TRIUMF

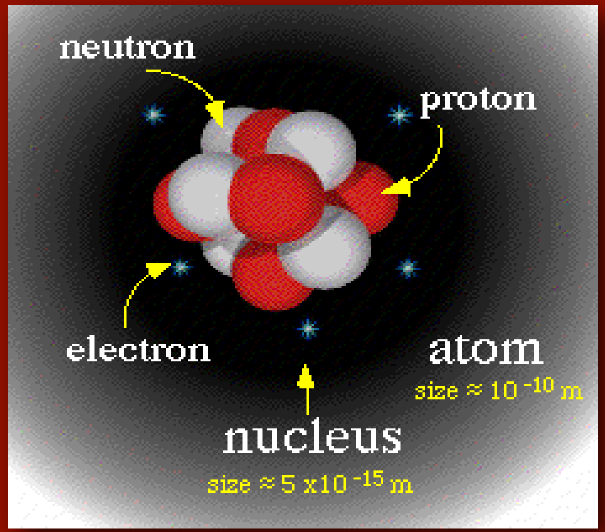
Canada's National Laboratory for Particle and Nuclear Physics
Laboratoire national canadien pour la recherche en physique nucléaire et en physique des particules

First Principle Calculation of Nuclear Response Functions

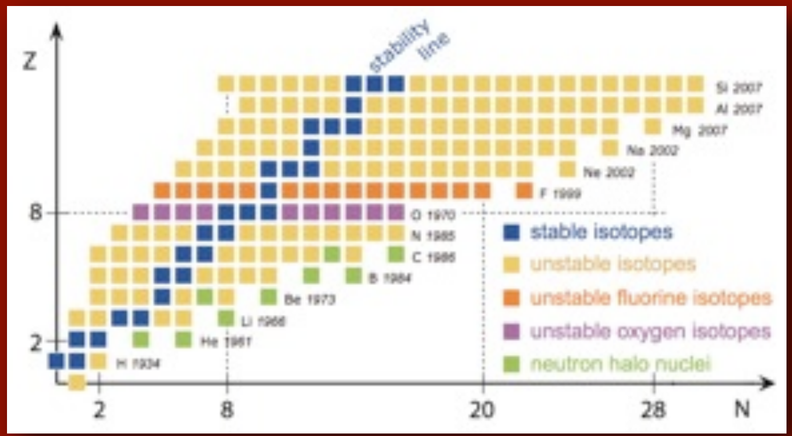
Sonia Bacca

TRIUMF Theory Group

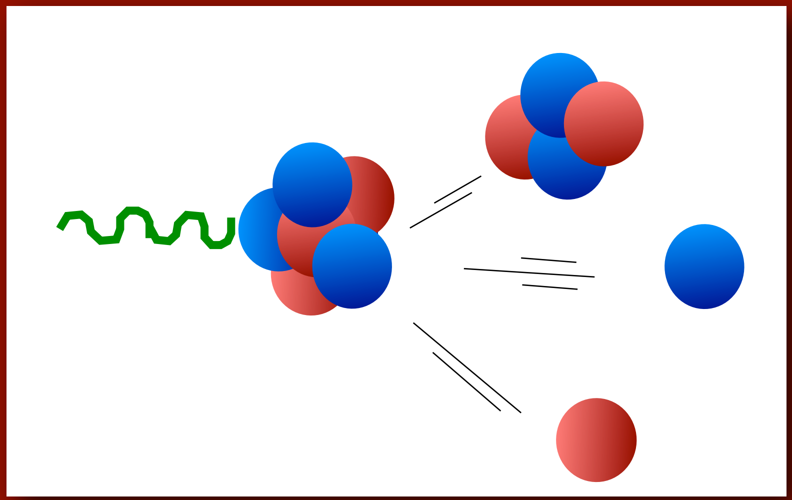
INT program on "Computational and Theoretical advances for Exotic isotopes in the Medium Mass Region"
April 19, 2013



The Atomic Nucleus



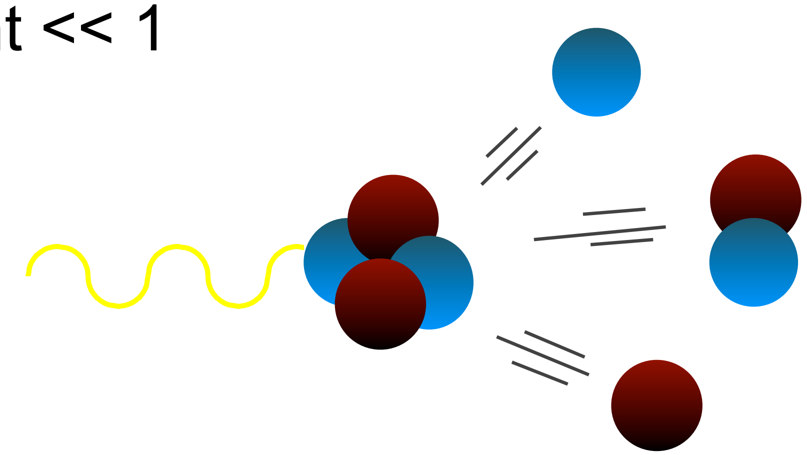
Nuclear Chart



Nuclear Reactions

Electro-weak reactions

- The coupling constant << 1



"*With the electro-weak probe, we can immediately relate the cross section to the transition matrix element of the current operator, thus to the structure of the target itself*"

[De Forest-Walecka, Ann. Phys. 1966]

$$\sigma \propto \left| \langle \psi_f | \hat{J}^\mu | \psi_0 \rangle \right|^2$$

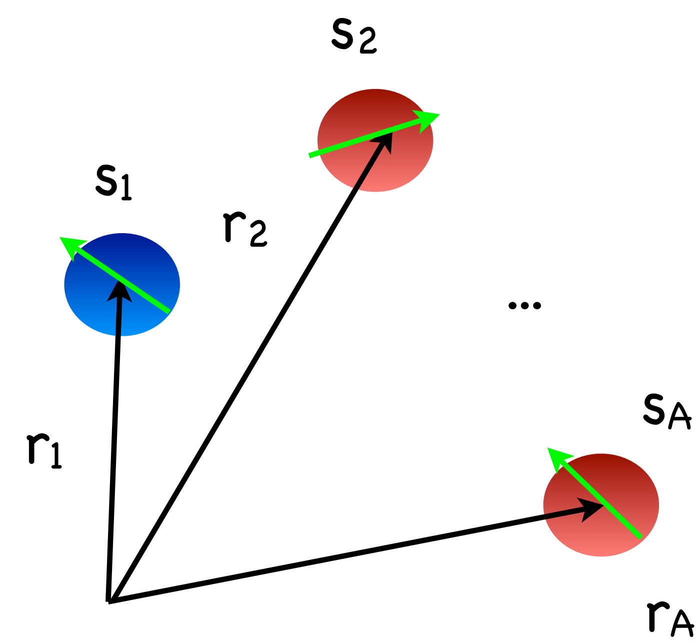
$$\sigma \propto R(q,\omega) \quad \text{with} \quad R(q,\omega) = \sum\!\!\!\!\!\!\!\int_f \left| \left\langle \psi_f | \hat{J}^\mu(q) | \psi_0 \right\rangle \right|^2 \delta(E_f - E_0 - \omega)$$

Nuclear Response Function

From "First Principles"

- Start from neutrons and protons as building blocks (centre of mass coordinates, spins, isospins)

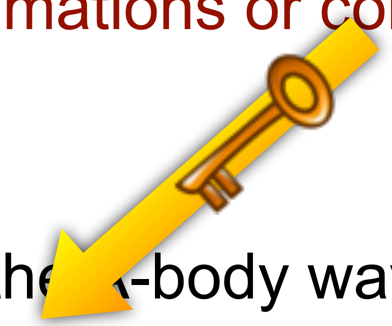
- Solve the (non-relativistic) quantum mechanical problem of A-interacting nucleons



$$H|\psi\rangle = E|\psi\rangle$$

$$H = T + V_{NN}(\Lambda) + V_{3N}(\Lambda) + \ldots$$

- Find numerical solutions with no approximations or controllable approximations

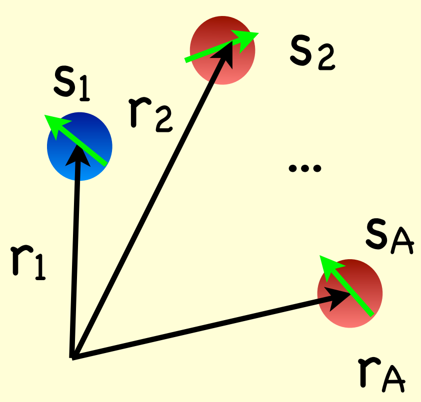


- Calculate low-energy observables form the A-body wave function and compare with experiment to test nuclear forces and provide predictions when experiments are hard or even not possible or help interpret new experiments

- Develop a strong predictive theory in the framework of light nuclei and then extend it towards heavier and neutron-rich systems

Ingredients

Nuclear Forces



$$H|\psi_i\rangle = E_i|\psi_i\rangle$$

$$H = T + V_{NN} + V_{3N} + \ldots$$

High precision two-nucleon potentials:
well constraint on NN phase shifts

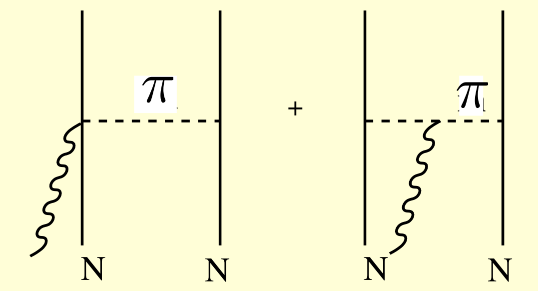
Three nucleon forces:
less known, constraint on A>2 observables

Traditional Nuclear Physics
AV18+UIX, ..., J_2

Effective Field Theory
N^2LO, N^3LO ...

Nuclear Currents

$$J^\mu = J^\mu_N + J^\mu_{NN} + \ldots$$



exchange currents

subnuclear d.o.f.

J^μ consistent with V

$$\nabla \cdot J = -i[V, \rho]$$

Final State Interaction

$$\sigma \propto |\langle \Psi_f | J^\mu | \Psi_0 \rangle|^2$$

Final state in the continuum at different energies and for different A

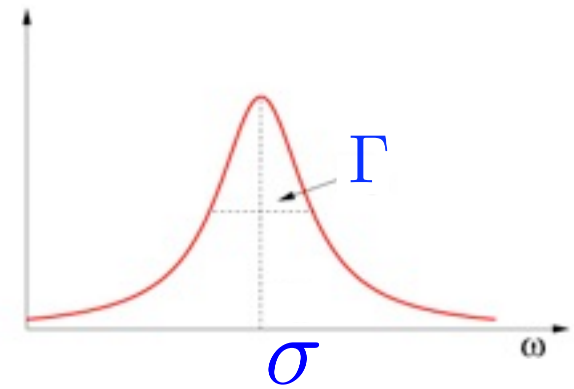
Final State Interaction

Exact evaluation of the final state in the continuum is limited in energy and A

Solution: The Lorentz Integral Transform Method Efros *et al.*, Nucl.Part.Phys. **34** (2007) R459

Response in the continuum

$$R(\omega) = \sum\!\!\!\!\!\!\!\int_f \left| \left\langle \psi_f \left| \hat{O} \right| \psi_0 \right\rangle \right|^2 \delta(E_f - E_0 - \omega)$$



$$L(\sigma, \Gamma) = \int d\omega \frac{R(\omega)}{(\omega - \sigma)^2 + \Gamma^2} = \langle \tilde{\psi} | \tilde{\psi} \rangle$$

$$(H - E_0 - \sigma + i\Gamma) \mid \tilde{\psi}\rangle = \hat{O} \mid \psi_0 \rangle$$

- Due to imaginary part Γ the solution $|\tilde{\psi}\rangle$ is unique
- Since the r.h.s. is finite, then $|\tilde{\psi}\rangle$ has bound state asymptotic behavior

$$L(\sigma, \Gamma) \xrightarrow{\text{inversion}} R(\omega)$$ with the exact final state interaction

You can use any good bound state method! e.g. Hyperspherical Harmonics, No Core Shell Model, Coupled Cluster Theory

Final State Interaction

Exact evaluation of the final state in the continuum is limited in energy and A

Solution: The Lorentz Integral Transform Method   Efros *et al.*, Nucl.Part.Phys. **34** (2007) R459

Response in the continuum

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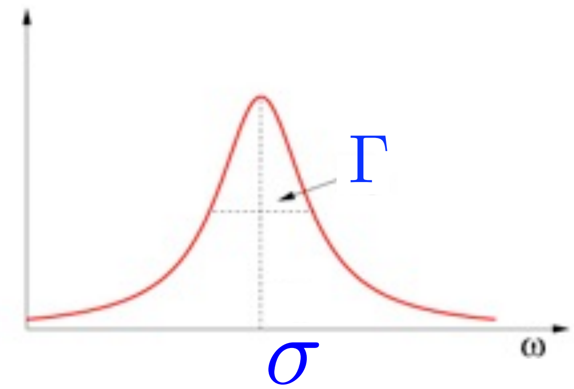


$$L(\sigma,\Gamma) = \int d\omega \frac{R(\omega)}{(\omega-\sigma)^2+\Gamma^2} = \langle \tilde{\psi} | \tilde{\psi} \rangle$$

$$(\omega-\sigma-i\Gamma)(\omega-\sigma+i\Gamma)$$

$$= \sum\!\!\!\!\!\!\int_f \left\langle \psi_0 | \hat{O} \frac{1}{E_f - E_0 - \sigma - i\Gamma} | \psi_f \right\rangle \left\langle \psi_f | \frac{1}{E_f - E_0 - \sigma + i\Gamma} \hat{O} | \psi_0 \right\rangle$$

$$= \sum\!\!\!\!\!\!\int_f \left\langle \psi_0 | \hat{O} \frac{1}{H - E_0 - \sigma - i\Gamma} | \psi_f \right\rangle \left\langle \psi_f | \frac{1}{H - E_0 - \sigma + i\Gamma} \hat{O} | \psi_0 \right\rangle$$

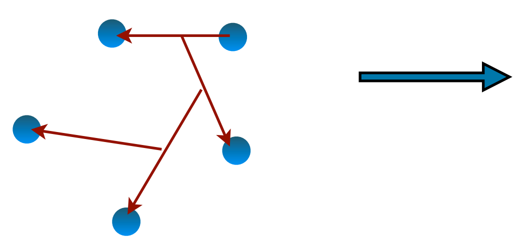
$$= \left\langle \psi_0 | \hat{O} \frac{1}{H - E_0 - \sigma - i\Gamma} \frac{1}{H - E_0 - \sigma + i\Gamma} \hat{O} | \psi_0 \right\rangle$$

$$\frac{1}{H - E_0 - \sigma + i\Gamma} \hat{O} | \psi_0 \rangle = \left| \tilde{\psi} \right\rangle$$

Hyperspherical Harmonics

A basis set, mostly used for A=3,4. Challenge to go up to A=7,8

- Few-body method - uses relative coordinates $|\psi(\vec{r}_1, \vec{r}_2, \ldots, \vec{r}_A)\rangle = |\varphi(\vec{R}_{CM})\Psi(\vec{\eta}_1, \vec{\eta}_2, \ldots, \vec{\eta}_{A-1})\rangle$



$\vec{\eta}_0 = \sqrt{A}\vec{R}_{CM}$ $\quad \vec{\eta}_1, \ldots, \vec{\eta}_{A-1}$

Recursive definition of hyper-spherical coordinates

ρ, Ω $\qquad \rho^2 = \sum_{i=1}^{A} r_i^2 = \sum_{i=1}^{A-1} \eta_i^2$

$$H_0(\rho, \Omega) = T_\rho - \frac{K^2(\Omega)}{\rho^2}$$

$$\Psi = \sum_{[K],\nu}^{K_{max},\nu_{max}} c_\nu^{[K]} e^{-\rho/2b} \rho^{n/2} L_\nu^n\left(\frac{\rho}{b}\right)[\mathcal{Y}_{[K]}^{\mu}(\Omega)\chi_{ST}^{\bar{\mu}}]_{JT}^{a}$$

Asymptotic	$e^{-a\rho}$	$\rho \to \infty$

Model space truncation $\quad K \leq K_{max}$ $\quad$ Matrix Diagonalization $\qquad \langle\psi|H_{(2)}|\psi\rangle = \frac{A(A-1)}{2}\langle\psi|H_{(A,A-1)}|\psi\rangle$

