JLab, Sep 27, '23

A brief hystory of the "basic model" of nuclei

R. Schiavilla, ODU/JLab

* The "basic model": focus on EW currents (late '60 through to early '00)

- the early phase
- the sequel
- nuclear axial current
- nuclear charge form factors
- realistic nuclear EW currents

* Advent of χEFT (post early '00)

The basic model

* Effective interactions and EW currents

$$H = \sum_i \frac{\bar{p}_i^{\,2}}{2m} + \sum_{i<j} v_{ij} + \sum_{i<j<k} V_{ijk} + \dots$$

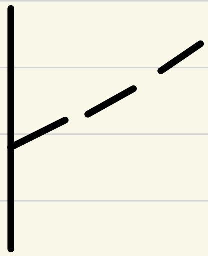
$$j^{EW} = \sum_i j_i + \sum_{i<j} j_{ij} + \sum_{i<j<k} j_{ijk} + \dots$$

* Assumptions:

(i) quarks in nuclei are in color singlet states like N (and low-lying excitations such as Δ)

(ii) series of interactions and currents converges rapidly

(iii) dominant terms in v_{ij} (j_{ij}) and V_{ijk} (j_{ijk}) due to π-exchange



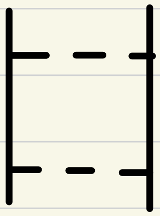
$$\frac{g_A}{2f_\pi} \tau_a \bar{\sigma}\cdot\bar{\nabla}\phi_a(\bar{r})$$

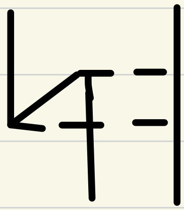
↖ pion field

Early phase

* G.E. Brown and collaborators' efforts to construct a realitic NN interaction from ME (late '60 to early '70)

* 2π-exchange in PS coupling led inevitably to overbinding

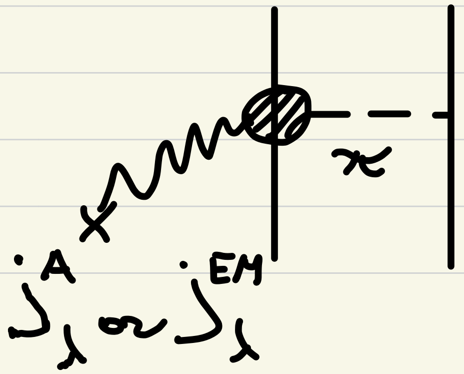




pair diagram

pair suppression built into Weinberg's chiral Lagrangian for πN interactions (PV coupling) revived efforts

* Concurrently, Chemtob and Rho ('71) constructed MEC from effective Lagrangians for π and vector mesons



ρ-exchange reduces tensor component induced by π-exchange in NN interaction and enhances effects of π-exchange current

* A pioneering study of axial MEC effects in ^{3}H β-decay with simple ^{3}H/^{3}He central w.f.'s

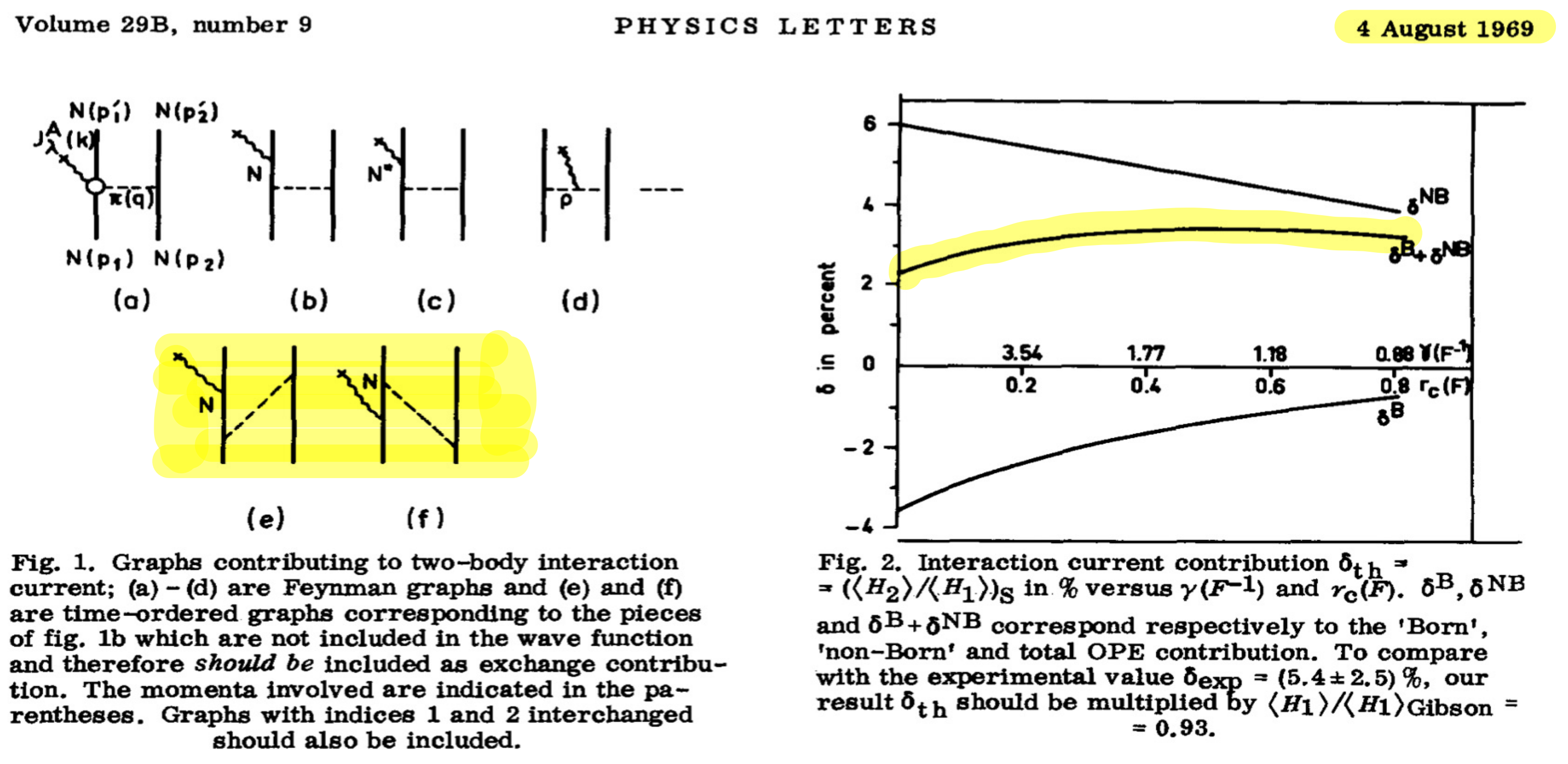


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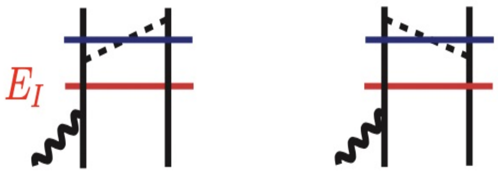
Fig. 1. Graphs contributing to two-body interaction current; (a) – (d) are Feynman graphs and (e) and (f) are time-ordered graphs corresponding to the pieces of fig. 1b which are not included in the wave function and therefore *should be* included as exchange contribution. The momenta involved are indicated in the parentheses. Graphs with indices 1 and 2 interchanged should also be included.

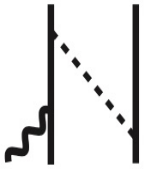
Fig. 2. Interaction current contribution $\delta_{th} = (\langle H_2\rangle/\langle H_1\rangle)_S$ in % versus $\gamma(F^{-1})$ and $r_c(F)$. δ^B, δ^{NB} and $\delta^B + \delta^{NB}$ correspond respectively to the 'Born', 'non-Born' and total OPE contribution. To compare with the experimental value $\delta_{exp} = (5.4 \pm 2.5)$ %, our result δ_{th} should be multiplied by $\langle H_1\rangle/\langle H_1\rangle_{\rm Gibson} = 0.93$.

Chemtob and Rho

* Comment:



$$= v^\pi \left(1 + \frac{E_i - E_I}{\cancel{2\,\omega_\pi}}\right) \frac{\cancel{1}}{E_i - E_I}\,\mathbf{j}^{\rm LO}$$

