Deuteron electrodisintegration with low-resolution potentials

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TRIUMF ab initio workshop 2017

NSCL

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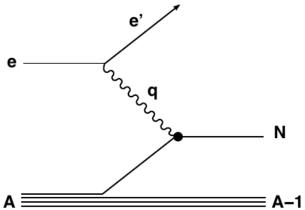
Basic Problem

- Goal: Extract nuclear properties from experiments and predict them with theory
- $$\frac{d\sigma}{d\Omega} \propto \left| \langle \psi_{\text{final}} \,|\, \hat{O}(q) \,|\, \psi_{\text{initial}} \rangle \right|^2$$
- $$\langle \underbrace{\psi_{\text{final}}}_{\text{structure}} \,|\, \overbrace{\hat{O}(q)}^{\text{reaction}} \,|\, \underbrace{\psi_{\text{initial}}}_{\text{structure}} \rangle$$

Nucleon knockout reaction



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- $\langle \underbrace{\psi_{\text{final}}}_{\text{structure}} \,|\, \overbrace{\hat{O}(q)}^{\text{reaction}} \,|\, \underbrace{\psi_{\text{initial}}}_{\text{structure}} \rangle$
- Use factorization to isolate individual components and extract process-independent nuclear properties

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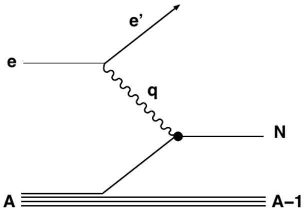
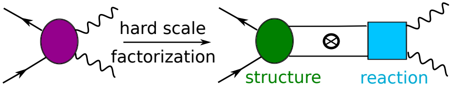
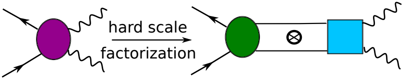


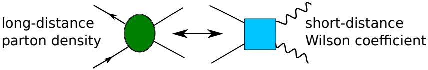


Factorization: Examples

High-E QCD



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



- Separation between long- and short-distance physics is not unique, but defined by the scale μ_f
- Form factor F_2 is independent of μ_f, but pieces are not
- $f_a(x,\mu_f^2 = Q^2)$ runs with Q^2 but is process independent

Low-E Nuclear

Observable: cross section

Structure model: spectroscopic factor

Reaction model: single-particle cross section

$$\sigma^{if} = \sum_{|J_i - J_f| \leq j \leq J_i + J_f} S_j^{if} \sigma_{sp}$$

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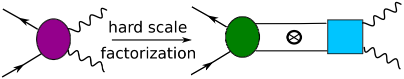

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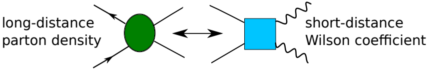

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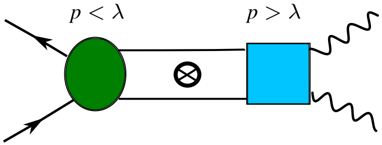
Open questions

- When does factorization hold?
- Which process-independent nuclear properties can we extract?
- What is the scale/scheme dependence of the extracted properties?

SRG makes scale dependence obvious

- Unitary transformations widely used to soften nuclear Hamiltonians leading to accelerated convergence
- SRG scale λ sets the scale for decoupling high- and low-momentum *and* separating structure and reaction



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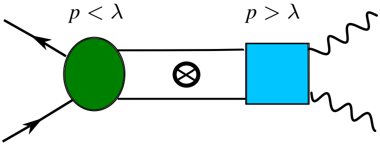

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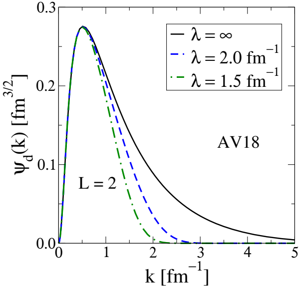
- Transformed wave function $\rightarrow$ no high momentum components
- $\sigma \sim \left|\langle\psi_f|\hat{O}|\psi_i\rangle\right|^2 \Rightarrow \hat{O}$ must change to keep observables invariant
- UV physics absorbed in operator (cf. Chiral EFTs)



Test ground: $^2\mathrm{H}\,(e, e'\,\mathrm{p})\,\mathrm{n}$

- Use deuteron electrodisintegration to investigate scale/scheme dependence of factorization between nuclear structure and nuclear reaction
- $\dfrac{d\sigma}{d\Omega} \propto (v_L f_L + v_T f_T + v_{TT} f_{TT} \cos 2\phi_p + v_{LT} f_{LT} \cos \phi_p)$
- $v_L,\ v_T, \ldots$- electron kinematic factors. $f_L,\ f_T, \ldots$- deuteron structure functions

