NUINT-2011

2p2h or not 2p2h?

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IN NUCLEAR PHYSICS AND RELATED AREAS

2p2h

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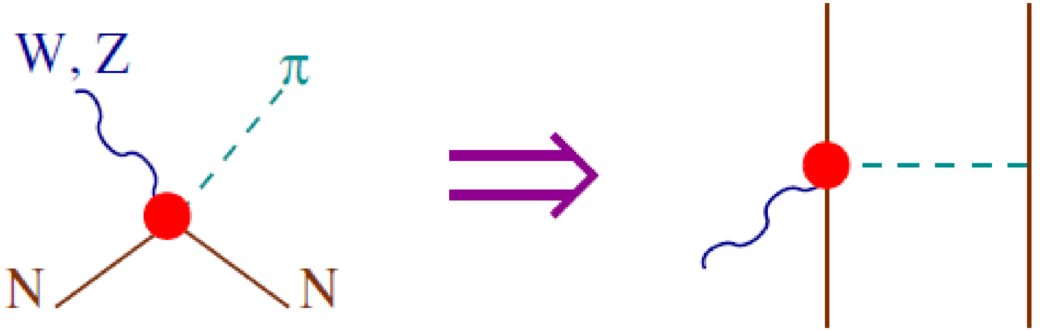
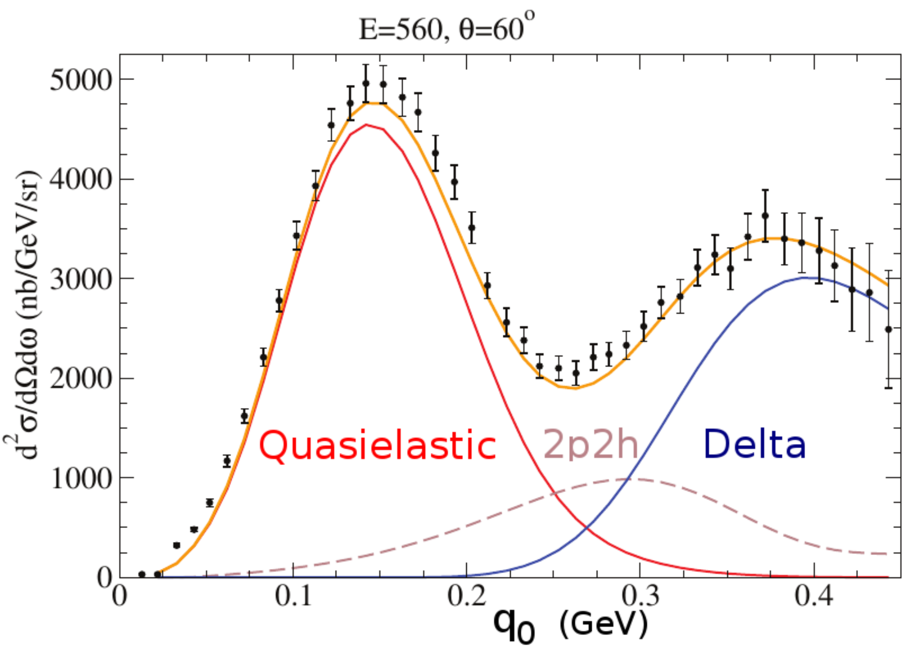
2p2h?

- 2-nucleon EW currents **exist** (are allowed by symmetries)



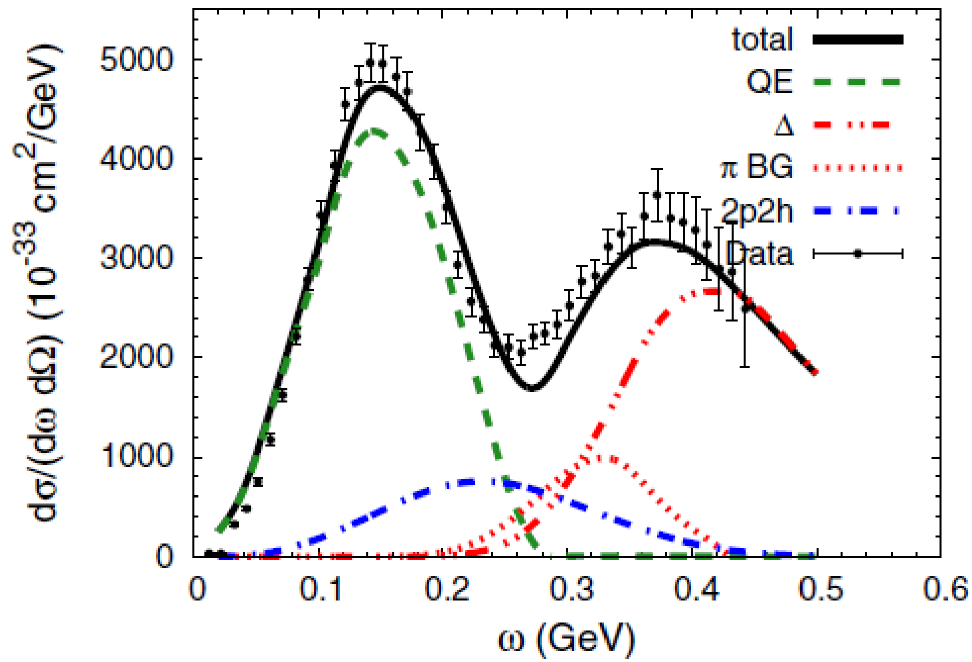
2p2h?

- 2-nucleon EW currents exist (are allowed by symmetries)
- Sizable 2p2h contributions can be inferred from A(e,e')X :



Megias et al., PRD 94 (2016)

Q^2 = 0.24 GeV^2 at the QE peak



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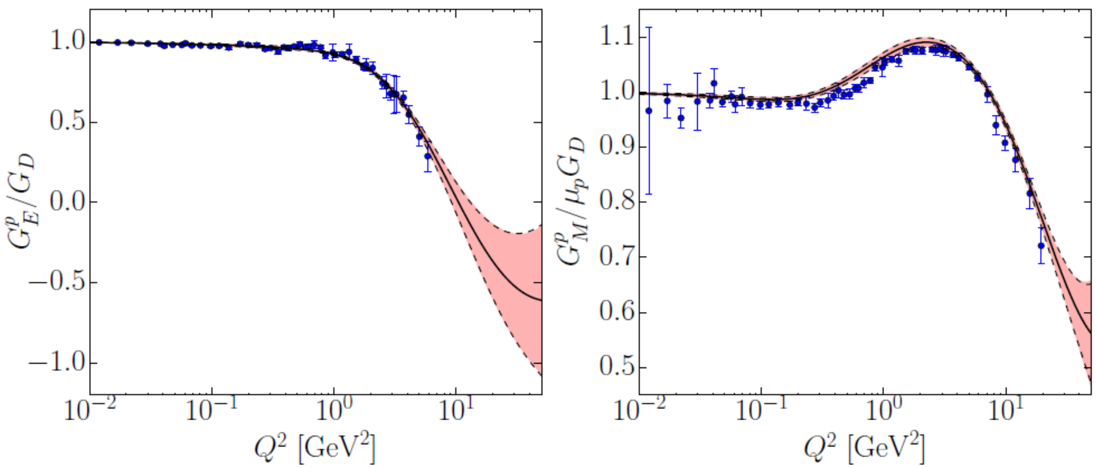

Ye et al., arXiv:1707.09063

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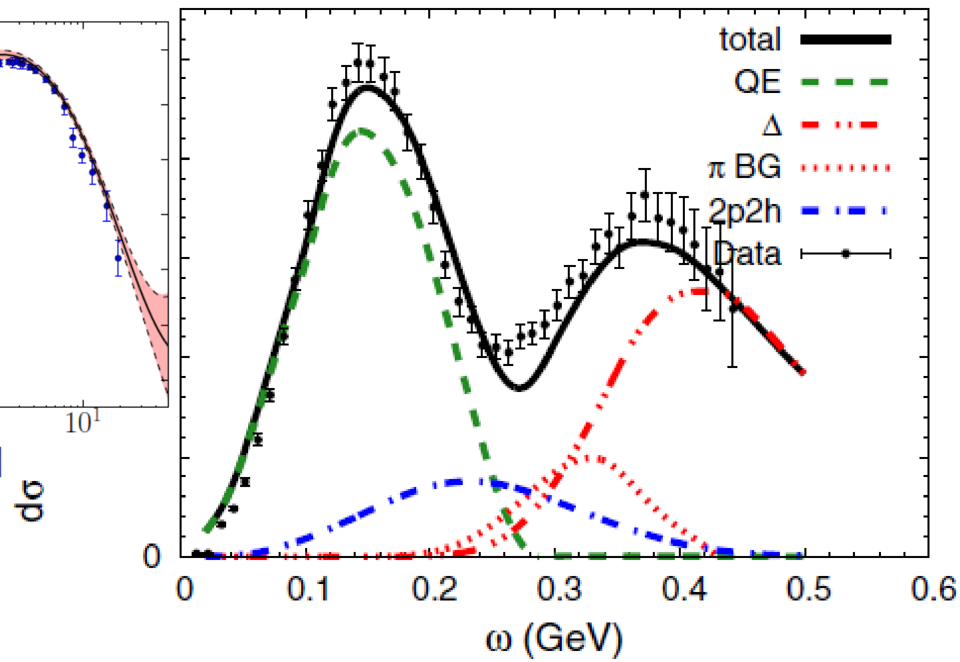

