Historical Review and Future Program for Neutrino Cross-Section Measurements and Calculations

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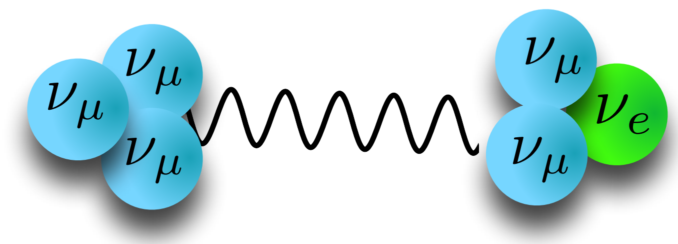
Fermilab

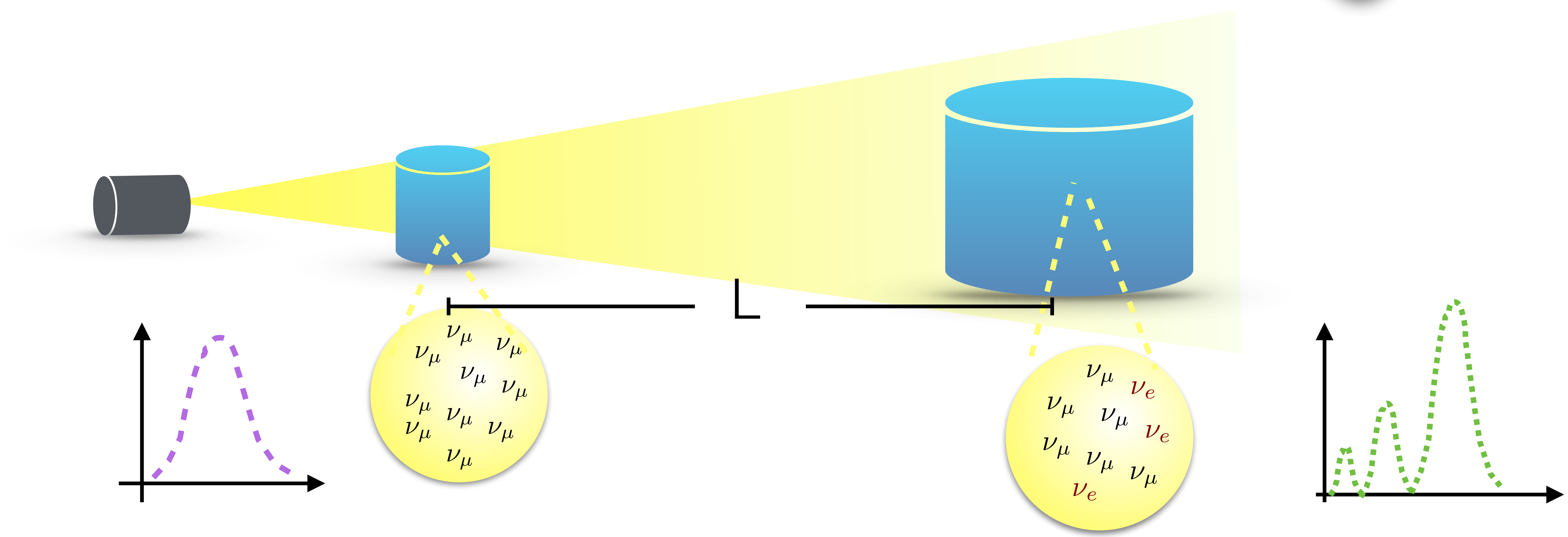
Outline

* Why cross sections are relevant for neutrino oscillation
* Past and present measurements of neutrino cross sections
* Theoretical models of neutrino cross sections
* Future program for neutrino cross section measurements and calculations

Addressing Neutrino-Oscillation Physics

$$P_{\nu_\mu \to \nu_e}(E, L) \sim \sin^2 2\theta \sin^2 \left(\frac{\Delta m^2 L}{4E}\right) \to \Phi_e(E, L)/\Phi_\mu(E, 0)$$





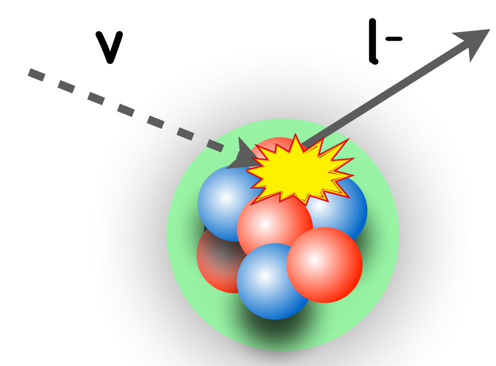
Detectors measure the neutrino interaction rate:

$$N_e(E_{\rm rec}, L) \propto \sum_i \Phi_e(E, L)\sigma_i(E) f_{\sigma_i}(E, E_{\rm rec}) dE$$

Reconstructed ν energy

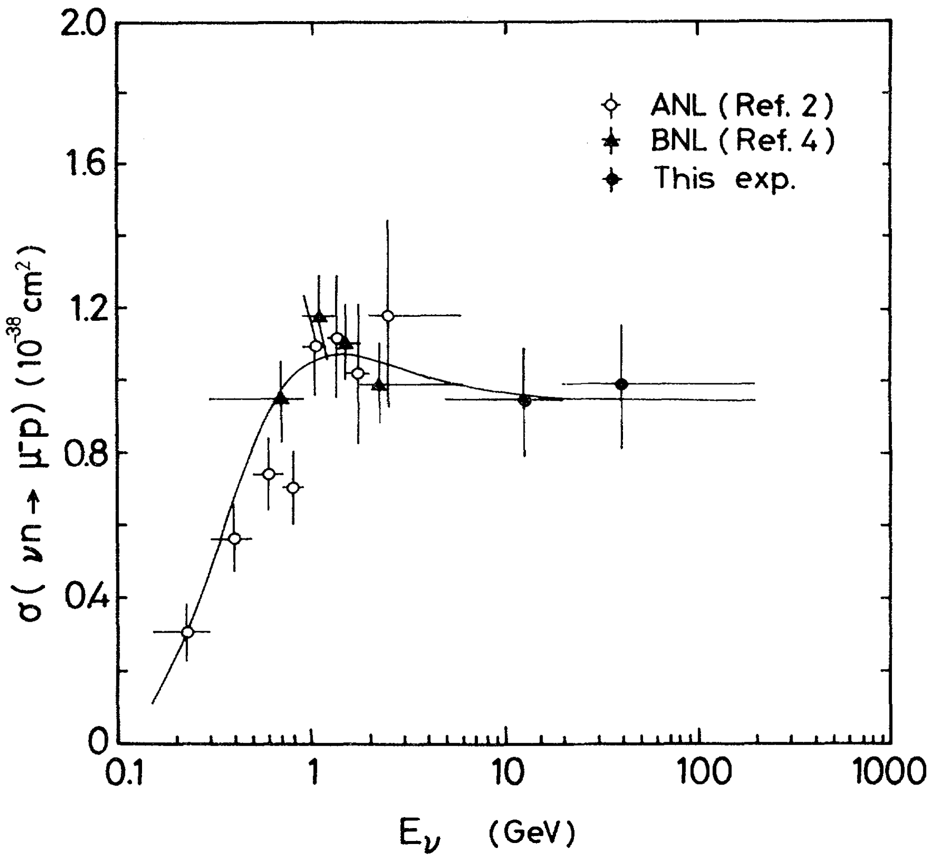
Cross Section

Smearing matrix



A quantitative knowledge of σ(E) and f_σ(E) is crucial to precisely extract ν oscillation parameters

To study neutrinos we need nuclei



✐ T. Kitagaki et al, Phys. Rev. D 28, 436 (1983)

Neutrino scattering extensively studied 1970-90's using deuterium-filled **bubble chambers**

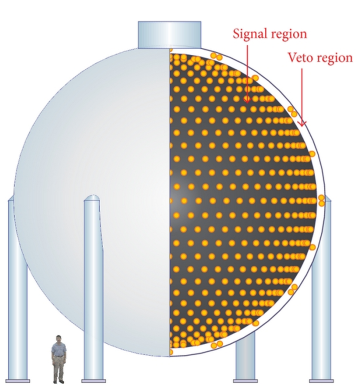
$$\mathcal{N}_{\text{hits}} = \sigma \times \Phi \times N$$

Targets

Bubble Chamber experiment at Fermilab

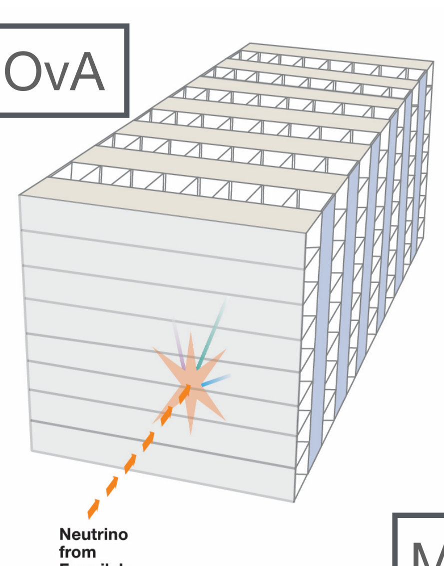
Utilize heavy target in neutrino detectors to maximize interactions→ understand nuclear structure

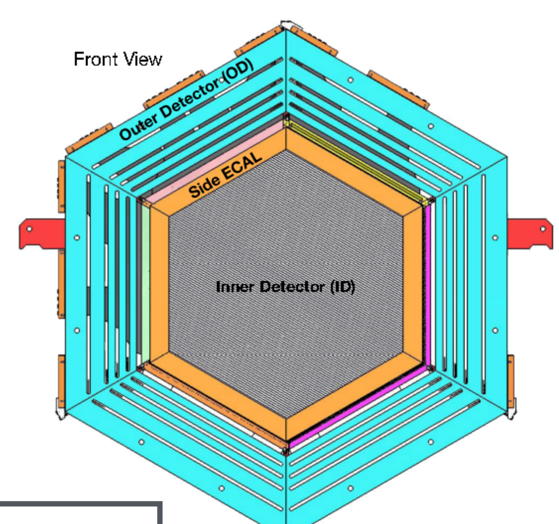
Carbon



MiniBooNE

NOvA



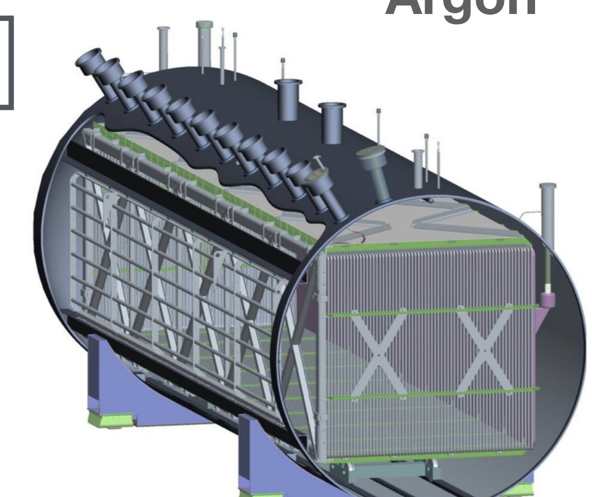


MINERvA

Oxygen

S-K

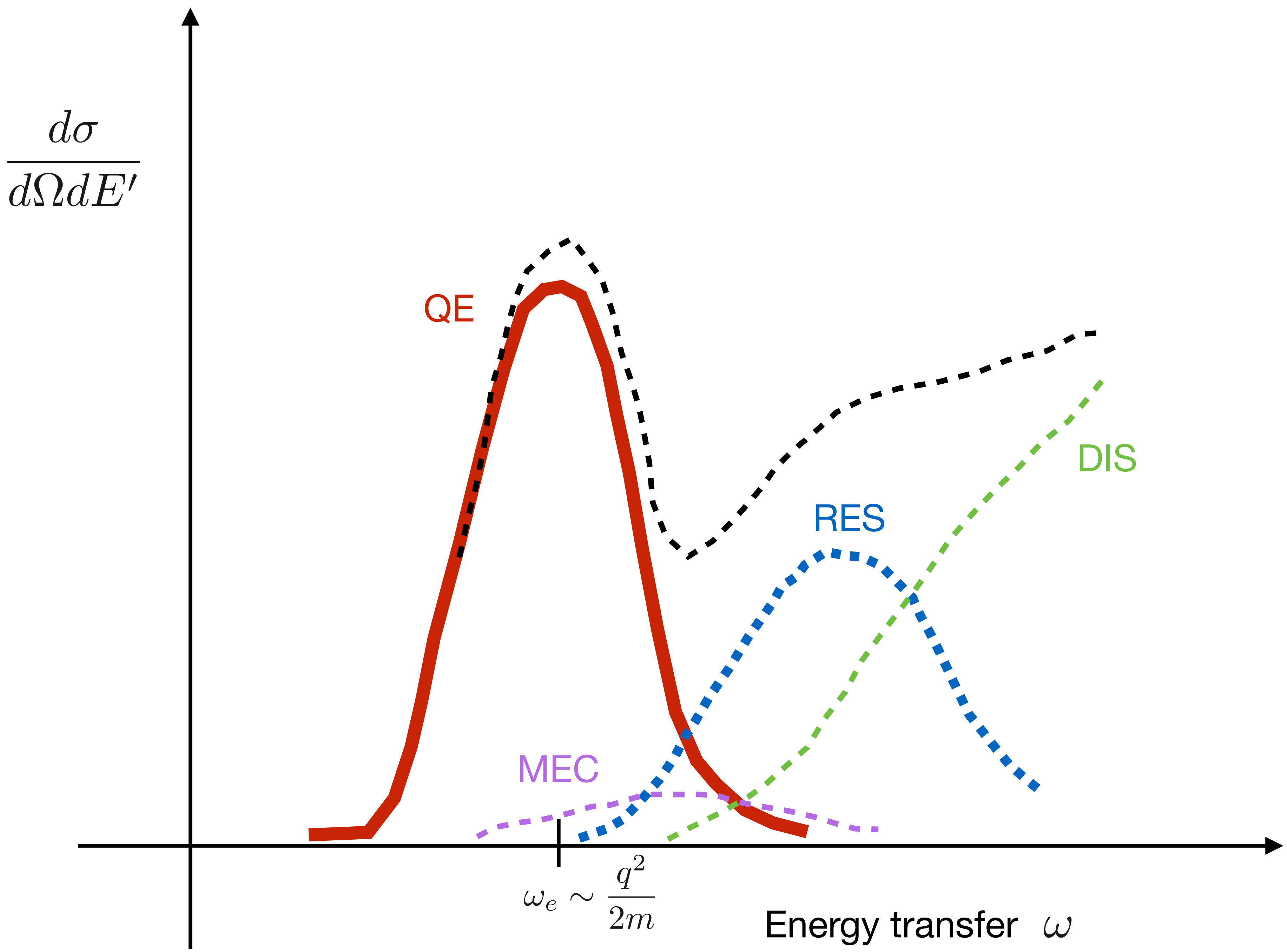
Argon

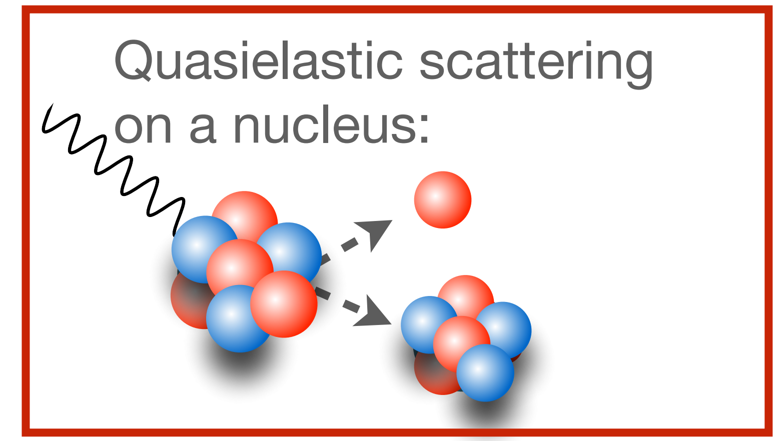


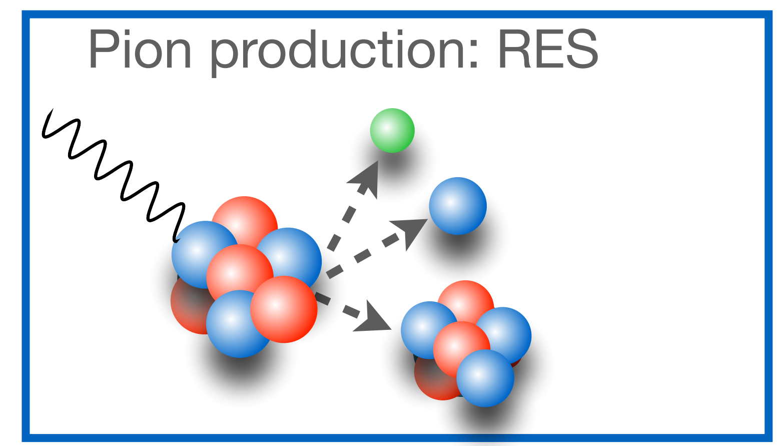
MicroBooNE

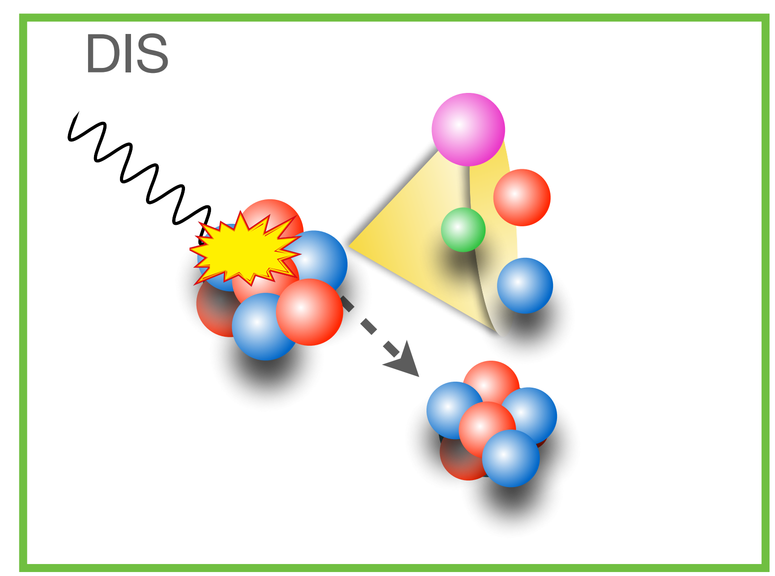
Lepton-nucleus cross section

Different reaction mechanisms contributing to lepton-nucleus cross section
—fixed value of the beam energy (monochromatic)







