Relativistic Aspects of Few Body Physics

Franz Gross -- Jlab and W&M

Outline

- ★ Overview (3)
- ★ Progress with the 2 and 3 nucleon problem (15)
- ★ Convergence of the Bethe-Salpeter equation (5)
- ★ Relativistic treatment of the spin 3/2 Δ (3)
- ★ Current conservation with relativistic optical potentials (4)

Acknowledgements

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  - Tobias Frederico
  - Vladimir Pascalutsa
  - Wayne Polyzou
  - Gianni Salme
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- ★ Research collaboration
  - Alfred Stadler (recent)
  - Wally Van Orden (early)
  - Dick Arndt (SAID)
  - Karl Holinde and Ruprecht Machleidt (Bonn code)
- ★ Advice
  - Nijmegen group (phase shifts and fitting)

First -- why use a relativistic theory?

- ★ NOT because
  - of size of $(v/c)^2$ corrections (although they may be large in some applications)
  - it is more accurate (it may not be)
  - it is "better" than EFT (it complements EFT)
- ★ Use a covariant theory for the following reasons
  - Intellectual: to preserve an exact symmetry (Poncare' invariance)
  - Practical: to calculate boosts and Lorentz kinematics consistently to all orders (essential when energies are of the order of 1 GeV)
  - Consistent: to use field theory for guidance in the construction of
    - forces (2⇔3 body consistency)
    - currents consistent with forces
  - Conceptual: for "phenomenological economy", and to understand the non relativistic limit:
    - spin 1/2 particles (Dirac equation)
    - interpretation of L•S forces (covariant scalar-vector theory of N matter)
    - efficient one boson exchange models of NN forces (?)

Overview of relativistic methods for a fixed number of particles

★ *Hamiltonian dynamics (Dirac classification)*

demand a Hilbert space of positive energy states -- i.e. QM

discard antiparticles and lose manifest cluster separability

- front form — light cone methods (Strikman, Sargsian, Miller, Pace, Salme, Frederico, Carbonell, and Karmanov,)
- instant form — standard quantum mechanics - with relativity (Schiavilla and Arenhovel)
- point form — kinematic Lorentz group; momentum not conserved (Klink)

★ *Field dynamics (based on field theory)*

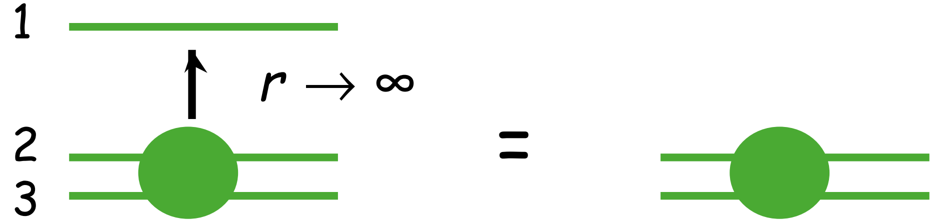
demand manifest cluster separability

requires negative energy states and we lose the Hilbert space

- Bethe- Salpeter — kinematic Poincaré group; 4-d (Tjon)
- Spectator — kinematic Poincaré group; 3-d (Gross, Van Orden, Stadler)
- equal time — integrate over x_0: (Tjon, Pascalutsa, Wallace)
- front form BS — integrate over x_+ (Carbonell and Karmanov)

Cluster separability -- 3-body example

- Definition: when one particle is far away, the interaction between the other two is the same as it would be without the third particle



- If $P = p_1 + p_2 + p_3 = 0$, and $p_1 \neq 0$, then the 23 amplitude is in a moving frame. The boost depends on the mass of the 2-body system.
- Hamiltonian dynamics is off-energy shell, $E_2 + E_3 \neq \sqrt{M_{23}^2 + \mathbf{p}_1^2}$. The energies of particles and subsystems do not match the free particle energies, and under boosts the cluster property is not easy to implement.
- Field dynamics is off-mass shell, $p_0 \neq \sqrt{m^2 + \mathbf{p}^2}$ Energy is conserved so boosts and cluster properties are easily satisfied, but off-mass shell $\Rightarrow$ negative energy states.

Progress with 2 and 3 nucleon systems

Progress with the 2- and 3-nucleon problem -- 1

Hamiltonian dynamics

- Excellent fits to the 2-body data to 350 MeV Lab energy
  - $\chi^2 \sim 1$/datum
  - *All relativistic corrections in the rest frame included phenomenologically*
- No solution of the full 3-nucleon problem (yet!)
  - S-wave Malfliet-Tjon potential: Glockle, Lee, and Coester, PRC **33**, 709 (1986)
  - V18 with *linear* boost corrections: J. Carlson, Pandharipande, and Schiavilla, PRC **47**, 484 (1993)
  - CDBonn with minimal relativity: Sammarruca and Machleidt, Few Body Systems **24**, 87 (1998)
- Three body forces needed to fit binding energy

Relativistic corrections to triton binding energy
0.2 (MeV)
{ 0.3 (boost) 0.1 (hamiltonian)
–0.3

Progress with the 2- and 3-nucleon problem -- 2

Hamiltonian dynamics

Recent study of relativistic effects in 3-nucleon problem*

*Keister and Polyzou, PRC **73**, 014005 (2006)

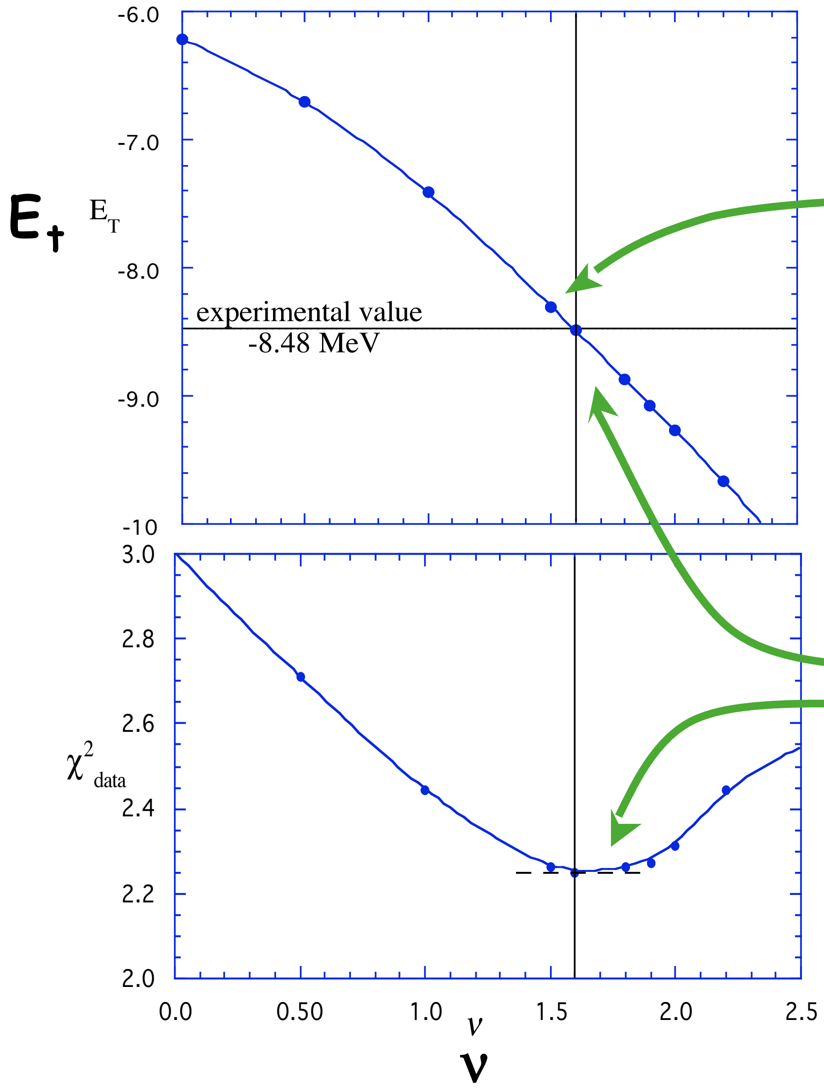
- ★ Supports the claim that effects (excluding pair terms) add positive correction to the triton binding
- ★ questions the transformation introduced by Kamada and Glockle [PRL **80**, 2547 (1998)]. In both relativistic and nonrelativistic theory, $p^2_{CM} = \frac{1}{2} m E_{\rm LAB}$, and hence the CM momenta in both relativistic and nonrelativistic equations should be the same. KG assume the CM energies are the same.
- ★ emphasizes that relativistic corrections are not unique

