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# Neutrino interactions - experimental and theoretical developments

Gabriel N. Perdue
Fermilab
August 2nd, 2017

# A review of neutrino-nucleus interactions: overview

**Story for today:**

- Strong recent progress by experiments - driven by improved understanding of modeling and the power of model independent measurements becoming the norm.
- Particle theorists are engaging with the problem - new focus on improved nucleon-level physics, bridging from free nucleons to a nuclear environment, and beginning to bring understandings about nuclear modeling from electron scattering into neutrinos.

**Pion production**

**Superscaling** **Lattice QCD**

**Nuclear Many Body Theory**

**Important Acknowledgements:**
This is a review, so I've drawn from numerous presentations by a variety of people. I've tried to provide attribution wherever I use a figure no matter how "small". Thank you to everyone who helped without knowing it!

Full disclosure - I work on MINERvA, GENIE, may show some biases…



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Introduction

# A very brief motivation

- Current and future neutrino oscillation experiments have a very ambitious program.
- U. Mosel, NuInt 2017: **DUNE is "an impossible" experiment**:
  - Flux not fully specified,
  - Beamline is over 1,000 km, diameter is over 1 km at Far Detector,
  - Cross sections are tiny ($10^{-11}$ mb) and plagued by numerous theory and experimental uncertainties,
  - Somehow we need to extract evidence of physics beyond the Standard Model!
- **Control of cross section systematics is a critical piece** - requires a multi-pronged effort involving theorists, experimenters, and and Monté Carlo authors all **working together**.
  - No single measurement or calculation will solve it all!

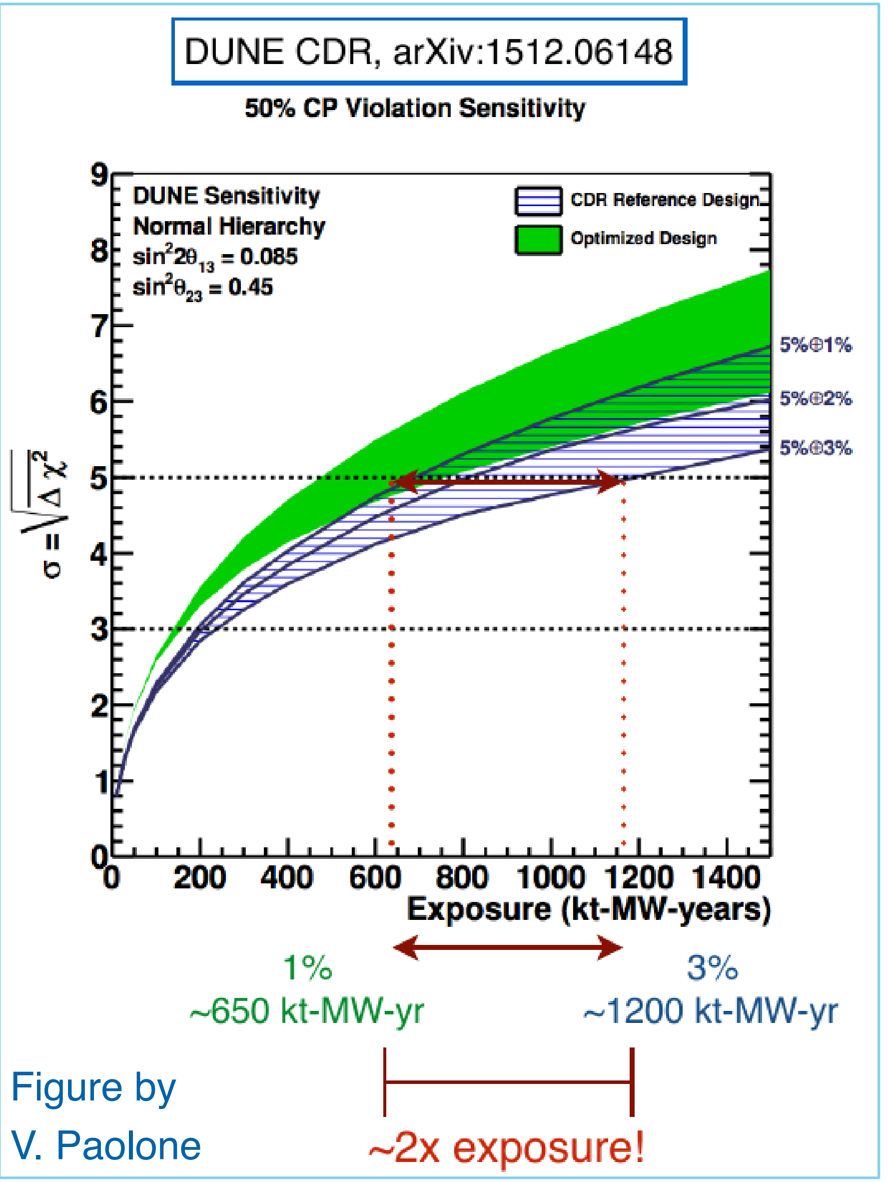
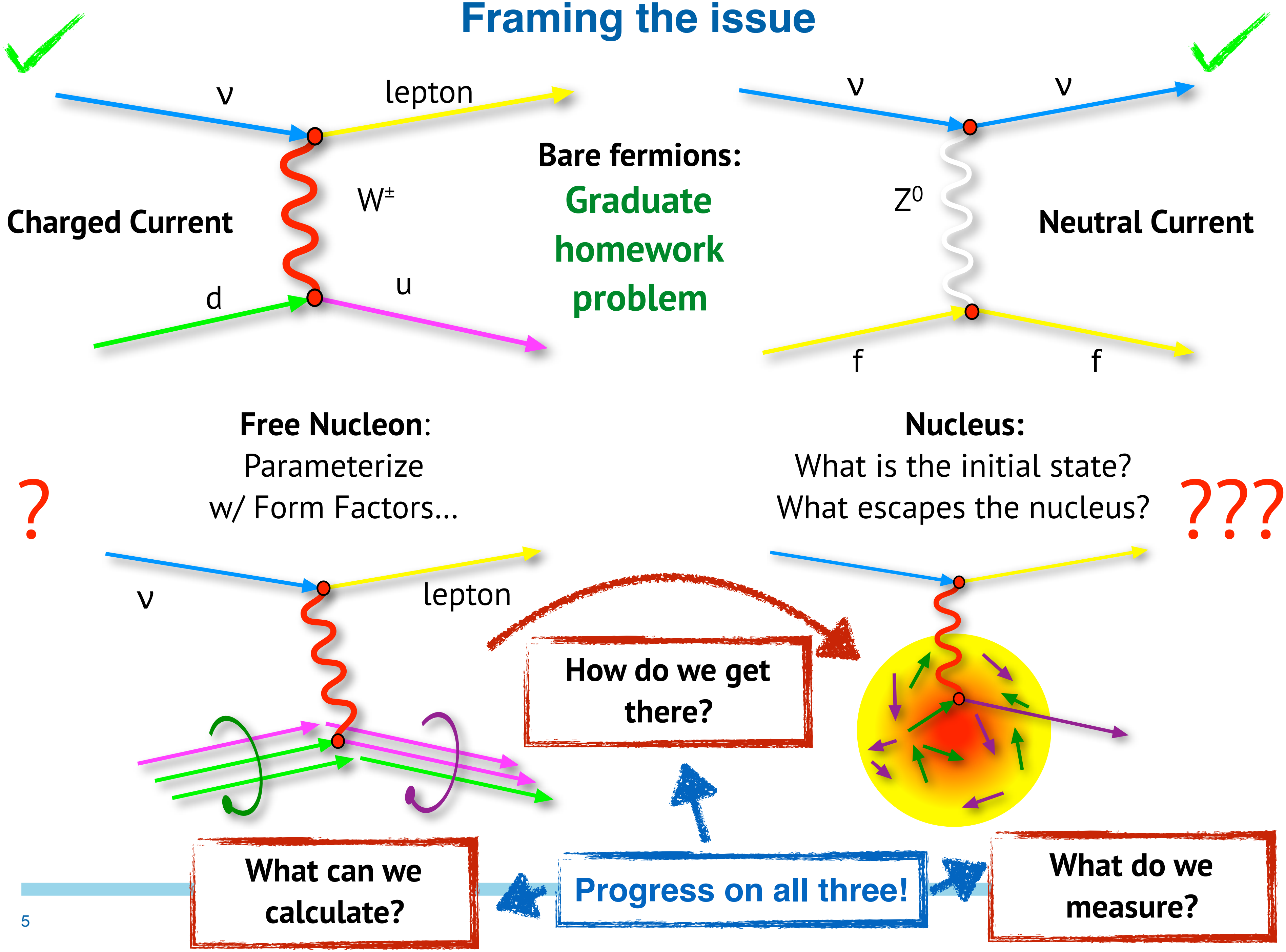


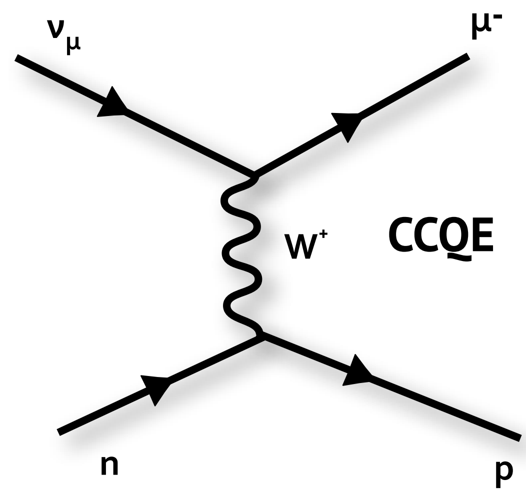

Figure by V. Paolone

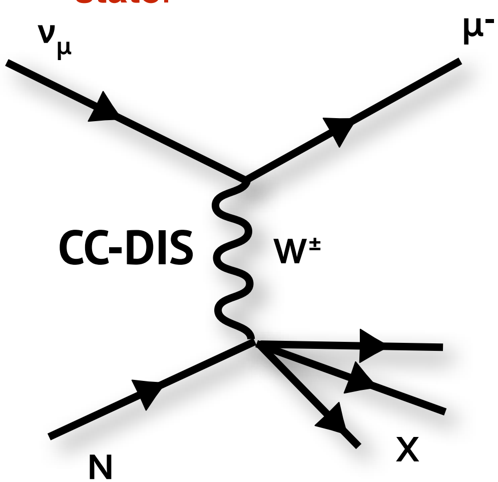
# Framing the issue

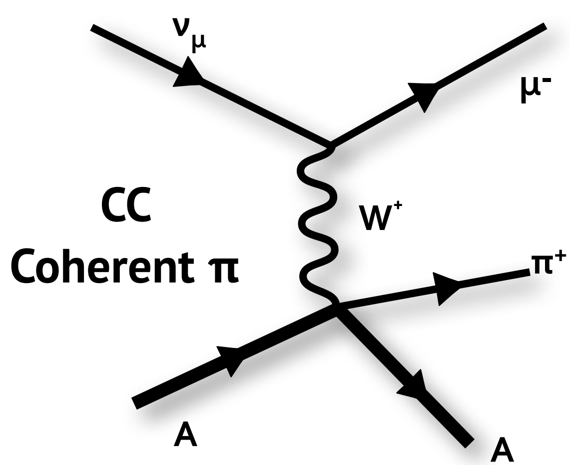


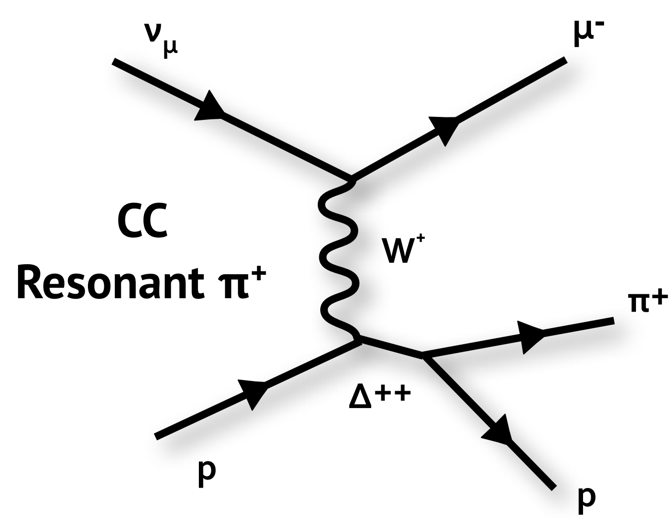
# Reaction Channel Menagerie: A Glossary

