Fermilab U.S. DEPARTMENT OF ENERGY Office of Science

RDWIA Analysis of Final-state interactions and MicroBooNE data

Alexis Nikolakopoulos

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Collaborators

Anthony M. Kelly (Fermilab, Notre-Dame)
Raul Gonzalez-Jimenez (UCM)
Noemi Rocco (Fermilab)
Josh Isaacson (Fermilab)
Kajetan Niewczas (UGent)
Federico Sanchez (Geneva)

Useful inputs : Noah Steinberg, A. Papadopoulou, A. Ankowski, N. Jachowicz, Ryan Plestid (Caltech), J. M. Udias (UCM), V. Pandey

What ?

- **Distorted wave calculations with realistic nuclear spectral functions**
- **Benchmarking of cascade models with optical potentials**
- **Comparison with MicroBooNE data**

Object and scope

- Assess effect of FSI and differences between intranuclear cascade models (INCs)
  → We use **NuWro**, **NEUT**, and **ACHILLES** INCs
  → **Benchmarking of INCs with quantum-mechanical optical potential calculations with consistent realistic inputs**

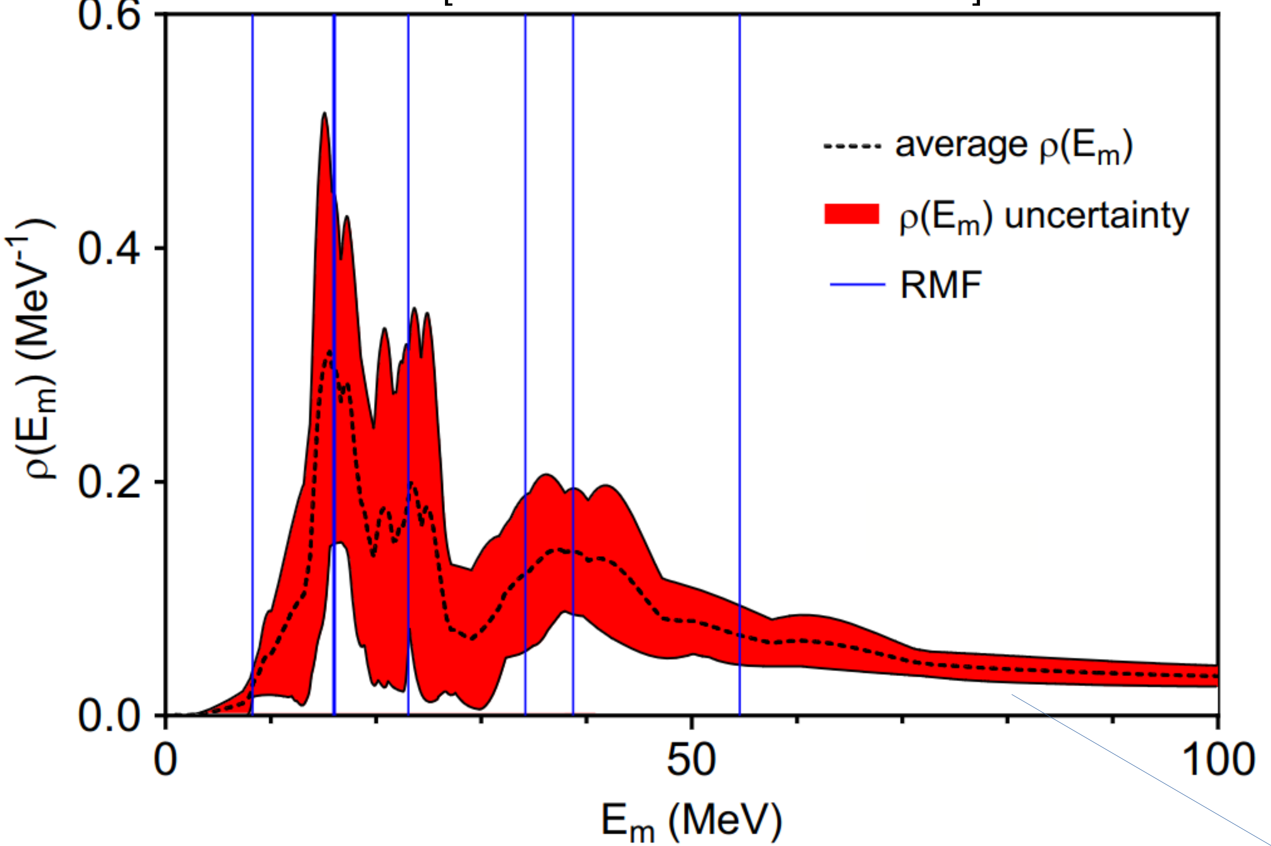
- Unfactorized RDWIA calculations with realistic nuclear spectral functions
  → Include smearing and partial occupancies + SRC contribution
  → Optical potential results consistent with analyses of (e,e'p)

- Application to MicroBooNE data for transverse kinematic imbalance

RDWIA calculations with spectral functions

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

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

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

-Relativistic Distorted Wave Impulse Approximation (RDWIA)

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

↓

Distorted wave function for final-state

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)

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

By treating the final-state wavefunction as a plane-wave:

$$\overline{\psi}(\mathbf{p}, \mathbf{k}_N, s_N) \to (2\pi)^{3/2}\delta(\mathbf{p} - \mathbf{k}_N)\overline{u}(\mathbf{k}_N, s_N)$$

Neglect all final-state interactions

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-Relativistic Distorted Wave Impulse Approximation (RDWIA)

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- 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’)

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

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

-Relativistic Distorted Wave Impulse Approximation (RDWIA)

↓ **Remove elastic FSI**

- Relativistic Plane Wave Impulse Approximation (RPWIA)

↓ **Project onto particle spinors**

- Plane-Wave Impulse Approximation (PWIA)

Remember

- All approaches use **the same initial state** (~spectral function) but different approximations for the matrix element → consistently check effect of FSI
- The **difference between PWIA and RPWIA is practically negligible** for following results

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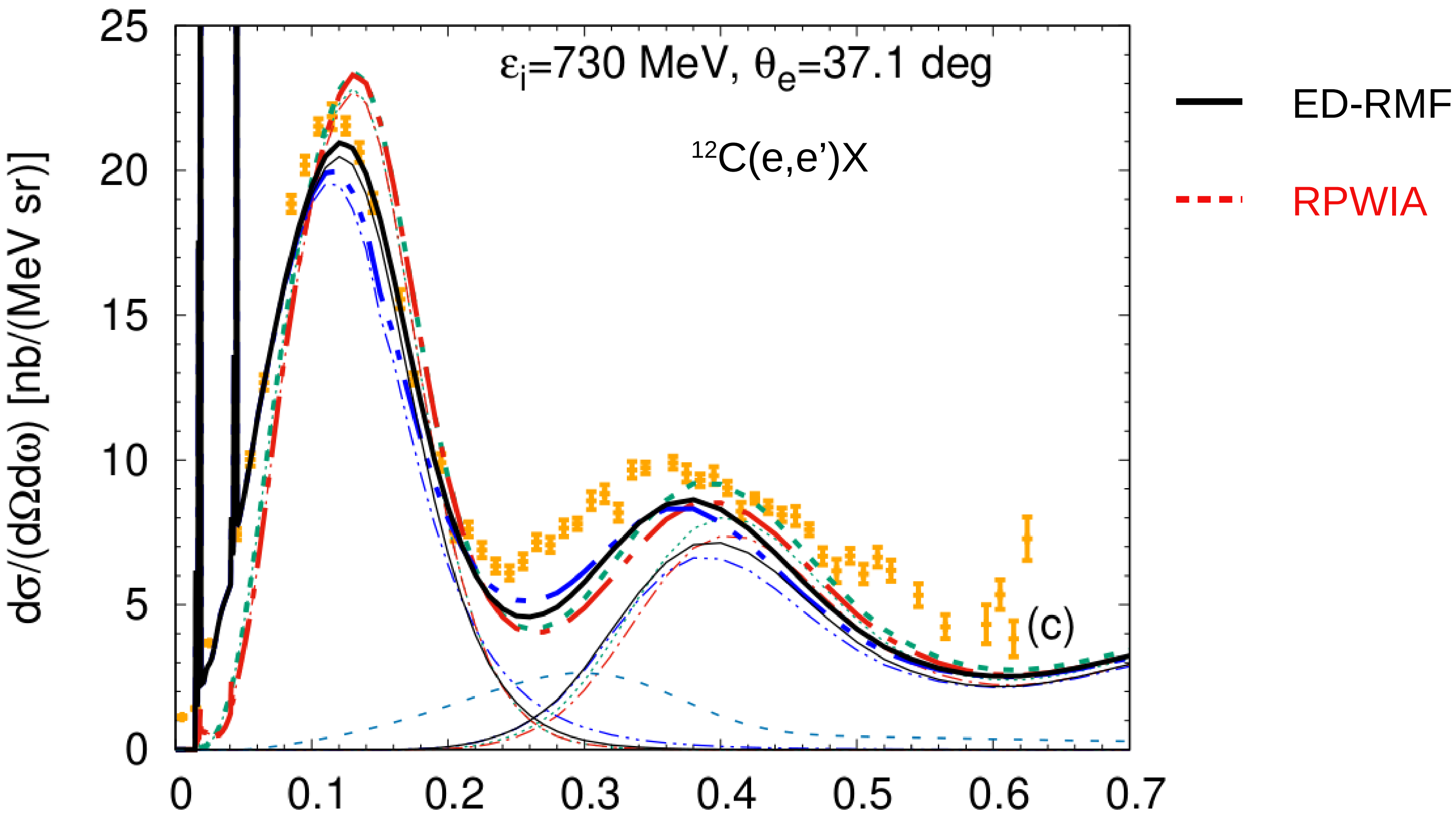
Terminology : RDWIA, RPWIA and PWIA & ED-RMF and ROP

