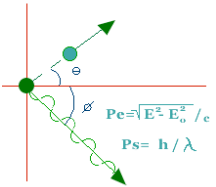


Neutron skins and high-momentum components in finite nuclei

SRC & EMC-Effect 6/8-12/2026 Berkeley



DOM activities: Wim Dickhoff

Bob Charity

Lee Sobotka

Louk Lapikas (e,e'p)

Henk Blok (e,e'p)

Hossein Mahzoon (Ph.D. 2015)

Mack Atkinson (Ph.D. 2019)

Natalya Calleya (Grad → 2026)

Ragib Ramon (Grad → 2027)

Cole Pruitt (Ph.D. 2019)

- Motivation → meaningful link between structure and reactions essential for the physics of rare isotopes
- Green's function method can accommodate SRC self-consistently in matter
- Green's functions/propagator method ↔ Causality by employing dispersion relations ↔ dispersive optical model (DOM)
 - Framework to link data at positive and negative energy (and to generate predictions for exotic nuclei as well as neutron skins)
- Revisiting the Nikhef results and analysis of (e,e'p) using the DOM (⁹⁰Zr)
- Weak charge results ↔ DOM description ↔ high momenta
- Improved DOM description of high momenta (⁴⁰Ca, ⁴⁸Ca, ⁵⁴Fe last week)
- Conclusion and outlook

Neutron skins and high momenta

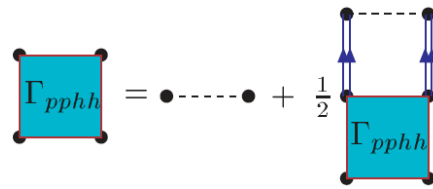
Full off-shell propagation in infinite matter at finite T

SCGF:
self-consistent
Green's functions
for SRC and tensor
effects

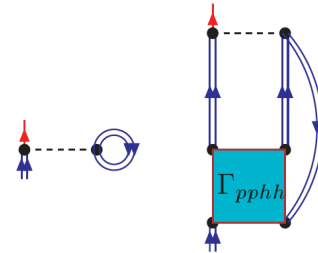
self-consistency
=> thermodynamically consistent

Arnau Rios
Arturo Polls†
W.D.

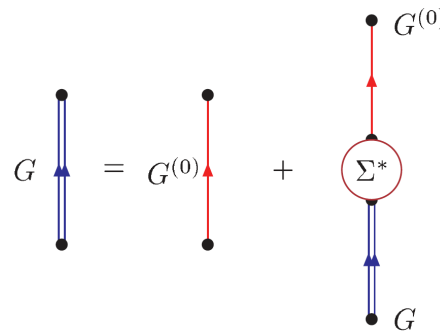
finite T avoids pairing
standard for AV18, CDBonn, N3LO, etc



Interaction in the
medium properly
treating **short-
range and tensor
correlations**

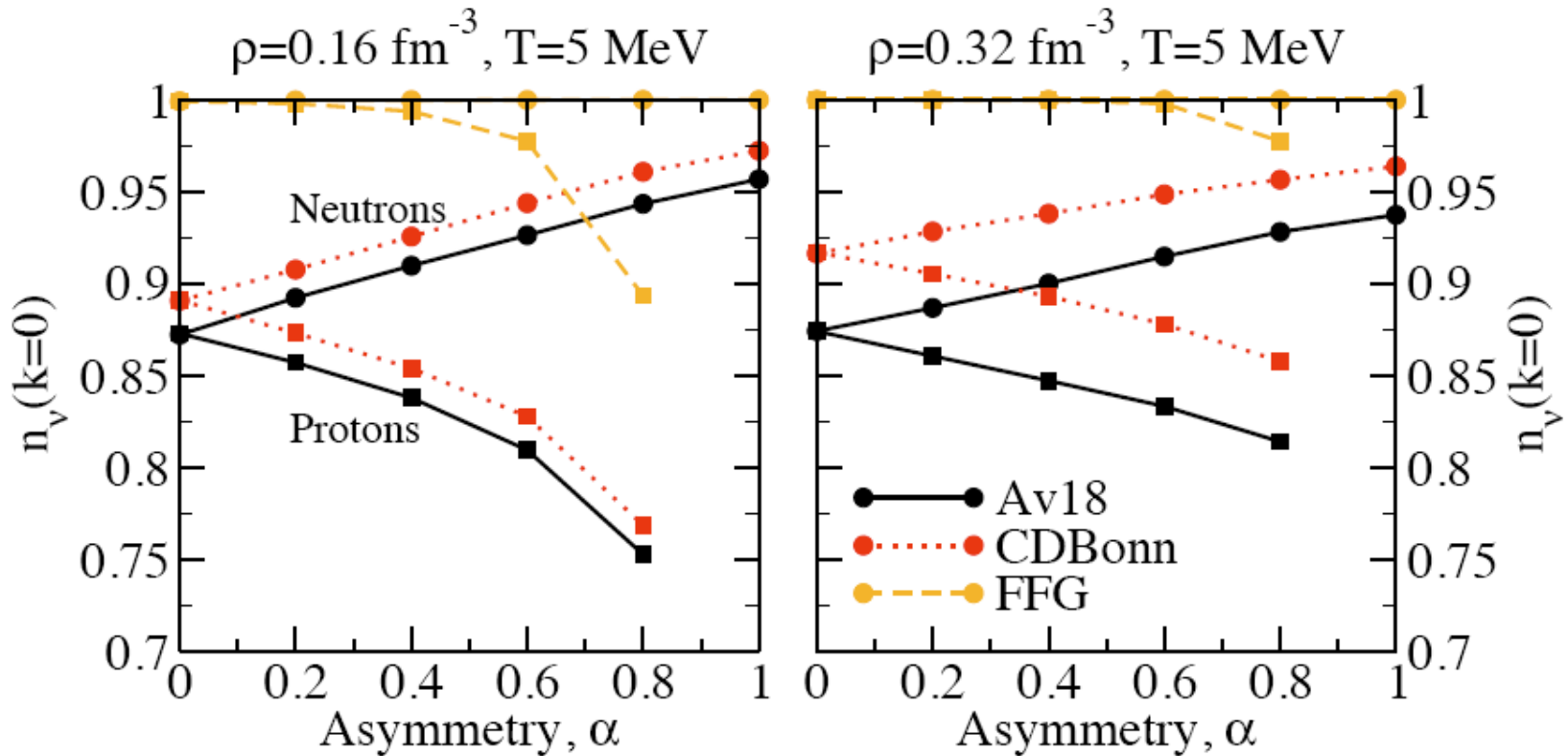


Self-energy =
complex potential in
nuclear matter



Dyson equation =>
Schrödinger equation
for dressed nucleons

Guidance from ab initio: Depletion as a function of asymmetry in matter treating short-range and tensor correlations



A. Rios, A. Polls, and W. H. Dickhoff
 Depletion of the nuclear Fermi sea.
[Phys. Rev. C79, 064308 \(2009\).](#)

Neutron skins and high momenta

Guidance from ab initio: depletion as a function of asymmetry

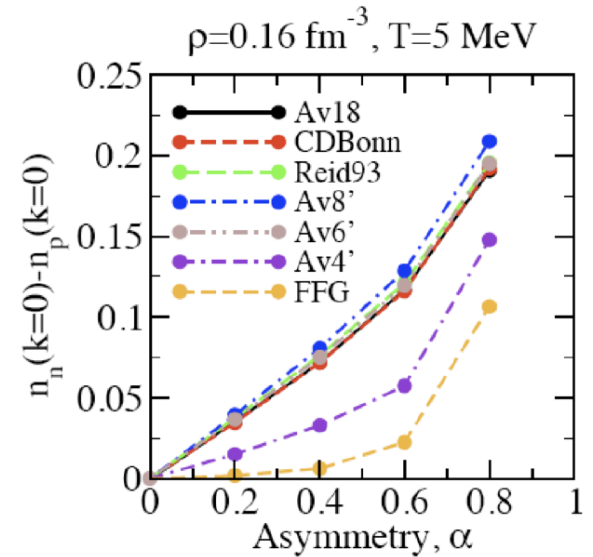
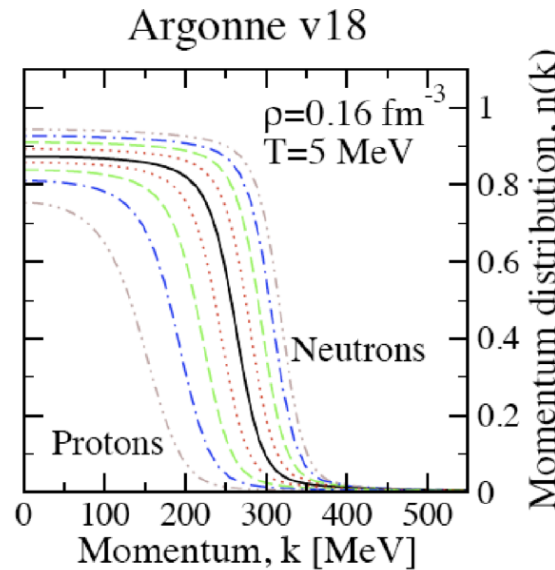
- Asymmetry dependence

SCGF:
self-consistent
Green's functions
for SRC and tensor effects

$$\alpha = \frac{N - Z}{N + Z}$$

- $\alpha=0.0$
- - - $\alpha=0.2$
- - - $\alpha=0.4$
- - - $\alpha=0.6$
- - - $\alpha=0.8$

A. Rios, A. Polls, and W. H. Dickhoff
Phys. Rev. C89, 044303 (2014)
Phys. Rev. C79, 064308 (2009)



- Full treatment of short-range and tensor correlations
- Incorporates/represents np dominance in matter \leftrightarrow influence of tensor force
- So more correlations for minority species
- EOS available as a function of T and asymmetry (and several $V_{NN} + V_{NNN}$)

Neutron skins and high momenta

Finite Nuclei

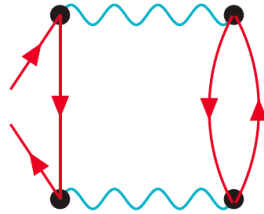
Such self-consistent calculations involving in-medium propagation are NOT available

Two effects associated with short-range correlations as in matter

- Depletion of the Fermi sea mean-field orbits
- Admixture of high-momentum components
to replace depleted strength

Location of high-momentum components simple argument

high momenta



require specific intermediate states

External line \mathbf{k} (large).

Intermediate holes $< k_F$, say total momentum ~ 0 .

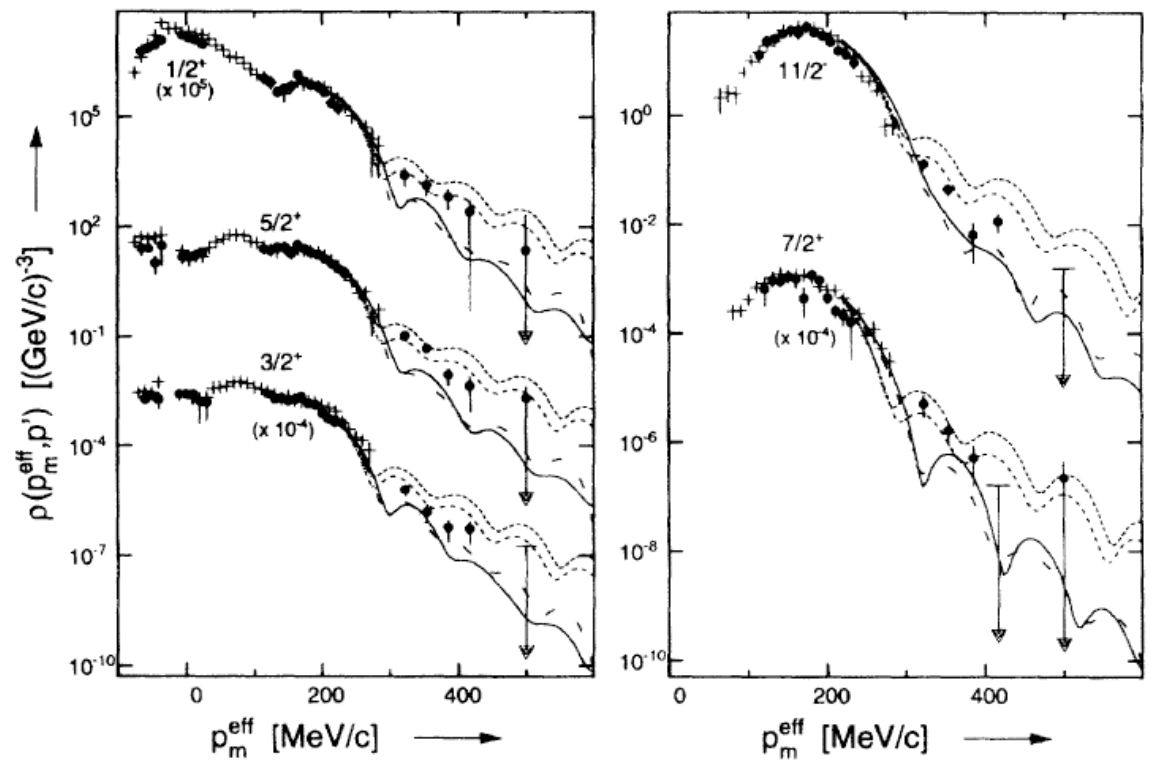
Momentum conservation: intermediate particle $-\mathbf{k}$

\Rightarrow Energy intermediate state $\sim \langle \varepsilon_{2h} \rangle - \varepsilon(\mathbf{k})$

