Light Front (LF) Nuclear Structure
Gerald A Miller, U. of Washington

- formulate the NN interaction on the light front
- solve the Weinberg equation for the deuteron
- prescription from FS 81 review constructs LF wave function from NR wf:
- how good is this approx at recoil momenta few hundred MeV?
- can we get the LF wf from NN potentials?
- Nuclear Many Body LF wave function inc. Correlations -Miller & Machleidt PRC60, 035202

- Relevance of LF wave functions for quasi-elastic scattering

stimulated by Ellie Long Proposal on Tensor asymmetries

work with John Terry REU

J R Cooke nucl-th/0112029 , Cooke & Miller PRC66, 034002

Miller, Prog. Nuc. Part. Phys. 45, 83

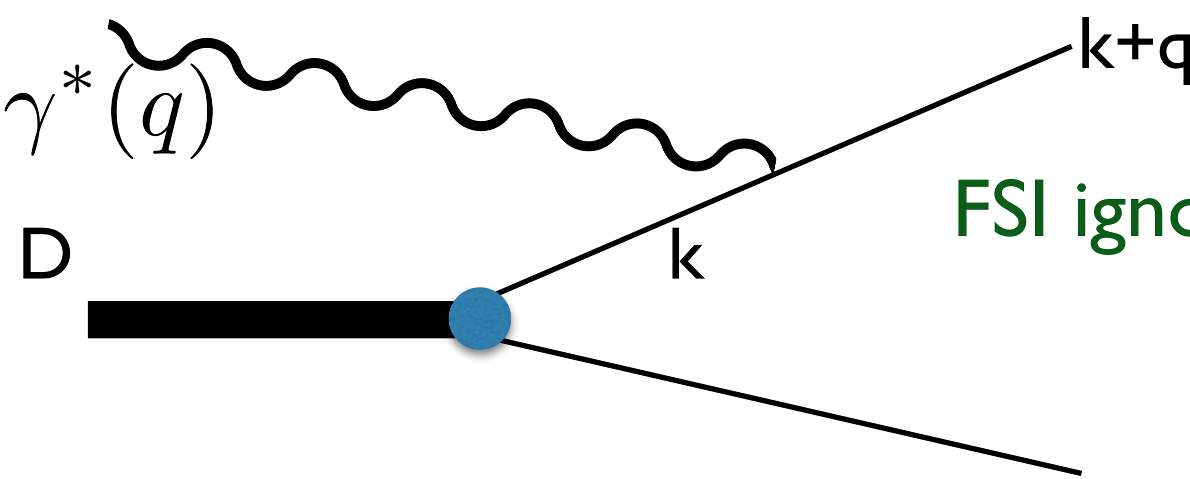
Tiburzi & Miller PRC81,035201

Light front quantization, Infinite momentum frame

$$\text{"}Time\text{"},\ x^+ = x^0 + x^3, \quad \text{"}Evolve\text{"},\ p^- = p^0 - p^3$$

$$\text{"}Space\text{"},\ x^- = x^0 - x^3, \quad \text{"}Momentum\text{"},\ p^+ \text{(Bjorken)}$$

$$Transverse\ position,\ momentum \quad \mathbf{b}, \mathbf{p} \qquad p^- = \frac{\mathbf{p}^2 + m^2}{p^+}$$



FSI ignored throughout

$\text{If Photon energy} >> \text{m and struck nucleon} \approx \text{on mass-shell}:$

$(k+q)^2 = m^2 \to k^+ q^- \approx Q^2,$ $\quad \frac{Q^2}{\nu^2} << 1$

FS '81

Integrate over k^-

$d\sigma \sim \Psi_D^2(\mathbf{k}, \frac{k^+}{P_D^+} \equiv \alpha)$

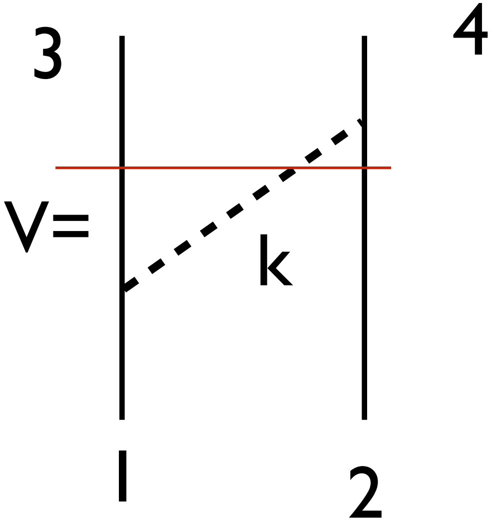
Are approximations valid at JLab 12- NO

Light front quantization, Infinite momentum frame

P^- is LF Hamiltonian, get from Lagrangian.

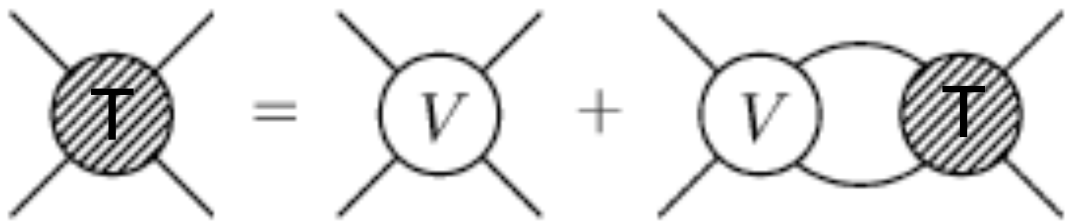
LF Schroedinger eq. $P^-|\Psi_D\rangle = M_D|\Psi_D\rangle$ Rest frame

One boson exchange



Usual Feynman diagram with recoil

Solve

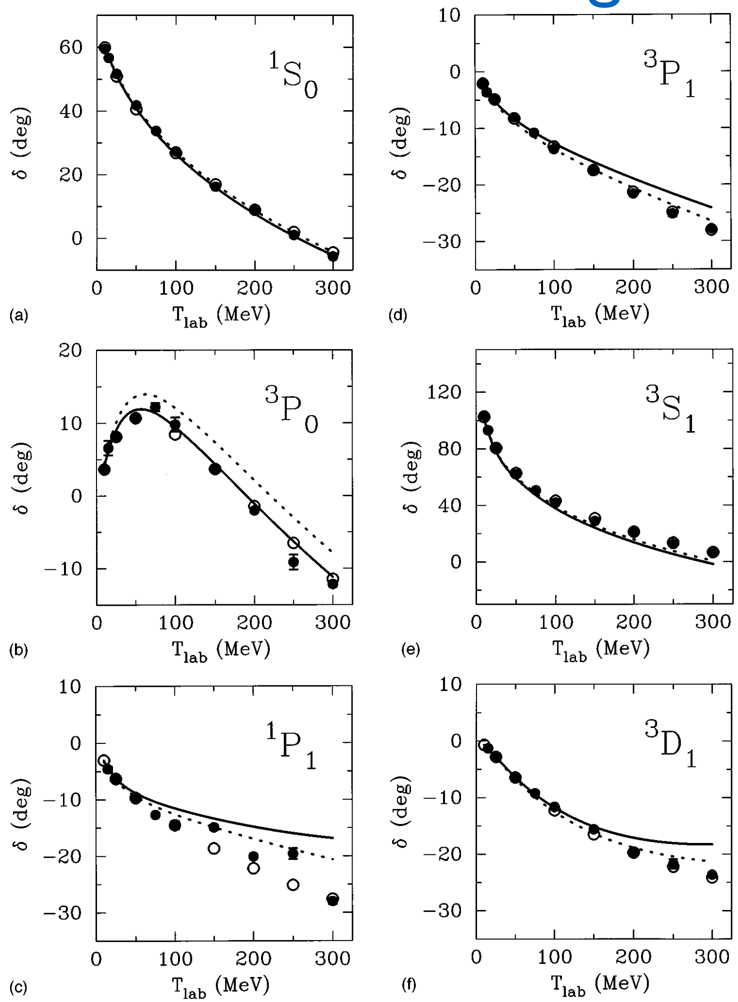


Weinberg equation= Lippmann-Schwinger eq with extra factor (~1) in Green's function

Miller & Machleidt PRC 60,035202

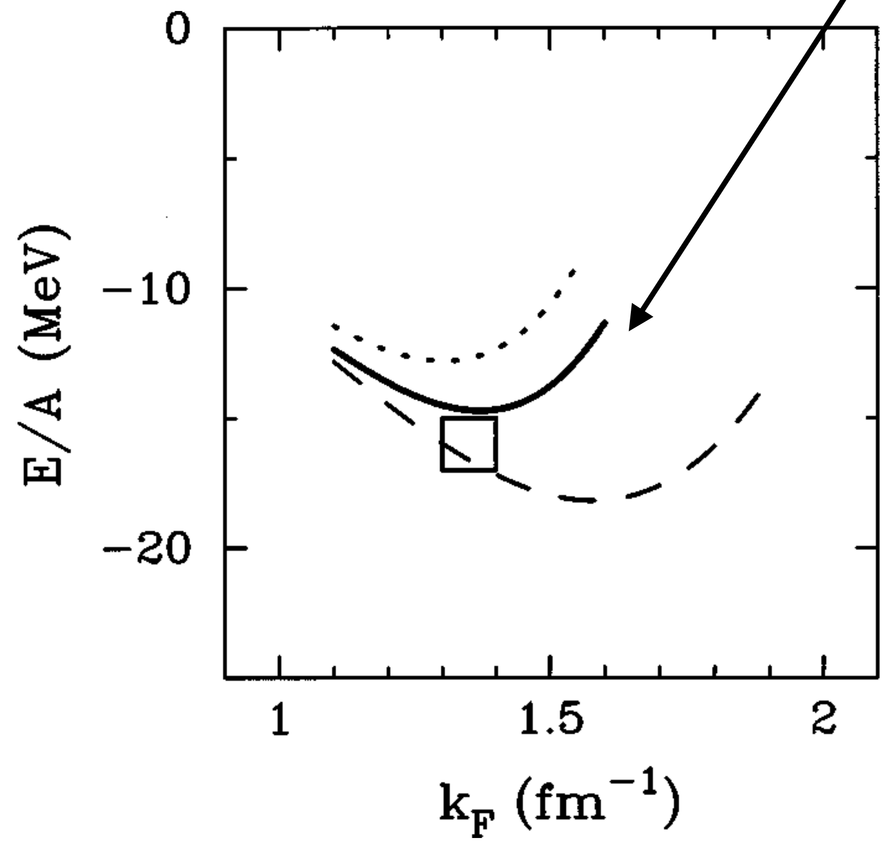
$\pi, \eta, \rho, \omega, a_0, \sigma$ exchange with extra factor in G