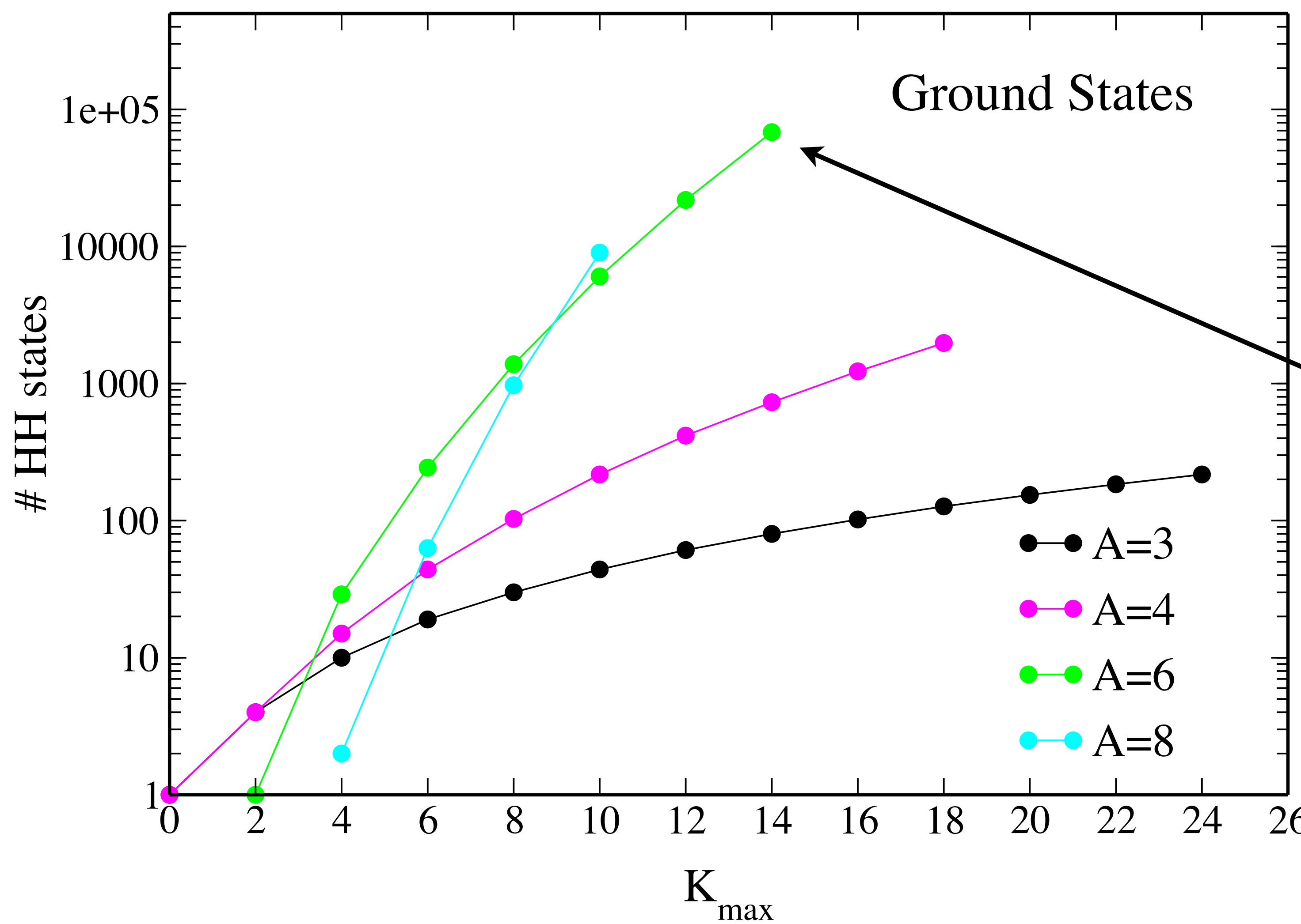
Can use local and non-local interactions

Most applications in few-body; challenge in A>4

Barnea and Novoselsky, Ann. Phys. 256 (1997) 192

Hyperspherical Harmonics Expansions

$$\Psi = \sum_{[K],\nu}^{K_{max},\nu_{max}} c_\nu^{[K]} e^{-\rho/2} \rho^{n/2} L_\nu^n(\rho) [\mathcal{Y}_{[K]}^{\mu}(\Omega) \chi_{ST}^{\bar{\mu}}]_{JT}^a$$



Total number of states:
#HH X #Hyper-radial states

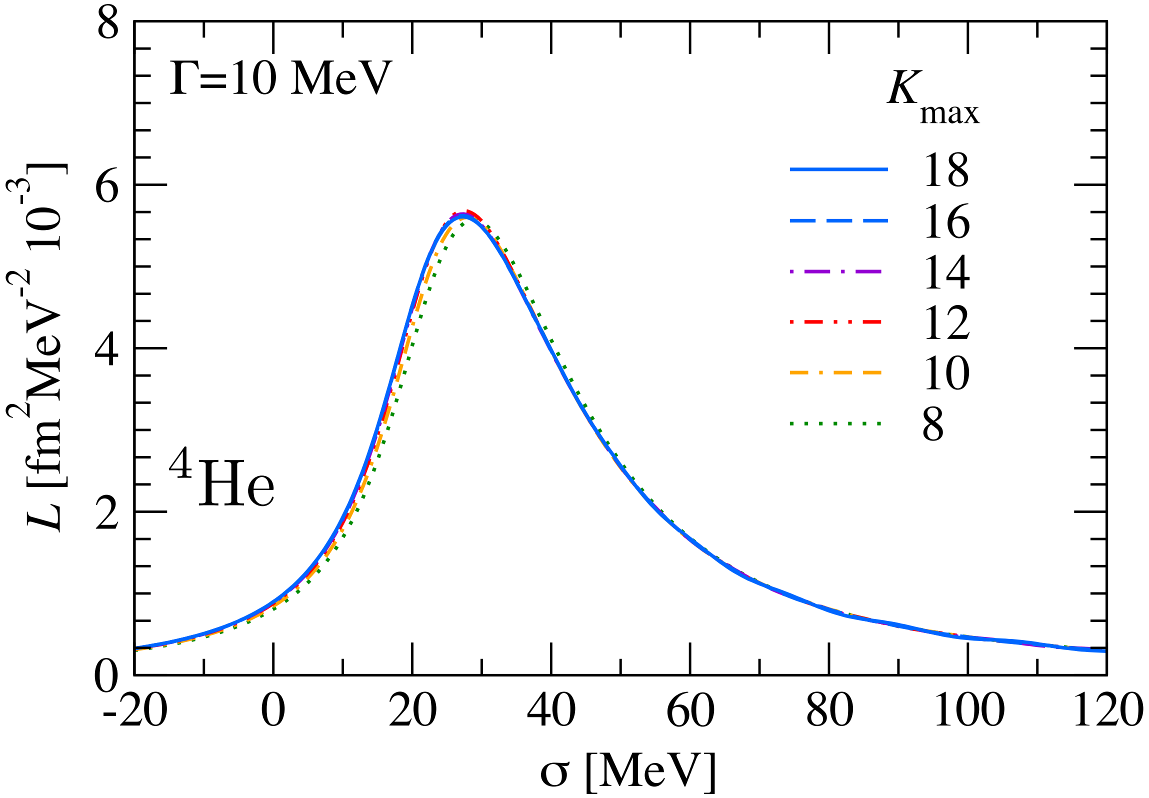
10^6 dense matrix

$$(H - E_0 - \sigma + i\Gamma) \mid \tilde{\psi}\rangle = \hat{O} \mid \psi_0\rangle$$

For the reactions expanding $\hat{O}|\psi_0\rangle$
increase of dimension by at least one order of magnitude of angular momentum is changed

The LIT with Hyperspherical Harmonics

Numerical example: Dipole Response Function of ^{4}He $\hat{O} = \hat{D}_z = \sum_i^Z (z_i - Z_{\rm cm})$ with NN(N^{3}LO)



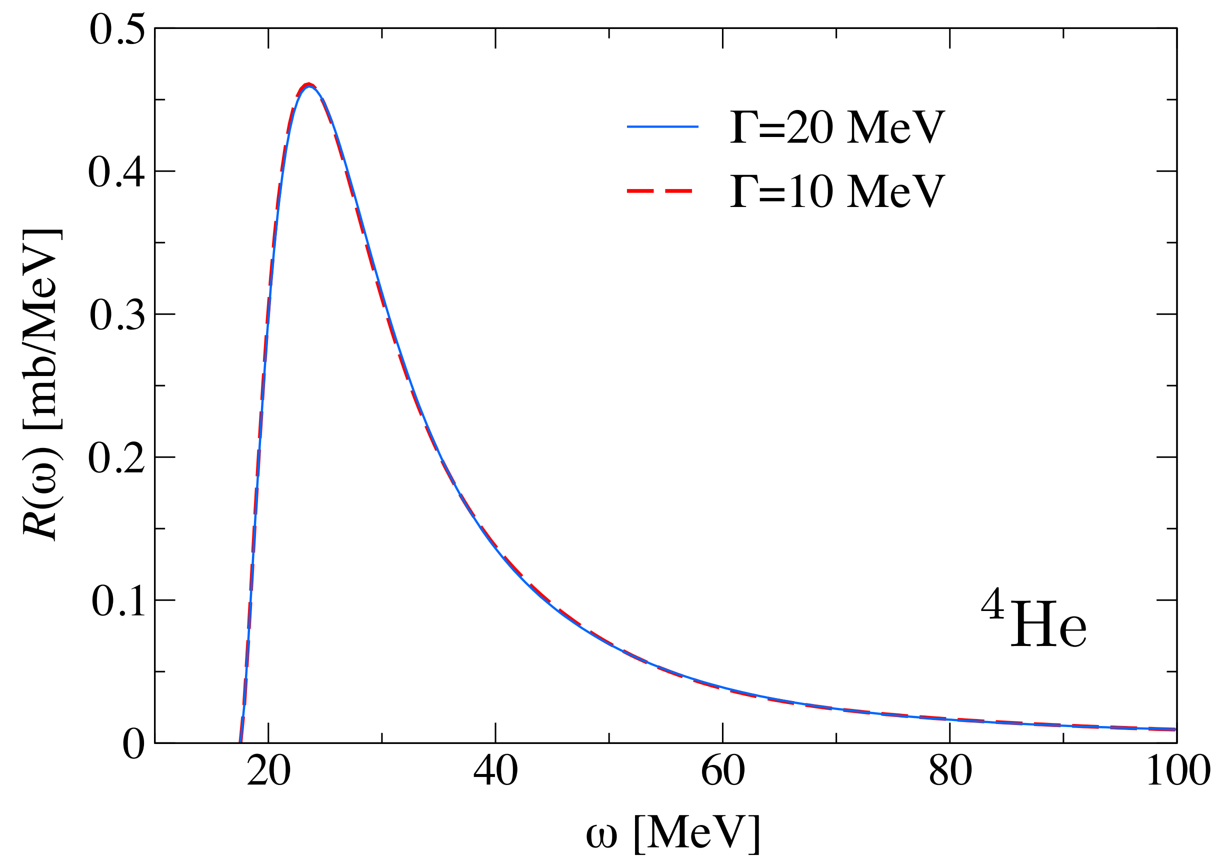
Inversion of the LIT

Ansatz

$$R(\omega) = \sum_i^{I_{\rm max}} c_i \chi_i(\omega, \alpha)$$

$$L(\sigma, \Gamma) = \sum_i^{I_{\rm max}} c_i \mathcal{L}[\chi_i(\omega, \alpha)]$$

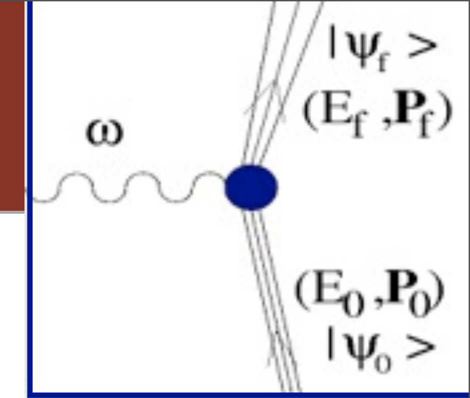
Least square fit of the coefficients c_i to reconstruct the response function

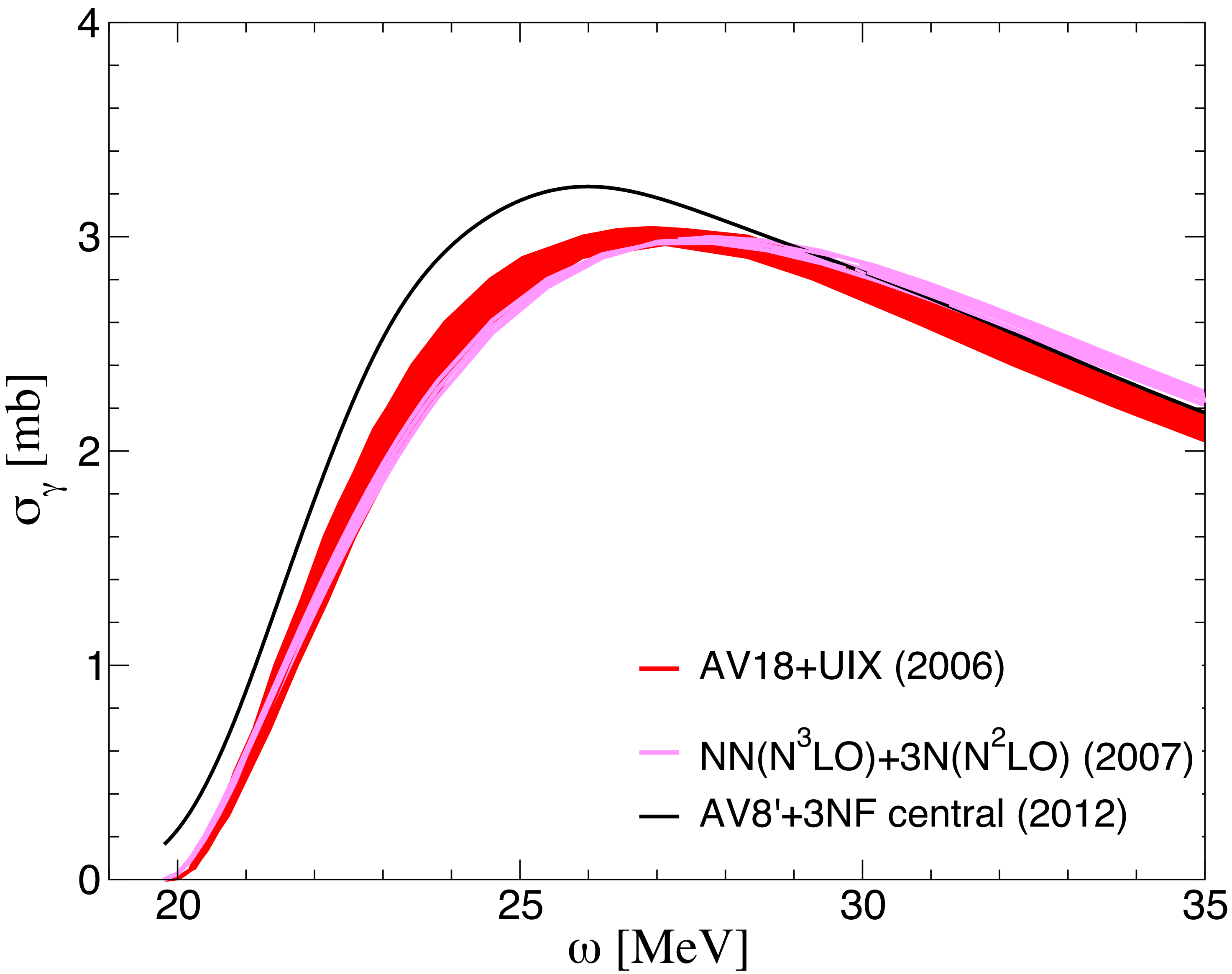


Some examples for A=4

- Photo-absorption
- Electron Scattering

Theory $\gamma + {}^4\text{He} \longrightarrow X$





$$\sigma_\gamma = \frac{4\pi^2\alpha}{3}\omega R^{E1}(\omega)$$

Traditional Hamiltonian
D.Gazit, S.B. et al. PRL 96 112301 (2006)

E_0 = -28.40 MeV

Hamiltonian from EFT
S.Quaglioni and P.Navratil PLB 652 (2007)

NN(N^{3}LO) Entem-Machleidt PRC68, 041001(R) (2003)
3N(N^{3}LO) local version from Navratil with
C_D=1 C_E=-0.029

