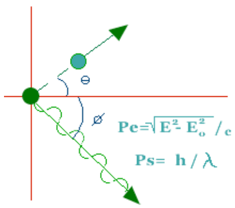
Latest developments and future applications of the dispersive optical model

INT 17-1a
3/16/2017

Washington University in St.Louis



Wim Dickhoff
Bob Charity
Lee Sobotka

Hossein Mahzoon (Ph.D.2015)
Mack Atkinson

Cole Pruitt
Shouwan Chen (Hefei U)
Natalya Calleya
Michael Keim

Recent review:
WD, Bob Charity, Hossein Mahzoon
J. Phys. G: Nucl. Part. Phys. 44 (2017) 033001

- Motivation
- Green's functions/propagator method
  - vehicle for ab initio calculations
  - as a framework to link data at positive and negative energy (and to generate predictions for exotic nuclei)

-> dispersive optical model (DOM <- Claude Mahaux)

- Recent DOM extension to non-local potentials
- Revisit the (e,e'p) data from NIKHEF
- Neutron skin in ^{48}Ca (importance of total xsections)
- Ongoing and future applications
- Conclusions

reactions and structure

Motivation

- Rare isotope physics requires a **much** stronger link between nuclear reactions and nuclear structure descriptions
- We need an ab initio approach for optical potential —> optical potentials must therefore become **nonlocal** and **dispersive**
- Current status to extract structure information from nuclear reactions involving strongly interacting probes **unsatisfactory**
- Intermediate step: dispersive optical model as originally proposed by Claude Mahaux —> some **extensions** discussed here

Optical potential <--> nucleon self-energy

- e.g. Bell and Squires --> elastic T-matrix = reducible self-energy
- e.g. Mahaux and Sartor Adv. Nucl. Phys. **20**, 1 (1991)
  - relate dynamic (energy-dependent) real part to imaginary part
  - employ subtracted dispersion relation

General dispersion relation for self-energy:

$$\text{Re}\ \Sigma(E) = \Sigma^{HF} - \frac{1}{\pi}\mathcal{P}\int_{E_T^+}^{\infty} dE' \frac{\text{Im}\ \Sigma(E')}{E - E'} + \frac{1}{\pi}\mathcal{P}\int_{-\infty}^{E_T^-} dE' \frac{\text{Im}\ \Sigma(E')}{E - E'}$$

Calculated at the Fermi energy $\varepsilon_F = \frac{1}{2}\left\{(E_0^{A+1} - E_0^A) + (E_0^A - E_0^{A-1})\right\}$

$$\text{Re}\ \Sigma(\varepsilon_F) = \Sigma^{HF} - \frac{1}{\pi}\mathcal{P}\int_{E_T^+}^{\infty} dE' \frac{\text{Im}\ \Sigma(E')}{\varepsilon_F - E'} + \frac{1}{\pi}\mathcal{P}\int_{-\infty}^{E_T^-} dE' \frac{\text{Im}\ \Sigma(E')}{\varepsilon_F - E'}$$

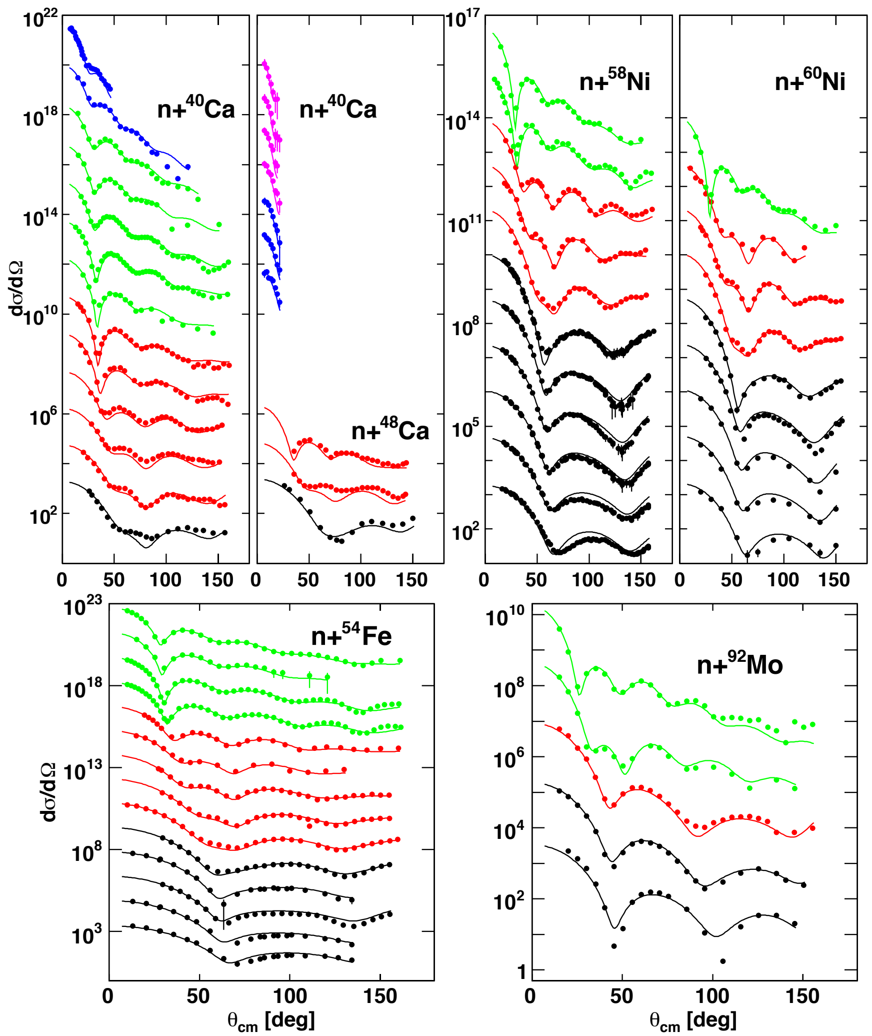
Subtract

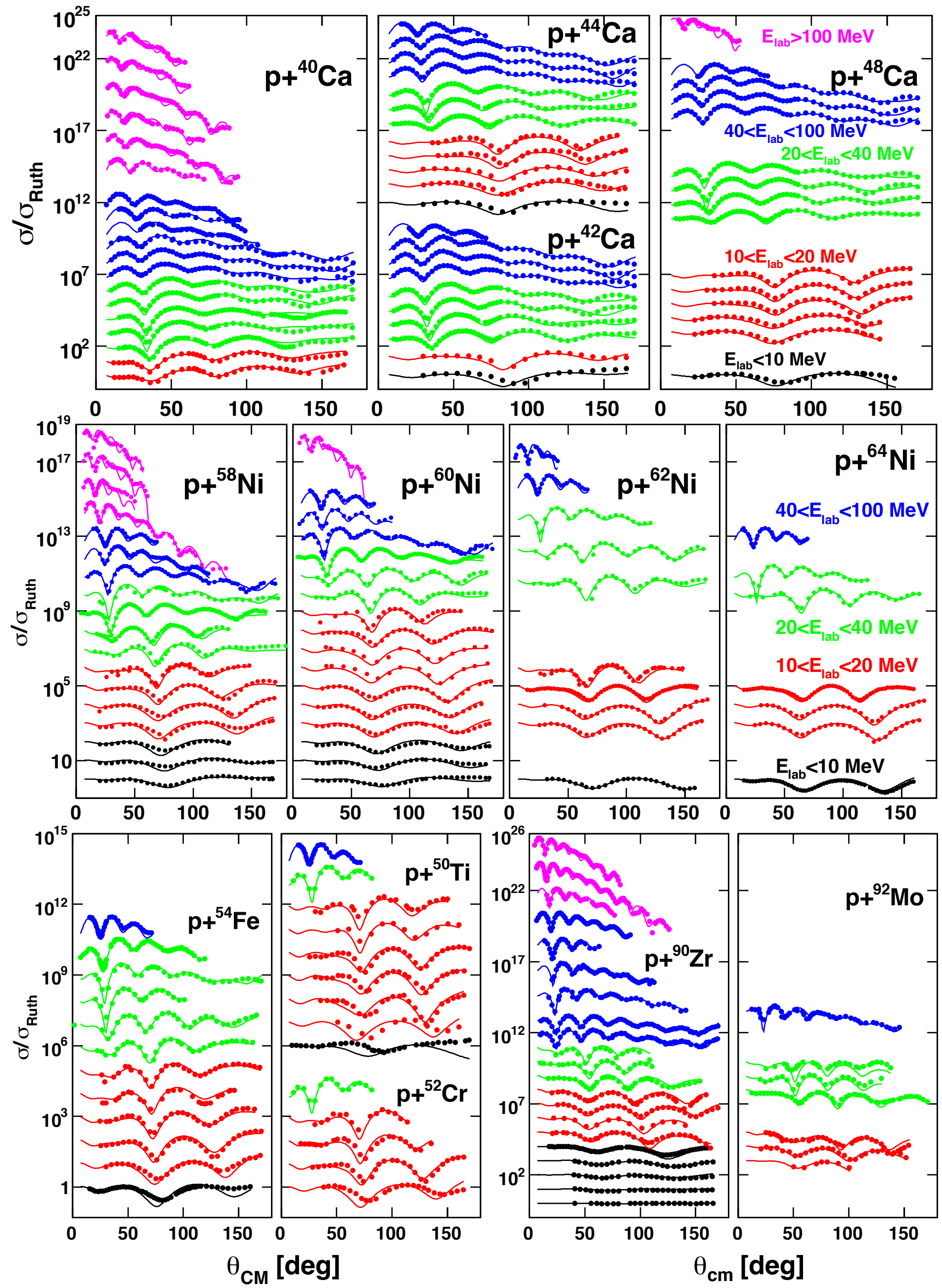
$$\text{Re}\ \Sigma(E) = \text{Re}\ \Sigma^{\widetilde{HF}}(\varepsilon_F)$$

$$- \quad \frac{1}{\pi}(\varepsilon_F - E)\mathcal{P}\int_{E_T^+}^{\infty} dE' \frac{\text{Im}\ \Sigma(E')}{(E - E')(\varepsilon_F - E')} + \frac{1}{\pi}(\varepsilon_F - E)\mathcal{P}\int_{-\infty}^{E_T^-} dE' \frac{\text{Im}\ \Sigma(E')}{(E - E')(\varepsilon_F - E')}$$

Elastic scattering data for protons and neutrons

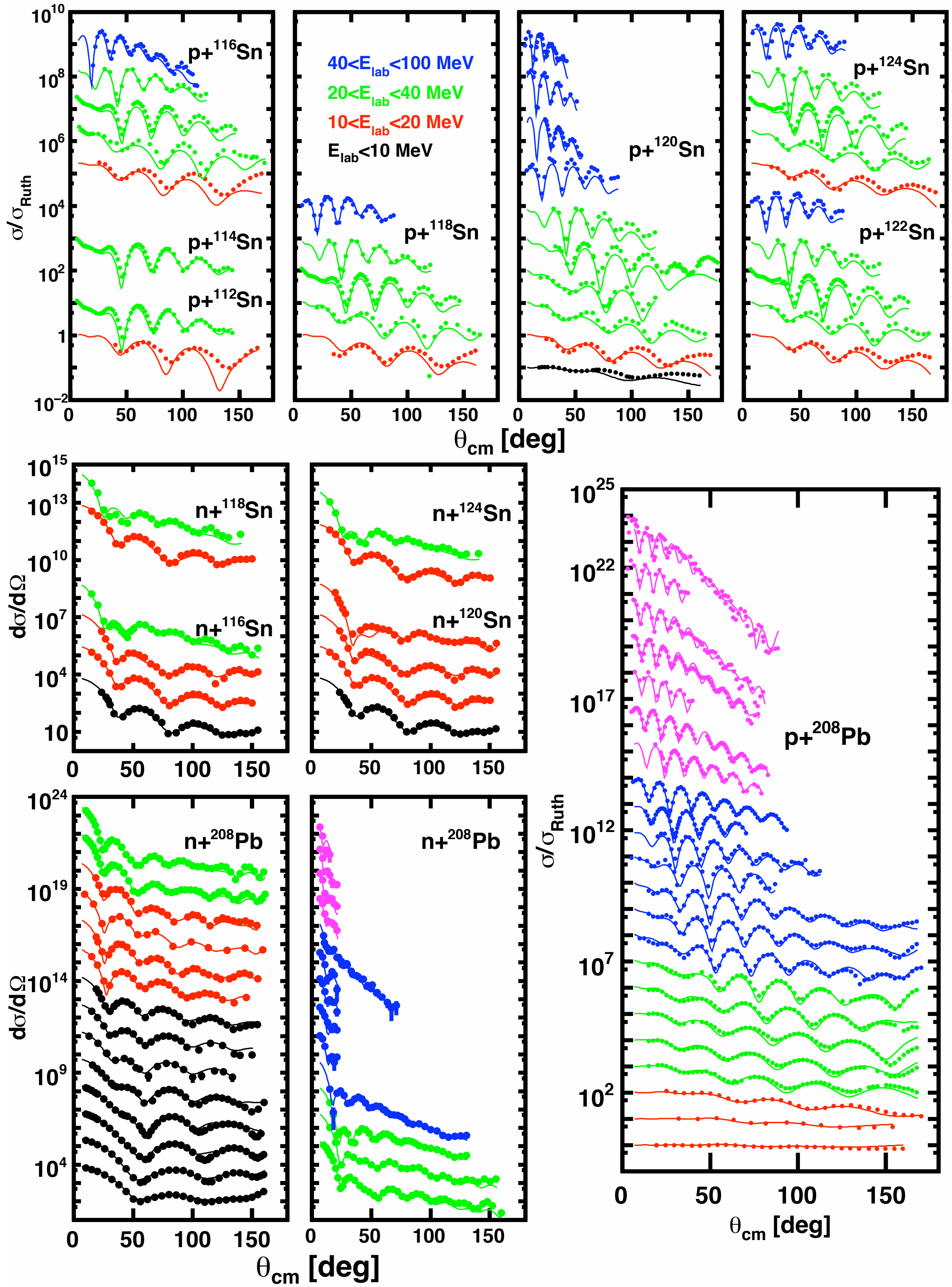
- **Local** DOM implementation





J. Mueller et al.
PRC83,064605 (2011), 1-32

reactions and structure



Local DOM analysis

J. Mueller et al.
PRC83,064605 (2011), 1-32

reactions and structure

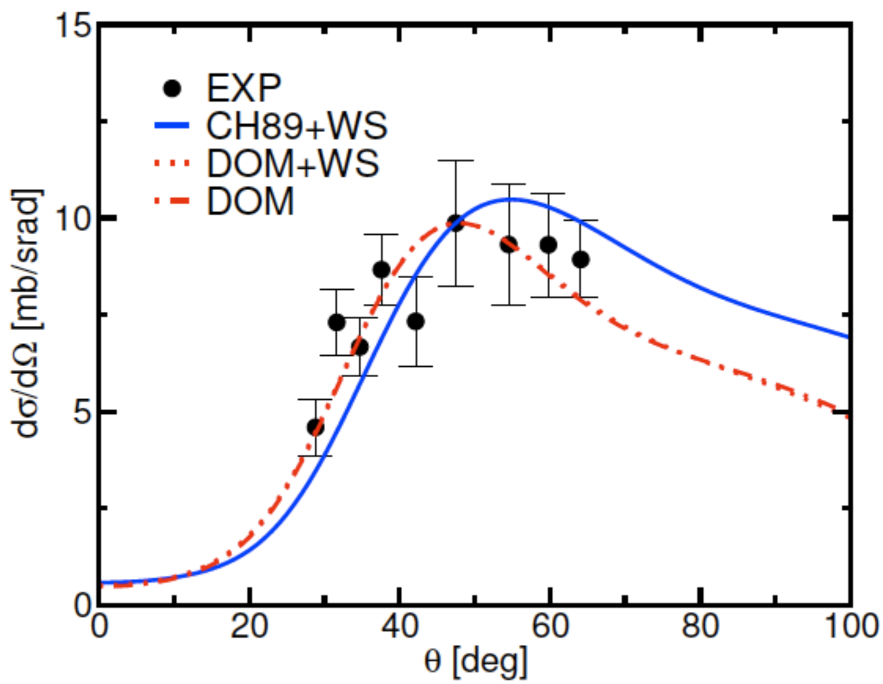
$^{132}Sn(d,p)$

How does it work when the potentials are extrapolated?