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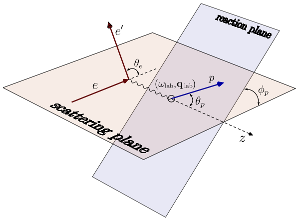
- $v_L,\ v_T, \ldots$- electron kinematic factors. $f_L,\ f_T, \ldots$- deuteron structure functions
- $f_L \sim \sum_{m_s, m_J} \left| \langle \psi_f | J_0 | \psi_i \rangle \right|^2$
- $f_L^\lambda \sim \left| \underbrace{\langle \psi_f | U_\lambda^\dagger}_{\psi_f^\lambda} \underbrace{U_\lambda\, J_0\, U_\lambda^\dagger}_{J_0^\lambda} \underbrace{U_\lambda\, | \psi_i \rangle}_{\psi_i^\lambda} \right|^2; \quad U_\lambda^\dagger U_\lambda = I; \quad f_L^\lambda = f_L$

  Components depend on the scale λ. Cross section does not!

Evolutionary effects



- ^{2}H $(e, e'$ p$)$ n calculations done using AV18 potential with $\lambda = \infty$ and $\lambda = 1.5$ fm^{-1}
- $f_L \sim \sum_{m_s, m_J} \left| \langle \psi_f | J_0 | \psi_i \rangle \right|^2$
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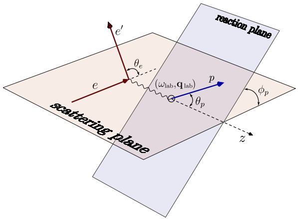

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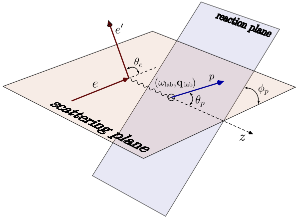
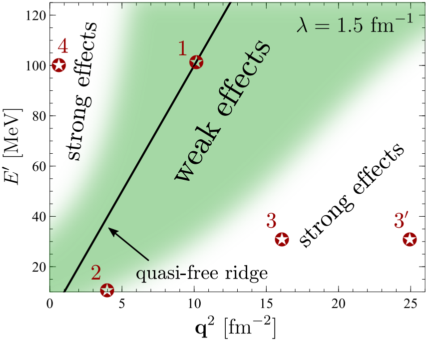
- Weak scale dependence at QFR which gets progressively stronger away from it

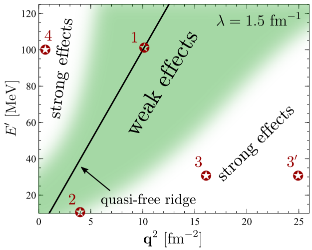


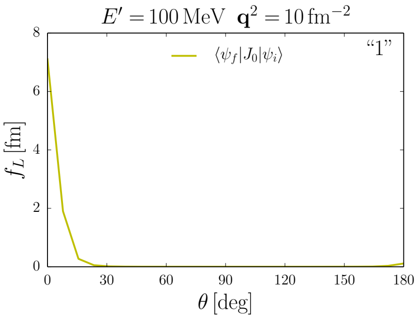


SNM et al., PRC **92**, 064002 (2015)

Results at QFR

- At the quasi-free ridge
  E' (in MeV) $\approx 10\,\mathbf{q}^2$ (in fm^{-2})
- $f_L \sim \sum_{m_s, m_J} \left| \langle \psi_f | J_0 | \psi_i \rangle \right|^2$
- Long-range part of the wave function probed at QFR $\rightarrow$ invariant under SRG evolution





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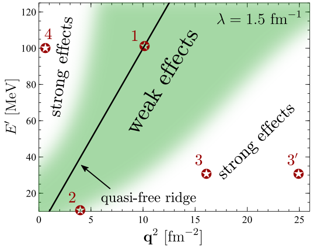

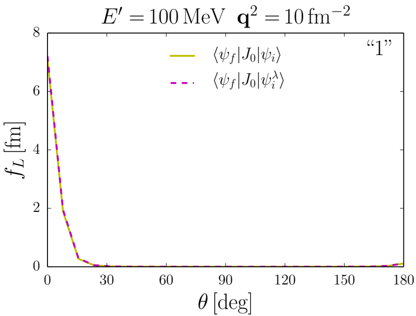

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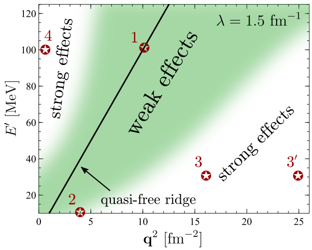

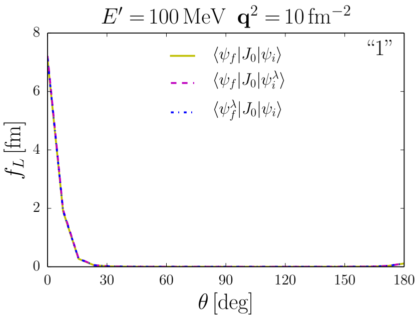

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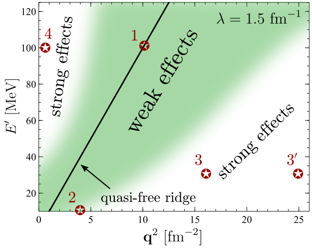

