Theory summary

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NuInt 2024, April 15–20, 2024, São Paulo, Brazil

Theory at NuInt’24

- ~20 theory talks

  Nuclear effects in electron and neutrino scattering in a variety of approaches, pion production, eta production, tau neutrino cross sections, BSM physics, …

- ~10 generator talks

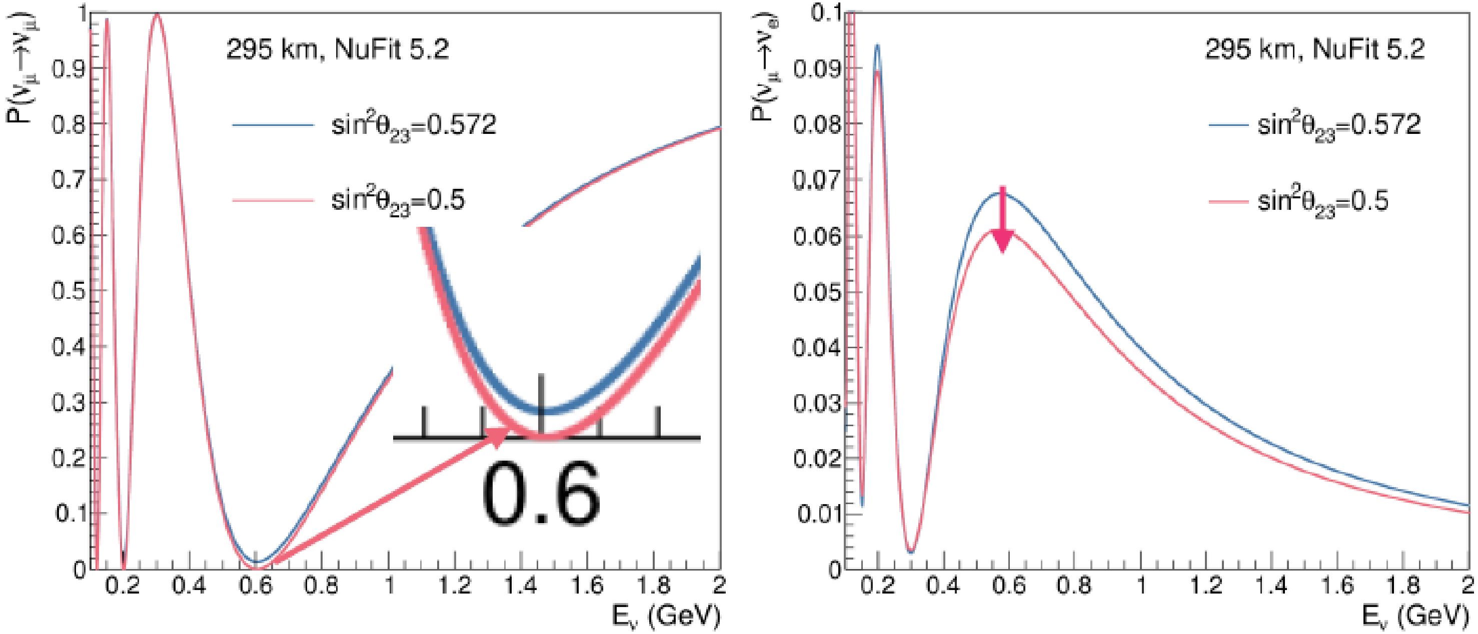
  GiBUU, NuWro, GENIE, NEUT, ACHILLES, HE interactions, gamma rays, INCL + ABLA, NUISANCE

- Many posters

I won’t be able to cover them, sorry!

What can go wrong?

- **Rate of appearance and disappearance**
  - Is the ν_e rate higher because of a larger value of δ_{CP}, or is your model for $\nu_e \rightarrow \nu_\mu$ wrong?
  - Is the increased rate of ν_μ due to $\sin^2\theta_{23}$, or a larger cross section?



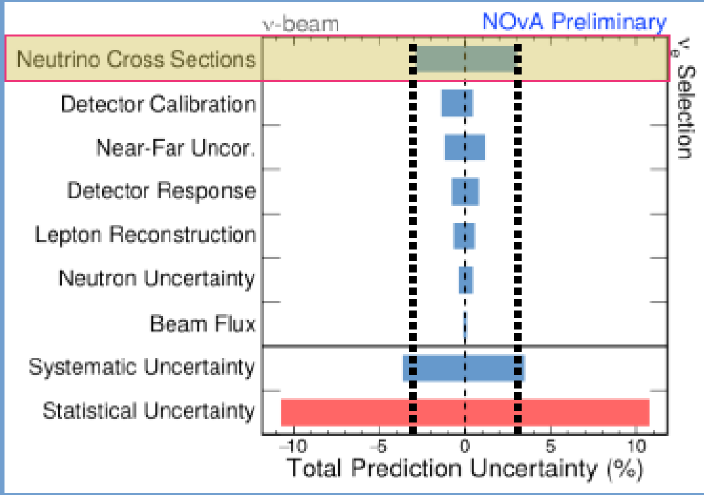
Clarence Wret

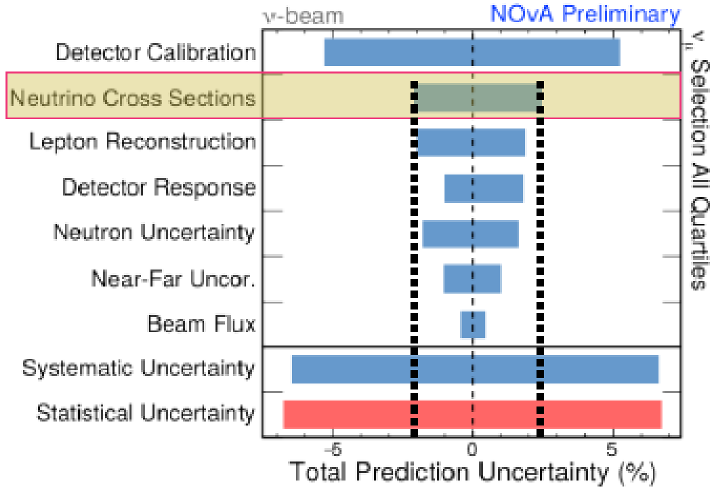
Additionally: How accurately is the smearing modeled?

Impact of systematics at the FD

- Neutrino cross-section uncertainties contribute **~3%** to number of ν_e on NOvA and T2K

M. Elkins, T. Nosek, Neutrino 2020 poster





Sample		Uncertainty source (%) Flux	Interaction	FD + SI + PN	Flux⊗Interaction (%)	Total (%)
1Rμ	ν	2.9 (5.0)	3.1 (11.7)	2.1 (2.7)	2.2 (12.7)	3.0 (13.0)
	$\bar{\nu}$	2.8 (4.7)	3.0 (10.8)	1.9 (2.3)	3.4 (11.8)	4.0 (12.0)
1Re	ν	2.8 (4.8)	3.2 (12.6)	3.1 (3.2)	3.6 (13.5)	4.7 (13.8)
	$\bar{\nu}$	2.9 (4.7)	3.1 (11.1)	3.9 (4.2)	4.3 (12.1)	5.9 (12.7)
1Re1de	ν	2.8 (4.9)	4.2 (12.1)	13.4 (13.4)	5.0 (13.1)	14.3 (18.7)

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Event counts at the FDs

Sample	T2K	NOvA	Hyper-Kamiokande	DUNE
N_μ^{rec} FHC	318	211	10000	7000
N_μ^{rec} RHC	137	105	14000	3500
N_e^{rec} FHC	108	82	3000	1500
N_e^{rec} RHC	16	33	3000	500

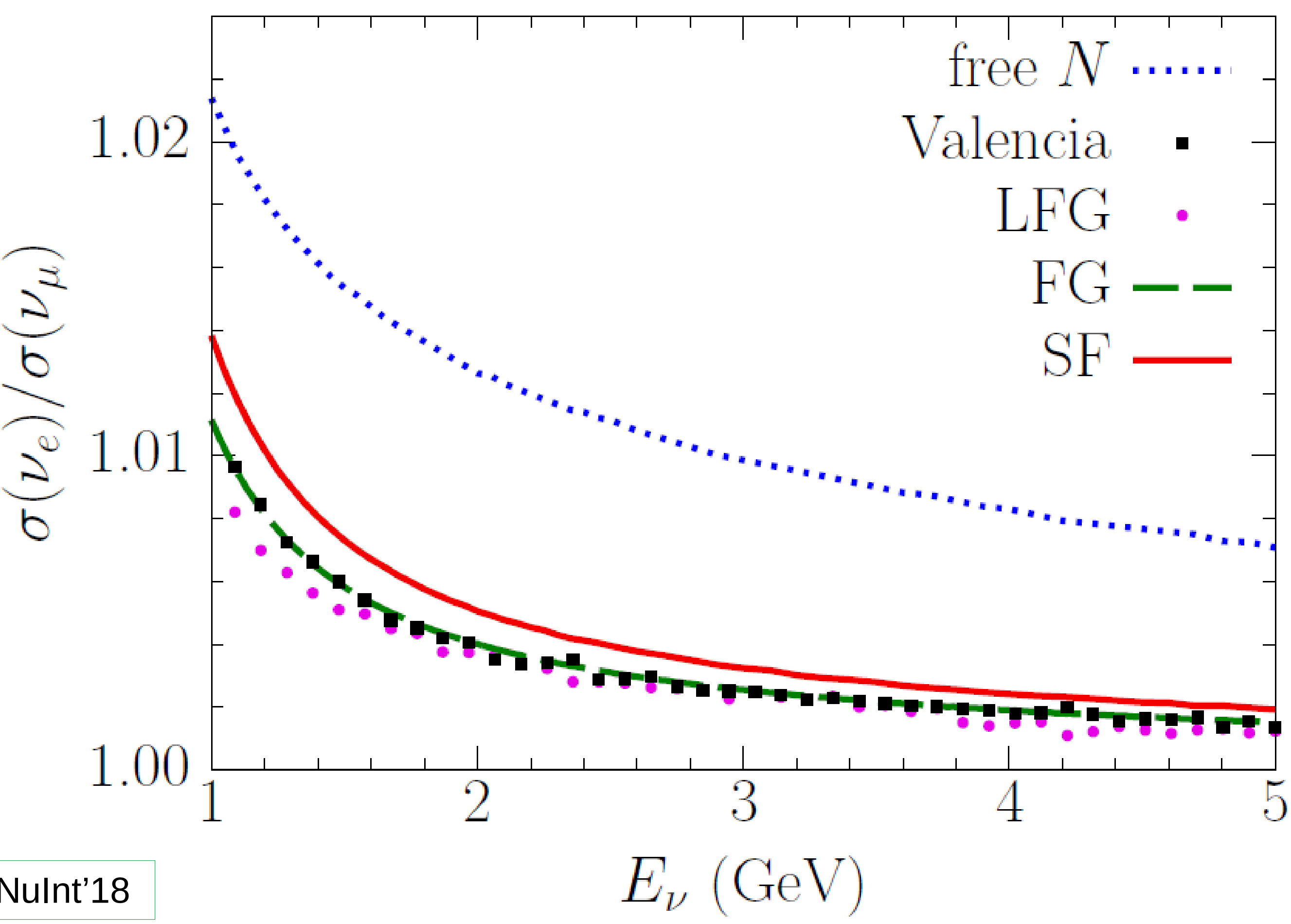
- HK and DUNE will have **enough events** to be limited by the **~3% (anti-)ν_e uncertainty**
- Current experiments at the **3-5% level** uncertainties*

*Exception of T2K's single-pion-below-threshold sample (10-15%)

What do I worry about?

- Will **(anti-)ν_e** uncertainties fall below 2-3%?
  - Critical for δ_{CP}, mass ordering, for both **atmospheric** and **accelerator** experiments, and **MiniBooNE LEE**
- Do we understand **transition, SIS and DIS** interactions sufficiently for **DUNE**?
  - Worry that the day DUNE ND turns on, it'll show how poorly we describe these samples
- Will we understand **nuclear effects in ^{40}Ar** nuclear in 10 years time?
- Will we understand **neutron final-state interactions** sufficiently to use them for e.g. **energy estimators** and **tagging events**?
- **ν_τ uncertainties** for **atmospheric neutrinos** and **mass ordering** sensitivity
- How do we diagnose **low momentum pion modelling**

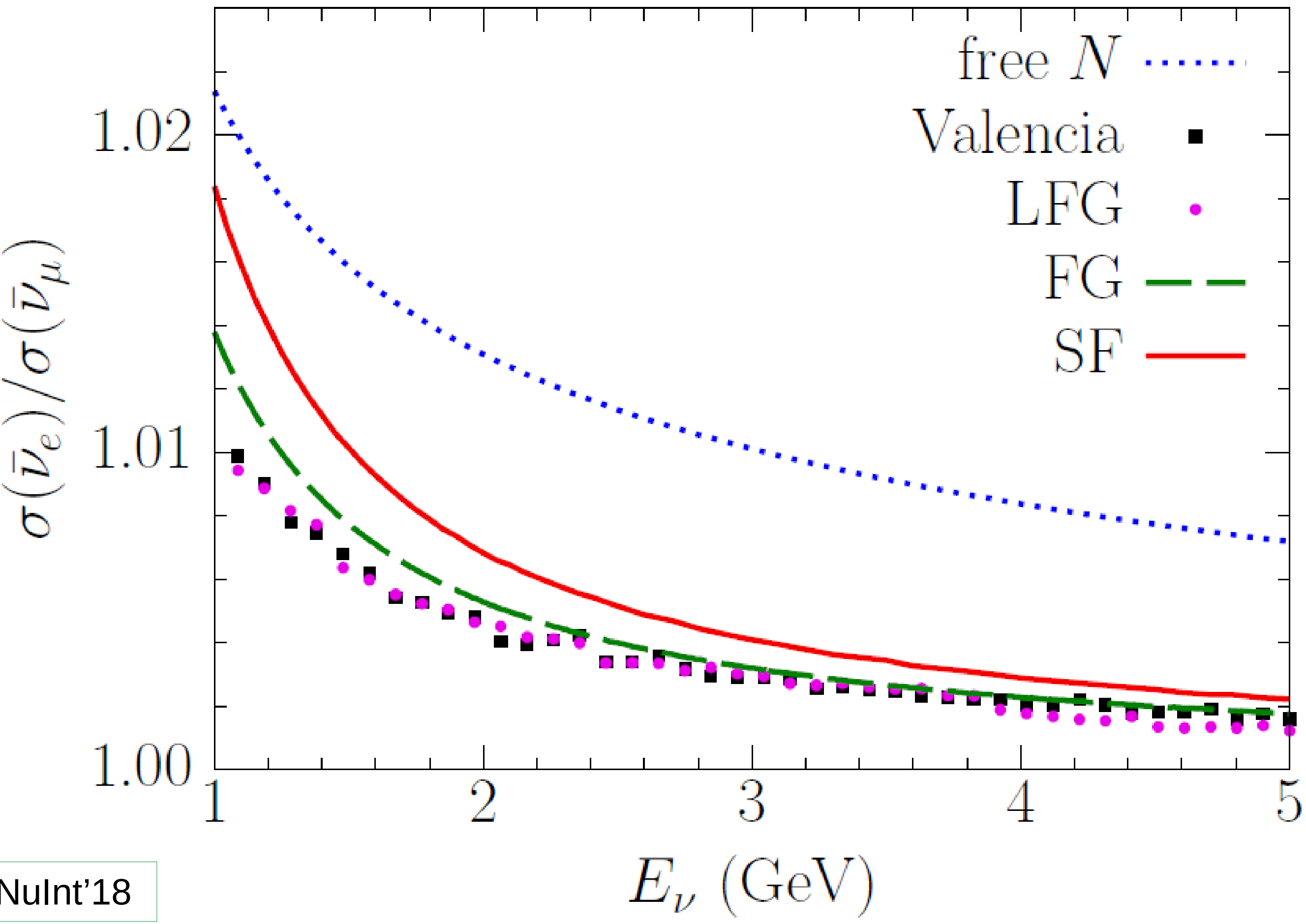
Cross sections' ratio for neutrinos



Contributions by A. M. A., J. Amaro *et al.*, V. Pandey *et al.*, J. E. Sobczyk

A. M. A. at NuInt'18

Cross sections' ratio for antineutrinos



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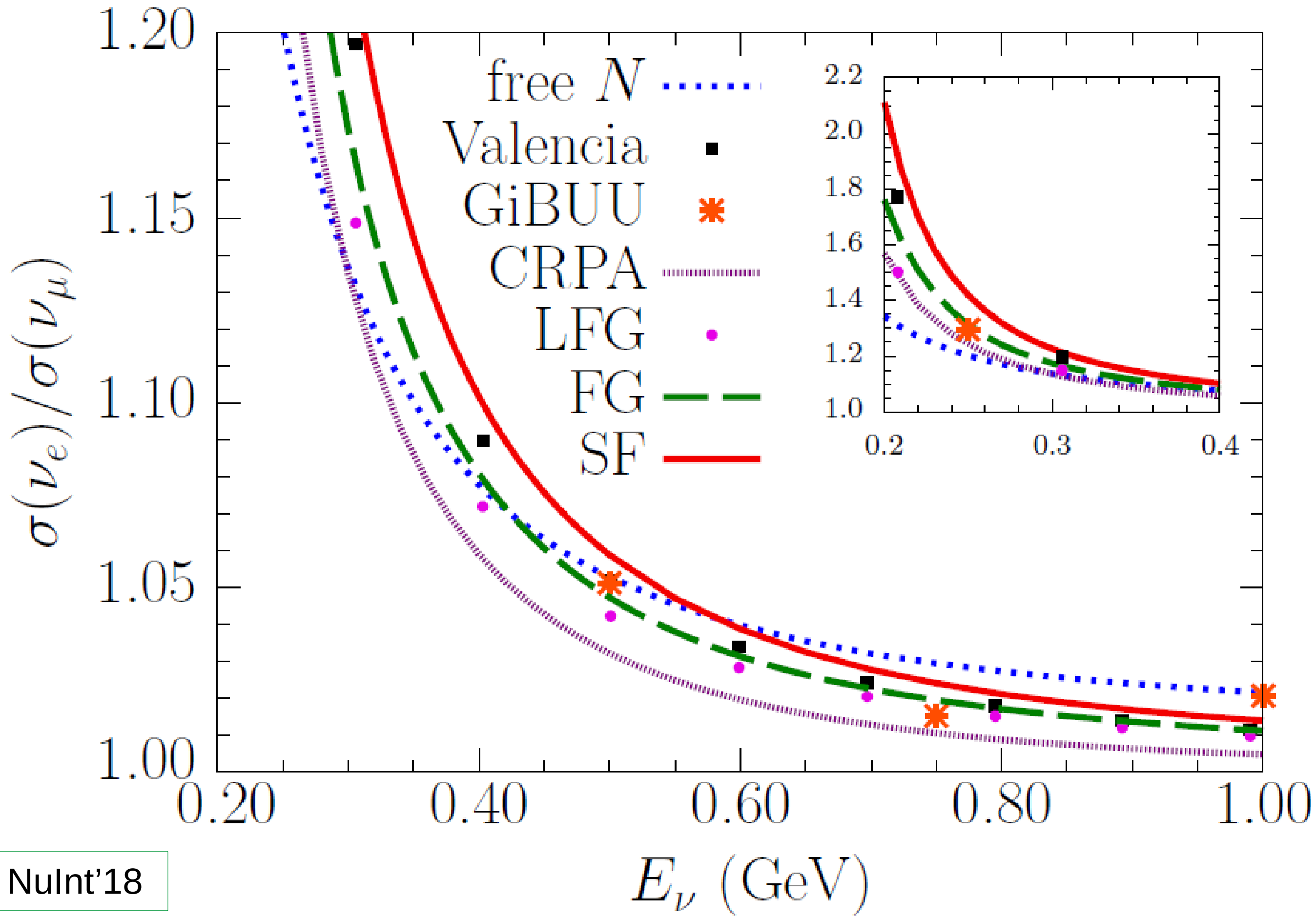

