Linking nuclear reactions and nuclear structure to on the way to the drip lines

DREB18
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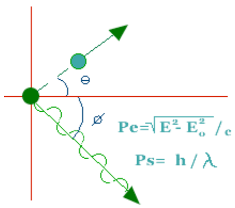


- Motivation
- Green's functions/propagator method
  - as a framework to link data at positive and negative energy (and to generate predictions for exotic nuclei)

-> 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

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

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 —> recent **extensions** discussed here

Dispersive Optical Model

- Claude Mahaux 1980s
  - connect traditional optical potential to bound-state potential
  - crucial idea: use the dispersion relation for the nucleon self-energy
  - smart implementation: use it in its subtracted form
  - applied successfully e.g. to ^{40}Ca and ^{208}Pb in a limited energy window
  - employed traditional volume and surface absorption potentials and a local energy-dependent Hartree-Fock-like potential
  - Reviewed in Adv. Nucl. Phys. **20**, 1 (1991)
- Radiochemistry group at Washington University in St. Louis: Charity and Sobotka propose to use the DOM for a sequence of Ca isotopes —> data-driven extrapolations to the drip line
  - First results PRL 97, 162503 (2006)
  - Subsequently —> attention to data **below** the Fermi energy related to ground-state properties —> Dispersive Self-energy Method (**DSM**)

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
  - contributions from the hole (structure) and particle (reaction) domain

General dispersion relation for self-energy:

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

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

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

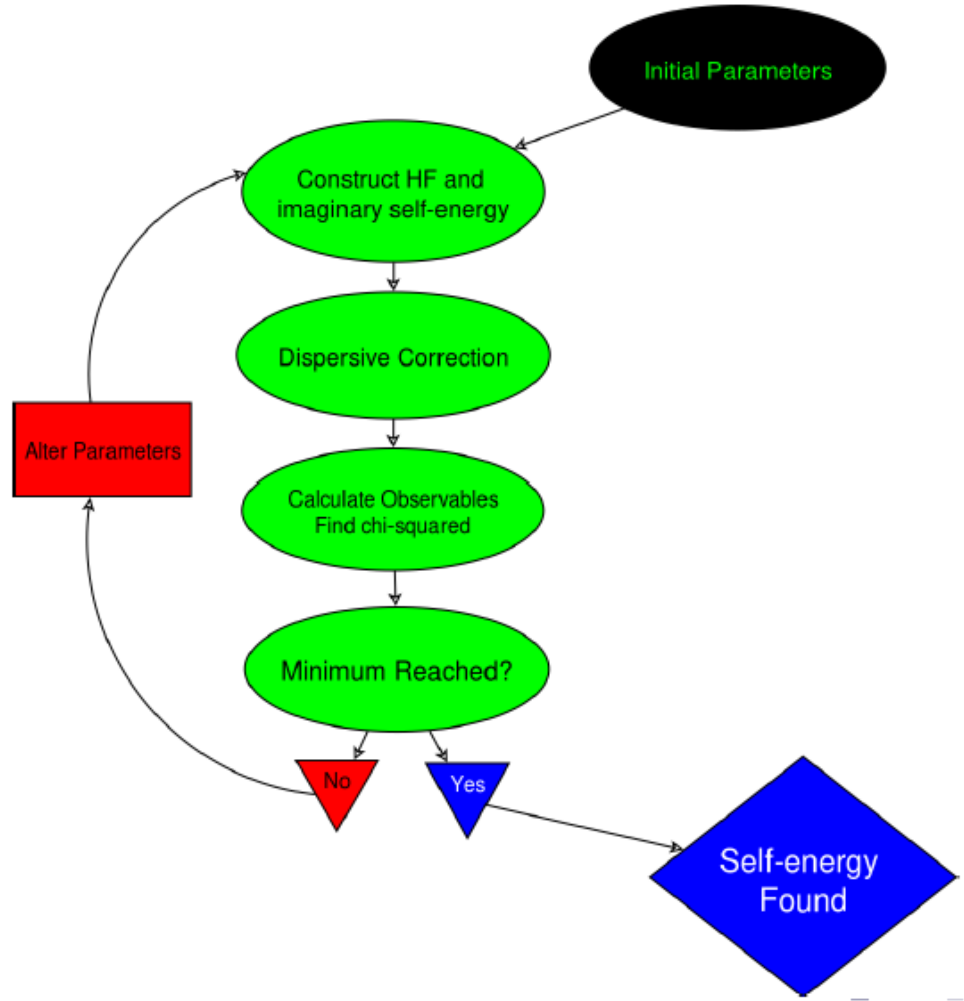
Subtract

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

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

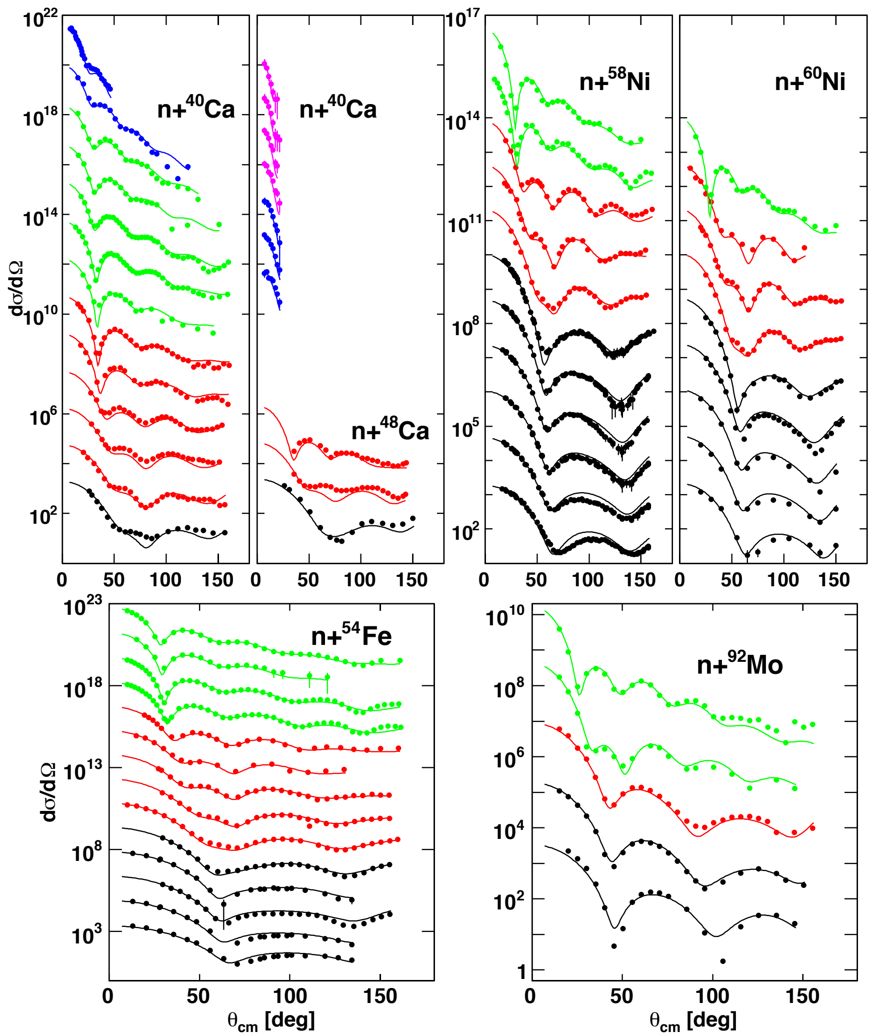
Functional form and fitting

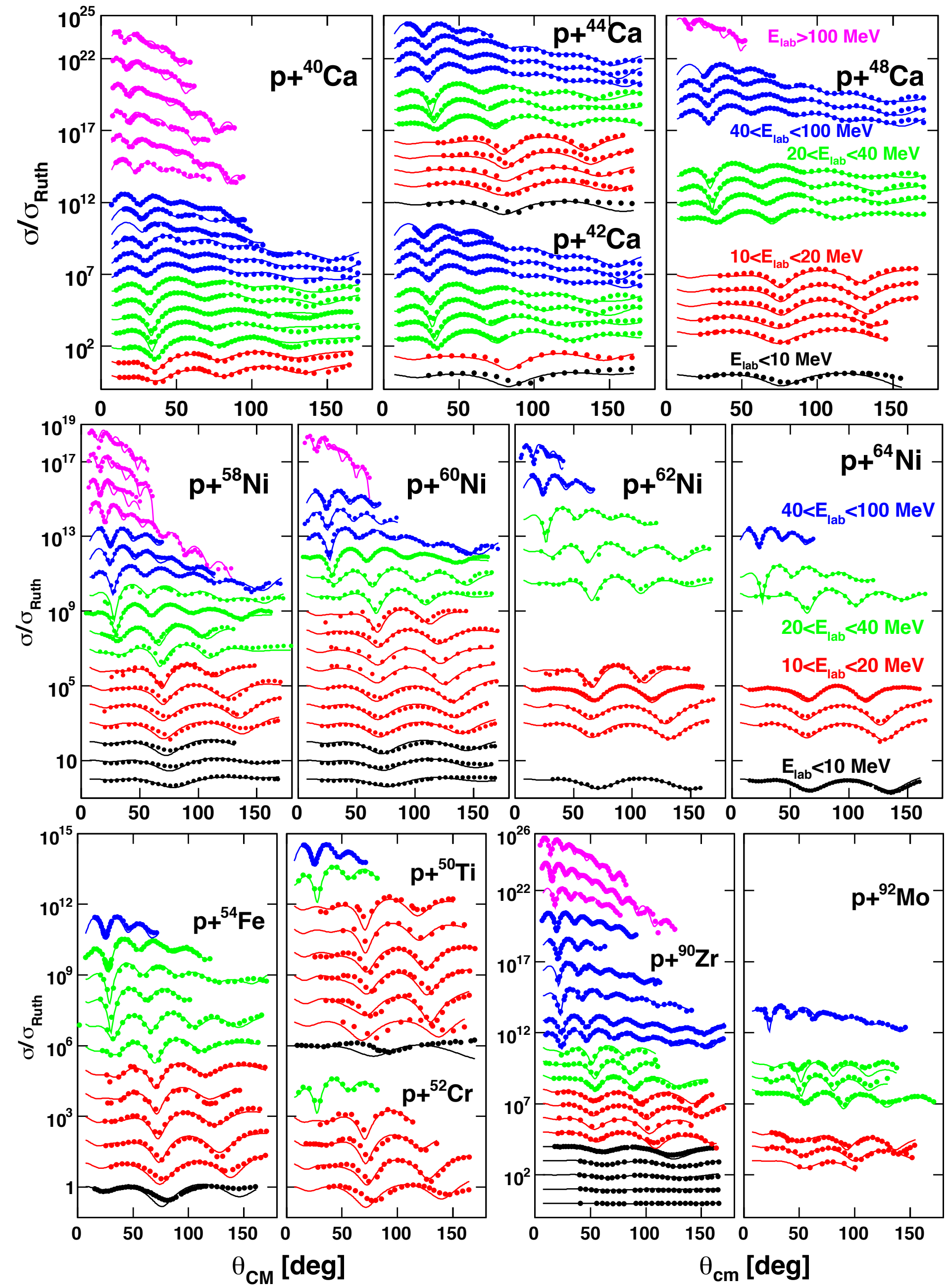
- Choice of potentials based on empirical knowledge
- Volume absorption —> WS
- Surface absorption —> WS'
- Coulomb
- Spin-orbit
- Hartree-Fock —> WS & WS'
- non-locality —> Gaussian
- E-dependence imaginary part <—> some theory
- Many parameters have canonical values



