NUINT2017
a very personal summary

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The Impossible Experiment

- Beam composition not fully known
- Beam energy badly known
- Beam diameter ~ 1 m at its source
- Beamline ~ 300 – 1300 km
- Beam diameter ~ 1 km at the detector
- Cross sections ~ 10^{-11} mb
- Only a small part of the final state known
- From all of this:

extract physics beyond the standard model!

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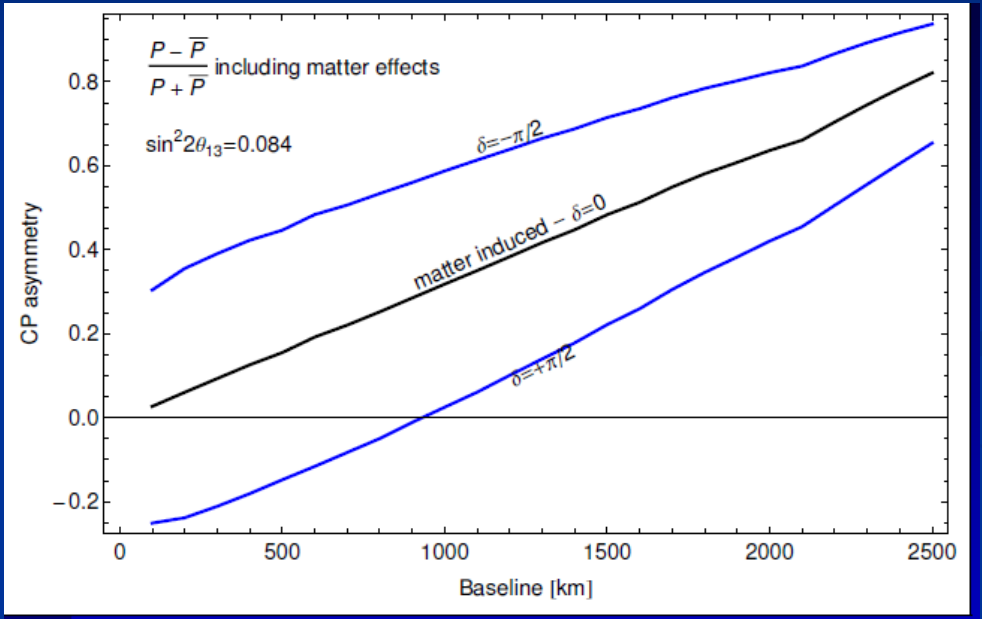
Oscillation Signal

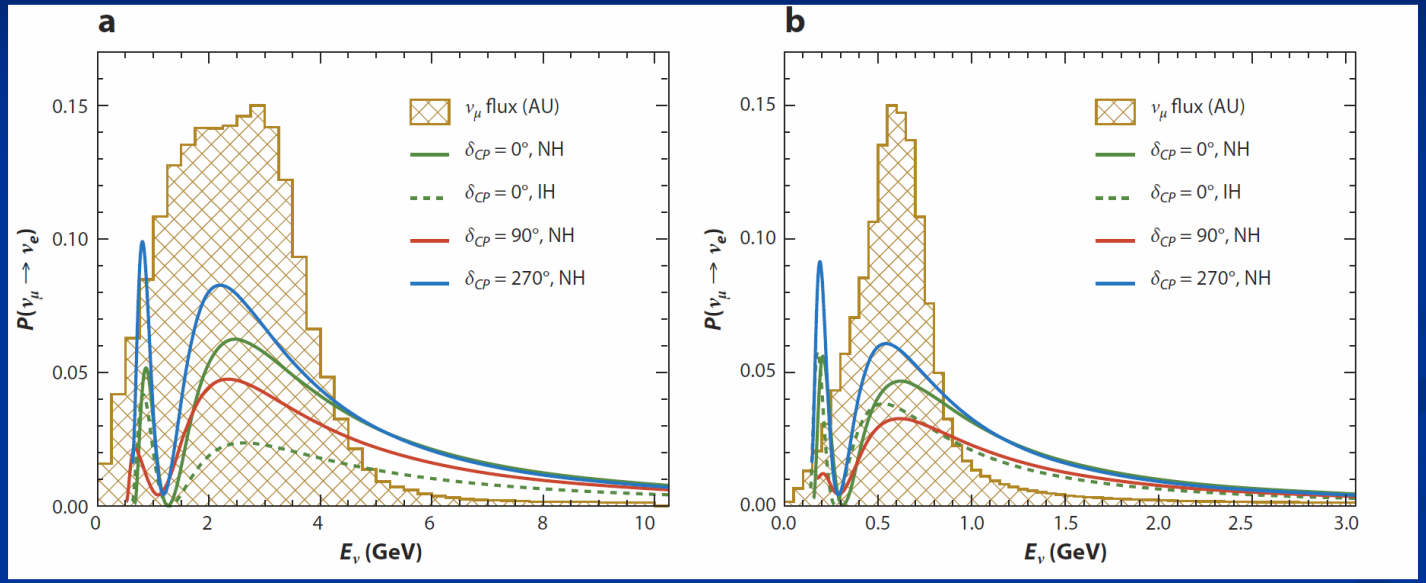


P. Huber

For baselines below 1500 km, the genuine CP asymmetry is at most $\pm 25\%$

For 75% of the parameter space in δ, the genuine CP asymmetry is as small as $\pm 5\%$

Oscillation Signals as $F(E_\nu)$



From:
Diwan et al,
Ann. Rev.
Nucl. Part. Sci 66
(2016)

DUNE, 1300 km

HyperK (T2K) 295 km

Energies have to be known within 100 MeV (DUNE) or 50 MeV (T2K)

Ratios of event rates to about 10%

Neutrino-Nucleus Interactions two aims

- ‚Fundamental': interest in response of nuclei to electroweak interactions
  ➔ Inclusive X-sections sufficient (for a start)
  Methods: GFMC, SF, Scaling
- ‚Practical': Oscillation experiments need control of energy reconstruction
  ➔ Full event description needed, inclusive is not enough!
  Methods: Generators

