Linking nuclear reactions and nuclear structure to predict neutron skins

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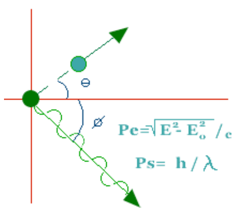
Washington University in St. Louis



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- Motivation
- Green's functions method
  - ab initio
  - as a framework to analyze experimental data (and extrapolate and predict properties of exotic nuclei)

--> dispersive optical model (DOM)

- Focus on recent DOM —> DSM developments
- Can do more than expected!
- Conclusions

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 —> in need of **extensions** some discussed here

reactions and structure

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

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

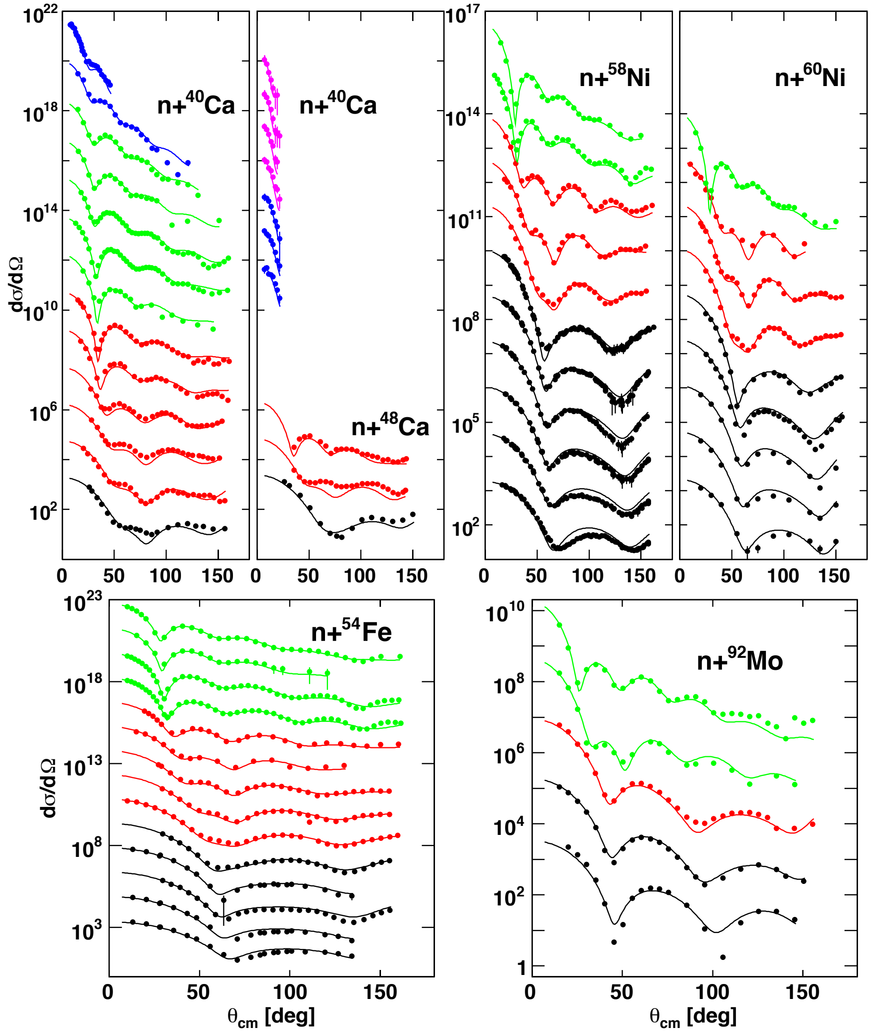
Subtract

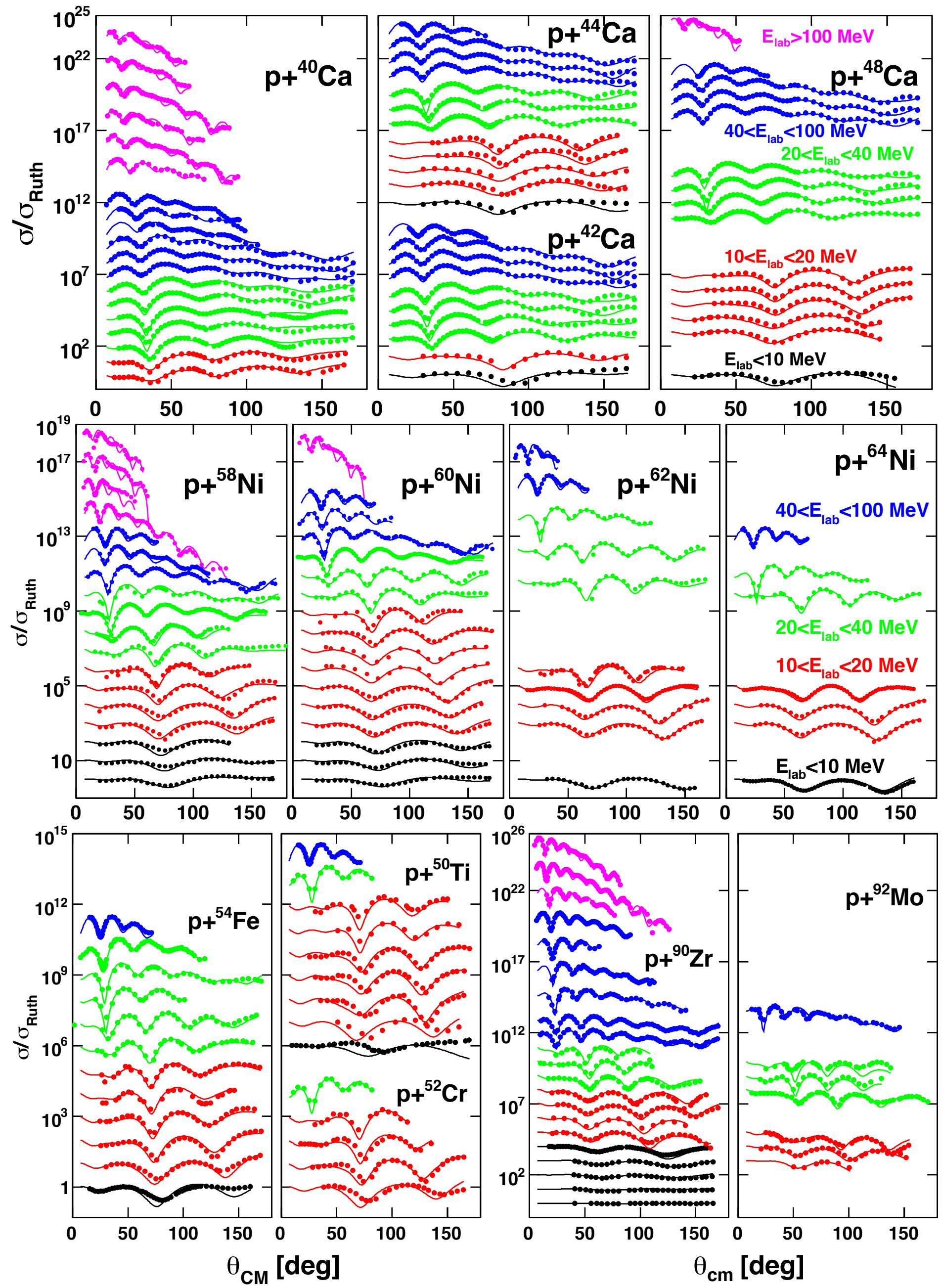
$$\text{Re }\Sigma(E) = \text{Re }\Sigma^{\widetilde{HF}}(\varepsilon_F)$$

