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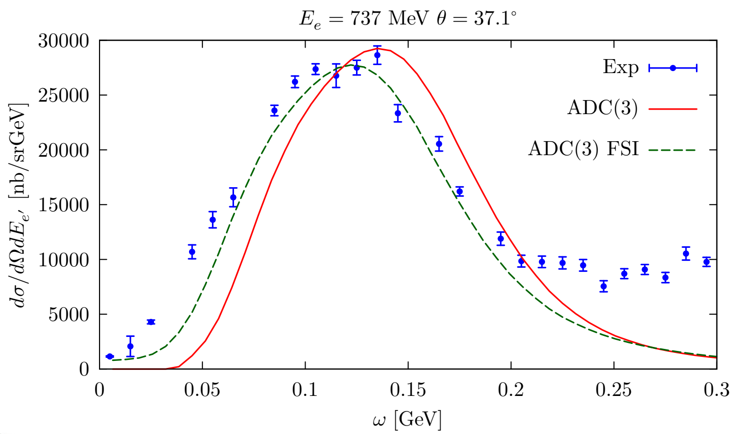
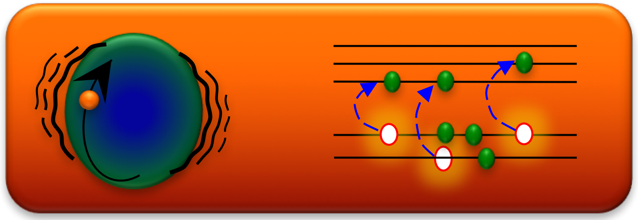
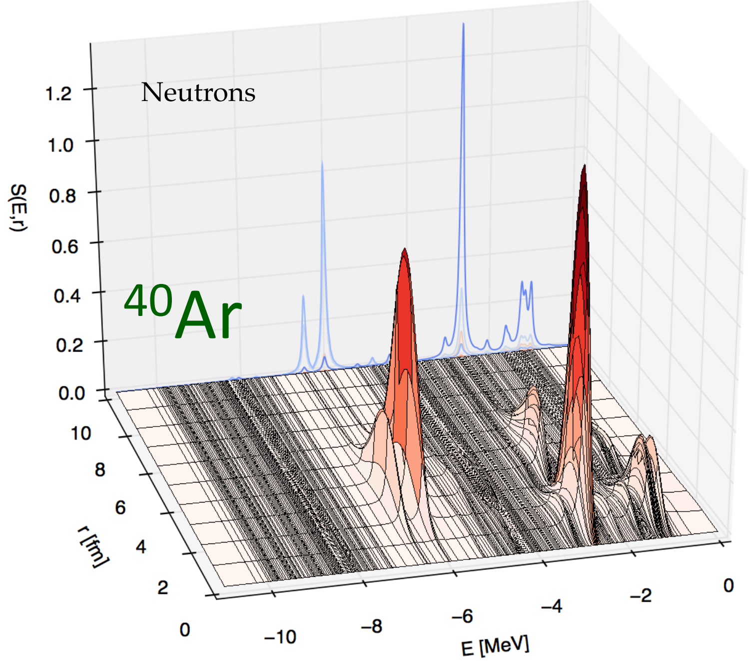
Neutrino and Electron Scattering off Nuclei with SCGF

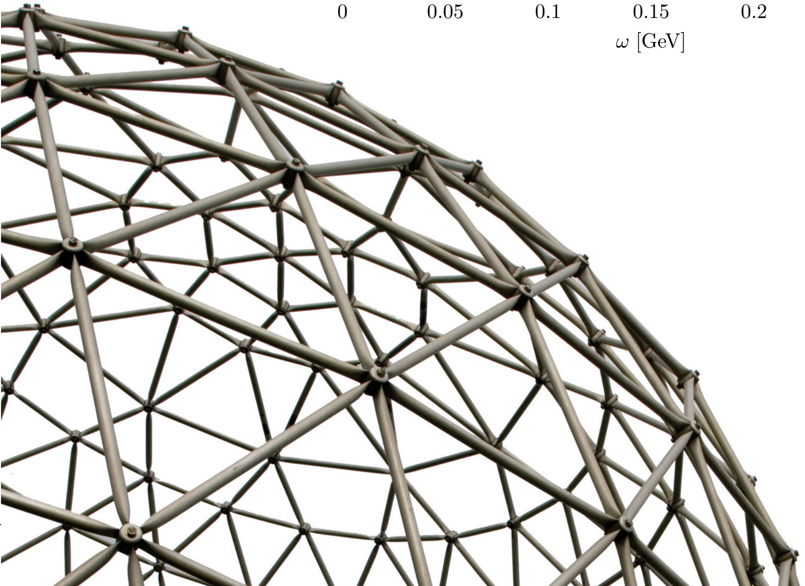
Carlo Barbieri — University of Surrey

2 October 2018



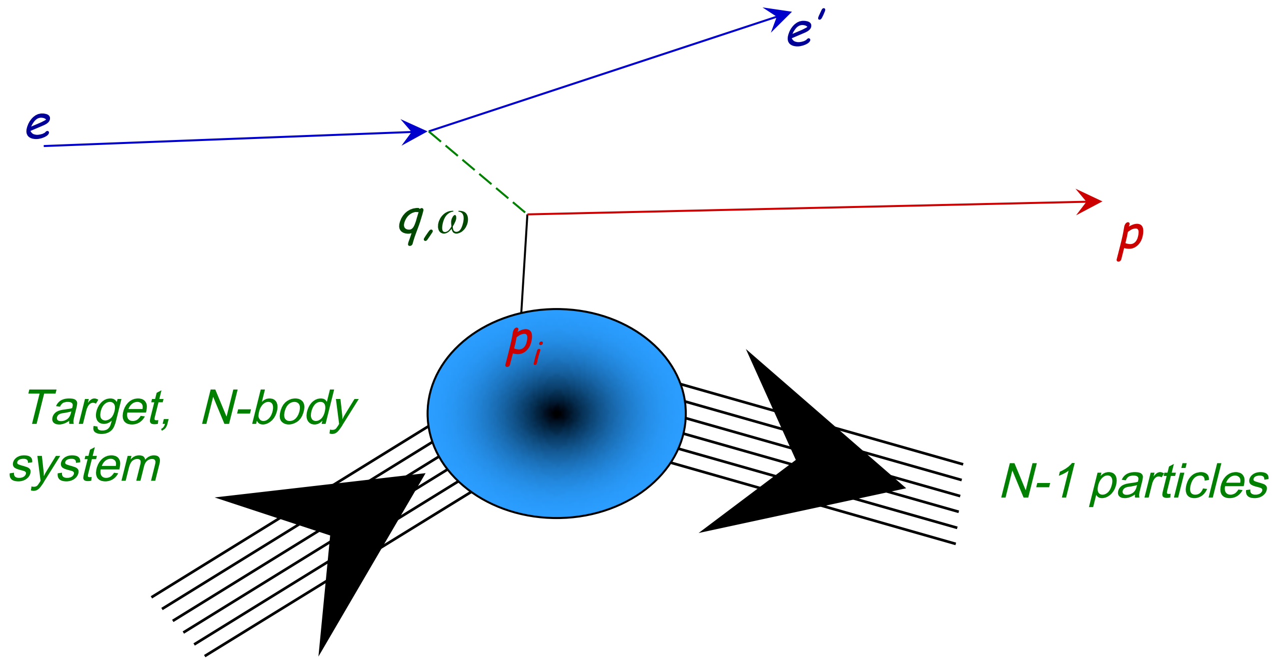






Spectroscopy via knock out reactions-basic idea

Use a probe (ANY probe) to eject the particle we are interested to:



In plane wave impulse approximation (PWIA):

$$\frac{d\sigma_{(e,e'p)}}{dE_{e'}\, d\Omega_{e'}\, d\Omega_p} = \sigma_{e\,p} \times S^h(p_m, E_m)$$

- Spectral distribution is crucial (in spite of "non observability"...)
- Targets are low-energy (ground) states
- Energy and momentum transfer can be high. What about currents? Breaking of EFT?
- Use e- scattering to constrain electroweak

Basic idea:

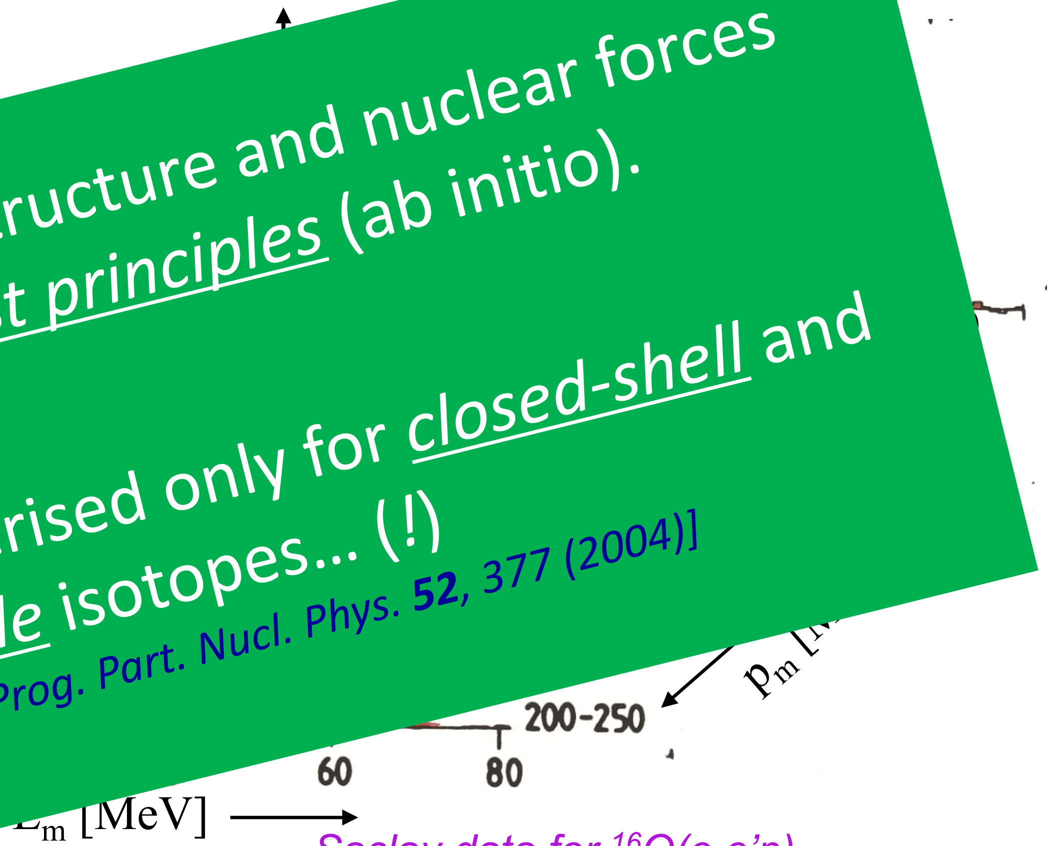
- we know, e, e' and p
- "get" *energy and momentum* of p_i: $p_i = k_e' + k_p - k_e$
  $E_i = E_e' + E_p - E_e$

Better to choose large transferred momentum and weak probes!!!

Concept of correlations

independent particle picture

Spectral function: distribution of
momentum (p_m) an... (E_m)



Saclay data for ^{16}O(e,e'p)
[Mougey et al., Nucl. Phys. A335, 35 (1980)]

Want to understand structure and nuclear forces *directly from first principles* (ab initio).

So far, fully characterised only for *closed-shell* and *stable* isotopes... (!)

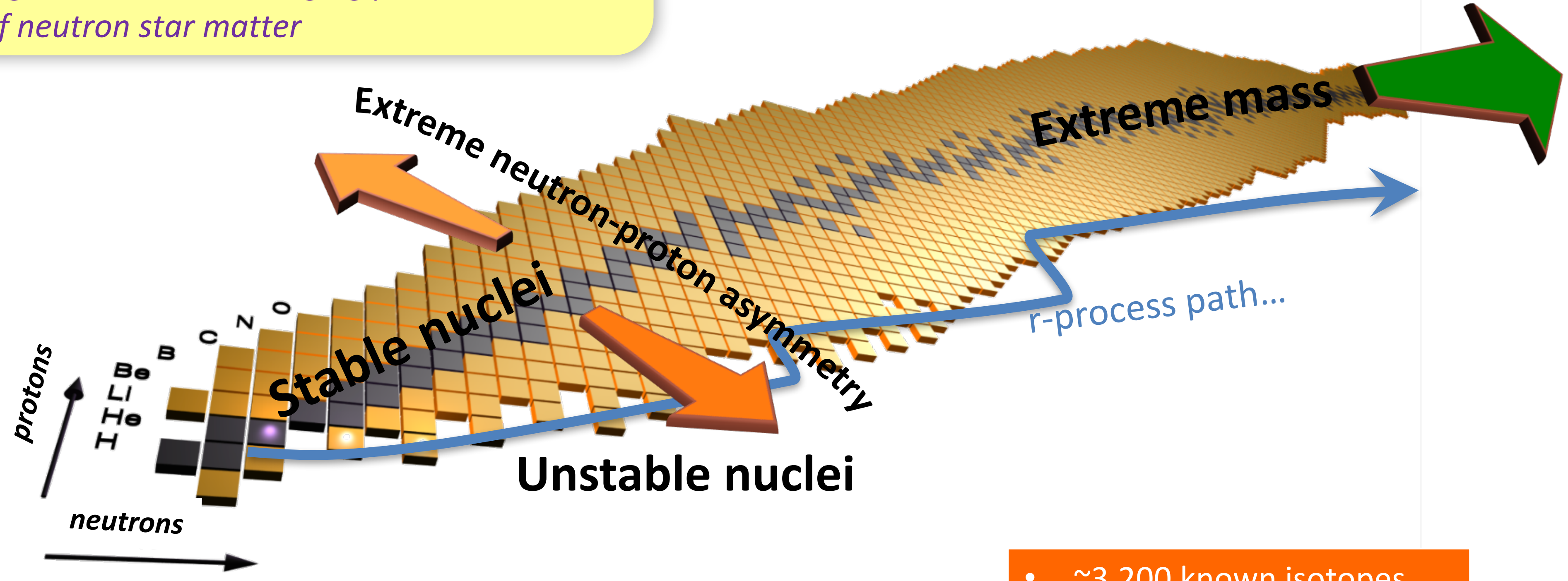
*[W. Dickhoff, CB, Prog. Part. Nucl. Phys. **52**, 377 (2004)]*

Understo... for a few stable closed shells:
*[CB and W. H. Dickhoff, Prog. Part. Nucl. Phys **52**, 377 (2004)]*

Current Status of low-energy nuclear physics

Composite system of interacting fermions
Binding and limits of stability
Coexistence of individual and collective behaviors
Self-organization and emerging phenomena
EOS of neutron star matter

Experimental programs RIKEN, FAIR, FRIB…



- ~3,200 known isotopes
- ~7,000 predicted to exist
- Correlation characterised in full for ~283 stable

Nature **473**, 25 (2011); **486**, 509 (2012)

Current Status of low-energy nuclear physics

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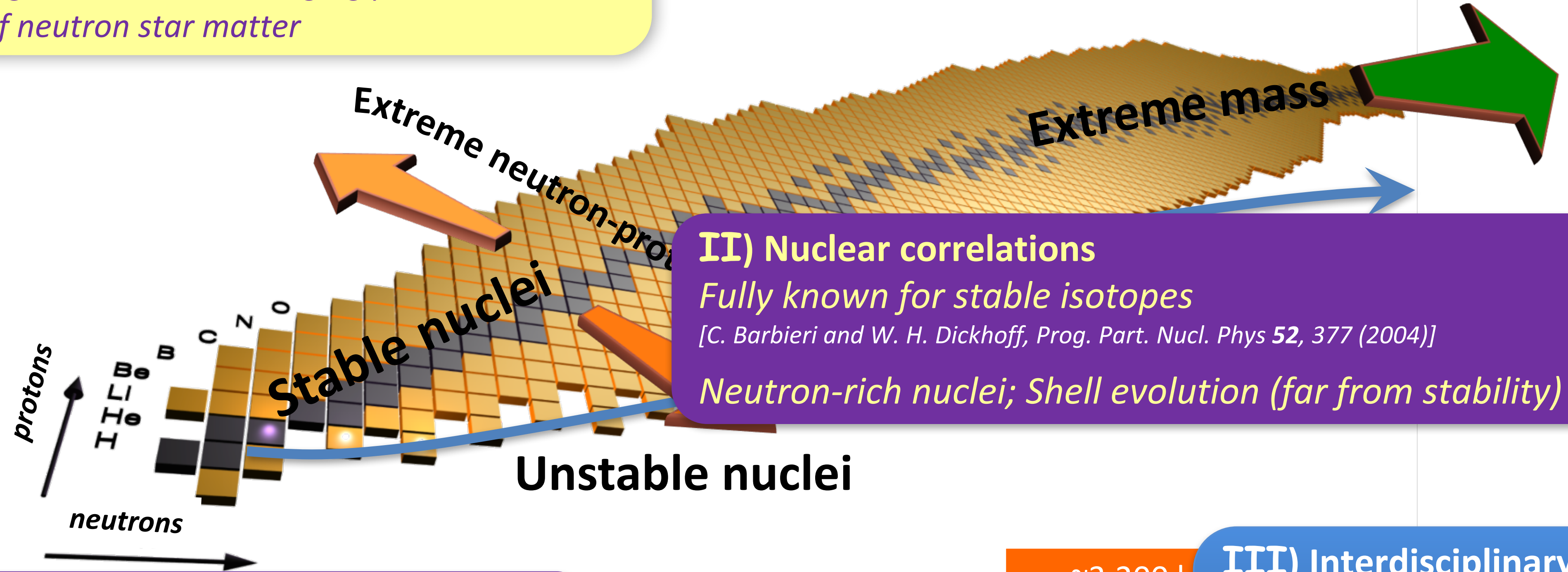
Experimental programs
RIKEN, FAIR, FRIB…



II) Nuclear correlations
Fully known for stable isotopes
[C. Barbieri and W. H. Dickhoff, Prog. Part. Nucl. Phys ***52****, 377 (2004)]*
Neutron-rich nuclei; Shell evolution (far from stability)

I) Understanding the nuclear force
QCD-derived; 3-nucleon forces (3NFs)
First principle (ab-initio) predictions

- ~3,200 k
- ~7,000 p
- Correlati
  in full fo

Nature **473**, 25

III) Interdisciplinary character
Astrophysics
Tests of the standard model
Other fermionic systems:
ultracold gasses; molecules;

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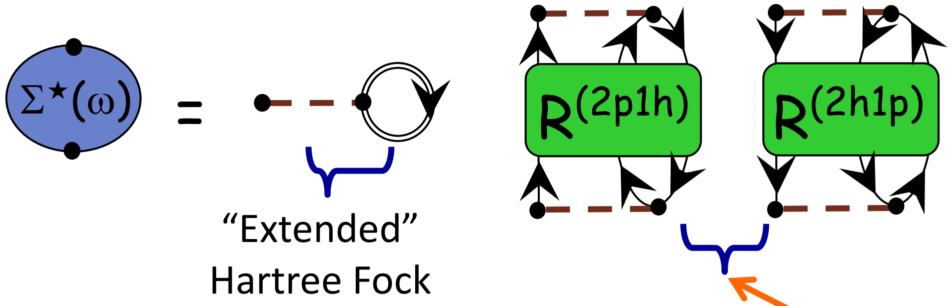
The FRPA Method in Two Words

Particle vibration coupling is the main mechanism driving the redistribution and fragmentation of particle strength—expecially in the quasielastic regions around the Fermi surface…