- Ingredients from local DOM
  - Overlap function
  - p and n optical potential
- Reaction model ADWA (Ron Johnson)
- MSU-WashU:--> N. B. Nguyen, S. J. Waldecker, F. M. Nuñes, R. J. Charity, and W. H. Dickhoff

Phys. Rev. C84, 044611 (2011), 1-9

- $^{40,48}Ca$, ^{132}Sn, $^{208}Pb(d,p)$



- Data: K.L. Jones et al., Nature 465, 454 (2010)
- E_d = 9.46 MeV $^{132}Sn(d,p)^{133}Sn$
  - CH89+ws --> $S_{1f7/2}$ =1.1
  - DOM --> $S_{1f7/2}$ =0.72

reactions and structure

Nonlocal DOM implementation PRL112,162503(2014)

- Particle number --> **nonlocal** imaginary part
- Ab initio FRPA & SRC --> different nonlocal properties above and below the Fermi energy Phys. Rev. C84, 034616 (2011) & Phys. Rev.C84, 044319 (2011)
- Include charge density in fit
- Describe high-momentum nucleons <--> (e,e′p) data from JLab

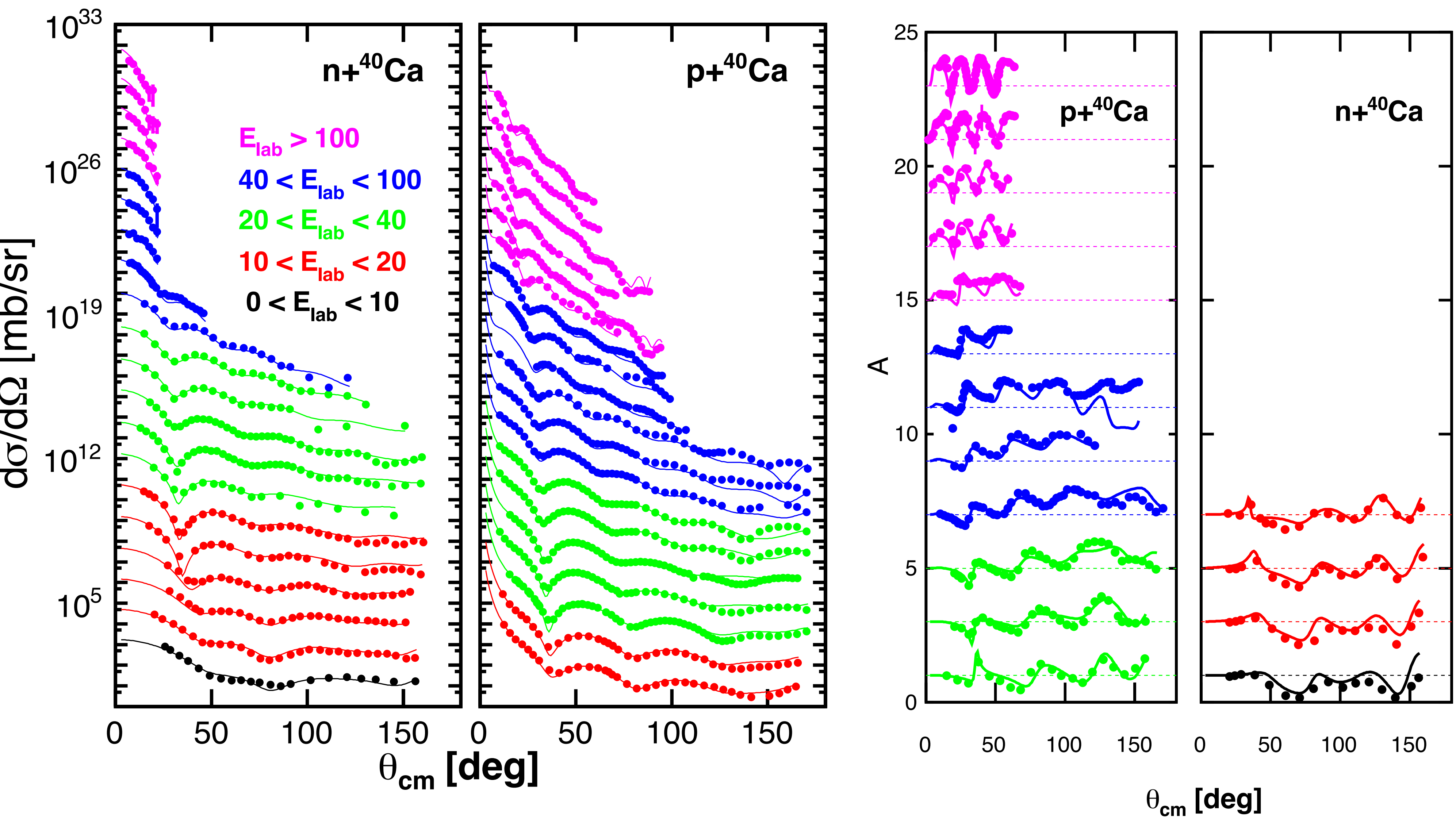
Implications

- Changes the description of hadronic reactions because interior nucleon wave functions depend on non-locality
- Consistency test of interpretation (e,e′p) reaction (see later)
- Independent "experimental" statement on size of three-body contribution to the energy of the ground state--> two-body only:

$$E/A = \frac{1}{2A}\sum_{\ell j}(2j+1)\int_0^\infty dk k^2 \frac{k^2}{2m} n_{\ell j}(k) + \frac{1}{2A}\sum_{\ell j}(2j+1)\int_0^\infty dk k^2 \int_{-\infty}^{\varepsilon_F} dE \; E S_{\ell j}(k;E)$$

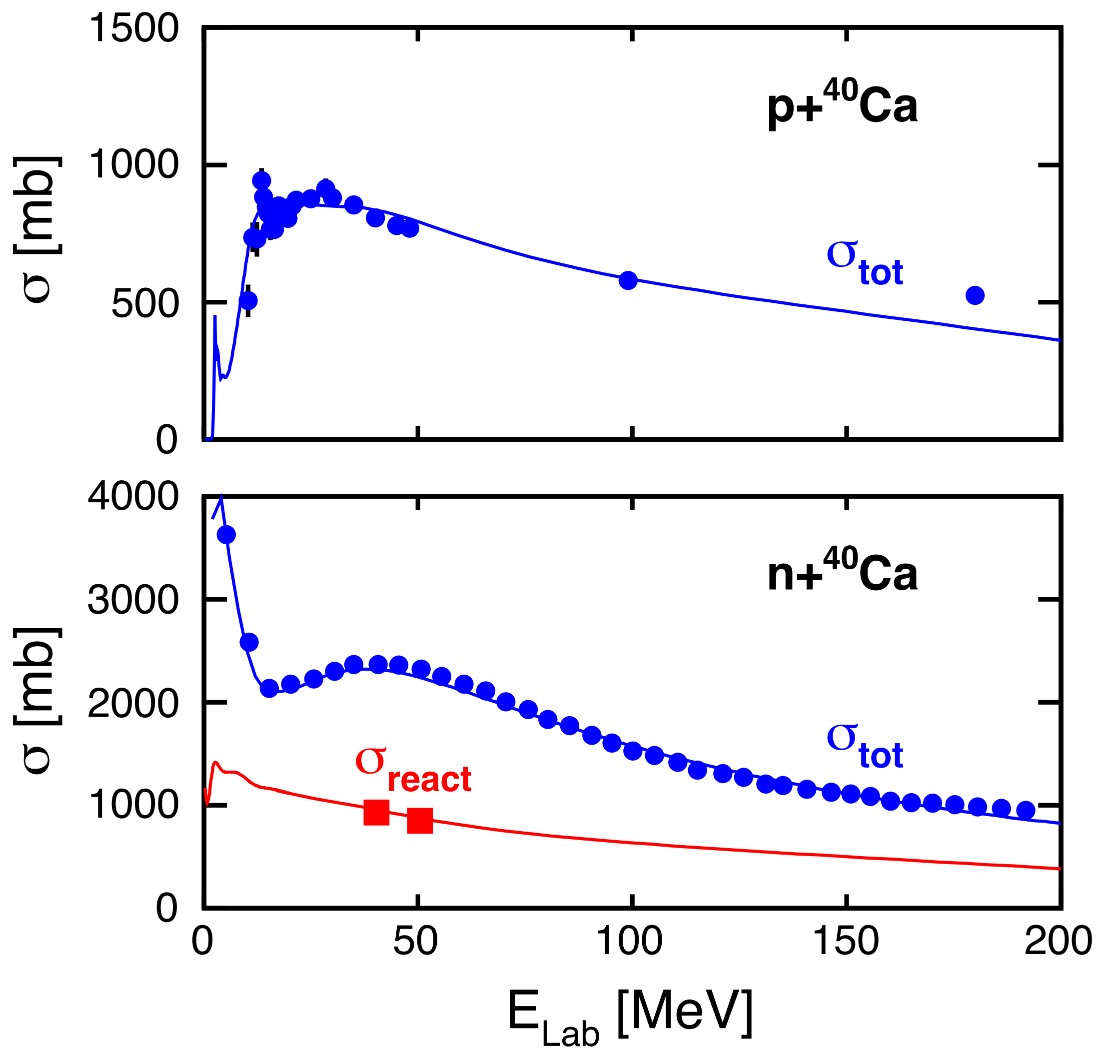
reactions and structure

Differential cross sections and analyzing powers



reactions and structure

Reaction (p&n) and total (n) cross sections

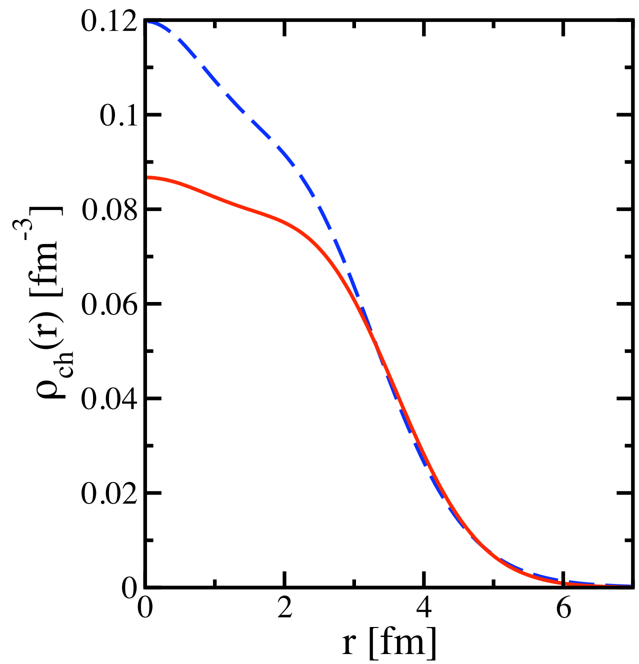


Critical experimental data—> charge density

Local version

radius correct…

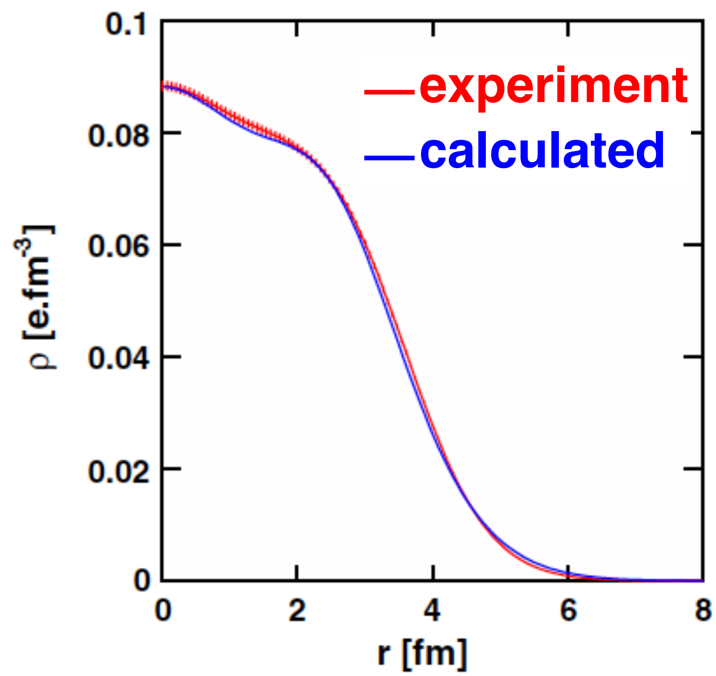
PRC82, 054306 (2010)