Gallsmeiter et al., PRD 94 (2016)

- EM 2p2h cannot be accommodated by nucleon FF uncertainties

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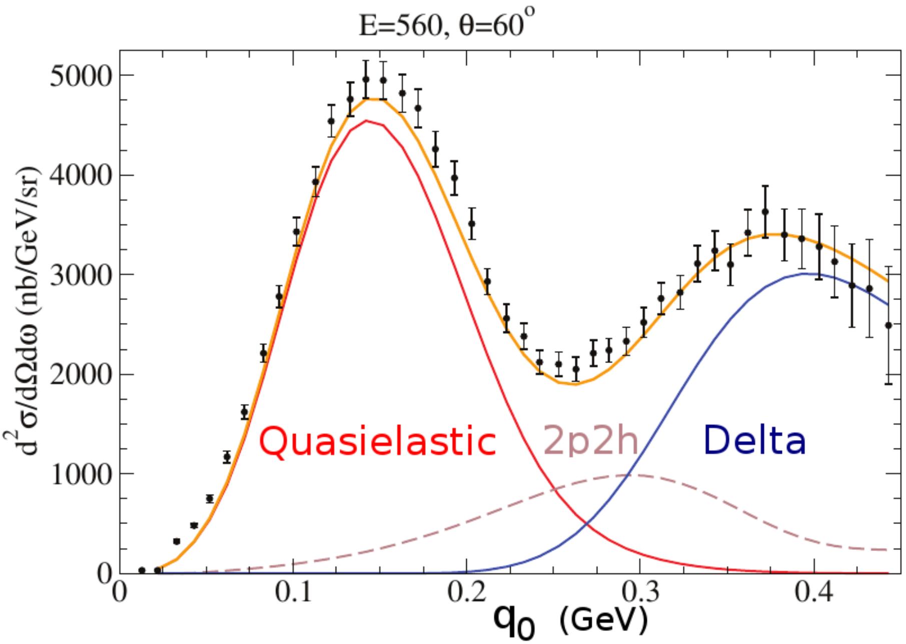

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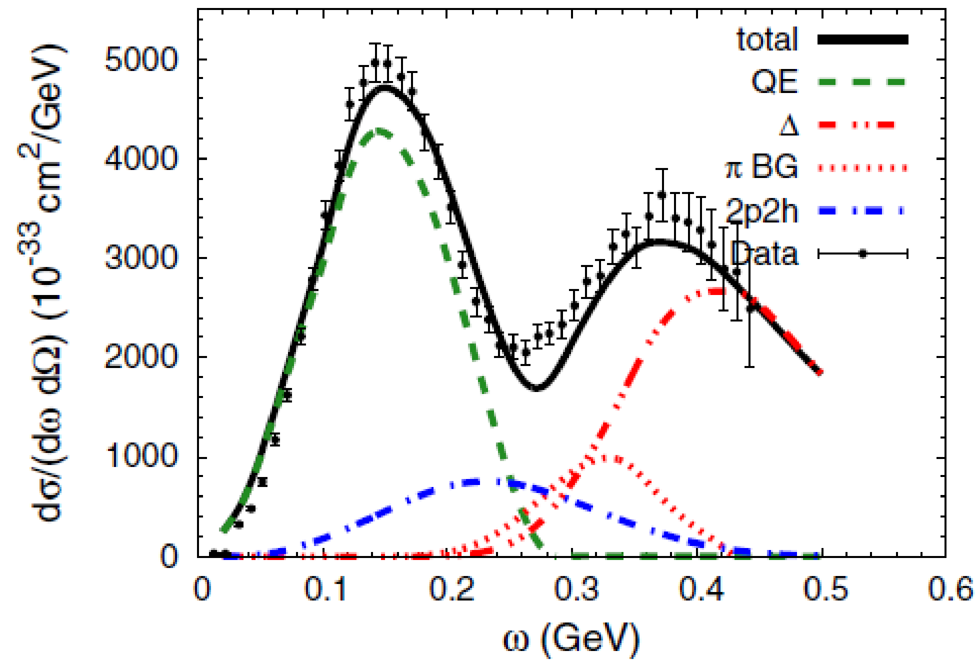
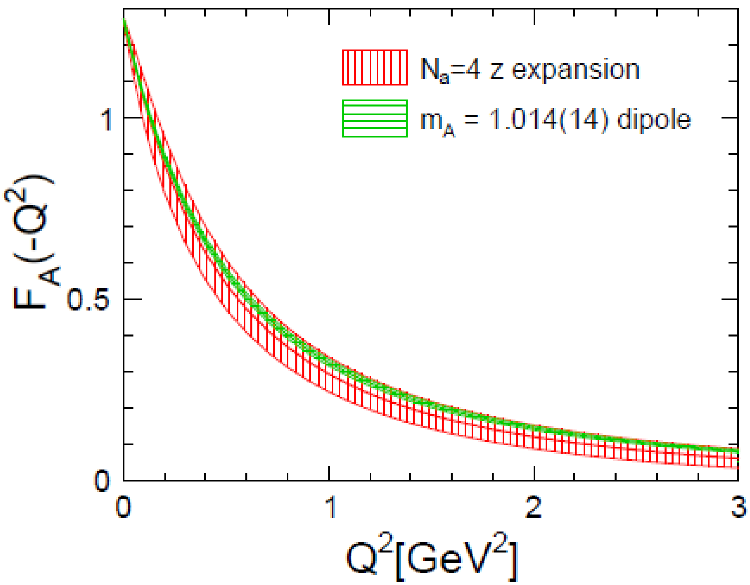


Gallsmeiter et al., PRD 94 (2016)

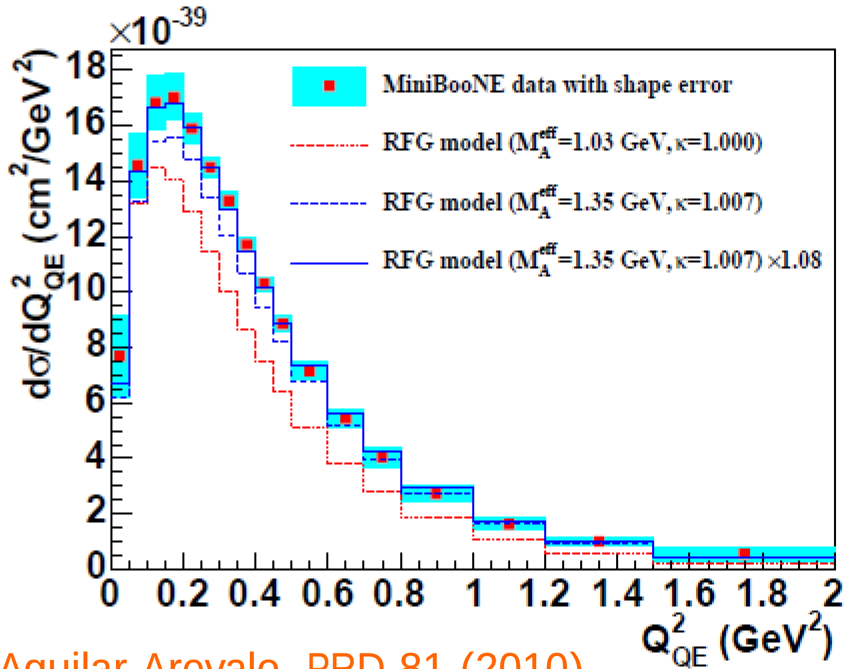
- With "reasonable" assumptions about QE and Δ peaks, 2p2h can be parametrized from (e,e') data. Bosted, Mamyan, arXiv:1203.2262

2p2h?

- 2-nucleon EW currents exist (are allowed by symmetries)
- How about the EW case? The situation is more uncertain...