\Rightarrow the higher k the more negative the location of its strength

\Rightarrow no high-momentum components near ε_F

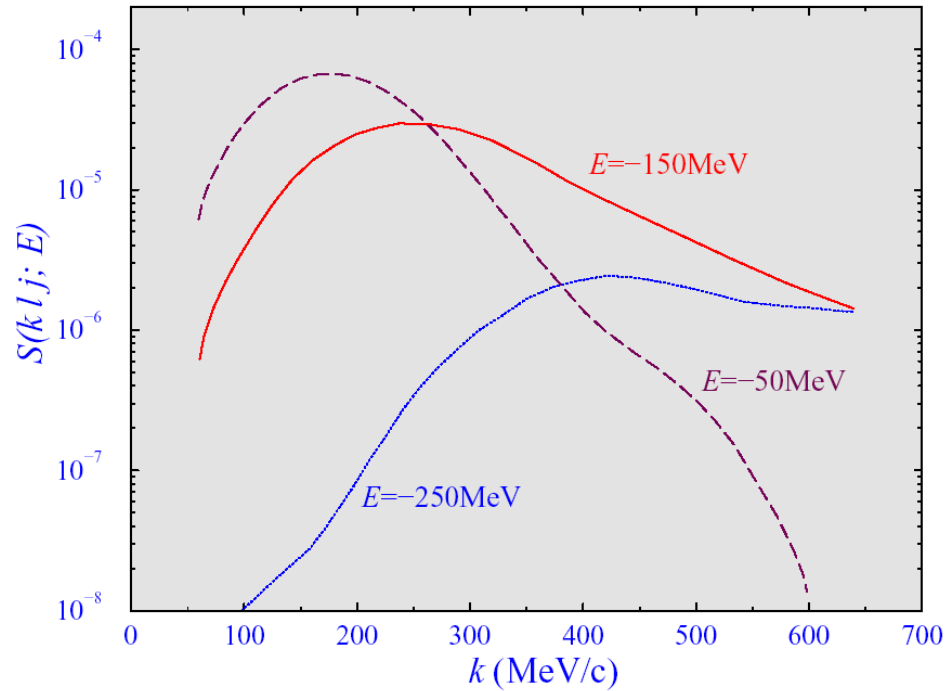
High-momenta near ϵ_F ?



I. Bobeldijk et al., Phys. Rev. Lett. 73, 2684 (1994) (e, e'p) \rightarrow NO!

Neutron skins and high momenta

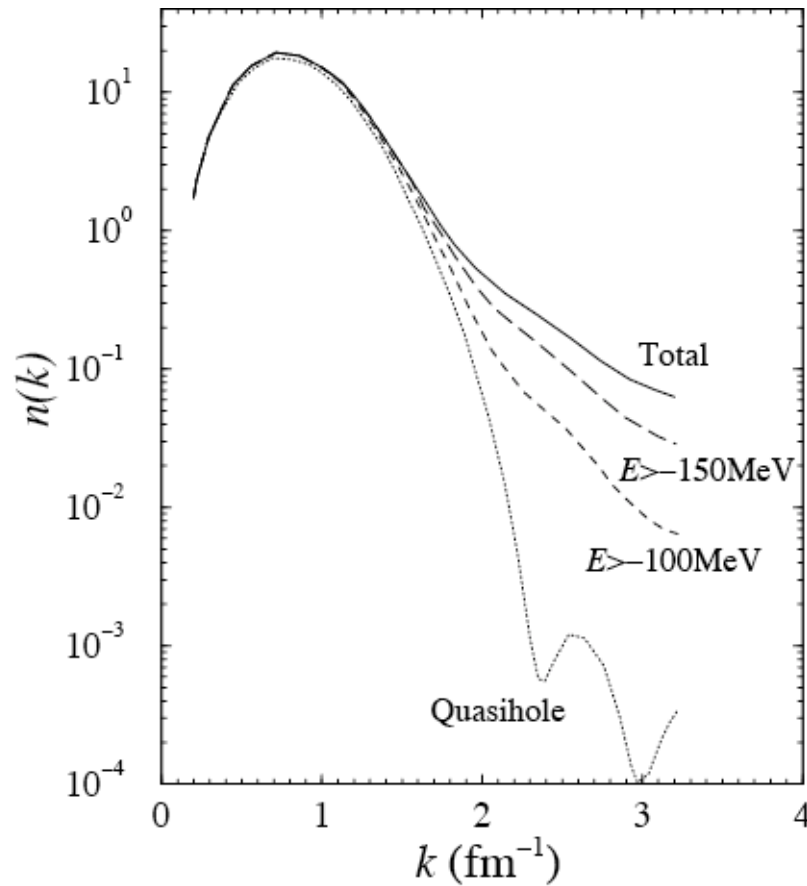
Prediction of high-momentum components



$p_{1/2}$ spectral function at fixed energies in ^{16}O

Phys. Rev. C49, R17 (1994)

Momentum distribution ^{16}O



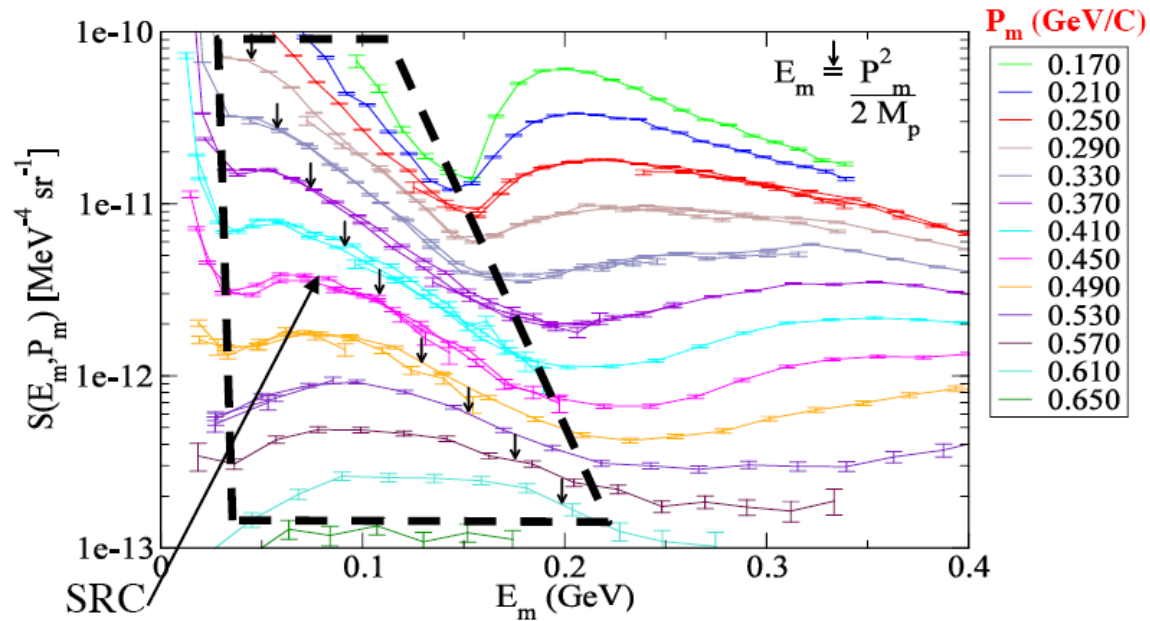
Confirms expectation:

High momentum nucleons
can be found at large
negative energies

Neutron skins and high momenta

What are the rest of the protons doing?

Jlab E97-006 Phys. Rev. Lett. 93, 182501 (2004) D. Rohe et al.



^{12}C

- Location of high-momentum components
- Integrated strength agrees with theoretical prediction Phys. Rev. C49, R17 (1994)
 - ⇒ 0.6 protons for ^{12}C

Neutron skins and high momenta

Green's functions \leftrightarrow nucleon self-energy \leftrightarrow DOM

- 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:

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

Calculated at the Fermi energy

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

$$\varepsilon_F = \frac{1}{2} \{ (E_0^{A+1} - E_0^A) + (E_0^A - E_0^{A-1}) \}$$

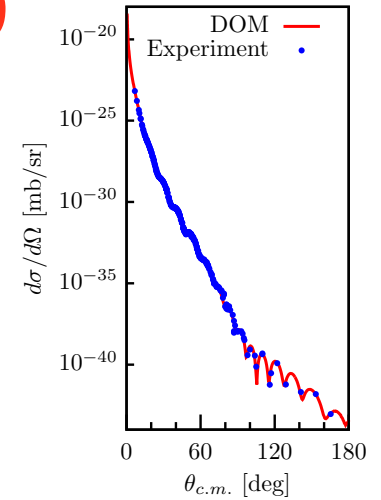
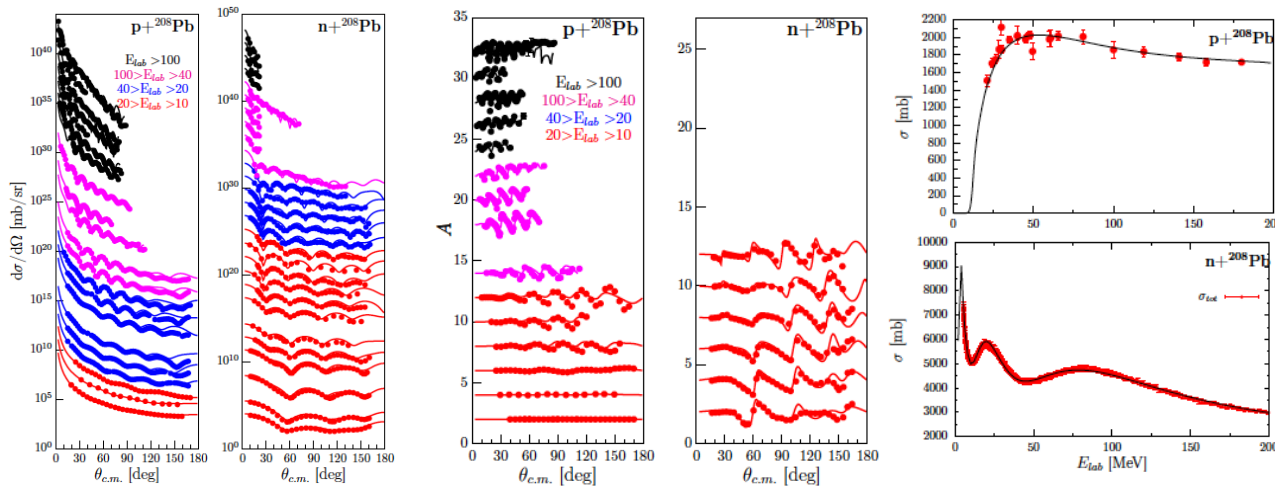
Subtract

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

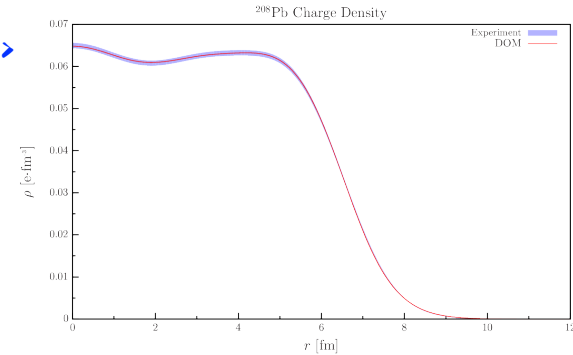
$$- \frac{1}{\pi} (\varepsilon_F - E) \mathcal{P} \int_{E_T^+}^{\infty} dE' \frac{\text{Im } \Sigma(E')}{(E - E')(\varepsilon_F - E')} + \frac{1}{\pi} (\varepsilon_F - E) \mathcal{P} \int_{-\infty}^{E_T^-} dE' \frac{\text{Im } \Sigma(E')}{(E - E')(\varepsilon_F - E')}$$

Dispersive Optical Model (St. Louis group)

- Mahaux & Sartor 1991
- Washington University group since 2006 now fully nonlocal
- ^{208}Pb



$E < 0 \rightarrow$



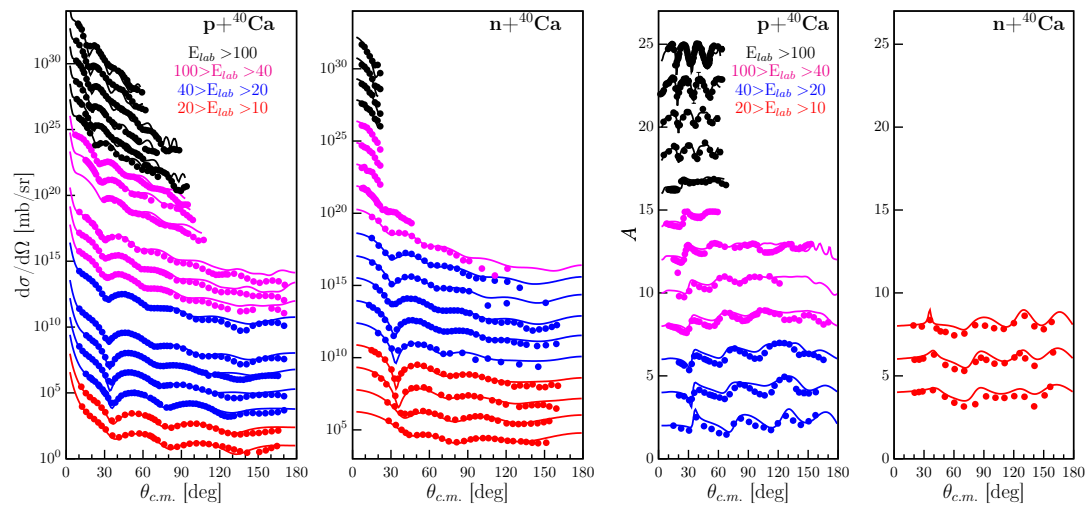
Indirectly:

- Predict neutron distribution \rightarrow skin

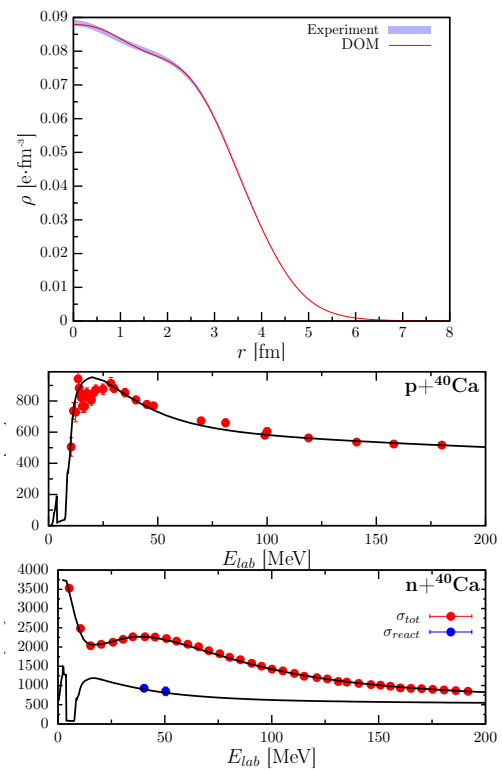
M. C. Atkinson, M. H. Mahzoon, M. A. Keim, B. A. Bordelon, C. D. Pruitt, R. J. Charity, and W. H. Dickhoff
 Phys. Rev. C 101, 044303 (2020), 1-15. [[arXiv:1911.09020](https://arxiv.org/abs/1911.09020)]

Neutron skins and high momenta

^{40}Ca



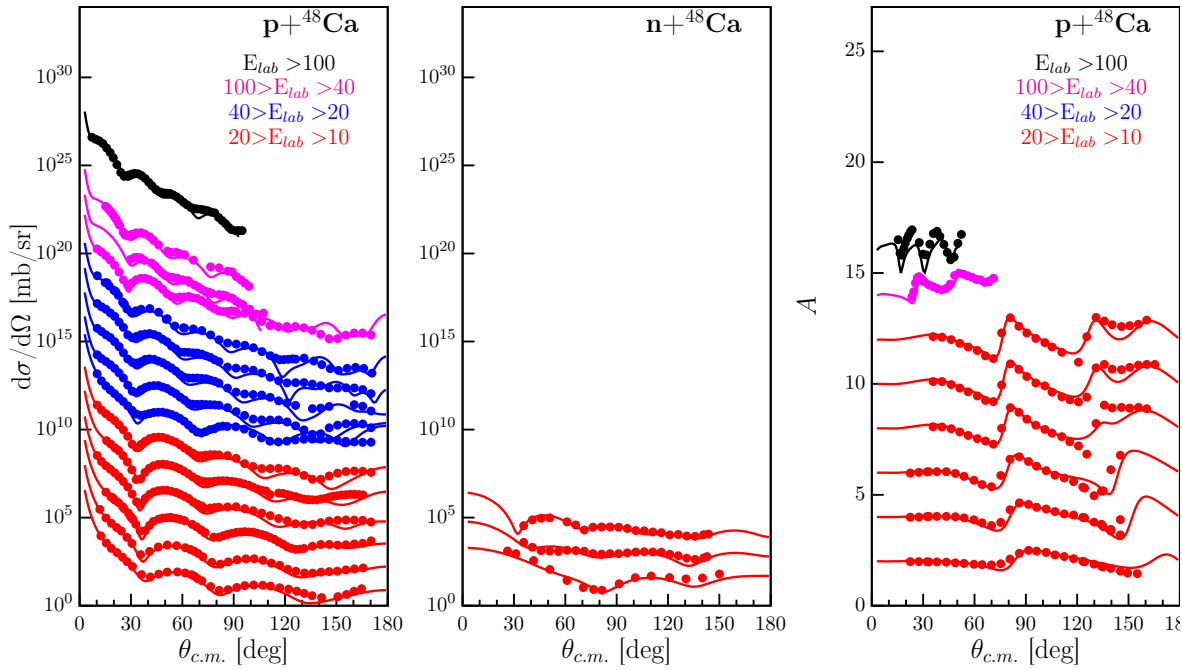
M.C. Atkinson *et al.*, PRC **98**, 044627 (2018)



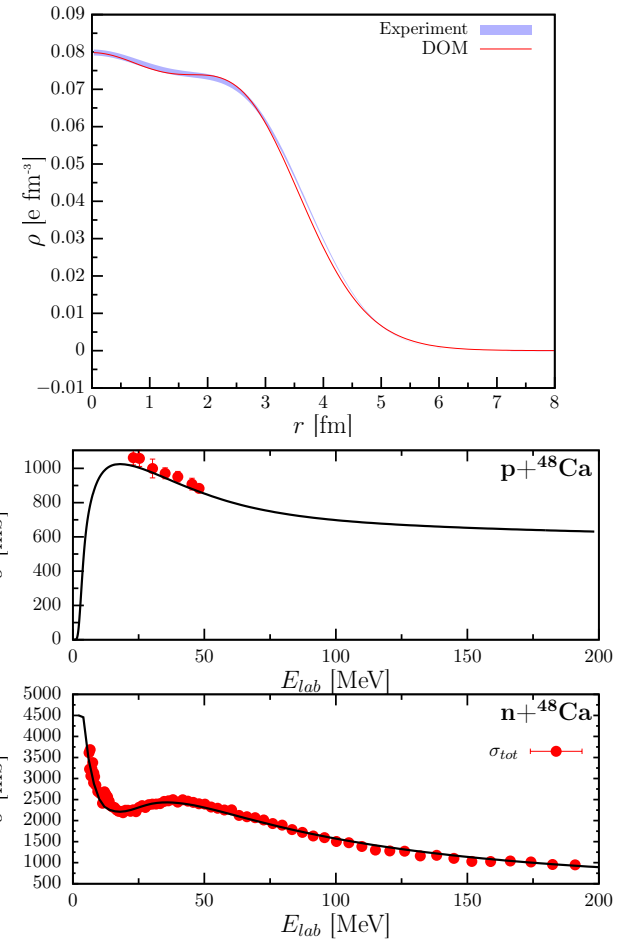
Neutron skins and high momenta

^{48}Ca

- Allows prediction of neutron properties



M. C. Atkinson and W. H. Dickhoff
[Phys. Lett. B 798, 135027 \(2019\), 1-6.](#)



Neutron skins and high momenta

Another look at $(e,e'p)$ data and spectroscopic factors

- Collaboration with Louk Lapikás and Henk Blok from Nikhef
- Data published at $E_p = 100$ MeV Kramer thesis Nikhef for $^{40}\text{Ca}(e,e'p)^{39}\text{K}$ Phys. Lett. B227, 199 (1989)
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) & sufficient energy for the knocked out proton
 - Overlap function:
 - WS with radius adjusted to shape of cross section
 - Depth adjusted to separation energy
 - Distorted proton wave from standard local non-dispersive "global optical potential"
 - Fit normalization of overlap function to data \rightarrow spectroscopic factor

Why go back there? \rightarrow transfer information to (p,pN) in inverse kinematics

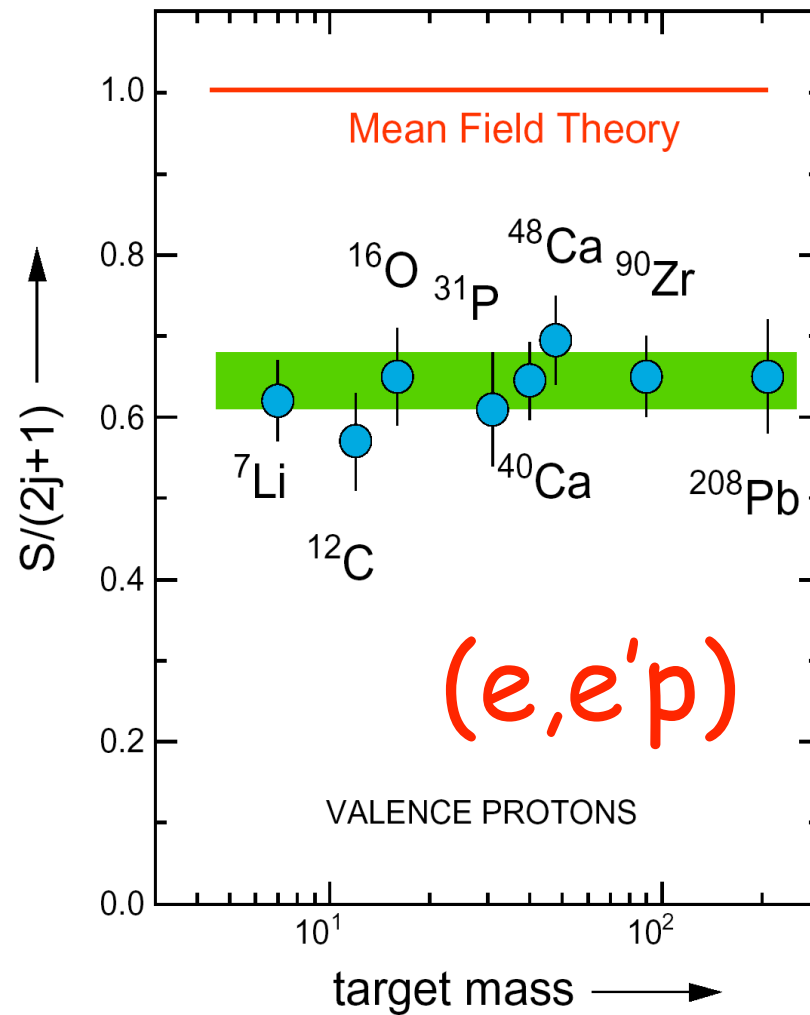
Removal probability for valence protons from NIKHEF data

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

$S \approx 0.65$ for valence protons
Reduction \Rightarrow both SRC and LRC

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

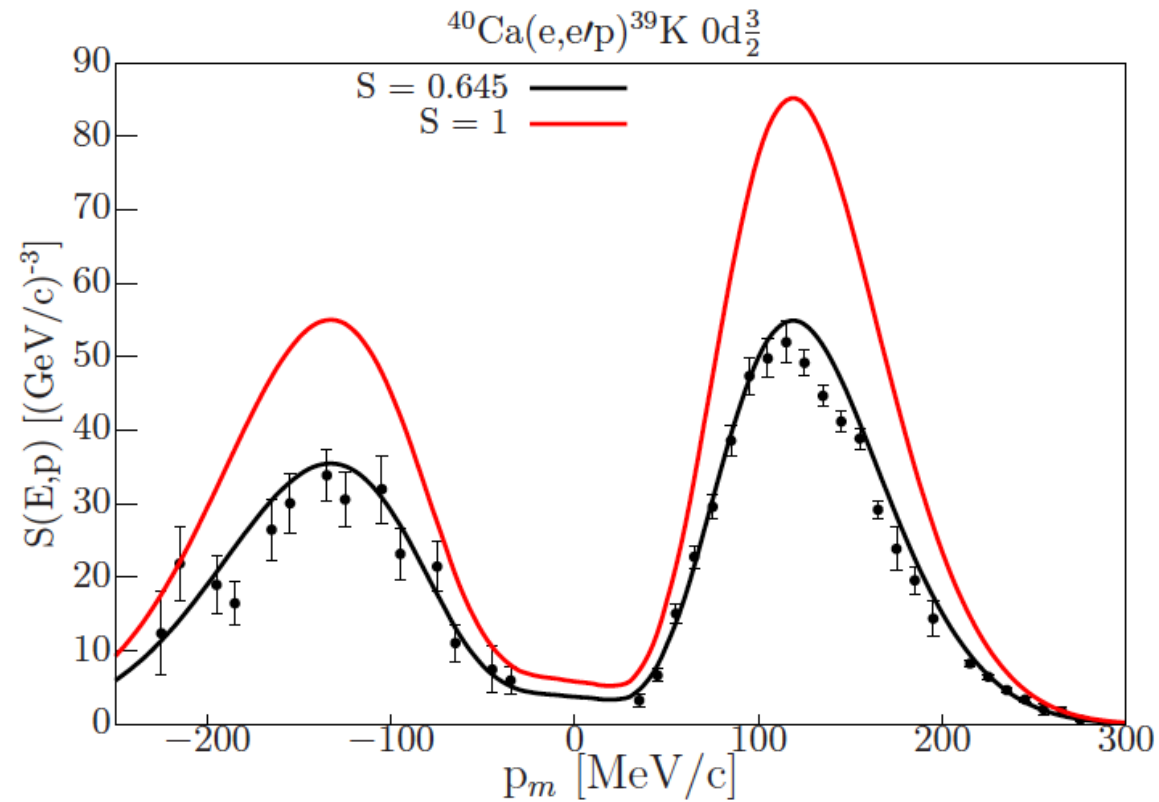
Why: details of the interior
scattering wave function
uncertain since non-locality is
not constrained (so far.....)
but now available for ^{40}Ca etc!