Charge density ^{40}Ca

Non-locality essential

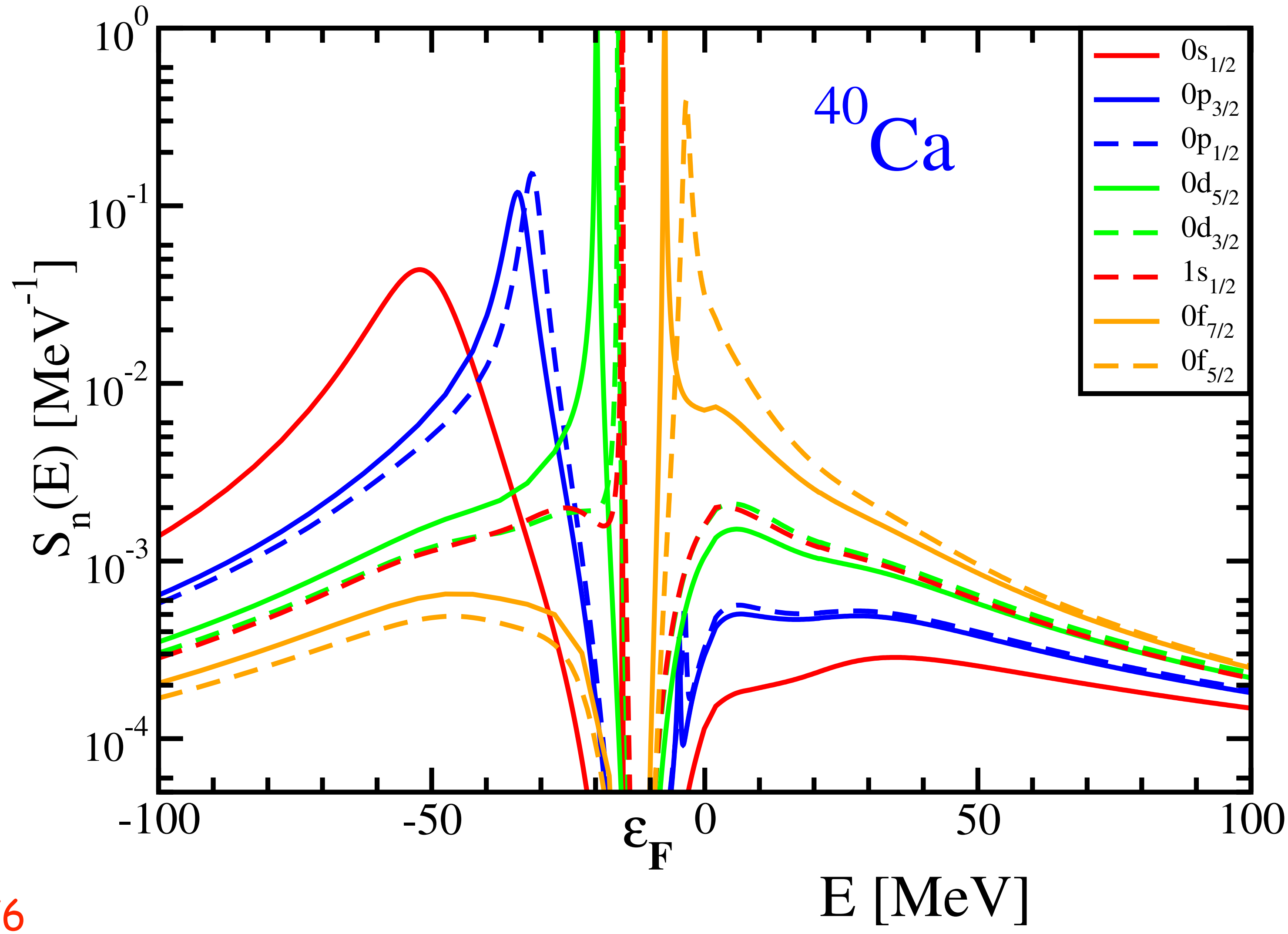
PRL 112,162503(2014)



High-momentum nucleons —> JLab can also be described —> E/A

Spectral function for bound states

- [0,200] MeV —> constrained by elastic scattering data



$S_{0d3/2}$= 0.76

$S_{1s1/2}$ = 0.78

0.15-0.25 larger than NIKHEF analysis!

PRC90, 061603(R) (2014)

Quantitatively

- Orbit closer to the continuum —> more strength in the continuum
- Note "particle" orbits
- Drip-line nuclei have valence orbits very near the continuum

Table 1: Occupation and depletion numbers for bound orbits in ^{40}Ca. $d_{nlj}[0,200]$ depletion numbers have been integrated from 0 to 200 MeV. The fraction of the sum rule that is exhausted, is illustrated by $n_{n\ell j} + d_{n\ell j}[\varepsilon_F, 200]$. Last column $d_{nlj}[0,200]$ depletion numbers for the CDBonn calculation.

orbit	$n_{n\ell j}$ DOM	$d_{n\ell j}[0,200]$ DOM	$n_{n\ell j} + d_{n\ell j}[\varepsilon_F, 200]$ DOM	$d_{n\ell j}[0,200]$ CDBonn
$0s_{1/2}$	0.926	0.032	0.958	0.035
$0p_{3/2}$	0.914	0.047	0.961	0.036
$1p_{1/2}$	0.906	0.051	0.957	0.038
$0d_{5/2}$	0.883	0.081	0.964	0.040
$1s_{1/2}$	0.871	0.091	0.962	0.038
$0d_{3/2}$	0.859	0.097	0.966	0.041
$0f_{7/2}$	0.046	0.202	0.970	0.034
$0f_{5/2}$	0.036	0.320	0.947	0.036

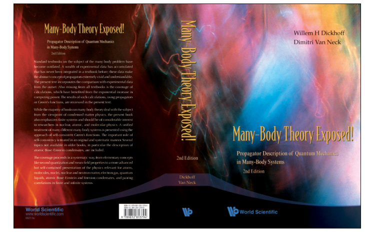
PRC90, 061603(R) (2014)

Another look at (e,e′p) data

- collaboration with Louk Lapikás and Henk Blok
- Data published at E_p = 100 MeV Kramer thesis NIKHEF for $^{40}Ca(e,e'p)^{39}K$
  Phys.Lett.B227(1989)199
  Results: $S(d_{3/2})$=0.65 and $S(s_{1/2})$=0.51…?
- More data at 70 and 135 MeV (only in a conference paper)
- What do these spectroscopic factor numbers really represent?
  - Assume DWIA for the reaction description
  - Use kinematics (momentum transfer parallel to initial proton momentum) favoring simplest part of the excitation operator (no two-body current)
  - Overlap function:
    - WS with radius adjusted to shape of cross section
    - Depth adjusted to separation energy
  - Distorted proton wave from standard "global optical potential"
  - Fit normalization of overlap function to data -> spectroscopic factor

Why go back there?

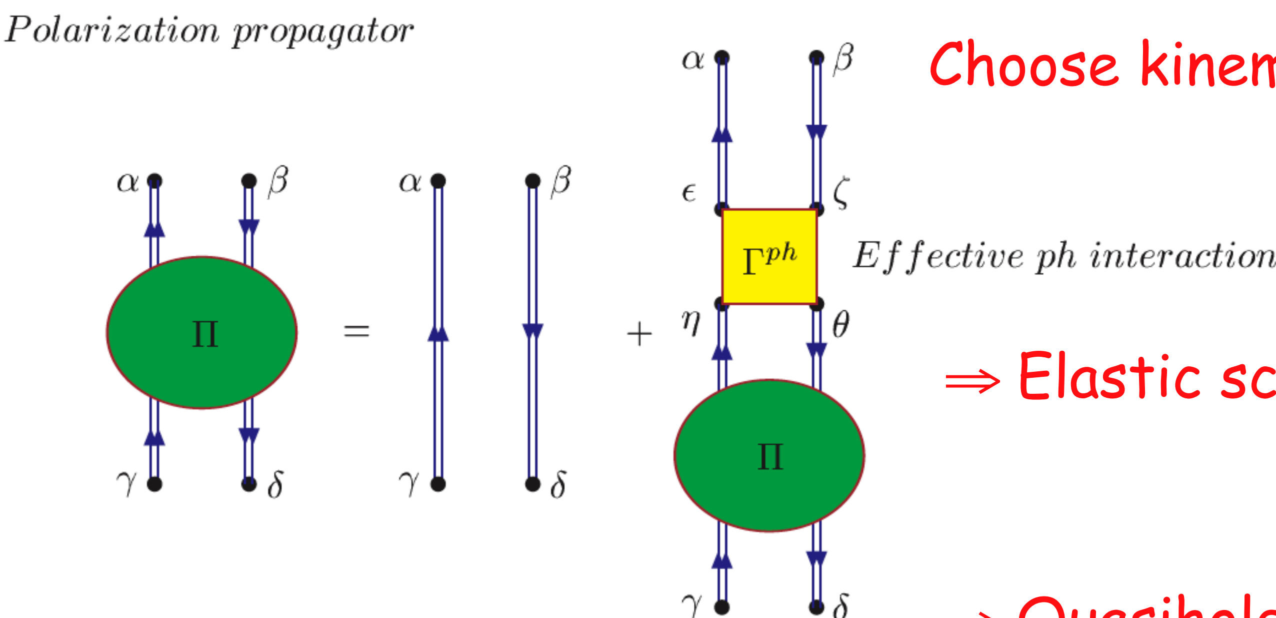
FSI and (e,e´p) ⇔ analysis



$\hat{O} = \sum_{\alpha,\beta} \langle\alpha| O |\beta\rangle \, a^\dagger_\alpha a_\beta$ Electron Scattering ⇒ one-body operator

$$\left| \langle \Psi_n^A | \hat{O} | \Psi_0^A \rangle \right|^2 = \sum \langle\alpha| O |\beta\rangle^* \langle\gamma| O |\delta\rangle \langle \Psi_0^A | a^\dagger_\alpha a_\beta | \Psi_n^A \rangle \langle \Psi_n^A | a^\dagger_\gamma a_\delta | \Psi_0^A \rangle$$

Requires (imaginary part of) **exact** polarization propagator



Choose kinematics: ⇒ only first term

$$\langle \Psi_m^{A+1} | a^\dagger_\alpha | \Psi_0^A \rangle$$

⇒ Elastic scattering (phenomenology)

$$\langle \Psi_n^{A-1} | a_\beta | \Psi_0^A \rangle$$

⇒ Quasihole wave function

"Absolute" spectroscopic factors?

reactions and structure

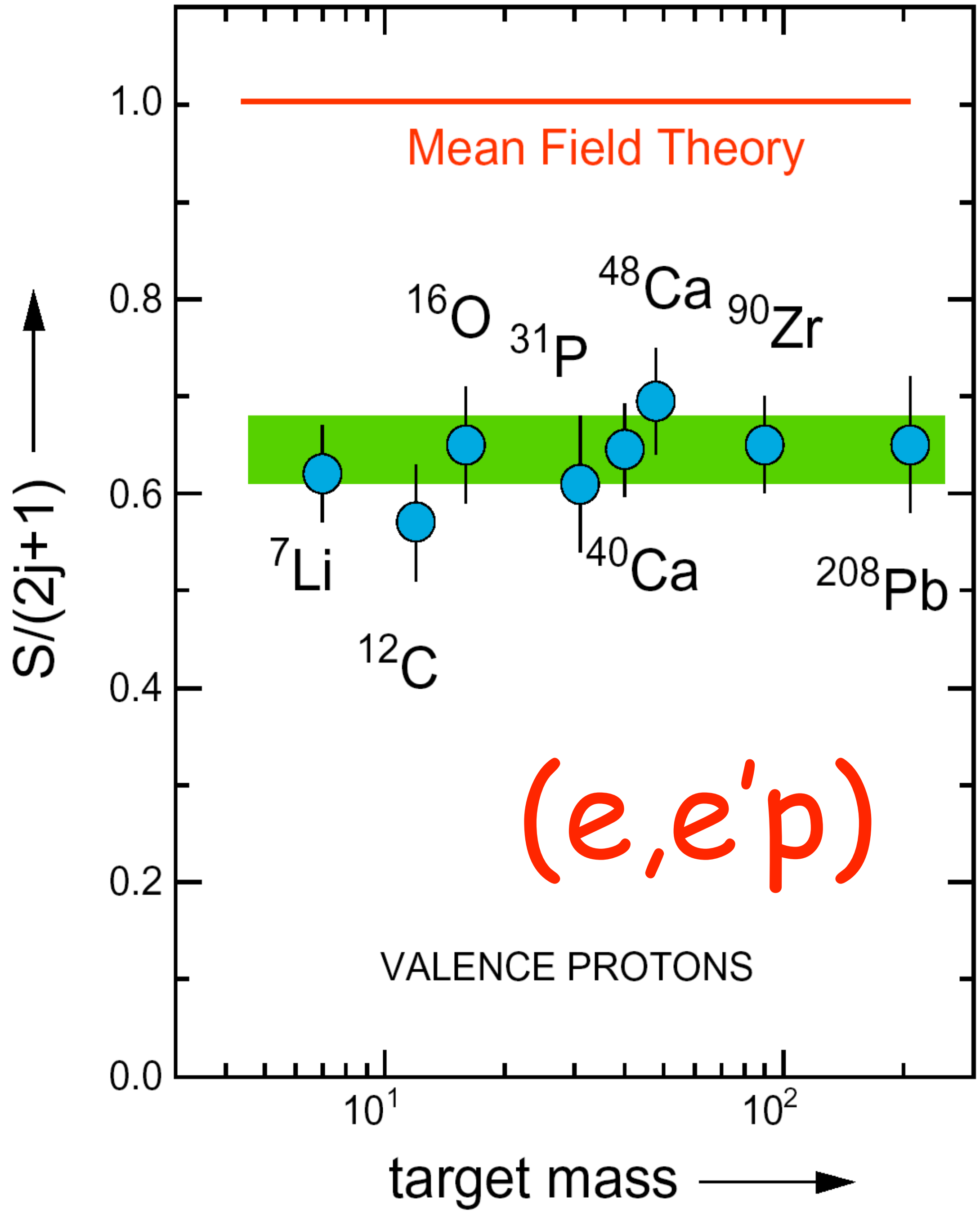
Removal probability for valence protons from NIKHEF data

L. Lapikás, Nucl. Phys. A553,297c (1993)

S ≈ 0.65 for valence protons
Reduction ⇒ both SRC and LRC

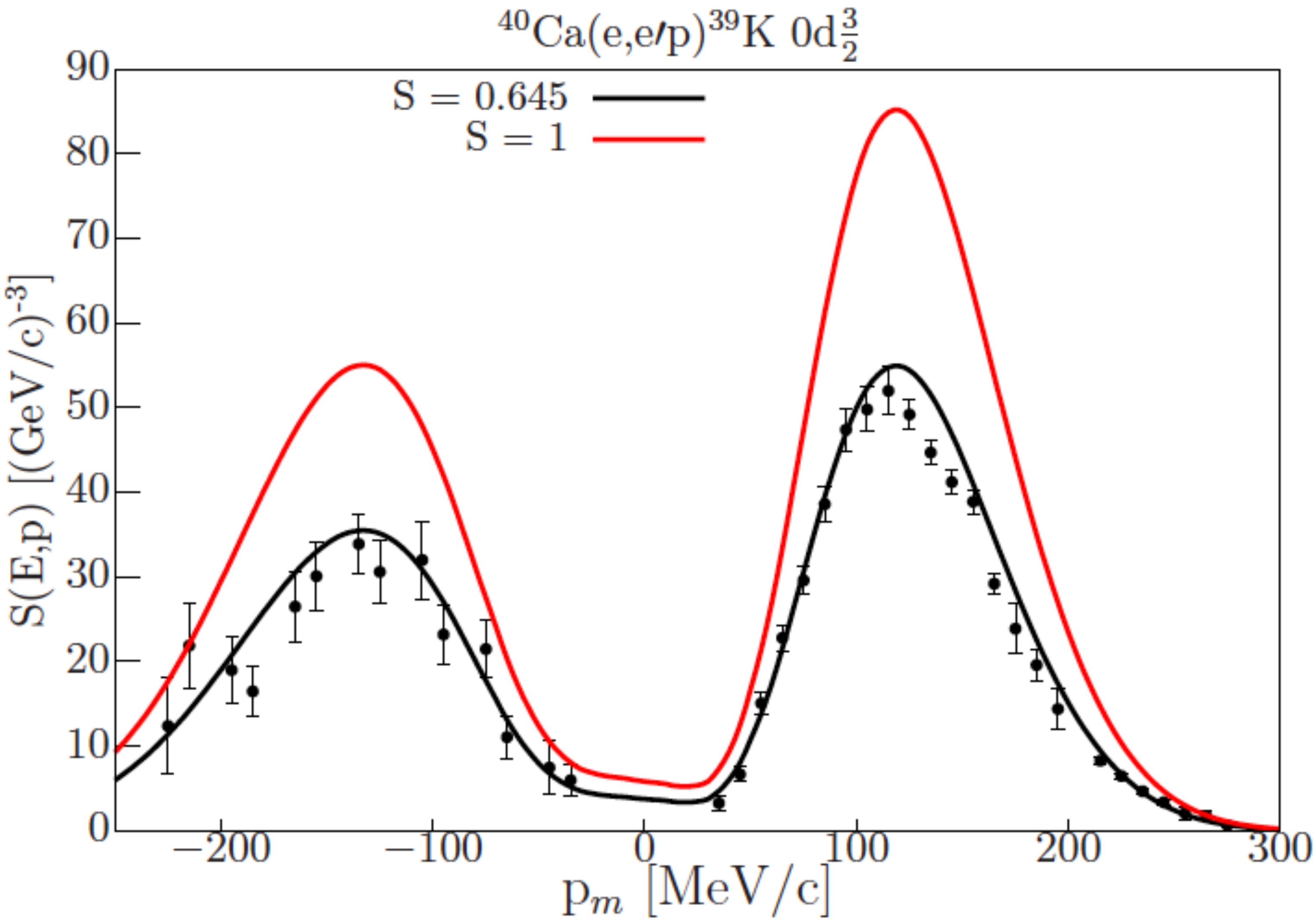
Weak probe but propagation in the nucleus of removed proton using standard optical potentials to generate distorted wave --> associated uncertainty ~ 5-15%

Why: details of the interior scattering wave function uncertain since non-locality is not constrained (so far.....)
but now available for ^{40}Ca!



