A study of nuclear effects in neutrino interactions using transverse kinematic imbalance

Xianguo Lu,[3] L. Pickering,[2] S. Dolan,[3] G. Barr,[3] D. Coplowe,[3]
Y. Uchida,[2] D. Wark,[3,4] M. Wascko,[2] A. Weber,[3,4] and T. Yuan[1]

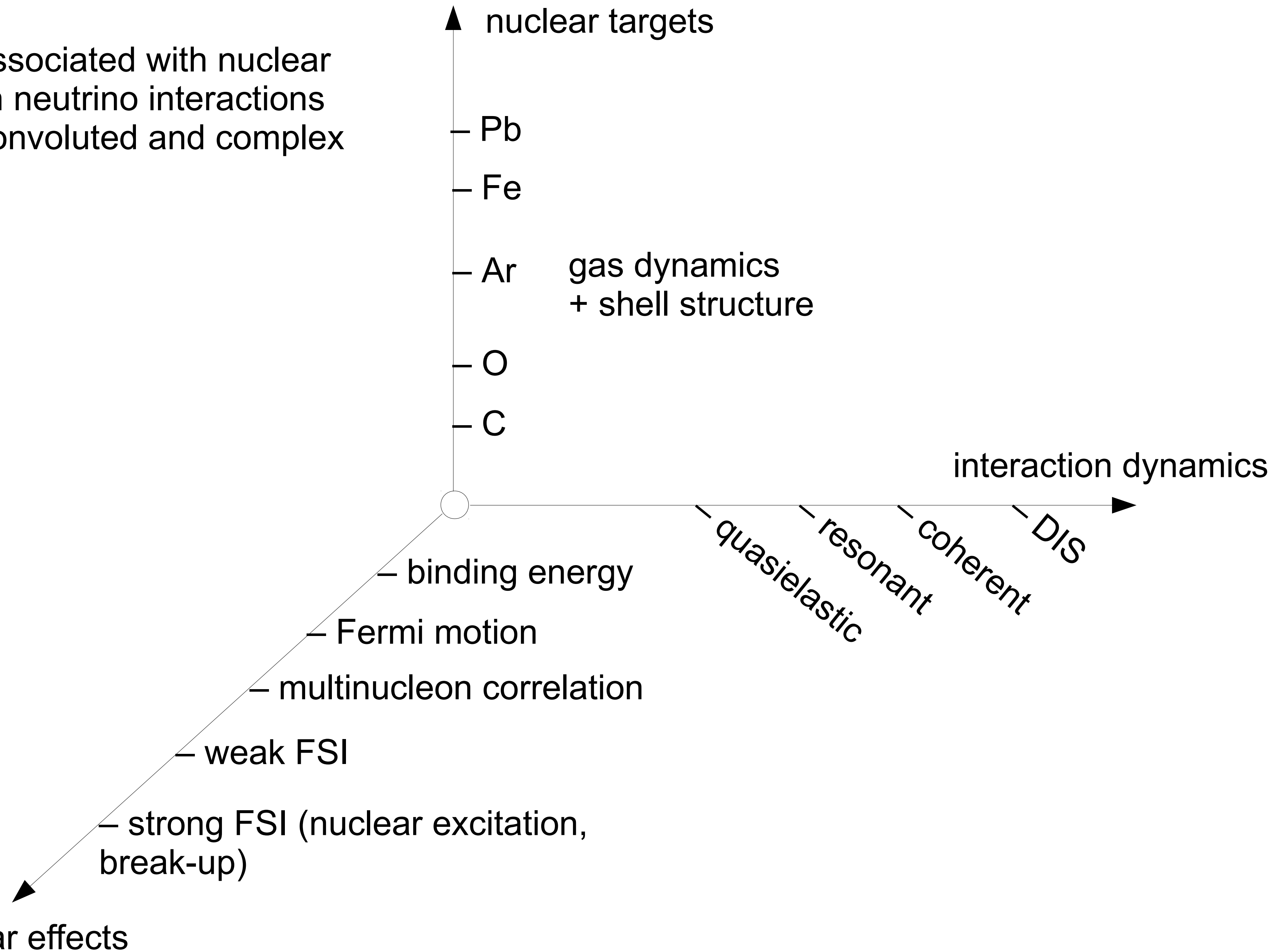
[1]*University of Colorado at Boulder, Department of Physics, Boulder, Colorado, USA*
[2]*Imperial College London, Department of Physics, London, United Kingdom*
[3]*Department of Physics, Oxford University, Oxford, Oxfordshire, United Kingdom*
[4]*STFC, Rutherford Appleton Laboratory, Harwell Oxford, Oxfordshire, United Kingdom*