Neutron skins and high momenta

NIKHEF analysis PLB227,199(1989)

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



Two papers ^{40}Ca and ^{48}Ca

Validity of the distorted-wave impulse-approximation description of $^{40}\text{Ca}(e, e'p)$ data using only ingredients from a nonlocal dispersive optical model

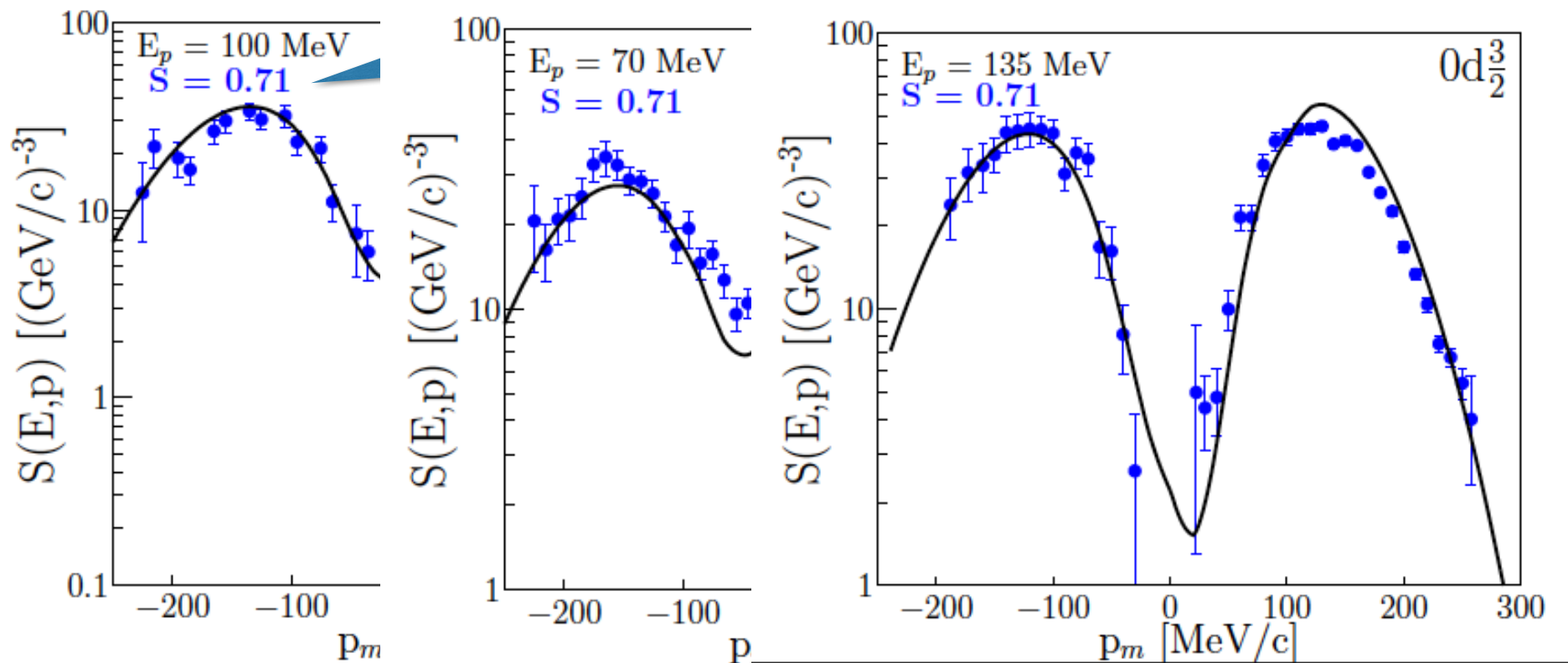
M. C. Atkinson¹, H.P. Blok^{2,3}, L. Lapikás², R. J. Charity⁴, and W. H. Dickhoff¹

Mack Atkinson et al., Phys. Rev. C98, 044627 (2018)

M. C. Atkinson and W. H. Dickhoff, Phys. Lett. B 798, 135027 (2019)

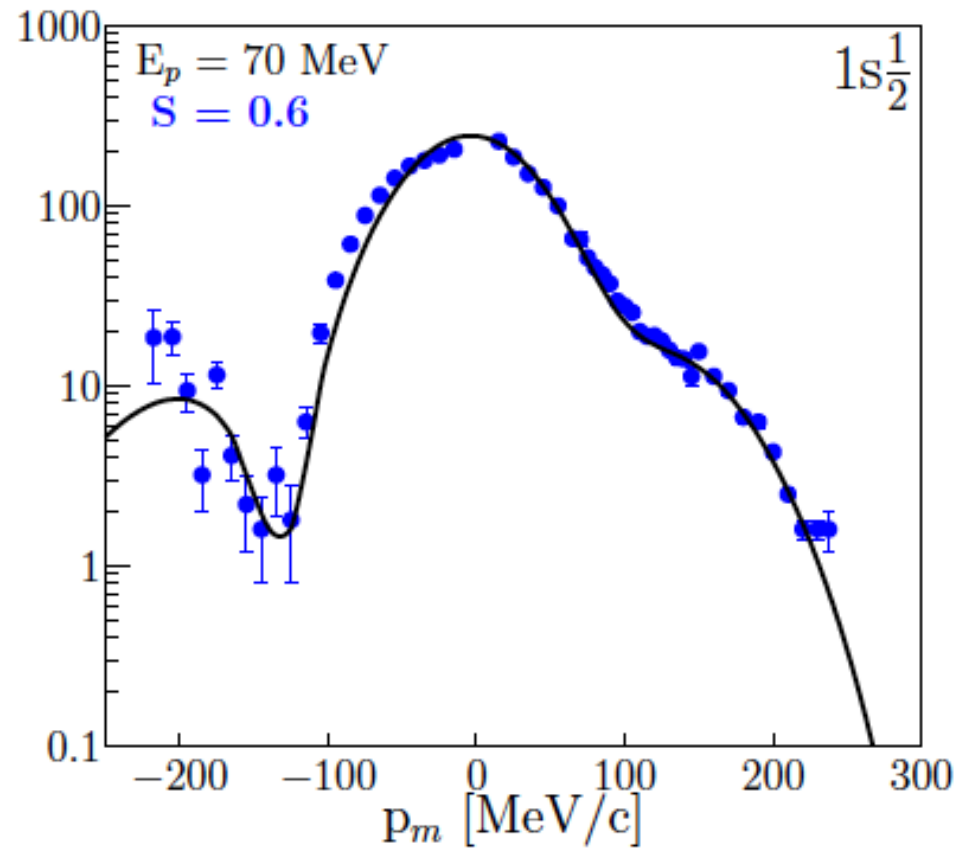
NIKHEF data PLB227,199(1989)

- NIKHEF: $S(d_{3/2})=0.65\pm 0.06$
- Only DOM ingredients



Includes NIKHEF data published for the first time

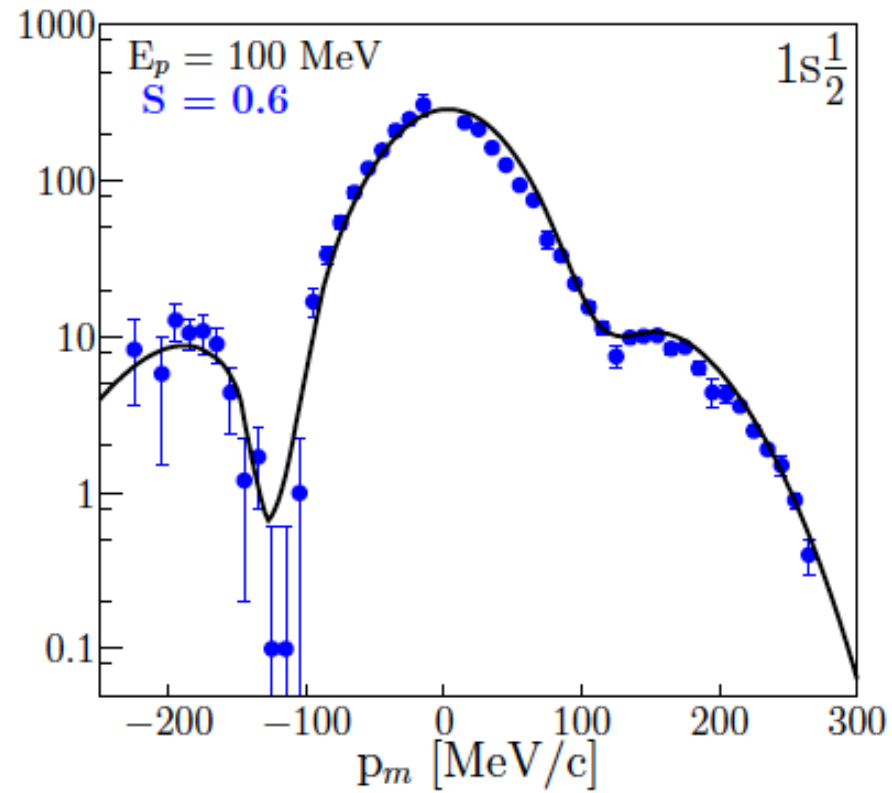
- Only DOM ingredients



Neutron skins and high momenta

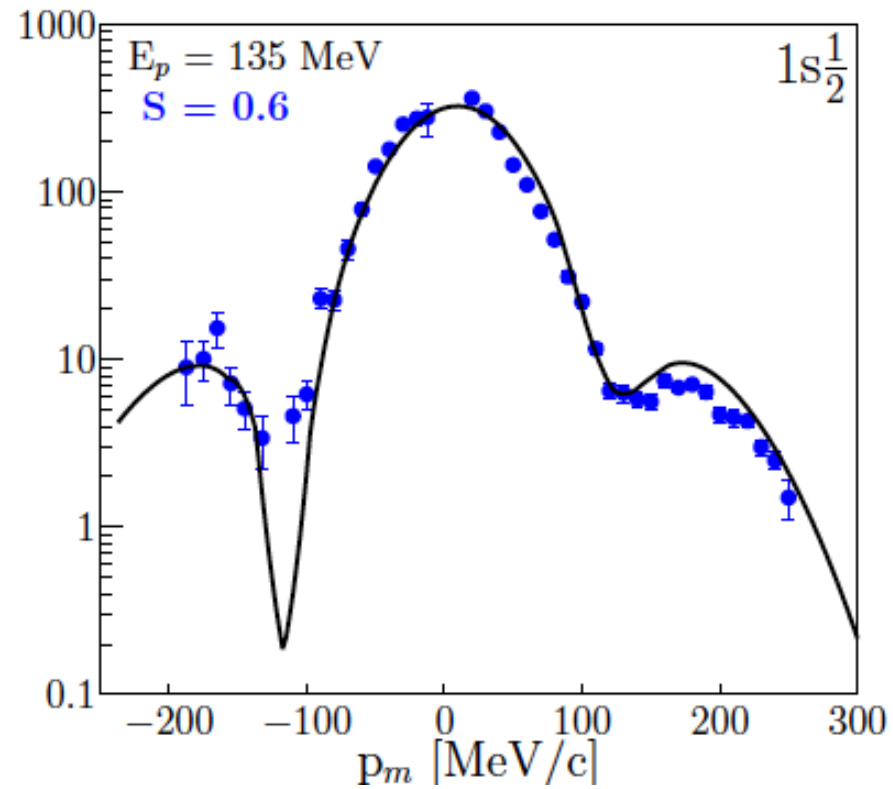
NIKHEF data PLB227,199(1989)

- NIKHEF: $S(s_{1/2})=0.51\pm 0.05$



NIKHEF data unpublished

- Only DOM ingredients



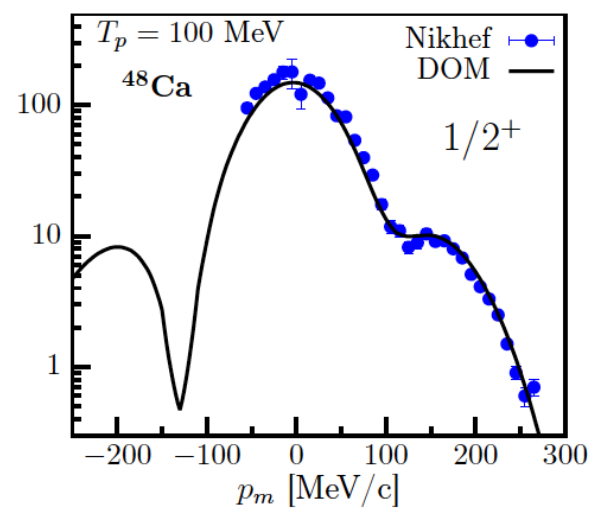
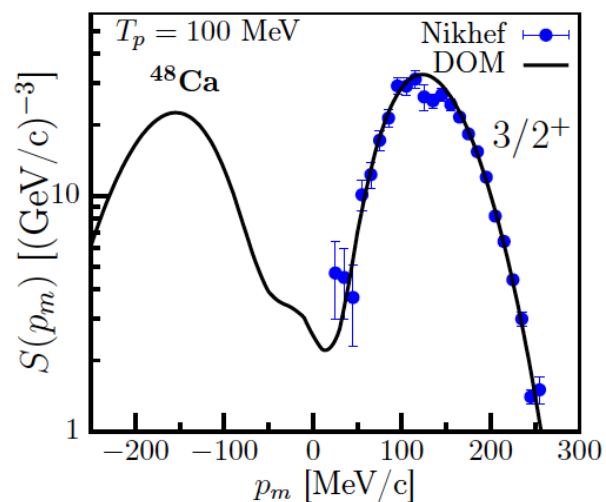
Neutron skins and high momenta