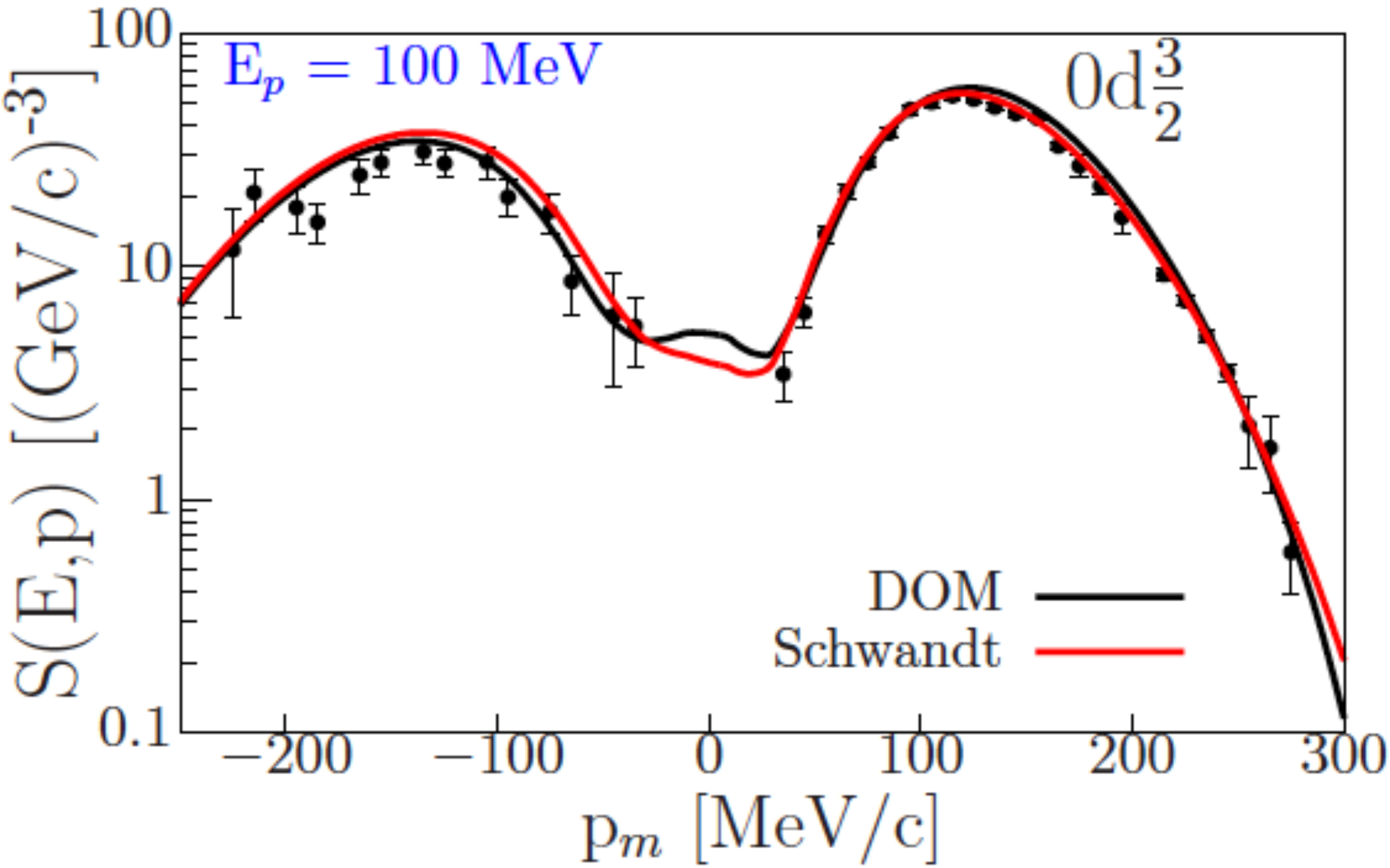
NIKHEF analysis

- Schwandt et al. (1981) optical potential



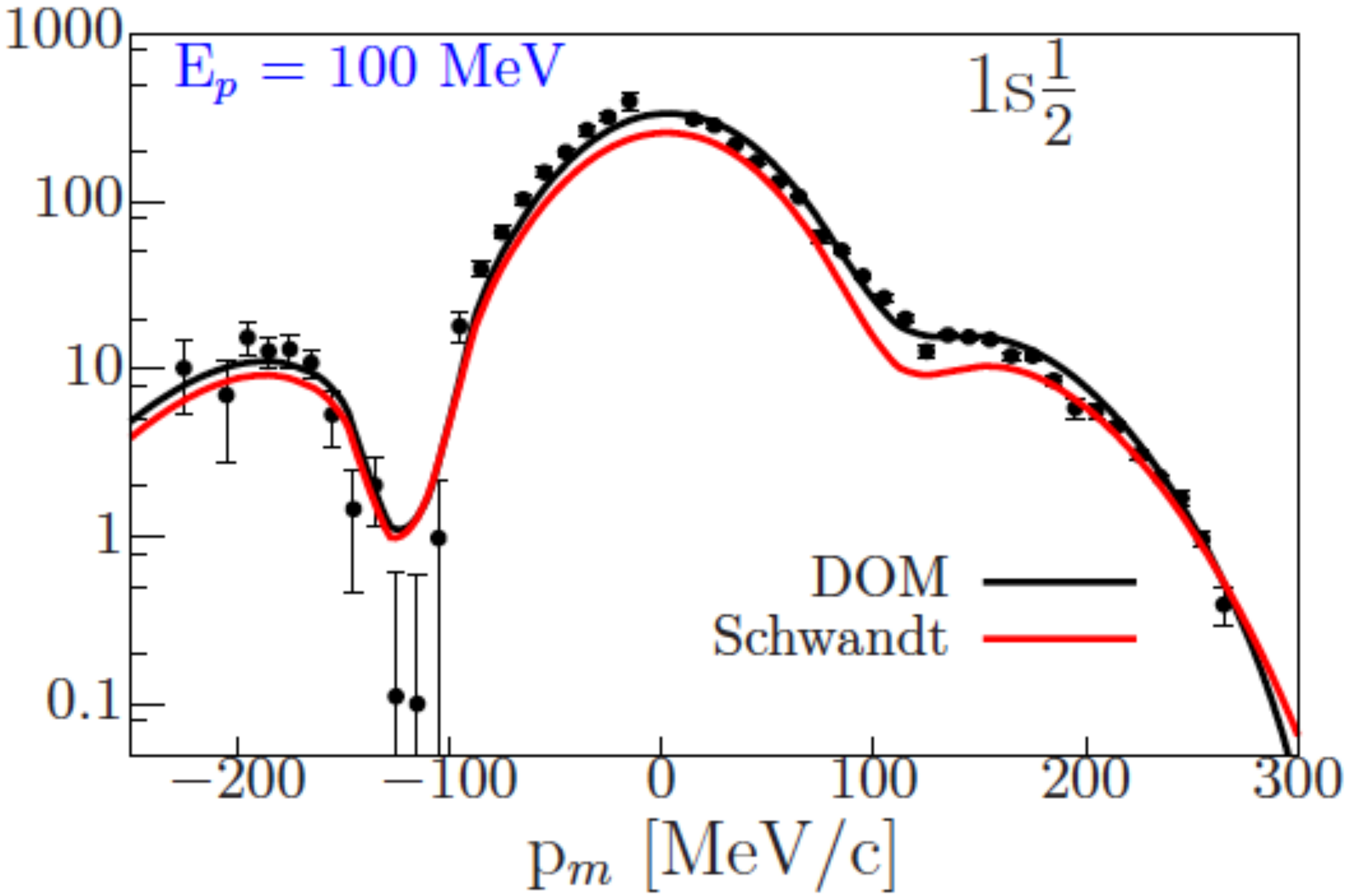
DOM non-local ingredients E_p = 100 MeV

- $S(d_{3/2})$=0.75 indirectly constrained by other data so **not** adjusted
- NIKHEF: $S(d_{3/2})$=0.65±0.06



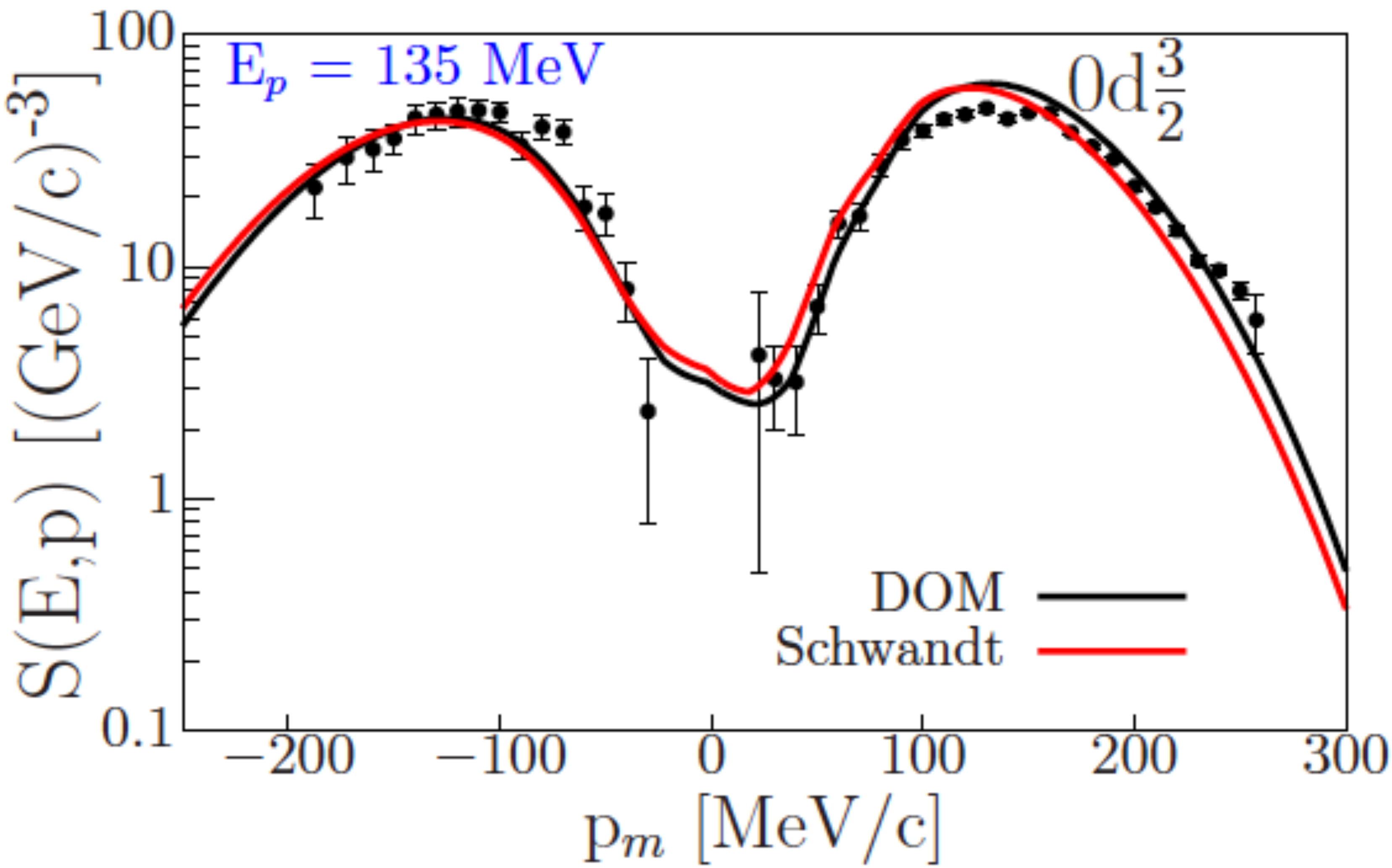
E_p = 100 MeV

- $S(s_{1/2})$=0.78 indirectly constrained by other data so **not** adjusted
- NIKHEF: $S(s_{1/2})$=0.51±0.05