Progress with the 2- and 3-nucleon problem -- 3

Field dynamics

- ★ New fits to the 2-body data to 350 MeV Lab energy [model WJC(2006)]
  - $\chi^2 \sim 1.6$/datum
  - Relativistic corrections pair terms and kinematics, even in the rest frame
- ★ solution for the triton using the spectator equation
  - Model W16 (1997) gave the best fit to the data and the correct binding without three body forces
  - New WJC(2006) also fits both the data and BE
  - corrections do to pair terms of three body origin = 0.26 MeV
- ★ OBE (or EBE) models predict NO three body forces

Progress with the 2- and 3-nucleon problem* -- 4



Results from earlier W16(1997) model

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 FG and Alfred Stadler , Phys. Rev. Letters **78** , 26 (1997)

Progress with the 2- and 3-nucleon problem -- 5

Field dynamics

Recent development of a realistic EBE model for the CS©

★ OBE: One Boson Exchange usually implies:

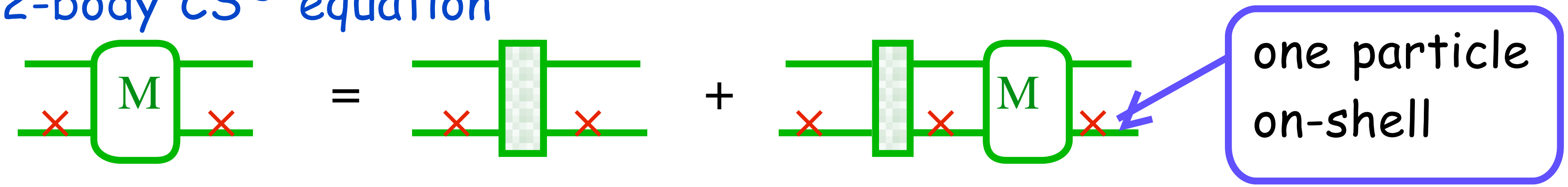
- only exchange *physical* bosons with masses less than or about one Gev, except for using the σ_0 (isoscalar) and σ_1 (isovector) to approximate TPE
- masses constrained to physical values

★ EBE: Effective Boson Exchange (defined today) differs:

- bosons are *effective* degrees of freedom only
- *except* for OPE, the masses, coupling constants, and quantum numbers are phenomenological
- general form constrained by relativistic field theory

Equations of the Covariant Spectator theory* (CS©)

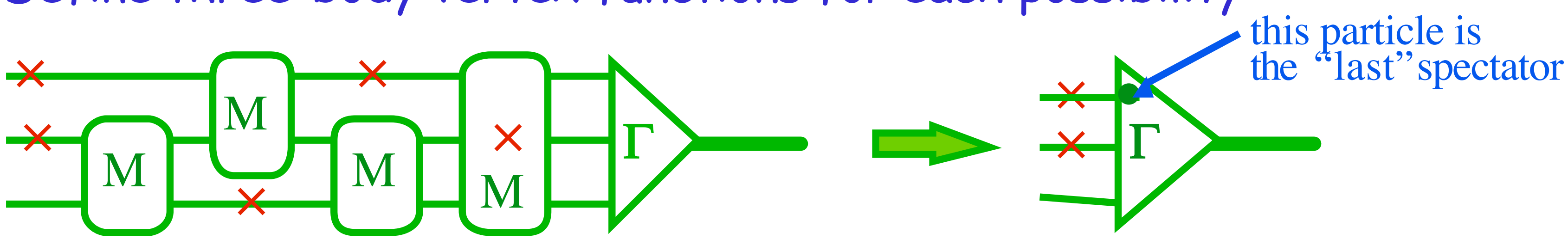
★ 2-body CS© equation



- ALL Poincare transformations are kinematic
- has a smooth one body limit

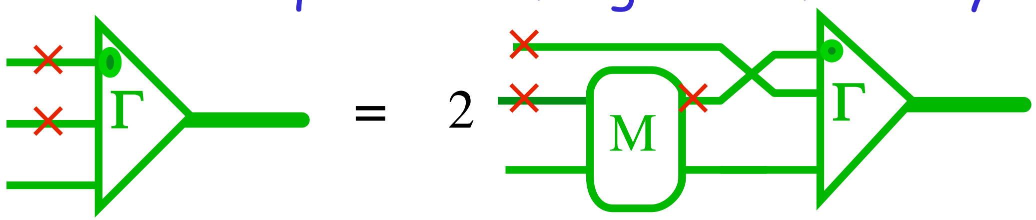
★ 3-body CS© equation

- Define three-body vertex functions for each possibility



- 3-body Faddeev-like equations emerge automatically:

Bound state equation for identical particles

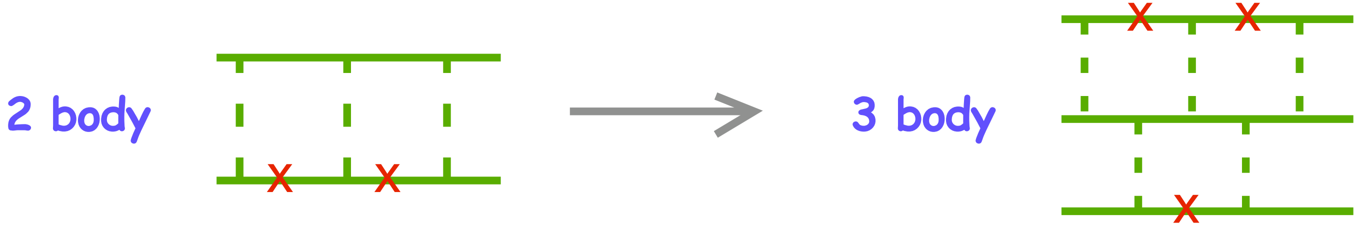


*FG, Phys. Rev. **186**, 1448 (1969)

