High-resolution probes of low-resolution nuclei: An OPE-RG-EFT perspective

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SRNC at an EIC workshop, September, 2018
The Ohio State University

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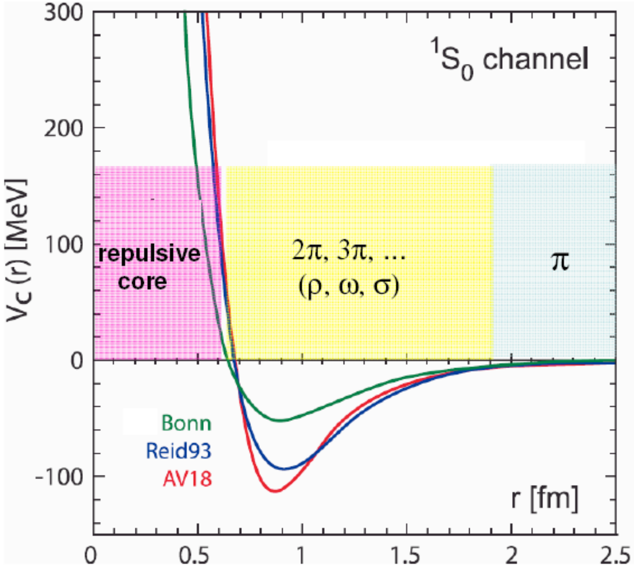
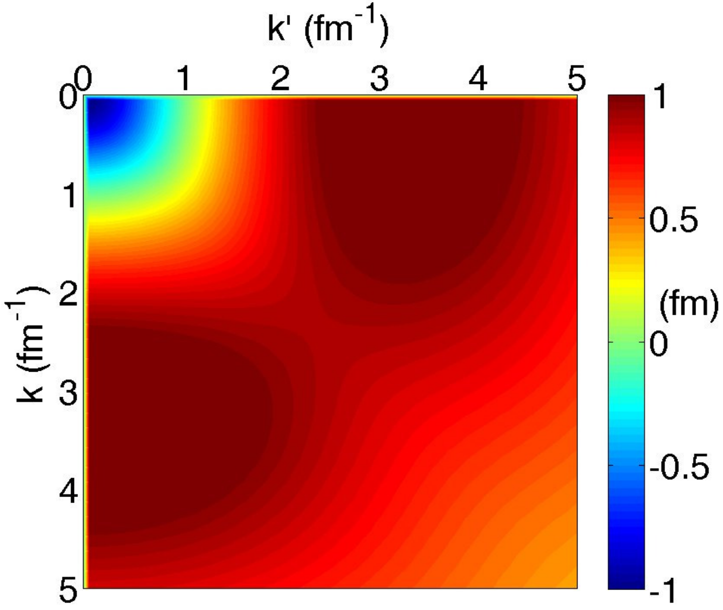
Eric Anderson (OSU)
Sushant More (OSU→MSU)
Nathan Parzuchowski (MSU→OSU)
plus many others on related topics

U.S. DEPARTMENT OF ENERGY
NSF
NUCLEI
Nuclear Computational Low-Energy Initiative

Resolution for nuclei tied to momentum cutoff in interaction





$$V_{L=0}(k,k') = \int d^3r\, j_0(kr)\, V(r)\, j_0(k'r) = \langle k|V_{L=0}|k'\rangle \implies V_{kk'} \text{ matrix}$$

In natural units for a large nucleus, typical relative momentum is about 1 fm^{-1} but repulsive core (cf. tensor) couples to high-k components ➔ nonperturbative.

Use renormalization group (RG) to evolve to lower resolution ➔ more perturbative.

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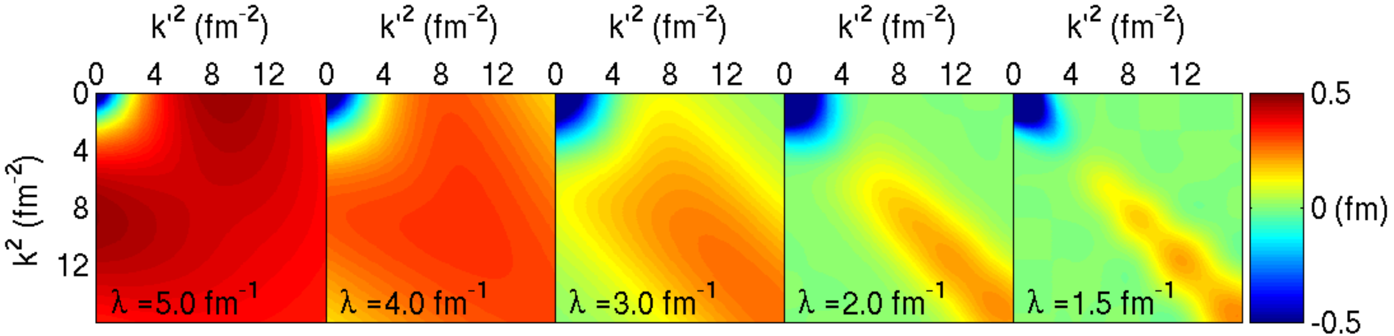
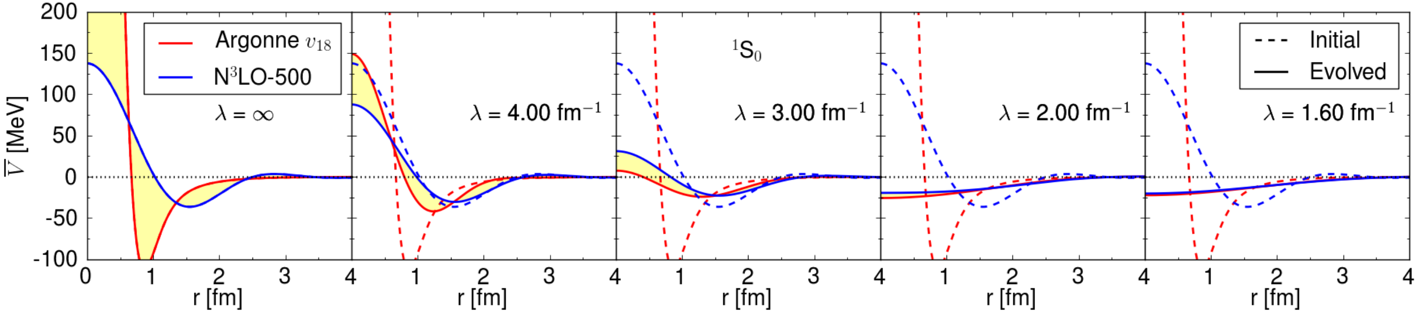


Flow equation (similarity) RG decouples in momentum space; melts core in r-space!



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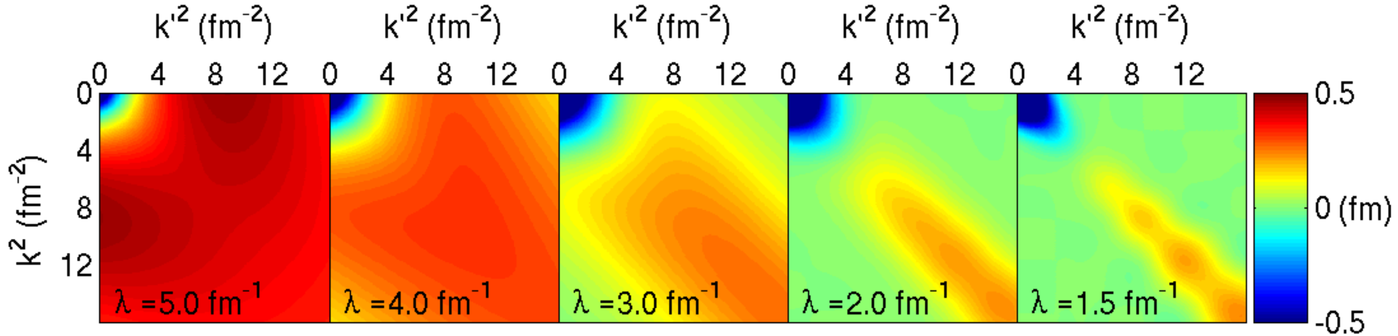

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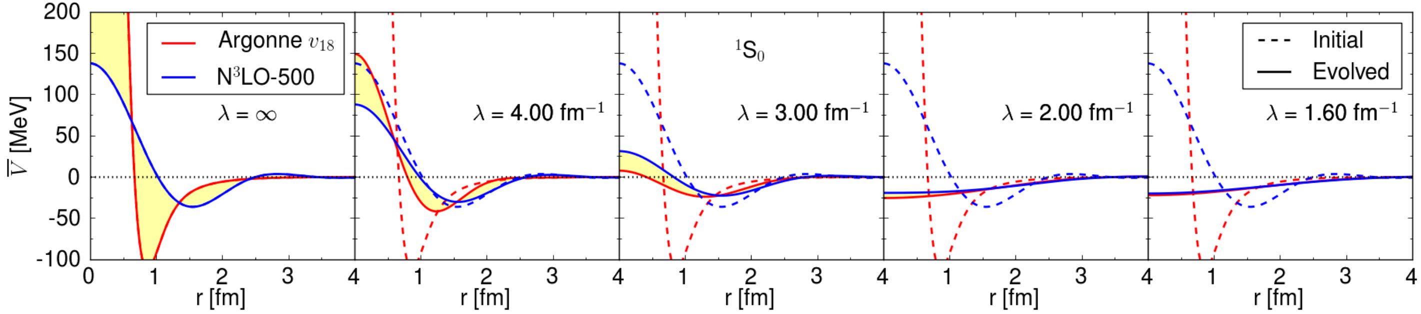
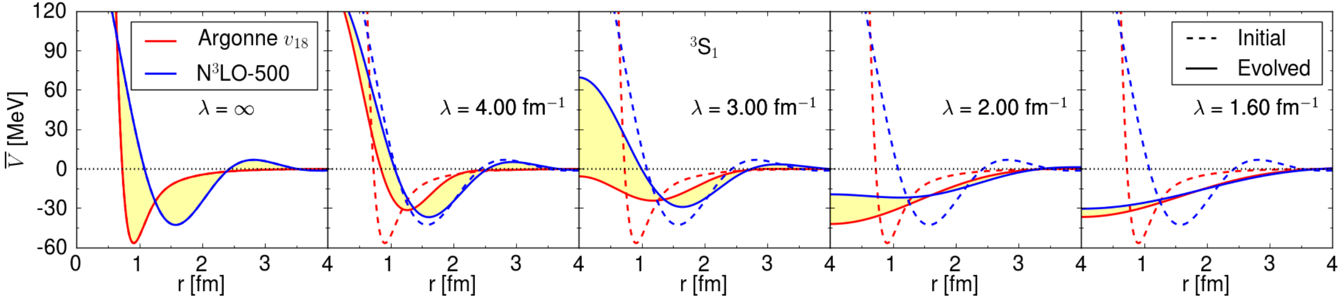


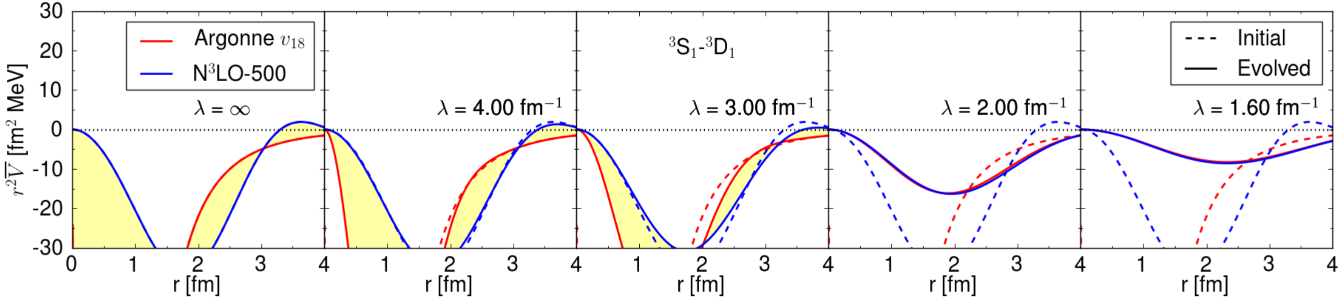
- Similarity RG is just *one way* to lower resolution in free space; technically nice.
- Different initial interactions look different (scheme) but flow to universal!
- Note: all operators change with RG evolution (not just Hamiltonian).

Resolution for nuclei tied to momentum cutoff in interaction

- Central part (S-wave) [Note: The V_λ's are all phase equivalent!]



- Tensor part (S-D mixing) [graphs from K. Wendt et al., PRC (2012)]



Local projection:

$$\overline{V}_\lambda(r) = \int d^3r' \; V_\lambda(r, r')$$

action of potential on low-k nucleons

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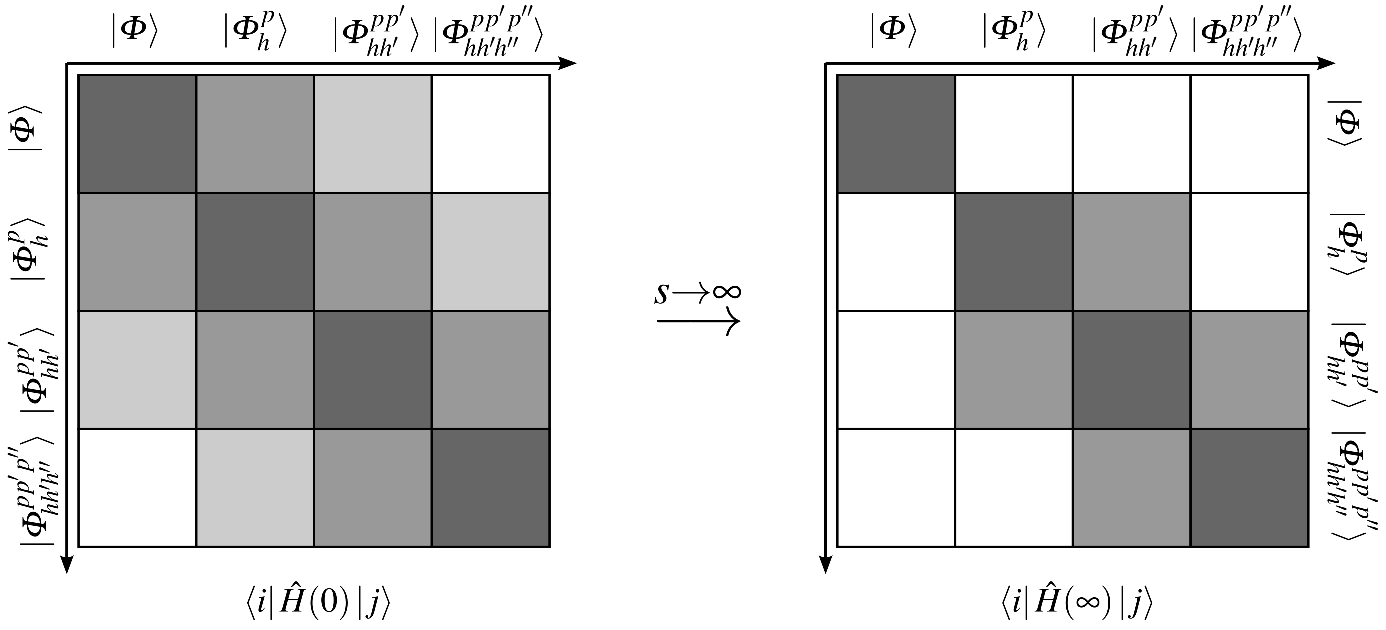
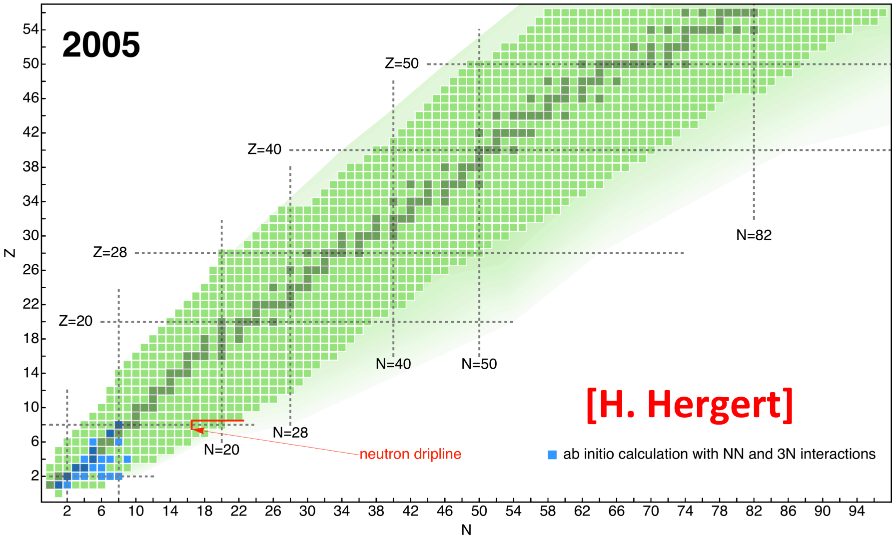


- In-medium SRG (IM-SRG) decouples excitations in-medium wrt *reference state.*
- Keeps leading induced many-body forces [see Hergert et al., arXiv:1612.08315].
- Note: all operators change with RG evolution (not just Hamiltonian).

