Nuclear models for long-baseline neutrino oscillation experiments and neutrinoless double beta decay : synergies

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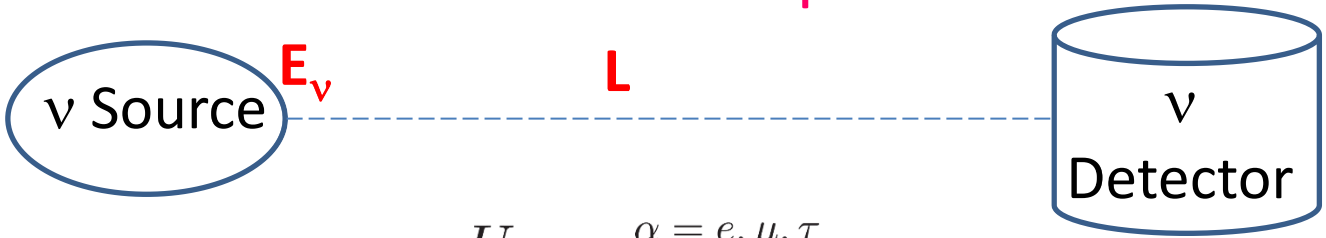
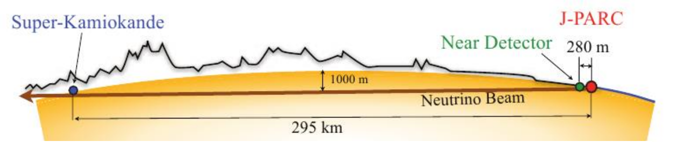
Neutrino oscillation experiments

$$\nu_\alpha \rightarrow \nu_\beta$$



$$\nu_\alpha = U_{\alpha i}\nu_i \qquad \alpha = e, \mu, \tau \quad i = 1, 2, 3$$



Number of detected events

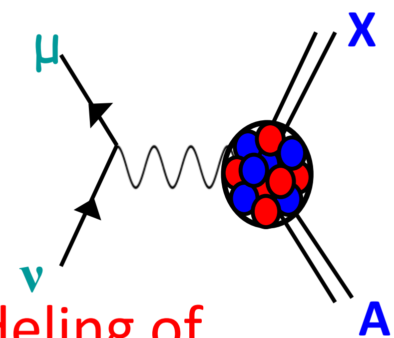
$$N_{\nu_\beta}(\overline{E_\nu}) \sim \int \Phi_{\nu_\alpha}(E_\nu) P_{\nu_\alpha \rightarrow \nu_\beta}(E_\nu, L, \{\Theta\}) \sigma_{\nu_\beta}(E_\nu) \epsilon_{\text{det.}} d(E_\nu, \overline{E_\nu}) dE_\nu$$

Reconstructed ν energy

ν flux	ν oscillation probability	ν cross section	Detector efficiency	Migration matrix

Modern accelerator-based neutrino oscillation experiments:

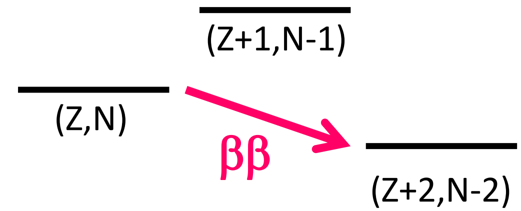
- Nuclear targets (C, O, Ar, Fe…)
- Neutrino energy is reconstructed



→ the knowledge and the modeling of neutrino-nucleus cross sections is crucial

Neutrinoless ββ decay

Double beta decay occurs between even-even nuclei bypassing the intermediate, more massive, odd-odd nucleus



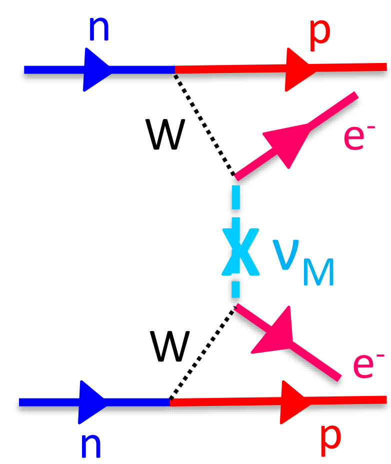
$$A(Z,N) \rightarrow A(Z+2,N-2) + 2e^- + 2\bar{\nu}_e$$

2νββ decay already observed

If neutrinos are their own antiparticles (Majorana particles) one can also observe:

$$\boxed{A(Z,N) \rightarrow A(Z+2,N-2) + 2e^-}$$

0νββ decay

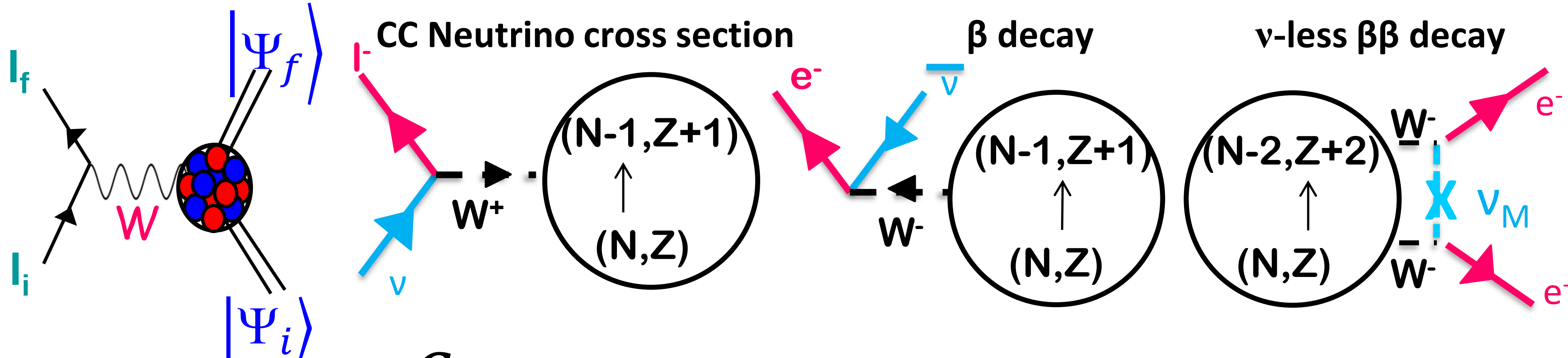


Important experimental program

$$\left[\tau_{1/2}^{0\nu}\right]^{-1} = G_{0\nu}\left|M_{0\nu}\right|^2 |\langle m_\nu \rangle|^2$$

- The rate of any kind of ββ decay depends on **nuclear matrix elements** and decisions about which and how much material to use in the experiments rely on our ability to calculate them accurately
- If 0νββ decay is actually observed, the **nuclear matrix elements** will play a key role in extracting information about neutrino masses

Generalities



$$\mathscr{L}_W = \frac{G}{\sqrt{2}} l^\mu h_\mu \qquad d\Gamma, d\sigma \propto L_{\mu\nu} W^{\mu\nu}$$

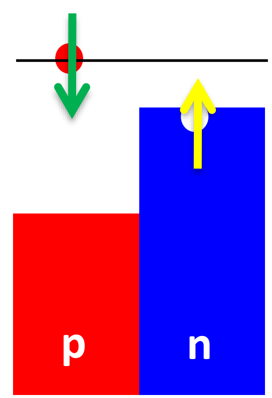
$$d\Gamma, d\sigma \sim (leptonic\ factors) \left| \langle \Psi_f | \hat{O} | \Psi_i \rangle \right|^2$$

Nuclear matrix elements

Example of nuclear excitation operator:
Gamow Teller

$$\hat{O}_{GT} = \sum_{i=1}^{A} \vec{\sigma}(i)\ \tau_-(i)$$

$\Delta S=1 \qquad \Delta T=1$



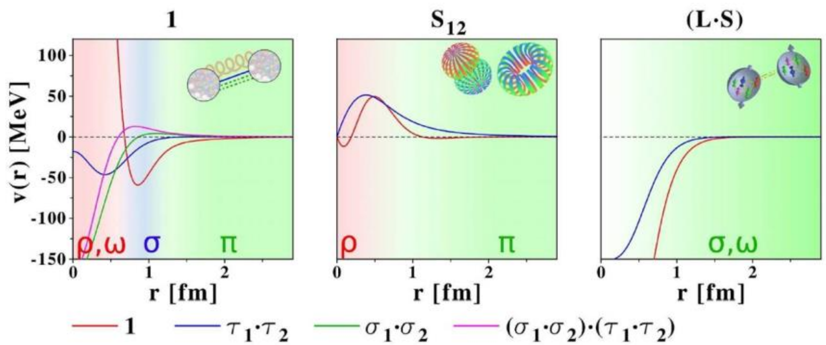
$$d\Gamma, d\sigma \sim (leptonic\ factors) \left|\langle \Psi_f | \hat{O} | \Psi_i \rangle\right|^2$$

- If we experimentally know the nuclear matrix elements: very good!

- Otherwise we need nuclear models

Two main "problems" of nuclear physics

- The nuclear interaction



- The nucleus is a many body system

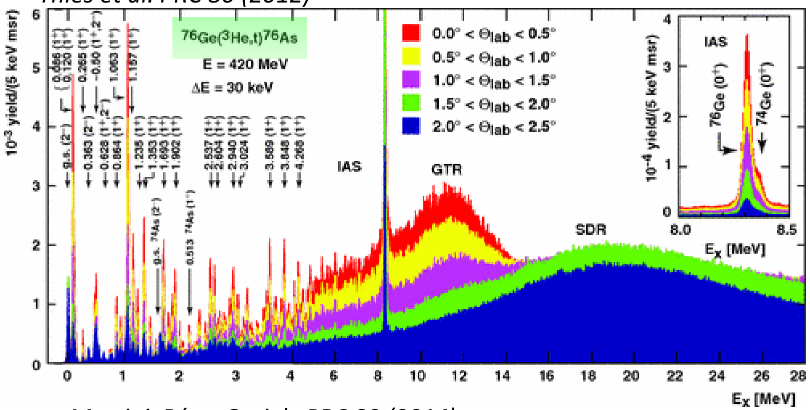
$$H = \sum_{i=1}^{A} \frac{p_i^2}{2m} + \sum_{i<j=1}^{A} V_{ij} + \sum_{i<j<k=1}^{A} V_{ijk} + \ldots$$

Different Nuclear forces, Different Many-Body methods, Different degrees of freedom (quarks, mesons, nucleons) depending on the domains one is interested in

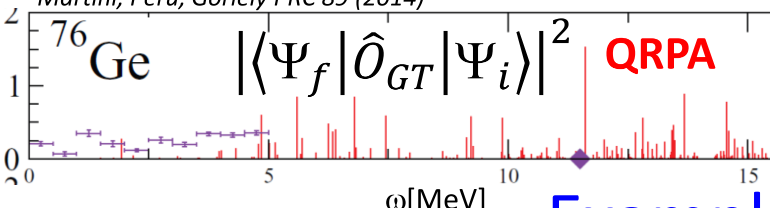
Calculating Matrix Elements is hard

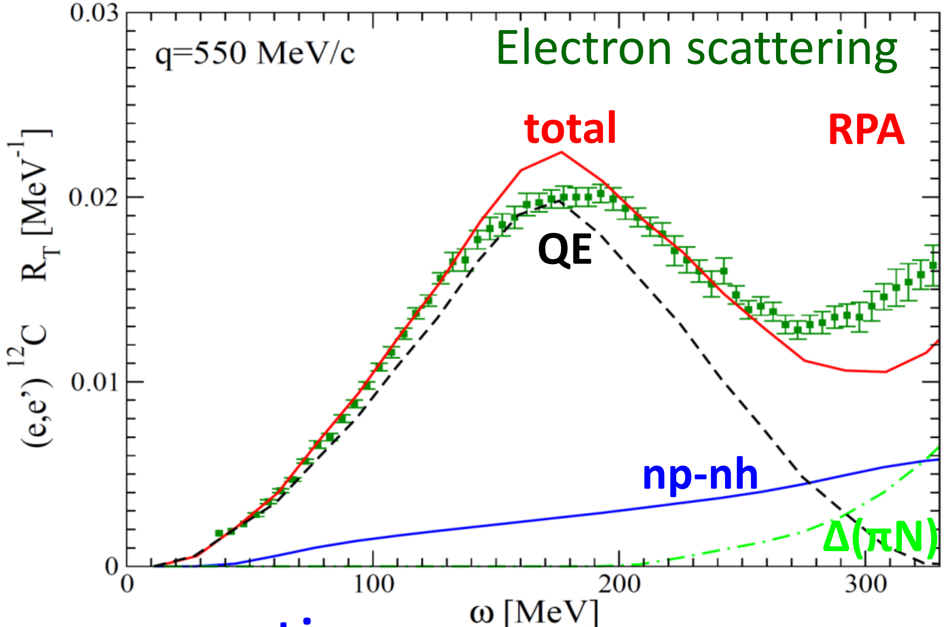
Examples of experimental and theoretical matrix elements

Thies et al. PRC 86 (2012)

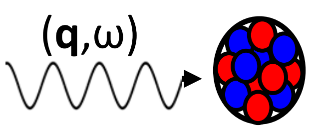


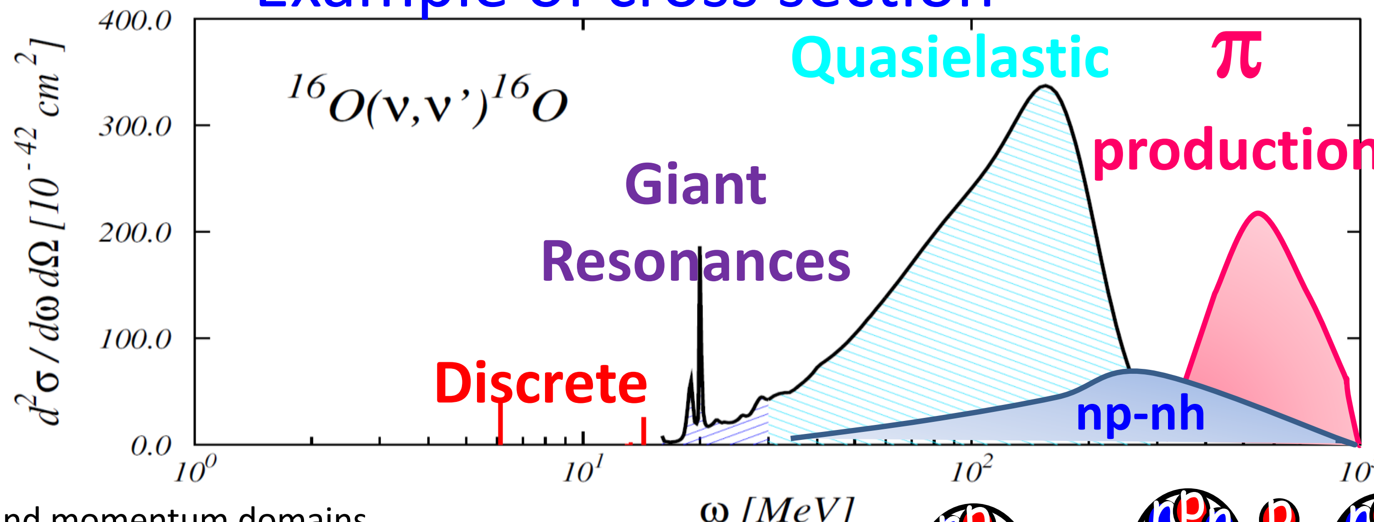
Martini, Péru, Goriely PRC 89 (2014)