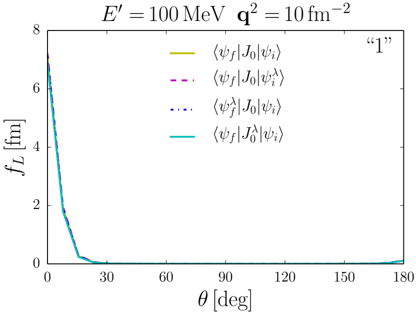

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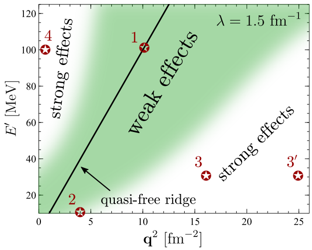

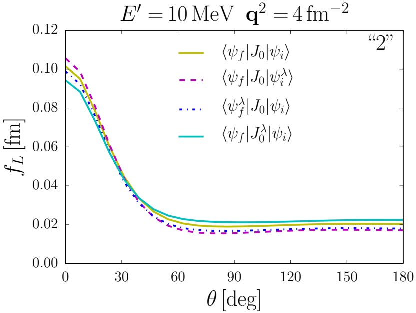

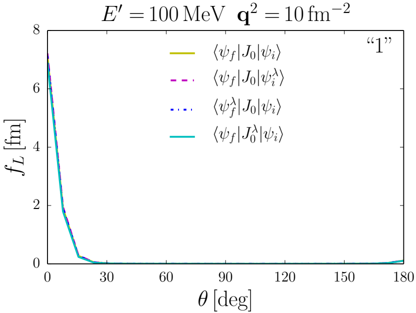

Results below QFR

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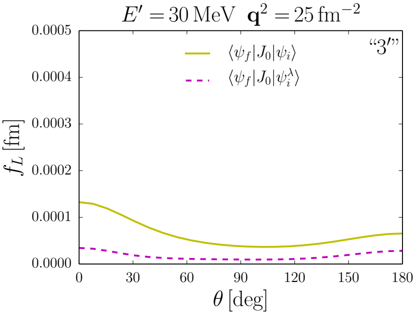
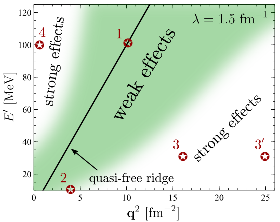
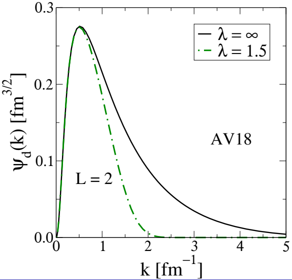
- Below QFR two terms add constructively
- Wave function in IA probed between 1.7 and 3.4 fm^{-1} $\Rightarrow |\langle\psi_f|J_0|\psi_i^\lambda\rangle| < |\langle\psi_f|J_0|\psi_i\rangle|$







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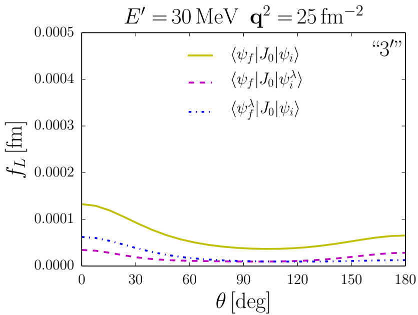

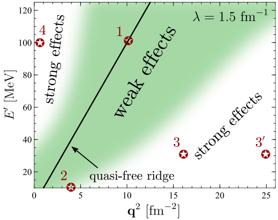

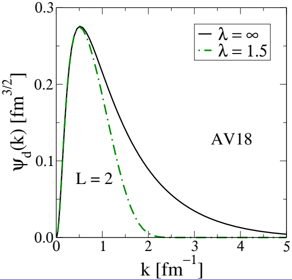

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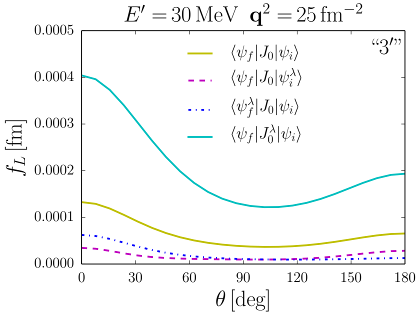

