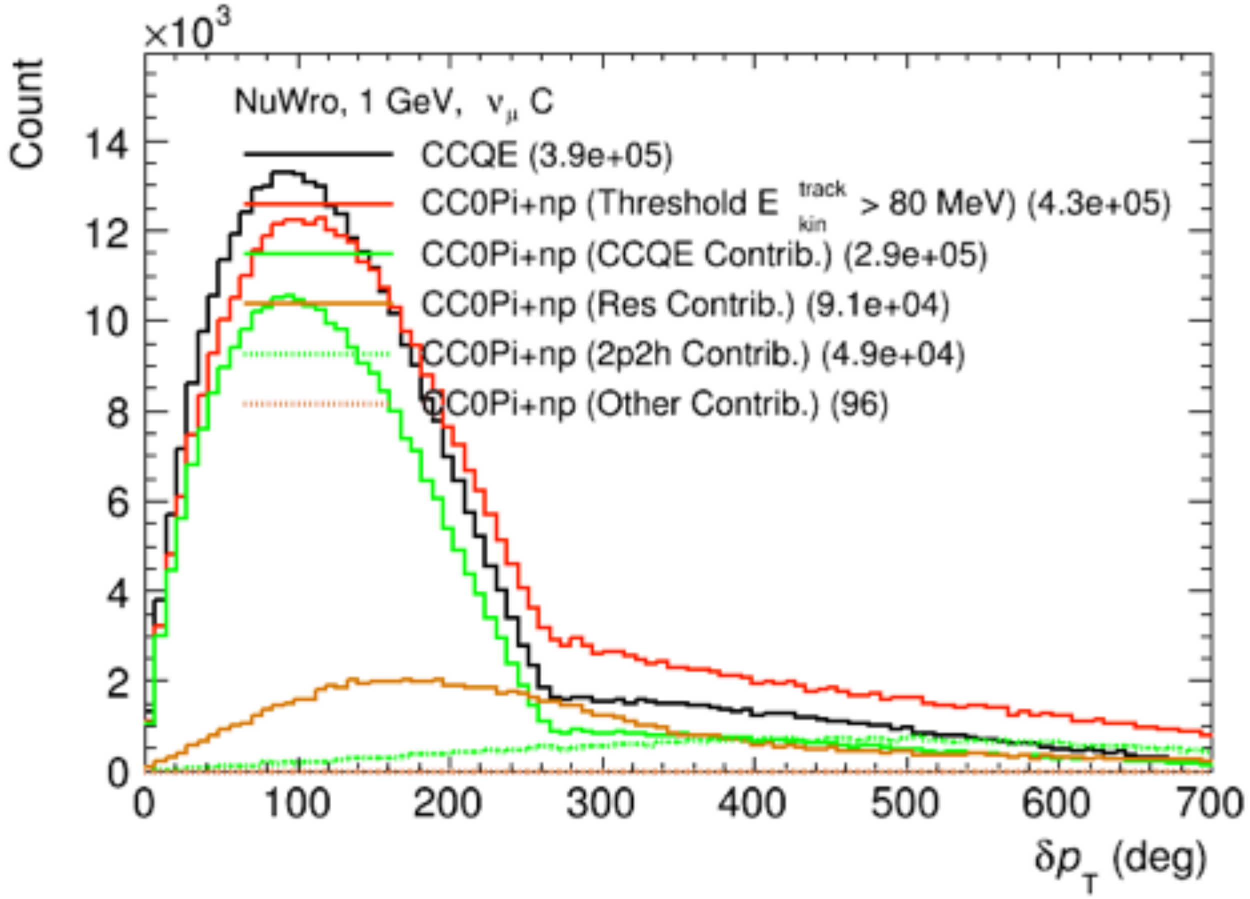