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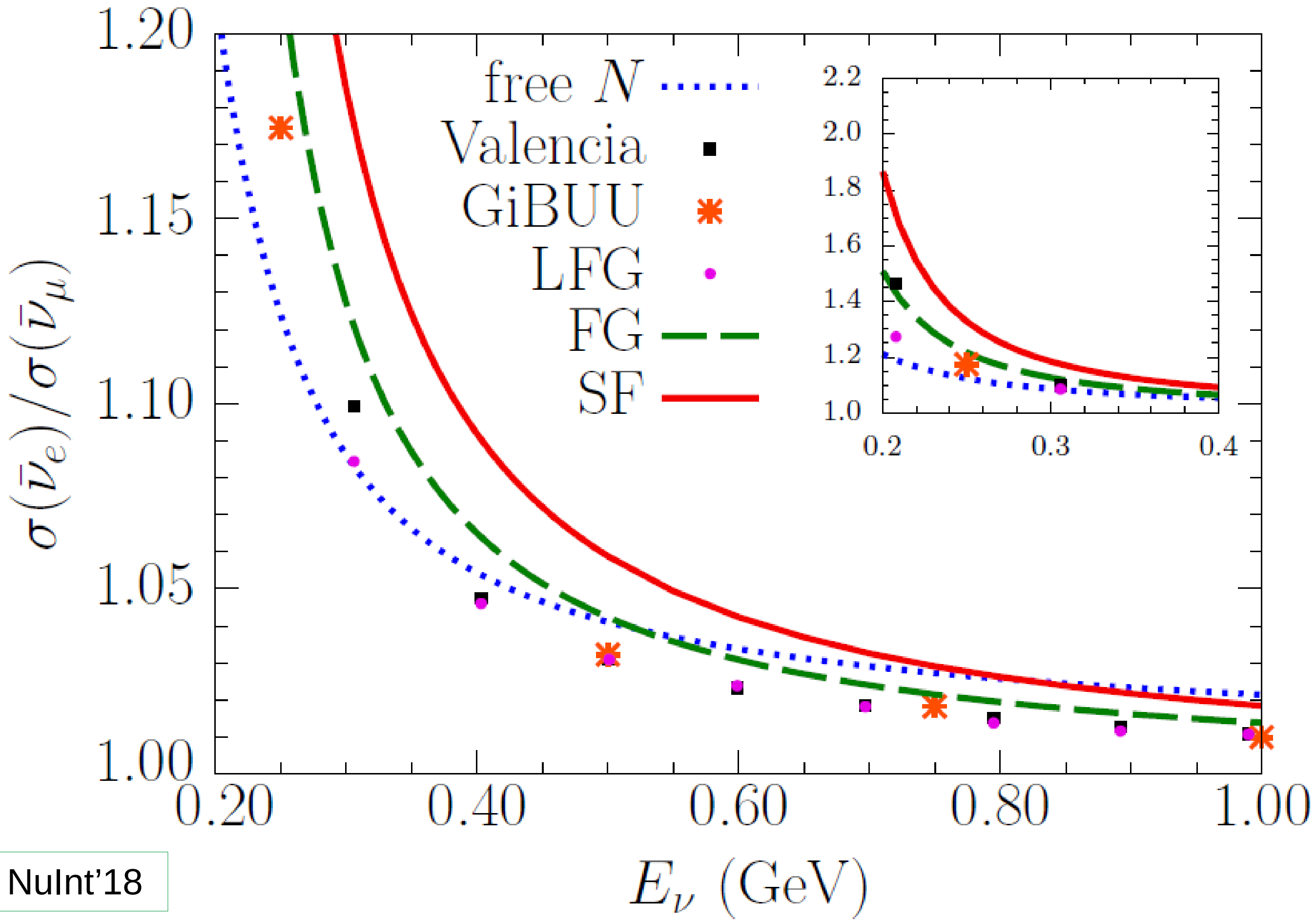

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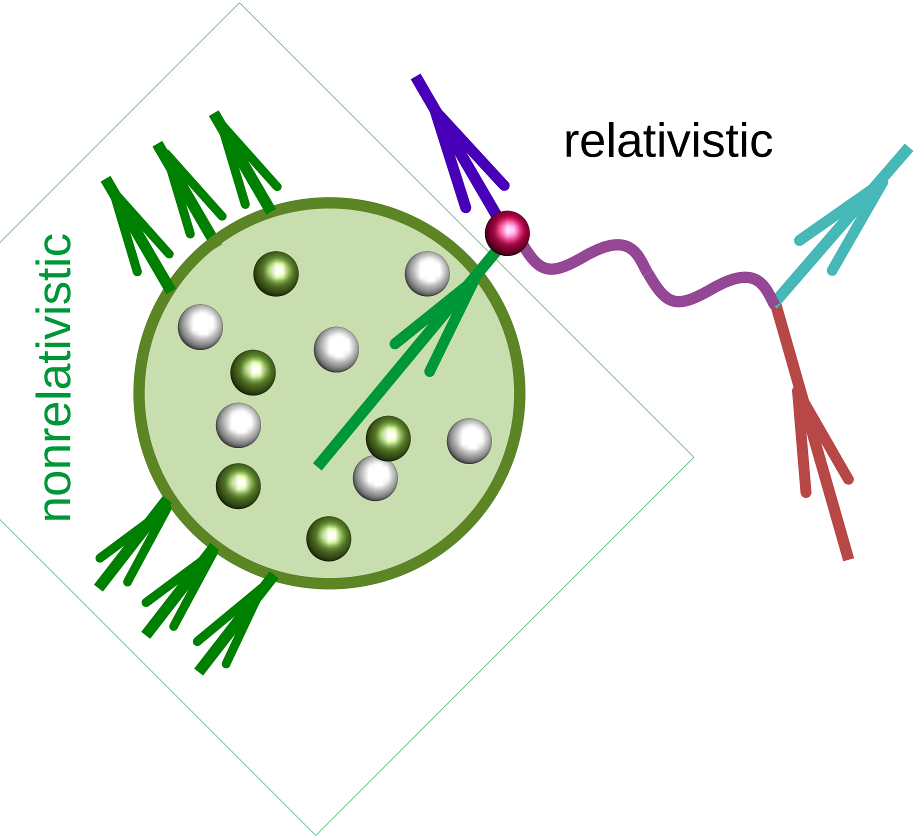
A. M. A. at NuInt'18

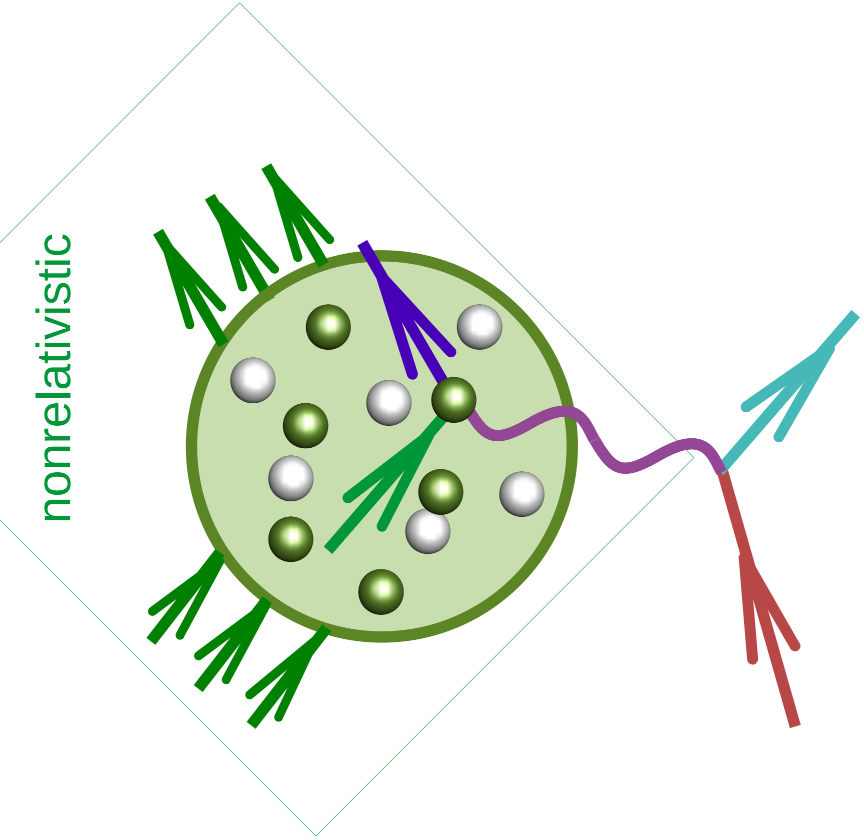
Crash course

Spectral function



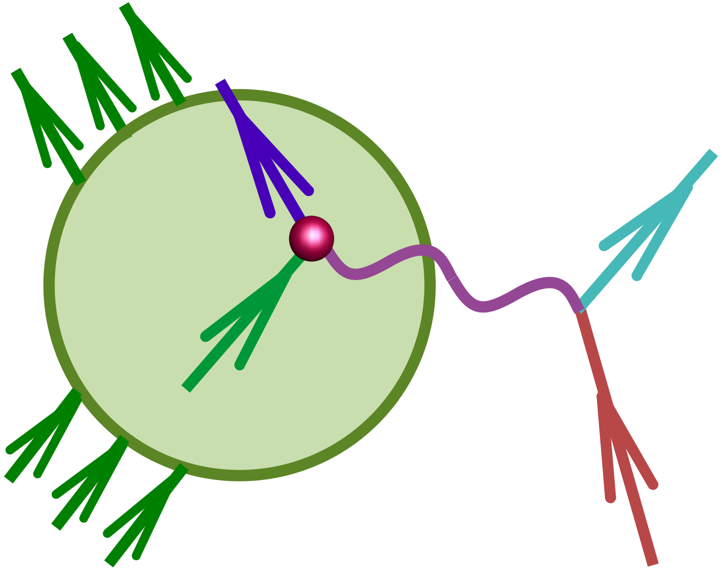
- Emphasis on the initial state (shell structure & SRC)
- Interaction (1 or 2 nucleons) factorized
- Final-state interactions treated as corrections
- Inclusive and exclusive cross sections
- Relativistic final states

Quantum Monte Carlo



- Emphasis on the nuclear dynamics
- Interaction not factorized
- Initial and final-state interactions treated consistently
- Nuclear responses and inclusive cross sections
- Relativistic effects treated as corrections

Relativistic mean field



- Emphasis on relativistic dynamics of the interaction
- Interaction not factorized
- Nucleus treated as a potential
- Initial and final-state interactions treated consistently
- Exclusive and inclusive cross sections
- Effects of interactions need to be added *ad hoc*
- SRCs treated as corrections

Multinucleon final states

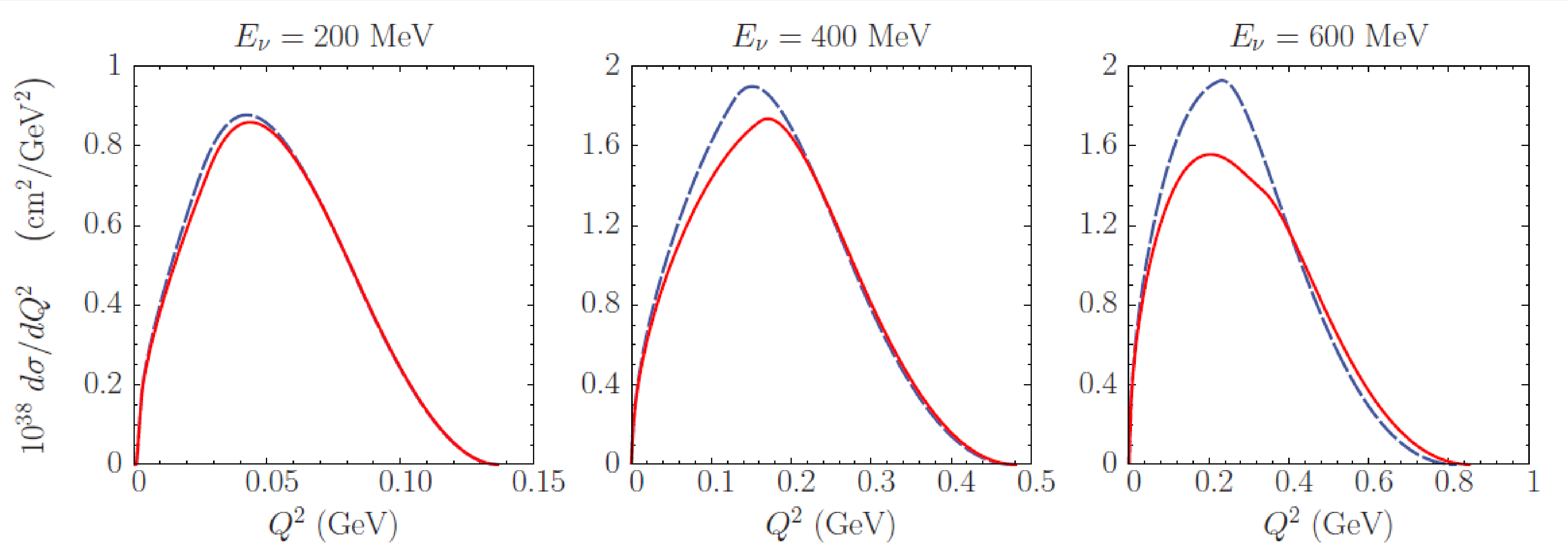
Two (or more) nucleons in the final state may come from

- initial-state correlations
- two-body reaction mechanisms, such as meson exchange currents (MEC)
- final-state interactions (intranuclear cascade)

We cannot distinguish these processes, so they would need to be added at the level of amplitudes, and they interfere.

Shimizu & Faessler, Nucl. Phys. A 333, 495 (1980)
Alberico *at al.*, Ann. Phys. 154, 356 (1984)

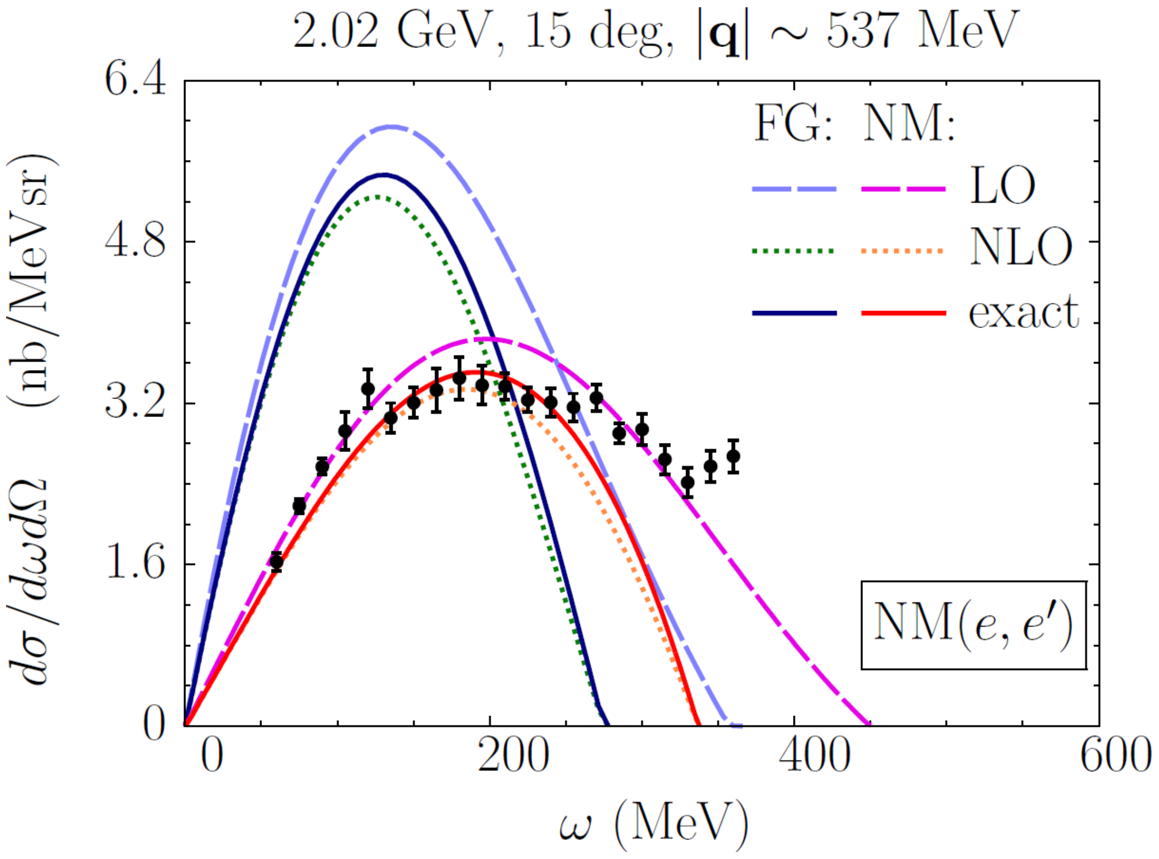
Importance of fully relativistic kinematics



A.M.A. & O. Benhar, PRC 83, 054616 (2011)

Sizable differences between the **relativistic** and **nonrelativistic** cross sections for neutrino energies *O*(500 MeV).

Importance of fully relativistic kinematics



A.M.A. & O. Benhar, PRC 83, 054616 (2011)

At |q| ~ 500 MeV, semi-relativistic result **5% lower** than the relativistic one.

Coulomb distortion effects

"These effects generally turn out to be sizable even for light nuclei … and introduce in the components of the nuclear response a dependence on all the kinematic variables of the incoming and outgoing electrons which in principle invalidates the Rosenbluth separation and makes the experimental determination of R_L and R_T **extremely complicated**.

…

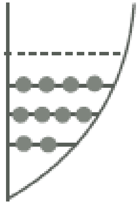
[W]hen L/T separation is obtained from the data at large scattering angles, small uncertainties in the cross-section measurement can lead to relatively large uncertainties in the extracted value of R_L"

Boffi *et al.*, *Electromagnetic response of atomic nuclei* (Clarendon, Oxford, 1996)

What did we learn?