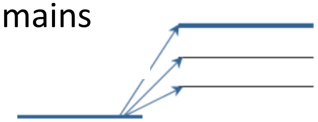


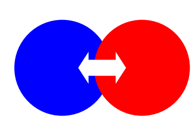
Example of cross section

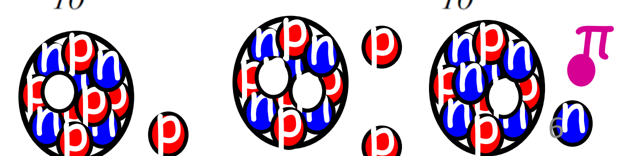




- Different energy and momentum domains
- Different Nuclear models
- Different Nuclei







Prelude: Two “Axial” puzzles

I) The M_A puzzle in the CC Quasielastic ν cross section on Carbon

$$\frac{\partial^2\sigma}{\partial\Omega\,\partial\epsilon'} = \frac{G_F^2\cos^2\theta_c}{2\pi^2}k'\epsilon'\cos^2\frac{\theta}{2}\left[\frac{(q^2-\omega^2)^2}{q^4}G_E^2 R_\tau + \frac{\omega^2}{q^2}G_A^2 R_{\sigma\tau(L)} + 2\left(\tan^2\frac{\theta}{2}+\frac{q^2-\omega^2}{2q^2}\right)\left(G_M^2\frac{\omega^2}{q^2}+G_A^2\right)R_{\sigma\tau(T)} \pm 2\frac{\epsilon+\epsilon'}{M_N}\tan^2\frac{\theta}{2}G_A G_M R_{\sigma\tau(T)}\right]$$

Nuclear dynamics → Nuclear Response Functions R(q,ω) ↔ Nuclear Matrix elements

Nucleon properties → Form factors: Electric G_E, Magnetic G_M, Axial G_A

Axial form factor:

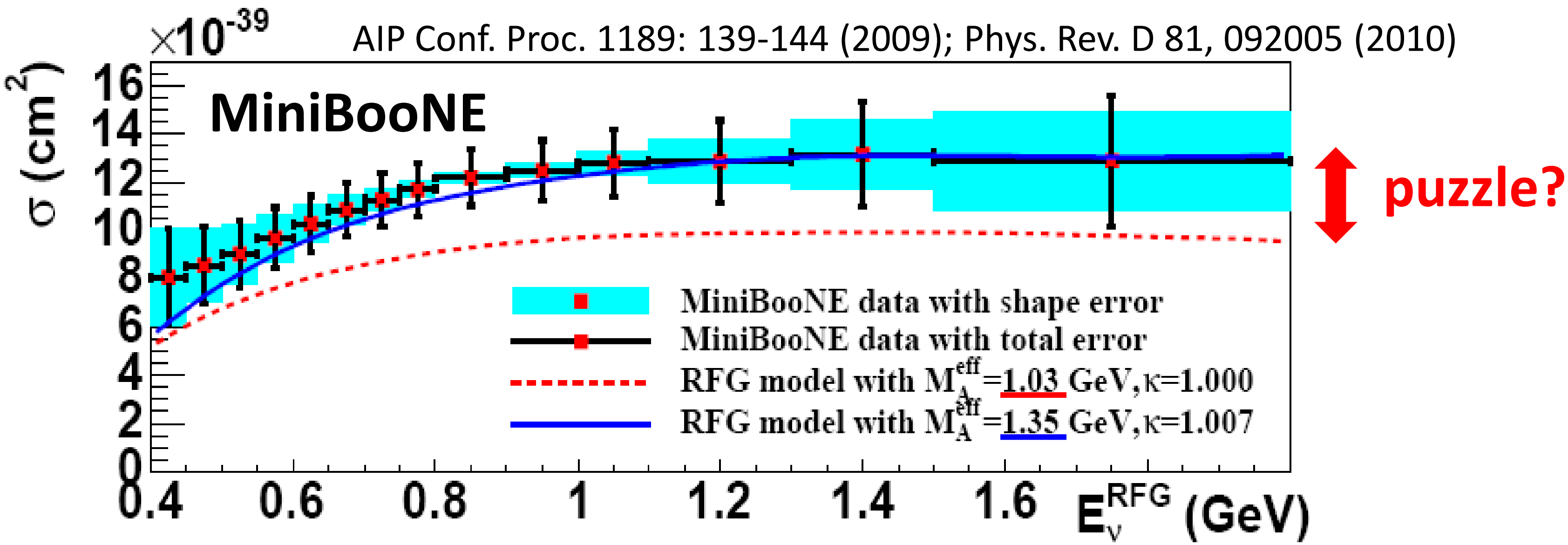
$$G_A(Q^2) = g_A(1+Q^2/M_A^2)^{-2}$$

$g_A = 1.26$ from neutron β decay

$$M_A = (1.026 \pm 0.021)\ GeV/c^2$$

from ν-deuterium CCQE and from π electroproduction

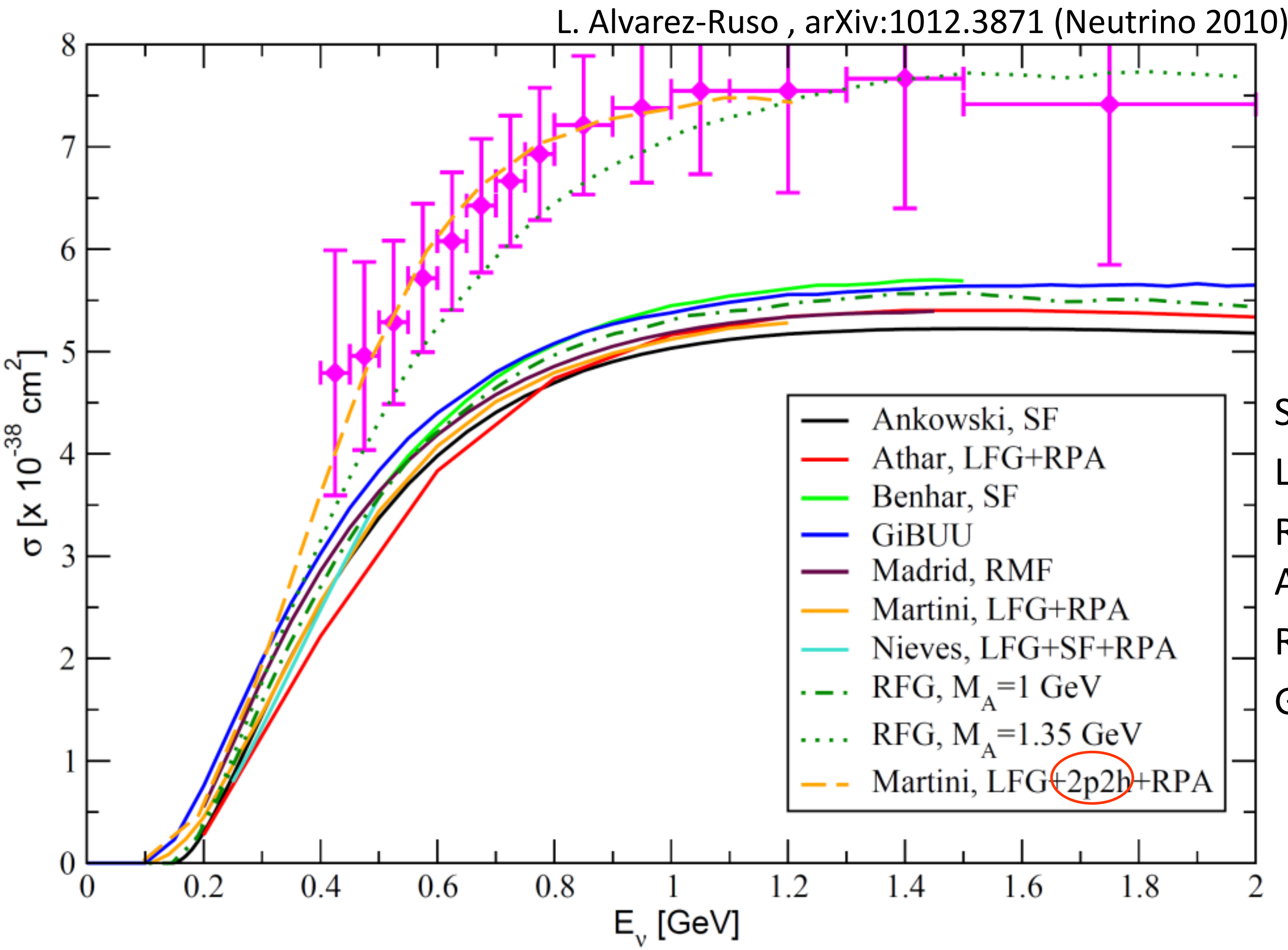
AIP Conf. Proc. 1189: 139-144 (2009); Phys. Rev. D 81, 092005 (2010)



Comparison with a prediction based on RFG using M_A=1.03 GeV reveals a discrepancy

In the Relativistic Fermi Gas (RFG) model an axial mass of 1.35 GeV is needed to account for data

Comparison of different theoretical models for Quasielastic



SF: Spectral Function

LFG: Local Fermi Gas

RPA: Random Phase Approximation

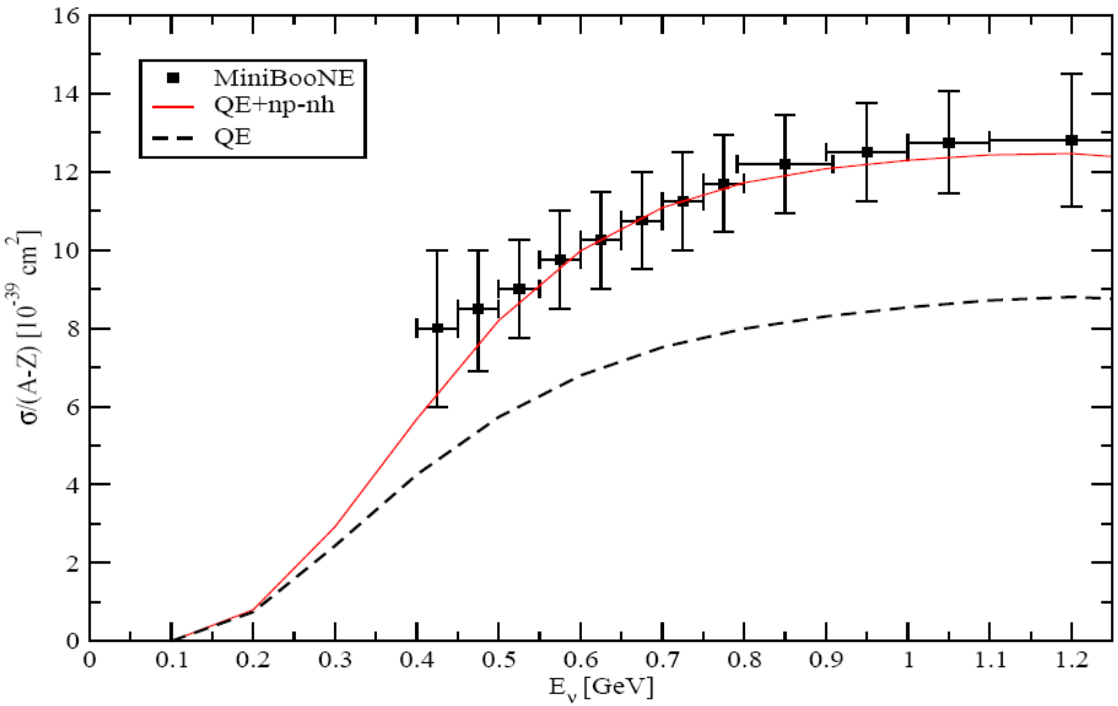
RMF: Relativistic Mean Field

GiBUU: Transport Equation

puzzle??

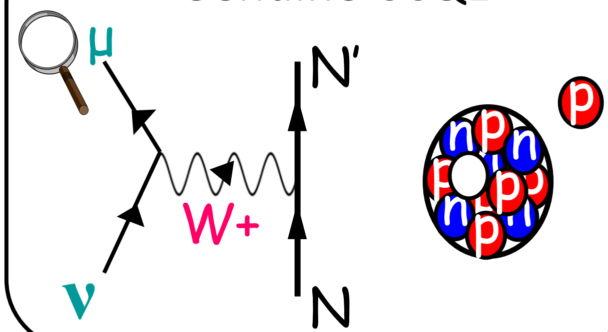
An explanation of this puzzle

Inclusion of the multinucleon emission channel
(np-nh = 2p-2h + 3p-3h)

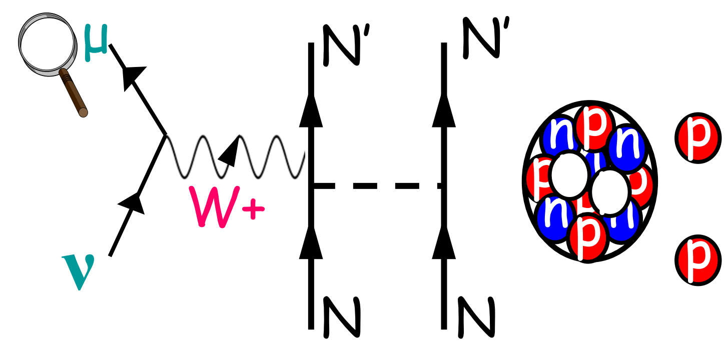


CCQE-like = Genuine CCQE + np-nh

Genuine CCQE



Two particles-two holes (2p-2h)



W+ absorbed by a pair of nucleons

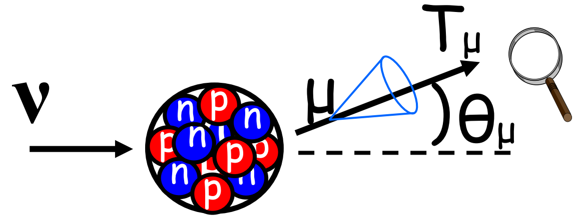
- NN correlations
- Meson Exchange Currents (MEC)