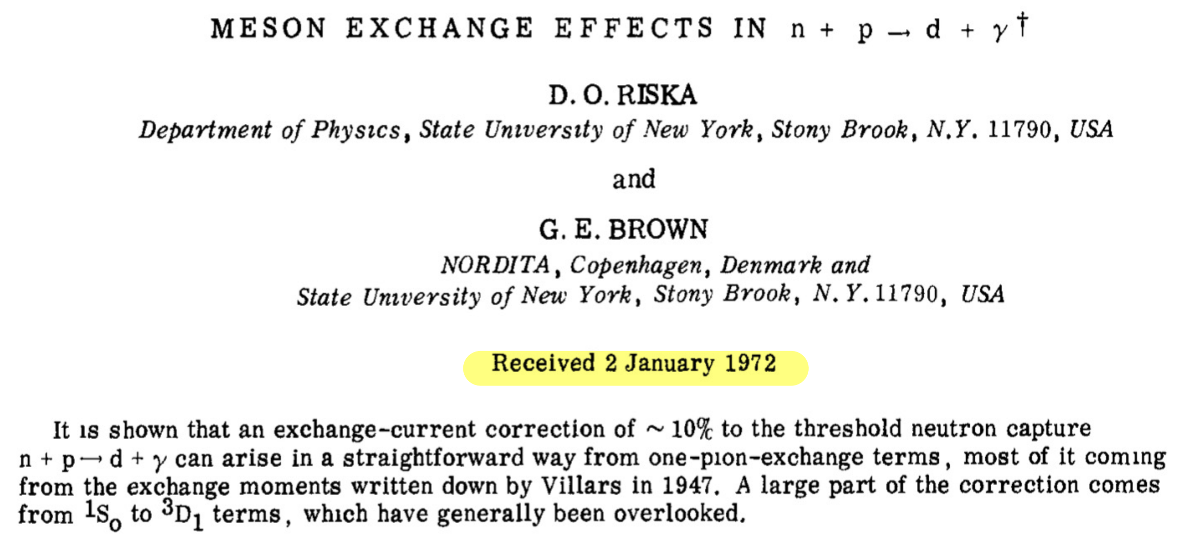


$$= -\cancel{\frac{v^\pi}{2\,\omega_\pi}\,\mathbf{j}^{\rm LO}}$$

cancel to leading order

The sequel

- G.E. Brown's interest in the role of MEC was stimulated by Chemtob-Rho calculation of ^3H β-decay
  - relevance of D-state components in few-body nuclei wave functions (Rho, '70; Blomqvist, '70)
- First demonstration that MEC play a role in photonuclear observables



MESON EXCHANGE EFFECTS IN $n + p \to d + \gamma$ †

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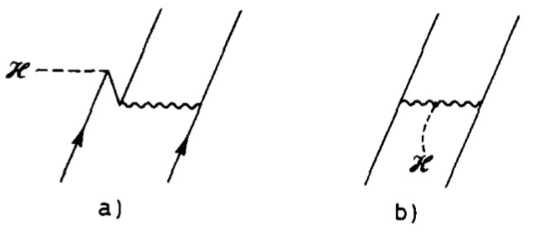
Received 2 January 1972

It is shown that an exchange-current correction of ~ 10% to the threshold neutron capture $n + p \to d + \gamma$ can arise in a straightforward way from one-pion-exchange terms, most of it coming from the exchange moments written down by Villars in 1947. A large part of the correction comes from $^1S_0$ to $^3D_1$ terms, which have generally been overlooked.

- MEC contributions:



a) Pair processes b) Pion current process

important in β-decay of ^3H (Blomqvist, '70)

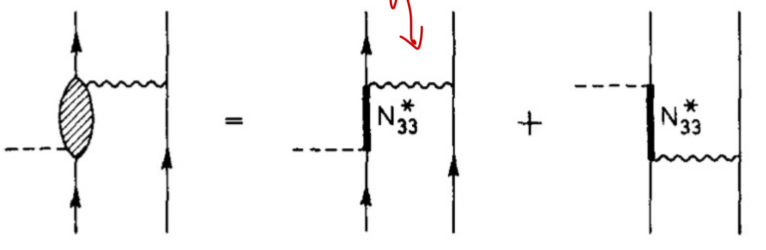
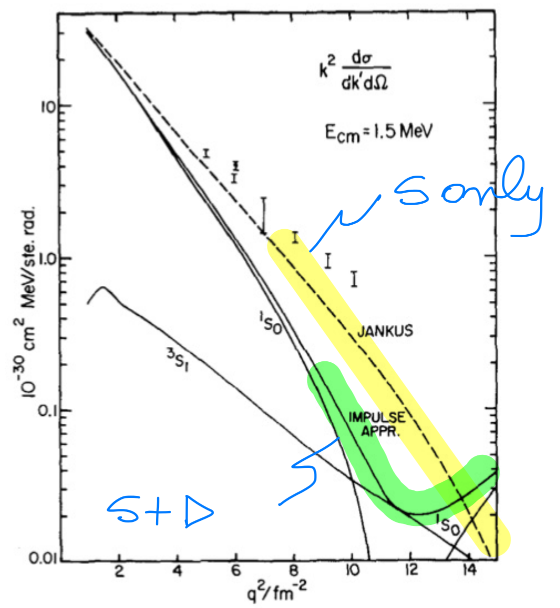


Fig. 2. Exchange-current correction arising from vertex corrections.

- Importance of $^3D_1 \to {}^1S_0$ transition

* And many other observables in which MEC play an important role

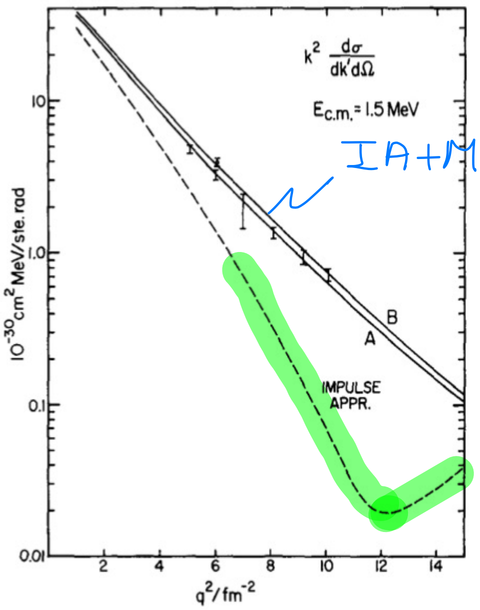
— d(e,e')pn at threshold



S only

S+D

Fig. 5. The impulse approximation cross section for $E_{c.m.} = 1.5$ MeV. The notation is the same as in fig. 4.

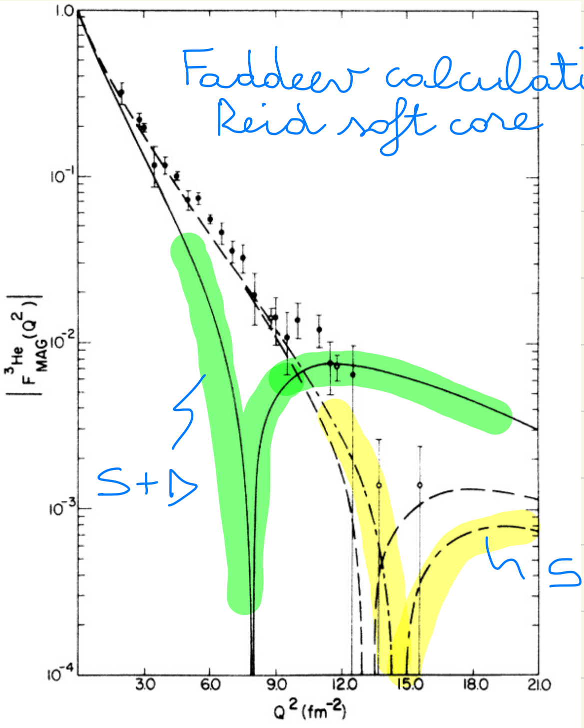


IA+MEC

Fig. 9. The cross section for $E_{c.m.} = 1.5$ MeV. The notation is the same as in fig. 8.

Hockert, Riska, Gari, and Huffman ('73)

— ^{3}He m.f.f.

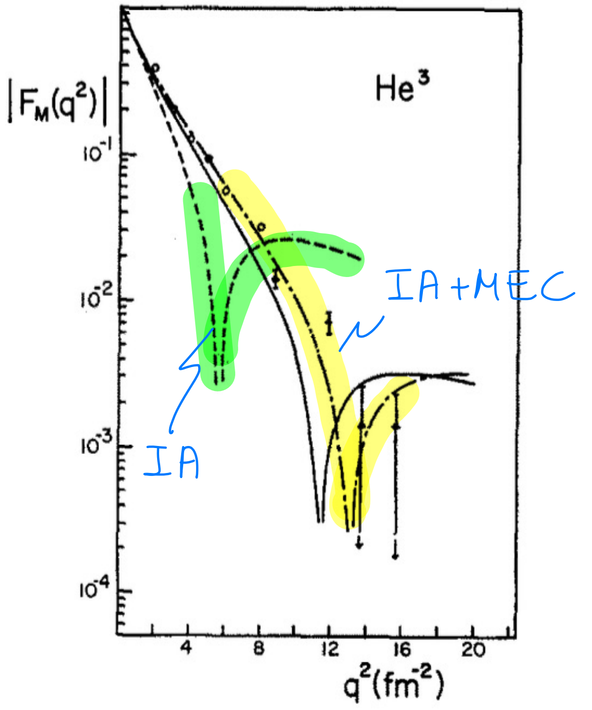


Faddeev calculation
Reid soft core

S+D

S only

Brandenburg, Kim, and Tubis ('74)



IA+MEC

IA

Barroso and Hadjimichael ('75)

— nd and n^{3}He radiative captures

M1 processes:

		σ_{exp} (mb)
	$^1H(n,\gamma)^2H$	334.2 (5)
suppressed	$^2H(n,\gamma)^3H$	0.508(15)
	$^3He(n,\gamma)^4He$	0.055(3)

