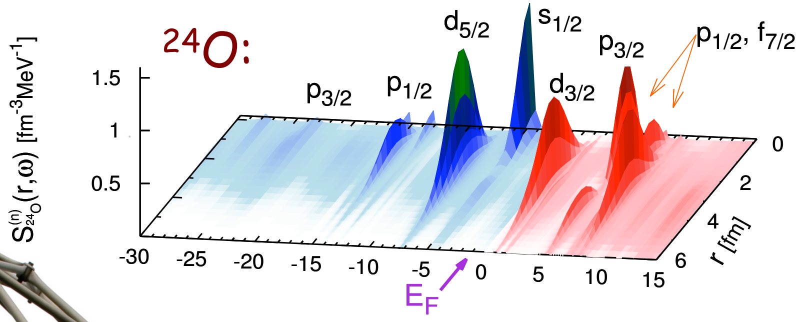
IPPP/NuSTEC topical meeting on Neutrino-Nucleus scattering
April 18-20, 2017

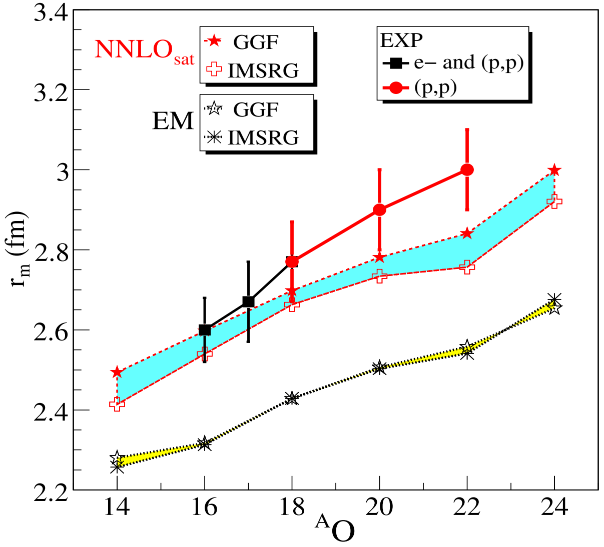
UNIVERSITY OF SURREY

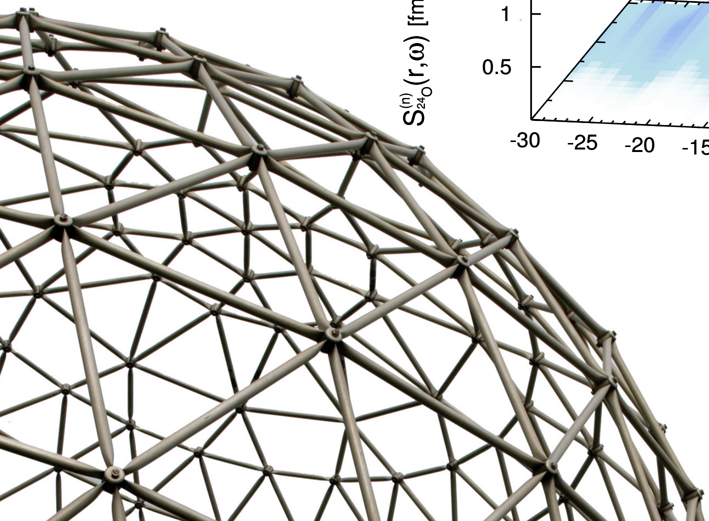
Nuclear correlations and FSI from an *ab initio* perspective

Carlo Barbieri — University of Surrey

18 April 2017







Outilne

- *Concept of spectral function*
- *The Self-consistent Green's funtion formalism*
- *(selected) Ab initio applications in medium mass nuclei*
- *SRC and high missing momenta in ^{12}C(e,e'p)*

Current Status of low-energy nuclear physics

Composite system of interacting fermions

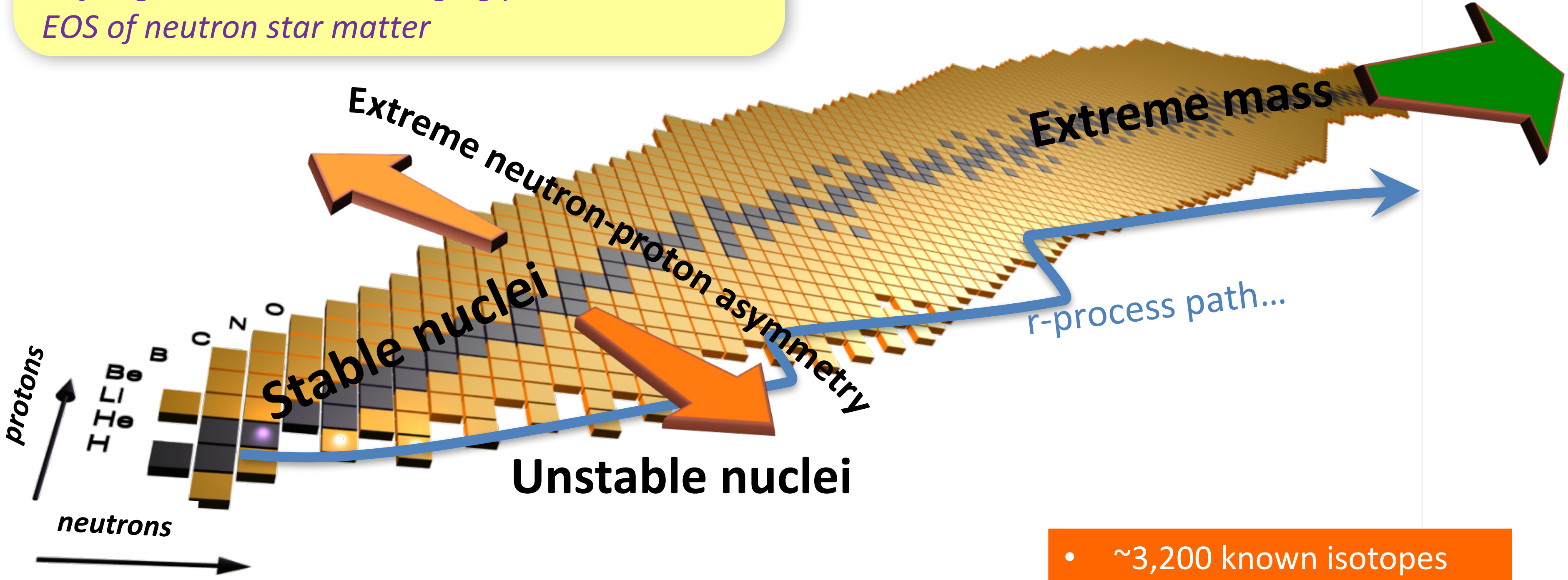
Binding and limits of stability

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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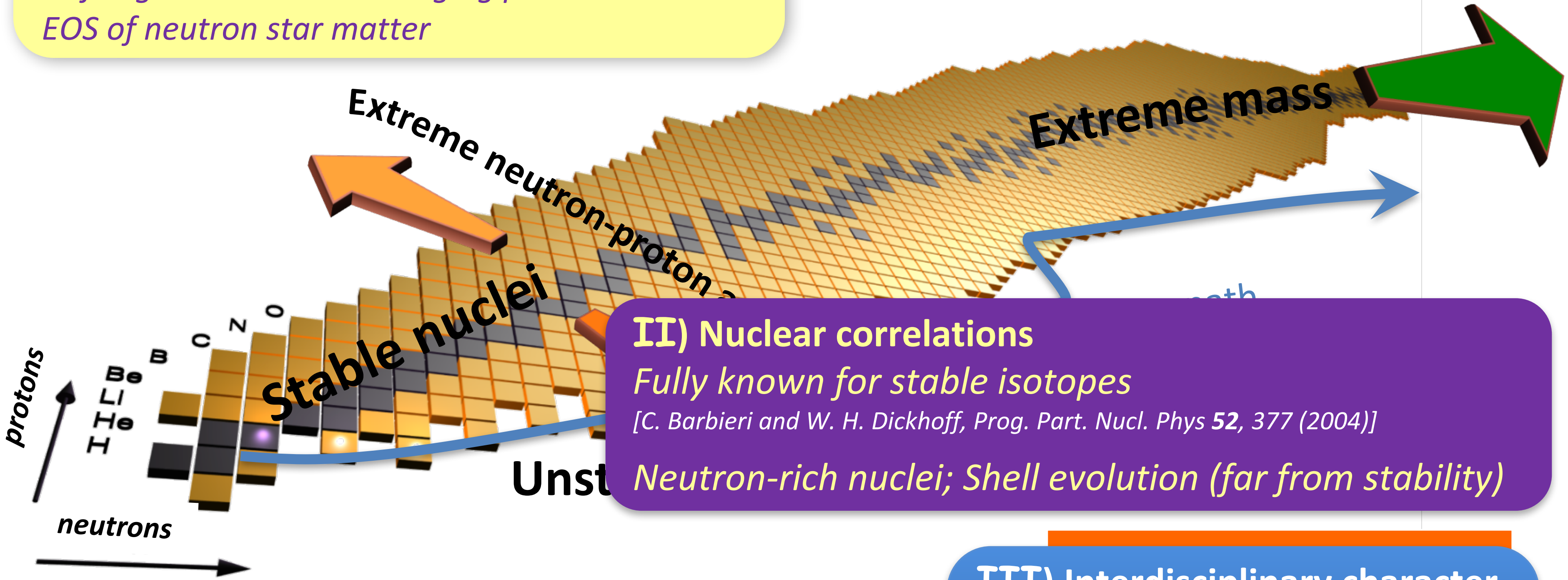


II) Nuclear correlations

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

III) Interdisciplinary character

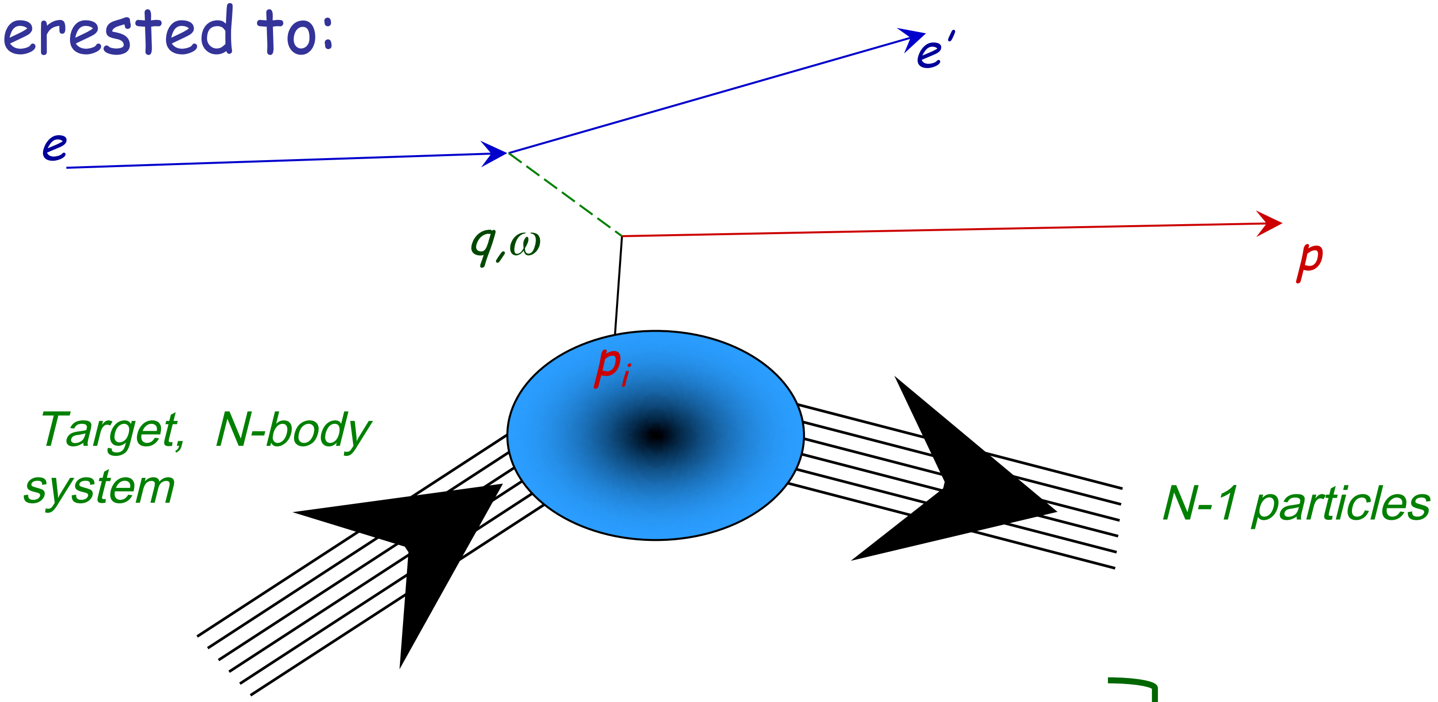
Astrophysics

Tests of the standard model

Other fermionic systems:
ultracold gasses; molecules;