- 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



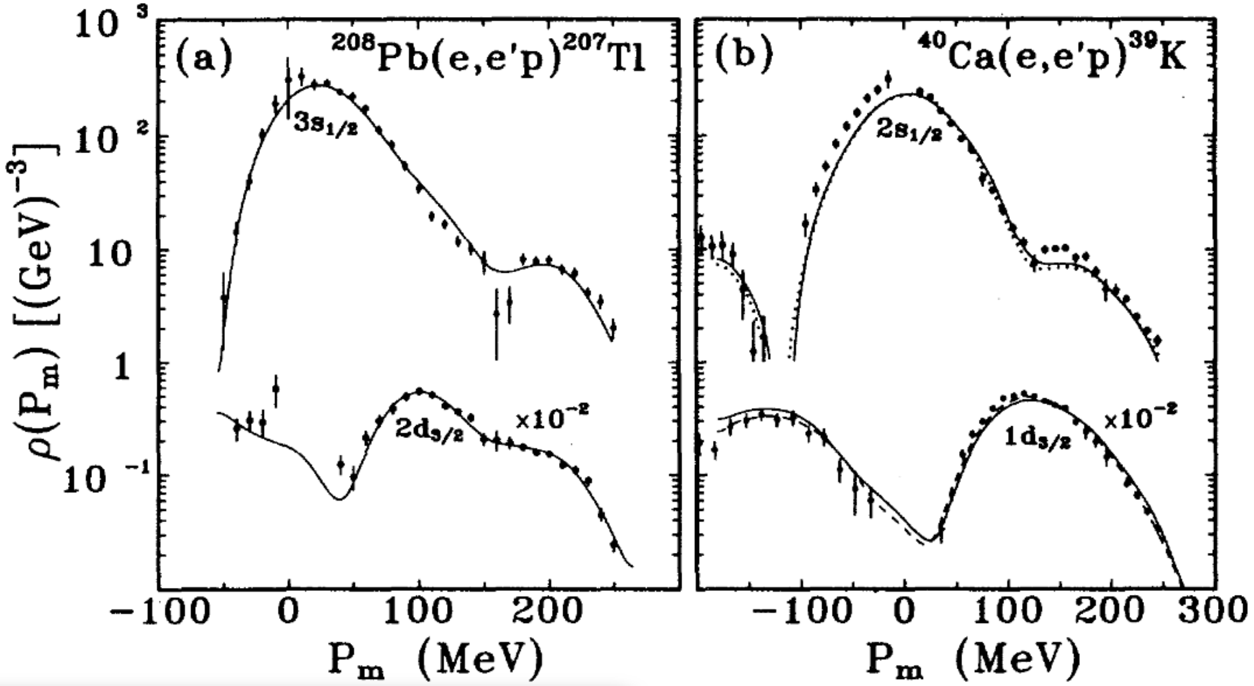
[R. Gonzalez-Jimenez et al Phys. Rev. C 100, 045501 (2019)]

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

- Relativistic Optical Potential (ROP)

$\overline{\psi}(\mathbf{p}+\mathbf{q},\mathbf{k}_N,s_N)$ → Final-state in **complex** energy-dependent potential
→ suitable for **FSI in exclusive** cross section

[Udias et al. PRC48, 2731]



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

Including recent Jlab analyses of ^{40}Ar & ^{48}Ti
[PRD 107, 012005]
[PRD 105, 112002]

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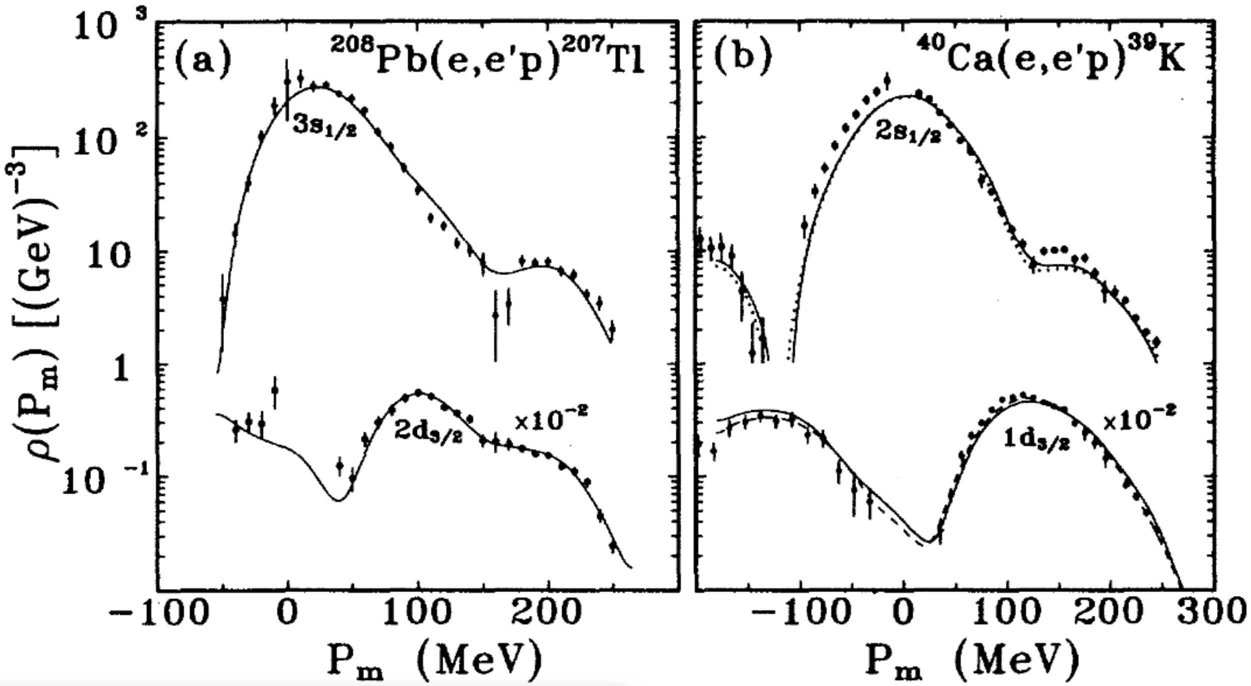

-'Standard' approach for FSI in exclusive (e,e'p) analysis in mean-field region

Including recent Jlab analyses of ^{40}Ar & ^{48}Ti [PRD 107, 012005] [PRD 105, 112002]

The optical potential **removes nucleon that undergoes inelastic FSI**

↔

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

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 $|X\rangle = |p\rangle|^{39}\mathrm{Ar}^*\rangle$

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

→ 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

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→ Classical approximation

$$\approx \underbrace{\sum_\alpha |\langle\Psi_0|T_{1b}|\psi_\alpha\rangle|^2}_{\text{ED-RMF}} \underbrace{P(X|\alpha)}_{\text{INC}}$$

→ Intranuclear Cascade

Can benchmark the INC with ROP using inputs 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

Benchmarking intranuclear cascade models for neutrino scattering with relativistic optical potentials

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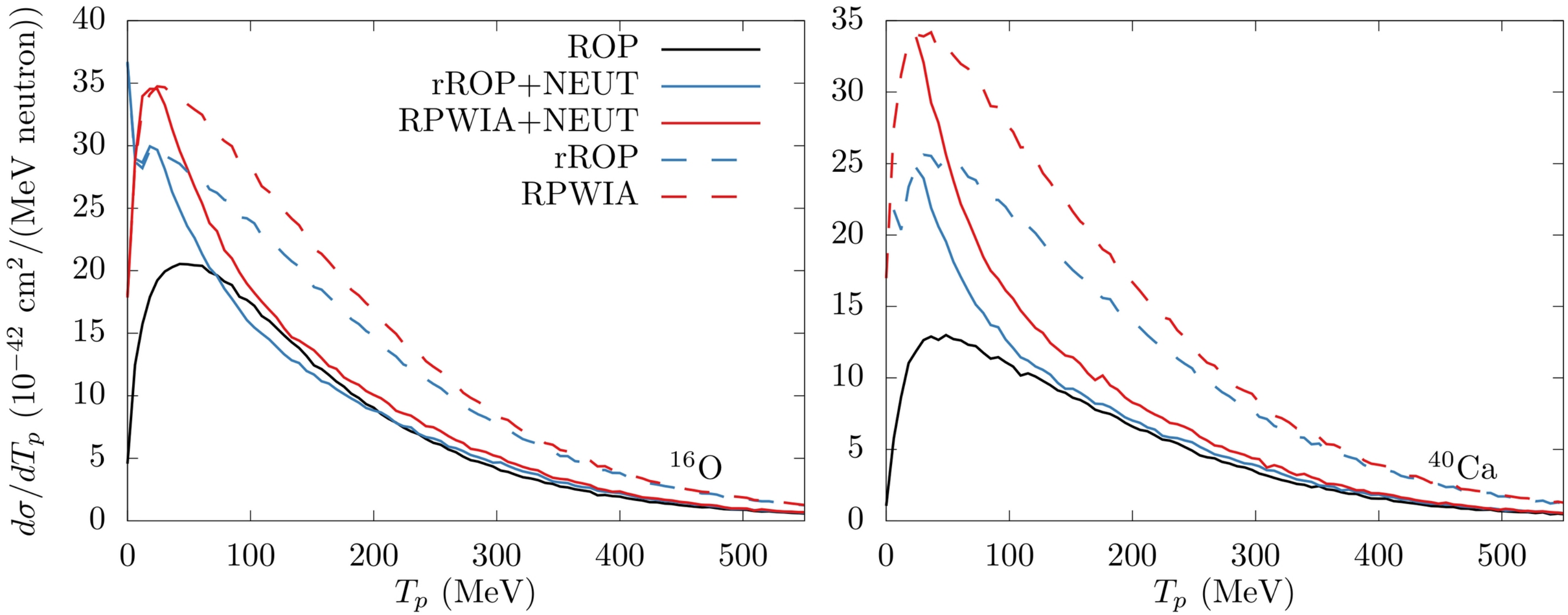
Flux-folded with T2K ND flux: NEUT INC

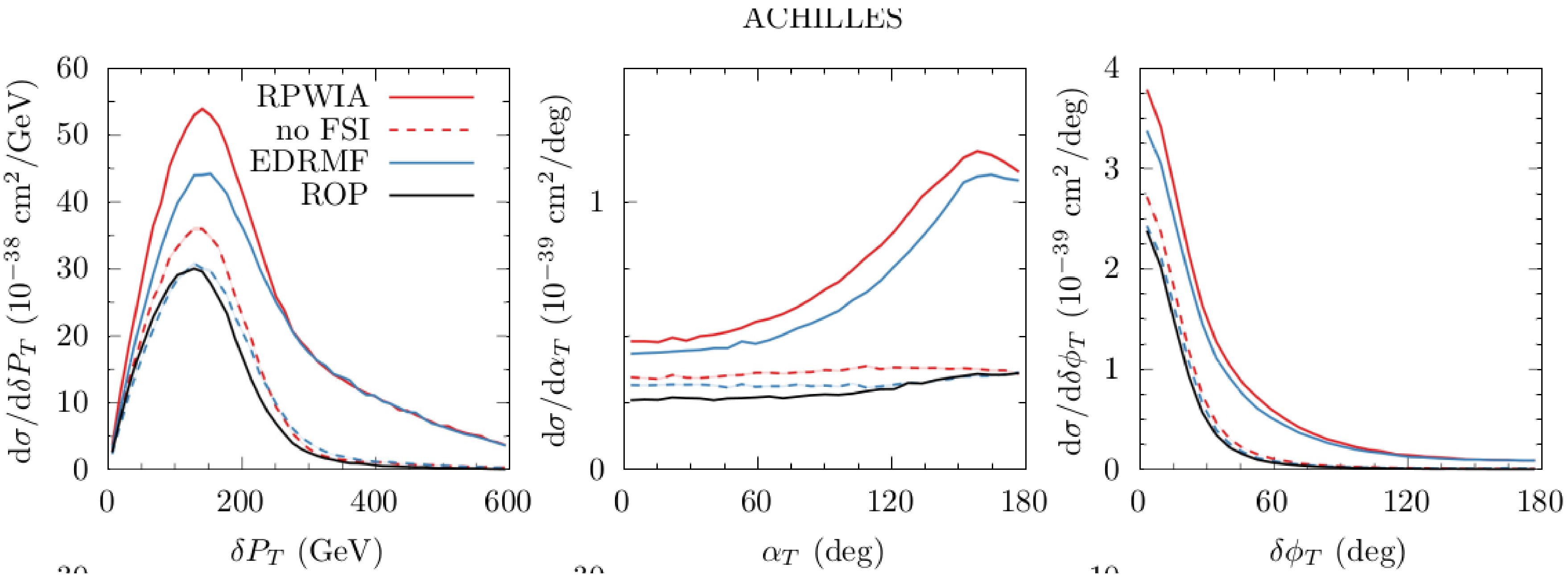


ROP and INC agree at large T_p but large disagreement for small T_p

Benchmarking INCs with RDWIA calculations for Argon

[In preparation]