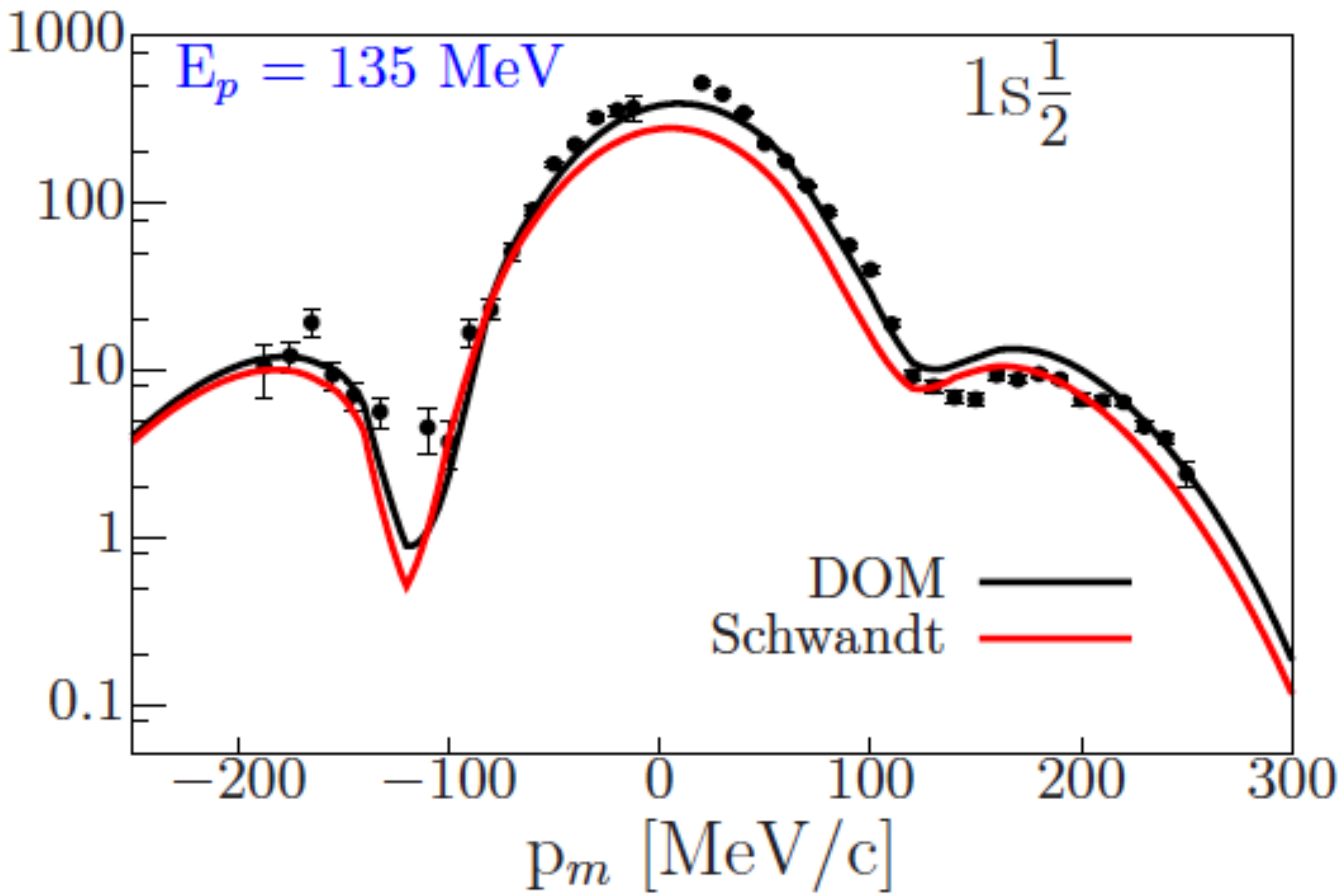
E_p = 135 MeV

- Still reasonable? Perhaps not…



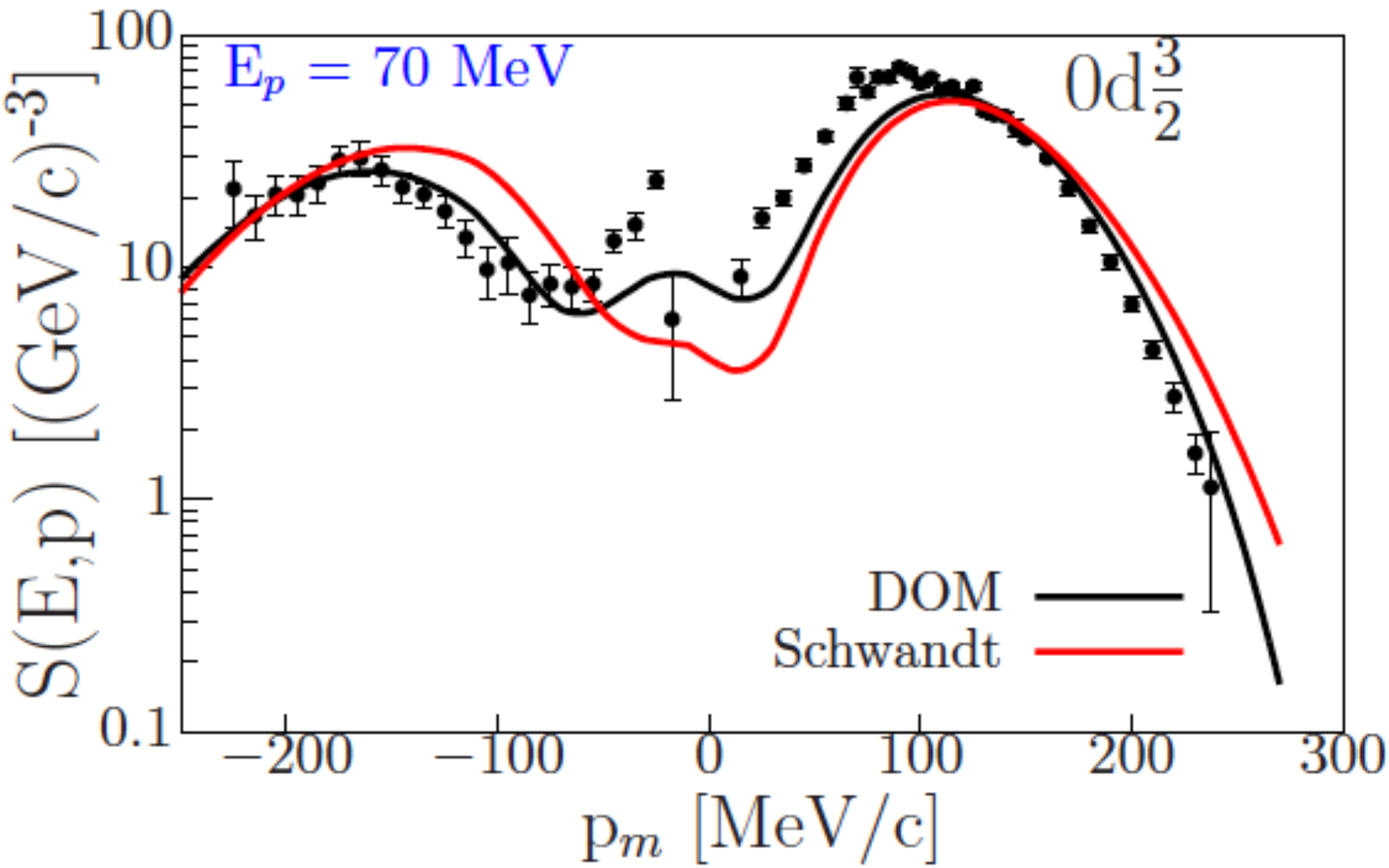
E_p = 135 MeV

- Too high excitation energy?



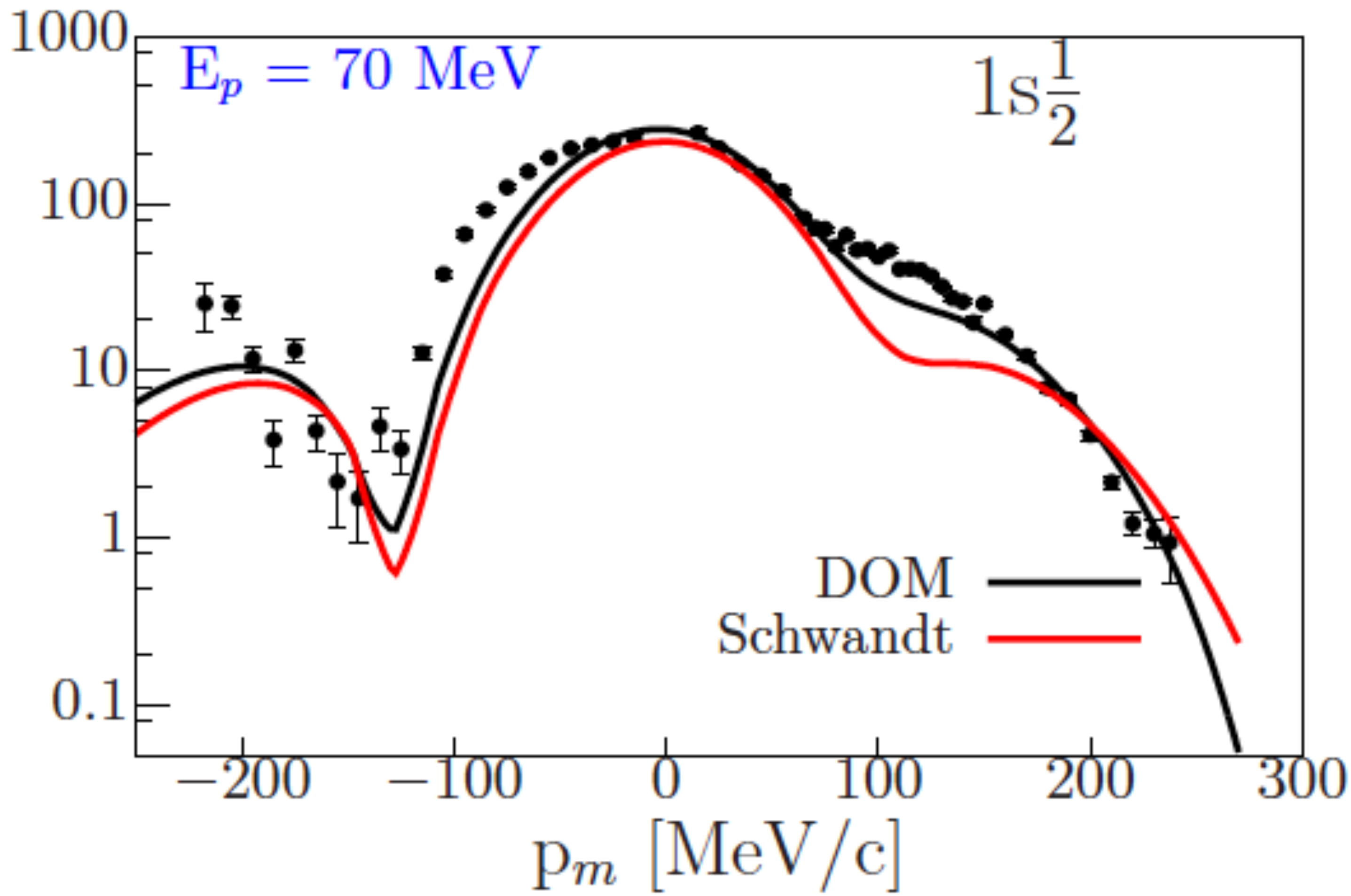
E_p = 70 MeV

- Reaction model no longer good enough and there is more transverse excitation



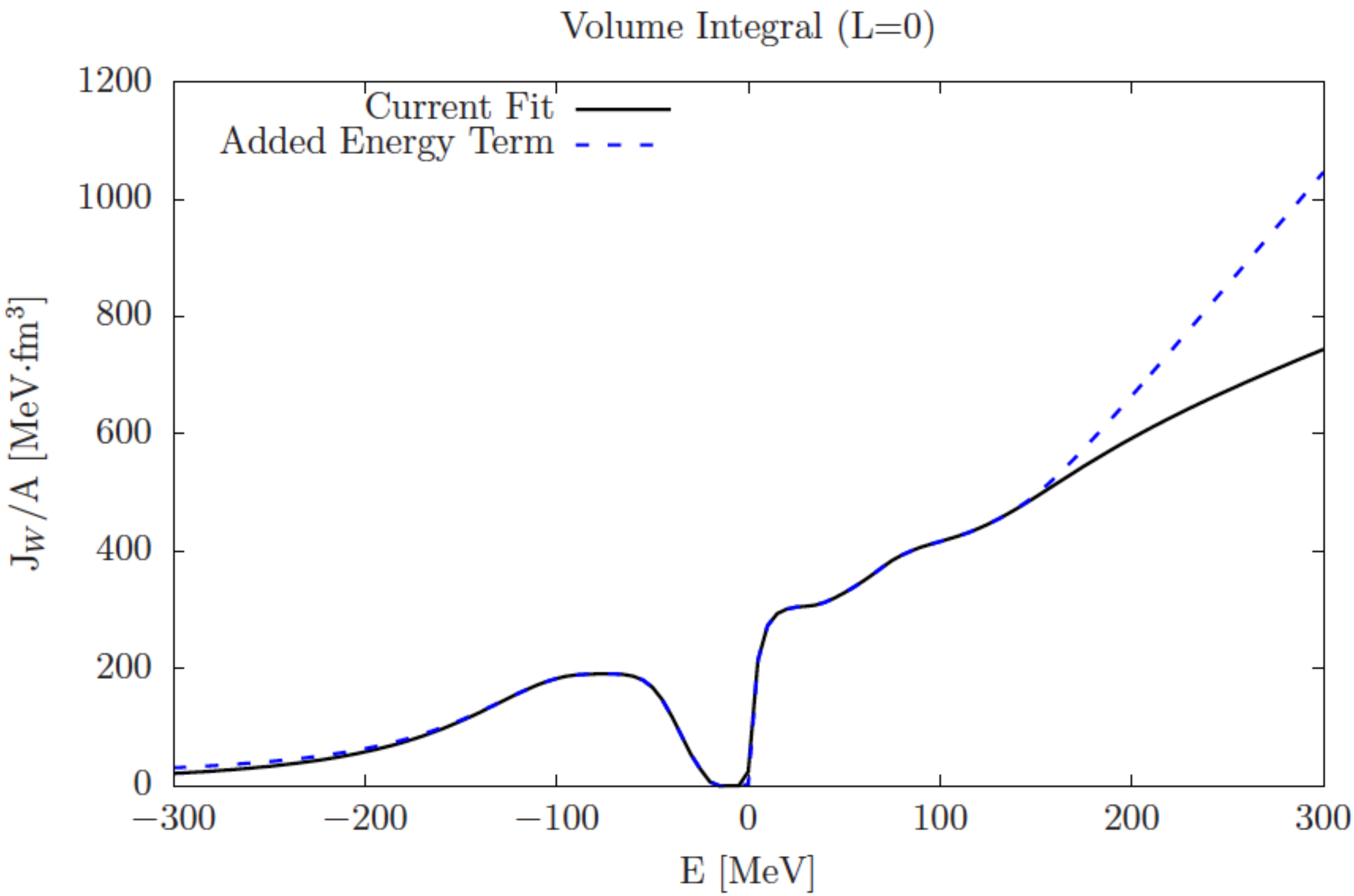
E_p = 70 MeV

- Limitation of (e,e'p)?



- What about further reducing the spectroscopic factor?
- What happens with other data?

