FACULTY
OF SCIENCES

DEPARTMENT OF PHYSICS AND ASTRONOMY

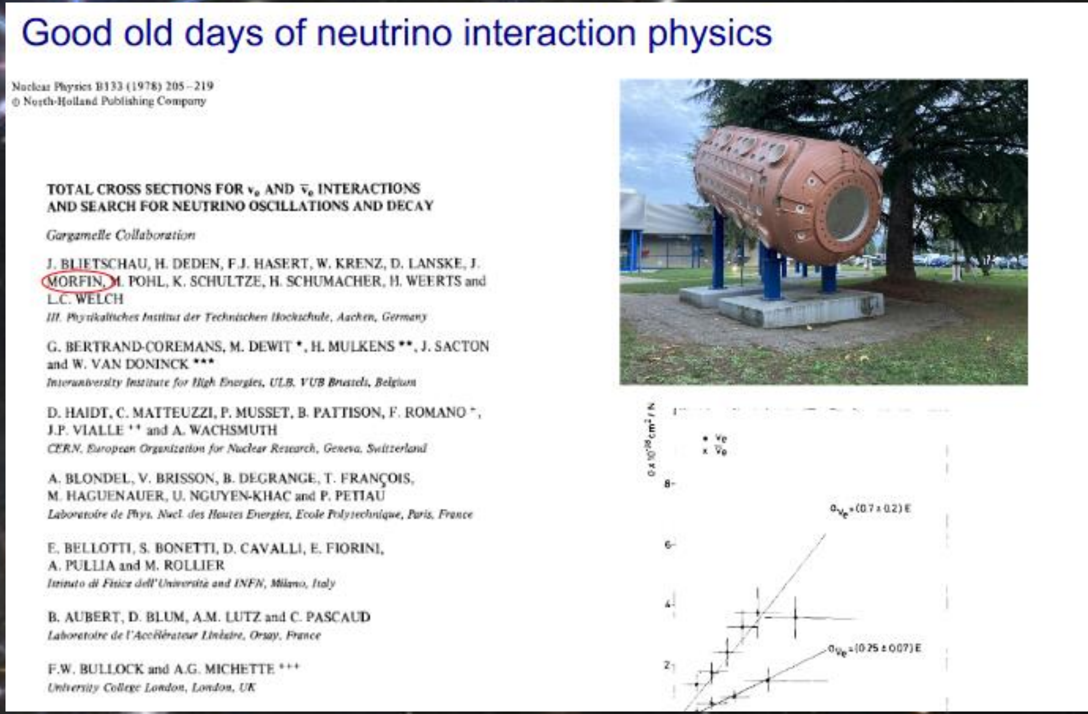
NuInt2022 : Theory summary and prospects

Natalie Jachowicz

GHENT
UNIVERSITY

Where do we come from ?

- Neutrino-nucleon/us interactions have been studied since the '70s



Nuclear Physics B133 (1978) 205 – 219
© North-Holland Publishing Company

TOTAL CROSS SECTIONS FOR ν_e AND $\bar{\nu}_e$ INTERACTIONS AND SEARCH FOR NEUTRINO OSCILLATIONS AND DECAY

Gargamelle Collaboration

J. BLIETSCHAU, H. DEDEN, F.J. HASERT, W. KRENZ, D. LANSKE, J. MORFIN, M. POHL, K. SCHULTZE, H. SCHUMACHER, H. WEERTS and L.C. WELCH
III. Physikalisches Institut der Technischen Hochschule, Aachen, Germany

G. BERTRAND-COREMANS, M. DEWIT *, H. MULKENS **, J. SACTON and W. VAN DONINCK ***
Interuniversity Institute for High Energies, ULB, VUB Brussels, Belgium

D. HAIDT, C. MATTEUZZI, P. MUSSET, B. PATTISON, F. ROMANO +, J.P. VIALLE ++ and A. WACHSMUTH
CERN, European Organization for Nuclear Research, Geneva, Switzerland

A. BLONDEL, V. BRISSON, B. DEGRANGE, T. FRANÇOIS, M. HAGUENAUER, U. NGUYEN-KHAC and P. PETIAU
Laboratoire de Phys. Nucl. des Hautes Energies, Ecole Polytechnique, Paris, France

E. BELLOTTI, S. BONETTI, D. CAVALLI, E. FIORINI, A. PULLIA and M. ROLLIER
Istituto di Fisica dell'Università and INFN, Milano, Italy

B. AUBERT, D. BLUM, A.M. LUTZ and C. PASCAUD
Laboratoire de l'Accélérateur Linéaire, Orsay, France

F.W. BULLOCK and A.G. MICHETTE +++
University College London, London, UK

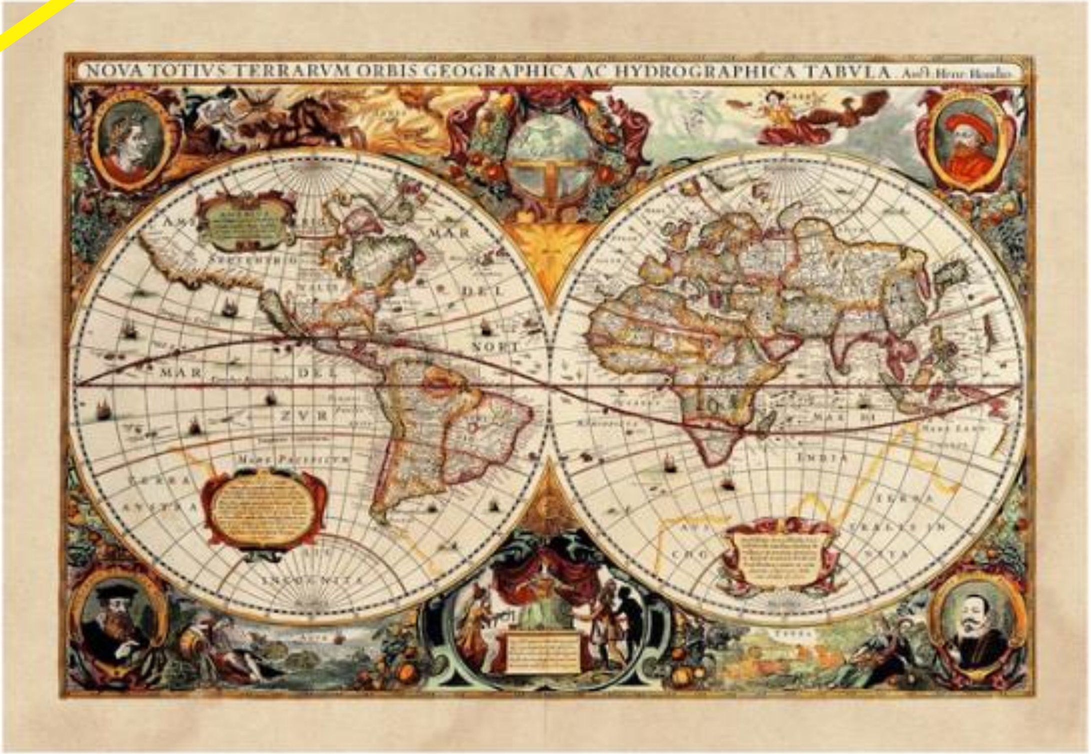
Teppei Katori's tal

- We have learnt a lot

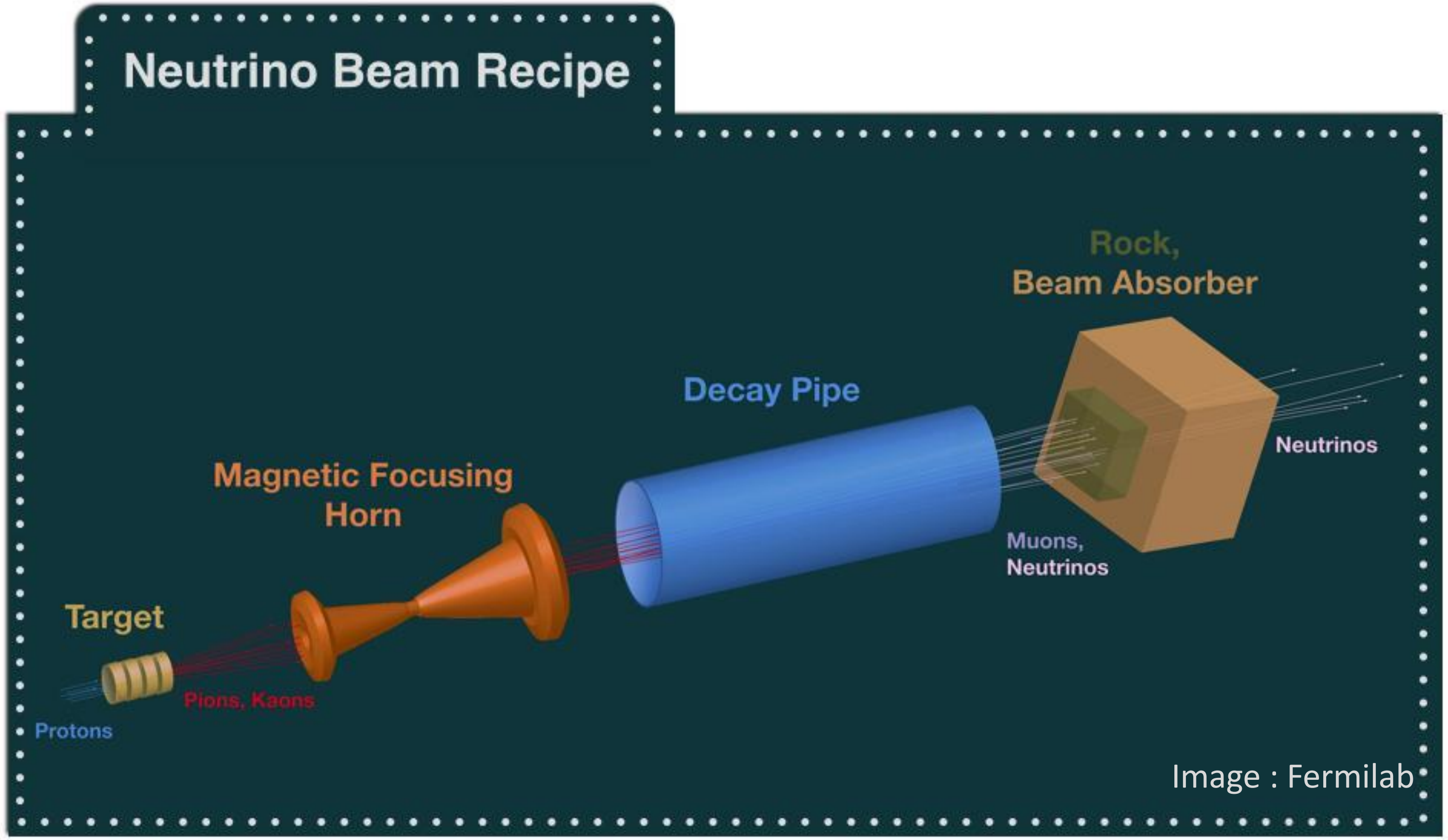
- The more we went into detail, the more we realized that a lot is not understood yet !

Where are we now ?

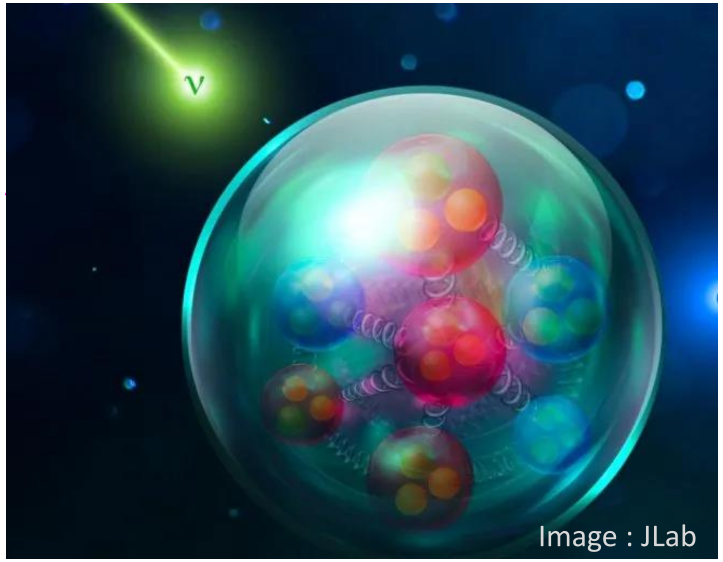
* All in all, the present knowledge of neutrino interactions appears to be still comparable to the knowledge of the geography of North America around 1650



Omar Benhar‘s Talk



- A detailed understanding of neutrino-nucleus interaction is pivotal for the accuracy of accelerator-based oscillation studies
- Near detector studies of neutrino cross sections provide valuable information about weak interactions and the axial structure of the nucleus

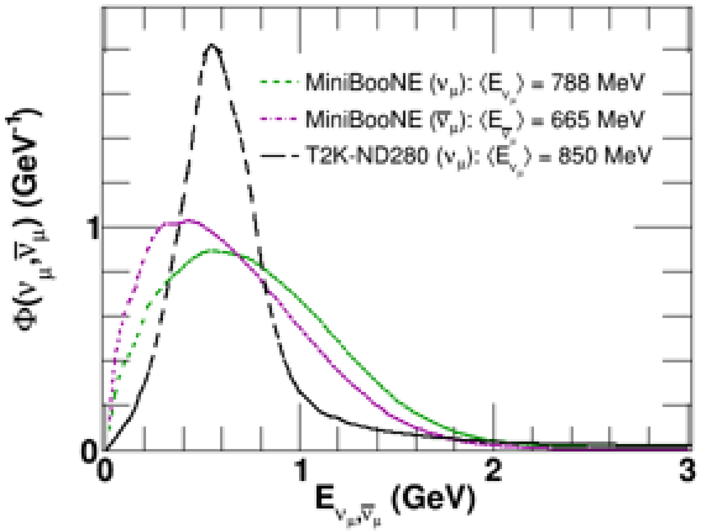


Oscillation analysis in a near/far detector experiment :

$$P_{\nu_i \to \nu_j} = sin^2 2\theta sin^2 \left(\frac{\Delta m^2}{4E} L \right)$$

$$\frac{N_{far}(\overline{E}_\nu)}{N_{near}(\overline{E}_\nu)} = \frac{\int \Phi(E_\nu)\sigma(E_\nu)P(\overline{E}_\nu|E_\nu)P_{i\to j}(E_\nu)dE_\nu}{\int \Phi(E_\nu)\sigma(E_\nu)P(\overline{E}_\nu|E_\nu)(E_\nu)dE_\nu}$$

Accelerator neutrinos : broad energy distribution



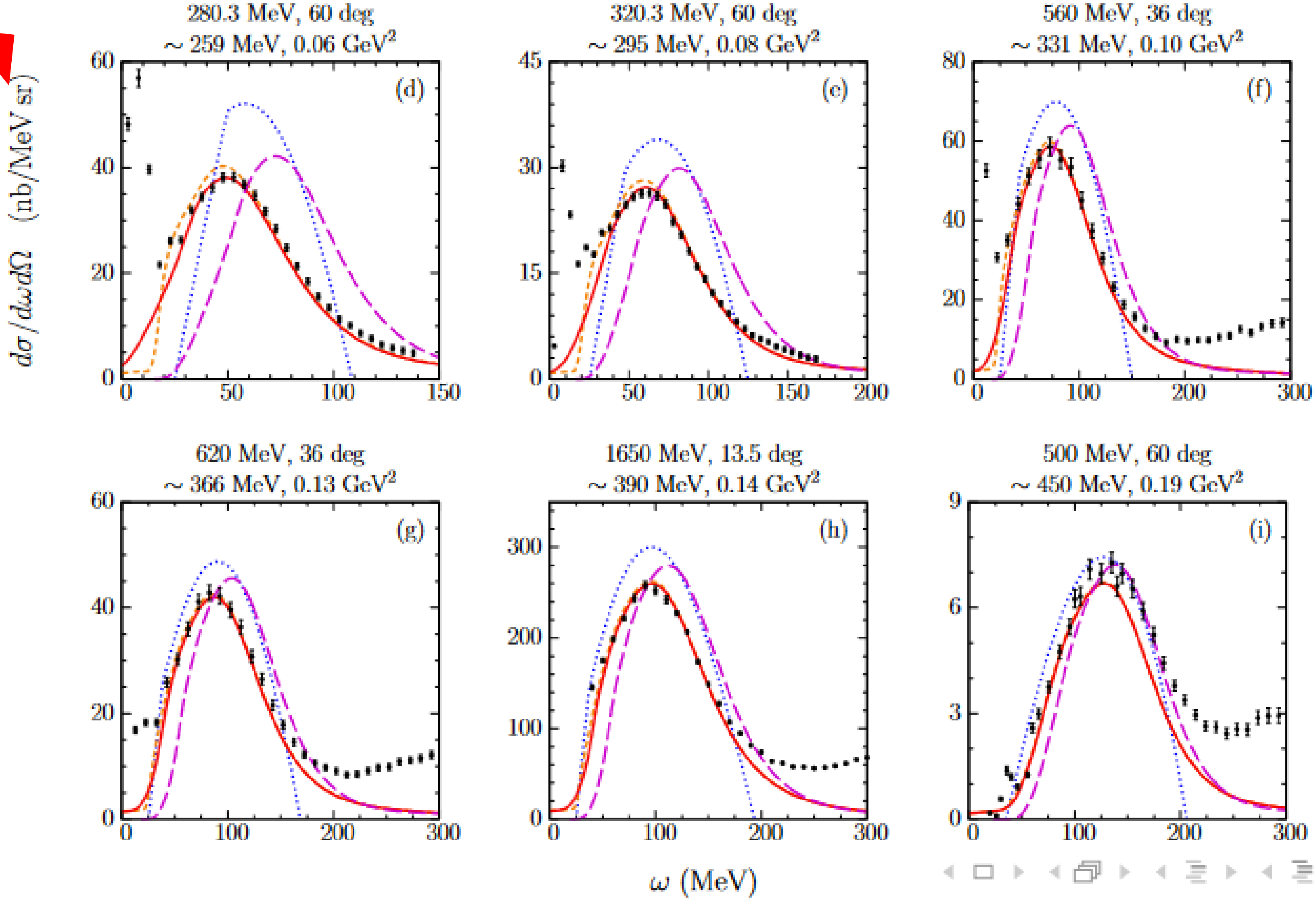
Reconstructed energy

$$\overline{E}_\nu = \frac{2M_n' E_l - (M_n'^2 + m_l^2 - M_p^2)}{2(M_n' - E_l + P_l \cos\theta)}$$

- Cross section, flux, detector efficiency, and oscillation probability are all energy dependent
- Energy dependent cross section information is needed
- Tension between event topology and genuine interaction mode
- Performant models need a consistent treatment of all relevant reaction mechanisms

Omar Benhar's talk

The trouble with flux average

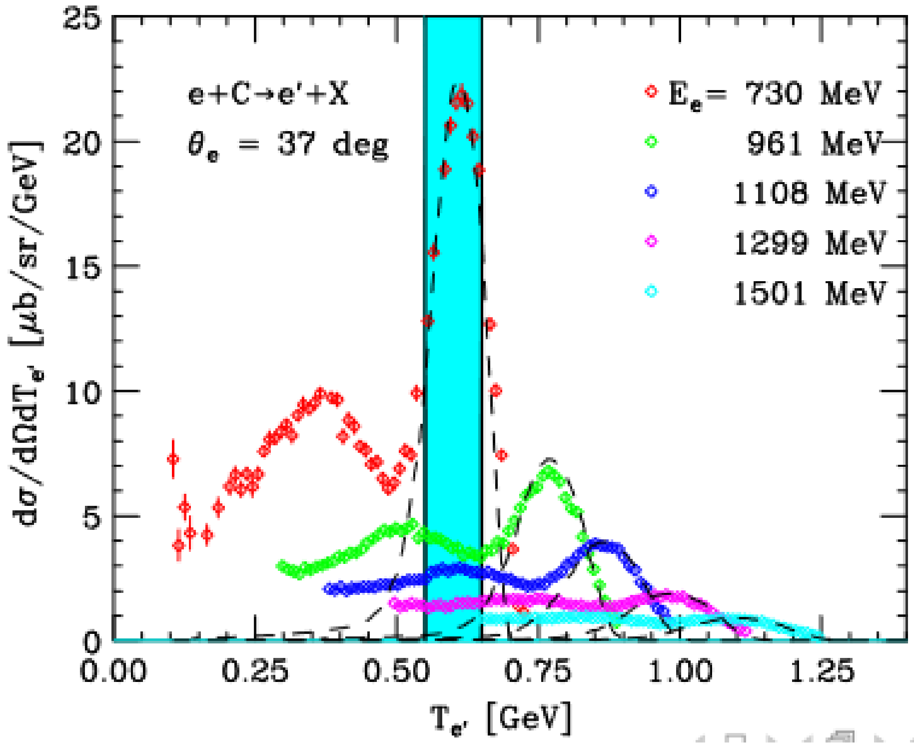


- Spectral function calculations
- inclusive e-scattering
- ☺ !