Meyer et al., PRD 93 (2016)



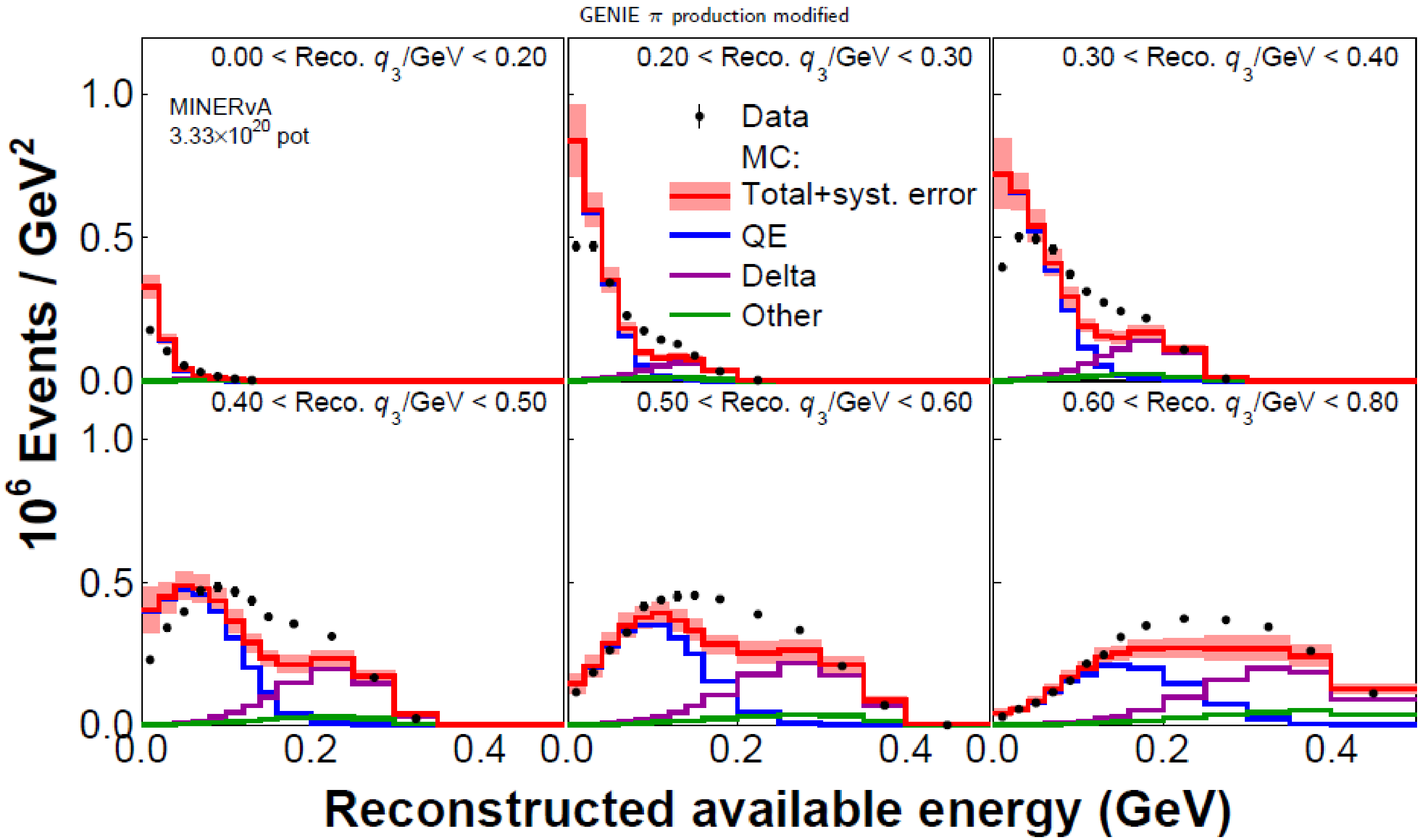
Aguilar-Arevalo, PRD 81 (2010)

- MiniBooNE data can be described with

M_A = 1.35 GeV ↔ $\langle r_A^2 \rangle$ = 0.26 fm^2 vs 0.46(22) fm^2 (z-expansion)

2p2h?

- 2-nucleon EW currents exist (are allowed by symmetries)
- How about the EW case? The situation is more uncertain, although MINERvA excess is in the region where 2p2h should be important.



P. Rodrigues @ NuInt 2015, Fermilab W&C

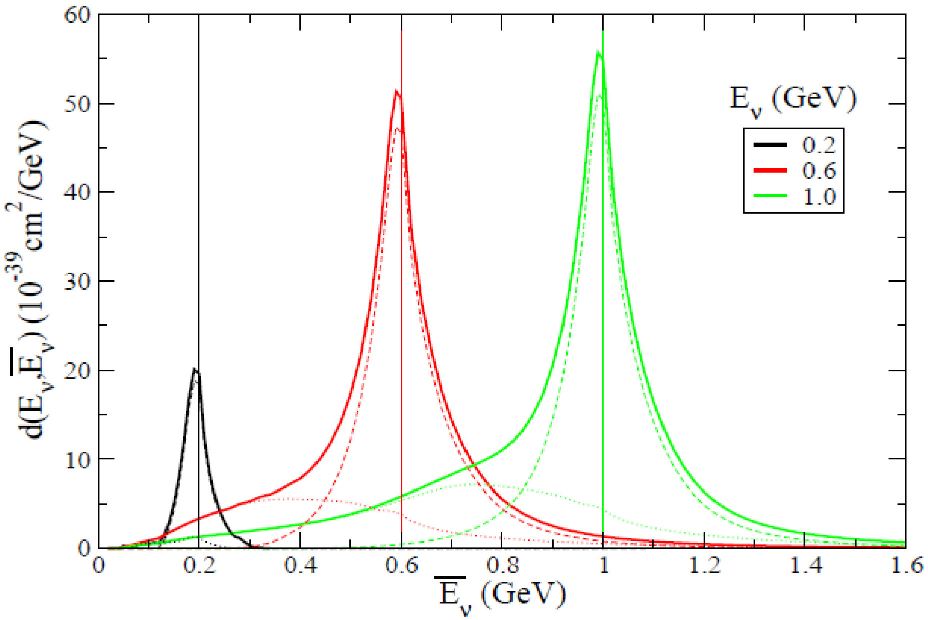
Why ν experiments (should) care?

- Broad fluxes ⇒ Neutrino energy is not known for individual events

$$P(\nu_\mu \to \nu_\tau) = \sin^2 2\theta_{23} \sin^2 \frac{\Delta m_{23}^2 L}{2E_\nu}$$

- 2p2h introduce a bias in (kinematic) E_ν reconstruction

$$E_\nu^{\mathrm{QE}} = \frac{2m_n E_\mu - m_\mu^2}{2(m_n - E_\mu + p_\mu \cos\theta_\mu)}$$



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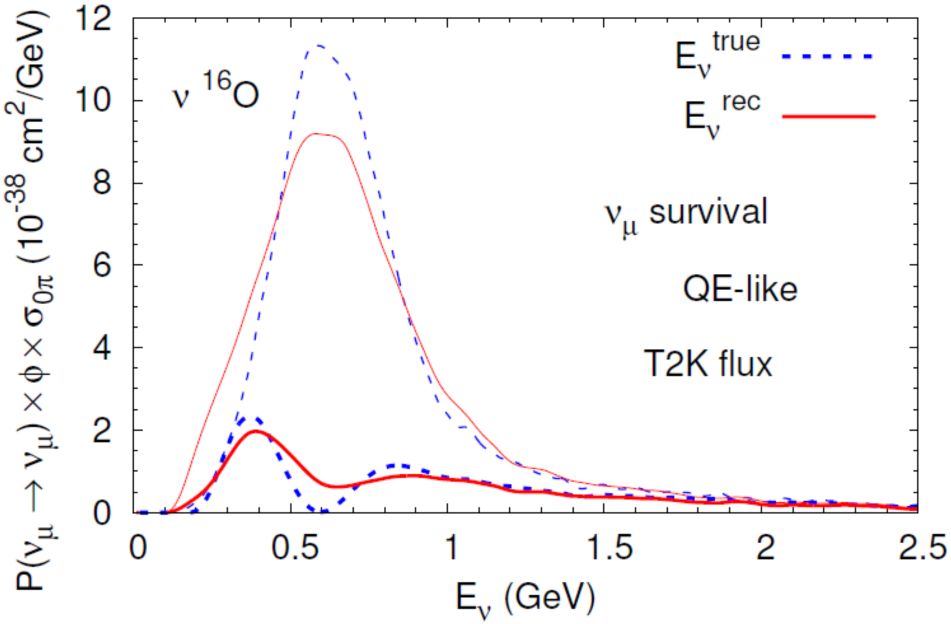
  - This has implications for oscillation measurements



Lalakulich, Mosel, PRC 86 (2012)

Why c.s. theorists should care?