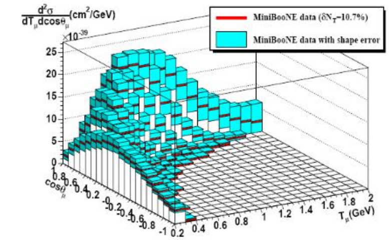
M. Martini, M. Ericson, G. Chanfray, J. Marteau, Phys. Rev. C 80 065501 (2009)

Agreement with MiniBooNE without increasing M_A

CCQE-like flux-integrated double differential cross section

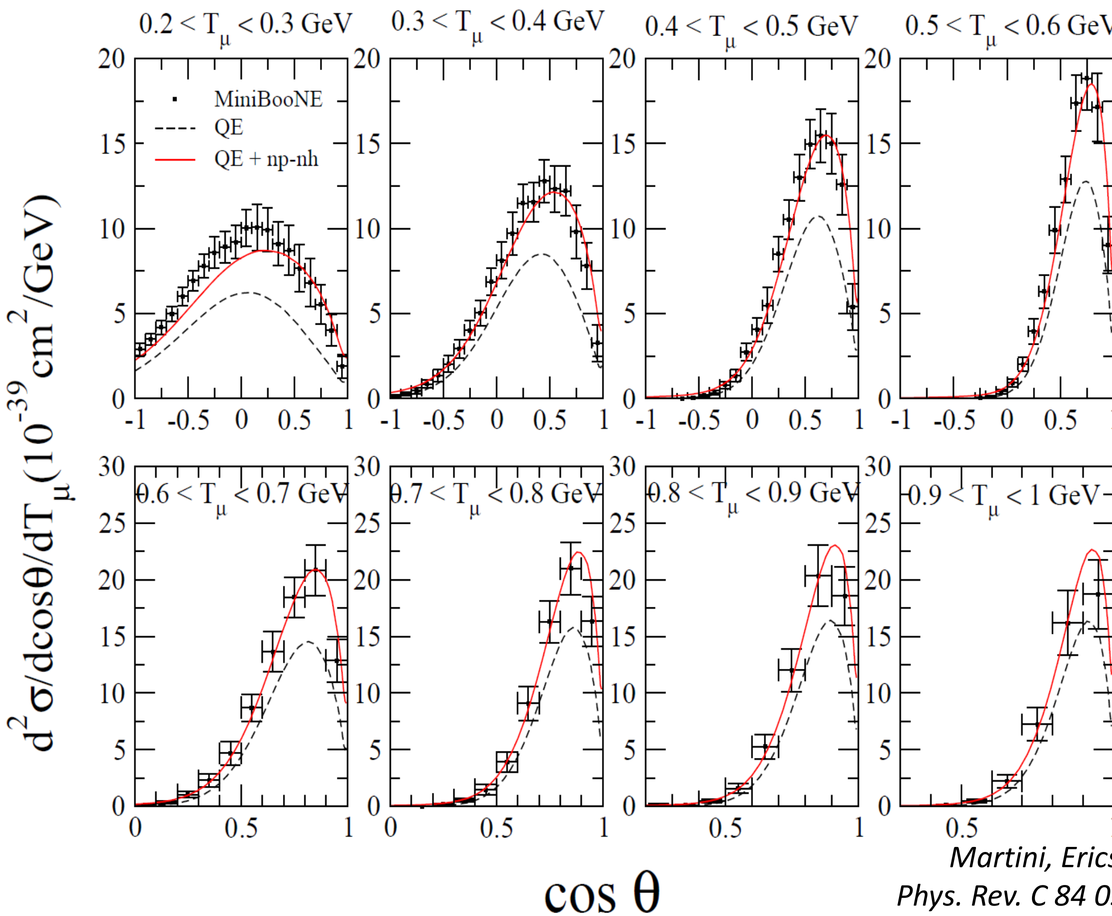
$$\frac{d^2\sigma}{dE_\mu d\cos\theta} = \int dE_\nu \left[\frac{d^2\sigma}{d\omega d\cos\theta}\right]_{\omega=E_\nu-E_\mu} \Phi(E_\nu)$$





MiniBooNE, Phys. Rev. D 81, 092005 (2010)

- Less model dependent than $\sigma(E_\nu)$
- Flux dependent

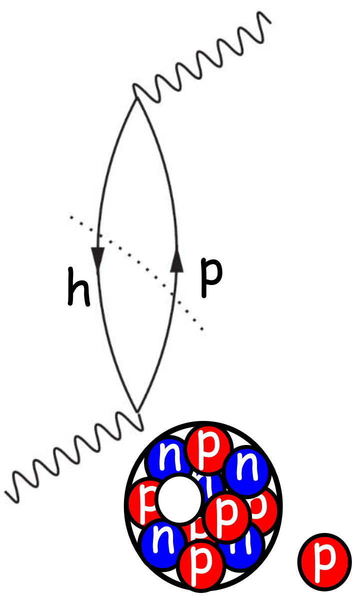


Martini, Ericson, Chanfray, Phys. Rev. C 84 055502 (2011)

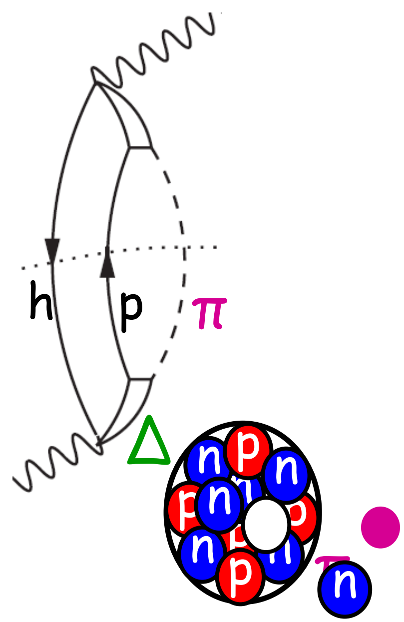
- Good agreement with data without increasing M_A by including NN correlations and MEC
- Similar conclusions by other approaches including the same contributions (discussed later)

Sketch of the model: nuclear response function in RPA

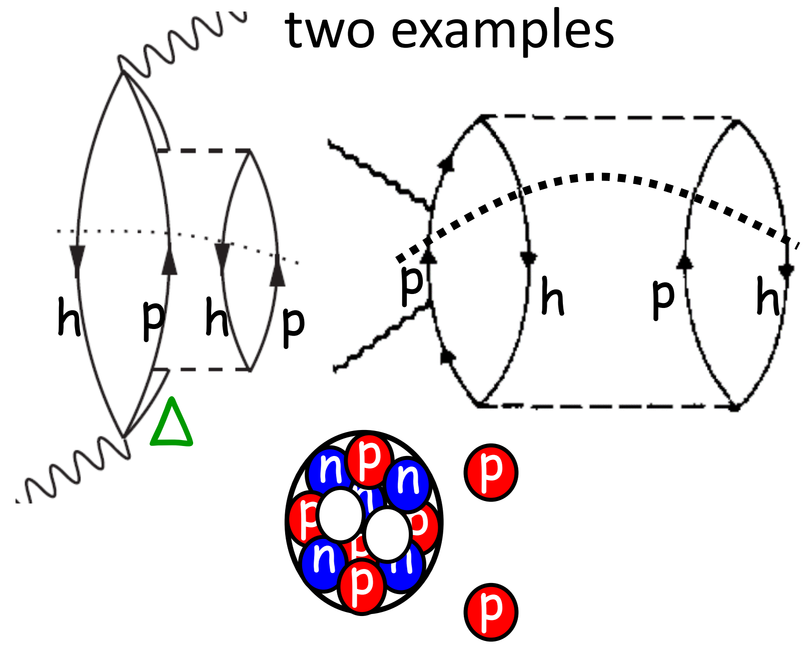
1p-1h QE

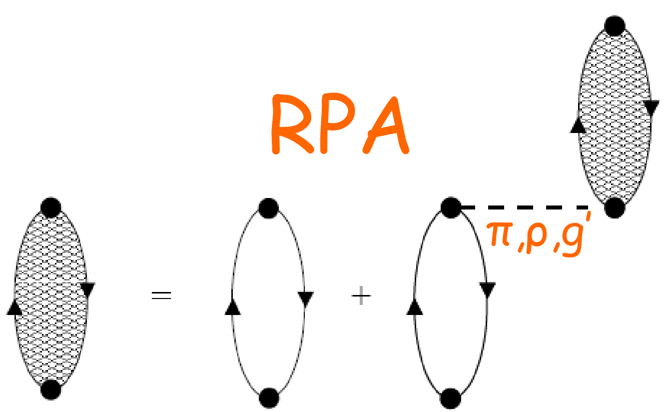


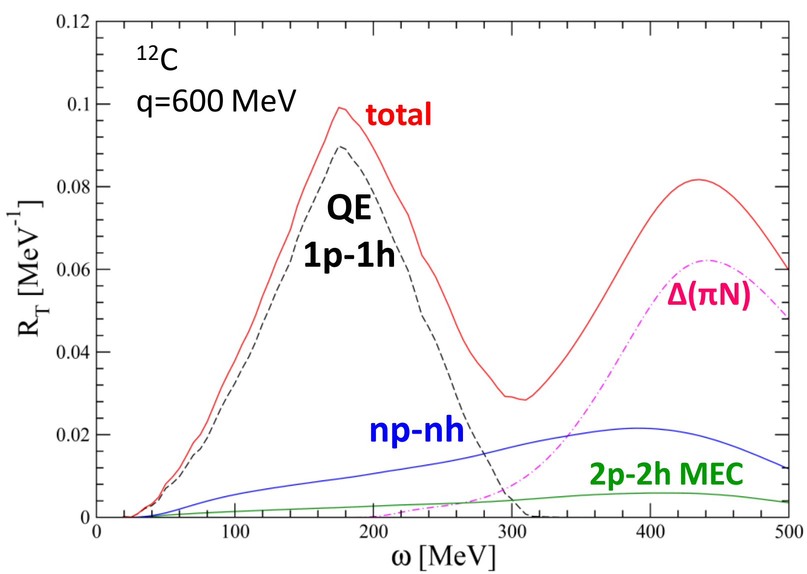
1p-1h 1π production



np-nh:
two examples





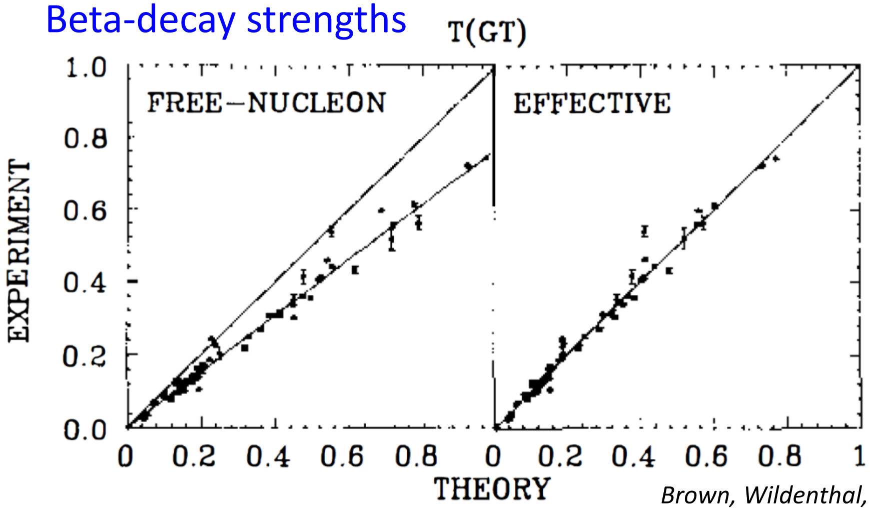


- Unified description of several channels
- Phenomenological many-body approach

"Axial" puzzle II) The quenching of g_A

Fifty-year old problem: Theoretical over-prediction of GT Matrix elements and related observables [single-beta rates, (p,n)-nucleus cross sections, 2ν double-beta rates]

Beta-decay strengths



Brown, Wildenthal, Ann. Rev. Nucl. Part. Sci 38 (1988)

$$[\tau^{\beta}_{1/2}]^{-1} \propto g_A{}^2 \, |M^{\beta}_{GT}|^2$$

Typical practice: "Renormalize" g_A to get correct results

g_A=1.26 ⟿ $g_A^{\text{eff}} \sim 1$

N.B. if g_A is renormalized in 0νββ decay
⇒ experiments are in trouble

$$\left[\tau^{0\nu}_{1/2}\right]^{-1} = G_{0\nu} \left|M_{0\nu}\right|^2 |\langle m_\nu \rangle|^2$$

$M_{0\nu} = g_A^2 M^{(0\nu)}$ **rates go as $(g_A)^4$**

Several suggestions about the sources of the quenching of the GT strength:

- Nucleons are effective degrees of freedom; non nucleonic degrees of freedom (e.g. Δ) are omitted
- Two-body currents contributions
- Short range correlations between nucleons
- Truncation of the many-nucleon Hilbert space

No consensus until very recent ab initio results

Parenthesis: Nuclear Interaction and Many Body Physics

Nuclear forces are usually associated to a family of Many-Body methods and they do not work well (or at all) if applied outside their domain

Two different approaches

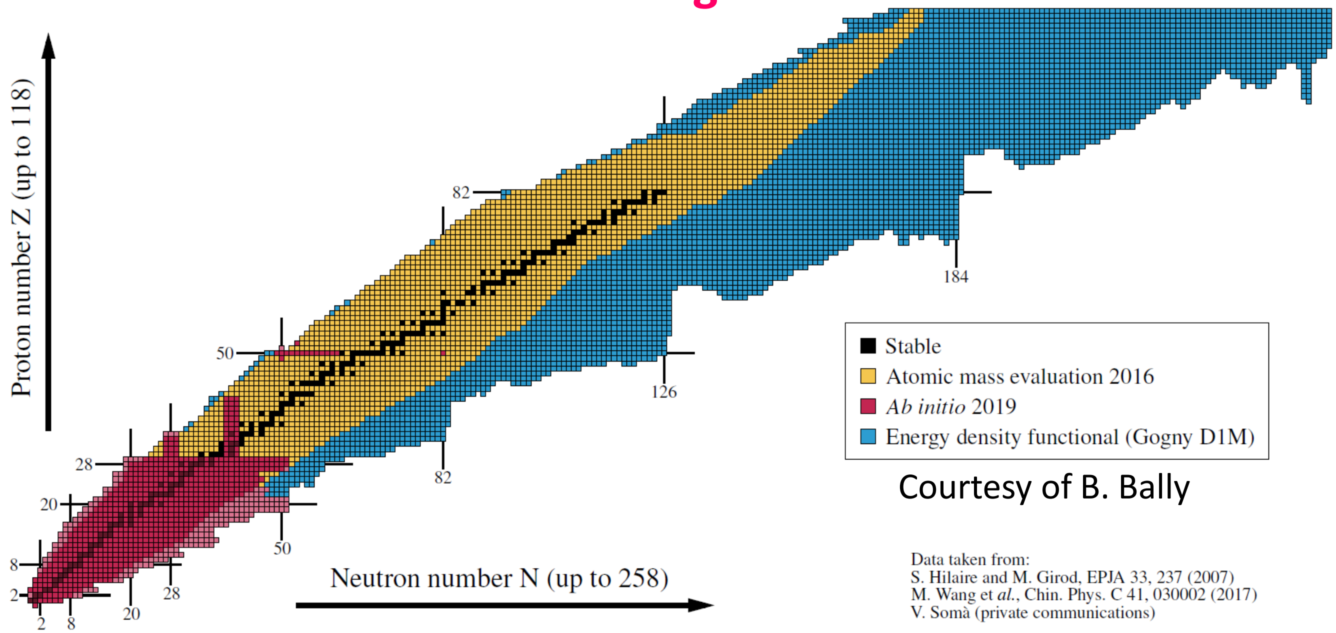
1 Realistic (more fundamental):