NN scattering



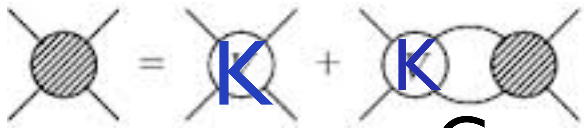
$$B_D = 2.245\ \text{MeV}$$

Nuclear Matter Saturation



The real problem- Bethe Salpeter Eq. (BSE)

T=



K is sum of irred. diagrams

G depends on 4-momenta-product of two Feynman propagators

Reduce to 3 dimensions:

ET: integrate over k^0. Ignore k^0 except in G. Sets relative time to 0.

LF: Integrate over k^-. Ignore k^- except in G. Sets relative τ =0

3 dimensional version of G is g_{ET} (Blankenbecler Sugar) or g_{LF} (Weinberg)

Puts BOTH particles on mass shell

No relation between wave functions in principle

Spectator on-shell- Gross equation- one particle off mass shell $k^2 - m^2 \neq 0$

PHYSICAL REVIEW C **81**, 035201 (2010)

Relation between equal-time and light-front wave functions

Gerald A. Miller*
Department of Physics, University of Washington, Seattle, Washington 98195-1560, USA

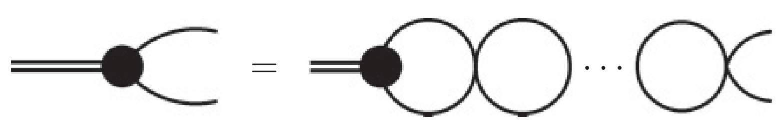
Brian C. Tiburzi†
Maryland Center for Fundamental Physics, Department of Physics, University of Maryland, College Park, Maryland 20742-4111, USA

(Received 29 November 2009; published 4 March 2010)

The relation between equal-time and light-front wave functions is studied using models for which the four-dimensional solution of the Bethe-Salpeter wave function can be obtained. The popular prescription of defining the longitudinal momentum fraction using the instant-form free kinetic energy and third component of momentum is found to be incorrect except in the nonrelativistic limit. One may obtain light-front wave functions from rest-frame, instant-form wave functions by boosting the latter wave functions to the infinite momentum frame.

- How bad is the problem?
- Is D non-relativistic?
- Is ^{3}He non-relativistic?
- Answer by using solutions of Bethe-S eqn.

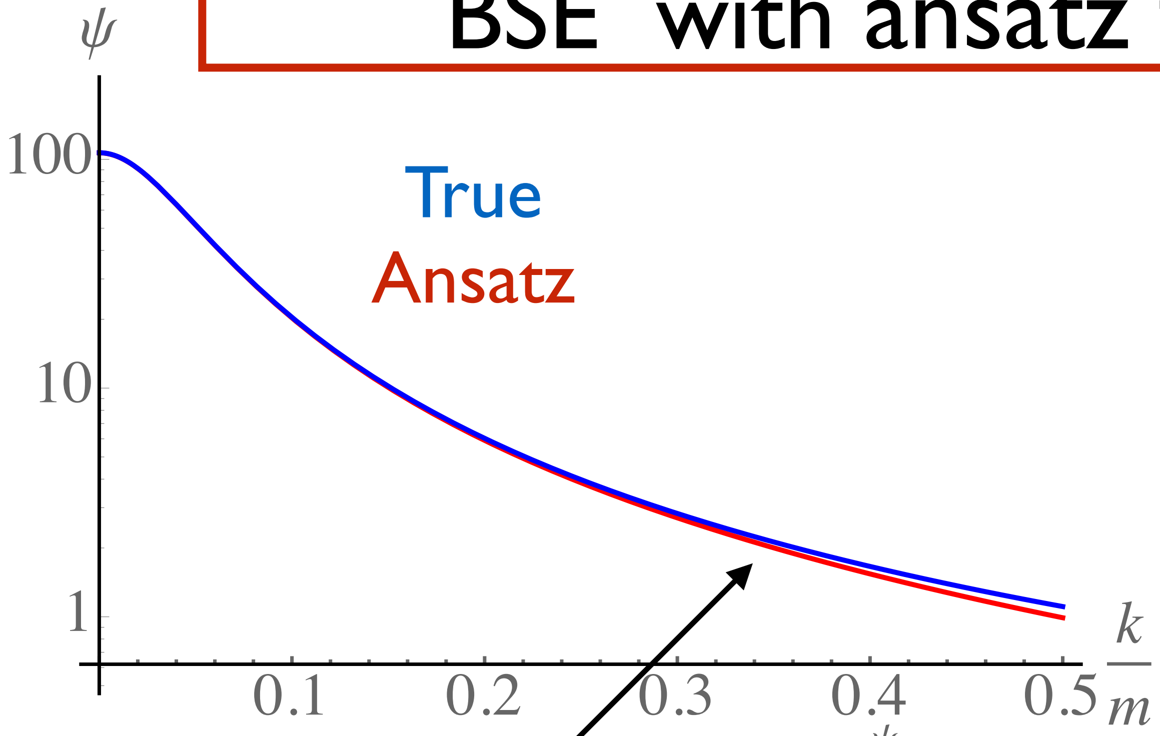
Model



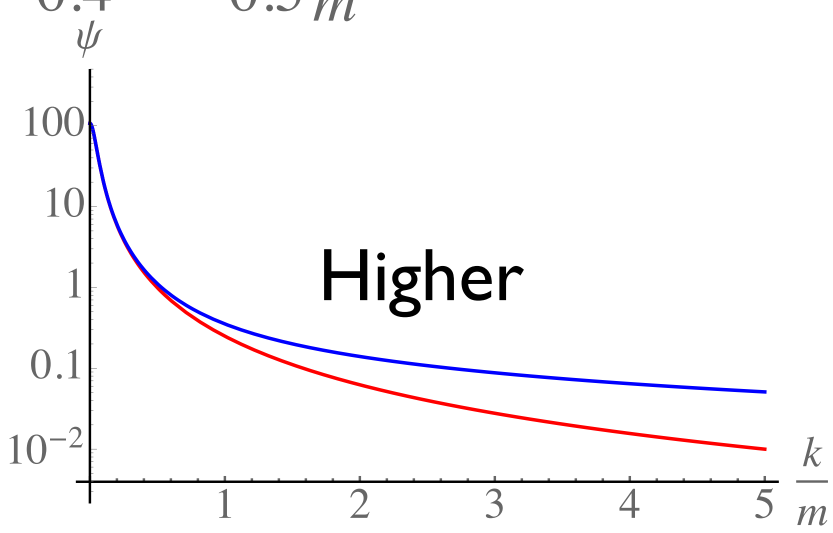
0'th order CH PT

FIG. 2. Bethe-Salpeter equation for a point interaction. The state is bound by the infinite chain of bubbles.

