SAPIENZA
UNIVERSITÀ DI ROMA

(Re)-Assessing the Role of Meson-Exchange-Currents in Lepton-Nucleus Interactions

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OUTLINE

- Preamble
- Qualitative features of MEC contributions emerging from early studies of electron-nucleus scattering
- Studies based on more realistic models of electron-nucleus scattering
  - Superscaling
  - Factorisation
- Specific issues associated with the description of neutrino-nucleus scatteing
  - Flux average
  - Contribution of axial current
- Results of recent studies
- Summary & Outlook

PREAMBLE

- Nuclear Many-Body Theory is based on the tenet—strongly supported by low-energy nuclear phenomenology—that nucleon dynamics below pion production threshold can be described by the Hamiltonian

$$H_A = \sum_{i=1}^{A} \frac{\mathbf{p}_i^2}{2m} + \sum_{j>i=1}^{A} v_{ij} + \dots ,$$

and the associated electro-weak current operator

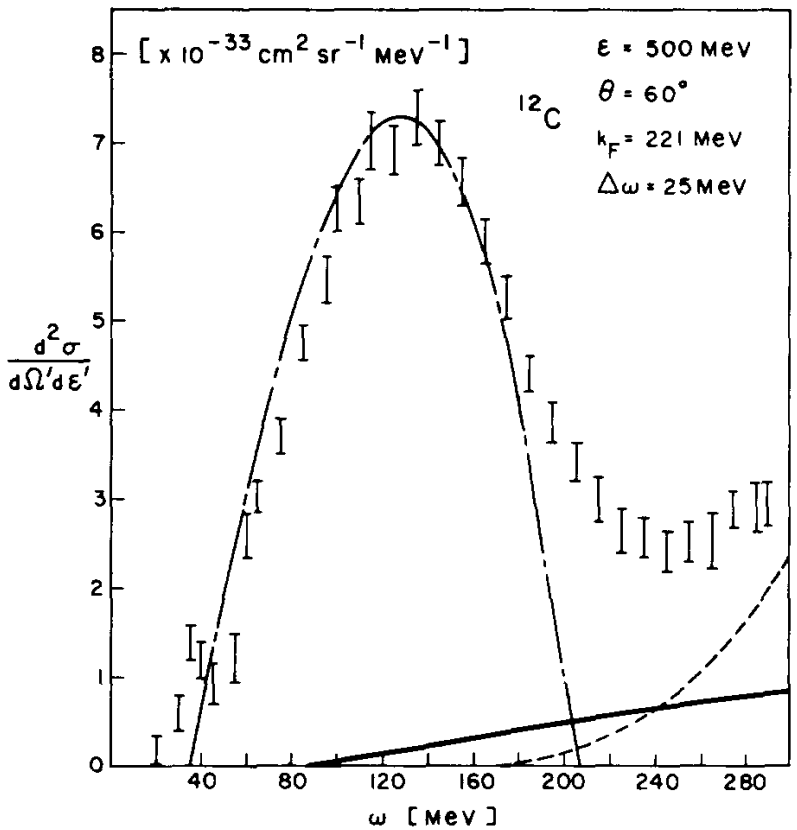
$$J_A(q) = \sum_{i=1}^{A} j_i + \sum_{j>i=1}^{A} j_{ij} + \dots .$$

- In the late 1970s, significant two-nucleon meson-exchange current (MEC) contributions, leading to the excitation of 2p2h final states, were advocated to explain inclusive electron scattering cross sections in the *dip* region, between the quasi-elastic and Δ-production peaks, corresponding to $\omega \approx Q^2/m$

Early electron scattering study

- The amount of strength needed to describe the data depends on the treatment of the one-nucleon current contributions

- Calculations by
  T.W. Donnellly
  et al., PLB **76**, 393 (1978).
  RFGM + MEC
- Data from E.J. Moniz
  et al., PRL **26**, 445 (1971)

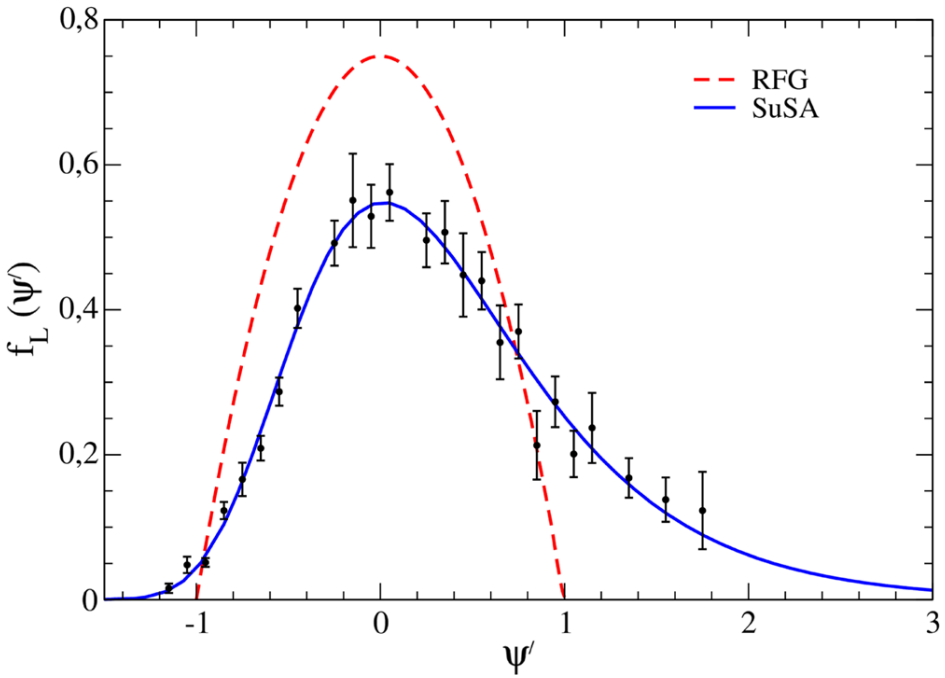


- Most studies only considered transitions to 2p2h final states, neglecting interference between 1p1h and 2p2h amplitudes altogether

Enter nuclear dynamics

- Taking into account the effects of nuclear dynamics not included in the RFGM leads to the appearance of sizeable asymmetric tails, originating from both initial state dynamics—primarily Short-Range Correlations (SRC)—and Final State Interactions (FSI)

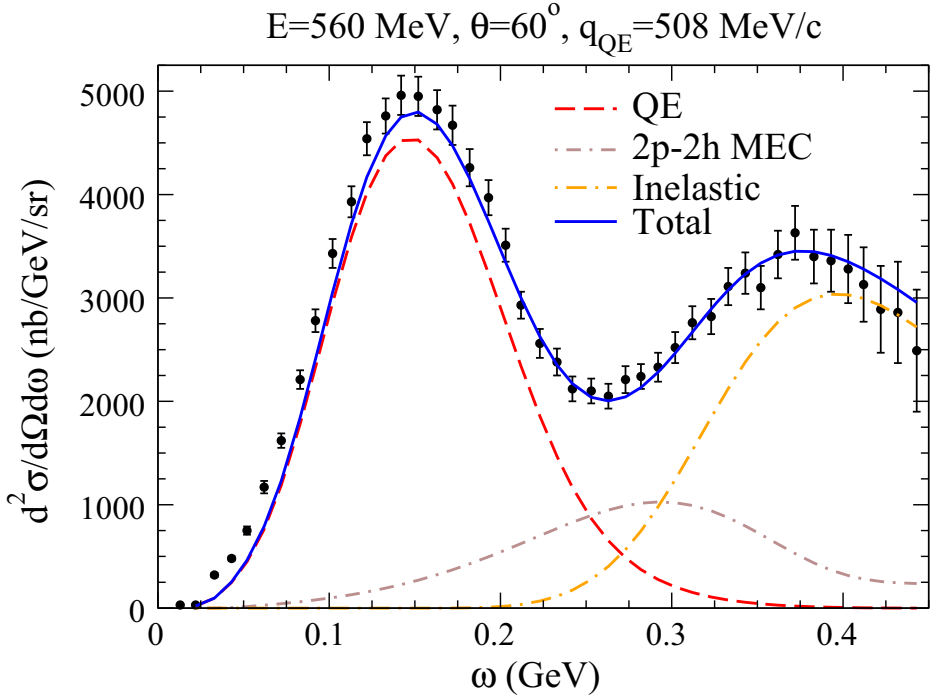
- J.E. Amaro *et al.*, Eur. Phys. J. Spec. Top. **230**, 4321 (2021)
- Data from J. Jourdan, NPA **603**, 17 (1996)



