

# Neutrino Scattering: Connections Across Theory and Experiment



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**Raúl González Jiménez**

**University of Seville, Spain**

NSTAR Workshop, Sevilla.  
7-11 September, 2026

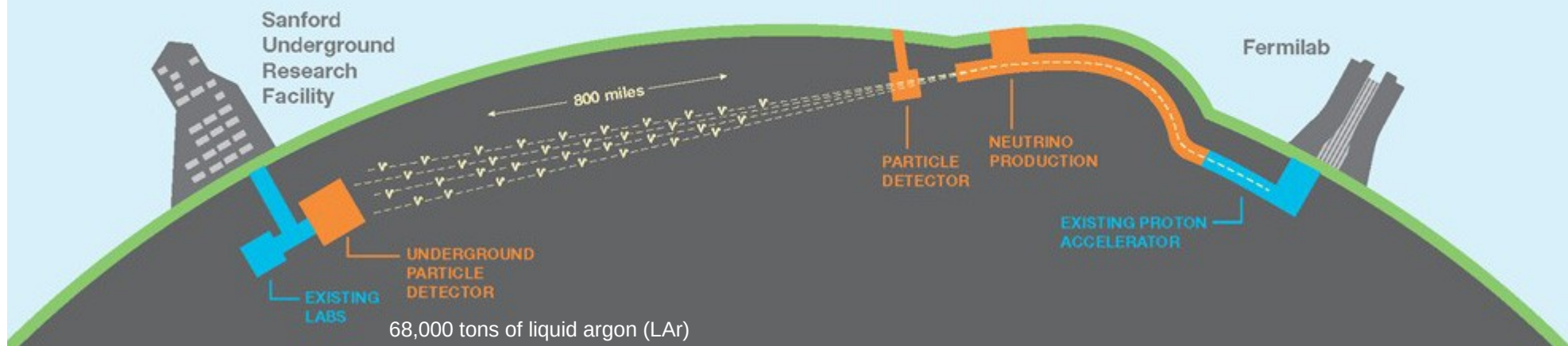
# Overview

1. Motivation: **neutrino energy reconstruction**
2. The *two-step* approach of **neutrino event generators**
3. **Inclusive** electron-scattering cross section
4. **Exclusive** electron-scattering cross section

# **Why Nuclear Models in Long-Baseline neutrino-oscillation programs?**

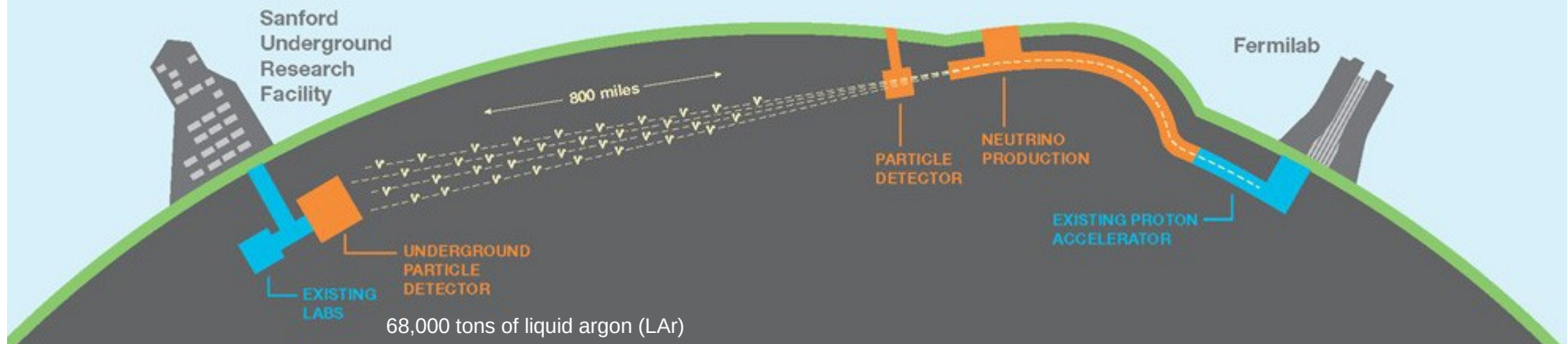
**Why Nuclear Models  
in Long-Baseline  
neutrino-oscillation programs?  
neutrino energy reconstruction**

# DUNE: Deep Underground Neutrino Experiment

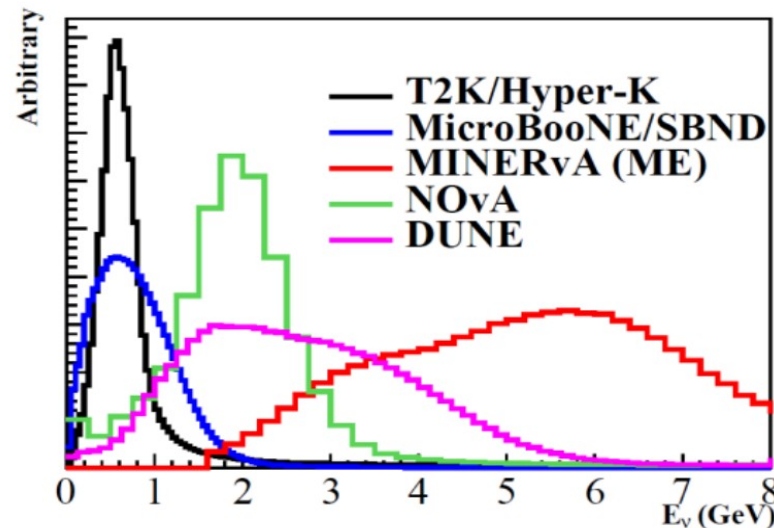


$$P_{a \rightarrow b} = \sin^2 2\theta \sin^2 \left( \frac{1.27 \Delta m^2 (\text{eV}^2) L (\text{km})}{E_\nu (\text{GeV})} \right),$$

# DUNE: Deep Underground Neutrino Experiment



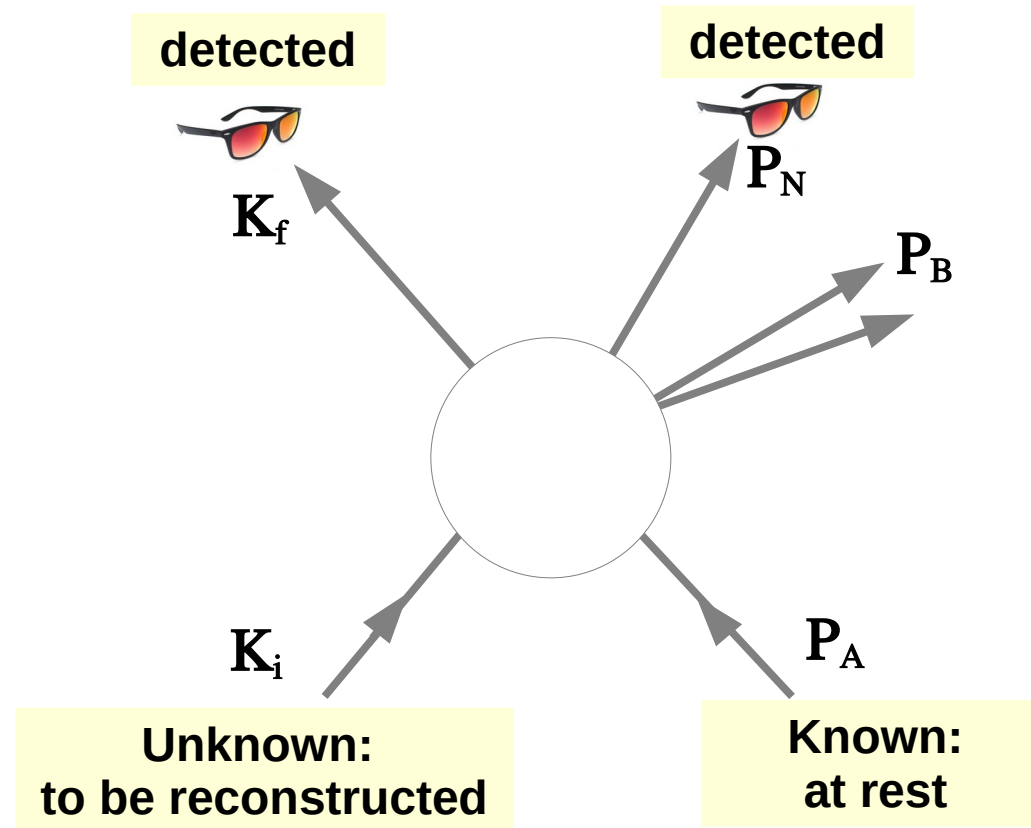
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neutrino fluxes

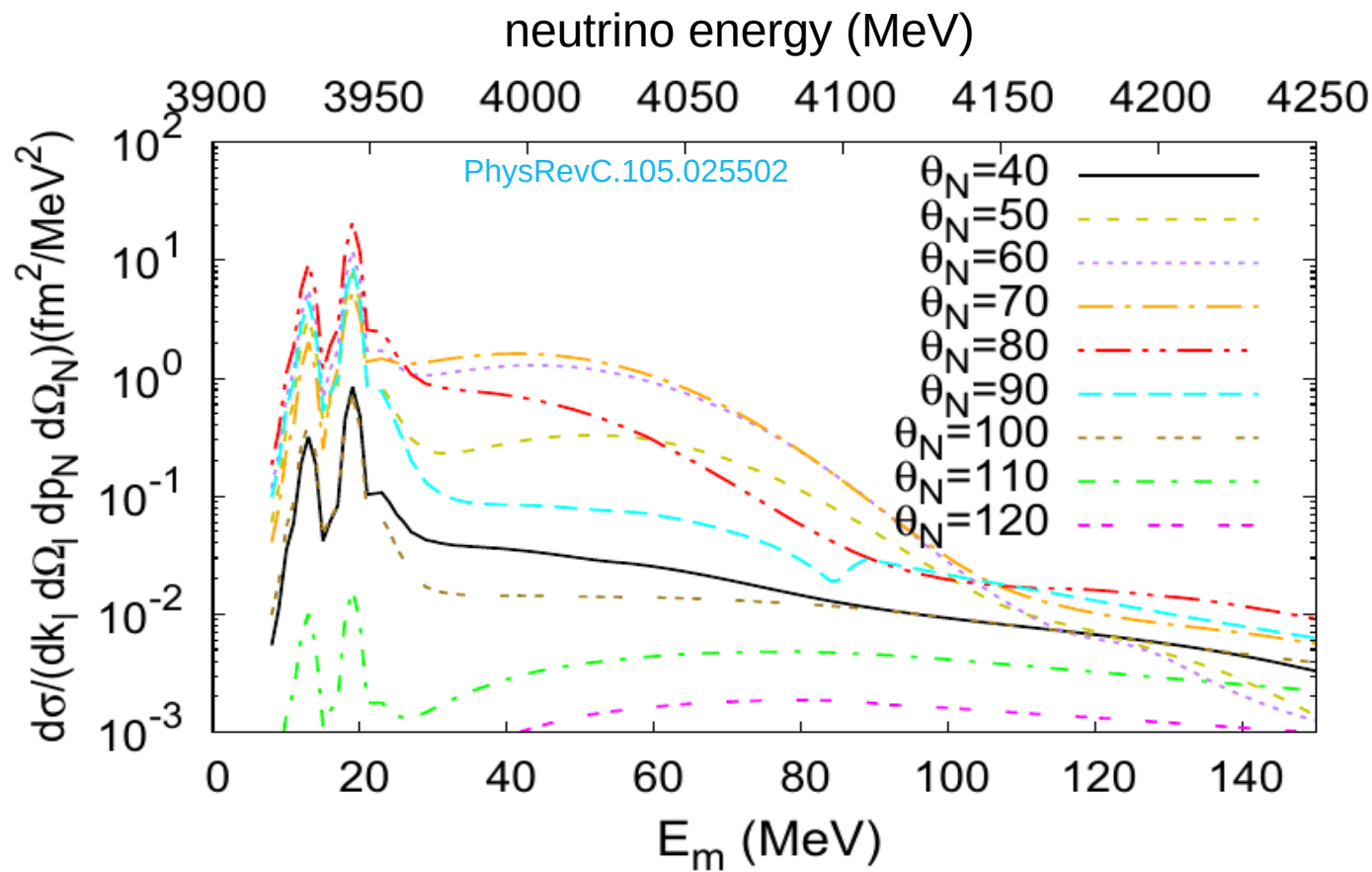
# Neutrino energy reconstruction

E.g., consider an event consisting in a muon and a proton



## Example of a kinematics:

$$E_f = 3800 \text{ MeV}, \theta_f = 7 \text{ deg}, T_N = 140 \text{ MeV}$$



6-differential cross section using the DUNE flux, shown as a function of the neutrino energy (top) and missing energy  $E_m$  (bottom axis).

**QE kinematics:**

$E_f = 3800$  MeV,

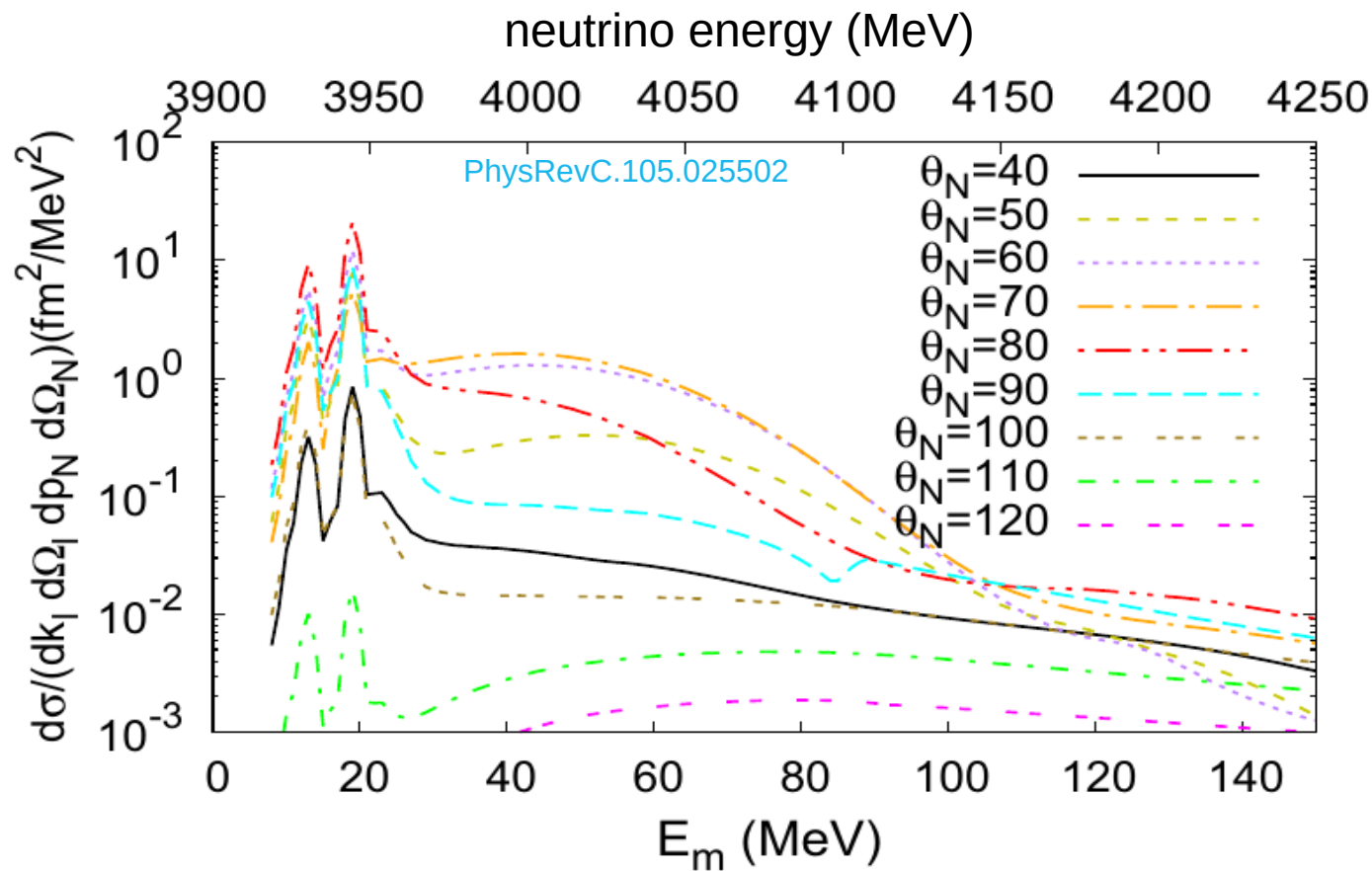
$\theta_f = 7$  deg,

$T_N = 140$  MeV,

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Each line corresponds to a different value of the proton scattering angle  $\theta_N$  (in degrees).

Actually, these cross section are (proportional to) the **probability distribution function of having an initial neutrino energy for the given muon and proton kinematics.**

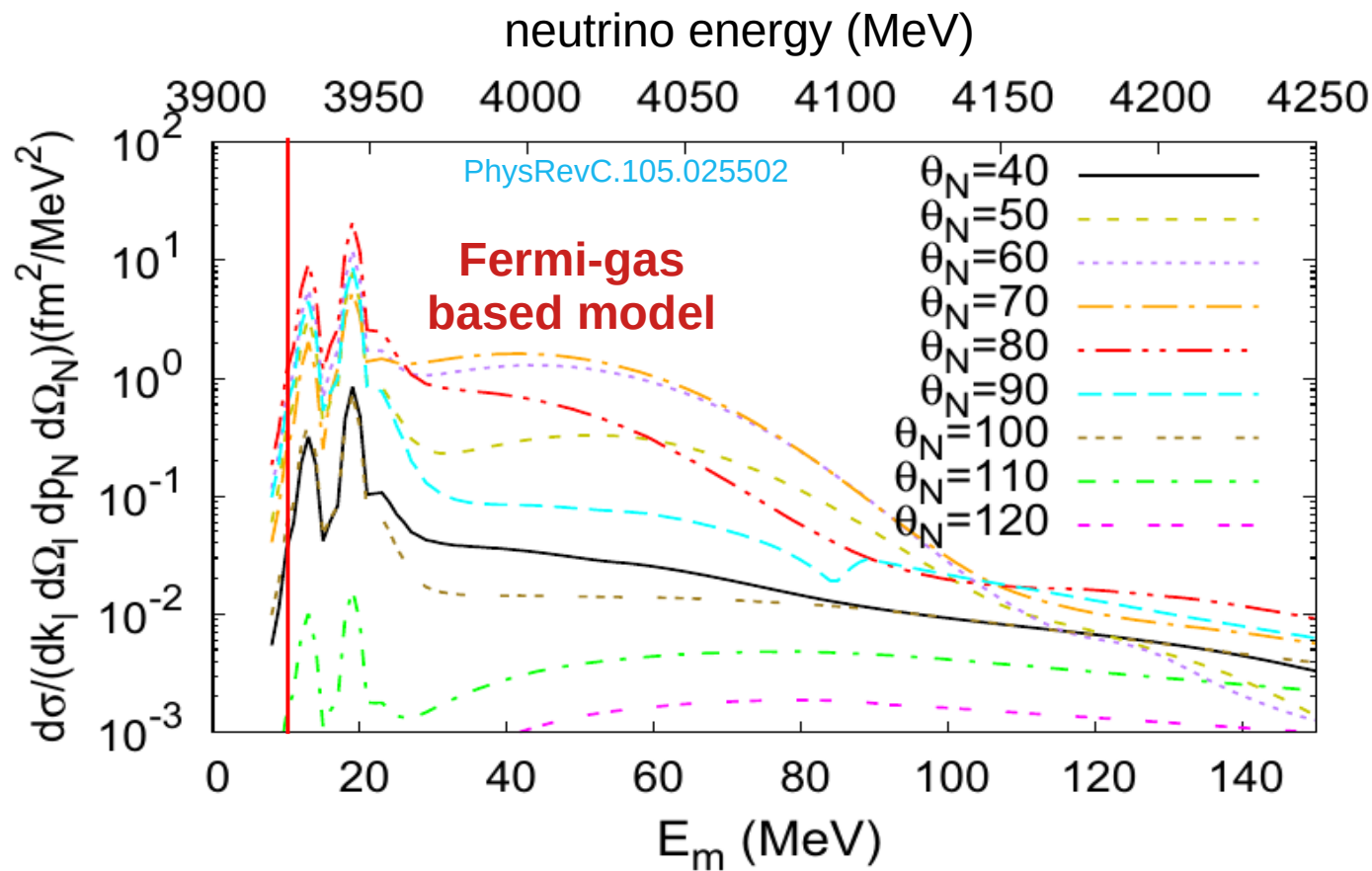


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Obviously, these distributions do depend on the nuclear model.

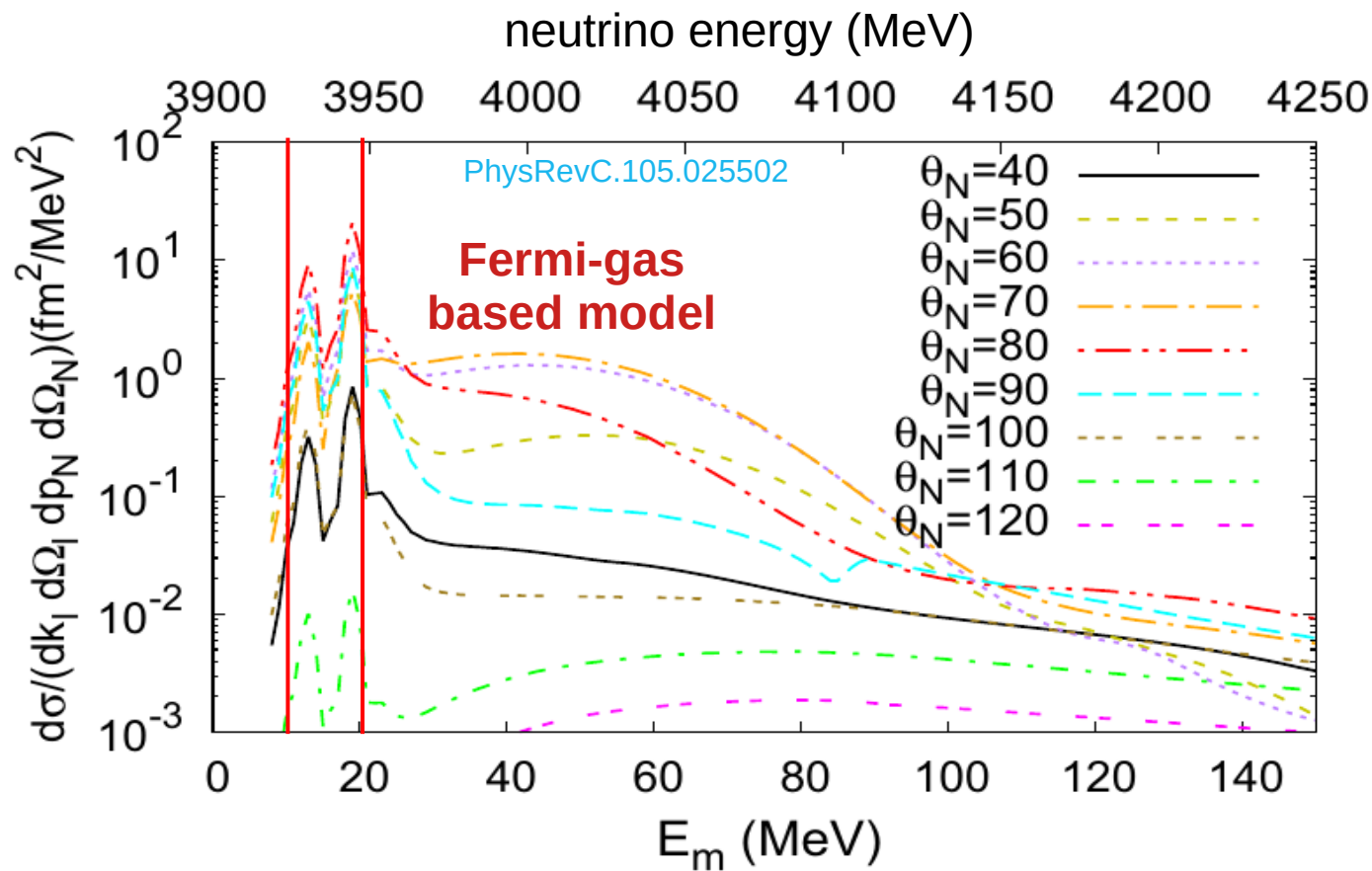


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In Fermi-gas based approaches, each event corresponds to a **unique neutrino energy**. Assuming a binding energy of 24 MeV, one gets:

| $\theta_N$ | $E_i \text{ (MeV)}$ |  |  |
|------------|---------------------|--|--|
| 40         | 3922                |  |  |
|            |                     |  |  |
|            |                     |  |  |
|            |                     |  |  |

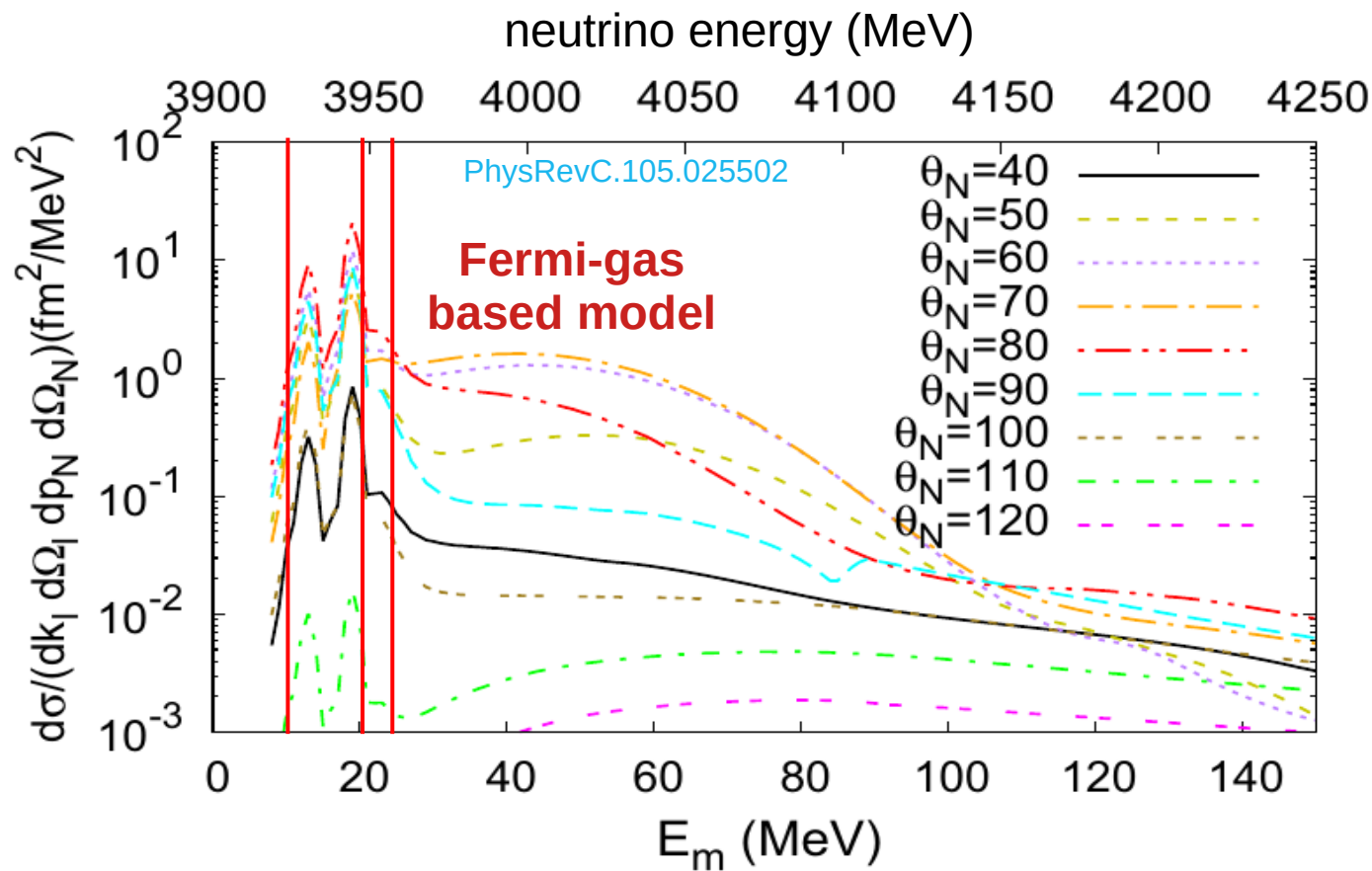


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| 50         | 3948        |  |  |
|            |             |  |  |
|            |             |  |  |