Elastic scattering data for protons and neutrons

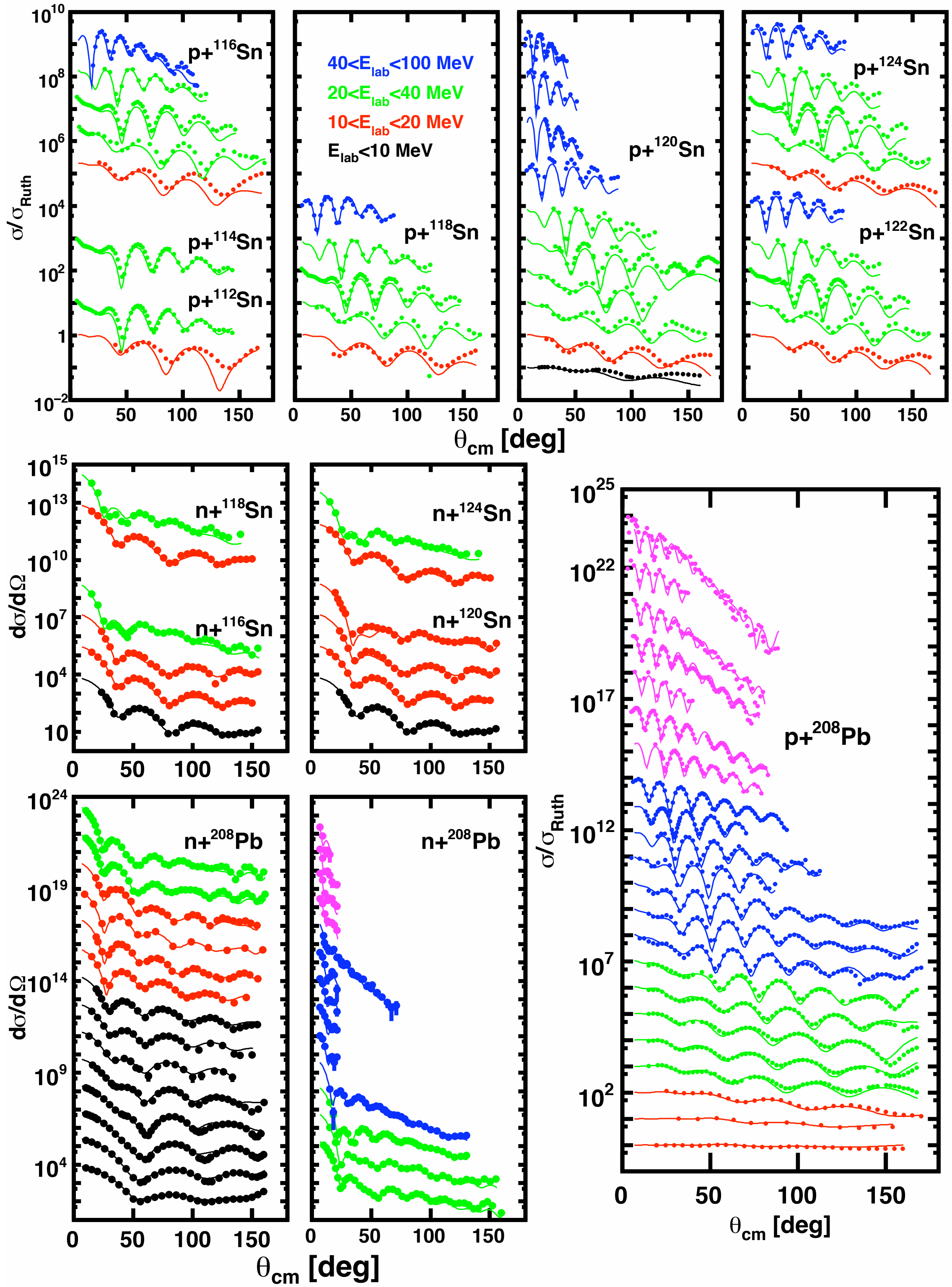
- **Local** DOM implementation





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

Nonlocal DOM implementation PRL112,162503(2014)

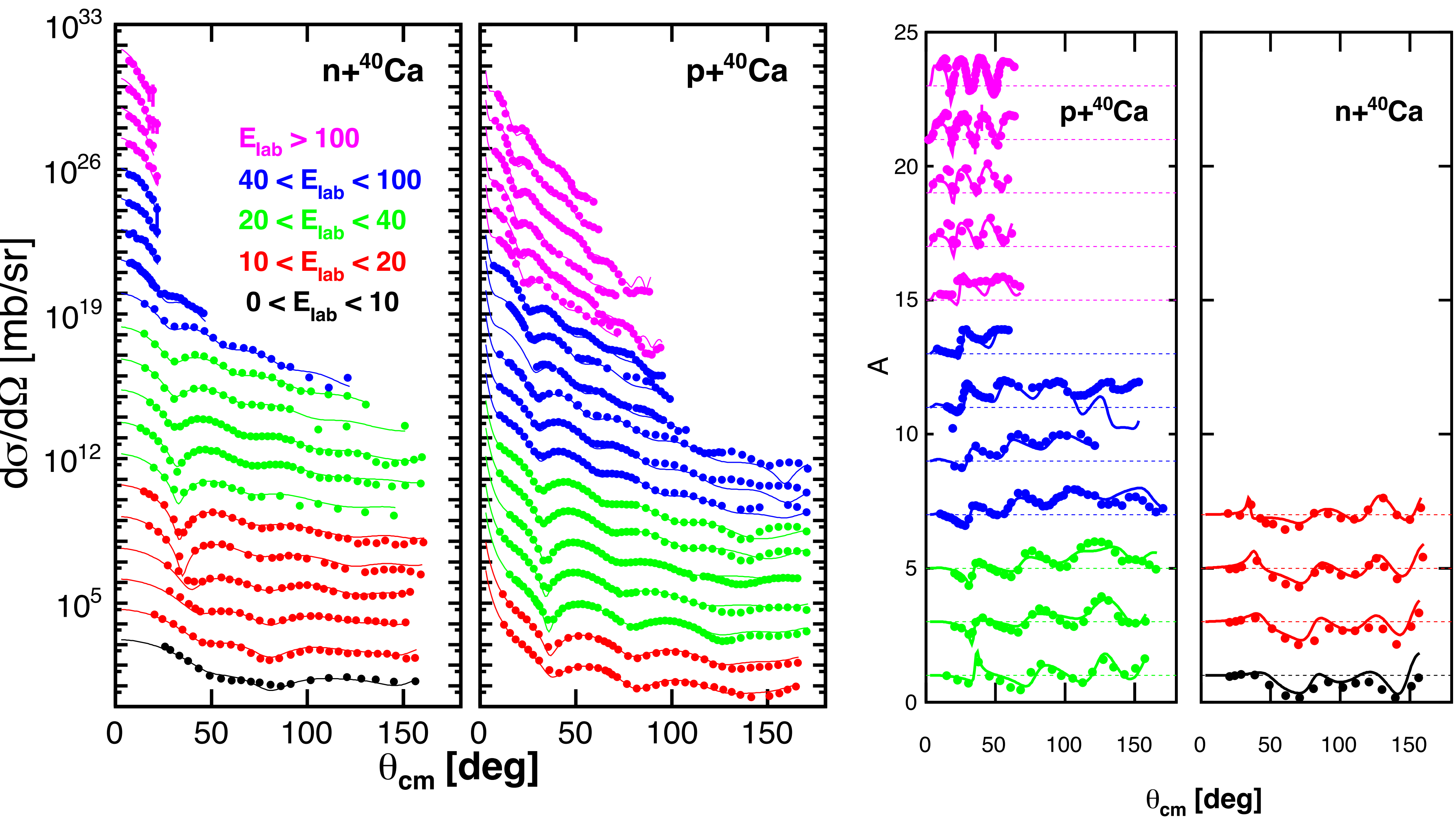
- Particle number --> **nonlocal** imaginary part
- Ab initio FRPA & SRC --> different nonlocal properties above and below the Fermi energy Phys. Rev. C84, 034616 (2011) & Phys. Rev.C84, 044319 (2011)
- Include charge density in fit
- Describe high-momentum nucleons <--> (e,e'p) data from JLab

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)

reactions and structure

Differential cross sections and analyzing powers

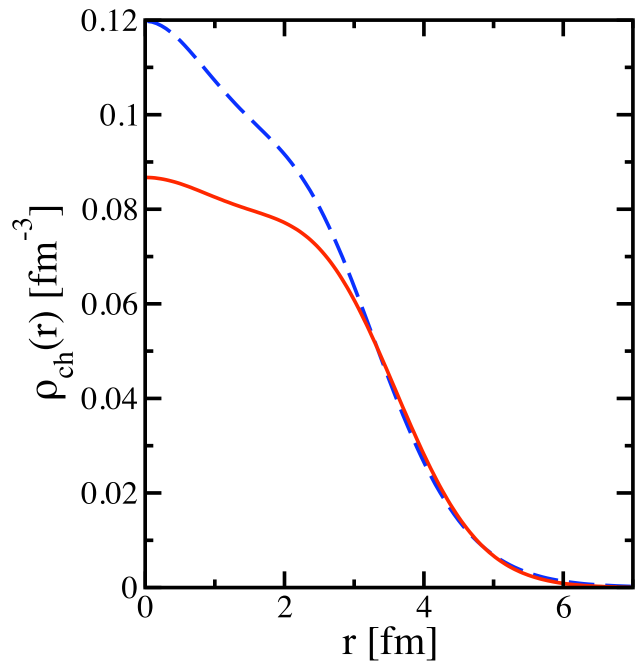


Critical experimental data—> charge density

Local version

radius correct…

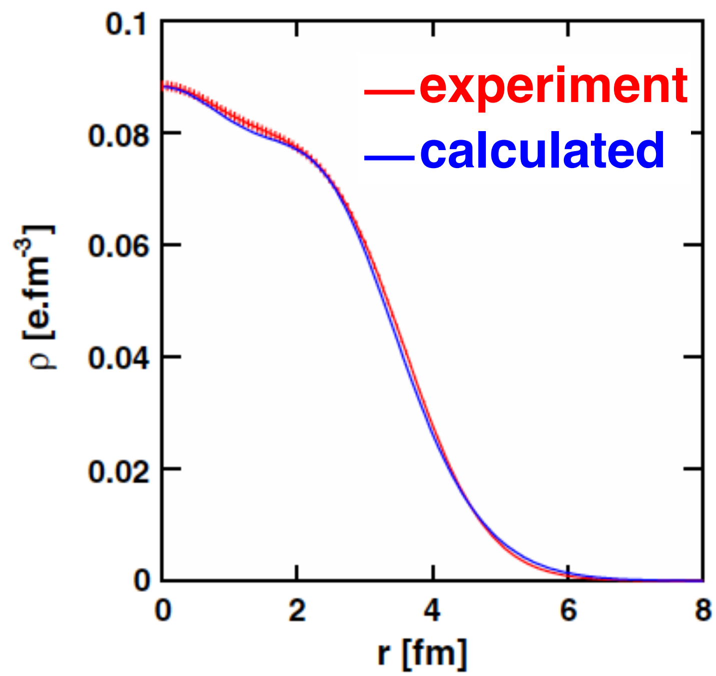
PRC82, 054306 (2010)



Charge density ^{40}Ca

Non-locality essential

PRL 112,162503(2014)