Spectroscopy via knock out reactions-basic idea

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



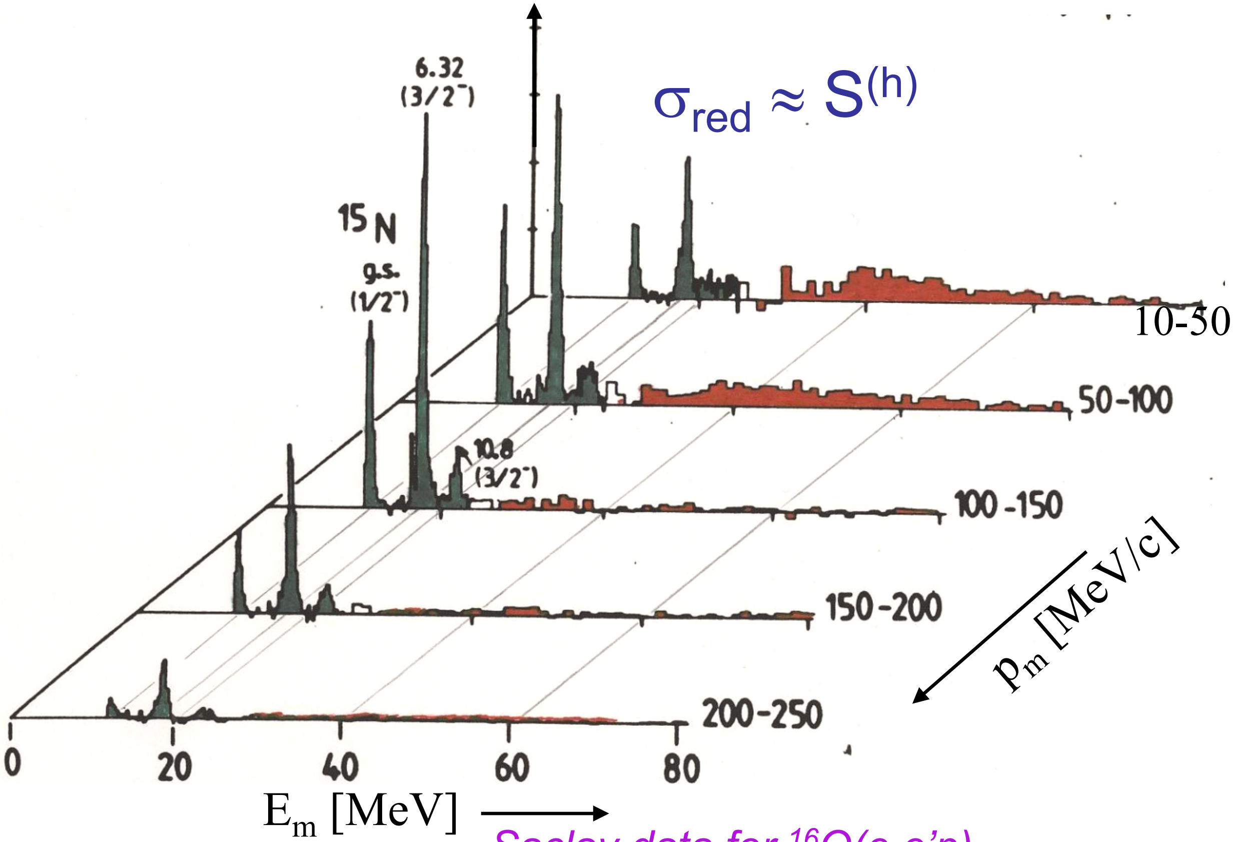
Basic idea:

- 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

Spectral function: distribution of momentum (p_m) and energies (E_m)



$\sigma_{red} \approx S^{(h)}$

Saclay data for $^{16}O(e,e'p)$

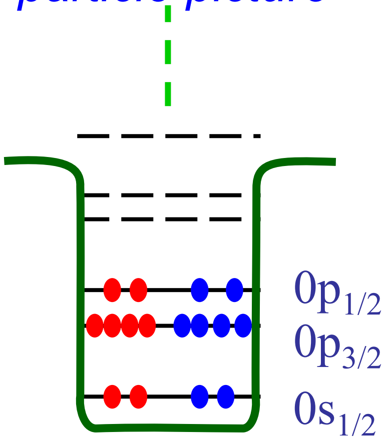
[Mougey et al., Nucl. Phys. A335, 35 (1980)]

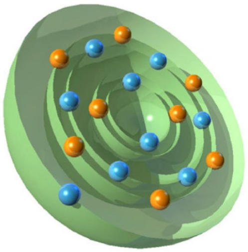
Understood for a few stable closed shells:

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

Concept of correlations

independent particle picture





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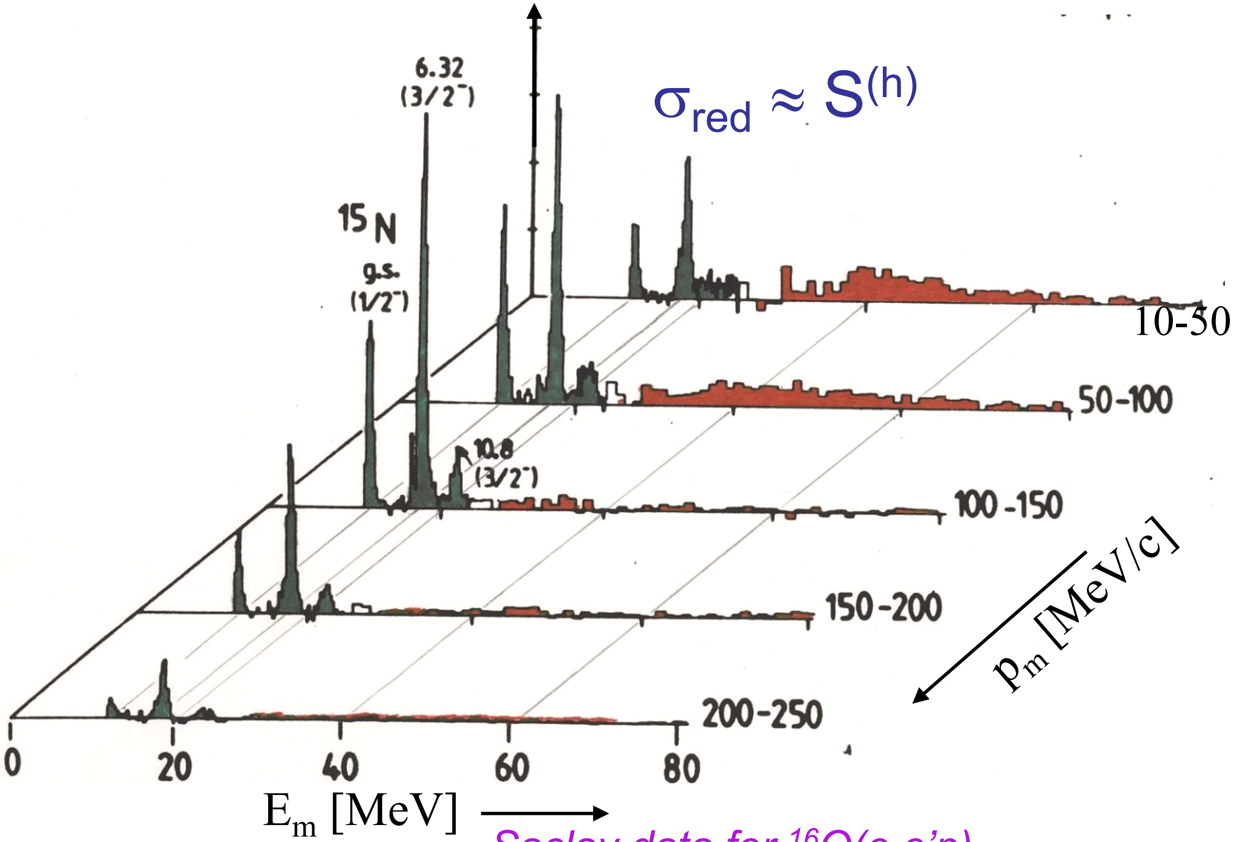

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Concept of correlations

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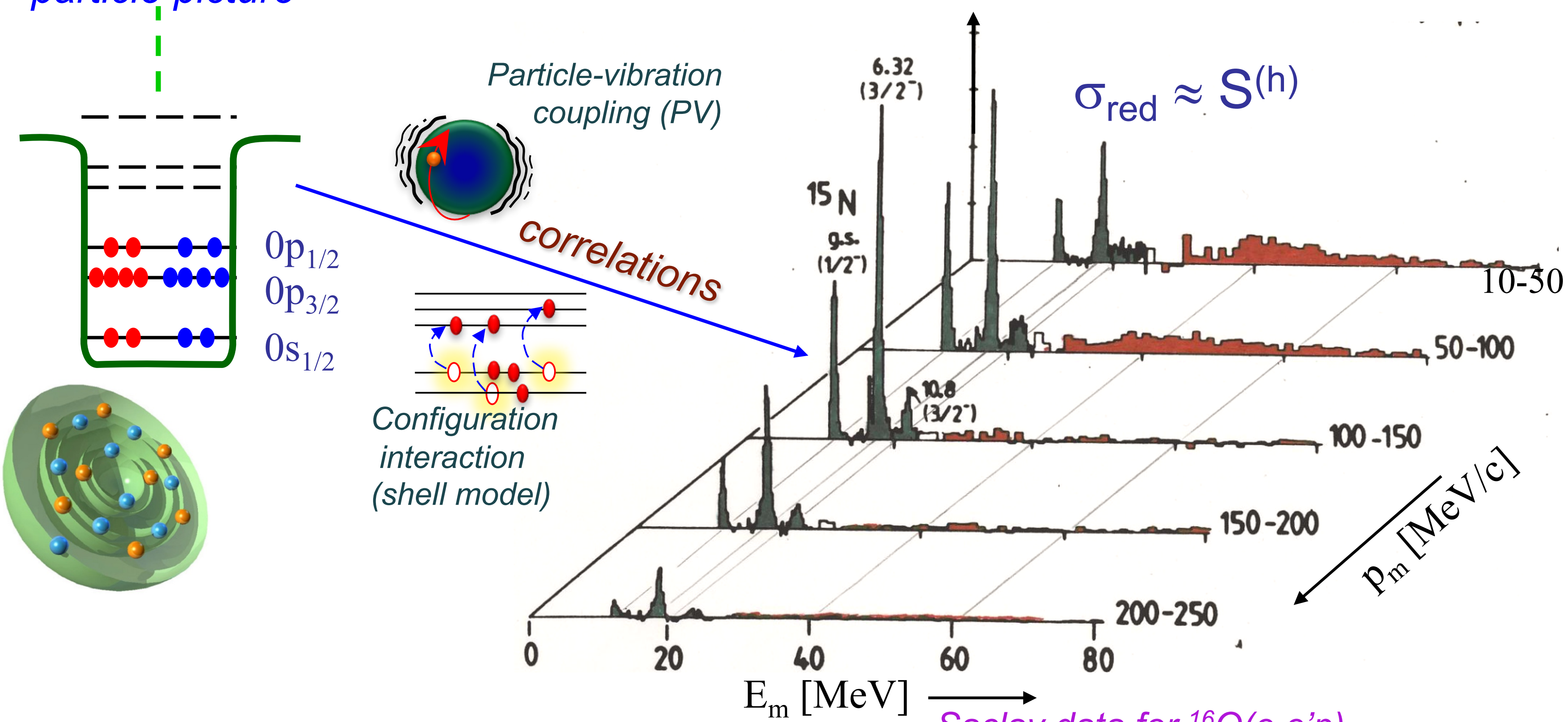

independent particle picture

Particle-vibration coupling (PV)

correlations

Configuration interaction (shell model)

$\sigma_{red} \approx S^{(h)}$

E_m [MeV] →

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Concept of correlations

independent particle picture

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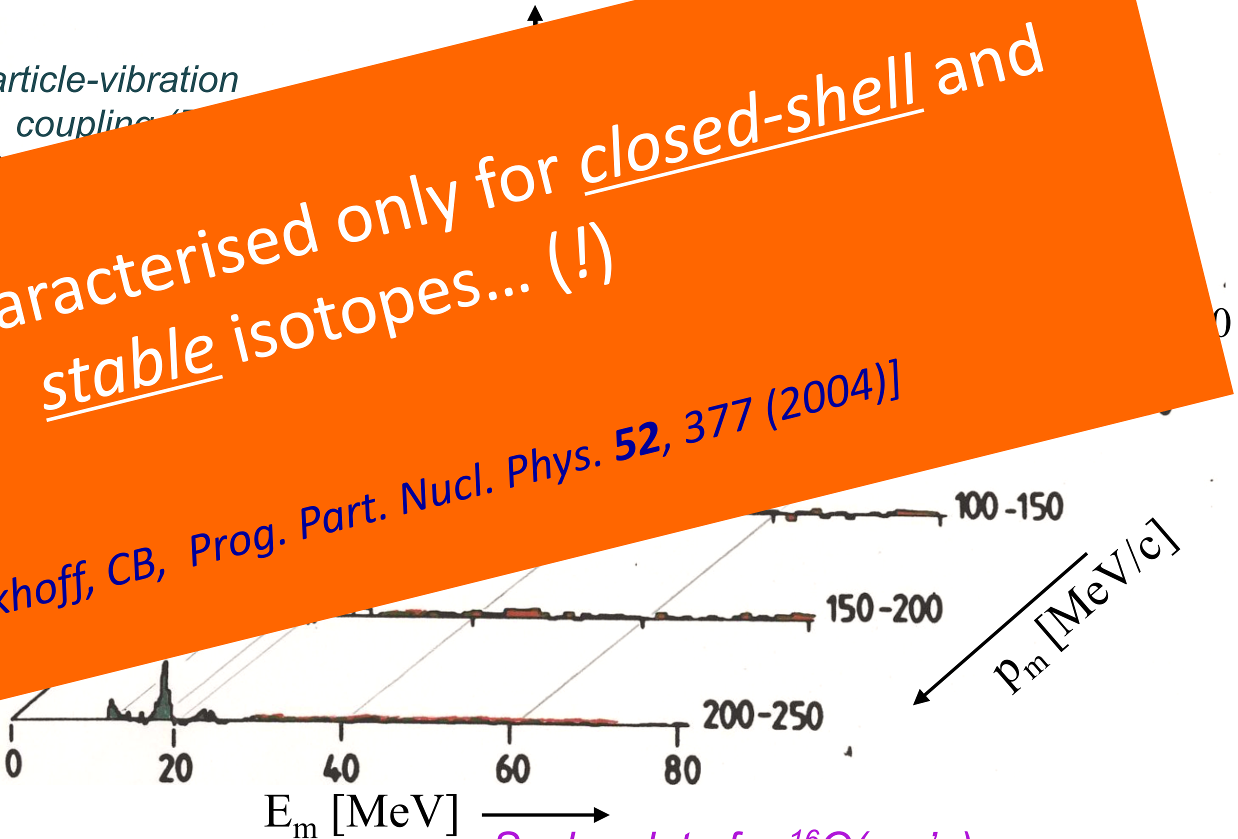


Saclay data for $^{16}O(e,e'p)$

[Mougey et al., Nucl. Phys. A335, 35 (1980)]

So far, fully characterised only for <u>*closed-shell*</u> and <u>*stable*</u> isotopes… (!)