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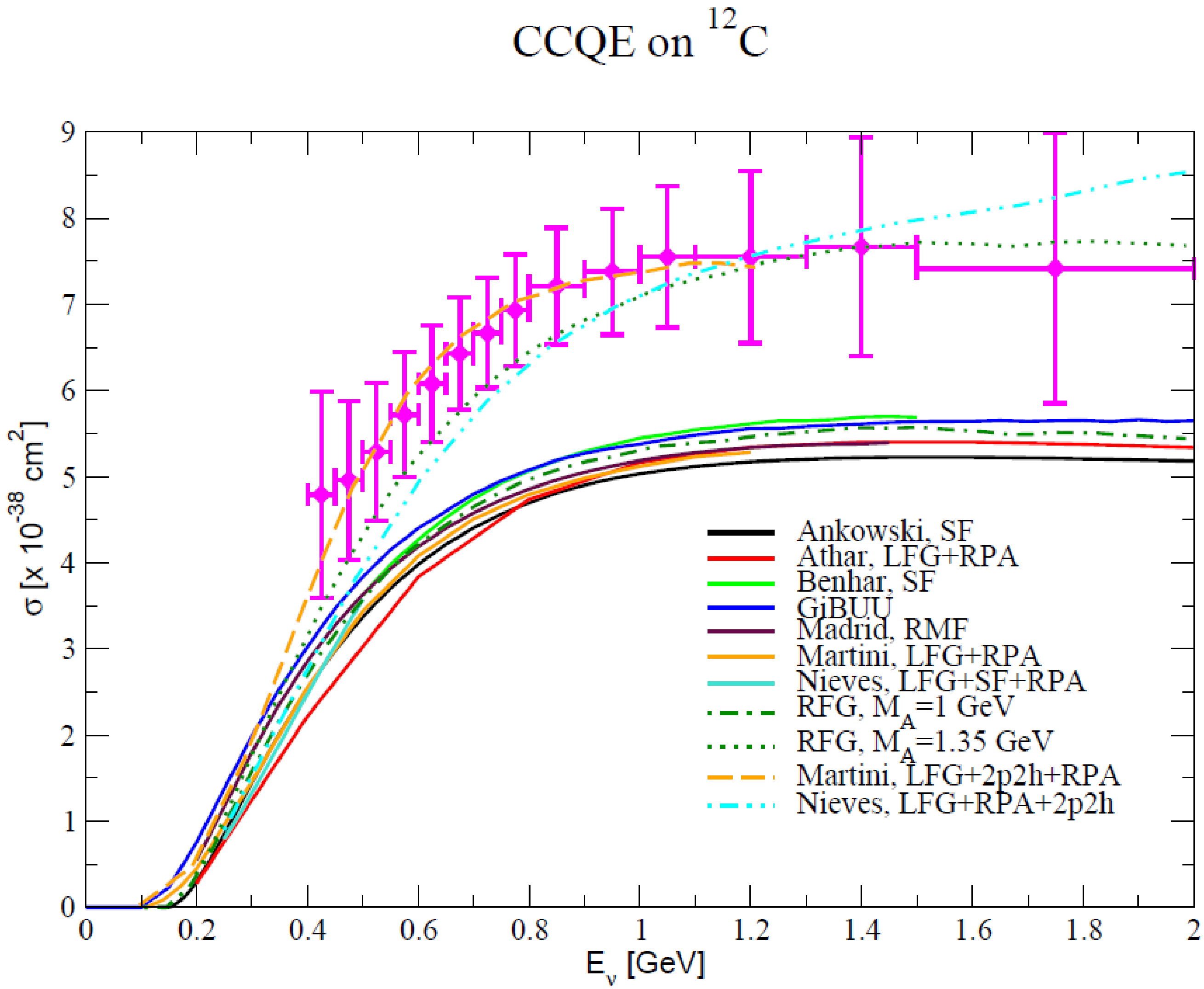
Why c.s. theorists should care?

- B ... al events
- 2 ...



LAR, Nieves, Hayato, New J. Phys. 16 (2014)

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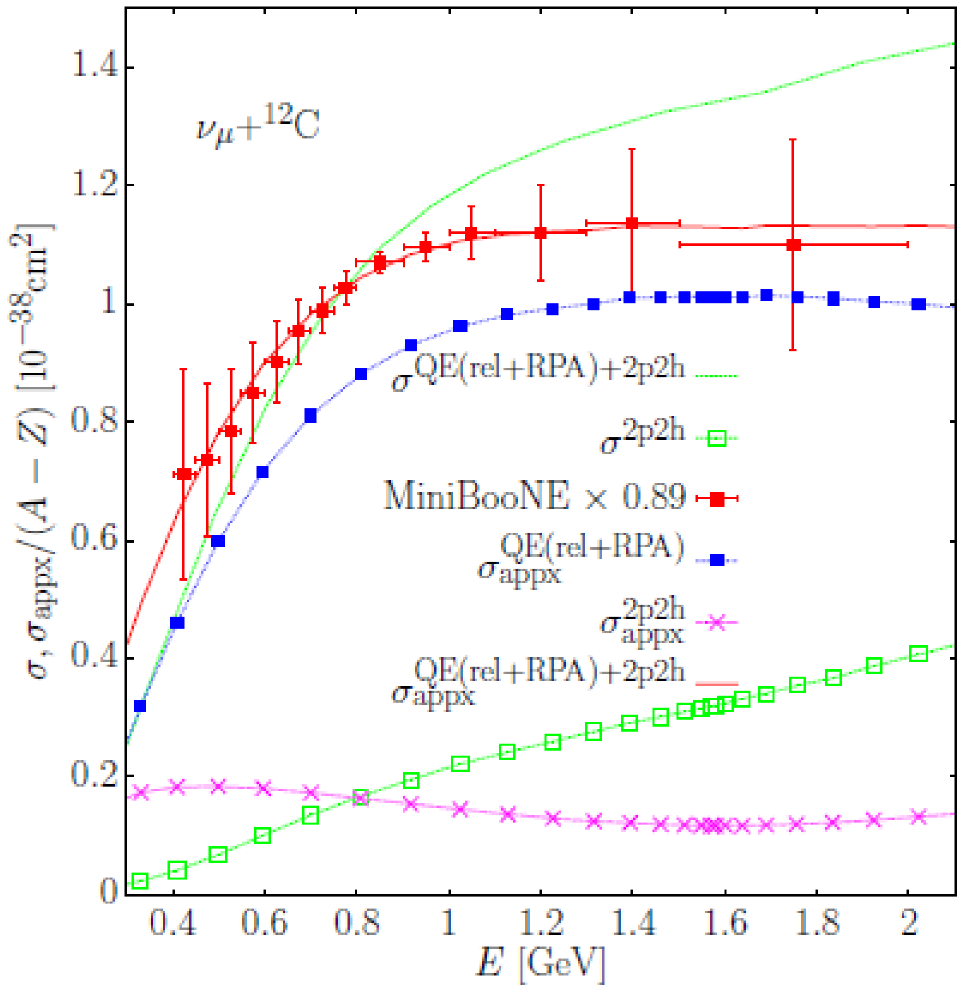
- 2p2h introduce a bias in (kinematic) E_ν reconstruction
  - This has implications for **theory vs data comparison**
  - Comparison to MiniBooNE CCQE-like integrated cross section requires $E_\nu \to E_\nu^{QE}$

$$\sigma(E_\nu^{\mathrm{QE}}) = \int dE_\mu d\cos\theta_\mu \langle \frac{d\sigma_{\mathrm{QE+2p2h}}}{dE_\mu d\cos\theta_\mu} \rangle \delta\left(E_\nu^{\mathrm{QE}} - \frac{2 m_n E_\mu - m_\mu^2}{2(m_n - E_\mu + p_\mu \cos\theta_\mu)} \right) .$$

Why c.s. theorists should care?

