NuFACT 2018

WG2 [Neutrino Scattering Physics] Summary

Vishvas Pandey (Virginia Tech)

Natalie Jachowicz (UGhent), Alessandro Lovato (ANL), Kajetan Niewczas (UGhent), Gabriel Perdue (FNAL), Luke Pickering (MSU)

NuFACT 2018, The 20th International Workshop on Neutrinos from Accelerators, August 12-18, 2018

Lots of interesting talk, exciting results, and fruitful discussion

- Total 23 talks = 8 Theory + 12 Experimental + 3 Generator

- I will try to cover as many of them as possible, apologies for the ones I am not able to cover. Please check them out – they are all vital and interesting!

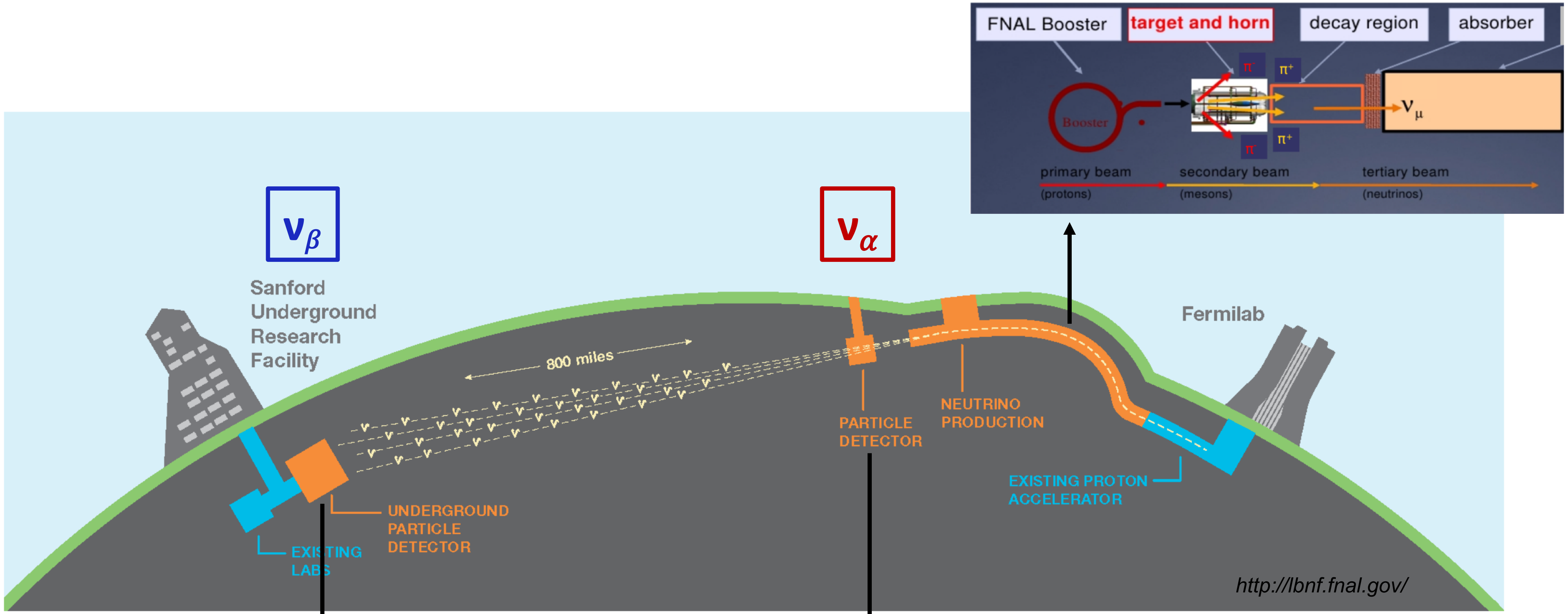
- Some of my comments/remarks will be subjective and are not immune to my biases and ignorance.

A quick recap of the focus of WG2

Many experiments at Intensity Frontier: Many goals to look for precision and new physics

- Long-Baseline Neutrino Experiments: **DUNE, NOvA, T2K**
- Short-Baseline Neutrino Experiments: **SBND, MicroBooNE, ICARUS**
- Scattering Experiments: **MINERvA, CAPTAIN, LArIAT**
- ....

An example of long-baseline neutrino experiment: DUNE



Oscillation Probability*:

$$P(\nu_\alpha \to \nu_\beta) \simeq \sin^2 2\theta \sin^2\left(\frac{\Delta m^2 L}{4E}\right)$$

two neutrino flavors, for simplicity

Event Rate at near detector:

$$N^{\alpha}_{\mathrm{ND}}(\boldsymbol{p}_{\mathrm{reco}}) = \sum_i \phi_\alpha(E_{\mathrm{true}}) \times \sigma^i_\alpha(\boldsymbol{p}_{\mathrm{true}}) \times \epsilon_\alpha(\boldsymbol{p}_{\mathrm{true}}) \times R_i(\boldsymbol{p}_{\mathrm{true}}; \boldsymbol{p}_{\mathrm{reco}})$$

Event Rate at far detector:

$$N^{\alpha\to\beta}_{\mathrm{FD}}(\boldsymbol{p}_{\mathrm{reco}}) = \sum_i \phi_\alpha(E_{\mathrm{true}}) \times P_{\alpha\beta}(E_{\mathrm{true}}) \times \sigma^i_\beta(\boldsymbol{p}_{\mathrm{true}}) \times \epsilon_\beta(\boldsymbol{p}_{\mathrm{true}}) \times R_i(\boldsymbol{p}_{\mathrm{true}}; \boldsymbol{p}_{\mathrm{reco}})$$

Prog. Part. Nucl. Phys. 100, 1 (2018)

- Can we extract the oscillation probability by taking the ratio of far to near detectors?

$$\frac{N_{\mathrm{FD}}^{\alpha\to\beta}(\boldsymbol{p}_{\mathrm{reco}}) = \sum_i \phi_\alpha(E_{\mathrm{true}}) \times P_{\alpha\beta}(E_{\mathrm{true}}) \times \sigma_\beta^i(\boldsymbol{p}_{\mathrm{true}}) \times \epsilon_\beta(\boldsymbol{p}_{\mathrm{true}}) \times R_i(\boldsymbol{p}_{\mathrm{true}}; \boldsymbol{p}_{\mathrm{reco}})}{N_{\mathrm{ND}}^{\alpha}(\boldsymbol{p}_{\mathrm{reco}}) = \sum_i \phi_\alpha(E_{\mathrm{true}}) \times \sigma_\alpha^i(\boldsymbol{p}_{\mathrm{true}}) \times \epsilon_\alpha(\boldsymbol{p}_{\mathrm{true}}) \times R_i(\boldsymbol{p}_{\mathrm{true}}; \boldsymbol{p}_{\mathrm{reco}})}$$

- Even for an ideal case of identical near and far detector and in the absence of any geometric or oscillation-induced differences between near and far fluxes - the ratio neither cancels out cross section dependencies nor reduces the problem into a simple rescaling.
  - The neutrino flavor at near and far detector are different (appearance experiment).
  - The neutrino flux and neutrino-nucleus cross sections are convoluted.

- In fact, it is not clear, how to interpret the ratio - what can be constrained with the ratio? How reliable extrapolations from near to far detector are?

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Main Goal of WG2 → The convolution $\boxed{\phi_\alpha \times \sigma^i_{\alpha/\beta}}$ for different neutrino flavors and different interaction types.

The (difficult) task in hand

Theory side*

- Description of the initial state of nucleus, covering known nuclear effects, e.g. correlatations, etc. Plus, this for many nuclei 12C, 16O, 40Ar, ….., etc.

- Description of electroweak response of the nucleus for different kinematics that cover, Giant-resonance, QE, dip-region, delta production, SIS and DIS region – in a coherently consistent way (reminder: quantum mechanism).

- Resulting into final states where outgoing particle and their energies are subject to be altered by FSI.

- For different neutrino flavours – ν_e , ν_μ

Experimental and Generator side*

- Observed final state topologies and their energies (altered by detector limitations) and *affected by physics in generators* which enters in not only by linking observed final states to interaction vertex but also affects the estimation of efficiencies, acceptances, background, etc.

- CCInclusice, CC0pi, CCpi0, CCpi+, ….., NC0pi, …….., etc.

** Not an exhaustive list.*

- This topic was also at the focus of *Round Table Discussion on Tuesday* – how to a create structure to bring nuclear theorists, neutrino experimentalist, and generator developer together.
- NuSTEC has been successful in creating a community service based collaboration.
- **But solving these issues require proper structure (changes) specially in terms of supporting nuclear theorists, who are more likely not funded to perform neutrino scattering calculations.**

Neutrino Scattering Theory Experiment Collaboration (NuSTEC) : http://nustec.fnal.gov

Collaboration of NP/HEP theorists, generator experts and ν experimentalists

- THEORISTS
- Luis Alvarez Ruso (co-spokesperson)
- Sajjad Athar
- Maria Barbaro
- Omar Benhar
- Richard Hill
- Patrick Huber
- Natalie Jachowicz
- Andreas Kronfeld
- Marco Martini
- Toru Sato
- Rocco Schiavilla
- Jan Sobczyk **(nuWRO)**

- EXPERIMENTALISTS
- Sara Bolognesi
- (Steve Brice)
- Raquel Castillo
- Dan Cherdack
- Steve Dytman **(GENIE)**
- Andy Furmanski
- Yoshinari Hayato **(NEUT)**
- Teppei Katori
- Kendall Mahn
- Camillo Mariani
- Jorge G. Morfín (co-spokesperson)
- (Ornella Palamara)
- Jon Paley
- Roberto Petti
- Gabe Perdue **(GENIE)**
- Federico Sanchez
- (Sam Zeller)

( ) indicates advisor

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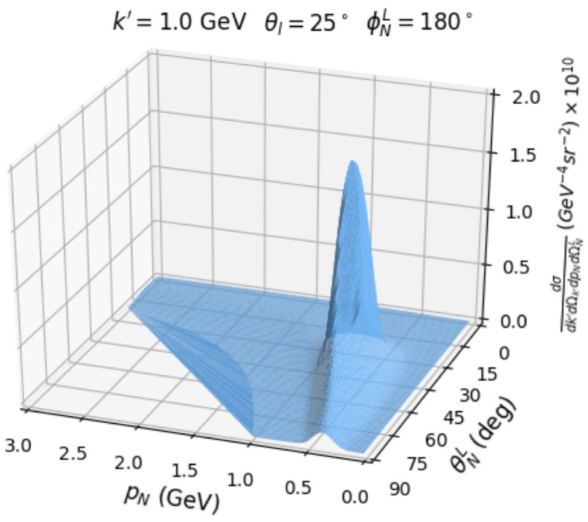
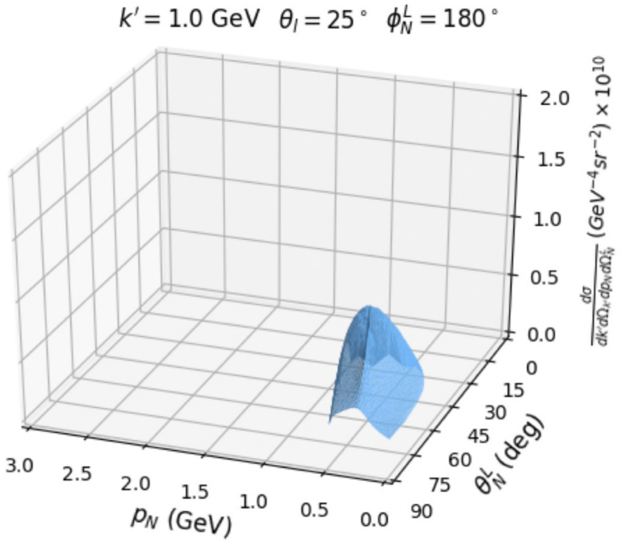
Slide from J. G. Morfín

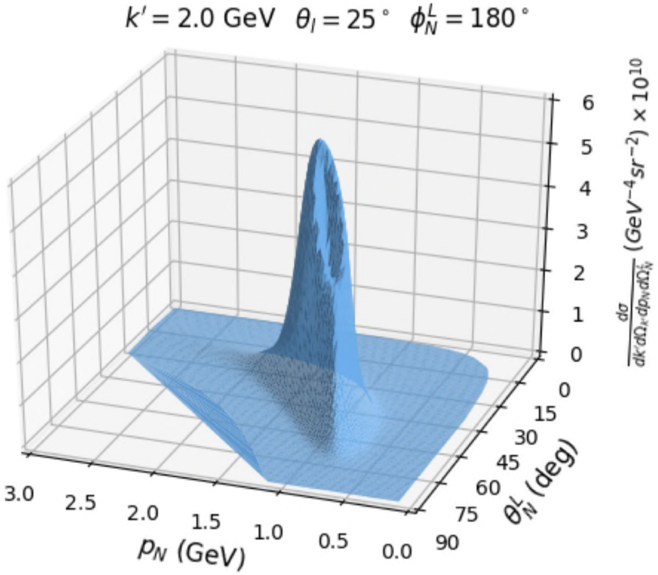
J. W. Van Orden

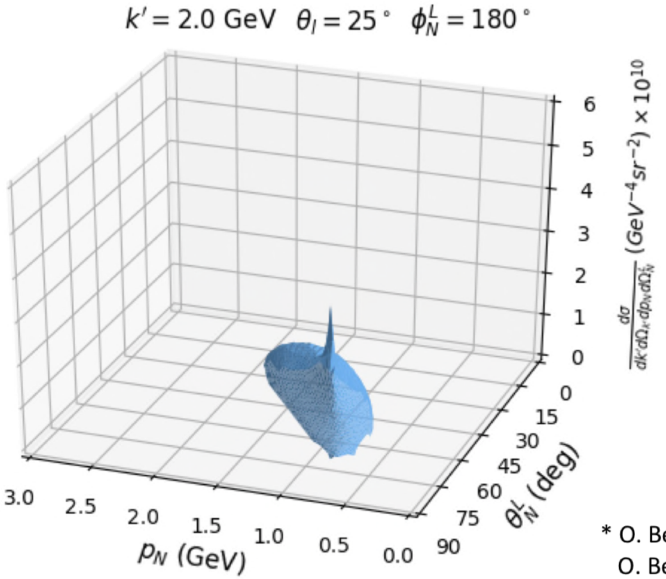
Spectral Function*

Local Density Spectral Function









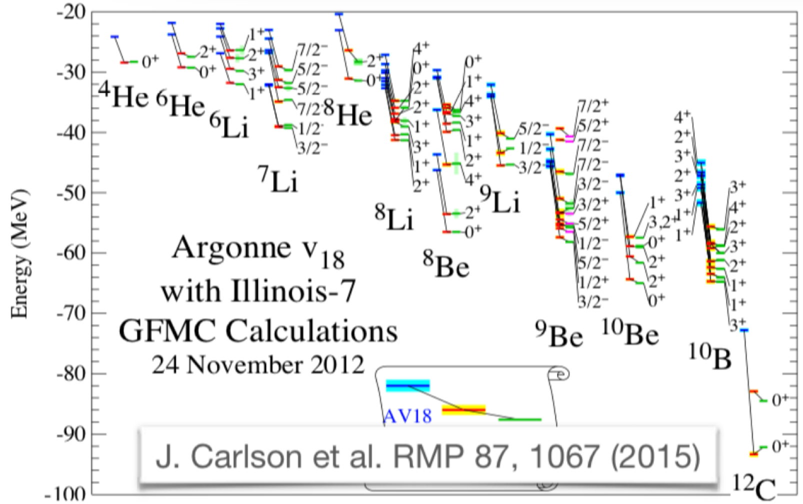
- Models that appear to fit inclusive cross sections may disagree significantly in predicting semi-inclusive cross sections.

* O. Benhar, A. Fabrocini, S. Fantoni, and I. Sick, Nucl. Phys. A579, 493 (1994).
O. Benhar, N. Farina, H. Nakamura, M. Sakuda, and R.Seki, Phys. Rev. D 72, 053005 (2005).

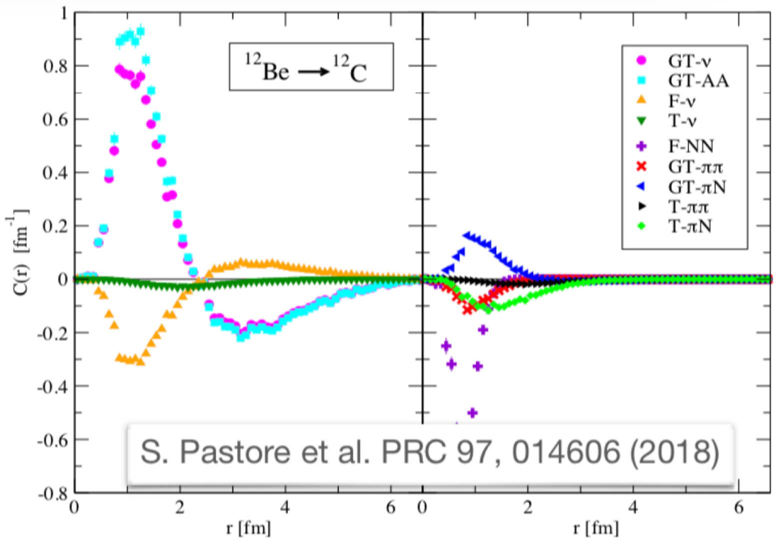
The *basic model* of nuclear Physics

A. Lovato

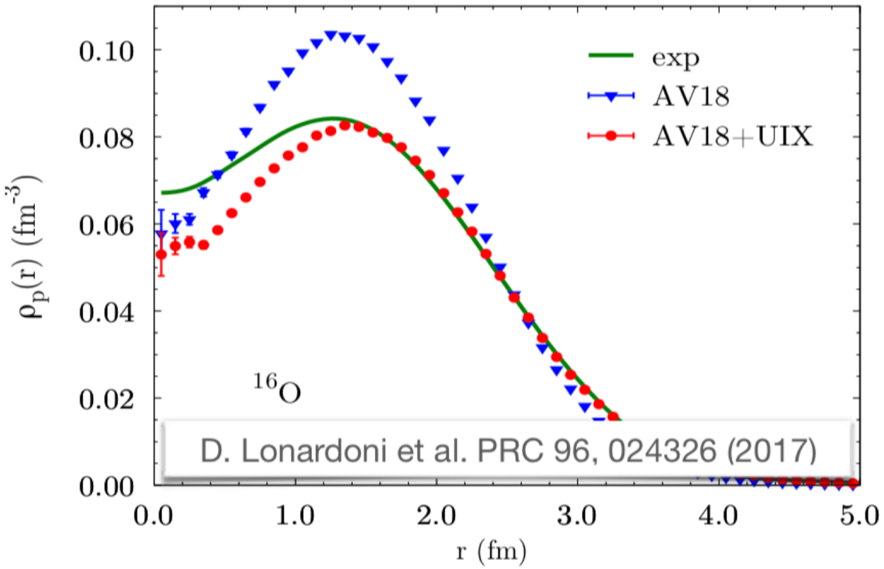
Nuclear effective field theories + Nuclear ab-initio methods



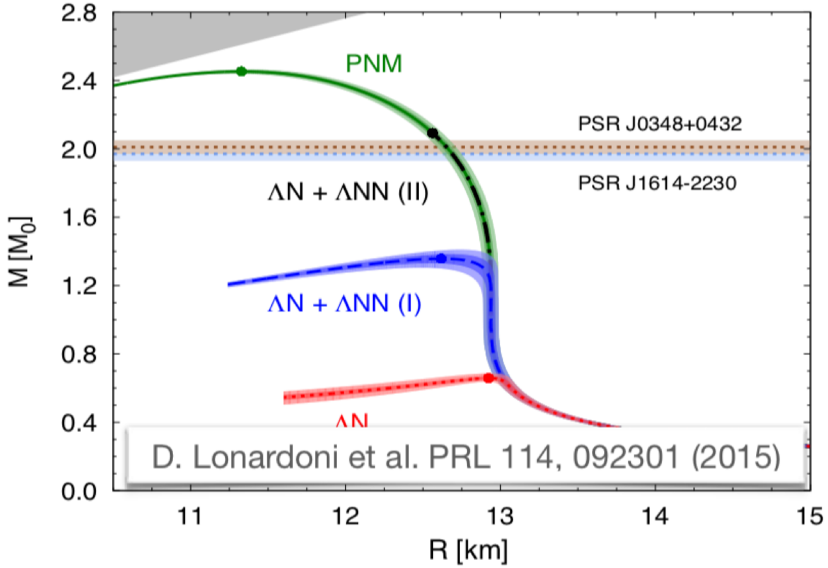
J. Carlson et al. RMP 87, 1067 (2015)



S. Pastore et al. PRC 97, 014606 (2018)



D. Lonardoni et al. PRC 96, 024326 (2017)

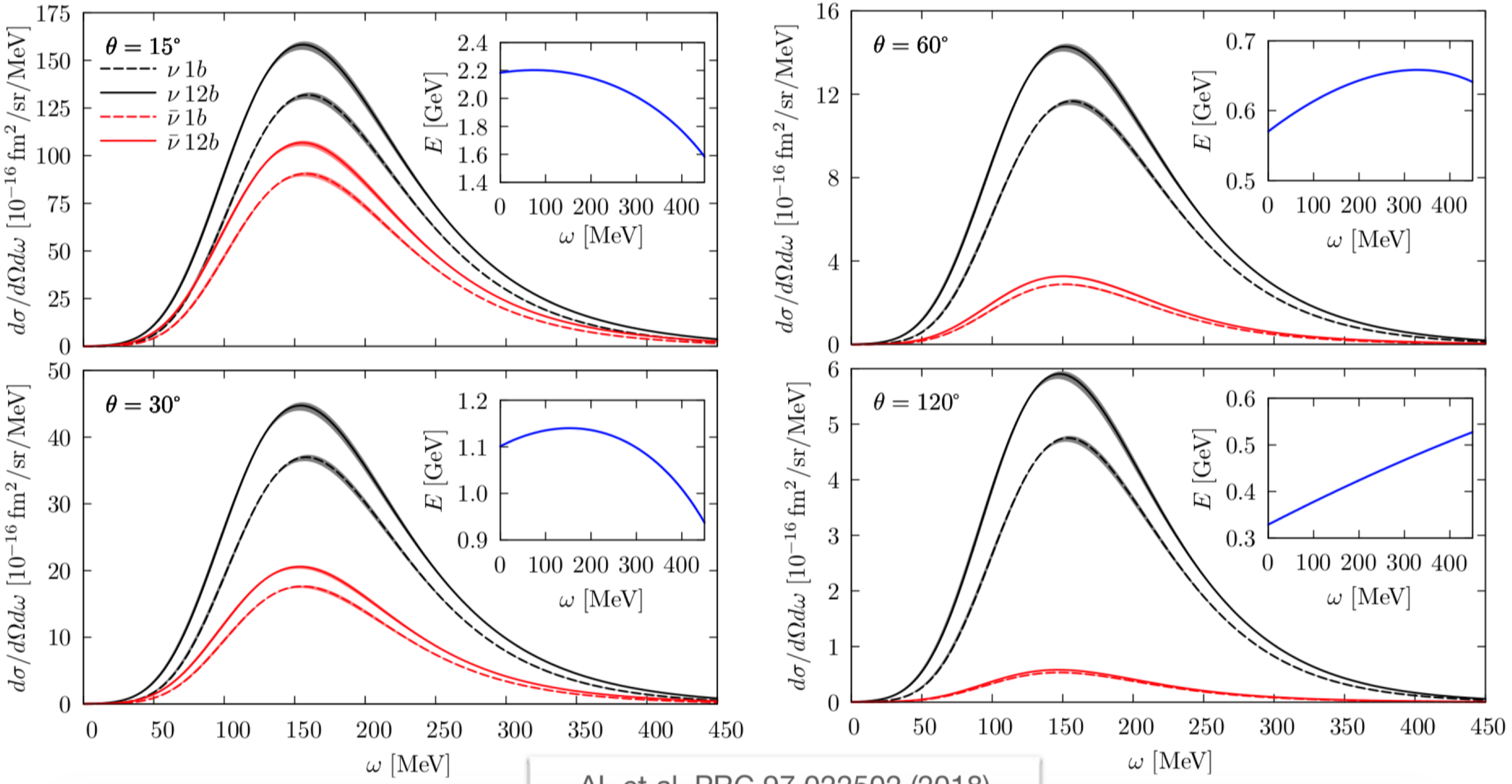


D. Lonardoni et al. PRL 114, 092301 (2015)

A. Lovato

^{12}C neutral-current cross-section

- We computed the neutrino and anti-neutrino differential cross sections for a fixed value of the three-momentum transfer as function of the energy transfer for a number of scattering angles