Low-resolution is natural for low-E nuclear structure at all A



- Progress for "ab initio" methods that use basis expansions at low resolution (cf. QMC)

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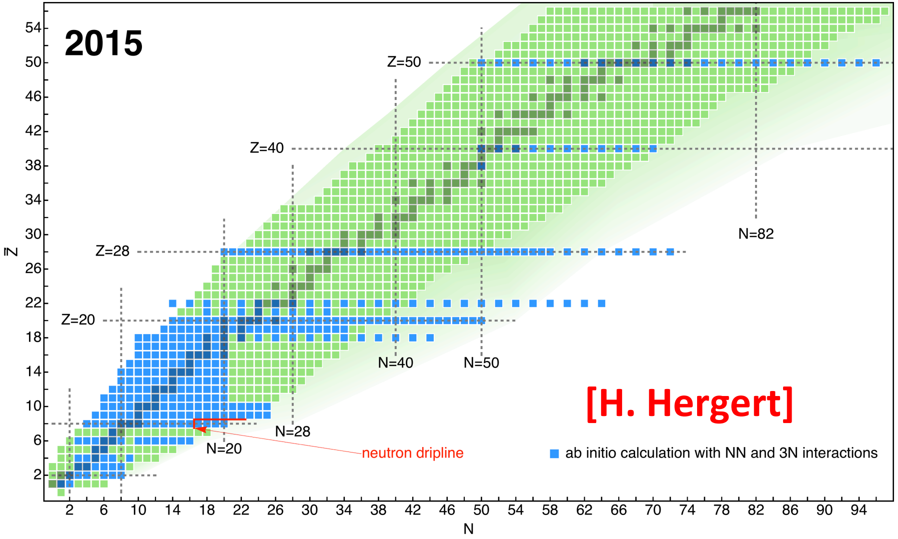

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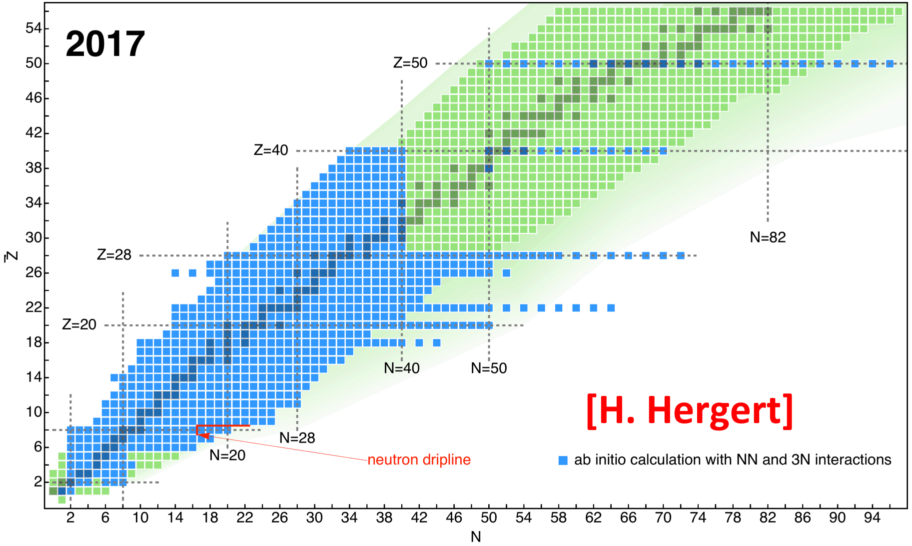

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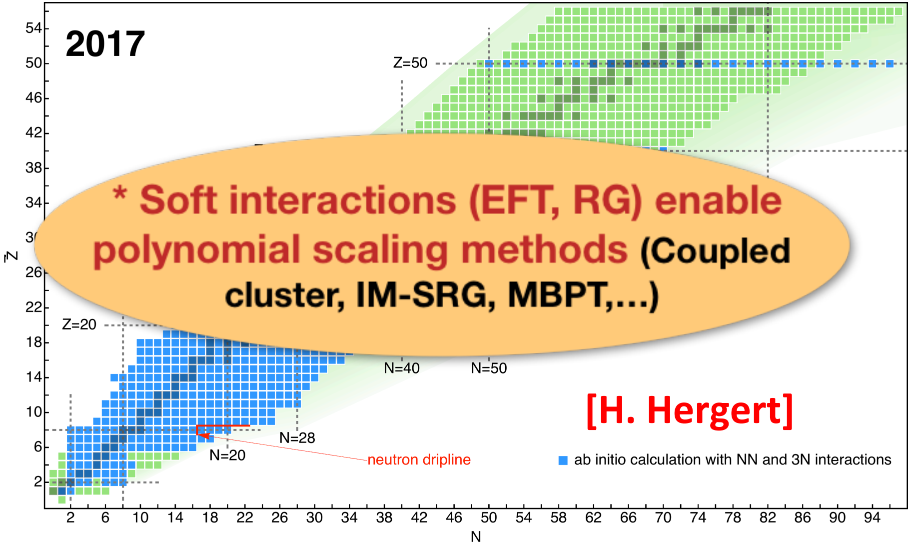

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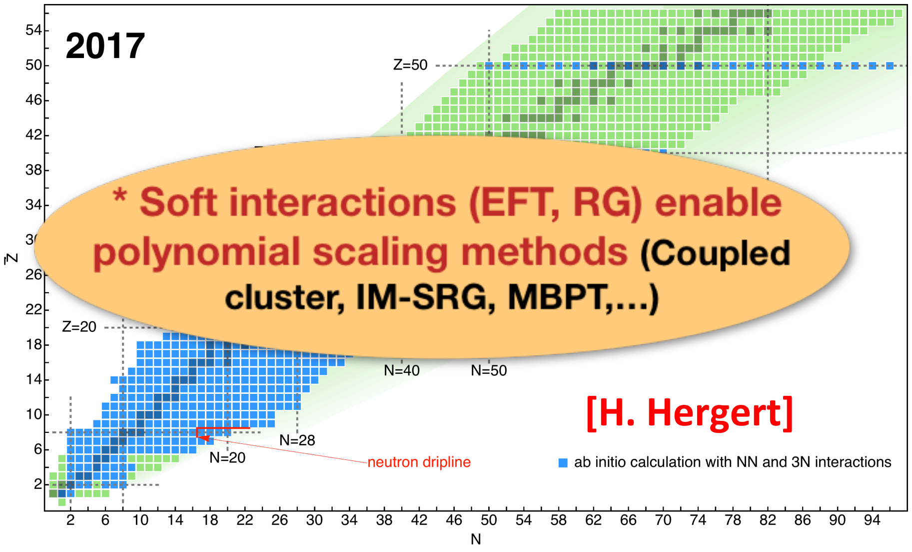

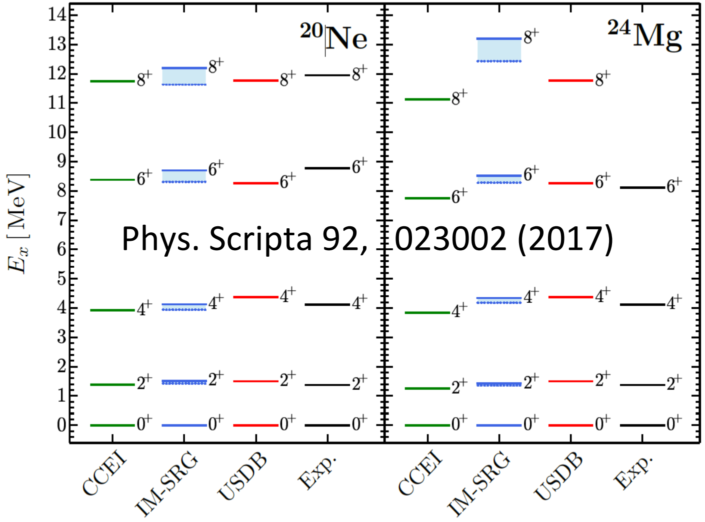

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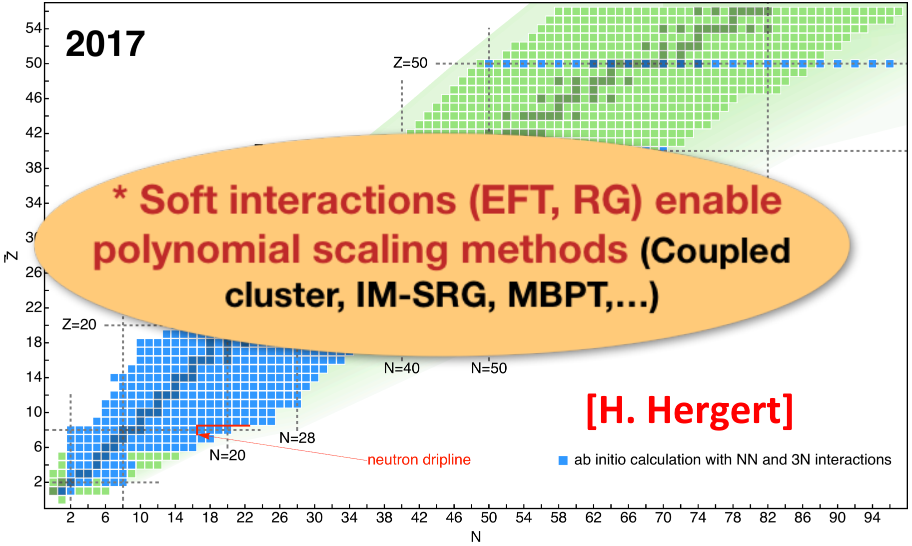

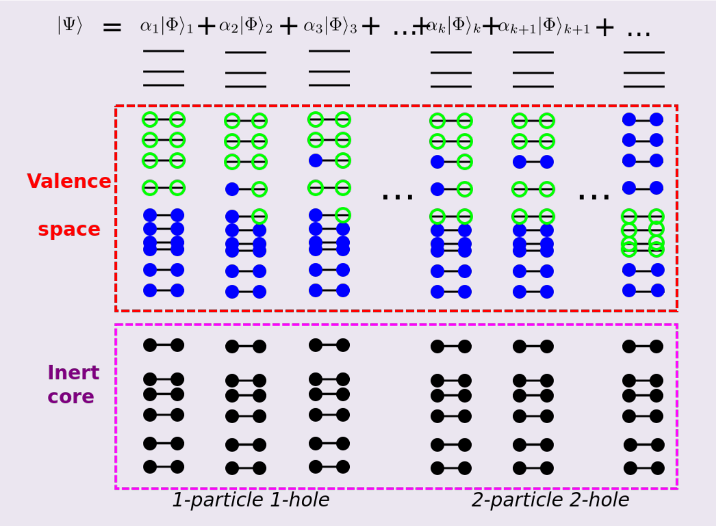

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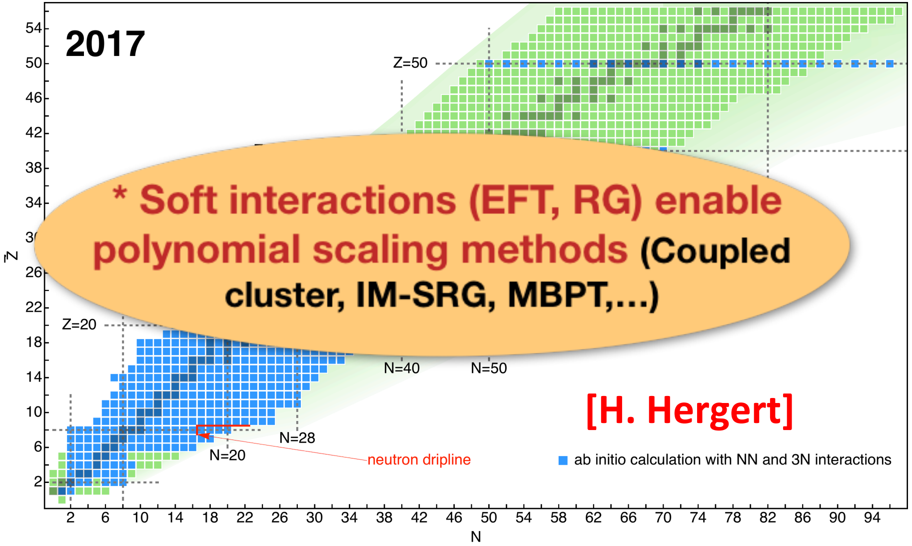

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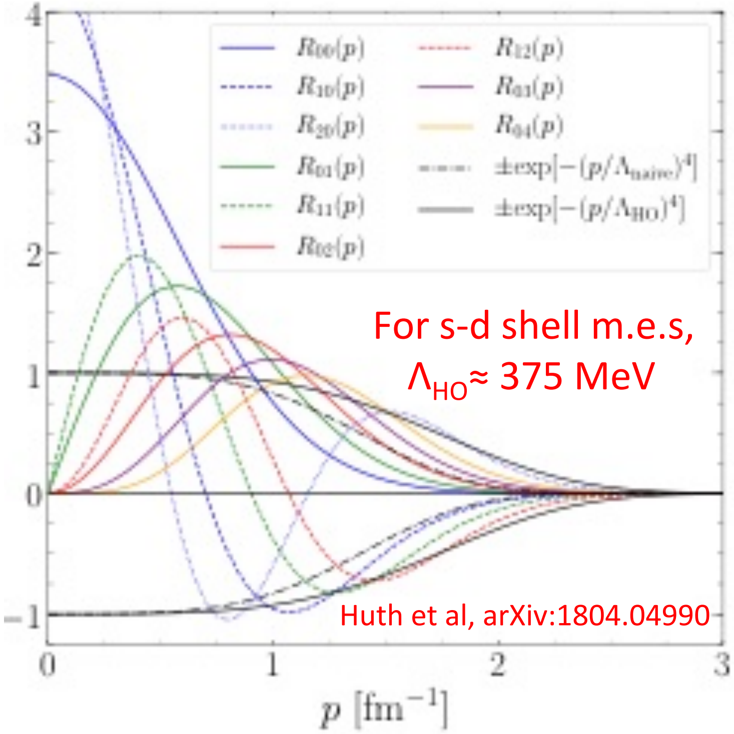

For s-d shell m.e.s, $\Lambda_{HO} \approx 375$ MeV

Huth et al, arXiv:1804.04990

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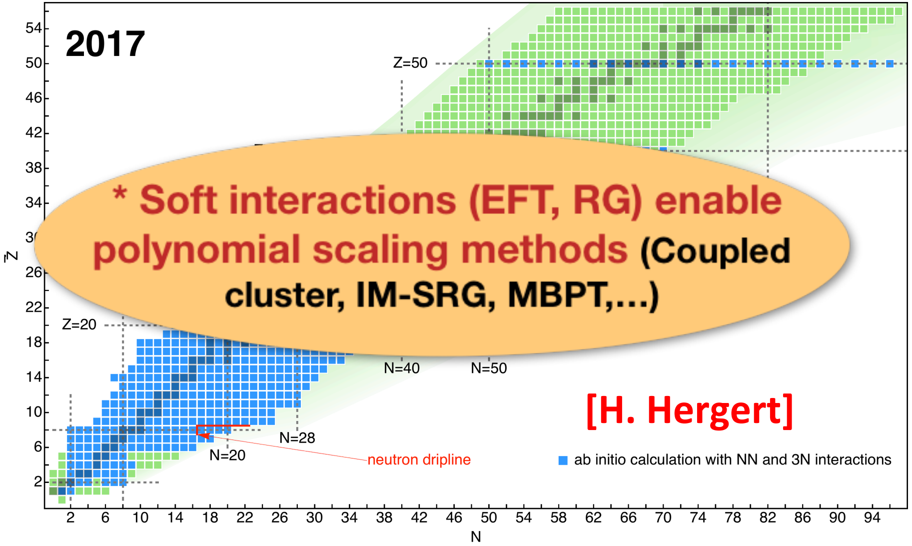

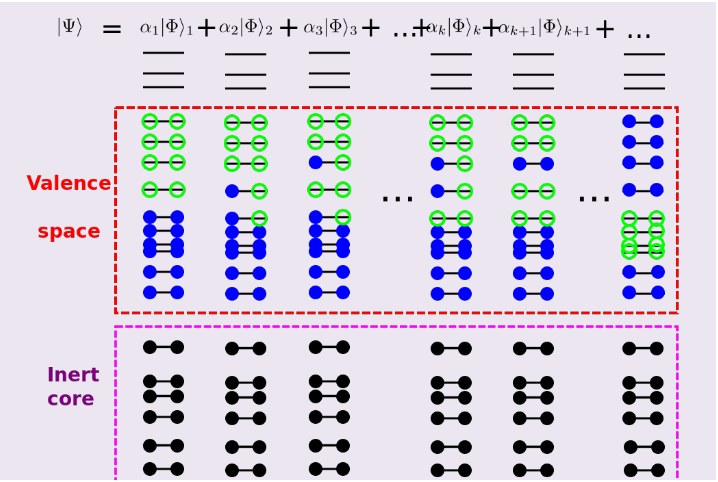

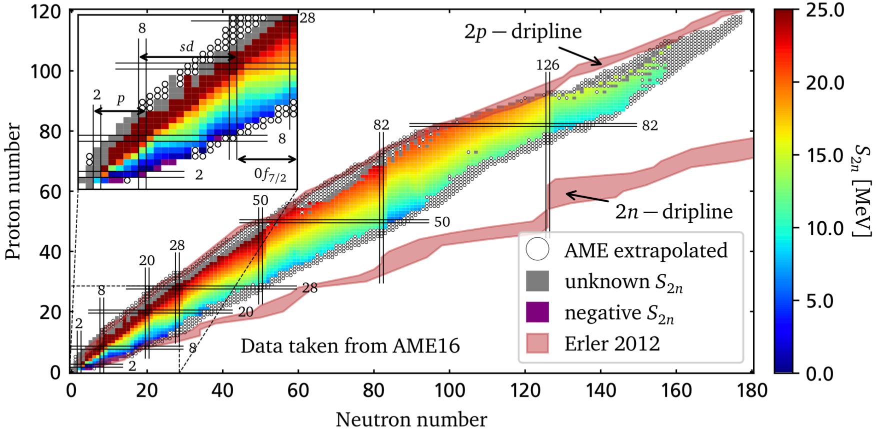

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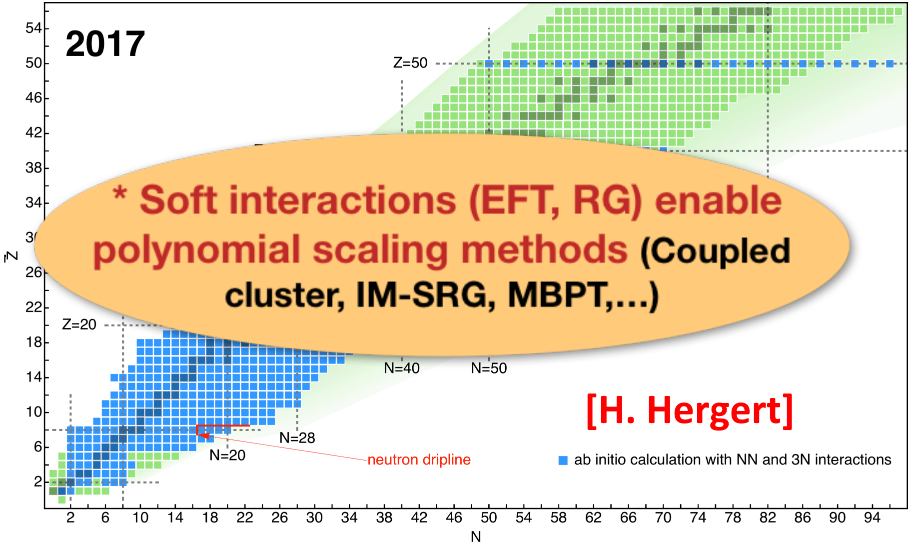

