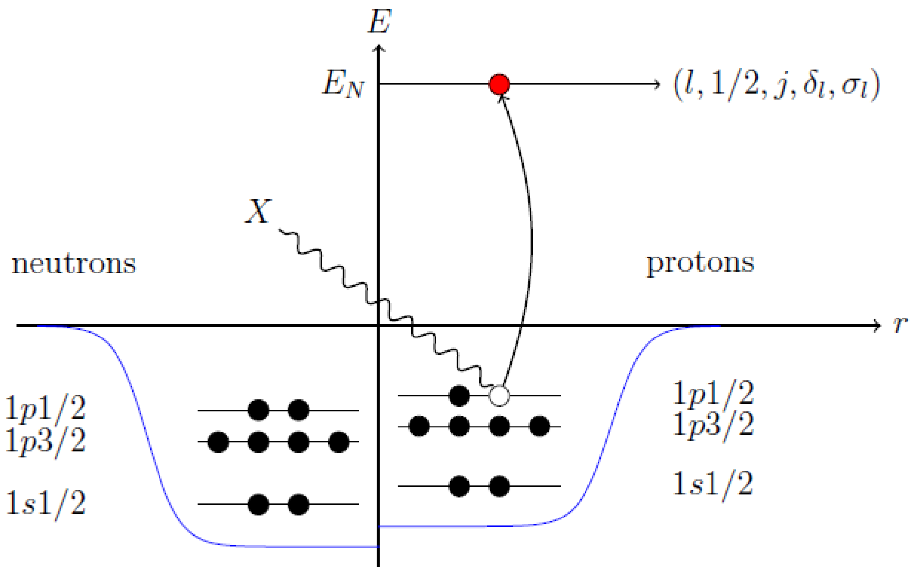
Final-State Interactions in inclusive and exclusive one-nucleon knockout

A. Nikolakopoulos (Fermilab)

In collaboration with
R. Gonzalez-Jimenez, J. M. Udias (UC Madrid), N. Jachowicz, V. Pandey (U Gent),
K. Niewczas (U Wroclaw), S. Dolan (CERN), F. Sanchez (U Geneva)

Self-consistent mean field



Mean field nucleus

- Mean field potential
- Single-particle wavefunctions
- Binding energies
- Orthogonal states (→ Pauli-blocking)

RMF

- Non-linear extended sigma-omega model

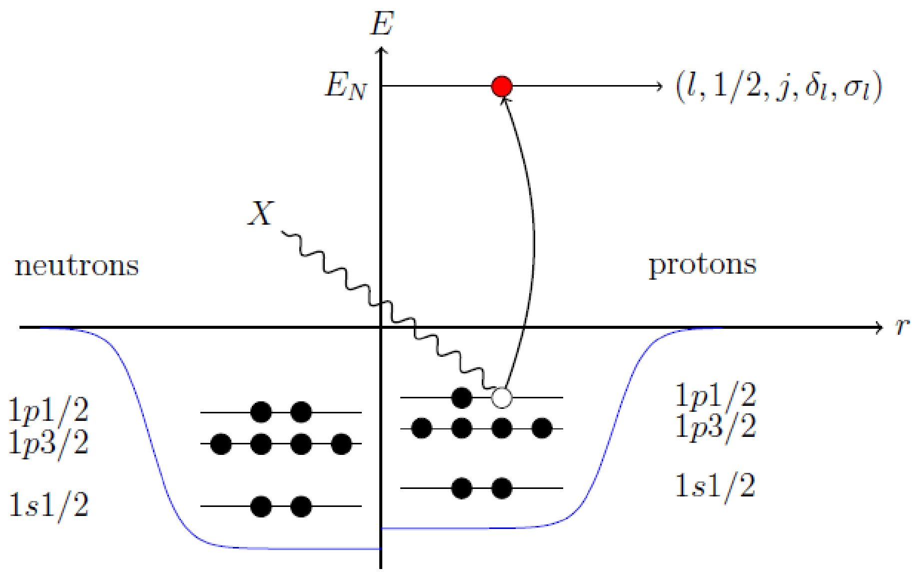
Extension of the original σ-ω Walecka model (Ann. Phys.83,491 (1974)).

HF-SkE2

- Hartree-Fock with extended Skyrme force

M. Waroquier et al. / Effective Skyrme-type interaction (I)
Nuclear Physics **A404** (1983) 269–297

Self-consistent mean field



Mean field nucleus

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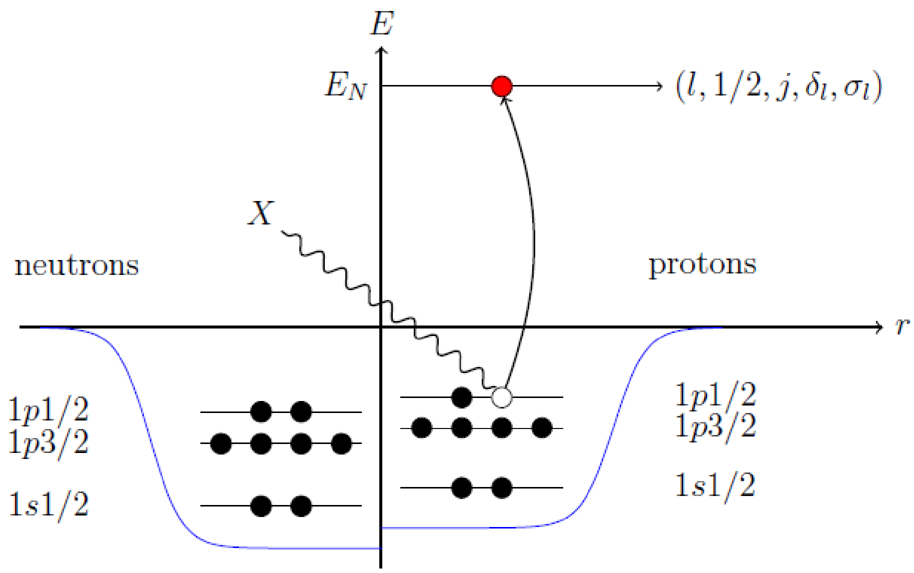
- Binding energies
- Orthogonal states (→ Pauli-blocking)

Effective interactions constrained by properties of nuclei and nuclear matter

	t_4 (MeV · fm^8)	K (MeV)	$(E/A)_{\text{n.m.}}$ (MeV)	k_F (fm^{-1})	m^*/m	a_τ (MeV)
SkE2	−15808.79	200	−16.0	1.33	0.72	29.7
SkE4	−12258.97	250	−16.0	1.31	0.75	30.0
SkIII	0.0	356	−15.87	1.29	0.76	28.2

	E/A	r_p	r_n	r_c	E/A	r_p	r_n	r_c
		^{16}O				^{40}Ca		
SkE2	−7.92	2.63	2.60	2.68	−8.56	3.37	3.31	3.42
SkE4	−7.96	2.65	2.62	2.70	−8.59	3.40	3.35	3.46
SkIII	−8.03	2.64	2.61	2.70	−8.57	3.41	3.36	3.46
exp	−7.98			2.71 [a])	−8.55		3.36 [e])	3.48 [b])
		^{90}Zr				^{132}Sn		
SkE2	−8.67	4.17	4.24	4.21	−8.36	4.62	4.84	4.66
SkE4	−8.71	4.22	4.29	4.26	−8.36	4.68	4.89	4.71
SkIII	−8.69	4.26	4.31	4.30	−8.36	4.73	4.90	4.78
exp	−8.71			4.27 [c])	−8.36			

Self-consistent mean field



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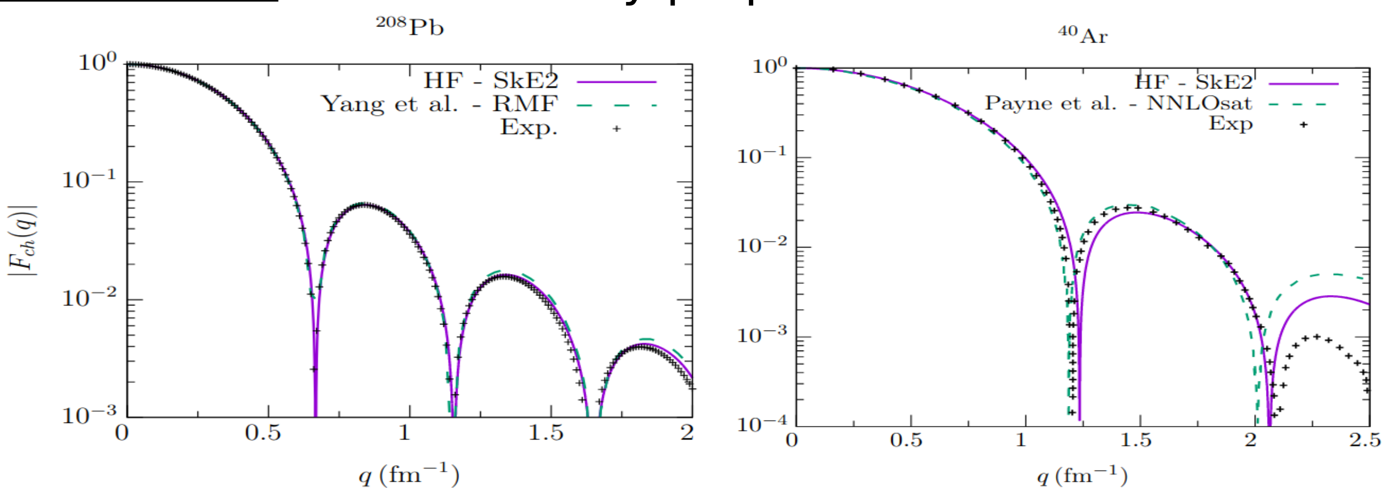
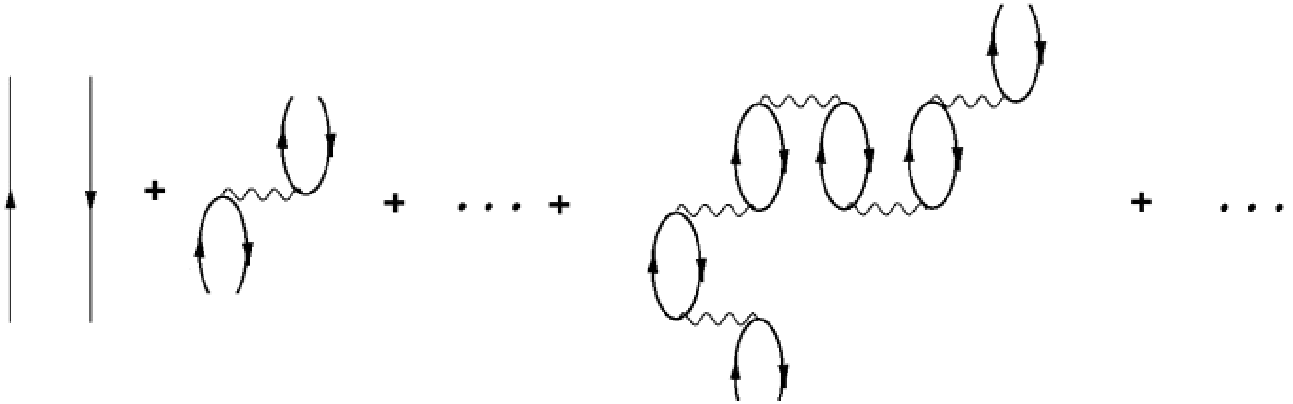


Charge (and weak) form factors in [N. Van Dessel et al. Arxiv:2007.03658]

HF-Skyrme mean field + Continuum RPA



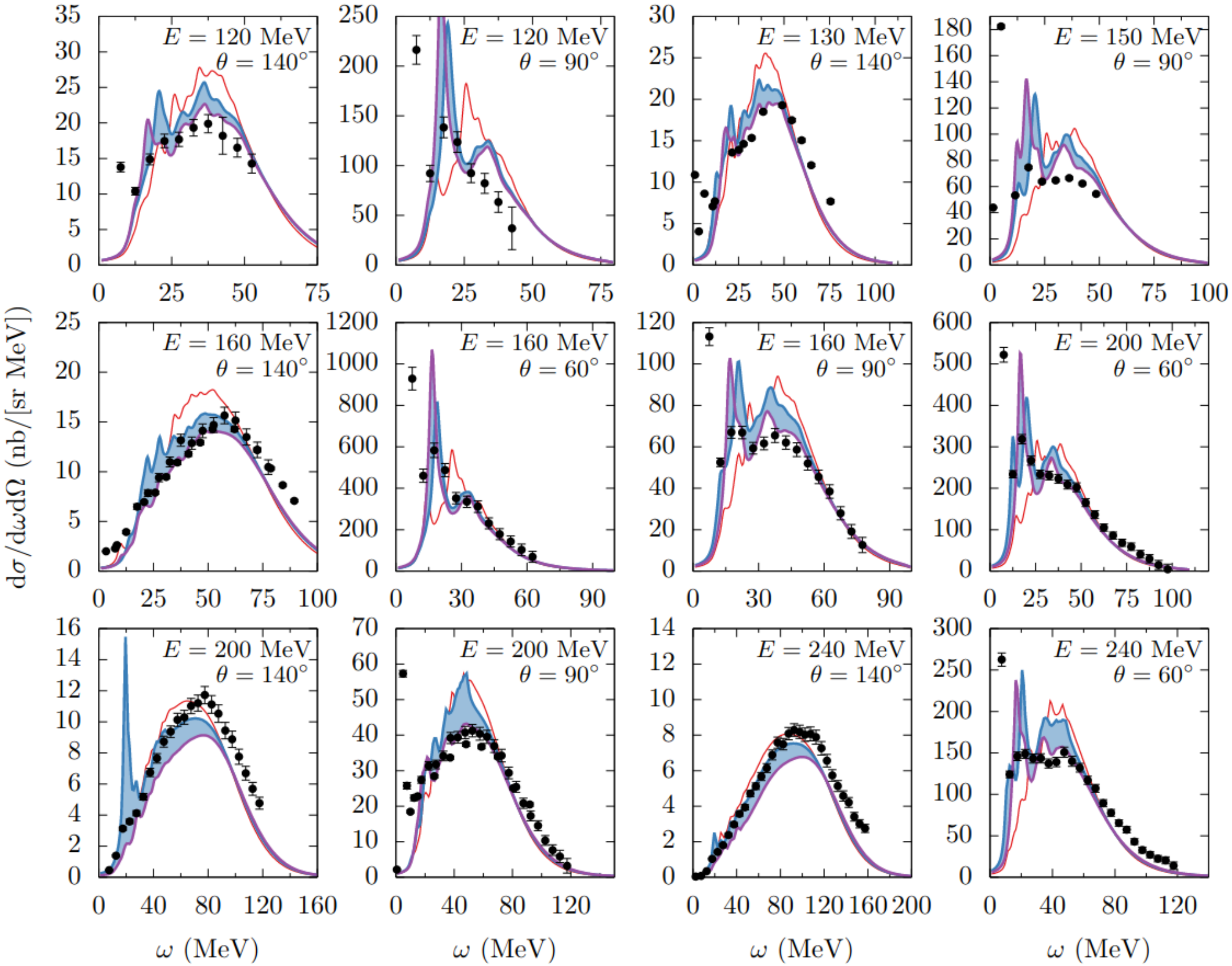
$$\Pi^{(RPA)}(x_1, x_2; \omega) = \Pi^{(0)}(x_1, x_2; \omega) + \frac{1}{\hbar} \int dx \int dx' \; \Pi^{(0)}(x_1, x; \omega) \, \widetilde{V}(x, x') \, \Pi^{(RPA)}(x', x_2; \omega)$$

Coordinate space formulation → No cut-off in momenta (full continuum)
Use the same Skyrme interaction for HF nucleus and in RPA

Takes into account collective d.o.f. : Giant Resonance region
: Quenching of QE peak at low Q^2

$$|\Psi_{RPA}\rangle = \sum_{c} \left\{ X_{(\Psi,C)} \left|ph^{-1}\right\rangle - Y_{(\Psi,C)} \left|hp^{-1}\right\rangle \right\}$$

Electron scattering ^{40}Ca



[A. Nikolakopoulos et al. PRC 103 (2021) 6, 064603]

(e,e') off Calcium

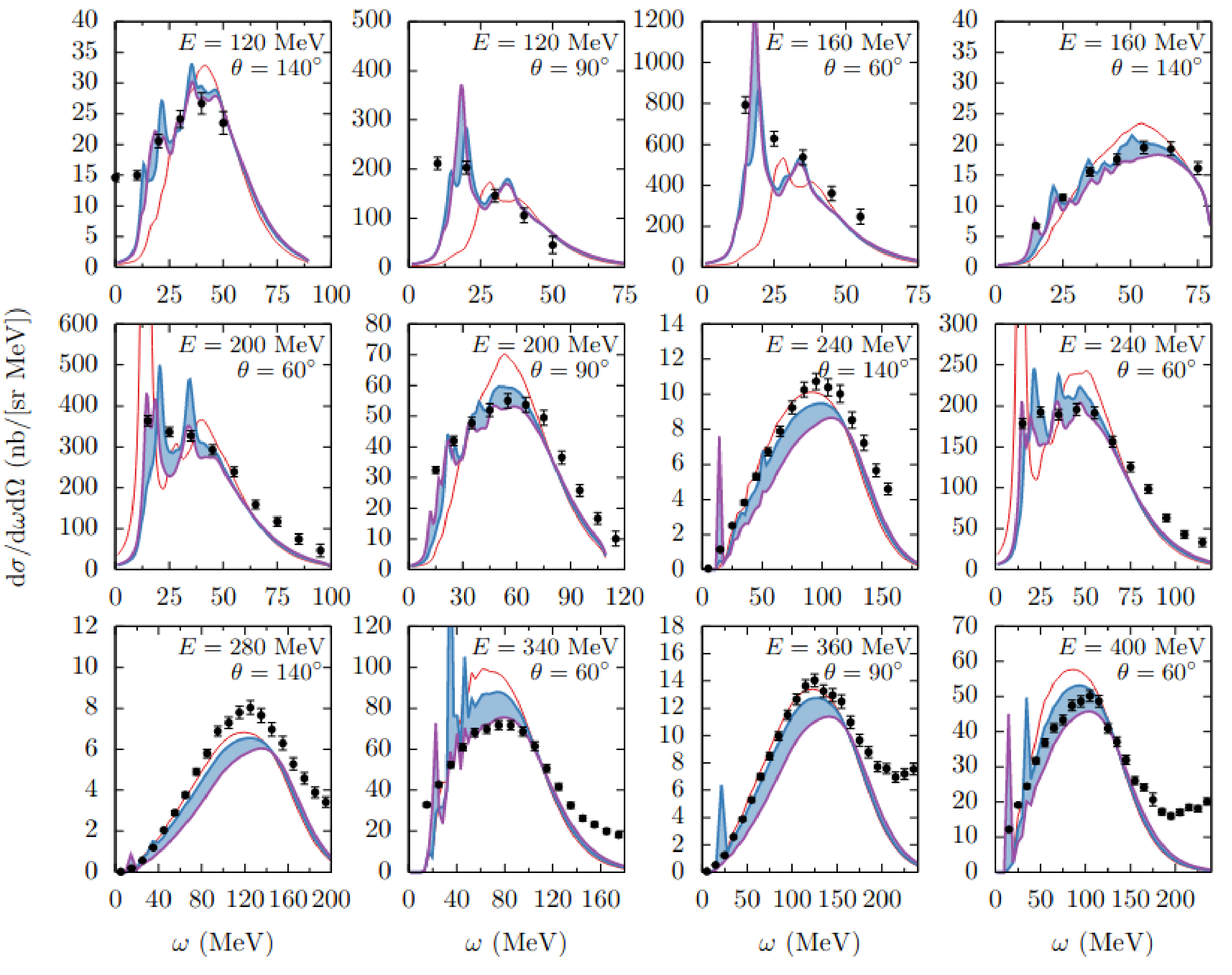
- Blue band uncertainty due to residual interaction in CRPA

$$V \to \frac{V}{(1+Q^2/\Lambda)^2}$$

- Cut off determined in

[V. Pandey, et al Phys. Rev. C 92, 024606 (2015)]

Electron scattering ^{56}Fe



(e,e') off Iron

- Blue band uncertainty due to residual interaction in CRPA

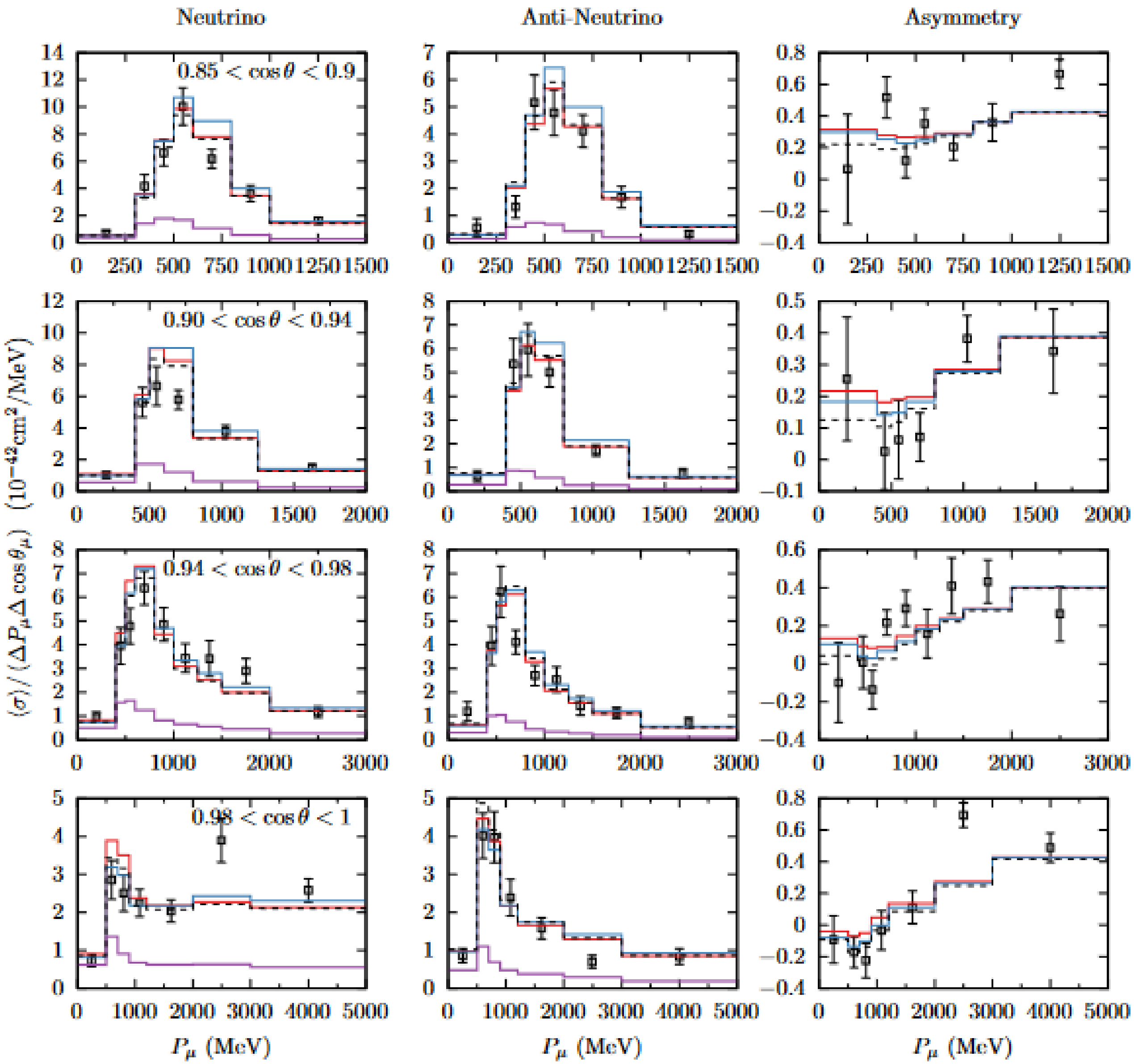
$$V \rightarrow \frac{V}{(1+Q^2/\Lambda)^2}$$