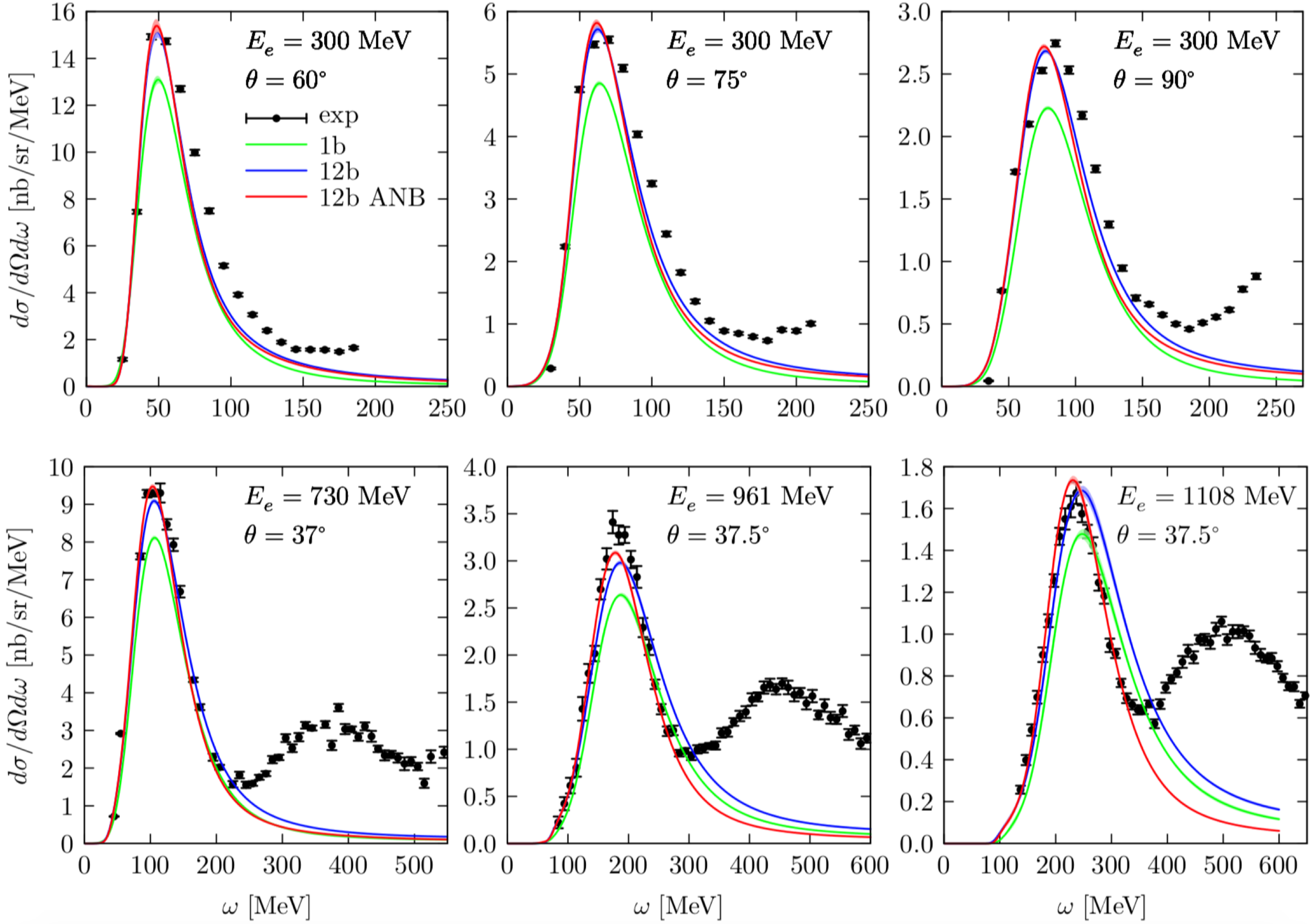


AL et al. PRC 97 022502 (2018)

N. Rocco et al. PRC 97 055501(2018)

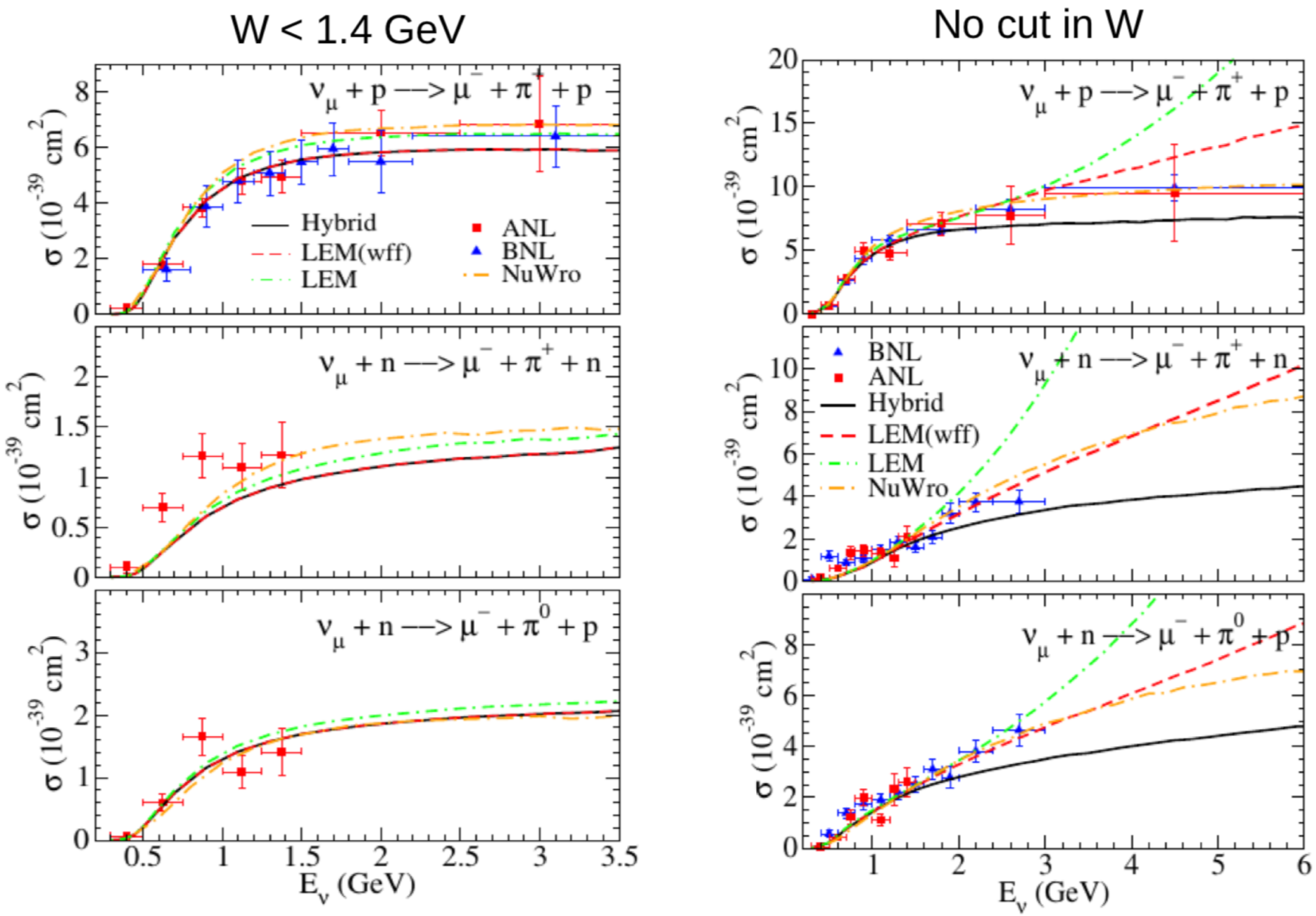
A. Lovato

Relativistic effects in a correlated system

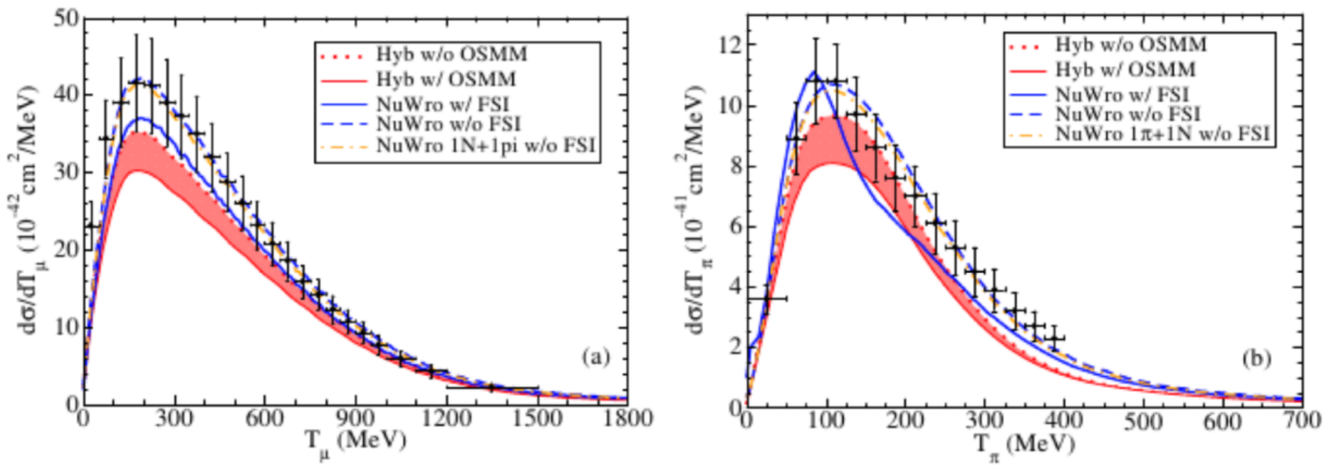


R. González Jiménez

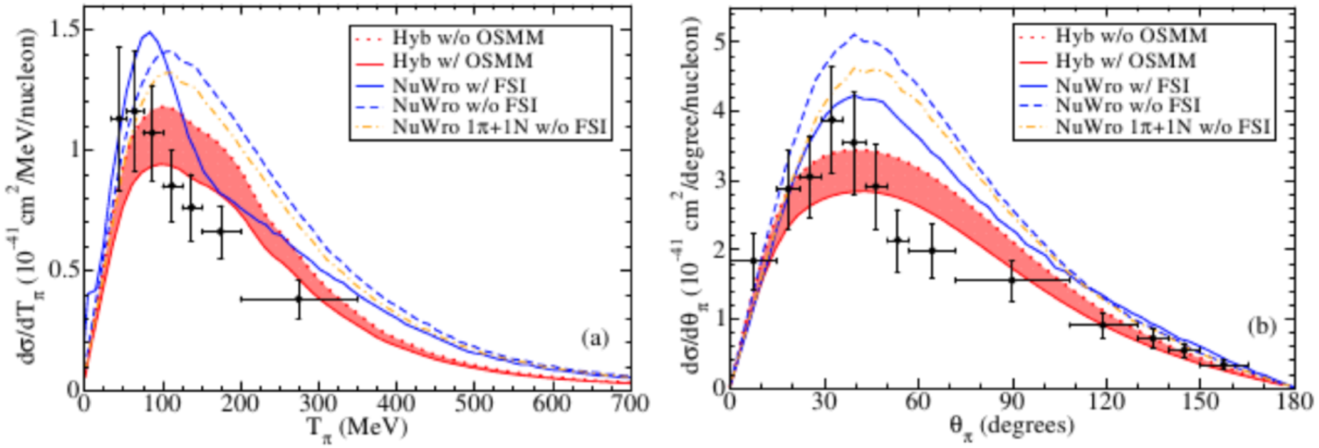
Hybrid model: results



MiniBooNE neutrino CC 1pion+.



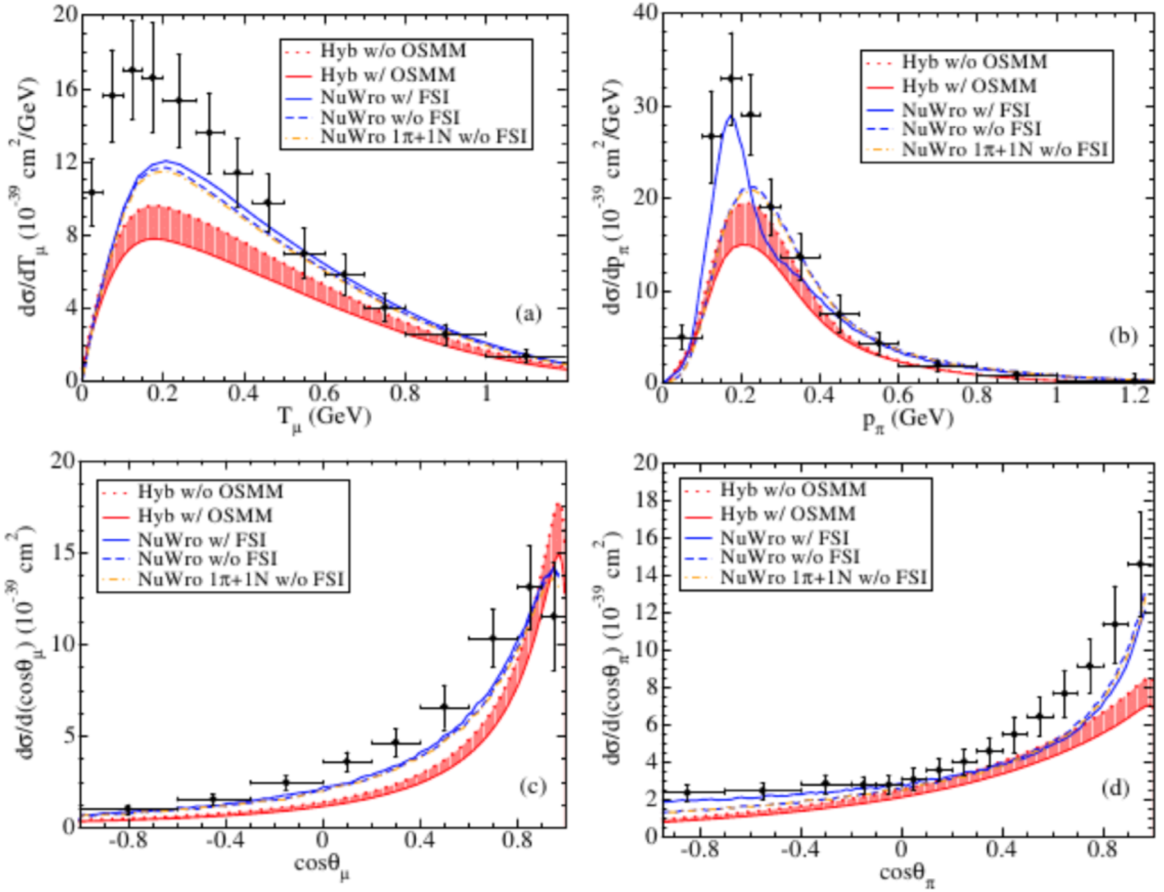
MINERvA neutrino CC 1pion+.



PRD 97, 013004 (2018)

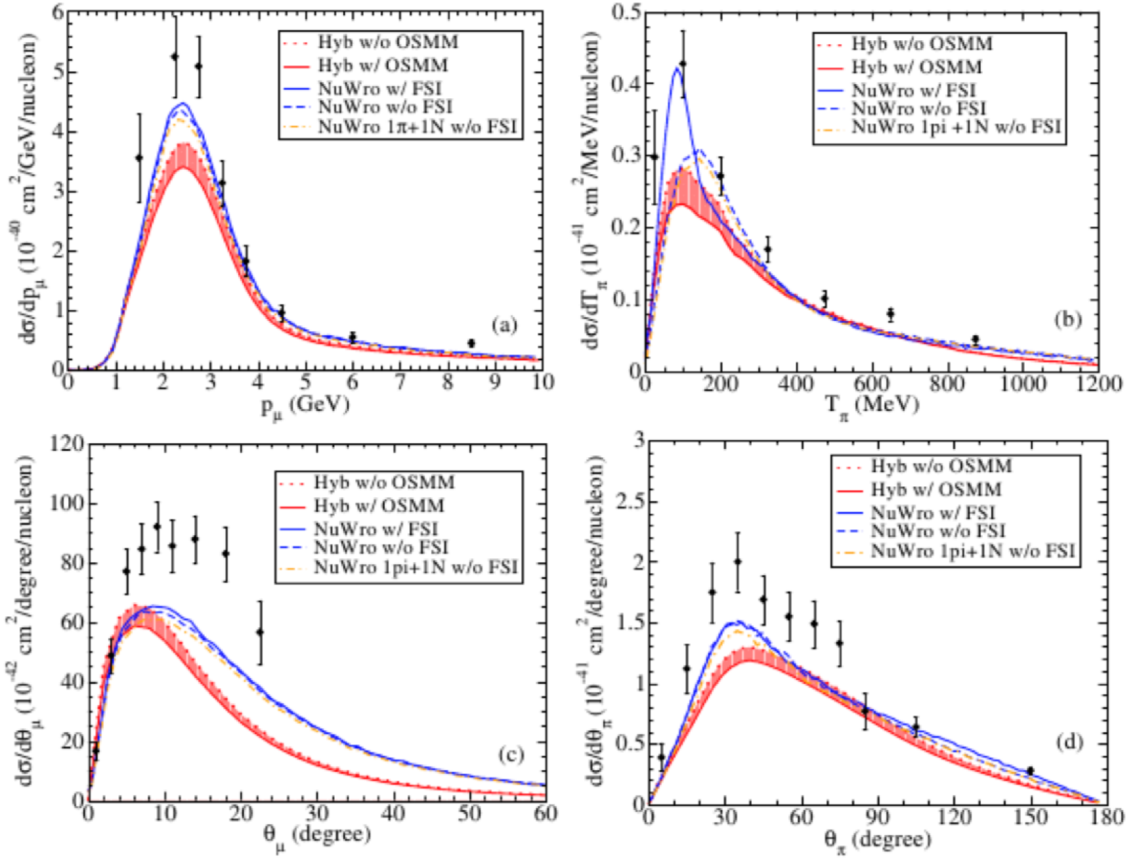
R. González Jiménez

MiniBooNE neutrino CC 1pion0.



PRD 97, 013004 (2018)

MINERvA neutrino CC 1pion0.



PRD 97, 013004 (2018)

Vector Form Factor from Lattice QCD

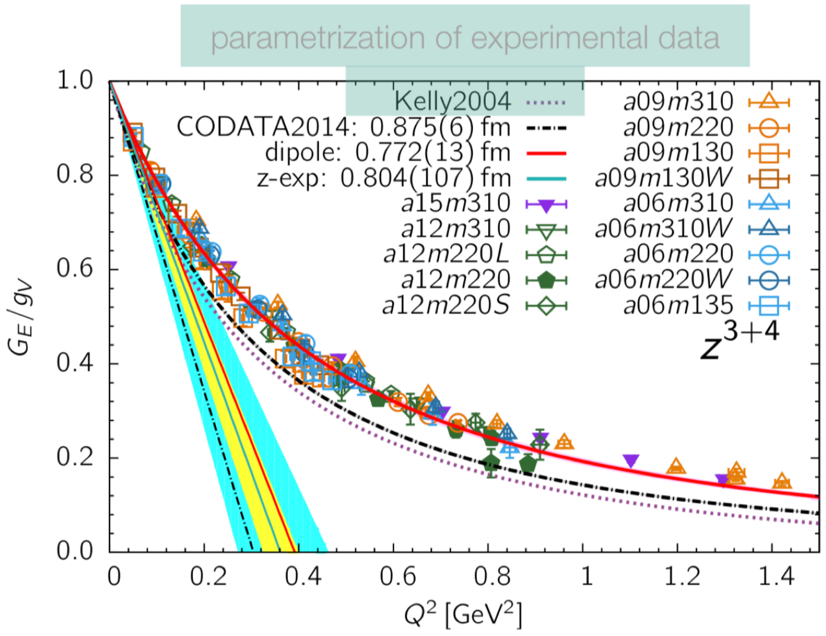
- Lattice QCD too high?
- Even continuum limit:

  $r_E = 0.80(11)$ fm,

  vs CODATA:

  $r_E = 0.875(6)$ fm.

- $G_E = F_1 - Q^2 F_2/M^2$.



Axial Form Factor from Lattice QCD

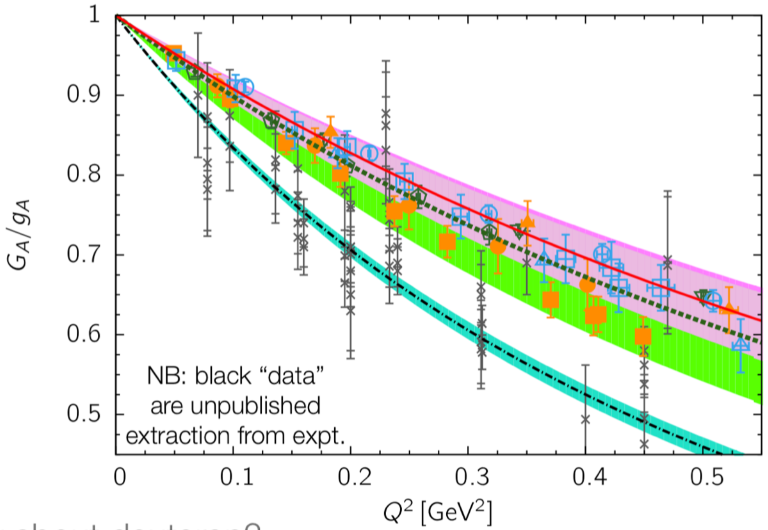
- Gupta, Jang, Lin, Yoon, Bhattacharya (PNDME) [arXiv:1705.06834]:
- $a \neq 0$ slope smaller than deuterium & other data.
- Even continuum limit:

  $r_A = 0.46(6)$ fm,

  vs Meyer *et al.*:

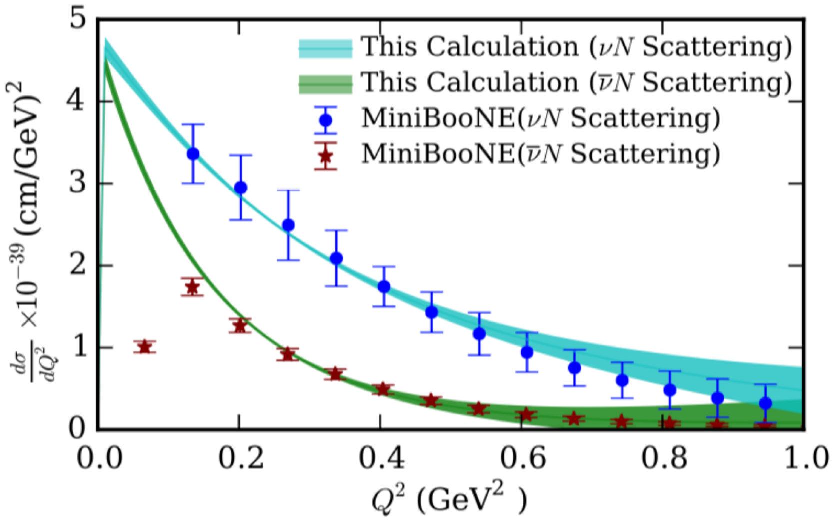
  $r_A = 0.68(16)$ fm.

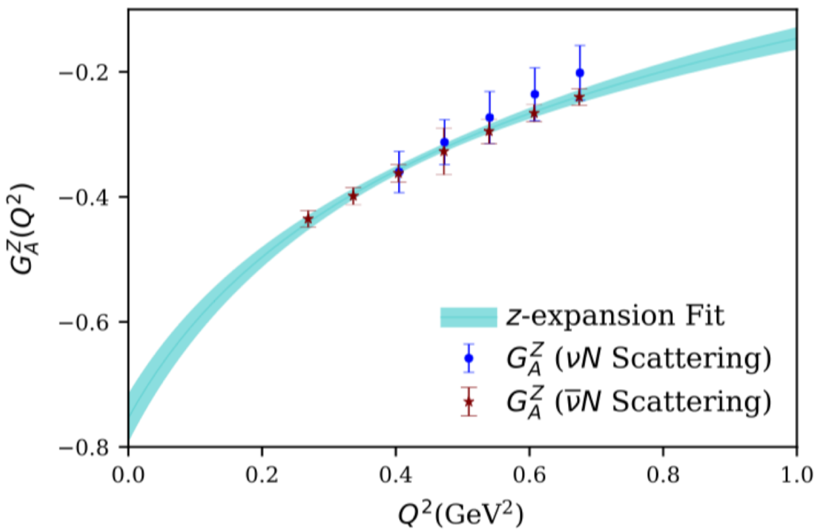
- What would 0.46 fm say about deuteron?