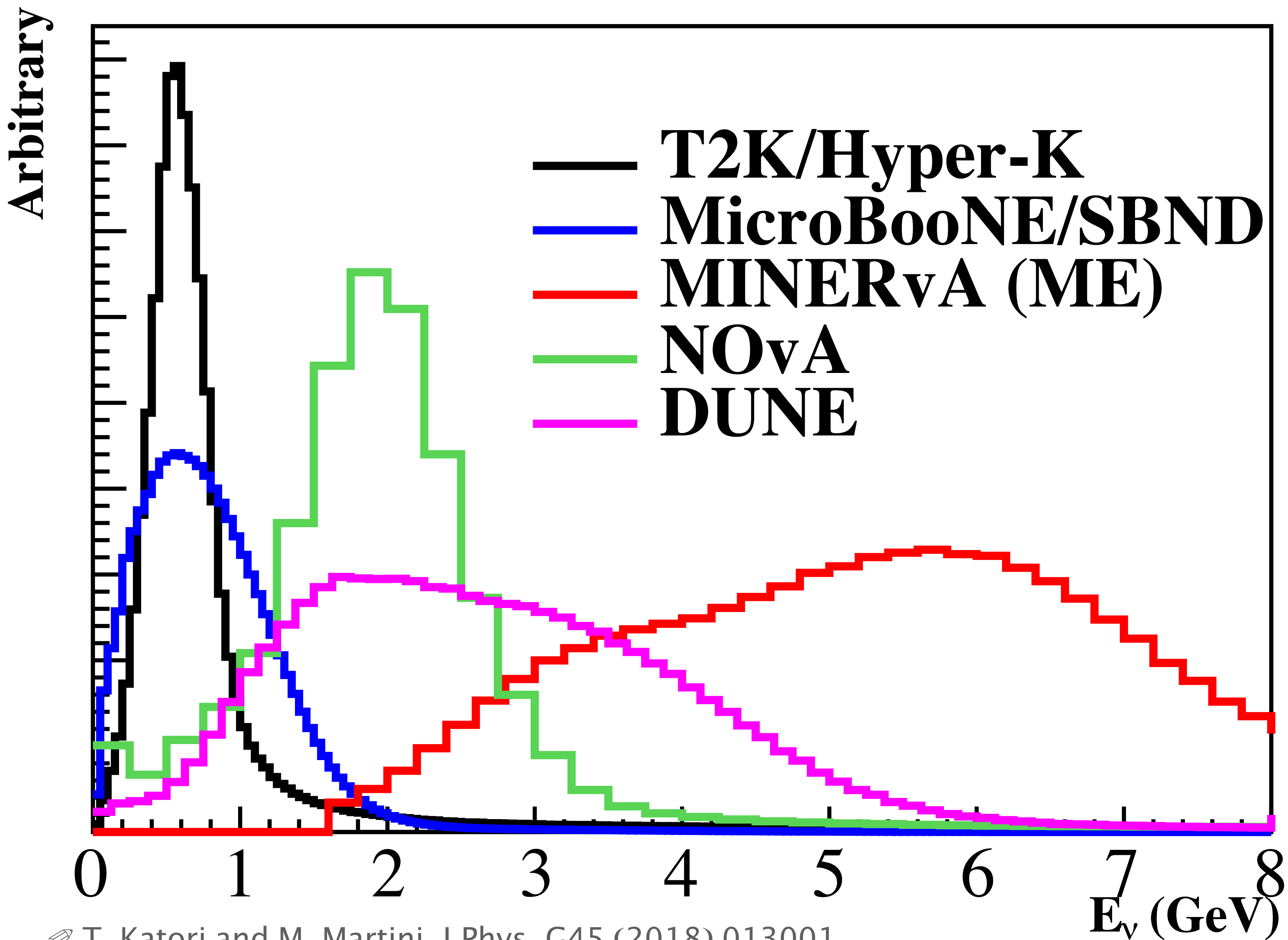


In neutrino experiments these contributions are not nicely separated

Neutrino fluxes for different experiments

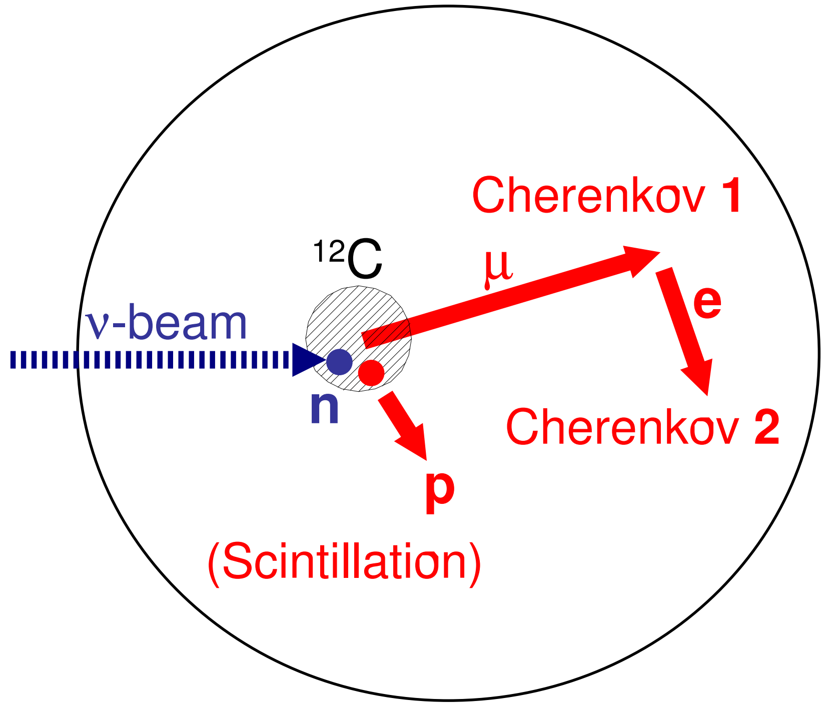
Energy distribution of neutrino fluxes

Present to Future: T2K, MicroBooNE, Nova, MINERvA, Hyper-Kamiokande, DUNE



✐ T. Katori and M. Martini, J.Phys. G45 (2018) 013001

MiniBooNE



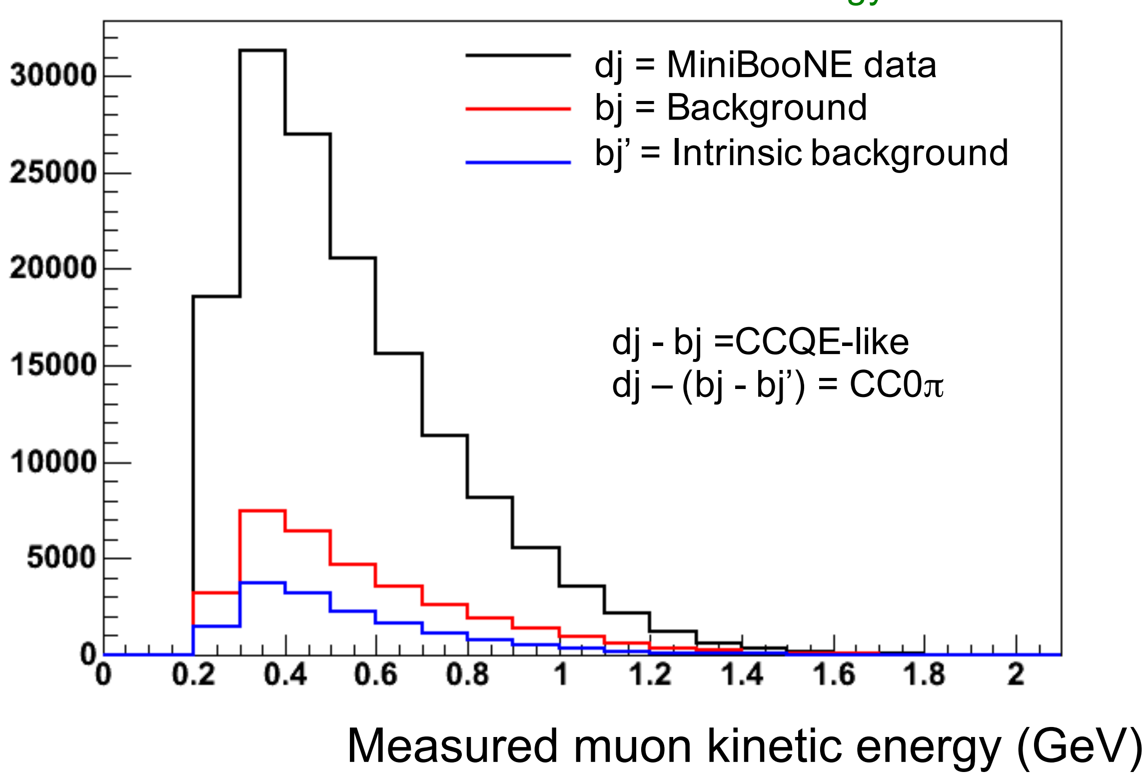
In MiniBooNE data analysis, an event is labeled as CCQE if **no final state pions** are detected in **addition to the outgoing muon.**

First measurement of the **double differential cross section** for CCQE scattering on ^{12}C

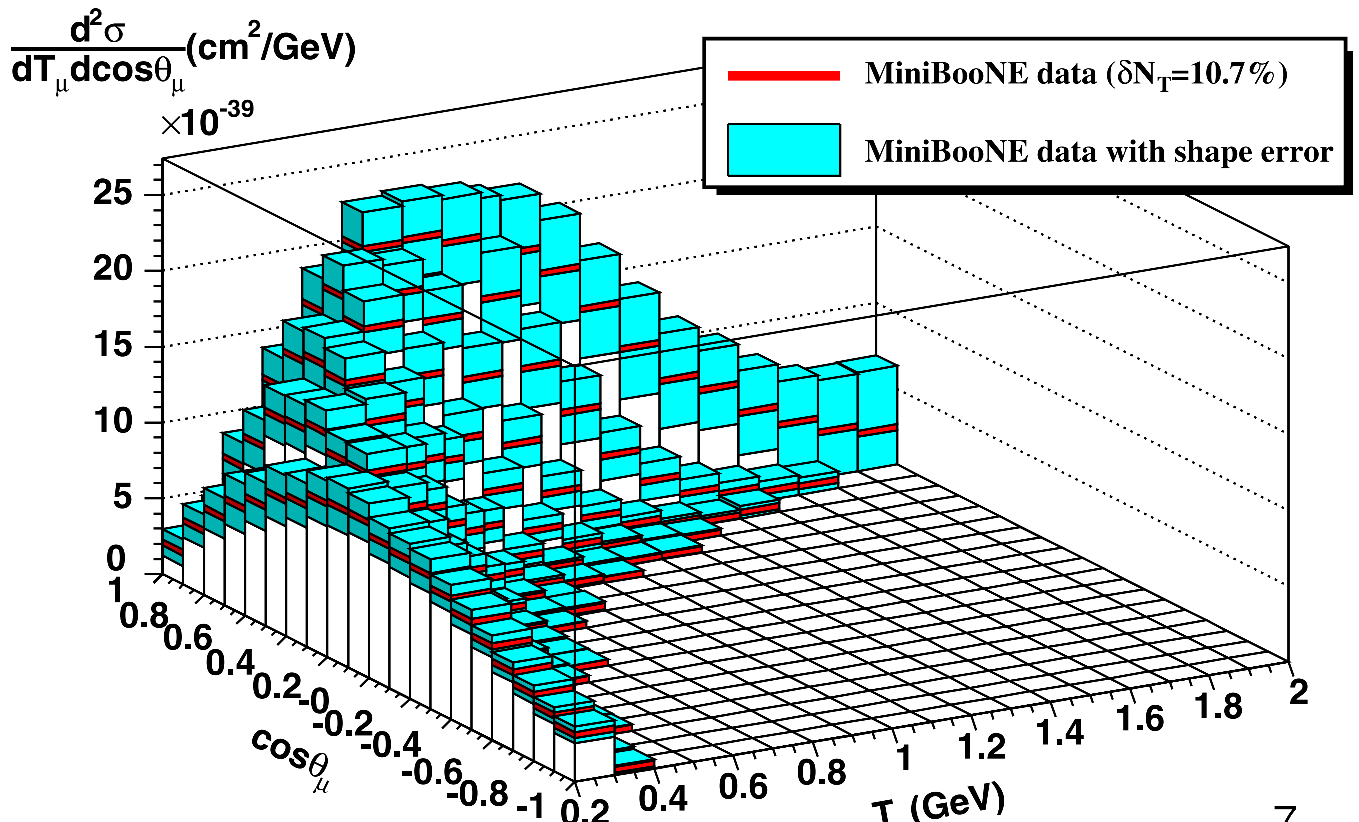
To explain the data careful evaluation of nuclear effects was required: **multi-nucleon emission** first identified

Intrinsic background: pion absorption in nuclei. It has to be simulated and subtracted.

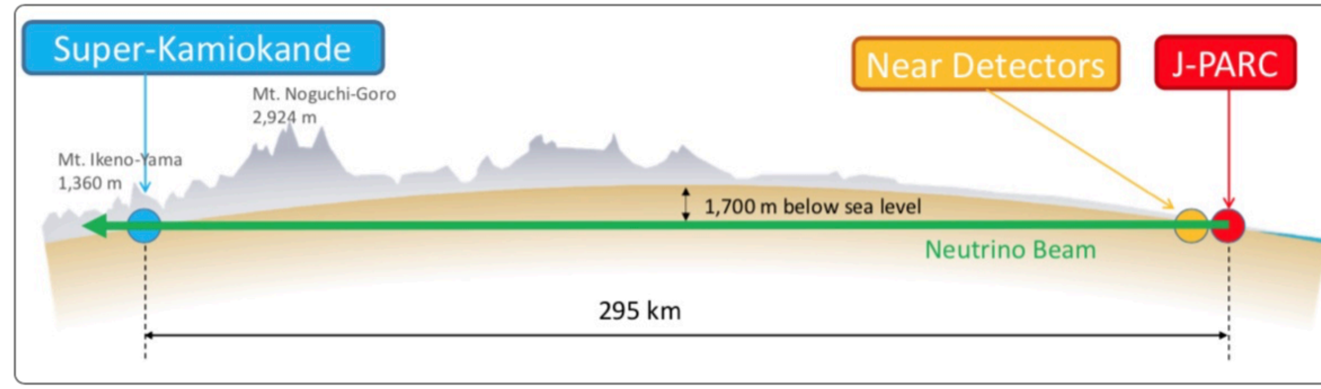
MiniBooNE CCQE candidate muon kinetic energy distribution



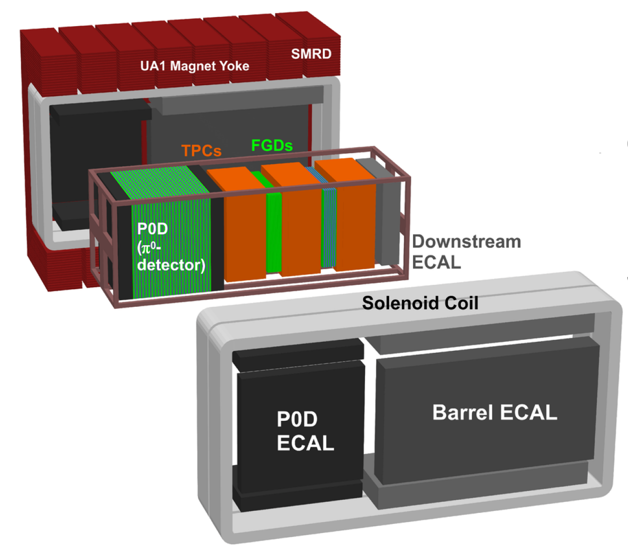
PHYSICAL REVIEW D **81,** 092005 (2010)



T2K



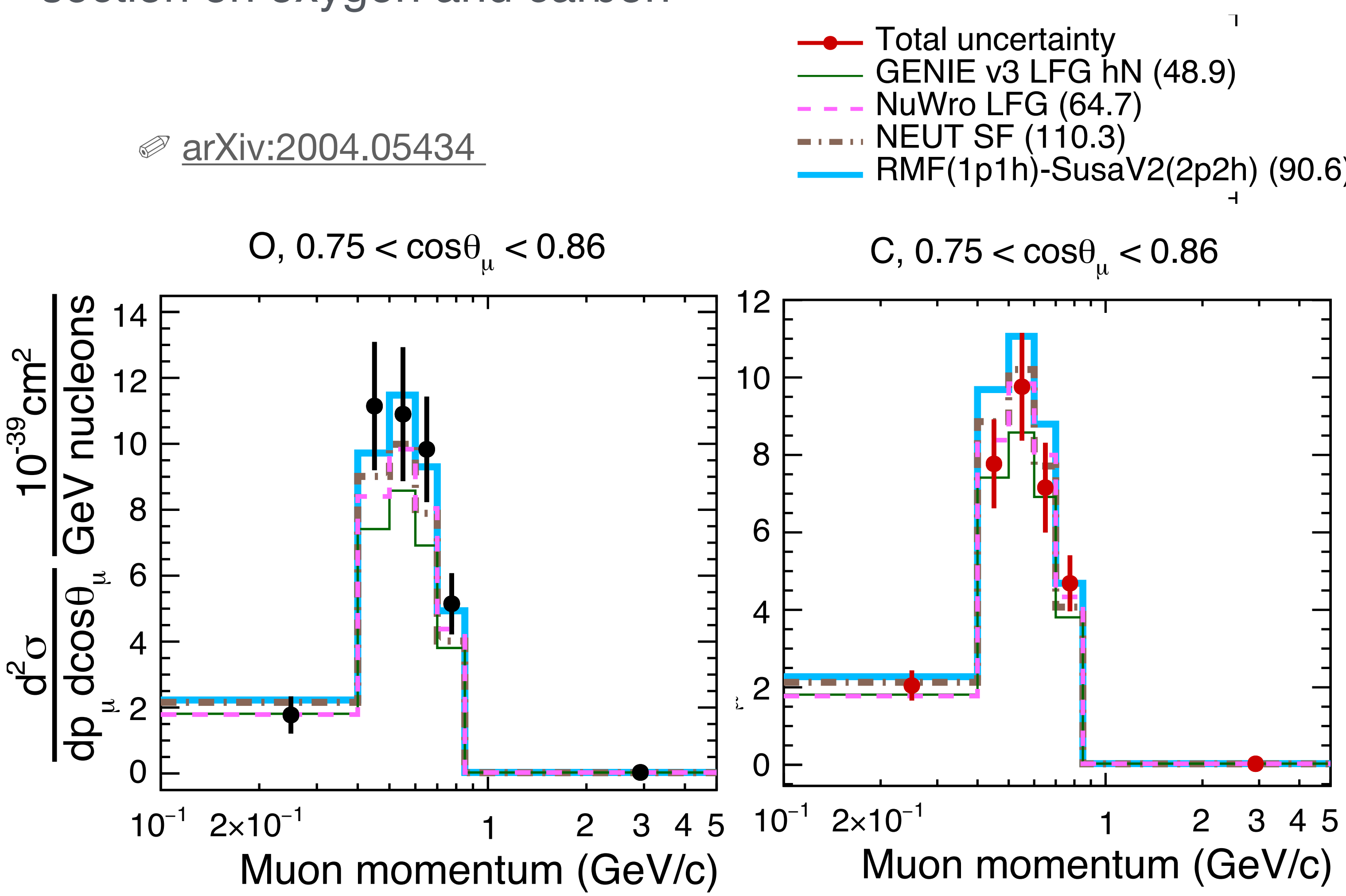
The T2K experiment data-taking started in January 2010 and continues in 2020 and beyond.
The **dominant process** at the peak energy of ~0.6 GeV is **CCQE scattering**.