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

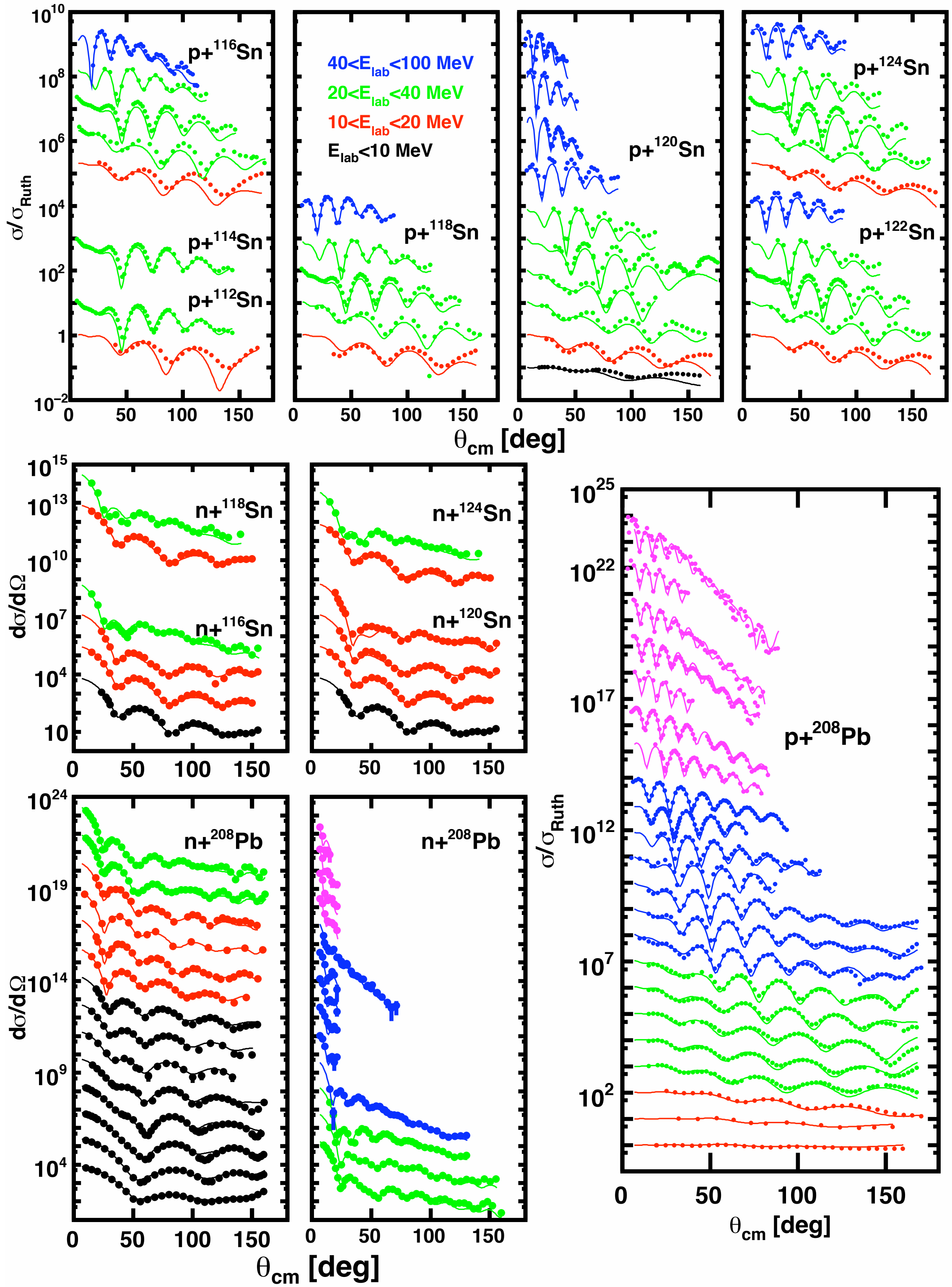
Elastic scattering data for protons and neutrons

- Local DOM implementation





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



Recent local DOM analysis --> towards global

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

reactions and structure

Nonlocal DOM implementation PRL112,162503(2014)

- Particle number --> **nonlocal** imaginary part
- Microscopic 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