- Postulate analytical form of the nucleon-nucleon force *"in the vacuum"* and adjust to nucleon scattering data, deuteron (and very light nuclei)
- Solve the many-body problem with this bare nucleon-nucleon interaction (**ab initio methods**)

2. Effective (more phenomenological):

- Choose a Many-Body methods, postulate analytical form of the force *"in the nuclear medium"* and adjust to some nuclear properties (nuclear matter and nuclei)
- Use the same Many-Body method and this « in medium » nucleon – nucleon interaction to study other nuclei and other nuclear properties

More fundamental…less global

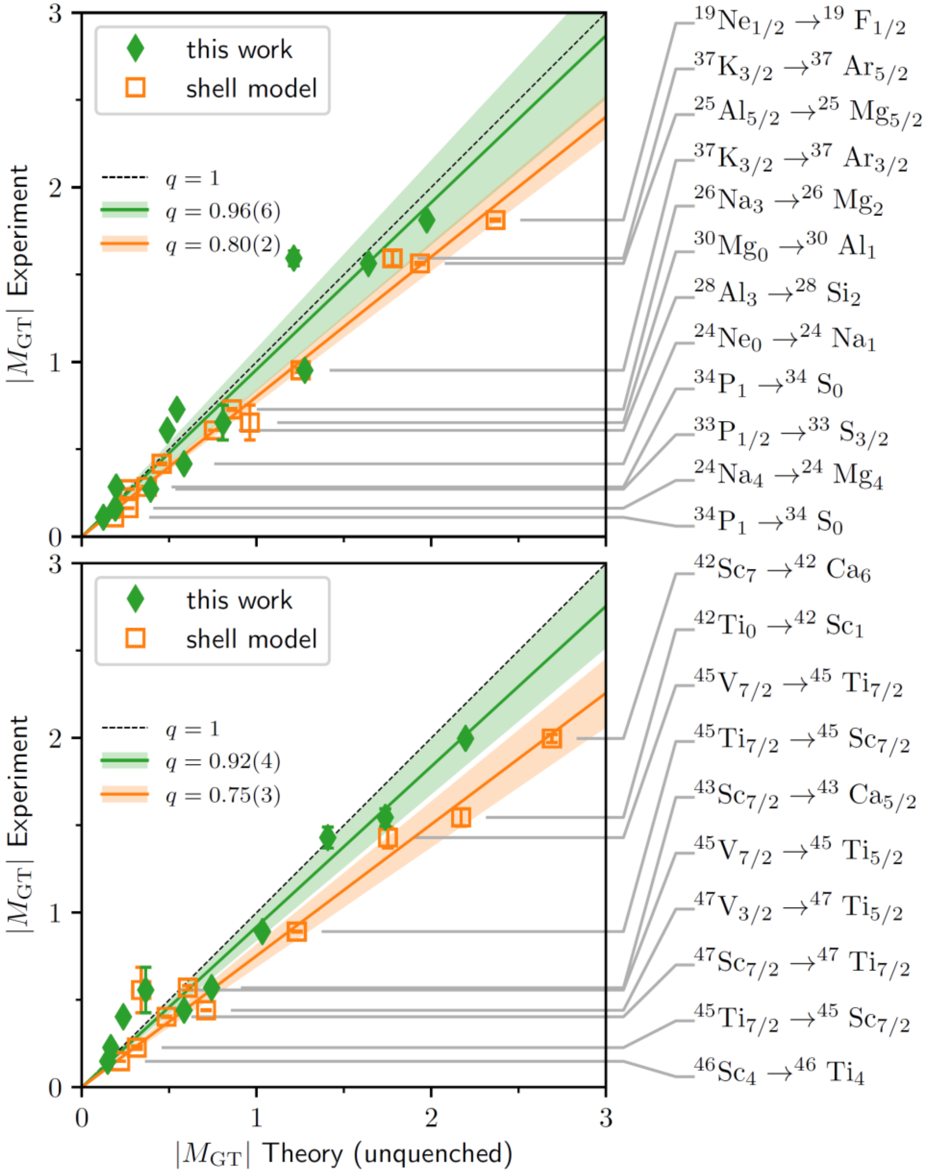


Courtesy of B. Bally

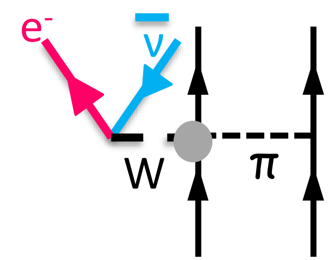
Data taken from:
S. Hilaire and M. Girod, EPJA 33, 237 (2007)
M. Wang et *al.*, Chin. Phys. C 41, 030002 (2017)
V. Somà (private communications)

The solution of the “g_A quenching” puzzle

Gysbers et al. Nature Phys. 15 428 (2019)



Ab initio calculations using chiral EFT including two-body Meson-Exchange Currents and additional nuclear correlations omitted by the shell model do not need any “quenching” to reproduce the β decay matrix elements



Chiral Effective Field Theory

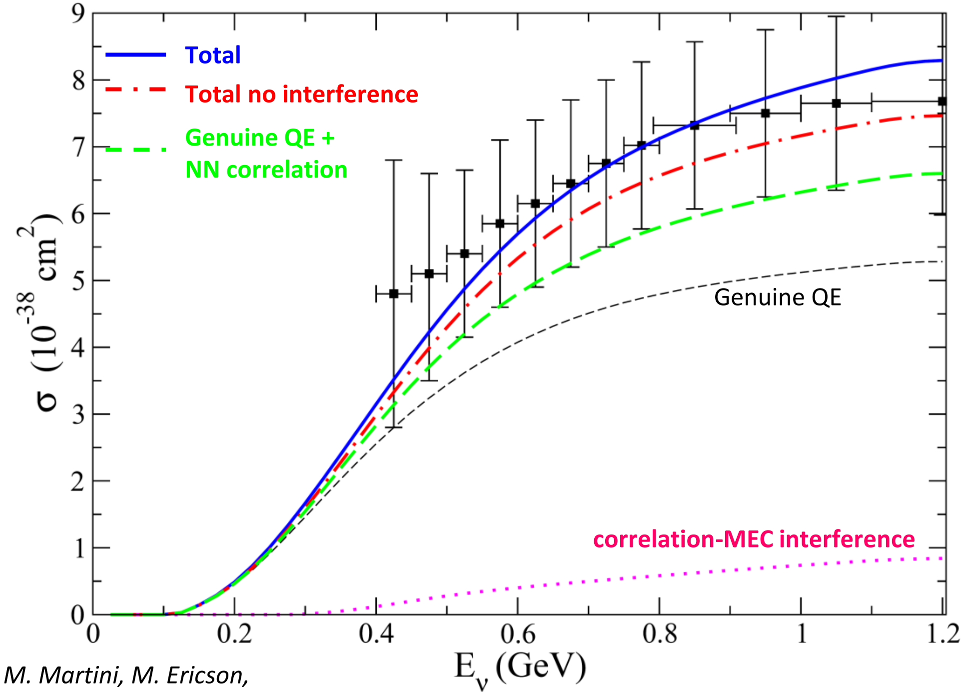
- low energy approach to QCD, nuclear structure energies
- Consistent treatment of nuclear many-body forces and electroweak currents

- Long-range physics given explicitly by pion-exchanges
- Short-range physics: contact interactions to fit

Same solution for the two "axial" puzzles

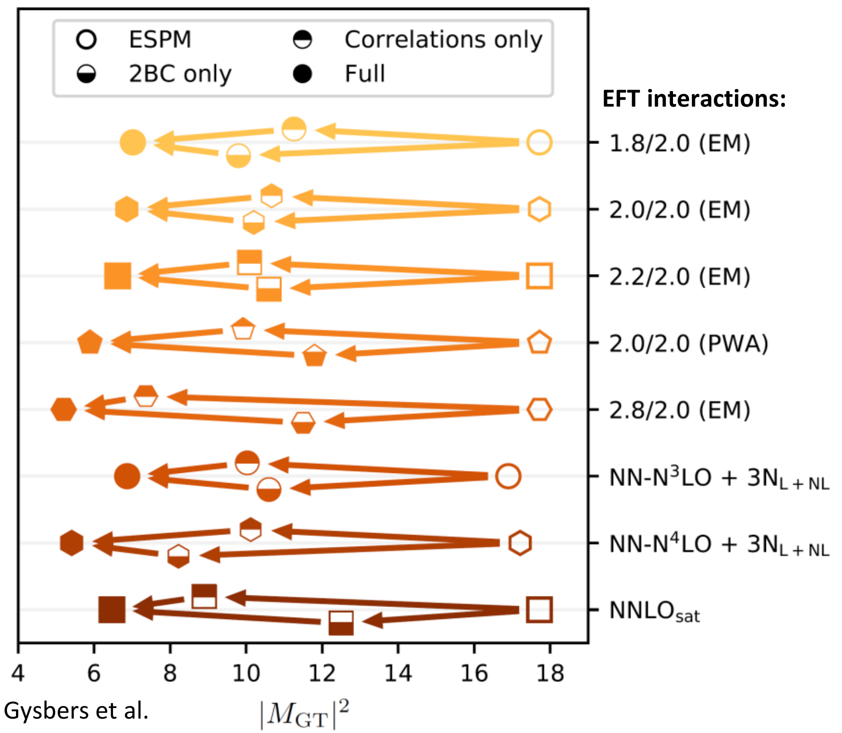
Relatively similar, complementary and important impact of nuclear correlations and 2-body (MEC) currents

Neutrino CCQE-like cross section on ^{12}C

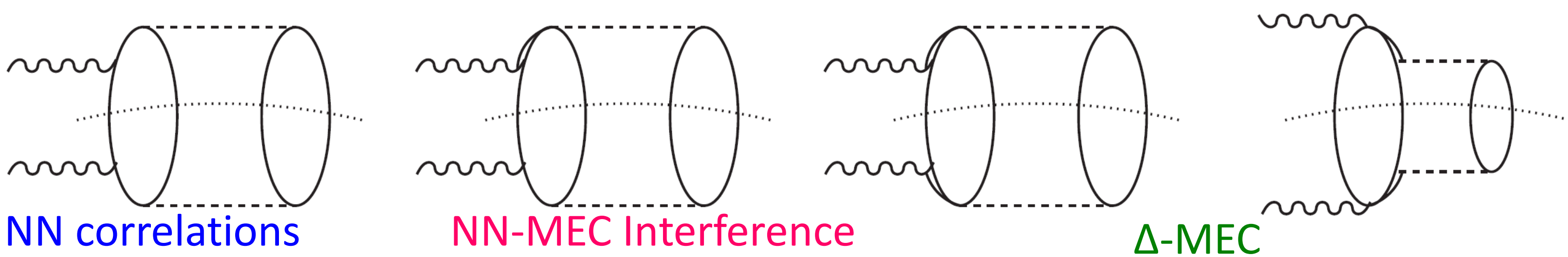


M. Martini, M. Ericson, G. Chanfray, J. Marteau

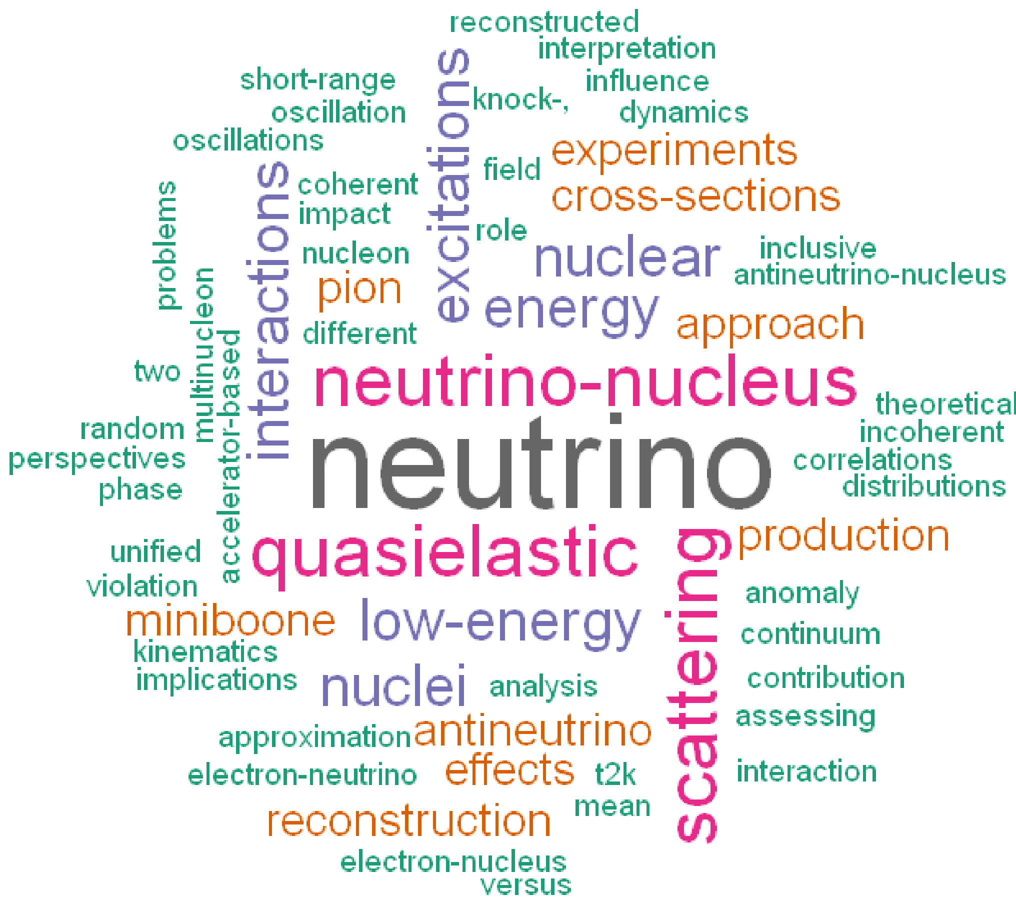
$|M_{GT}|^2$ for the β decay of ^{100}Sn



Gysbers et al.



