Interface entre physique des neutrinos et physique nucléaire

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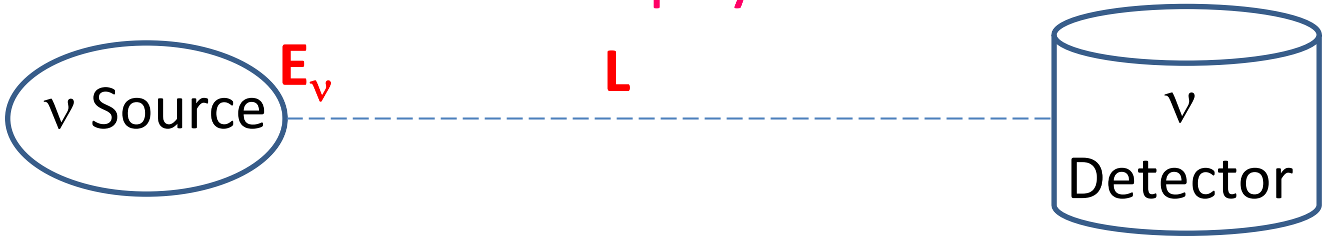
Neutrino physics

$\nu_\alpha \to \nu_\beta$



Number of events

$$N_\beta \sim \Phi_{\nu_\alpha}(E_\nu)\,\sigma_{\nu_\beta}(E_\nu)\,\varepsilon_{det.}\,P_{\nu_\alpha \to \nu_\beta}(\{\Theta\}, E_\nu)$$

ν flux	ν cross section	Detector efficiency	ν oscillation probability

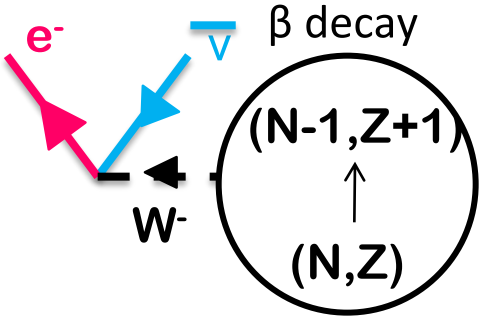
Hot topics of recent years where **nuclear physics** plays a crucial role:

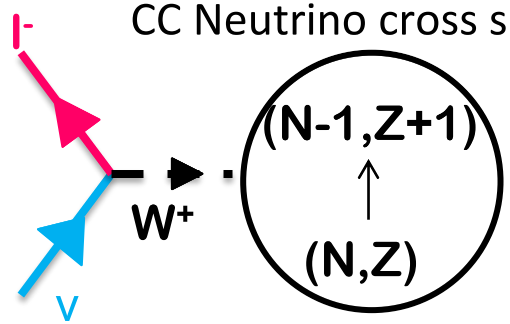
- $\bar{\nu}$ Flux in reactor experiments (β decay of fission fragments) [$E_\nu \sim$ MeV]
  [D. Lhuillier talk]
- ν-nucleus cross sections in accelerator experiments [$E_\nu \sim$ GeV]
  [S. Bolognesi talk]

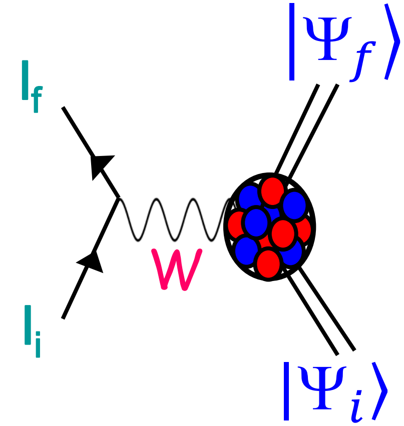
Another hot topics:

- Nuclear matrix elements for ν-less Double-Beta decay
  [M. Bongrand talk]

Generalities







$$w_{i\to f} = \frac{2\pi}{\hbar}\,\rho\,|\langle f|H_W|i\rangle|^2$$ Fermi Golden Rule

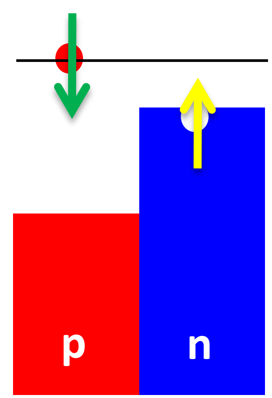
$$\mathscr{L}_W = \frac{G}{\sqrt{2}}\, l^{\mu}\, h_{\mu}$$

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

Example of nuclear excitation operator: Gamow Teller

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

$\Delta S=1$ $\Delta T=1$ $\Delta J^{\pi}=1^+$

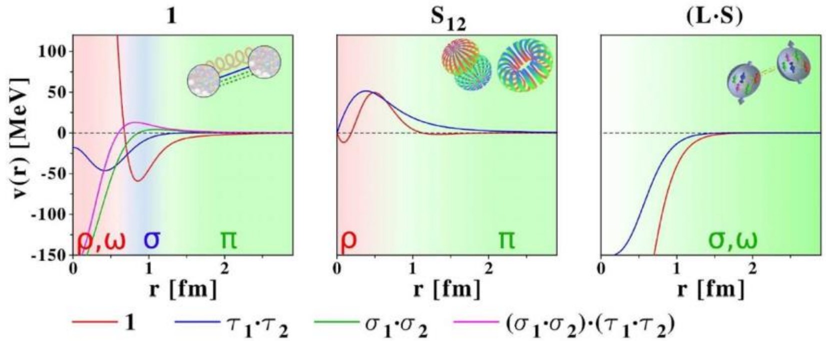


$$d\Gamma, d\sigma \sim (leptonic\ factors) \boxed{\left|\langle \Psi_f | \hat{O} | \Psi_i \rangle\right|^2}$$

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

Two main problems of nuclear physics

- The nuclear interaction



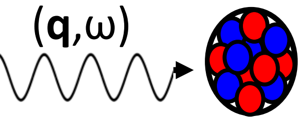
- The nucleus is a many body system

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

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 excitations induced by the same excitation operator (στ)

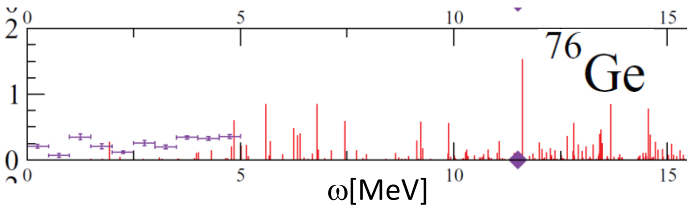


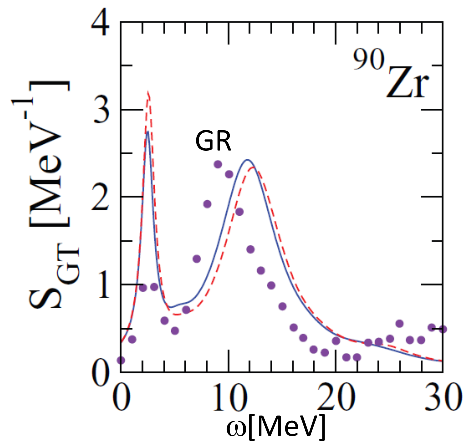
$$\left|\langle\Psi_f|\hat{O}_{GT}|\Psi_i\rangle\right|^2$$

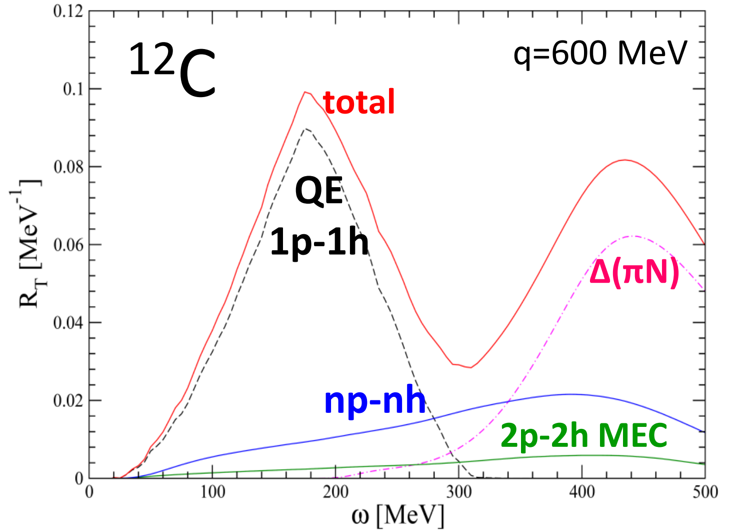
- Different Nuclei
- Different energy domains

⬇

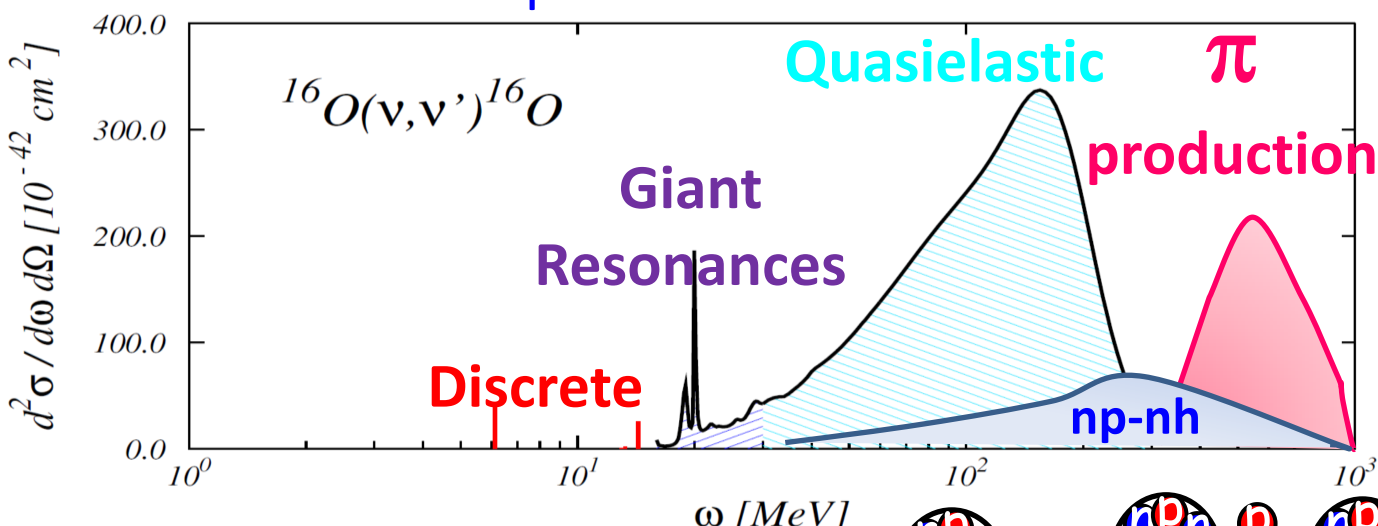
Different Nuclear models
(e.g. HFB+QRPA ; LFG+RPA)

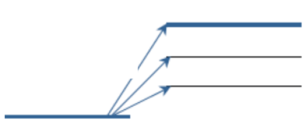


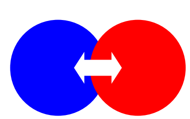


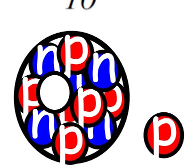


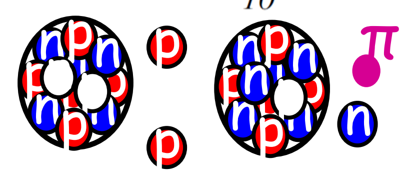
Example of cross section











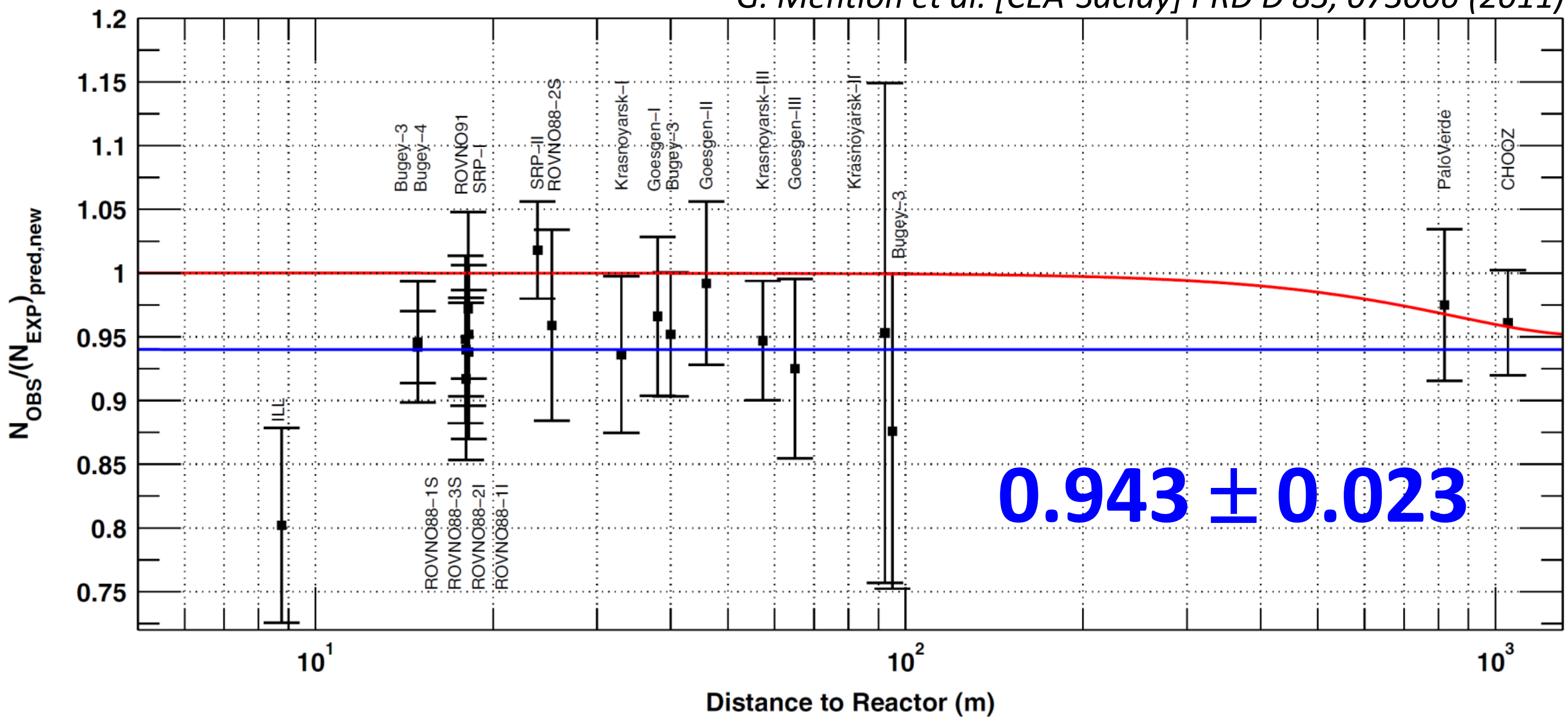
Reactor Antineutrino spectrum

The Reactor Anomaly

Reevaluation of the reactor flux in 2011 [Mueller et al. and Huber]:
3% higher than previous estimate [Schreckenbach et al. 1985 and Hahn et al. 1989]

