PN12 Workshop

November 5, 2004

Franz Gross

JLab and W&M

Outline:

- Introduction
- Proposed outline for a white paper
- The parable of the blind man and the elephant
- Nuclear politics in 2004
- Discovery class experiments

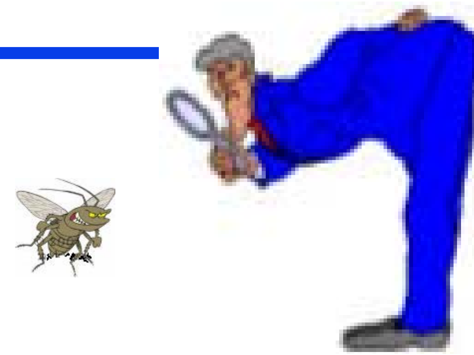
Proposed outline for a white paper

- Compelling questions:
  - What is the nature of the effective hadron-hadron interactions, and how can they be understood from QCD?
  - How does the structure of nucleons change in the nuclear medium?
  - How are the effective hadron-hadron interactions changed by the nuclear medium?
- Coherent theme (the parable of the blind man):
  - Hadron d.o.f. and quark/gluon d.o.f. are dual and complementary. Each is most efficient in certain limits (or distance scales). What are these distance scales, and how is the physics explained in the transition regions?
- Experiments with discovery potential and the physics behind them

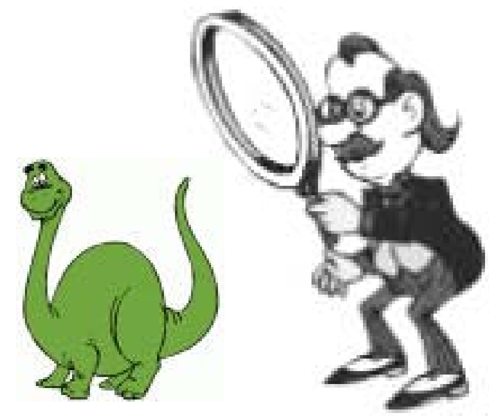
The parable of the blind man and the elephant

- Theorem: The hadronic and quark-gluon bases are equivalent
- QCD is an elephant (hopefully not a white one)
  - one blind man sees nucleons
  - another blind man sees pions (solitons)
  - another blind man sees quarks
  - quark clusters
  - mean fields
  - • • • •
- these are all aspects of QCD
- what scales are appropriate to each?

The scale defines the model



- low momenta -- EFT
- modest momenta -- *CHM*
- quark cluster models
- QGS
- • • • •
- very high energies -- pQCD



What is the *Consistent Hadronic Model (CHM)*?

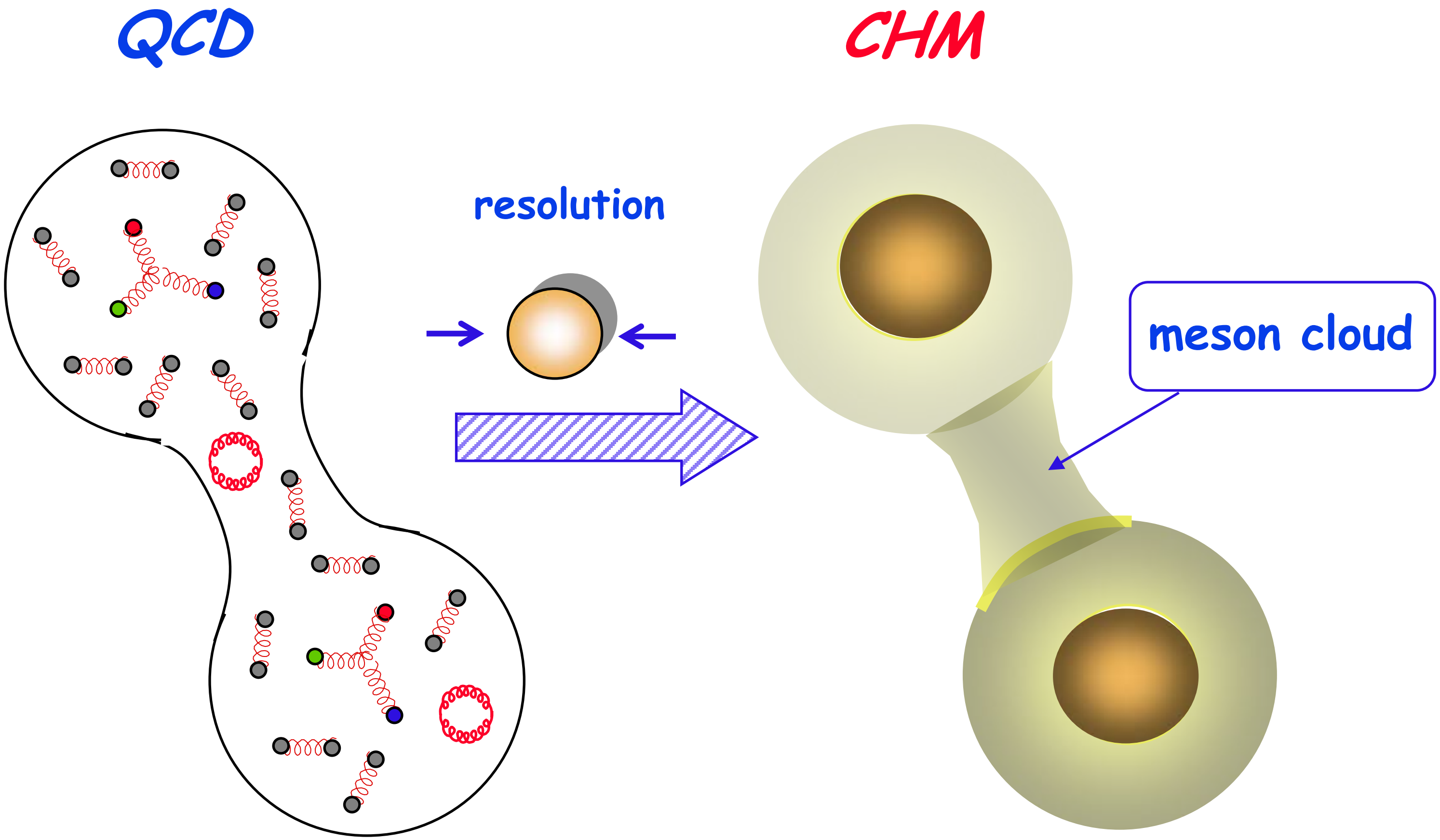
- Nucleons and mesons are treated as point-like particles (or, their quark structure is assumed to be negligible)
- *Consistency:* many body forces, currents, and final state interactions must all be based on the same dynamics
- Implications
  - the longitudinal current operator is constrained by the *NN* interaction and current conservation

$$j^\mu = j^\mu_{\rm trans} + j^\mu_{\rm long}$$

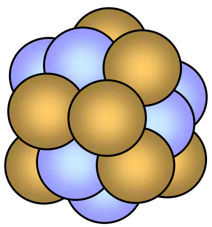
$$q_\mu\, j^\mu_{\rm trans} = 0 \qquad q_\mu\, j^\mu_{\rm long}(p_f, p_i) = S^{-1}(p_i) - S^{-1}(p_f)$$