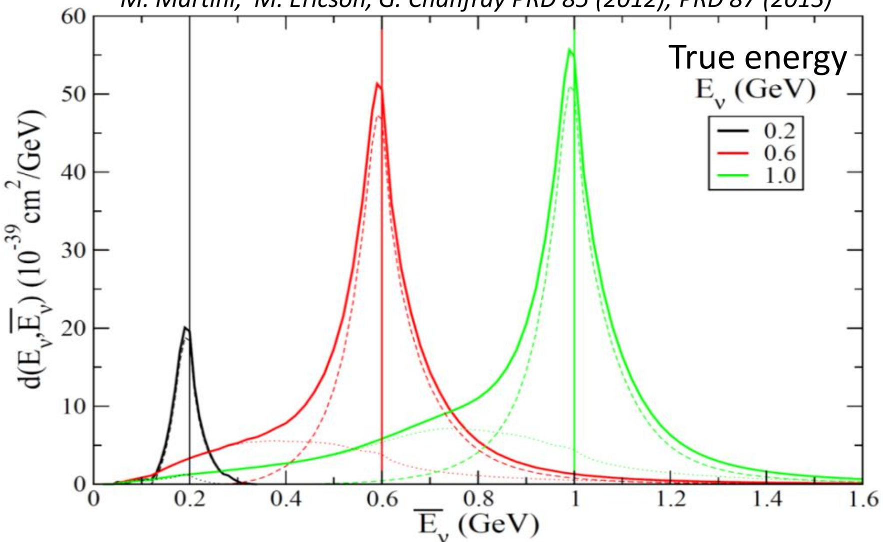
Further details on nuclear models for LBL oscillation experiments



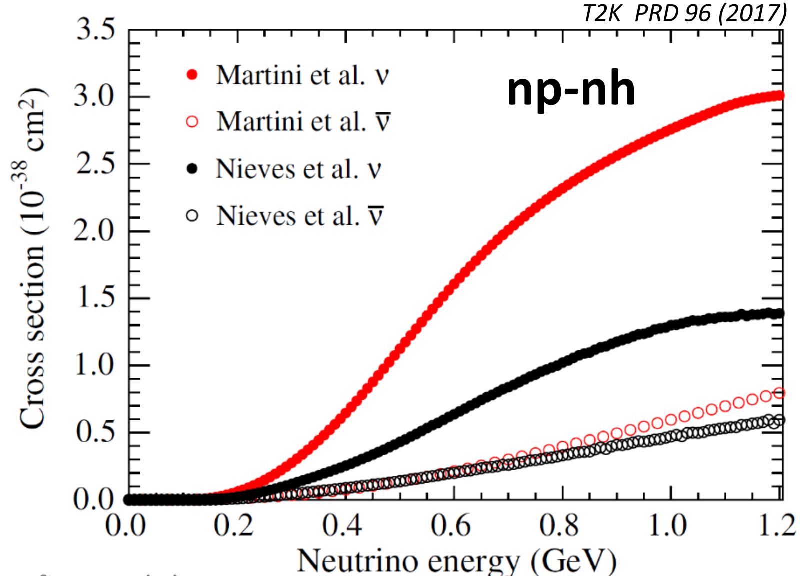
The np-nh channel (nuclear correlations and 2-body currents)

- A lot of interest in these last 10 years
- Explanation of the axial mass puzzle
- It was not included in the generators used for the analyses of ν cross sections and oscillations experiments
- The effort to include this np-nh channel in several Monte Carlo is in progress
- One of the most important sources of systematic errors in oscillation experiments since it **affects the neutrino energy reconstruction**
- Several theoretical calculations agree on its crucial role but there are differences on the results obtained for this channel

M. Martini, M. Ericson, G. Chanfray PRD 85 (2012); PRD 87 (2013)



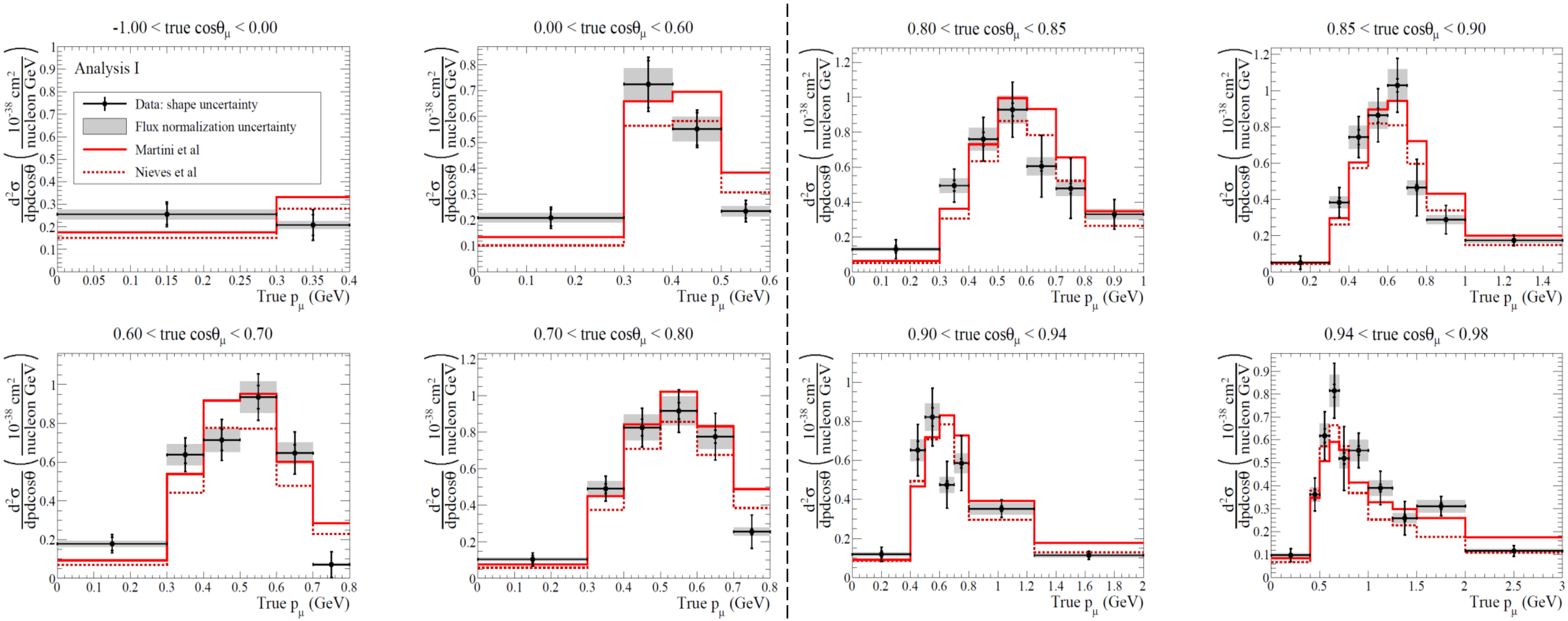
T2K PRD 96 (2017)



A T2K measurement more model independent: **$d^2\sigma$ CC0π**

CC0π = CCQE-like without subtraction of π absorption background

T2K collaboration: Abe et al. Phys. Rev. D 93 11012 (2016)

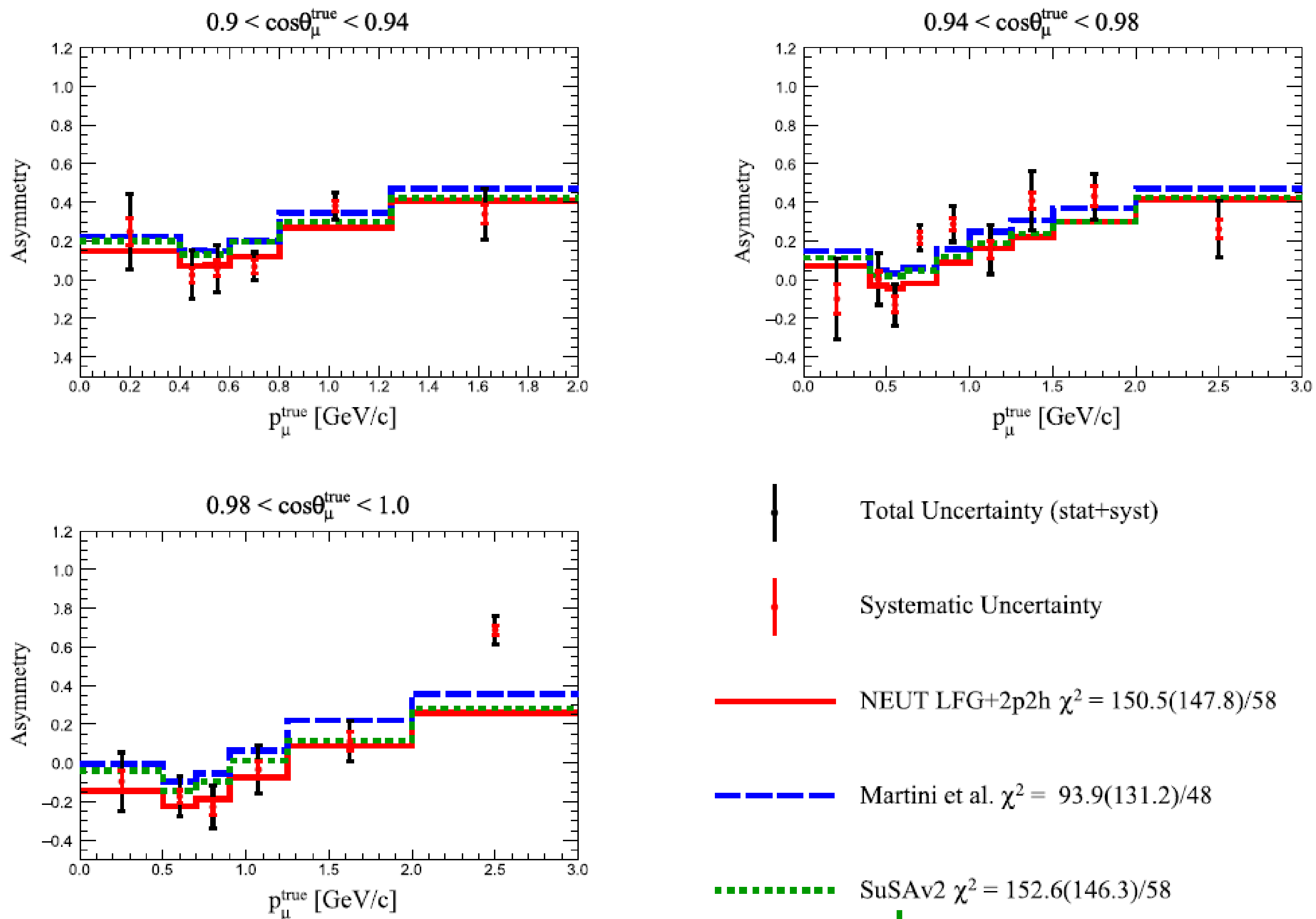


The two theoretical models including np-nh are compatible with data at this level of experimental accuracy

PHYSICAL REVIEW D **101,** 112001 (2020)

First combined measurement of the muon neutrino and antineutrino charged-current cross section without pions in the final state at T2K

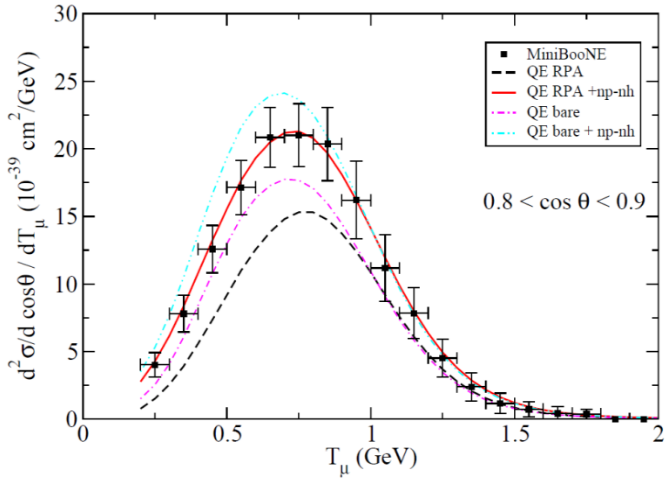
$$\frac{\nu-\bar{\nu}}{\nu+\bar{\nu}}$$



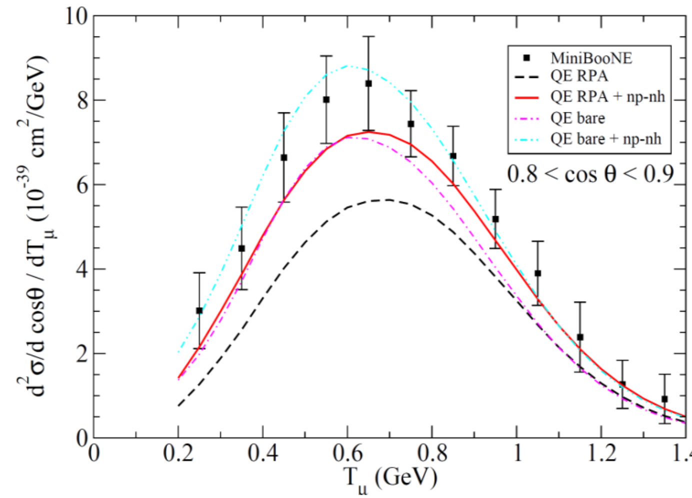
[Maria Barbaro talk]

ν $\bar{\nu}$

Martini et al.

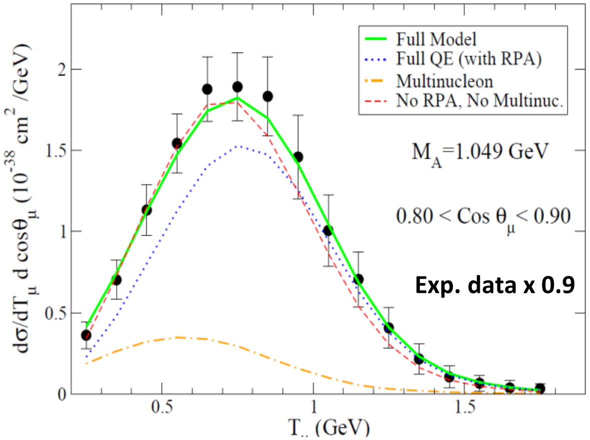


PRC 84 (2011)

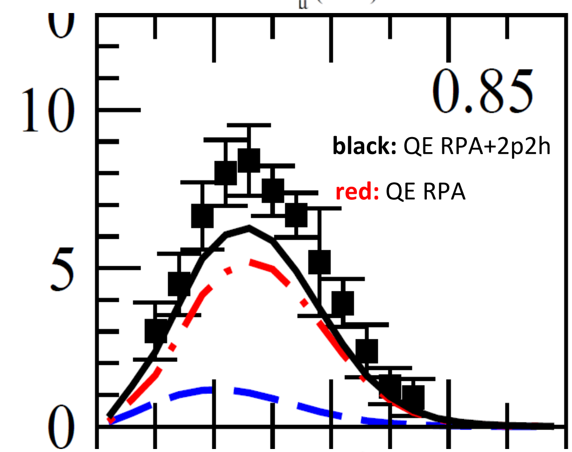


PRC 87 (2013)

Nieves et al.