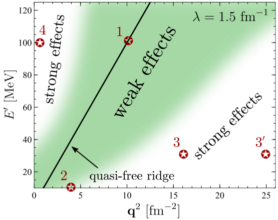

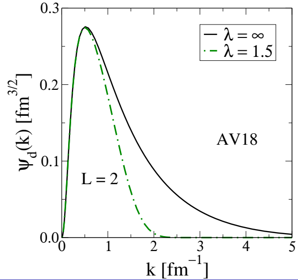

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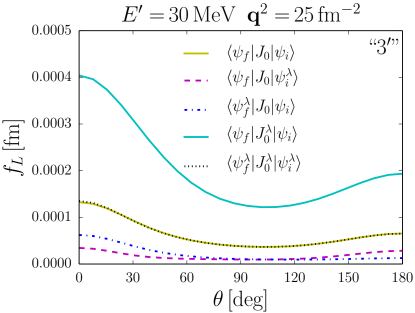

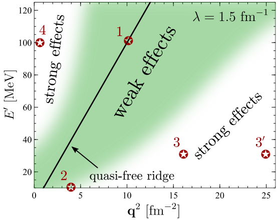

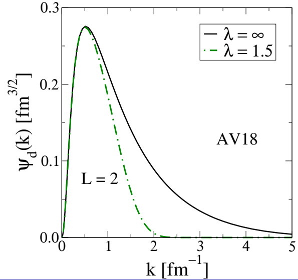

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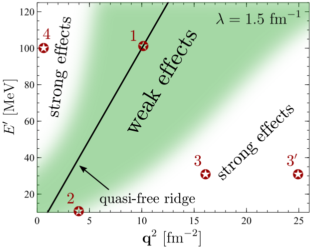

- Scale dependence qualitatively different above the quasi-free ridge
- $\langle \psi_f | J_0 | \psi_i \rangle = \underbrace{\langle \phi | J_0 | \psi_i \rangle}_{\text{IA}} + \underbrace{\langle \phi | t^\dagger G_0^\dagger J_0 | \psi_i \rangle}_{\text{FSI}}$
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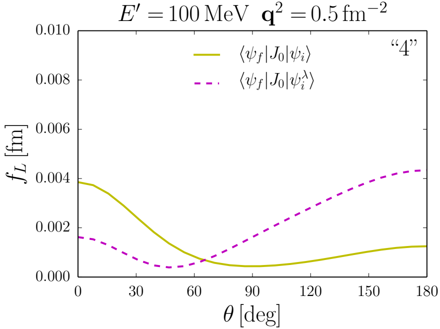

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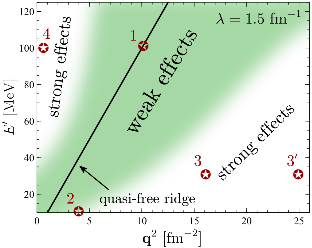

- Scale dependence qualitatively different above the quasi-free ridge
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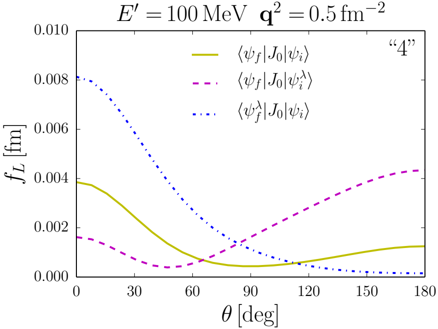
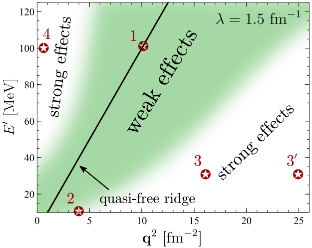
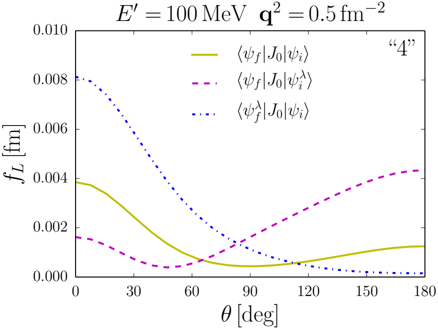
- Above QFR two terms add destructively
- Can be explained by looking at the effect of evolution on the overlap matrix elements [SNM et al., PRC **92**, 064002 (2015)]



Results above QFR



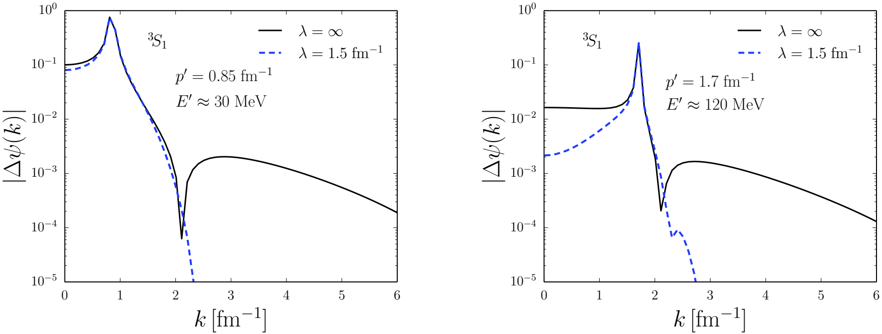
- Scale dependence qualitatively different above the quasi-free ridge
- $\langle \psi_f | J_0 | \psi_i \rangle = \underbrace{\langle \phi | J_0 | \psi_i \rangle}_{\text{IA}} + \underbrace{\langle \phi | t^\dagger G_0^\dagger J_0 | \psi_i \rangle}_{\text{FSI}}$
- Above QFR two terms add destructively
- Can be explained by looking at the effect of evolution on the overlap matrix elements [SNM et al., PRC **92**, 064002 (2015)]
- Scale dependence depends on the kinematics, but in a *systematic* way



