Reconstruction of energy spectra of neutrino beams independent of nuclear effects

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Science & Technology Facilities Council

3789; 4357

Introduction

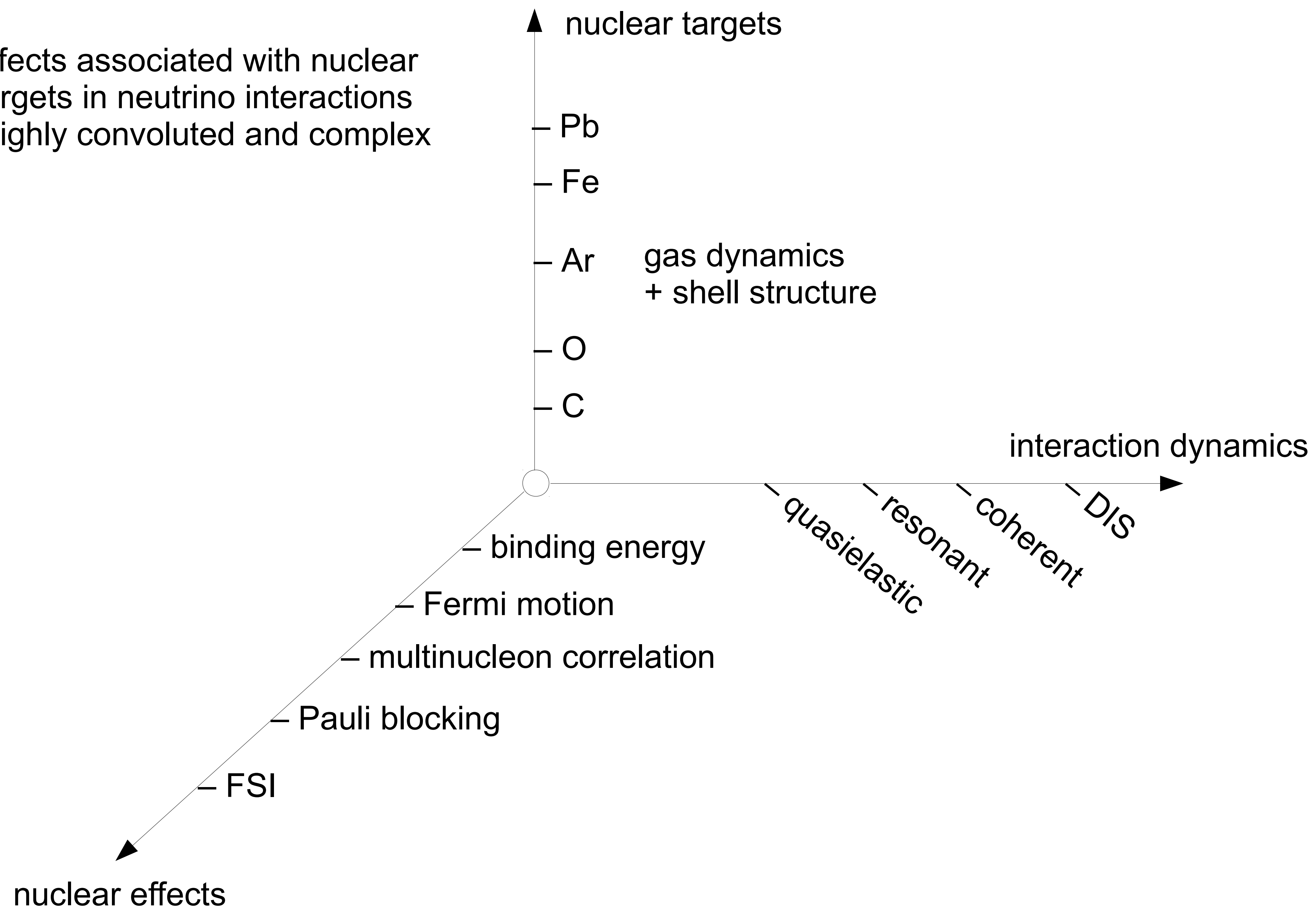
10th International Workshop on Neutrino-Nucleus Interactions in the Few-GeV Region (NuInt15) is difficult:

We see but can NOT control individual nucleons in a nucleus.

(or, can we?)

