FACULTY OF SCIENCES
DEPARTMENT OF PHYSICS AND ASTRONOMY

Theory of neutrino interactions

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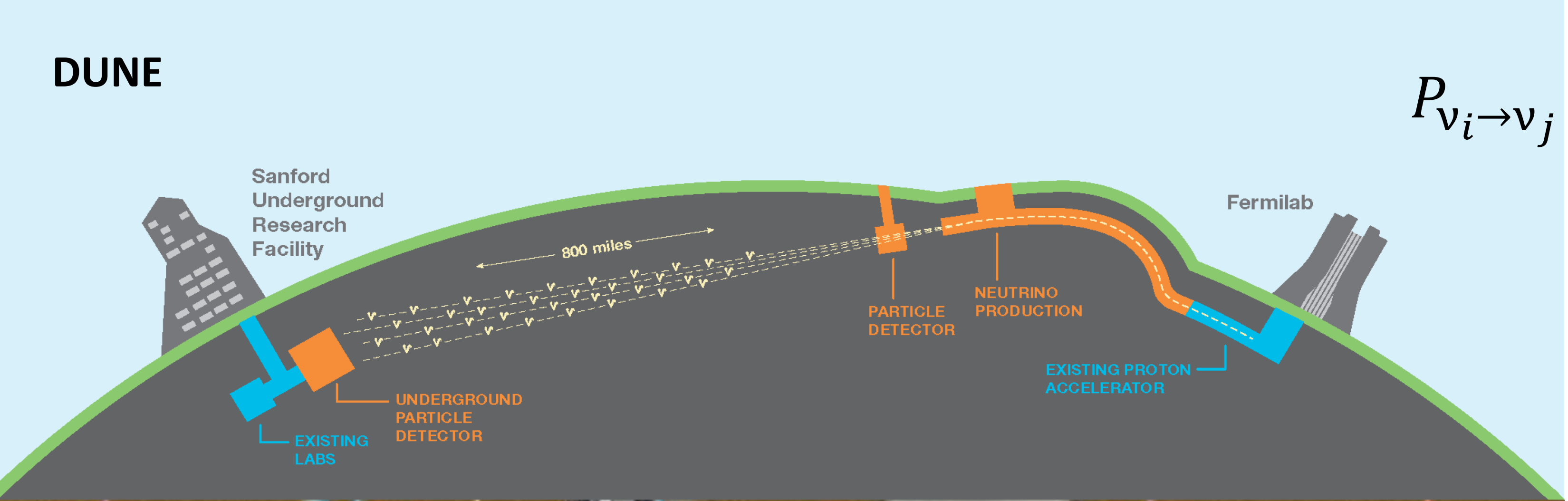
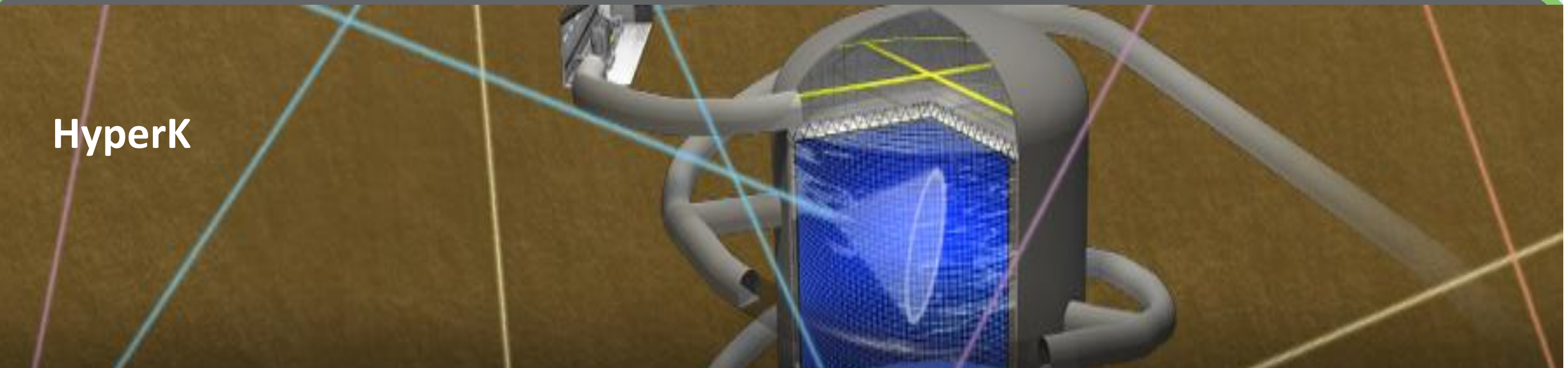
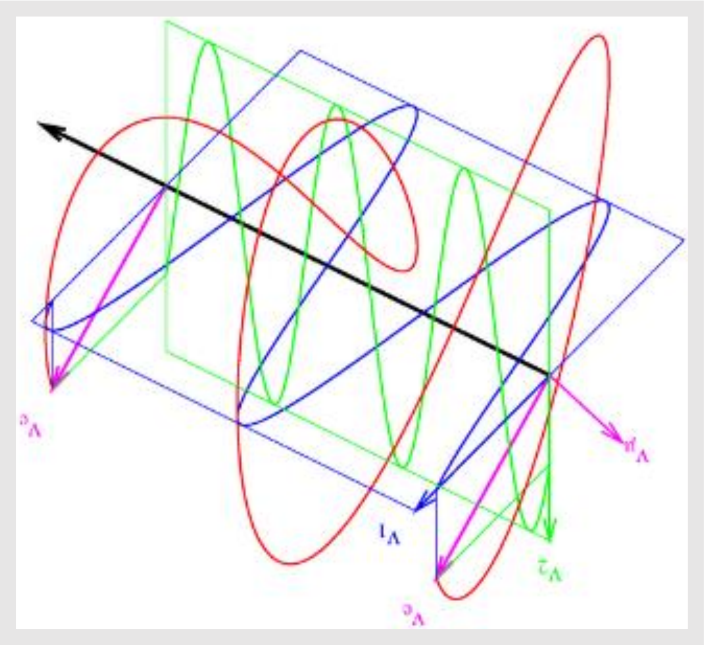
Motivation : Accelerator-based Neutrino-Oscillation Experiments

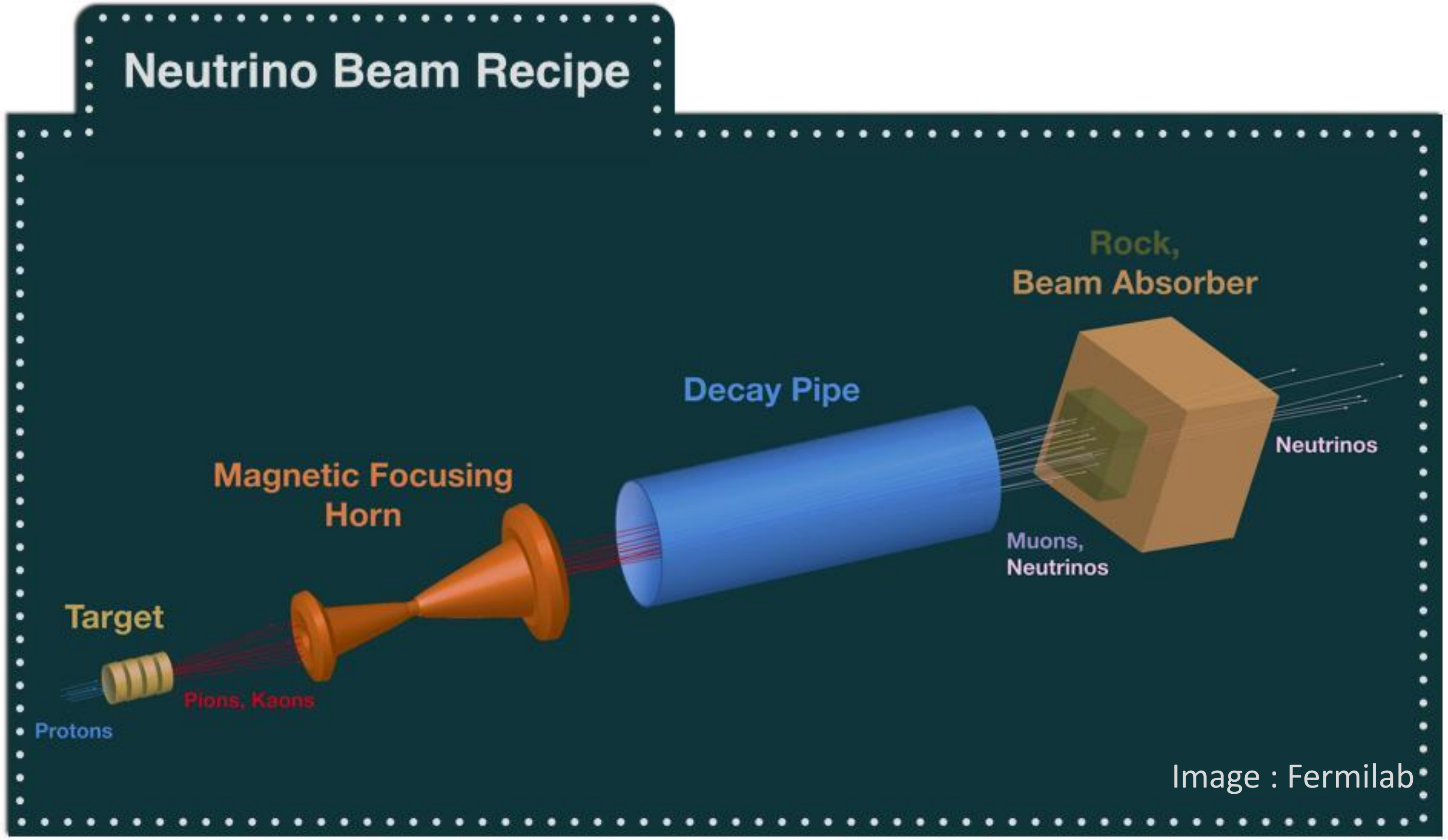
- ν_μ are produced, part of them is detected in the near detector
- Neutrinos propagate from near to far detector, neutrino oscillations occur underway
- Neutrinos are detected in the far detector
- *Count* different neutrino flavors at near and far detector
- Extract information about mass differences and mixing angles, parity violating phase .... from different observations between near and far detector





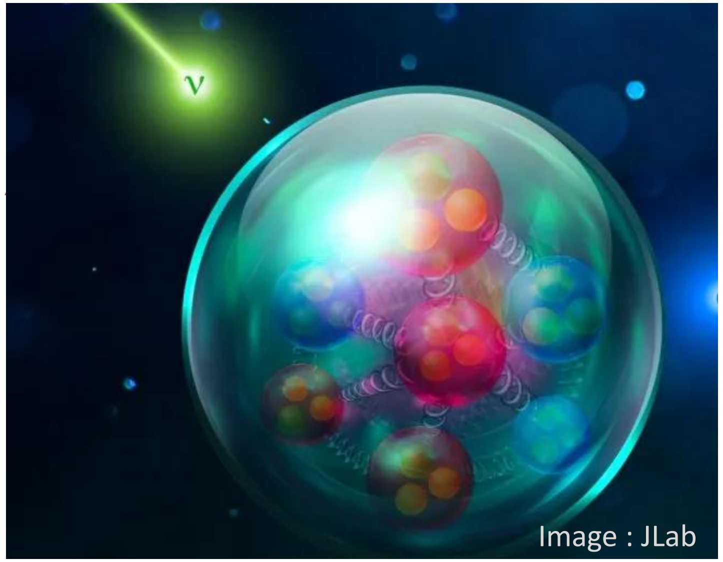
$$P_{\nu_i \rightarrow \nu_j} = sin^2 2\theta sin^2 \left(\frac{\Delta m^2}{4E} L \right)$$





See Laura Field's talk for an experimental overview !

- 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

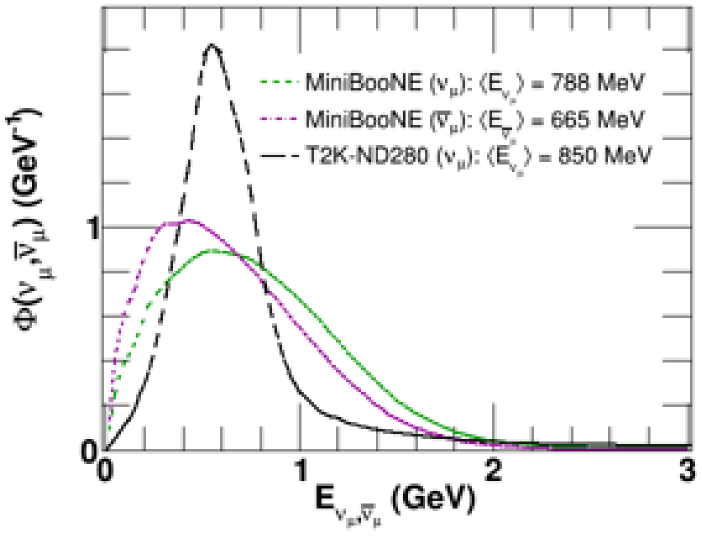


Oscillation analysis in a near/far detector experiment :

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

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

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

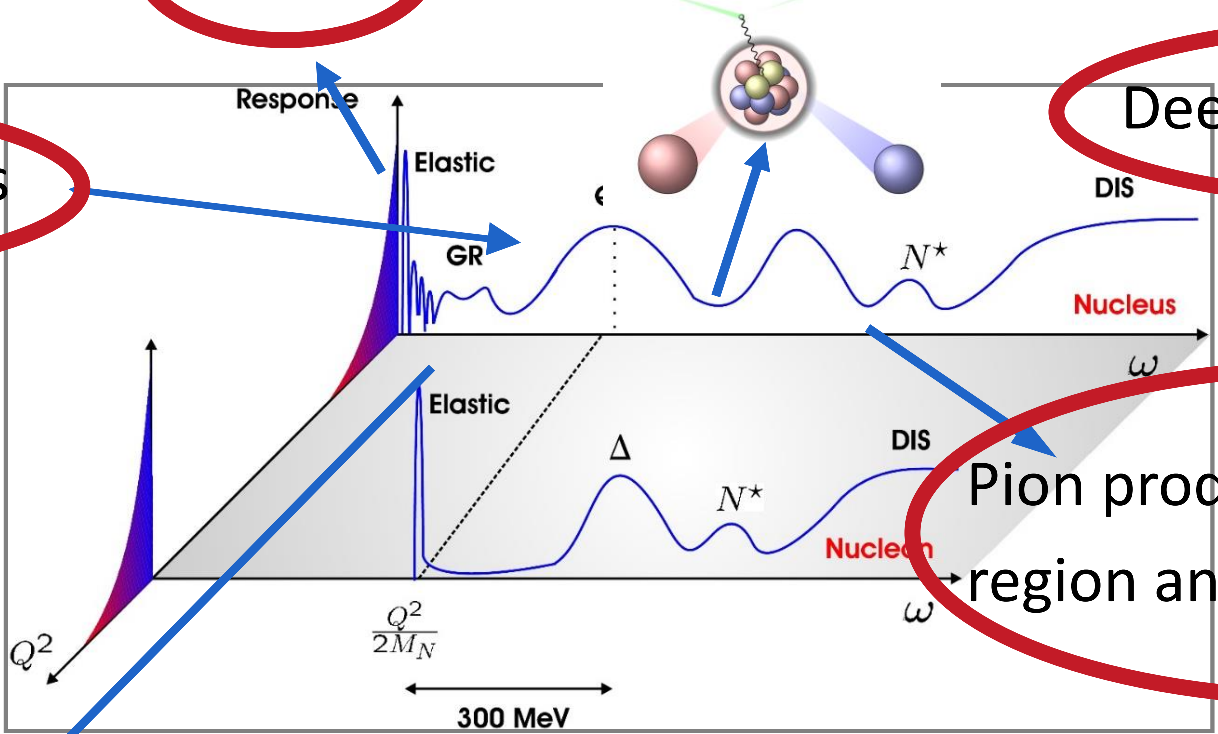
Overview

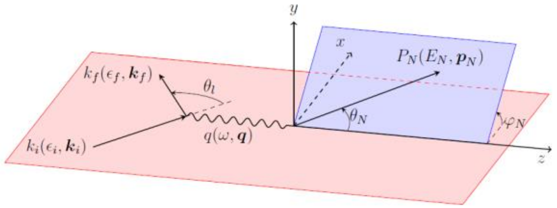
CEvNS

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

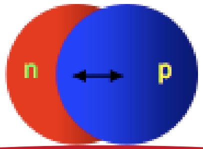
Quasi-elastic processes

Deep Inelastic Scattering



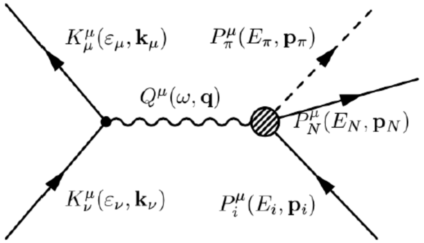


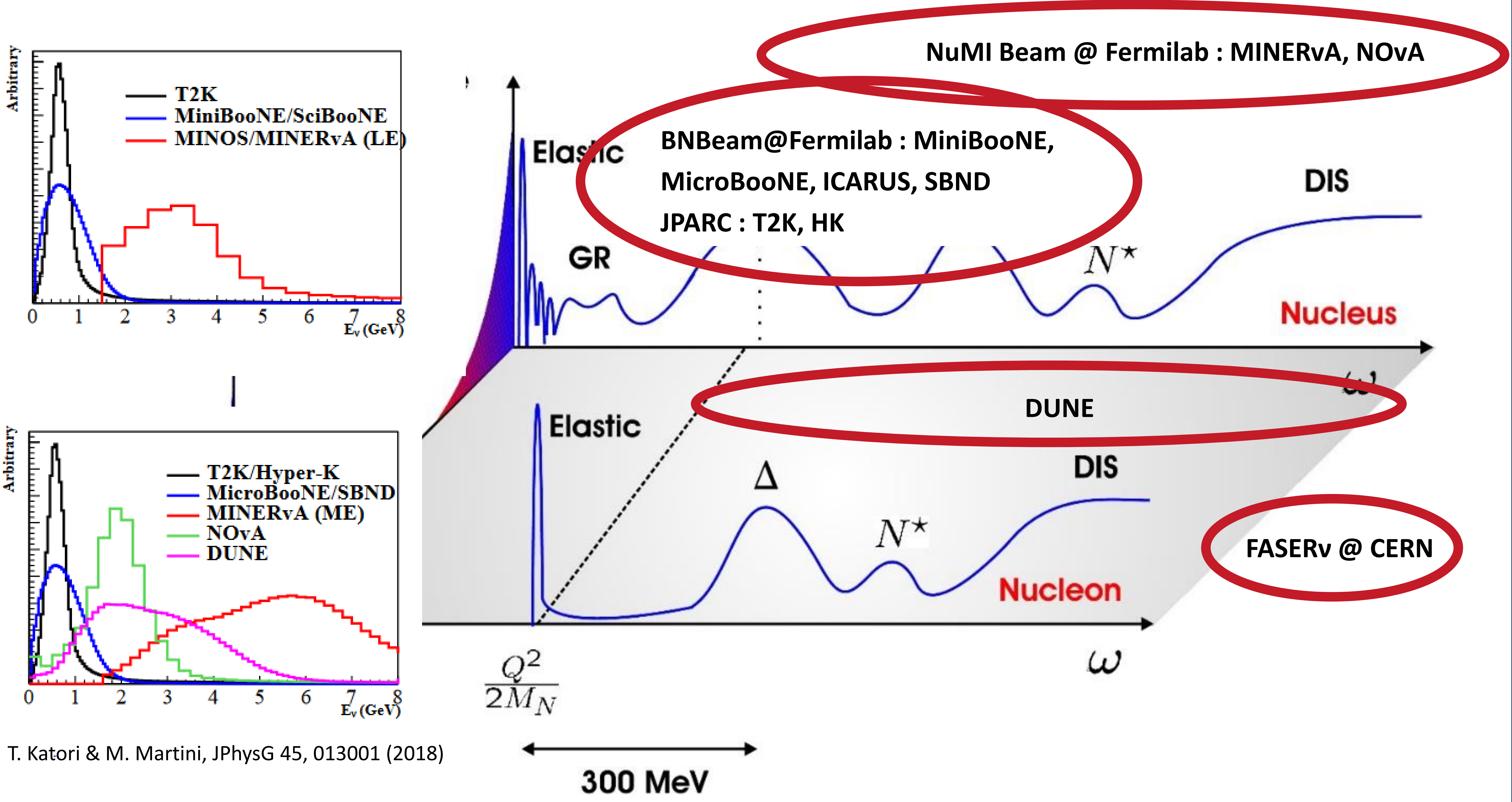
Pion production in the delta region and beyond