  - the transverse current is not constrained, and therefore free to be fixed
  - three body forces are constrained by two body dynamics
- The *CHM* could be relativistic -- there are many choices

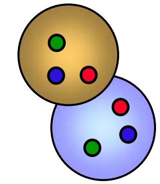
The Consistent Hadronic Model *(CHM)* is an effective theory of *QCD*

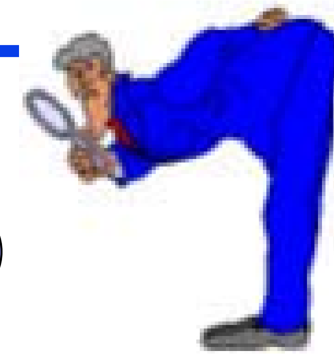


Nuclear politics in 2004



What is best??





big scale	smaller scale
nucleons	quark bags
Short Range Correlations	6 quark bags
$\Delta\Delta$ components and EFT contact terms	hidden color states
meson exchange	quark exchange
sigma meson	two-pion exchange with Δ's and $\pi\pi$ interactions
off-shell nucleons	off-shell quarks
covariant spectator theory	light-front QM
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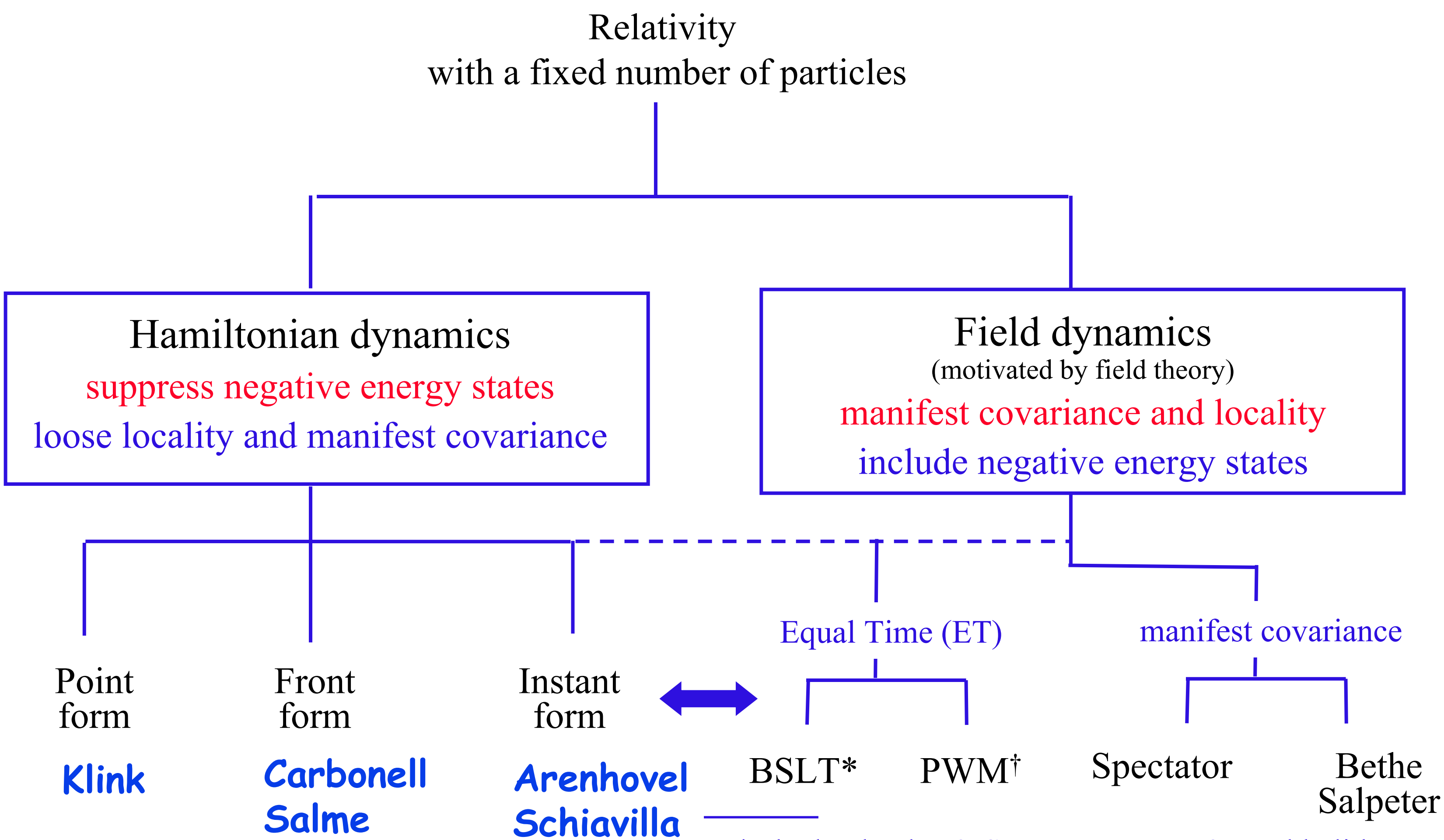
There are many choices of relativistic theory



*Blankenbecler & Sugar, Logunov & Tavkhelidze
†Phillips, Wallace, and Mandelzweig

Hamiltonian dynamics: Dirac classifications of 1947 (Salme)