Introduction

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



Introduction

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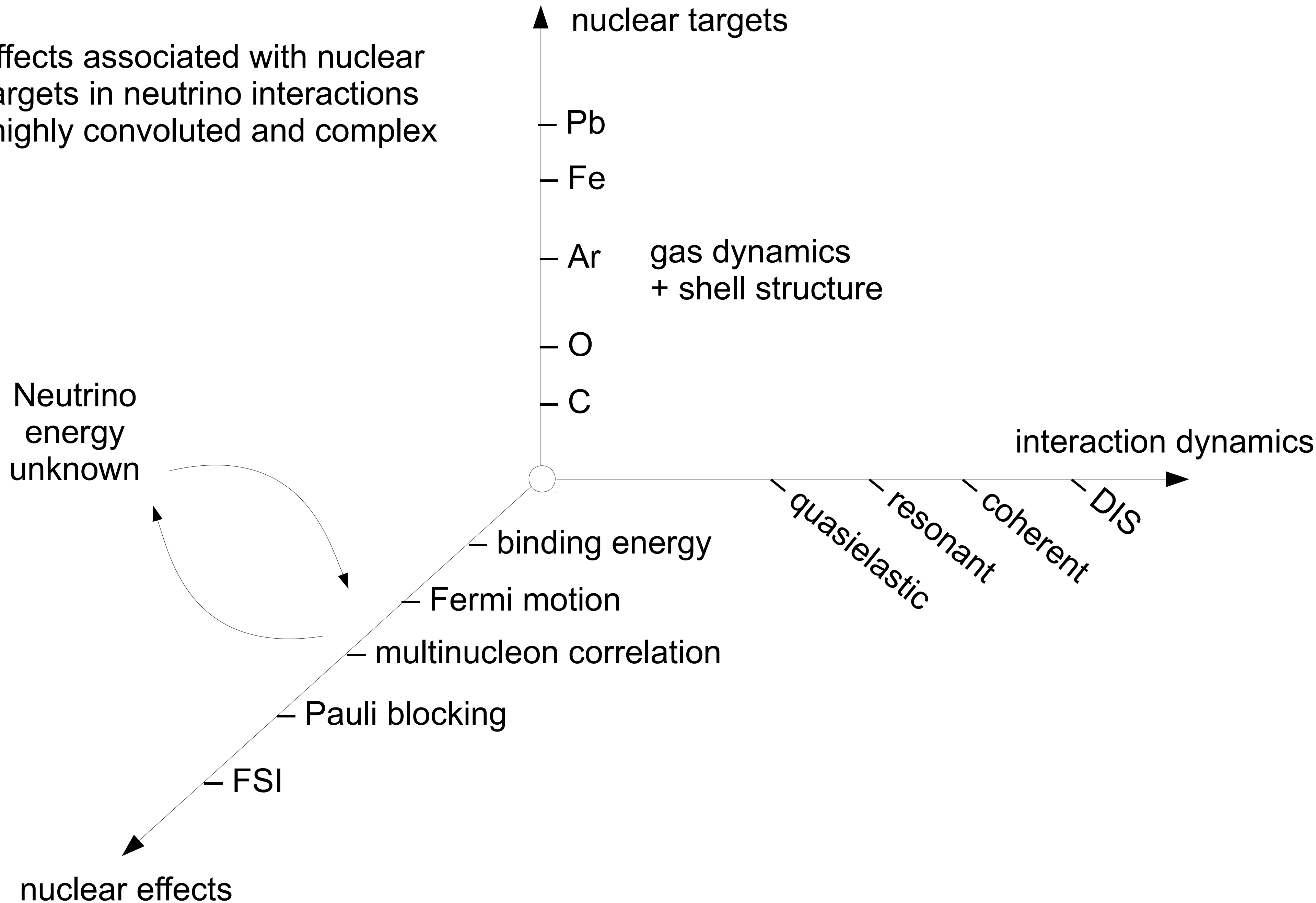
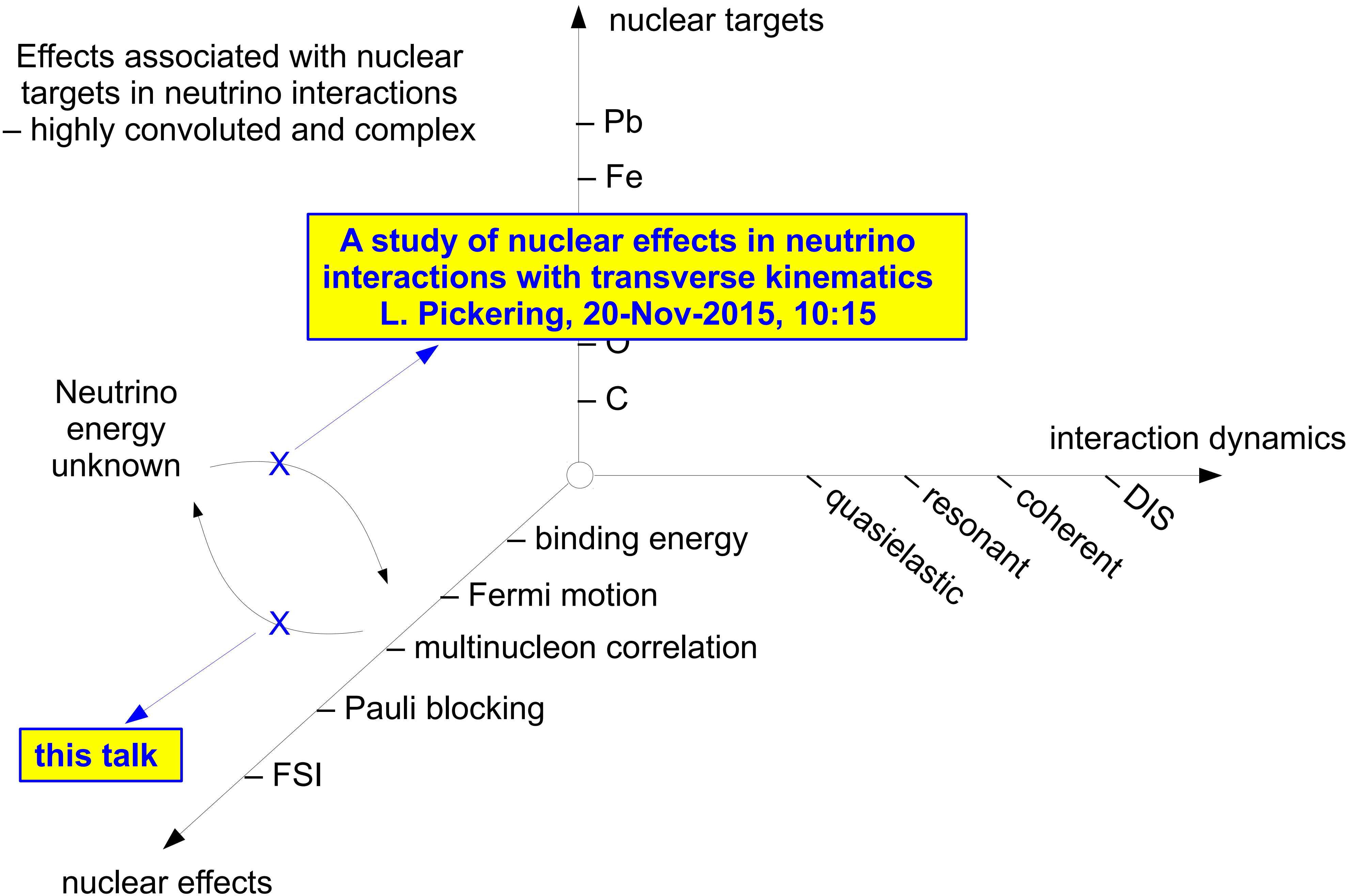
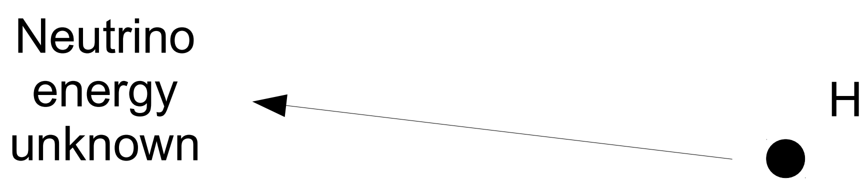


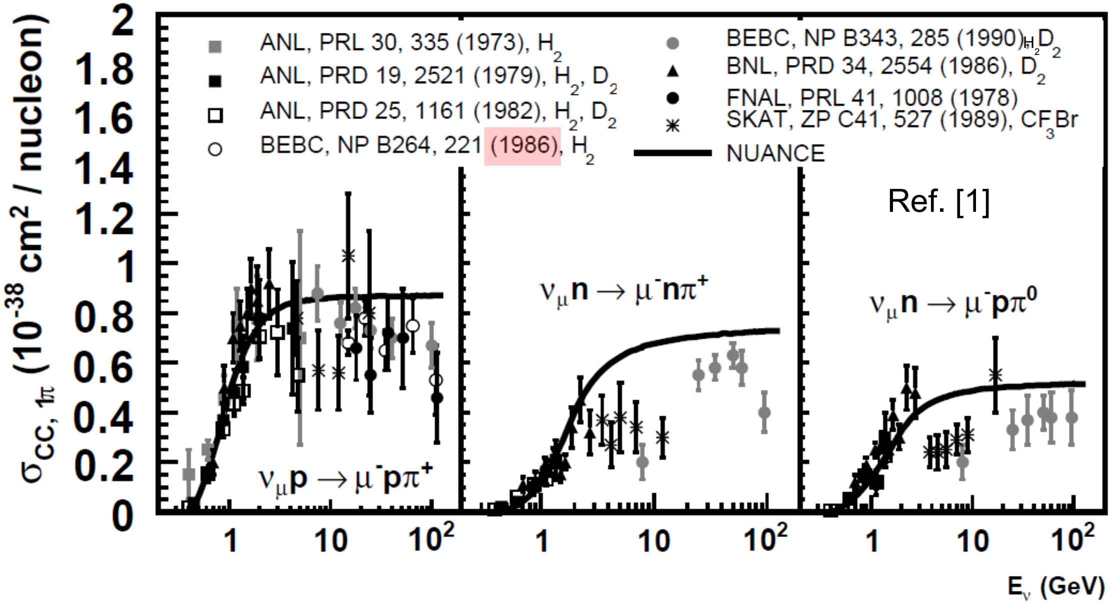
Effects associated with nuclear targets in neutrino interactions – highly convoluted and complex





this talk

- Pure hydrogen
  - Technical requirement:
    - bubble chamber (historical: 73, 79, 78, 82, 86) or high pressure gas chamber



In the last ~30 years there has been no new measurement of (anti)neutrino interactions on pure hydrogen. **But soon there will be** → see later slides)

  - Safety issue: explosive
    - "*Since the use of a liquid H2 bubble chamber is excluded in the ND hall **due to safety concerns**, ...*" [2]

[1] K. A. Olive et al. (Particle Data Group Collaboration), Review of particle physics, Chin. Phys. C 38, 090001 (2014).
[2] C. Adams et al. (LBNE Collaboration), Reports No. BNL-101354-2013-JA, No. BNL-101354-2014-JA, No. FERMILAB-PUB-14-022, and No. LA-UR-14-20881, 2013.