Neutrino Phenomenology

- Pragmatic inputs:
  - vector form factors from ep scattering (z parametrization) [Ye *et al.*, arXiv:1707.09063];
  - $s\bar{s}$ form factor from lattice QCD [χQCD, arXiv:1705.05849];
  - extract $F_A(Q^2(z))$ from MiniBooNE;
  - compare with BNL E734.
- Sufian, Liu, Richards, Lattice 2018.





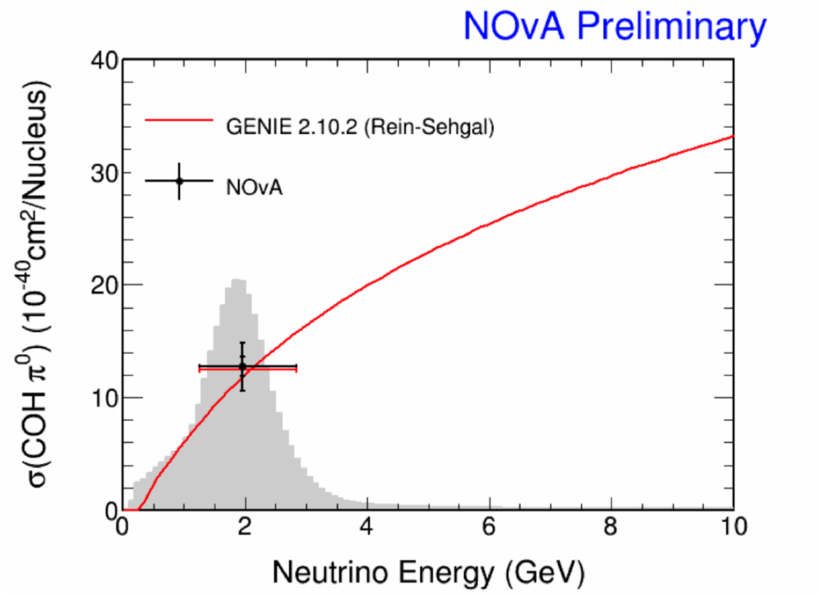
Current NOvA Cross Section Analyses

M. Judah

- CC Inclusive
  - Muon neutrino
  - Electron neutrino
- CC muon neutrino semi-[ex,in]clusive
  - Charged Pion
  - Zero Pion
  - 2p2h
  - Neutral Pion ← Results
- NC
  - Coherent Neutral Pion ← Results
  - Inclusive Neutral Pion
- Others
  - Neutrino-on-electron
  - Booster neutrino at NOvA

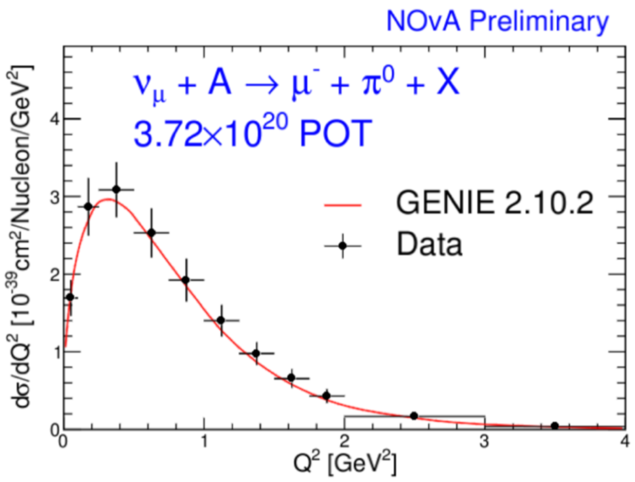
NC Coherent π^0 Results

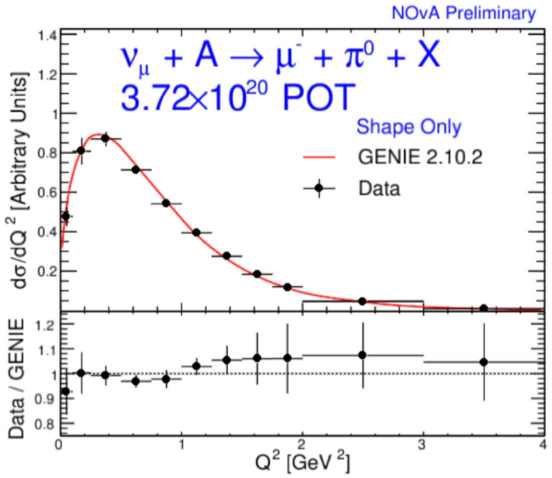
M. Judah



Source	$\delta(\%)$
Calorimetric Energy Scale	3.4
Background Modeling	10.0
Control Sample Selection	2.9
EM Shower Modeling	1.1
Coherent Modeling	3.7
Rock Event	2.4
Alignment	2.0
Flux	9.4
Total Systematics	15.3
Signal Sample Statistics	5.3
Control Sample Statistics	4.1
Total Uncertainty	16.7

Differential Cross Section - Q^2





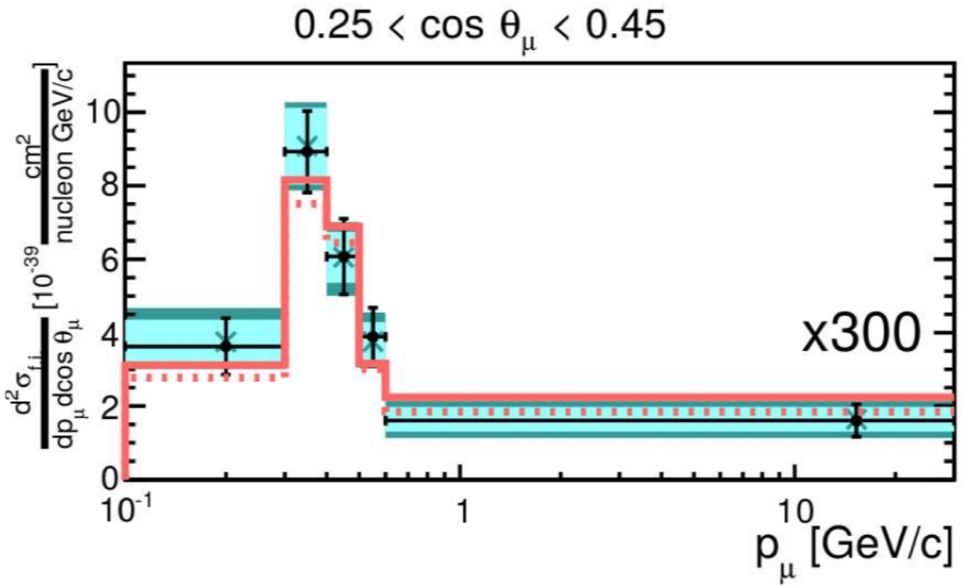
- Measured cross section is 7% higher than GENIE prediction
- Data suggests a slightly harder Q^2 shape than predicted by GENIE

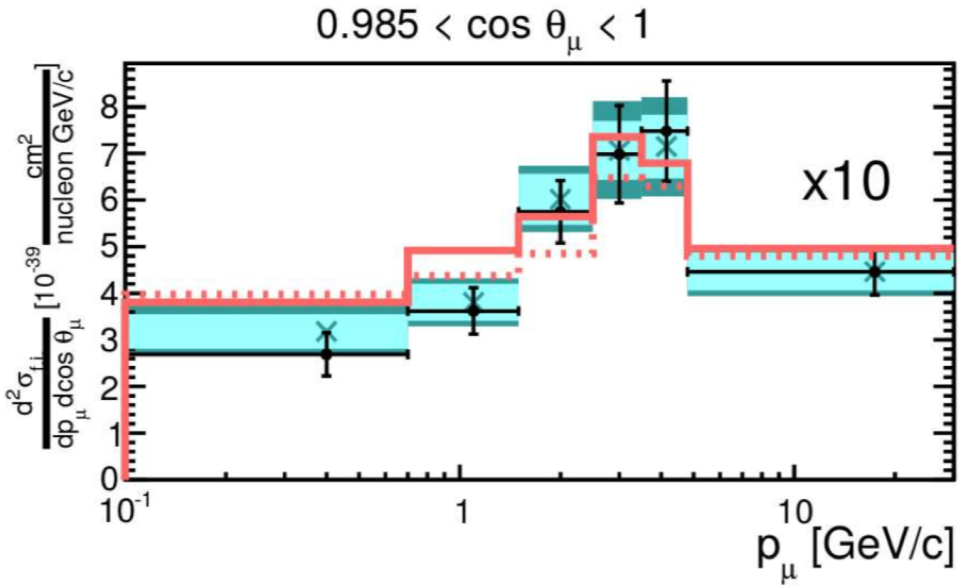
CC-inclusive

A. Garcia

C. Wret

- Consistent differences between NEUT 5.3.2 and GENIE 2.8.0 throughout the phase space: roughly normalisation





- Expanded selection possible in future 0 and 1π analyses: on towards exclusive channels!
- Being incorporated into the ND280 fitting for OA
  - *Details of the T2K oscillation analyses*, D. Sgalaberna, Thu. 2.30pm

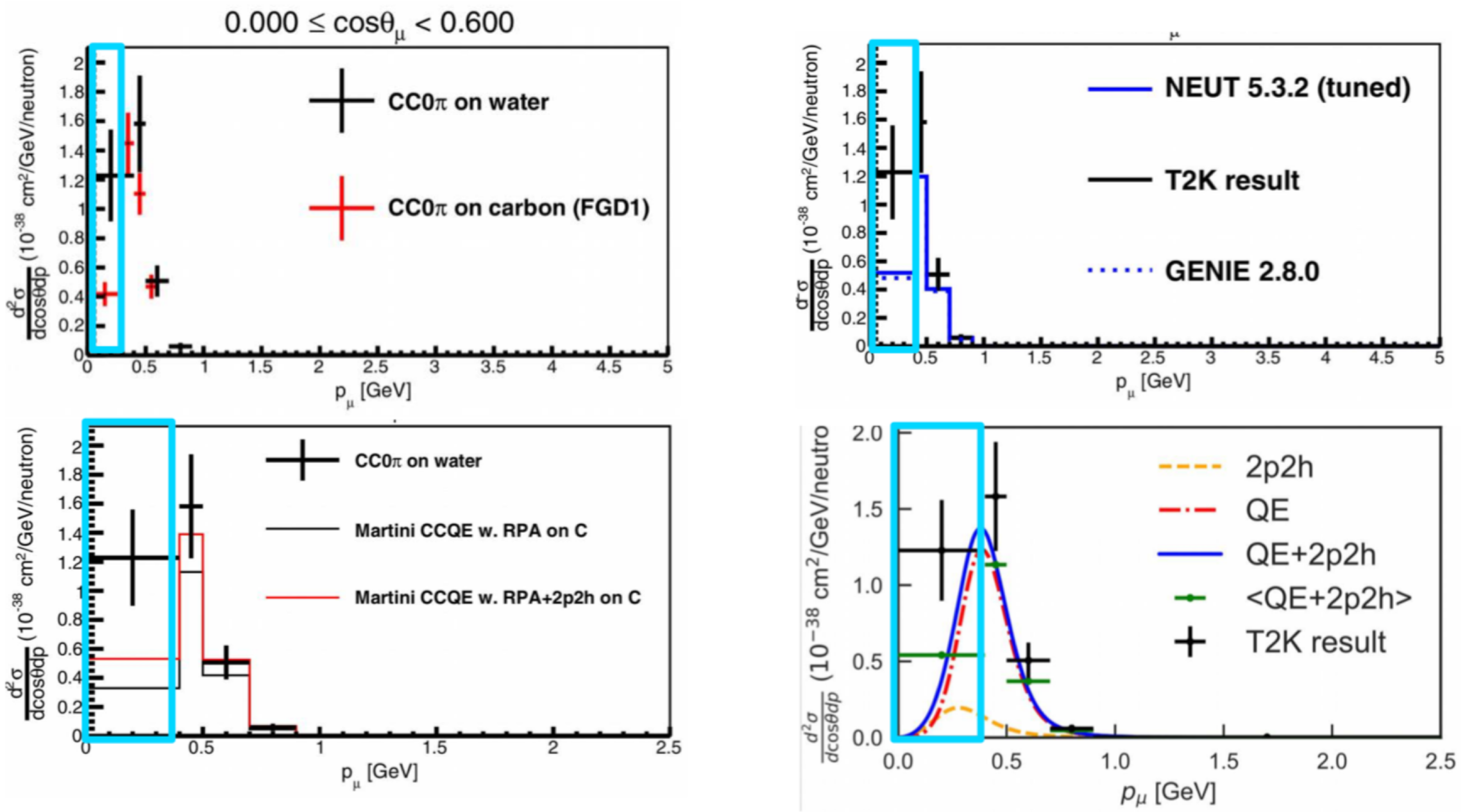
PRD93 112012
PRD97 012001

CC0π

S. Bolognesi, A. Furmanski, T. Campbell, T. Yuan

C. Wret

- Previous result on FGD1 C_8H_8 compared to first H_2O measurement
- C_8H_8 vs H_2O is crucial systematic for T2K ND280 → SK propagation



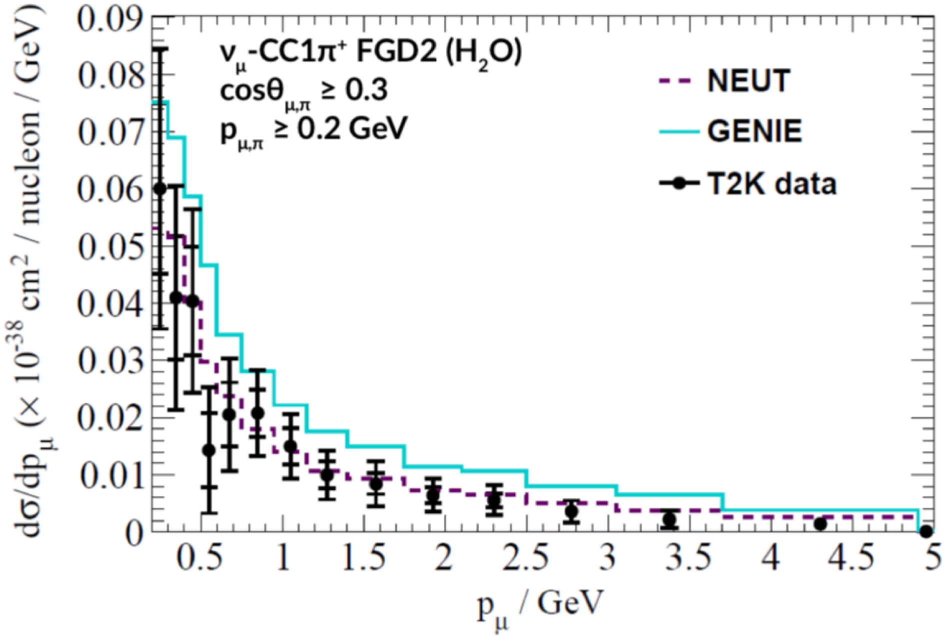
- Low momentum, high angle region under-predicted throughout
  - Region of largest difference between water and carbon: nuclear effect?
- Complimentary anti-ν_μ cross section, coming to arxiv

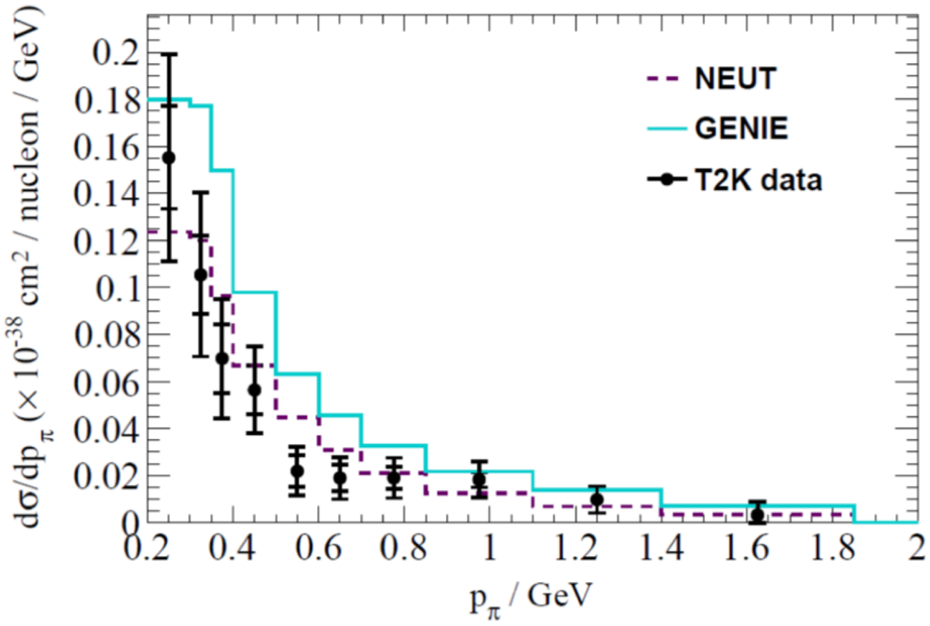
CC1π±

L. Cremonesi, J. Schwehr, M. Hogan, D. Cherdack

C. Wret

- Important background for T2K oscillation (signal at NOvA and DUNE)
  - Nuclear model less tested with 1π data; clever analyses needed!
- CC1π+ H_2O FGD2 analysis saw too large GENIE cross section
  - Low statistics limits the power of the data: next analyses doubles

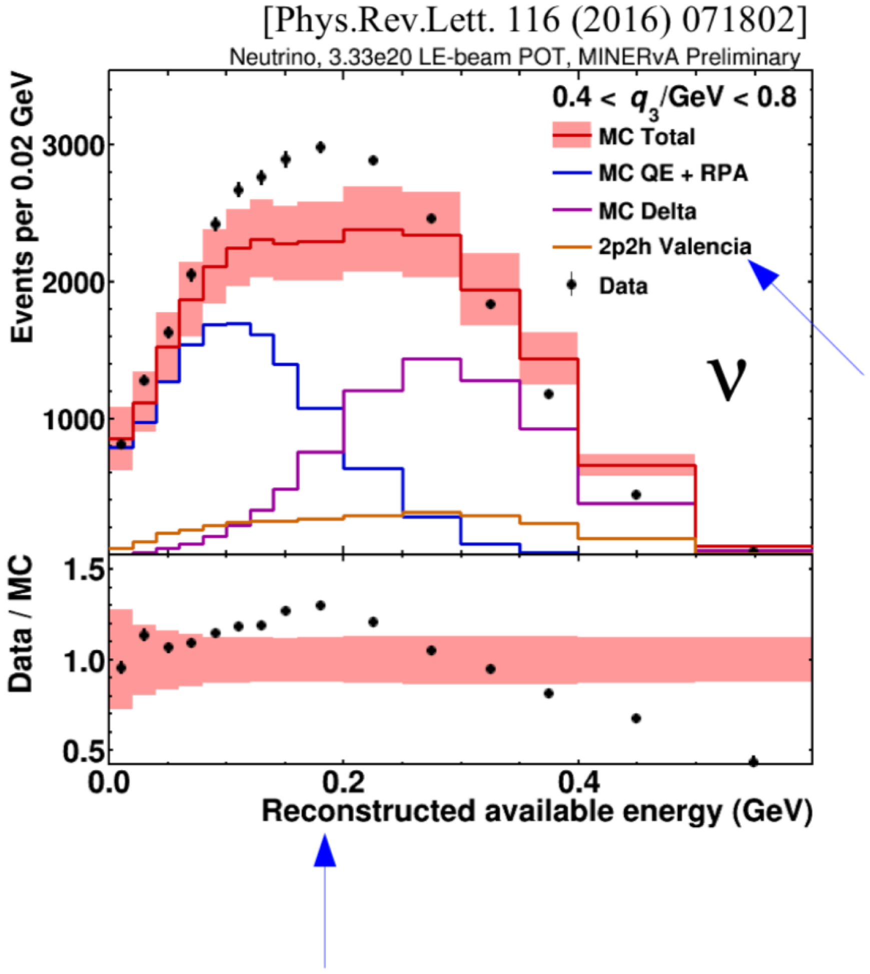


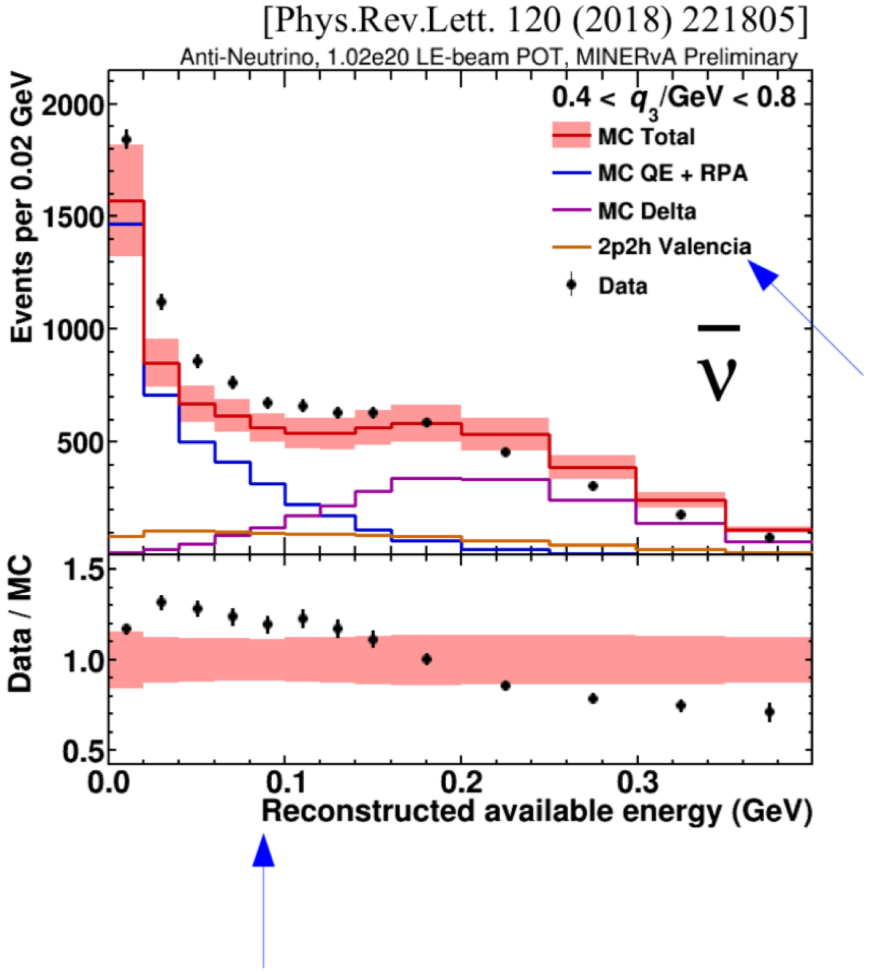


- Complementary selection on P0D, coming to arxiv
  - Different detector with larger statistics and acceptance
  - P0D fiducial target (not H_2O only)

