Rescattering in cascade models with RDWIA inputs

Alexis Nikolakopoulos
Workshop on neutrino event generators
Fermilab 15 March 2023

Outline

1 How FSI in exclusive one-nucleon knockout is described:
Optical potential approach

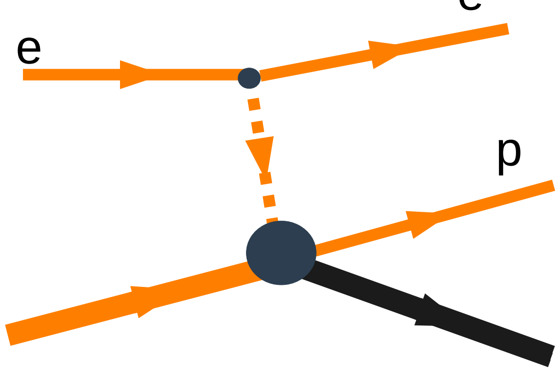
2 Comparison of the optical potential and the NEUT cascade

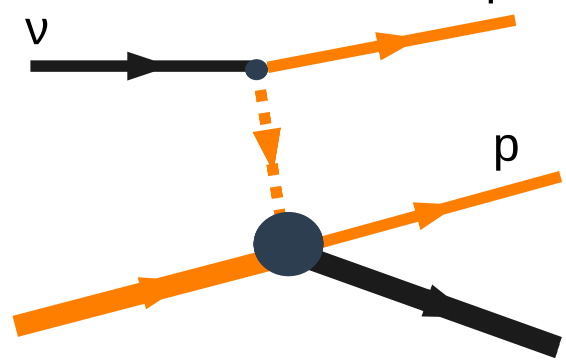
3 What is the input to the cascade ? :
How does the generator decide on hadrons from inclusive cross section?

Electron and neutrino scattering: Similar in theory, not in experiment

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

$\langle \Psi_f | \quad \langle \Psi_i |$ → Strong interaction: nuclear many-body states
The 'same physics' in A(e,e' p) X and A(ν,μ p)X





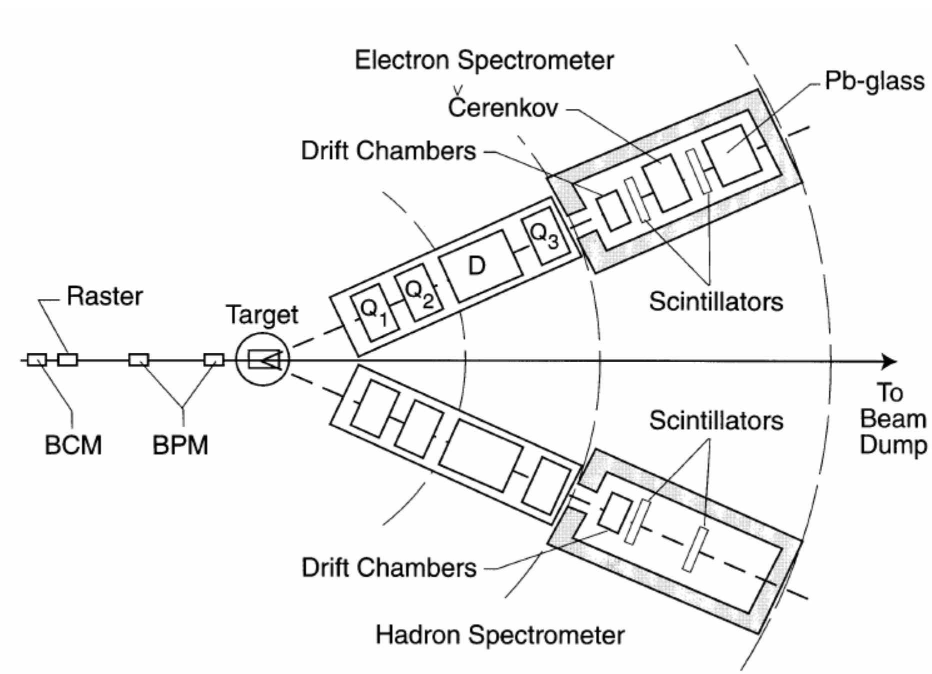
Experimental conditions are different!

A(e,e' p)X → (semi)-exclusive

A(ν,μ p)X → (semi)-inclusive

Electron and neutrino scattering: Similar in theory not in experiment

$\langle \Psi_f |$ $\langle \Psi_i |$ → Strong interaction: nuclear many-body states
The 'same theory' in A(e,e' p) B and A(ν,μ p)B



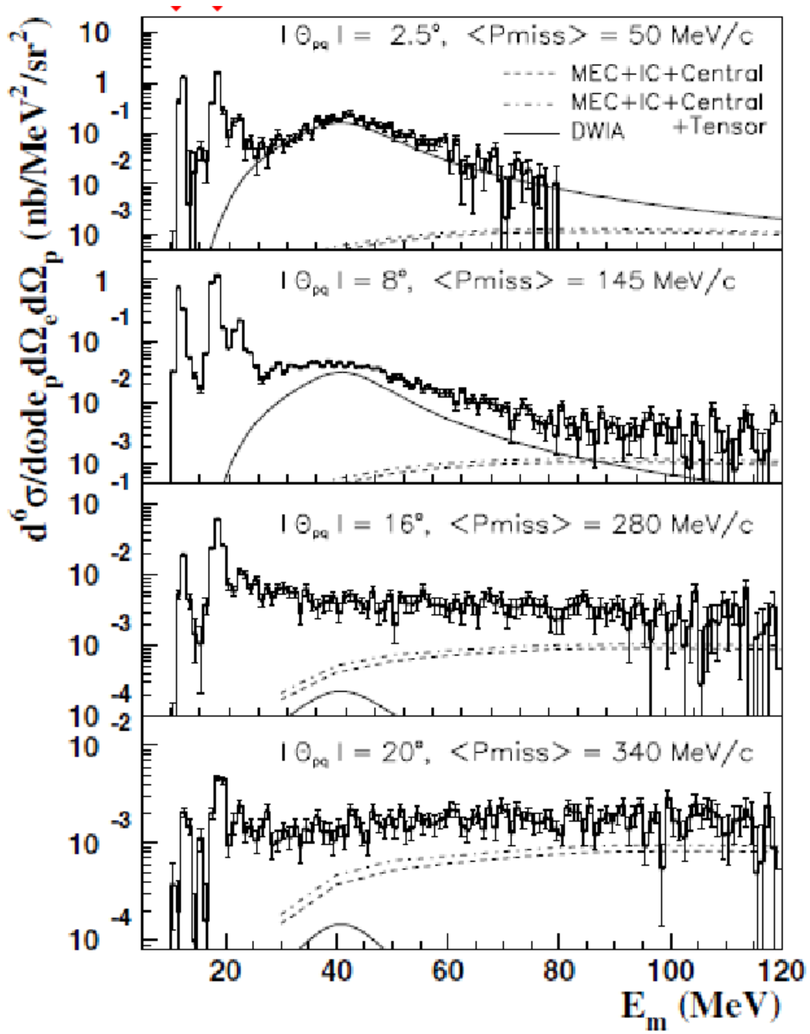
JLAB Hall A [PRC 42 38]

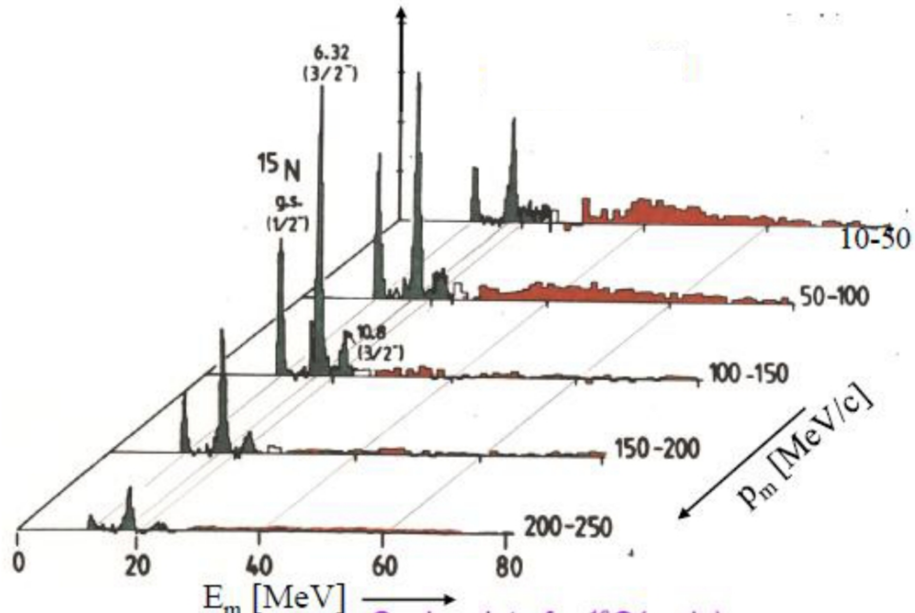
Very different experiments

- Fixed kinematics of e', p
- Known incoming energy!