NuWro Group Meeting
2-Nov-2015

3659

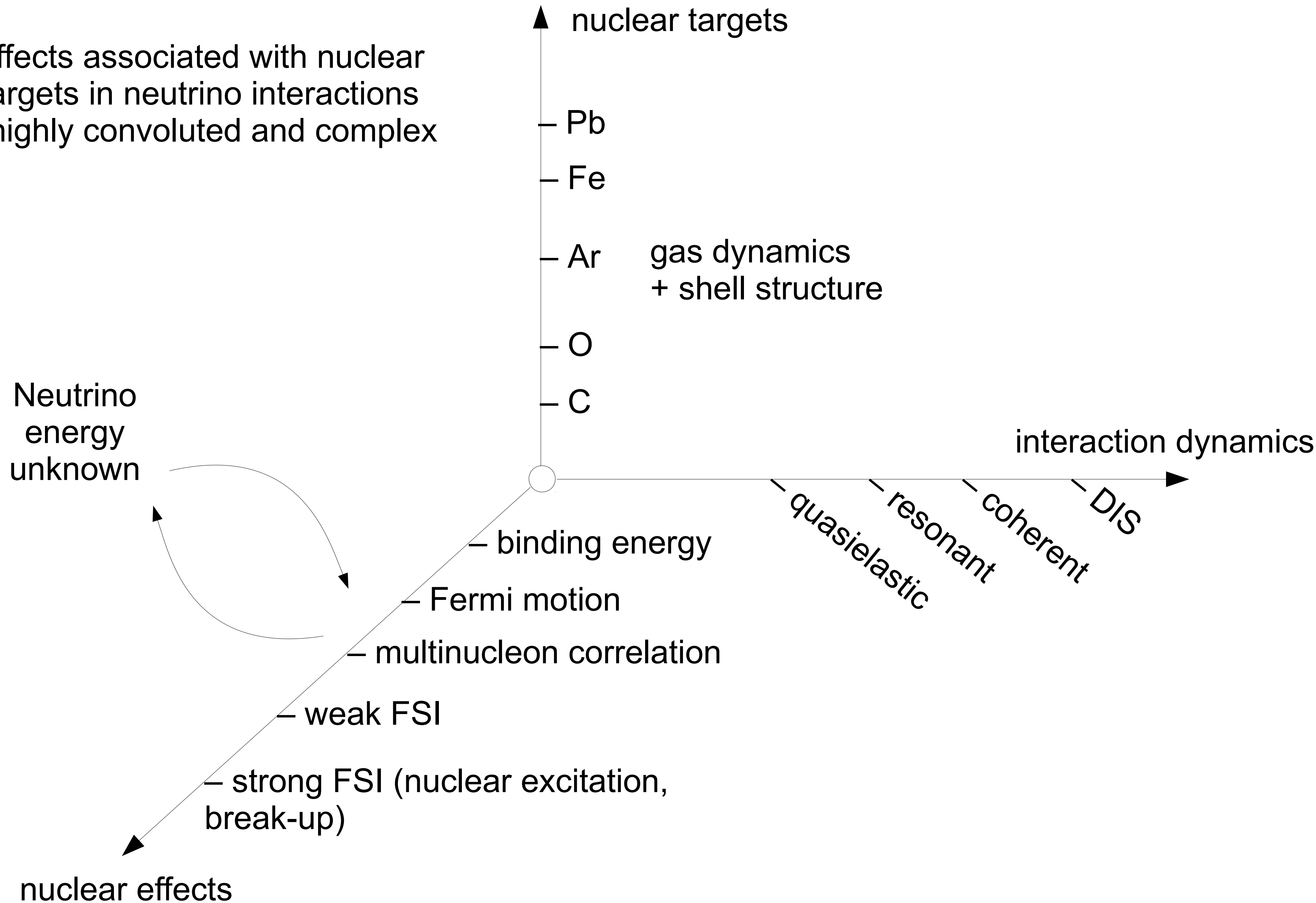
Introduction

Effects associated with nuclear targets in neutrino interactions – highly convoluted and complex