Coupled cluster theory

Reference state (Hartree-Fock): $|\Psi\rangle = a_i^\dagger a_j^\dagger \ldots a_k^\dagger |0\rangle$



Include **correlations** through e^T operator

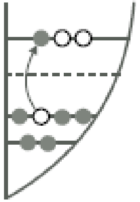
$$\mathscr{H}_N \, e^T |\Psi\rangle = E \, e^T |\Psi\rangle$$

- ✓ Controlled approximation through truncation in T
- ✓ Polynomial scaling with A (predictions for ^{132}Sn and ^{208}Pb)

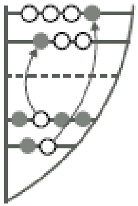
1p1h 2p2h

Expansion: $T = \sum t_a^i a_a^\dagger a_i + \frac{1}{4} \sum t_{ab}^{ij} a_a^\dagger a_b^\dagger a_i a_j + \ldots$

singles



doubles

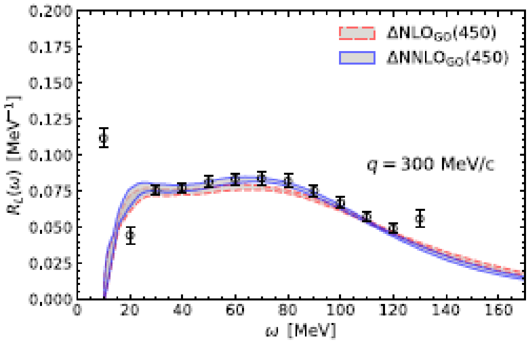


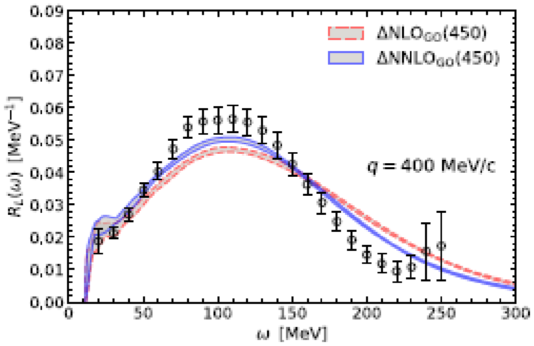
G. Hagen, T. Papenbrock, M. Hjorth-Jensen, D. J. Dean, Rep. Prog. Phys. 77, 096302 (2014).

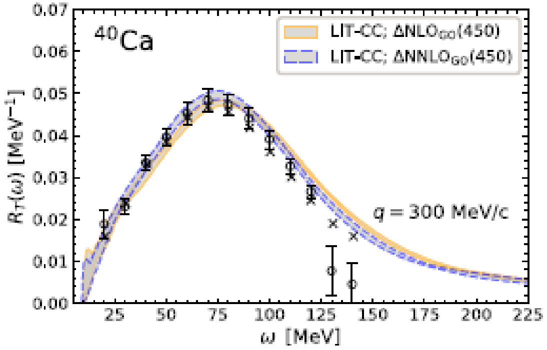
Joanna Sobczyk

Chiral expansion for ^{40}Ca

(Electromagnetic responses)







- ✓ Two orders of chiral expansion
- ✓ Convergence better for lower q (as expected)
- ✓ Higher order brings results closer to the data

B. Acharya, S. Bacca, JES et al. Front. Phys. 1066035(2022)

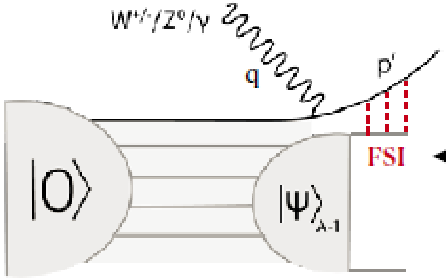
JES, B. Acharya, S. Bacca, G. Hagen; arXiV: 2310.03109

Nonrelativistic calculations, only 1-body currents

Joanna Sobczyk

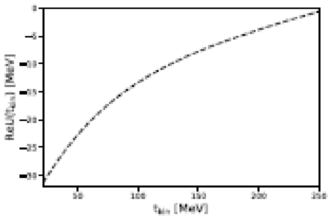
^{16}O spectral function

Error propagation to cross sections



Phenomenological optical potential

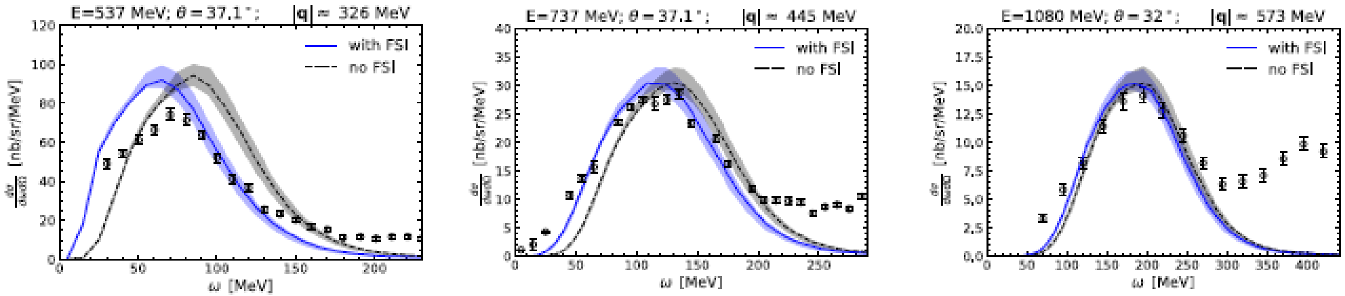
$E_{p+q} \rightarrow E_{p+q} + \mathrm{Re}U(t_{kin})$



E. D. Cooper et al. *Phys.Rev.C* 47, 297–311

growing **q** momentum transfer → final state interactions play minor role

Scattering off ^{16}O



JES , S. Bacca, *Phys.Rev.C* 109 044314

Only the real part of the optical potential

Joanna Sobczyk

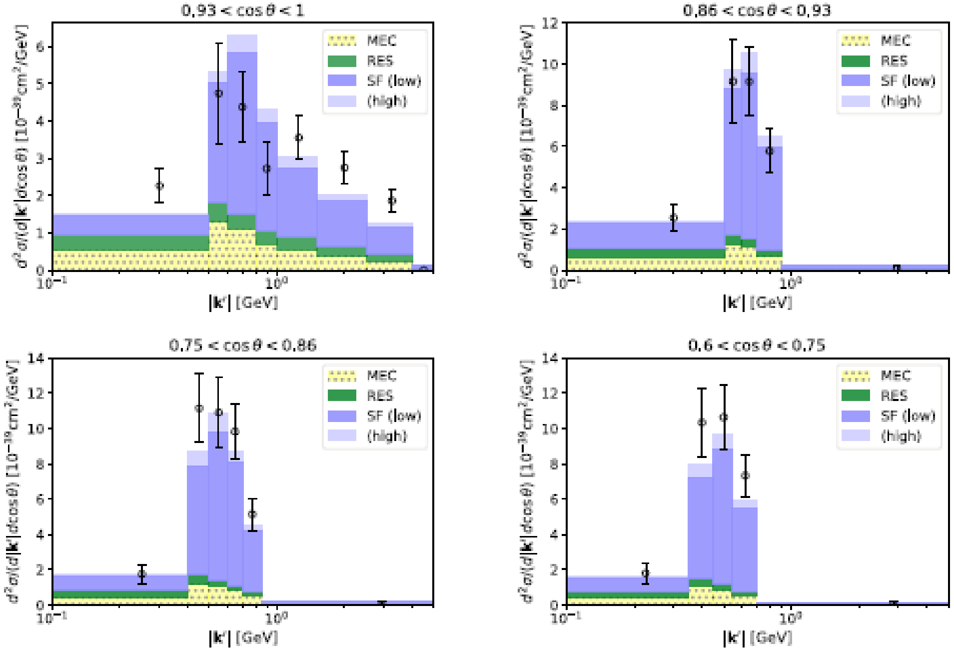
^{16}O spectral function

Error propagation to cross sections

$$\nu_\mu + ^{16}\mathrm{O} \to \mu^- + X$$

- Comparison with T2K long baseline ν oscillation experiment
- CC0π events
- Spectral function implemented into NuWro MC generator

Data: Phys. Rev. D101, 112004 (2020)

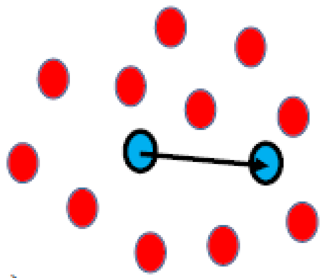


JES , S. Bacca, *Phys.Rev.C* 109 044314

Joanna Sobczyk

Generalized contact formalism

- **Nuclear short-range correlations – beyond mean-field effects**
- **Generalized Contact Formalism:** $\Psi(r_1, r_2, \ldots, r_A) \xrightarrow{r_{12}\to 0} \varphi(\boldsymbol{r}) \times A\left(\boldsymbol{R}, \{\boldsymbol{r}_k\}_{k\neq 1,2}\right)$
  - Consistent and comprehensive description of short-range correlated pairs at leading order
  - Accurate description of large-momentum transfer **electron scattering reactions**
- **Short-range expansion:**
  - **Systematic framework** with organized subleading contributions
  - Valid for larger distances / lower momenta
  - Various observables can be described (kinetic and potential energy, $0\nu\beta\beta,\ldots$)
- **3N SRCs**



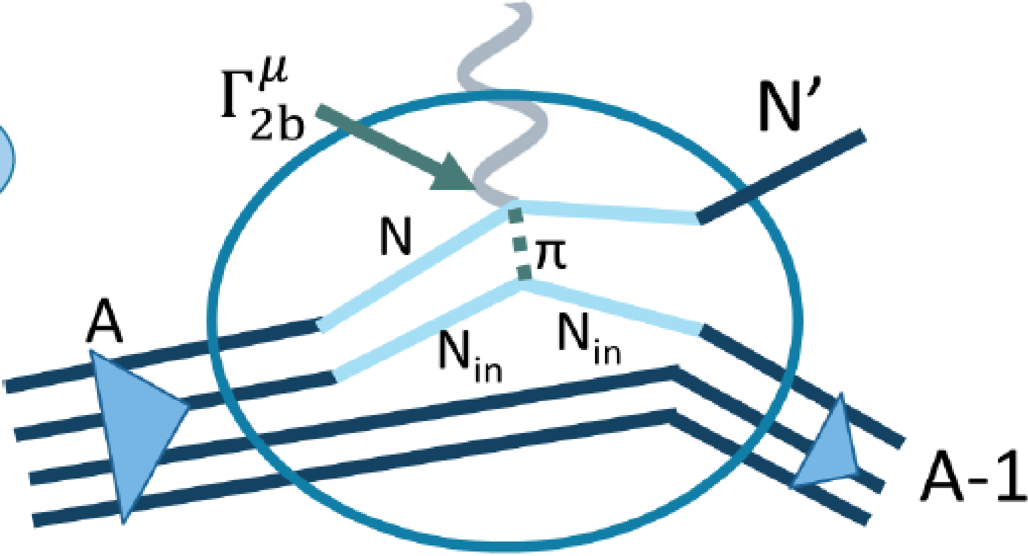
Ronen Weiss

Meson exchange currents

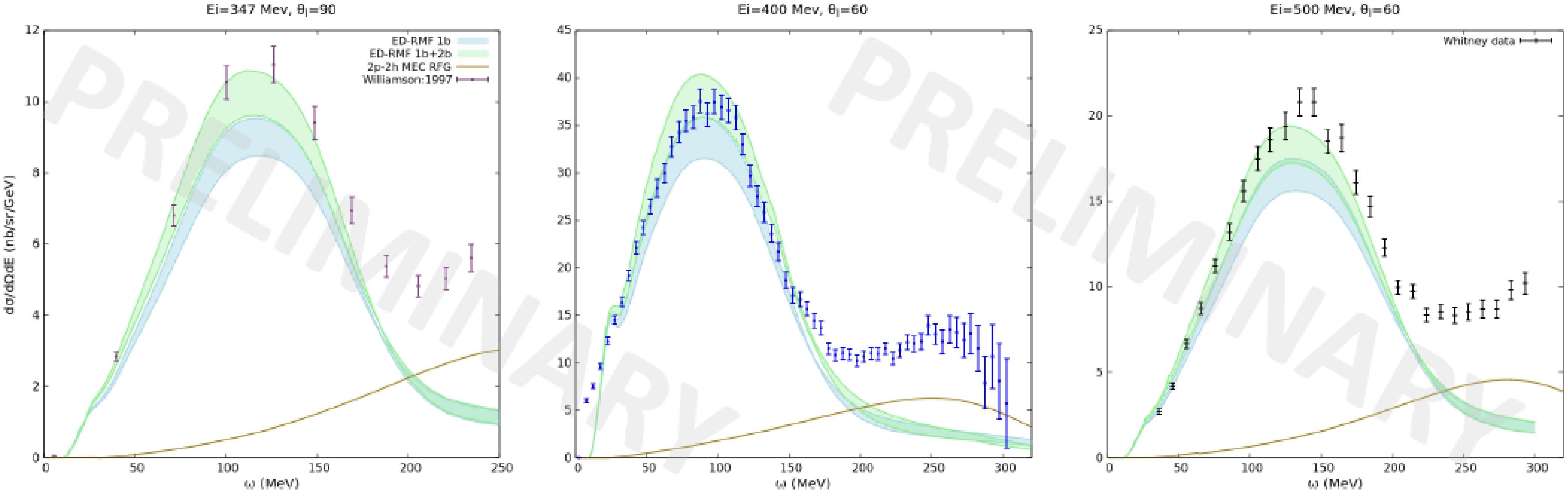
- We include **one-pion exchange effects** by incorporating **two-body meson-exchange currents** with a final paticle-hole state.

$$J^{\mu}_{had} = J^{\mu}_{had,1b} + J^{\mu}_{had,2b}$$

- The **1p-1h excitation** occurs when one of the outgoing nucleons of the two-particle two-hole interaction remains bound to the nucleus.

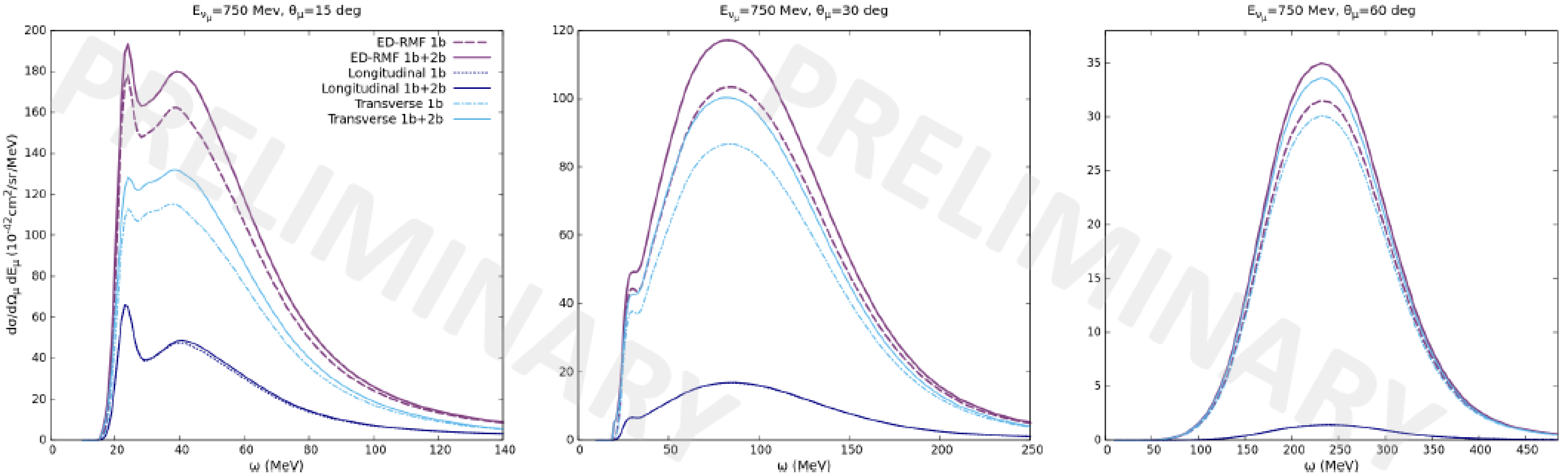


^{40}Ca electromagnetic inclusive cross section



Data: discovery.phys.virginia.edu/research/groups/qes-archive/data/40Ca.html

^{12}C-ν_μ inclusive cross section

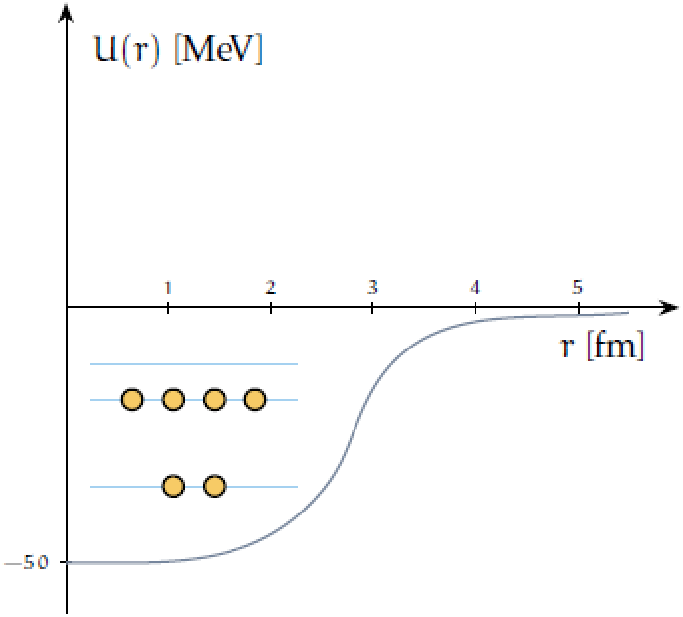


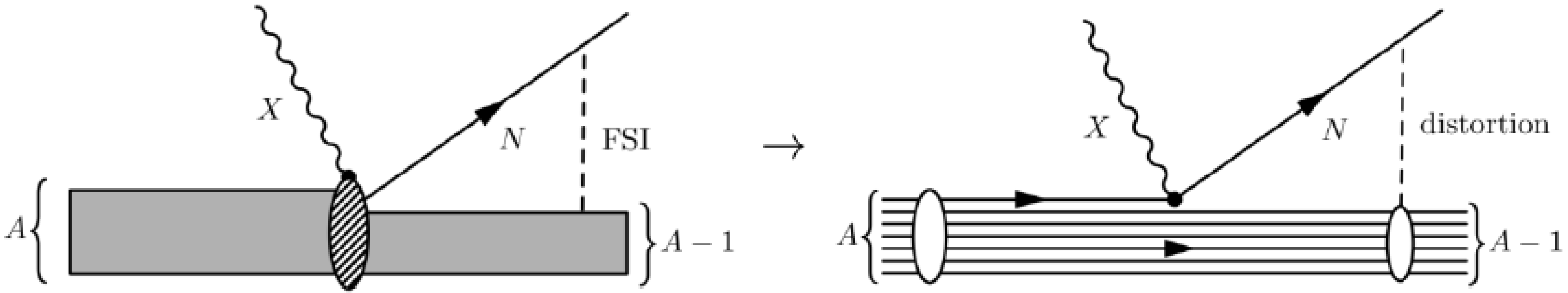
Our nuclear framework

→ Nucleons are solutions to the Schrödinger equation in a **mean-field potential**

→ We calculate single-particle states with the **Hartree-Fock** procedure and SkE2 NN force