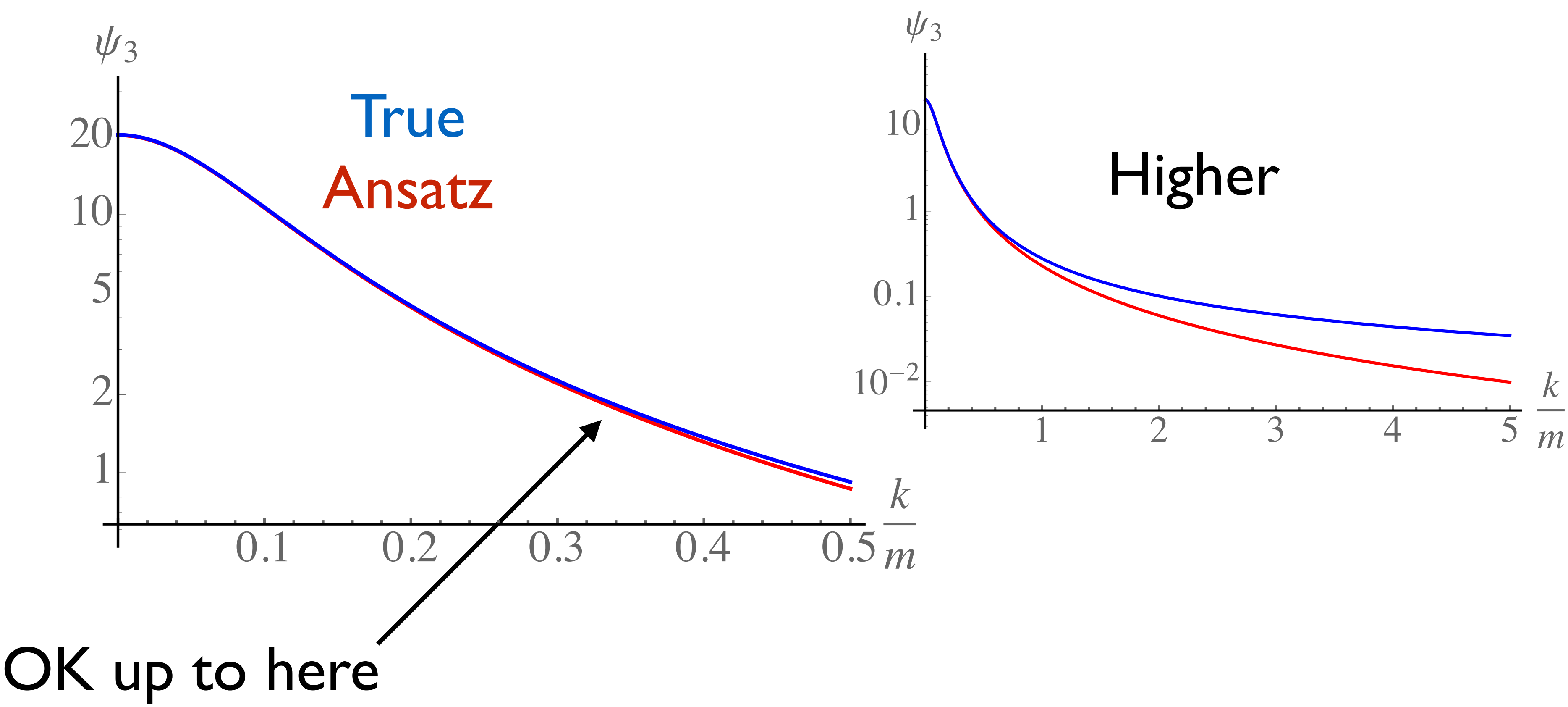
Deuteron Compares true LFD from BSE with ansatz from ET



OK up to here



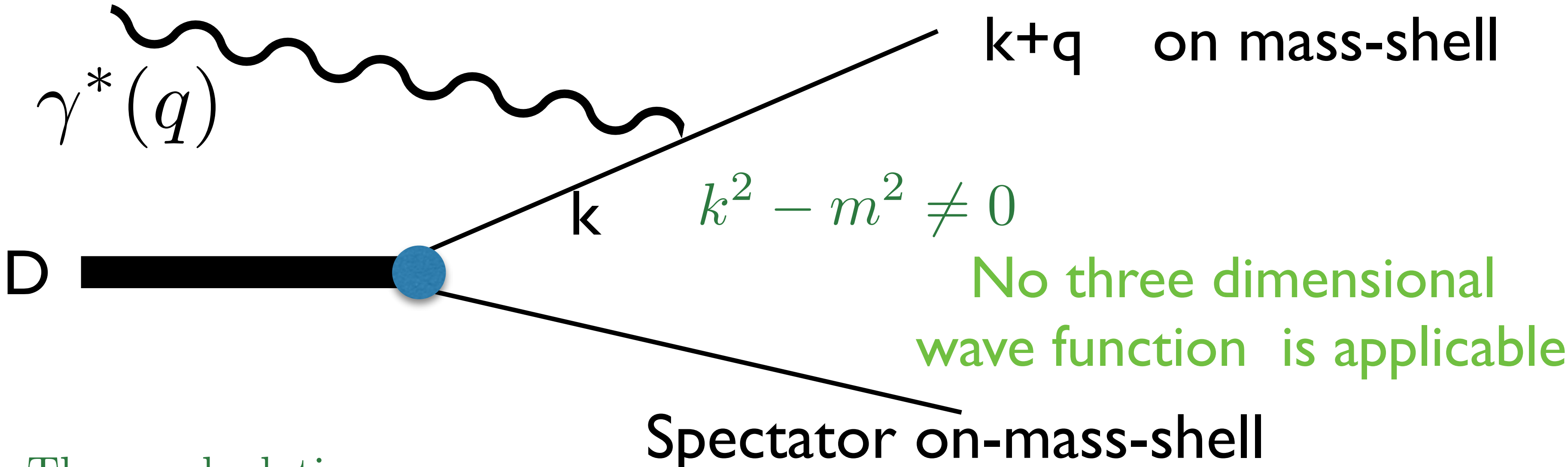
^{3}He Compare true LFD from BSE with ansatz from ET



Are light front or equal time wave functions relevant?

- Light front wave functions - on-mass shell $k_i^2 = m^2$
- Same for equal time wave functions Mismatch!
- Answer this question through explicit example - point interaction model used above
- Space-like Form factors -use of light front wave functions gives exact results- GAM Phys.Rev. C80 (2009) 045210
- What about quasi-elastic scattering?

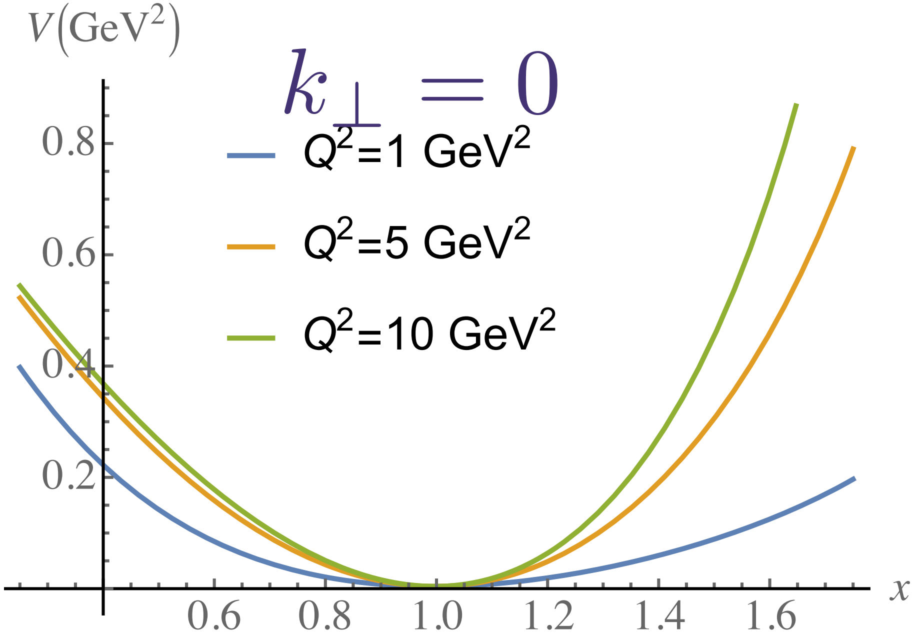
quasi-elastic scattering

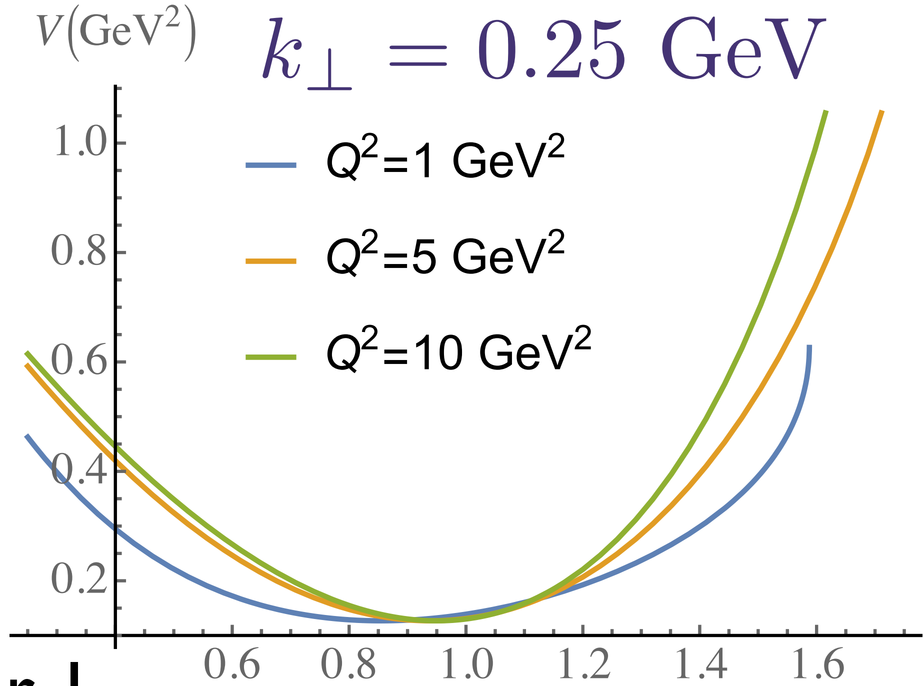


Three calculations

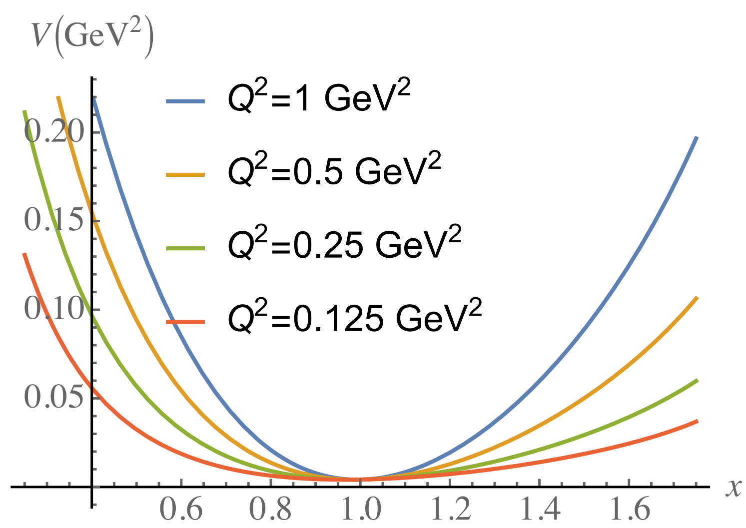
1. Exact
2. On- shell $k^2 = m^2$ in 4-momentum conservation delta function
3. As in 2, Bjorken limit $\frac{Q^2}{\nu^2} << 1$