Omar Benhar's talk

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
- different reaction mechanisms contribute to the cross section at fixed muon energy and emission angle
- This feature clearly emerges from the analysis of electron-scattering data corresponding to different beam energies



→For neutrinos, we have to work hard(er) ...

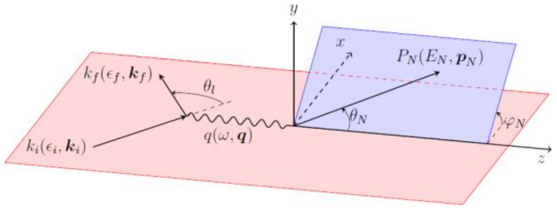
Overview

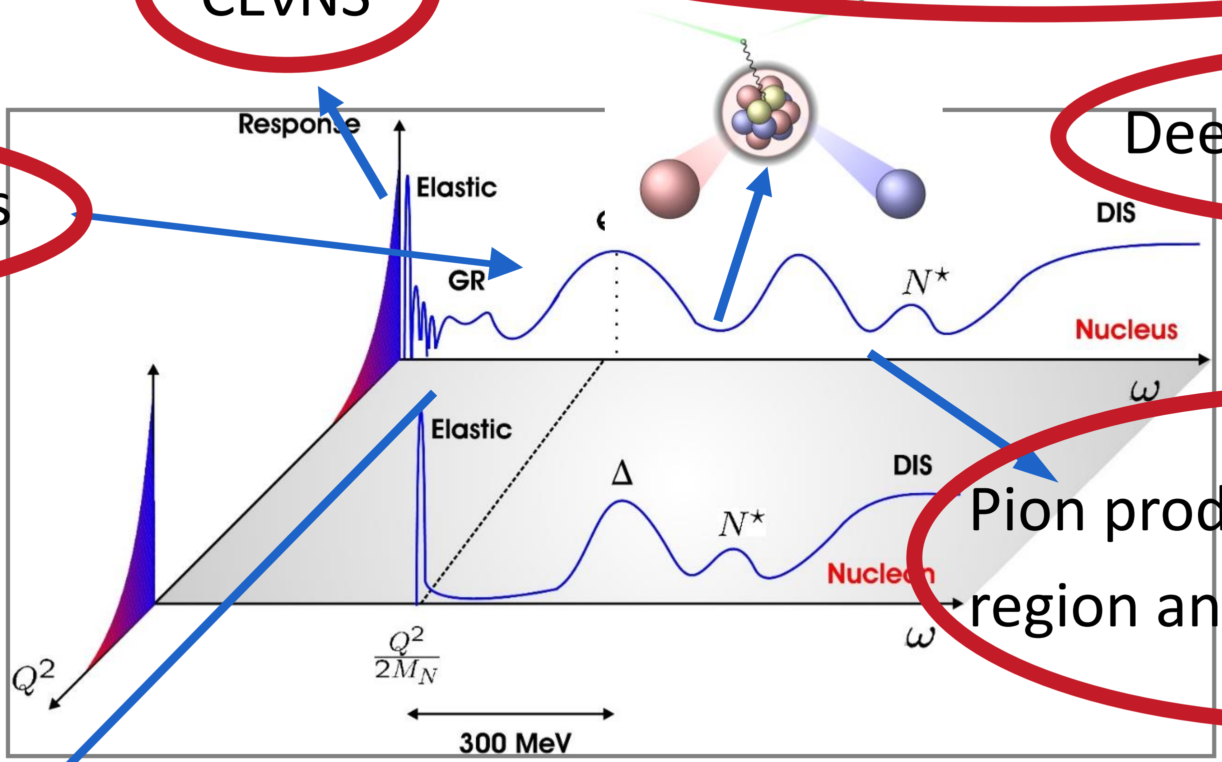
CEvNS

multinucleon mechanisms and 2-nucleon knockout processes in the dip region

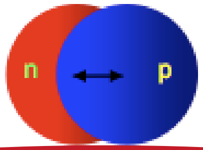
Quasi-elastic processes

Deep Inelastic Scattering



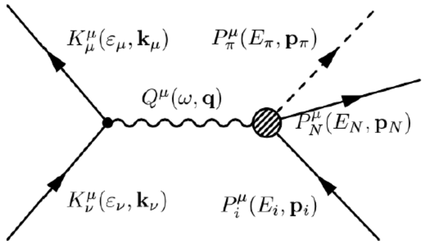


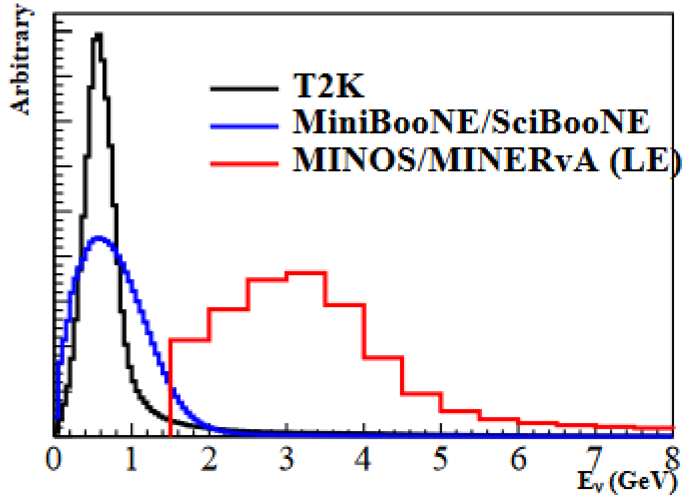
Pion production in the delta region and beyond

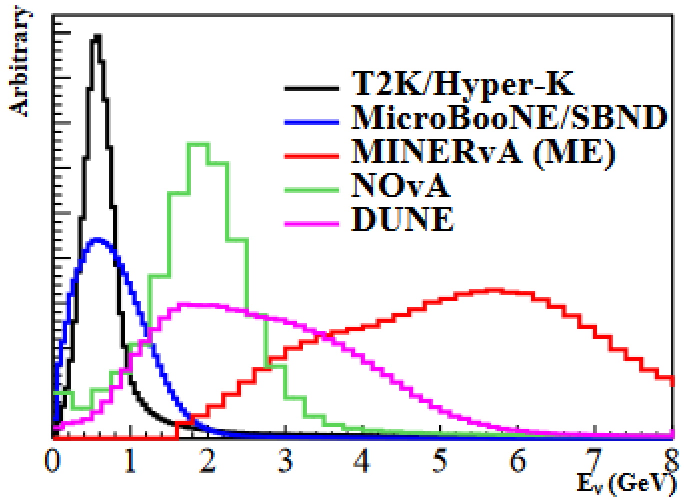


Low energy collective excitations

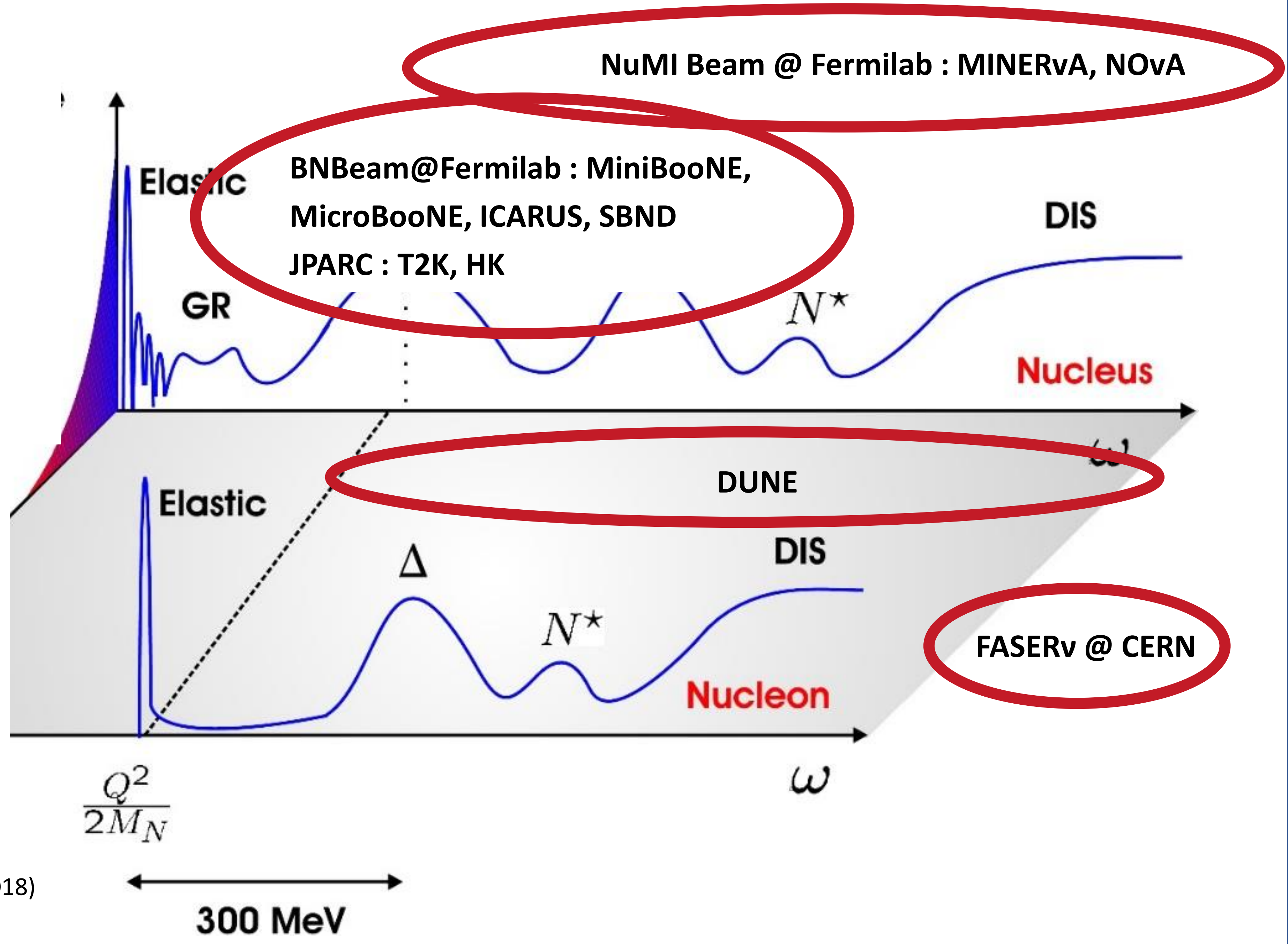
Rich nuclear physics program !



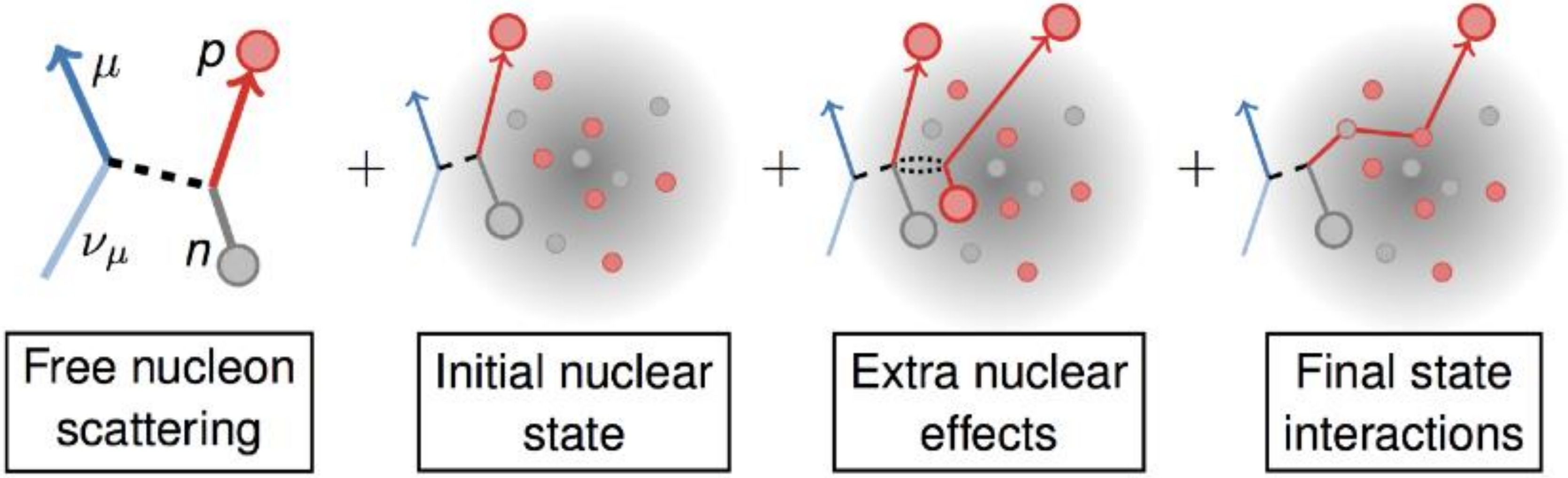




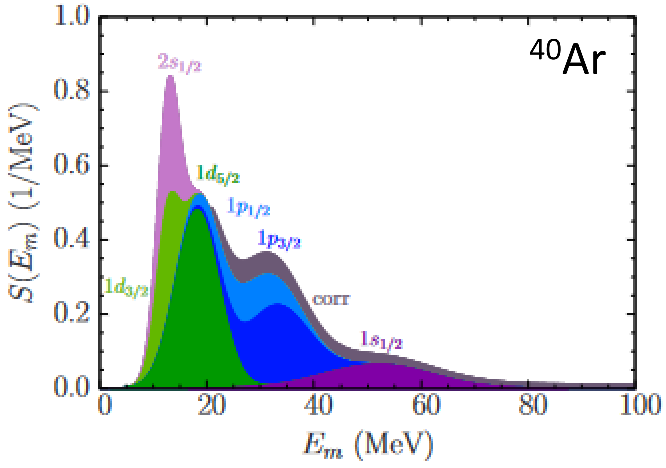
T. Katori & M. Martini, JPhysG 45, 013001 (2018)



What is going on between initial and final state ... ?

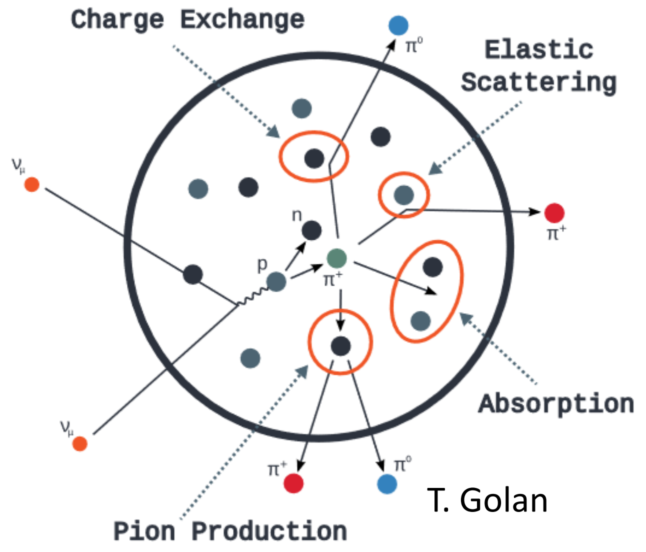


K. Niewczas @ NuFACT2021



arXiv:2203.01748

- Partially taken into account by some of the nuclear models
- MC Generators used for oscillation analyses tend to rely on efficient but approximate models



T. Golan

Where are we now ?

Three things we need to model

(a non exhaustive list)

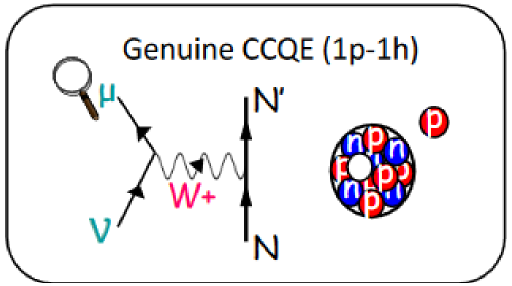
1. Relative contribution of CCQE and other processes in our far detector samples
    - *So we know how often we mis-reconstruct E_ν*

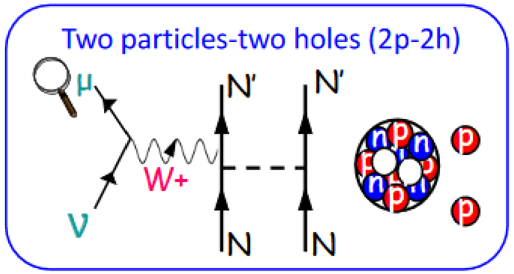
2. Initial state nucleon momentum and energy
    - *So we know how wide (and biased) our CCQE E_ν reconstruction is*

3. Neutrino energy dependence of cross sections
    - *So we know how to extrapolate from our ND to our FD*

S. Dolan on T2K cross section modeling

Quasi elastic versus multinucleon knockout processes



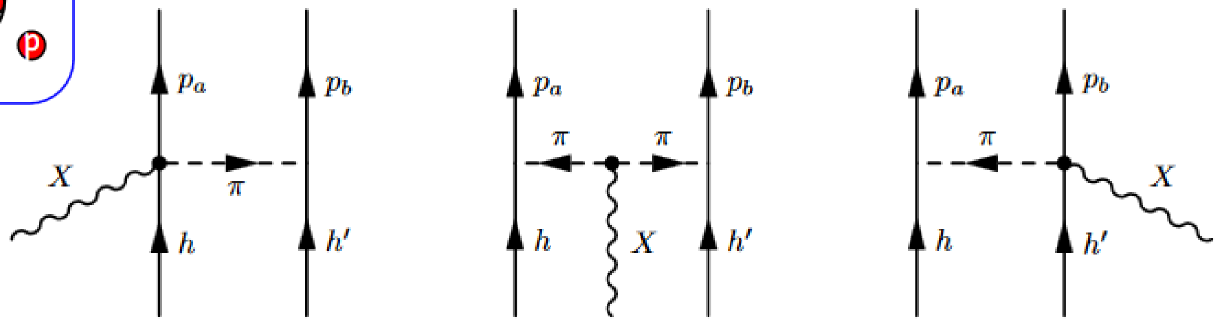


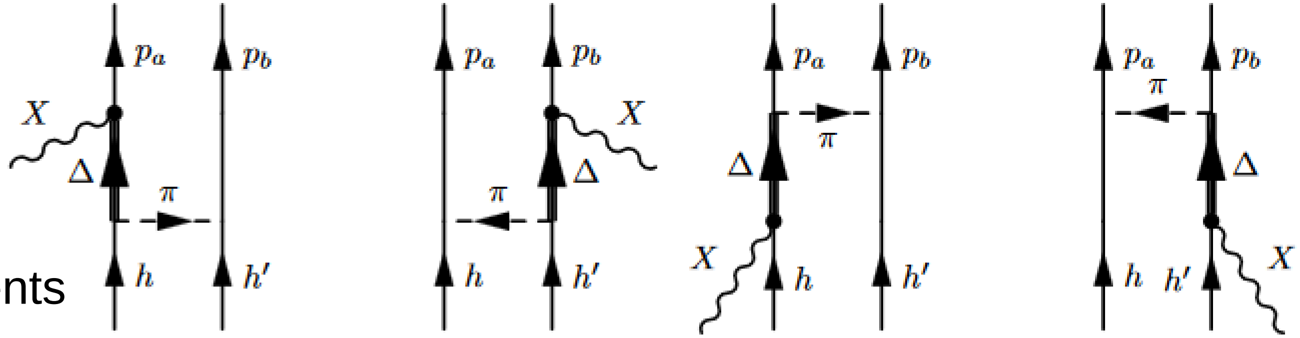
- QE processes are dominating the signal in experiments with average energies of a couple of hundreds of MeVs
- A thorough understanding of the QE cross section is extremely important as it is pivotal for energy reconstruction and oscillation analysis
- Correct identification of the reaction mechanism is important but not straightforward