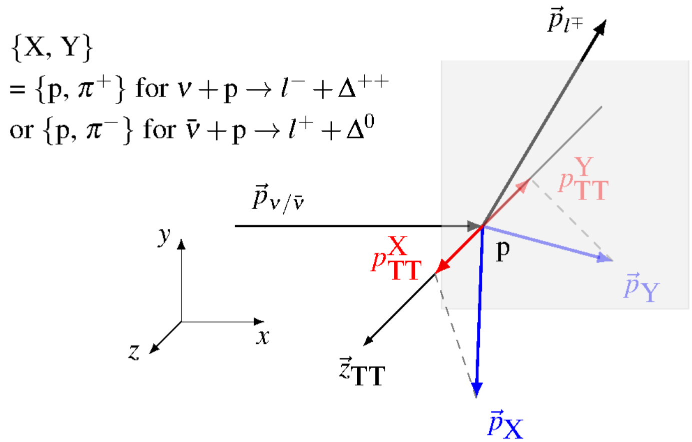
Introduction

- Mixed target like polystyrene ("hydrogen-doping" in nuclei)
  - Events from hydrogen and other nuclei not distinguishable, only statistical subtraction between two target materials: "*... the (anti)neutrino interactions off a hydrogen target can only be extracted with a* ***subtraction method from the composite materials*** *of the ND targets.*"[1]
  - In Phys.Rev. D92 (2015) 5, 051302 we introduce a technically much more accessible way of using hydrogen as target, which enables
    - Neutrino energy spectra reconstruction independent of nuclear effects
    - (Anti)Neutrino-hydrogen cross section
    - Direct measurement of nuclear effects
- Outline
  - Double-transverse kinematics
  - Systematics
  - Demonstration with T2K MC
  - Application in current experiments ←
  - Potentials in future experiments

[1] C. Adams et al. (LBNE Collaboration), Reports No. BNL-101354-2013-JA, No. BNL-101354-2014-JA, No. FERMILAB-PUB-14-022, and No. LA-UR-14-20881, 2013.

- Lepton-proton interaction to 3 charged particles: $l\,\mathrm{p} \rightarrow l'\,\mathrm{X}\,\mathrm{Y}$
  - Leading order realization in standard model:

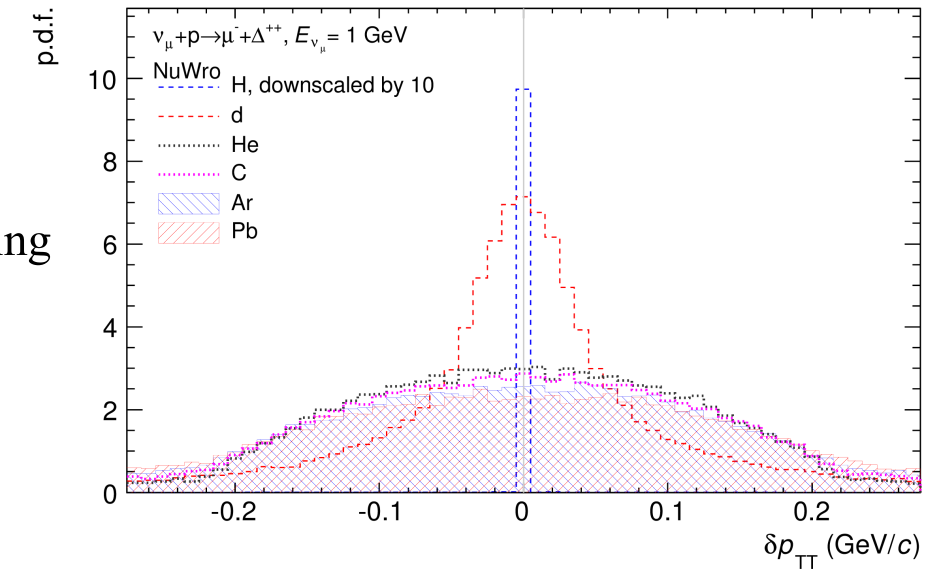
$$\{\mathrm{X},\mathrm{Y}\} = \{\mathrm{p},\pi^+\} \text{ for } \nu+\mathrm{p}\rightarrow l^- + \Delta^{++} \text{ or } \{\mathrm{p},\pi^-\} \text{ for } \bar{\nu}+\mathrm{p}\rightarrow l^+ + \Delta^0$$



HIGHLY SYMMETRICAL SYSTEMS

- Double-transverse momentum imbalance

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

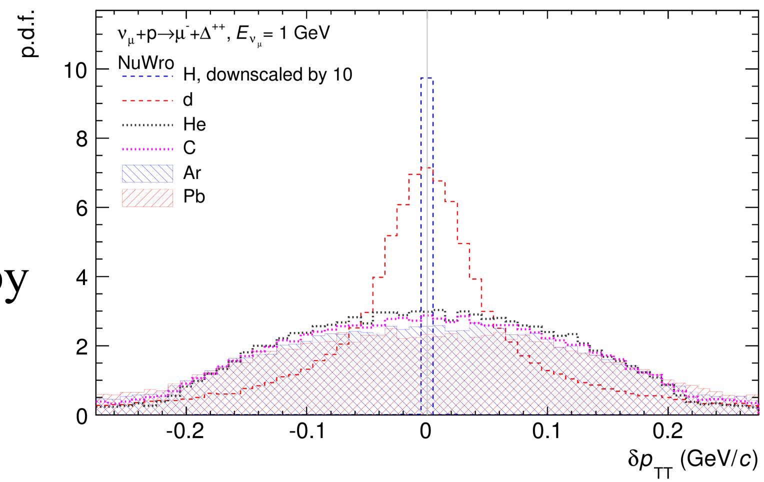


  - 0 for hydrogen
  - Heavier nuclei: irreducible symmetric broadening
    - by Fermi motion O(200 MeV)
    - further by FSI
  - After reconstruction → see demonstration
    - Still symmetric
    - Hydrogen shape is only detector response → *"Improving the detector resolution … eventually an event-by-event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

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

Systematics

- $\delta p_{TT} \neq 0$ but under the hydrogen peak
  - Accidental nuclear background can be removed by
    - tagging nuclear emission caused by FSI →
    - pion FSI that changes event topology
  - Non-exclusive process (e.g. DIS) can be removed by
    - vetoing neutron, π^0, γ →