- One- and two-nucleon current contributions should be treated consistently, within a unified realistic model

More advanced models: SuSA

- In the phenomenological superscaling model (SuSA) the single-nucleon knock out contribution to the cross section is obtained from electron scattering data
- MEC contributions computed within the RFGM, including only transitions to 2p2h final states



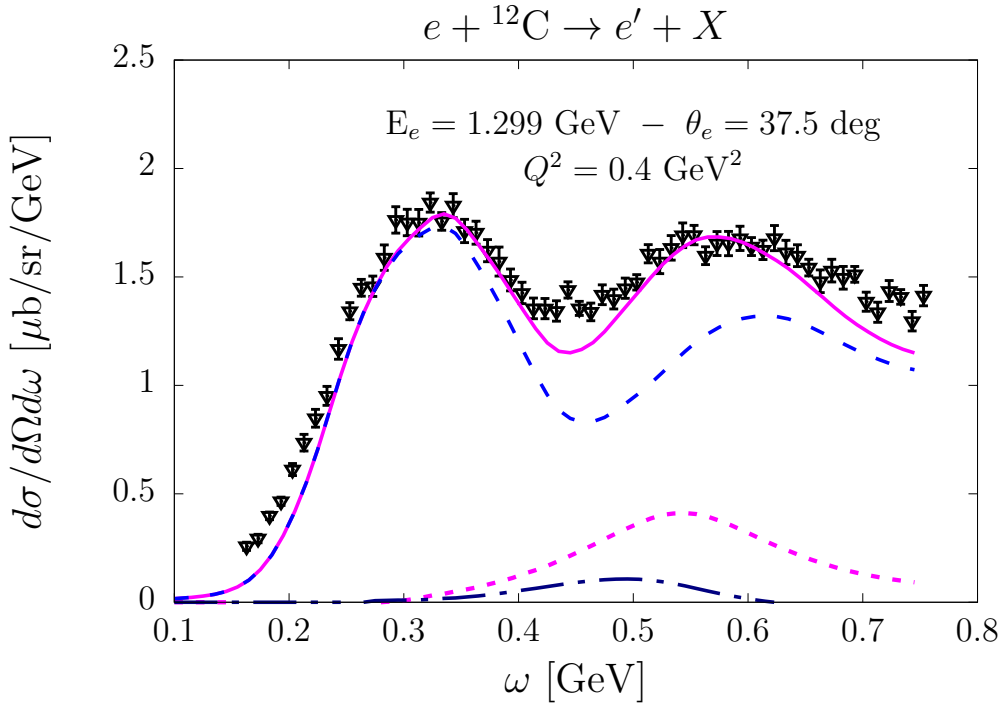
- J.E. Amaro *et al.*, Eur. Phys. J. Spec. Top. **230**, 4321 (2021)
- Carbon data from P. Barreau *et al.*, NPA **402**, 515 (1983)

- The SuSA model is inherently unable to take into account interference between 1p1h and 2p2h amplitudes

More advanced models: Factorisation

- Factorisation of the nuclear cross section allows to treat one- and two-body current contributions within a consistent framework, using spectral functions obtained from a state-of-the-art microscopic model of nuclear dynamics and fully relativistic current operators

- N. Rocco *et al.*, PRL **116**, 192501 (2016)
- Carbon data from R. Sealock *et al.*, PRL **62**, 1350 (1989)

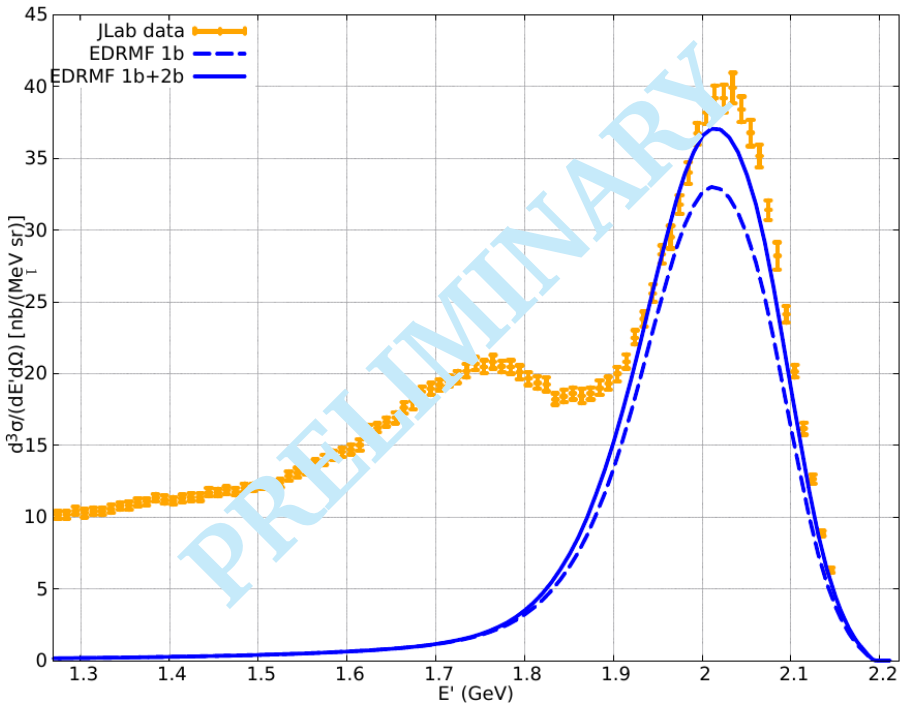


- Transitions to 1p1h final state induced by the two-nucleon current are neglected

Recent studies: ED-RMF model

- ⋆ Relativistic Mean-Field Model, extended to consistently describe FSI and corrected to account for ground-state correlations;
  T. Franco-Munoz *et al.* arXiv:2203.09996 [nucl-th]
- ⋆ Fully relativistic current operators, transitions to 1p1h final states and interference contributions included

- ⋆ Figure courtesy of Raul Gonzáles-Jiménez
- ⋆ Data from H. Dai *et al.* PRC **99**, 054608 (2019)
- ⋆ The two-body current contribution, yielding $\sim 20\%$ of the full cross section, peaks at $\omega \approx Q^2/2m$