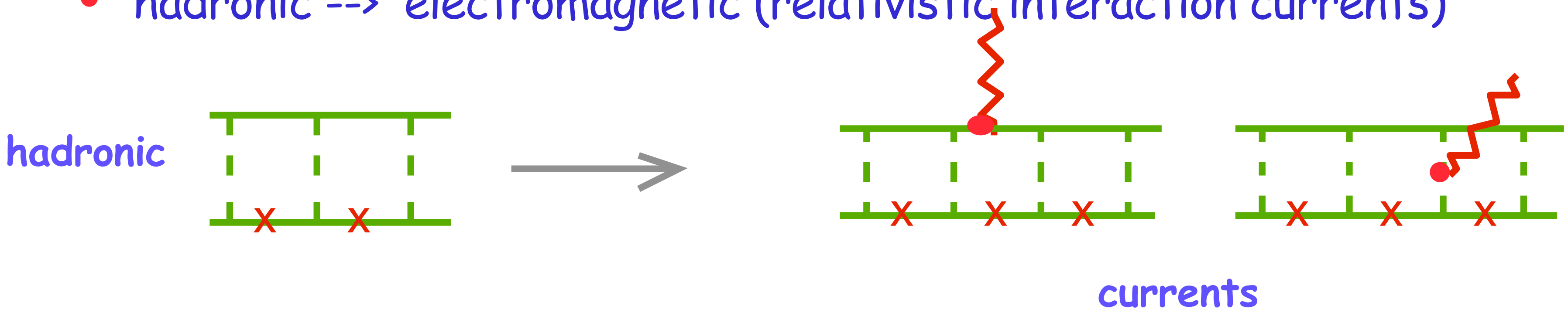
Progress with the 2- and 3-nucleon problem -- 6

Advantages of an EBE or OBE model

- ★ Connection to field theory:
- ★ Consistency:
  - 2-body --> 3-body with NO relativistic three body forces



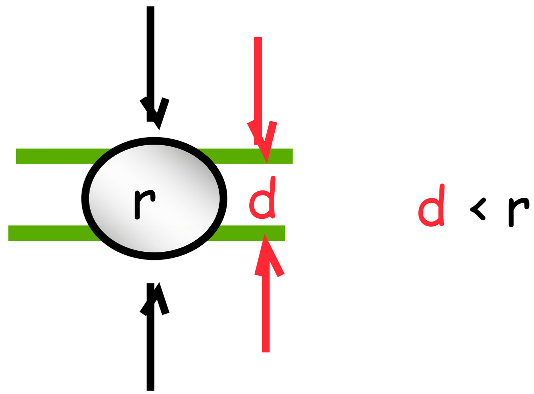
  - hadronic --> electromagnetic (relativistic interaction currents)

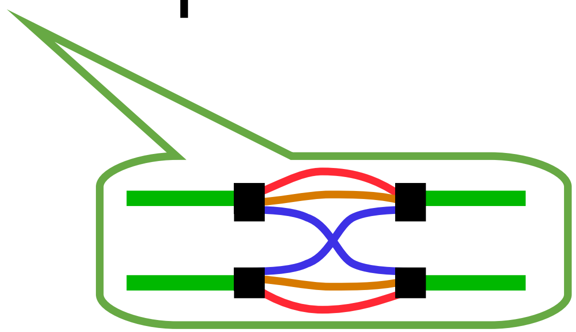


Progress with the 2- and 3-nucleon problem -- 7

Problems with the traditional OBE model

- ★ TBE is neglected (cancellation theorem proved only for scalar exchanges)
- ★ TPE is certainly important: using σ_0 and σ_1 exchanges to approximate TPE violates the spirit of OBE
- ★ Isgur's arguments:
  - exchanging bosons over a distance small compared to their size make little sense
  - why isn't quark exchange more important?
- ★ AND, IT DOESN'T WORK (!)

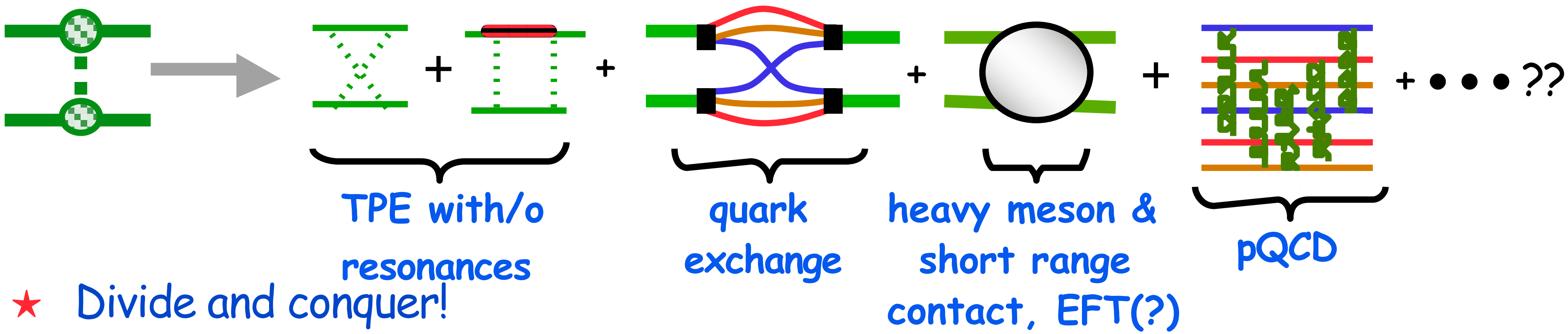




Progress with the 2- and 3-nucleon problem -- 8

Advantages of the EBE model

- ★ mesons are "effective" and are not identified with physical mesons. NO crossed diagrams are needed; they are already included.



- ★ Divide and conquer!
  - Part A: the effective bosons are determined phenomenologically and parameterize the most general interaction and include
    - TBE
    - quark exchange, etc., etc,
  - Part B: properties of the bosons calculated from fundamental principals
- ★ AND, IT WORKS!

Progress with the 2- and 3-nucleon problem -- 9

Structure of the new EBE model

- ★ Most general on-shell kernel has 5 invariants for *each isospin*, written in terms of PS, S, V(g), V(f), A couplings
- ★ pion masses constrained, and mass of V(g) = V(f), leaving 20-4=16 parameters — 16
- ★ off-shell coupling included so far
  - pion (small admixture of $\gamma_5 \neq \gamma_5 \not{q}$ off shell) — 2
  - scalar (addition of $\mathbf{1}\left(m-\not{p}\right)+\left(m-\not{p}'\right)\mathbf{1}$ term) — 2
  - vector (addition of $\gamma^\mu\left(m-\not{p}\right)+\left(m-\not{p}'\right)\gamma^\mu$ term) — 2
- ★ 3 from factor masses (N, π, and all others) — 3

Total: 25

Definitions of the EBE parameters

- Only a few off-shell terms added to the kernel so far
- Scalar: σ_0 and σ_1

$$\Lambda(p',p) = g_s + \frac{\nu_S}{2m}\left[2m - \not{p}' - \not{p}\right]$$

zero on-shell

- Pseudoscalar: π and η

$$\Lambda(p',p) = i g_P \left\{\gamma^5 - \frac{1-\nu_P}{2m}\left[\left(m - \not{p}'\right)\gamma^5 + \gamma^5\left(m - \not{p}\right)\right]\right\}$$