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Fundamentals

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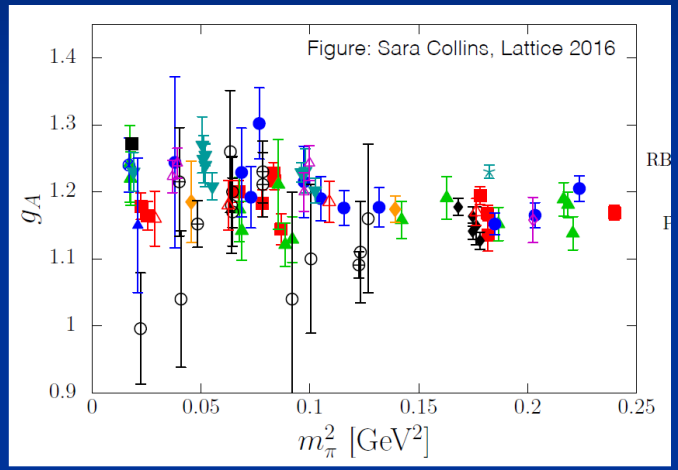
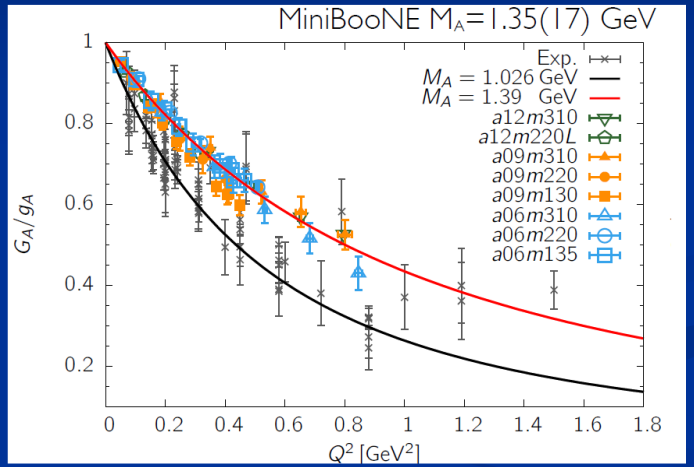
Axial Props from Lattice

„All they do is calculate masses of hadrons that we know anyway“ (Harry Lipkin)





Phiala Shannahan

No longer true!

Lattice gives M_A ~ 1.3 GeV, still in constrast to data

Lattice has come a long way and still has to go some way to come to the true experimental numbers. Theory can never replace a good experiment

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From Quarks to Nucleons

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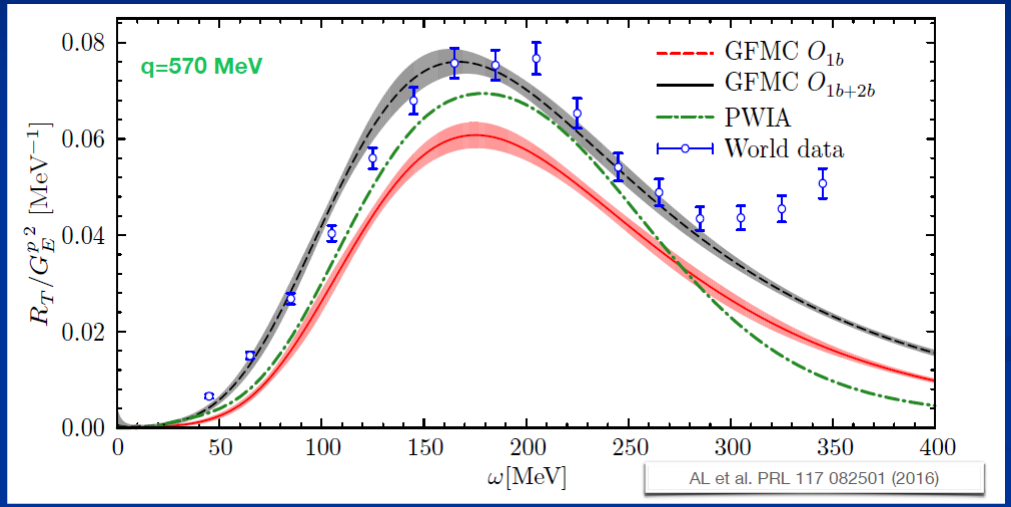
Nuclear Many Body Theory

electromagnetic response Lovato, Carlson



Calculations done in Euclidean time, but neutrino event evolution needs real time

Impressive agreement up to QE peak, then probably overestimate because of Delta tails

Nuclear Many-Body Theory and Neutrino Physics

- NMBT gives the best possible info on nuclear many-body responses, ab initio
- Generators can be tuned with NMBT results
- but they also can be tuned with experiment

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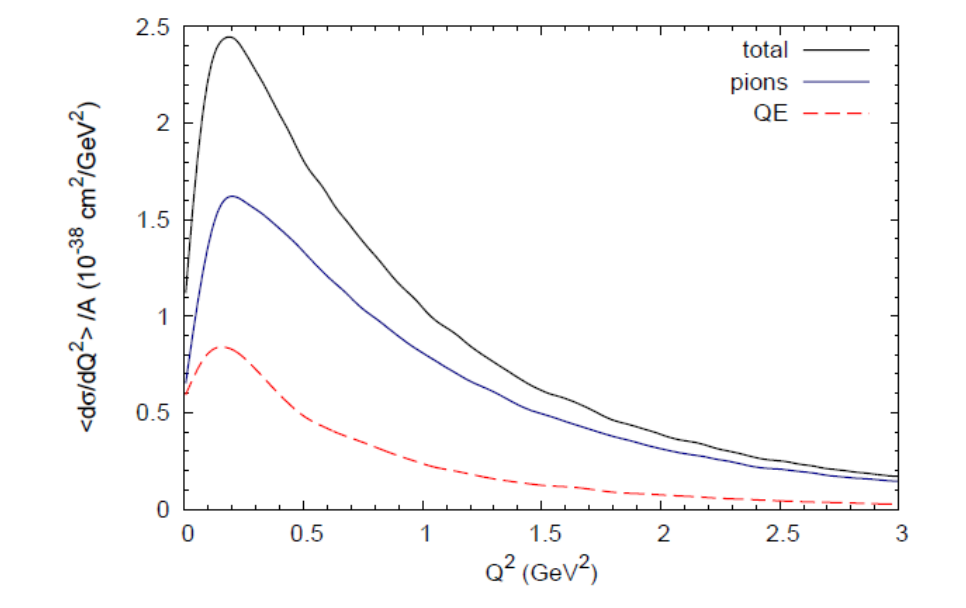
Now to the Practical (less fundamental)

- Two observations:
  - Nuclei are bound (not all theories/generators have that)
  - At MINERvA/DUNE all processes, QE + 2p2h+N*+DIS contribute in the same nucleus (not all generators have that)

The Grand Picture



DUNE beam

Pions (from resonances and DIS) dominate (2/3),
QE (true QE and 2p2h) smaller (1/3), at T2K the ratios are interchanged

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QE

- Consistent framework for QE with line of improvements
  1. Relativistic global Fermi Gas
  2. Relativistic local Fermi Gas
  3. Semiclassical nuclear binding
  4. Spectral Functions
  5. Ab initio weak response of nuclei
- QE data can never be better than understanding of pion production, QE is always mixed with other processes, even at the QE peak

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Nuclei are bound!