Low energy collective excitations

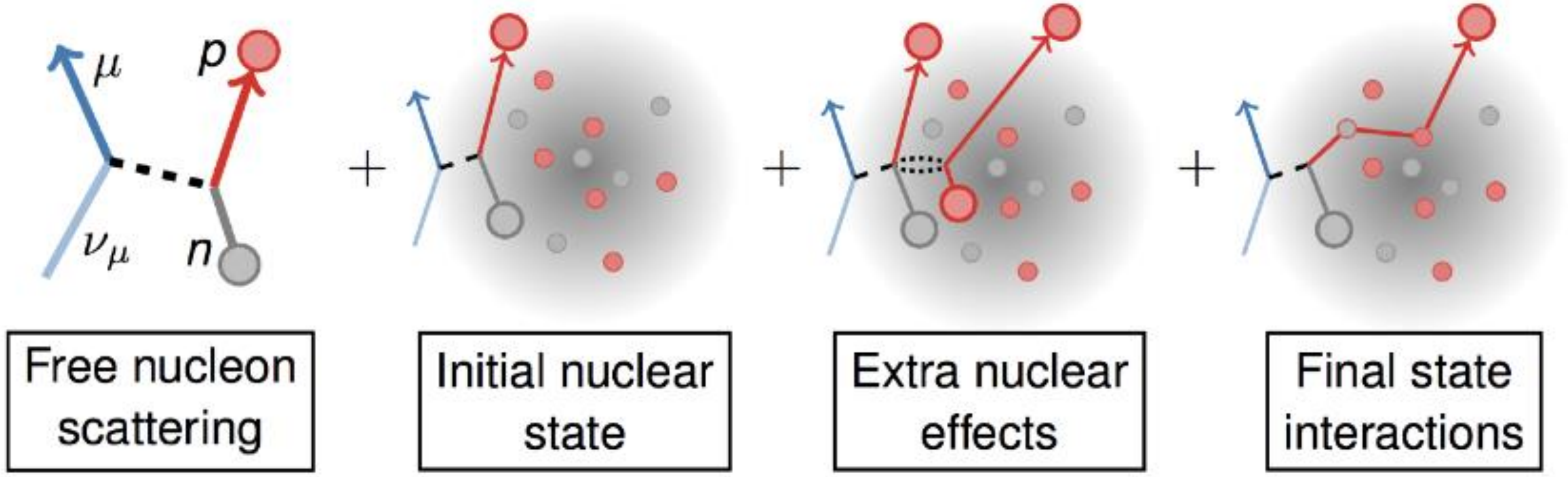
Rich nuclear physics program !



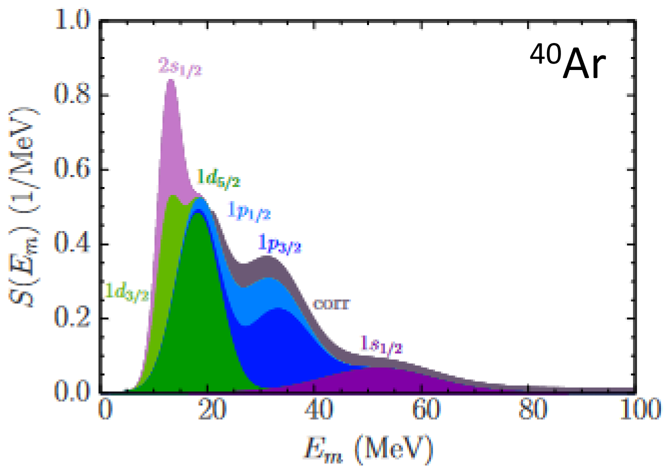


T. Katori & M. Martini, JPhysG 45, 013001 (2018)

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

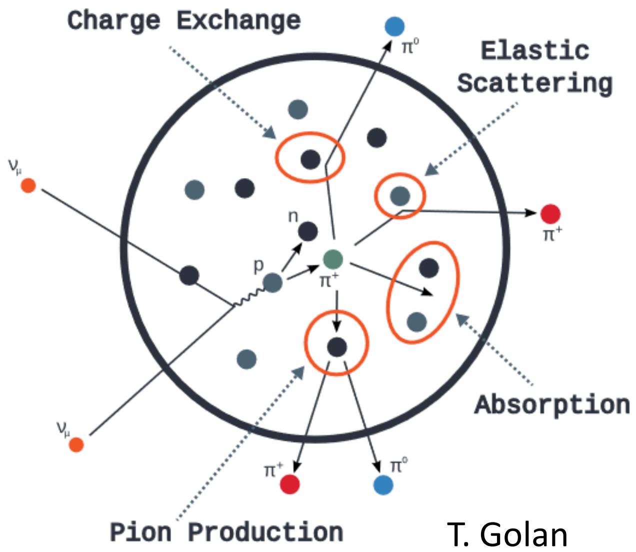


K. Niewczas @ NuFACT2021



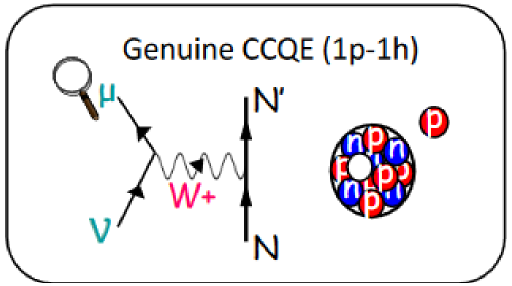
arXiv:2203.01748

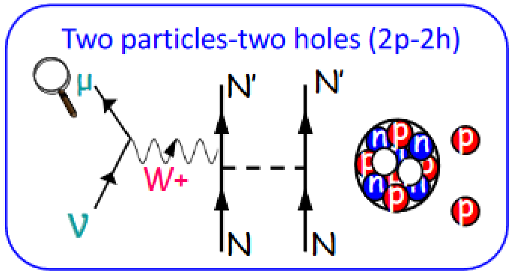
- Partly taken into account by some of the nuclear models
- MC Generators used for oscillation analyses tend to rely on efficient but approximate models



T. Golan

Quasi elastic versus multinucleon knockout processes



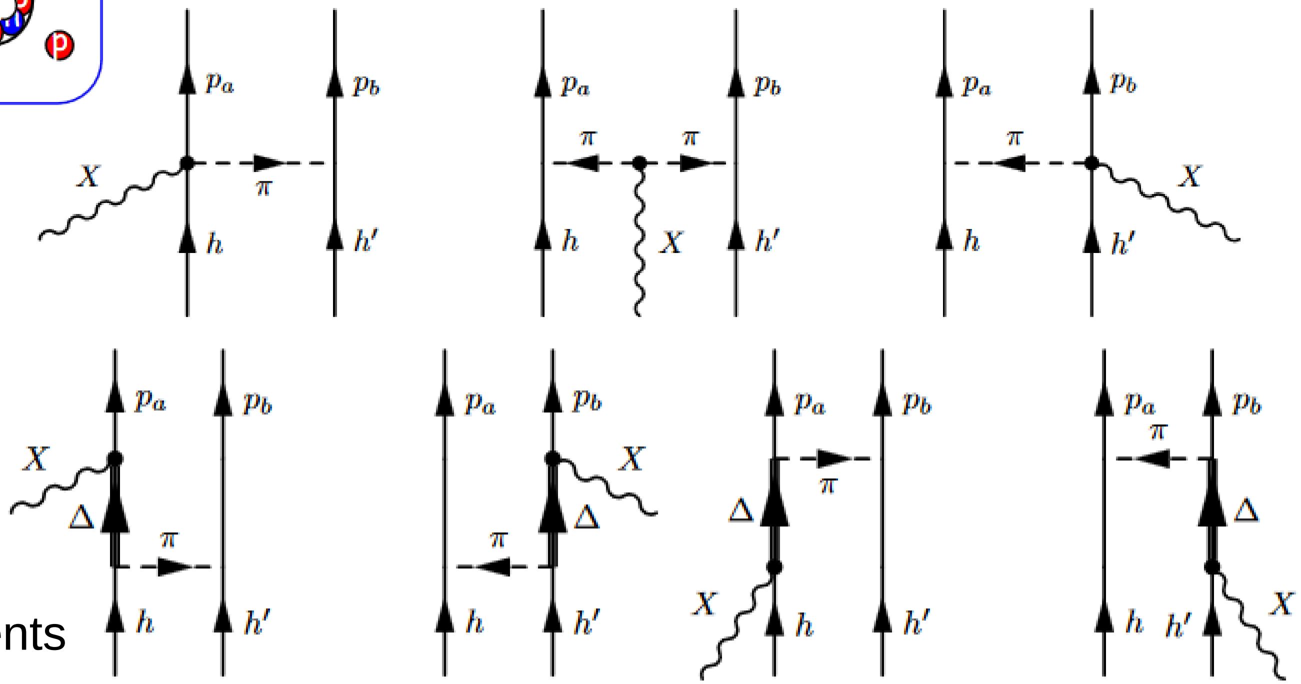


- QE processes are dominating the signal in experiments with average energies of a couple of hundreds of MeVs
- A thorough understanding of the QE cross section is extremely important as it is pivotal for energy reconstruction and oscillation analysis
- Correct identification of the reaction mechanism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

Meson-exchange currents

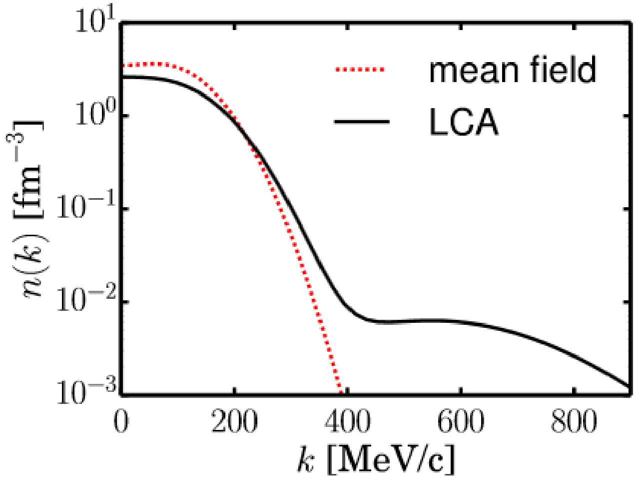
Seagull

Pion in flight



Delta currents

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



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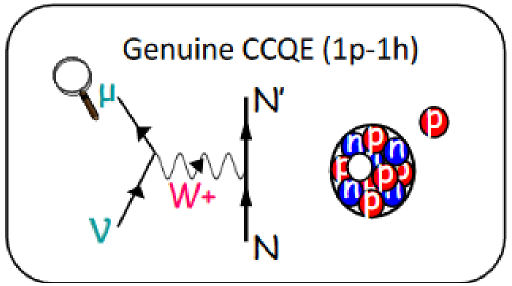
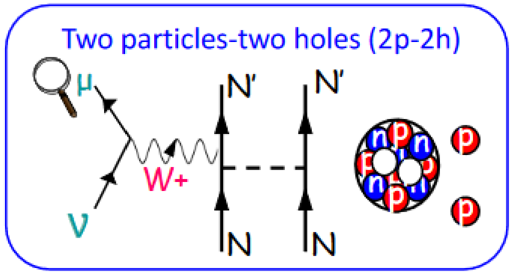


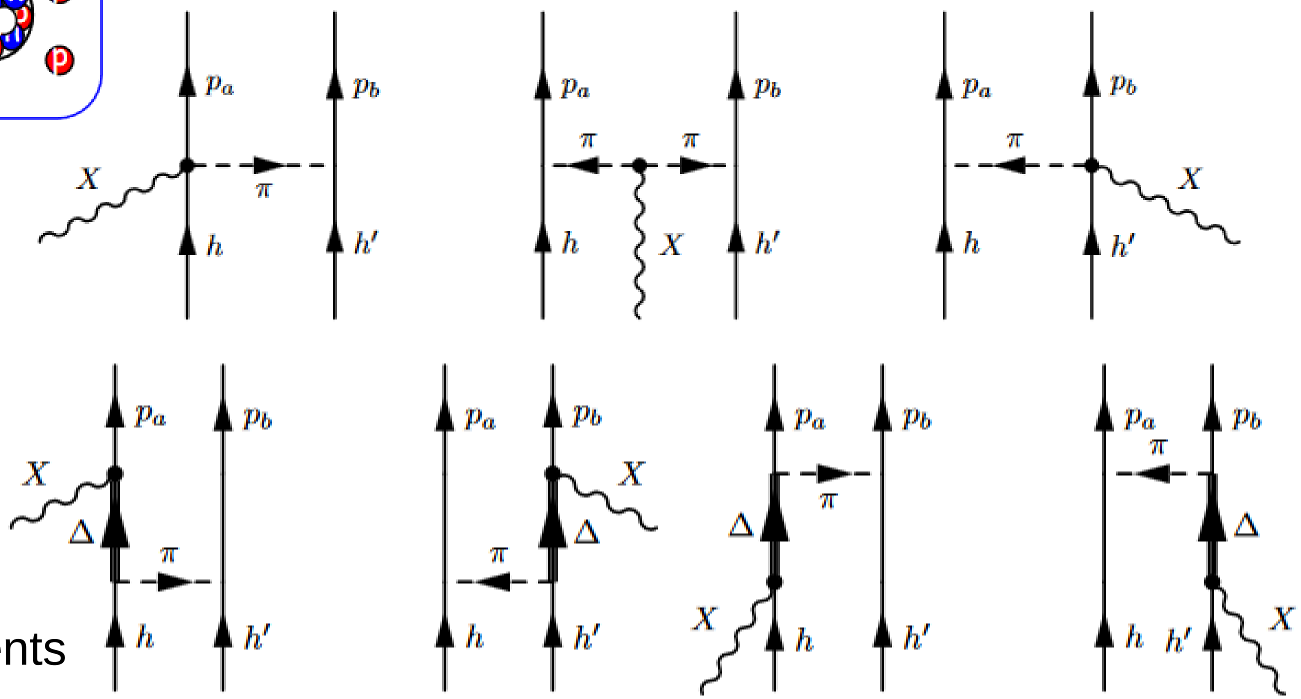


When an electroweak boson interacts with a pair of nucleons which are correlated through short-range correlations or through the exchange of a meson, this will cause the knockout of one or both of the particles from the nucleus.