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

Understood for a few stable closed shells:

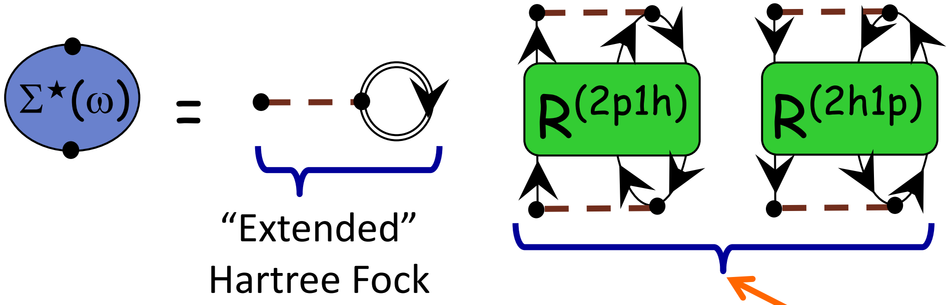
[CB and W. H. Dickhoff, Prog. Part. Nucl. Phys ***52****, 377 (2004)]*

Ab-Initio SCGF approaches

The FRPA Method in Two Words

Particle vibration coupling is the main cause driving the distribution of particle strength—on both sides of the Fermi surface…

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

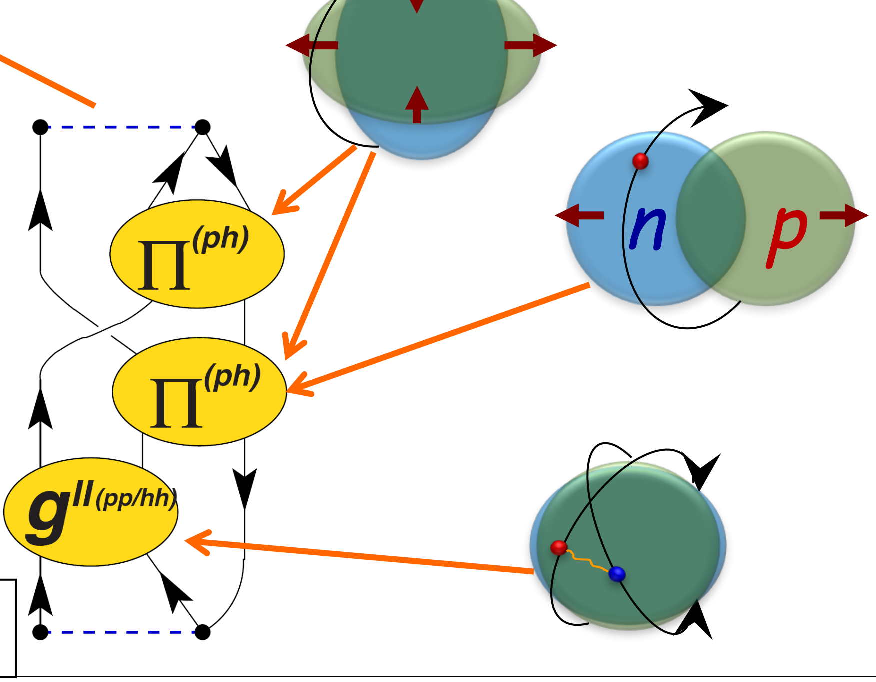


"Extended"
Hartree Fock

- A complete expansion requires _all types_ of particle-vibration coupling

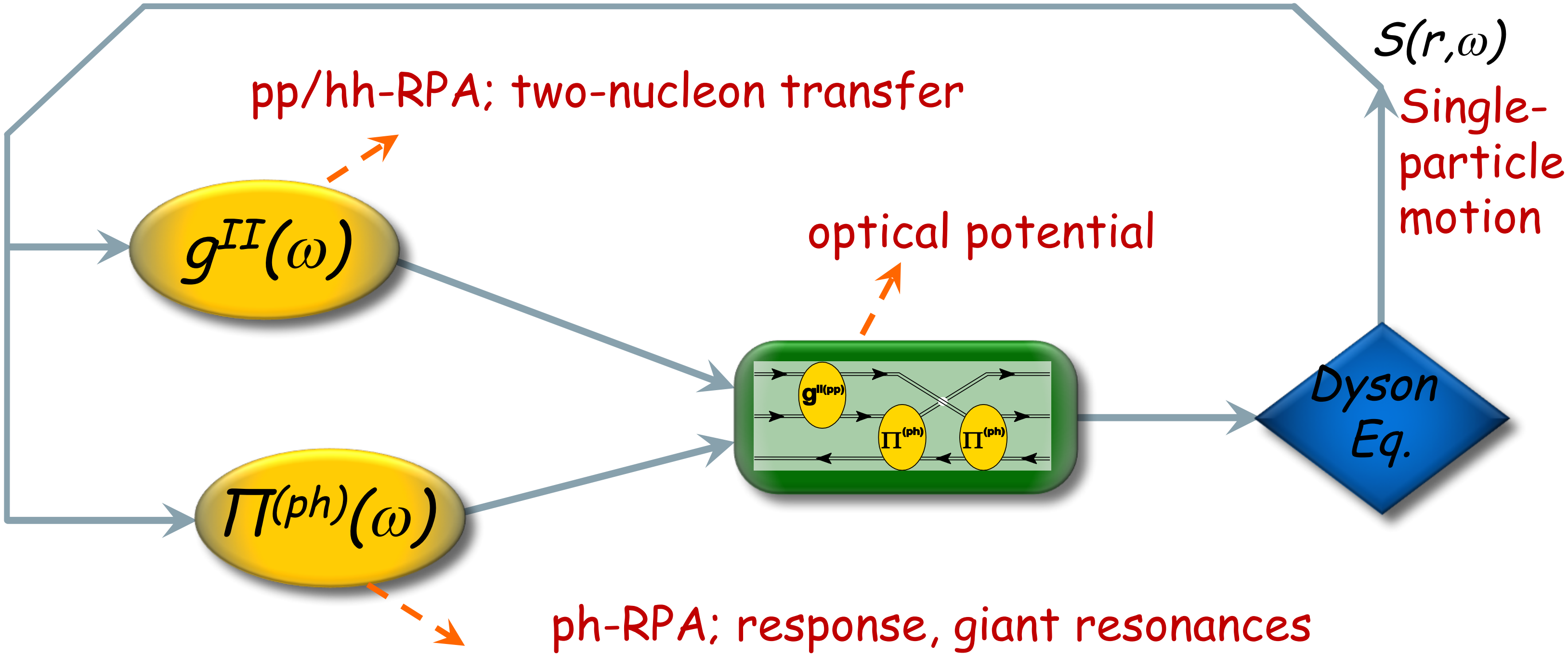
…these modes are all resummed exactly and to all orders in a *ab-initio* many-body expansion.

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



↑ ≡ *particle*   ↓ ≡ *hole*

Self-Consistent Green's Function Approach



$S(r,\omega)$

Single-particle motion

pp/hh-RPA; two-nucleon transfer

$g^{II}(\omega)$

optical potential

Dyson Eq.

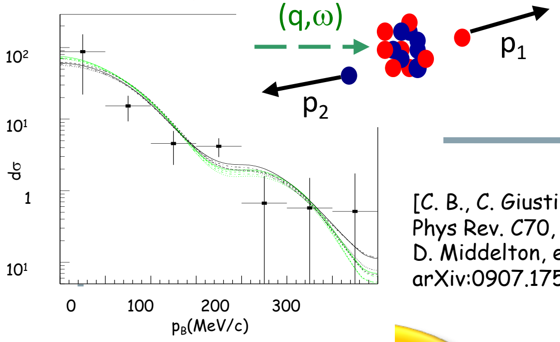
$\Pi^{(ph)}(\omega)$

ph-RPA; response, giant resonances

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

Self-Consistent Green's Function Approach

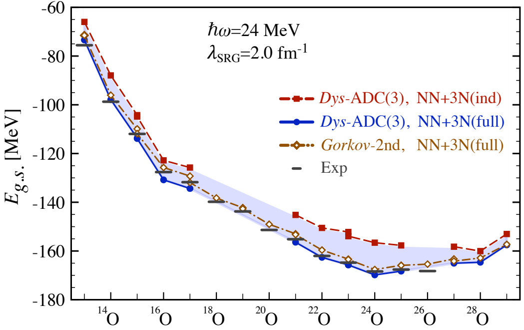
^{16}O(e,e'pn)^{14}N @ MAINZ



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

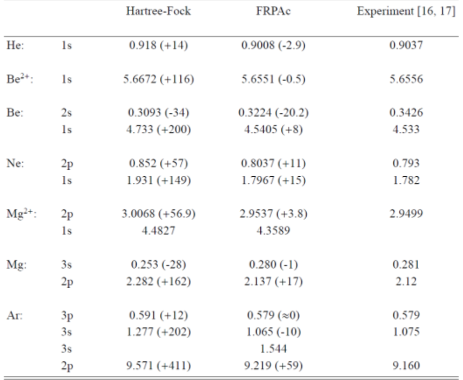
Binding energies

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

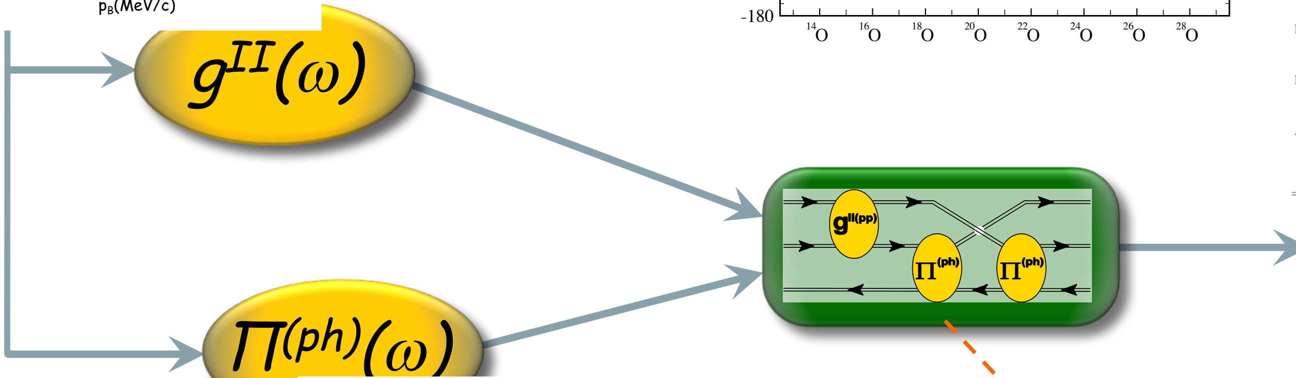


Ionization energies/ affinities, in atoms

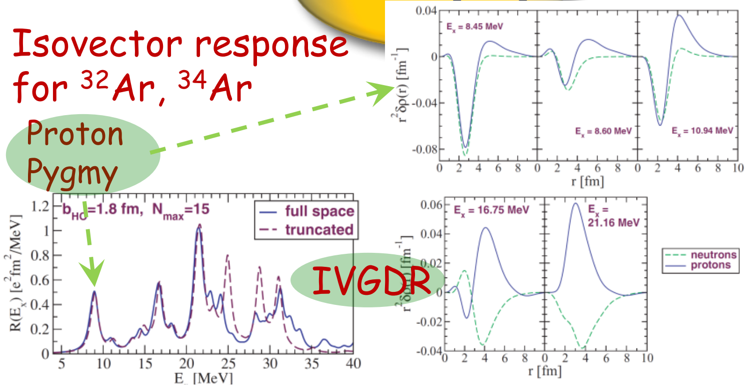
[CB, D. Van Neck,
AIP Conf.Proc.1120,104 ('09) & in prep]



		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

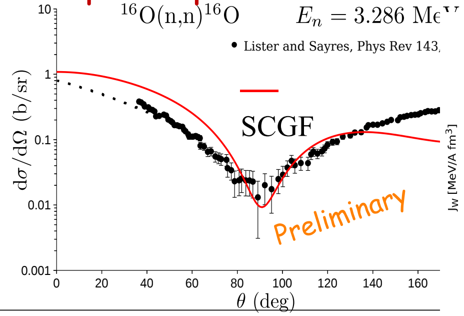


Isovector response for ^{32}Ar, ^{34}Ar

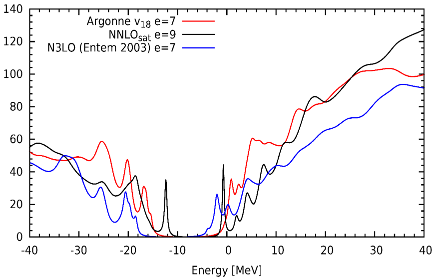


[C. B., K. Langanke, et al., Phys Rev. C77, 024304 (2008)]

Optical potential

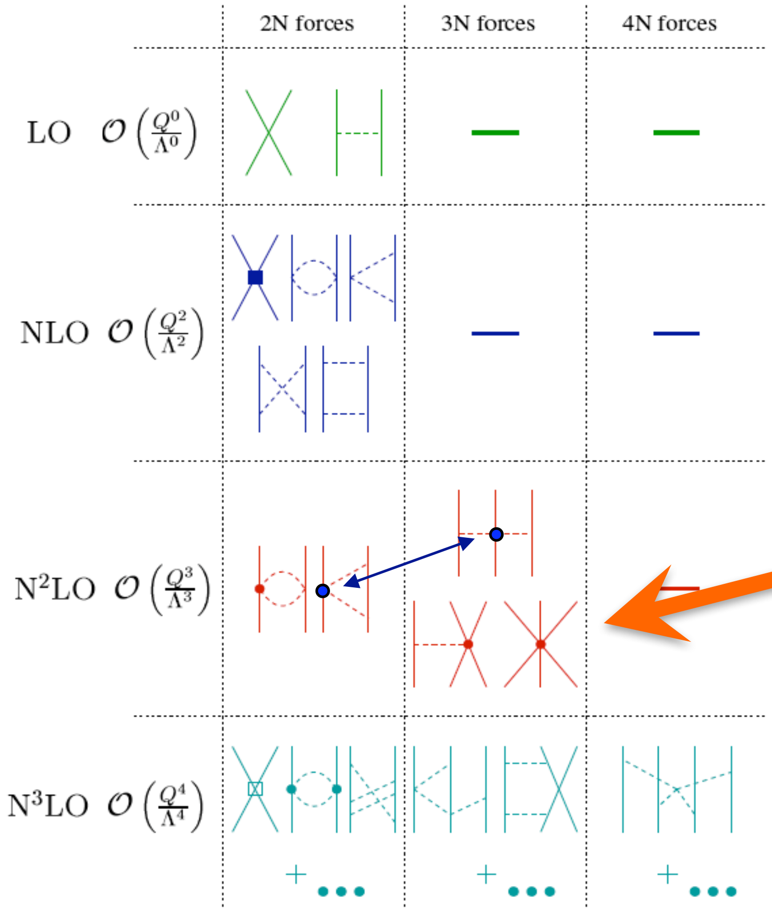


arXiv:1612.01478 [nucl-th]