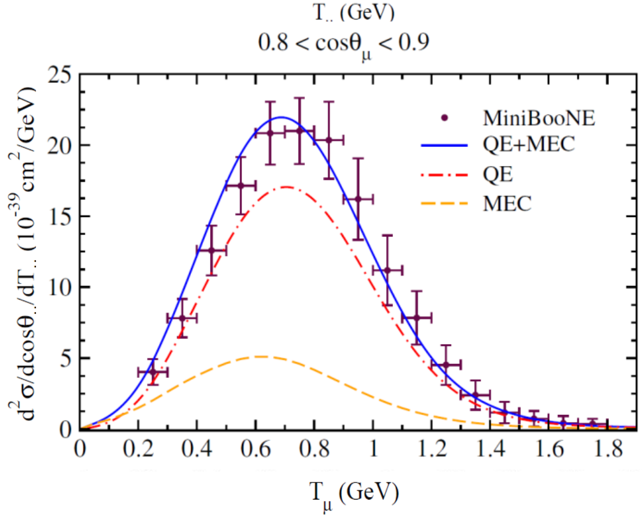


PLB 707 (2012)

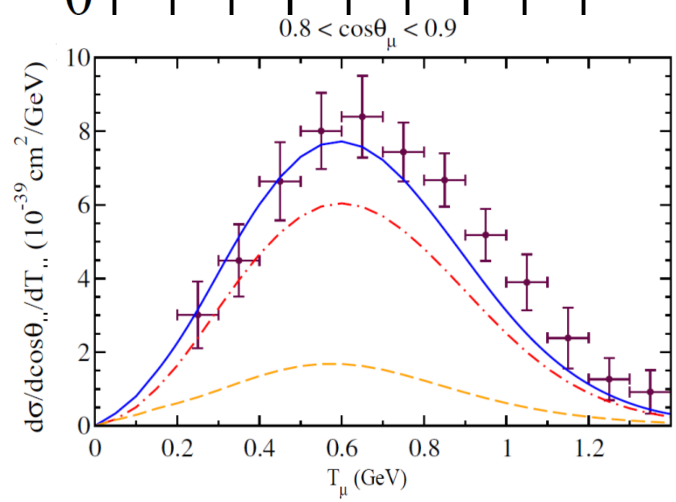


PLB 721 (2013)

SuSAv2



PRD 94 (2016)



PRD 94 (2016)

Main difficulties in the np-nh sector

$$W^{\mu\nu}_{2p-2h}(\mathbf{q},\omega) = \frac{V}{(2\pi)^9}\int d^3p'_1 d^3p'_2 d^3h_1 d^3h_2 \frac{m_N^4}{E_1E_2E'_1E'_2}\theta(p'_2-k_F)\theta(p'_1-k_F)\theta(k_F-h_1)\theta(k_F-h_2)$$
$$\underbrace{\langle 0|J^\mu|\mathbf{h}_1\mathbf{h}_2\mathbf{p}'_1\mathbf{p}'_2\rangle\langle\mathbf{h}_1\mathbf{h}_2\mathbf{p}'_1\mathbf{p}'_2|J^\nu|0\rangle}_{\text{matrix elements}}\delta(E'_1+E'_2-E_1-E_2-\omega)\delta(\mathbf{p}'_1+\mathbf{p}'_2-\mathbf{h}_1-\mathbf{h}_2-\mathbf{q})$$

- 7-dimensional integrals $\int d^3h_1 d^3h_2\; d\theta'_1$ of thousands of terms
- Huge number of diagrams and terms
- Divergences (angular distribution; NN correlations contributions)
- Calculations for all the kinematics compatible with the experimental neutrino flux

Computing very demanding

Hence different approximations by different groups:

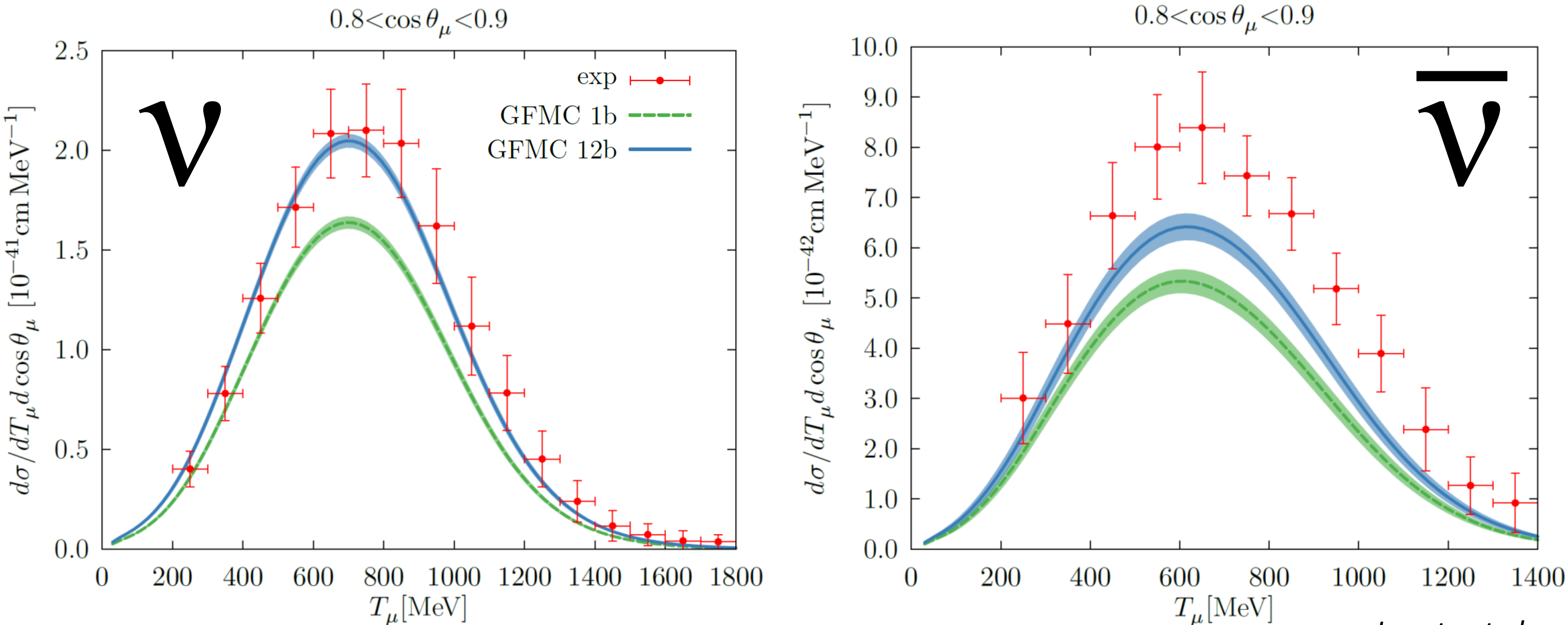
- choice of subset of diagrams and terms;
- different prescriptions to regularize the divergences;
- reduce the dimension of the integrals (7D --> 2D if non relativistic; 7D -->1D if $h_1 = h_2 = 0$)

$\Rightarrow$ Different final results by different groups

$\Rightarrow$ Different final results for ν and antiν

First ab-initio calculation of flux-integrated double differential cross sections

Ab initio: state-of-the-art description of nuclear ground state and correlations



The important role of two-body currents is confirmed

Lovato et al. *Phys.Rev.X* 10 (2020)

Details of the approach (Green's Function Monte Carlo):

- Nuclear interaction in the **Hamiltonian**: V_{ij}Argonne AV18; V_{ijk}Illinois IL7
- Electroweak **Currents**: non relativistic expansion; π and ρ Meson Exchange Currents

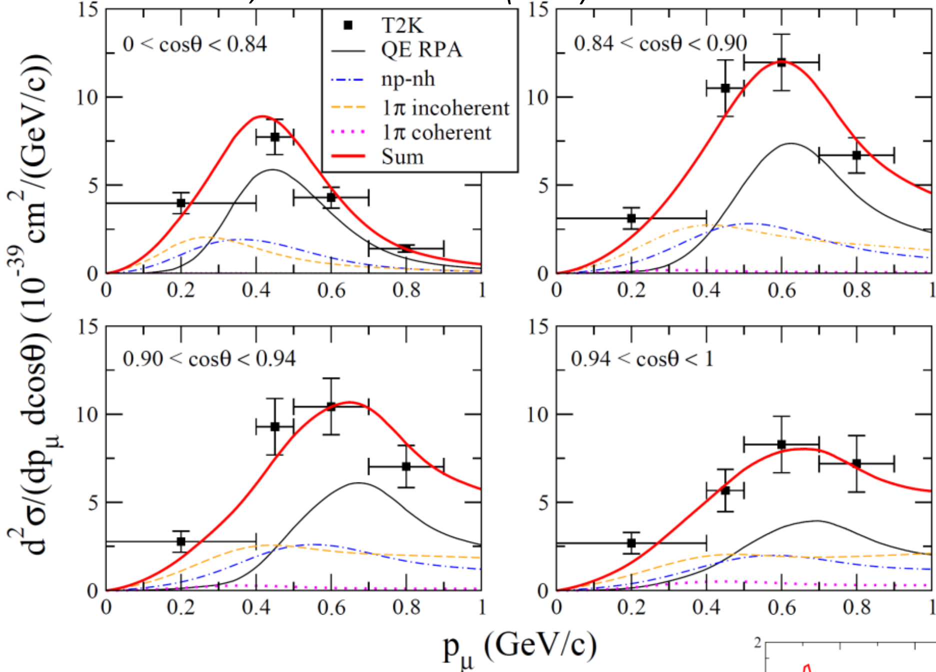
Limitations:

- Static limit for Δ MEC
- It cannot describe the Δ peak region; no mechanisms for real pion production

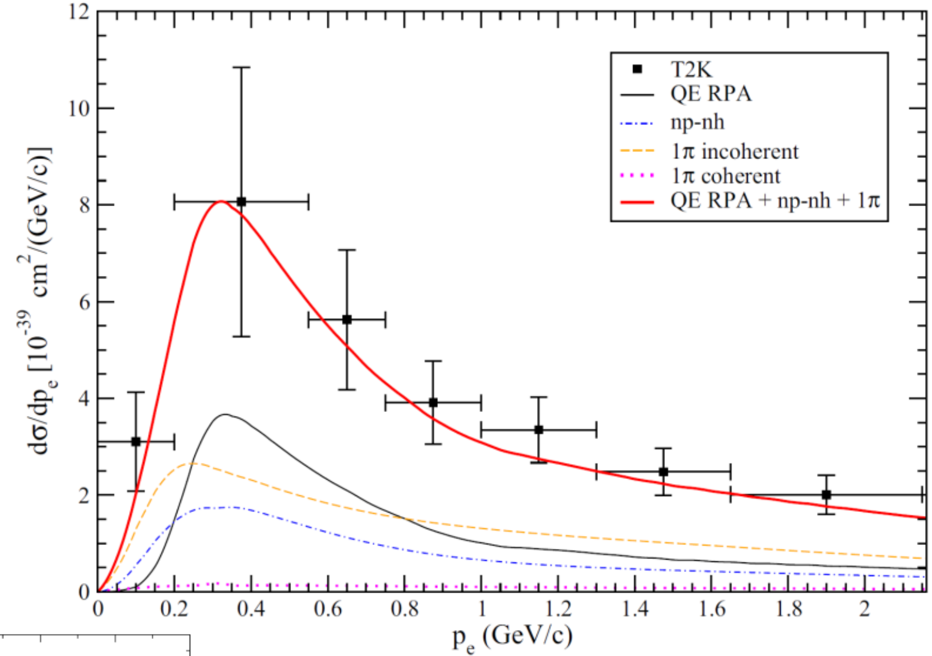
Different contributions in CC inclusive T2K flux-integrated differential cross sections

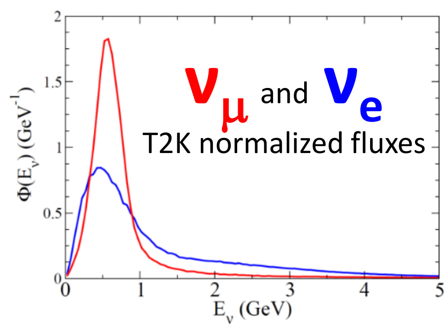
ν_μ ν_e

M. Martini, M. Ericson PRC 90 (2014)



M. Martini et al. PRC 94 (2016)



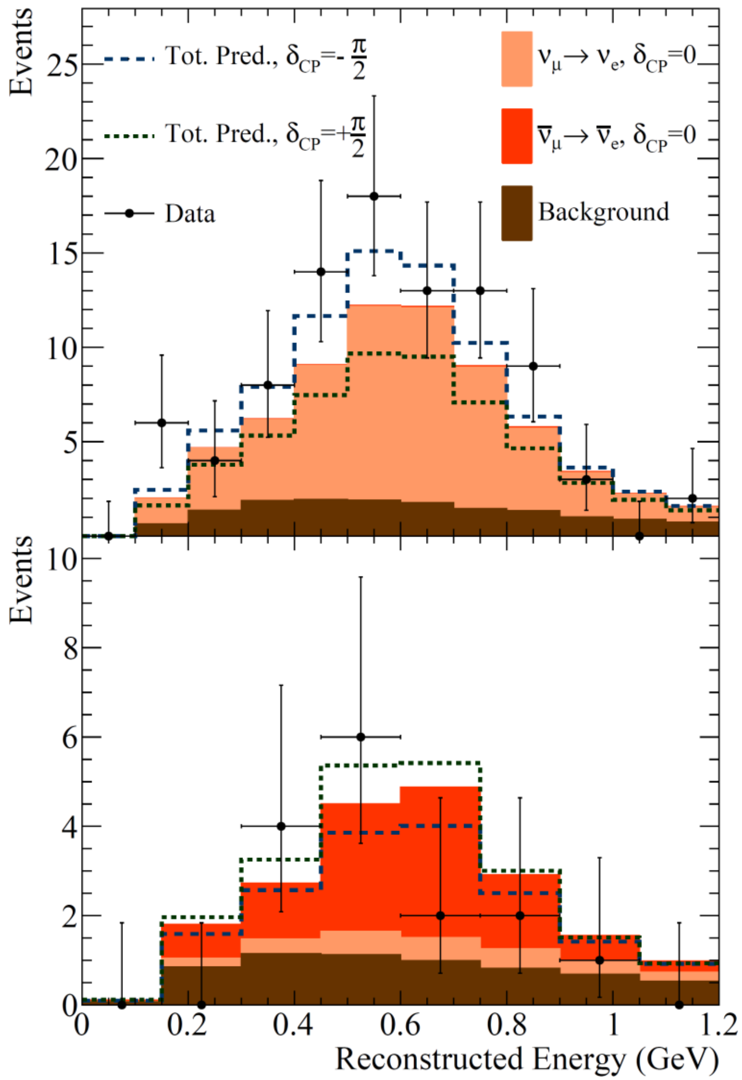


Remind:

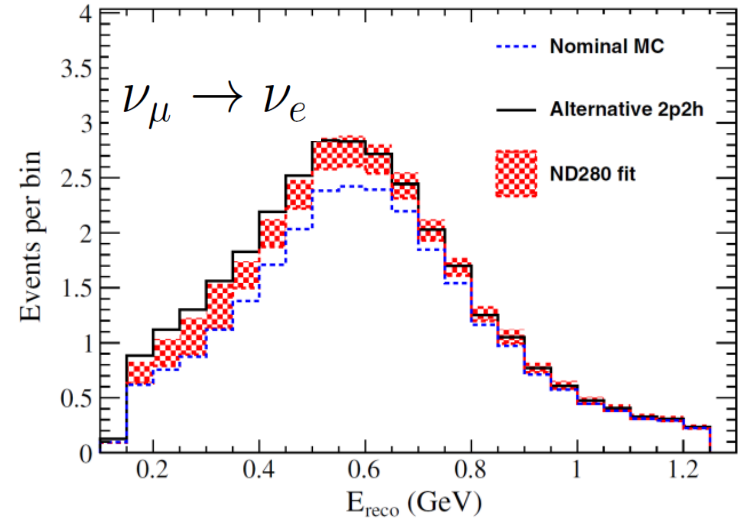
A precise and simultaneous knowledge of $\nu_\mu, \nu_e, \bar{\nu}_\mu, \bar{\nu}_e$ cross sections is important in connection to the oscillation experiments aiming at the search for CP violation in the lepton sector

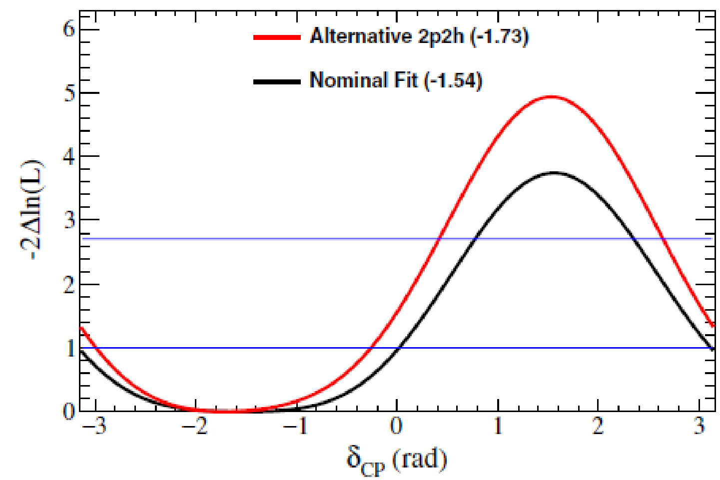
$\nu_\mu \rightarrow \nu_e$ T2K results and studies on δ_{CP}

T2K Nature (2020)



Example of impact of 2p-2h differences on oscillation analyses





T2K PRD 96 (2017)

More recent: 2101.03779

Neutrino-nucleus cross sections: Present studies and perspectives

- Exclusive cross sections and hadronic variables

  Many models used up to now to compare with the neutrino flux-integrated differential cross sections are not directly applicable for exclusive studies. More nuclear response functions contribute.

- Generalization of models to asymmetric nuclei (in particular Argon)

  Differences between neutron and proton densities and energies should be taken into account

Some results for genuine QE and 1π production
Very few results for 2-body current contributions

[Maria Barbaro talk]

- From meson(s) production to Deep-Inelastic Scattering

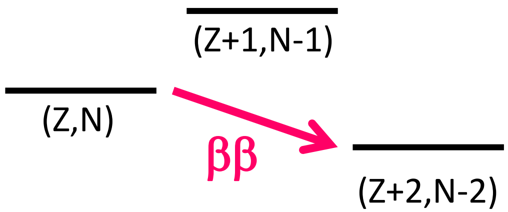
  Recent Review: *M. Sajjad Athar and J. Morfin, J.Phys.G 48 (2021) 3*

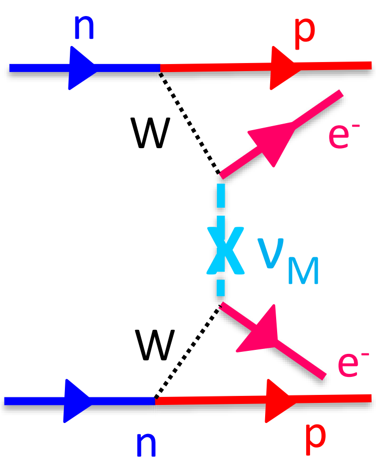
- Low-energy neutrino scattering

  Giant Resonances, discrete excitations, CEvNS

[Vishvas Pandey talk]

Nuclear matrix elements for neutrinoless Double-Beta decay





0νββ nuclear matrix elements

$$M_{(0\nu)} = M^{GT}_{(0\nu)} - \frac{g_V^2}{g_A^2} M^{F}_{(0\nu)} + \dots$$

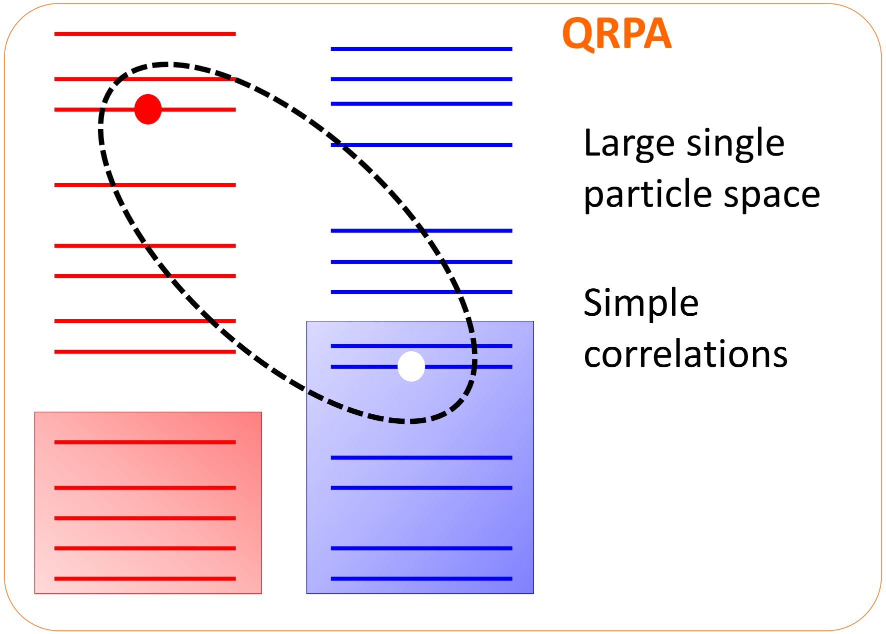
$$M^{GT}_{(0\nu)} = \langle f | \sum_{a,b} H(r_{ab}, \bar{E}) \vec{\sigma}_a \cdot \vec{\sigma}_b \tau_a^+ \tau_b^+ | i \rangle \qquad M^{F}_{(0\nu)} = \langle f | \sum_{a,b} H(r_{ab}, \bar{E}) \tau_a^+ \tau_b^+ | i \rangle$$

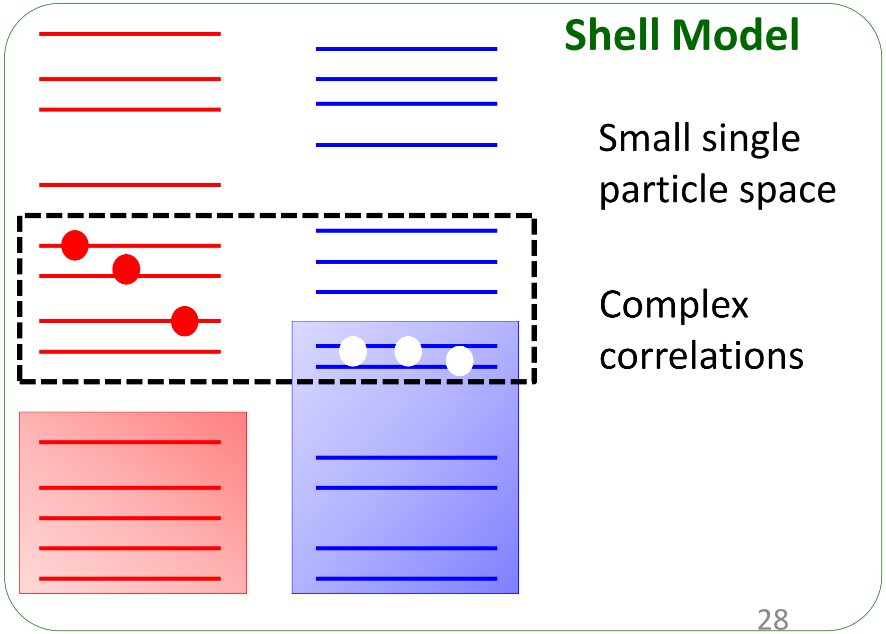
Calculating Matrix Elements is hard

- Most of relevant nuclei are heavy (A > 75) and complicated
- Never measured
- Structure of initial and final nuclear ground states quite different ⇒ matrix element small and sensitive

Different models, different approximations, different NN interaction

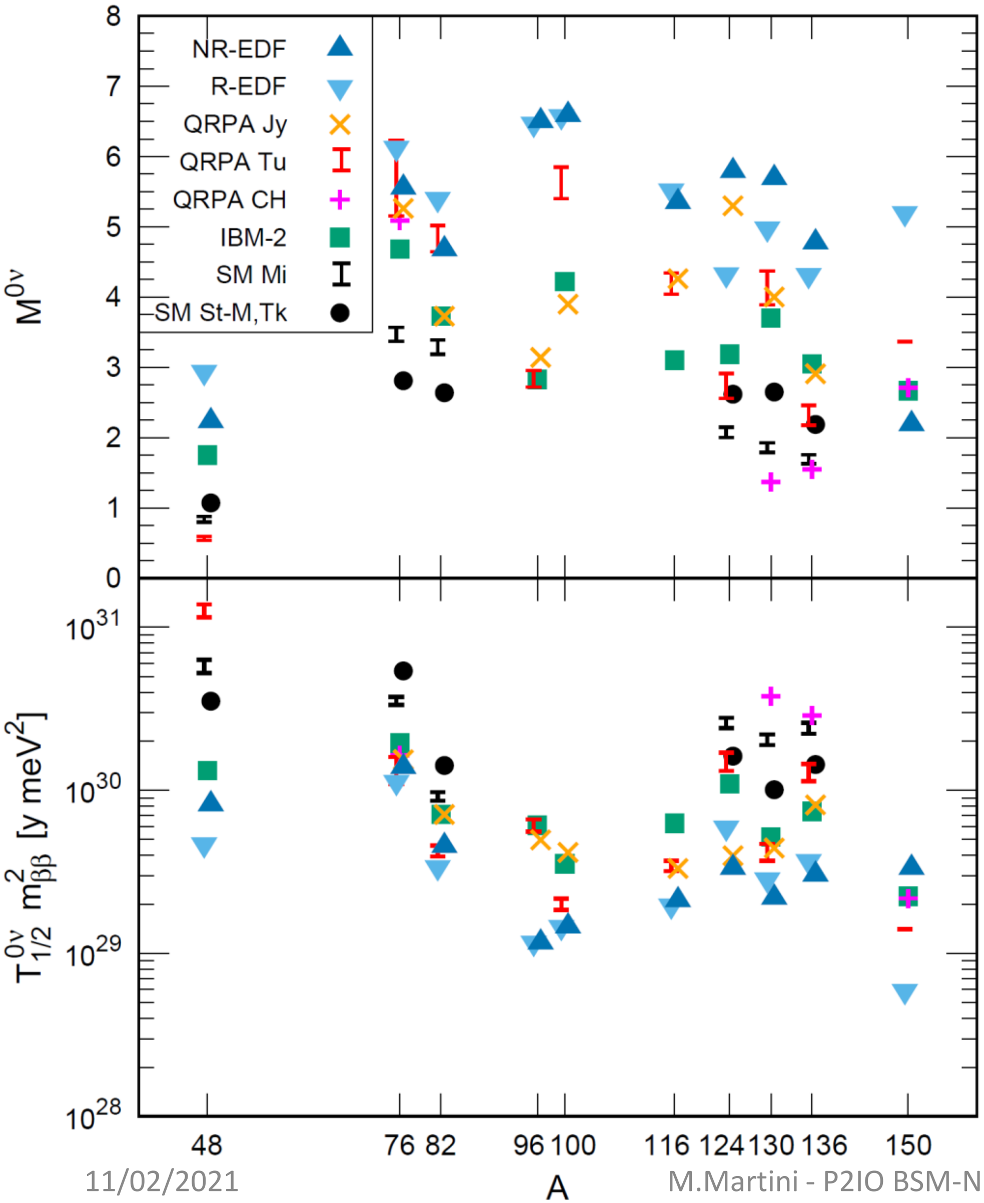
Pictorial representation of two between the most used phenomenological models :