Evolution effects on individual components

- $f_L \propto \sum_{m_s, m_J} \langle \psi_f | J_0 | \psi_i \rangle = \sum_{m_s, m_J} \langle \psi_f^\lambda | J_0^\lambda | \psi_i^\lambda \rangle$
- Looked at effects of evolution on the observable f_L
- Look at changes due to evolution for individual components and their implications
- Evolution of ψ_{deut}: suppression of high-momentum components $\rightarrow$ accelerated convergence of nuclear structure calculations

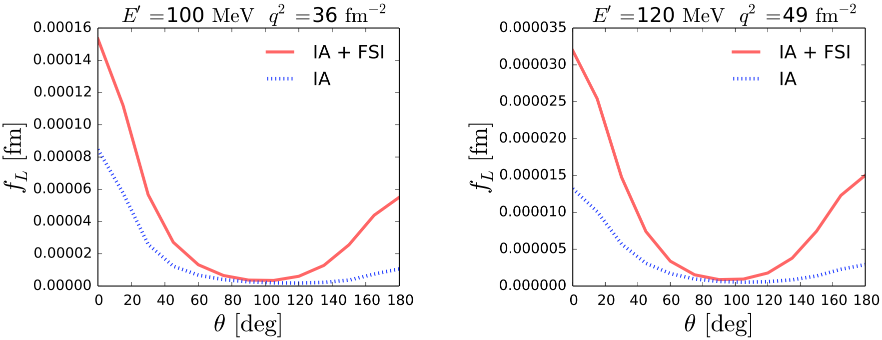
Evolving the final state



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

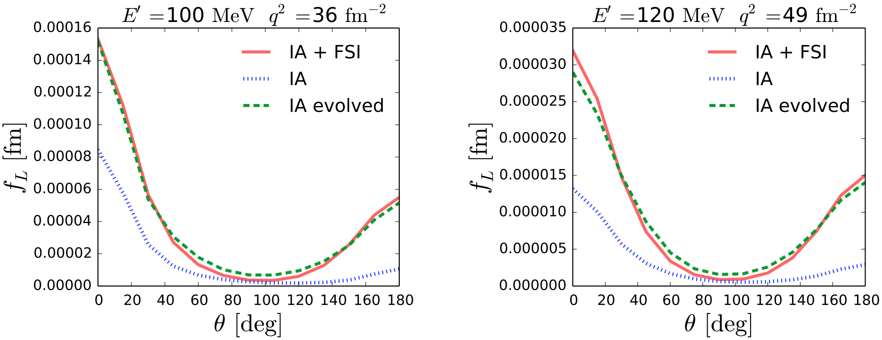
- For $p' \gtrsim \lambda$, $\psi_f^\lambda(p';k)$ localized around the outgoing momentum p'

Evolution minimizes FSI contribution



- Local decoupling $\Rightarrow$ increased validity of IA

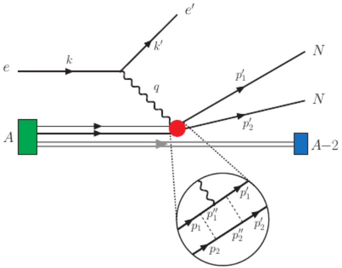
Evolution minimizes FSI contribution



- Local decoupling ⇒ increased validity of IA
- $f_L(\langle\psi_f|J_0|\psi_i\rangle) \approx f_L(\langle\phi|J_0^\lambda|\psi_i^\lambda\rangle)$

Current evolution story

- Varying λ shuffles the physics between short- and long-distance parts
- λ decreases $\rightarrow$ blob size increases. One-body current operator develops two and higher body components

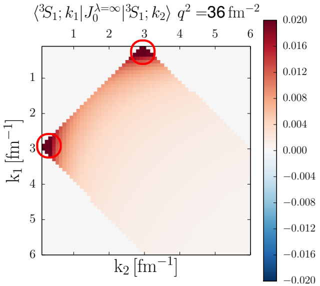


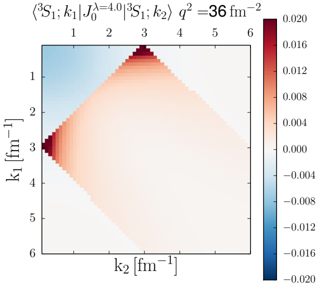
at high resolution

- $\langle \mathbf{k}_1 T_1 | J_0(\mathbf{q}) | \mathbf{k}_2 T = 0 \rangle =$
$$\frac{1}{2}\left(G_E^p + (-1)_1^T G_E^n\right) \delta(\mathbf{k}_1 - \mathbf{k}_2 - \mathbf{q}/2) + \frac{1}{2}\left((-1)_1^T G_E^p + G_E^n\right) \delta(\mathbf{k}_1 - \mathbf{k}_2 + \mathbf{q}/2)$$
- Naive expectation: RG changes to $J_0(q)$ complicates reaction calculations