Some of the Poincaré transformations are kinematic; others involve the dynamics

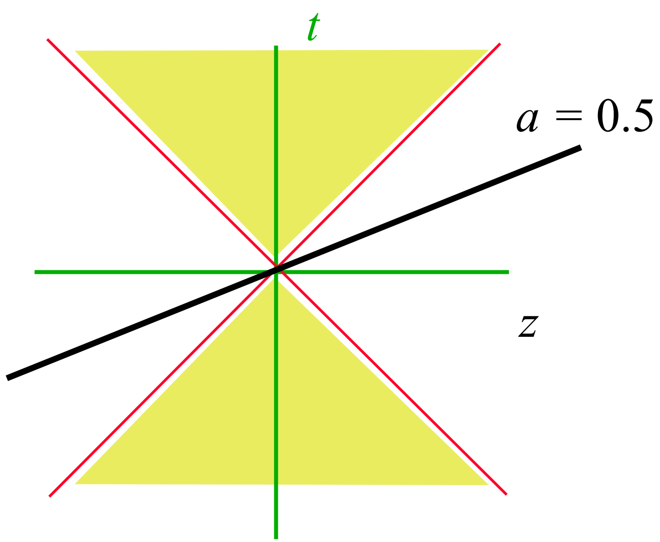
- Plane forms

$$t - a\,z = 0$$
$$-1 \le a \le 1$$

$a \le 1$: instant form — 6+4

$a = 1$: front form — 7+3

Limit not continuous



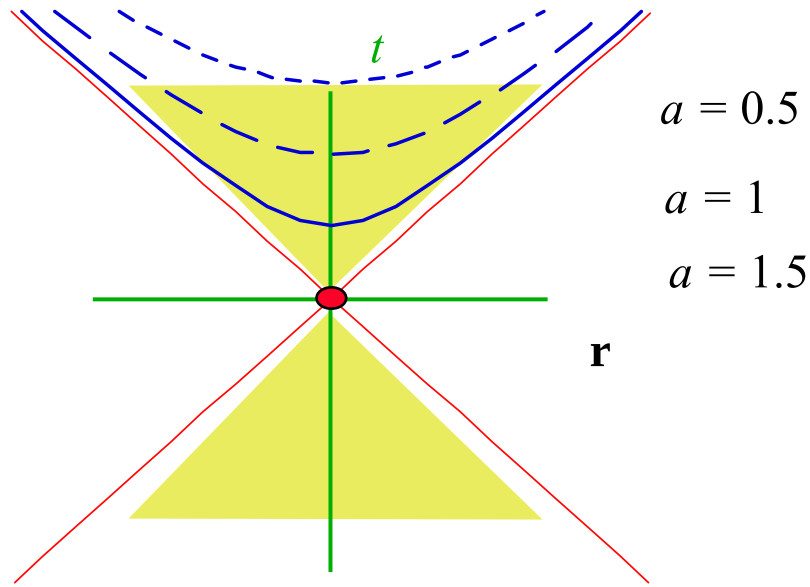
light front *light* **front**

- Hyperbolic forms

$$t = \sqrt{(\mathbf{r}^2 + a^2)}$$

$a = 0$: point form on the light cone

$a = \infty$: instant form

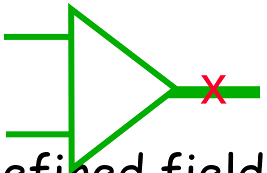


light front *light front*

Field dynamics has a connection to field theory

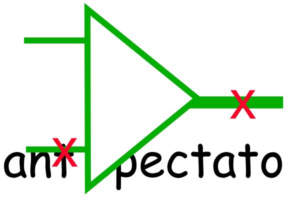
- The Bethe-Salpeter amplitude is a well defined field theoretic matrix element:

$$\Psi(x_1,x_2)=\langle 0|\,T\big(\psi(x_1)\,\psi(x_1)\big)|\,d\rangle$$



- The covariant spectator amplitude is *also* a well defined field theoretic amplitude:

$$\Psi(x_1)=\langle N\,|\,\psi(x_1)\,|\,d\rangle$$



- Equations for the Bethe-Salpeter and the covariant spectator* amplitudes can be derived from field theory
  - Both are manifestly covariant under *all* Poincaré transformations
  - Both incorporate negative energy (antiparticle) states

*O. W. Greenberg's "n-quantum approximation"

Discovery class experiments

Discovery class experiments I

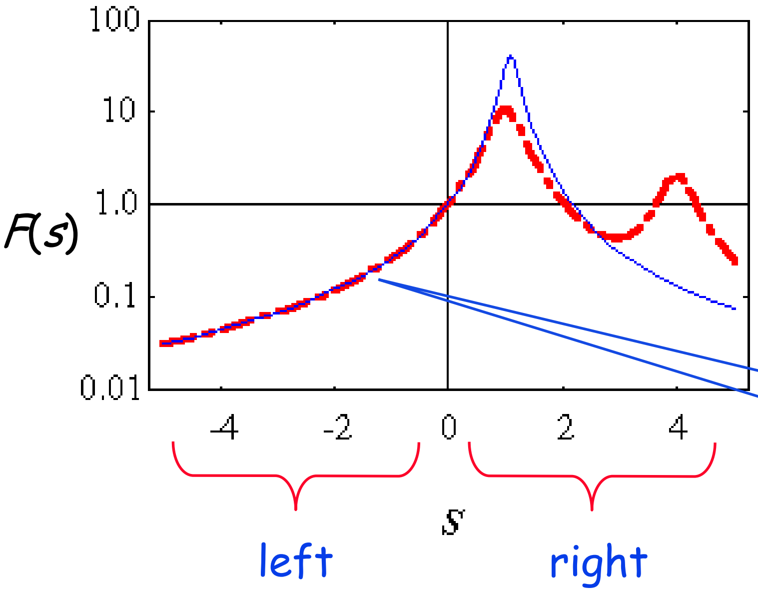
- Deuteron elastic scattering
  - Measure the deuteron B form factor to high Q^2 (can do with 6 GeV)
    - very sensitive to short range dynamics
  - Measure T_{20} (or related quantities T_{11}, etc) to high Q^2
- Deuteron inelastic scattering at threshold
  - Threshold $D \Rightarrow {}^1S_0$ transition is pure isovector and complements elastic scattering
- Photodisintegration of the deuteron to the highest energy
  - see if the description in terms of the total NN cross section holds up
  - see if scaling persists
- Three nucleon elastic form factors (BOTH ^{3}He AND ^{3}H) tritium target
  - separate I=0 and I=1 form factors to test the CHM

Deuteron form factors
and inelastic scattering at threshold

Present description is very successful

- All three form factors well described by the CHM (the spectator calculations of van-Orden, etal, and the the instant form calculations of Schiavilla, etal.)
- How can that be?
  - "Left hides right"
  - Off shell degrees of freedom of the current operator are adjusted to fit -- and must be tested in other experiments
  - the momenta are not so large!
    - at Q^2 = 6 GeV^2, and $Q/4$ ~ 600 MeV

"Left hides right"



$$F_1(s) = \frac{1.033^2 + 0.03}{(1.033 - s)^2 + 0.03}$$

$$F_2(s) = \frac{1.1\left(1 - \frac{0.2}{16.1}\right)}{(1 - s)^2 + 0.1} + \frac{0.2}{(4 - s)^2 + 0.1}$$

- Compare the "left-hand-side" of form factors with two different resonance structures
- Under certain conditions they are indistinguishable

in this case, the two functions agree on the left-hand side to 1%!