- Vector: ρ and ω

$$\Lambda(p',p) = g_V \left\{\gamma^\mu + \frac{\kappa_V}{2m} i\sigma^{\mu\nu}\left(p' - p\right)_\nu + \frac{\nu_V}{2m}\left[\left(m - \not{p}'\right)\gamma^\mu + \gamma^\mu\left(m - \not{p}\right)\right]\right\}$$

- Axial vector: H1 and A1

$$\Lambda(p',p) = g_A \left\{\gamma^\mu \gamma^5\right\}$$

Note: axial vector tensor couplings add no new structures

Parameters from the new WJC (25) as3.2.3 8/7/06

	$g^2/4\pi$	mass	f/g	off-shell ν
pi + and pi +	13.73	exp	---	0.01
eta	4.24	exp	---	1.72
sigma (I=0)	2.93	404	---	-4.65
sigma (I=1)	1.10	558	---	3.95
omega	3.80	508	0.06	0.56
rho	1.17	773	4.44	-1.82
axial vector (I=0)	-0.12	528	0.00	0.00
axial vector (I=1)	-0.17	513	0.00	0.00

form factor masses:

N = 1717

π = 2401

meson = 1329

Fit to the 2001 data:

χ^2/datum = 1.16

Three-nucleon bound state energy as3.2.3 8/7/06

		negative energy contribution
★ $^1S_0$ and $^3S_1$-$^3D_1$; (+) energy states only (5 channels)	-9.058	
★ all states to J=1; (+) energy states only (14 channels)	-8.364	
★ all up to J=1 (includes (-) energy; 28 channels)	-8.064	0.300
★ up to J=2 (52 channels)	-8.222	0.295
★ up to J=3 (76 channels)	-8.316	0.238
★ up to J=4 (100 channels	-8.362	0.245
★ up to J=5 (124 channels)	-8.390	0.258
★ up to J=6 (148 channels)	-8.390	0.261

★ experimental value -8.48

preliminary

Comments on WJC(25)

- The g_π that emerges from the fit agrees with Nijmegen
- the off-shell pion coupling (ν_π) is very small in agreement with chiral symmetry
- the meson masses that were adjusted are all near 500 MeV as expected if a dispersion integral is saturated by a mass near the 2π =280 MeV threshold. Only the rho is larger.
- the g_A^2 couplings are negative! What does this mean? (Results are not final!)
- the I=0 off-shell sigma coupling (ν_σ) can be adjusted to give the exact 3-body binding energy without any significant change in the χ^2/datum
- 3-body binding energies will become part of the fitting procedure!

Progress with the 2- and 3-nucleon problem -- conclusion

★ Hamiltonian dynamics

- Excellent fits to NN data with χ^2=1/datum
- 3 -body bound state calculations can be made relativistic with uncertainties of ~0.2 MeV; 3-body forces are several times larger
- There are uncertainties in how to go from nonrelativistic to relativistic

★ Field Dynamics

- Exchange of effective bosons, not real ones (except for the pion) better approximates the physics. Removes several long-standing issues.
- Axial vector mesons needed for the most general expansion of the kernel
- New fits to the NN data are a dramatic improvement. With 25 parameters, relativistic model gives a χ^2=1.16/datum, competitive with the best nonrelativsitic models.
- 3-body calculations give accurate binding energies without 3-body forces

★ Field Dynamics provides an economy and an effective theory of forces

Recent progress in Field Dynamics

- ★ Convergence of the BS equation
- ★ Relativistic treatment of the spin 3/2 Δ
- ★ Current conservation with relativistic optical potentials

Convergence of the Bethe-Salpeter equation -- 1

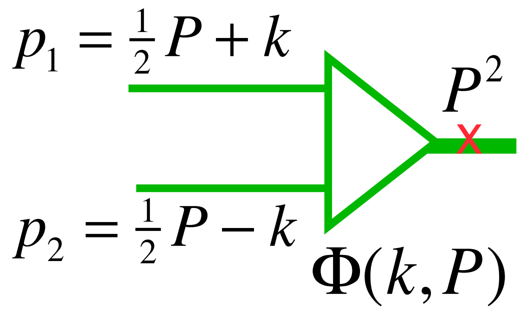
- ★ Exact BS kernel is the sum of ALL 2-nucleon irreducible processes. The ladder sum is only the simplest approximation:

- ★ at 4th order, we must add the crossed ladder

- ★ The BS equation in ladder approximation converges only if the ladder is close to the exact result and the crossed ladder is small

Convergence of the BS equation -- 2*

*Karmanov and Carbonell, Eur.Phys.J.A27:1, 2006;
Carbonell and Karmanov, Eur.Phys.J.C



- ★ Carbonell and Karmanov use the Nakanishi representation
- ★ The BS amplitude, Φ, depends on 2 variables: k^2 and $k\cdot P$, with $P^2=M^2$
- ★ Brief derivation: Starting from Feynman parameterization of the propagators

$$\frac{1}{A_+A_-} = \frac{1}{2}\int_{-1}^{1}\frac{dz}{\left(A_+\frac{1}{2}(1+z)+\frac{1}{2}A_-(1-z)\right)^2} = \frac{1}{2}\int_{-1}^{1}\frac{dz}{\left(m^2-\frac{1}{4}M^2-k^2-z\,P\cdot k-i\varepsilon\right)^2}$$

the Nakanishi representation includes additional the singularities that arise from the exchange of mesons:

$$\Phi(k,P) = \frac{1}{2}\int_{-1}^{1}dz\int_{0}^{\infty}d\gamma\,\frac{g(\gamma,z)}{\left(\gamma+m^2-\frac{1}{4}M^2-k^2-z\,P\cdot k-i\varepsilon\right)^3}$$

Convergence of the BS equation -- 3

- C&K Solve the BS equation in Minkowski space by inserting the Nakanishi representation and integrating over the light cone using the projection

$$\int_{-\infty}^{\infty} \Phi(k+\beta\omega, P)\, d\beta$$

  where ω is a light-like vector: $\omega^2=0$.

- The equation for the spectral function becomes

$$\int_0^{\infty} \frac{d\gamma' g(\gamma',z)}{\left(\gamma+\gamma'+m^2-\frac{1}{4}(1-z^2)M^2\right)^2} = \int_0^{\infty} d\gamma' \int_{-1}^{1} dz' V(\gamma z, \gamma' z')\, g(\gamma', z')$$

  where V is related to the kernel of the BS equation. It has no singularities and can be solved numerically.