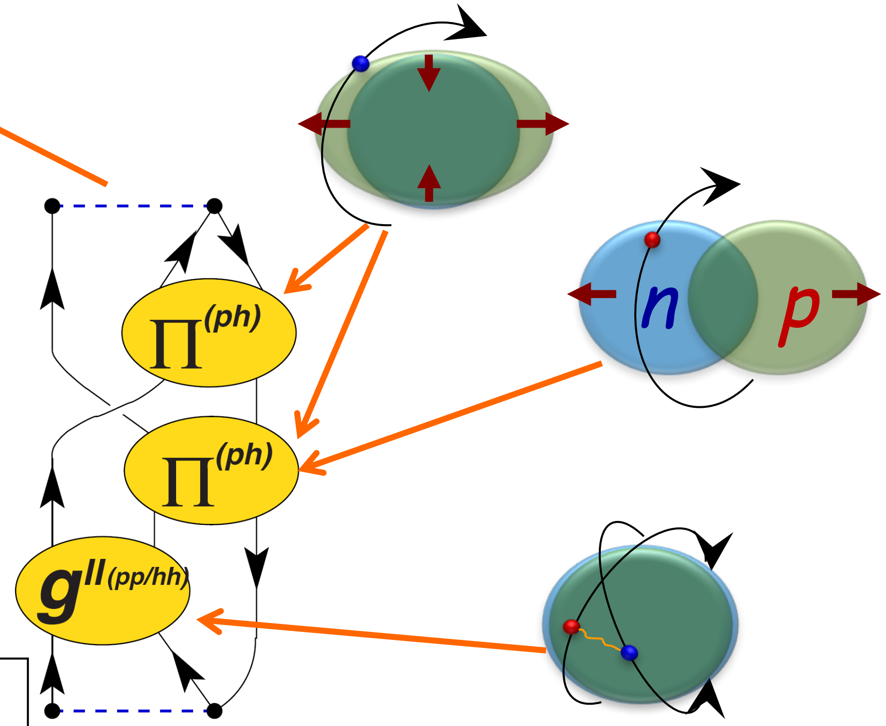
CB et al.,
Phys. Rev. C**63**, 034313 (2001)
Phys. Rev. A**76**, 052503 (2007)
Phys. Rev. C**79**, 064313 (2009)

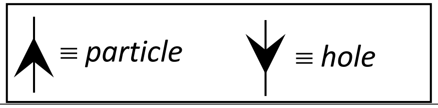


- A complete expansion requires *all types* of particle-vibration coupling

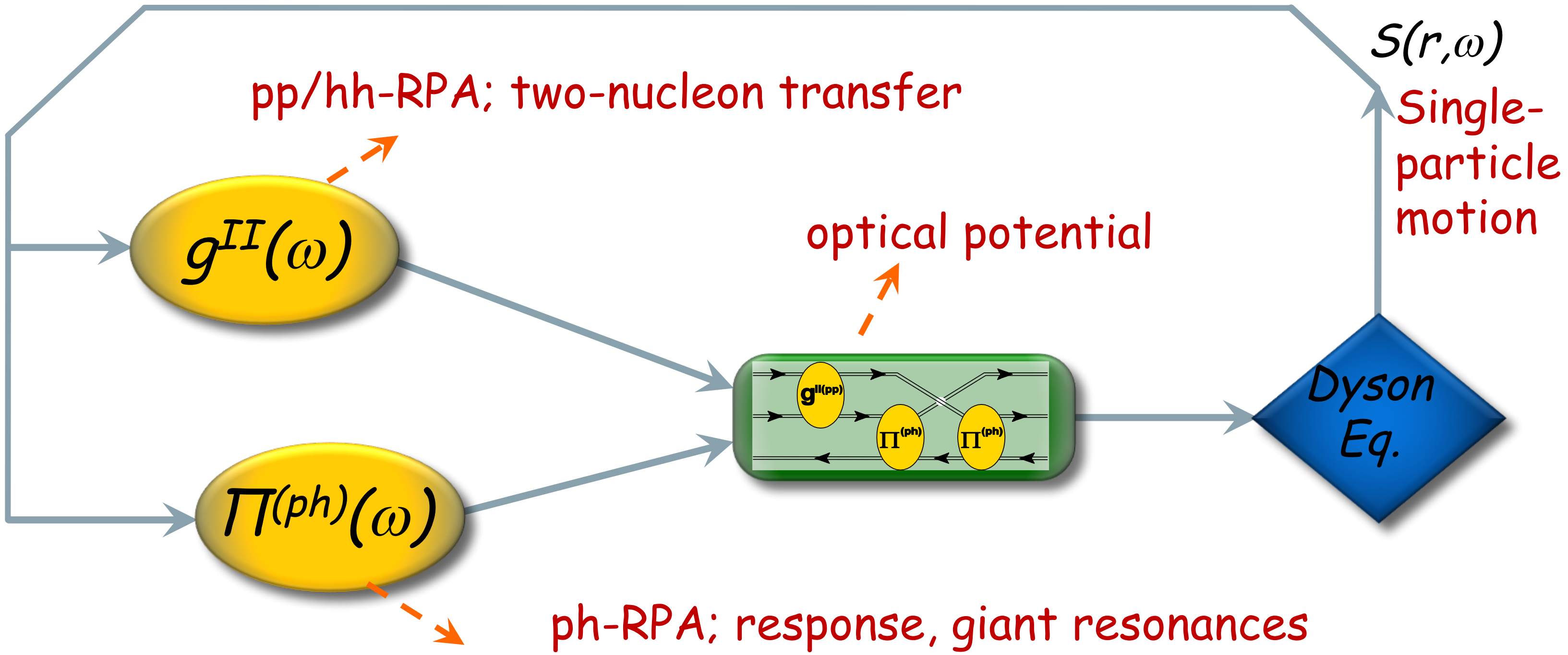
  …these modes are all resummed exactly and to all orders in a *ab initio* many-body expansion.

- The Self-energy $\Sigma^\star(\omega)$ yields *both* single-particle states and scattering





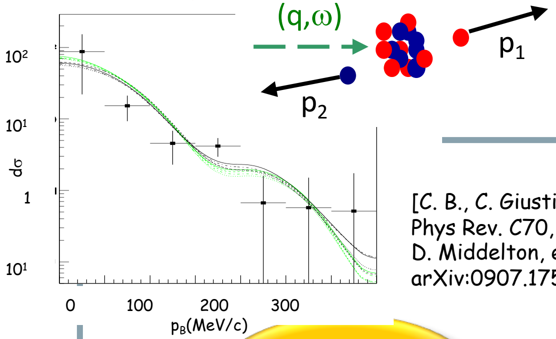
Self-Consistent Green's Function Approach



- Global picture of nuclear dynamics
- Reciprocal correlations among effective modes
- Guaranties *macroscopic conservation laws*

Self-Consistent Green's Function Approach

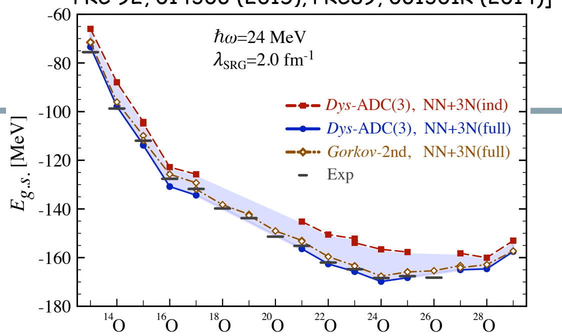
$^{16}O(e,e'pn)^{14}N$ @ MAINZ



[C. B., C. Giusti, et al.
Phys Rev. C70, 014606 (2004)
D. Middelton, et al.
arXiv:0907.1758; EPJA in print]

Binding energies

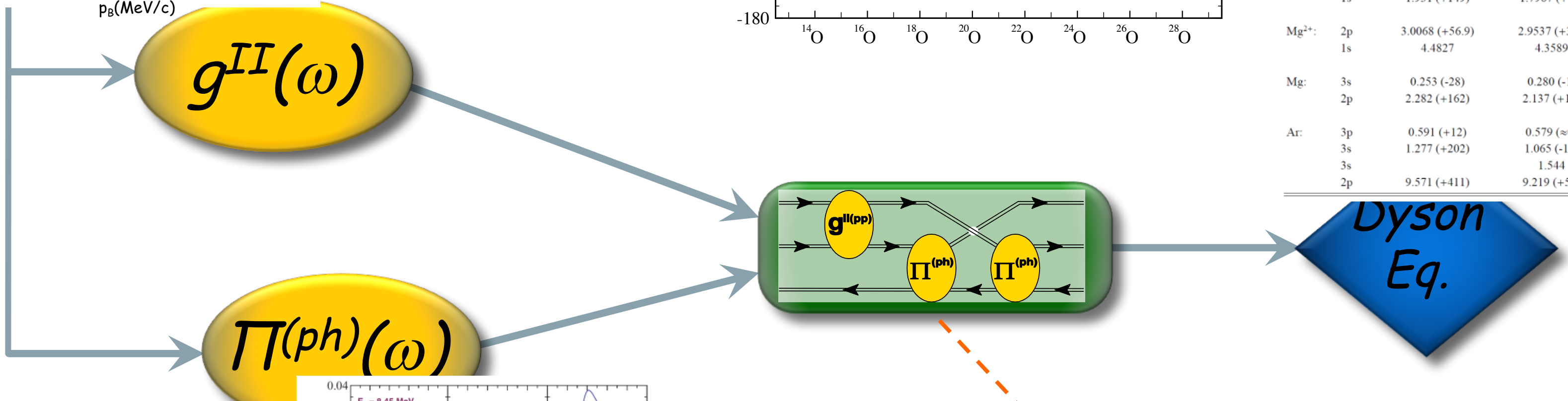
[PRL. 111, 062501 (2013),
PRC 92, 014306 (2015), PRC89, 061301R (2014)]



Ionization energies/ affinities, in atoms

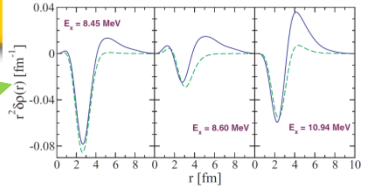
[CB, D. Van Neck,
AIP Conf.Proc.1120,104 ('09) & in prep]

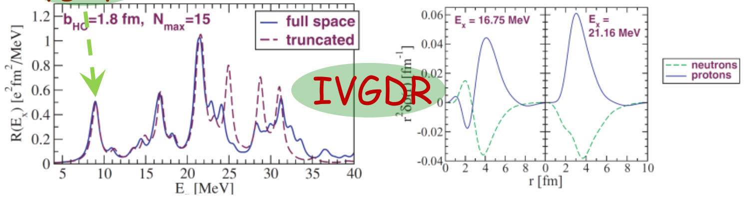
		Hartree-Fock	FRPAc	Experiment [16, 17]
He:	1s	0.918 (+14)	0.9008 (-2.9)	0.9037
Be^{2+}:	1s	5.6672 (+116)	5.6551 (-0.5)	5.6556
Be:	2s	0.3093 (-34)	0.3224 (-20.2)	0.3426
	1s	4.733 (+200)	4.5405 (+8)	4.533
Ne:	2p	0.852 (+57)	0.8037 (+11)	0.793
	1s	1.931 (+149)	1.7967 (+15)	1.782
Mg^{2+}:	2p	3.0068 (+56.9)	2.9537 (+3.8)	2.9499
	1s	4.4827	4.3589	
Mg:	3s	0.253 (-28)	0.280 (-1)	0.281
	2p	2.282 (+162)	2.137 (+17)	2.12
Ar:	3p	0.591 (+12)	0.579 (≈0)	0.579
	3s	1.277 (+202)	1.065 (-10)	1.075
	3s		1.544	
	2p	9.571 (+411)	9.219 (+59)	9.160



Isovector response for ^{32}Ar, ^{34}Ar

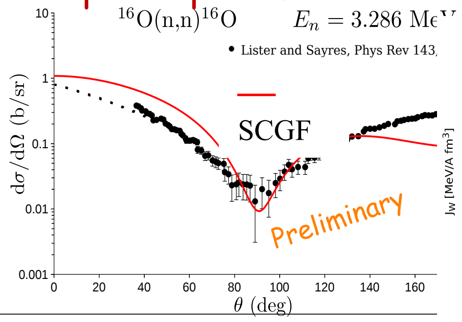
Proton Pygmy



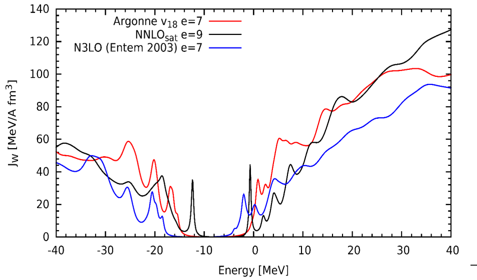


[C. B., K. Langanke, et al., Phys Rev. C77, 024304 (2008)]

Optical potential



arXiv:1612.01478 [nucl-th]



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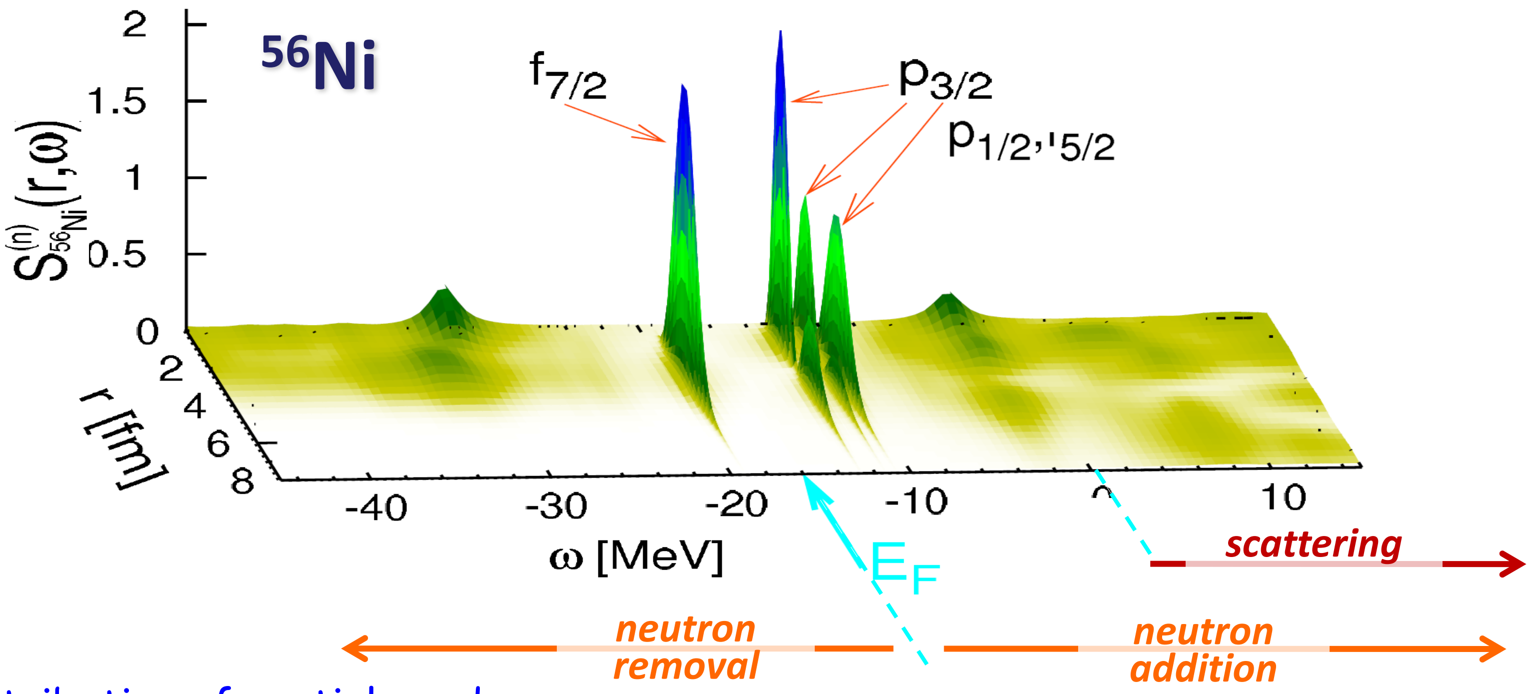
One-nucleon spectral function

$$S^{p,h}(r,\omega) = \mp\frac{1}{\pi}\,\mathrm{Im}\,g(r=r';\omega)$$

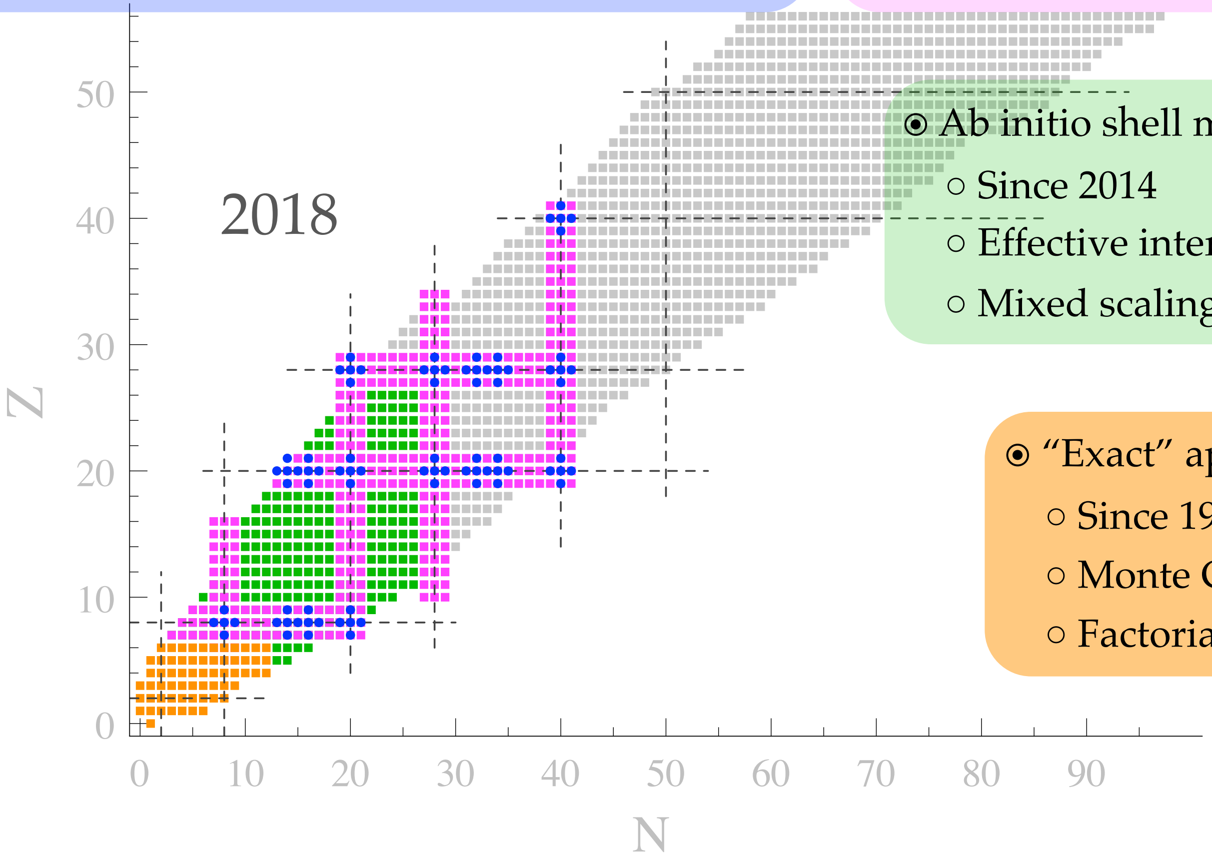


Distribution of particle and hole neutron states in ^{56}Ni

W. Dickhoff, CB, Prog. Part. Nucl. Phys. 53, 377 (2004)
CB, M.Hjorth-Jensen, Pys. Rev. C**79**, 064313 (2009)

Reach of ab initio methods across the nuclear chart

- Approximate approaches for closed-shell nuclei
  - Since 2000's
  - SCGF, CC, IMSRG
  - Polynomial scaling
- Approximate approaches for open-shells
  - Since 2010's
  - GGF, BCC, MR-IMSRG
  - Polynomial scaling



- Ab initio shell model
  - Since 2014
  - Effective interaction via CC/IMSRG
  - Mixed scaling
- "Exact" approaches
  - Since 1980's
  - Monte Carlo, CI, …
  - Factorial scaling