The increase in predicted neutrino fluxes triggered a re-analysis of existing reactor data

G. Mention et al. [CEA-Saclay] PRD D 83, 073006 (2011)

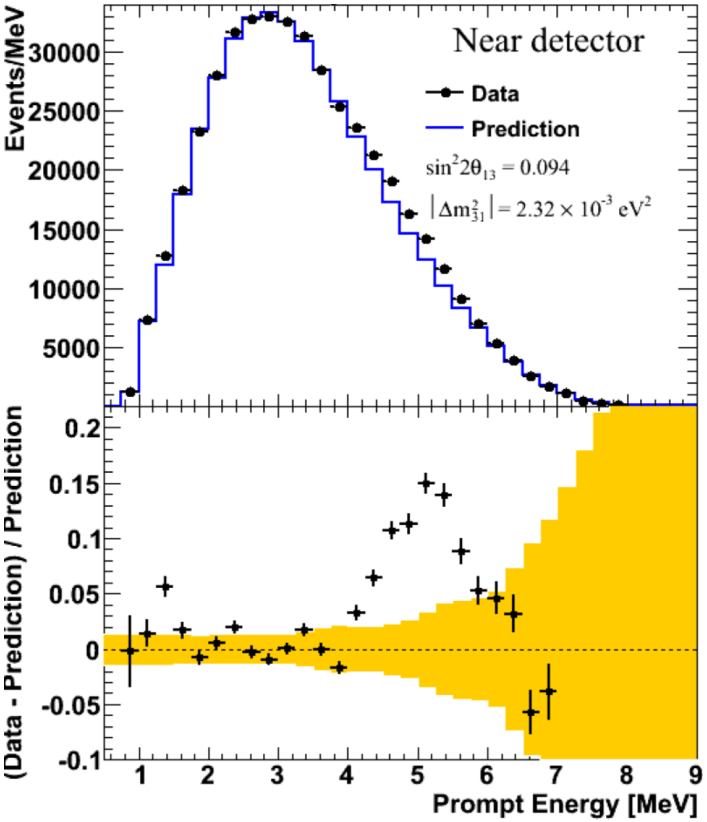


$\Rightarrow$ The experiments at L $>$ 10 meters missed on average ~6% of the expected signal

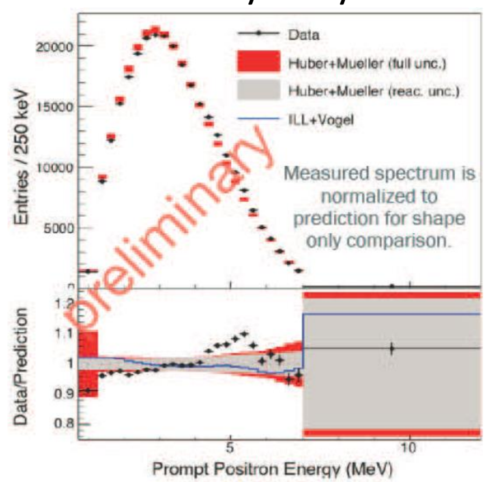
Signature of new physics (sterile neutrino) or problem with the reactor flux determination?

The 5 MeV bump

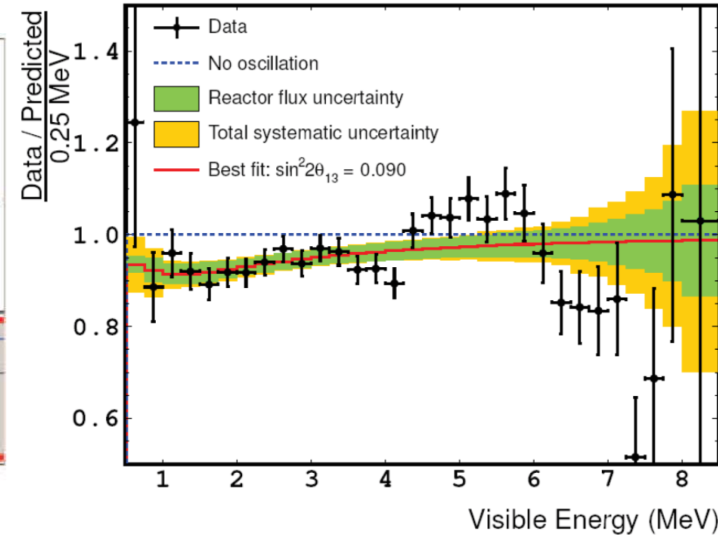
RENO



Daya Bay



Double CHOOZ



$$E_{prompt} \approx E_\nu + (M_p - M_n - M_e) + 2M_e$$

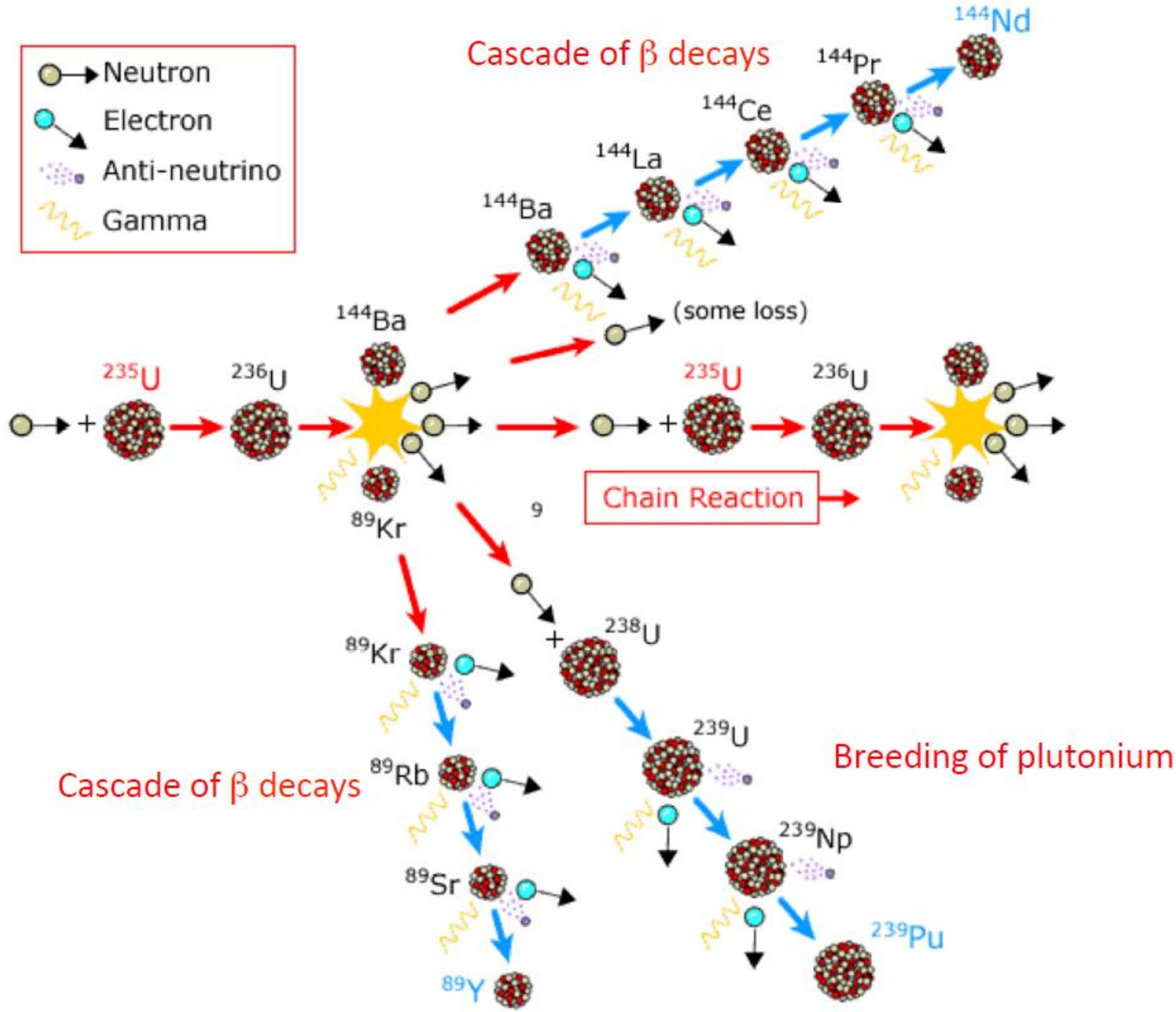
"Bump" or shoulder at 4-6 MeV of the positron (5-7 MeV of the neutrino) energy

Observed by all three reactor experiments and not predicted theoretically

The theoretical calculation, until now, does not describe this spectrum feature

What is its origin ?

Electron antineutrinos produced by the β decay of fission fragments



Antineutrino spectrum emitted by a reactor

~ 6 $\bar{\nu}_e$ emitted per fission

~ 200 MeV per fission

A typical reactor emits ~ 6 × 10^{20} $\bar{\nu}_e$ per each GW of the thermal energy power

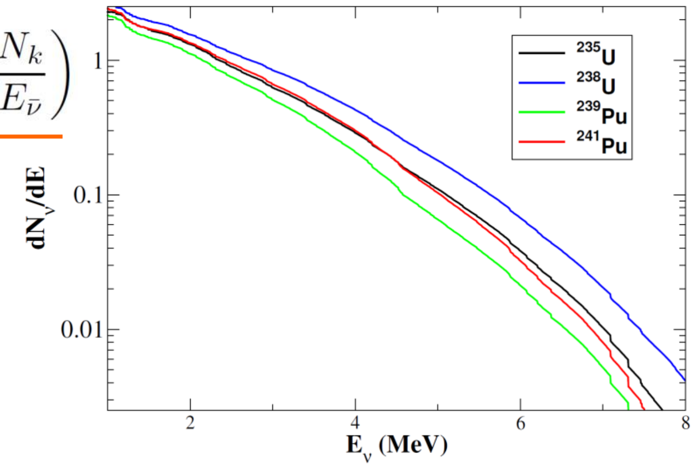
Total $\bar{\nu}_e$ spectrum

$$\Phi_{\bar{\nu}}(E_{\bar{\nu}},t) = \frac{P_{th}(t)}{\sum_{k=^{235}U,^{238}U,^{239}Pu,^{241}Pu} \alpha_k(t)\epsilon_k} \sum_{k=^{235}U,^{238}U,^{239}Pu,^{241}Pu} \alpha_k(t)\left(\frac{dN_k}{dE_{\bar{\nu}}}\right)$$

thermal power

fraction of fissions from isotope k

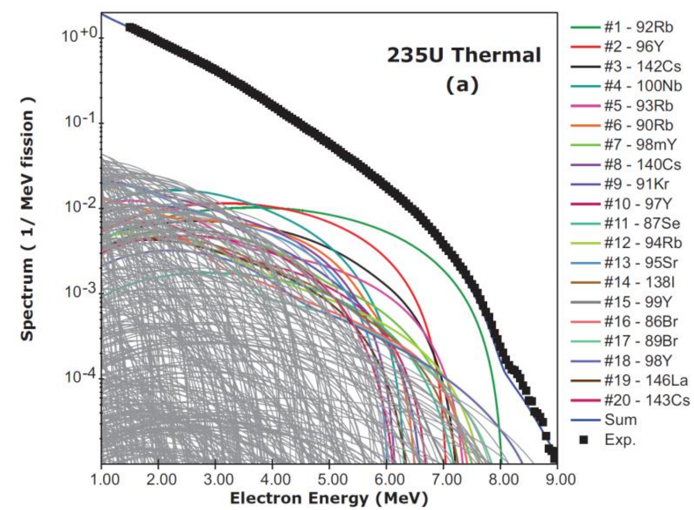
Mean energy released per fission



$\bar{\nu}_e$ spectrum per fission

$$\frac{dN_k}{dE_{\bar{\nu}}} = \sum_{\text{fission products}=1}^{N_{fp}} Y_{fp}(Z,A,t) S_{fp}(E_{\bar{\nu}})$$

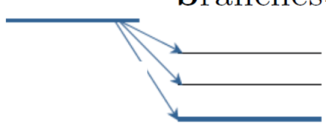
Number of β decays of the Z,A fragment at time t
→ cumulative fission yield (independent of t)
(how often is a given isotope produced in fission)



$\bar{\nu}_e$ spectrum of one fission product

$$S_{fp}(E_{\bar{\nu}}) = \sum_{\text{branches}=1}^{N_b} BR^b_{fp} S^b_{fp}(Z,A,E^b_{0\ fp},E_{\bar{\nu}})$$