Experimental conditions determine the theoretical tools for $\langle \Psi_f |$

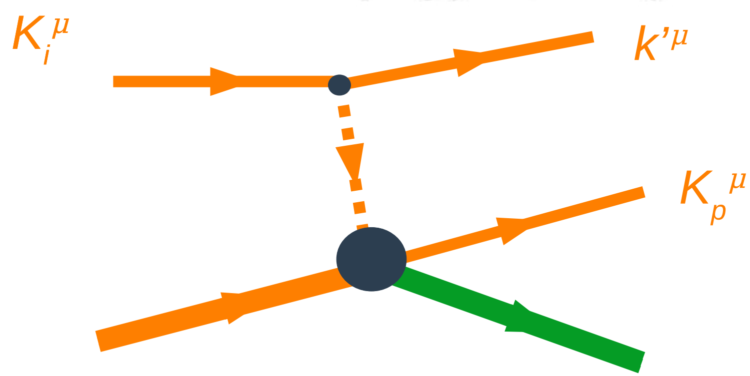
Exclusive electron scattering: Missing energy distributions





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

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



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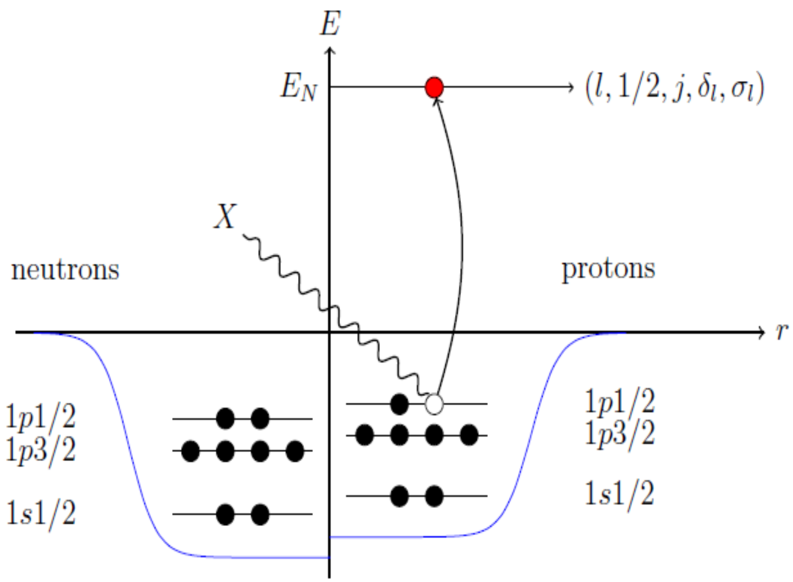
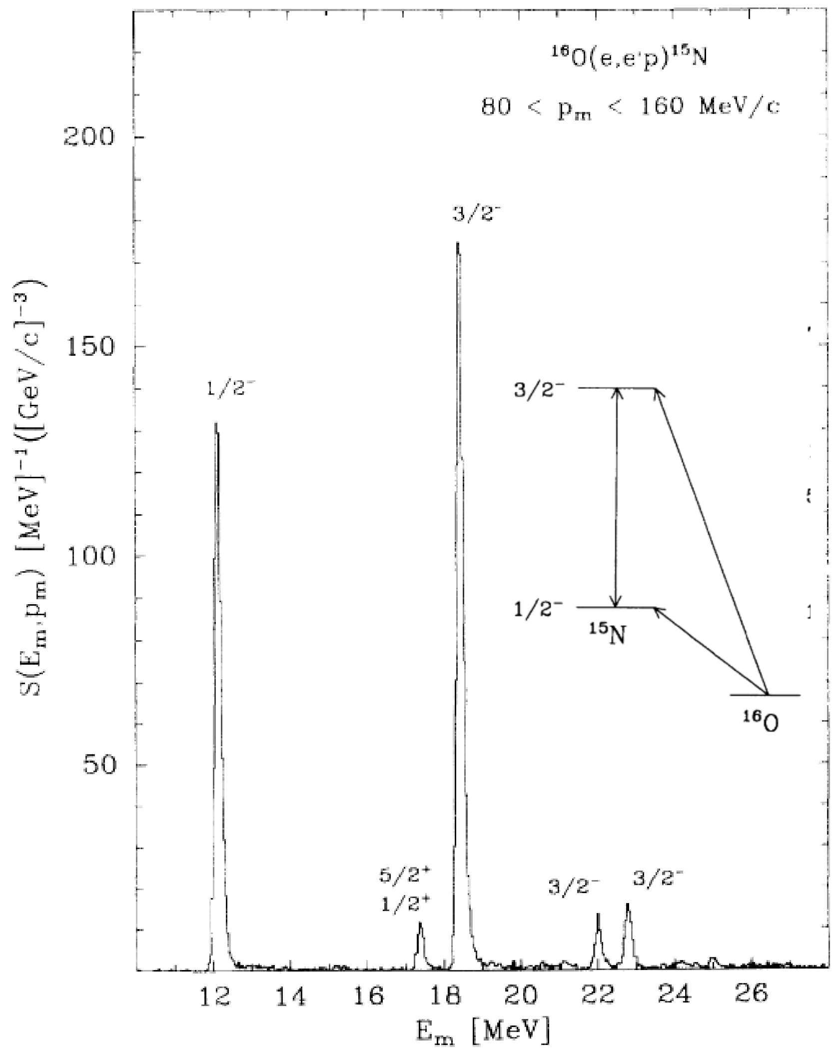
Exclusive electron scattering



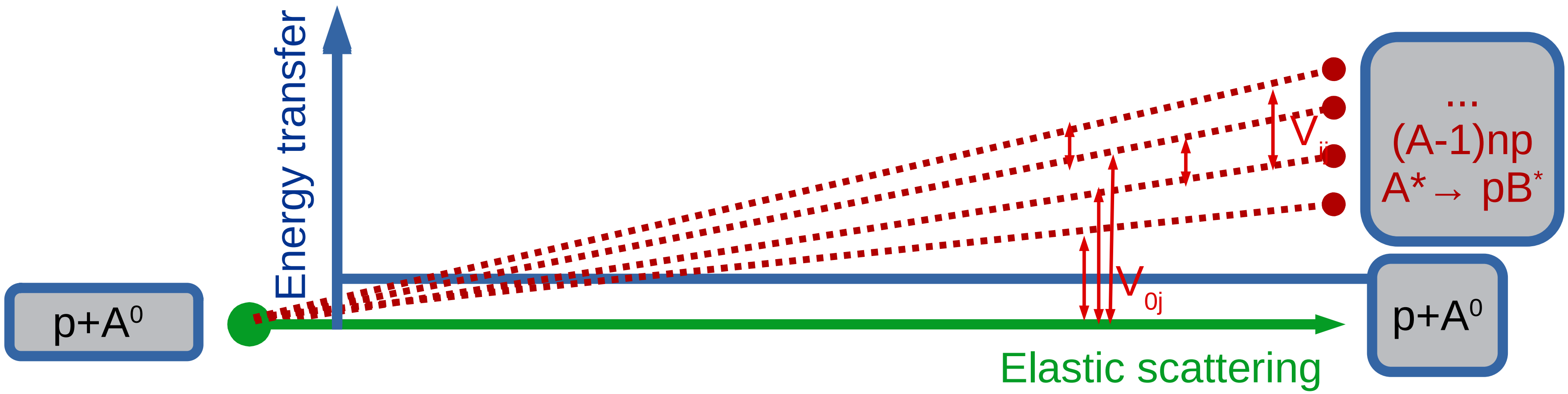
$$\mathcal{M} = j_{lep,\mu} \langle \Psi_f | \mathcal{O}^{\mu} | \Psi_i \rangle$$

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



Pure 1-proton knockout from a nuclear shell
How do we describe this state ?