Meson-exchange currents

Seagull

Pion in flight



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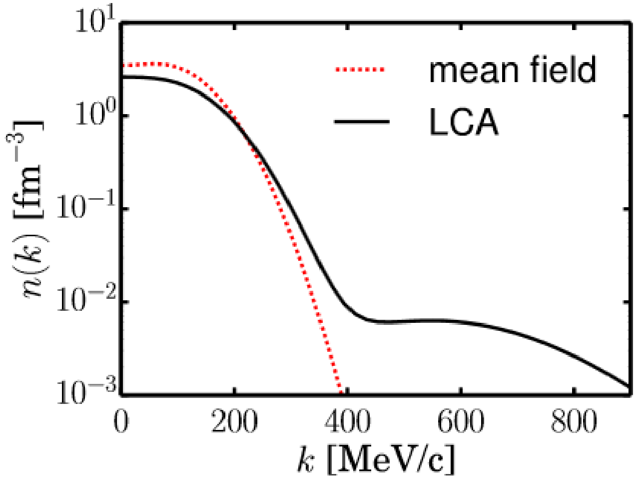
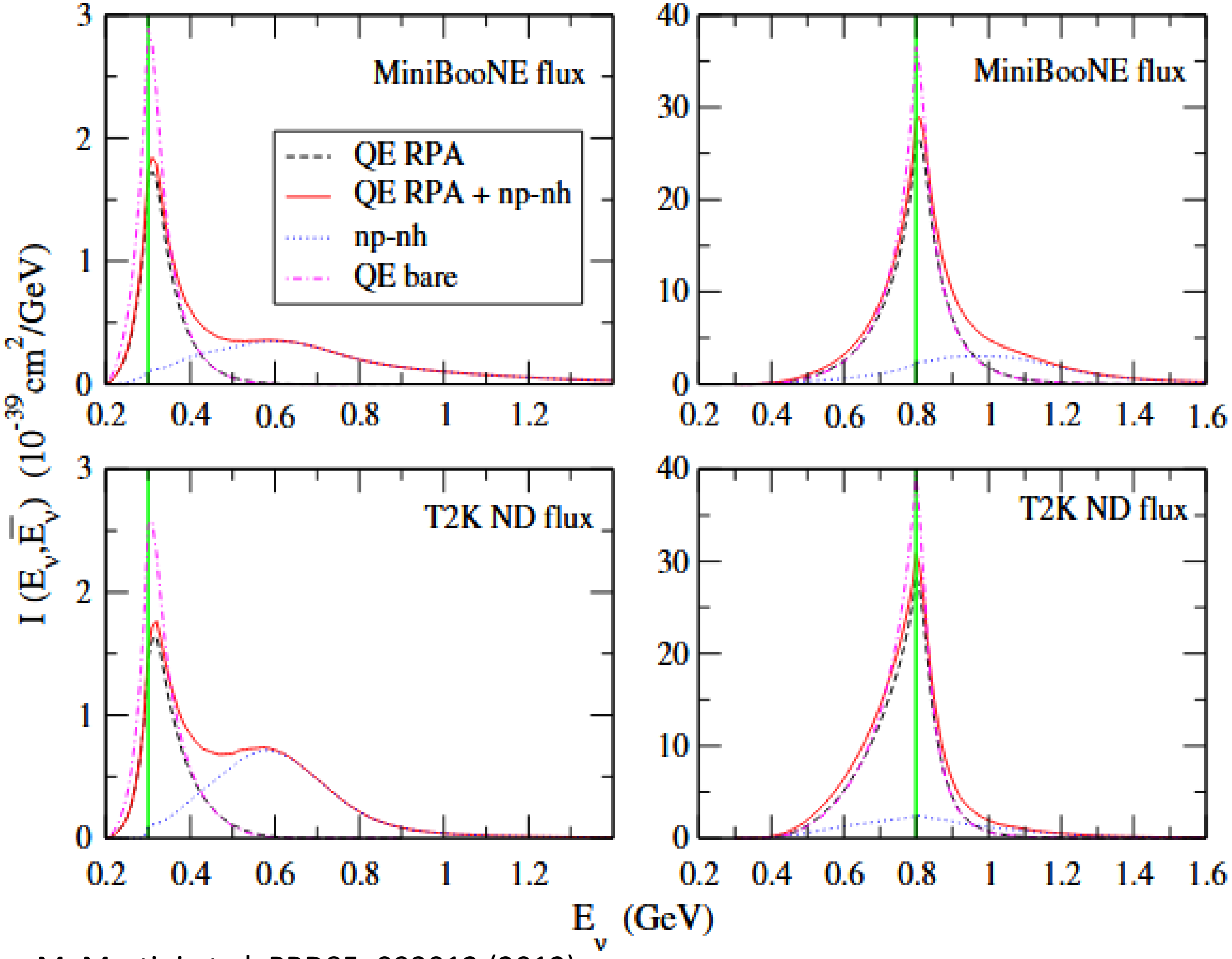
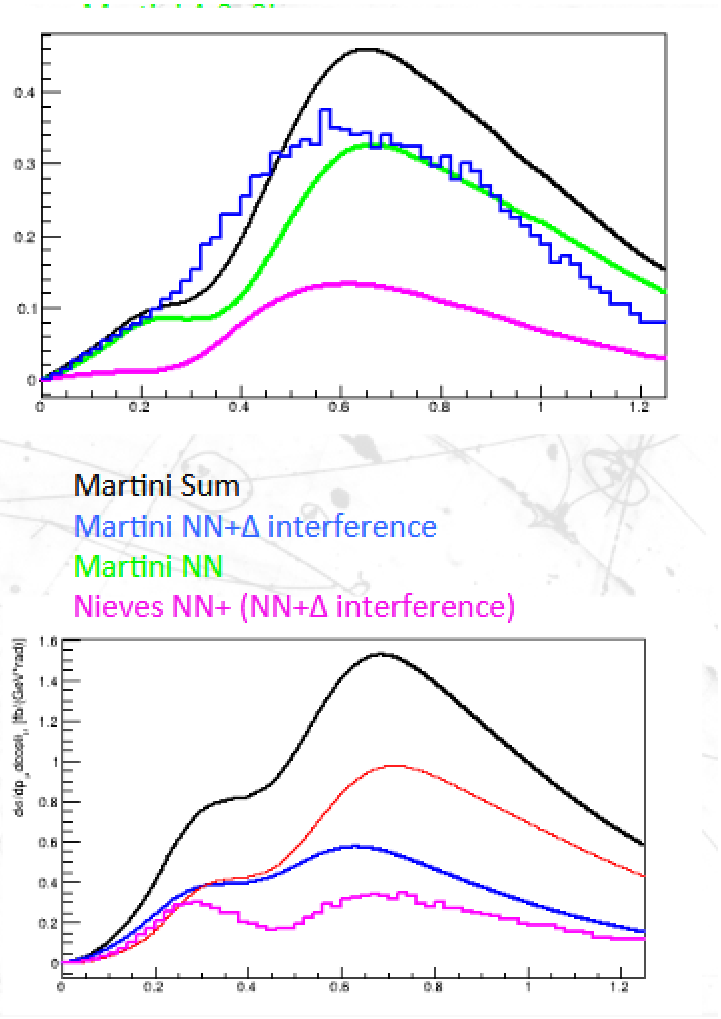


Multinucleon effects affect energy reconstruction !



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

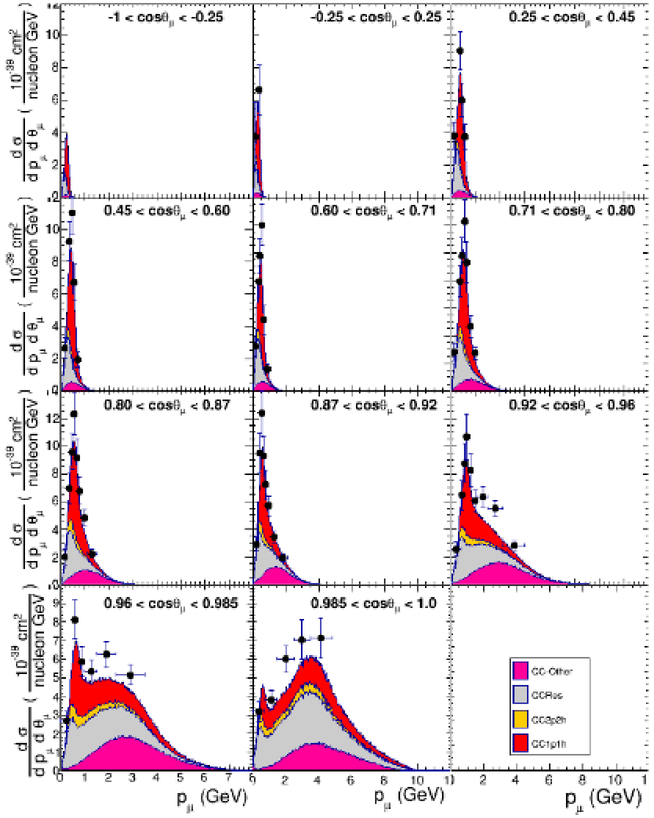


F. Sanchez, NuInt2017

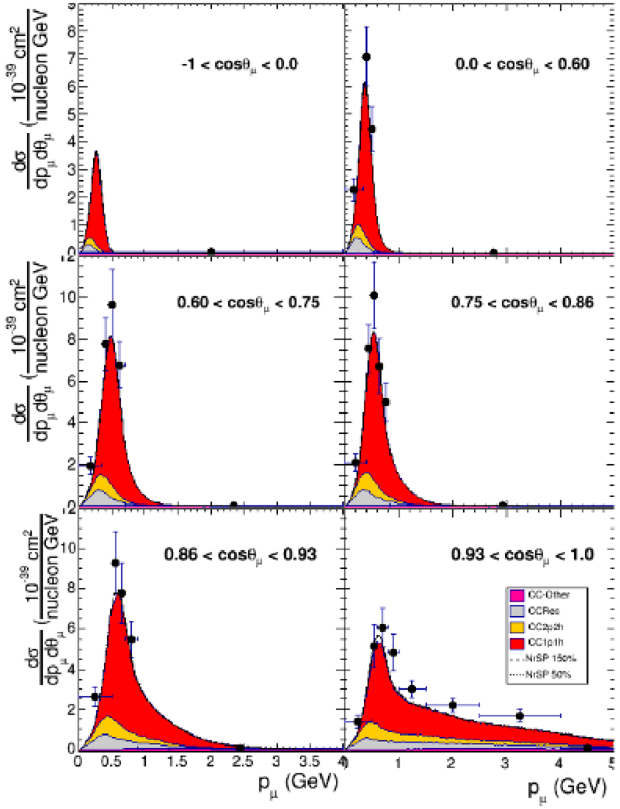
Quasi elastic versus multinucleon knockout processes

- 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

T2K CC inclusive



T2K CC0π



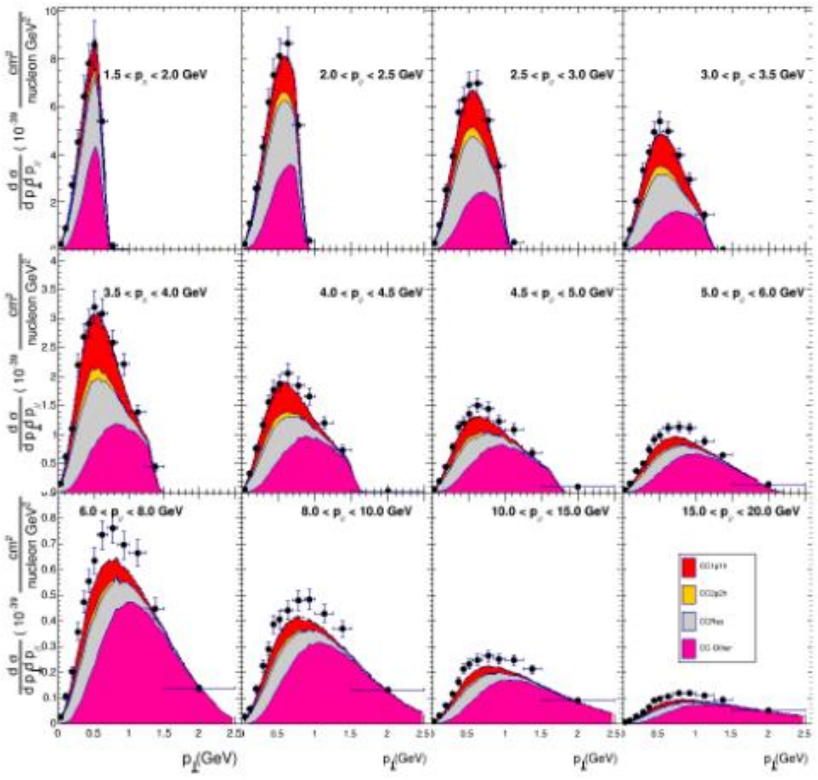
- ➢ Considerable part of the strength is stemming from non-QE processes

B. Bourguille et al. Journal of High Energy Physics 2021, 4
NEUT + LFG + RPA (Valencia)

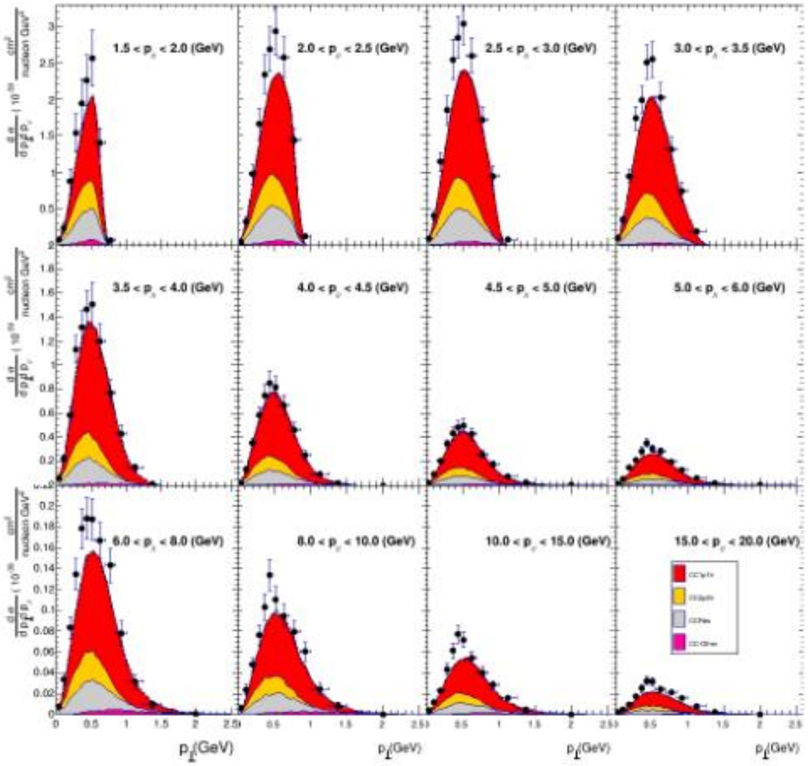
Quasi elastic versus multinucleon knockout processes

- QE processes are dominating the signal in experiments with average energies of a couple of hundreds of MeVs
- Energy reconstruction is based on QE(like) or CC0π events
- A thorough understanding of the QE cross section is extremely important as it is pivotal for the oscillation analysis
- Correct identification of the reaction mechanism is important but not straightforward

MINERvA CC inclusive



MINERvA CC0π



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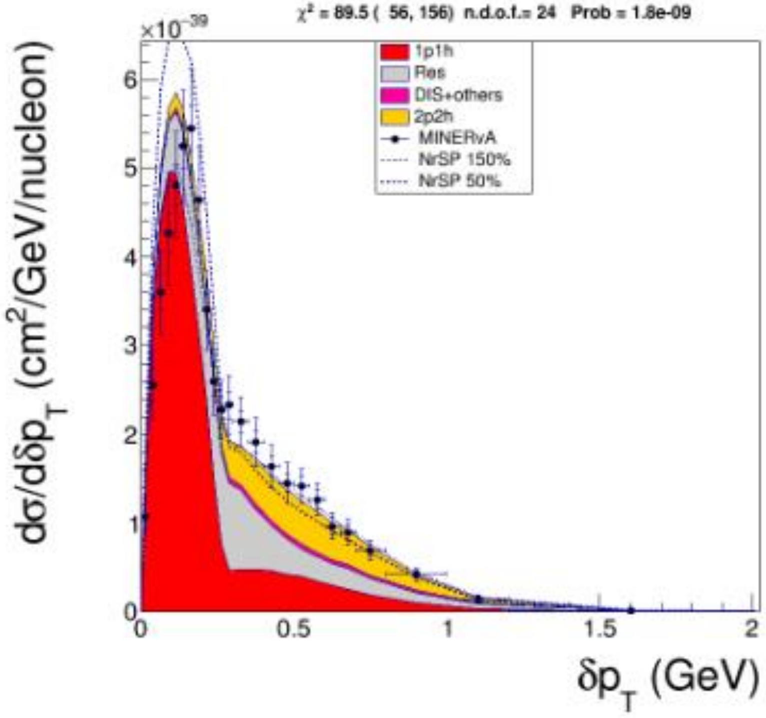
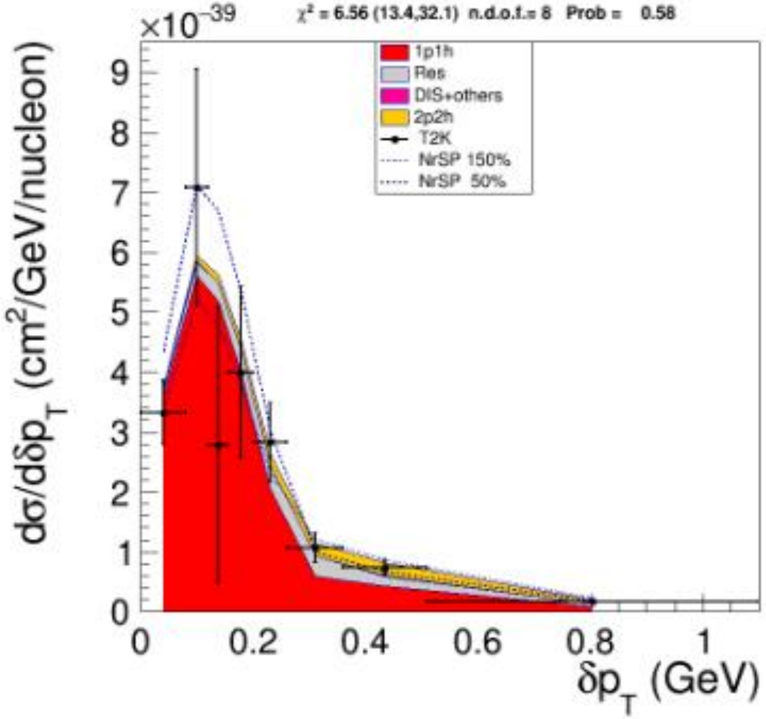
MINERvA CC0π1p



MINERvA CC0π



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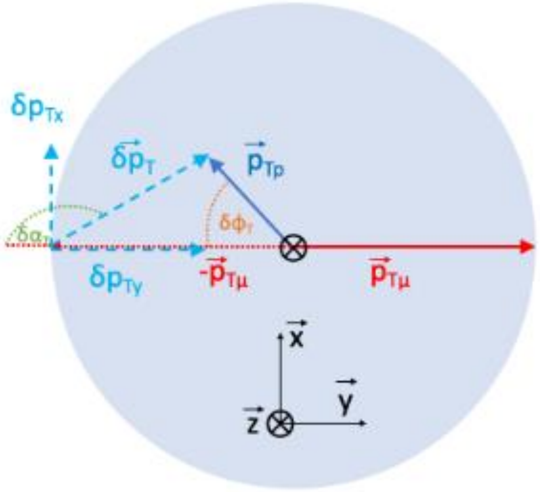