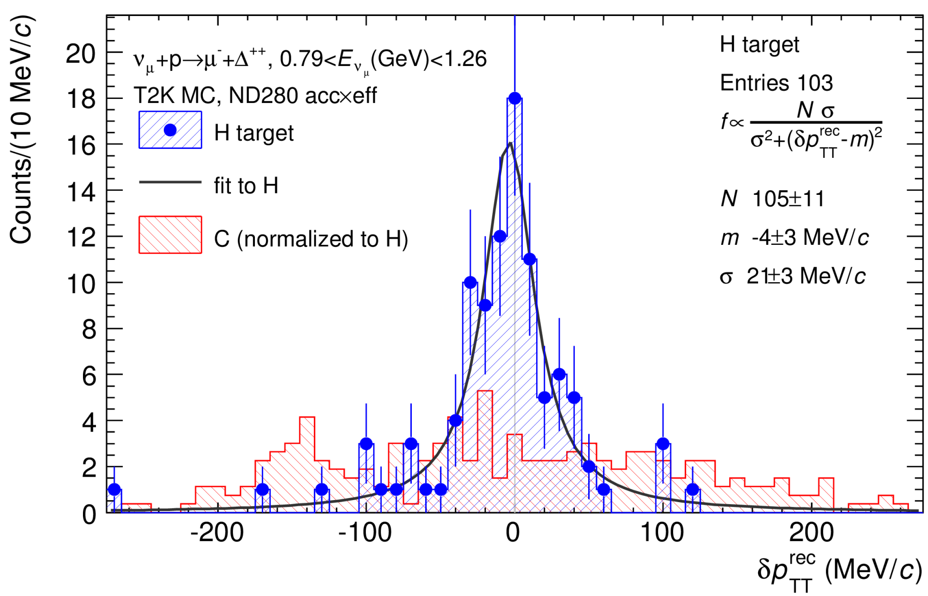


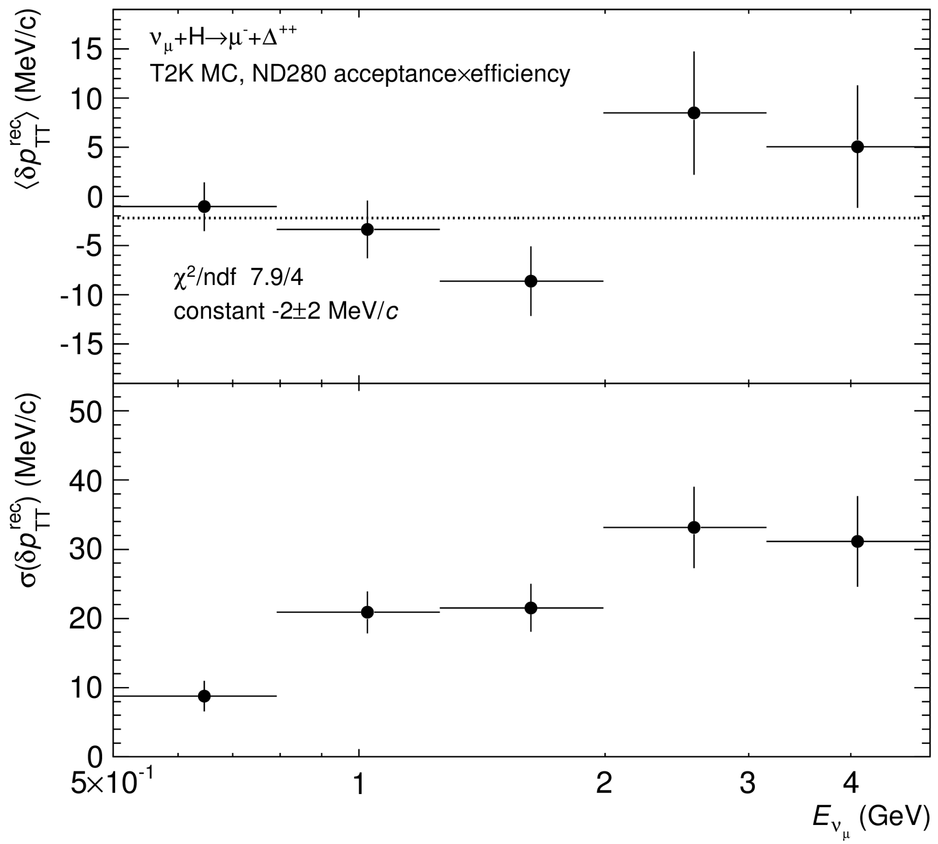
- $\delta p_{TT} = 0$
  - Higher mass resonances, non-resonant background
    - can be removed by explicit kinematic (*W, t*)
    - not background by redefinition of signal/background → *topological definition,* ***most relevant for energy measurement***: "*alternatively one could extend the definition of the production channel to include all contributions that have* ***exclusive pπ^+*** *final states*"[1]
  - "Wrong sign" background
    - can be removed by explicit kinematic – W(pμ) has no resonance peak
    - stopped pions – advantage of resonance production [2]

[1] Phys.Rev. D92 (2015) 5, 051302 [2] MiniBooNE, Phys. Rev. D 84, 072005 (2011)

Demonstration

- T2K-ND280 MC[1]
  - Neut + realistic detector simulation
  - FGD: polystyrene (CH) target
  - TPC: momentum, dE/dx
- Reconstructed δp_{TT}
  - Energy dependence typical for trackers

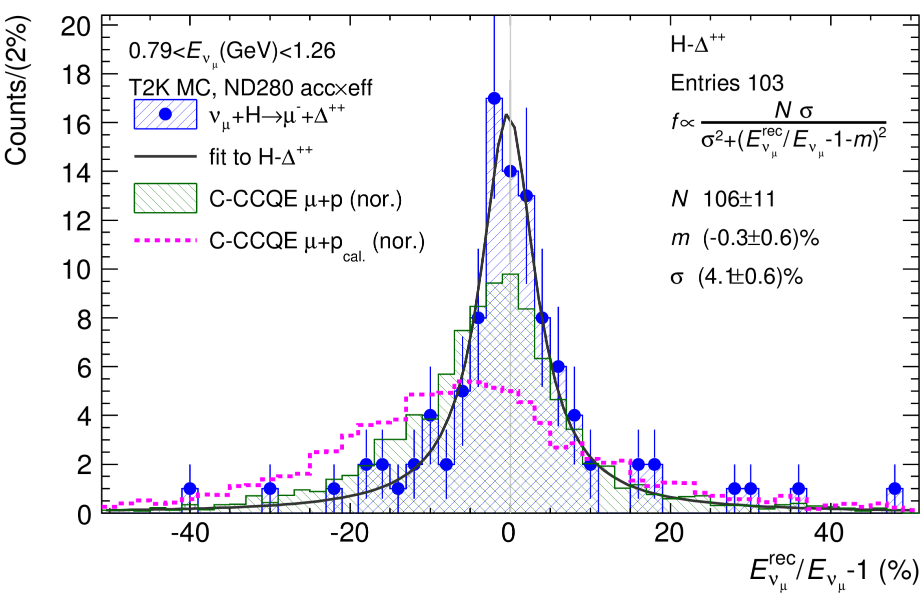


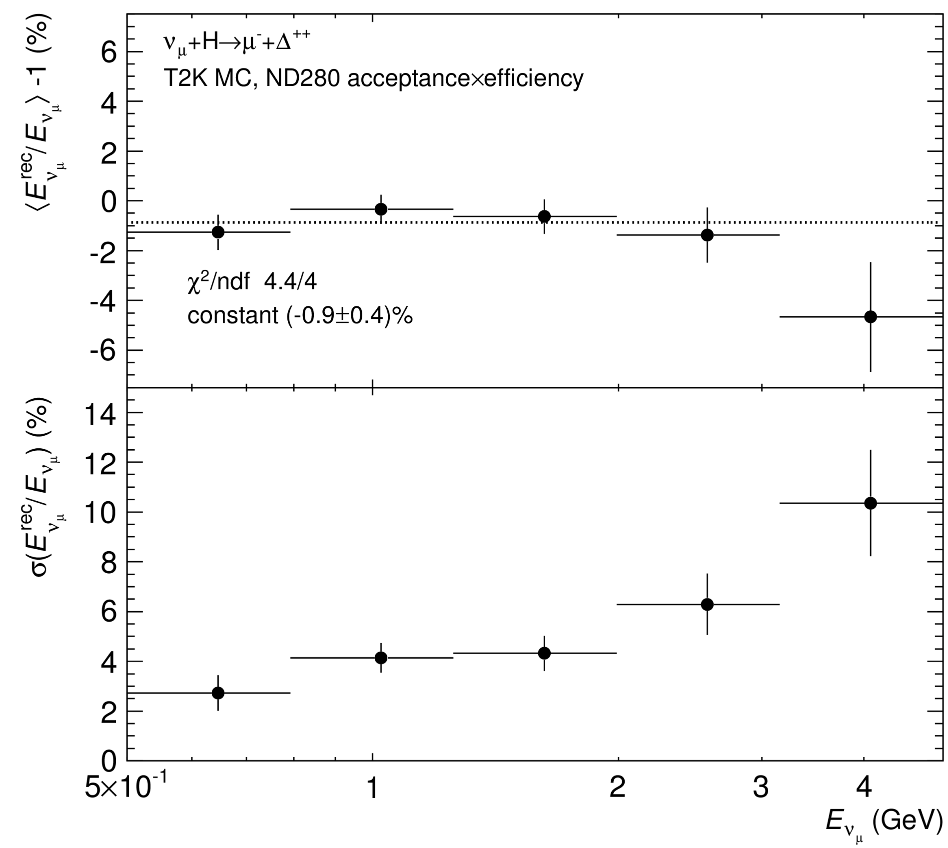


[1] Nucl. Instrum. Meth. A 659, 106 (2011)

