Energy reconstruction and final-state interactions in proton knockout

Alexis Nikolakopoulos

NOW 2024,

7th September 2024

Neutrino-nucleus cross section in oscillation analysis

A measurement in a neutrino experiment:

$$\frac{dN}{dX} = \int dE_\nu \Phi(E_\nu) K(E_\nu, X)$$

Is an integral transform with complicated kernel

$$\frac{dN}{d|\vec{p}_1|} = \int \underbrace{d\Omega_1\, d\vec{p}_2 \cdots d\vec{p}_n}_{\text{Phase space(E)}}\ \underbrace{\epsilon(\vec{p}_1, \cdots, \vec{p}_n)}_{\text{efficiency}} \int dE_\nu \underbrace{\Phi(E_\nu)}_{\text{Flux}} \underbrace{\frac{d\sigma(E_\nu)}{d\vec{p}_1 \cdots d\vec{p}_n}}_{\text{Cross section}}$$

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Oscillation analysis

Constrain and determine uncertainty on K(E,X)

Compare predictions with different ϕ(E) to measurement

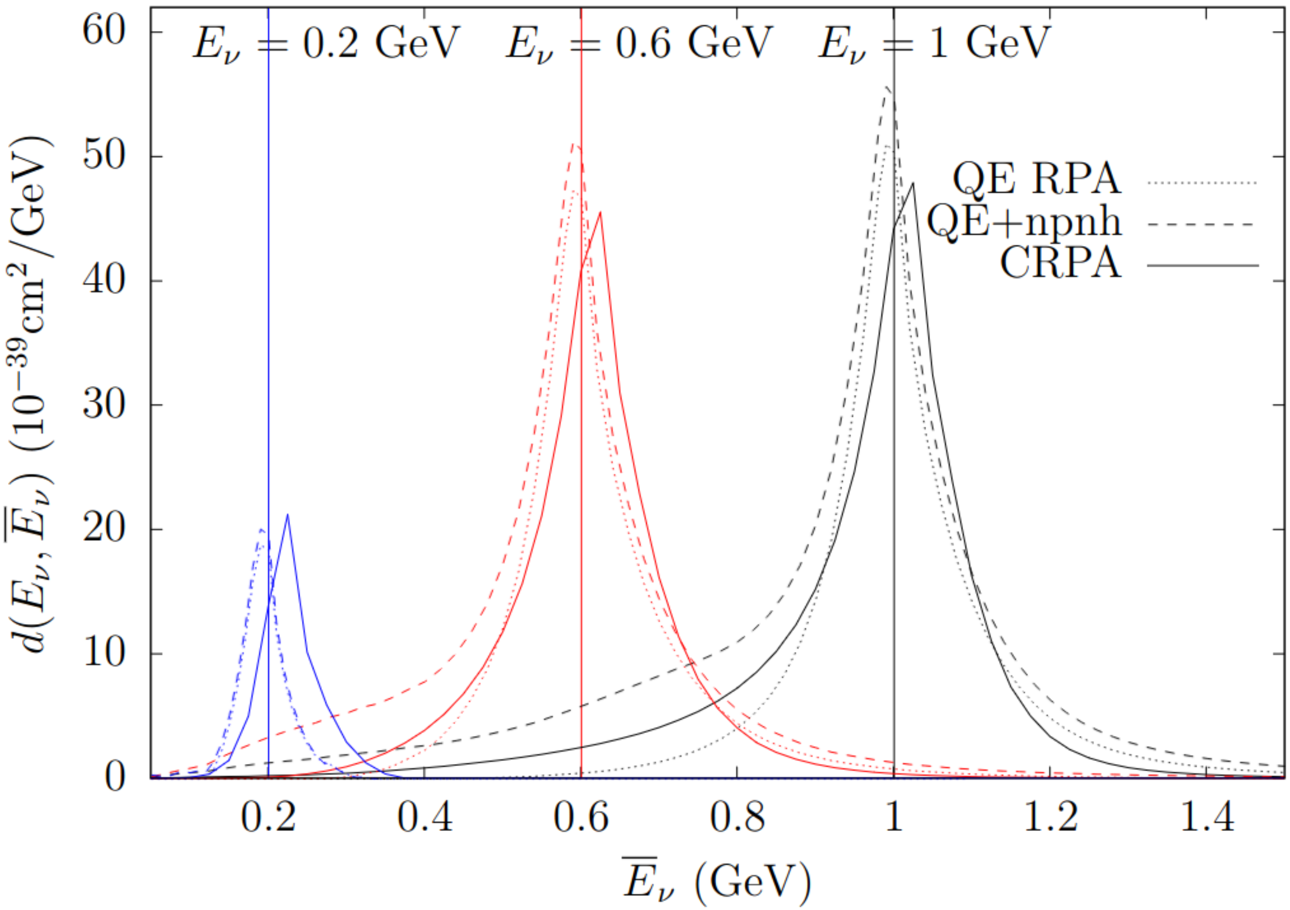
Uncertainty, constraints, and flexibility in K(E,X)
Determine possible precision of analysis

Neutrino-nucleus cross section in oscillation analysis

MiniBooNE use a 1-d observable

$$\frac{dN}{dX} = \int dE_\nu \Phi(E_\nu) K(E_\nu, X) \qquad X = \overline{E}_\nu = \frac{2M'_n E_l - ({M'_n}^2 + m_l^2 - M_p^2)}{2(M'_n - E_l + P_l \cos\theta)}$$

[arxiv:1808.07520]



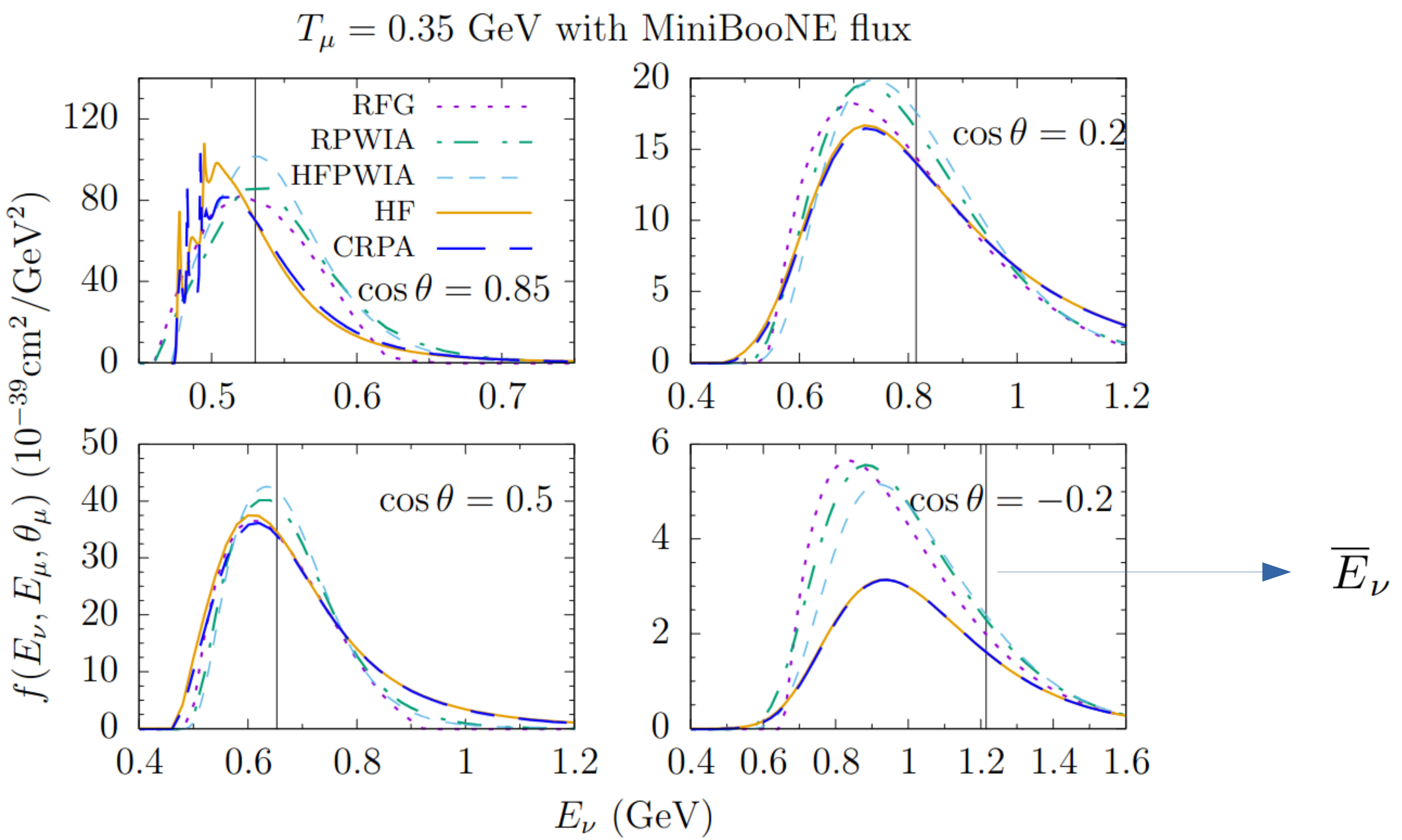
Width and model-dependence of distribution affect oscillation analyses

More observables → more information

[arxiv:1808.07520]

$$\frac{dN}{dX} = \int dE_\nu \Phi(E_\nu) K(E_\nu, X)$$

$X = (T_\mu, \theta_\mu)$

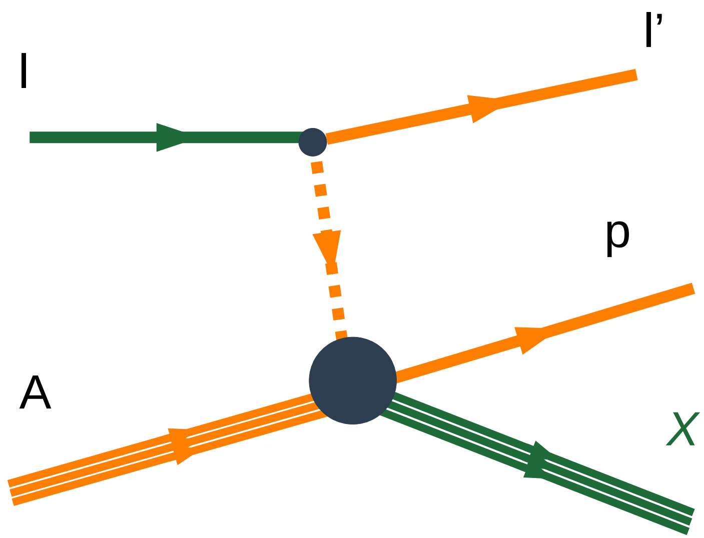


Smearing determined by inclusive double differential CS

From inclusive to semi-inclusive with LArTPCs → 1μ1p events

$$\langle \frac{d^6\sigma}{\mathrm{d}k_l \mathrm{d}\Omega_l \mathrm{d}p_N \mathrm{d}\Omega_N} \rangle = \int dE \phi(E) \frac{d^6\sigma(E)}{\mathrm{d}k_l \mathrm{d}\Omega_l \mathrm{d}p_N \mathrm{d}\Omega_N}$$

$X = (K_\mu, K_N)$

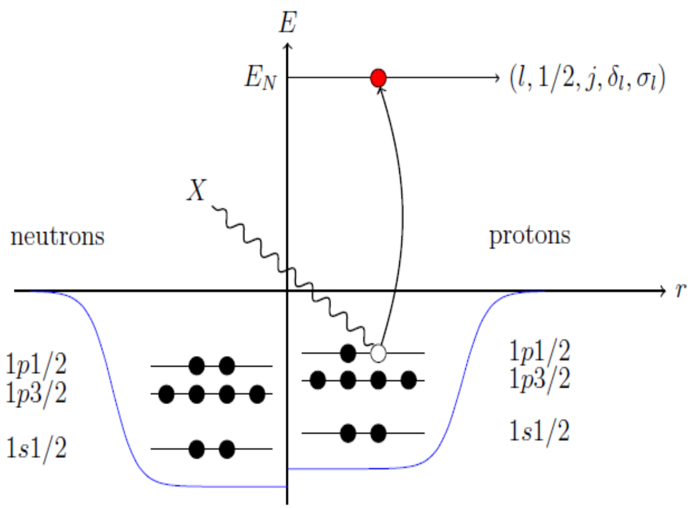


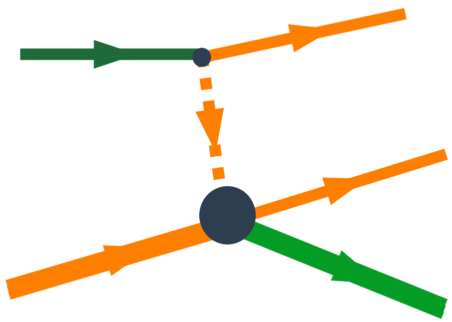
$X = (M_B^0 + E_m + T_B(p_m), \mathbf{p}_m)$

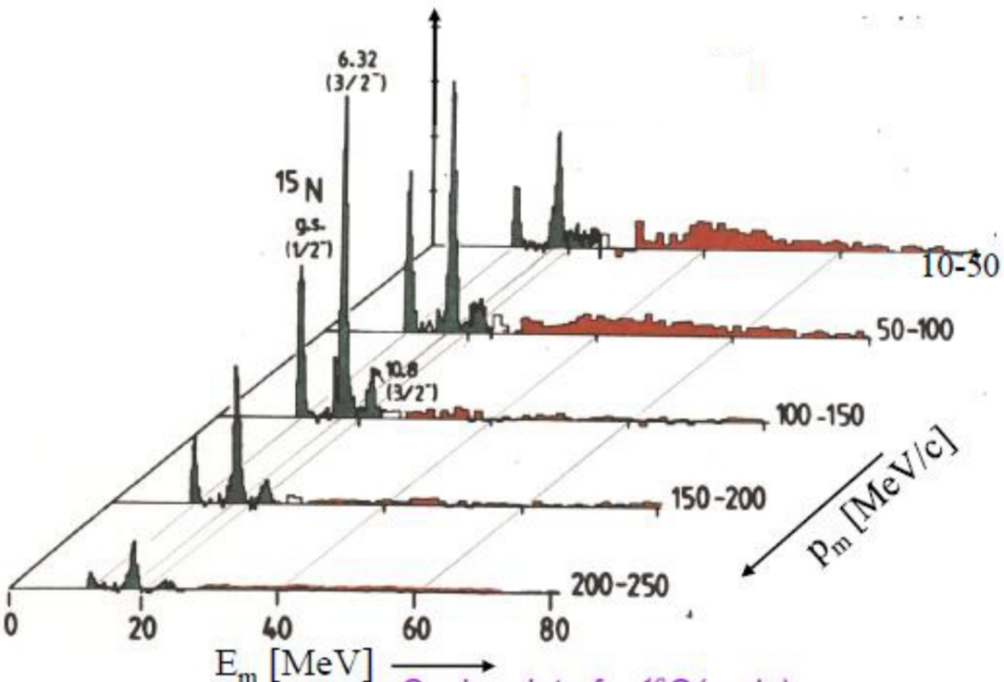
Missing energy $E_m = E_l - E_{l'} - T_N - T_B$

Missing momentum $|\mathbf{p}_m| = |\mathbf{k}_l - \mathbf{k}_{l'} - \mathbf{k}_N|$

Exclusive electron scattering: Missing energy distributions







Saclay data for $^{16}O(e,e'p)$

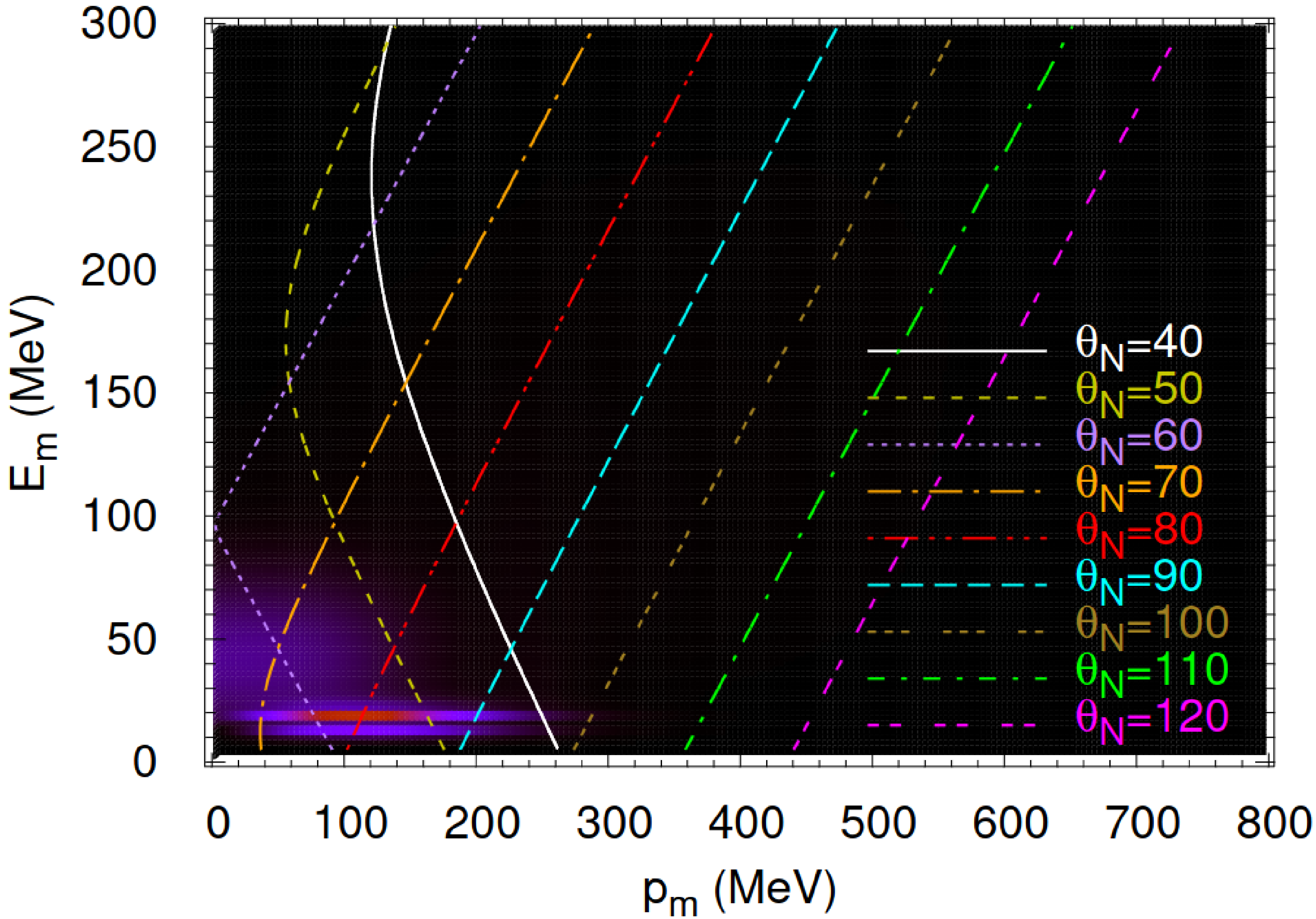
[Mougey et al., Nucl. Phys. A335, 35 (1980)]