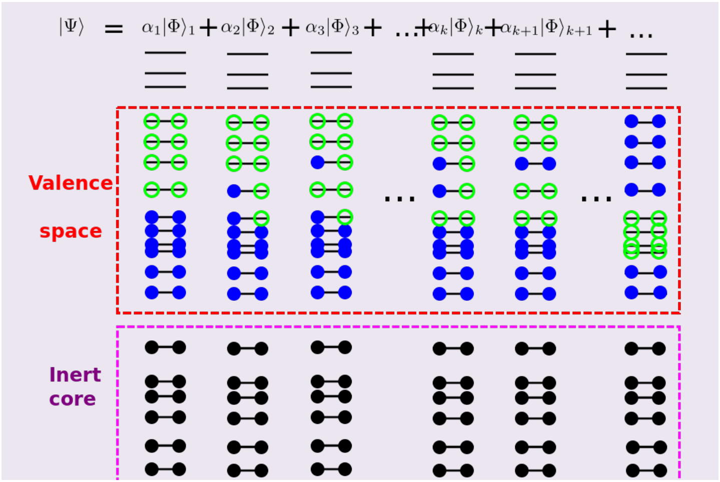

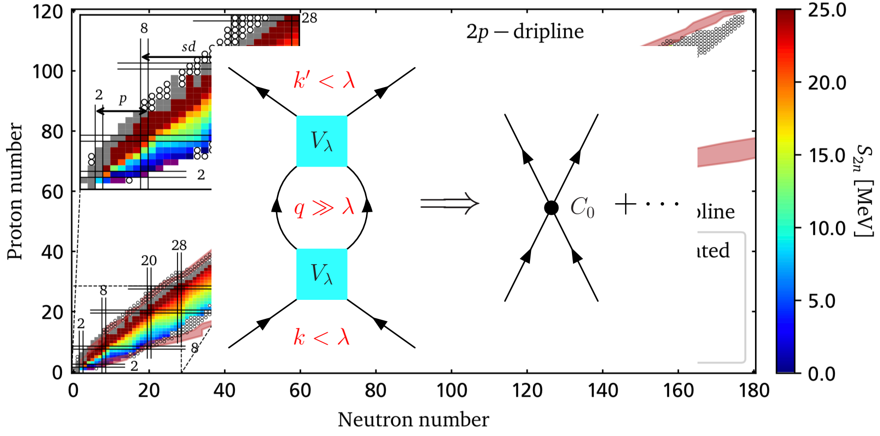

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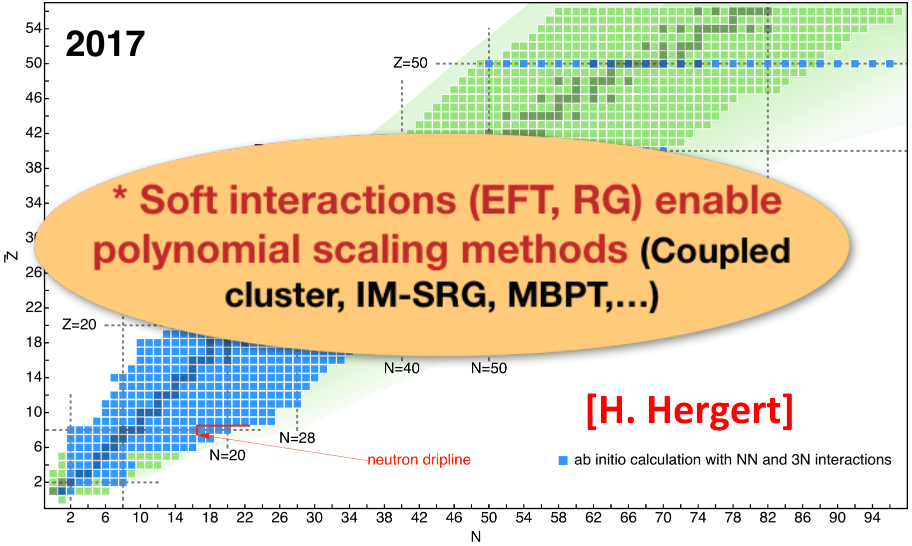

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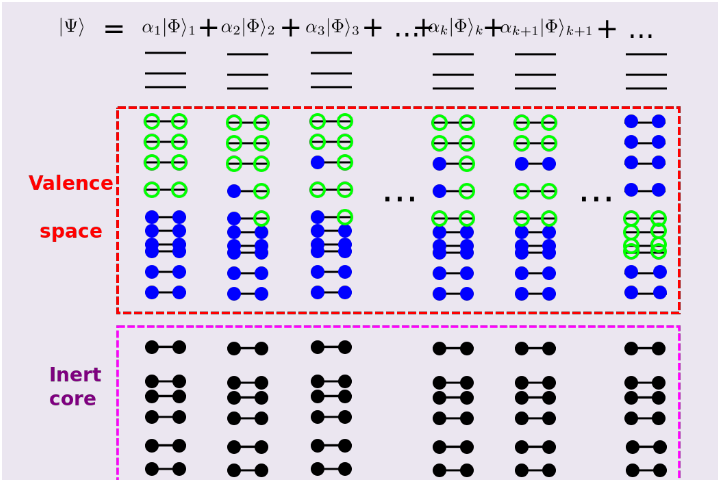

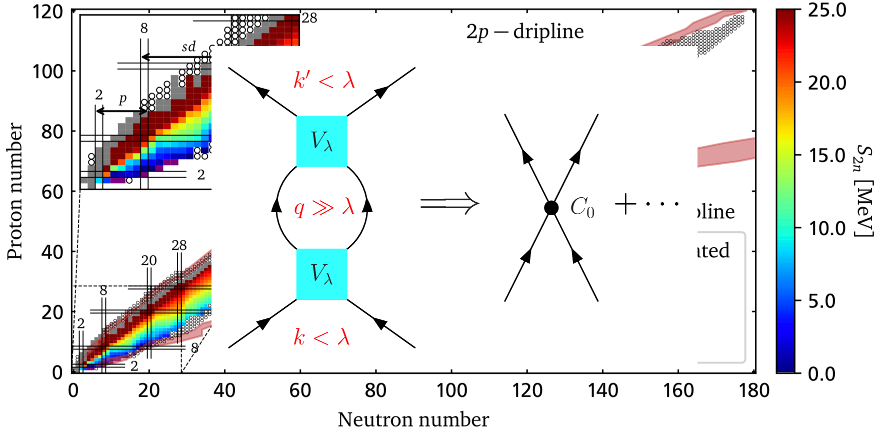

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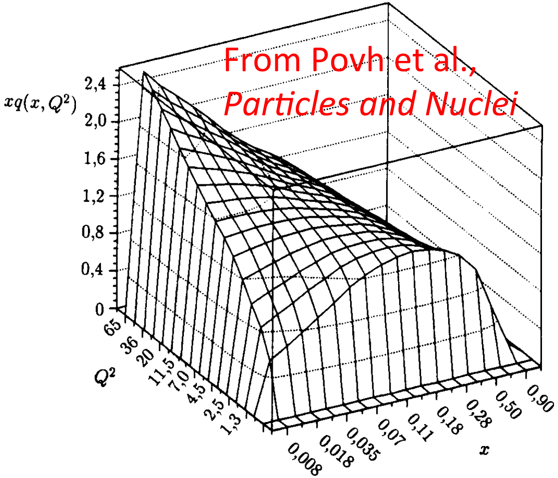
All have correlations: a Slater determinant reference state ≠ independent particle model!

Scale dependence of momentum distributions from RG



- The quark distribution $q(x, Q^2)$ is scale *and* scheme dependent
- $x\, q(x, Q^2)$ measures the share of momentum carried by the quarks in a particular x-interval
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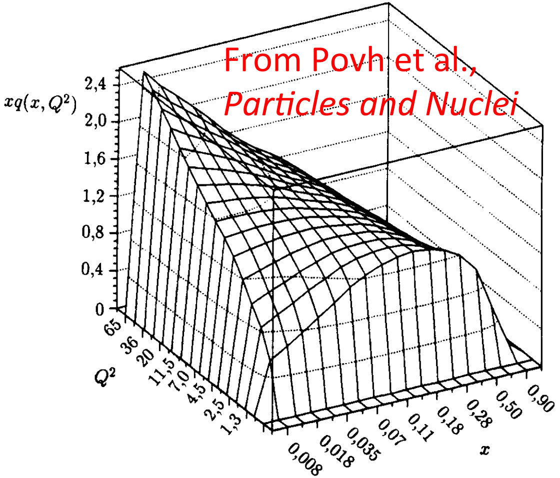

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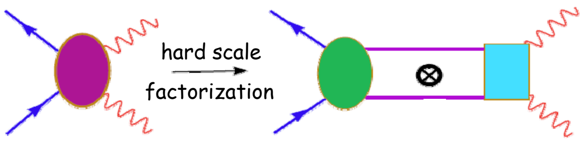
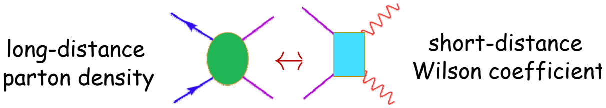


$$F_2(x, Q^2) \sim \sum_a f_a(x, \mu_f) \otimes \widehat{F}_2^a(x, Q/\mu_f)$$



Separation between long- and short-distance physics is not unique!

Observable (e.g. form factor) is independent of factorization scale, but pieces are not.

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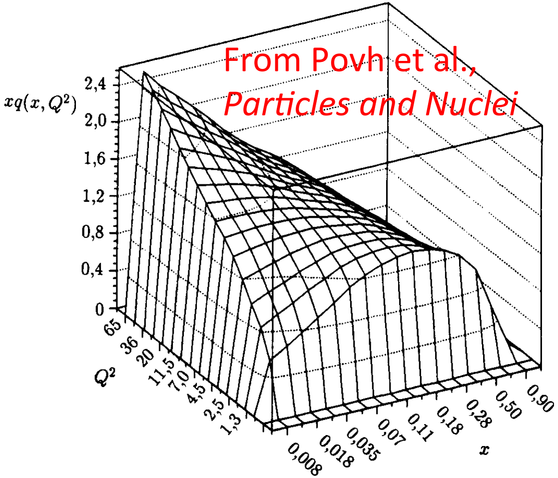

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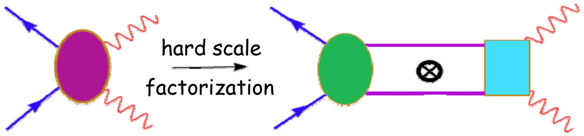

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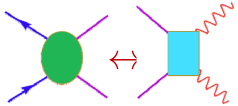

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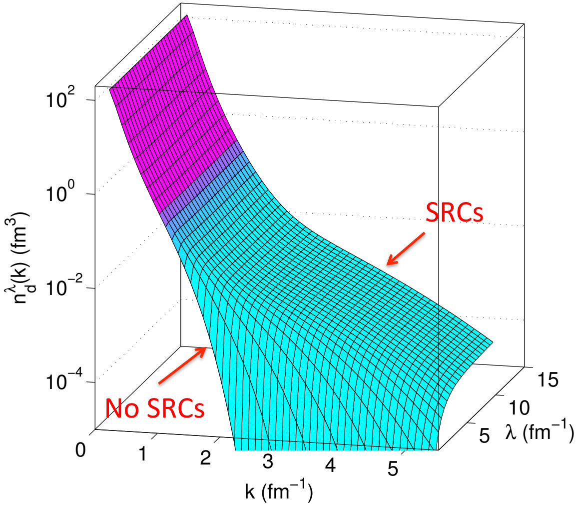

- Deuteron momentum distribution is scale *and* scheme dependent
- Initial AV18 potential evolved with SRG from $\lambda = \infty$ to $\lambda = 1.5\,\mathrm{fm}^{-1}$
- High momentum tail shrinks as λ decreases (lower resolution)

Matching chiral effective field theory to QCD

$$\langle\Psi|\mathcal{O}_{\mathrm{QCD}}|\Psi'\rangle = \langle\Psi|\sum_i \mathcal{O}^{(i)}_{\mathrm{EFT}}|\Psi'\rangle$$

- Operators not forbidden are compulsory
- Symmetries limit what is allowed
- Complete set of operators order-by-order
- Power counting based on *naturalness*

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- For chiral EFT, apply NDA (naïve dimensional analysis) to estimate coefficients:

$$\mathcal{L}_{\chi\mathrm{eft}} = c_{lmn} \left(\frac{N^\dagger (\cdots) N}{f_\pi^2 \Lambda_\chi} \right)^l \left(\frac{\pi}{f_\pi} \right)^m \left(\frac{\partial^\mu, m_\pi}{\Lambda_\chi} \right)^n f_\pi^2 \Lambda_\chi^2$$

$$f_\pi \sim 100\,\mathrm{MeV}, \qquad 1000 \geq \Lambda_\chi \geq 500 \Longrightarrow \frac{1}{7} \leq \frac{\rho_0}{f_\pi^2 \Lambda} \leq \frac{1}{4}$$

- NDA works for fits to χPT, NN scattering, …
- *Always* have 1-, 2-, many-body operators!

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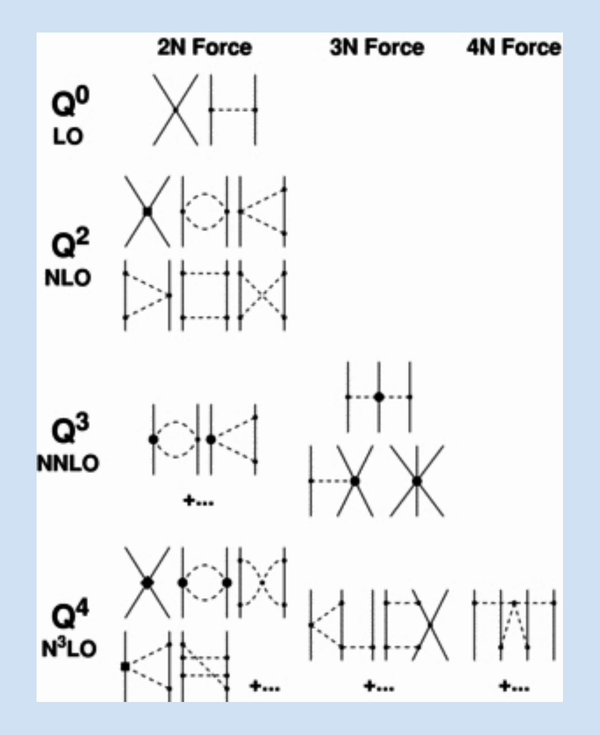

- Ope … ulsory
- Sym …
- Com … -order
- Pow … ess
- For … mensional anal…

$\mathcal{L}_{\chi\rm eft} =$ … $\frac{m_\pi}{\ldots\chi}\Big)^n f_\pi^2 \Lambda_\chi^2$

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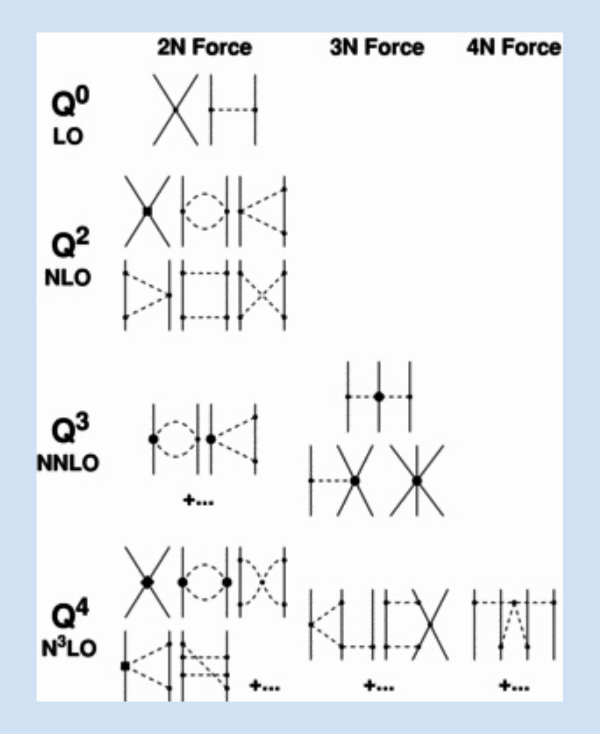

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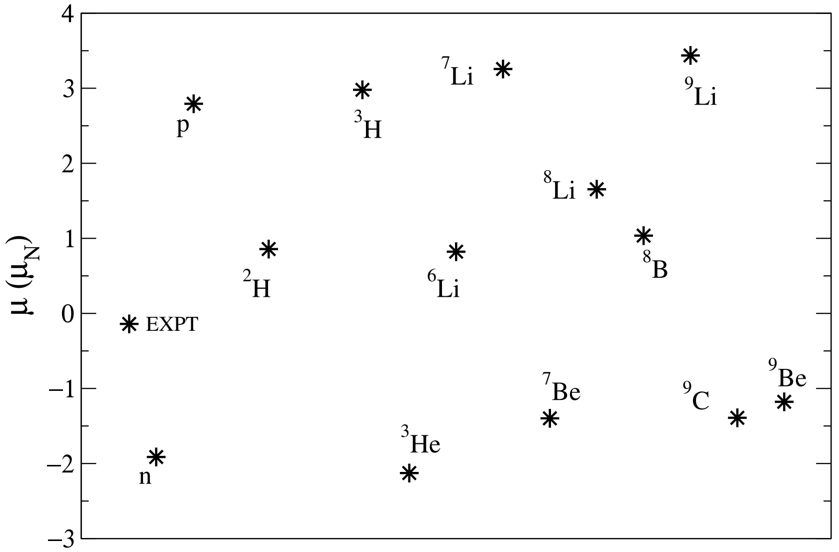