- ^{3}H and ^{4}He bound states are approximate eigenstates of the 1b M1 operator

$$\mu(1b)|^3H\rangle \simeq \mu_p |^3H\rangle$$

ignoring D-state components

- $\langle nd|\mu(1b)|^3H\rangle \simeq 0$ by orthogonality

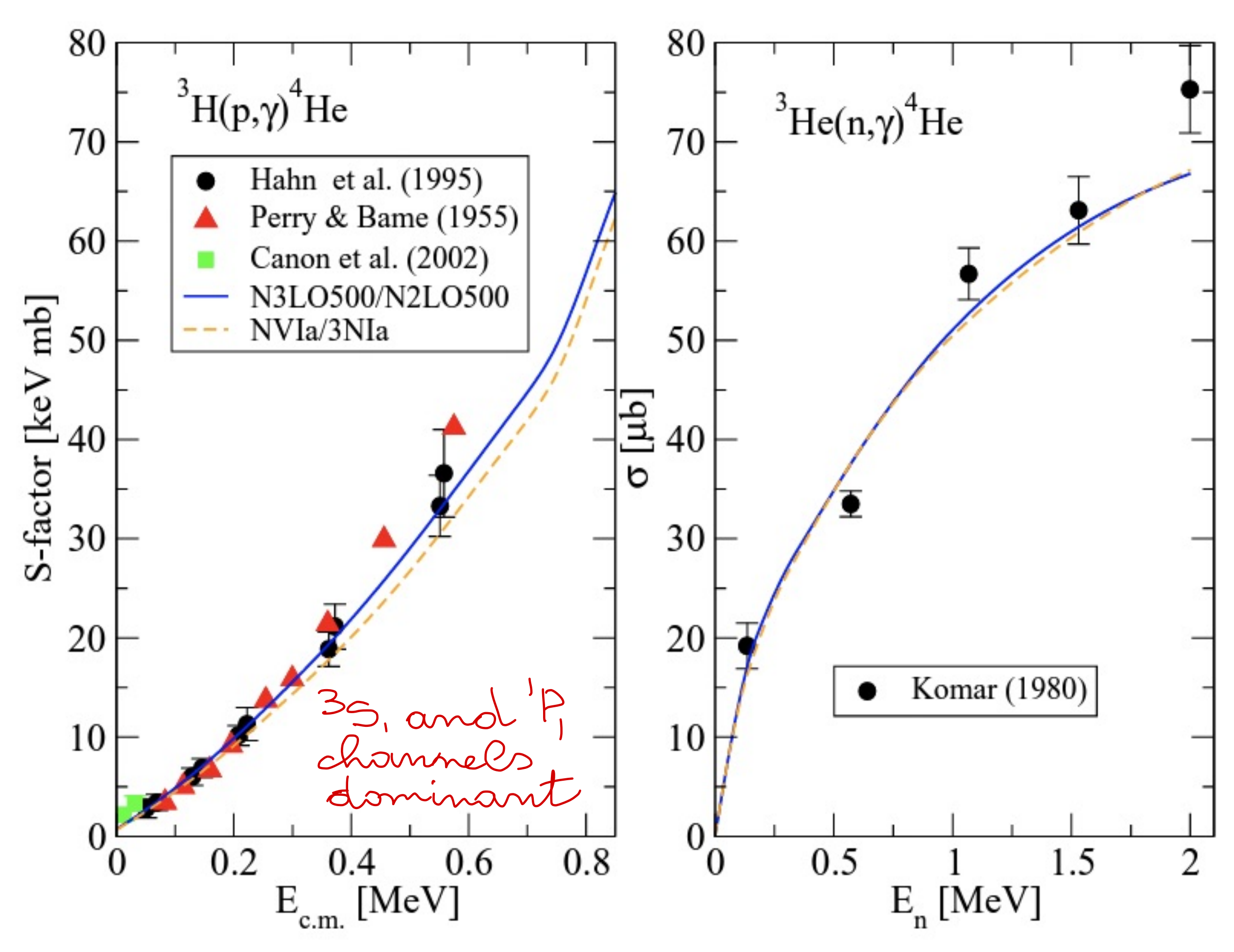
- Of course, 1b M1 does contribute (D-state components), but MEC account for

$\sim$ 50% of σ_{exp} in nd (Hadjimichael, '73)

$\sim$ 80% of σ_{exp} in n^{3}He (Towner and Khanna, '81)

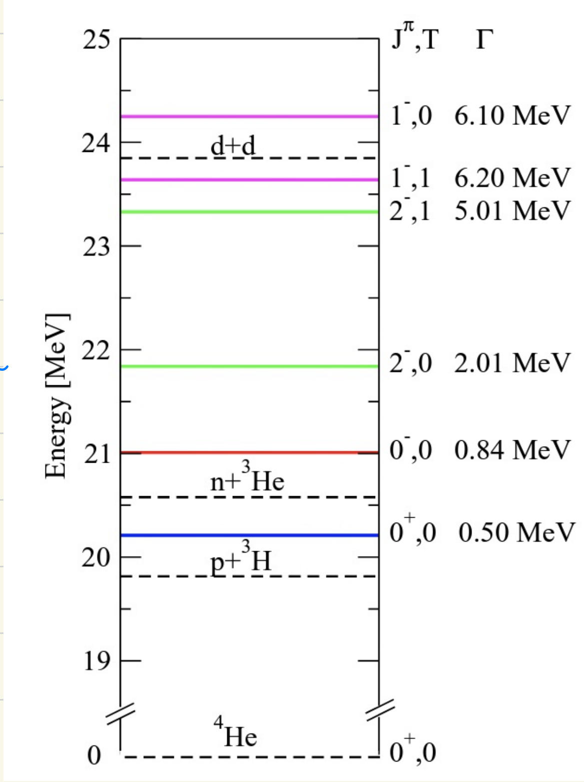
- Theoretical estimates for these radiative captures have been (and continue to be) refined by our group ('90-present) and others (Friar et al)

- State-of-the-art calculation (Viviani et al, '22)



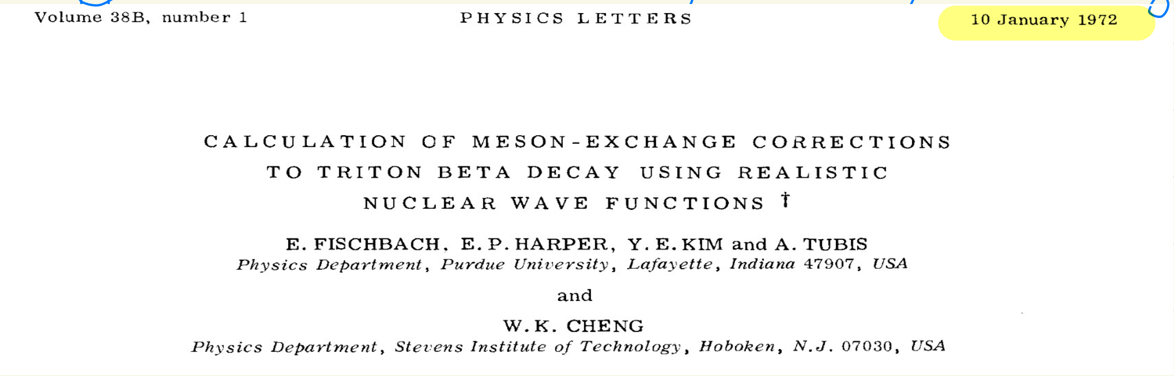
$^3S_1$ and $^1P_1$ channels dominant

low-energy spectrum of ^4He



Nuclear axial current

- Role of axial MEC in ^{3}H β-decay was confirmed



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CALCULATION OF MESON-EXCHANGE CORRECTIONS TO TRITON BETA DECAY USING REALISTIC NUCLEAR WAVE FUNCTIONS †

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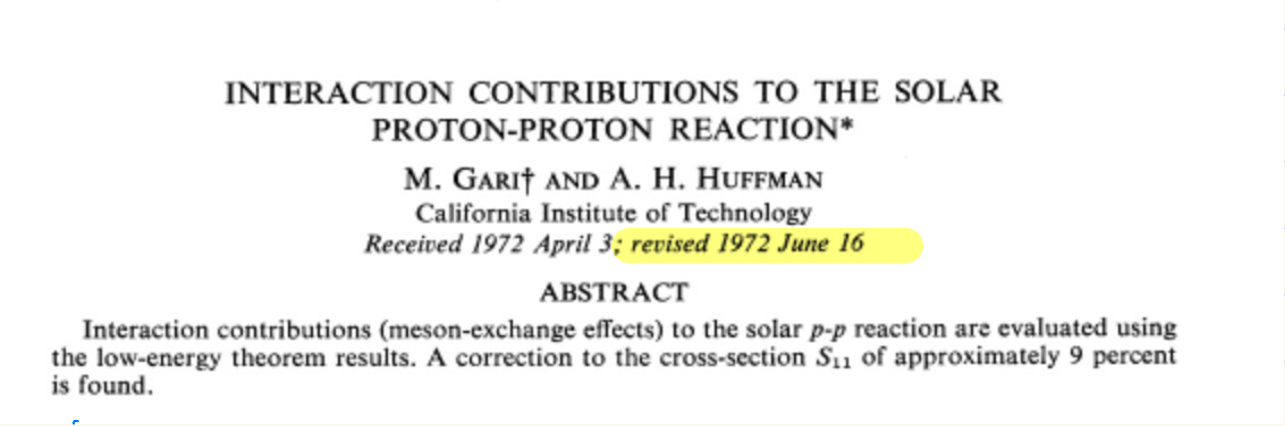
- MEC-induced enhancement of ^{1}H(p, e^+ ν_e)^{2}H cross section relevant in solar physics