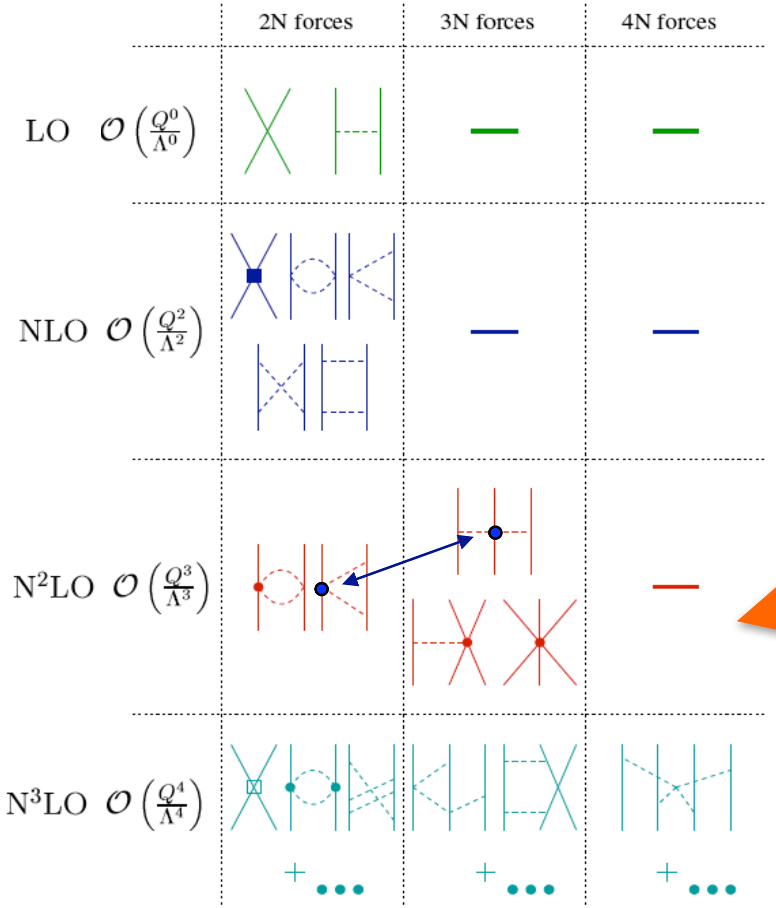
Slide, courtesy of V. Somà

Chiral EFT interactions
and
3-nucleon forces

in mid-mass isotopes

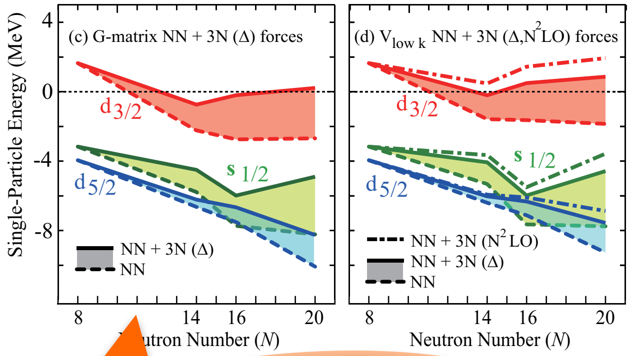
Realistic nuclear forces form Chiral EFT

Chiral EFT for nuclear forces:



(3NFs arise naturally at N2LO)

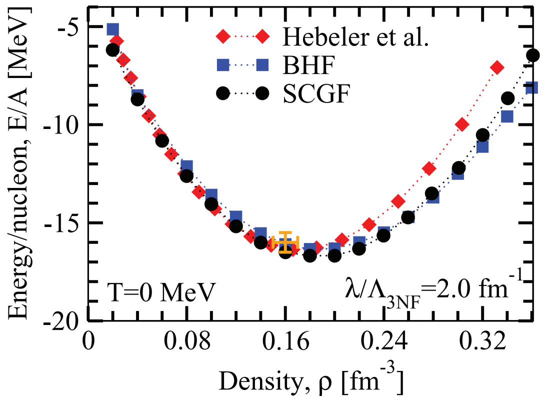
Single particle spectrum at E_{fermi}:



[T. Otsuka et al., Phys Rev. Lett **105**, 032501 (2010)]

Need at LEAST 3NF!!!
("cannot" do RNB physics without…)

Saturation of nuclear matter:



[A. Carbone et al., Phy.s Rev. C **88**, 044302 (2013)]

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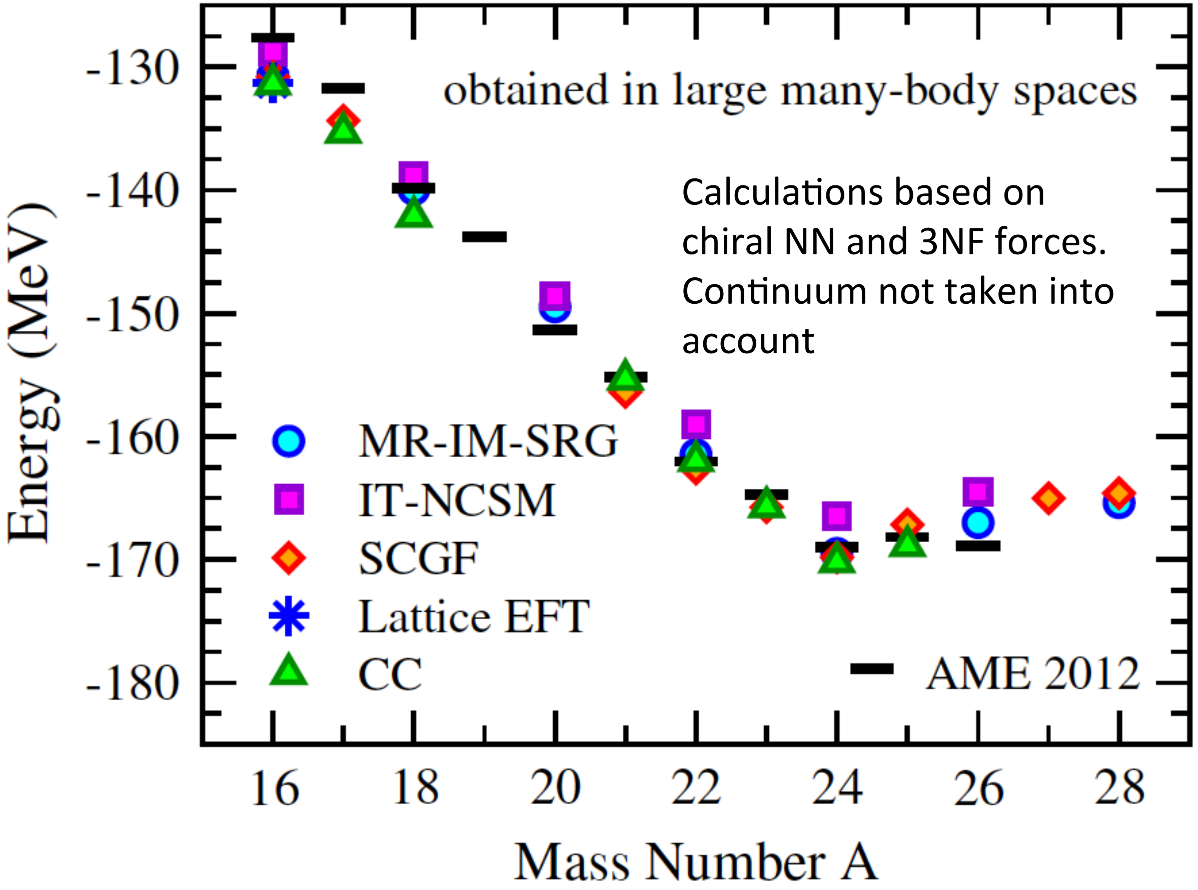
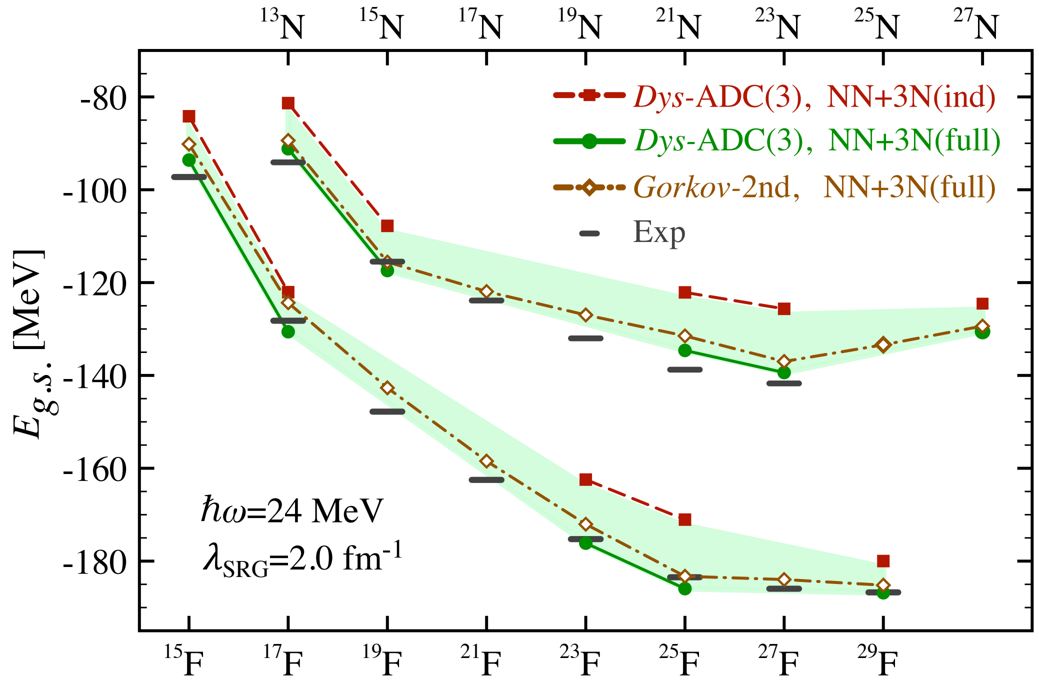
Benchmark of ab-initio methods in the oxygen isotopic chain



Hebeler, Holt, Menendez, Schwenk, Ann. Rev. Nucl. Part. Sci. in press (2015)

A. Cipollone, CB, P. Navrátil, Phys. Rev. Lett. **111**, 062501 (2013)
and Phys. Rev. C **92**, 014306 (2015)

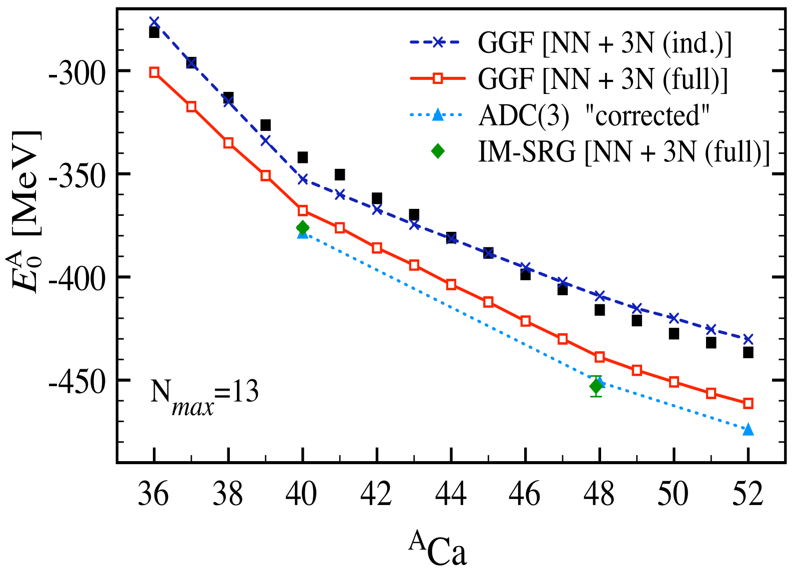


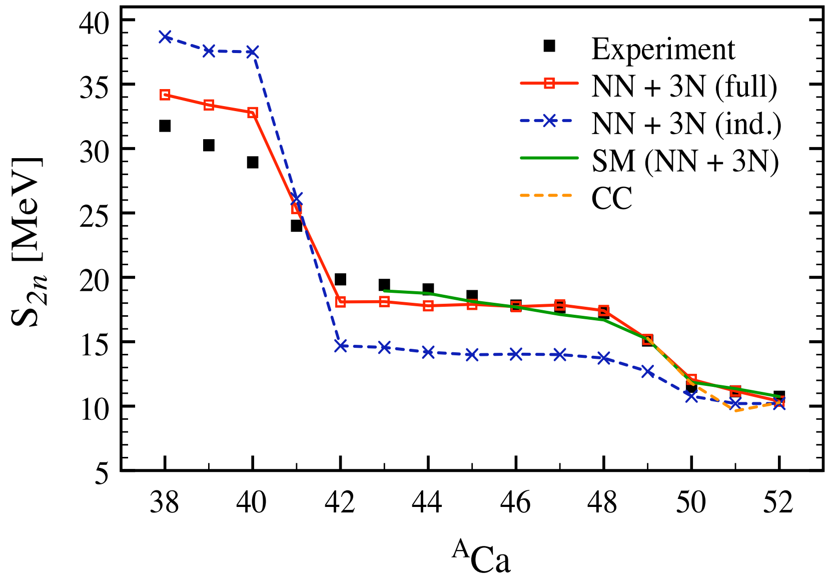
→ 3NF tensor and 3NF near flourine's dripline

N3LO (Λ = 500Mev/c) chiral NN interaction evolved to 2N + 3N forces ($2.0 fm^{-1}$)
N2LO (Λ = 400Mev/c) chiral 3N interaction evolved ($2.0 fm^{-1}$)

Calcium isotopic chain

Ab-initio calculation of the whole Ca: *induced* and full 3NF investigated





→ *induced* and full 3NF investigated

→ genuine (N2LO) 3NF needed to reproduce the energy curvature and S_{2n}

→ N=20 and Z=20 gaps overestimated!

→ Full 3NF give a correct trend but over bind!

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V. Somà, CB *et al.* Phys. Rev. C**89**, 061301R (2014)

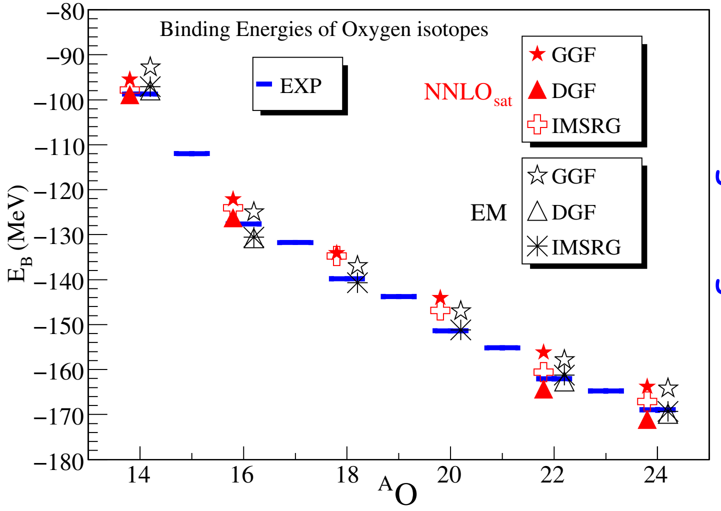
PRL 117, 052501 (2016) PHYSICAL REVIEW LETTERS week ending 29 JULY 2016

Radii and Binding Energies in Oxygen Isotopes: A Challenge for Nuclear Forces

V. Lapoux,[1,*] V. Somà,[1] C. Barbieri,[2] H. Hergert,[3] J. D. Holt,[4] and S. R. Stroberg[4]

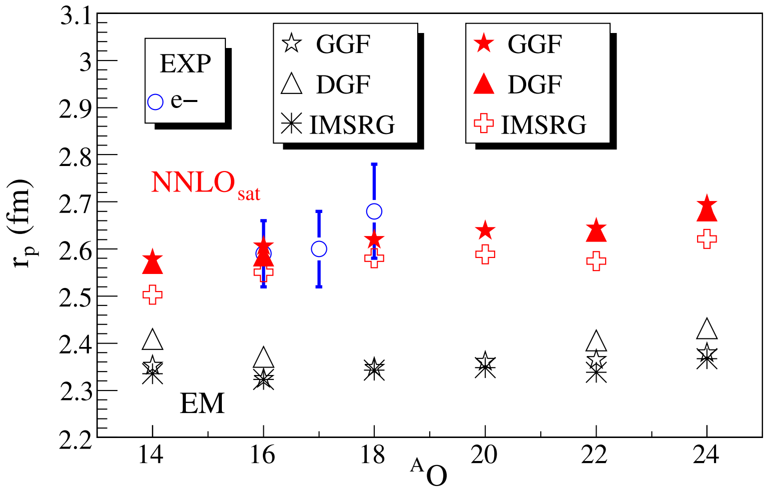
- New fits of chiral interactions (NNLOsat) highly improve comparison to data

- Deficiencies remain for neutron rich isotopes

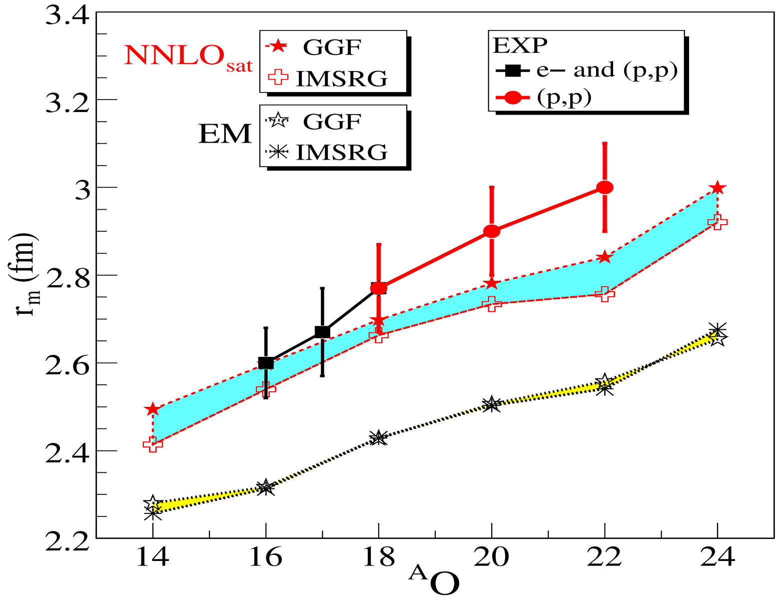


binding energies

FIG. 1. Oxygen binding energies. Results from SCGF and IMSRG calculations performed with EM [20–22] and NNLO$_{sat}$ [26] interactions are displayed along with available experimental data.



proton radii



matter radii

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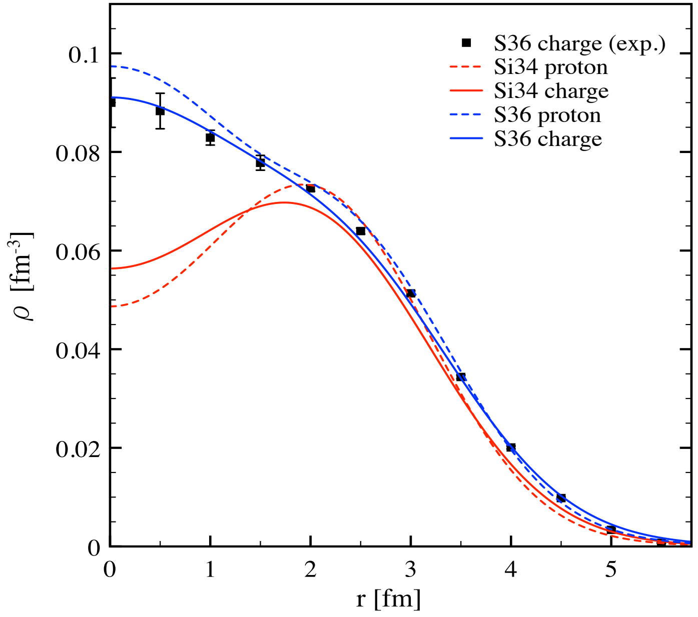
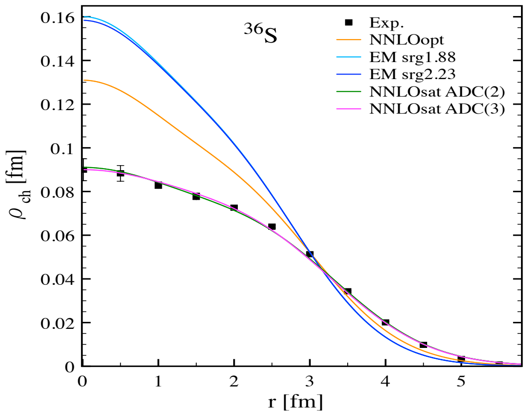
Bubble nuclei… ^{34}Si prediction