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



Some findings:

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

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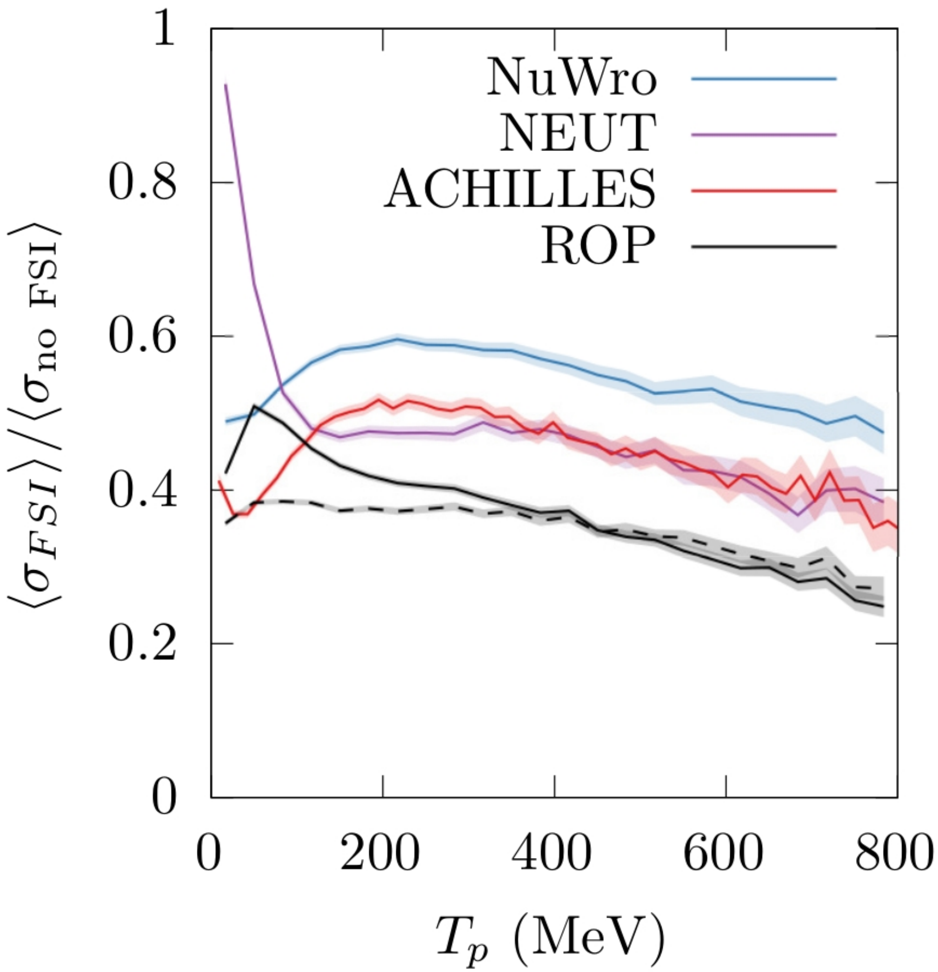
Benchmarking INCs with RDWIA calculations for Argon

[In preparation]

Comparison of T_p dependence in different INCs



Ratio **OUT/INPUT**
→ independent of INPUT in INC
= 'INC Transparency'

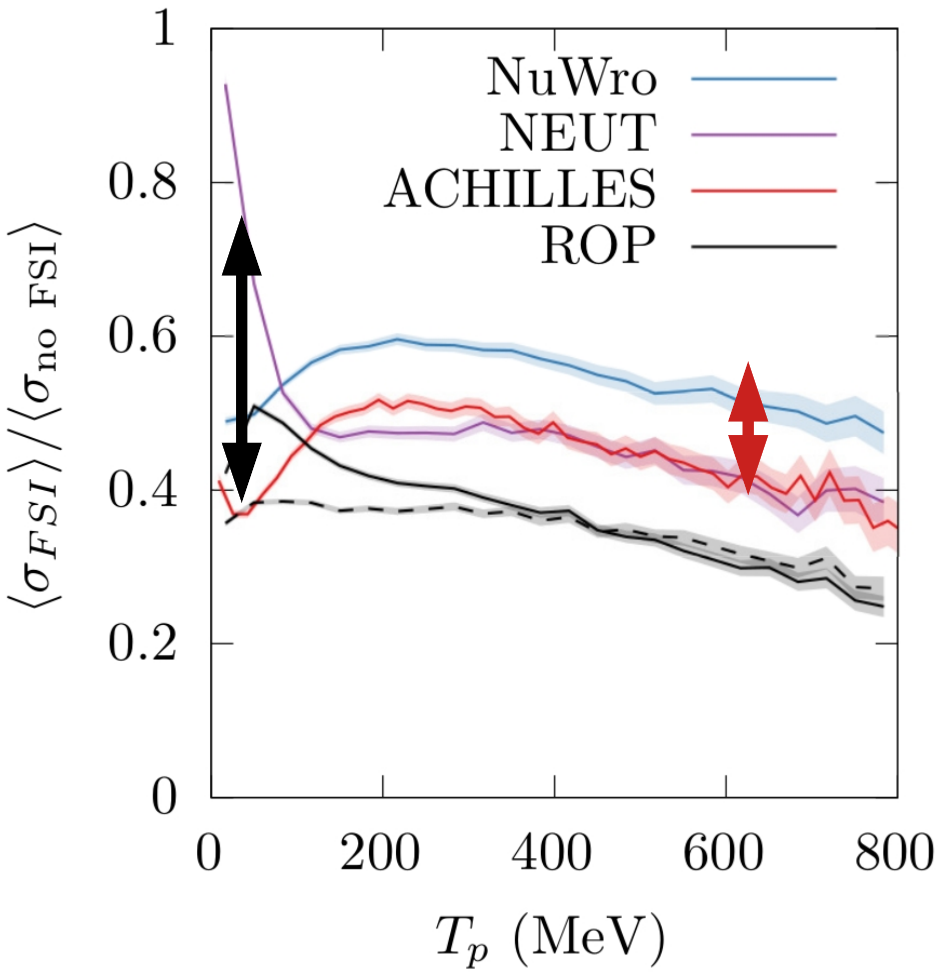
- **No full agreement with ROP**

  Ratio depends on INPUT!
  – EDRMF
  - - RPWIA

Benchmarking INCs with RDWIA calculations for Argon

[In preparation]

Comparison of T_p dependence in different INCs



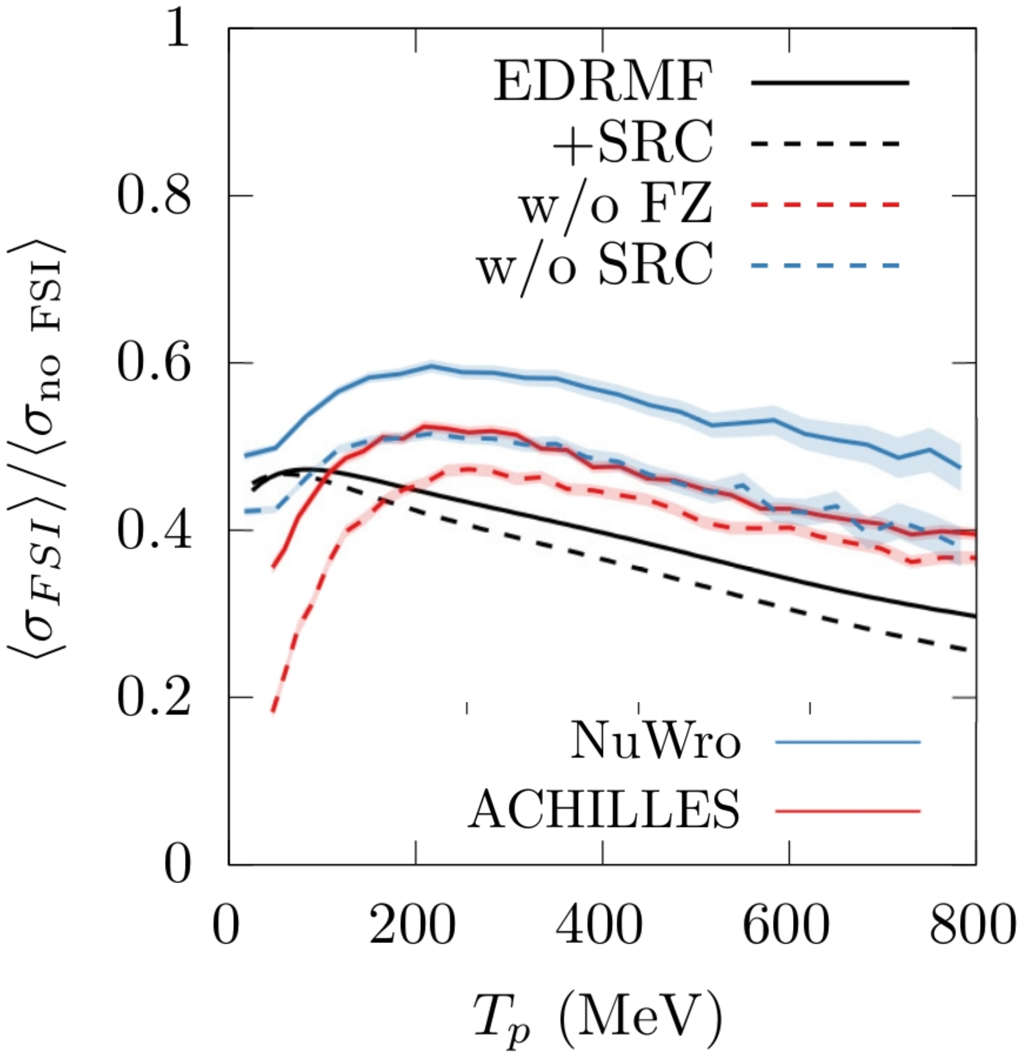
Ratio **OUT/INPUT**
→ independent of INPUT in INC
= 'INC Transparency'