Virtuality $V \equiv m^2 - k^2$





V is very large except for x near 1

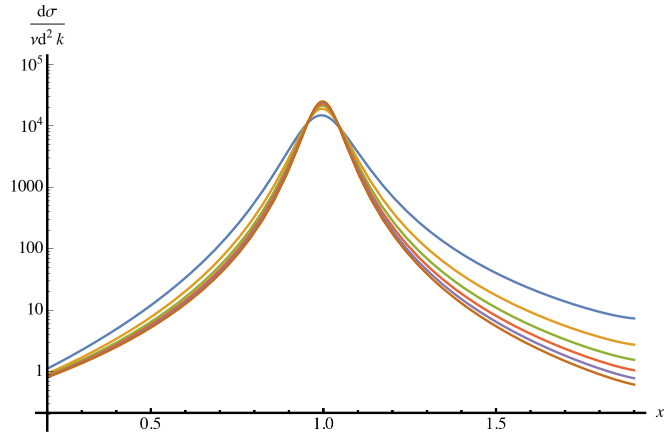


Low Q^2 - V is small- low energy NP

Model exact cross sections

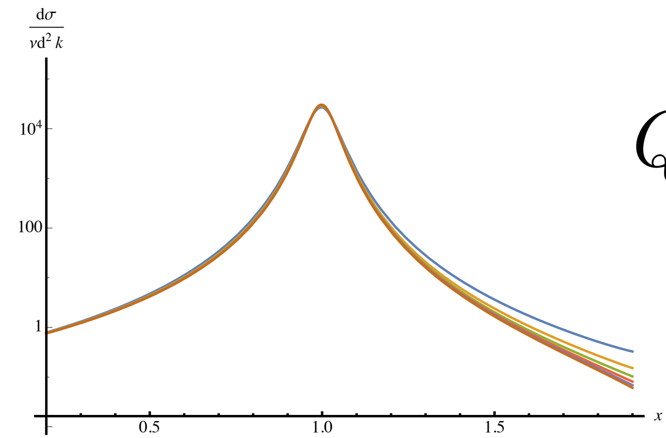
$$\frac{d\sigma}{\nu\, d^2 k}$$

Scaling at large Q²



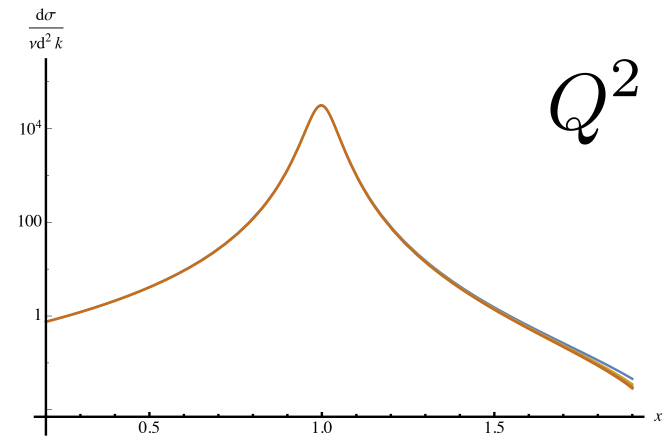
x

$Q^2 = 1 - 6\ \mathrm{GeV}^2$



x

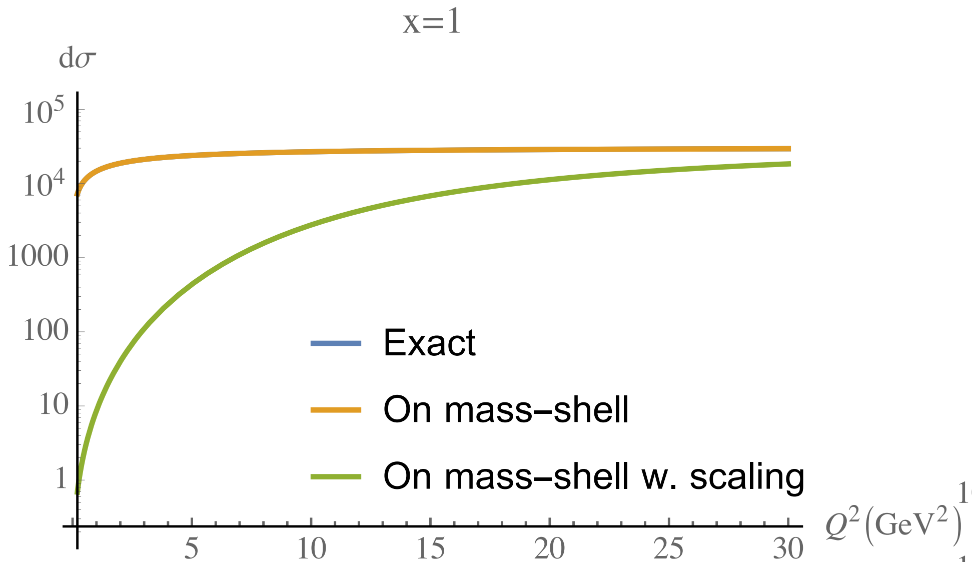
$Q^2 = 10 - 60\ \mathrm{GeV}^2$

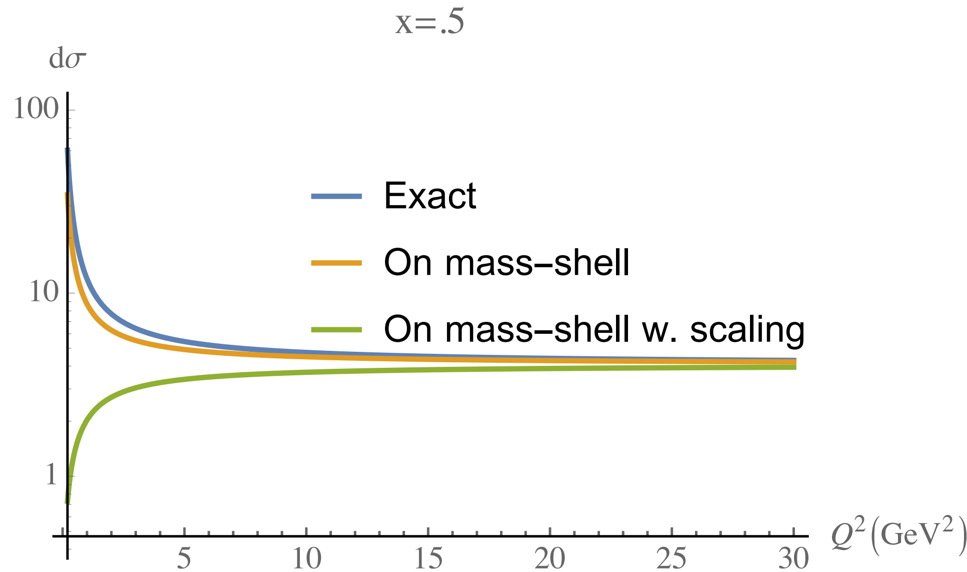


x

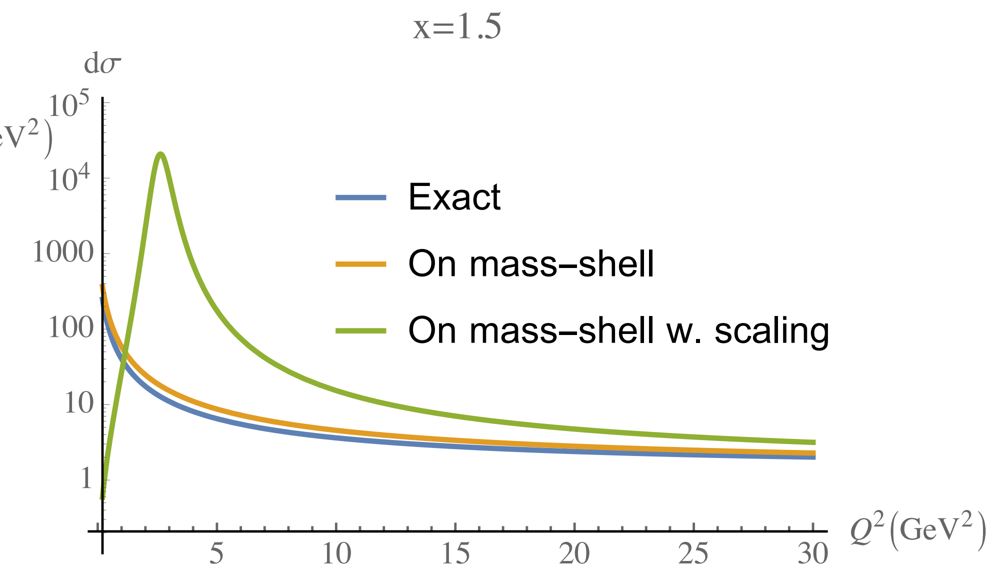
$Q^2 = 100 - 600\ \mathrm{GeV}^2$