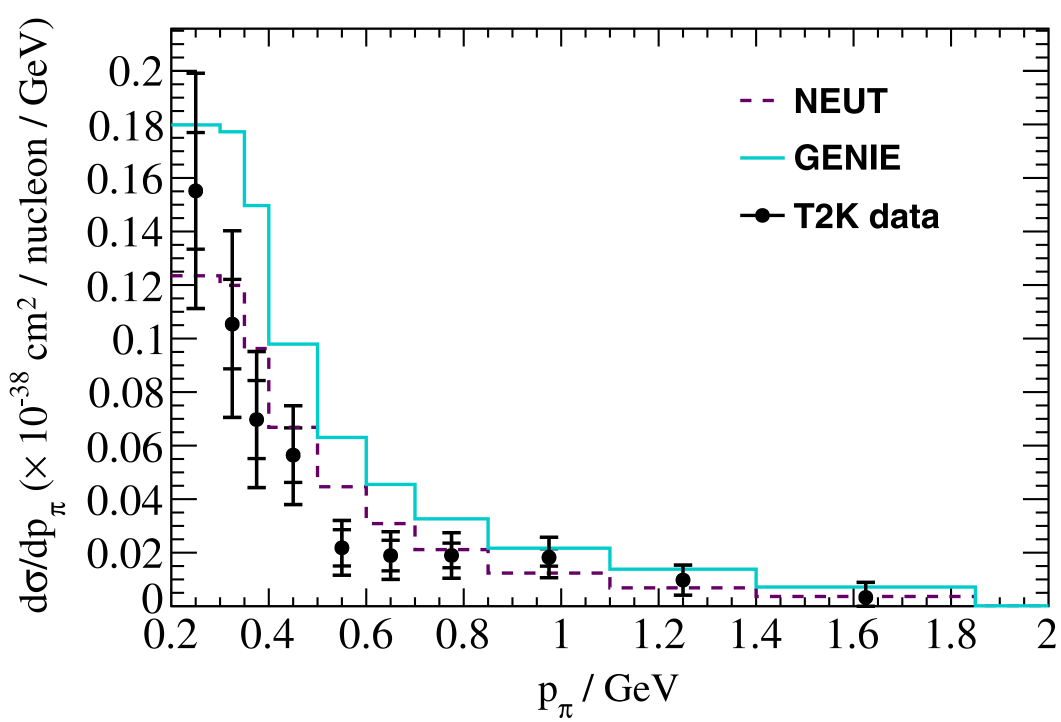
ND280: the off-axis detector provide precise measure of neutrino cross section

Simultaneous measurement of ν_μ-CC0π cross section on oxygen and carbon

✐ arXiv:2004.05434



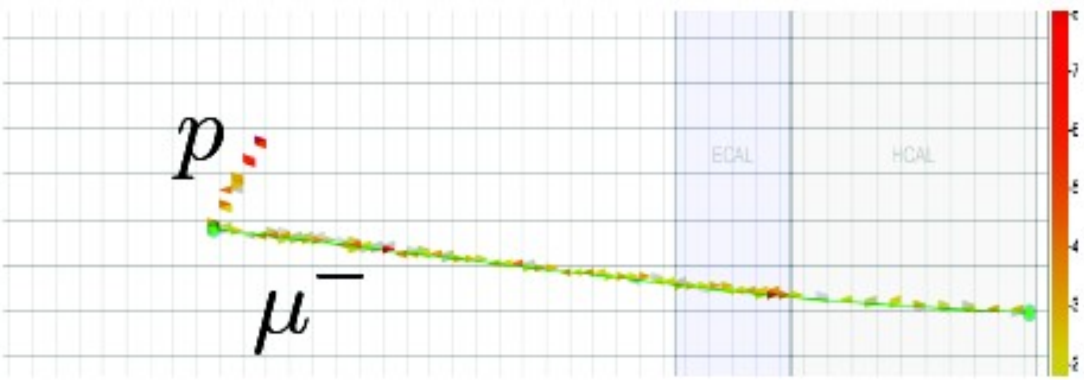
First CCπ+ results on water



✐ Phys. Rev. D 95, 012010 (2017)

MINERvA

MINERvA is the first neutrino experiment in the world to use a **high-intensity beam** to study neutrino reactions with a **variety of nuclei**: He,C,O,Pb and Fe. Strongly constraints neutrino interactions



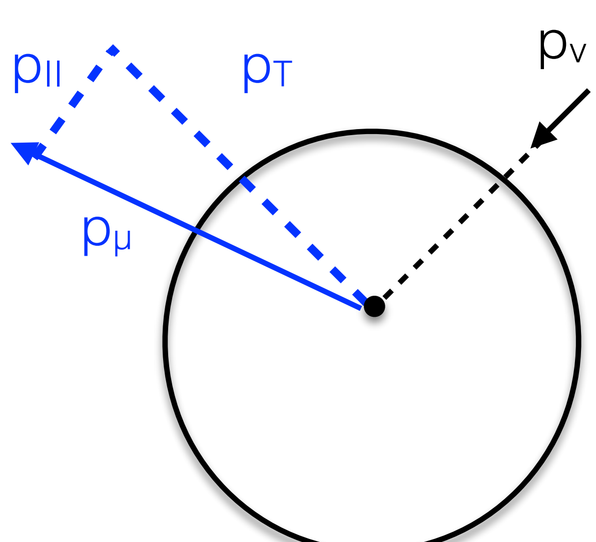
Fine-grained scintillator tracker allows to identify and precisely measure outgoing protons and μ. Probe **nuclear effects** using **the transverse imbalance of p and μ**

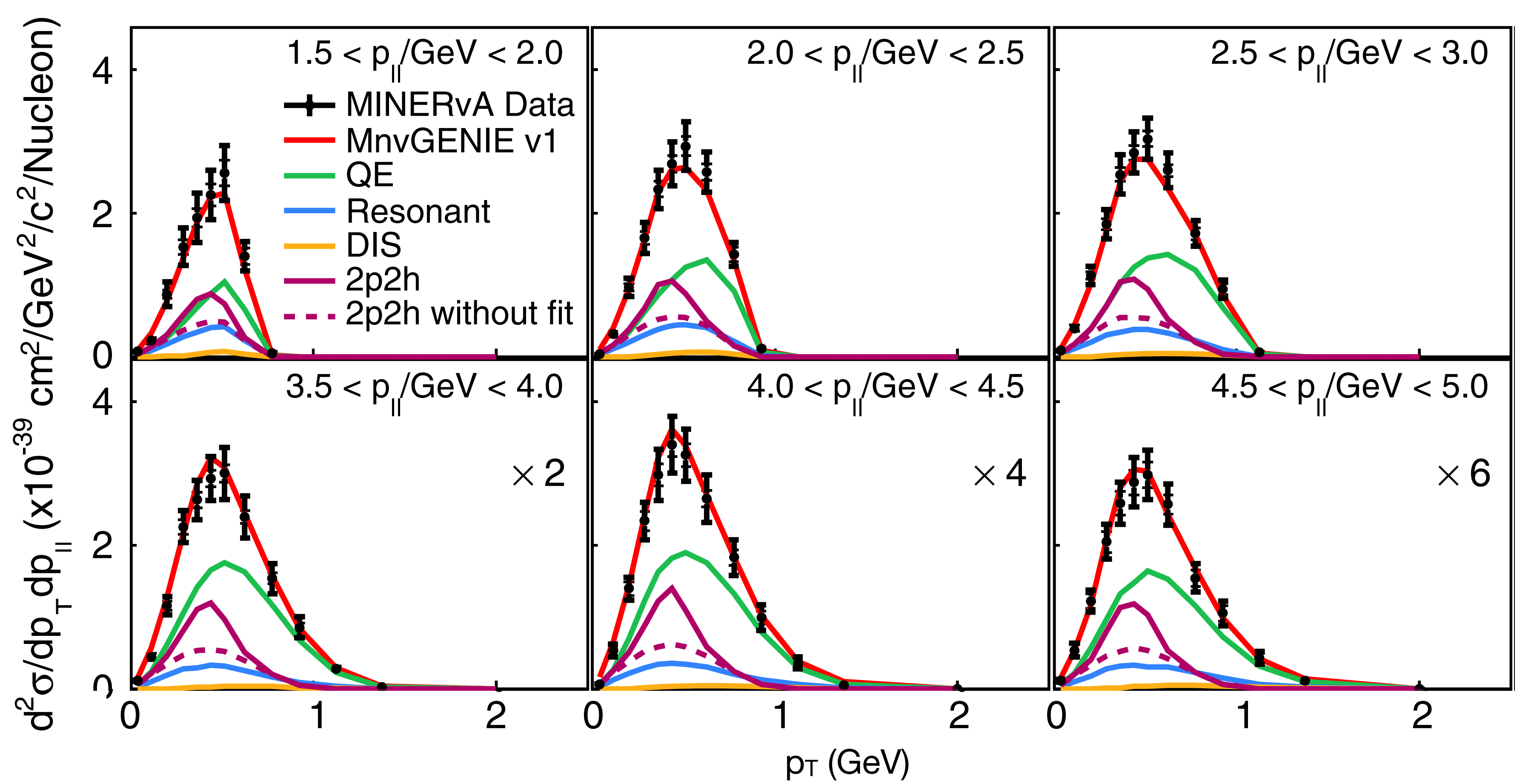
✐ Lu, X.G. et al, Phys Rev Lett.121 (2018) no 2, 022504

✐ T2K, Phys. Rev. D 98 (2018), 032003

Full double differential cross section projected using the kinematics of the μ:

✐ Phys. Rev. D 99 , 012004 (2019)

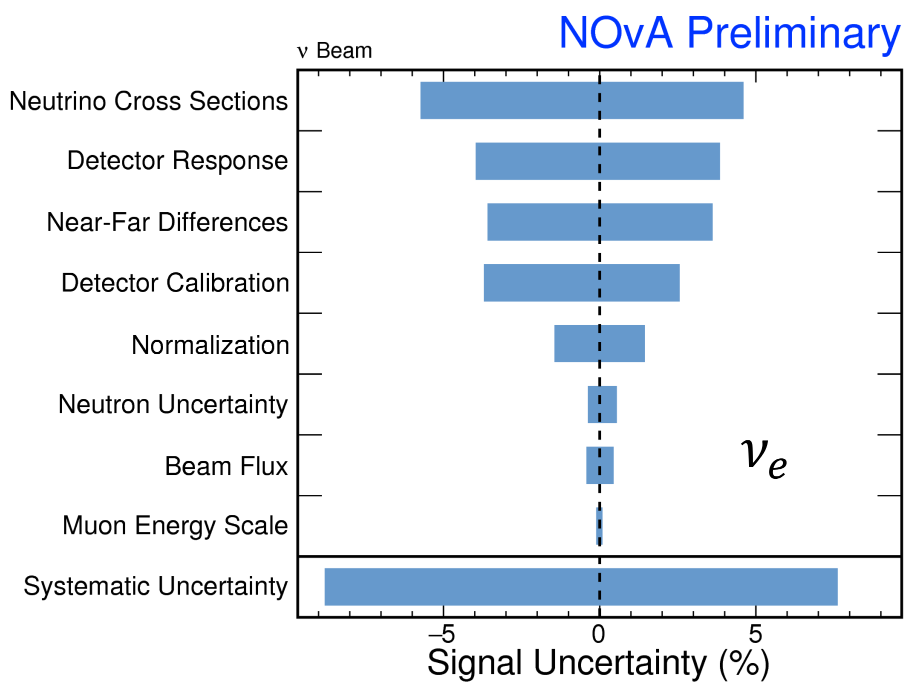




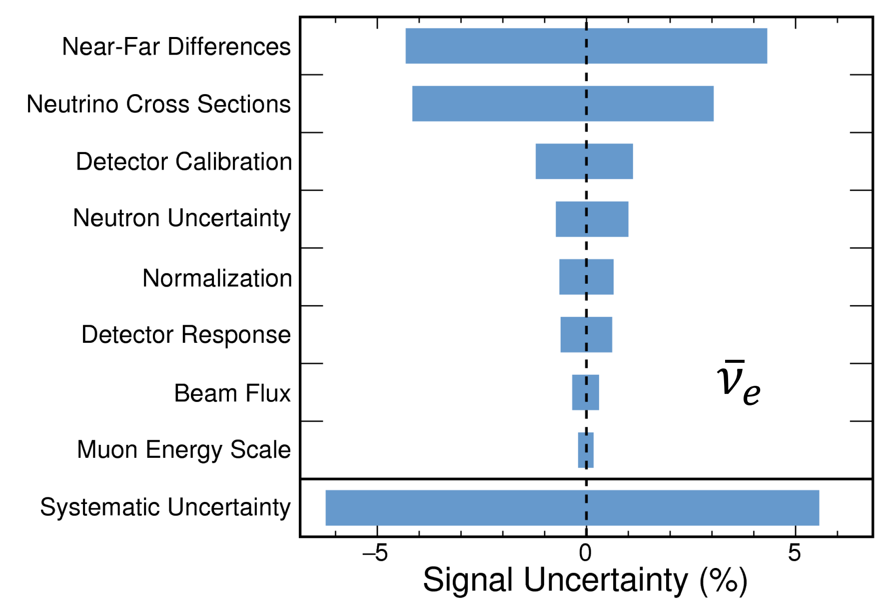
NOvA

The neutrino flux in the NOvA ND is a narrow band beam peaked at 1.9 GeV, between 1.1 and 2.8 GeV

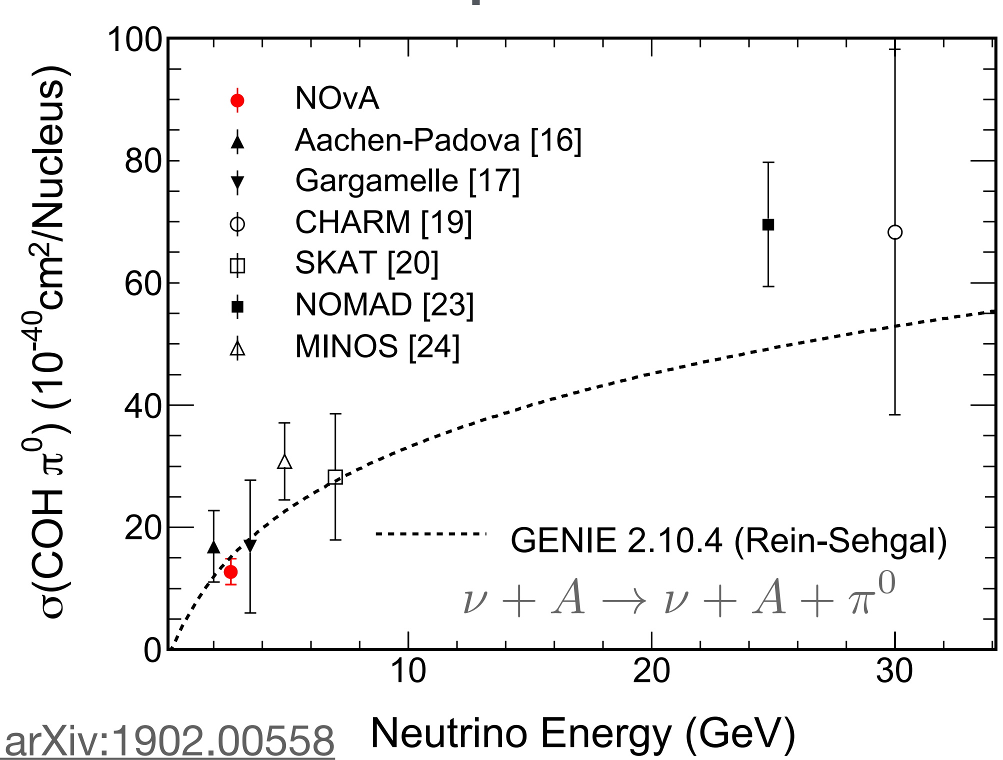
Cross section modeling is one of the **leading systematic uncertainties** for NOvA's measurements.



✐ Taken from: S.K.Lin's talk @ SUSY 2019

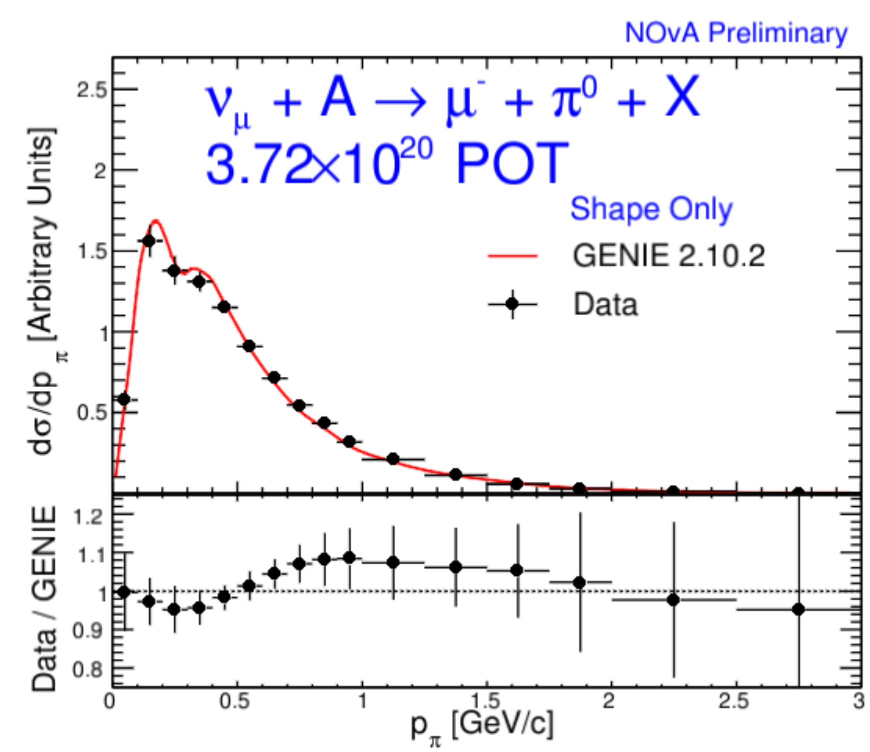


NC **coherent π0 production** on a carbon:



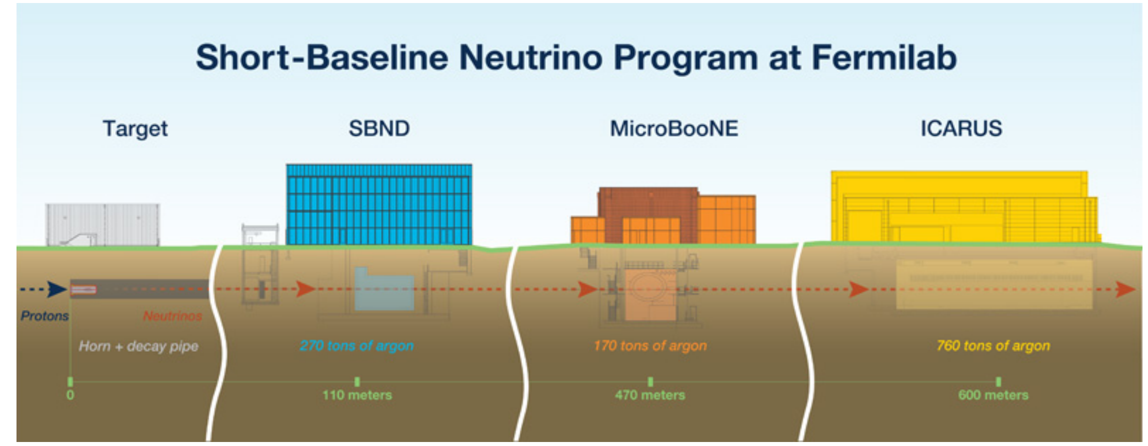
✐ arXiv:1902.00558

ν_μ CC π^0 seminclusive results: both RES and DIS



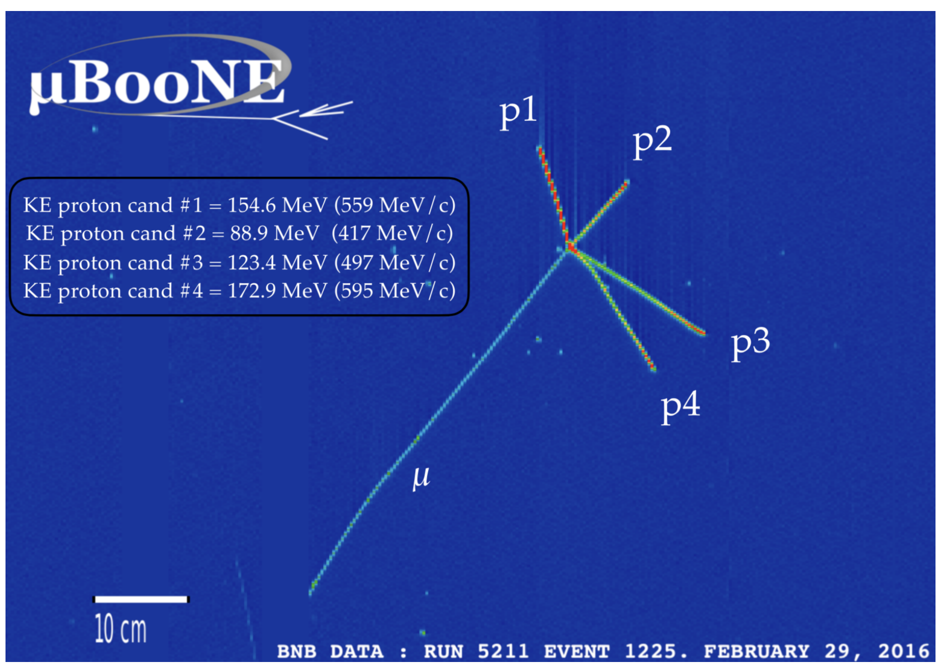
MicroBooNE

Multiple LAr-TPC detectors at different baselines along the Booster Neutrino Beam will search for **high Δm^2 neutrino oscillation:** resolve the source MiniBooNE low energy excess



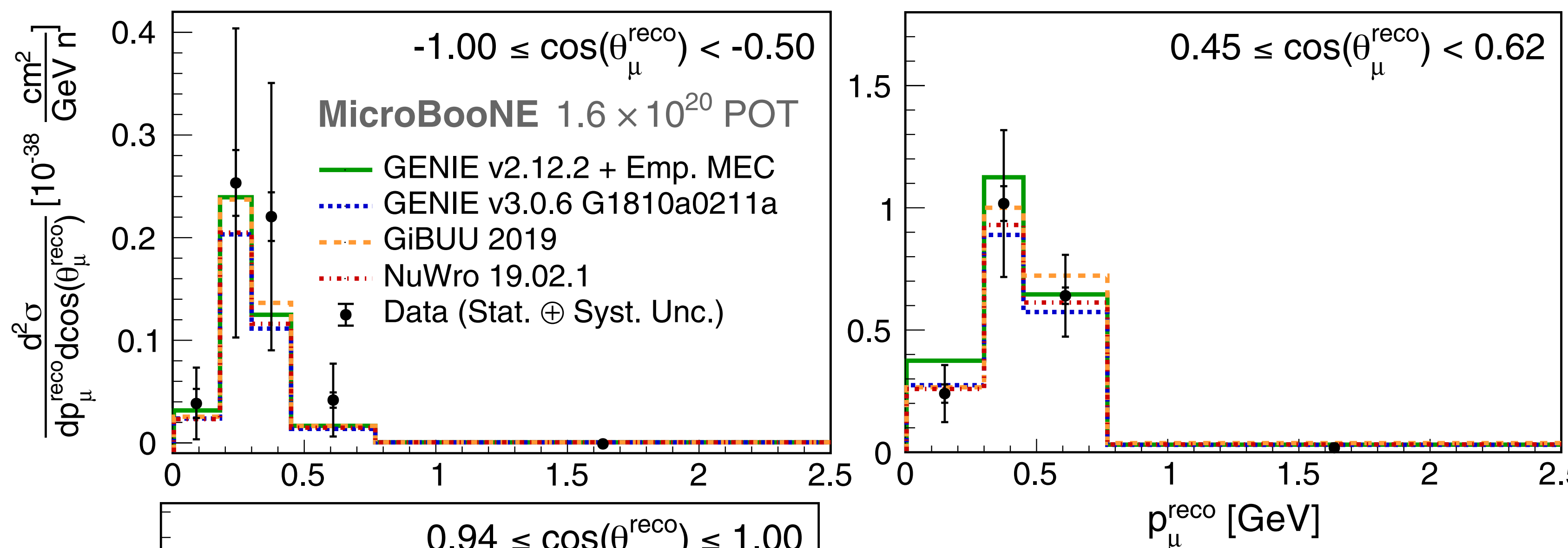
MicroBooNE precision measurements **ν-Ar** cross sections in the hundreds-of-MeV to few-GeV energy range

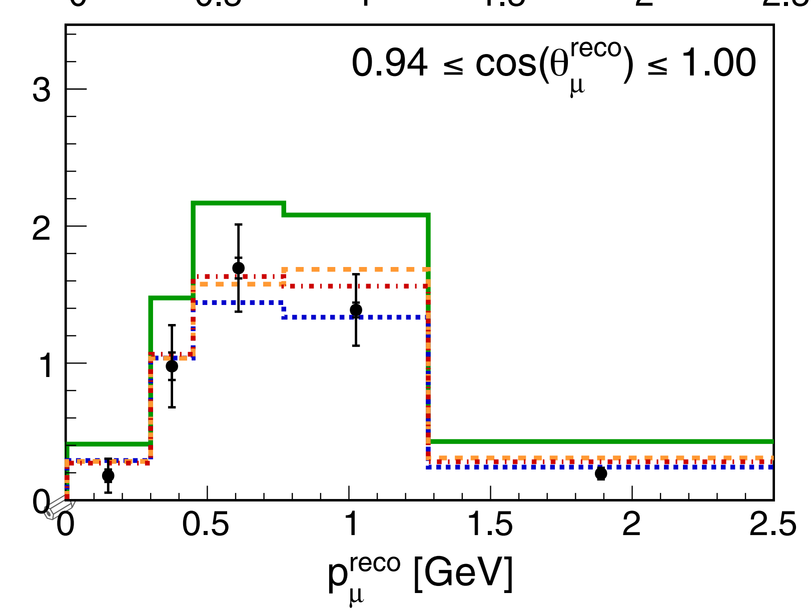
Multiple proton emission



Important test for: nuclear physics model for multi-nucleon emission and event generator predictions for proton multiplicity and kinematics

First measurement of ν_μ **CC double-differential** inclusive cross sections on Ar at $\langle E_\nu \rangle = 0.8$ GeV





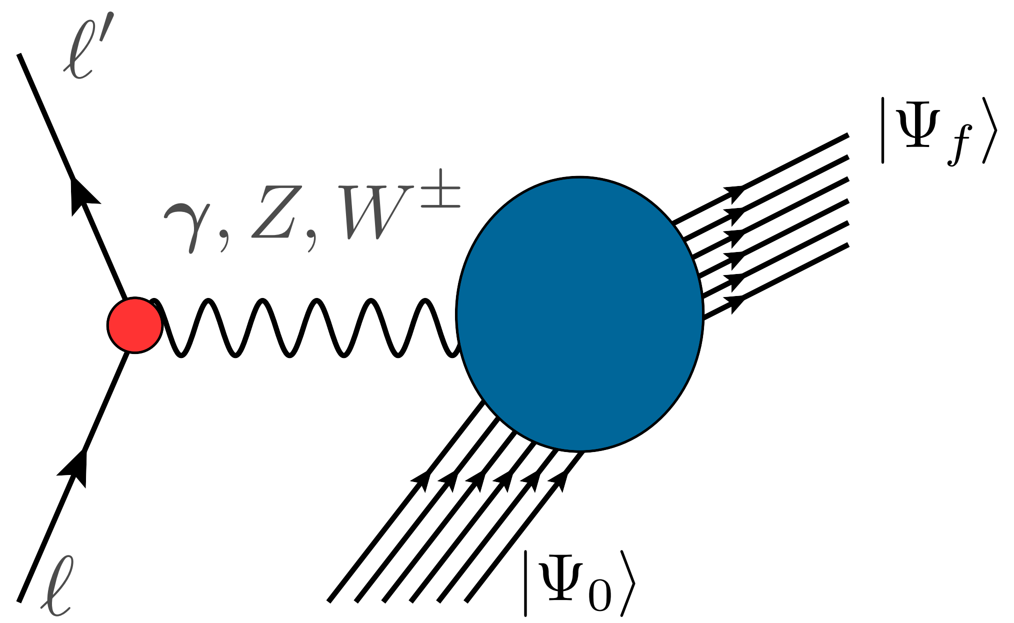
Provides a test for the details of neutrino cross section models

✐ Phys.Rev.Lett. 123, 131801 (2019)

Theory of lepton-nucleus scattering

The cross section of the process in which a lepton scatters off a nucleus is given by

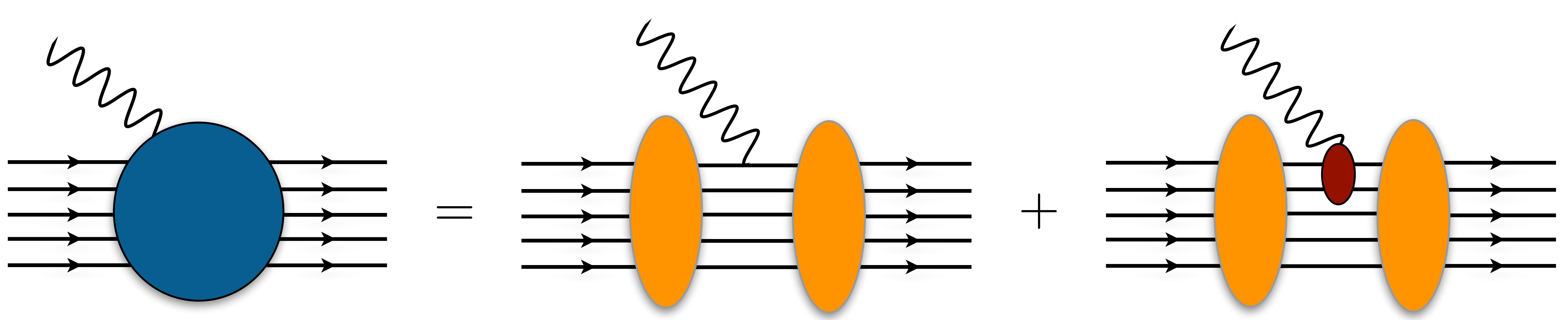
$$d\sigma \propto L^{\alpha\beta} R_{\alpha\beta}$$



The initial and final wave functions describe many-body states:

$$|0\rangle = |\Psi_0^A\rangle \;, |f\rangle = |\Psi_f^A\rangle, |\psi_p^N, \Psi_f^{A-1}\rangle, |\psi_k^\pi, \psi_p^N, \Psi_f^{A-1}\rangle \ldots$$

One and two-body current operators

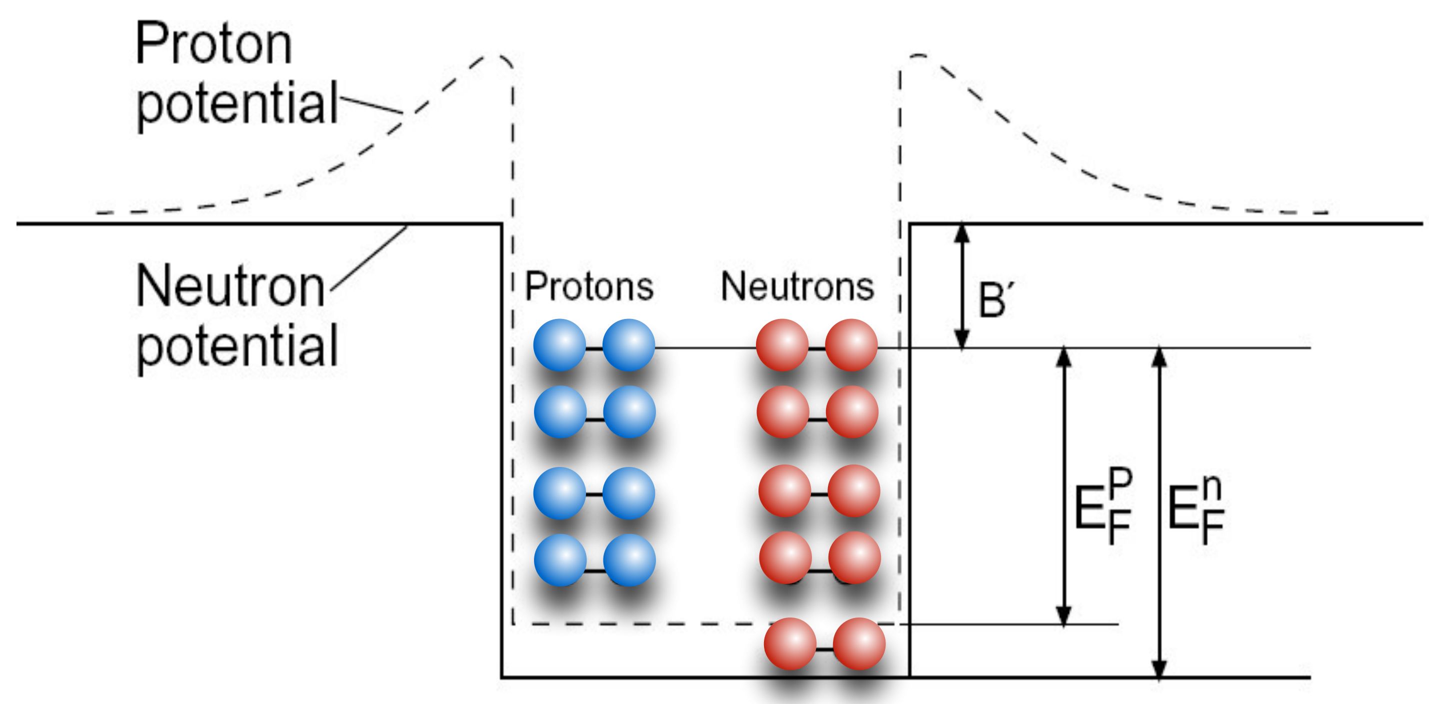


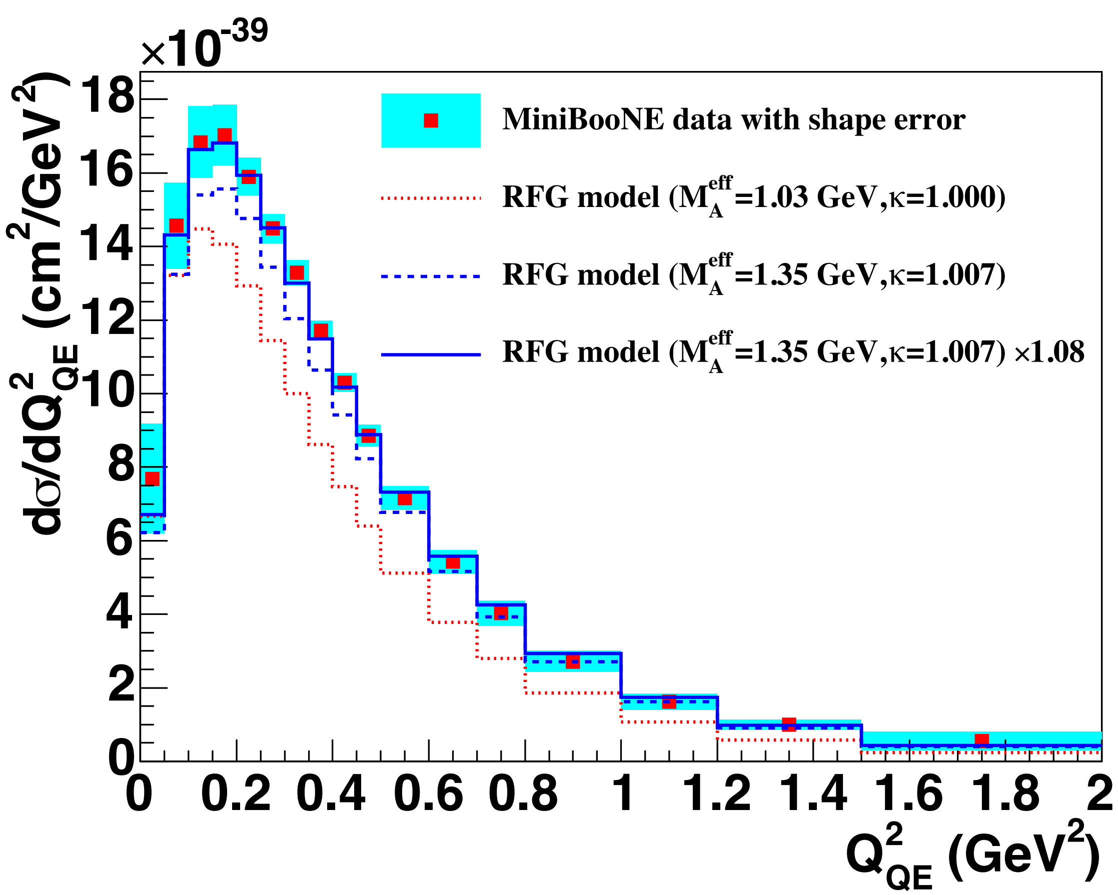
Global Fermi gas: independent particles

Protons and neutrons are considered as **moving freely** within the nuclear volume

Simple picture of the nucleus: only **statistical correlations** are retained (Pauli exclusion principle)

The energy of the highest occupied state is the **Fermi energy: E_F , B' constant binding energy**