Meson-exchange currents

Seagull

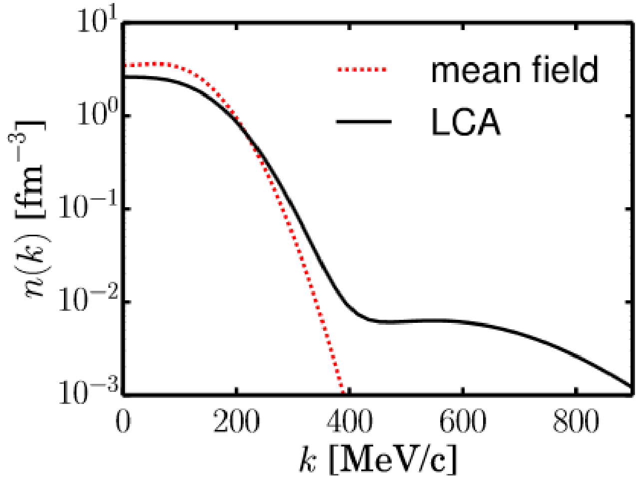
Pion in flight



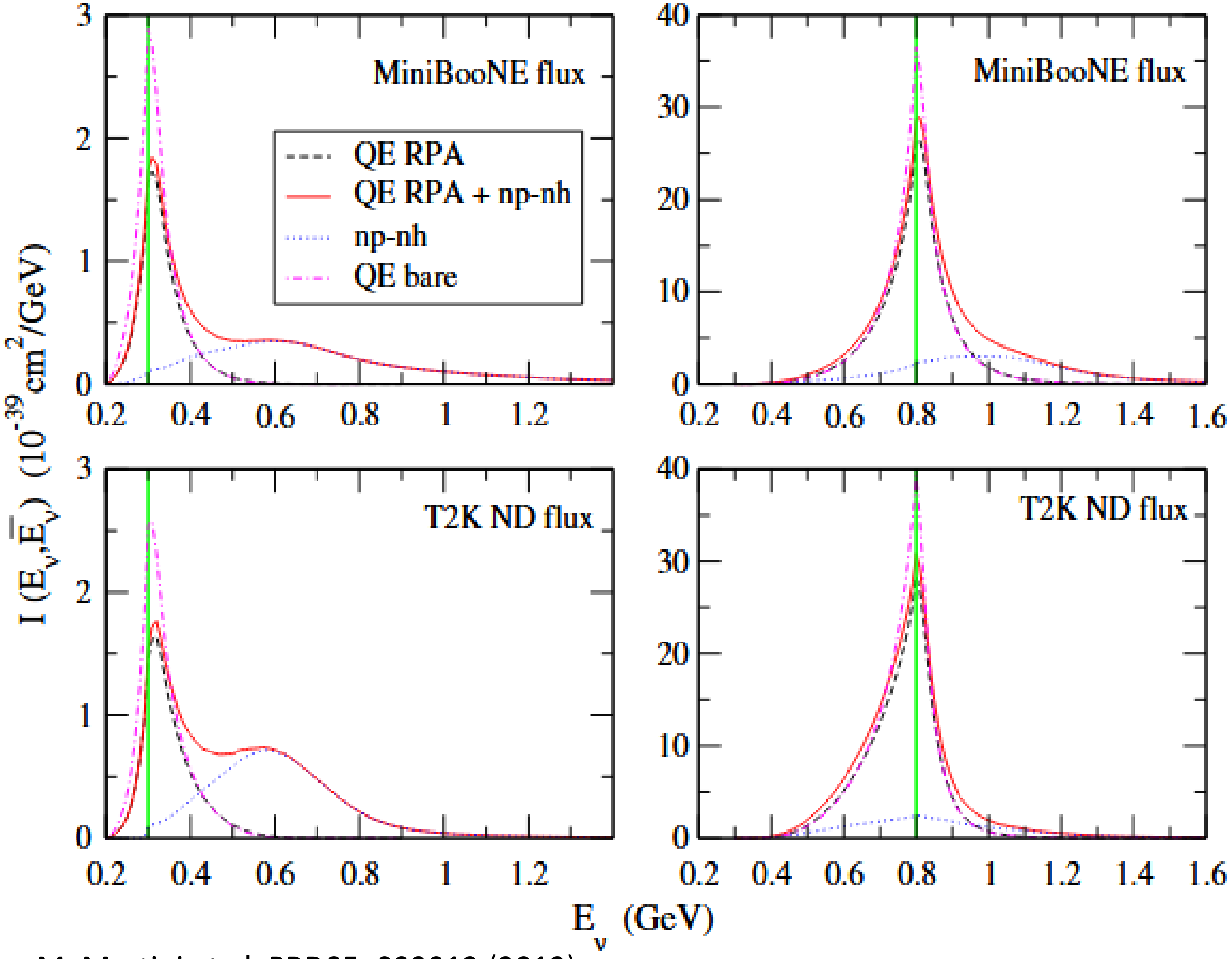


Delta currents

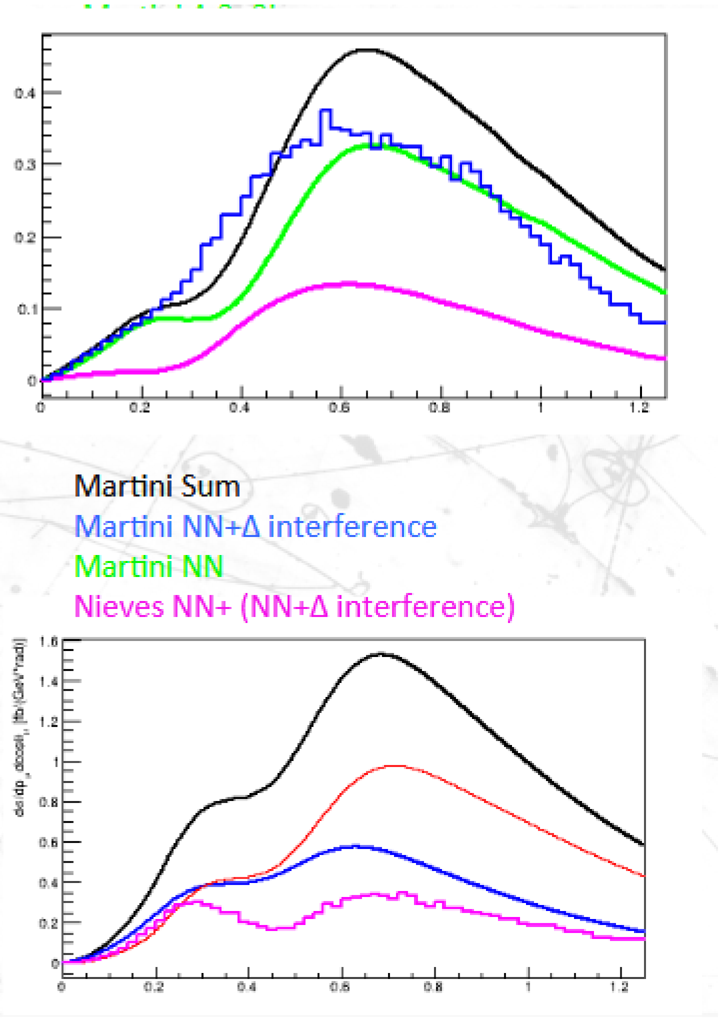
IPM single-particle orbitals are depleted by **short range correlations** and higher momentum states are populated



Multinucleon effects affect energy reconstruction !



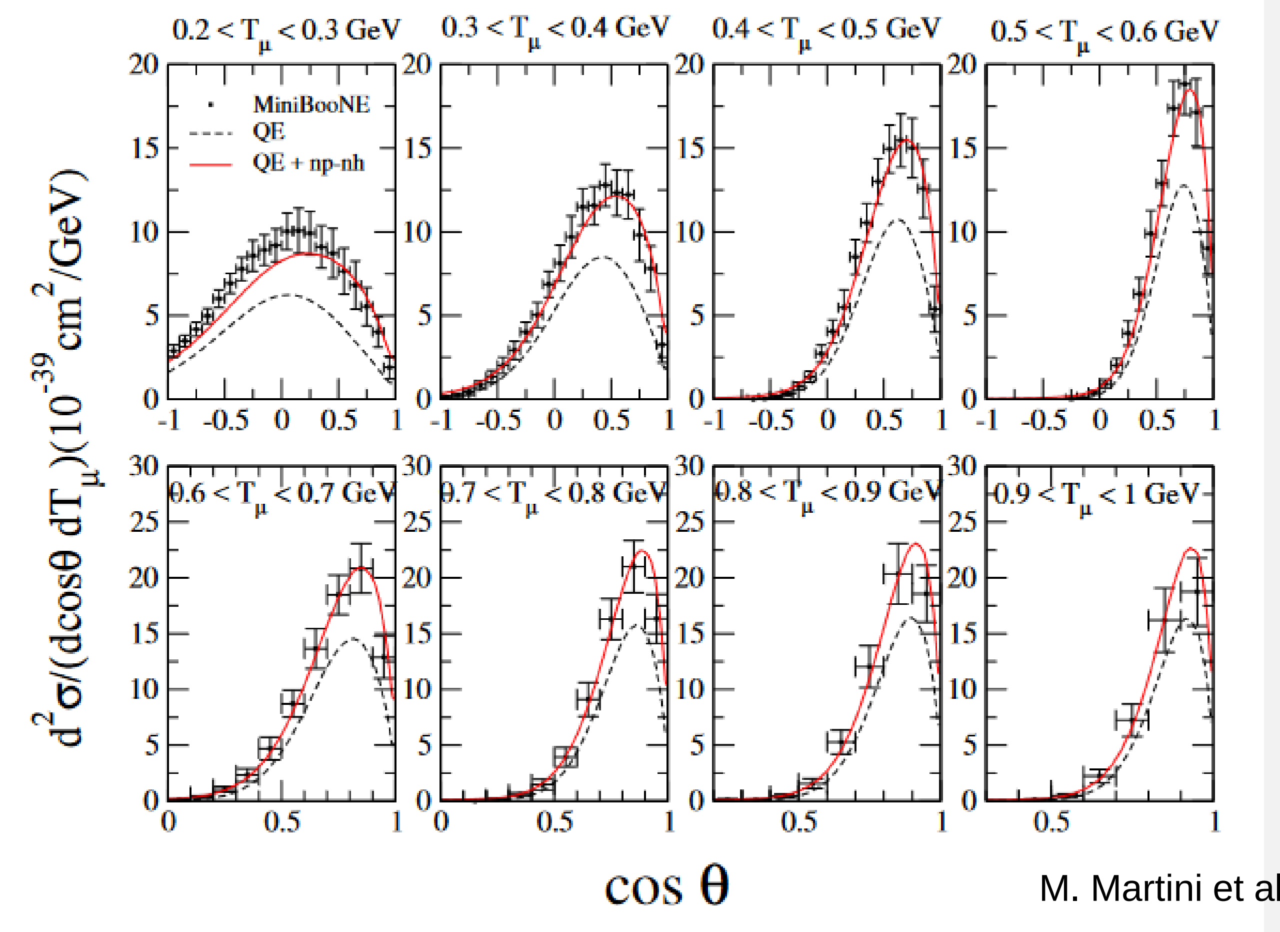
M. Martini et al. PRD85, 093012 (2012)



F. Sanchez, NuInt2017

Modeling QE(like) cross sections

- Several effective approaches are on the market for the description of (inclusive) cross sections
  - Efficient and performant
  - Often factorized

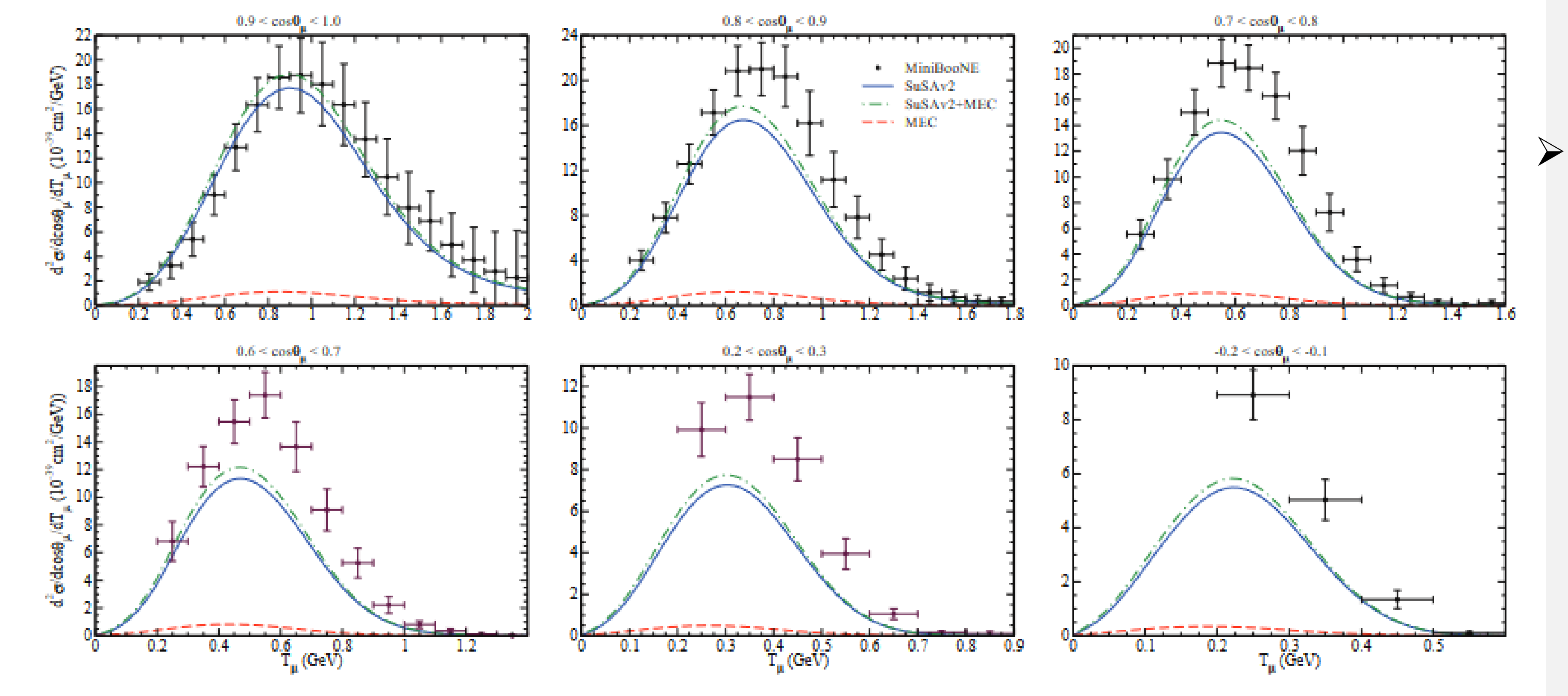


M. Martini et al, PRC84, 055502

➢ Fermi gas approach
  - including correlations
  - Including np-nh contributions

Modeling QE(like) cross sections

- Several effective approaches are on the market for the description of (inclusive) cross sections
  - Efficient and performant
  - Often factorized

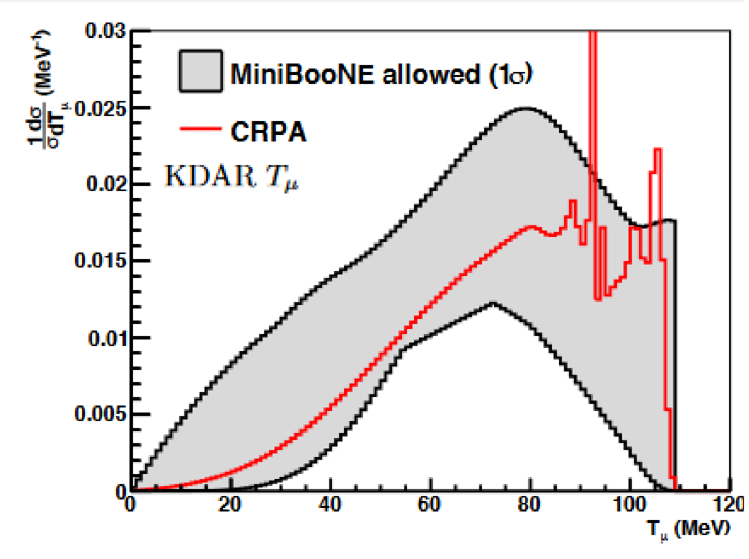


- Superscaling approach
  - SuSAv2 based on RMF calculations
  - Including meson-exchange contributions

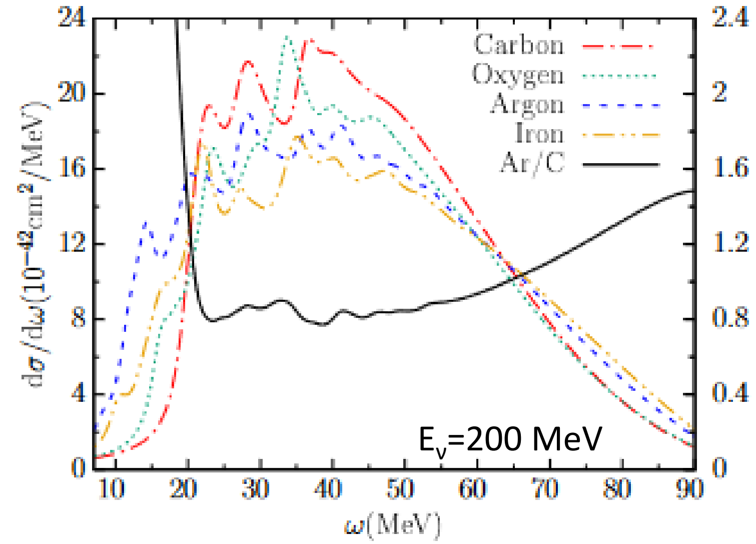
G. Megias et al, PRD 91, 073004

Modeling QE(like) cross sections

- Several effective approaches are on the market for the description of (inclusive) cross sections
  - Efficient and performant
  - Often factorized
- Mean-field models capture a lot of nuclear medium effects in an efficient way