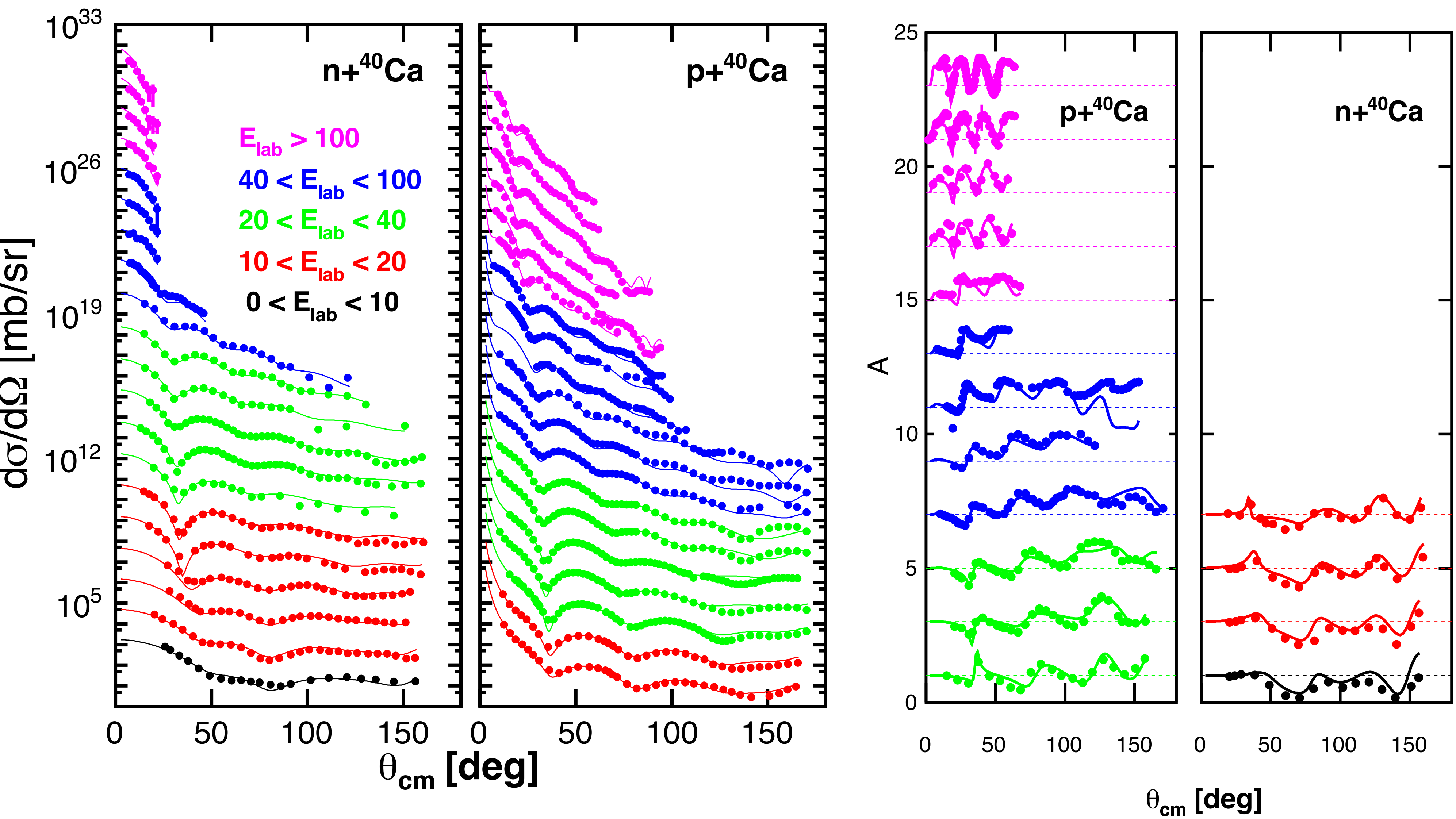
Implications

- 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:

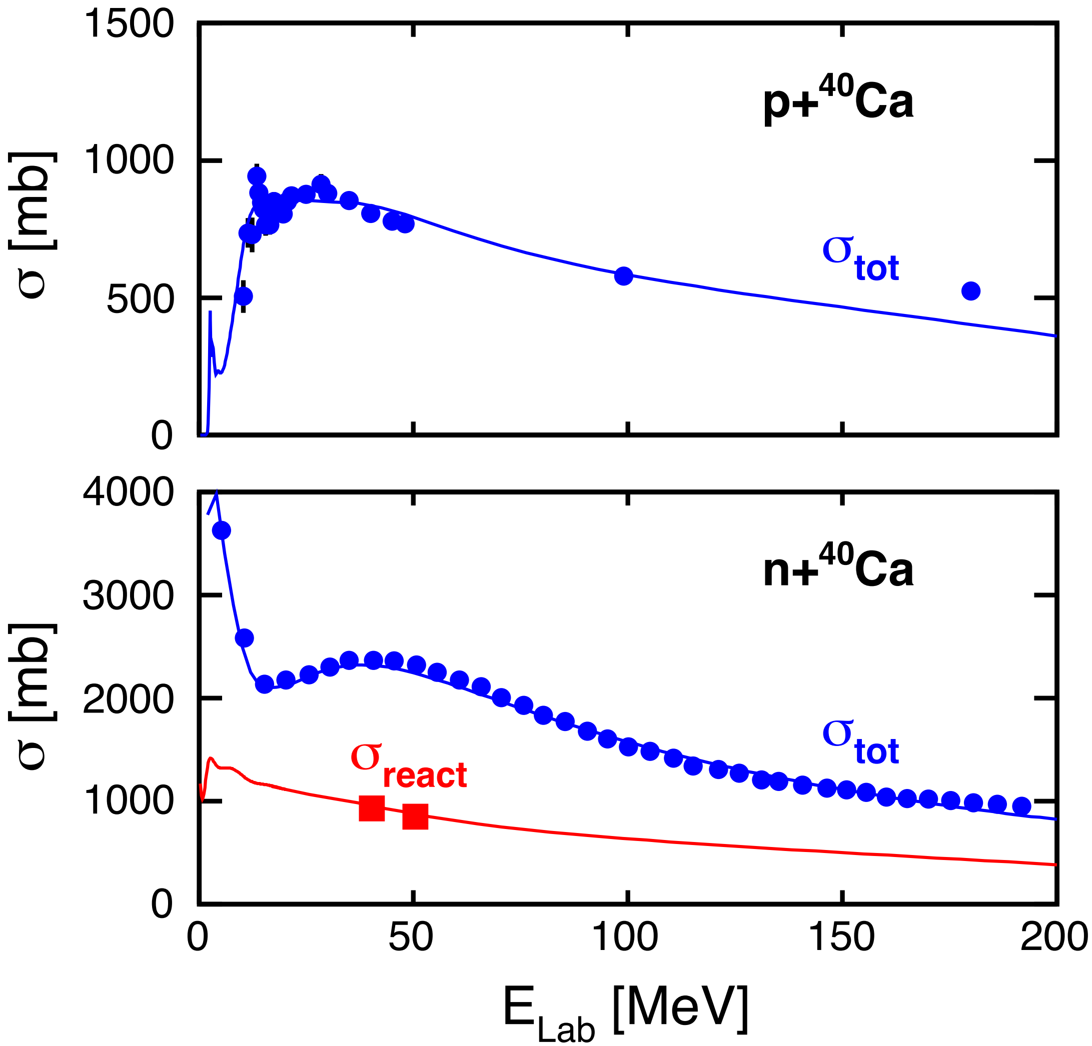
$$E/A = \frac{1}{2A}\sum_{\ell j}(2j+1)\int_0^\infty dk k^2 \frac{k^2}{2m} n_{\ell j}(k) + \frac{1}{2A}\sum_{\ell j}(2j+1)\int_0^\infty dk k^2 \int_{-\infty}^{\varepsilon_F} dE\ E S_{\ell j}(k;E)$$