- Charged current: exchange a W boson; neutral current: exchange a Z (not shown) - no charged lepton in the final state for NC.
  - CCQE : Charged-Current Quasi-Elastic
  - CC $\pi^{\pm}$, $\pi^0$
    - Coherent (no break-up) & Resonance Production
  - Deep Inelastic Scattering (DIS - scatter on a parton)
- **Our descriptive language is something of a historical accident**. These terms are really only proper when discussing scattering on **free nucleons**.
  - When scattering on nuclei, final state interactions (FSI) mix up the particles leaving the nucleus, making this sort of assignment impossible.
  - Modern language prefers **specification by visible particles in the final state**.

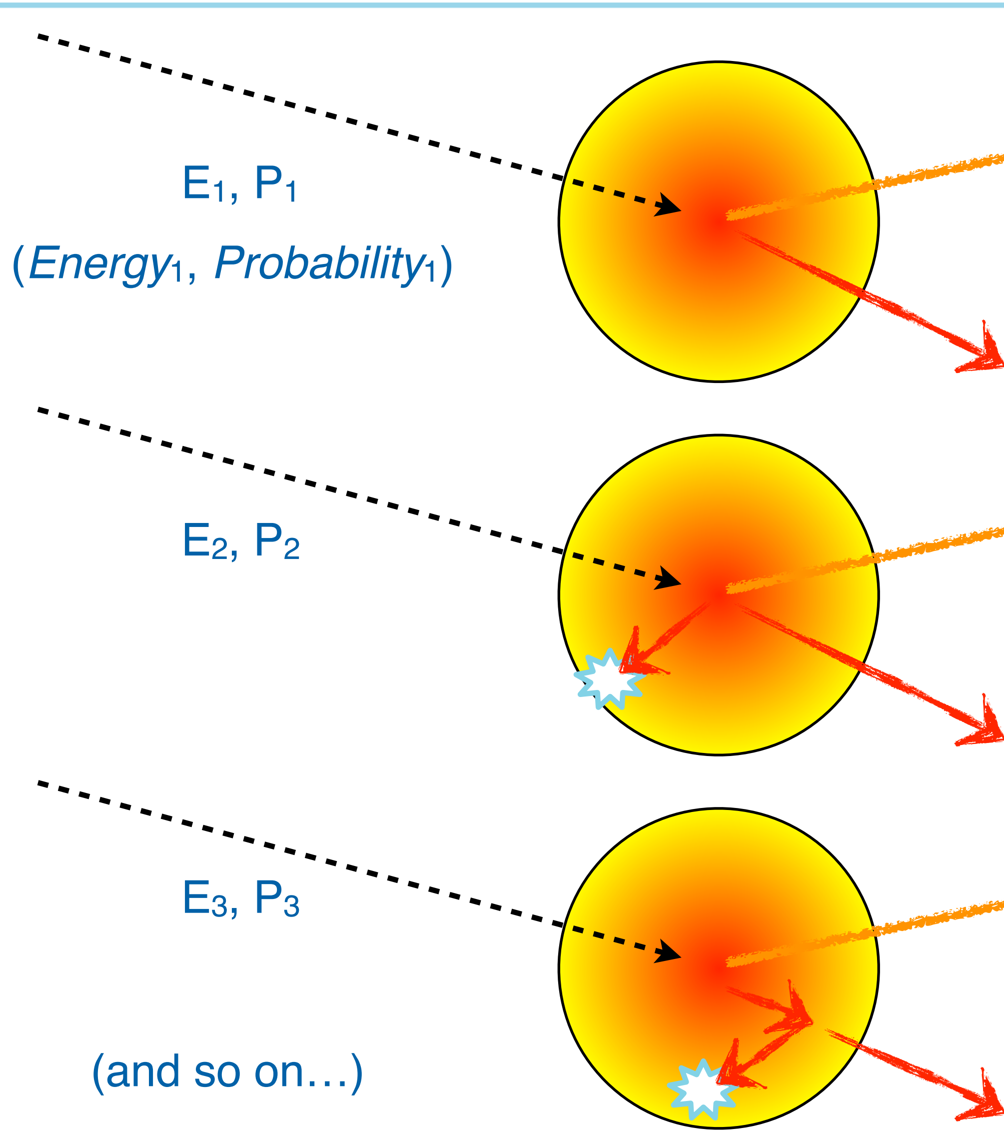


# The Basic Problem: we must interpret with *models*




We must leverage every possible observable!

**$E \sim E_1P_1 + E_2P_2 + E_3P_3 + \ldots$**

Need to integrate - we interpret results statistically using *event generators.*

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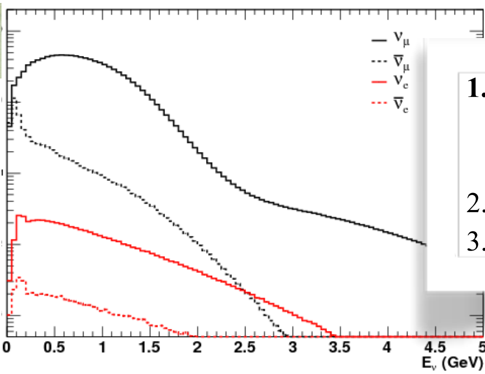
# Organizing the challenges - NuSTEC

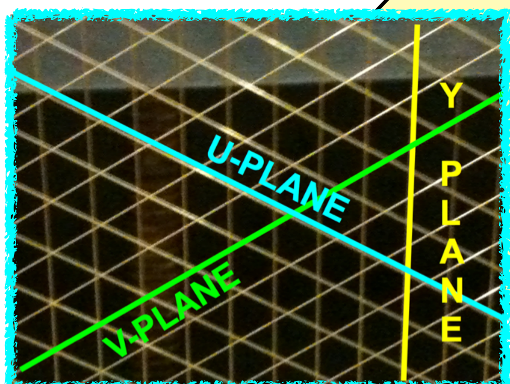
- New paper from NuSTEC (http://nustec.fnal.gov) outlines the **current challenges** facing the field of neutrino-nucleus scattering
  - https://arxiv.org/abs/1706.03621 (I am one of the authors)
- The paper summarizes
  - the impact of **interaction uncertainties on oscillation physics**,
  - the role of **event generators** in accelerator-based neutrino experiments,
  - how **electron-nucleus scattering** experiments inform our understanding of neutrino-nucleus scattering,
  - our **current understanding of the various interaction channels** (ranging from the elastic regime through deep inelastic scattering).
- This presentation was inspired by the structure of the NuSTEC paper, with additional emphasis specifically on new results from the past year.
  - NOTE: while neutrino flux estimation is *central* to understanding the results of neutrino-nucleus scattering experiments, we don't have space to do the topic justice here.

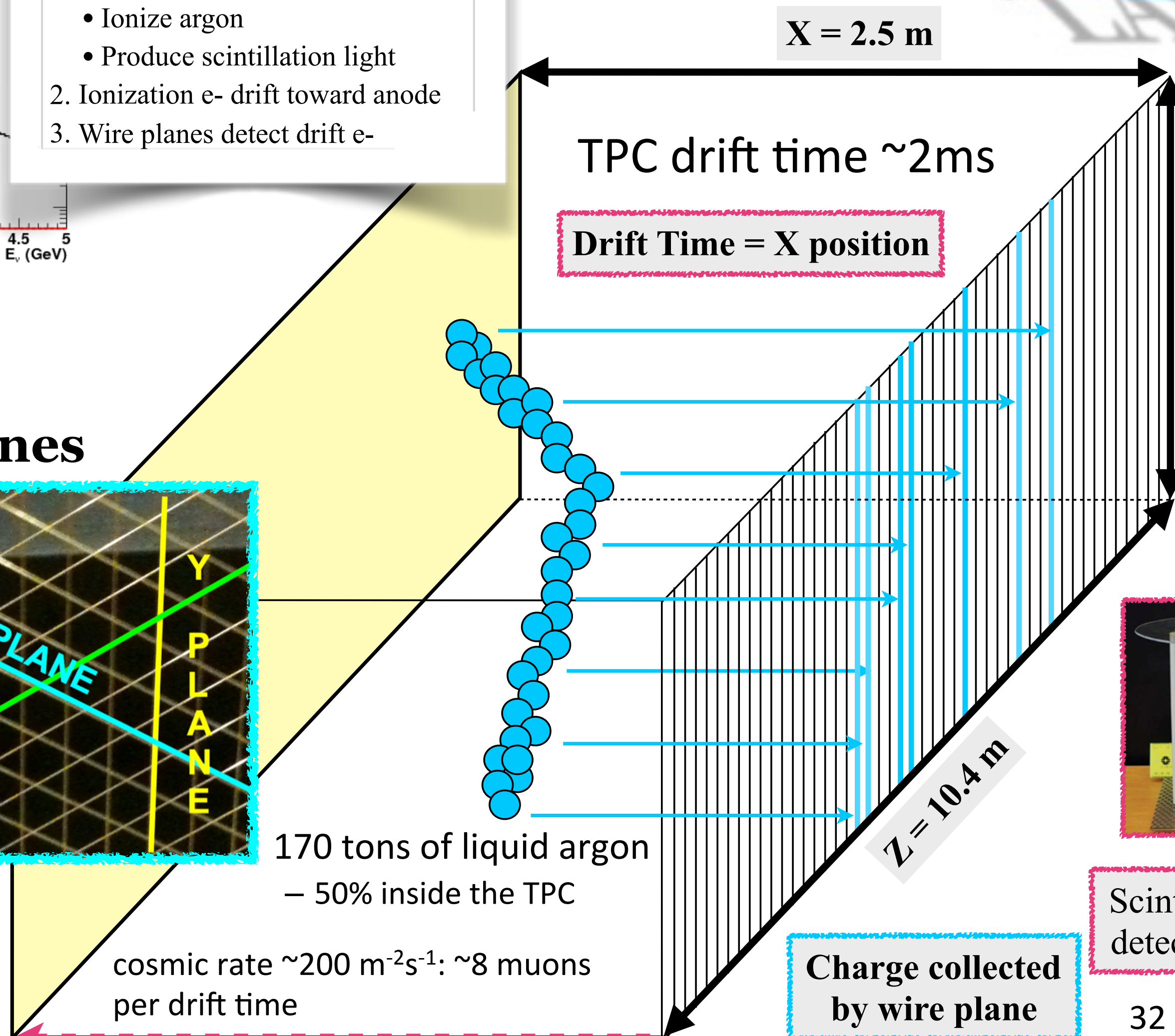
# New Results: Experiment




1. **Charged particles interact in Ar**
   - Ionize argon
   - Produce scintillation light
2. Ionization e- drift toward anode
3. Wire planes detect drift e-