B. Bourguille et al. Journal of High Energy Physics 2021, 4
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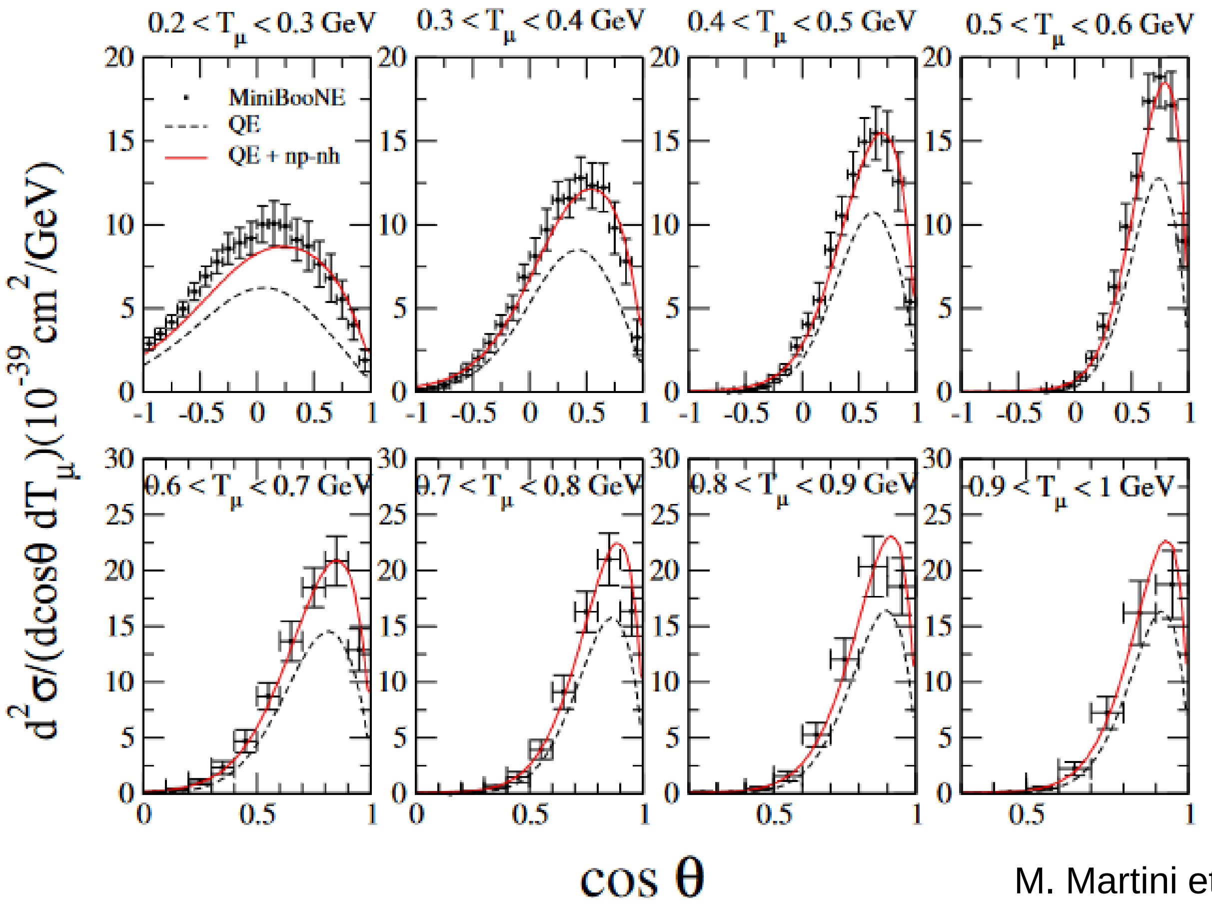
Modeling QE(like) cross sections

- 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



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

M. Martini et al, PRC84, 055502

Modeling QE(like) cross sections

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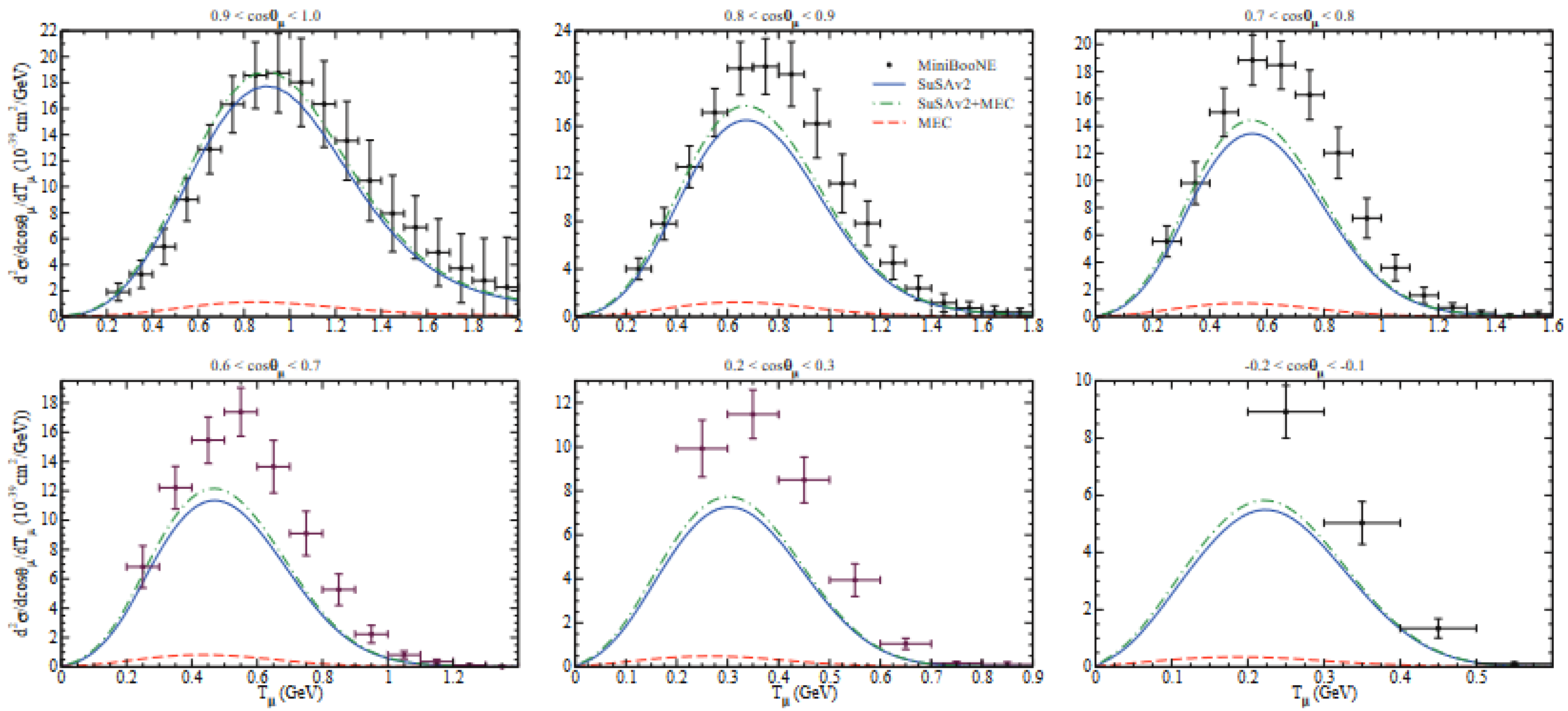

G. Megias et al, PRD 91, 073004

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

Modeling QE(like) cross sections

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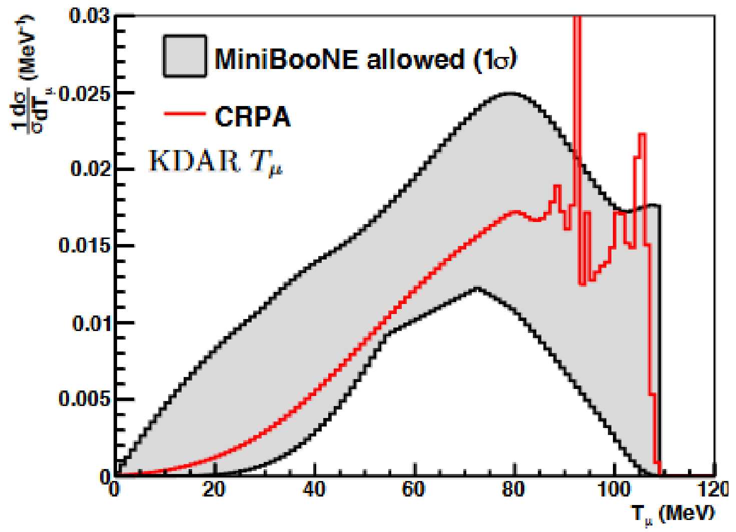
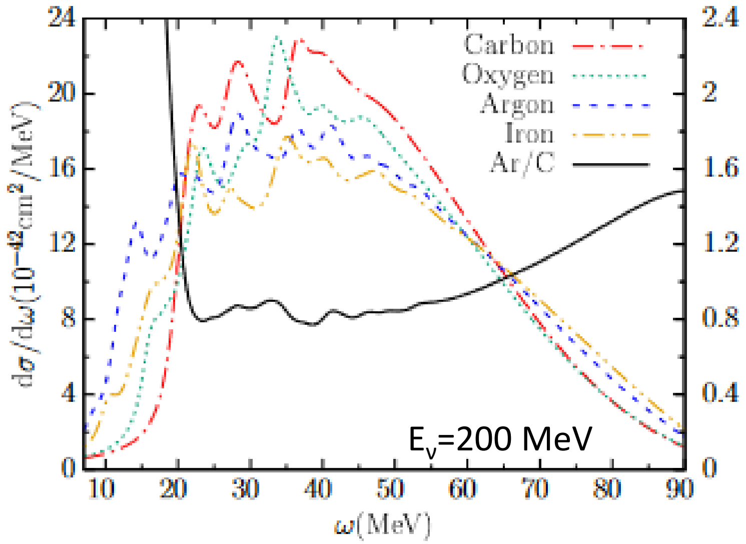


A. Nikolakopoulos et al, PRC103, 064603



N. Van Dessel et al, PRC97, 044616

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

Modeling QE(like) cross sections

- Several effective approaches are on the market for the description of (inclusive) cross sections
  - Efficient and performant
  - Often factorized
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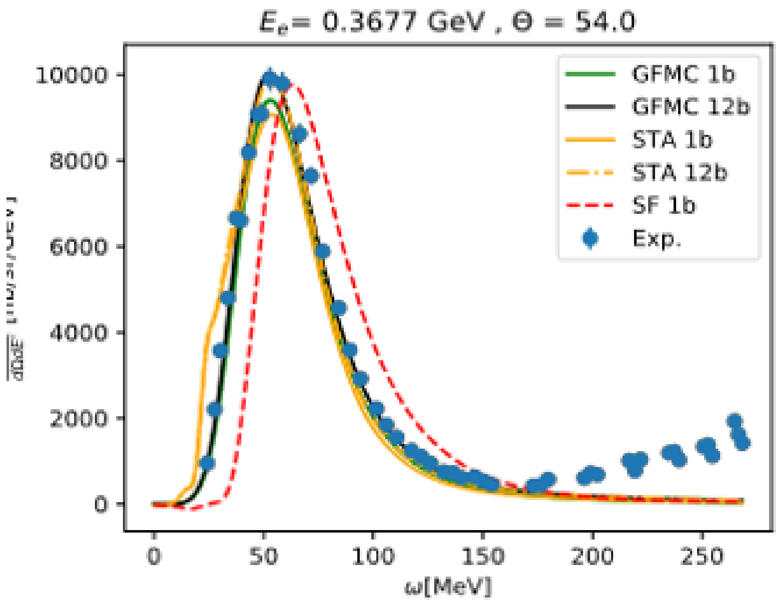
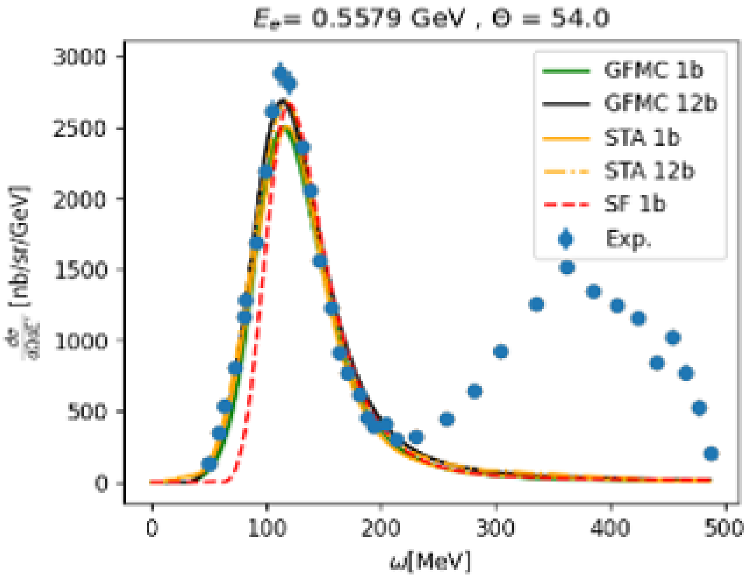
- e -^{3}H: inclusive cross section

L. Andreoli, J. Carlson, A. Lovato, S. Pastore, NR, arXiv::2108.10824





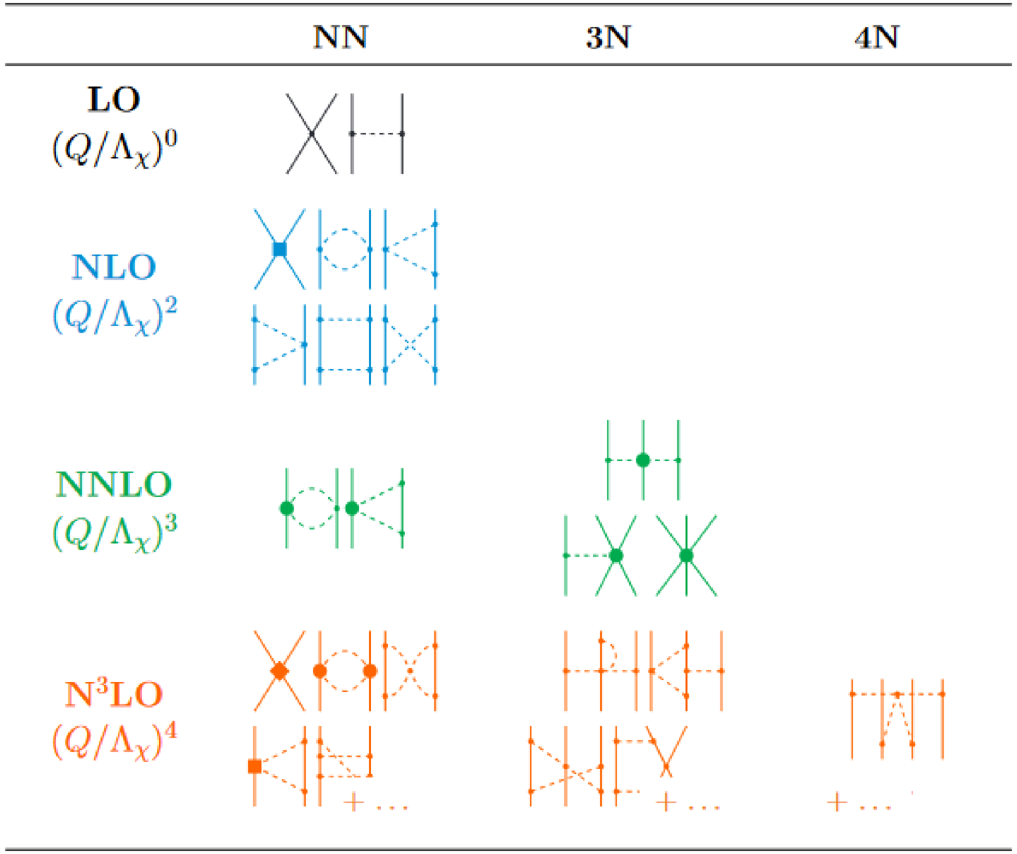
➢ Spectral function calculations

N. Rocco @ NuFACT2021

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

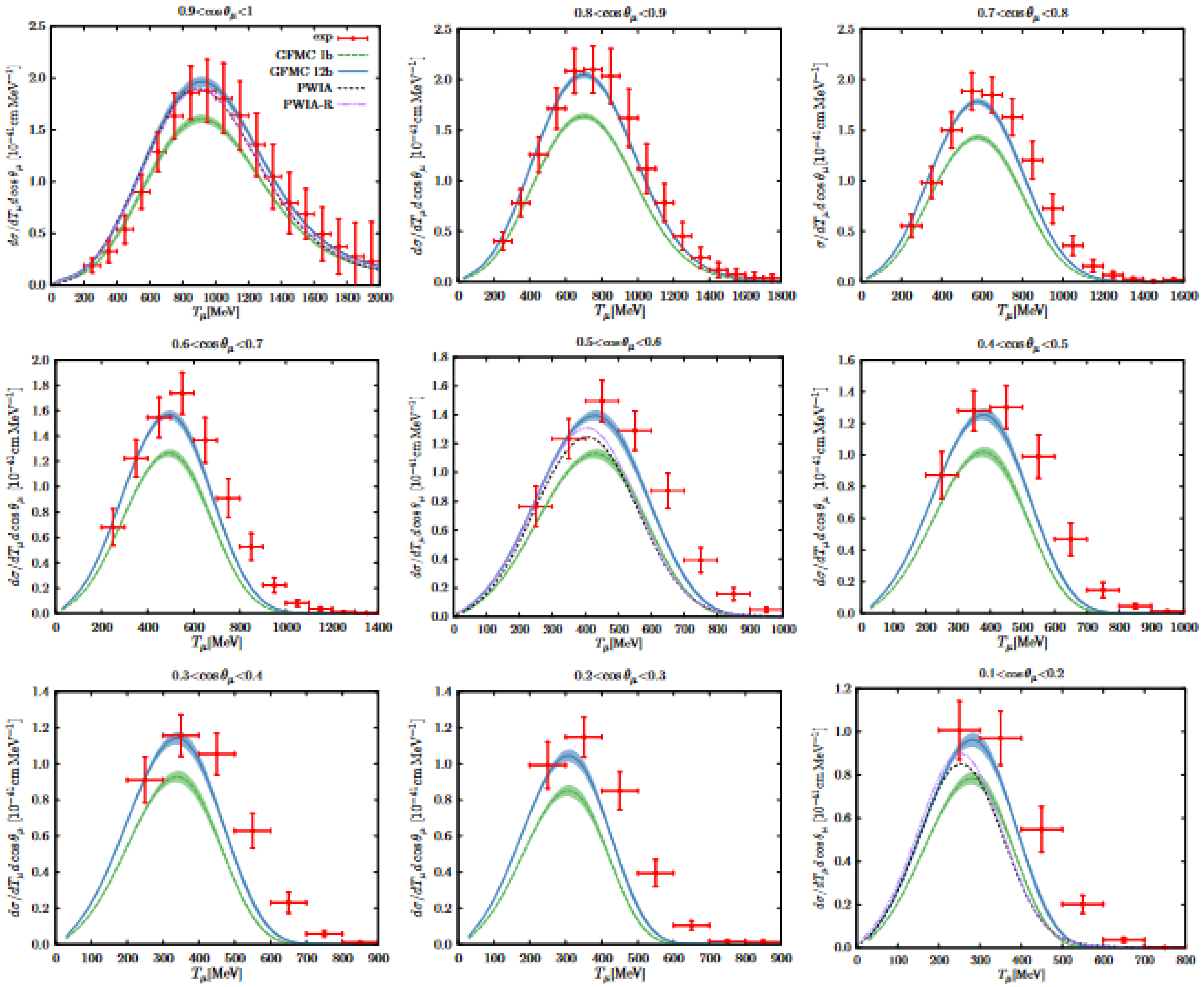
$$H = \sum_i \frac{\mathbf{p}_i^2}{2m} + \sum_{i<j} v_{ij} + \sum_{i<j<k} V_{ijk} + \ldots$$



