Fermilab U.S. DEPARTMENT OF ENERGY Office of Science

Final-state interactions in neutrino experiments

Alexis Nikolakopoulos
Workshop on Neutrino Scattering at Low and Intermediate Energies
MITP 27 June 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

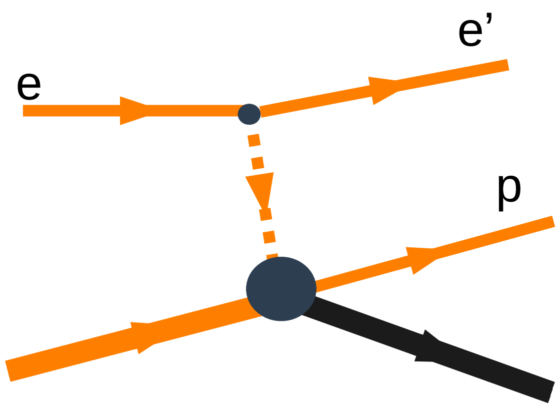
3 What is the input to the cascade ?

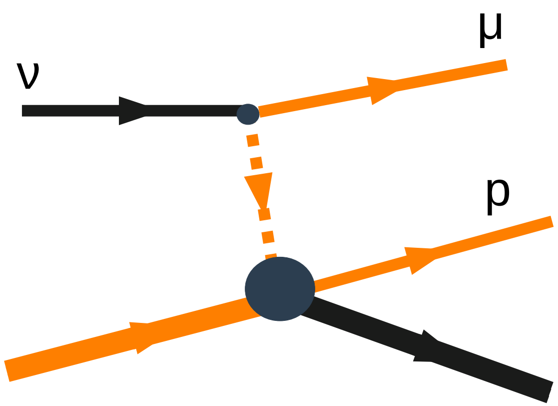
4 Intermediate-energy measurements: neutrinos from Kaon decay-at-rest

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

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

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



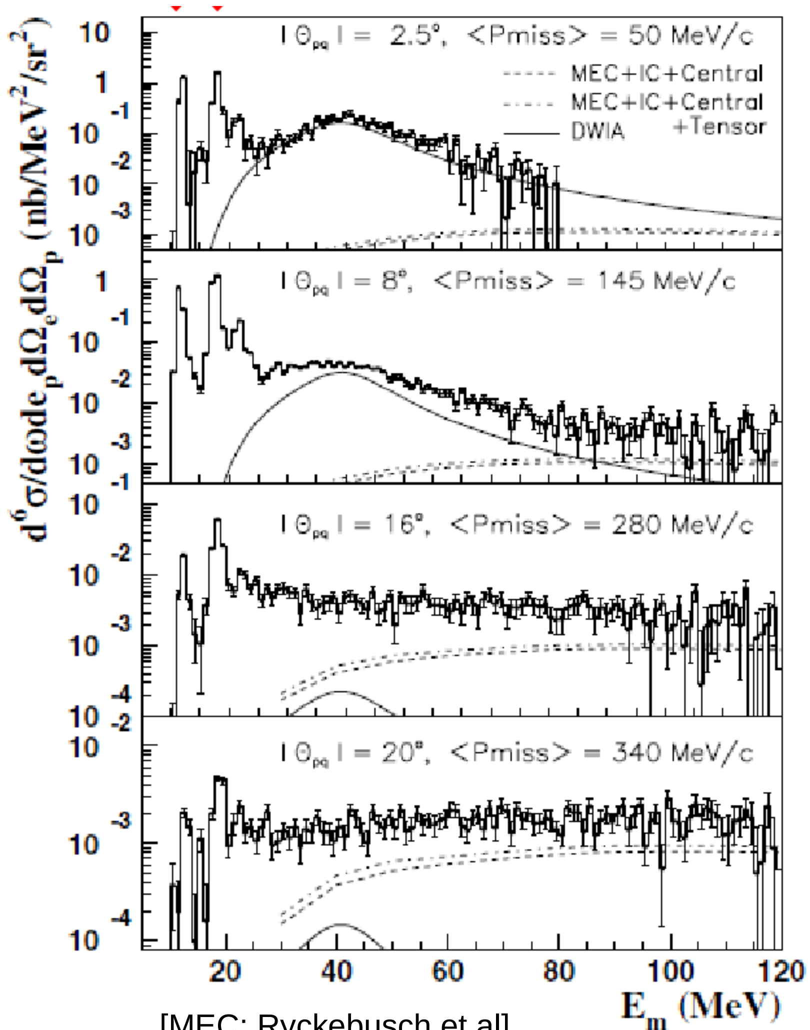


Experimental conditions are different!

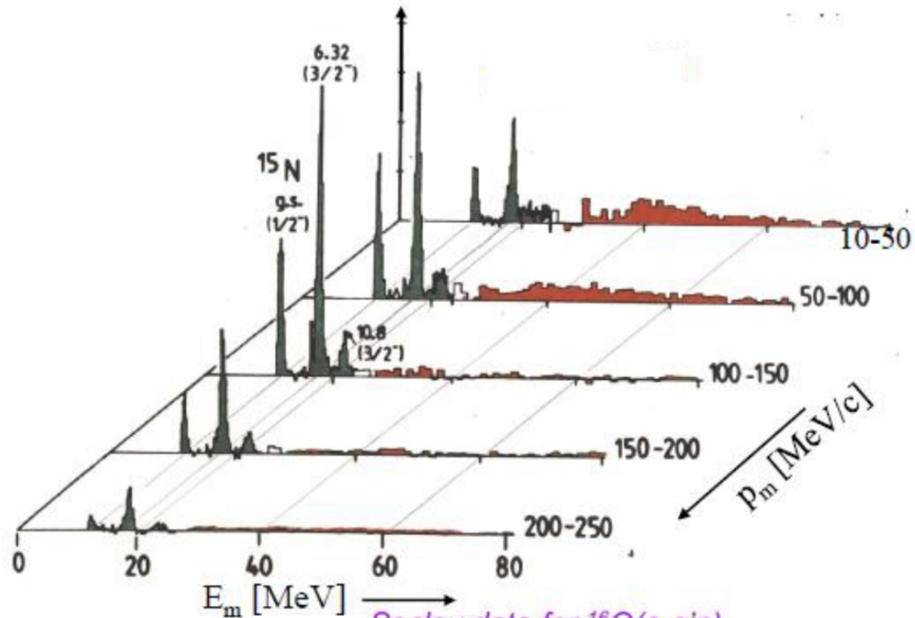
A(e,e’ p)X $\longrightarrow$ (semi)-exclusive

A(ν,μ p)X $\longrightarrow$ (semi)-inclusive

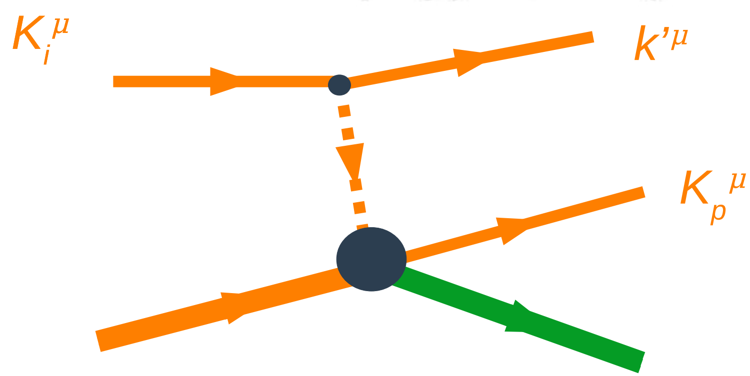
Exclusive electron scattering: Missing energy distributions



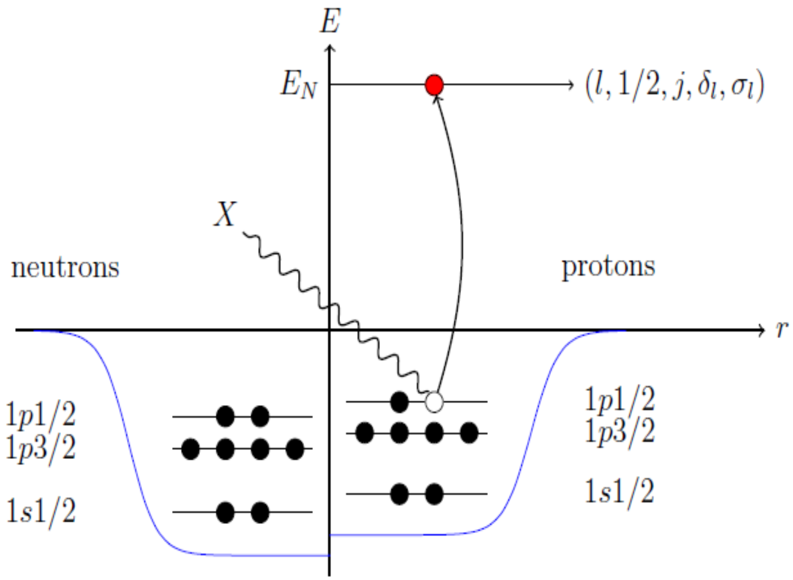
[MEC: Ryckebusch et al]



Saclay data for $^{16}O(e,e'p)$
[Mougey et al., Nucl. Phys. A335, 35 (1980)]