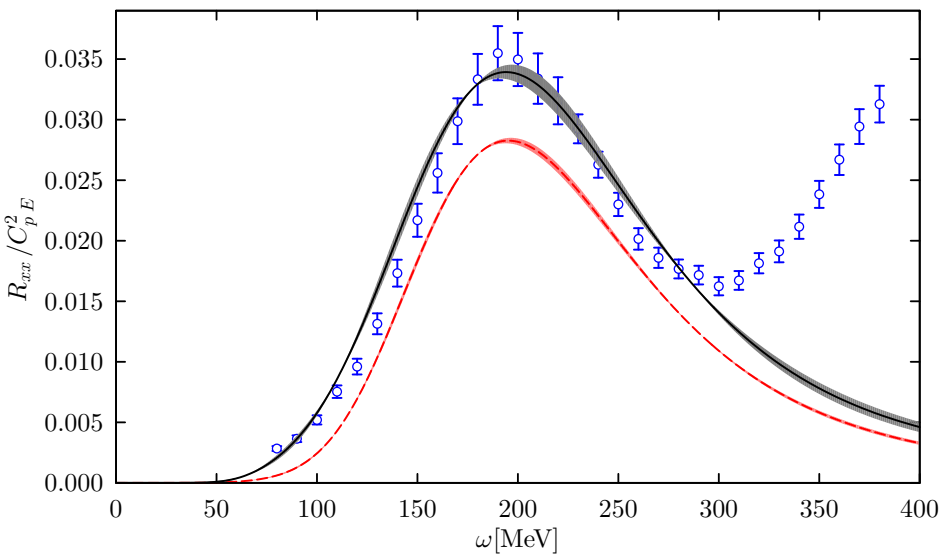


- ⋆ Distinct energy dependence of MEC contributions

HINTS FROM GFMC CALCULATIONS

- ⋆ The Green Function Monte Carlo (GFMC) technique allows one to perform *ab initio* calculations of the nuclear response in the non relativistic regime. All one- and two-body current contributions, including interference, consistently taken into account

- ⋆ Lovato *et al.*, PRC **91**, 062501 (2015); red: one-body current only; blue: full calculation
- ⋆ Transvere response of Carbon at $q = 600$ MeV from J. Carlson *et al.* PRC **65**, 024002 (2002);

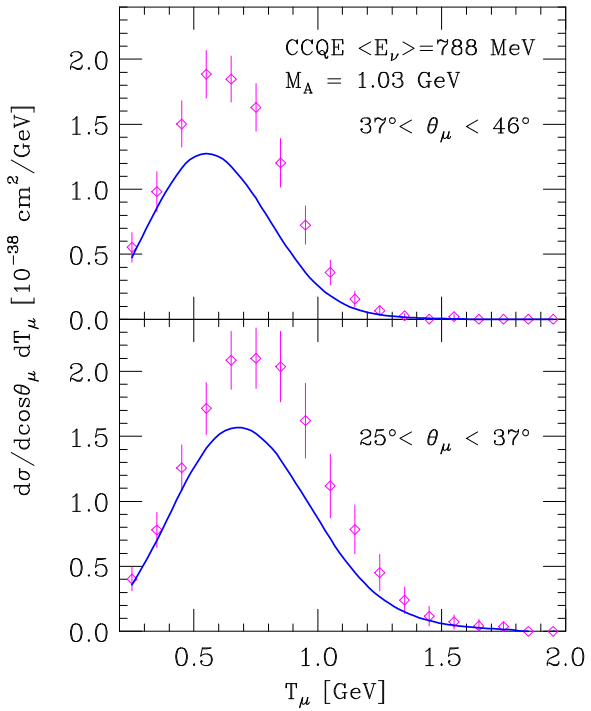


- ⋆ Transitions to 1p1h final states and interference appear to play a critical role

NEUTRINO-NUCLEUS INTERACTIONS

- State-of-the-art models of electron-nucleus scattering largely fail to explain the measured neutrino cross sections in terms of single-nucleon knock out induced by the one-body current

- Benhar *et al.* PRL **105**, 132301 (2010)
- MiniBooNE data, PRD **81**, 092005 (2010)

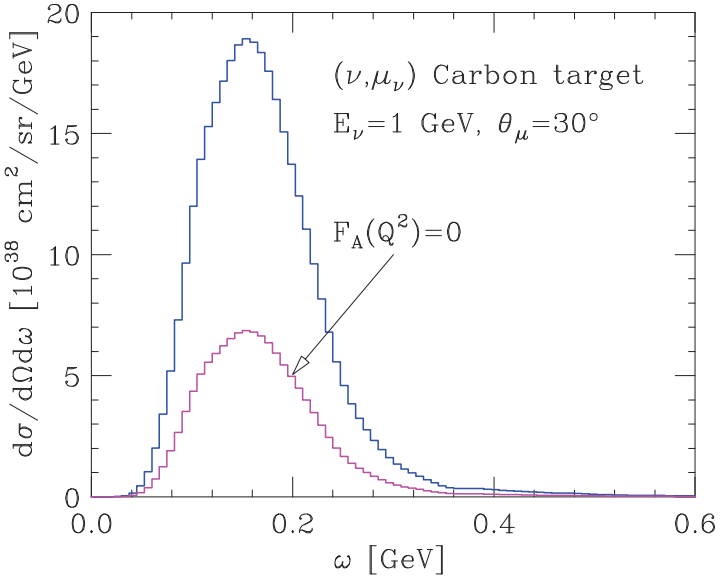


Processes involving MEC—somewhat misleadingly referred to as 2p2h contributions—have been advocated as the main source of the missing strength

NEUTRINO-NUCLEUS INTERACTIONS

- Compared to the electron-nucleus cross sections, the measured neutrino-nucleus cross sections involve two important differences:
  - the average over a broad neutrino flux, which severely hampers a clear-cut identification of different reaction mechanisms
  - a large contribution of the axial-vector current

- Jen *et al.* PRD **90**, 093004 (2014); dipole fit with $M_A = 1.03$ GeV



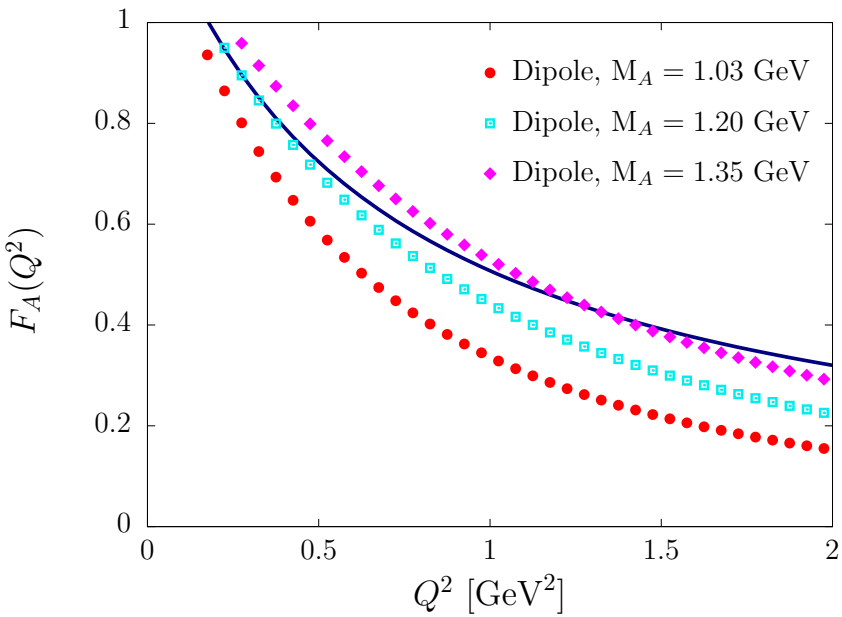
- The size of the contribution from two-nucleon currents is largely driven by the uncertainty on the axial structure of the nucleon

Q^2-DEPENDENCE OF THE AXIAL FORM FACTOR

- ⋆ The available data—from, e.g., MiniBooNE [PRD **81**, 092005 (2010)] and T2K [PRD **92**, 112003 (2015)] can be explained by significantly increasing the nucleon axial mass from its *canonical* value $M_A = 1.03\,\text{GeV}$. However, in the absence of a convincing motivation, this prescription appears to be largely arbitrary