Pastore et al., AV18 wfs with χEFT currents

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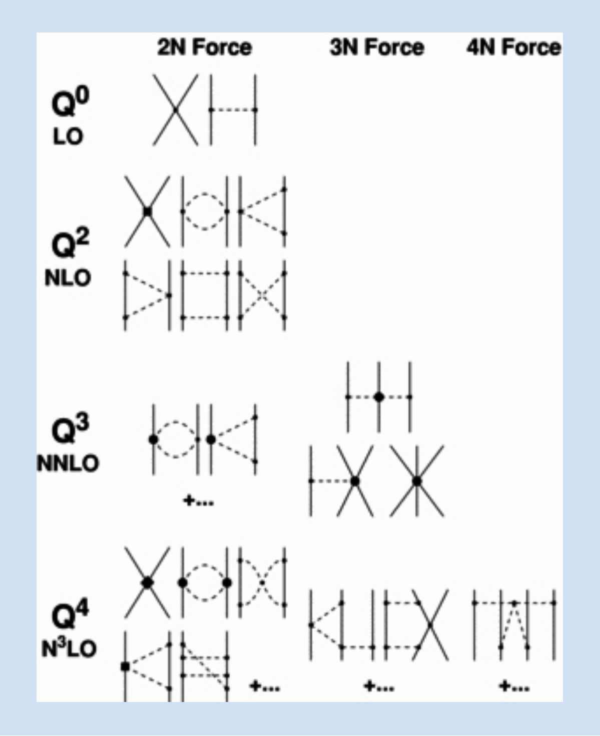

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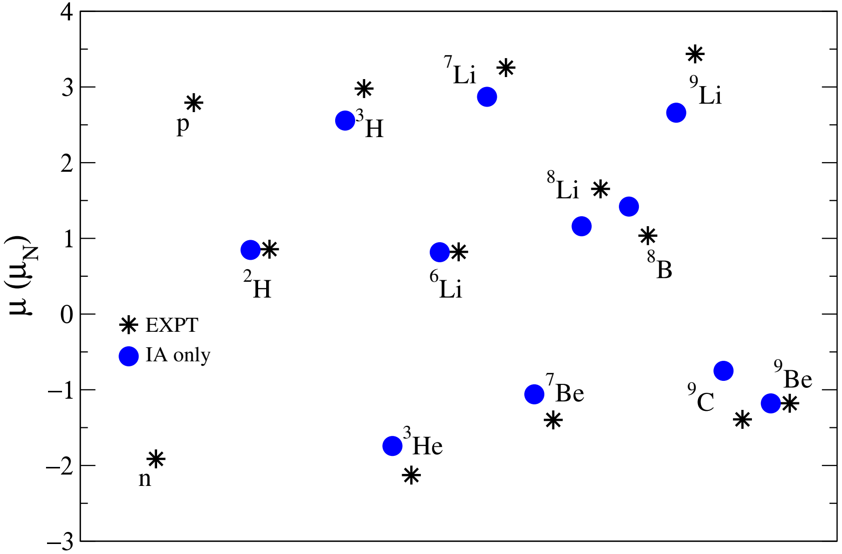

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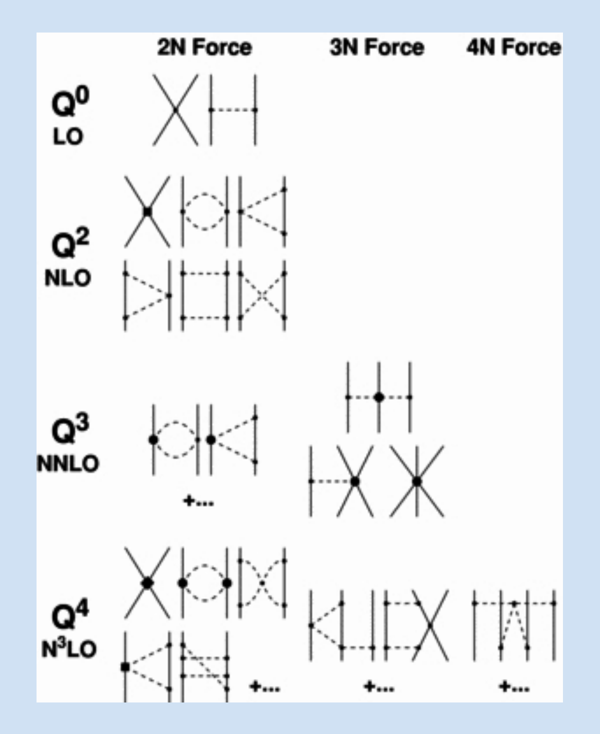

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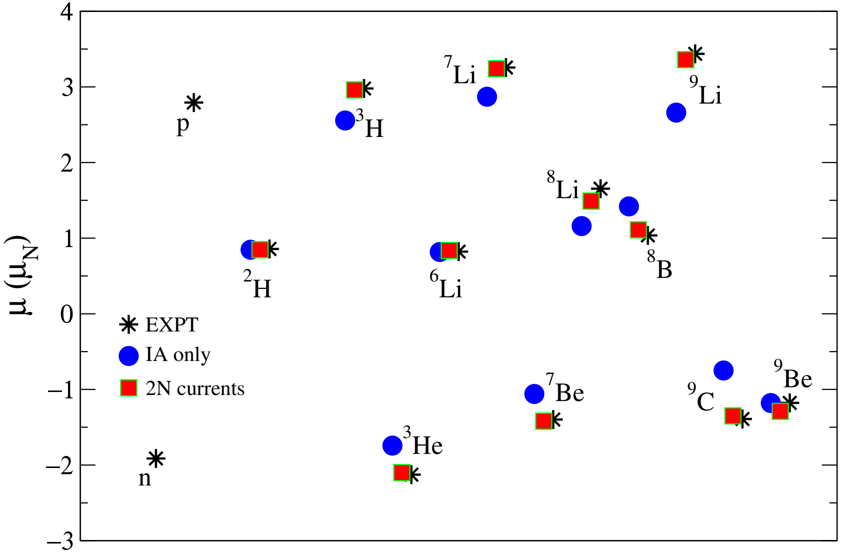

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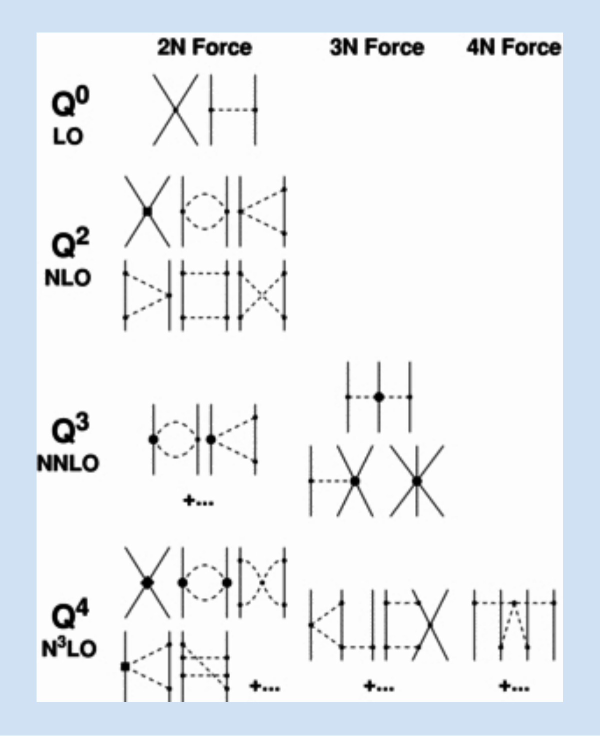
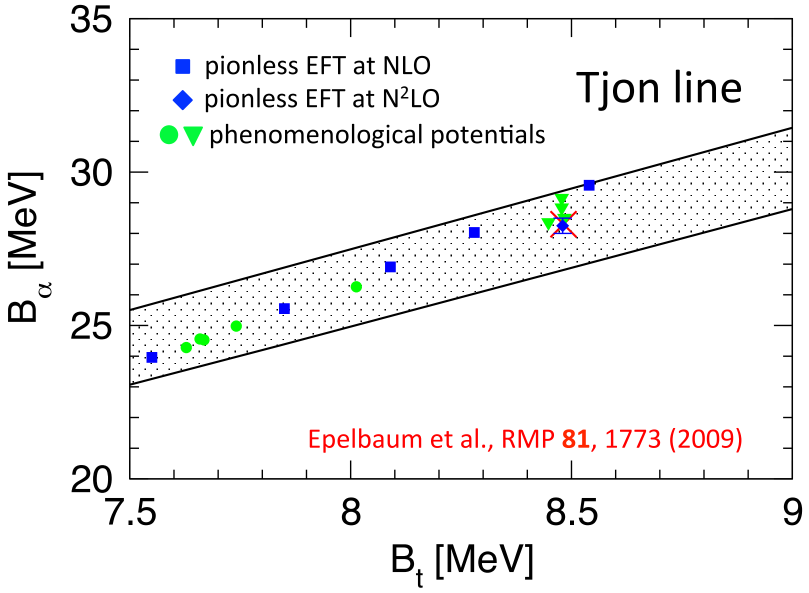


If the same operator dominates
➔explains correlated quantities



Cold atoms near unitarity: an OPE-RG-EFT perspective

E. Braaten et al., arXiv:1008.2922 + …

System of fermions with short-range interactions with large scattering length a.

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System of fermions with short-range interactions with large scattering length a.

Described by QFT formulation of Zero-Range Model ➔``pionless EFT'':

$$\mathcal{H} = \sum_\sigma \frac{1}{m} \nabla\psi_\sigma^\dagger \cdot \nabla\psi_\sigma^{(\Lambda)} + \frac{g(\Lambda)}{m}\psi_1^\dagger\psi_2^\dagger\psi_2\psi_1^{(\Lambda)} + \mathcal{V}_{\mathrm{external}} \qquad g(\Lambda) = \frac{4\pi a}{1 - 2a\Lambda/\pi}$$

UV cutoff Λ is required to make matrix elements of these operators well defined.

Cold atoms near unitarity: an OPE-RG-EFT perspective

E. Braaten et al., arXiv:1008.2922 + …

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Contact $C = \int d^3R\, g(\Lambda)^2 \langle \psi_1^\dagger \psi_2^\dagger \psi_2 \psi_1^{(\Lambda)}(\boldsymbol{R}) \rangle$ is in many universal relations because dominant op.

E.g., momentum density at large **k** from small |**r**|: $n_\sigma(\boldsymbol{k}) \to C/k^4$ [from non-analytic r!]

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E.g., momentum density at large **k** from small |**r**|: $n_\sigma(\boldsymbol{k}) \to C/k^4$ [from non-analytic r!]

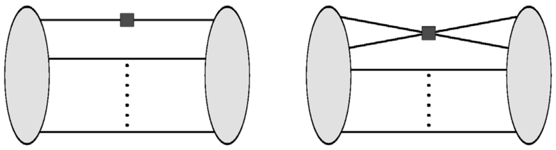
Note that the *ratio* of $\psi_1^\dagger\psi_2^\dagger\psi_2\psi_1^{(\Lambda)}(\boldsymbol{R})$ in different states will be finite from cancellation!

Preview: SRCs and the EMC effect in EFT [see Jiunn-Wei's talk]

Chen and Detmold, Phys. Lett. B 625 (2005)
Chen et al., Phys. Rev. Lett. 119 (2017)

Q: How can we describe hard partonic processes using EFT for low-energy QCD?

A: OPE factors hard/soft parts and gives moments of PDFs as matrix elements of local twist-2 QCD operators ➔ match to leading nucleon operators in EFT



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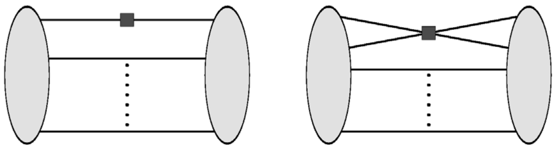

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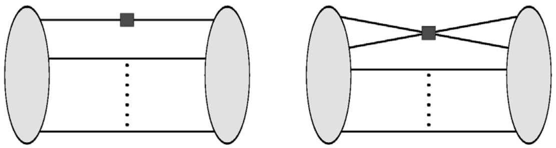

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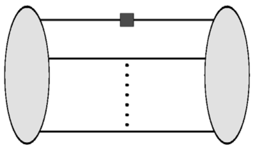

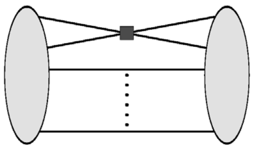

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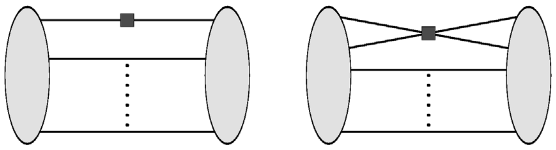

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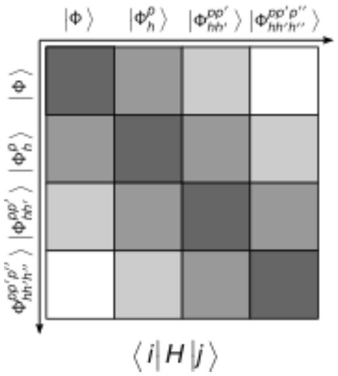
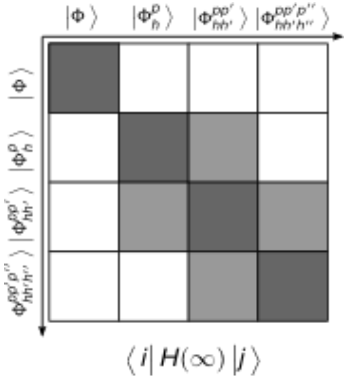
We see a_2 is from physics *below* scale Λ; can we calculate it in low-resolution nuclei?

IM-SRG(2) calculations of a_2 [in progress by Parzuchowski, Bogner, rjf]



$$\frac{dH(s)}{ds} = [\eta(s), H(s)]$$



$$\hat{\rho}_{21}(s=0) = \frac{1}{2}\sum_{\alpha,\beta}\int d\mathbf{R}\, N^{\dagger}_{\alpha} N^{\dagger}_{\beta} N_{\beta} N_{\alpha}$$

$$\frac{d\hat{\rho}_{21}(s)}{ds} = [\eta(s), \hat{\rho}_{21}(s)]$$

$$\langle \Psi_0|\hat{\rho}_{21}|\Psi_0\rangle = \langle \Phi|\hat{\rho}_{21}(\infty)|\Phi\rangle$$

Opportunities

access heavier nuclei (here up to A = 40)
access wider range of interactions**
(not limited to local interactions)

Challenges

QMC cleanly extrapolates to r = 0
(vs. implicit smearing due to truncated HO basis)
impact of IM-SRG(2) truncation errors?

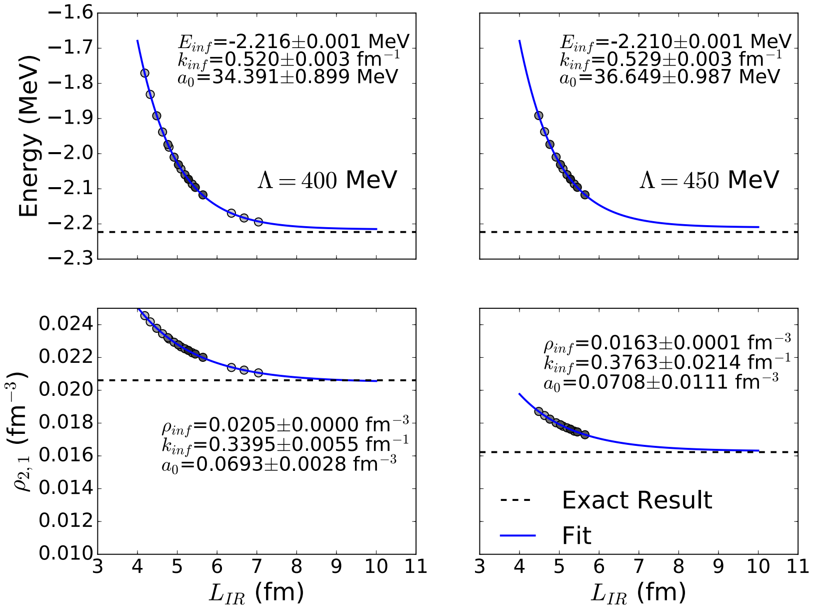
** here we use the semi-local n4lo NN interaction of Reinert, Krebs, and Epelbaum arXiv:1711.08821

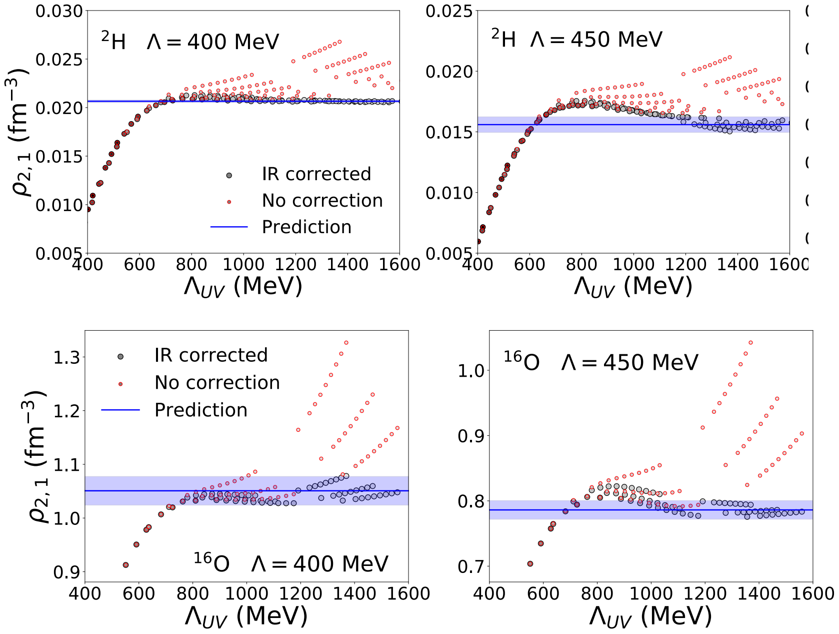
IR and UV extrapolations of $\rho_{2,1}$

Truncated HO basis ==> IR cutoff (box size L_{IR}) and UV cutoff:

$$L_{IR} \sim \sqrt{2(2n+l)_{\max}+3}\; b$$

$$\Lambda_{UV} \sim \sqrt{2(2n+l)_{\max}+3}\; b^{-1}$$

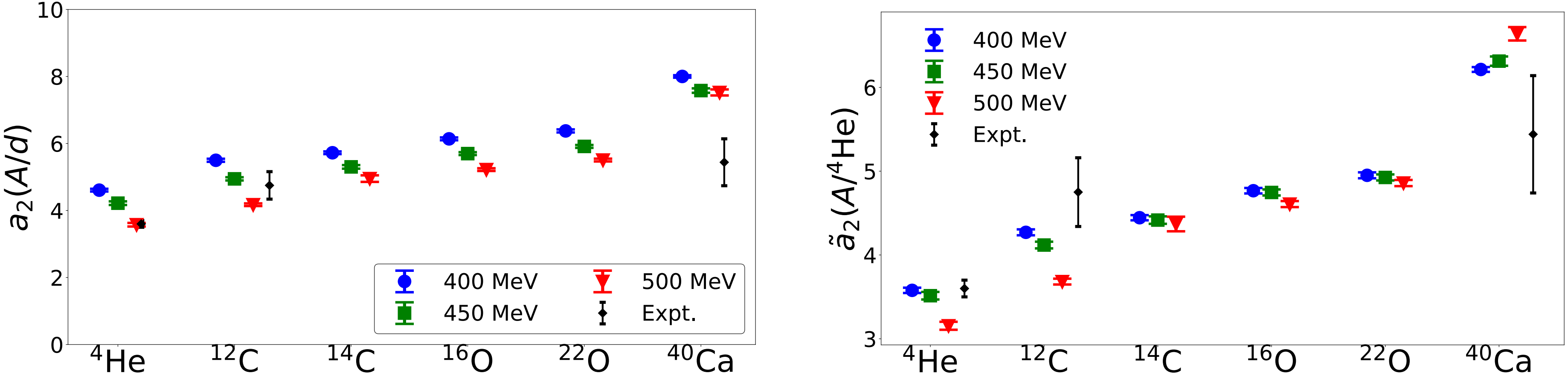




$$\rho_{2,1}(L_{IR}) = \rho_{2,1}(\infty) + a_0 e^{-k_\infty L_{IR}}$$

Motivated by energy/radii formulas in More et al. PRC87 (2013), but needs further work

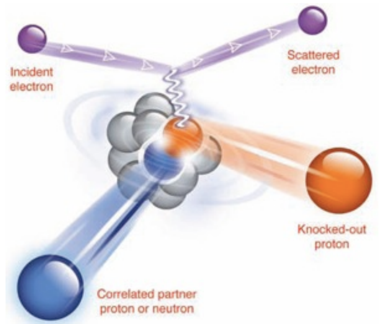
Preliminary results for a_2



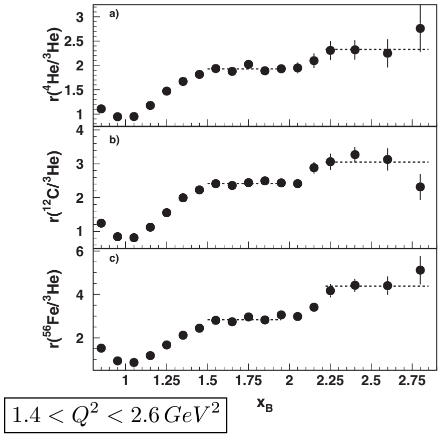
Systematic Λ dependence, but in part due to treatment of deuteron; ratio to He better

Status: Need to better control UV/IR convergence and IM-SRG(2) truncation errors (and estimate EFT truncation error) before concluding if a_2 is scale-independent.