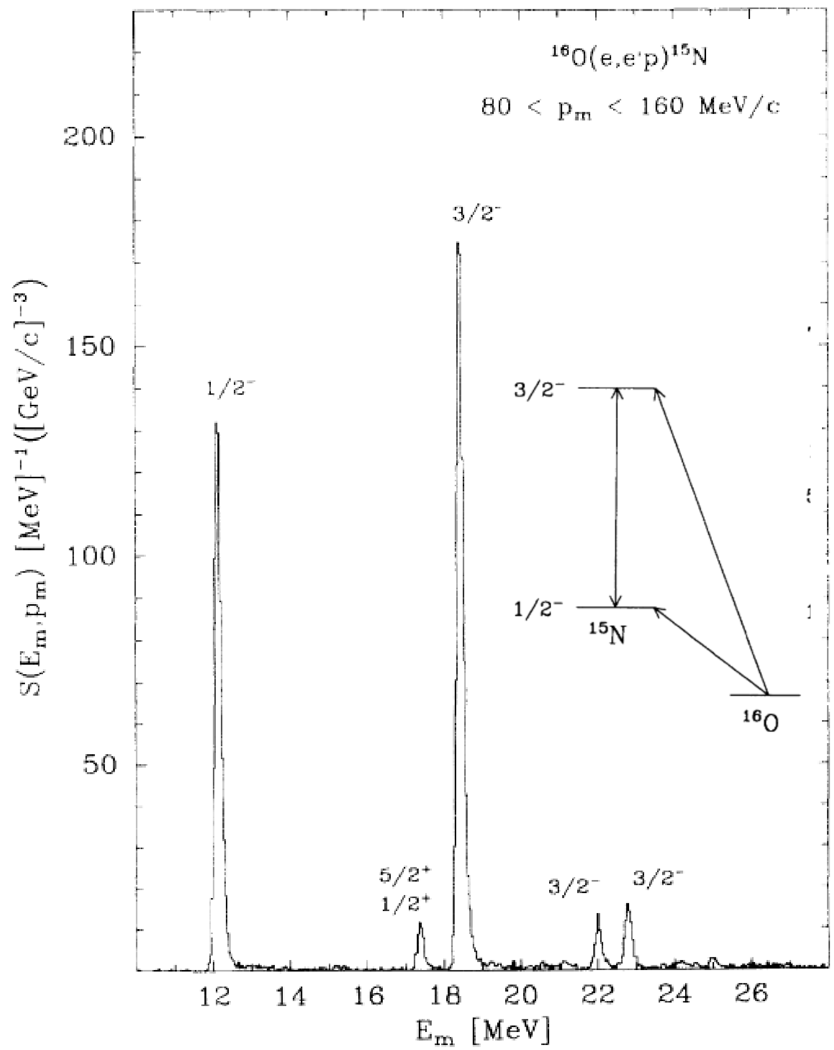


Exclusive electron scattering



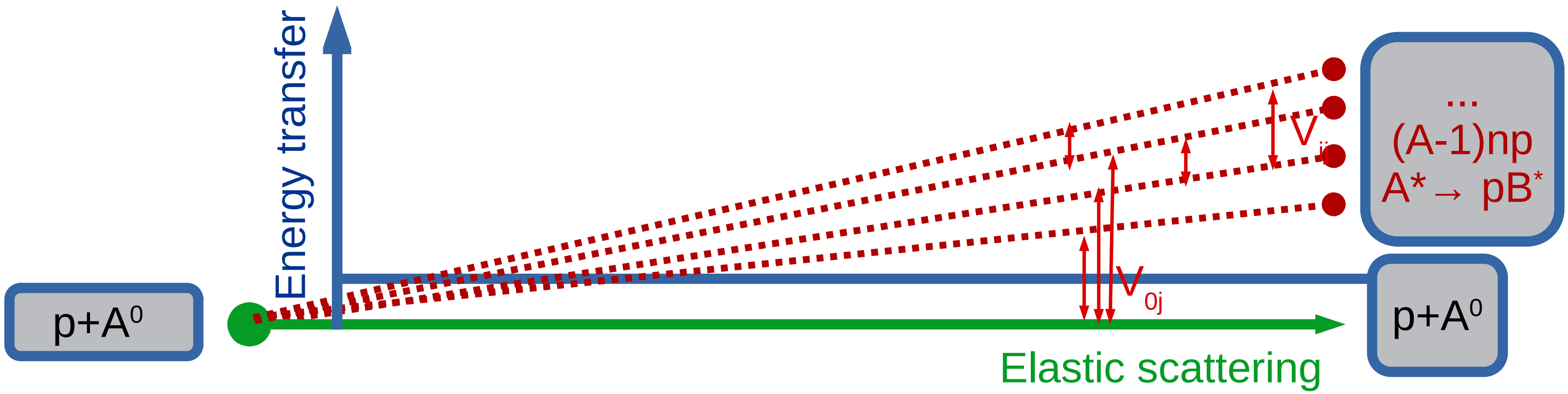
$$\mathcal{M} = j_{lep,\mu} \langle \Psi_f | \mathcal{O}^\mu | \Psi_i \rangle$$

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



Direct 1-proton knockout from a nuclear shell

Optical potential approach



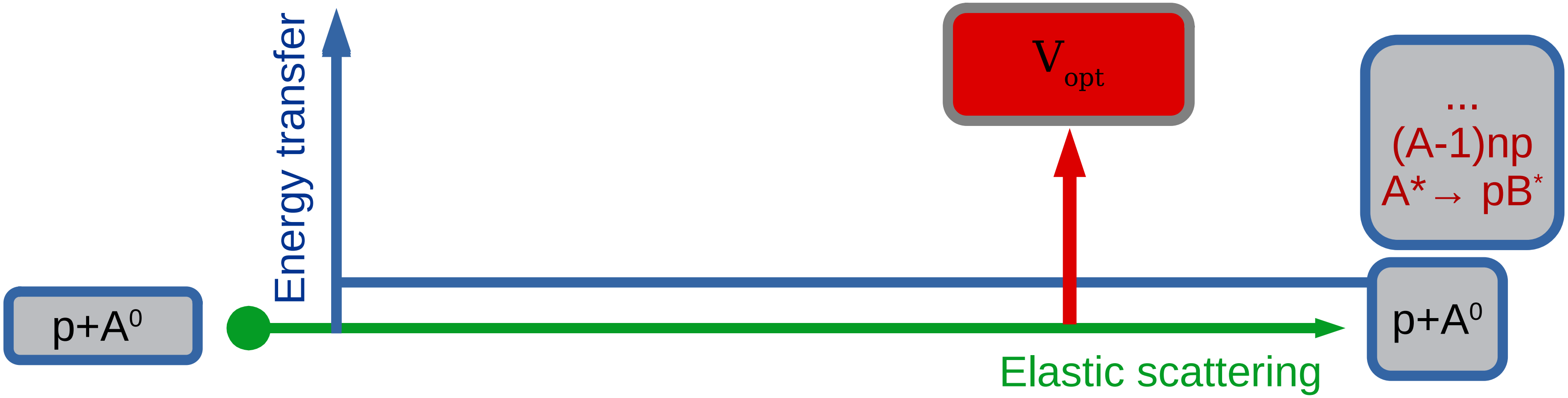
$$(H_{00} - E)|\phi_0\rangle = -V_{0j}|\phi_j\rangle \ (j > 0)$$

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

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

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

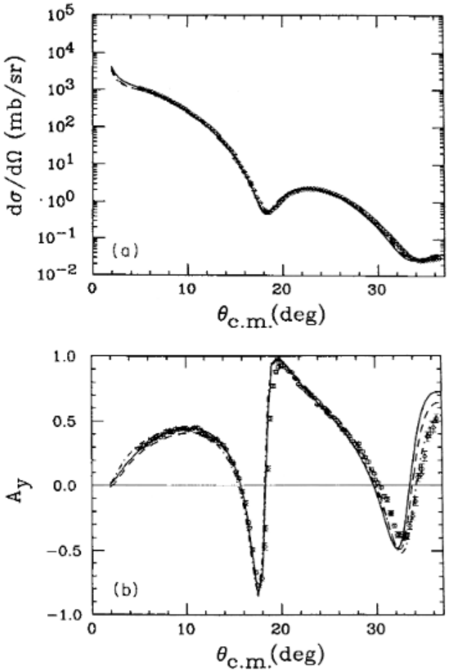
PHYSICAL REVIEW C VOLUME 47, NUMBER 1 JANUARY 1993

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

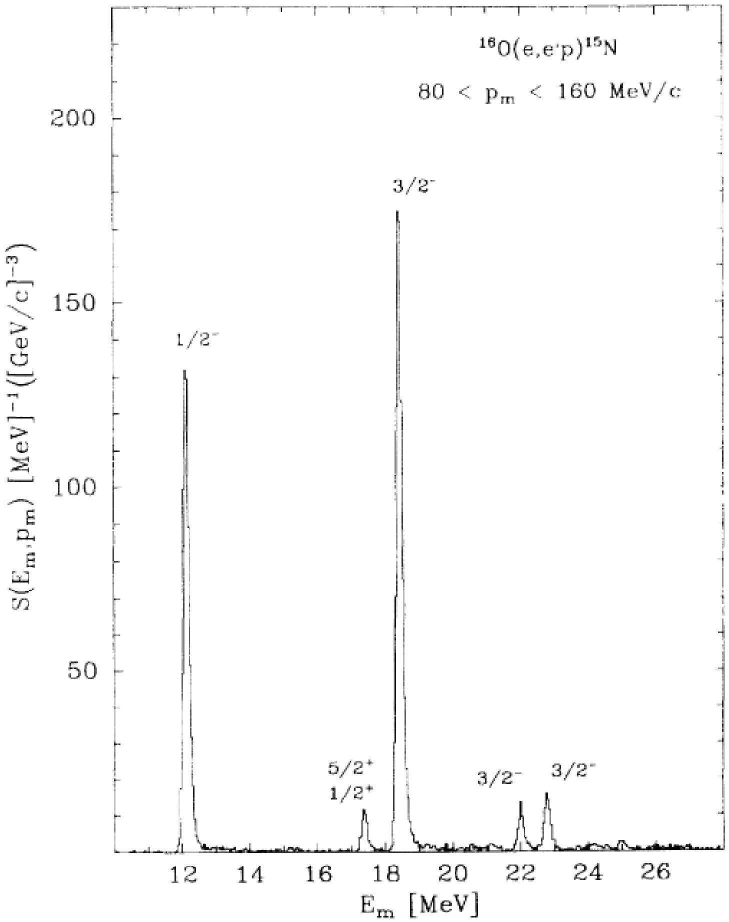
R. L. Mercer
IBM Thomas J. Watson Research Center, Yorktown Heights, New York 10598
(Received 31 August 1992)