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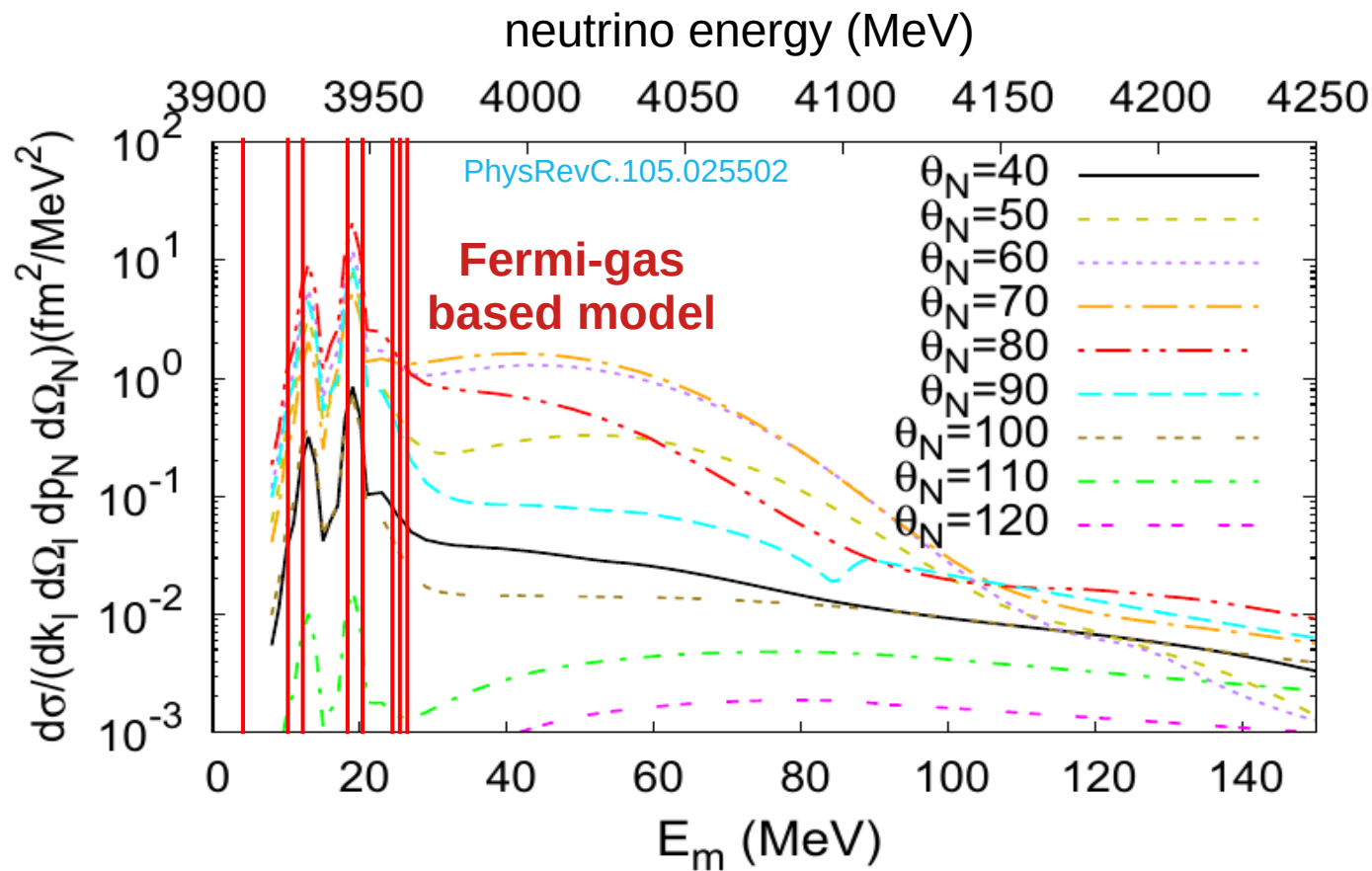
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| 50         | 3948        |  |  |
| 60         | 3961        |  |  |
|            |             |  |  |

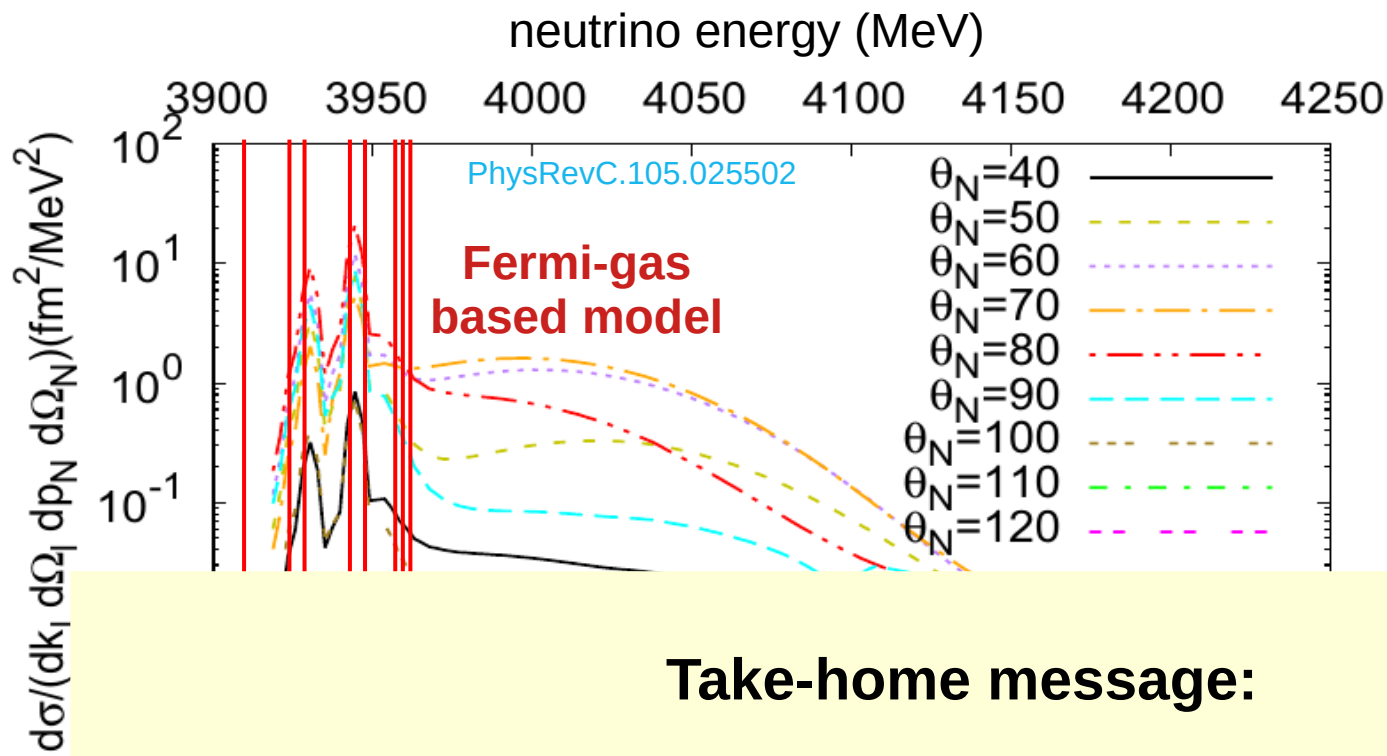


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| $\theta_N$ | $E_i$ (MeV) | $\theta_N$ | $E_i$ (MeV) |
|------------|-------------|------------|-------------|
| 40         | 3922        | 80         | 3957        |
| 50         | 3948        | 90         | 3945        |
| 60         | 3961        | 100        | 3929        |
| 70         | 3963        | 110        | 3910        |



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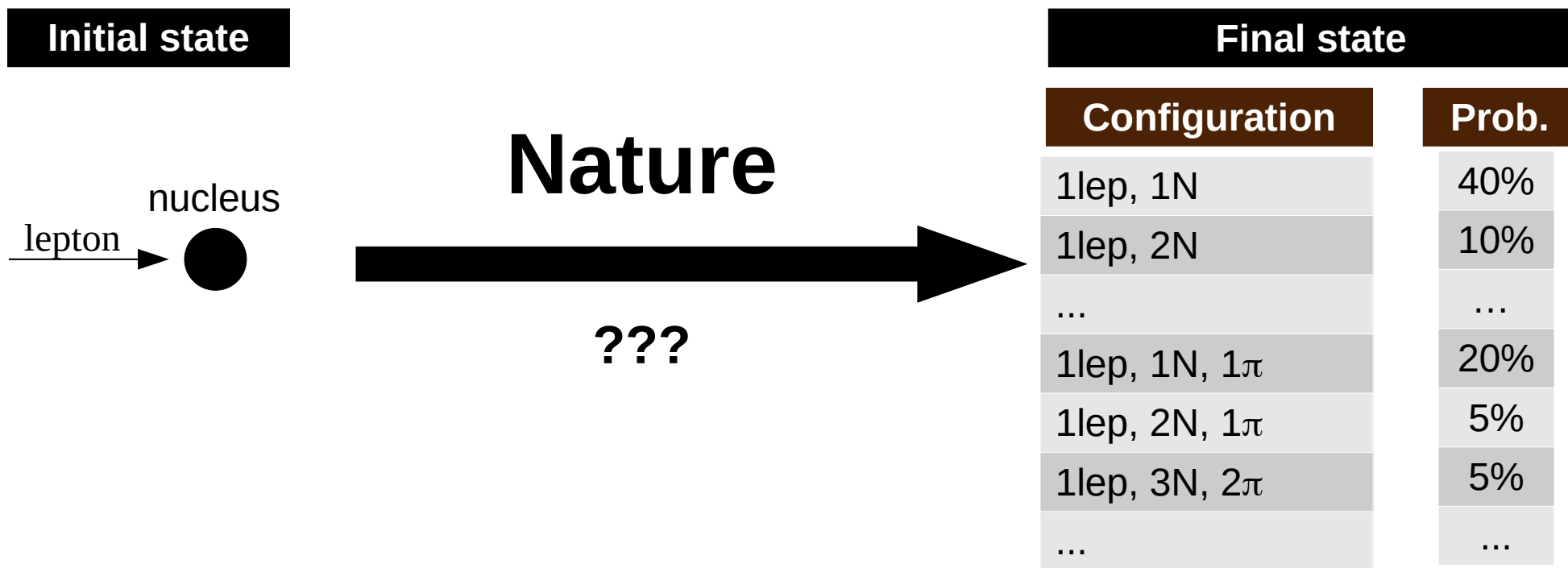
## Take-home message:

Neutrino energy reconstruction depends on the theoretical models

The better the nuclear model is, the better the estimate of the neutrino energy.

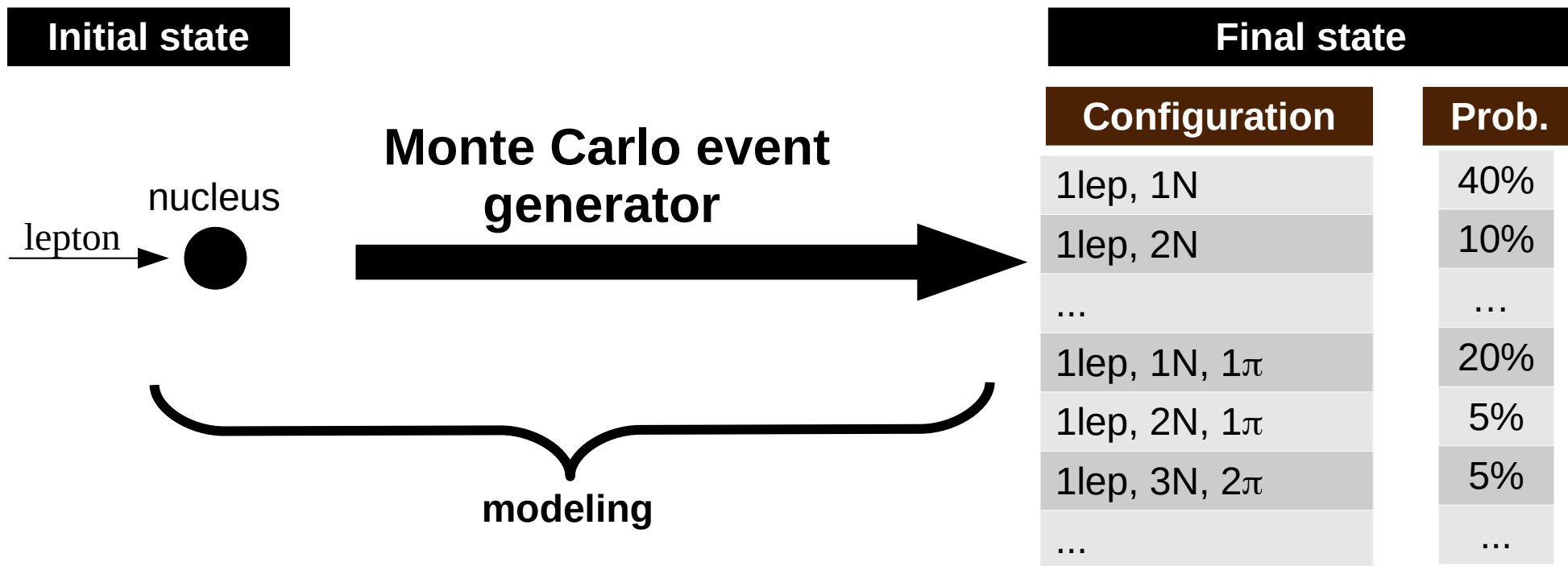
|    |      |     |      |
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# Monte Carlo neutrino event generators



**Nature:** there is an initial state and a final state, she does not inform us about what happens in the middle.

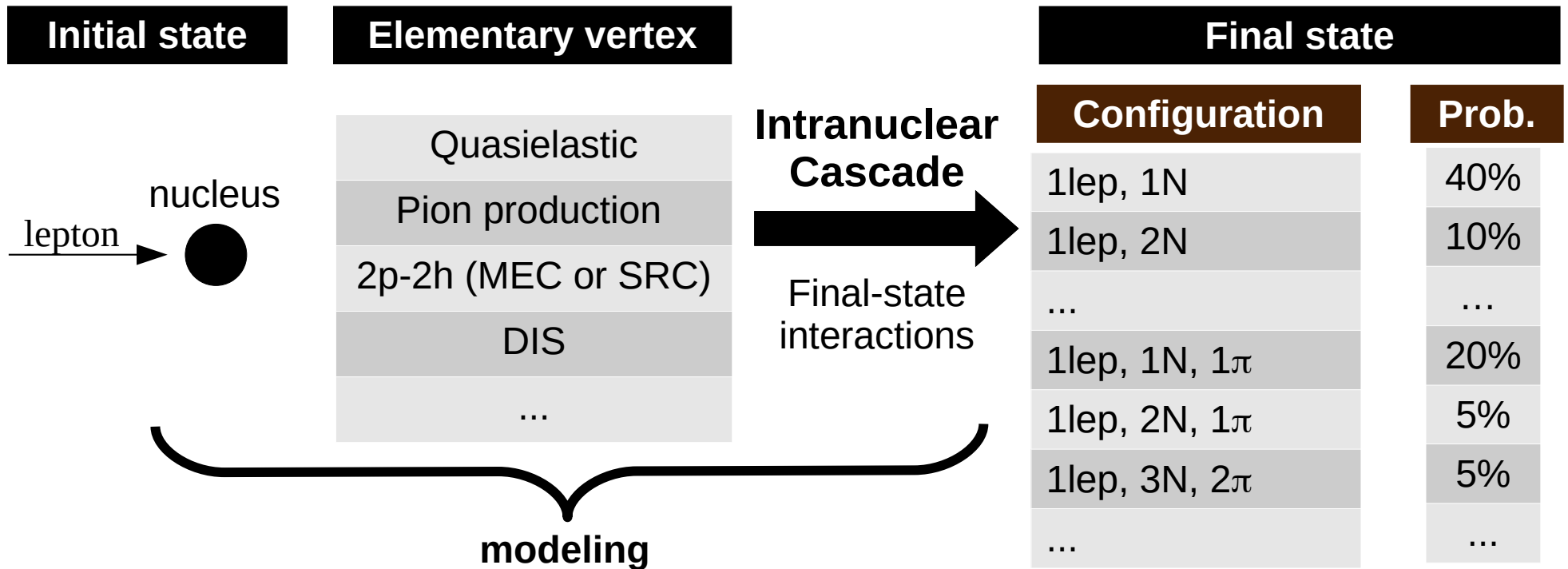
In a scattering experiment, the lepton-nucleus interaction happens many times, so one finds many different final-state configurations, each one with a given probability.



## MC event generators...

the goal is to get the same final state configurations as in Nature.

# HOW ?



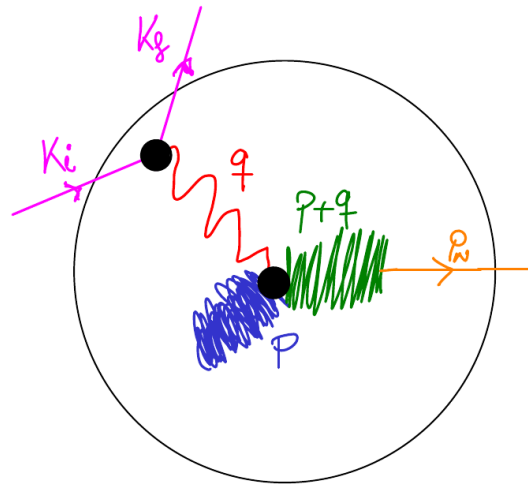
MC event generators...

Two steps:

(1): Reaction channel (elementary vertex).

(2): Intranuclear Cascade provides the hadron multiplicity of the final state.

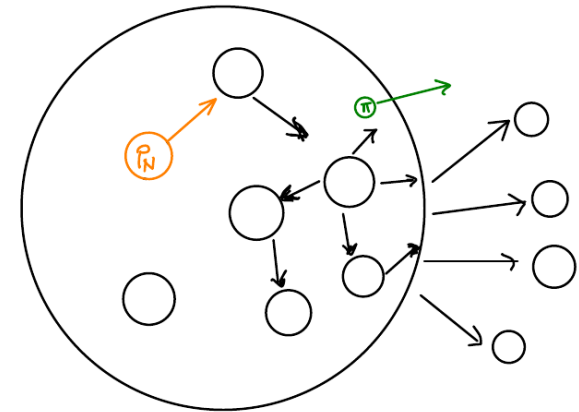
A possible **interpretation** is:  
there is a time separation...



This happens first

**elementary-vertex  
model**

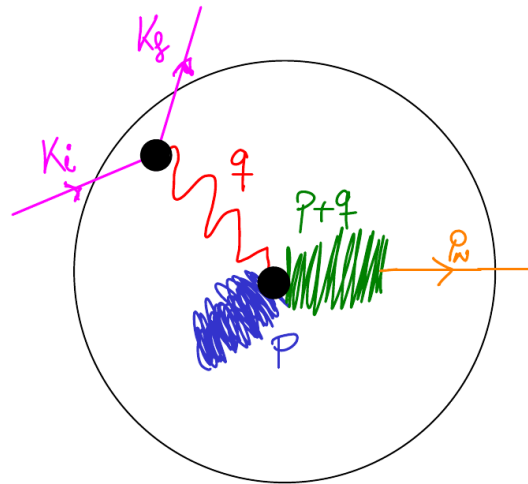
Some time goes by...



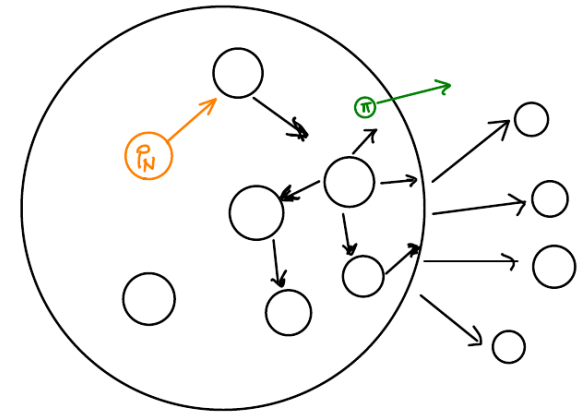
Then, re-scattering can happen

**Intranuclear cascade  
(INC) model**

A possible **interpretation** is:  
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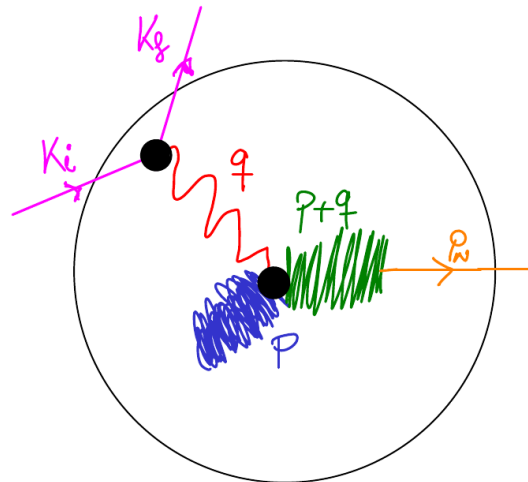
This happens first



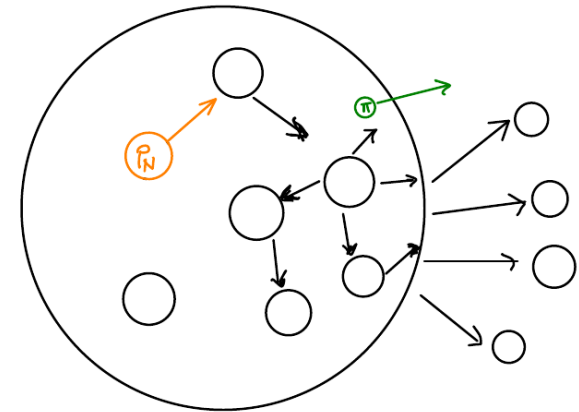
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**Is this *two-step* process  
what happens in Nature ???**

A possible **interpretation** is:  
there is a time separation...



This happens first



Then, re-scattering can happen

**Which ingredients do we include at  
each step ???**

# **Inclusive (e,e') cross section**

# Relativistic Fermi gas

A relativistic gas of non-interacting fermions in the thermodynamic limit.

## Set of nuclear effects:

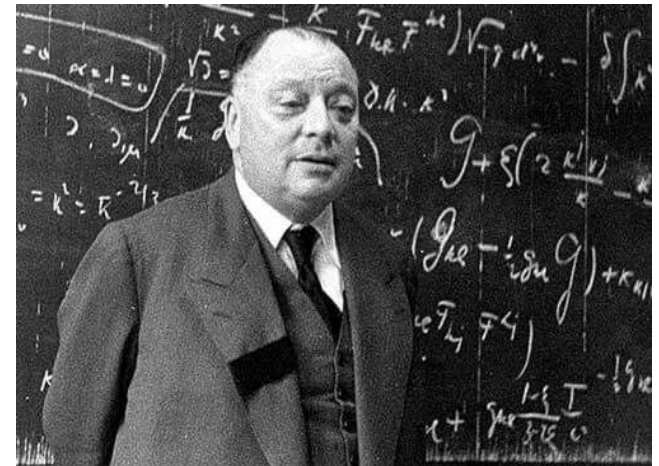
1. Inside a nucleus, the nucleons are moving: **Fermi motion**.
2. **Pauli's exclusion principle**.
3. *Ad hoc* **binding energy**.