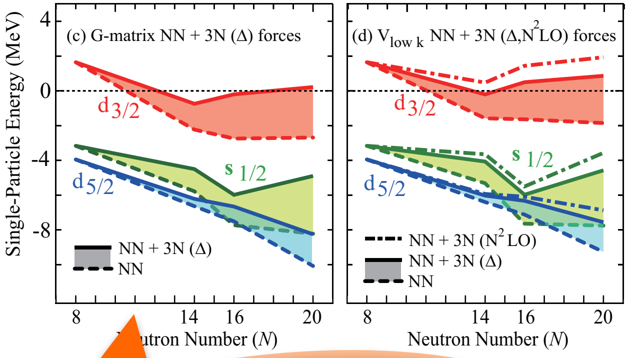
Modern realistic nuclear forces

Chiral EFT for nuclear forces:



(3NFs arise naturally at N2LO)

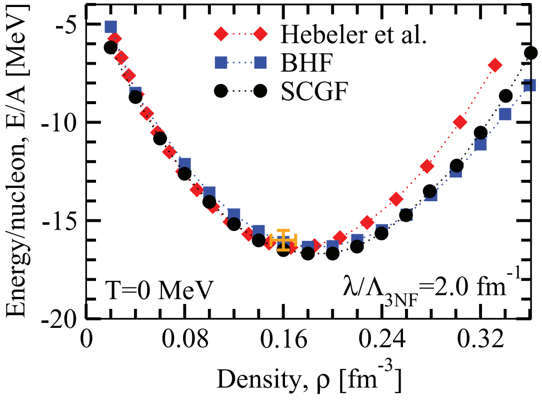
Single particle spectrum at E_{fermi}:



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

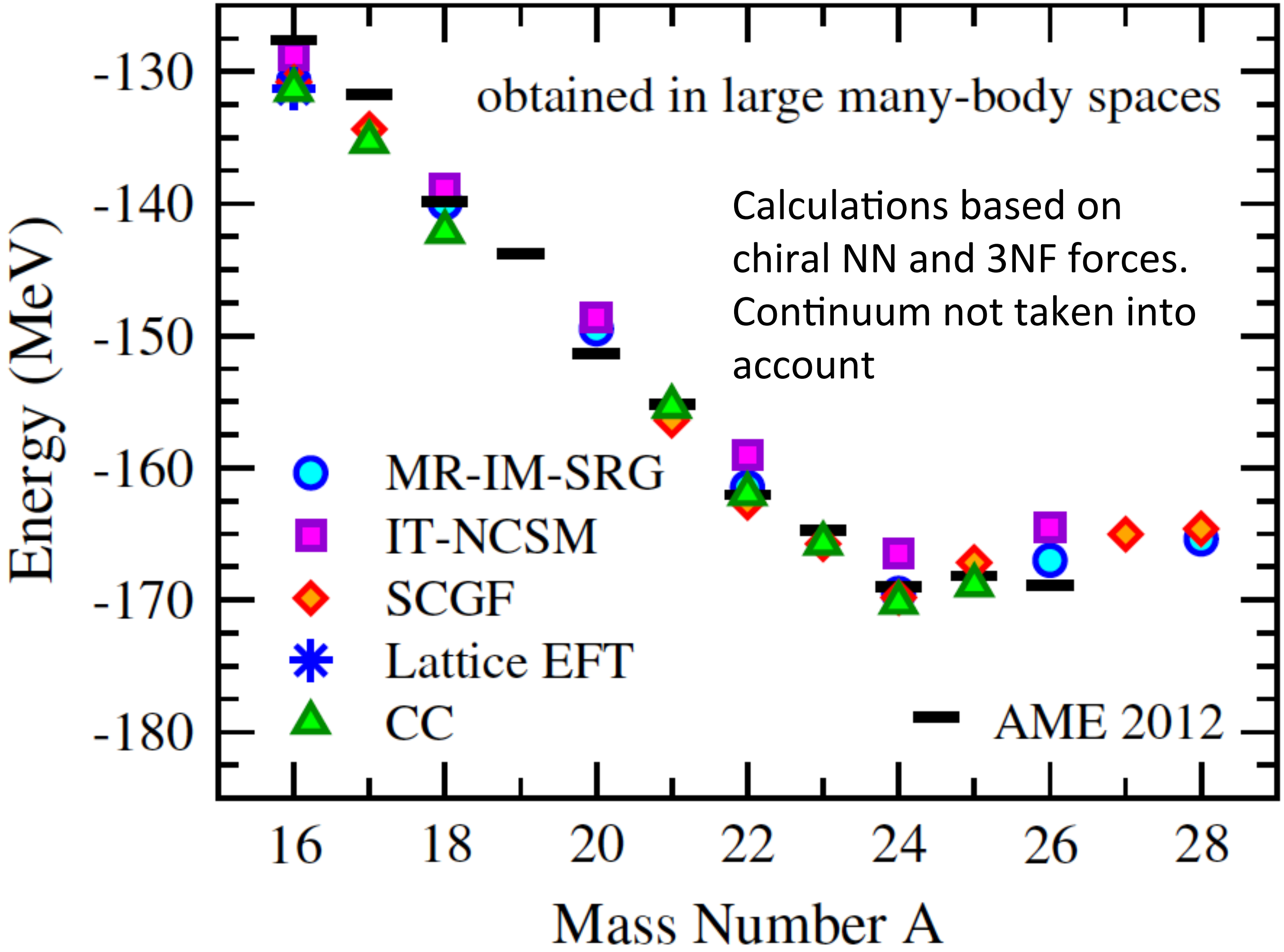
Need at LEAST 3NF!!!
("cannot" do RNB physics without…)

Saturation of nuclear matter:



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

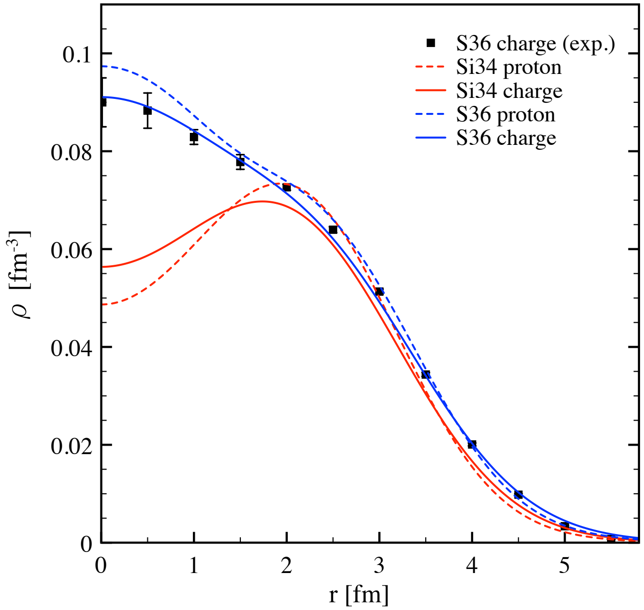
Benchmark of ab-initio methods in the oxygen isotopic chain



Calculations based on chiral NN and 3NF forces. Continuum not taken into account

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

Bubble nuclei… ^{34}Si prediction



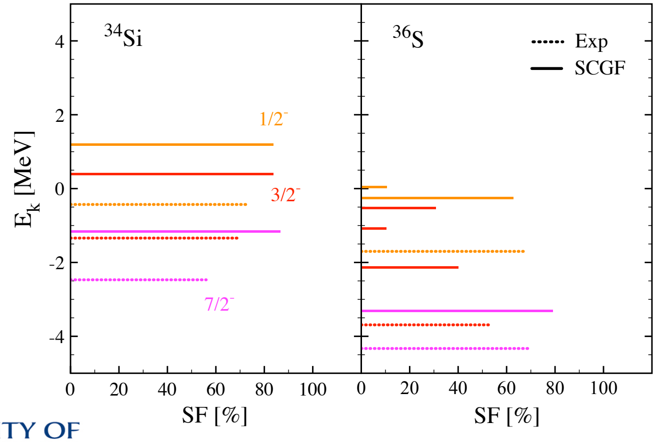
Duguet, Somà, Lecuse, CB, Navrátil,
Phys.Rev. C**95**, 034319 (2017)

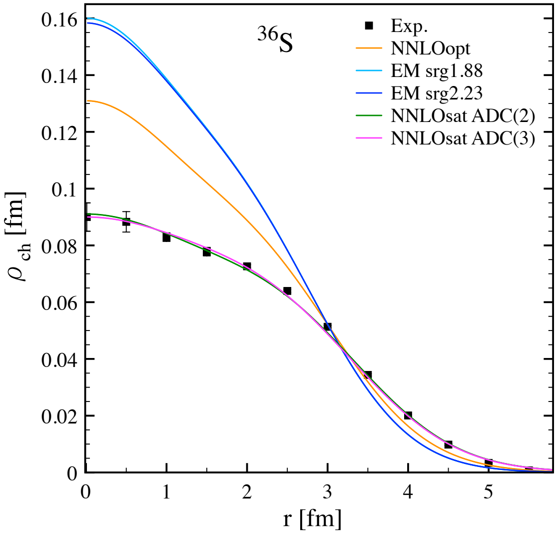
- ^{34}Si is unstable, charge distribution is still unknown

- Suggested central depletion from mean-field simulations

- *Ab-initio* theory confirms predictions

Validated by charge distributions and neutron quasiparticle spectra:





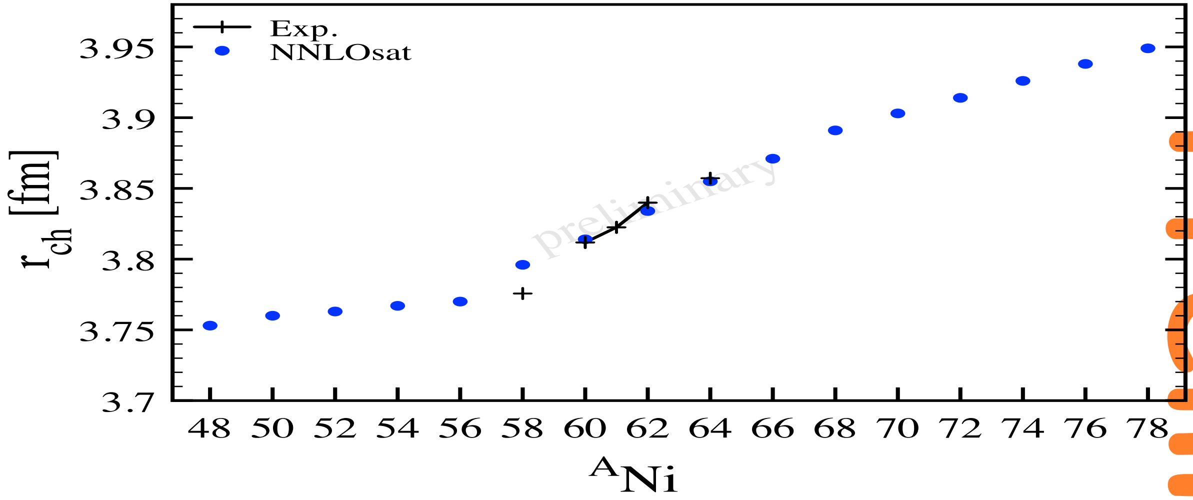
charge radii in the pf shell

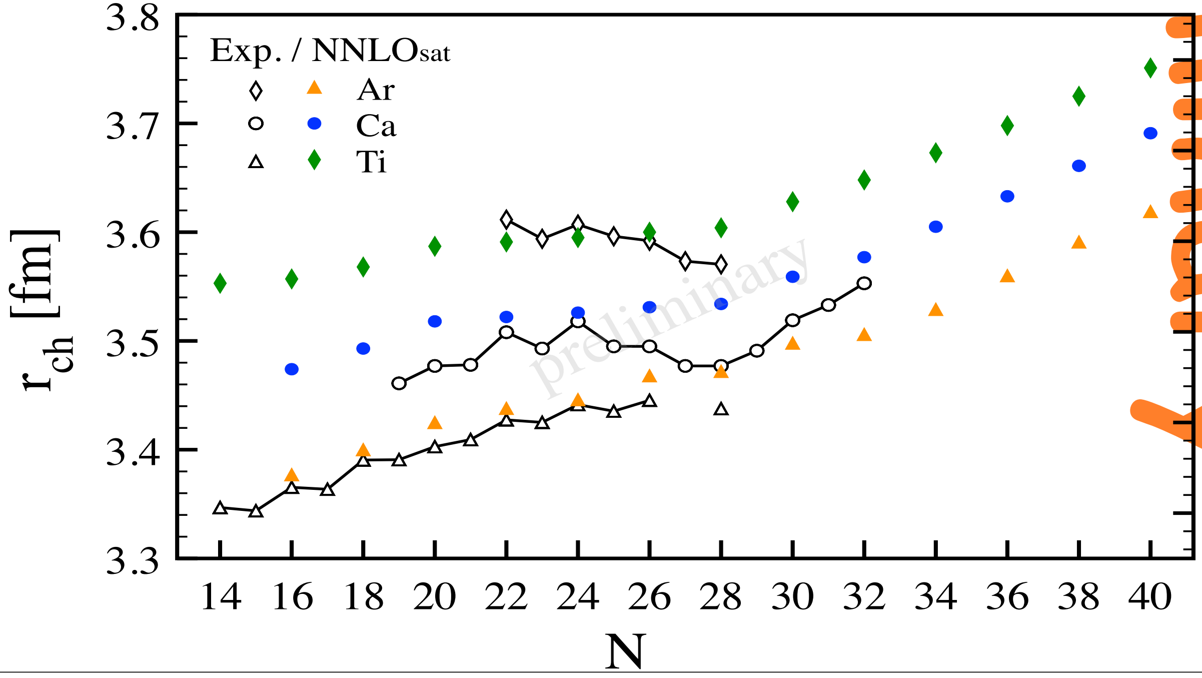
Size of radii not prefect but remains overall correct throughout the ***pf*** shell with NNLO-sat.