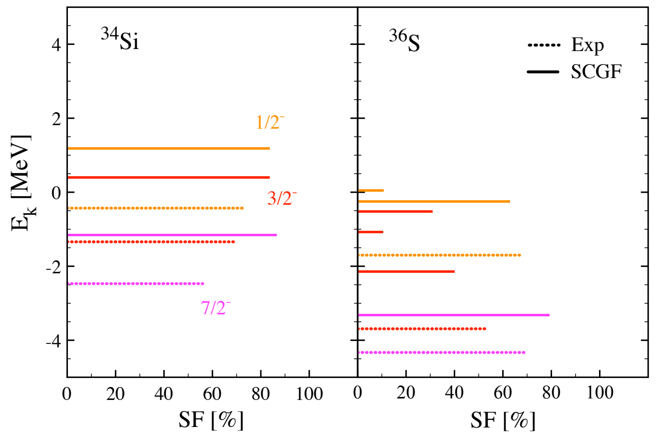


Duguet, Somà, Lecuse, CB, Navrátil,
Phys.Rev. C**95**, 034319 (2017)

- ^{34}Si is unstable, charge distribution is still unknown
- Suggested central depletion from mean-field simulations
- *Ab-initio* theory confirms predictions
- Other theoretical and experimental evidence:
  Phys. Rev. ***C 79****, 034318 (2009),*
  Nature Physics ***13****, 152–156 (2017).*

Validated by charge distributions and neutron quasiparticle spectra:





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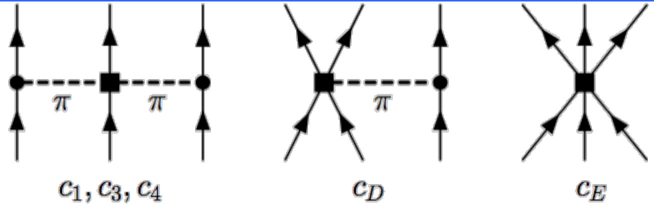
Local vs. non-local chiral N^2LO NNN interaction — by P. Navrátil

- Local: chiral N^3LO NN+ N^2LO 3N500
  - c_D=-0.2 c_E=-0.205 (^{3}H E_{gs}=-8.48 MeV)
  - ^{4}He



<H>=-28.4939   <V3b_2pi>= -5.8819   <V3b_D>= -0.2206   <V3b_E>= 1.2665

- Non-local: chiral N^2LO_{sat} NN+3N
  - c_D=+0.8168 c_E=-0.0396 (^{3}H E_{gs}=-8.53 MeV)
  - ^{4}He

<H>=-28.4596   <V3b_2pi>= -4.7260   <V3b_D>= 1.3897   <V3b_E>= 0.4174

- Local/Non-local: chiral N^3LO NN+ N^2LO

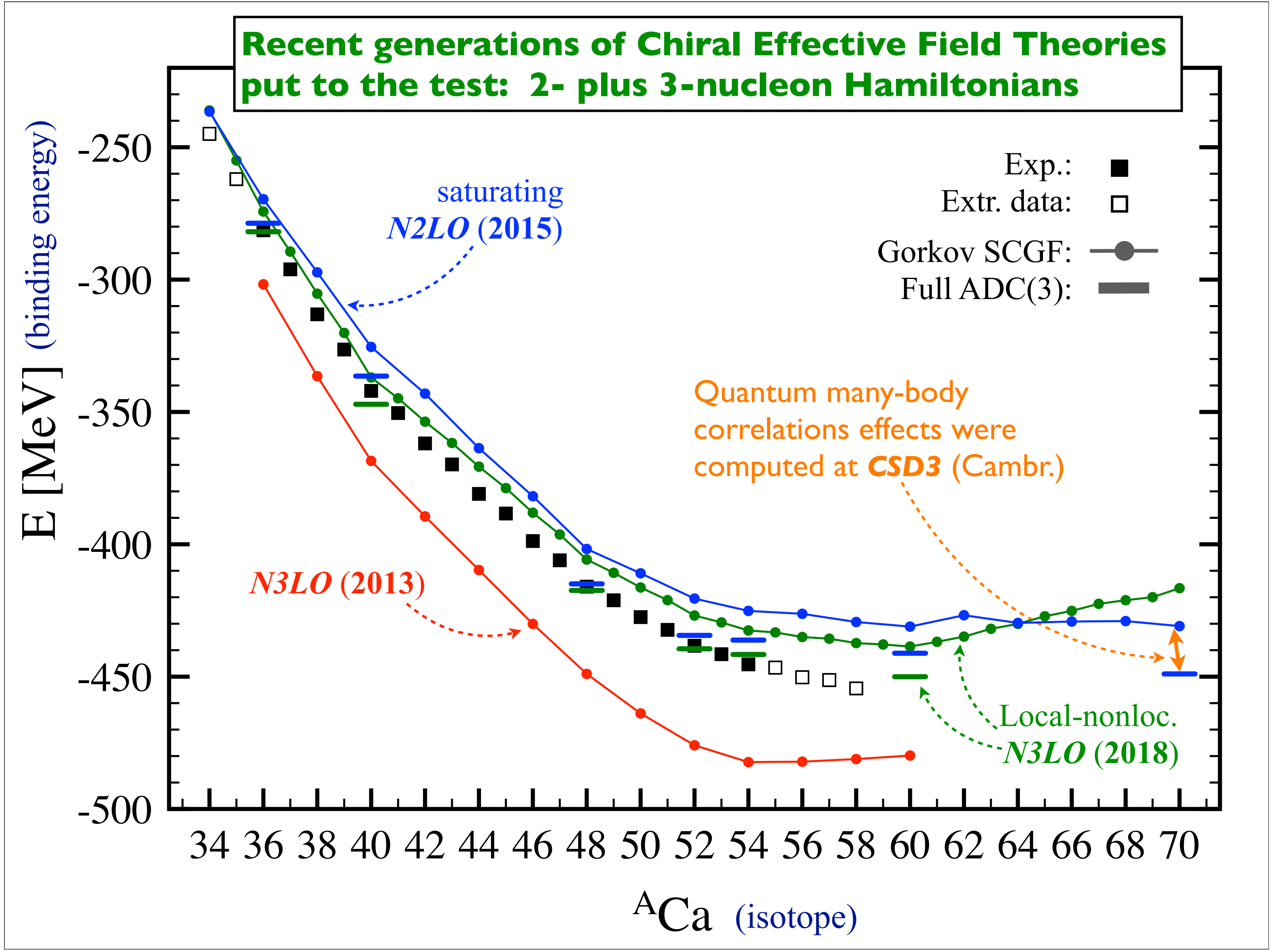
$$F(\tfrac{1}{2}(\pi_1^2+\pi_2^2);\Lambda_{nonloc})\, W_1^Q(\Lambda_{loc})\, F(\tfrac{1}{2}(\pi_1^2+\pi_2^2);\Lambda_{nonloc})$$

Use completeness in HO basis to calculate products of *F W F*

  - c_D=+0.7 c_E=-0.06 (^{3}H E_{gs}=-8.44 MeV)
  - ^{4}He

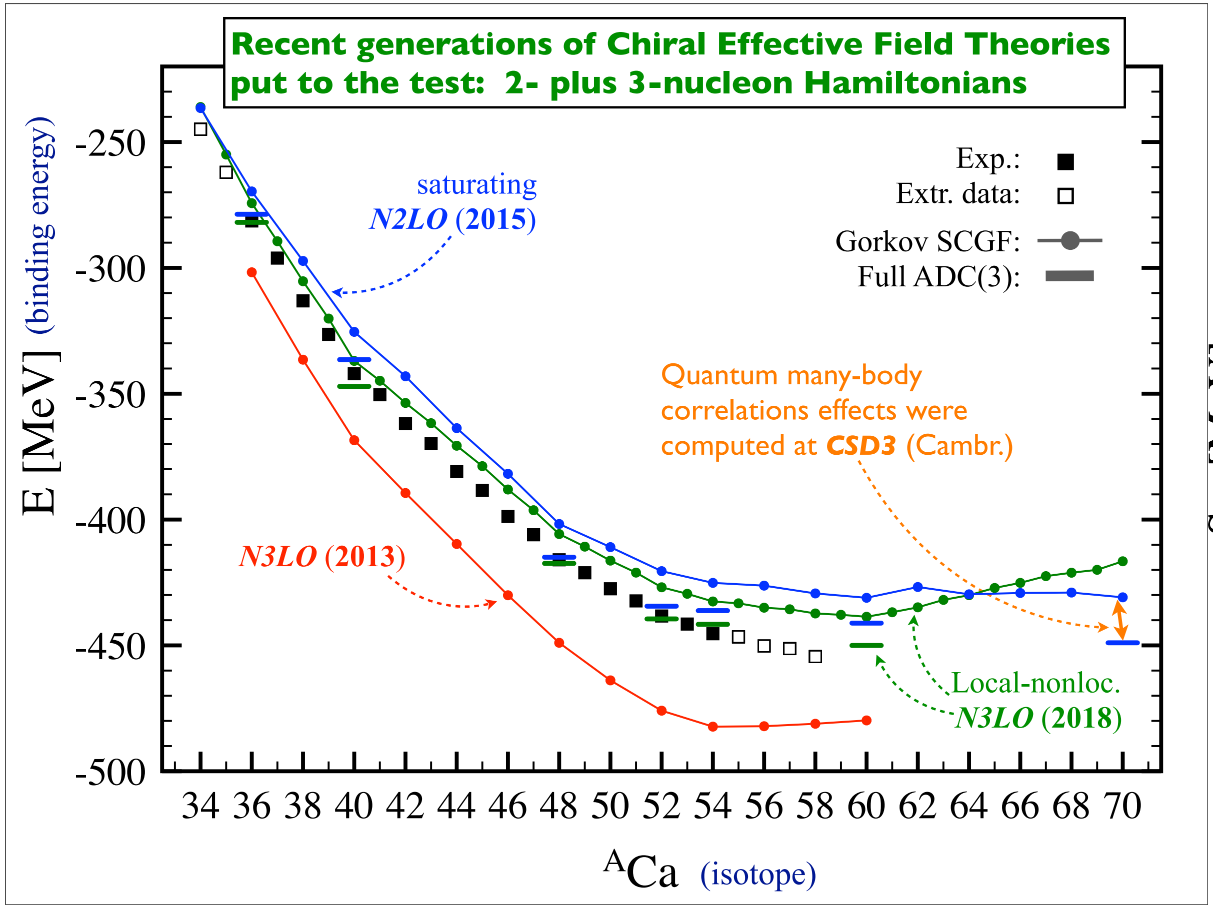
<H>=-28.2530   <V3b_2pi>= -4.8124   <V3b_D>= 0.7414   <V3b_E>= 0.4255

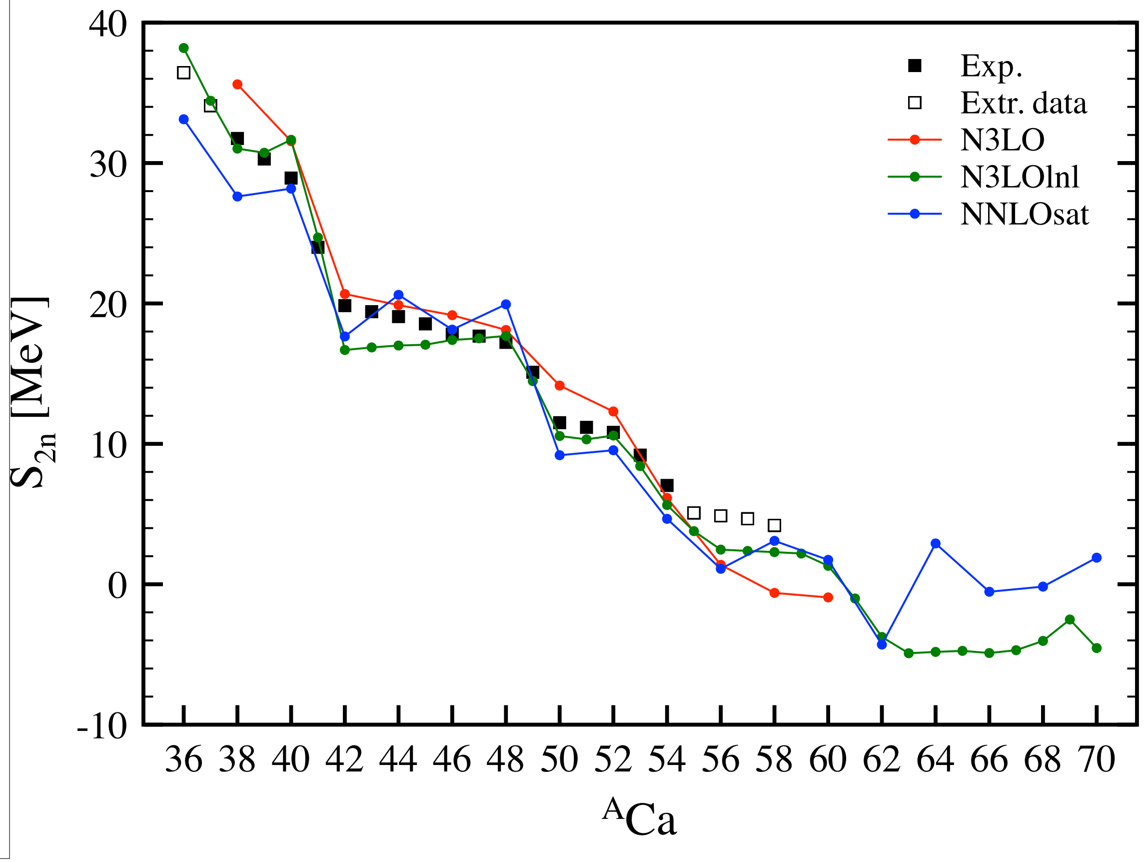
Comparison of nuclear forces - ^{A}Ca



V. Somà, F. Raimondi, CB, P. Navrátil, T. Duguet, in preparation

Comparison of nuclear forces - ^{A}Ca



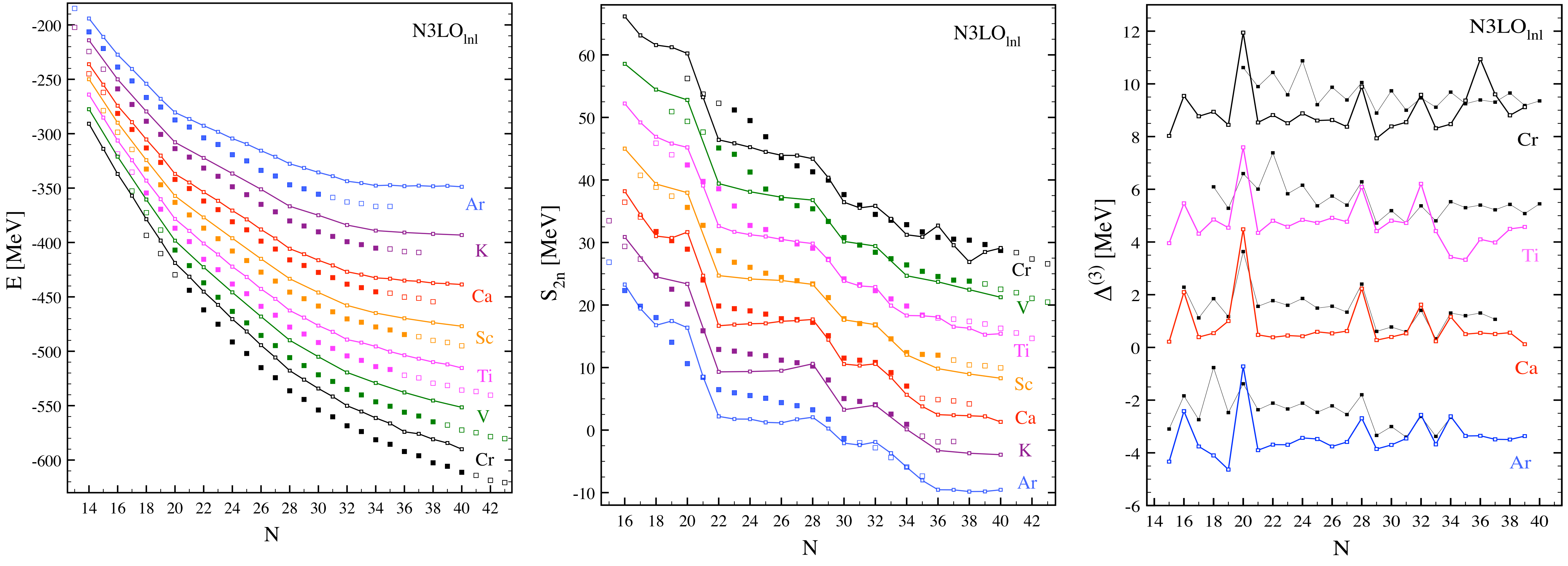


V. Somà, F. Raimondi, CB, P. Navrátil, T. Duguet, in preparation

N3LO(500) + nln 3NF

SCGF – Gorkov-ADC(2)

PRELIMINARY



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V. Somà, F. Raimondi, CB, P. Navrátil, T. Duguet, in preparation

Masses in the Ti isotopic chain

- High precision measurements at TITAN (TRIUMF):
  Newly developed Multiple-Reflection Time-of-Flight Mass Spectrometer (MR-TOF-MS)

- Weak shell closure at N=32 (quenched w.r.t. ^{52}Ca)

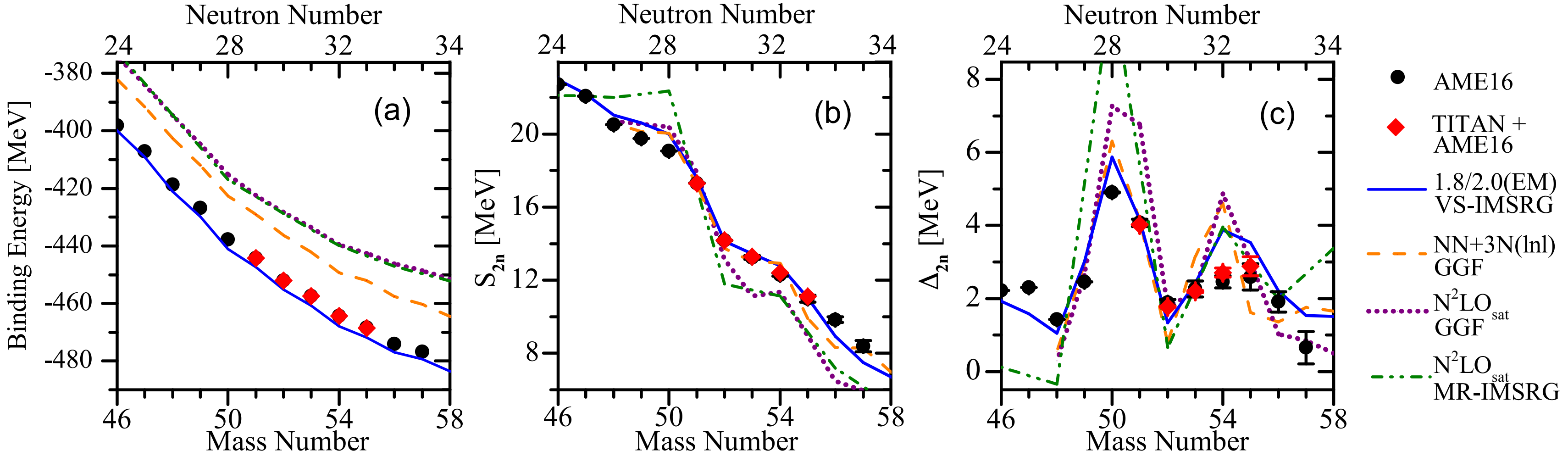

FIG. 4. The mass landscape of titanium isotopes is shown from three perspectives: (a) absolute masses (shown in binding energy format), (b) its first "derivative" as two-neutron separation energies (S_{2n}), and (c) its second "derivative" as empirical neutron-shell gaps (Δ_{2n}). Both theoretical *ab-initio* calculations (lines) and experimental values (points) are shown.