2p2h-*like* Enhancement

X. Lu



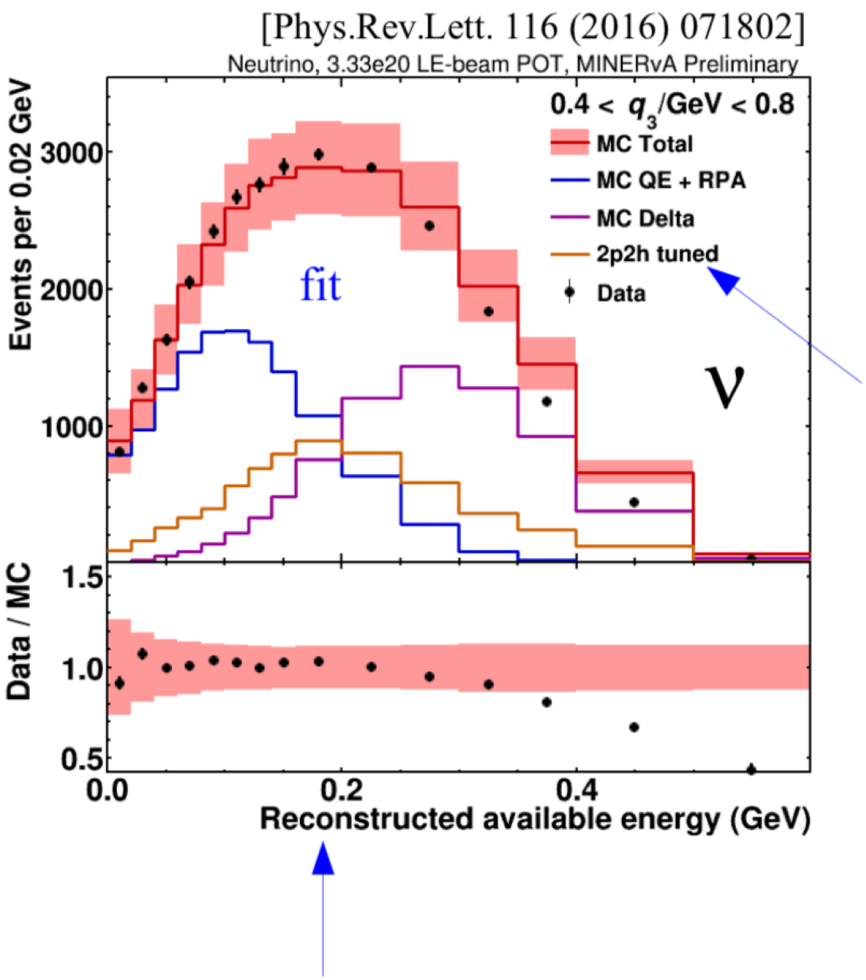


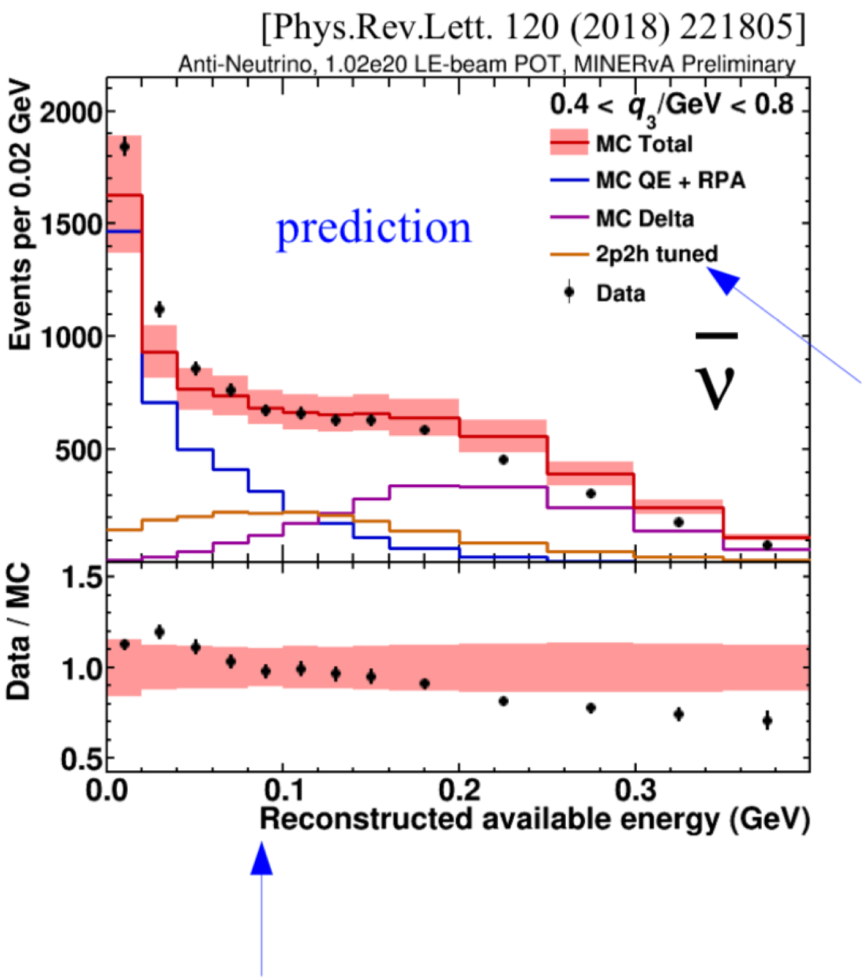
- QE and RES are separated
- With base model, large model deficit seen at intermediate available energy between QE and RES

base model: GENIE + RPA + Valencia 2p2h [Phys. Rev. C 83, 045501, Phys. Rev. D 88, 113007, arXiv:1705.02932]

2p2h-*like* Enhancement

X. Lu

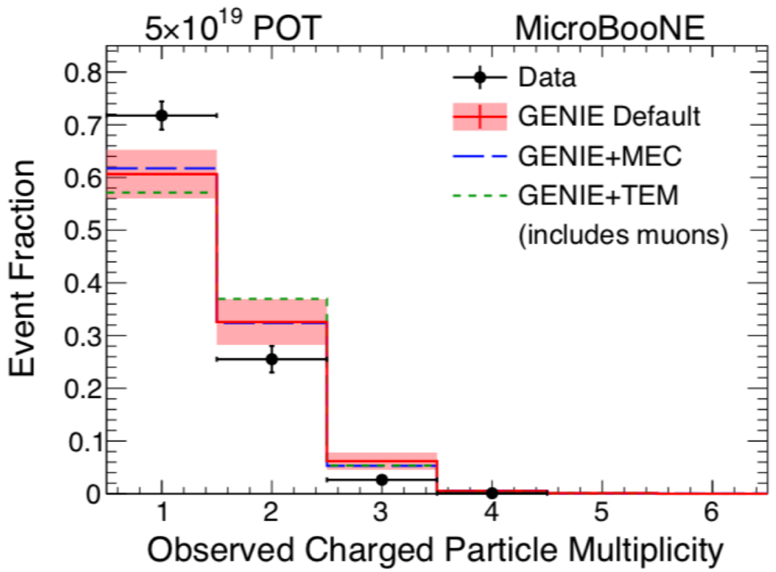




- Weight up 2p2h events (by choice) to match ν data.
  - Resulting tuned model: 50% increase in overall size, 2× in dip region.
- Tuned model *predicts* $\bar{\nu}$ data well.
  - Such 2p2h-*like* enhancement is universal.

Charged Particle Multiplicity(CPM)

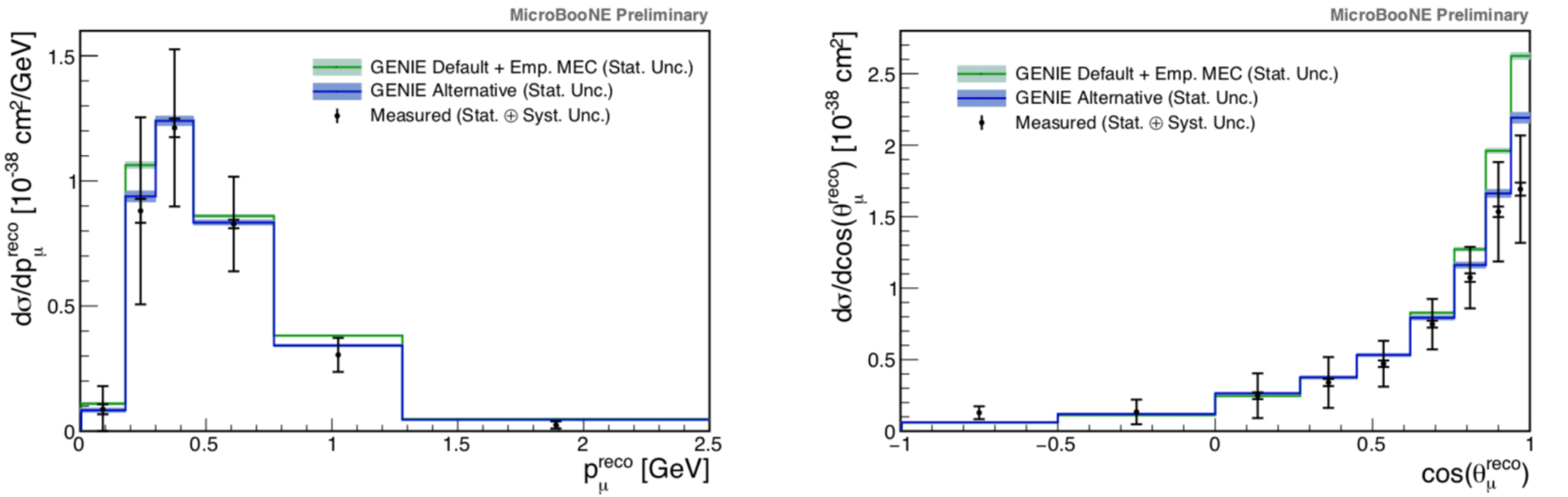
L. Jiang



- Data favors lower multiplicity compared to all three simulations.
- Simulation agrees with data at the 2σ level.
- No efficiency correction and unfolding.
- MEC: Meson exchange current; TEM: Transverse enhancement model.

CC inclusive Event Selection and Cross Section Measurement

X. Lu



- Two GENIE models sets were used in the analysis: Default and Alternative.
- Differential cross sections with respect to muons momentum and $\cos\theta_\mu$ shows agreements in both these two model sets.
- Working on the double differential cross sections.

Model element	Default	Alternative
Nuclear Model	Bodek-Ritchie Fermi Gas	Local Fermi Gas
Quasi-elastic	Llevellyn-Smith	Nieves
MEC	Empirical	Nieves
Resonant	Rein-Sehgal	Berger-Sehgal
Coherent	Rein-Sehgal	Berger-Sehgal
FSI	hA	hA2014

MEC: Meson Exchange Current.
Nieves Model accounts for long range nuclear (RPA) correlations, final states interaction (FSI) and Coulomb corrections.

SBND For Rare Cross Sections

J. Zennamo

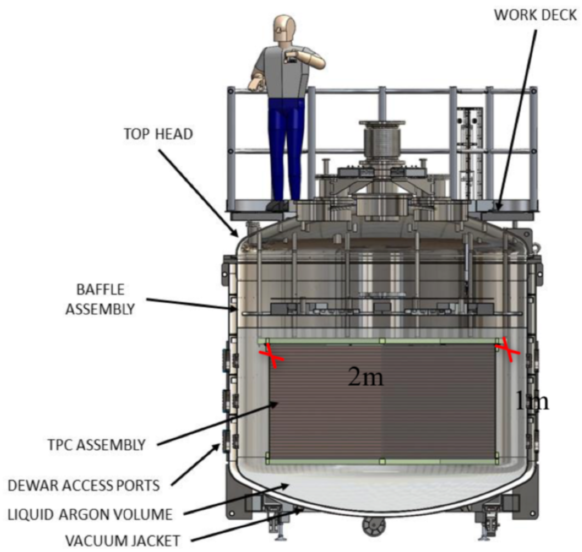
- These incredible event rates will enable us to probe rare processes
  - Modern measurements of neutrino production of hyperons, charm-baryons, and other rare processes enabled with 100s of events
- Using >10,000 ν_e CC interactions to directly study low energy ν_e+argon scattering

3 year event rates

Charged Current	
ν_μ Inclusive	5,389,168
$\rightarrow 0\pi$	3,814,198
$\longrightarrow 0p$	27,269
$\longrightarrow 1p$	1,261,730
$\longrightarrow 2p$	1,075,803
$\longrightarrow \geq 3p$	1,449,394
$\rightarrow 1\pi^+ + X$	942,555
$\rightarrow 1\pi^- + X$	38,012
$\rightarrow 1\pi^0 + X$	406,555
$\rightarrow 2\pi + X$	145,336
$\rightarrow \geq 3\pi + X$	42,510
$\rightarrow K^+K^- + X$	521
$\rightarrow K^0\bar{K}^0 + X$	582
$\rightarrow \Sigma_c^{++} + X$	294
$\rightarrow \Sigma_c^{+} + X$	98
$\rightarrow \Lambda_c^{+} + X$	672
ν_e **Inclusive**	$\approx$ **12,000**

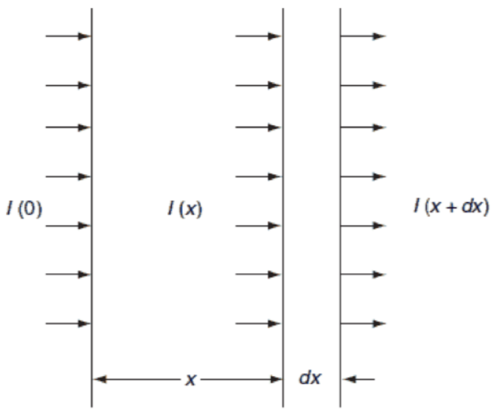
CAPTAIN detector

- Cryostat
  - Capacity: 10 tons
- TPC
  - Hexagonal prism with 1m vertical drift, 1m apothem, 2000 channels, 3mm pitch, 5 instrumented tons
- Photon detection system
- Laser calibration system
- Same cold electronics and electronics chain as MicroBooNE



Measuring the neutron cross section

- First result absolute inclusive cross section, followed by differential exclusive cross sections.
- Survival probability of neutrons decreases exponentially as a function of depth in detector and only depends on cross section and target density.
- Fit an exponential to the starting positions of the tracks and you get the cross section.
- Data binned in energy bins where cross section doesn't change as much.



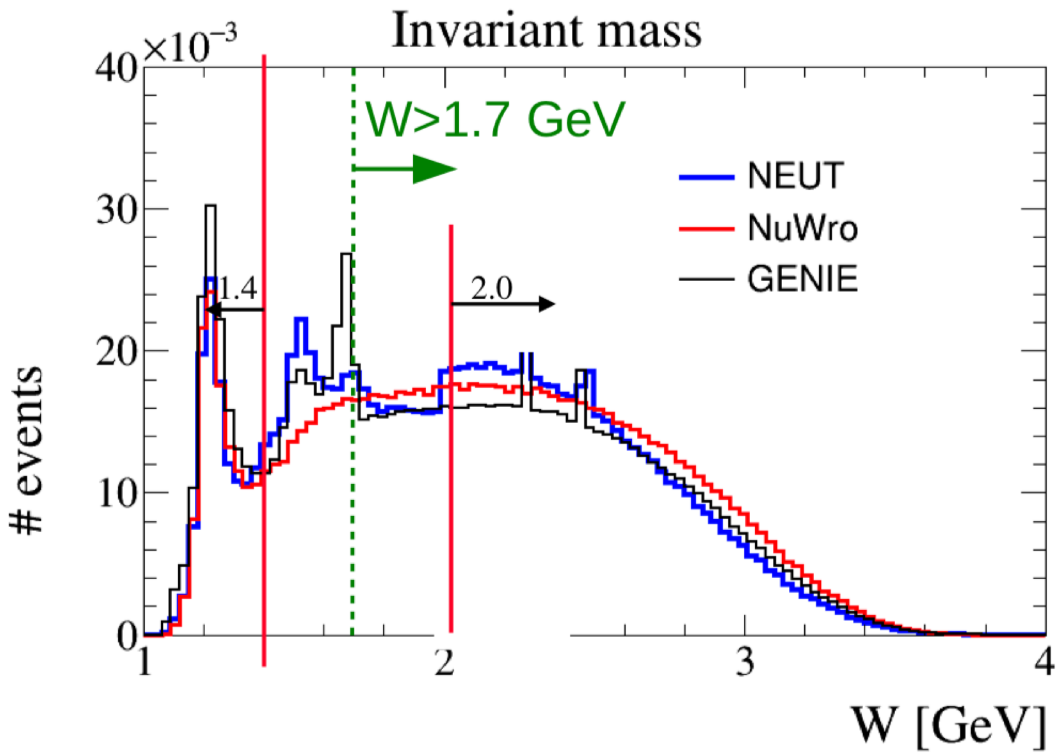
$$I(x) = I_0 e^{-N\sigma x}$$

N = atomic density of Argon

The General Landscape – Comparison of Generators

J. G. Morfín

- We use the invariant mass of the hadronic system: $W^2 = M^2 + Q^2 (1 - x) / x$ to classify the type of interaction we are studying.
- By far the majority of contemporary studies in ν-nucleus interactions have been of QE and Δ production that is $W \leq 1.4$ GeV
- However, there is plenty of activity going on above this W cut! For example with a 6 GeV ν on Fe – excluding QE.



- ***over 50% of the DUNE events*** have W greater than the Delta mass (W ≈≥ 1.4 GeV),

C. Bronner- 2016

2

J. G. Morfín

Conclusions DIS

- All high-statistics neutrino data is off nuclear targets. Need nuclear correction factors to include data off nuclei in global fits with nucleon data to determine nucleon PDFs.

- Current nuclear correction factors in GENIE use B-Y model that gives only ν-isoscalar Fe correction factor that is then then used for ALL nuclei.

- Nuclear correction factors (R) and, consequently, the nuclear parton distribution functions are found to be **different** for neutrino-Fe scattering compared to charged lepton-Fe. **One experiment and one nucleus.**

- **There is now fresh evidence that these so-called DIS partonic nuclear effects (EMC effect) continue down into the SIS region with W < 2.0 GeV!** (Low-Q scaling, duality, and the EMC effect – Arrington et al.)

What is "Duality"

J. G. Morfín

- Relationships between meson–hadron and quark–gluon degrees of freedom.
- Quark–hadron duality is a general feature of strongly interacting landscape.
- There exist examples where low-energy hadronic phenomena, averaged over appropriate energy intervals, closely resemble those at higher energies, calculated in terms of quark-gluon degrees of freedom.
- Duality is an important ingredient for the Bodek-Yang model that GENIE, NEUT, NuWro employ.
- Originally studied and confirmed in e-N scattering – how about ν-N scattering? There is essentially no high-statistics ν-N experimental data with W>1.4 GEV for tests! Rely on **models** for resonances and essentially **ONE** theoretical look at duality in ν-N scattering.
  - $F_2^{ep\ en}$: Duality HOLDS in electron–nucleon scattering
  - $F_2^{\nu p\ \nu n}$: In neutrino–nucleon scattering duality does NOT hold for proton and neutron individually
  - $F_2^{\nu p\ \nu n}$: Duality HOLDS for the averaged structure functions. Need equal number of neutrons and protons…

24

Still Curious about SIS and DIS Scattering?

NuSTEC Workshop on Shallow- and Deep- Inelastic Scattering –

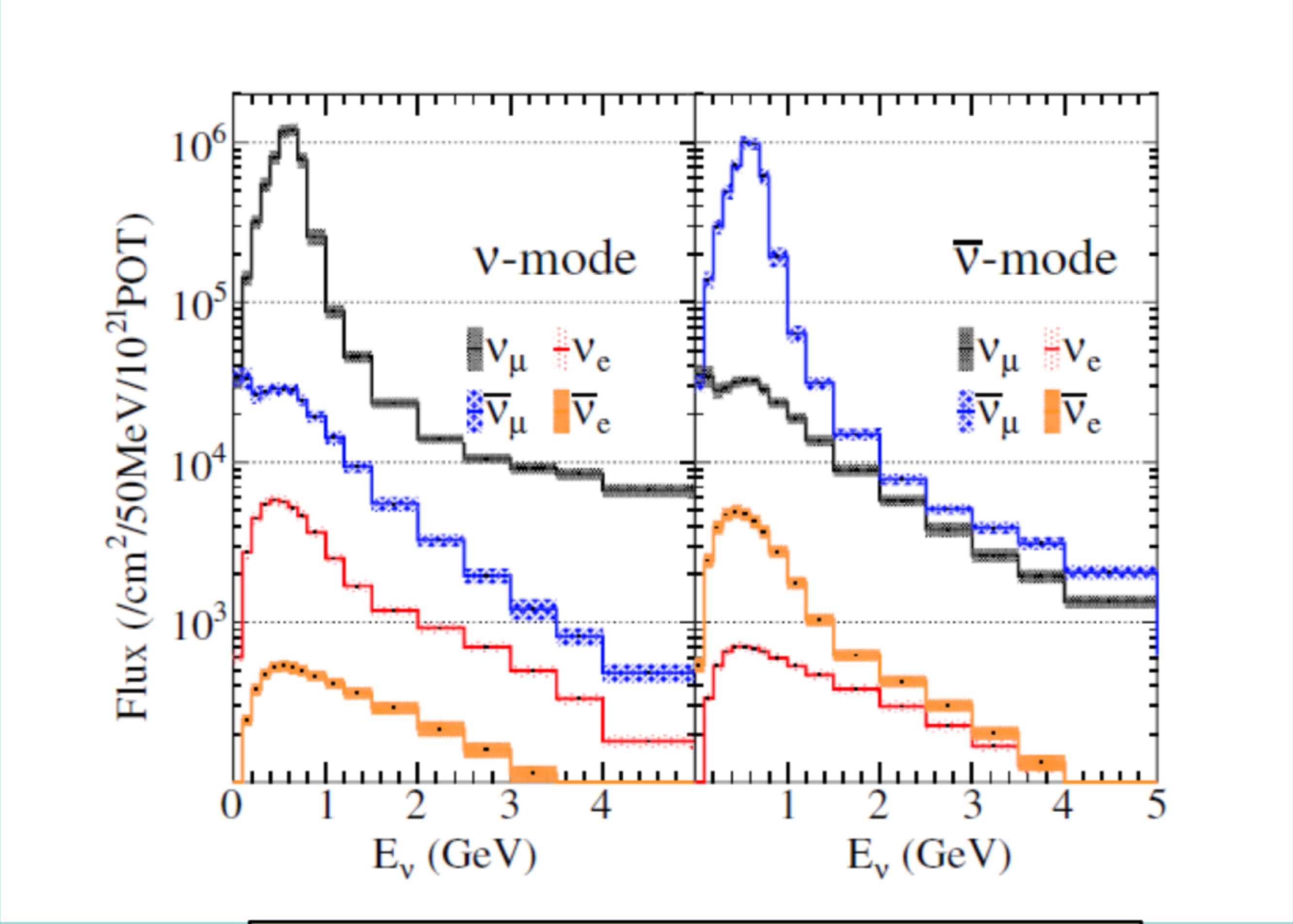
Just before (11-13 October) and in same location as NuInt18

https://indico.cern.ch/event/727283/

Measurement in near detector

A. M. Ankowski

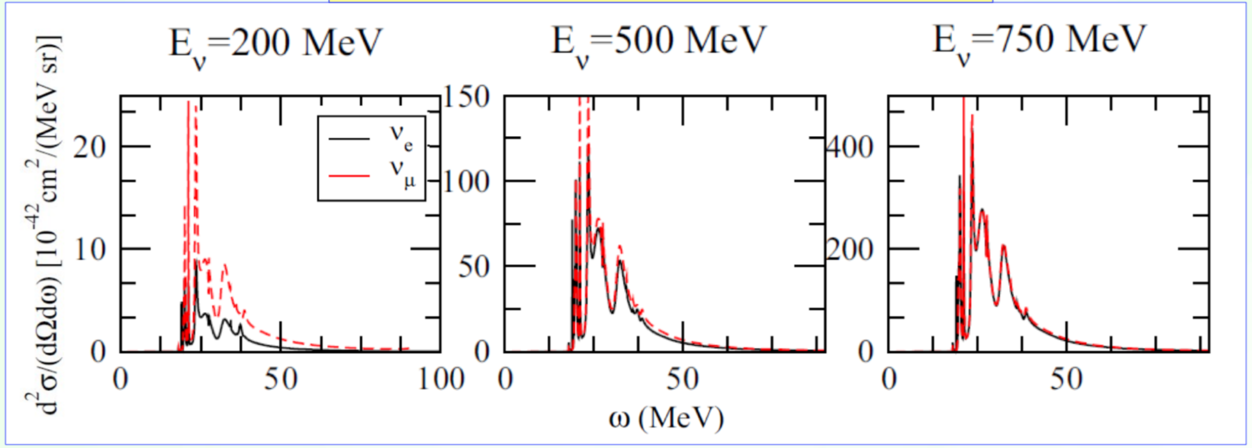
Event statistics lower ~100 times for ν_e's then for ν_μ's.
Higher flux and detector-response uncertainties.