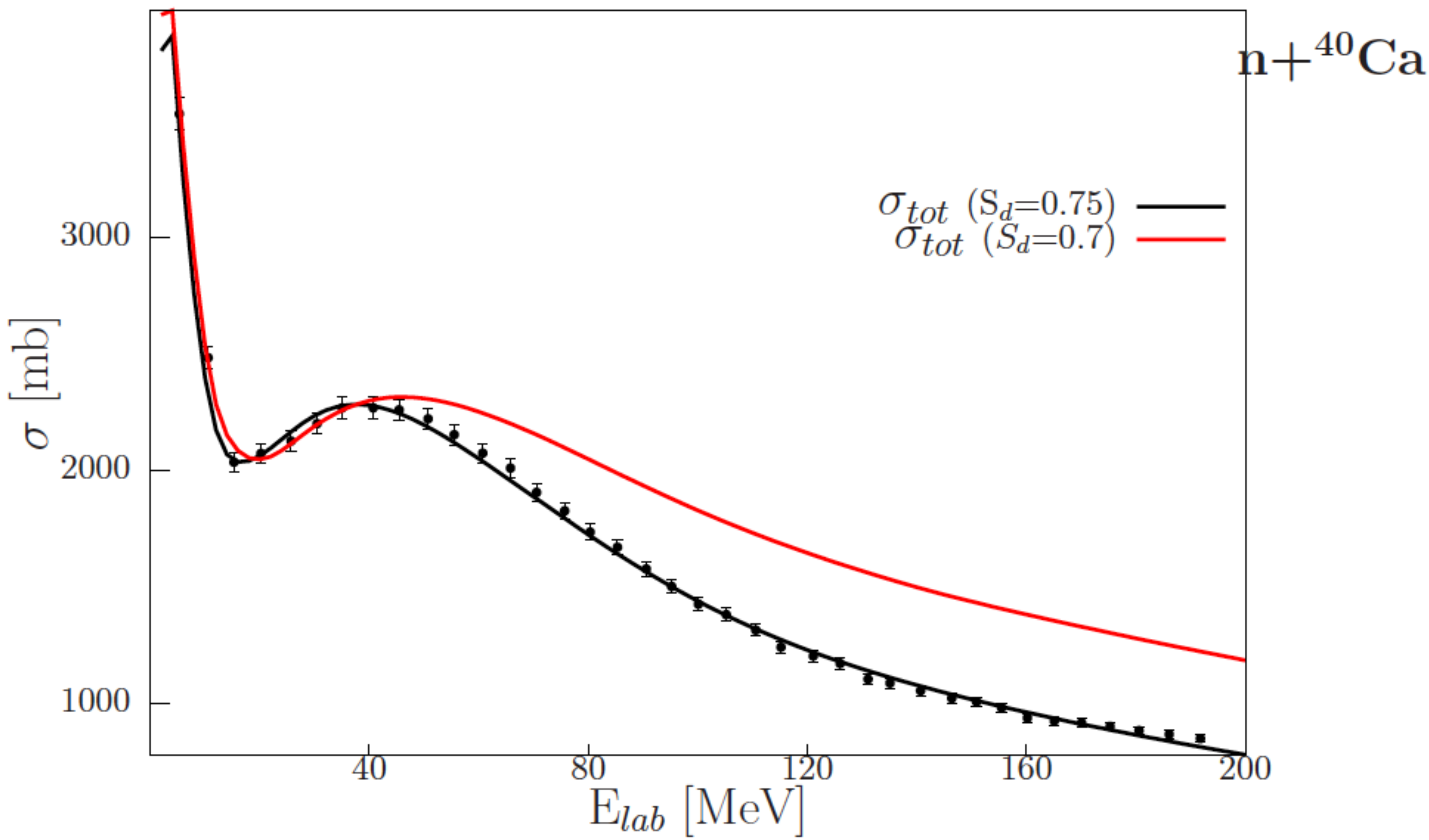
Remove strength to higher energy



reactions and structure

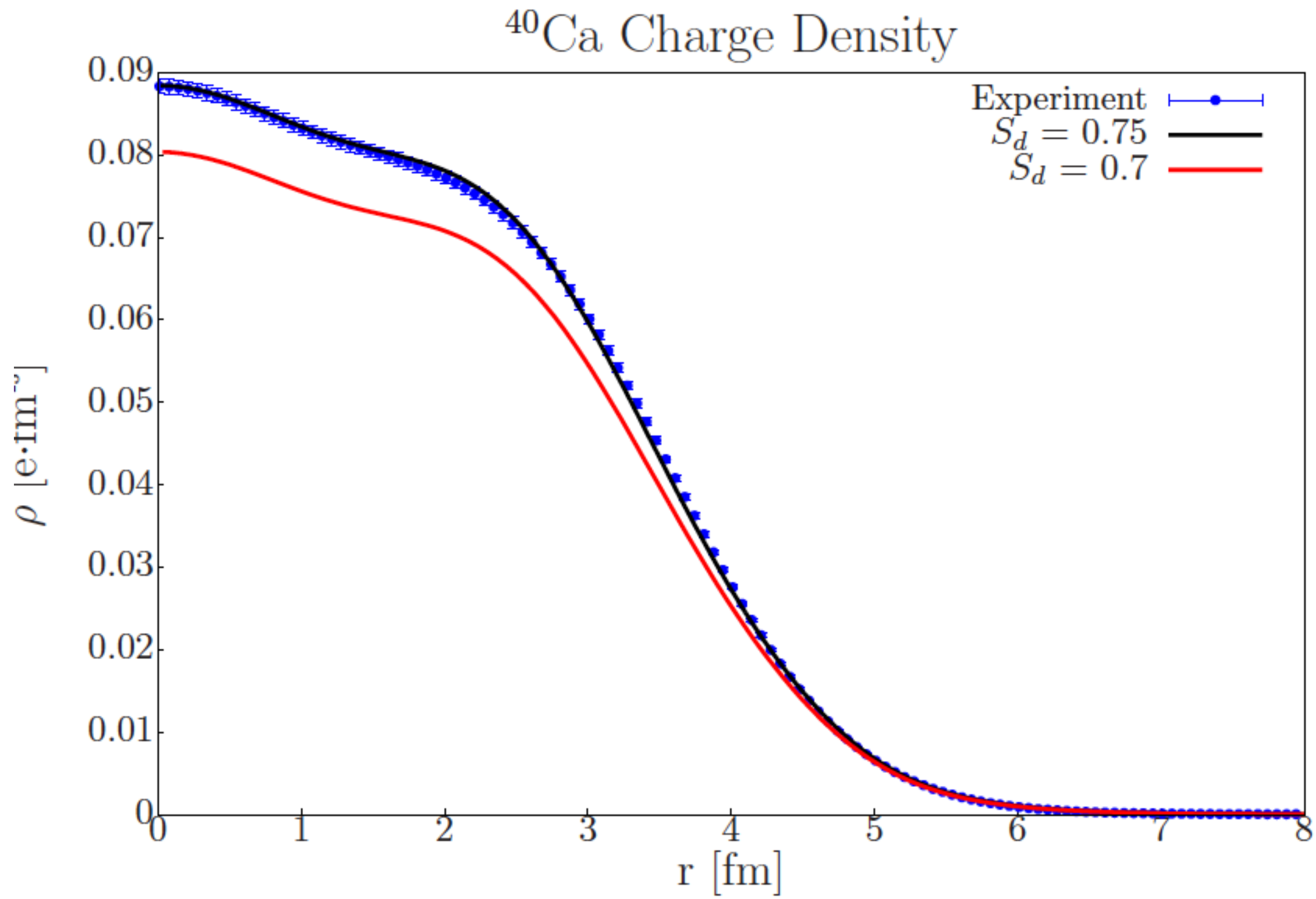
Problems

- Total neutron cross section



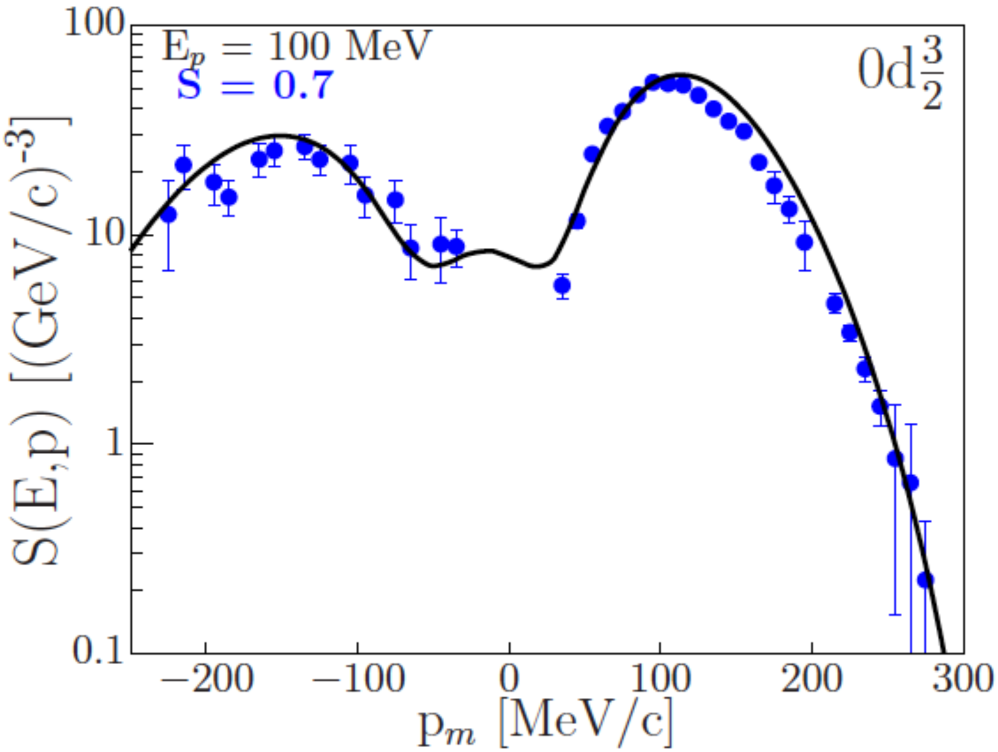
reactions and structure

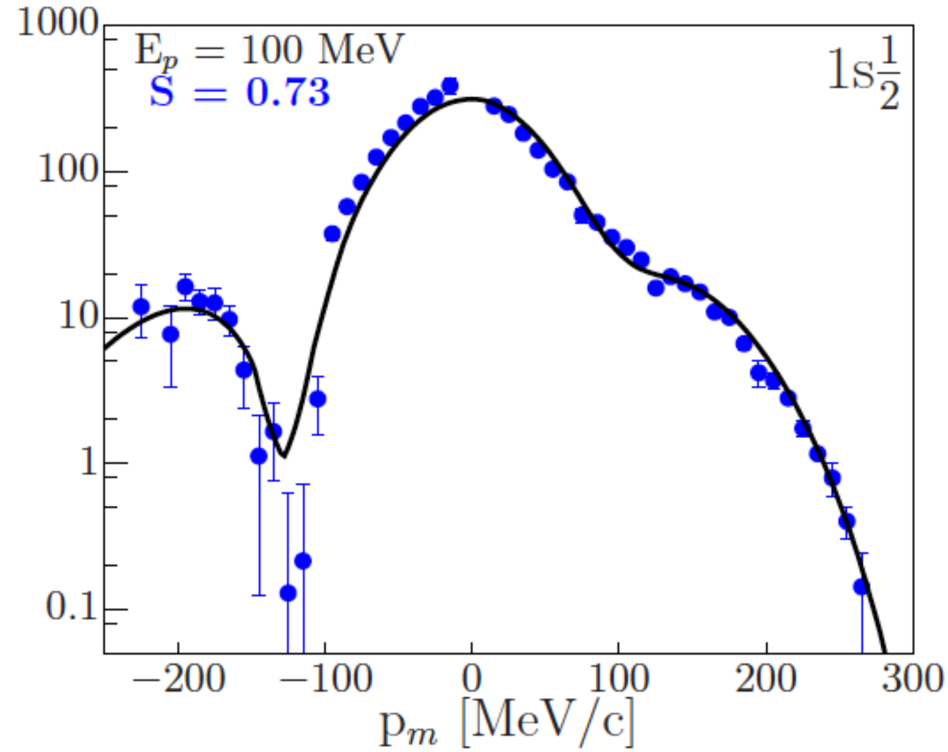
More problems



Only looking at (e,e'p) data

- Visual slightly better with smaller normalization
- But larger values seem ruled out





Message

- Nonlocal dispersive potentials yield consistent input
- Constraints from other data generate spectroscopic factors ~ 0.75 in ^{40}Ca
- Implications for transfer reactions significant
- (p,2p) reaction for stable targets can be constrained
- Consistent with inelastic electron scattering data

Lessons from the past probably forgotten?

PHYSICAL REVIEW C VOLUME 45, NUMBER 6 JUNE 1992

High resolution electron scattering from high spin states in ^{208}Pb

J. P. Connelly,* D. J. DeAngelis, J. H. Heisenberg, F. W. Hersman, W. Kim, M. Leuschner, T. E. Milliman, and J. Wise†
Department of Physics, University of New Hampshire, Durham, New Hampshire 03824

C. N. Papanicolas
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(Received 2 March 1992)

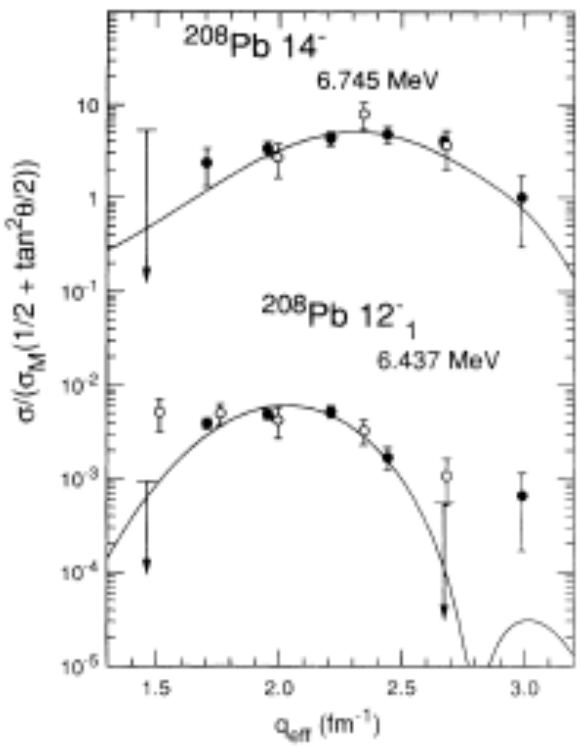


FIG. 4. $M14$ (6.745 MeV) and $M12$ (6.347 MeV) form factors with DWBA Woods-Saxon fits. The 6.745 MeV form factor is scaled by 1000. Forward angle data are represented by the open data points; the 155° data are presented by the solid data points.

TABLE I. High spin transitions seen in this experiment with the dominant 1p-1h configuration and the normalization factor (N_q) of the Woods-Saxon DWBA fits to the data. An asterisk indicates the assignment of J^π is from this experiment.