- for individual events

- ruction
  omparison
  ated cross section



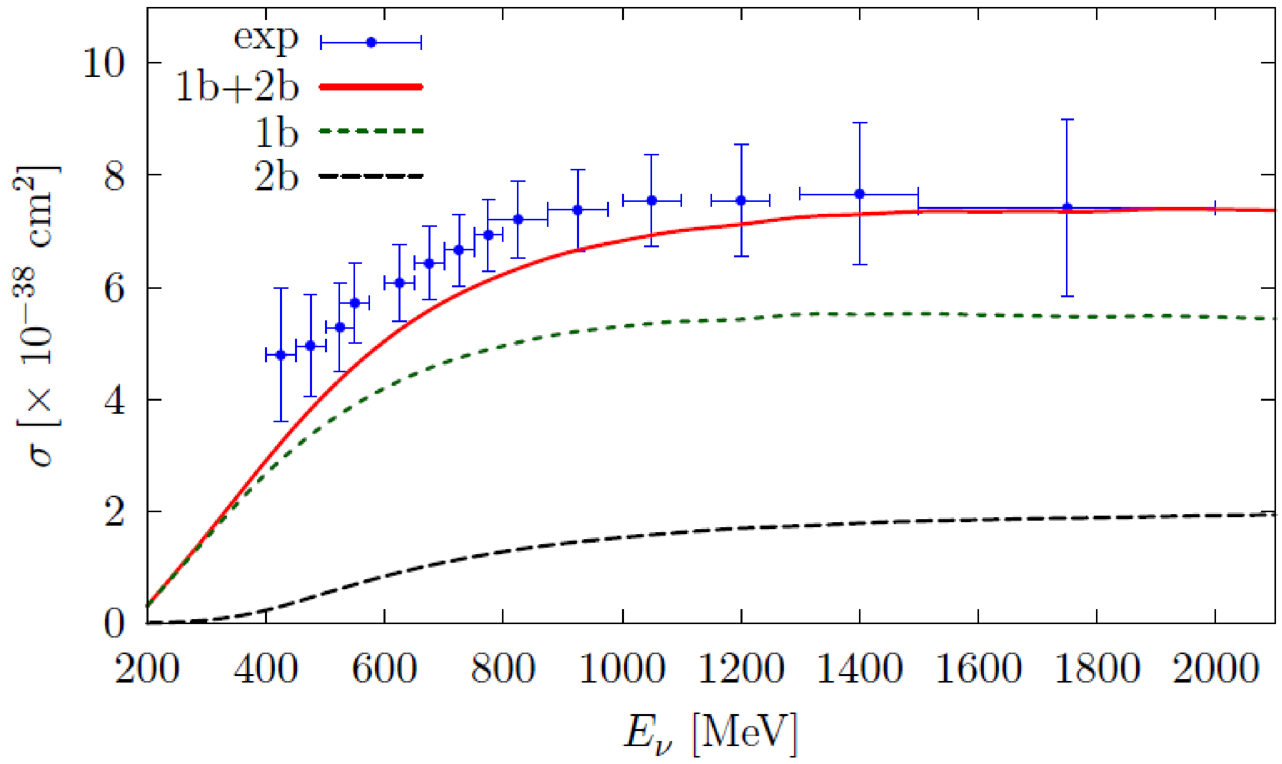
Nieves et al, Phys.Rev. D85 (2012)

$$\sigma(E_\nu^{QE}) = \int dE_\mu d\cos\theta_\mu \langle \frac{d\sigma_{QE+2p2h}}{dE_\mu d\cos\theta_\mu} \rangle \delta \left(E_\nu^{QE} - \frac{2m_n E_\mu - m_\mu^2}{2(m_n - E_\mu + p_\mu \cos\theta_\mu)} \right) .$$

Why c.s. theorists should care?

- CC0π total cross section: MiniBooNE data events

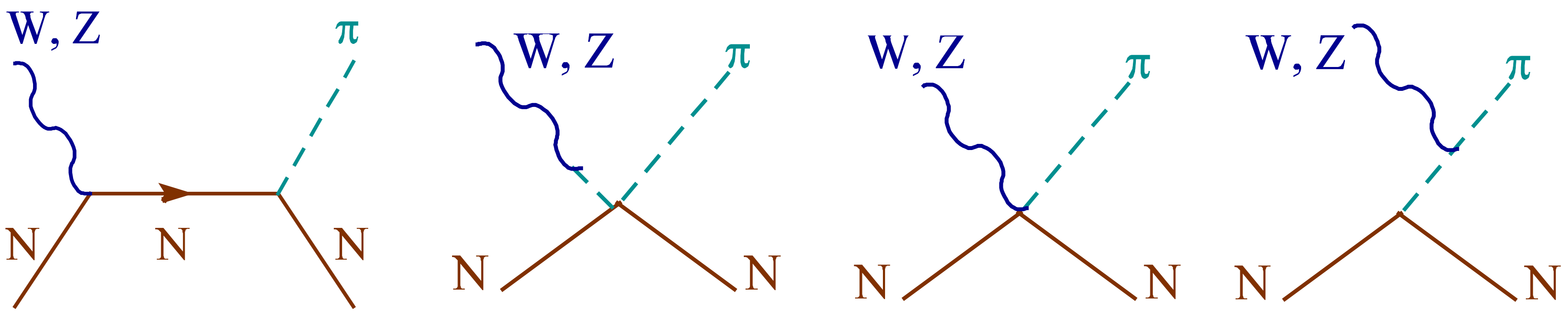
- ction



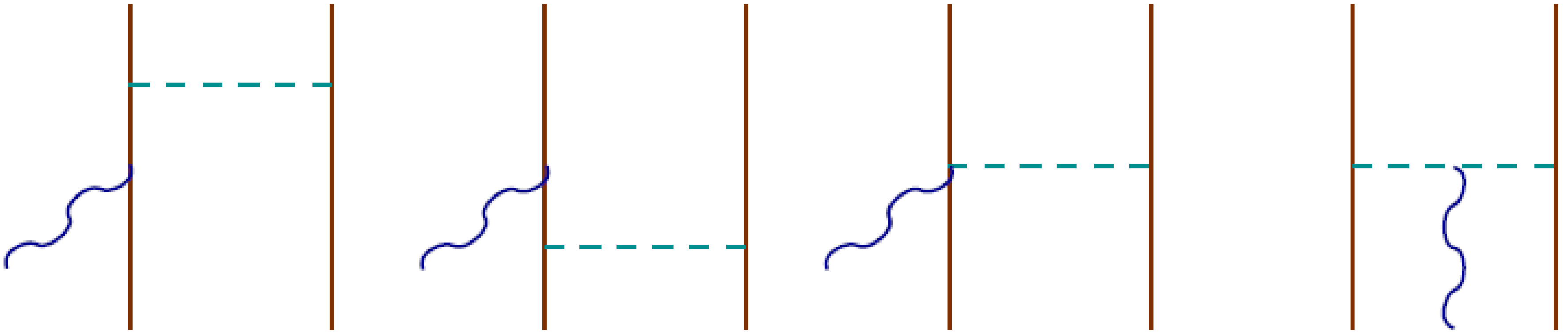
Rocco @ INT 2018

$$\sigma(E_\nu^{\rm QE}) = \int dE_\mu d\cos\theta_\mu \langle \frac{d\sigma_{\rm QE+2p2h}}{dE_\mu d\cos\theta_\mu} \rangle \delta\left(E_\nu^{\rm QE} - \frac{2m_n E_\mu - m_\mu^2}{2(m_n - E_\mu + p_\mu \cos\theta_\mu)}\right) .$$