- **NEUT & ACHILLES:**
  - Low-T_p differences
- **NuWro & ACHILLES:**
  - Treatment of SRCs

Benchmarking INCs with RDWIA calculations for Argon

[In preparation]

Effect of SRC treatment in INC



- **SRC in INC increase the transparency**

- Larger effect in NuWro
- Masked by formation-time in ACHILLES
- NuWro w/o SRC and nominal ACHILLES agree

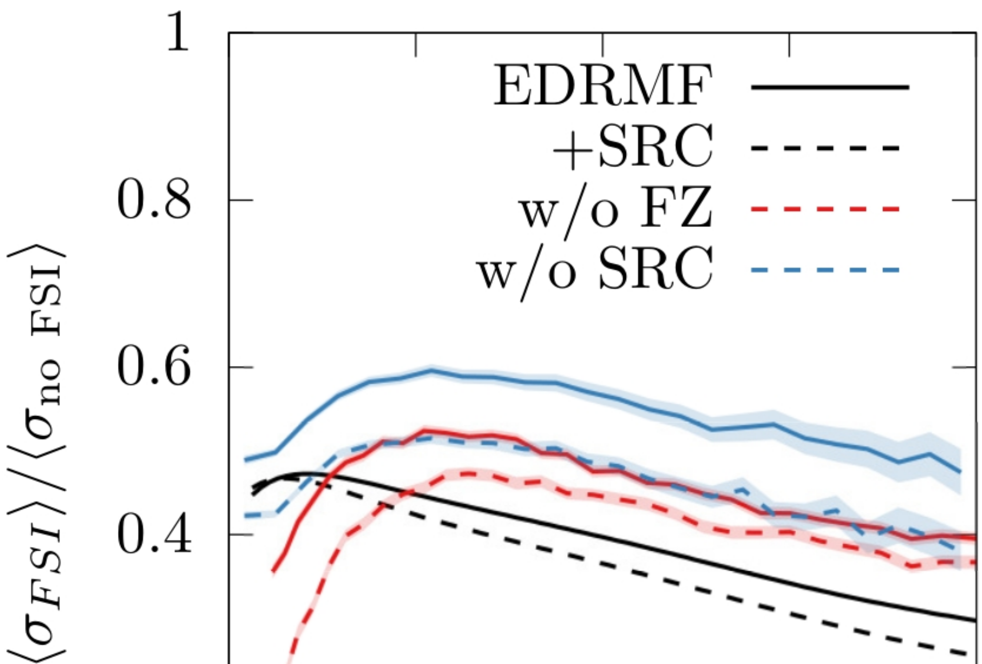
- **No full agreement with ROP**

- ROP has no ‘explicit’ SRC
  → Treats wavefunctions consistently
  → **Decrease** in ratio with SRC (depends on input!)

Benchmarking INCs with RDWIA calculations for Argon

[In preparation]

Effect of SRC treatment in INC



- **SRC in INC increase the transparency**

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- ROP has no ‘explicit’ SRC

ROP is used in analyses to determine spectral function

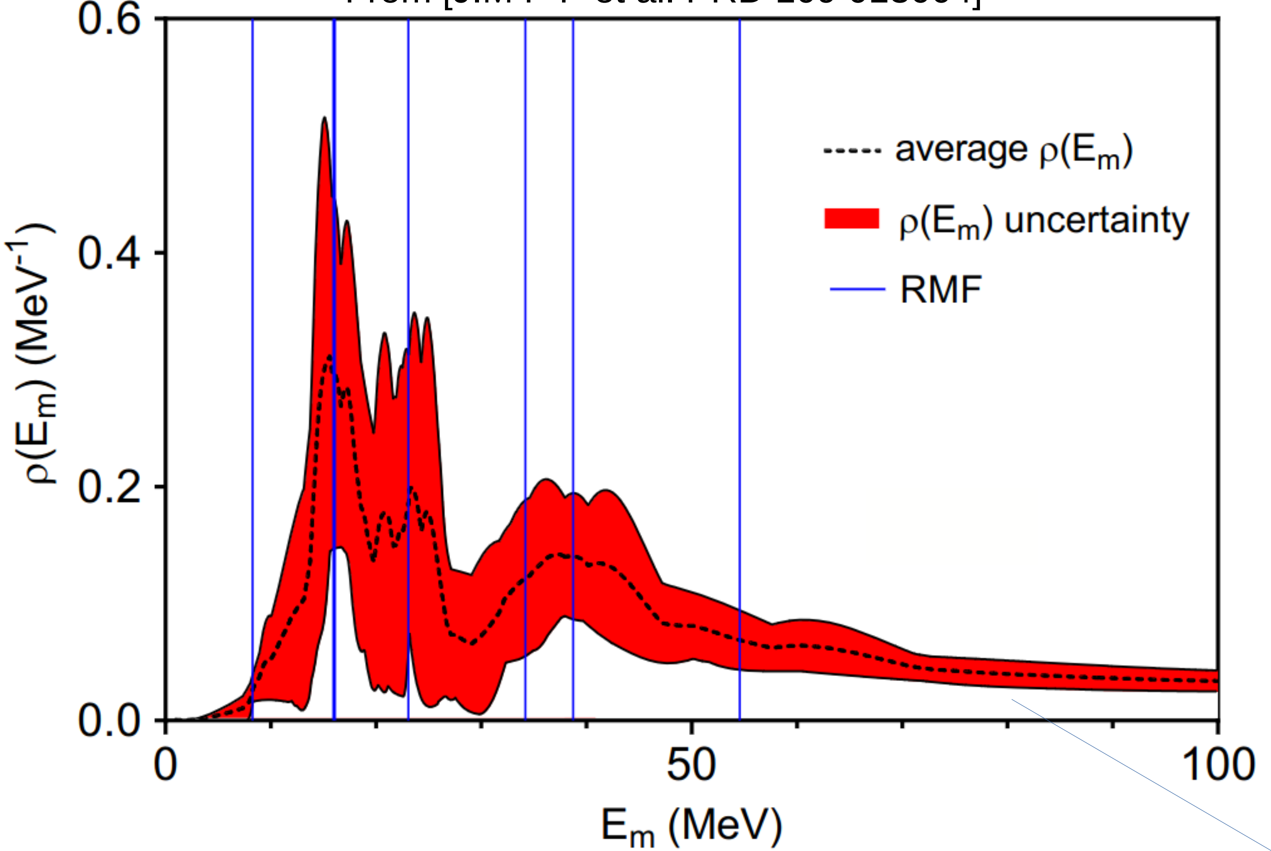
No definite benchmark/uncertainty on INC or ROP for lepton scattering

→ New (e,e’p) datasets with E_m cuts ?

RDWIA calculations with spectral functions

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]



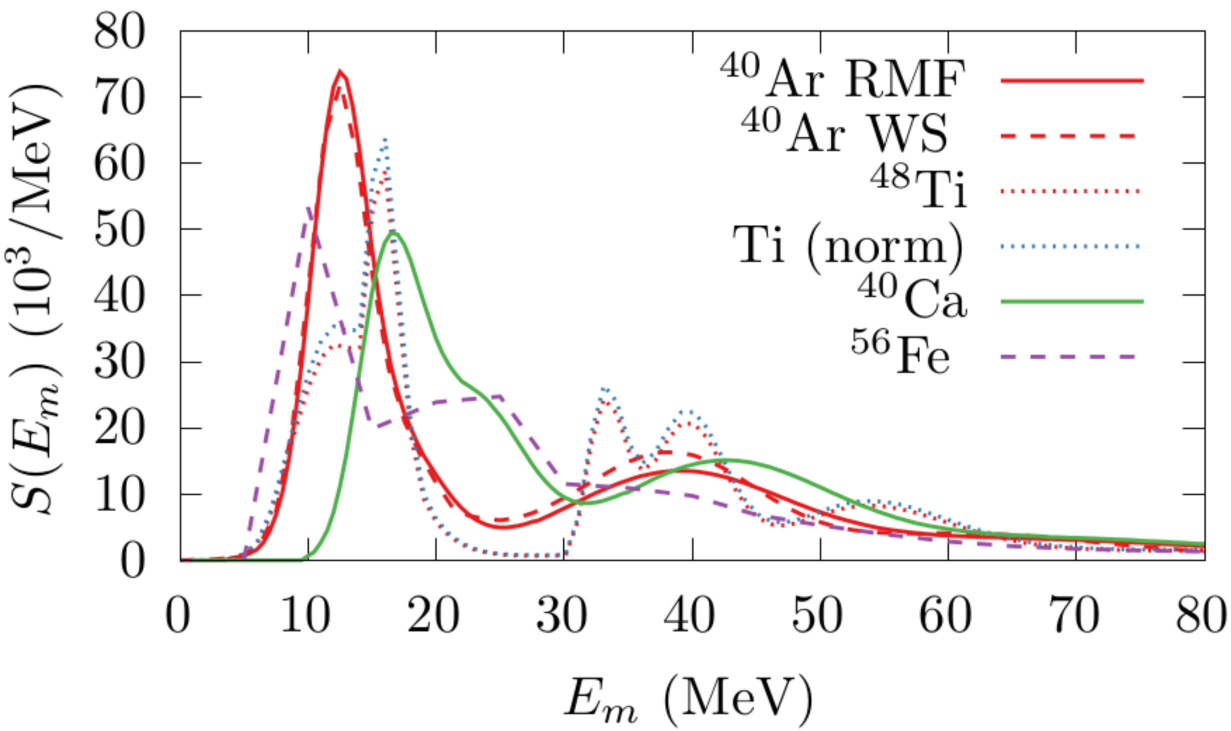
mean field → mean field + src

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

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 $\mathbf{N_\kappa}$ and $\boldsymbol{\varrho(E_m)}$