- LESSON:

THE RIGHT-HAND NUCLEON RESONANCE STRUCTURE CANNOT BE INFERRED UNIQUELY FROM THE LEFT-HAND STRUCTURE

- The deuteron form factors do not "see" the resonances

Off-shell currents in the Spectator theory

- To conserve current, the current operator must satisfy the WT identity

$$q_\mu j_N^\mu(p',p) = S^{-1}(p) - S^{-1}(p')$$

- The spectator models use a *nucleon form factor, h(p).* This means that the nucleon propagator can be considered to be dressed

- one solution (the simplest) is

$$S(p) = \frac{h^2(p)}{m - \not{p}} = \frac{h^2(p)}{\Delta_-(p)}$$

$$j^\mu(p',p) = F_0 \left\{ F_1\, \gamma^\mu + F_2 \frac{i\sigma^{\mu\nu} q_\nu}{2m} \right\} + G_0\, F_3\, \Lambda_-(p')\, \gamma^\mu\, \Lambda_-(p)$$

$$F_0 = \frac{h(p)}{h(p')}\left(\frac{m^2 - p'^2}{p^2 - p'^2}\right) - \frac{h(p')}{h(p)}\left(\frac{m^2 - p^2}{p^2 - p'^2}\right)$$

$$G_0 = \left(\frac{h(p')}{h(p)} - \frac{h(p)}{h(p')}\right)\frac{4m^2}{p^2 - p'^2}$$

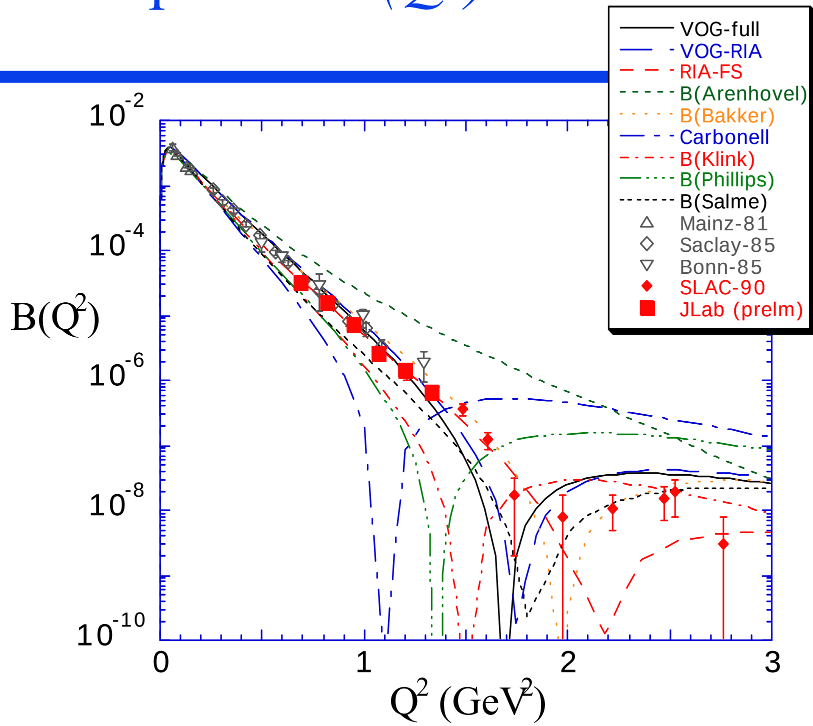
off-shell effects

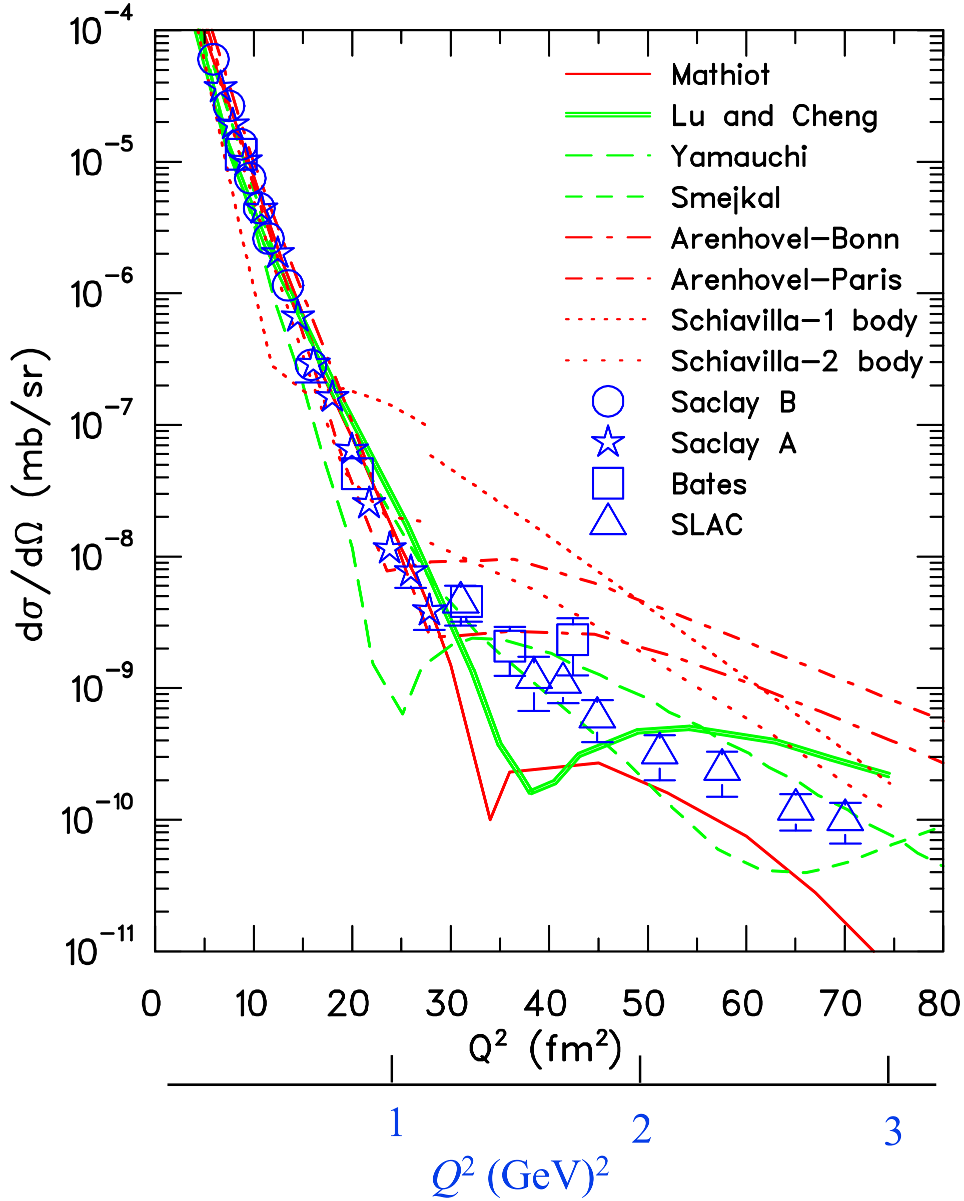
- $F_3(Q^2)$ is unknown, except $F_3(0)=1$. $F_3(Q^2)$ can be fixed from the deuteron form factors