- Comparison between the results of Park et al. [PRD **105**, 054505 (2022)] (full line) obtained from lattice QCD, and the dipole parametrisation

$$F_A(Q^2) = g_A\left(1+Q^2/M_A^2\right)^{-1}$$

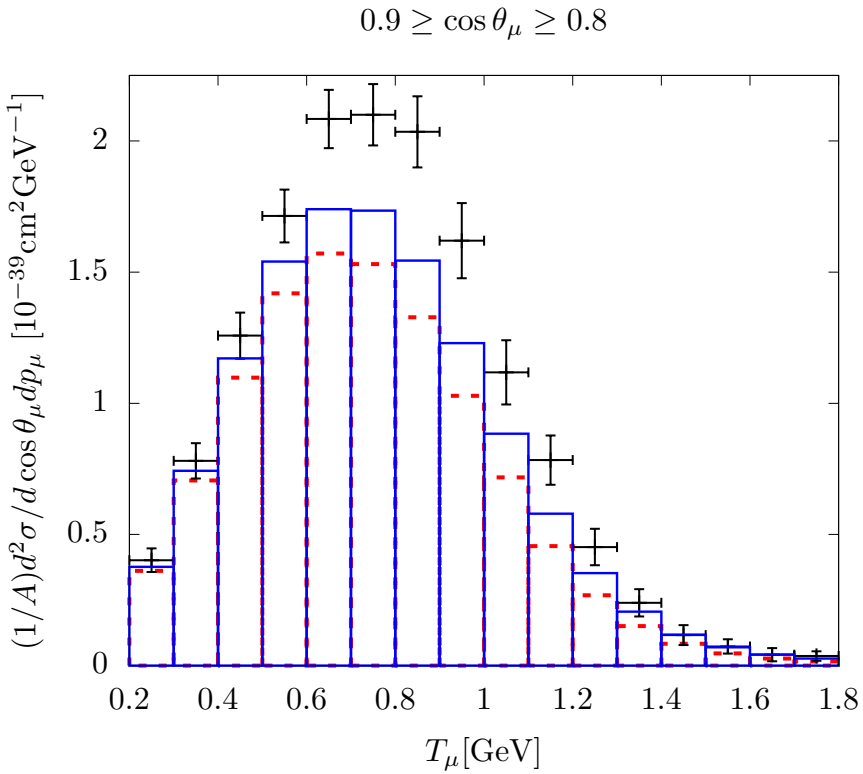


- ⋆ At $Q^2 \lesssim 0.5\,\text{GeV}^2$ the dipole fit with $M_A = 1.2\,\text{GeV}$ is remarkably close to the results of Park *et al*,

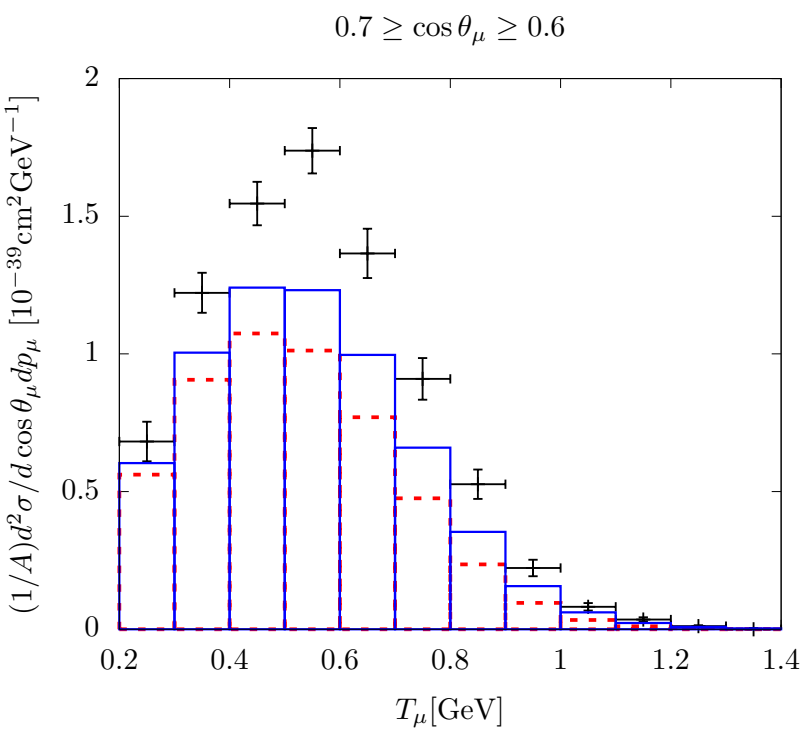
COMPARISON TO MINIBOONE DATA (FROM OB'S TALK AT NUINT22)

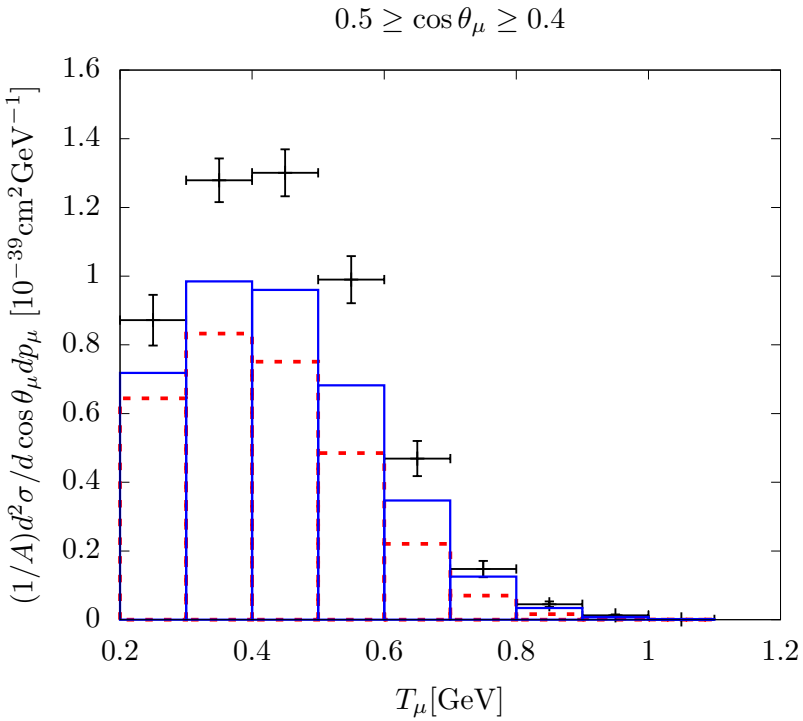
- ⋆ Replacing the $M_A = 1.03$ MeV dipole parametrisation with the lattice QCD axial form factor of Parks *et al.* leads to a $\sim 10 - 15\%$ enhancement of the single-nucleon knock out cross section, entailing a corresponding reduction of the missing strength

- ⋆ Theoretical calculations carried out using a realistic model of the carbon spectral function [same as in PRL **105**, 132301 (2010)]