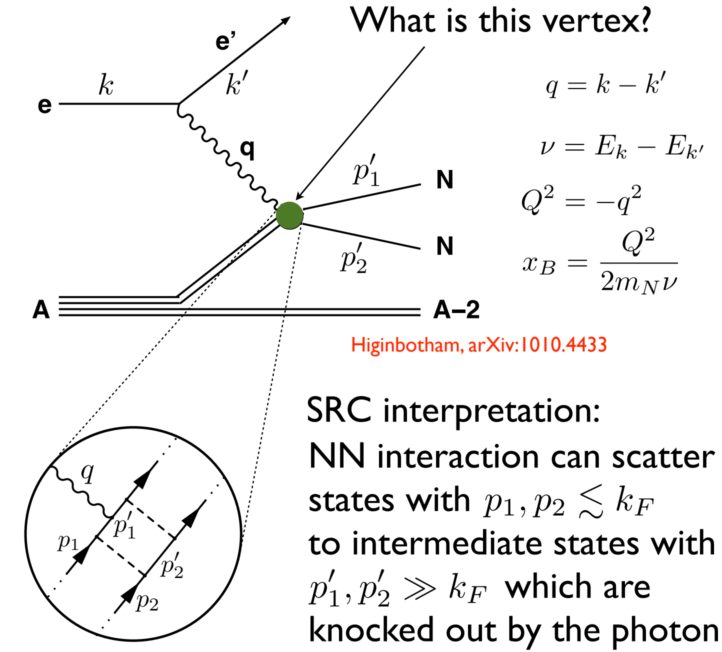
Large Q^2 scattering at different RG decoupling scales



Subedi et al., Science 320, 1476 (2008)



Egiyan et al. PRL 96, 1082501 (2006)



Higinbotham, arXiv:1010.4433

SRC interpretation:
NN interaction can scatter states with $p_1, p_2 \lesssim k_F$ to intermediate states with $p_1', p_2' \gg k_F$ which are knocked out by the photon

SRC explanation relies on high-momentum nucleons in structure

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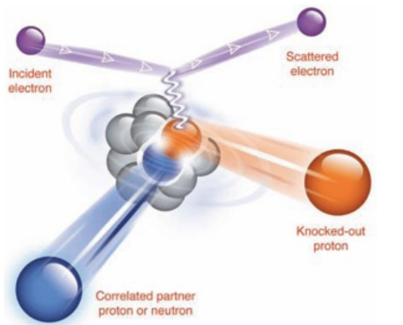

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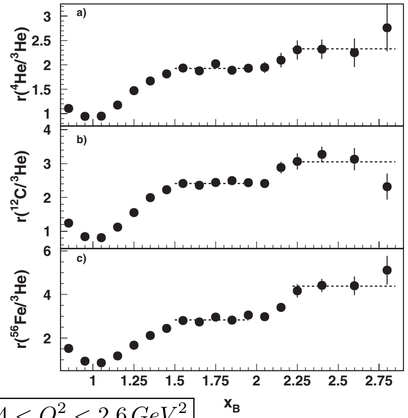
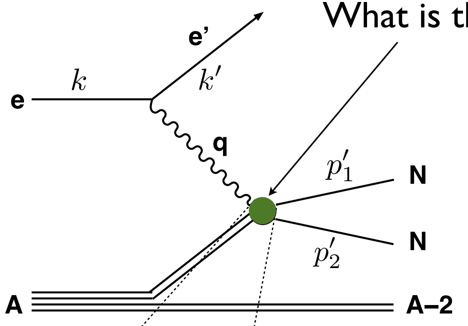


$1.4 < Q^2 < 2.6\, GeV^2$

Egiyan et al. PRL 96, 1082501 (2006)

What is this vertex?



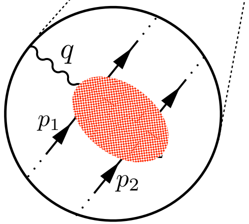
$q = k - k'$

$\nu = E_k - E_{k'}$

$Q^2 = -q^2$

$x_B = \dfrac{Q^2}{2m_N\nu}$

Higinbotham, arXiv:1010.4433



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---

How to explain cross sections in terms of low-momentum interactions?

Vertex depends on the resolution!

RG evolution changes physics *interpretation* but not cross section!

SRG changes resolution with unitary transformations

[Note: the following discussion is more general than the SRG.]

- The cross section is *guaranteed* to be the same from $\widehat{U}^\dagger \widehat{U} = 1$

$$
\begin{aligned}
d\sigma &\sim \sum \delta(\omega + E_i - E_f) |\langle \Psi_f | \widehat{\rho}(\mathbf{q}) | \Psi_i \rangle|^2 \\
&= \sum \delta(\omega + E_i - E_f) |\langle \Psi_f | (\widehat{U}^\dagger \widehat{U}) \widehat{\rho}(\mathbf{q}) (\widehat{U}^\dagger \widehat{U}) | \Psi_i \rangle|^2 \\
&= \sum \delta(\omega + E_i - E_f) |(\langle \Psi_f | \widehat{U}^\dagger)(\widehat{U} \widehat{\rho}(\mathbf{q}) \widehat{U}^\dagger)(\widehat{U} | \Psi_i \rangle)|^2
\end{aligned}
$$

  but the pieces are different now.

- Schematically, the SRG has $\widehat{U} = 1 + \frac{1}{2}(U - 1) a^\dagger a^\dagger a a + \cdots$
  - U is found by solving for the unitary transformation in the $A = 2$ system (this is the easy part!)
  - The $\cdots$'s represent higher-body operators
  - One-body operators ($\propto a^\dagger a$) gain many-body pieces
    (EFT: there are always many-body pieces at some level!)
  - Both initial and final states are modified (and therefore FSI)

U-factorization with SRG [Anderson et al., arXiv:1008.1569]

- Factorization: $U_\lambda(k,q) \to K_\lambda(k) Q_\lambda(q)$ when $k < \lambda$ and $q \gg \lambda$
- Operator product expansion for nonrelativistic wf's (see Lepage)

$$\Psi_\alpha^\infty(q) \approx \gamma^\lambda(q) \int_0^\lambda p^2 dp\, Z(\lambda) \Psi_\alpha^\lambda(p) + \eta^\lambda(q) \int_0^\lambda p^2 dp\, p^2\, Z(\lambda)\, \Psi_\alpha^\lambda(p) + \cdots$$

- Construct unitary transformation to get $U_\lambda(k,q) \approx K_\lambda(k) Q_\lambda(q)$

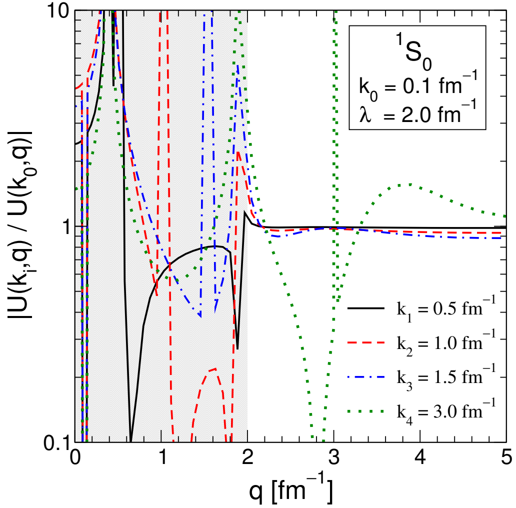
$$U_\lambda(k,q) = \sum_\alpha \langle k|\psi_\alpha^\lambda\rangle \langle \psi_\alpha^\infty|q\rangle \to \Big[\sum_\alpha^{\alpha_{low}} \langle k|\psi_\alpha^\lambda\rangle \int_0^\lambda p^2 dp\, Z(\lambda) \Psi_\alpha^\lambda(p)\Big] \gamma^\lambda(q) + \cdots$$

- Test of factorization of U:

$$\frac{U_\lambda(k_i,q)}{U_\lambda(k_0,q)} \to \frac{K_\lambda(k_i) Q_\lambda(q)}{K_\lambda(k_0) Q_\lambda(q)},$$

so for $q \gg \lambda \Rightarrow \dfrac{K_\lambda(k_i)}{K_\lambda(k_0)} \xrightarrow{\text{LO}} 1$

- Look for plateaus: $k_i \lesssim 2\,\text{fm}^{-1} \lesssim q$
  $\Longrightarrow$ it works!
- Leading order $\Longrightarrow$ contact term!



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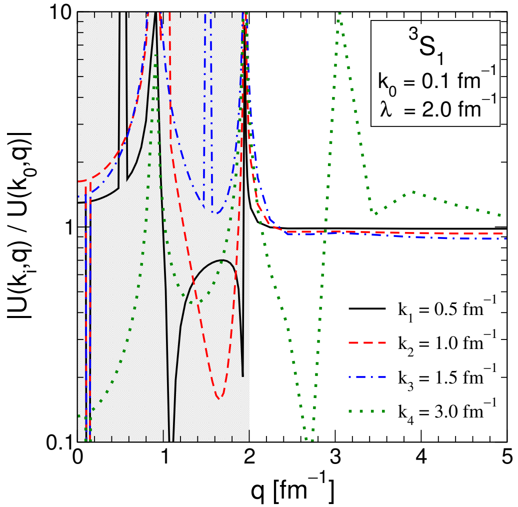
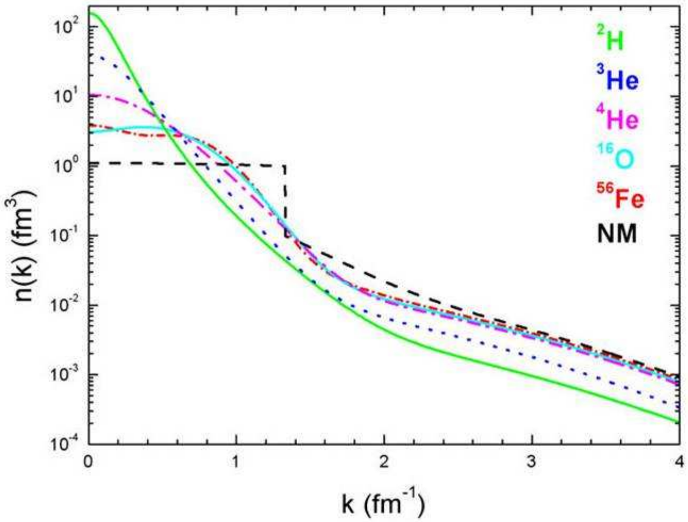


Nuclear scaling from RG factorization (schematic!)

- RG unitary transformation with scale separation: $\widehat{U} \to U_\lambda(k, q)$
- Factorization: when $k < \lambda$ and $q \gg \lambda$, $U_\lambda(k, q) \to K_\lambda(k) Q_\lambda(q)$

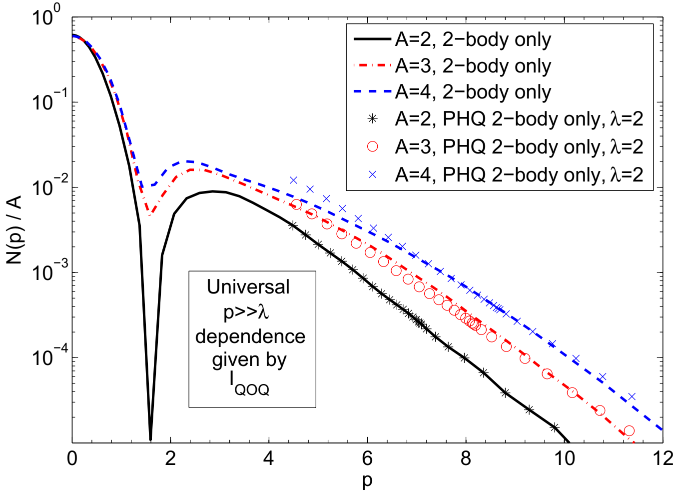
$$\frac{n_A(q)}{n_d(q)} = \frac{\langle A|a_{\mathbf{q}}^\dagger a_{\mathbf{q}}|A\rangle}{\langle d|a_{\mathbf{q}}^\dagger a_{\mathbf{q}}|d\rangle} \underset{\widehat{U}^\dagger\widehat{U}=1}{\overset{\text{RG}}{\Longrightarrow}} \widehat{U}|d\rangle \to |\widetilde{d}\rangle\ , \ \widehat{U}|A\rangle \to |\widetilde{A}\rangle\ , \ \widehat{U}a_{\mathbf{q}}^\dagger a_{\mathbf{q}}\widehat{U}^\dagger$$

$\Longrightarrow n_A(q) \approx C_A n_D(q)$ at large q



[From C. Ciofi degli Atti and S. Simula]

Test case: A bosons in toy 1D model



[Anderson et al., arXiv:1008.1569]
[also Bogner, Roscher, arXiv:1208.1734]

Nuclear scaling from RG factorization (schematic!)

- RG unitary transformation with scale separation: $\widehat{U} \to U_\lambda(k, q)$
- Factorization: when $k < \lambda$ and $q \gg \lambda$, $U_\lambda(k, q) \to K_\lambda(k) Q_\lambda(q)$

$$\frac{n_A(q)}{n_d(q)} = \frac{\langle \widetilde{A} | \widehat{U} a^\dagger_{\mathbf{q}} a_{\mathbf{q}} \widehat{U}^\dagger | \widetilde{A} \rangle}{\langle \widetilde{d} | \widehat{U} a^\dagger_{\mathbf{q}} a_{\mathbf{q}} \widehat{U}^\dagger | \widetilde{d} \rangle} = \frac{\langle \widetilde{A} | \int U_\lambda(k', q') \delta_{q'q} U^\dagger_\lambda(q, k) | \widetilde{A} \rangle}{\langle \widetilde{d} | \int U_\lambda(k', q') \delta_{q'q} U^\dagger_\lambda(q, k) | \widetilde{d} \rangle}$$

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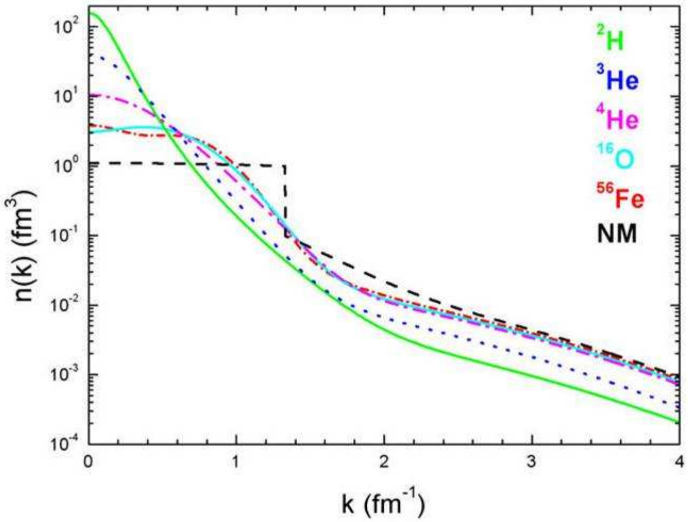

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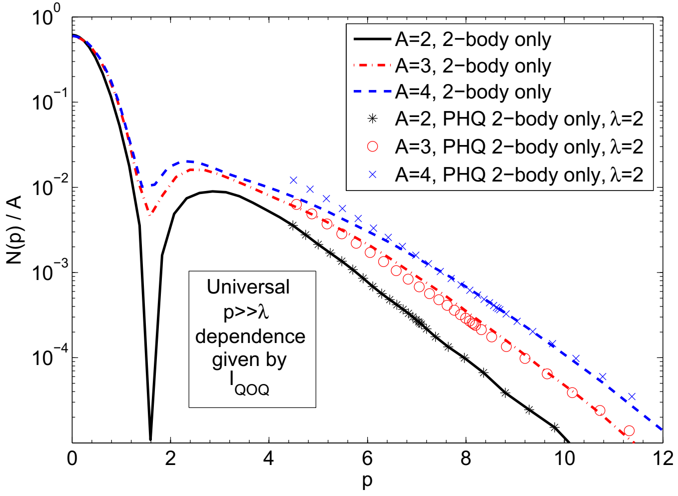