		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]

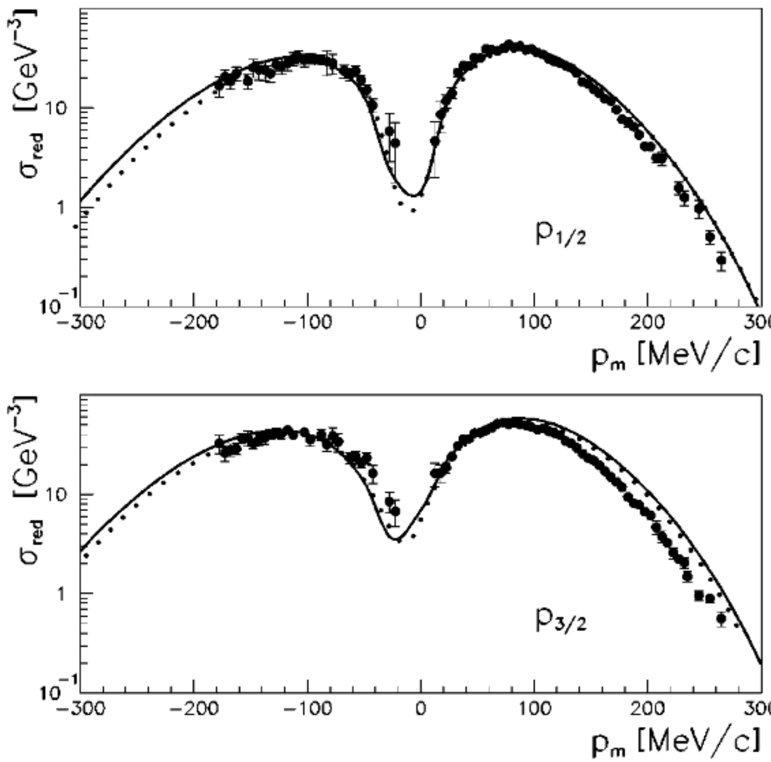


FIG. 11. The reduced cross section (σ_{red}) of the $^{16}O(e,e'p)$ reaction as a function of the recoil momentum p_m for the transitions to the $1/2^-$ ground state and to the $3/2^-$ excited state of ^{15}N, in

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

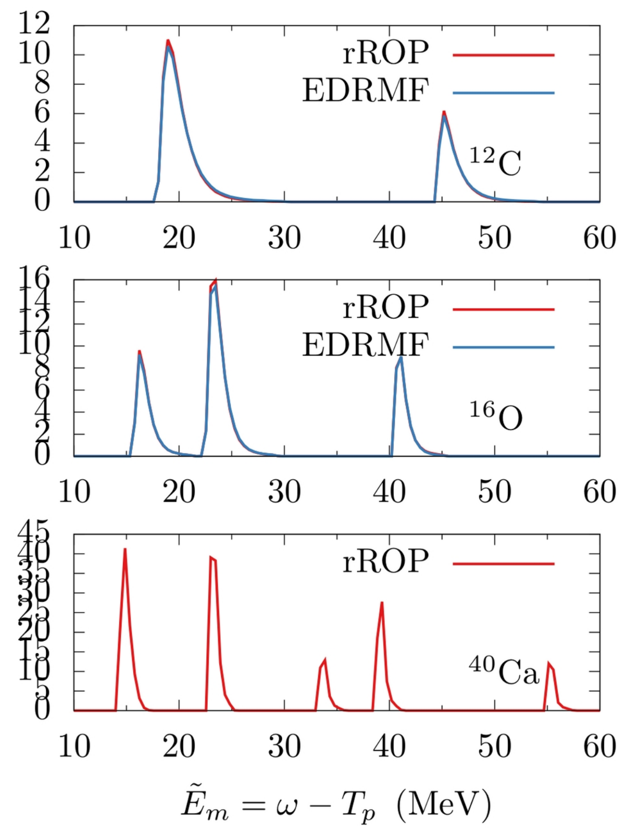
Events according to **unfactorized** five-fold differential nucleon knockout cross section

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



Where do the protons go ?: explicit modeling of 'rescattering'

Neutrino event generators use intra-nuclear cascade models (INCs)

- Hadrons move in the nucleus on classical trajectories
- Density and in-medium cross section determine mean-free-path
- Interaction produces secondary hadrons that are propagated through
- Stochastically determines final-state content

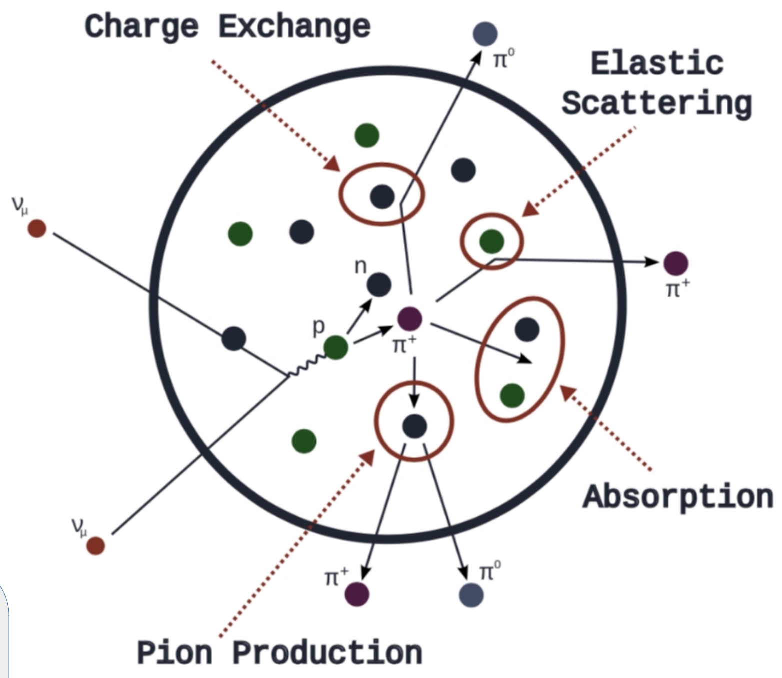


Fig: T. Golan

Black box

$$\mathrm{INC}(\alpha_i) = P(\beta_f \mid \alpha_i)$$

Produce a distribution of configurations β_f

From some input state α_i

Thinking about INCs: knockout cross sections

Production $Q + A \to p + X$ of a state $|pX\rangle = |p\rangle$ (exclusive)

$$|\langle\Psi_i|J^\mu|p\rangle|^2 = |\sum_\alpha \langle\Psi_i|J^\mu|\psi_\alpha\rangle\langle\psi_\alpha|p\rangle|^2$$

$$\approx \sum_\alpha \langle\Psi_i|J^\mu|\psi_\alpha\rangle^2\langle\psi_\alpha|p\rangle^2$$

Classical approximation

Replace formal sum by energy-momentum conserving single-nucleon states

$$p_{as} = p_Q + p_A - p_X$$

$$\sum_p \langle\Psi_i|J^\mu|\psi_p(p_{as})\rangle^2\langle\psi_p(p_{as})|p\rangle^2$$

And approximate by cascade:

$$\sum_p \langle\Psi_i|J^\mu|\psi_p(p_{as})\rangle^2 P(\vec{p}|\vec{p}_{as})$$

Thinking about INCs: knockout cross sections

$$\sum_p \langle \Psi_i | J^\mu | \psi_p(p_{as}) \rangle^2 P(\vec{p} | \vec{p}_{as})$$

Inclusive cross section

INC

- Classical approximation
- Truncation of sum
- Loss of full info (J,s,r,p_X,…)
- ...

This is generally how the INC is used in neutrino event generators

But…

Not all approaches deal with states that have a suitable p_{as}

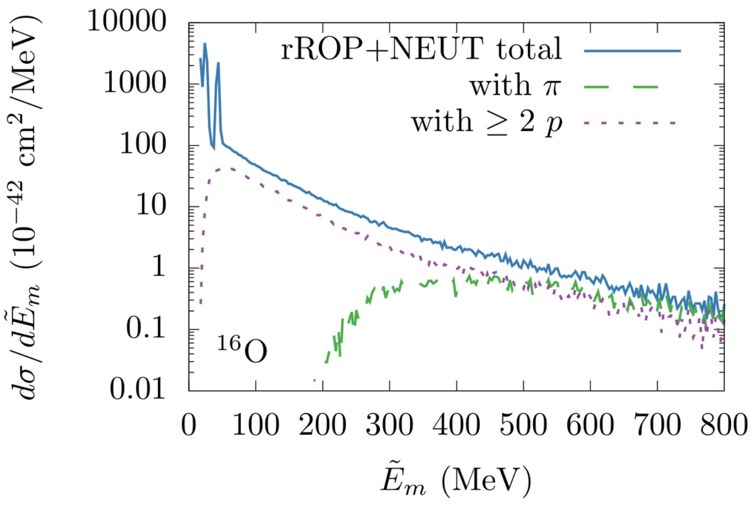
Many approaches don't provide nucleon information at all