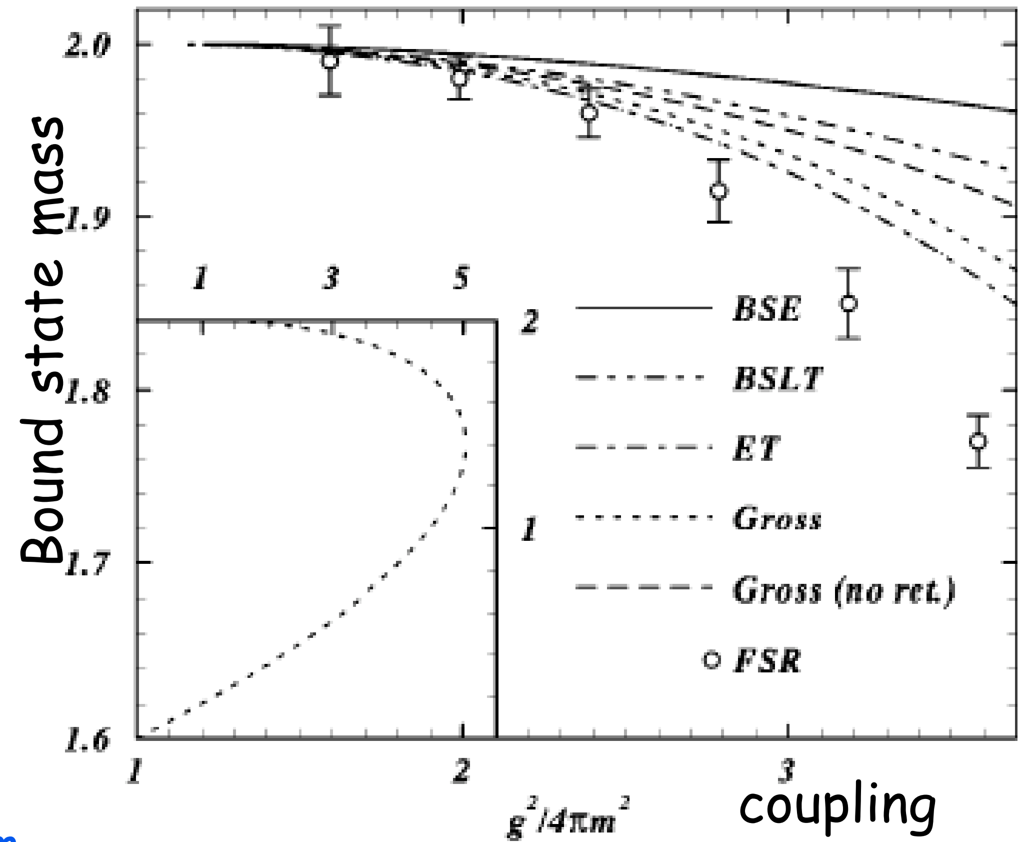
- What do we find?

Convergence of the BS equation -- 4

- For $\chi^2\varphi$ theory BE vs. g^2
  - Exact sum of ladders and crossed ladders from the Feynman-Schwinger method*
  - BS equation in (in ladder approximation) ladder fails!
  - Quasipotential equations best
- Crossed ladder contribution too small

*Nieuwenhuis and Tjon, PRL 77, 814 (1996),
*Cetin Savkli , FG, and John Tjon , Phys. Atom. Nucl.68:842,2005, Yad.Fiz.68:874,2005 and unpublished

$m_1 = m_2 = 1; \quad \mu = 0.15$



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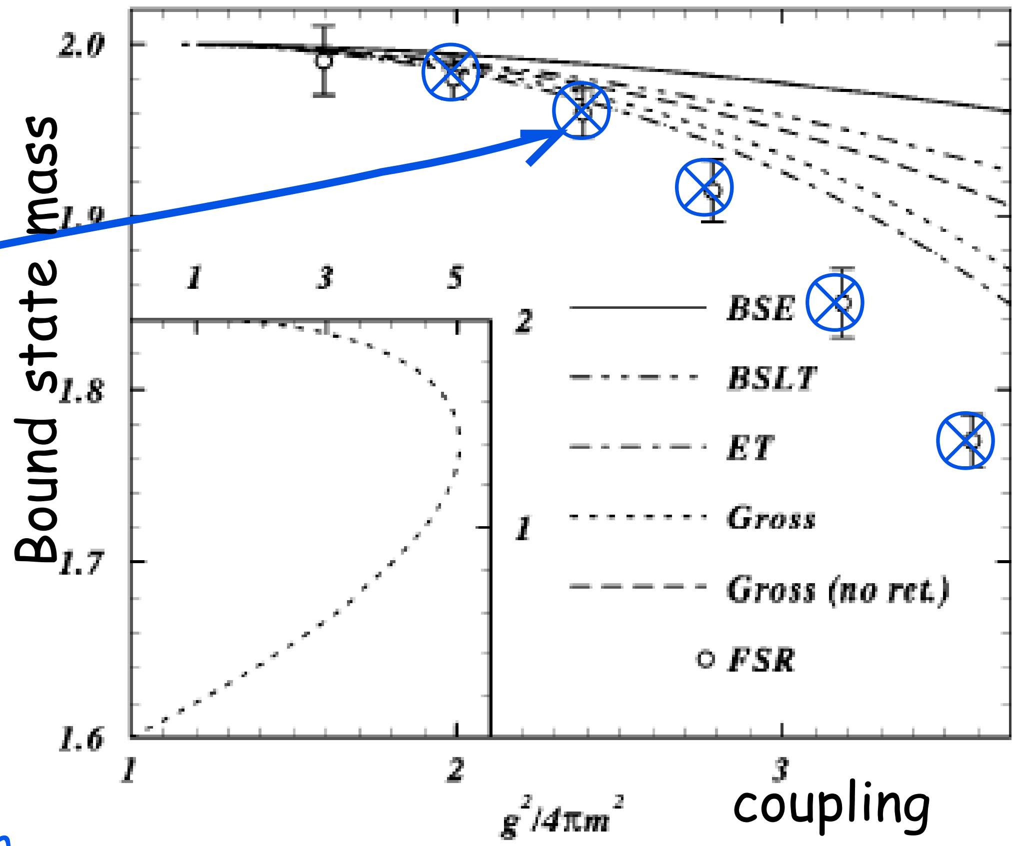

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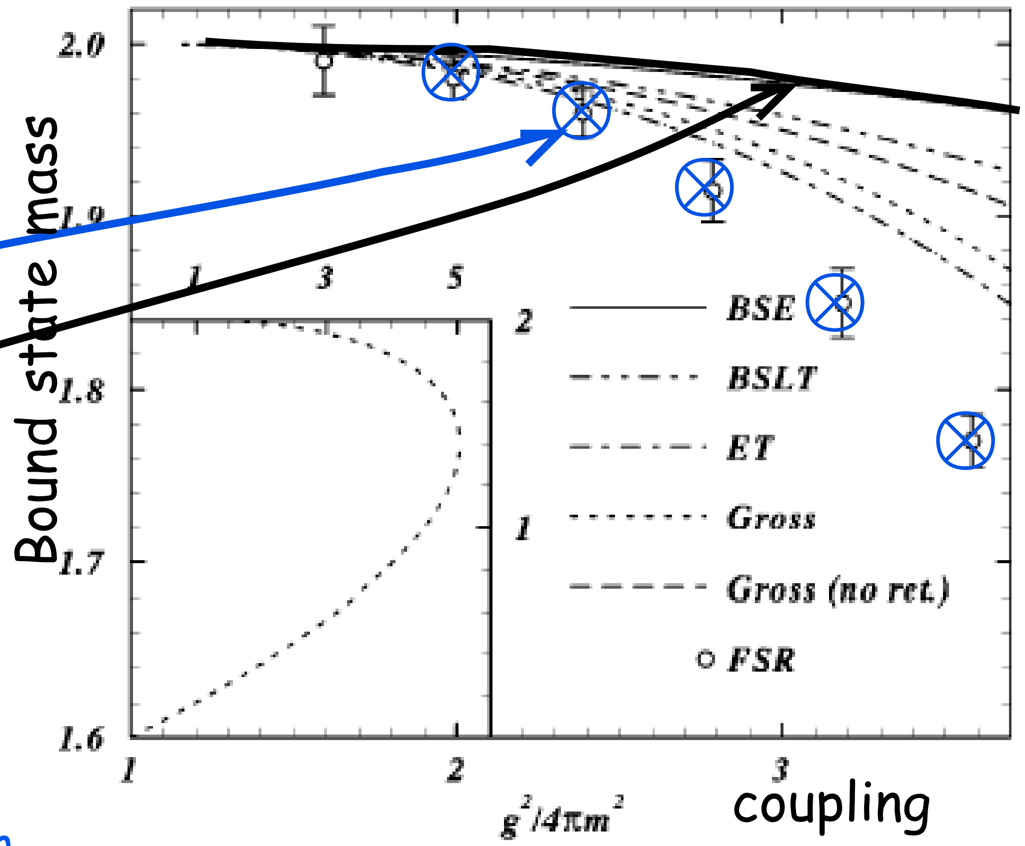