This suggests that saturation is indeed under control.

➔ Improvements of many-body truncations beyond 2nd order Gorkov will also be relevant.

(work in progress!)

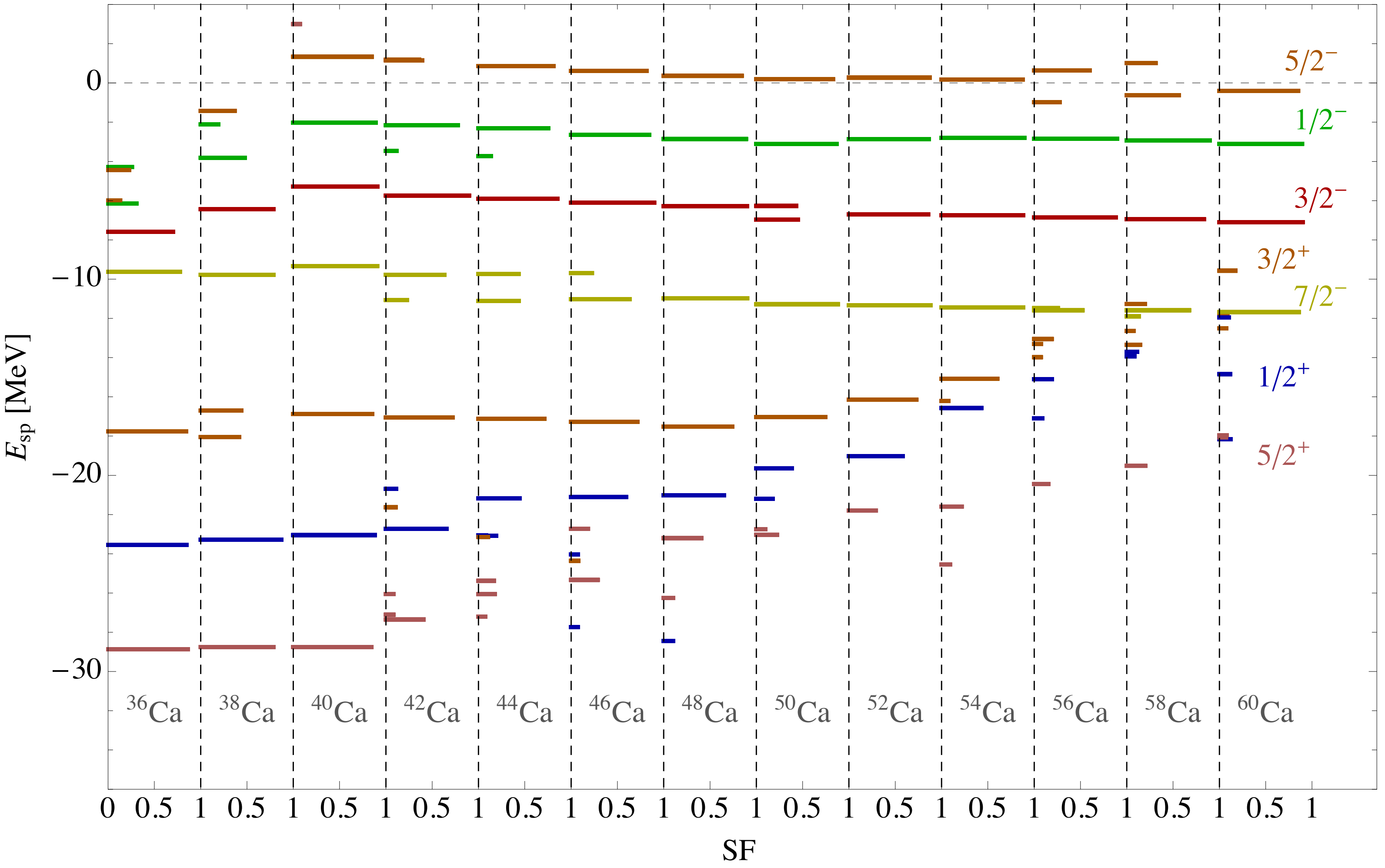




Preliminary

Ca neutron spectral distributions @ 2nd order

NN(N3LO500-EM) + 3NFs(NNLO400) at λ_{SRG}=2.0/fm

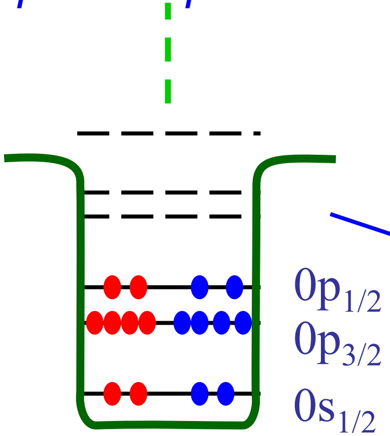


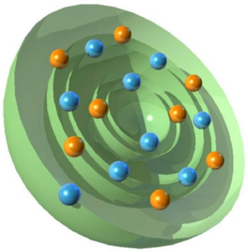
→ High-accuracy calculation for ^{40}Ar, ^{44}Ti is in progress (N. Rocco, Royal Soc./CNR Fellow)

Spectroscopic factors

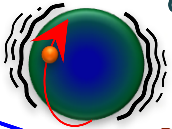
Concept of correlations

independent particle picture

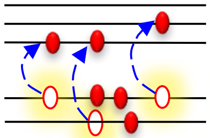




Particle-vibration coupling (PV)

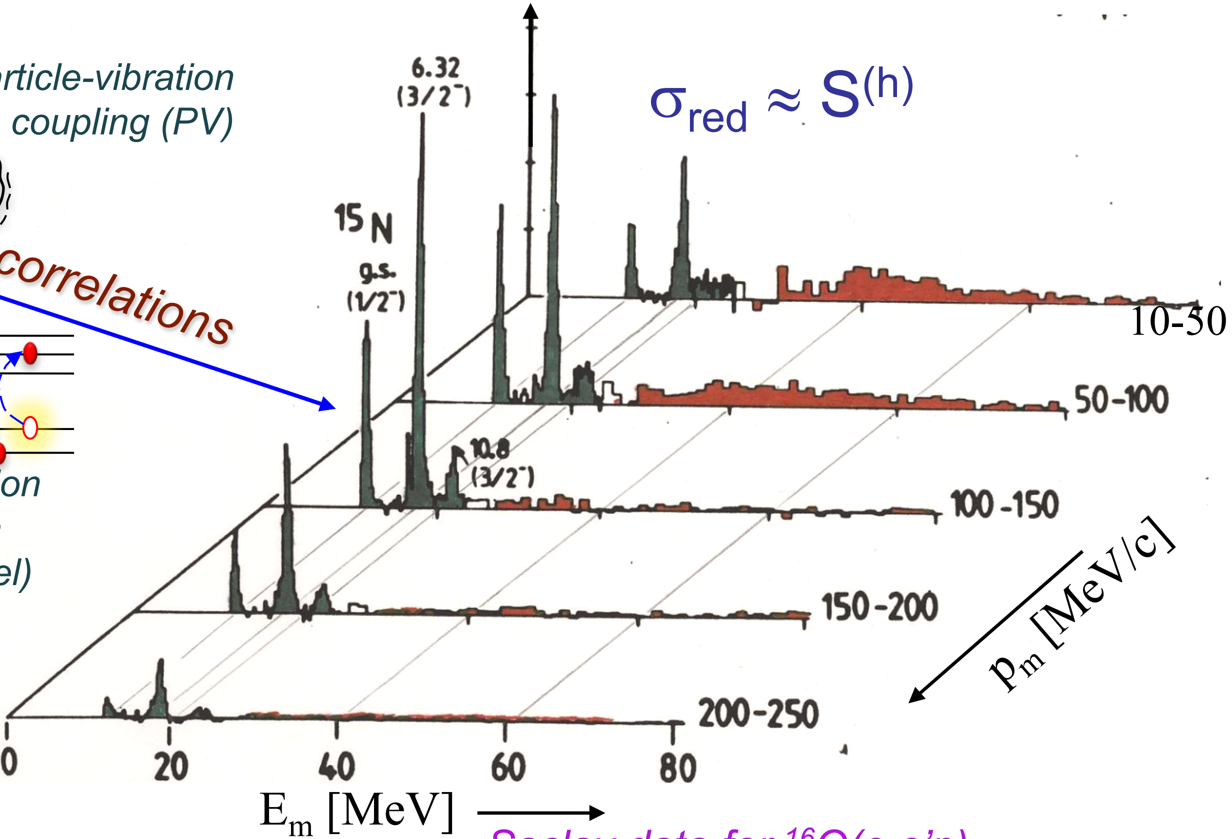


correlations



Configuration interaction (shell model)

Spectral function: distribution of momentum (p_m) and energies (E_m)



$\sigma_{red} \approx S^{(h)}$

Saclay data for $^{16}O(e,e'p)$

[Mougey et al., Nucl. Phys. A335, 35 (1980)]

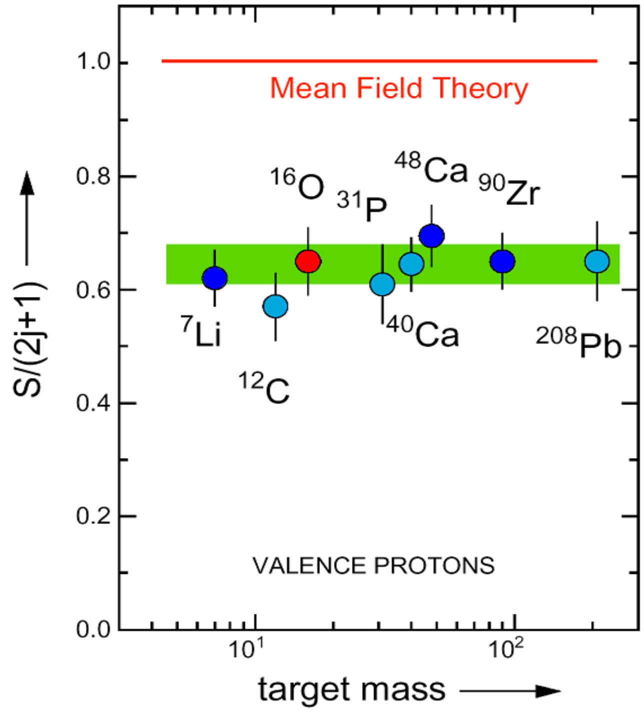
Understood for a few stable closed shells:

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

Quenching of SF in stable nuclei

Nucl. Phys. A553 (1993) 297c

NIKHEF:



A common misconception about SRC:

"The quenching is constant over all stable nuclei, so it must be a short-range effect"

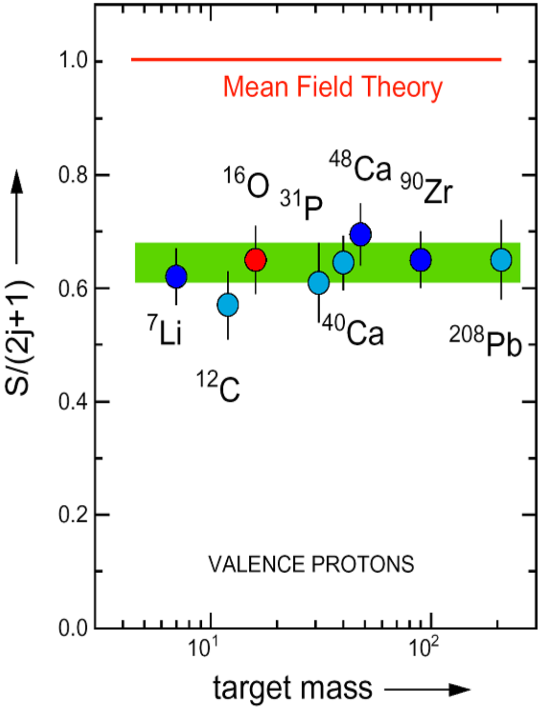
Actually, NO!

All calculations show that SRC have just a small effect at the Fermi surface. And the correlation to the experimental p-h gap is much more important.

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

Quenching of SF in stable nuclei

NIKHEF:
Nucl. Phys. A553 (1993) 297c



	$S_{p1/2}$	$S_{p3/2}$
• Short-range correlations oriented methods:		
– VMC [Argonne, '94]	0.90	
– GF(SRC) [St.Louis-Tübingen '95]	0.91	0.89
– FHNC/SOC [Pisa '00]	0.90	
• Including particle-phonon couplings:		
– GF(FRPA) [St.Louis '01]	0.77	0.72
[CB et al., Phys. Rev. C**65**, (02)]		
• Experiment:	0.63	0.67±0.07 (estimated uncertainty)

SRC are present and verified experimentally

BUT the are NOT the dominant mechanism for quenching SF!!!