INTERACTION CONTRIBUTIONS TO THE SOLAR PROTON-PROTON REACTION*

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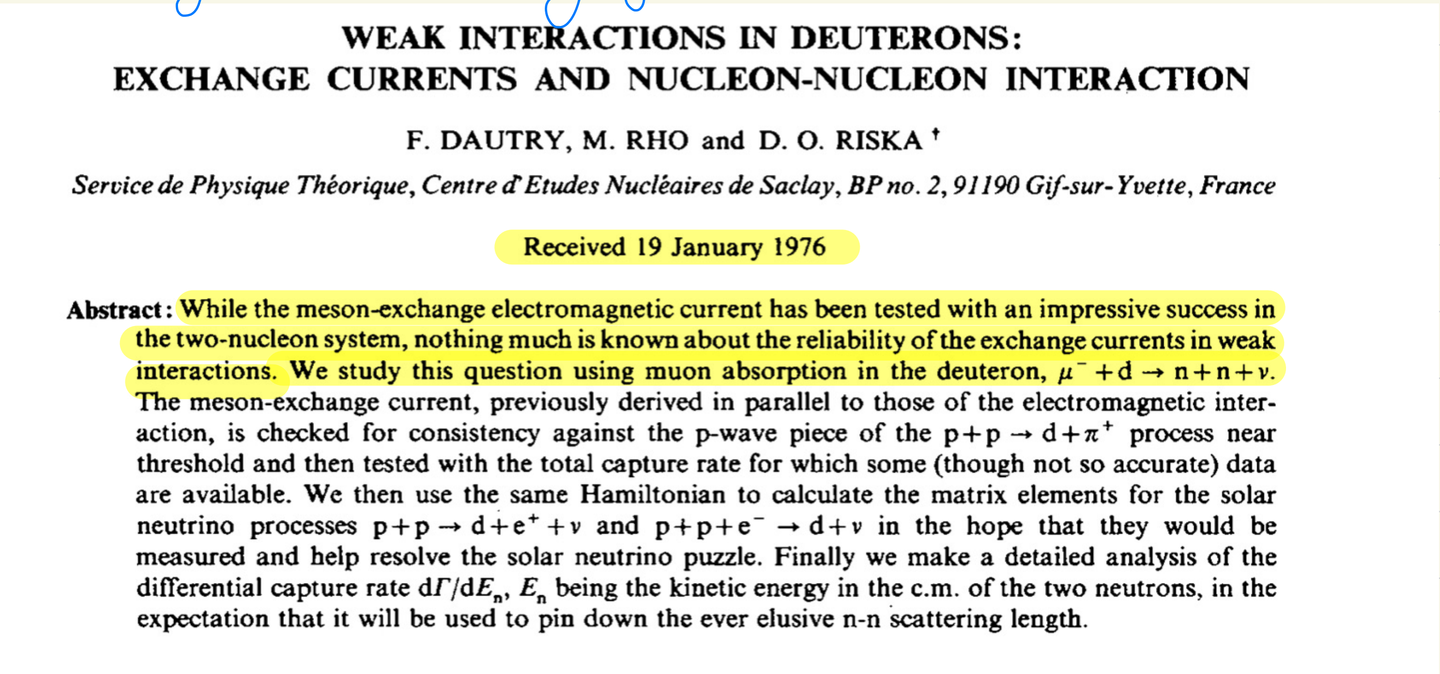
California Institute of Technology

Received 1972 April 3; revised 1972 June 16

ABSTRACT

Interaction contributions (meson-exchange effects) to the solar *p-p* reaction are evaluated using the low-energy theorem results. A correction to the cross-section S_{11} of approximately 9 percent is found.

- Testing the modeling of axial MEC



WEAK INTERACTIONS IN DEUTERONS: EXCHANGE CURRENTS AND NUCLEON-NUCLEON INTERACTION

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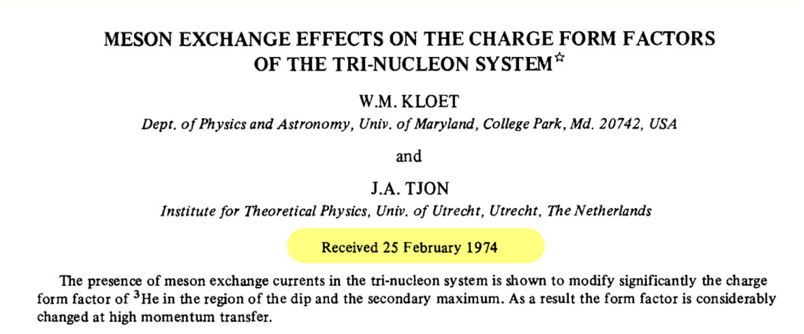
Received 19 January 1976

Abstract: While the meson-exchange electromagnetic current has been tested with an impressive success in the two-nucleon system, nothing much is known about the reliability of the exchange currents in weak interactions. We study this question using muon absorption in the deuteron, $\mu^- + d \rightarrow n + n + \nu$. The meson-exchange current, previously derived in parallel to those of the electromagnetic interaction, is checked for consistency against the p-wave piece of the $p + p \rightarrow d + \pi^+$ process near threshold and then tested with the total capture rate for which some (though not so accurate) data are available. We then use the same Hamiltonian to calculate the matrix elements for the solar neutrino processes $p + p \rightarrow d + e^+ + \nu$ and $p + p + e^- \rightarrow d + \nu$ in the hope that they would be measured and help resolve the solar neutrino puzzle. Finally we make a detailed analysis of the differential capture rate $d\Gamma/dE_n$, E_n being the kinetic energy in the c.m. of the two neutrons, in the expectation that it will be used to pin down the ever elusive n-n scattering length.

Nuclear charge form factors

- Phenomenological success of EM MEC was mainly due to $\gamma\pi N$ coupling
- Corresponding contributions to nuclear charge operator involve higher powers of the momentum transfer
- Kloet and Tjon pointed out that there is a sizable contribution in the $^3He/^3H$ charge f.f.



MESON EXCHANGE EFFECTS ON THE CHARGE FORM FACTORS OF THE TRI-NUCLEON SYSTEM☆

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Received 25 February 1974

The presence of meson exchange currents in the tri-nucleon system is shown to modify significantly the charge form factor of ^{3}He in the region of the dip and the secondary maximum. As a result the form factor is considerably changed at high momentum transfer.

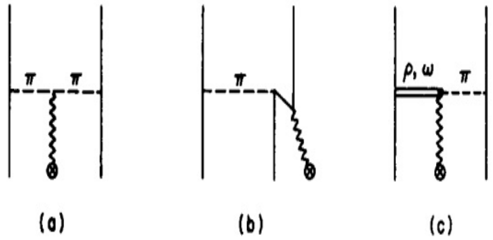
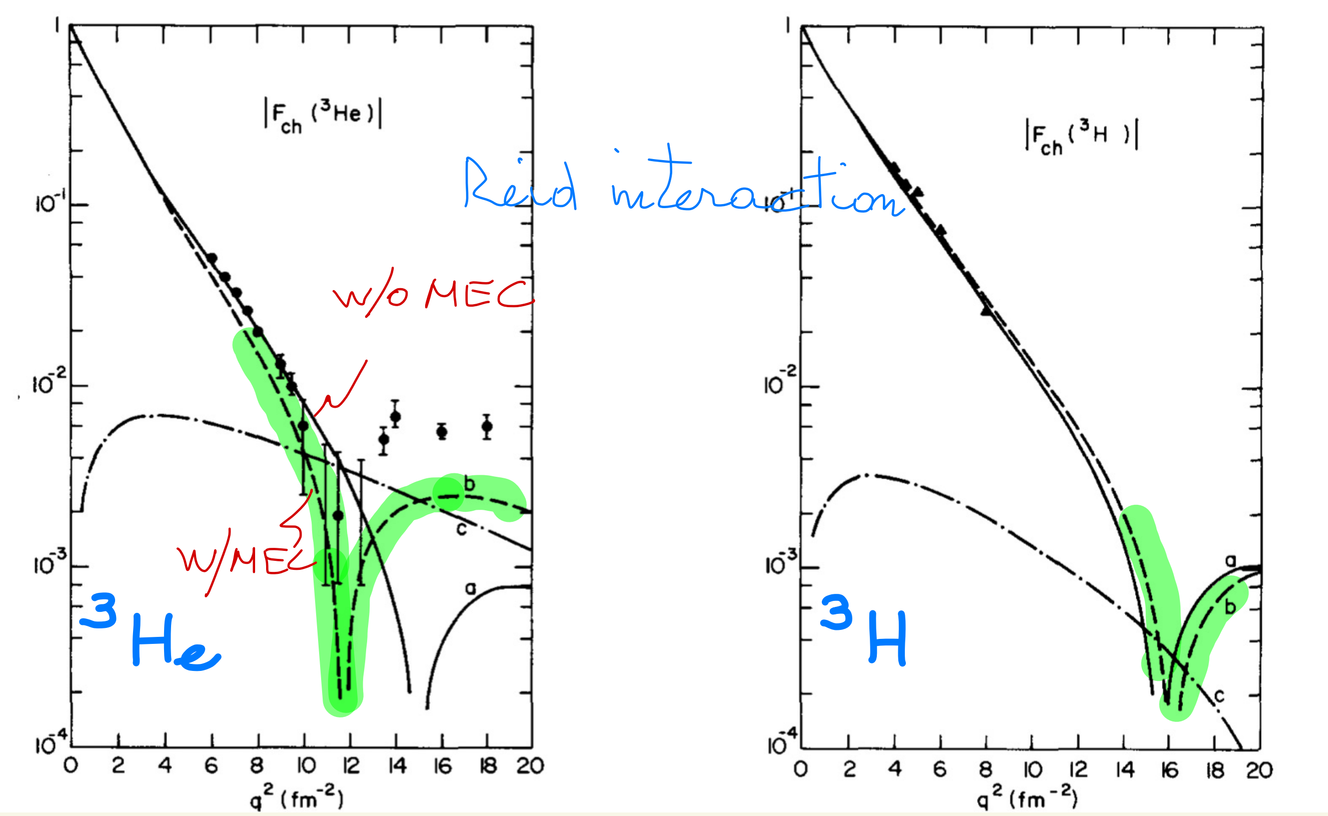


Fig. 1. Diagrams considered for meson exchange effects on the charge form factors.