- see if the F_3 so determined works at higher Q^2 and explains the three-body form factors

- The off shell current parameterizes the modification of the nucleon in the "medium"

Threshold electrodisintegration compare to $B(Q^2)$





Comparable measurements over similar Q^2 regions

More accurate data (particularly to establish the minimum -- if any), and separation of the independent structure functions would stimulate theory

Deuteron photo-disintegration

100's of channels excited in photodisintegration at 4 GeV

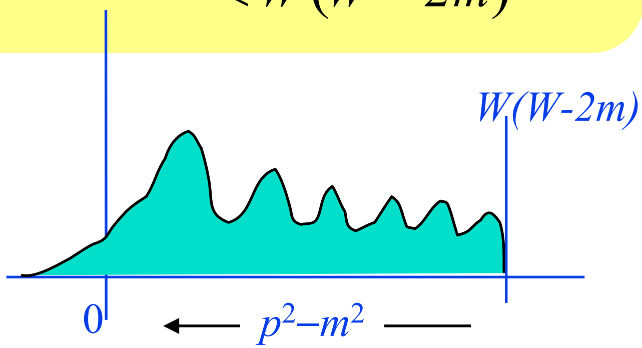
numbers of N*N* channels that are excited

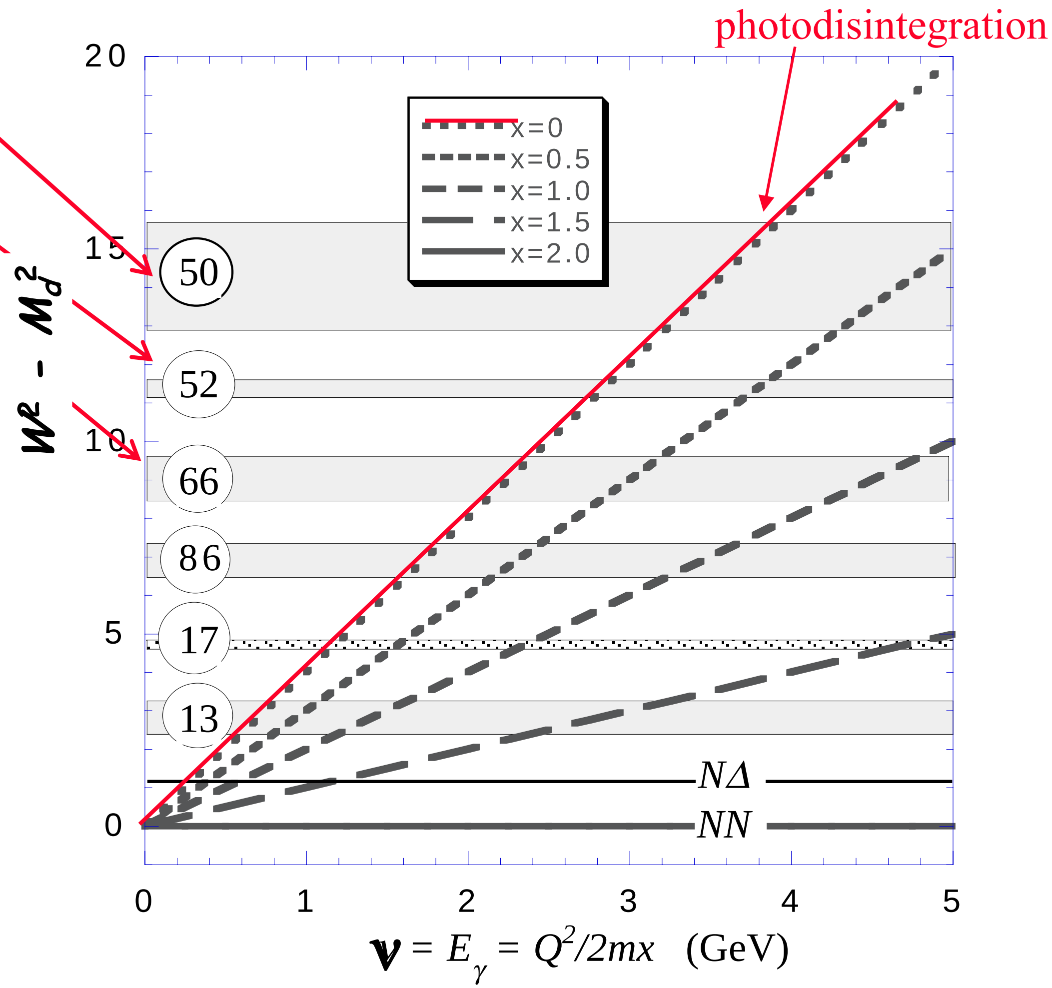
a total of 286 channels composed of two well established resonances!