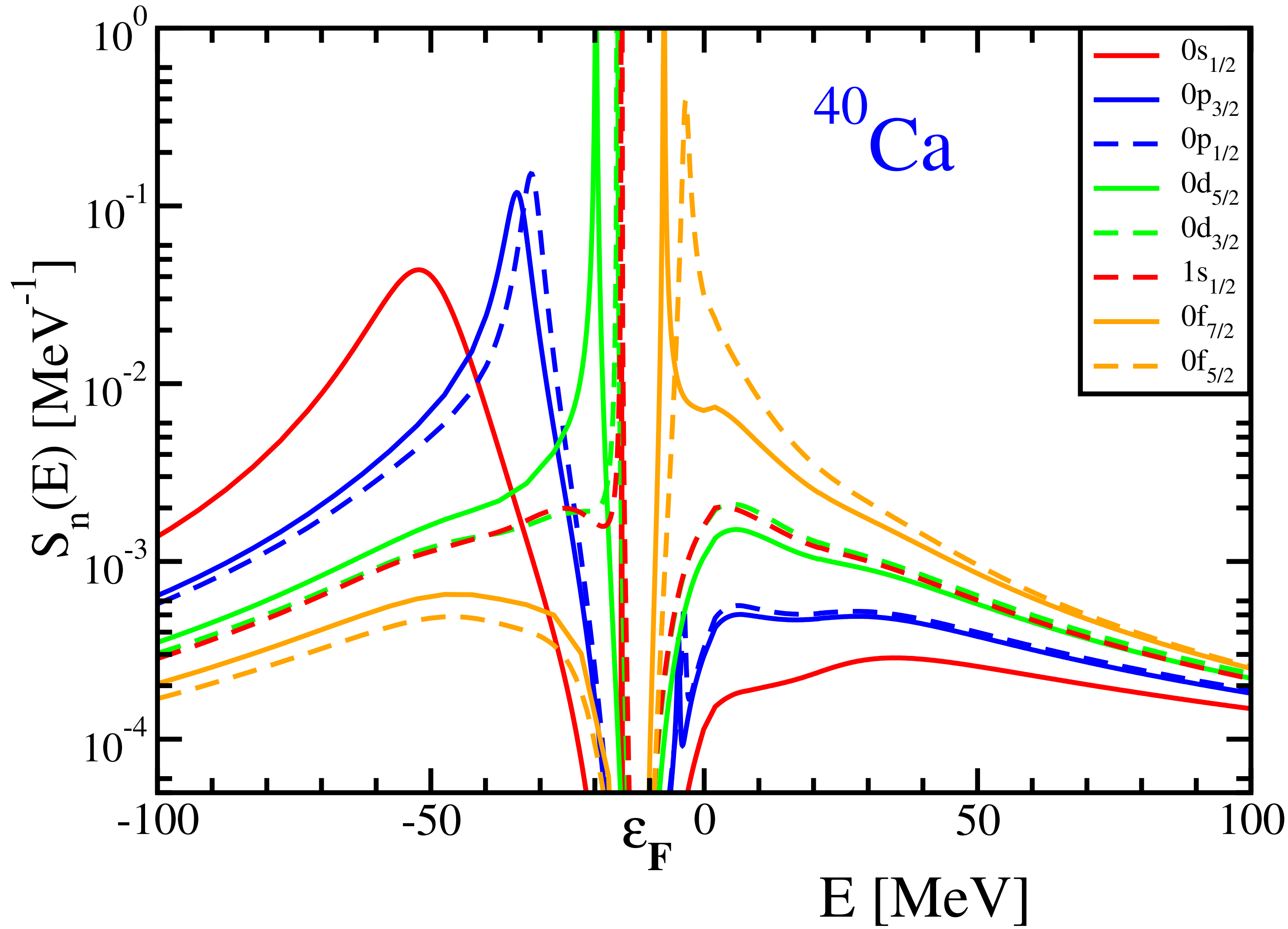


High-momentum nucleons —> JLab can also be described —> E/A

reactions and structure

Spectral function for bound states

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



Emptiness constrained!

PRC90, 061603(R) (2014)

reactions and structure

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? —> "THE" DIRECT REACTION reactions and structure

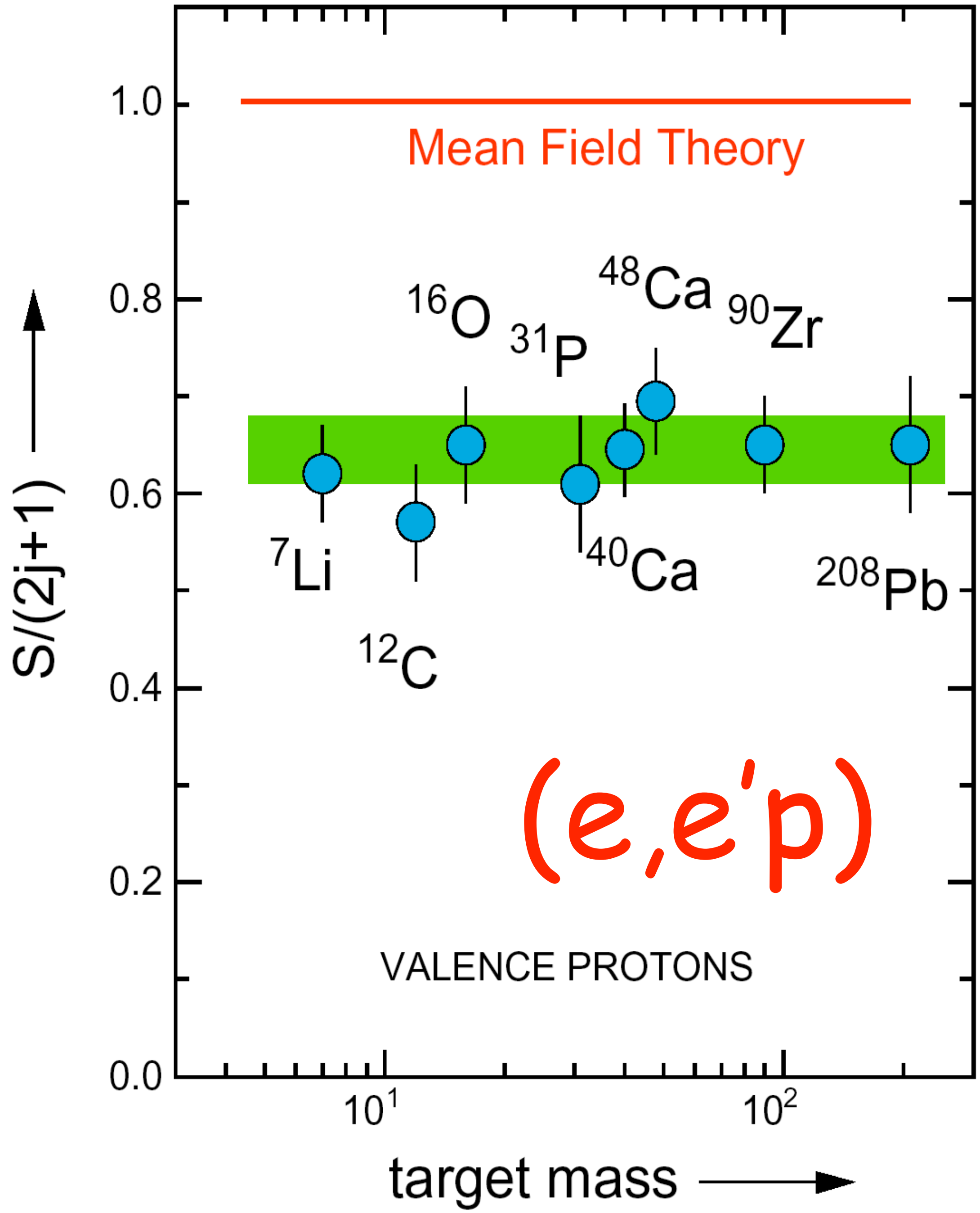
Removal probability for valence protons from NIKHEF data

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%

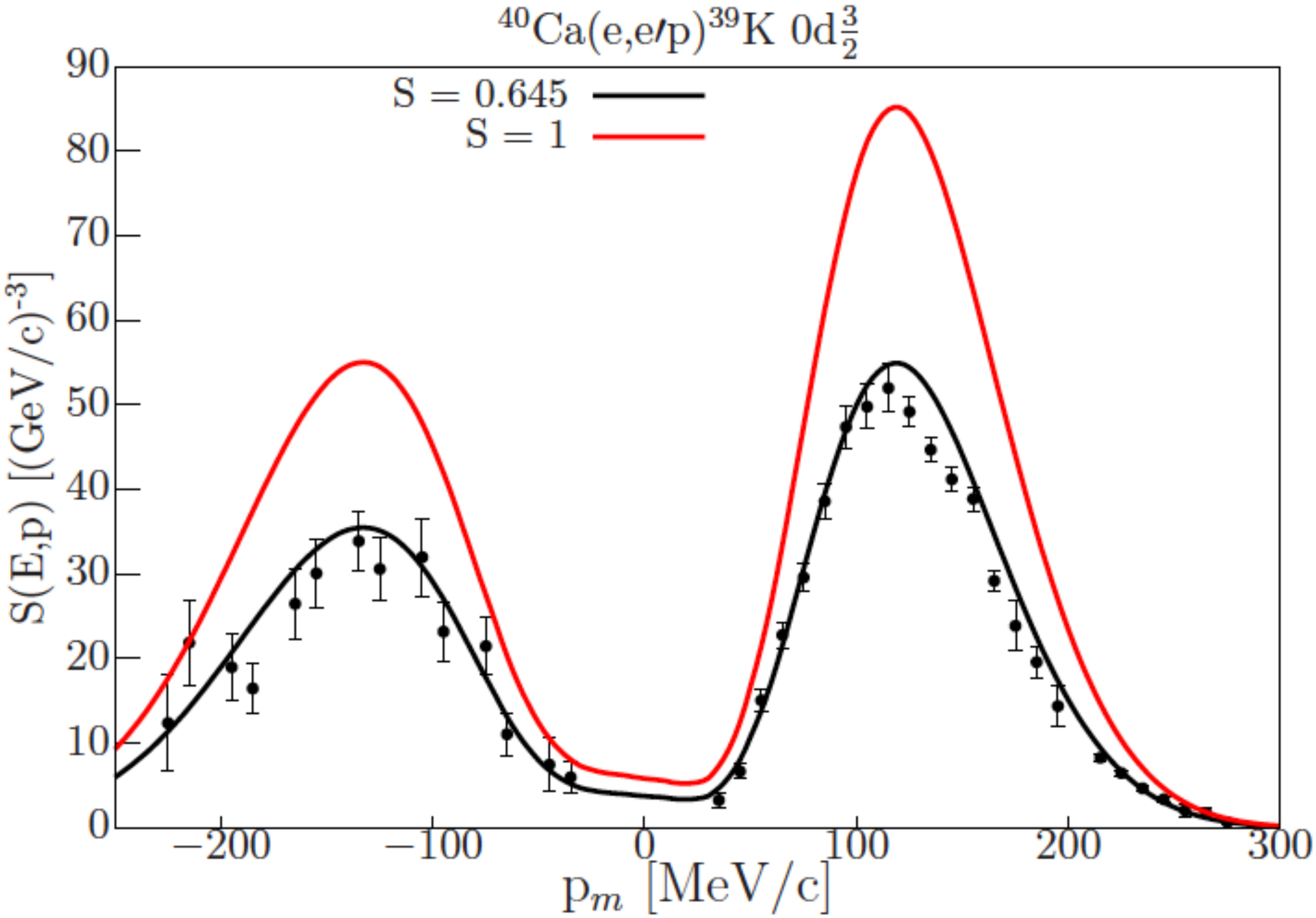
Why: details of the interior scattering wave function uncertain since non-locality is not constrained (so far…..)
but now available for ^{40}Ca!



reactions and structure

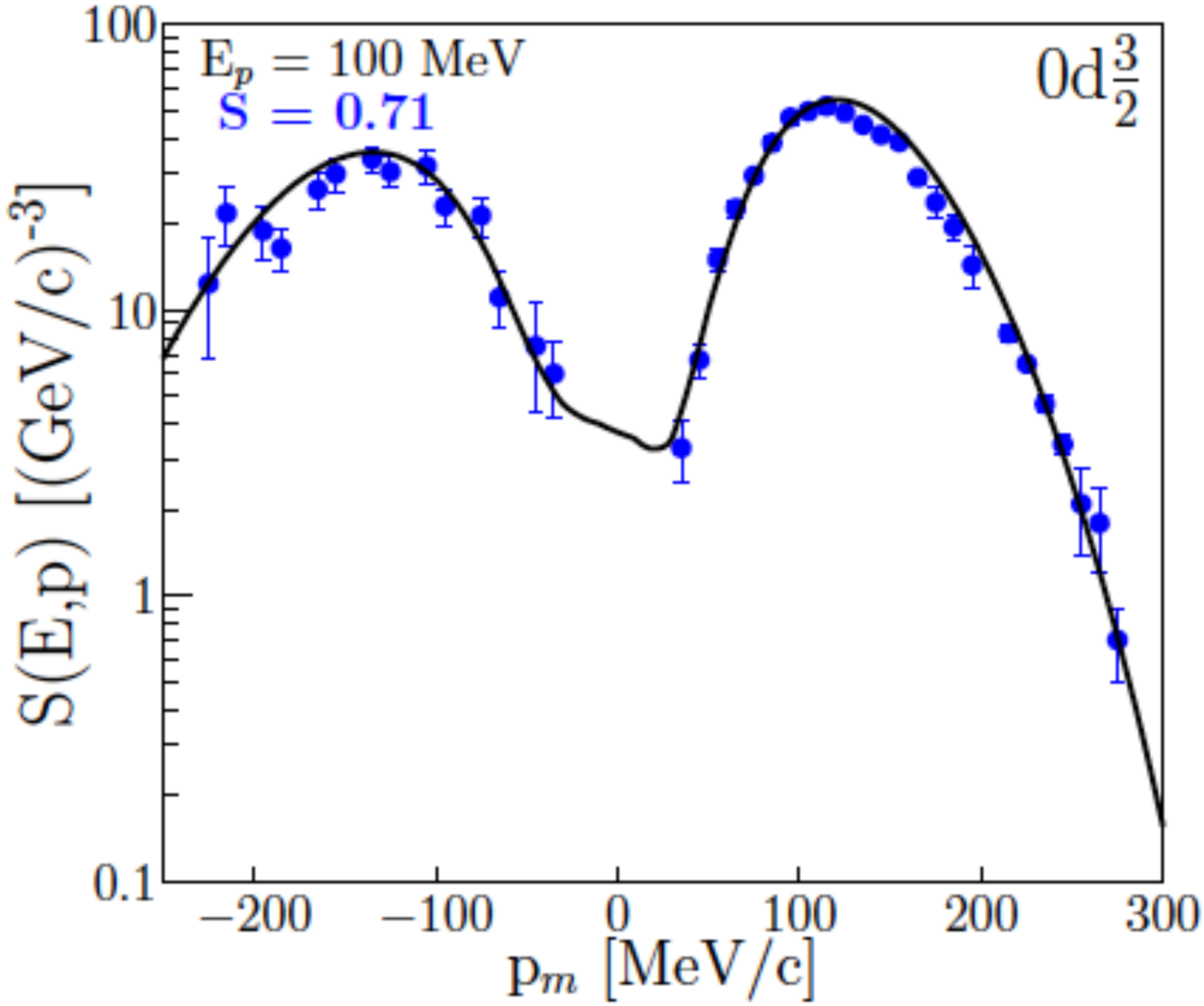
NIKHEF analysis PLB227,199(1989)