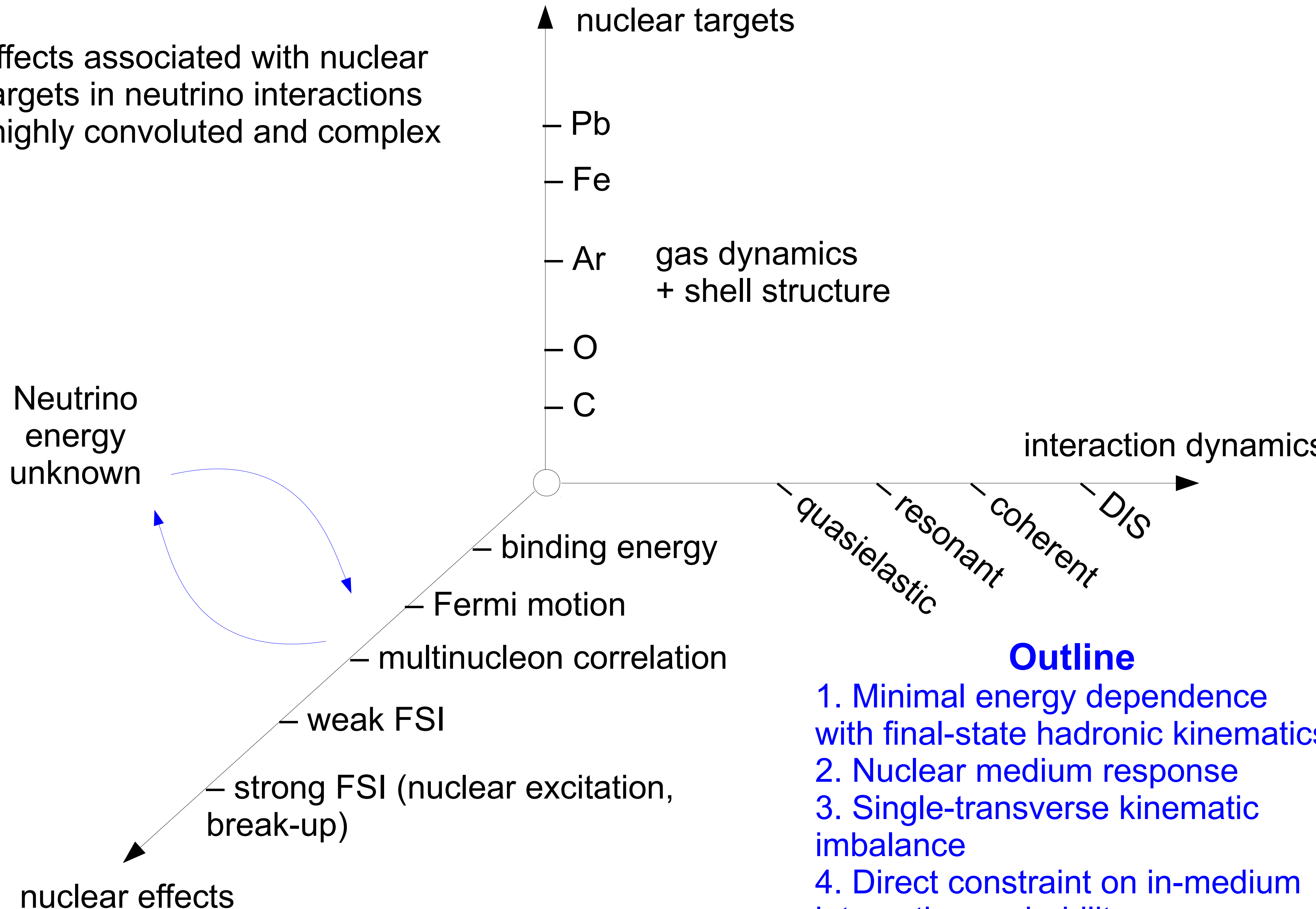
Introduction

Effects associated with nuclear targets in neutrino interactions – highly convoluted and complex



Introduction

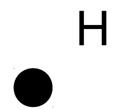
Effects associated with nuclear targets in neutrino interactions – highly convoluted and complex



Outline

1. Minimal energy dependence with final-state hadronic kinematics
2. Nuclear medium response
3. Single-transverse kinematic imbalance
4. Direct constraint on in-medium interaction probability