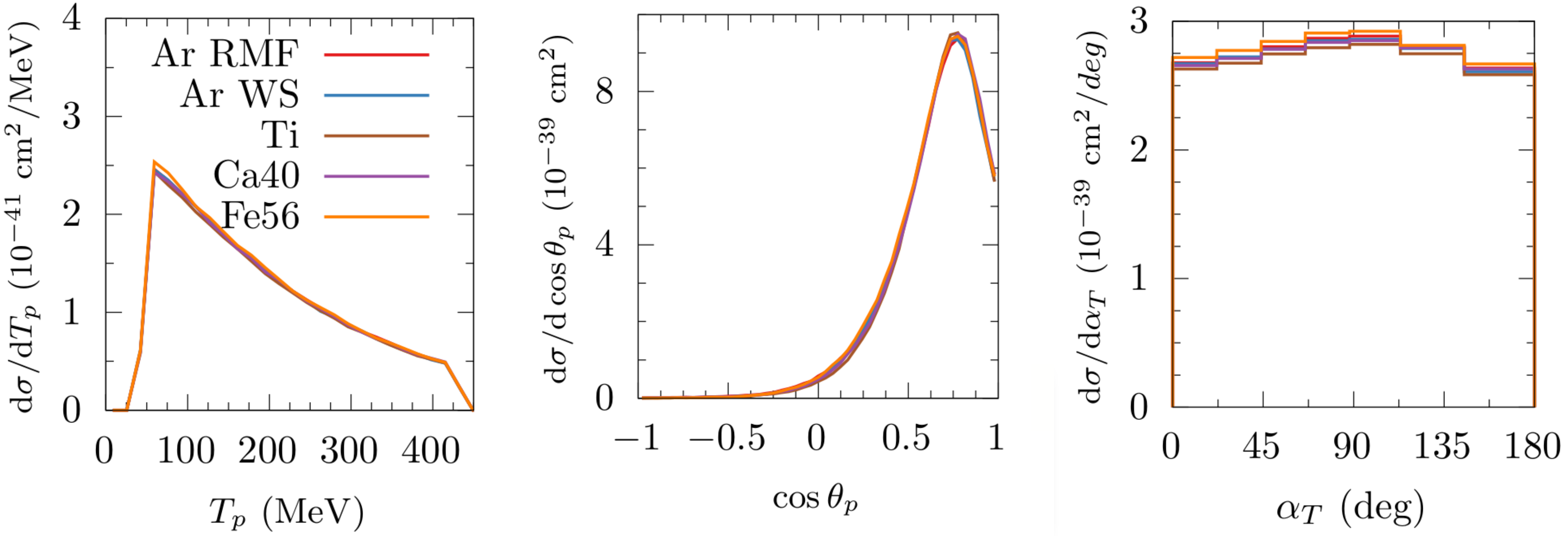


- ^{40}Ar spectral functions [Butkevich PRC 85, 065501] & [Jlab, PRD 107, 012005]
- ^{48}Ti from Jlab [PRD 107, 012005]
- ^{56}Fe [Benhar et al. NPA 579, 493]
- ^{40}Ca [Butkevich PRC 85, 065501]

Large variation in E_m profiles to check sensitivity of observables

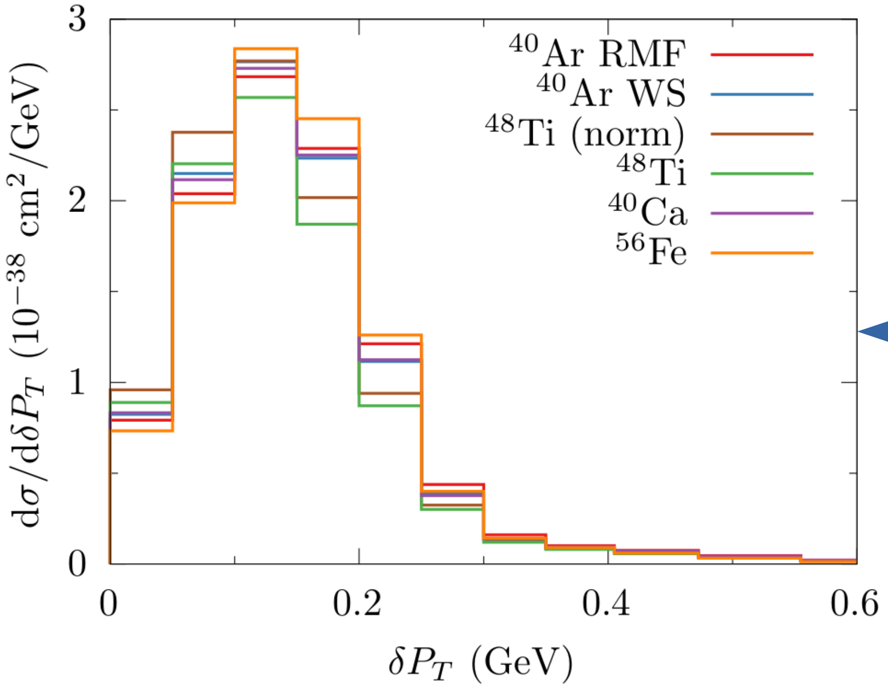
Sensitivity to variations in the spectral functions: PWIA calculations

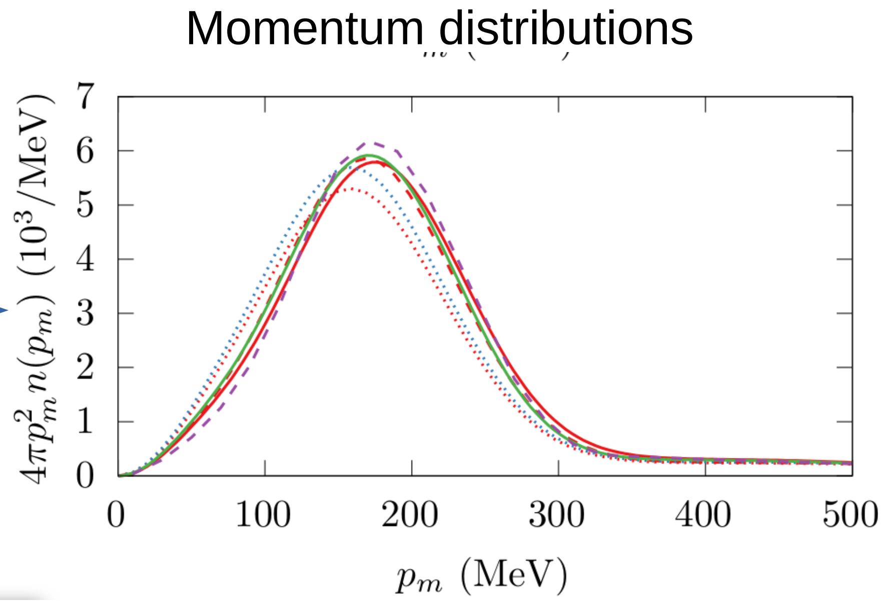
Observables for MicroBooNE flux-averaged signal



-Negligible differences between different spectral-functions **for observables that do not correlate p_p and p_μ**

Sensitivity to variations in the spectral functions: PWIA calculations



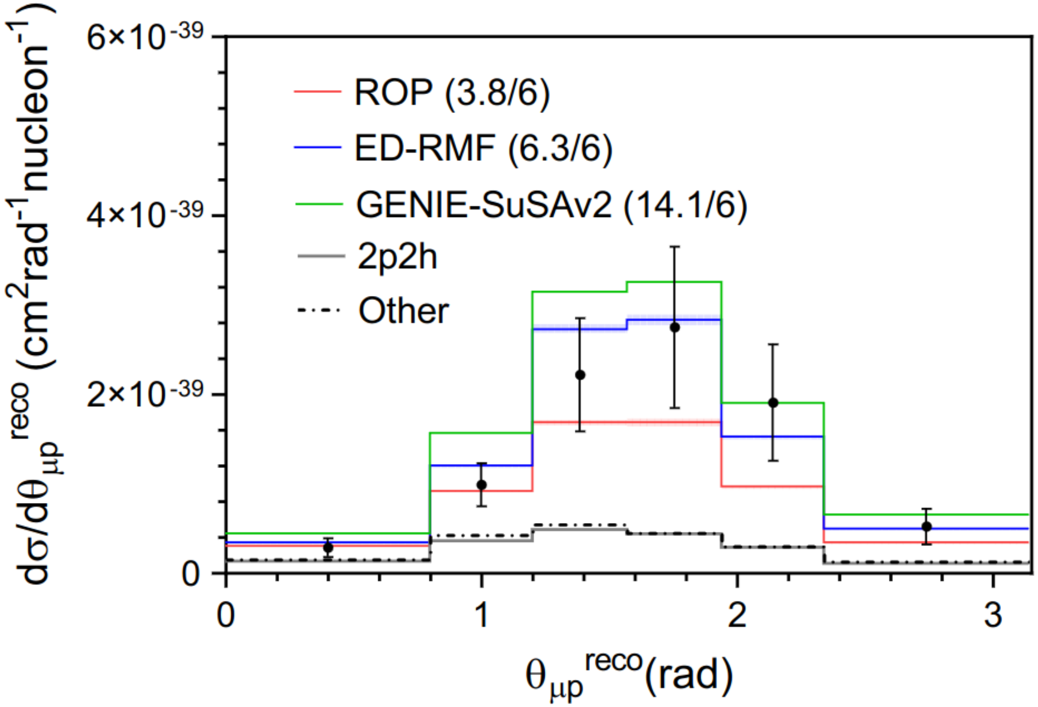


-Negligible differences between different spectral-functions **for observables that do not correlate p_p and p_μ**

-dP_T is **sensitive to momentum distribution**
→ Almost **universal** for realistic spectral functions
→ **Titanium is the outlier!**

Sensitivity to variations in the spectral functions

Checking detailed dependence on SF for ^{40}Ar in [J.M F-P et al. PRD 109 013004]