- Cut off determined in

[V. Pandey, et al Phys. Rev. C 92, 024606 (2015)]

[A. Nikolakopoulos et al. PRC 103 (2021) 6, 064603]

T2K data



Asymmetry

T2K measurement

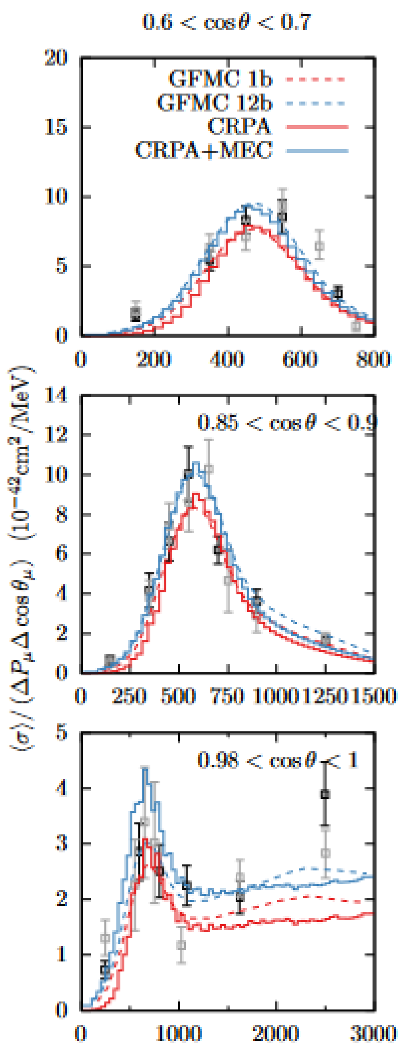
SuSAv2 MEC (RFG calculation)
[G. D. Megias et al. PRD91, 073004 (2015)]

Add Hydrogen in anti-neutrino reactions

Dashed lines: assumption of isospin symmetry (neglect Coulomb effects)

Asymmetry quite model-independent

GFMC ab-initio results

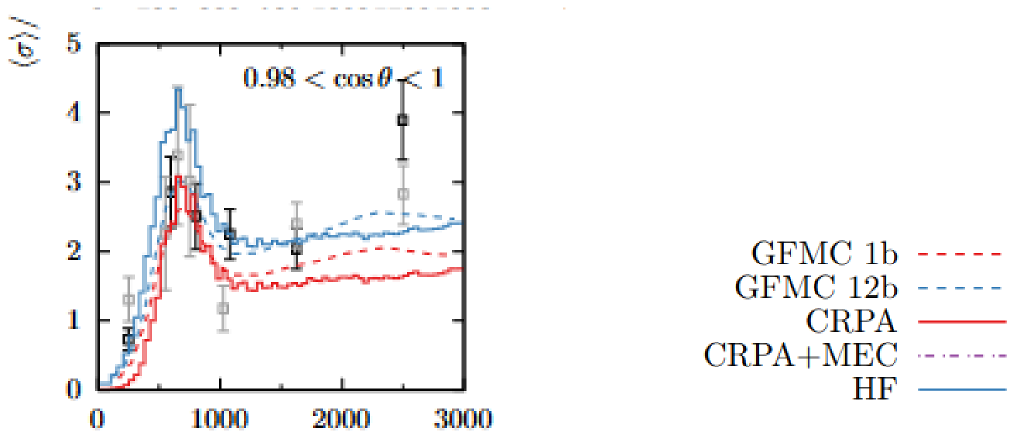


GFMC results

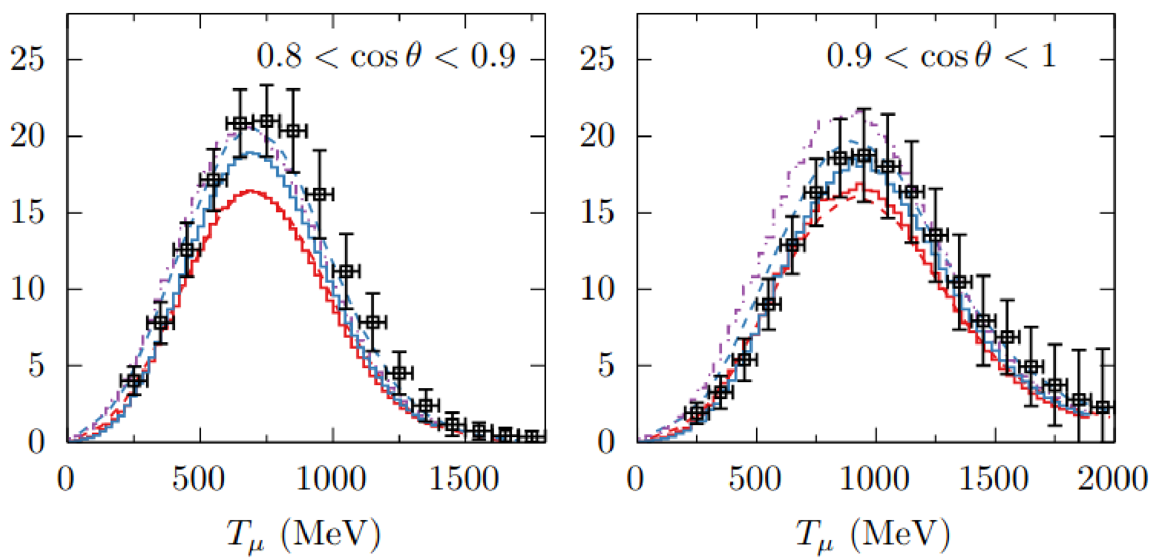
- Consistent treatment of one- and two-body currents!
- CRPA & GFMC 1b are similar
- CRPA + SuSAv2 MEC & GFMC 1+2b Similar in backward bins
- Discrepancies in forward low-P_μ region

GFMC:
A. Lovato, J. Carlson, S. Gandolfi, N. Rocco, and R. Schiavilla, Phys. Rev. X 10, 031068 (2020)

GFMC ab-initio results



MiniBooNE



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Treatment of final-state nucleon

Same initial-state nucleon, different treatments of final-state wavefunction

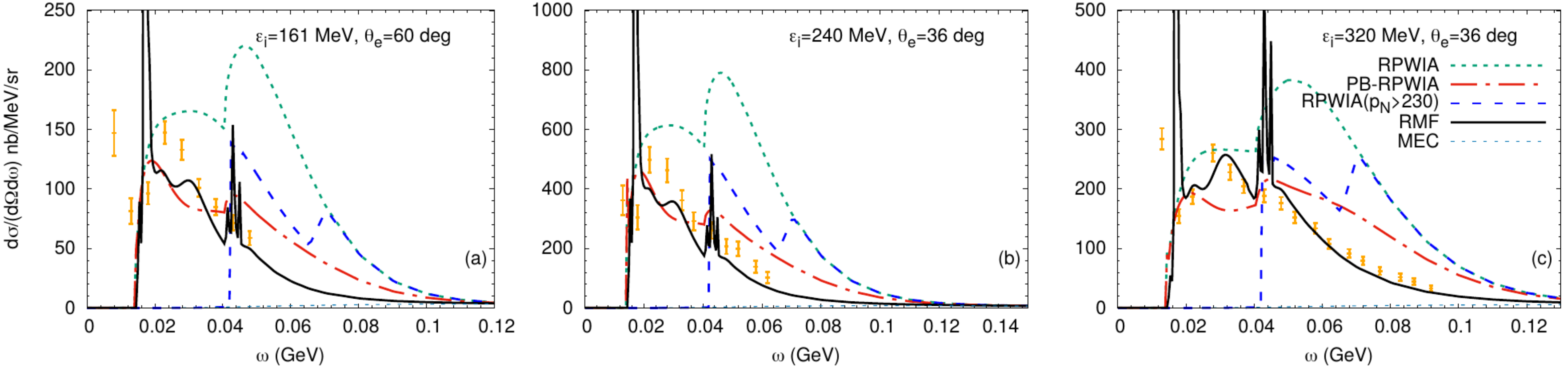
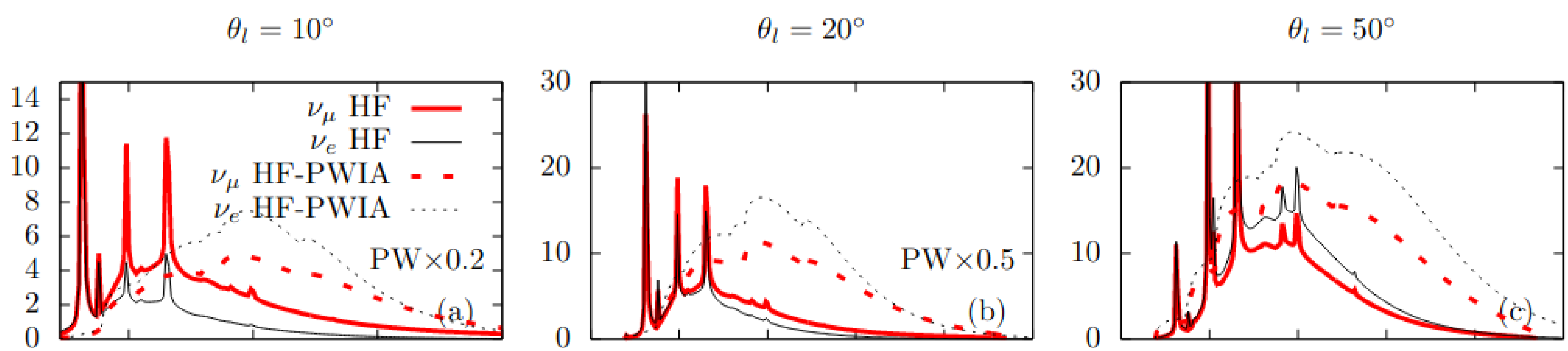


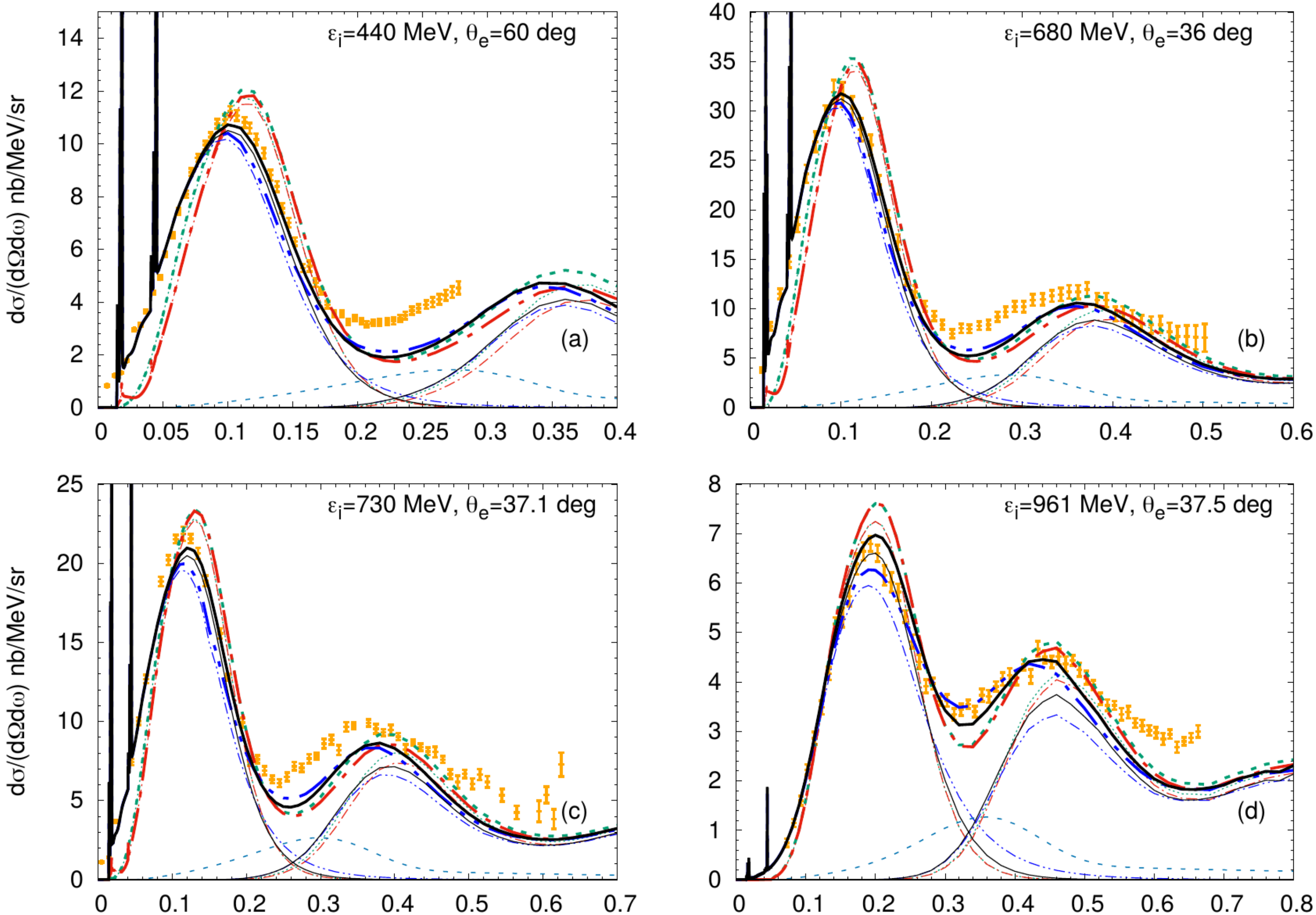
FIG. 4: QE predictions for the process $^{12}C(e,e')$ with the RPWIA, PB-RPWIA, RPWIA($p_N > 230$), and RMF



ν + ^{40}Ar (CC) at E_ν = 200 MeV

Treatment of final-state nucleon

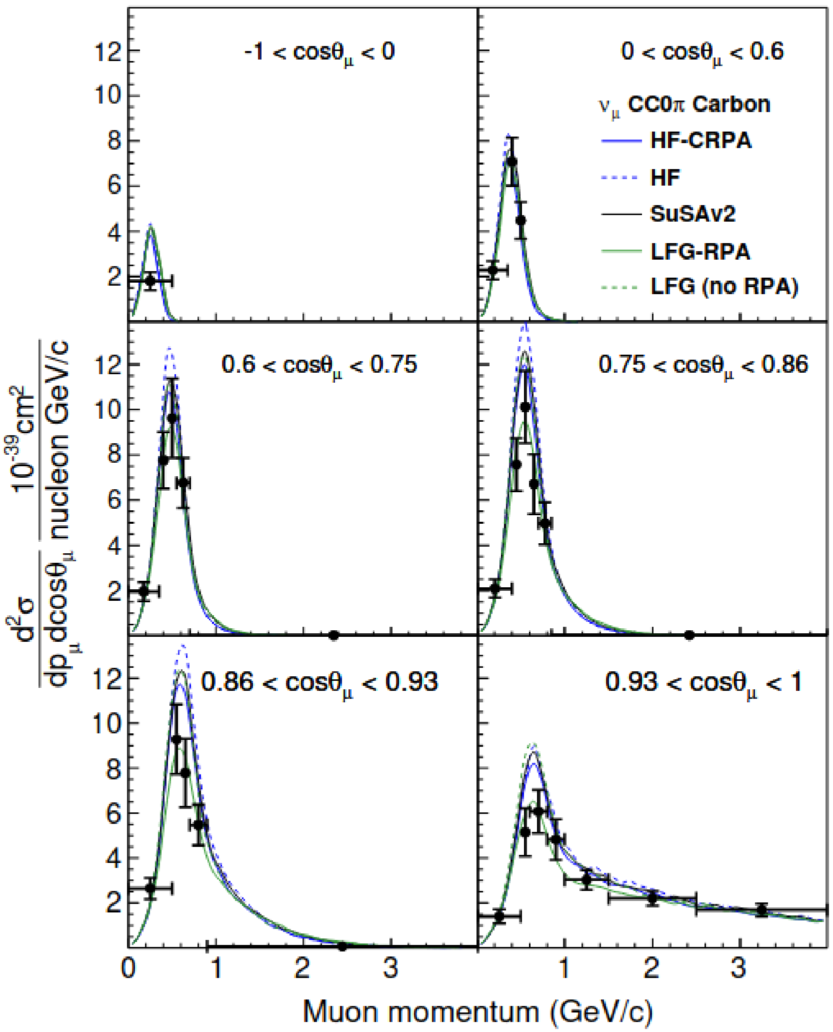
Same initial-state nucleon, different treatments of final-state wavefunction



RPWIA

RDWIA

Inclusive cross sections in generators



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]

[1] *CERN, European Organization for Nuclear Research, Geneva, Switzerland*[*]
[2] *Department of Physics and Astronomy, Ghent University, Proeftuinstraat 86, B-9000 Gent, Belgium*[†]
[3] *School of Physics, University of Bristol, Bristol BS8 1TL, United Kingdom*
[4] *Fermi National Accelerator Laboratory, Batavia, IL 60502, USA*
[5] *Department of Physics, University of Florida, Gainesville, FL 32611, USA*[‡]
(Dated: November 2, 2021)

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]

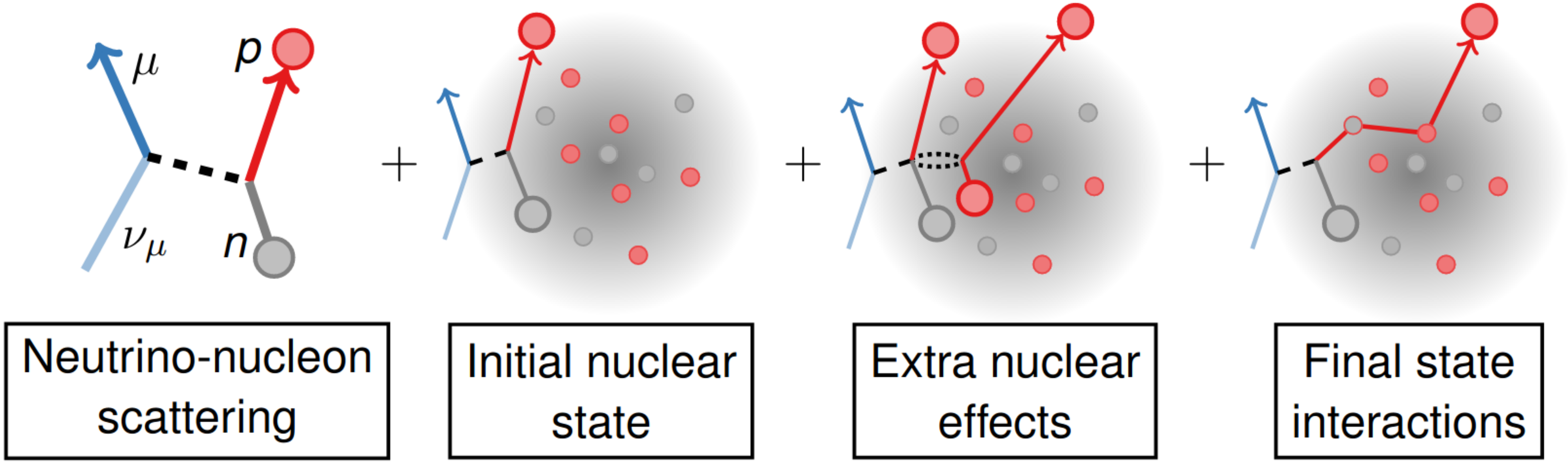
[1] *IN2P3-CNRS, Laboratoire Leprince-Ringuet, Palaiseau 91120, France*
[2] *DPhP, IRFU, CEA Saclay, 91191 Gif-sur-Yvette, France*
[3] *CERN, European Organization for Nuclear Research, Geneva, Switzerland*
[4] *University of Tokyo, Institute for Cosmic Ray Research, Research Center for Cosmic Neutrinos, Kashiwa, Japan*
(Dated: February 21, 2020)

Reproduce exactly the inclusive results

But lose information about nucleon observables

Inclusive cross sections in generators

The idealized version of the event generator:

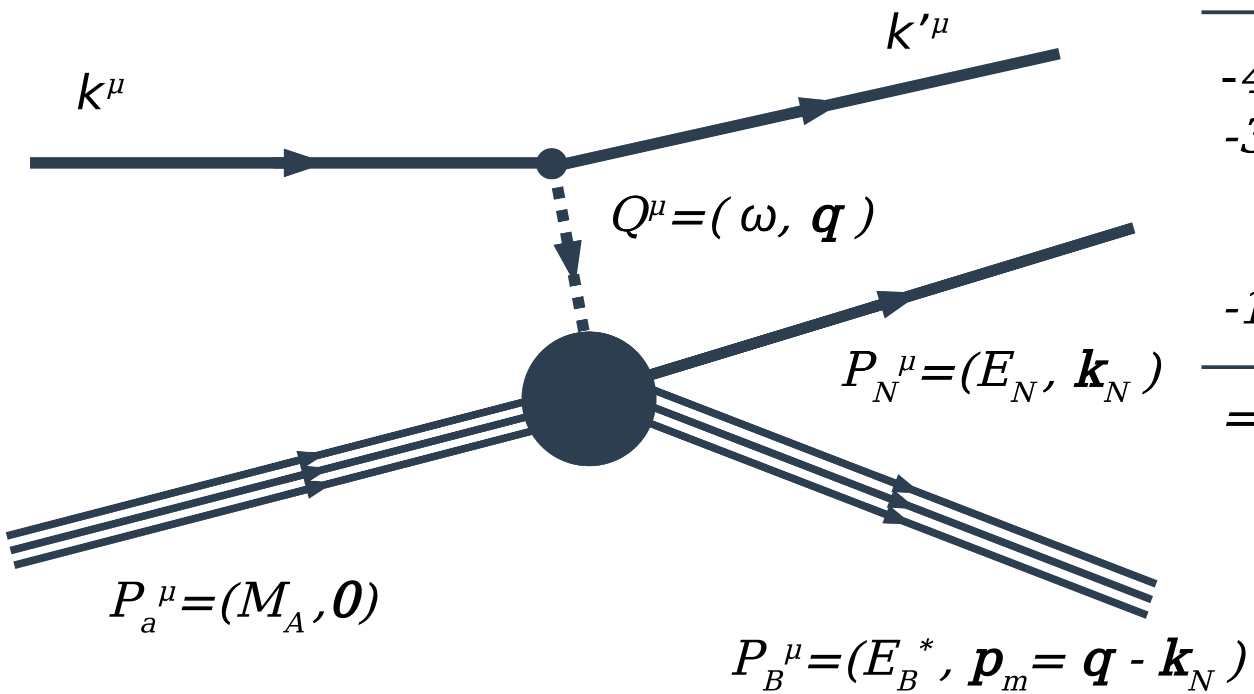


[Fig. From K. Niewczas]

When an inclusive calculation is implemented:
(part of) the initial-state, the 'extra effects' and the FSI are included

It is not possible to obtain the hadron information from inclusive CS

Kinematics of single-nucleon knockout



Given k^μ and P_a^{μ} : $3 \cdot 4$

$= 12$ d.o.f

$-4 : k^\mu + P_a^{\mu} = k'^\mu + P_N^{\mu} + P_B^{\mu}$

$-3 : \quad k'^2 = m'^2,$

$\quad P_N^2 = M_N^2,$

$\quad P_B^2 = M_B^{*2}$

$-1 : R^\nu_{\ \mu} k^\mu = k^\nu$ (φ' trivial)

$= 4$ d.o.f

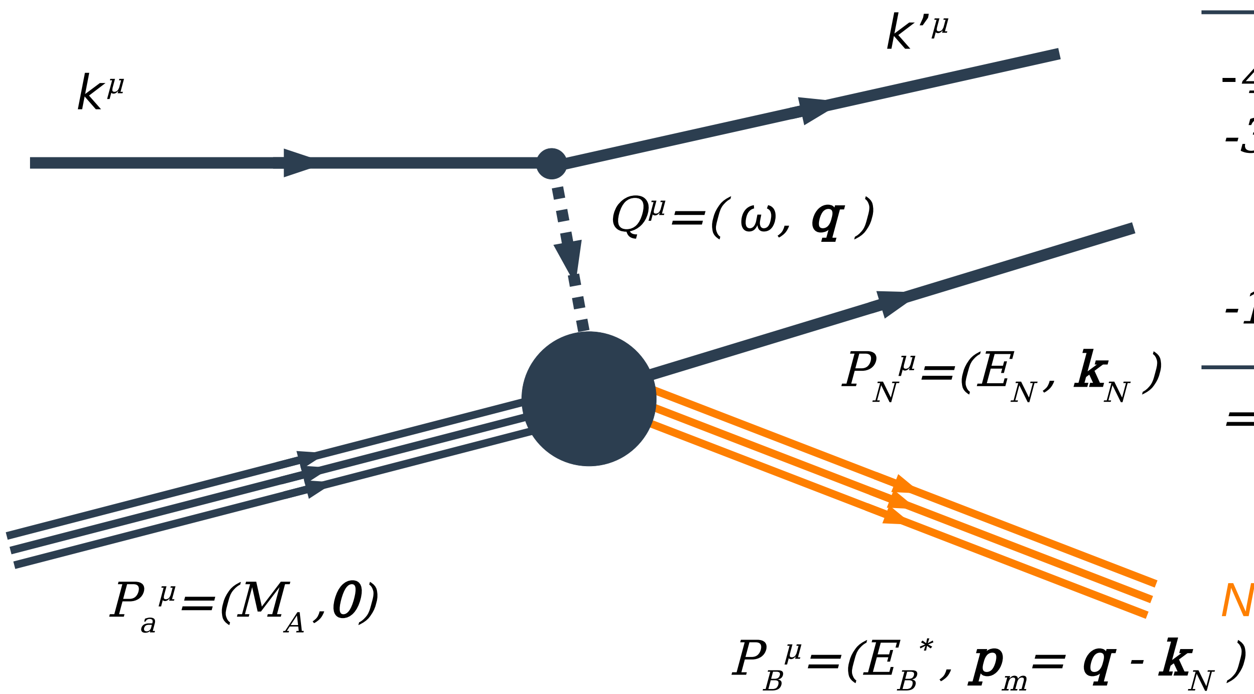
E', $\cos\theta'$, $\cos\theta_N$, φ_N

All particles:

$P_X \cdot P_X = M_X^2$

No ‘off-shell’ initial nucleon

Kinematics of single-nucleon knockout



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-3 : $k'^2 = m'^2$,

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$P_B^2 = M_B^2$

-1 : $R^\nu{}_\mu k^\mu = k^\nu$ (φ' trivial)

$= 4$ d.o.f

E' , $\cos\theta'$, $\cos\theta_N$, φ_N

Non-trivial parameter M_B^2

All particles:

$P_X \cdot P_X = M_X^2$

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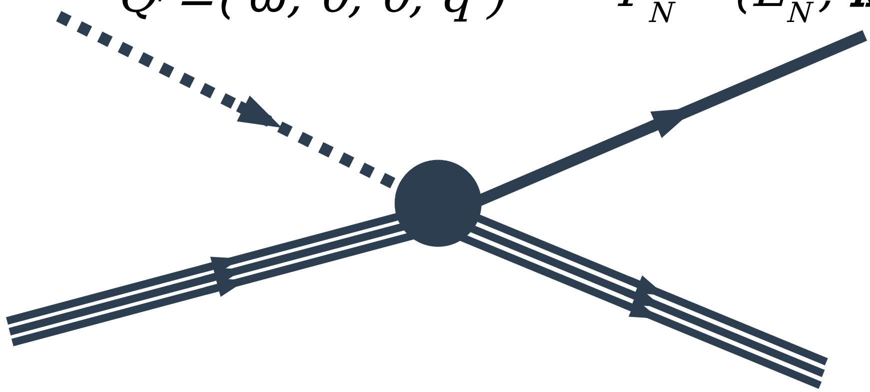
Kinematics of single-nucleon knockout

$Q^\mu = (\omega, 0, 0, q)$ $\quad P_N^{\mu} = (E_N, \boldsymbol{k}_N)$



$P_a^{\mu} = (M_A, \boldsymbol{0})$ $\quad P_B^{\mu} = (E_B, \boldsymbol{p}_m = \boldsymbol{q} - \boldsymbol{k}_N)$

given $\omega\ q\ \cos\theta_N\ \varphi_N$

$$E_m = E_i - E_f - T_N - T_B = M_B + M_N - M_A. \quad (2)$$

The total energy of the residual system is

$$E_B = T_B + M_B = \sqrt{M_B^2 + |\vec{p}_m|^2}, \quad (3)$$

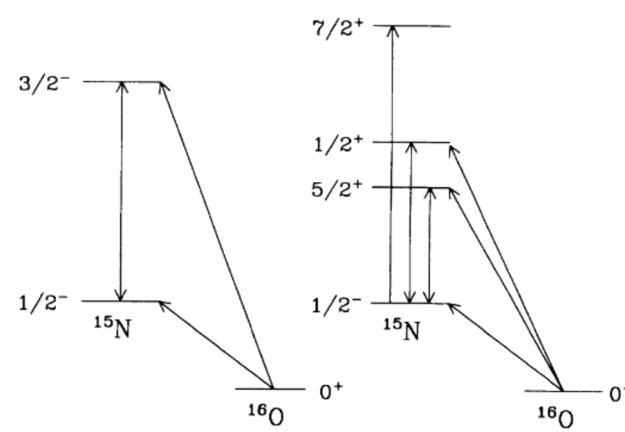
and its momentum is the missing momentum

$$\vec{p}_m = \vec{k}_i - \vec{k}_f - \vec{k}_N. \quad (4)$$

All particles:
$P_X \cdot P_X = M_X^2$

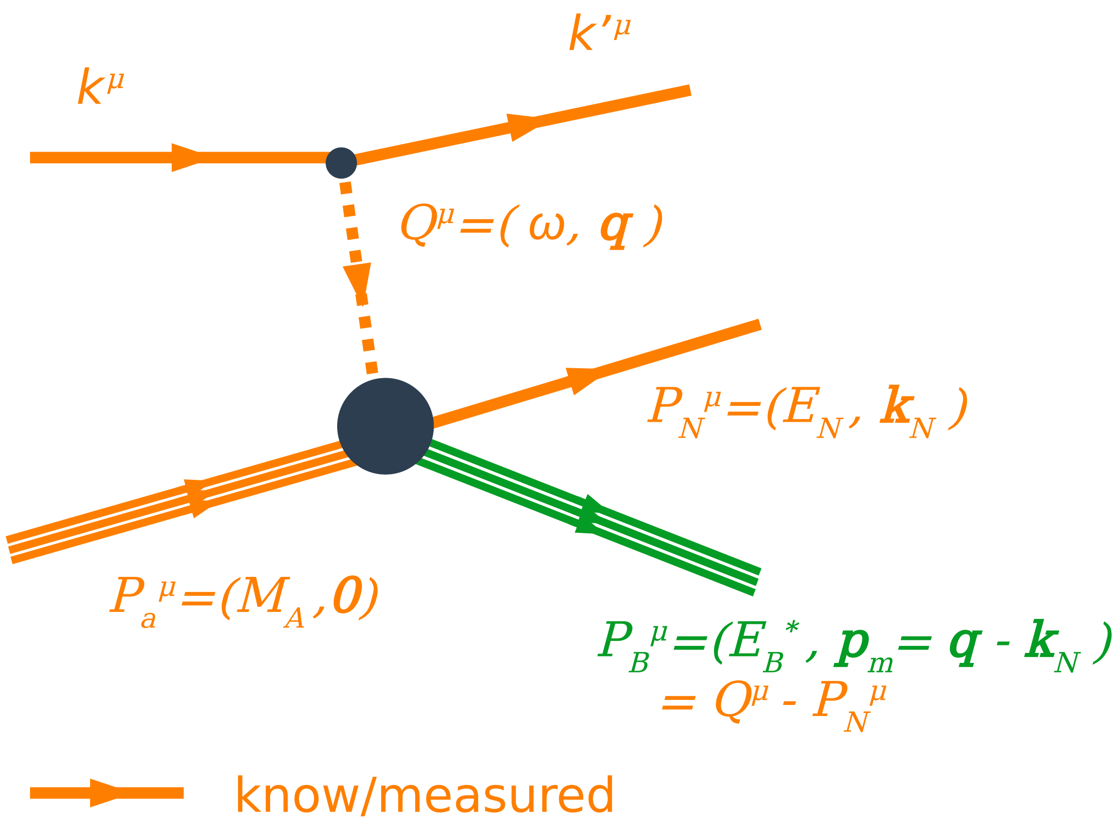
+Nuclear model
→ Available states

$M_B = M_B^{\,0} + E_{ex} \approx (M_A - M_N) + E_{ex}$
$\rightarrow E_{ex} \approx E_m$

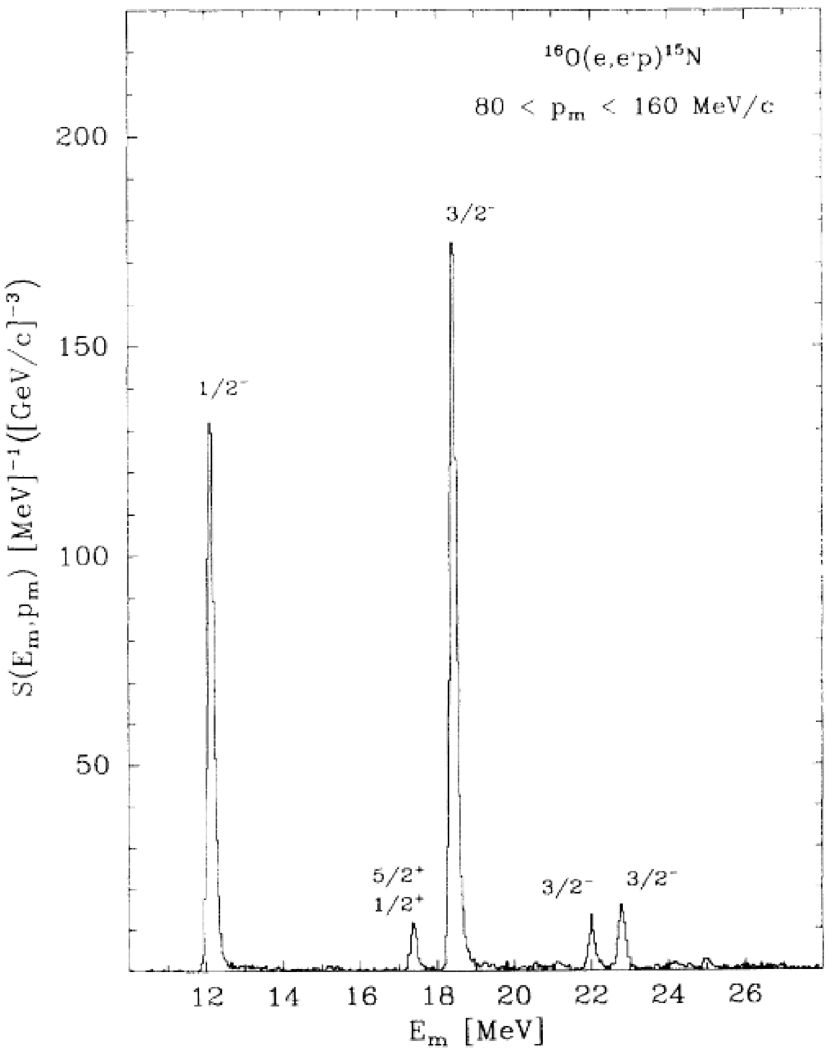


[M. Leuschner et al. PRC49, 955 (1994)]

Exclusive electron scattering



Exclusive conditions : everything is known



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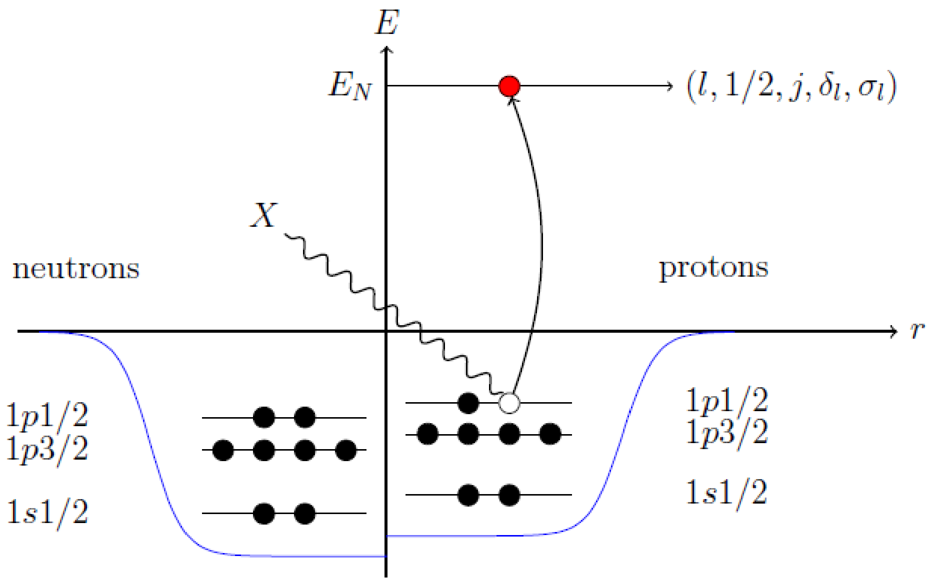
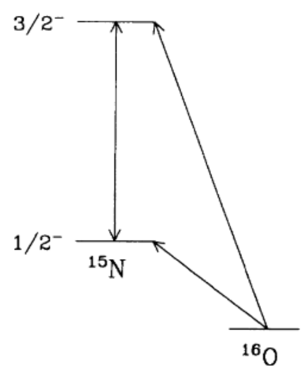
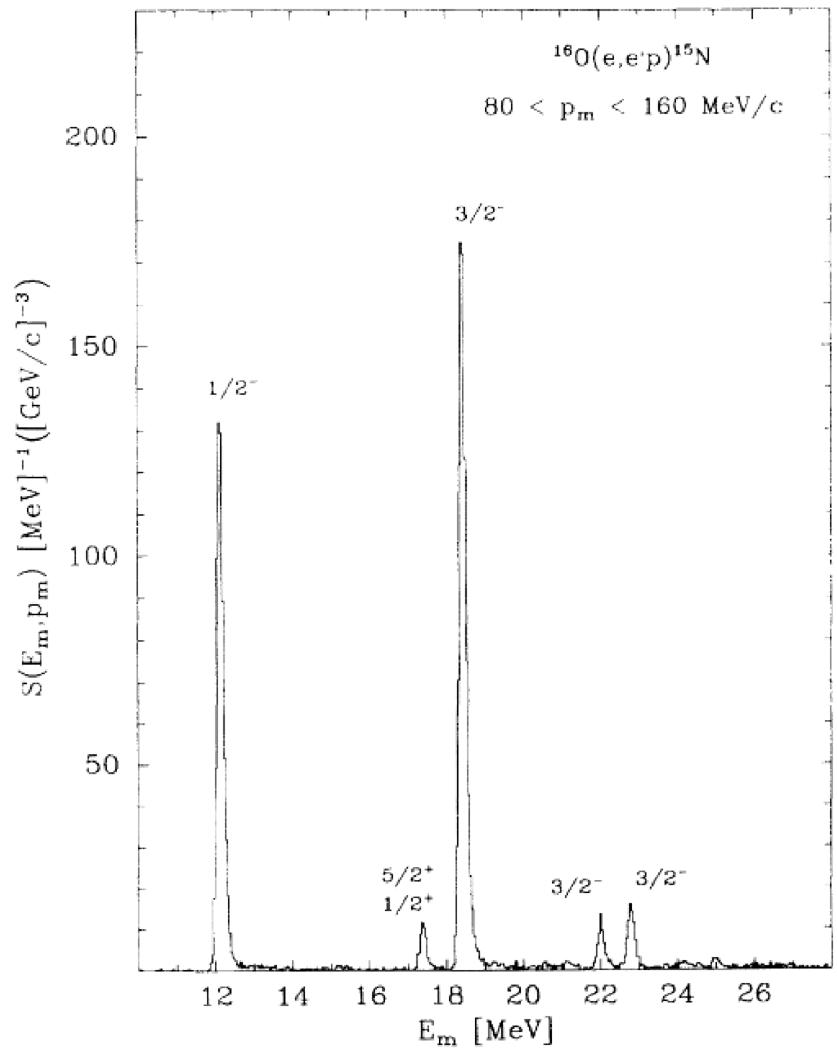
Independent particle model



Quantum numbers:
angular momentum
Energy

No momentum eigenstates





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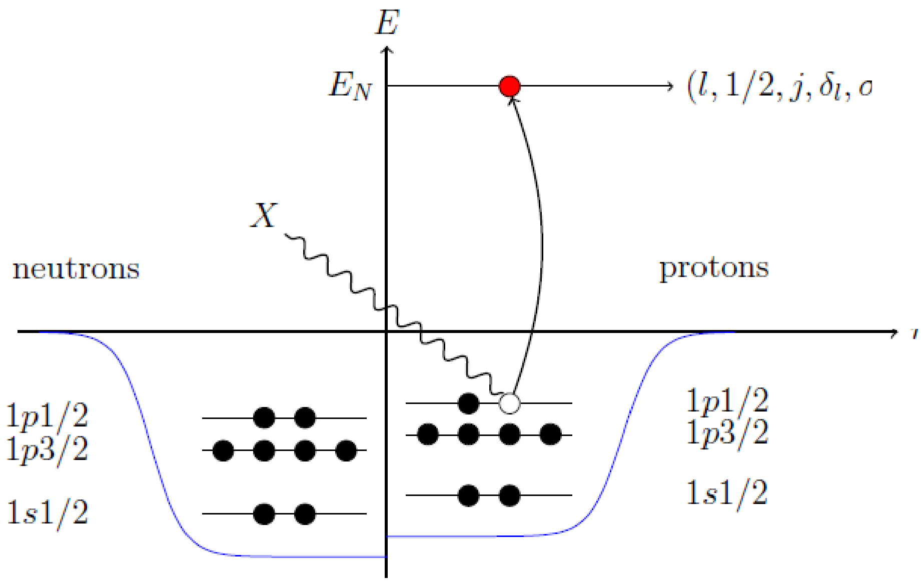
Independent particle model



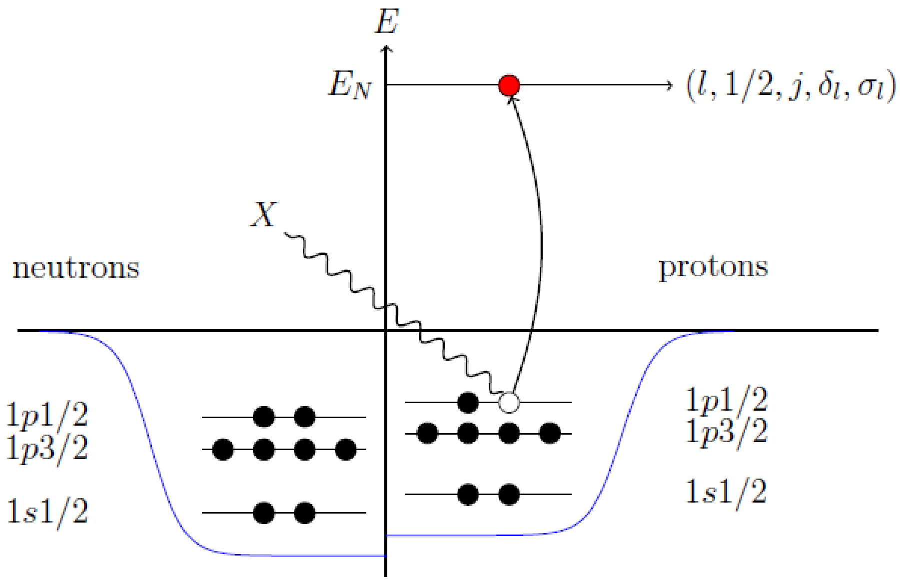
$$J^{\mu}_{\kappa,n}(m_j, s_N, Q, k_N) =$$
$$\int d\vec{r} e^{i\vec{q}\cdot\vec{r}} \; \overline{\Psi}(\vec{r}, s_N, k_N)\mathcal{O}^{\mu}(Q)\psi^{m_j}_{\kappa}(\vec{r}).$$

$$[E - V(r)]\,\Psi(\vec{r}, s_N, k_N) = [\alpha \cdot \hat{\mathbf{p}}(\vec{r}) - \beta(S(\vec{r}) - M_N)]\,\Psi(\vec{r}, s_N, k_N)$$

$$V_{strong}(r) \to 0 \quad S_{strong}(r) \to 0 \quad \text{for } r \to \infty (\approx 5 \text{ fm})$$