Introduction



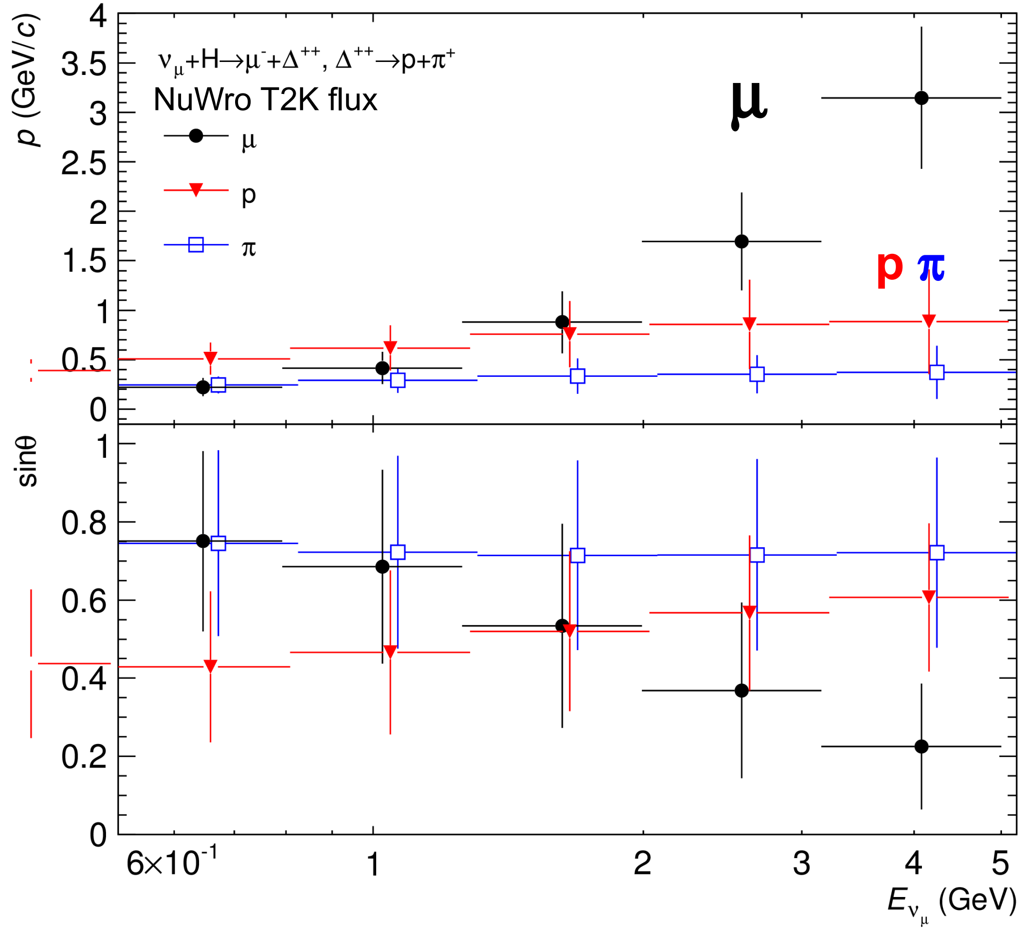
Outline

5. Reconstruction of energy spectra of neutrino beams independent of nuclear effects

Minimal energy dependence with final-state hadronic kinematics

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

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 $E_\mathrm{N}^2 = p_\mathrm{N}^2 + m_\mathrm{N}^2$



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

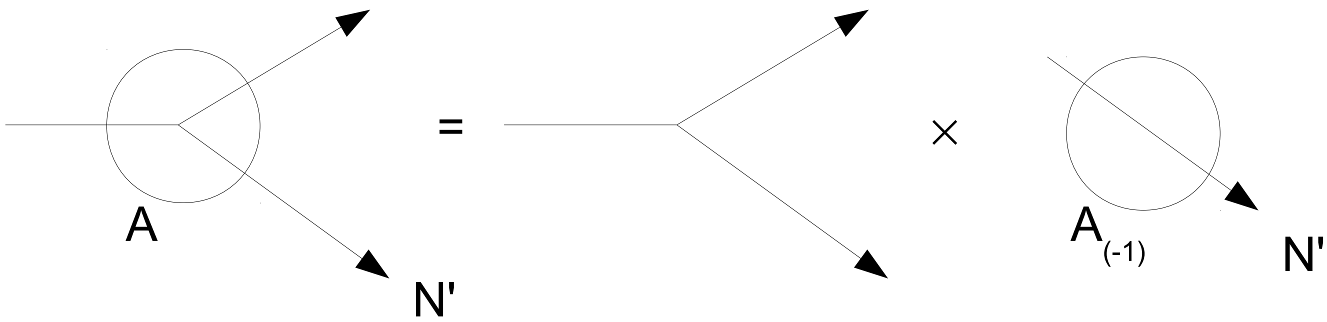
Fermi motion isotropic, ~ 0 on average

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

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

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

Factorization assumption:



FSI
(not considering absorption or charge exchange)

FSI all determined by N' momentum.

Two-step approach:

1. In-medium interaction probability τ_f

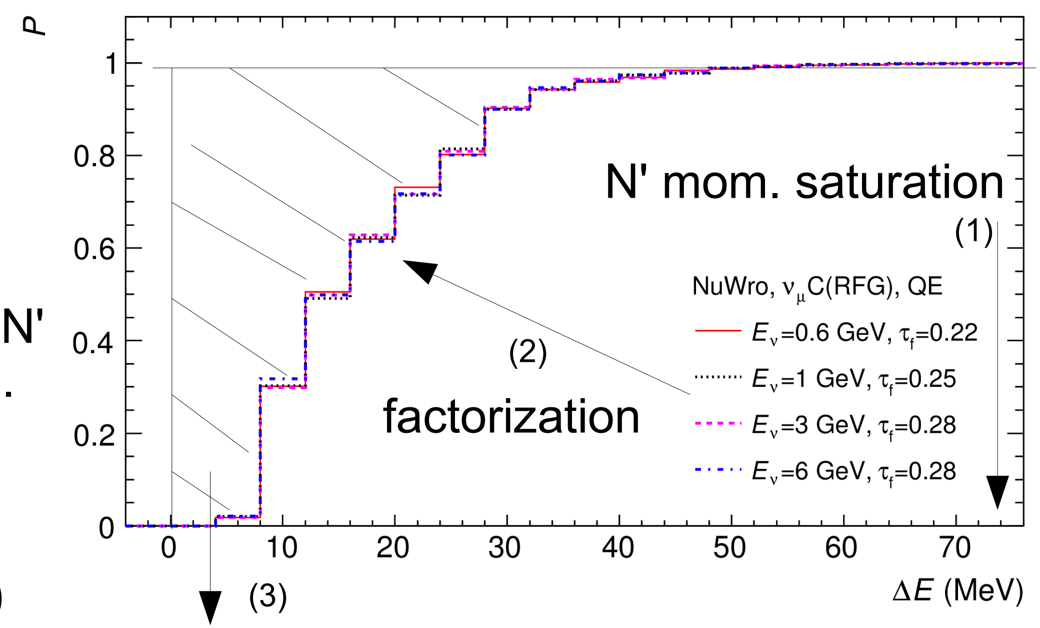
(1-τ_f is the fraction not having FSI at all).