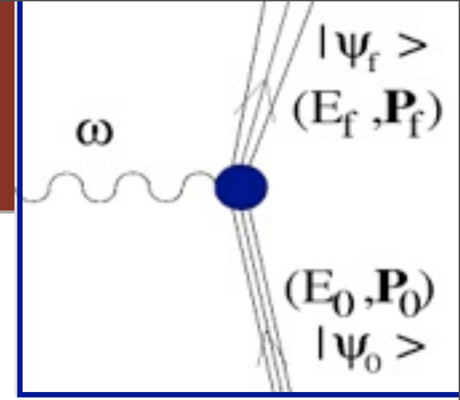
E_0 = -28.36 MeV

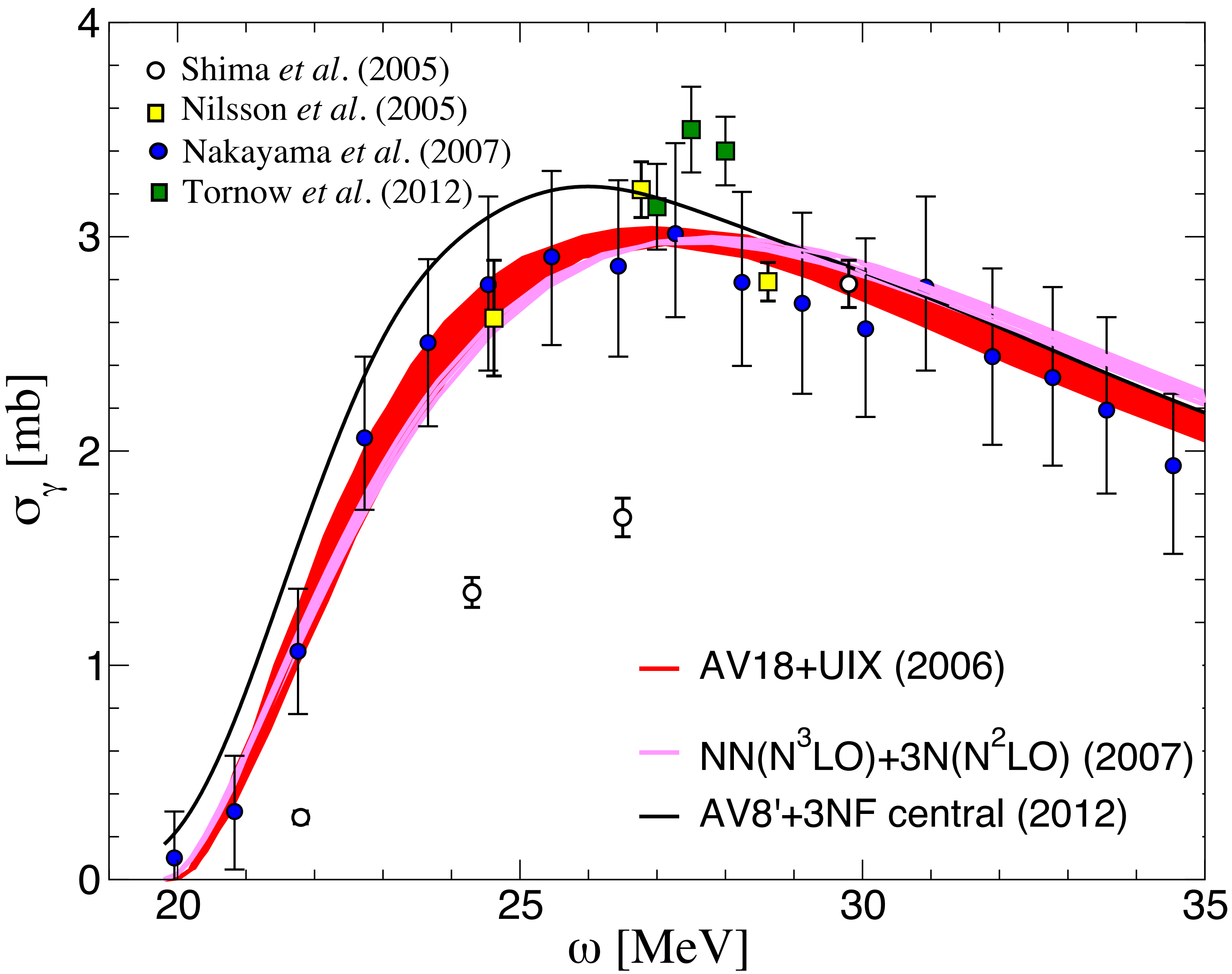
Realistic NN + phenomenological central 3NF
W.Horiuchi et al. PRC 85 054002 (2012)

E_0 = -28.44 MeV

⇒ Moderate sensitivity to the Hamiltonian used; theory variation about 10% in peak

Theory/Experiment $\gamma + {}^4\mathrm{He} \longrightarrow X$





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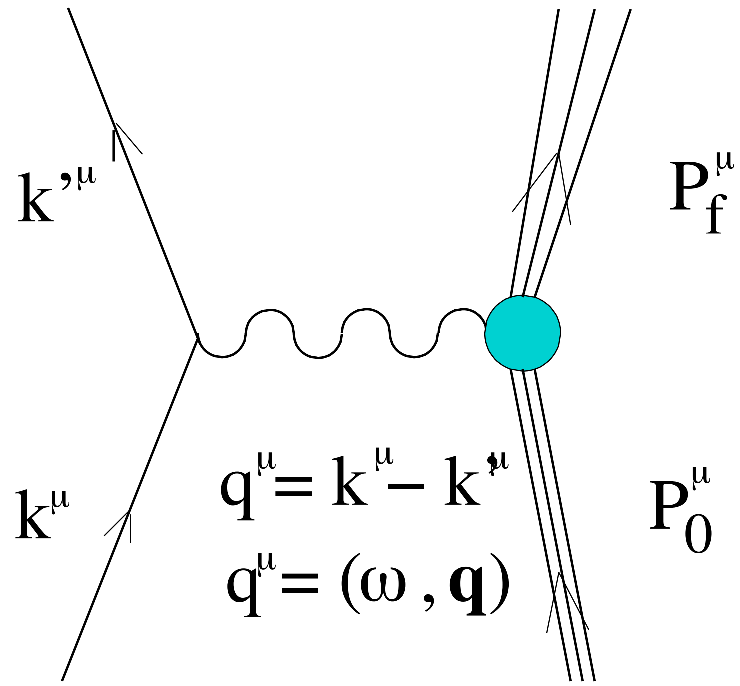
E_0 = -28.44 MeV

- Moderate sensitivity to the Hamiltonian used; theory variation about 10% in peak
- More recent experimental activity seems to confirm higher data with peak around 27 MeV
- Theoretical precision is better than experimental error

Inelastic e-Scattering $^4He(e,e')X$



Virtual Photon

$$(\omega, \mathbf{q})$$

can vary independently

Inclusive cross section A(e,e')X

$$\frac{d^2\sigma}{d\Omega d\omega} = \sigma_M \left[\frac{Q^4}{\mathbf{q}^4} R_L(\omega, \mathbf{q}) + \left(\frac{Q^2}{2\mathbf{q}^2} + \tan^2 \frac{\theta}{2} \right) R_T(\omega, \mathbf{q}) \right]$$

with $Q^2 = -q_\mu^2 = \mathbf{q}^2 - \omega^2$ and θ scattering angle

and σ_M Mott cross section

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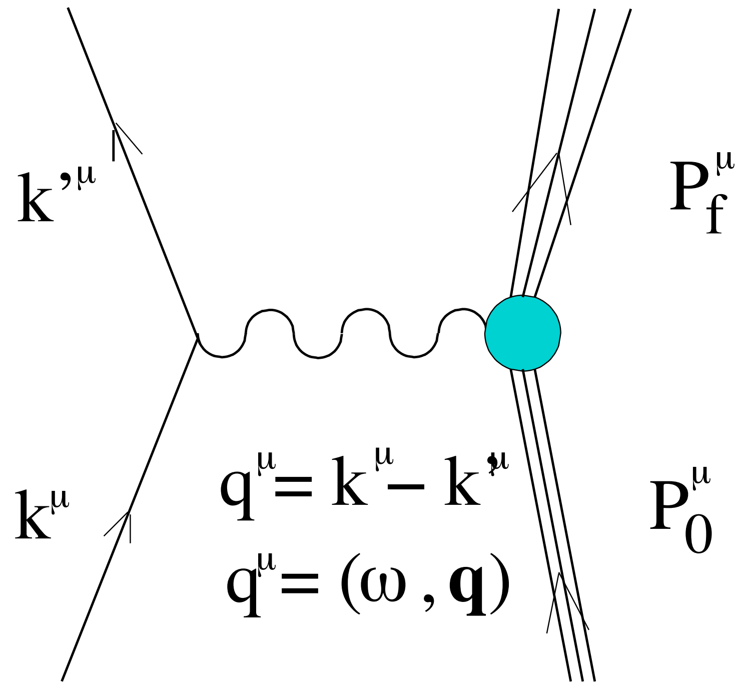
Inelastic e-Scattering $^4He(e,e')X$



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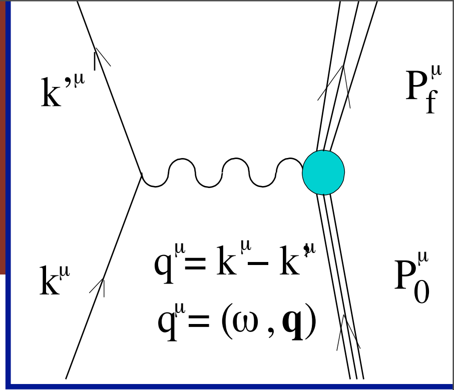
$$R_L(\omega, \mathbf{q}) = \sum_f |\langle \Psi_f | \rho(\mathbf{q}) | \Psi_0 \rangle|^2 \delta \left(E_f - E_0 - \omega + \frac{\mathbf{q}^2}{2M} \right)$$

two-body currents are not important

$$R_T(\omega, \mathbf{q}) = \sum_f |\langle \Psi_f | J_T(\mathbf{q}) | \Psi_0 \rangle|^2 \delta \left(E_f - E_0 - \omega + \frac{\mathbf{q}^2}{2M} \right)$$

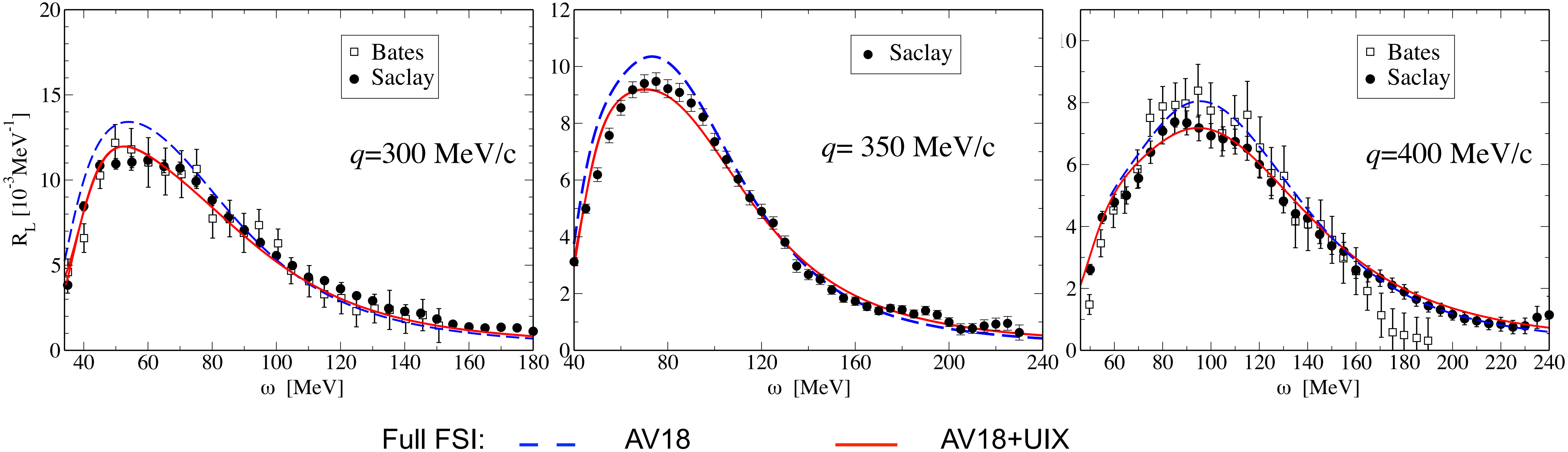
Inelastic e-Scattering $^4He(e,e')X$



Calculation of $R_L(\omega, \mathbf{q})$ with the LIT

Medium-q kinematics Searching for 3NF effects

S.B. et al., PRL 102, 162501 (2009)



- 3NF reduce the peak of 10%
- Comparison with experiment improves with 3NF

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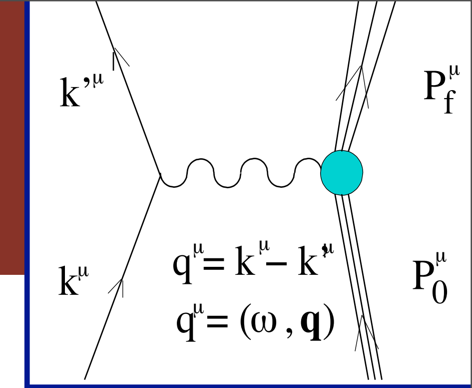
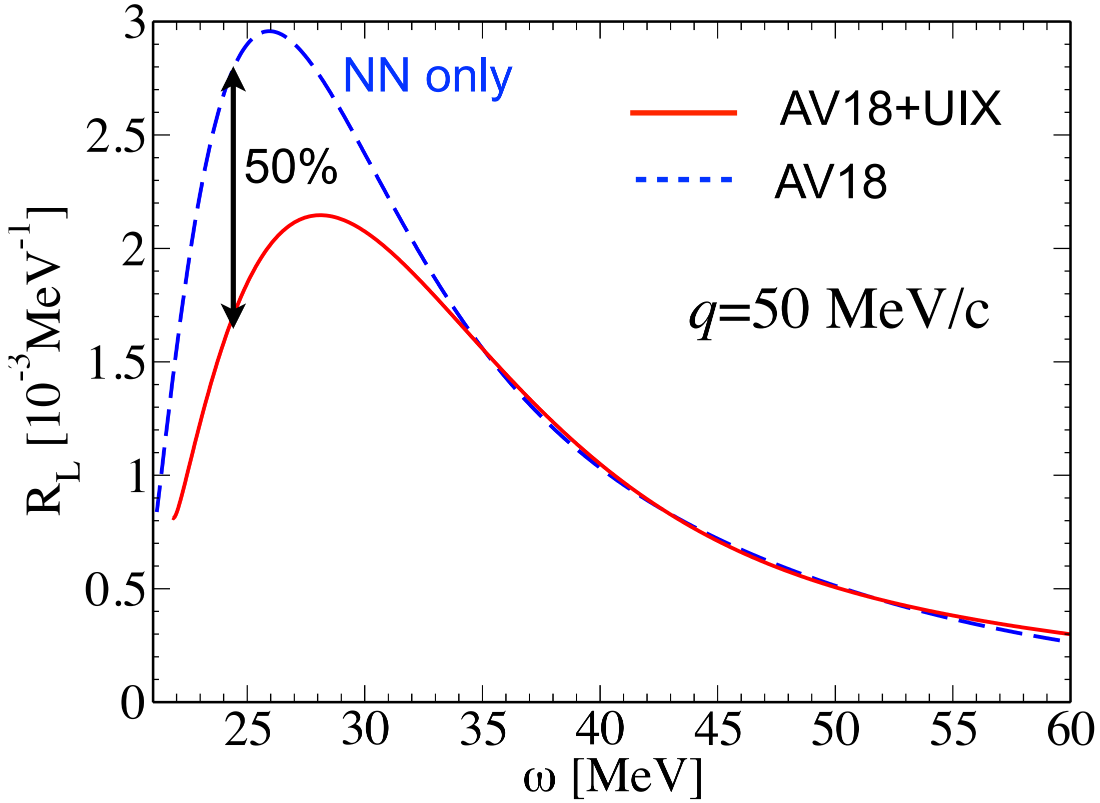
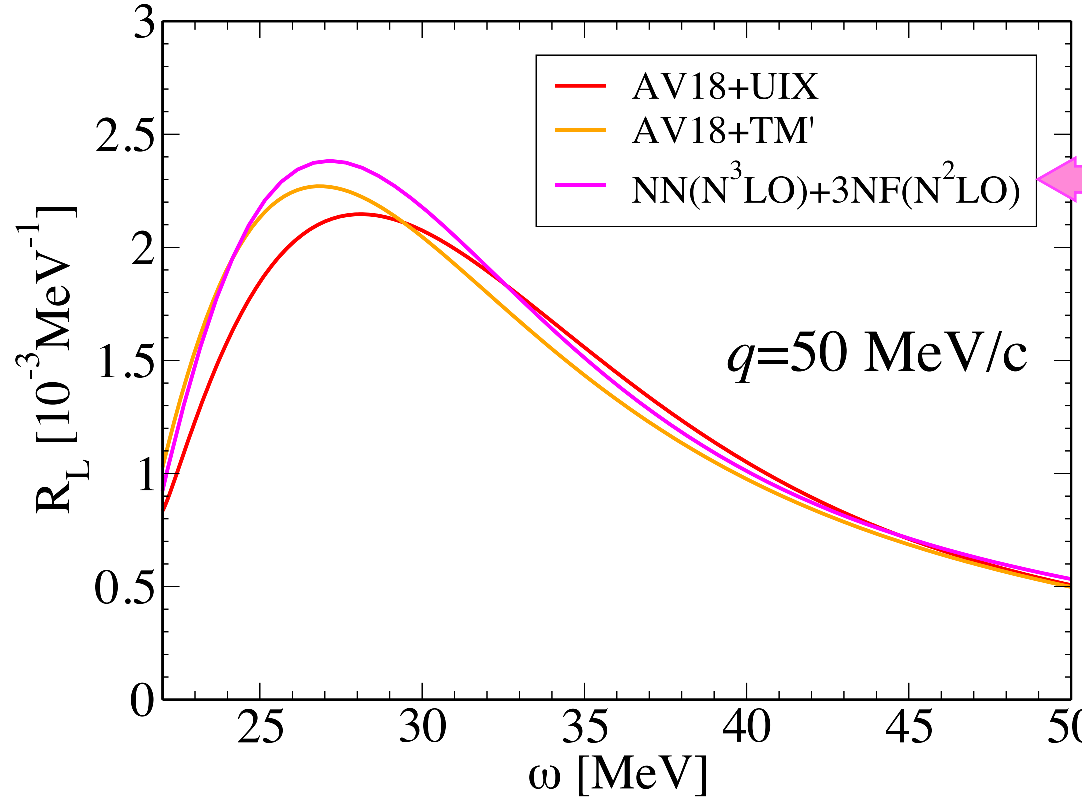
Inelastic e-Scattering $^4He(e,e')X$



Low-q kinematics



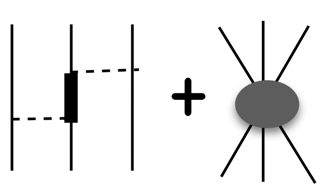
different 3N Hamiltonians

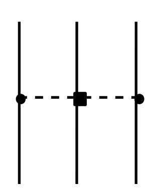


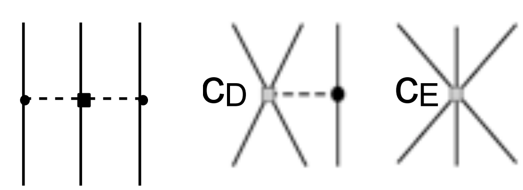
χ EFT forces preliminary

- Strong 3NF effect at low q
- It is not a simple binding effect!