Direct nucleon knockout dominated by distinct shell-model peaks

→ Residual system with low excitation energy E_m

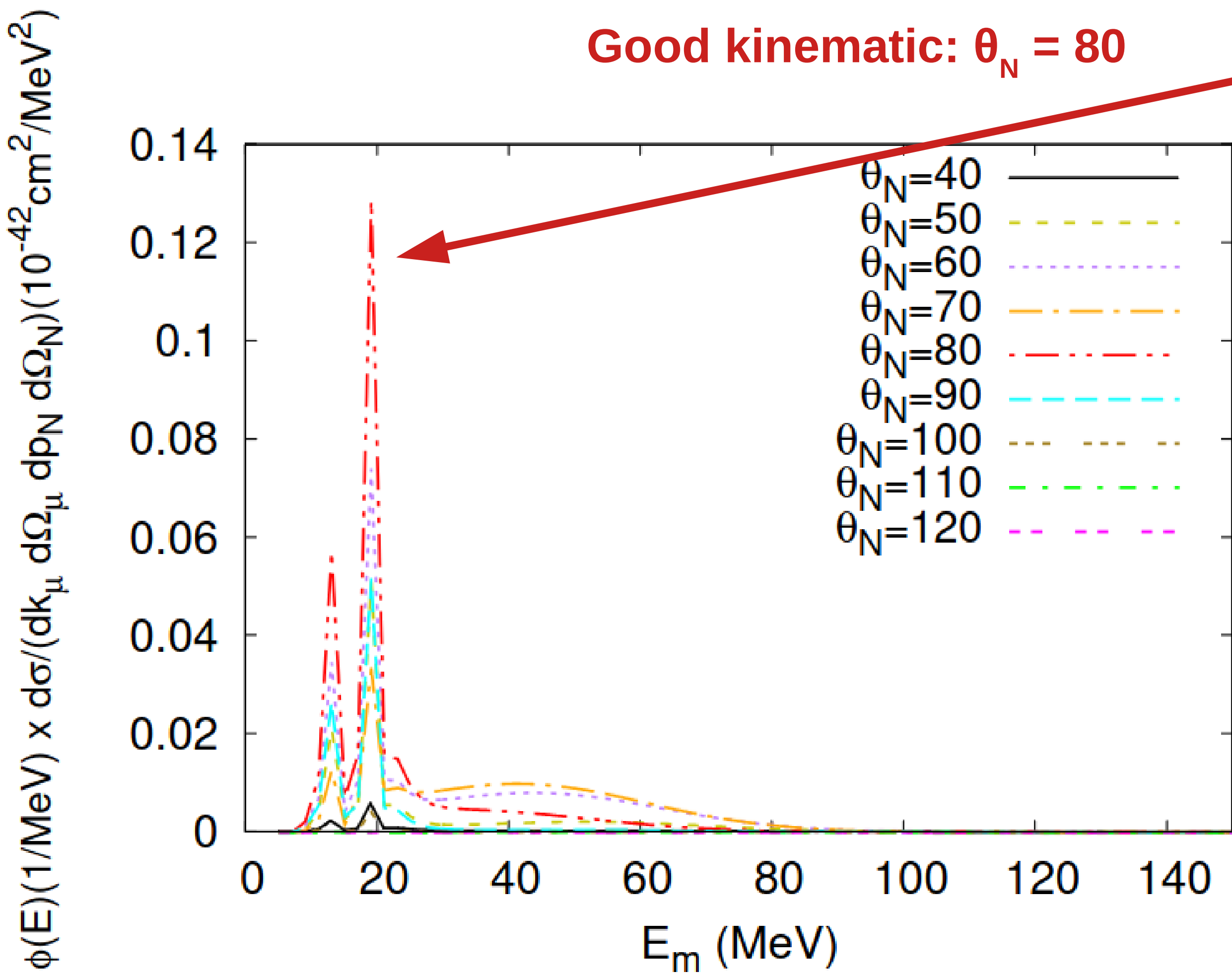
Neutrino scattering: energy reconstruction for 1μ1p events
[R. Gonzalez-Jimenez et al. arxiv:2104.01701]

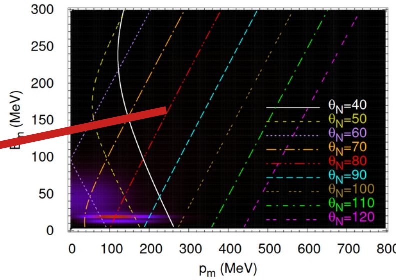
Fixed k_{μ}, k_N → E_ν defines a trajectory in E_m,p_m space



'Good kinematics' (θ_N = 80) → cross low-E_m peaks at small p_m

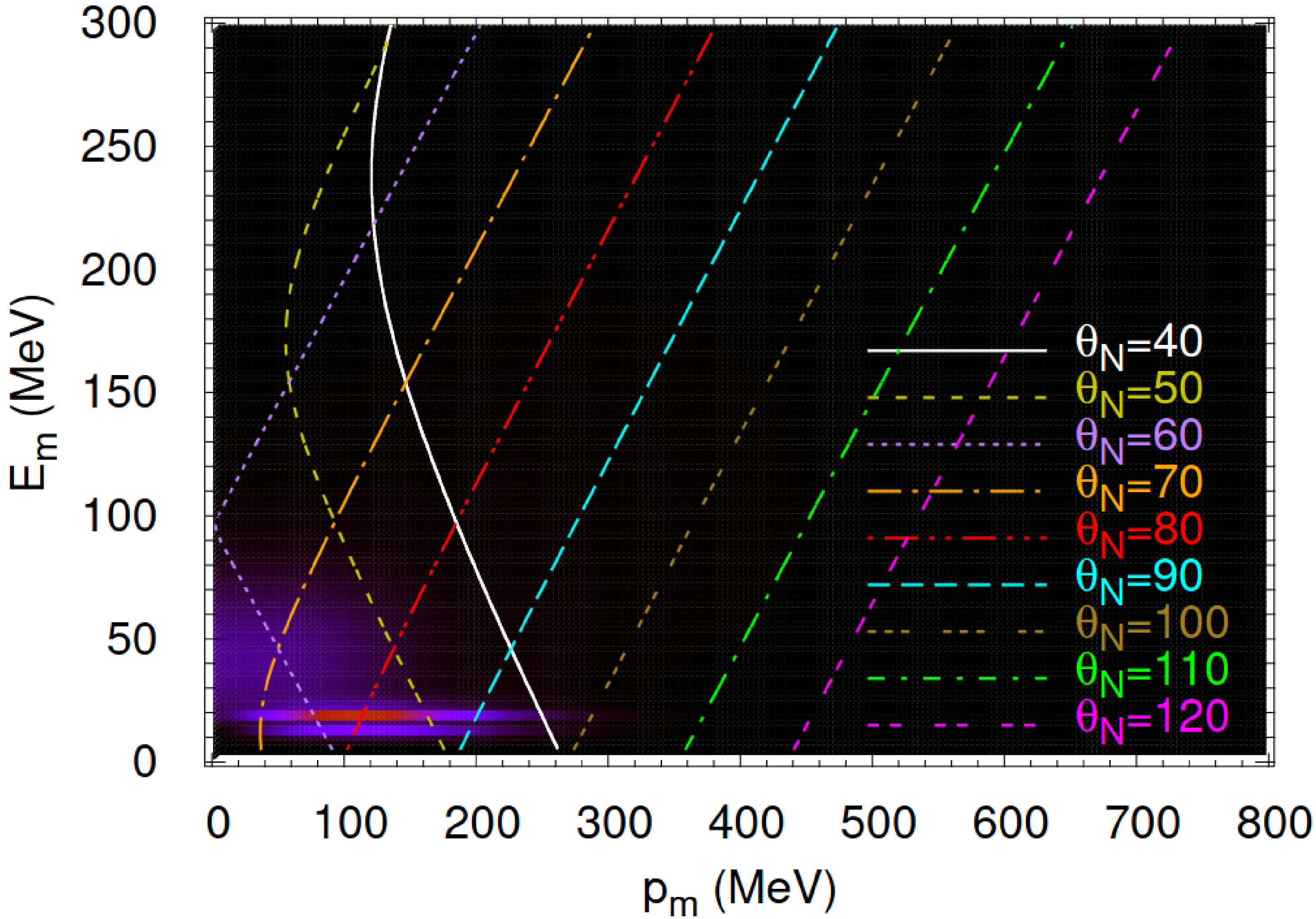
Neutrino scattering: energy reconstruction for 1μ1p events
[R. Gonzalez-Jimenez et al. arxiv:2104.01701]





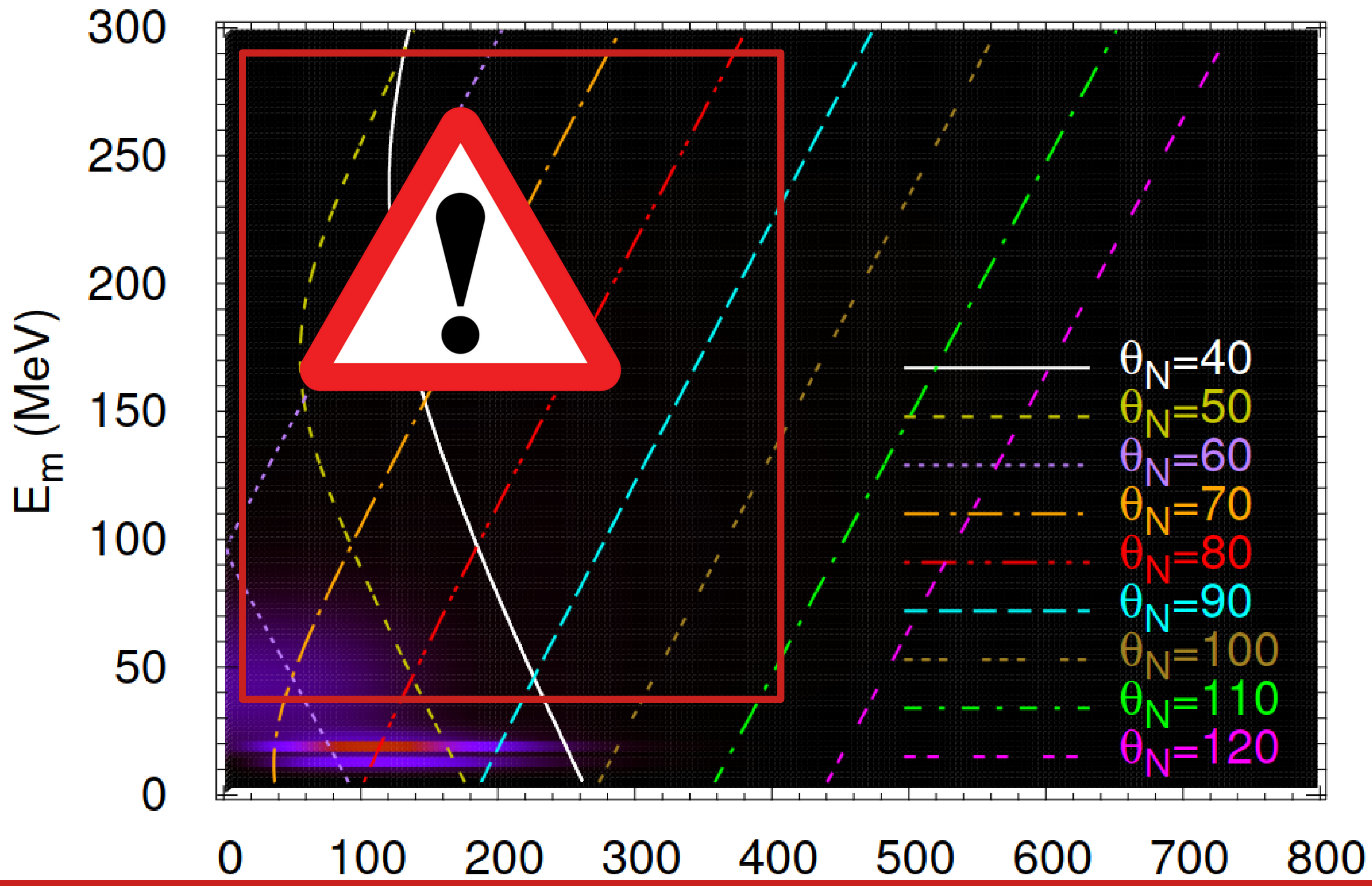
Good kinematics → Energy estimator with narrow uncertainty!
Sub-percent energy reconstruction → [arxiv:2104.017101]

Neutrino scattering: energy reconstruction for 1μ1p events
[R. Gonzalez-Jimenez et al. arxiv:2104.01701]



'Good kinematics'→ percent-level energy reconstruction [arxiv:2104.017101]

Neutrino scattering: energy reconstruction for 1μ1p events
[R. Gonzalez-Jimenez et al. arxiv:2104.01701]



!Problem!

2 – nucleon knockout, pion-production, final-state interactions, …

Populate the high-E_m region

Neutrino scattering: energy reconstruction for 1μ1p events

[F

This talk: Final-state interactions in nucleon knockout

Based on

[A. Nikolakopoulos , A. Ershova, R. Gonzalez-Jimenez, J. Isaacson, A.M. Kelly, K. Niewczas, N. Rocco, F. Sanchez, **arxiv:2406.09244**]

[A. Nikolakopoulos , R. Gonzalez-Jimenez, N. Jachowicz, K. Niewczas, F. Sanchez, J.M. Udias, **PRC 105, 054603**]

(Other efforts, e.g. electron-muon neutrino interactions in extra slides)

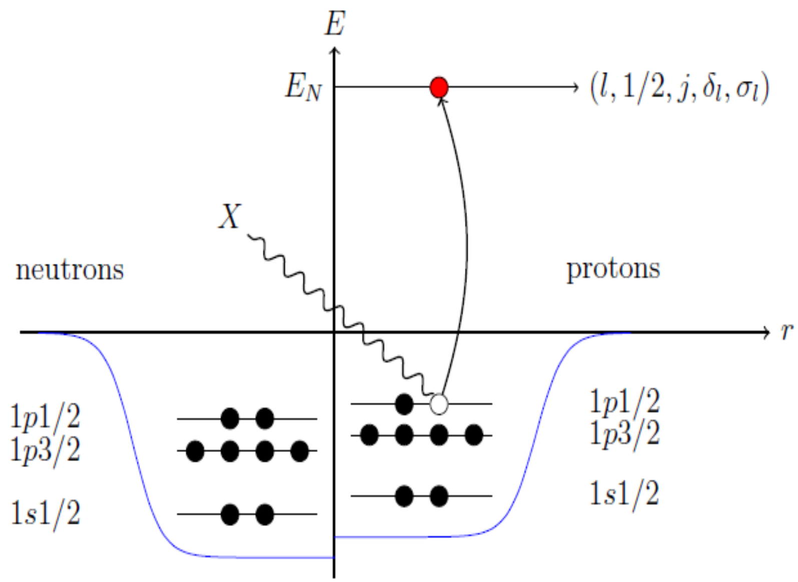
0 100 200 300 400 500 600 700 800

!Problem!