Message

- Nonlocal dispersive potentials yield consistent input but are constrained by **other** experimental data
- Constraints from these other data generate spectroscopic factor $\rightarrow S(d_{3/2})=0.71$ in ^{40}Ca for ground state transition
- Using experimental $s_{1/2}$ strength distribution: 2.5 MeV state $\rightarrow S(s_{1/2})=0.60$
- NIKHEF 0.65 ± 0.06 and 0.51 ± 0.05 , respectively (local)
- DWIA validated for $(e,e'p)$ including the choice of kinematics and energy domain as implemented at Nikhef

$^{48}\text{Ca}(e,e'p)$

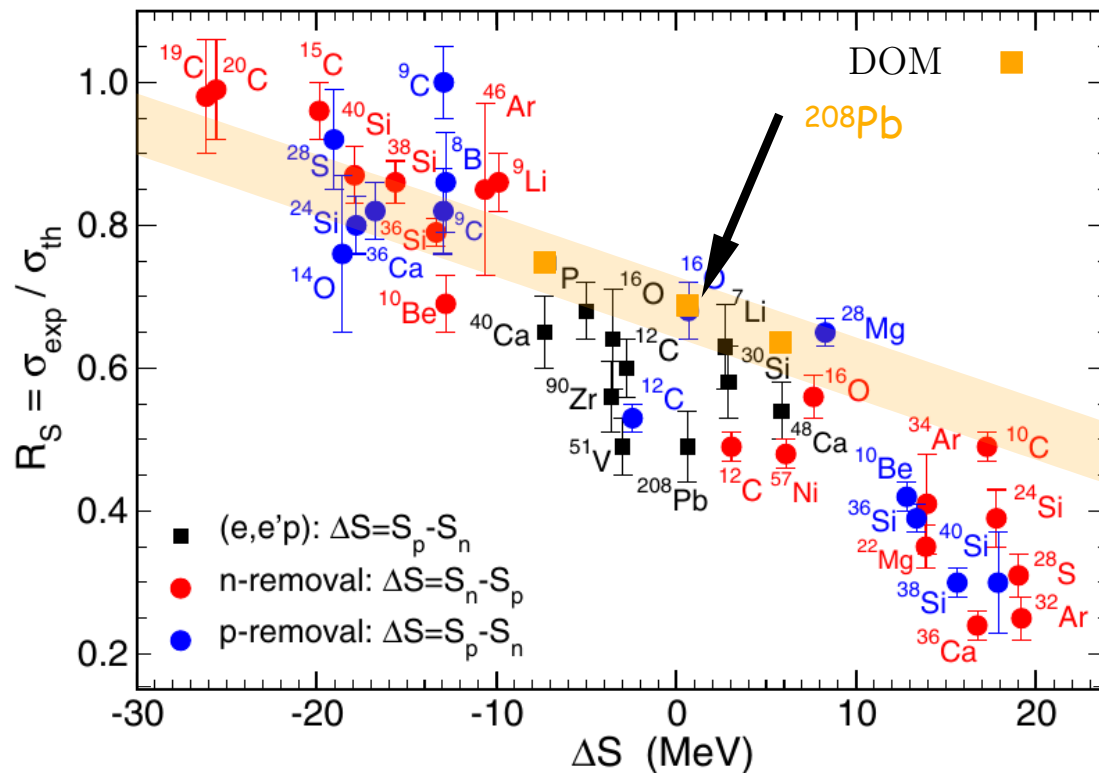
- $d_{3/2}$ spectroscopic factor reduced to 0.60 from 0.71 in ^{40}Ca
- after local energy correction \rightarrow from 0.60 to $S(d_{3/2})=0.58$
- and from 0.64 $\rightarrow S(s_{1/2}) = 0.55$



- No further adjustments! All ingredients provided by DOM
- **Both structure and reaction properties allowed to change when 8 n added**

Compare with Gade plot

Very near the Fermi energy in ^{40}Ca and ^{48}Ca from (e,e'p) \rightarrow error band

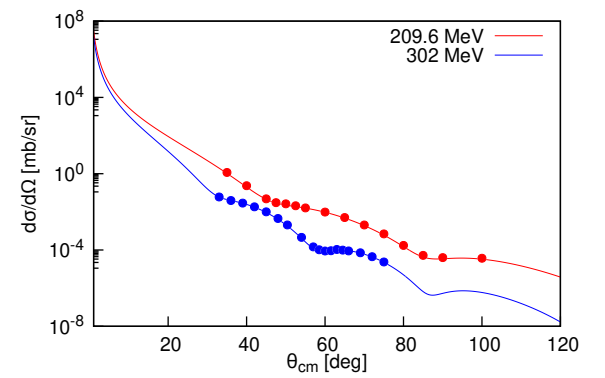
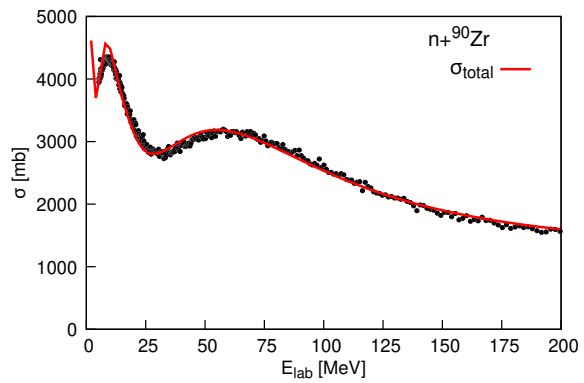
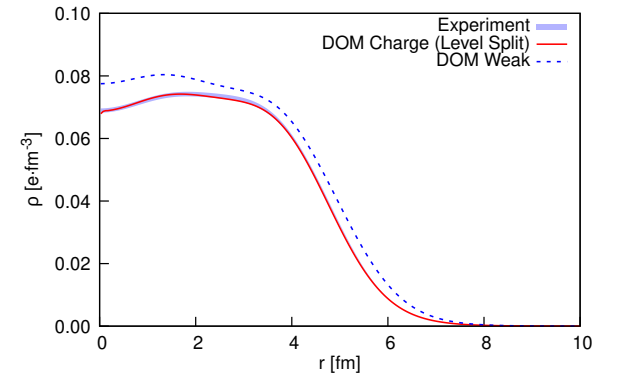
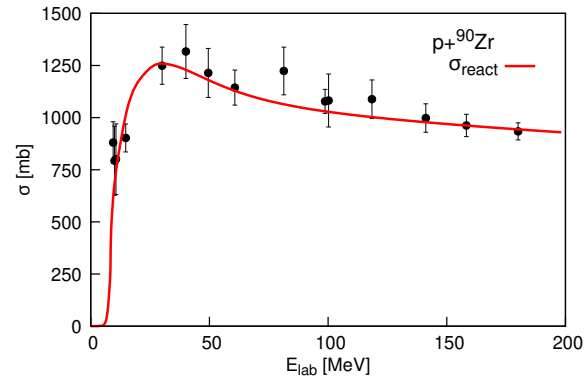
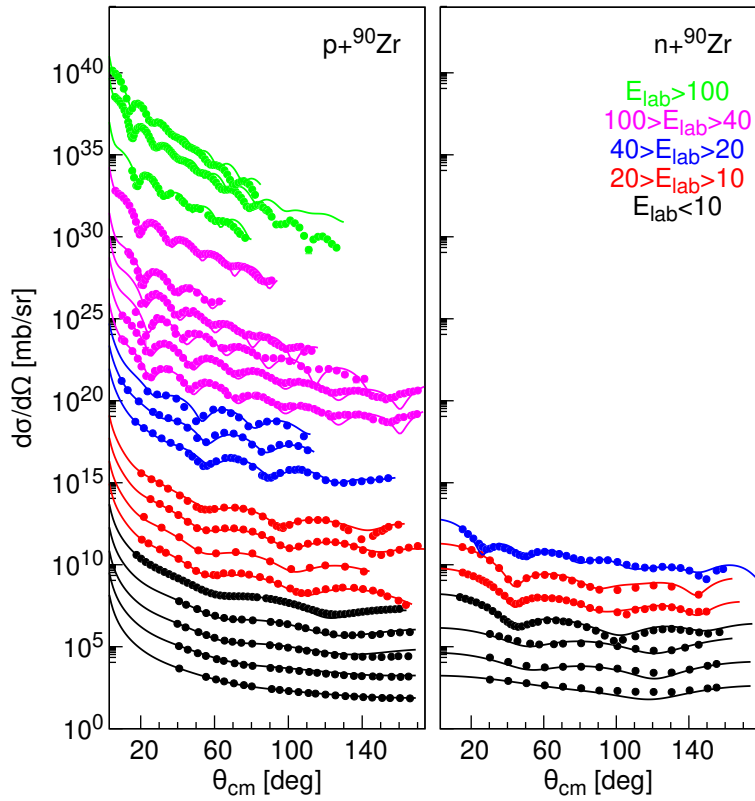


Quenching sp strength review: Aumann et al, Prog. Part. Nucl. Phys. 118, 103847 (2021)

New DOM application: ^{90}Zr

- Semi-magic
- Excellent $(e,e'p)$ data for valence orbits
- Establish DOM result for neutron skin

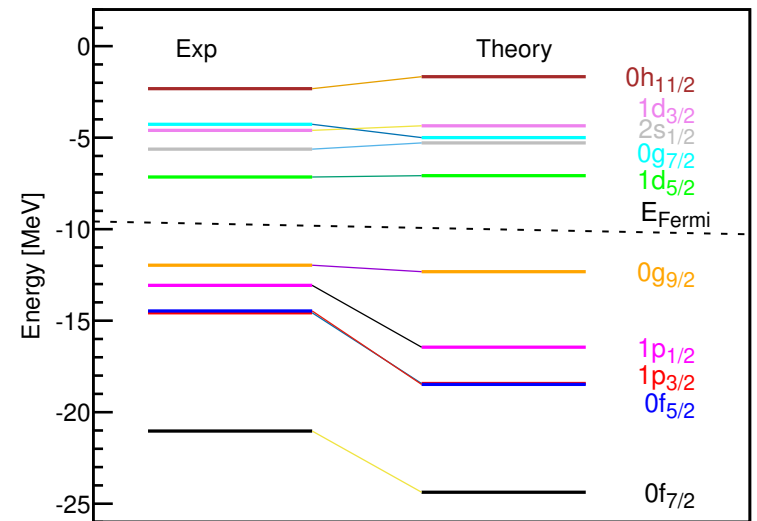
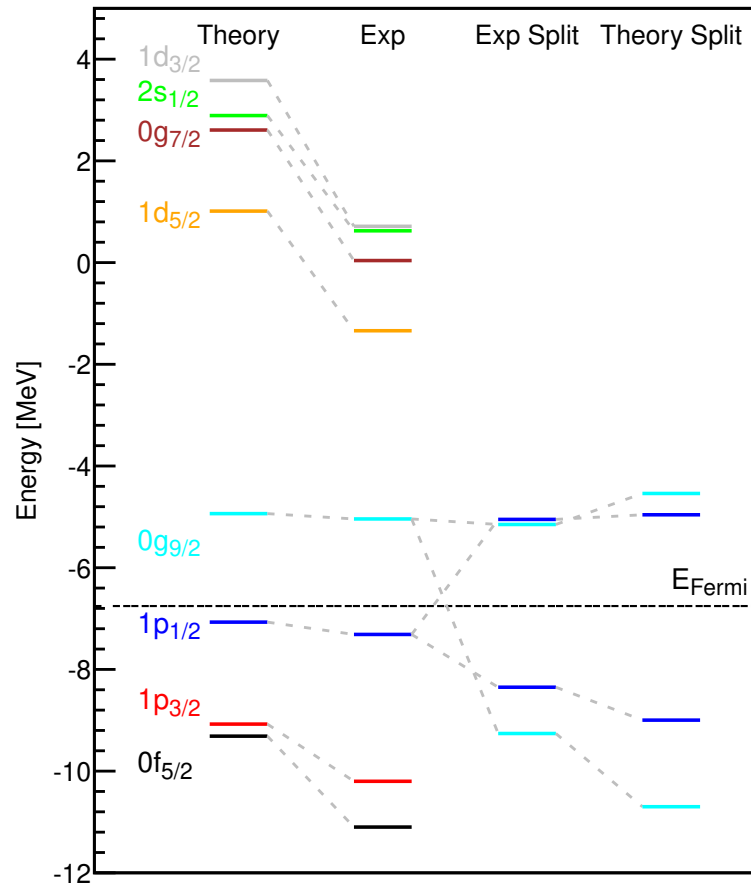
^{90}Zr