- Trivial, but often forgotten in generators
- Even if you some final state interactions for the initial state (NuWro), you better have the same potential also for the outgoing particles!
  Mechanics 101:
  steps in a potential lead to infinite forces.

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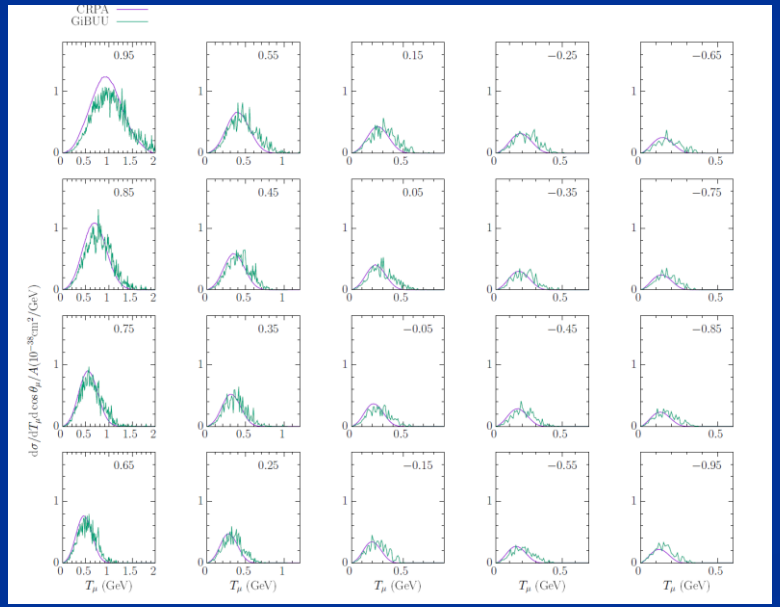
Binding Potentials from HF or from EDF

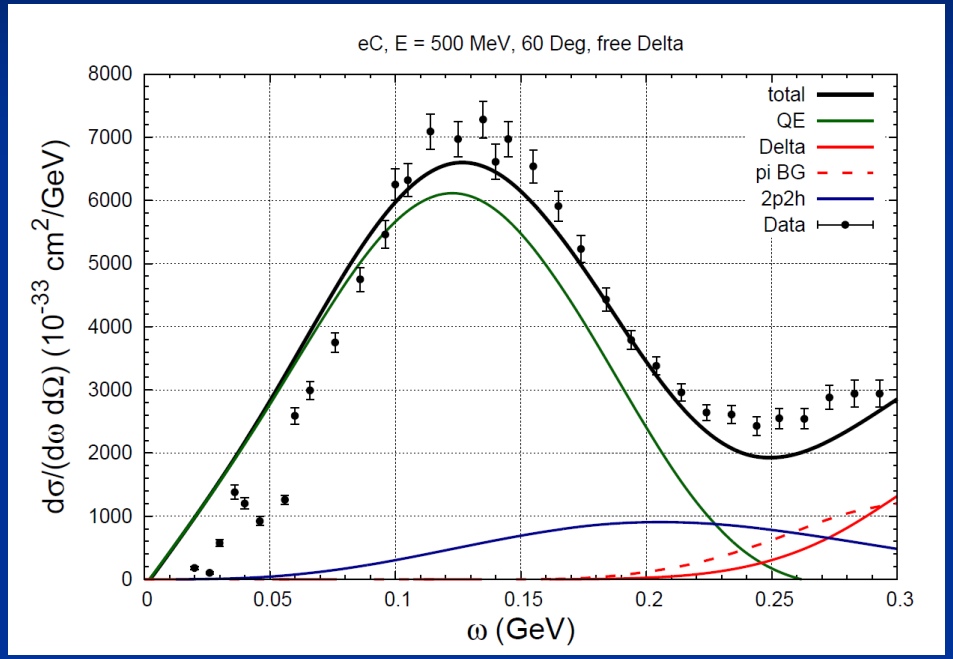
- Ghent group did the first HF calculation for neutrino reactions, build RPA on top of that. Excellent agreement with GiBUU for QE in full kinematical range for Ar40 in BNB flux => robust prediction for QE



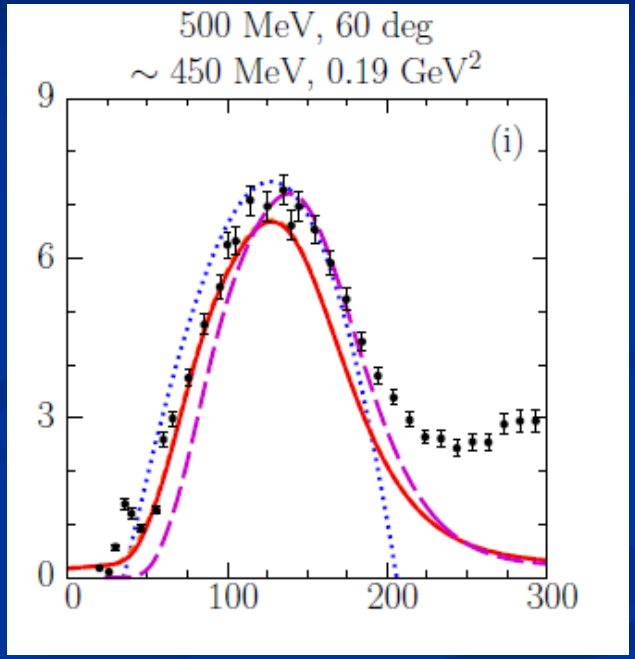
Nils van Dessel, Natalie Jachowicz, et al