Quenching of absolute spectroscopic factors

Overall quenching of *spectroscopic factors* is driven by:

SRC → *~10%*

part-vibr. coupling → *dominant*

"shell-model" → *in open shell*

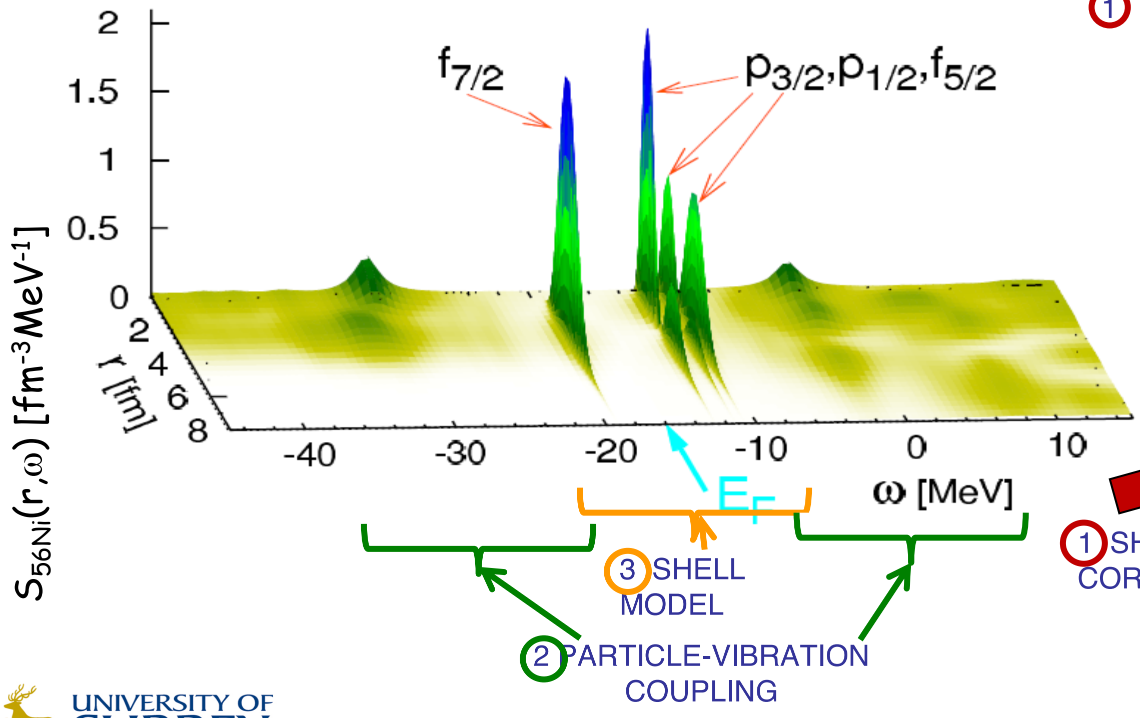
[CB, *Phys. Rev. Lett.* **103**, 202520 (2009)]

…with analogous conclusions for ^{48}Ca

	10 osc. shells			Exp. [30]	1p0f space		
	FRPA (SRC)	full FRPA	FRPA $+\Delta Z_\alpha$		FRPA	SM	ΔZ_α
^{57}Ni:							
$\nu 1p_{1/2}$	0.96	0.63	0.61		0.79	0.77	-0.02
$\nu 0f_{5/2}$	0.95	0.59	0.55		0.79	0.75	-0.04
$\nu 1p_{3/2}$	0.95	0.65	0.62	0.58(11)	0.82	0.79	-0.03
^{55}Ni:							
$\nu 0f_{7/2}$	0.95	0.72	0.69		0.89	0.86	-0.03
	①	② + ③			③		

^{57}Ni

^{55}Ni



③ SHELL MODEL

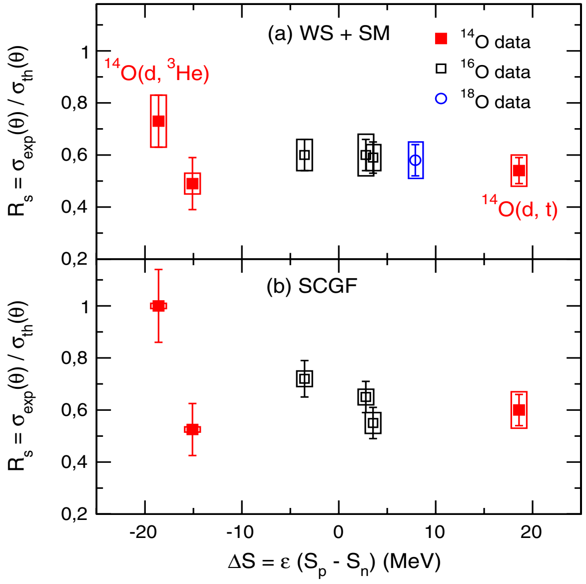
② PARTICLE-VIBRATION COUPLING

$$Z_\alpha = \int d^3r\, |\psi_\alpha^{overlap}(\mathbf{r})|^2 = \left.\frac{1}{1-\frac{\partial \Sigma_{\hat\alpha\hat\alpha}(\omega)}{\partial\omega}}\right|_{\omega=\varepsilon_\alpha}$$

① SHORT RANGE CORRELATIONS

Z/N asymmetry dependence of SFs

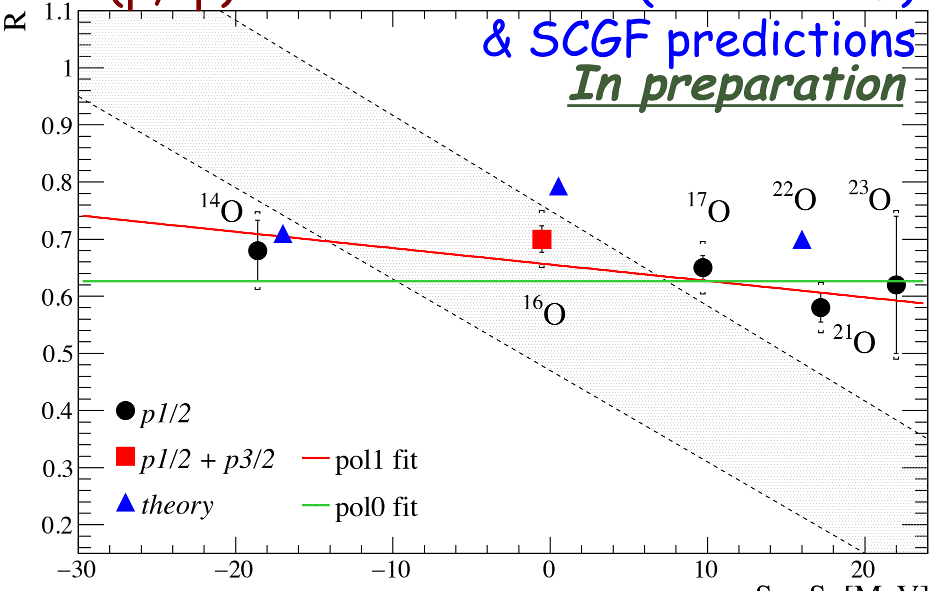
$^{14}O(d,t)^{13}O$ and $^{14}O(d,^3He)^{13}N$ transfer reactions @ SPIRAL

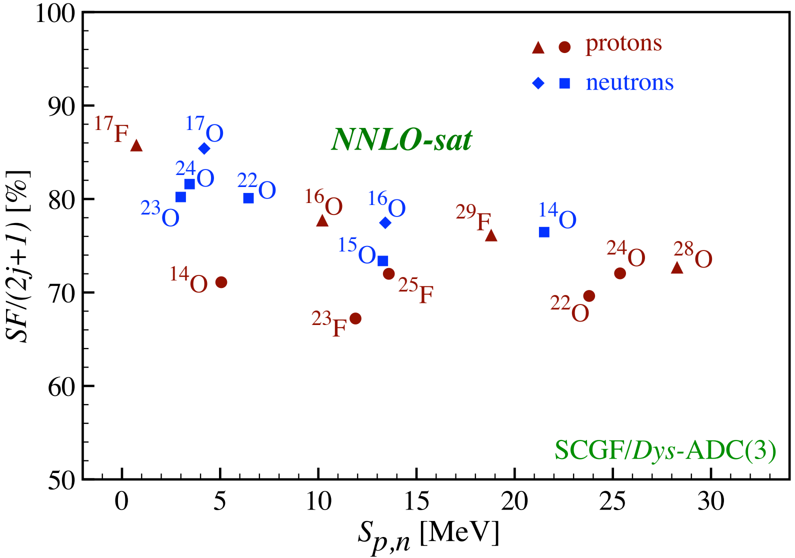


[F. Flavigny et al, PRL**110**, 122503 (2013)]

$^AO(p,2p)^{A-1}N$ data at GSI (R3B-LAND) & SCGF predictions

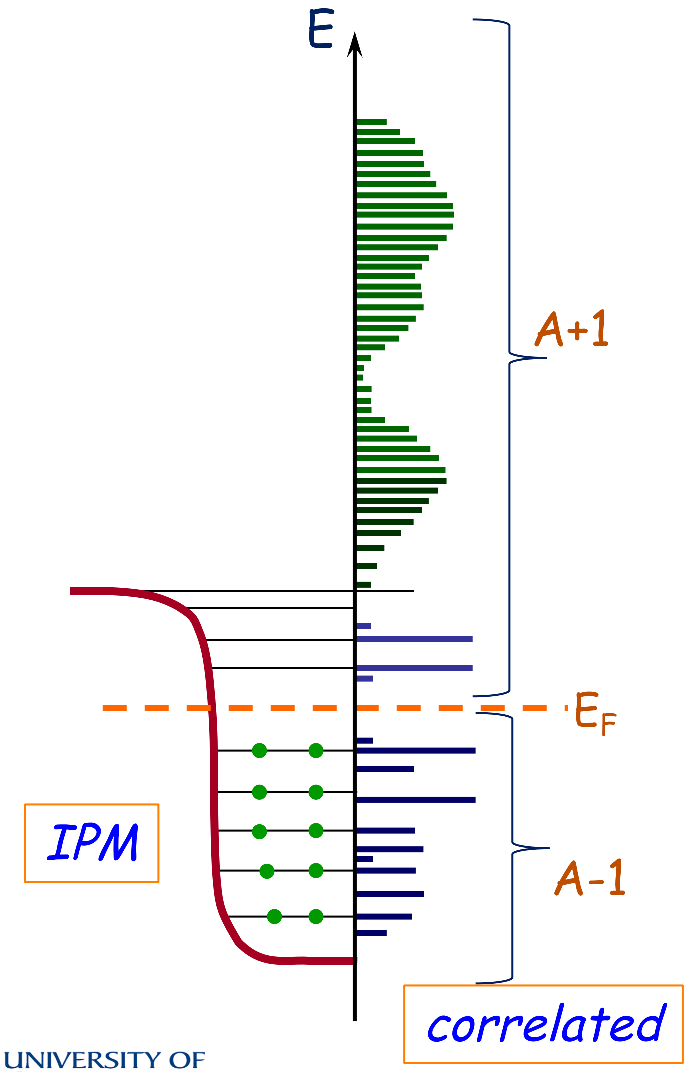
In preparation



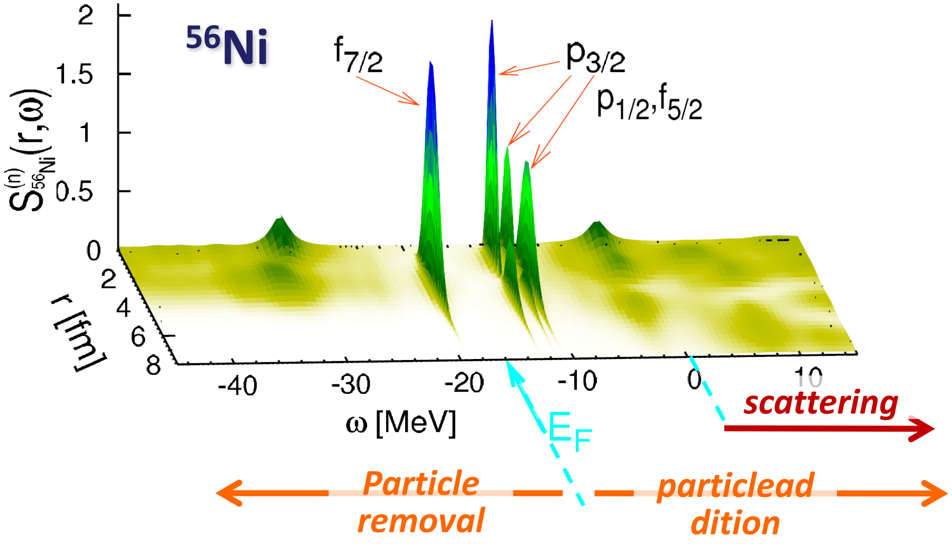


Calculated spectroscopic factors are:
- independent of asymmetry
- correlated to p-h gaps

Independent particle model (or "FG") vs correlated spectral function



Correlated (low-energy (long-range) structure:



Short-range correlations (SRC)

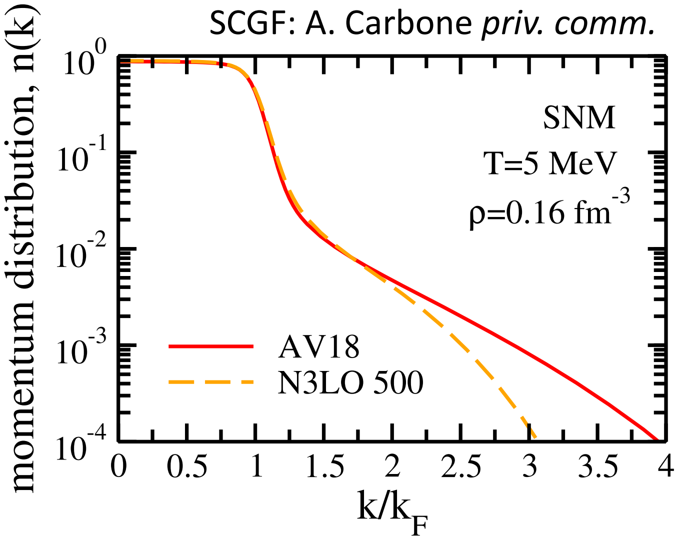
Where can one “see” these??

High momentum components – where are they?