Enrico Fermi

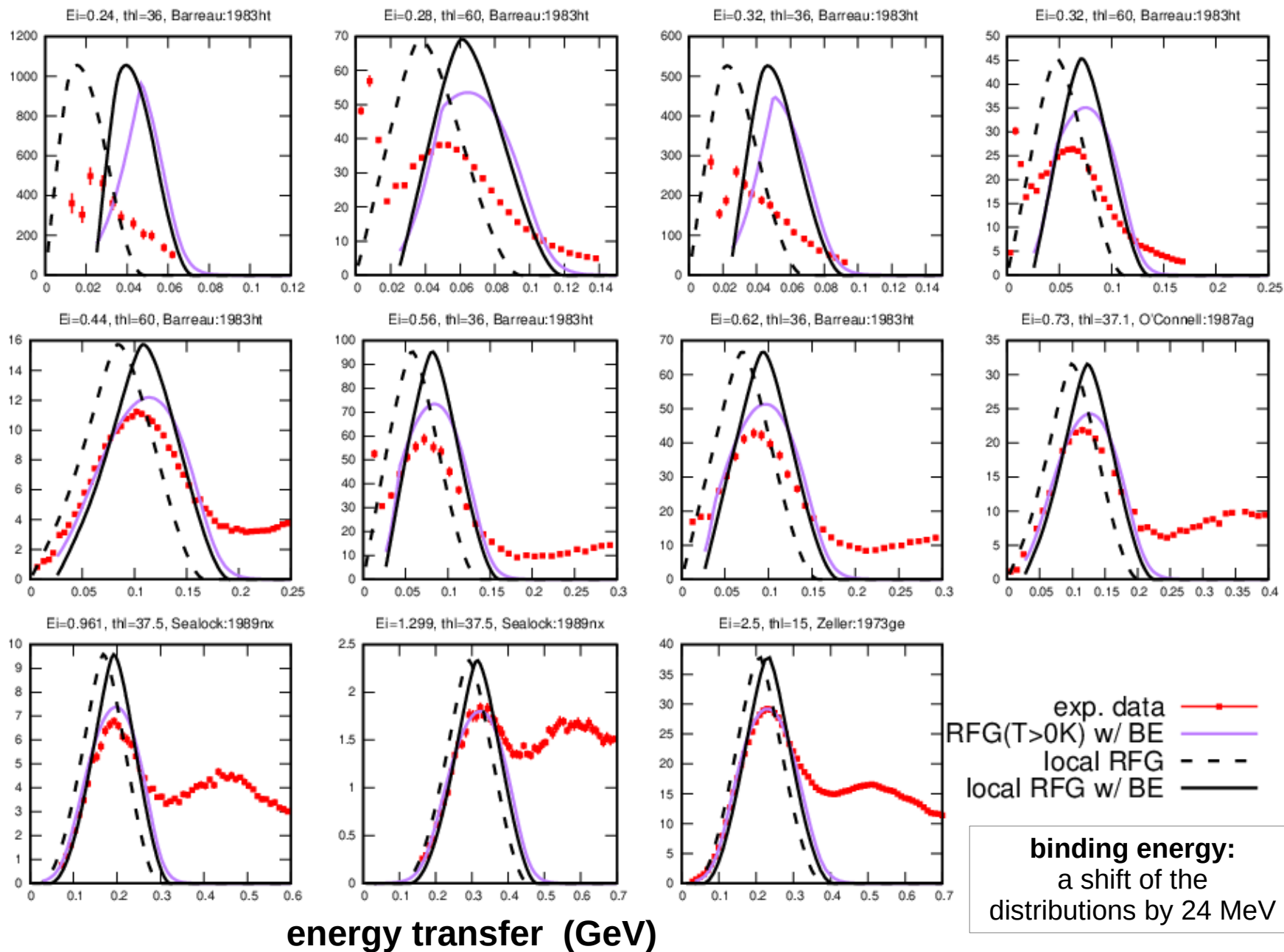


Paul Dirac

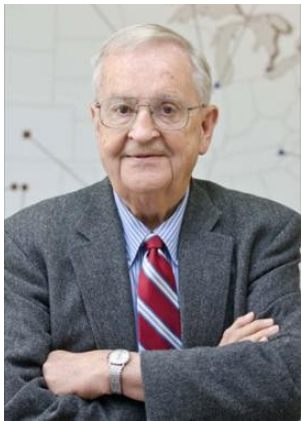


Wolfgang Pauli

# $^{12}\text{C}(e,e')$



# Independent-particle (relativistic) shell model



J. Dirk Walecka



Brian Serot

**Example: a relativistic mean-field model.**

**Wave equation** with strong potentials:

$$[-i\boldsymbol{\alpha} \cdot \boldsymbol{\nabla} + V(r) + \beta (M + S(r))] \Psi(\mathbf{r}) = E\Psi(\mathbf{r})$$

The solutions are energy eigenstates, representing the nucleons in the levels:

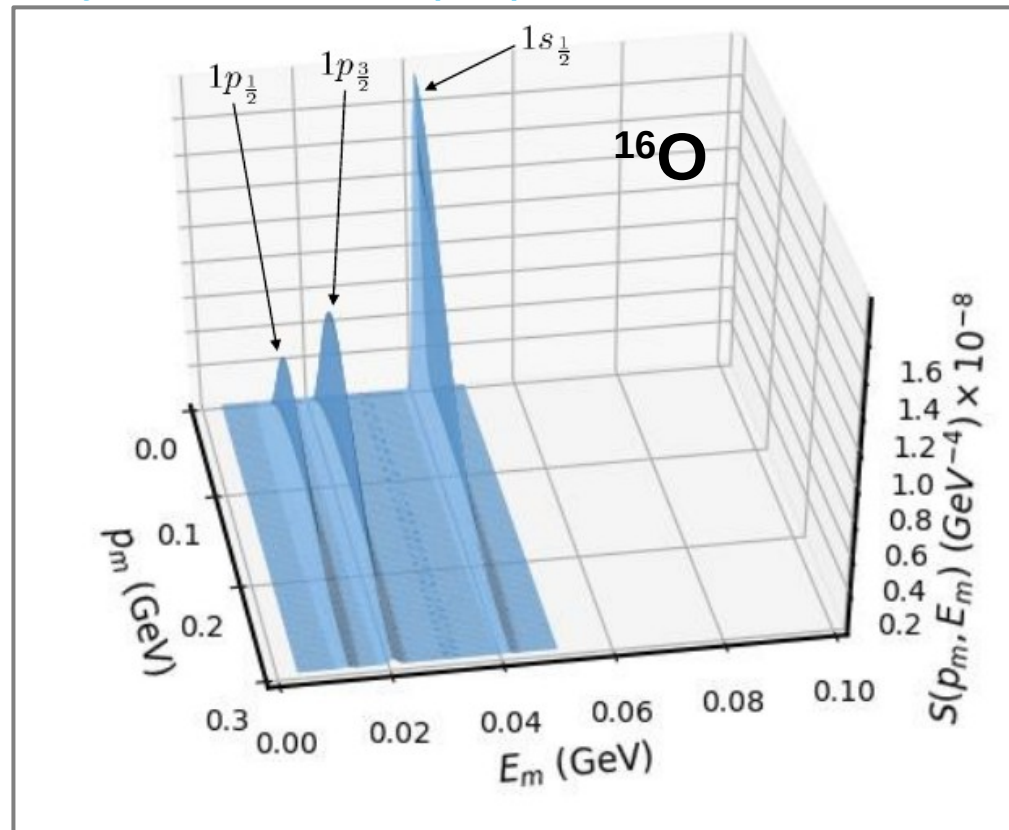
$$\Psi_k^{m_j}(\mathbf{r}) = \begin{pmatrix} g_k(r)\varphi_k^{m_j}(\Omega_r) \\ if_k(r)\varphi_{-k}^{m_j}(\Omega_r) \end{pmatrix},$$

“The **initial-state spectral function (SF)** gives the probability density of knocking out a nucleon from the nucleus, giving to the system an energy  $E_m$  and a momentum  $\mathbf{p}_m$ .”

**Spectral function** in the IPSM:

$$S(E_m, p_m) = \sum_{\kappa} n_{\kappa}(p_m) \delta(E_m - E_m^{\kappa})$$

Phys. Rev. C 100, 044620 (2019)

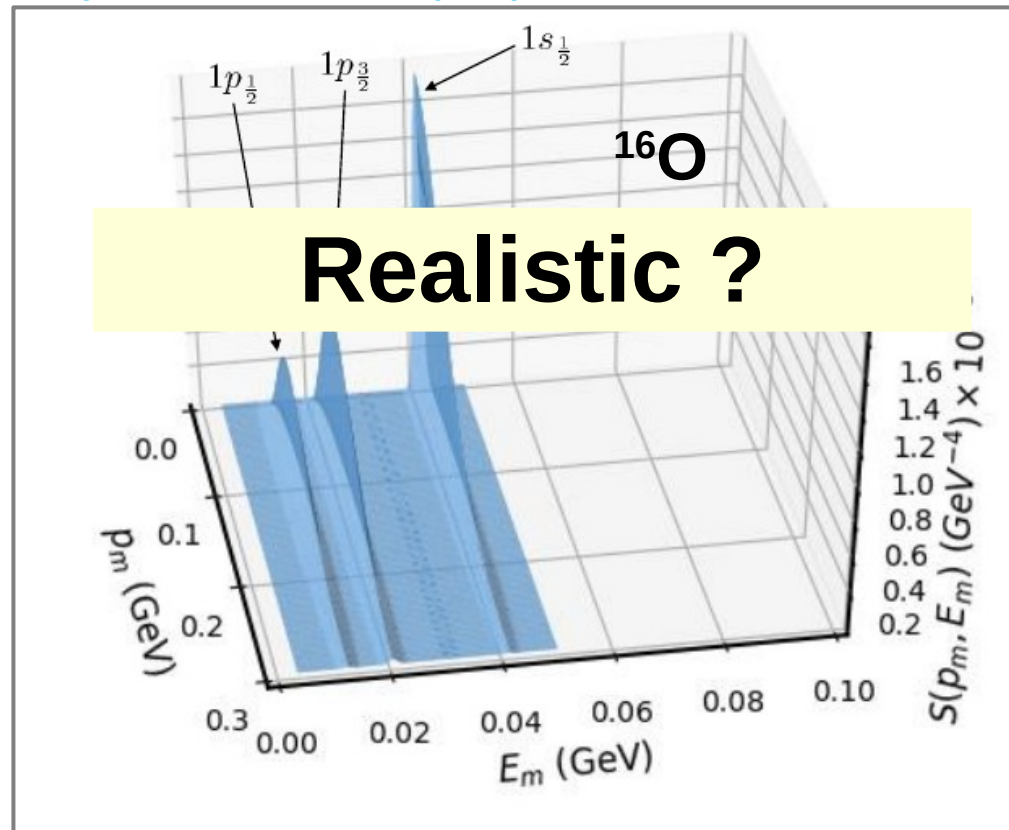


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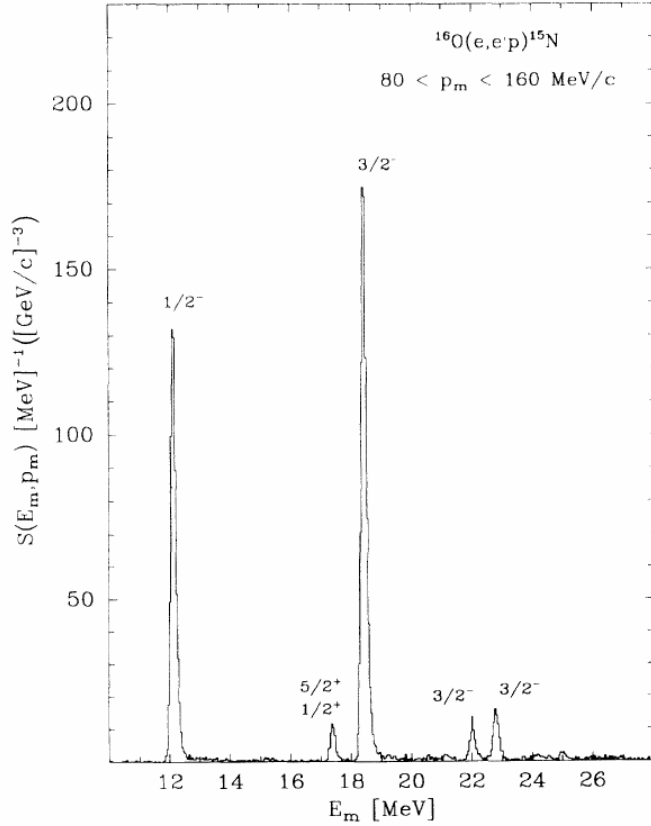
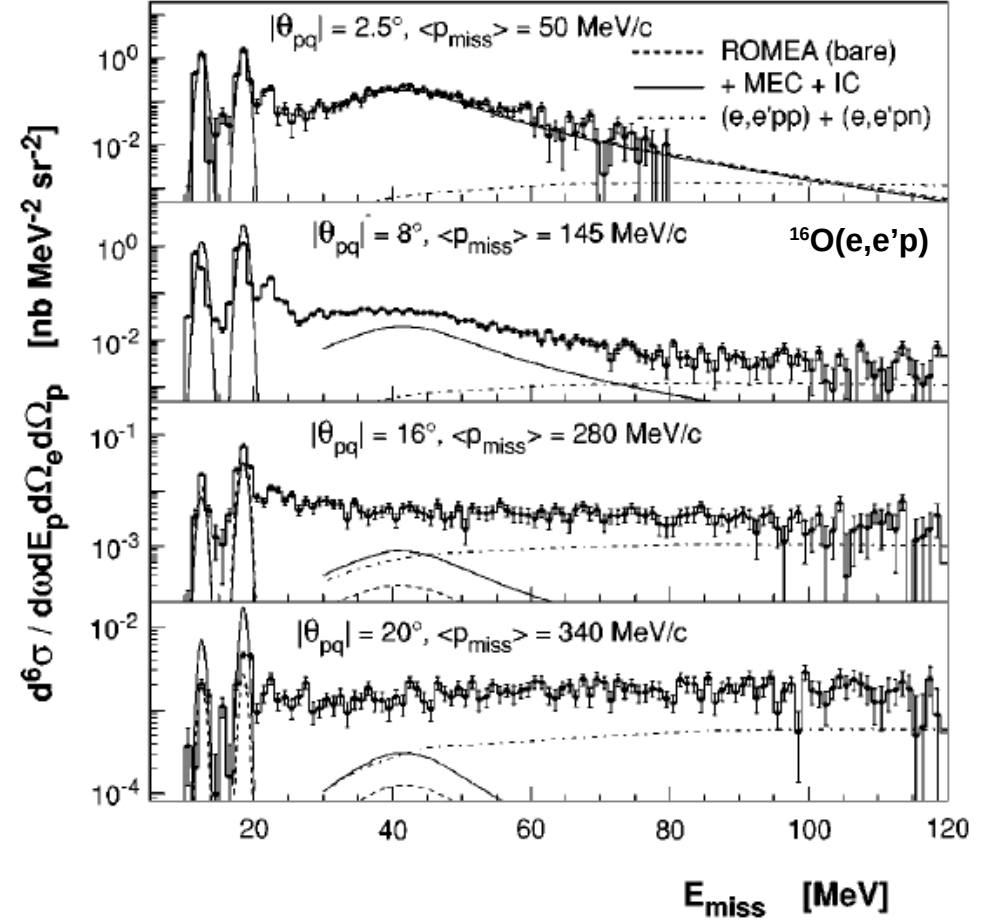


FIG. 1.  $^{16}\text{O}(e, e'p)^{15}\text{N}$  missing energy spectrum for the kinematics centered about  $p_m = 120 \text{ MeV}/c$ .



$$E_m \equiv \omega - T_N - T_B = M_B^* + M - M_A.$$

## Effects beyond the independent-particle shell model:

Experimentally one observes:

- + fragmentation of the strength
- + more levels
- + width at the peaks, especially in deep levels
- + spectroscopic factors (  $< 1$  )
- + Short Range Correlations:  $\sim 20\%$  of the nucleons appear in the high  $E_m$  and  $p_m$  region.

These effects could be (somehow) included in **a more realistic representation of the spectral function;**

extracted using, e.g., *ab initio* models, and/or experimental data, like (e,e'p).

# Plane-wave impulse approximation (PWIA) with a realistic spectral function

$$\frac{d\sigma(k_e)}{d\mathbf{k}'_e d\mathbf{p}_p} = S(E_m, p_m) \sigma_{e-p}^{\text{off-shell}}(\mathbf{k}'_e, \mathbf{p}_p)$$

# The spectral function (SF): the Rome approach

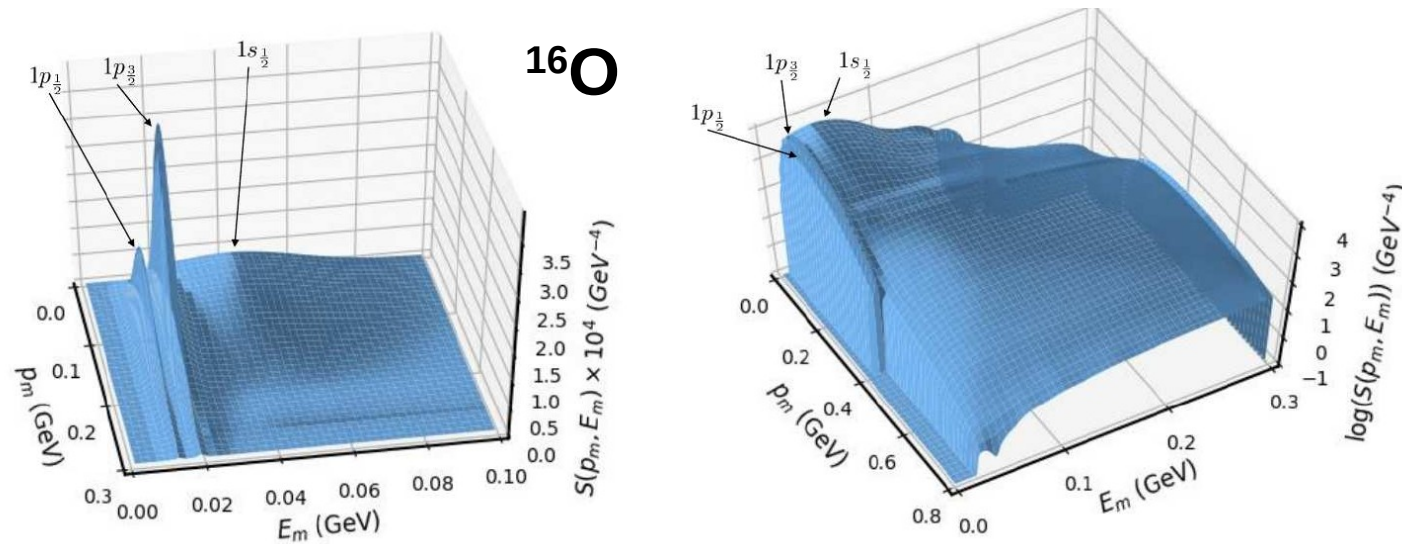
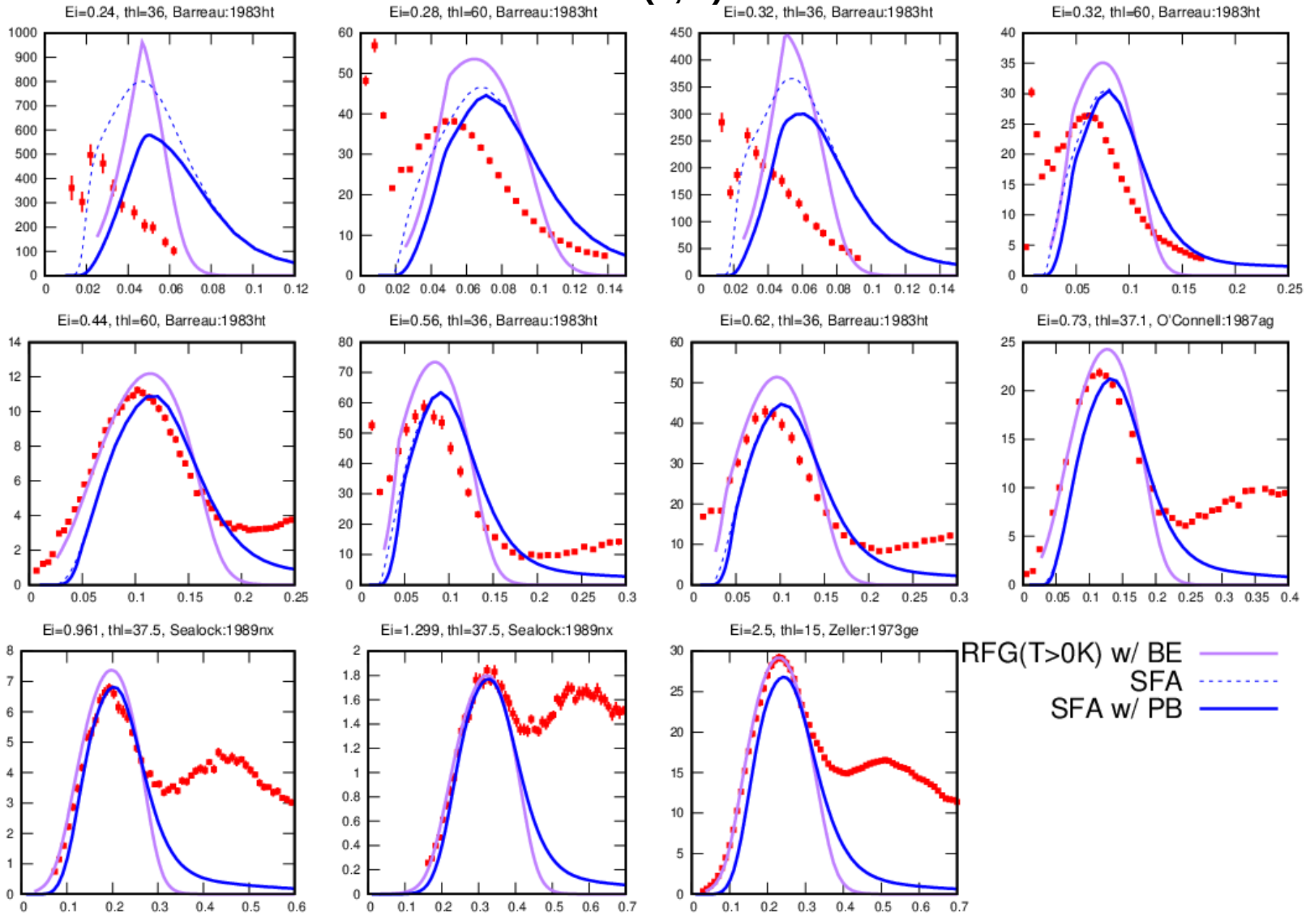


Image from [Phys. Rev. C 100, 044620 \(2019\)](#); spectral function from [Nuclear Physics A 579, 493 \(1994\)](#); [Phys. Rev. D 72, 053005 \(2005\)](#)

$$S(E_m, p) = S_{\text{mean field}}(E_m, p) + S_{\text{SRC}}(E_m, p),$$

$$S_{\text{mean field}}(E_m, p) = \sum_{\kappa} n_{\kappa}(p) \rho(E_m),$$

# $^{12}\text{C}(e,e')$



energy transfer (GeV)

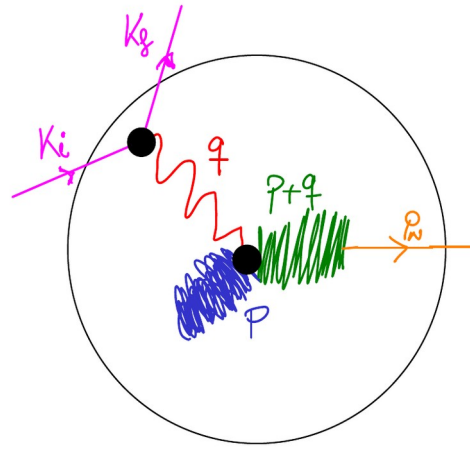
We have already included all the available information about the initial state, from theory and/or experiment.

**What is missing?**

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## What is missing?

A consistent treatment of the initial and final states:

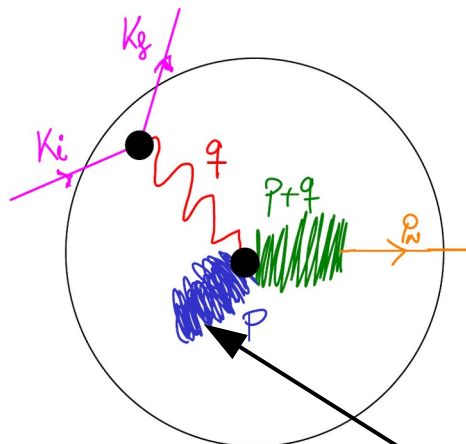


$$J_{had}^{\mu} = \int d\mathbf{p} \, \bar{\Psi}_F(\mathbf{p} + \mathbf{q}, \mathbf{p}_N) \, \mathcal{O}_{\text{one body}}^{\mu} \, \Psi_B(\mathbf{p})$$

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Bound state from an IPSM

We have already included all the available information about the initial state, from theory and/or experiment.

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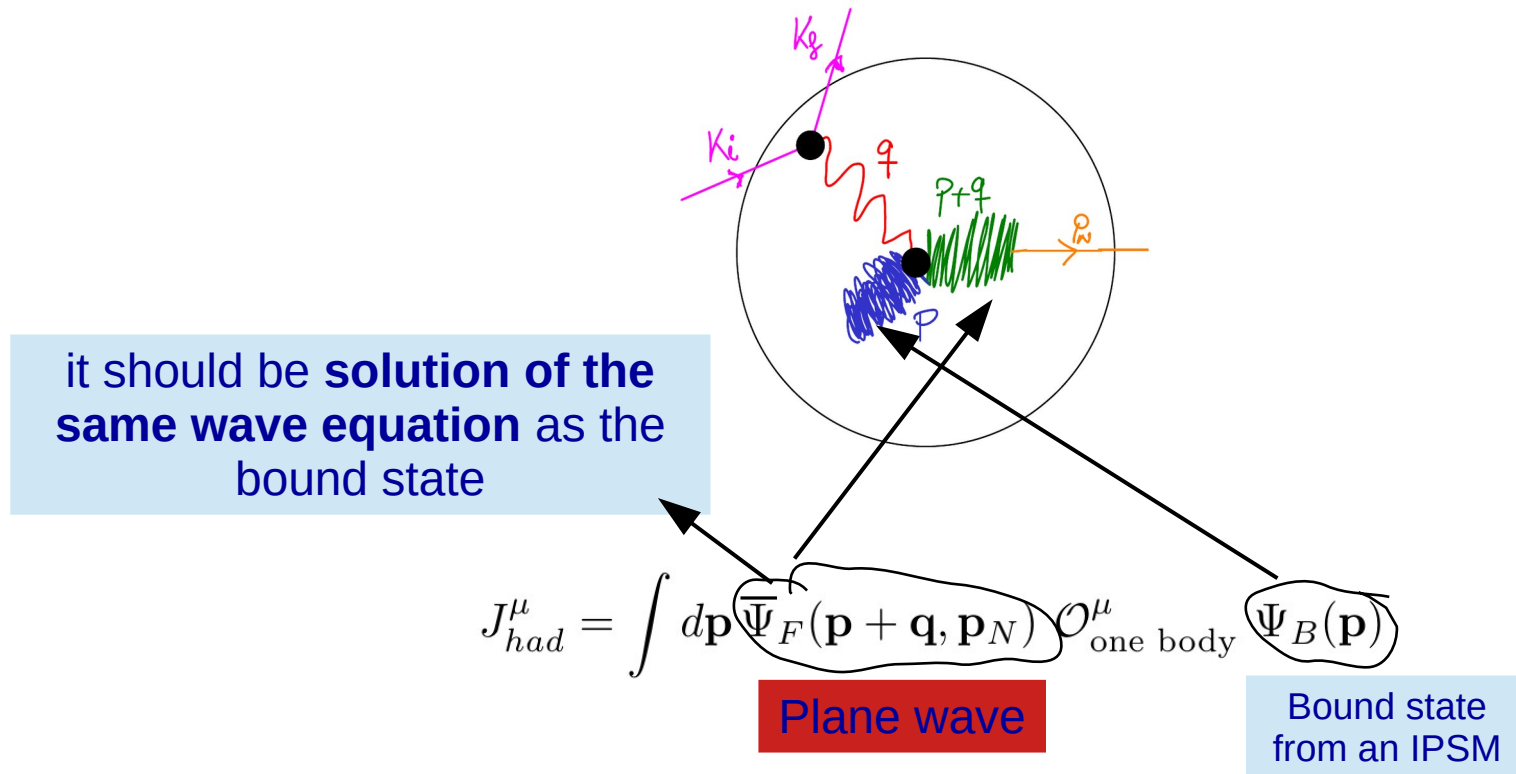
A consistent treatment of the initial and final states:

$$J_{had}^{\mu} = \int dp \underbrace{\Psi_F(\mathbf{p} + \mathbf{q}, \mathbf{p}_N)}_{\text{Plane wave}} \mathcal{O}_{\text{one body}}^{\mu} \underbrace{\Psi_B(\mathbf{p})}_{\text{Bound state from an IPSM}}$$

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A consistent treatment of the

This ensures:

- + **orthogonality** of the states (Pauli blocking),
- + **vector current conservation**,
- + **distortion** of the final nucleon (elastic FSI) is incorporated