- Schwandt et al. (1981) optical potential
- BSW from adjusted WS



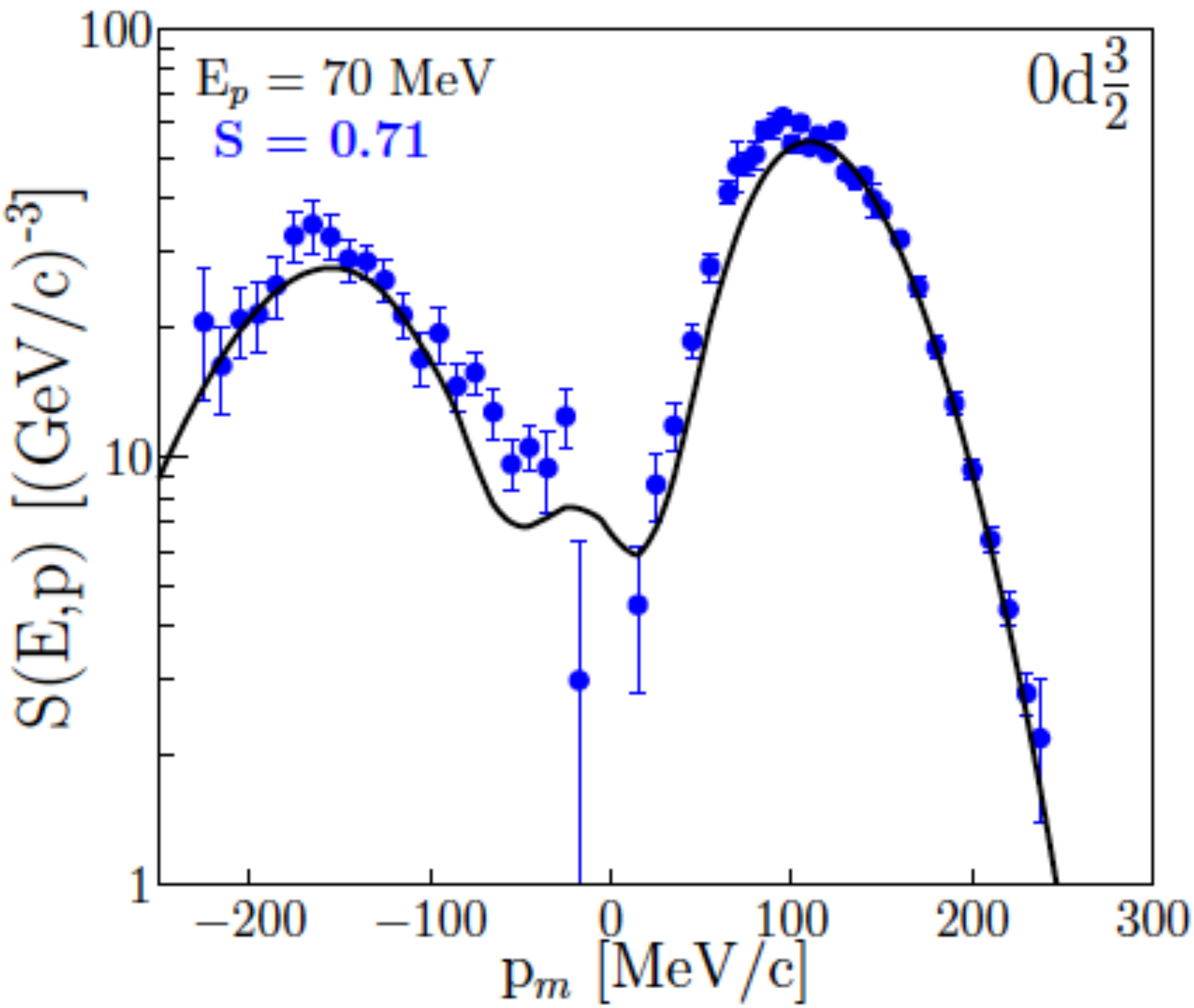
NIKHEF data PLB227,199(1989)

- NIKHEF: $S(d_{3/2})=0.65\pm0.06$
- Only DOM ingredients



NIKHEF data unpublished for 70 and 135 MeV protons

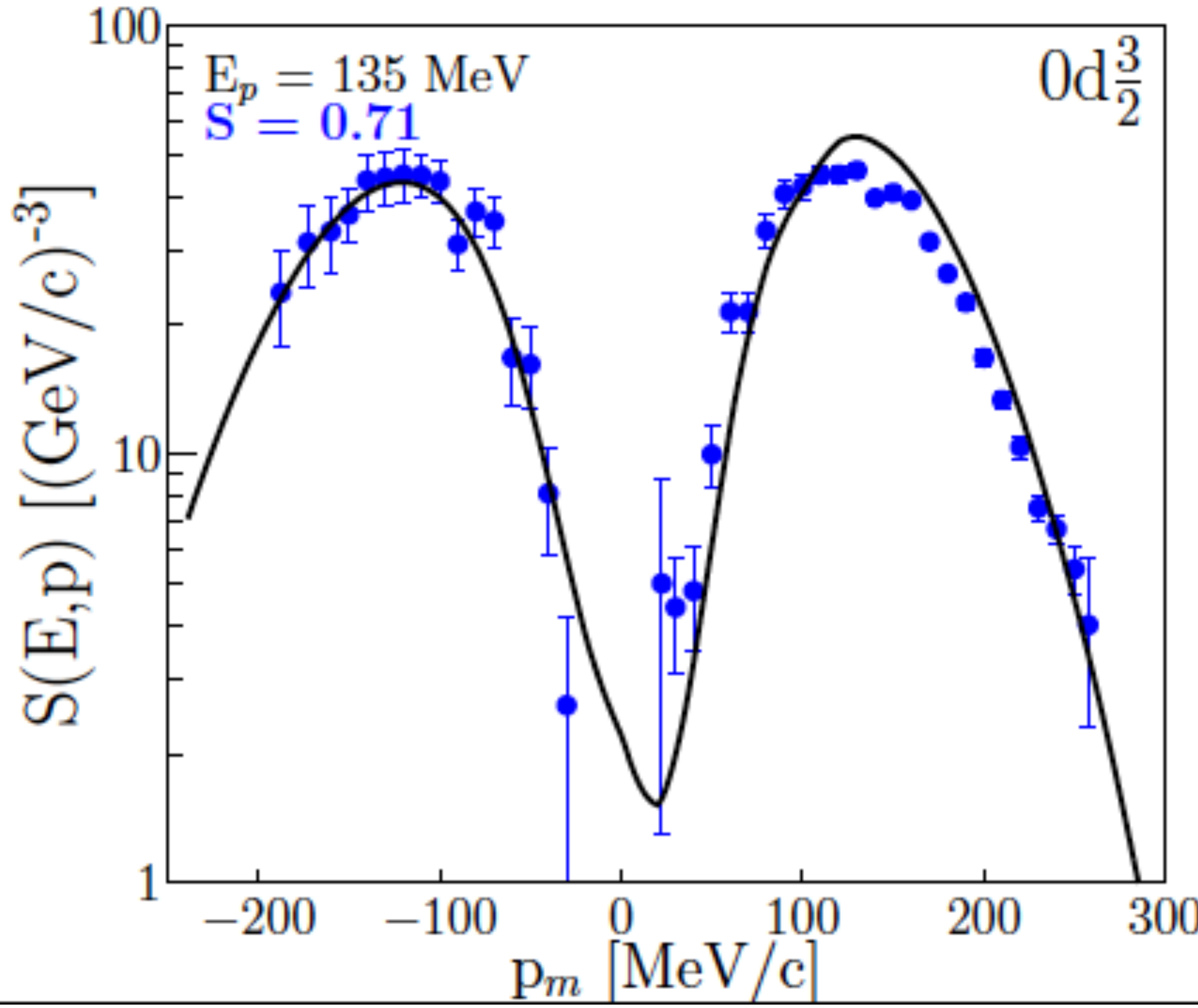
- Only DOM ingredients and modified DWEEPY code from C. Giusti
- Collaboration: M.Atkinson, L. Lapikás, H. Blok, W.D. in preparation