Optical potential approach



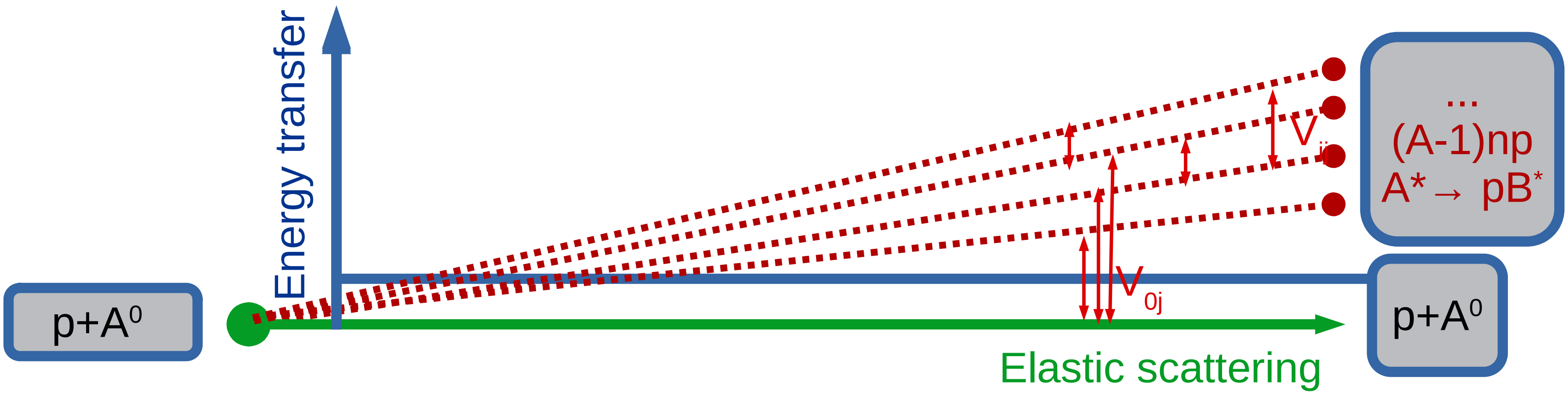
Coupled channels problem, separate out elastic channel

$$(H_{00} - E)|\phi_0\rangle = -V_{0j}|\phi_j\rangle \ (j > 0)$$

$$(H_{ij} - E)|\phi_j\rangle = -V_{j0}|\phi_0\rangle \ (i, j > 0)$$

$$H_{ij} = H^{free}\delta_{ij} + V_{ij}^{nA} + \epsilon_i \delta ij$$

Optical potential approach



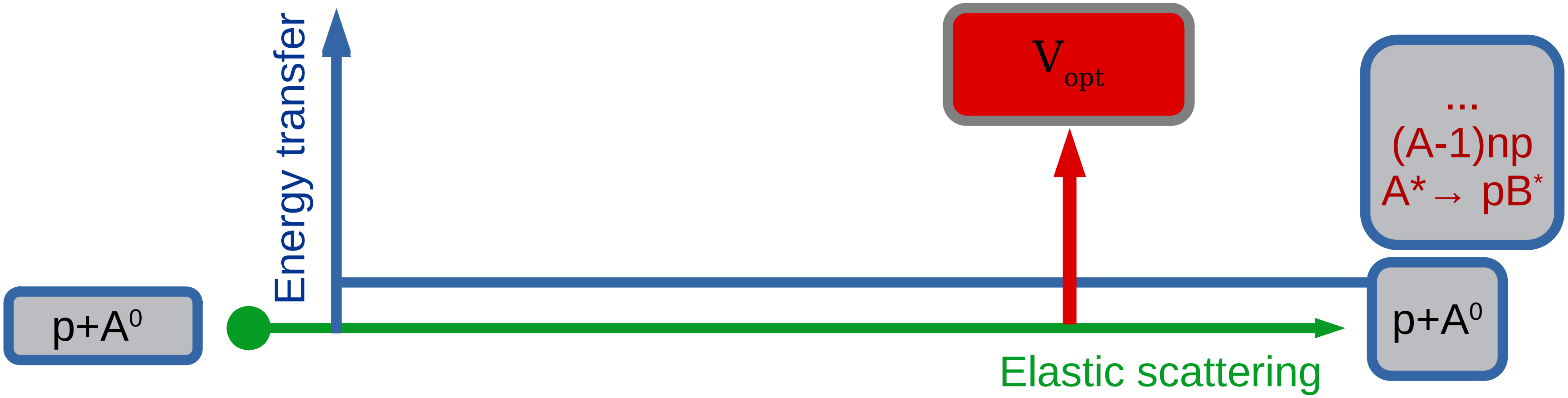
$$(H_{00} - E)|\phi_0\rangle = -V_{0j}|\phi_j\rangle \; (j > 0)$$

$$(H_{ij} - E)|\phi_j\rangle = -V_{j0}|\phi_0\rangle \; (i, j > 0)$$

$$\left[H^{free} + V_{00}^{nA} + V_{0j}\frac{1}{E - H_{ij} + i\eta}V_{j0} - E\right]|\phi_0\rangle$$

Coupled channels problem → Effective one-body problem as a formal solution

Optical potential approach



$$\left[H^{free} + V_{00}^{nA} + V_{0j}\frac{1}{E - H_{ij} + i\eta}V_{j0} - E\right]|\phi_0\rangle$$

$$\approx \left[H^{free} + \mathcal{V}^{opt} - E\right]|\phi_0\rangle$$

Coupled channels problem → Effective one-body problem with optical potential

The (empirical) relativistic optical potential

PHYSICAL REVIEW C VOLUME 47, NUMBER 1 JANUARY 1993

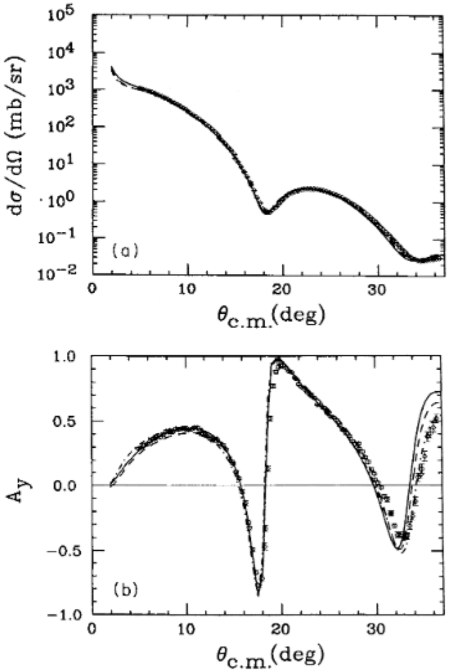
Global Dirac phenomenology for proton-nucleus elastic scattering

E. D. Cooper, S. Hama, and B. C. Clark
Department of Physics, The Ohio State University, Columbus, Ohio 43210

R. L. Mercer
IBM Thomas J. Watson Research Center, Yorktown Heights, New York 10598

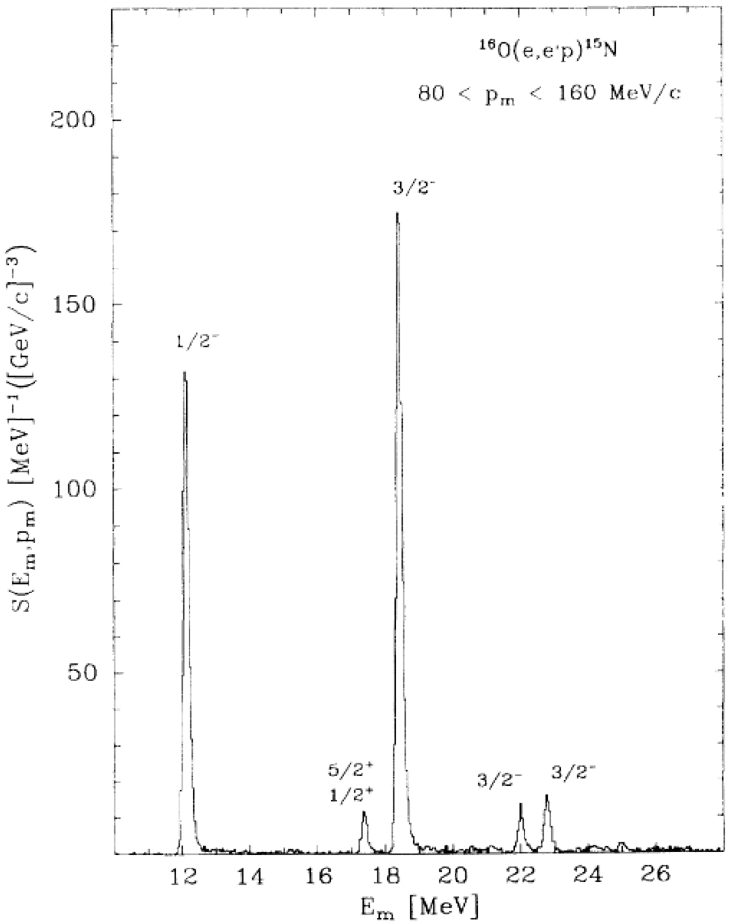
(Received 31 August 1992)

		σ_R(mb)				
			EDAD-fit			
Target	T_p (MeV)	EDAI-fit	fit 1	fit 2	fit 3	Reference
^{12}C	29.00	420.2	435.5	433.1	422.7	[6]
	30.30	415.9	429.0	425.6	414.2	[7]
	49.00	358.8	363.0	348.4	327.7	[6]
	49.48	357.4	361.8	347.0	326.1	[8]
	61.40	323.3	335.6	317.0	294.8	[9]
	65.00	313.5	329.0	309.7	287.4	[10]
	122.00	202.2	269.0	254.4	230.5	[11]
	160.00	177.8	252.3	246.4	215.2	[11]
	200.00	177.6	243.0	243.9	205.0	[11–13]
	300.00	201.1	233.0	235.4	194.9	[14]
	398.00	215.8	227.4	218.6	199.1	[15]
	494.00	227.2	223.7	203.0	211.6	[16]
	797.50	238.4	235.3	209.9	250.0	[17,18]
	1040.00	198.6	259.4	243.8	232.2	[19,20]