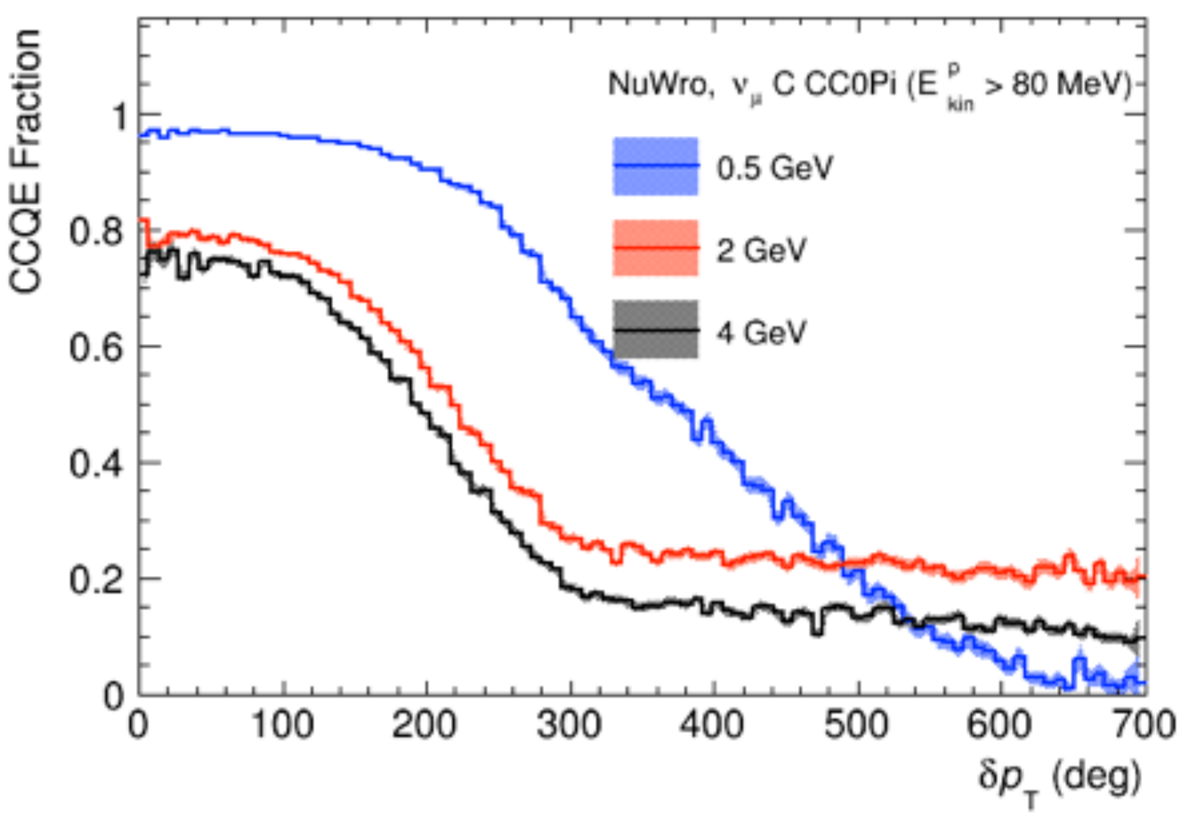