$0\nu\beta\beta$ nuclear matrix elements calculations

*J. Engel and J. Menéndez, Rept.Prog.Phys. 80 (**2017**)*



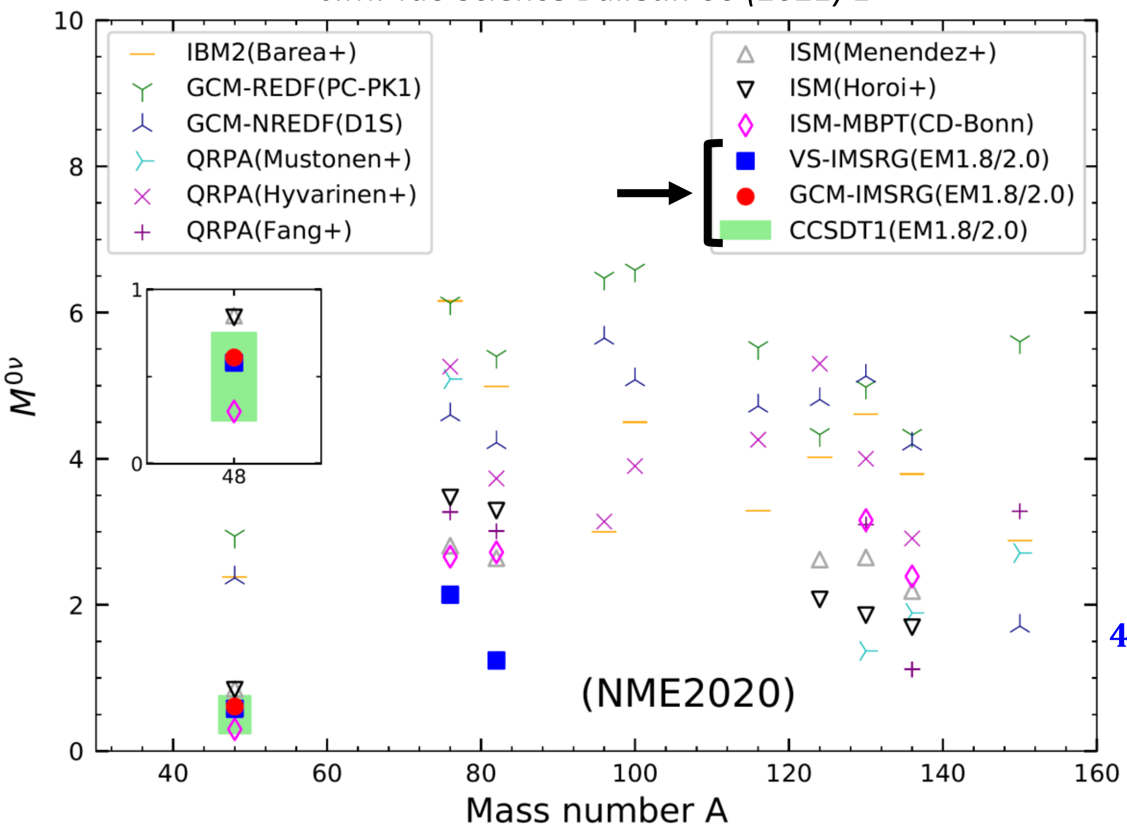
- Large spread
- Factors 2 or 3 of difference between different approaches $\Leftrightarrow$ factor 10 for $T^{0\nu}_{1/2}$
- EDFs: large NME
  QRPA: wider range
  SM: small NME
- Uncertainty can't be quantified.

Recently it started an effort of the community to go to some more first principles approaches:
ab initio methods

Recent ab initio calculations of $0\nu\beta\beta$ matrix elements using chiral EFT

Complete nuclear correlations included in ab initio calculations

J.M. Yao Science Bulletin 66 (2021) 1



Generator Coordinate Method – In Medium Similarity Renormalization Group

^{48}Ca *J.M. Yao et al. PRL 124 (2020)*

Coupled Cluster with Singles Doubles and Triples excitations

^{48}Ca *S. J. Novario et al. arxiv: 2008.09696*

Valence Space – In Medium Similarity Renormalization Group

^{48}Ca ^{76}Ge ^{82}Se *A. Belley et al. PRL 126 (2021)*

Good News: agreement between the different ab initio calculations for Calcium-48

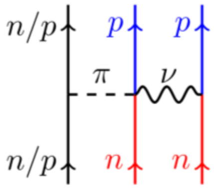
Bad News: NME 25-45% smaller than phenomenological shell model
If confirmed, not good for experiment

Two-body currents and new contact operator in $0\nu\beta\beta$ using chiral EFT

Chiral interactions describe low-energy, low-momentum physics (e.g. β and $2\nu\beta\beta$ decays)

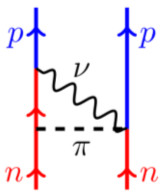
How do they work at large energy and momenta? (e.g. $0\nu\beta\beta$ $\omega \approx$ few MeV, $q \approx 10^2$ MeV, or ν scattering)

Two-body currents



- Estimations of this contributions suggest that two-body currents are smaller in $0\nu\beta\beta$ than in β decay (remember the solution of g_A quenching puzzle)

J. Menendez et al. PRL 107 (2011)

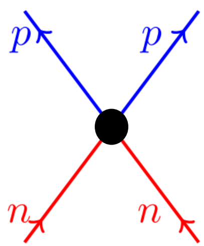


L. Wang et al. PRC 98 (2018)

- Neutron can be excited to any empty level, leading to linear divergence

Unknown high-energy ν exchange physics prevents complete analysis of 2-body currents

Short-range contact term



V. Cirigliano et al. PRL120 (2018)

- Usual light neutrino exchange must be supplemented, even at leading order in chiral EFT, by short-range operator (representing high-energy ν exchange)
- Very recent first estimation of the coupling coefficient

V. Cirigliano et al. 2012.11602 ; 2102.03371

New (computational very demanding) studies on two-body currents contributions put in stand-by until a firm handle on the value of the contact term coefficient

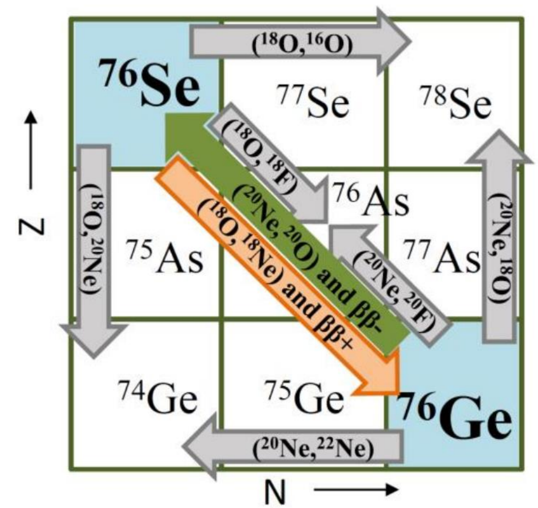
Contrasting effects from physics neglected up to now are expected

Significant work remains to do before any claims to final NME can be made

0νββ decay and Double charge exchange reactions

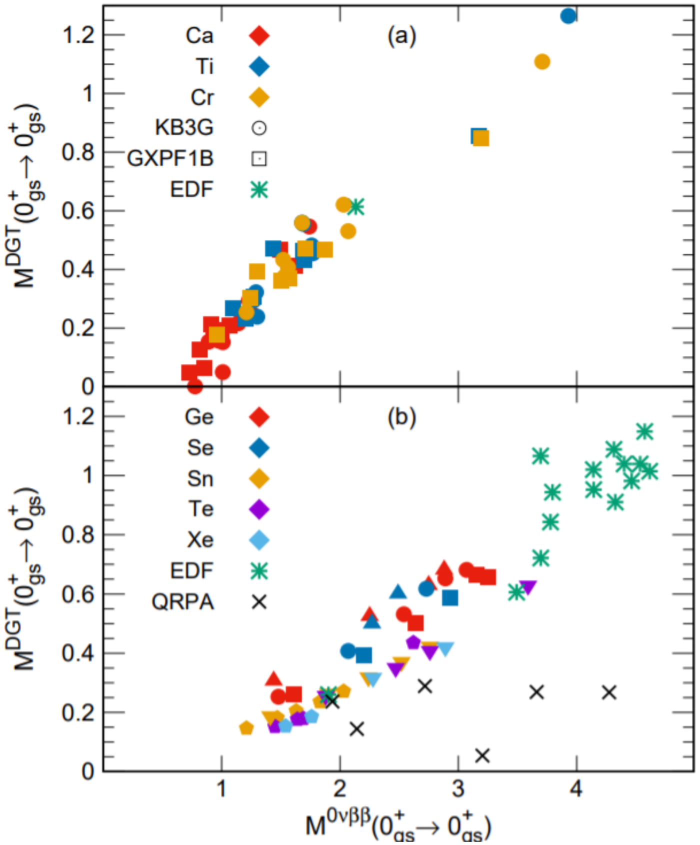
Recent experimental plans at INFN-LNS Catania and RIKEN on double charge exchange reactions, such as $^{76}Ge(^{20}Ne, ^{20}O)\ ^{76}Se$

The initial and final state nucleus wave functions in strong double charge exchange reactions and 0νββ decay are the same and the transition operators are similar



F. *Cappuzzello* et al., EPJA 54 (2018)

N. Shimizu, J. Menendez, K. Yako PRL 120 (2018)



Correlations of 0νββ with Double Gamow-Teller matrix elements holds across nuclear chart

Experiments may access Double GT transitions

[Francesco Cappuzzello talk]

Nuclear models for LBL oscillation experiments and $0\nu\beta\beta$ decay

Summary

Nuclear correlations and two-body currents play a central role for a precise determination of neutrino cross sections and $0\nu\beta\beta$ Nuclear Matrix Elements

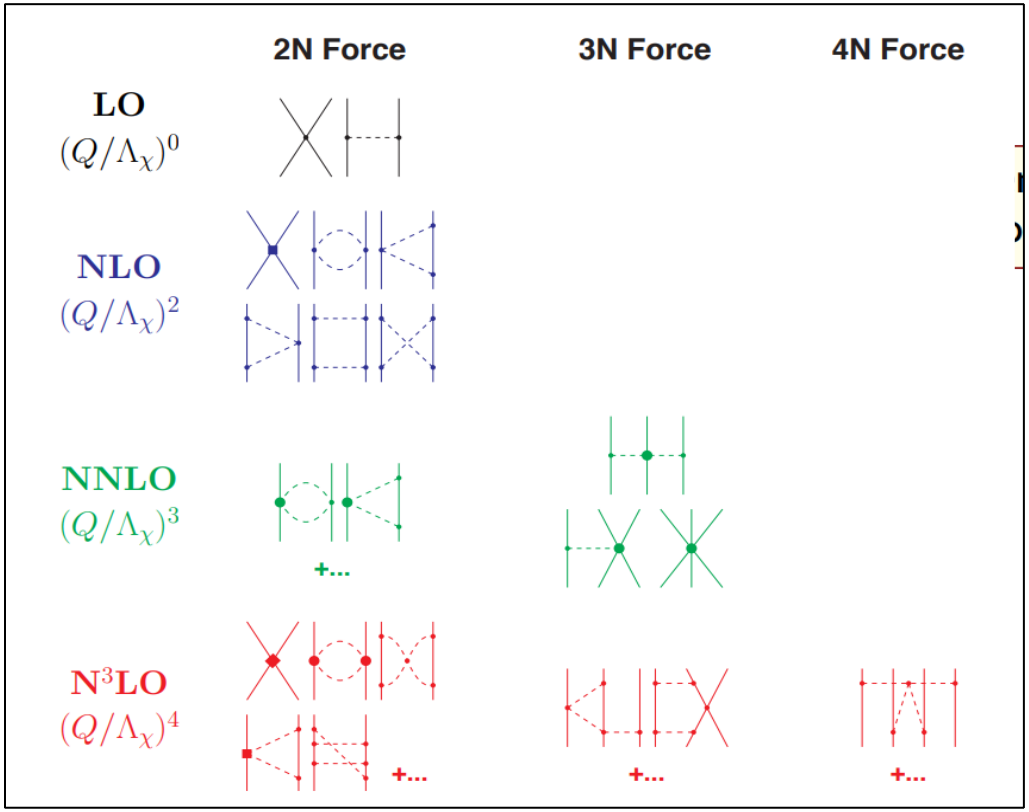
- Important results in these last years by phenomenological and ab initio approaches
- Recent ab initio calculations allowed complete inclusion of nuclear correlations
- Some limitations on two-body currents employed in ab-initio approaches when large energy and/or momentum transfer are considered

Important work remains to do before to reach the few-percent precision in neutrino cross sections required by next generation LBL experiment and before any claims on final values of $0\nu\beta\beta$ Nuclear Matrix Elements can be made

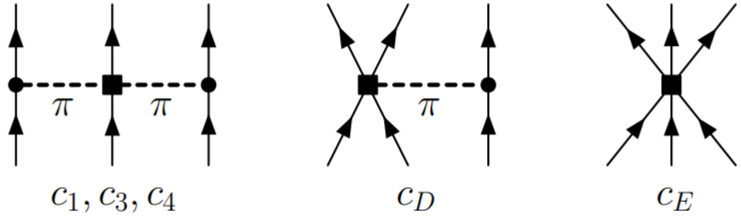
Spares

Chiral forces and currents

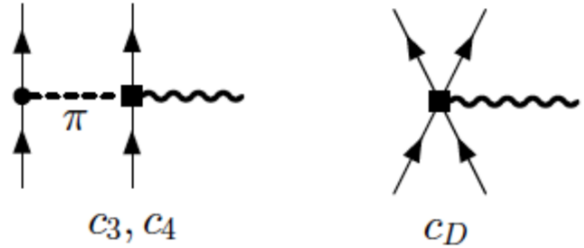
Consistent treatment of nuclear many-body forces and electroweak currents



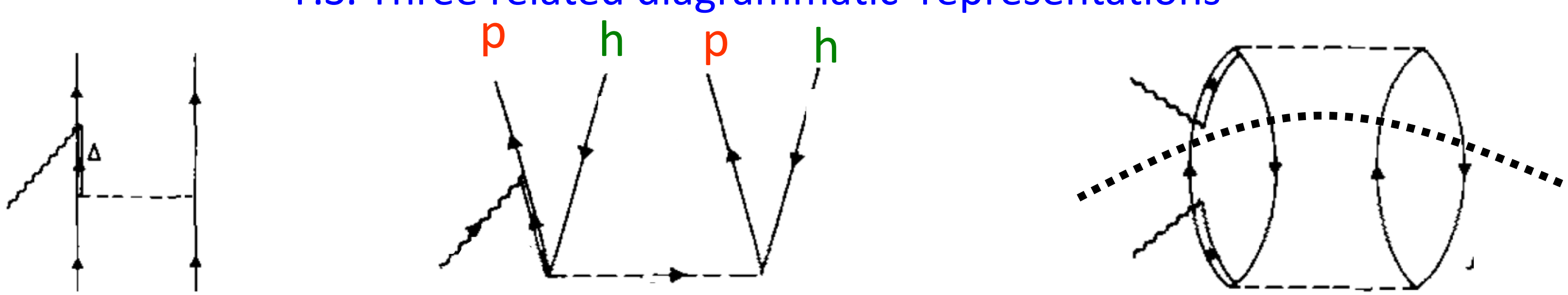
3-body force at NNLO:



2-body currents:



P.S. Three related diagrammatic representations



2-body current

2p-2h matrix element

2p-2h response