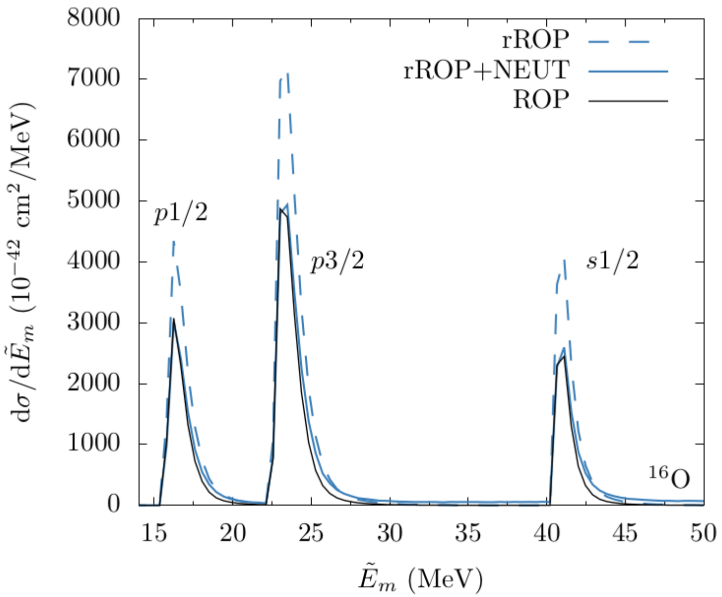
→ The generator has to 'make them up'

The asymptotic momentum might not capture the optimal degrees-of-freedom:

E.g. At low energy transfer: excitation energy and spin-parity are better

Cascade model with rROP inputs



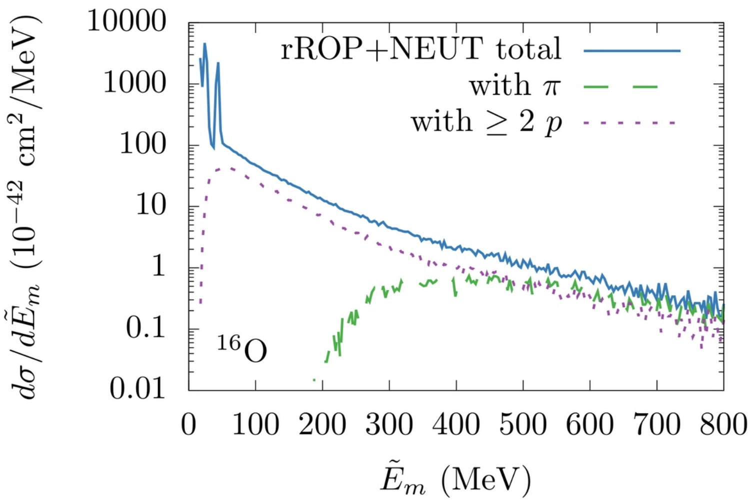


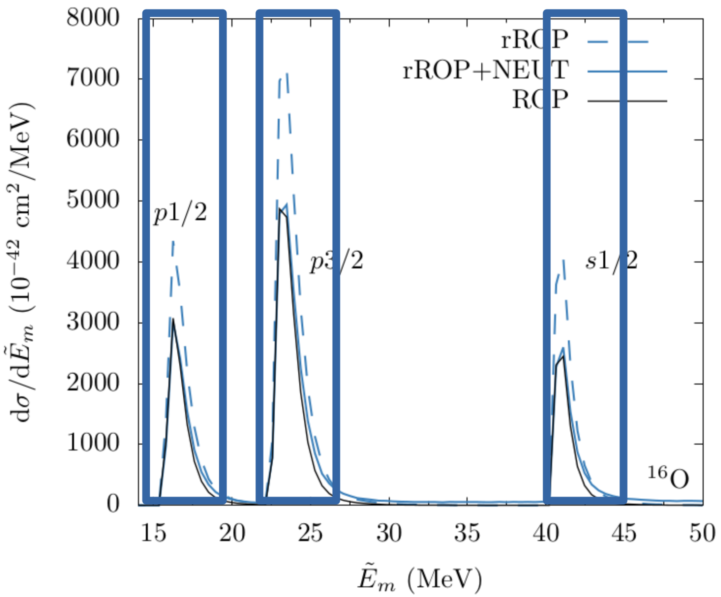
$$\tilde{E}_m = E_i - E_l - T_p$$

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 after INC agrees with ROP predictions
- A ‘consistent’ picture emerges between inclusive and exclusive results

Cascade model with rROP inputs



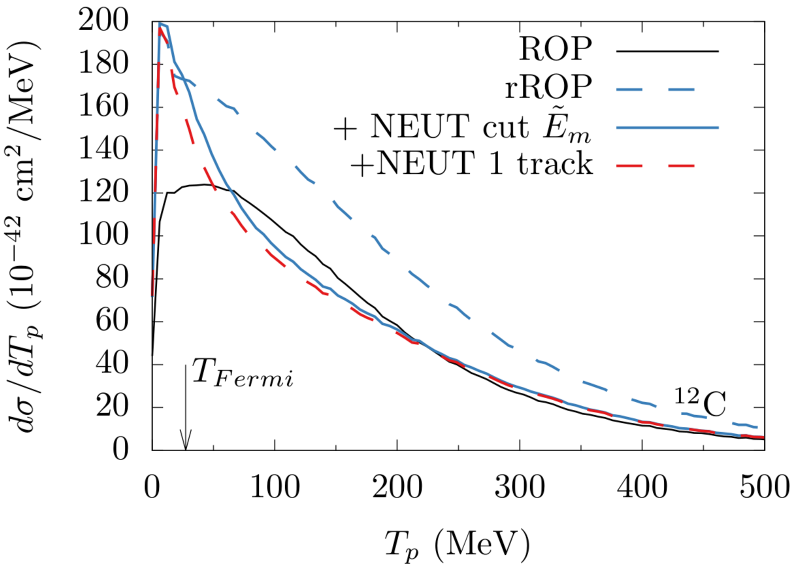


$$\tilde{E}_m = E_i - E_l - T_p$$

T2K flux-folded calculations

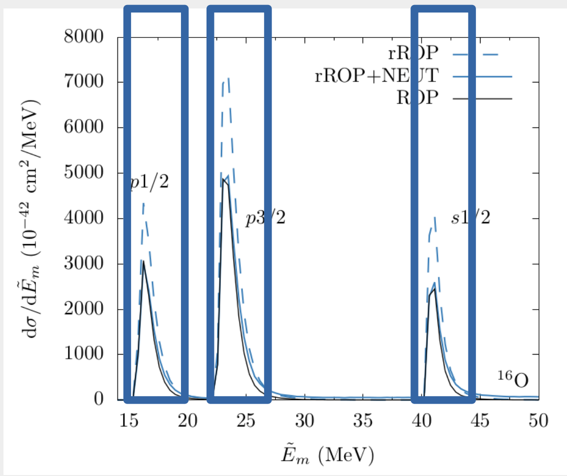
- Cascade moves strength from shell model peaks to larger E_m
  => Rescattering into different final states
- Strength of shell model peaks agrees with ROP predictions
- Make kinematic cuts like in (e,e'p)
  => Remove the rescattering
  => exclusive conditions