Mean field potentials can be very good
Nuclear structure theory relies on them

Test with Electron Data: : QE + Res

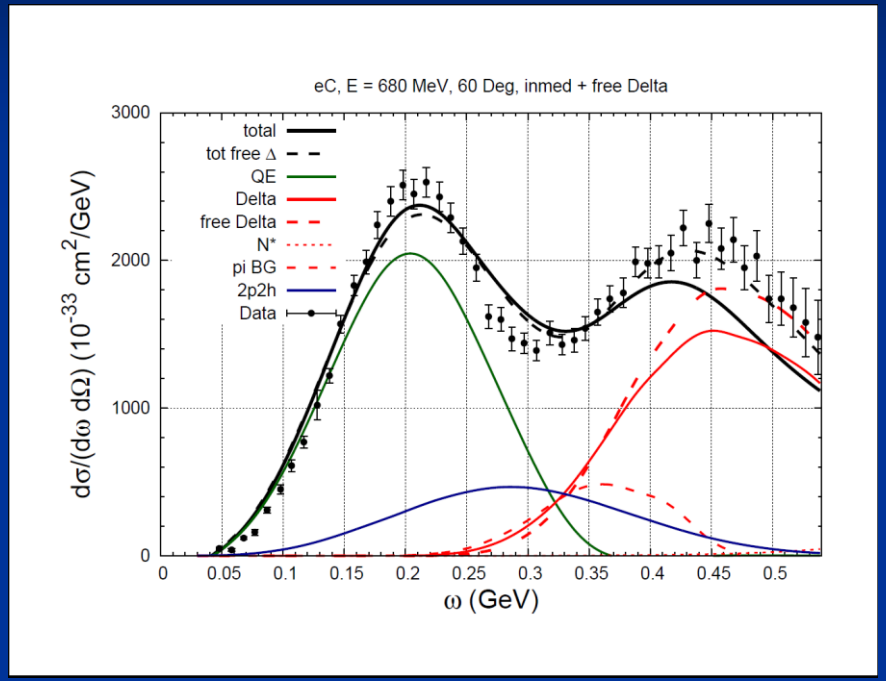


GiBUU 2016

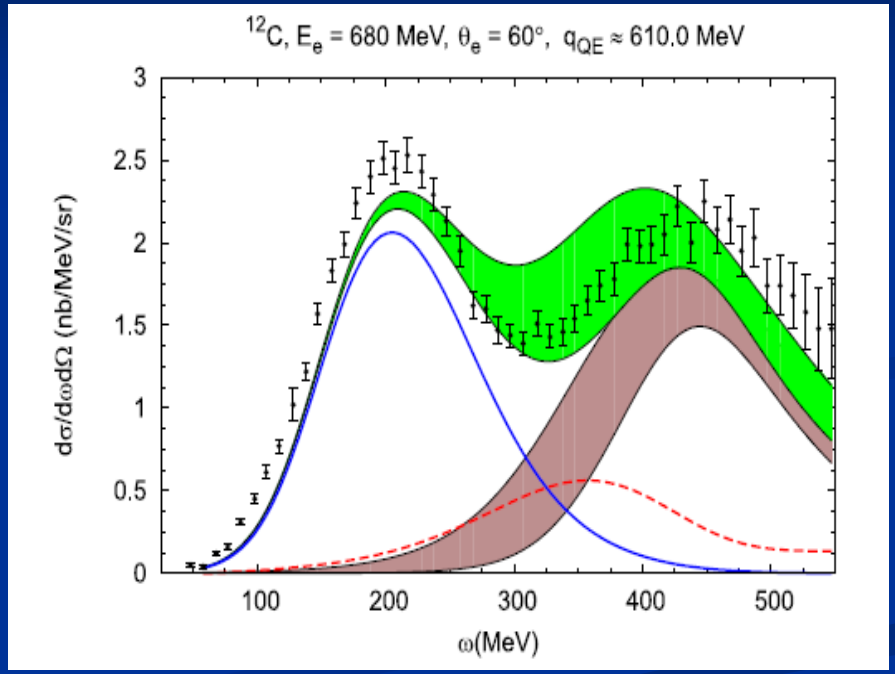


Ankowski. Benhar, Sakuta

Test with Electron Data : QE + Res



GiBUU



Scaling: M.V. Ivanov et al, J.Phys. G43 (2016) 045101

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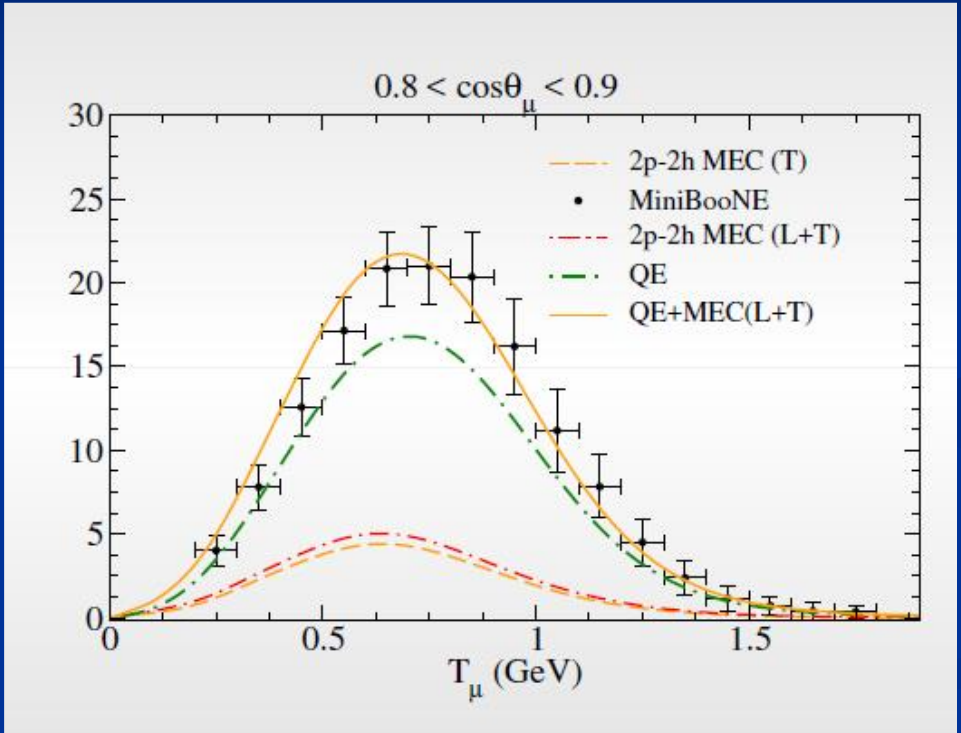
Scaling + 2p2h