EFT for the current

- $\langle \psi_f | J_0(q) | \psi_i \rangle = \langle \psi_f^\lambda | J_0^\lambda(q) | \psi_i^\lambda \rangle$
- Low-momentum component of $J_0^\lambda(q)$ most relevant





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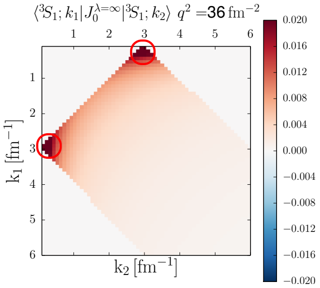

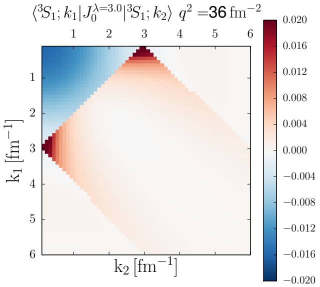

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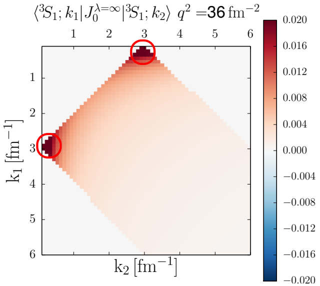

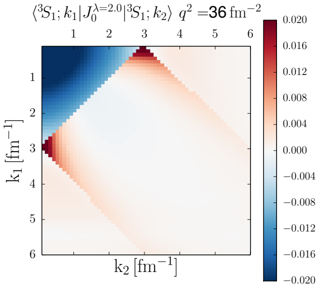

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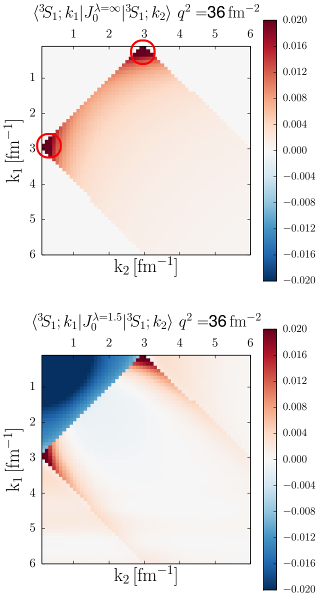

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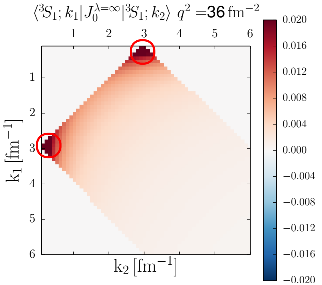
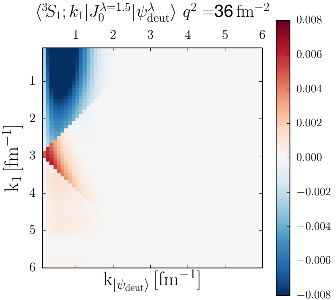
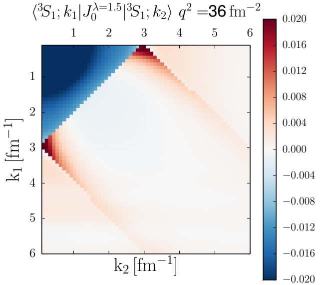
- Low-momentum component of $J_0^\lambda(q)$ most relevant
- $\langle {}^3S_1; k_1 | J_0^\lambda(q) | {}^3S_1; k_2 \rangle$
$= g_0^q + g_2^q (k_1^2 + k_2^2) + \cdots$

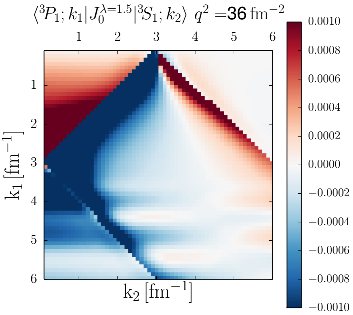






EFT for the current

- $\langle {}^3P_1; k_1 | J_0^\lambda(q) | {}^3S_1; k_2 \rangle = g_1^q\, k_1 + \cdots$
- $\langle {}^3D_2; k_1 | J_0^\lambda(q) | {}^3S_1; k_2 \rangle = g_{2,\,D}^q\, k_1^2 + \cdots$
- $\langle \psi_f^\lambda | J_0^\lambda(q) | \psi_i^\lambda \rangle \approx \langle \psi_f^\lambda | J_0^\lambda(q) | \psi^\lambda_{i\ {}^3S_1} \rangle$