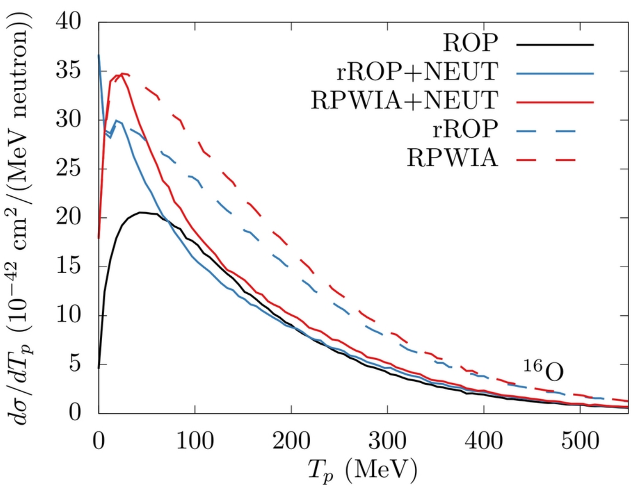
Cascade model with rROP inputs

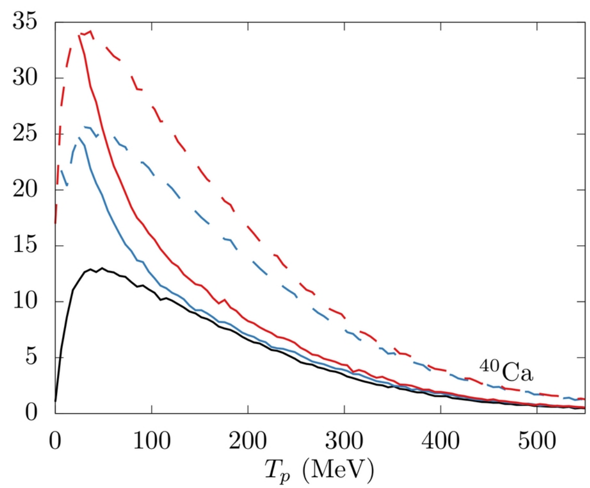


T2K flux-folded calculations

With missing energy cuts





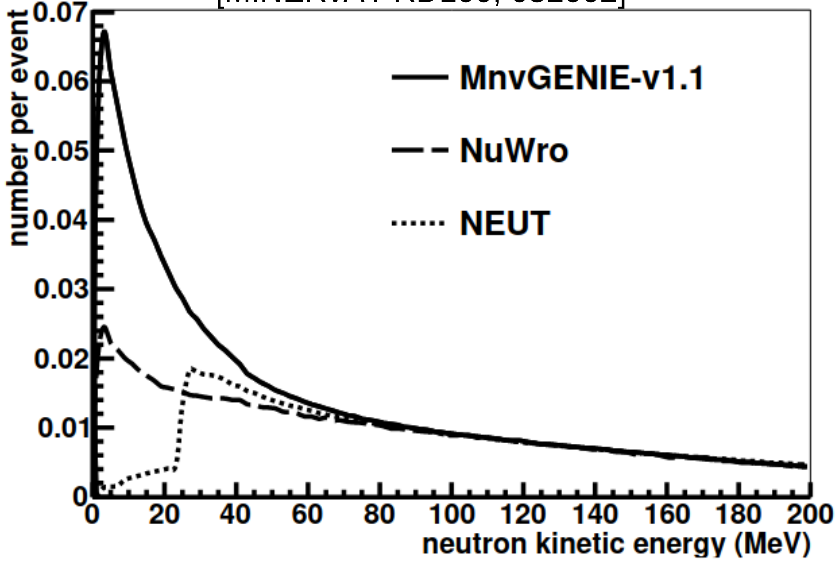


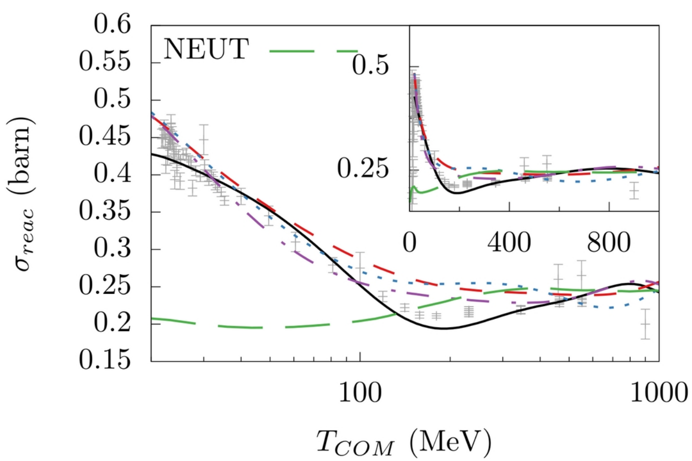
The INC = ROP for high T_p

For T_p < 100
differences of up to 100% !

Discrepancies at low-T_N

[MINERvA PRD100, 052002]





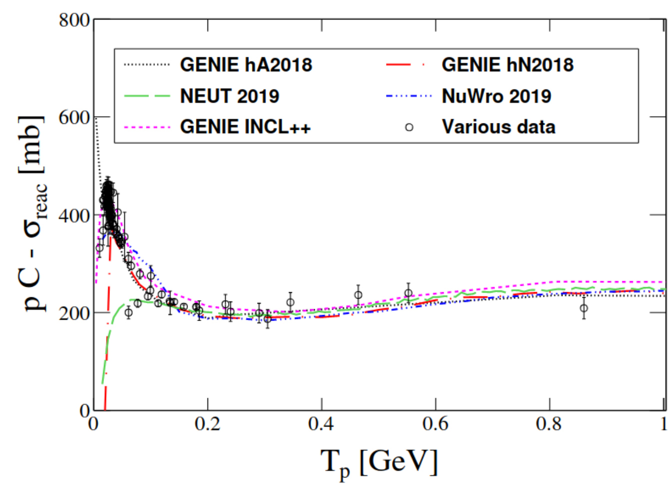
T2K flux-folded calculations

The INC = ROP for high T_p

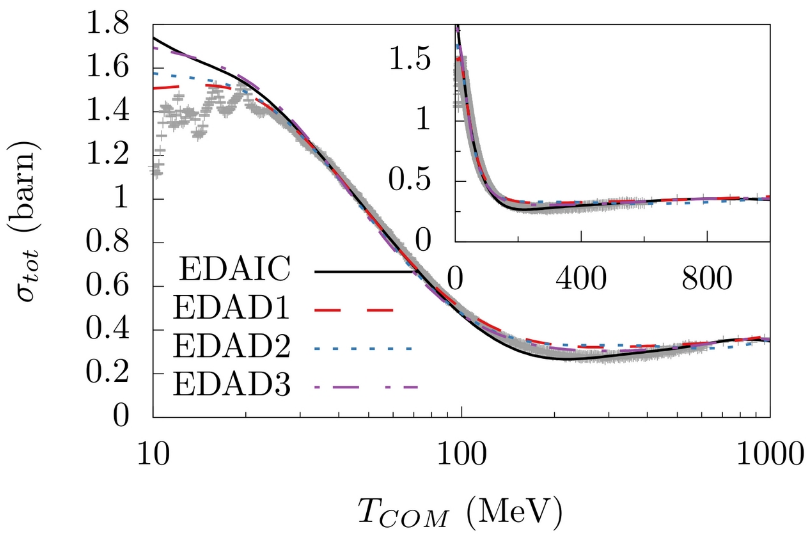
For $T_p < 100$
differences of up to 100% !

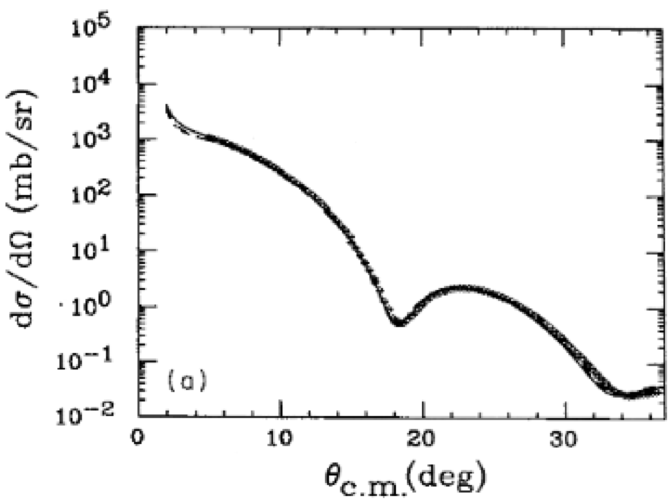
Constraints for cascades:
Reaction cross section

[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

Thinking about INCs

$\mathrm{INC}(\alpha_i) = P(\beta_f \mid \alpha_i)$: Inputs α_i: **p, r** of a set of hadrons

In ν-interactions kinematics are given by a nuclear model
e.g. plane-wave impulse approximation
Local Fermi gas

What if there is no suitable **p** available ?

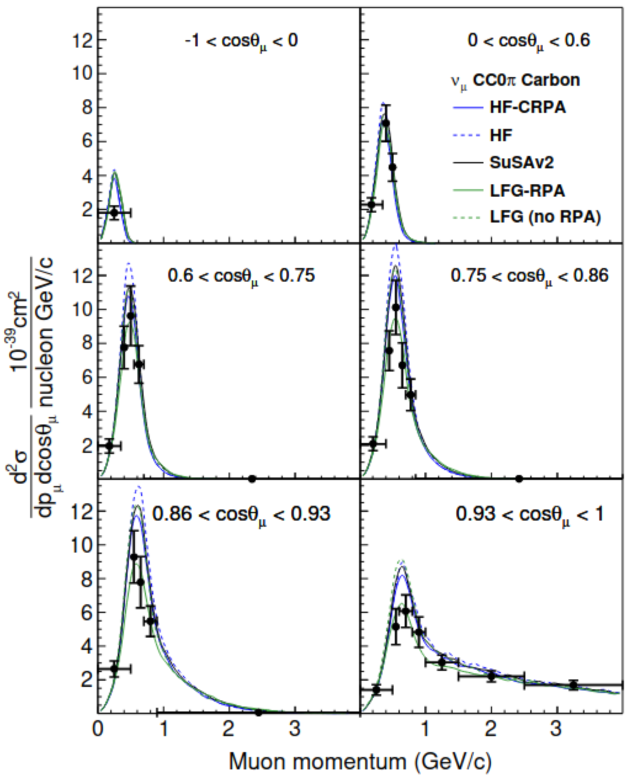
Article

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

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]

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

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

- Full consistent description of exclusive kinematics 1e1p

Article

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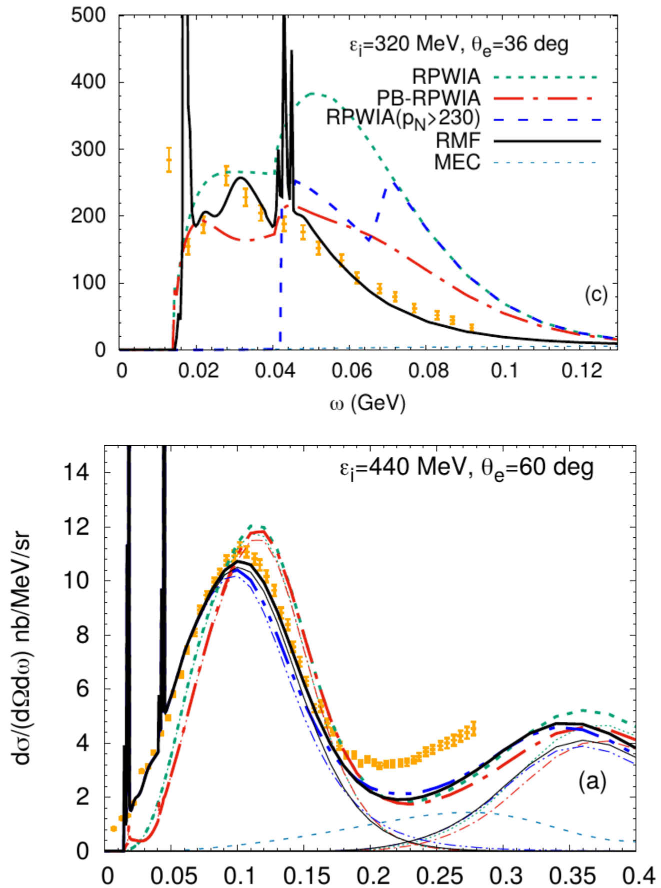