	AV18+UIX	AV18+TM'	NN(N³LO)+3NF(N²LO)
B.E./MeV	28.40	28.46	28.36(2)

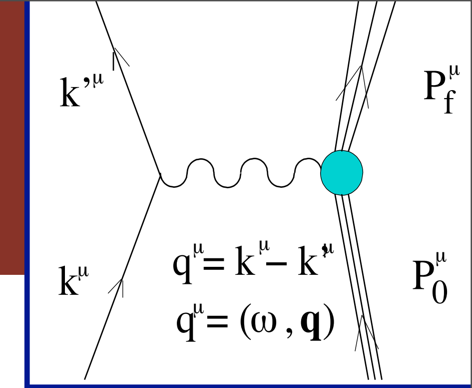






- Stimulating new experiments: MAMI taken data q ≥150 MeV/c; S-DALINAC will maybe take data at lower q

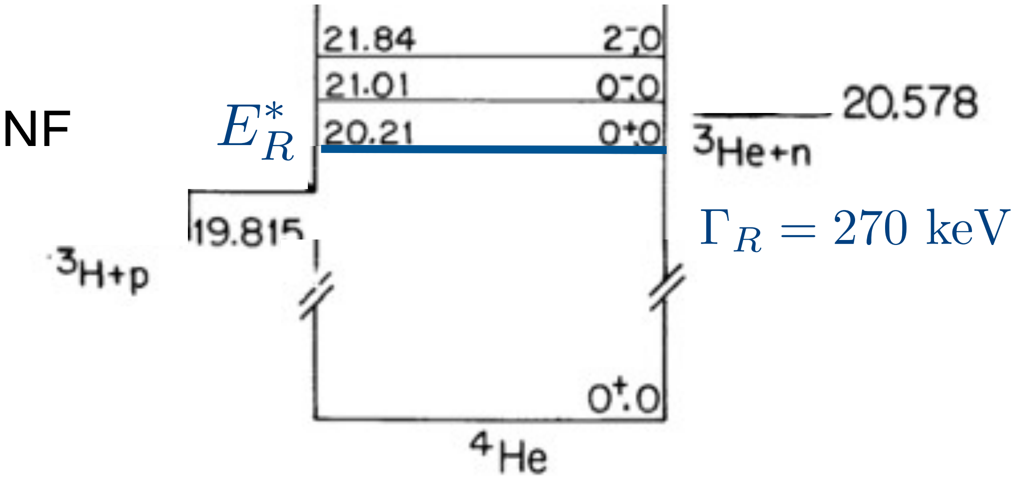
Monopole Resonance $^4He(e,e')0^+$

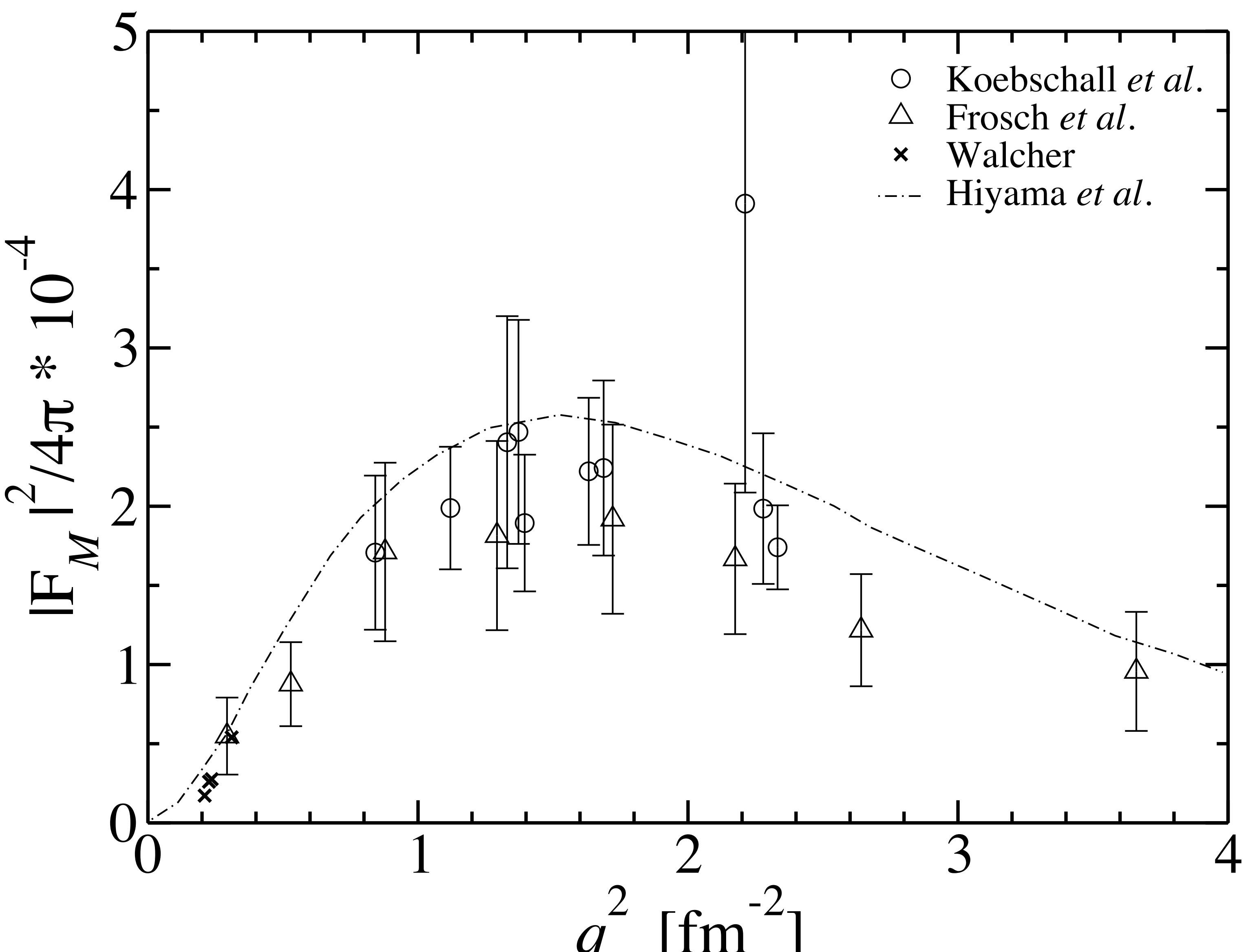


Resonant Transition Form Factor
$0_1^+ \longrightarrow 0_2^+$

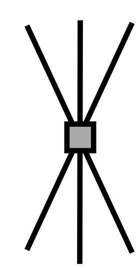
$$|F_{\mathcal{M}}(q)|^2 = \frac{1}{Z^2}\int d\omega R^{\text{res}}_{\mathcal{M}}(q,\omega)$$

First ab-initio calculation: Hiyama *et al.*, PRC **70** 031001 (2004)
obtained good description of data with phenomenological central 3NF

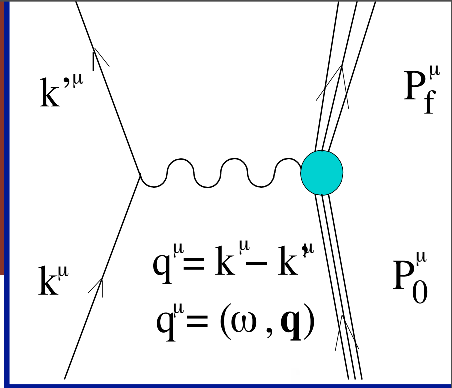




AV8' + central 3NF
E_0 = -28.44 MeV
E_0^{exp}= -28.30 MeV



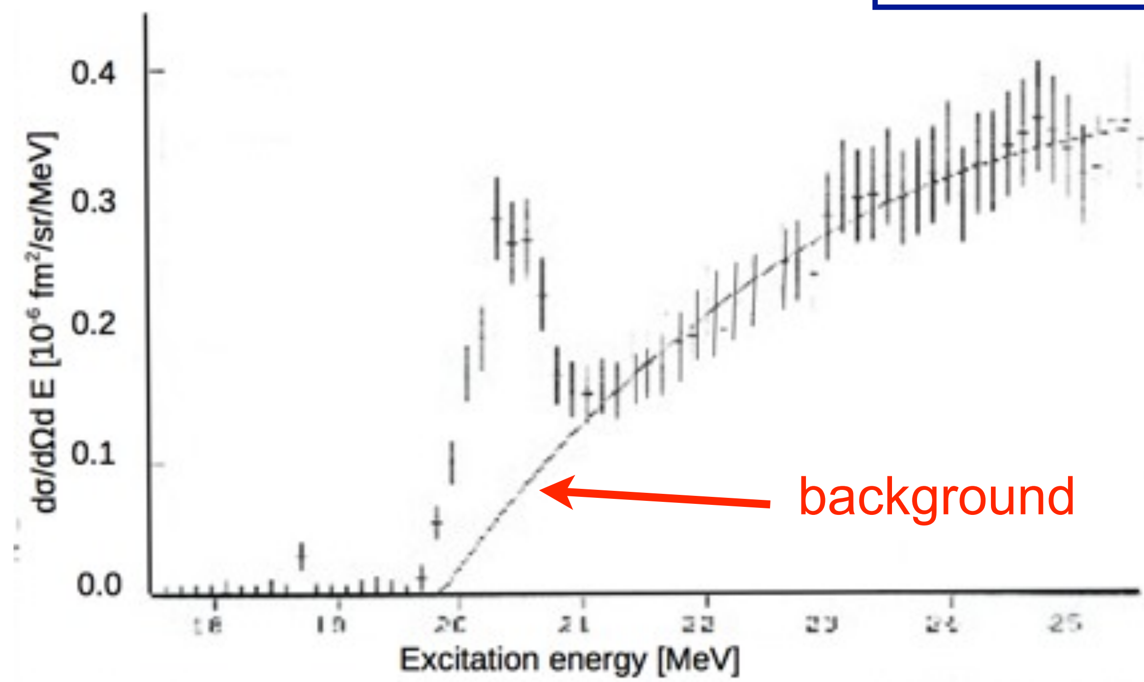
Monopole Resonance ^{4}He(e,e')0$^+$



In proximity of the resonance
both in theory and experiment

$$R_{\mathcal{M}}(q,\omega) = R^{\rm res}_{\mathcal{M}}(q,\omega) + R^{\rm bg}_{\mathcal{M}}(q,\omega) \quad (\star)$$

Nucl. Phys. A405, 648 (1983)



We use a square integrable basis (HH) to calculate the LIT (not the response)
rigorous because of finite Γ

$$\mathcal{L}_{\mathcal{M}}(q,\sigma,\Gamma) = \frac{\Gamma}{\pi}\sum_{\nu=1}^{N}\frac{|\langle\Psi_\nu|\mathcal{M}(q)|\Psi_0\rangle|^2}{(\sigma - e_\nu + E_0)^2 + \Gamma^2}$$

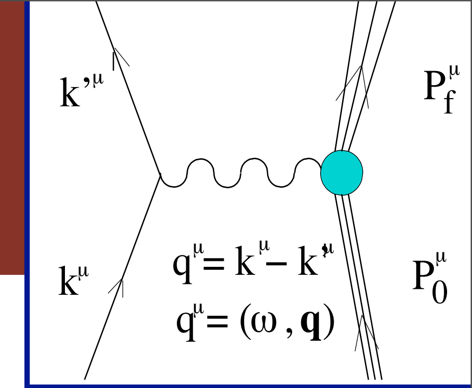
where Ψ_ν, e_ν are eigenstate and eigenvalues of H on our basis

We see ONE very pronounced strength $|\langle\Psi_{\nu_R}|\mathcal{M}(q)|\Psi_0\rangle|^2$ located at the energy

$$e_\nu - E_0 = E^*_R$$

Exploit the power of the LIT method (calculate the far continuum) to subtract the background

Monopole Resonance $^4He(e,e')0^+$



In proximity of the resonance
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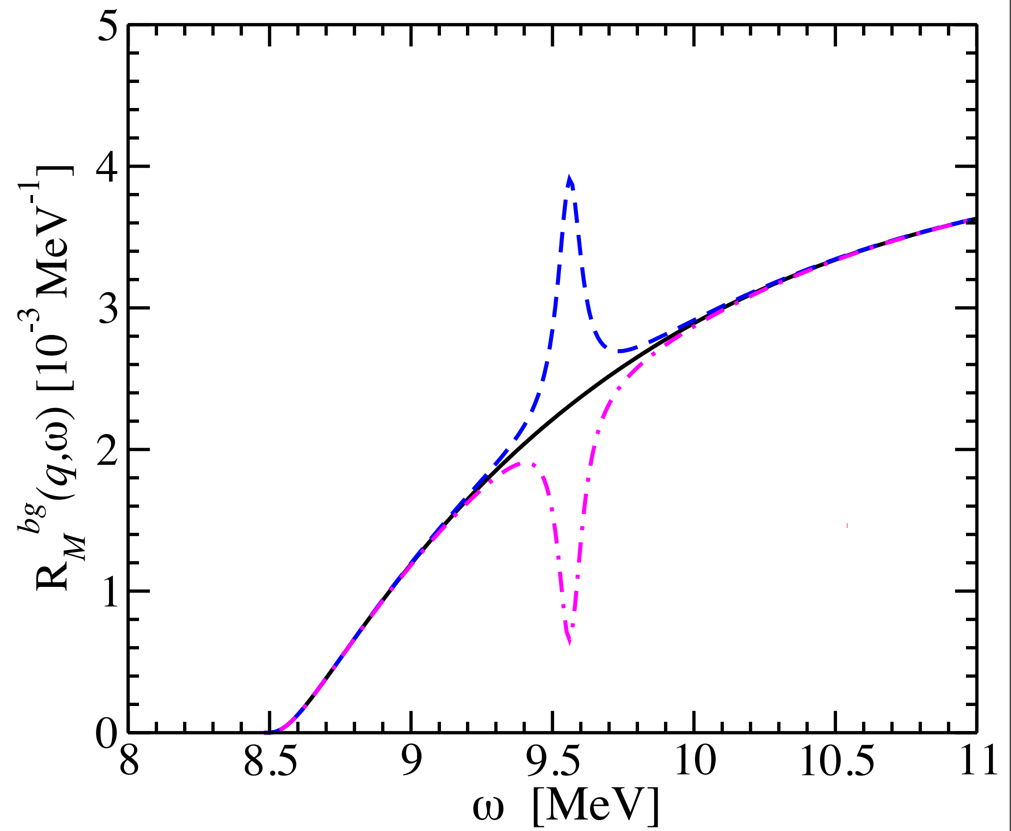
$$R_{\mathcal{M}}(q,\omega) = R_{\mathcal{M}}^{\rm res}(q,\omega) + R_{\mathcal{M}}^{\rm bg}(q,\omega) \quad (\star)$$



Inversion of the LIT

ansatz

$$\mathcal{R}_{\mathcal{M}}(q,\omega) = \sum_i c_i \chi_i(\omega,\alpha)$$

$$\mathcal{L}_{\mathcal{M}}(\sigma,\Gamma) = \sum_i c_i \mathcal{L}[\chi_i(\omega,\alpha)]$$

least square fit of c_i

0

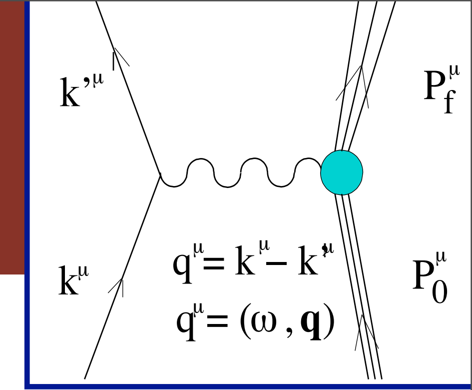
$$f_R(q)\frac{\Gamma}{\pi}\frac{1}{(\sigma - E_R + E_0)^2 + \Gamma^2}$$

LIT of a delta by numerically choosing

$$\gamma \ll \Gamma$$

Fit $f_R(q)$ to obtain a smooth background $\rightarrow f_R(q)$ is related to the resonant form factor