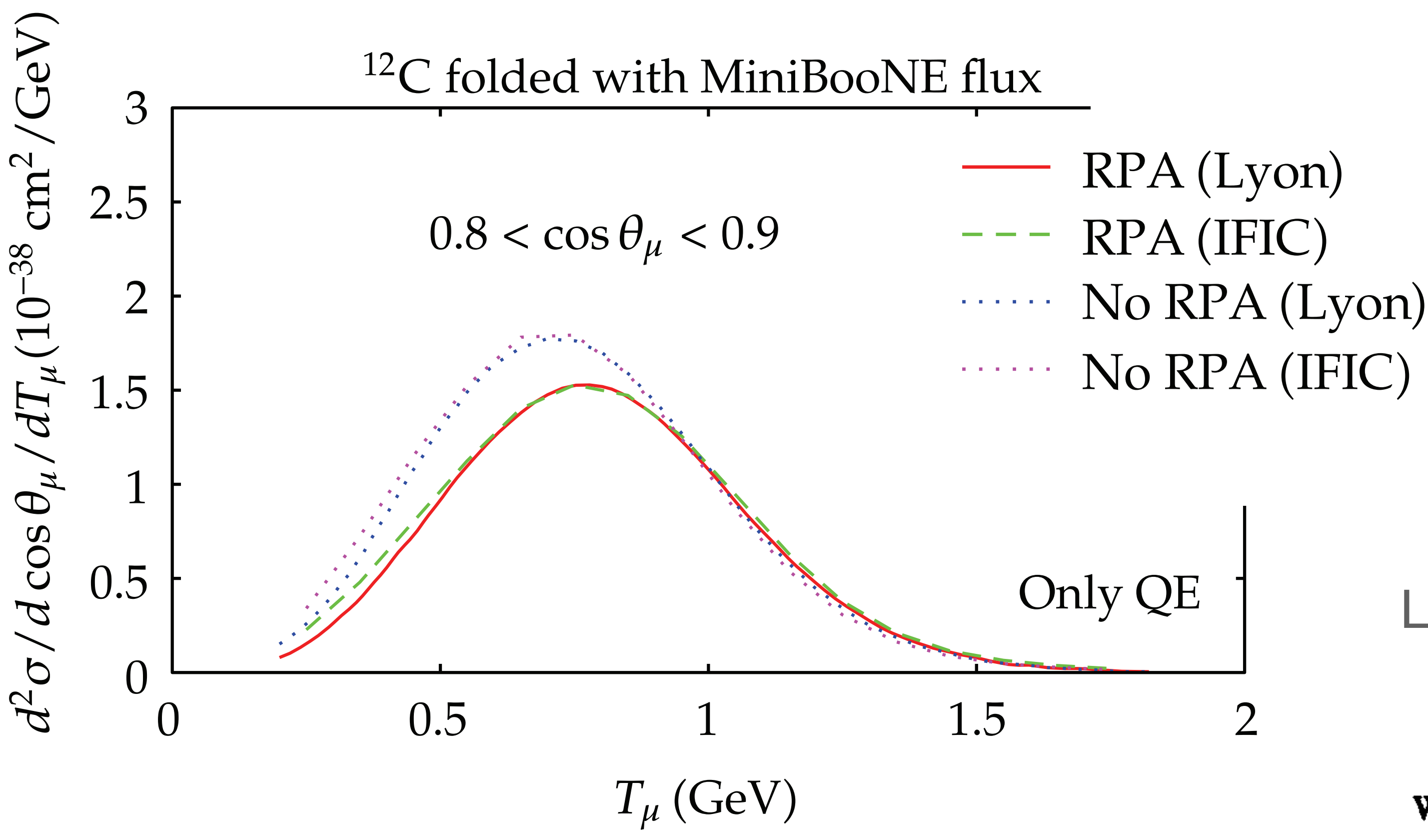
The Global Fermi gas model has been widely used in comparisons of neutrino scattering data.

MiniBooNE data analysis to reproduce the data: M_A~1.35 GeV is incompatible with former measurements in bubble chamber: M_A~1.03 GeV

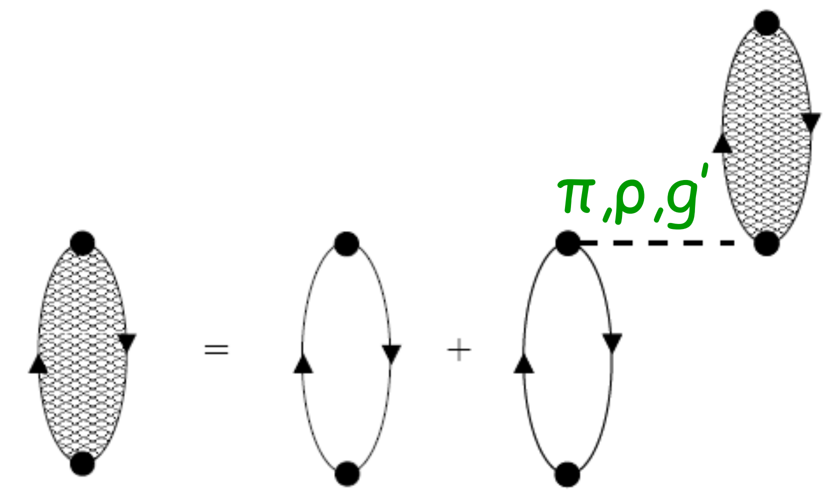
Nuclear effects can explain the axial mass puzzle

✐ MiniBooNE collaboration, PRD 81 (2010) 092005

Valencia - Lyon models



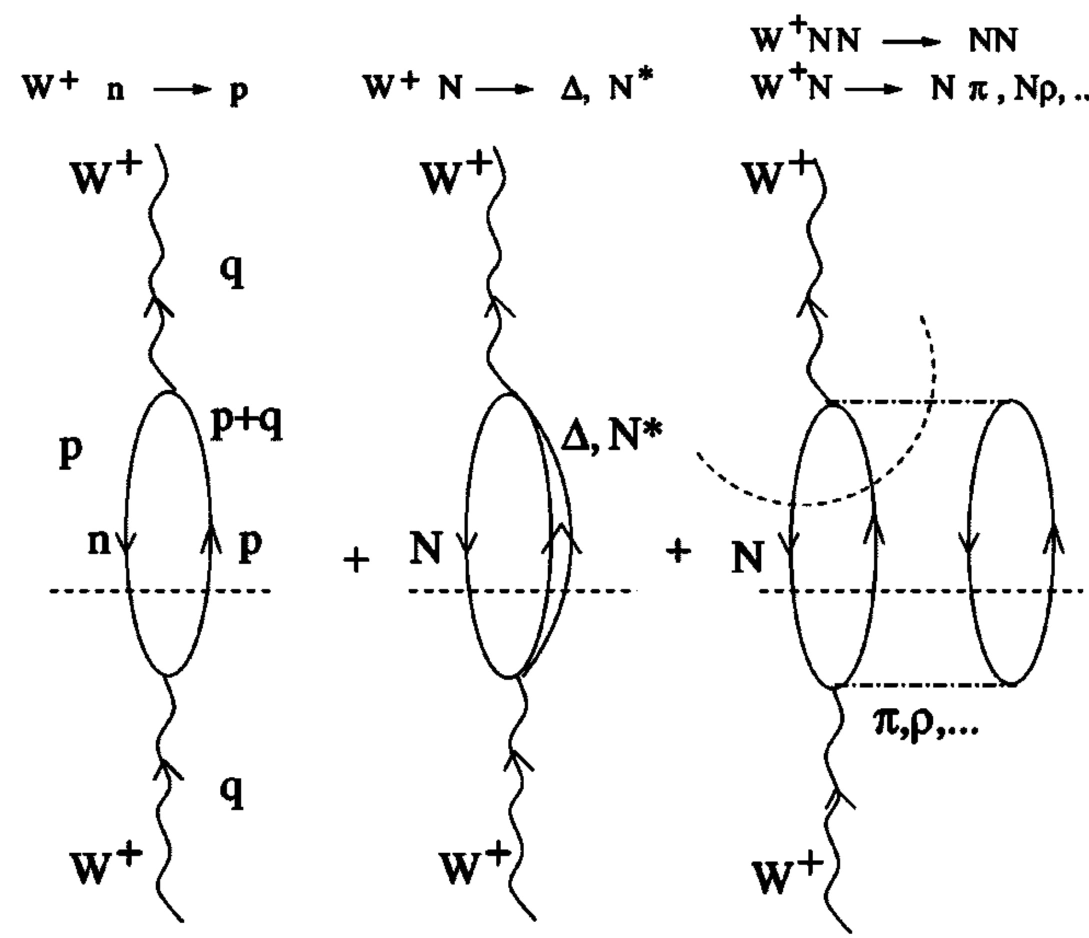
✐ Morfin, Nieves, Sobczyk Adv.High Energy Phys. 2012 934597



Long-range NN correlations are included in the RPA

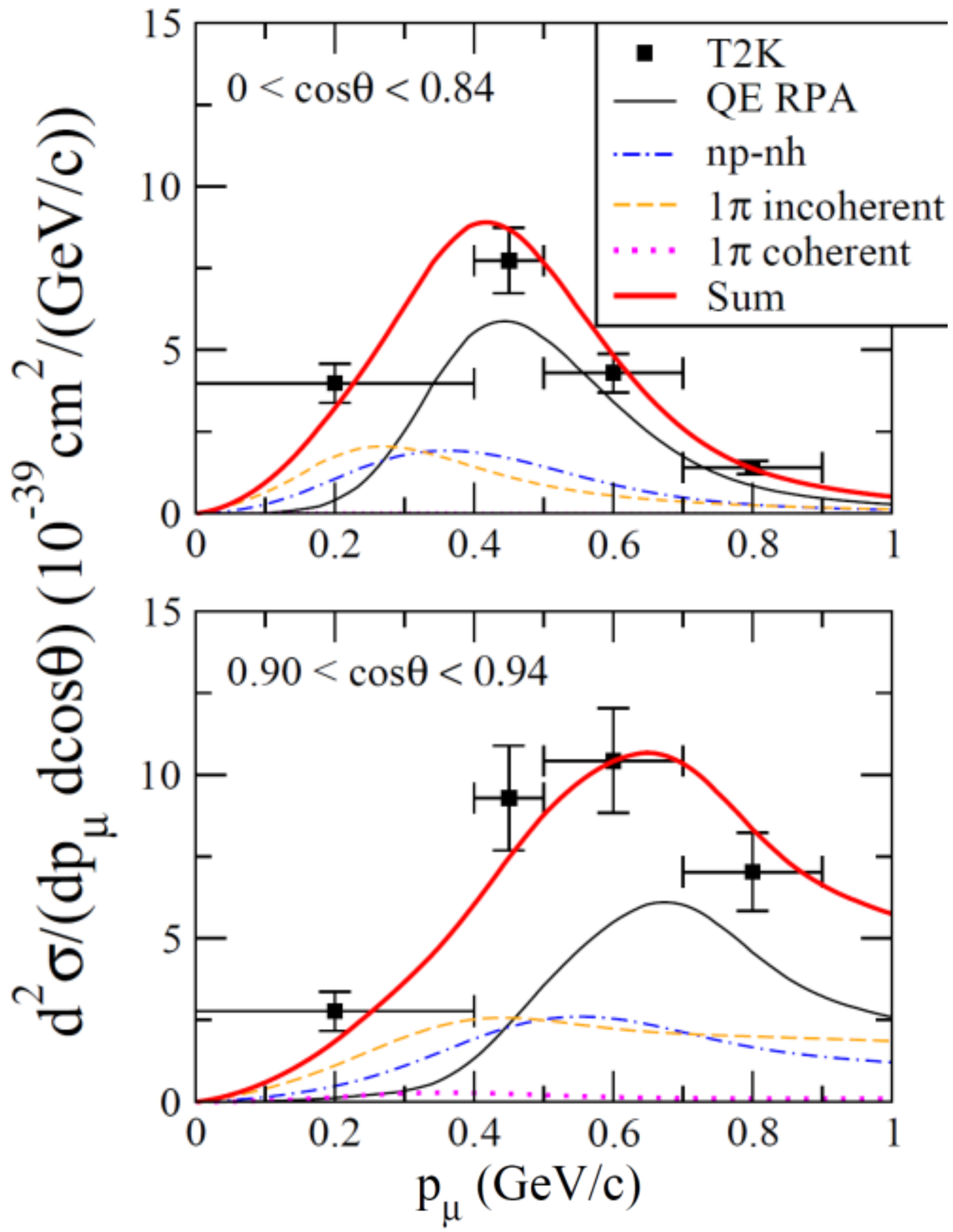
This approach allows for a unified treatment of different reaction mechanisms

QE, two-nucleon emission, π-production are obtained performing different cuts on the internal lines of the W-boson self energy: **Optical theorem**

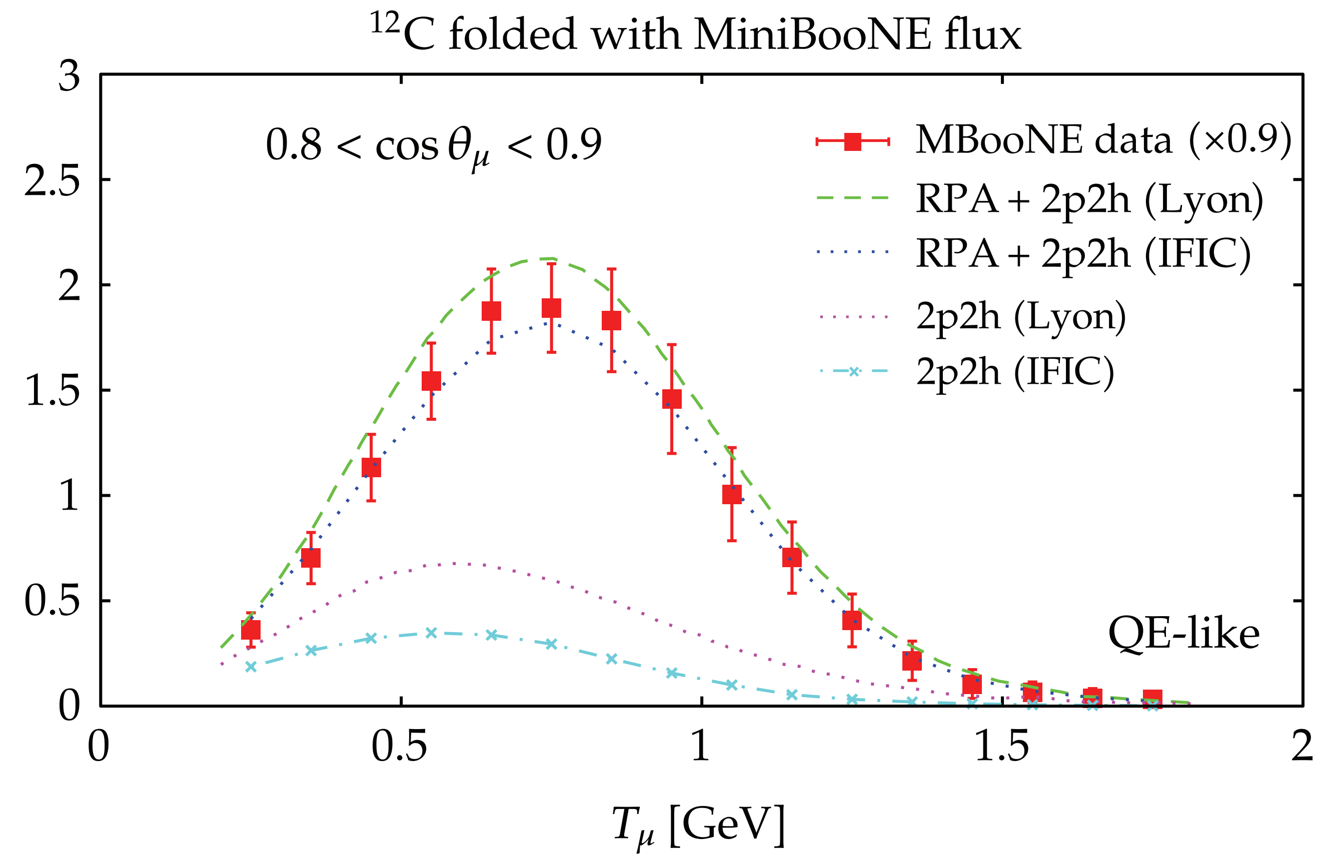


Valencia - Lyon models

Multi-nucleon emission first proposed as a solution of the **MiniBooNE axial-mass puzzle** in Martini et al, PRC 80, 065501 (2009)



✎ M. Martini et al, Phys.Rev.C90,025501(2014)



✎ Morfin, Nieves, Sobczyk Adv.High Energy Phys. 2012 934597

The Valencia and Lyon model have been tested in the CCQE-like, CC0π and CC inclusive data for different experiments

They are currently implemented in different EG

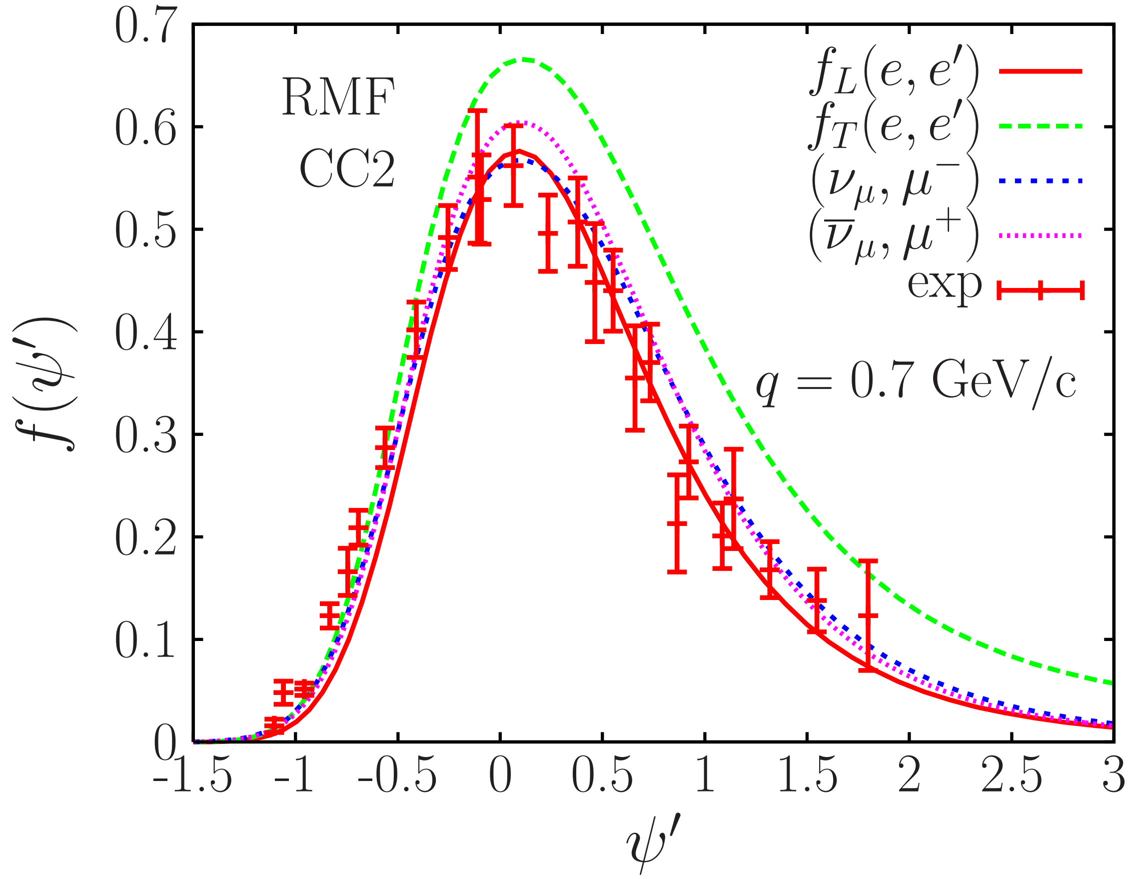
The inclusion of RPA effects more relevant at low-q^2 yielding shape distortion in the QE cross section