Energy (MeV)	J^π	1p-1h configuration	N_q
5.010	9^+	$\nu(2g_{9/2}, 1i^{-1}_{13/2})$	0.54±0.01
5.260	9^{+*}	$\pi(1h_{9/2}, 1h^{-1}_{11/2})$	0.53±0.04
5.291	11^{+*}	$\nu(2g_{9/2}, 1i^{-1}_{13/2})$	0.38±0.03
5.860	11^{+*}	$\nu(1i_{11/2}, 1i^{-1}_{13/2})$	0.61±0.05
5.954	9^{+*}	$\nu(1i_{11/2}, 1i^{-1}_{13/2})$	0.50±0.05
		$\pi(2f_{7/2}, 1h^{-1}_{11/2})$	0.19±0.03
6.110	12^+	$\nu(1i_{11/2}, 1i^{-1}_{13/2})$	0.39±0.06
6.283	10^{-*}	$\nu(1j_{15/2}, 1i^{-1}_{13/2})$	0.64±0.07
6.437	12^-	$\nu(1j_{15/2}, 1i^{-1}_{13/2})$	0.46±0.07
6.745	14^-	$\nu(1j_{15/2}, 1i^{-1}_{13/2})$	0.53±0.04
6.833	$(8^-)^*$	$\pi(1i_{13/2}, 1h^{-1}_{11/2})$	0.58±0.05
6.859	9^{-*}	$\pi(1i_{13/2}, 1h^{-1}_{11/2})$	0.55±0.02
6.879	7^{-*}	$\pi(1i_{13/2}, 1h^{-1}_{11/2})$	0.39±0.01
6.884	10^{-*}	$\pi(1i_{13/2}, 1h^{-1}_{11/2})$	0.32±0.09
7.064	12^-	$\pi(1i_{13/2}, 1h^{-1}_{11/2})$	0.32±0.05
7.086	12^{-*}	$\pi(1i_{13/2}, 1h^{-1}_{11/2})$	0.18±0.02

New DOM results for ^{48}Ca

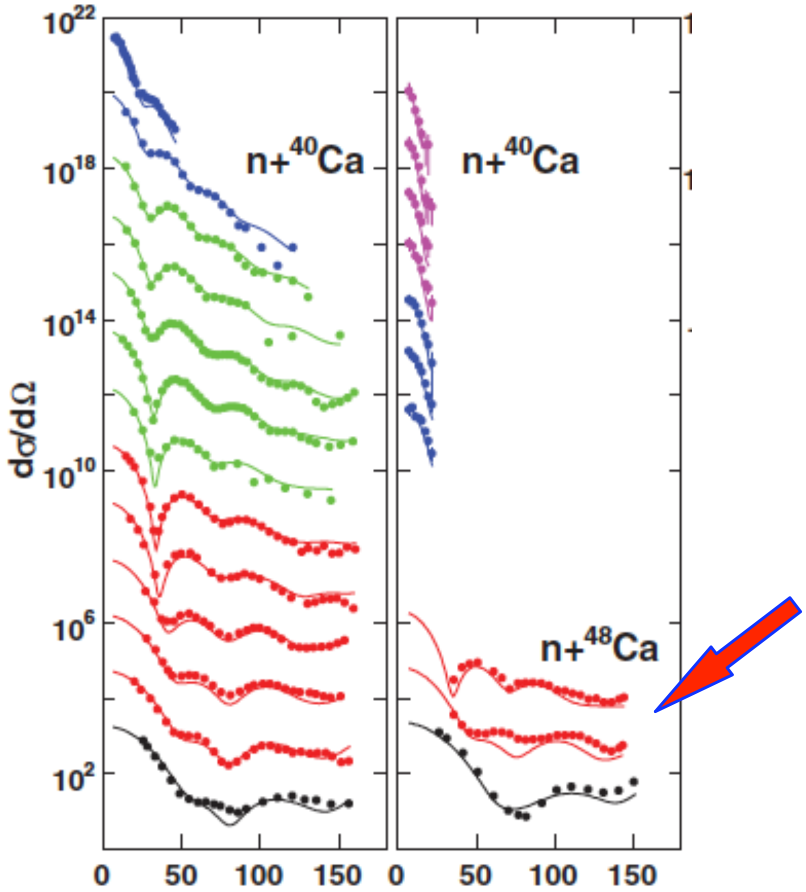
- Change of proton properties when 8 neutrons are added to ^{40}Ca?

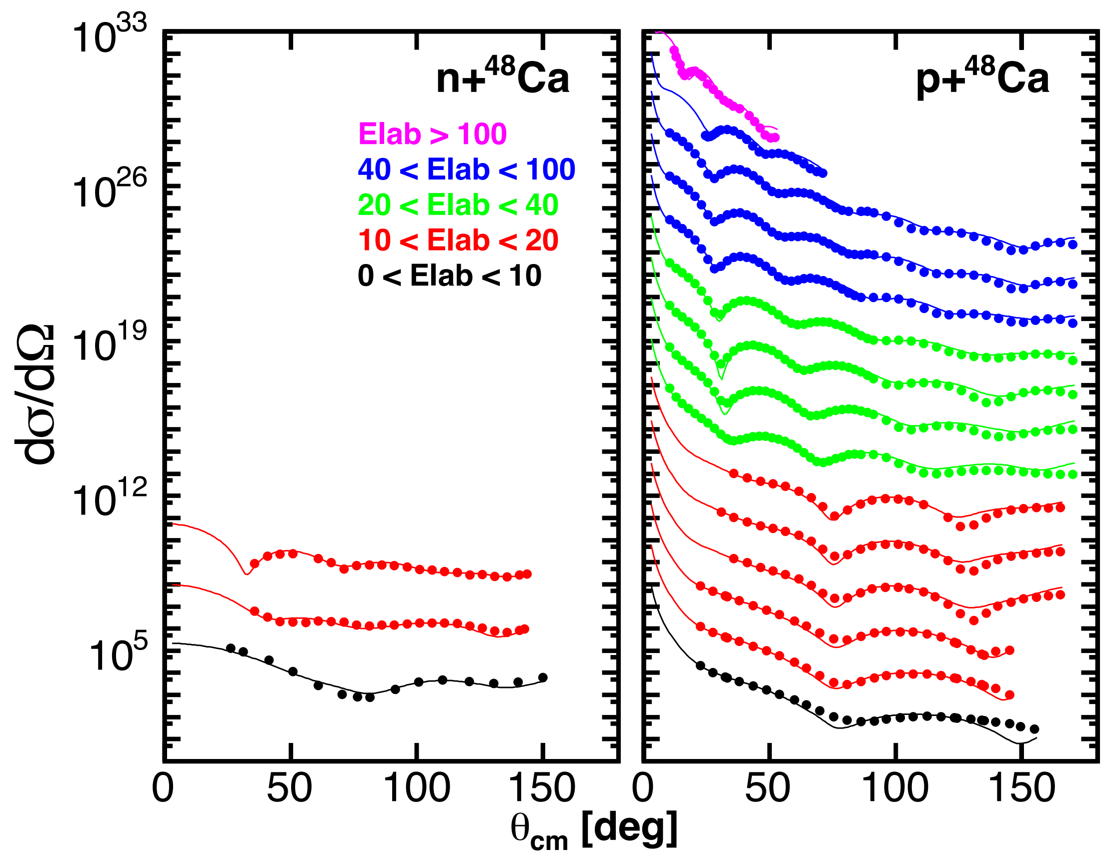
- Change of neutron properties?

- Can hard to measure quantities be indirectly constrained?

What about neutrons?

- ^{48}Ca —> charge density has been measured
- Recent neutron elastic scattering **data** —> PRC83,064605(2011)
- Local DOM **OLD** Nonlocal DOM **NEW**

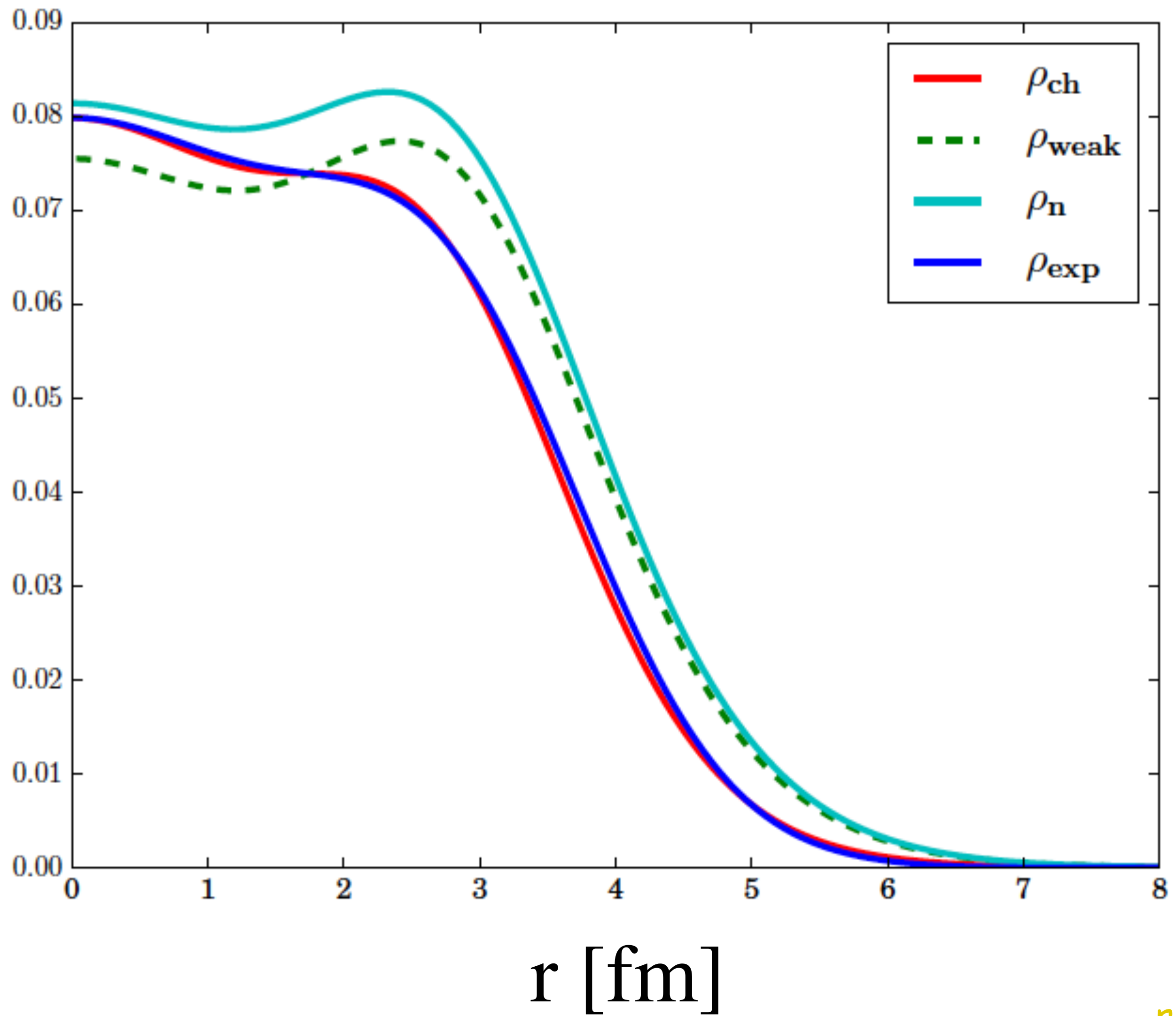




reactions and structure

Results ^{48}Ca

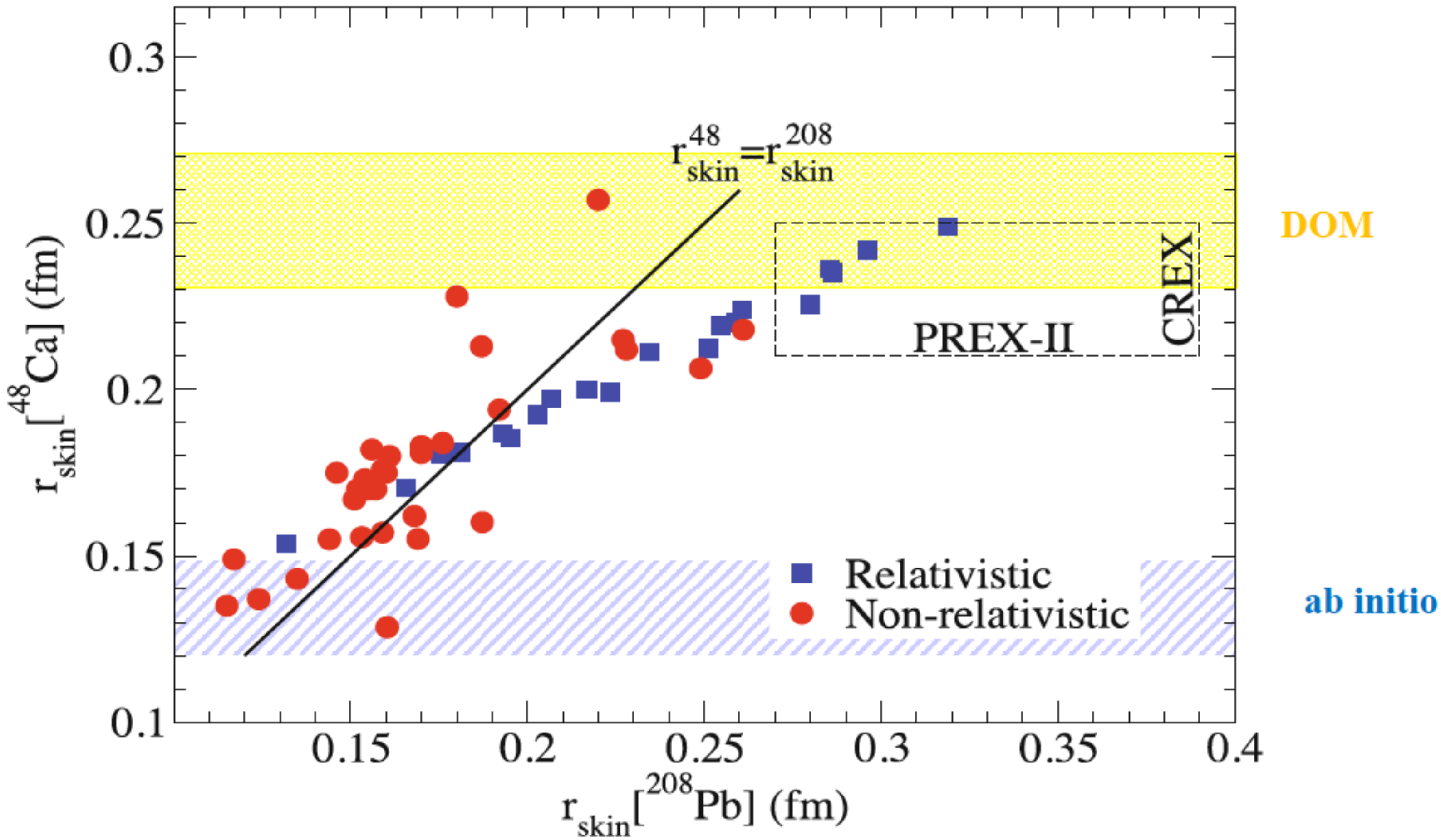
- Density distributions
- DOM —> neutron distribution —> R_n-R_p



Comparison of neutron skin with other calculations and future experiments…

- Figure adapted from

C.J. Horowitz, K.S. Kumar, and R. Michaels, Eur. Phys. J. A (2014)