off-shell mass

cm 3-momentum

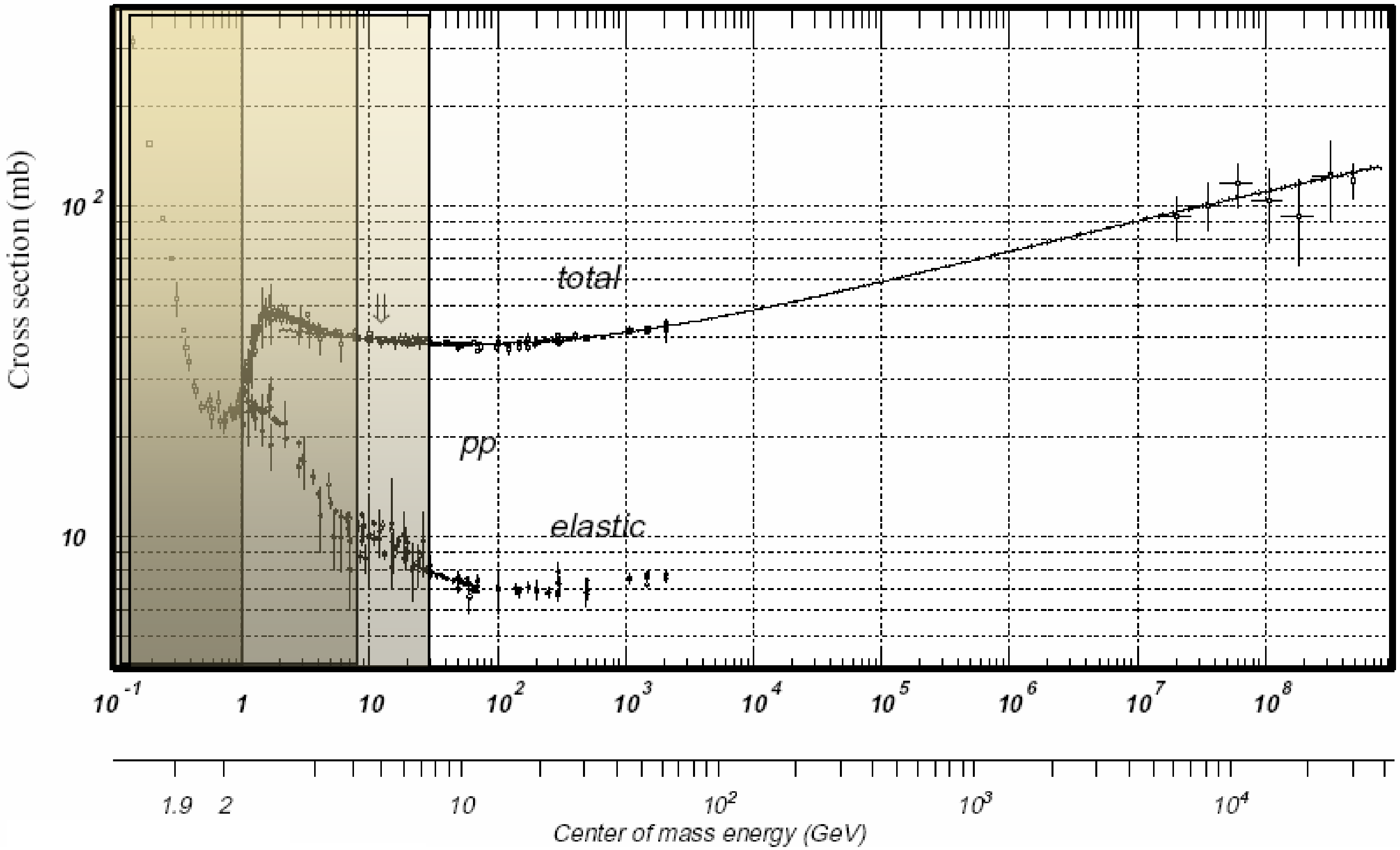
$$p^2 - m^2 = W^2 - 2WE_p$$
$$< W(W - 2m)$$





IN DEUTERON PHOTODISINTEGRATION, THE "RIGHT-HAND" RESONANCES ARE EXPOSED

total *NN* cross sections



12 Gev photons

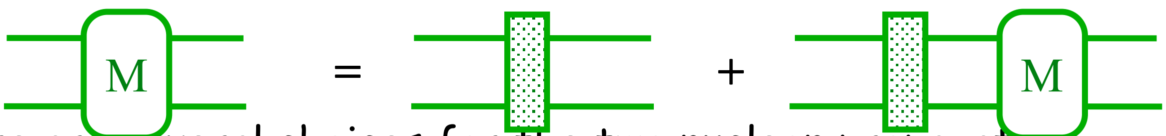
High energy photodisintegration probes deep into the inelastic region -- JLab's entrée into *NN* scattering

Jefferson Lab

Three body form factors

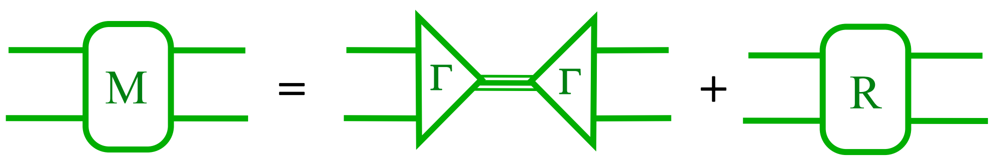
Theory overview (two body scattering)

- The two-body scattering amplitude is constructed by summing the irreducable two-body kernel *V* (the *NN* "force" or the *NN* "potential") to all orders. The solution is non-perturbative.
- The sum is obteined by solving the relativistic integral equation



there are several choices for the two nucleon propagator

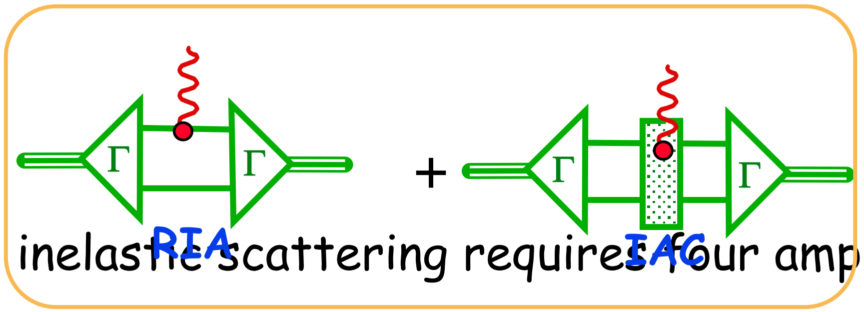
- the covariant spectator theory has been developed locally
- if a bound state exists, there is a pole in the scattering amplitude

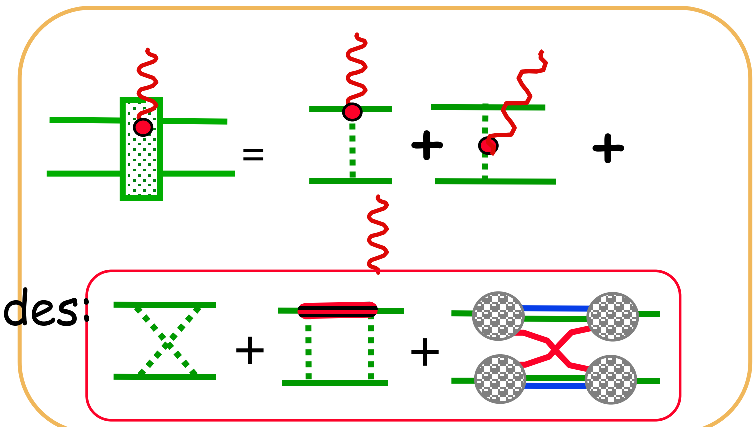


residue: finite at the pole

Theory overview (2 body currents)