[Phys. Rev. C 100, 045501 (2019)]

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 of the kinematics 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

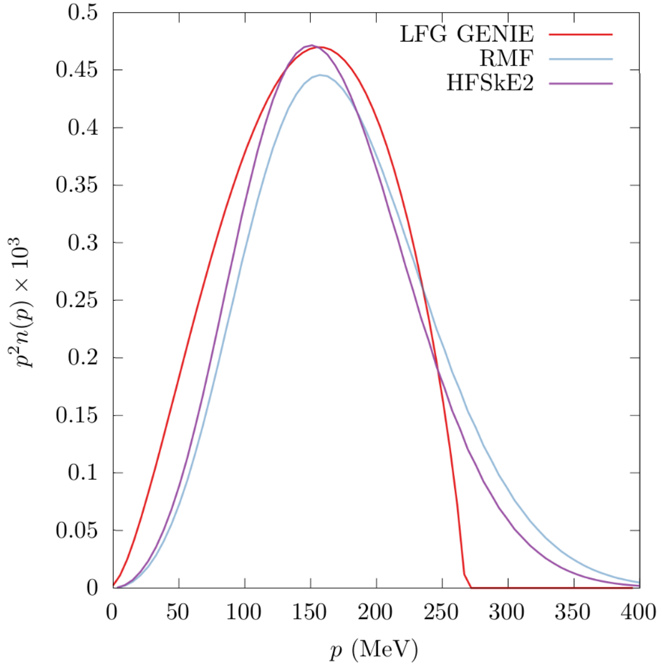
$$\frac{\mathrm{d}\sigma(E_\nu)}{\mathrm{d}E_l \mathrm{d}\cos\theta_l} = G^2 \frac{k_l}{E_\nu} L_{\mu\nu} \int \mathrm{d}\Omega_N \sum_{n,\kappa} H^{\mu\nu}_{n,\kappa}(\omega, q, \Omega_N, E_{n,\kappa})$$

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

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

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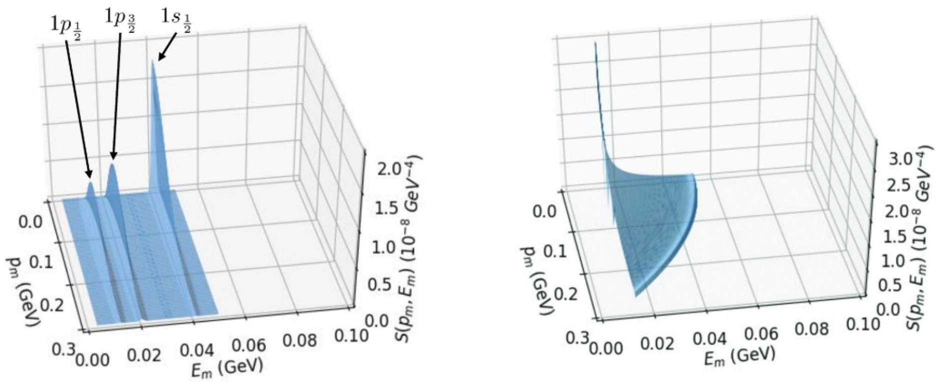
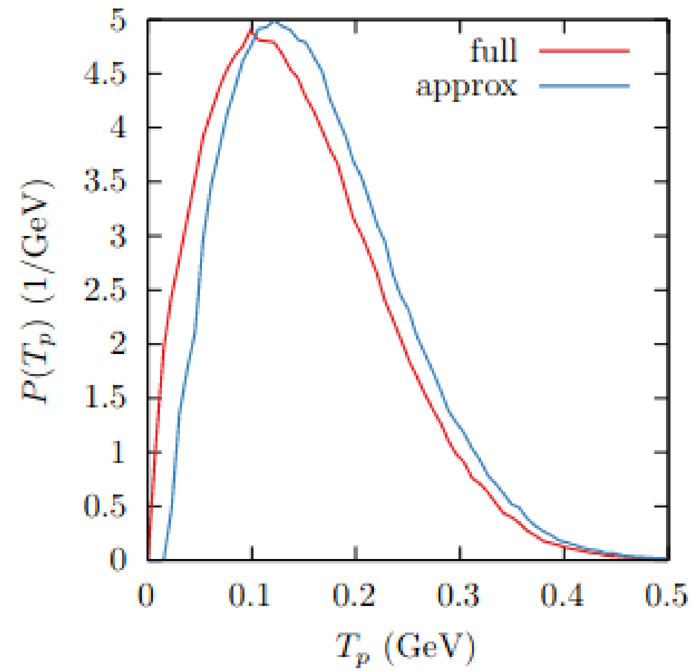
!! 2. Compute $E_m^2 = p_m^2 + M_N^2$

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)

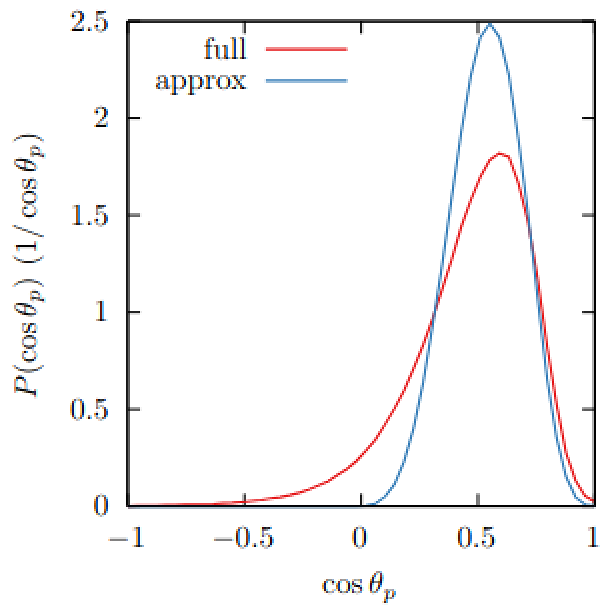
!! 2. Compute $E_m^2 = p_m^2 + M_N^2$

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

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

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

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

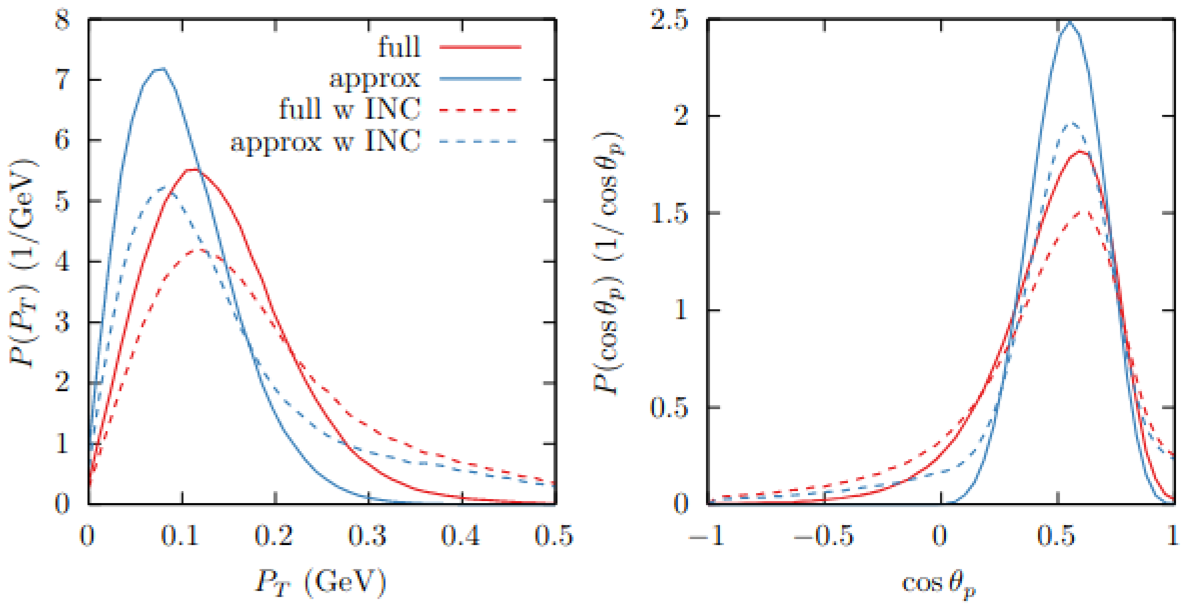


Serious differences in angular distributions!

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!