Wave function behaves like a momentum state only for large radius

Relativistic plane-wave impulse approximation



$$J^{\mu}_{\kappa,n}(m_j, s_N, Q, k_N) = \int d\vec{r} e^{i\vec{q}\cdot\vec{r}}\ \overline{\Psi}(\vec{r}, s_N, k_N)\mathcal{O}^{\mu}(Q)\psi^{m_j}_{\kappa}(\vec{r}).$$

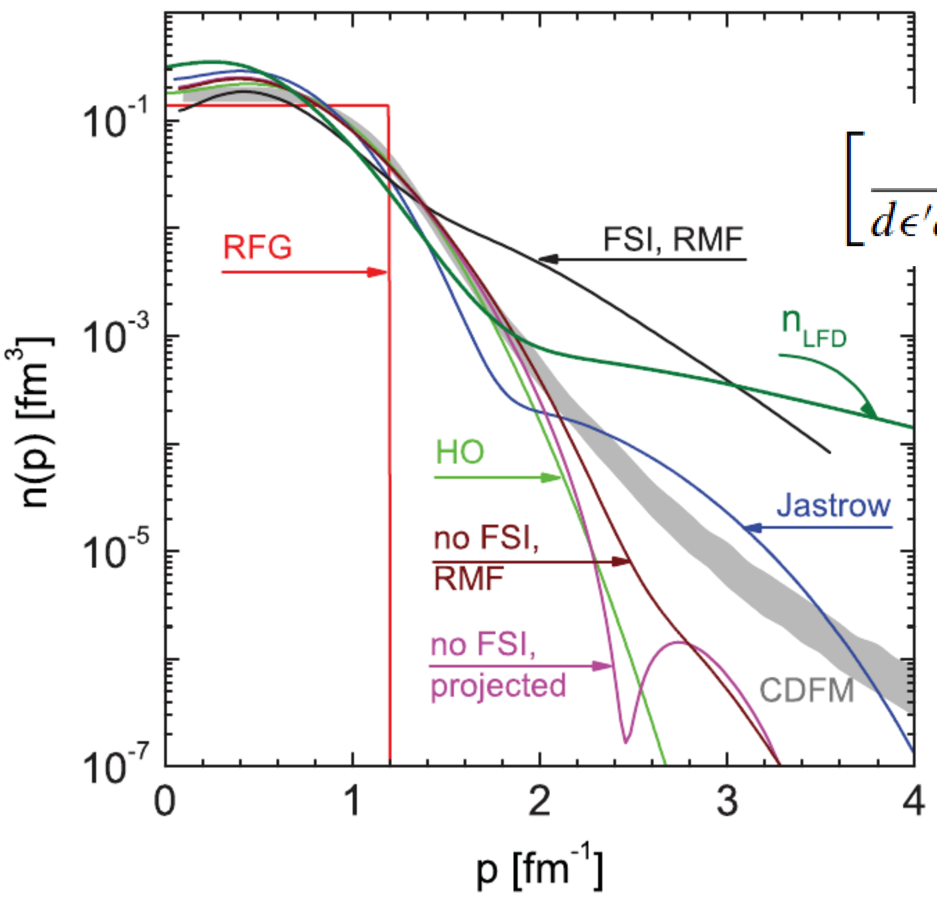
With plane-wave $\overline{\Psi}_{pw}(\vec{r}, k_N, s) = \overline{u}(k_N, s)e^{-i\vec{r}\cdot\vec{k}_N}$

$$J^{\mu}_{n,\kappa} = (2\pi)^{3/2}\ \overline{u}(k_N, s)\mathcal{O}^{\mu}\phi^{m_j}_{\kappa}(\vec{p}_m)$$

The squared matrix element is ‘proportional’ to $n(p_m) = \sum_{\kappa, m_j} |\phi^{m_j}_{\kappa}(p_m)|^2$

With distorted-wave : probe a broader region in momentum space

Factorization in PWIA and (R)DWIA



[A. N. Antonov et al. PRC83, 045504]

In the PWIA there is exact factorization

$$\left[\frac{d\sigma}{d\epsilon' d\Omega' dp_N d\Omega_N}\right]^{\mathrm{PWIA}}_{(e,e'N)} = K\sigma^{eN}(q,\omega;p,\mathcal{E},\phi_N)S(p,\mathcal{E}),$$

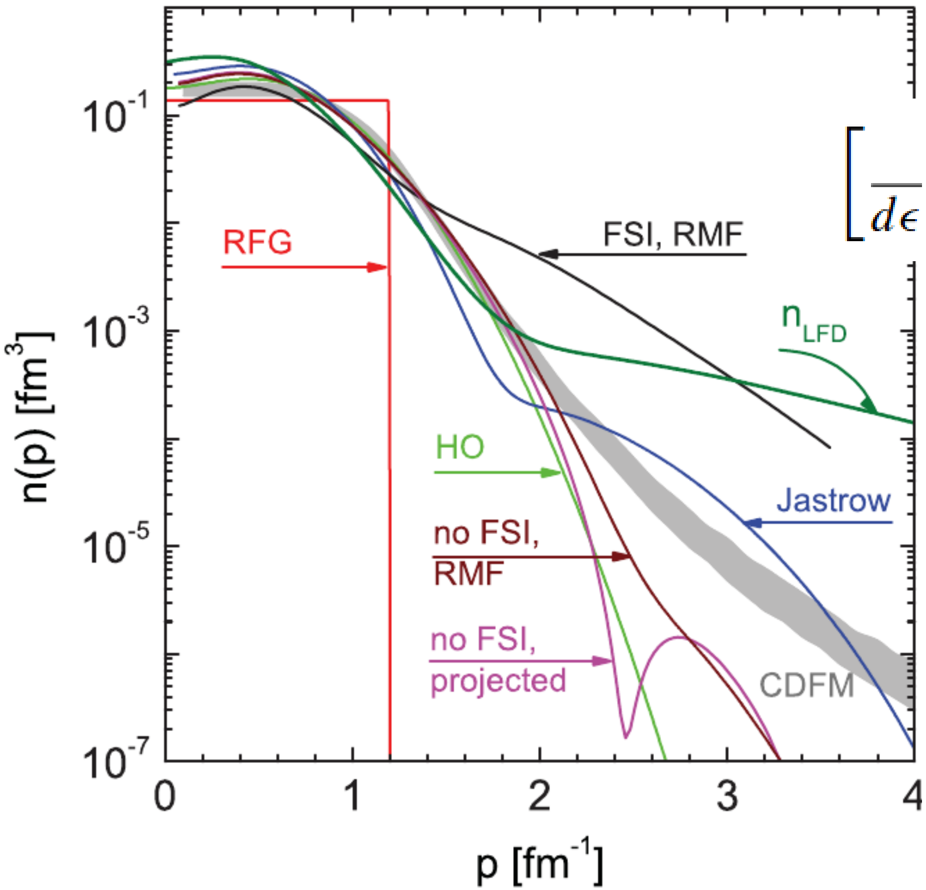
Can define ‘distorted’ *n(p)*

$$\rho(p) = n^{\mathrm{dist}}(p) = \frac{\left[\frac{d\sigma}{d\Omega' d\epsilon' d\Omega_N}\right]_{\mathrm{FSI}}}{K\sigma^{eN}}.$$

(Depends on ω,q,$T_{N,}$ *$\cos\theta_N$, φ_N in principle*)

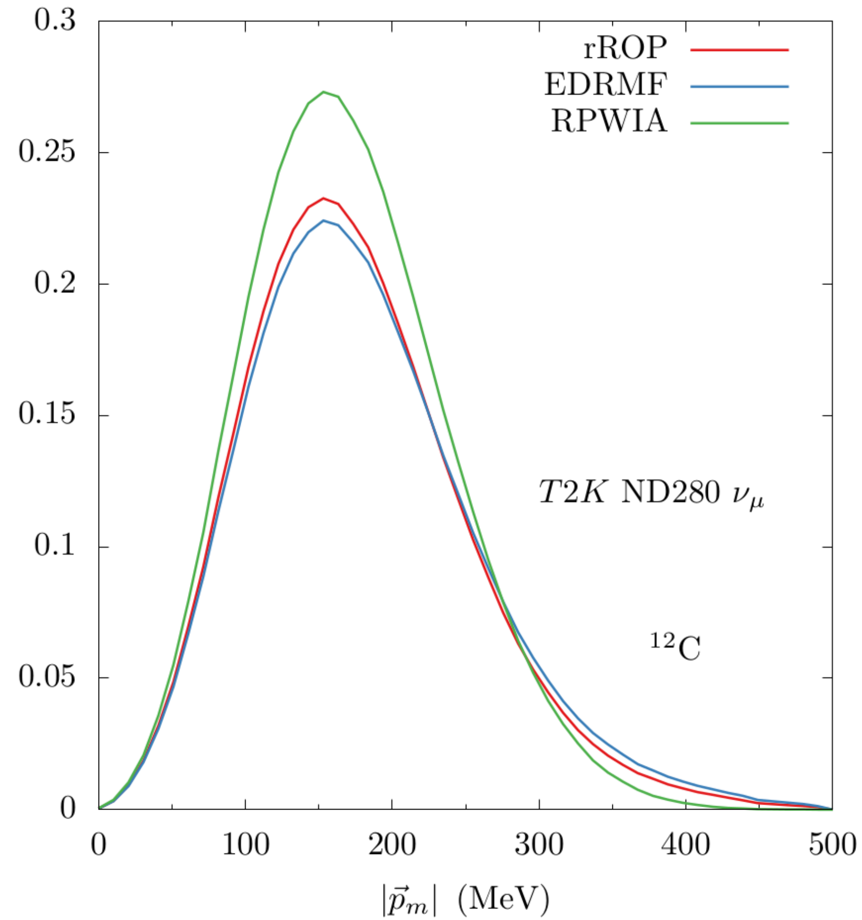
Different models with <u>same initial state</u>

Factorization in PWIA and (R)DWIA



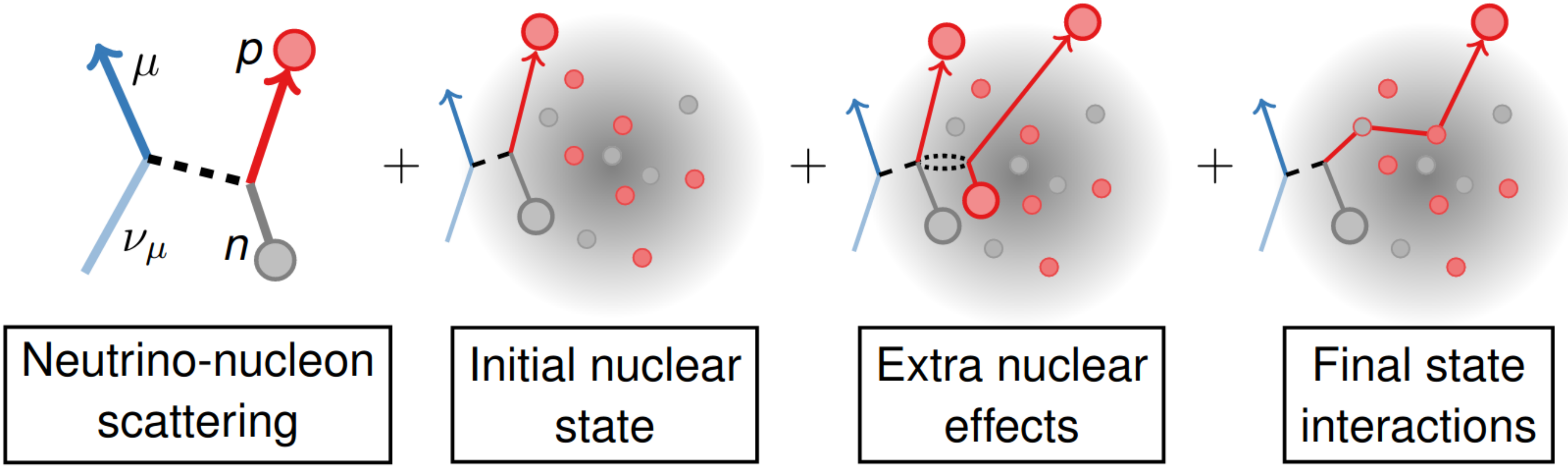
[A. N. Antonov et al. PRC83, 045504]

Missing momentum distribution for T2K



Different models with <u>same initial state</u>

From inclusive to exclusive



[Fig. from K. Niewczas]

Input to the generator here:

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

$$G^2 \frac{k_l}{E_\nu} \left[L_{00}\tilde{H}^{00} - 2L_{03}\tilde{H}^{03} + L_{33}\tilde{H}^{33} + \frac{L_{11}+L_{22}}{2}\left(\tilde{H}^{11}+\tilde{H}^{22}\right) + 2L_{12}\mathrm{Im}\tilde{H}^{12} \right]$$

As function of ω, q

Nucleon variables in GENIE

Input to the generator is inclusive cross section:

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

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 $E_m^2 = p_m^2 + M_N^2$

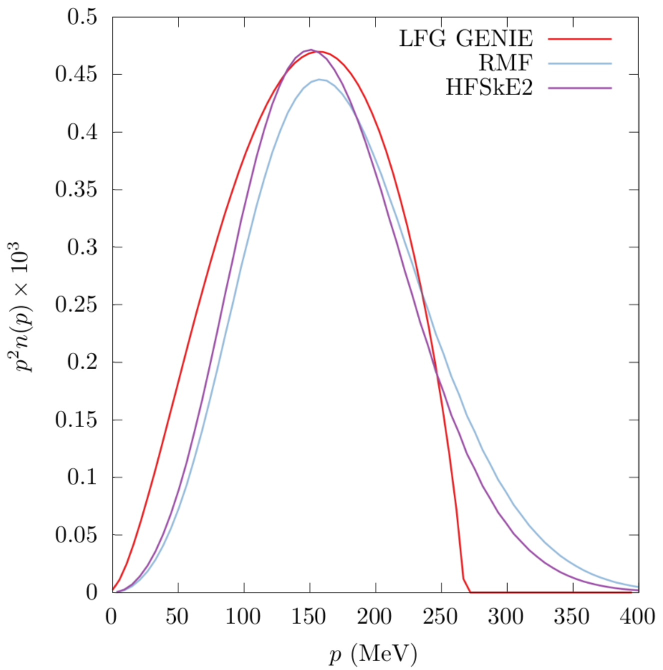
3. $E_N = E_m + \omega - E_b(q)$

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

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

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

5. Give residual momentum to remnant



Nucleon variables in GENIE and RDWIA

Input to the generator is inclusive cross section:

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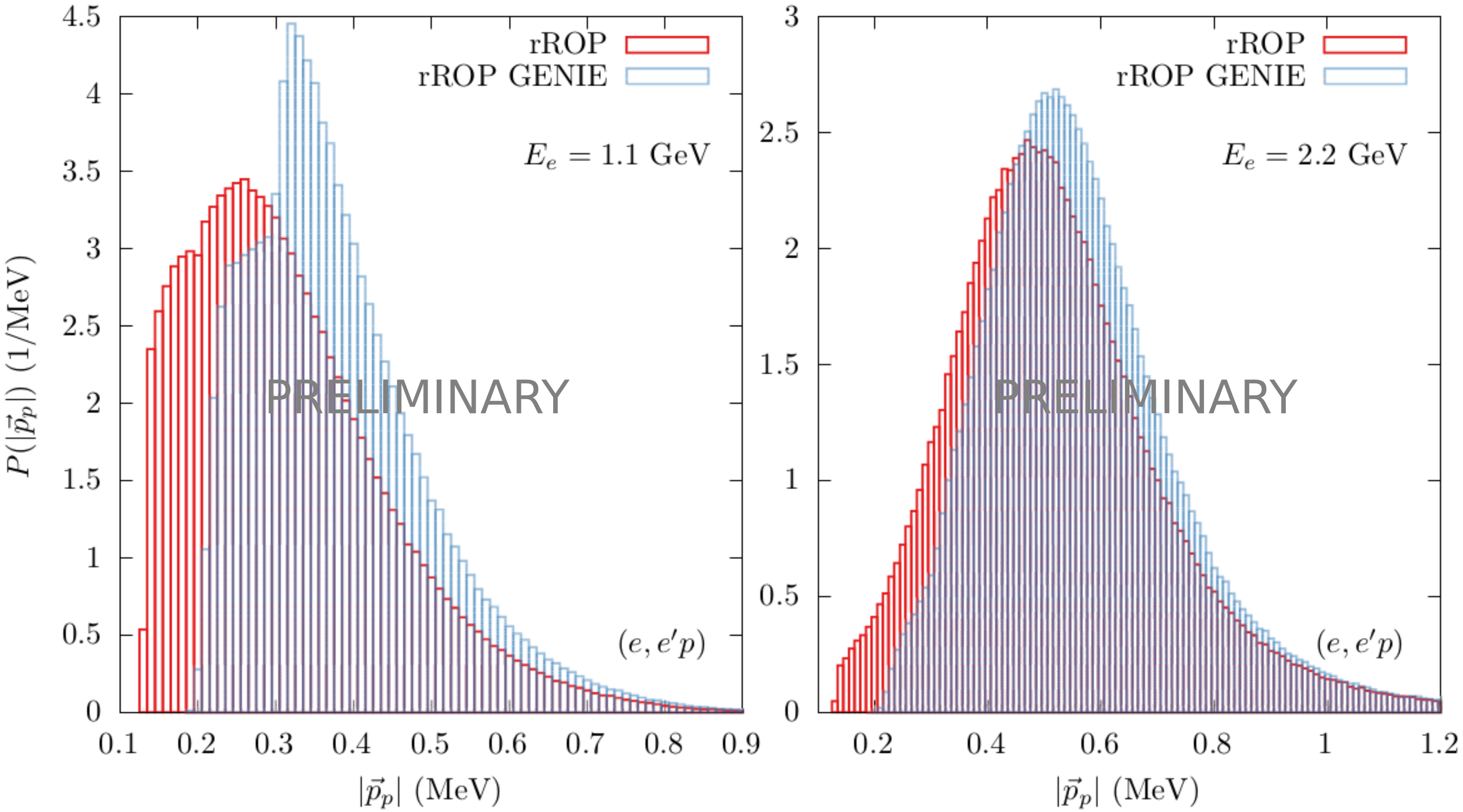
Same inclusive cross sections different nucleon observables



(e,e’p) at fixed Incoming energy

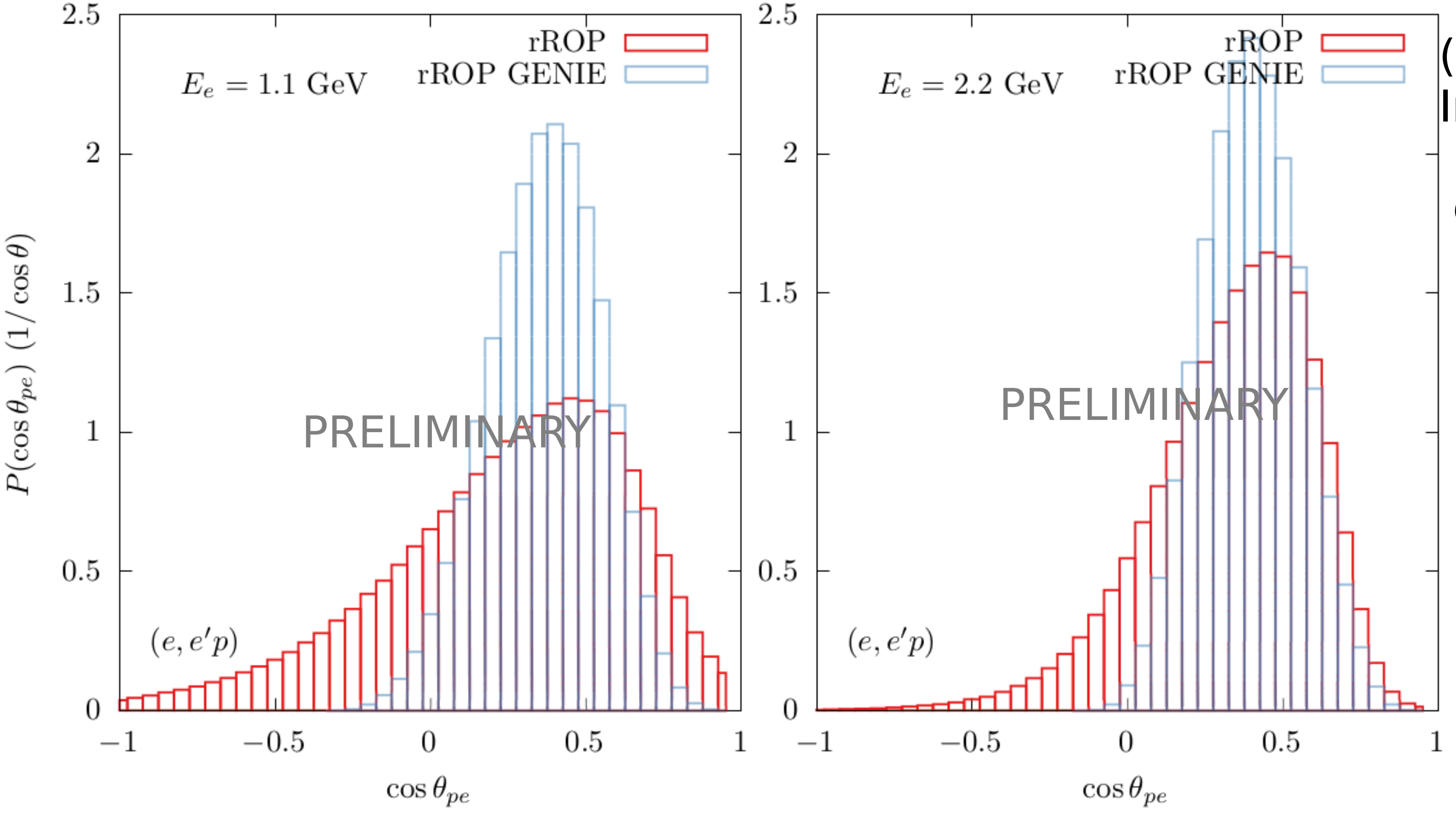
$\Theta_{e'} > 10^o$

Nucleon variables in GENIE and RDWIA

Input to the generator is inclusive cross section:

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

Same inclusive cross sections different nucleon observables



(e,e'p) at fixed Incoming energy

$\Theta_{e'} > 10^{o}$

Benchmarking intra-nuclear 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] *Department of Physics and Astronomy, Ghent University, B-9000 Gent, Belgium*
[2] *Theoretical Physics Department, Fermilab, Batavia, IL 60510, USA*
[3] *Grupo de Física Nuclear, Departamento de Estructura de la Materia, Física Térmica y Electrónica, Facultad de Ciencias Físicas, Universidad Complutense de Madrid and IPARCOS, CEI Moncloa, Madrid 28040, Spain*
[4] *University of Wrocław, Institute of Theoretical Physics, Plac Maxa Borna 9, 50-204 Wrocław, Poland*
[5] *University of Geneva, Section de Physique, DPNC, Geneva, Switzerland*

arXiv:2202.01689v1 [nucl-th] 3 Feb 2022

A direct comparison of RDWIA with relativistic optical potential (ROP) with (NEUT) intra-nuclear cascade (INC) model

1.) Differences and similarities between RDWIA and INC

2.) Consistent input from the RDWIA for the INC

3.) Event selection to compare ROP and INC

4.) The actual comparison

Empirical relativistic optical potential (ROP)

PHYSICAL REVIEW C VOLUME 47, NUMBER 1 JANUARY 1993

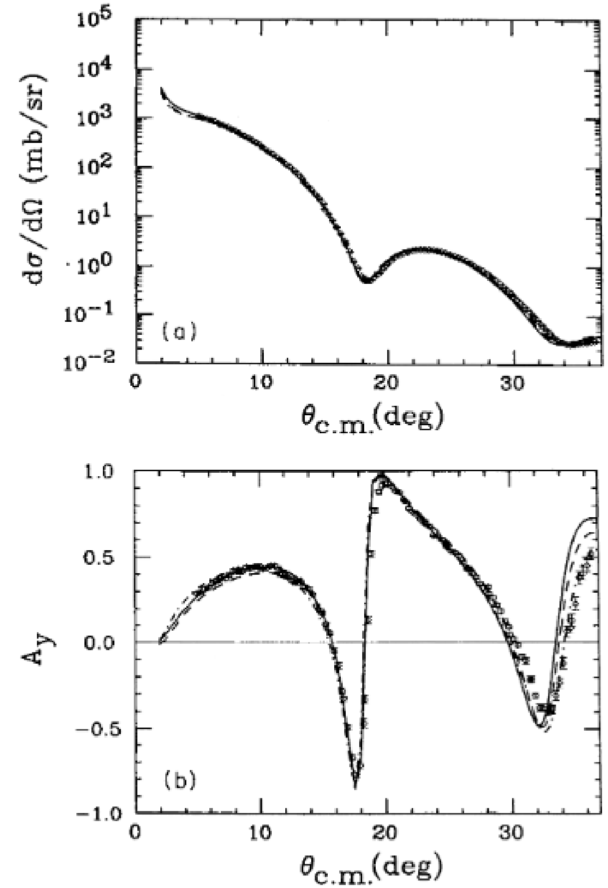
Global Dirac phenomenology for proton-nucleus elastic scattering

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)

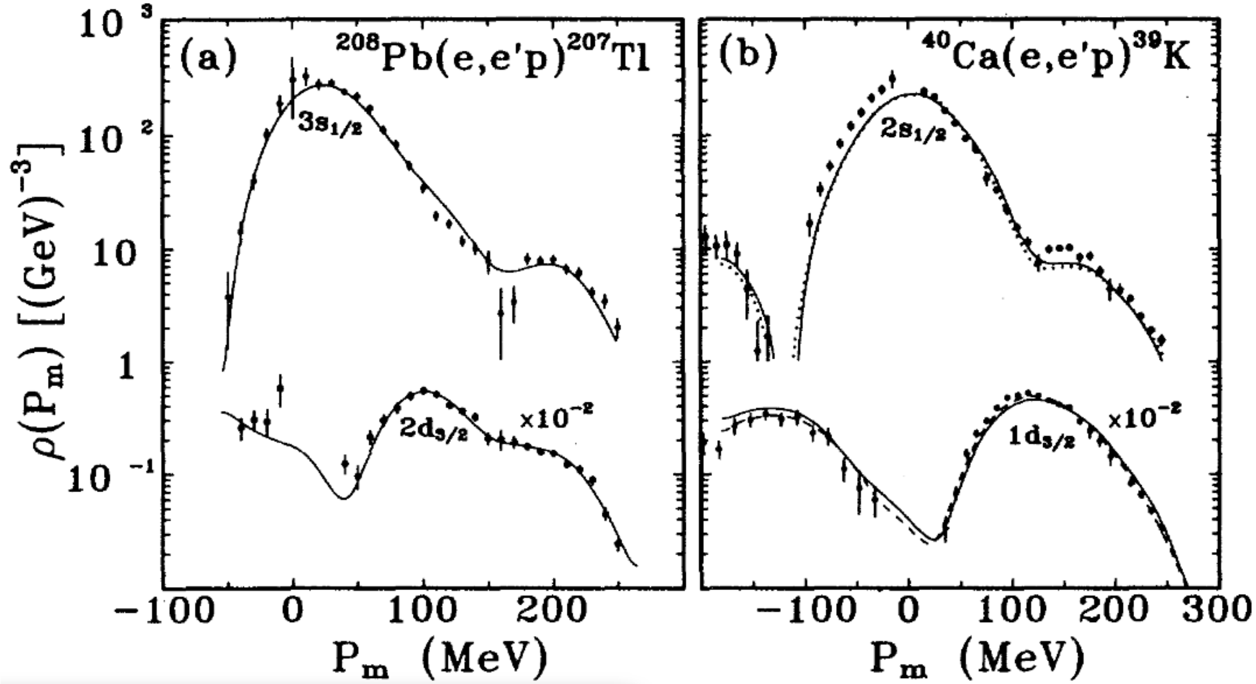
Target	T_p (MeV)	σ_R(mb) EDAI-fit	EDAD-fit fit 1	fit 2	fit 3	Reference
^{12}C	29.00	420.2	435.5	433.1	422.7	[6]
	30.30	415.9	429.0	425.6	414.2	[7]
	49.00	358.8	363.0	348.4	327.7	[6]
	49.48	357.4	361.8	347.0	326.1	[8]
	61.40	323.3	335.6	317.0	294.8	[9]
	65.00	313.5	329.0	309.7	287.4	[10]
	122.00	202.2	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]



Nucleus-specific and nucleus-dependent
Potentials fit to elastic proton-nucleus
scattering

RDWIA with ROP for exclusive (e,e'p)

[Udias et al. PRC48, 2731]



[Meucci et al. PRC64, 014604]

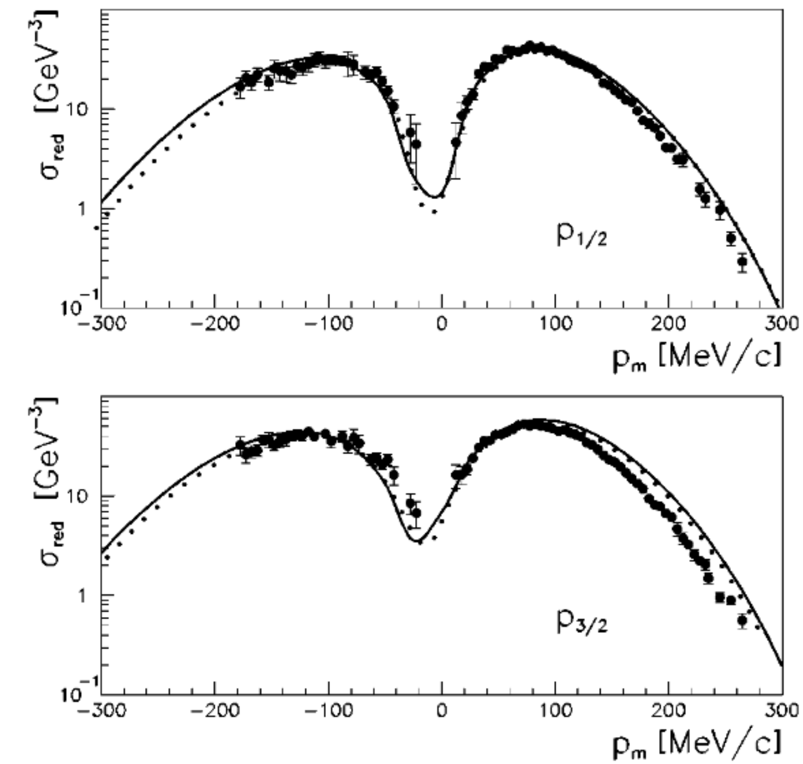
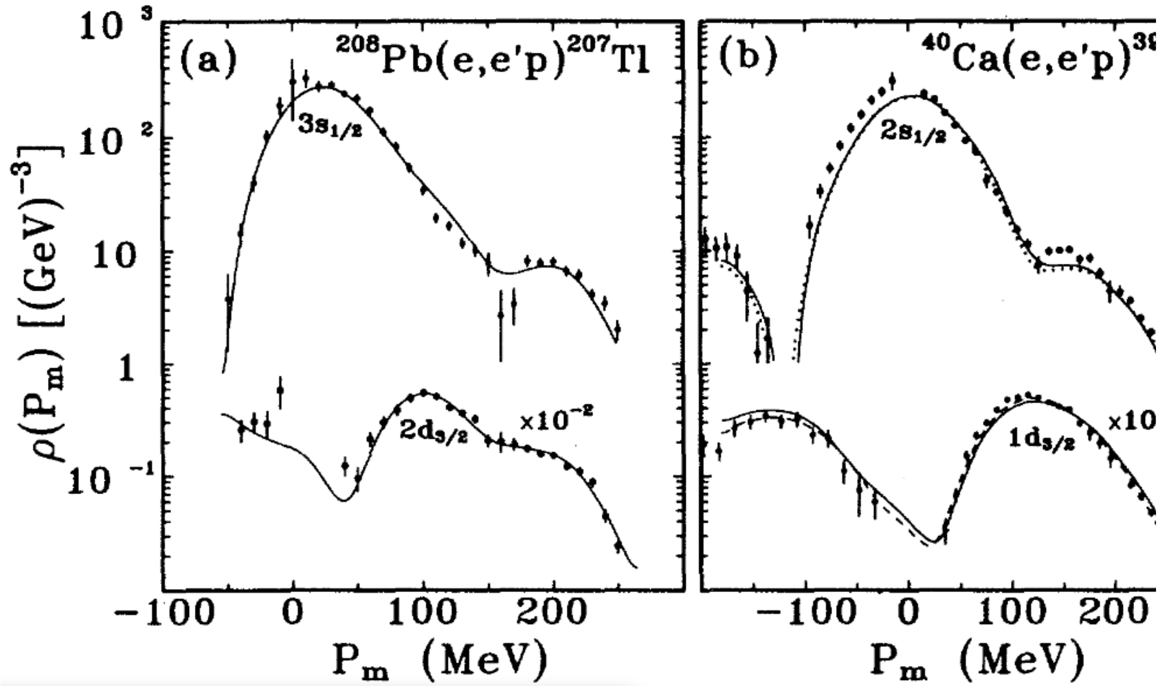
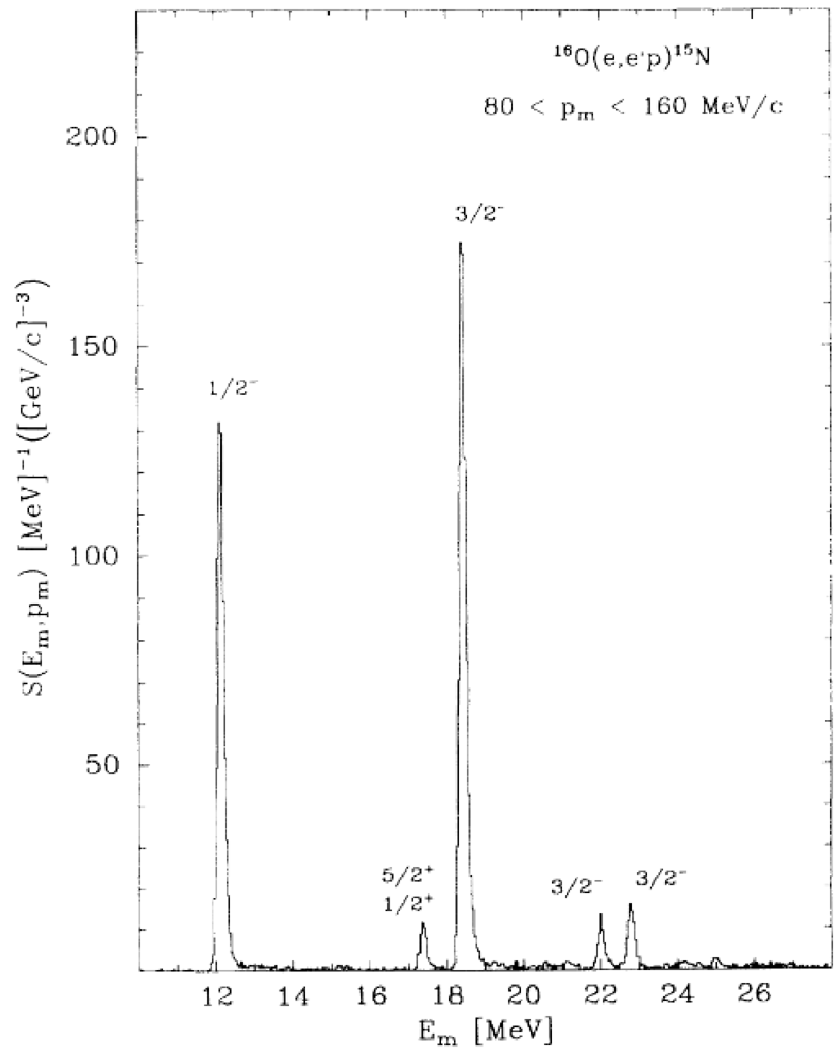


FIG. 11. The reduced cross section ($\sigma_{\rm red}$) of the ^{16}O$(e,e'p)$ reaction as a function of the recoil momentum p_m for the transitions to the $1/2^-$ ground state and to the $3/2^-$ excited state of ^{15}N, in

RDWIA with ROP for exclusive (e,e'p)

[Udias et al. PRC48, 2731]



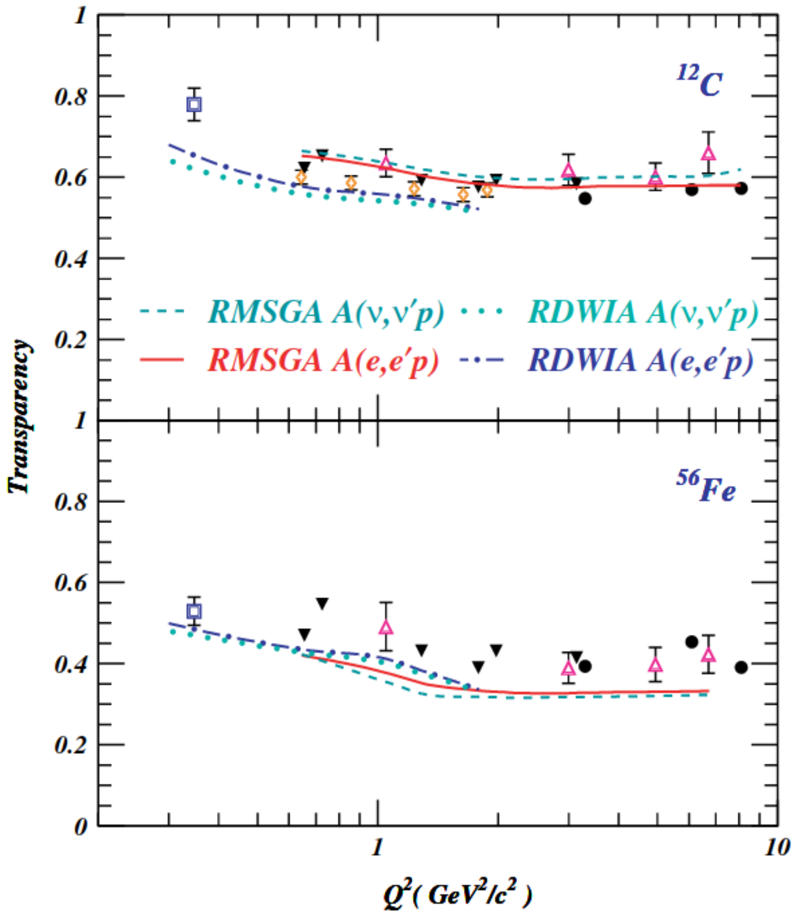


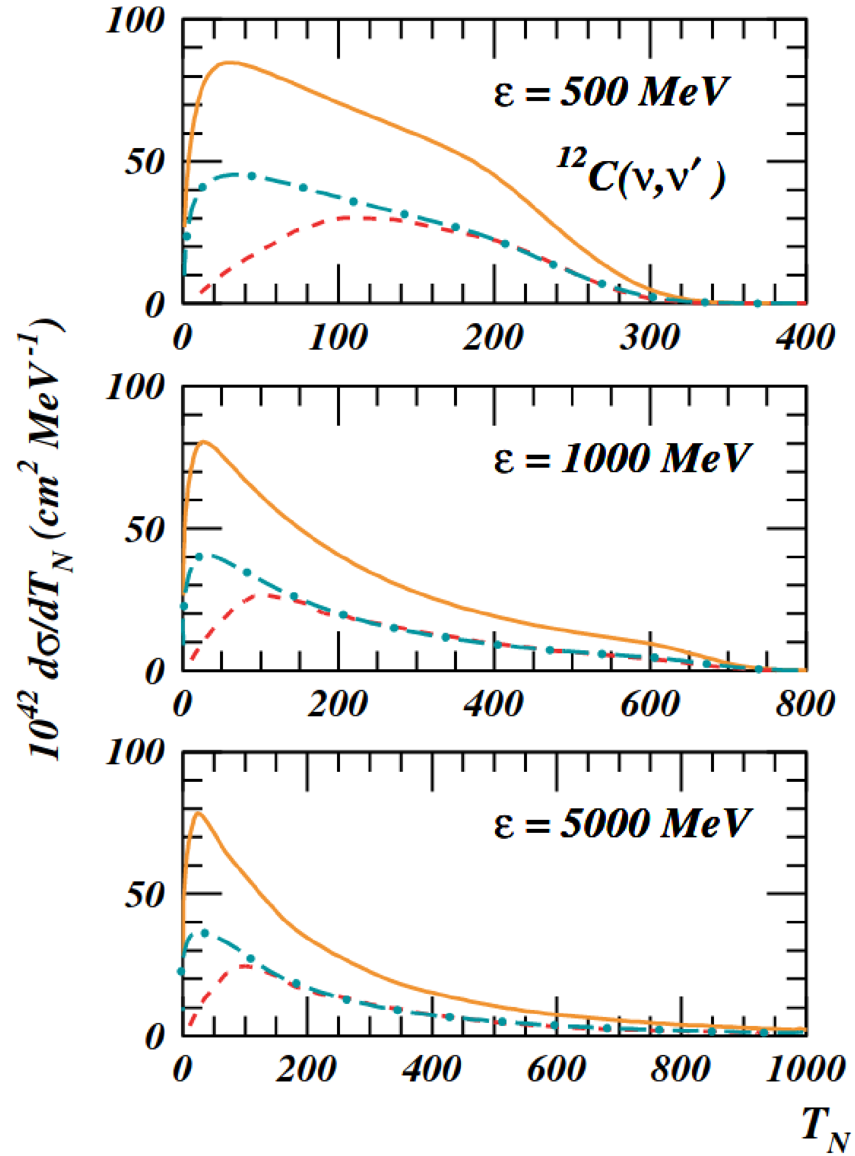
[M. Leuschner et al. PRC49, 955 (1994)]

Imaginary part of the potential removes
Strength lost in inelastic FSI
i.e. FSI which changes E_m considerably

RDWIA with ROP for exclusive (e,e'p)

[M.C. Martinez et al. PRC73 024607]





Imaginary part of the potential removes
Strength lost in inelastic FSI
i.e. FSI which changes E_m considerably

NEUT Cascade model

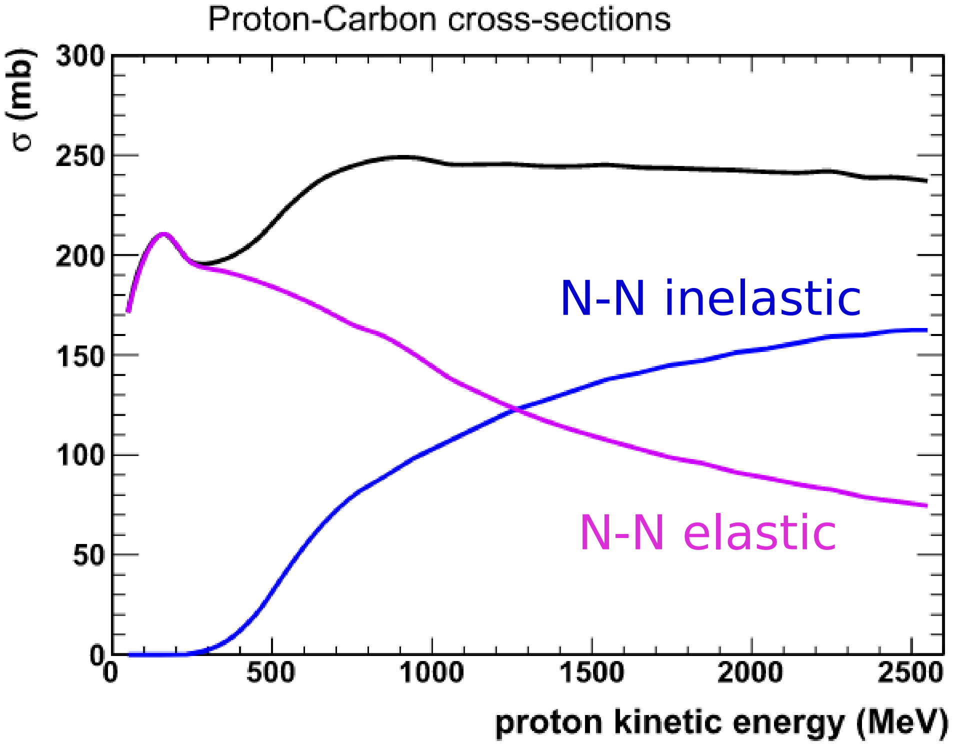
1.) Nucleon propagates in straight lines with step of 0.2 fm