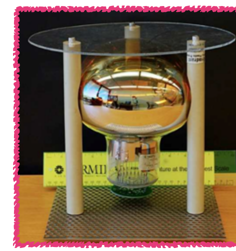
## Three Wire Planes




170 tons of liquid argon
– 50% inside the TPC

cosmic rate ~200 $m^{-2}s^{-1}$: ~8 muons per drift time



**Charge collected by wire plane**

Scintillation Light detected by PMTs

32 eight-inch PMTs for scintillation light (fast)

**Cathode @ 70 kV (plate)**

**Electric Field ~270 V/cm**

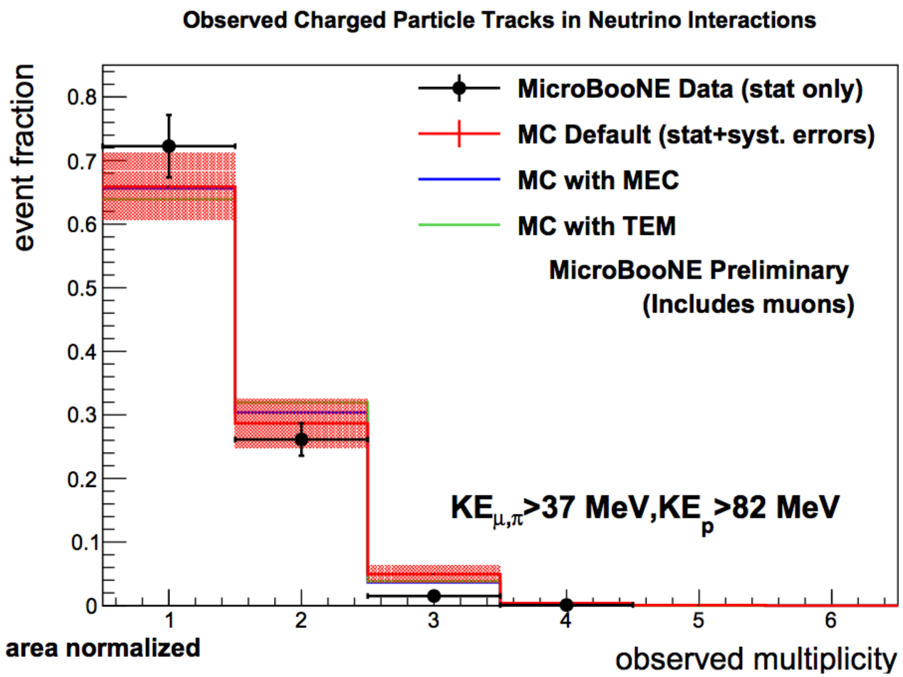
**Anode (wire plane)**

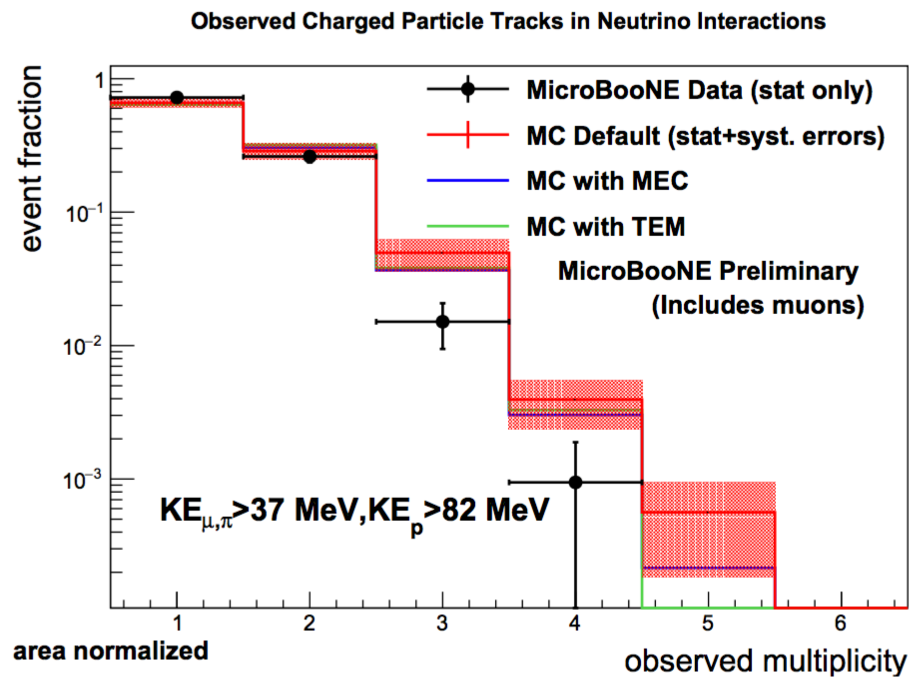
Figures: Kazuhiro Terao, SLAC & Andy Furmanski, Manchester

R. Acciarri et al 2017 *JINST* **12** P02017 **@Microboone**

# Charged particle multiplicities

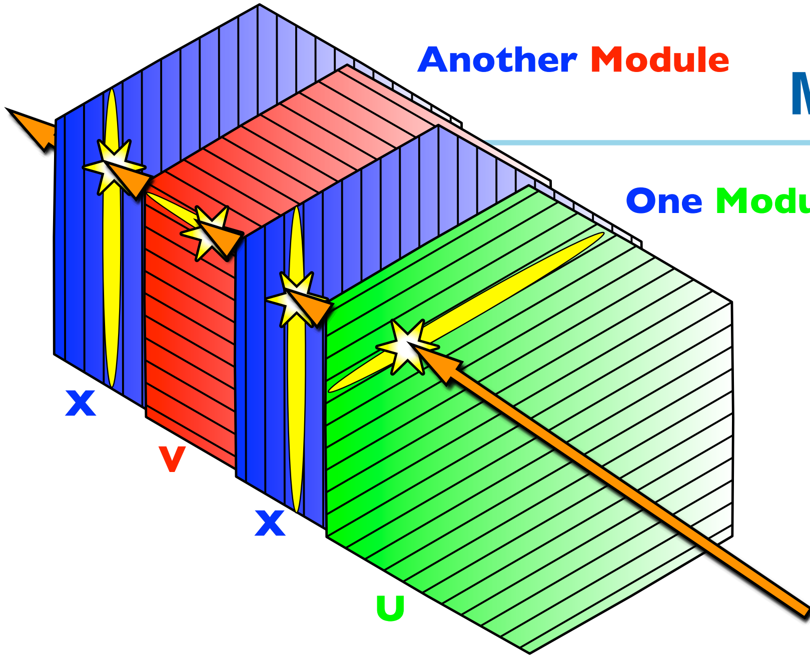
- **Model independent quantity!**
- Contained events with conservative quality requirements, fitting neutrino and cosmic components in 4 samples of varying purity.
- No efficiency or acceptance corrections, no separation into particle type, no background subtraction, conservative thresholds, and **systematics are not final**.

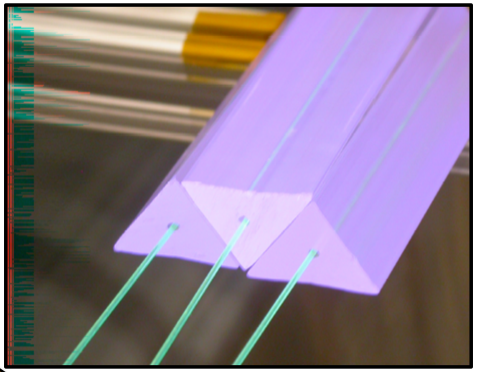



- See also
  - A. Rafique from Tuesday morning on charged particle multiplicities in MicroBooNE.