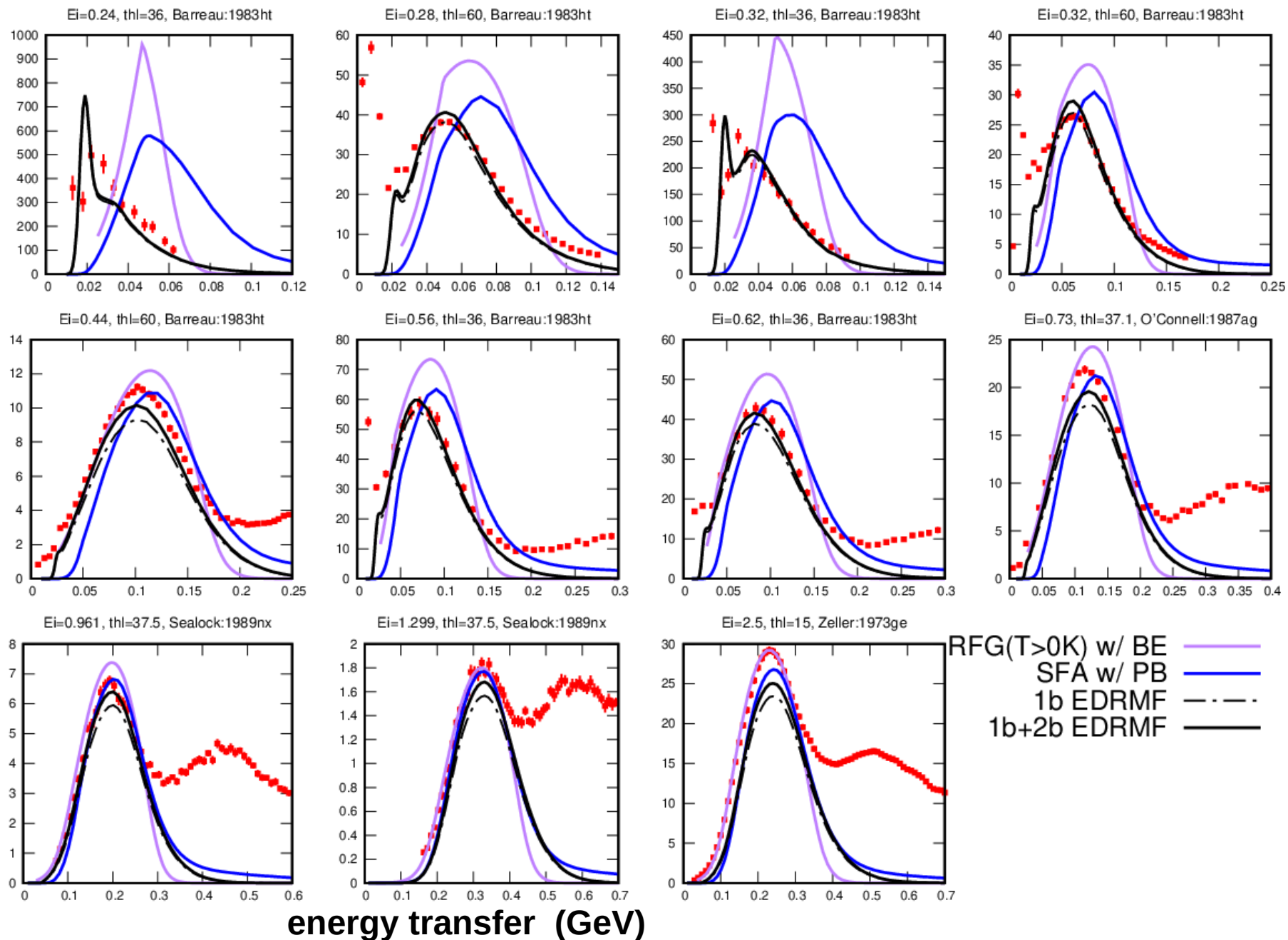
it should be **solution of the same wave equation** as the bound state

$$J_{had}^{\mu} = \int d\mathbf{p} \, \overline{\Psi}_F(\mathbf{p} + \mathbf{q}, \mathbf{p}_N) \mathcal{O}_{\text{one body}}^{\mu} \Psi_B(\mathbf{p})$$

Plane wave

Bound state from an IPSM

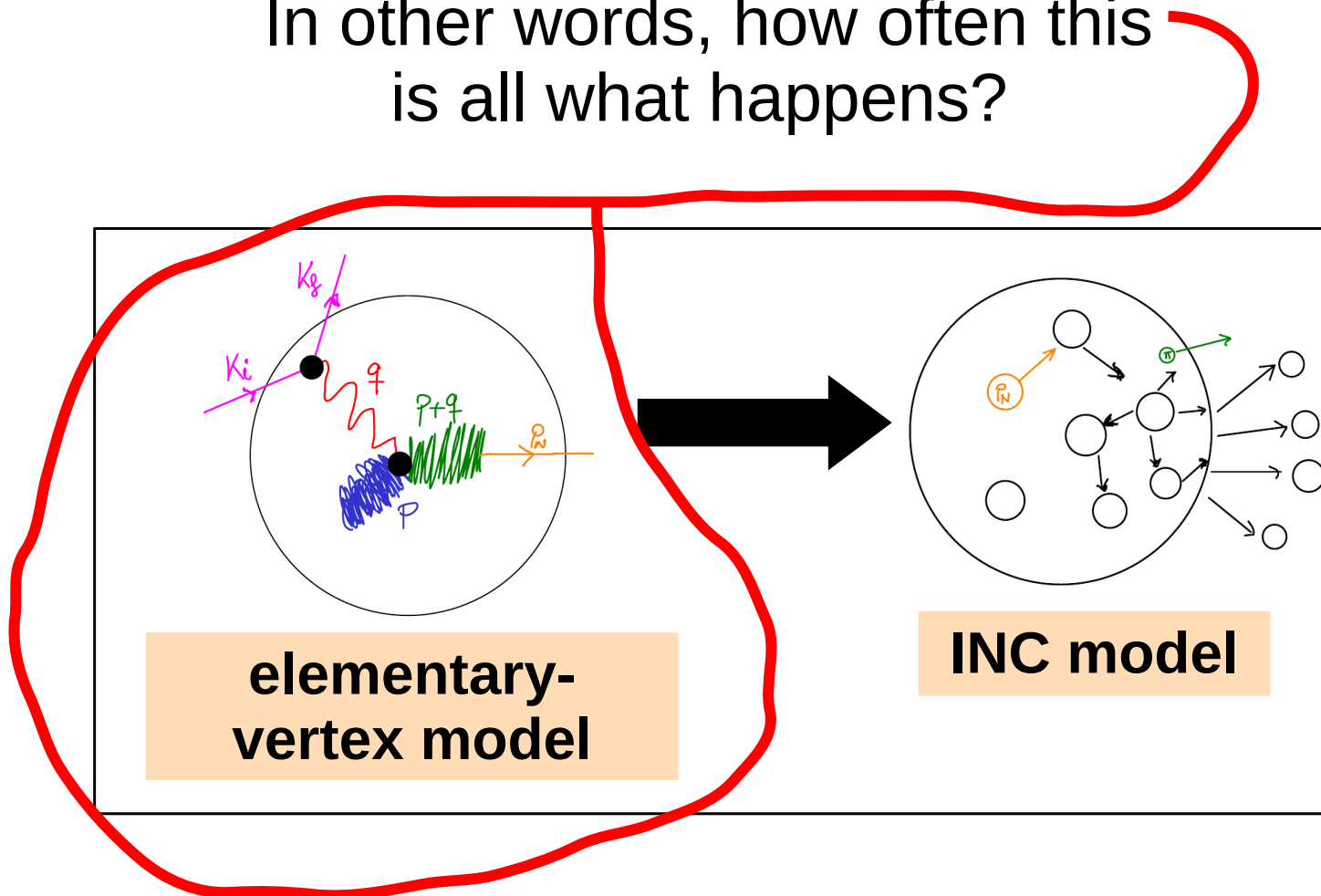
# $^{12}\text{C}(e,e')$



**How much of the inclusive strength corresponds to the “true” one-nucleon knockout process?**

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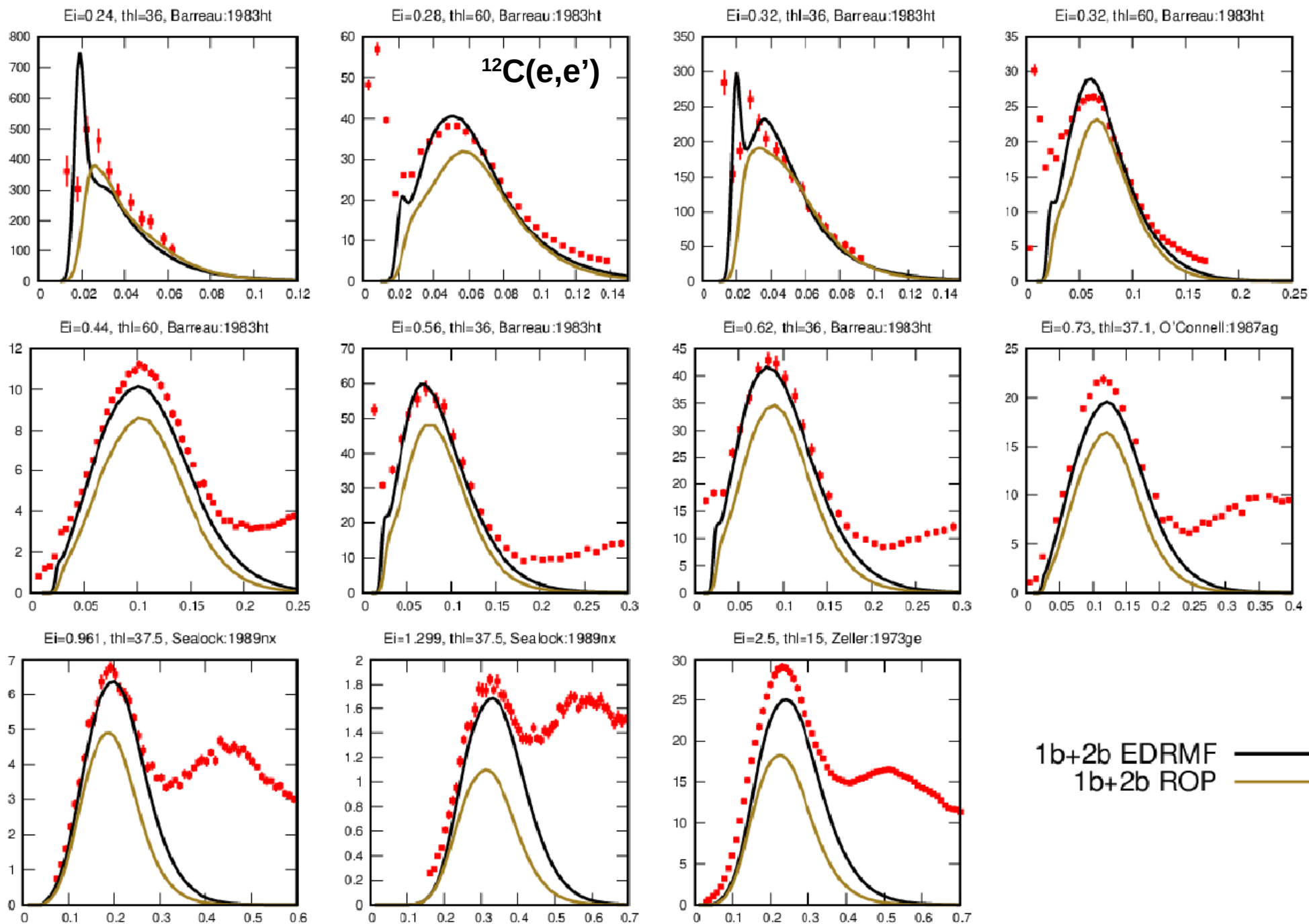
In other words, how often this is all what happens?



**How much of the inclusive strength corresponds to the “true” one-nucleon knockout process?**

The RDWIA estimates it using a **complex-optical potential** for the final-nucleon wave function

Intranuclear Cascade estimates it as the fraction of events in which the knocked-out nucleon does not interact in its way out  
(==> **nuclear Transparency**)



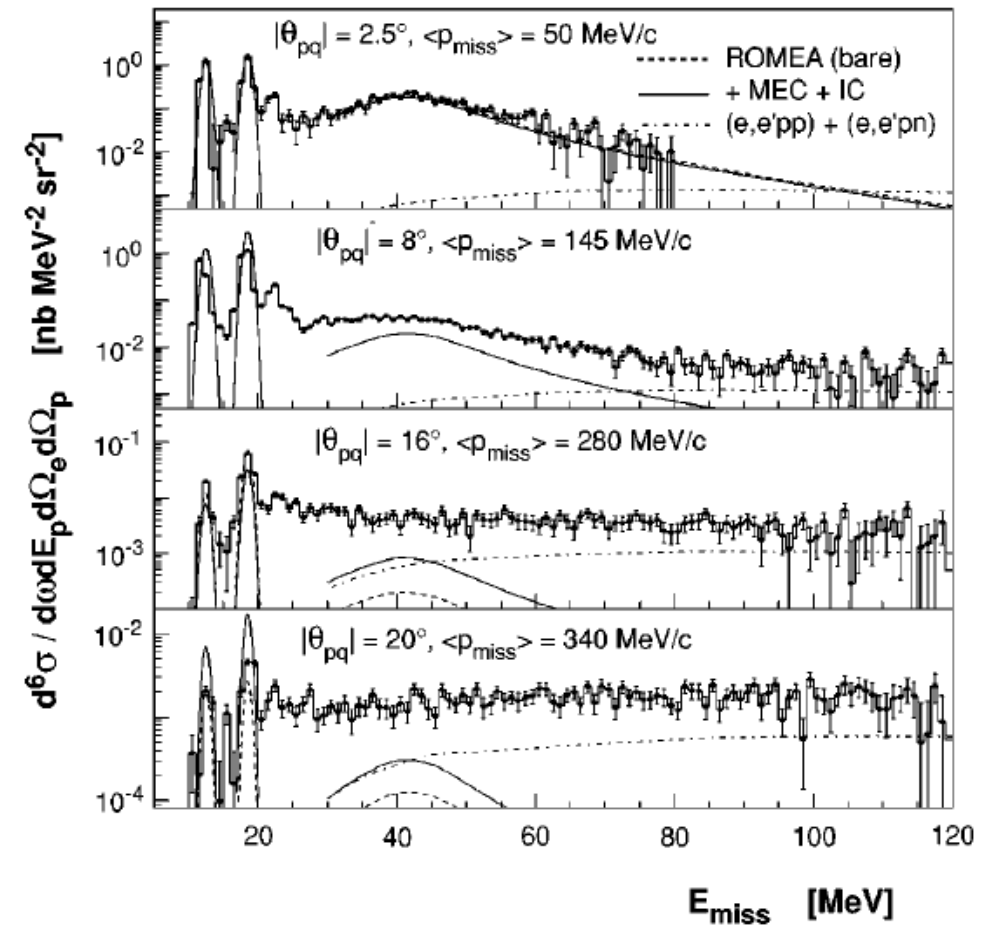
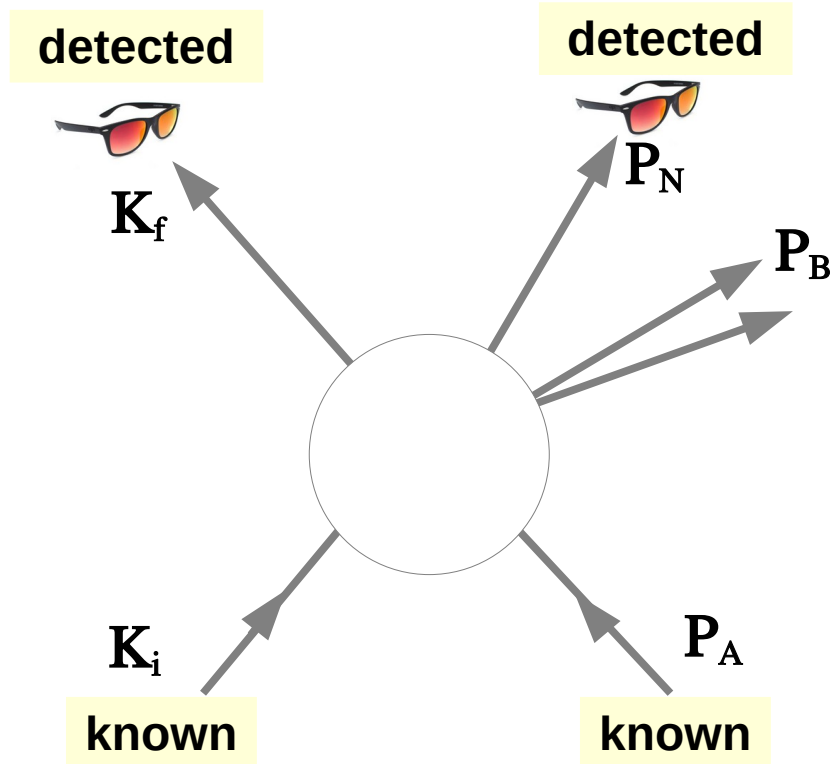
energy transfer (GeV)

# **Exclusive (e,e'p) cross section**

# A(e,e'p) experiments

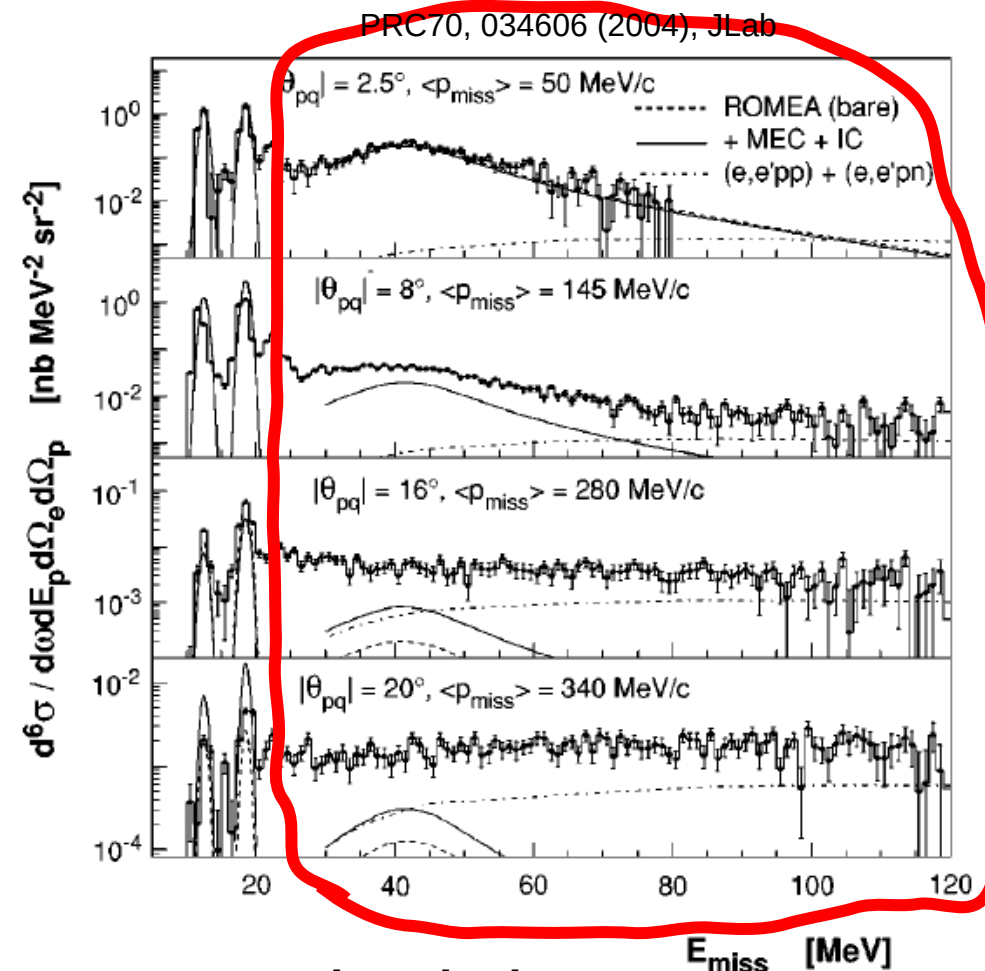
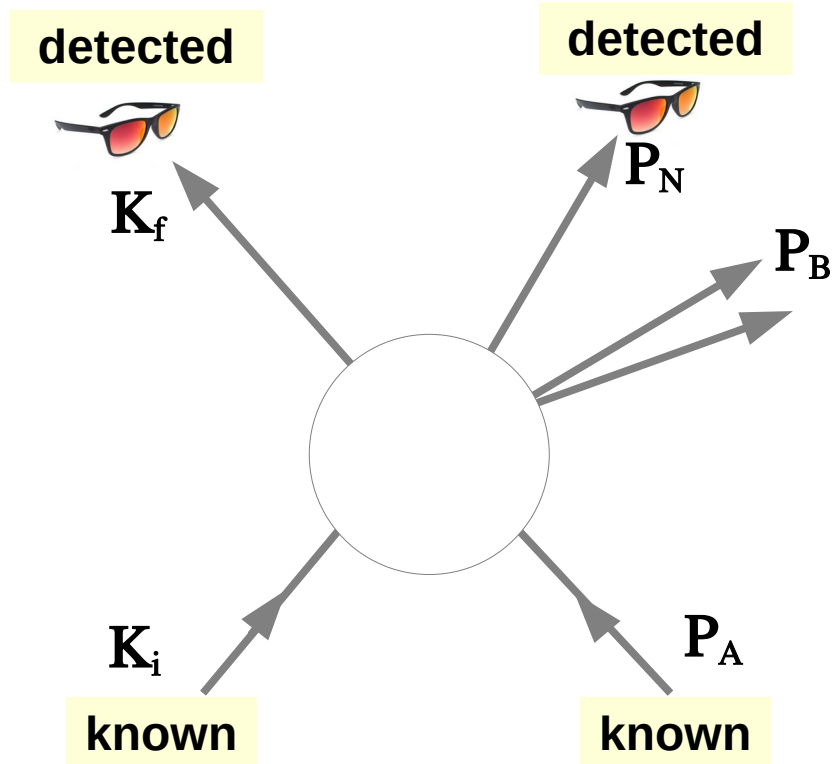
$^{16}\text{O}(e,e'p)$

PRC70, 034606 (2004), JLab



# A(e,e'p) experiments

$^{16}\text{O}(e,e'p)$

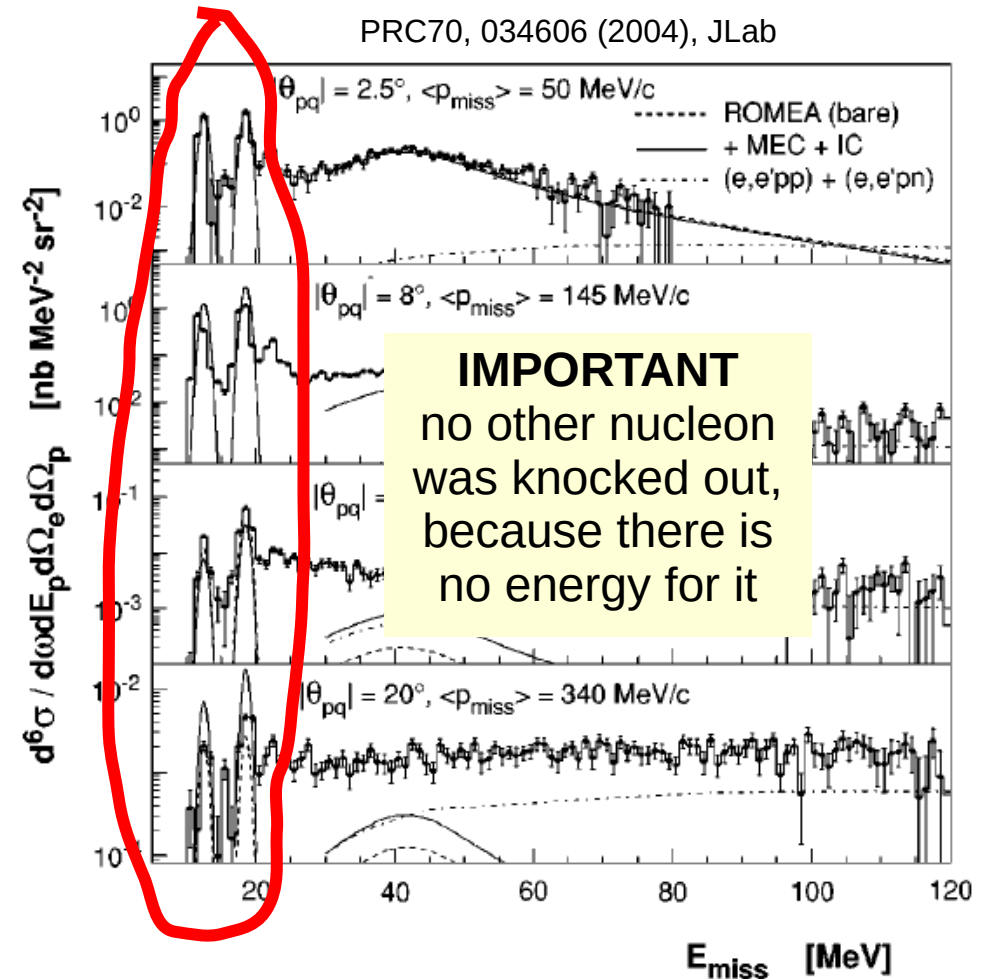
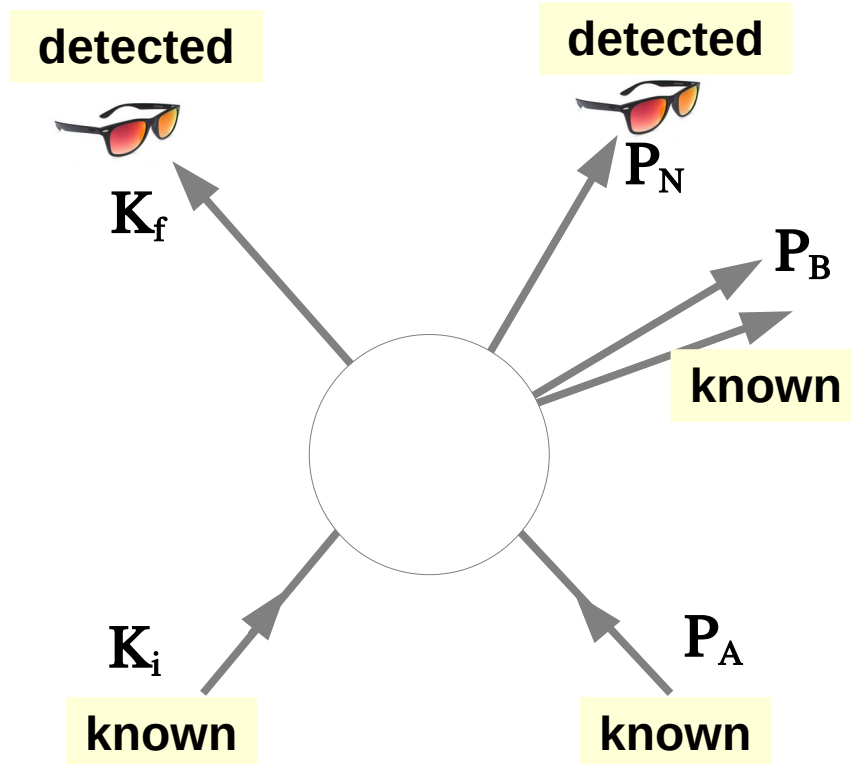


**semi-exclusive**

We know the energy and momentum of the residual system, but we do **not** know its composition: 1, 2, 3 knockout nucleons...?

# A(e,e'p) experiments

$^{16}\text{O}(e,e'p)$



## Exclusive

If we stay below the 2N knockout threshold, then we know that the residual system is the  $A-1$  nucleus, in the ground or an excited state.