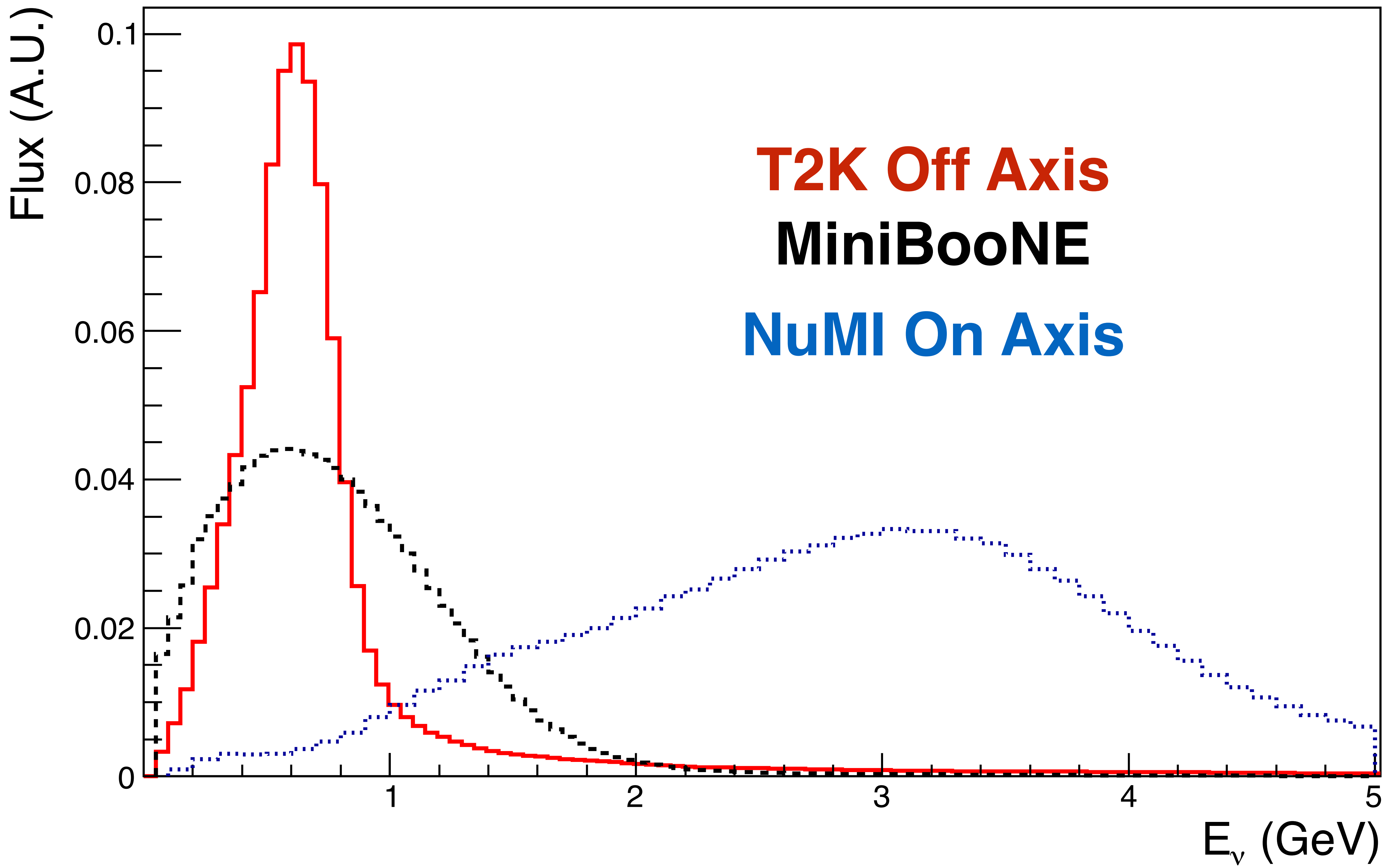