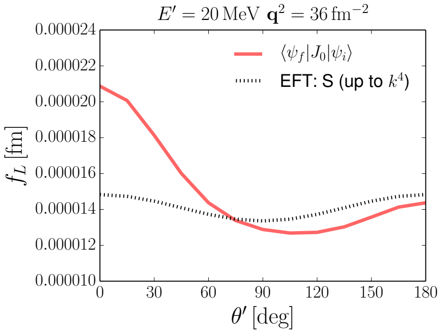


- $\langle \psi_f^\lambda | J_0^\lambda | \psi^\lambda_{i\ {}^3S_1} \rangle =$

$$\langle \psi_f^\lambda | {}^3S_1 \rangle \underbrace{\langle {}^3S_1 | J_0^\lambda | {}^3S_1 \rangle}_{\text{use EFT exp.}} \langle {}^3S_1 | \psi^\lambda_{i\ {}^3S_1} \rangle + \langle \psi_f^\lambda | {}^3P_1 \rangle \underbrace{\langle {}^3P_1 | J_0^\lambda | {}^3S_1 \rangle}_{\text{use EFT exp.}} \langle {}^3S_1 | \psi^\lambda_{i\ {}^3S_1} \rangle + \cdots$$

Results from low-momentum potential

- $\langle \psi_f^\lambda | J_0^\lambda(q) | \psi_{\text{deut}}^\lambda \rangle$
  $= g_0^q \;\; \psi_f^{\lambda *}(r)\, \psi_{\text{deut}}^\lambda(r) \Big|_{r=0} + \cdots$



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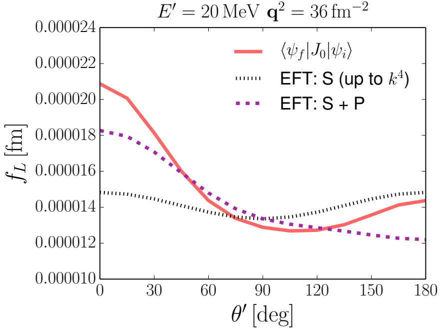

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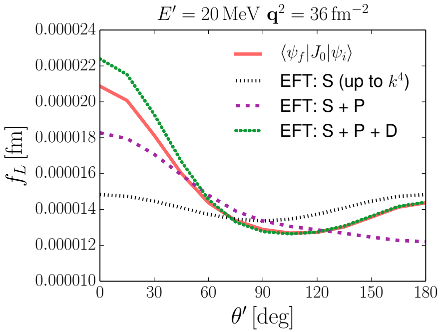
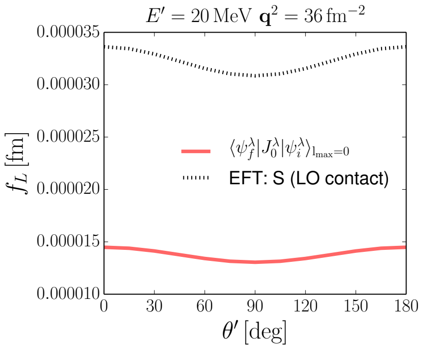
  $= g_0^q \; \psi_f^{\lambda\,*}(r)\, \psi_{\text{deut}}^\lambda(r)\Big|_{r=0} + \cdots$
- $f_L^{\text{from EFT}} \approx f_L^{\text{exact}}$
- Agreement made better by going to higher order terms in EFT expansion



Convergence in partial wave channels



- $\langle \psi_f^\lambda | J_0^\lambda | \psi_i^\lambda \rangle_{\mathrm{l_{max}=0}} \equiv \langle \psi_f^\lambda; {}^3S_1 | J_0^\lambda{}_{\mathrm{exact}} | \psi_i^\lambda; {}^3S_1 \rangle$

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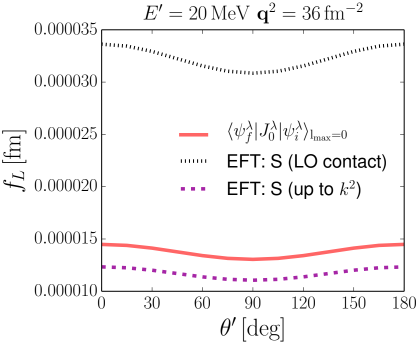

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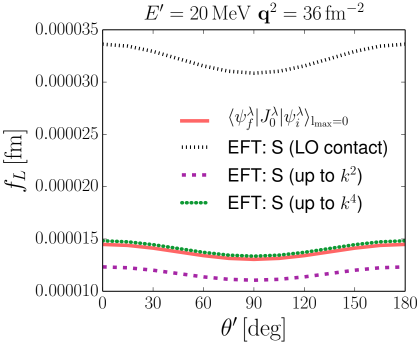