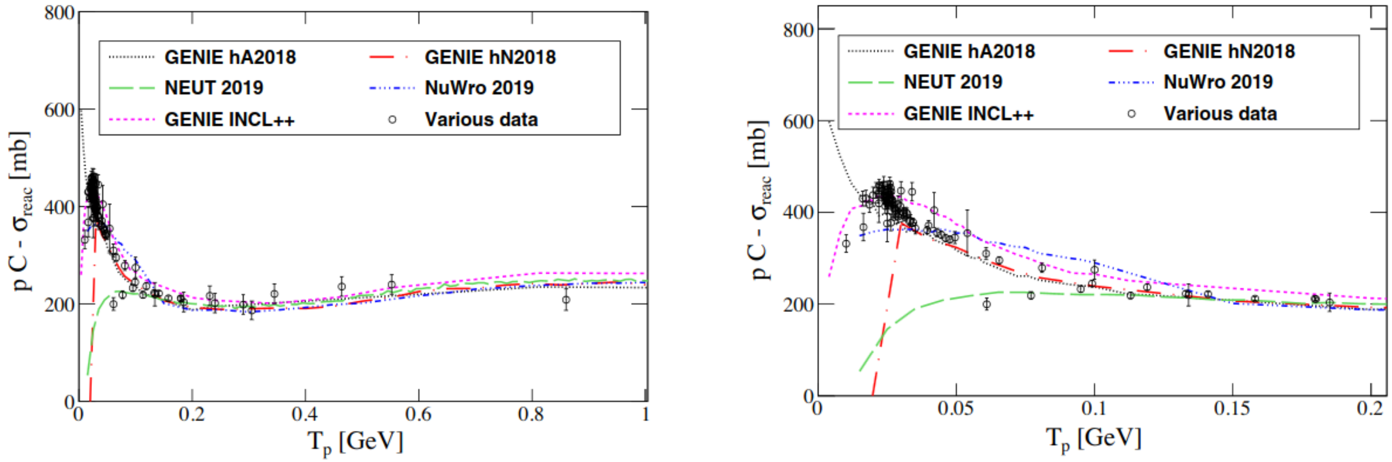
Shape differences biggest in P_T and angular distributions

Fermilab

Thinking about INCs

$\mathrm{INC}(\alpha_i) = P(\beta_f \mid \alpha_i)$: Inputs α_i: **p, r** of a set of hadrons

S. DYTMAN *et al.* PHYS. REV. D **104**, 053006 (2021)



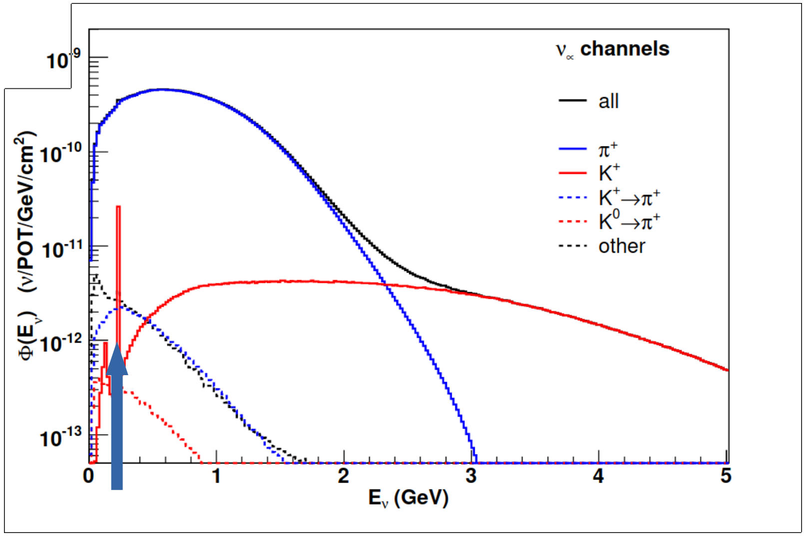
Works well even at low-T_p !

But **should it ?** Could more variables be used as input to the INC ?

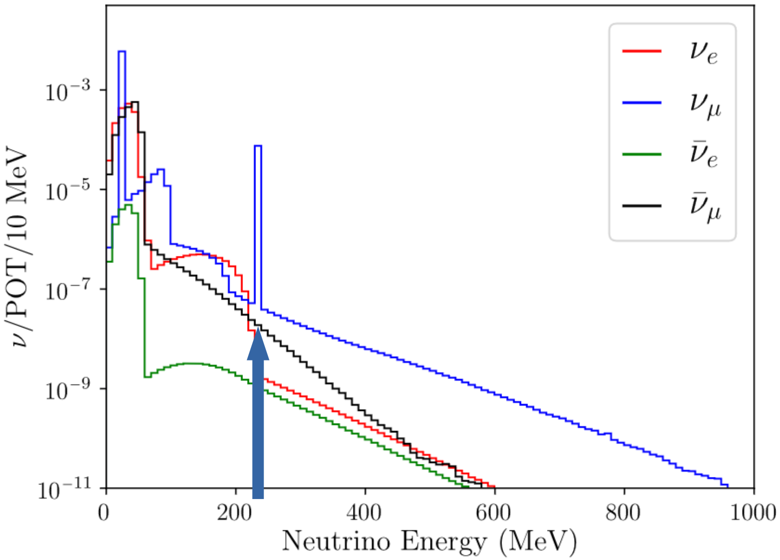
At low excitation energy outgoing nucleon kinematics are almost meaningless

Muon neutrinos from stopped Kaon's in the absorber

MiniBooNE



JSNS²

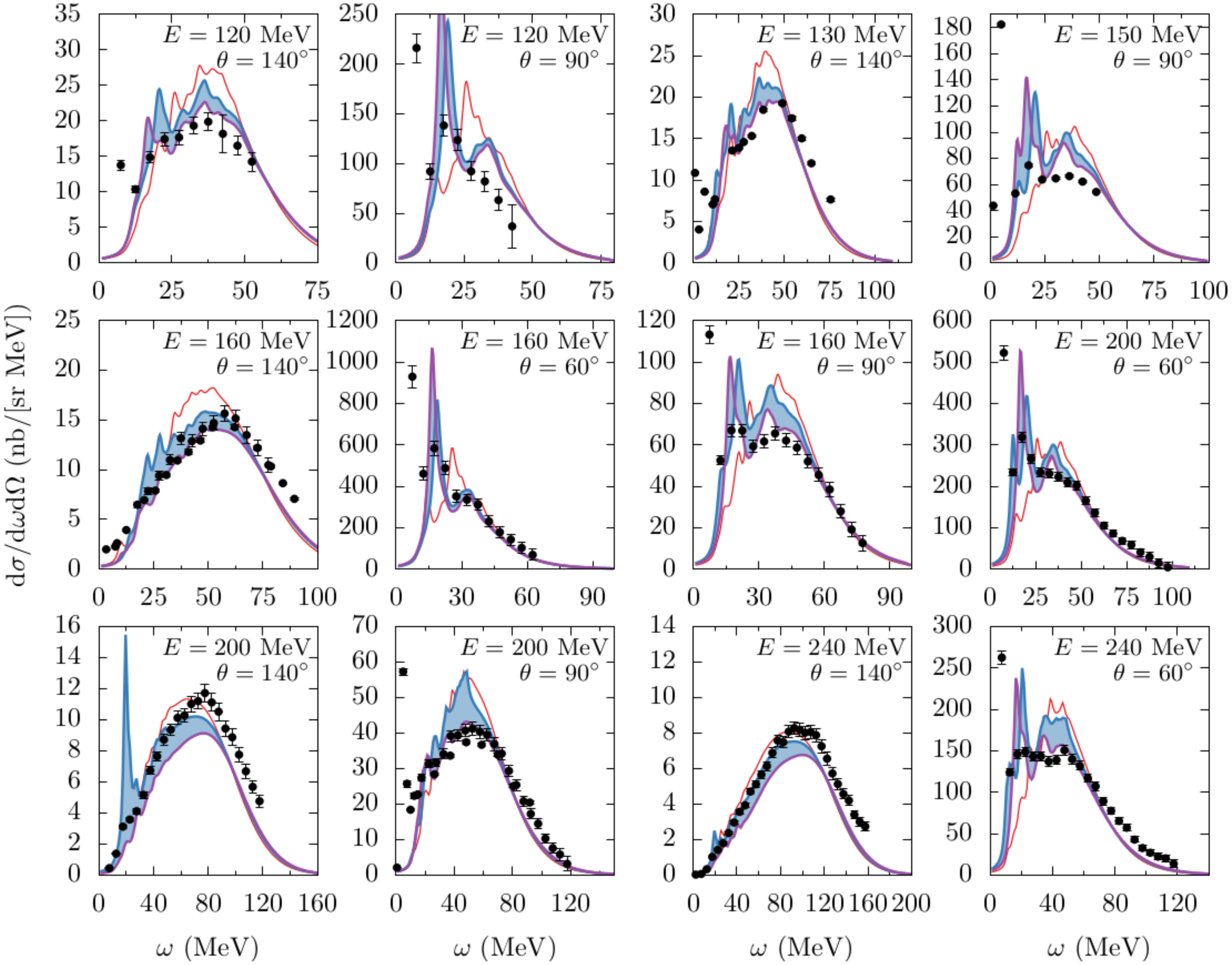


KDAR produces ν_μ with E_ν = 236 MeV

Can be a challenge for FSI modeling

Electron scattering in KDAR phase-space: ^{40}Ca

(See N. Jachowicz Talk on Monday)