Fit to elastic proton-nucleus scattering data

Exclusive electron scattering with Optical potential: 'standard approach'



[Meucci et al. PRC64, 014604]

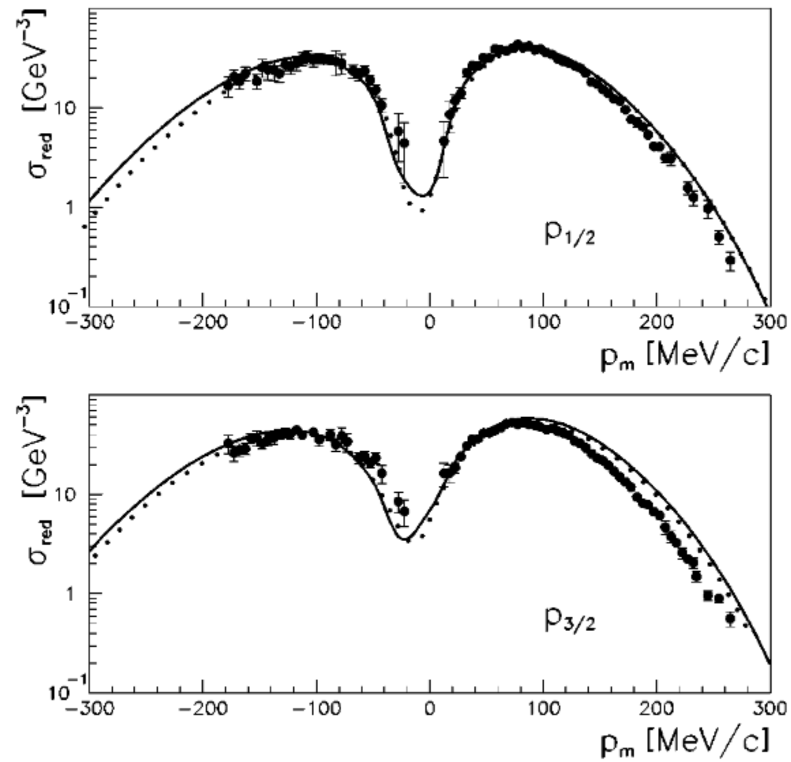
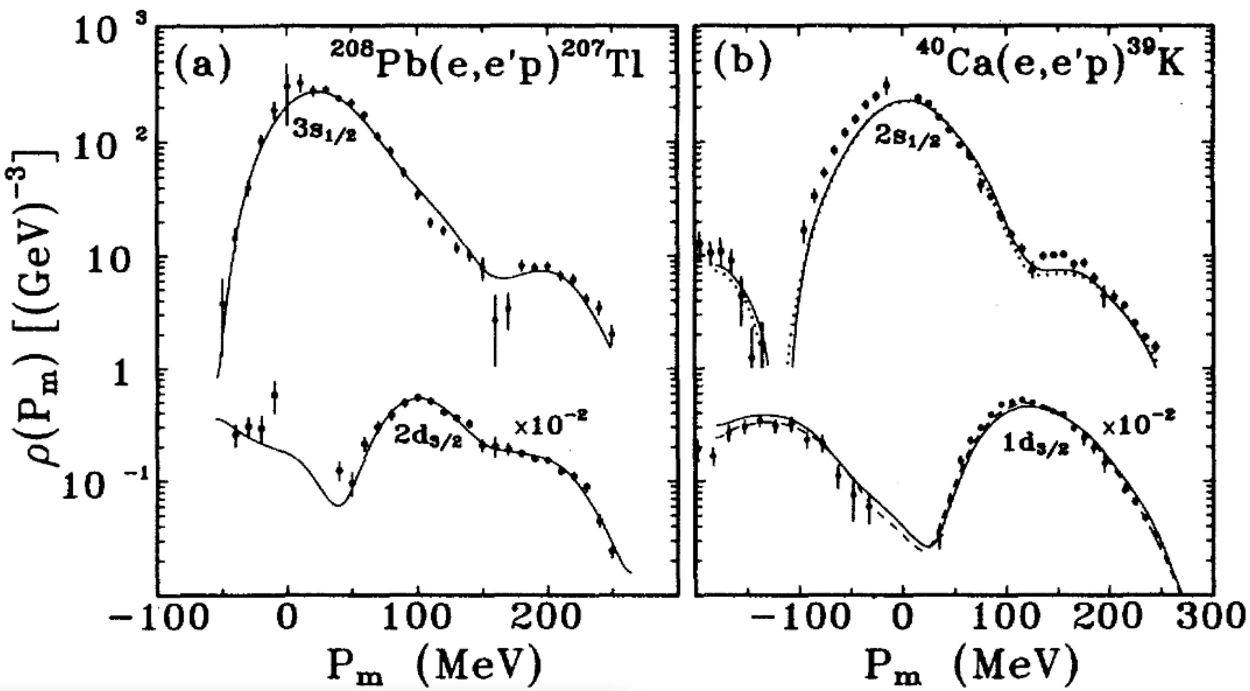


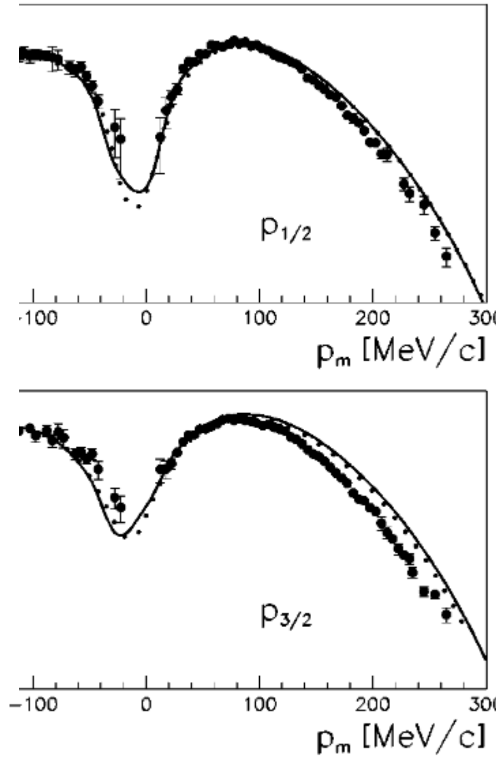
FIG. 11. The reduced cross section (σ_{red}) of the $^{16}O(e,e'p)$ reaction as a function of the recoil momentum p_m for the transitions to the $1/2^-$ ground state and to the $3/2^-$ excited state of ^{15}N, in

Exclusive electron scattering with Optical potential: ‘standard approach’

[Udias et al. PRC48, 2731]



[Meucci et al. PRC64, 014604]



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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]

1. Input to NEUT INC

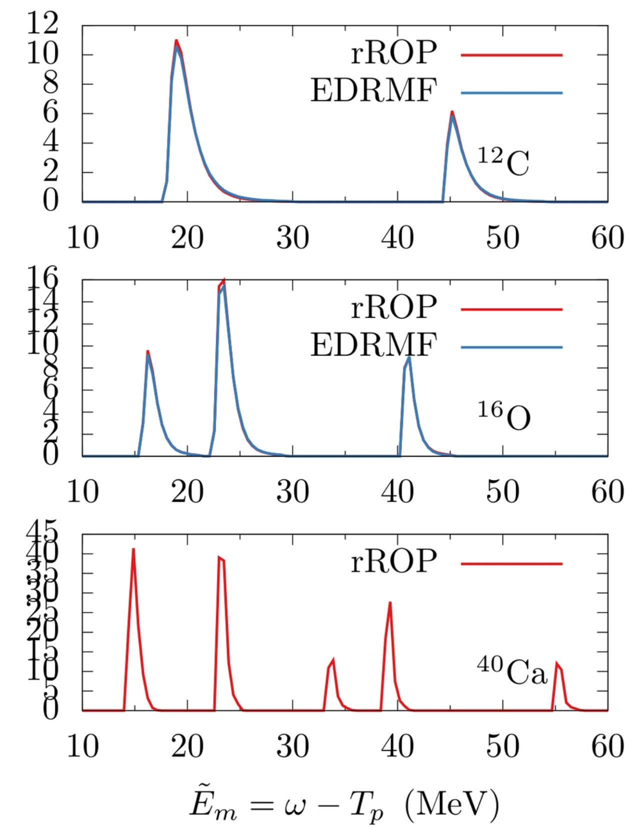
Events according to **unfactorized** five-fold differential nucleon knockout cross section