SuSav2 model

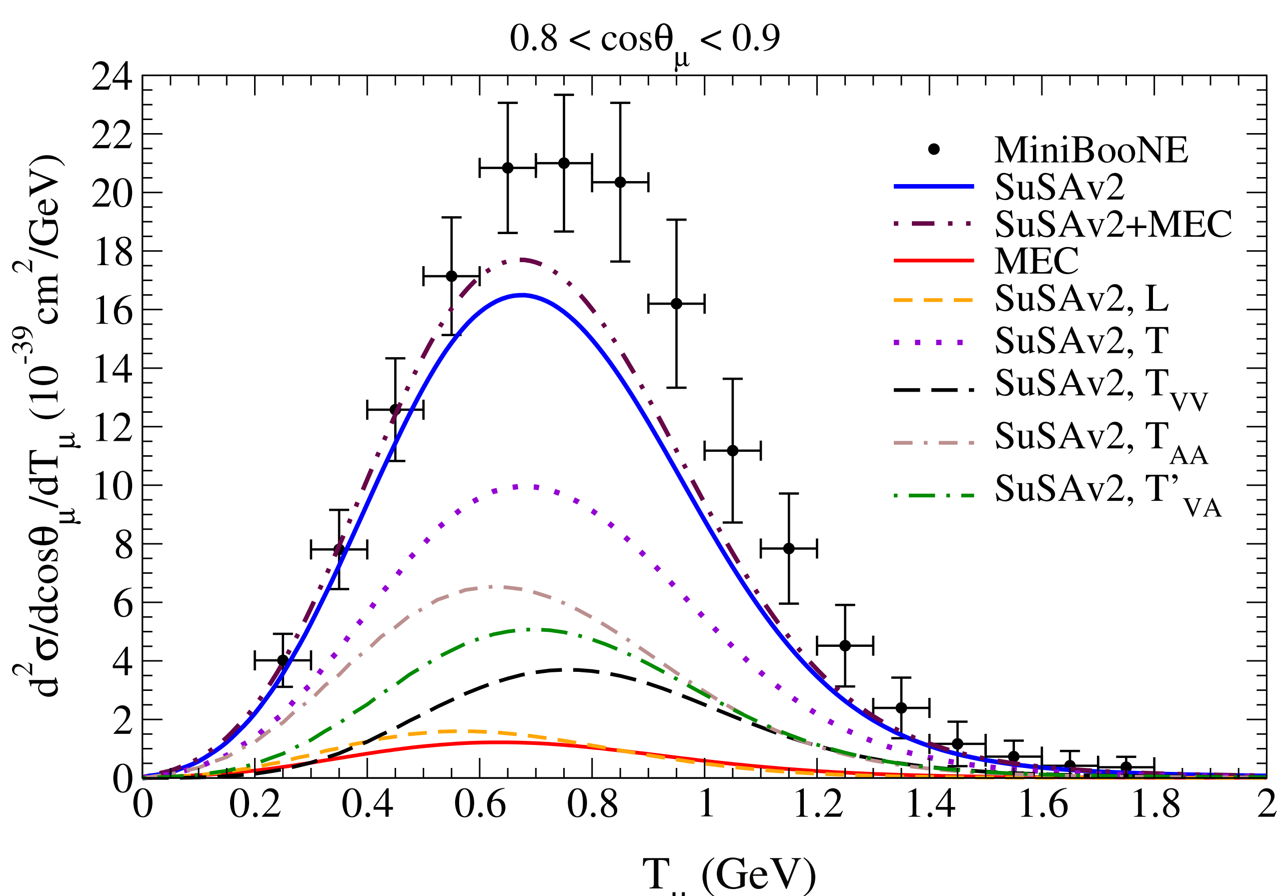
SuSA utilizes the longitudinal scaling function extracted from electron scattering data to obtain both electron and neutrino cross sections

Relativistic Mean Field (RMF): more rigorous approach to compute the scaling functions. Reproduces the T enhancement displayed by data and incorporates final sate interactions but limited to intermediate kinematics.

J.A. Caballero et al, Phys,Lett.B.653, 2007



SuSav2: provides a description of the responses based on RMF behavior at lower q, while for higher q it mimics RPWIA trends.



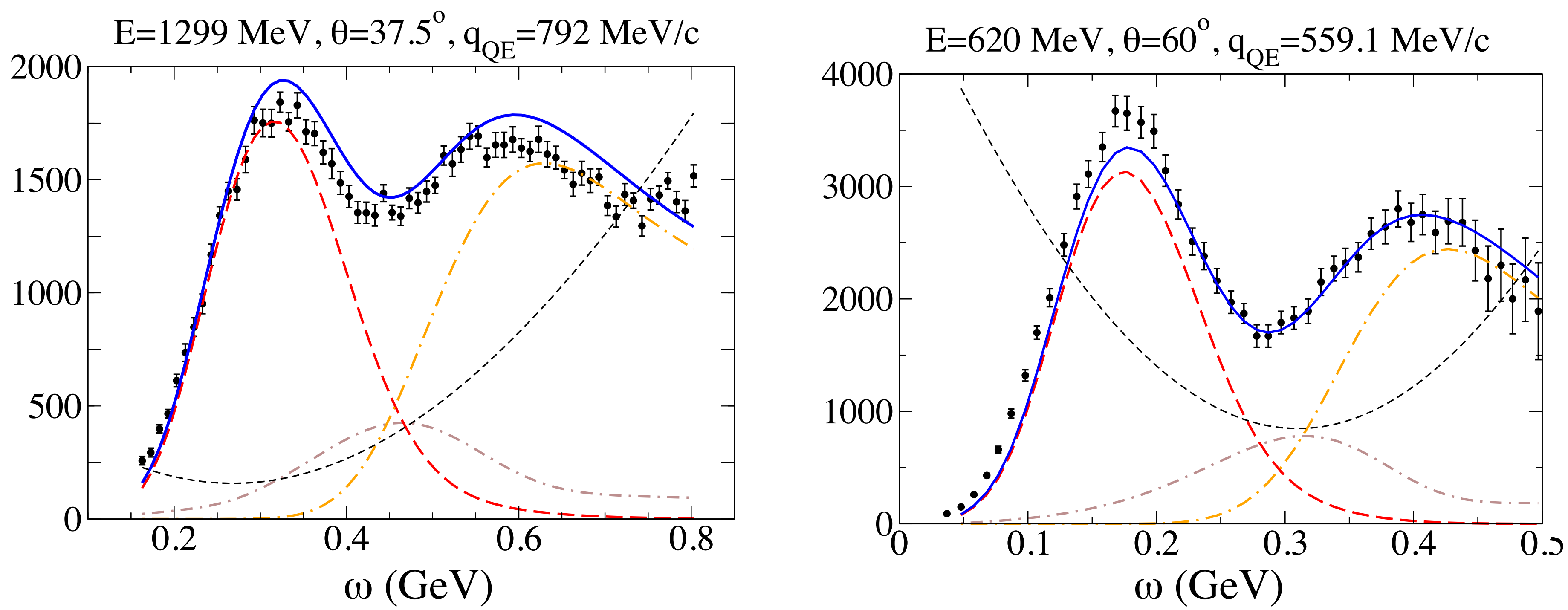
G,D.Megias et al, PRD.91.073004

Meson Exchange Currents : 2p2h included is based on a RFG calculation with fully relativistic currents

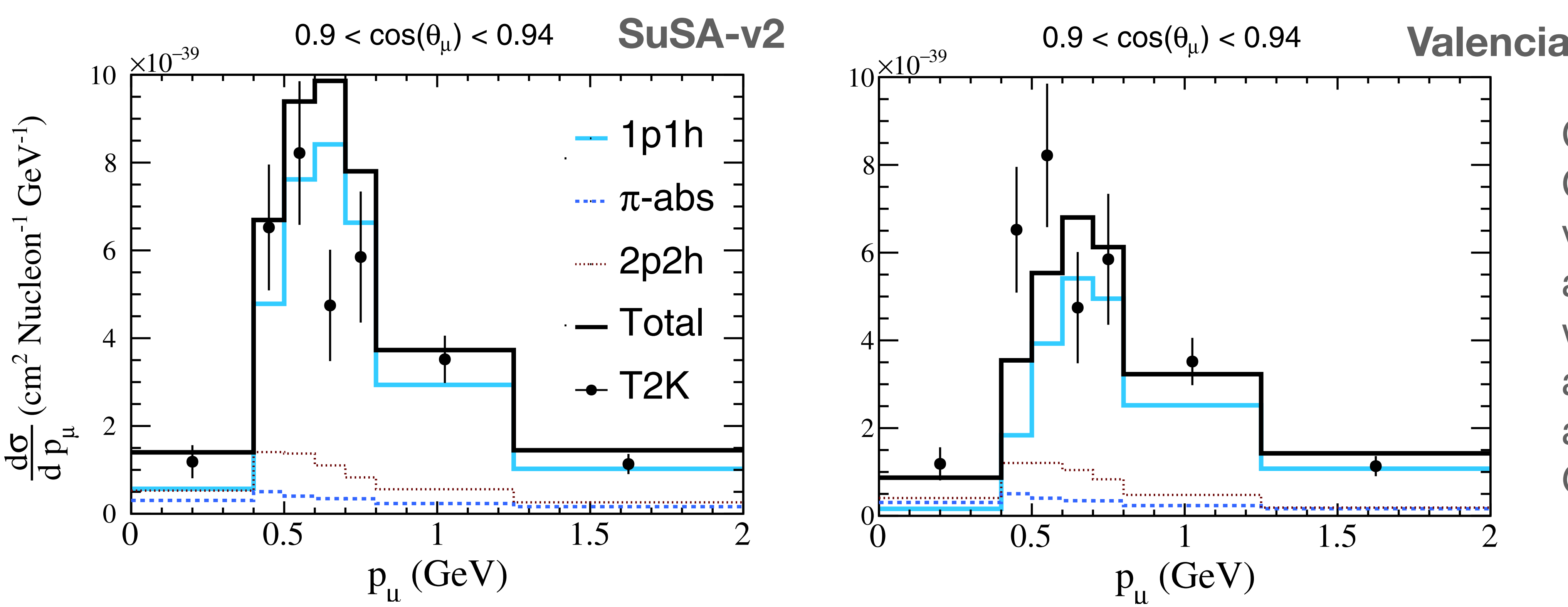
SuSav2 model

G.D.Megias et al, Phys Rev D 94. 013012 (2016)

Extensive comparison with electron scattering data $^{12}C(e,e')$ double differential cross section



S. Dolan et al, Phys Rev D 101 no.3, 033003 (2020)

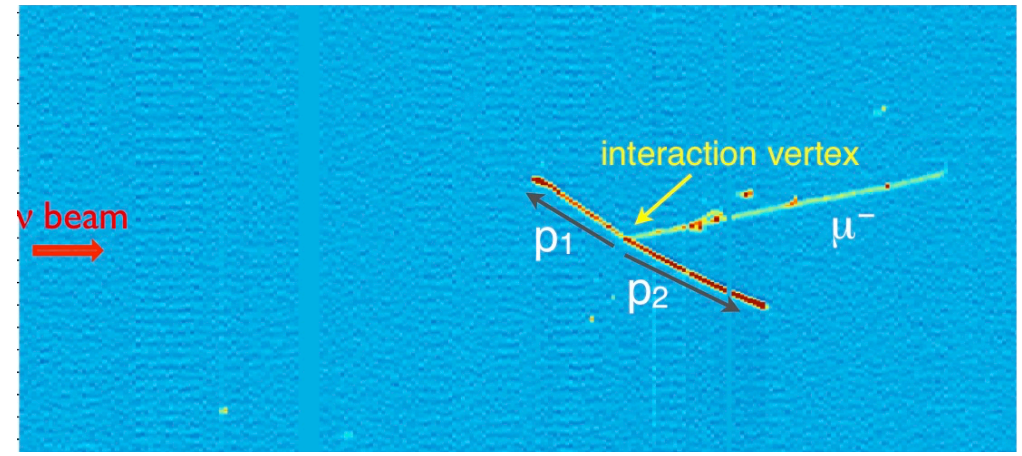


Comparison of the T2K CC0π measurement of νμ-C with the SuSAv2 and Valencia models each with an additional pion-absorption contribution as implemented in GENIE.

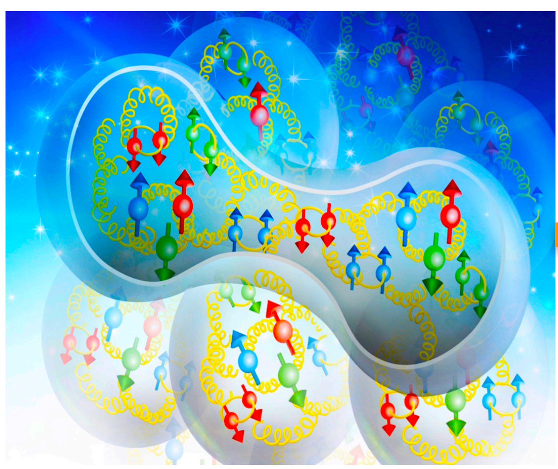
Nuclear many-body theory

Neutrino experiment are becoming more and more sensitive to the complexity of nuclear dynamics.

Same starting point for different many-body methods:
Effective Field Theory interactions and currents

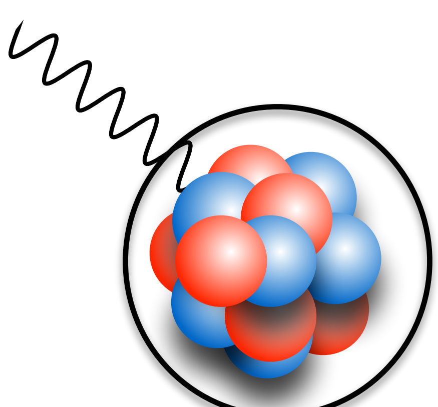


Argoneut

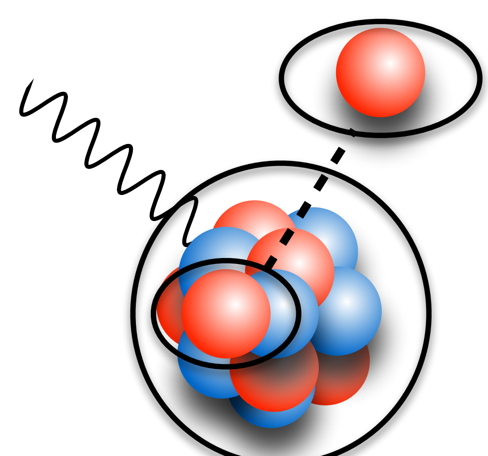


$$H = \sum_i \frac{\mathbf{p}_i^2}{2m} + \sum_{i<j} v_{ij} + \sum_{i<j<k} V_{ijk} + \dots$$

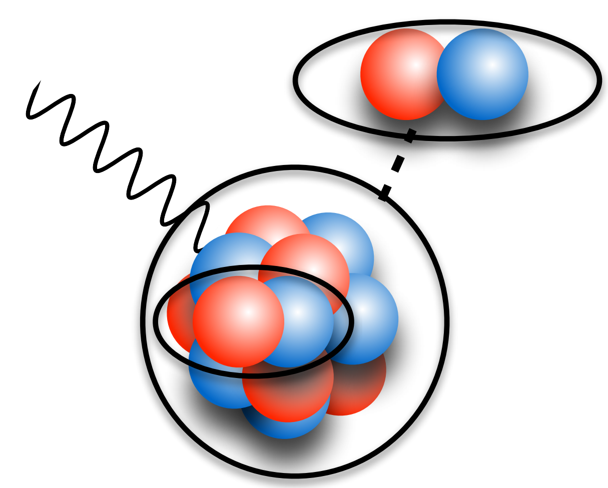
Green's Function Monte Carlo



Spectral Function (SF)



Short-time Approximation (STA)