- By far, the dominant contribution is from

$$\rho_\pi(\bar{q}) = \frac{e}{8m}\frac{g_A^2}{f_\pi^2}(\bar{\tau}_1\cdot\bar{\tau}_2+\tau_{2z})\frac{\bar{\sigma}_1\cdot\bar{q}\;\bar{\sigma}_2\cdot\bar{k}_2}{k_2^2+m_\pi^2} + 1 \Longleftrightarrow 2$$

also derived in χEFT (Phillips, '03)

- It plays a crucial role in few-nucleon charge F.F.'s, less prominent in heavier nuclei (where shell structure is prominent)

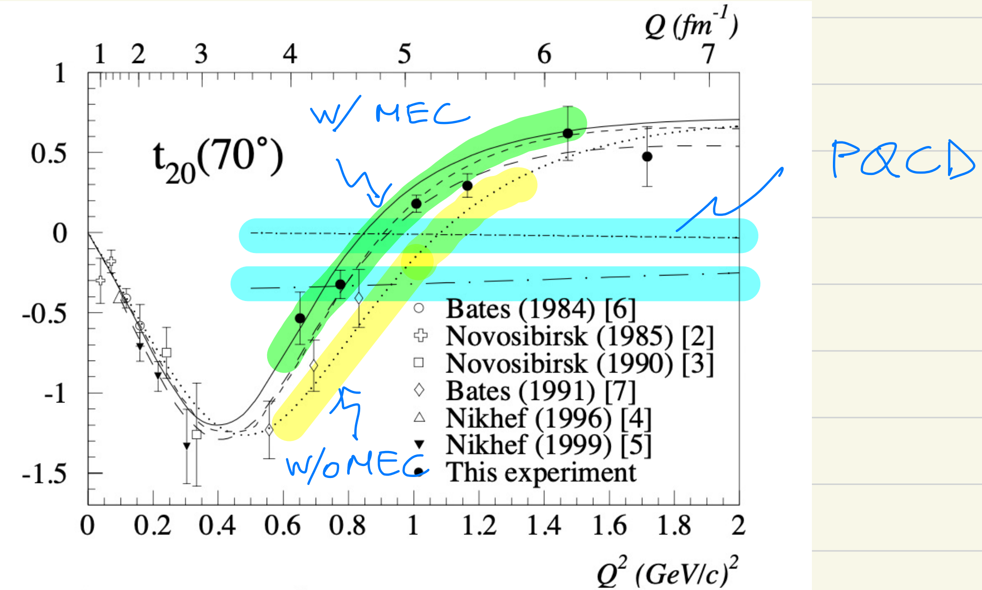
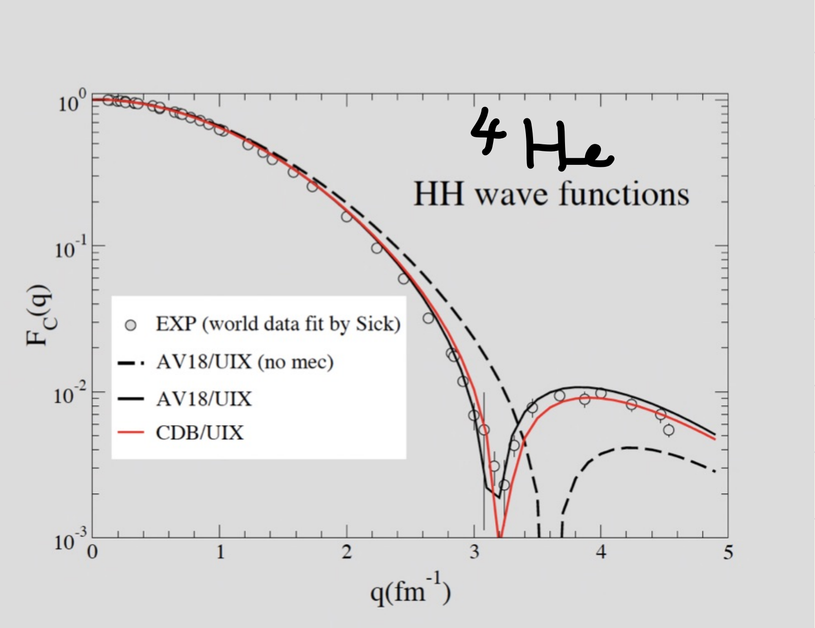
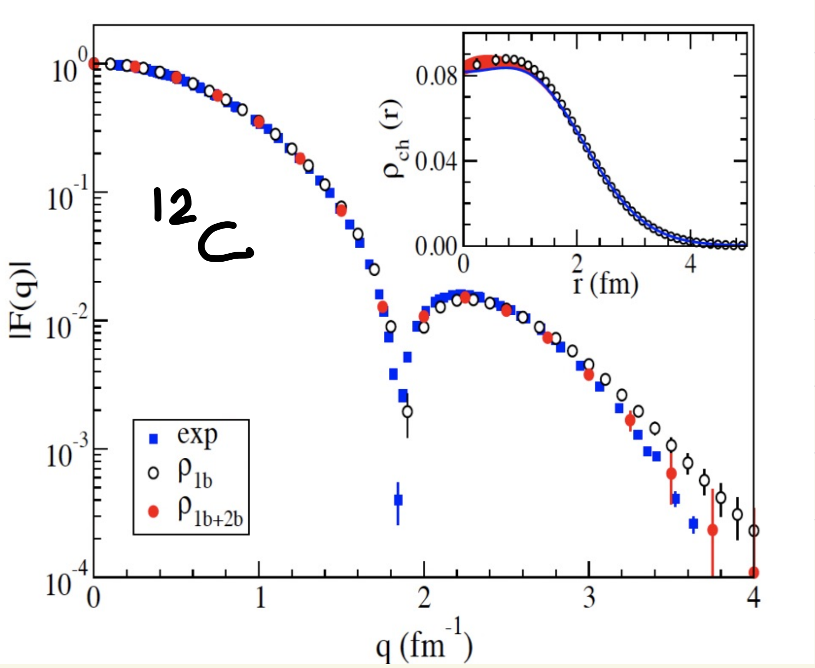


FIG. 2. t_{20} at $\theta_e=70°$ compared to theoretical predictions; dotted line (NRIA) and full line (NRIA+MEC+RC) [19]; relativistic models with dashed line [21] and long dashed line [22]; pQCD calculations with dashed-dotted line [23] and long dashed-dotted line [24].





Realitic nuclear EW currents

* By mid '90 – early '00 a number of high-quality realistic NN interactions become available (χ^2/datum $\simeq 1$): Nijmegen models, AV18, and CD Bonn

$$v_{ij} = \underbrace{v^0_{ij}}_{\text{static}} + v^p_{ij} \sim \text{p-dependent}$$

isospin dependent piece of v^0_{ij}

$$v^{\sigma\tau}_{ij}(k) = \Big[\underbrace{v_\tau(k)}_{v_{PS}(k)} + k^2 \underbrace{v_{\sigma\tau}(k)}_{2v_\rho(k)+v_\pi(k)}\,\bar\sigma_i\cdot\bar\sigma_j + \underbrace{v_{t\tau}(k)}_{v_\rho(k)-v_\pi(k)}\,S_{ij}(\bar k)\Big]\bar\tau_i\cdot\bar\tau_j$$

Riska ('85), Gross and Riska ('87), Schiavilla et al ('89)

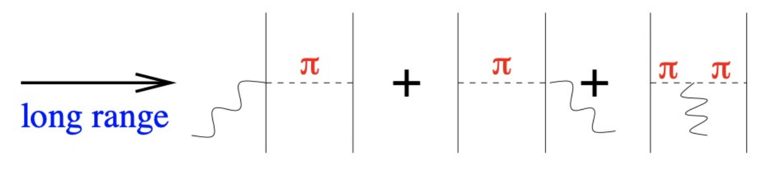
* Construct effective π and ρ currents out of $v_\pi(k)$, $v_\rho(k)$, and $v_{PS}(k)$ projected out of (isospin-dependent) $v^{\sigma\tau}_{ij}$

$$j^\pi_{ij}(v^{\sigma\tau}) = 3i(\bar\tau_i\times\bar\tau_j)_z\, v_\pi(k_j)\left[\bar\sigma_i - \frac{\bar k_i - \bar k_j}{k_i^2 - k_j^2}\,\bar\sigma_i\cdot\bar k_i\right]\bar\sigma_j\cdot\bar k_j + i \rightleftarrows j$$