2. Kinematic cuts on NEUT result

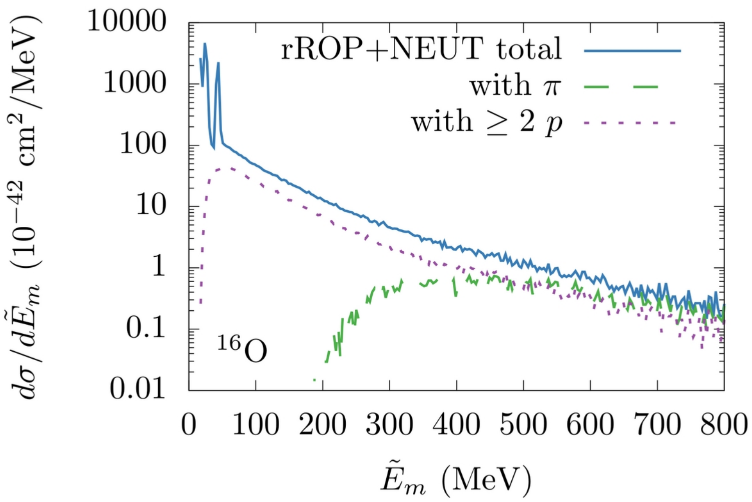
Select events with E_m in shell-model

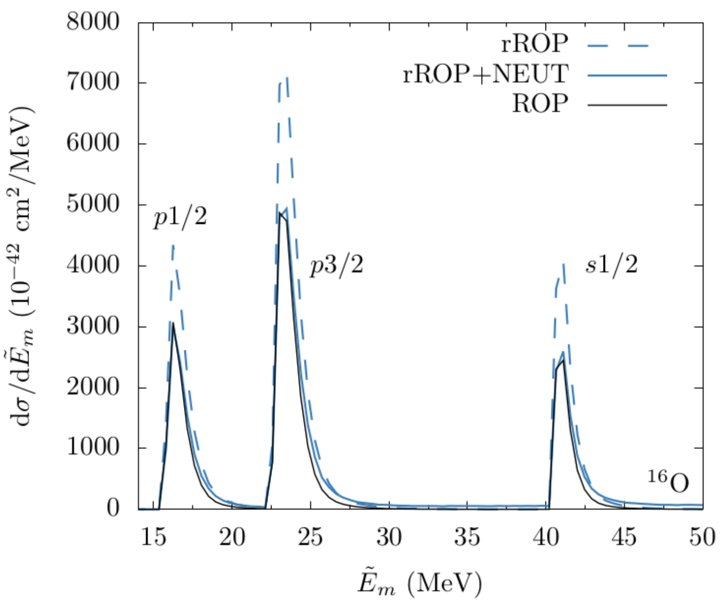
Is an ‘exclusive’ signal like in (e,e’p)

Cascade can be compared to ROP



Cascade model with rROP inputs



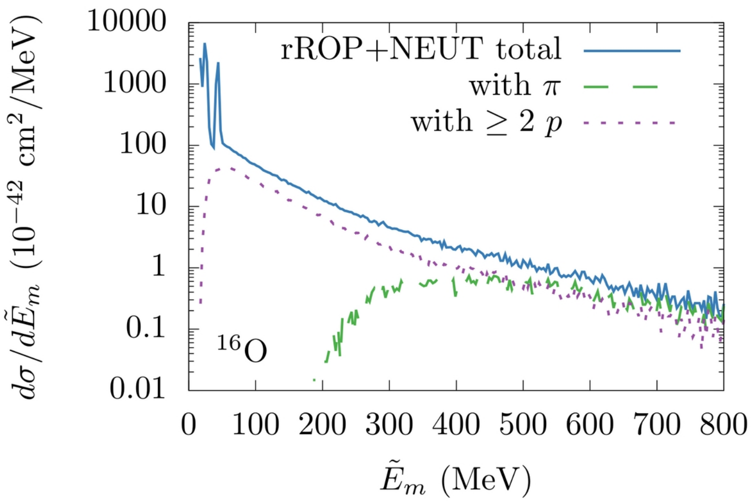


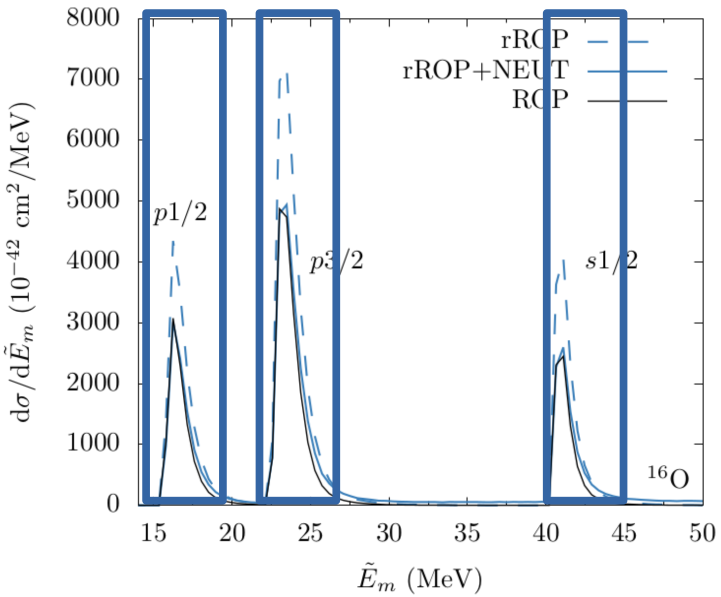
$$\tilde{E}_m = E_i - E_l - T_p$$

T2K flux-folded calculations

- Cascade moves strength from shell model peaks to larger E_m
  => Rescattering into different final states
- Strength of shell model peaks agrees with ROP predictions
- A nice consistent picture emerges between inclusive and exclusive results

Cascade model with rROP inputs



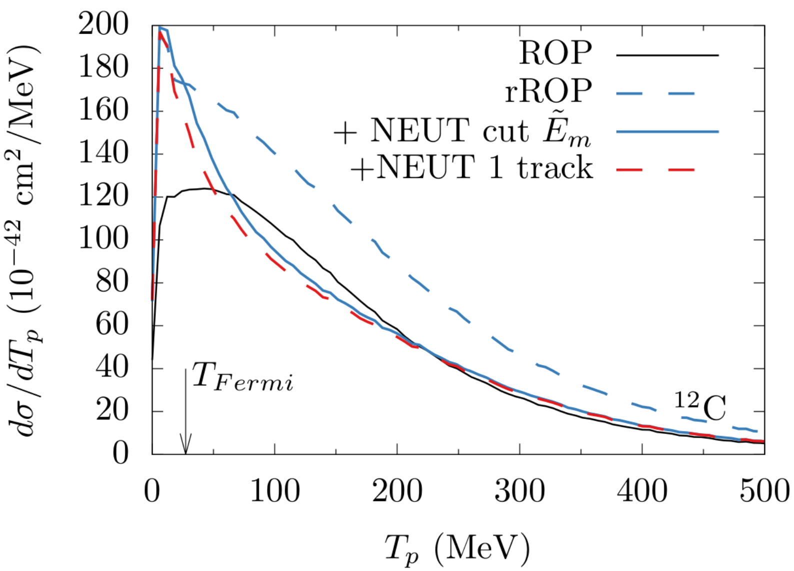


$$\tilde{E}_m = E_i - E_l - T_p$$

T2K flux-folded calculations

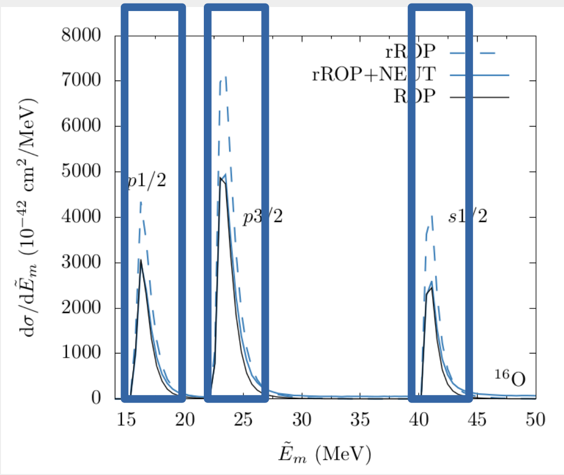
- Cascade moves strength from shell model peaks to larger E_m
  => Rescattering into different final states
- Strength of shell model peaks agrees with ROP predictions
- Make kinematic cuts like in (e,e'p)
  => Remove the rescattering
  => exclusive conditions