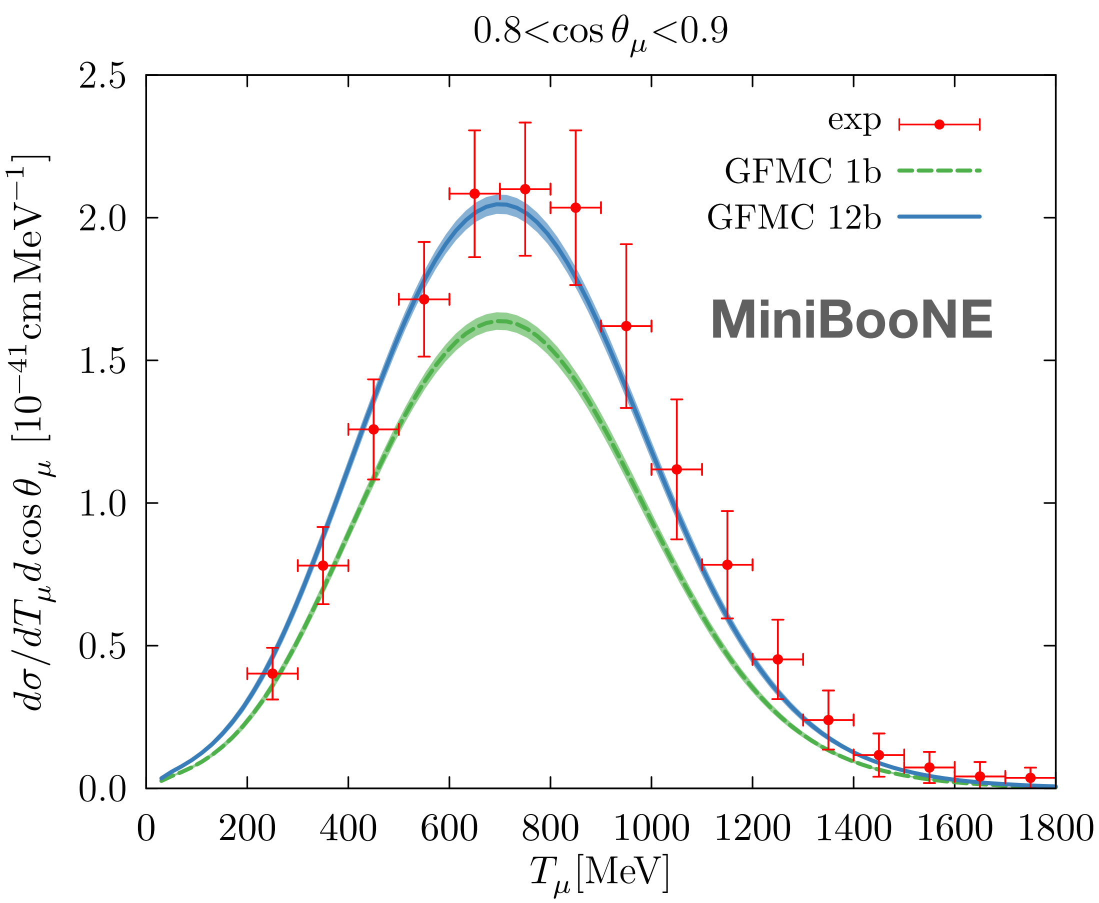


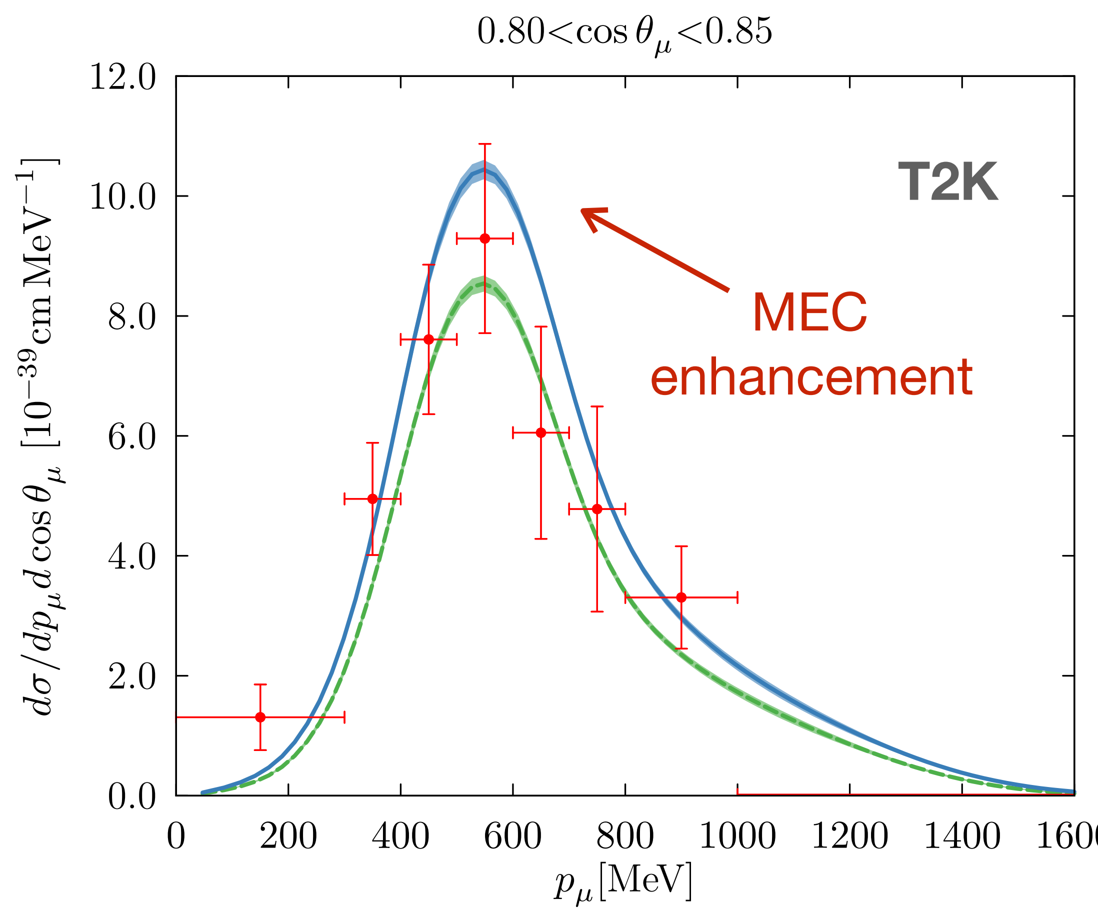
Green’s Function Monte Carlo

GFMC accurately solves the Schrödinger equation for nuclei up to ^{12}C using high performance computing

Virtually exact results for nuclear electroweak responses in the **quasi-elastic region** up to moderate values of **q**.
Initial and final state interactions fully accounted for.

✐A.Lovato, J. Carlson, S. Gandolfi, NR, and R. Schiavilla, arXiv:2003.07710



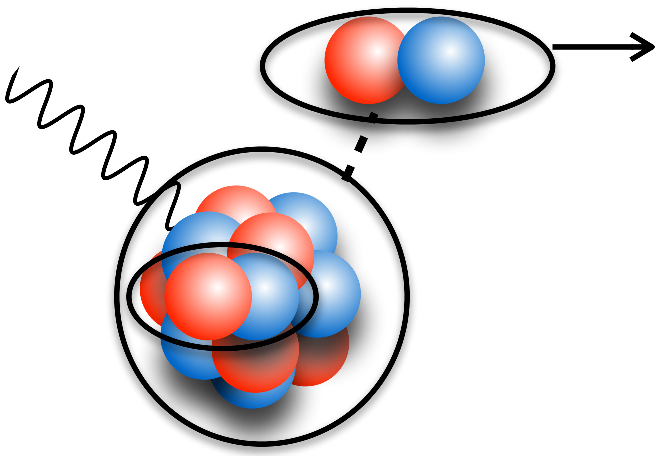


T2K flux is the most suitable one for the GFMC calculations (nonrelativistic)

Short Time Approximation

The STA method utilizes QMC techniques to predict the response function of nuclei in the quasielastic region.

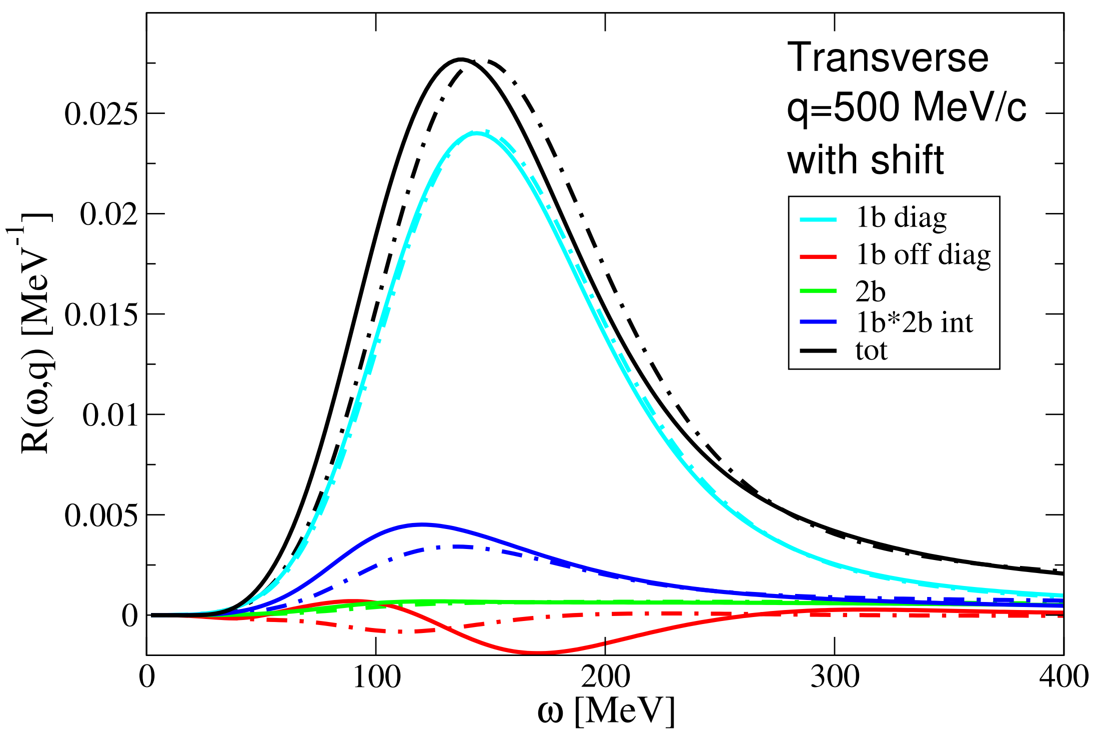
Assumption: for short times (moderate **q**) only the active pair of nucleons propagate

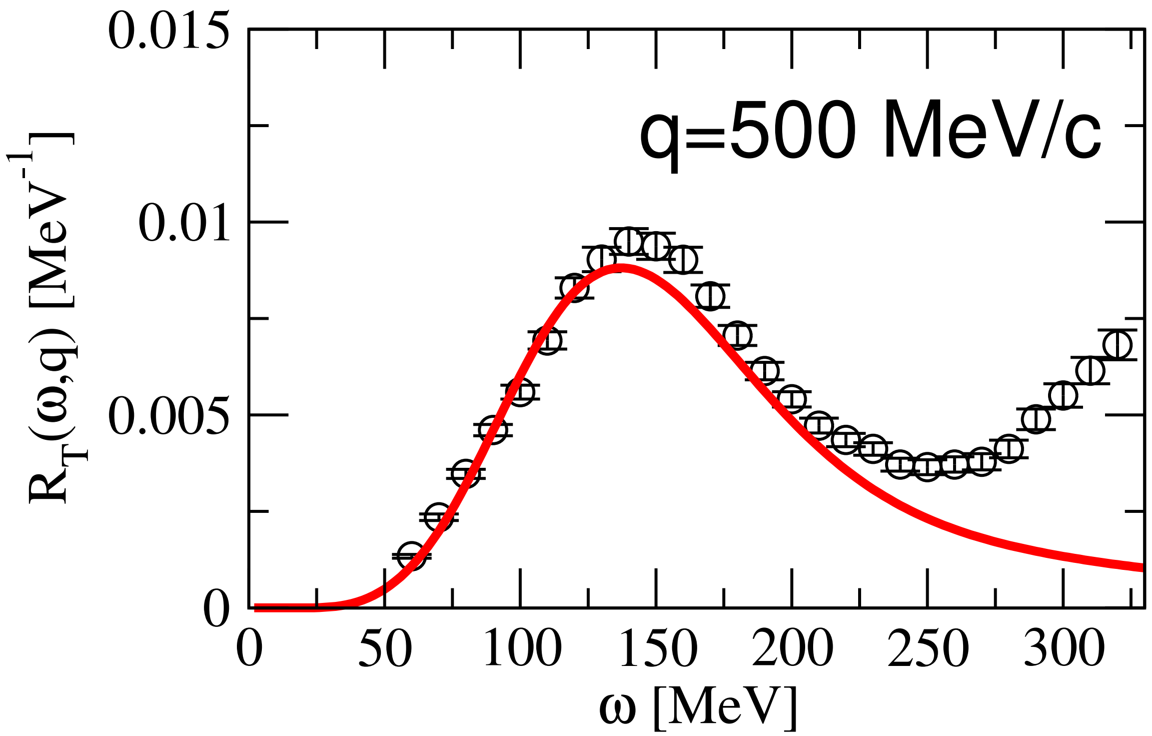


Interaction effects at the two-nucleon level are fully retained, and the **interference between one- and two-body terms** are consistently accounted for, access to exclusive channels

Electromagnetic responses of ^{4}He:

S. Pastore et al, Phys.Rev.C 101 (2020) 4, 044612

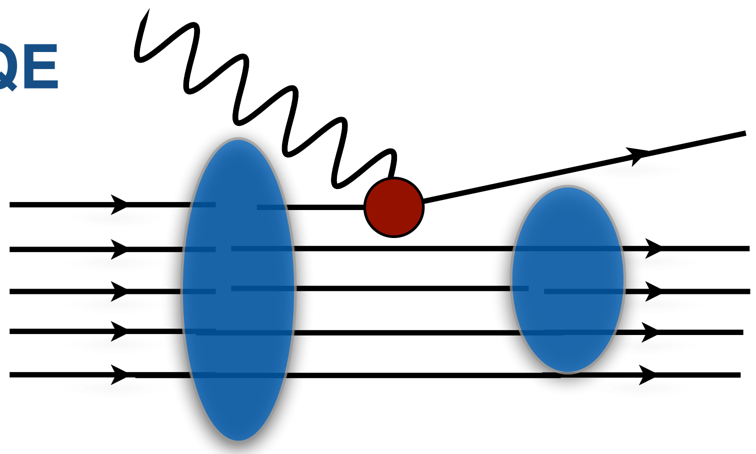




Factorization Scheme and Spectral Function

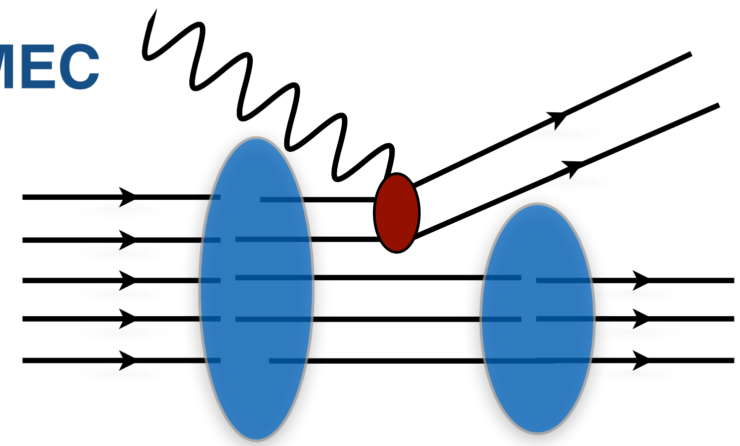
For sufficiently large values of |**q**|, the **factorization scheme** can be applied

QE



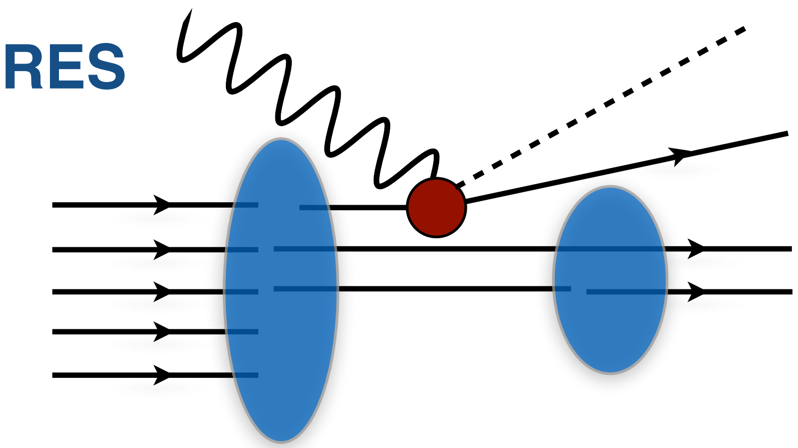
$$|f\rangle \to |p\rangle \otimes |f_{A-1}\rangle$$

MEC



$$|f\rangle \to |pp'\rangle_a \otimes |f_{A-2}\rangle$$

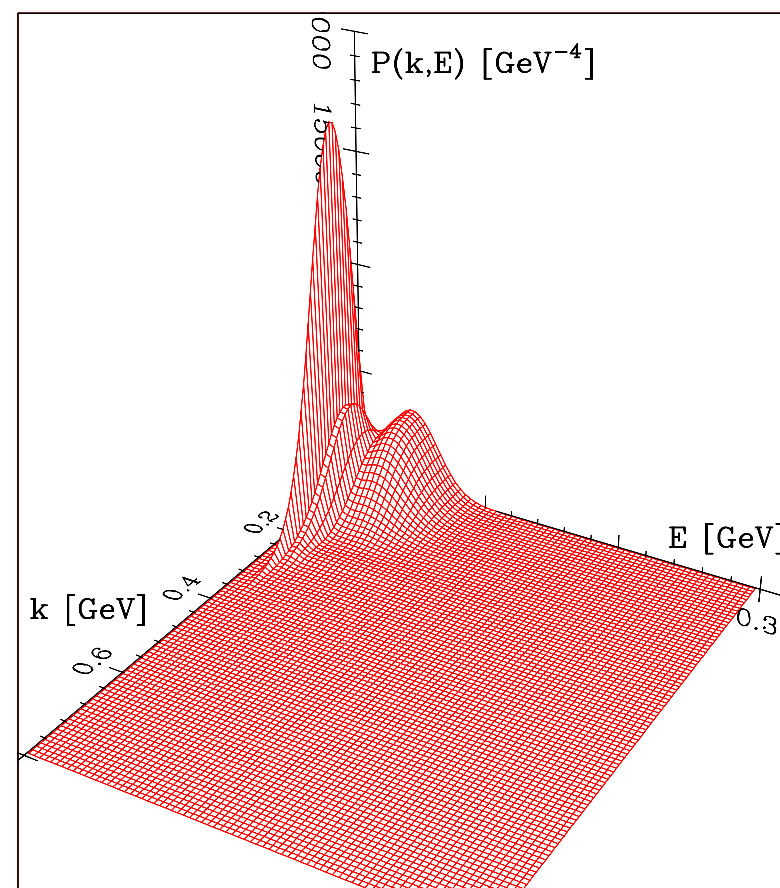
RES



$$|f\rangle \to |p_\pi p\rangle \otimes |f_{A-1}\rangle$$

The intrinsic properties of the nucleus are described by the **Spectral Function**→ effective field theory and nuclear many-body methods

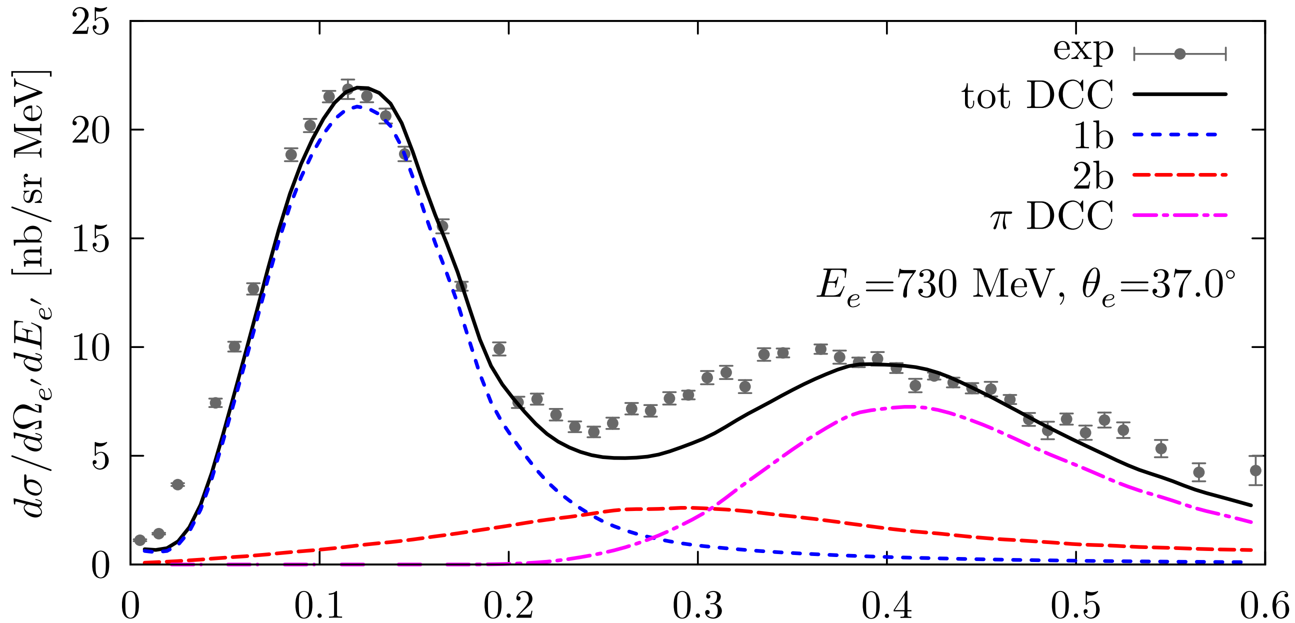
$$d\sigma_A = \int dE d^3k \; d\sigma_N P(\mathbf{k}, E)$$