Abe *et al.* (T2K), PRL 116, 181801 (2016)

CCQE ν_μ and ν_e cross sections at 5°

M. Martini *el al.*, PRC **94**, 015501 (2016)

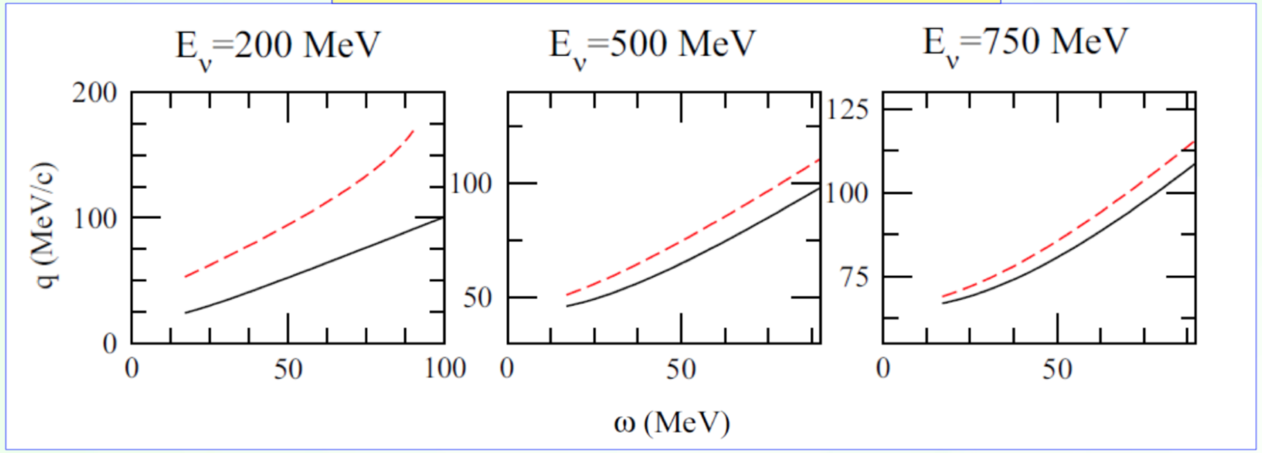


Conclusion: While at higher energies the ν_μ and ν_e cross sections practically coincide, at low energies and small scattering angles the ν_μ cross section is **higher** than the ν_e one.

13

CCQE ν_μ and ν_e cross sections at 5°

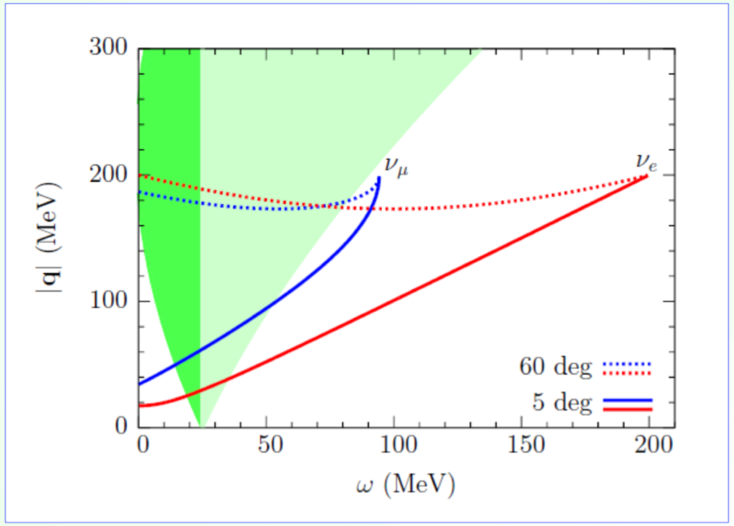
M. Martini *el al.*, PRC **94**, 015501 (2016)



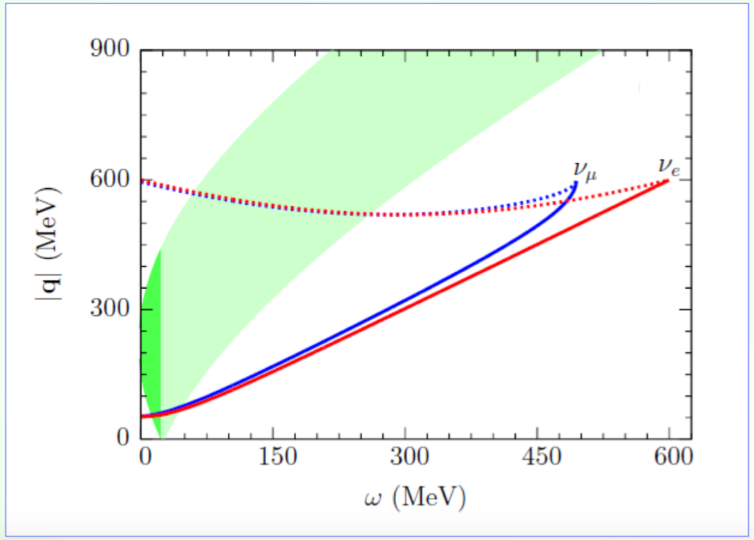
Conclusion: this behavior is related to the differences in the momentum transfer between the ν_μ and ν_e scattering.

A. M. Ankowski

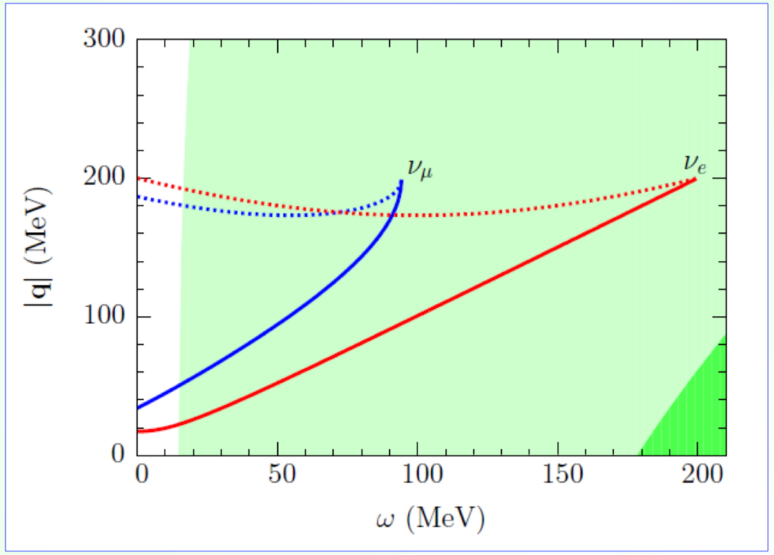
RFG, CCQE scattering at 200 MeV



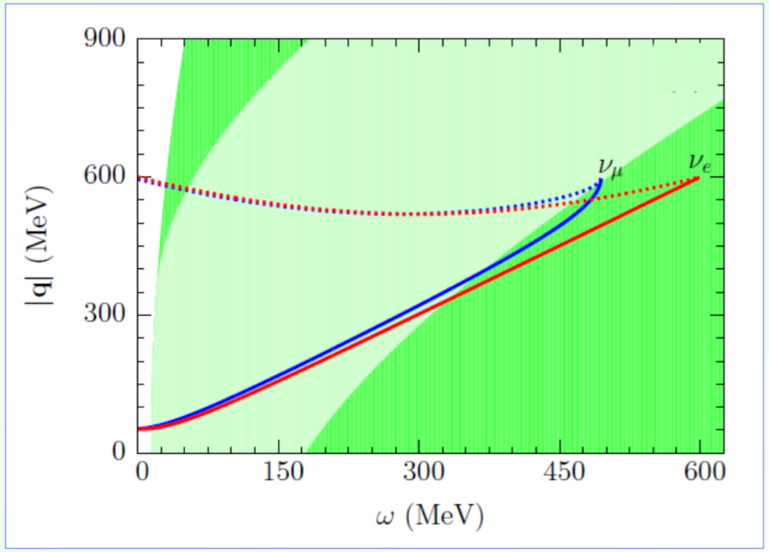
RFG, CCQE scattering at 600 MeV



SF, CCQE scattering at 200 MeV



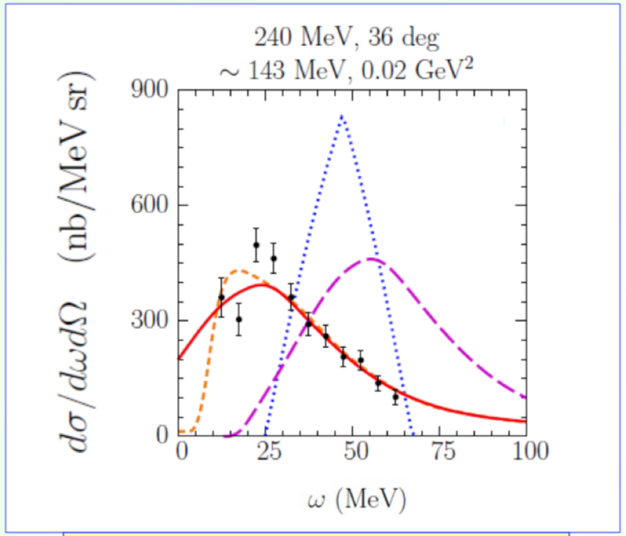
SF, CCQE scattering at 600 MeV



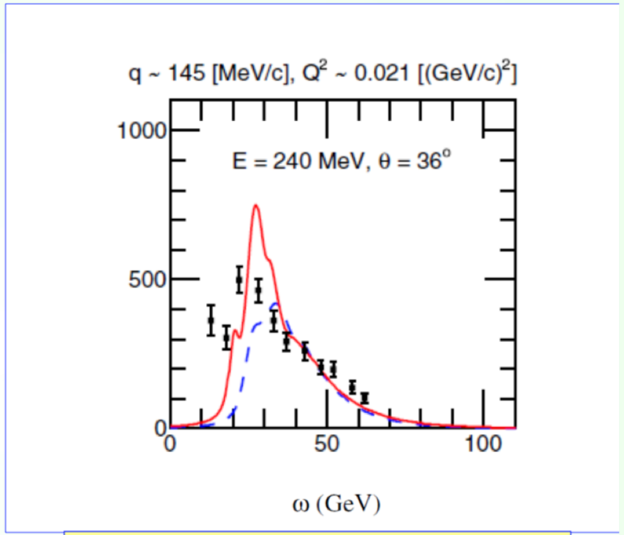
- Details of nuclear model can qualitatively change the mass dependence of the cross section.
- The behavior is driven by the phase-space availability, rather than the kinematics.

A. M. Ankowski

Nuclear models are converging



AMA *et al.*,
PRD **91**, 033005 (2015)



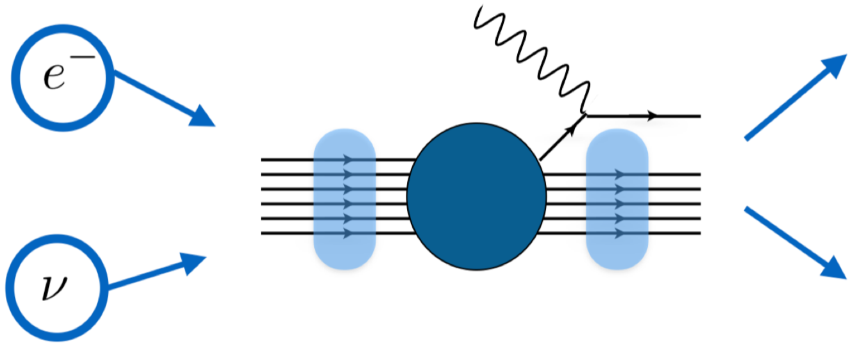
V. Pandey *et al.*,
PRC **92**, 024606 (2015)

See also: G. D. Megias *et al.*, PRC **94**, 013012 (2016);
J. E. Sobczyk, PRC **96**, 045501 (2017)

Model differences

- Models developed to reproduce inclusive electron-scattering data may give similar results starting from different physics assumptions.
- Treating the initial states differently, they lead to different exclusive cross sections (hadron distributions).
- For long-baseline neutrino experiments, particularly those using calorimetric energy reconstruction, exclusive cross sections are essential.

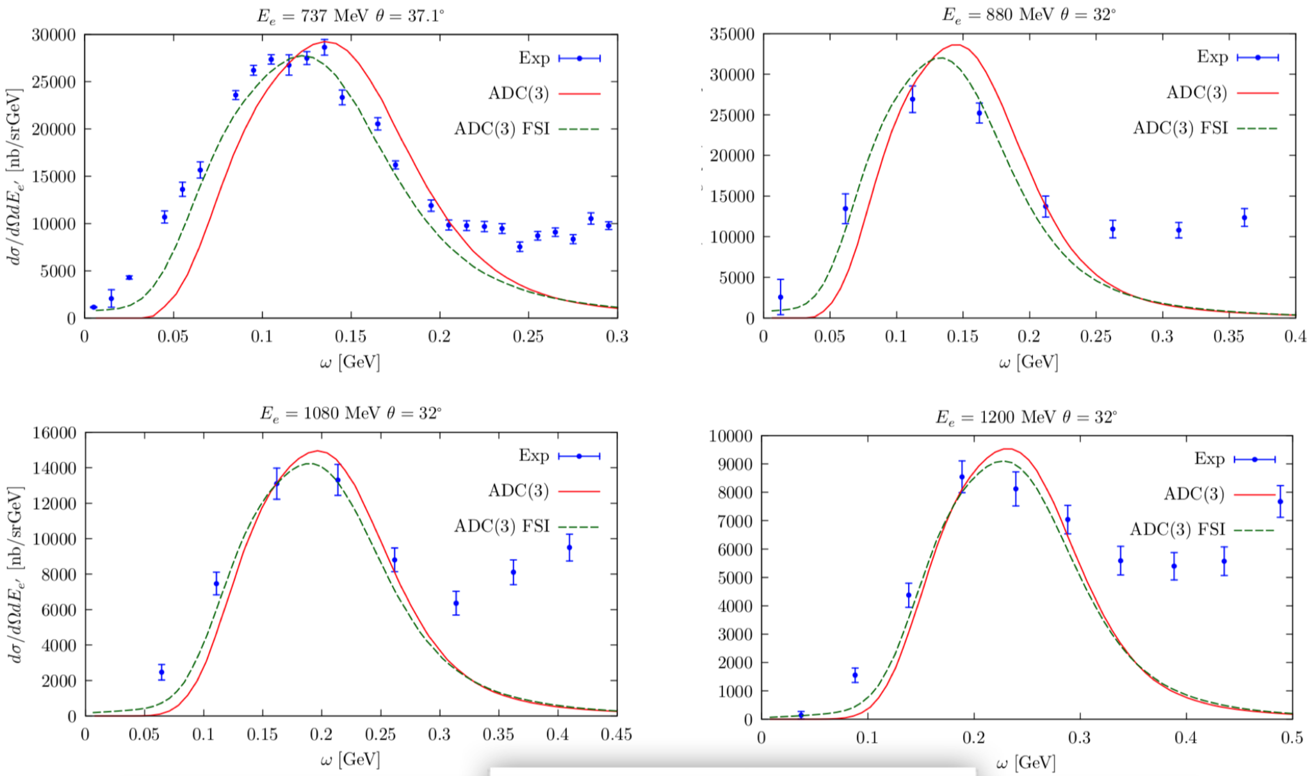
N. Rocco



Self Consistent Green's Function

Correlated Basis Function

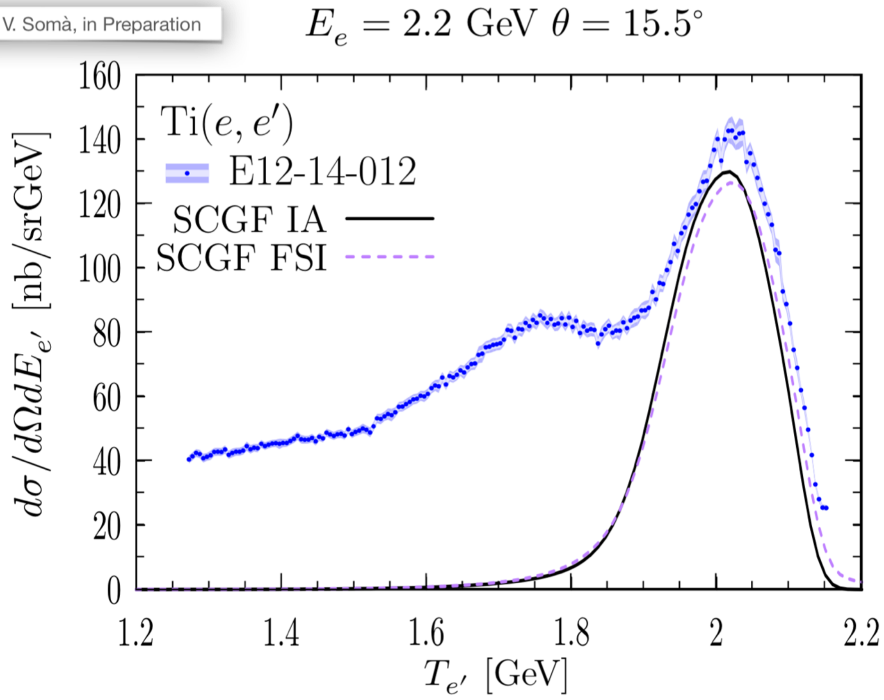
^{16}O(e,e') cross sections within the SCGF approach



NR, C. Barbieri, Phys.Rev. C98 (2018) 025501

Preliminary results for ^{48}Ti(e,e') cross sections

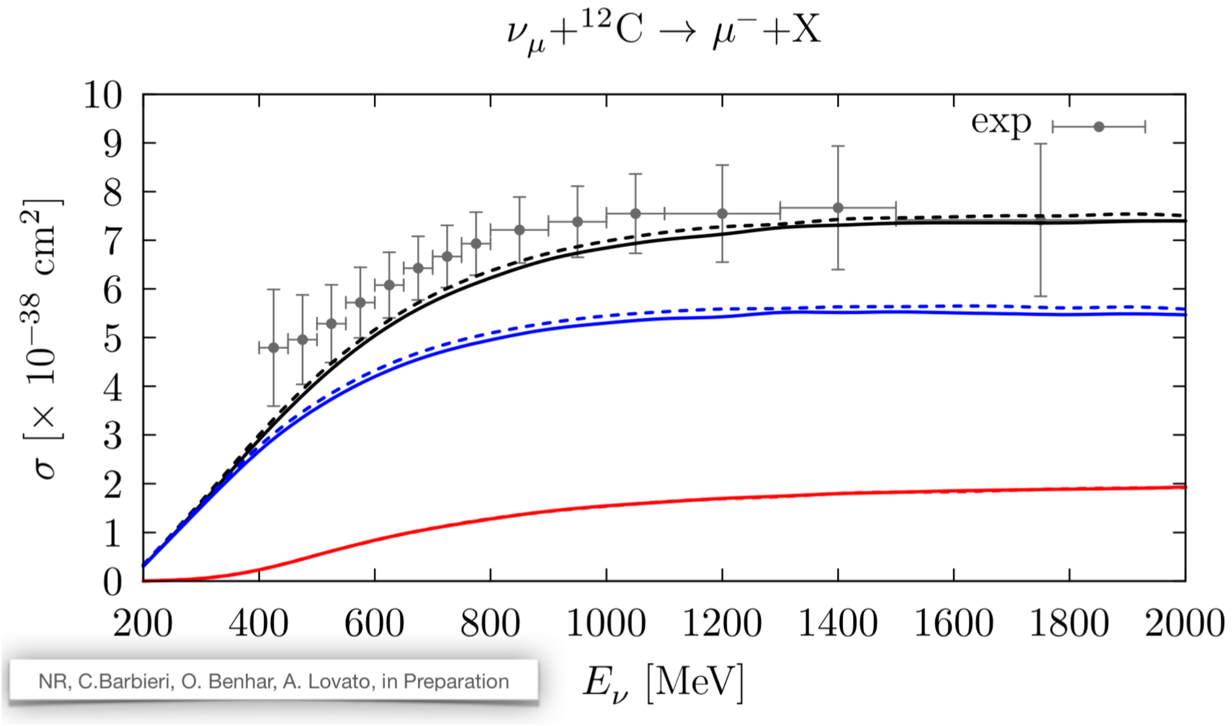
C. Barbieri, NR, V. Somà, in Preparation



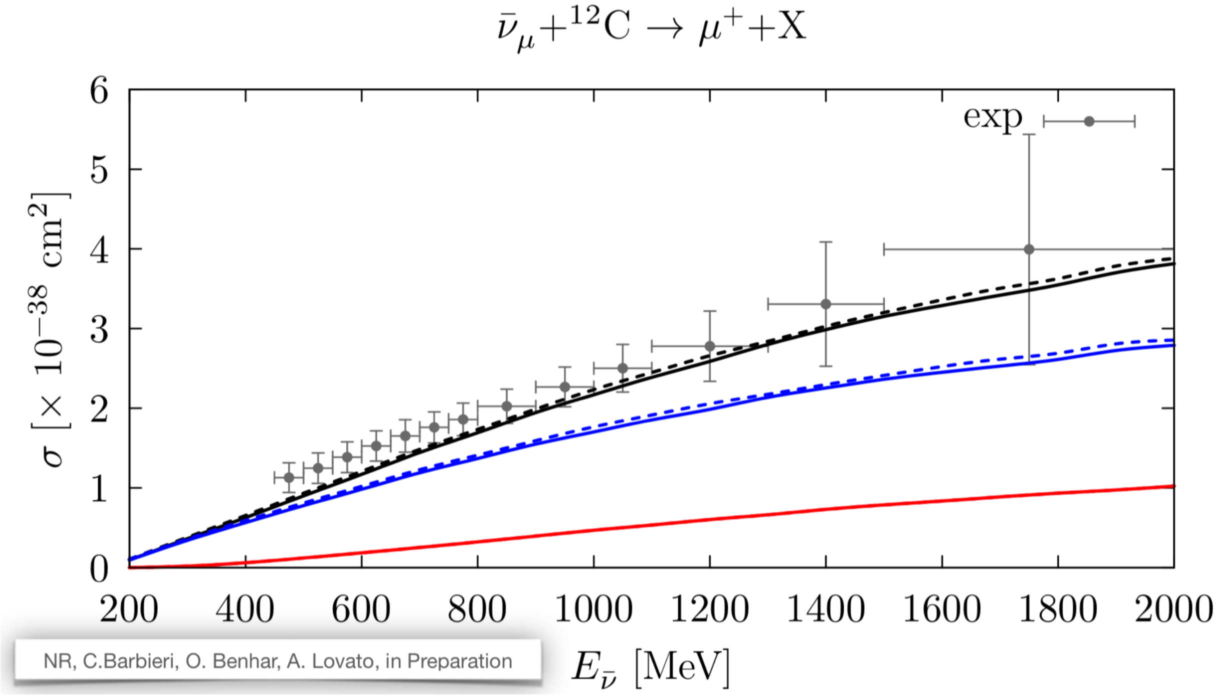
✤ Experimental data: Jefferson Lab Hall A Collaboration, Phys.Rev. C98 (2018) no.1, 014617

N. Rocco

CCQE neutrino -^{12}C total cross section

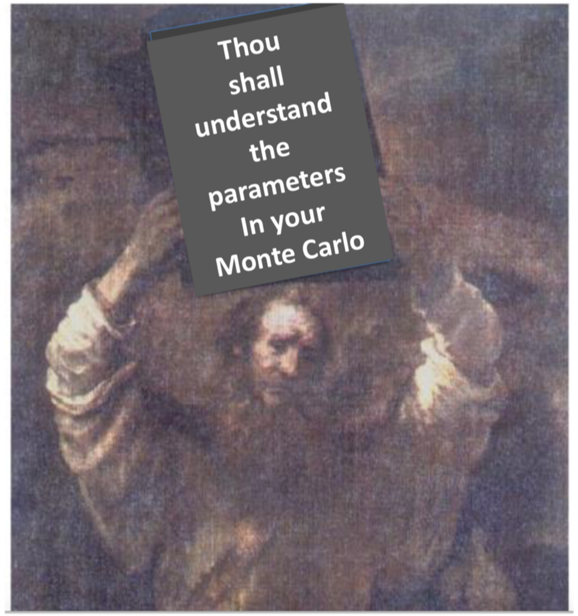


CCQE antineutrino -^{12}C total cross section



A. Bodek

https://arxiv.org/abs/1801.07975



For QE electron scattering the energy momentum δ function and the final state nucleon energy are given by

$$\delta[(E_i+\nu)-E_f]$$
$$E_f=\sqrt{(q+k)^2+M^2}. \qquad (1)$$

$E_i = f(\mathcal{E})$

$\mathcal{E}$ = binding/removal energy parameter

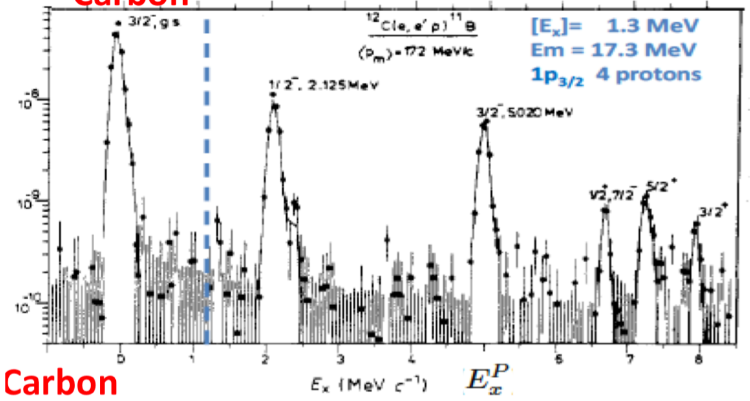
Which is defined differently

in GENIE: Excitation energy $\mathcal{E} = E_x(P,N)$

In NEUT: Smith-Moniz Interaction energy $\mathcal{E} = \epsilon_{SM}^{\prime P,N}$

other applications: Interaction energy $\mathcal{E} = \epsilon_R^{P,N}$.