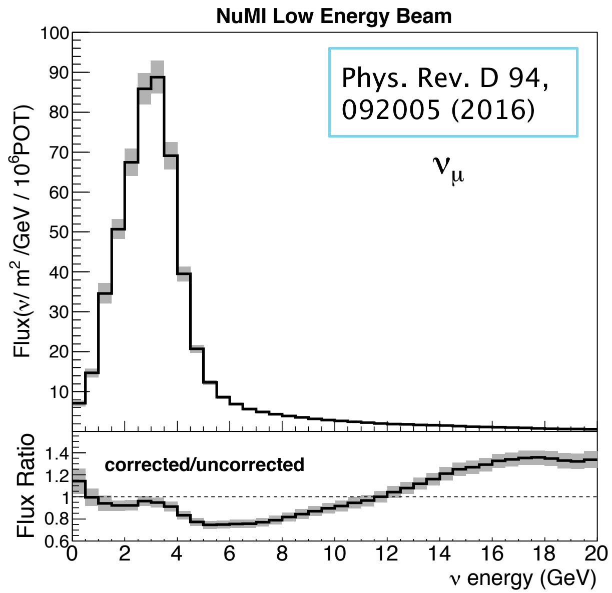
# MINERvA - Neutrino Scattering

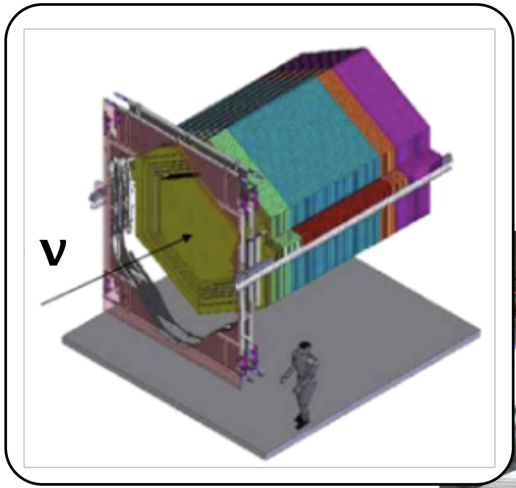


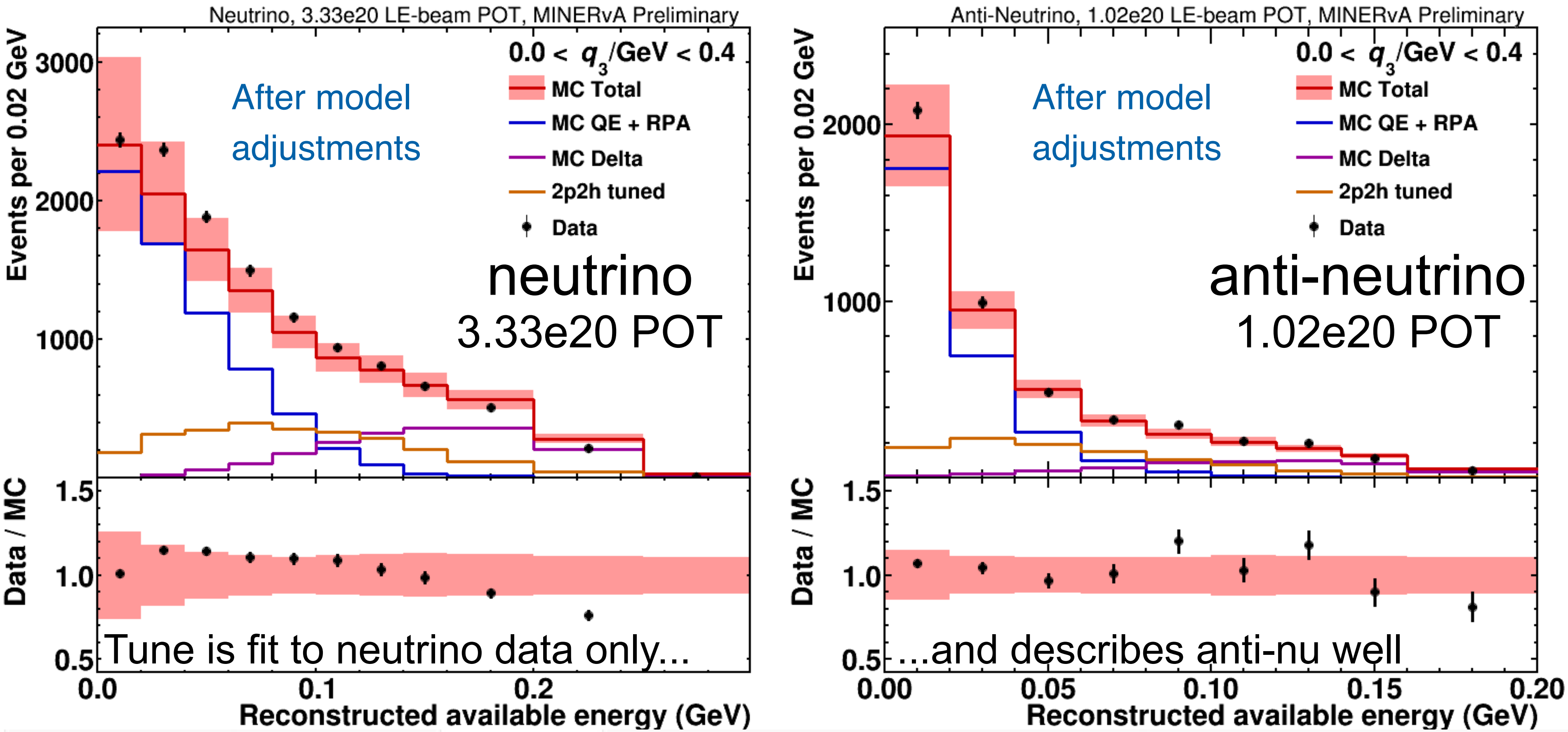
**@minervaexpt**

- Fine-grained, **high-resolution scintillator tracker** for detailed kinematic reconstruction of neutrino-nucleus interactions.
- **Cross-section** program.
- Nuclear effects with a **variety of target materials** ranging from Helium to Lead.




**Improved modeling:** By adding a weak charge screening model ("RPA"), a 2p2h model (Valencia), and re-weighting the 2p2h using hadronic energy for *neutrinos,* MINERvA is able to find very good agreement between their simulation and the *antineutrino* distributions as well.




Rodrigues, Demgen, Miltenberger et al. [MINERvA] PRL 116 071802

Valverde, Amaro, Nieves PLB 638 (2006) 325 with unpub. followup by F. Sanche plus muon capture uncertainty and implementation R. Gran, arXiv:1705.02932

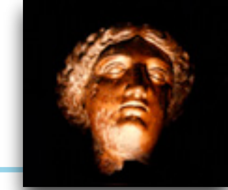
Nieves, Ruiz Simo, Vicente Vacas PRC83 (2011) 045501

Gran, Nieves, Sanchez, Vicente Vacas PRD 88 (2013) 113007

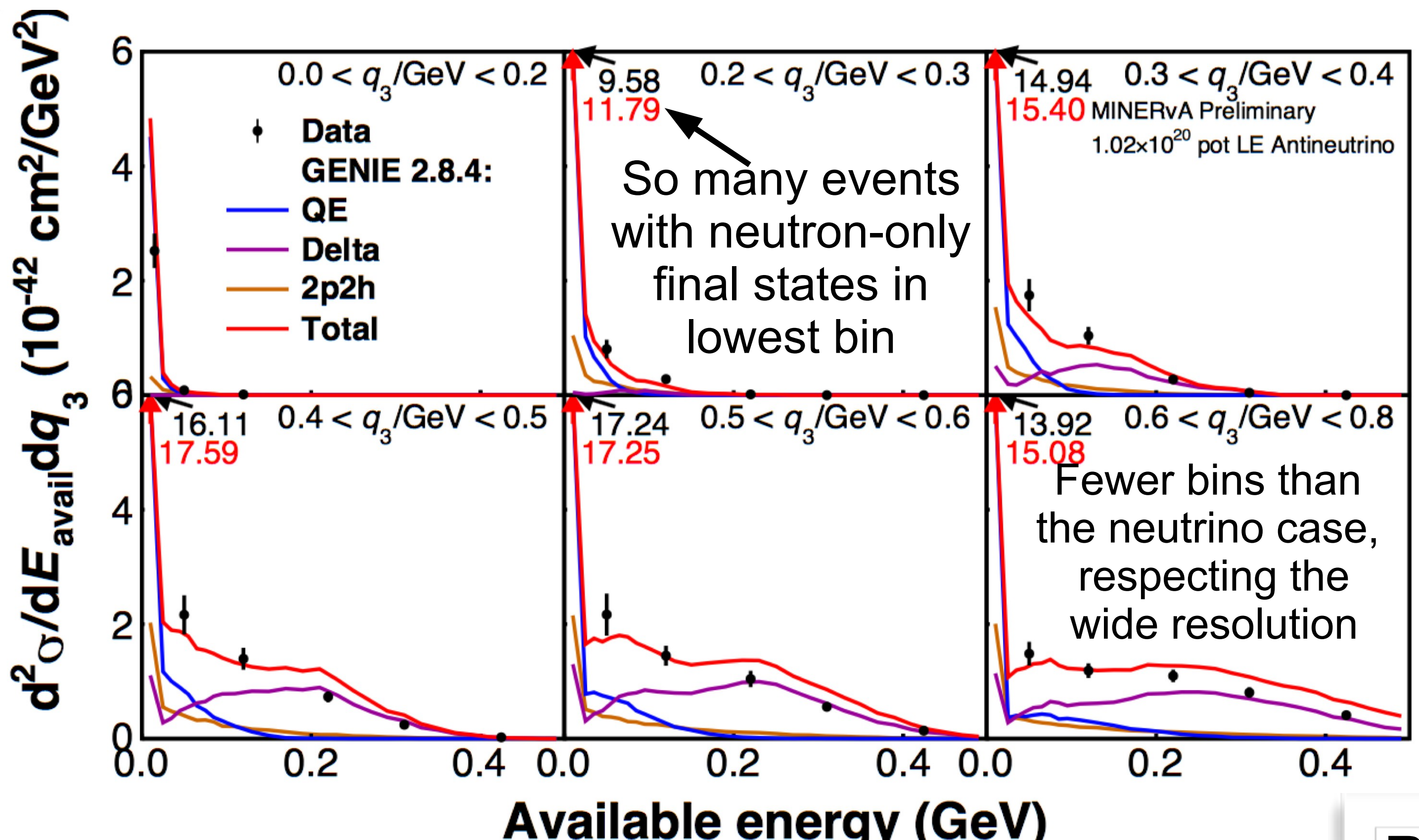
Rik Gran

NuInt17, Toronto

# Antineutrino CC inclusive “low recoil” cross sections



- Leverage improved modeling: Electron scattering “style” measurement in variables meant to separate QE, resonance peaks and isolate “dip region” 2p2h contributions.
  - Available Energy = proton KE + charged pion KE + neutral pion E + electron and photon E




(& J. Kleykamp here at DPF)

Rik Gran

NuInt17, Toronto

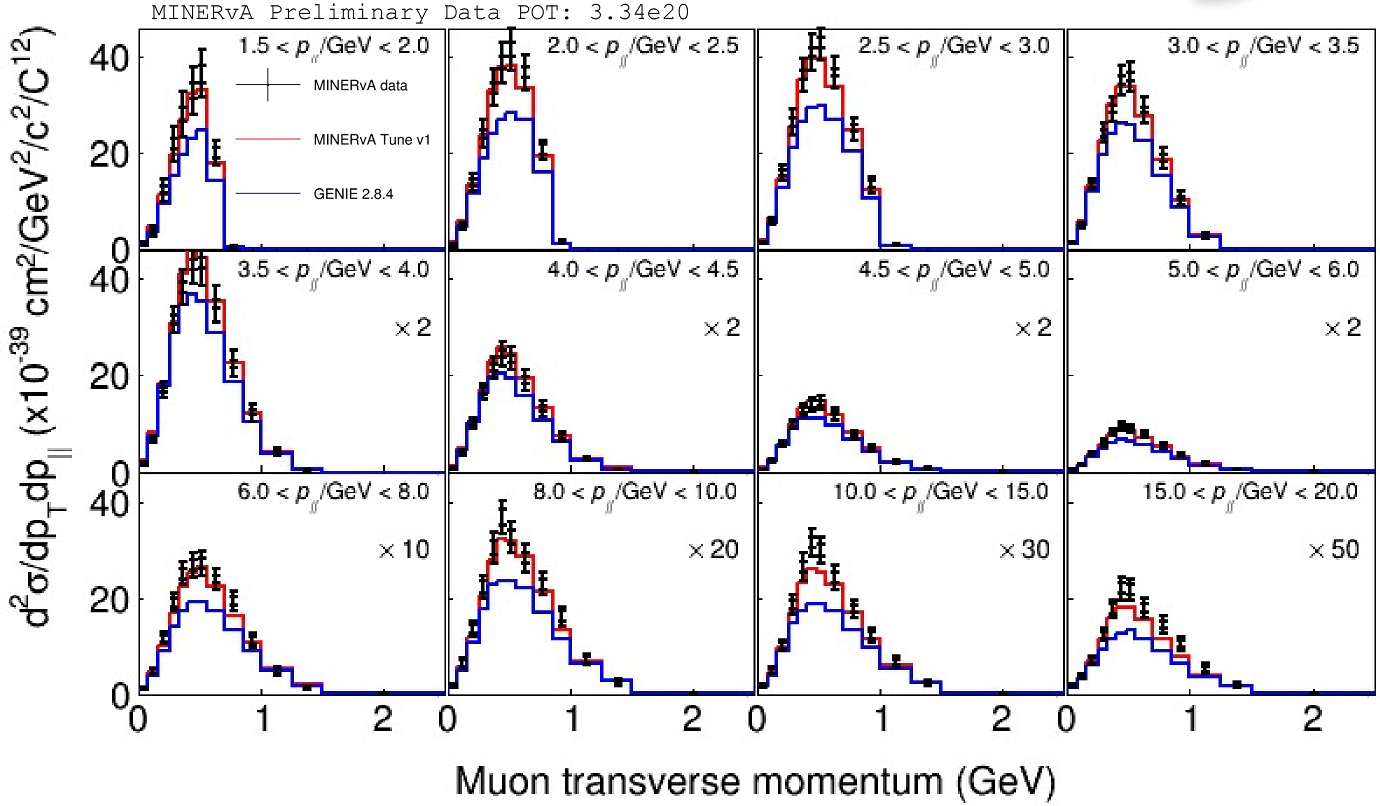
# MINERvA double-differential CCQE-like cross sections