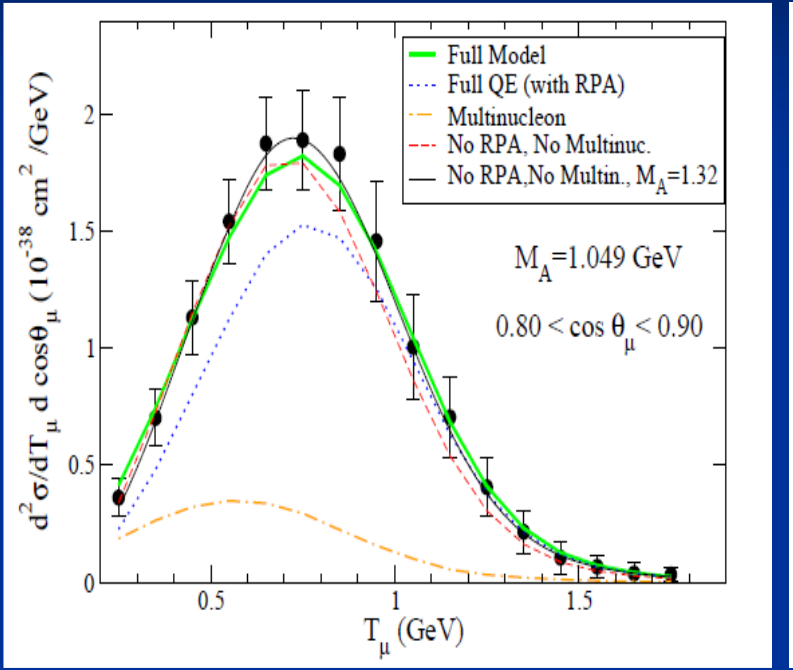


J. Caballero:
SUSAv2 for QE
2p2h from microscopic calculation: note that it is nearly perfectly transverse (as assumed in GiBUU)

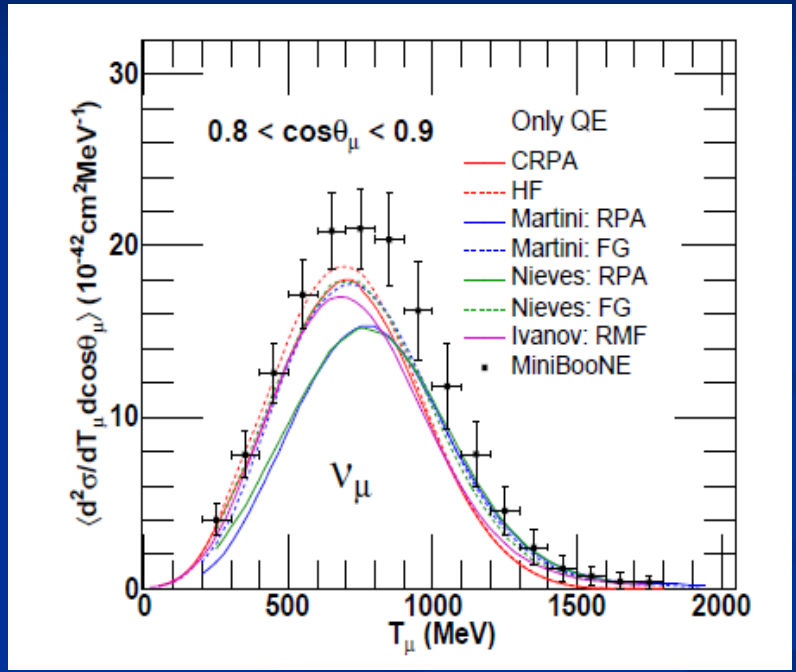
RPA: essential or not so essential?

- A first (trivial) property of nuclei:
  They are bound
- But:
  - none of the generator nuclei are bound
  - the Martini/Nieves nuclei are not bound
- If nucleons are bound in a potential well, then RPA correlations are much less essential
  (but play a role at small Q^2)

RPA: essential or not so essential?



Nieves



Pandey, Jachowicz

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2p2h: Achievements and Problems

- Big achievement: microscopic calculations for 2p2h processes now available and feasible (Ruiz-Simo et al, Caballero et al)
- Open Problems:
  - All calculations restricted to Δ-resonance regime, good for T2K, but not for MINERvA, DUNE
  - Calculations work in free Fermi gas basis: no binding!
- Way out for higher energies:
  empirical analyses of electron-data?!

Pion Production

- Consistent Framework for Pion Production
  1. Elementary production, needs weak formfactors
  2. Nuclear production, based on impulse approximation
  3. Problem: *t*-channel background processes
  4. Problem: *t*-channel background for 2 pi production
  5. Multipion through higher resonances (SIS) and DIS

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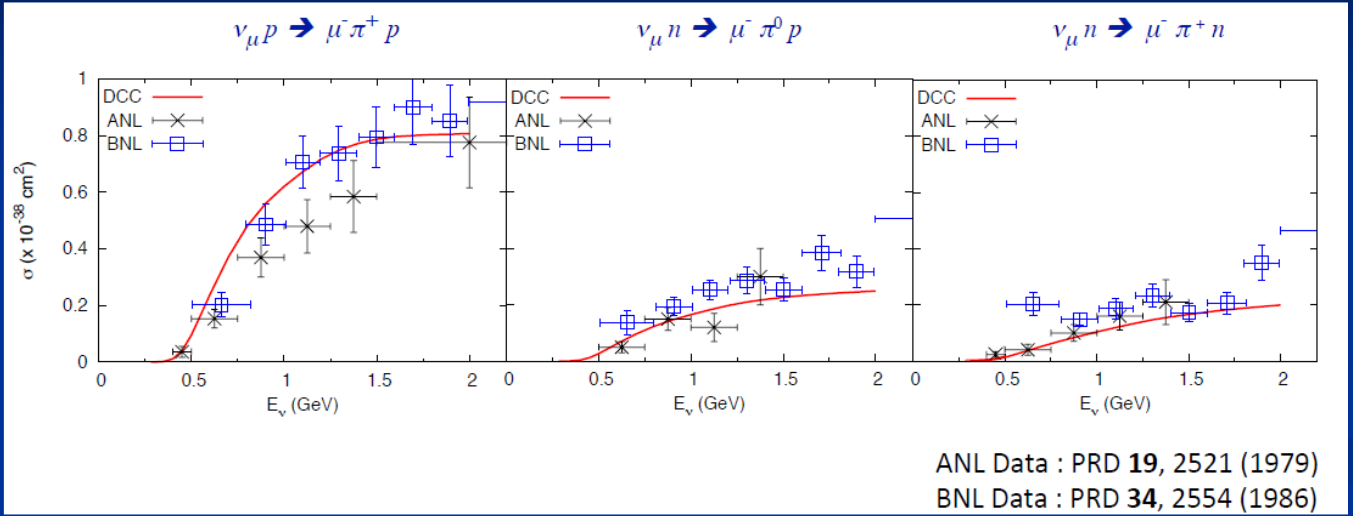
Pion Production

- At treshold: A. Hiller-Blin gets excellent description of photo-pion data when including the Delta (instead of summing higher and higher order in chiPT): obviously got the right physical degrees of freedom
- In resonance regime: Satoshi Nakamura has full coupled-channel calculation, consistent for electromagnetic and weak excitations
- And for higher excitations Athar and Sing have a theory for calculating strange particle production!