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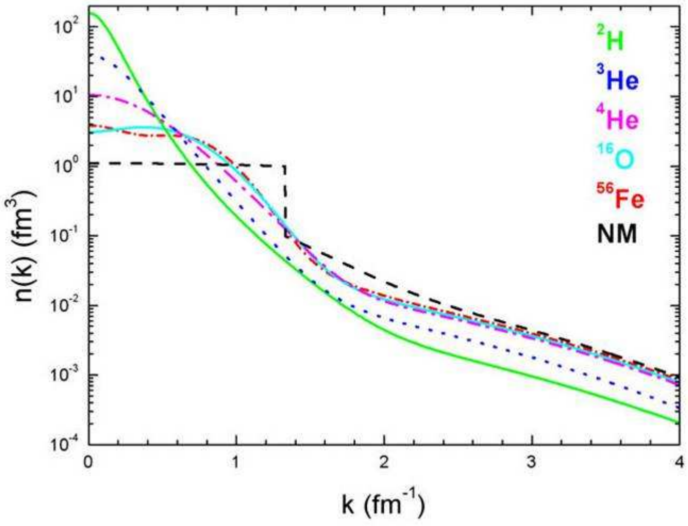

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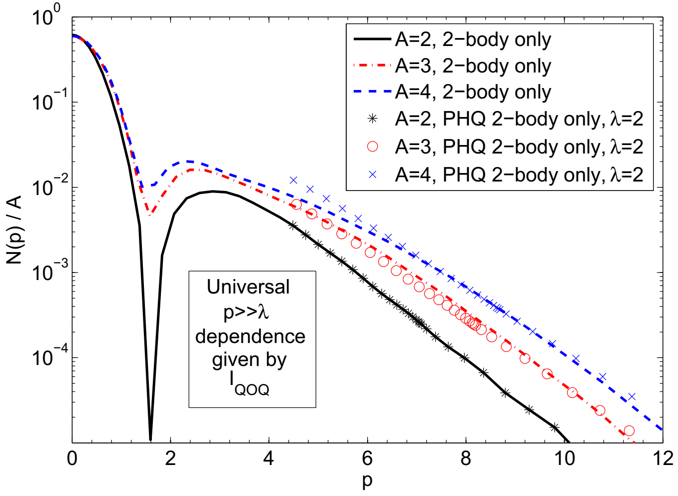

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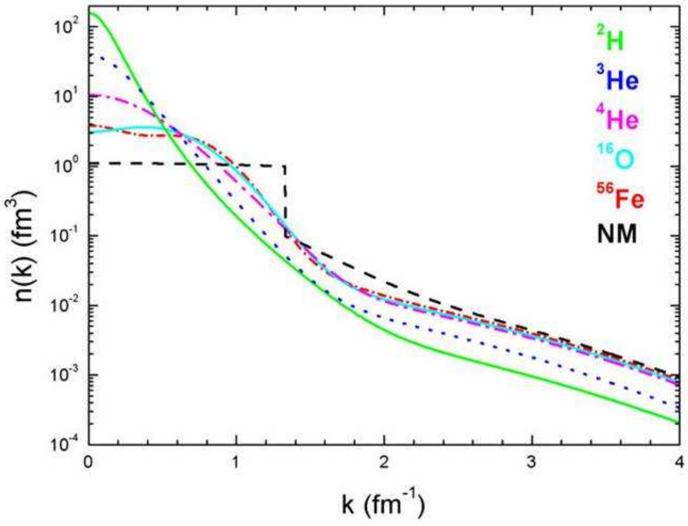

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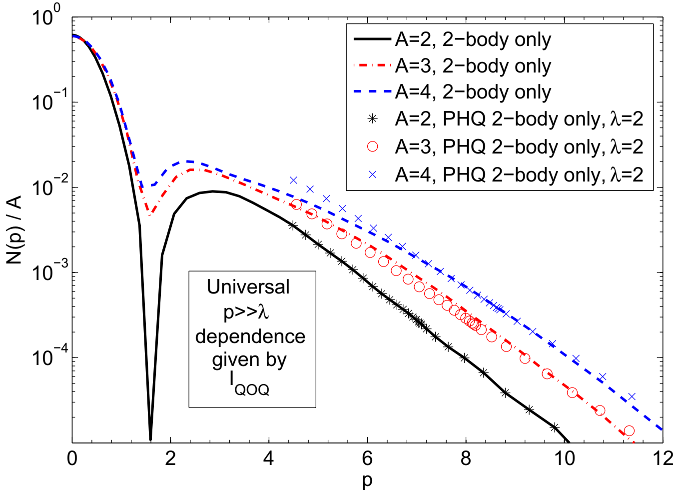

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Test ground for scale dependence: ^{2}H(e,e′p)n

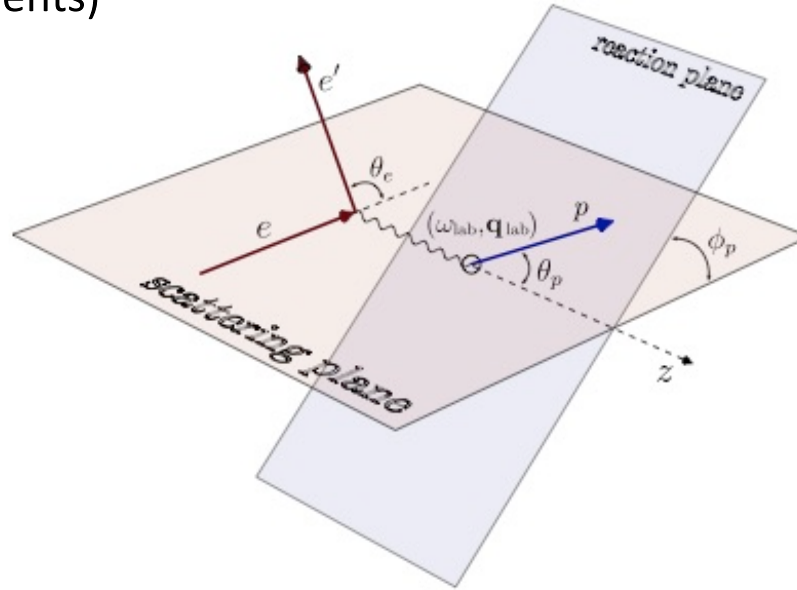
More, Bogner, rjf, PRC96, 2017

Simplest knockout process (no induced 3N forces/currents)

- Use AV18 as "hard" interaction, evolve with SRG
- Treat non-relativistically for all kinematics

Focus on longitudinal structure function f_L

$$f_L \sim \sum_{m_s, m_J} \left| \langle \psi_f | J_0 | \psi_i \rangle \right|^2$$



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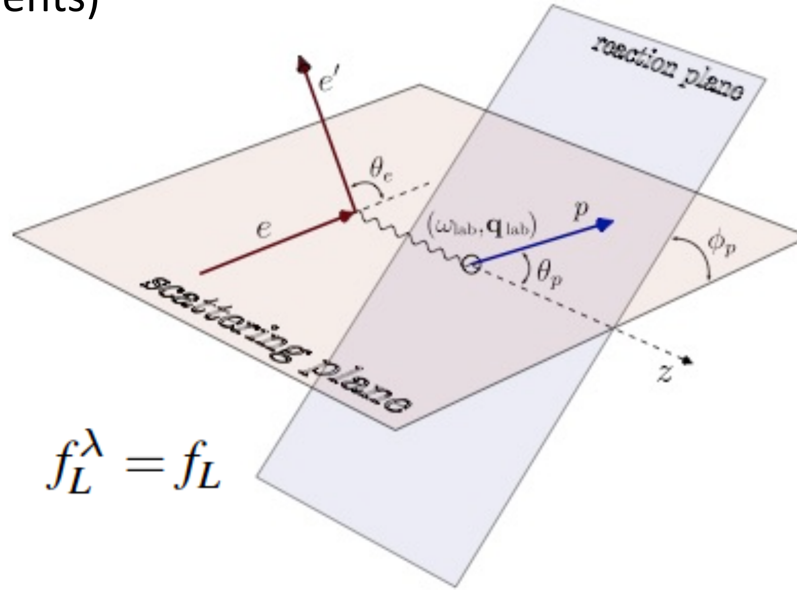

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$$f_L^\lambda \sim \left| \underbrace{\langle \psi_f | U_\lambda^\dagger}_{\psi_f^\lambda} \underbrace{U_\lambda J_0 U_\lambda^\dagger}_{J_0^\lambda} \underbrace{U_\lambda | \psi_i \rangle}_{\psi_i^\lambda} \right|^2; \quad U_\lambda^\dagger U_\lambda = I; \quad f_L^\lambda = f_L$$

Components (deuteron wf, transition operator, FSI) are scale-dependent; total is not!

Test ground for scale dependence: $^{2}H(e,e'p)n$

More, Bogner, rjf, PRC96, 2017

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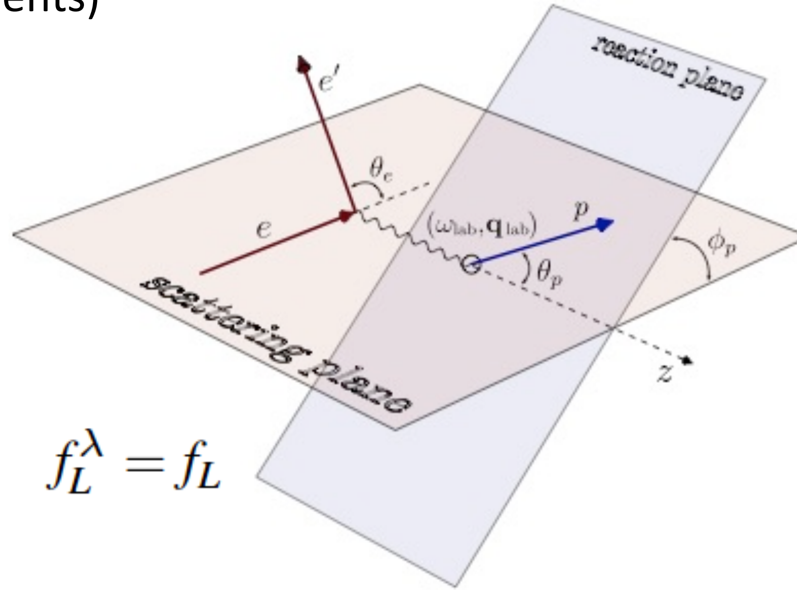

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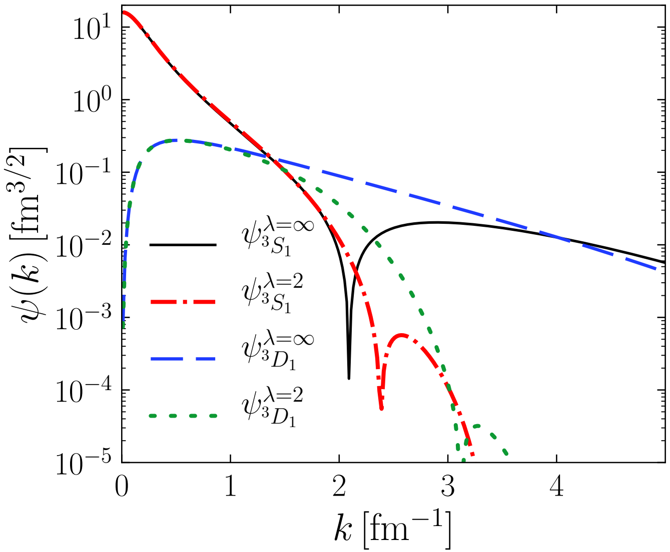
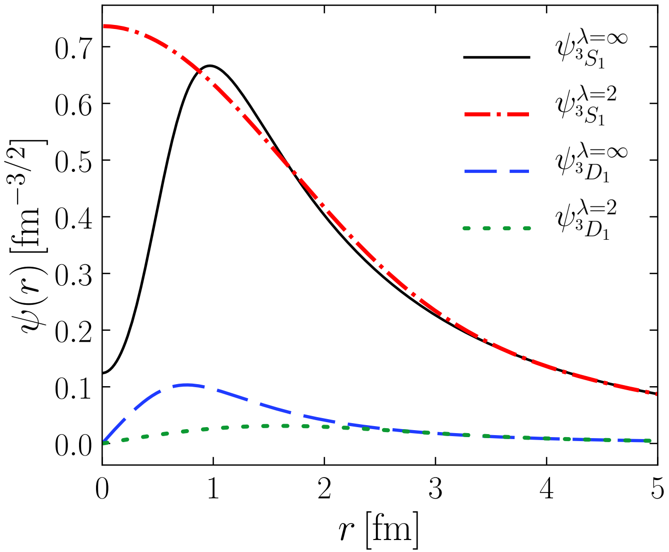
Components (deuteron wf, transition operator, FSI) are scale-dependent; total is not!

Are some resolutions "better" than others? E.g., in a given kinematics, can FSI be minimized with different choices of λ??

Deuteron wave function evolution





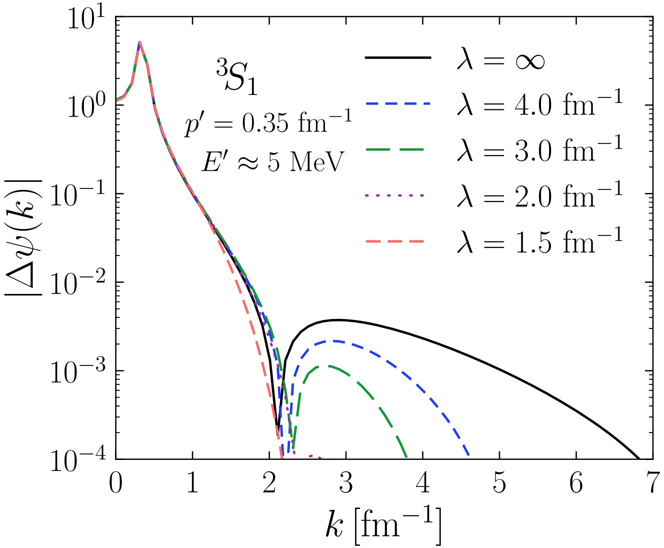
k < λ components invariant <==> RG preserves long-distance physics

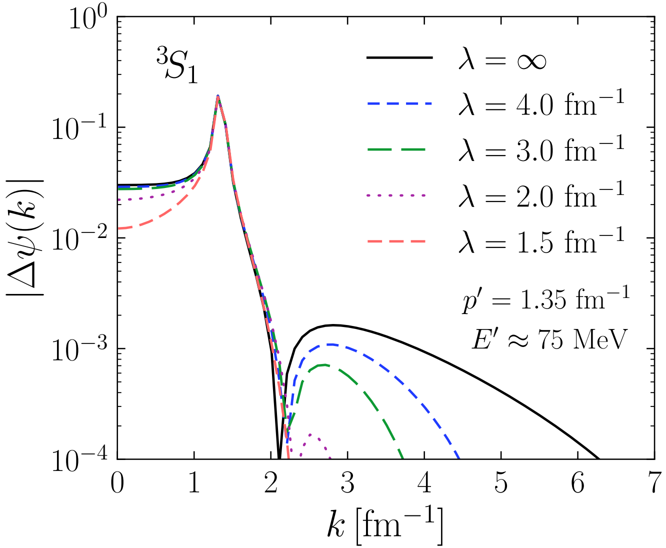
k > λ components suppressed <==> short-range correlations blurred out

Folklore: Simple wave functions at low λ <==> more complicated operators?

especially for high q processes?

Final-state wave function evolution



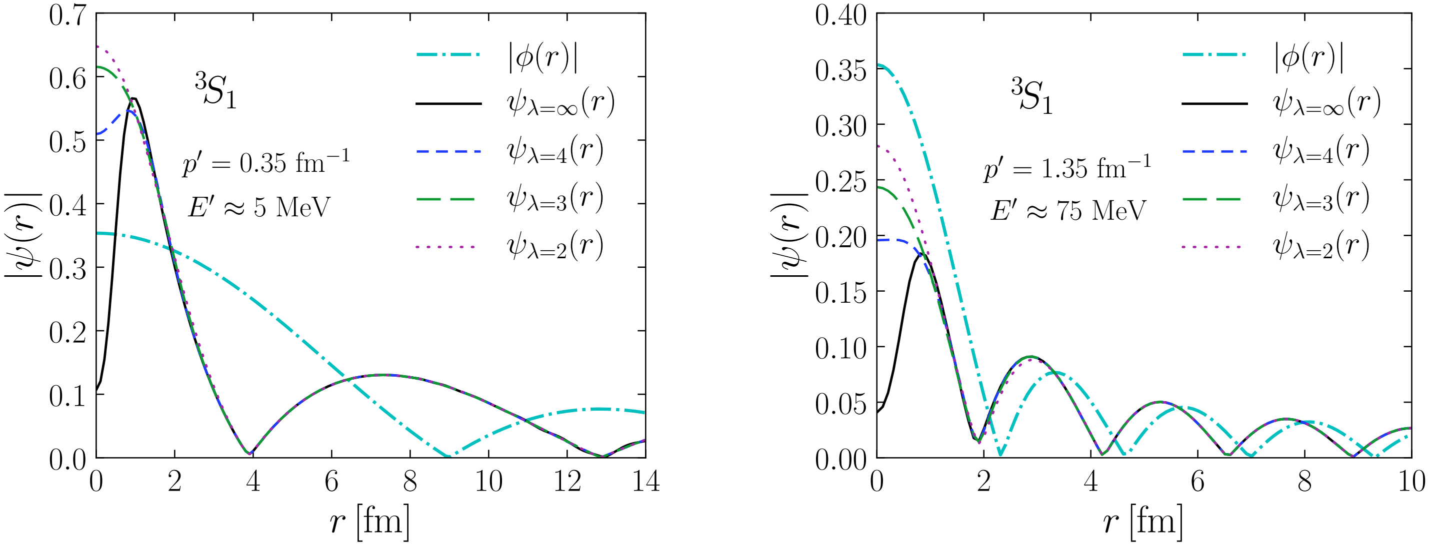


$$\psi_f^{\lambda}(p';k) = \underbrace{\phi_{p'}}_{\text{IA}} + \underbrace{\Delta\psi_{\lambda}(p';k)}_{\text{FSI}}$$

- High-k tails suppressed with evolution
- For $p' \gtrsim \lambda$, $\Delta\psi_f^{\lambda}(p';k)$ localized around outgoing p′