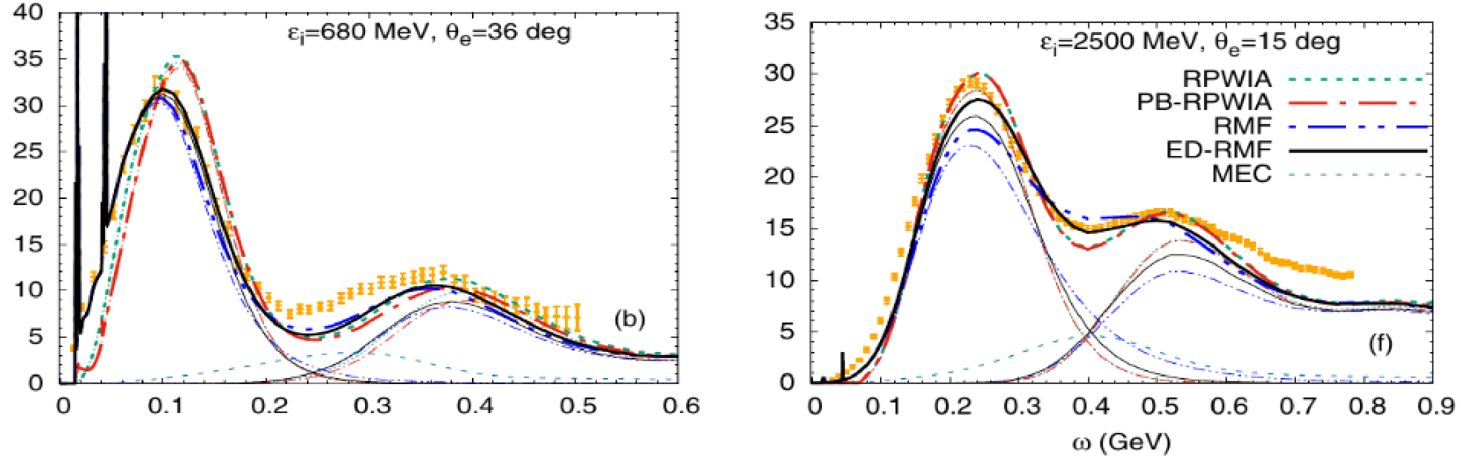
A. Nikolakopoulos et al, PRC103, 064603



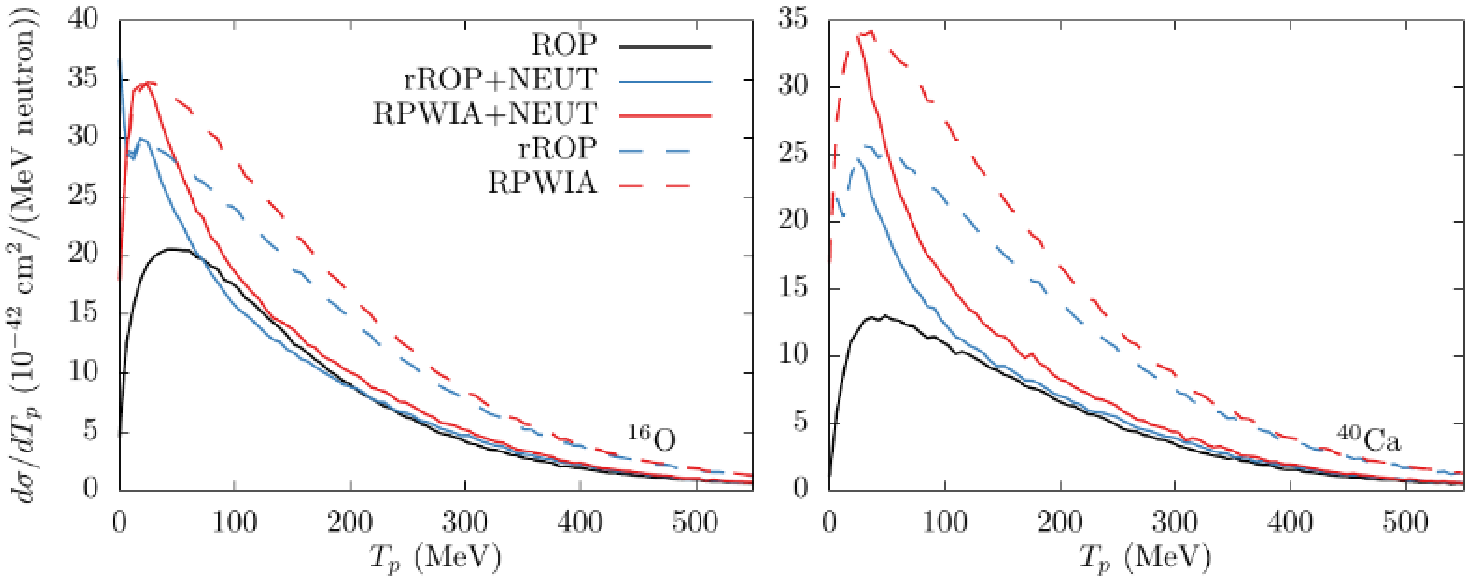
N. Van Dessel et al, PRC97, 044616

- ➢ Hartree-Fock mean field
  - including long-range RPA correlations

Raul Gonzalez-Jimenez's talk



Distortion of the outgoing nucleon (= FSI in a Quantum Mechanical way) is important at intermediate energies too !!!



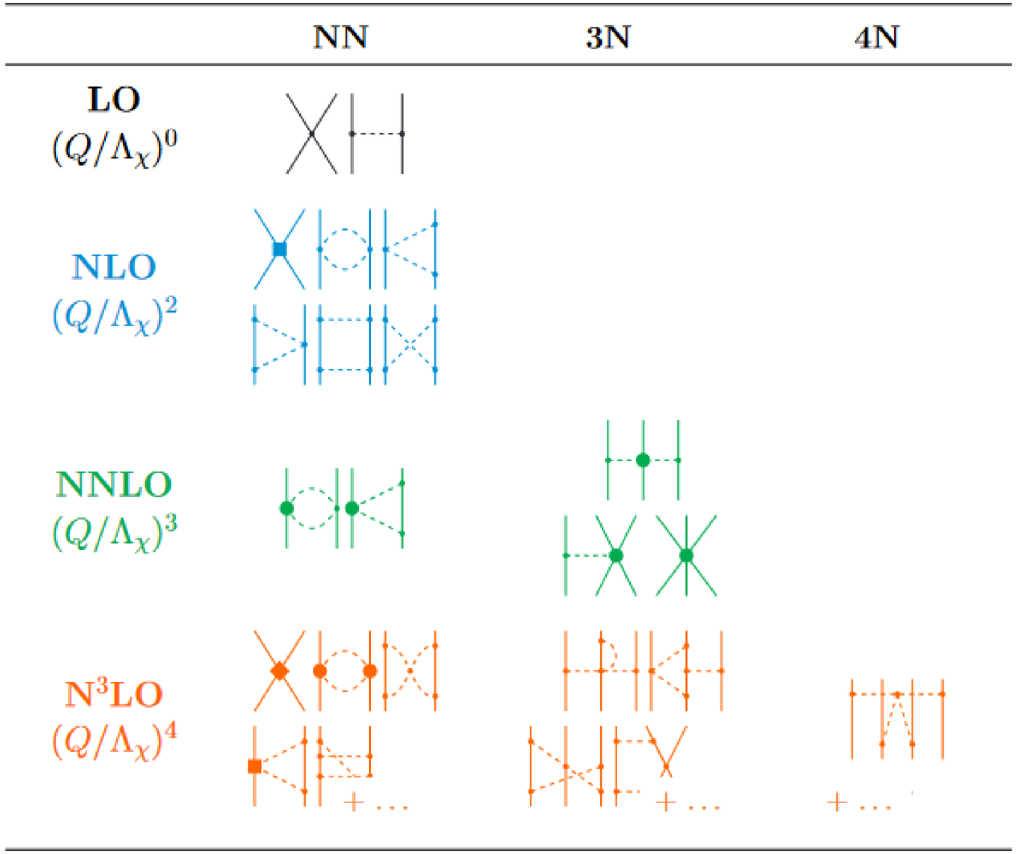
Quantum mechanical description of distortion final-state nucleon wave function

- also affects inclusive cross sections (real part of the optical potential)
- Is crucial for the description of hadrons in final state

Modeling QE(like) cross sections

Recent years have seen the coming-of-age of **ab-initio calculations for neutrino-nucleus cross section** predictions and the development of auxiliary techniques to provide predictions for a variety of processes, targets and kinematics

$$H = \sum_i \frac{\mathrm{p}_i^2}{2m} + \sum_{i<j} v_{ij} + \sum_{i<j<k} V_{ijk} + \ldots$$

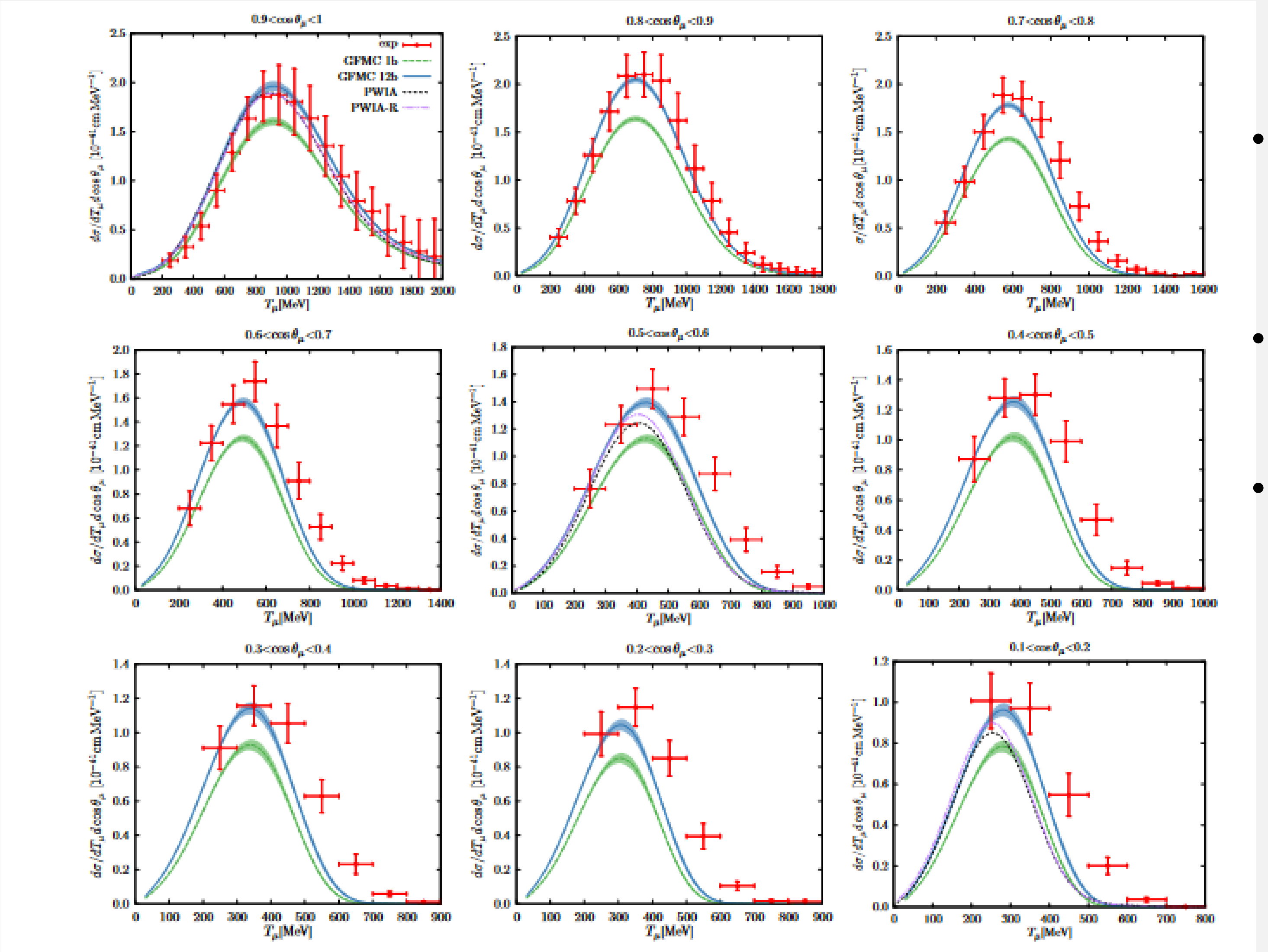


H. Hergert

Ab initio results

- In principle exact, realistic Hamiltonian e.g. AV18 in GFMC
- Computationally intensive and only applicable to the inclusive response
- Light nuclei
- Non-relativistic
- Static Δ

Noah Steinberg

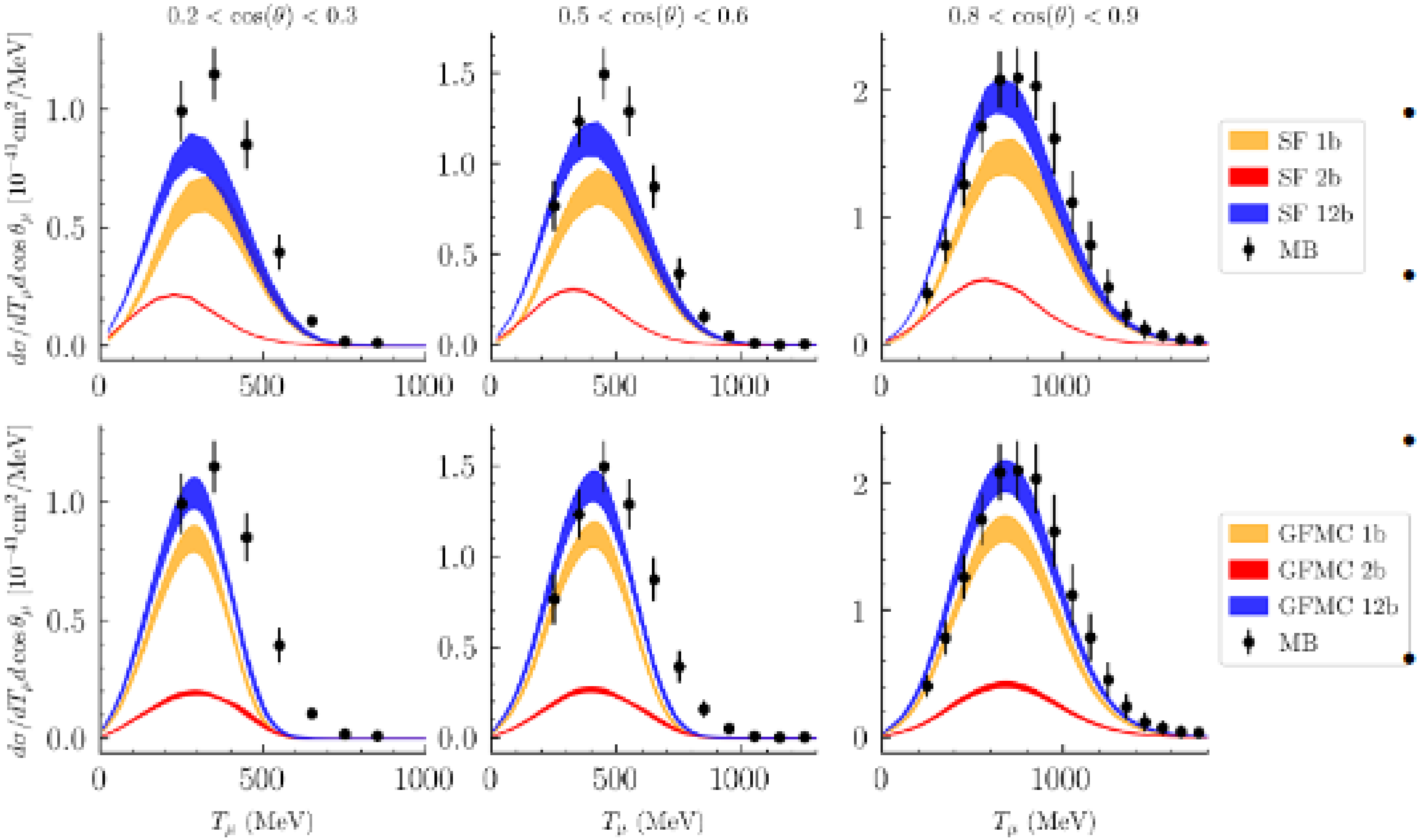


A. Lovato et al, PRX 10, 031068

- MiniBooNE flux-folded double differential cross sections per target neutron for ν_μ-CCQE scattering on ^{12}C in a Green's Function Monte Carlo approach
- include the effects of many-body correlations induced by the interactions in the initial and final states
- account for the interference between one- and two-body current contributions