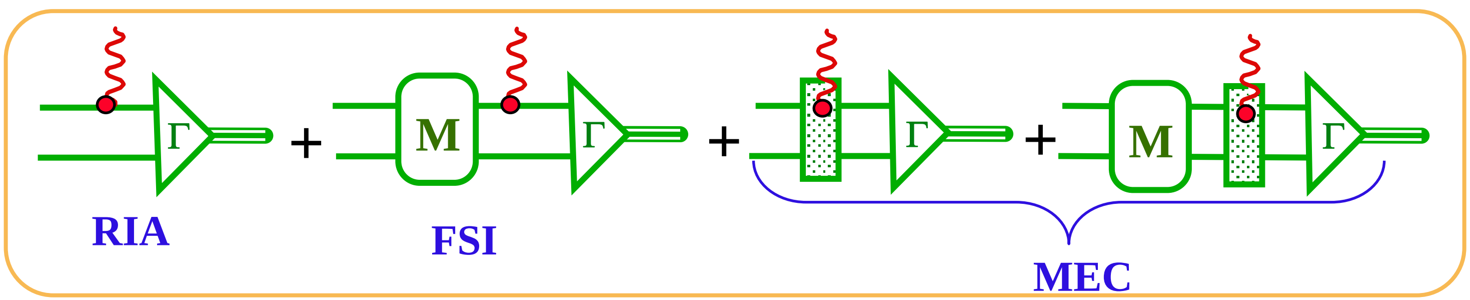
- Gauge invariant, two-body currents can then be constructed from the scattering theory. Only a finite number of amplitudes are needed:*
- there are two amplitudes for elastic scattering, which are gauge invariant if the IAC is properly constructed





IAC: photon must couple to all charged particles inside of V

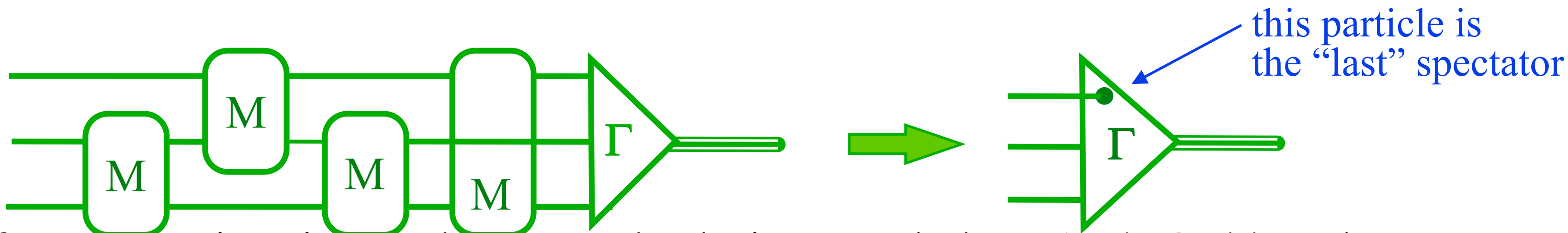
- inelastic scattering requires four amplitudes:



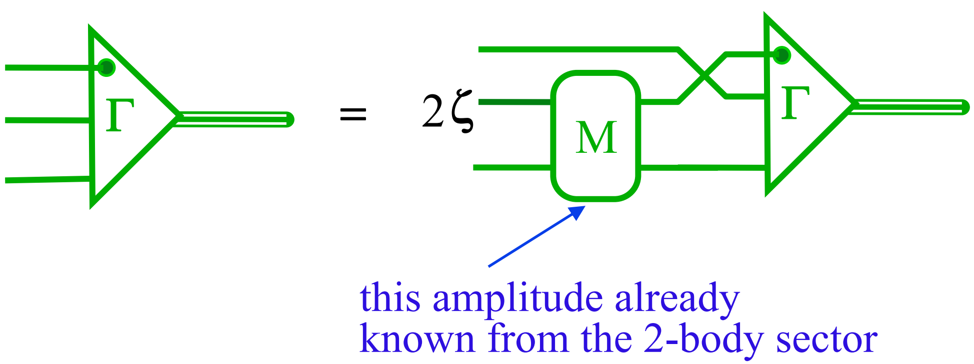
*FG and D.O. Riska

Theory overview (3 body bound state)

- three-body scattering amplitudes and vertex functions are constructed from the two-body solutions. If there no three body forces, there are three kinds of vertex function, depending on which pair was the last to interact:



- for identical nucleons, this gives the (relativistic) three body Faddeev (or AGS) equations for the relativistic vertex

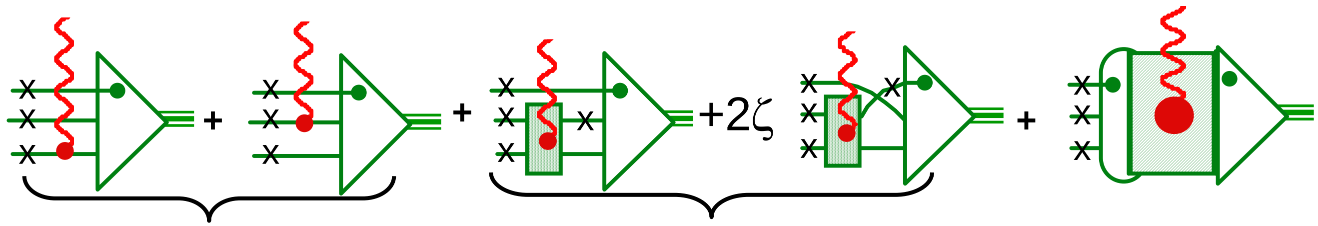


These equations in the covariant spectator theory* were solved exactly by Alfred Stadler**
($32 \rightarrow 148$ channels!)

*Alfred Stadler, FG, and Michael Frank, Phys. Rev. C 56, 2396 (1997)
**Alfred Stadler and FG, Phys. Rev. Letters 78, 26 (1997)