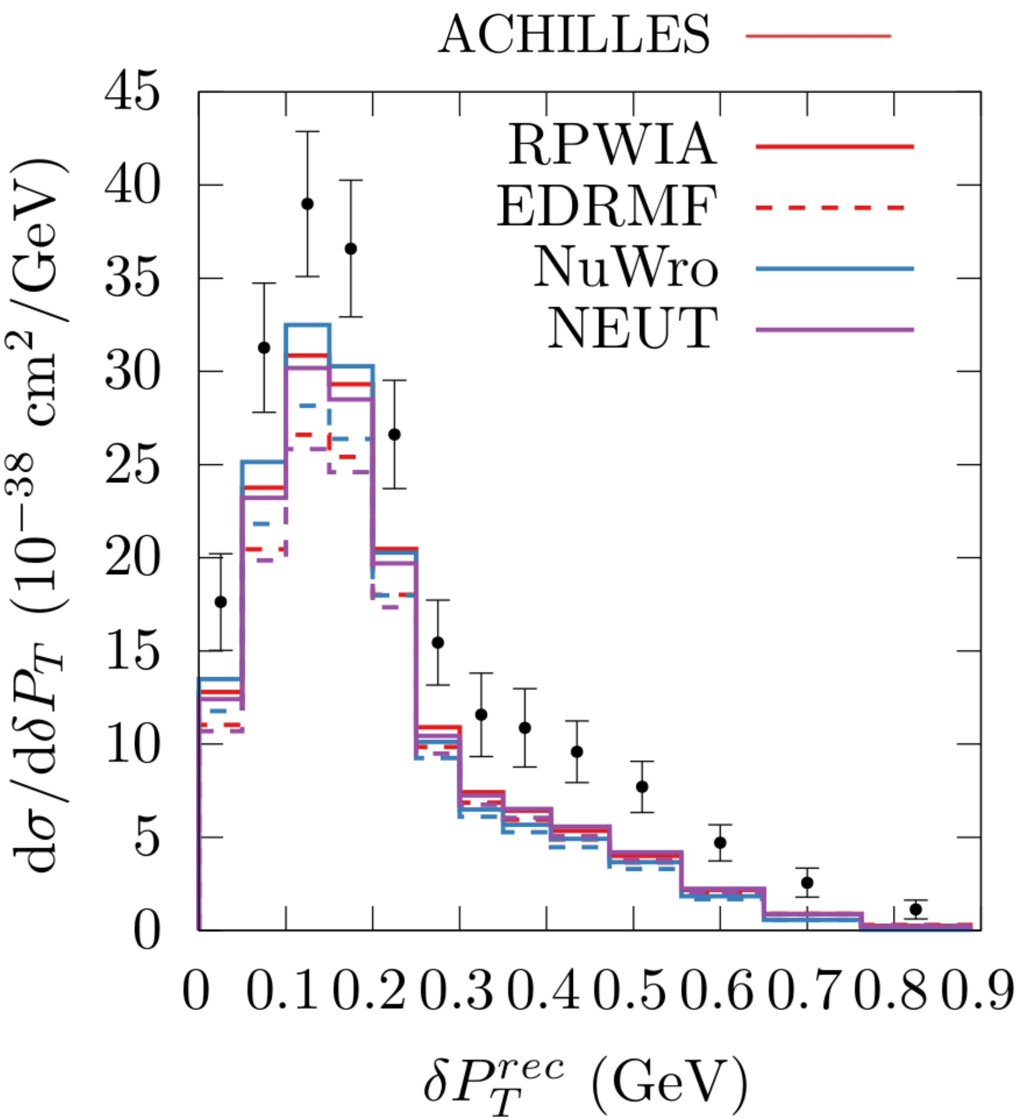


We conclude that for MicroBooNE data the ^{40}Ar RMF choice is realistic enough → Subdominant to FSI effects

Data not sensitive to missing-energy profile
But reconstructed energy is → [R. Gonzalez-Jimenez et al. PRC 105 025502]

RDWIA calculations for MicroBooNE data

[In preparation]



- Differences between INC become smaller with proton kinematic cuts MicroBooNE
- RPWIA → ED-RMF consistent **~10%** reduction
- Overall underprediction of data **expected** : no higher energy interactions (2p2h, SPP, …)
- Underprediction of low-dP$_T$
  → Axial form factor ?
  → Interference with 2-body ?
  → Remove correlations ?

RDWIA calculations for MicroBooNE data

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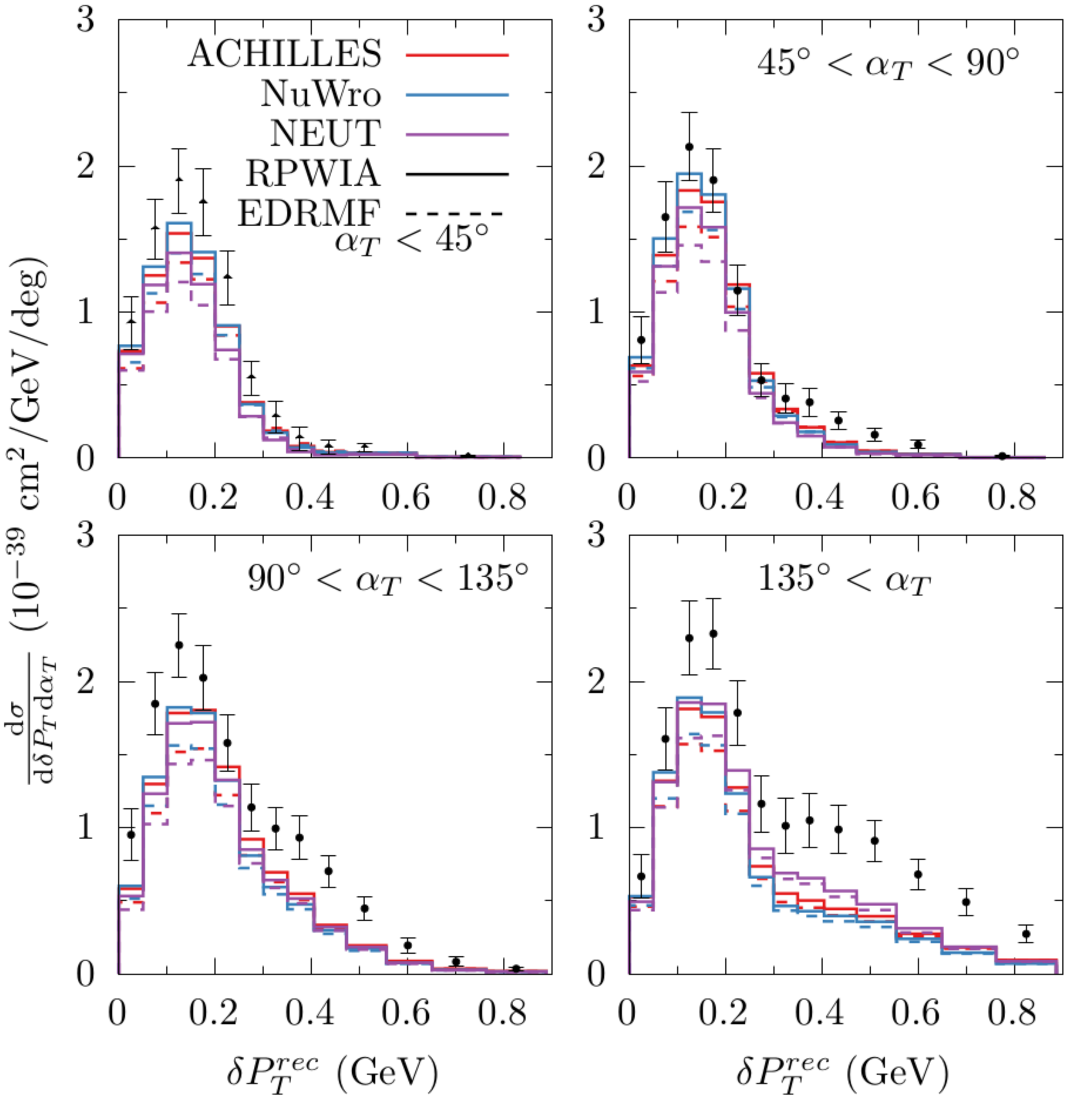


Double differential in dP_T and α_T
→ effect of FSI is clear

Picture remains:

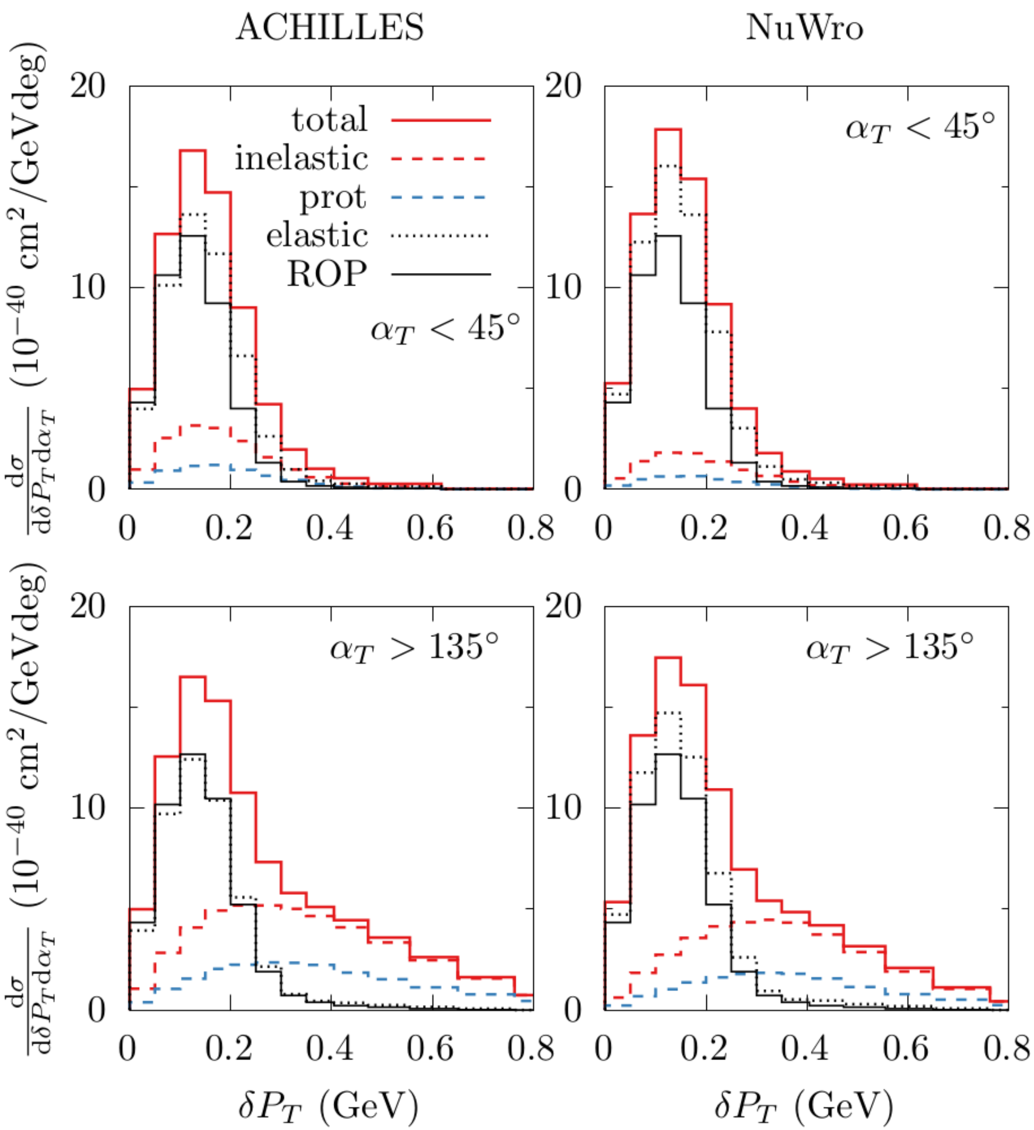
- 10% reduction in MF region in ED-RMF

-Underprediction high α_T
→ expected

-Low-α_T and dPT ???