H. Hergert

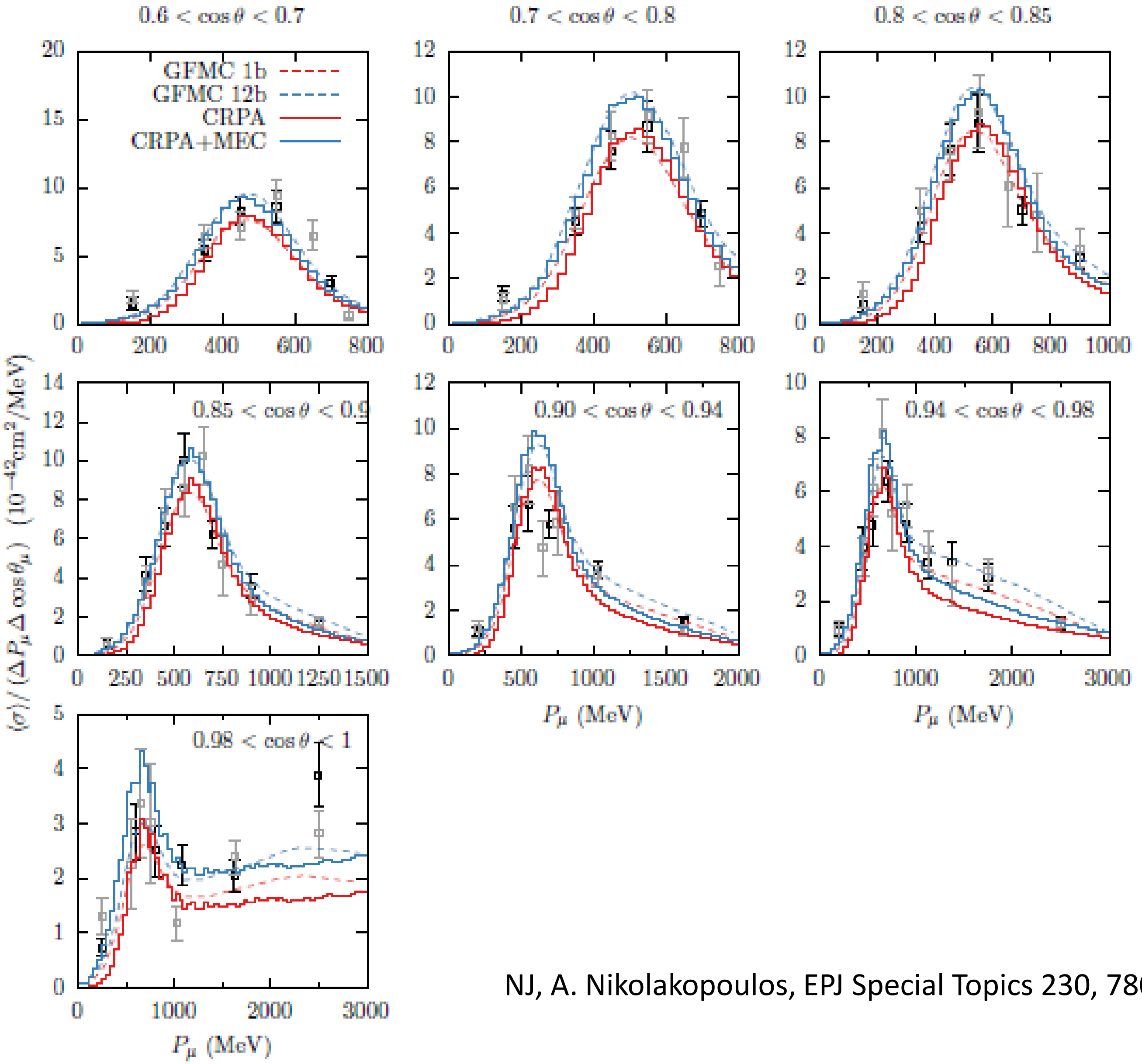
Ab initio results

- Exact
- Computationally intensive and only applicable to the inclusive response
- Light nuclei
- Non-relativistic



- 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

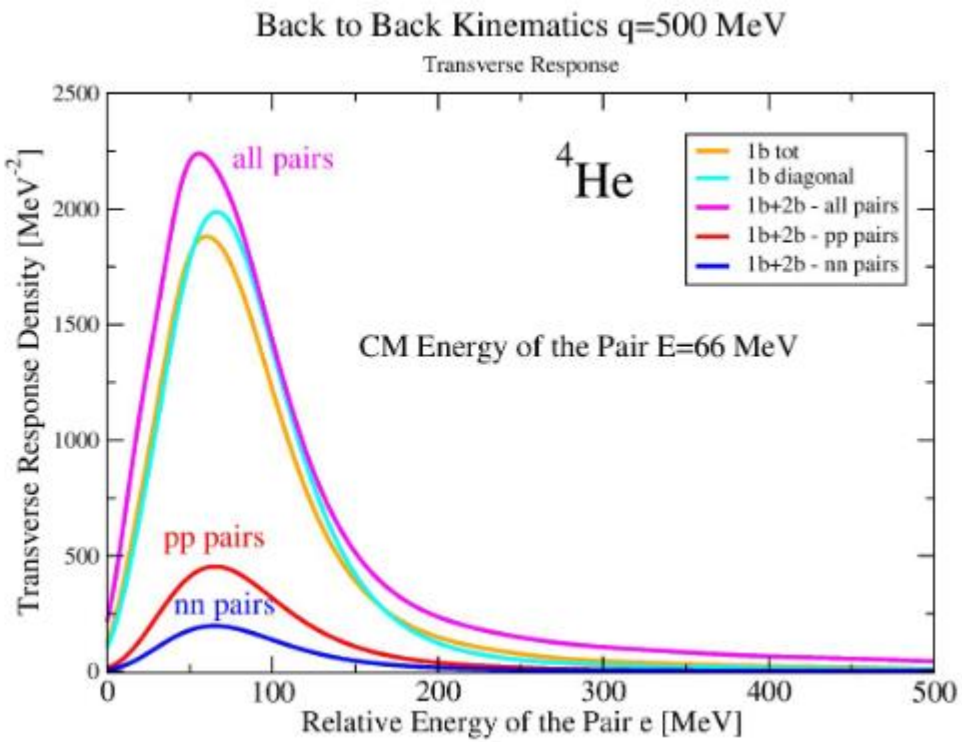
A. Lovato et al, PRX 10, 031068



- 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

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

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

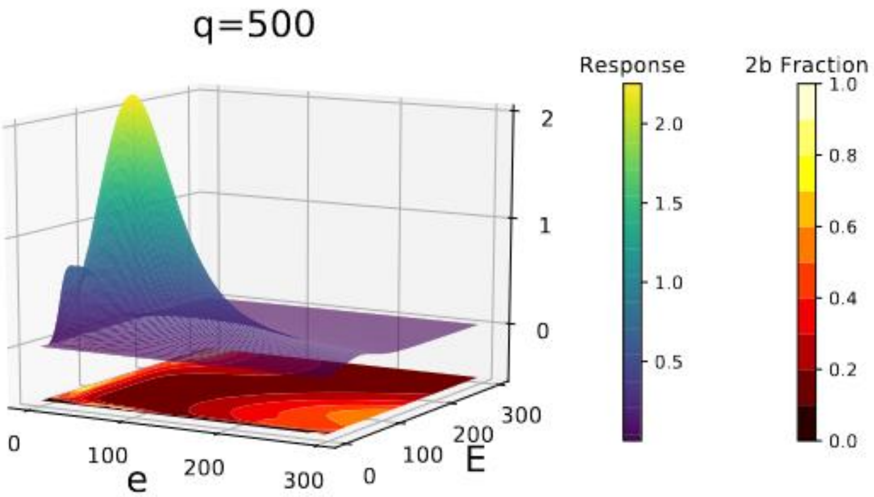
- Based on factorization
- Retains 2-body contributions and correctly accounts for interference

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

- 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

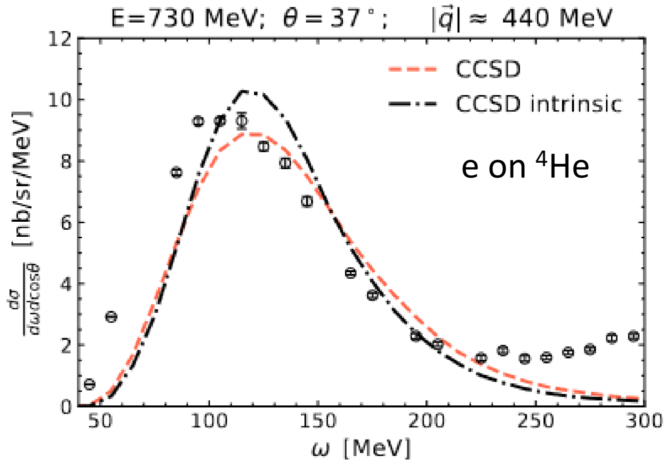


Coupled-cluster theory predictions for coherent scattering processes

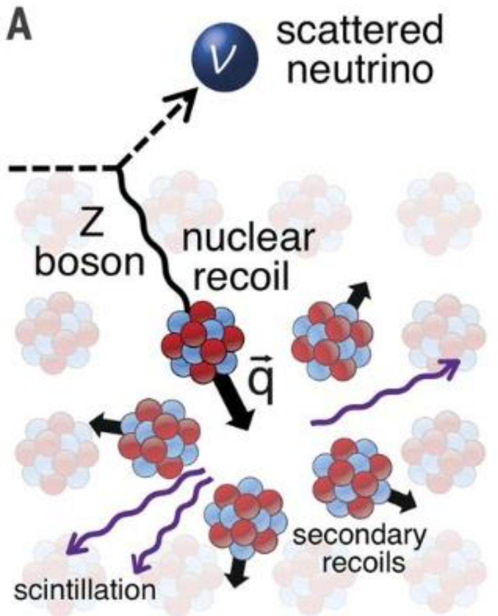
- Cross section large compared to inelastic processes at small energies
- Mainly sensitive to the neutron distribution
- Interesting prospects for BSM searches

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

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



J.E. Sobczyk et al. arXiv:2205.03592

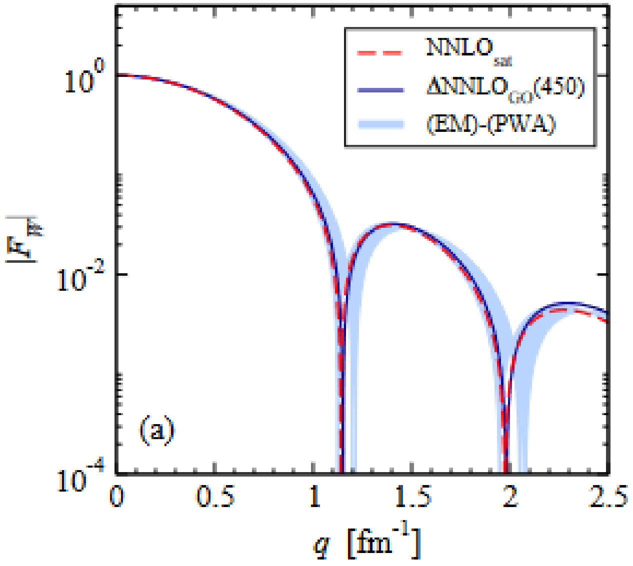


Nuclear Hamiltonian inspired by effective field theories

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

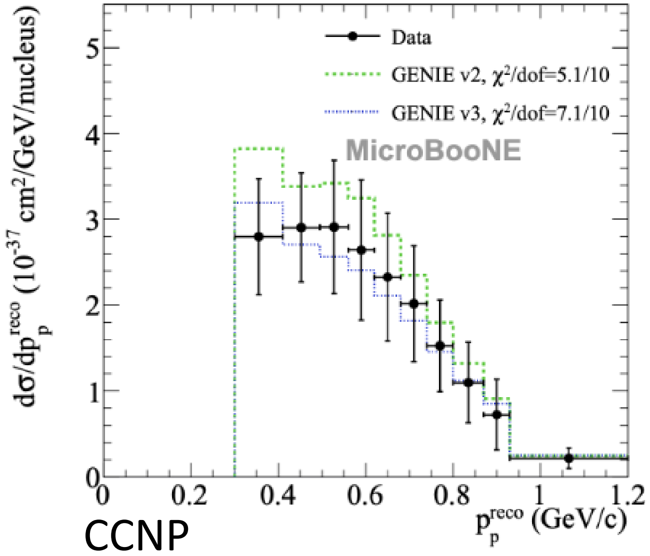
Including correlations

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

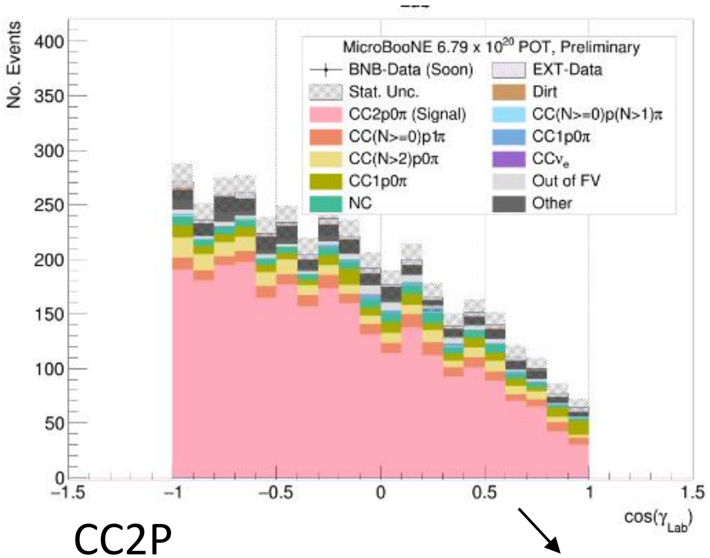


C. Payne et al, PRC100, 061304

Keeping pace with experimental progress : semi-inclusive and exclusive cross sections



CCNP



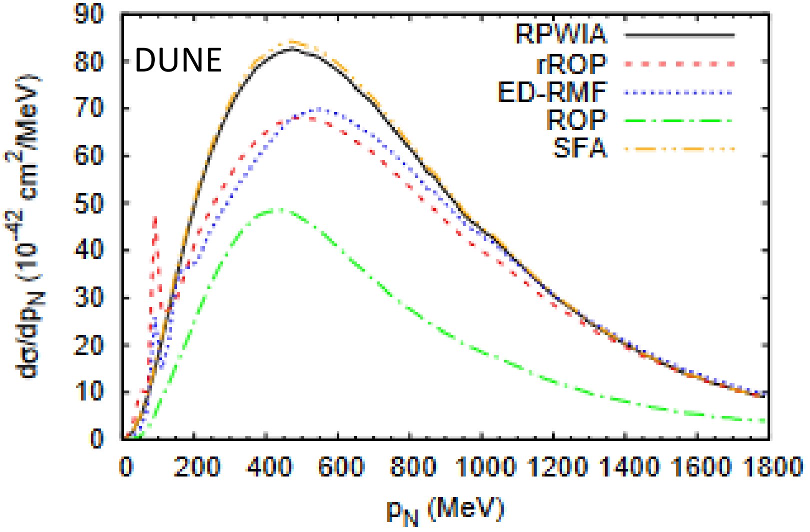
CC2P

Opening angle between protons in lab frame

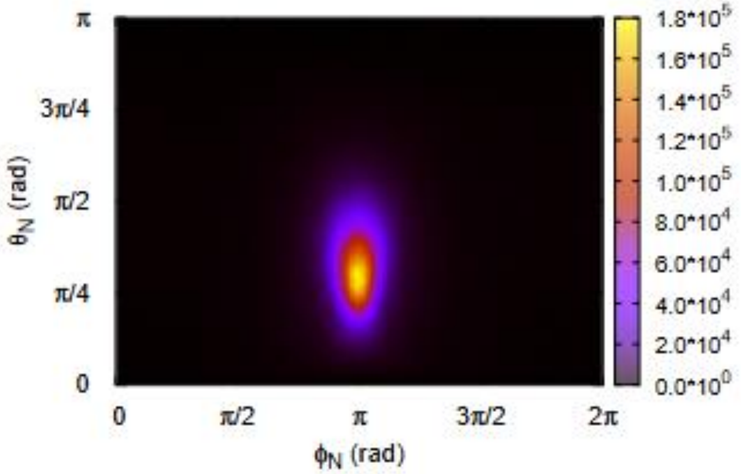
Samantha Sword-Fehlberg @ NuFact20/21

Theoretical extensions needed :

- Extra response functions
- Appropriate description of the outgoing nucleon wave function in the nuclear medium