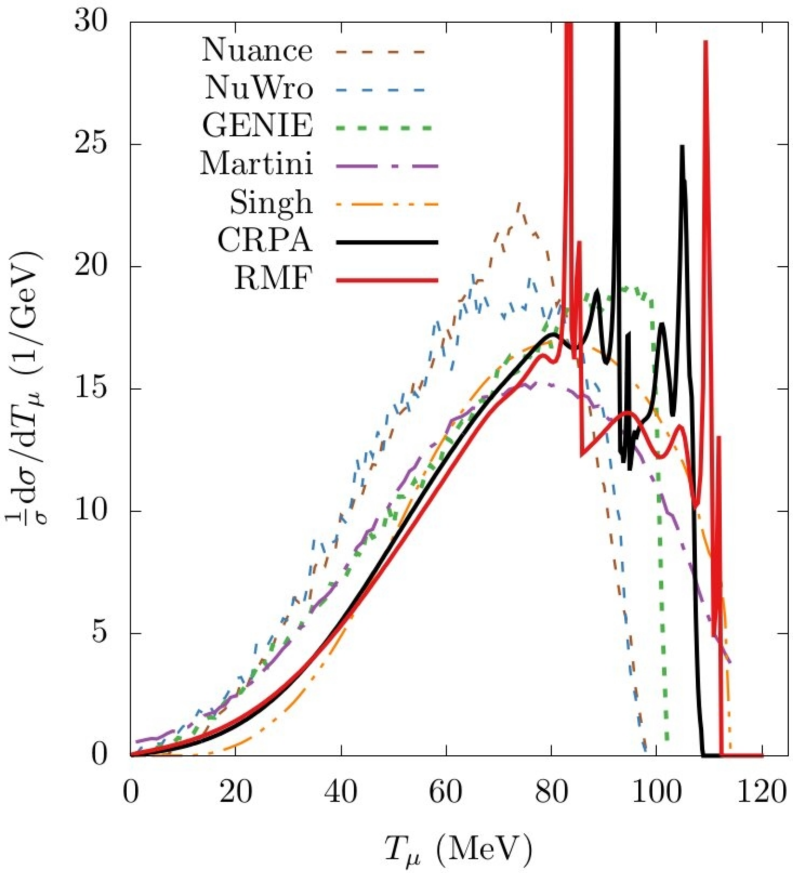
Sk-HF
CRPA w cut-off
CRPA

Clear contribution from Collective d.o.f

→ transition region between 'quasielastic' and collective d.o.f

Fermilab

MiniBooNE comparison: Model comparisons & Total cross sections



Shape-only comparisons of different models

Model	$\Delta\chi^2$	χ^2 Prob.	σ (10^{-39}cm^2)
Nuance	2.64	0.45	1.4
NuWro	2.07	0.56	1.3 + 0.4 (np-nh)
GENIE	0.95	0.81	1.75
Martini	2.15	0.54	1.3 + 0.2 (np-nh)
Singh	3.90	0.27	0.91
CRPA	3.20	0.36	1.58
RMF	3.49	0.27	1.56
RFG	1.69	0.64	1.66
RFG34	4.16	0.25	1.38
MB data	-	-	2.7 ± 1.2

Total cross sections

Most ~ 1.5 – 1.7 10^{-39} cm2/N

RFG34 & NUANCE ~ 1.4 10^{-39} cm2/N

Singh ~ 0.91 10^{-39} cm2/N

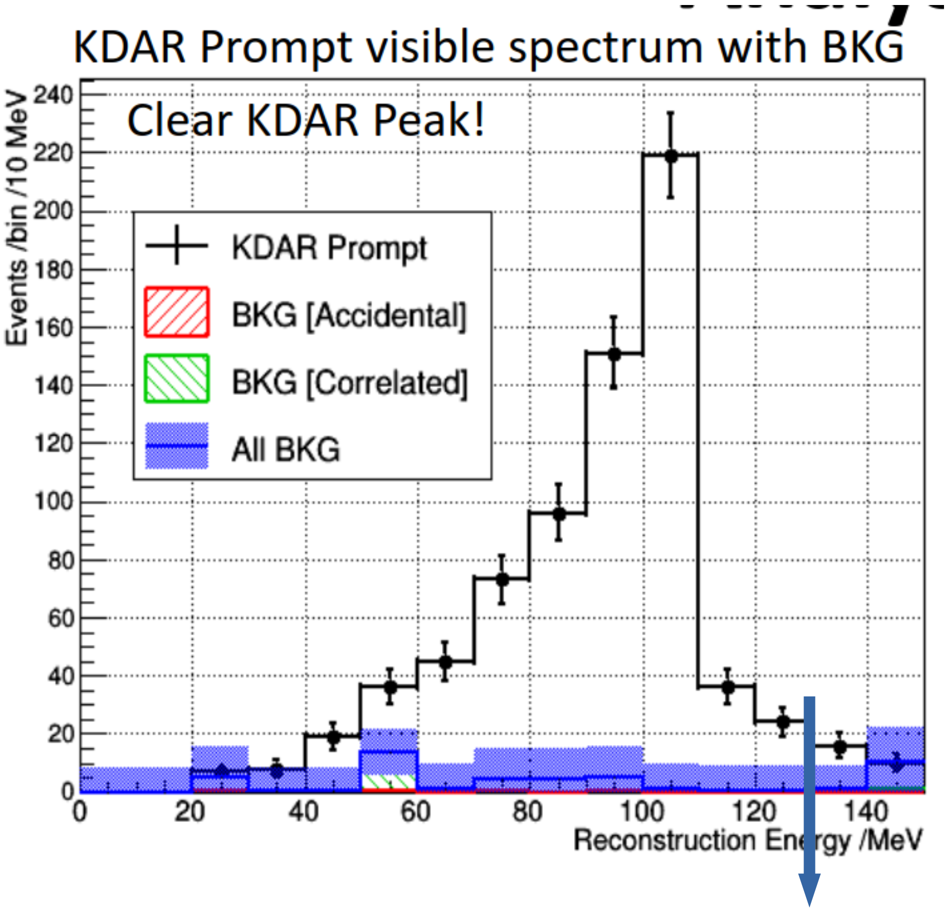
see also [Prog.Part.Nucl.Phys. 129 (2023) 104019]

JSNS^2 measurement
(from Hyoungku Jeon talk NuFACT22)

Measure the total visible energy:

$E_{vis} = E_\nu - m_\mu - T_X$

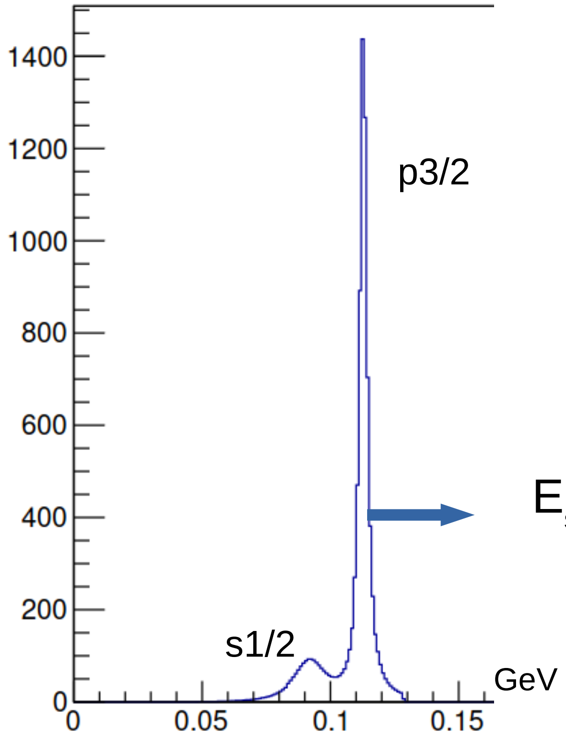
Sensitive to specific decay channel of nucleus



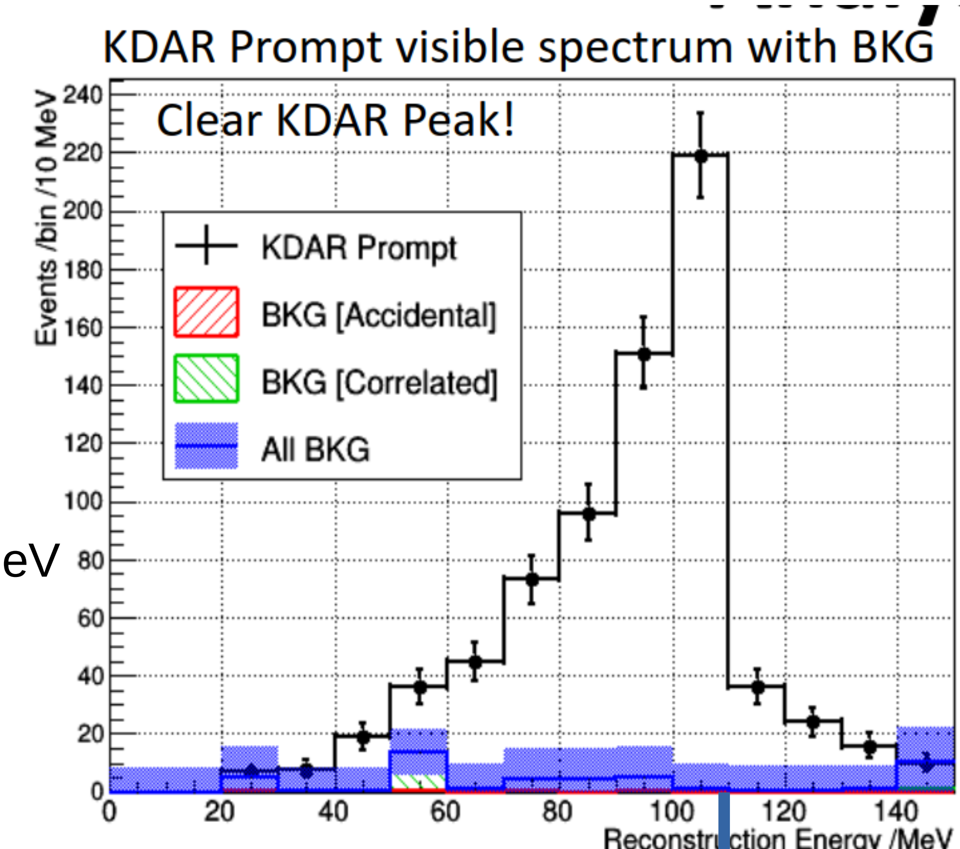
$E_{vis}^{max} = E_\nu - m_\mu$

JSNS^2 measurement

Missing energy spectrum (ν,μ p)



$E_s \approx 16$ MeV



$E_\nu - m_\mu - E_s$

RMF calculation exclusive (no FSI)
w Benhar spectral function

Clear smearing of spectrum in data
Need good final-state approach

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

- Should be expected to break down at low excitation energies

- **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/...