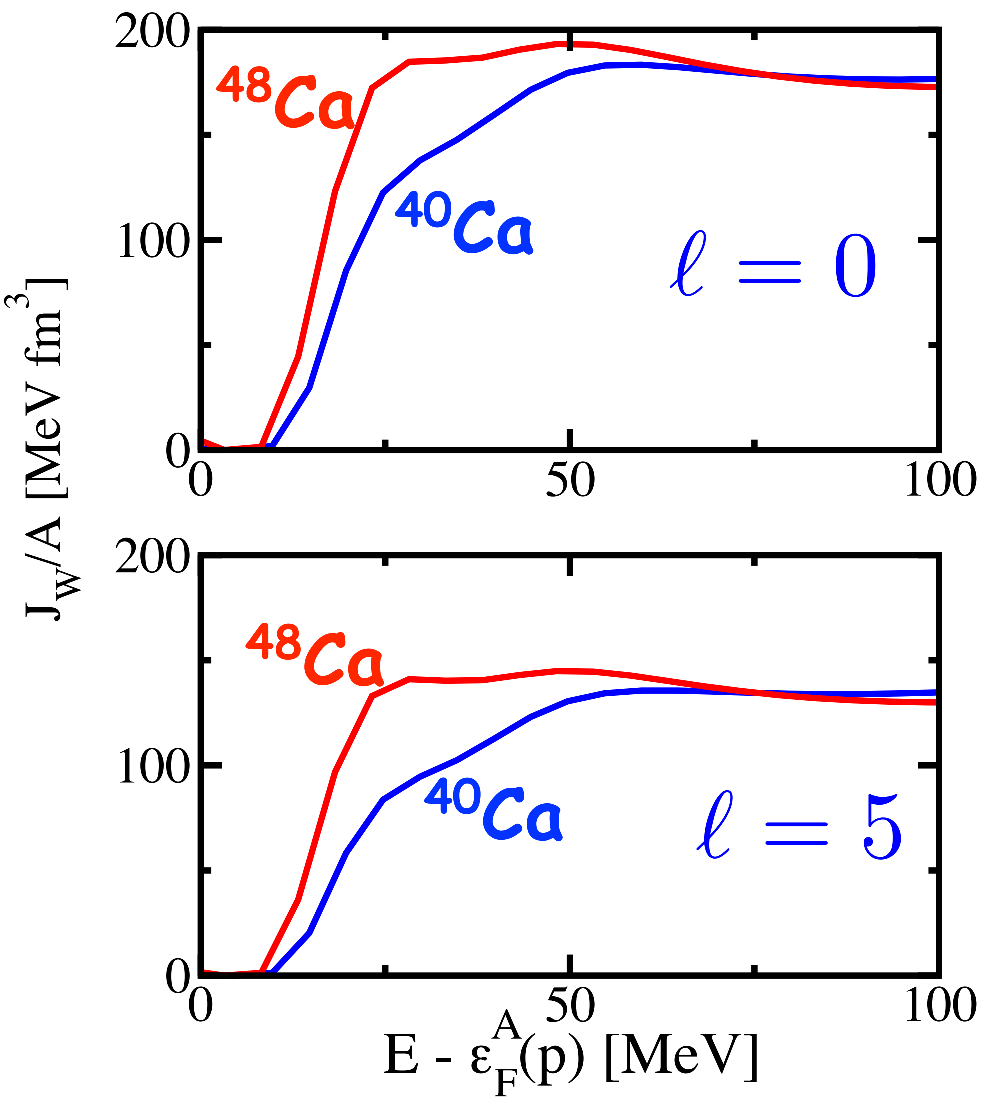
- "Ab initio":

G. Hagen et al., Nature Phys. 12, 186 (2016)

--> drip line

Volume integrals for $^{40-48}Ca$

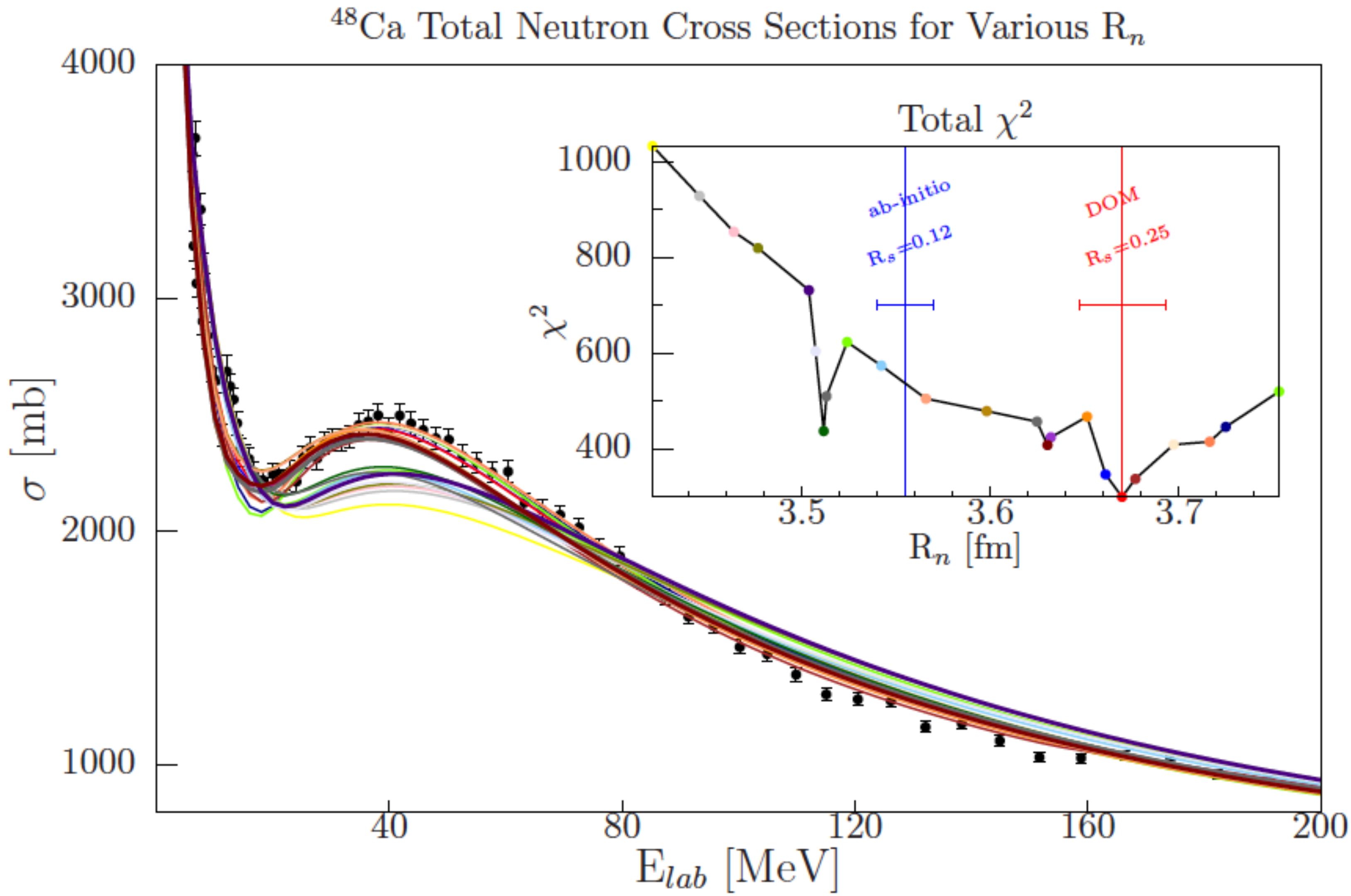
Protons see the **same** interior but a **different** surface!



--> drip line

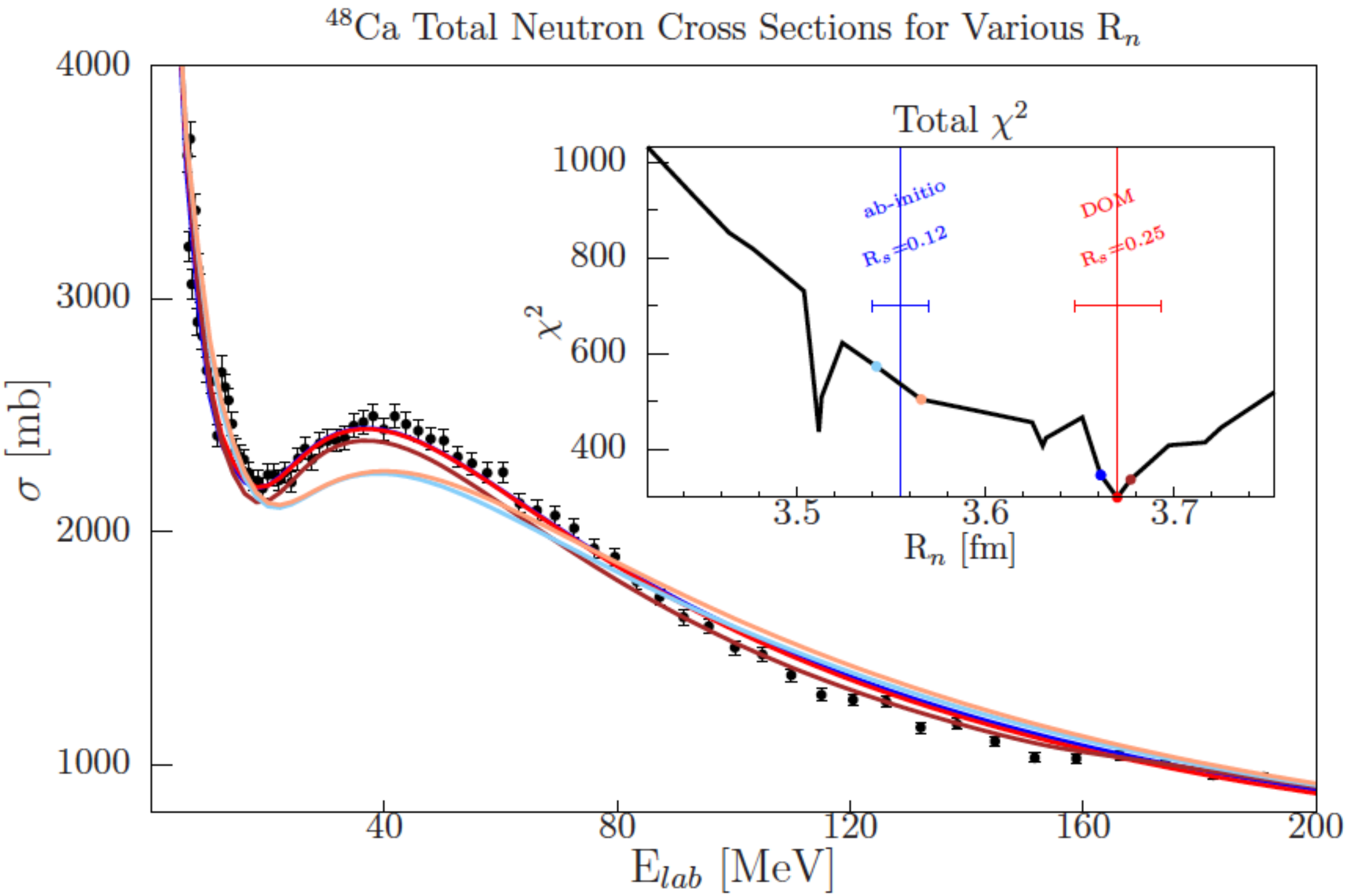
Constraining the neutron radius

- How robust is this result



--> drip line

Less clutter



- CREX will decide!

--> drip line

Quantitative comparison of ^{40}Ca and ^{48}Ca

Spectroscopic factors	^{40}Ca	p ^{48}Ca	n ^{48}Ca
$0d_{3/2}$	0.76	0.65 ↓	0.80 ↑
$1s_{1/2}$	0.78	0.71 ↓	0.83 ↑
$0f_{7/2}$	0.73	0.59 ↓	0.84 ↑

reactions and structure

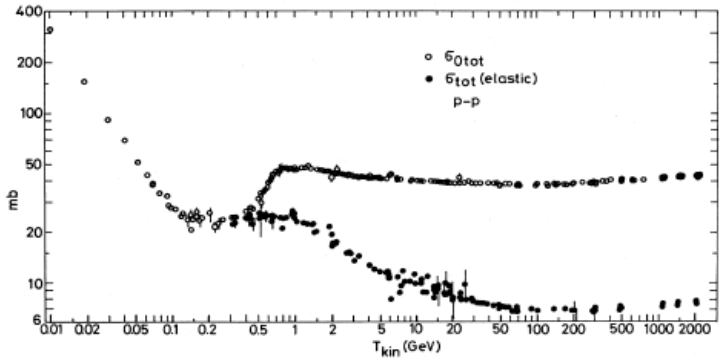
Ongoing work

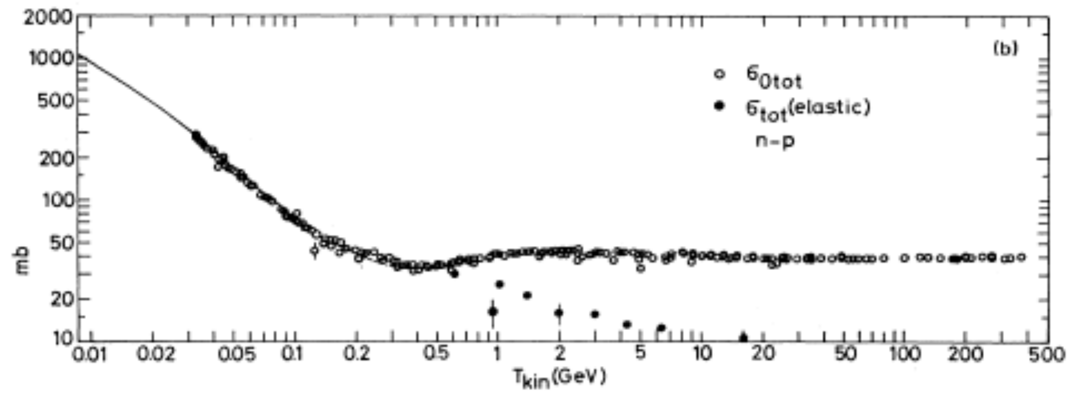
- ^{208}Pb fit —> neutron skin prediction
- ^{48}Ca(e,e′p)
- ^{112}Sn and ^{124}Sn total neutron cross sections being analyzed
- future ^{64}Ni measurement of total neutron cross section
- ^{14,20}O elastic proton scattering
- Local then nonlocal fit to Sn, Ni, O isotopes
- Integrate DOM ingredients with (d,p) - (n,γ) surrogate- and (p,d) codes
- Insert correlated Hartree-Fock contribution from realistic NN interactions in DOM self-energy—> tensor force included in mean field
- Extrapolations to the respective drip lines available
- Analyze energy density as a function of density and nucleon asymmetry
- **Ab initio optical potential calculations initiated CC and Green's function method**

reactions and structure

Future plans

- Include higher energy data (proton elastic scattering) using a Dirac formulation





- (p,2p) and (p,pn) reactions
- extend DOM to deuteron
- Construct functional derivative of DOM self-energy —> excited states

- Improve functional form of self-energy (computationally expensive)

Conclusions

- It is possible to link nuclear reactions and nuclear structure
- Vehicle: **nonlocal** version of **Dispersive Optical Model** (Green's function method) as developed by Mahaux —> DSM
- Can be used as input for analyzing nuclear reactions
- Can predict properties of exotic nuclei
- "Benchmark" for ab initio calculations: e.g. V_{NNN} —> binding
- Can describe ground-state properties
  - charge density & momentum distribution
  - spectral properties including high-momentum Jefferson Lab data
- **Elastic scattering determines depletion of bound orbitals**
- Outlook: **reanalyze** many reactions with nonlocal potentials...
- For N ≳ Z sensitive to properties of neutrons —> weak charge prediction, **large neutron skin**, perhaps more...

Polarization data in ^{40}Ca

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supplement