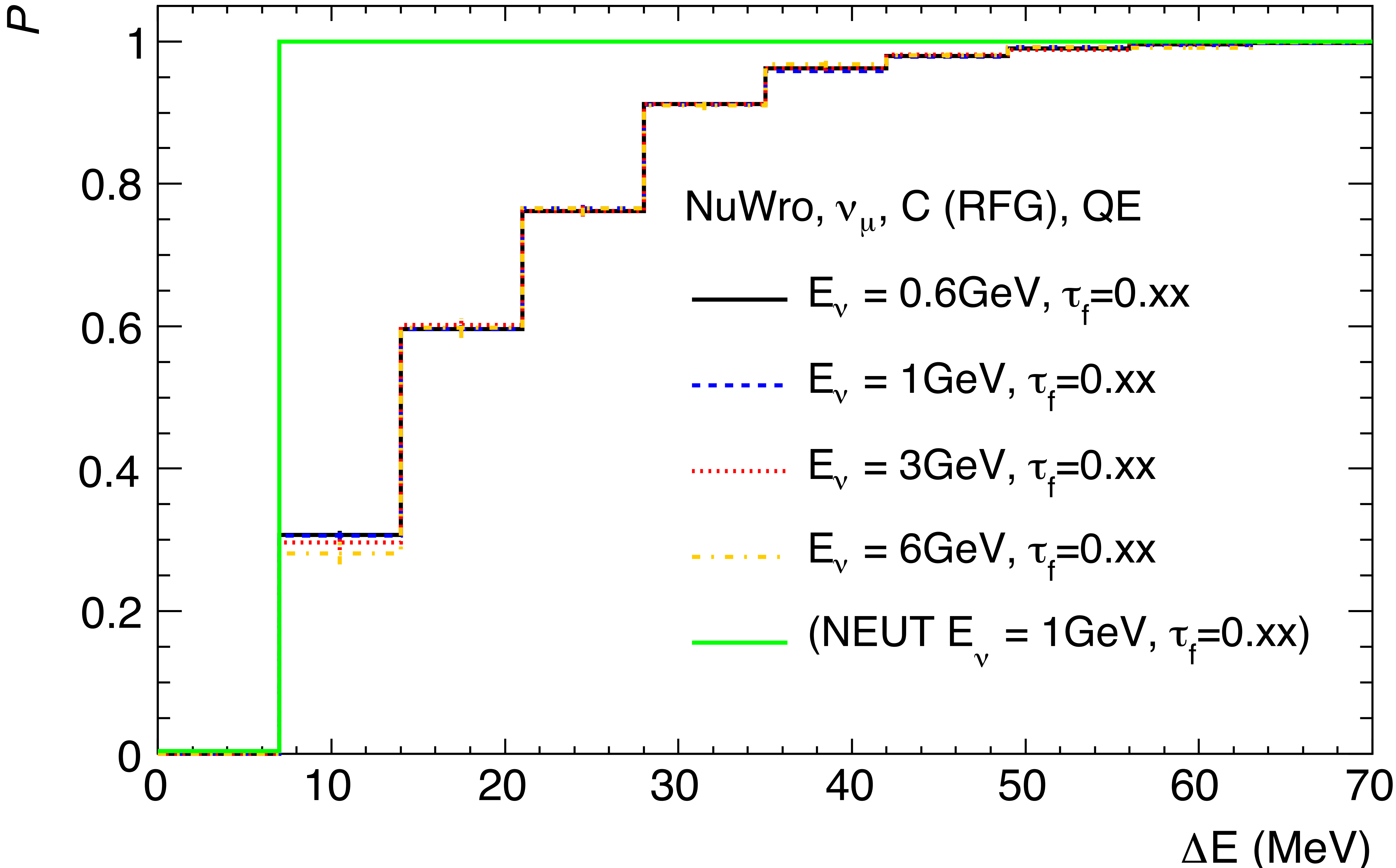


Fluxes Used.



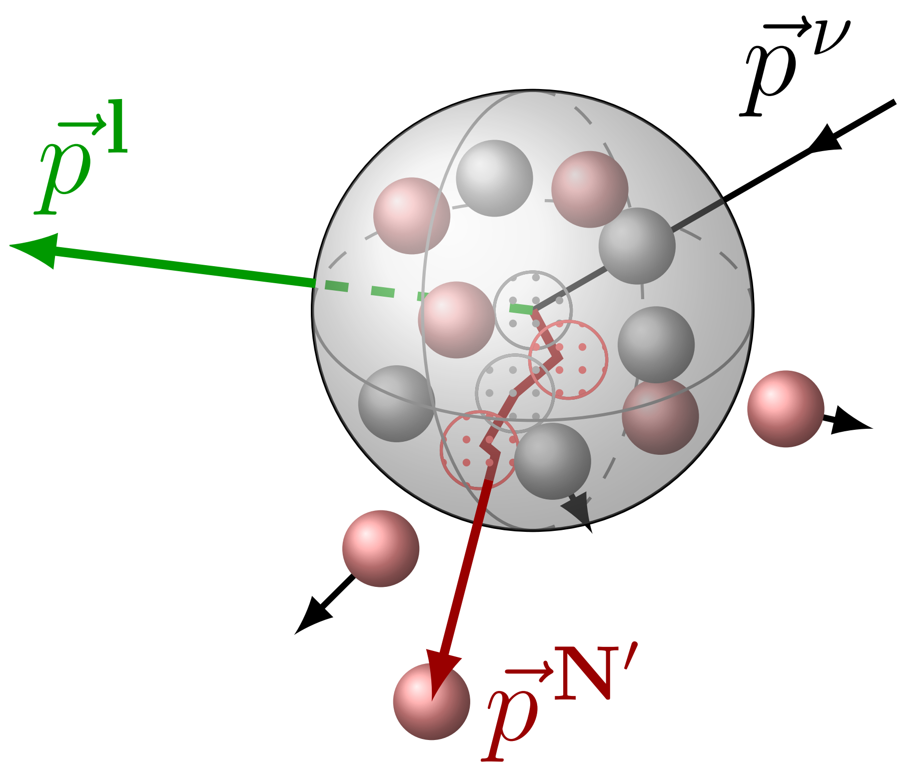
- Fluxes from NuWro input: https://github.com/cjusz/nuwro/tree/master/data/beam