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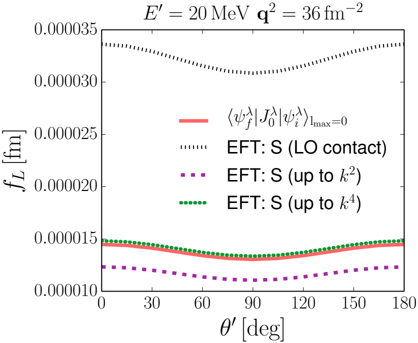
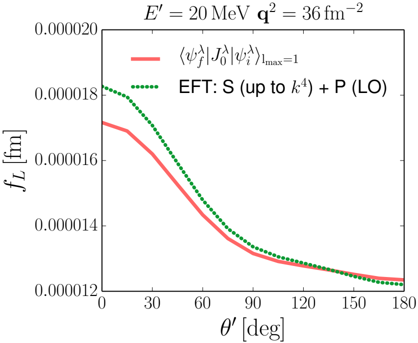
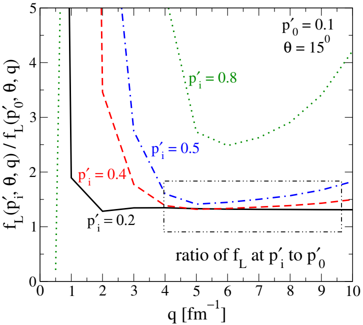


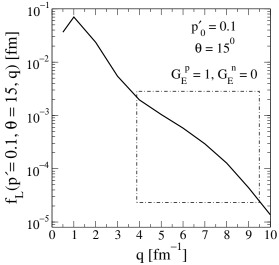


- $\langle\psi_f^\lambda|J_0^\lambda|\psi_i^\lambda\rangle_{l_{max}=0} \equiv \langle\psi_f^\lambda;{}^3S_1|J_0^\lambda{}_{\mathrm{exact}}|\psi_i^\lambda;{}^3S_1\rangle$
- $\langle\psi_f^\lambda|J_0^\lambda|\psi_i^\lambda\rangle_{l_{max}=1} \equiv \langle\psi_f^\lambda;{}^3S_1|J_0^\lambda{}_{\mathrm{exact}}|\psi_i^\lambda;{}^3S_1\rangle + \sum_{i=0,1,2}\langle\psi_f^\lambda;{}^3P_i|J_0^\lambda{}_{\mathrm{exact}}|\psi_i^\lambda;{}^3S_1\rangle$
- $\langle{}^3P_i;k_1|J_0^\lambda{}_{\mathrm{EFT}}|{}^3S_1;k_2\rangle_{\mathrm{LO}} \equiv g_{P_i}\,k_1$

q-factorization of f_L

- $f_L \equiv f_L(p', \theta; q)$
  p' and θ: outgoing nucleon
  q: momentum transfer
- For $p' \ll q$, f_L scales with q
  $f_L(p', \theta; q) \to g(p', \theta) B(q)$
- Note that f_L is a strong function of q





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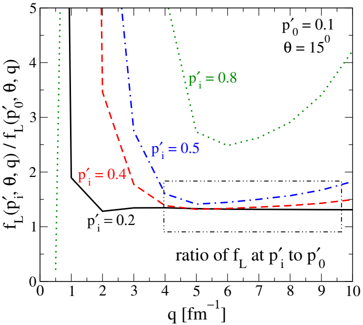
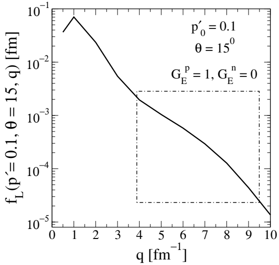
  $f_L(p', \theta; q) \to g(p', \theta) B(q)$
- Note that f_L is a strong function of q
- Follows from the LO term in EFT expansion:
  $\langle \psi_f^\lambda | J_0^\lambda(q) | \psi_{\mathrm{deut}}^\lambda \rangle \approx g_0^q \; \psi_f^{\lambda\,*}(p'; r)\, \psi_{\mathrm{deut}}^\lambda(r) \Big|_{r=0}$





Summary and Moving Forward

- Scale dependence abounds... in a systematic way which can be accounted for
- Conventional wisdom: low-resolution potentials ill-suited for (high-q) reactions calculations ✗
  $\rightarrow$ RG changes to $\widehat{O}_q$ tractable
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To do:

- Make the EFT picture more quantitative
- Extend to $A > 2$. Basis for consistent construction of operators
- Consistently extract process-independent quantities from experiments
  $\rightarrow$ What is the best scale to use?
  $\rightarrow$ What are the controlled approximations that we can make?
  $\rightarrow$ Model dependence of SRC, spectroscopic factors, . . .

Back up