Approach to scaling



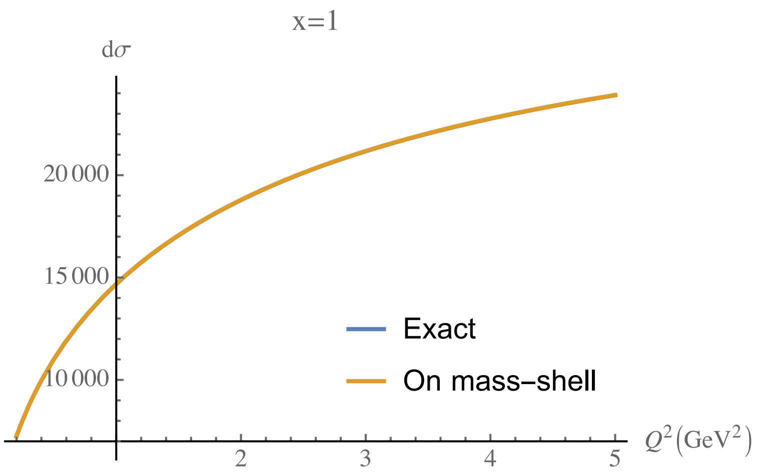


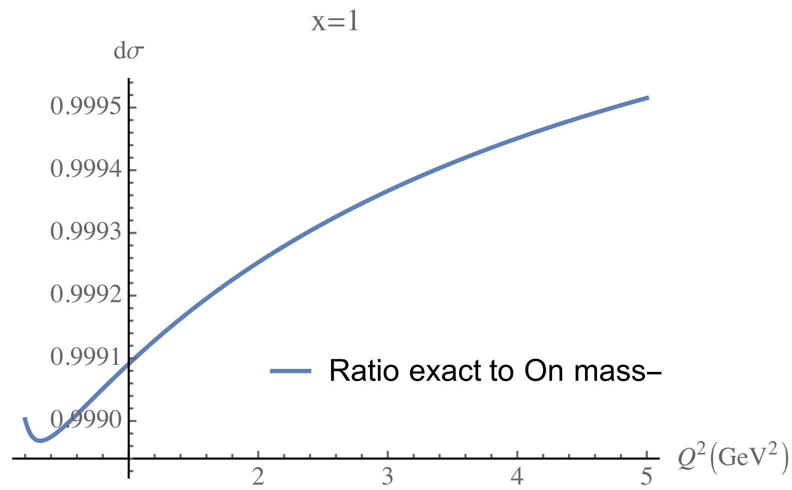
Scaling requires high Q2



On-shell seems ok in log plot

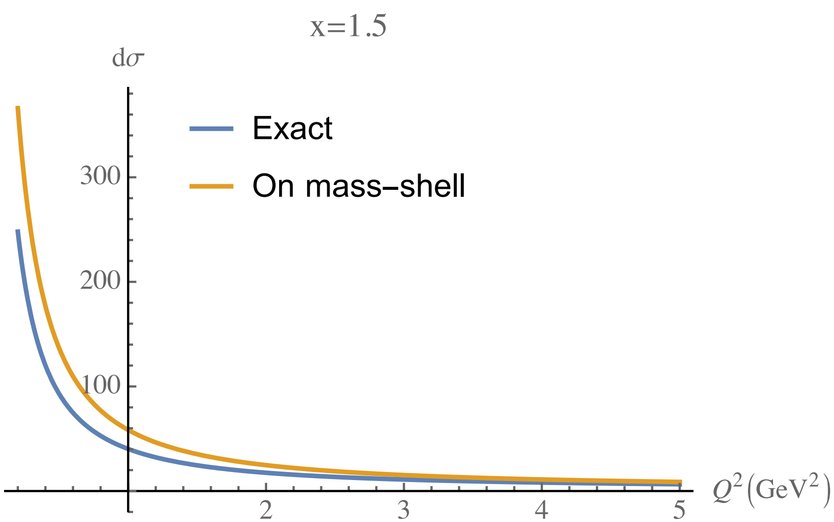
Low Q, x=1 (Long's)exp't

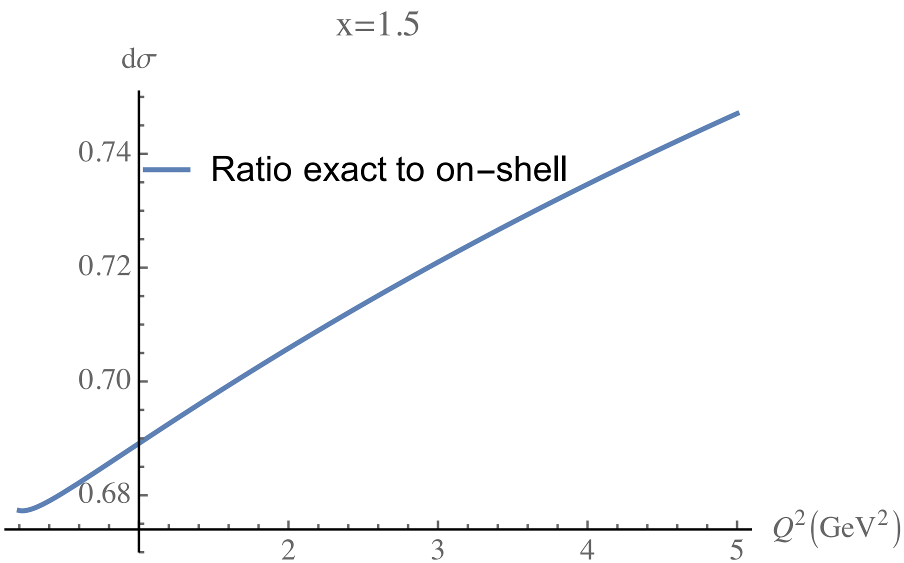




On-mass shell approximation V=0 is OK
can us standard wave functions

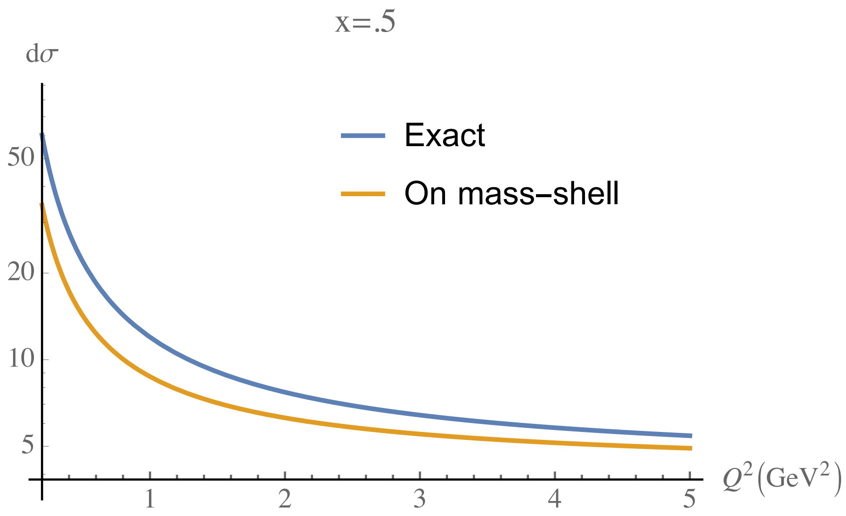
Low Q, x=1.5

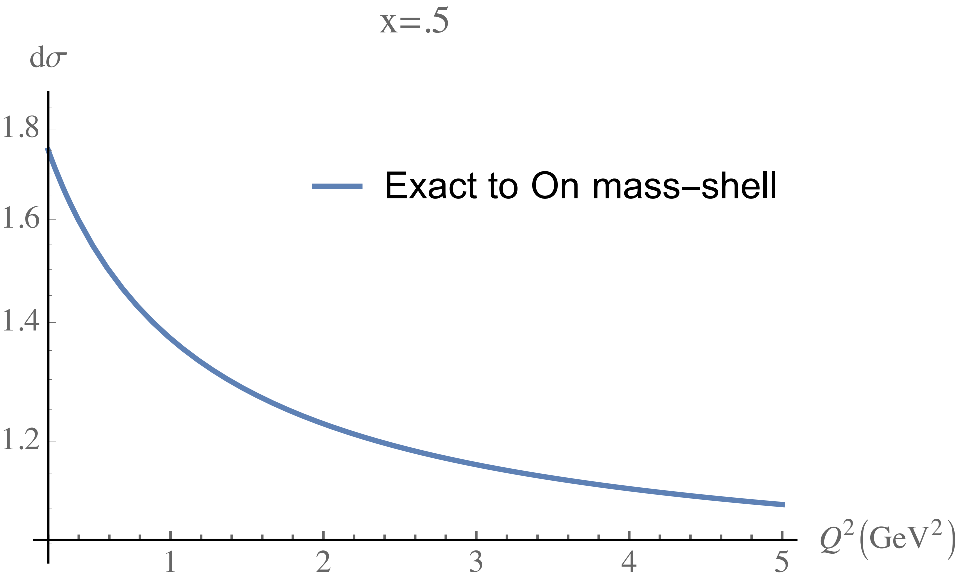




Significant error by assuming on shell-
can't use standard wave functions
spectator on-shell is ok