2 – nucleon knockout, pion-production, final-state interactions, …

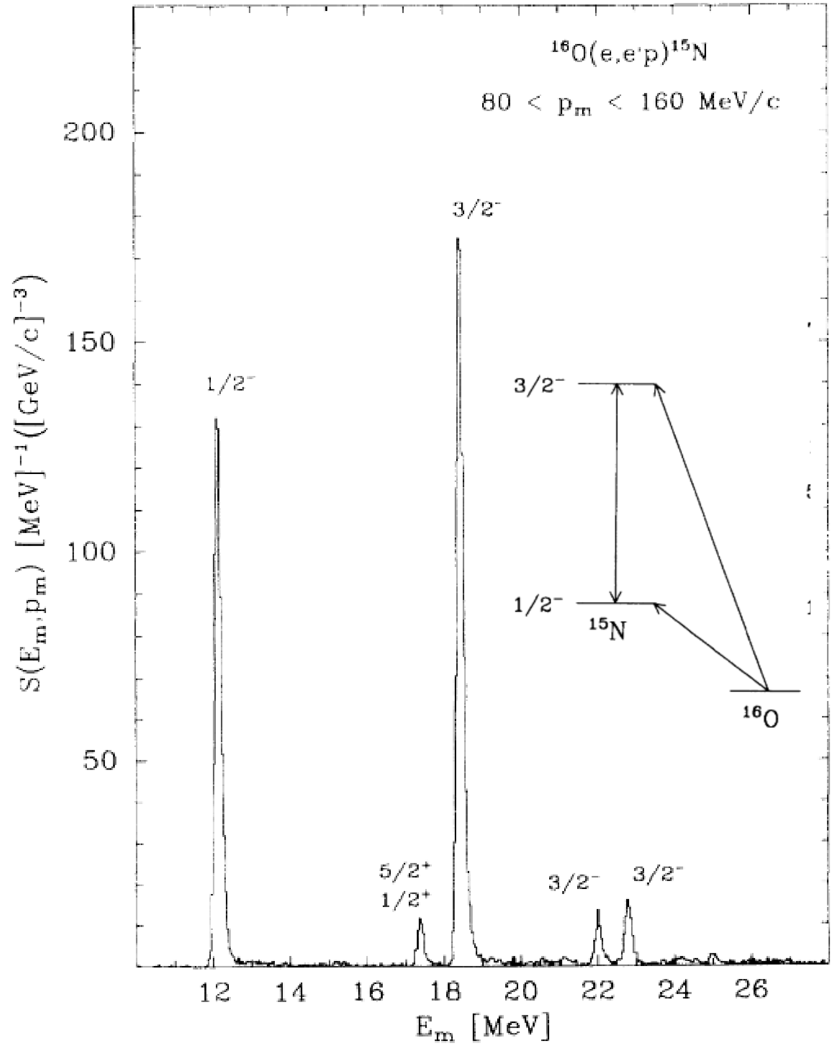
Populate the high-E_m region

Final-state interactions in exclusive (e,e'p) : optical potential



$$\mathcal{M} = j_{lep,\mu} \langle \Psi_f | \mathcal{O}^\mu | \Psi_i \rangle$$

$$\langle \Psi_f | = \langle \phi_p | \langle {}^{15}N^* |$$

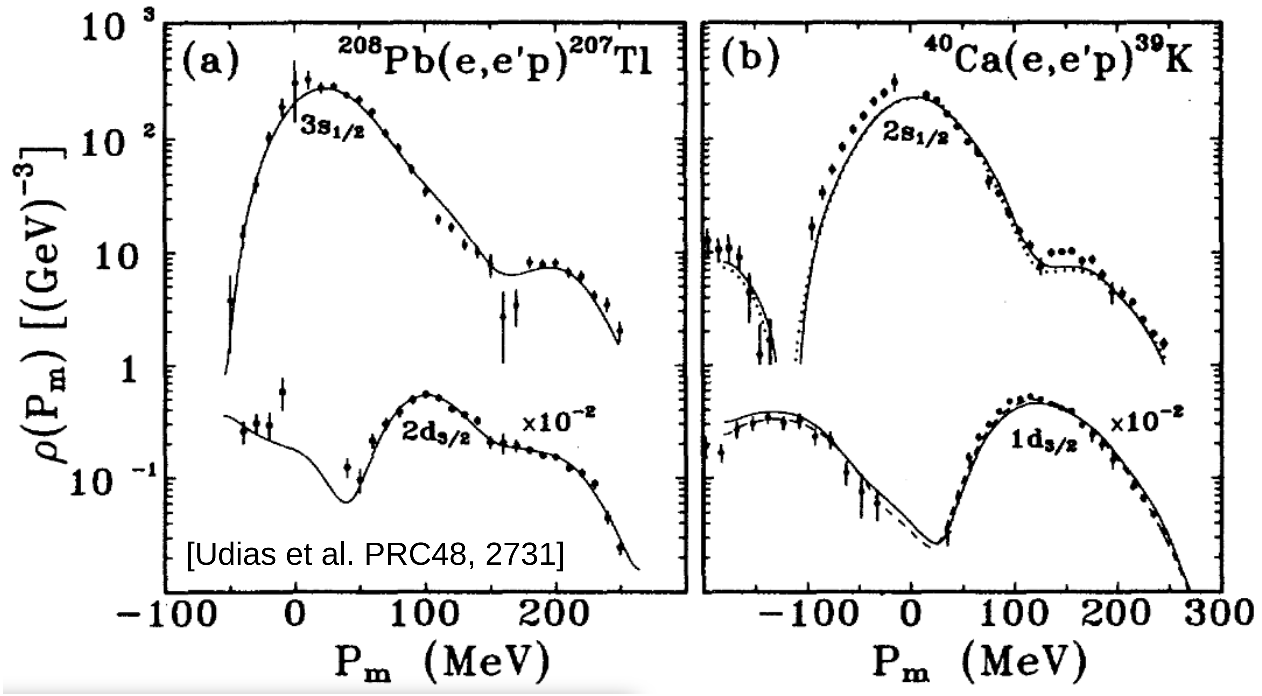


→ **Outgoing proton does not exchange energy with residual system**

Final-state interactions in exclusive (e,e'p) : optical potential

$$\mathcal{J}_{\kappa}^{m_j}(Q, P_N) = \int \mathrm{d}\mathbf{p}\ \overline{\psi}(\mathbf{p}+\mathbf{q}, \mathbf{k}_N, s_N)\ \mathcal{O}^{\mu}\ \psi_{\kappa}^{m_j}(\mathbf{p})$$

Final-state : solution of Dirac equation in optical potential



-'Standard' approach for FSI in exclusive (e,e'p) analysis

e.g.
Jlab analyses of ^{40}Ar, ^{48}Ti
[PRD 107, 012005]
[PRD 105, 112002]

Final-state interactions in exclusive (e,e'p) : optical potential

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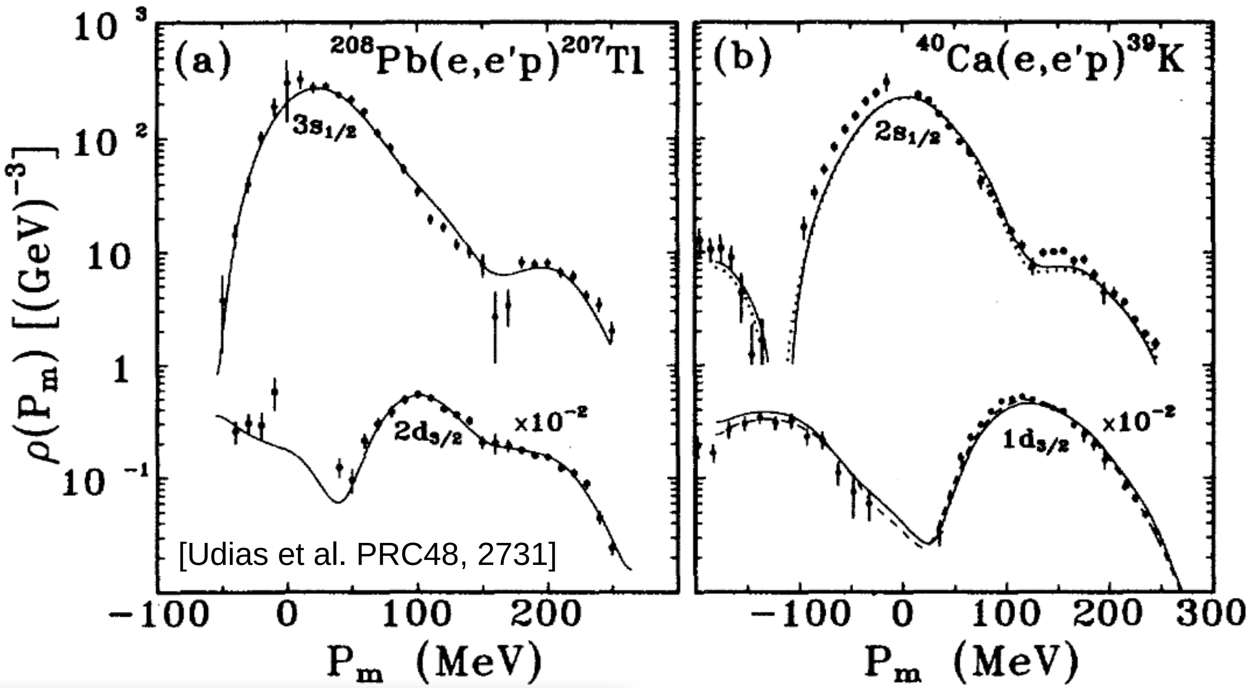

-'Standard' approach for FSI in exclusive (e,e'p) analysis

e.g.
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[PRD 107, 012005]
[PRD 105, 112002]

The optical potential **removes nucleons that undergo inelastic FSI**

↔

In neutrino experiments want to know **where the nucleon goes**

Where do the protons go ?: Intranuclear Cascade model (INC)

- ED-RMF
FSI in inclusive interactions

-INC
FSI for (semi-)exclusive channels

- ROP
FSI in single exclusive channel

Production of final-state $|X\rangle = |p\rangle|^{39}\mathrm{Ar}^*\rangle$

$$|\mathcal{M}|^2 \approx |\sum_\alpha \langle\Psi_0|T_{1b}|\psi_\alpha\rangle\langle\psi_\alpha|X\rangle|^2,$$

→ Restrict to 1-body operator

$$\approx \sum_\alpha |\langle\Psi_0|T_{1b}|\psi_\alpha\rangle|^2|\langle\psi_\alpha|X\rangle|^2$$

→ Classical approximation

$$\approx \sum_\alpha |\langle\Psi_0|T_{1b}|\psi_\alpha\rangle|^2 P(X|\alpha).$$

→ Intranuclear Cascade

Where do the protons go ?: Intranuclear Cascade model (INC)

- ED-RMF
FSI in inclusive

-INC
FSI for relevant (semi-)exclusive channels

- ROP
FSI in single exclusive channel

Production of final-state $|X\rangle = |p\rangle|^{39}\mathrm{Ar}^*\rangle$

$$|\mathcal{M}|^2 \approx \Big|\sum_\alpha \langle\Psi_0|T_{1b}|\psi_\alpha\rangle\langle\psi_\alpha|X\rangle\Big|^2,$$

ROP → Restrict to 1-body operator

$$\approx \sum_\alpha |\langle\Psi_0|T_{1b}|\psi_\alpha\rangle|^2|\langle\psi_\alpha|X\rangle|^2$$

→ Classical approximation

$$\approx \sum_\alpha |\langle\Psi_0|T_{1b}|\psi_\alpha\rangle|^2 P(X|\alpha)$$

ED-RMF **INC** → Intranuclear Cascade

Can benchmark the INC with Optical potential with same nuclear model
For direct proton knockout

PHYSICAL REVIEW C **105**, 054603 (2022)

Benchmarking intranuclear cascade models for neutrino scattering with relativistic optical potentials

A. Nikolakopoulos,[1,2,*] R. González-Jiménez,[3] N. Jachowicz,[1] K. Niewczas,[1,4] F. Sánchez,[5] and J. M. Udías[3]

Input to the INC

Fully differential events from RDWIA or RPWIA

For 1μ1p

Cuts on the INC results

Single proton events where proton does not lose Energy → no inelastic FSI

↓

Can be compared to ROP results

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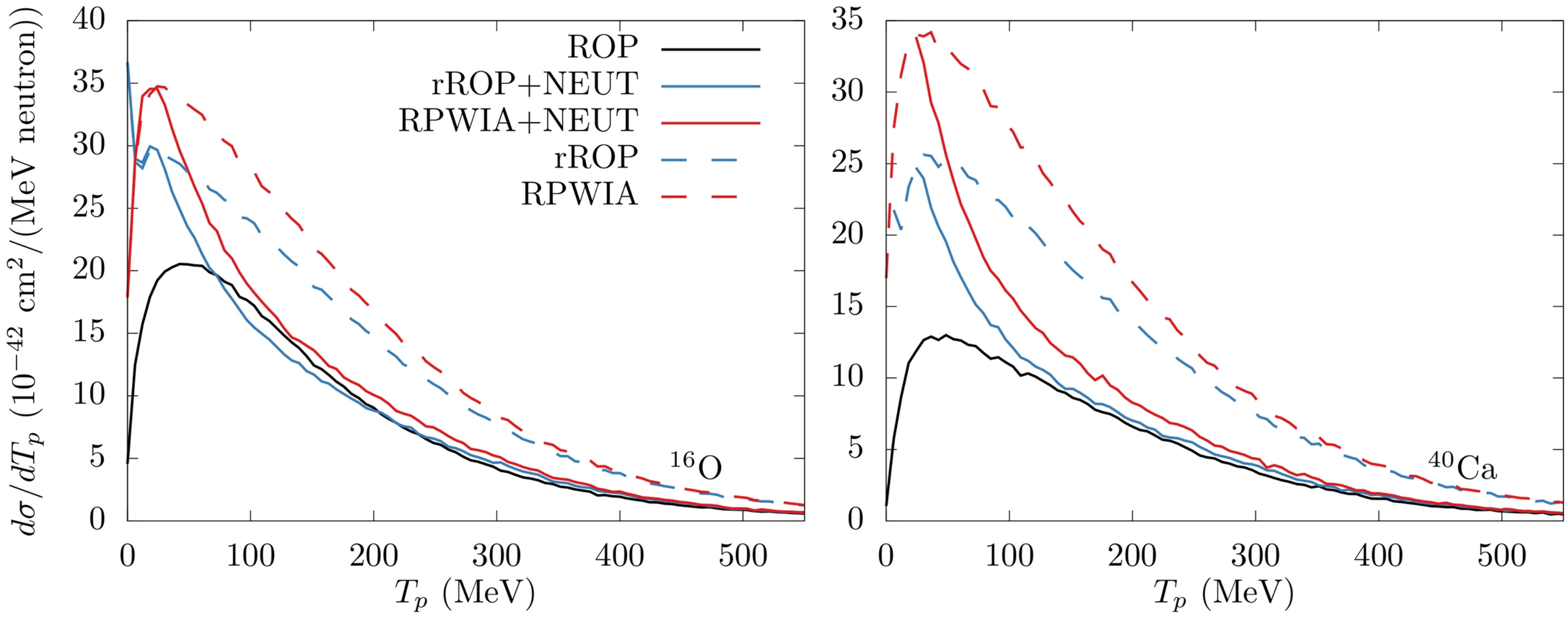
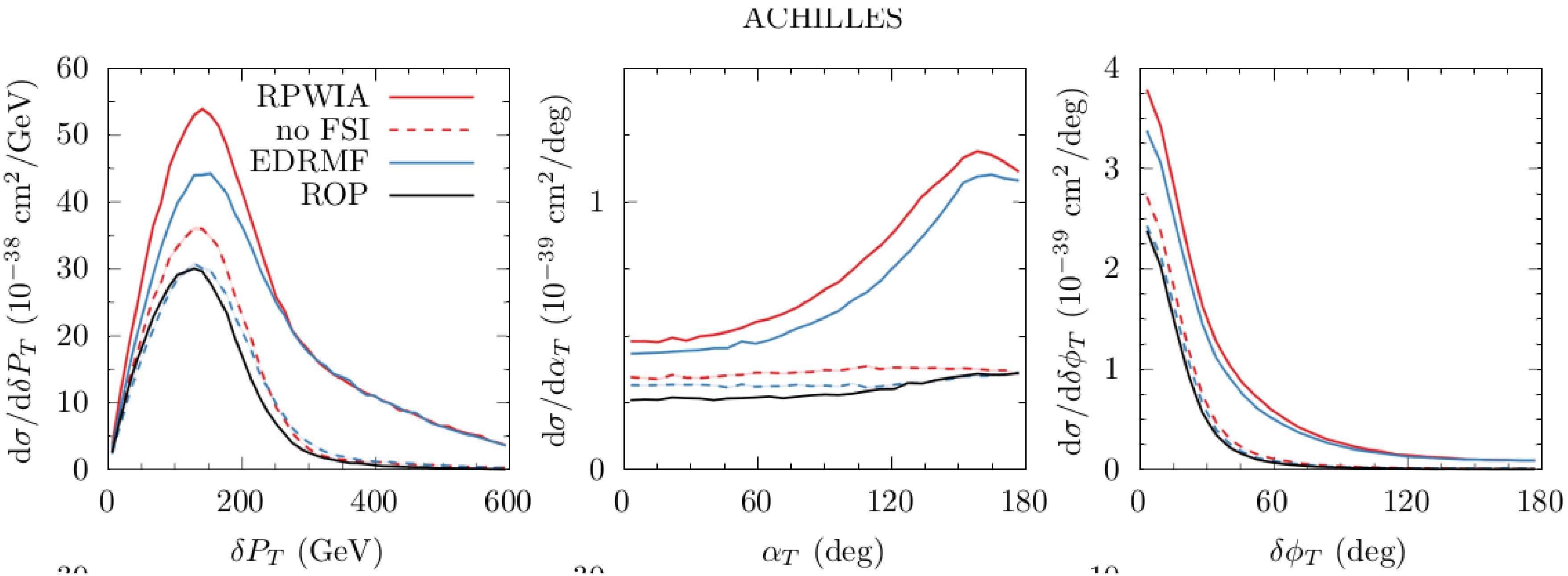
Flux-folded with T2K ND flux: NEUT INC



ROP and INC **agree at large T_p** but **large disagreement for small T_p**

Neutrino-induced proton knockout from argon in MicroBooNE [Arxiv:2406.09244]

- Flux-folded results for MicroBooNE
- ACHILLES, INCL, NEUT, and NuWro INC models
- Large set of kinematic distributions for comparison
- Detailed comparisons in backup slides



Some findings:

- Agreement depends on input calculation (ED-RMF ↔ RPWIA)
- Large differences between INCs (low T_p & treatment of correlations)
- No full agreement between any INC and ROP

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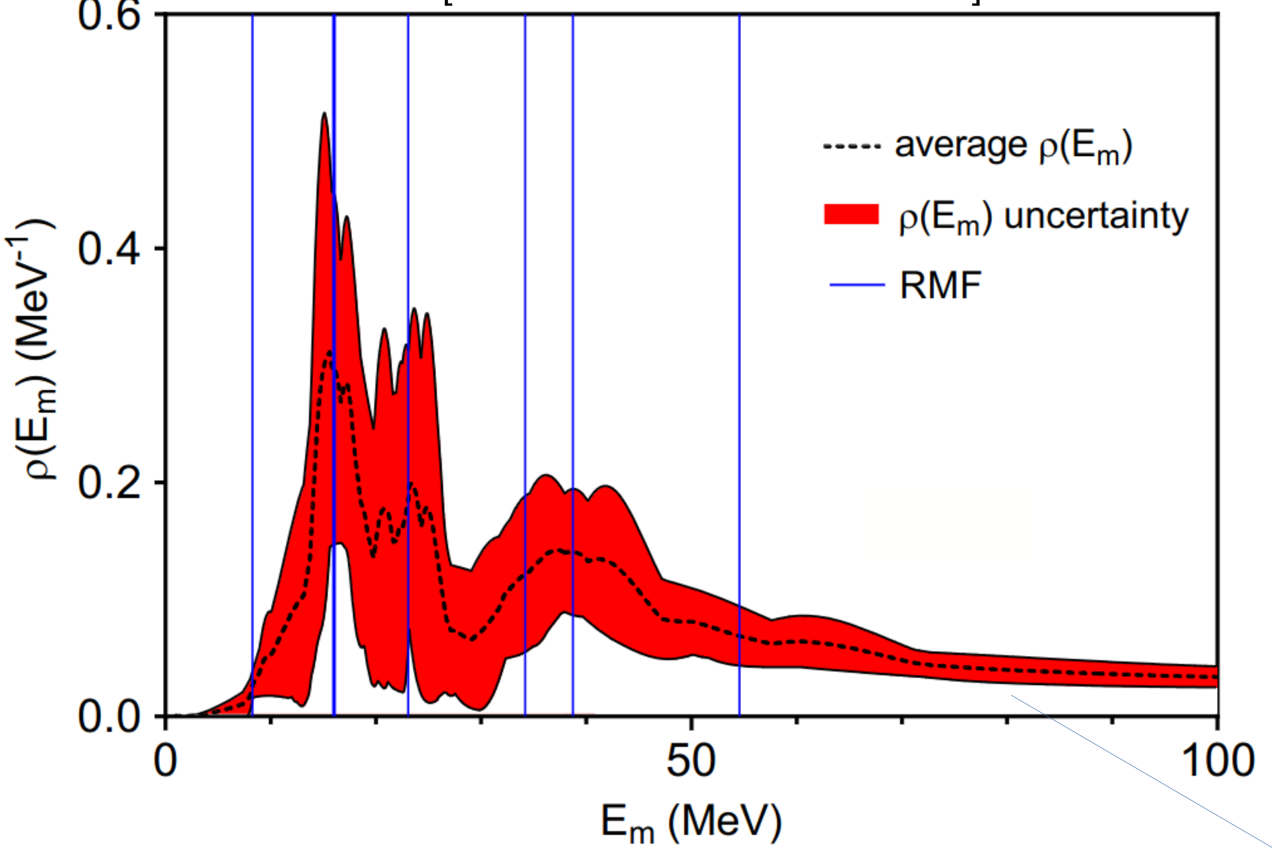
RDWIA calculations with realistic spectral functions for MicroBooNE