Nuclear Emission and Invisible Energy

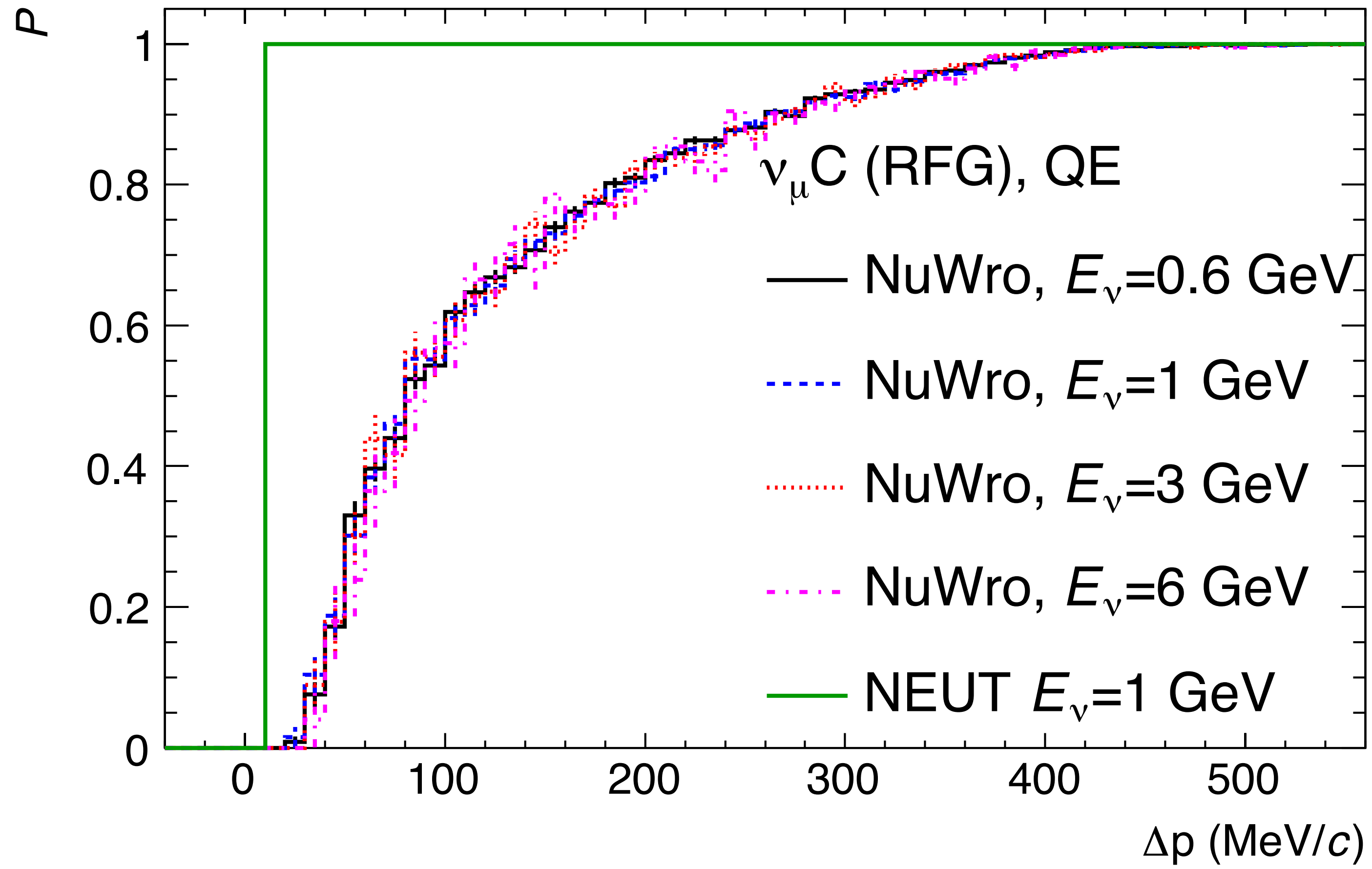


NEUT and NuWro show different Nuclear breakup probabilities as a function of energy transfer to the nucleus.