Fiducial, QE-like:

**Model independent!**

ν-Result

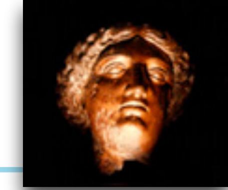
Daniel Ruterbories
NuInt 2017

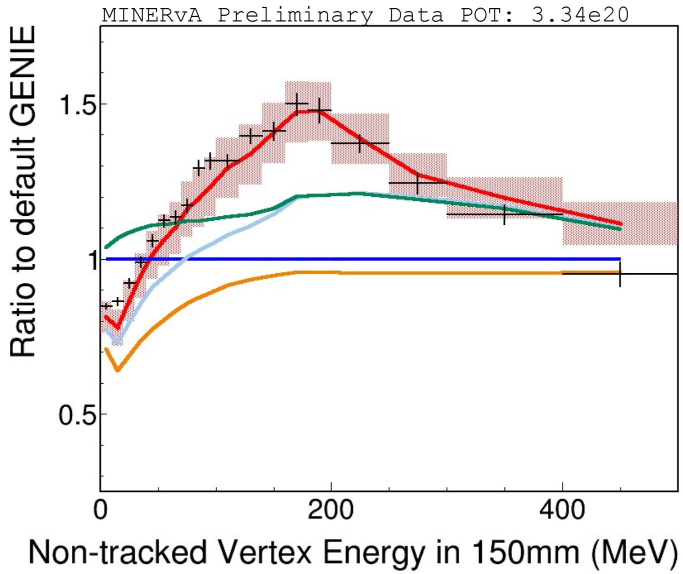


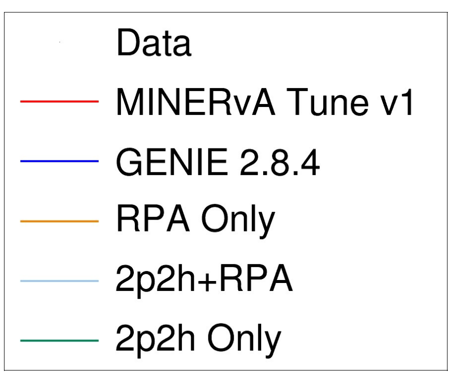

**(& J. Kleykamp here at DPF)**

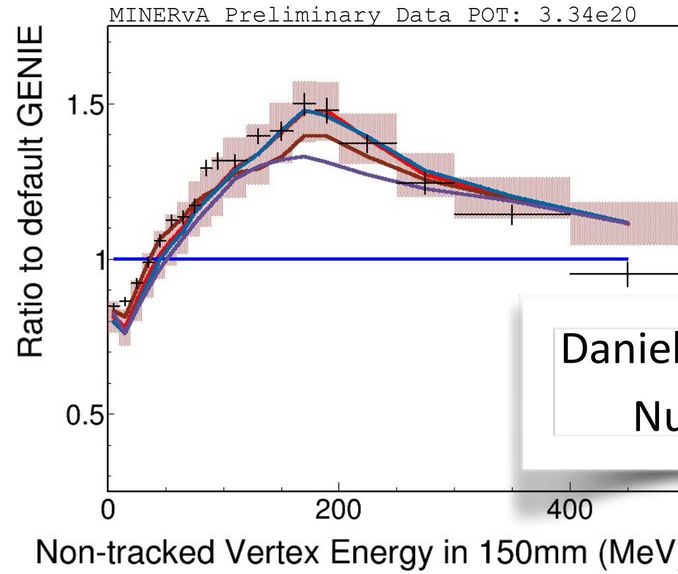
Similar results available for anti-neutrinos, see C. Patrick FNAL JETP, 2016 June 17

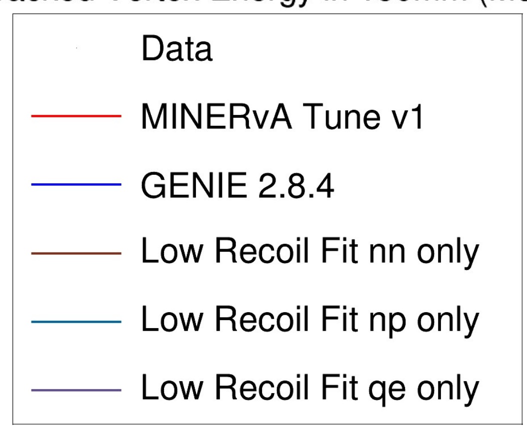
# Double-differential CCQE-like vertex E: model evolution






Daniel Ruterbories
NuInt 2017

**(& J. Kleykamp here at DPF)**

**Improved modeling!**

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Rodrigues, Demgen, Miltenberger et al. [MINERvA] PRL 116 071802

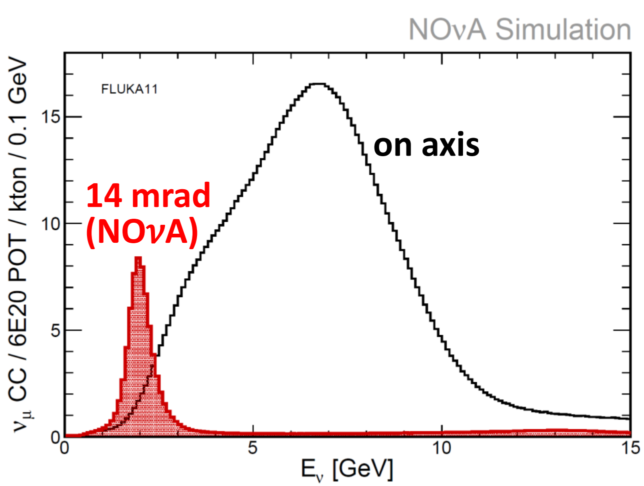
# More MINERvA cross sections at DPF

- See also
  - D. Rimal from Tuesday morning on Deep Inelastic Scattering in MINERvA.
  - L. Ren from Tuesday morning on antineutrino to neutrino charged-current cross section ratios in MINERvA.
  - A. Bercellie from Tuesday afternoon on the nuclear A-dependence of Quasi-elastic scattering in MINERvA.
  - J. Kleykamp from Tuesday afternoon on the double-differential CCQE cross section with lepton kinematics in MINERvA.

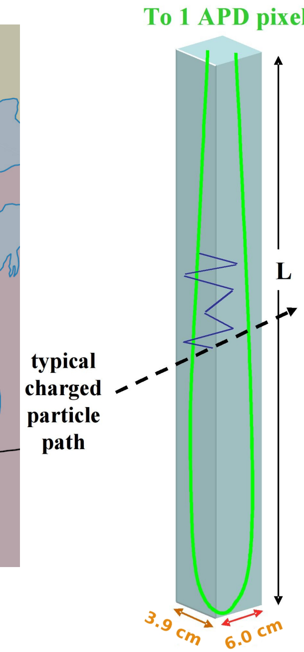
# NOvA

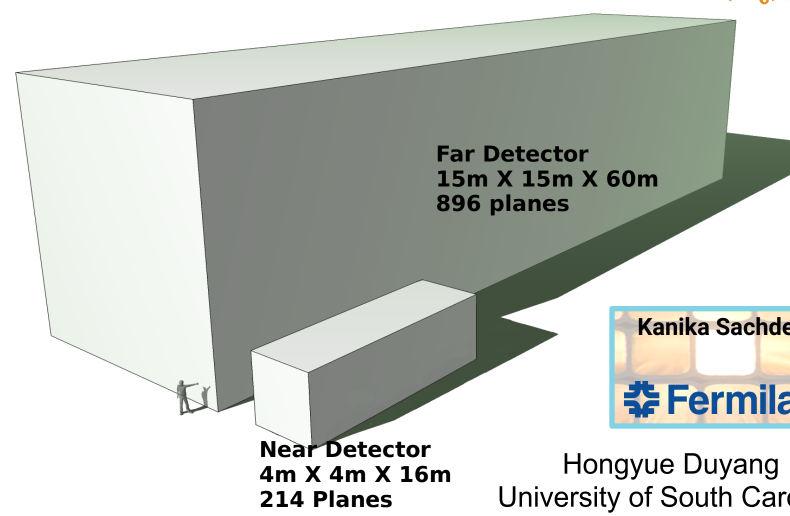
**@novaexperiment**

* NOvA (NuMI Off-axis $\nu_e$ Appearance) is a neutrino oscillation experiment
  * Baseline of 810 km
  * NuMI, beam of mostly $\nu_\mu$
  * 14 mrad off-axis from the beam
  * Two functionally identical detectors
* Oscillation channels accessible to NOvA:
  * $\nu_\mu(\bar{\nu}_\mu)$ to $\nu_e(\bar{\nu}_e)$ (appearance)
  * $\nu_\mu(\bar{\nu}_\mu)$ to $\nu_\mu(\bar{\nu}_\mu)$ (disappearance)








Kanika Sachdev

Fermilab

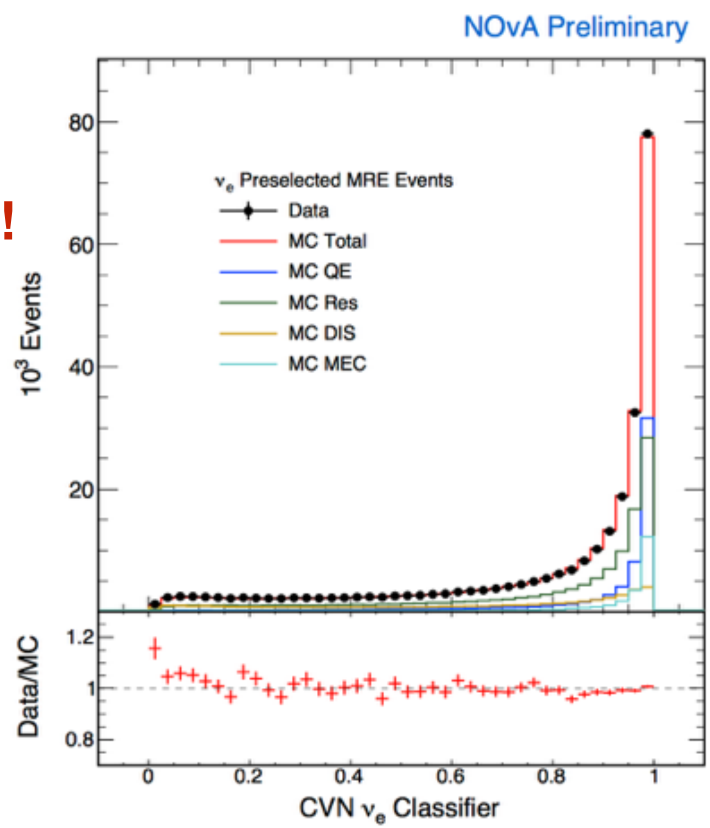
Hongyue Duyang
University of South Carolina