See: [J. M. Franco-Patino et al. PRD 109, 013004] & [R. Gonzalez-Jimenez et al. PRC 105, 025502]

From [J.M F-P et al. PRD 109 013004]



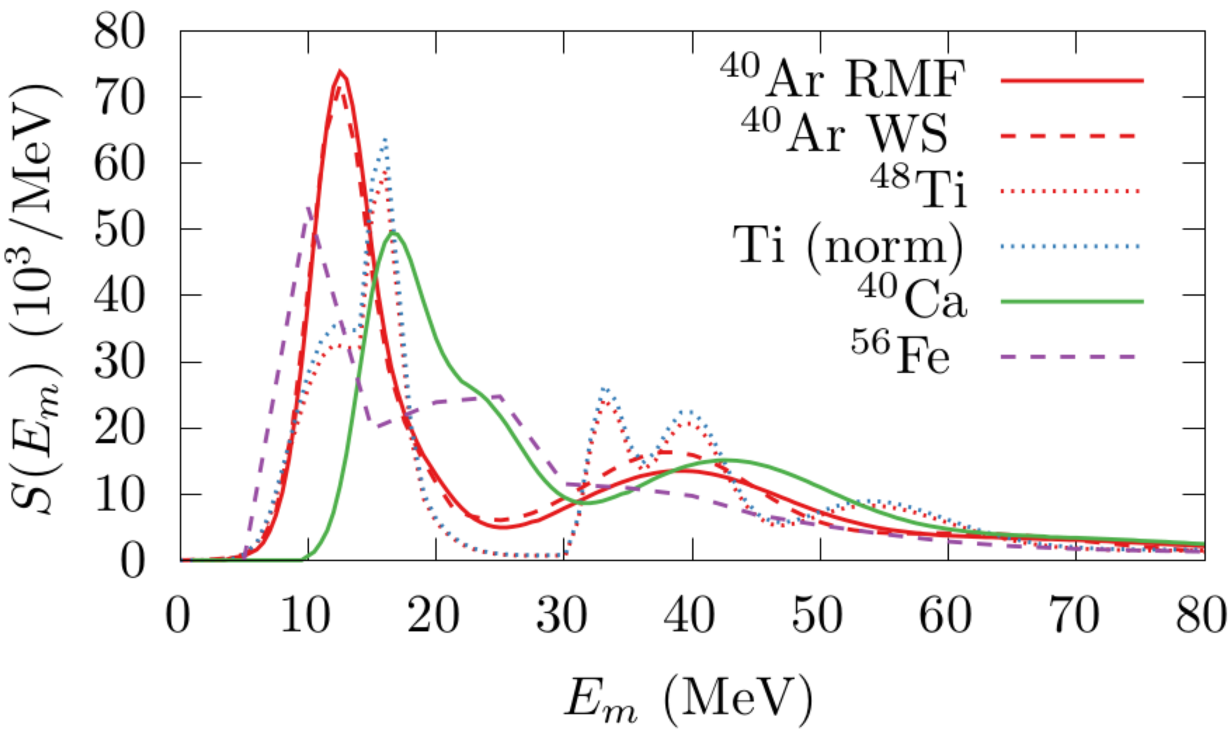
mean field → mean field + src

$$\delta(E_i - E_f)\sum_f |\mathcal{M}_{if}| = L_{\mu\nu}\sum_\kappa (2J_\kappa+1)\delta(E_m - E_\kappa)H^{\mu\nu}_\kappa(Q,P_N) \quad \rightarrow \quad L_{\mu\nu}\left\{\sum_\kappa N_\kappa \rho_\kappa(E_m) H^{\mu\nu}_\kappa(Q,P_N) + \rho_{corr}(E_m) H^{\mu\nu}_{corr}(Q,P)\right\}$$

RDWIA calculations with spectral functions for MicroBooNE

$$L_{\mu\nu}\left\{\sum_{\kappa} N_{\kappa}\rho_{\kappa}(E_m) H^{\mu\nu}_{\kappa}(Q,P_N) + \rho_{corr}(E_m) H^{\mu\nu}_{corr}(Q,P)\right\}$$

Choices of **N_κ** and **$\varrho(E_m)$**



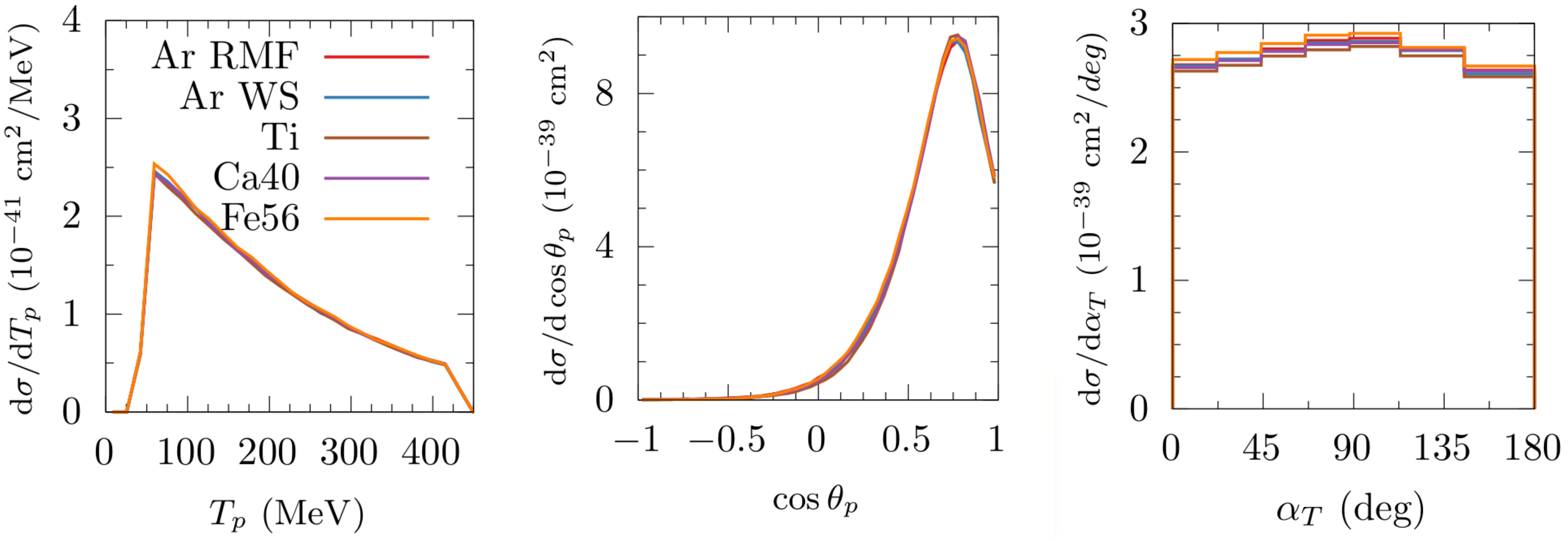
- ^{40}Ar spectral functions
  [Butkevich PRC 85, 065501]
  & [Jlab, PRD 107, 012005]
- ^{48}Ti from Jlab
  [PRD 107, 012005]
- ^{56}Fe
  [Benhar et al. NPA 579, 493]
- ^{40}Ca
  [Butkevich PRC 85, 065501]

Large variation in E_m profiles to check sensitivity of observables

Sensitivity to variations in the spectral functions: PWIA calculations

[Arxiv:2406.09244]

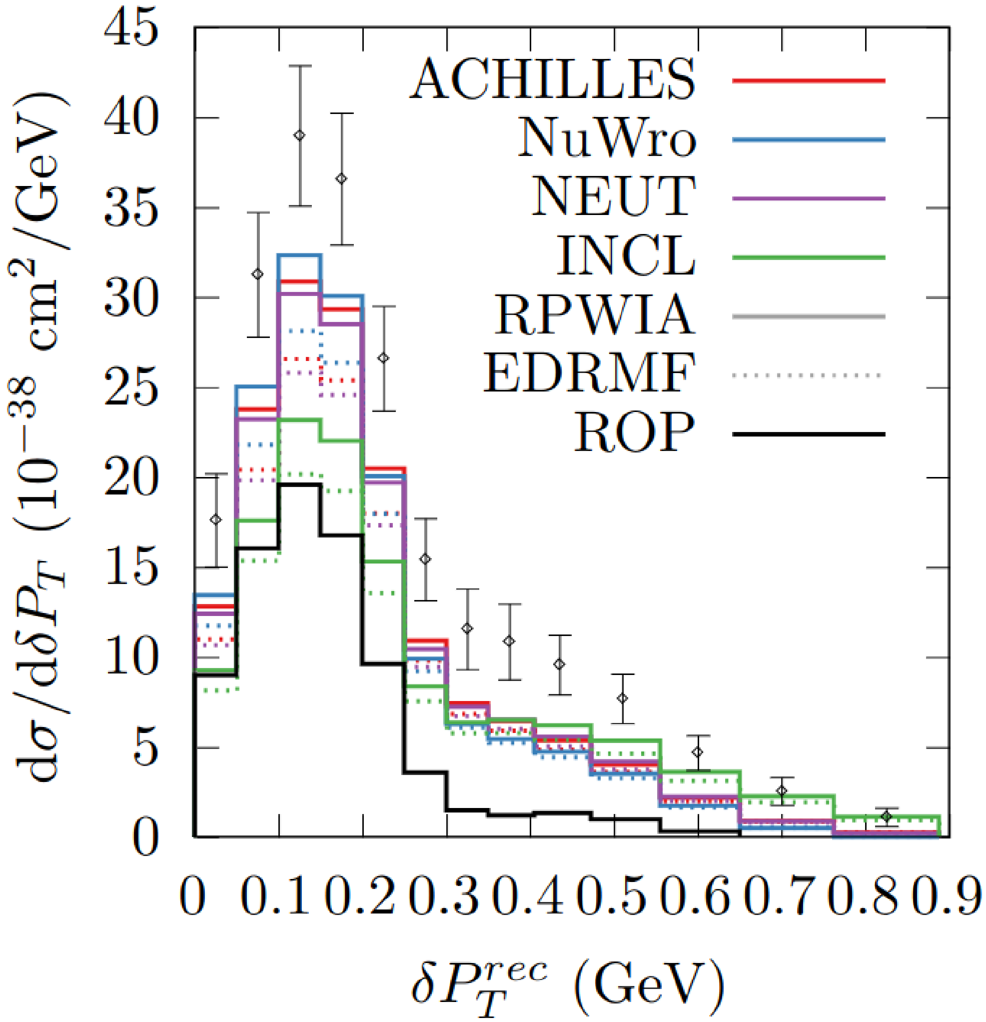
Observables for MicroBooNE flux-averaged signal



- **Negligible differences** between different spectral-functions **for observables that do not correlate p_p and p_μ**
- **Mild sensitivity only to p_m distributions**
- **Current MicroBooNE data not sensitive to missing energy distributions**

Comparisons to MicroBooNE data

[Arxiv:2406.09244]



Isolate the effect of the INC

→ exact same inputs for each

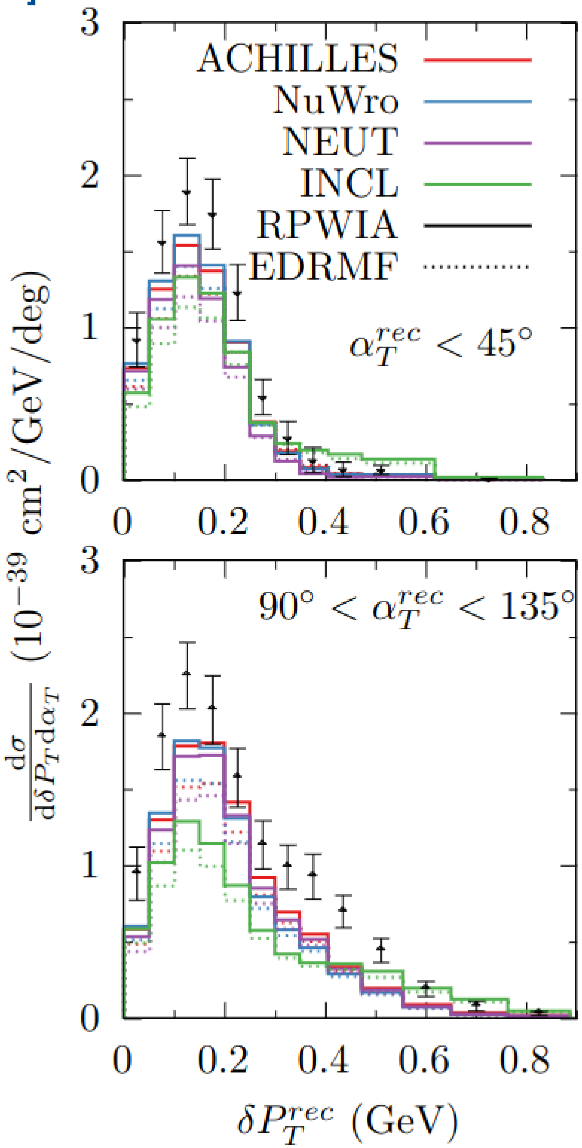
Realistic final-state nucleon wave-functions

→ 10% effect

(Can generate events + Implementation in NEUT underway)

Comparisons to MicroBooNE data

[Arxiv:2406.09244]



Isolate the effect of the INC

→ exact same inputs for each

Realistic final-state nucleon wave-functions

→ 10% effect

Cut on α_T

→ reduce rescattering for small α_T

→ Still sizeable contribution of resc

→ ROP alone cannot reproduce data

Low α_T dP_T underpredicted

→ Increase axial coupling ??

→ **Need to include the interference with 2-body currents!**

- **1-proton knockout could provide excellent energy-resolution**
  → Backgrounds non-trivial !

- **RDWIA + realistic spectral function + INC**
  = most comprehensive description of single-nucleon knockout
  → No full agreement with recent MicroBooNE data

Where to go from here?

Theory

*** Interference with 2-body currents needs to be included !**

See e.g. [T. Franco Munoz et al. PRC108, 064608] [Lovato et al. , 2312.12545]

*** Two-nucleon and single pion production (SPP) contributions**

→ ACHILLES: will soon include 2-body interference + SPP with full FSI
→ NEUT: will include RDWIA calculations with SF
→ NuWro: new SPP [2405.0512] and 2-N [K. Niewczas Phd] implementations

Experiment

*** High statistics in SBND can test 'good event' selection in 1μ1p in LarTPC**

*** New electron scattering data in non-trivial kinematic regions**
→ A1 at MAMI, e4ν at Jlab take electron data for ν program (+ more facilities ?!)

Other stuff

Terminology : RDWIA, RPWIA and PWIA & ED-RMF and ROP

-Relativistic Distorted Wave Impulse Approximation (RDWIA)

$$\mathcal{J}_{\kappa}^{m_j}(Q, P_N) = \int \mathrm{d}\mathbf{p}\ \overline{\psi}(\mathbf{p}+\mathbf{q}, \mathbf{k}_N, s_N)\ \mathcal{O}^{\mu}\ \psi_{\kappa}^{m_j}(\mathbf{p})$$

- Relativistic Plane Wave Impulse Approximation (RPWIA)

$$\mathcal{J} = (2\pi)^{3/2}\ \overline{u}(\mathbf{k}_N, s_N)\ \mathcal{O}^{\mu}\ \psi_{\kappa}^{m_j}(\mathbf{k}_N - \mathbf{q})$$

- Plane-Wave Impulse Approximation (PWIA)

The initial state is assumed proportional to a positive-energy spinor:

$$\psi_{\kappa}^{m_j}(\mathbf{p}) \propto f(|\mathbf{p}|)u(\mathbf{p})$$

One obtains a factorized expression ('spectral function approach')

$$\frac{d\sigma(E_\nu)}{dp_\mu d\Omega_\mu d\Omega_p dp_N} = \frac{G_F^2 \cos^2\theta_c}{(2\pi)^2} \frac{p_\mu^2 p_N^2}{E_\nu E_\mu} \frac{M_N^2}{E_N \overline{E}} L_{\mu\nu} h^{\mu\nu}_{s.n.} S(E_m, p_m)$$