E. Leistenschneider *et al., CB*, Phy. Rev. Lett. , 0 (2018) – ***TITAN*** coll. @ TRIUMF

Electron and neutrino scattering off nuclei

N. Rocco, CB, Phys. Rev. C**98**, 025501 (2018).

N. Rocco, CB, O. Benhar, A. De Pace, A. Lovato, arXiv:1810.0wxyz (in prep)

Lepton-nucleon cross section

$$\left(\frac{d\sigma}{dT' d\cos\theta'}\right)_{\nu/\bar{\nu}} = \frac{G^2}{2\pi}\frac{k'}{2E_\nu}\left[\hat{L}_{CC}R_{CC} + 2\hat{L}_{CL}R_{CL} + \hat{L}_{LL}R_{LL} + \hat{L}_T R_T \pm 2\hat{L}_{T'}R_{T'}\right],$$

Nuclear structure is in the hadronic tensor:

$$\begin{aligned}
R_{CC} &= W^{00} \\
R_{CL} &= -\frac{1}{2}(W^{03} + W^{30}) \\
R_{LL} &= W^{33} \\
R_T &= W^{11} + W^{22} \\
R_{T'} &= -\frac{i}{2}(W^{12} - W^{21}),
\end{aligned}$$

$$W^{\mu\nu} = \sum_f \langle 0|j^{\mu\,\dagger}|f\rangle\langle f|j^\nu|0\rangle\delta(E_0 + \omega - E_f)$$

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Lepton-nucleon cross section

$$\left(\frac{d\sigma}{dT' d\cos\theta'}\right)_{\nu/\bar\nu} = \frac{G^2}{2\pi}\frac{k'}{2E_\nu}\left[\hat L_{CC}R_{CC} + 2\hat L_{CL}R_{CL} + \hat L_{LL}R_{LL} + \hat L_T R_T \pm 2\hat L_{T'}R_{T'}\right] ,$$

Nuclear structure is in the hadronic tensor:

$$W^{\mu\nu}(\mathbf{q},\omega) = \int \frac{d^3k}{(2\pi)^3} dE\, P_h(\mathbf{k},E)\frac{m^2}{e(\mathbf{k})e(\mathbf{k}+\mathbf{q})} \times \sum_i \langle k|j_i^{\mu\dagger}|k+q\rangle\langle k+q|j_i^\nu|k\rangle \times \delta(\omega + E - e(\mathbf{k}+\mathbf{q})) ,$$

$$W_{2b}^{\mu\nu}(\mathbf{q},\omega) = \frac{V}{2}\int d\tilde E \frac{d^3k}{(2\pi)^3} d\tilde E' \frac{d^3k'}{(2\pi)^3}\frac{d^3p}{(2\pi)^3} \times \frac{m^4}{e(\mathbf{k})e(\mathbf{k}')e(\mathbf{p})e(\mathbf{p}')} P_h^{\rm NM}(\mathbf{k},\tilde E)P_h^{\rm NM}(\mathbf{k}',\tilde E') \times \sum_{ij}\langle k\,k'|j_{ij}^{\mu\dagger}|p\,p'\rangle\langle p\,p'|j_{ij}^\nu|k\,k'\rangle \times \delta(\omega + \tilde E + \tilde E' - e(\mathbf{p}) - e(\mathbf{p}')) . \qquad (41)$$

Two models of the Spectral function

$$P_h(\mathbf{k},E) = \frac{1}{\pi}\sum_{\alpha\beta}\tilde\Phi_\beta^*(\mathbf{k})\tilde\Phi_\alpha(\mathbf{k}) \times \mathrm{Im}\langle\psi_0^A|a_\beta^\dagger \frac{1}{E + (H - E_0^A) - i\epsilon} a_\alpha|\psi_0^A\rangle$$

SCGF/ADC(3) using chiral NNLOsat

$$P_h(\mathbf{k},E) = P_h^{1h}(\mathbf{k},E) + P_h^{\rm corr}(\mathbf{k},E) .$$

$$P_h^{1h}(\mathbf{k},E) = \sum_{\alpha\in\{F\}} Z_\alpha|\phi_\alpha(\mathbf{k})|^2 F_\alpha(E - e_\alpha)$$

$$P_h^{\rm corr}(\mathbf{k},E) = \int d^3R\, \rho_A(\mathbf{R})P_{h,\,NM}^{\rm corr}(\mathbf{k},E;\rho_A(\mathbf{R}))$$

CBF using AV18+UIX (see Benhar's talk)

N. Rocco, CB, O. Benhar, de Pace , A. Lovato, arXiv:1810.0wxyz (in preparation)

Lepton-nucleon cross section

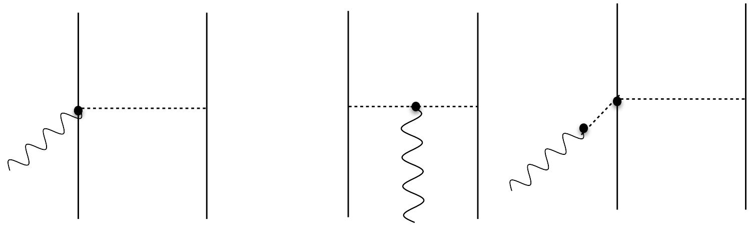
$$\left(\frac{d\sigma}{dT'd\cos\theta'}\right)_{\nu/\bar{\nu}} = \frac{G^2}{2\pi}\frac{k'}{2E_\nu}\left[\hat{L}_{CC}R_{CC} + 2\hat{L}_{CL}R_{CL} + \hat{L}_{LL}R_{LL} + \hat{L}_T R_T \pm 2\hat{L}_{T'}R_{T'}\right],$$

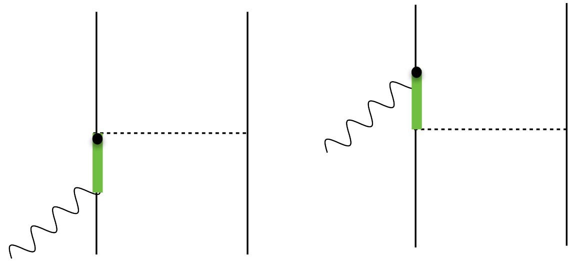
Nuclear structure is in the hadronic tensor:

$$W^{\mu\nu}(\mathbf{q},\omega) = \int \frac{d^3k}{(2\pi)^3} dE\, P_h(\mathbf{k},E) \frac{m^2}{e(\mathbf{k})e(\mathbf{k}+\mathbf{q})} \times \sum_i \langle k|j_i^{\mu\dagger}|k+q\rangle\langle k+q|j_i^\nu|k\rangle \times \delta(\omega + E - e(\mathbf{k}+\mathbf{q})),$$

$$W_{2b}^{\mu\nu}(\mathbf{q},\omega) = \frac{V}{2}\int d\tilde{E}\frac{d^3k}{(2\pi)^3}d\tilde{E}'\frac{d^3k'}{(2\pi)^3}\frac{d^3p}{(2\pi)^3} \times \frac{m^4}{e(\mathbf{k})e(\mathbf{k}')e(\mathbf{p})e(\mathbf{p}')}P_h^{\rm NM}(\mathbf{k},\tilde{E})P_h^{\rm NM}(\mathbf{k}',\tilde{E}') \times \sum_{ij}\langle k\,k'|j_{ij}^{\mu\,\dagger}|p\,p'\rangle\langle p\,p'|j_{ij}^\nu|k\,k'\rangle \times \delta(\omega + \tilde{E} + \tilde{E}' - e(\mathbf{p}) - e(\mathbf{p}')). \qquad (41)$$

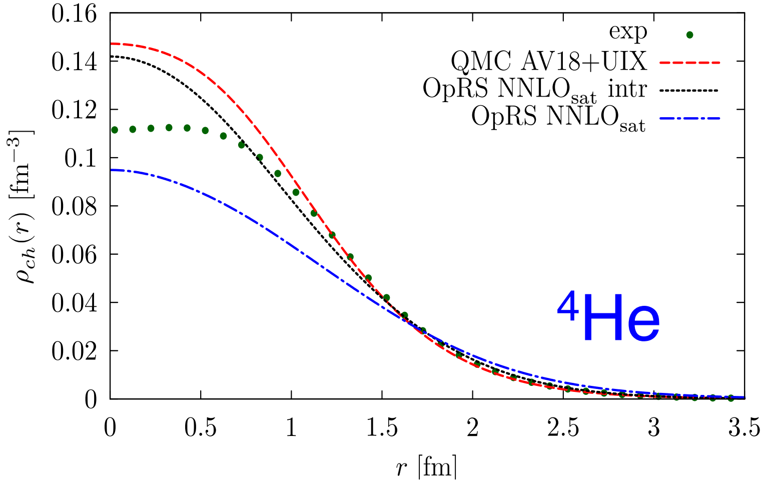
- Two-body diagrams contributing to the axial and vector responses

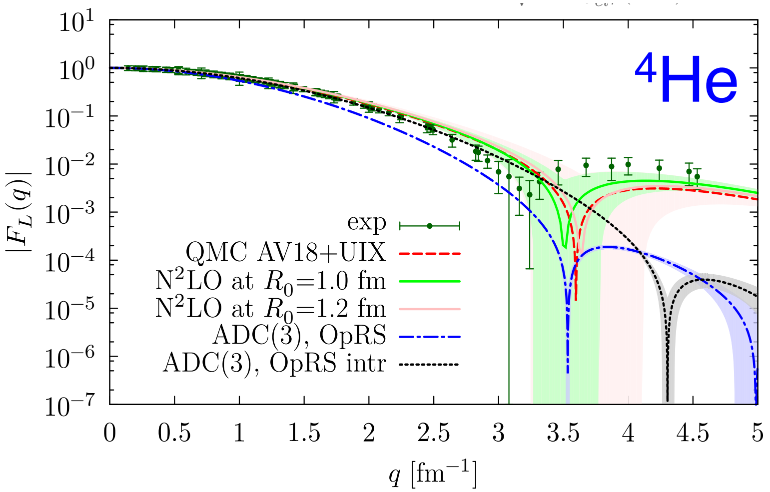


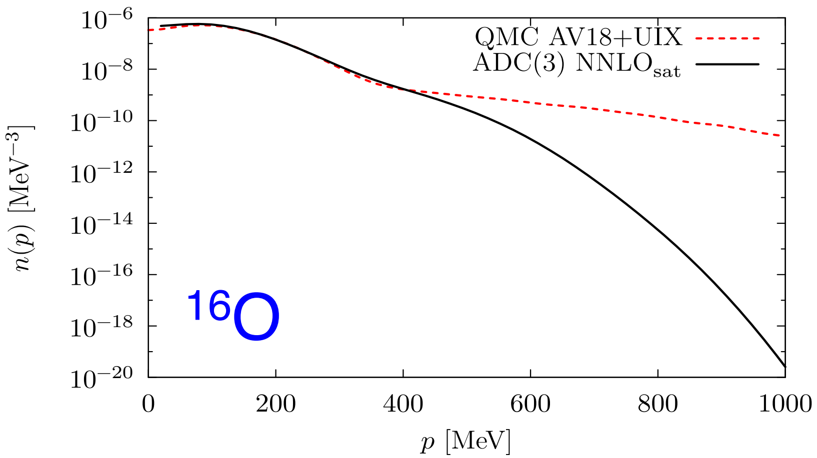


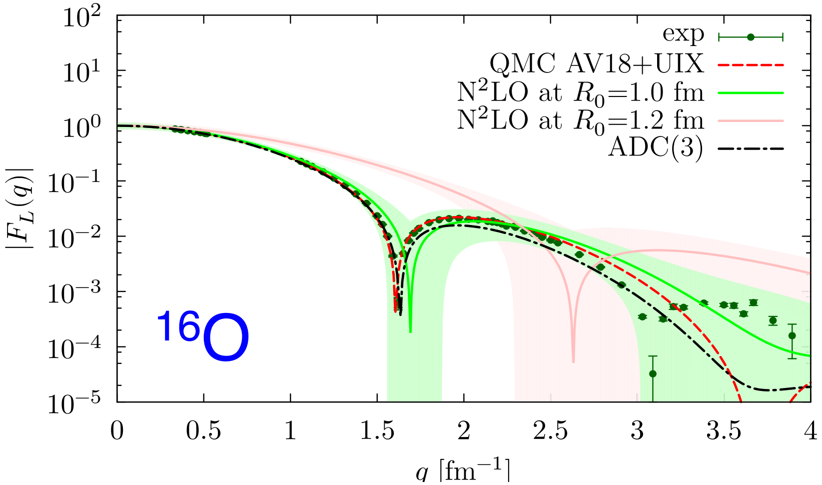
Prediction for chrg./mom. distributions and form factors

$$F_L(\mathbf{q}) = \frac{1}{Z}\frac{G_E^p(Q_{el}^2)\tilde{\rho}_p(q) + G_E^n(Q_{el}^2)\tilde{\rho}_n(q)}{\sqrt{1+Q_{el}^2/(4m^2)}}$$









- *Calculations from the spectral functions obtained using SCGF*
- *Based on the saturating chiral N2LO-sat nuclear force*
- *Comparison to QMC calculations based on local chiral forces and/or AV18+UIX*
  [PRC96, 024326 ('17)
  PRC96, 054007 ('17)
  PRC97, 044318 ('18)]

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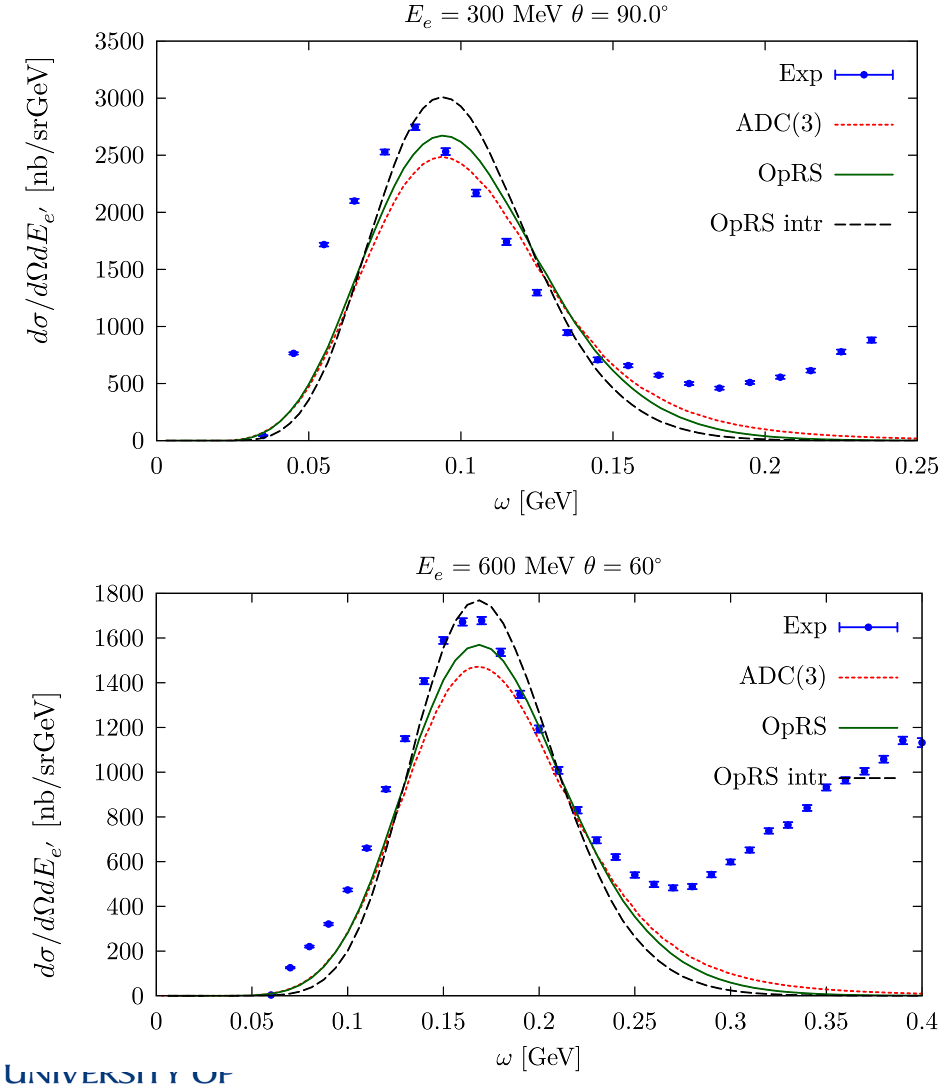
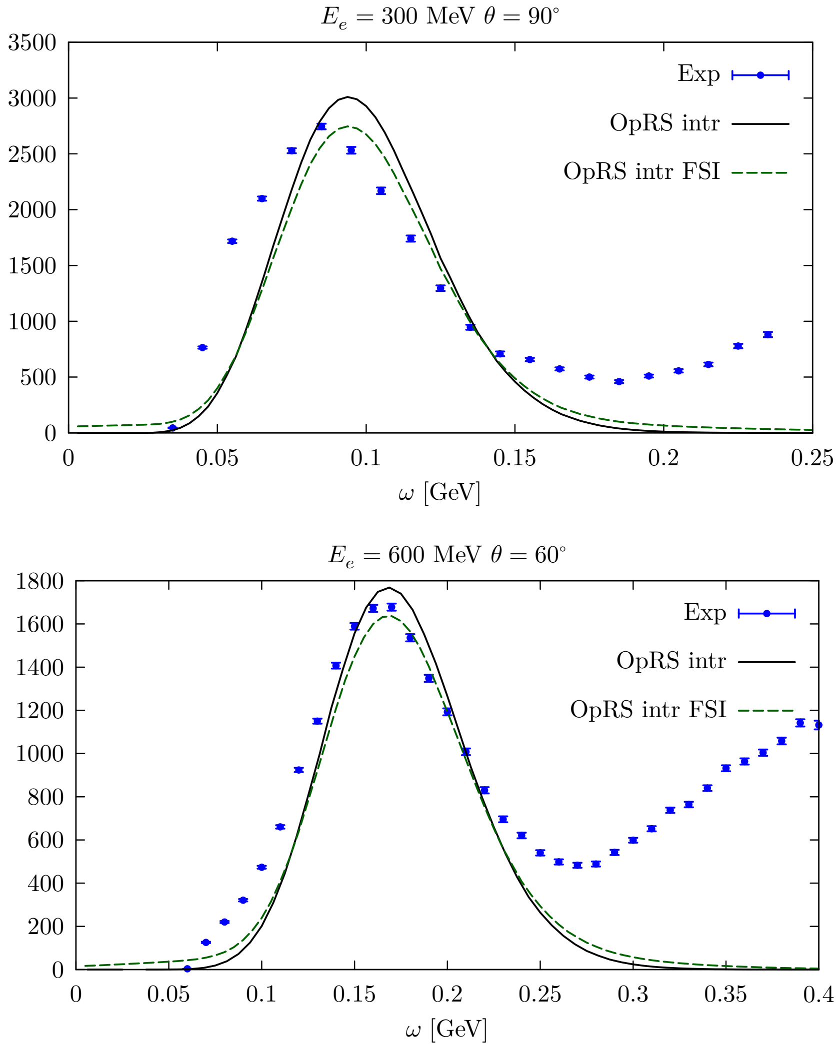
N. Rocco, CB, Phys. Rev. C**98**, 025501 (2018).

^4He-e^- cross sections from the SCGF Spect. Fnct.