Carbon



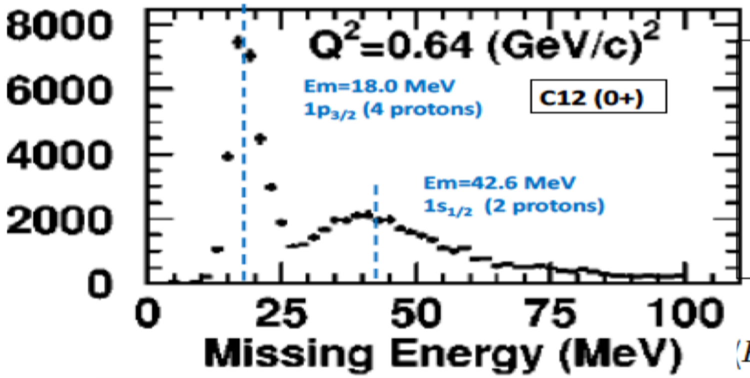
1P (1/2)

ee'P high resolution 1p1h
Here Ex is measured

$$\langle E_m^P\rangle = S^P + \langle E_x^P\rangle.$$

Carbon
Sp=16 MeV

ee'P high resolution 1p1h
here Em is measured



Define peak or most probable value as [Em]

Define average as <Em>
For neutrino experiments

2p2h Em>80 GeV)

$\langle E_m^P$

A. Bodek

Symbol	
$E_x^{P,N}$	Spectator Nucleus Excitation Used in spectral functions implemented in GENIE[1]
$S^{P,N}$ $= M_{A-1} + M_{p,n} - M_A$	Separation Energy Nuclear Data Tables (measured) [19,20]
$E_m^{P,N}=S^{P,N}+E_x^{P,N}$	removal (or missing) energy used in spectral functions
$\epsilon_R^{P,N}=E_m^{P,N}+T_{A-1}$ $T_{A-1} =$ $= \sqrt{k^2+M_{A-1}^2}-M_{A-1}$ $\approx \frac{k^2}{2M_{A-1}}$	interaction energy is $\epsilon_R^{P,N}$ $E_i = M - \epsilon_R^{P,N}$ used in $E_\nu^{QE-\mu}$, $Q^2_{QE-\mu}$, and Q^2_{QE-P}, also used in effective spectral functions[8]
$\epsilon'^{(P,N)}_{SM}=\epsilon_R^{P,N}+T_{av}^{P,N}$ $T=\sqrt{k^2+M^2}-M$ $\langle k^2\rangle = 0.6K_F^2$	$\epsilon'^{(P,N)}_{SM}$ is Smith Moniz[11] Interaction energy $E_i = M+T-\epsilon'^{(P,N)}_{SM}$ used in NEUT-NUANCE[3,4]

We can extract interaction and removal energy parameters from electron scattering data from a variety of modern experiments in three different ways.

Best $\langle E_m^P\rangle^{SF}$

1. The *mean* removal energy extracted for tests of the Kotlun[15] sum rule from $ee'p$ spectral functions.

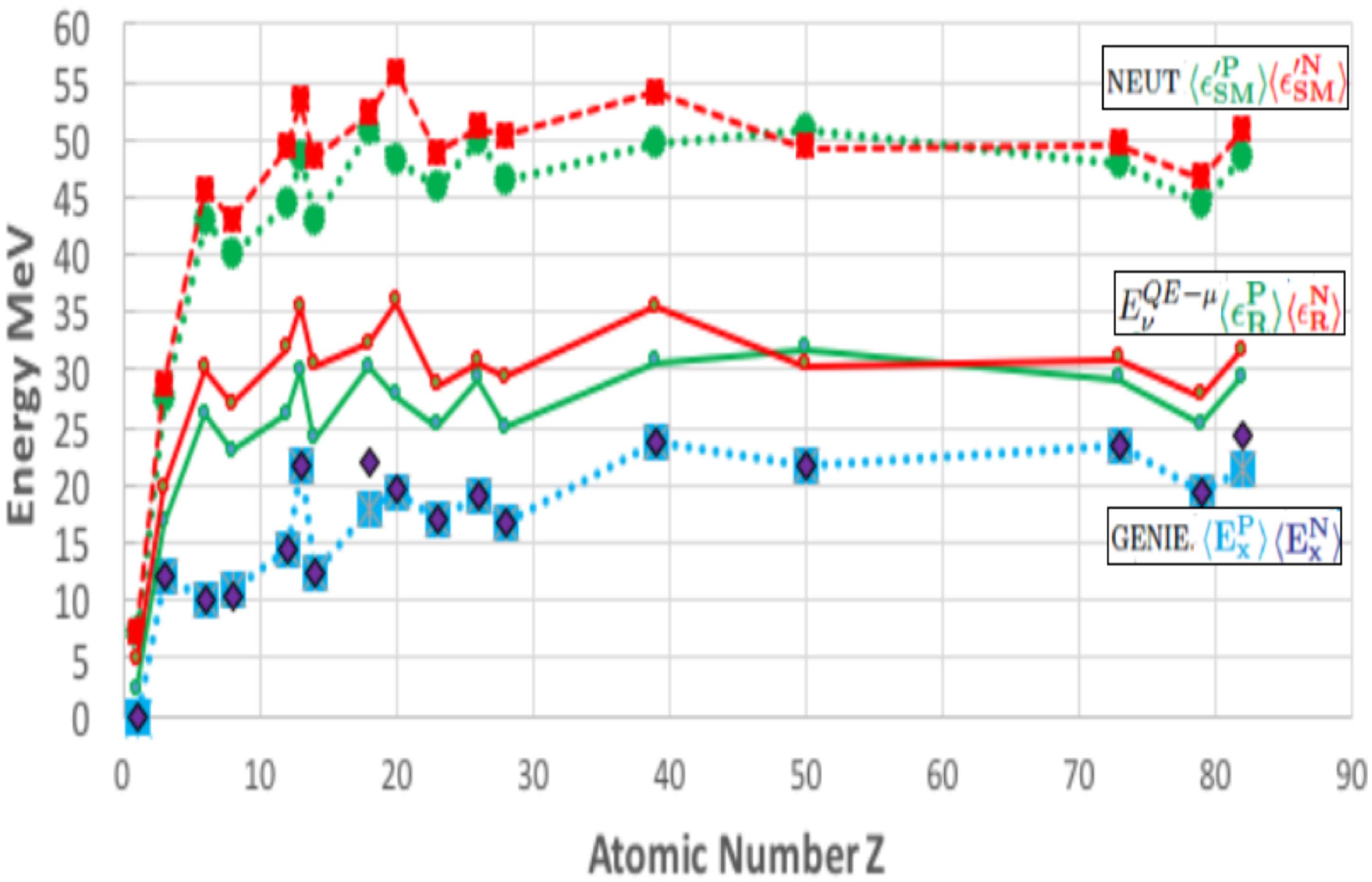
2nd Best $\langle E_m^P\rangle^{levels}$

2. The *mean* removal energy extracted from the weighted average of the removal energies of shell-model energy levels as measured in $ee'p$ experiments. EM levels

Not as good

3. The location of the QE *peak* in inclusive e-A scattering (e.g. Moniz et. al.) with additional corrections described below.

All should agree if done correctly



People have been using 27 MeV for Carbon. Genie users should use 10 MeV, Neut users should use 46 MeV 24

A. Bodek

Red is of interest to neutrino experiments: carbon, oxygen, argon, calcium, iron, lead

$^A_Z Nucl$	$\langle\epsilon_R^{P,N}\rangle$ relativ. corected		$\langle\epsilon_{SM}^{P,N}\rangle$ SMITH-MONIZ	$\langle E_x^{P,N}\rangle$ BODEK-RITCHIE	
	$E_m+T^{P,N}_{A-1}$		$\epsilon_R^{P,N}+T$	$E_m^{P,N}-S^{P,N}$	
	use for $E_\nu^{QE-\mu}$ $Q^2_{QE-\mu}$ Q^2_{QE-P} $\langle\epsilon_R^P\rangle$	$\langle\epsilon_R^N\rangle$	used in **NEUT** interaction energy $\langle\epsilon_{SM}^{P}\rangle,\langle\epsilon_{SM}^{N}\rangle$	used in **GENIE** excitation energy $\langle E_x^P\rangle,\langle E_x^N\rangle$	Measurment method used
(^2_1H)	4.7	4.7	7.2, 7.2	0.0, 0.0	Binding energy
^6_3Li	18.4±3	19.7 ±3	27.5, 28.8	12.2, 12.2	$\langle\epsilon_R\rangle^{levels}$ Tokyo [24, 25, 26]
$^{12}_6C$	27.5±3	30.1±3	43.0, 45.6	10.1, 10.0	Koltun SR $\langle\epsilon_R\rangle^{SF}$ Jlab Hall C [22]
$^{16}_8O$	24.1±3	27.0±3	40.1, 43.0	10.9, 10.2	$\langle\epsilon_R\rangle^{levels}$ Jlab Hall A [28]
$^{24}_{12}Mg$	27.0±3	31.8±3	44.5, 49.3	14.5, 14.5	updated $\langle\epsilon_R^P\rangle^{Moniz}$ [4]
$^{27}_{13}Al$	30.6±3	35.4±4	48.5, 53.3	21.6, 21.6	$\langle\epsilon_R\rangle^{levels}$ Tokyo [24, 25, 26]
$^{28}_{14}Si$	24.7±3	30.3±3	42.8, 48.4	12.4, 12.4	Koltun SR $\langle\epsilon_R\rangle^{SF}$ Saclay [23]
$^{40}_{18}Ar$	30.9±4	32.3±4	50.8, 52.2	17.8, 21.8	$\langle\epsilon_R\rangle^{levels}$ Tokyo [24, 25, 26] +Shell model
$^{40}_{20}Ca$	28.2±3	35.9±4	48.1, 55.8	19.4, 19.8	Koltun SR $\langle\epsilon_R\rangle^{SF}$ Saclay [23]
$^{50}_{23}V$	25.6±3	28.6±4	45.8, 48.8	17.0, 17.0	$\langle\epsilon_R\rangle^{levels}$ Tokyo [24, 25, 26]
$^{56}_{26}Fe$	29.6±3	30.6±3	50.0, 51.0	19.0, 19.0	Koltun SR $\langle\epsilon_R\rangle^{SF}$ Jlab Hall C [22]
$^{58.7}_{28}Ni$	25.4±3	29.4±3	46.3, 50.3	16.8, 16.8	Koltun SR $\langle\epsilon_R\rangle^{SF}$ Saclay [23]
$^{89}_{39}Y$	31.0±3	35.4±3	49.7, 54.1	23.6, 23.6	updated $\langle\epsilon_R^P\rangle^{Moniz}$ [4]
$^{118.7}_{50}Sn$	32.0±3	30.4±3	50.9, 49.3	21.7, 21.7	updated $\langle\epsilon_R^P\rangle^{Moniz}$ [4]
$^{181}_{73}Ta$	29.3±3	31.0±3	47.8, 49.5	23.3, 23.3	updated $\langle\epsilon_R^P\rangle^{Moniz}$ [4]
$^{197}_{79}Au$	25.4±3	27.7±3	44.4, 46.7	19.5, 19.5	Koltun SR $\langle\epsilon_R\rangle^{SF}$ Jlab Hall C [22]
$^{208}_{82}Pb$	29.5±3	31.7±3	48.5, 50.7	21.4, 24.2	updated $\langle\epsilon_R^P\rangle^{Moniz}$ [4]

$$E_\nu^{QE\text{-}\mu} = \frac{2(M_n')E'_{\mu\text{-}} - ((M_n')^2 + m_\mu^2 - (M_p')^2)}{2\cdot[(M_n') - E'_{\mu\text{-}} + (\sqrt{(E'_{\mu\text{-}})^2 - m_\mu^2})\cos\theta_{\mu\text{-}}]} \quad (39)$$

$$Q^2_{QE\text{-}\mu} = -m_\mu^2 + 2E_\nu^{QE}(E'_{\mu\text{-}} - \sqrt{(E'_{\mu\text{-}})^2 - m_\mu^2}\cos\theta_{\mu\text{-}}).$$

$$Q^2_{QE\text{-}P} = (M_n')^2 - (M_p')^2 + 2M_n'[M_p + T_p - M_n'].$$

Binding energy is the largest systematic error in Δm^2_{32}

The two-neutrino transition probability can be written as

$$P_{\nu_\alpha\to\nu_\beta}(L) = \sin^2 2\vartheta \sin^2\left(1.27\frac{(\Delta m^2/\mathrm{eV}^2)(L/\mathrm{km})}{(E_\nu/\mathrm{GeV})}\right).$$

The location of the first oscillation maximum in neutrino energy $(E_\nu^{1st-min})$ is when the term in brackets is equal to $\pi/2$. An estimate of the extracted value of Δm^2 is given by:

$$\Delta m^2 = \frac{2E_\nu^{1st-min}}{1.27\pi L}. \quad (2)$$

For example, for the T2K experiment[12] $L = 295$ Km, and E_ν is peaked around 0.6 GeV. The T2K experiment[12] reports a value of

$$\Delta m^2_{32} = (2.434 \pm 0.064)\times 10^{-3}\ \mathrm{eV}^2.$$

S. Dennis, talk at Nufact 2018, Virginia Tech, Blacksburg,

A 15 MeV change in binding energy yields a change in the extracted value of Δm^2_{32} of

$0.031 \times 10^{-3}\ \mathrm{eV}^2$

With our analysis the binding energy uncertainty is 3 MeV so this error is reduced by a factor of 5

Combined analysis:
Christoph Andreas Ternes
Nufact 2018

Δm^2_{32} **=(2.50 +- 0.03)**$\times 10^{-3}\ \mathrm{eV}^2$

Need to make sure that binding Energy is treated consistently Between experiments.

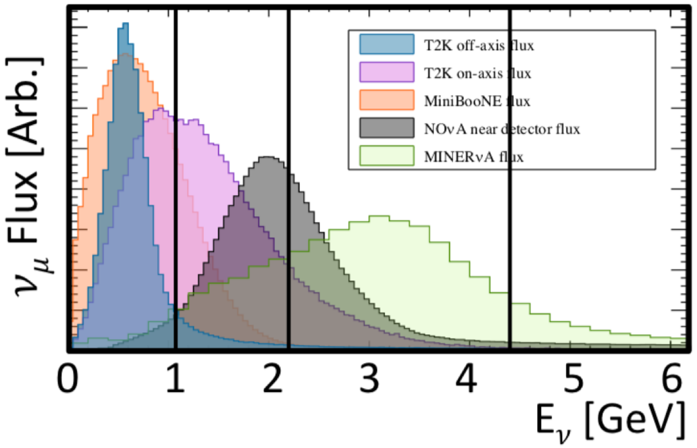
25

L. Weinstein

CLAS6 Data (million events)

	1.1 GeV	2.2 GeV (e,e')	2.2 GeV (e,e'p)	4.4 GeV (e,e')	4.4 GeV (e,e'p)
3He	Not done	24	9	4	1
4He	Not done	46	17	8	3
12C	Not done	30	11	5	2
56Fe	Not done	1	0.5	0.4	0.1

E2a data only.
E2b has more 4.6 GeV 3He and 56Fe
Eg2 has 5 GeV d, C, Al, Fe, and Pb



L. Weinstein

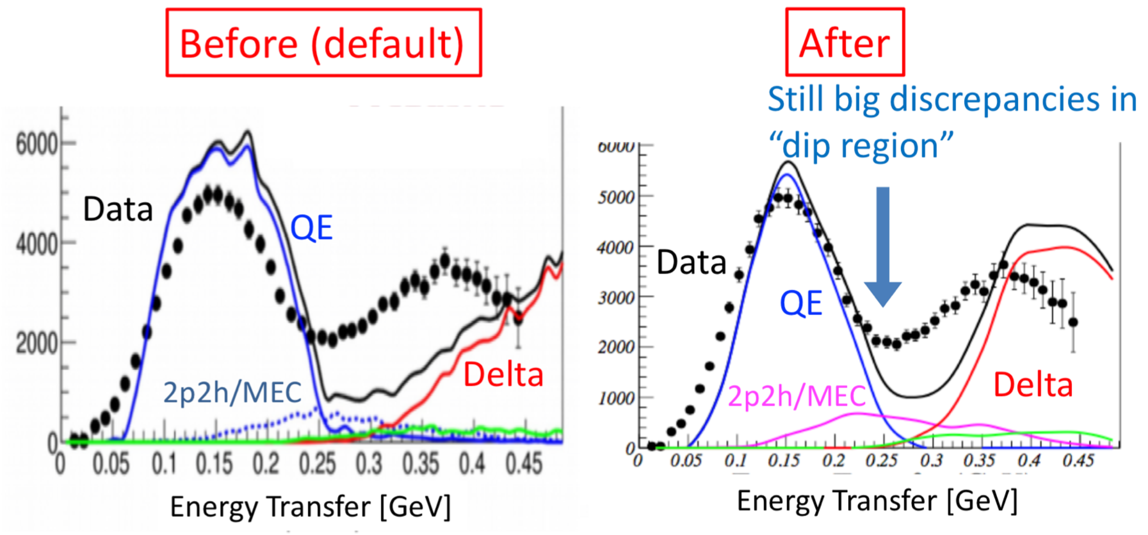
We're Also Improving Genie

1. Corrected expression for Mott cross section in QE
2. MEC/2p2h
   1. Added boost back to lab frame
   2. Corrected mass for cluster of particles
   3. Corrected Form Factors
3. Resonance
   1. Replaced old calculation with GSL Minimizer (now gives correct peak location)
   2. Switched to Berger-Seghal model
   3. Used corrected coupling constant for EM interactions
4. Nucleon momentum distributions
   1. Switched to Local Fermi Gas Model

Beginning work on NuWro and GiBUU.
Consulting with the relevant experts on each code.

We're Also Improving Genie

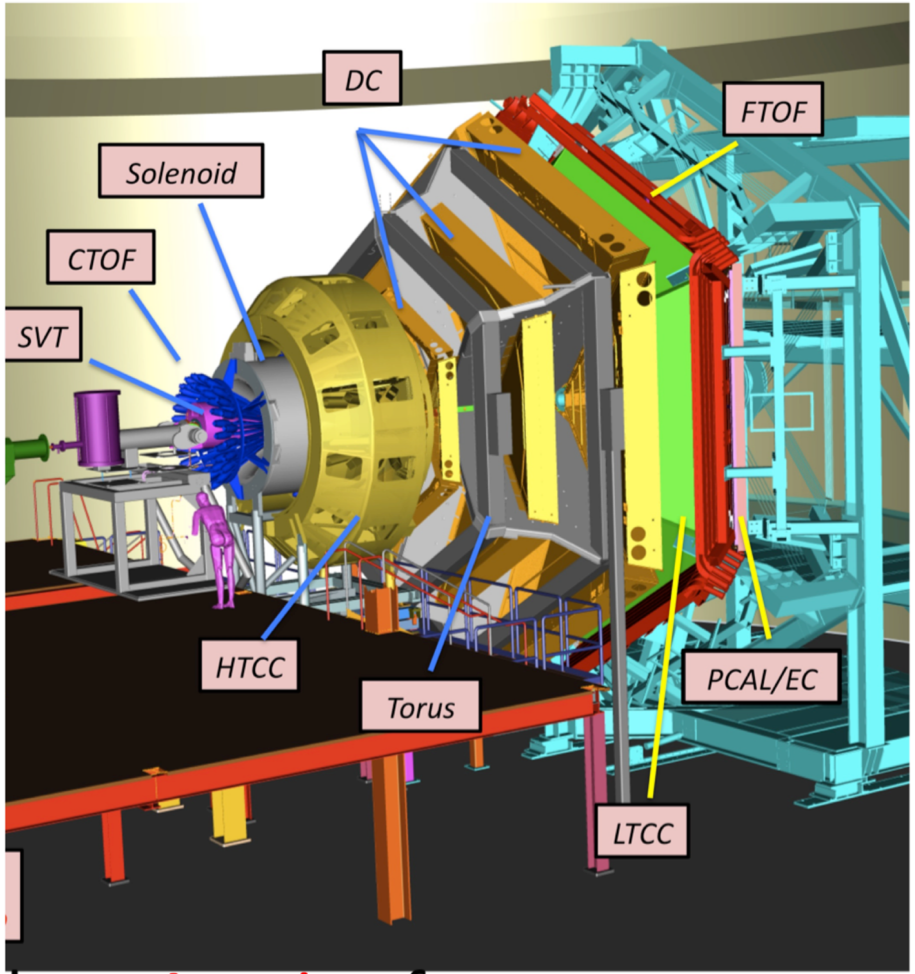
C(e,e') 560 MeV $\theta = 60^o$



e4ν CLAS12

CLAS12

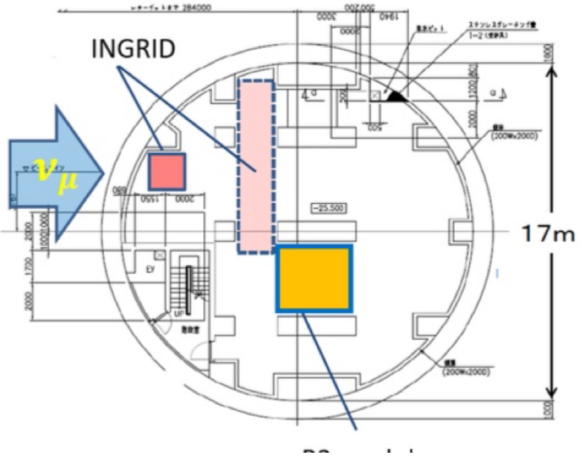
- forward detector (8 – 40°)
  - Toroidal magnetic field
  - $\frac{\delta p}{p} \sim 0.5$—1%
  - Neutrons:
    - 50% effi for p > 1 GeV/c
    - $\frac{\delta p}{p} \sim$ 10-15% for 1 GeV/c
- Hermetic central detector (40 – 135°)
  - 5 T solenoidal field
  - Neutron effi ~ 10—15%
  - Neutron $\frac{\delta p}{p}$: 60 ps @ 0.3 m

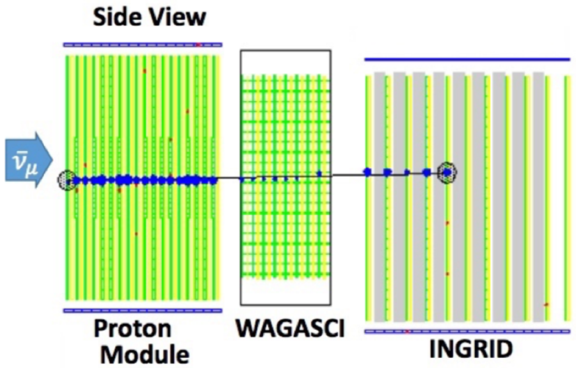


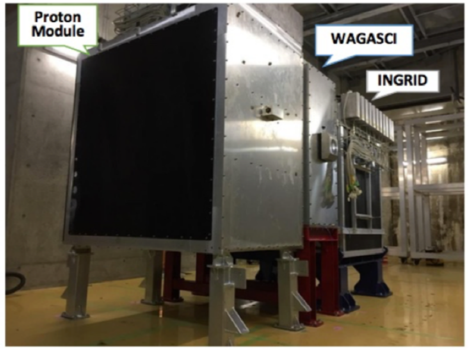
- 45 beam days approved with an A rating for
  - 1.1, 2.2, 4.4, and 6.6 GeV beam energies
  - d, He, C, O, Ar, and Sn targets

WAGASCI Detector setup

- WAter Grid And SCIntillator experiment (WAGASCI) consists of three modules in the near detector facility for T2K.
- The detector is 1.5° off-axis from the main T2K beam.
- Consists of a proton module, Hydrocarbon target.
- WAGASCI, water/scintillator target
- INGRID module, iron/scintillator target.