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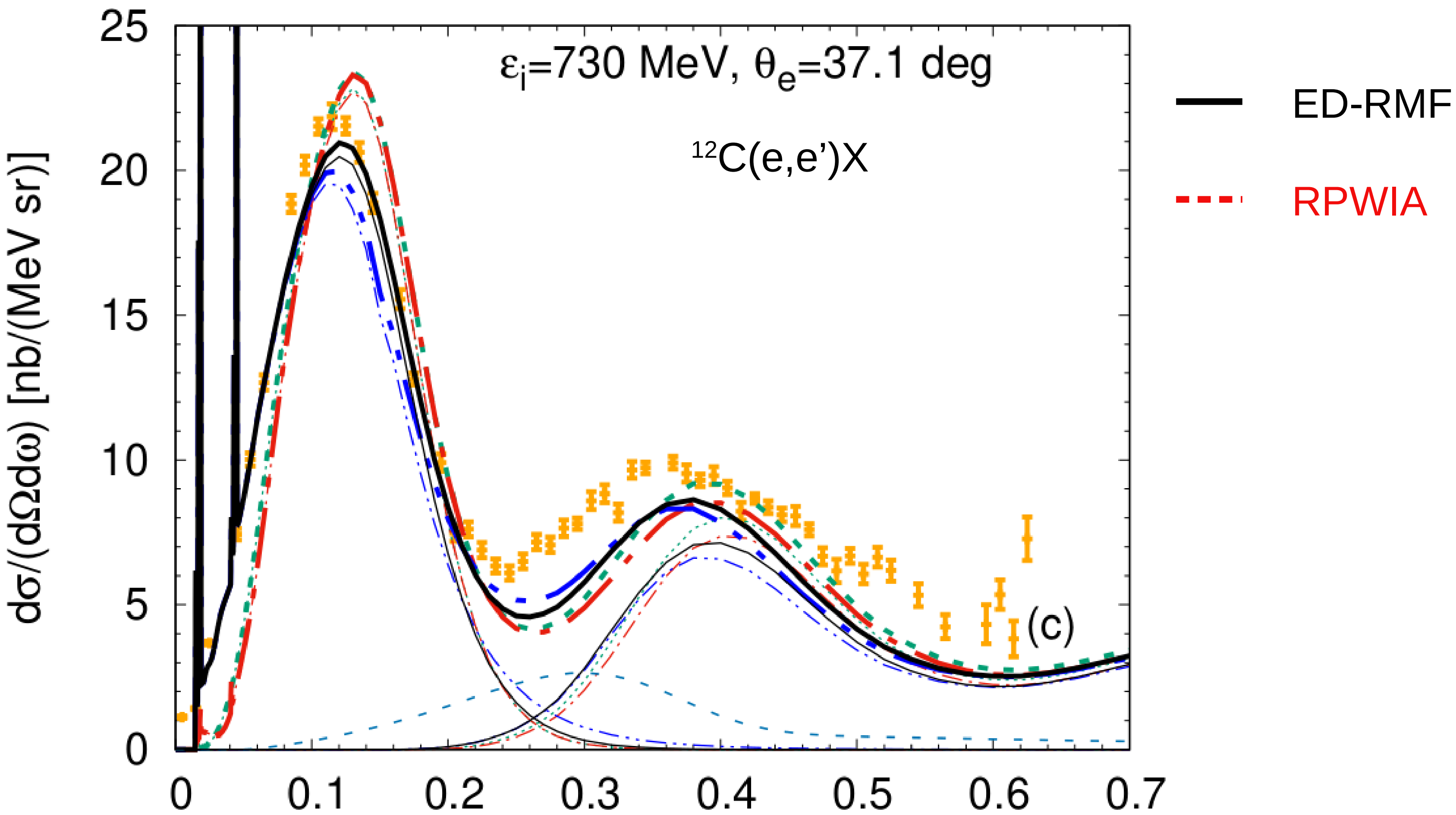
Terminology : RDWIA, RPWIA and PWIA & ED-RMF and ROP

- Energy-Dependent Relativistic Mean-Field (ED-RMF)

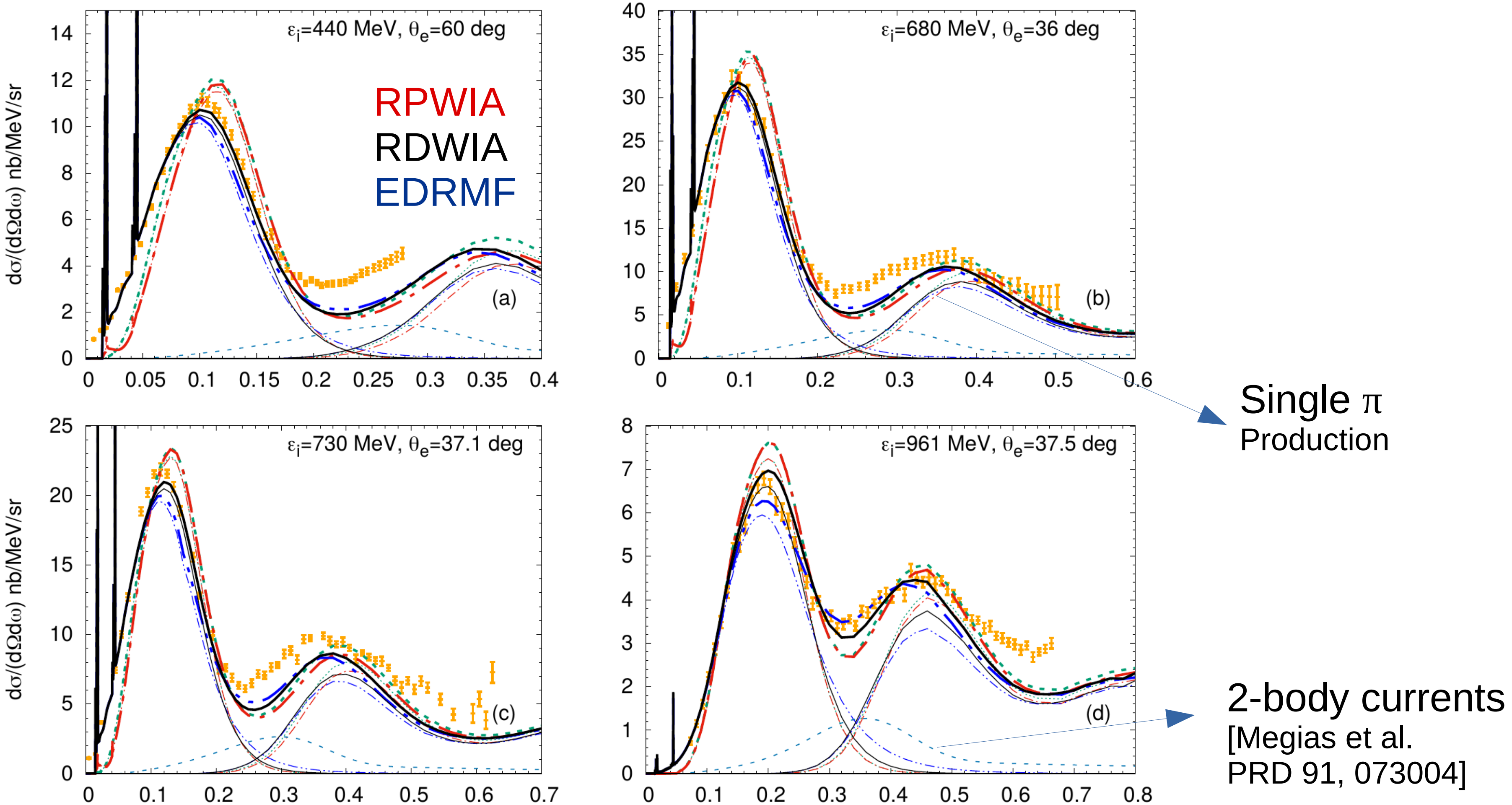
$\overline{\psi}(\mathbf{p}+\mathbf{q}, \mathbf{k}_N, s_N)$ → Final-state in **real** Energy-Dependent potential
→ suitable for **FSI in inclusive** cross section



[R. Gonzalez-Jimenez et al Phys. Rev. C 100, 045501 (2019)]

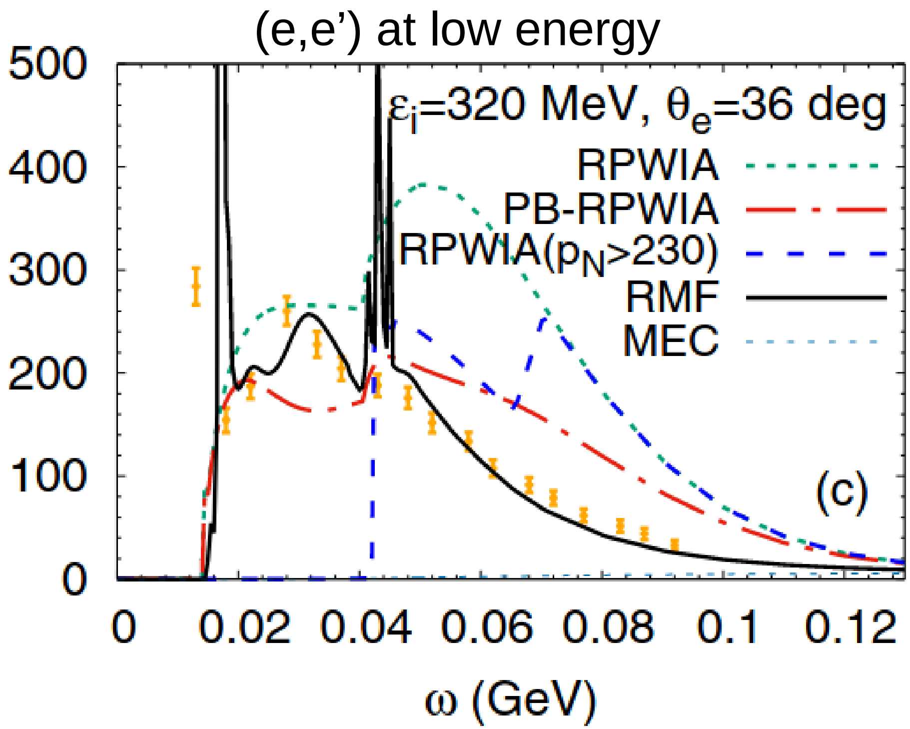
Inclusive electron scattering off a RMF nucleus

[R. Gonzalez-Jimenez, A. Nikolakopoulos, N. Jachowicz, J.M. Udias PRC 100, 045501 (2019)]



Nucleon knockout from a RMF nucleus: consistent initial & final-states

[R. Gonzalez-Jimenez, A. Nikolakopoulos, N. Jachowicz, J.M. Udias PRC 100, 045501 (2019)]

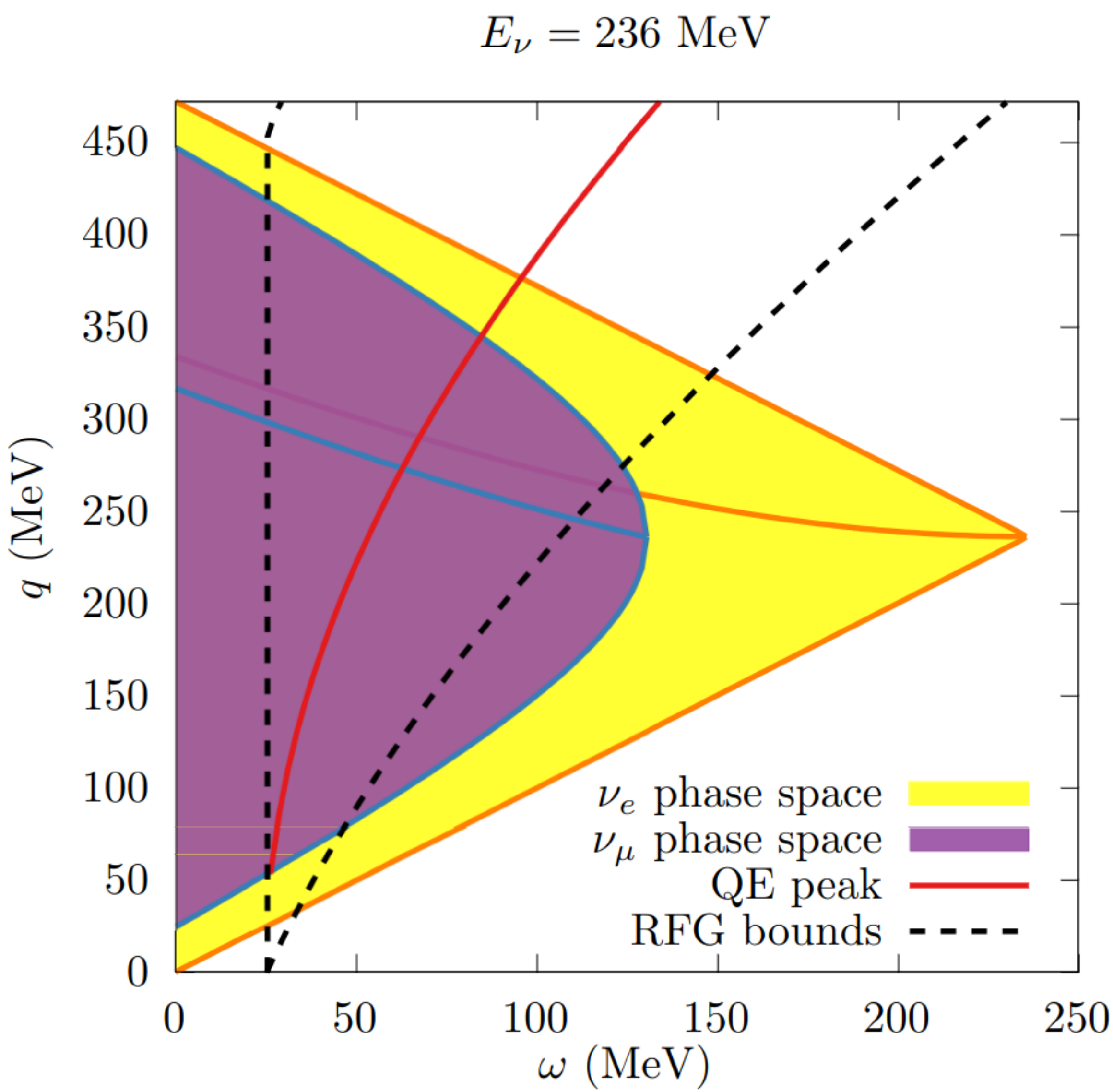


- Consistent states are crucial at low energies
  → provided by RMF
  → ED-RMF = RMF
  by construction at low-energy
- Consistent states are orthogonal => Pauli-Blocking

'Pauli-Blocked' RPWIA (PB-RPWIA): orthogonalize with respect to bound-states

$$|\Psi^{s_N}(\mathbf{p}_N)\rangle = \left|\psi^{s_N}_{pw}(\mathbf{p}_N)\right\rangle - \sum_{\kappa,m_j}\left[C^{m_j,s_N}_{\kappa}(\mathbf{p}_N)\right]^{\dagger}\left|\psi^{m_j}_{\kappa}\right\rangle \qquad C^{m_j,s_N}_{\kappa}(\mathbf{p}_N) \equiv \left\langle\psi^{s_N}_{pw}(\mathbf{p}_N)\middle|\psi^{m_j}_{\kappa}\right\rangle.$$

Electron- and muon neutrino interactions



Neutrino interactions are constrained in near-detector: **Mostly ν_μ measurements**

In ν_e appearance or CP violation measurements:

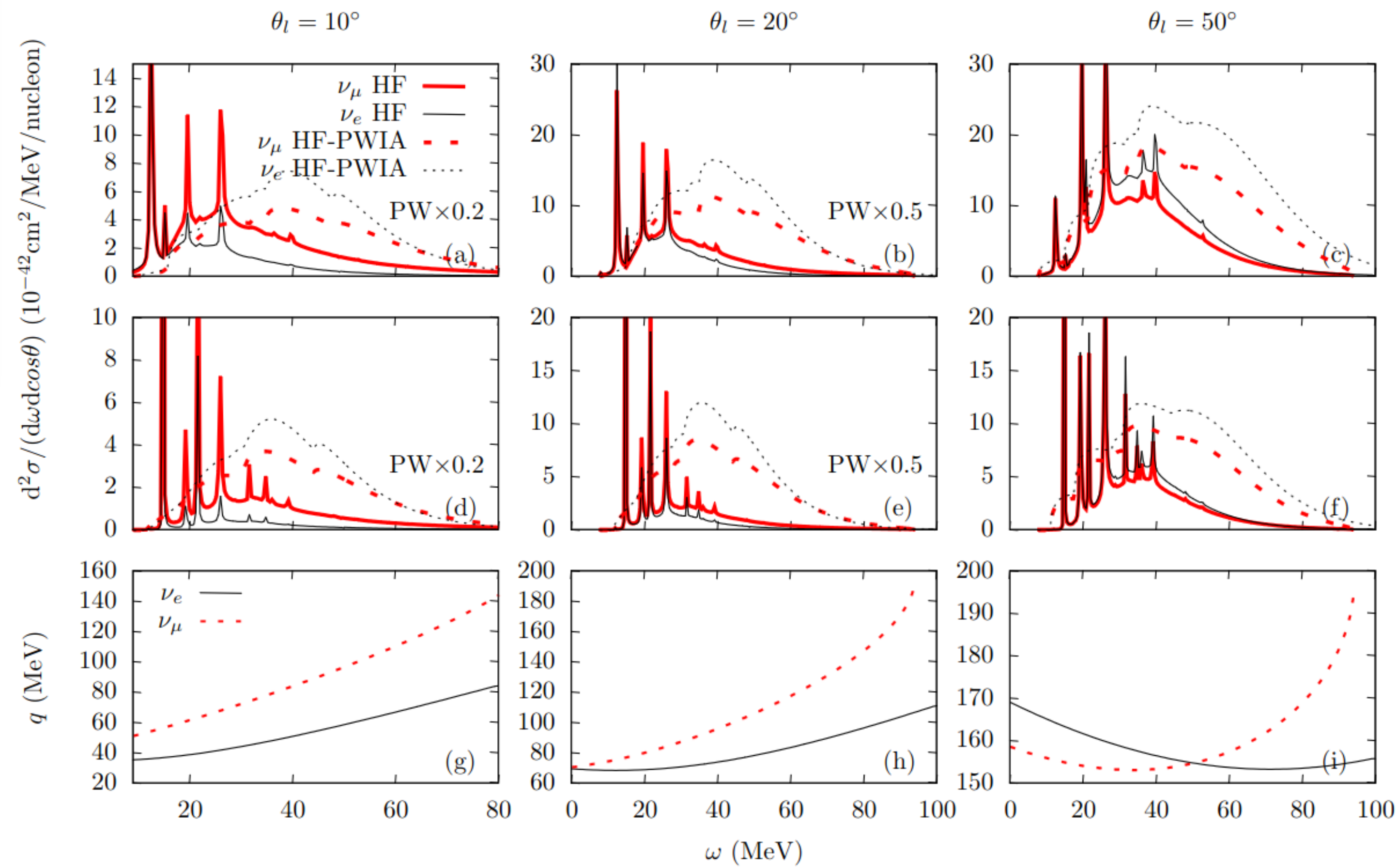
Physics that affects (anti)-ν interactions of different flavours differently can lead to systematic uncertainty

At high-E:
Cross sections are ~ the same

Low-E:
Naive expectation: electron CS larger because of phase space

Electron- and muon neutrino interactions at low energy

[A. Nikolakopoulos et al. PRL 123, 123, 052501 (2019)]



At low energy-momentum transfer ν_μ cross sections are larger than ν_e

$$q = \sqrt{E_\nu^2 + P_l^2 - 2\cos\theta_l E_\nu P_l} \approx E_\nu - \sqrt{(E_\nu - \omega)^2 - m_l^2}$$