Nuclear Breakup and FSI Probability



Nuclear emission changes FS topology and carries energy from interacting particles



$$\Delta p = |\vec{p}_{\nu^l} + \vec{p}_N - \vec{p}_l - \vec{p}_{N'}|$$

- Different FSI models predict very different nuclear emission probabilities as a function of momentum transfer to the nucleus.
- Nuclear emission directly responsible for mis-reconstructed neutrino energy—interaction mode ambiguity, neutral emission.
- Parameterise the probability of an FSI by

$$\tau_f = \frac{N^{\mathrm{sel}}_{\Delta p > 10\mathrm{MeV}/c}}{N^{\mathrm{sel}}}$$

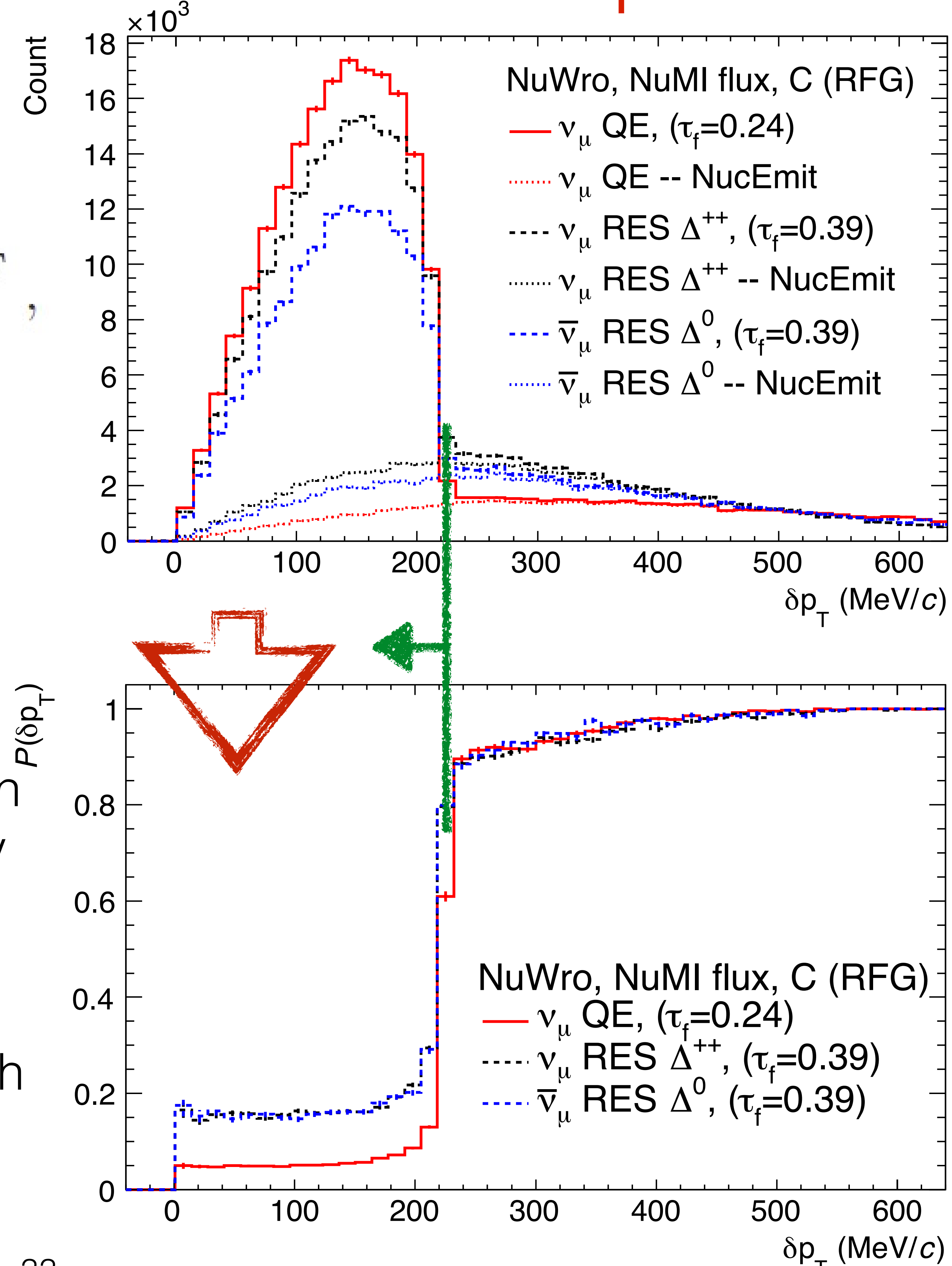
Probability of Nuclear Breakup

L. Pickering

$$\Delta p = |\vec{p}_{\nu^l} + \vec{p}_N - \vec{p}_l - \vec{p}_{N'}|$$

$$P\left(\delta p_{\mathrm{T}}\right) \sim \begin{cases} \tau_{\mathrm{f}} \left\langle P\left(\Delta p\right)\right\rangle, & \text{for } \delta p_{\mathrm{T}} \lesssim p_{\mathrm{F}} \\ \left\langle P\left(\Delta p\right)\right\rangle, & \text{for } \delta p_{\mathrm{T}} \gtrsim p_{\mathrm{F}} \end{cases},$$

- **Below the Fermi momenta,** δp_T is mostly generated by Fermi motion.
- This region is dominated by events with no nuclear emission.
- The probability of nuclear emission in this region should be suppressed by $(1-\tau_f)$.
- *P* measurable in topology-based selections (CC1p0Pi, CC1p1Pi+) with vertex energy and extra protons.



Code Used.

- Developed code to translate the native outputs of NEUT and GiBUU to a RooTracker-like format.
  - **NEUT**: `https://github.com/luketpickering/NeutToRooTracker`