Demonstration

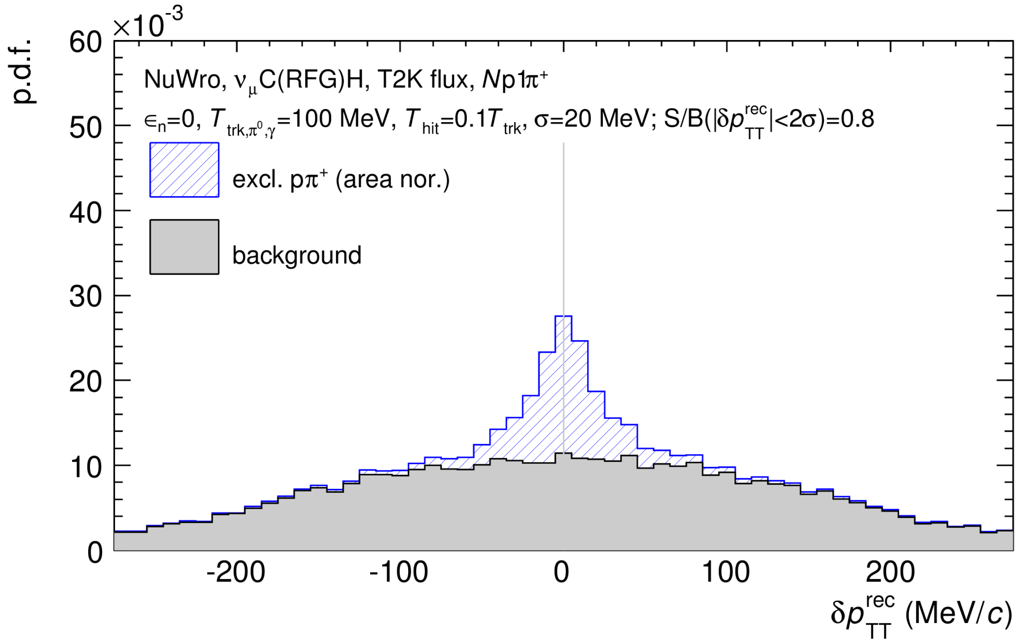
- Reconstructed E_ν from true hydrogen sample
  - More accurate than CCQE on carbon
- Energy dependence
  - Constant energy scale
  - Resolution typical for tracker





Application in Current Experiments

- **Direct measurement of neutrino-hydrogen cross section (signal: exclusive $p\pi^+$)**
  - Simple performance projection [see L. Pickering's talk] of T2K-like detector using NuWro+T2K flux on CH:
    - neutrons not detectable
    - Track, π^0, γ threshold: kinetic energy 100 MeV
    - Hit (vertex activity) threshold: 10% track threshold
    - δp_{TT} resolution 20 MeV (Cauchy)
  - Selection: CCNp1π^+, no veto on nuclear emission*, no veto on neutrals



ν_μ - $p\pi^+$	S/B in 2σ	improv.
nominal	0.8	

(*secondary proton and activity above hit threshold below track threshold)

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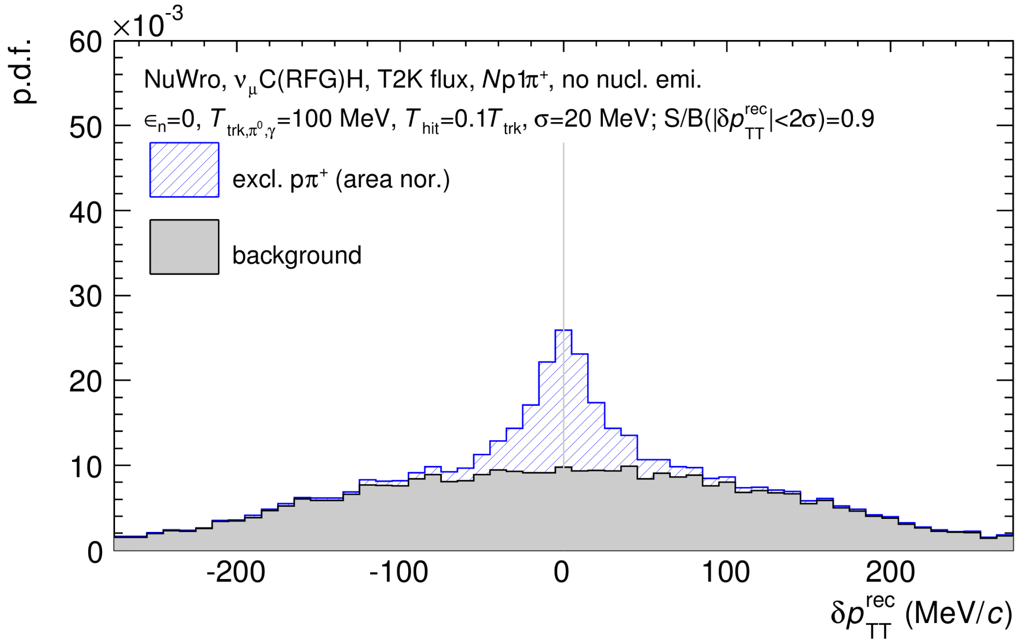

ν_μ - $p\pi^+$	S/B in 2σ	improv.
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veto N.E.	0.9	1.1

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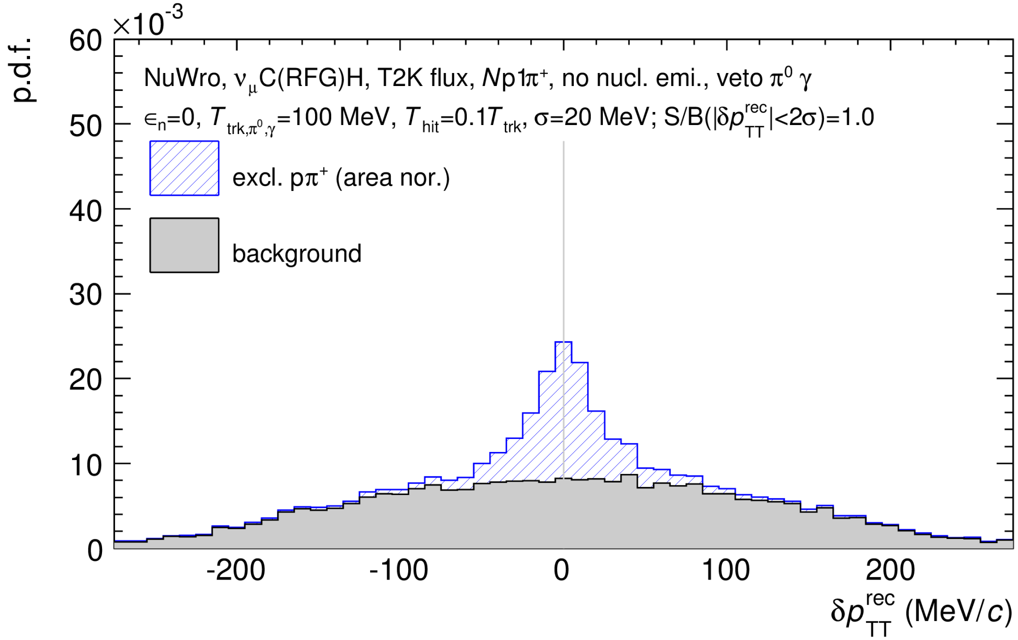