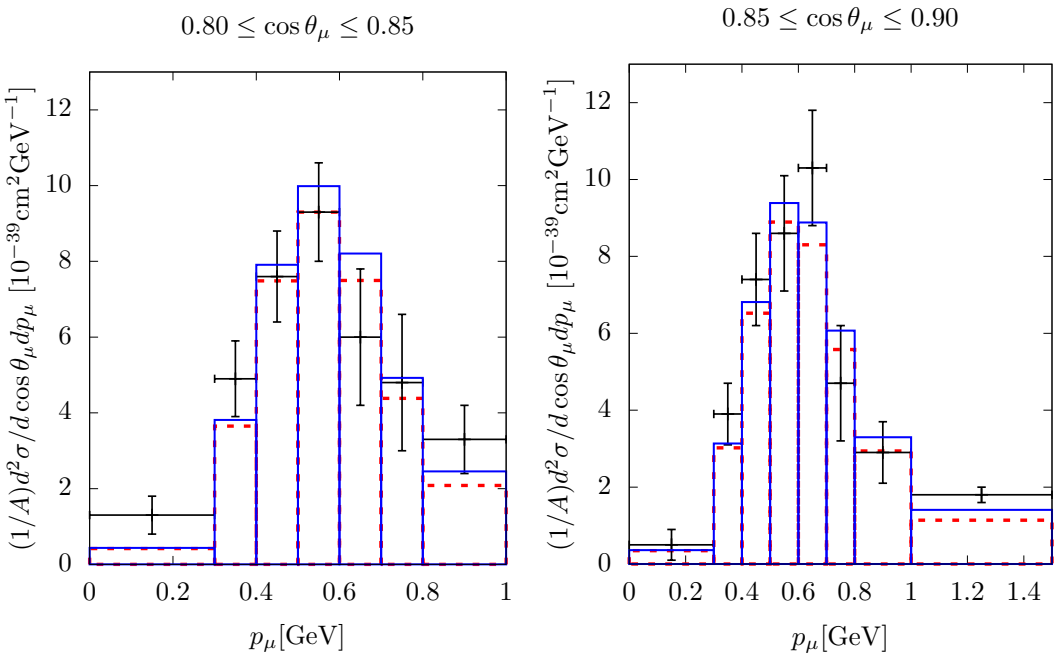
- ⋆ Similar pattern observed at all muon emission angles





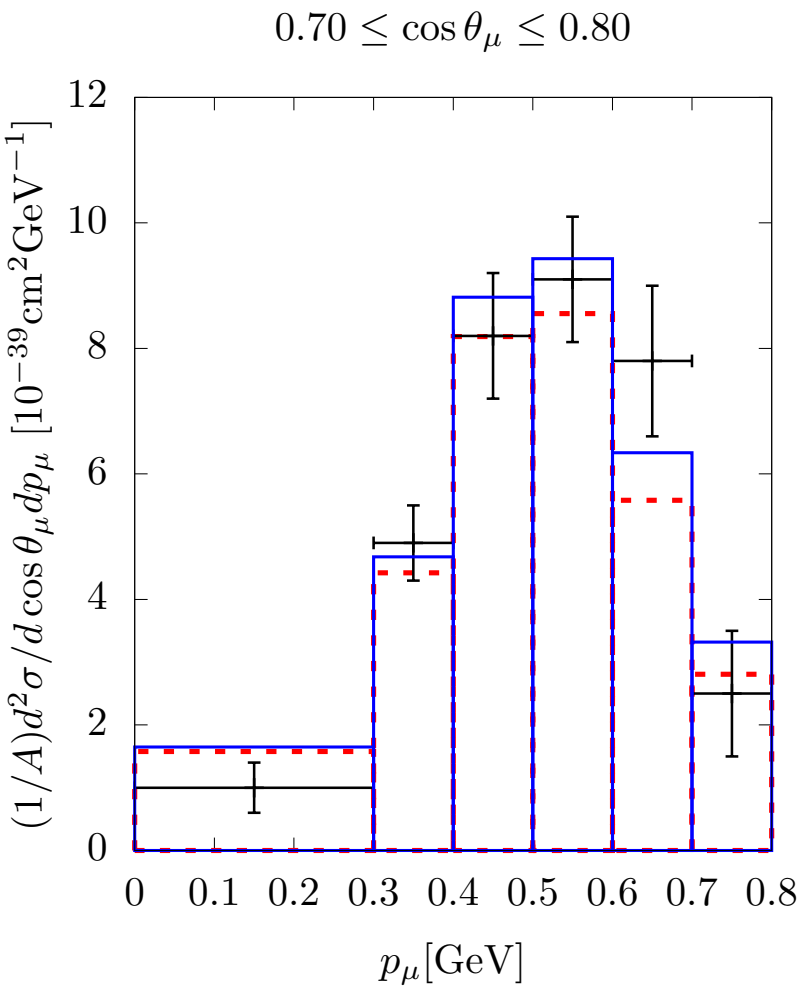
COMPARISON TO T2K DATA (FROM OB'S TALK AT NUINT22)

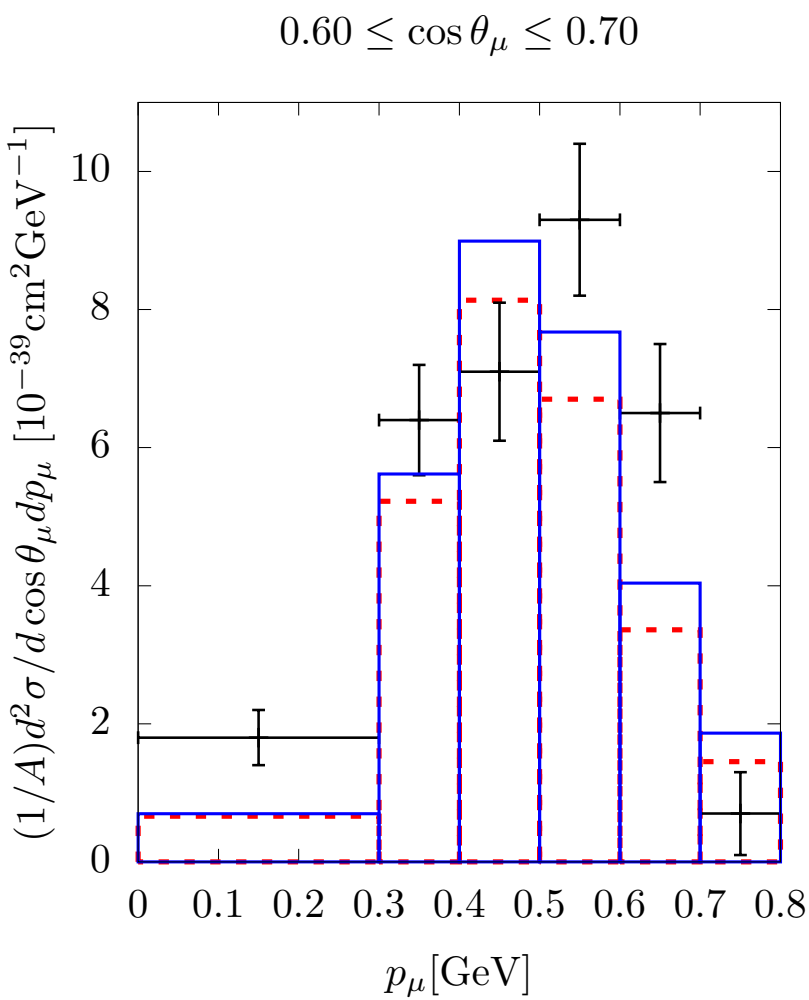
- A comparison to T2K CCQE data [K. Abe et al.. PRD 93, 112012 (2016)] suggests in this instance there is less room for contributions other than single-nucleon knock out



- This observation is consistent with the results of the analysis of T2K data based on the dipole parametrisation of the axial form factor, yielding $M_A = 1.26$ GeV (to be compared with $M_A = 1.35$ GeV reported by MiniBooNE)