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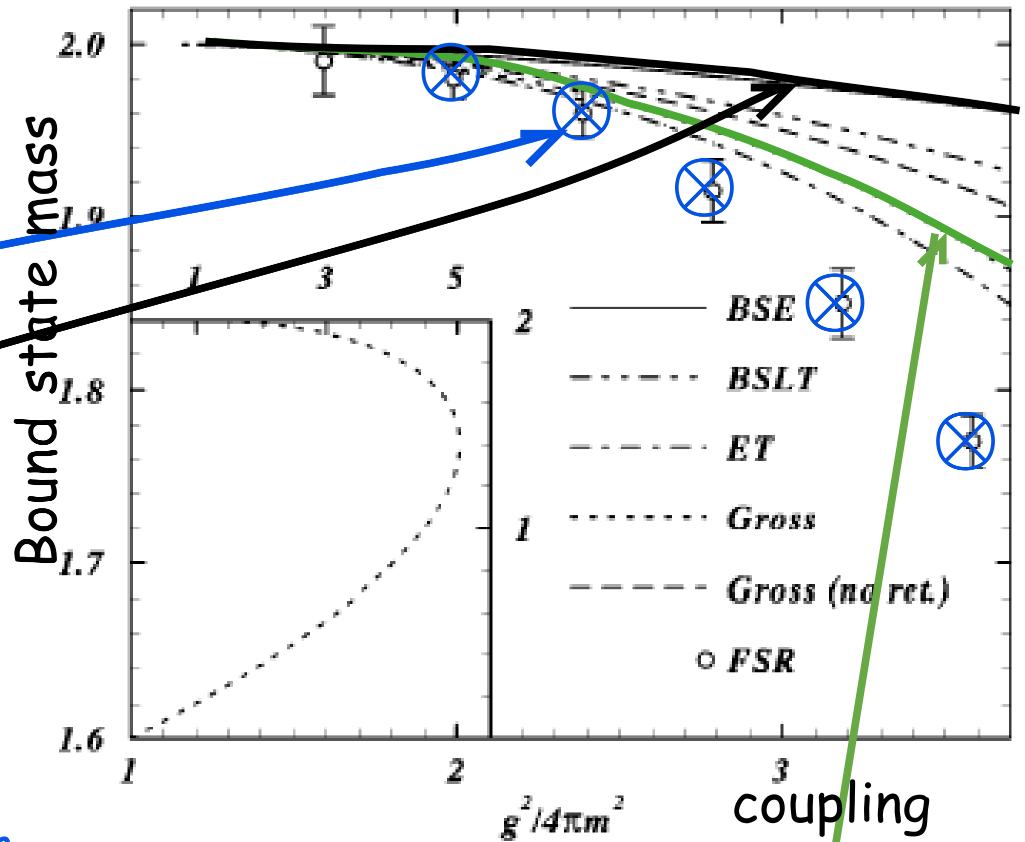

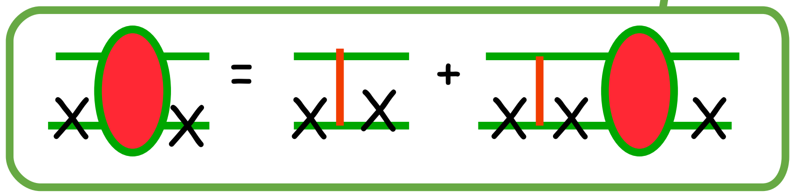

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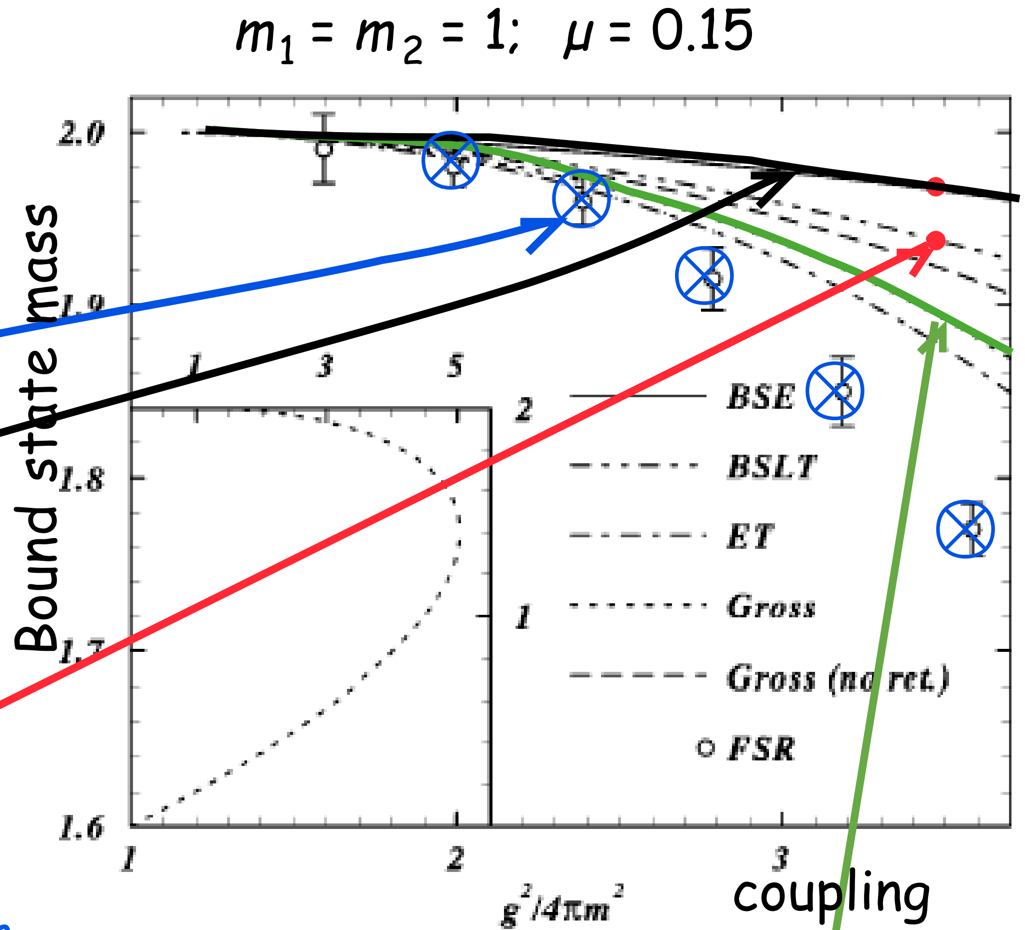