reactions and structure

Differential cross sections and analyzing powers



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

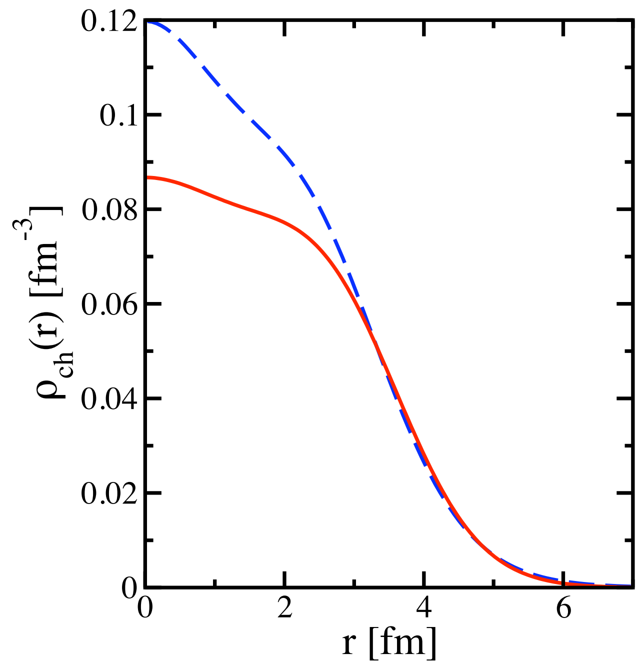


Critical experimental data—> charge density

Local version

radius correct…

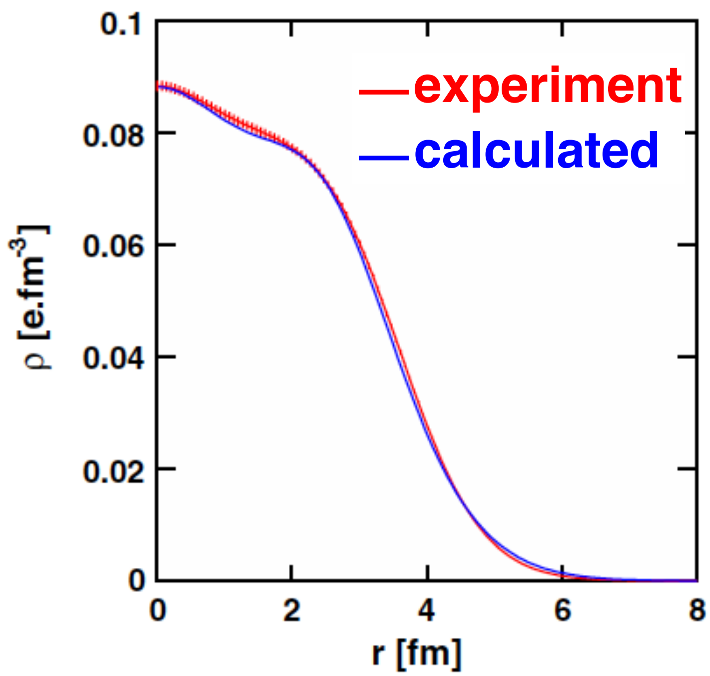
PRC82, 054306 (2010)