2.) Check for interaction based on density and in-medium nucleon-nucleon CS

3.) Pauli-blocking: Reaction products must be above p_{Fermi}

4.) Track created particles on the way

Eur. Phys. J. Spec. Top. (2021) 230:4469–4481



Differences with ROP:

Explicit description of reaction products

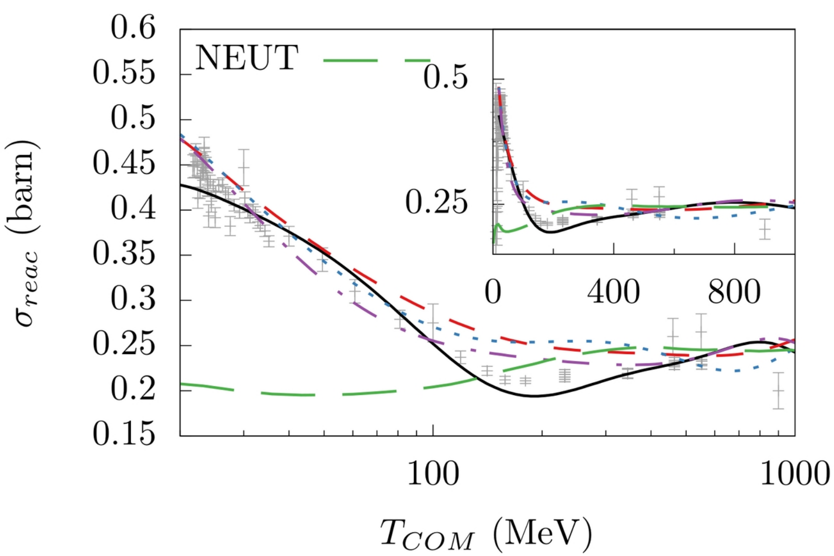
No elastic FSI

Interactions only with constituent nucleons

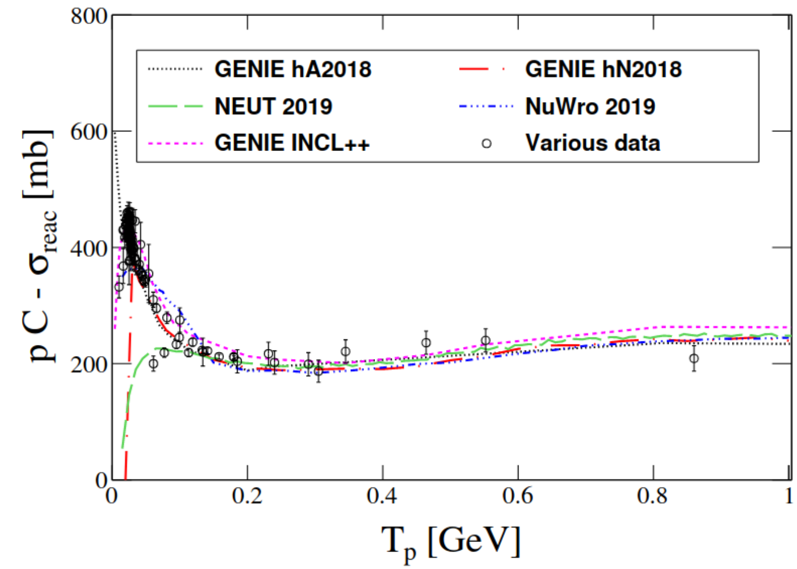
Cascade does not affect inclusive CS

Nucleon – nucleus scattering

Used as benchmark (and/or input) to INC

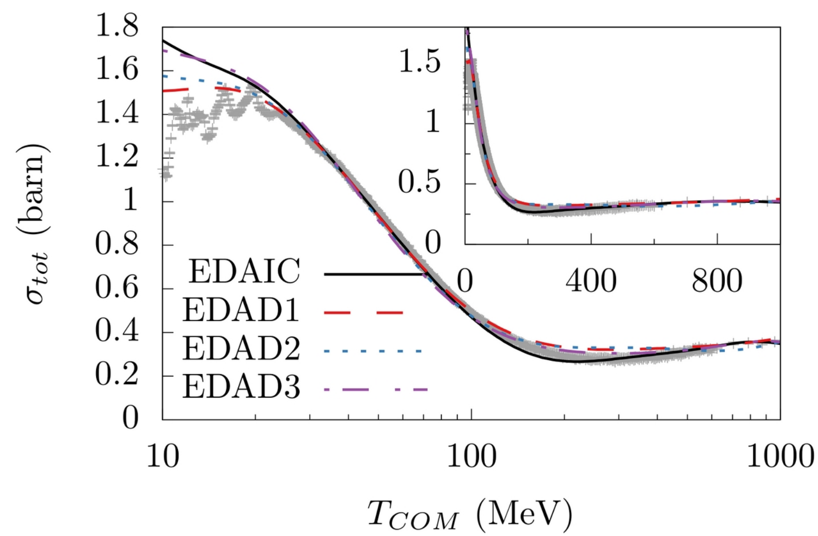


[Dytman et al. PRD104, 053006]



$$\sigma_{tot} = \sigma_{reac} + \sigma_{el}$$

In NEUT σ_{el} is not modeled



Avoiding incl-excl mismatch: rROP input

Generated unfactorized RDWIA events as input to cascade

Events are 1p 1μ with T2K flux
Distributed according to →

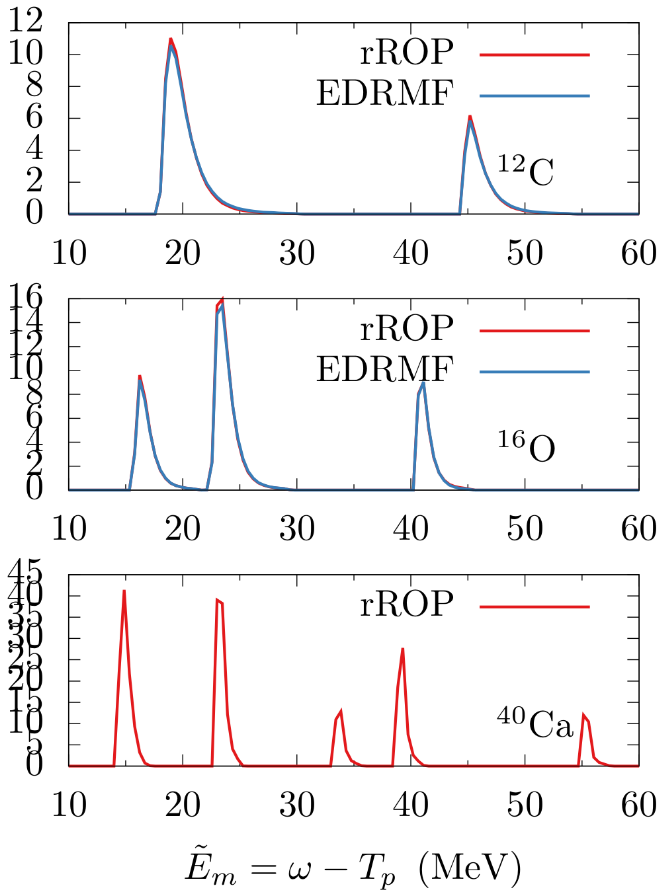
$$\langle \frac{d^6\sigma}{\mathrm{d}k_l \mathrm{d}\Omega_l \mathrm{d}p_N \mathrm{d}\Omega_N} \rangle = \int \mathrm{d}E_m \, \phi(E) \times \mathcal{F} \frac{k_l^2 p_N^2 M_B^*}{(2\pi)^5 E_B f_{rec}} \ell_{\mu\nu} H^{\mu\nu} \, ,$$

Avoiding incl-excl mismatch: rROP input

Generated unfactorized RDWIA events as input to cascade

Events are 1p 1μ with T2K flux

Single-particle states for GS are included →



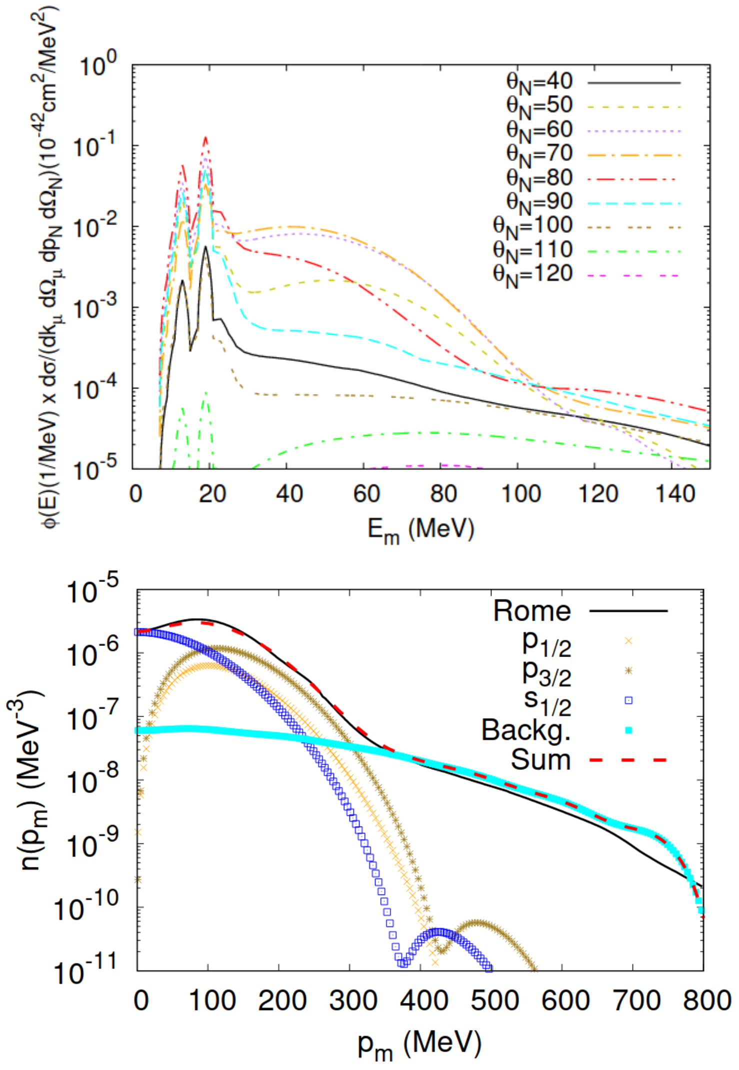
Avoiding incl-excl mismatch: rROP input

Generated unfactorized RDWIA events as input to cascade

Events are 1p 1μ with T2K flux

Single-particle states for GS

See [RGJ et al. PRC105, 025502] →
For inclusion of effective SF



Avoiding incl-excl mismatch: rROP input

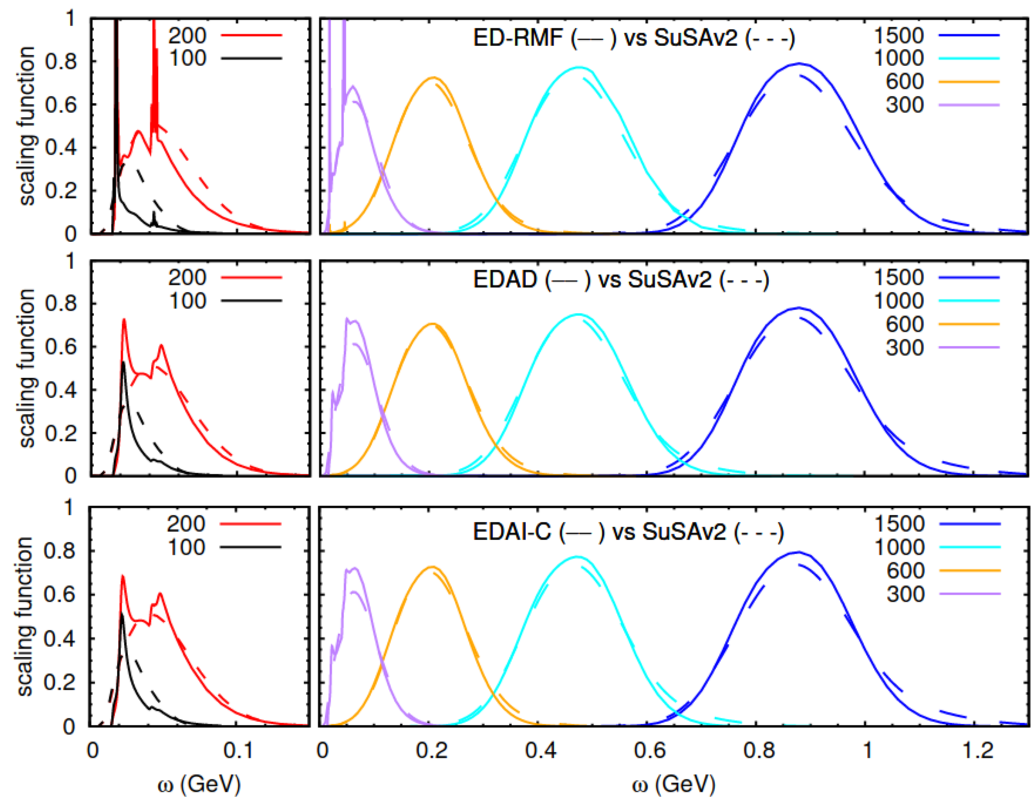
Generated unfactorized RDWIA events as input to cascade

Events are 1p 1μ with T2K flux

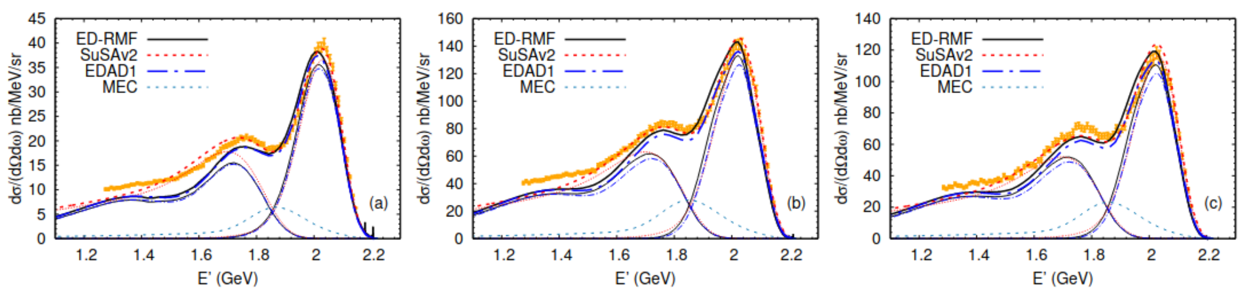
Single-particle states for GS

Motivation:

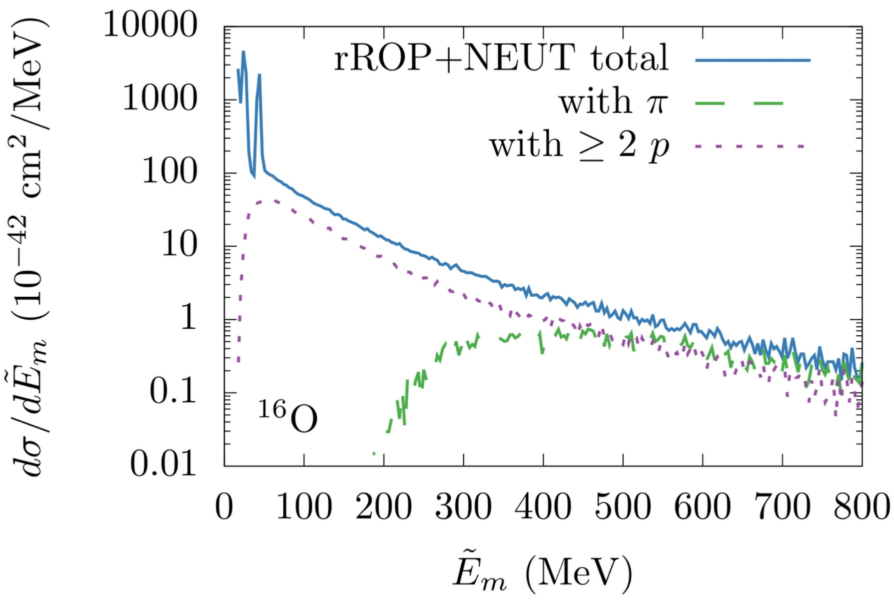
- Realistic inclusive cross section is retained with cascade
- rROP modifies dispersion relation in nucleus → not included in cascade ’elastic FSI’

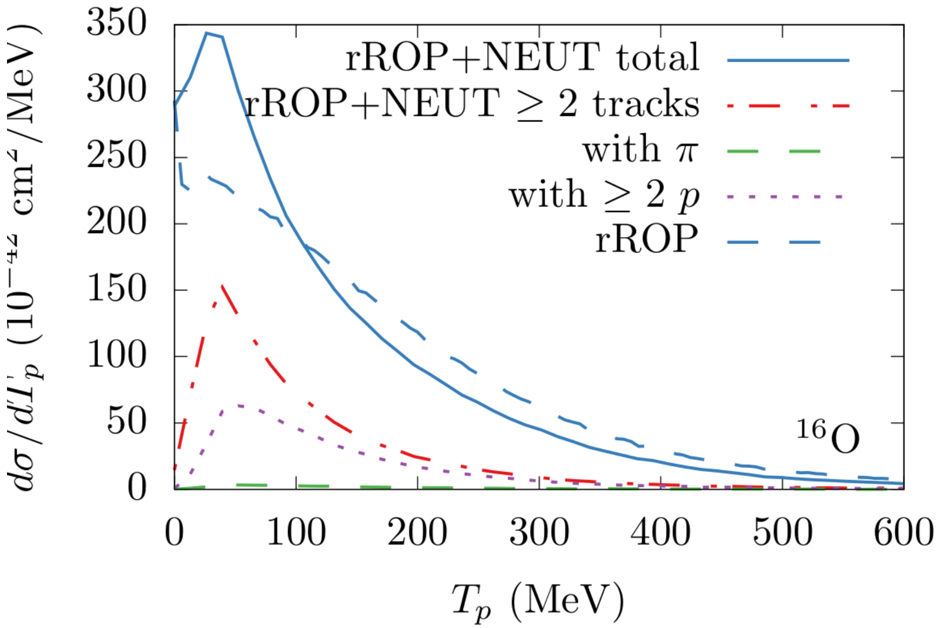


[RGJ et al. PRC101, 015503]



NEUT Cascade with rROP input





Simplified missing energy:

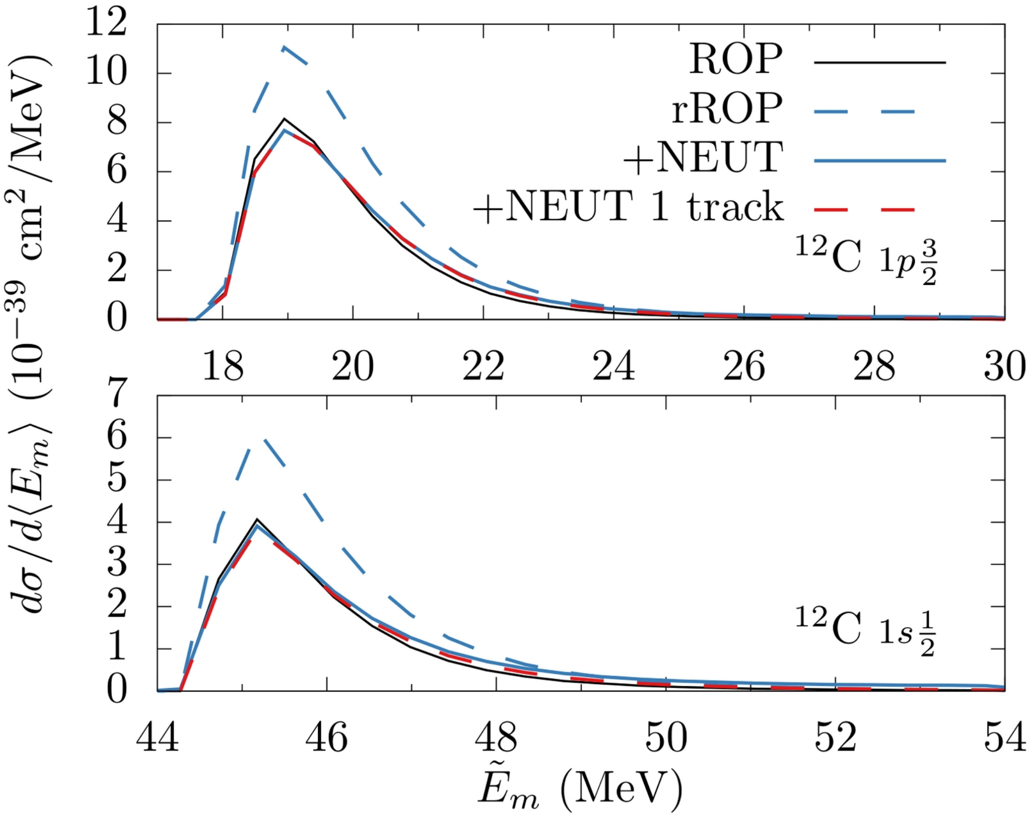
$$\tilde{E}_m = E_i - E_l - T_p$$

T_p is leading proton

RDWIA with ROP removes inelastic FSI from signal

→ Need to remove it from NEUT output

Selecting ‘elastic’ events



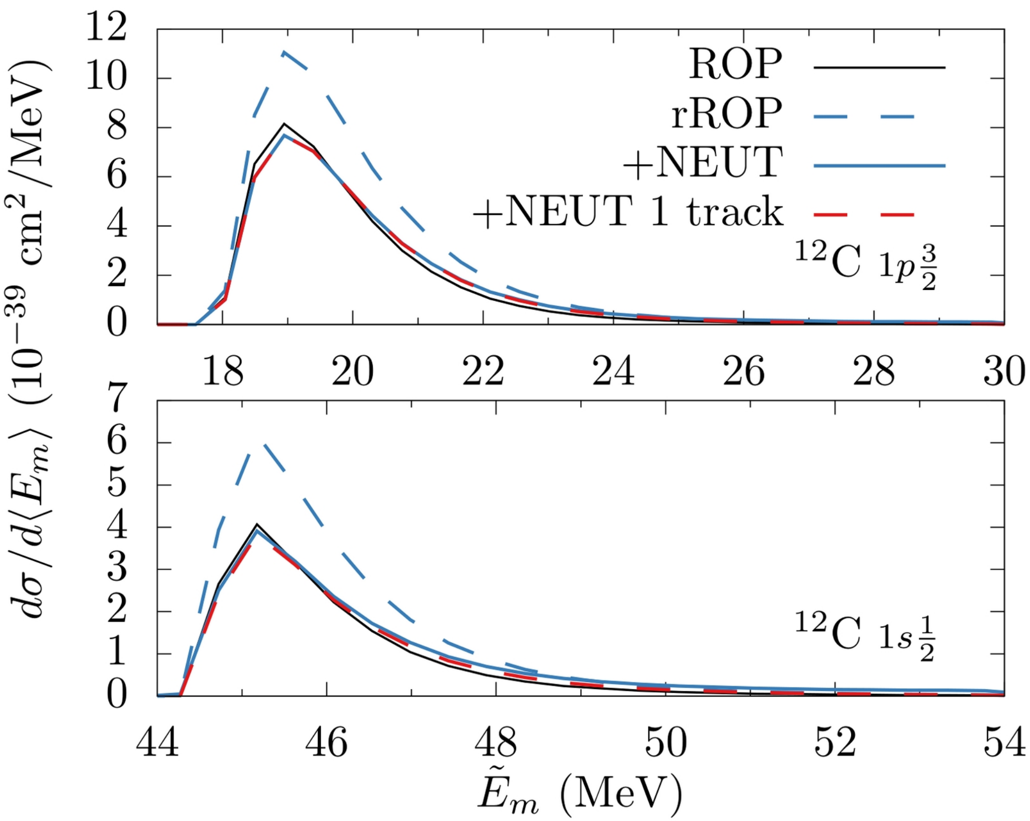
In NEUT any interaction will produce additional particle tracks