PW Impulse approximation:



Adding FSI:



Based on the saturating chiral N2LO-sat nuclear force

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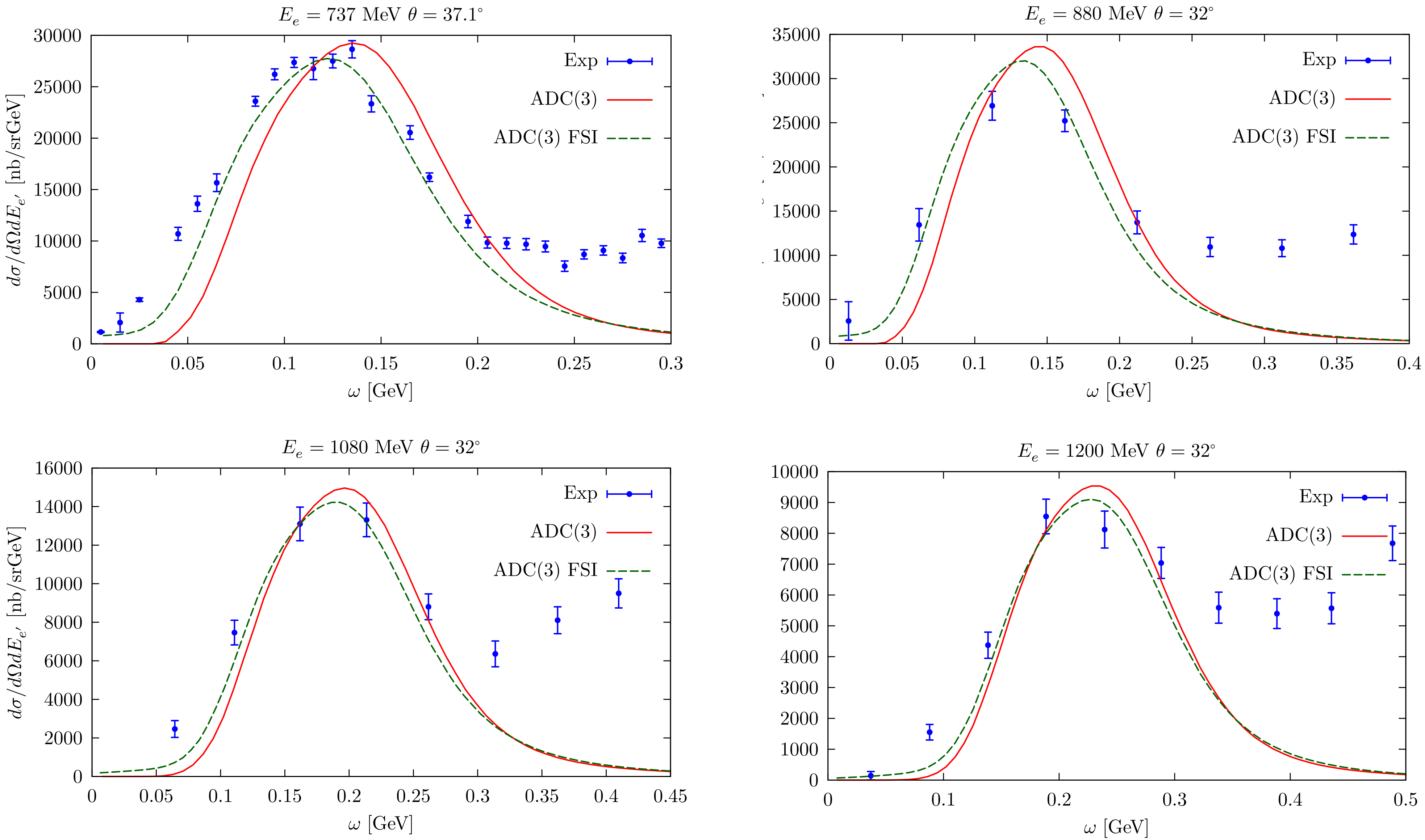
N. Rocco, CB, Phys. Rev. C**98**, 025501 (2018).

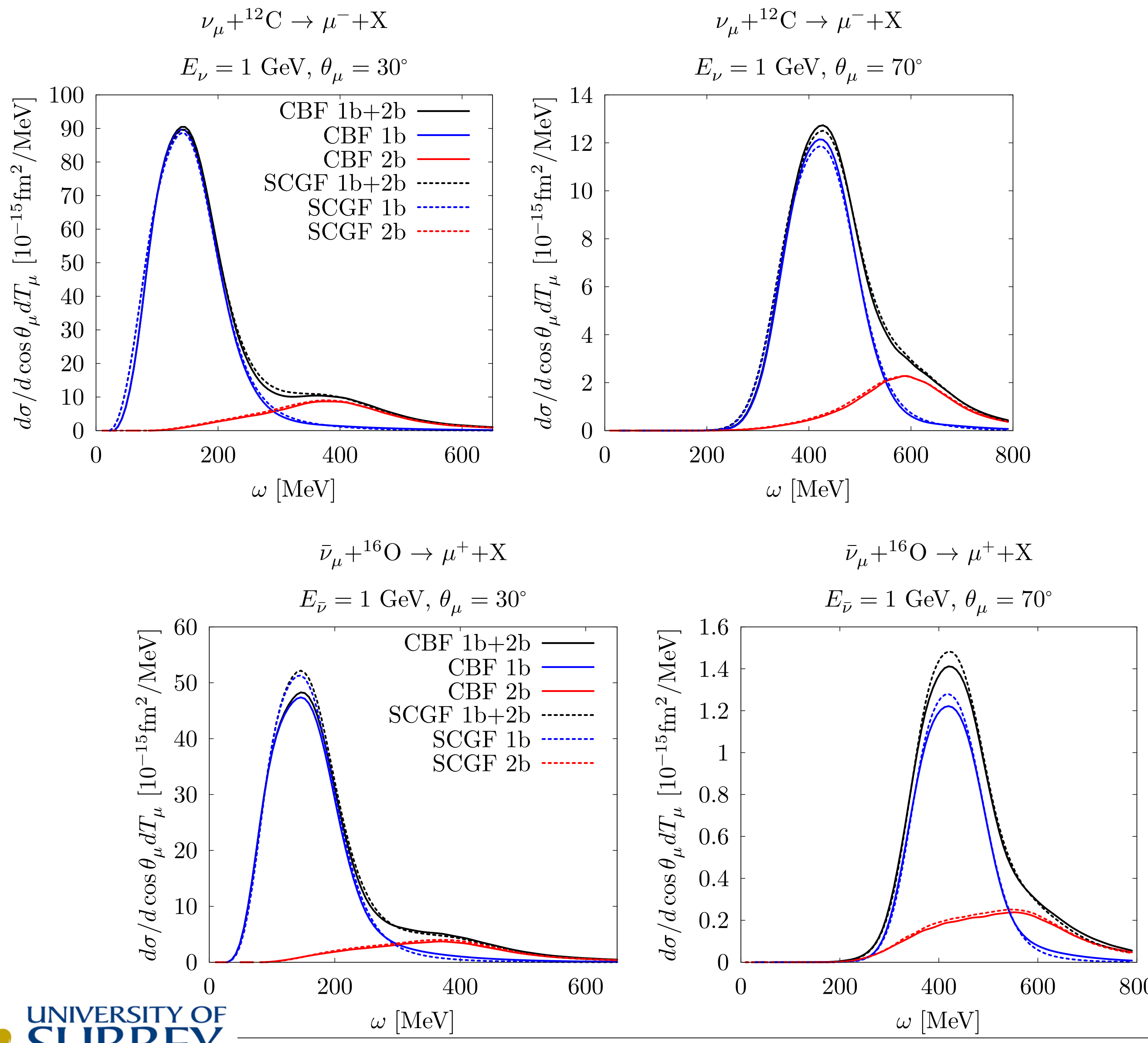
^{16}O-e$^-$ cross sections from the SCGF Spect. Fnct.



Based on the saturating chiral N2LO-sat nuclear force

N. Rocco, CB, Phys. Rev. C**98**, 025501 (2018).

Charged-current reaction for 1 GeV neutrinos



One-body current describe quasi elastic peak

Difference between CBF(AV18) and SCGF(NNLOsat) from 1-b terms

Two-body currents fiull up dip region

Missing Delta and meson emission contributions

X-sec. droppin with scattering angle

N. Rocco, CB, O. Benhar, A. De Pace , A. Lovato, arXiv:1810.0wxyz (in preparation)

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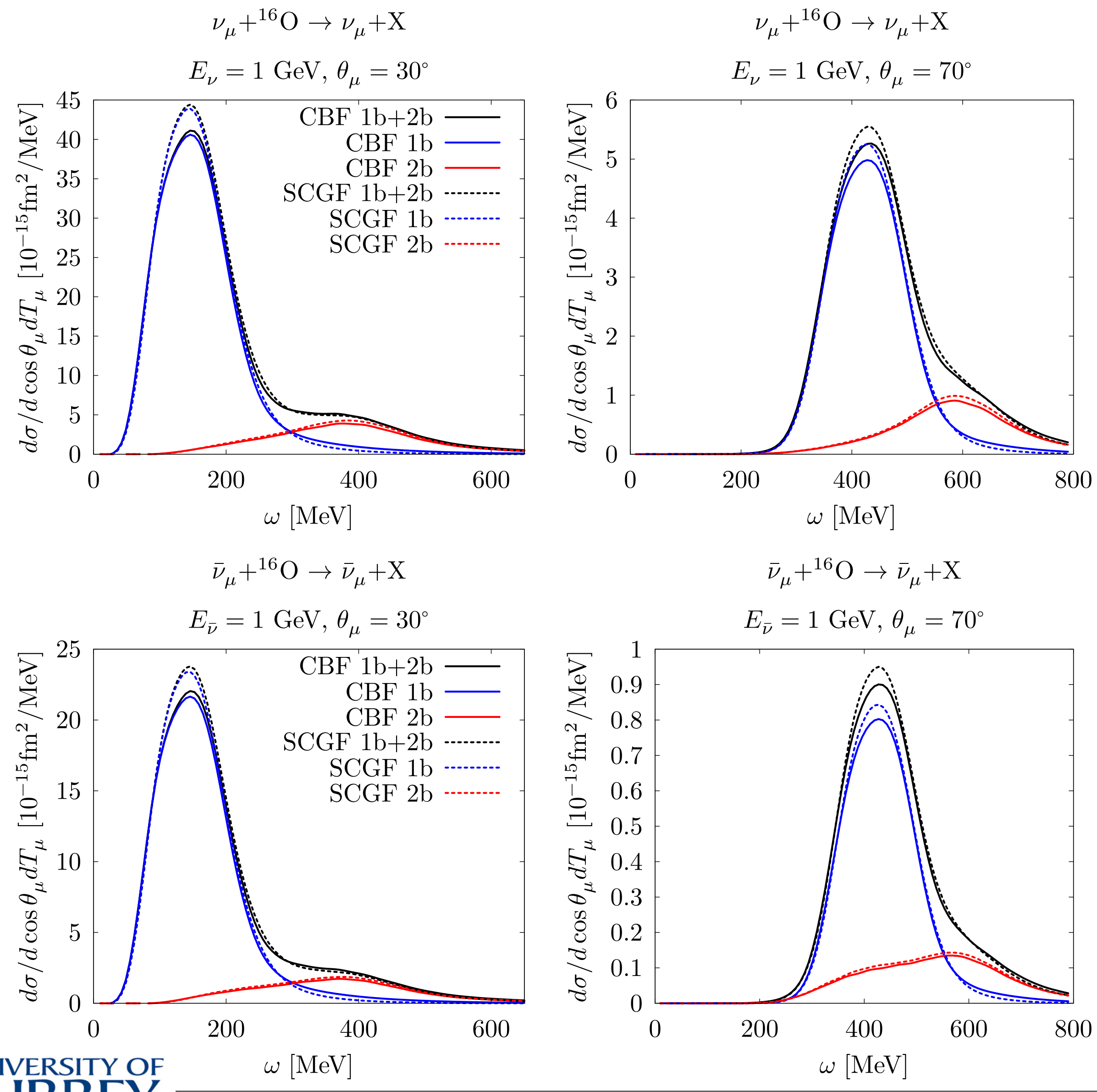
Neutral-current reaction for 1 GeV neutrinos



One-body current describe quasi elastic peak

Difference between CBF(AV18) and SCGF(NNLOsat) from 1-b terms

Two-body currents fiull up dip region

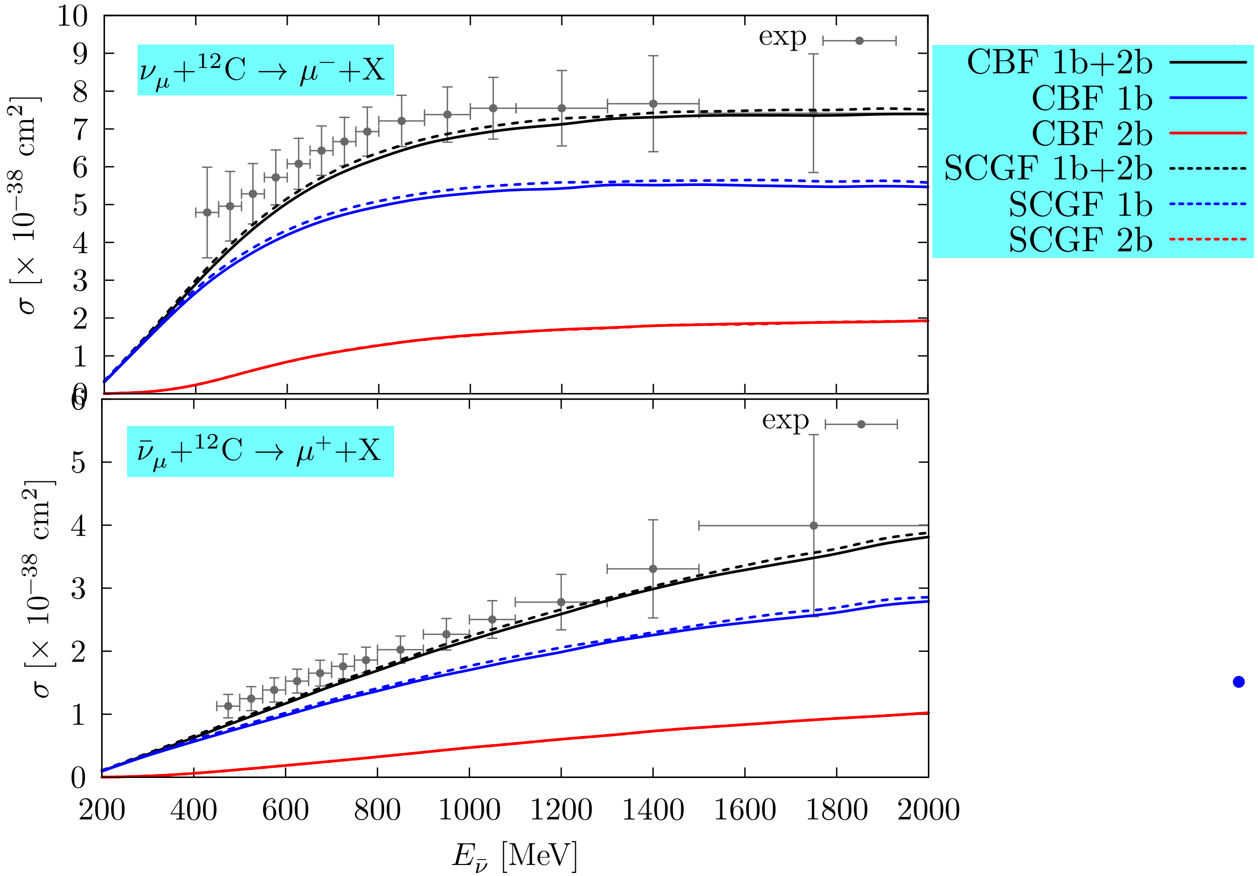
Missing Delta and meson emission contributions

X-sec. droppin with scattering angle

N. Rocco, CB, O. Benhar, A. De Pace , A. Lovato, arXiv:1810.0wxyz (in preparation)

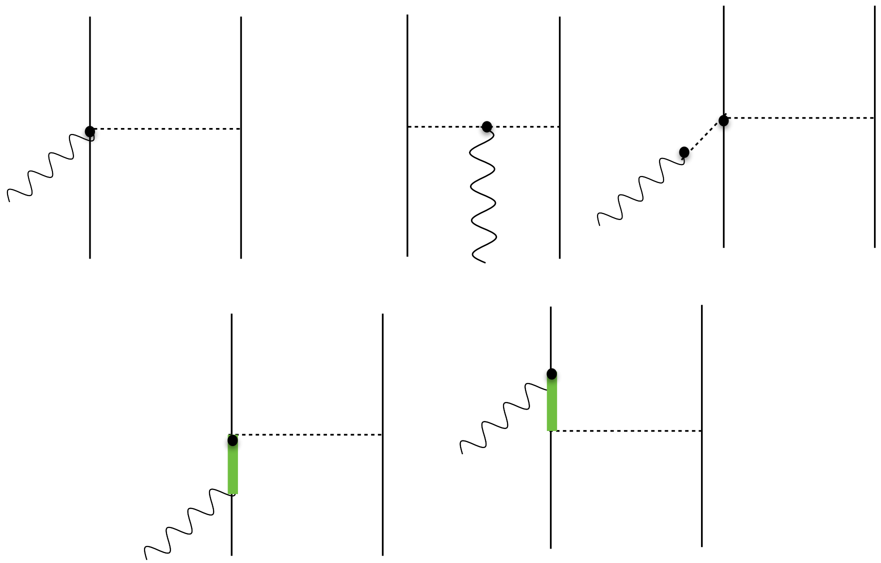
Role of two-body (meson exchange) currents in ν-A

CC0π total cross section: MiniBooNE data



The 2p2h contribution is needed to explain the magnitude of the total cross section

- Two-body diagrams contributing to the axial and vector responses



- Preliminary implementation discards 1b-2b interference:

$$W^{\mu\nu}_{2p2h} = W^{\mu\nu}_{ISC} + W^{\mu\nu}_{MEC} + W^{\mu\nu}_{int}$$

N. Rocco, CB, O. Benhar, A. De Pace , A. Lovato, arXiv:1810.0wxyz (in preparation)

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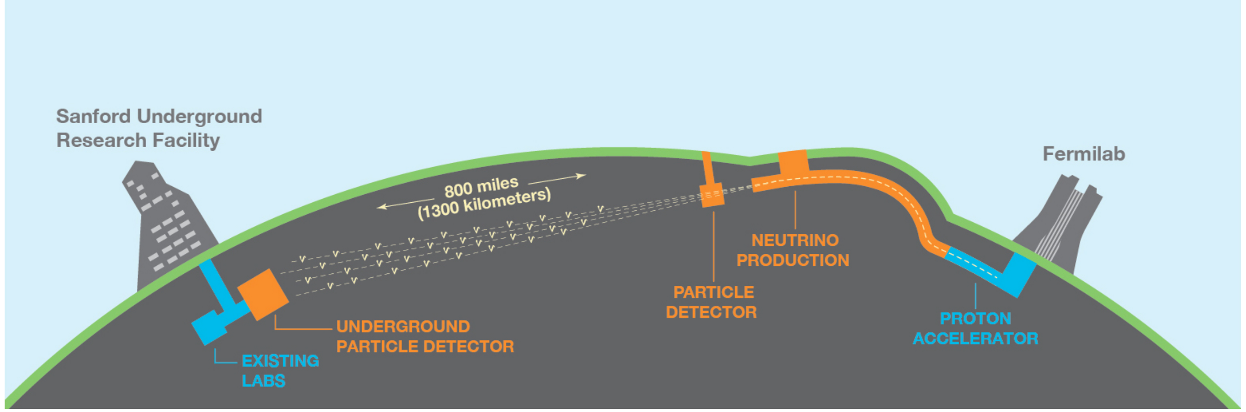
Neutrino Oscillations – next generation experiments



DUNE experiment will measure long base line neutrino oscillations to:

- Resolve neutrino mass hierarchy
- Search for CP violation in weak interaction
- Search for other physics beyond SM

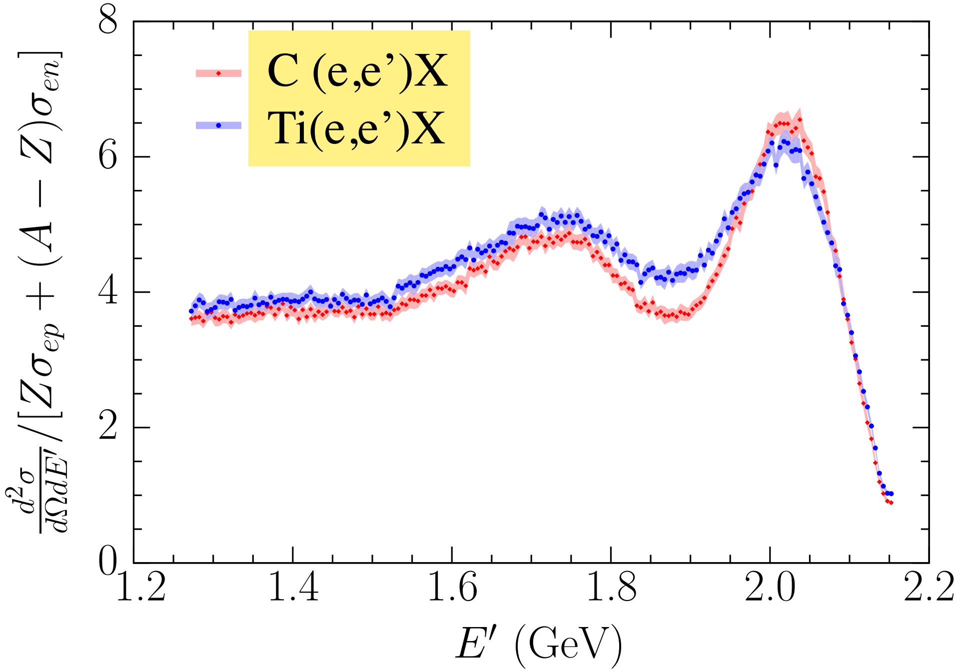
Liquid Argon projection chamber is being used. It will require one order of magnitude (20% → 2%) improvement in theoretical prediction for ν-^{40}Ar cross sections to achieve proper event reconstruction.