- LO ChPT for $\nu_l\, N \rightarrow l\, \pi\, N'$

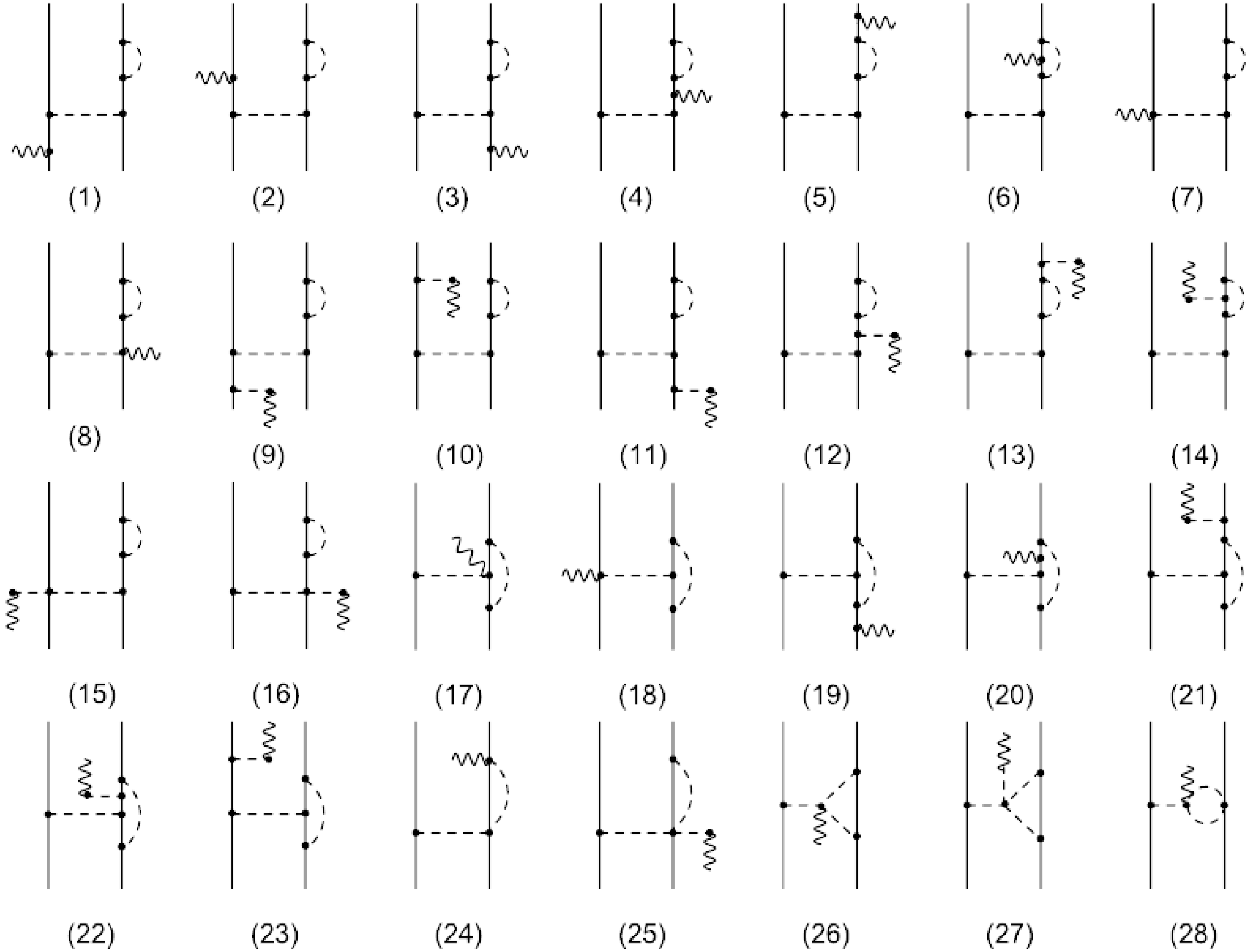


leads to



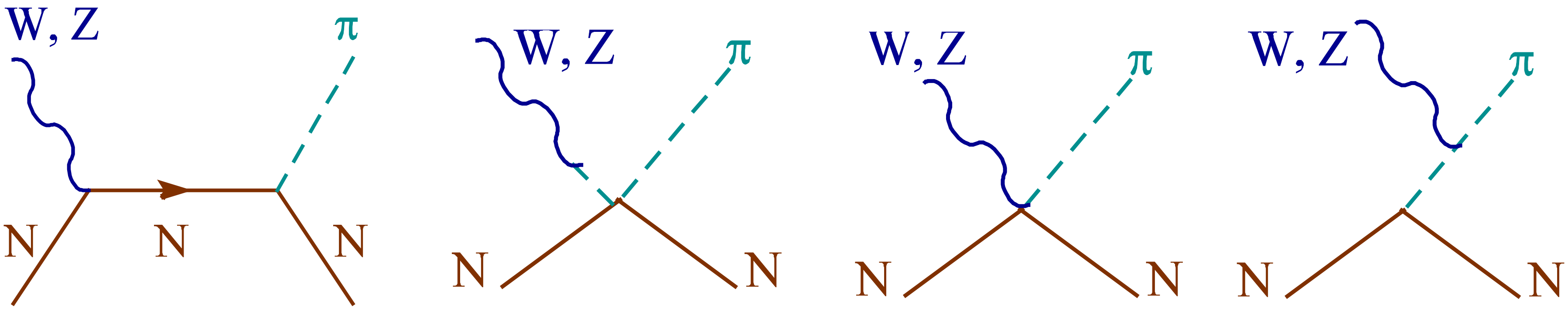
2-nucleon currents in EFT

- In Chiral EFT e.g. Baroni et al., PRC93 (2016), Krebs et al, Ann. Phys. 378 (2017)
  - two-nucleon, non-relativistic axial currents

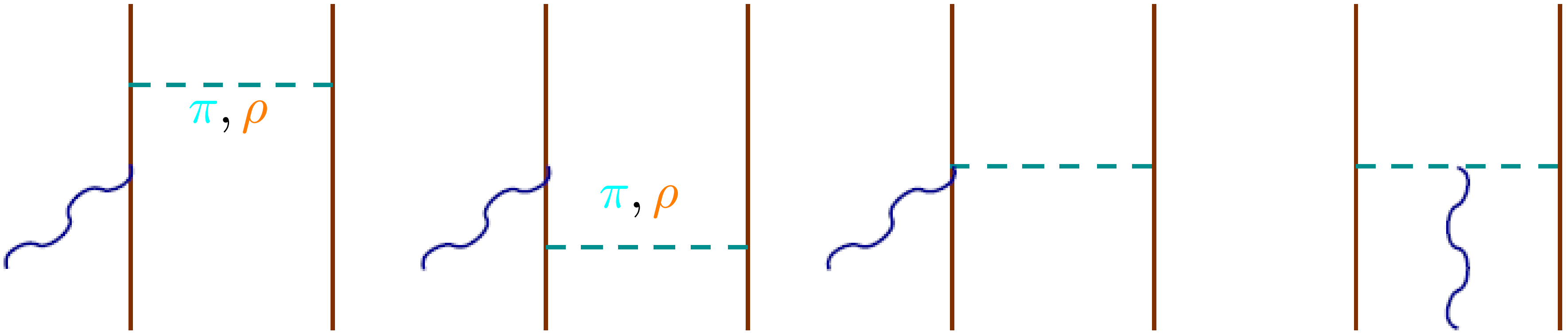


Two-nucleon currents

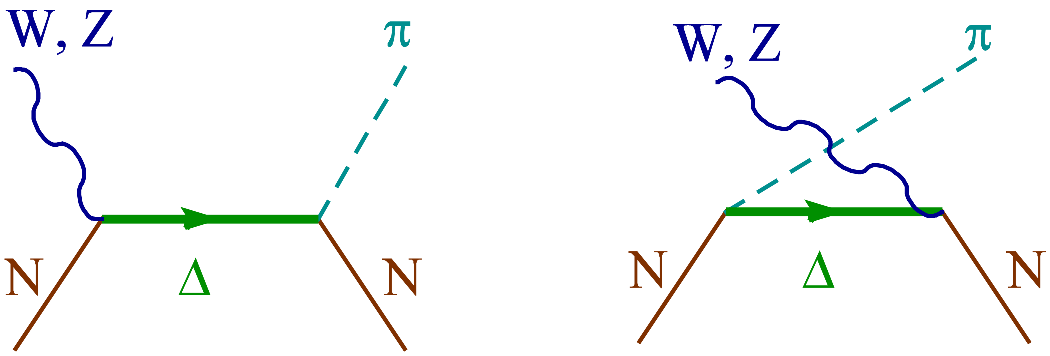
- Form factors are usually introduced to go to higher momenta



leads to



Two-nucleon currents



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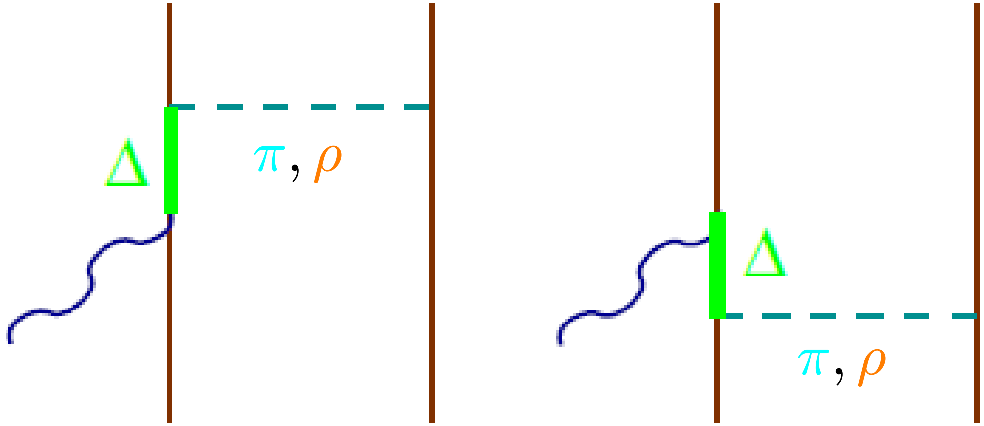
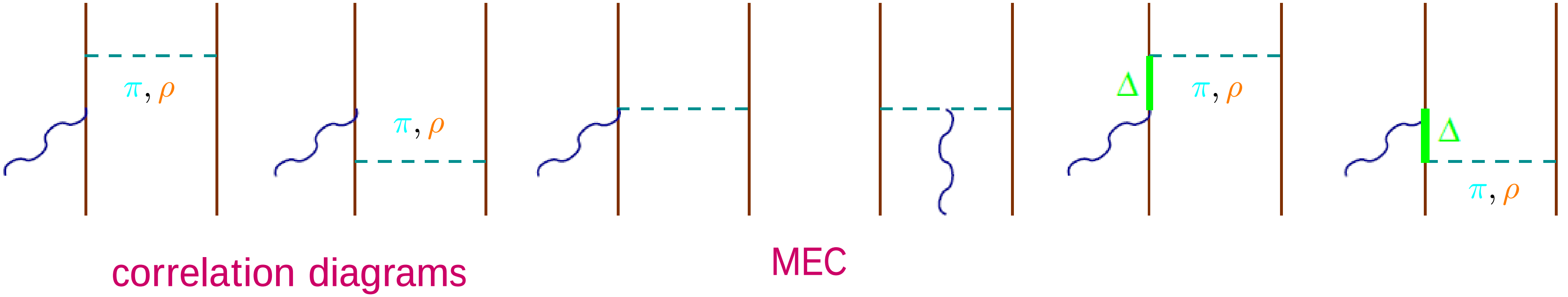
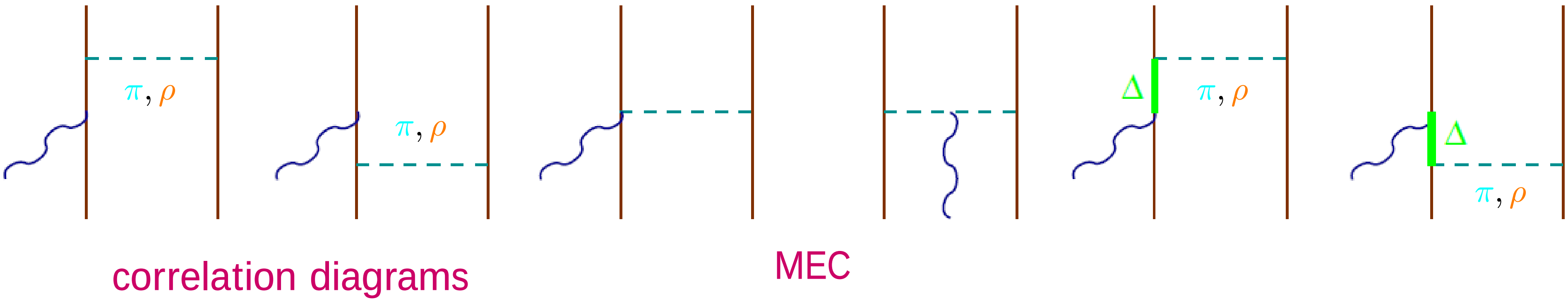