2. Energy-momentum transfer $(\Delta E, \Delta\vec{p})$ from N' to the nucleus, only non-zero when there is FSI.

Medium response:

Nuclear emission: nucleus being excited or broken-up, emitting particles. Probability: *P(ΔE)*

In practice, slow emission = no emission.



Intrinsically invisible energy (in a perfect detector)

Nuclear medium response

$$\langle E_{\rm inv} \rangle = \tau_{\rm f} \int \Delta E \eta\left(\Delta E\right) \left[1 - P\left(\Delta E\right)\right] {\rm d}\Delta E,$$

$\langle E_{\rm inv} \rangle$: (intrinsically) invisible energy

$\tau_{\rm f}$: In-medium interaction probability

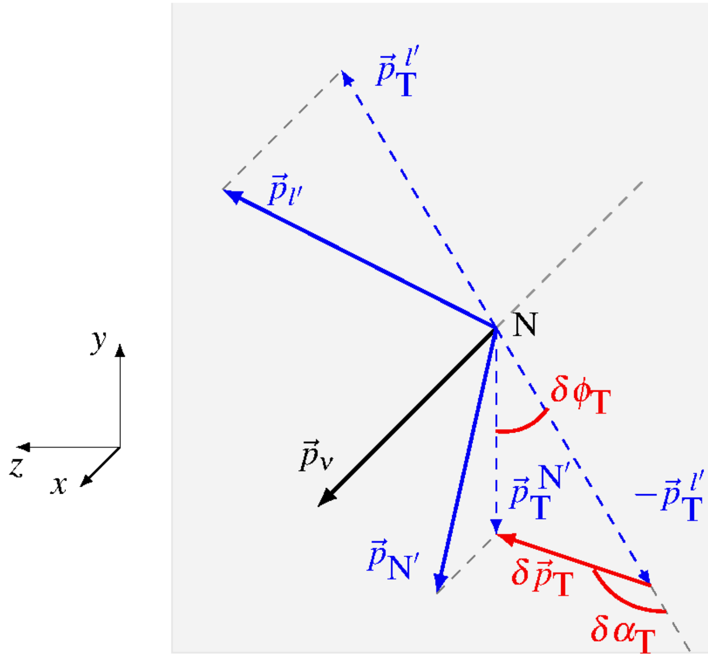
$\eta(\Delta E)$: distribution of ΔE in case of FSI

ΔE: (in-medium) energy transfer

P(ΔE) hasn't beem experimentally constrained *yet*.
Significance:
1. precise neutrino energy measurement (with calorimetry)
2. in hydro-nucleus target, high P(ΔE) nuclei more easy to be tagged and better for neutrino-hydrogen interaction selection (more discussions in later slides)
3. important to describe measured vertex energy

However, ΔE and ΔP not experimentally accessible in ν-A scattering.
"Next of kin" is found → next slide