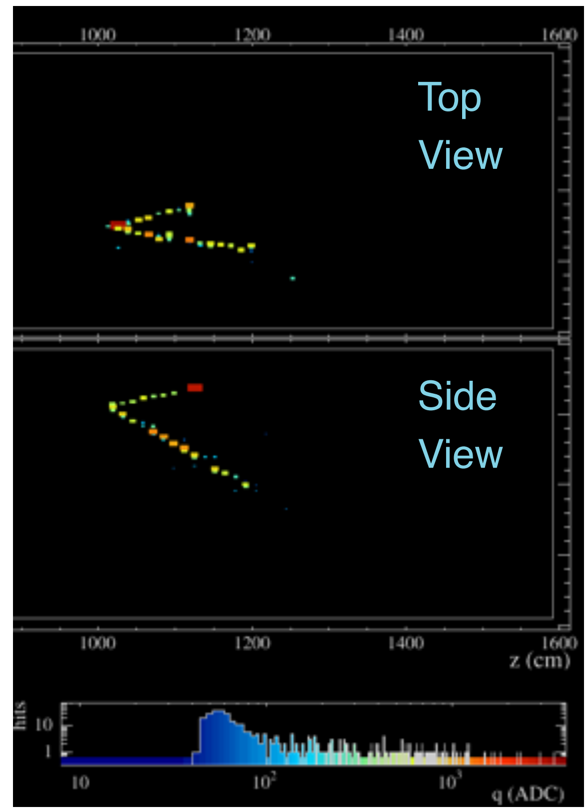
| Far Detector (FD) | Near Detector (ND) |
| --- | --- |
| 14 kt, $\gtrsim$ 344,000 channels | 0.3 kt, $\gtrsim$ 20,000 channels |
| On surface | 100 m below surface |
| 810 km from source | 1 km from the NuMI |

# Electron neutrino inclusive cross sections

- Analysis is very advanced.
- Excellent control of systematics through data-driven samples - here **“Muon Removal Event” sample** to benchmark performance of **convolutional neural net** used for particle ID.

**Improved modeling!**




J. Paley
NuInt 2017

**& P. Ding at DPF!**



**More efficient reconstruction!**

# NC coherent pion production in NOvA

**Improved modeling!**

Measured flux-averaged cross-section:

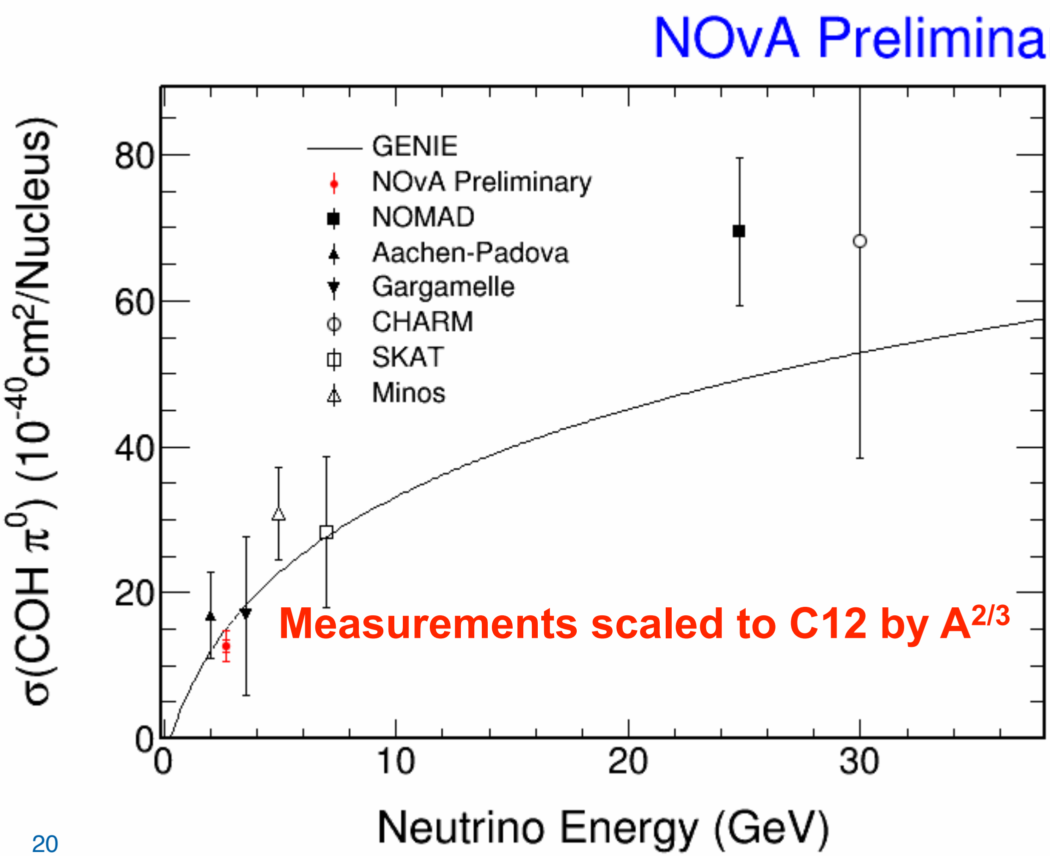
**$\sigma = 14.0 \pm 0.9(\text{stat.}) \pm 2.1(\text{syst.}) \times 10^{-40} \text{cm}^2/\text{nucleus}$**

Total uncertainty 16.7%, systematic dominant.

Work in progress:

- CC $\pi^0$
- NC $\pi^0$
- CC $\pi^+/\pi^-$

## NC Coherent $\pi^0$




| 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 |

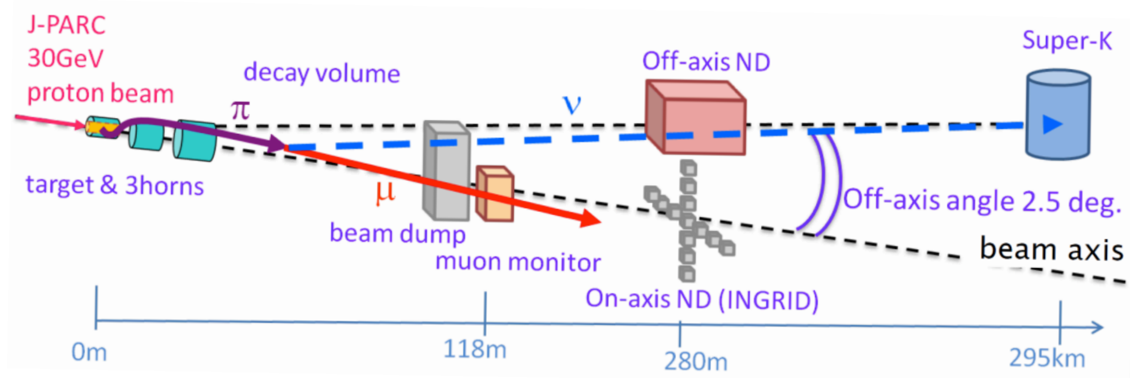
Hongyue Duyang **(& this conference!)**
NuInt 2017

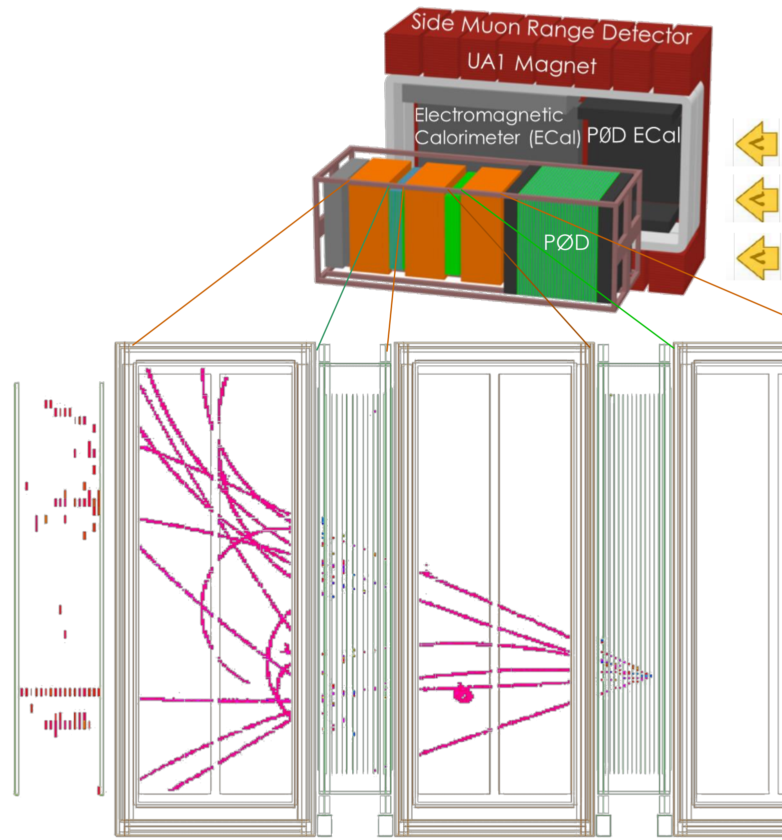
# More NOvA cross sections at DPF

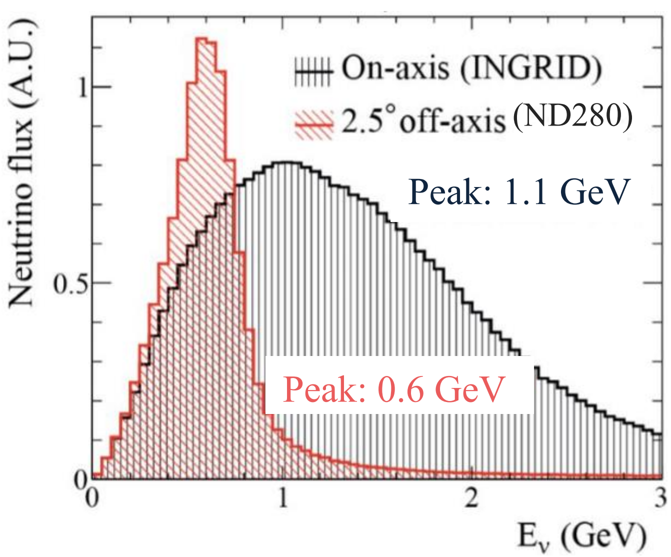
- See also
  - D. Kalra from Tuesday morning on Inclusive NC neutral pion production.
  - H. Duyang from Tuesday morning on NC coherent neutral pion production.
  - B. Behera from Tuesday afternoon on an alternative measurement of the inclusive muon neutrino CC cross section in NOvA.
  - A. Tsaris from Tuesday afternoon on charged pion semi-inclusive CC cross sections in NOvA.
  - P. Ding from Tuesday afternoon on electron neutrino CC inclusive cross sections in NOvA.
  - J. Bian from Tuesday afternoon on neutrino-electron elastic scattering for flux constrains in NOvA.