Low Q, x=0.5



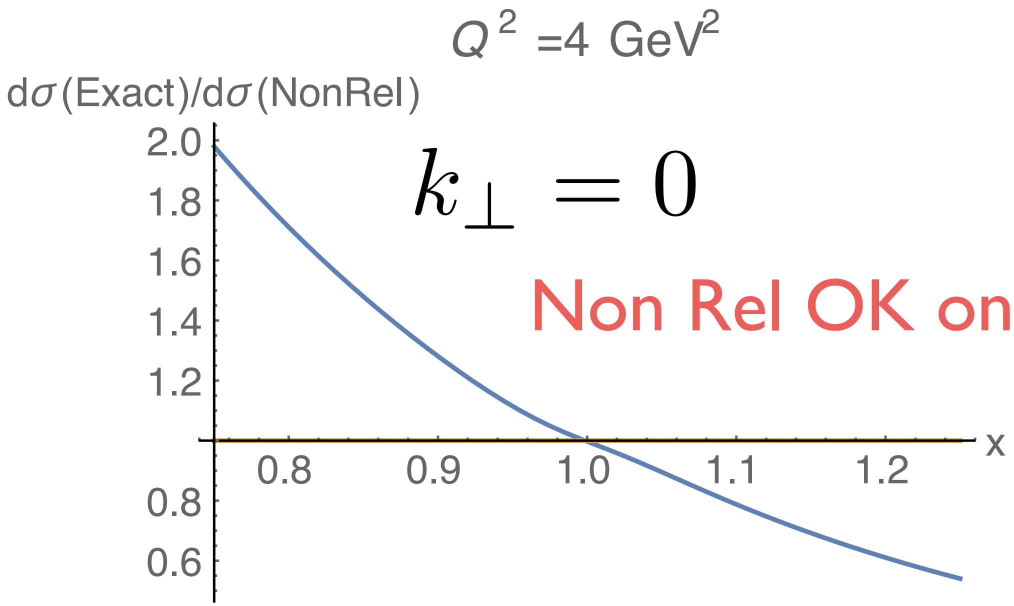


Significant error by assuming on shell

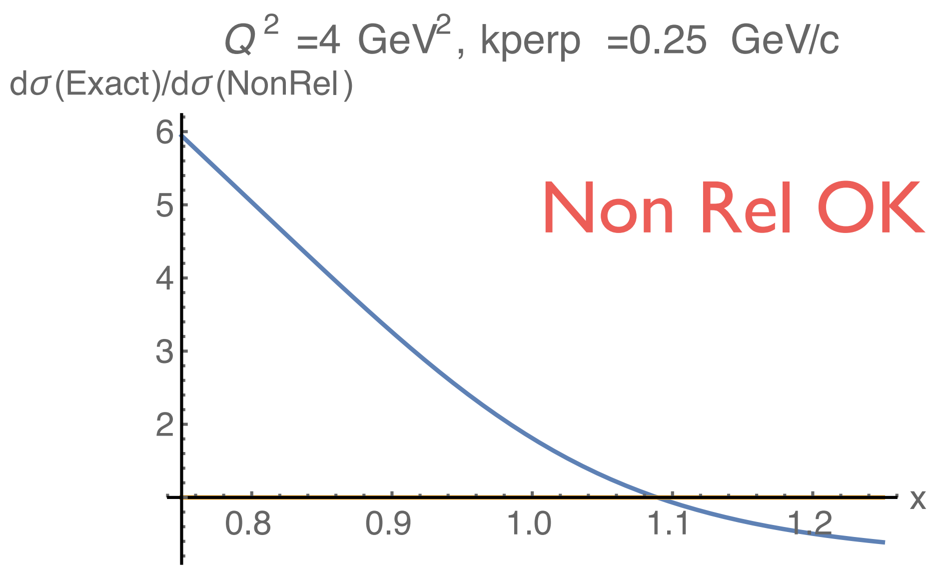
can't use standard wave functions

spectator on-shell is ok

Non-relativistic approximation



Non Rel OK only near x=1



Non Rel OK only near x=1.1

Summary

- formulate the NN interaction on the light front - get from BSE
- solve Weinberg equation for the deuteron -done
- prescription from FS 81 review constructs LF wave function from NR wf: study with exact solutions of BSE
- how good is this approx at recoil momenta few hundred MeV?-seems ok up to about 250-300 MeV more study needed
- can we get the LF wf from NN potentials?-seems ok
- Relevance of LF wave functions- OK for space-like form factors
- Quasi-elastic at Q^2< 15 GeV^2, LF wave function No Good, Need spectator wf if x is not very near 1
- Non-relativistic approximation is not good except in narrow range of x, depends on k_perp

Spares follow

The APS Council and the DNP have endorsed the establishment of the

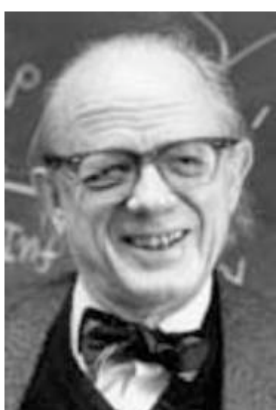
Herman Feshbach Prize in Nuclear Physics

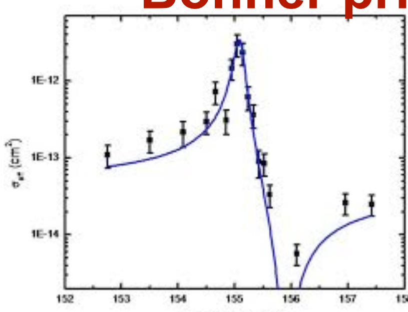
Purpose: To recognize and encourage outstanding research in theoretical nuclear physics. The prize will consist of $10,000 and a certificate citing the contributions made by the recipient. The prize will be presented biannually or annually.

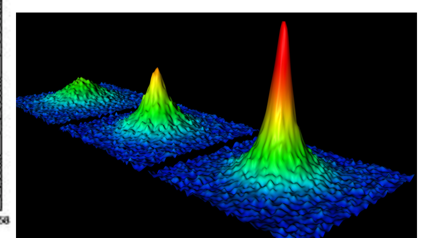
Herman Feshbach was a dominant force in Nuclear Physics for many years. The establishment of this prize depends entirely on the contributions of institutions, corporations and individuals associated with Nuclear Physics. So far, significant contributions have been made by MIT, the DNP, ORNL/U.Tenn, JSA/SURA, BSA, Elsevier Publishing, TUNL, TRIUMF, MSU, and a number of individuals. More than $150,000 has been raised, primarily through institutional contributions. **It is very important that physicists make contributions to carry the endowment over the $200,000 mark, so that the Prize will be eligible to be awarded annually.** Please help us reach that goal by making a contribution. Go online at http://www.aps.org/ Look for the support banner and click APS member (membership number needed) and look down the list of causes.

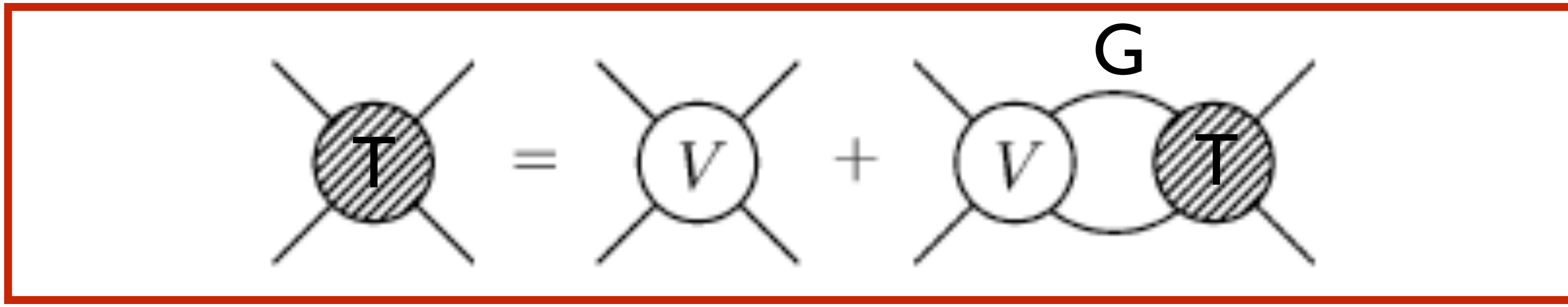
If you have any questions, please contact G. A. (Jerry) Miller UW, <miller@uw.edu>.

If annual- number of experimentalists winning Bonner prize goes up by >50%









$$G \sim \frac{1}{\alpha(1-\alpha)} \frac{d^2 p_\perp d\alpha}{P^2 - \frac{p_\perp^2 + m^2}{\alpha(1-\alpha)}}$$

$$\textbf{define } p_z : \frac{p_\perp^2 + m^2}{4\alpha(1-\alpha)} = p_\perp^2 + p_z^2 + m^2 = \vec{p}^{\,2} + m^2$$

$$G \sim \frac{m^2}{\sqrt{\vec{p}^{\,2} + m^2}} \frac{d^3 p}{p_i^2 - p^2} \quad \text{Usual propagator with extra factor}$$

Extra factor is close to unity for D wave function

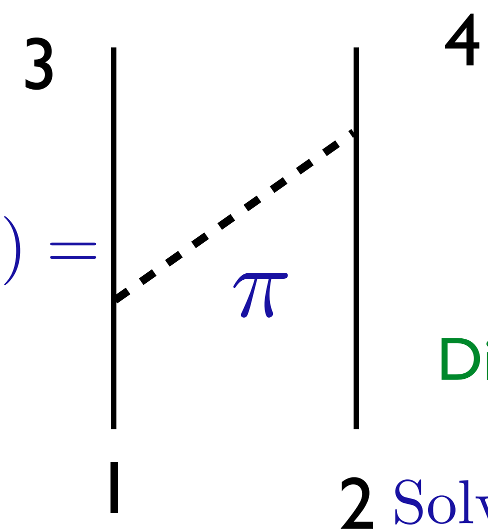
Jason Cooke nucl-th/0112029, Cooke & Miller PRC66, 034002

Solves LF Schroedinger eq (LFSSE)

$$\left[P_0^- + V(P^-)\right]|\Psi_D\rangle = P^-|\Psi_D\rangle \qquad P^- = 2m - B \quad \text{rest frame}$$

Manifest rotational invar. broken

$V(P^-) =$



$$= g^2 \frac{1}{P^- - k_3^- - k_2^- - k_\pi^-}$$

Different meson propagator than Machleidt Miller

Solve LSSE using transformation from α to k_z:

$$\alpha = \frac{k^+}{P^+} = \frac{k^+}{2M - B} = \frac{1}{2}\frac{\sqrt{\vec{k}^2 + m^2} + k_z}{\sqrt{\vec{k}^2 + m^2}}$$

Solve w. rot. inv. in $\perp$ plane (polar coords)

Computed B depends on magnetic quantum number!