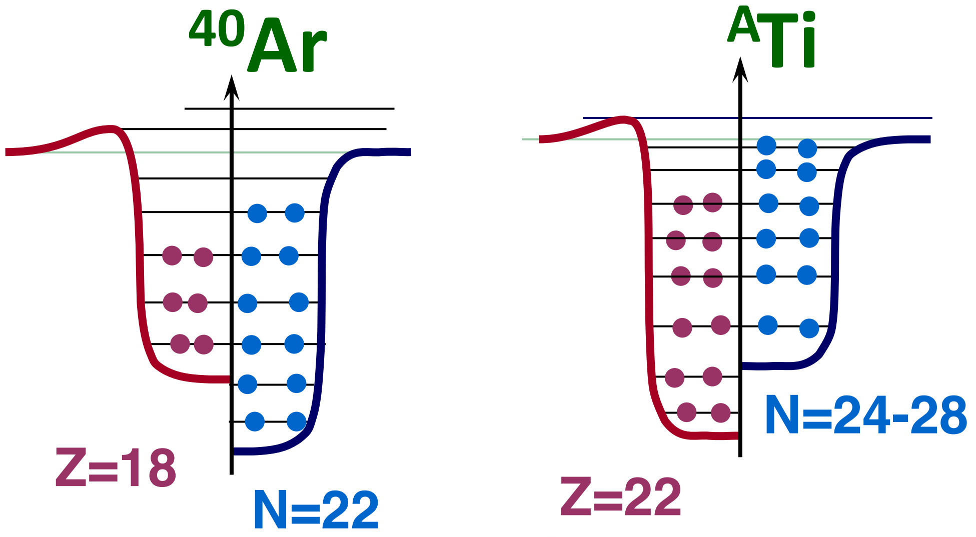
➔ **Need good knowledge of ^{40}Ar spectral functions and consistent structure-scattering theories.**

Spectral function for ^{40}Ar and Ti

Jlab experiment E12-14-012 (Hall A)

Phys. Rev. C 98, 014617 (2018)

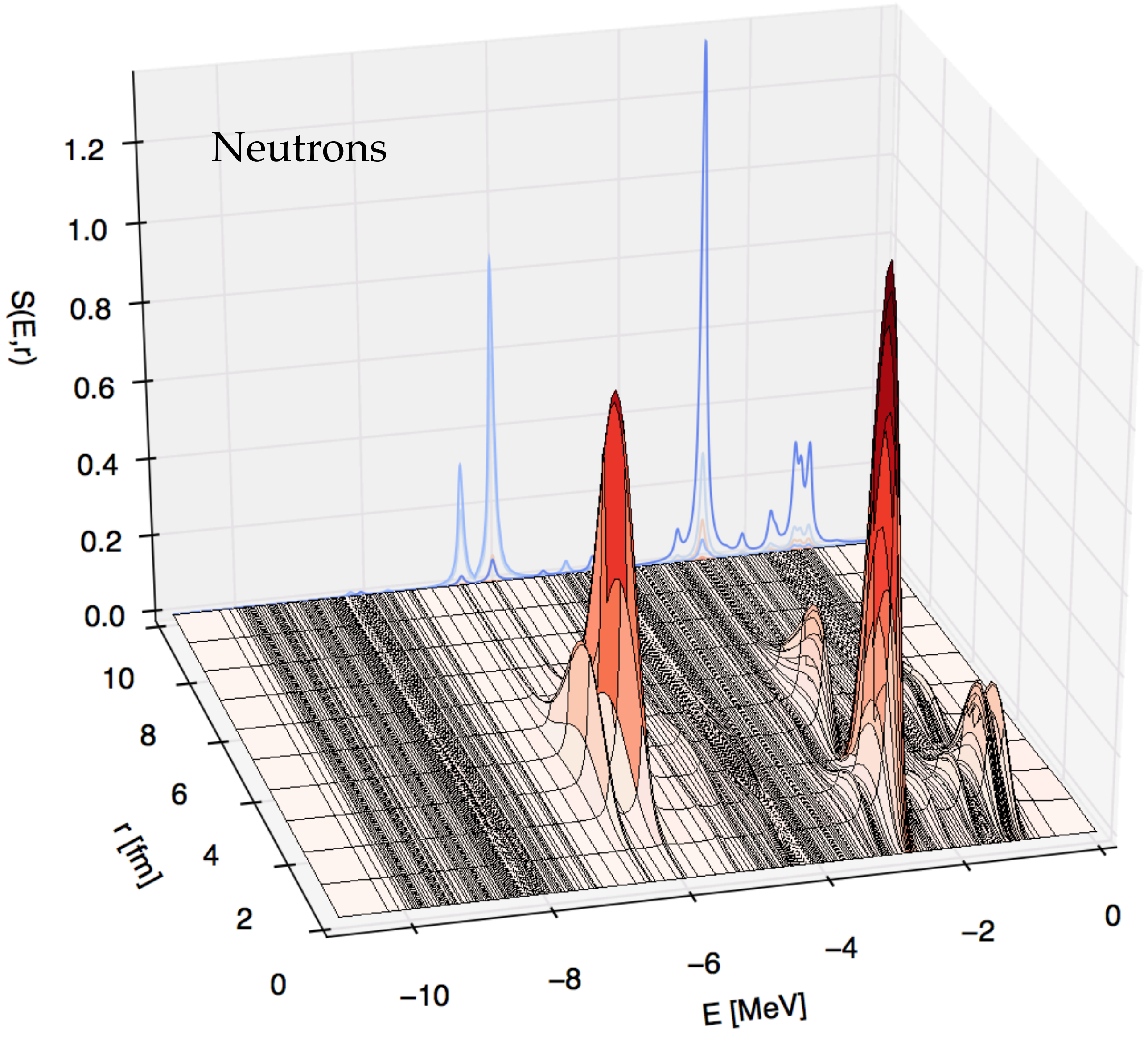




Proton distribution in Ti similar to neutron in ^{40}Ar ??

^{40}Ar(e,e'p) and Ti(e,e'p) data being analyzed

Spectral function for ^{40}Ar



- Experimental datat now available for Jlab: H. Dai et al., arXiv:1803.01910
- Ab initio simulations based on the ADC(2) truncation of the N2LO-sat Hamiltoninan

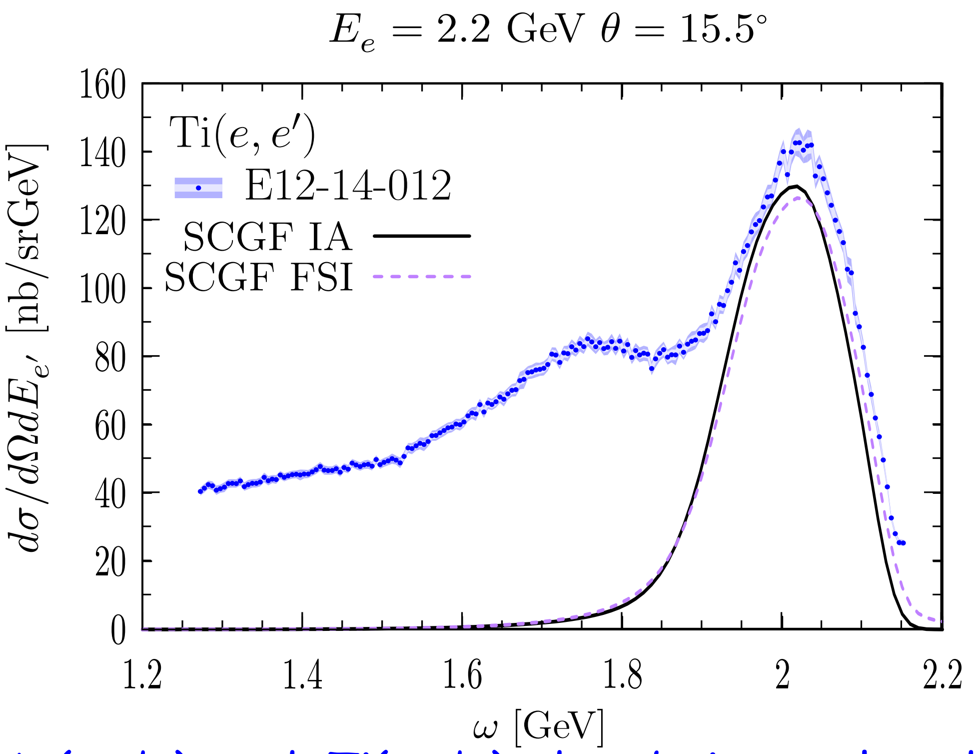
➔ Want validation of initial state correlation <u>before</u> they are implementer in neutrino-^{40}Ar simulations

N. Rocco, V. Somà, CB, in preparation

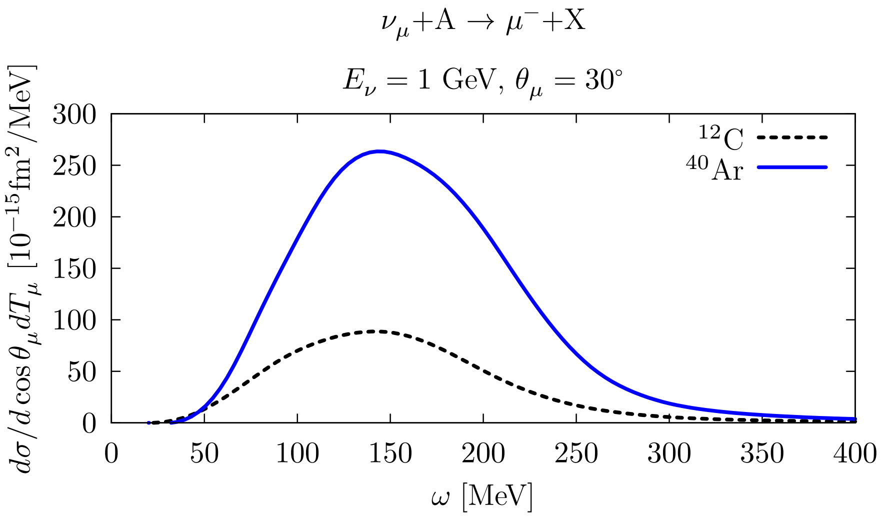
Electron and ν scattering on ^{40}Ar and Ti

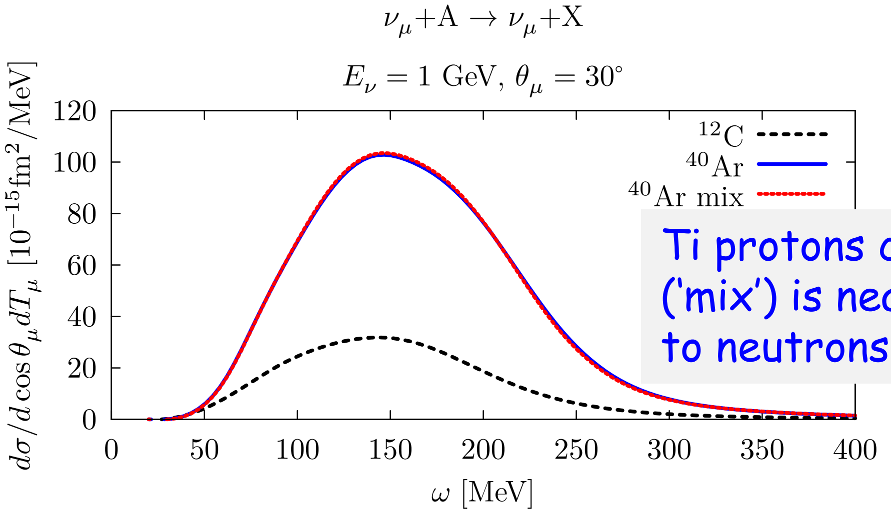
Jlab experiment E12-14-012 (Hall A)

Phys. Rev. C 98, 014617 (2018)



^{40}Ar(e,e′p) and Ti(e,e′p) data being analyzed





Ti protons contribution ('mix') is nearly identical to neutrons in ^{40}Ar.

N. Rocco, CB and V. Somà, in preparation.

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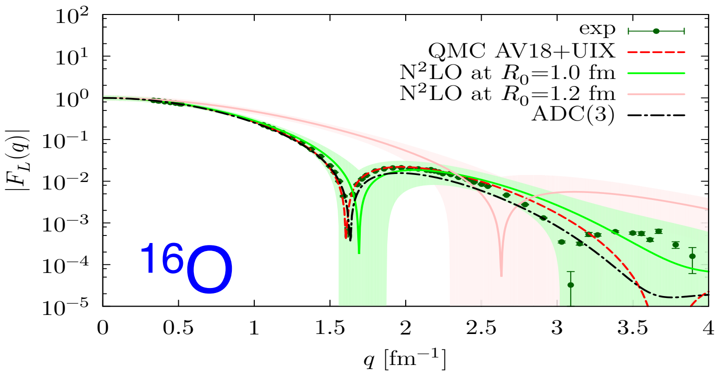
Summary

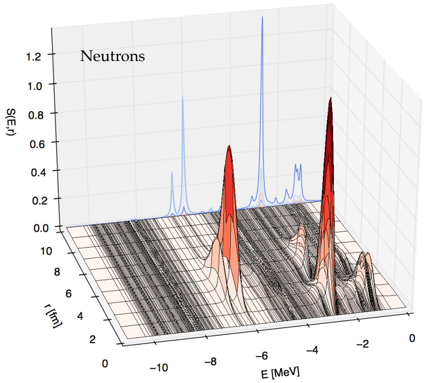
Thank you for your attention!!!

Saturating chiral interactions and 3N forces:

→ *Description of nuclear g.s. in the pf shell is improved-especially in the trends w.r.t. iso-sopin asymmetry.*

→ *Radii: newer generations of chiral interaction can give satisfactory radii.*





Applications to electron and neutrino scattering:

→ *Spectral functions are extracted naturally from the SCGF formalism.*

→ *good reproduction of charge/momentum distribution and electron scattering.*

→ *Inclusion of electroweak currents (1b and 2b) underway (by N. Rocco).*

UNIVERSITY OF SURREY — ***A. Cipollone***, *A. Rios*, *A. Idini*, ***F. Raimondi***

cea — *V. Somà, T. Duguet*

A. Lovato, ***N. Rocco***

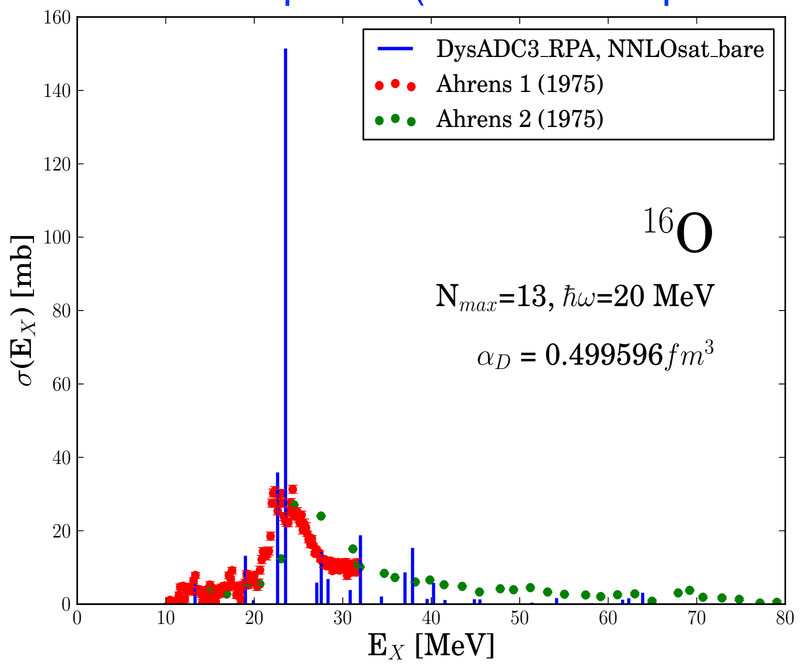
ECT* — ***A. Carbone***

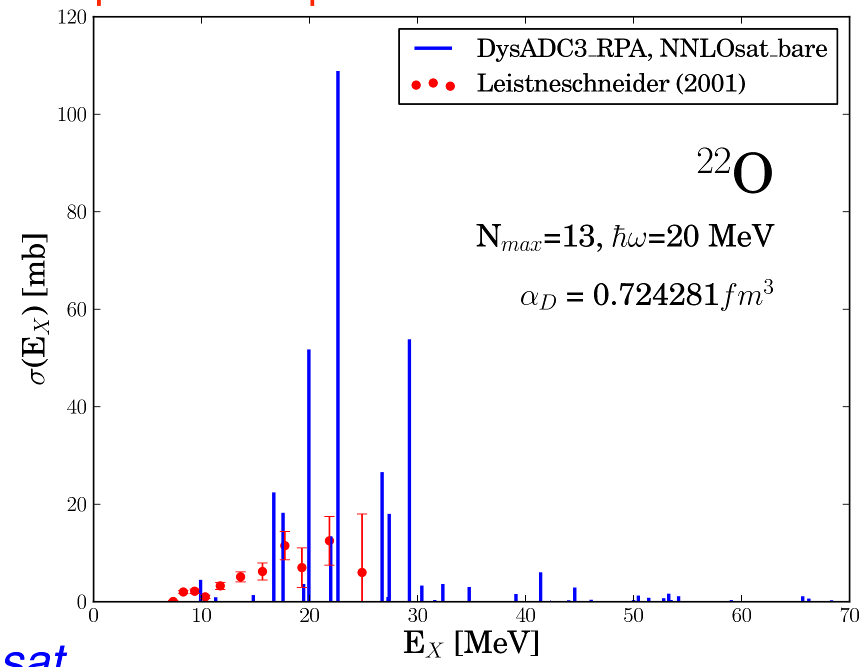
TRIUMF — *P. Navratil*

SAPIENZA UNIVERSITÀ DI ROMA — *O. Benhar*

Results for Oxygen isotopes

σ from RPA response (discretized spectrum) vs σ from photoabsorption and Coulomb excitation





NNLO*sat*

- GDR position of ^{16}O reproduced
- Hint of a soft dipole mode on the neutron-rich isotope

Dipole polarizability α_D (fm^3)			
Nucleus	SCGF	CC/LIT	Exp
^{16}O	0.50	0.57(1)	0.585(9)
^{22}O	0.72	0.86(4)	0.43(4)