reactions and structure

NIKHEF data unpublished

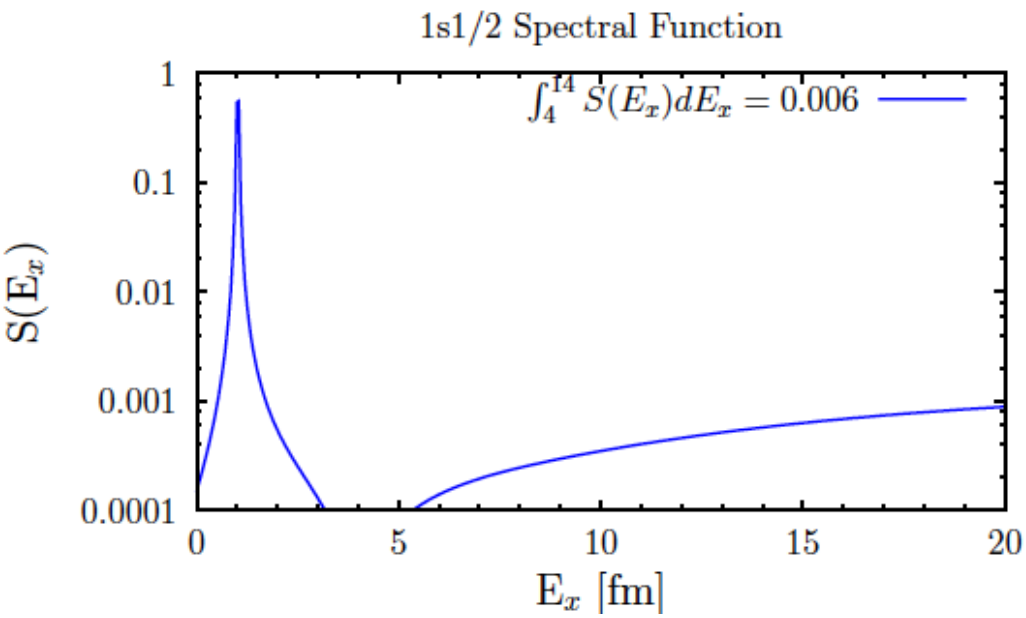
- Only DOM ingredients

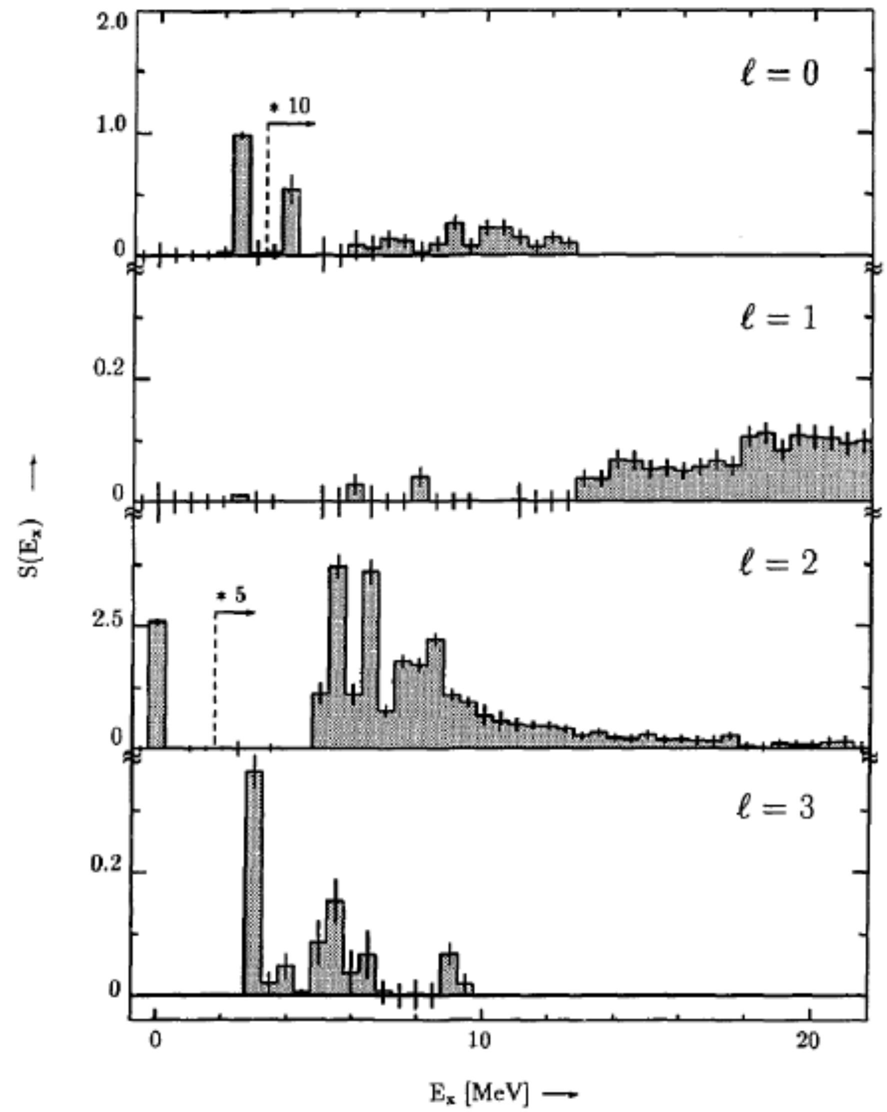


- at this energy DWIA may no longer be the whole story

Thesis G. J. Kramer (1990)