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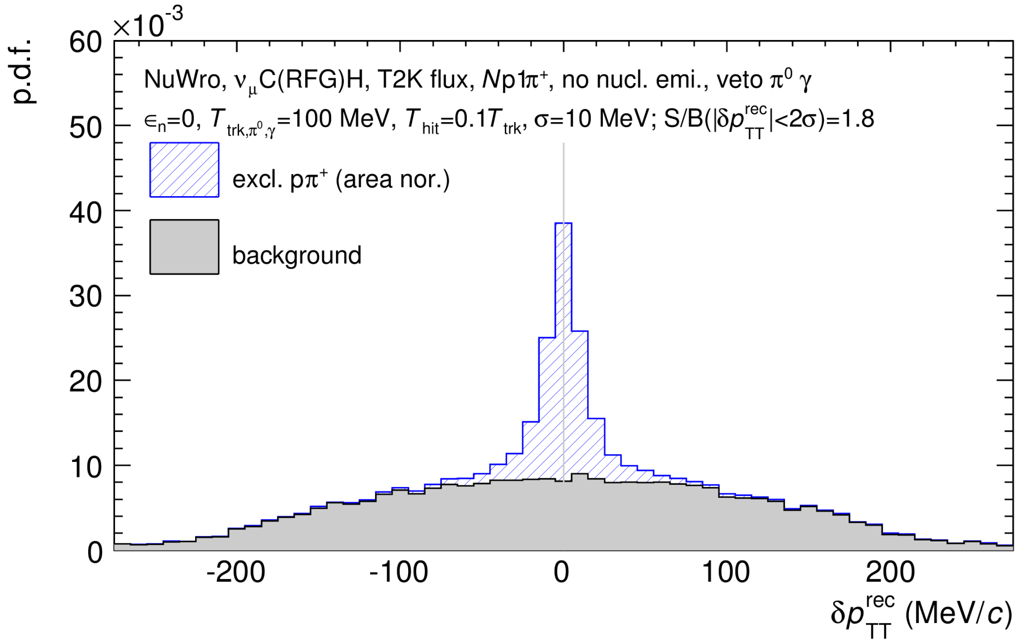
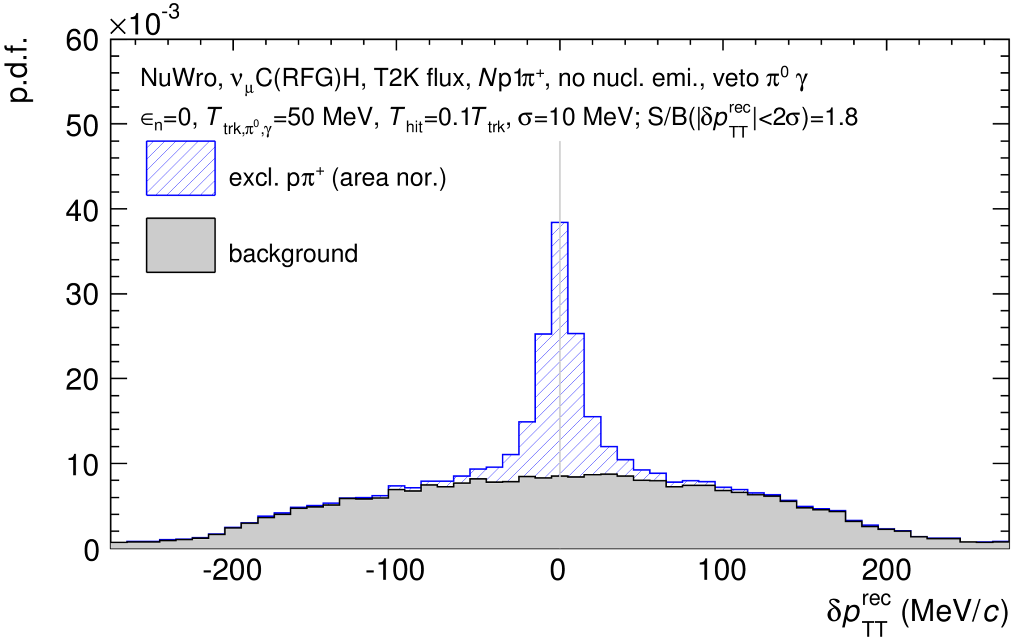
    - Track, π^0, γ threshold: kinetic energy 100 MeV
    - Hit (vertex activity) threshold: 10% track threshold
    - δp_{TT} resolution 10 MeV (Cauchy) via e.g. B-field 0.2 → 0.4 T (capable to 0.8 T)
  - Selection: CCNp1π^+, veto nuclear emission (N.E.), veto π^0, γ above threshold



ν_μ - $p\pi^+$	S/B in 2σ	improv.
nominal	0.8	
veto N.E.	0.9	1.1
veto π^0, γ	1.0	1.1
tracking	1.8	1.8

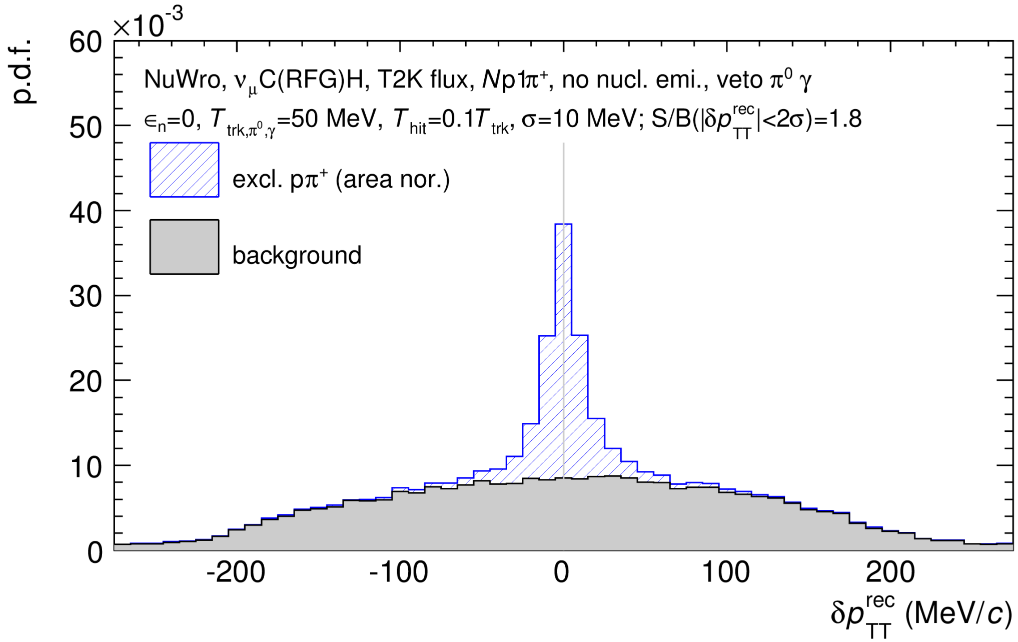
- **Direct measurement of neutrino-hydrogen cross section (signal: exclusive $p\pi^+$)**
  - Simple performance projection [see L. Pickering's talk] of T2K-like detector using NuWro+T2K flux on CH:
    - neutrons not detectable
    - Track, π^0, γ threshold: kinetic energy 50 MeV via e.g. optimizing target geom. (Optimal thresholds depend on the signal and bk xsec.)
    - Hit (vertex activity) threshold: 10% track threshold
    - δp_{TT} resolution 10 MeV (Cauchy) via e.g. B-field 0.2 → 0.4 T (capable to 0.8 T)
  - Selection: CCNp1π^+, veto nuclear emission (N.E.), veto π^0, γ above threshold



ν_μ - $p\pi^+$	S/B in 2σ	improv.
nominal	0.8	
veto N.E.	0.9	1.1
veto π^0, γ	1.0	1.1
tracking	1.8	1.8
threshold	1.8	1.0
	overall	2.3

Application in Current Experiments

- **Direct measurement of neutrino-hydrogen cross section (signal: exclusive $p\pi^+$)**
  - Simple performance projection [see L. Pickering's talk] of T2K-like detector using NuWro+T2K flux on CH:
    - neutrons not detectable
    - Track, π^0, γ threshold: kinetic energy 50 MeV via e.g. optimizing target geom. (Optimal thresholds depend on the signal and bk xsec.)
    - Hit (vertex activity) threshold: 10% track threshold
    - ***δp_{TT} resolution*** 10 MeV (Cauchy) via e.g. B-field 0.2 → 0.4 T (capable to 0.8 T) — Most critical improvement
  - Selection: CCNp$1\pi^+$, veto nuclear emission (N.E.), veto π^0, γ above threshold



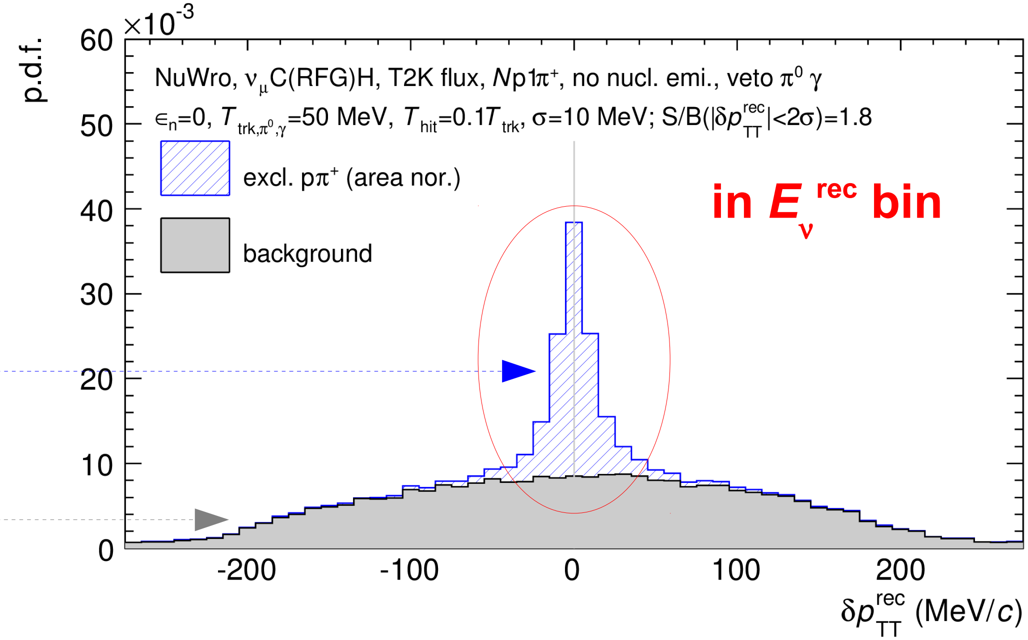
ν_μ - $p\pi^+$	S/B in 2σ	improv.
nominal	0.8	
veto N.E.	0.9	1.1
veto π^0, γ	1.0	1.1
tracking	***1.8***	***1.8***
threshold	1.8	1.0
	overall	2.3