Noah Steinberg's talk : comparison between GFMC and SF calculations

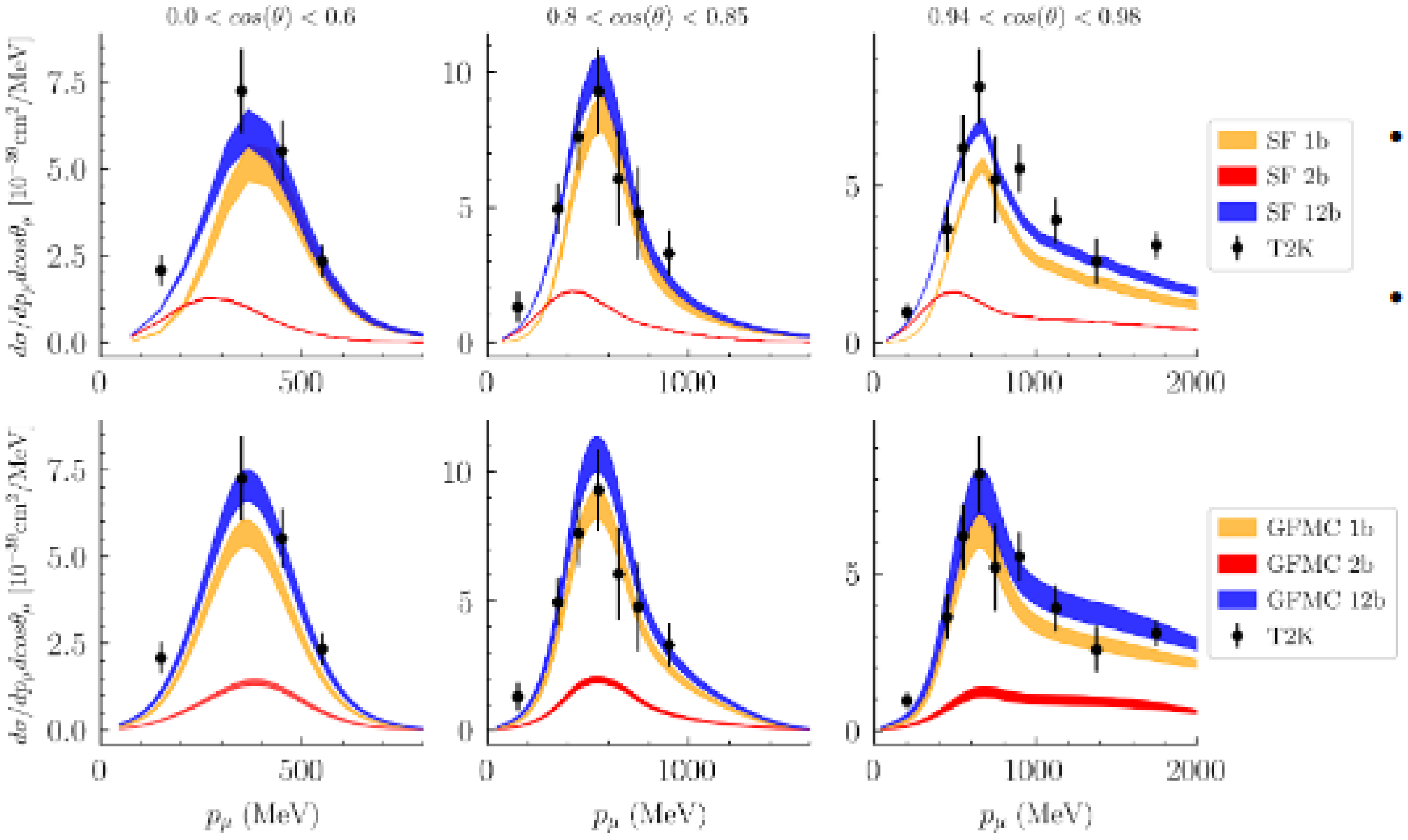
MiniBooNE – 1 and 2 Body Breakdown



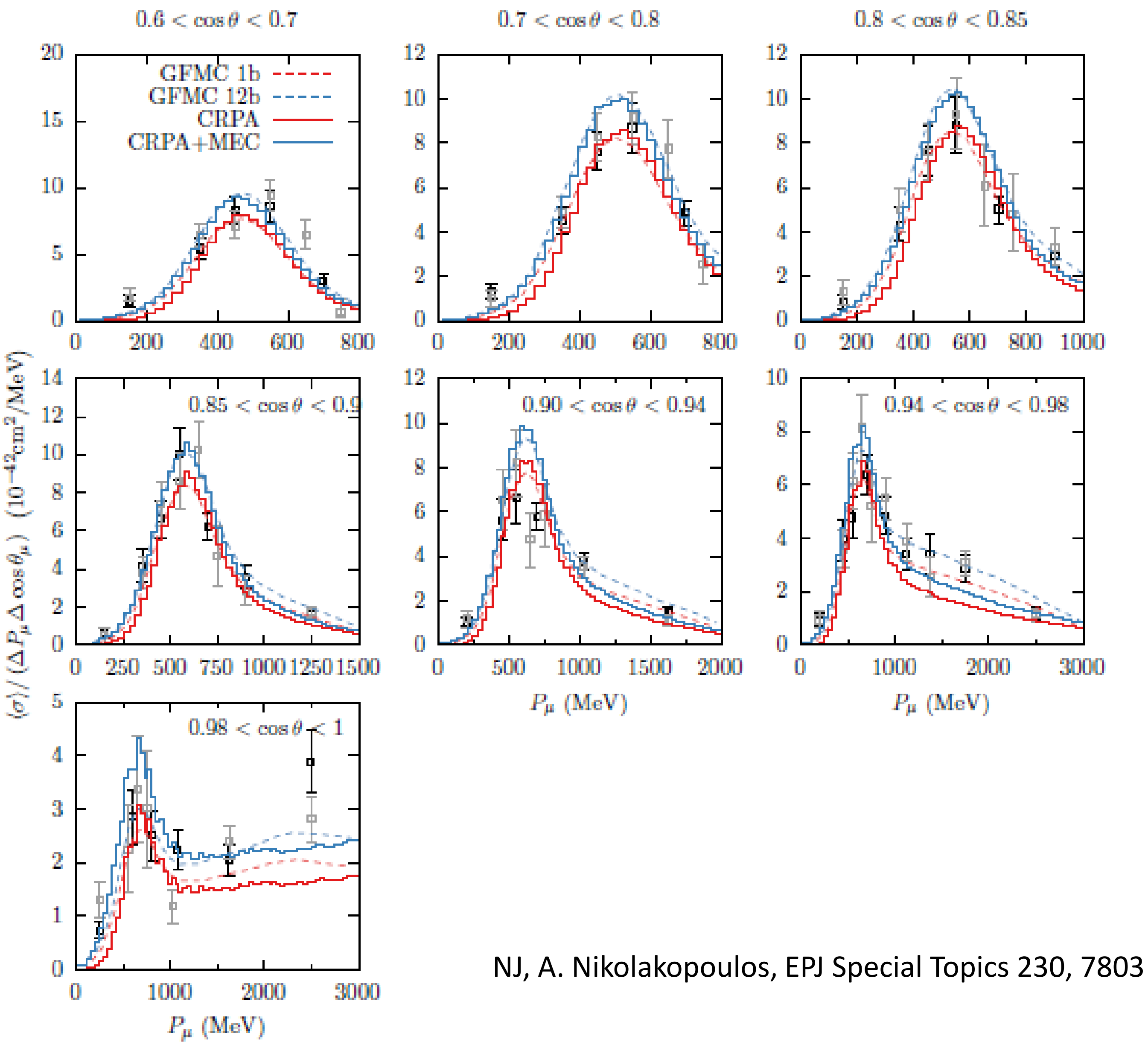
- Separate 1 Body and 2 Body contributions
- SF and GFMC show deficit for small cos θ
- Model dependent pion subtraction at small T_μ
- GFMC non-relativistic nature means disagreements at large Q^2
- SF and GFMC 2 Body peaks shifted b/c of interference effects

Noah Steinberg's talk : comparison between GFMC and SF calculations

T2K – 1 and 2 Body Breakdown



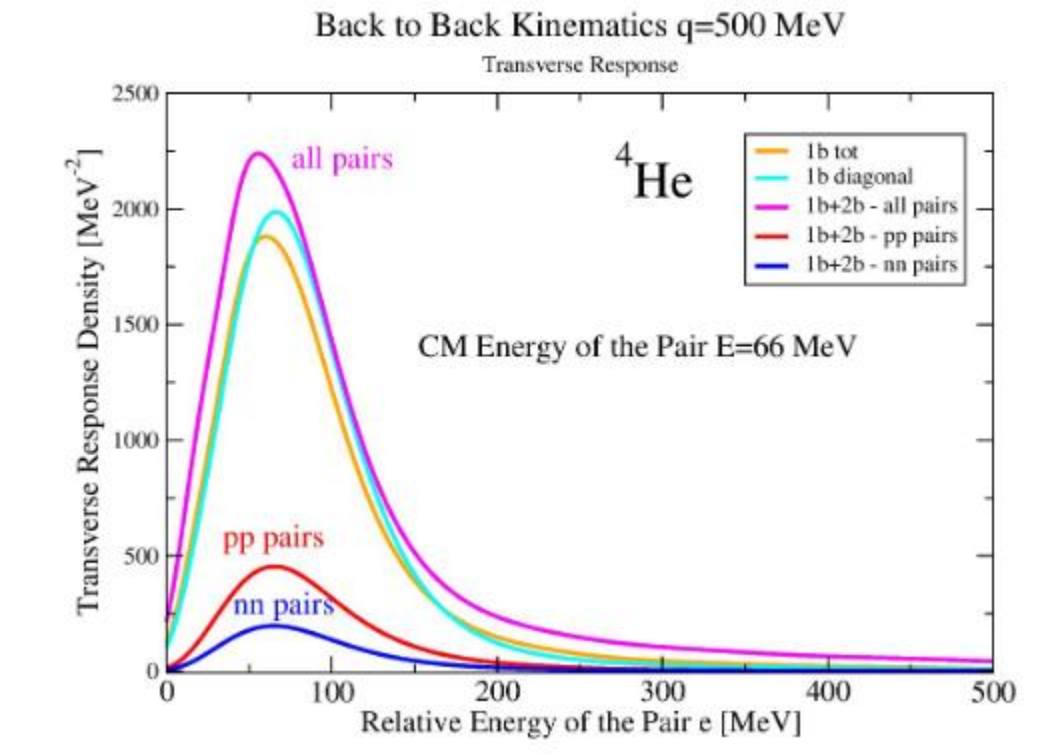
- GMFC and SF provide excellent agreement
- T2K flux peaks at lower energies
- SF and GFMC 2 Body peaks shifted b/c of interference effects



NJ, A. Nikolakopoulos, EPJ Special Topics 230, 7803

- T2K flux-folded double differential cross sections per target neutron for ν_μ-CCQE scattering on ^{12}C in a Green's Function Monte Carlo approach
- Comparing ab-initio calculations with mean-field-based calculations
- Include long-range correlations in CRPA and added 2p-2h contributions

Short-time approximation : go beyond the restriction to inclusive processes in ab-initio approaches and provides more exclusive information



S. Pastore et al, PRC101, 044612

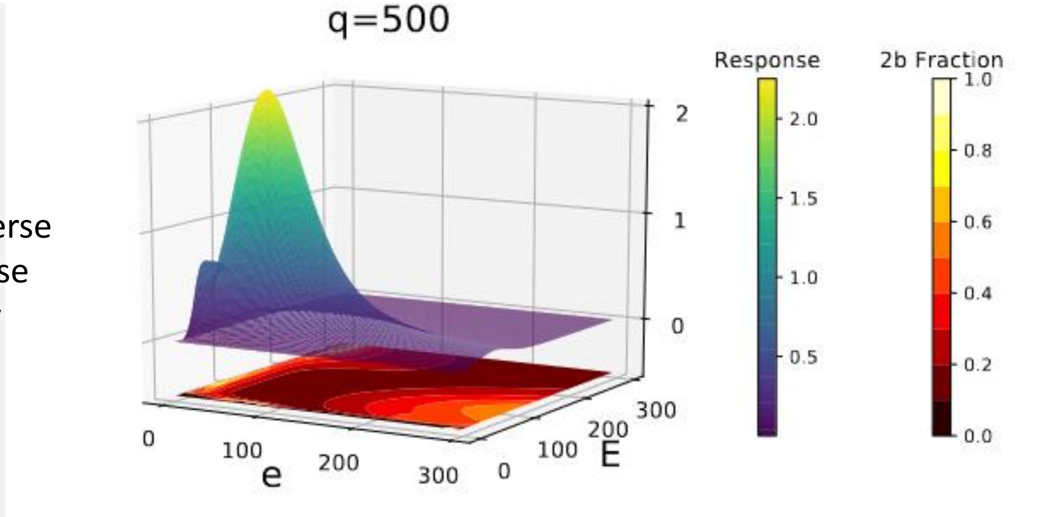
- Based on factorization
- Retains 2-body contributions and correctly accounts for interference

$$H = \sum_i \frac{\mathbf{p}_i^2}{2m} + \sum_{i<j} v_{ij}$$

- Response functions account for scattering off pairs of interacting nucleons

$$R(q,\omega) \sim \int \delta\left(\omega + E_0 - E_f\right)\, dP'\, dp' \mathcal{D}(p', P'; q)$$

Transverse response density

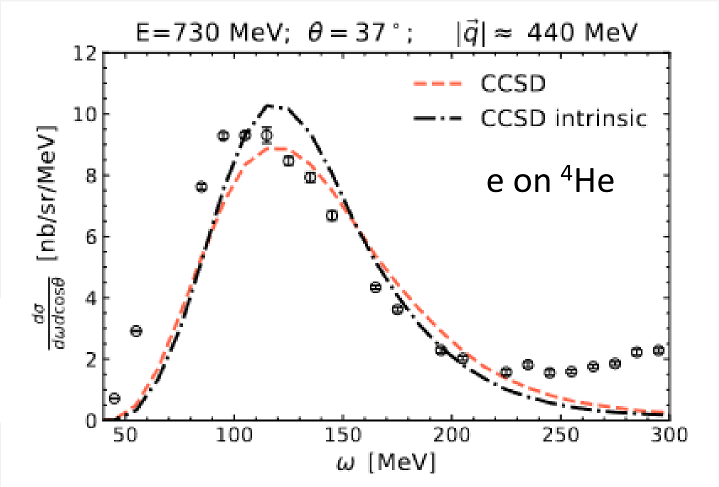


Coupled-cluster theory predictions for **coherent scattering** processes

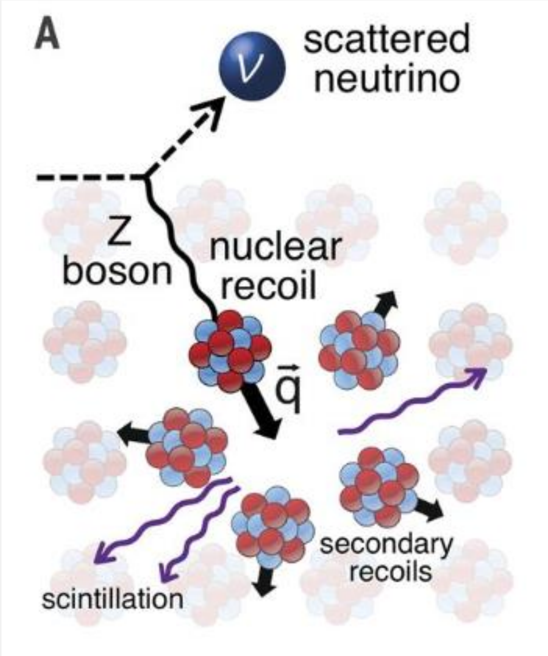
- Cross section large compared to inelastic processes at small energies
- Mainly sensitive to the neutron distribution
- Interesting prospects for BSM searches, see **Doojin Kim's talk** !

$$\frac{d\sigma}{dT} = \frac{G_F^2}{\pi} M_A \left(1 - \frac{T}{E_i} - \frac{M_A T}{2E_i^2}\right) \frac{Q_W^2}{4} F_W^2(Q^2)$$

$$F_W(Q^2) = \frac{1}{Q_W}\left[\left(1 - 4\sin^2\theta_W\right) f_p(\vec{q})F_p(Q^2) - f_n(\vec{q})F_n(Q^2)\right]$$



J.E. Sobczyk et al. arXiv:2205.03592

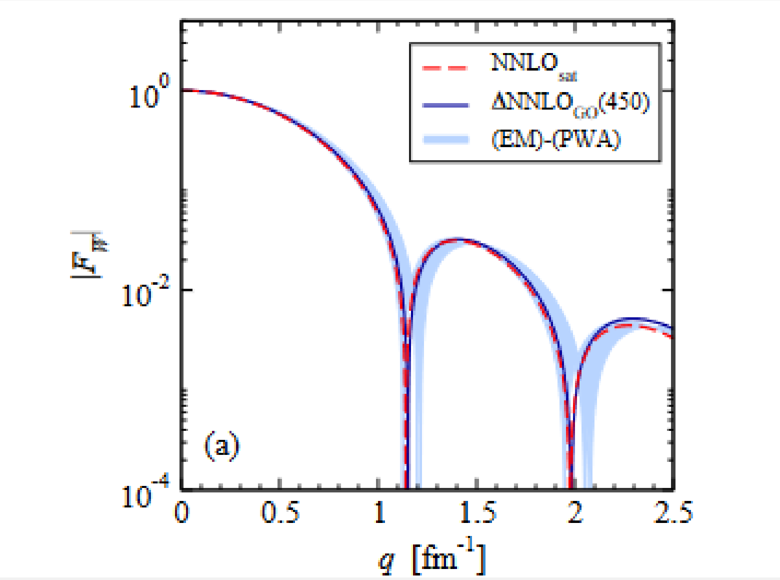


Nuclear Hamiltonian inspired by effective field theories

$$\overline{H}_N = e^{-T} H_N e^{T}$$

Including correlations

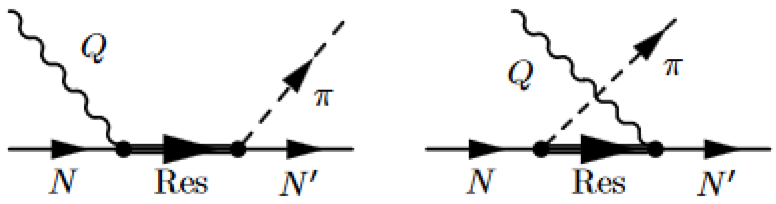
$$T = \sum t_a^i a_a^\dagger a_i + \sum t_{ab}^{ij} a_a^\dagger a_b^\dagger a_i a_j + \ldots$$



C. Payne et al, PRC100, 061304

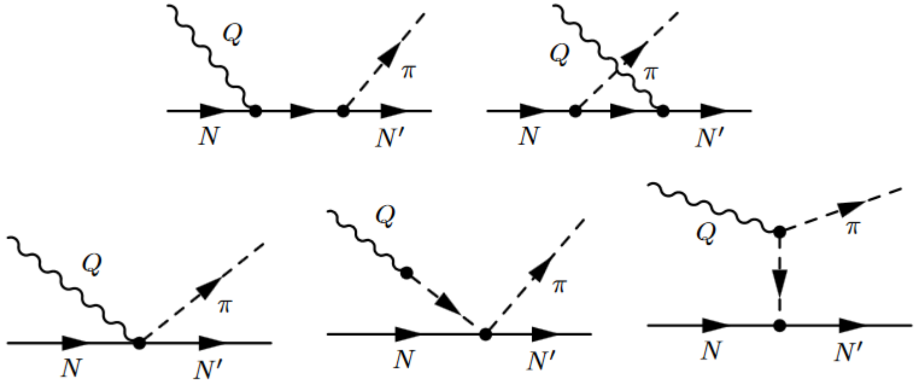
Pion Production

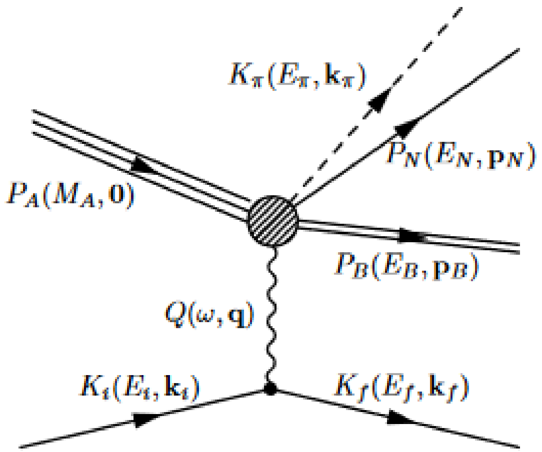
Resonances

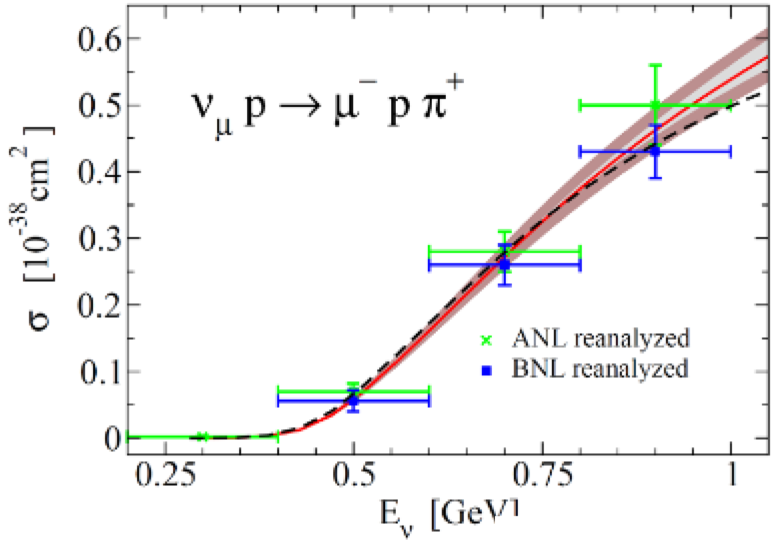


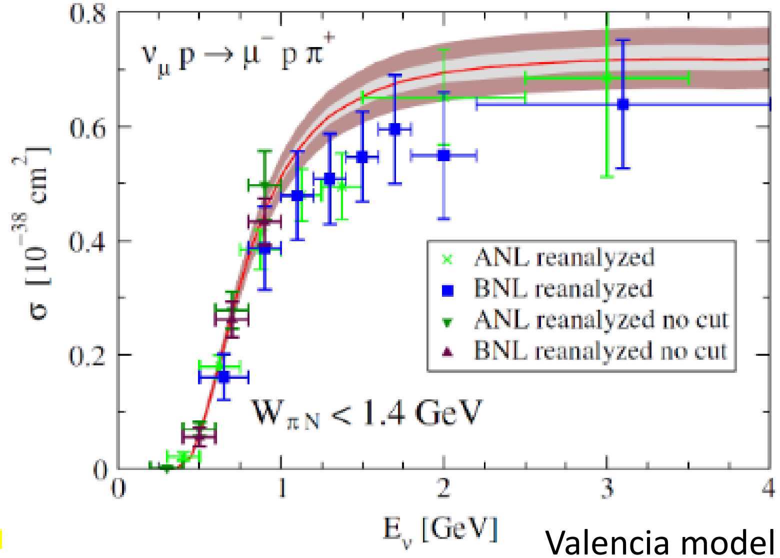
+

ChPT background









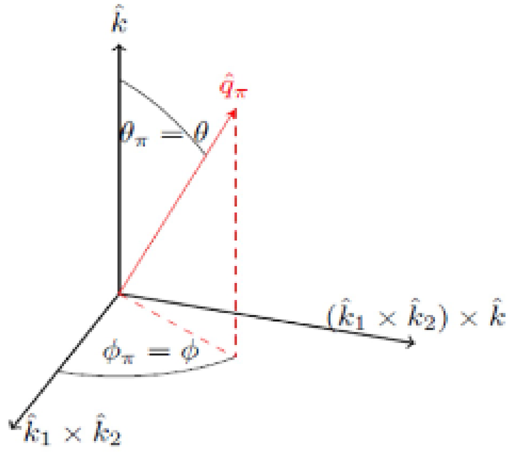
Valencia model

- Single pion production in Delta region relatively well understood
- Important background channel for quasi-elastic cross section measurements as the produced pions may be re-absorbed in the nuclear medium or remain otherwise unobserved, leading to a CC0π topology mimicking a QE event