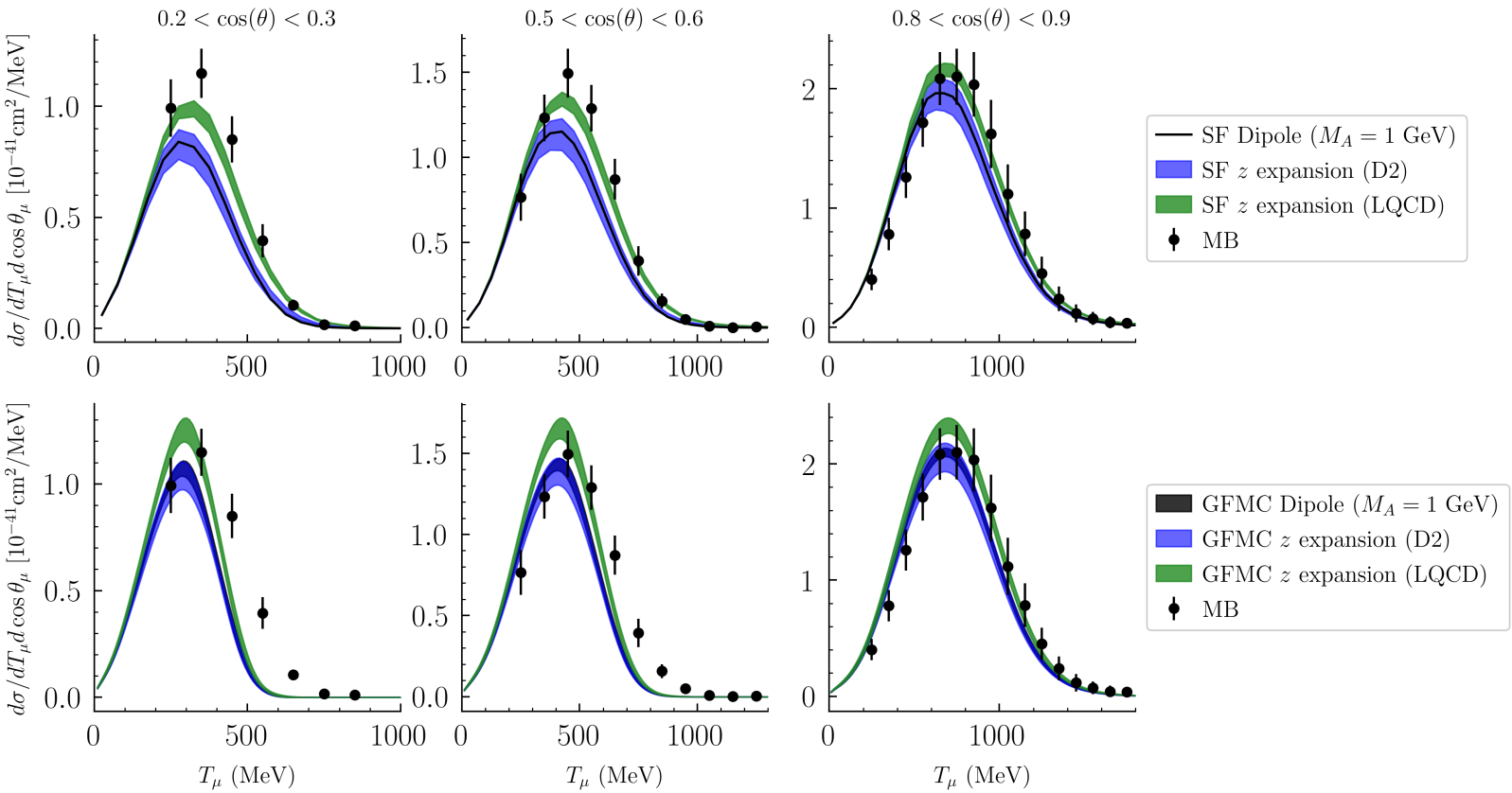
- Similar pattern observed at all muon emission angles





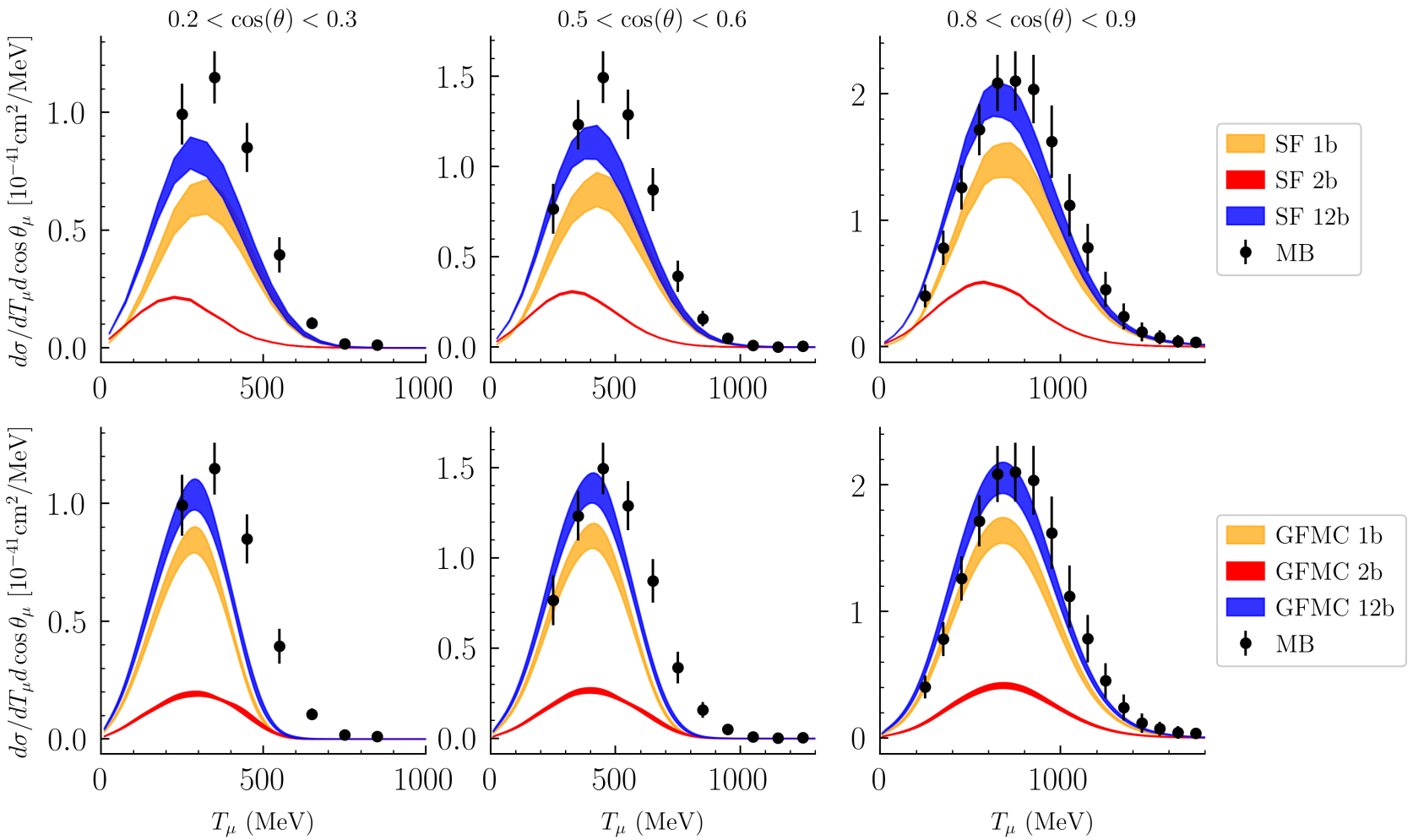
SIMILAR ANALYSIS BY SIMONS *et al.* (ARXIV:2210.02455 [HEP-PH])