Monopole Resonance $^4He(e,e')0^+$

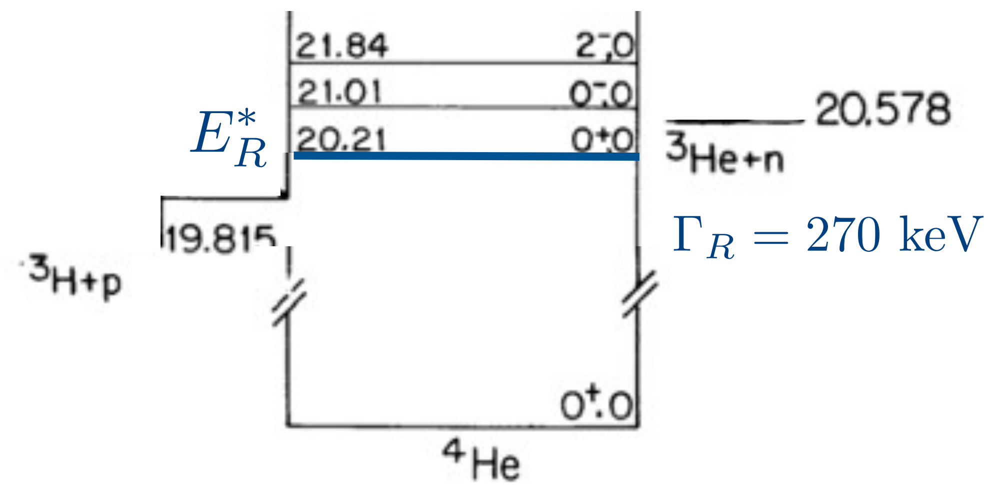


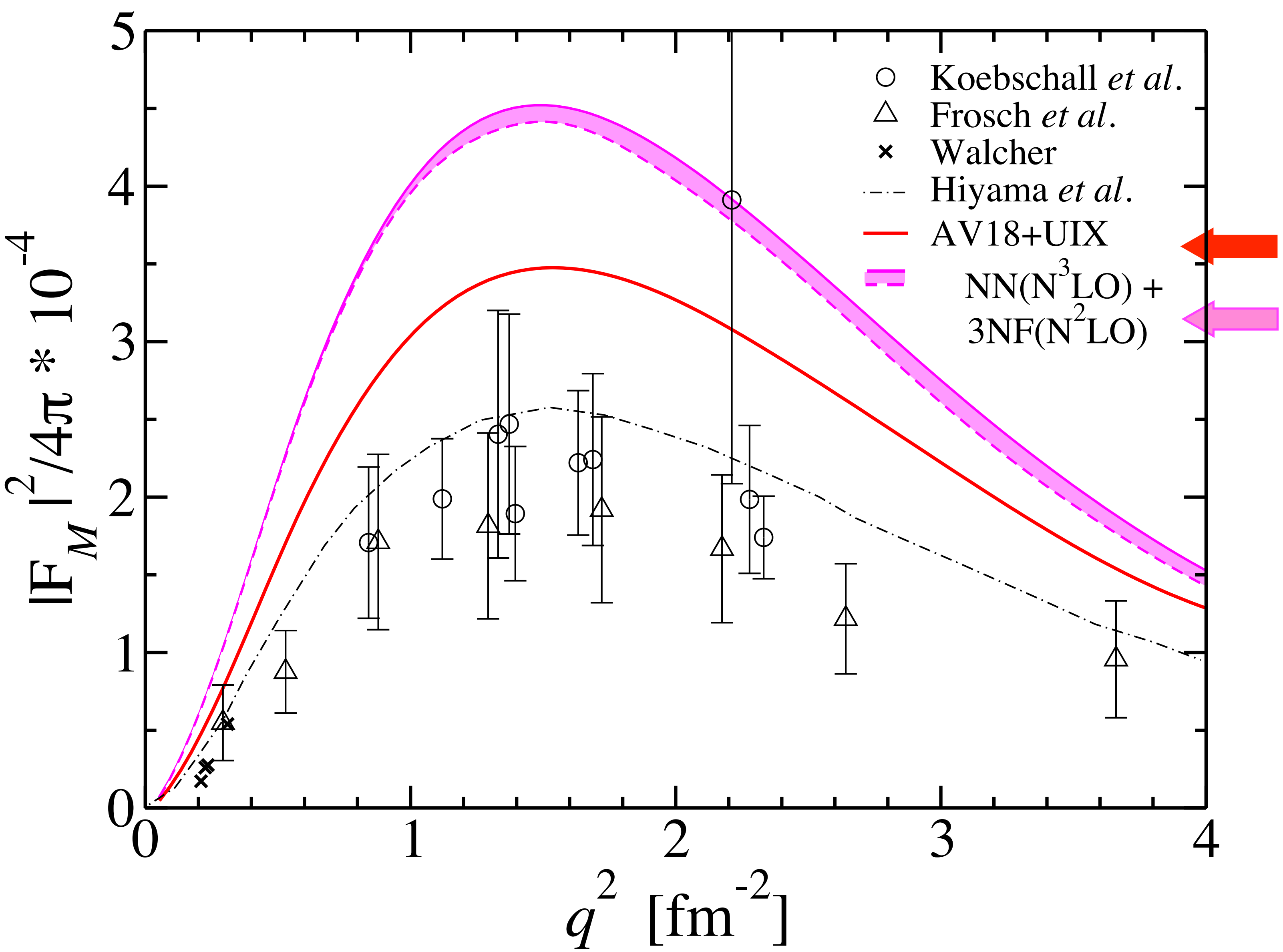
Resonant Transition Form Factor
$0_1^+ \longrightarrow 0_2^+$

$$|F_{\mathcal{M}}(q)|^2 = \frac{1}{Z^2}\int d\omega R^{\rm res}_{\mathcal{M}}(q,\omega)$$

First ab-initio calculation with realistic three-nucleon forces and with the Lorentz Integral Transform method

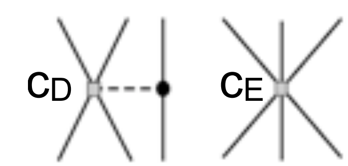
S.B. *et al.*, PRL **110**, 042503 (2013)





conventional forces

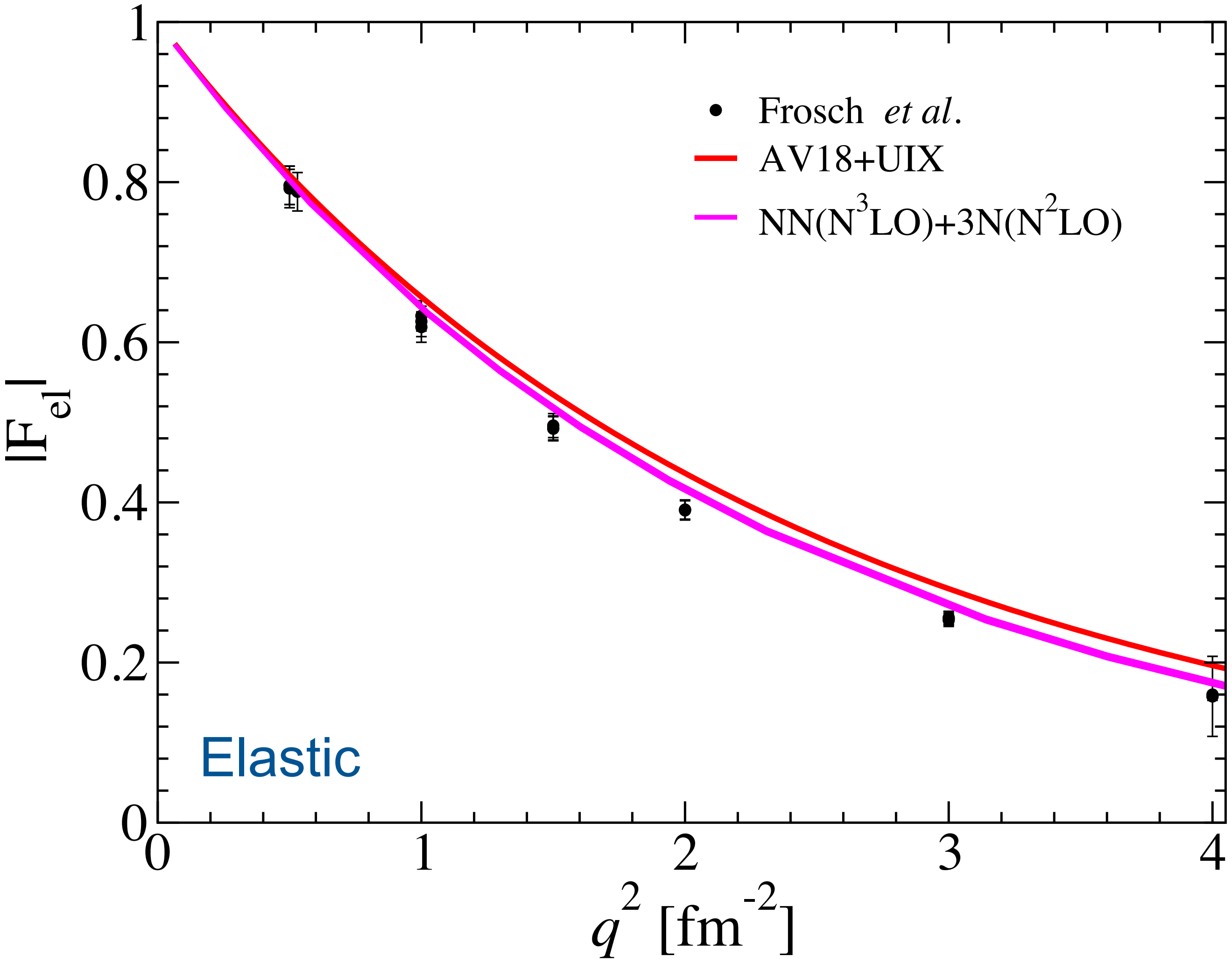
χEFT forces

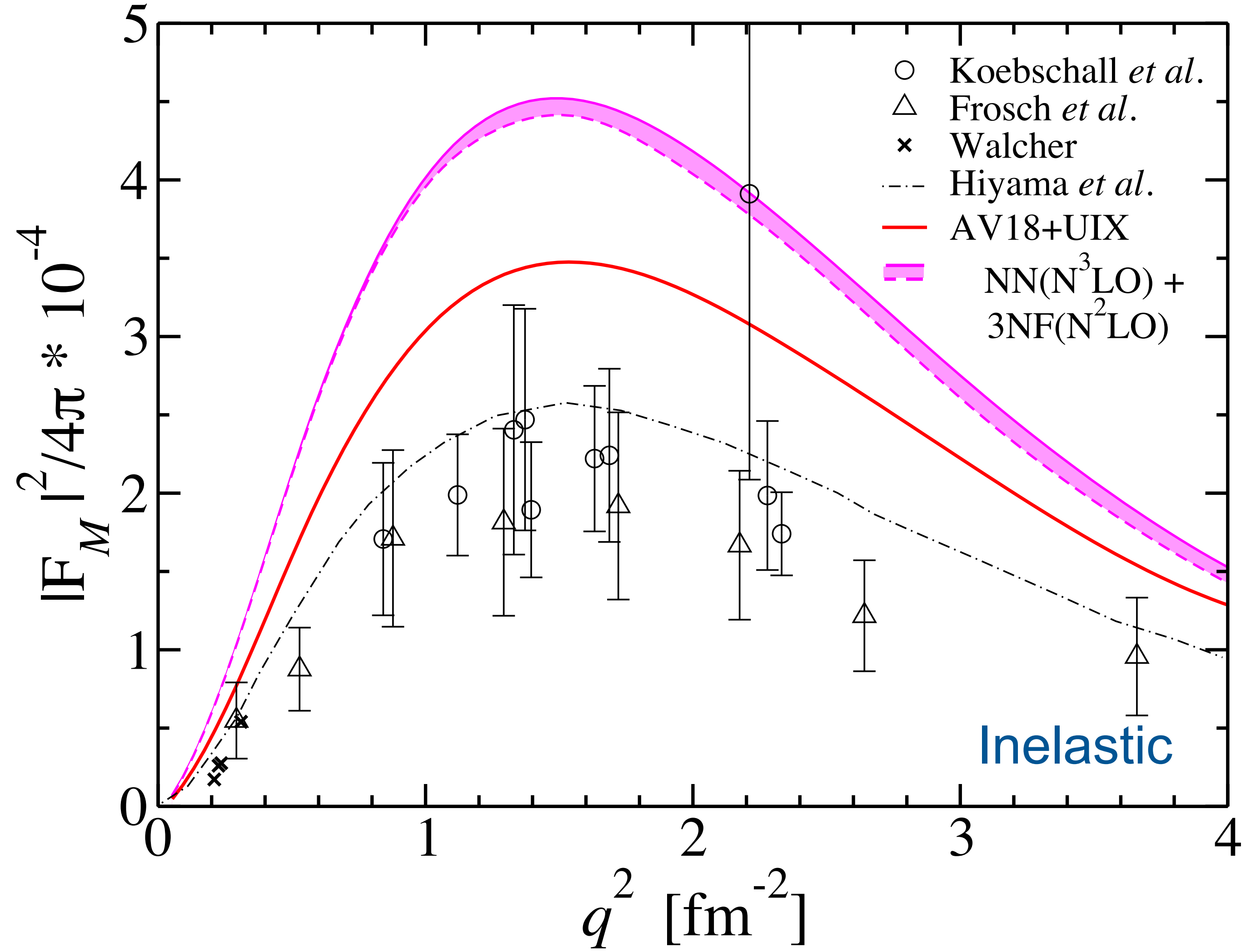


Two-sets of value of the three-nucleon forces low energy constants C_D , C_E difference in the short-range part

Sensitivity to Nuclear Hamiltonians

S.B. *et al.*, PRL **110**, 042503 (2013)



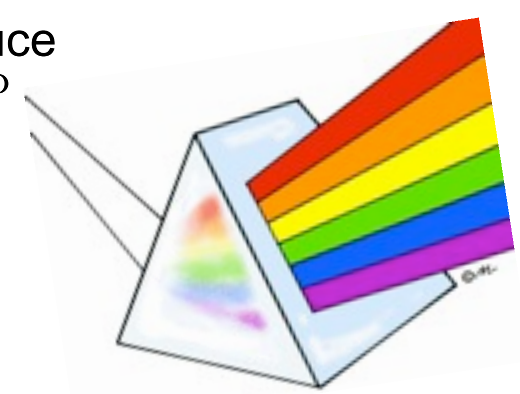


The inelastic monopole resonance acts as a prism to nuclear Hamiltonians.

AV8' + central 3NF	E_0	= -28.44 MeV
AV18+UIX	E_0	= -28.40 MeV
NN(N³LO)+3NF(N²LO)	E_0	= -28.36 MeV

E_0^{exp} = -28.30 MeV

H reproduce $E_0^{\rm exp}$



spectrum in $|F_{\mathcal{M}}|^2$

Analysis of this result

Realistic three-nucleon forces do not reproduce the data for $|F_{\mathcal{M}}|^2$
Particularly large difference are found with chiral EFT potentials.
This is unexpected! What can be the source of this behaviour?

- Numerics? Our calculations are well converged (few % level) in the HH basis

$K_{\max}$	12	14	16	18
$10^4 \lvert F_{\mathcal{M}} \rvert^2$	4.59	4.75	4.85	4.87

- Many-body charge operators?

Conventional Nuclear Physics

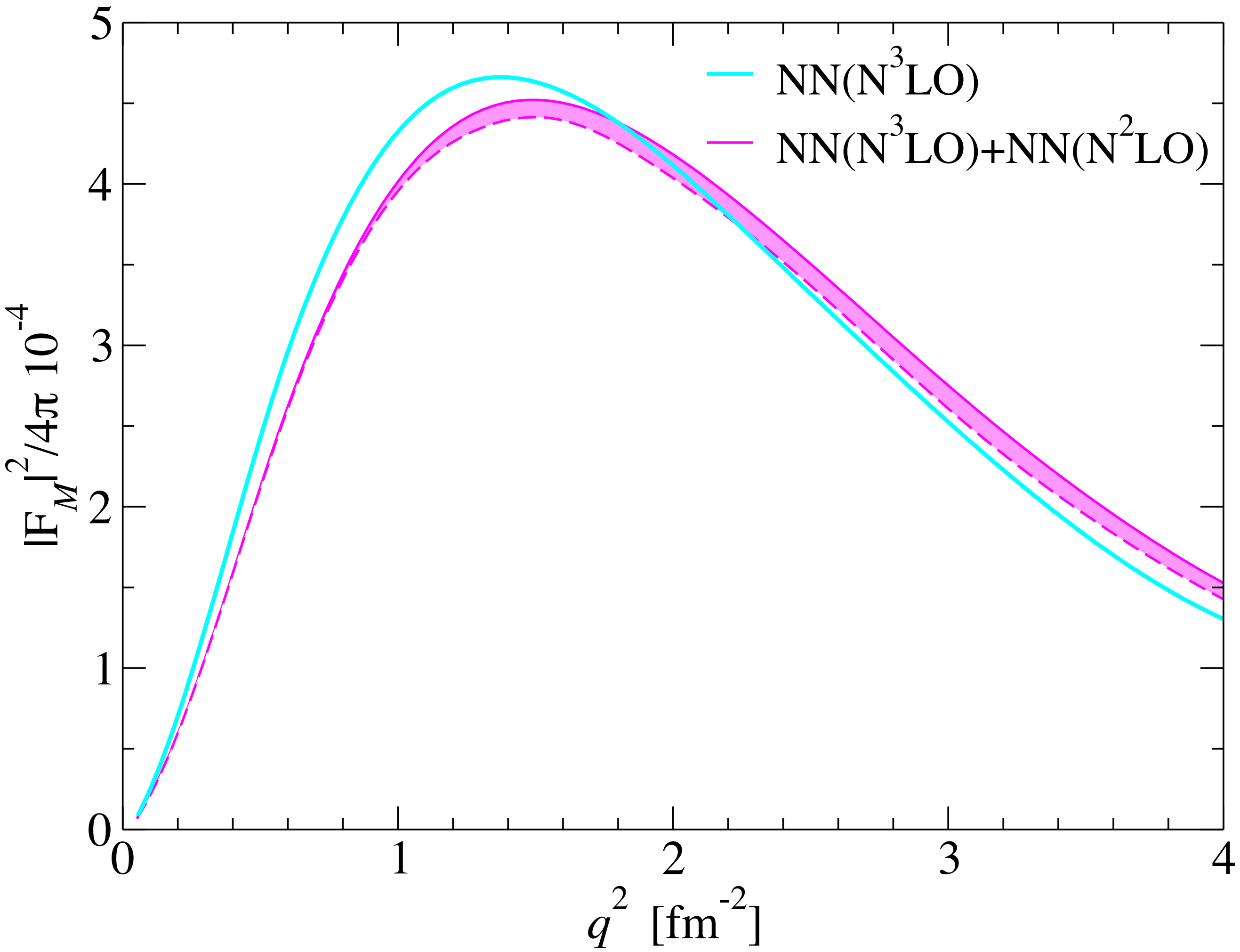
Impulse approximation valid for elastic form factor below 2 fm^{-1}
Viviani *et al.*, PRL **99** (2007) 112002

EFT approach

work done by Park *et al.,* Epelbaum, Koelling *et al.,* Pastore *et al.,* many-body operators appear at high oder in EFT

- Higher order 3NF (N^3LO)?