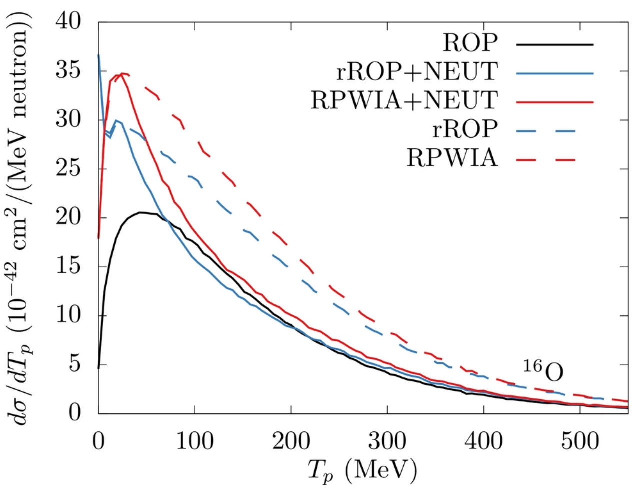
Cascade model with rROP inputs

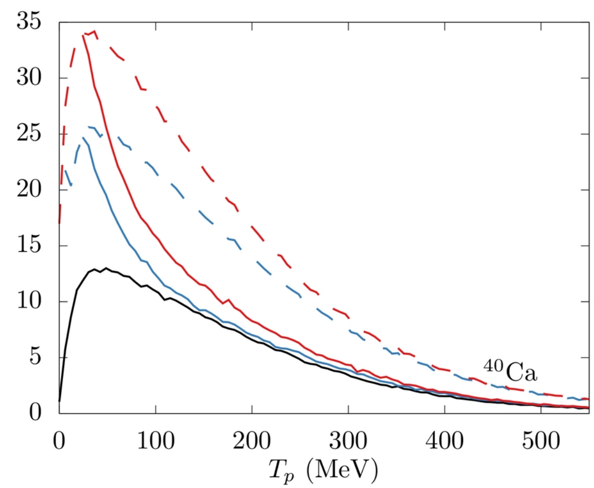


T2K flux-folded calculations

With missing energy cuts





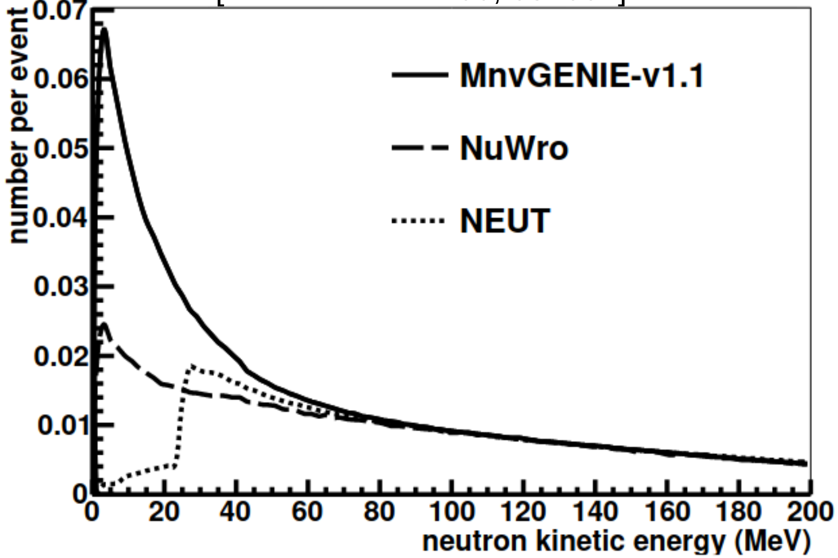


The INC = ROP for high T_p

For T_p < 100
differences of up to 100% !

Discrepancies at low-T_N

[MINERvA PRD100, 052002]

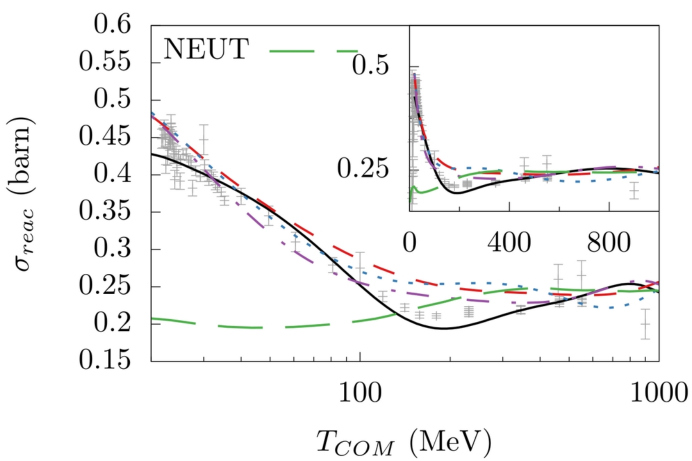


T2K flux-folded calculations

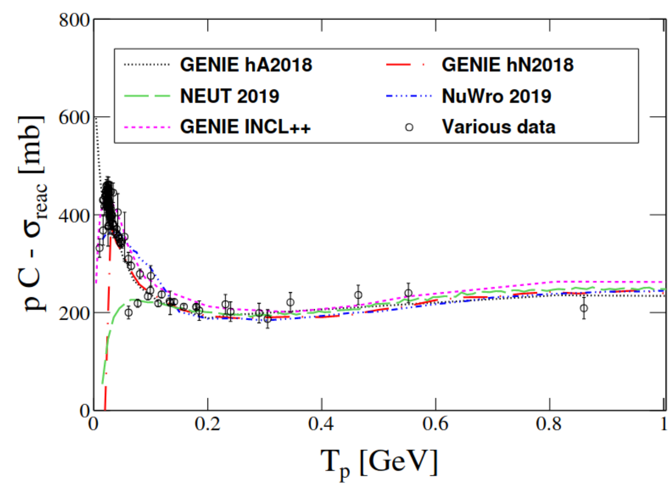
The INC = ROP for high T_p

For T_p < 100
differences of up to 100% !

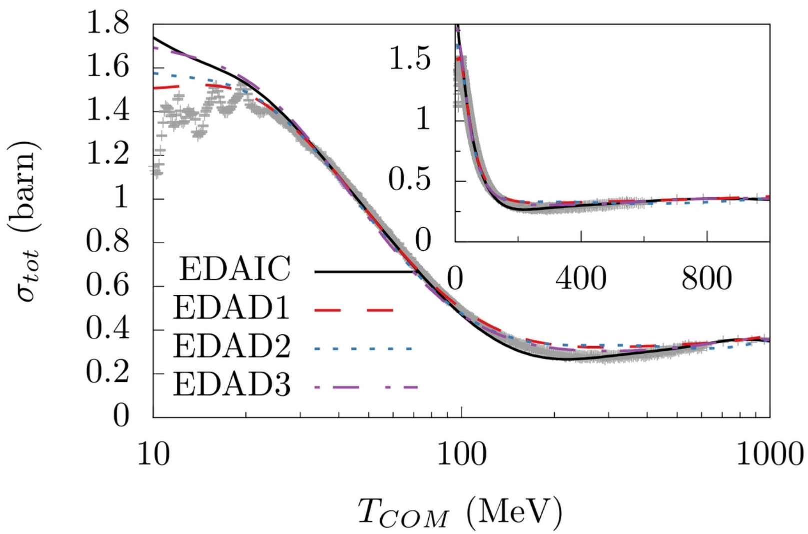
Constraints for cascades:
Reaction cross section

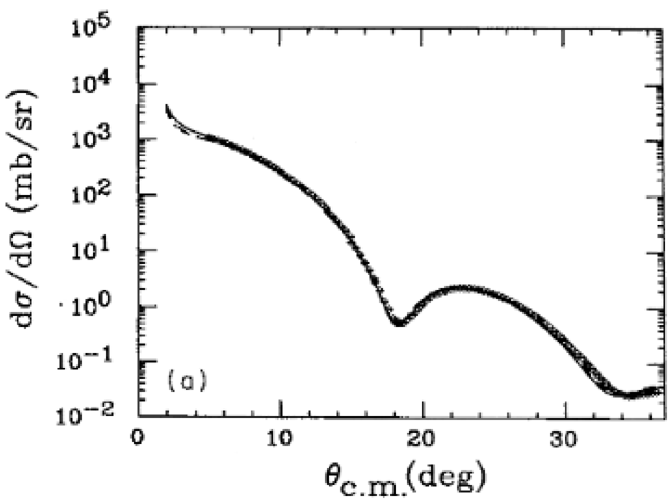


[Dytman et al. PRD104, 053006]



What the INC can learn from optical potentials





T2K flux-folded calculations

The INC = ROP for high T_p

For T_p < 100
differences of up to 100% !