Pion Production in Resonance Region



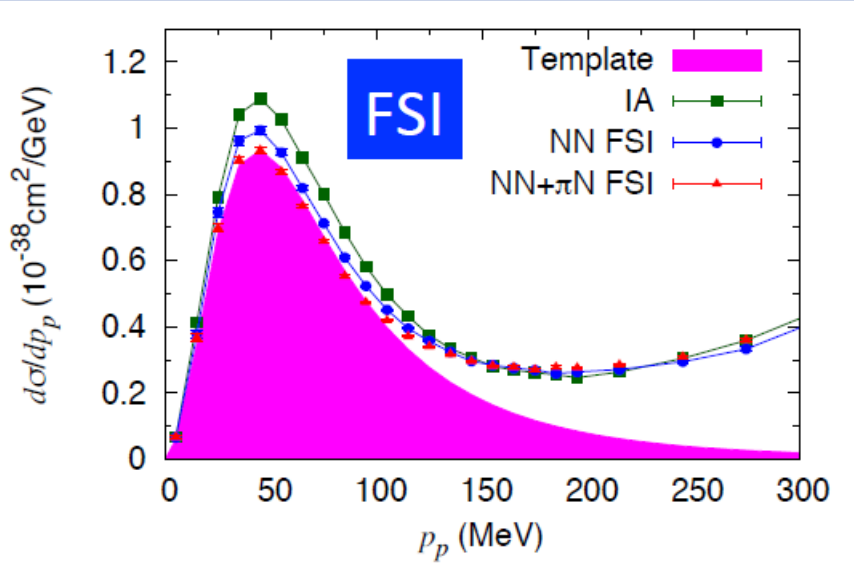
S. Nakamura

Intriguing puzzle:

1. pi+ data on p agree better with (old) Brookhaven data
2. Reasonable description of nu n -> pi+ data

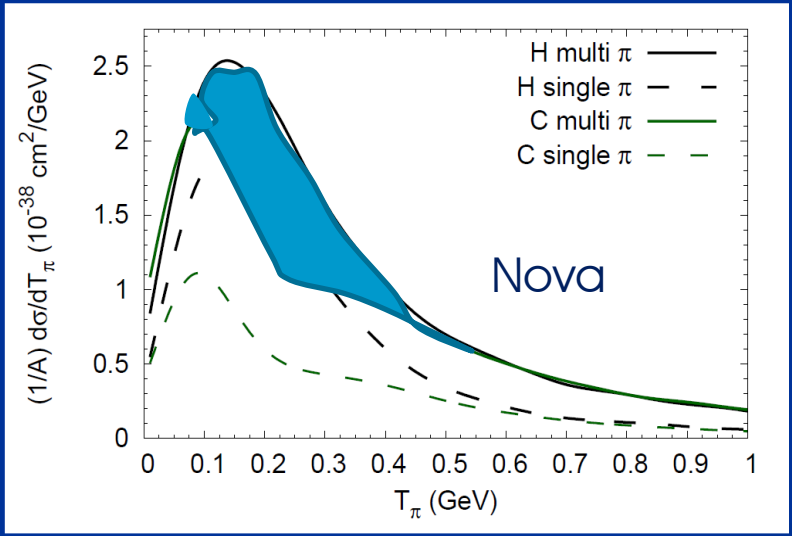
Pion Production in Resonance Region

- S. Nakamura attacked one nagging, important problem: to get nucleon data from Deuterium targets: the standard Fermi-motion folding method underestimates X-section by about 10-15%. Should we increase the ANL X-sections in the generators by that amount?



FSI on pions

- A truism: pions experience strong final state interactions (limits any plane wave attempts)



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Generator Resistance against Nuclear Theory

- Generators still use Rein-Sehgal! Even in new developments (Kabirnezhad -> NEUT)
- Nobody else in Nuclear Physics uses RS for resonances!
- Generators have been told this over and over again: no consequence!
- There is now perfect theory:
  CC analysis Nakamura, Sato et al.
- If too complicated: use MAID phenomenological analysis

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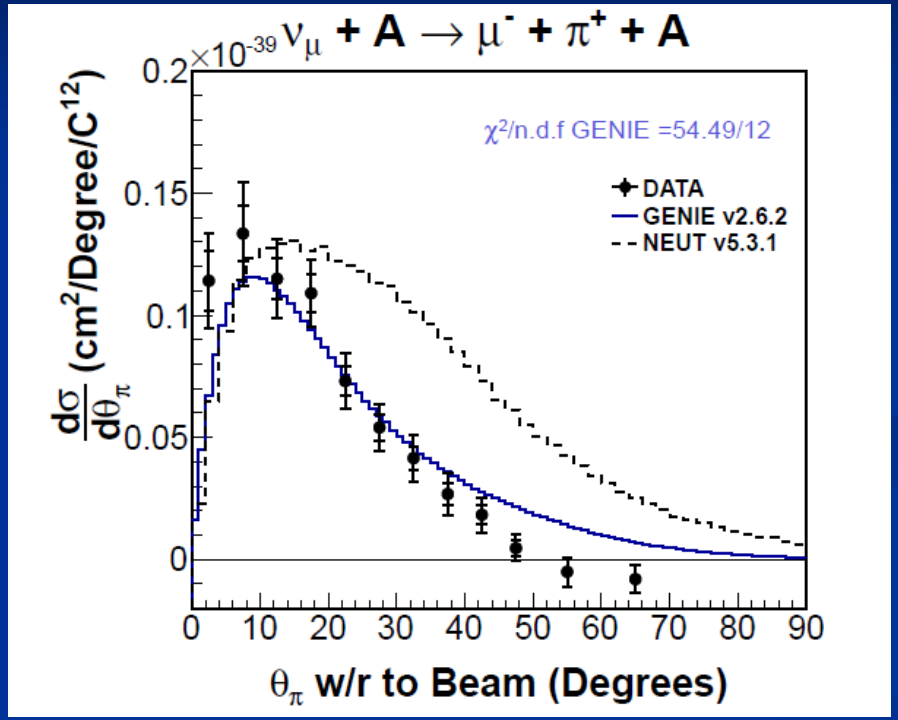
Coherent Pion Production