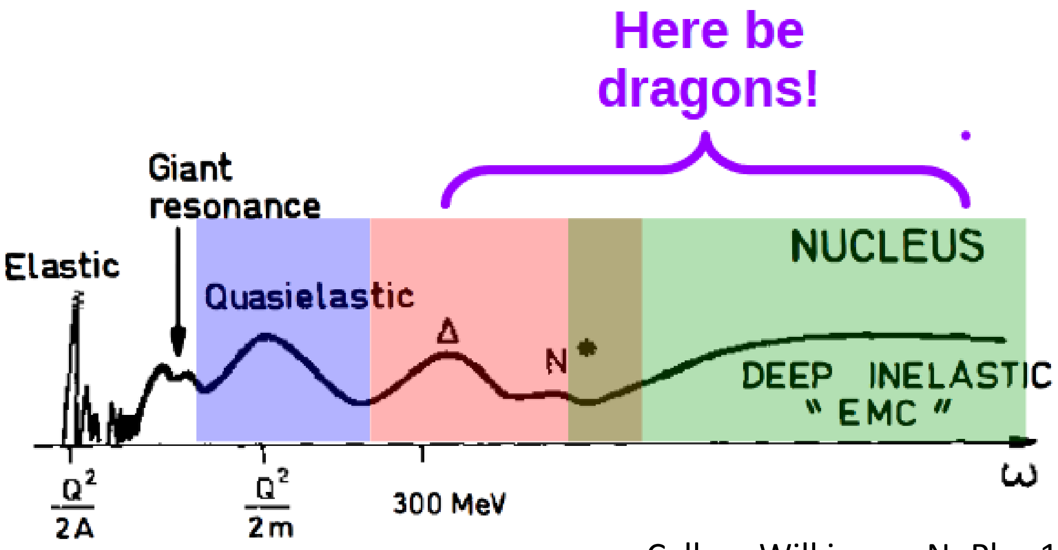


- Relativistic optical model predictions for semi-inclusive processes
- Allows to identify kinematic regions where events are less likely to be affected by FSI effects
- More exclusive modeling can provide guidance for more effective energy reconstruction



R. Gonzalez-Jimenez et al, PRC 105, 025502

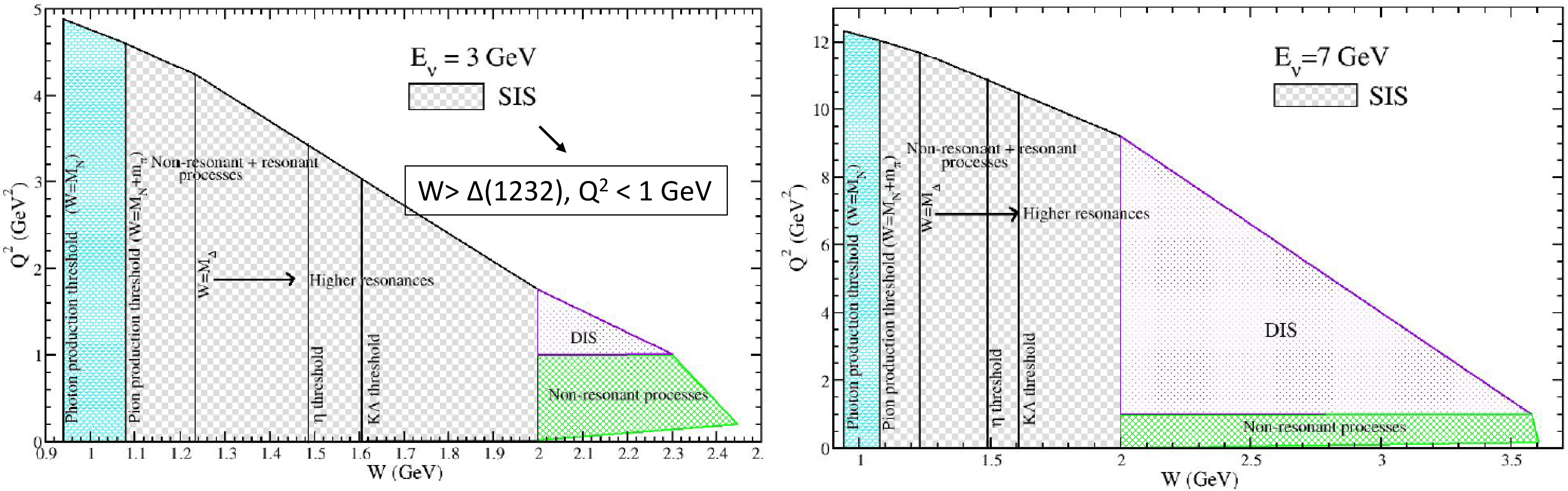
The Delta region and the transition to Shallow and Deep Inelastic Scattering



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 contributions 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
- 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



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

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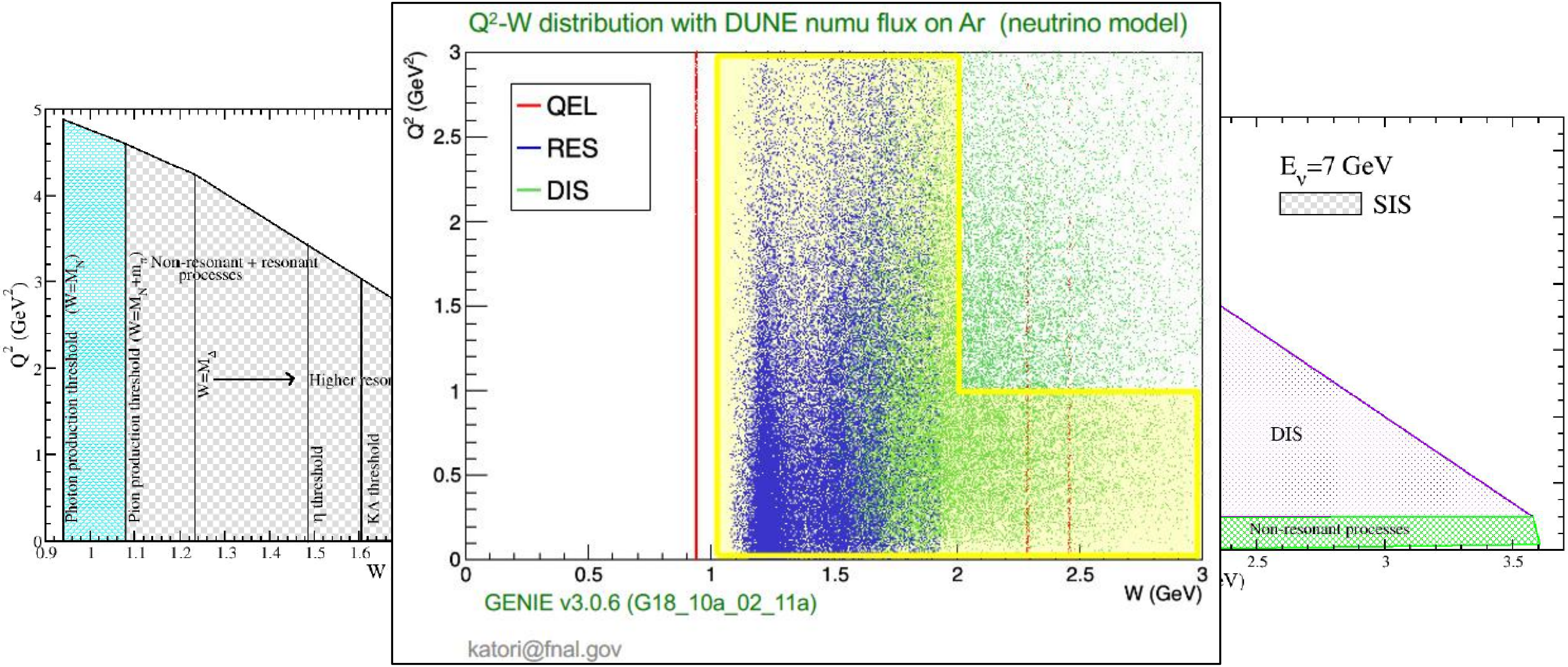
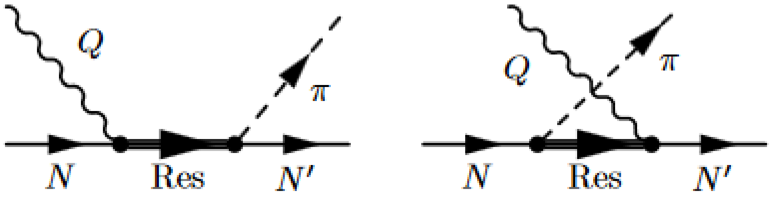


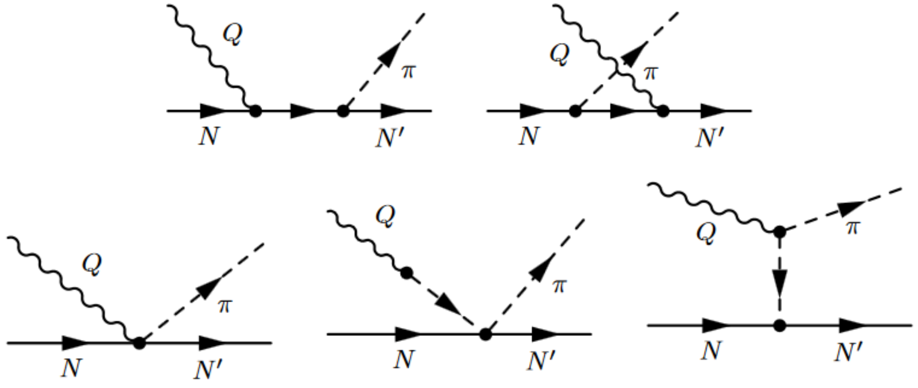
Pion production

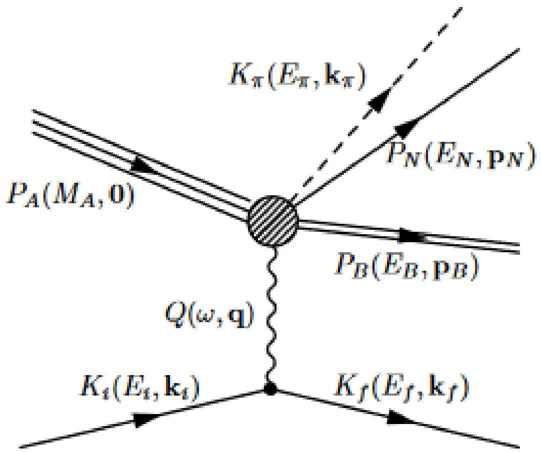
Resonances

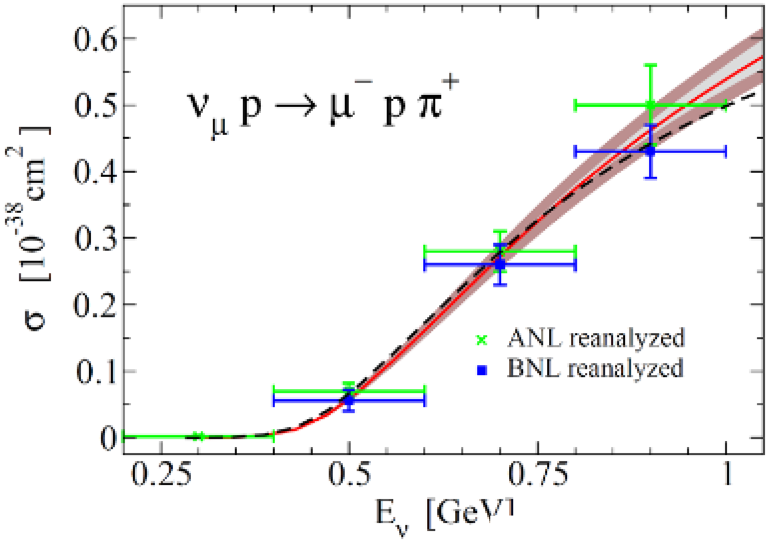


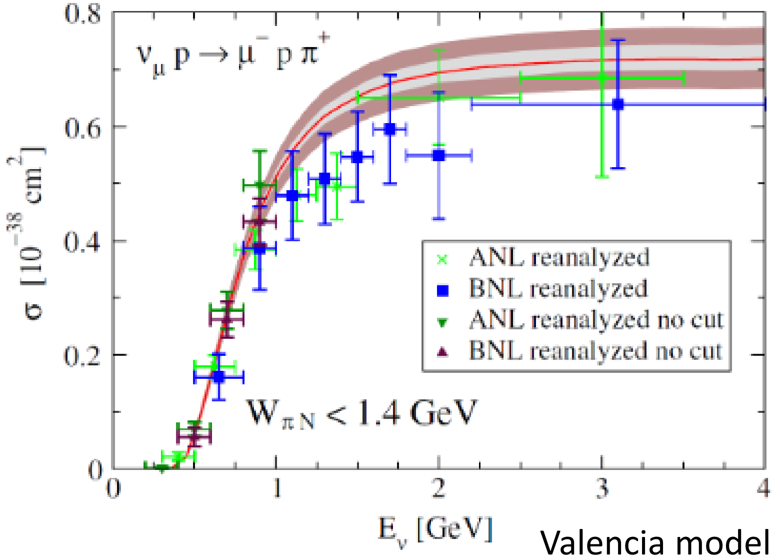
+

ChPT background





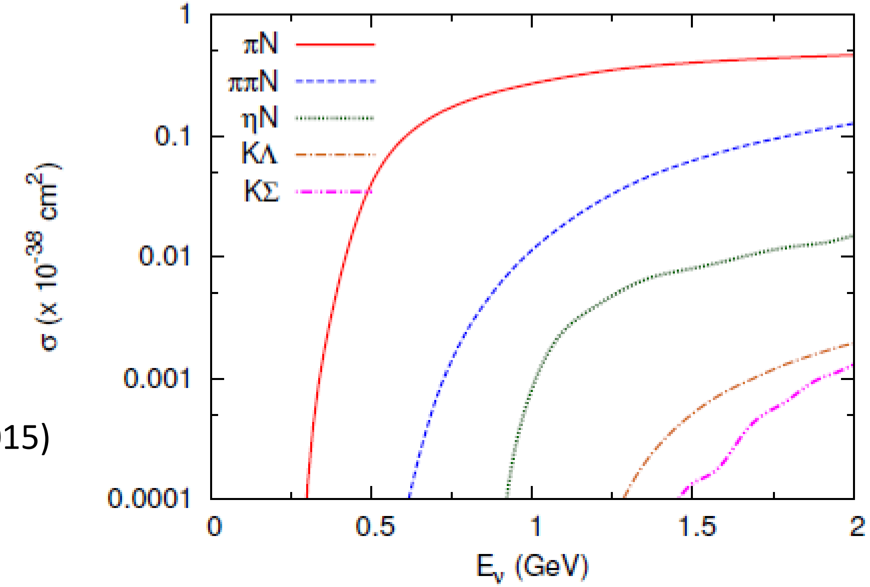




Valencia model

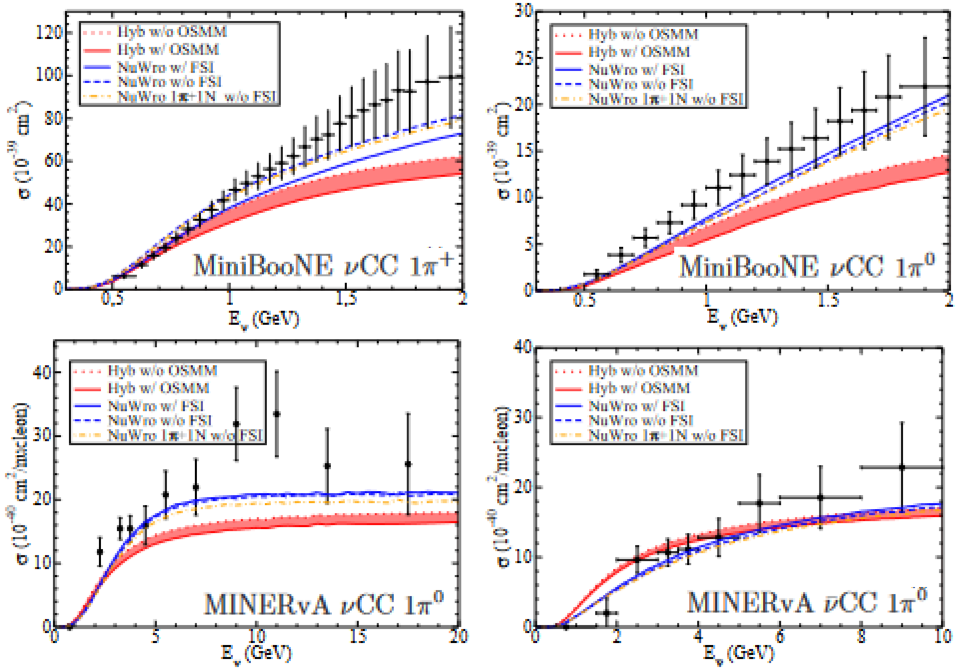
- Single pion production in Delta region relatively well understood
- Important background channel for quasi-elastic cross section measurements as the produced pions may be re-absorbed in the nuclear medium or remain otherwise unobserved, leading to a CC0π topology mimicking a QE event