# Exclusive experiments: $^{16}\text{O}(e,e'p)^{15}\text{N}$

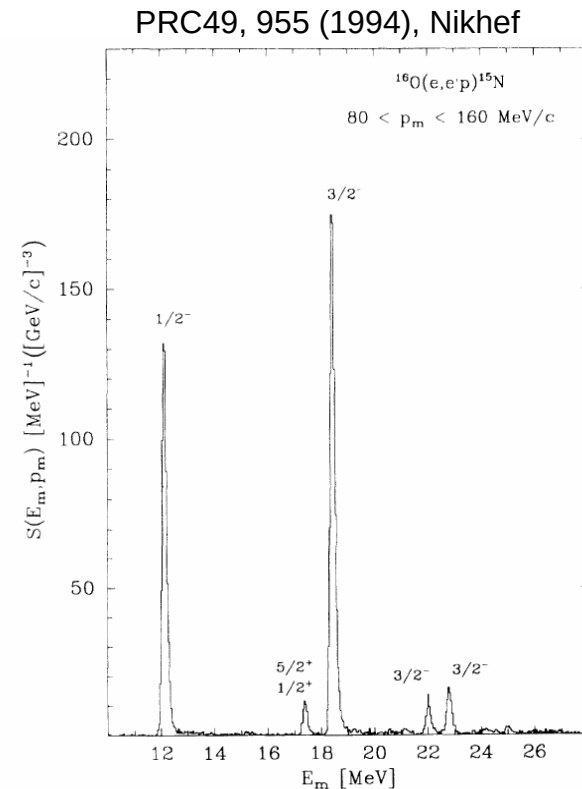
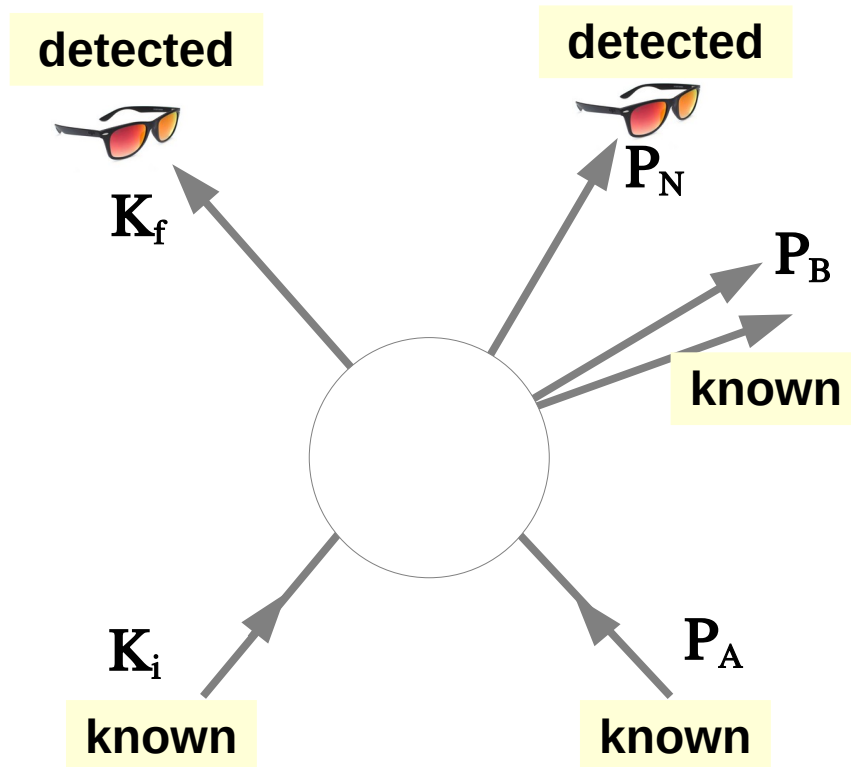


FIG. 1.  $^{16}\text{O}(e,e'p)^{15}\text{N}$  missing energy spectrum for the kinematics centered about  $p_m = 120 \text{ MeV}/c$ .

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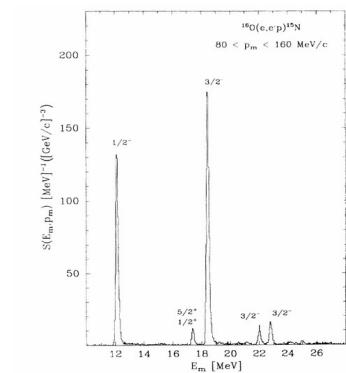
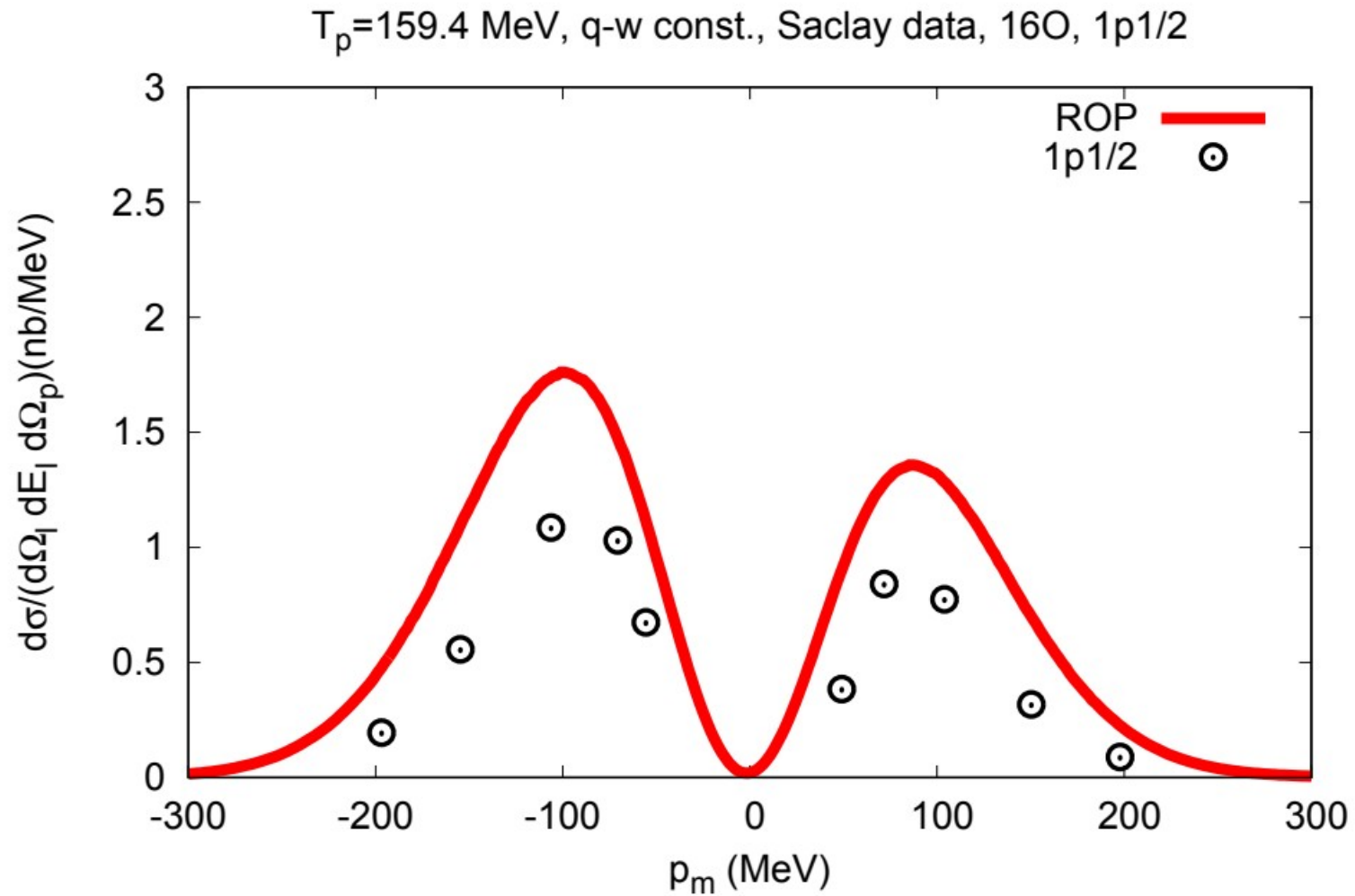


FIG. 1.  $^{16}\text{O}(e,e'p)^{15}\text{N}$  missing energy spectrum for the kinematics centered about  $p_m = 120 \text{ MeV}/c$ .



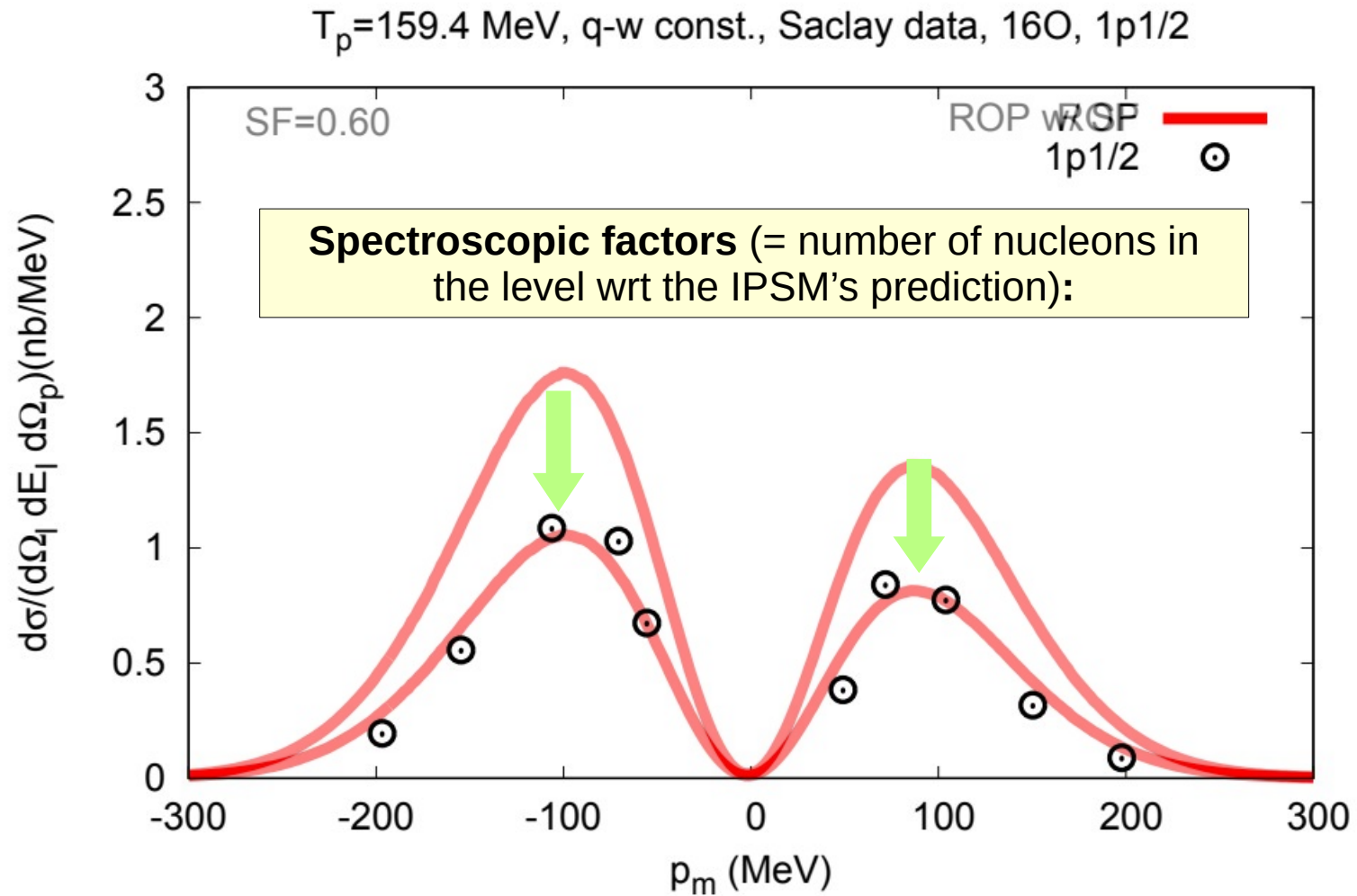
Key:

**ROP** = IPSM, final nucleon from Dirac equation with relativistic **complex** optical potential



Key:

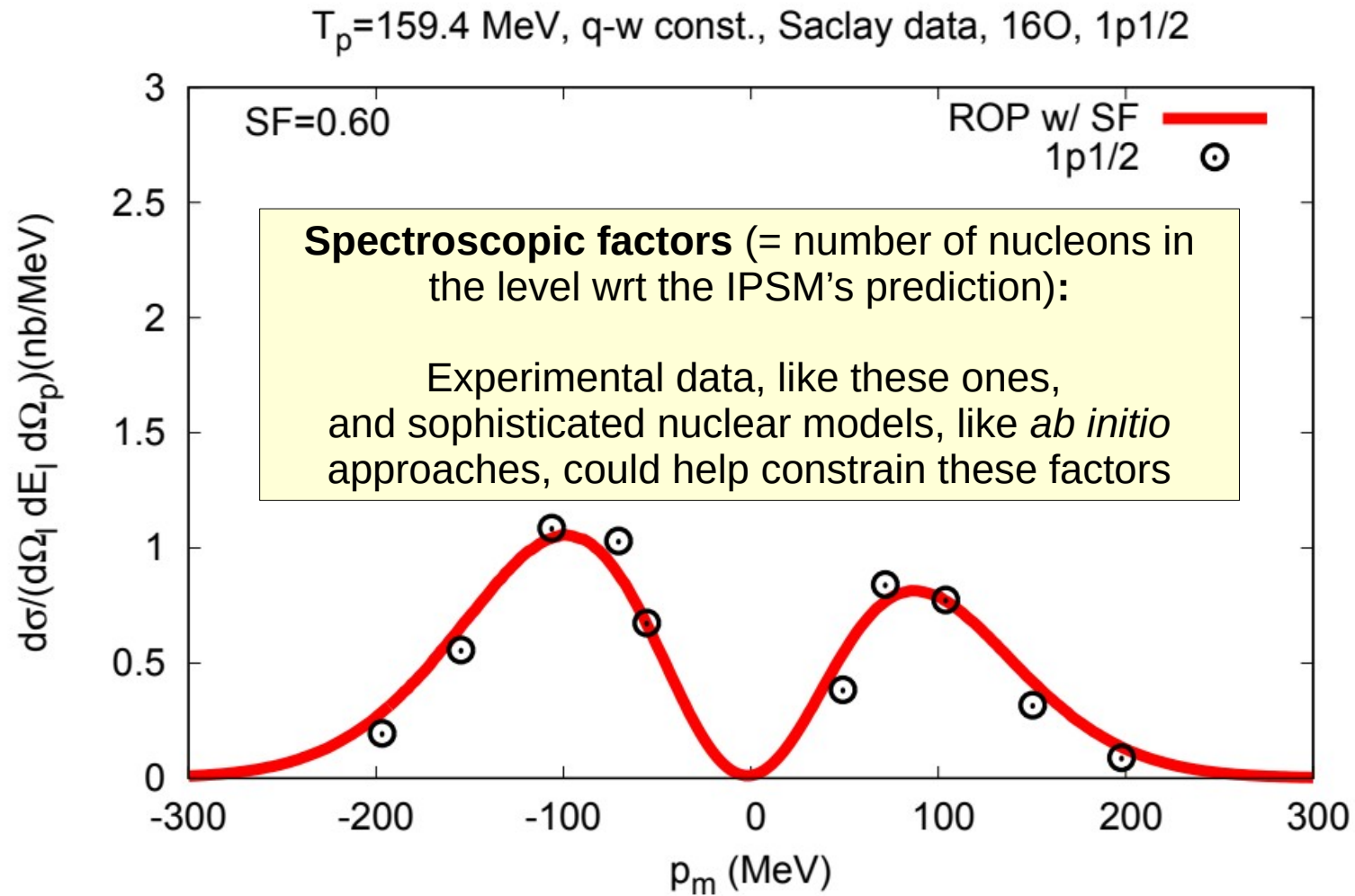
**ROP** = IPSM, final nucleon from Dirac equation with relativistic **complex** optical potential



**Key:**

**ROP** = IPSM, final nucleon from Dirac equation with relativistic **complex** optical potential

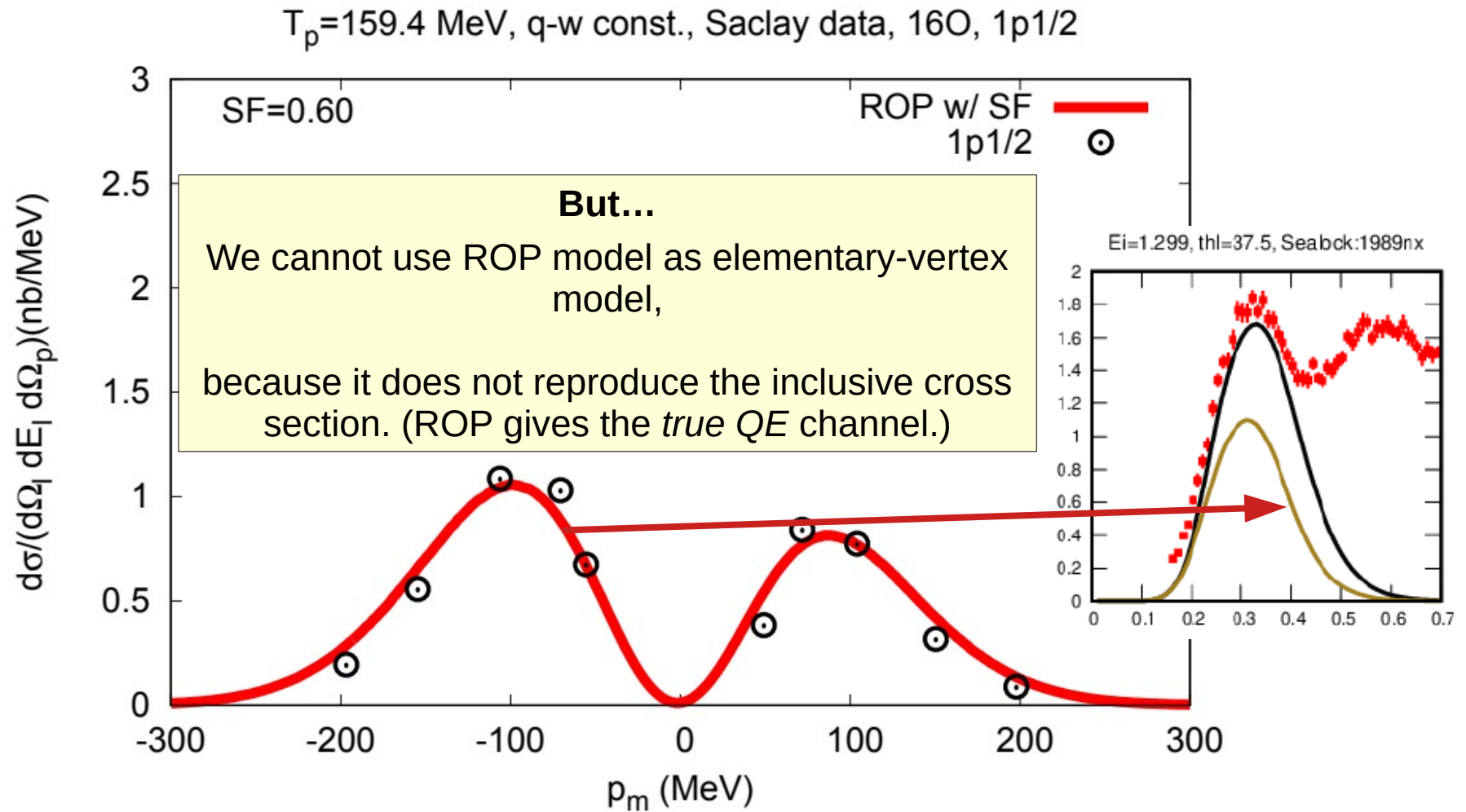
**SF** = spectroscopic factor



**Key:**

**ROP** = IPSM, final nucleon from Dirac equation with relativistic **complex** optical potential

**SF** = spectroscopic factor



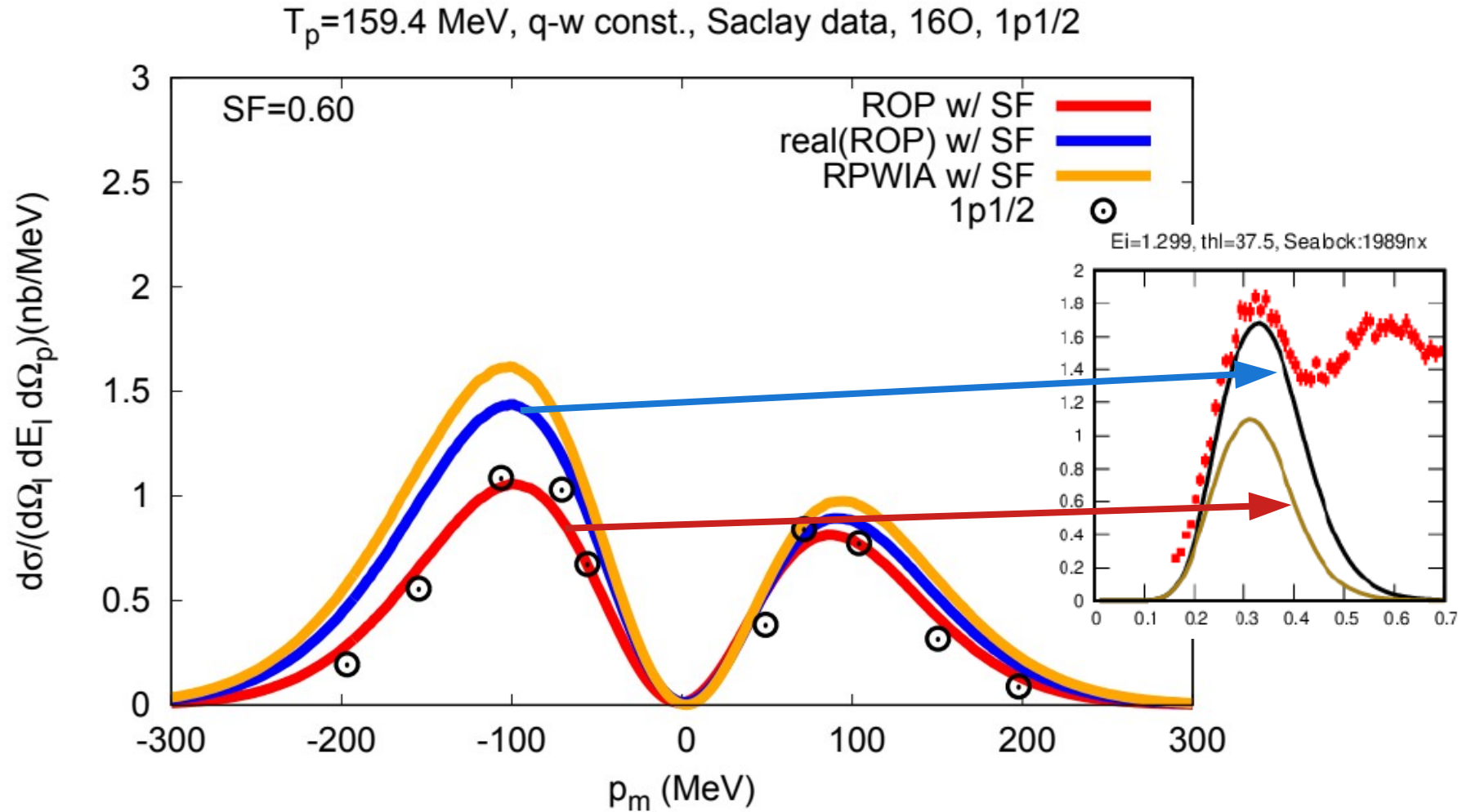
**Key:**

**ROP** = IPSM, final nucleon from Dirac equation with relativistic **complex** optical potential

**SF** = spectroscopic factor

**real(ROP)** = IPSM, final nucleon from Dirac equation with relativistic **real** optical potential

**RPWIA** = IPSM, final nucleon is a plane wave



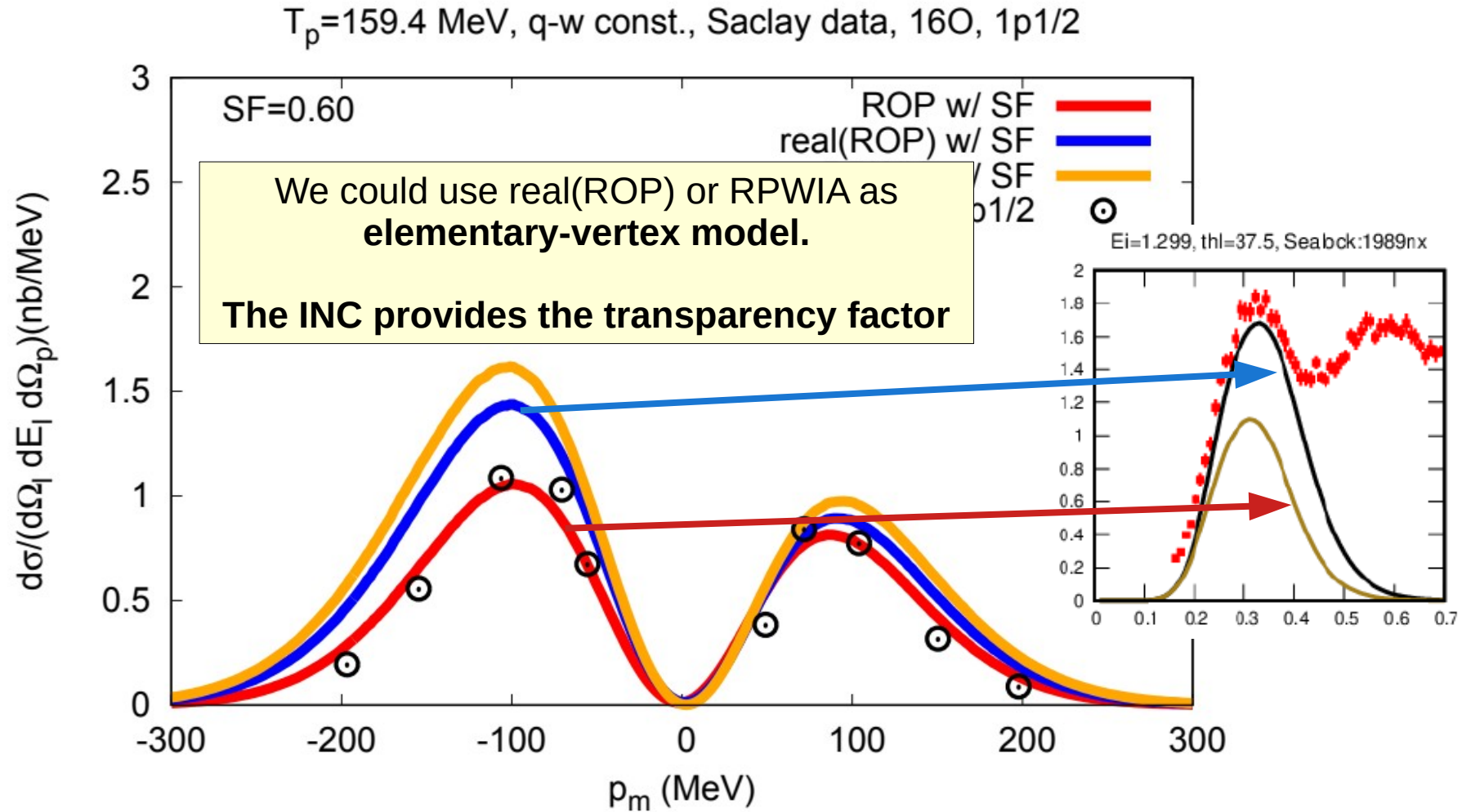
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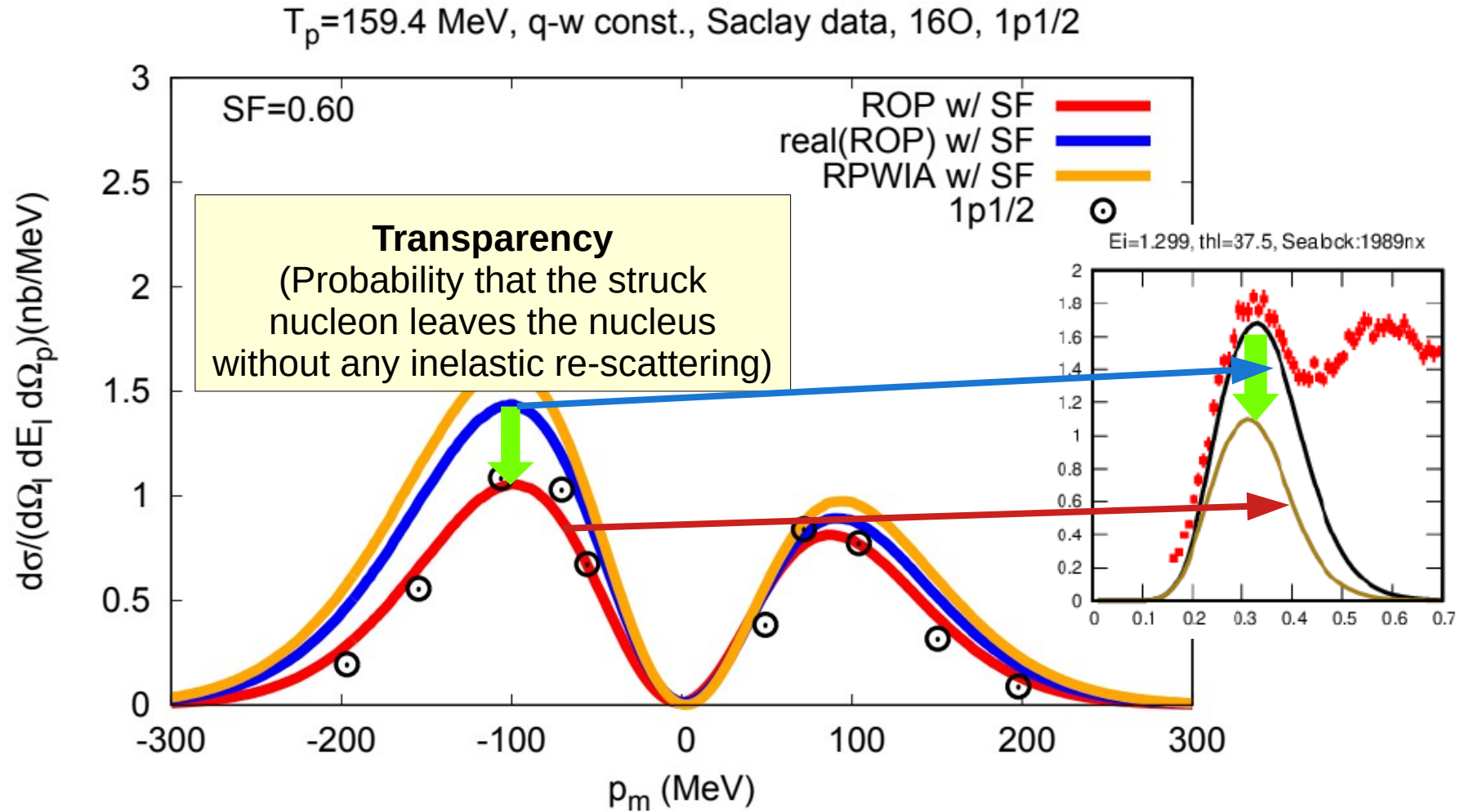
**ROP** = IPISM, final nucleon from Dirac equation with relativistic **complex** optical potential