→ We describe outgoing nucleons as **continuum states** of the nuclear potential





Short-range correlations

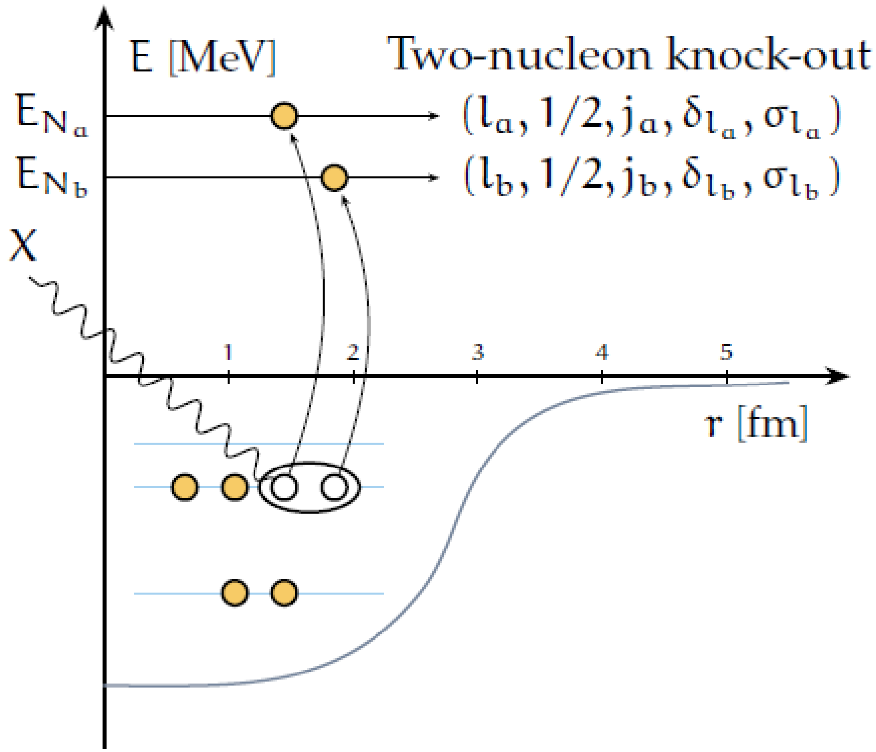
→ Nucleons with strongly **overlapping wave functions** for a short period of time

$$\hat{\mathcal{J}}^{\text{eff}}_{\nu} \simeq \sum_{i=1}^{A} \hat{\mathcal{J}}^{[1]}_{\nu}(i) + \sum_{i<j}^{A} \hat{\mathcal{J}}^{[1],\text{SRC}}_{\nu}(i,j)$$

with

$$\hat{\mathcal{J}}^{[1],\text{SRC}}_{\nu}(i,j) = \left[\hat{\mathcal{J}}^{[1]}_{\nu}(i) + \hat{\mathcal{J}}^{[1]}_{\nu}(j)\right]\hat{l}(i,j)$$

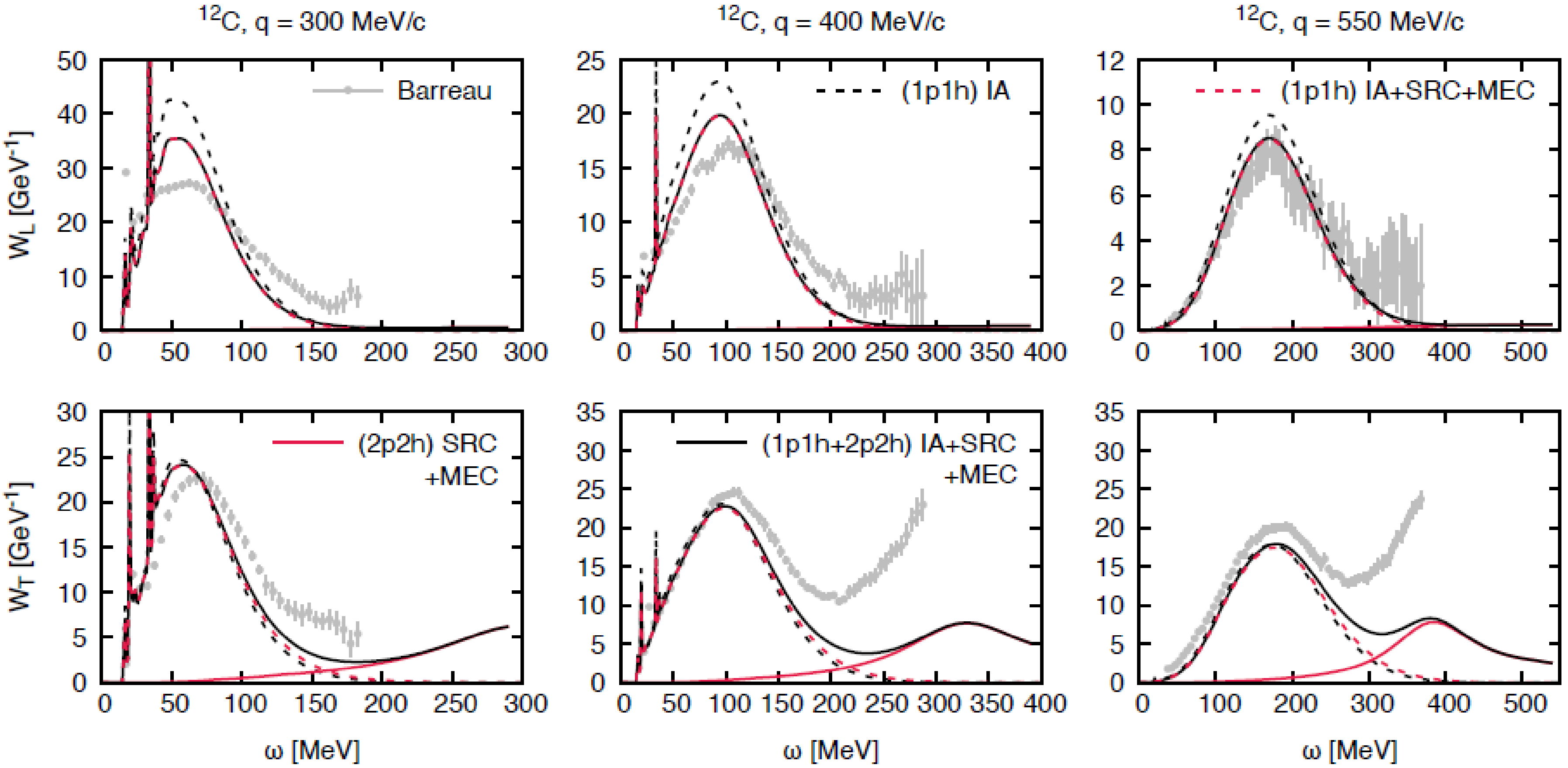
→ The correlation operator $\hat{l}(i,j)$ includes **central**, **tensor**, and **spin-isospin correlations**



→ First corrections to the **independent-particle model** picture for 1p1h

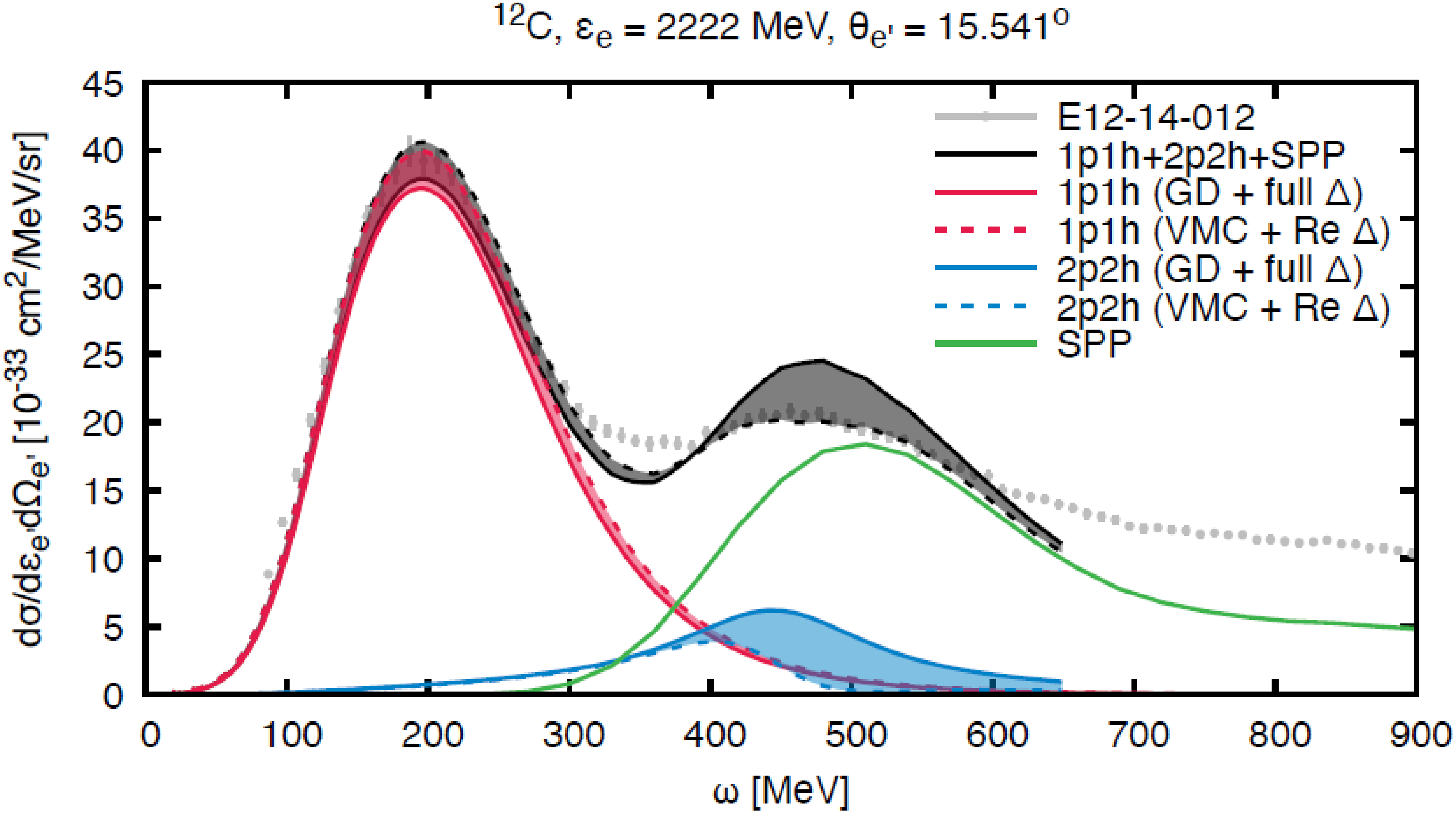
→ **Two-body currents** also leading to **two-nucleon knock-out** reactions

Consistent modeling of two-body currents: electron scattering



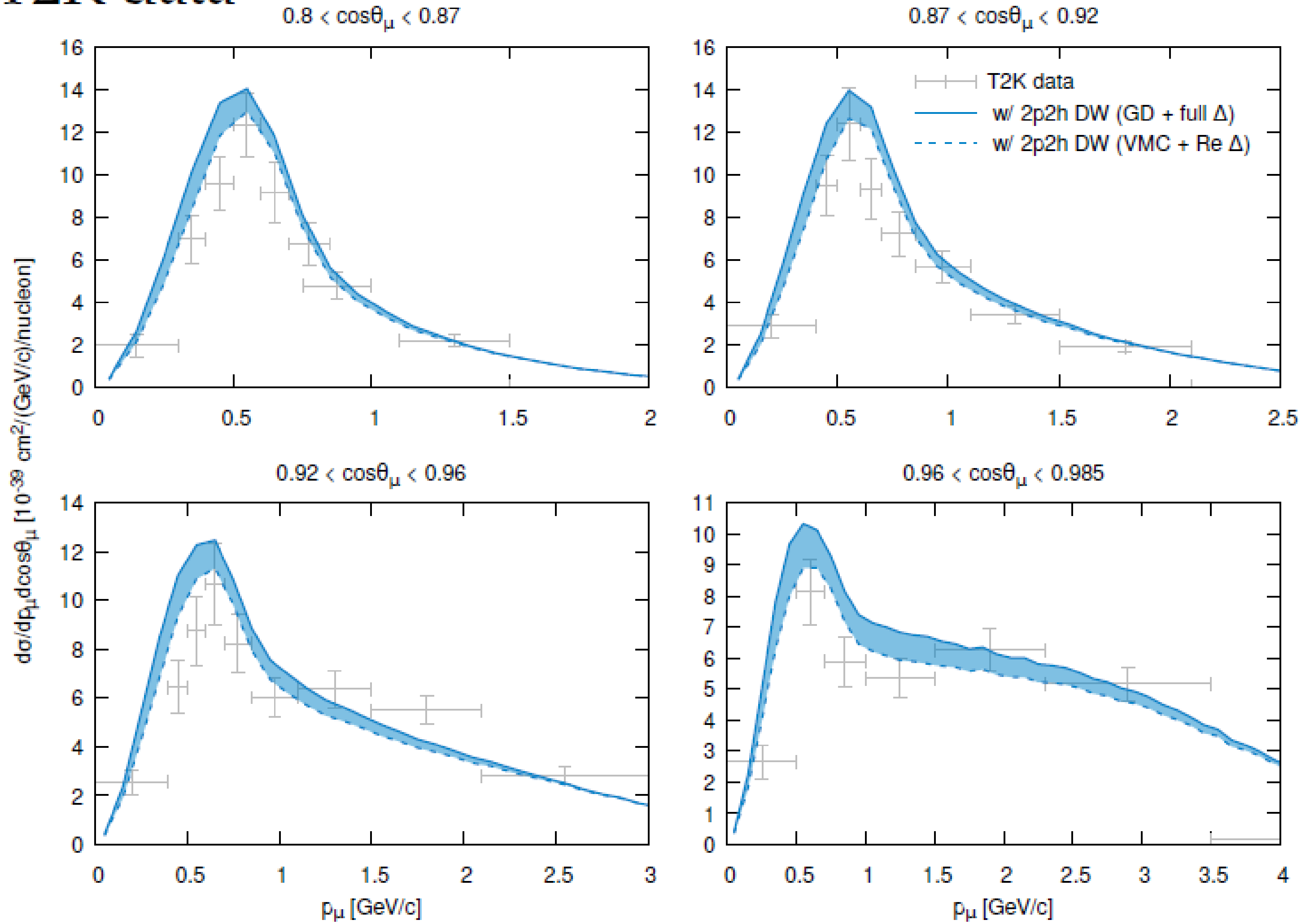
→ **Coherent sum of SRC and MEC** enhances our predictions

JLab Hall A data



→ Combining variation in given d.f. provides **flexibility in describing QE and Δ peaks**

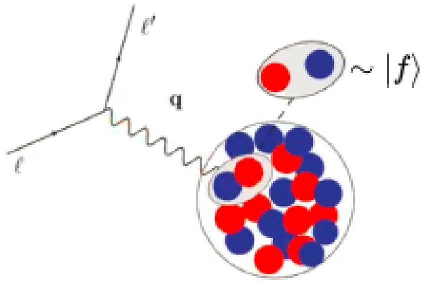
Inclusive T2K data



Short-time approximation

S. Pastore, J. Carlson, S. Gandolfi, R. Schiavilla, and R. B. Wiringa PRC101(2020)044612

Describe electroweak scattering from A>=12 without losing two-body physics, account for exclusive processes, Incorporate relativistic effects



Response functions

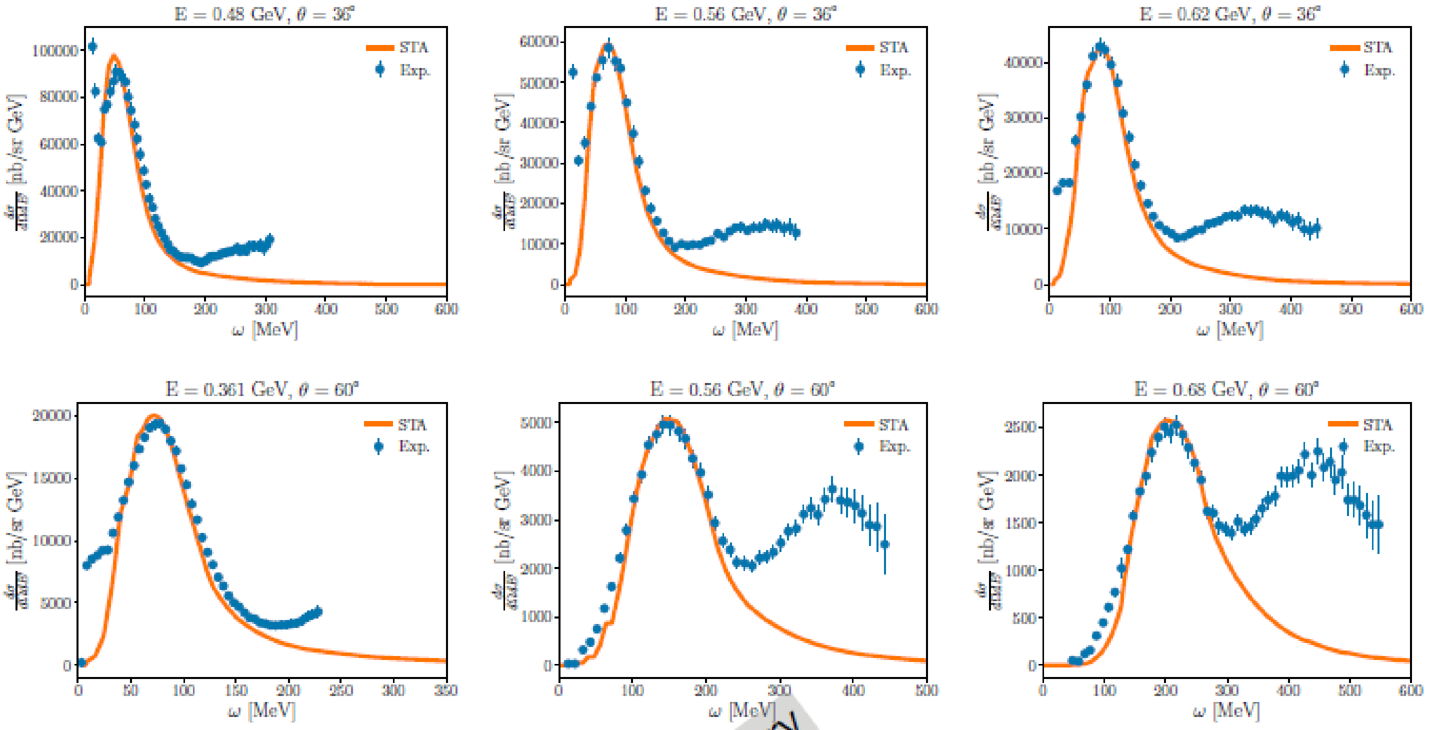
$$R_\alpha(q,\omega) = \sum_f \delta(\omega + E_0 - E_f)|\langle f|O_\alpha(\mathbf{q})|0\rangle|^2$$

$$R_\alpha(q,\omega) = \int_{-\infty}^{\infty} \frac{dt}{2\pi} e^{i(\omega+E_i)t} \langle \Psi_i | O_\alpha^\dagger(\mathbf{q}) e^{-iHt} O_\alpha(\mathbf{q}) | \Psi_i \rangle$$

$$\begin{aligned} O^\dagger e^{-iHt} O &= \left(\sum_i O_i^\dagger + \sum_{i<j} O_{ij}^\dagger\right) e^{-iHt} \left(\sum_{i'} O_{i'} + \sum_{i'<j'} O_{i'j'}\right) \\ &= \sum_i O_i^\dagger e^{-iHt} O_i + \sum_{i\neq j} O_i^\dagger e^{-iHt} O_j \\ &+ \sum_{i\neq j} \left(O_i^\dagger e^{-iHt} O_{ij} + O_{ij}^\dagger e^{-iHt} O_i \right. \\ &\left. + O_{ij}^\dagger e^{-iHt} O_{ij} \right) + \dots \end{aligned}$$