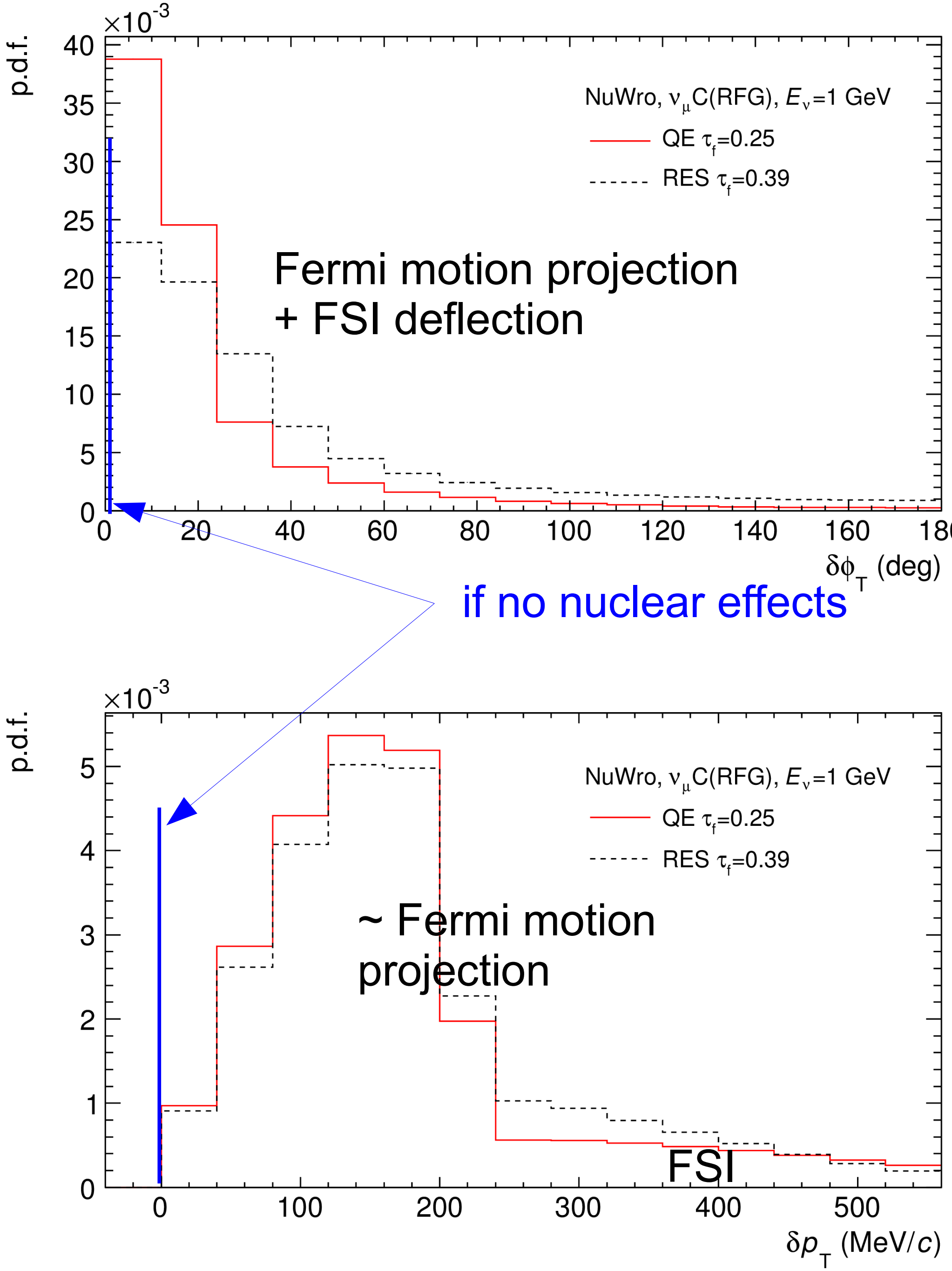
Single-transverse kinematic imbalance



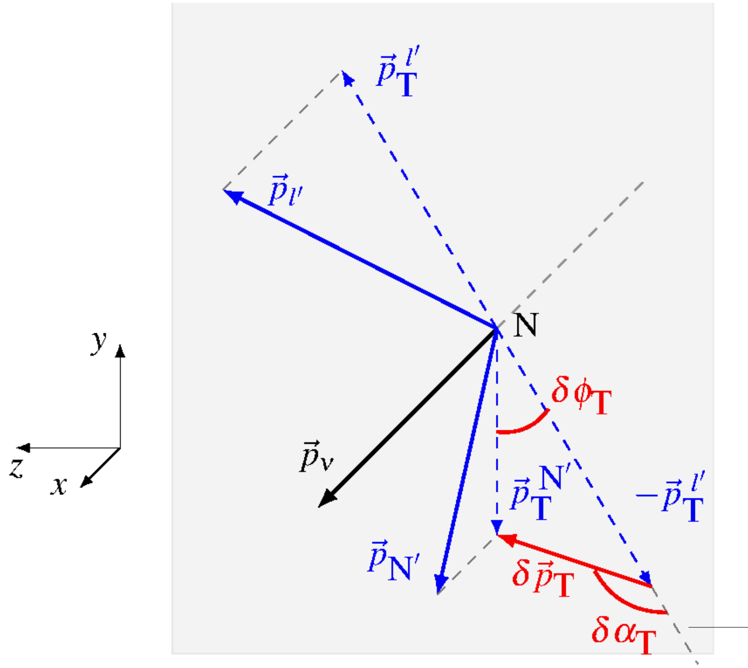
$$\delta\phi_T \equiv \arccos \frac{-\vec{p}_T^{\,l'} \cdot \vec{p}_T^{\,N'}}{\left|\vec{p}_T^{\,l'} \cdot \vec{p}_T^{\,N'}\right|},$$

$$\delta\vec{p}_T \equiv \vec{p}_T^{\,l'} + \vec{p}_T^{\,N'},$$

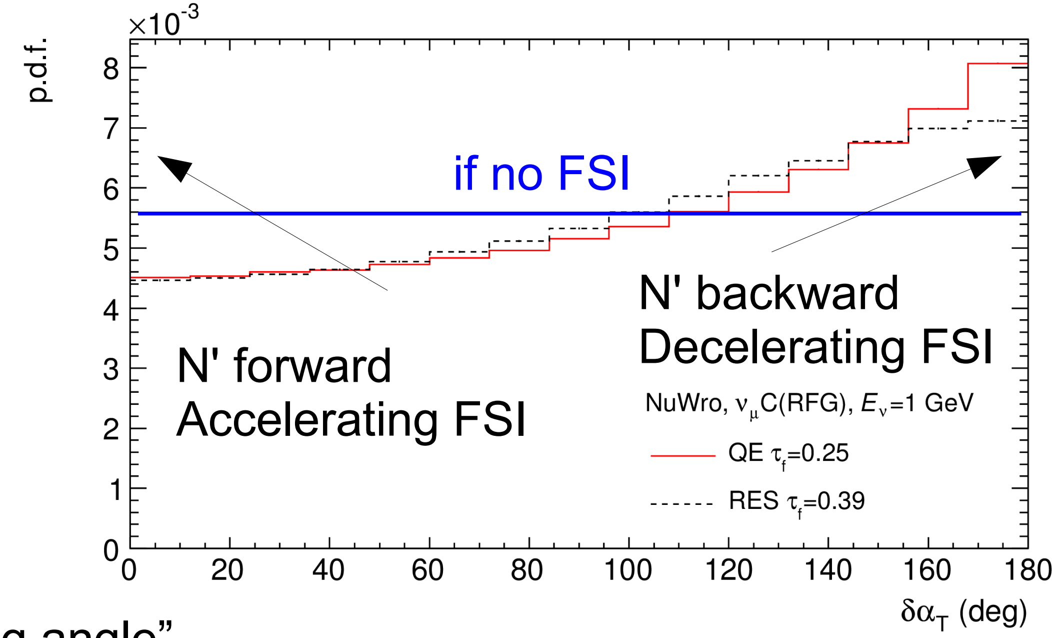
$$\delta\alpha_T \equiv \arccos \frac{-\vec{p}_T^{\,l'} \cdot \delta\vec{p}_T}{\left|\vec{p}_T^{\,l'} \cdot \delta\vec{p}_T\right|},$$