# T2K

- Oscillation experiment (far detector Superkamiokande) with high granularity, **magnetized** near detector complex for comprehensive cross section program on Carbon, Oxygen.
  - **P0D** contains water layers, scintillator, and absorbers.
  - **TPC** and **segmented scintillator** modules.



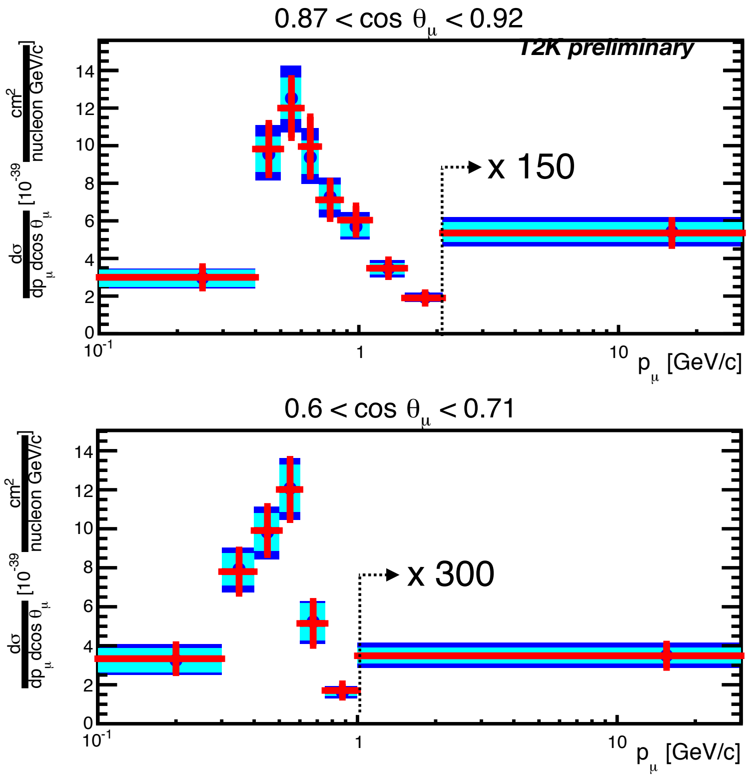



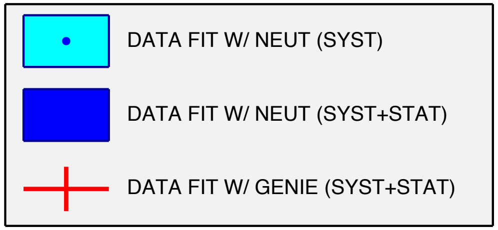
# Inclusive 2d muon-neutrino cross sections on plastic

- Inclusive measurements are high purity and **relatively insensitive to problems modeling the hadronic response**.
- Update a result from 2013 (PRD 87) with 5x the statistics and better reconstruction and event selection.

- Robust cross-section measurement (same results with two models).



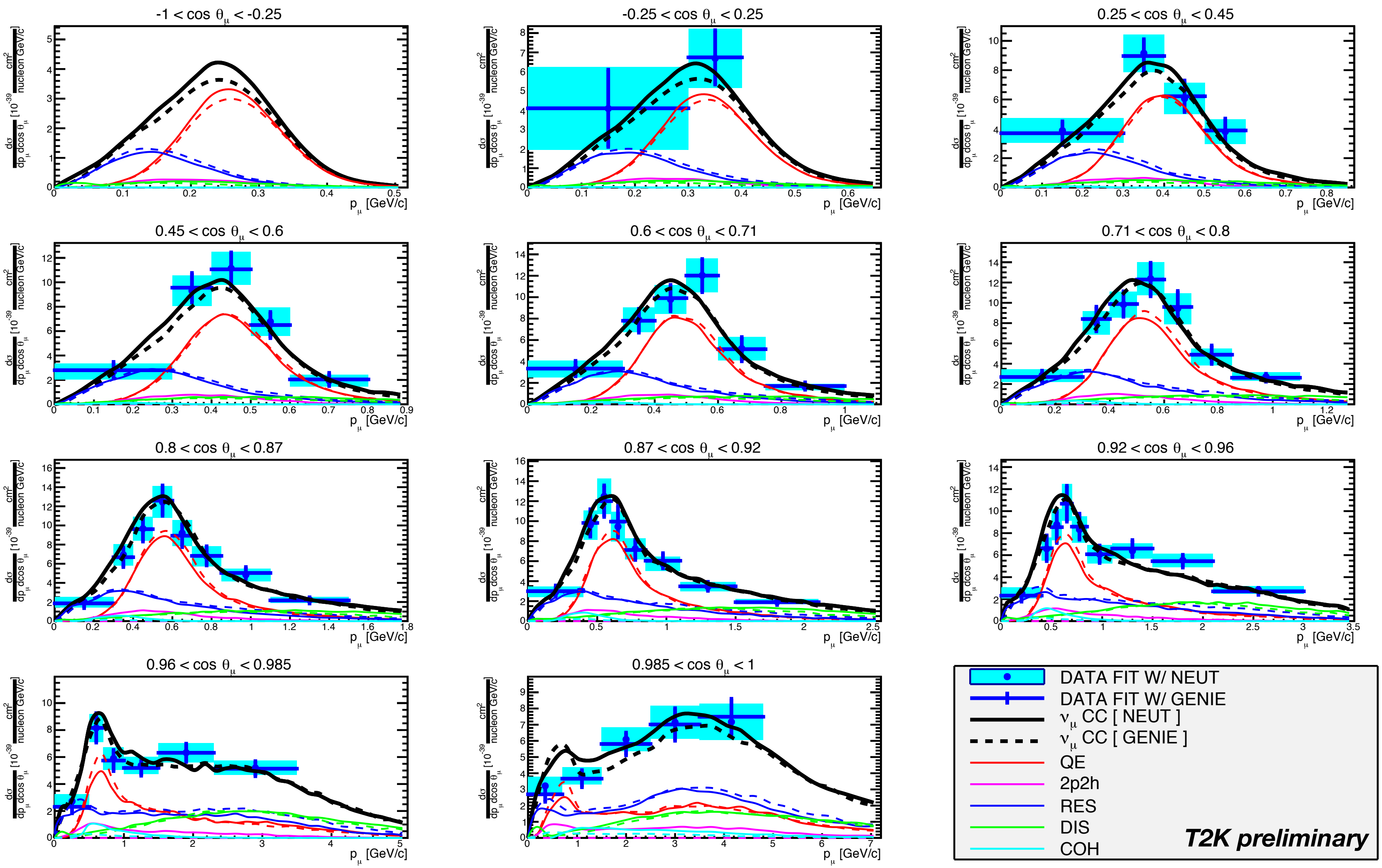

Momentum in an angle bin




Fiducial, inclusive:

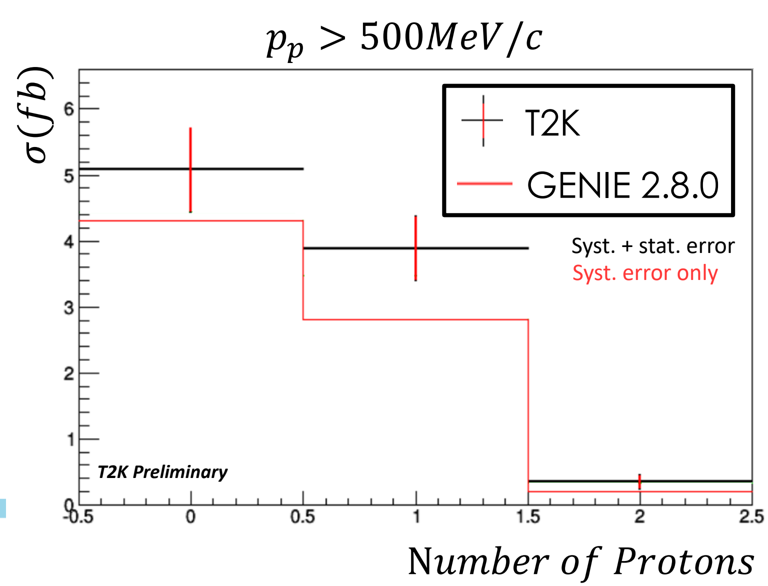
**Model independent!**

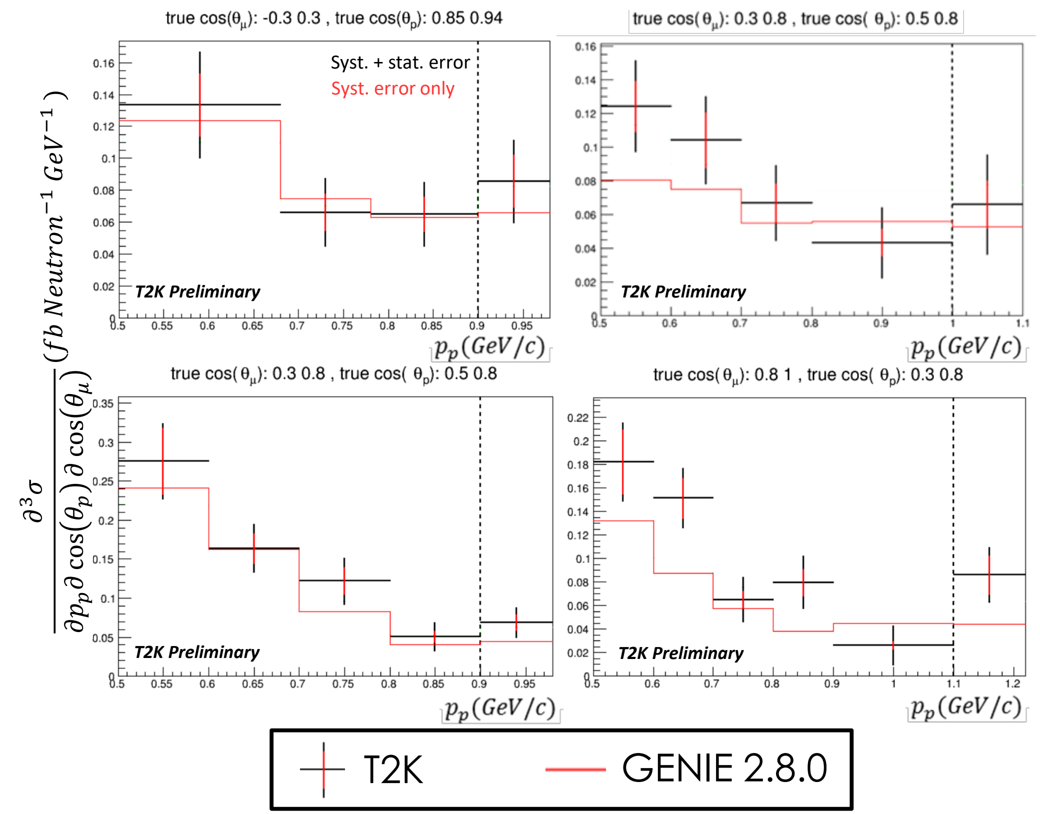
# Inclusive 2d muon-neutrino cross sections on plastic



# Charged current “zero pion” with μ + p kinematics

- **Fiducial flux-integrated cross section** in bins of $\cos(\theta_\mu)$ $\cos(\theta_p)$ and $p_p$ ($p_p > 500$ MeV/c).
- May also extract the **number of protons** with $p_p > 500$ MeV/c.
- Excess is observed over GENIE 2.8.0 (no 2p2h model in 2.8.0).