Cooke nucl-th/0112029, Cooke & Miller PRC66, 034002
Dynamics

- Chiral Lagrangian with $\pi, \eta, \rho, \omega, \delta, \sigma$
- Two meson exchange!
- Explicit P^- dependence

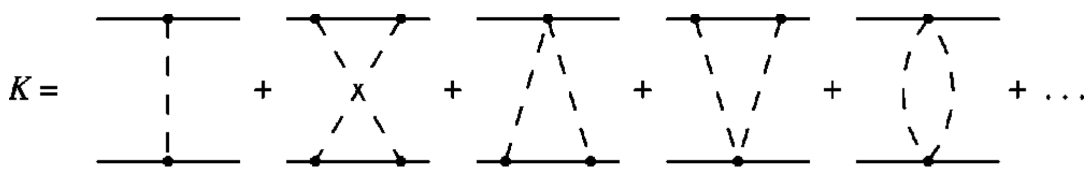
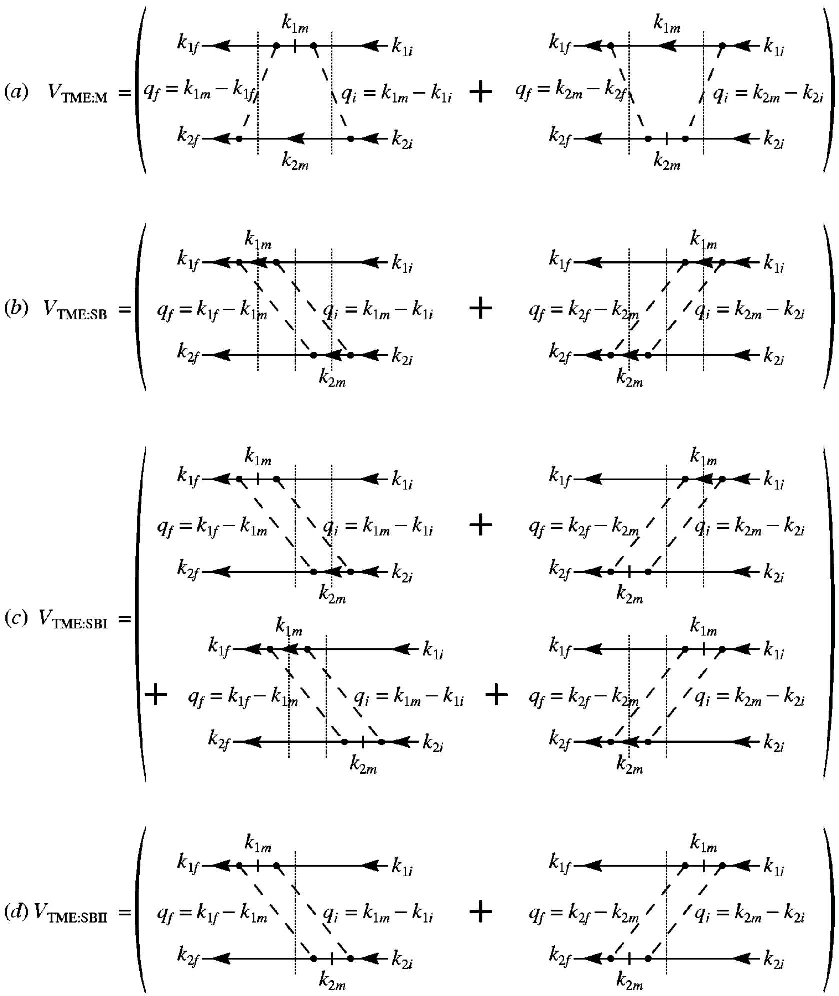


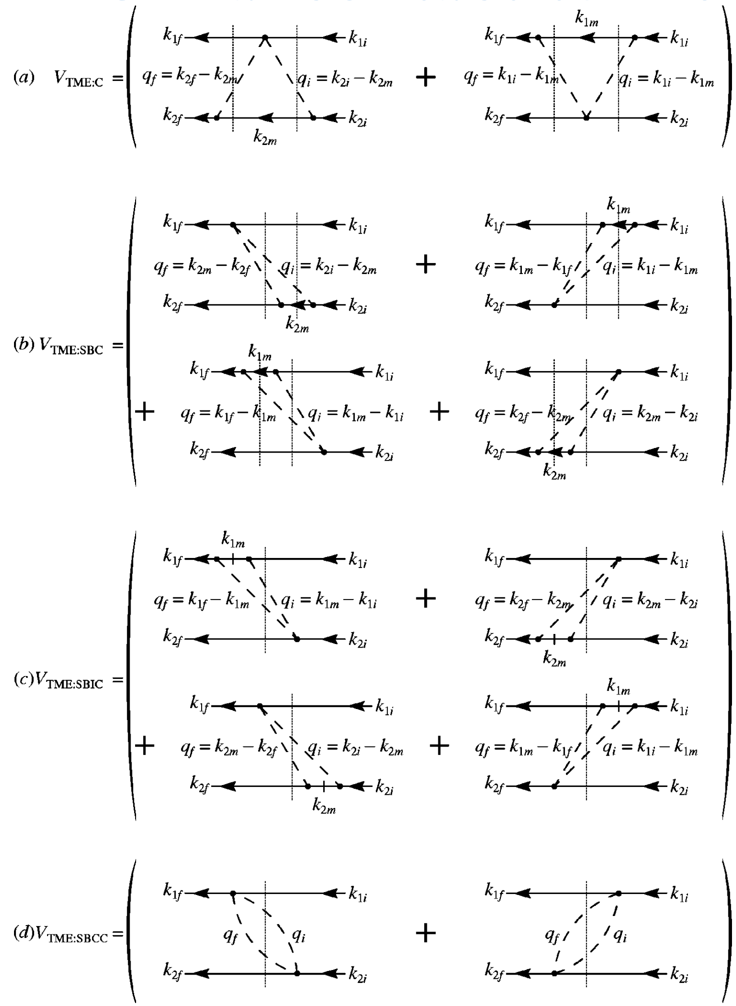
FIG. 1. The first several terms of the full kernel for the Bethe-Salpeter equation of the nuclear model with chiral symmetry.

Cooke nucl-th/0112029, Cooke & Miller PRC66, 034002
Two Meson Dynamics

Instantaneous terms



Chiral contact terms



Restoring Rot. Inv.