$$j^\rho_{ij}(v^{\sigma\tau}) = \dots$$

exactly conserved relative to v^0_{ij}

* $\bar{j}^\pi_{ij}(v^{\sigma\tau})$

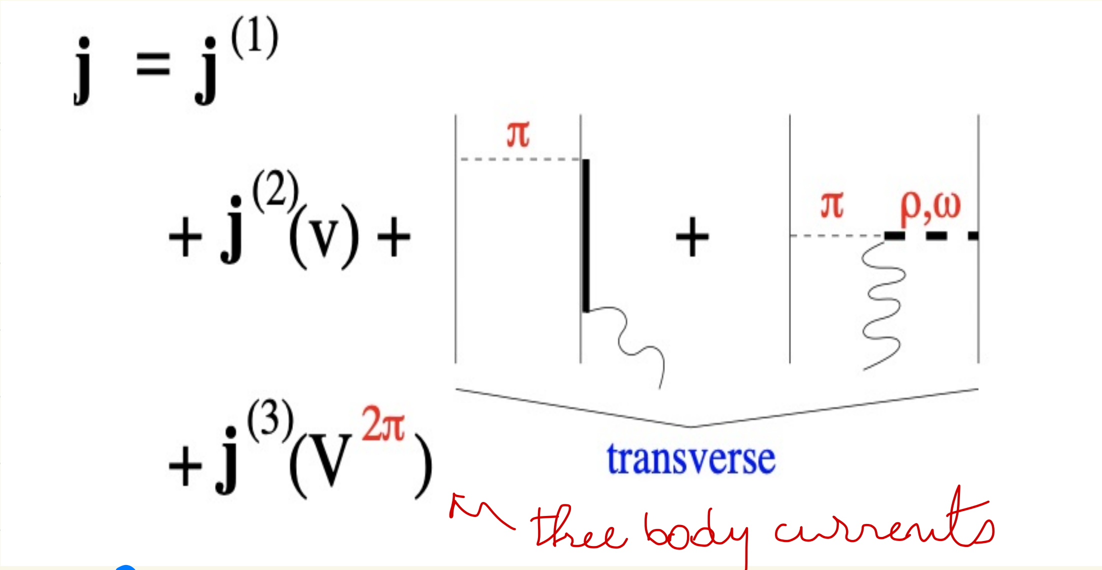


* Currents from v_{ij}^{p} via minimal substitution in explicit p-dependence as well as in implicit one

$$\bar{\tau}_i\cdot\bar{\tau}_j = -1 + (1+\bar{\sigma}_i\cdot\bar{\sigma}_j)\underbrace{e^{i(\bar{r}_{ji}\cdot\bar{p}_i + \bar{r}_{ij}\cdot\bar{p}_j)}}_{P^{ij}_{space}}$$

$$P^{ij}_{space}\,P^{ij}_{\sigma}\,P^{ij}_{\tau} = -1$$

* A realistic EM current, Marcucci et al ('05)

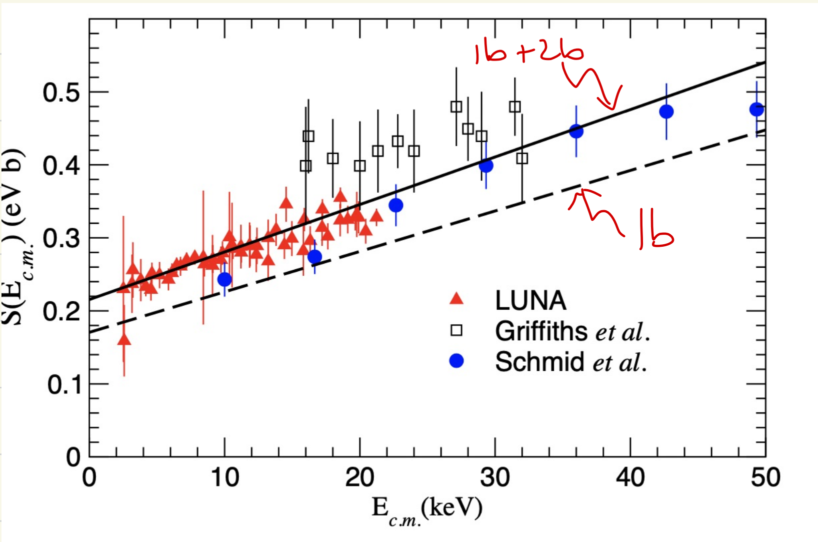


$$\mathbf{j} = \mathbf{j}^{(1)} + \mathbf{j}^{(2)}(v) + \ldots + \mathbf{j}^{(3)}(V^{2\pi})$$

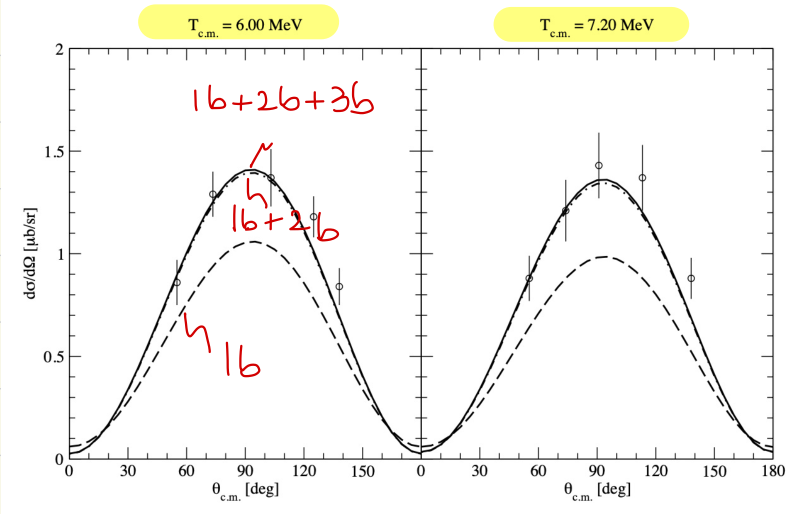
three body currents

* **Low energy:**

$^2H(p,\gamma)^3He$



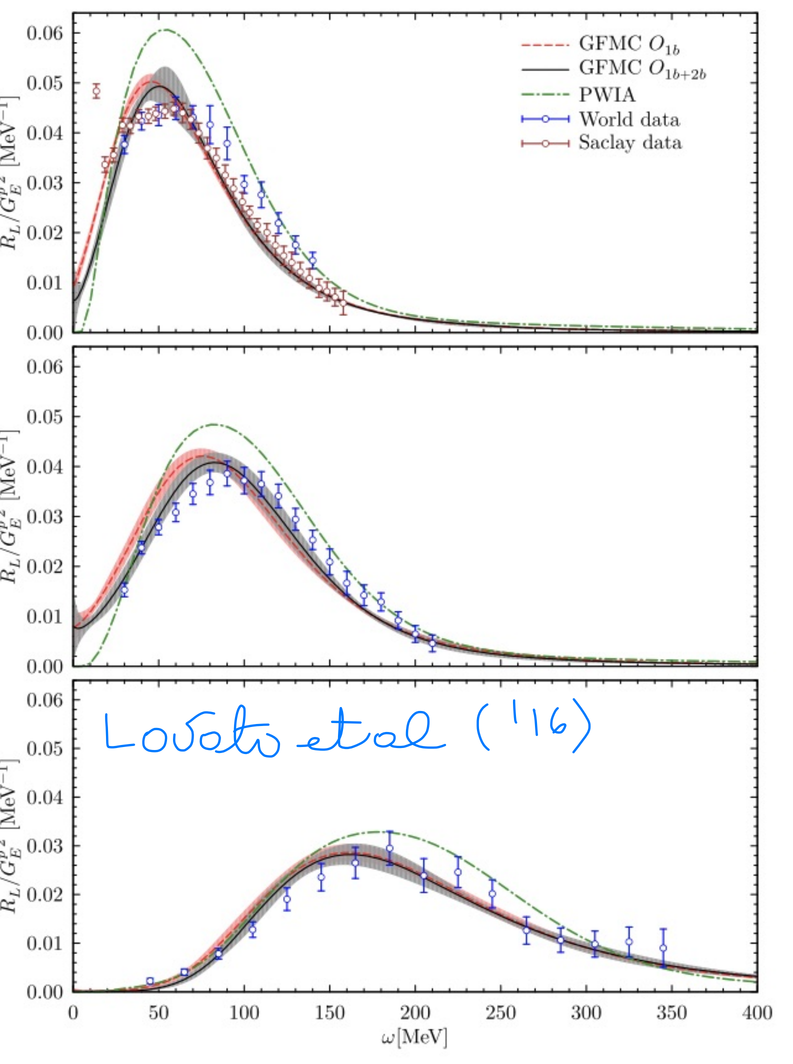
$^2H(n,\gamma)^3H$



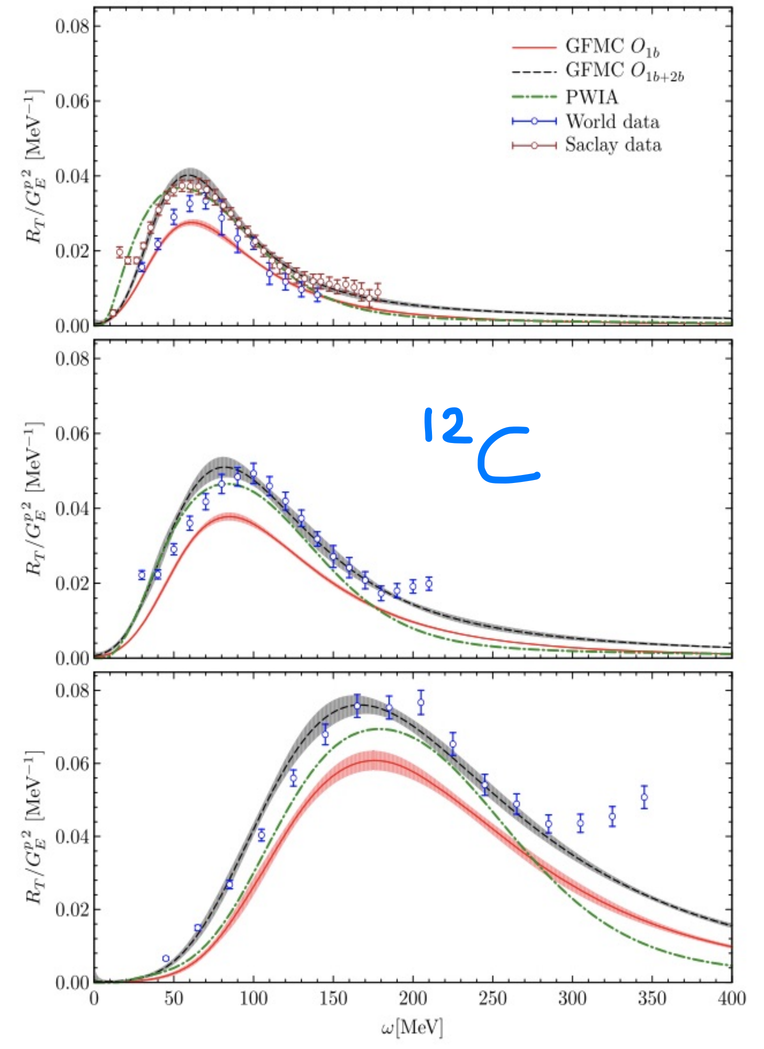
* Many-body (3b and 4b) terms in nuclear charge operator give negligible contributions in charge f.f.'s, Riska and Radomski ('77)