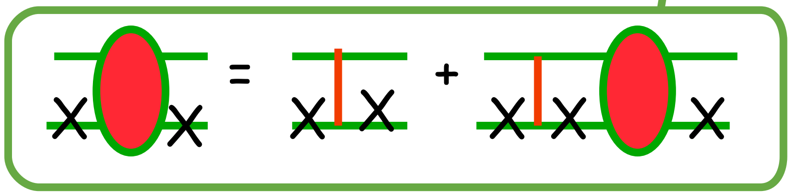

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Convergence of the BS equation -- conclusion

The BS equation, in summing all ladders and crossed ladders,

- ★ does not do as well as the spectator equation
- ★ converges slowly!

Relativistic treatment of the spin 3/2 Δ^* -- 1

*Pascalutsa, Phys. Rev. D **58** , 096002 (1998)
Pascalutsa and Timmermans , Phys. Rev. C **60**, 042201 (1999)
Pascalutsa and Phillips, Phys. Rev. C **68** , 055205 (2003)
Pascalutsa and Vanderhaeghen , Phys.Lett. **B63** , 31 (2006)

★ Old treatment of the Δ included spurious spin 1/2 components

$$S_{\mu\nu}(P) = \frac{1}{M - \not{P} - i\varepsilon}\left(g_{\mu\nu} - \frac{1}{3}\gamma_\mu\gamma_\nu - \frac{2}{3M^2}P_\mu P_\nu - \frac{1}{3M}\left(\gamma_\mu P_\nu - P_\mu\gamma_\nu\right)\right)$$

$$= \frac{1}{M - \not{P} - i\varepsilon}P^{(3/2)}_{\mu\nu} + \frac{2}{3M^2}(M + \not{P})P^{(1/2)}_{22,\mu\nu} + \frac{1}{\sqrt{3}M}\left(P^{(1/2)}_{12,\mu\nu} + P^{(1/2)}_{21,\mu\nu}\right)$$

where $$P^{(3/2)}_{\mu\nu} = g_{\mu\nu} - \frac{1}{3}\gamma_\mu\gamma_\nu - \frac{1}{3P^2}\left(\not{P}\gamma_\mu P_\nu + P_\mu\gamma_\nu\not{P}\right)$$

$$P^{(1/2)}_{22,\mu\nu} = \frac{P_\mu P_\nu}{P^2}; \quad P^{(1/2)}_{12,\mu\nu} = \frac{P^\rho i\sigma_{\mu\rho}P_\nu}{\sqrt{3}P^2}; \quad P^{(1/2)}_{21,\mu\nu} = \frac{P_\mu P^\rho i\sigma_{\rho\nu}}{\sqrt{3}P^2}$$

Note that spin 1/2 parts are all linear in P_μ or P_ν

Relativistic treatment of the spin 3/2 Δ -- 2

★ Pascalutsa considers the strong gauge invariance of the spin 3/2 field (needed to reduce the number of degrees of freedom to 4X2=8 to 4)

★ Conclusion is that strong gauge invariant couplings are needed

- the couplings often used in the past were

$$\bar{\psi}_N \Theta^{\mu\nu} \Psi_{\Delta\mu} \partial_\nu \phi_\pi \quad \text{with} \quad \Theta^{\mu\nu} = g^{\mu\nu} - \left(z + \tfrac{1}{2}\right)\gamma_\mu \gamma_\nu$$

where z is the "off-shell" parameter

- strong gauge invariance requires $\Theta^{\mu\nu} P_\nu = 0.$ This constraint insures that all spin 1/2 parts of the propagator vanish, and is not satisfied by previous couplings

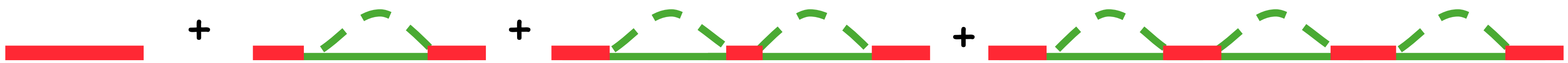
- Pascalutsa uses

$$\bar{\psi}_N \Theta^{\mu\nu} \Psi_{\Delta\mu} \partial_\nu \phi_\pi = \bar{\psi}_N \gamma_5 \gamma_\mu \varepsilon^{\mu\nu\rho\sigma} \left(\partial_\rho \Psi_{\Delta\sigma} - \partial_\sigma \Psi_{\Delta\rho}\right) \partial_\nu \phi_\pi$$

$$\Rightarrow \bar{\psi}_N \gamma_5 \gamma_\mu k_{\pi\nu} \varepsilon^{\mu\nu\rho\sigma} \left(P_\rho \Psi_{\Delta\sigma} - P_\sigma \Psi_{\Delta\rho}\right)$$

Relativistic treatment of the spin 3/2 Δ -- Conclusion

- ★ The strong gauge invariant treatment solves a long standing problem -- the Δ can now be treated and a pure spin 3/2 particle.
- ★ Technical simplifications abound. The bubble sum can be computed easily:



$$P_{\mu\nu} \quad + \Theta_{\mu\rho} B g^{\rho\rho'} \Theta_{\rho'\nu} \quad + \Theta_{\mu\rho} B g^{\rho\rho'} \Theta_{\rho'\sigma} B g^{\sigma\sigma'} \Theta_{\sigma'\nu} \quad + \Theta_{\mu\rho} B g^{\rho\rho'} \Theta_{\rho'\sigma} B g^{\sigma\sigma'} \Theta_{\sigma'\omega} B g^{\omega\omega'} \Theta_{\omega'\nu} + \cdots$$

$$= \frac{\Theta_{\mu\nu}}{1-B}$$

See: FG and Surya, Phys. Rev. **C** 47, 703 (1993)

- ★ A relativistic Effective Field Theory can be (and has been) developed

Current conservation with relativistic optical potentials* -- 1

*J. W. Van Orden, nucl-th/0605031

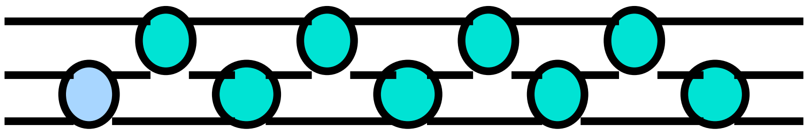
- Long standing problem -- how to do a gauge invariant calculation of $A(e,e'p)X$ when A is large. The usual matrix element is

$$J^\mu = \langle \psi_{p',s'} | \Gamma^\mu(q) | \psi_{n\kappa m} \rangle$$

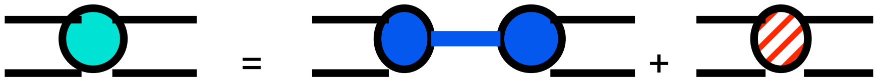
- Problem is that the optical potential used in the Hamiltonian is not the same for initial and final states.
- For this reason it does not conserve current.
- Problem was solved for $A=3$ some time ago.
- New result is to construct optical potential from exact result
- $A=3$ result will be generalized to all A.