Charge density ^{40}Ca

Non-locality essential

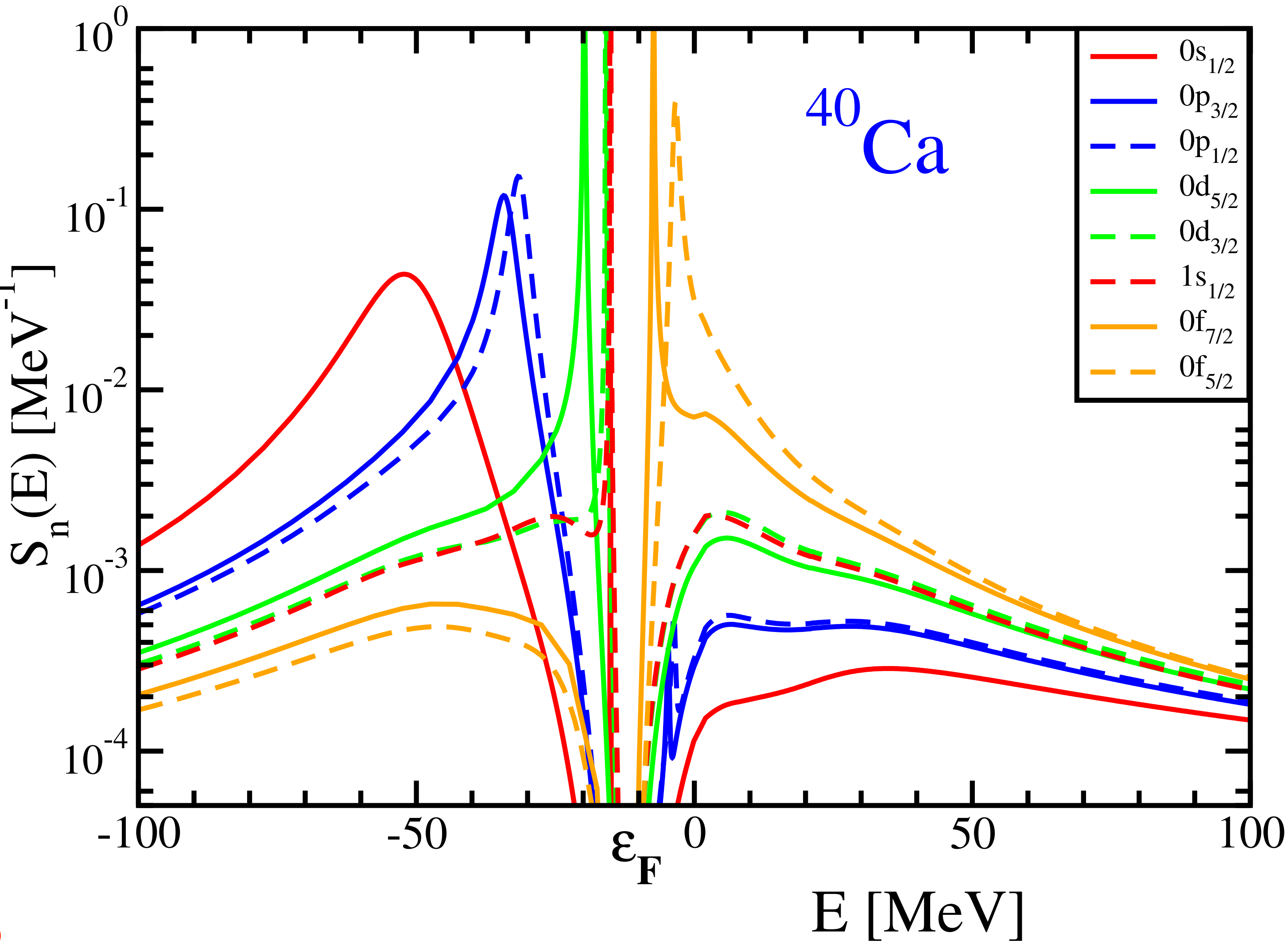
PRL 112,162503(2014)



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 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

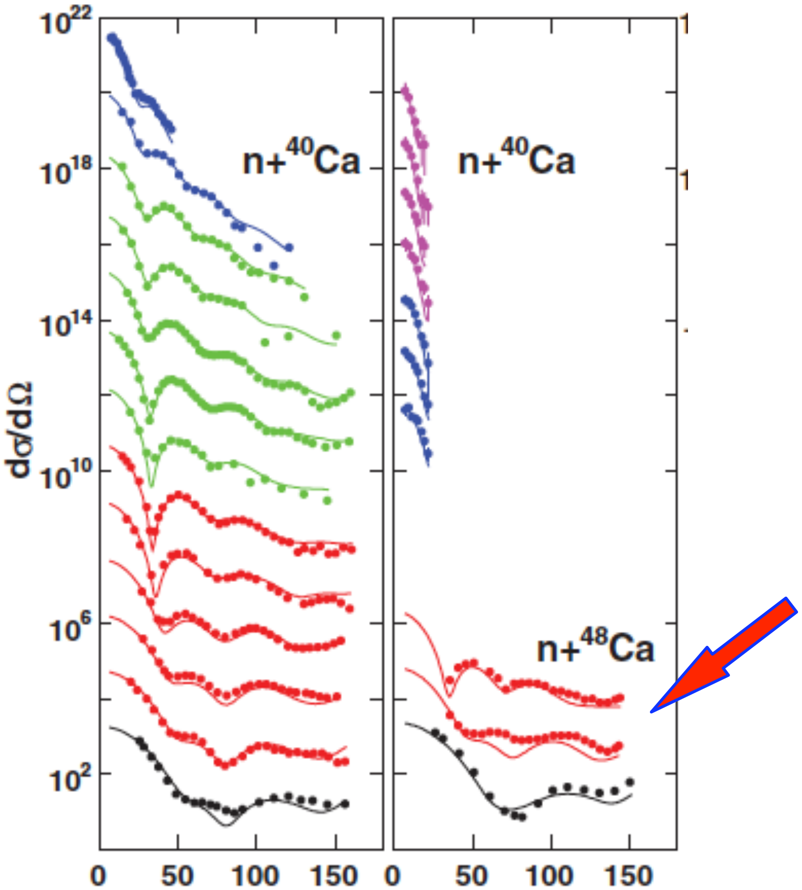
PRC90, 061603(R) (2014)