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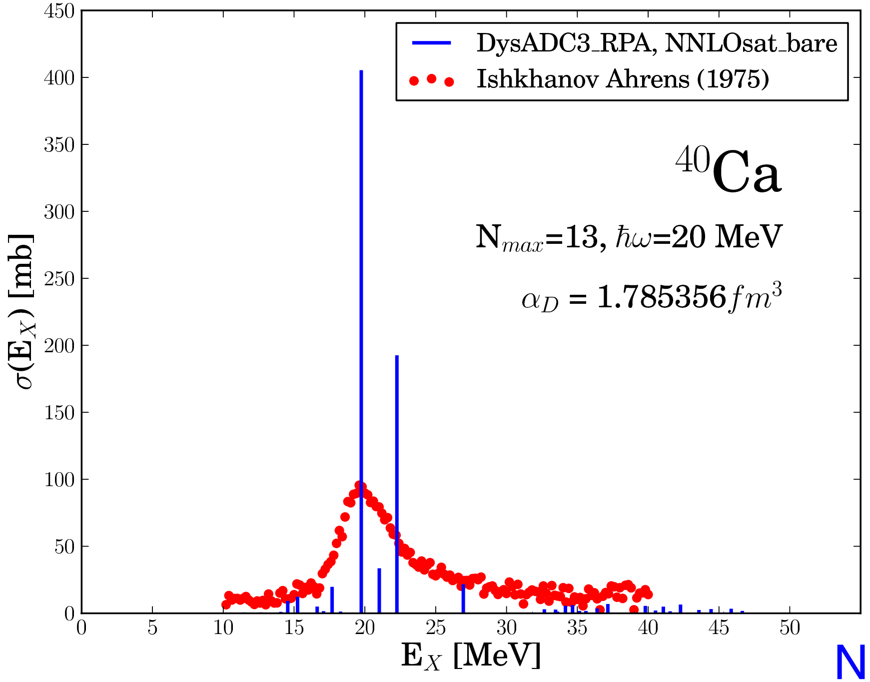
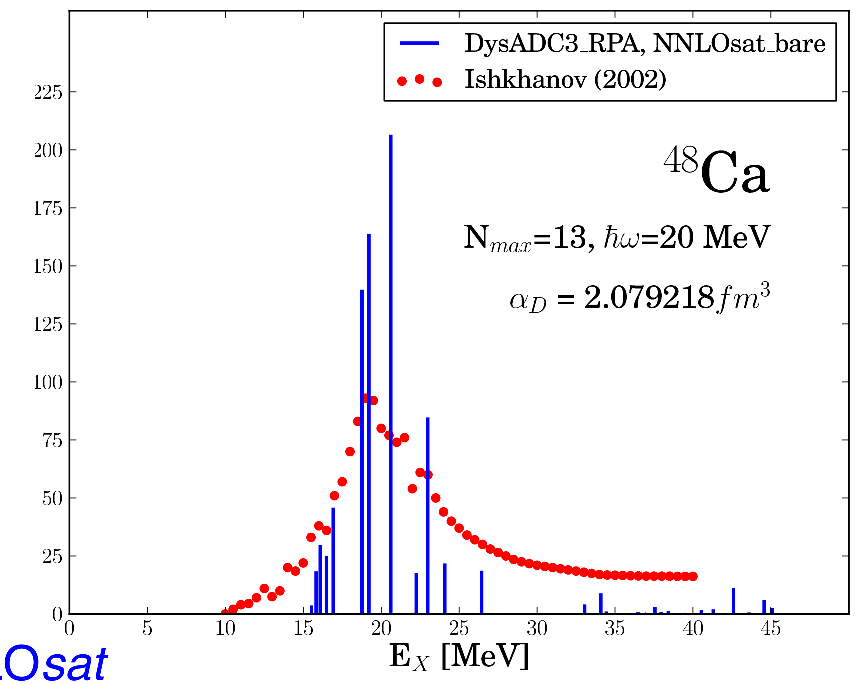
F. Raimondi, CB, arXiv:1711.04698 + in prep.

Results for Calcium isotopes

σ from RPA response (discretized spectrum) vs σ from photoabsorption and Coulomb excitation





NNLO*sat*

- Positions of GDRs reproduced

Dipole polarizability α_D (fm^3)			
Nucleus	SCGF	CC/LIT	Exp
^{40}Ca	1.79	1.47 $(1.87)_{thresh}$	1.87(3)
^{48}Ca	2.08	2.45	2.07(22)

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F. Raimondi, CB, arXiv:1711.04698 + in prep.

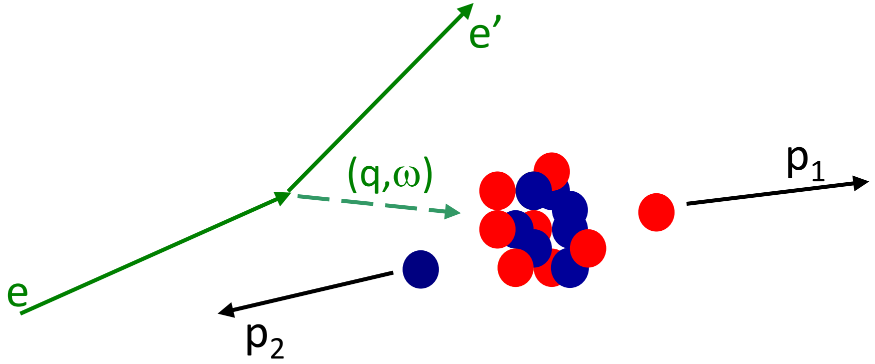
Two-nucleon emission

CB, C. Giusti, et al., Phys Rec C**70** , 014606 (2004)

D. Middelton et al.: Eur. Phys. J. A 29, 261–270 (2006)
Eur. Phys. J. A 43, 137–143 (2010)

M. Makek et al.: Eur. Phys. J. A 52, 298 (2016)

Calculating (e,e'pN) cross sections @ low energy



The reaction rate is:

$$\frac{d^8\sigma}{dE_0' d\Omega dE_1' d\Omega_1' d\Omega_2'} = K\Omega_f f_{\rm rec} |j_\mu J^\mu|^2$$

K, Ω_f, $f_{\rm rec}^{-1}$ and j_μ are known.

The hadronic current J^μ is the non-trivial part

The hadronic current is:

$$J^\mu(\boldsymbol{q}) = \int \langle \Psi_f | \hat{J}^\mu(\boldsymbol{r}) | \Psi_i \rangle e^{i\boldsymbol{q}\cdot\boldsymbol{r}} d\boldsymbol{r} = \int \Psi_f^*(\boldsymbol{r}_1\boldsymbol{\sigma}_1, \boldsymbol{r}_2\boldsymbol{\sigma}_2) J^\mu(\boldsymbol{r}, \boldsymbol{r}_1\boldsymbol{\sigma}_1, \boldsymbol{r}_2\boldsymbol{\sigma}_2) \times \Psi_i(\boldsymbol{r}_1\boldsymbol{\sigma}_1, \boldsymbol{r}_2\boldsymbol{\sigma}_2) e^{i\boldsymbol{q}\cdot\boldsymbol{r}} d\boldsymbol{r} d\boldsymbol{r}_1 d\boldsymbol{r}_2 d\boldsymbol{\sigma}_1 d\boldsymbol{\sigma}_2$$

Final state: $\Psi_f^*(\boldsymbol{r}_1\boldsymbol{\sigma}_1, \boldsymbol{r}_2\boldsymbol{\sigma}_2)$ → 3-body scatt.: Opt. pot.

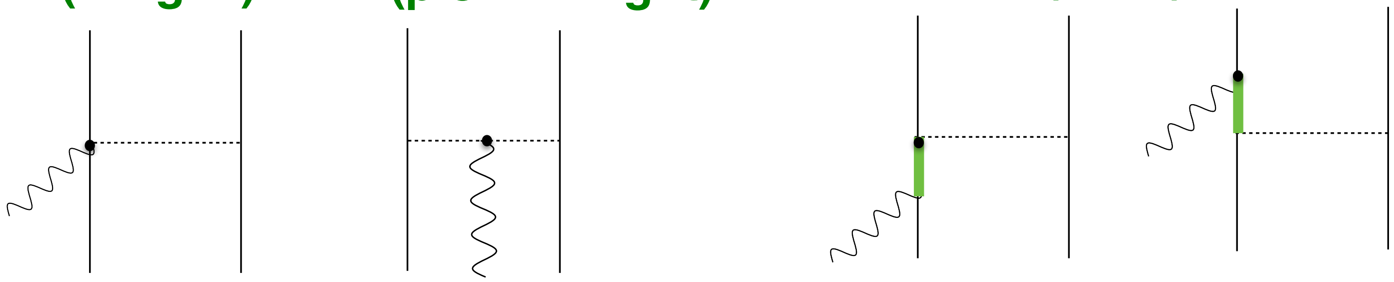
Initial state: $\Psi_i(\boldsymbol{r}_1\boldsymbol{\sigma}_1, \boldsymbol{r}_2\boldsymbol{\sigma}_2)$ → nucl. structure (S^{hh})

Reaction current: $J^\mu(\boldsymbol{r}, \boldsymbol{r}_1\boldsymbol{\sigma}_1, \boldsymbol{r}_2\boldsymbol{\sigma}_2)$ = $J^{(1\text{-body})}$ + $J^{(2)}$

direct

two-body currents

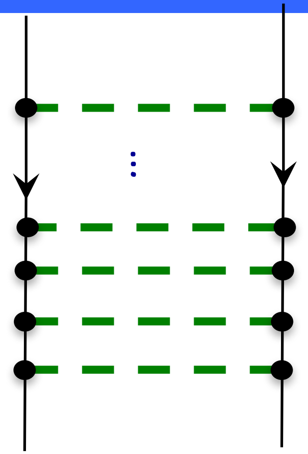
(seagull) (pion-in-flight) (delta)



C. Giusti et al., Eur. Phys. J. A 33, 29 (2007) [theory]

Correlated 2-nucleon wave function

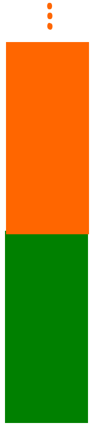
$$X^i_{abJ} = \langle \Psi^{i,A-2}_J \| (c_{\tilde{\beta}} c_{\bar{\alpha}})_J \| \Psi^A_0 \rangle$$



Obtained from RPA resummation of ladder diagrams (similarly to shell model configuration mixing between two-nucleon states):

Direct calculations of correlations are possible in a finite space **P** (e.g. 4-10 osc. shells – NO CORE) which is complete for LRC:

$$P\hat{H}_{\text{eff}}P|\Phi_i\rangle = E_i|\Phi_i\rangle$$



Effects from SRC are then included by calculating ladders in the excluded space **Q**:

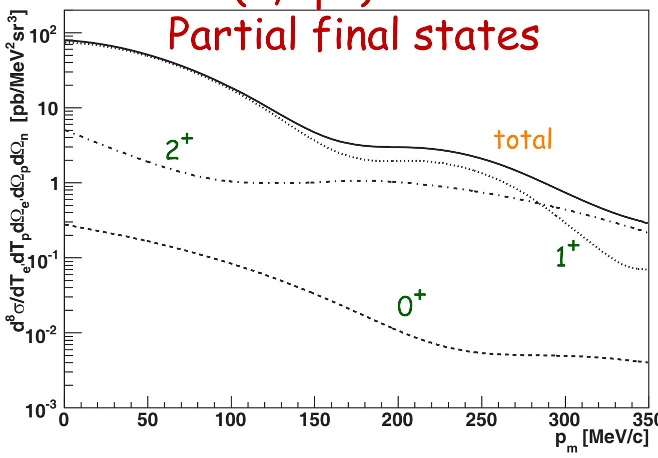
$$|\Psi_i\rangle = (1+\hat{\mathcal{X}})|\Phi_i\rangle = |\Phi_i\rangle + |\mathcal{X}_i\rangle$$

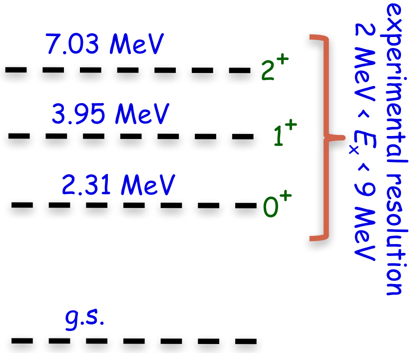
$$|\Psi\rangle = |\Phi\rangle + \frac{Q}{\omega - Q\hat{T}Q + i\eta}\hat{G}(\omega)|\Phi\rangle \qquad \hat{G}(\omega) = \hat{V} + \hat{V}\frac{Q}{\omega - Q\hat{T}Q + i\eta}\hat{G}(\omega)$$

CB, C. Giusti, et al., Phys Rec C70 , 014606 (2004)

Proton-neutron emission from 16O

$^{16}O(e,e'pn)^{14}C$
Partial final states



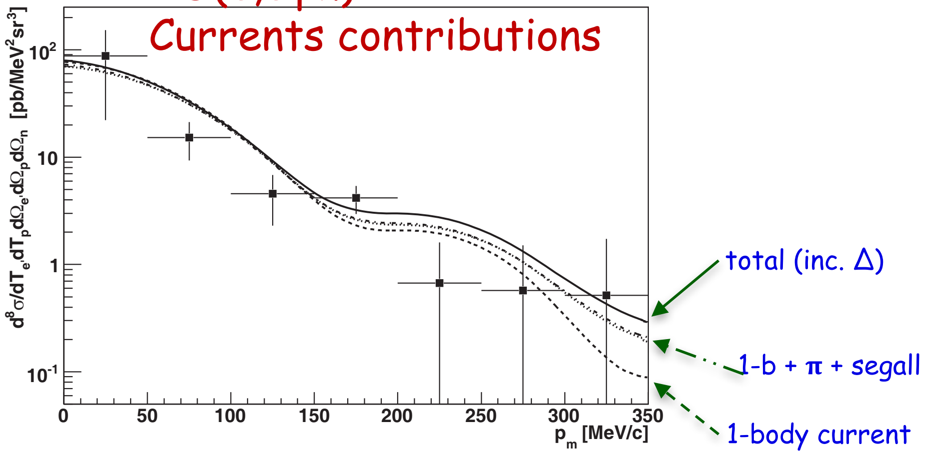


Experiments at MAMI

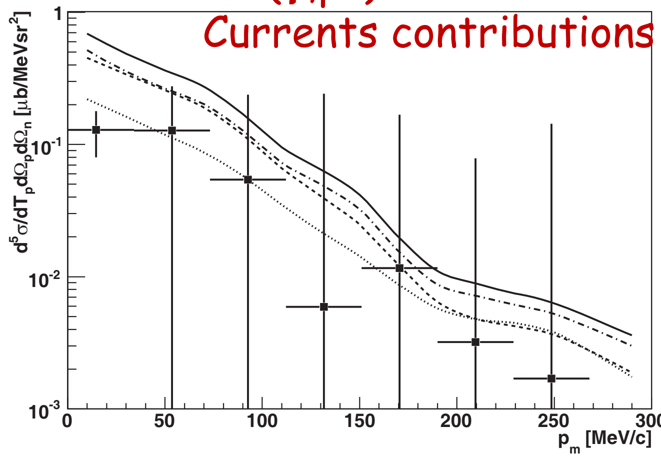
D. Middelton et al.,C. Giiusti, CB,
Eur. Phys. J. A 29, 261–270 (2006)
Eur. Phys. J. A 43, 137–143 (2010)

Eur. Phys. J. A 52, 298 (2016)

$^{16}O(e,e'pn)^{14}C$
Currents contributions

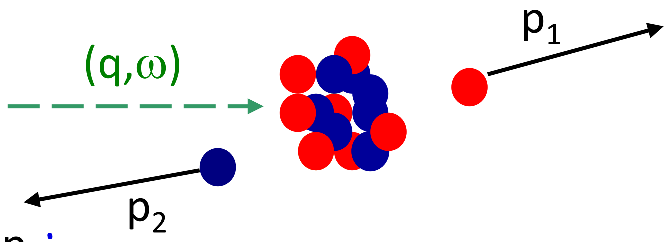


$^{16}O(\gamma,pn)^{14}C$
Currents contributions

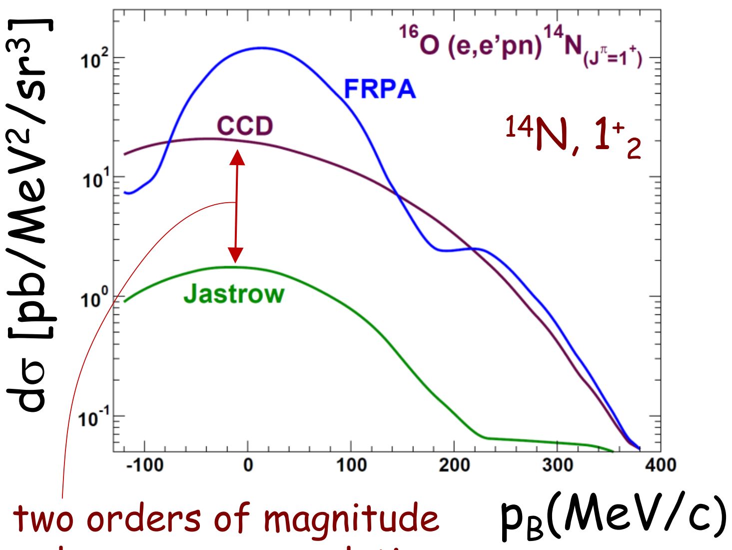


Correlations in proton-neutron knock out

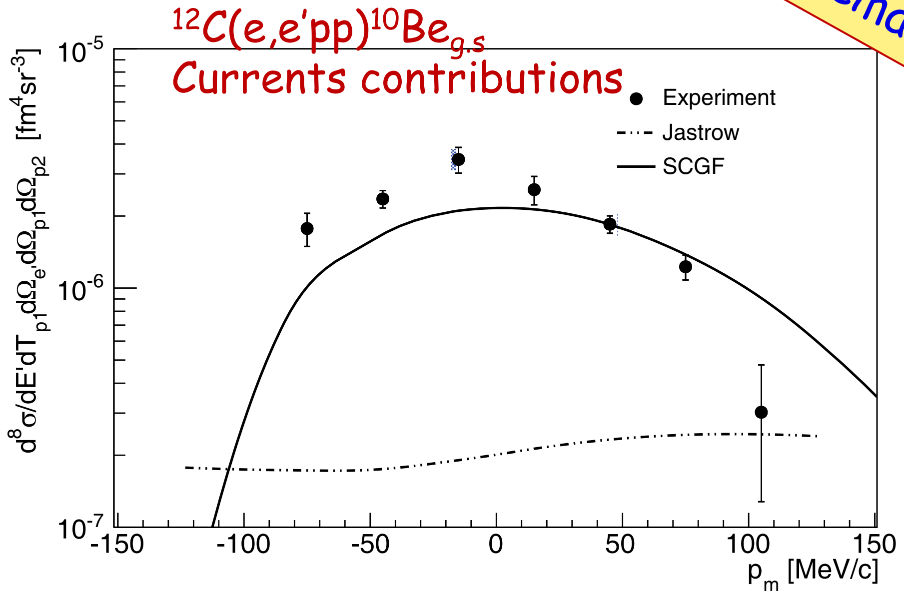
- $^{16}O(e,e'pn)^{14}N$
- initial wave function from SCGF or 'CCM'
- Pavia model for final state interactions
- Integrated x-secs. plotted vs. $p_B \equiv q - p_1 - p_2$:



Long range corrl. effects may be dominant in appropriate kinematics



- two orders of magnitude from long-range correlations.



$p_B \equiv q - p_1 - p_2$

H. Muether, Giusti et al, Phys Rev C (1999) -- CCD
CB, C. Giusti, et al., Phys Rec **C70** , 014606 (2004) -- SCGF

Experiment at MAMI Eur. Phys. J. A 52, 298 (2016)

Can we learn something form (e,e'pN) at MESA ??

- Direct two-nucleon emission directly sensitive to currents (2N currents too!)
- Low-energy correlation effects may be relevant in appropriate kinematics
- Old experiments very difficult and difficult E/p resolution

  ➔ BUT what about MESA??

- Viable way to test currents and interaction theories/models?
- Applications from EFT/ab initio? (though FSI requitre optical models…)
- Utility to constrain $\beta\beta$-decay??