MINERvA data

2 very different curves from the very same theory (Rein-Sehgal)

Even in Delta region no consensus: static propagator (Alvarez-Ruso) vs dynamic theory (Praet, Leitner, Nakamura)

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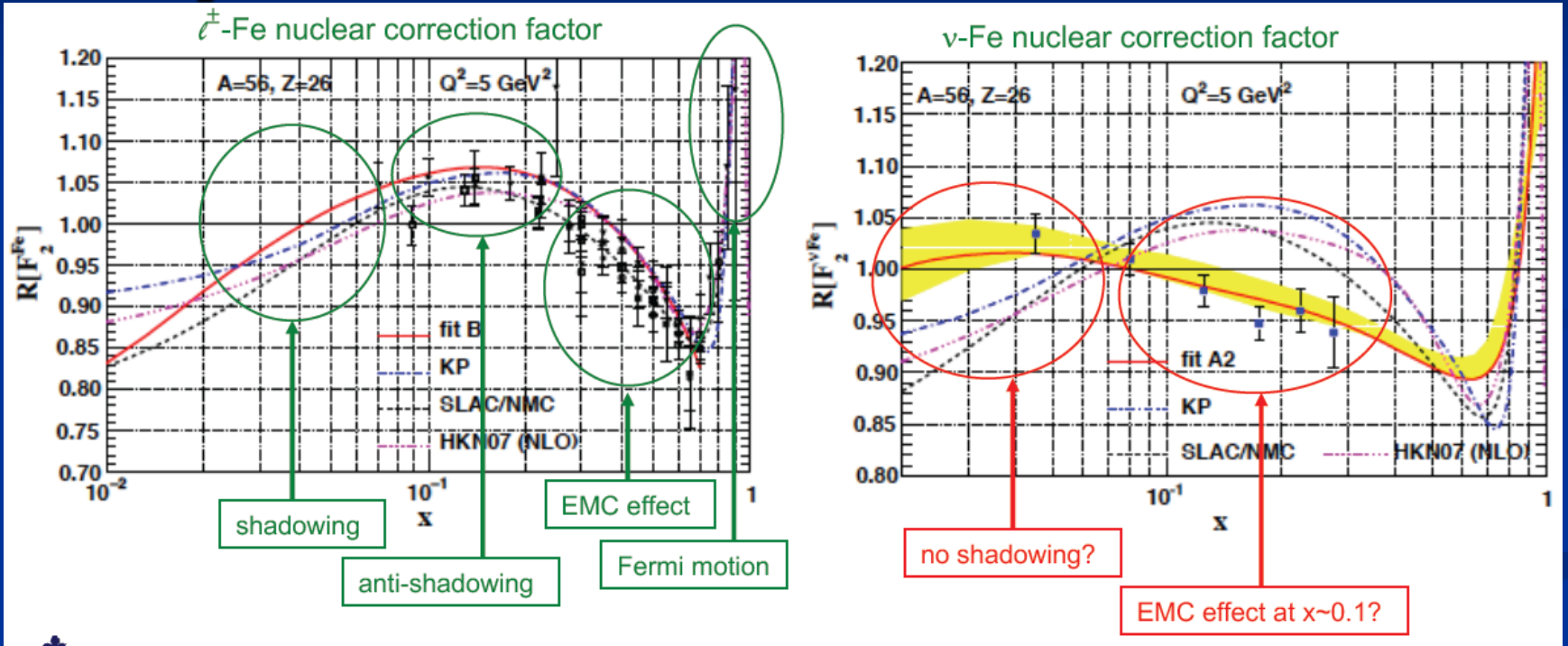
The BIG PROBLEM: Why are neutrinos not shadowed?



DIS Puzzle

- Nuclear structure functions do depend on nuclear medium: EMC theory has still not converged, but first hints now that electromagnetic and weak responses are different (Haider)

- One essential difference between e- and ν-scattering: x has to be reconstructed for ν!

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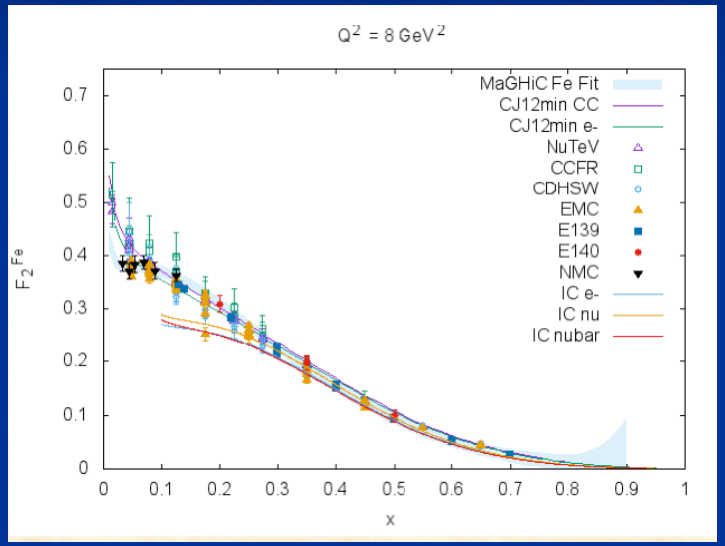
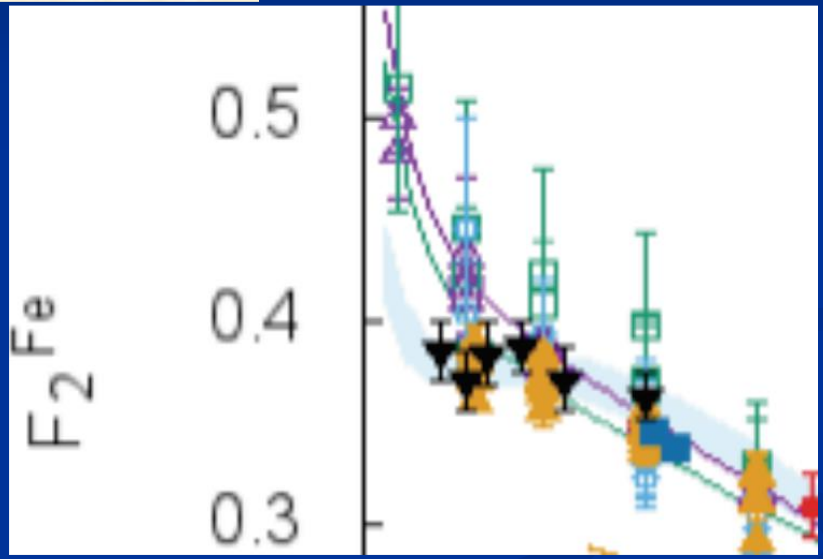
DIS Puzzle