Unlikely...

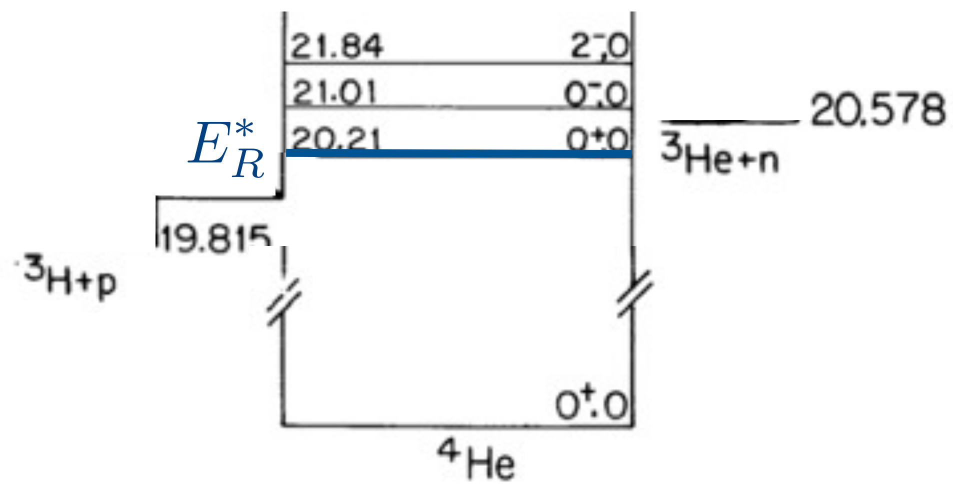


Analysis of this result

- Location of the resonance?

AV8' + central 3NF E_R^* = 20.25 MeV
AV18+UIX E_R^* = 21.00(20) MeV
NN(N^3LO)+3NF(N^2LO) E_R^* = 21.01(30) MeV

E_R^* = 20.21 MeV



The “realistic Hamiltonians” fail to reproduce the correct position of the 0^+_2 resonance

More theoretical work needed to understand this.

- Can this be measured again?

Extension to medium-mass nuclei

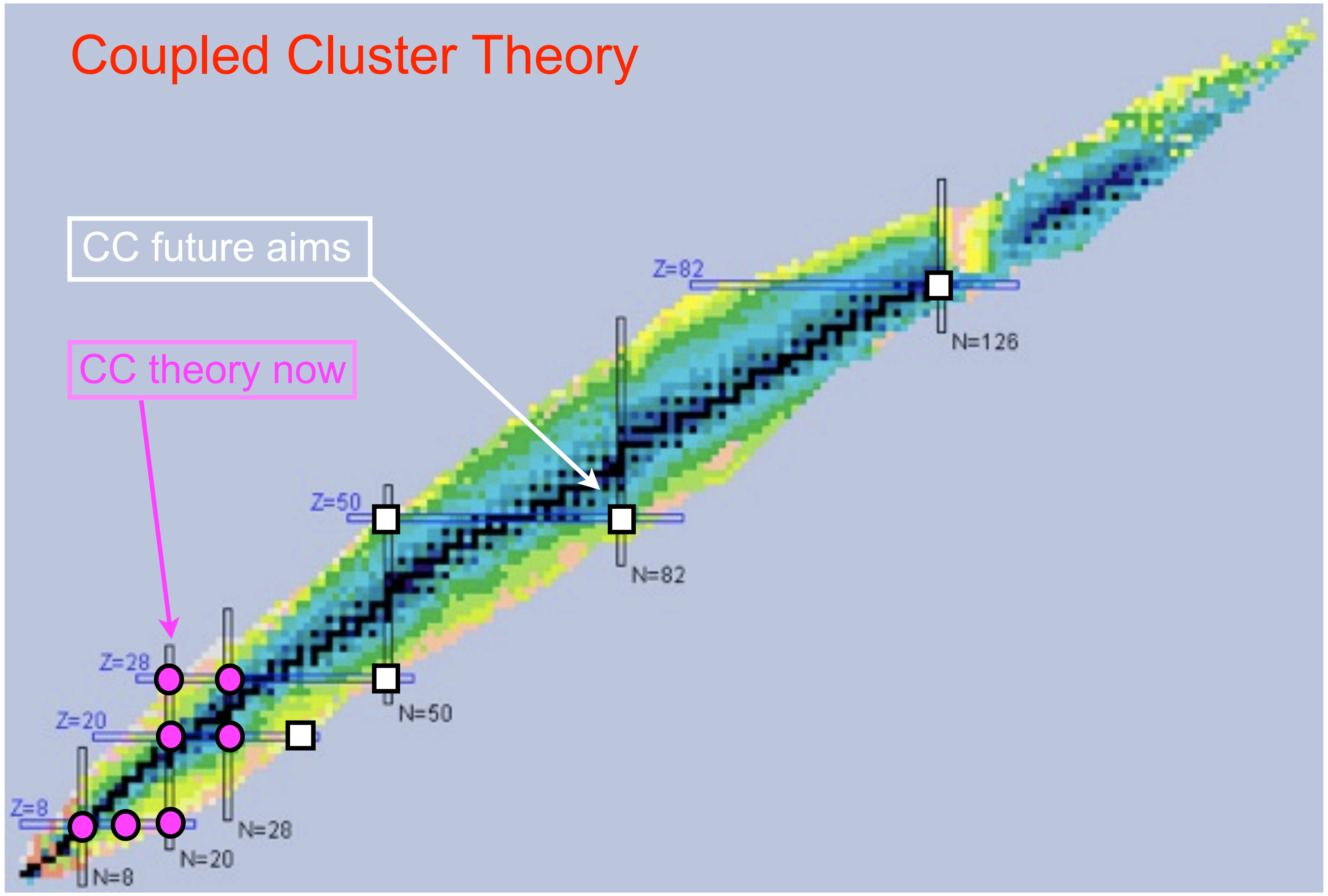
One example for A=16

- Photo-absorption

TRIUMF

Extension to medium-mass nuclei

Develop new many-body methods that can extend the frontiers to heavier and neutron nuclei



- CC is optimal for closed shell nuclei (±1, ±2)

Uses particle coordinates

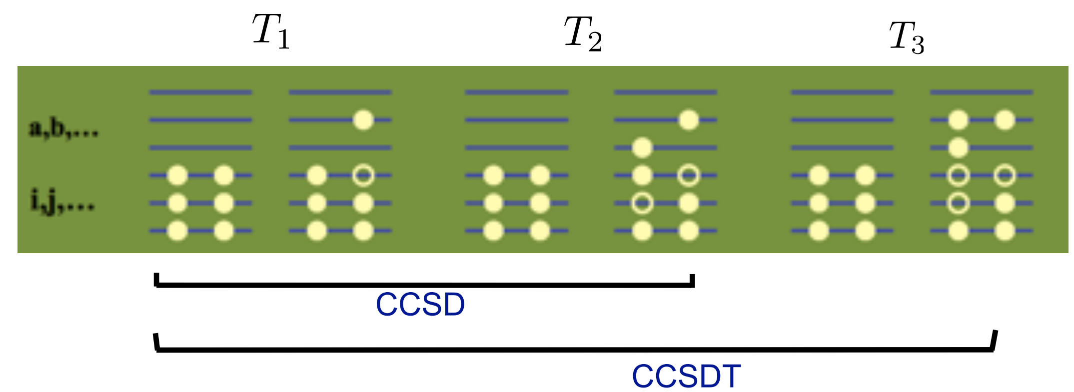
$$|\psi_0(\vec{r}_1, \vec{r}_2, ..., \vec{r}_A)\rangle = e^T |\phi_0(\vec{r}_1, \vec{r}_2, ..., \vec{r}_A)\rangle$$

reference SD with any sp states

$T = \sum T_{(A)}$ cluster expansion

$$T_1 = \sum_{ia} t_i^a a_a^\dagger a_i$$

$$T_2 = \frac{1}{4} \sum_{ij,ab} t_{ij}^{ab} \; a_a^\dagger a_b^\dagger a_j a_i \qquad \cdots$$



For the ground state energy

$$E_0 = \langle\phi_0|e^{-T} H e^T|\phi_0\rangle \qquad \bar{H} = e^{-T} H e^T$$

similarity transformed Hamiltonian

$$0 = \langle\phi_i^a|e^{-T} H e^T|\phi_0\rangle$$

$$0 = \langle\phi_{ij}^{ab}|e^{-T} H e^T|\phi_0\rangle$$

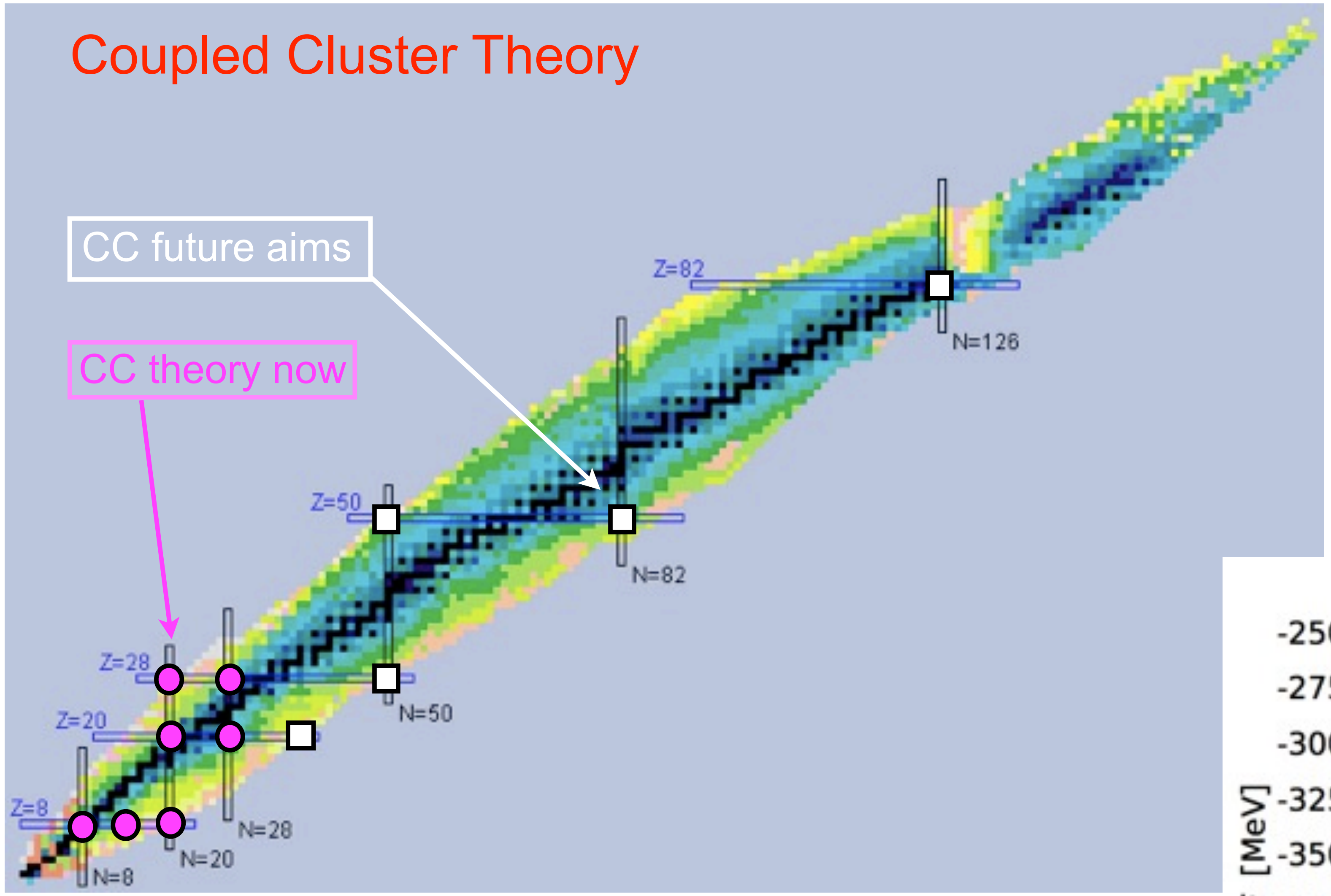
Leads to CCSD equations for the t-amplitudes

Model space truncation $N \leq N_{max}$

Computational load $n_o^2 n_u^4$

Extension to medium-mass nuclei

Develop new many-body methods that can extend the frontiers to heavier and neutron nuclei



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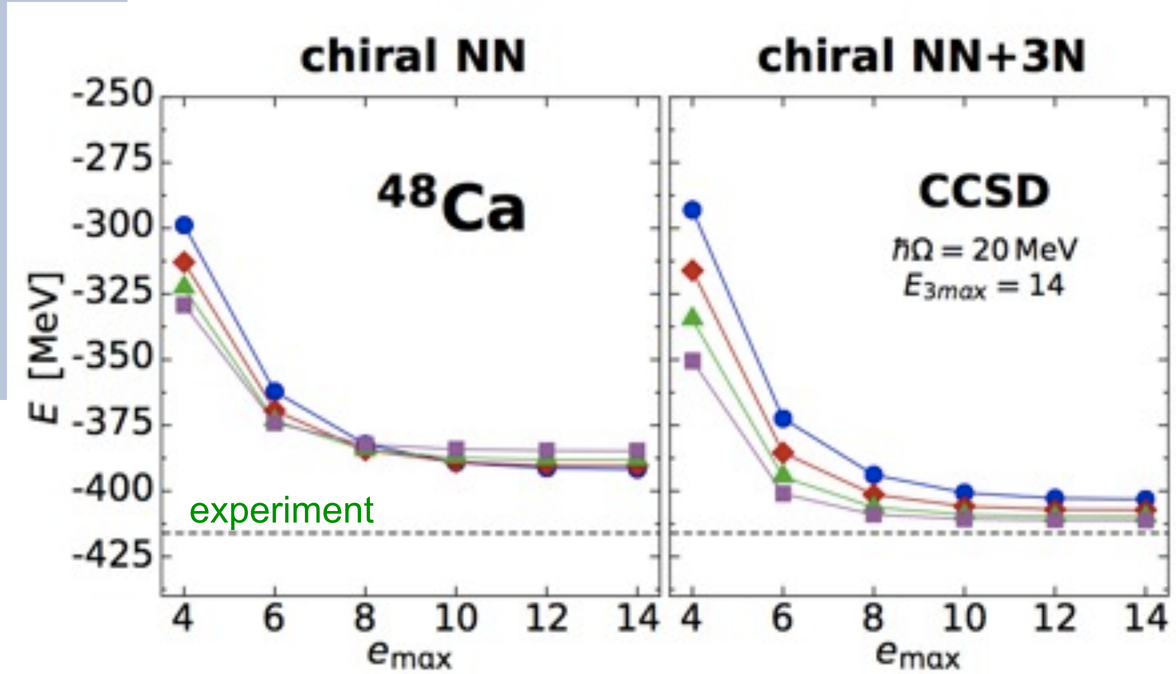
$$|\psi_0(\vec{r}_1, \vec{r}_2, ..., \vec{r}_A)\rangle = e^T |\phi_0(\vec{r}_1, \vec{r}_2, ..., \vec{r}_A)\rangle$$

reference SD with any sp states



R. Roth *et al.*, Phys. Rev. Lett. **109**, 052501 (2012)

CC is a very mature theory for g.s., see e.g.

Hagen *et al.* PRL **101**, 092502 (2008),PRC **82**, 03433 (2010)
PRL **108**, 242501 (2012), PRL **109**, 032502 (2012)

What about electro-weak reactions?

LIT+CC can possibly extend calculations of inelastic reactions into medium-mass nuclei!