Two-nucleon currents



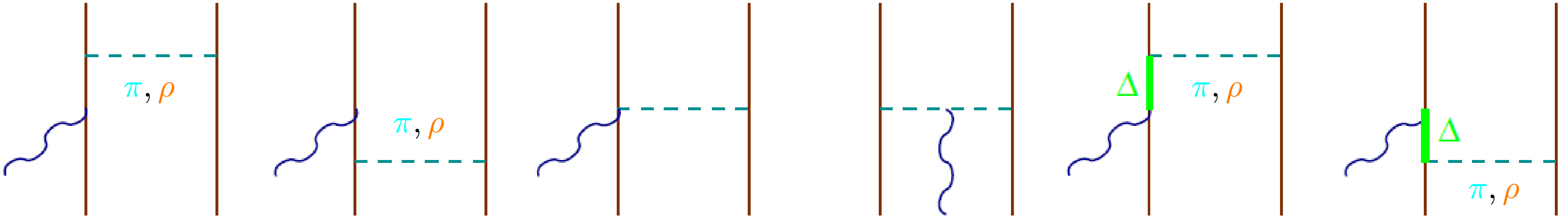
- In the relativistic Fermi gas model they can
  - be ignored
    - SUSA embeds them in scaling function
    - Price to pay: no (partial) current conservation
    - 2-body Δ-currents (with π exchange) accounted but suppressed at the Δ peak to avoid double counting with the Δ scaling function

Two-nucleon currents



- In nuclear-matter many-body calculations adapted to finite nuclei using the local density approximation
  - correlation diagrams “regularized” by $\mathrm{Im}(\Sigma_N)$ (Nieves et al.)
  - warning: included in the QE part (and not always)
  - 2-body Δ-currents (with π + ρ exchange)

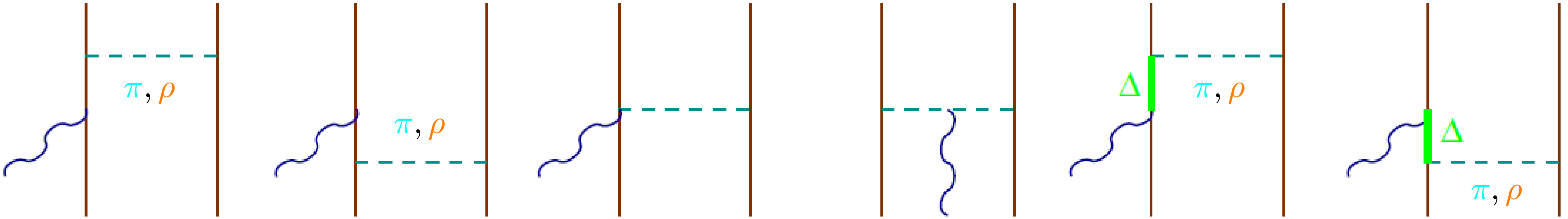
Two-nucleon currents



correlation diagrams MEC

- In mean field models they can (in principle) be incorporated in the initial/final nucleon wave functions
  - w.f. are single-particle Hartree-Fock states (Jachowicz et al.)
  - same w.f. used in MEC
  - MEC ⇒ 2p2h but also 1p1h
  - No Δ
  - MEC only accounts for a small fraction of the missing strength in the dip region

Two-nucleon currents



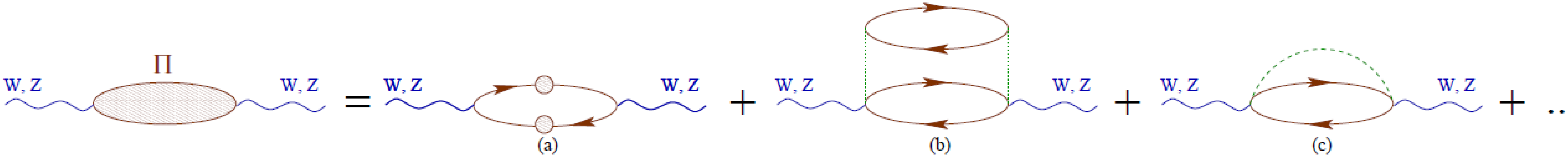
correlation diagrams

MEC

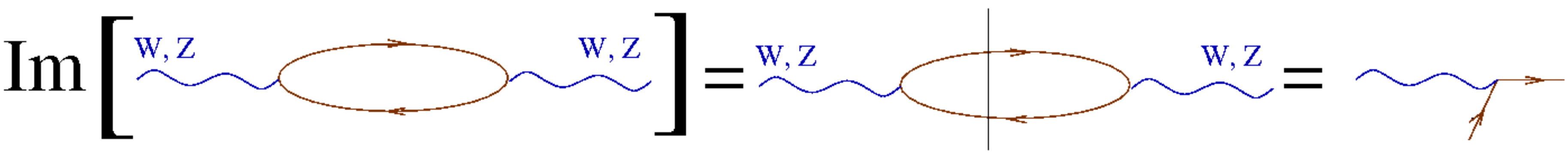
- Built in the spectral function of holes and particles (Benhar et al.)
- MEC are calculated using a two-nucleon spectral function in the initial state
- Interference between MEC and correlation amplitudes, given in terms of the overlap function between target ground state and (A-1) system

Polarization propagator

$$W^{\alpha\beta}_{(s,a)} = -\frac{1}{\pi}\,\mathrm{Im}\,\Pi^{\alpha\beta}_{(s,a)}$$



- Cutkosky rules:



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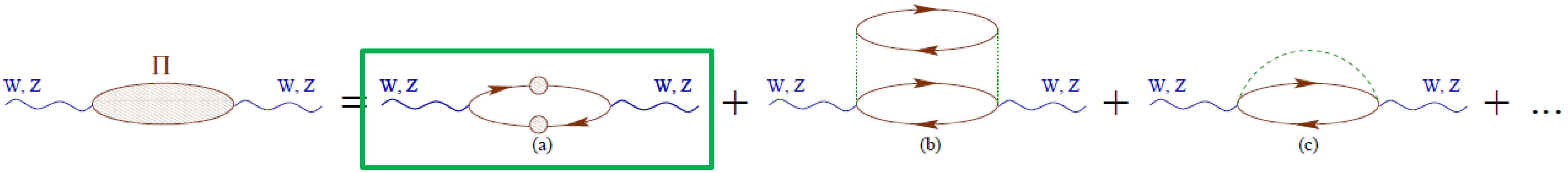
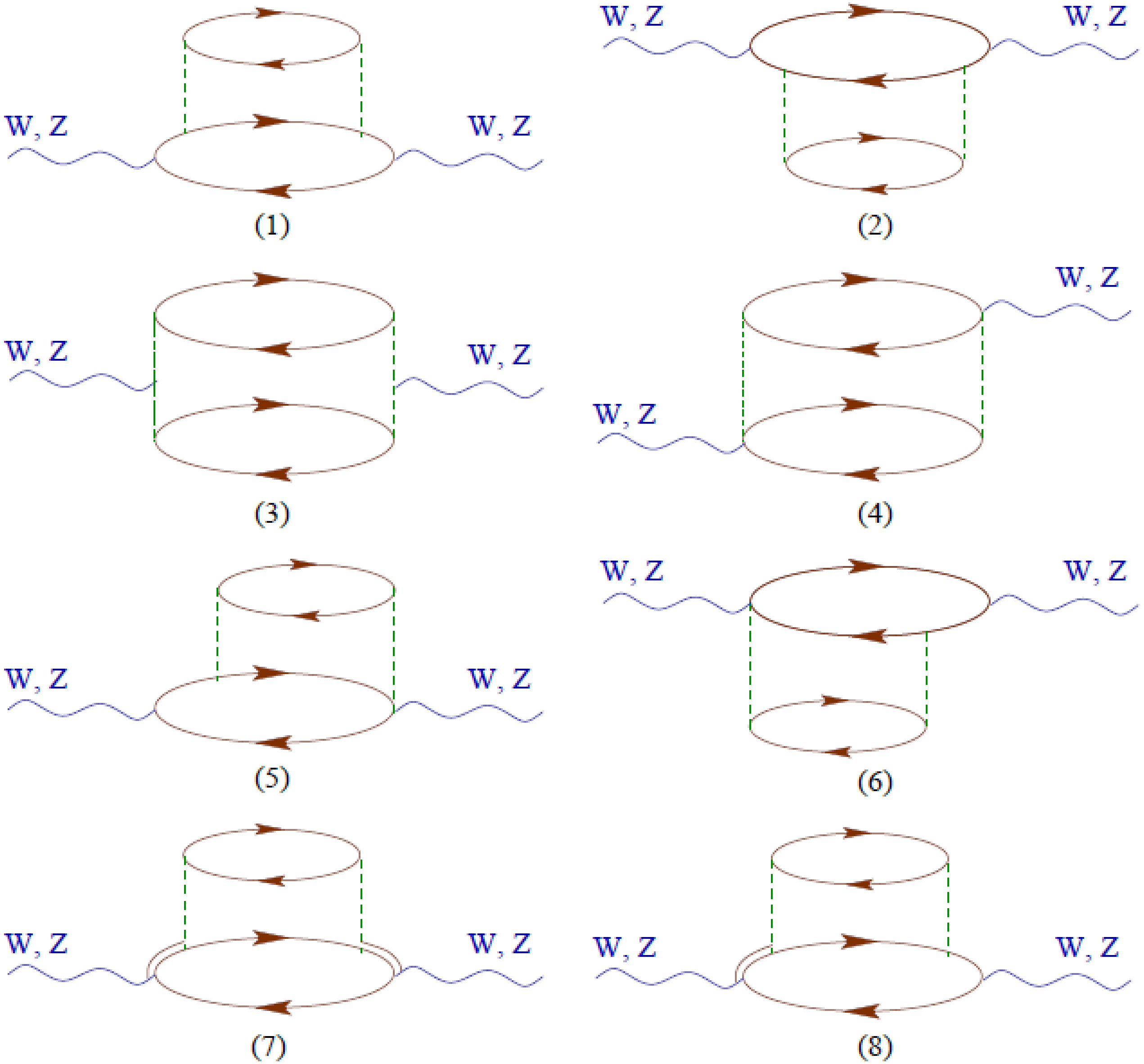


$$\mathrm{Im}\,\Pi^{\alpha\beta}_{(s,a)} = -2\pi^2 \int \frac{d^4p}{(2\pi)^4} H^{\beta\alpha}_{(s,a)} \mathcal{A}_p(p+q)\,\mathcal{A}_h(p)$$

Polarization propagator

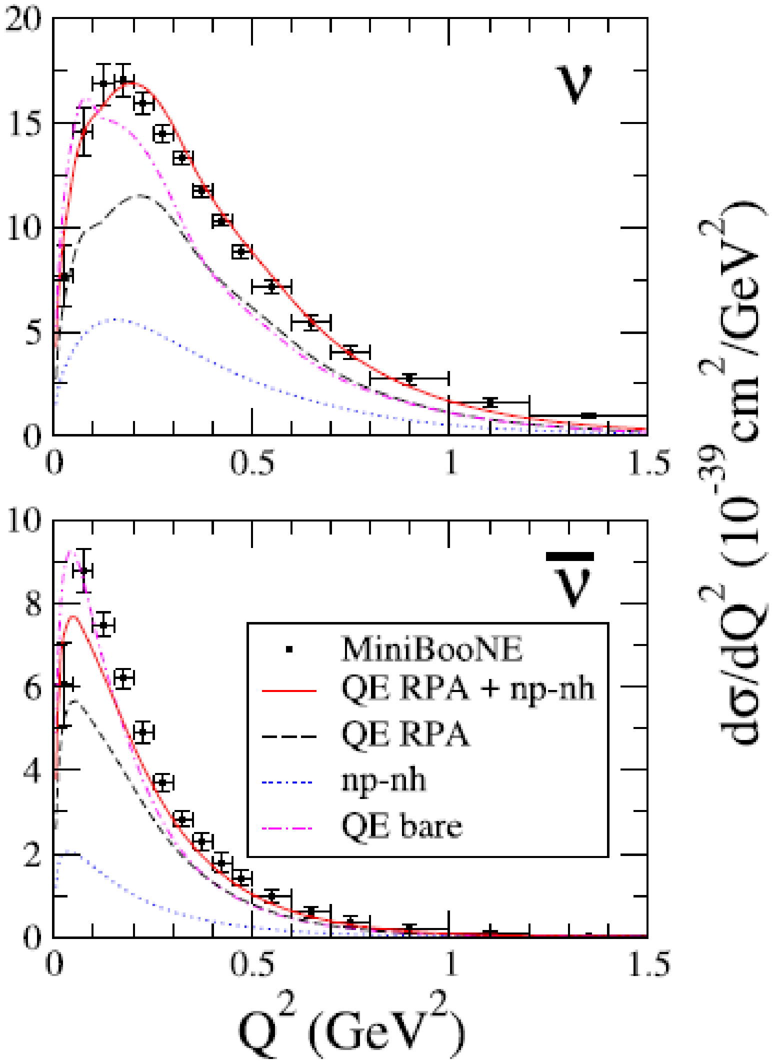


Two-nucleon currents

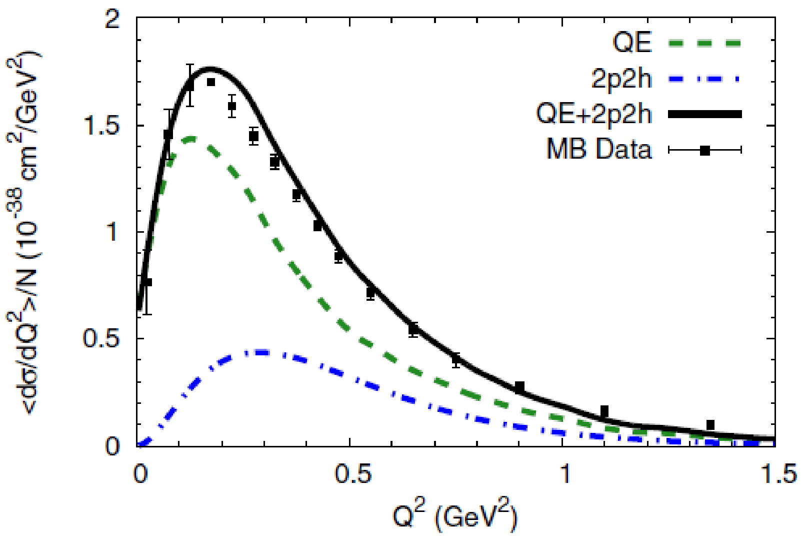
- Martini et al.
- Assumption: only transverse response $R_{\sigma\tau}(T)$
- $R_{\sigma\tau}(T)$ taken from an (e,e`) calculation Alberico et al.

- GiBUU
- Assumption: only transverse interaction
- Structure function W_1 taken from Bosted, Mamyan, arXiv:1203.2262

Two-nucleon currents



Martini et al.



GiBUU

Outlook

- 2-nucleon EW currents exist.
- QE-like c.s. receives a sizable contribution from them
- Relevant for oscillation experiments
- Open issues:
  - model discrimination and tuning
  - extension to higher energy transfers
  - consistent implementation in MC generators