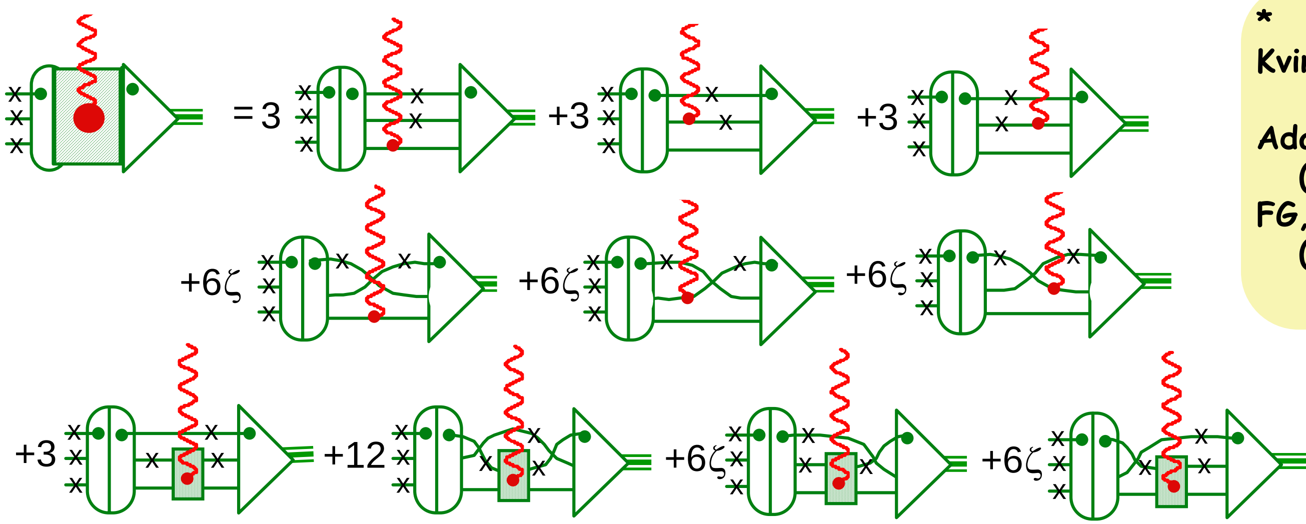
Theory overview (3 body currents - in the spectator theory)*

- The gauge invariant three-body breakup current in the spectator theory (with on-shell particles labeled by an x) requires many diagrams



RIA IAC FSI

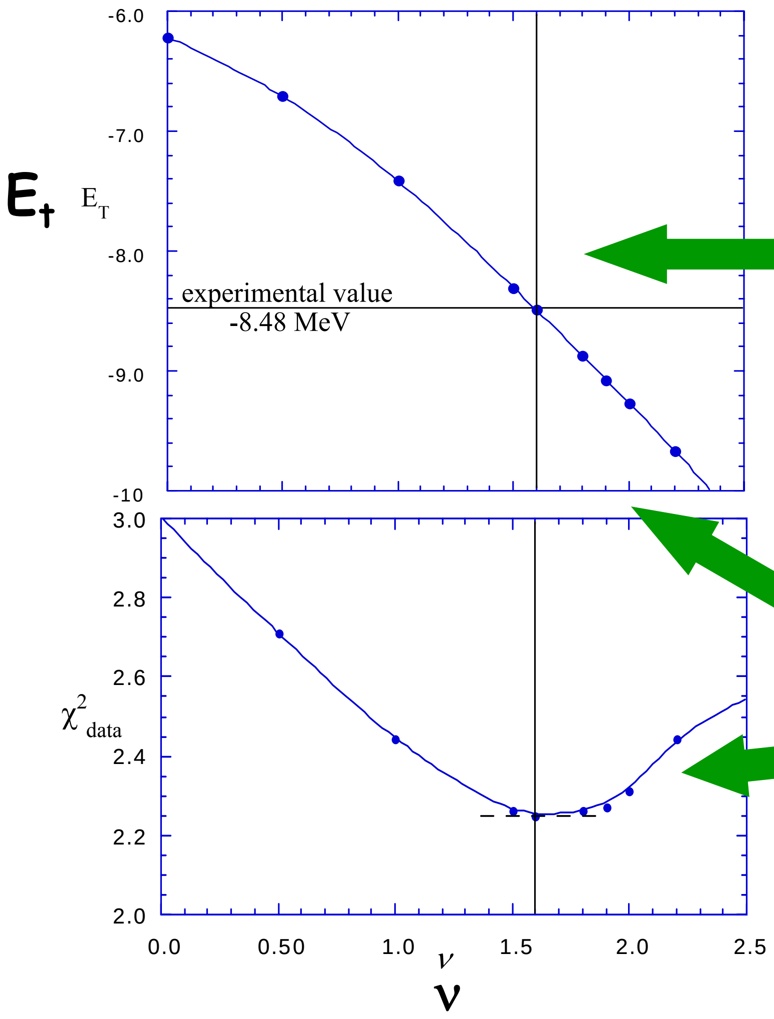
where the FSI term is



*
Kvinikhidze & Blankleider, PRC 56, 2973 (1997)
Adam & Van Orden (submitted)
FG, A. Stadler, & T. Pena (published, PRC)

Form factors currently being calculated by Stadler& student

Relativistic off-shell effects in ^3H binding*



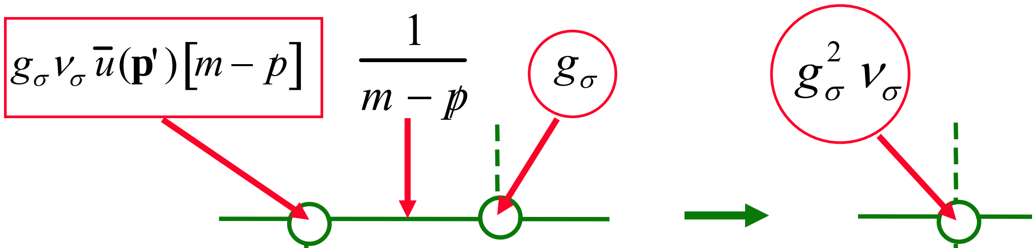
It turns out that the relativistic calculation of the three body binding energy is sensitive to a new, relativistic off-shell coupling (described by the parameter ν). Non-zero ν is equivalent to effective three-body (and n-body forces).

The value of ν that gives the correct binding energy is close to the value that gives the best fit to the two-body data!

*three body calculations done with Alfred Stadler, Phys. Rev. Letters **78**, 26 (1997)

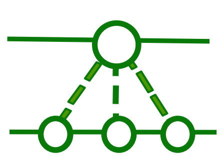
Should off-shell effects be excluded? an empty debate

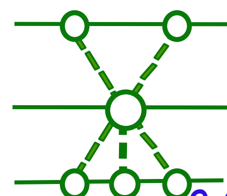
- Off shell effects ⟷ contact interactions
  - the off-shell term removes a propagator and shrinks the interaction to a point



  - This can happen in sequence with two or many bodies

3 meson exchange force





3 nucleon force

  - A theory with off-shell couplings ⟷ to another theory with NO off-shell couplings but and infinite set of selected contact interactions!

Discovery class experiments II

- (e,e'), (e,e'N) and (e,e'2N) from both few-body and large nuclei
  - look for the limits of the CHM in few body nuclei -- measure at forward direction to supress FSI
  - look for SRC
  - extend EMC measurements
  - look at large Q^2 and $x > 1$
- (e,e'K) to tag strangeness [(e,e'D) to tag charm, if possible]
- $(\vec{e},e'\vec{p})$ polarization transfer on ^{4}He and large nuclei to test modification of the proton in the nuclear medium
- "proton driver" at Fermilab: pure antineutrino beam for EMC studies to complement JLab measurements (Ron Ransome)

END