- $s_{1/2}$ strength fragmented
- Not yet included in DOM

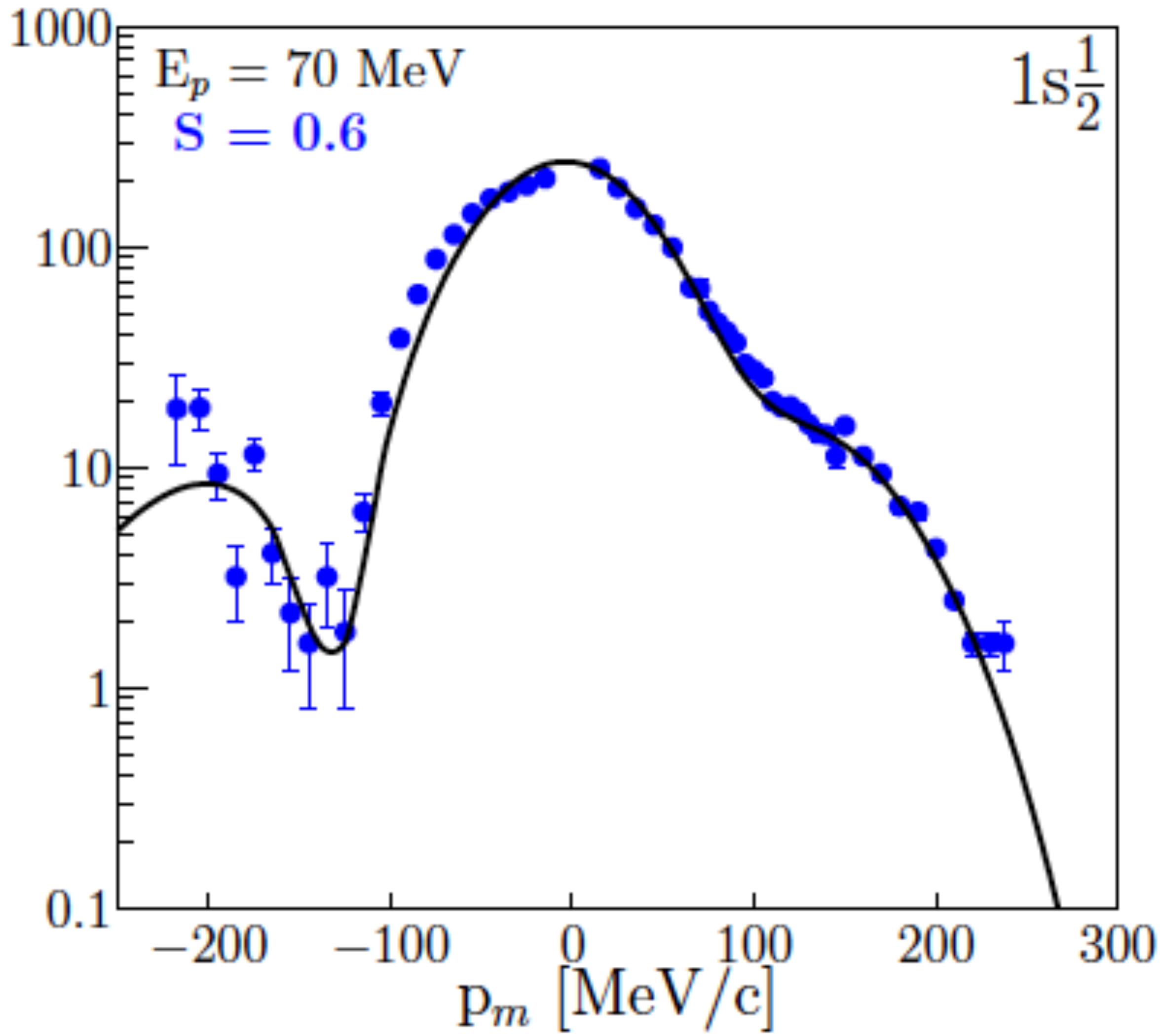




- Corrects DOM spectroscopic factor to 0.61 for state at 2.5 MeV

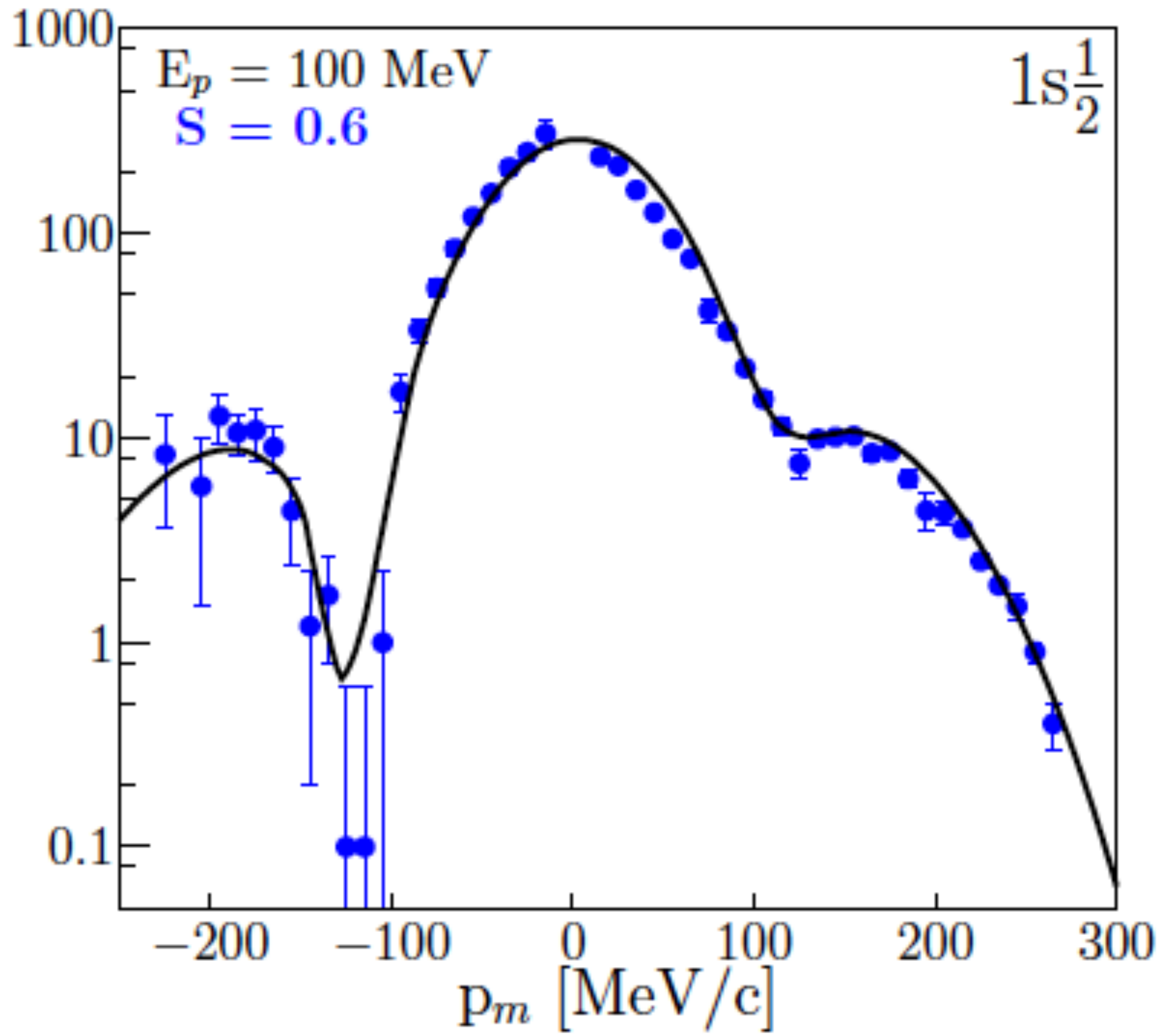
NIKHEF data unpublished

- Only DOM ingredients



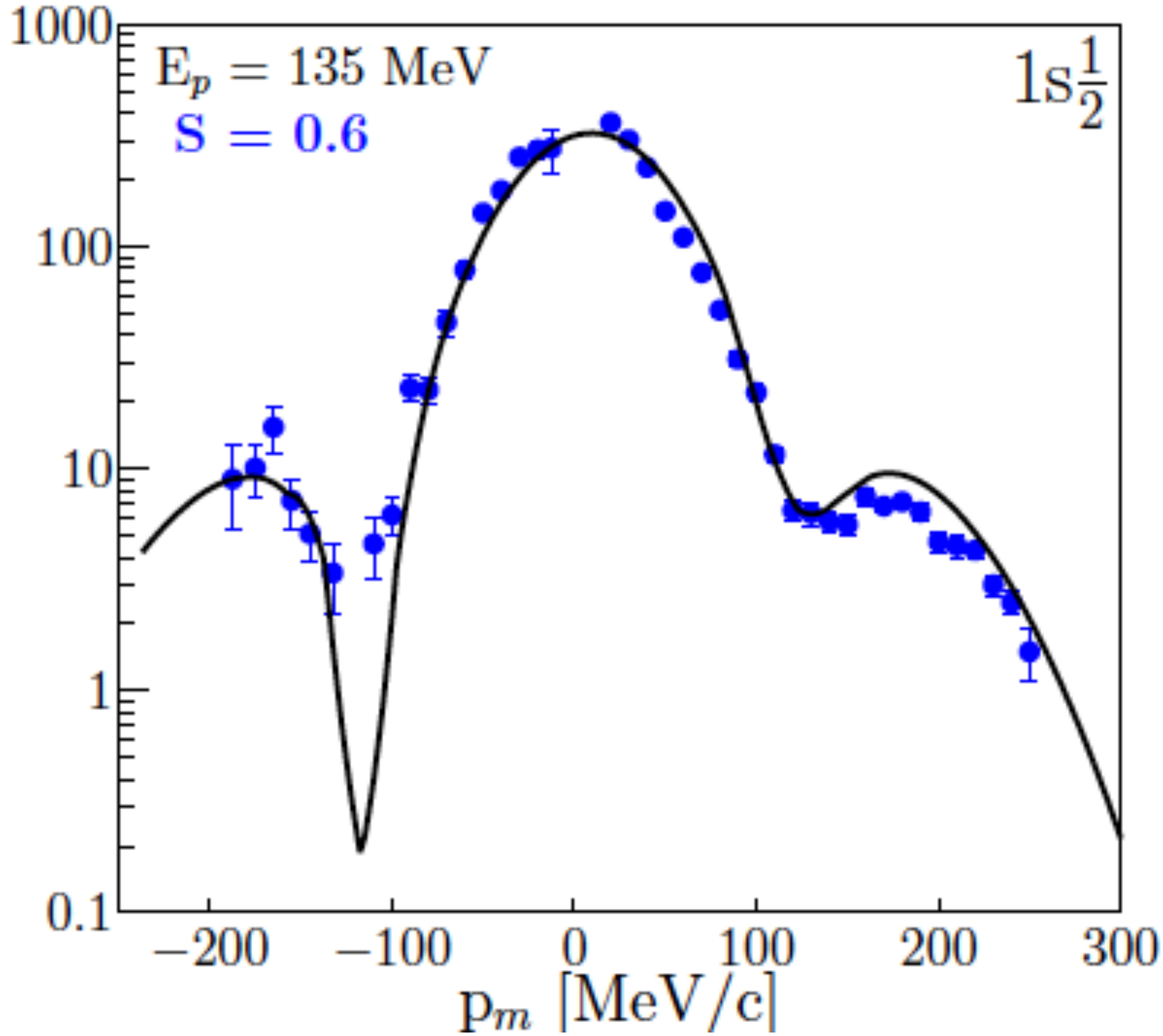
NIKHEF data PLB227,199(1989)

- NIKHEF: $S(s_{1/2})=0.51\pm0.05$



NIKHEF data unpublished

- Only DOM ingredients



Message

- Nonlocal dispersive potentials yield consistent input and gives a correct description of the (e,e′p) for certain kinematics

- Constraints from other data generate spectroscopic factors $S(d_{3/2})=0.71$ in ^{40}Ca for ground state transition
- Experimental $s_{1/2}$ strength distribution: 2.5 MeV $S(s_{1/2})=0.61$
- NIKHEF 0.65±0.06 and 0.51±0.05, respectively (local potentials)
- Slight increase due to nonlocal potentials for distorted waves

- Implications for transfer reactions significant and under study
- (p,2p) reaction for stable targets can be constrained/calibrated and then extended to unstable one

Reviewed in Prog. Part. Nucl. Phys. 52 (2004) 377-496

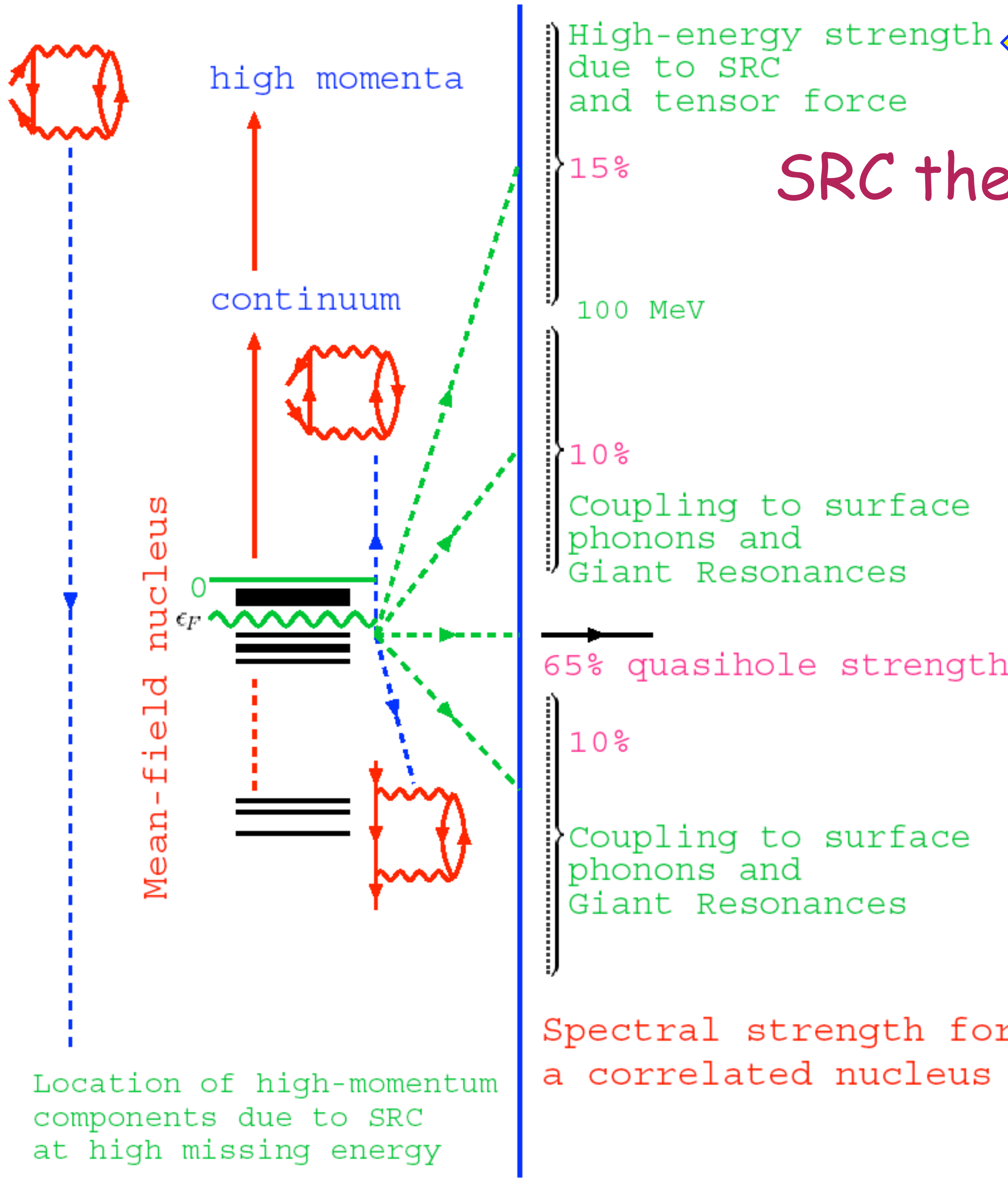
Location of single-particle strength in closed-shell (stable) nuclei

For example:
protons in ^{208}Pb

SRC

JLab E97-006

Phys. Rev. Lett. 93, 182501 (2004) D. Rohe et al.



SRC theory

Elastic nucleon scattering

NIKHEF (e,e'p) data
L. Lapikás
Nucl. Phys. A553,297c (1993)

reactions and structure

DOM results for ^{48}Ca

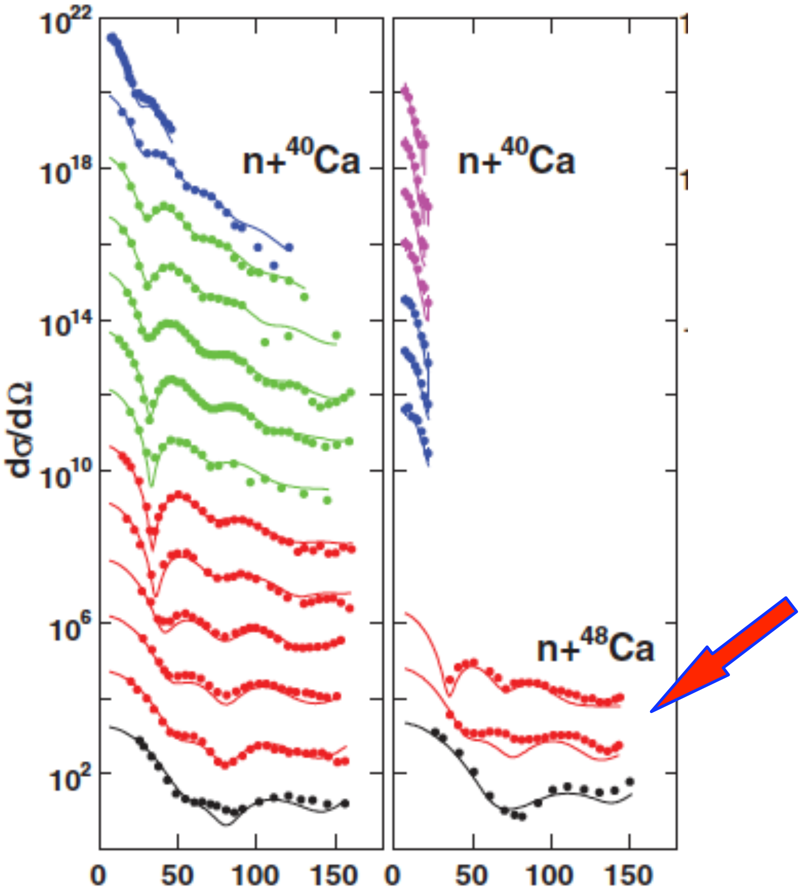
- Change of proton properties when 8 neutrons are added to ^{40}Ca?

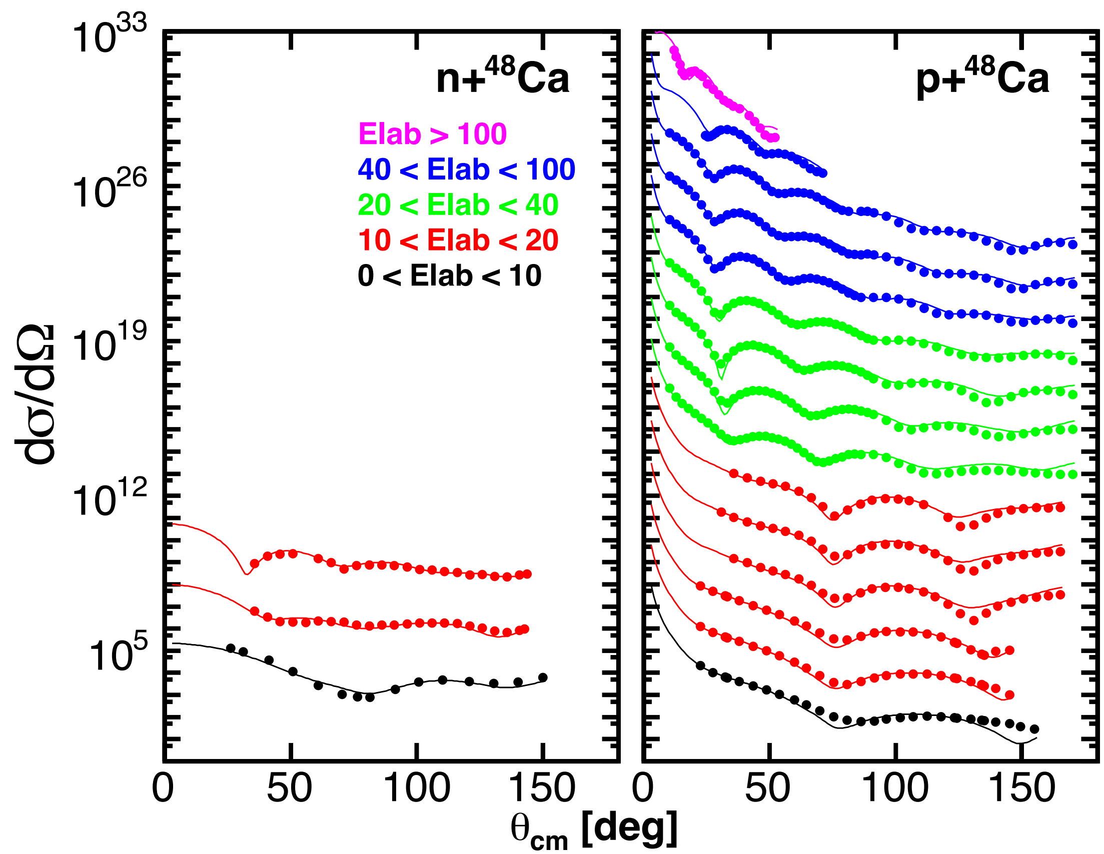
- Change of neutron properties?