Ragib Ramon, M.C. Atkinson, WD

Neutron skins and high momenta

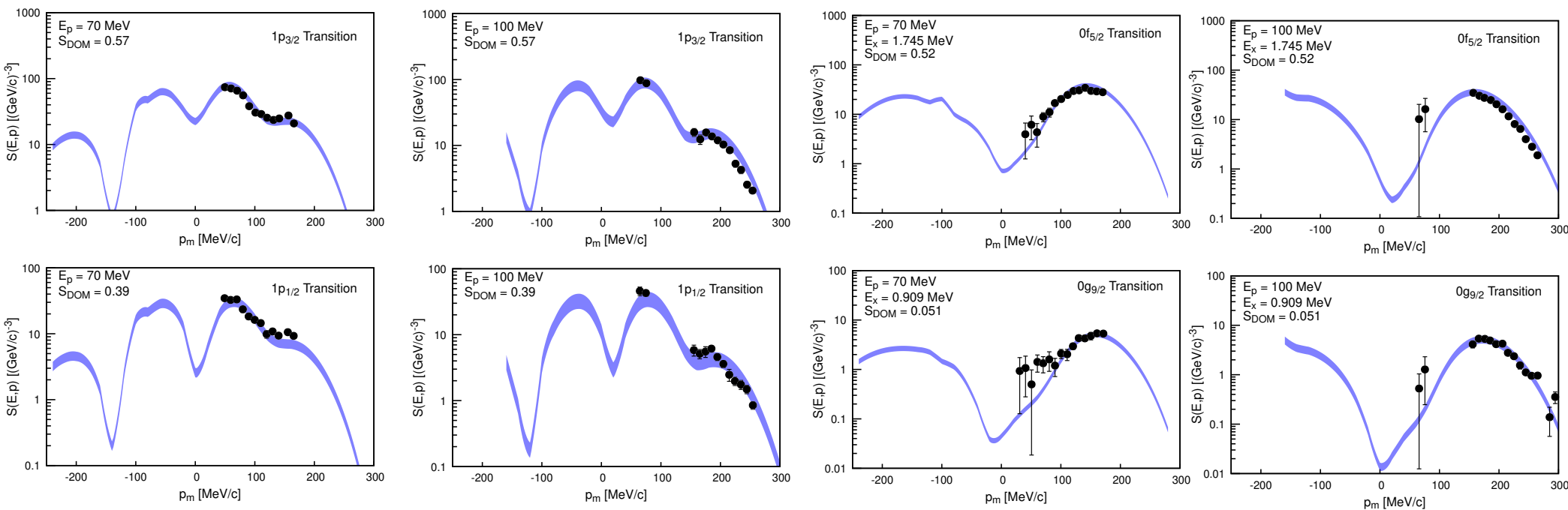
Levels



Neutron skins and high momenta

^{90}Zr and $(e,e'p)$ data NIKHEF 1988

- Proton open shell \rightarrow valence sp strength split above and below Fermi energy



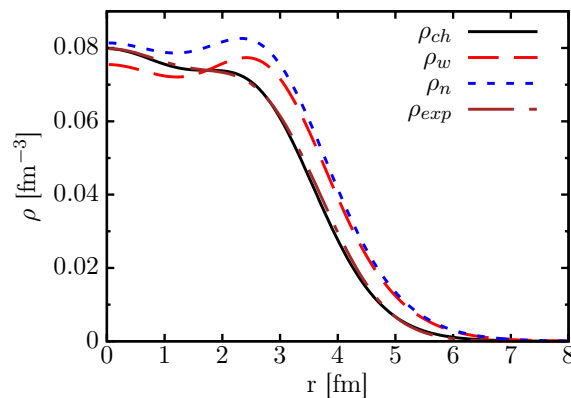
Neutron skins and high momenta

Neutron skins

- Important observable
- Link with neutron stars
- Hard to measure cleanly → only PREX and CREX

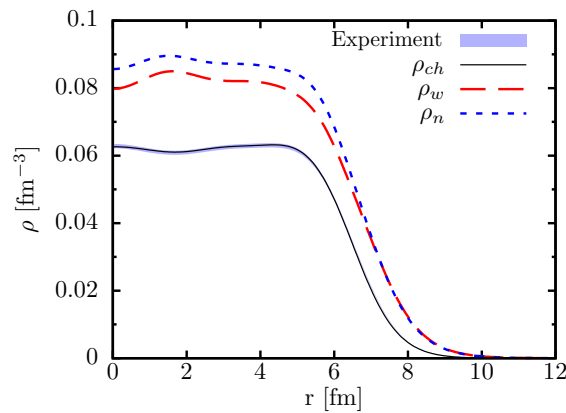
Neutron skins in ^{48}Ca and ^{208}Pb from DOM predictions

- DOM 2017



M. H. Mahzoon, M. C. Atkinson, R. J. Charity, and W. H. Dickhoff
[Phys. Rev. Lett. **119**, 222503 \(2017\), 1-5.](#)

- DOM 2020

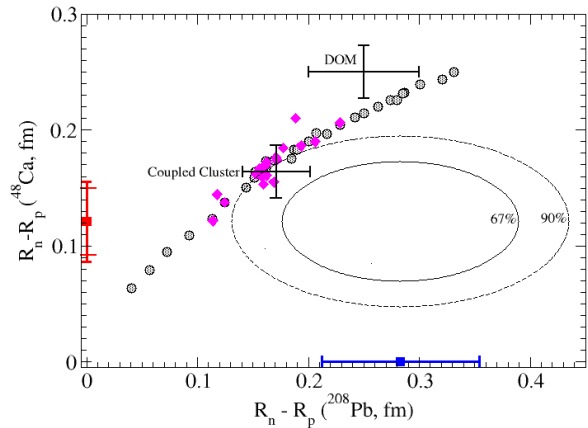


M. C. Atkinson, M. H. Mahzoon, M. A. Keim, B. A. Bordelon, C. D. Pruitt, R. J. Charity, and W. H. Dickhoff
[Phys. Rev. C **101**, 044303 \(2020\), 1-15.](#)

Neutron skins and neutron stars

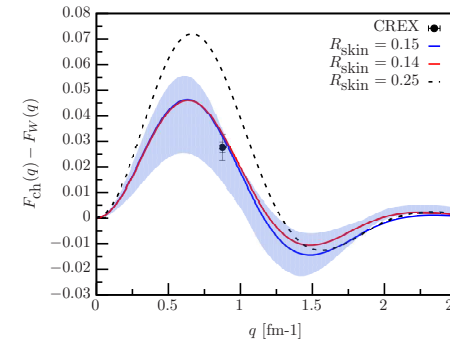
Precision Determination of the Neutral Weak Form Factor of ^{48}Ca (The CREX Collaboration)

D. Adhikari et al. (CREX Collaboration), Phys. Rev. Lett. 129 (2022). 042501 (2022)

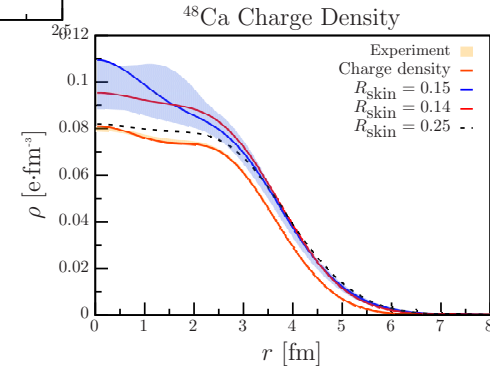


Our recent analysis \rightarrow N. L. Calleya, M. C. Atkinson, and W. H. Dickhoff

Phys. Lett. B863 (2025), 139371, 1-6.

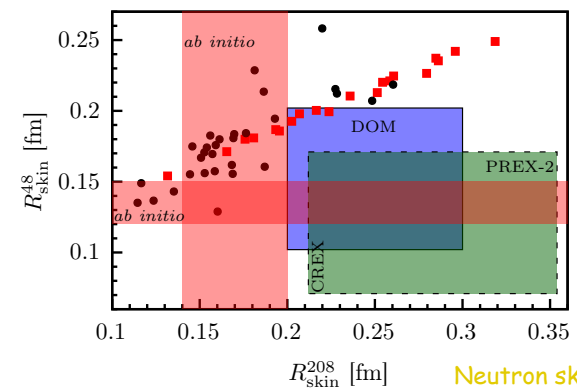


Success!



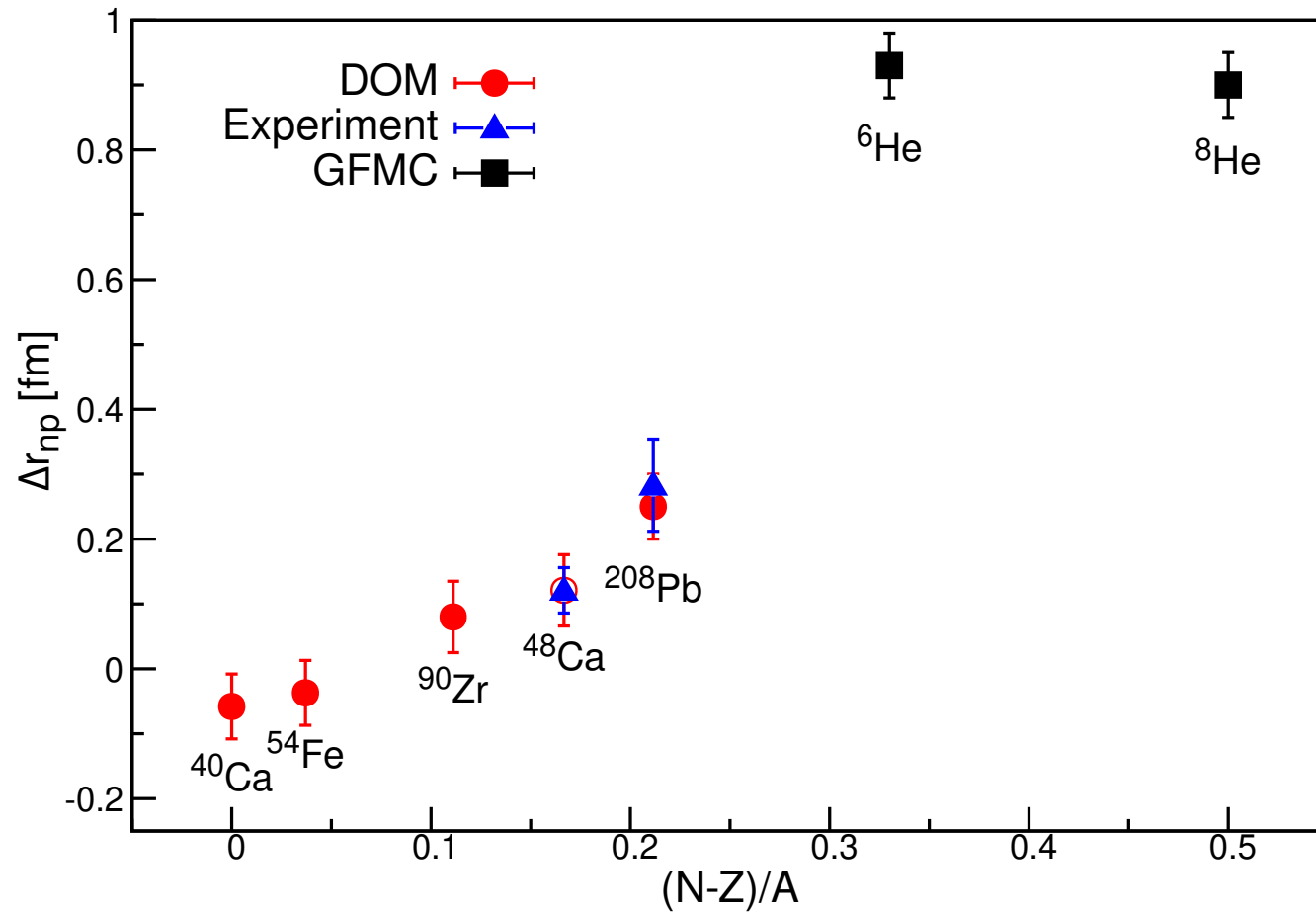
CREX surprise and puzzle from Jefferson Lab data \rightarrow
Neutron skin in nuclei and neutron star equation of state:
Why is the skin small in ^{48}Ca and large in ^{208}Pb ?

Using the dispersive optical model (DOM) our group can
explain the skin of both ^{48}Ca and ^{208}Pb .



Neutron skins and high momenta

Results including all DOM analyzed nuclei plus 2 GFMC results

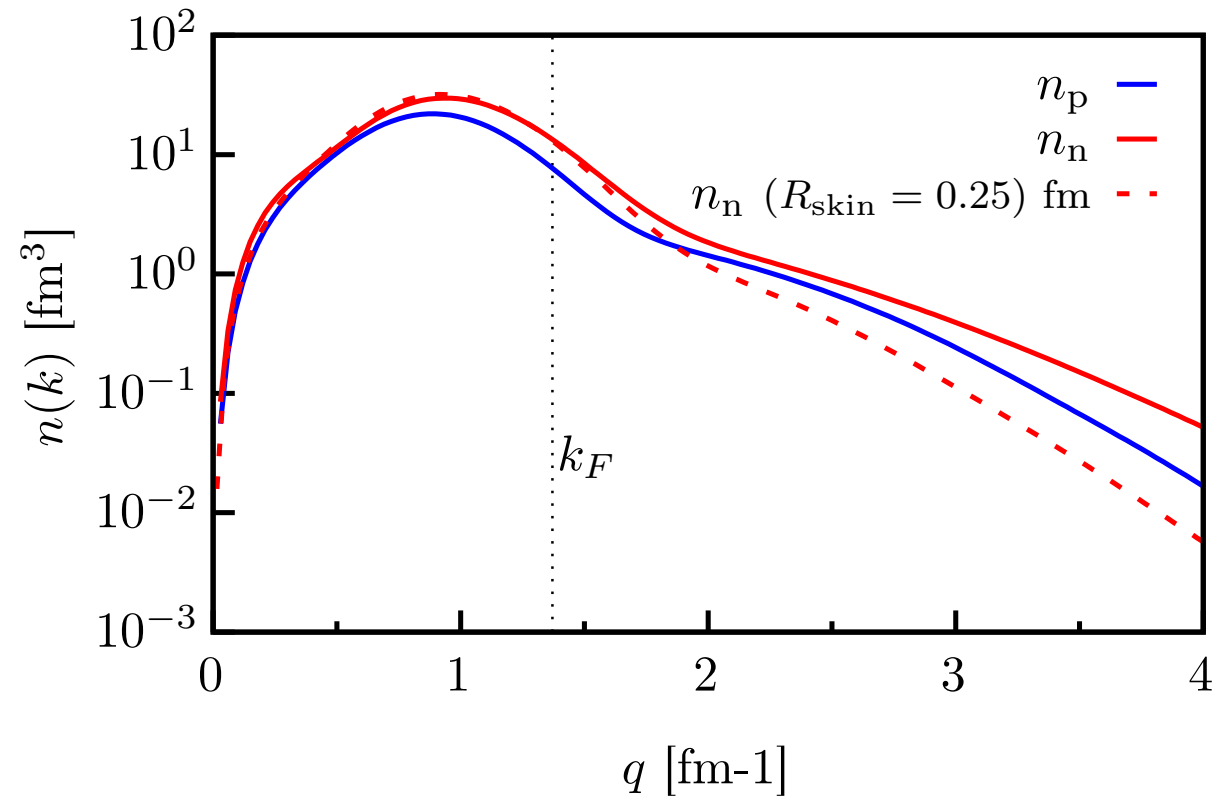


High momenta

- So far: DOM factorizes energy dependence and geometry
- → cannot properly describe high-momentum spectral functions