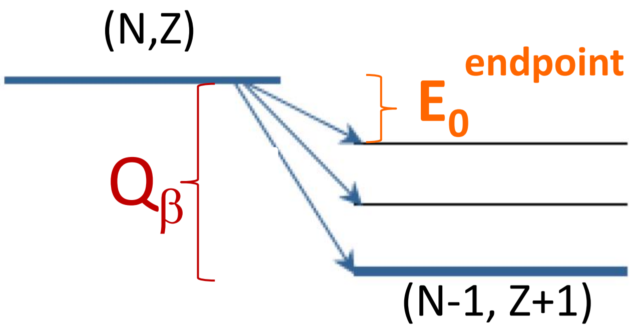
Branching ratios



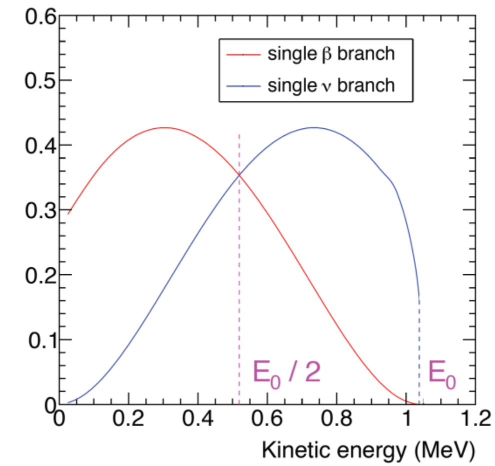
β deacy $\bar{\nu}_e$ (or associated e) spectrum

Electron and antineutrino spectrum associated with fission is composed of ~6 000 beta decay branches from the decay of the neutron rich fission fragments

The β decay spectrum



If the electron spectrum is known, it can be "converted" into the antineutrino spectrum, because in each branch $E_\nu = E_0 - E_e$



$$S^b_{fp} = (lepton\ factors)\ \left|\langle\Psi_f|\hat{O}|\Psi_i\rangle\right|^2$$

$$S^b_{fp} = K \underbrace{p_e E_e (E_0 - E_e)^2}_{\text{lepton phase space factor}} \underbrace{F(Z, E_e)}_{\text{Fermi Function}} \underbrace{C(Z, E_e)}_{\textbf{Shape Factor}} \underbrace{(1 + \delta(Z, A, E_e))}_{\text{Subdominant corrections}}$$

The shape Factor $\boxed{C(Z, E_e)}$

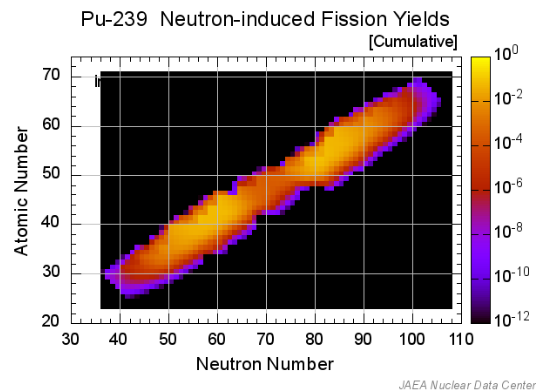
- Accounts for the energy or momentum dependence of the **nuclear matrix elements**
- $C(Z,E_e)=1$ for allowed decays [Gamow-Teller ($\sigma\tau$) and Fermi (τ)]
- $C(Z,E_e)\neq 1$ for forbidden decays $\Rightarrow$ **crucial role of nuclear physics**

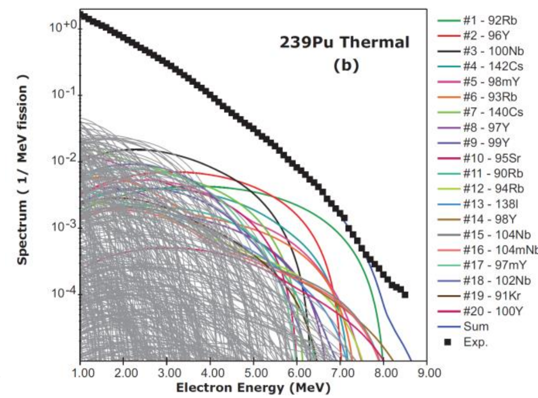
Two ways to determine the reactor antineutrino spectrum

I) The "ab initio" **summation** method

Add the beta decay spectra of all fission fragments. It requires the knowledge of the fission yields, half-lives, branching ratios, endpoints of all beta branches, and spectrum shape of each of them.

~800 nuclei ~6 000 β branches





II) The electron spectrum **conversion** method

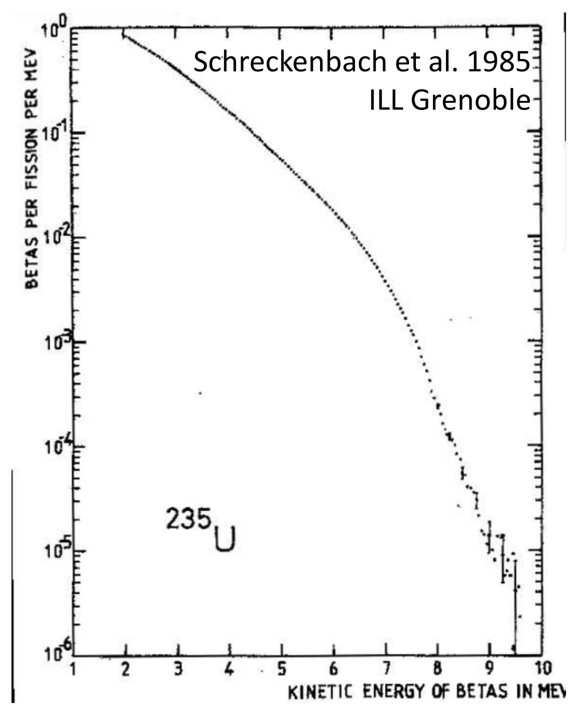
Measure the electron spectrum associated with fission and convert it into the neutrino spectrum

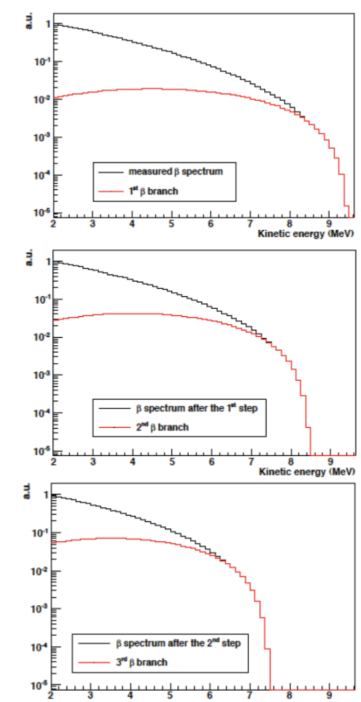
1- Fit total e- spectrum with a sum of 30 effective β branches determined by iterative method (instead of ~ 6000 real branches)

2- Convert each effective e- branches to ν branches using the fact that the electron and neutrino share the available energy of each decay

3- Sum all converted ν branches to get total ν spectrum

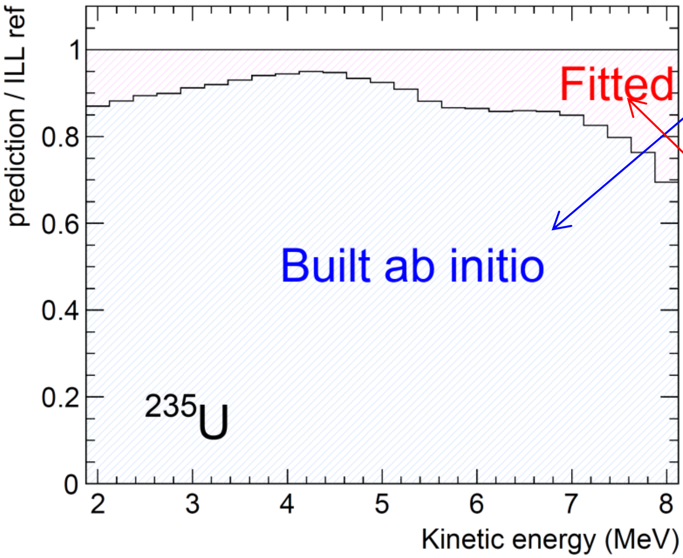
The ILL ^{235}U, ^{239}Pu, ^{241}Pu converted ν spectra have been the reference spectra from the '80 up to 2011





The 2011 flux reevaluation of the Saclay group (Mueller et al) and Huber

The Mixed Approach



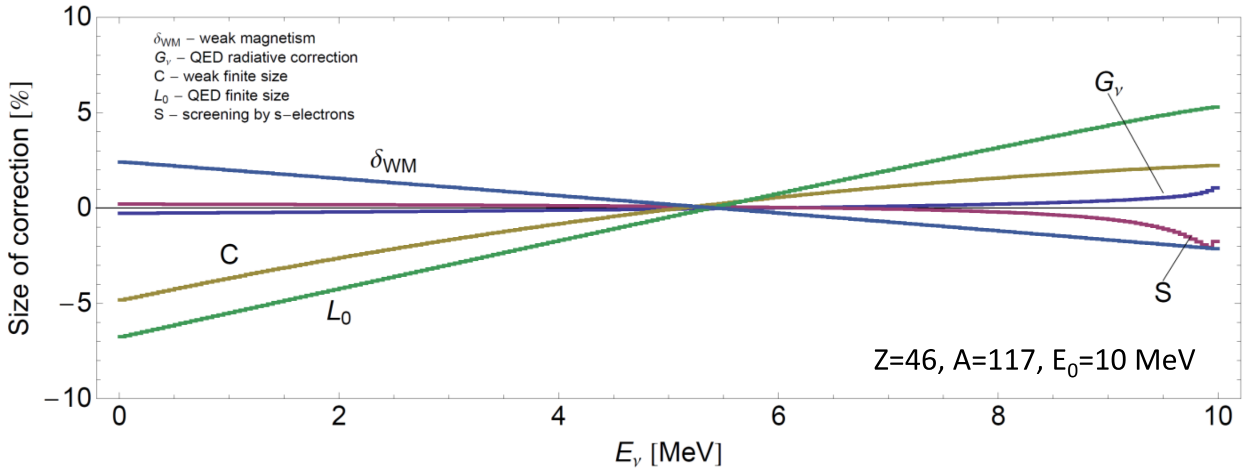
Mueller et al. PRC 83 (2011)

- **Ab initio:** "true" distribution of all known β branches describes **>90%** of ILL e- data ⇒ reduces sensitivity to virtual branches approximations
- **Conversion** for the residual: five effective branches are fitted to the remaining **10%** ⇒ Suppresses error of full ab initio approach

This mixed approach unexpectedly revealed biases in the previous conversion procedure induced by the treatment of the **correction terms to the Fermi theory**

$$Kp_eE_e(E_0-E_e)^2F(Z,E_e)C(Z,E_e)(1+\delta(Z,A,E_e))$$

New conversion of the total ILL β spectra



Huber PRC 84 (2011)

Branch-by-branch application of shape corrections

The main cause of the upward shift in the reactor spectrum evaluation of Mueller et al. and Huber is the more careful treatment of the finite size and weak magnetism corrections

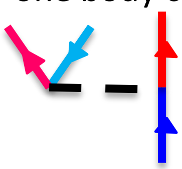
The weak magnetism correction

The interaction of the out-going electron with the magnetic moment $\vec{m} = \frac{1}{2}\int d^3x[\vec{x} \times \vec{J}_v(\vec{x})]$ of the daughter nucleus leads to a weak magnetism correction.

The form of the correction is determined by the interference of the magnetic (transverse) distribution of the vector current J_V and the spin distribution of the axial current J_A

Approximations:

- Non relativistic
- Allowed GT transitions
- Only one body currents (I.A.)



$$\Rightarrow \quad \delta_{WM} = \frac{4E_e}{3g_A M}\left(1 - \frac{m_e^2c^4}{2E_e^2}\right)\left[\frac{\langle \vec{l}\rangle}{\langle \vec{\sigma}\rangle} + (\mu_p - \mu_n)\right]$$

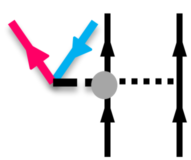
In principle, the nuclear matrix element ratio $\frac{\langle \vec{l}\rangle}{\langle \vec{\sigma}\rangle} = \frac{\langle \Psi_f | \sum_{k=1}^{A} \vec{l}(k)\tau_-(k) | \Psi_i \rangle}{\langle \Psi_f | \sum_{k=1}^{A} \vec{\sigma}(k)\tau_-(k) | \Psi_i \rangle}$ **should be evaluated for each transition**

- Further approximation: $\langle \vec{l}\rangle = -\frac{\langle \vec{\sigma}\rangle}{2}$

$$\delta_{WM} \approx \frac{4}{3}\frac{\mu_p - \mu_n - 1/2}{g_A M}E_e\left(1 - \frac{m_e^2c^4}{2E_e^2}\right) \approx 0.5\% E_e/\mathrm{MeV}$$

This is the correction used by Mueller et al. and Huber

- **$\langle \vec{l}\rangle$ evaluations**
- **two-body currents contributions**



will modify the above δ_{WM} correction

Theoretical calculations are needed

First Forbidden β decays

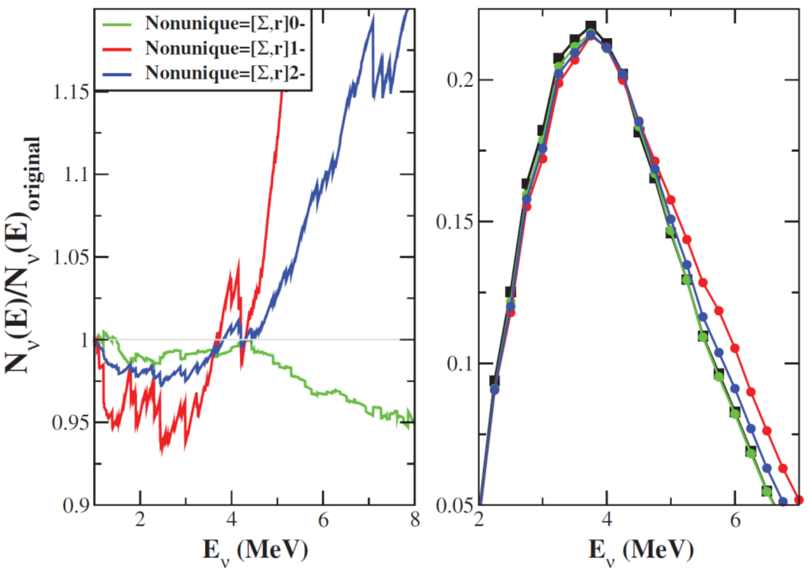
In the allowed β decays (GT and Fermi) the nuclear total angular momentum is changed by no more than one unit ($|\Delta J| \leq 1$) and the parity is not changed ($\pi_i \pi_f = +1$).