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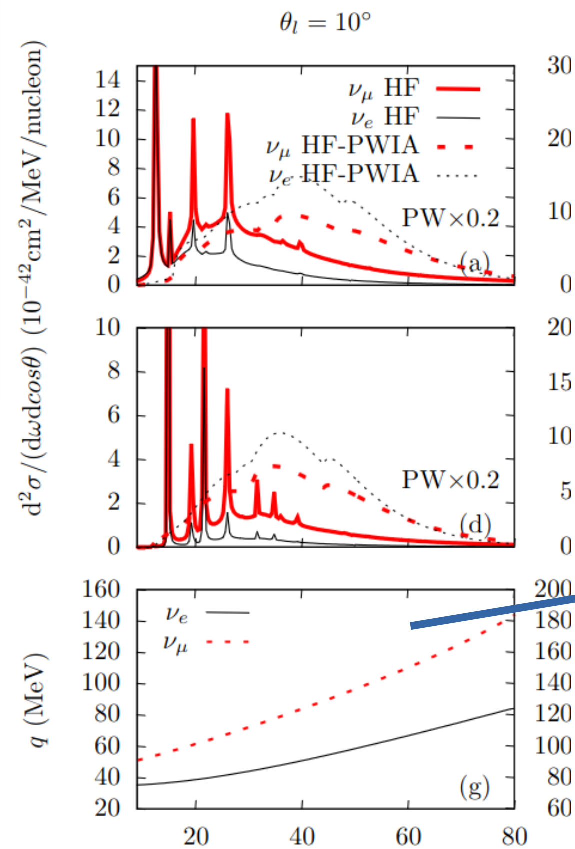
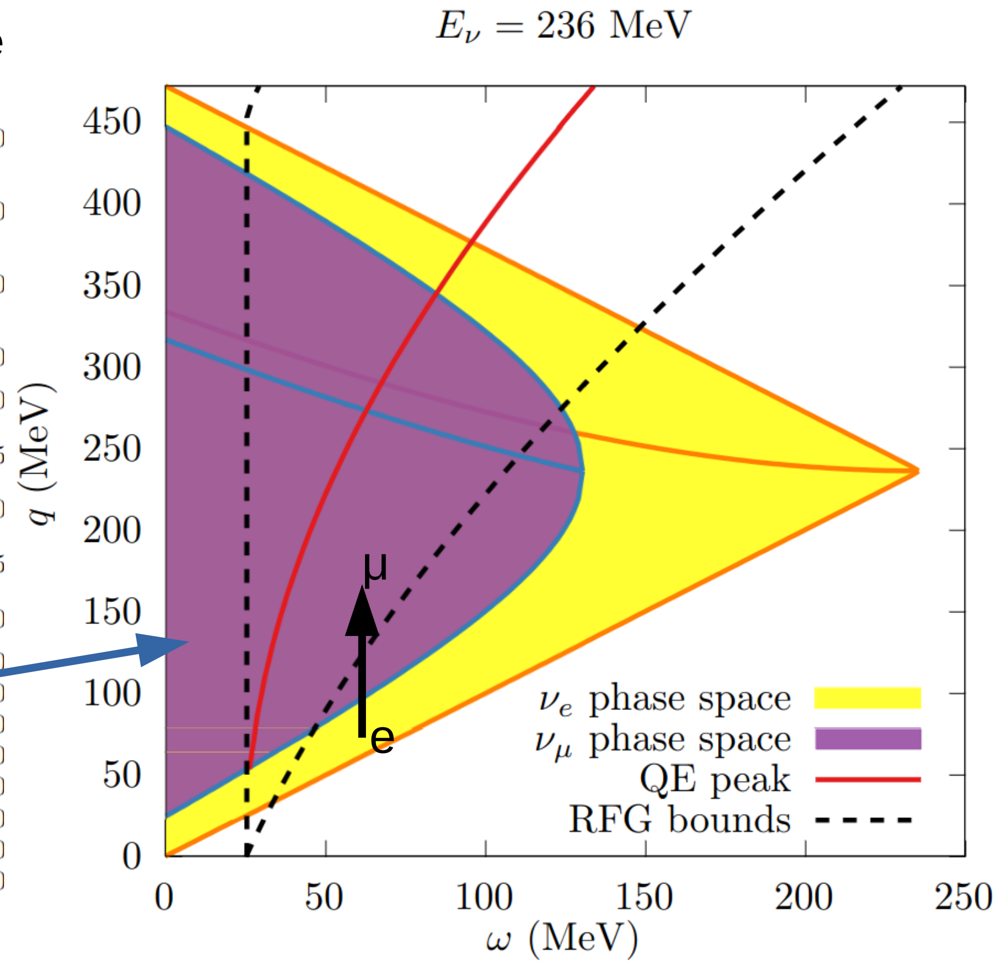
Electron- and muon neutrino interactions at low energy

[A. Nikolakopoulos e





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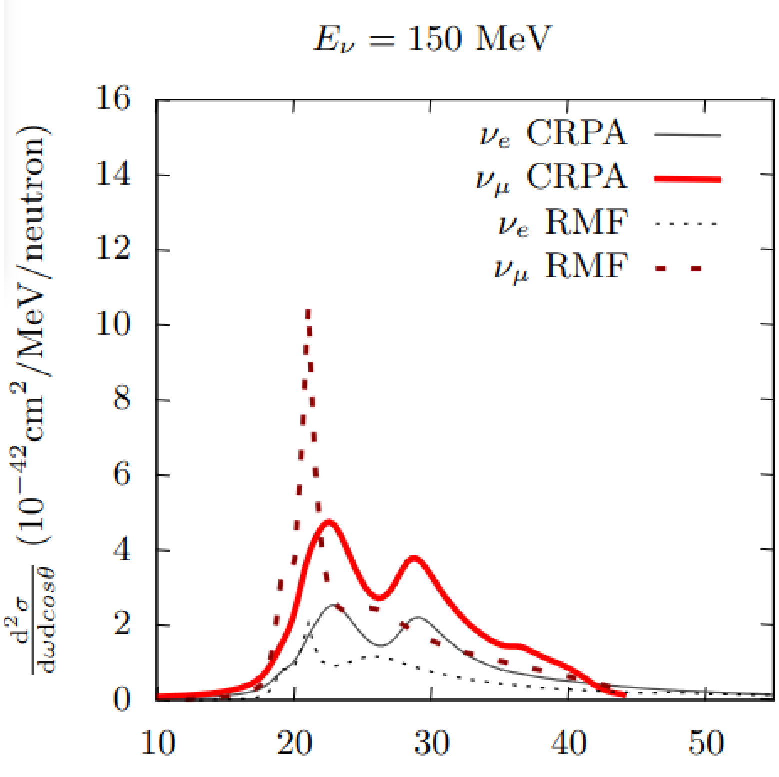
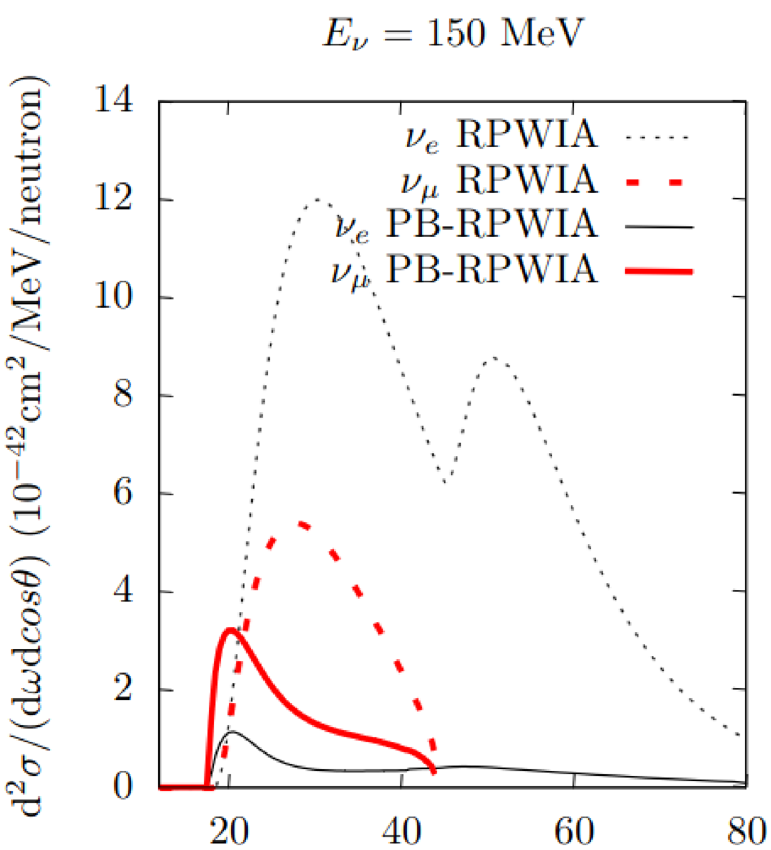
Electron- and muon neutrino interactions at low energy

[A. Nikolakopoulos et al. PRL 123, 123, 052501 (2019)]

Can be understood from the orthogonality with bound states



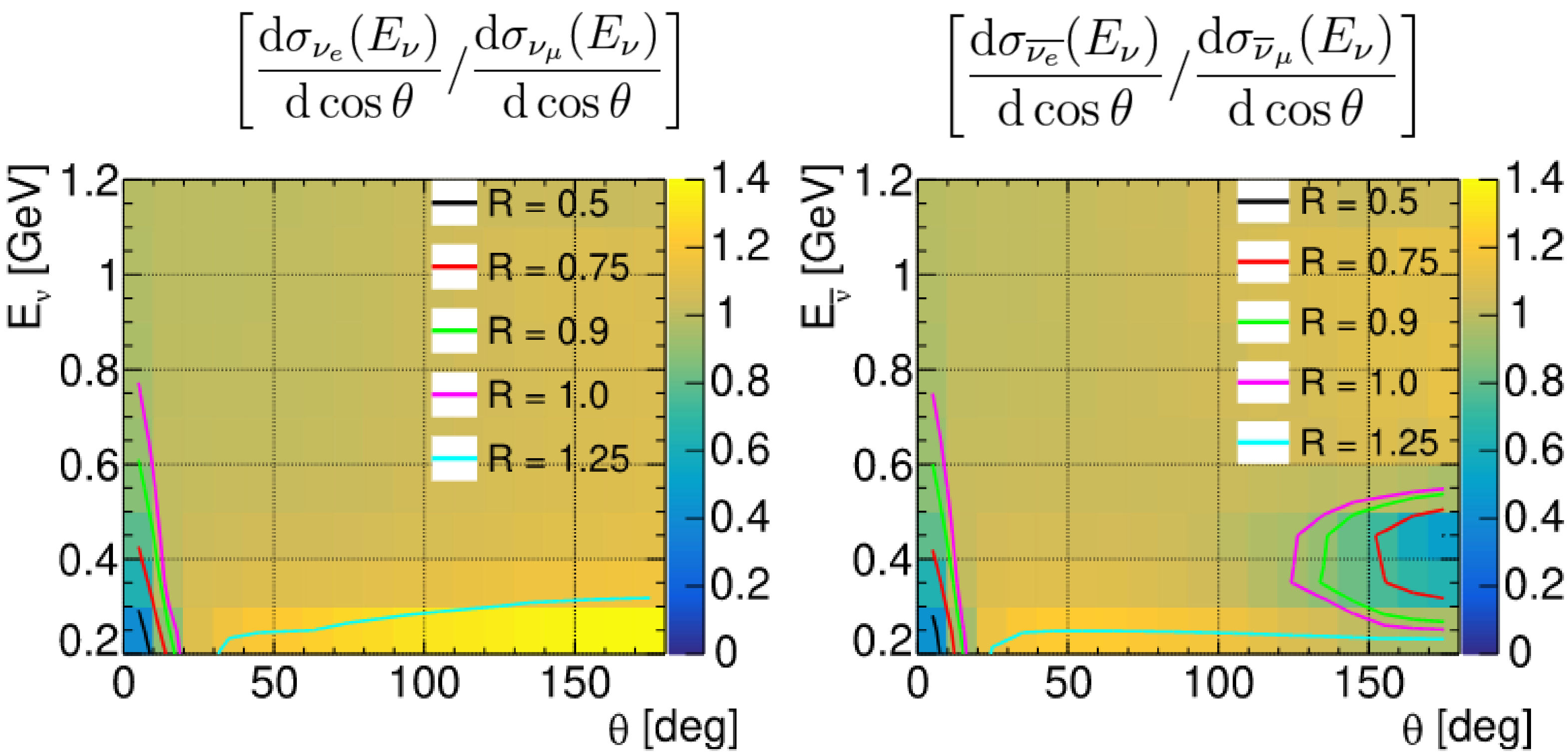


Fermilab

Uncertainties on the $\overset{(-)}{\nu}_e/\overset{(-)}{\nu}_\mu$ and $\nu_e/\bar{\nu}_e$ cross-section ratio from the modelling of nuclear effects at 0.2 to 1.2 GeV neutrino energies and their impact on neutrino oscillation experiments

T. Dieminger,[1,*] S. Dolan,[2,†] D. Sgalaberna,[1,‡] A. Nikolakopoulos,[3]
T. Dealtry,[4] S. Bolognesi,[5] L. Pickering,[6] and A. Rubbia[1]

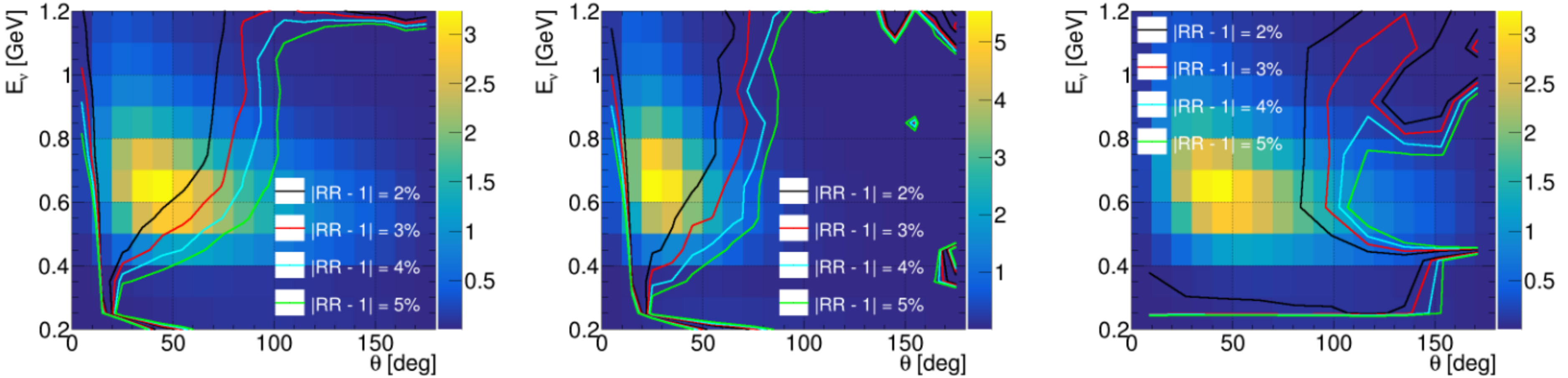
arXiv:2301.08065v3 [hep-ph] 5 Apr 2023



Assessing model-dependence: double ratios

$$RR^{\text{Model 1/Model 2}}_{\nu_\alpha/\nu_\beta}(E_\nu,\theta) = \frac{R^{\text{Model 1}}_{\nu_\alpha/\nu_\beta}(E_\nu,\theta)}{R^{\text{Model 2}}_{\nu_\alpha/\nu_\beta}(E_\nu,\theta)}$$

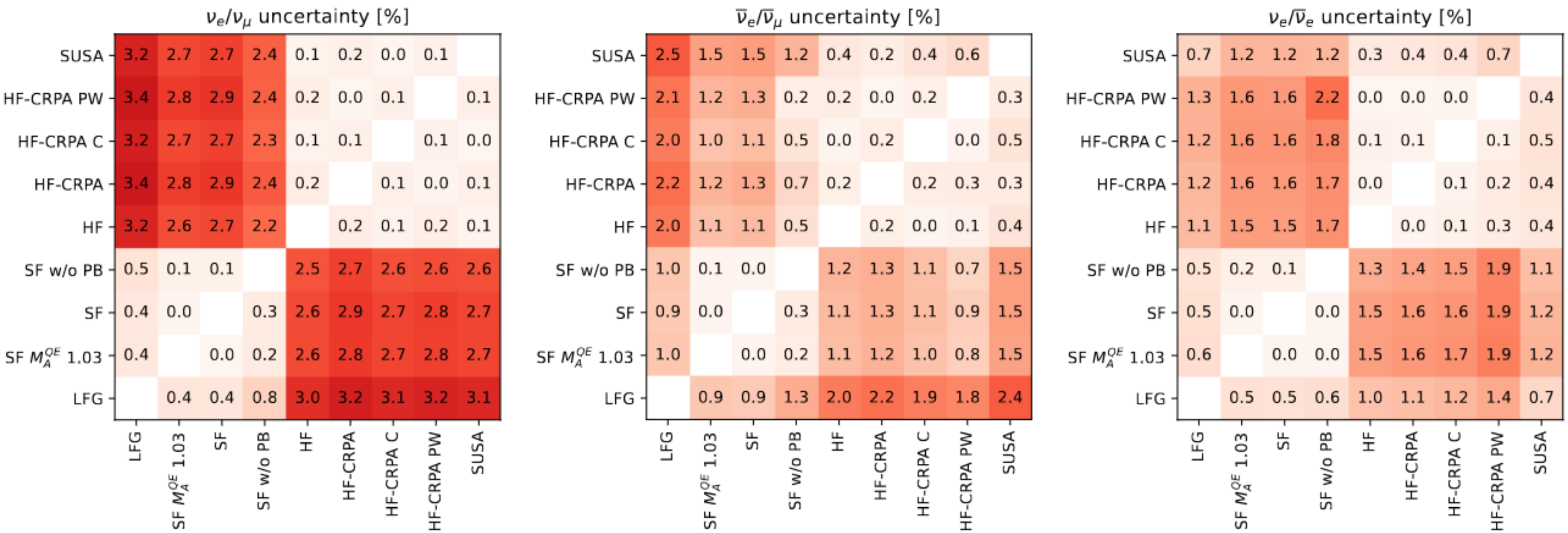
$RR^{CRPA/SF}_{\nu_e/\nu_\mu}$ $\quad$ $RR^{CRPA/SF}_{\overline{\nu}_e/\overline{\nu}_\mu}$ $\quad$ $RR^{CRPA/SF}_{\nu_e/\overline{\nu}_e}$



High-angle region in T2K is most relevant

Assessing model-dependence

Uncertainty from averaging model-differences *in Ratio* over predicted event rate