"local decoupling" Dainton et al. PRC 89 (2014)

Final-state wave function evolution

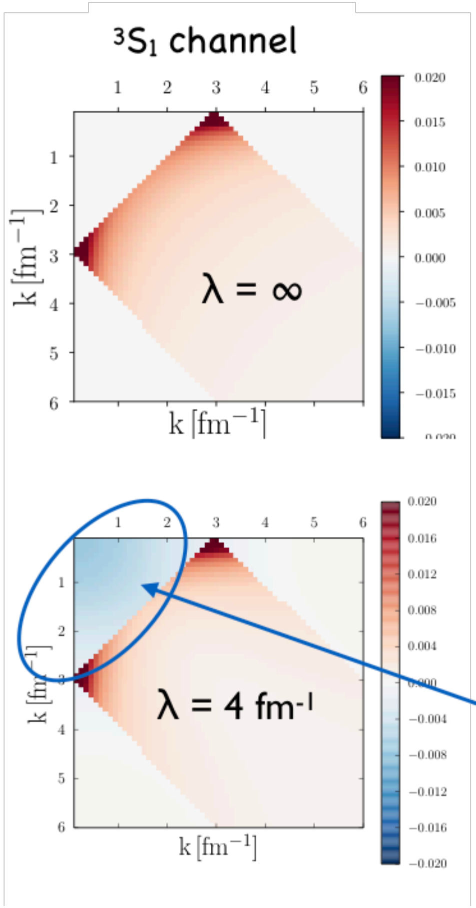


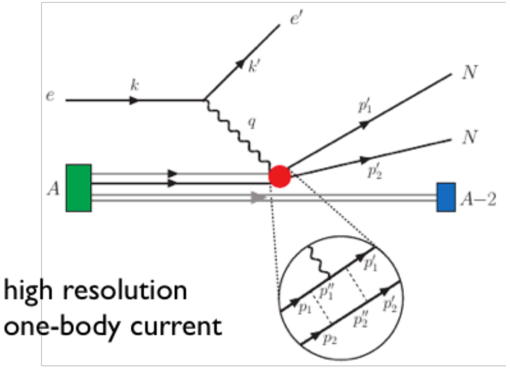
$$\psi_f^\lambda(p';k) = \underbrace{\phi_{p'}}_{\text{IA}} + \underbrace{\Delta\psi_\lambda(p';k)}_{\text{FSI}}$$

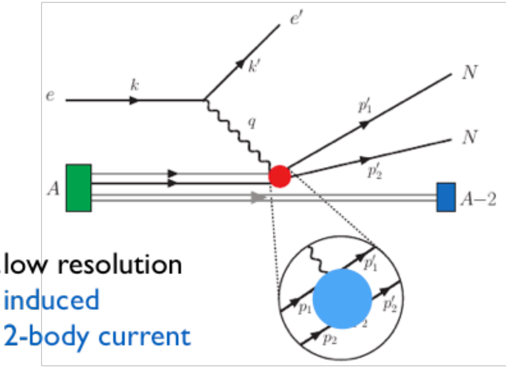
- Correlation “wound” at small r smoothed out under evolution
- Long-distance tail invariant (phase shifts preserved)

Current operator evolution

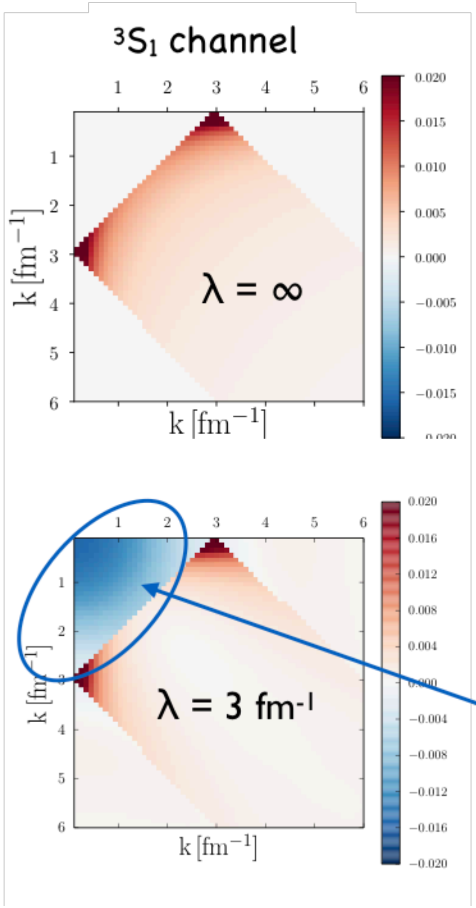
$q^2 = 36\ \mathrm{fm}^{-2}$



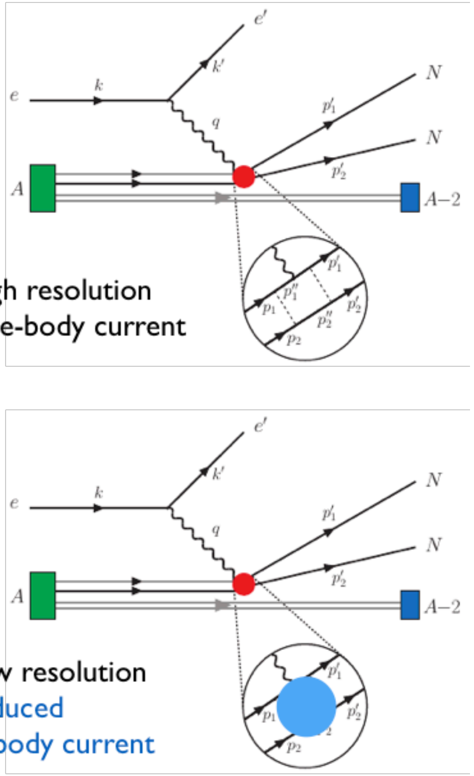




Current operator evolution



$q^2 = 36\ fm^{-2}$

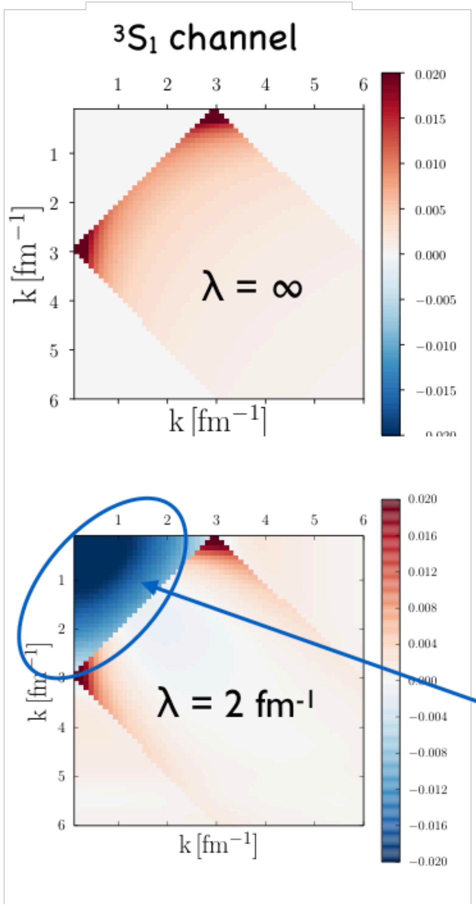


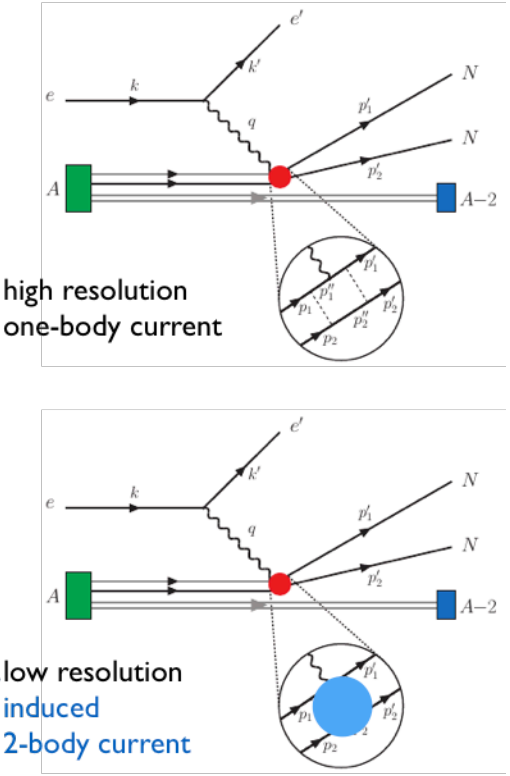
high resolution
one-body current

low resolution
induced
2-body current

Current operator evolution

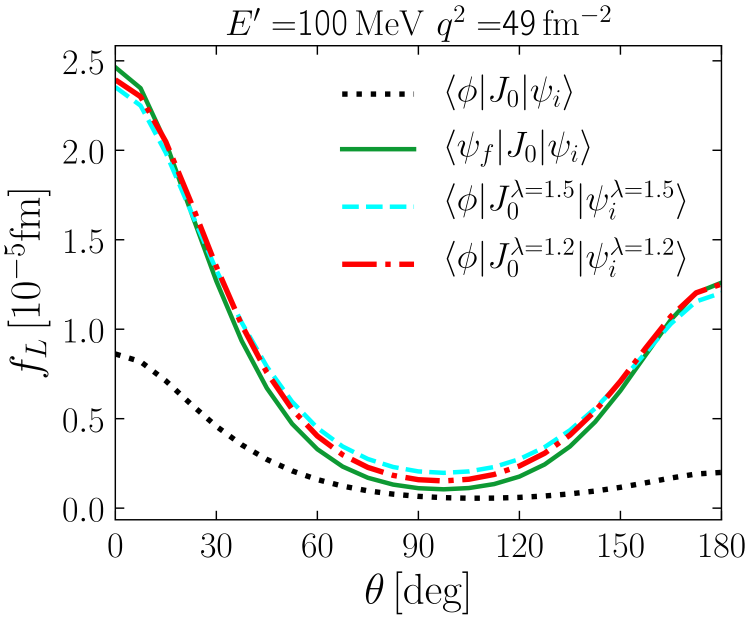
$q^2 = 36\ \mathrm{fm}^{-2}$





λ dependence of Final State Interactions

Look at kinematics relevant to SRC studies



x_B=1.64, Q^2= 1.78 GeV^2

FSI sizable at large λ
but negligible at low-resolution!

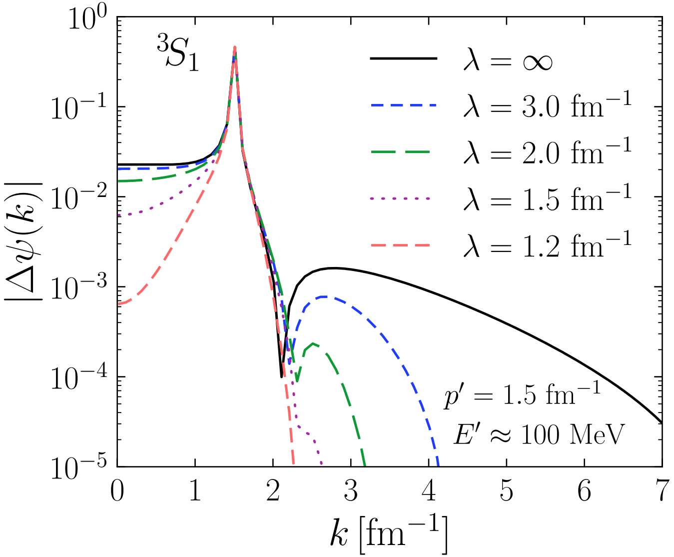
Folklore:

shouldn't hard processes be complicated in low resolution (λ << q) pictures?

Why are FSI so small at low λ ?

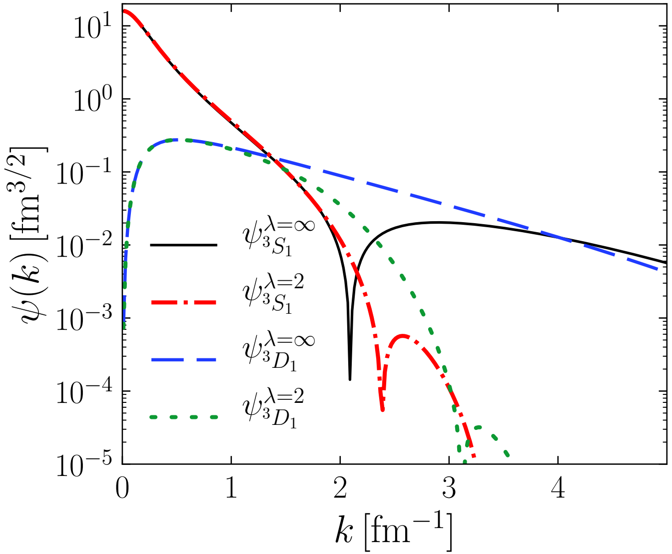
λ dependence of Final State Interactions

final state wf (interacting piece)



For p′ ≳ λ, interacting part of final state wf localized at k ≈ p′

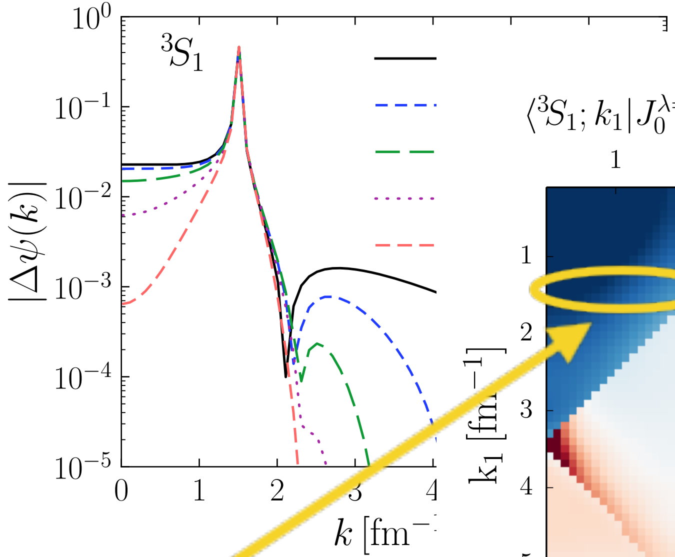
initial state (deuteron) wf



Dominant support of deuteron wf at k ≲ λ

λ dependence of Final State Interactions

final state wf (interacting piece)



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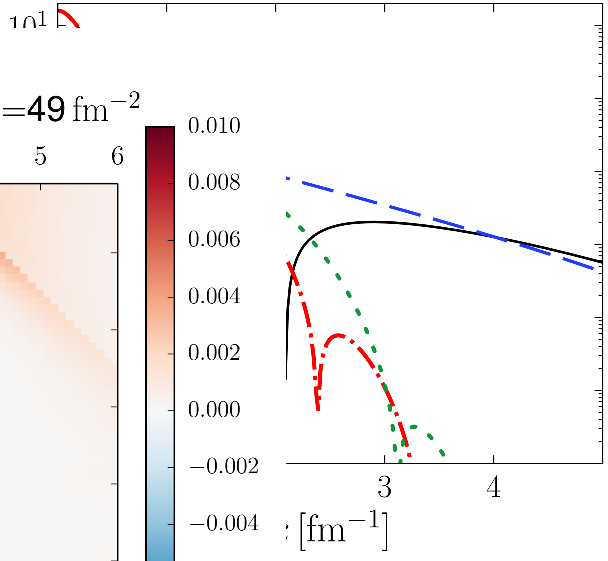
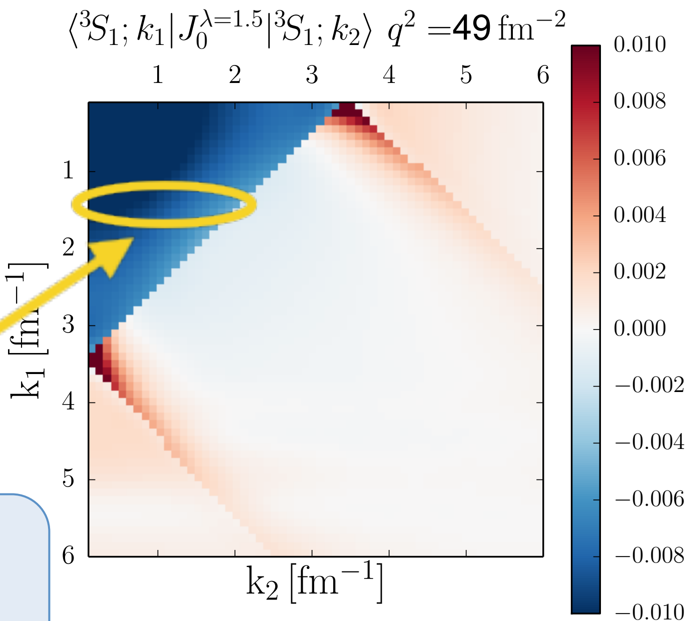




t of deuteron wf at k ≲ λ

$J_{\mathbf{q}}^{\lambda}(k', k)$

probed by transition

(smooth and non-singular)

∴ FSI ~ T(p’,p’)

(small!)

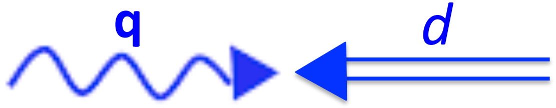
Simple pictures at high and low resolution

Can we account for the cross section at *both* high and low resolution with simple pictures?