**SF** = spectroscopic factor

**real(ROP)** = IPISM, final nucleon from Dirac equation with relativistic **real** optical potential

**RPWIA** = IPISM, final nucleon is a plane wave



**Key:****ROP** = IPSM, final nucleon from Dirac equation with relativistic **complex** optical potential**SF** = spectroscopic factor**real(ROP)** = IPSM, final nucleon from Dirac equation with relativistic **real** optical potential**RPWIA** = IPSM, final nucleon is a plane wave

**Key:**

**ROP** = IPSM, final nucleon from Dirac equation with relativistic **complex** optical potential

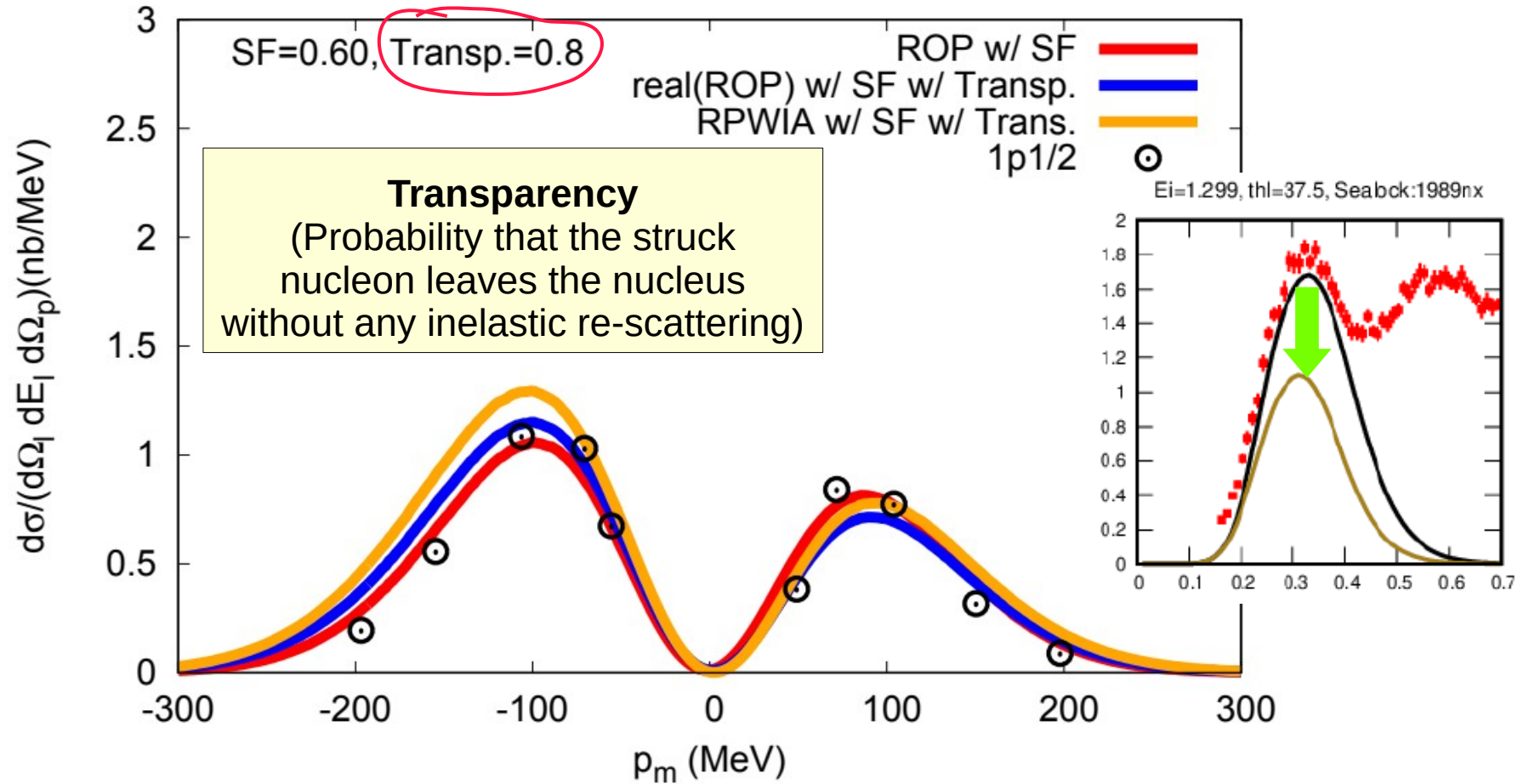
**SF** = spectroscopic factor

**real(ROP)** = IPSM, final nucleon from Dirac equation with relativistic **real** optical potential

**RPWIA** = IPSM, final nucleon is a plane wave

**Transp.** = Transparency factor

$T_p = 159.4$  MeV,  $q$ -w const., Saclay data,  $^{16}\text{O}$ ,  $1p_{1/2}$



**Key:**

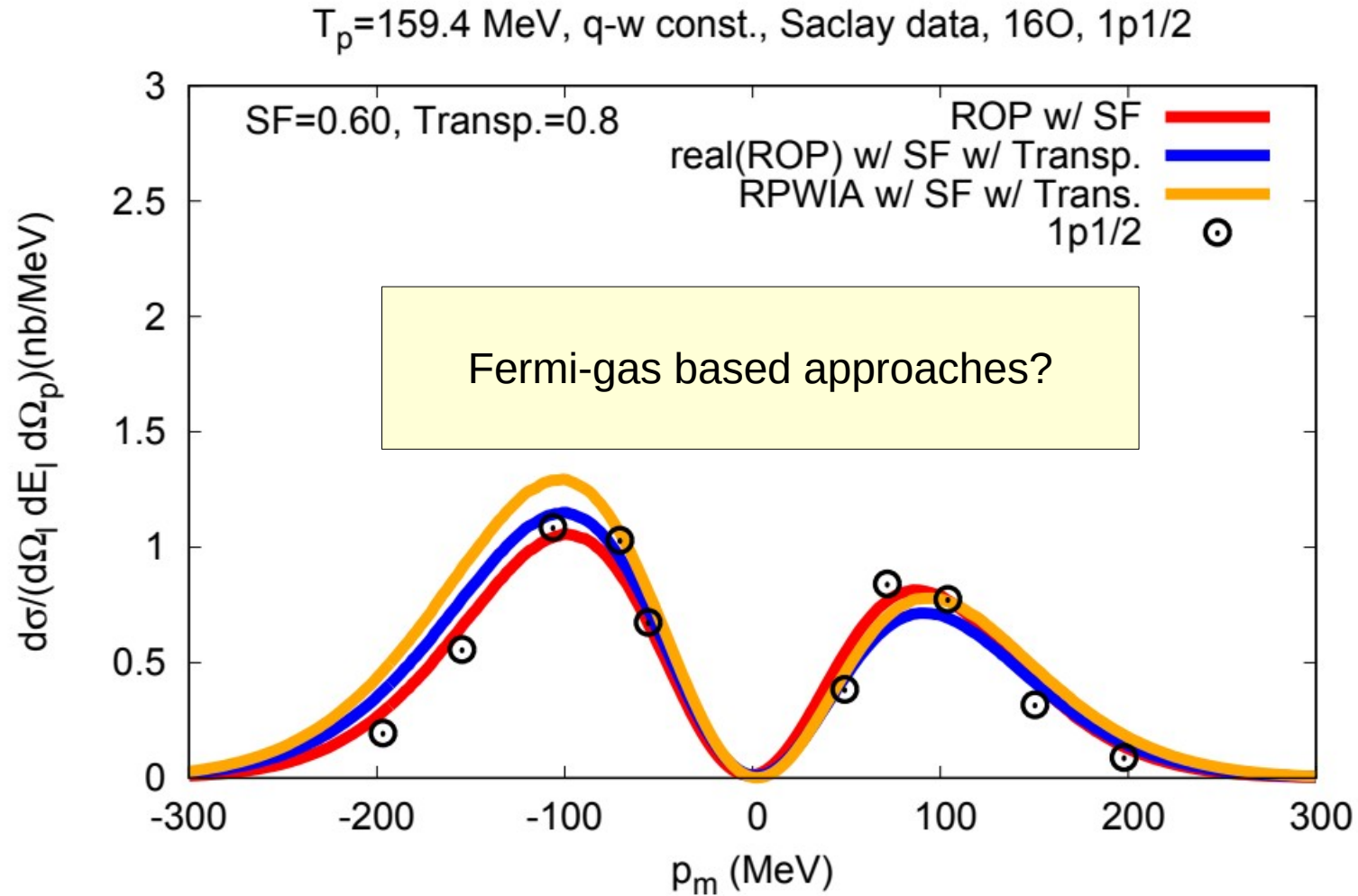
**ROP** = IPSM, final nucleon from Dirac equation with relativistic **complex** optical potential

**SF** = spectroscopic factor

**real(ROP)** = IPSM, final nucleon from Dirac equation with relativistic **real** optical potential

**RPWIA** = IPSM, final nucleon is a plane wave

**Transp.** = Transparency factor



**Key:**

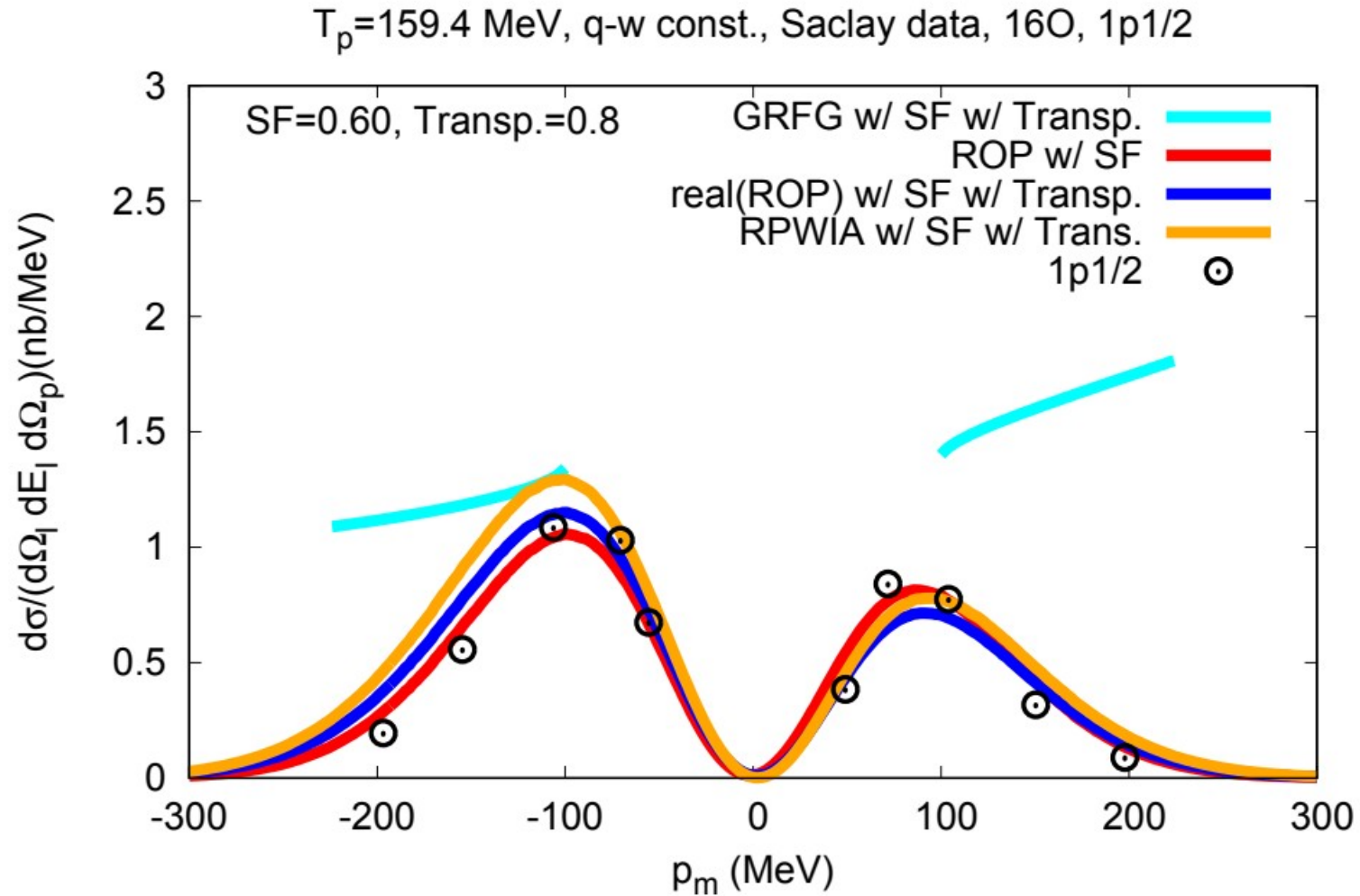
**ROP** = IPSM, final nucleon from Dirac equation with relativistic **complex** optical potential

**SF** = spectroscopic factor

**real(ROP)** = IPSM, final nucleon from Dirac equation with relativistic **real** optical potential

**RPWIA** = IPSM, final nucleon is a plane wave

**Transp.** = Transparency factor



**Key:**

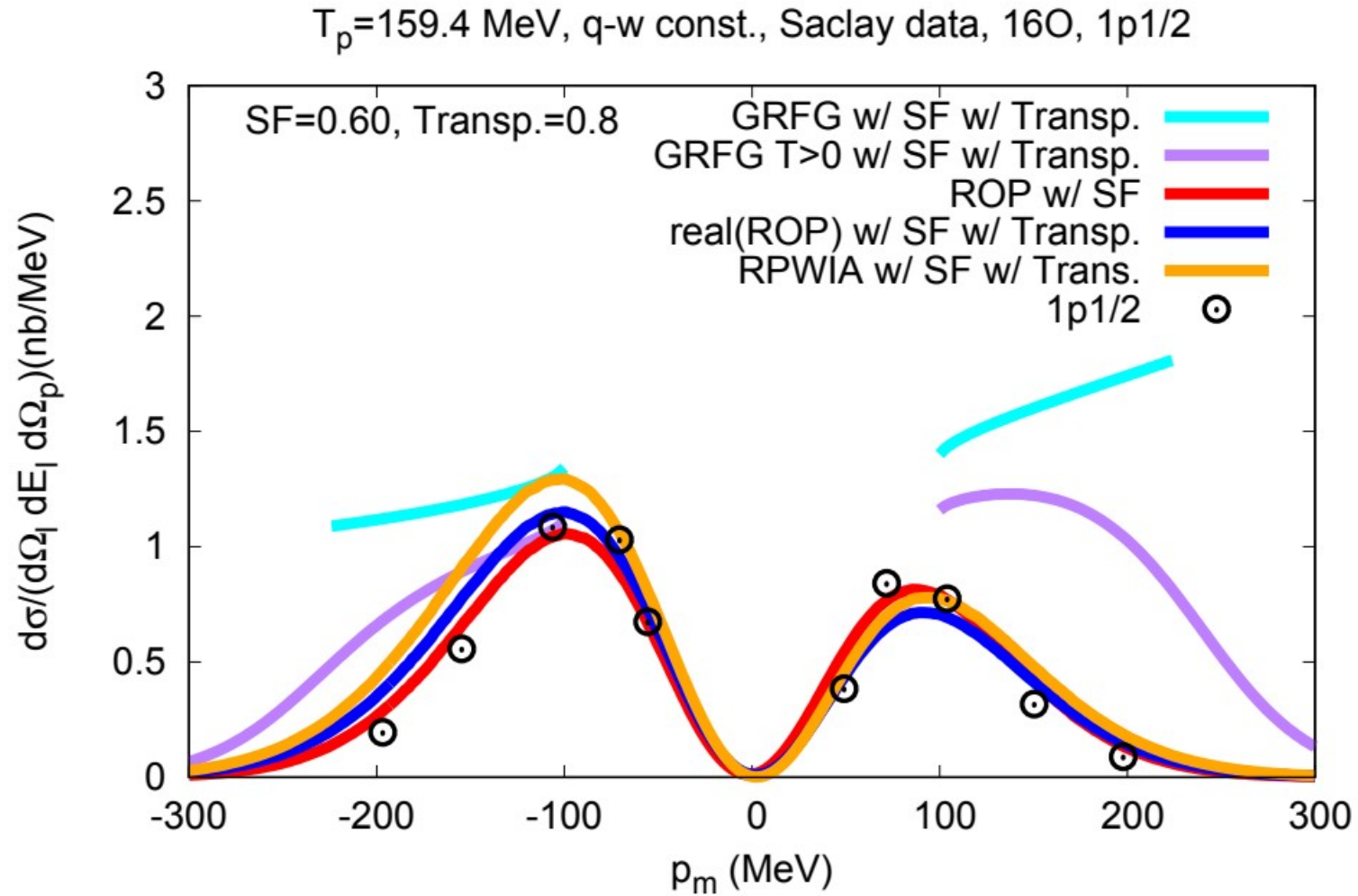
**ROP** = IPSM, final nucleon from Dirac equation with relativistic **complex** optical potential

**SF** = spectroscopic factor

**real(ROP)** = IPSM, final nucleon from Dirac equation with relativistic **real** optical potential

**RPWIA** = IPSM, final nucleon is a plane wave

**Transp.** = Transparency factor



**Key:**

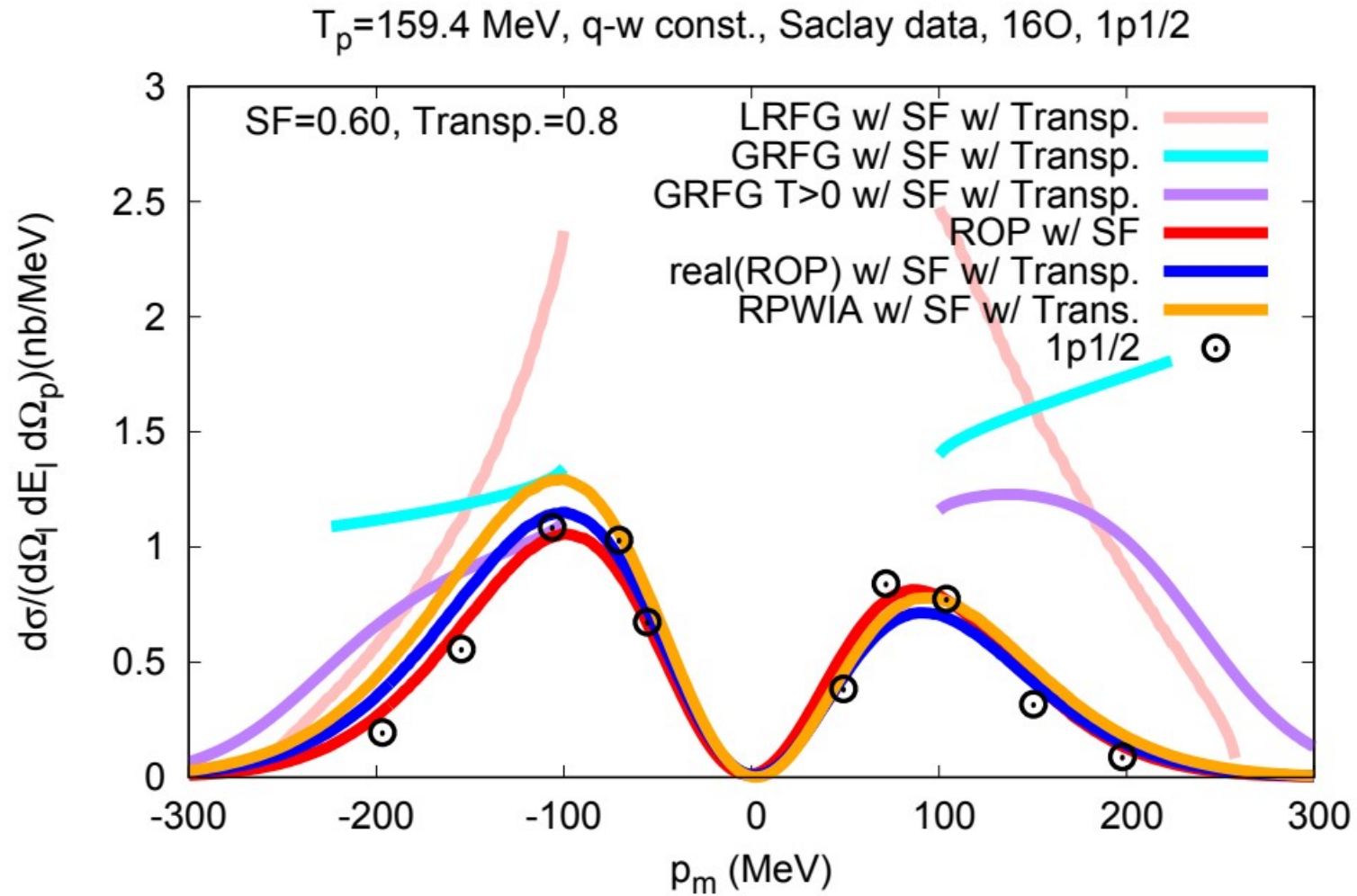
**ROP** = IPSM, final nucleon from Dirac equation with relativistic **complex** optical potential

**SF** = spectroscopic factor

**real(ROP)** = IPSM, final nucleon from Dirac equation with relativistic **real** optical potential

**RPWIA** = IPSM, final nucleon is a plane wave

**Transp.** = Transparency factor



**Key:**

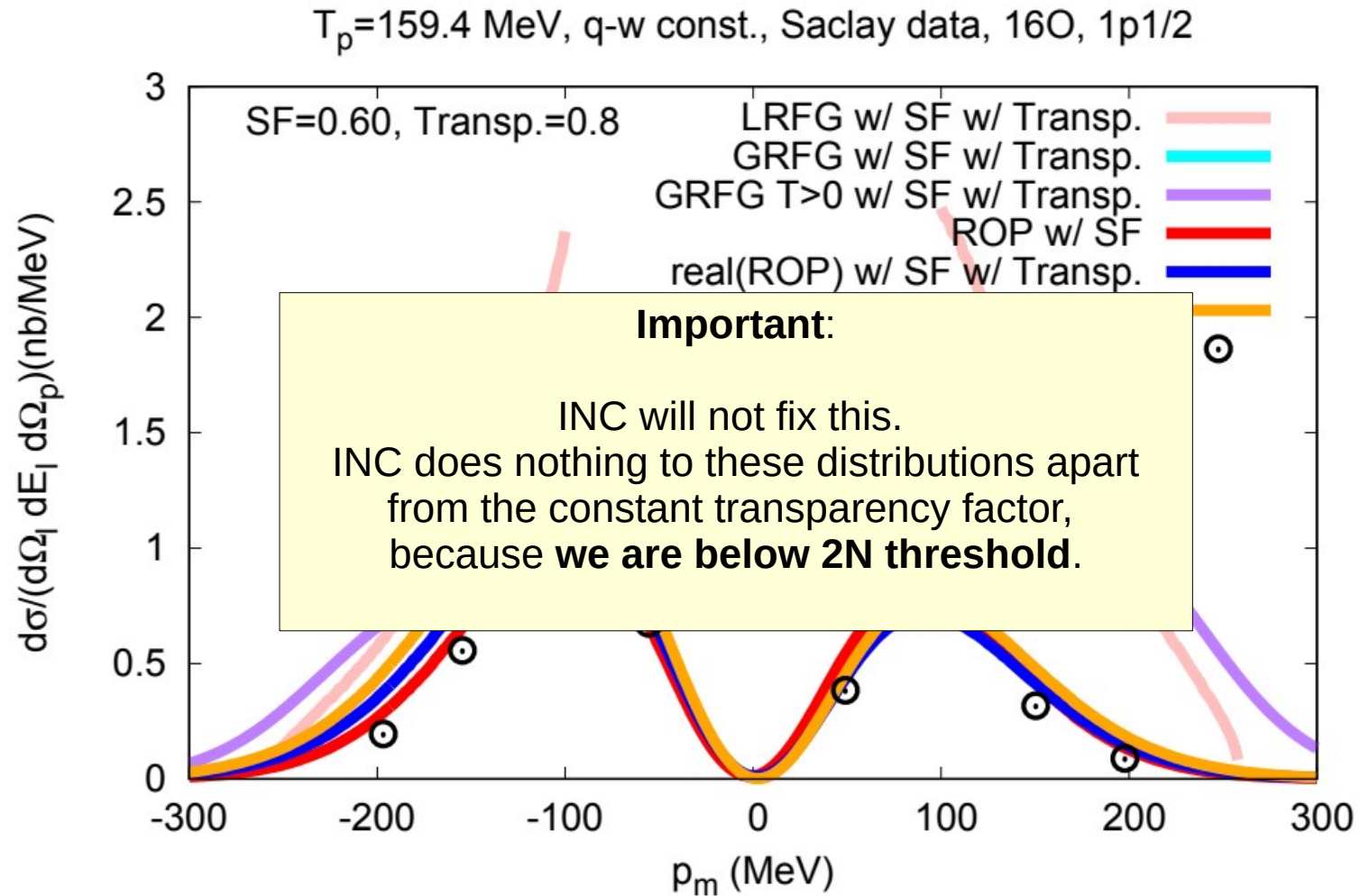
**ROP** = IPSM, final nucleon from Dirac equation with relativistic **complex** optical potential