LIT with Coupled Cluster Theory

$$L(\sigma,\Gamma) = \int d\omega \frac{R(\omega)}{(\omega-\sigma)^2+\Gamma^2}$$

S.B., N.Barnea, G.Hagen, G.Orlandini, T.Papenbrock, arXiv:1303.7446

$$L(\sigma,\Gamma) = \left\langle \tilde{\Psi} | \tilde{\Psi} \right\rangle \rightarrow \left\langle \tilde{\Psi}_L | \tilde{\Psi}_R \right\rangle = \langle \Phi_0 \hat{L}(z) | \hat{R}(z^*) \Phi_0 \rangle$$ with $z = E_0 + \sigma + i\Gamma$

$$\hat{R}_0 + \sum_{ia} \hat{R}_i^a \hat{c}_a^\dagger \hat{c}_i + \frac{1}{4} \sum_{ijab} \hat{R}_{ij}^{ab} \hat{c}_a^\dagger \hat{c}_b^\dagger \hat{c}_j \hat{c}_i + \ldots$$

$$\hat{L}_0 + \sum_{ia} \hat{L}_i^a \hat{c}_i^\dagger \hat{c}_a + \frac{1}{4} \sum_{ijab} \hat{L}_{ij}^{ab} \hat{c}_i^\dagger \hat{c}_j^\dagger \hat{c}_b \hat{c}_a + \ldots$$

The Schrödinger-like eq. becomes

$$(\bar{H} - z^*) \overbrace{\hat{R}(z^*) |\Phi_0\rangle}^{|\tilde{\Psi}_R\rangle} = \bar{\Theta} |\Phi_0\rangle$$ with $\bar{\Theta} = e^{-T} \Theta e^{T}$ similarity transformed operator

$$\hat{R}(z^*) \bar{H} |\Phi_0\rangle = E_0 \hat{R}(z^*) |\Phi_0\rangle$$

$$[\bar{H}, \hat{R}(z^*)] |\Phi_0\rangle = (z^* - E_0) \hat{R}(z^*) |\Phi_0\rangle + \bar{\Theta} |\Phi_0\rangle$$

Right EoM to find the amplitudes of $\hat{R}$

$$\langle \Phi_0 | [\hat{L}(z), \bar{H}] = \langle \Phi_0 | \hat{L}(z)(z - E_0) + \langle \Phi_0 | \bar{\Theta}^\dagger$$

Right EoM to find the amplitudes of $\hat{L}$

LIT with Coupled Cluster Theory

Dipole Response Function

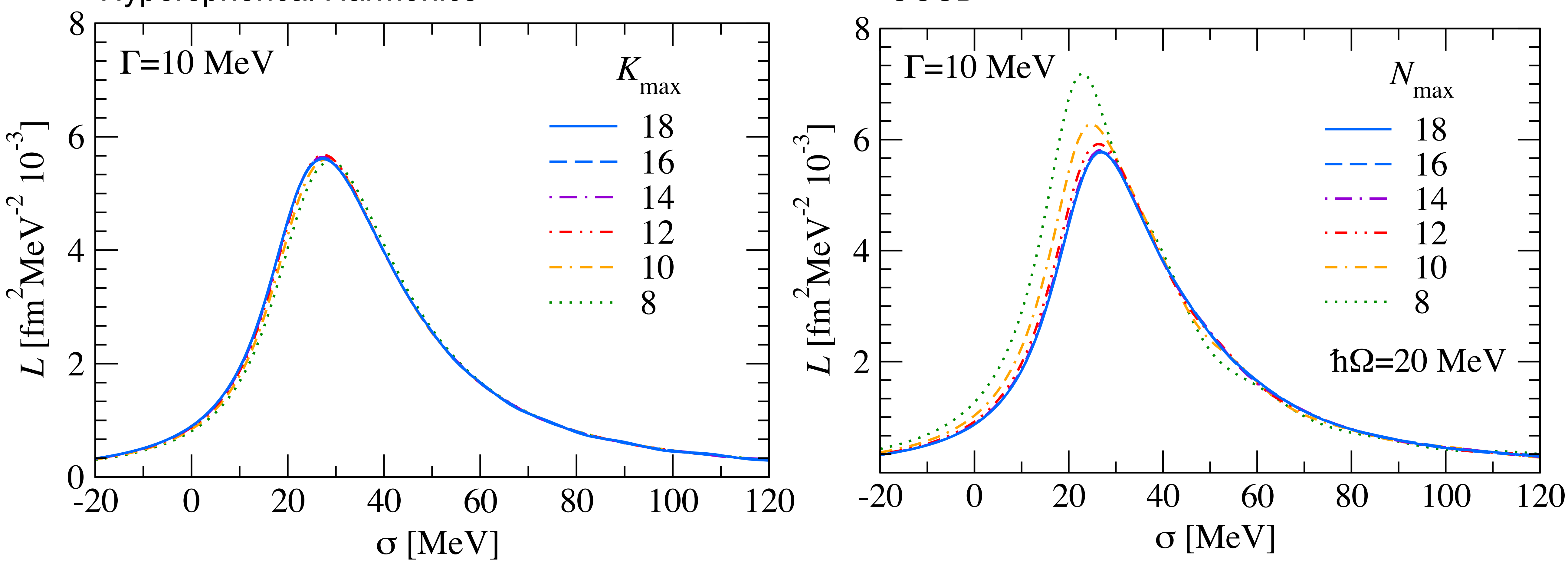
S.B., N.Barnea, G.Hagen, G.Orlandini, T.Papenbrock, arXiv:1303.7446

Validation on ^{4}He with NN forces derived from χEFT (N^{3}LO)

→ Convergence in the model space expansion

Hyperspherical Harmonics

CCSD



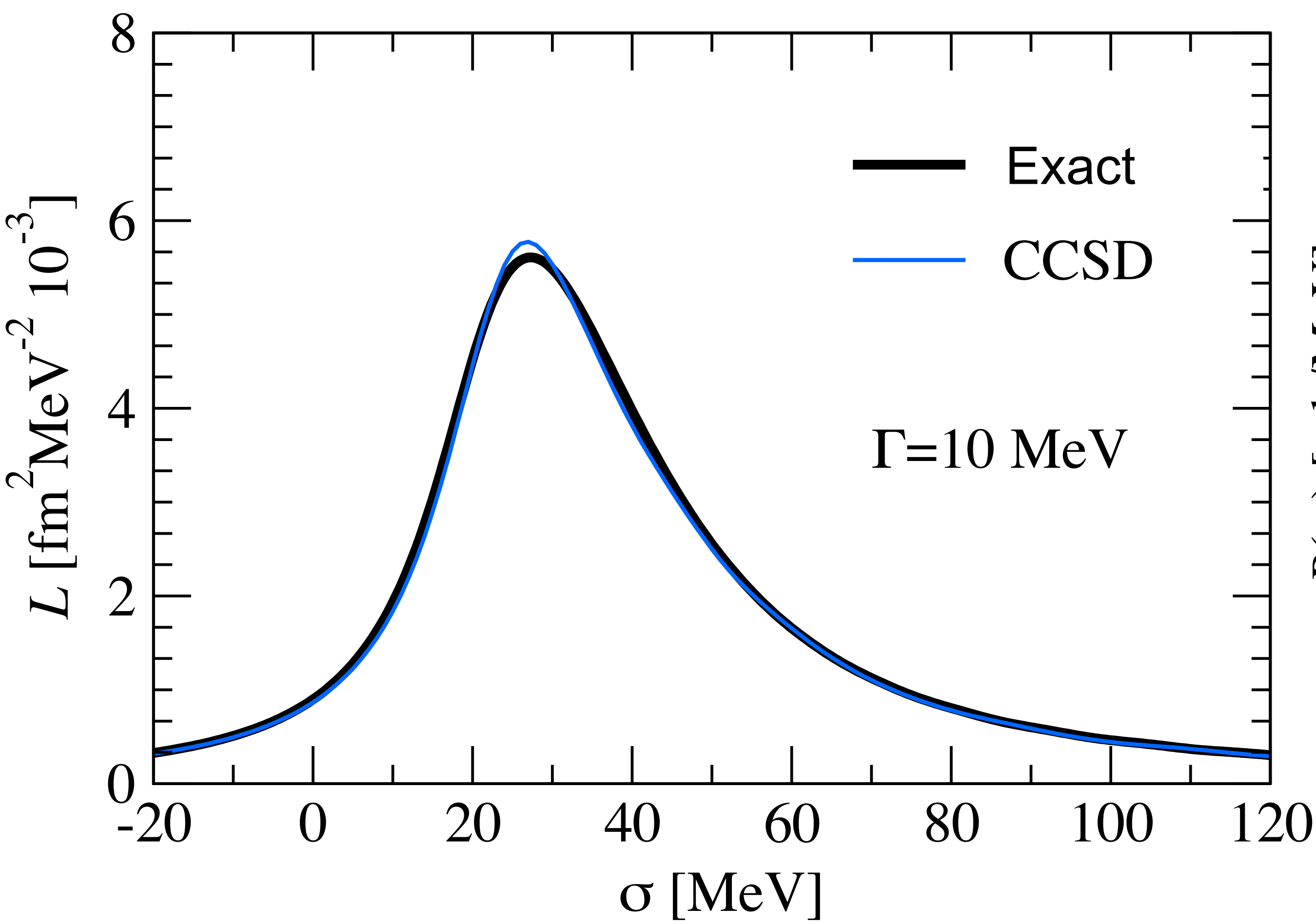
LIT with Coupled Cluster Theory

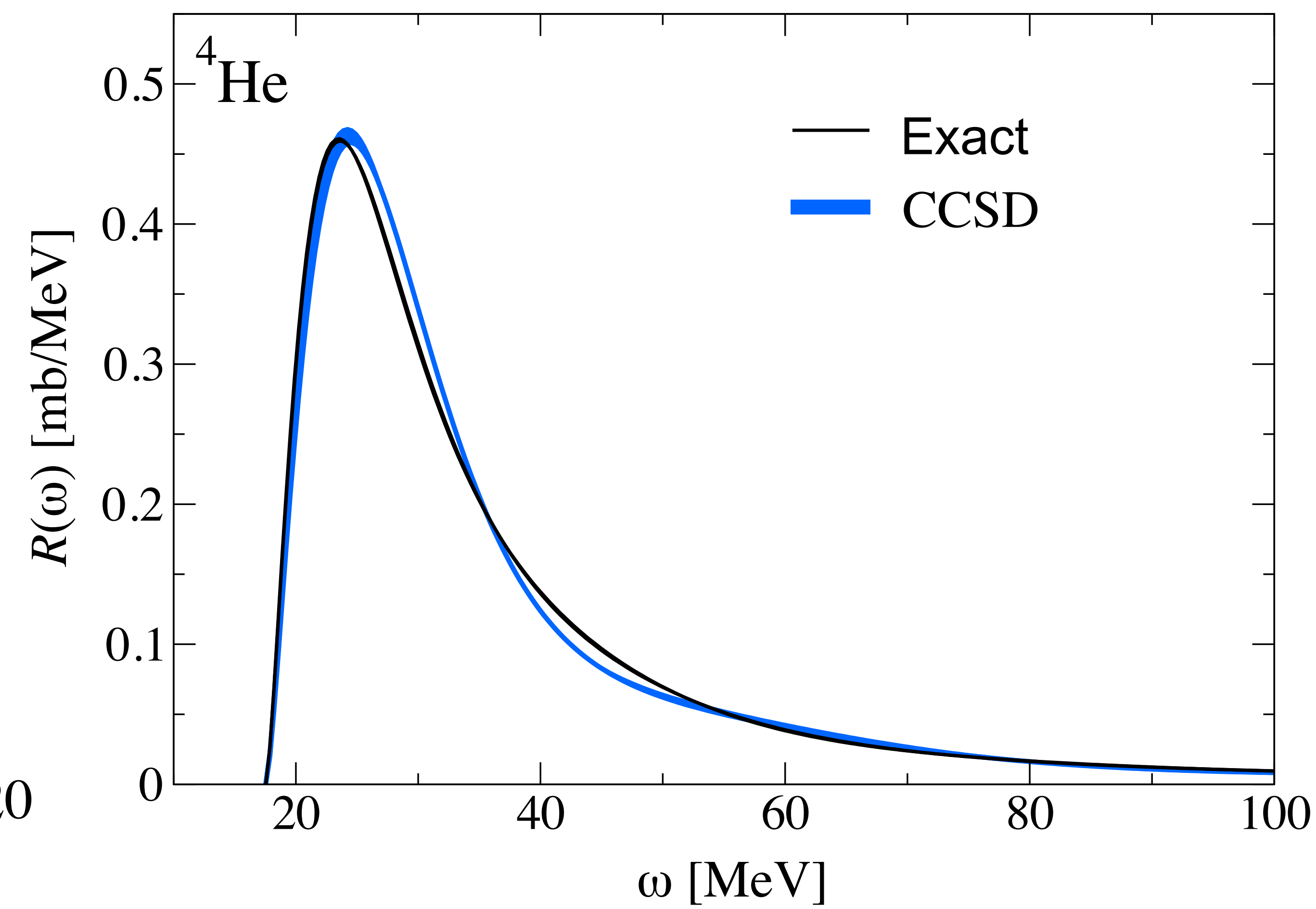
Dipole Response Function

S.B., N.Barnea, G.Hagen, G.Orlandini, T.Papenbrock, arXiv:1303.7446

Validation on ^{4}He with NN forces derived from χEFT (N^{3}LO)

➡ Comparison of CCSD with exact hyperspherical harmonics





The comparison with exact theory is very good!