- Up to W≈2GeV the ANL-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



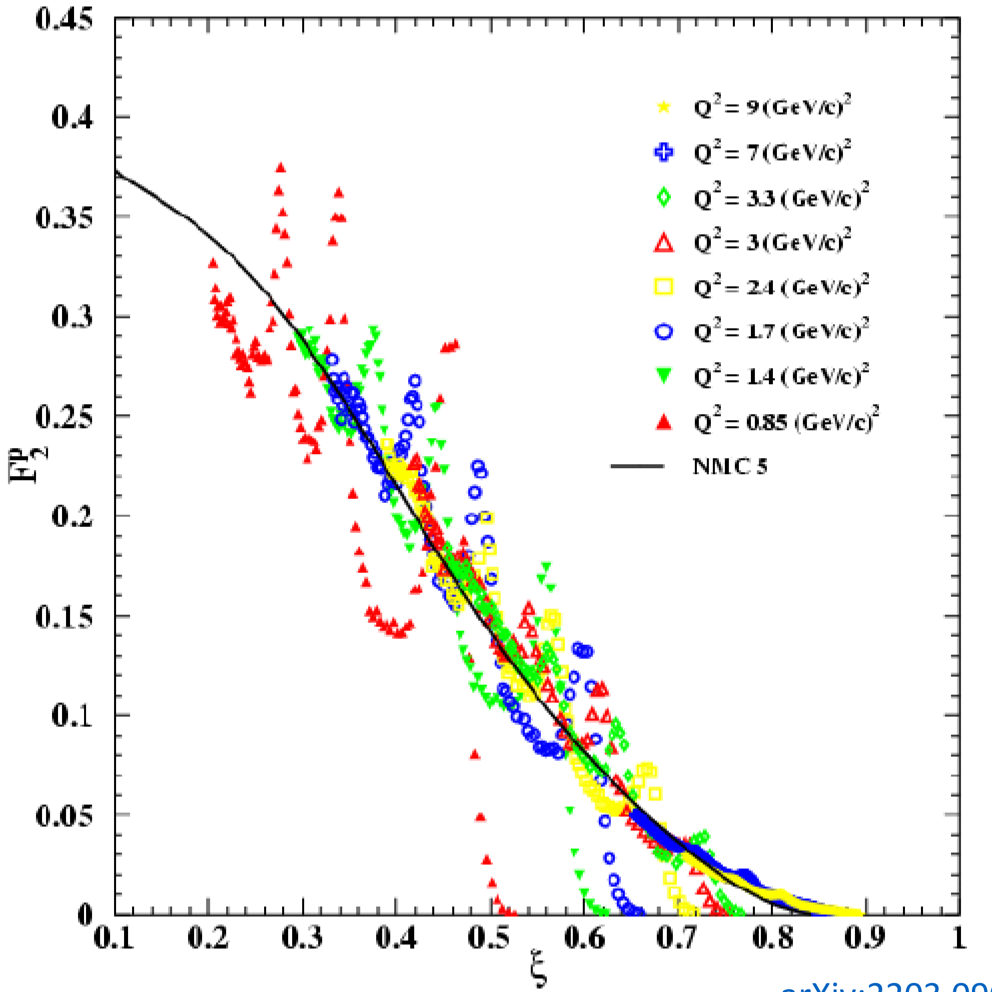
Hybrid model results for single-pion production cross-section including Regge description at higher energies to overcome problems with low-energy descriptions

R. Gonzalez-Jimenez et al.,PRD 97

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

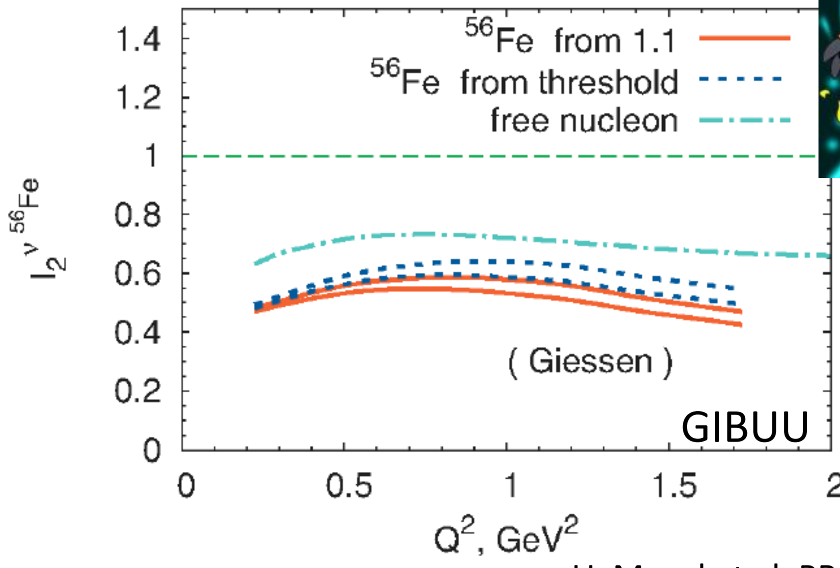
Electron-scattering : resonances (Jlab E94-110 data) follow the extrapolated DIS curve



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)

$$\mathcal{I}_j(Q^2_{RES}, Q^2_{DIS}) = \frac{\int_{\xi_{min}}^{\xi_{max}} d\xi F_j^{RES}(\xi, Q^2_{RES})}{\int_{\xi_{min}}^{\xi_{max}} d\xi F_j^{DIS}(\xi, Q^2_{DIS})}$$

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

LQCD constraints

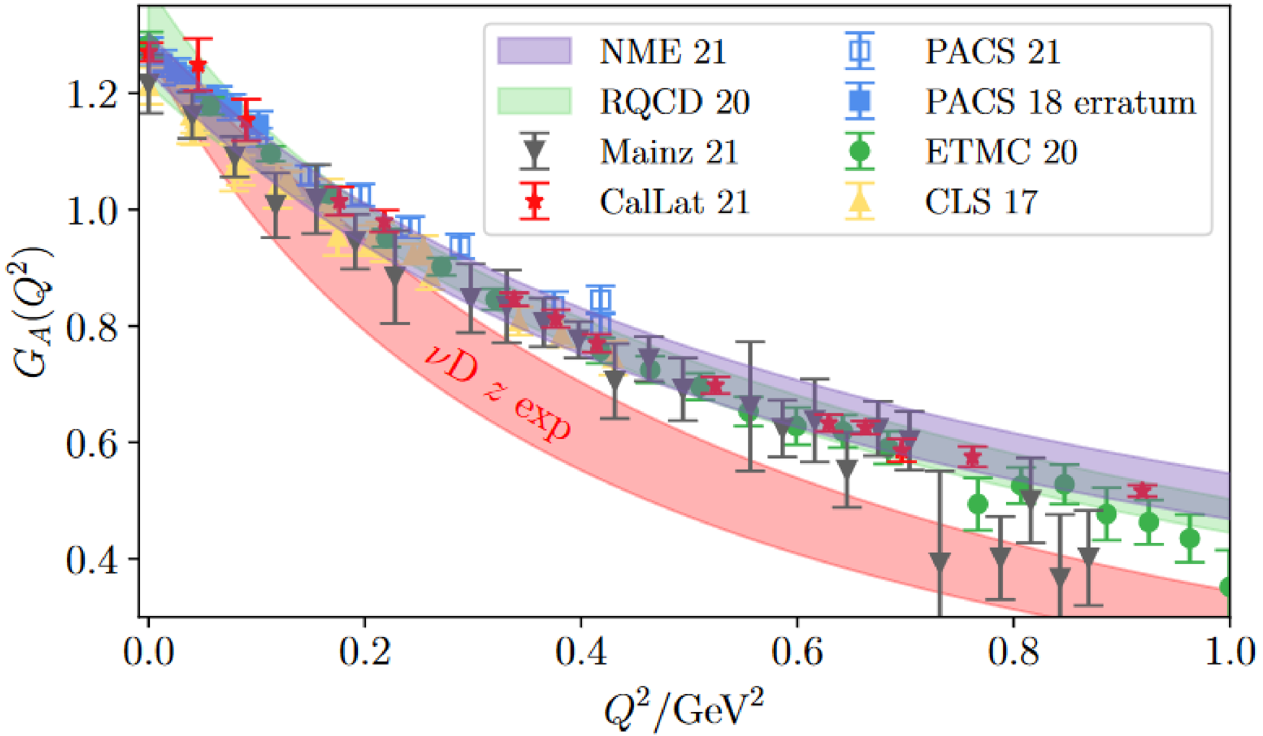
Neutrino-nucleon form factors constitute a major source of uncertainty in neutrino scattering modeling

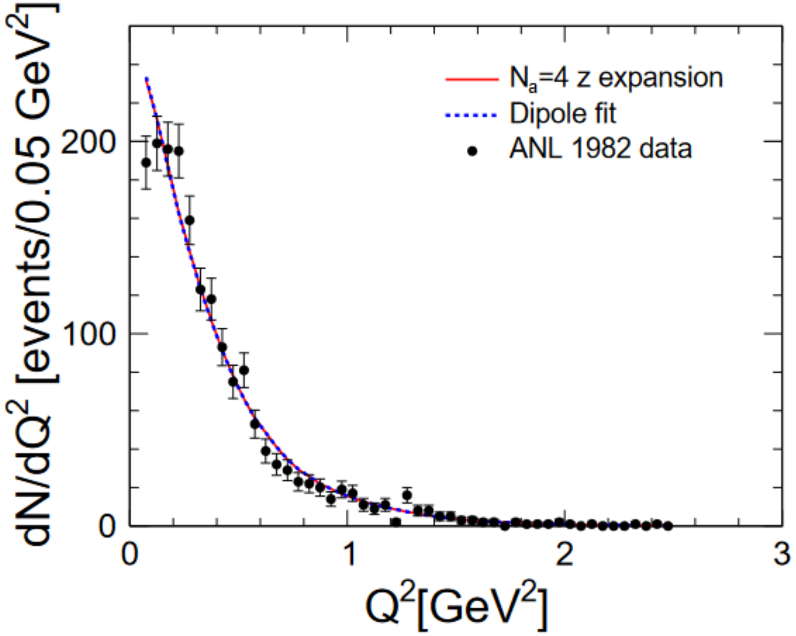
- Weak vector form factors are well constrained by electron scattering experiments
- Q^2 evolution of the axial form factor is not well-known, mainly based on old bubble chamber data (ANL, BNL, FNAL)

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

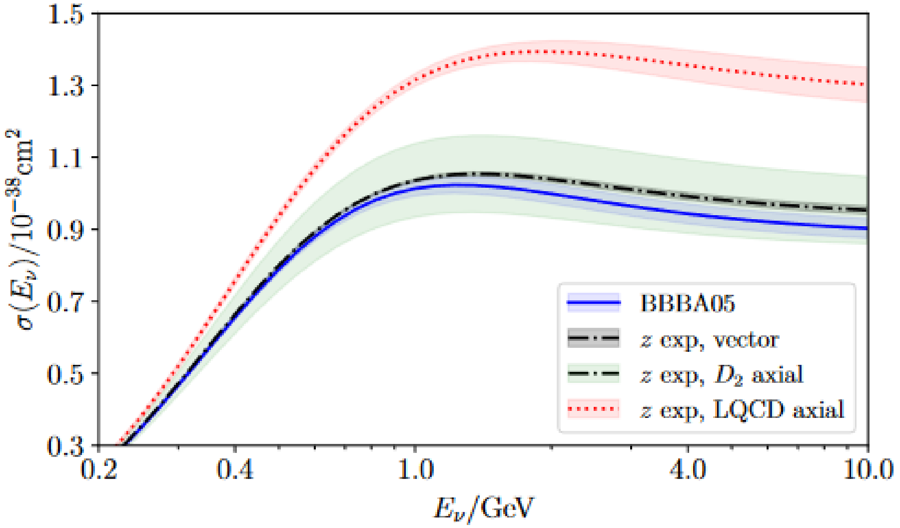
β-decay (g_A)

'free' parameter (M_A)





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

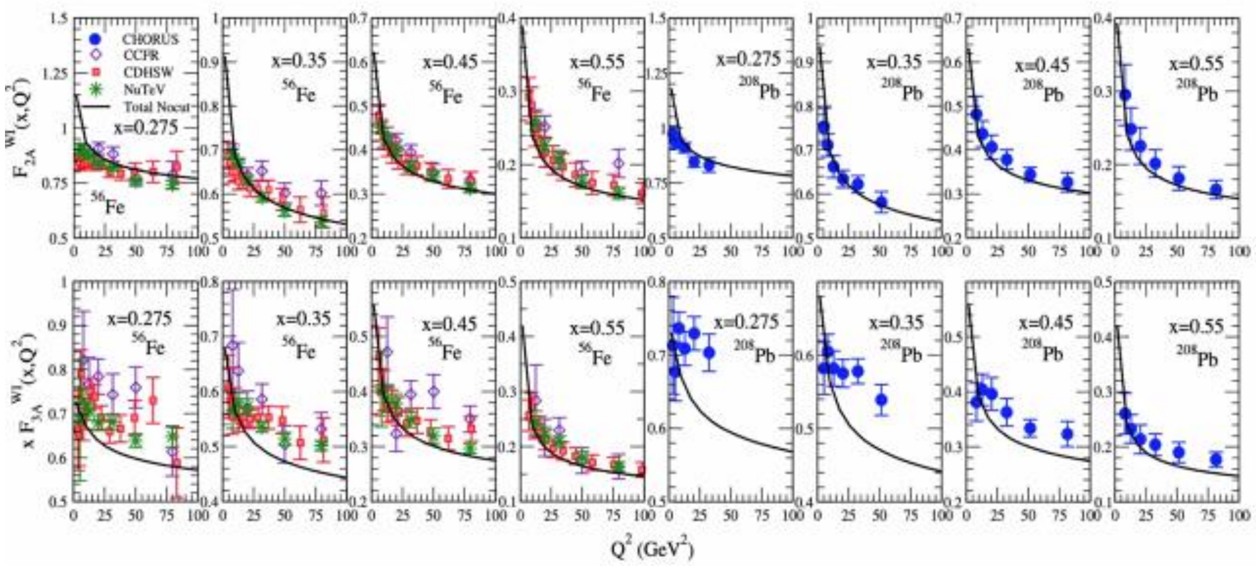


Neutrino cross section on a free nucleon :
- Improved LQCD prediction owing to better control of excited state contamination
- Softer slope of the axial form factor's Q^2 dependence leads to enhanced cross section on the nucleon
- Considerable reduction of the uncertainty

A. Meyer et al arXiv:2201.01839

Further future opportunities for neutrino scattering from LQCD :
- Extend LQCD calculations toward resonance production 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

Nuclear Model Structure Functions and Data PHYS. REV. D **101**, 033001 (2020)



Constraints from electron scattering

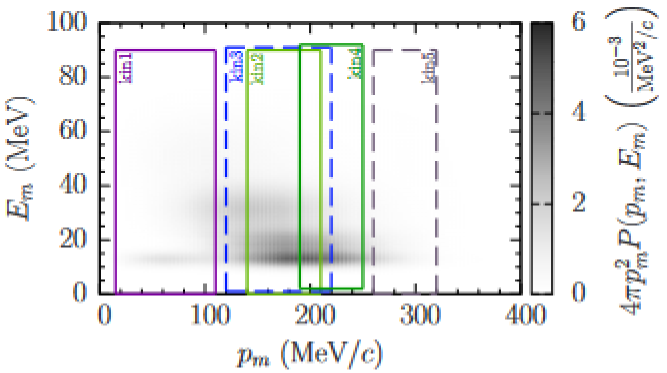
Benchmarking with electron scattering results JLab E12-14-012 :

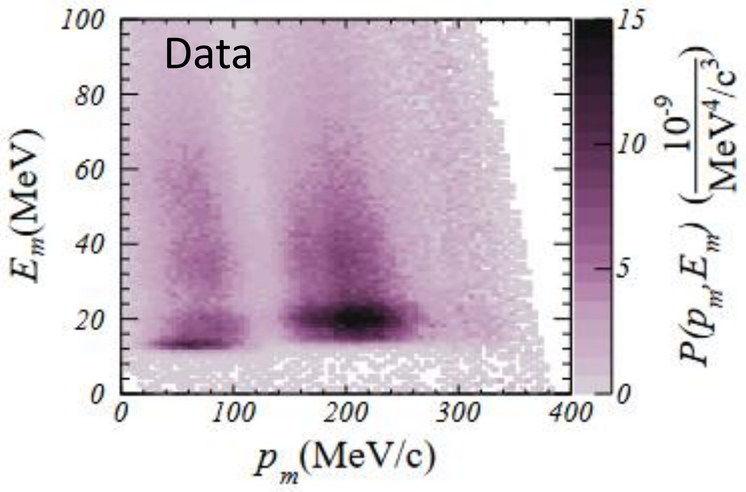
- electron scattering @ 2.22 GeV on ^{40}Ar and ^{48}Ti
- Selected kinematics
- Aiming at studying the spectral function

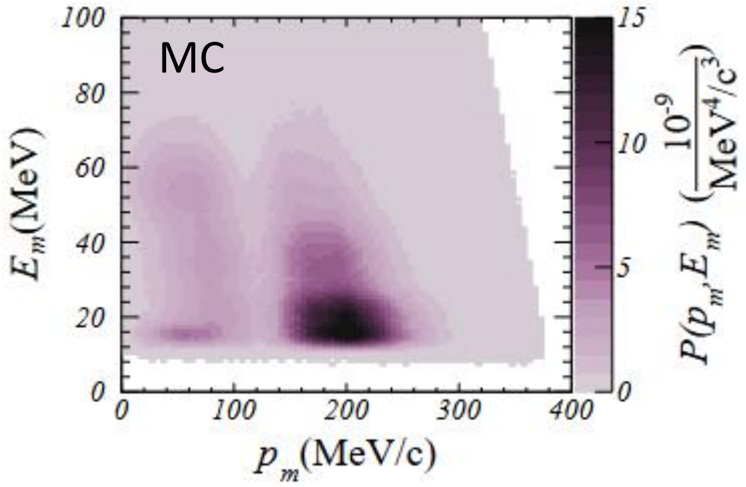
See also Or Hen's talk on e4v !

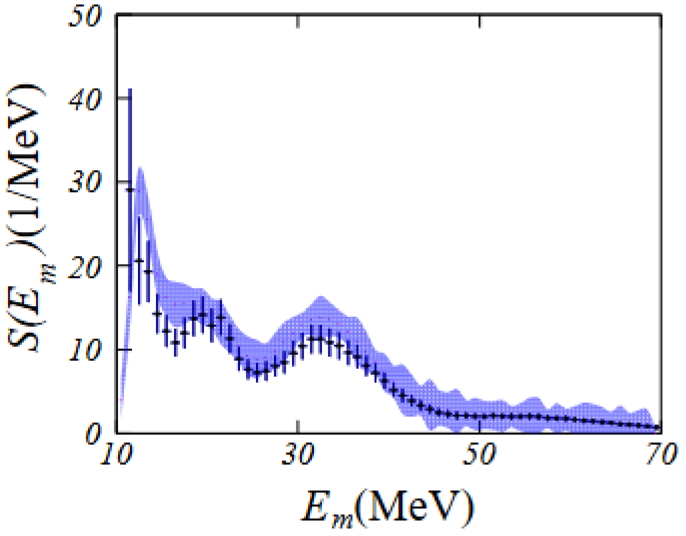
TABLE I. Kinematics settings used to collect the data analyzed here.