→ 1 track events ‘nothing happens’

→ Is equivalent to selecting missing energy from the shell-model region

A cut on E_m makes NEUT and ROP comparable

Selecting 'elastic' events



In NEUT any interaction will produce additional particle tracks

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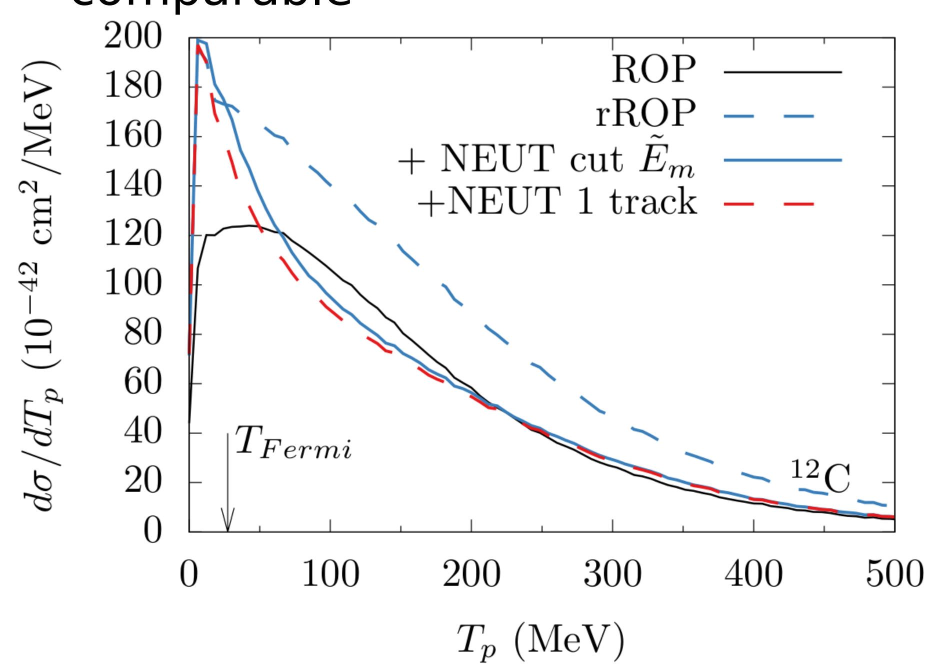
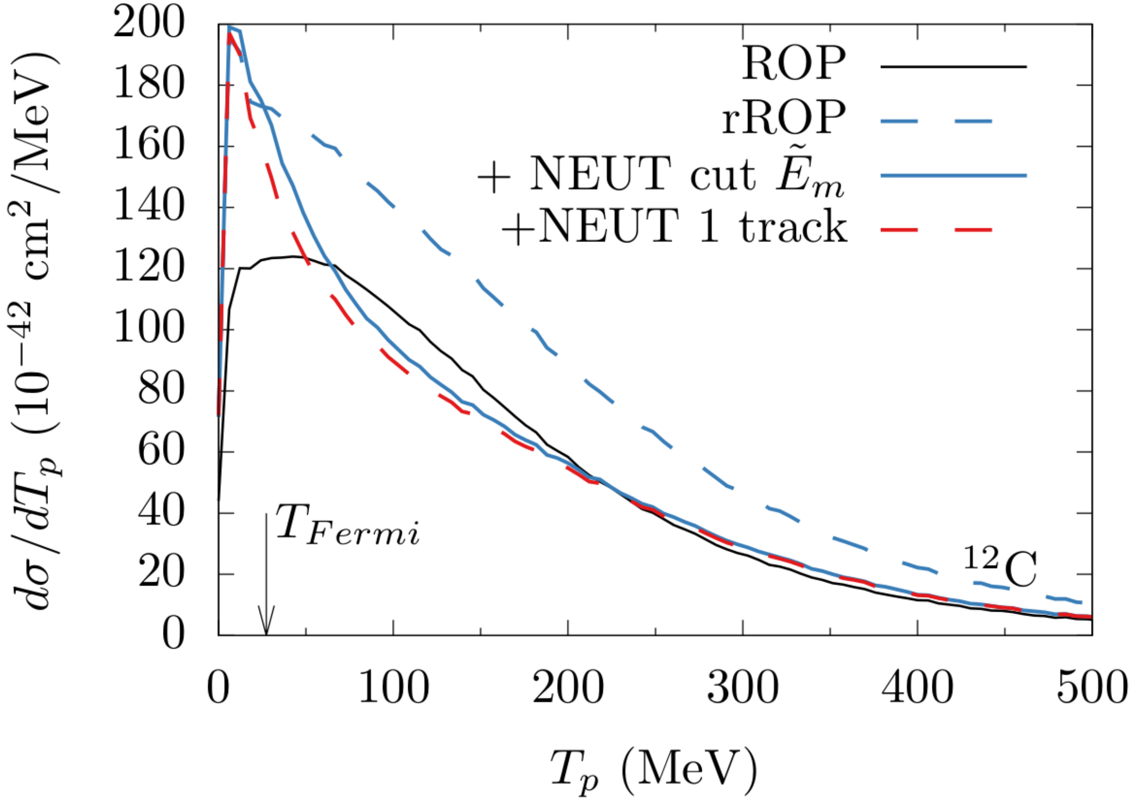
A cut on E_m makes NEUT and ROP comparable



rROP+NEUT and ROP for carbon

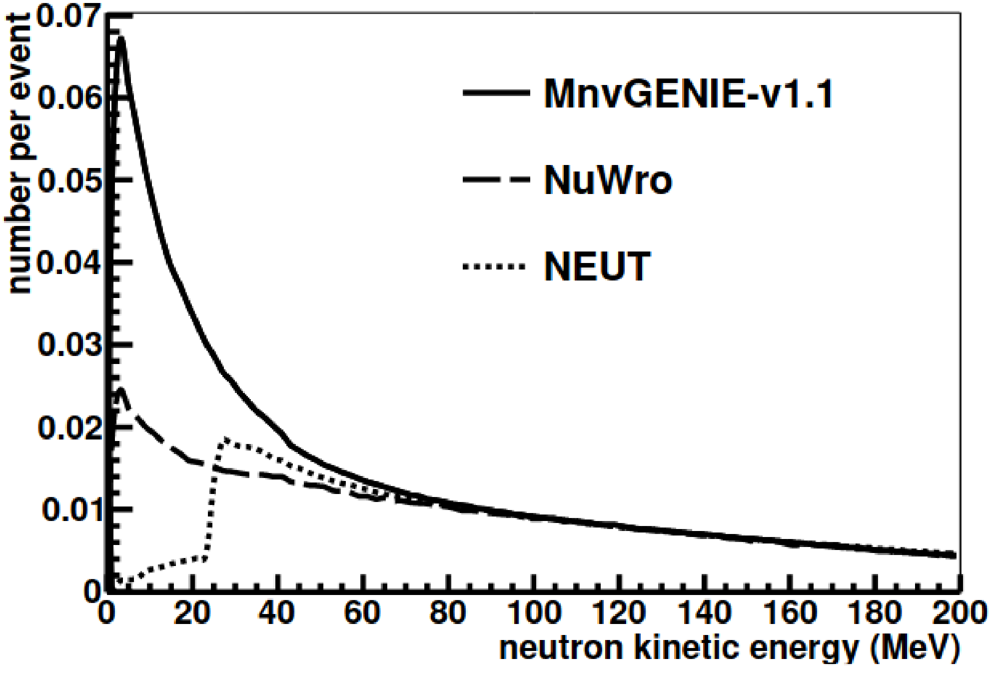


Agreement for T_p large (T_p > 150 MeV)

Disagreement at small T_p

Below (local) T_F : Pauli-blocking
The cascade lets all nucleons escape without interaction

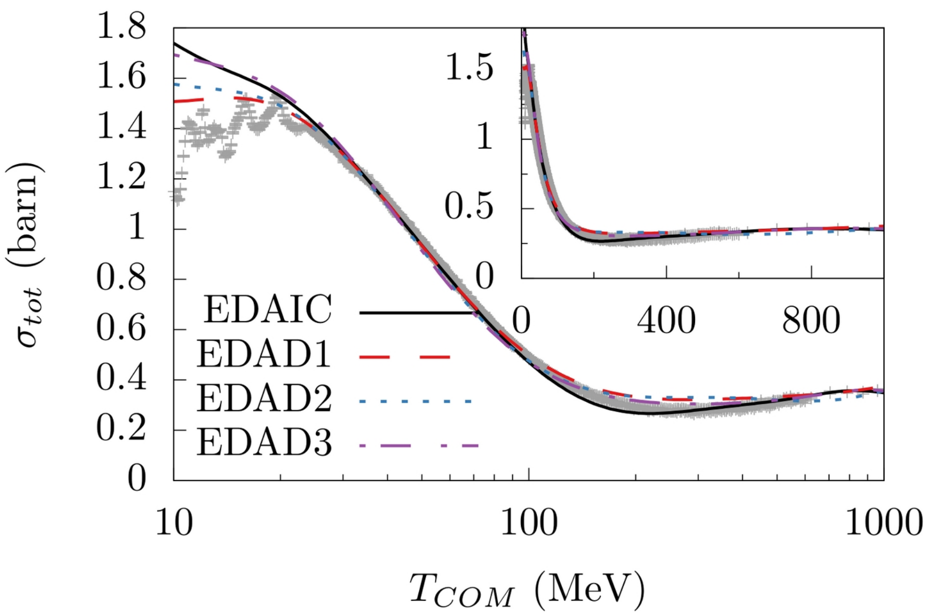
rROP+NEUT and ROP for carbon

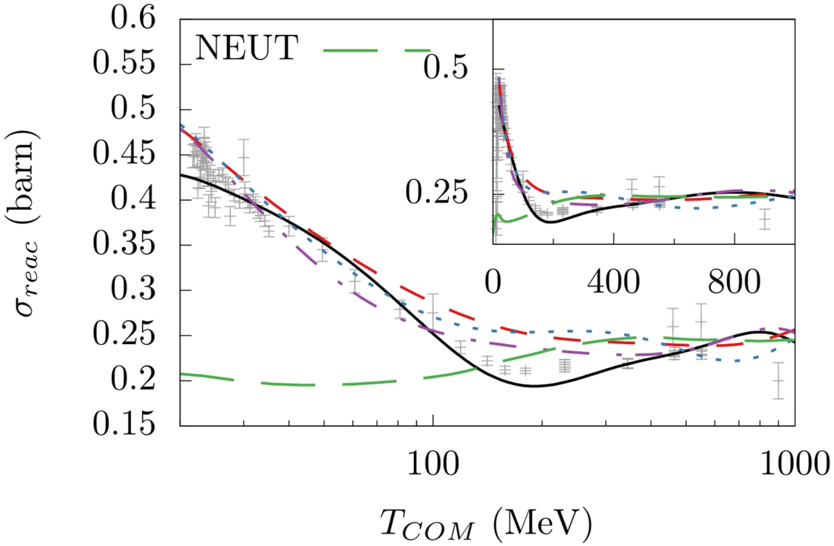


[MINERvA PRD100, 052002]

Important:
E.g. large differences in produced neutrons at low T_n

rROP+NEUT and ROP for carbon



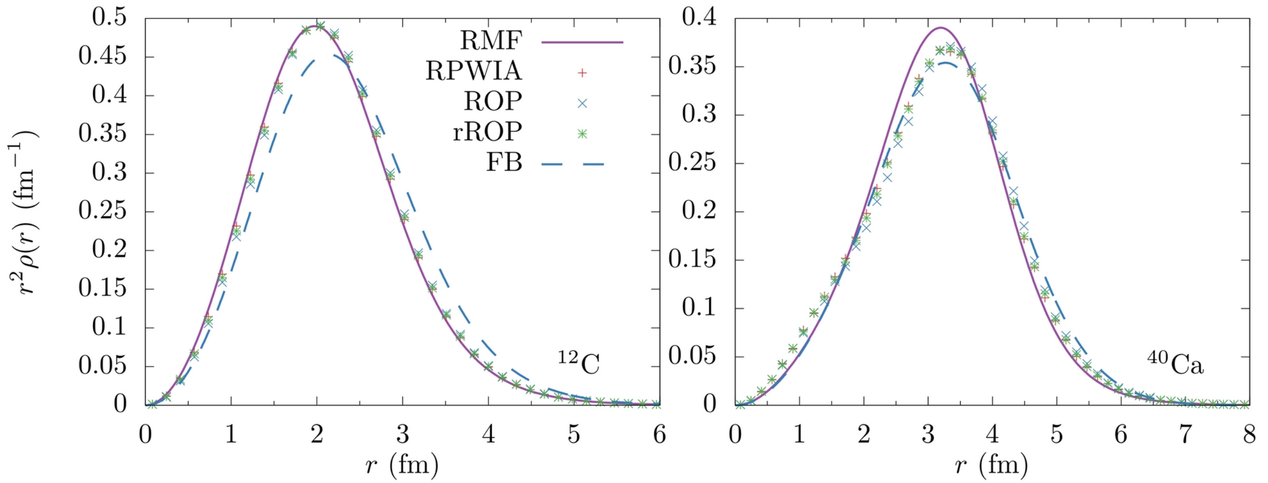


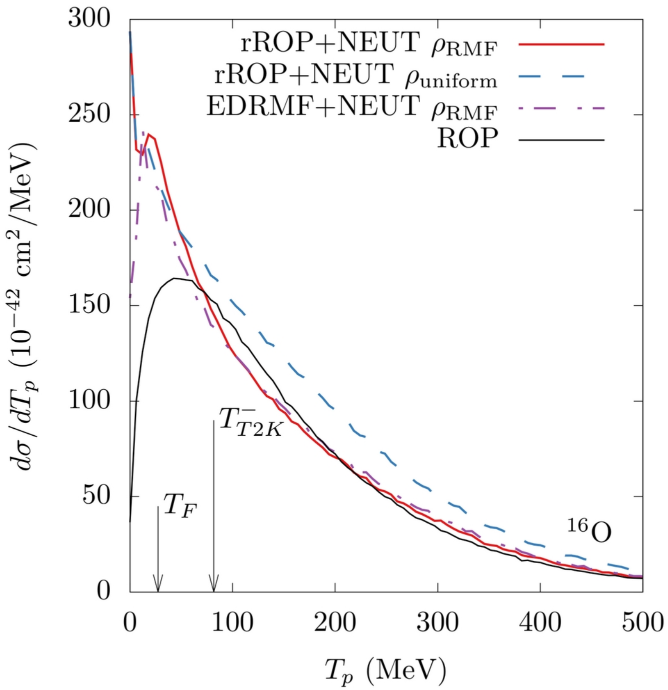
Important:
E.g. large differences in produced neutrons at low T_n

At small energy optical model 'breaks down'

Should be more suitable than INC

Dependence on radius



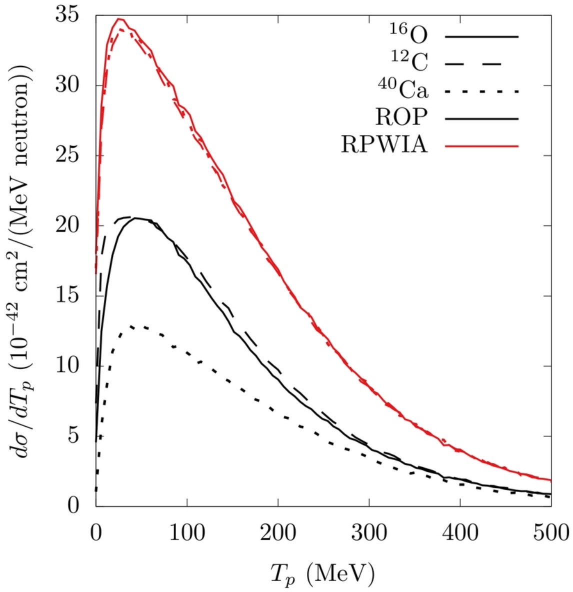


Introduce events at CS-weighted density

→ Resulting distribution similar to GS density

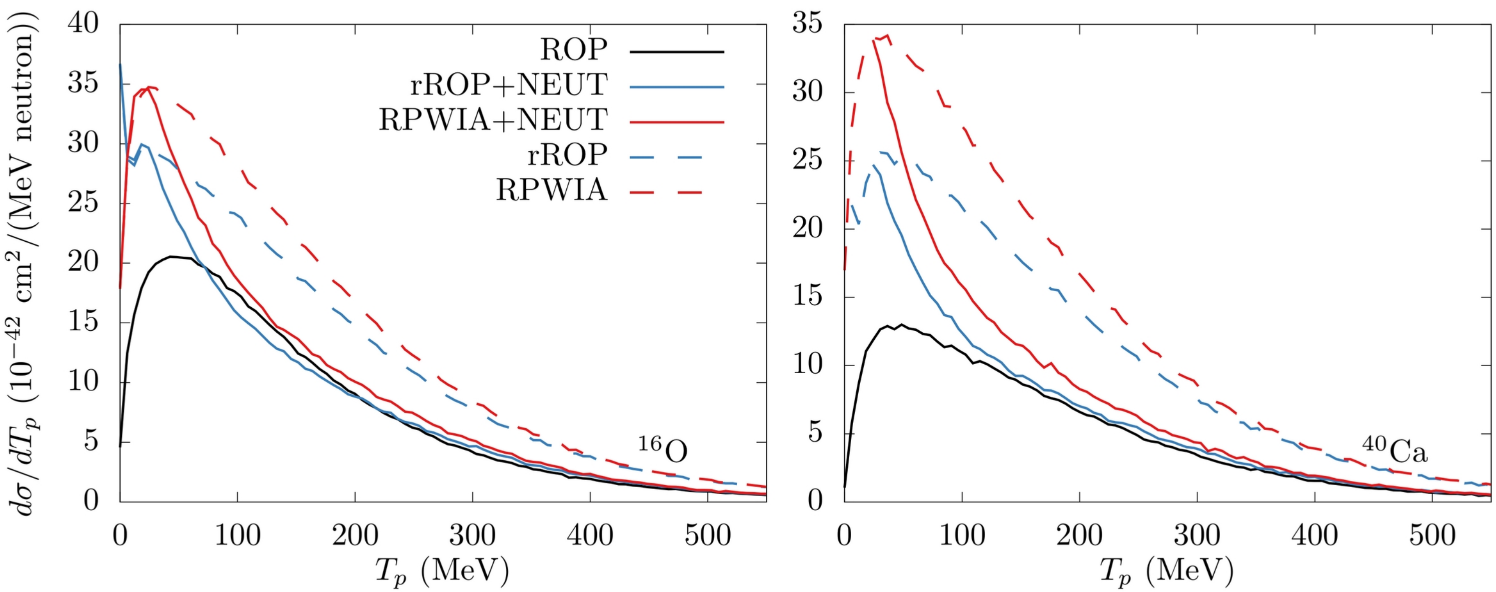
→ Agreement between ROP and INC is lost when uniform sperical density is used

A-dependence

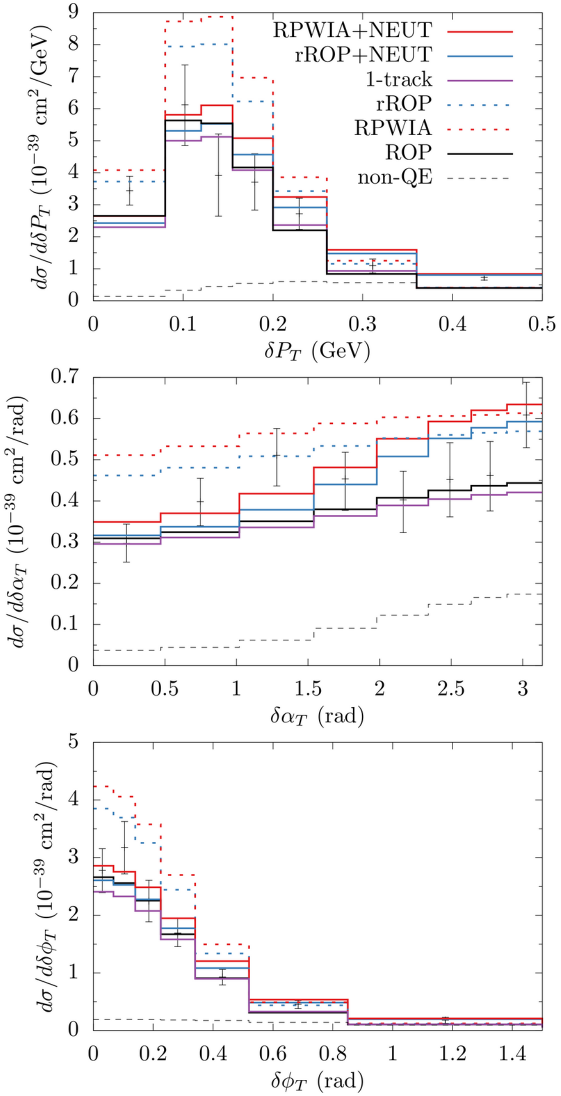


RPWIA cross section scales per active nucleon
ROP cross section does not (transparency decreases with A)