- 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**

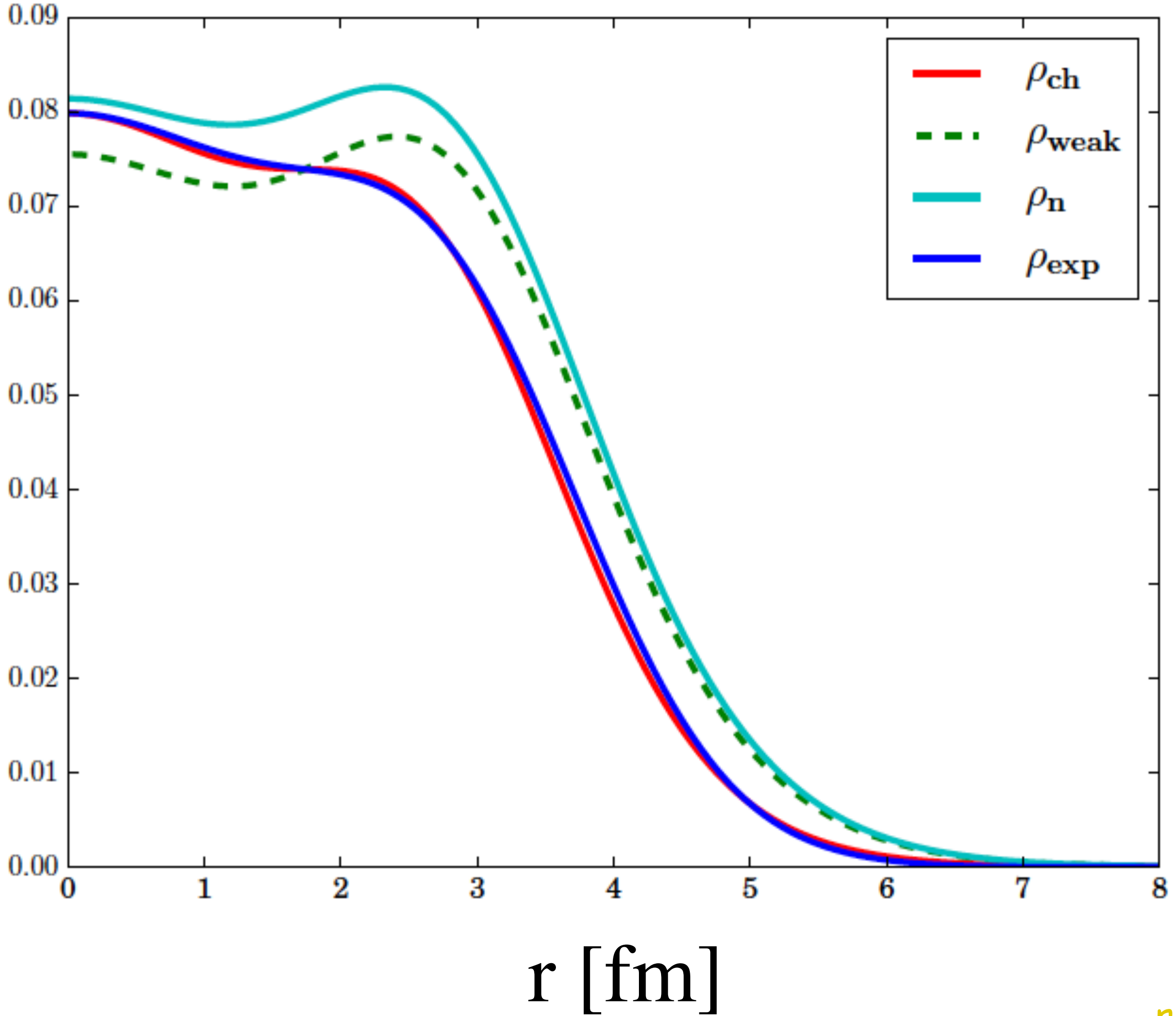




reactions and structure

Results ^{48}Ca

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

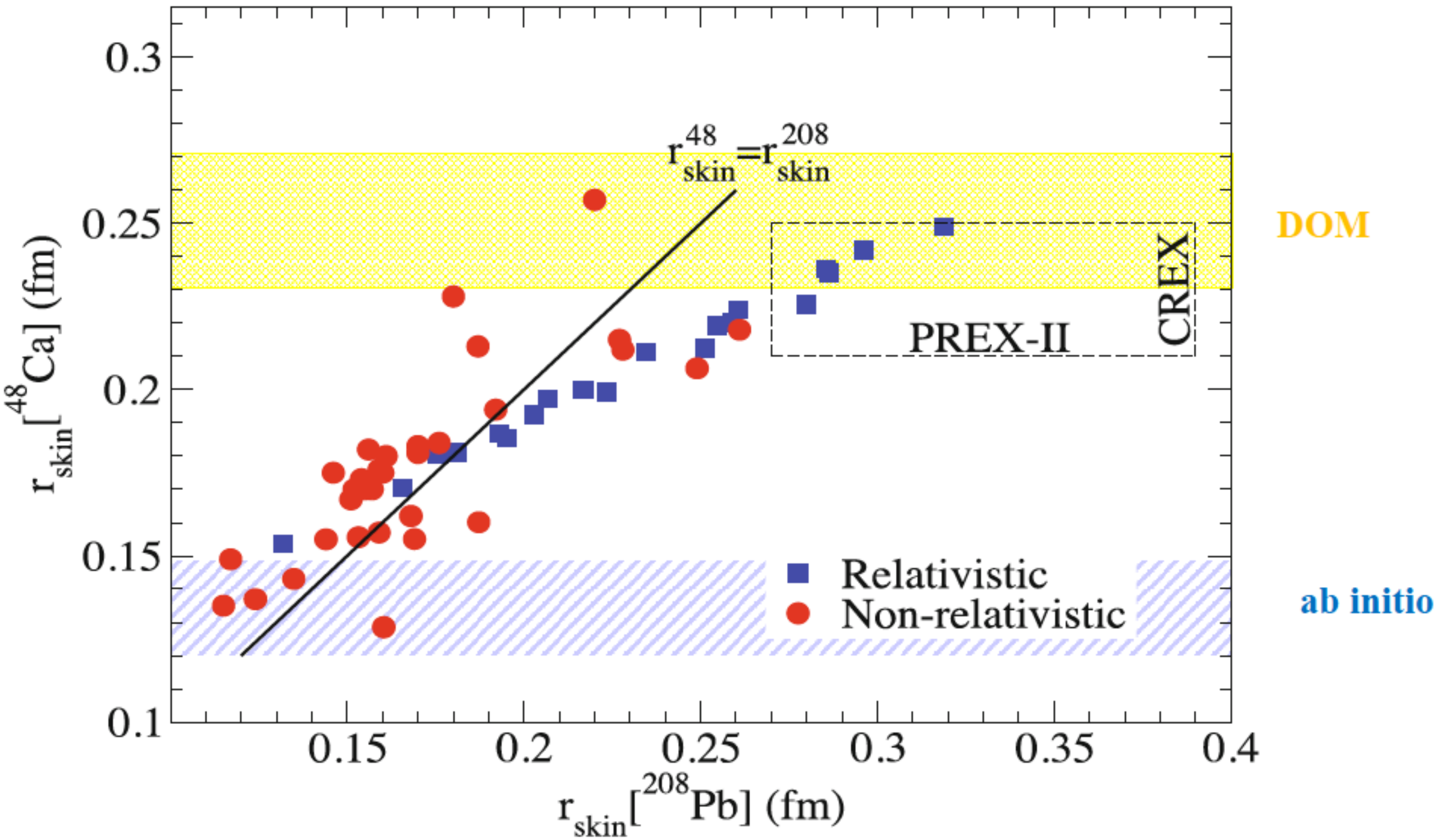


reactions and structure

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)



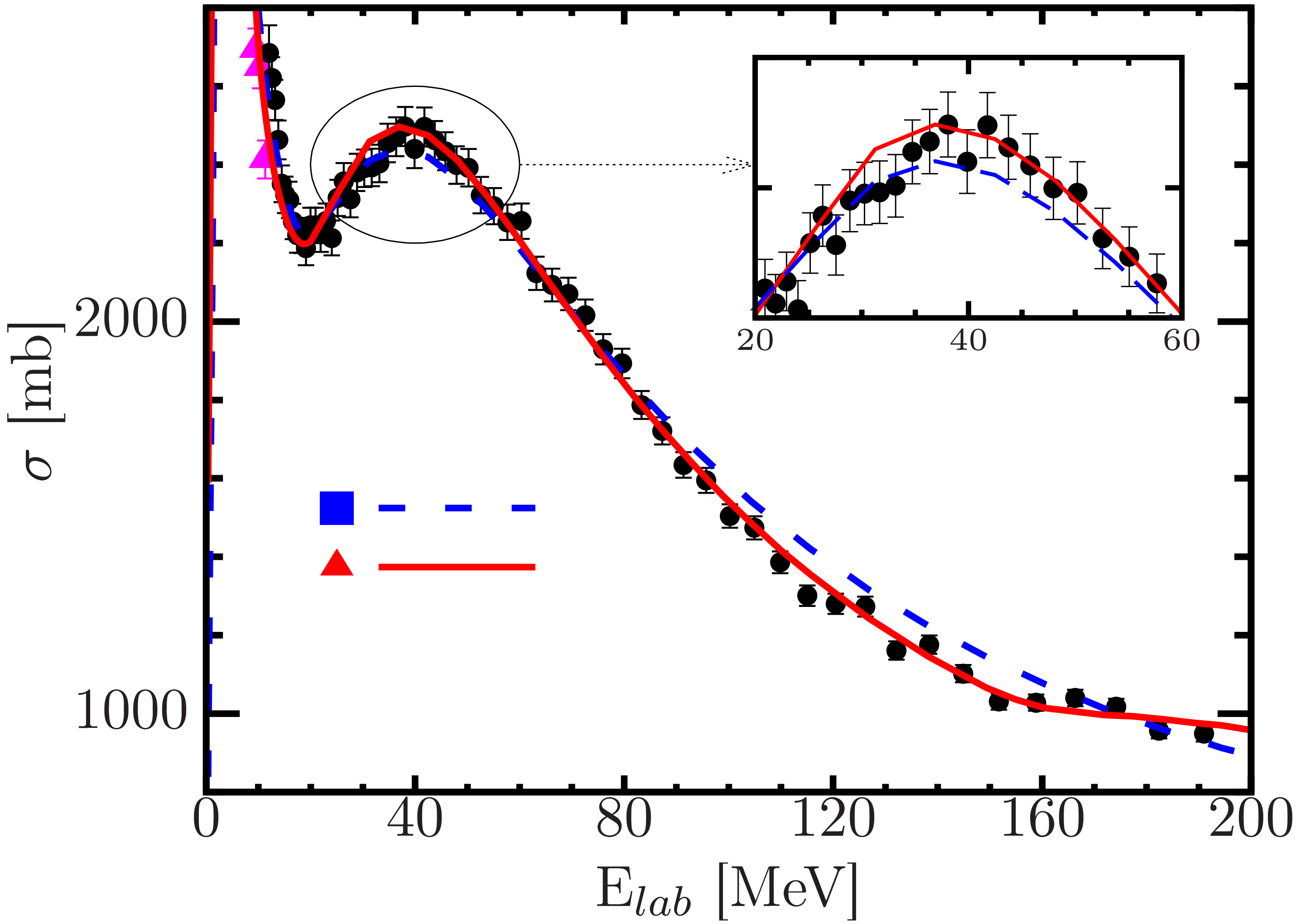
- "Ab initio":