Single-transverse kinematic imbalance



"boosting angle"



Previous measurement:

NOMAD (2009): $\delta\phi_T$, δp_T QE event selection

MINERvA (2015): $\delta\phi_T$ QE-like evnts

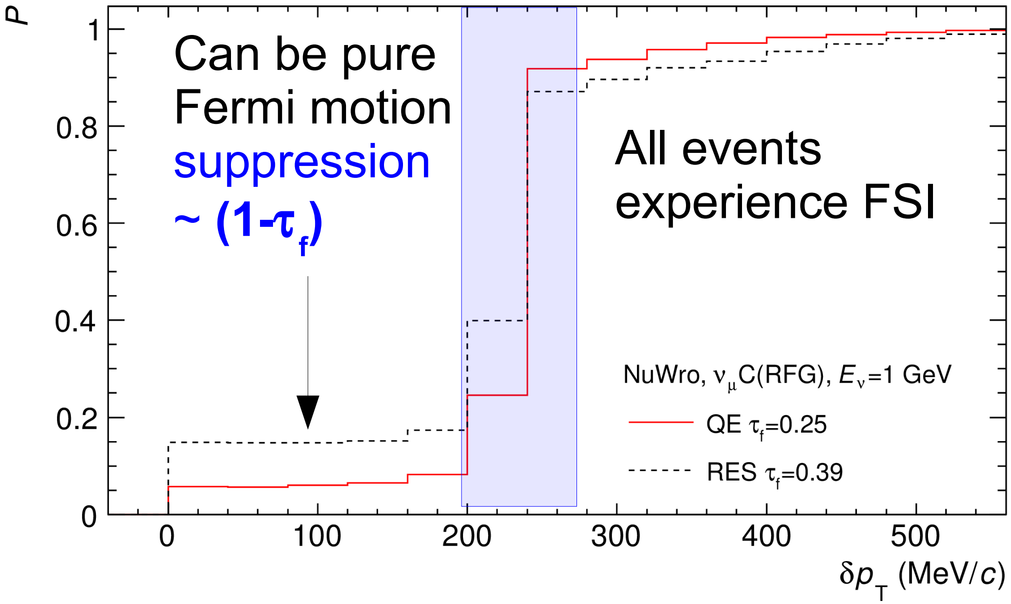
T2K-INGRID: $\delta\phi_T$ QE event selection

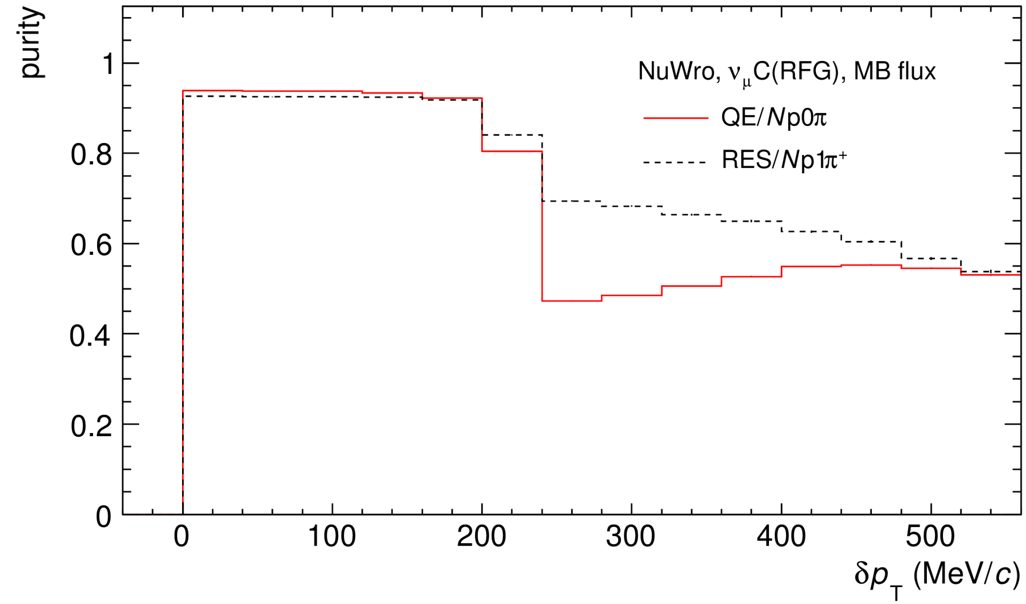
No published measurement for "boosting angle" $\delta\alpha_T$

None of them is studied in RES.