Cross section analysis

Proposed measurements

- Ongoing analysis
- $\bar{\nu_\mu}$ CC inclusive interaction
- Will measure cross sections on H2O, CH, and Fe per nucleon
- σ_{H2O}, σ_{CH}, σ_{Fe}
- Will also produce cross section ratios.

Kinematic cuts

- Forward enhanced : Angle < about 30° .
- Requiring momentum of produced muon 0.4 GeV/c < 1 GeV/c

Analysis

- Target: H_2O, CH, Fe
- 1.5° off-axis.
- Beam mean energy : 0.86 GeV.

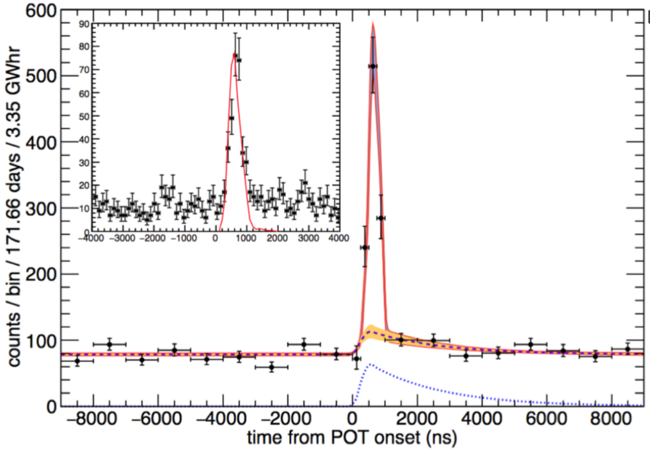
Previous analysis

- TN322: INGRID Water Module
- Target: H_2O, CH, Fe
- On-axis Beam mean energy : 1.5 GeV.

S. Hedges

Neutrino-Nucleus Interactions on ^{208}Pb

- Originally deployed LS cell in shielding to be used by CsI detector (2.2 tons lead)
- Best fit of the excess due to neutrino-induced neutrons was 0.97 ± 0.33 n/GWHr/kg of Pb
  - Factor ~1.7 smaller than calculated in [11]
  - Additional neutron shielding deployed around the CsI detector
  - Dedicated experiment designed to study interaction



[10]

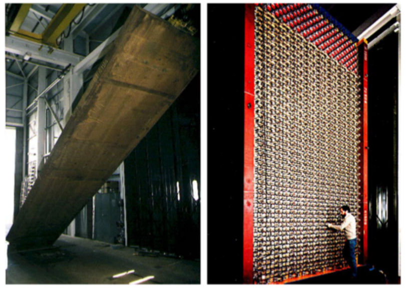
Neutrino-Nucleus Interactions on ^{56}Fe

- Iron is a common shielding material
- Previous flux-averaged measurement by KARMEN[13]:

  $2.51 \pm 0.83 \pm 0.42 \times 10^{-40}$ cm^2
- Proposed as target for supernova neutrino detectors such as OMNIS
- LVD sensitive to supernova neutrino-Fe interactions through NC channel

$$\nu_e + {}^{56}\mathrm{Fe} \rightarrow {}^{56}\mathrm{Co}^* + e^-$$
$$\Downarrow$$
$$^{56-y}\mathrm{Co} + x\gamma + yn$$

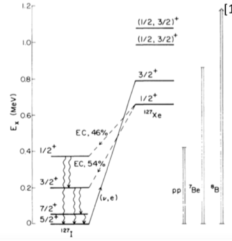
$$\nu_x + {}^{56}\mathrm{Fe} \rightarrow {}^{56}\mathrm{Fe}^* + \nu_x'$$
$$\Downarrow$$
$$^{56-y}\mathrm{Fe} + x\gamma + yn$$

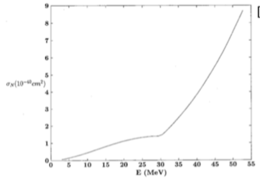

[14]

Neutrino-Nucleus Interactions on ^{127}I

- ^{127}I proposed[17] as potential for a solar/supernova neutrino detector
  - Utilized similar to radiochemical approach used at Homestake with ^{37}Cl[18]
  - Charged-current threshold of 789 keV, used to determine ratio of ^{7}Be to ^{8}B solar neutrino flux
  - Larger cross section
- Work done to understand GT strength distribution for ^{127}I in (p,n)[19], (He,t)[20], angular correlation[21] experiments
- Inclusive cross section calculated by Mintz and Pourkaviani[22]

$$\nu_e + {}^{127}\mathrm{I} \rightarrow {}^{127}\mathrm{I}^{(*)} + e^-$$

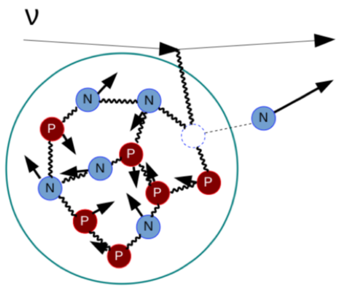

[17]


[22]

Model building

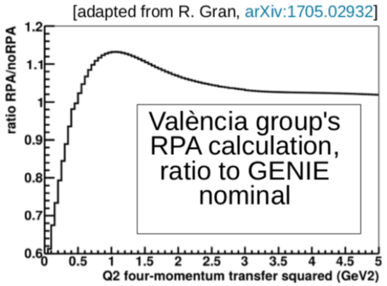
Theory work and **other experiments' data** have shown that default GENIE 2.12 (our base model) needs some important adjustments...

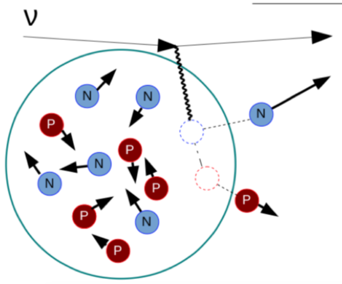
(fuller discussion in J. Wolcott, FNAL Neutrino Seminar, Apr. 23 2018; paper forthcoming)



Effective nuclear "screening" from collective excitations: treated with "**RPA**".

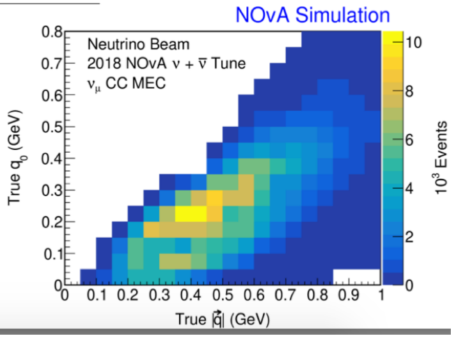
We use Valencia group calculation for QE; also speculatively apply to RES based on hints in external data





Multinucleon knockout (2p2h)

We enable GENIE "Empirical MEC", retune it based on our data



Nuclear model

Evaluating cross section uncertainties

Depend heavily on GENIE's reweight system...

Primary process uncertainties

QE: M_A, Vector FF, Pauli supp...

RES: M_A, M_V, Δ decay isotropy...

DIS: Bodek-Yang parameters, transition region ("non-resonant background" scale), ...

COH: Rein-Sehgal M_A, R_0, ...

Final-state model (hA) uncertainties

Nucleon, pion elastic, inelastic, chg ex., abs. reaction probabilities

Hadron mean free paths

(~50 reweight knobs in all)

...and build custom knobs for our growing library of GENIE 'adjustments':

MEC model for **2p2h** (q^μ shape, E_ν shape, nn/np composition)

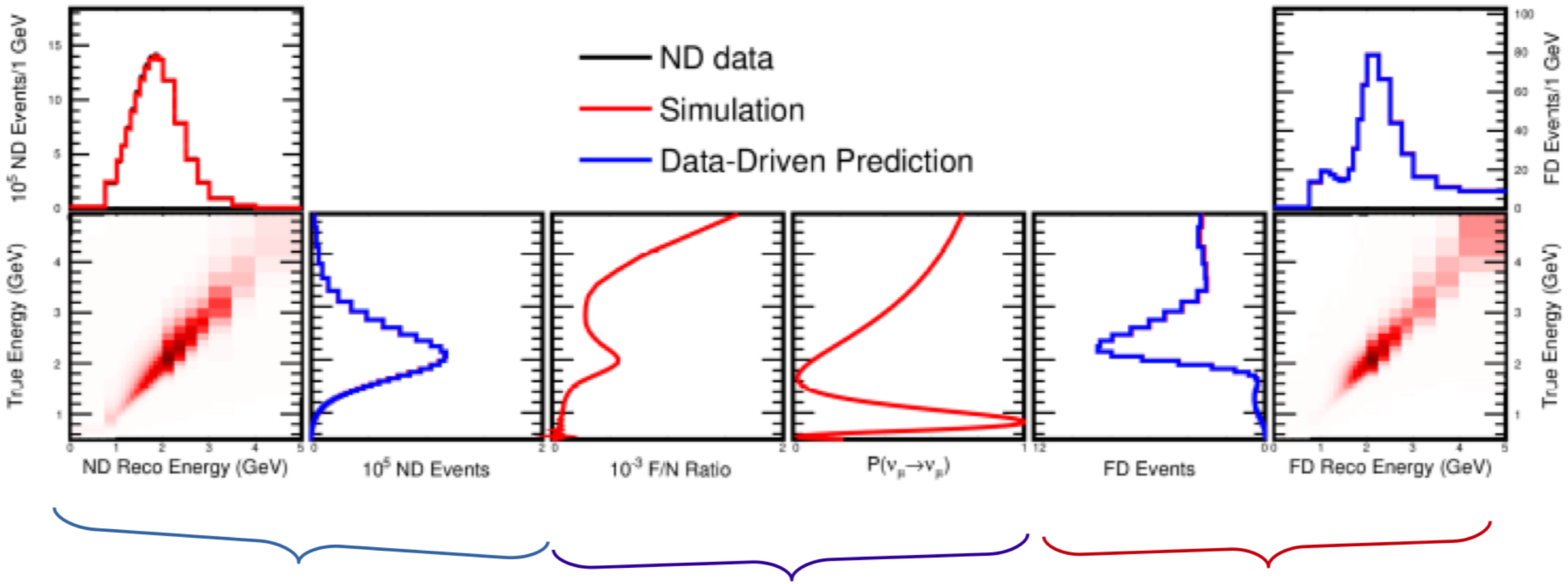
RPA-QE (based on València treatment; histograms from R. Gran)

RPA-RES (conservative "on" vs "off")

J. Wolcott

ν_μ disappearance: "extrapolation"

To produce a data-driven prediction at FD, based on ND:



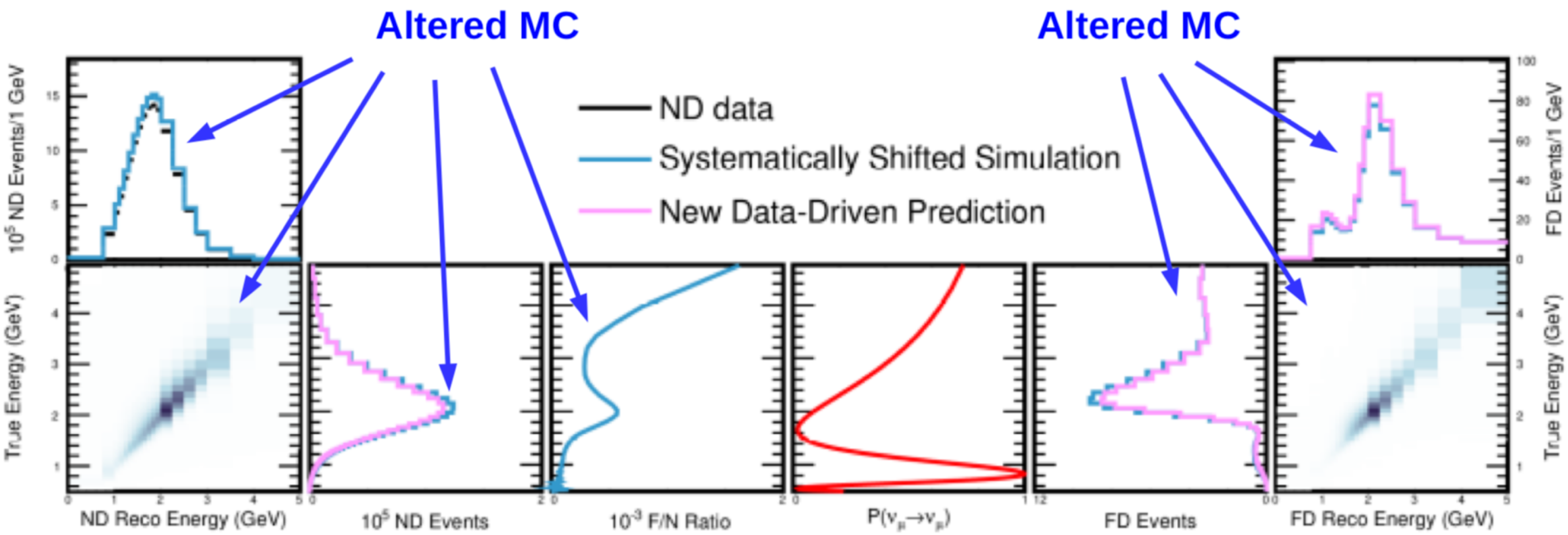
True energy distribution is corrected so that reconstructed data & MC agree at the ND...

...modified true energy distribution is propagated through predicted geometric beam dispersion & acceptance ratio, oscillations...

... and "extrapolated" reconstructed energy distribution computed to compare to data

“Extrapolation” and uncertainties

J. Wolcott



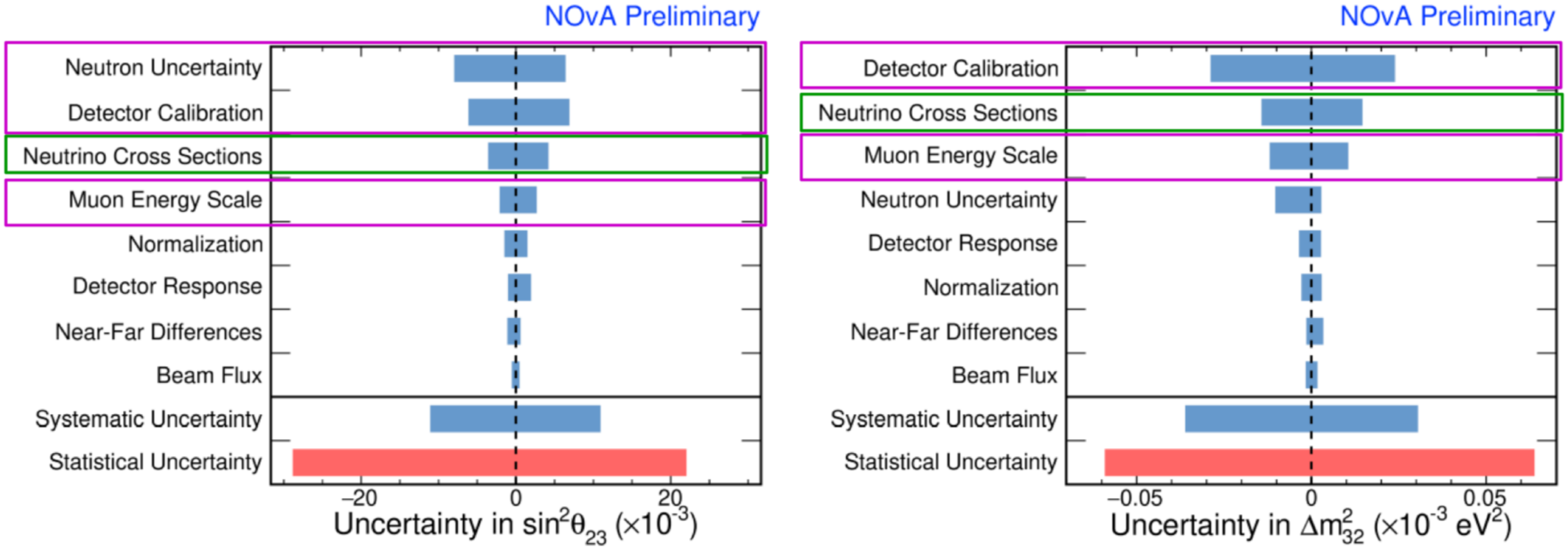
We simulate the effect of our cross section systematics' *residual* effect after extrapolation

by re-doing the entire analysis for each systematic

and use the difference to extrapolated nominal MC as nuisance parameters in our oscillation fits

Effect on analysis

J. Wolcott



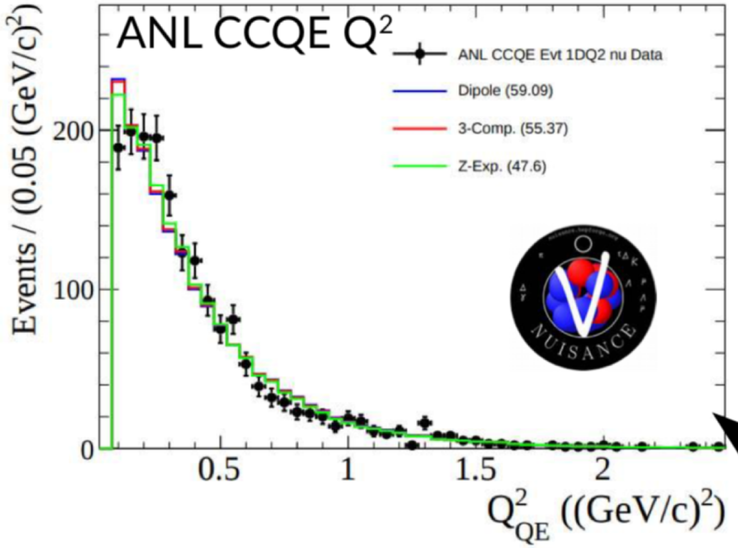
(Uncertainty on joint $\nu + \bar{\nu}$, $\nu_\mu + \nu_e$ fit)

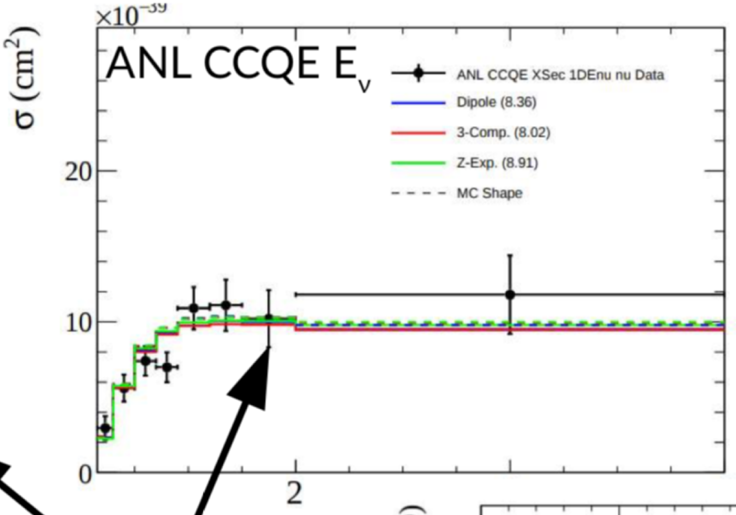
Cross section systematics are not dominant systematic uncertainties due to detector design & power of extrapolation.

But... dedicated **test beam program** (see A. Sutton, poster #205) will drive detector response uncertainty down in the future, so soon enough cross sections will likely be atop the list...

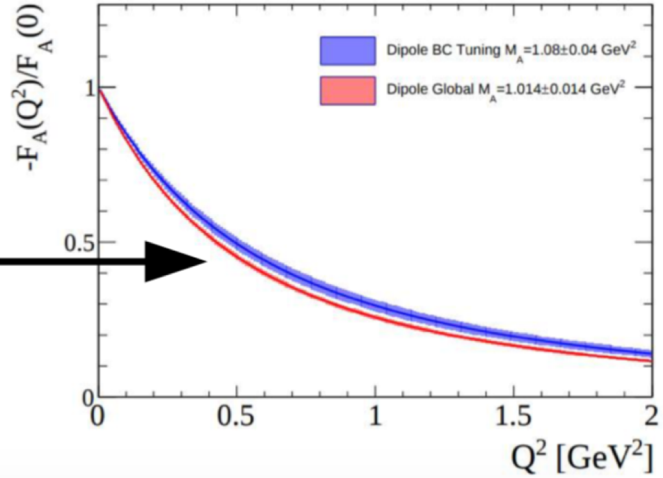
External constraints, CC0π

- M_A^{QE} is initially set to 1.2 GeV/c², but entirely free in ND280 fit
  - Fitting to corrected ANL, BNL, FNAL data, M_A^{QE} = 1.08 ± 0.04 GeV
  - Also fit alternative form-factors, z-expansion and three component





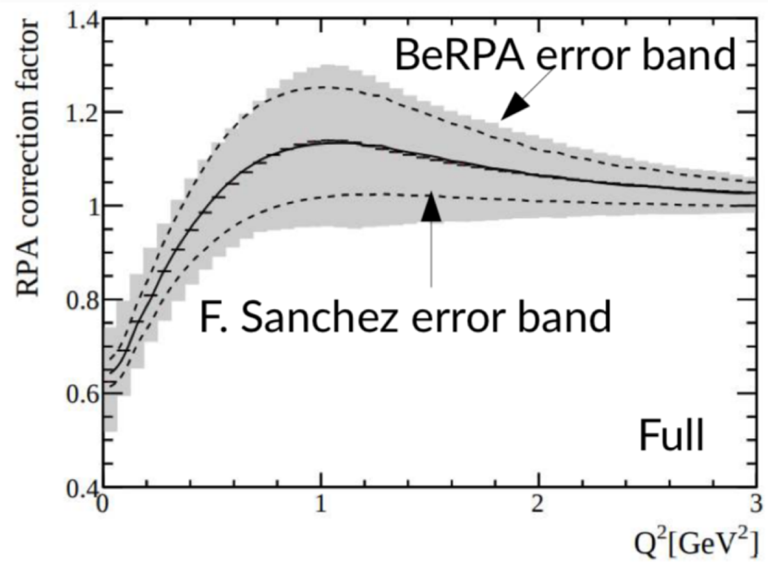
- Z-expansion and three-component better fit than dipole
- Error band for z-expansion is ~constant with Q²: not the case for dipole

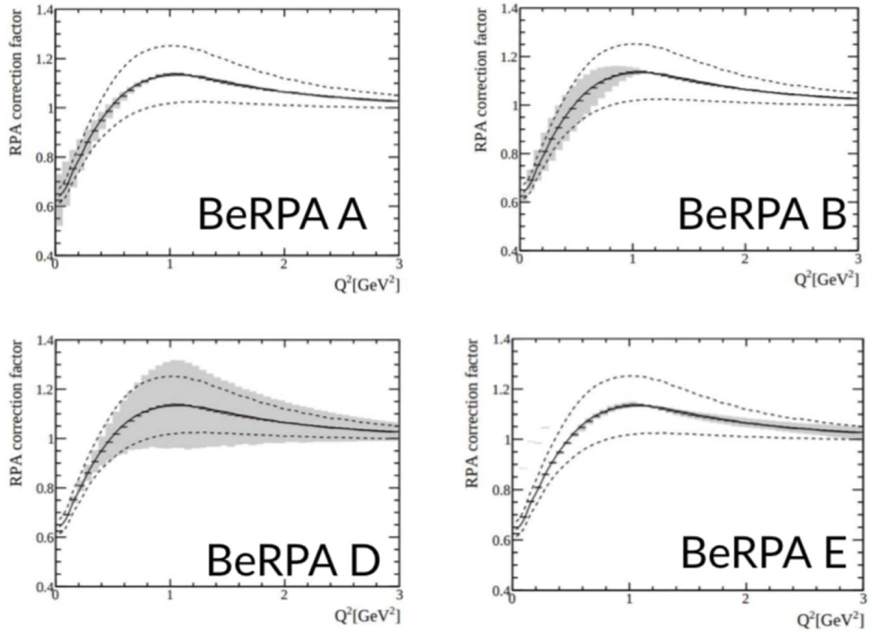


External constraints, CC0π

Phys. Rev. D 88, 113007

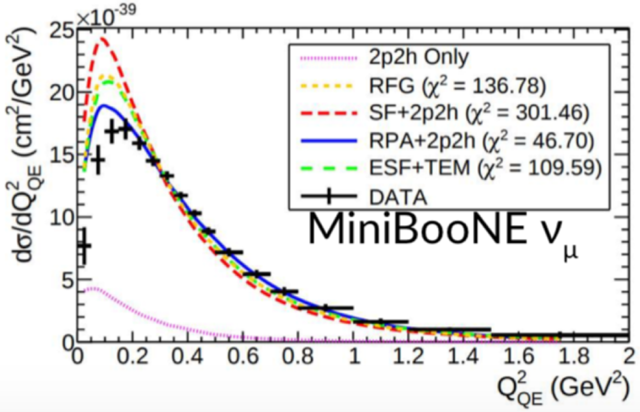
- 5 RPA parameters constrained by the 1σ band from F. Sanchez