Constraints for cascades:
Reaction cross section

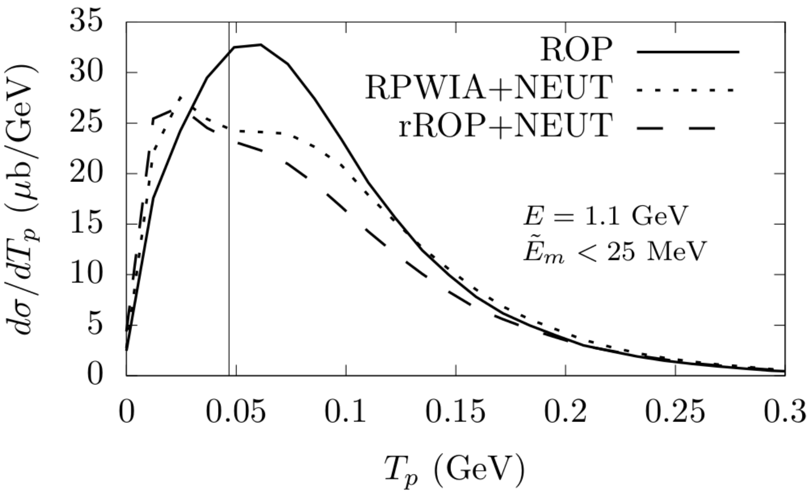
This study:

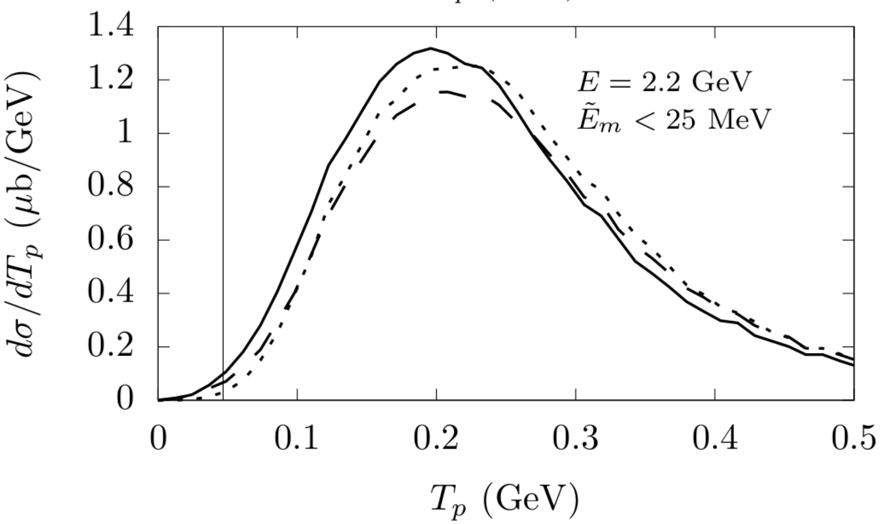
- Brings the constraints from the analysis of *elastic* and total cross sections
- Gives a **quantum-mechanical** benchmark in the low-T_N region

What the INC can learn from optical potentials

$\tilde{E}_m < 25$ MeV

→ **No 2p2h, RES, inelastic FSI**





This study:

- Brings the contraints from the analysis of *elastic* and total cross sections
- Gives a **quantum-mechanical** benchmark in the low-T_N region

Ultimately we should test with data

- Results for e4nu kinematics with a strict E_m cut

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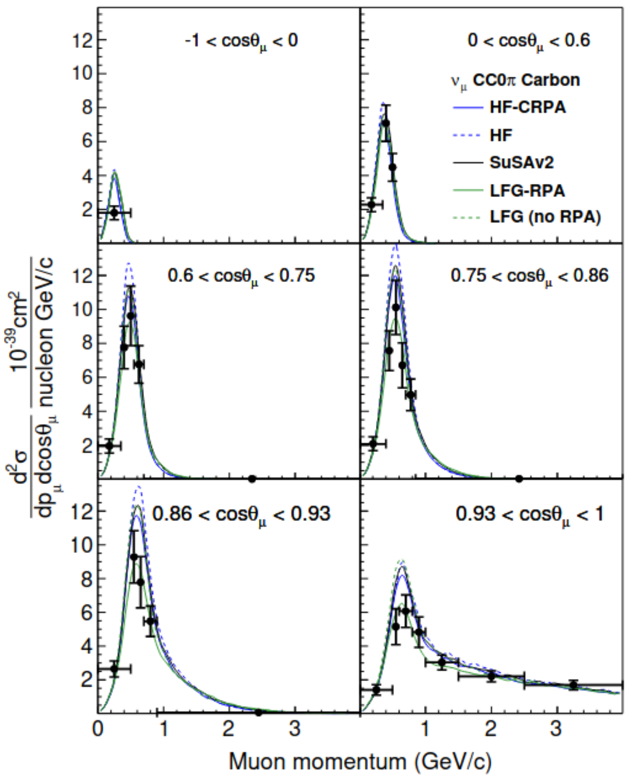
Article

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]

[arXiv:2302.12182]

The question:
How do event generators generate hadrons from the **inclusive** cross section ?



Implementation of the SuSAv2-MEC 1p1h and 2p2h models in GENIE and analysis of nuclear effects in T2K measurements

S. Dolan,[1,2,3] G.D. Megias,[1,2,4] and S. Bolognesi[2]

Implementation of the CRPA model in the GENIE event generator and analysis of nuclear effects in low-energy transfer neutrino-nucleus interactions

S. Dolan,[1] A. Nikolakopoulos,[2] O. Page,[3] S. Gardiner,[4] N. Jachowicz,[2] and V. Pandey[5]

Implementation of SuSAv2, HF-CRPA, LFG+RPA (Valencia), SuSA-MEC, ... provide the **inclusive** cross section

=> The information on outgoing nucleon is not available

(Similar issues with MEC responses, Resonance production, ...)

Article

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[arXiv:2302.12182]

$$P(E_l, \theta_l, T_N, \Omega_N) = \sum_{M_B} \frac{d^4\sigma(E_e, M_B)}{dE_{e'}\, d\cos\theta_{e'}\, d\Omega_N}.$$

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

- Full consistent description of exclusive kinematics 1e1p

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Article

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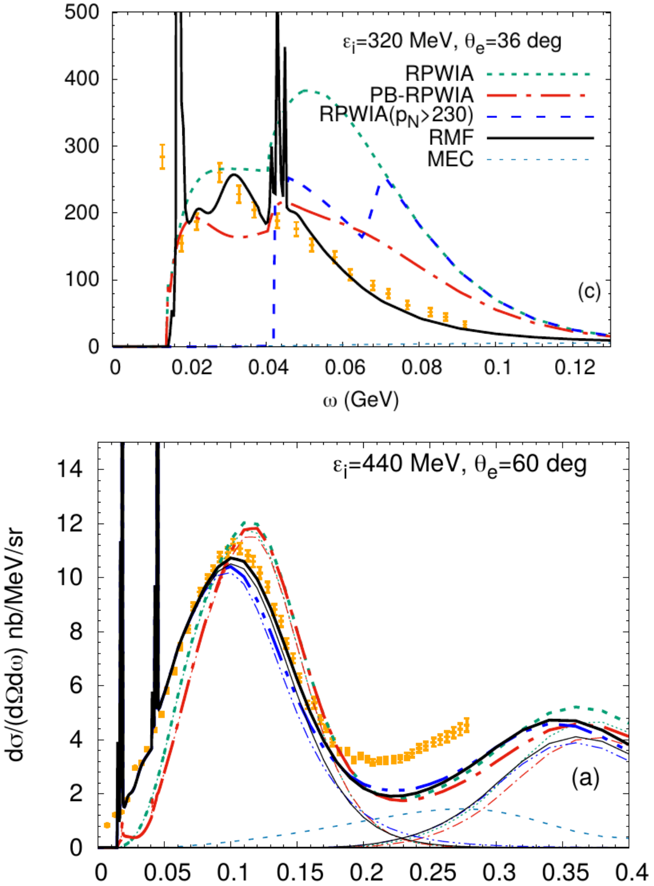

[Phys. Rev. C 100, 045501 (2019)]

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!)

Article

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

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

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

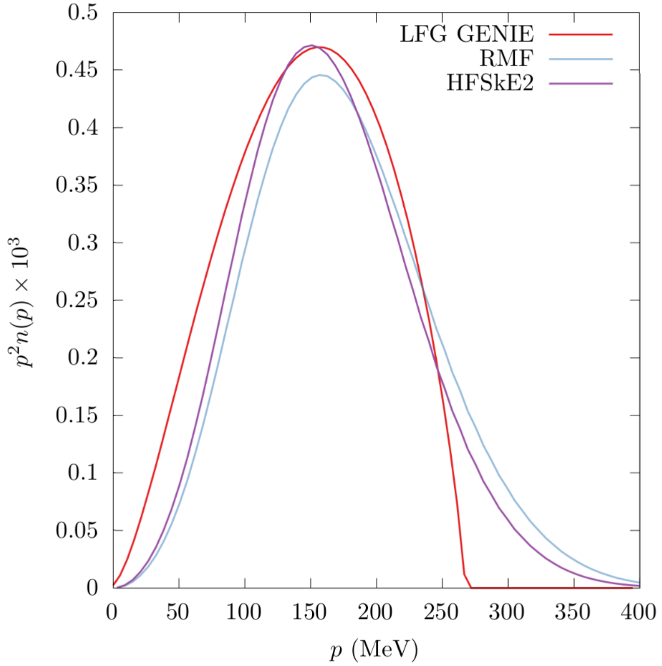
$$\frac{\mathrm{d}\sigma(E_\nu)}{\mathrm{d}E_l\mathrm{d}\cos\theta_l} = G^2\frac{k_l}{E_\nu}L_{\mu\nu}\int \mathrm{d}\Omega_N \sum_{n,\kappa} H^{\mu\nu}_{n,\kappa}(\omega, q, \Omega_N, E_{n,\kappa})$$