RDWIA calculations for MicroBooNE data

[In preparation]



Double differential in dP_T and α_T
→ effect of FSI is clear

Picture remains:
Underprediction high α_T
→ expected

Low-α_T ???

-Composition of signal
→ INC dependent
→ Significant contribution of Inelastic events

→ Could be removed with **electron scattering with E_m cut**

Conclusions and outlook

- **Detailed comparison of NEUT, ACHILLES, NuWro INCs with optical potentials**

  - No full agreement of any INC with the optical potential
  - Differences in low-T_p region and due to treatment of SRC's

  → (e,e'p) over large hadron phase space with cut on E_m ?
  → Assessment of the classical approximation underlying the INC

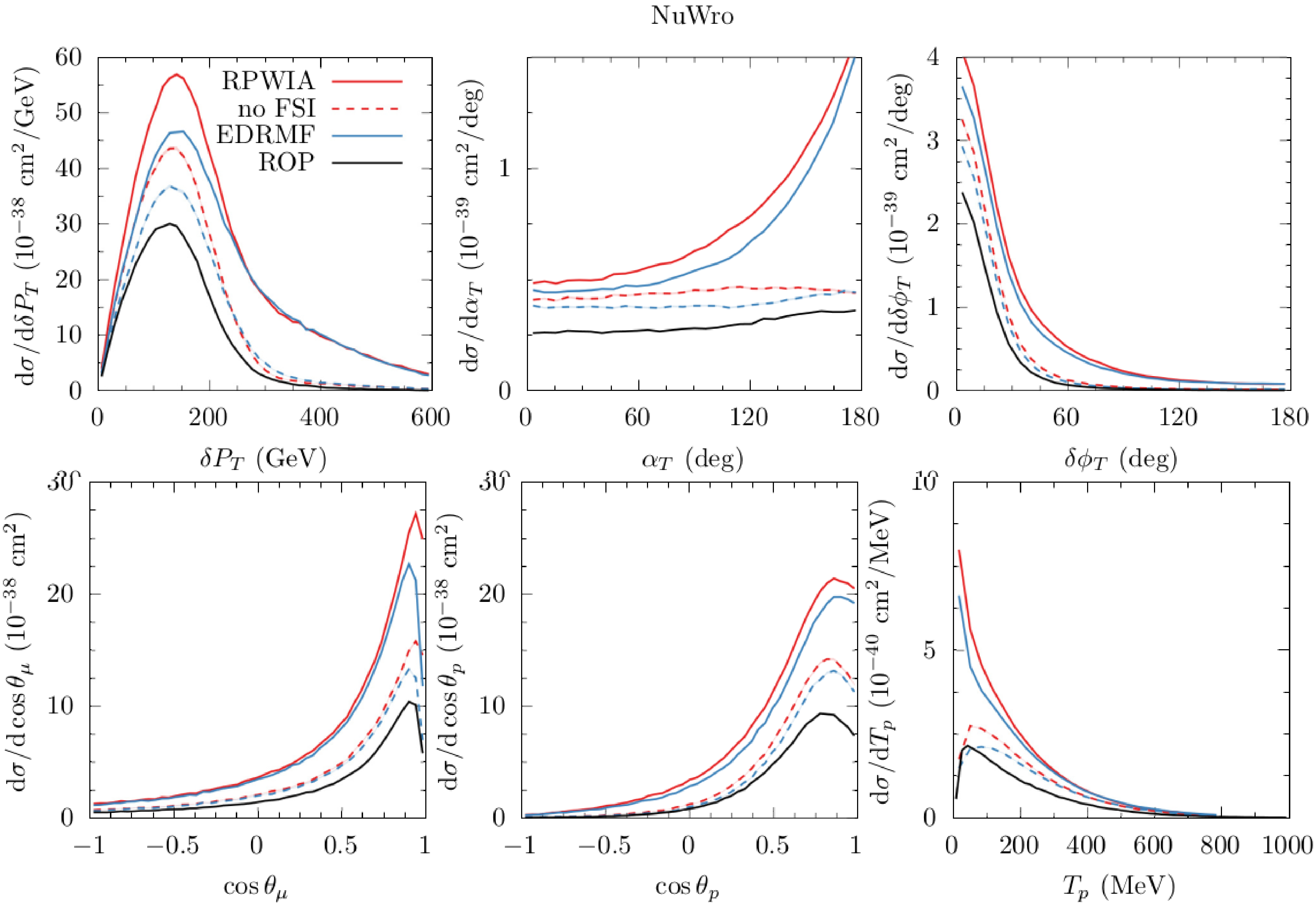
- **RDWIA results with realistic spectral functions for scattering on ^{40}Ar**

  - Constructed consistently with description for (e,e'p) and (e,e')
  - Small dependence on choice of *realistic* spectral function
  - RDWIA leads to ~ 10 % reduction compared to typical PWIA
  - General underprediction of data in the low-dP_T region

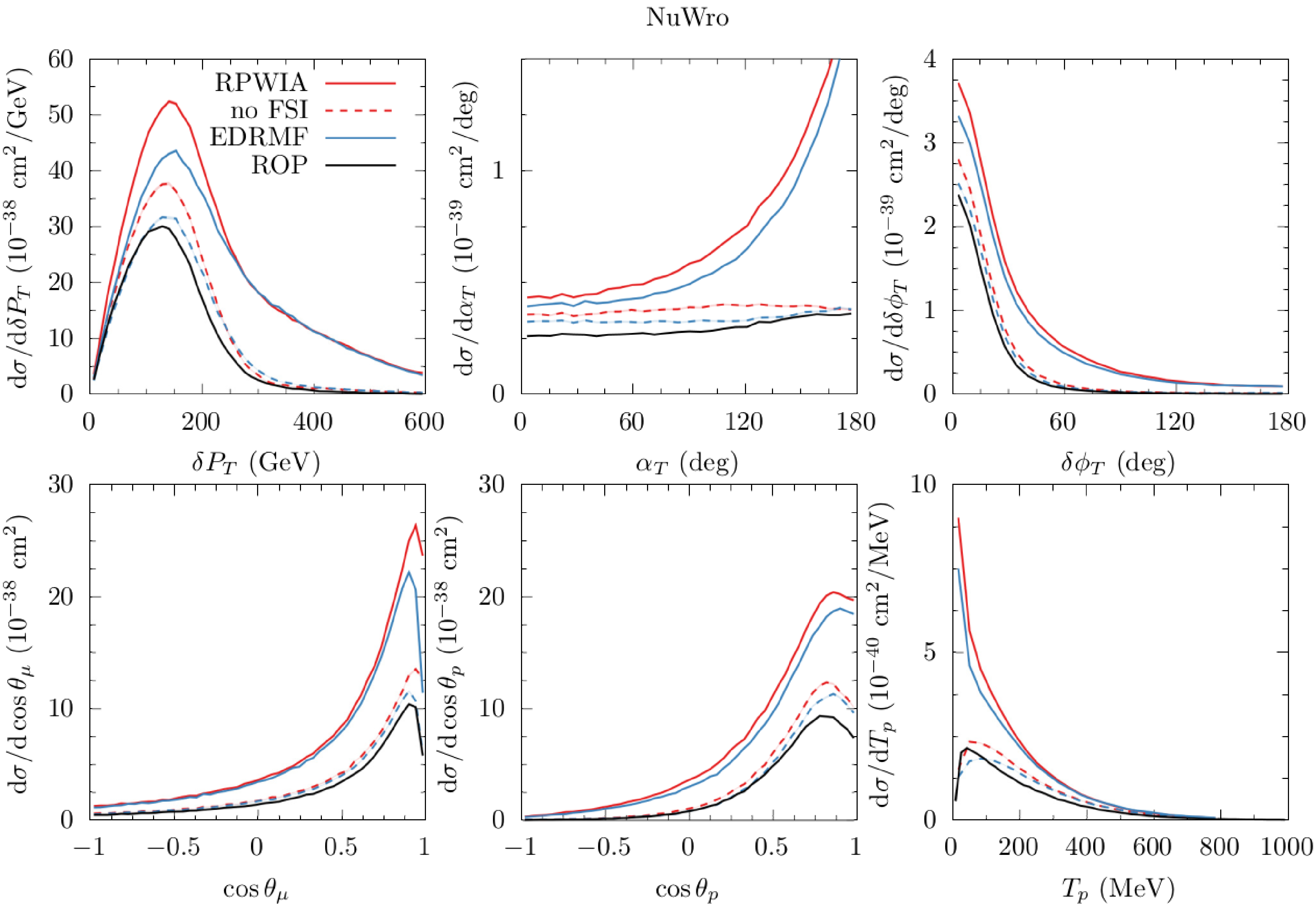
  → Include interference with 2-body currents
  e.g [T Franco-Munoz et al. PRC 108 064608]
  [Lovato et al arxiv:2312.12545]
  → Measurements sensitive to the missing-energy distribution ?
  e.g. [Baudis et al arxiv:2310.15633]