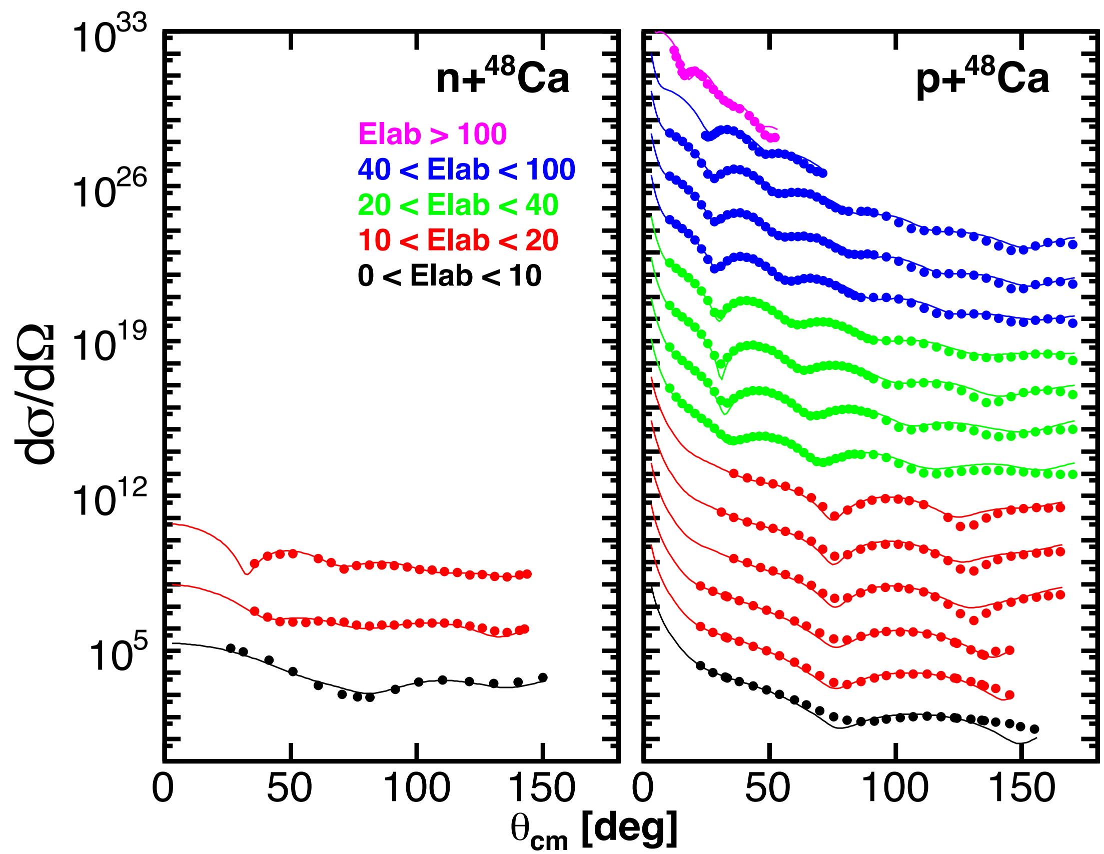
New DOM results for ^{48}Ca

- 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?

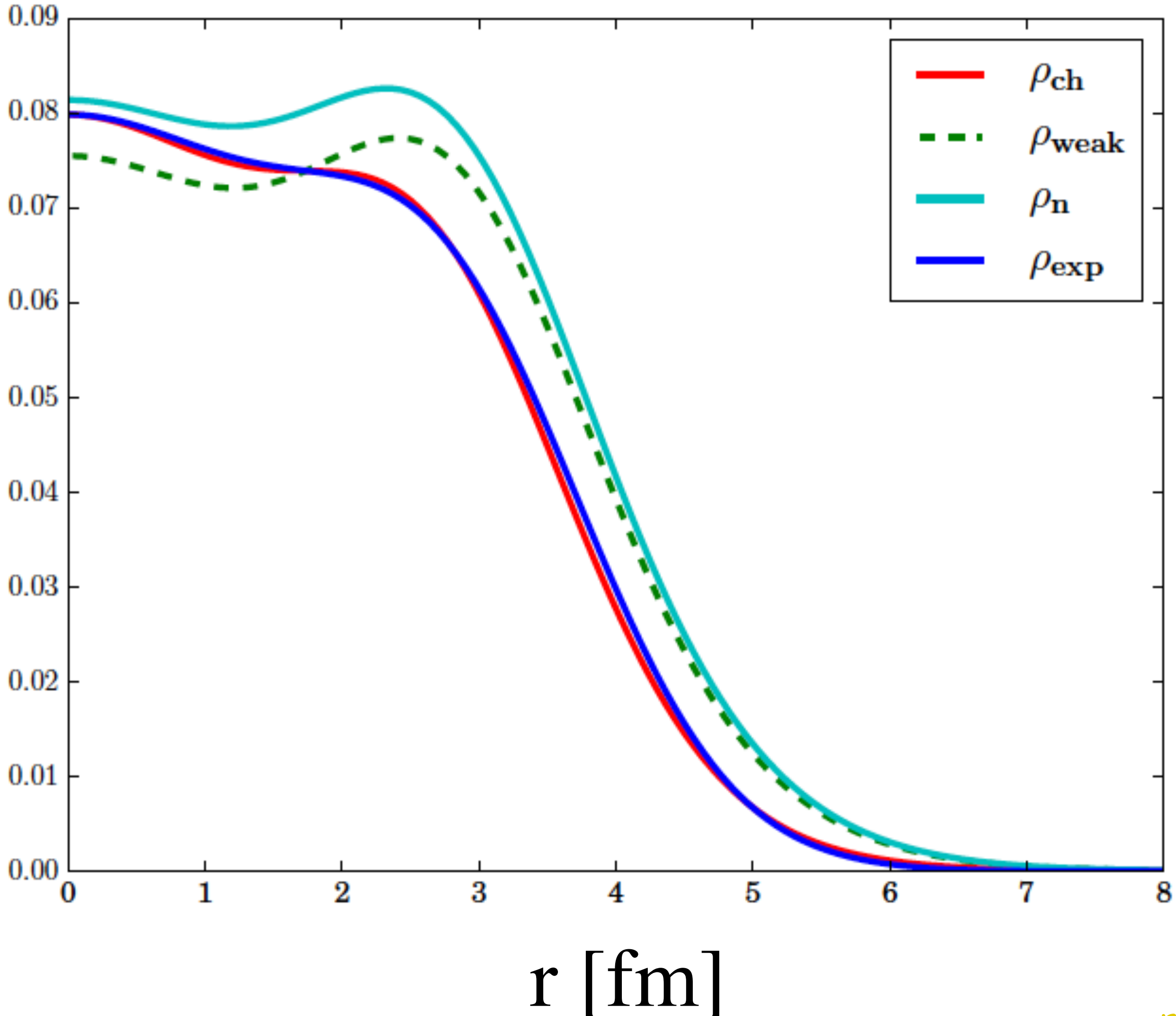
- ^{48}Ca —> charge density has been measured
- Recent neutron elastic scattering **data** —> PRC83,064605(2011)
- Local DOM **OLD** Nonlocal DOM **NEW**