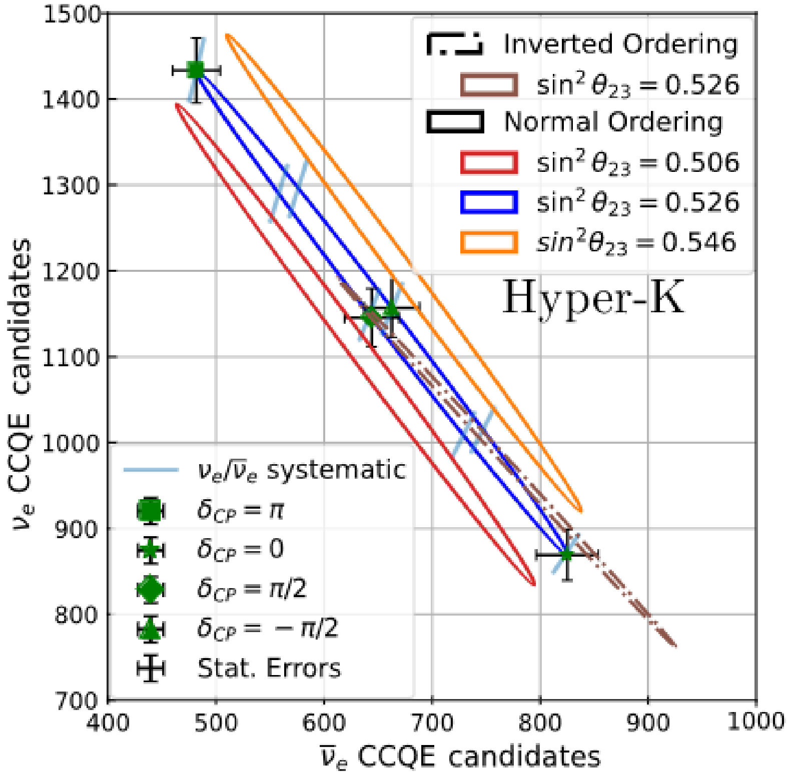


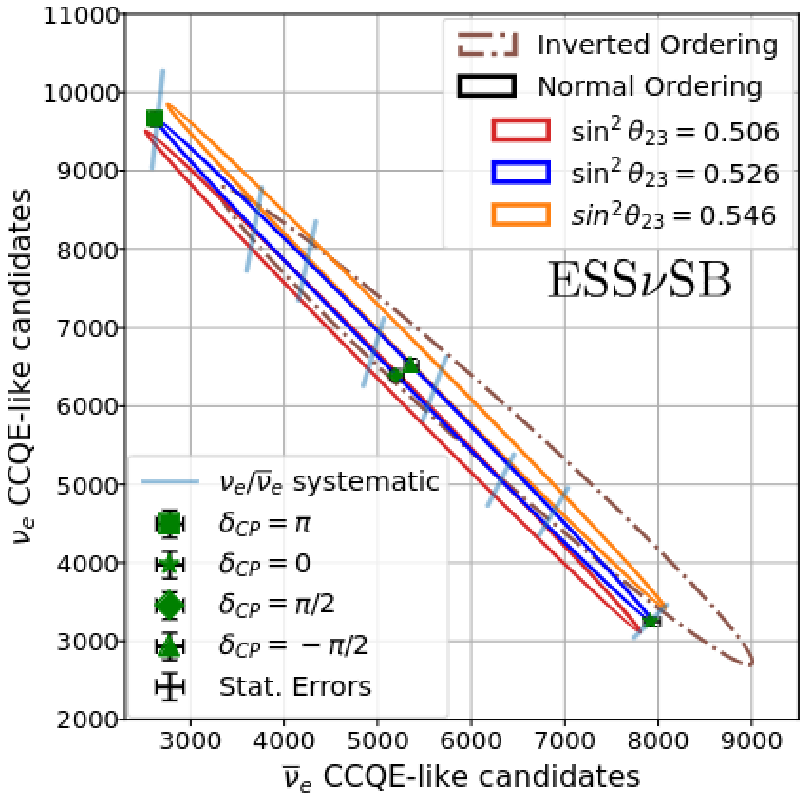
Quite robust when varying parameters within one model

Two ‘sets’: LFG and PWIA+SF and mean-field based models
(or NEUT generator vs. other calculations ?)

Assessing impact on appearance experiment: bi-event plots

$$\nu_\mu \to \nu_e \quad \text{and} \quad \overline{\nu}_\mu \to \overline{\nu}_e$$





1) Not significant for $sin\delta_{CP}$

2) Increases degeneracy in $sin^2\theta_{23}$

Magnitude 2-4% percent: uncertainty in line with values used in experiment

Article

From inclusive to semi-inclusive one-nucleon knockout in neutrino event generators

Alexis Nikolakopoulos [1,*], Steven Gardiner [1], Afroditi Papadopoulou [2], Stephen Dolan [3] and Raúl González-Jiménez [4]

$$P(E_l, \theta_l, T_N, \Omega_N)$$

Replace by
'factorized approach'

We get the GENIE version based on **the same** inclusive cross section!

We generate events for (e,e'p) in RDWIA with **real potential**

- Full consistent description of exclusive kinematics 1e1p
- Integrate over the proton → get the correct inclusive cross section (=includes 'elastic' FSI!)
- For every event we **replace** the nucleon kinematics by the GENIE prediction (SuSAv2 implementation)

Nucleon kinematics from inclusive cross section in GENIE

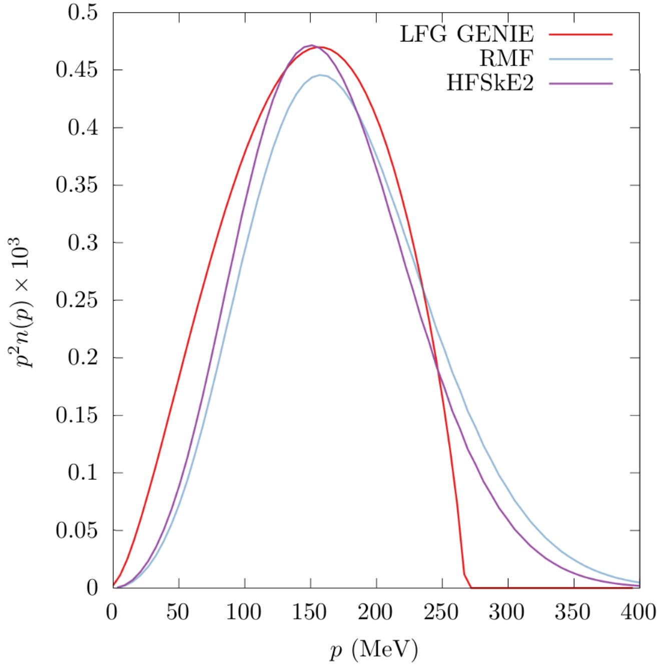
$$\frac{d\sigma(E_\nu)}{dE_l d\cos\theta_l} = G^2 \frac{k_l}{E_\nu} L_{\mu\nu} \int d\Omega_N \sum_{n,\kappa} H^{\mu\nu}_{n,\kappa}(\omega, q, \Omega_N, E_{n,\kappa})$$

Lost nucleon information → Need to generate it in GENIE

1. Draw initial nucleon $\mathbf{p}_m$ from $p^2\, n(p)$ (e.g. LFG)

!! 2. Compute $E_m^2 = p_m^2 + M_N^2$

3. $E_N = E_m + \omega - E_b(q)$



Nucleon kinematics from inclusive cross section in GENIE

$$\frac{d\sigma(E_\nu)}{dE_l d\cos\theta_l} = G^2 \frac{k_l}{E_\nu} L_{\mu\nu} \int d\Omega_N \sum_{n,\kappa} H^{\mu\nu}_{n,\kappa}(\omega, q, \Omega_N, E_{n,\kappa})$$

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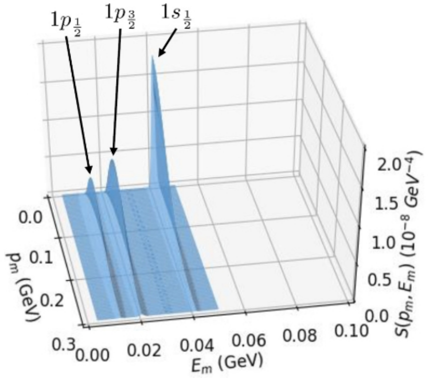
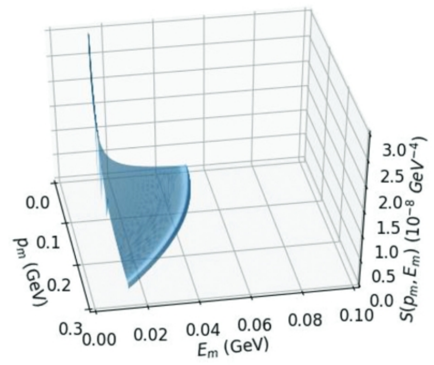
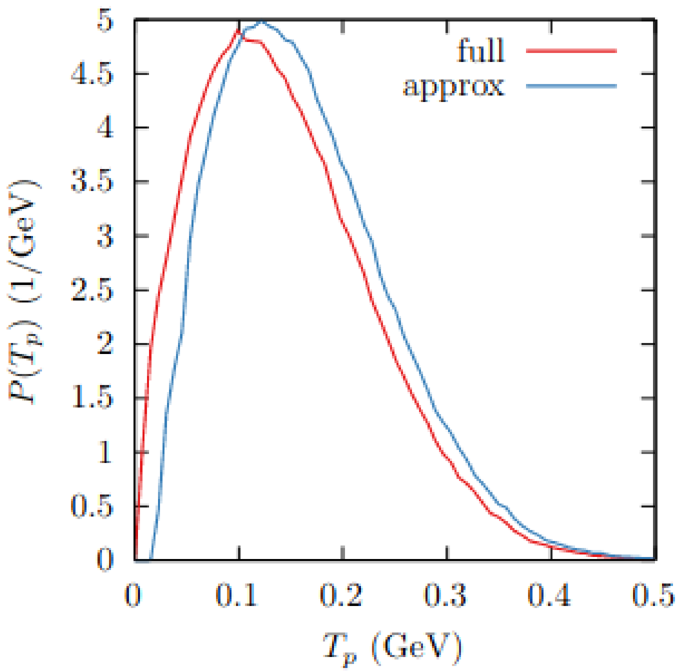
3. $E_N = E_m + \omega - E_b(q)$

Get a shift in total energy spectrum → LFG $E_m^2 = p_m^2 + M_N^2$ is not realistic!





[V. Orden & Donnelly PRC 100 044620]



E4nu kinematics E = 1.15 GeV

Nucleon kinematics from inclusive cross section in GENIE

$$\frac{\mathrm{d}\sigma(E_\nu)}{\mathrm{d}E_l \mathrm{d}\cos\theta_l} = G^2 \frac{k_l}{E_\nu} L_{\mu\nu} \int \mathrm{d}\Omega_N \sum_{n,\kappa} H^{\mu\nu}_{n,\kappa}(\omega, q, \Omega_N, E_{n,\kappa})$$

Lost nucleon information → Need to generate it in GENIE

1. Draw initial nucleon $\mathbf{p}_m$ from $p^2\, n(p)$ (e.g. LFG)

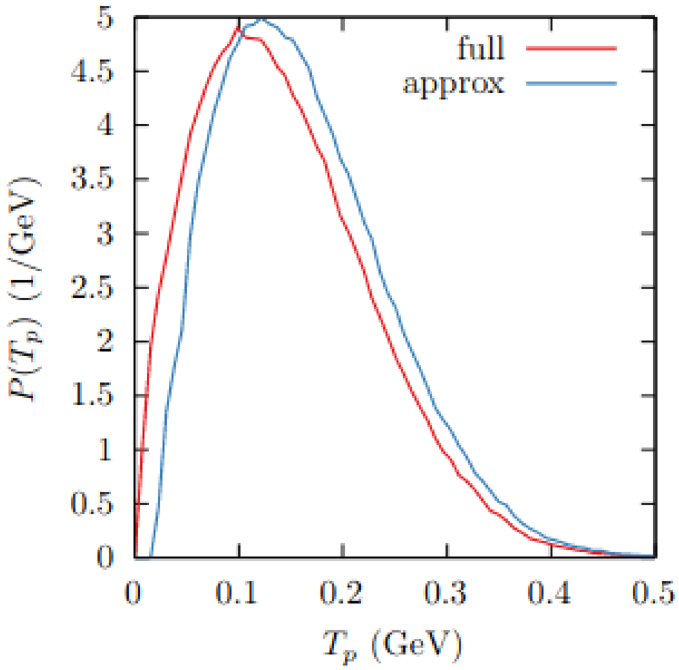
!! 2. Compute $E_m^2 = p_m^2 + M_N^2$

3. $E_N = E_m + \omega - E_b(q)$

4. $k_N^2 = E_N^2 - M_N^2$

!! $$|\mathbf{p}_m + \mathbf{q}| \neq k_N = \sqrt{E_N^2 - M_N^2}$$

→ $$\mathbf{k}_N = \frac{k_N}{|\mathbf{p}_m + \mathbf{q}|}(\mathbf{p}_m + \mathbf{q})$$



Nucleon kinematics from inclusive cross section in GENIE

$$\frac{\mathrm{d}\sigma(E_\nu)}{\mathrm{d}E_l \mathrm{d}\cos\theta_l} = G^2 \frac{k_l}{E_\nu} L_{\mu\nu} \int \mathrm{d}\Omega_N \sum_{n,\kappa} H^{\mu\nu}_{n,\kappa}(\omega, q, \Omega_N, E_{n,\kappa})$$

Lost nucleon information → Need to generate it in GENIE

1. Draw initial nucleon $\mathbf{p}_m$ from $p^2\, n(p)$ (e.g. LFG)

!! 2. Compute $E_m^2 = p_m^2 + M_N^2$

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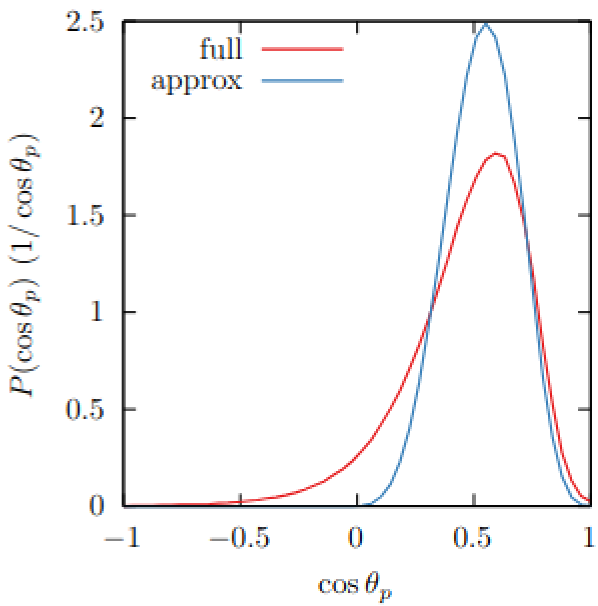
!! $|\mathbf{p}_m + \mathbf{q}| \neq k_N = \sqrt{E_N^2 - M_N^2}$

→ $$\mathbf{k}_N = \frac{k_N}{|\mathbf{p}_m + \mathbf{q}|}(\mathbf{p}_m + \mathbf{q})$$

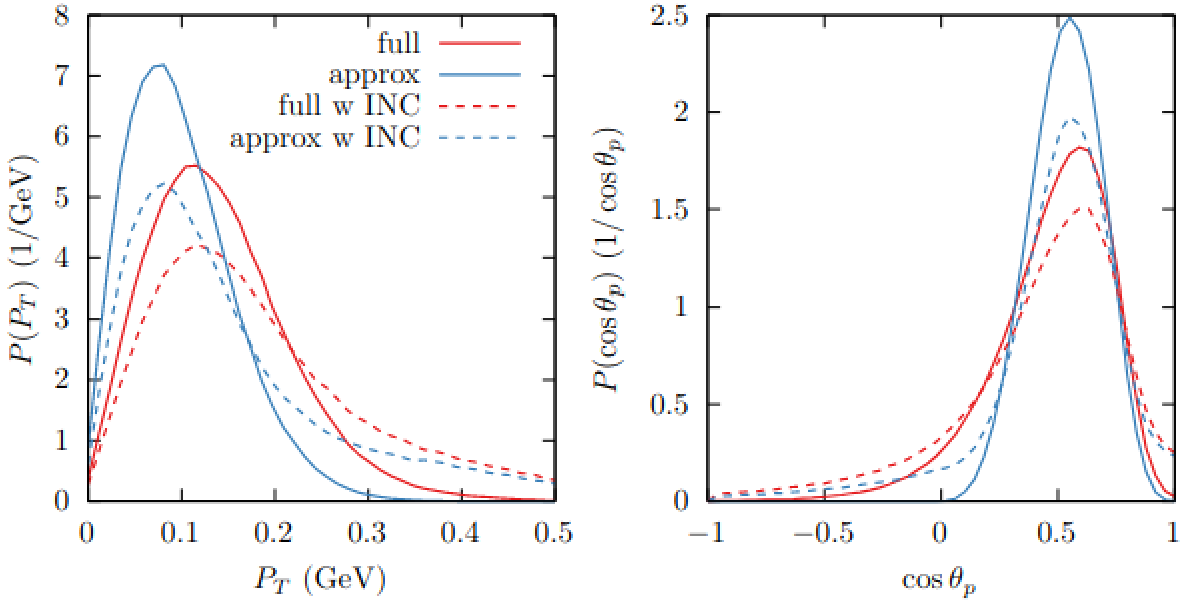


Serious differences in angular distributions!