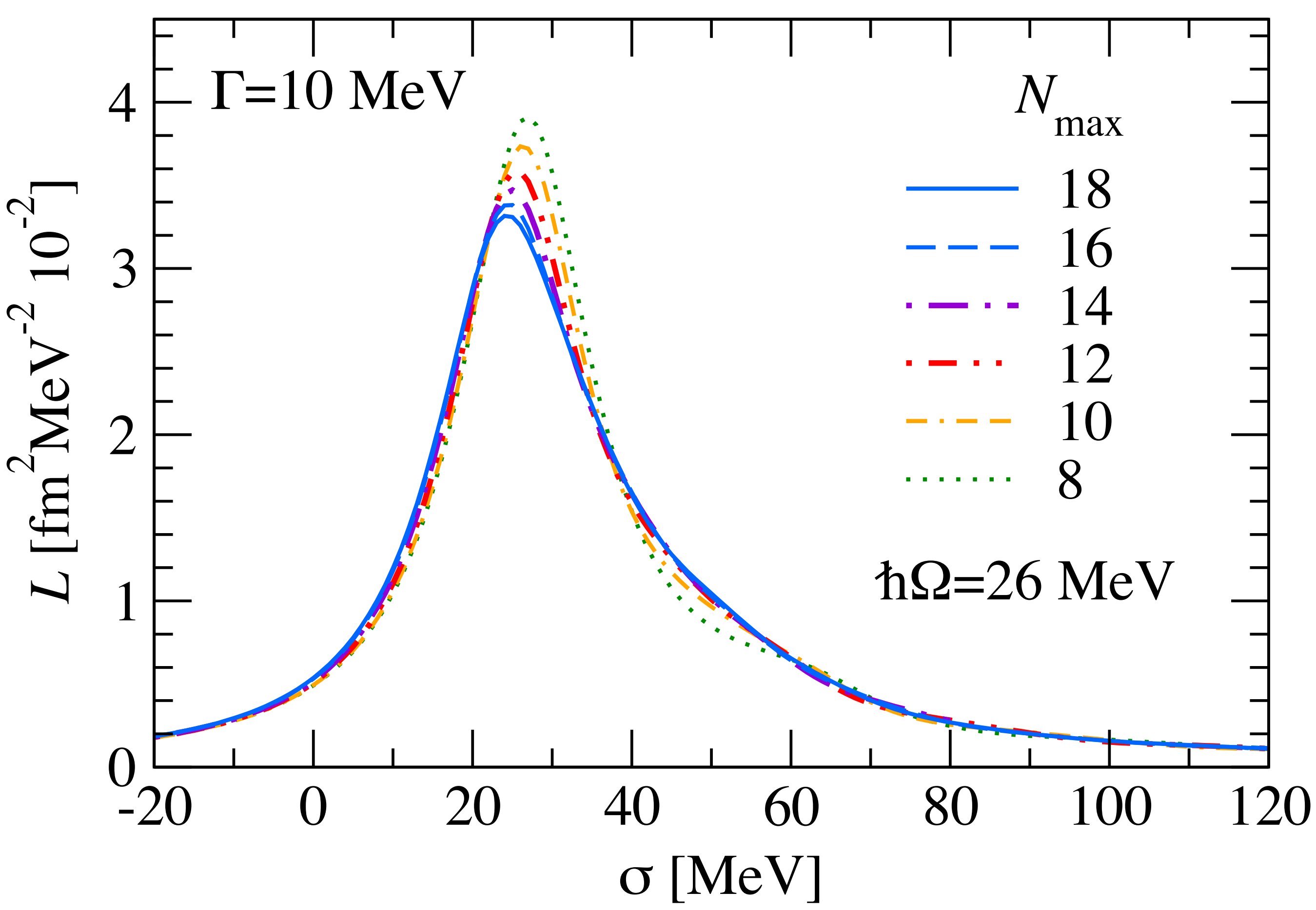
LIT with Coupled Cluster Theory

Dipole Response Function

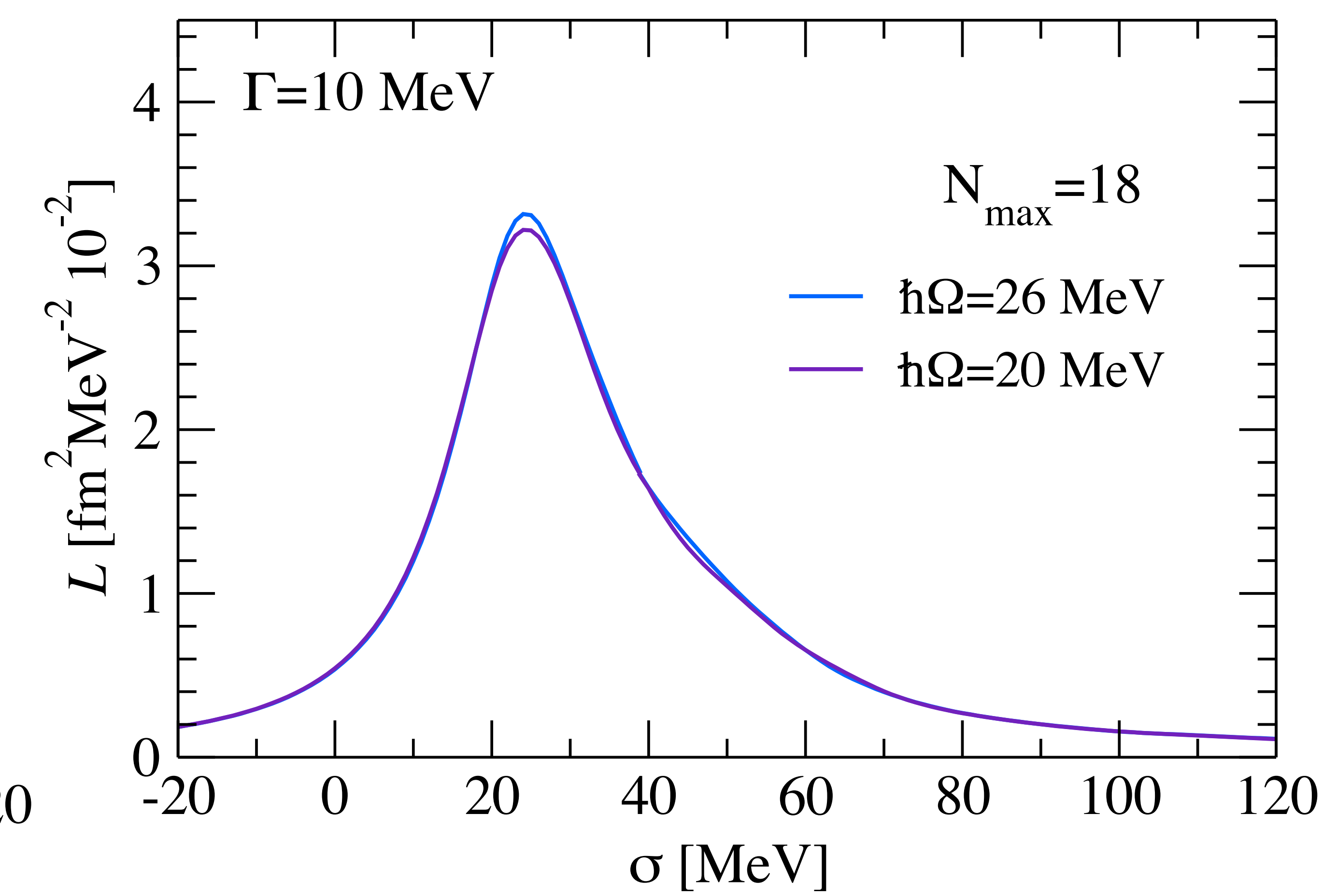
S.B., N.Barnea, G.Hagen, G.Orlandini, T.Papenbrock, arXiv:1303.7446

Extension to ^{16}O with NN forces derived from χEFT (N^3LO)

➡ Convergence in the model space expansion



Good convergence!



Small HO dependence: use it as error bar

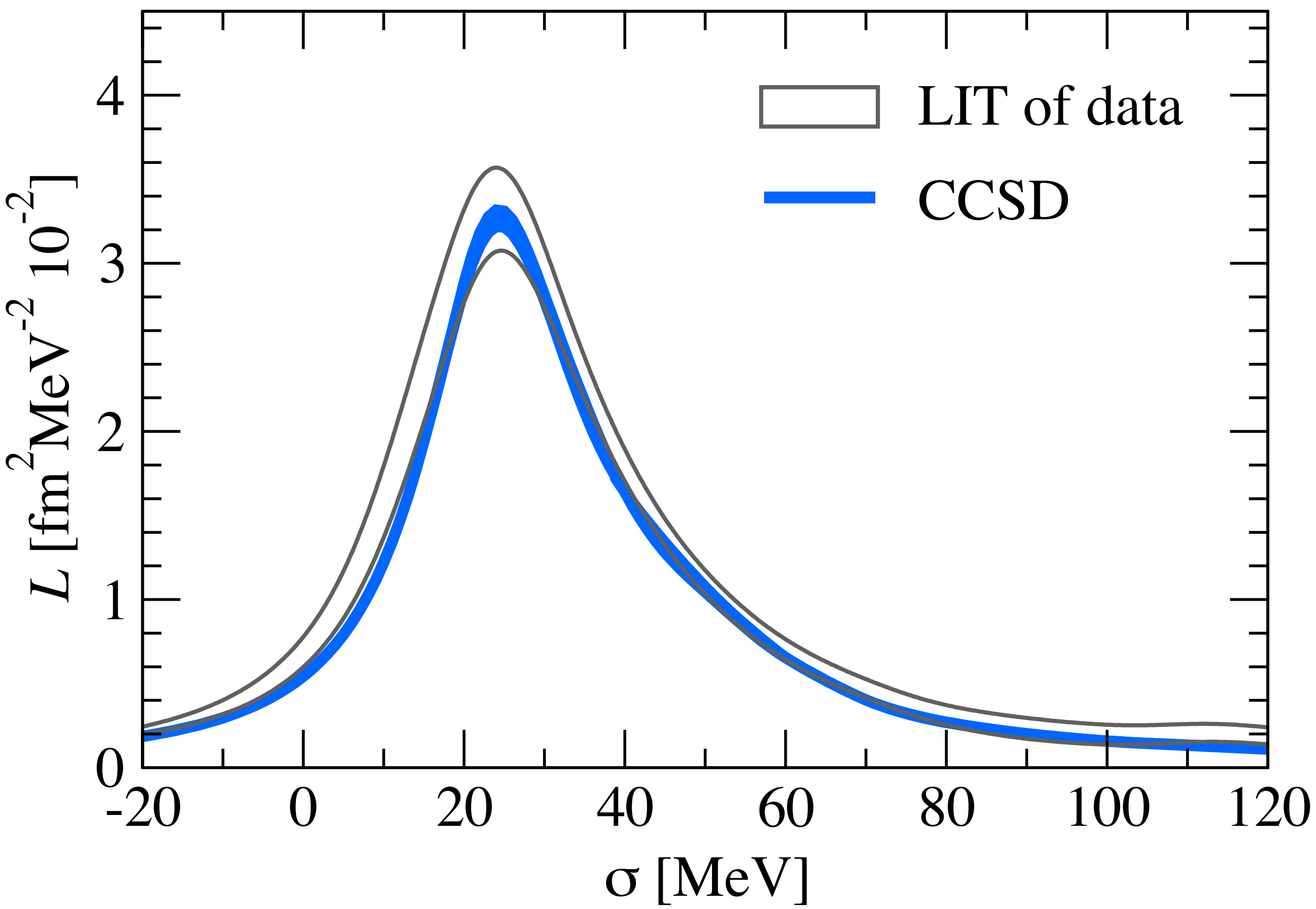
LIT with Coupled Cluster Theory

$$L(\sigma,\Gamma) = \int d\omega \frac{R(\omega)}{(\omega-\sigma)^2+\Gamma^2}$$

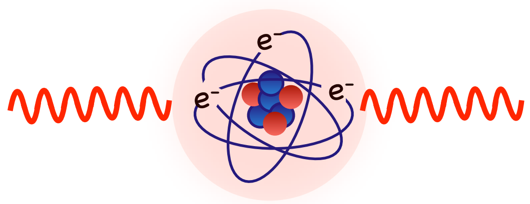
S.B., N.Barnea, G.Hagen, G.Orlandini, T.Papenbrock, arXiv:1303.7446

Extension to ^{16}O with NN forces derived from χEFT (N^{3}LO)

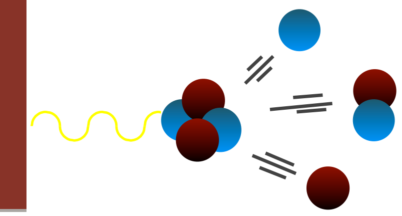
⇨ Comparison with experiment



Data: target absorption experiment with γ



LIT with Coupled Cluster Theory

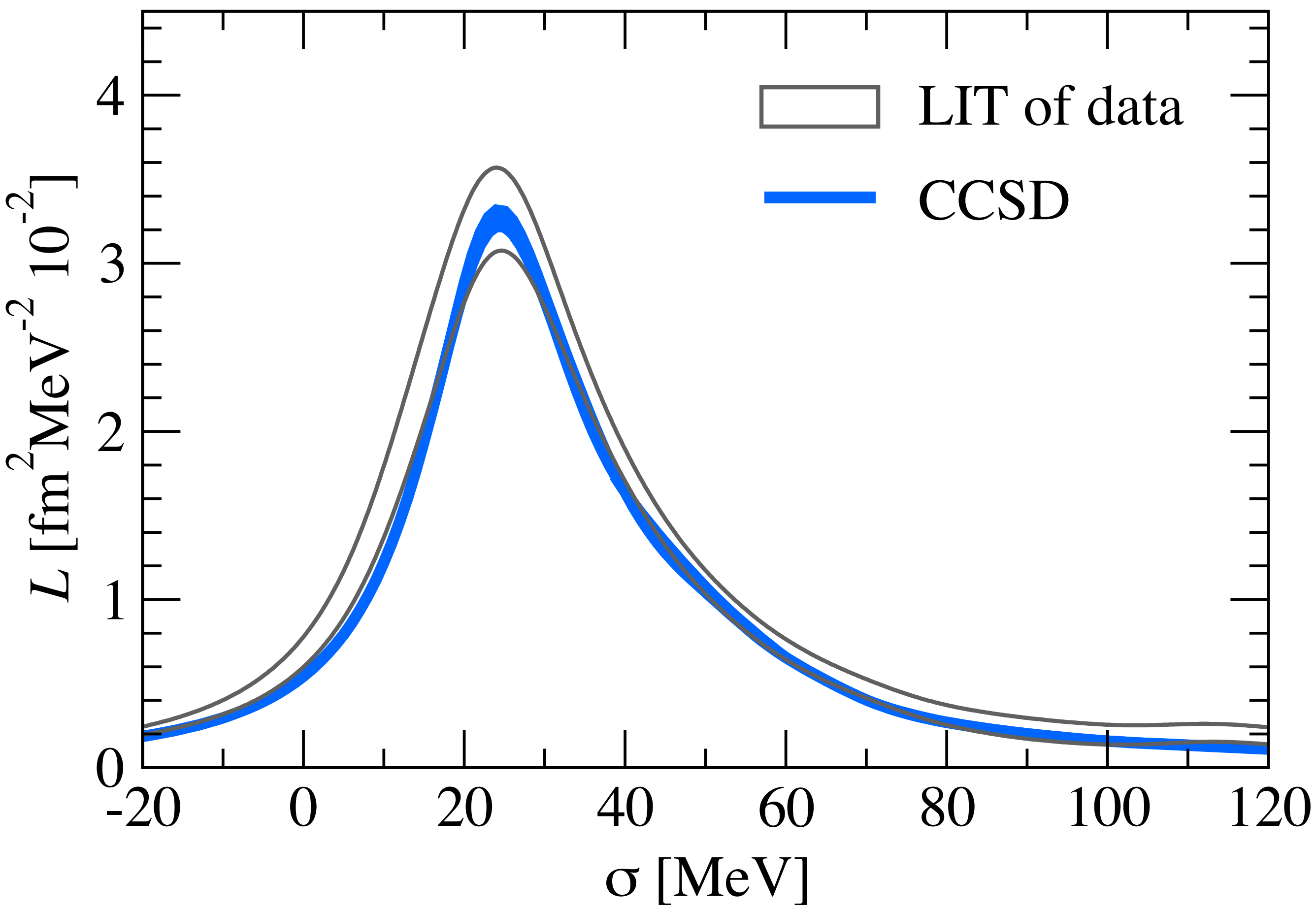


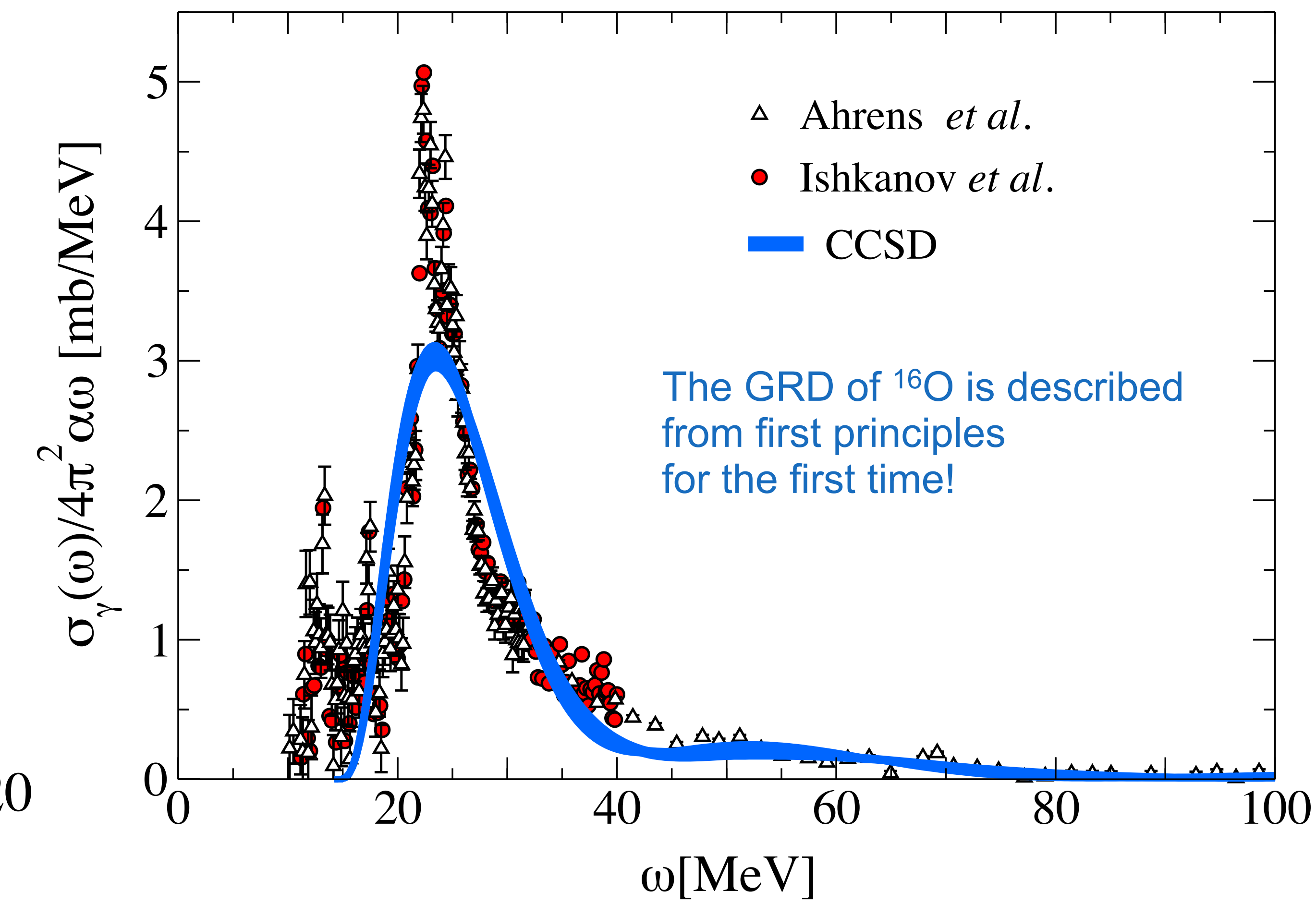
$$L(\sigma,\Gamma) = \int d\omega \frac{R(\omega)}{(\omega - \sigma)^2 + \Gamma^2}$$

S.B., N.Barnea, G.Hagen, G.Orlandini, T.Papenbrock, arXiv:1303.7446

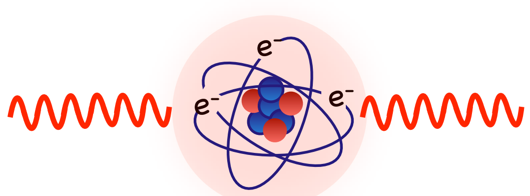
Extension to ^{16}O with NN forces derived from χEFT (N^3LO)

➡ Comparison with experiment

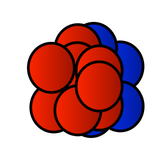




Data: target absorption experiment with γ



Giant Dipole Resonance



protons ⟷ neutrons

Sonia Bacca

TRIUMF

Conclusions and Outlook

- Nuclear response functions are very rich observables to test our understanding on nuclear forces
- Extending these calculations to medium mass nuclei is possible and very exciting

Perspectives

- Dipole response function in ^{40}Ca, ^{48}Ca, electric dipole polarizability
  Dipole response function of neutron-rich Oxygen isotope
- Quadrupole or monopole excitation of medium mass nuclei
  ⇒ need extension of LIT/CCSD to two-body operator
- Magnetic transitions for medium mass nuclei with two-body currents
  ⇒ need extension of LIT/CCSD to two-body operator
- Add triples and three-nucleon forces

Thanks to my collaborators

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Thank you!