Results ^{48}Ca

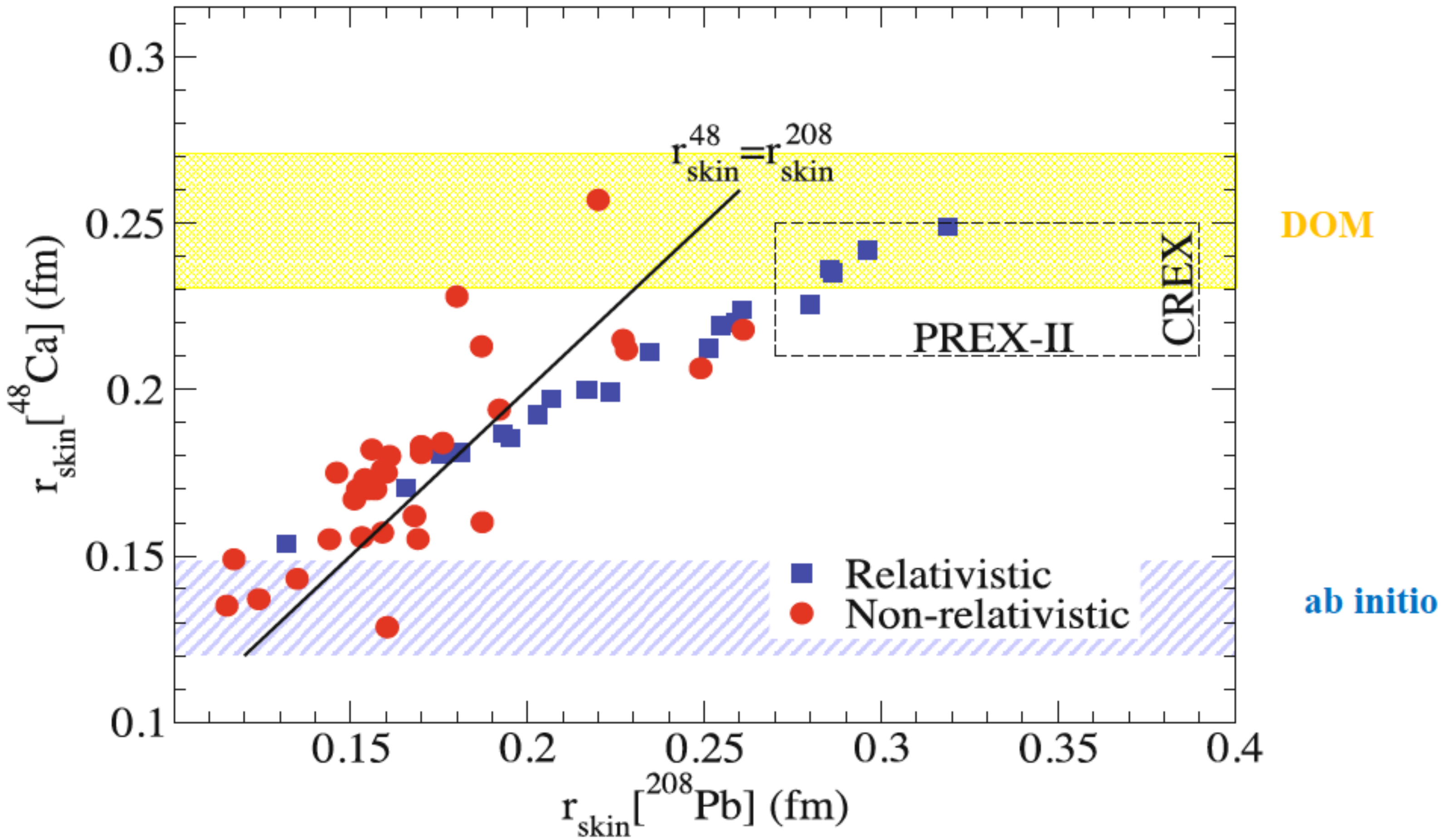
- Density distributions
- DOM —> neutron distribution —> R_n-R_p



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)



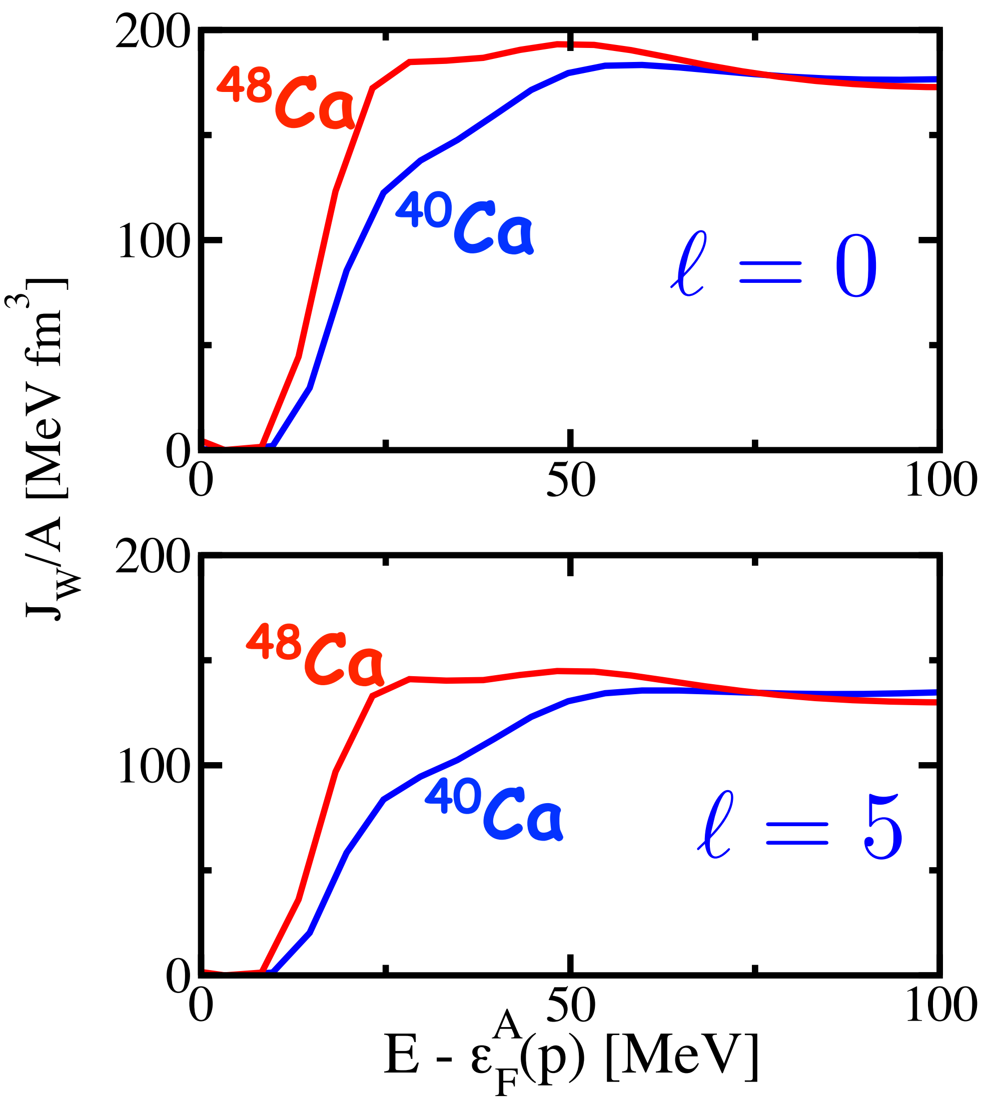
- "Ab initio":