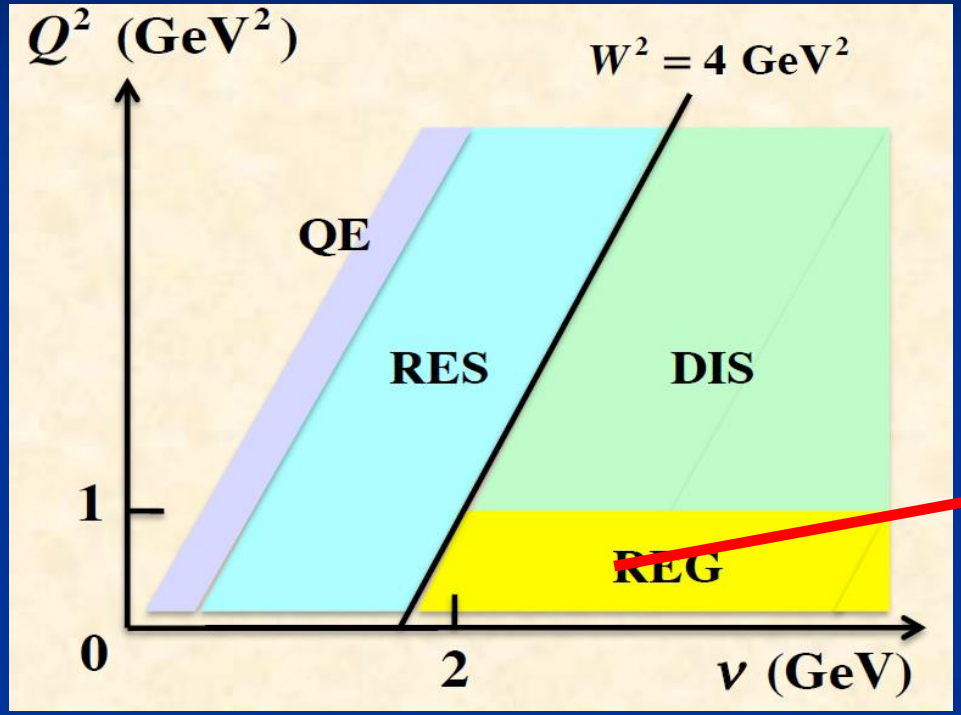
N. Kalantarians, E. Christy, and C. Keppel,
arXiv:1706.02002



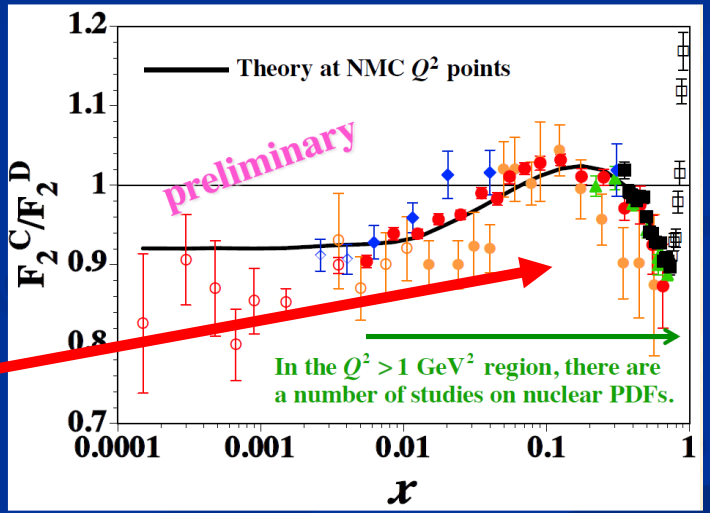


How good is x-reconstruction???

High nonDIS Excitations



$$F_2(x,Q^2) = w(x,Q^2;x_0,Q_0^2)F_2(x_0,Q_0^2)$$



not a nuclear phenomenon

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Practical Theory

- Generators are absolutely essential!
  The best exp. Equipment is useless without them.
- Generators thus have to be as good as your latest Ar40 detector ➔ this needs scientific brains + money
- Generators need state-of-the-art nuclear theory

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Practical Theory

- Inclusives Dilemma:
  1. „Best possible“ theory for inclusives is about 25 years old, J. Nieves reminded us of that when reading from the old Valencia papers
  2. The best, most modern theory (GFMC e.g.) is still not applicable to actual neutrino experiments.
- Then let us get at least the „best possible“ theory into the generators.

Practical Theory

- Exclusives have no Dilemma:
  - Full final state evolution can (and must) be done with state-of-the-art: Quantum-kinetic transport (well established in other fields of physics and even in nuclear physics (QGP).
- As for any old car there comes a time when further repairs and patches no longer are efficient in terms of time and money and a new car has to be bought!

Requirements for a good generator

- A good generator with potential for predictions in a new target/energy regime must be based on nuclear theory, consistent for all processes, must not be a patchwork of different recipes. Danger of separately tuning ‚linked parameters‘
- A good generator must be open and well documented in
  - its physics content
  - its numerical algorithms
- The DUNE generator must undergo the same scrutiny by experts as the hardware (technical reviews, design repts)

Theorist's Need

- Theorists need to be loved. Need:
  - Recognition (proper citations)
    - Experimenters that actually read and discuss their papers
  - Lively discussion culture
    (with other theorists and experimenters)
    - Challenges and Critical Feedback (from experimenters). Need to write papers differently: point out difficulties in describing data. Do not immediately tune all problems away.
  - Money (grant support)

THE END

- Thanks to the organizers:
  - my first longer-term experience of Toronto
  - a week full of physics that led me to ask many questions