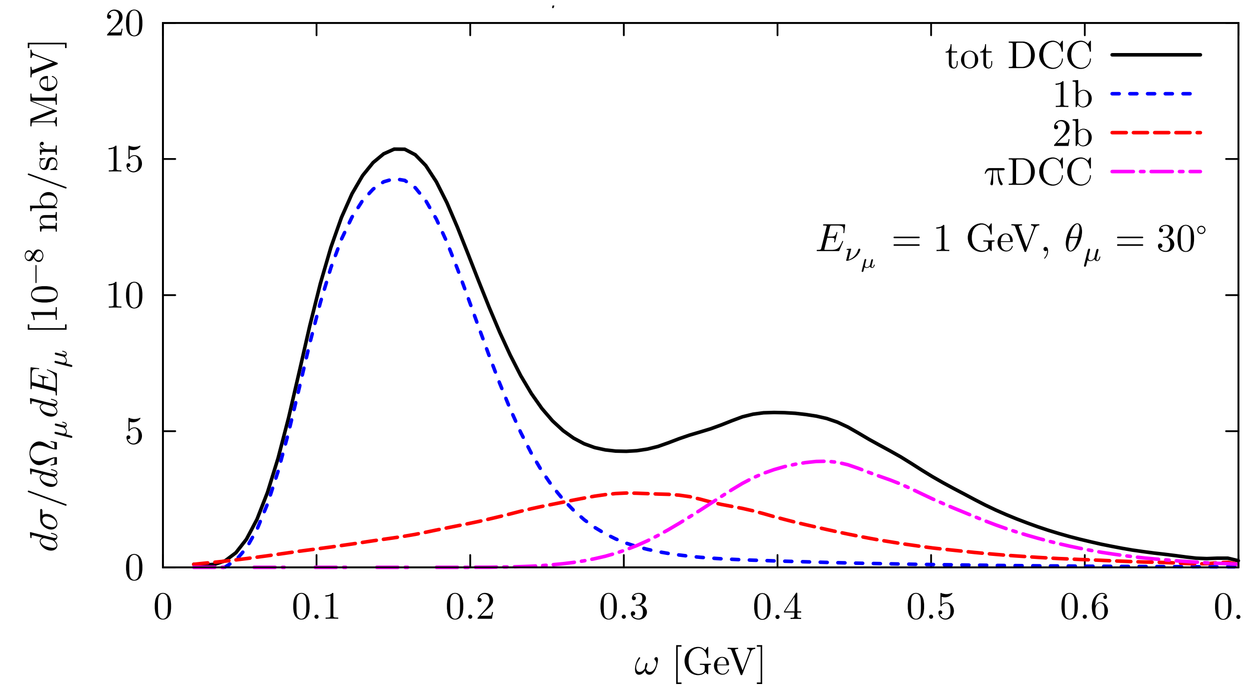


O. Benhar, A. Fabrocini, and S. Fantoni, Nucl. Phys. A505, 267 (1989).

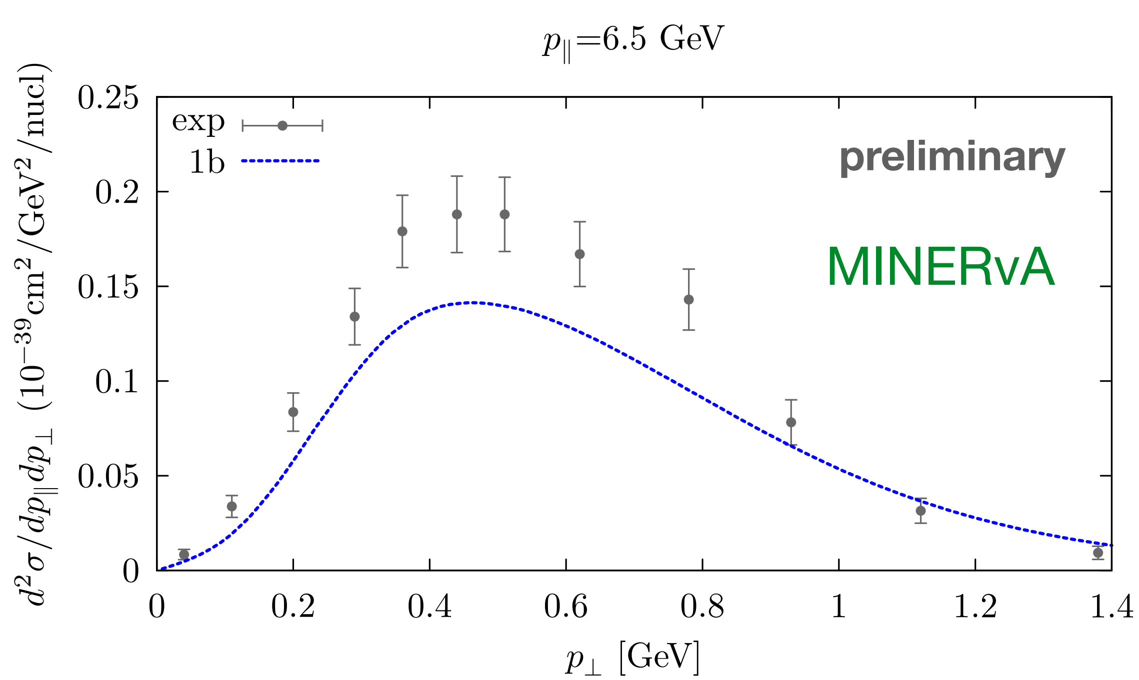
Factorization Scheme and Spectral Function

✐ NR, et al, Phys. Rev. C 100 (2019) no.4, 045503





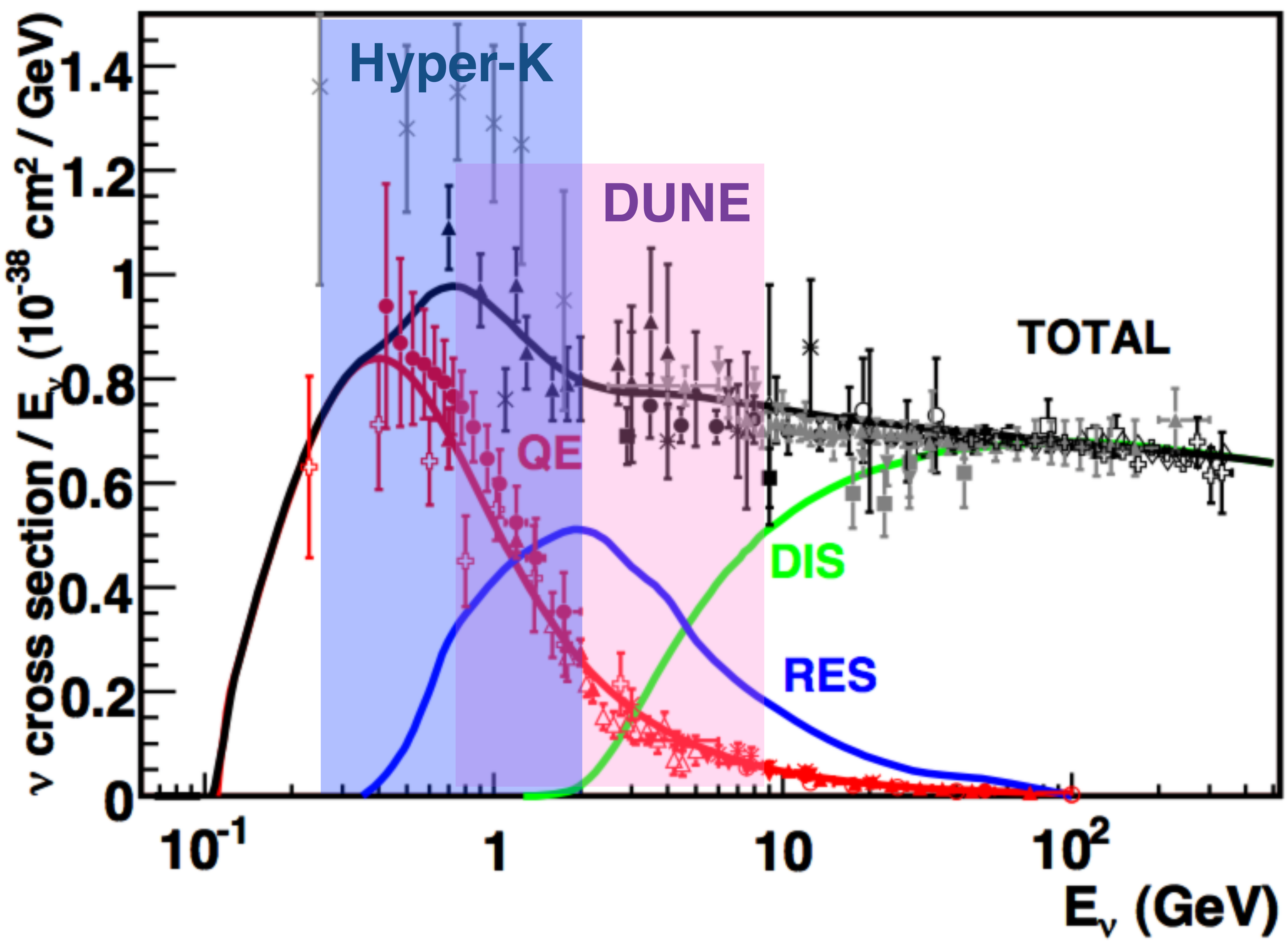
- Spectral function formalism including the **one-** and **two-body current** contributions and the **pion production** amplitudes (ANL-Osaka model) for electron and neutrino ^{12}C-scattering



Preliminary comparison with CC0π data on ^{12}C from MINERvA using μ kinematics. Only the one body current operator has been included. Next steps: **inclusion of MEC and π production and absorption**

Future experiments and theory efforts

DUNE and Hyper-K high-precision measurement of neutrino oscillation parameter → accurate cross section predictions supplemented by theoretical uncertainty



Electron for Neutrinos: constrain interaction models used in ν energy reconstruction

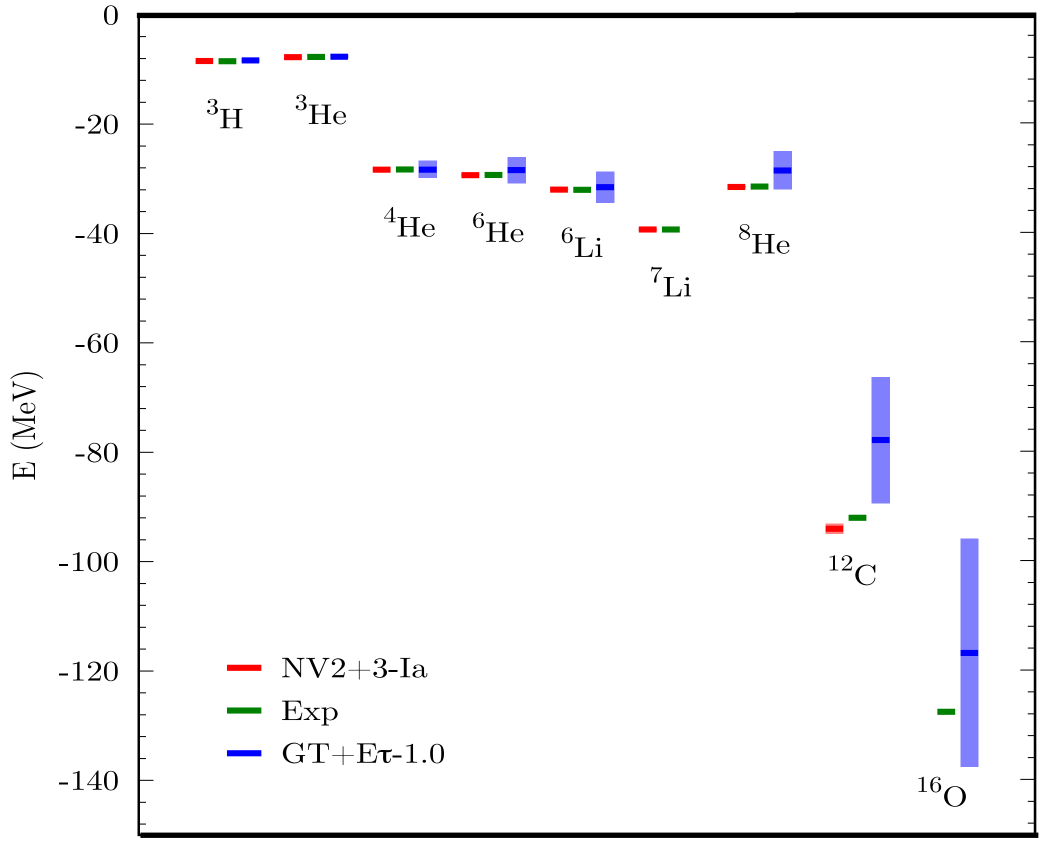
Jlab E12-14-012 experiment: study the properties of Ar nucleus by electron scattering. The data cover different reaction mechanisms

QE-RES: rich set of new cross section measurements T2K, MINERvA, NOvA, MicroBooNE

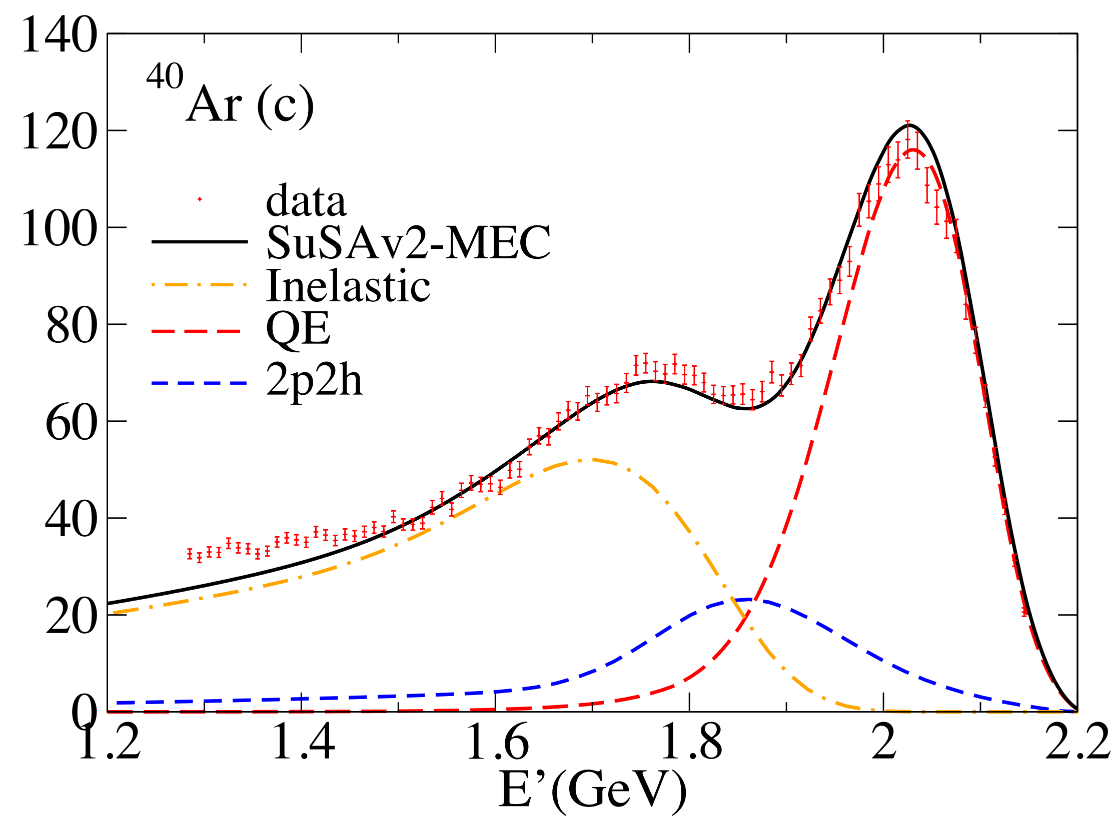
DIS: data and new analyses from MINERvA on different nuclei

Future experiments and theory efforts

S.Gandolfi, D.Lonardoni, et al, *Front.Phys.* 8 (2020) 117



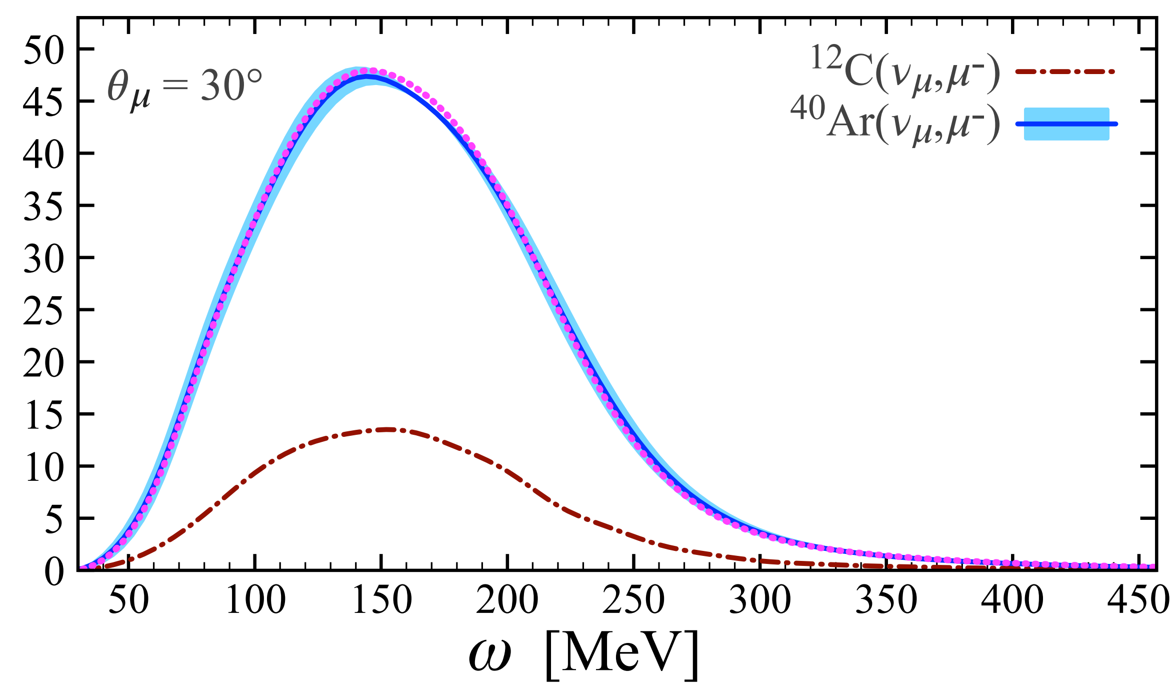
M. Barbaro, et al, Phys.Rev.C 99 (2019) 4, 042501



Theoretical uncertainty estimate: truncation of the chiral expansion and statistical uncertainty of the ab-initio method

Using more approximate methods, first calculations of lepton-Ar cross sections

Controlled approximation of the nuclear-many body problem are needed to include relativistic effects. Benchmark with ab-initio results



C.Barbieri, NR, V.Somà, PRC 100 (2019) 6, 062501

Thank you for your attention!