**SF** = spectroscopic factor

**real(ROP)** = IPSM, final nucleon from Dirac equation with relativistic **real** optical potential

**RPWIA** = IPSM, final nucleon is a plane wave

**Transp.** = Transparency factor



# Exclusive experiments: $^{40}\text{Ca}(e,e'p)^{39}\text{K}$

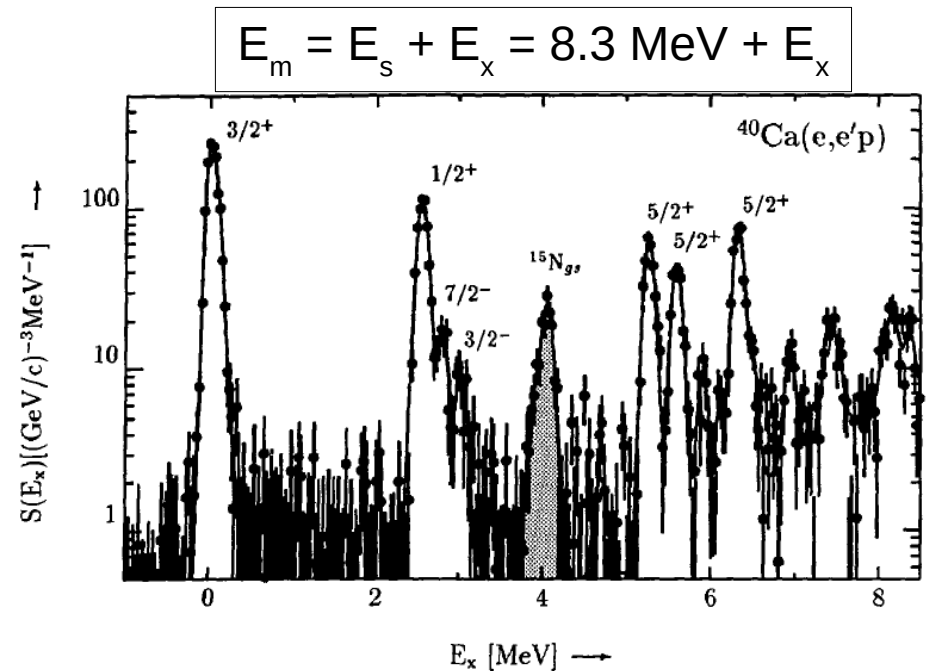
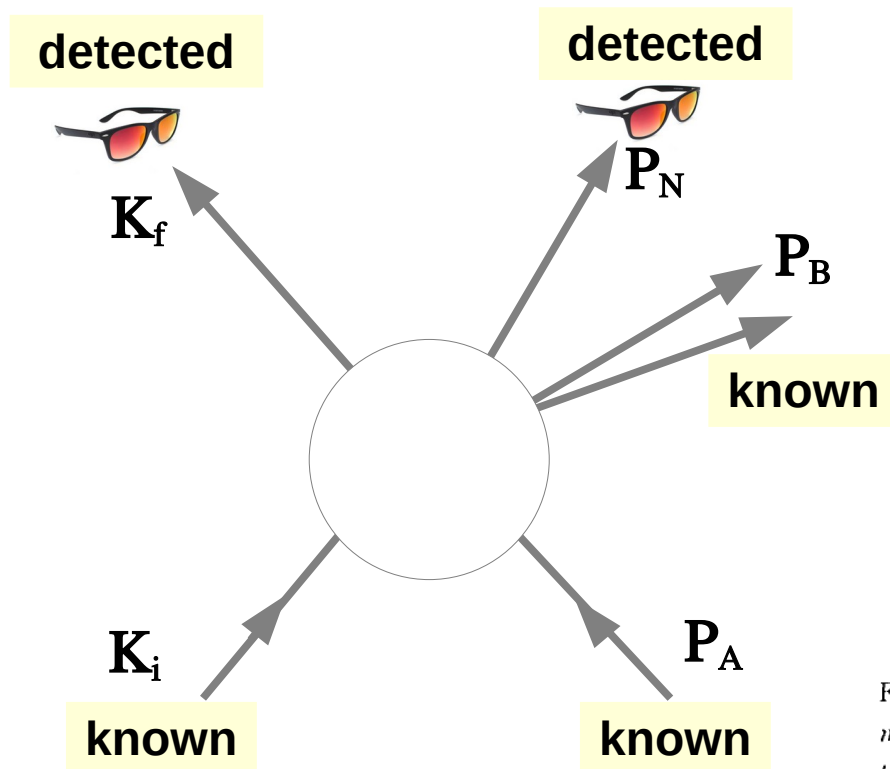
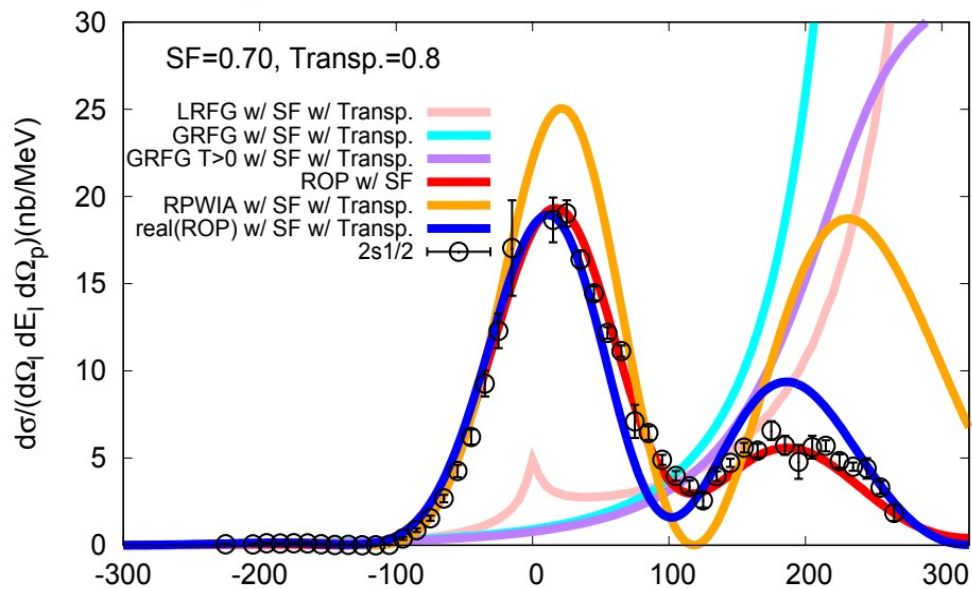


Figure 4.3: A typical excitation-energy spectrum for the reaction  $^{40}\text{Ca}(e,e'p)$  at a missing momentum of 100 MeV/c. Some strongly excited states are indicated with their spin and parity. The curve represents a fit to the data. G. Kramer's PhD Thesis (1990) Universiteit van Amsterdam

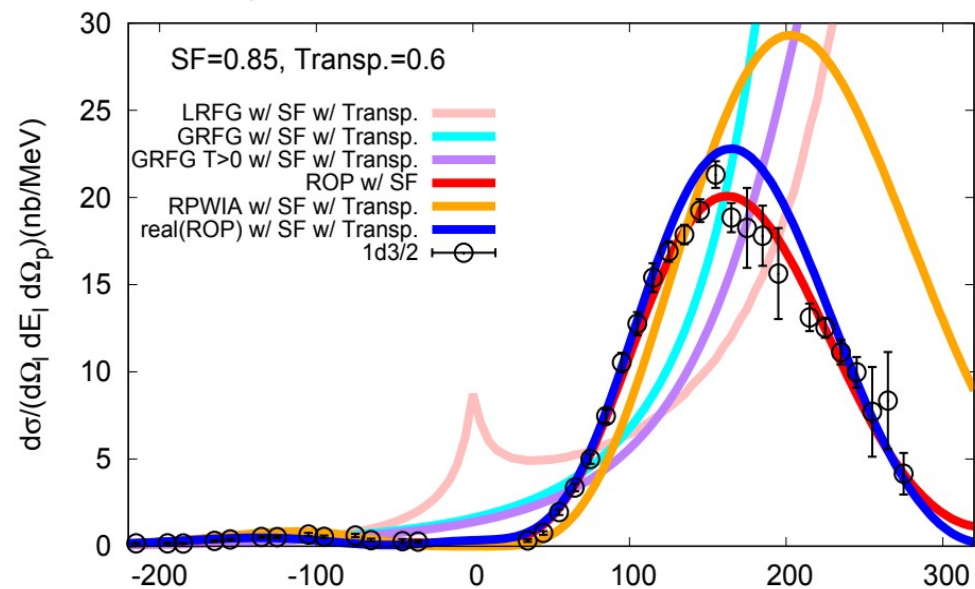
## Exclusive

If we stay below the 2N knockout threshold, we know that the residual system is the A-1 nucleus, in the ground or an excited state.

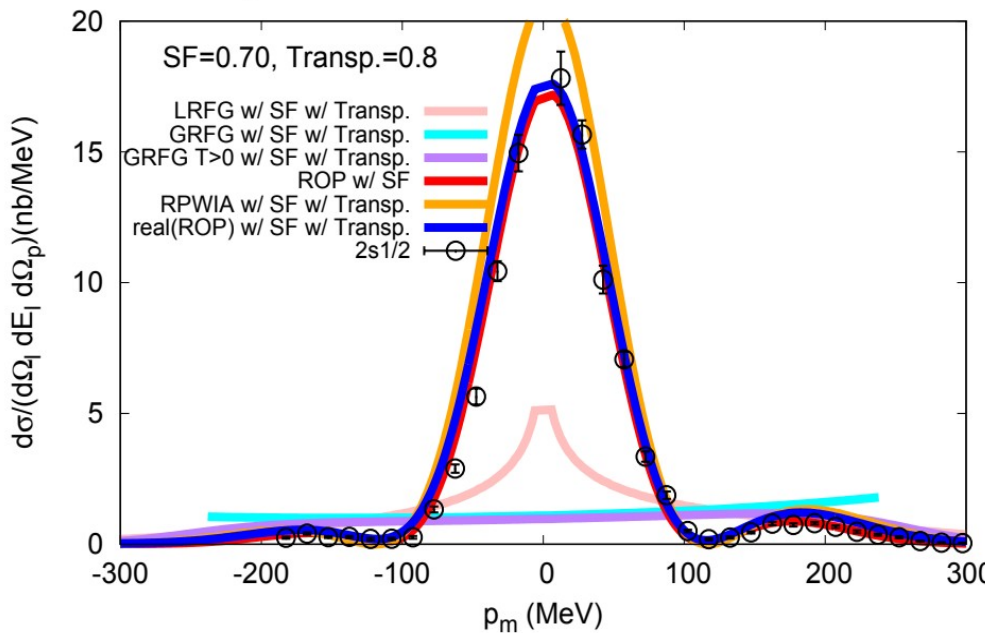
$T_p=100$  MeV, parallel kin, Nikhef data, 40Ca, 2s1/2



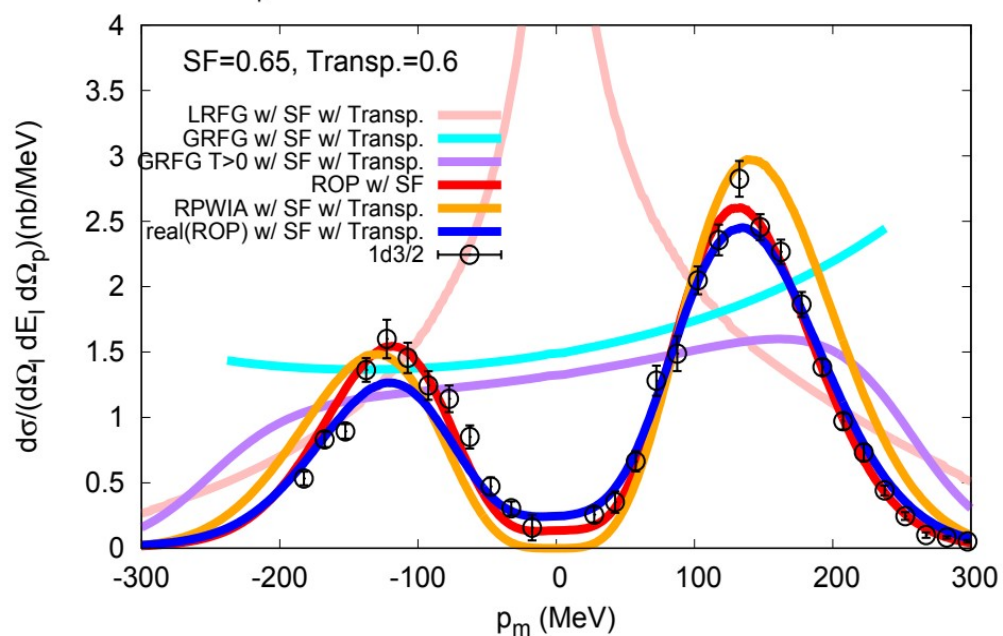
$T_p=100$  MeV, parallel kin, Nikhef data, 40Ca, 1d3/2



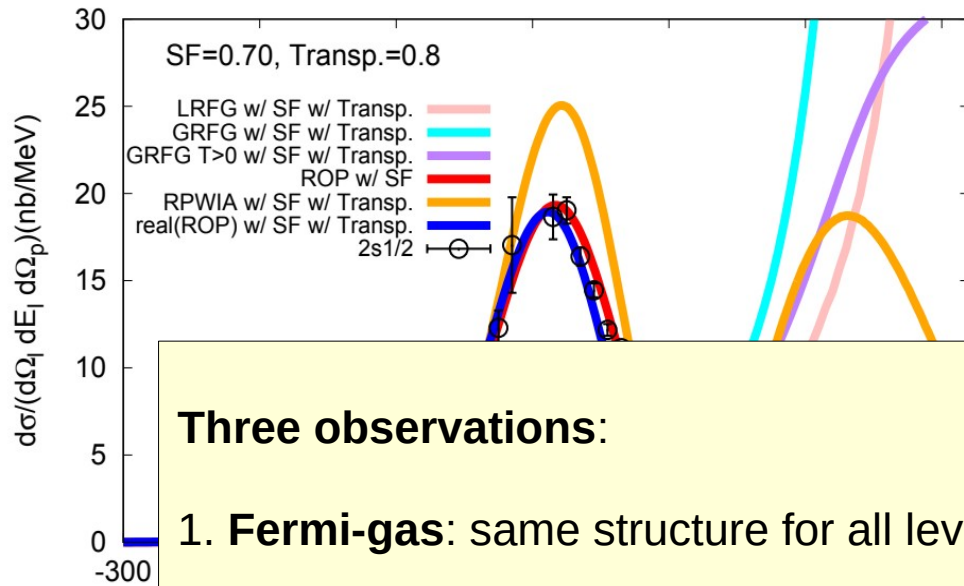
$T_p=100$  MeV, q-w const., Nikhef data, 40Ca, 2s1/2



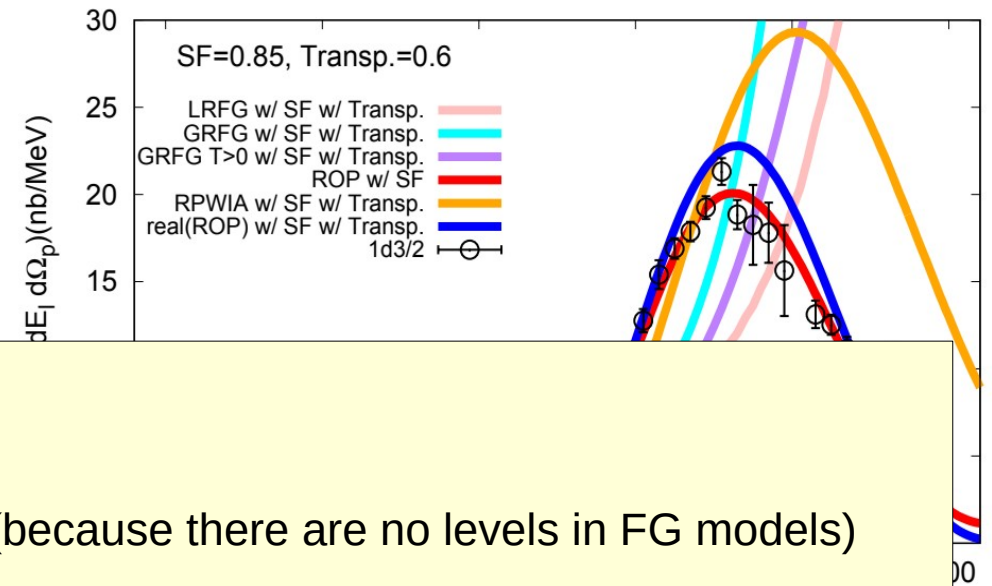
$T_p=100$  MeV, q-w const., Nikhef data, 40Ca, 1d3/2



$T_p=100$  MeV, parallel kin, Nikhef data, 40Ca, 2s1/2

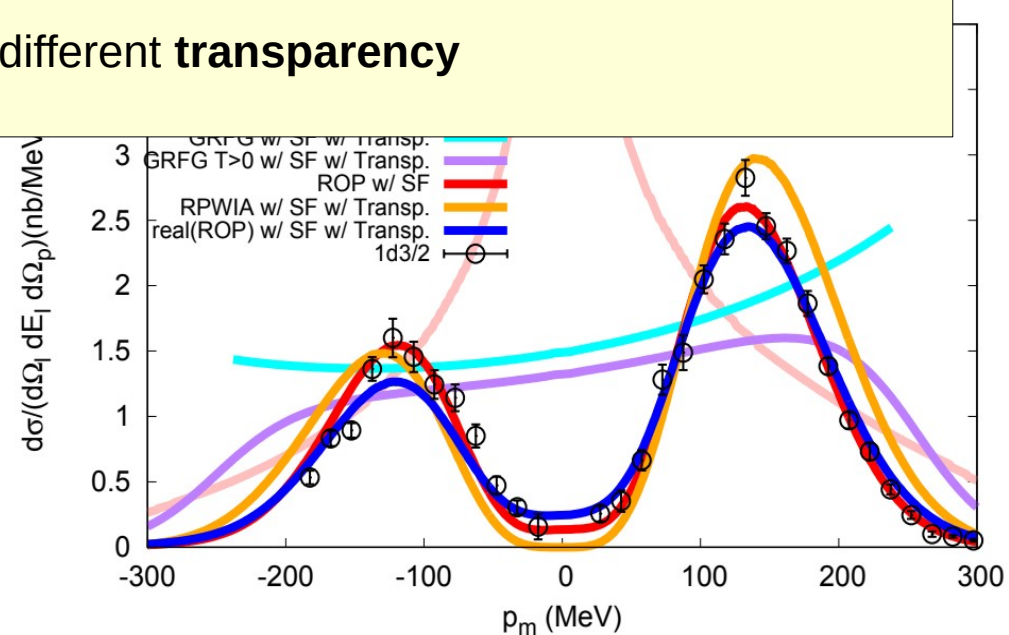
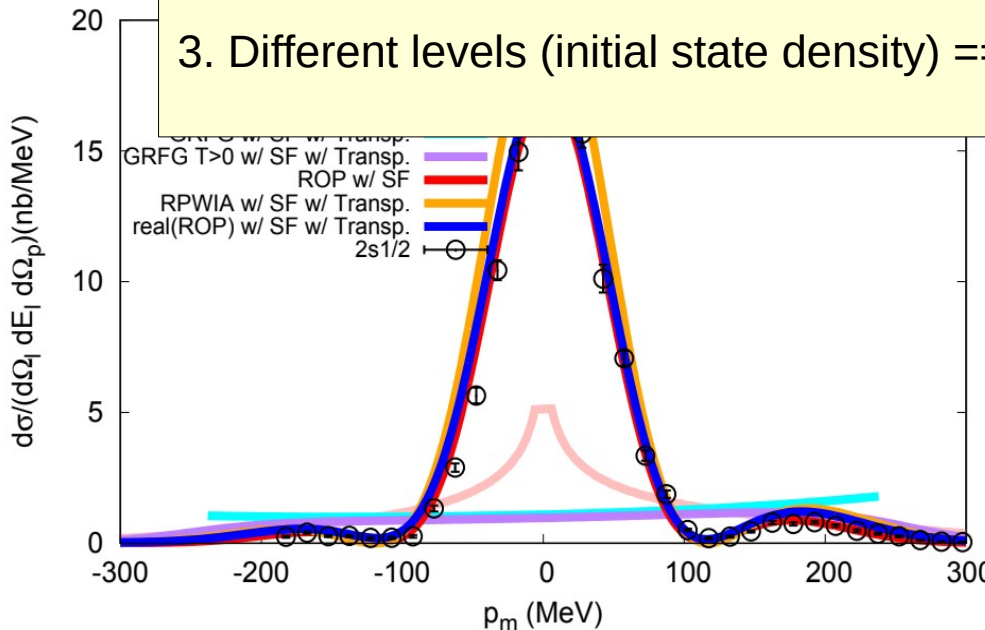


$T_p=100$  MeV, parallel kin, Nikhef data, 40Ca, 1d3/2



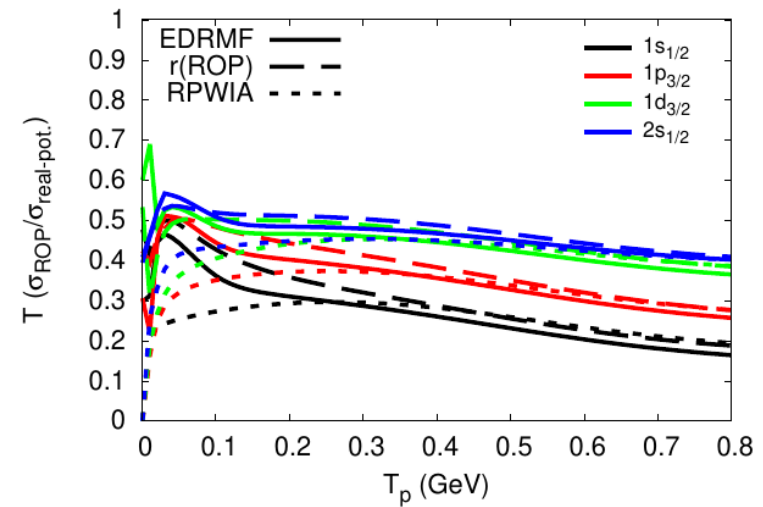
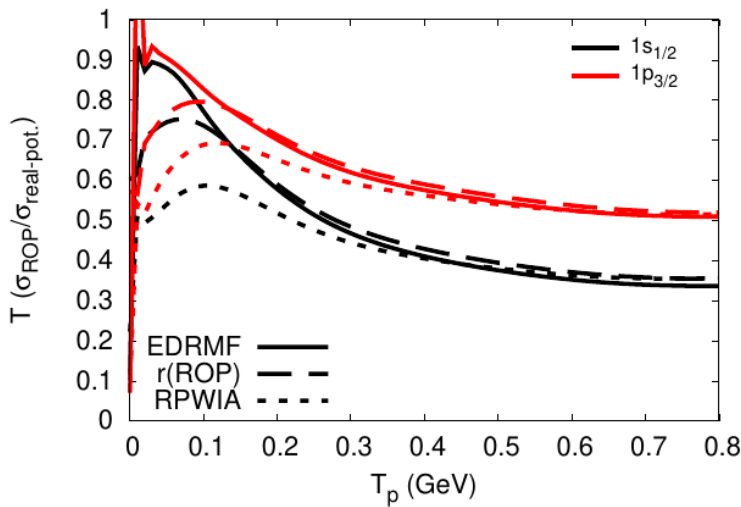
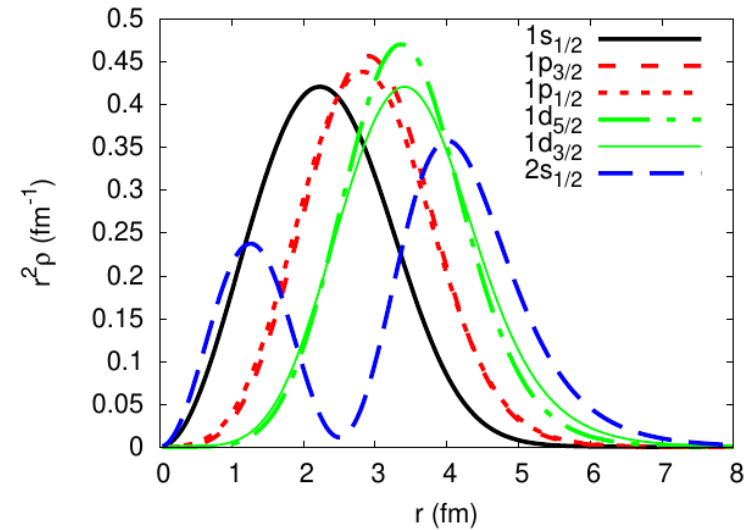
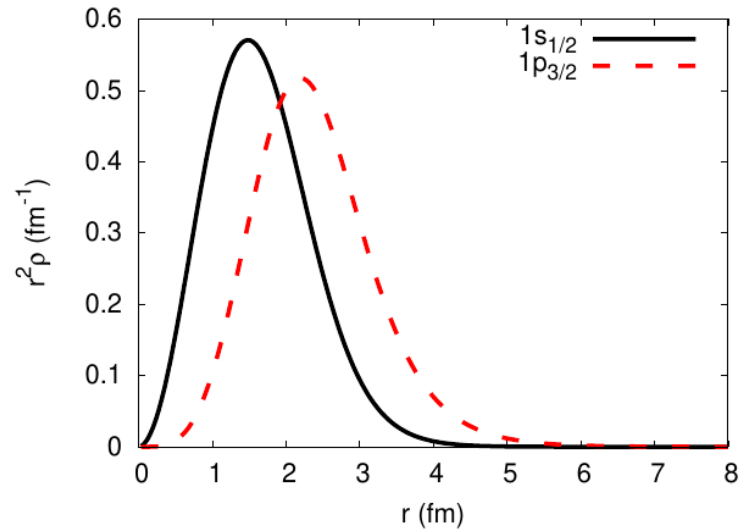
### Three observations:

1. **Fermi-gas**: same structure for all levels (because there are no levels in FG models)
2. **'plane waves' x transparency** is superior to **'Fermi gas' x transparency**, but not as good as **'distorted waves' x transparency**
3. Different levels (initial state density) ==> different **transparency**



### 3. Different levels ==> different transparency

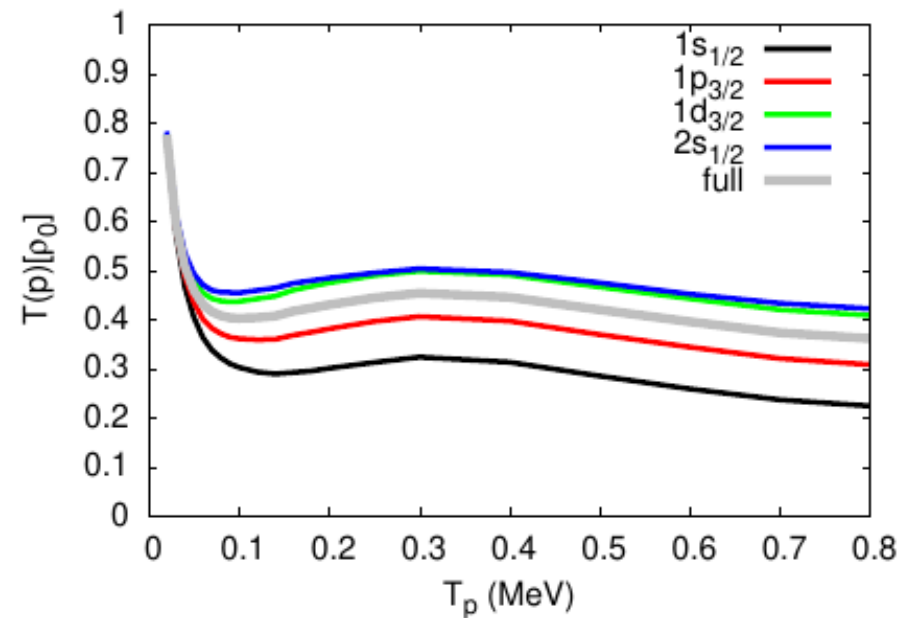
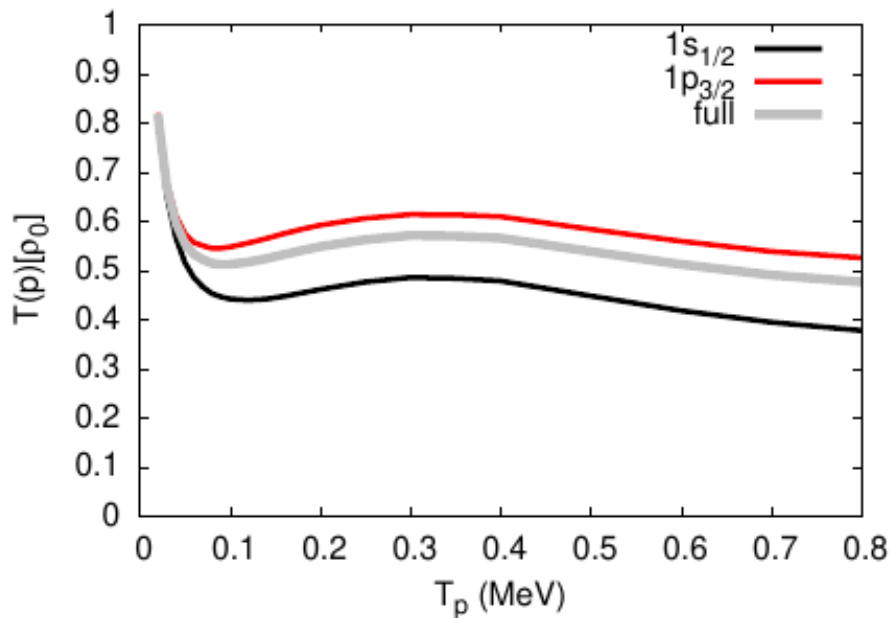
in other words, the transparency depends on where (which level) the nucleon originated;  
in other words, the transparency depends on the density.