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

--> drip line

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

- Protons see the same interior but a different surface!



--> drip line

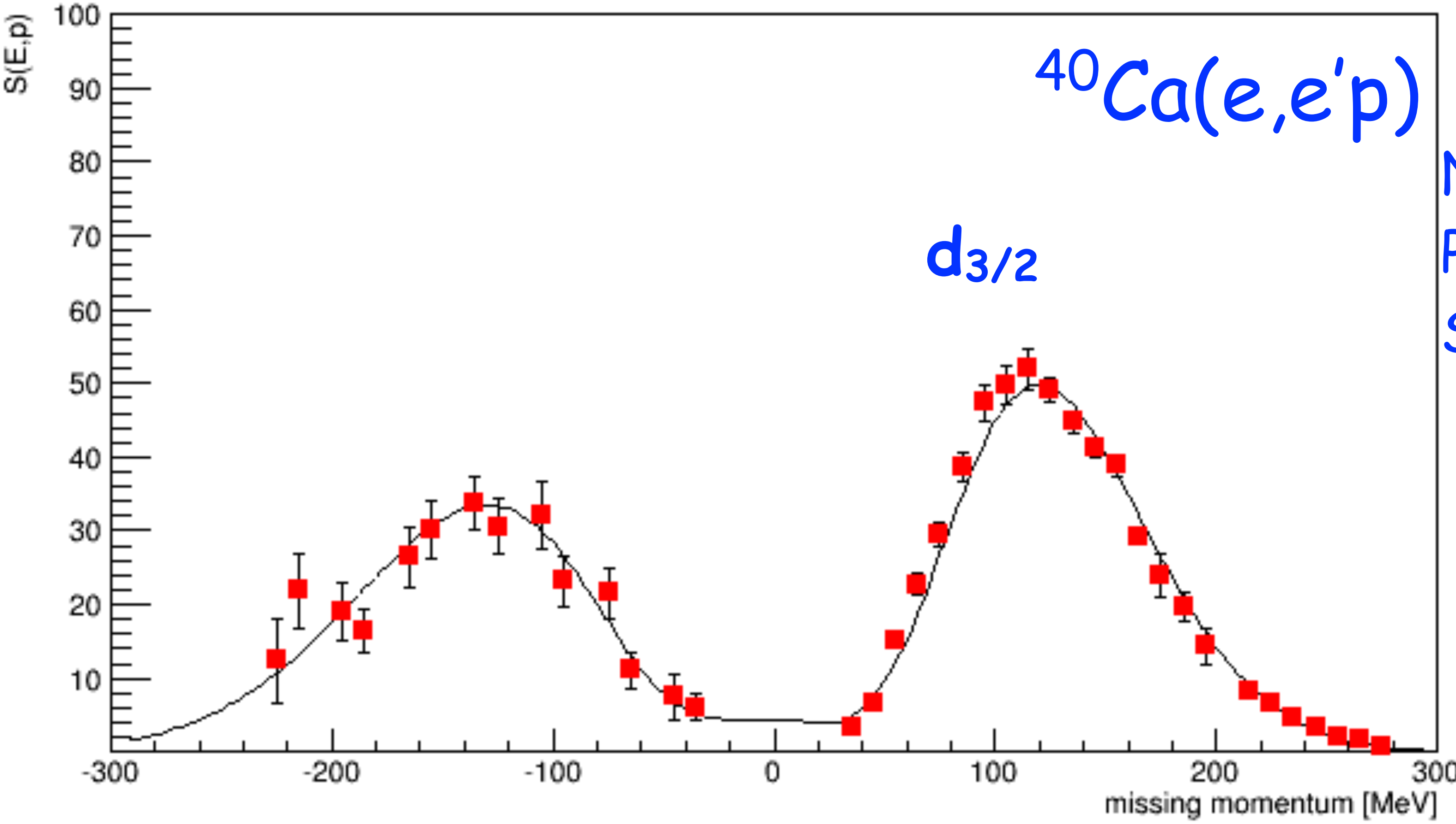
Quantitative comparison of ^{40}Ca and ^{48}Ca

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

Very recent analysis (preliminary)

- NIKHEF (e,e'p) data with only DOM input (Atkinson in progress)
- Confirms larger spectroscopic factors ~0.8
- —> Consequences for analysis of ALL nuclear reactions



NIKHEF
PLB227(1989)199
$S(d_{3/2})$=0.65

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...

reactions and structure