The sum over all final states is replaced by a two nucleon propagator

Cross sections results for ^{12}C



Preliminary

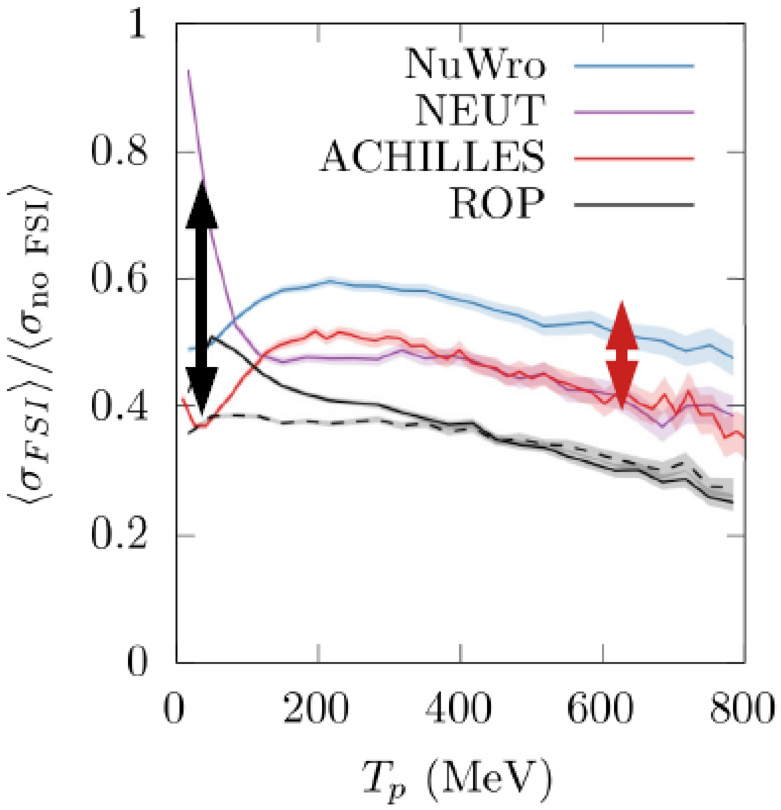
Nonrelativistic calculations

Lorenzo Andreoli

Benchmarking INCs with RDWIA calculations for Argon

[In preparation]

Comparison of T_p dependence in different INCs

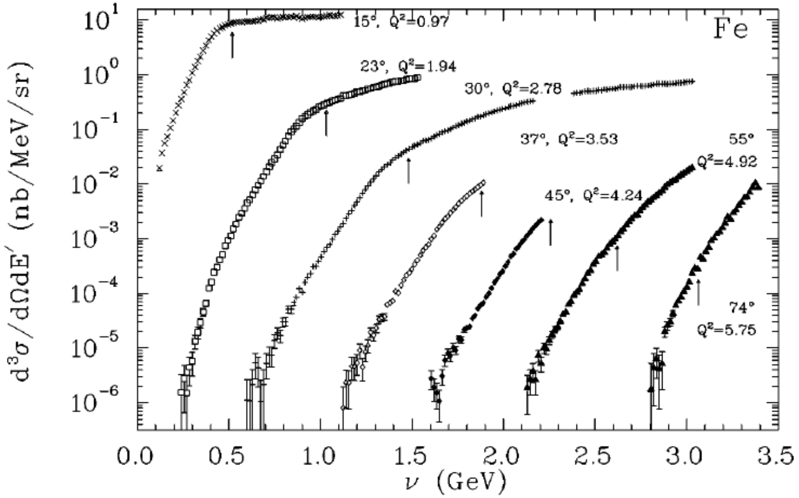


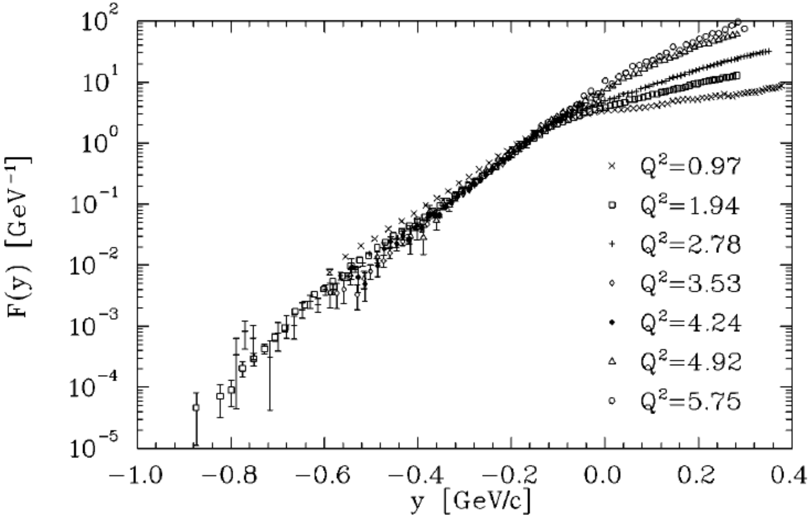
Ratio **OUT/INPUT**
→ independent of INPUT in INC
= 'INC Transparency'

- **NEUT & ACHILLES:**
  - Low-T_p differences
- **NuWro & ACHILLES:**
  - Treatment of SRCs

Alexis Nikolakopoulos

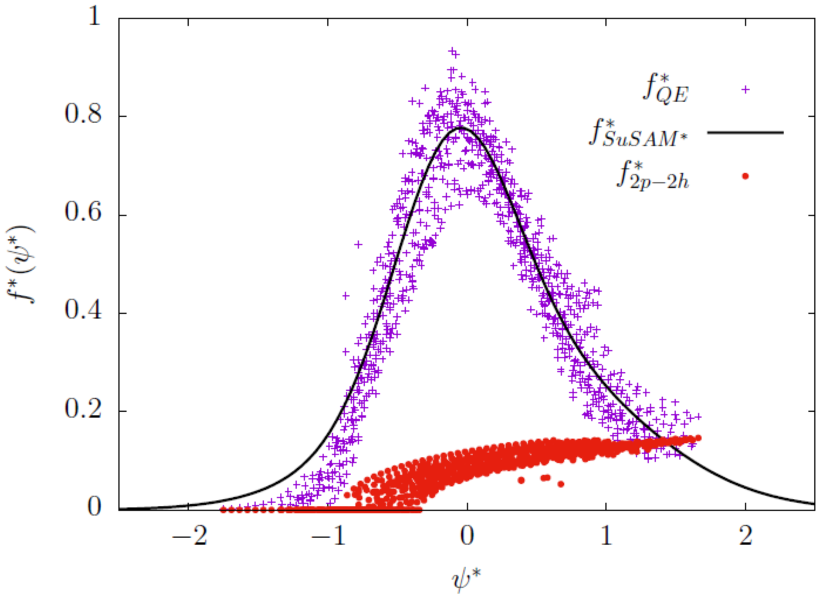
Superscaling

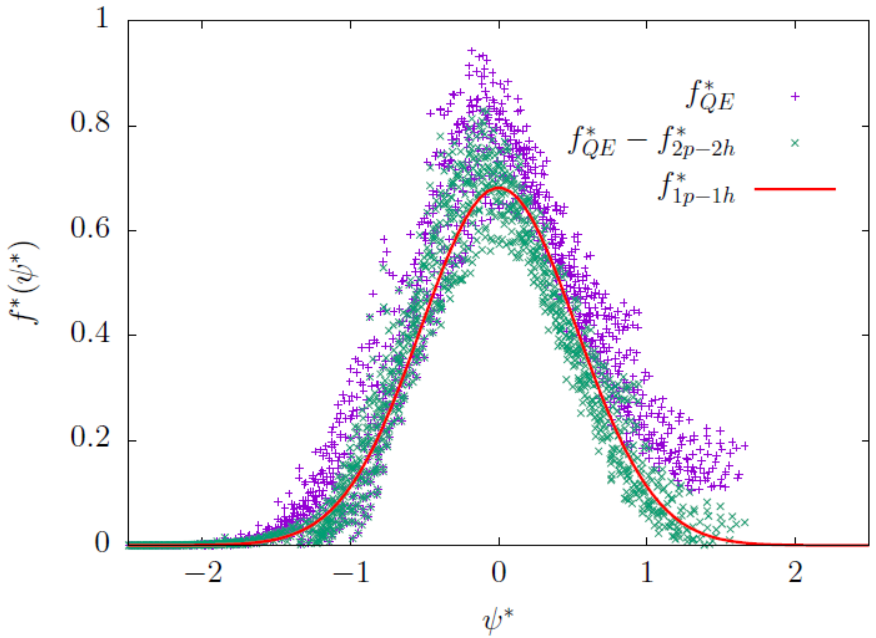




Arrington *et al.*, PRL 82, 2056 (1999)

Superscaling

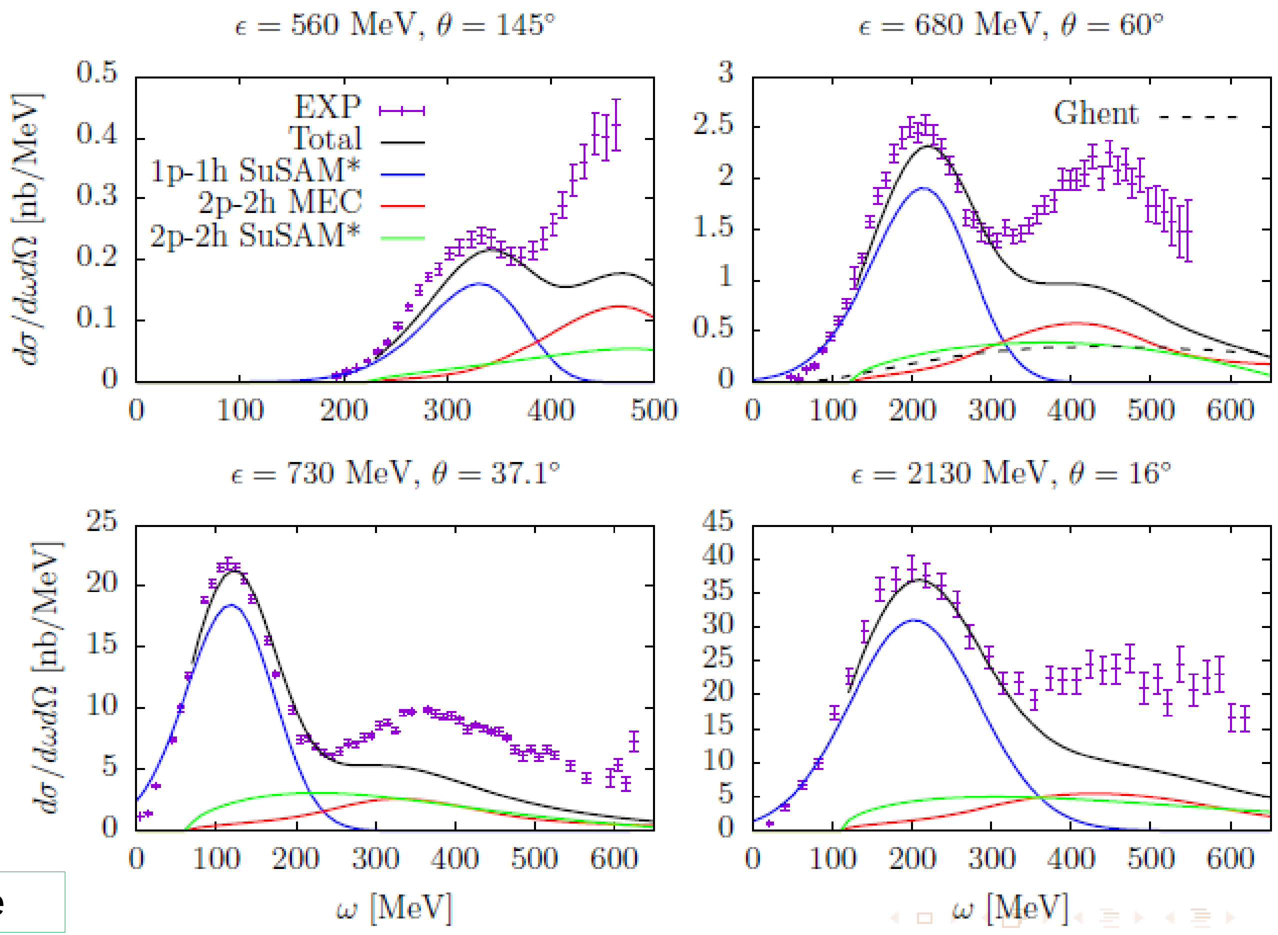




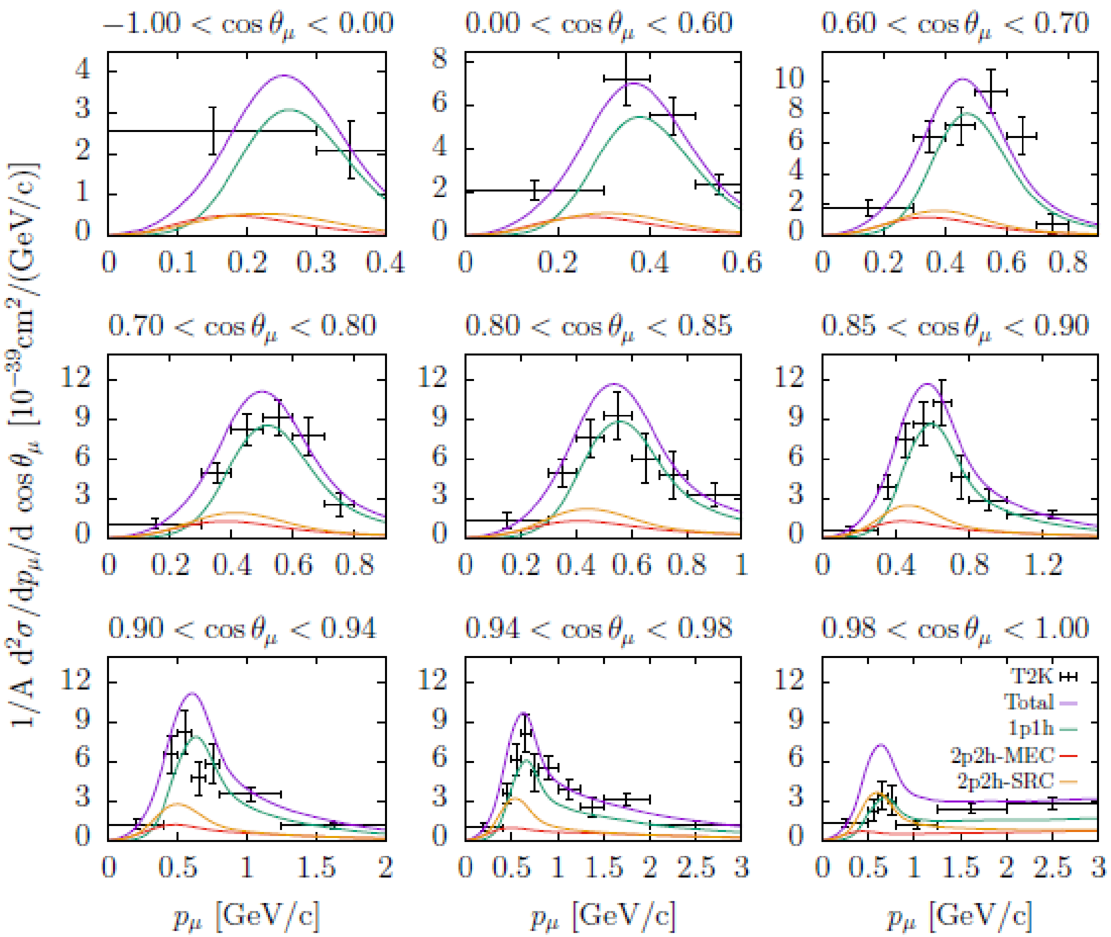
$$\frac{d\sigma}{d\omega\, d\Omega} = f(\psi')(N\sigma_{en} + Z\sigma_{ep})$$

Paloma Casalé

Results - $^{12}C(e,e')$

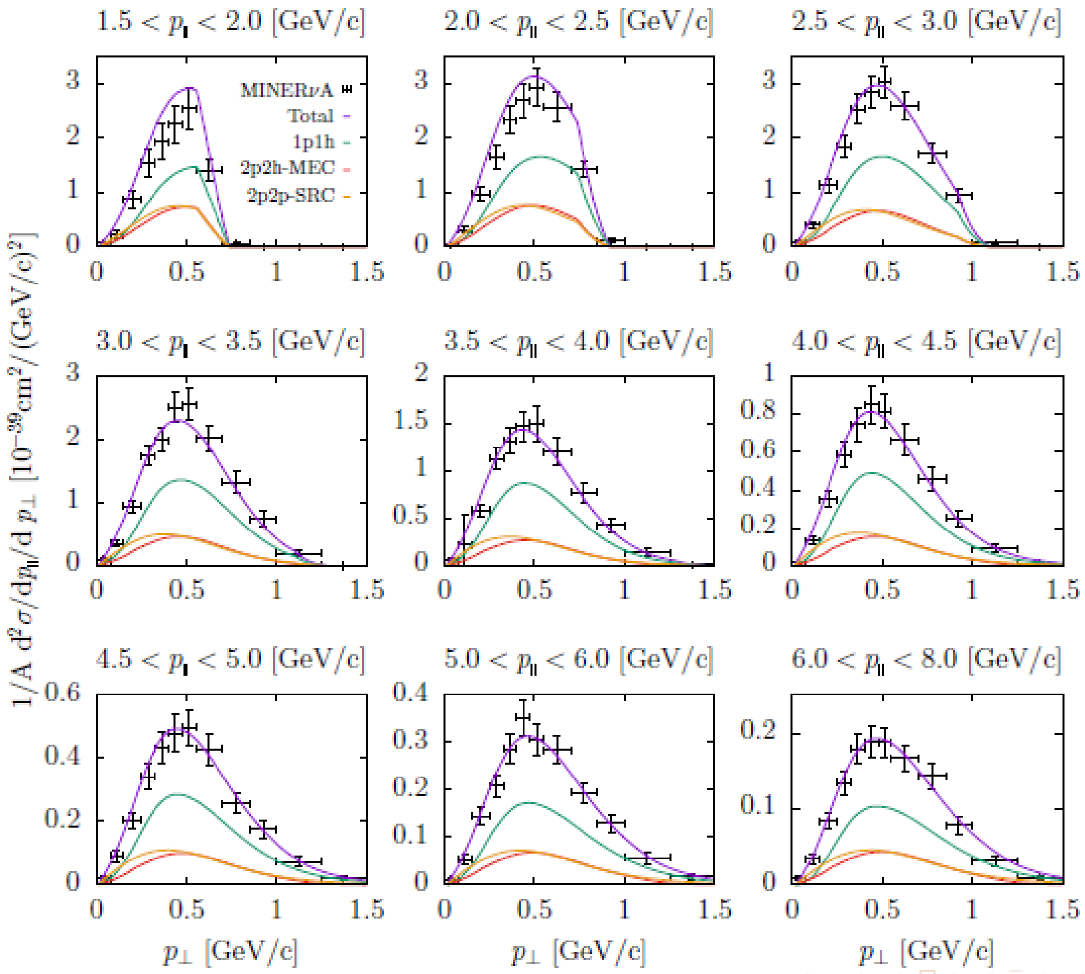


Results-T2K



$-1.00 < \cos\theta_\mu < 0.00$
$0.00 < \cos\theta_\mu < 0.60$
$0.60 < \cos\theta_\mu < 0.70$
$0.70 < \cos\theta_\mu < 0.80$
$0.80 < \cos\theta_\mu < 0.85$
$0.85 < \cos\theta_\mu < 0.90$
$0.90 < \cos\theta_\mu < 0.94$
$0.94 < \cos\theta_\mu < 0.98$
$0.98 < \cos\theta_\mu < 1.00$
$1/A\ d^2\sigma/dp_\mu/d\cos\theta_\mu\ [10^{-39}cm^2/(GeV/c)]$
p_μ [GeV/c]
T2K
Total
1p1h
2p2h-MEC
2p2h-SRC