First forbidden decays are suppressed by $(pR)^2 \ll 1$. But they do occur if the selection rules $\pi_i \pi_f = -1$, $\Delta J \leq 2$ require them.

The fission fragments are neutron rich and in many of them the least bound neutrons and protons are in states of opposite parity. **Among the ~6000 beta decay branches, about 25% are first forbidden decays.**

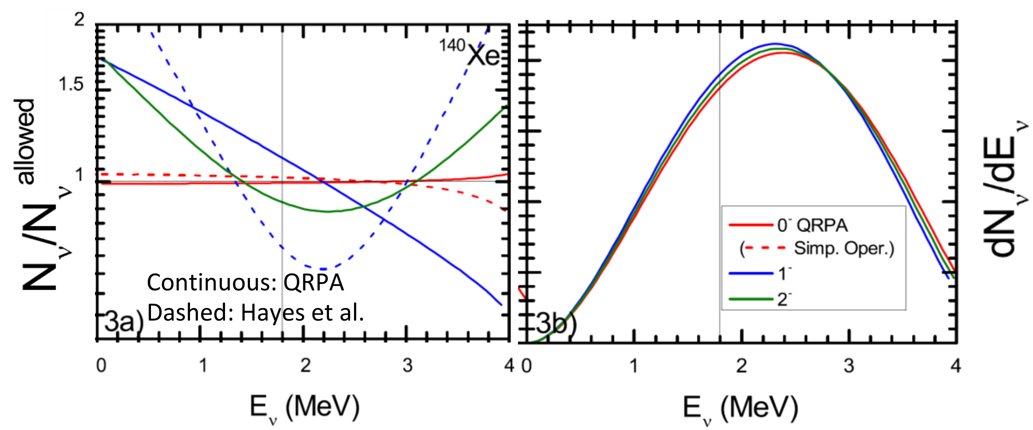
Unlike for the GT decays with only 1 operator, there are up to **6 operators for the first forbidden** decays that can interfere.

$$C(Z, E_e) = \left| \left\langle \Psi_f \middle| \hat{O}_{FF} \middle| \Psi_i \right\rangle \right|^2$$ **Different shapes** **(and different WM corrections)**



Hayes et al. PRL 112 (2014)

- Different treatments of FF can lead to spectra that differ in shape and magnitude
- FF are large source of uncertainty



Fang and Brown, PRC 91 (2015)

- Microscopic nuclear structure QRPA calculations
- The actual FF decays are more complicated than the form assumed by Hayes et al.

Reactor antineutrino spectrum - conclusions

- It is difficult to quantify the true reactor flux uncertainty
- The assumed uncertainty of ~2.7% of Mueller et al. and Huber was based on the assumption that the shapes of all β decays are known
- Considering the uncertainties related to the weak magnetism and first forbidden transitions leads to the conclusions (Vogel, Hayes,..) that ~5% uncertainty could be a more realistic estimate
- The observation of the 4-6 MeV "bump" not predicted in the calculated spectrum, also indicates that the predictions could be not as accurate as initially thought

For the moment we cannot use the `reactor anomaly' as an argument for or against the existence of the sterile neutrino

How to proceed?

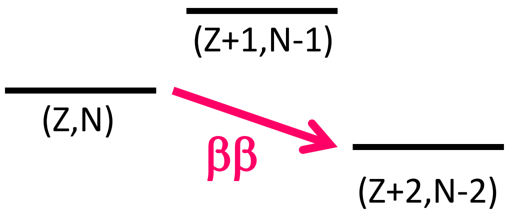
i) Perform accurate measurement using research reactors at small distance

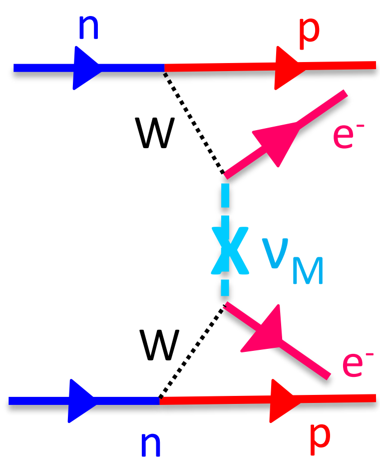
ii) Accurately measure the spectrum shape of the ~20 most important first forbidden decays

iii) Reevaluate the systematic uncertainties using as input microscopic theoretical calculations (e.g. QRPA) when nuclear data are not available

p.s. research activity with strong overlap with nuclear astrophysics
(in particular with r-processes nucleosynthesis)

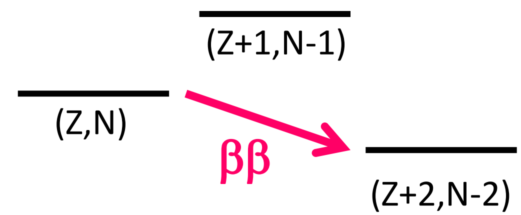
Nuclear matrix elements for neutrinoless Double-Beta decay





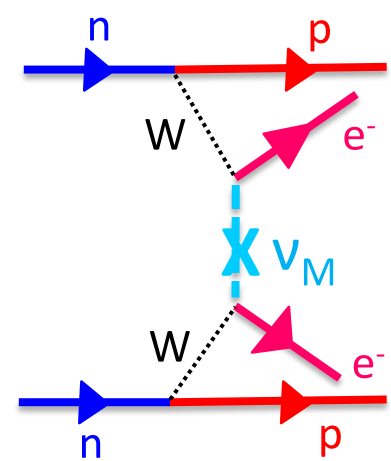
Neutrinoless ββ decay

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

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

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

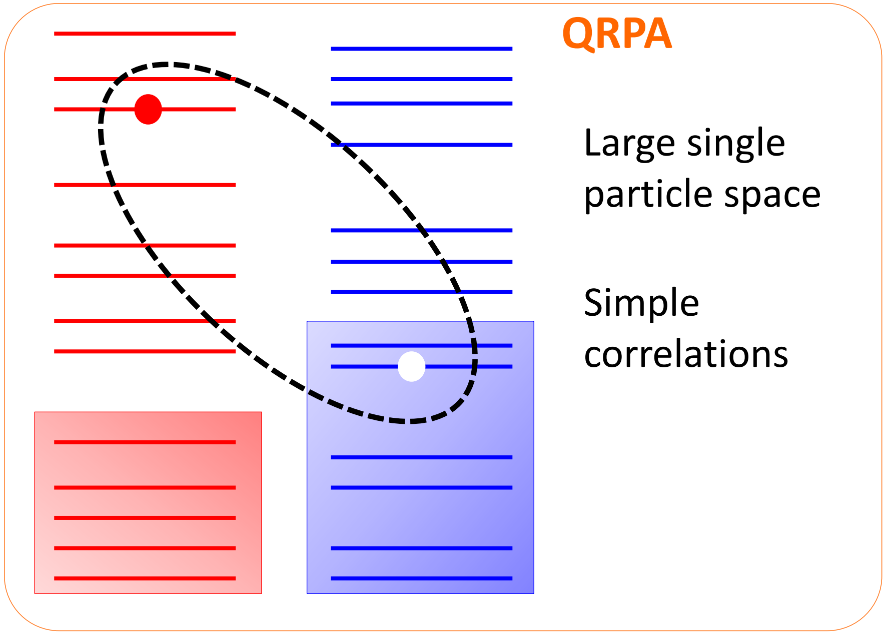
$$M^{GT}_{(0\nu)} = \langle f | \sum_{a,b} H(r_{ab}, \bar{E}) \vec{\sigma}_a \cdot \vec{\sigma}_b \tau_a^+ \tau_b^+ | i \rangle \qquad M^{F}_{(0\nu)} = \langle f | \sum_{a,b} H(r_{ab}, \bar{E}) \tau_a^+ \tau_b^+ | i \rangle$$

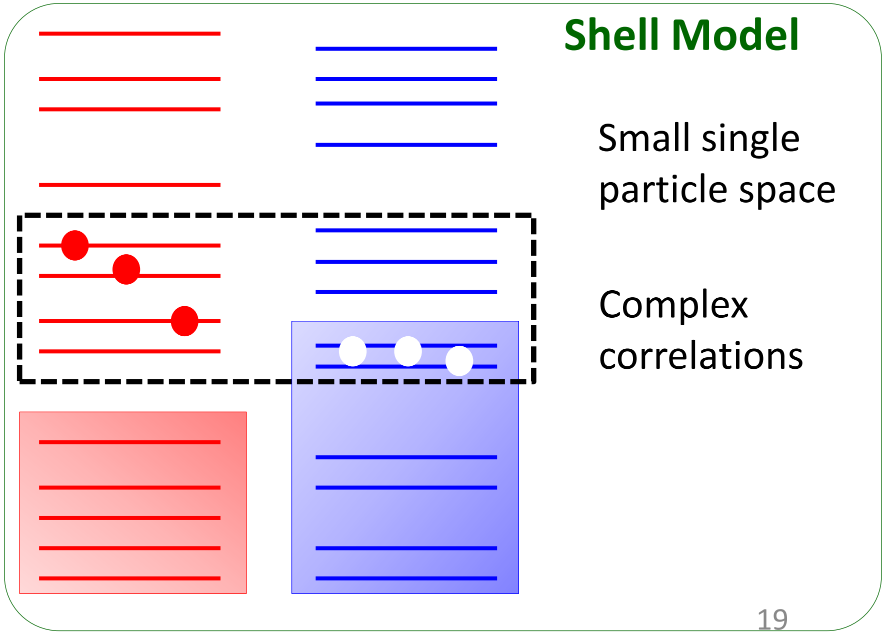
Calculating Matrix Elements it's hard

- Relevant nuclei heavy (A > 75) and complicated
- Never measured; nothing to calibrate to
- Structure of initial and final nuclear ground states quite different ⇒ matrix element small and sensitive

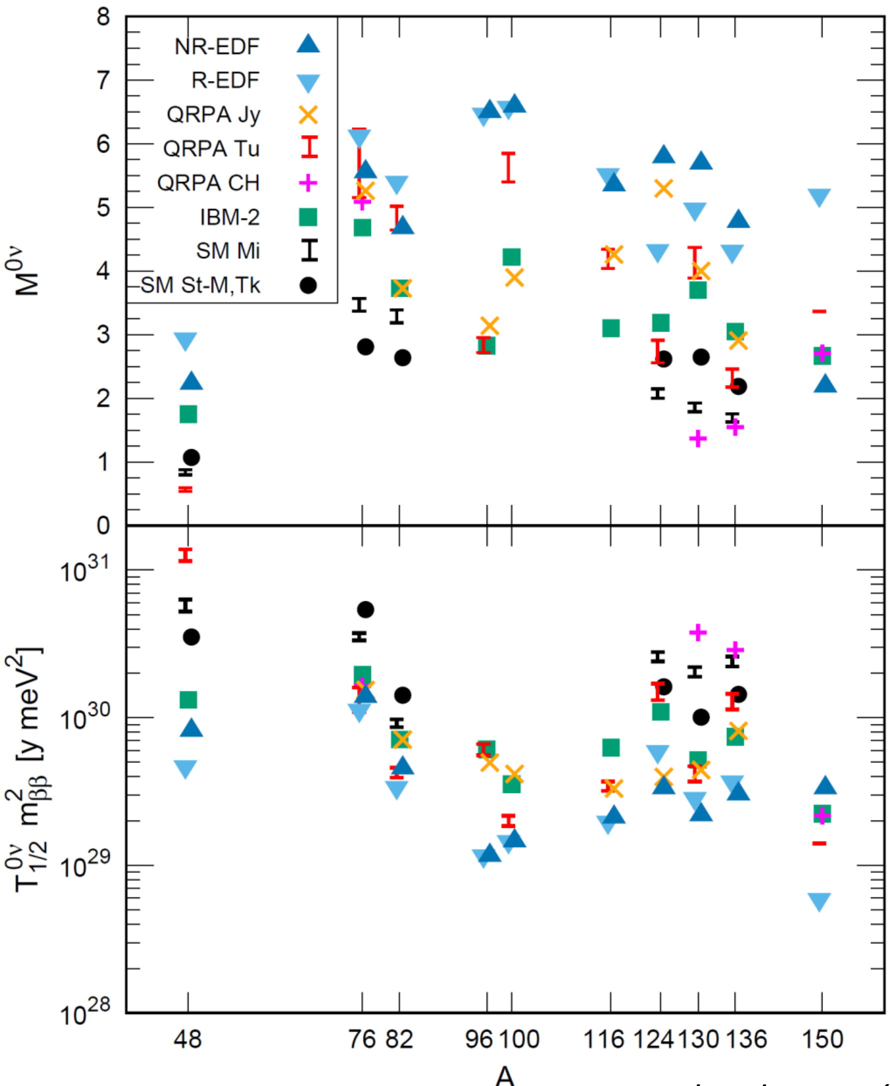
Different nuclear models, different approximations, different NN effective interaction

e.g.:





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



J. Engel and J. Menéndez, arXiv: 1610.06548

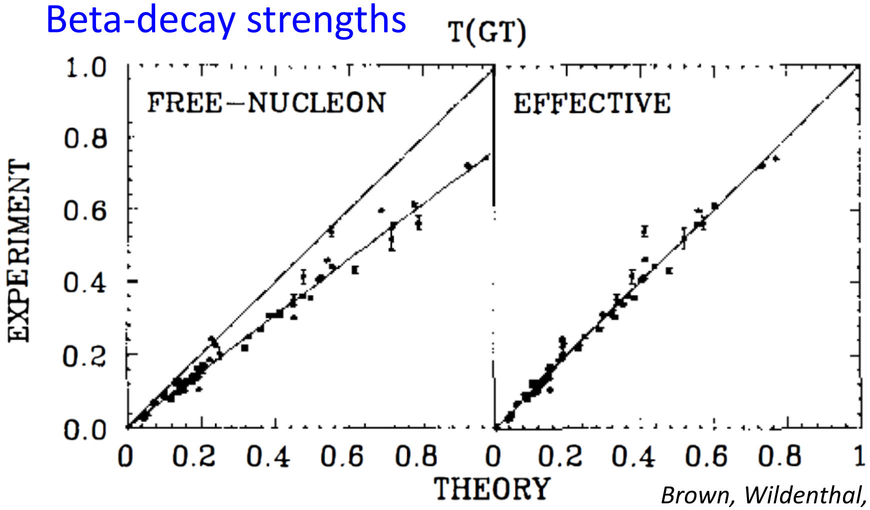
- Large uncertainties
- Factors 2 or 3 of difference between different approaches
- Same approach (e.g. QRPA) with different nuclear forces leads to different results

p.s. g_A is unquenched for all the plotted results

Quenching of the GT strength and “renormalization of g_A”

Forty(?)-year old problem: GT Matrix elements and related observables [(p,n)-nucleus cross sections, single-beta rates, 2ν double-beta rates] are over-predicted by the theory

Beta-decay strengths



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

Solution: Not Yet Clear

Since

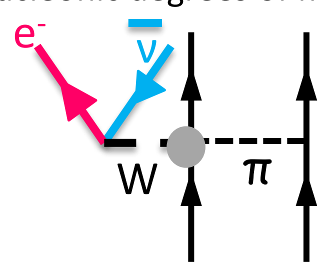
$$[\tau^{\beta}_{1/2}]^{-1} \propto g_A{}^2 \, |M^{\beta}_{GT}|^2$$

Typical practice: “Renormalize” g_A to get correct results

$$g_A = 1.26 \quad \rightsquigarrow \quad \boldsymbol{g_A{}^{\mathrm{eff}} \sim 1}$$

Several possible 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



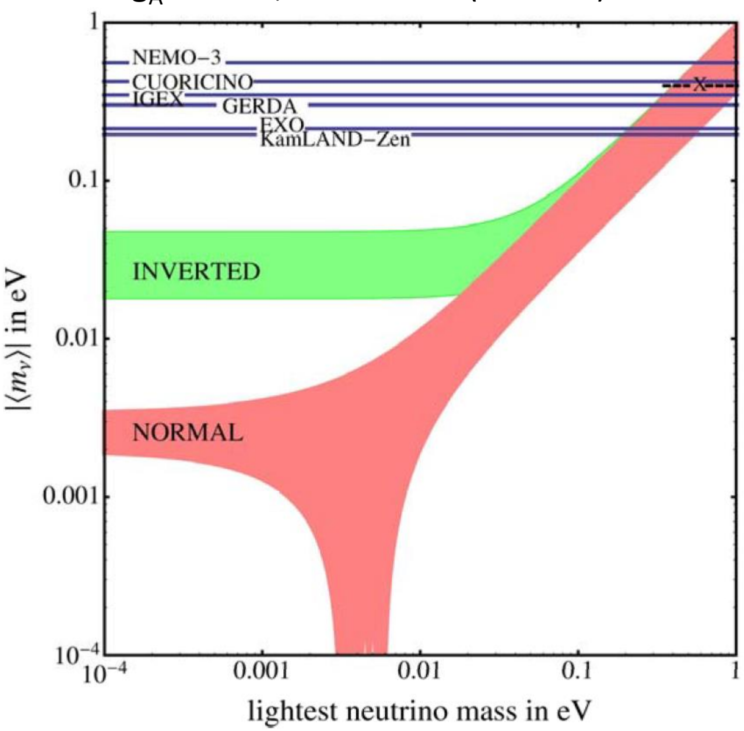
If g_A is renormalized in 0ν decay ⇒ experiments are in trouble

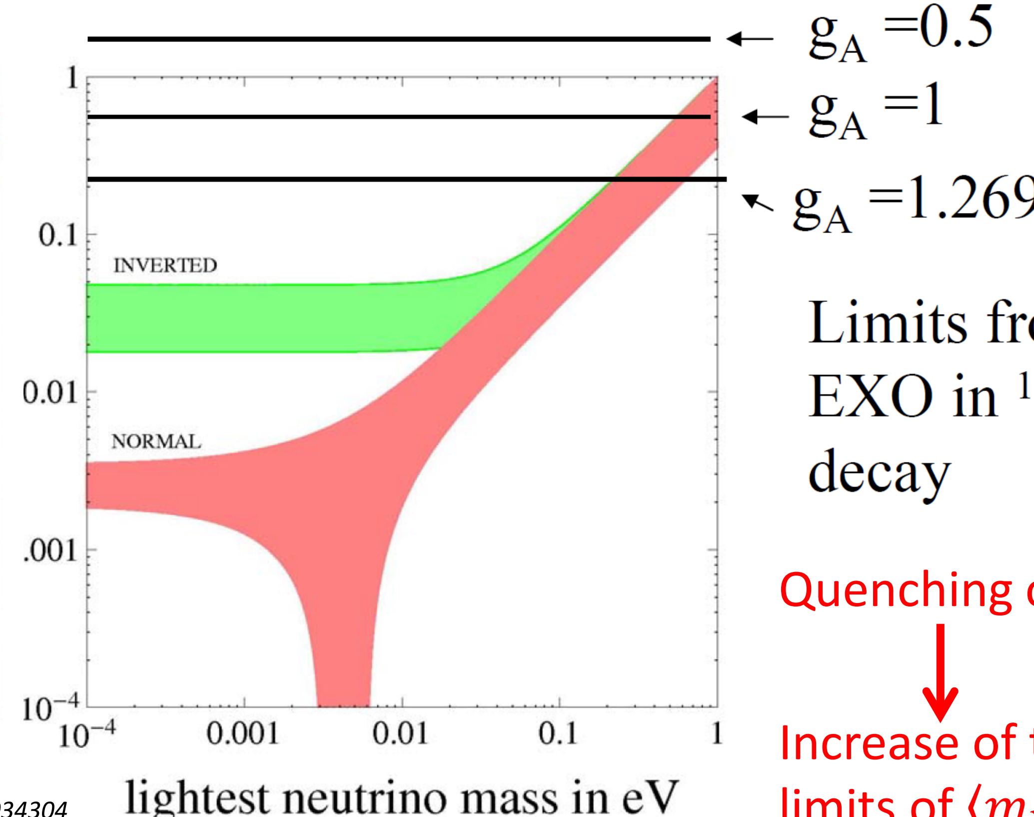
$$\left[\tau_{1/2}^{0\nu}\right]^{-1} = G_{0\nu}\left|M_{0\nu}\right|^2 |\langle m_\nu\rangle|^2 \qquad M_{0\nu} = g_A^2 M^{(0\nu)}$$

rates go as $(g_A)^4$

$$\langle m_\nu\rangle = \sum_{k=ligth} (U_{ek})^2 m_k = \left| |U_{e1}^2|\, m_1 + |U_{e2}^2|\, m_2 e^{i\alpha} + |U_{e3}^2|\, m_3 e^{i\beta} \right|$$

g_A=1.269 ; NME:IBM2 (Iachello)





Barea, Kotila, Iachello, Phys.Rev. C91 (2015), 034304

Limits from EXO in ^{136}Xe decay

Quenching of g_A

↓

Increase of the limits of $\langle m_\nu\rangle$

Neutrino-nucleus cross sections in accelerator-based oscillation experiments

Neutrino oscillation experiments

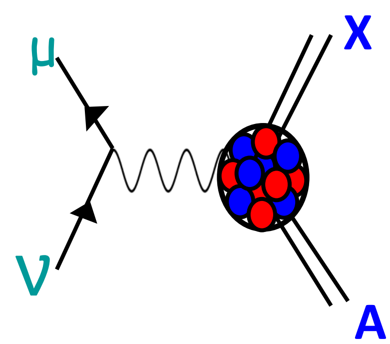
Number of events

$$N_\beta \sim \Phi_{\nu_\alpha}(E_\nu)\, \sigma_{\nu_\beta}(E_\nu)\, \varepsilon_{det.}\, P_{\nu_\alpha \to \nu_\beta}(\{\Theta\}, E_\nu)$$

ν flux (prediction)	ν cross section (model)	Detector efficiency	ν Energy in the oscillation probability

Modern accelerator-based neutrino oscillation experiments:

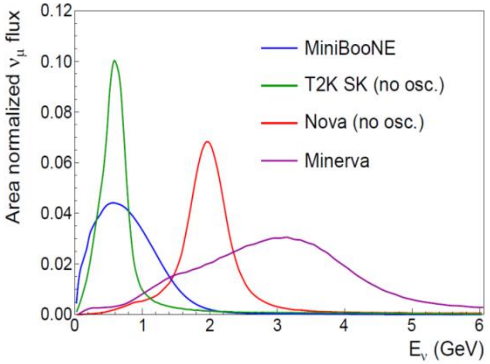
- Nuclear targets (C, O, Ar, Fe...)
- The neutrino energy is reconstructed from the final states



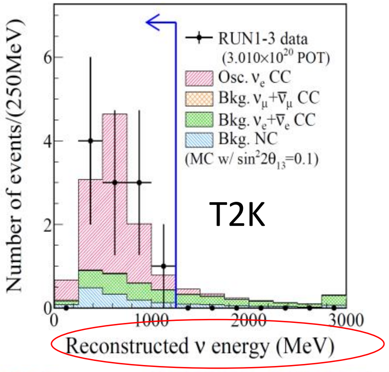
→ the knowledge of the neutrino-nucleus cross section is crucial

Some crucial points of the accelerator-based ν experiment

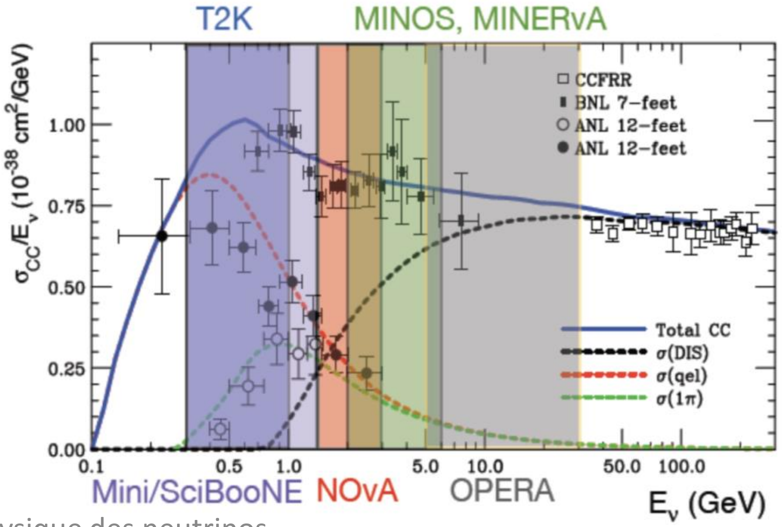
- Neutrino beams are not monochromatic (at difference with respect to electron beams).
  They span a wide range of energies



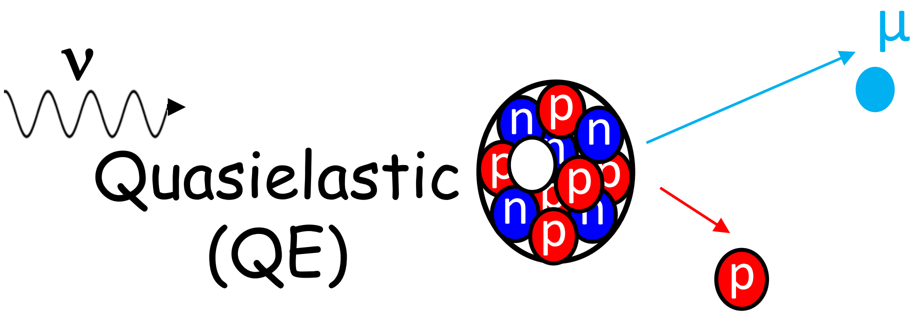
- The neutrino energy is reconstructed from the final states of the reaction (typically from CC Quasielastic events)



- Different reaction mechanisms contribute to the cross section in the modern experiments

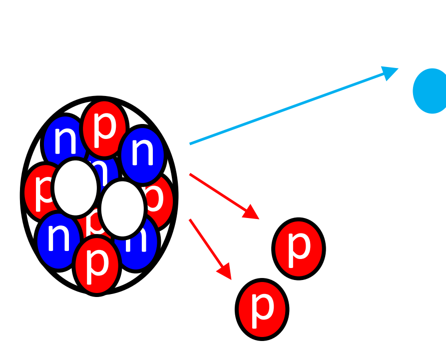


Neutrino - nucleus interaction @ $E_\nu \sim O$ (1 GeV)

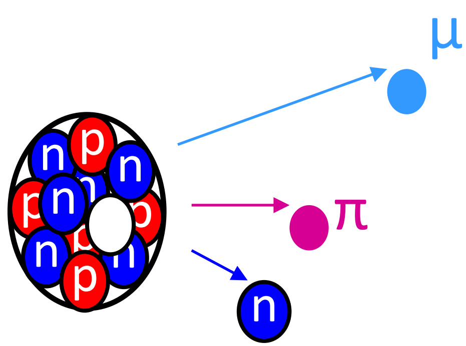


Quasielastic
(QE)

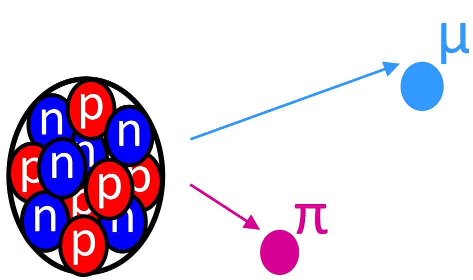
Two Nucleons
knock-out
(2p-2h)