Minoo Kabirnezhad's talk

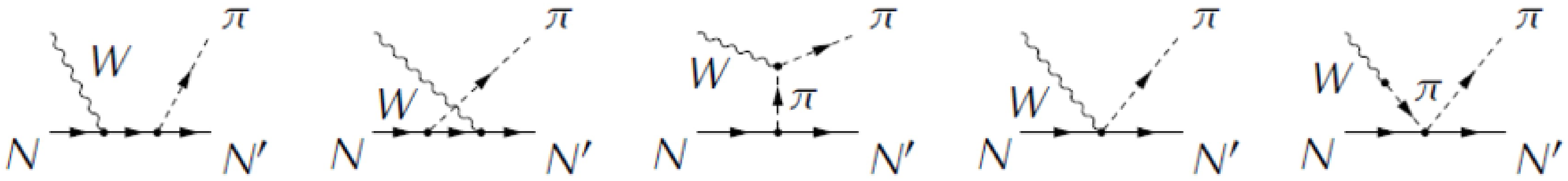
MK-model

M. Kabirnezhad,
Phys. Rev. D **97**, 013002



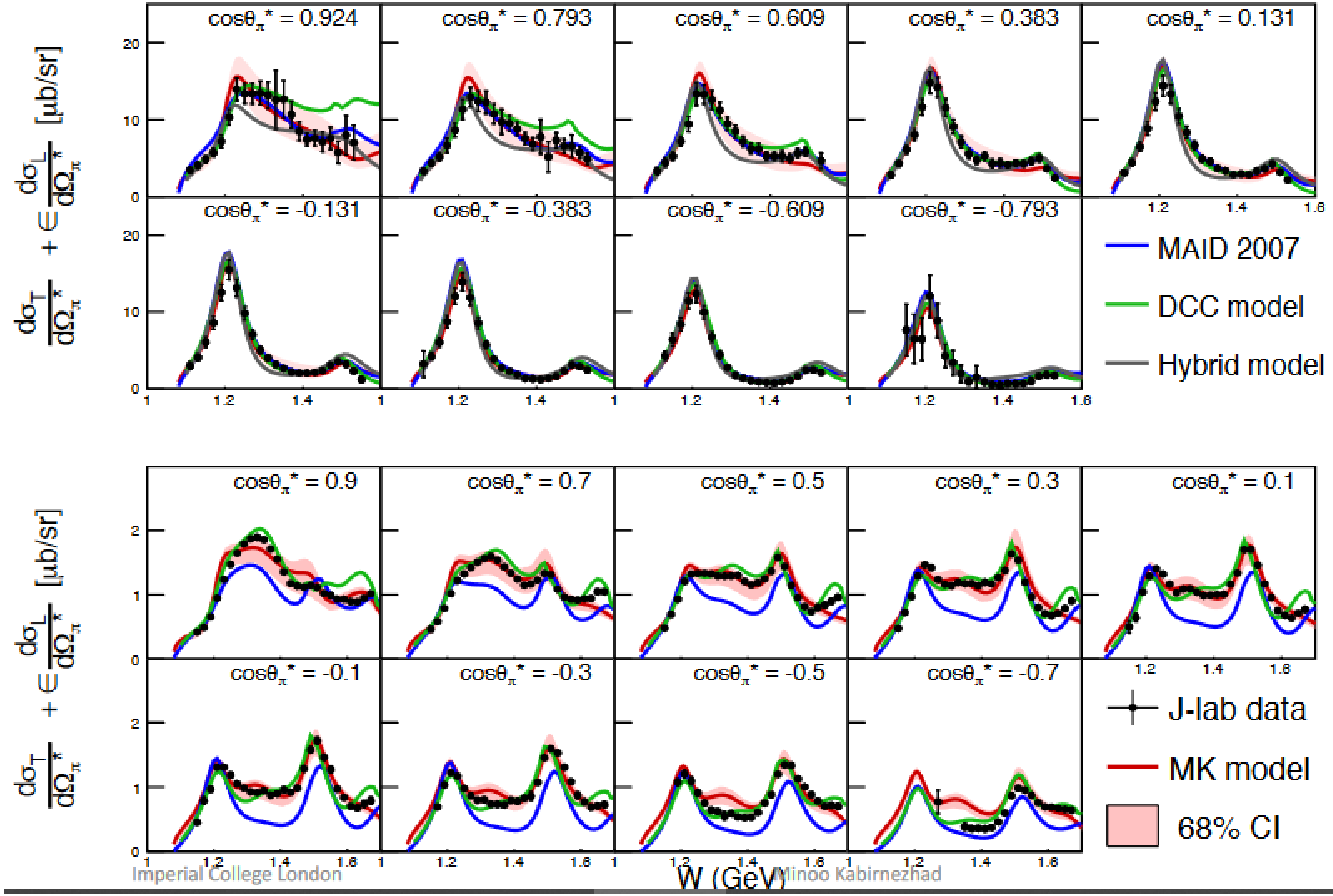
- MK model is a model for single pion production i.e. resonant and nonresonant interactions including **the interference effects**.
- Uses Rein-Sehgal model with Graczyk-Sobczyk form-factor to describe resonant interaction (17 resonances) up to W=2 GeV.
- Lepton mass is included.
- Non-resonant background is defined by a set of diagrams determined by HNV model.

E. Hernandez, J. Nieves and M. Valverde,
Phys. Rev. D **76** (2007) 033005



Minoo Kabirnezhad

$$ep \rightarrow en + \pi^+$$

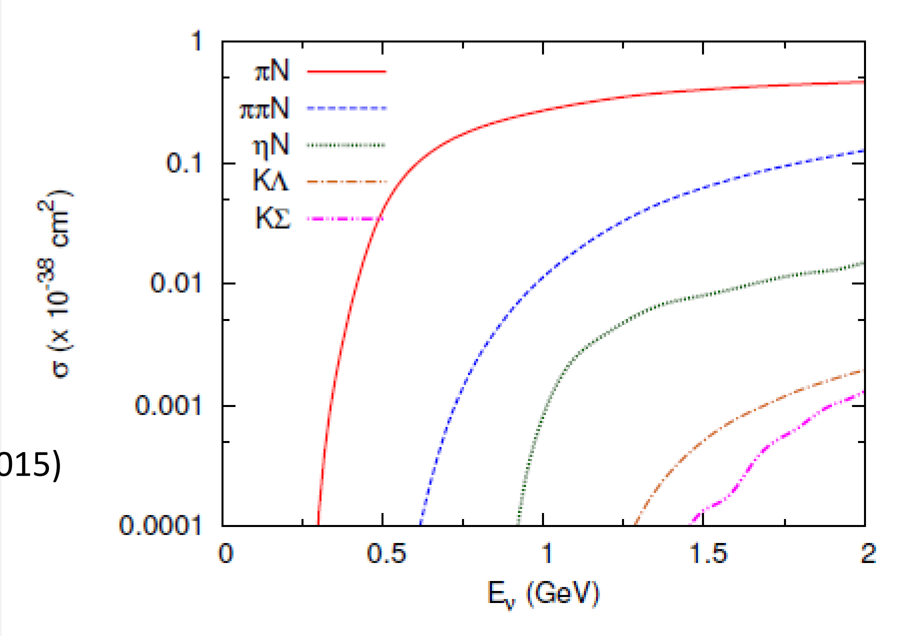


E= 1.515 GeV
Q^2=0.4 GeV^2
1.1<W<1.41 GeV

E= 5.754 GeV
Q^2=2.05 GeV^2
1.15<W<1.67 GeV

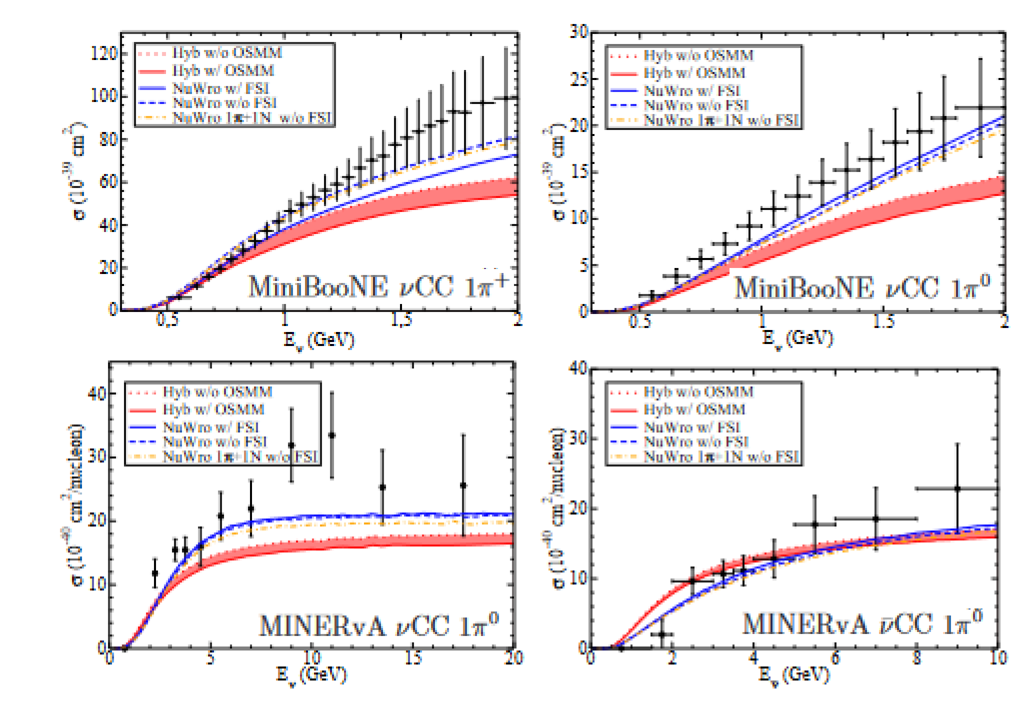
- For neutrinos, the axial contribution is only poorly constrained by data

- Up to W≈2GeV the Osaka dynamic coupled cluster (DCC) model offers a state-of-the-art description of neutrino-induced meson production



S. Nakamura et al, PRD92, 074024 (2015)

- At higher energies, alternate techniques need to be developed

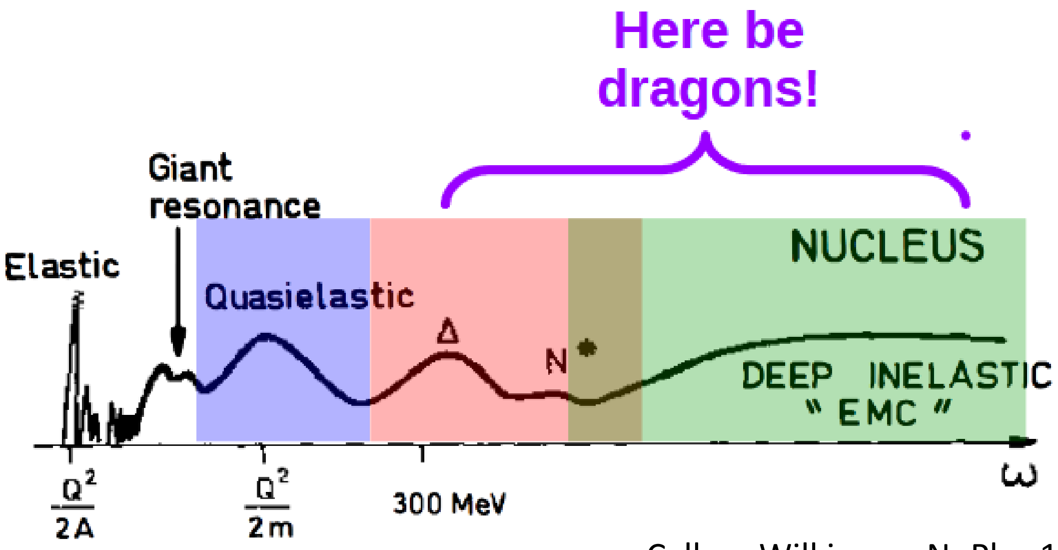


Hybrid model results for single-pion production cross-section including Regge description at higher energies to overcome problems with low-energy descriptions

Non-trivial influence of nuclear medium

R. Gonzalez-Jimenez et al.,PRD 97

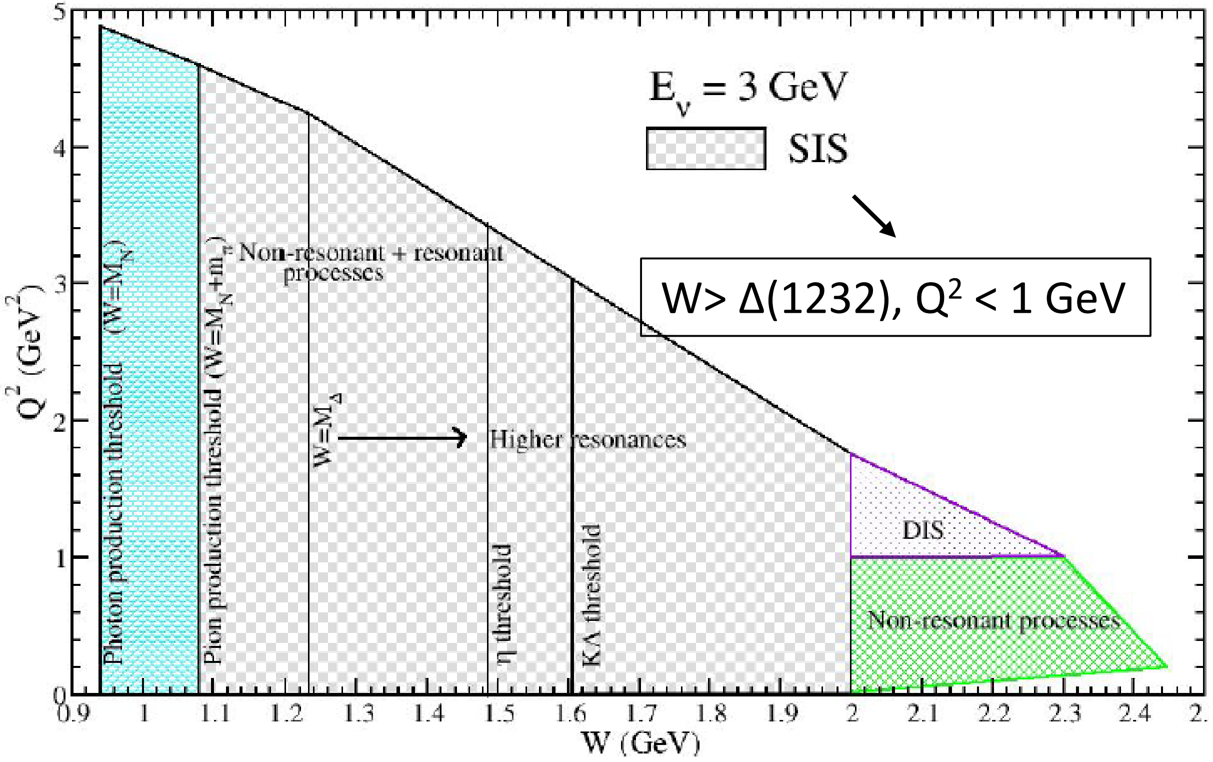
The transition to the Shallow and Deep Inelastic Scattering region

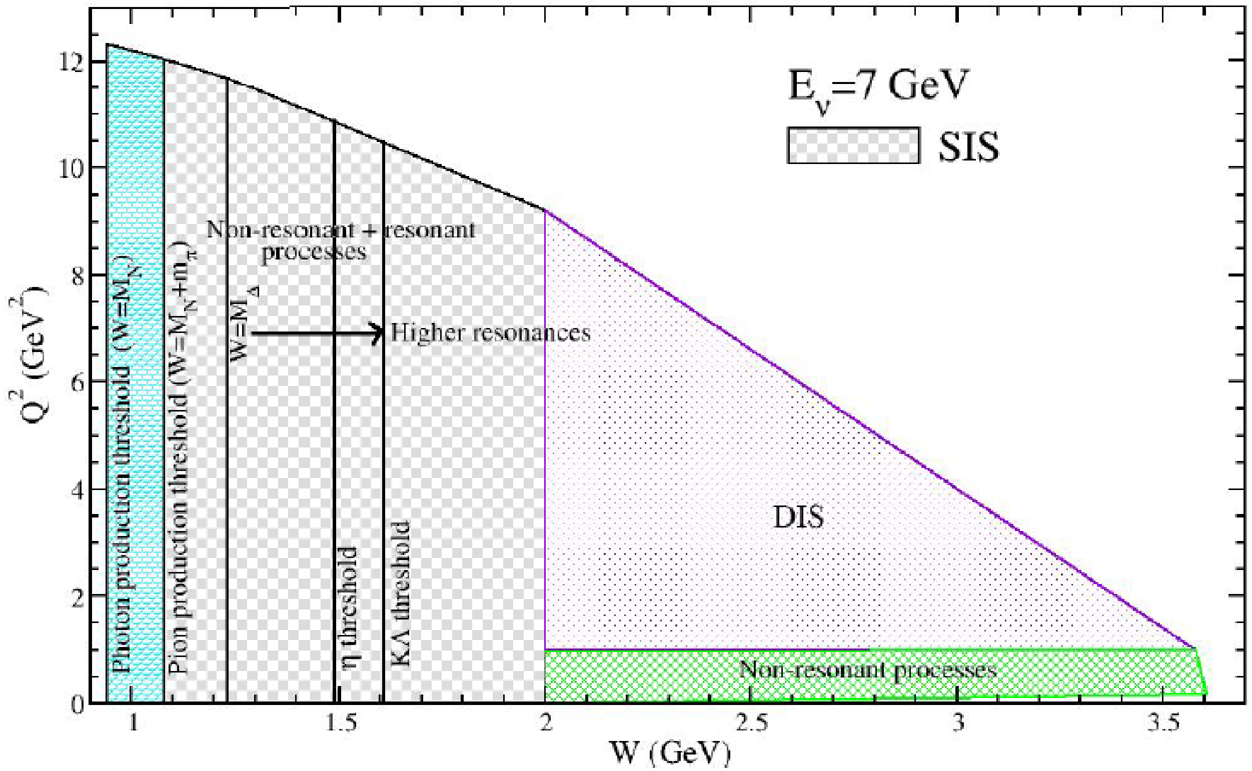


Callum Wilkinson, NuPhys19

- Around W≈1080, reactions are dominated by Δ excitation and single-pion production
- At W above the delta region, various baryon resonances, non-resonant backgrounds and interferences contribute