Problem with ^{48}Ca high momenta

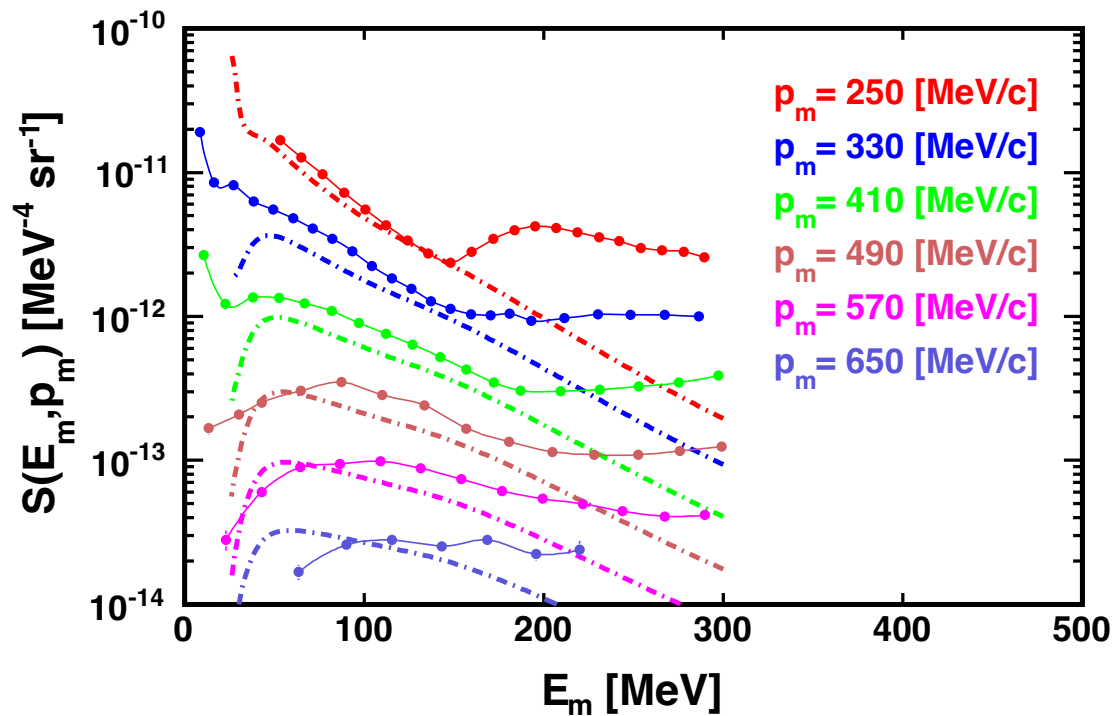
- Skin OK
- But neutrons with smaller radius generate more high momenta above protons



Jefferson Lab data

- Pion/isobar contributions cannot be described
- Rescattering contributes some cross section

C. Barbieri and L. Lapikás Phys. Rev. C 70, 054612 (2004)



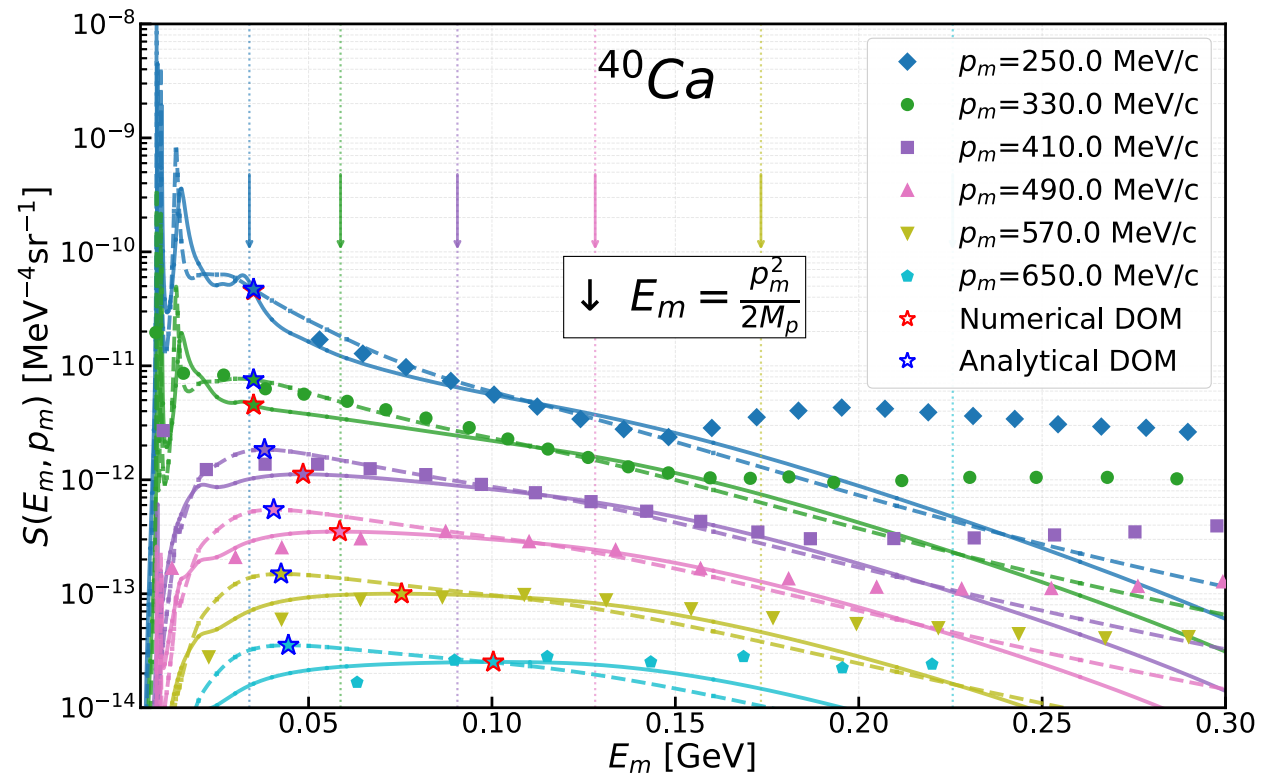
D. Rohe et al.

DOM: Phys. Rev. Lett. 112, 162503 (2014)

Neutron skins and high momenta

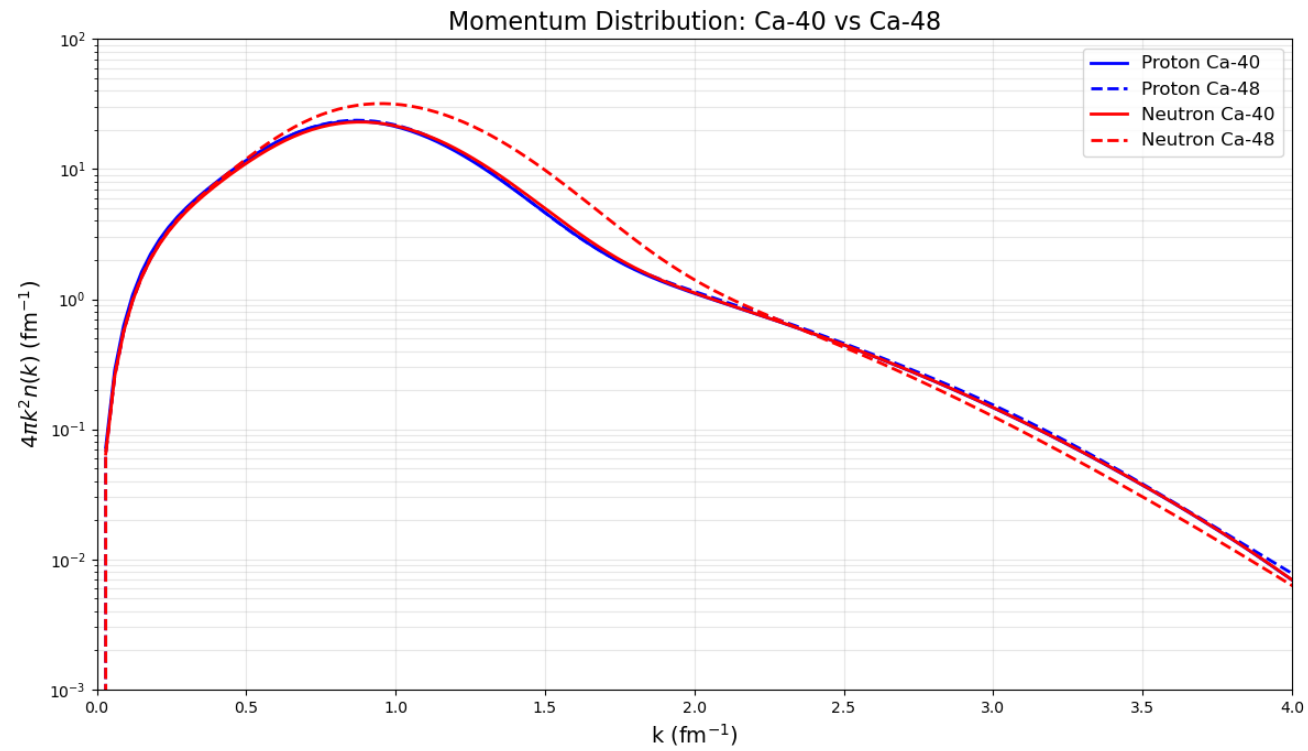
Absorption in smaller volume with increasing missing energy

- DOM extension: numerical dispersion relations



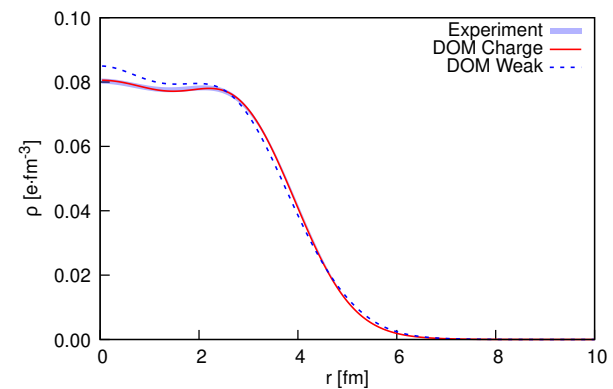
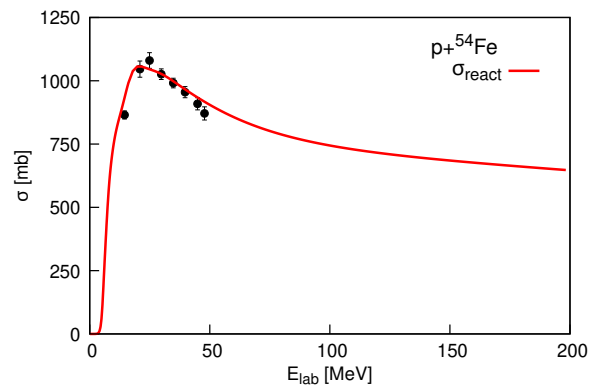
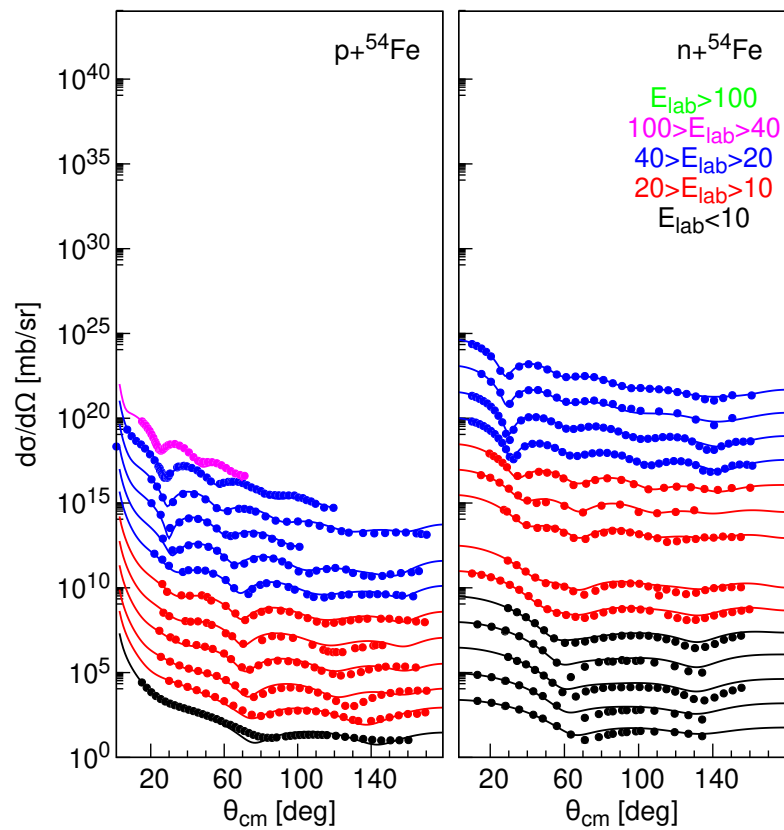
$n(k)$