PRC66, 034002

Uses only
2 pion exch
in 2BE

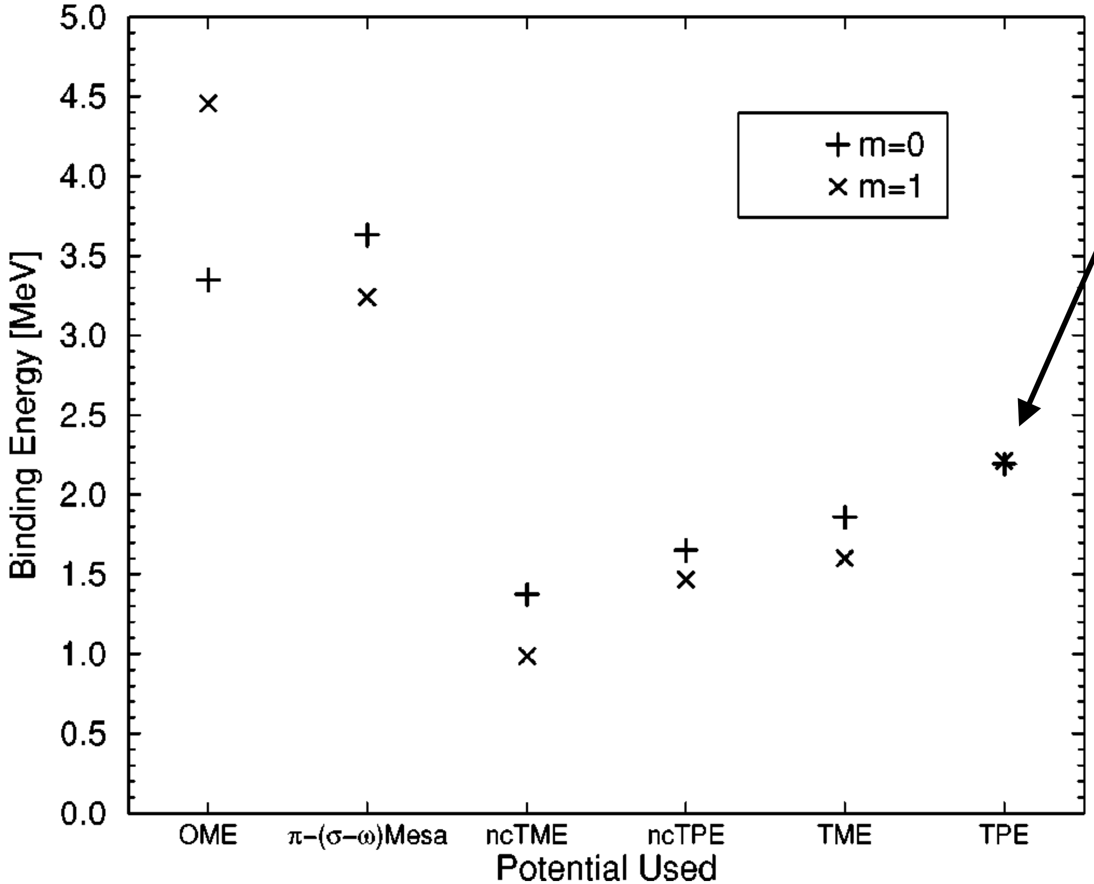


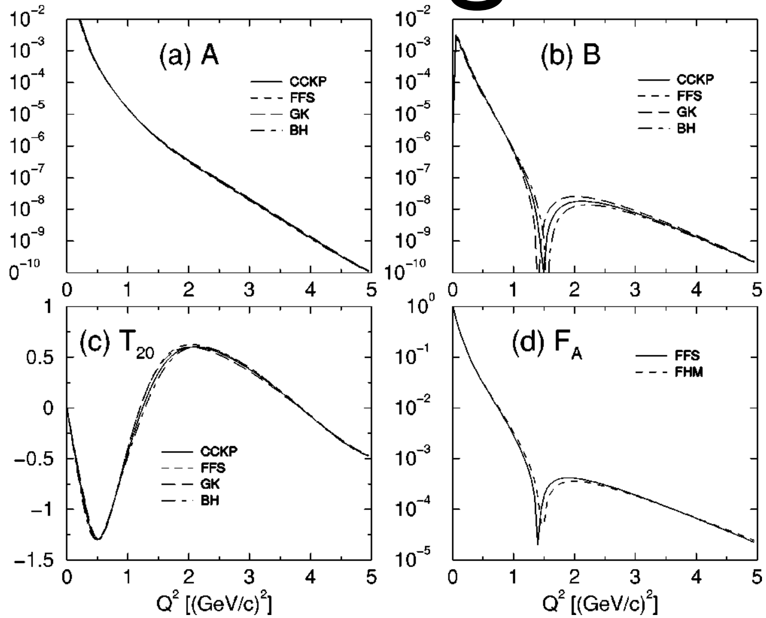
FIG. 9. The values of the binding energy for the $m=0$ and $m=1$ states for different nucleon-nucleon light-front potentials. The σ

Restoring RI in form factors

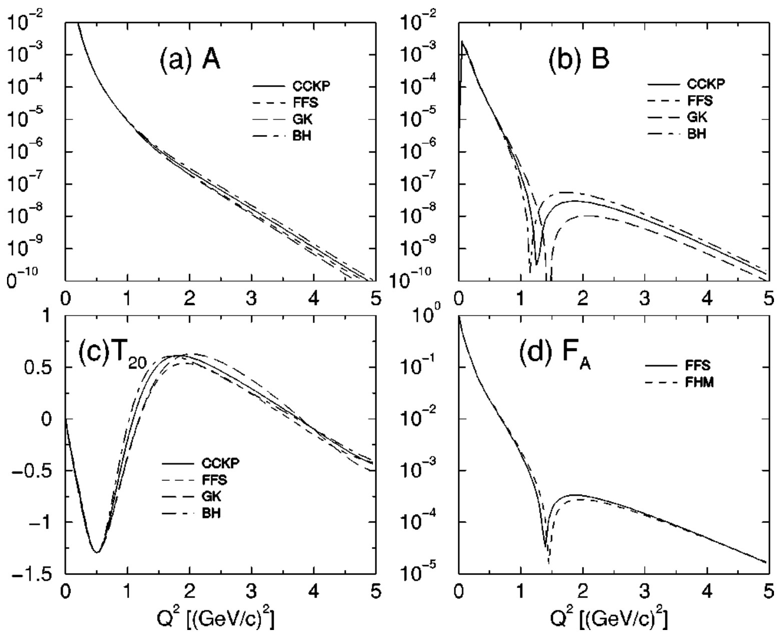
- Rotational invariance gives angular condition FS
- Angular condition is upheld better when Deut is computed using only one meson exchange OME potentials than two meson exchange TME
- However, form factors do not depend much on choice of bad currents

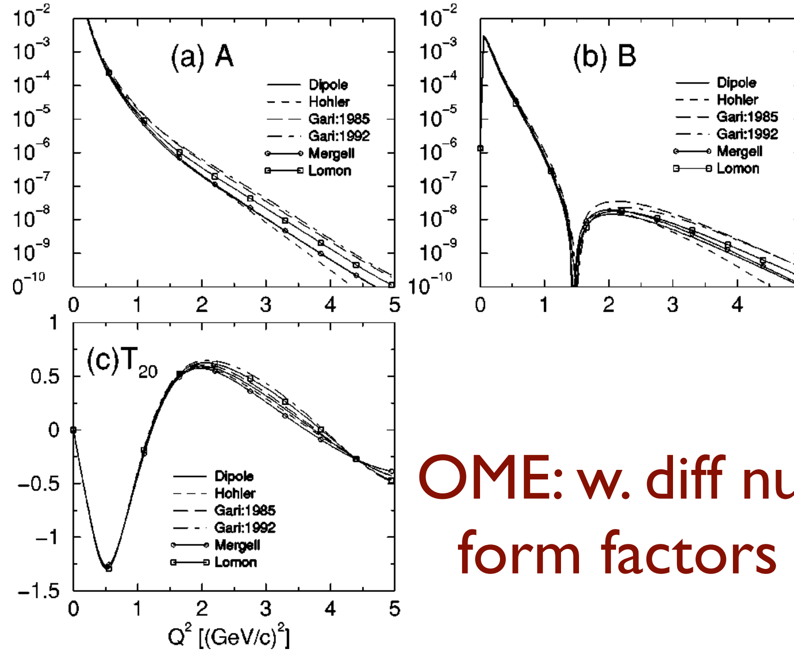
Restoring? RI in form factors

OME

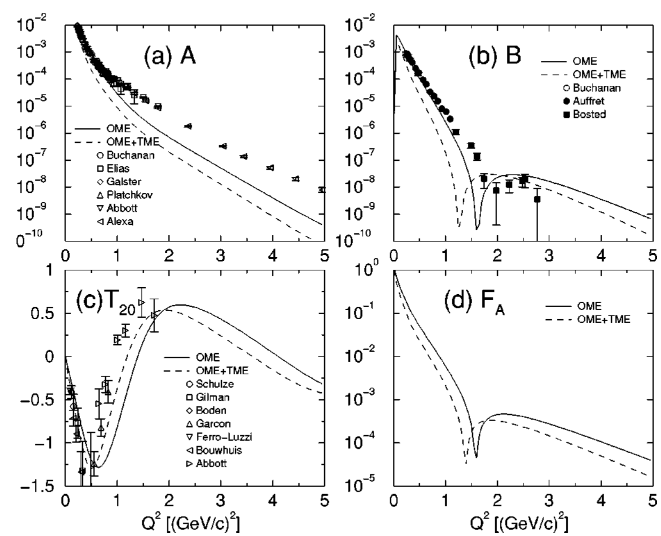


TME

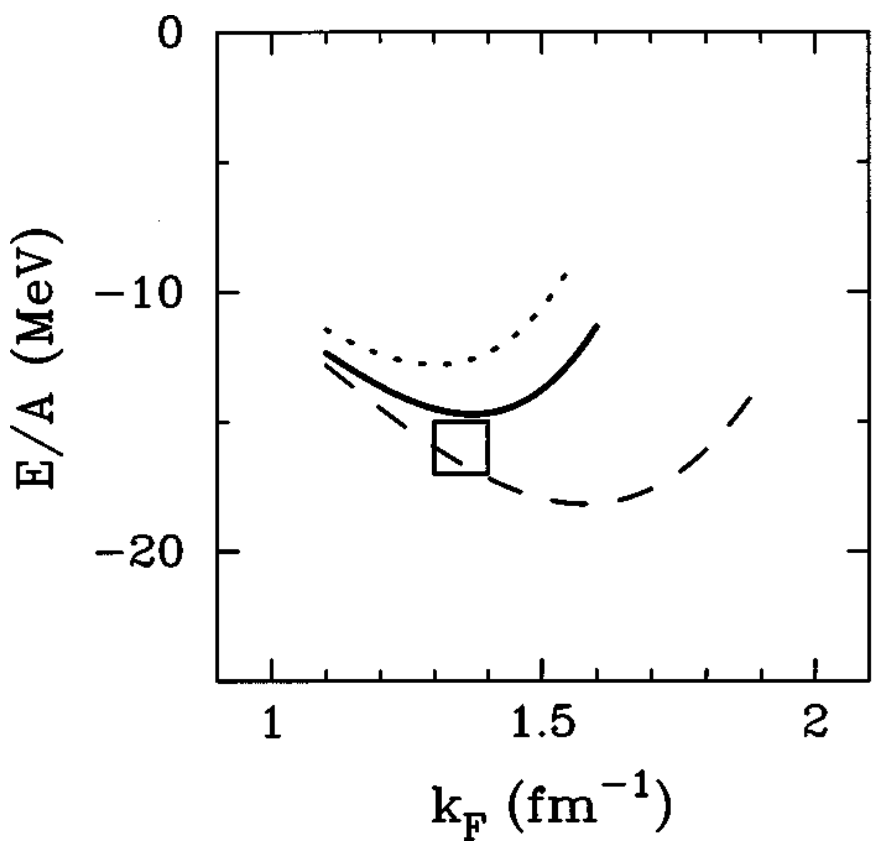




OME: w. diff nucleon form factors



Miller & Machleidt PRC 60,035202
Nuclear Matter Saturation



Solid -our light front
Dashed- ET formalism