Application in Current Experiments

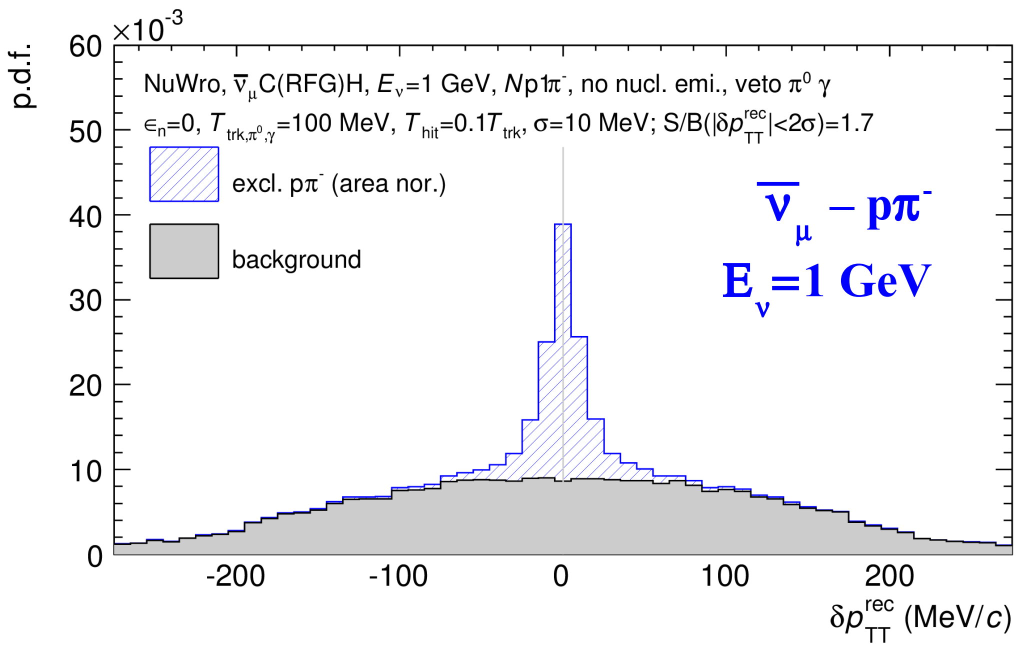
3) bin in reconstructed E_ν + exclusive $p\pi^+$ extraction = nuclear-free ν flux measurement

2) pure detector resolution allowing multiple signal extraction method

1) 1D projection of Fermi motion w/ FSI smearing

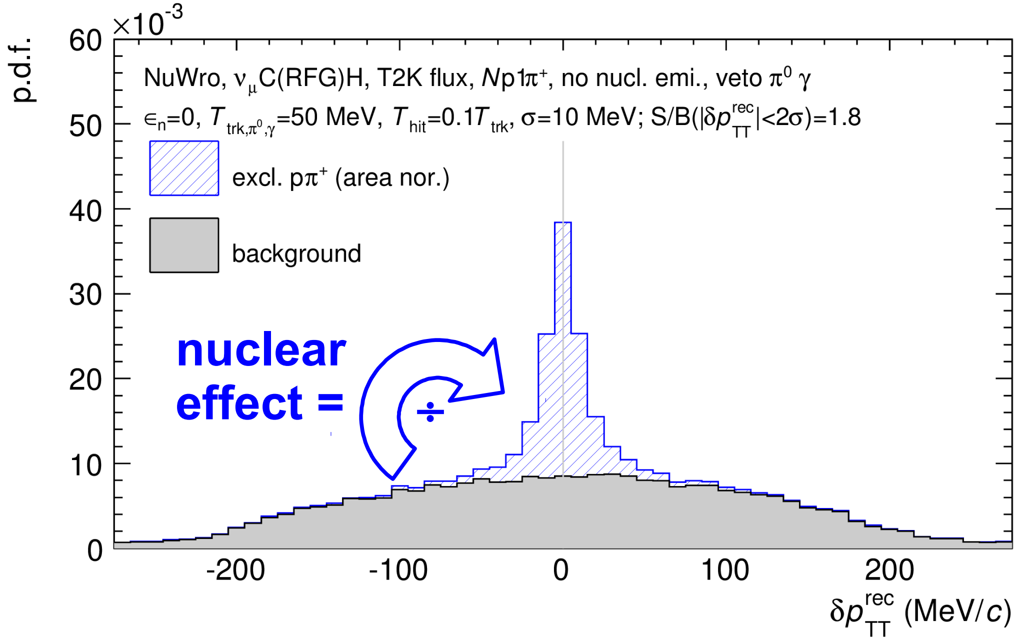


- **Direct measurement of antineutrino-hydrogen cross section (signal: exclusive $p\pi^-$)**



Application in Current Experiments

- **Direct measurement nuclear effects on nuclear target**
  - Due to nuclear effects, $\sigma_A/\sigma_H \neq Z$
  - Nuclear effect = $\sigma_A/Z\sigma_H$ (deviation from 1)
    - Signal/background definition may be subtle
  - *"The yield ratio between the hydrogen signal and the remaining contribution from the other target nuclei is a precise measurement of the associated nuclear effects* ***with cancellation of detection acceptance and efficiencies*** *for both targets."*[1]



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

Potentials in Future Experiments

- Production threshold ~ 300 – 500 MeV, cross section maximum after 2 – 3 GeV
  - Higher energy flux by NuMI and LBNF optimal
- LAr
  - Superb tracking and calorimetry properties
  - Ar as neutrino target does not have advantage in terms of energy reconstruction quality
  - Hydrogen-doping?
- Highly symmetrical systems for nu/anti-nu detection $\nu/\bar{\nu} + \mathrm{p} \to l^{\mp} + \Delta \to l^{\mp} + \mathrm{p} + \pi^{\pm}$
  - Advantage for CPV measurement?

Summary

- Pure neutrino-hydrogen interaction can be extracted from mixed target with double-transverse momentum imbalance δp_{TT}, all feasible with current technology (e.g. consider ALICE TPC tracking resolution):
  - **Nuclear-free neutrino flux measurement**
  - (Anti)Neutrino-hydrogen interaction
  - Direct measurements nuclear effects
- On-going measurement in T2K

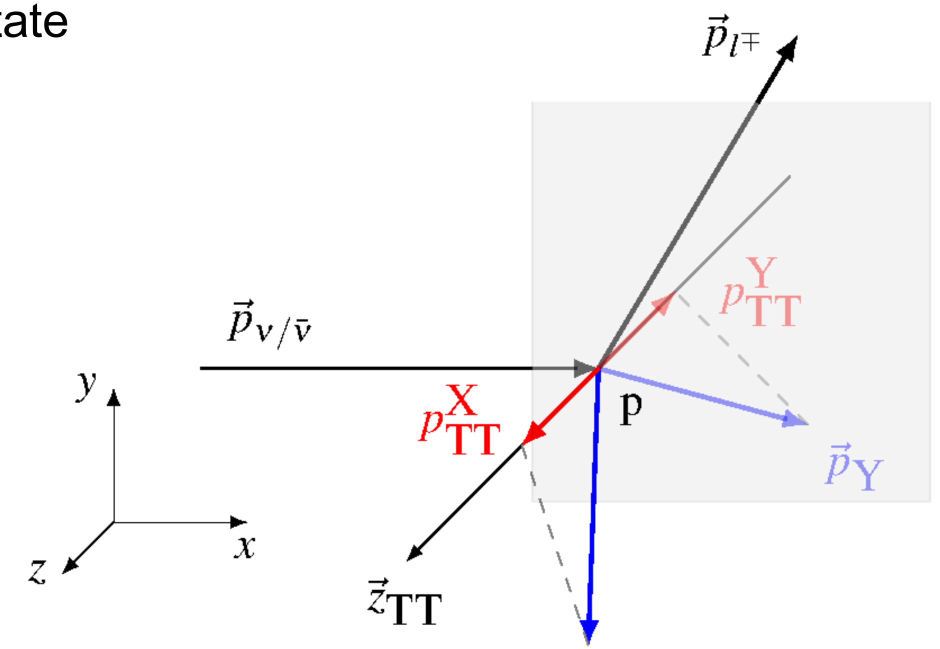
Nuclei are friends

  - Base for hydrogen doping: convenient and safe.
  - Nuclear effect problem principally solvable – all influence can be avoided by improving tracking resolution.
  - Prefer stronger nuclear effects to suppress background.