- Makes more sense



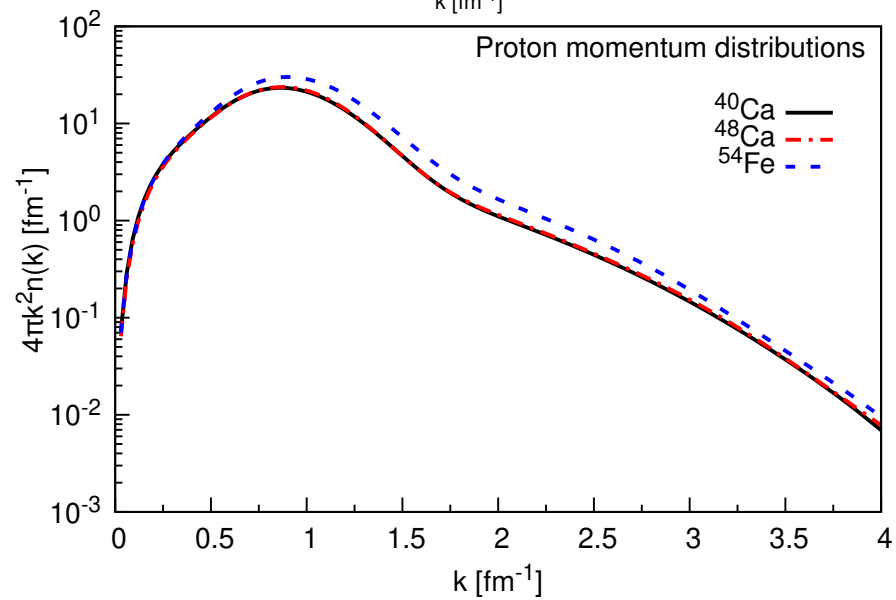
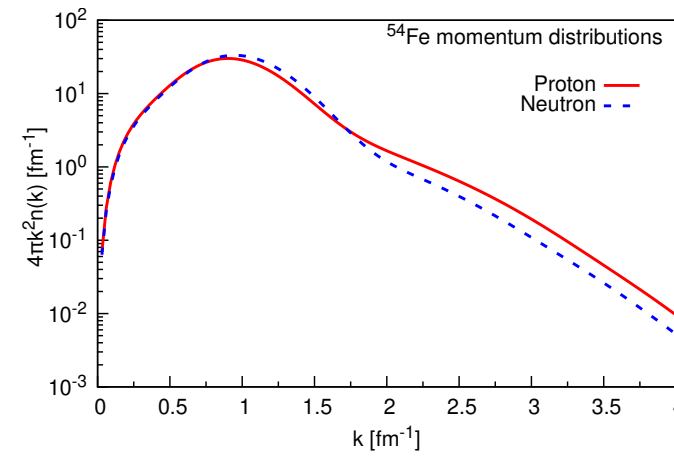
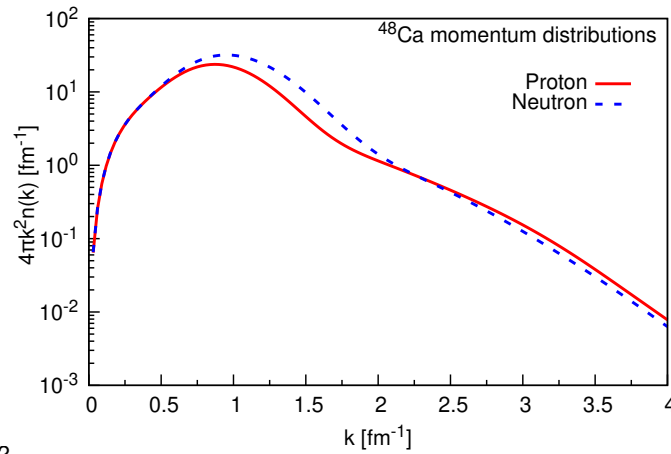
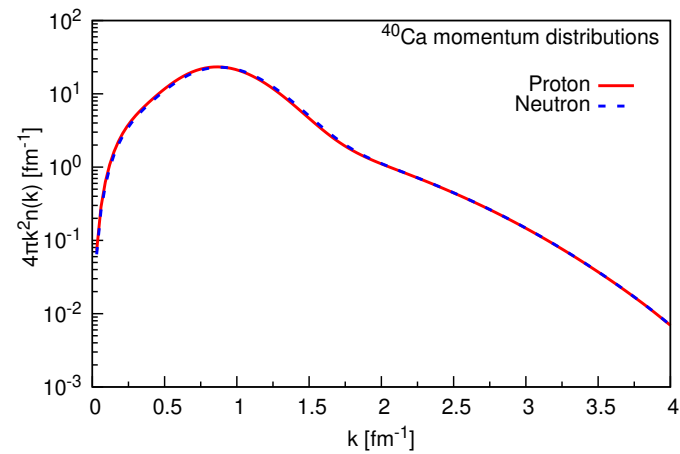
Neutron skins and high momenta

^{54}Fe



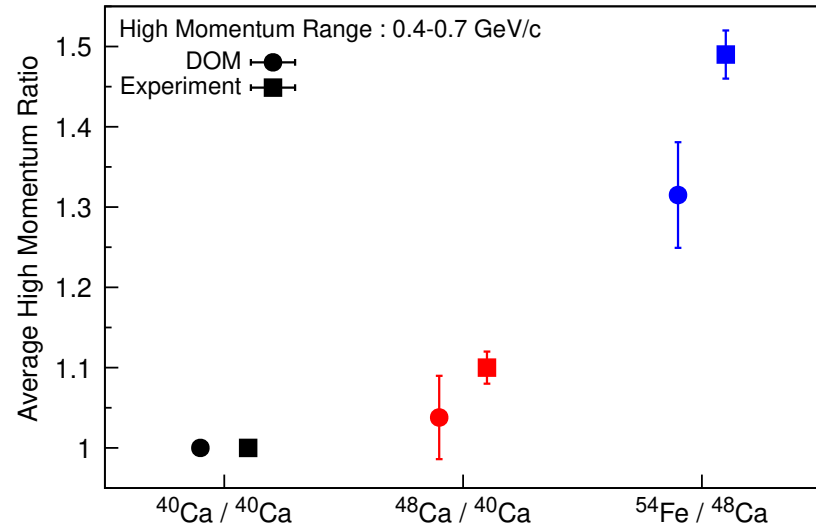
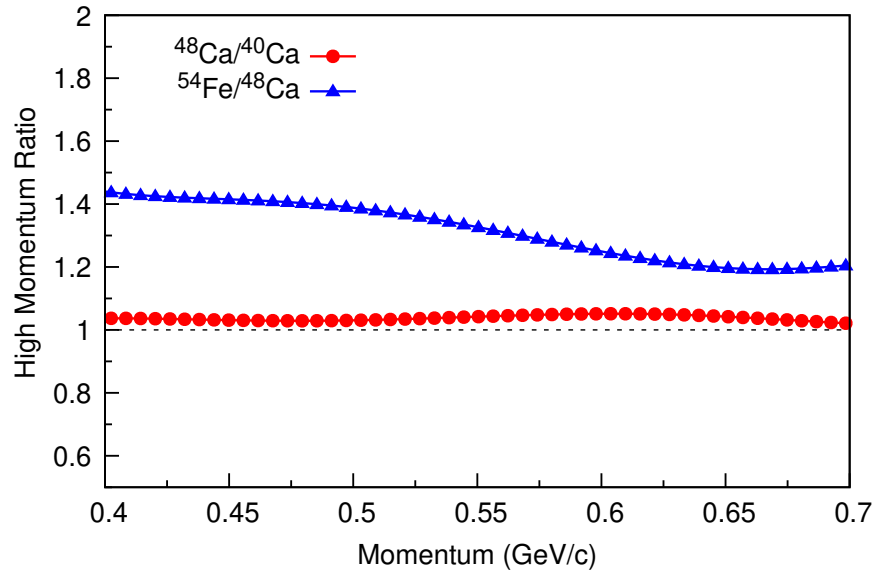
Neutron skins and high momenta

Momentum distributions



Neutron skins and high momenta

CaFe interest

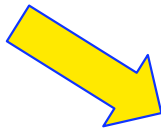


Neutron skins and high momenta

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

For example: protons in ^{208}Pb

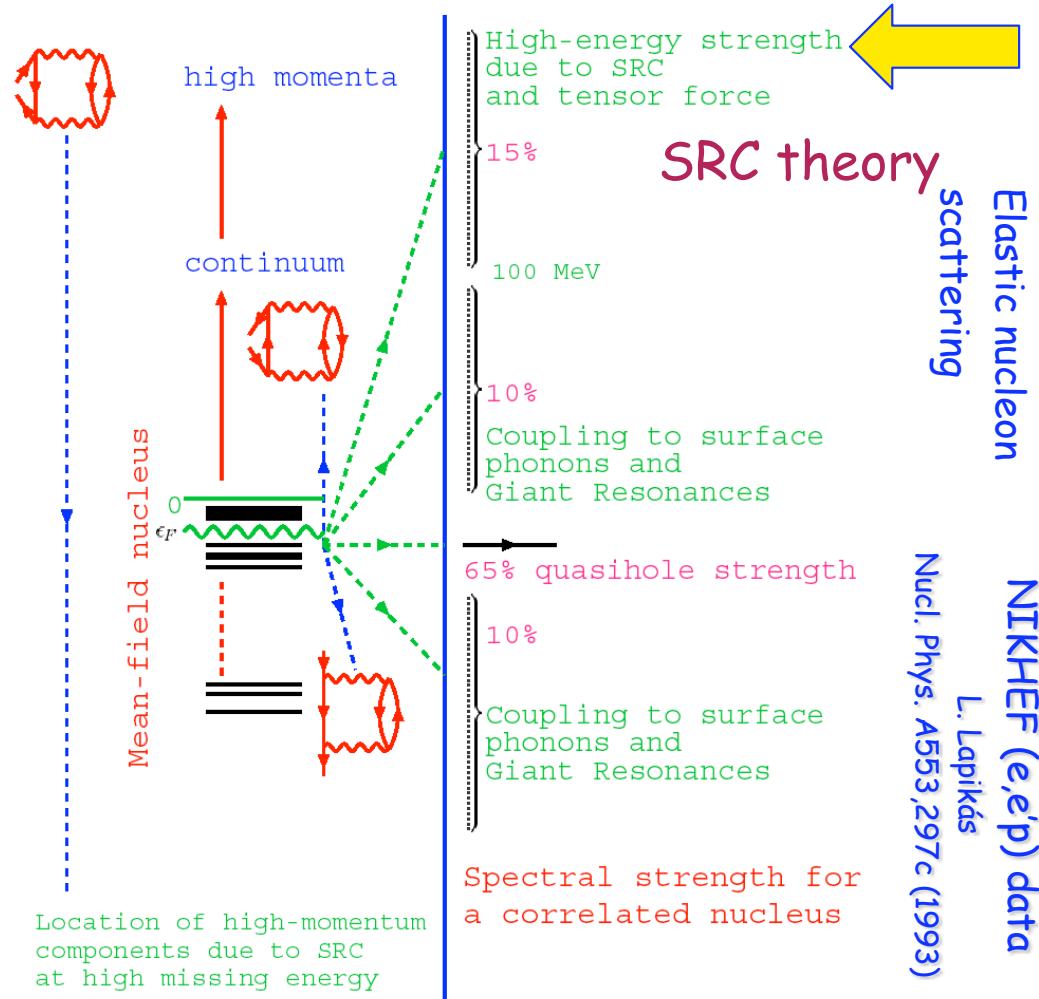
SRC



JLab E97-006

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

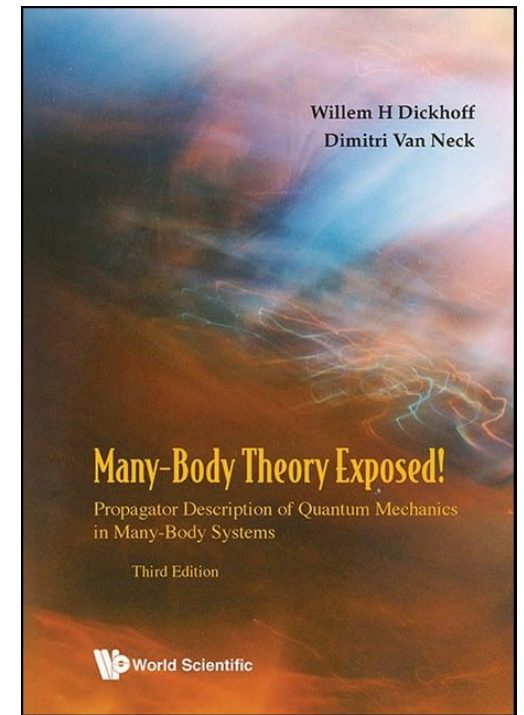
Reviewed in Prog. Part. Nucl. Phys. 52 (2004) 377-496



Neutron skins and high momenta

Electron experiments are tops

- DOM can do many things
- Green's functions the only way to deal with the scattering domain
- We used a link between neutron skins and high momenta to improve DOM
- Many things except the most recent ones in 3rd edition (1008 pages)



Neutron skins and high momenta