Work in final neutron-proton rest frame at $\theta = 0^\circ$

Assume photon momentum absorbed entirely by proton

Scattering on the quasi-free ridge:



Before

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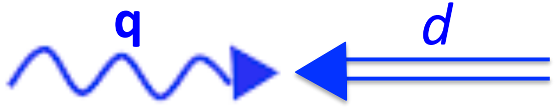

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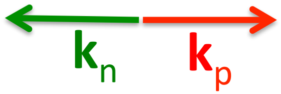

After $p'_f \approx q/2$

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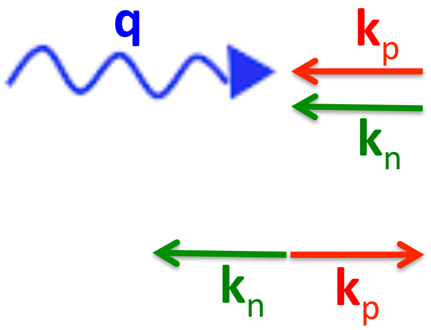

Before $p'_i \approx 0$

After $p'_f \approx q/2$

Deuteron wave function probed at low momentum

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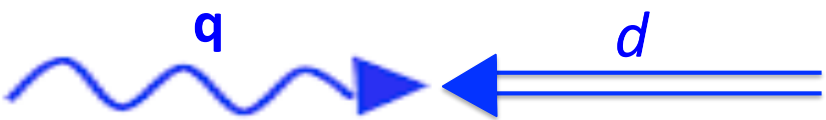
Scattering near threshold with SRC kinematics:



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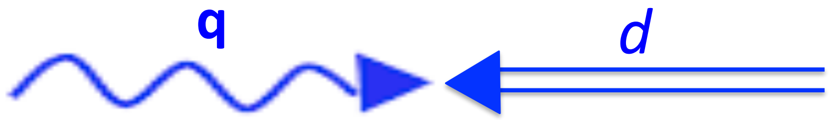
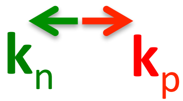


Before



After $p_f' \approx$ small

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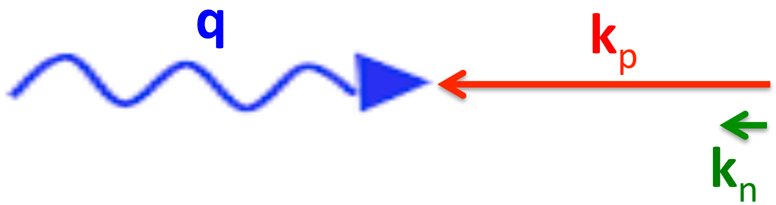
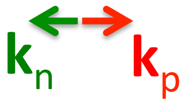


Before $p_i' \approx$ large



After $p_f' \approx$ small

Cross section from short-range correlation

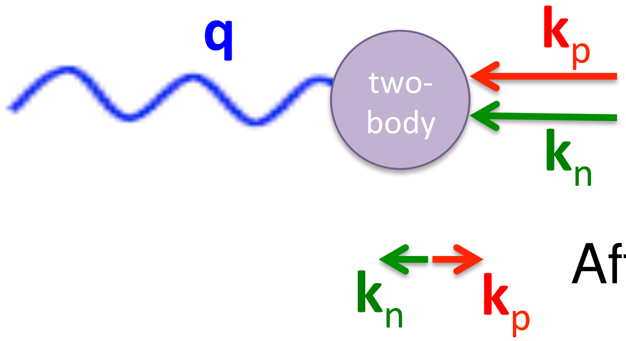
Simple pictures at high and low resolution

Can we account for the cross section at *both* high and low resolution with simple pictures?

Work in final neutron-proton rest frame at $\theta = 0^\circ$

Assume photon momentum absorbed entirely by proton

Scattering near threshold with SRC kinematics:



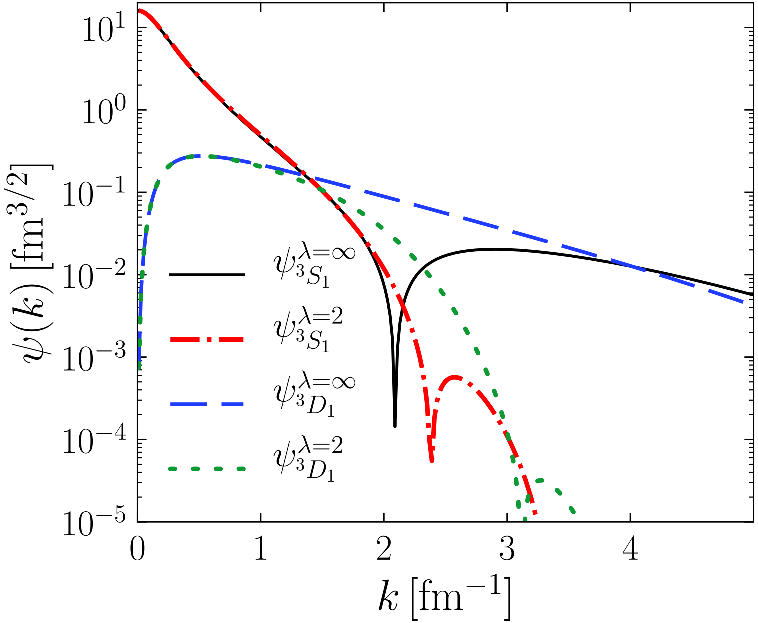
Before $p_i' \approx$ low

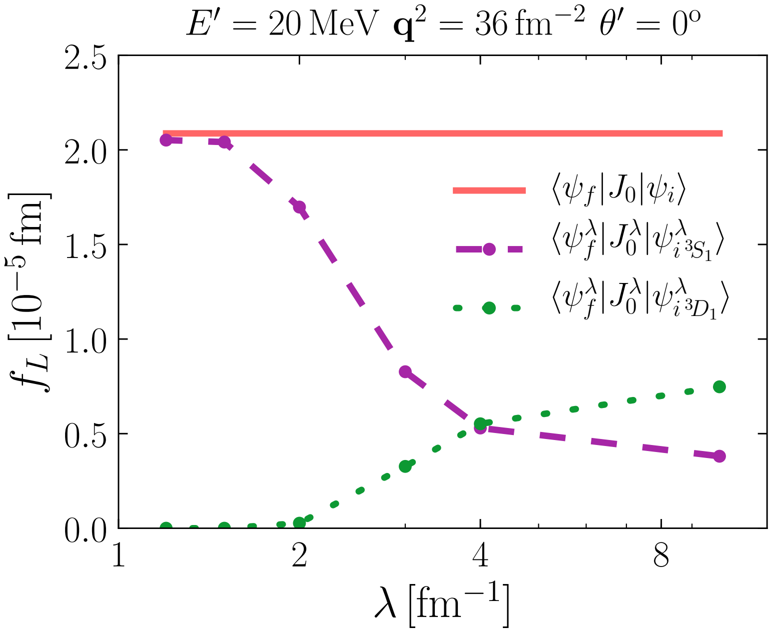
After $p_f' \approx$ small

Cross section from low momentum!

Scale (λ) dependence of interpretations

- Analysis/interpretation of a reaction involves understanding which part(s) of the wave functions are probed (highly scale dependent!)
- E.g., sensitivity to D-state w.f. in large $\mathbf{q}^2$ processes



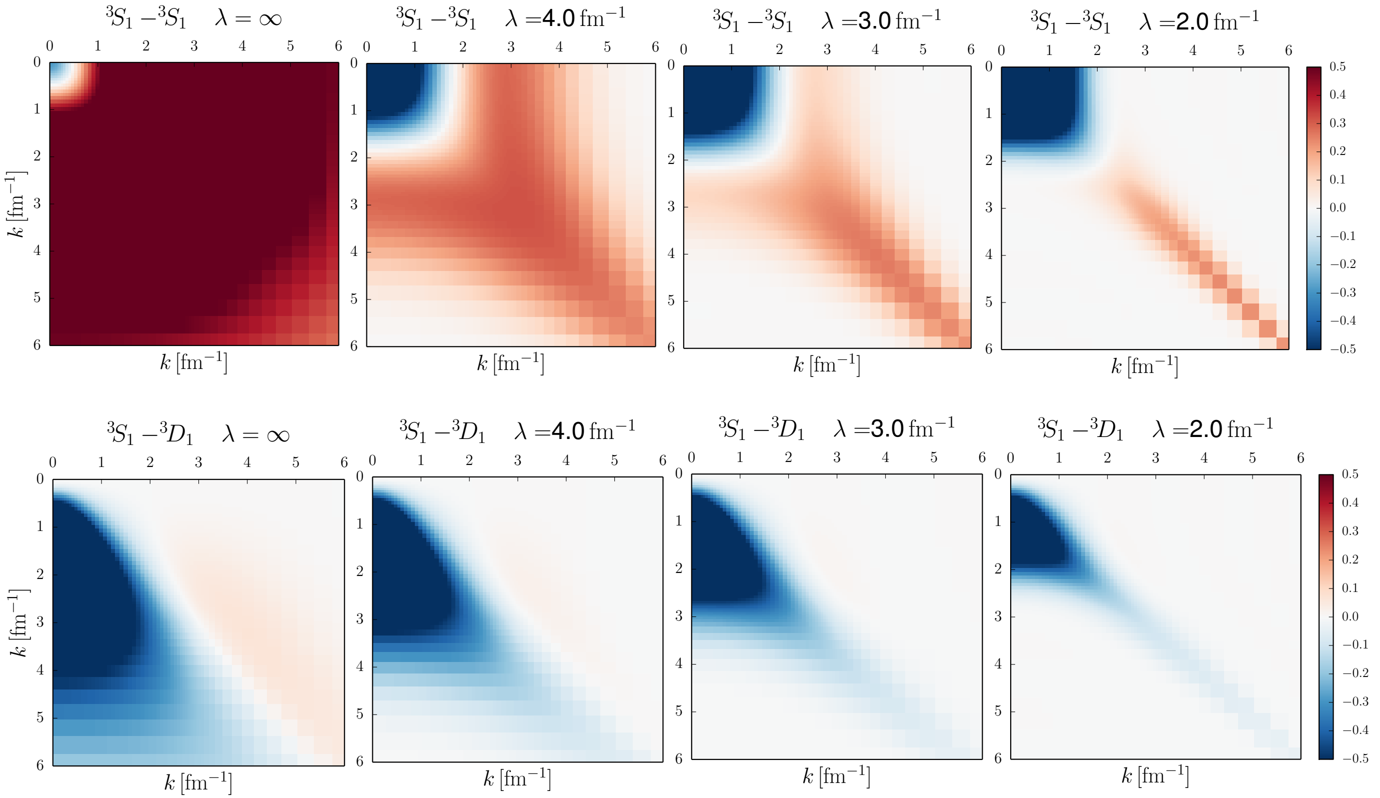


Summary: The OPE-RG-EFT perspective

- Is consistent with the full range of controlled many-body calculations
- Can connect with QCD analysis of hard processes
- Helps identify correlations (find common leading operator)
- Allows separation of A dependence and reaction dependence
- Makes it possible to estimate relative contributions of operators
- Allows for systematic corrections and uncertainty quantification
- Highlights scale and scheme dependence of quantities like the tail of the momentum distribution and of physics *interpretations*

Back-up Slides

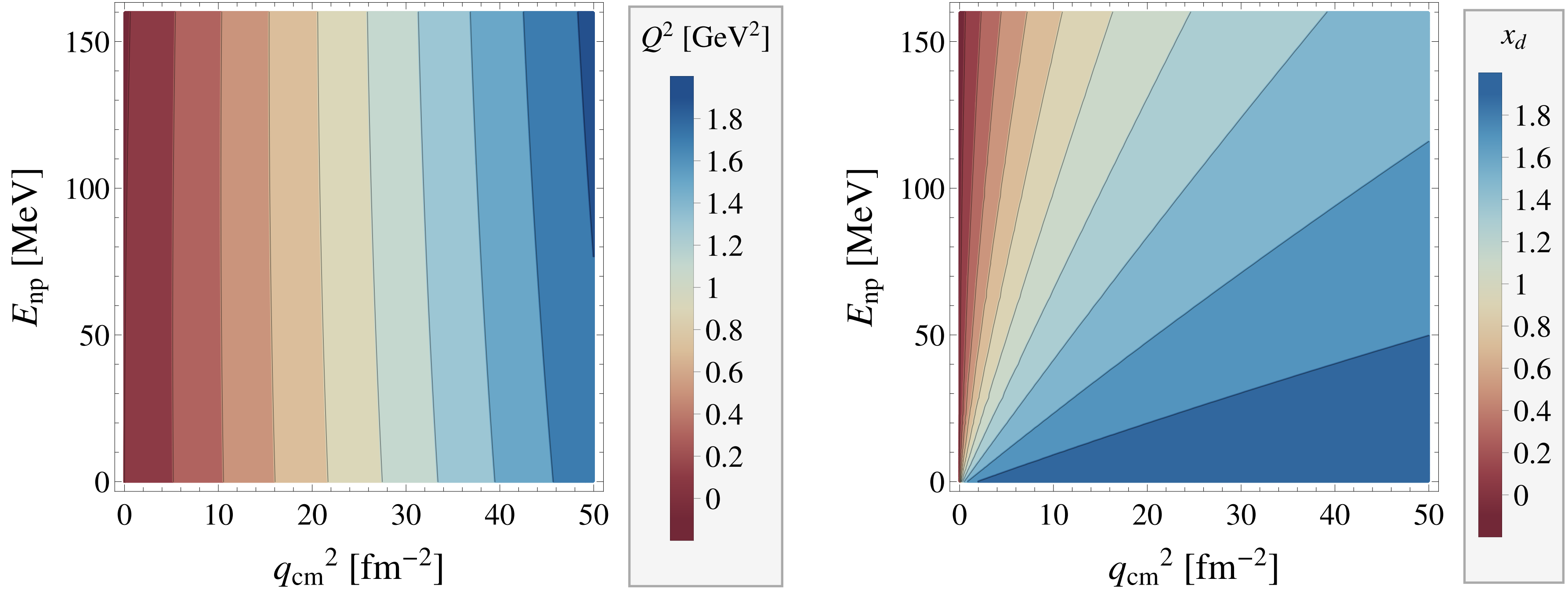
SRG evolution of AV18 potential $dH_s/ds = [[G_s, H_s], H_s]$, $G_s = T$



Notes: unitary transformation $\widehat{O}_\lambda = \widehat{U}_\lambda \widehat{O}_{\lambda=\infty} \widehat{U}_\lambda^\dagger$; λ sets decoupling scale:

$V_\lambda(k,k') \approx V_{\lambda=\infty}(k,k') e^{-\left(\frac{k^2-k'^2}{\lambda^2}\right)^2}$ (nonlocality!); scheme dependence from G_s

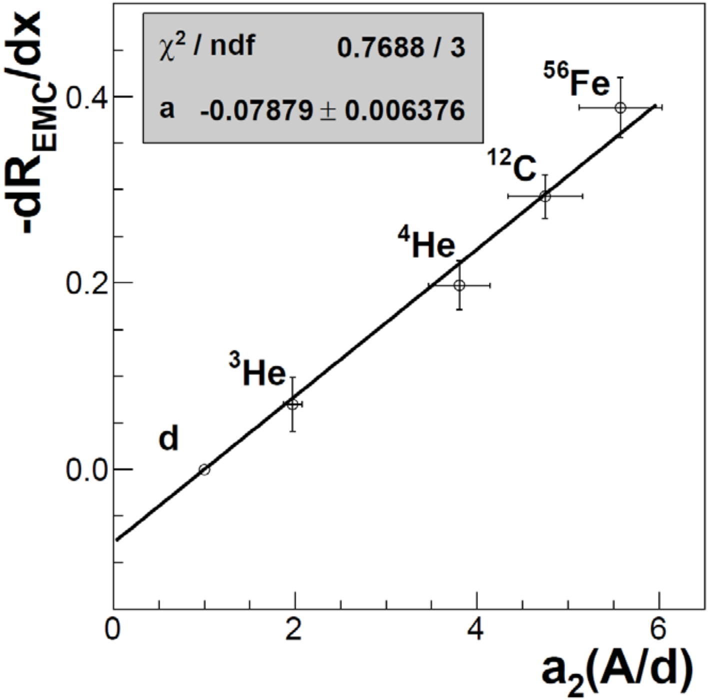
Kinematic variables transformation



In the rest frame of outgoing nucleons, E' is their energy
and $\boldsymbol{q}_{\rm c.m.}$ is the three-momentum transfer by the virtual photon.

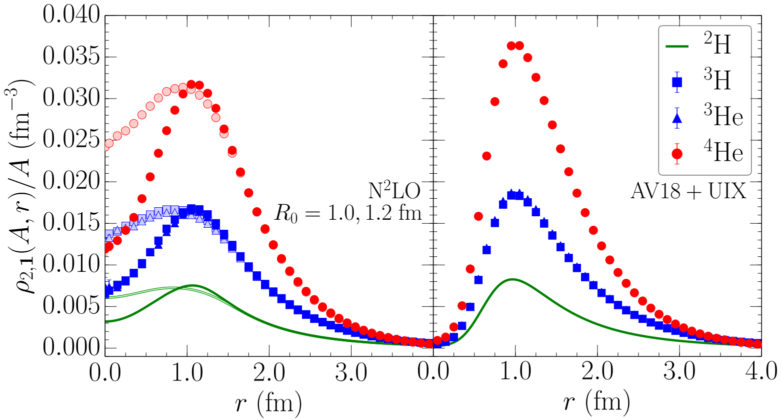
Preview: SRCs and the EMC effect in EFT

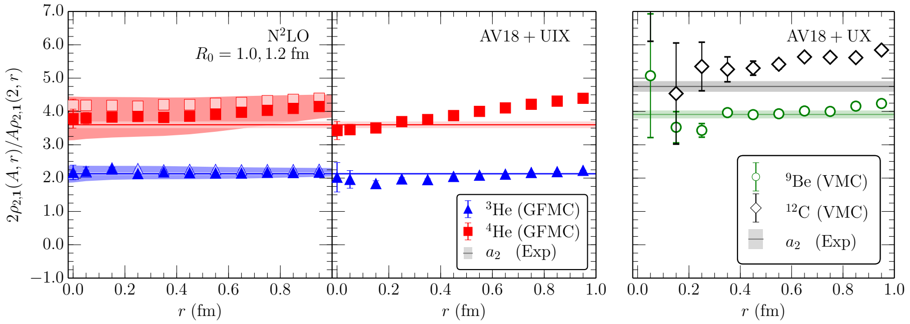
Chen et al., Phys. Rev. Lett. 119 (2017)



L.B. Weinstein, et al., Phys. Rev. Lett. 106, 052301 (2011)

$$a_2(A) = \frac{2}{A}\frac{\rho_{2,1}(A,0)}{\rho_{2,1}(2,0)}$$





Recent explosion of chiral EFT interactions

Interactions from 2003-4: EM(500, 600 MeV) or family of EGM potentials; used similar non-local regulators and similar fits to NN, 3N

New generation NN+3N interactions [references at end]

- **Non-local:** updated EMN and new soft; Ekstrom et al. sim, sat, and with Δs
- **Local** (for QMC): Gezerlis et al. nucleons only; Piarulli et al. with Δs
- **Semi-local:** Bochum-Julich group, SCS (x-space) and SMS (p-space)

Issues: power counting, regulator artifacts, EFT convergence, fitting protocols, fine-tuning, over/under-fitting, parameter redundancies, how to do UQ?

Parameter estimation issues repeat with LECs for currents and for other EFTs