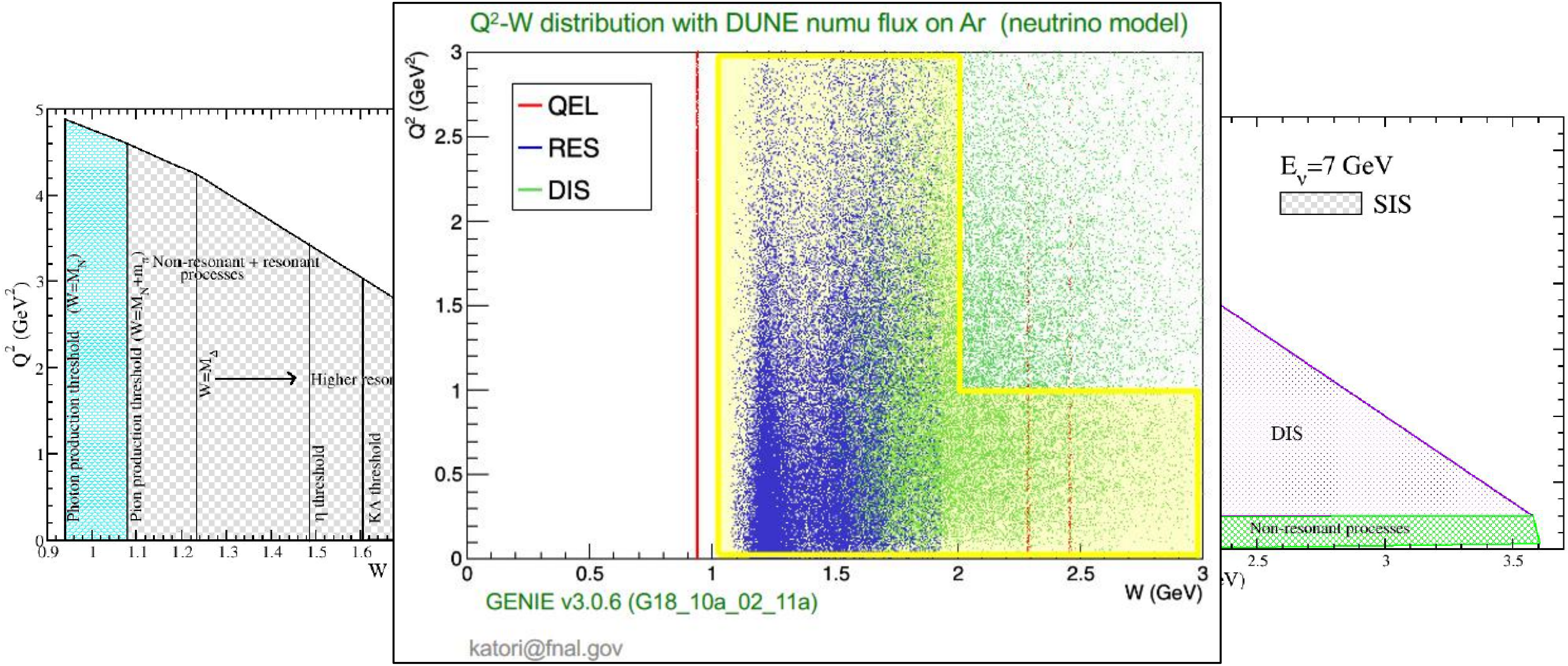
- This kinematic region is not well understood or studied, both experimentally and theoretically
- A considerable fraction of events at higher incoming energies are from these SIS and DIS regions e.g. around 50% for DUNE





Snowmass WP on theoretical tools for neutrino scattering, L. Alvarez Ruso et al, arXiv:2203.09030

- This kinematic region is not well understood or studied, both experimentally and theoretically
- Important background channel for quasi-elastic cross section measurements as the produced pions may be re-absorbed in the nuclear medium or remain otherwise unobserved, leading to a CC0π topology mimicking a QE event
- A considerable fraction of events at higher incoming energies are from the SIS and DIS regions e.g. around 50% for DUNE

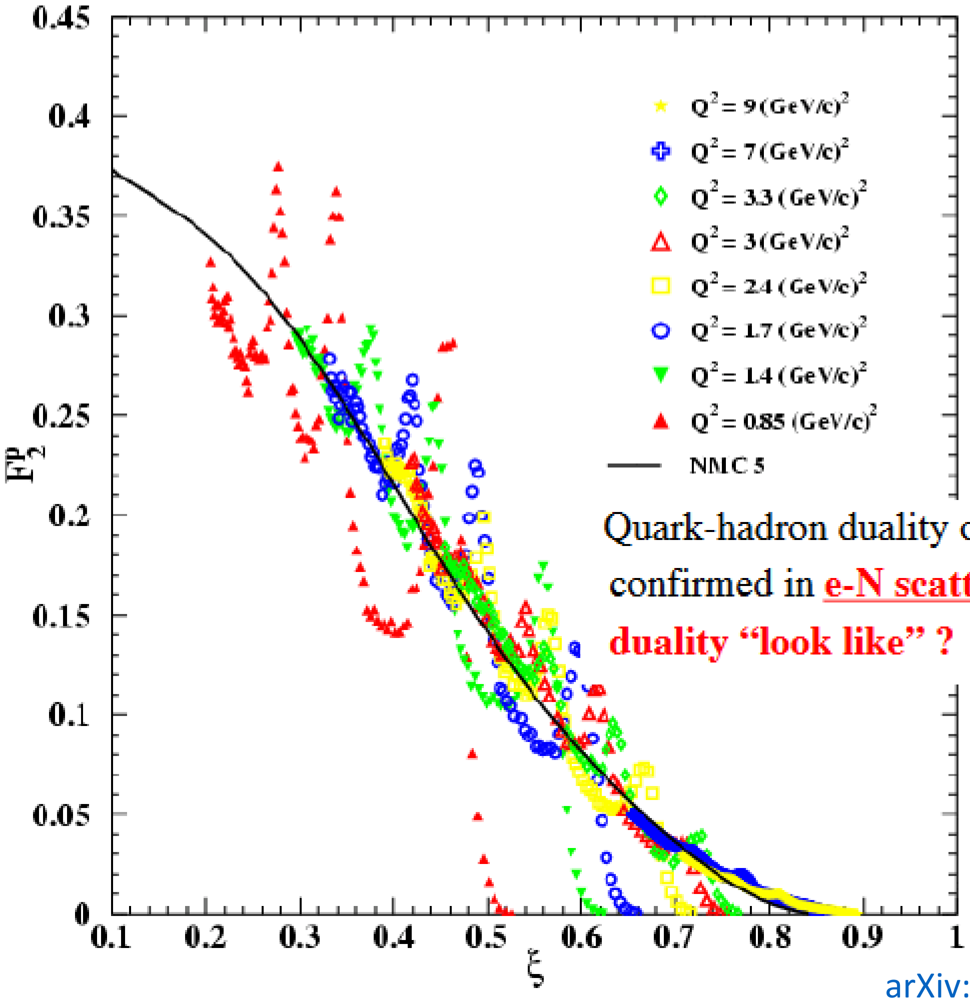


Duality and the transition from nucleon to partonic degrees of freedom

The phenomenology of the transition to partonic degrees of freedom is assessed by Bloom-Gillman duality

Jorge Morfin's talk

Electron-scattering : resonances (Jlab E94-110 data) follow the extrapolated DIS curve

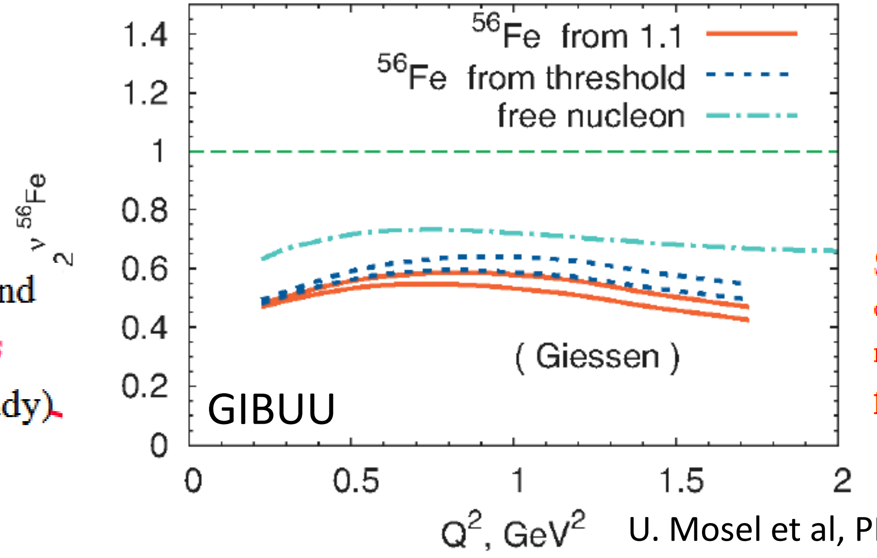


Quark-hadron duality originally studied and confirmed in **e-N scattering – what does duality "look like" ?** (Jlab **e-proton** Study)

arXiv:2203.09030

For neutrinos, the situation is less clear :

- Data is limited to low-statistics hydrogen and deuterium bubble chamber data from the 70s and 80s
- For computations the integrated resonance strength tends to account for only ~50% of the observed signal



U. Mosel et al, PRC96, 015503 (2017)

Stress the importance of including the **non-resonant** pion production!

Strong suggestion here that **for neutrinos:**
duality holds for isoscalar nucleon ($F_2^{\nu p} + F_2^{\nu n}$)/2.

What does that imply for **duality for nuclei with large neutron excess??**

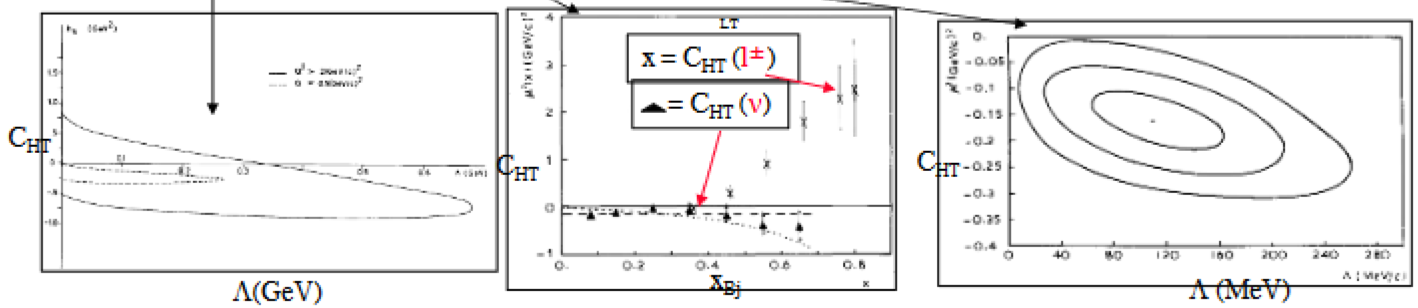
Alternatively : extrapolating from pQCD@DIS to non-pQCD@SIS

Jorge Morfin

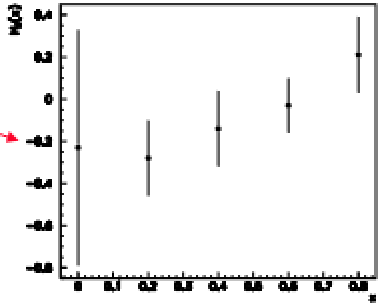
Speaking of Higher Twist – what about HT ν - A?

Growing evidence suggesting HT for ν - A is **NOT** the same as e-A

- From pQCD, with Q^2 evolution proportional to $1/\log(Q^2/\Lambda^2)$, extend into the non-pQCD regime and consider $1/Q^2$ effects: TMC and HT: $F_2^A \rightarrow F_2^A\left[1+\frac{C_{HT}^A}{Q^2}\right]$
- Gargamelle (CF_3Br) & BEBC (Ne/H) SPS experiments, LO QCD & TMC applied:



- Alekhin and Kataev – Higher Twist from CCFR F_2 and xF_3



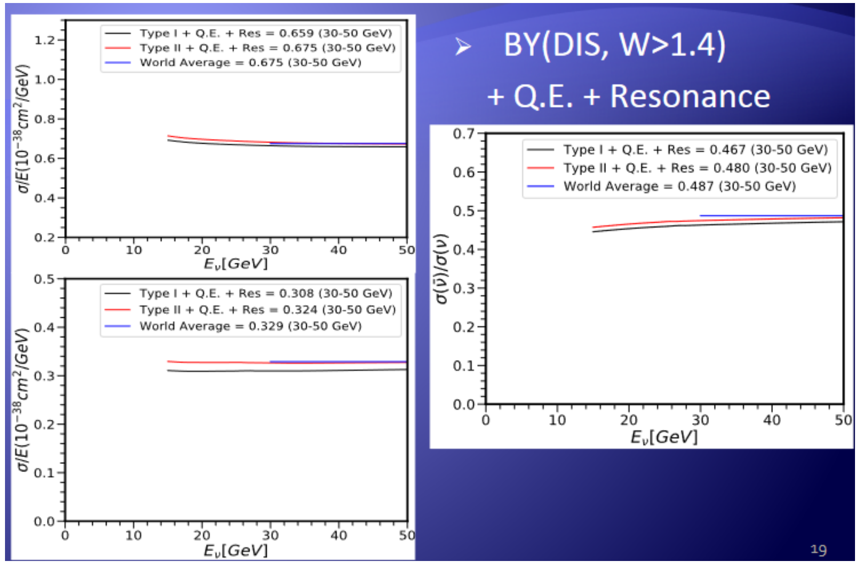
- That is C_{HT} in neutrino scattering:

smaller & negative!

Need completed MINERvA SIS and DIS analyses and better understanding of HT in neutrino scattering!

DIS : updated Bodek-Yang model

- Challenges in e/μ-N DIS
  - High x PDFs at low Q^2
  - Resonance region overlapped with a DIS contribution
  - Hard to extrapolate DIS contribution to low Q^2 region from high Q^2 data due to non-perturbative QCD effects



- BY Effective LO model with ξw describe all e/μ DIS and resonance data as well as photo-production data (down to Q^2=0): provide a good reference for vector SF for neutrino cross section
- dσ/dxdy data favor updated BY(DIS) type II model
- BY(DIS) type II model (low Q^2: axial>vector) provide a good reference for neutrino cross sections. Low energy neutrino experiments can normalize their data to our model to extract their flux
- Model also works well down to W=1.4 GeV, thus providing overlap with resonance models
- Future improvement: use very high-x data (nCTEQ effort)

Tackling problems and uncertainties

Several avenues must be pursued to improve our knowledge on neutrino-nucleus scattering and keep up with experimental developments and needs :

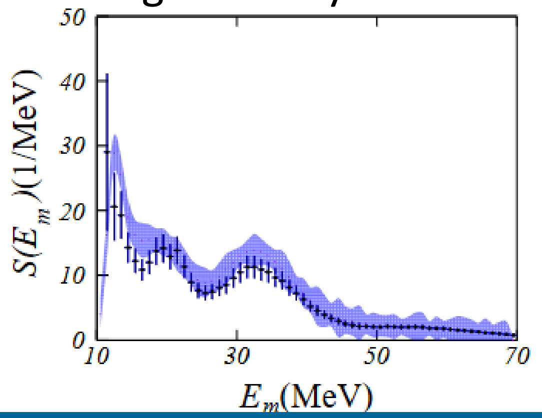
- Further theory efforts

Systematic errors due to ν cross section and flux uncertainties are dominant ($\sim$ 3%) ...

It is faster and cheaper to pay a theoretician to reduce 2 % your systematics than building huge detectors!

Guillermo Megias NuInt18

- More neutrino data on nuclei and nucleons
- New H/D experiment
- Constraints from electron scattering : talks by Camillo Mariani and Noah Steinberger



JLab E12-14-012

LQCD constraints

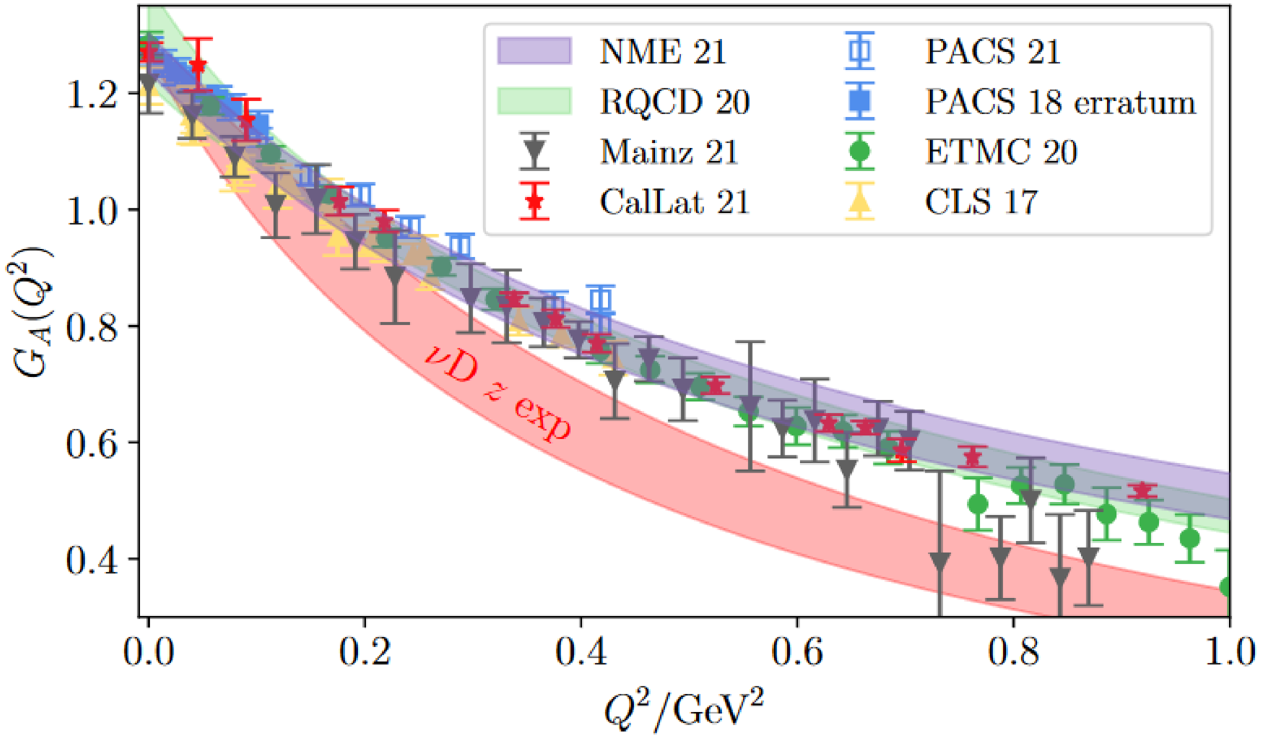
Neutrino-nucleon form factors constitute a major source of uncertainty in neutrino scattering modeling

- Weak vector form factors are well constrained by electron scattering experiments
- Q^2 evolution of the axial form factor is not well-known, mainly based on old bubble chamber data (ANL, BNL, FNAL)

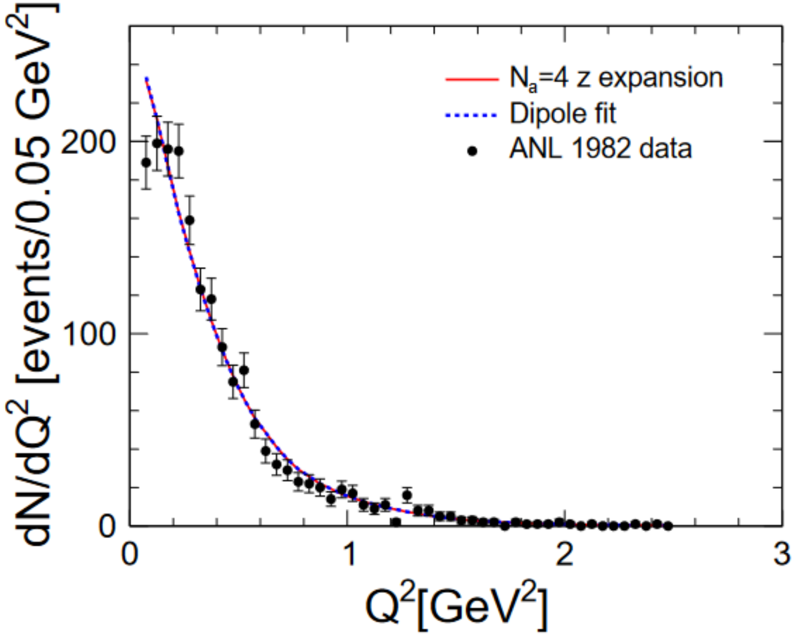
$$F_A(Q^2) = \frac{g_A}{(1+Q^2/M_A^2)^2}$$