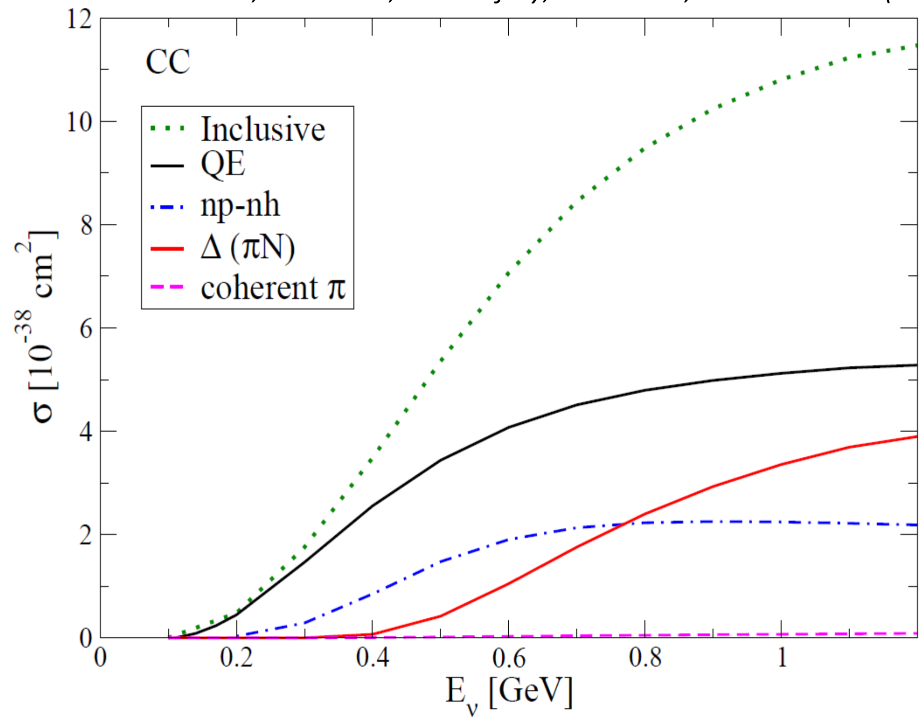
Incoherent
π production



Coherent
π production



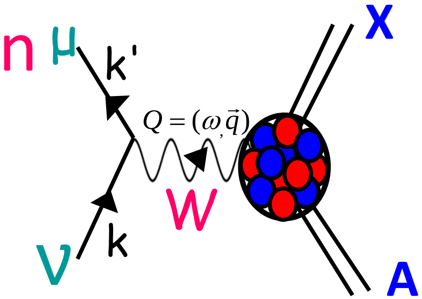
M. Martini, M. Ericson, G. Chanfray, J. Marteau, PRC 80 065501 (2009)



Different processes are entangled

Neutrino-nucleus cross section

$$\mathcal{L}_W = \frac{G_F}{\sqrt{2}} \cos\theta_C l_\mu J^\mu$$



$$d\sigma \propto L_{\mu\nu} W^{\mu\nu}$$

$$L_{\mu\nu} = k_\mu k'_\nu + k'_\mu k_\nu - g_{\mu\nu} k \cdot k' \pm i\varepsilon_{\mu\nu\kappa\lambda} k^\kappa k'^\lambda$$

Leptonic tensor

$$W^{\mu\nu} = \sum_f \langle \Psi_f | J^\mu(Q) | \Psi_i \rangle^* \langle \Psi_f | J^\nu(Q) | \Psi_i \rangle \delta(E_i + \omega - E_f)$$

Hadronic tensor

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

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

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

Isovector R_τ (τ); Isospin Spin-Longitudinal $R_{\sigma\tau(L)}$($\tau\ \sigma\cdot q$); Isospin Spin Transverse $R_{\sigma\tau(T)}$($\tau\ \sigma \times q$)

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

Form Factors and cross section

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

Standard dipole parameterization

Vector

$$Q^2 = q^2 - \omega^2$$

$$\underline{G_E(Q^2)} = \underline{G_M(Q^2)}/(\mu_p-\mu_n) = (1+Q^2/M_V^2)^{-2}$$

$$M_V = 0.84\,\mathrm{GeV}/c^2$$

Axial

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

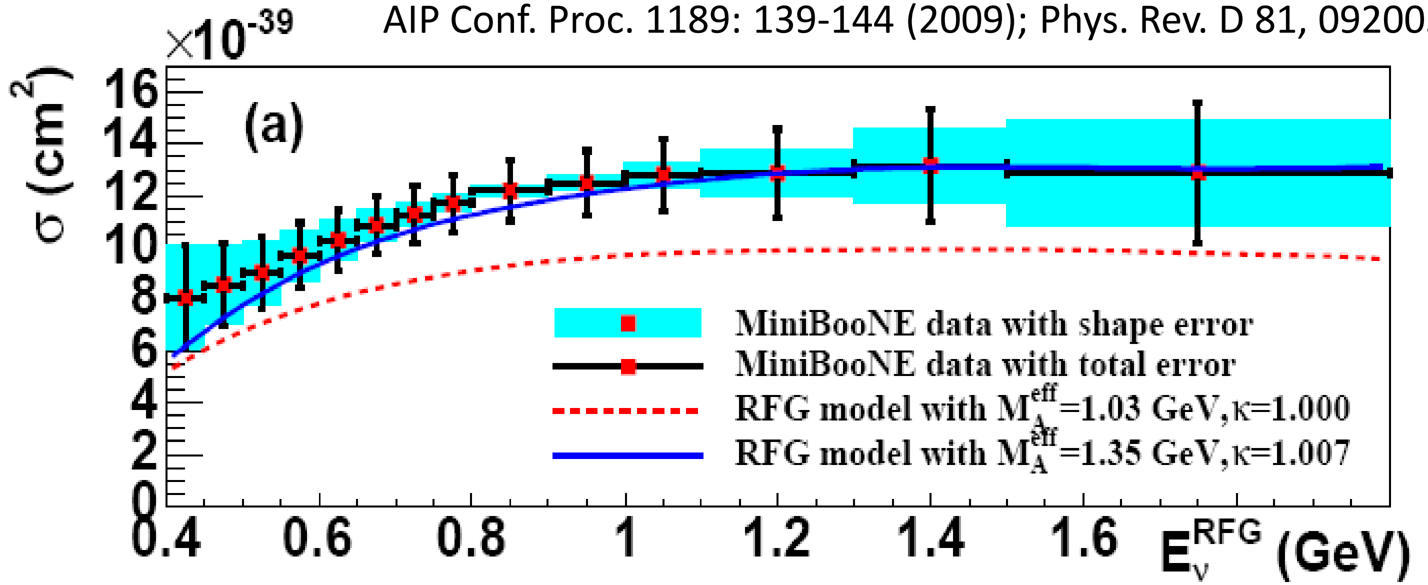
$g_A = 1.26$ from neutron β decay

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

from ν-deuterium CCQE and
from π electroproduction

MiniBooNE CC Quasielastic cross section on Carbon and the M_A puzzle

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



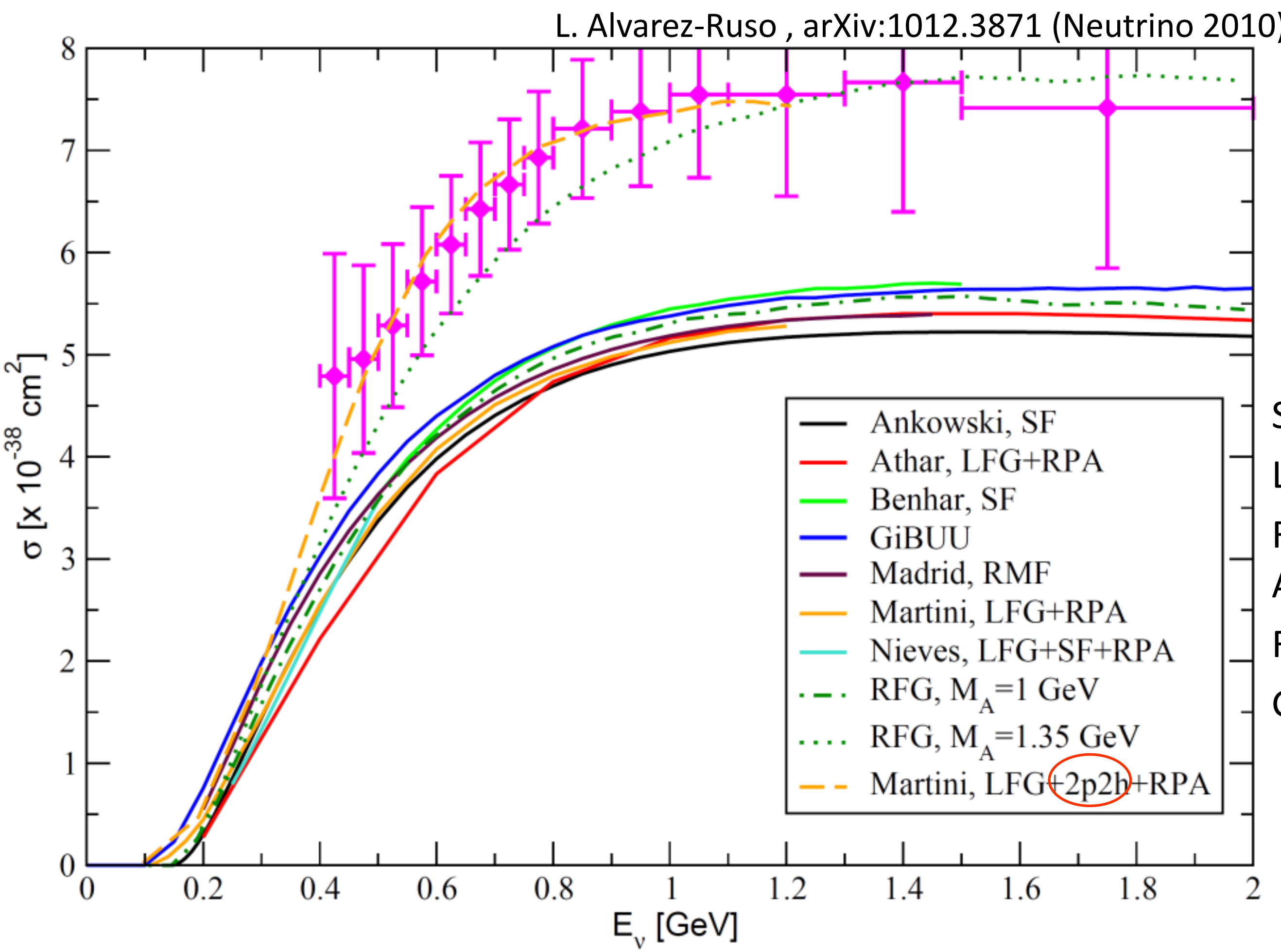
Comparison with a prediction based on RFG using M_A=1.03 GeV (standard value) reveals a discrepancy

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

p.s. Relativistic Fermi Gas: Nucleus as ensemble of non interacting fermions (nucleons)

puzzle??

Comparison of different theoretical models for Quasielastic



SF: Spectral Function

LFG: Local Fermi Gas

RPA: Random Phase Approximation

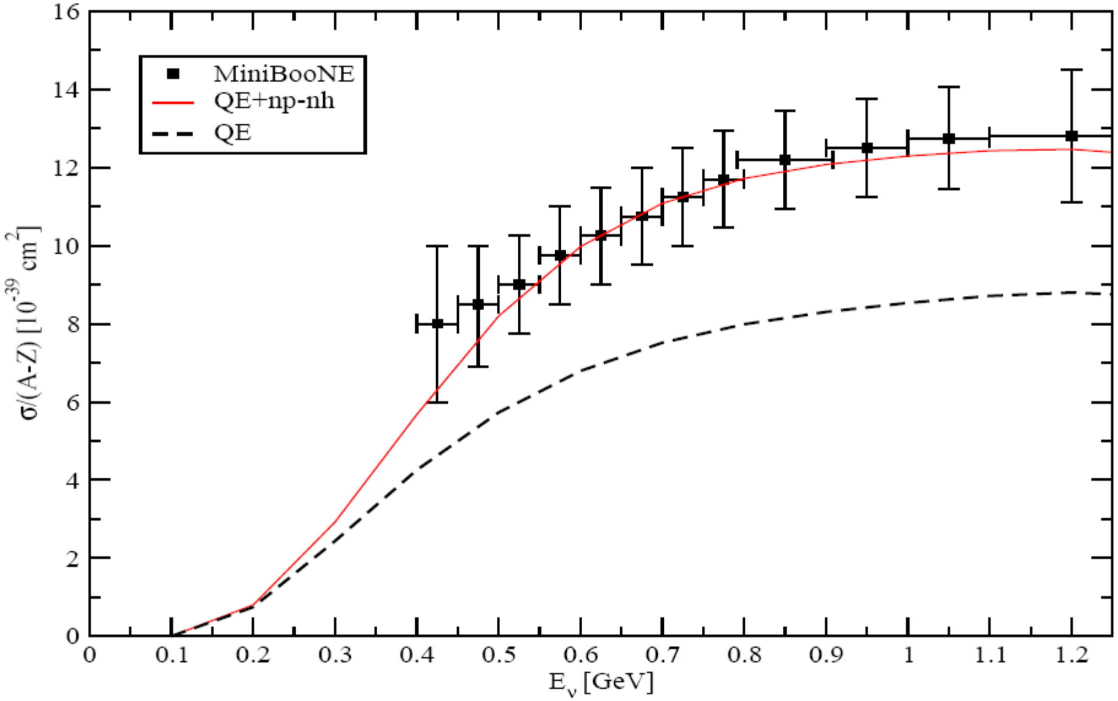
RMF: Relativistic Mean Field

GiBUU: Transport Equation

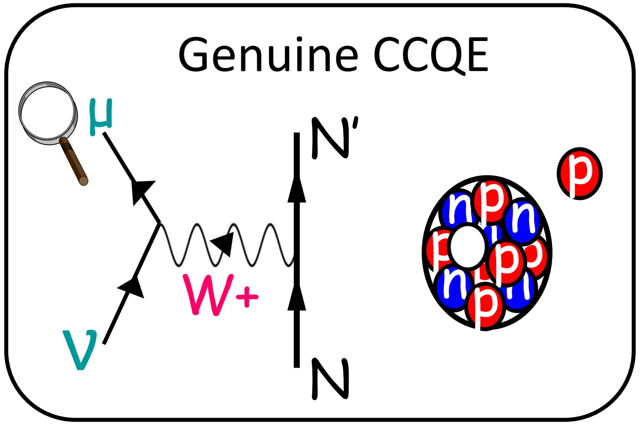
puzzle??