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

--> drip line

Constraining the neutron radius

- Using total neutron cross sections



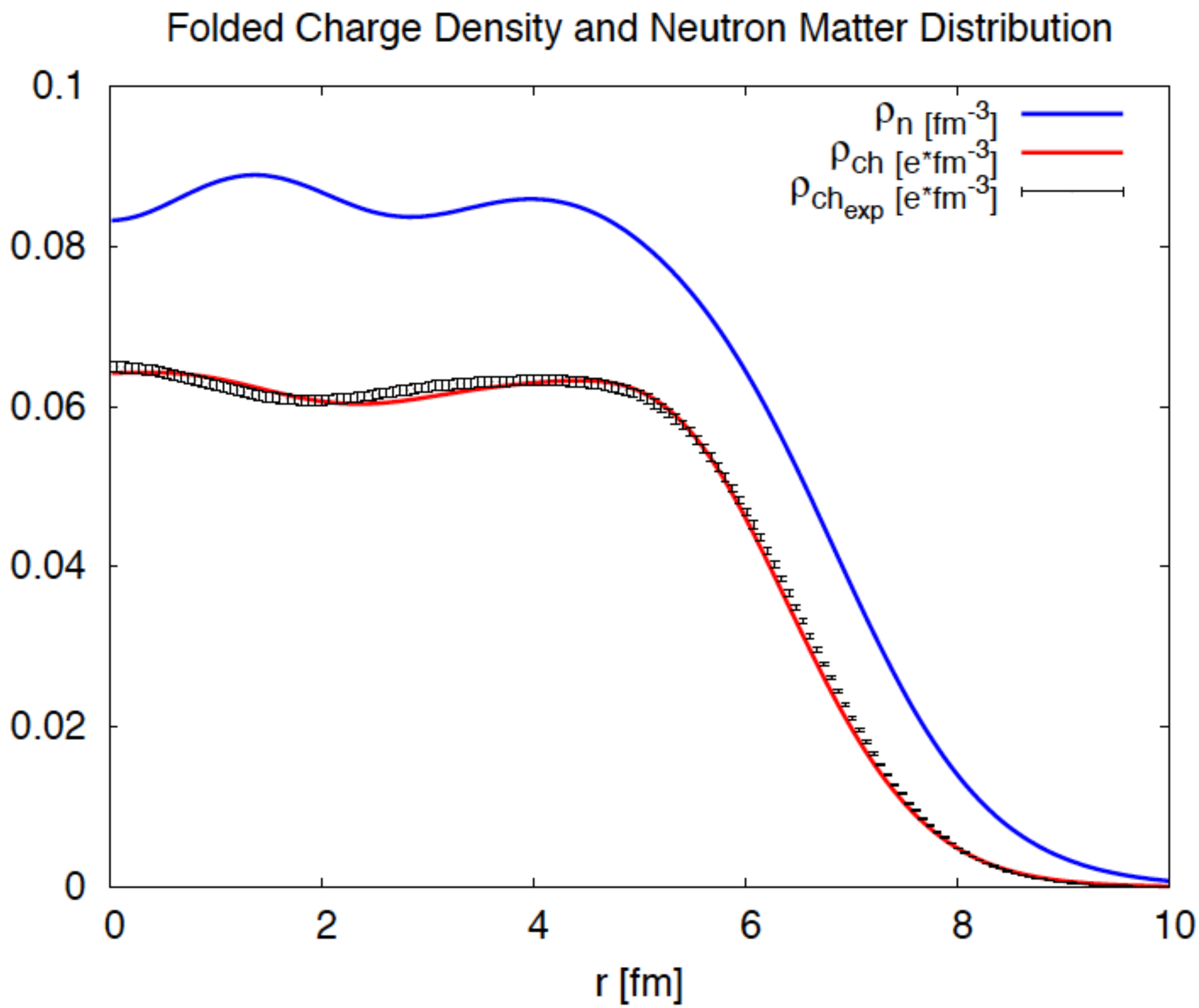
- M.H. Mahzoon, M.C. Atkinson, R.J. Charity, W.D.

Phys. Rev. Lett. **119**, 222503 (2017)

--> drip line

^{208}Pb Charge density

- Possible to get a good charge density (preliminary)



Comparison of neutron skin with other calculations and future experiments…

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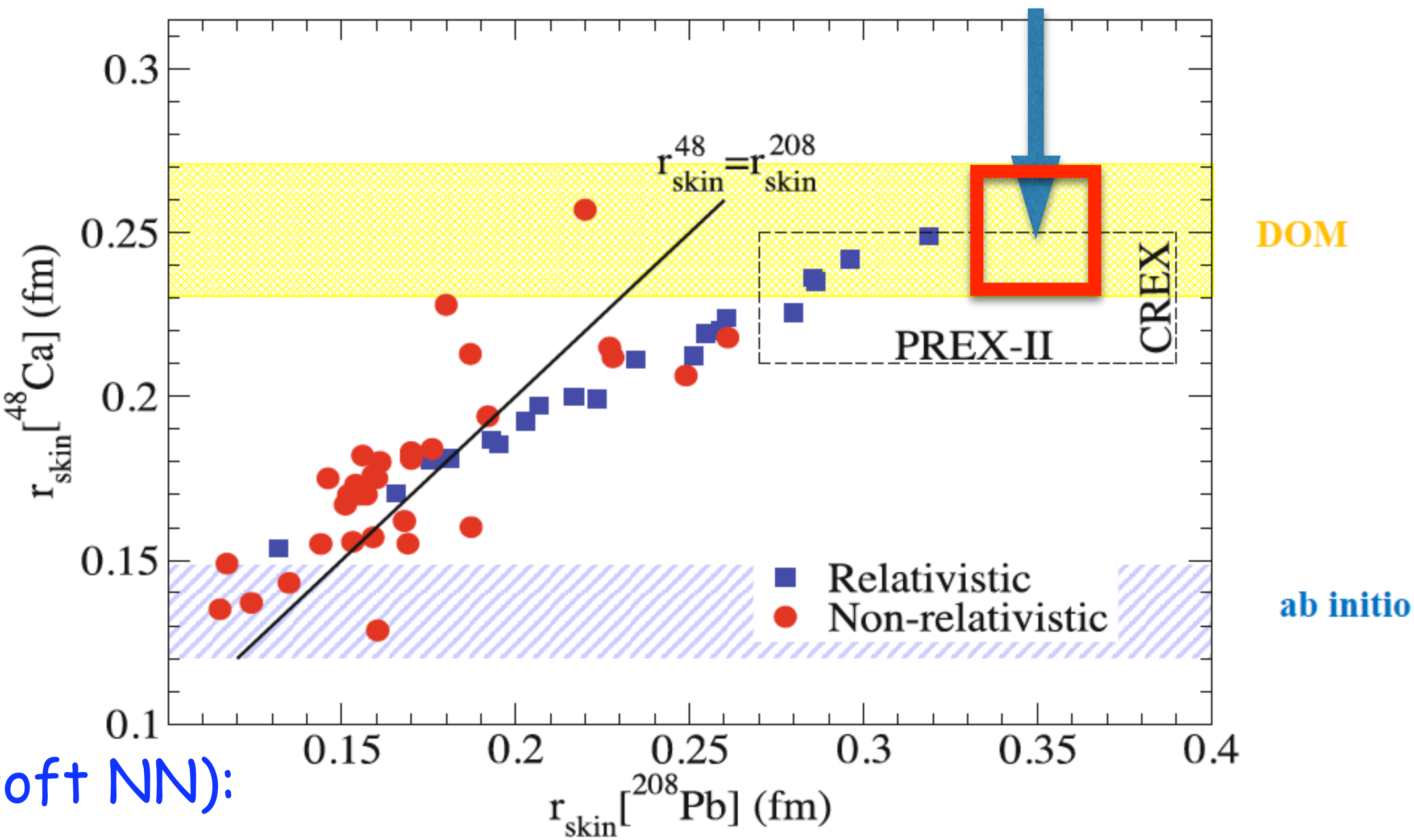


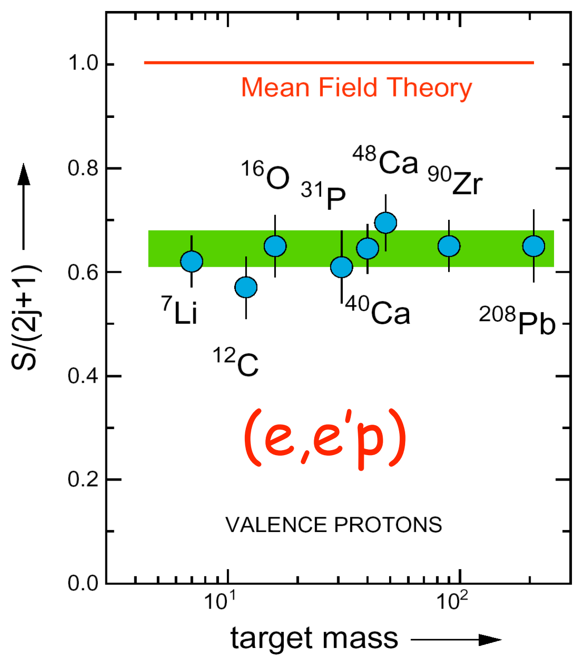
- Ab initio (soft NN):

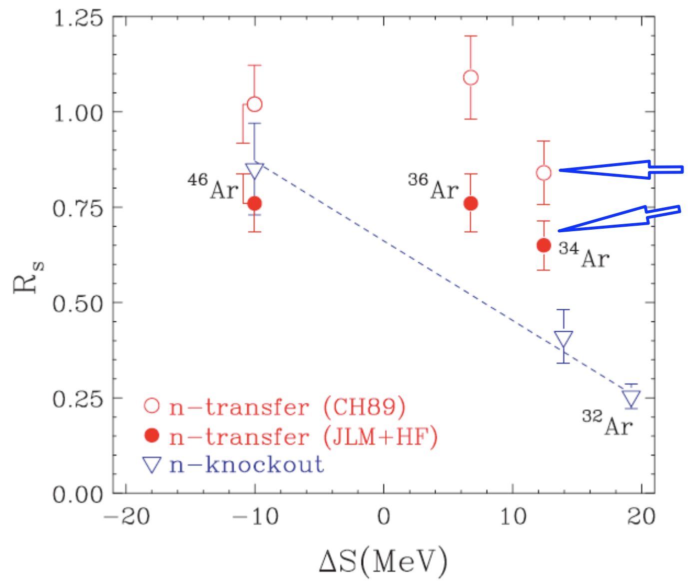
G. Hagen et al., Nature Phys. 12, 186 (2016)

--> drip line

Linking nuclear reactions and nuclear structure —> DOM

Correlations from nuclear reactions





Different optical potentials --> different reduction factors for transfer reactions

Spectroscopic factors > 1 ???

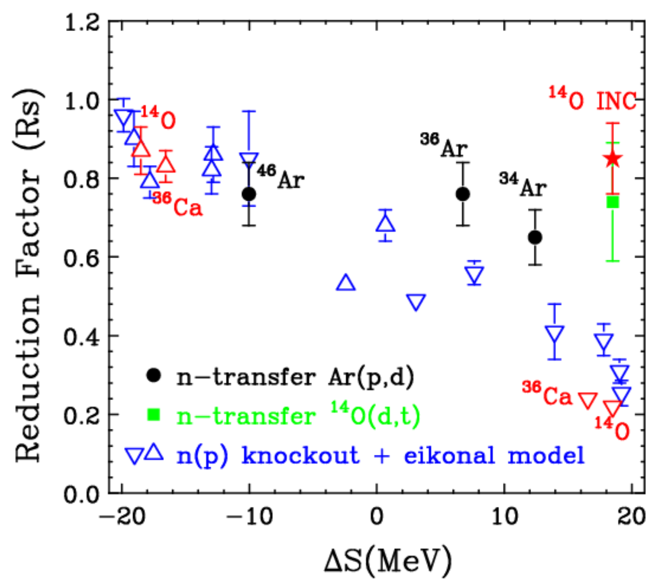
PRL 93, 042501 (2004) HI

PRL 104, 112701 (2010) Transfer

In (e,e'p) proton still has to get out of the nucleus —> optical potential

Nucl. Phys. A553,297c (1993)

Consistent with DOM analysis!



Summary —> Jenny Lee

Different reactions different results???

… recent work

Still unresolved —> Darmstadt workshop in July 2018

Ongoing work

- ^{208}Pb fit —> neutron skin prediction
- ^{48}Ca(e,e′p)
- ^{112}Sn and ^{124}Sn total neutron cross sections being analyzed
- ^{64}Ni measurement of total neutron cross section just completed
- Local then nonlocal fit to Sn, and Ni 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 becoming available necessitating inclusion of pairing in the DOM
- 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

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
- 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...