NEUT results similar for C, O, and Ca
Slightly better for rROP compared to RPWIA



Transverse Kinematic Imbalance



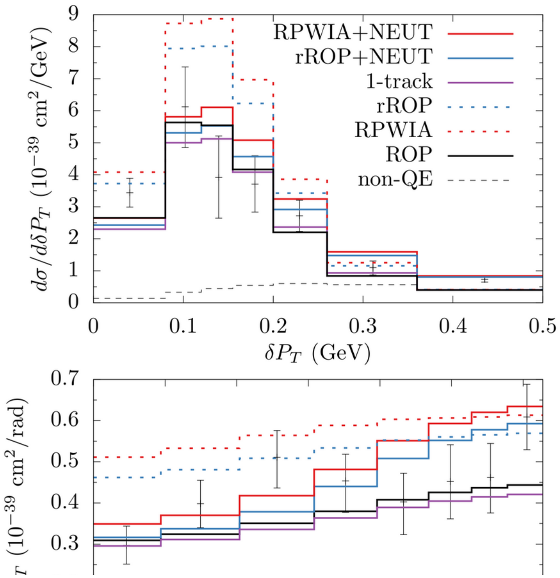
Non-QE from [Bourguille et al. JHEP04(2021)004]

Because p_p > 450 MeV low energy differences are not seen

Effect of non-elastic FSI visible in P_T and α_T

Large non-QE ‘background’ not separable from FSI effects

Transverse Kinematic Imbalance



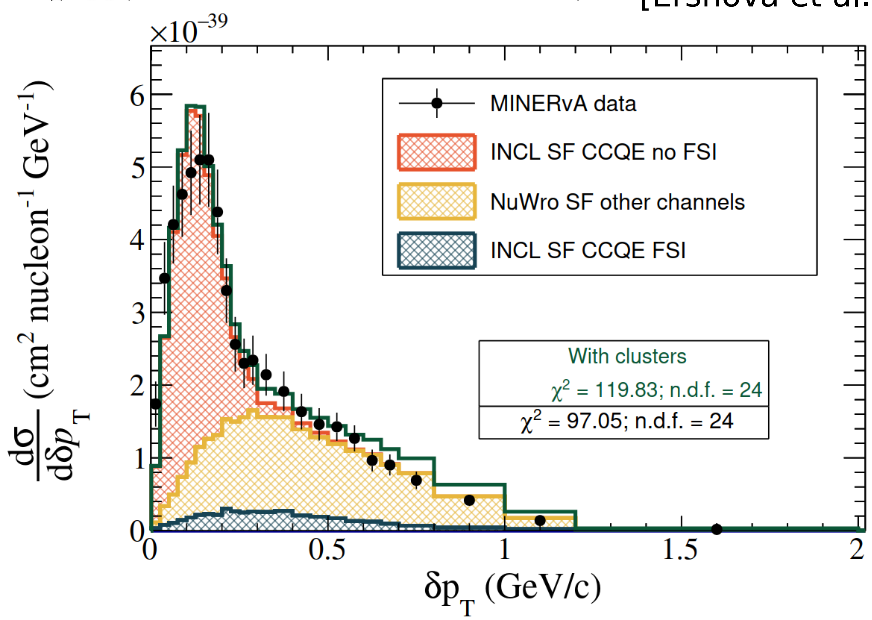
Because p_p > 450 MeV low energy differences are not seen

Effect of non-elastic FSI visible in P_T and α_T

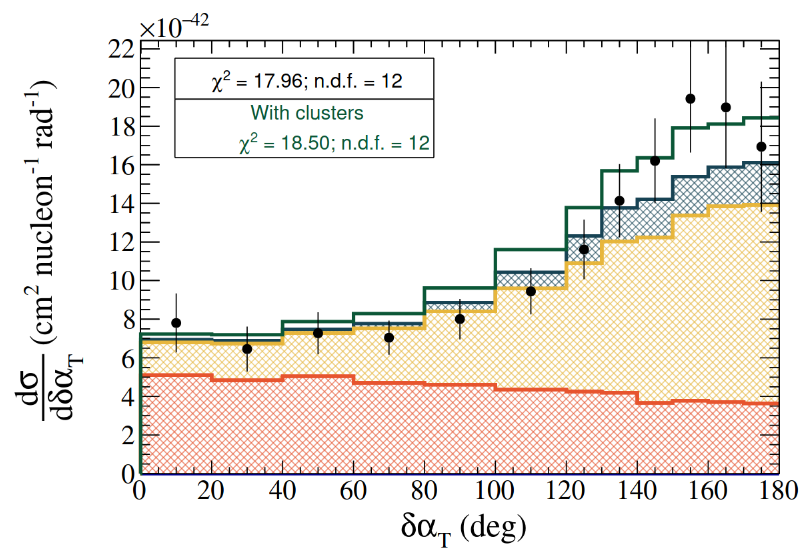
Large non-QE ‘background’ not separable from FSI effects

Similar degeneracy in MINERvA data:

[Ershova et al. ArXiv:2202.10402]

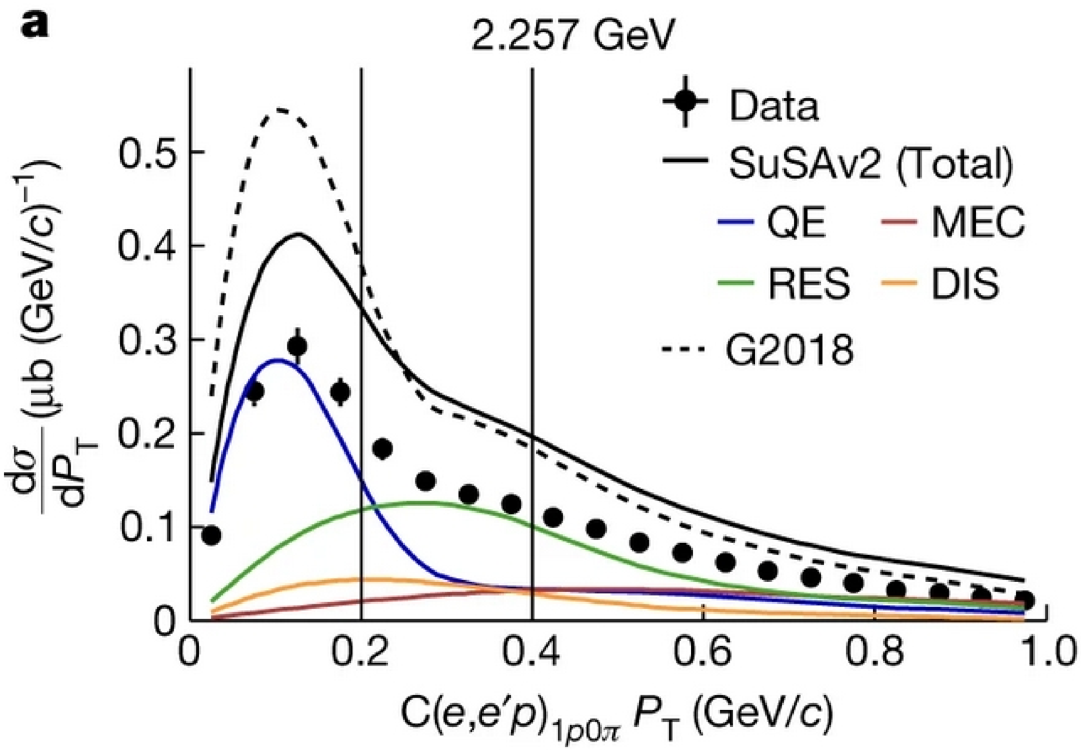


N

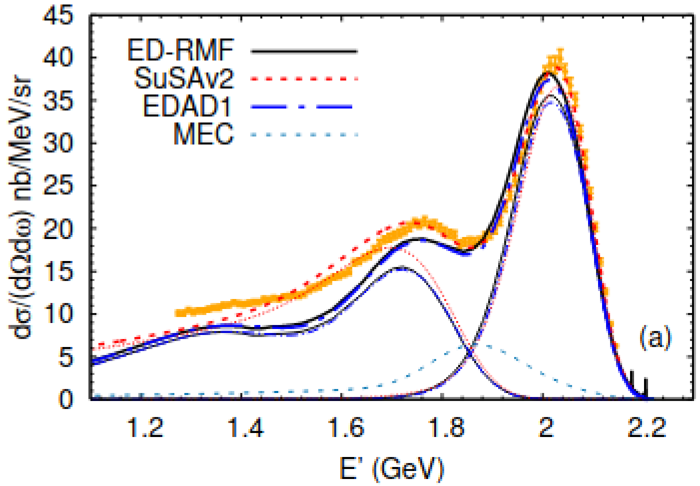


Degeneracy of interaction channels

Is reduced, but not removed by fixing incoming energy



[M. Khachatryan et al. Nature 599, 565]



[RGJ et al. PRC101, 015503]

Degeneracy of interaction channels

Is reduced, but not removed by fixing incoming energy

Is removed by restricting the energy/momentum of residual system

Restricted kinematics

$$l + A \rightarrow l' + N + B$$

Unrestricted kinematics

exclusive
(e,e’p)

Fixed nucleon and lepton kinematics

Severely restrict E_m

Learn nuclear structure and Reduce FSI and kinematic effects

Fixed-E experiment
(ν_l,l’p) or (e,e’p)

Range of nucleon and lepton kinematics

<u>Restrict E_m to probe specific interaction mechanisms</u>

Accelerator
(ν_l,l’p)

Range of nucleon and lepton kinematics

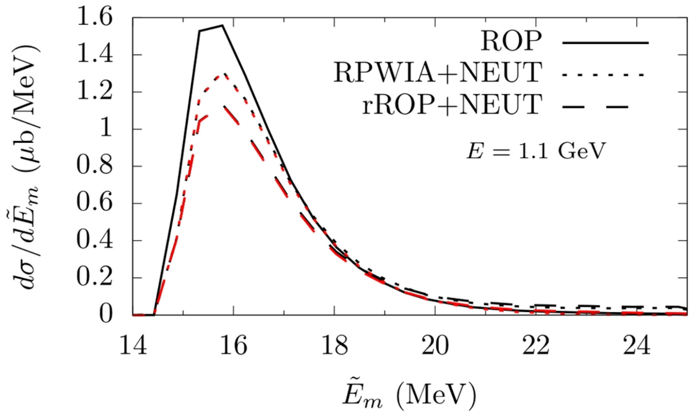
No E_m restriction possible

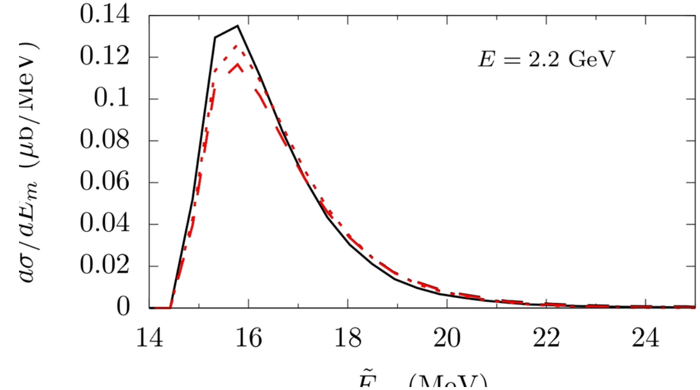
Degeneracy of interaction channels

Fixed-E experiment (e,e’p) in CLAS

Range of nucleon and lepton kinematics

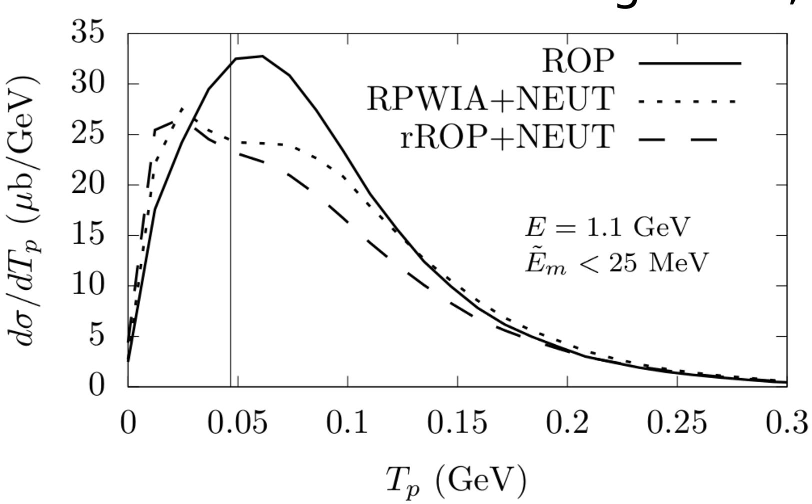
<u>Restrict E_m to probe specific interaction mechanisms</u>

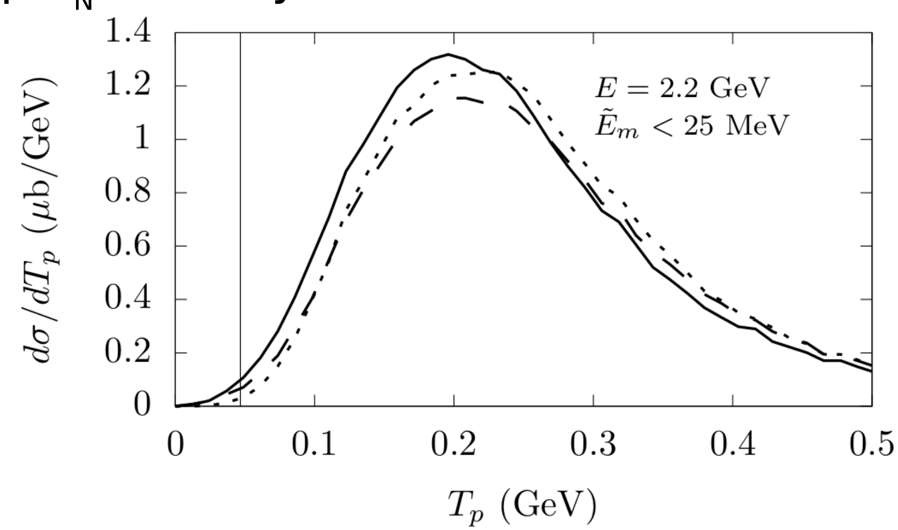




$$\tilde{E}_m < 25 \text{ MeV} \longrightarrow$$ No 2p2h, RES, inelastic FSI

But with full range of ω, q, T_N to study FSI





Conclusions

- (R)DWIA calculations in mean-field provide a robust description of inclusive electron scattering over a large mass range and reasonable agreement with neutrino data

- Serves as the basis for additional nuclear effects like in RPA

- Implementation of inclusive cross sections in event generators do not provide nucleon observables. The nucleon distributions obtained in the generator do not agree with exclusive RDWIA calculations

- Unfactorized 1 nucleon knockout calculations over the whole phase space can be used to generate events

- Direct comparison of optical potential approach and nuclear cascade is possible and sets constraints on cascade model from elastic p-A

- Agreement for high Energy and different targets validates the cascade
- Disagreement for low energy requires assessment!

- Restricting energy of the residual hadron system through fixed incoming energy can isolate interaction mechanisms and provide further insight in FSI

Hartree-Fock with effective Skyrme interaction

$$-\nabla\left[\frac{\hbar^2}{2m_q^*(\boldsymbol{r})}\nabla\phi_{\alpha_q}(\boldsymbol{r})\right]+[U_q(\boldsymbol{r})-i\boldsymbol{W}_q(\boldsymbol{r})\cdot(\nabla\times\sigma)]\phi_{\alpha_q}(\boldsymbol{r})=\varepsilon_{\alpha_q}^{\mathrm{HF}}\phi_{\alpha_q}(\boldsymbol{r})\,.$$

Density dependent effective mass and potential:

$$\frac{\hbar^2}{2m_q^*}(\boldsymbol{r})=\frac{\hbar^2}{2m_q}+\tfrac{1}{4}(t_1+t_2)\rho_{\mathrm{tot}}(\boldsymbol{r})+\tfrac{1}{8}(t_2-t_1)\rho_q(\boldsymbol{r})+\tfrac{1}{24}t_4(\rho_{\mathrm{tot}}^2(\boldsymbol{r})-\rho_q^2(\boldsymbol{r}))\,.$$

$$\begin{aligned}U_q(\boldsymbol{r})=t_0[(1+\tfrac{1}{2}x_0)\rho_{\mathrm{tot}}-(\tfrac{1}{2}+x_0)\rho_q]+\tfrac{1}{4}(t_1+t_2)\tau_{\mathrm{tot}}+\tfrac{1}{8}(t_2-t_1)\tau_q\\ +\tfrac{1}{8}(t_2-3t_1)\nabla^2\rho_{\mathrm{tot}}+\tfrac{1}{16}(3t_1+t_2)\nabla^2\rho_q+\tfrac{1}{4}t_3(\rho_{\mathrm{tot}}^2-\rho_q^2)\\ -\tfrac{1}{2}W_0'(\nabla\cdot\boldsymbol{J}_{\mathrm{tot}}+\nabla\cdot\boldsymbol{J}_q)+\delta_{qp}V^C(\boldsymbol{r})+\tfrac{1}{24}t_4[2\rho_{\mathrm{tot}}\tau_{\mathrm{tot}}-2\rho_q\tau_q\\ +\tfrac{5}{2}\rho_q\nabla^2\rho_q-\tfrac{5}{2}\rho_{\mathrm{tot}}\nabla^2\rho_{\mathrm{tot}}+\tfrac{5}{4}(\nabla\rho_q)^2-\tfrac{5}{4}(\nabla\rho_{\mathrm{tot}})^2+\tfrac{1}{2}J_{q'}^2]\,,\end{aligned}\tag{2.11}$$

With density:

$$\rho_q(\boldsymbol{r})=\sum_{\alpha_q\gamma_q}\rho_{\alpha\gamma}^{(q)}\phi_{\alpha_q}^*(\boldsymbol{r})\phi_{\gamma_q}(\boldsymbol{r})\,,$$

→ Iterate for self-consistent solution

Relativistic mean field with nlsω interaction

$$\begin{aligned}\mathcal{L} &= \overline{\Psi}\left(i\gamma_\mu\partial^\mu - M\right)\Psi + \frac{1}{2}\left(\partial_\mu\sigma\partial^\mu\sigma - m_\sigma^2\sigma^2\right) - U(\sigma)\\ &- \frac{1}{4}\Omega_{\mu\nu}\Omega^{\mu\nu} + \frac{1}{2}m_\omega^2\omega_\mu\omega^\mu - \frac{1}{4}\mathbf{R}_{\mu\nu}\mathbf{R}^{\mu\nu} + \frac{1}{2}m_\rho^2\boldsymbol{\rho}_\mu\boldsymbol{\rho}^\mu - \frac{1}{4}F_{\mu\nu}F^{\mu\nu}\\ &- g_\sigma\overline{\Psi}\sigma\Psi - g_\omega\overline{\Psi}\gamma_\mu\omega^\mu\Psi - g_\rho\overline{\Psi}\gamma_\mu\boldsymbol{\tau}\boldsymbol{\rho}^\mu\Psi - g_e\frac{1+\tau_3}{2}\overline{\Psi}\gamma_\mu A^\mu\Psi\,.\end{aligned}$$

Extension of the original σ-ω Walecka model (Ann. Phys.83,491 (1974)).

$$U(\sigma) = \tfrac{1}{3}g_2\sigma^3 + \tfrac{1}{4}g_3\sigma^4$$

$$\left[\hat{\alpha}\cdot\hat{\mathbf{p}} + \beta\left(m_N + S(r)\right) - \left(E - V(r)\right)\right]\psi = 0,$$

Where:

$$S(r) = g_\sigma\sigma(r)$$

$$V(r) = g_\omega\omega^0(r) + g_\rho\tau_3\rho_3^0(r) + e\frac{1+\tau_3}{2}A^0(r).$$

$$\begin{aligned}\left(\nabla^2 - m_\sigma^2\right)\sigma(r) &= g_\sigma\rho_s(r) + g_2\sigma^2(r) + g_3\sigma^3(r),\\ \left(\nabla^2 - m_\omega^2\right)\omega^0(r) &= g_\omega\rho_B(r),\\ \left(\nabla^2 - m_\rho^2\right)\rho_3^0(r) &= g_\rho\rho_I(r),\\ \nabla^2\sigma(r) &= -e\rho_e(r),\end{aligned}$$

Main approximations:

1) Mean-field approximation:

$\omega_\mu \rightarrow \langle\omega_\mu\rangle$ $\quad\sigma \rightarrow \langle\sigma\rangle$ $\quad\boldsymbol{\rho}_\mu \rightarrow \langle\boldsymbol{\rho}_\mu\rangle$

2) Static limit:

$\partial^0\omega_0 = \partial^0\boldsymbol{\rho}_0 = \partial^0\sigma = 0$ $\quad\omega_\mu = \delta_{\mu 0}\omega_0\,,\quad \boldsymbol{\rho}_\mu = \delta_{\mu 0}\boldsymbol{\rho}_0$

3) Spherical symmetry for finite nuclei:

$\omega_0 = \omega_0(r)$ $\quad\boldsymbol{\rho}_0 = \boldsymbol{\rho}_0(r)$ $\quad\sigma = \sigma(r)$

Solving the RPA equations in coordinate space

One gets coupled self-consistent integral equation for the radial transition densities :

$$\langle \Psi_0 || X_{\eta J} || \Psi_C(J;E) \rangle_r \quad = \quad - \langle h || X_{\eta J} || p(\varepsilon_{ph}) \rangle_r$$
$$+ \quad \sum_{\mu,\nu} \int dr_1 \int dr_2 \; U^J_{\mu\nu}(r_1, r_2) \; \mathcal{R} \left(R^{(0)}_{\eta\mu;J}(r, r_1; E) \right) \; \langle \Psi_0 || X_{\nu J} || \Psi_C(J;E) \rangle_{r_2}$$

Solved numerically by discretizing on a mesh in coordinate space
Translates into a matrix inversion for the transition densities:

$$\rho_C^{RPA} \; = \; - \frac{1}{1 - R\,U} \; \rho_C^{HF}$$