- MiniBooNE data analysed using the GFMC and SF formalisms and different prescriptions for the axial form factor

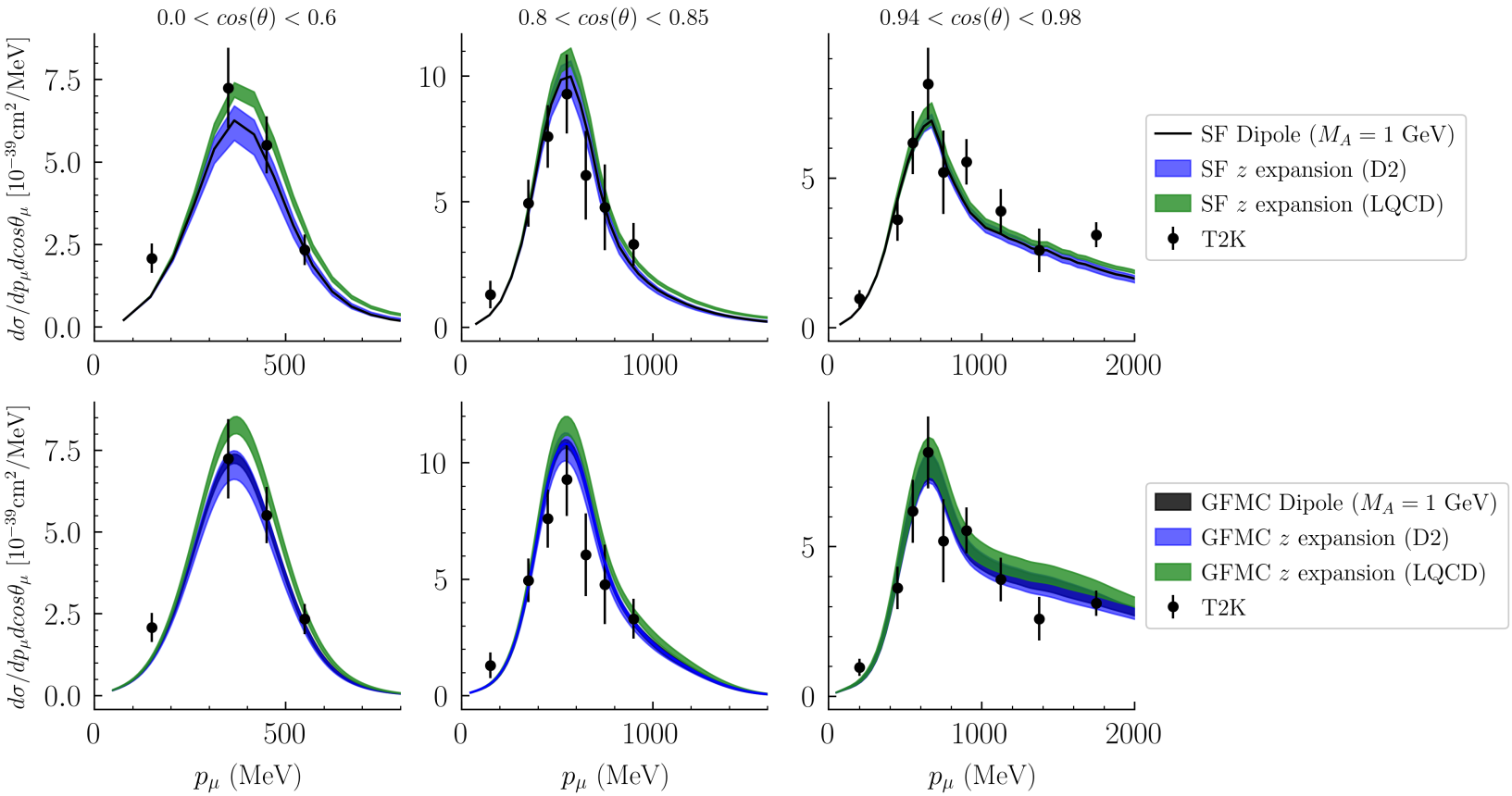


One- and two-nucleon current contributions

- ⋆ SF results do not include interference



Comparison to T2K data



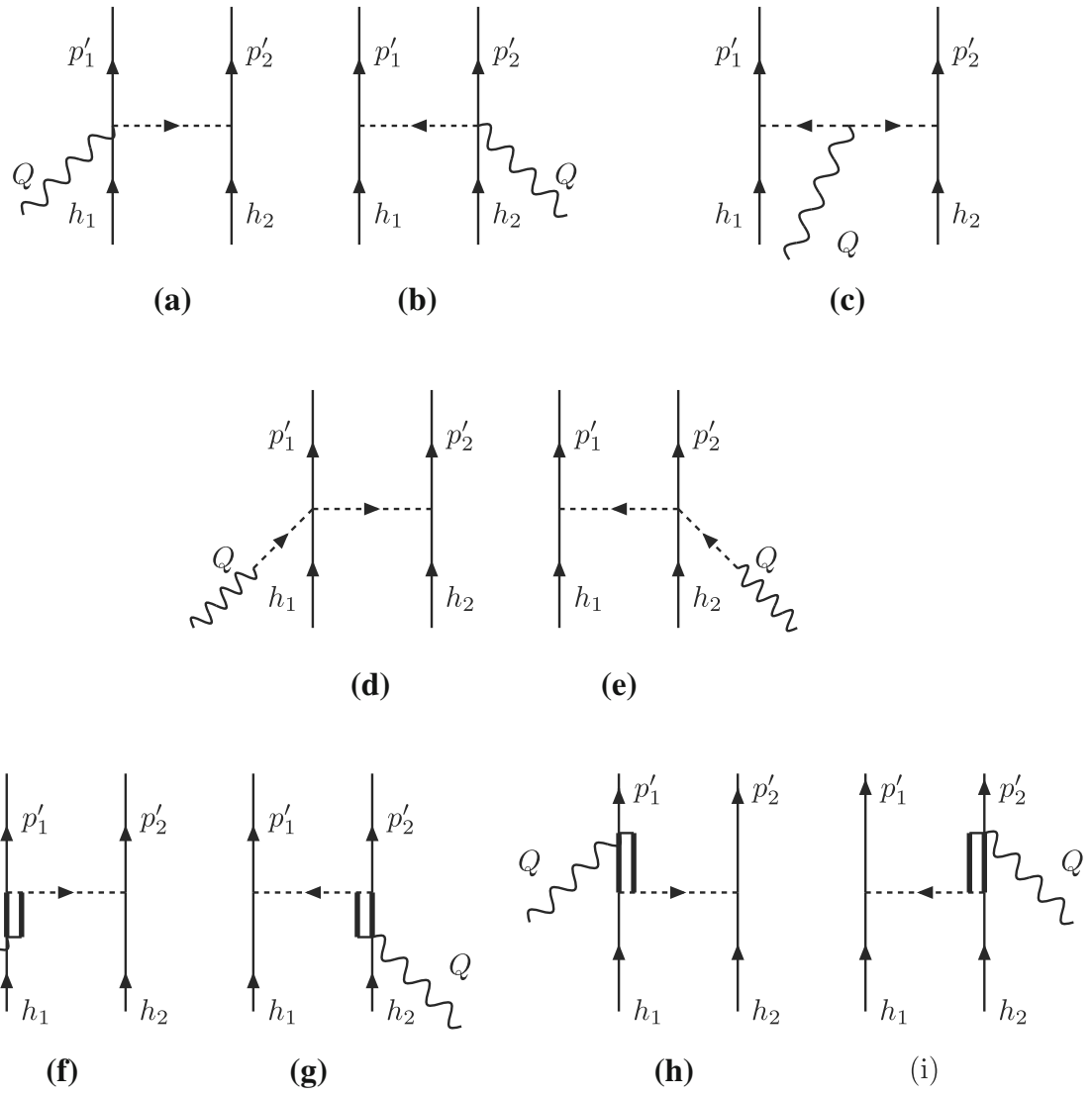
Summary & Outlook

- The measured neutrino-nucleus cross sections exposed specific features of MEC contributions which had not, or could not, been studied by electron scattering experiments
- One- and two-nucleon contributions to the nuclear cross sections must be treated *consistently* within a *realistic* model of nuclear dynamics, including *interference* and using *fully relativistic currents*
- Recent results suggest that the role of interference contributions involving 1p1h transitions induced by MEC, which received little or no attention in electron scattering studies, may, in fact, be important
- While, in general, MC simulation are inherently unable to include interference effects, the distinct energy dependence emerging in the MEC 1p1h sector naturally lends itself to a simplified treatment based on, yes, a modification of the nucleon form factors.