Results-MINERνA



Model: SuSAv2-inelastic

The contribution analysed depends of the limits of the integral and the parametrization used

- TrueDIS (Deep inelastic scattering)

$W_x^{min} = 2.1\ GeV;\ \ W_x^{max} = m_N + \omega - E_s$

Bodek-Ritchie/ Bosted-Christy/ Parton Distribution Function

- RES (Resonances)

$W_x^{min} = m_N + m_\pi;\ \ W_x^{max} = 2.1\ GeV$

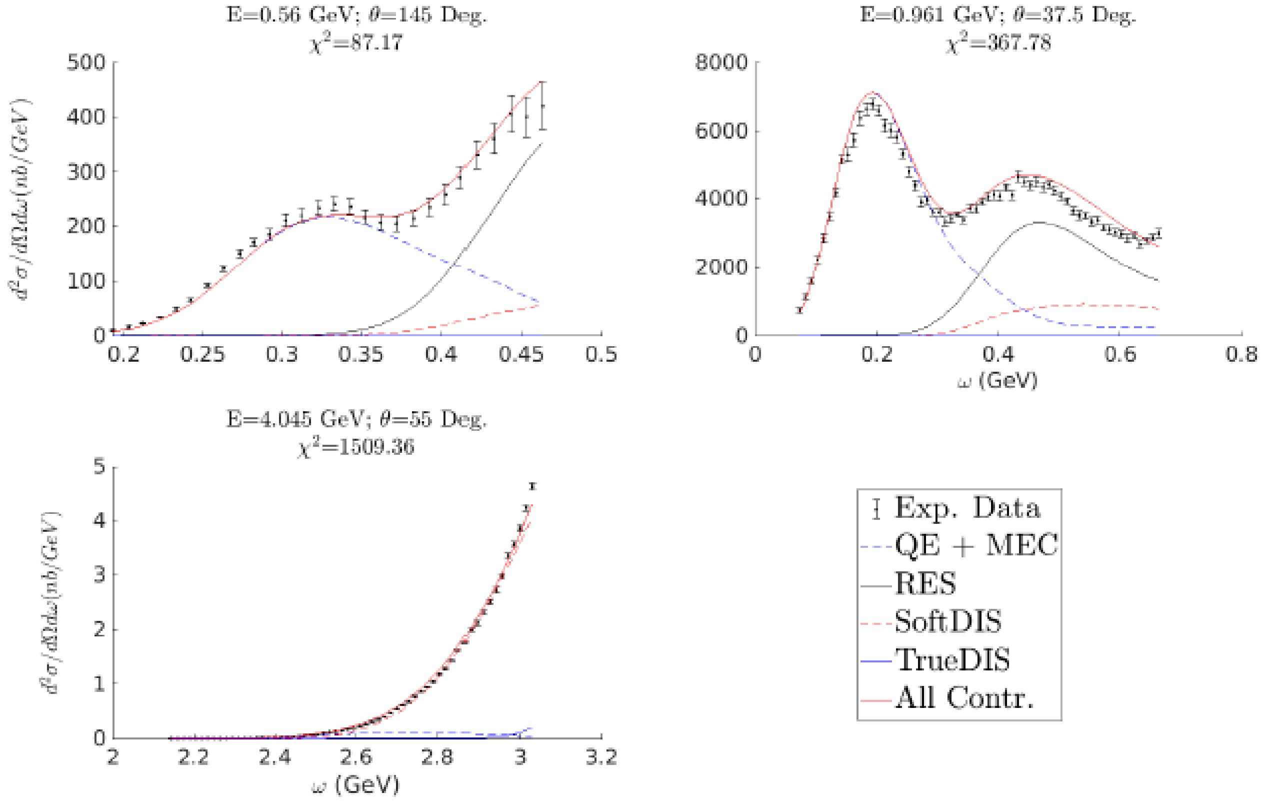
Dynamical Coupled Channels

- SoftDIS (Deep inelastic scattering in the resonance region)

$W_x^{min} = m_N + m_\pi;\ \ W_x^{max} = 2.1\ GeV$

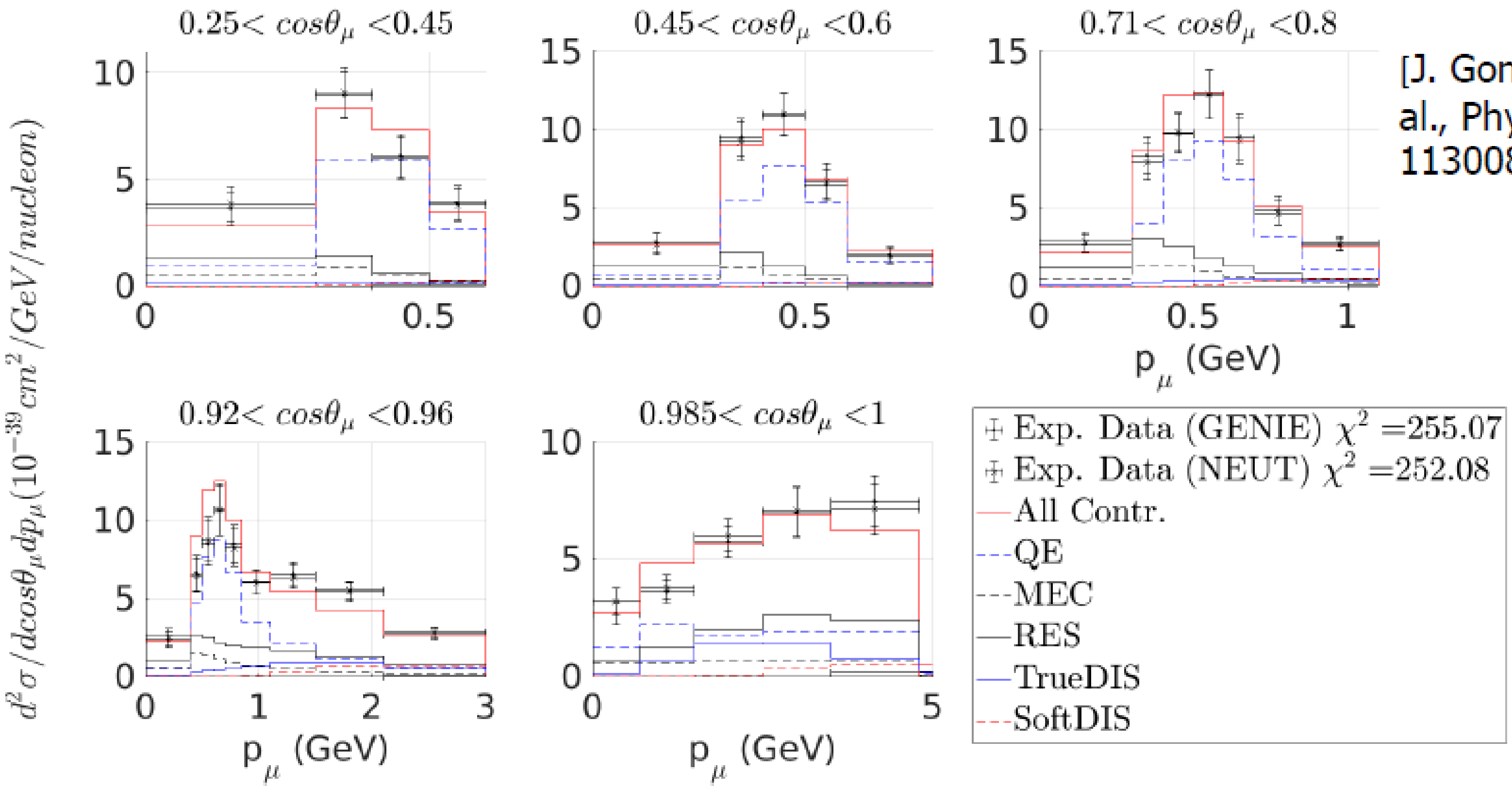
Dynamical Coupled Channels and Bodek-Ritchie/Bosted-Christy

Results: Electron scattering



[J. Gonzalez-Rosa et al., Phys. Rev. D 108, 113008 (2023)].

Results: T2K



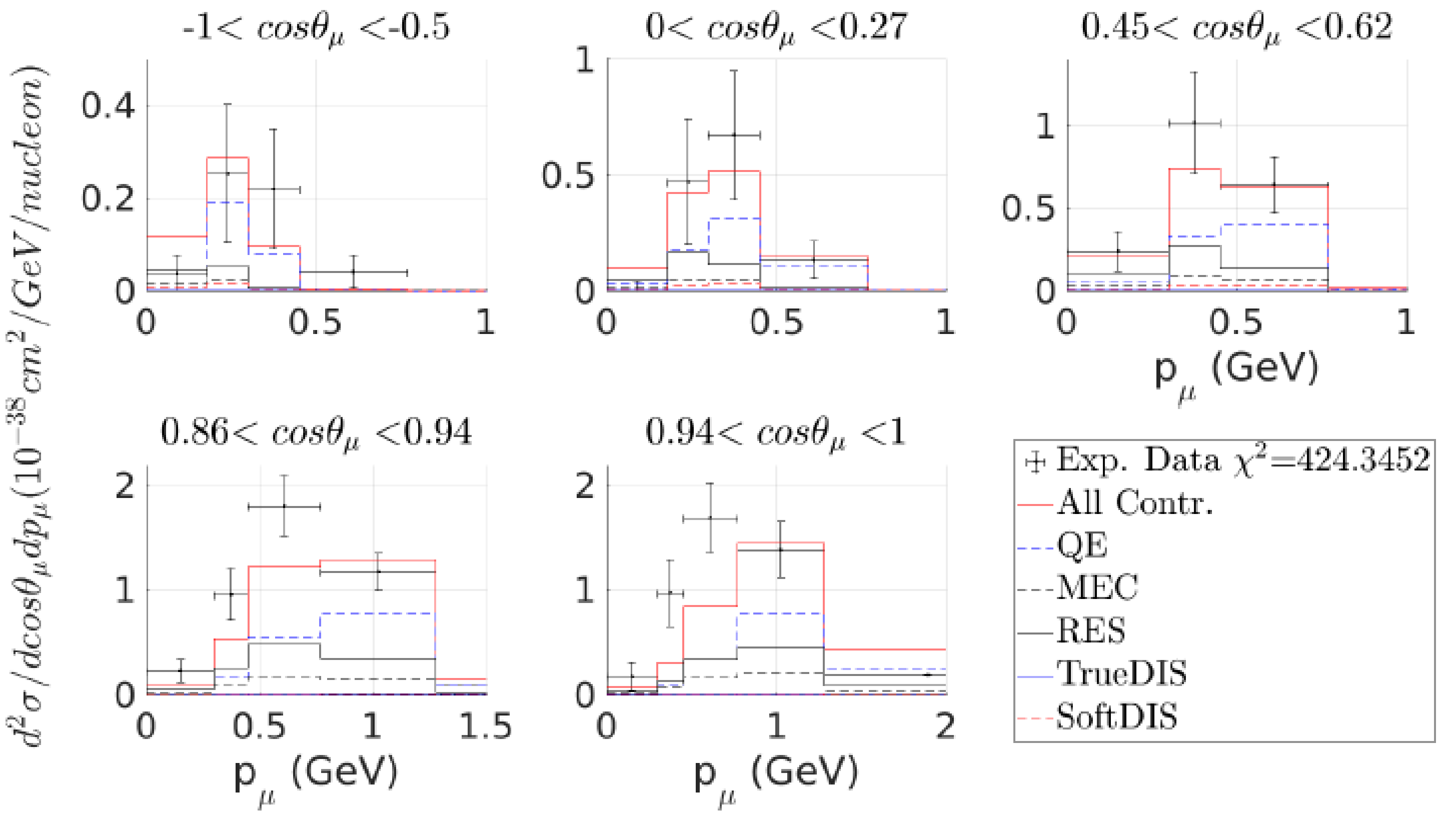
[J. Gonzalez-Rosa et al., Phys. Rev. D 108, 113008 (2023)].

$\chi^2 = 218.3$ (GENIE)

$\chi^2 = 192.0$ (NEUT)

T2K CC ν_μ, $< E_{\nu_\mu} > \sim 0.6\ GeV$

Results: MicroBooNE



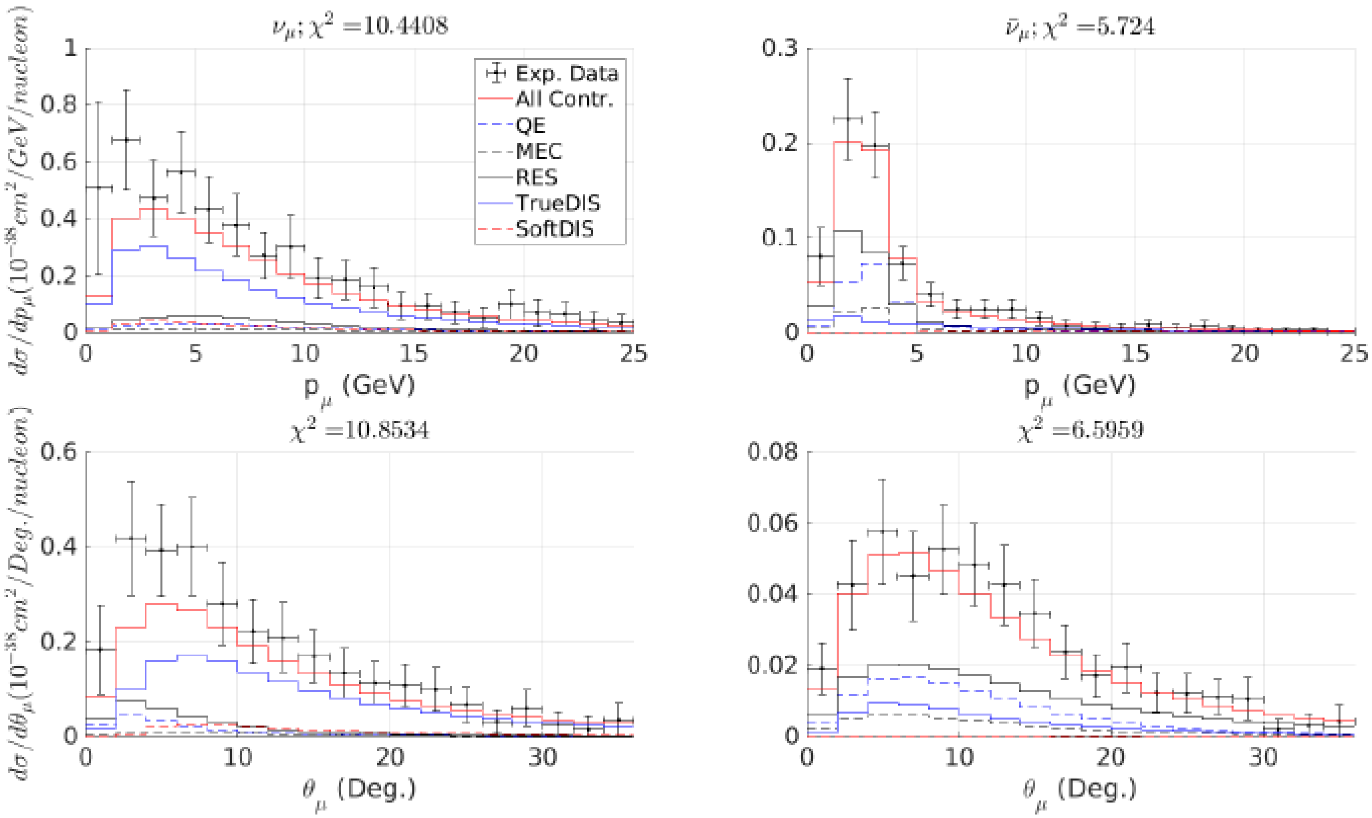
[J. Gonzalez-Rosa et al., Phys. Rev. D 108, 113008 (2023)].

$\chi^2 = 103.9$
(GENIEv3)

MicroBooNE CC $\nu_\mu, < E_{\nu_\mu} > \sim 0.8$ GeV

Jesus Gonzalez-Rosa

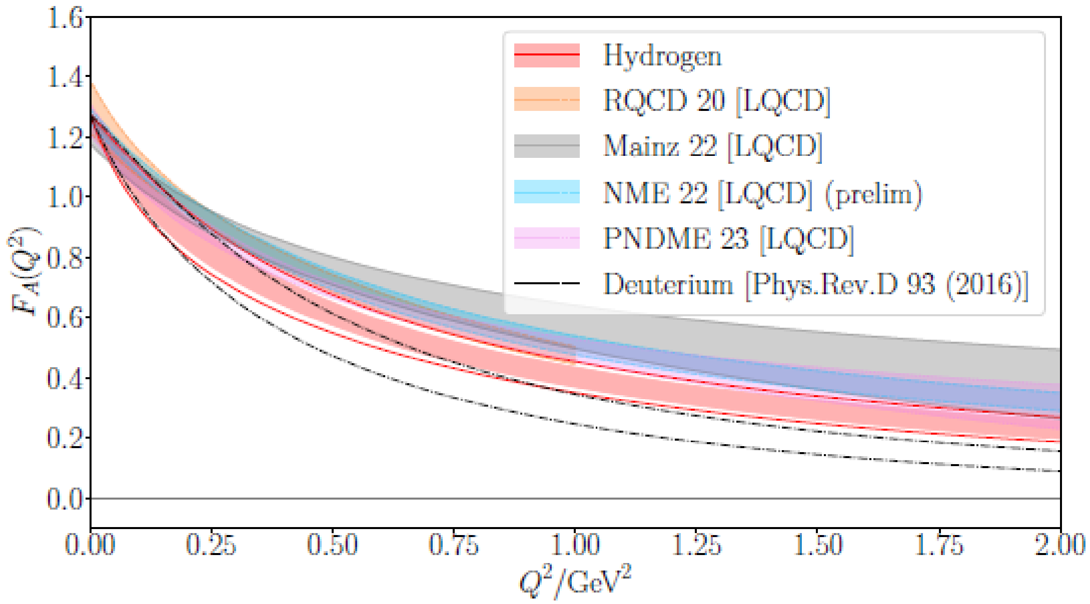
Results: ArgoNEUT



[J. Gonzalez-Rosa et al., Phys. Rev. D 108, 113008 (2023)].