β-decay

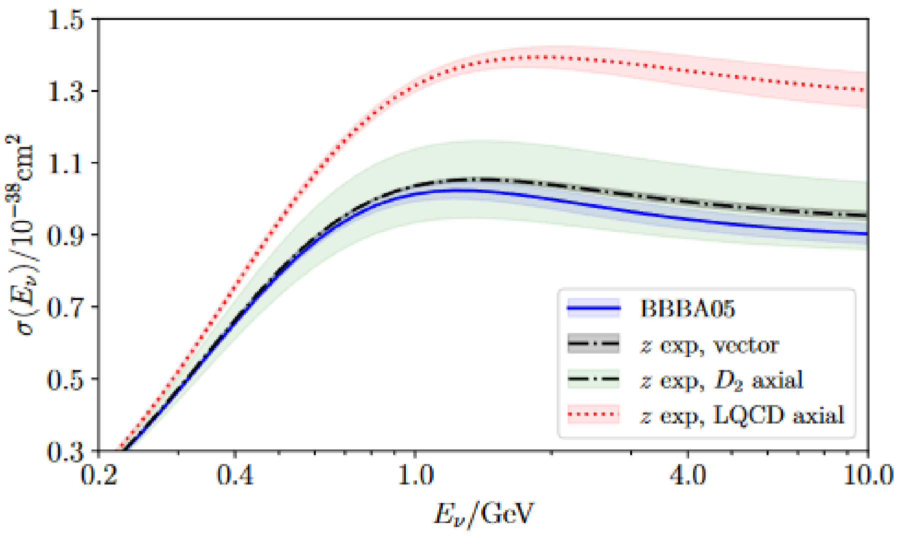
'free' parameter



Aaron Meyer's talk



A. Meyer et al, PRD93, 113015 (2016)



Neutrino cross section on a free nucleon :

- Improved LQCD prediction owing to better control of excited state contamination
- Softer slope of the axial form factor's Q^2 dependence leads to enhanced cross section on the nucleon
- Considerable reduction of the uncertainty

A. Meyer et al arXiv:2201.01839

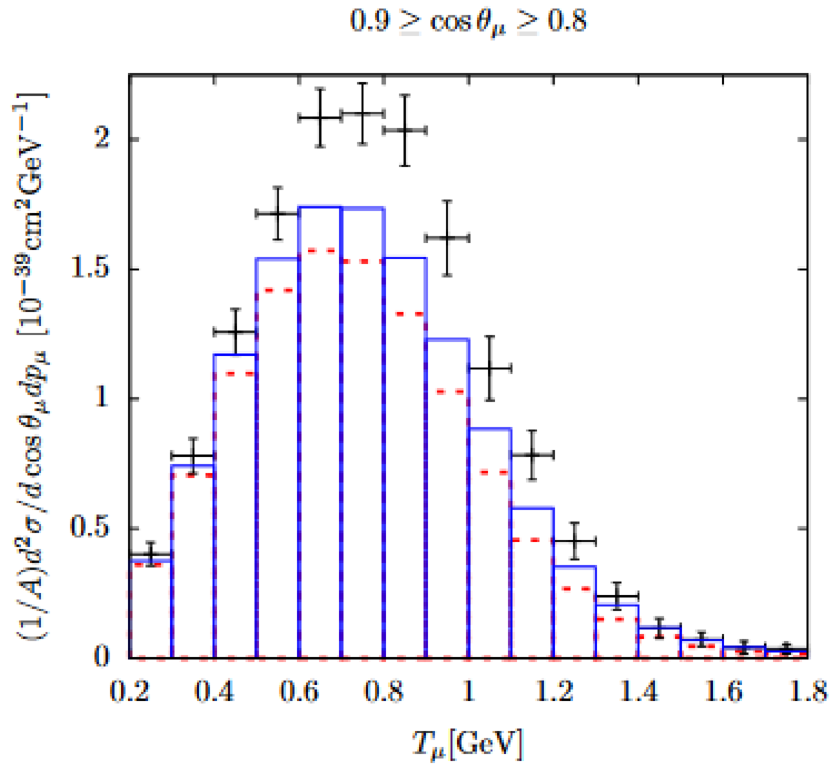
Further future opportunities for neutrino scattering from LQCD :

- Extend LQCD calculations toward resonance production and the SIS region to better inform effective nuclear theories
- Information on nucleon-nucleon correlations to lift degeneracies between ν–nucleon and nuclear effects that hamper modeling efforts and data comparison for ν–nucleus scattering
- DIS structure functions with systematic error budgets

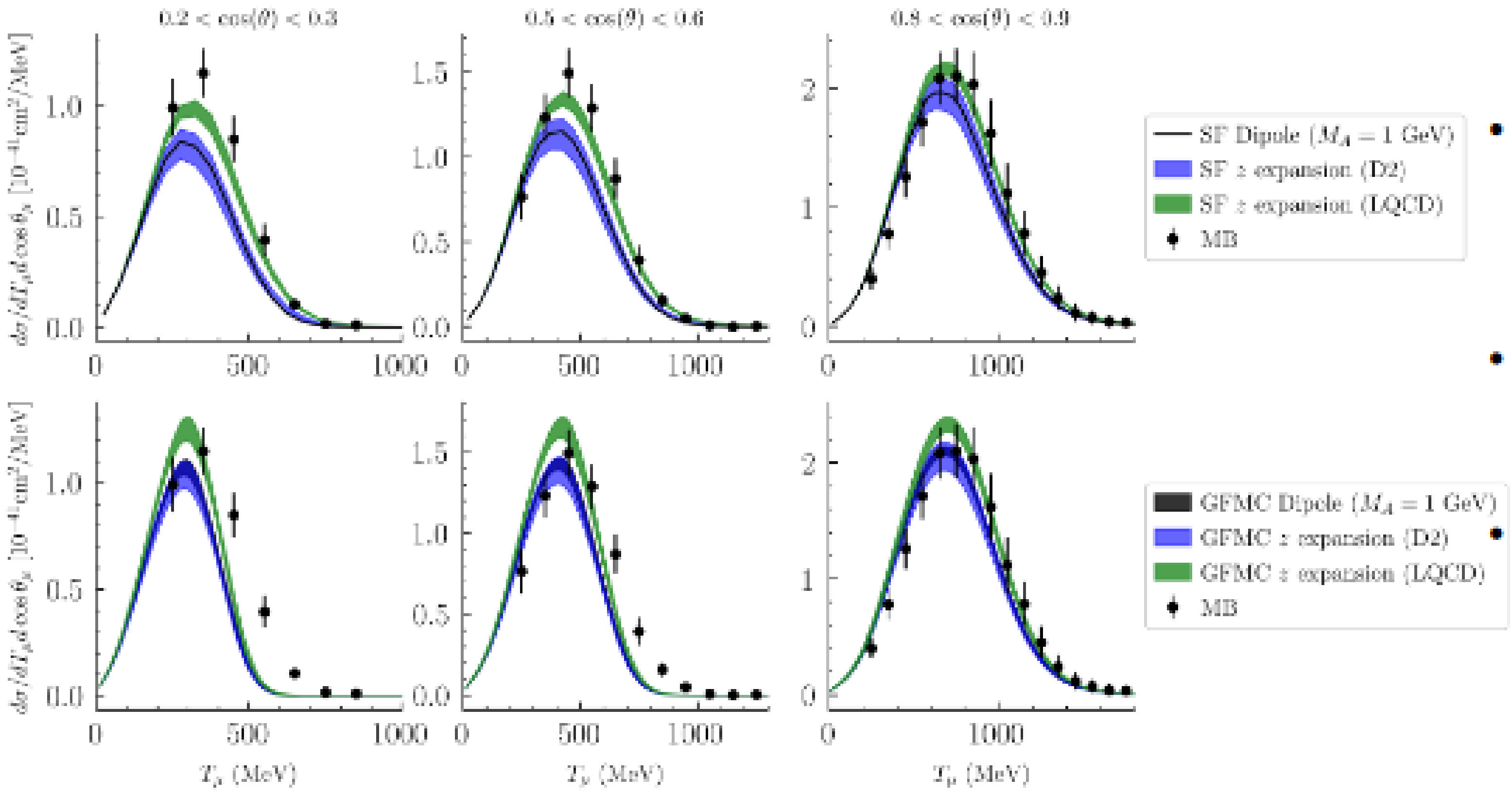
Omar Benhar's talk

- ⋆ Replacing the $M_A = 1.03$ MeV dipole parametrisation with the lattice QCD axial form factor leads to a $\sim 10-15\%$ enhancement of the single-nucleon knock out cross section, suggesting a corresponding reduction of the MEC contribution

MiniBooNe data

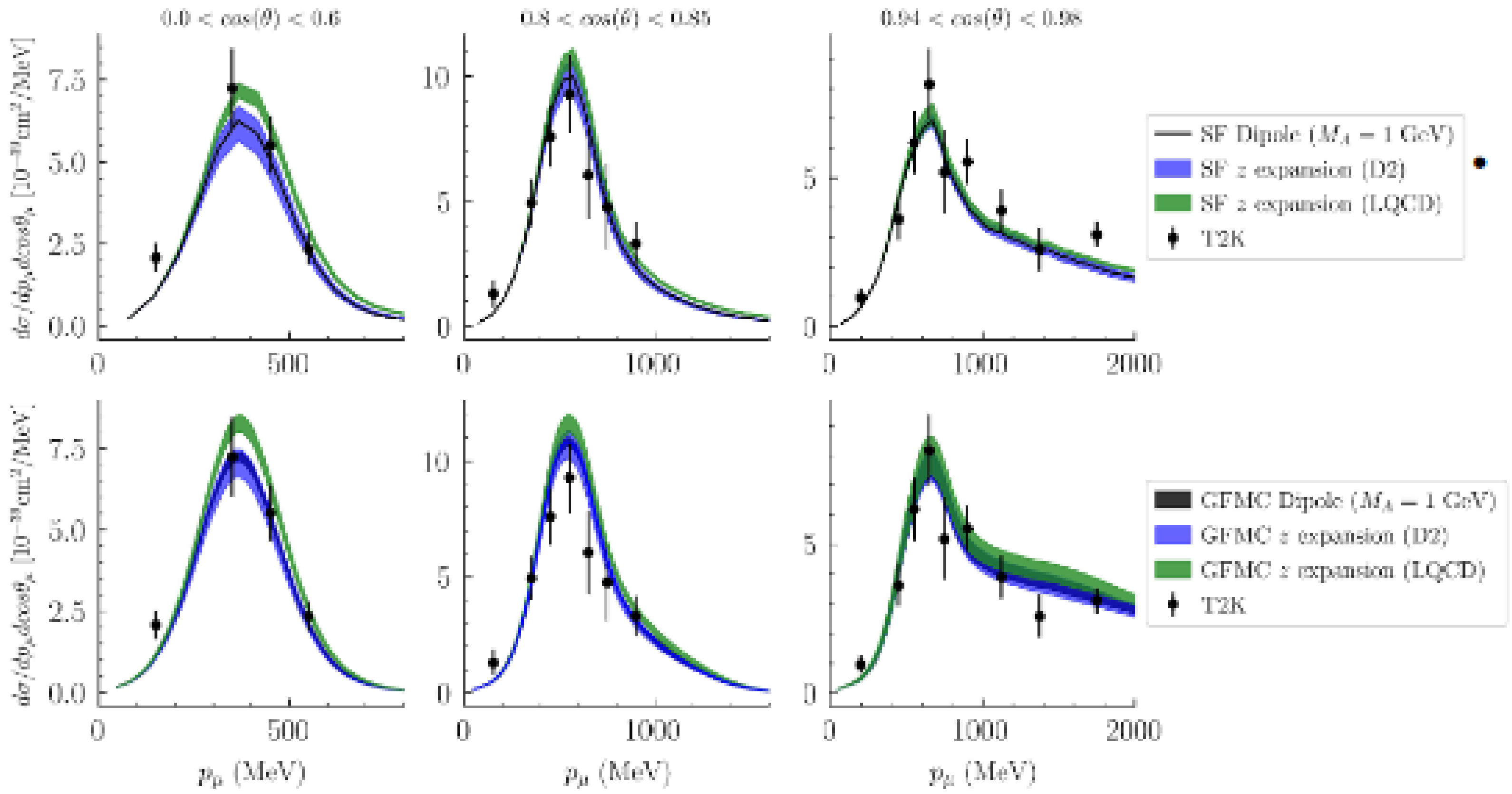


MiniBooNE – Form Factor Breakdown



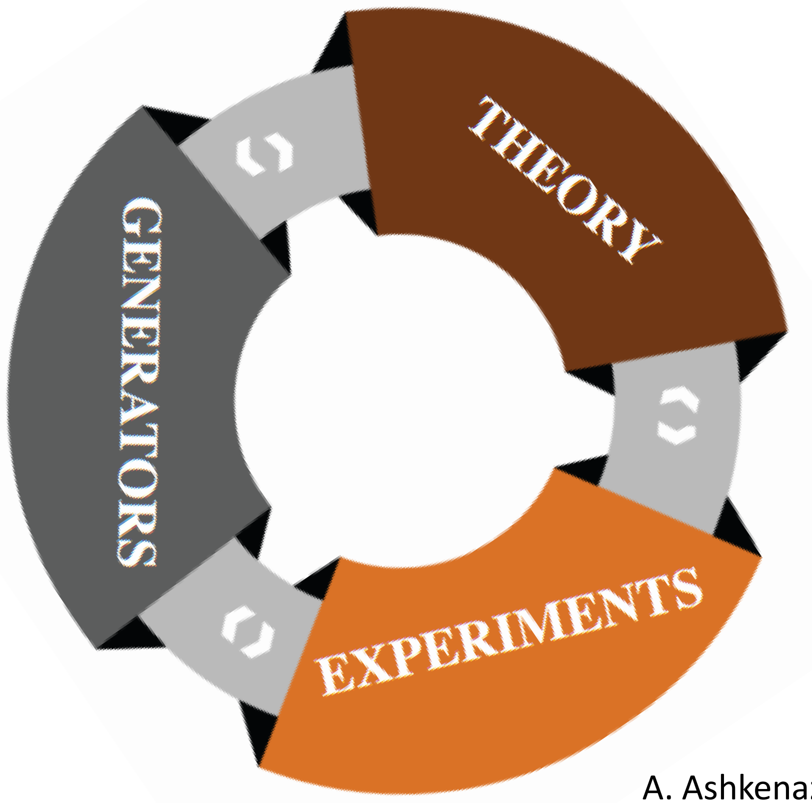
- Dipole vs. LQCD z expansion vs. D2 z expansion
- Universal 10-20% increase in normalization with LQCD z expansion
- SF agreement better with LQCD z expansion
- GFMC disagreement regardless of form factor

T2K – Form Factor Breakdown



- T2K comparison fairly independent of parameterization
- Mostly due to T2K's lower beam energy and thus Q^2 where form factors agree

Conclusions – prospects for neutrino-nucleus scattering



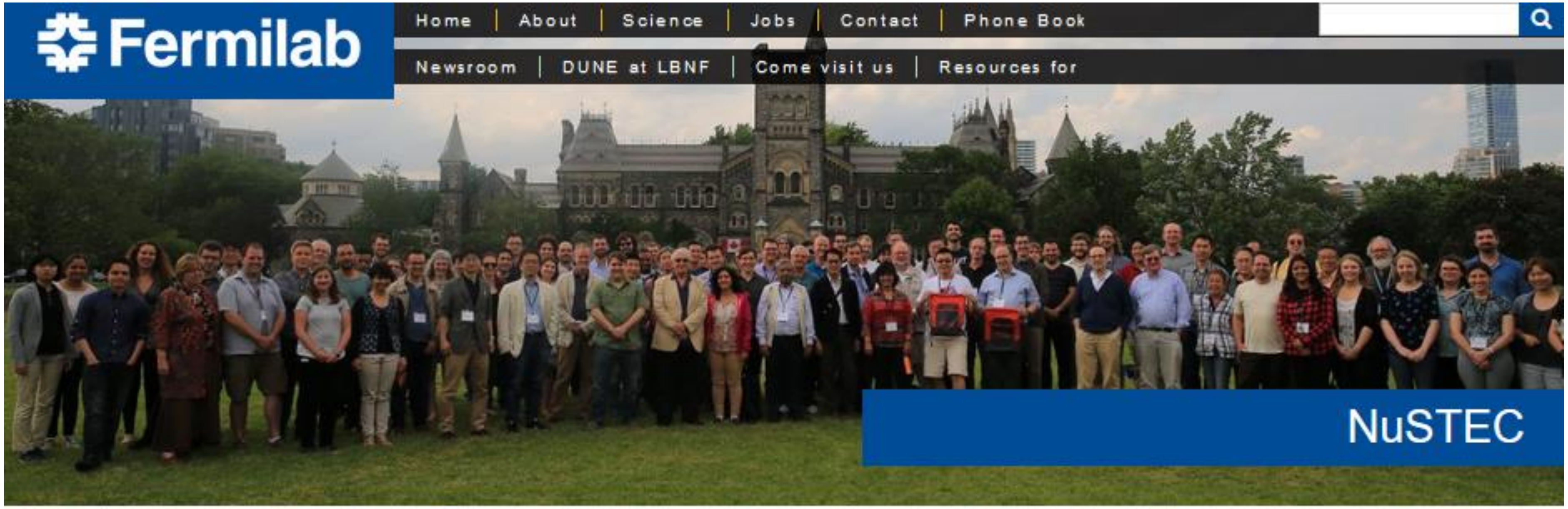
A. Ashkenazi

- The convoluted problem presented to neutrino-nucleus modeling by the neutrino oscillation program requires intensive efforts in several domains
- Experimental progress must be met by theoretical advances in neutrino interaction modeling
- Theory needs constraints, limited by the current lack of data and flux uncertainties
- Progress will require :

✓ Extensive collaboration between theorists, experimentalists and generator developers
✓ Input from electron scattering
✓ Experimental constraints, new H/D measurements would be great !
✓ More theory efforts
✓ Generators need to be equipped with more detailed cross section models

These are exactly the goals of the **NuSTEC** collaboration !

https://nustec.fnal.gov/



Home

- NuSTEC News
- NuSTEC school
- NuInt conference series
- Workshops, conferences, schools
- Cross Experiment Working Group (CEWG)
- Cross Theory and Generators Working Group
- Long-term Community Planning
- Outreach
- Publications Working Group

NuSTEC: Neutrino Scattering Theory Experiment Collaboration

What is NuSTEC?

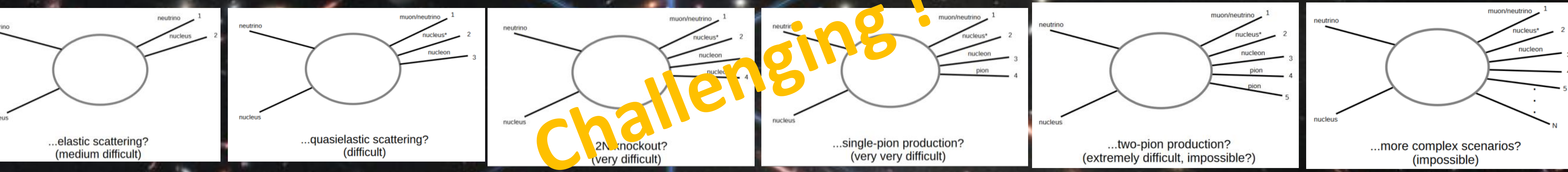
NuSTEC is a collaboration of theorists and experimentalists promoting and coordinating efforts between:

- Theorists – studying neutrino nucleon/nucleus interactions and related problems
- Experimentalists – primarily those actively engaged in neutrino-nucleus scattering experiments as well as those trying to understand oscillation experiment systematics. Electron scattering experimentalists are certainly welcome.
- Generator builders – actively developing/modifying the model of the nucleus as well as the behavior of particles in/out of the nucleus within generators.

The main goal is to improve our understanding of neutrino interactions with nucleons and nuclei and, practically, get that understanding in our event generators.

Where should we go from here ?

- The upcoming generation of experiments needs cross section calculations with unprecedented accuracy and reliable uncertainty estimates



Raul Gonzalez-Jimenez

- We have to tackle the currently existing degeneracy between nucleon uncertainties and nuclear effects, and between cross section and flux uncertainties
- We need calculations for more exclusive processes
- Argon targets
- Especially in the kinematic region beyond the quasielastic and the delta region, a lot of open issues remain
- Combine strength of microscopic quantummechanical modeling and generator approaches to FSI and make sure theoretical progress finds it way to generators

Snowmass WP on theoretical tools for neutrino scattering, L. Alvarez Ruso et al, arXiv:2203.09030