* Intermediate energy:

$R_L(q,\omega)$ $R_T(q,\omega)$



Lovato et al ('16)



^{12}C

* EM current (and charge) operators contain no free parameters and are consistent with short-range behavior of v_{ij} (and $V_{ijk}^{2\pi}$)

* A realistic axial current: effective π and ρ exchange terms (AV18) + Δ contributions with g_A^* fixed by reproducing exp GT m.e. in ^{3}H β decay; Marcucci et al ('00)

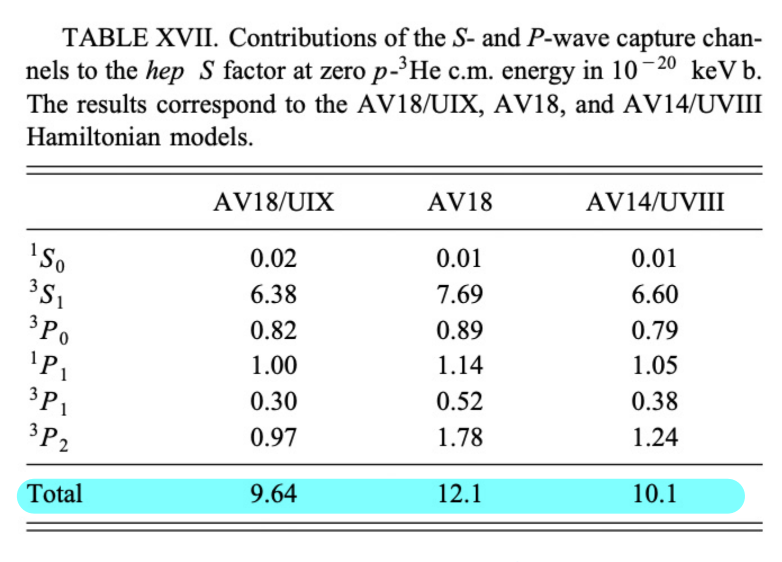


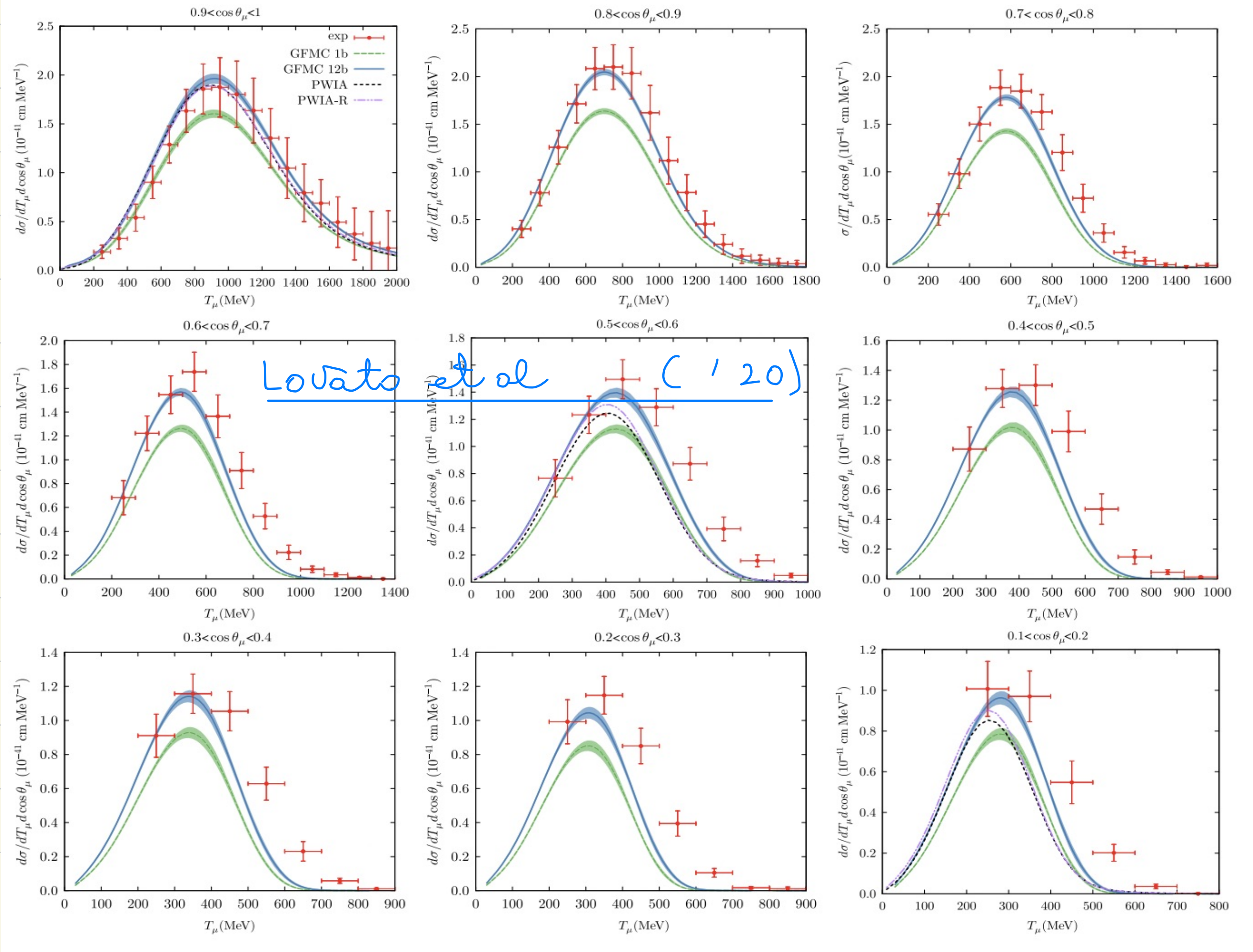
TABLE XVII. Contributions of the *S*- and *P*-wave capture channels to the *hep* *S* factor at zero *p*-^{3}He c.m. energy in 10^{-20} keV b. The results correspond to the AV18/UIX, AV18, and AV14/UVIII Hamiltonian models.

	AV18/UIX	AV18	AV14/UVIII
$^1S_0$	0.02	0.01	0.01
$^3S_1$	6.38	7.69	6.60
$^3P_0$	0.82	0.89	0.79
$^1P_1$	1.00	1.14	1.05
$^3P_1$	0.30	0.52	0.38
$^3P_2$	0.97	1.78	1.24
Total	9.64	12.1	10.1

^{3}He$(p,e^+\nu_e)^4$He S factor

suppressed at 1b level

^{12}C(ν_μ,μ^-) and MiniBooNE data



Lovato et al ('20)

χEFT formulation of the basic model

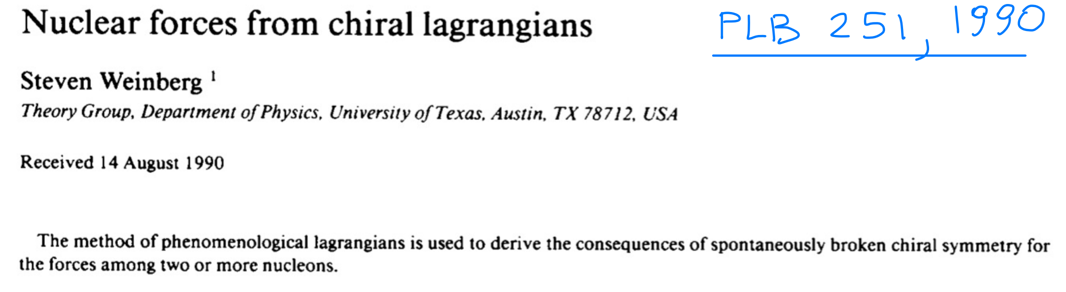
- Lagrangians describing π and N (and Δ) interactions are expanded in powers of Q/Λ_χ

- Their construction was codified in a number of papers (Gasser and Leutwyler, 1984; Gasser, Sainio, and Švarc, 1988; Bonn group, 1992 and 2000)

$$\mathcal{L} = \mathcal{L}^{(1)}_{\pi N} + \mathcal{L}^{(2)}_{\pi N} + \mathcal{L}^{(3)}_{\pi N} + \cdots + \mathcal{L}^{(2)}_{\pi\pi} + \mathcal{L}^{(4)}_{\pi\pi} + \cdots$$