ArgoNEUT CC ν_μ, $< E_{\nu_\mu} > \sim 9.6\ GeV$; CC$\bar{\nu}_\mu$, $< E_{\nu_\mu} > \sim 3.6\ GeV$

Hydrogen–Deuterium Comparison Summary



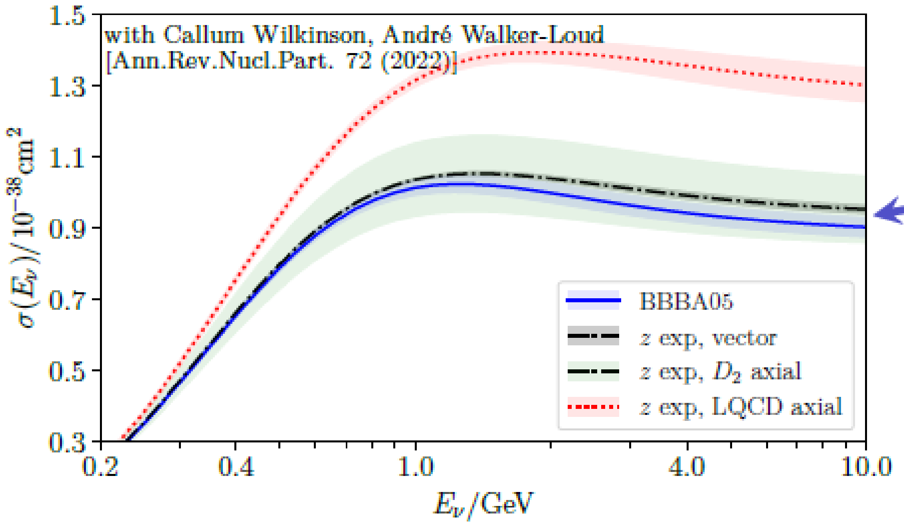
LQCD “prediction”: deuterium fits underestimate axial form factor at high Q^2

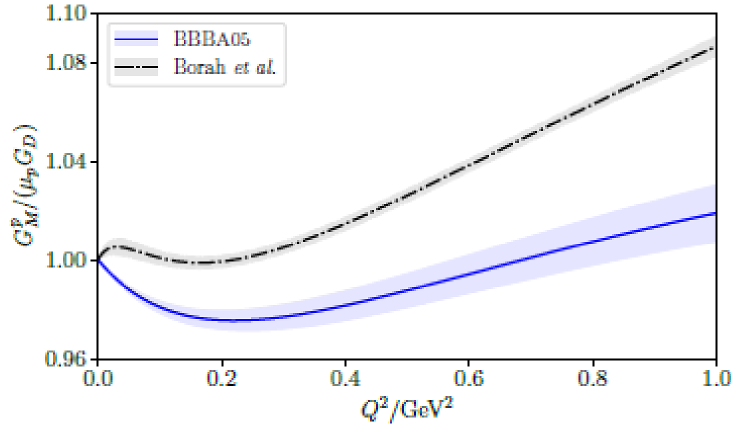
Unphysical deuterium fit degerancy between floating normalization, axial form factor

Independent of norm degeneracy, hydrogen & deuterium shapes mutually incompatible

We need more modern hydrogen data!

Free Nucleon Cross Section





LQCD prefers 30-40% enhancement of ν_μ CCQE cross section

recent Monte Carlo tunes require 20% enhancement of QE

[Phys.Rev.D 105 (2022)] [2206.11050 [hep-ph]]

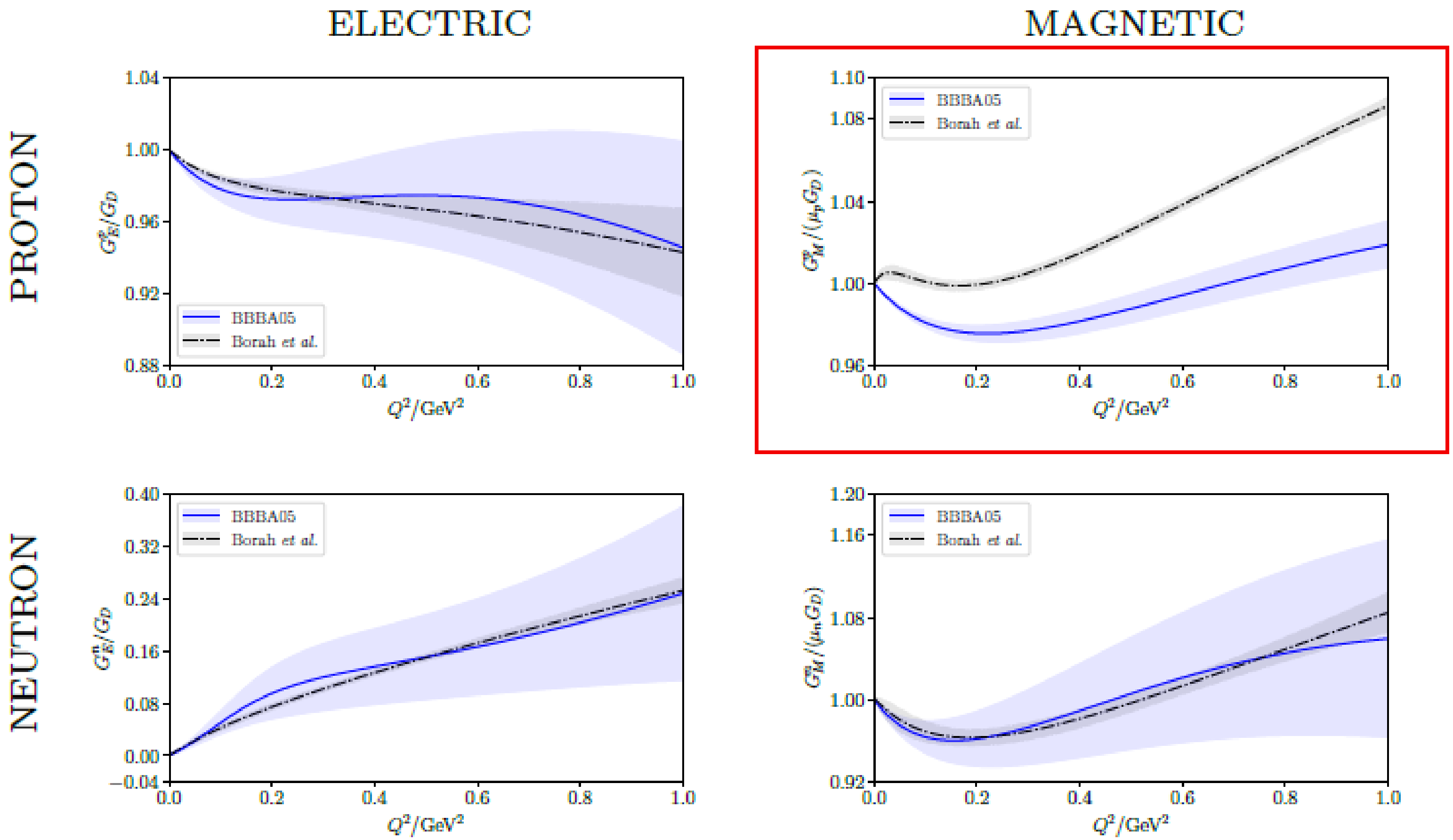
Sensitive to vector form factor tension with improved precision [Phys.Rev.D 102 (2020)] [Nucl.Phys.B Proc.Suppl. 159 (2006)]

(red uncertainty vs black−blue difference)

$\Longrightarrow$ vector form factors will limit precision in near future

Aaron Meyer

Vector Form Factors - Proton/Neutron

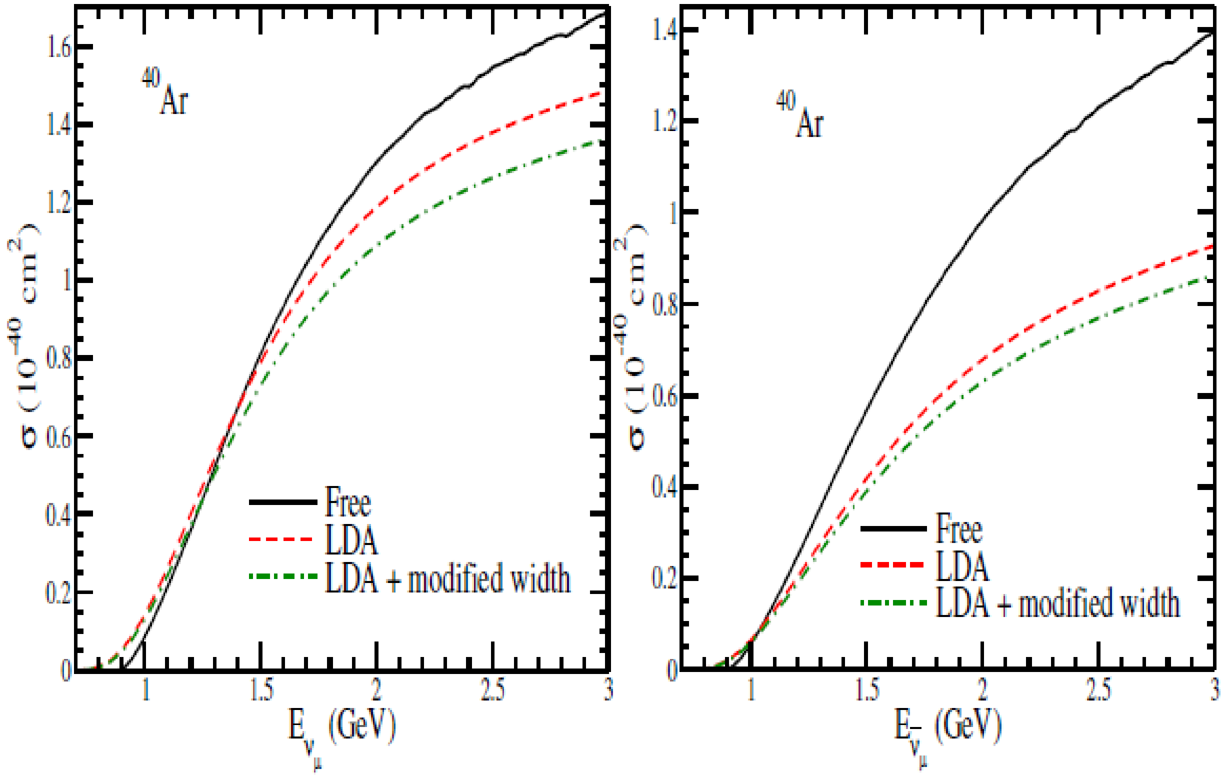


Borah *et al.*, PRD 102, 074012 (2020)

Large tension in proton magnetic form factor

Aaron Meyer

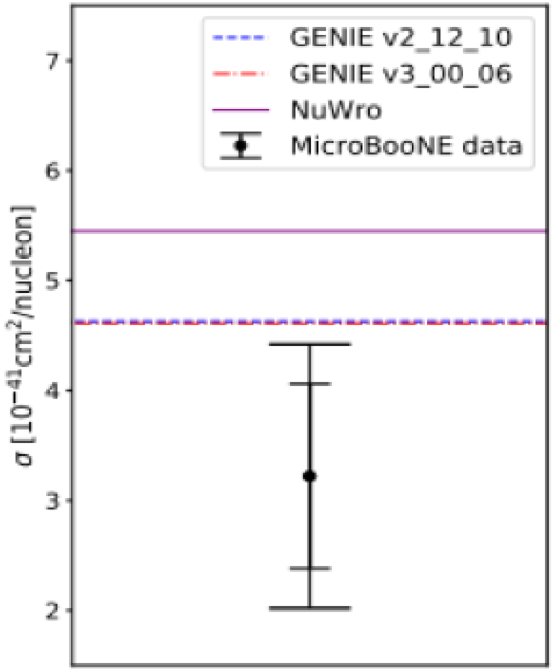
σ per interacting nucleon for the CC neutrino (left) and antineutrino (right) from ^{40}Ar nuclear target



AF, MSA, SKS, Paper in preparation

MicroBooNE η production result

$$\langle\sigma\rangle = (3.22 \pm 0.84 \pm 0.86) \times 10^{-41}\ \text{cm}^2/\text{nucleon}$$



Phys. Rev. Lett. 132, 151801 (2024)

- $\langle\sigma\rangle_{\text{free}} = 1.87 \times 10^{-41}\ \text{cm}^2/\text{nucleon}$
- $\langle\sigma\rangle_{^{40}\text{Ar}} = 1.78 \times 10^{-41}\ \text{cm}^2/\text{nucleon}$

- GENIE $v2\_12\_10$: $4.63 \times 10^{-41}\ \text{cm}^2/\text{nucleon}$
- GENIE $v3\_00\_06G18\_10a\_02\_11a$: $4.61 \times 10^{-41}\ \text{cm}^2/\text{nucleon}$
- NuWro 19.02.1: $5.45 \times 10^{-41}\ \text{cm}^2/\text{nucleon}$
- NEUT v5.4.0: $11.9 \times 10^{-41}\ \text{cm}^2/\text{nucleon}$

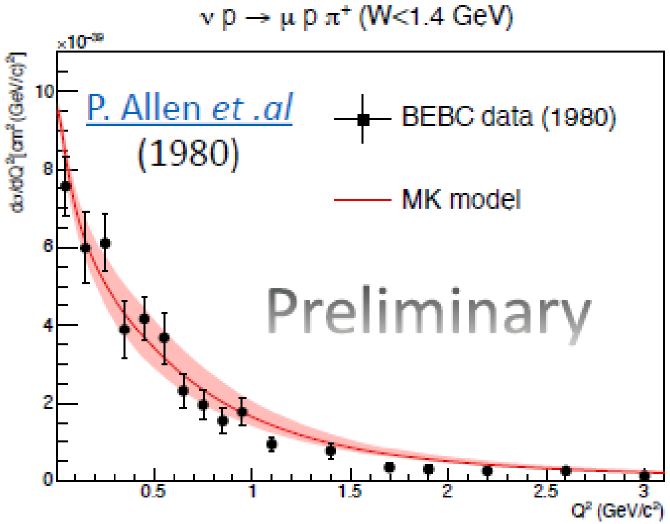
Further reduction expected due to FSI

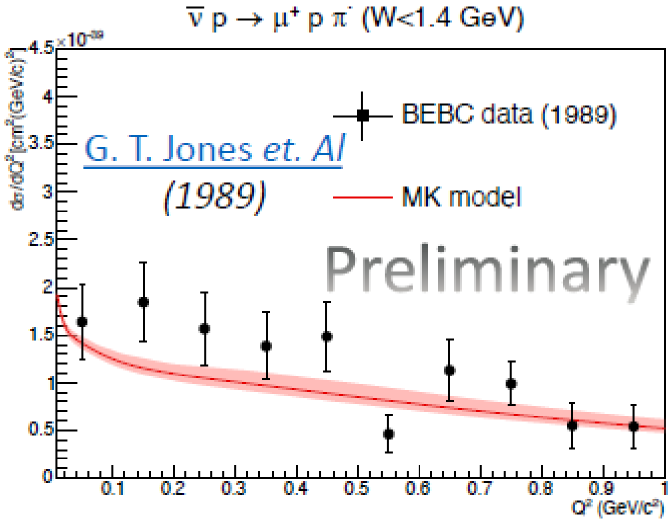
MK model

- The MK model is applicable in the resonance region (W < 2.0 GeV), covering both resonance and nonresonant interactions.
- It utilises a form-factor model (Meson Dominance) that complies with the **unitary condition**, respects **CVC and PCAC**, and is consistent with QCD principles. Consequently, the model provides accurate predictions across both low and high Q^2 regions.
- All form factors (neutron, proton, CC, and NC) are determined through a **joint fit** incorporating approximately 50,000 data points on **electron, photon, pion, and neutrino scattering data,** providing **covariance matrix**.

Highlight 1 (neutrino vs anti-neutrino)

- By employing an advanced model for the form factors and incorporating data from both neutrino and anti-neutrino interactions, we can ensure a reliable prediction for both types of interactions.

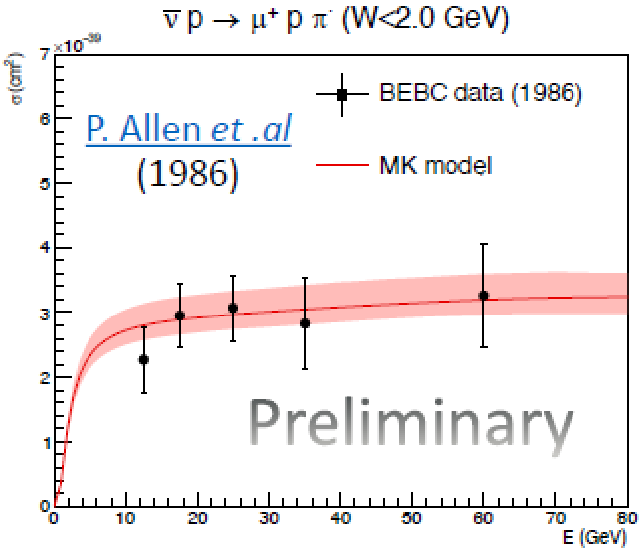


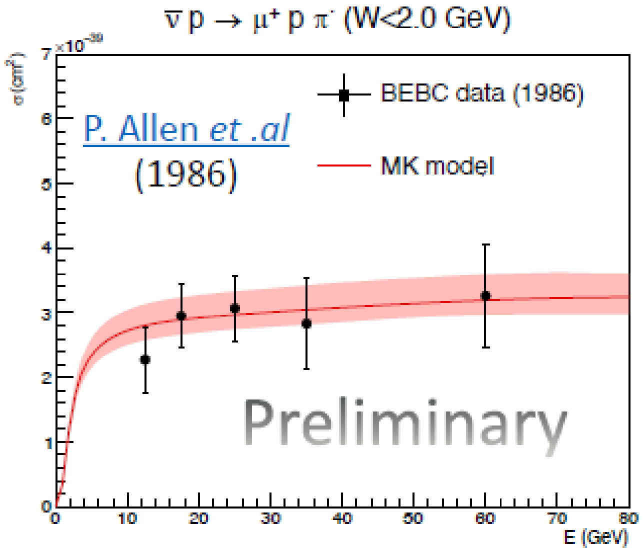


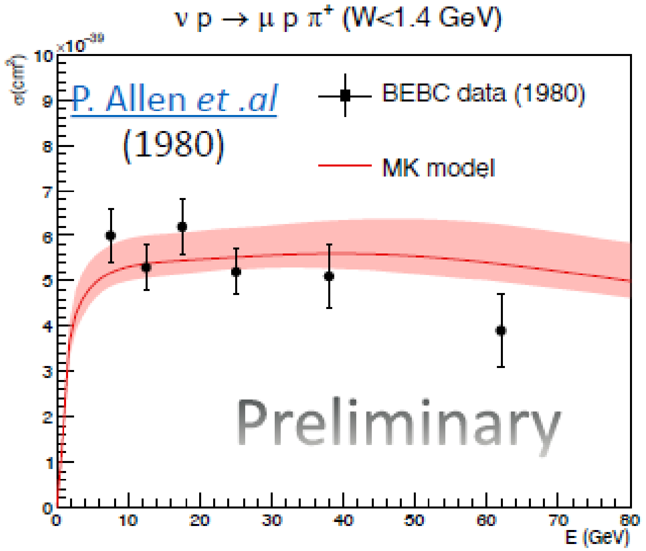
Minoo Kabirnezhad

Highlight 1 (neutrino vs anti-neutrino)

- Integrated cross section





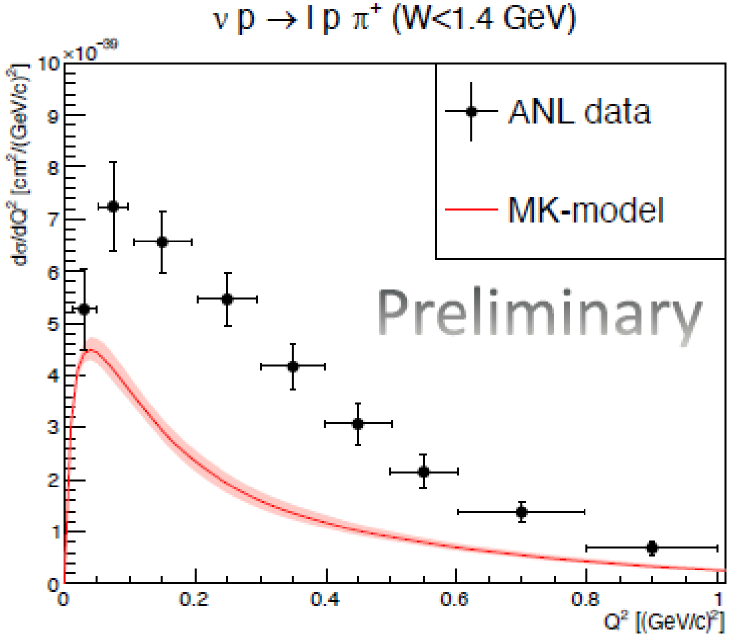


Minoo Kabirnezhad

Highlight 3: Low Q^2 region

- The model is designed to address the low Q^2 region, where existing models struggle to predict empirical data:

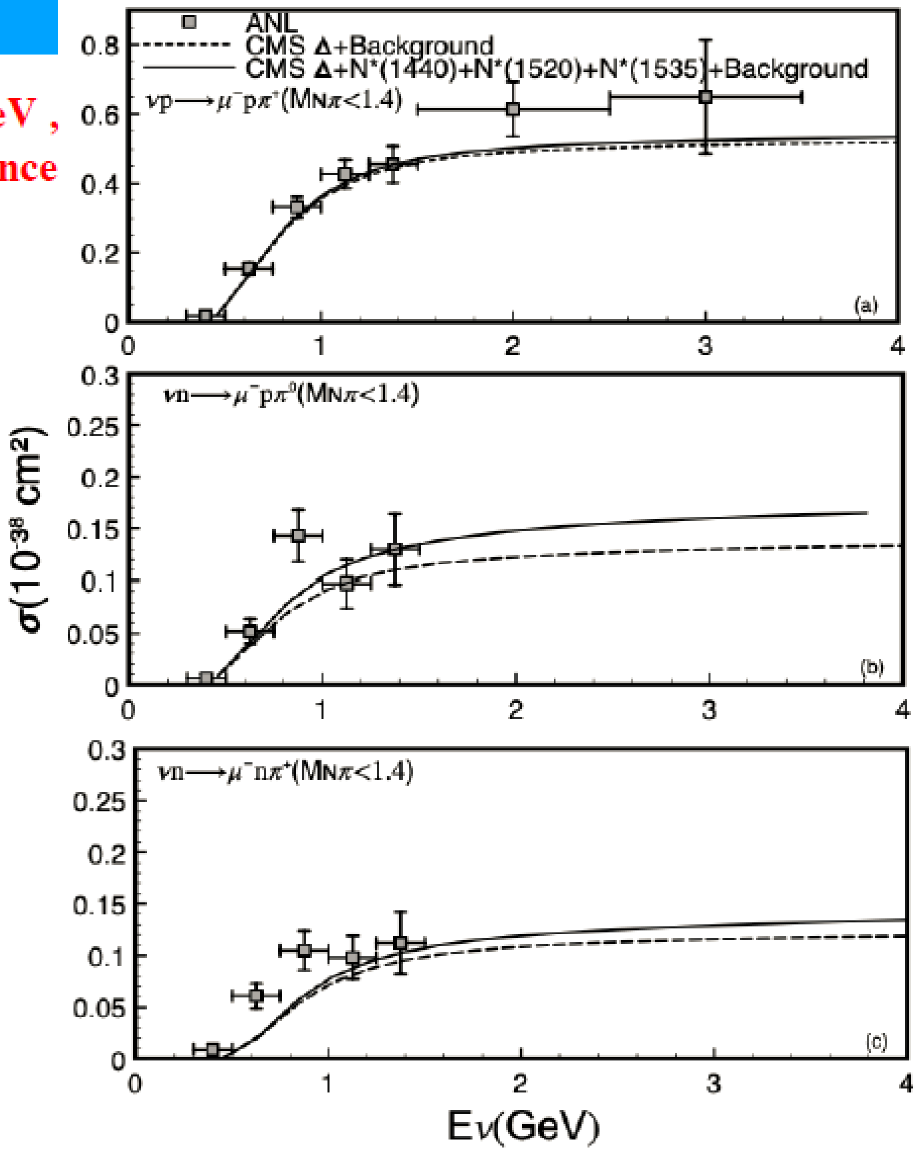
- This ANL data is not included in the fit.
- The proton/deuteron ratio is similar to neutron/deuteron in electron scattering measurements.
- This ANL data on deuterium is utilised to fit the axial form factor in event generators.



Minoo Kabirnezhad

Total cross sections

Results with $M_{\pi N} < 1.4$ GeV , Δ and Δ plus 2nd resonance region (old ANL data)



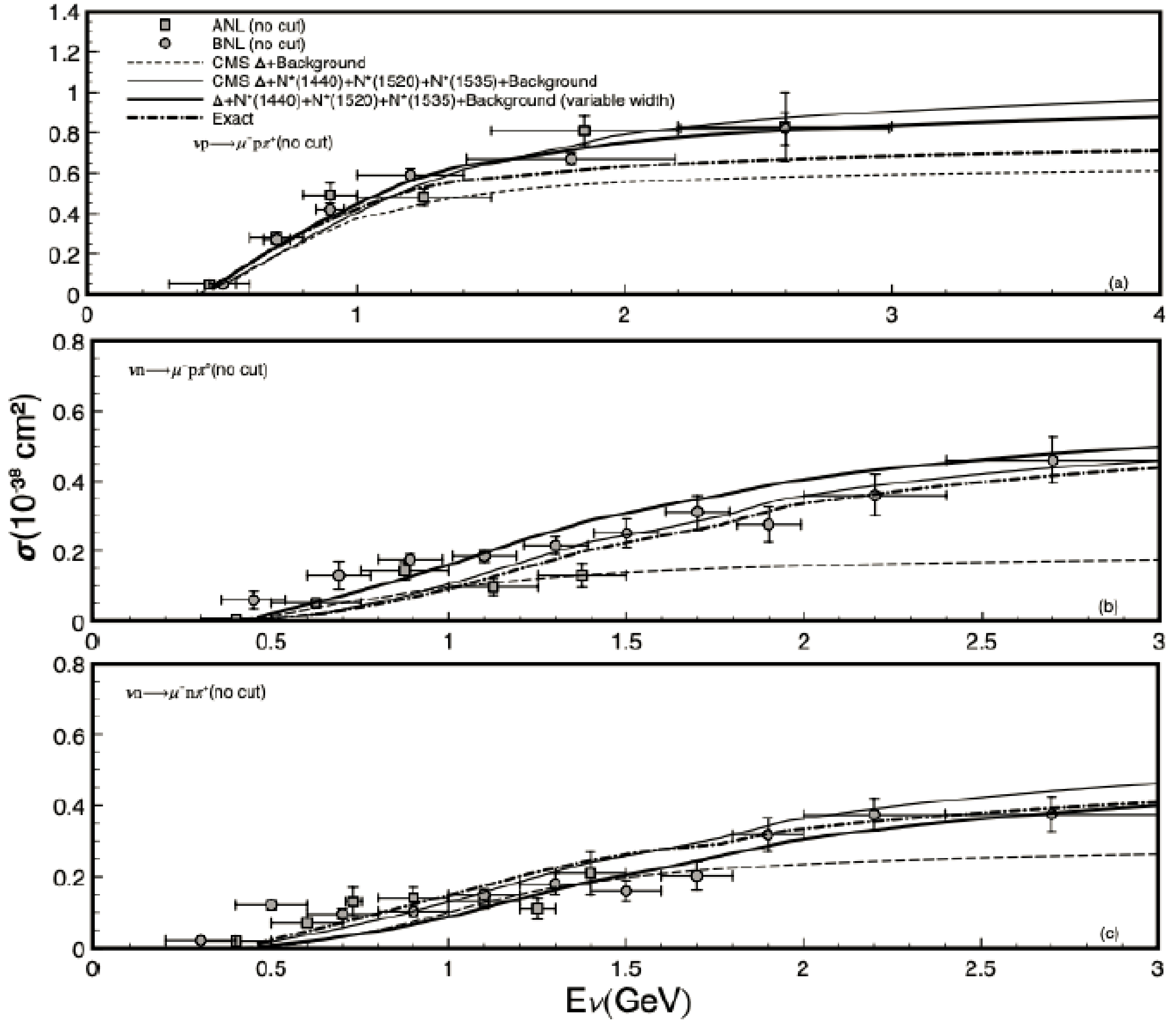
- We use CMS approach previously implemented to get, strong and weak parameters for the Δ, with $M_{\pi N} < 1.4$ GeV.
- The effect of adding 2nd resonance region depends on the channel, for $E_\nu = 3.0, 1.5, 1.5$ GeV we get a 4%, 17% and 10% of contribution respectively.

Alejandro Mariano

Comparison with reanalyzed ANL and BNL

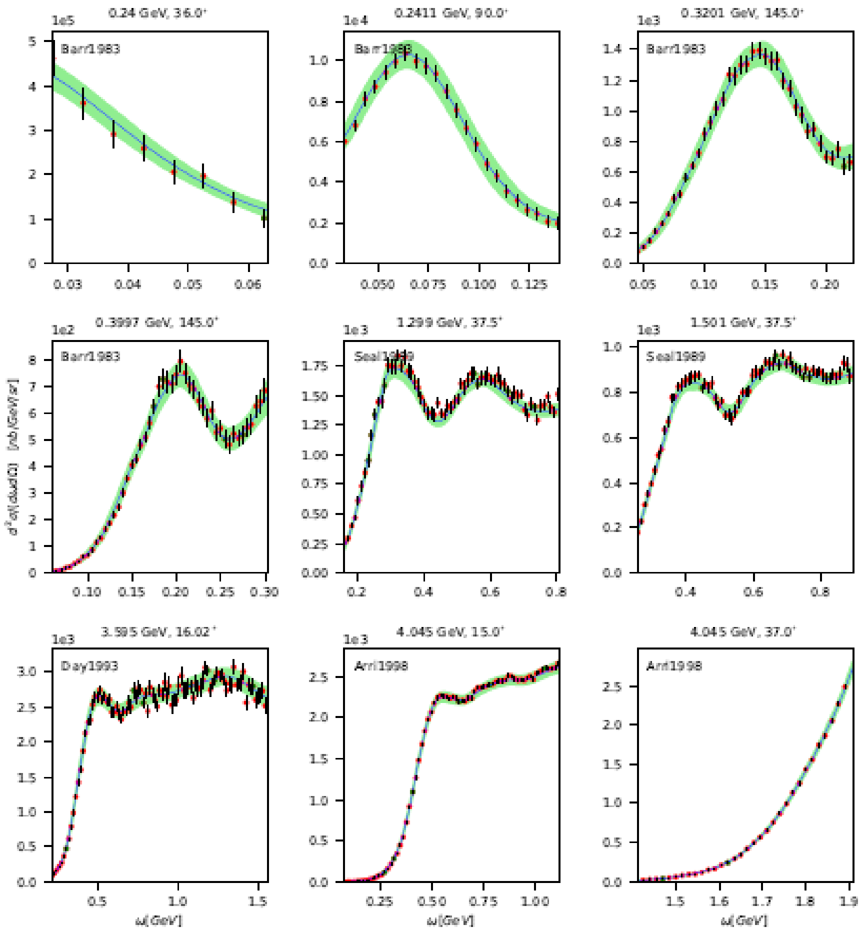
- The increase in the cross section due additional resonances is persistent and the best working approach is CMS as before . We will use χ^2/dof in spite we are not fitting anything.

- We have also shown results with variable widths, which are not consistent without vertex corrections, since there are works with this approach. Also we show results with the exact propagator, which has a more complex structure and one should consistently include the rescattering in the total amplitude.

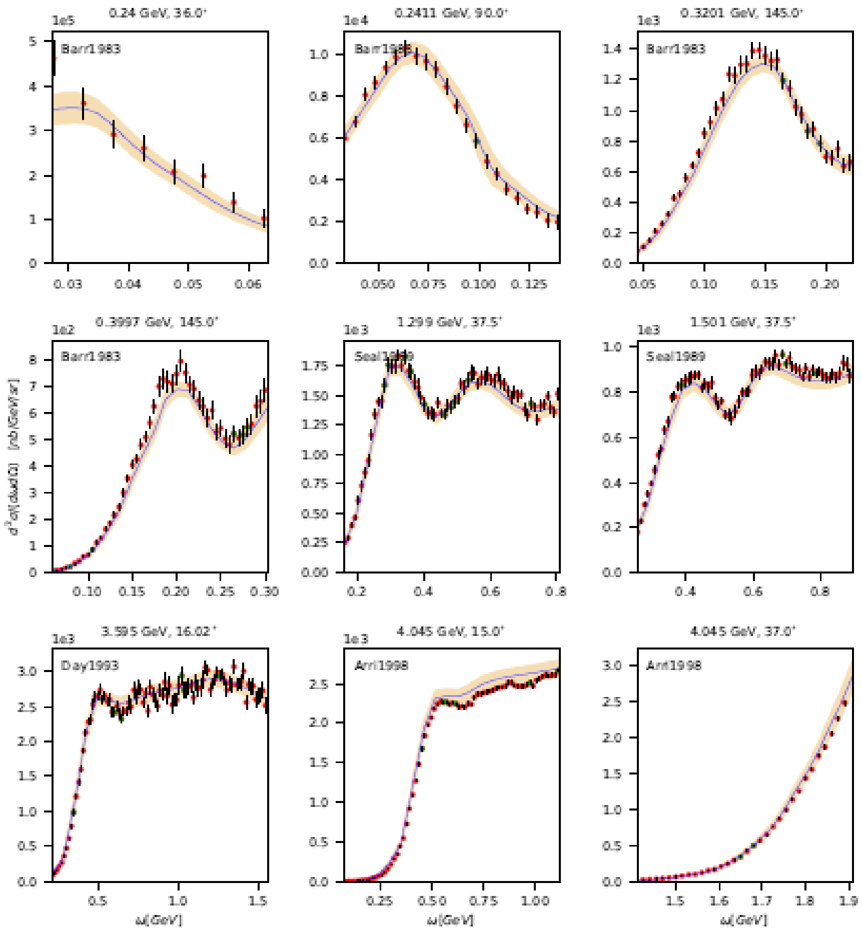


Alejandro Mariano

Model A (bootstrap)



Model B (MC dropout)



Krzysztof Graczyk

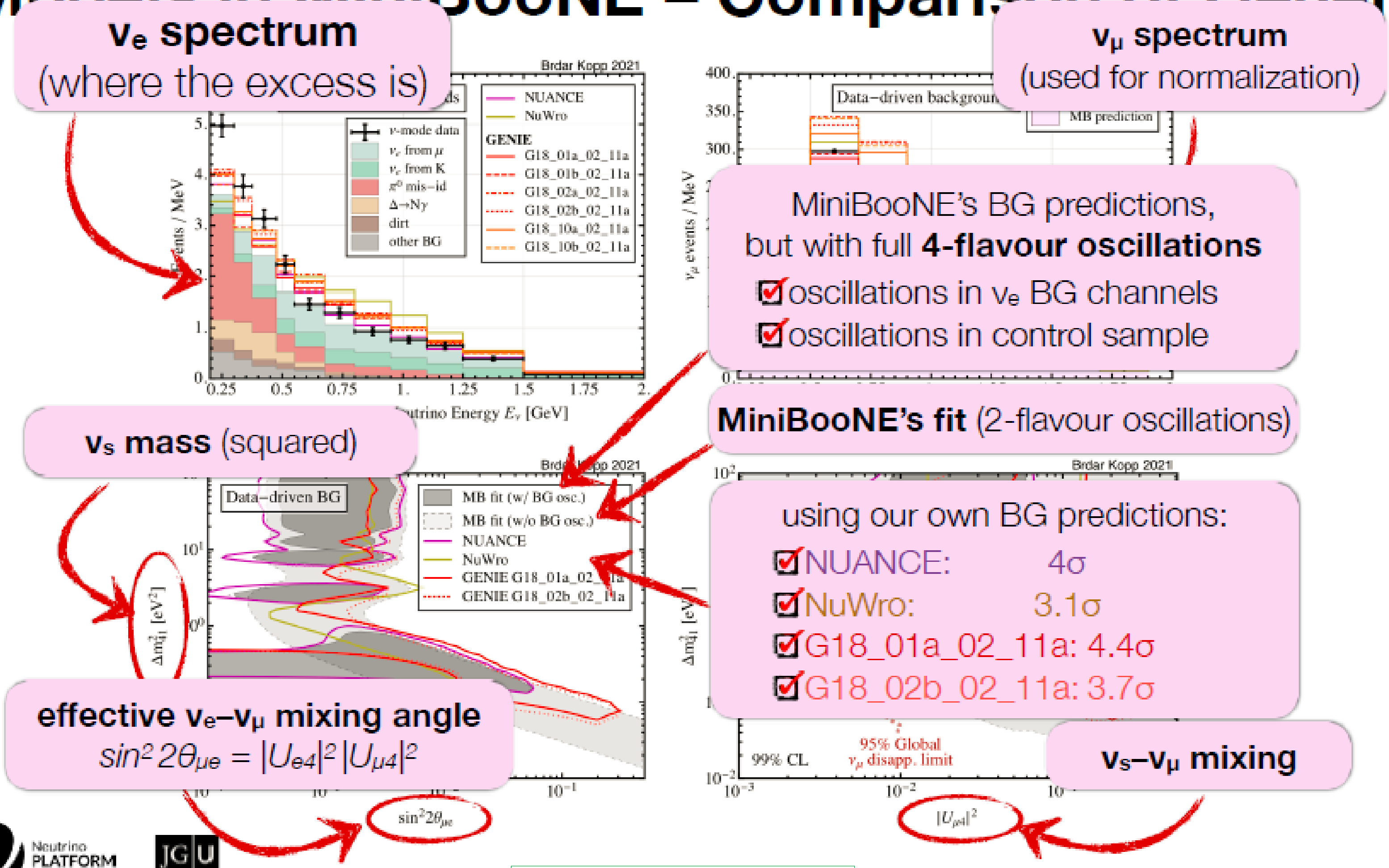
https://github.com/bekowal/CarbonElectronNeuralNetwork

Consistency of the data normalization

Abbrev.	Norm. uncert.	model A λ_k	model B $\lambda_k(p = 0.01)$
Arri1995	4.0%	1.01	1.02
Arri1998	4.0%	1.00	0.96
Bagd1988	10.0%	1.03	1.06
Bara1988	3.7%	1.01	0.98
Barr1983	2.0%	0.99	1.02
Dai2018	2.2%	1.00	0.97
Day1993	3.4%	0.99	0.98
Fomi2010	4.0%	1.01	0.96
O'Con1987	5.0%	1.02	1.01
Seal1989	2.5%	1.02	1.04
Whit1974	3.0%	0.93	0.93

- A tension between Whit1974 and the rest of datasets?

3+1 Models in MiniBooNE – Comparison of Generators



High-energy studies

- Alfonso Andres Garcia Soto: High-energy neutrino-matter interaction cross-sections in neutrino event generators

- Farhana Zaidi: Nuclear medium effects in ν_τ-A scattering at DUNE energies

- Jorge Morfin: The Physics of SIS – target mass correction and higher twist

- Yu Seon Jeong: Neutrino Cross Sections for collider neutrinos

Summary

- The success of the neutrino-oscillation program (DUNE and Hyper-Kamiokande) requires reliable cross sections.
  - ➔ **The requirement for precision will steadily increase.**
- Theory and generator developments needed for many years to come.
- Plenty of new experimental data need to be understood.
  - ➔ **We need to grow as a community to meet the demands of the oscillation program and ensure its full potential is realized.**

Our needs

- Inclusive and exclusive cross sections for electron scattering on nuclear targets, especially argon and oxygen. Both data and theory predictions.
  - Neutron multiplicities and spectra for argon. Proton knockout from titanium may be a simple way forward.
- The transition from resonance production to deep-inelastic scattering requires our attention. The problem is challenging, particularly relevant for DUNE.
- More efficient theory implementation in Monte Carlo generators.
- New measurements from the short-baseline program will shed new light on intranuclear cascades. Expect the unexpected!
- Uncertainties and regions of validity for the theory predictions.


Thank you!