Momentum distribution:

$$n(k) = \int_{-\infty}^{\varepsilon_F^-} d\omega \; S^{(h)}(k,\omega)$$

- High k components are found at high missing energies

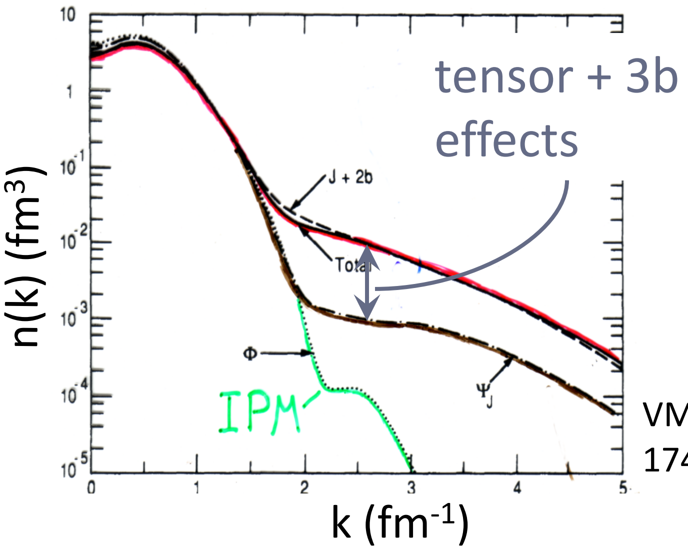

SCGF: A. Carbone *priv. comm.*

- *Short-range repulsion in r-space*
←→ strong potential at large momenta

- *A complication: the nuclear interaction includes also a tensor term (from Yukawa's meson meson exchange):*

$$S_{12} = 3(\vec{\sigma}_1 \cdot \hat{r})(\vec{\sigma}_2 \cdot \hat{r}) - 1$$

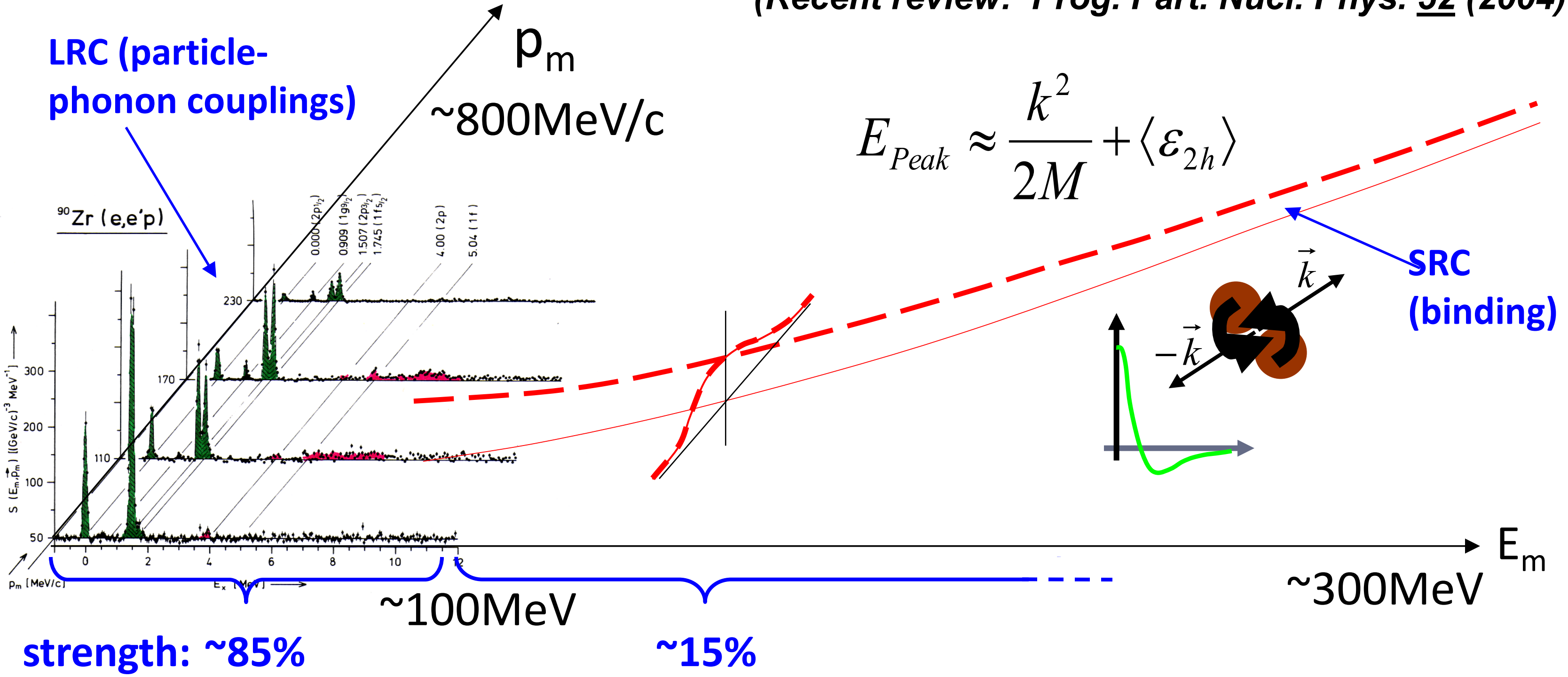
→ interaction amog 2 dipoles!!!!!!



VMC: PRC46, 1741 ('92)

Distribution of (All) the Nuclear Strength

(Recent review: Prog. Part. Nucl. Phys. 52 (2004) 337.)



LRC (particle-phonon couplings)

$$E_{Peak} \approx \frac{k^2}{2M} + \langle \varepsilon_{2h} \rangle$$

SRC (binding)

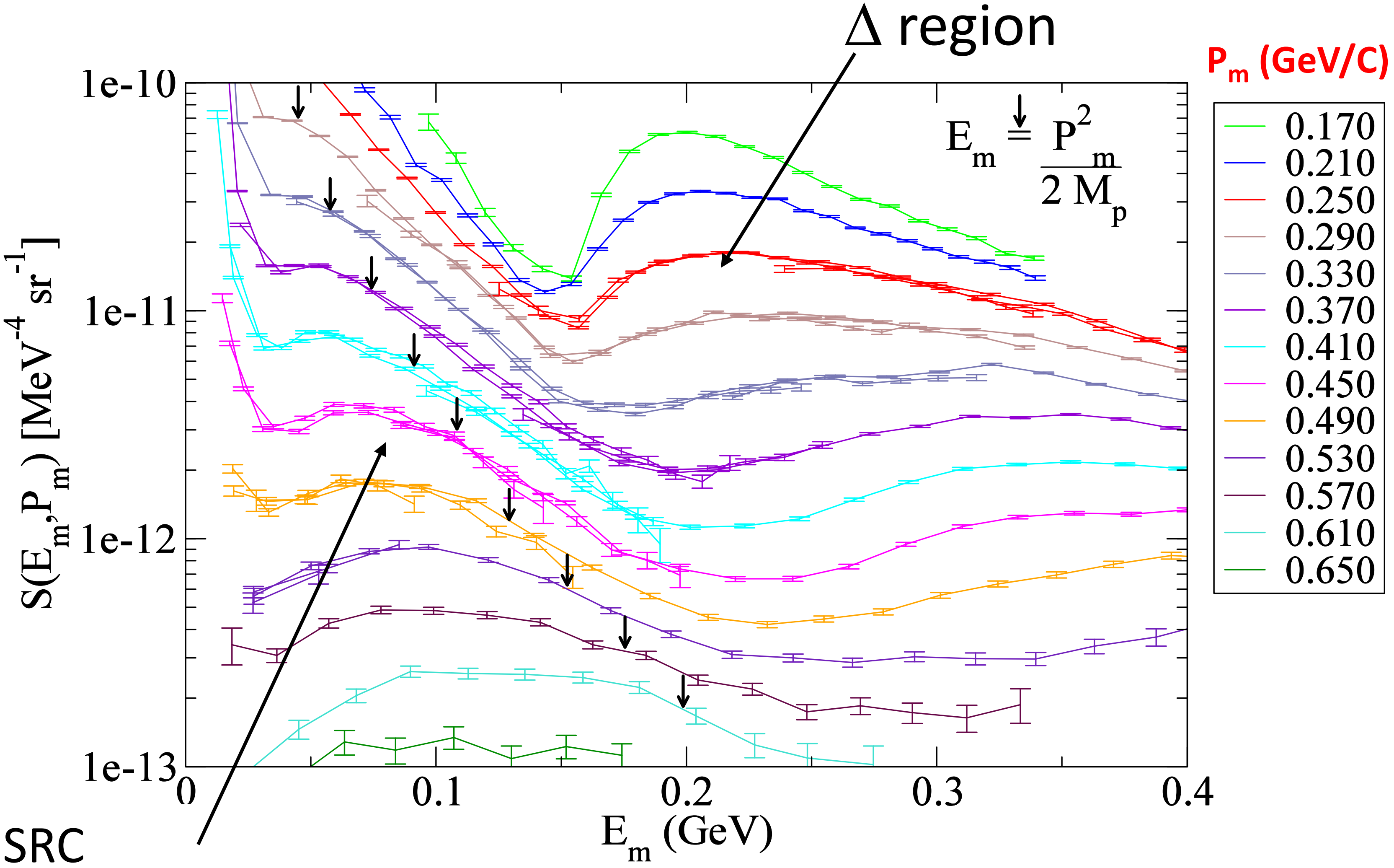
strength: ~85%

~15%

Interest in short range correlations:

- a fraction of the total number of nucleons:
  - ~10% in light nuclei (VMC, FHNC, Green's function)
  - 15-20% in heavy systems (CBF, Green's function)
- can explain up to 2/3 of the binding energy [see ex. PRC51, 3040 ('95) for ^{16}O]
- influence NM saturation properties [see ex. PRL90, 152501 ('03)]

Spectral strength of ^{12}C from exp. E97-006



SRC
correlations

D.Rohe, et. al, Eur. Phys. J. A17, 349 (2003),
Phys Rev. Lett. 93 182501 (2004).

Theory vs. measured strength - I

- About 0.6 protons are found in the correlated region:

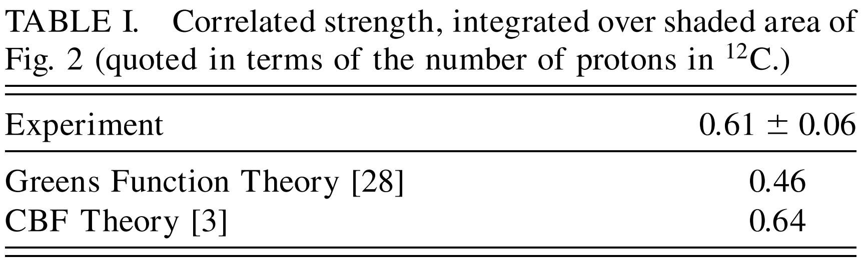


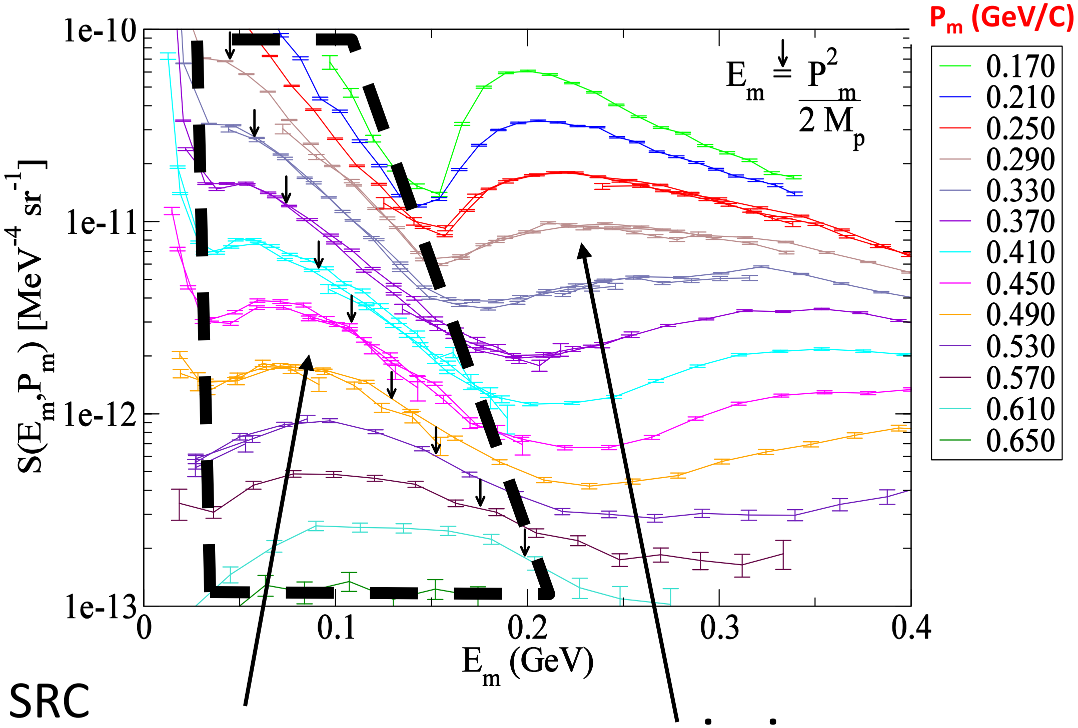
TABLE I. Correlated strength, integrated over shaded area of Fig. 2 (quoted in terms of the number of protons in ^{12}C.)

Experiment	0.61 ± 0.06
Greens Function Theory [28]	0.46
CBF Theory [3]	0.64

→in good agreement with early theoretical predictions!

- what about the position of the peak?