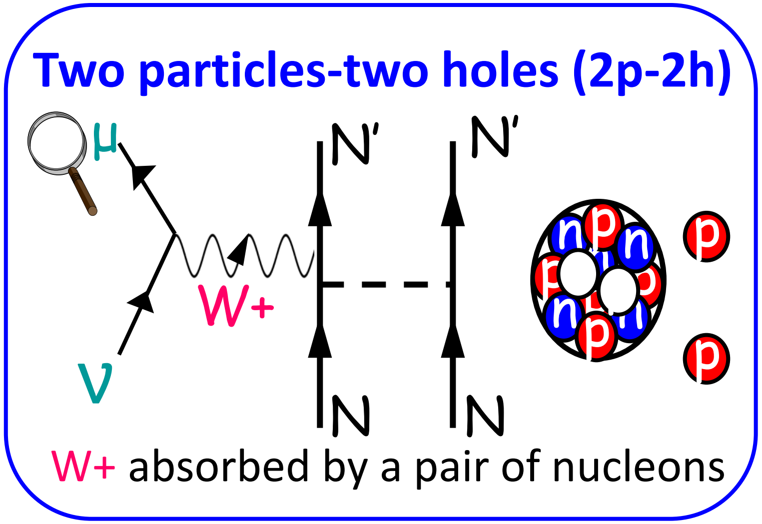
An explanation of this puzzle

Inclusion of the multinucleon emission channel (np-nh)



CCQE-like = Genuine CCQE + np-nh



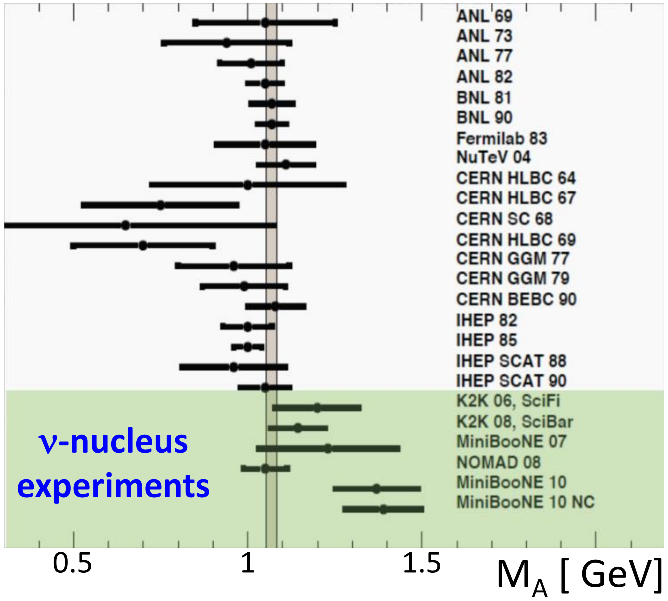


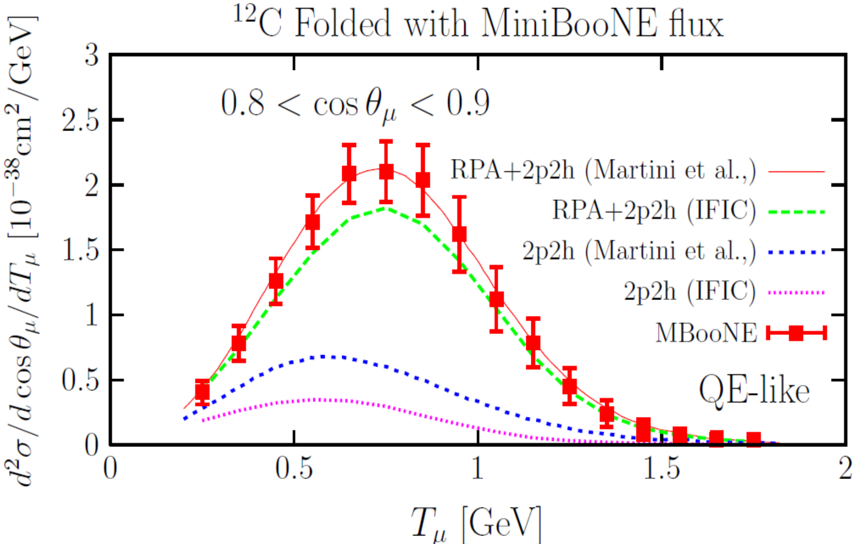
M. Martini, M. Ericson, G. Chanfray, J. Marteau [IPN Lyon], Phys. Rev. C 80 065501 (2009)

Agreement with MiniBooNE without increasing M_A

The multinucleon emission channel (or np-nh, or 2p-2h)

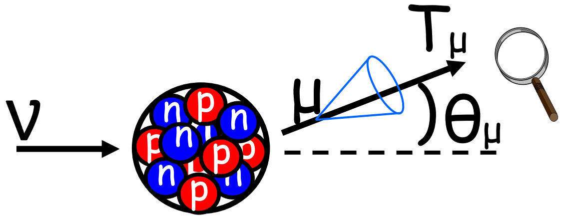
- A lot of interest in these last years
- Explanation of the axial mass puzzle
- It was not included in the generators used for the analyses of ν cross sections and oscillations experiments
- Today there is an effort to include this np-nh channel in several Monte Carlo
- Several theoretical calculations agree on its crucial role but there are some differences on the results obtained for this channel
- One of the most important source of the cross section uncertainties (systematic errors in oscillation experiments)

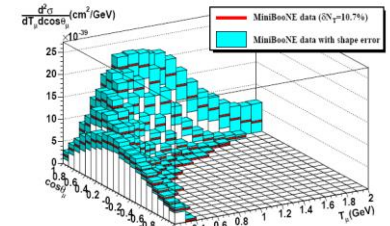




CCQE-like flux-integrated double differential cross section

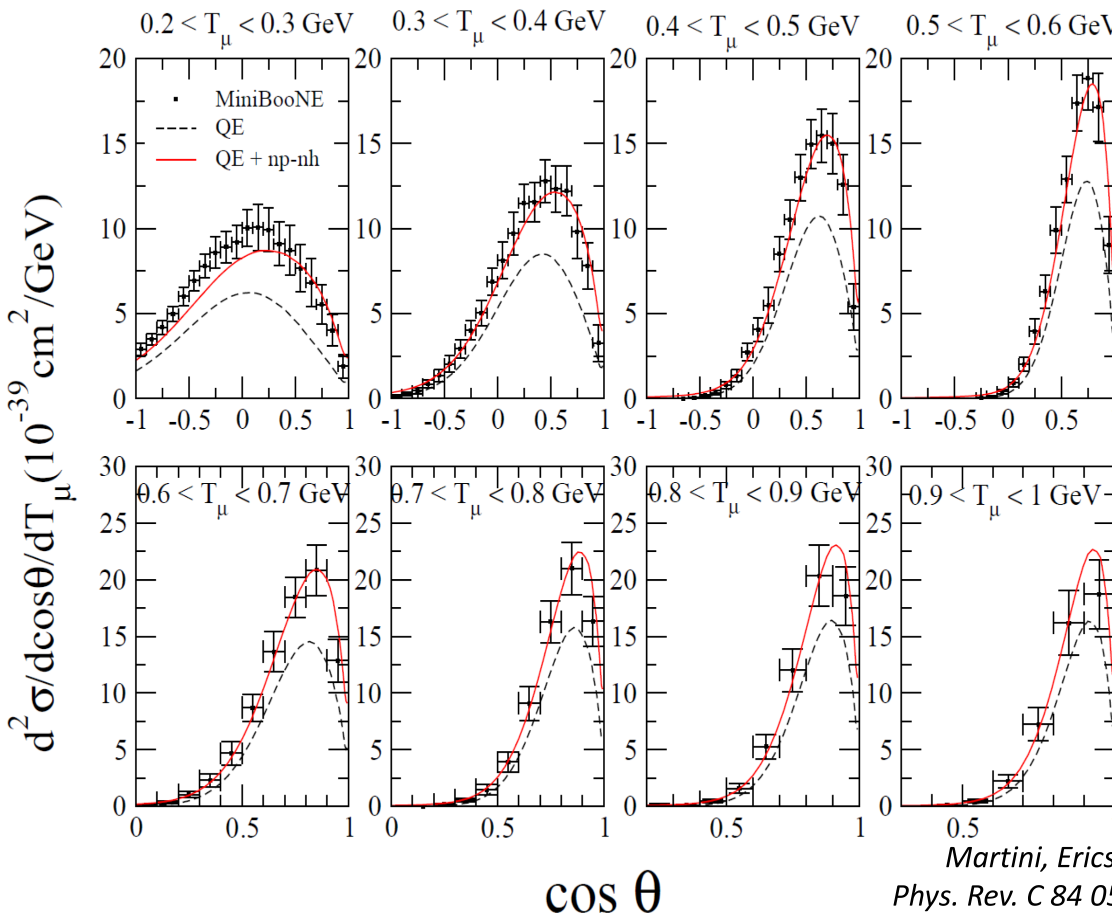
$$\frac{d^2\sigma}{dE_\mu d\cos\theta} = \int dE_\nu \left[\frac{d^2\sigma}{d\omega d\cos\theta}\right]_{\omega=E_\nu-E_\mu} \Phi(E_\nu)$$





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

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



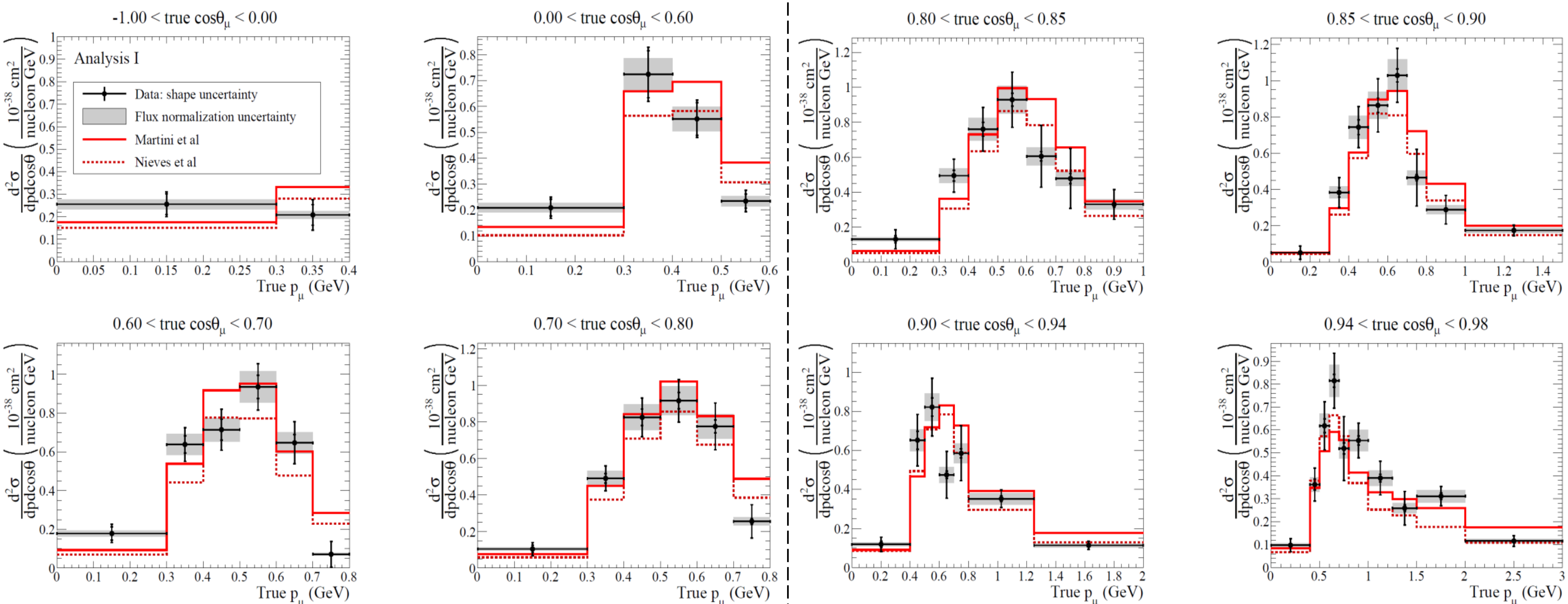
Martini, Ericson, Chanfray, Phys. Rev. C 84 055502 (2011)

Flux-integrated differential cross section is the point where theorists and experimentalists meet for neutrino interaction physics

A recent 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)

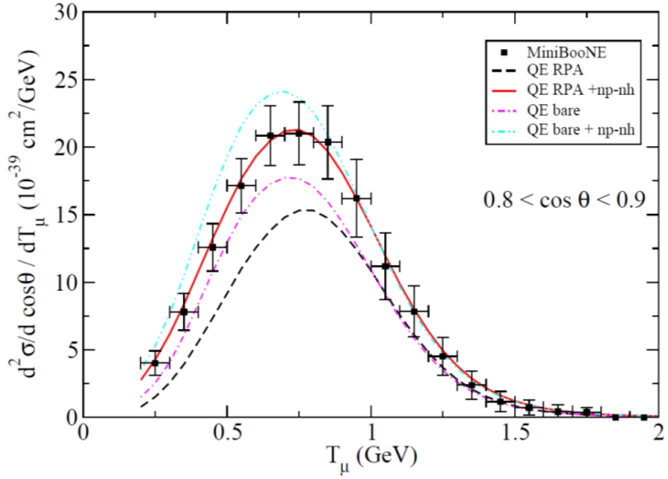


Martini et al.
Nieves et al.