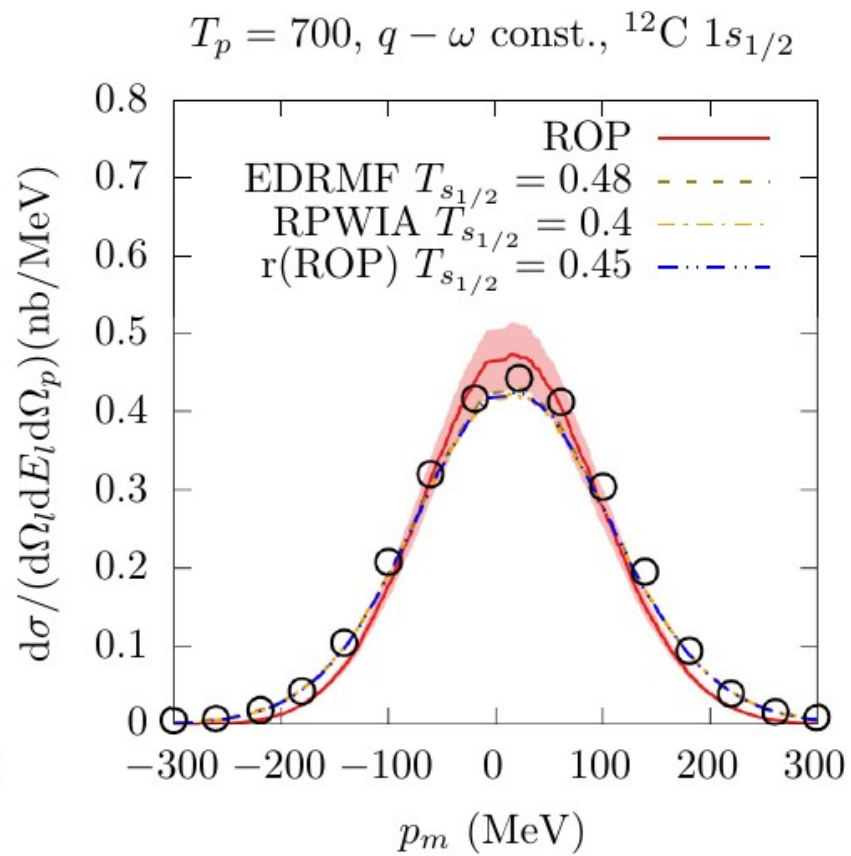
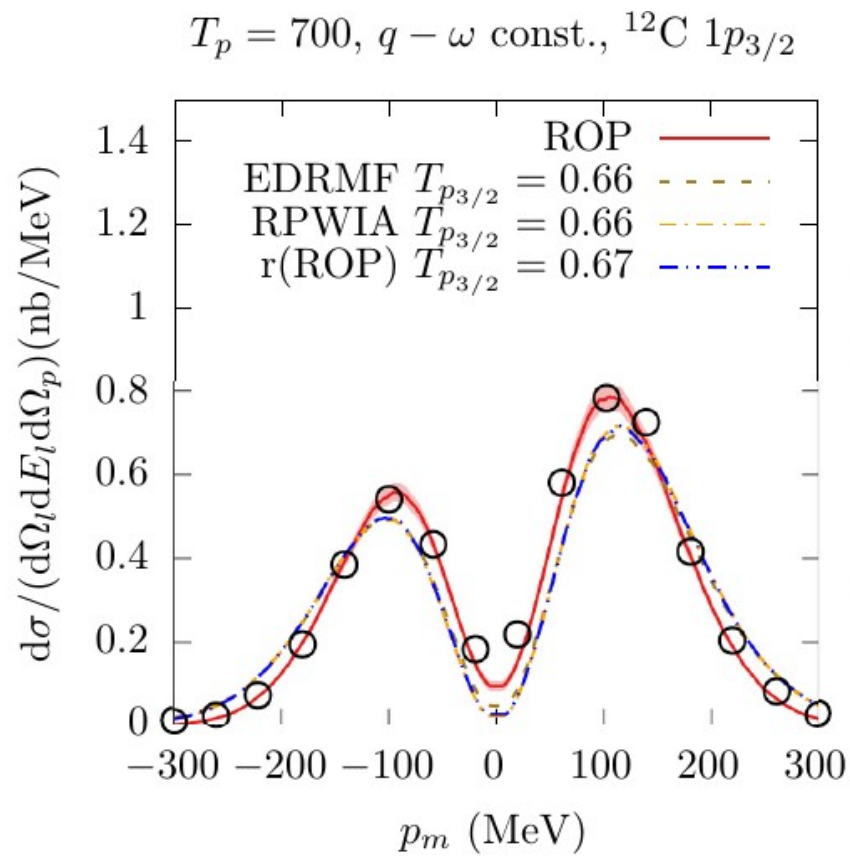


### 3. Different levels ==> different transparency

in other words, the transparency depends on where (which level) the nucleon originated;  
in other words, the transparency depends on the density.

**This feature could be implemented easily in a MC event generator!!!**





# SUMMARY

**1) Intranuclear cascade (INC) does NOT affect the inclusive (e,e') cross section**

==> A realistic model for the elementary vertex is needed.

**2) The elementary-vertex model should provide information on the hadron(s)** that will be propagated through the cascade.

**3) Exclusive (e,e'p) scattering data** are useful to improve:

+ elementary-vertex models,

+ and a basic feature of the INC: the **transparency**.

**4) Elastic FSI** (or nucleon distortion) is important, it should be accounted for in the elementary-vertex model.

**5) Nuclear transparency depends on the level** from which the knockout nucleon originated. This feature could be easily implemented in event generators.

**6) “Distorted-wave model (with real potentials) + INC”** is a feasible approach to improve current modeling of **nuclear effects in event generators**.

# Thanks!!!

# **additional slides**

# Which ingredients do we include at each step ???

## Inclusive (e,e') cross section:

$$\frac{d\sigma}{d\mathbf{k}_{\text{electron}}} = \int d\mathbf{p}_{\text{hadrons}} \frac{d\sigma}{d\mathbf{k}_{\text{electron}} d\mathbf{p}_{\text{hadrons}}}$$

Fully determined by the elementary-vertex model, i.e., it does not depend on the INC model.

➡ The elementary-vertex model should be such that the inclusive cross section is well reproduced.

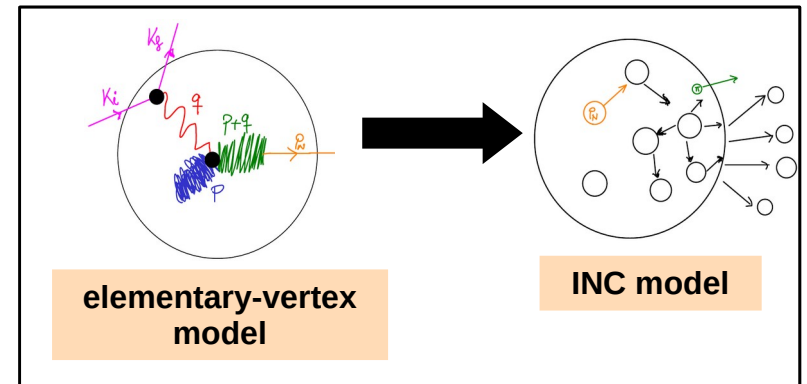
Ingredients needed: Distortion (elastic FSI), Pauli blocking, binding energy, correlations.

## Exclusive (e,e'p) cross section:

The role of the INC is simply to scale down the elementary-vertex cross section by a constant (**transparency**) factor.

Ingredients needed: the previous ones + shell structure and correct transparency factor.

**Transparency factor** is fully determined by the INC model.

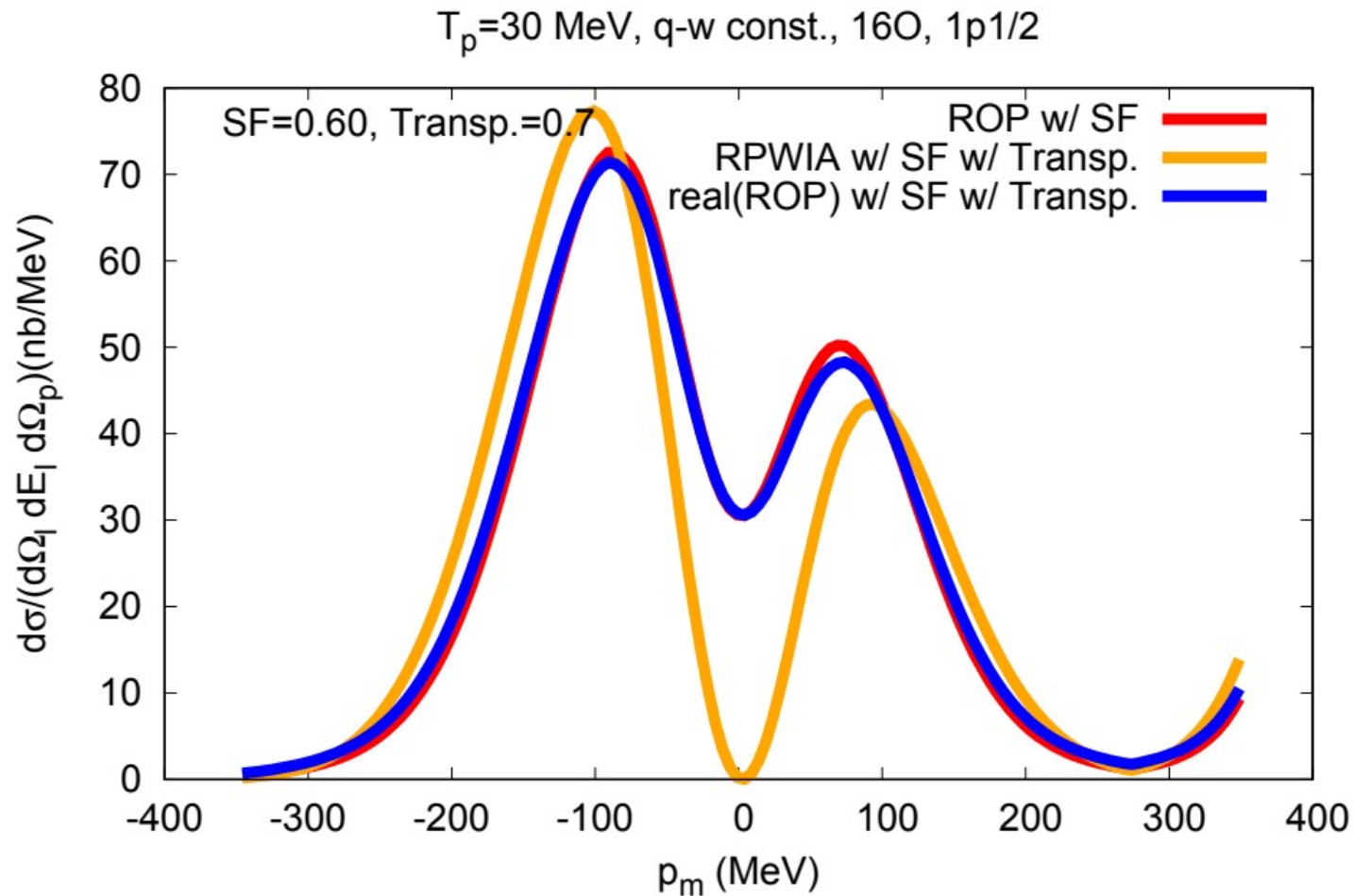


# Summary of separation energies (SE) for p, n, p+n, p+p, n+n,... for $^{12}\text{C}$ and $^{40}\text{Ar}$

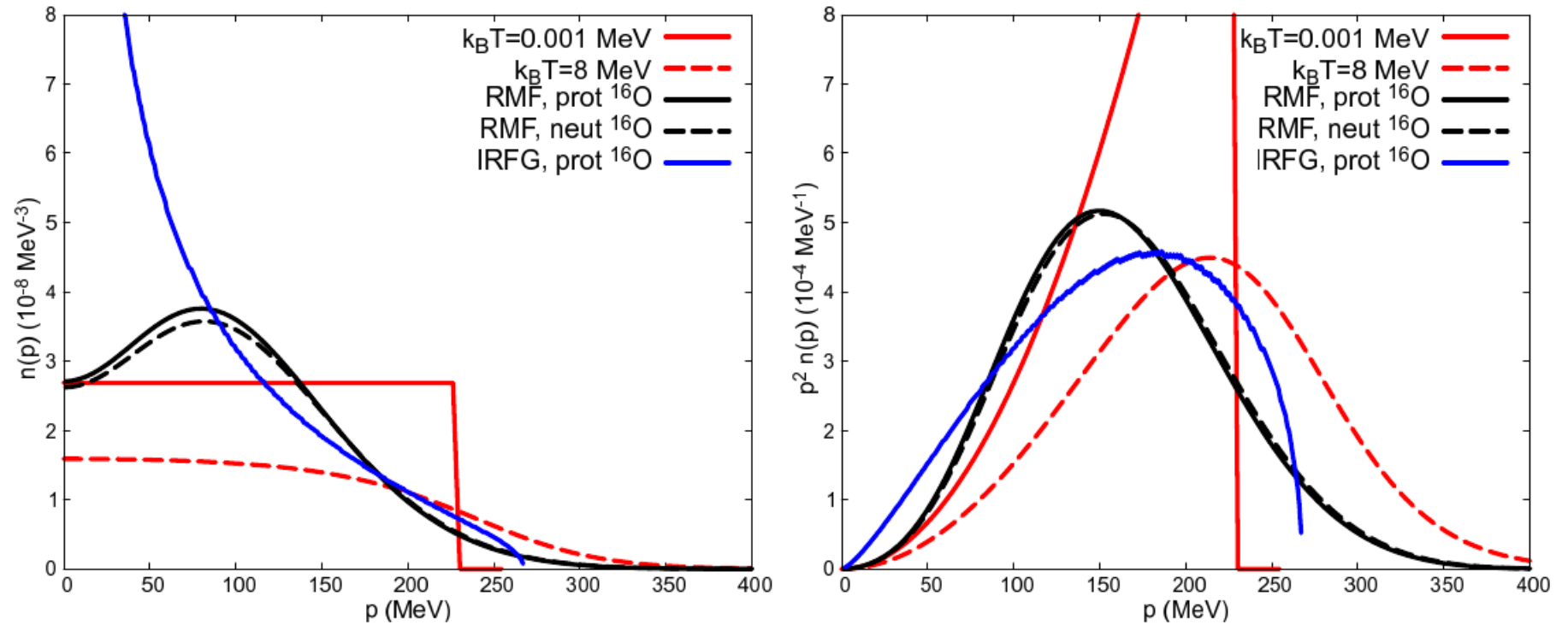
|                  | One nucleon knockout |            | Two-nucleon knockout |              |              | Three-nucleon knockout |               |               |             | Deuterium knockout    |
|------------------|----------------------|------------|----------------------|--------------|--------------|------------------------|---------------|---------------|-------------|-----------------------|
|                  | p SE (MeV)           | n SE (MeV) | p+n SE (MeV)         | p+p SE (MeV) | n+n SE (MeV) | 3p SE (MeV)            | 2p+n SE (MeV) | p+2n SE (MeV) | 3n SE (MeV) | $^2\text{H}$ SE (MeV) |
| $^{12}\text{C}$  | -15.96               | -18.72     | -27.41               | -27.19       | -31.84       | -46.82                 | -34.00        | -35.85        | -53.12      | -25.19                |
| $^{40}\text{Ar}$ | -12.53               | -9.87      | -20.60               | -22.76       | -16.47       | -37.91                 | -26.74        | -26.71        | -32.36      | -18.38                |

2. 'plane waves' \* transparency, better than 'Fermi gas'\*transparency,  
but not as good as 'distorted waves' \* transparency

Clearer for lower nucleon kinetic energies

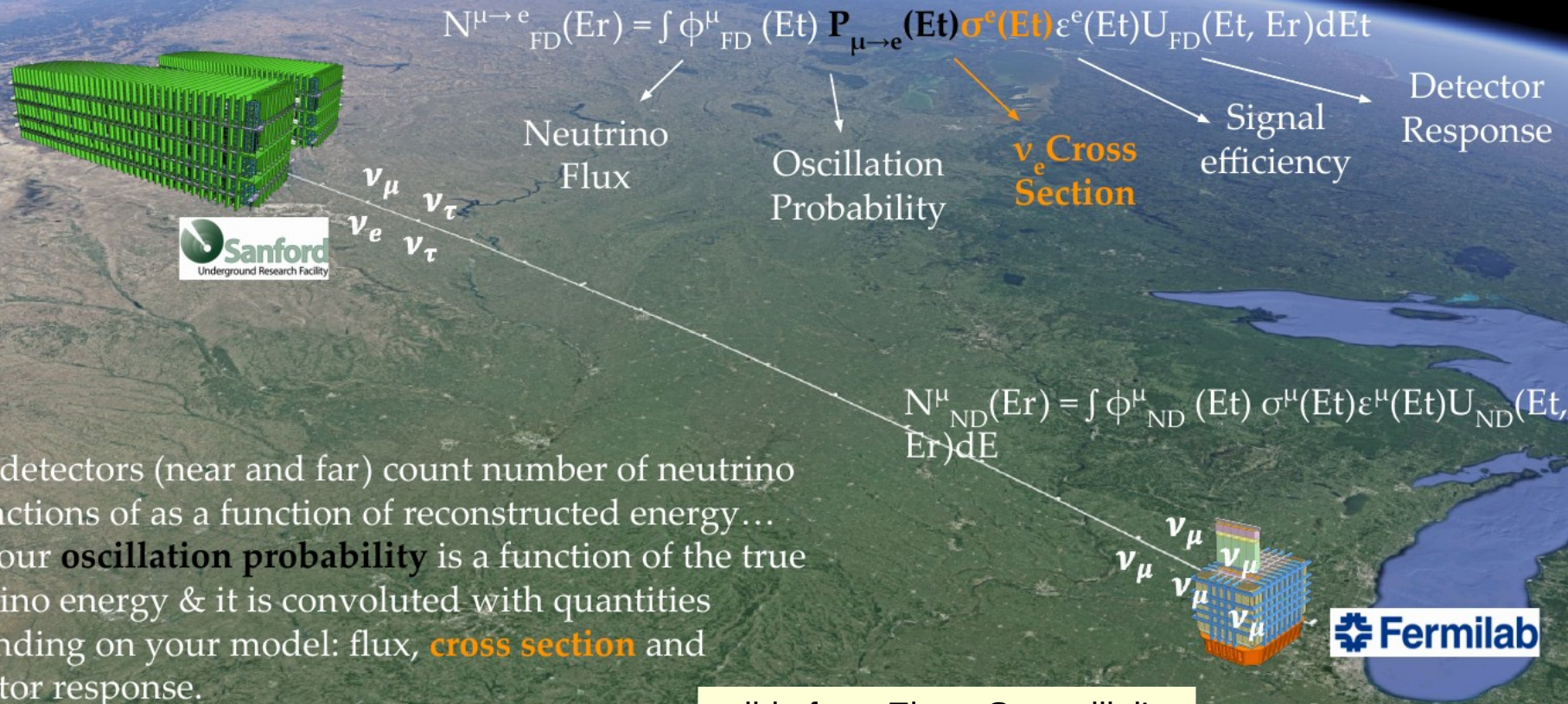


## Momentum distributions



# $\nu$ -oscillations experiment 101

**STEP 1:** Making a beam  
**STEP 2:** Checking twice  
**STEP 3:** Gonna find out  
 if you've more of one type



Your detectors (near and far) count number of neutrino interactions of as a function of reconstructed energy... but your **oscillation probability** is a function of the true neutrino energy & it is convoluted with quantities depending on your model: flux, **cross section** and detector response.

slide from Elena Gramellini's talk in NuFact 2023

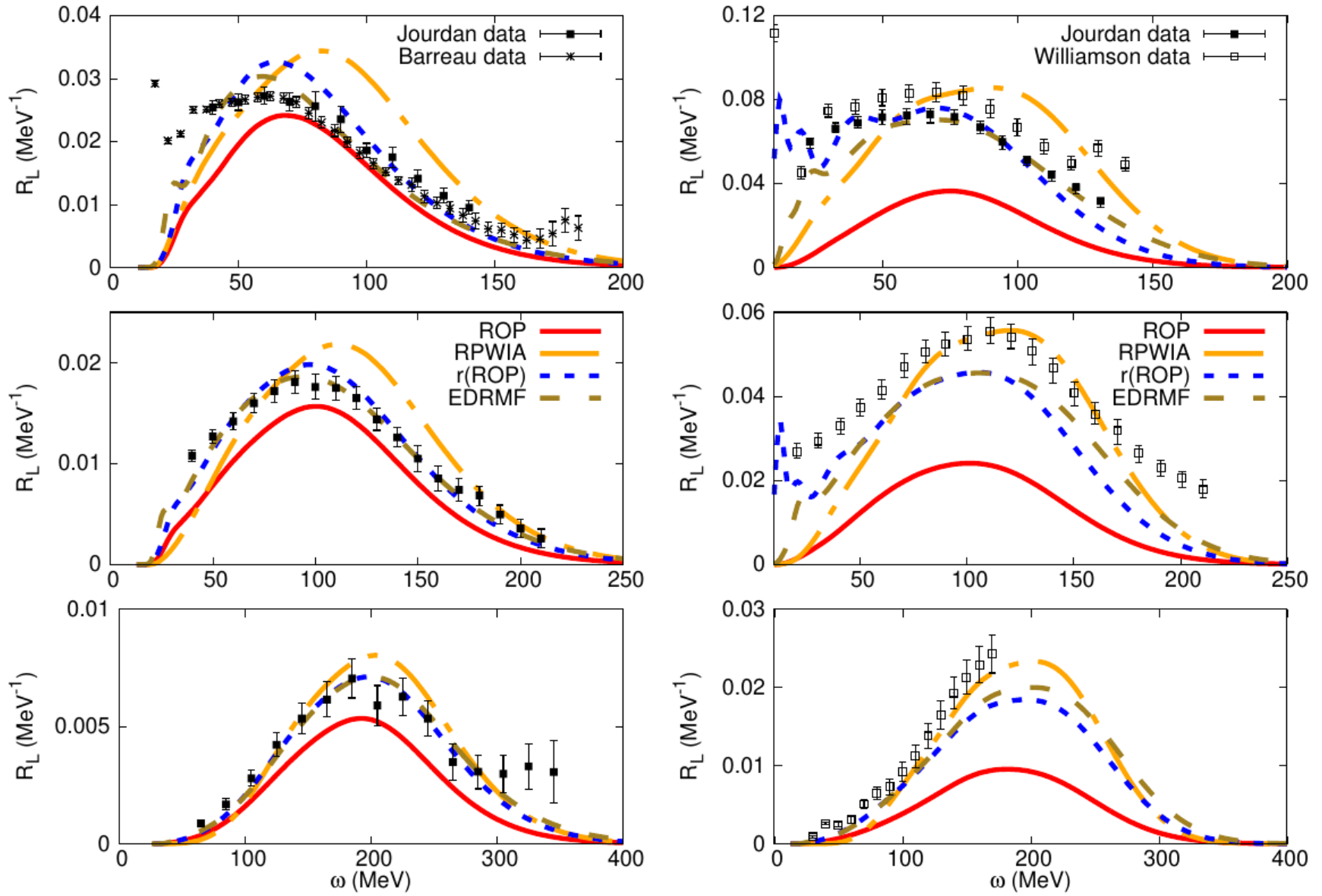


FIG. 4. EDRMF,  $r(\text{ROP})$  and ROP predictions compared to  $R_L$   $^{12}\text{C}$  data from [60] [61] (left panels) and  $^{40}\text{Ca}$  data from [61]–[64] (right panels). Each panel corresponds to a fixed  $q$ : 300, 380 and 570 MeV (left panels); and 300, 380 and 550 MeV (right panels).