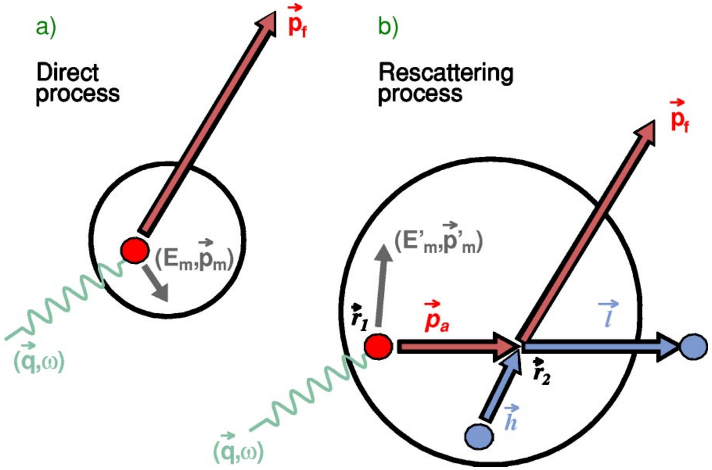
D.Rohe, et. Al,
Eur. Phys. J.
A17, 349 (2003)
PRL93 182501 (2004)



SRC correlations

π emission

(Simple) rescattering model of FSI forhigh-E_m/p_m



← Semi-classical (and Glauber-inspired) model for re-scattering effects

π-production at very high missingenergies -- response functions from MAID database

$$\frac{d^6\sigma_{rescatt.}}{dE_0\; d\Omega_{\hat{k}_o} dE_f\; d\Omega_{\hat{p}_f}} = \sum_{a,N'=1,2,3} \int d\mathbf{r}_1 \int d\mathbf{r}_2 \int_0^\omega dT_a\; \rho_N(\mathbf{r}_1)\;\; \frac{|\mathbf{p}_a| E_a\; S^h_a(|\mathbf{q}-\mathbf{p}_a|,\omega-E_a)\;\sigma^{cc}_{ea}}{M\;(\mathbf{r}_1-\mathbf{r}_2)^2}$$

$$\times g_{aN'}(|\mathbf{r}_1-\mathbf{r}_2|)\; P_T(p_a;\mathbf{r}_1,\mathbf{r}_2)\;\rho_{N'}(\mathbf{r}_2)\;\; \frac{d^3\sigma_{aN'}}{dE_f\; d\Omega_{\hat{p}_f}}\; P_T(p_f;\mathbf{r}_2,\infty)$$

$$\frac{d^6\sigma_{\pi emiss.}}{dE_0\; d\Omega_{\hat{k}_o} dE_f\; d\Omega_{\hat{p}_f}} = \Gamma_v \sum_{a=p,n} \mathcal{T} \int d\mathbf{k}_\pi\; \frac{W^2\;|\mathbf{p}_f|}{(\omega-E_f-\omega_\pi)\;\omega_\pi\;k_\gamma}\; S^h_a(|\mathbf{p}_b|,E_b)$$

$$\times\,[R^a_T + \varepsilon_L\; R^a_L + \varepsilon\; cos(2\phi)\; R^a_{TT} + \sqrt{2\varepsilon_L(1+\varepsilon)}\; cos(\phi)\; R^a_{LT}]$$

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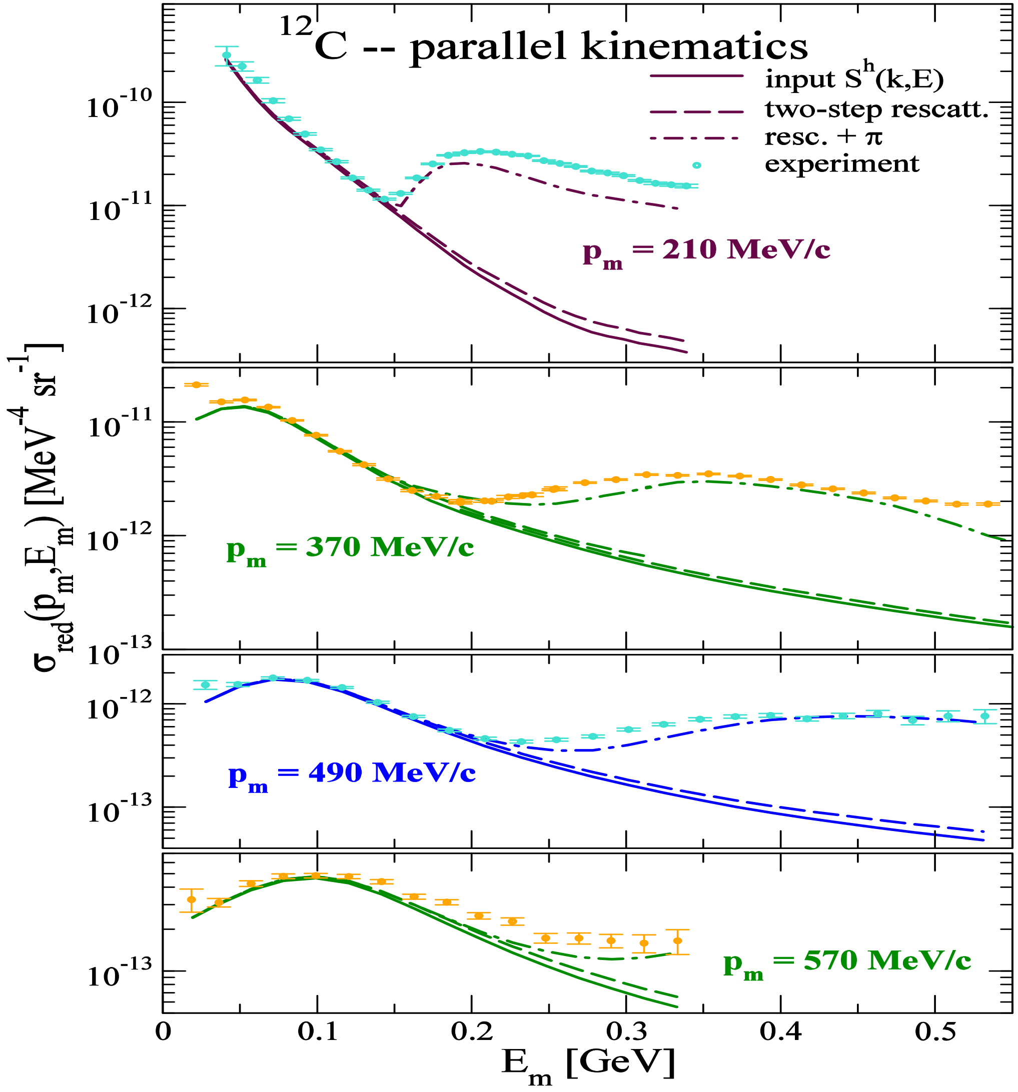
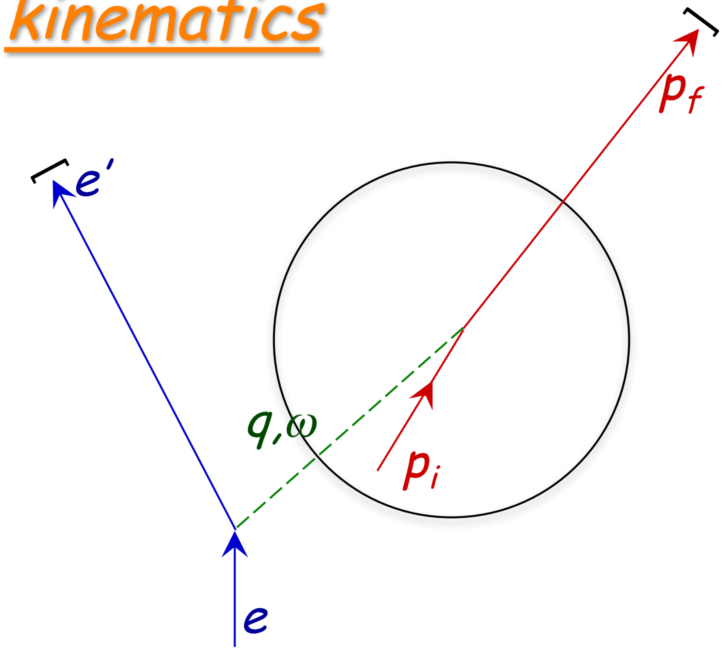
CB et. al. Phys Rev C 70, 054612 (2004); Nucl Phys B159 (Proc. Suppl.) 174 (2006)

Experimental high missing energies – ^{12}C



Parallel kinematics



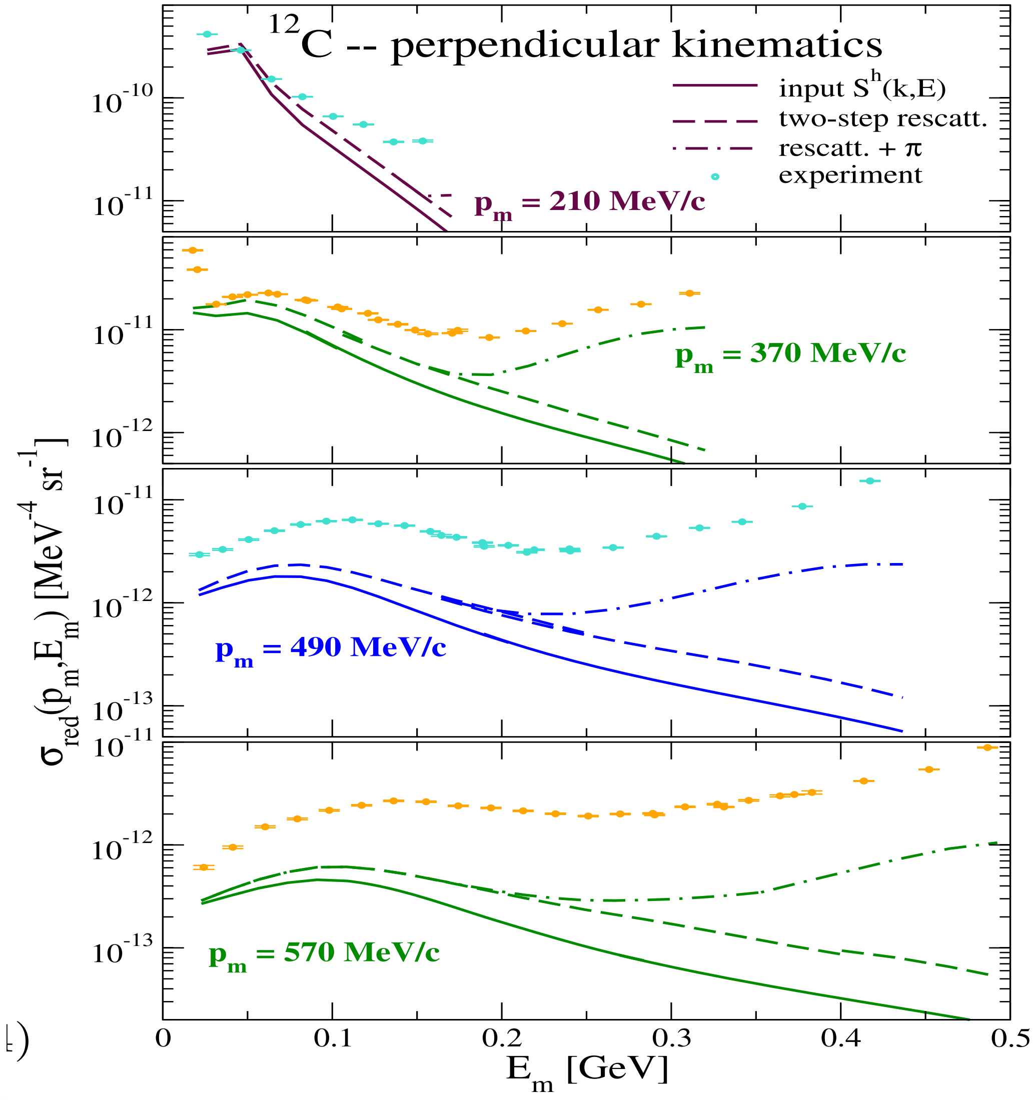
***π*-production at very high missing energies**

Q^2=0.4(Gev/c)^2; beam: 3.3GeV; p_f=1–2 GeV

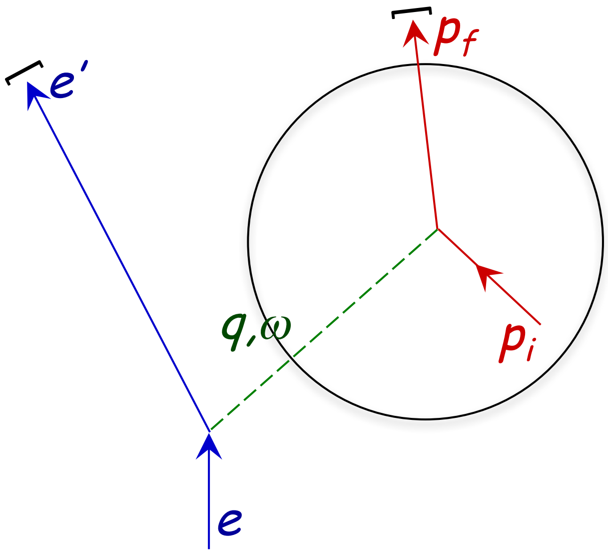
CB et. al. Phys. Lett. <u>B608</u> 47 (2005)

Nucl Phys <u>B159</u> (Proc. Suppl.) 174 (2006)

Experimental high missing energies – ^{12}C



Perpendicular kinematics



π-production at very high missing energies

$Q^2=0.4(\text{Gev/c})^2$; beam: 3.3GeV; p_f=1–2 GeV

CB et. al. Phys. Lett. B608 47 (2005)
Nucl Phys B159 (Proc. Suppl.) 174 (2006)

Summary

Thank you for your attention!!!

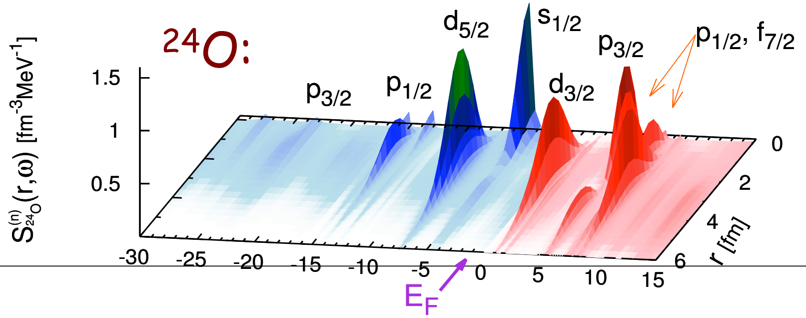
Mid-masses and chiral interactions:

→ *One-body spectral function S(E,p) is interpreted as a distribution of particles both in energy and momentum. → picking up nucleons at different momenta means taking them from different separation energies (roughly speaking). This can affect reactions rates (e.g. Fermi gas a too poor descirption for neutrino scattering).*

→ *New fits of chiral interaction are promising for low-energy observables and for scattering. → Ab initio nuclear theory now capable to give very high precision prediction of nuclear structure (consistent electroweak currents need to be developed… e.g. to estimate uncertainties in preditctions).*

→ *Ab initio calcuation fro spect. Function in progress.. :) – in the low-energy region*

→ *SRC and high momentum tail: there are experimental data that can be understood in these terms. Improvements of FSI would be useful here too.*



And thanks to my collaborators…

Thank you for your attention!!!

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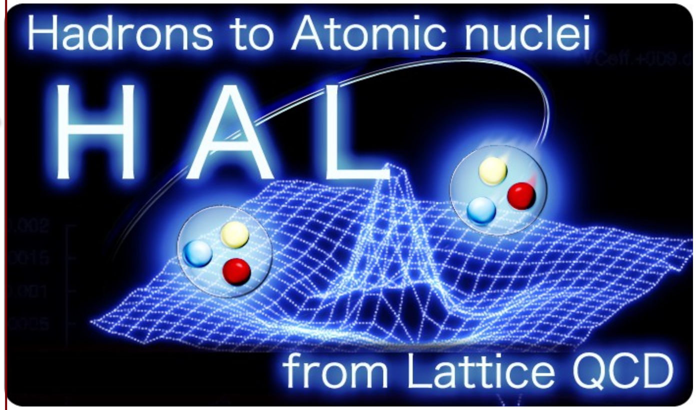

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