Other stuff

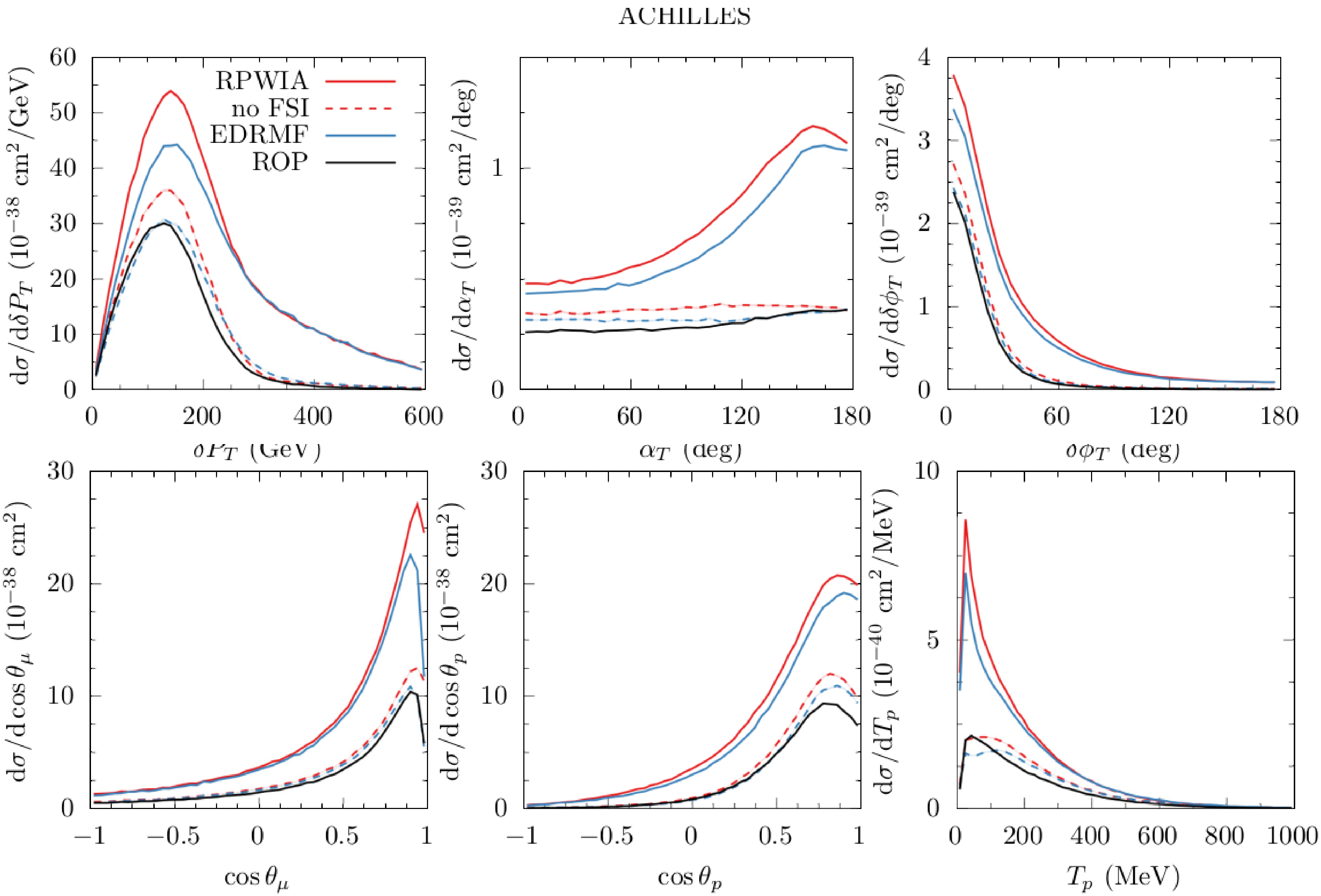
NuWro with SRC effect in Mean-free path



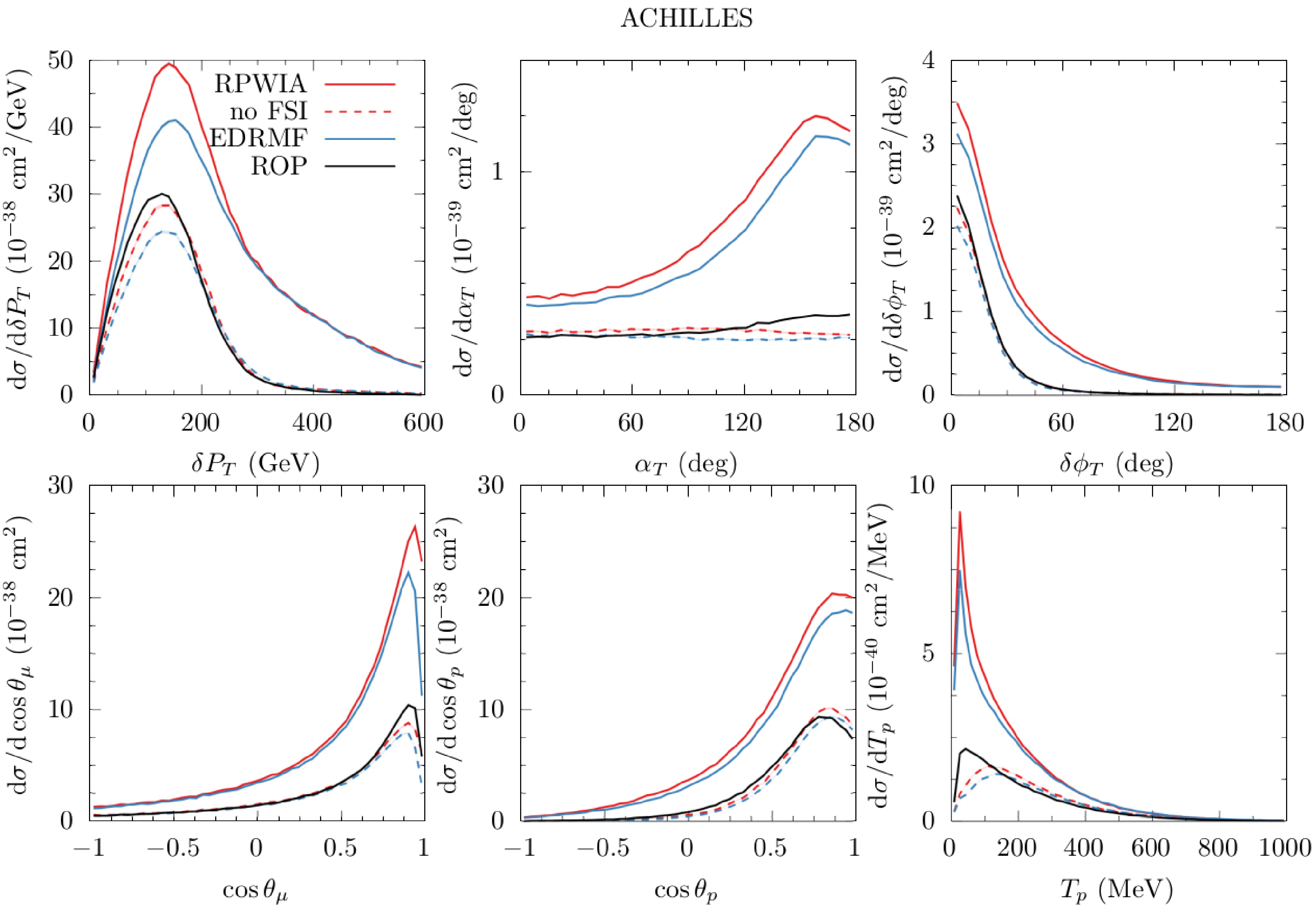
NuWro without SRC effect in Mean-free path



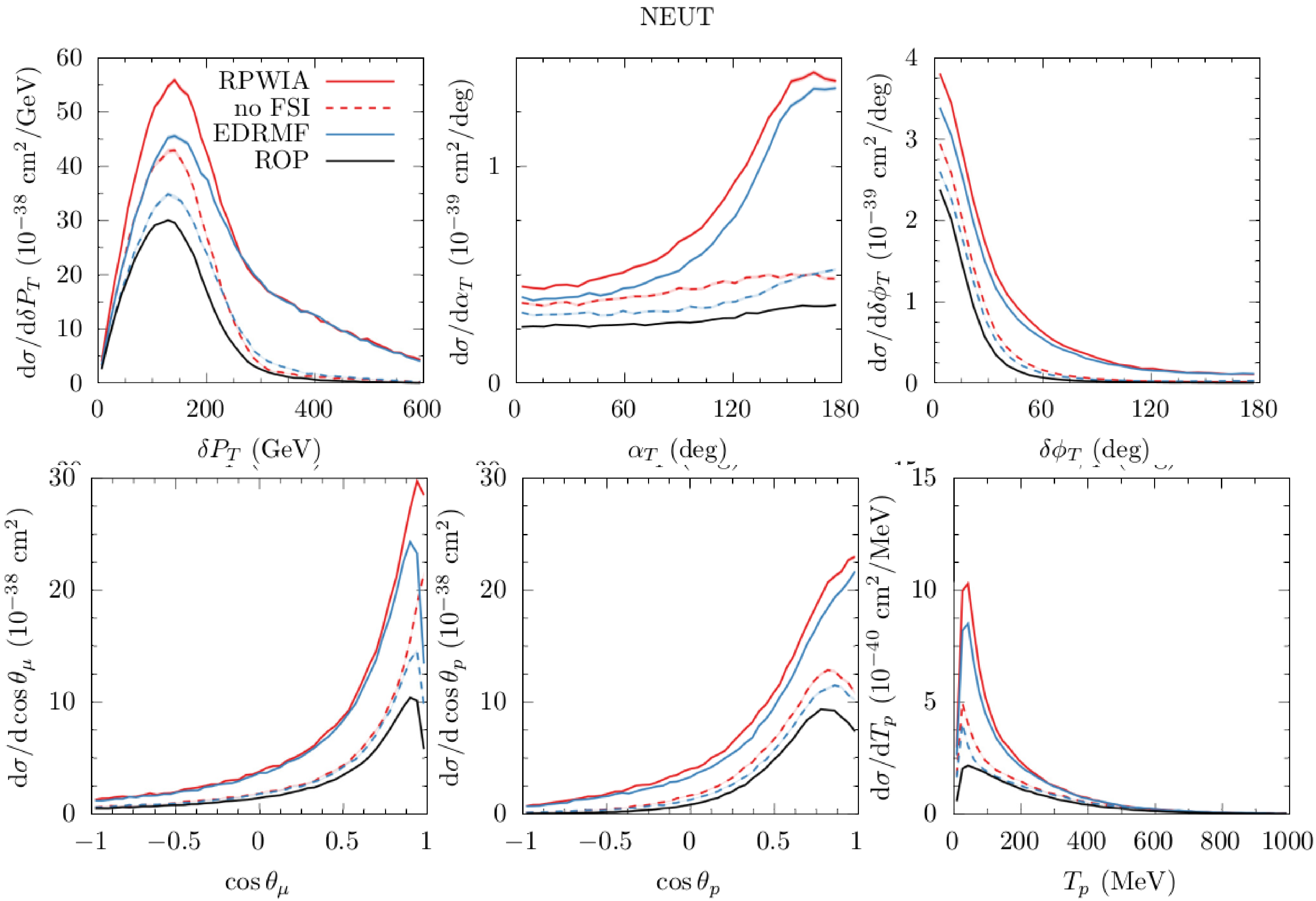
ACHILLES with Formation time



ACHILLES without Formation time



NEUT



NEUT
RPWIA
no FSI
EDRMF
ROP
$d\sigma/d\delta P_T$ (10^{-38} cm^2/GeV)
δP_T (GeV)
$d\sigma/d\alpha_T$ (10^{-39} cm^2/deg)
α_T (deg)
$d\sigma/d\delta\phi_T$ (10^{-39} cm^2/deg)
$\delta\phi_T$ (deg)
$d\sigma/d\cos\theta_\mu$ (10^{-38} cm^2)
$\cos\theta_\mu$
$d\sigma/d\cos\theta_p$ (10^{-38} cm^2)
$\cos\theta_p$
$d\sigma/dT_p$ (10^{-40} cm^2/MeV)
T_p (MeV)