	E'_e (GeV)	θ_e (deg)	Q^2 (GeV^2/c^2)	$\lvert\mathbf{p}'\rvert$ (MeV/c)	$T_{p'}$ (MeV)	$\theta_{p'}$ (deg)	$\lvert\mathbf{q}\rvert$ (MeV/c)	p_m (MeV/c)	E_m (MeV)
kin1	1.777	21.5	0.549	915	372	−50.0	865	50	73
kin2	1.716	20.0	0.460	1030	455	−44.0	846	184	50
kin3	1.799	17.5	0.370	915	372	−47.0	741	174	50
kin4	1.799	15.5	0.291	915	372	−44.5	685	230	50
kin5	1.716	15.5	0.277	1030	455	−39.0	730	300	50









(b) $140 < p_m < 210$ MeV/c

Reduce nuclear uncertainties, improve knowledge about Ar nucleus

JLab Hall A Collaboration arXiv:2203.01748

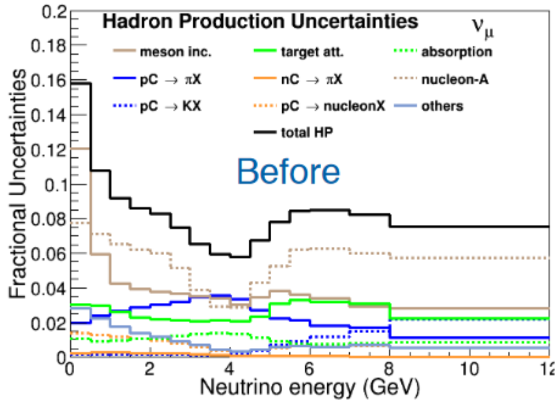
Hadron experiments

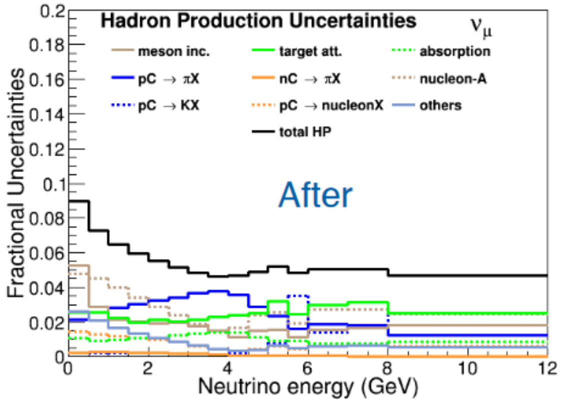
Hadron scattering experiments offer additional tools to facilitate neutrino-nucleus scattering studies and modeling

- Experiments rely on number of hadrons that were produced and focused before decaying to neutrinos to estimate flux
- Flux uncertainties are a limiting systematic in experiment
- Flux uncertainties hinder data to provide strong constraints for theoretical modeling

EMPHATIC : hadron scattering and production study to

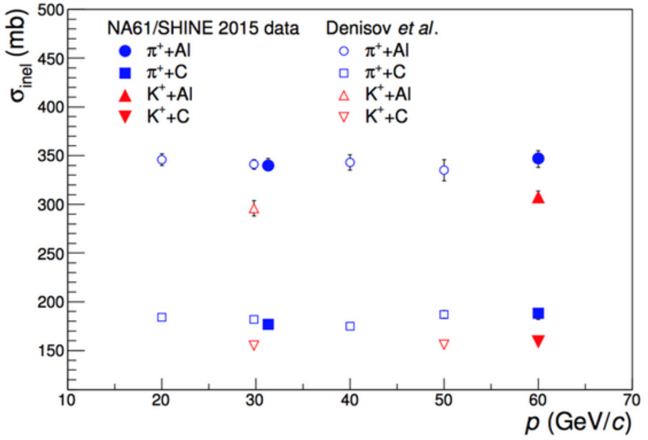
- reduce neutrino flux uncertainties caused by hadron production uncertainties by factor ~2
- table-top size experiment,
- focused on precision hadron production measurements on various targets, large angular acceptance
- relatively low proton momenta < 15 GeV





NA61/SHiNE :

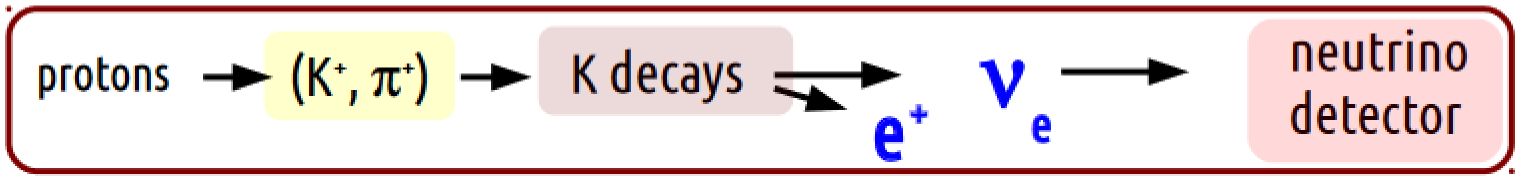
- pion and kaon production measurements
- using replica targets (T2K, NuMI target, LBNF)
- Higher incident particle momenta > 15 GeV



Controlling the neutrino beam

ENUBET : Enhanced NeUtrino Beams from kaon Tagging :

- assessing flux by monitoring the decay in which the neutrinos are produced
- Aiming at a 1% precision for the neutrino flux

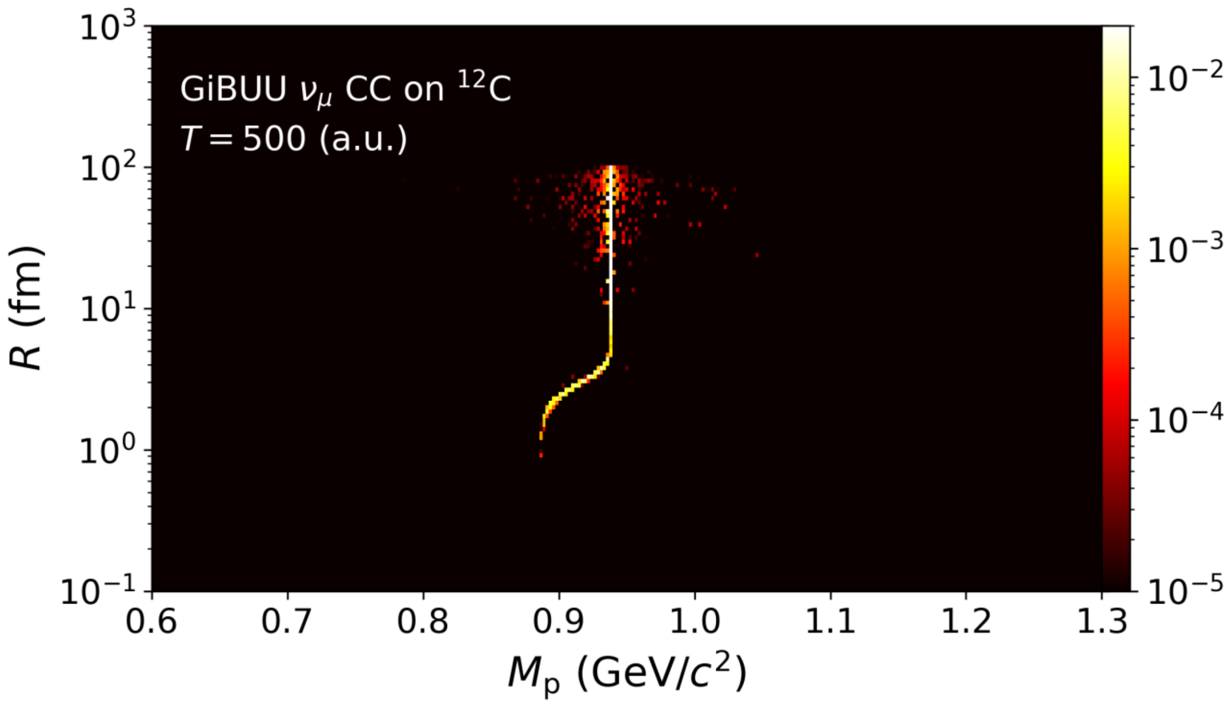


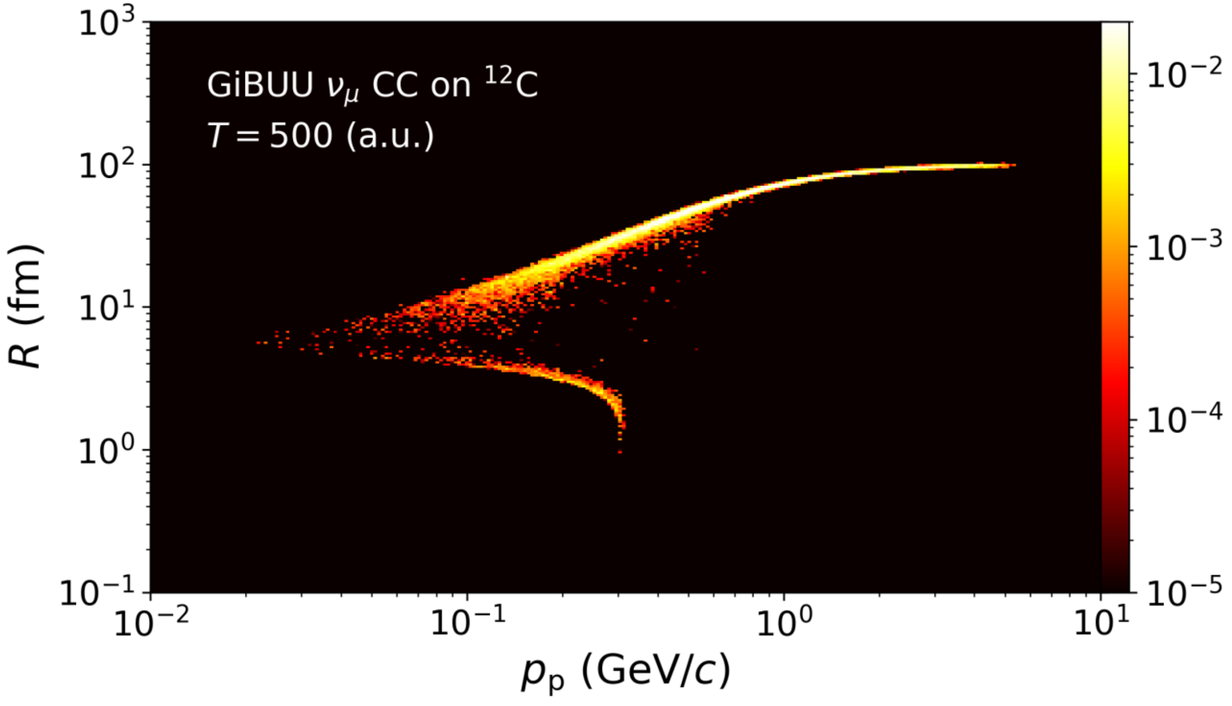
A. Longhin

More in Xianguo Lu's talk !

Event generators : bridges between theory and data

Credit: Kaile WEN@IHEP, Xianguo LU@Warwick





† Proton in GiBUU final-state transport
R: radial position, M_p: mass, p_p: momentum

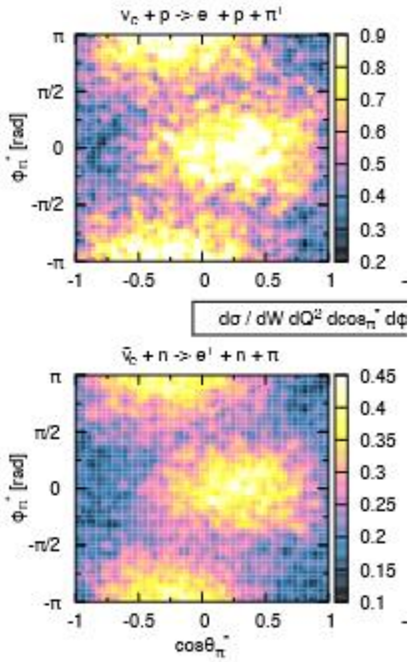
- Theoretical models tend to concentrate on the description of the primary vertex
- Generators (GENIE, NEUT, NuWro, GIBUU) provide more detailed information about secondary processes obtained in a semi-classical cascade description
- Trade-off between sophistication in models and numerical performance

Challenges in generator developments :

- Microscopic input for vertex – more exclusive descriptions
- Standardized interfaces

- Default NuWro
- Free nucleon
- Fixed kinematics:

$E = 1$ GeV
$Q^2 = 0.1$ GeV^2
$W = 1230$ MeV



- Ghent LEM
- Free nucleon
- Fixed kinematics:

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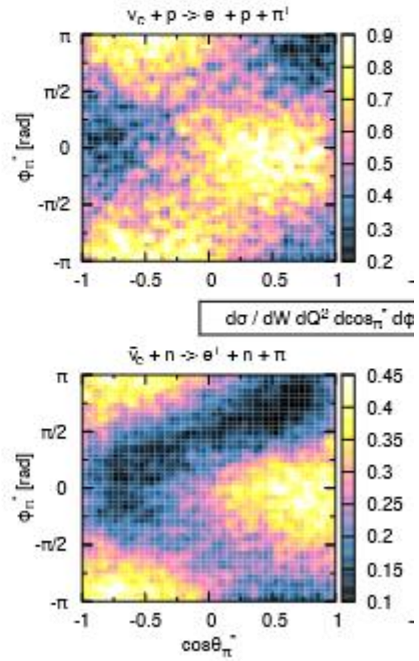
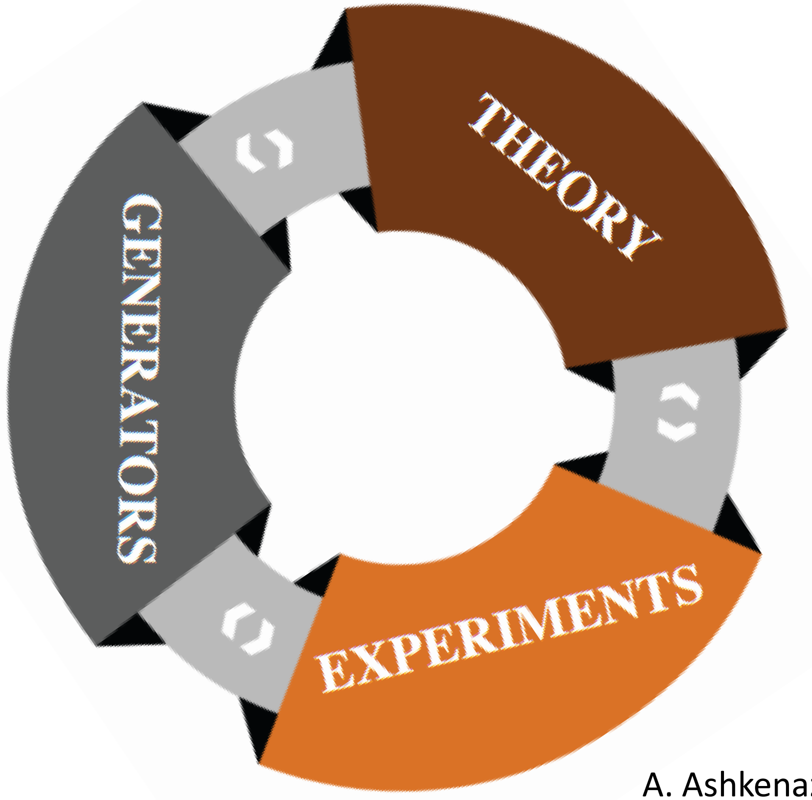
$Q^2 = 0.1$ GeV^2
$W = 1230$ MeV



Need to go beyond isotropic approaches in MC generators and include detailed microscopic calculation results in the simulation

K. Niewczas et al, PRD 103, 053003

Conclusions (1)



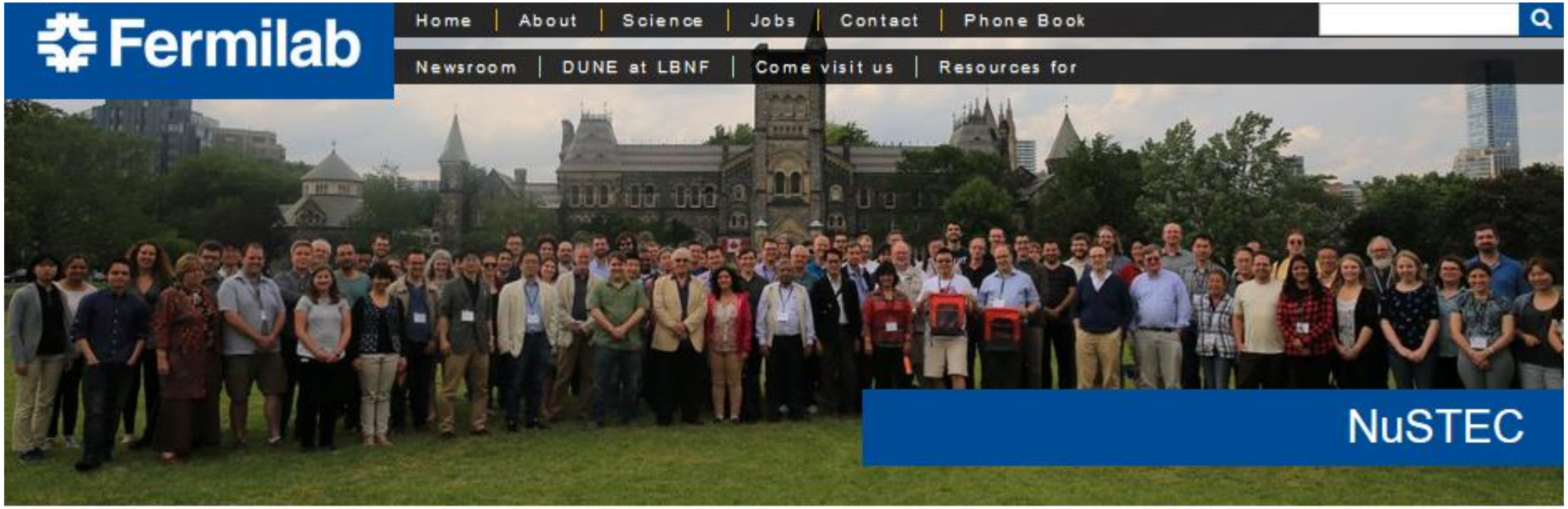
A. Ashkenazi

- 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
✓ 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.

Conclusions (2)

- Neutrino-nucleus cross sections constitute an important source of uncertainties in accelerator-based oscillation experiments
- Recent years have witnessed considerable progress in the description of inclusive processes
- Theory efforts towards more exclusive descriptions are important to keep pace with the experimental progress using LArTPC detectors
- Especially in the kinematic region beyond the quasielastic and the delta region, a lot of open issues remain