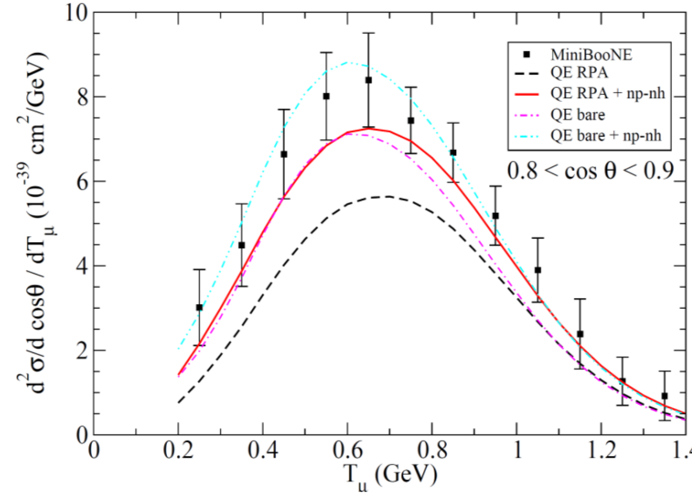
The two theoretical models including np-nh are compatible with data
at present level of experimental accuracy

ν $\bar{\nu}$

Martini et al.

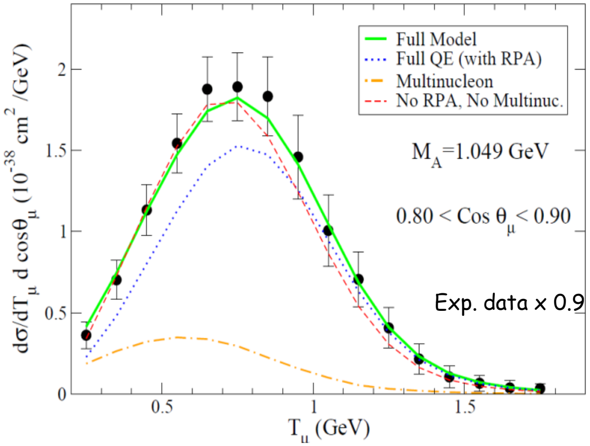


PRC 84 (2011)

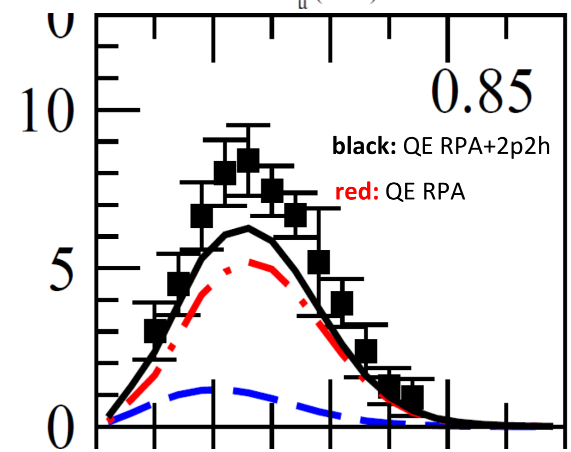


PRC 87 (2013)

Nieves et al.

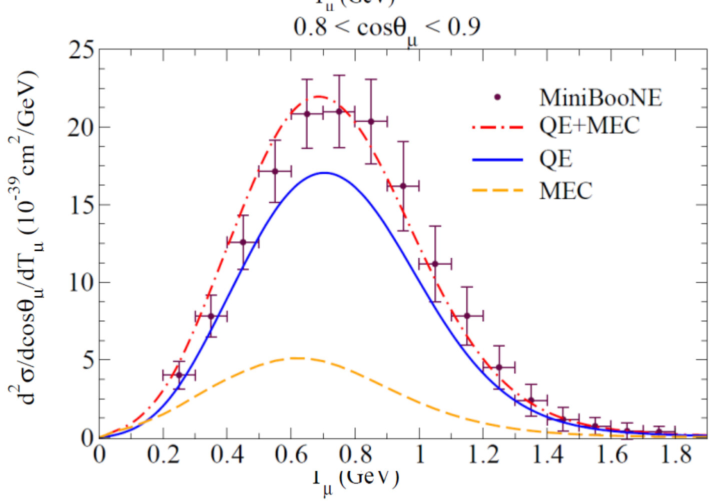


PLB 707 (2012)

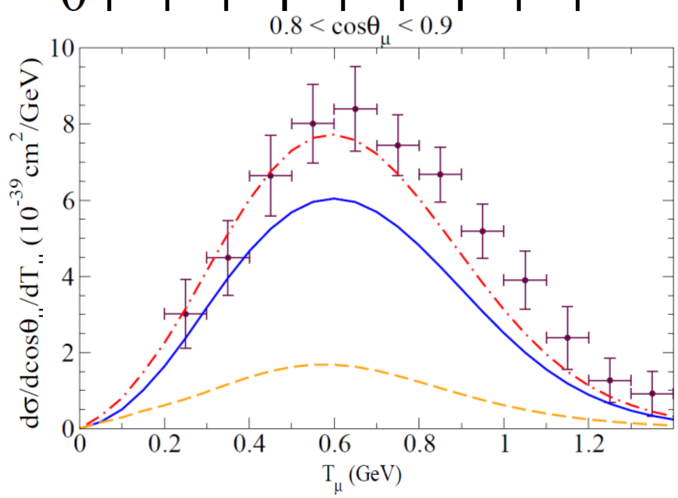


PLB 721 (2013)

Megias et al.



PRD 94 (2016)



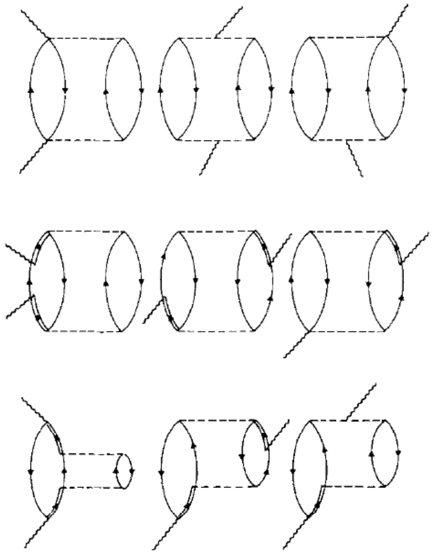
PRD 94 (2016)

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

Nuclear effects generate an asymmetry between ν and antiν which has to be fully mastered for CP violation experiments

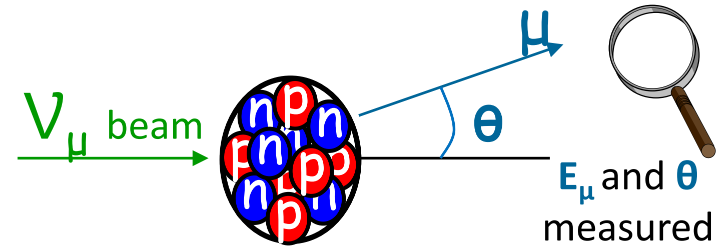
Neutrino energy reconstruction and neutrino oscillations

Reconstructed ν energy

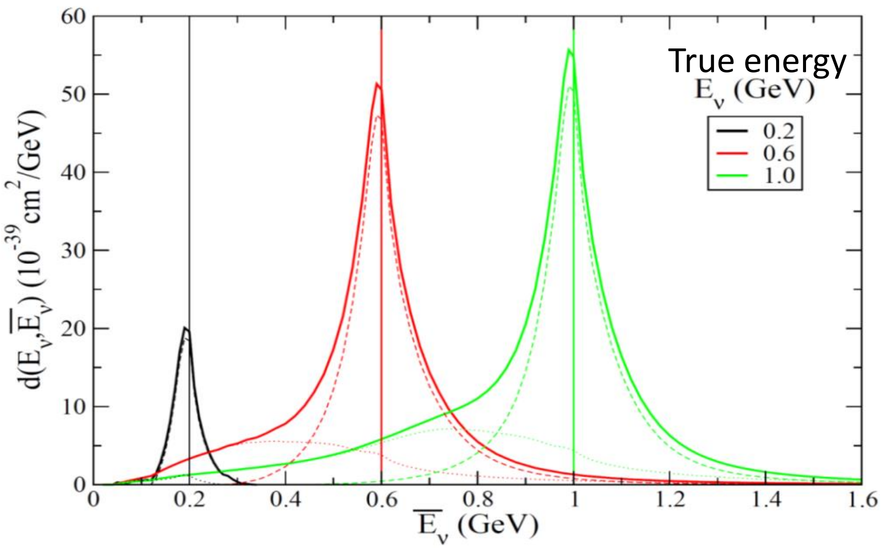
(via two-body kinematics)

$$\overline{E_\nu} = \frac{E_\mu - m_\mu^2/(2M)}{1 - (E_\mu - P_\mu \cos\theta)/M}$$

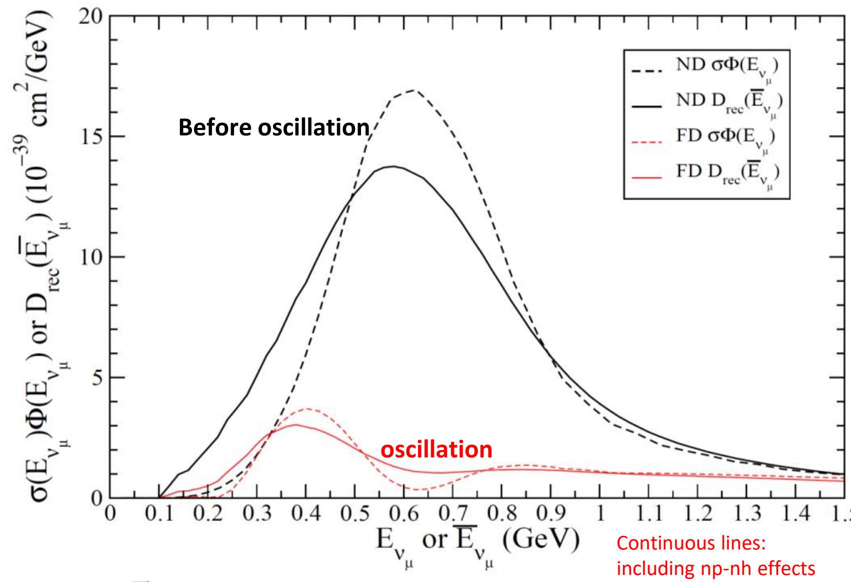
$\nu_\mu\, n \rightarrow \mu^- p$

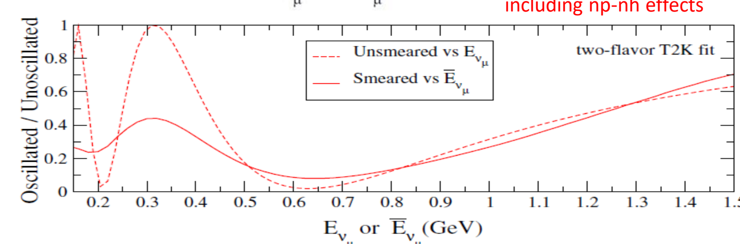


ν energy distribution



νμ disappearance T2K





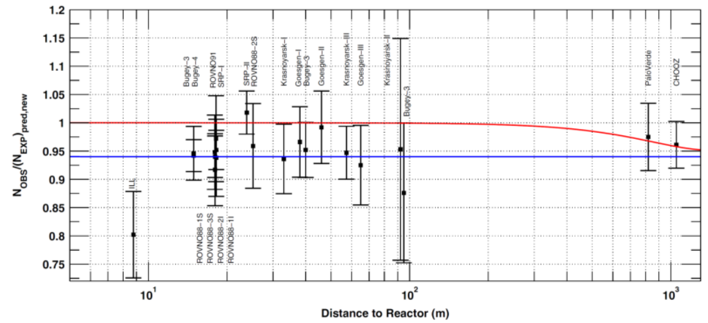
- Distributions not symmetrical around Eν
- Crucial role of np-nh: low energy tail

M. Martini, M. Ericson, G. Chanfray,
Phys. Rev. D 85 093012 (2012); Phys. Rev. D 87 013009 (2013)

Neutrino energy reconstruction and neutrino oscillation analysis are affected by np-nh

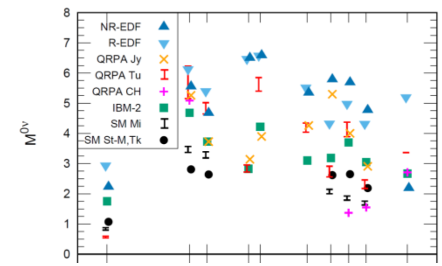
Summary and conclusions

- $\bar{\nu}$ Flux in reactor experiments



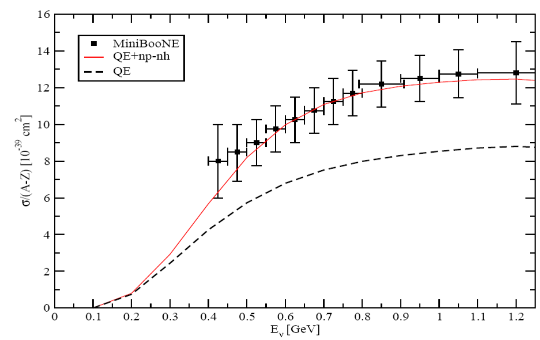
- Reactor anomalies or nuclear physics?
- Weak magnetism corrections and first forbidden transitions crucial in the β spectra of fission products

- Nuclear matrix elements for $0\nu\beta\beta$ decay



- Factors 2 or 3 of difference between different approaches
- If g_A is "renormalized" experiments are in trouble

- ν-nucleus cross sections in accelerator experiments



- Multinucleon excitations explain the M_A puzzle, are crucial to reproduce several cross sections but are difficult to treat
- Multinucleon excitations (previously ignored in the Monte Carlos) are one of the most important sources of systematic errors and affect the neutrino oscillation analyses

In the precision era of neutrino physics nuclear physics is "incontournable"

One recent review paper for each subject

- $\bar{\nu}$ Flux in reactor experiments

- Anna C. Hayes and Petr Vogel, *"Reactor Neutrino Spectra",* arXiv: 1605.02047

- Nuclear matrix elements for $0\nu\beta\beta$ decay

- Jonathan Engel and Javier Menéndez, *"Status and Future of Nuclear Matrix Elements for Neutrinoless Double-Beta Decay: A Review",* arXiv: 1610.06548

- ν-nucleus cross sections in accelerator experiments

- Teppei Katori and Marco Martini, *"Neutrino-Nucleus Cross Sections for Oscillations Experiments",* arXiv: 1611.07770