Nucleon kinematics from inclusive cross section in GENIE

$$\frac{d\sigma(E_\nu)}{dE_l d\cos\theta_l} = G^2 \frac{k_l}{E_\nu} L_{\mu\nu} \int d\Omega_N \sum_{n,\kappa} H^{\mu\nu}_{n,\kappa}(\omega, q, \Omega_N, E_{n,\kappa})$$

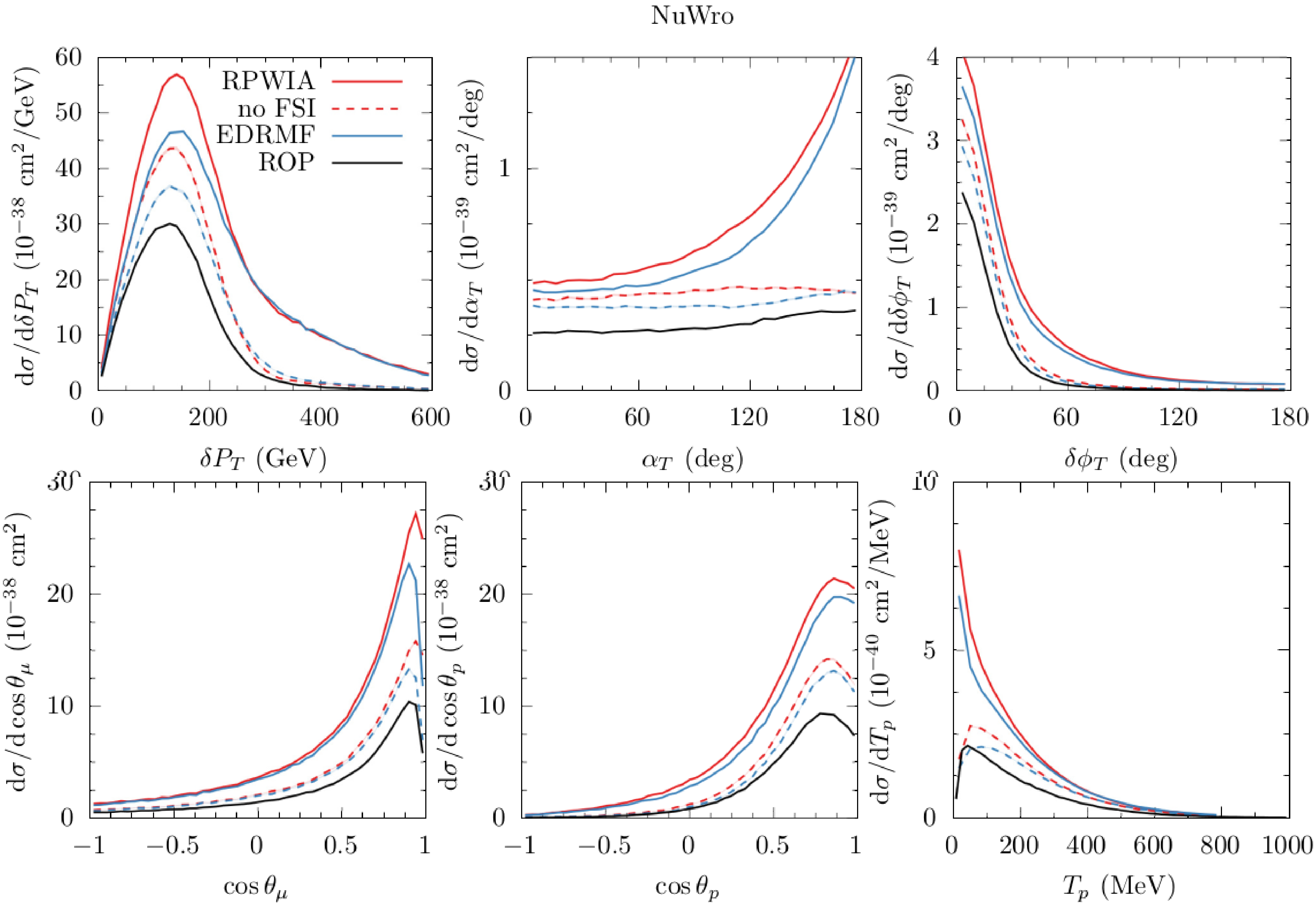
Lost nucleon information → Need to generate it in GENIE



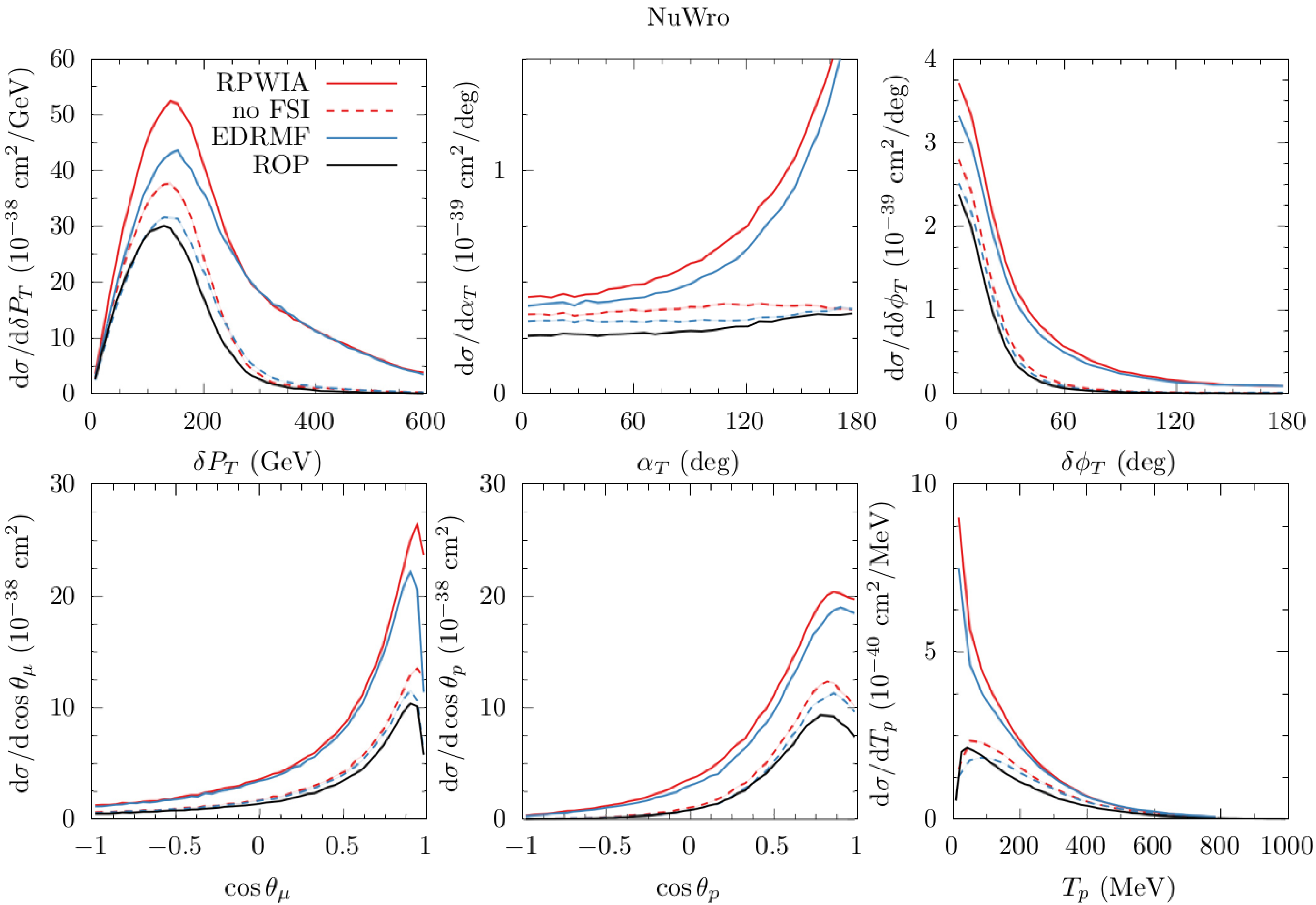
Results for e4nu kinematics E=1.159 including the GENIE cascade!

Shape differences biggest in P_T and angular distributions

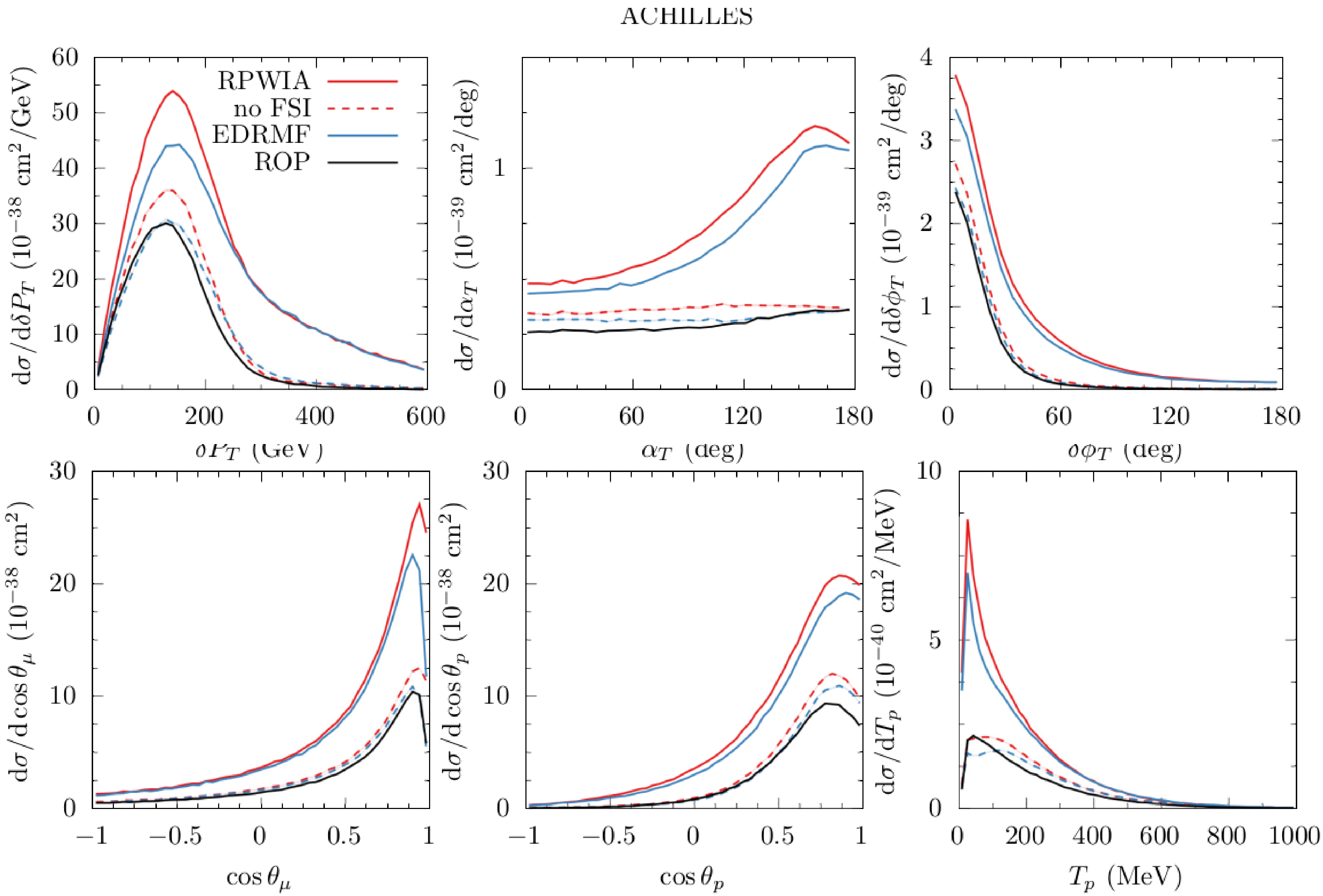
NuWro with SRC effect in Mean-free path



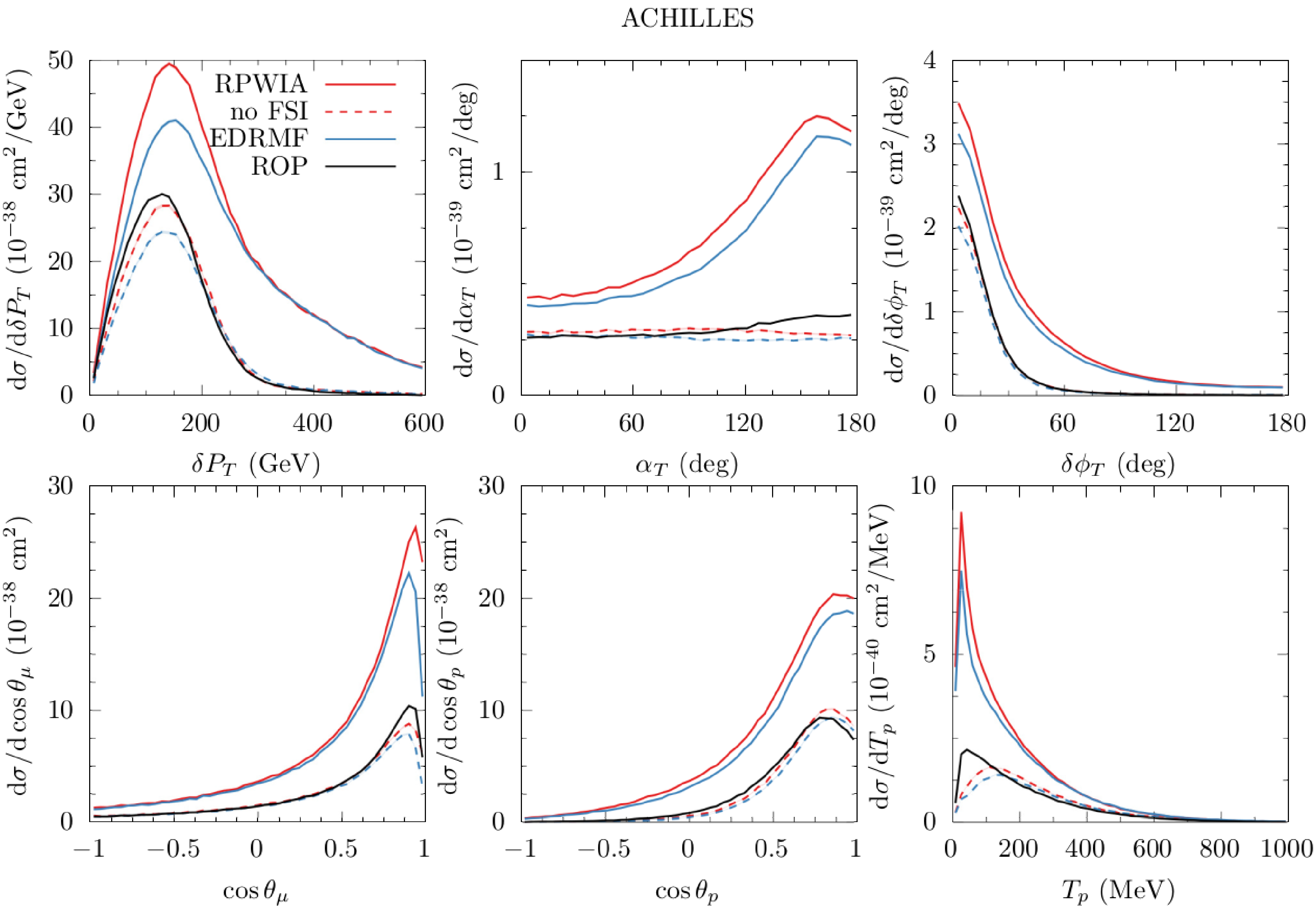
NuWro without SRC effect in Mean-free path



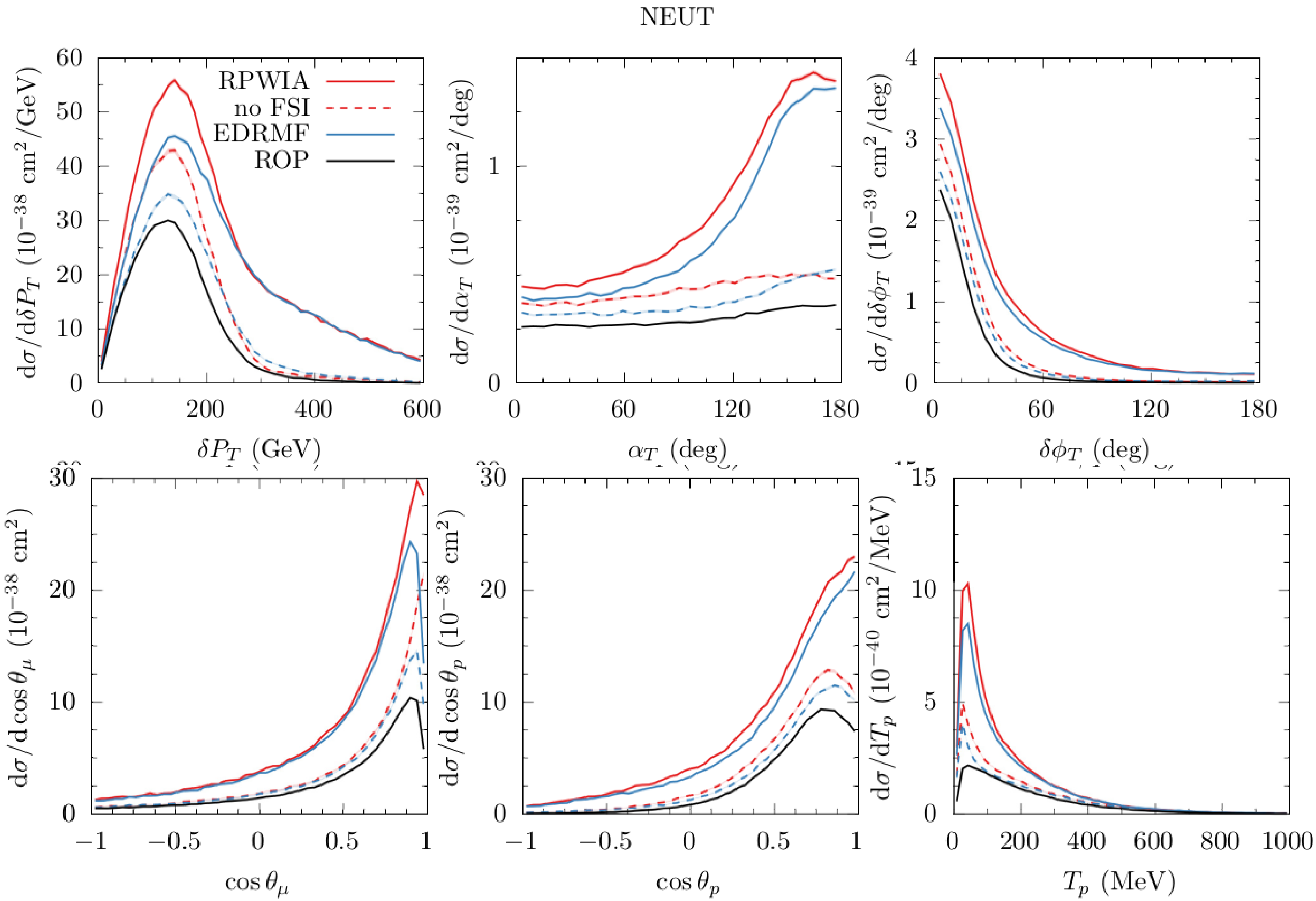
ACHILLES with Formation time



ACHILLES without Formation time



NEUT



NEUT
RPWIA
no FSI
EDRMF
ROP
dσ/dδP_T (10^-38 cm^2/GeV)
δP_T (GeV)
dσ/dα_T (10^-39 cm^2/deg)
α_T (deg)
dσ/dδφ_T (10^-39 cm^2/deg)
δφ_T (deg)
dσ/d cos θ_μ (10^-38 cm^2)
cos θ_μ
dσ/d cos θ_p (10^-38 cm^2)
cos θ_p
dσ/dT_p (10^-40 cm^2/MeV)
T_p (MeV)