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



Nucleon kinematics from inclusive cross section in GENIE

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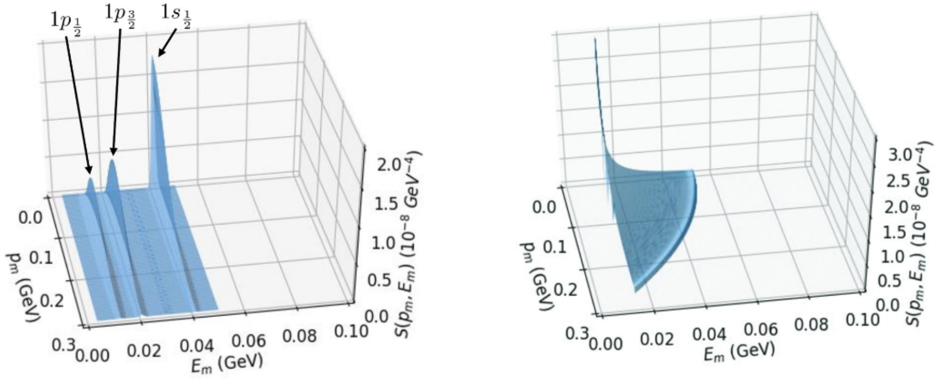
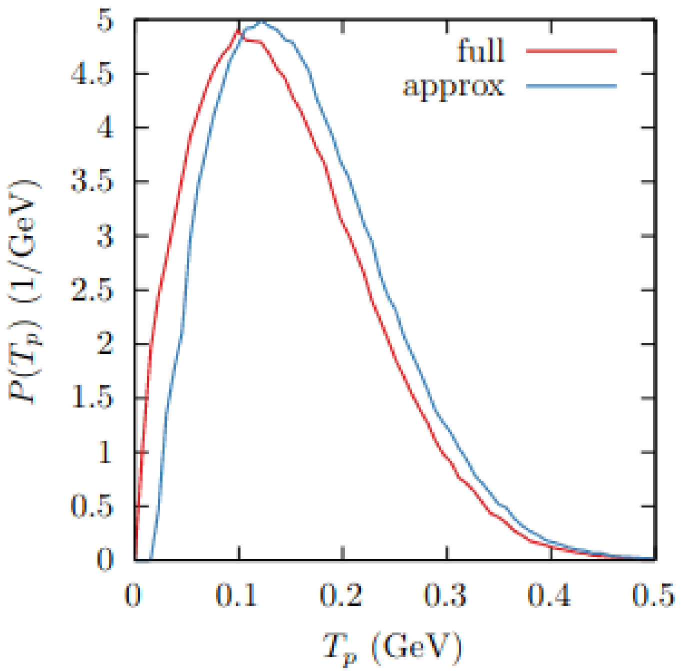
3. $E_N = E_m + \omega - E_b(q)$

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

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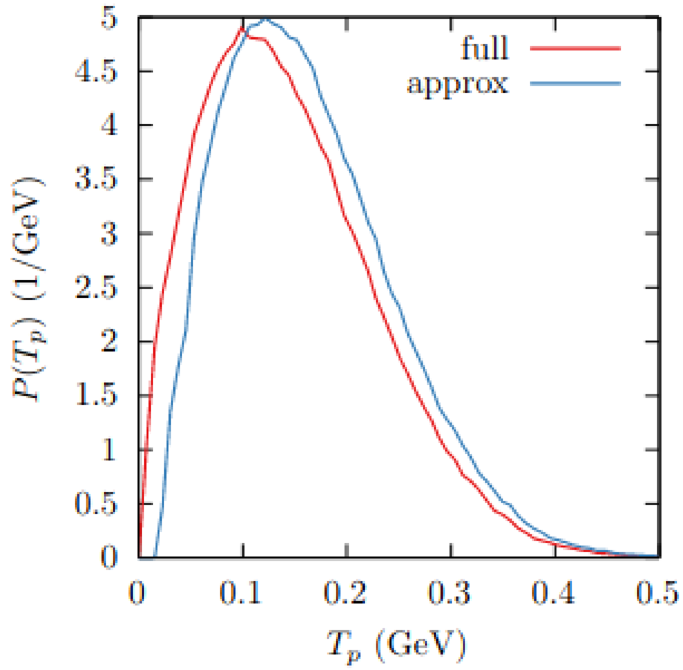
!! 2. Compute $E_m^2 = p_m^2 + M_N^2$

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

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

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

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



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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)

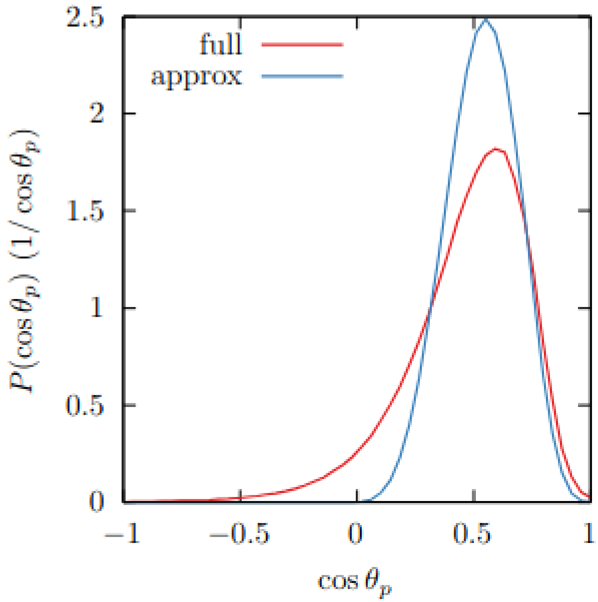
!! 2. Compute $E_m^2 = p_m^2 + M_N^2$

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

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

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

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

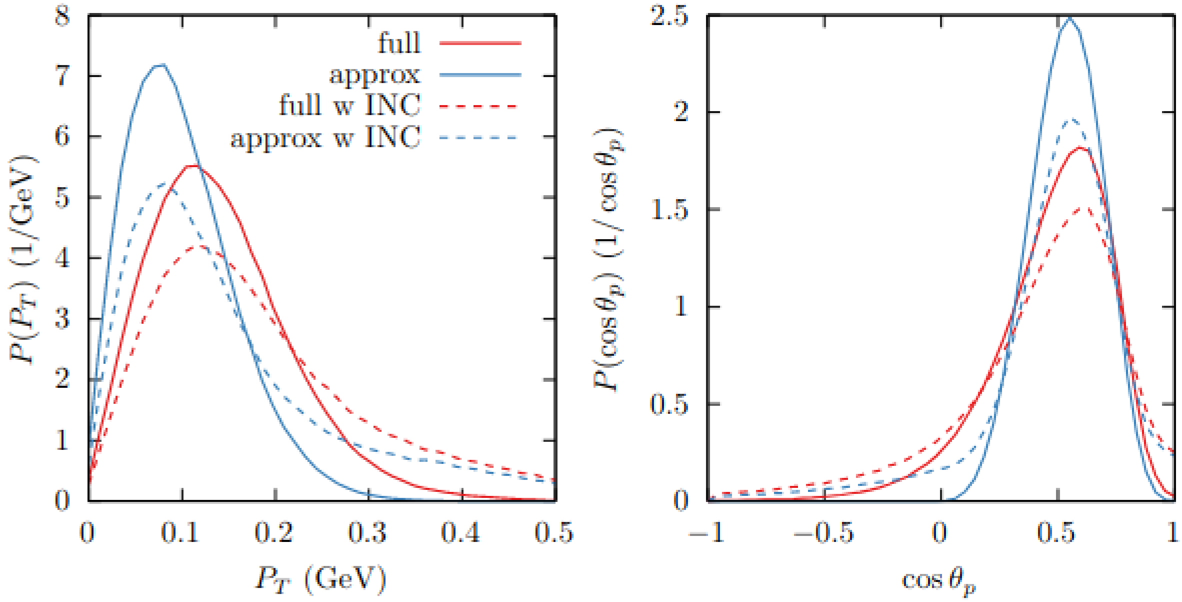


Serious differences in angular distributions!

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



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

Shape differences biggest in P_T and angular distributions

Conclusions

- The ROP and INC approaches use nucleon-nucleus scattering to constrain FSI, in different ways.

- A consistent comparison of the NEUT INC and optical potential shows that there is quantitative agreement at large kinetic energies.
  For small kinetic energy the differences are up to 100% !!

- The ROP should be more reliable in this comparison, but the true answer is unknown! Should measure (e,e'p) over large phase space with cut on missing energy

- Results of the generator will depend crucially on the input to the INC!
- Current implementations (necessarily) use unrealistic approximations

- **Unfactorized Events** for flux-averaged signals over the whole phase space can be generated combined with INC provides inclusive and exclusive CS
  → **You can use these for validation/error estimation/…
  of your own INC/simulation/...**