BACKUP

Double-Transverse Symmetry

Consider 3-body CC final state



$$\vec{z}_{TT} \equiv \vec{p}_{\nu} \times \vec{p}_{l} / |\vec{p}_{\nu} \times \vec{p}_{l}|$$

No nuclear effects → 4-momentum conservation applicable

z: symmetric between X and Y

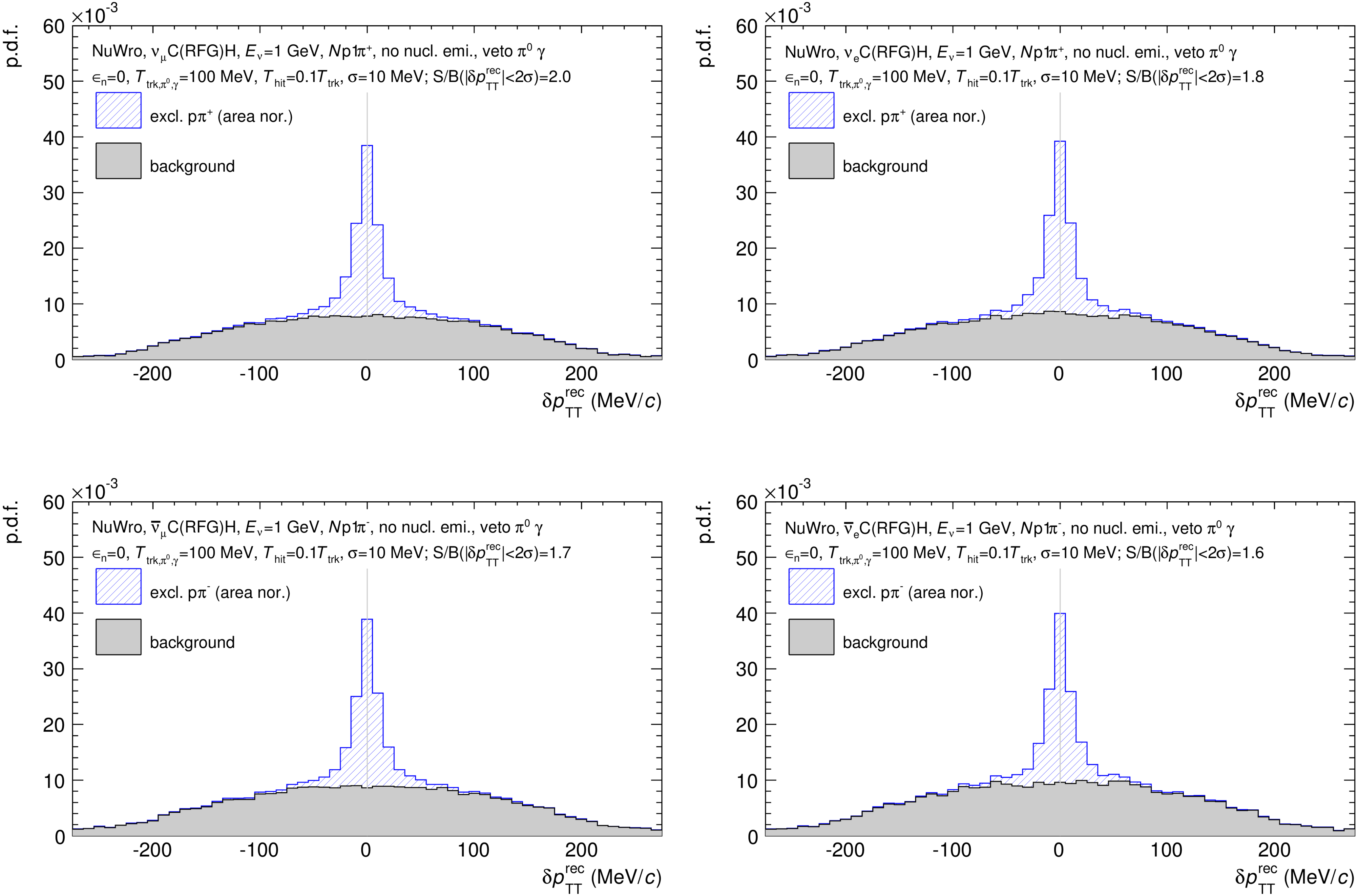
y: symmetric between X+Y and lepton → difficult to realize after reconstruction

x: $E_{\nu} = \Sigma_{\text{final state}}$ longitudinal momentum

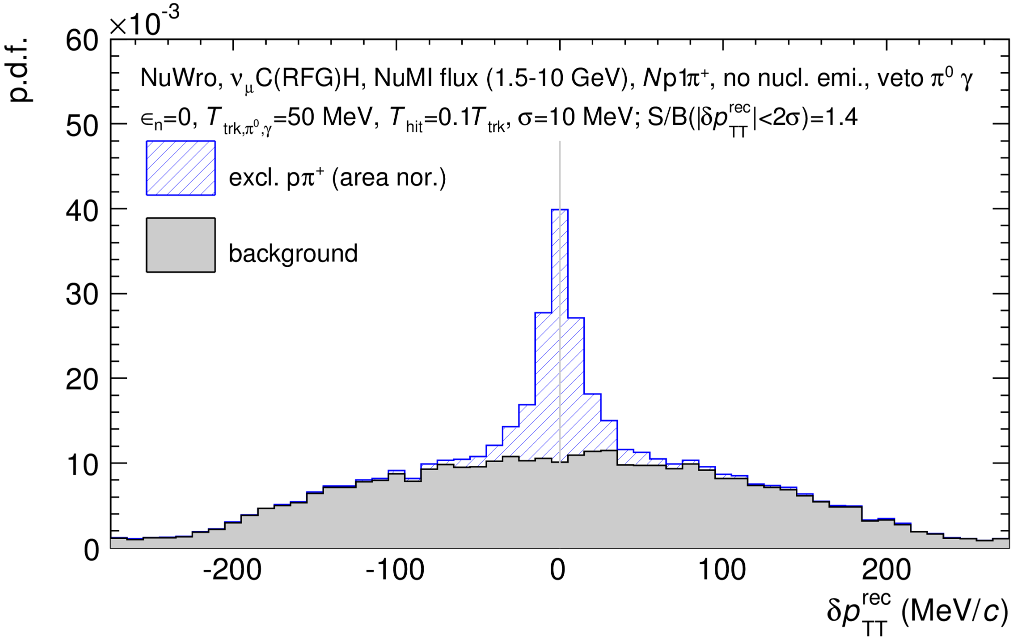
E: $E_{\nu} = \Sigma_{\text{final state}}$ energy – $m_{\text{initial nucleon}}$

→ x or E depends on calorimetry / tracking / PID performance

1 GeV (anti)ν_μ vs. (anti)ν_e



ν_μ NuMI



×10⁻³
p.d.f.
NuWro, ν_μC(RFG)H, NuMI flux (1.5-10 GeV), Np1π⁺, no nucl. emi., veto π⁰ γ
ε_n=0, T_trk,π⁰,γ=50 MeV, T_hit=0.1T_trk, σ=10 MeV; S/B(|δp_TT^rec|<2σ)=1.4
excl. pπ⁺ (area nor.)
background
δp_TT^rec (MeV/c)

END