- $\mathcal{L}^{(n)}$ also include contact $(\bar{N}N)(\bar{N}N)$ type interactions parametrized by LECs, accounting for short range terms beyond multi-π exchange

- A series of papers by Weinberg (1990-1992) provided initial impetus for the development of nuclear χEFT



Nuclear forces from chiral lagrangians

PLB 251, 1990

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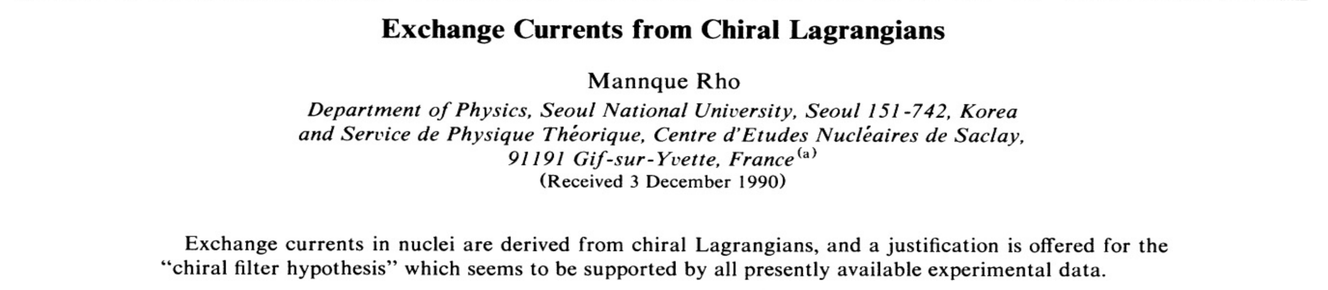
Received 14 August 1990

The method of phenomenological lagrangians is used to derive the consequences of spontaneously broken chiral symmetry for the forces among two or more nucleons.

- With applications to exchange currents by Rho



VOLUME 66, NUMBER 10 PHYSICAL REVIEW LETTERS 11 MARCH 1991

Exchange Currents from Chiral Lagrangians

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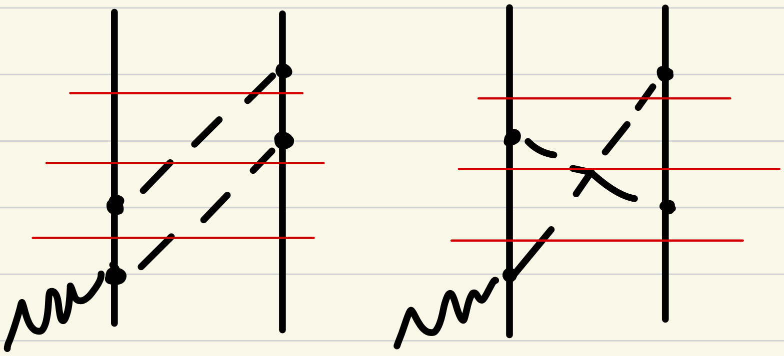
(Received 3 December 1990)

Exchange currents in nuclei are derived from chiral Lagrangians, and a justification is offered for the "chiral filter hypothesis" which seems to be supported by all presently available experimental data.

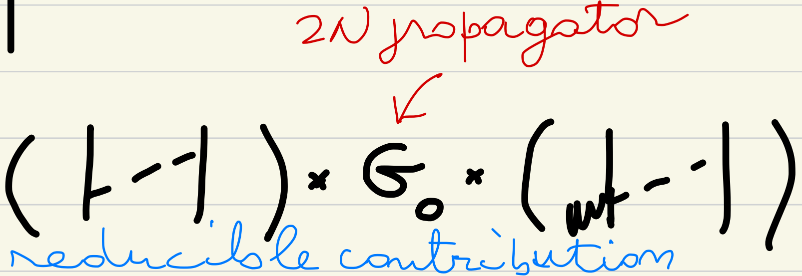
* First systematic (albeit incomplete) derivation of loop corrections in HBPT soon followed (Park, Min, and Rho, 1993–1996)

* And applications to $np \to d\gamma$ and proton weak captures on ^1H and ^3He (Park, Kubodera, Min, Rho et al, '93–'03); deuteron static properties and f.f.'s (Phillips, '03)

* Park et al only retained irreducible contributions (following Weinberg's prescription)



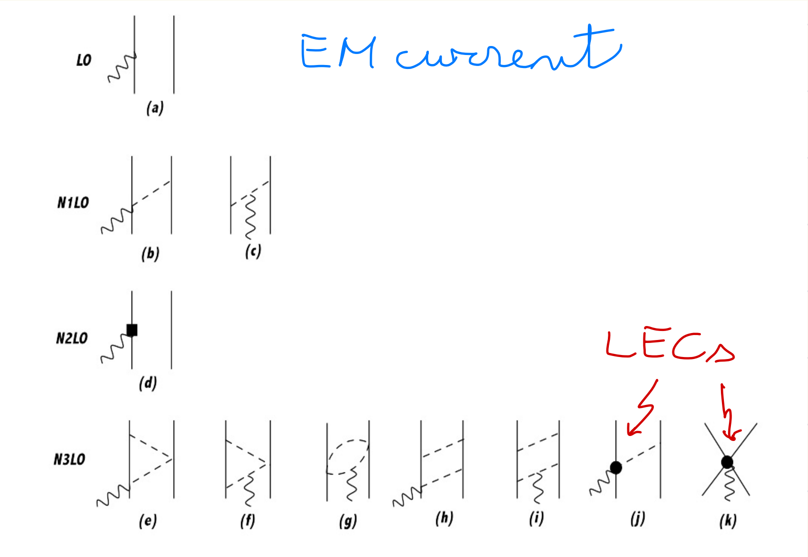
However the iteration only generates part of reducible contribution

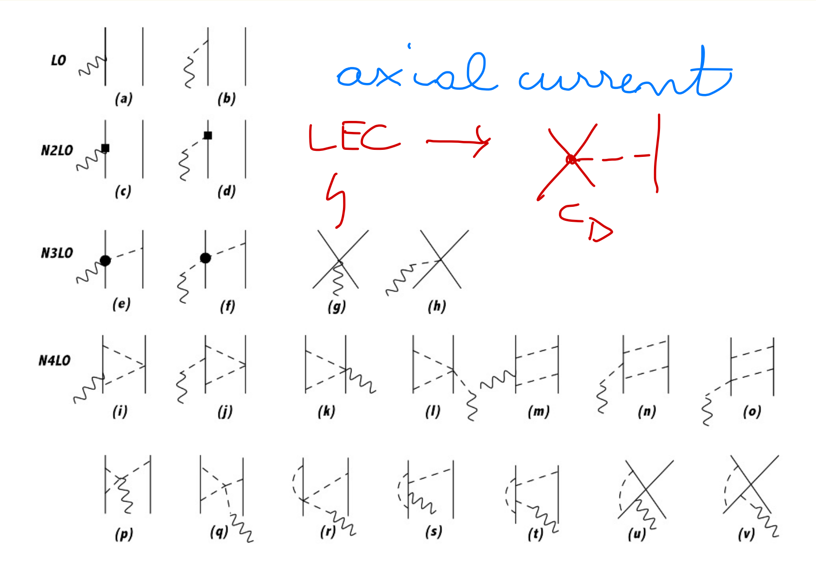


left over must be accounted for (Pastore, Schiavilla, Goity, '08)

* Such an approach can be turned into a systematic method consistent with power counting (Pastore et al '11), but analysis increases in complexity with increasing order

* Method has been applied to obtain vector currents (Pastore et al, '09 – '11; Piarulli et al, '13) and axial currents (Baroni et al, '16)





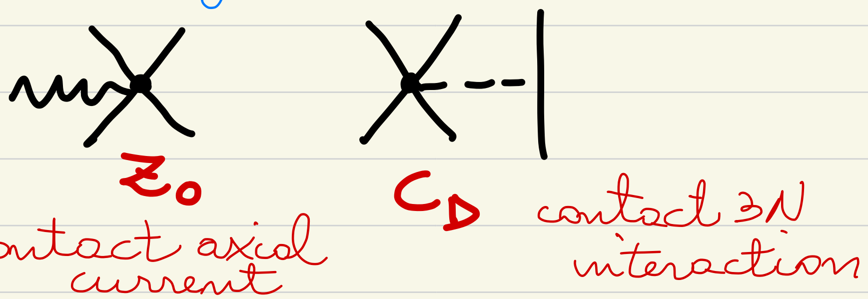
* Alternative method adopted by the Bochum/Bonn group based on the Okubo unitary transformation decoupling the N only state space from the state space with π, N, ... ('09 – '17)

* Vector 2b currents are the same in the two approaches, but axial 2b currents differ (box diagrams); Bochum/Bonn also retains non static terms (neglected by our group)

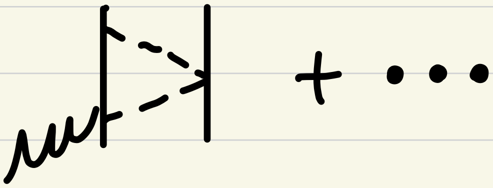
Summary

* χEFF versus ME formulation of the basic model:

- From a conceptual standpoint:
  - consistent treatment of nuclear interactions and currents



  - systematic inclusion of 2π exchange effects



  - "systematically improvable"

- From the standpoint of nuclear phenomenology:
  - description of experimentally measured properties in the two formulations is of similar quality