  - **GiBUU**: `https://github.com/luketpickering/GiBUU-t2k-dev`
- Transverse-focussed analysis framework which takes RooTracker input, with modular customisations available for different flavours of RooTracker input (e.g. different generators will have subtle differences/extra information).
  - **NuTRAPAnalysis**: `https://github.com/luketpickering/NuTRAPAnalysis`
- All questions/comments/issues welcome `lp208[at]ic[dot]ac[dot]uk` or GitHub issue tracker!
- Caveat: You need a C++11 enabled compiler!

Generator Versions

- NEUT: 5.3.3
- GENIE: 2.8.6
- GiBUU: release 1.6
- NuWro: 11q

Can we see π^-

- Non-exhaustive previous measurements:
  - MINERvA CC $\pi\pm$ production: arXiv:1406.6415 -- FERMILAB-PUB-14-193-E.
  - MINERvA CCCoh $\pi\pm$: arXiv:1409.3835 -- Phys. Rev. Lett. 113, 261802 (2014).
  - The Zeller/Formaggio review arXiv:1305.75131 -- Rev. Mod. Phys. 84, 1307 (2012) which contain some results on D2 and CF3Br targets.

- From an FSI/SI standpoint:
  - TAPS: Solid BaF2 calorimeter.
  - GENIE 2.10 User and Physics Manual
    - Figure 2.17 -- contains comparisons of $\pi\pm$ thin target data with INC calculations.
    - The GENIE FSI hA model assumes that $\pi+$ FSI $\simeq\pi-$ FSI.
      - —This is the default FSI model in GENIE v2.4.0 [sic], the public version as of now. It uses identical cross section for $\pi+$ and $\pi-$ and for p and n.—
  - GiBUU
    - Various, but bits towards the end such as Fig. B.53. show that I wouldn't expect $\pi-$ to disappear more much more frequently, in flight, than a $\pi+$.