In RES, nuclear effects in anti-nu can be studied! (T2K anti-nu (RHC) flux file to be included in NuWro release?)

Direct constraint on in-medium interaction probability





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

Fermi motion uncorrelated to in-medium momentum transfer (2% effect)

Challenging measurement
Requiring
impurity < true nuclear emission probability

Extensions

- Multinucleon correlations
  - Initial state in-medium energy-momentum transfer
  - Emission of correlated nucleons: initial state nuclear emission

    → non-distinguishable from final-state transfer and emission

    → same probabilistic approach can be applied!

    → FSI, multinucleon correlations could be separated by comparing QE, RES, 2π production
- Applications in e-A scattering: more kinematic imbalance can be used to study common nuclear effects. How about testing with eWro? And reanalyzing historical e-A data? Factorization means that e-A FSI = ν-A FSI.

Double-Transverse Symmetry

- Δ(1232) for ν and anti-ν,

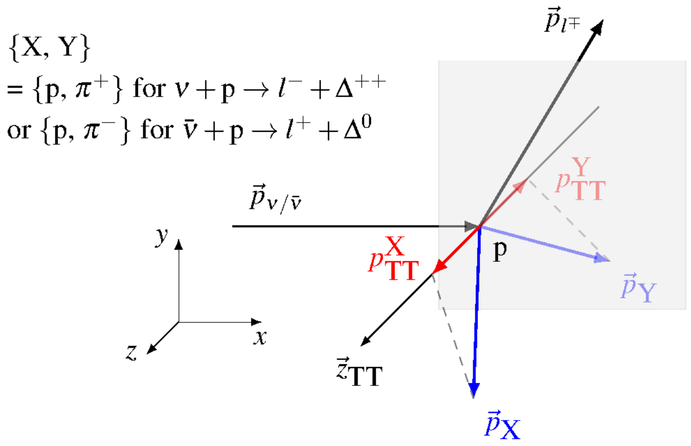
  highly symmetrical systems:

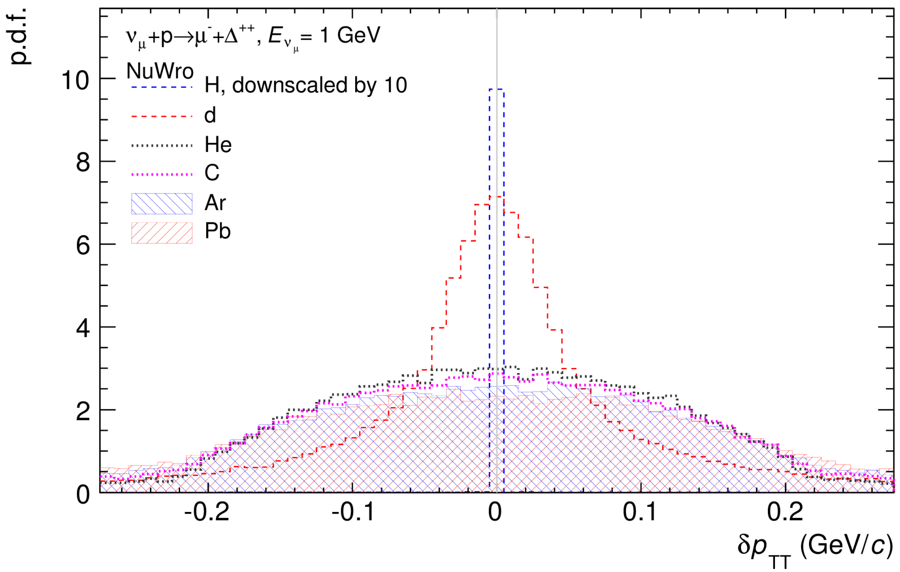
  $$\{X, Y\} = \{p, \pi^+\} \text{ for } \nu + p \to l^- + \Delta^{++} \text{ or } \{p, \pi^-\} \text{ for } \bar{\nu} + p \to l^+ + \Delta^0$$

- Double-transverse momentum imbalance

  $$\delta p_{TT} \equiv p_{TT}^{p} + p_{TT}^{\pi}$$

  - 0 for hydrogen
  - Symmetric broadening – irreducible
    - by Fermi motion *O*(200 MeV)
    - further by FSI
  - After reconstruction
    - Still symmetric
    - Hydrogen shape is only detector response → *"Improving the detector resolution … eventually an event-by-event selection of hydrogen interactions"*[1]
    - ν energy resolution only detector response → simultaneously improved with selection.





[1] Phys.Rev. D92 (2015) 5, 051302

Summary

- Extensive examination of kinematic imbalance in ν-A scattering has been done: single-transverse and double-transverse
- Rich physics program, *terra incognita*
- Experimental status: T2K measurement on-going, MINERvA measurement (Oxford group) about to start

- NuWro is excellent! Has been great fun to play with it!

BACKUP

END