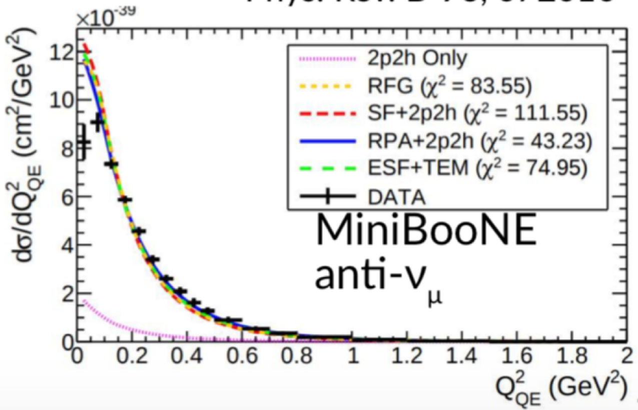




- RFG chosen over SF (Benhar)
  - Fit to MiniBooNE and MINERvA data

Phys. Rev. D 93, 072010

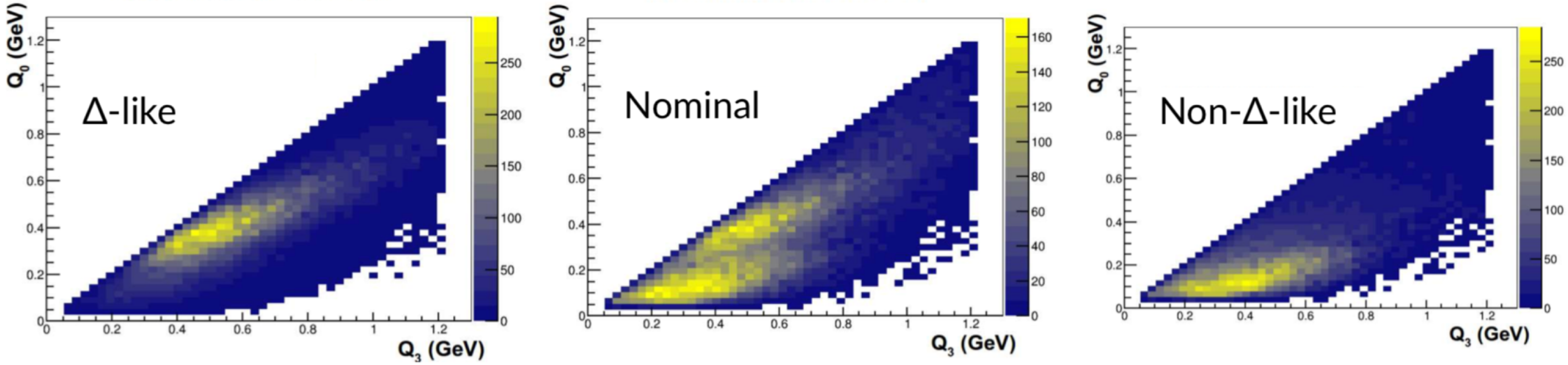




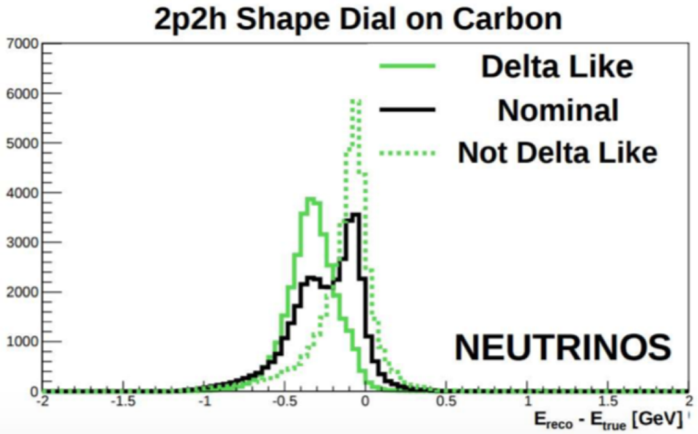
C. Wret

External constraints, 2p2h

- 2p2h shape parameter puts the 2p2h as Delta-like or non-Delta like in Nieves model
  - Separated for Carbon and Oxygen and correlated 30%

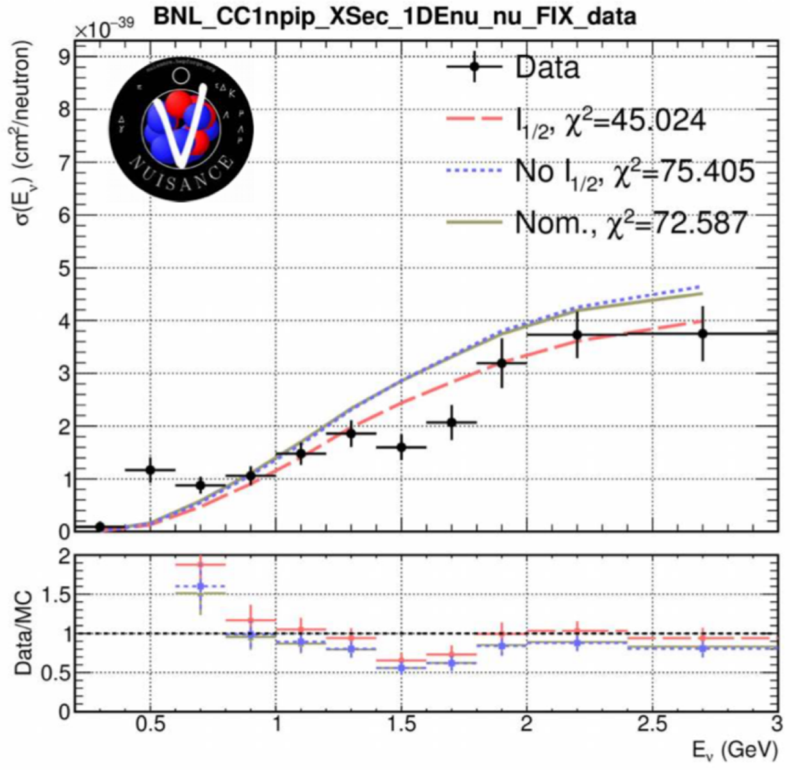


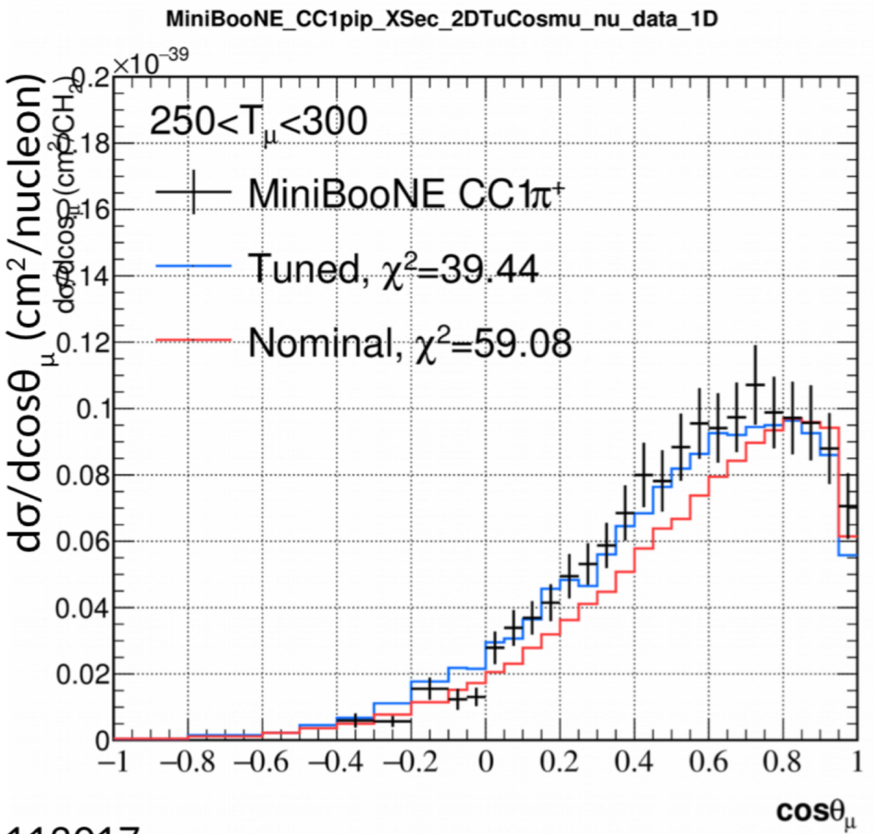
- 2p2h normalisation parameters for ν and anti-ν
- Constrained 2p2h C→O extrapolation normalisation parameter: 30% uncertainty
- No constraints from external data



External constraints, CC1π

- Rein-Sehgal tuned to nucleon data* in all channels, W < 2.0 GeV
  - Cross-checked against FNAL and GGM, and the W < 1.4 and W < 1.6 GeV data
  - Parameter inflation to roughly cover predictions for MiniBooNE and MINERvA in muon variables





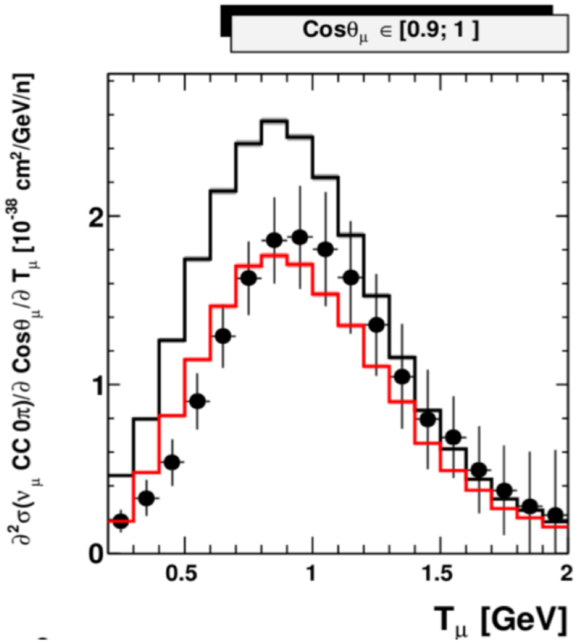
*ANL, BNL correction in Phys. Rev. D 90, 112017

GENIE version 2.12.X

Models	Default	Example of Alternative
Nuclear Model	Bodek-Ritchie Relative Fermi Gas(RFG with short-range correlations)	Local Fermi Gas(LFG) effective spectral function model
CCQE	Llewellyn-Smith	Nieves
MEC	Empirical	Nieves
Resonance	Rein-Sehgal	Berger-Sehgal
FSI	hA	tuned hA
Nonresonant	Scaled Bodek-Yang	Scaled Bodek-Yang
Diffractive		Rein's Model
Charm Production	QEL-CC: Kovalenko's model DIS-CC: Aivazis' model	QEL-CC: Kovalenko's model DIS-CC: Aivazis' model DIS-CC: Alam Simo Athar model
SingleK Production		
LAMBDA Production		QEL: Pais's model

- Nieves QE Model: includes Random Phase Approximation(RPA), in-medium propagator effects and Coulomb effect.
- Berger-Sehgal: Lepton Mass Correction.
- Bodek-Yang vs Scaled Bodek-Yang: scaled Bodek-Yang uses a factor that decreases model strength to get agreement with data.
- hA : is tuned to π^{+}-^{56}Fe and p-^{56}Fe data, then extrapolated to other targets based on $A^{2/3}$ scaling(where A is the atomic number).

GENIE version 2.12.X: default vs alternate



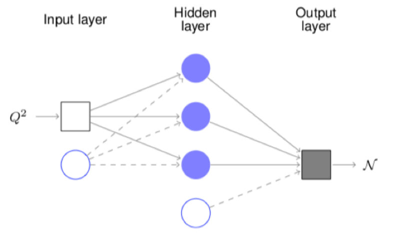
- Black Dots: MiniBooNE QE data; Black Curve L-S; Red Curve: Nieves.
- Figure on the left side shows double differential cross section with respect of the muon's momentum of the CC QE from MiniBooNE.

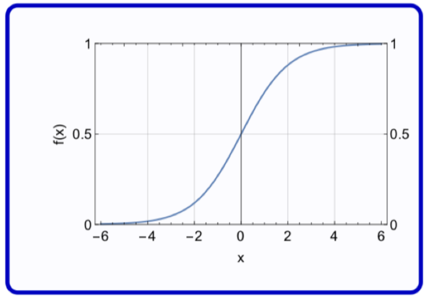
E. Saúl Sala

Neural networks

Feed-forward NN in a multilayer perceptron (MLP) configuration:

- Nonlinear map $\mathcal{N} : \mathbb{R}^{\text{in}} \mapsto \mathbb{R}^{\text{out}}$





- For every unit:

$$y_{i,k} = f^{i,k}\left(\sum_{u \in \text{previous layer}} w_u^{i,k} y_{u,k-1}\right)$$

Activation function:

- $f(x) = \frac{1}{1+\exp(-x)}$.

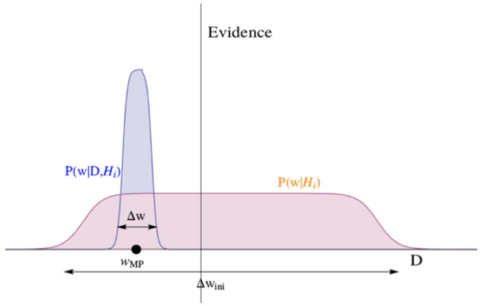
Bayesian framework for MLP

Evaluating the evidence:

- For many problems the posterior has a strong peak at $\mathbf{w}_{\text{MP}}$

$$\underbrace{\mathcal{P}(\mathcal{D} \mid \mathcal{N}_M)}_{\text{Evidence}} \approx \underbrace{\mathcal{P}(\mathcal{D} \mid \mathbf{w}_{\text{MP}}, \mathcal{N}_M)}_{\text{Best fit likelihood}} \underbrace{\mathcal{P}(\mathbf{w}_{\text{MP}} \mid \mathcal{N}_M)\, \Delta\mathbf{w}}_{\text{Occam factor}}$$

- Interpretation of the Occam factor for one parameter:



Occam factor penalizes complex models:

- Δw is the posterior uncertainty in w
- Assume uniform on large interval Δw_{ini}
- $\mathcal{P}(w_{\text{MP}} \mid \mathcal{N}_M) = \frac{1}{\Delta w_{ini}}$

$$\text{Occam factor} = \frac{\Delta w}{\Delta w_{ini}} \rightarrow \frac{V(\text{Posterior})}{V(\text{Prior})}$$

J.C. MacKay, Neural Computation 4, 415 (1992)

Analysis of ANL data

Neutrino-induced CCQE: $\nu_\mu(k) + n(p) \to \mu^-(k') + p(p')$

$$\frac{d\sigma_{\nu n}}{dQ^2} = \frac{G_F^2 m_N^2}{8\pi E_\nu^2}\left[A(Q^2) + B(Q^2)\frac{(s-u)}{m_N^2} + C(Q^2)\frac{(s-u)^2}{m_N^4}\right]$$

- A, B, C are functions of $F_{1,2}^V(Q^2)$ and $F_{A,P}(Q^2)$.
- $F_{1,2}^V(Q^2)$ from electron scattering data. $F_P(Q^2)$ given in terms of $F_A(Q^2)$
- Events:

$$N^{th} = \int_0^\infty dE_\nu \frac{d\sigma}{dQ^2}(E_\nu, F_A, Q^2)\phi(E_\nu)$$

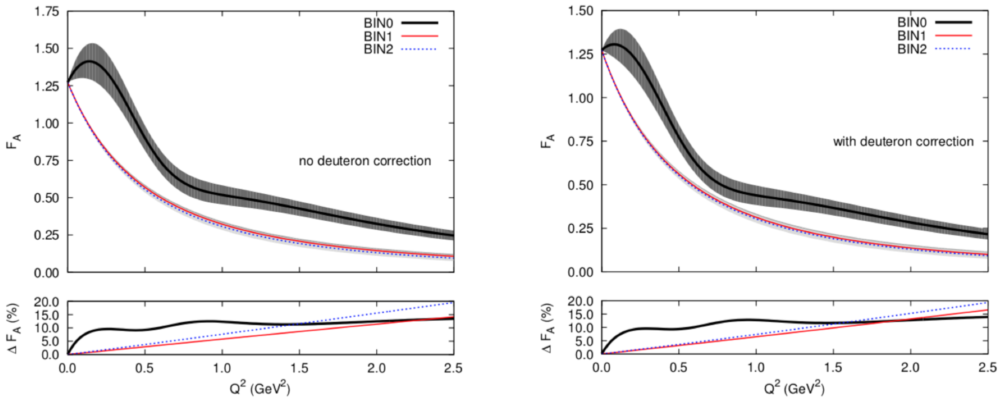
- Neutrino flux:

$$\phi(E_\nu) = p\frac{1}{\sigma(E_\nu, F_A)}\frac{dN}{dE_\nu}$$

-

$$\chi^2 = \left(\frac{F_A(0) - g_A}{\Delta g_A}\right)^2 + \sum_{i=k}^{n_{\text{ANL}}} \frac{(N_i - N_i^{th})^2}{N_i} + \left(\frac{1-p}{\Delta p}\right)^2 \qquad \Delta p = 20\%$$

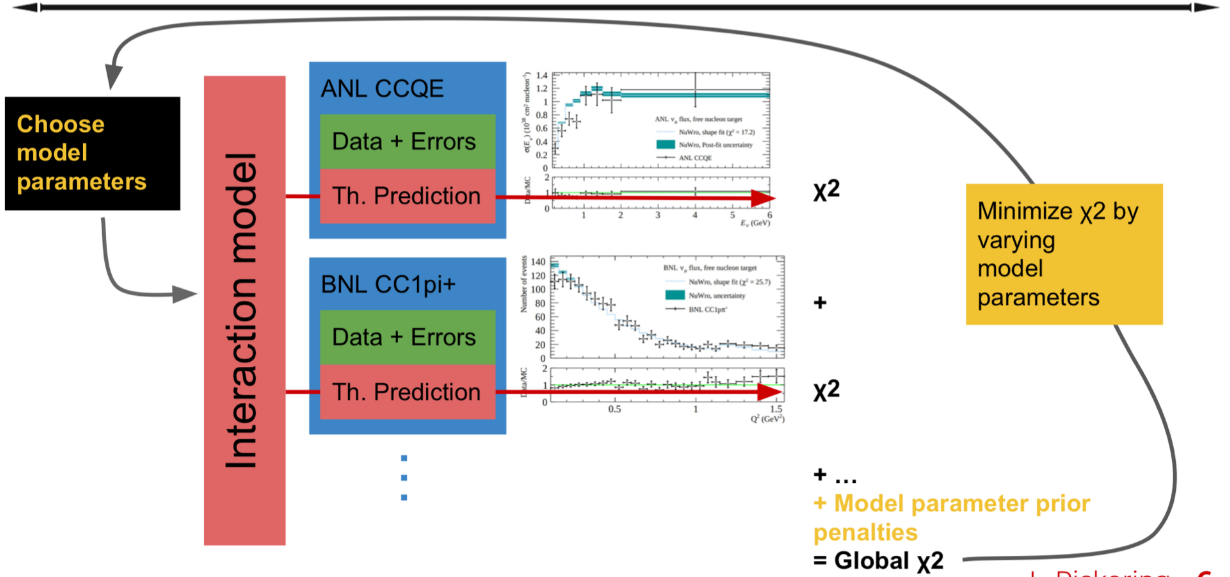
Best fits; $F_A(Q^2)$ functions:



- BIN0: all ANL bins included.
  - $r_A^2 < 0$ **incompatible with previous results.**
- BINk: ANL bins without the first k bins.

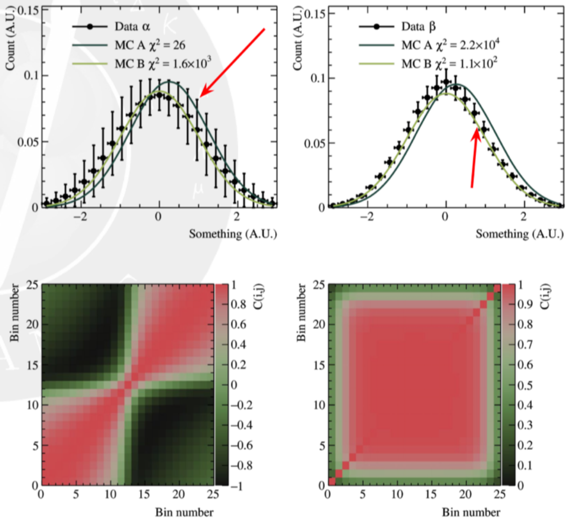
L. Pickering

Anatomy of a Cross-section Fit



What you expected?

Systematic parameter allows shift in Something. *e.g.* separation energy



Systematic parameter allows normalization change. *e.g.* flux uncertainty.

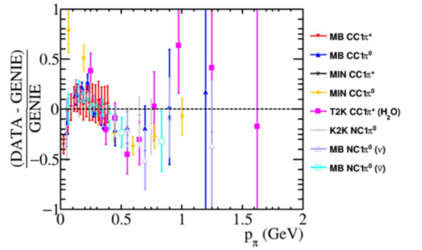
MICHIGAN STATE UNIVERSITY

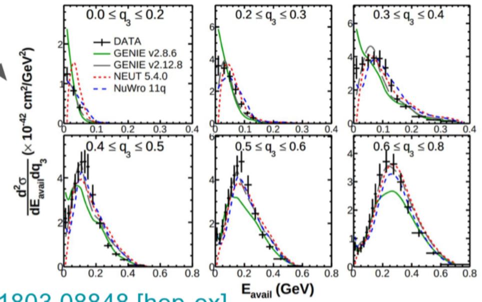
What a NUISANCE

- Global neutrino scattering data comparator and model fitter:
  - Contains hundreds of published data sets with associated errors and signal definitions.
  - **The most valuable part of NUISANCE is the person-hours that have been spent checking that these are implemented correctly as possible!**
- Applies experimental signal definitions to MC events from: GENIE, NEUT, NuWro, GiBUU, HepMC, ...
- Links to MC event generator interaction systematic uncertainty tools for model parameter fitting.
- Code is open source so analyses can be reproduced and extended: https://nuisance.hepforge.org/

Why NUISANCE might be right for you

- Consistently comparing your model predictions to many data-sets.
- Producing comparisons to your new data set with a variety of MCs --- without having to be an expert.
- Ensuring that comparisons to your data are done correctly.
- Tools make cross-section parameter fitting mechanically simple:
  - **But, garbage in → garbage out.**
  - Choice of data, choice of parameters, structure of fit is the tough bit.





1803.08848 [hep-ex]

Lots of interesting talk, exciting results, and fruitful discussions

- Total 23 talks = 8 Theory + 12 Experimental + 3 Generator

- Thanks to all the speakers and participants!

The (difficult) task in hand

Theory side

- Description of the initial state of nucleus, covering known nuclear effects, e.g. correlatations, etc. Plus, this for many nuclei 12C, 16O, 40Ar, ….., etc.

- Description of electroweak response of the nucleus for different kinematics that cover, Giant-resonance, QE, dip-region, delta production, SIS and DIS region – in a coherently consistent way (reminder: quantum mechanism).

- Resulting into final states where outgoing particle and their energies are subject to be altered by FSI.

- For different neutrino flavours – ν_e , ν_μ

Experimental and Generator side:

- Observed final state topologies and their energies (altered by detector limitations) and *affected by physics in generators* which enters in not only by linking observed final states to interaction vertex but also affects the estimation of efficiencies, acceptances, background, etc.

- CCInclusice, CC0pi, CCpi0, CCpi+, ….., NC0pi, …….., etc.

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- Many interesting developments and lots of hard work both at theoretical and experimental front.

- But as a community we need to consider that solving these issues is a huge task and it will require proper structural changes specially in terms of supporting nuclear theorists, who are more likely not funded to perform neutrino scattering calculations.

- Are we getting close to where we plan to be? Or we are making it more complicated by taking (hard-working) short-cut (by trying to fix it through Frankenstein-like mix ups)?

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Theory

- Desc
  nucle

- Desc
  delta

- Resu

- For d

Experi

- Obse
  gene
  estin

- CCIn

Nevertheless, we have exciting future ahead! Let's hope for the best!