Current conservation with relativistic optical potentials -- 2

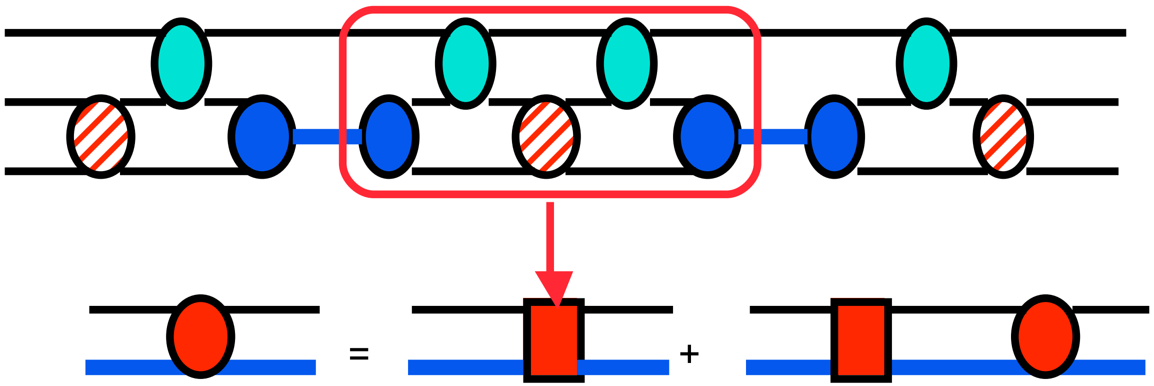
★ To illustrate the problem, consider non-identical nucleons with 12 and 23 interactions only. The most general Feynman diagram is



★ Isolate the deuteron (23) bound state contribution



★ Then the optical potential for 1 scattering from the 23 bound state is

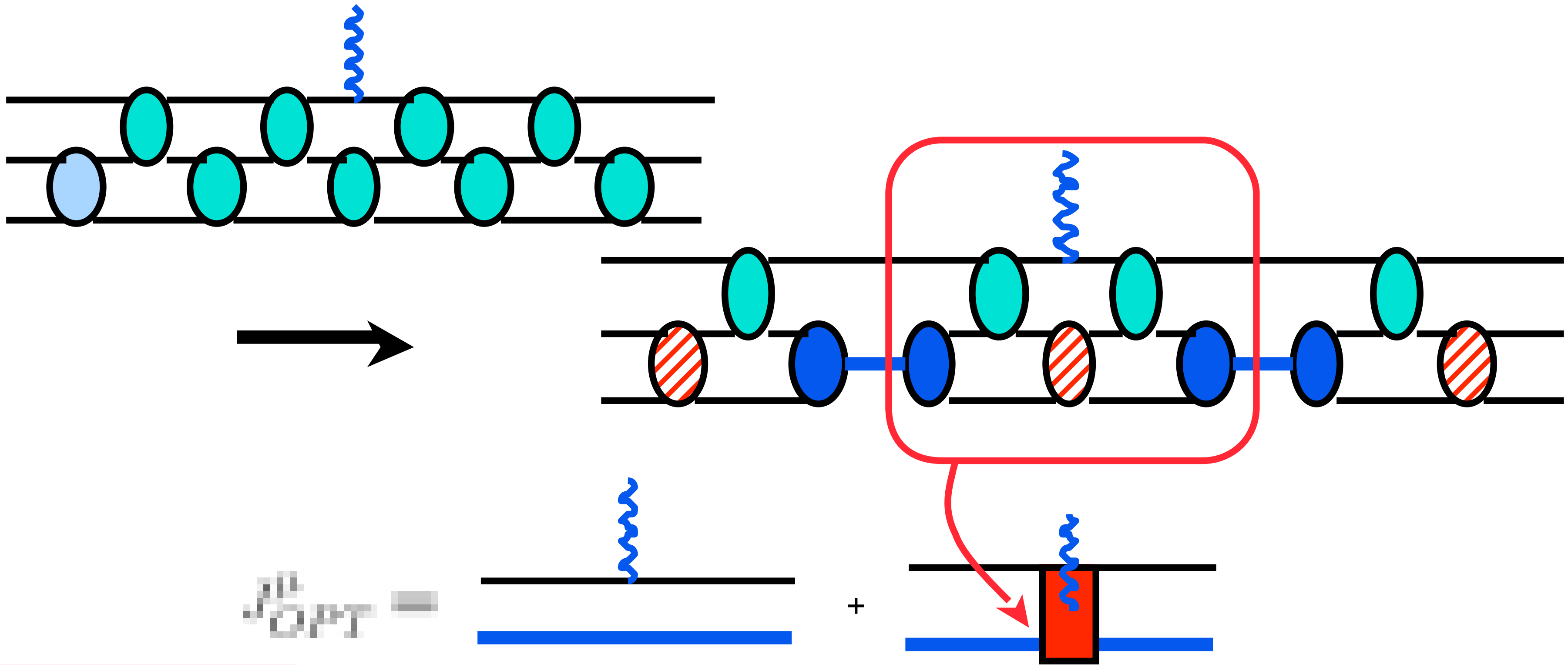


Current conservation with relativistic optical potentials -- 3

★ The optical potential for particle 1 +(23) is a 3-body T matrix with

- *no bound state poles for particles 2 and 3*
- *first and last interactions cannot be a 2-body scattering between 2 & 3*

★ Add current interaction with particle 1



Current conservation with relativistic optical potentials -**conclusion**

- Combining this with the construction of conserved currents introduced in 1987* and proved for three body interactions** we can show that this construction conserves current.
- This will provide a systematic basis for optical model approximations.

*FG and Riska, PRC **36**, 1928 (1987)

**Kvinikhidze & Blankleider, PRC 56, 2973 (1997)
Adam & Van Orden, PRC 71: 034003 (2005)
FG, A. Stadler, & T. Pena, PRC 69: 034007 (2004)

Overall Conclusions

- ★ Progress with the 2 and 3 nucleon systems using CS © Field Dynamics
  - new accurate fit to the NN data with $\chi^2 \sim 1.16$/datum
  - correct 3-body binding energy without 3-body forces
  - manifestly covariant with cluster separability and all spin effects included
- ★ BS equation with 4th order crossed ladder kernel has been solved
  - uses Nakanishi representation and a new light-cone projection technique
  - convergence is not good.
- ★ Major advance in the relativistic treatment of spin 3/2 states
  - strong gauge invariance limits the number of degrees of freedom
  - propagators reduce to spin 3/2 projection operators with spurious spin 1/2 degrees of freedom decoupled from the physics
  - relativistic EFT of N and Δ coupled system
- ★ Development of a current conserving optical model for (e,e'p) applications

- END

Phase shifts -- comparison between EBE-C and Nijmegen

A large discrepancy!