Thank you!

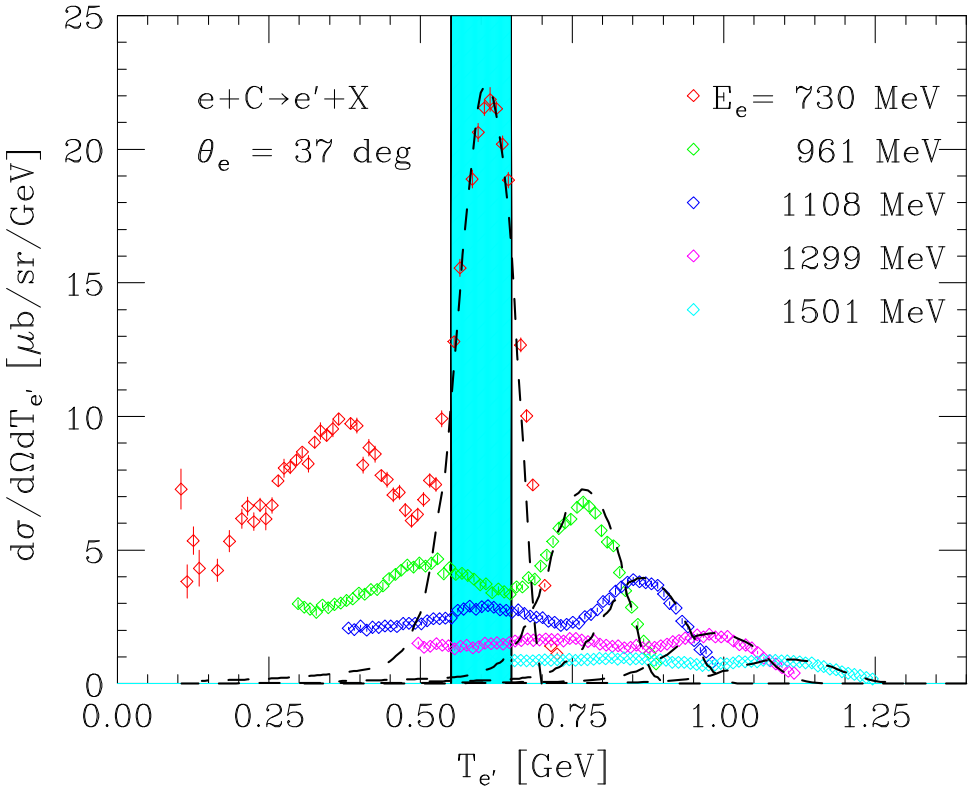
Backup slides

PROCESSES INVOLVING TWO-NUCLEON CURRENTS



THE TROUBLE WITH FLUX AVERAGE

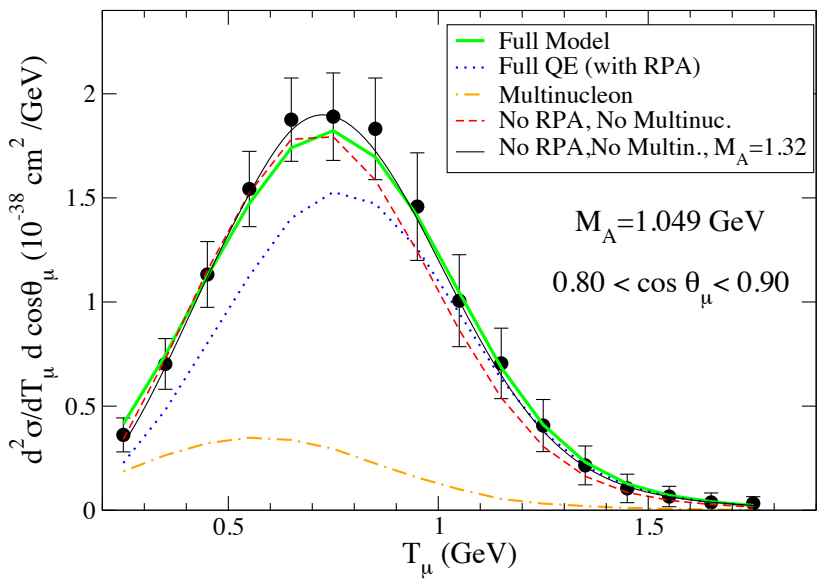
- In neutrino-nucleus interactions, e.g. , $\nu_\mu + A \to \mu^- + X$, the beam energy is unknown, and so is the energy transfer . As a consequence, different reaction mechanisms contribute to the cross section at fixed muon energy and emission angle
- This problem clearly emerges from the analysis of electron-scattering data corresponding to different beam energies



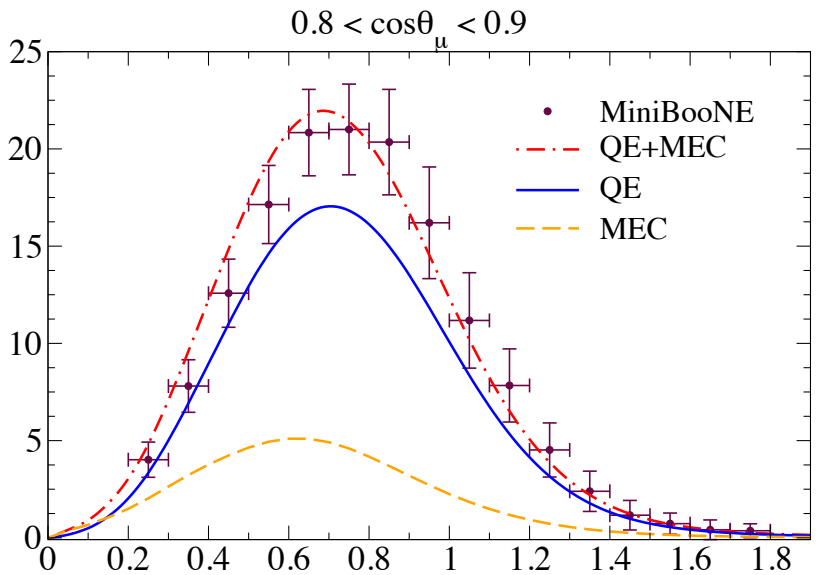
IDENTIFICATION OF DIFFERENT MECHANISMS

- ⋆ While involving somewhat different assumptions, several models agree in predicting that the MiniBooNE data can be explained taking into account the contribution of processes involving two-nucleon currrents (MEC), associated with 2p2h final states

- Valencia model: Nieves *et al*



- Superscaling: Megias *et al*



- ⋆ Assessing the role of the 2p2h sector requires an accurate description of the dominant single-nucleon knock out process