Fiducial, QE-like:

**Model independent!**

# New Results: Theory

# Overarching themes

- The **particle theory community** has begun to really **engage with neutrino interactions** (the field has long been of interest to nuclear theorists).
- We've begun to organize problems more clearly around **leptonic, nucleon, and nuclear effects** in the full picture, with particle theorists beginning to work more vigorously on the first two.
  - Our model involves going from quarks to nucleons and again to nuclei. For precision, we "**need to control both form factors and nuclear effects**" and we must **properly separate them** (G. Paz, NuInt 2017).
    - e.g., $M_A$ from the dipole parameterization of the vector axial form factor is often presented with inflated uncertainties to cover *nuclear* modeling effects. **It is time to do better** than that and recent work shows us how.
  - Our understanding of *proper* nucleon level uncertainties has leapt forward, but **understanding how to fully leverage this information in a nuclear context** is important and will help direct all of our efforts (R. Hill, Radiative Corrections at the IF, Perimeter Inst. 2017).
  - **Nuclear modeling must first succeed with electrons**: good progress here!

# Lattice QCD and neutrino-nucleus scattering

- **New neutrino-nucleon data will be hard to come by**, making lattice contributions potentially critical.
- While not precisely new (and not exactly a lattice result), lattice theorists have already re-defined the way neutrino physicists talk about the axial form factor. We have **started to phase out the dipole form factor in favor of the model-independent z-expansion**:

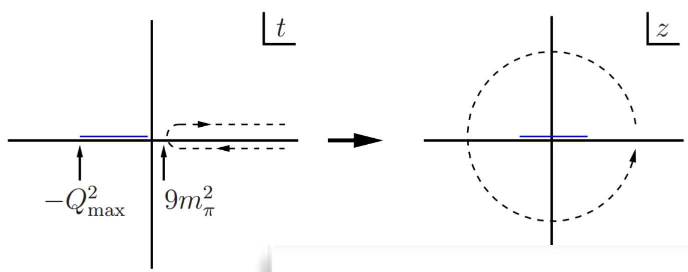
z-expansion: conformal mapping taking kinematically allowed region ($t = -Q^2$) to $|z| < 1$.

PHYSICAL REVIEW D **84,** 073006 (2011)

**Model-independent determination of the axial mass parameter in quasielastic neutrino-nucleon scattering**

Bhubanjyoti Bhattacharya, Richard J. Hill, and Gil Paz

$$z(t; t_0, t_c) = \frac{\sqrt{t_c - t} - \sqrt{t_c - t_0}}{\sqrt{t_c - t} + \sqrt{t_c - t_0}} \qquad F_A(z) = \sum_{n=0}^{\infty} a_n z^n \qquad t_c = 9m_\pi^2$$




Aaron S. Meyer (asmeyer2012@uchicago.edu)

University of Chicago/Fermilab

Radiative Corrections at the Intensity Frontier of Particle Physics

$$F_A^{\text{dipole}}(Q^2) = \frac{g_A}{\left(1 + \frac{Q^2}{m_A^2}\right)^2}$$

(Llewellyn-Smith, 1972)

[Phys.Rept.3 (1972),261]

# Lattice QCD showcase: $g_A$ and $G_A(Q^2)$

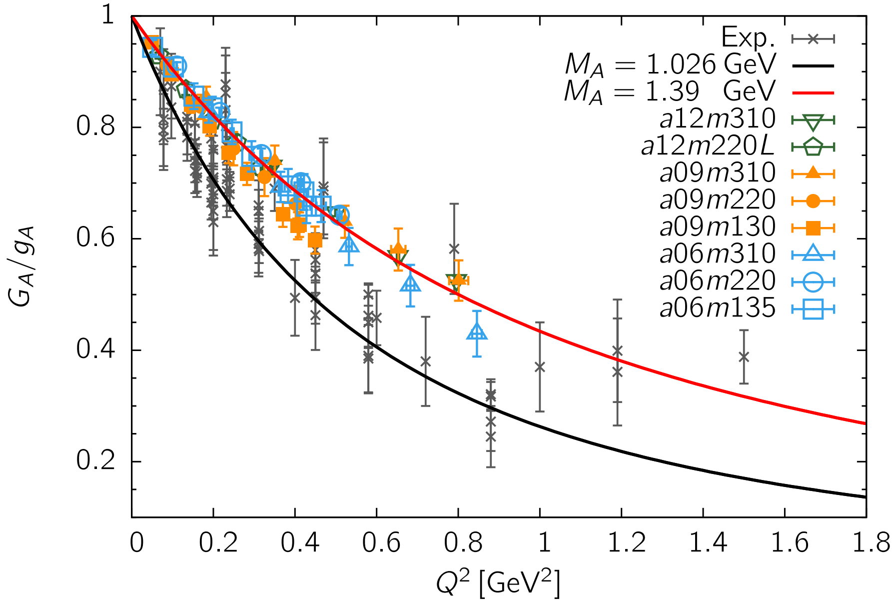


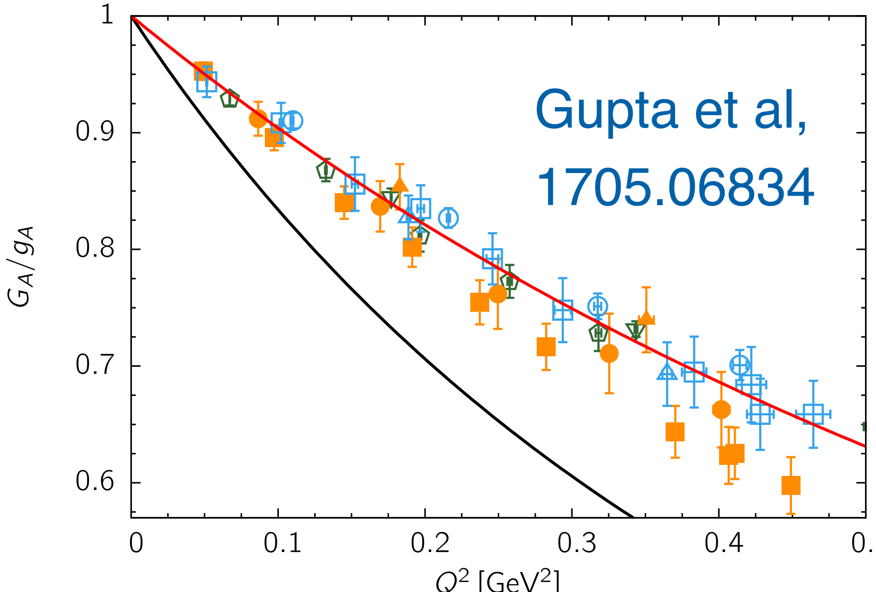
- Nucleon axial charge and form factor
- Lots of activity in the past year!
  - LHPC 1703.06703
  - ETMC 1705.03399
  - CLS 1705.06186
  - PNDME 1705.06834
  - Also $g_A$: CalLat 1704.01114

| Ref. | $g_A$ | $\langle r_A^2 \rangle$ [fm$^2$] |
|---|---|---|
| LHPC | 1.208(6)(16)(1)(10) | 0.213(6)(13)(3)(0) |
| CalLat | 1.278(21)(26) | – |
| ETMC | 1.212(33)(22) | 0.267(9)(11) |
| CLS | $1.278(68)(^{+00}_{-87})$ | $0.360(36)(^{+80}_{-88})$ |
| PNDME | 1.195(33)(20) | 0.22(7)(3) |

Under the dipole approximation:
(some here are dipole, some z-exp.)

$$G_A(Q^2) = \frac{g_A}{(1 + \frac{Q^2}{{M_A}^2})^2} \qquad \langle r_A^2 \rangle = \frac{12}{{M_A}^2}$$



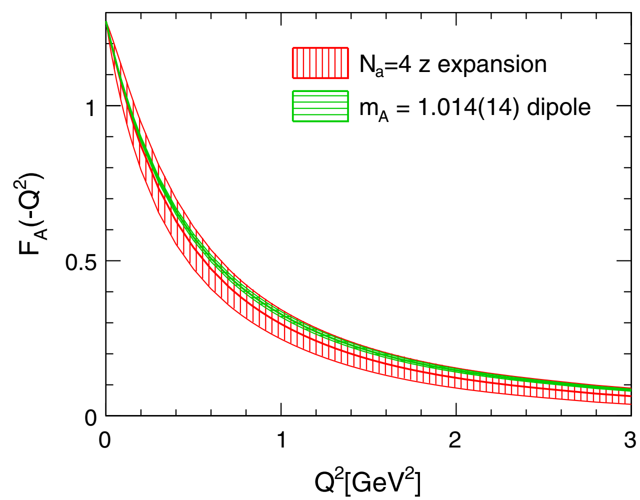
Measurement from re-analysis

# Precise nucleon form factors

PHYSICAL REVIEW D **93**, 113015 (2016)

- **Nucleon inputs** will play an important role in assessing the overall nuclear uncertainties, whether they come from calculations or measurement.
  - For another calculation, see e.g. Meyer, Hill, Kronfeld, Li and Simone, arXiv 1610.04593
    - Also, new (this week!) nucleon vector form factors from Ye, Arrington, Hill and Lee in arXiv 1707.09063
- Re-analyzing existing **deuterium data using the z-expansion** from above is important for properly specifying the axial-vector form factor and its uncertainties.

Meyer, Betancourt, Gran, Hill (2016)

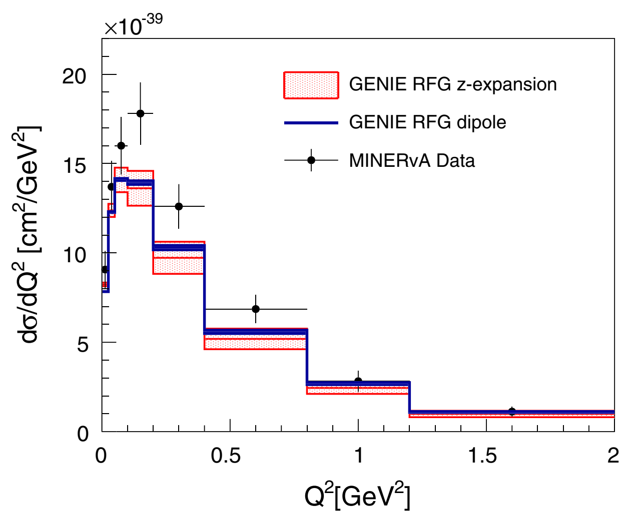


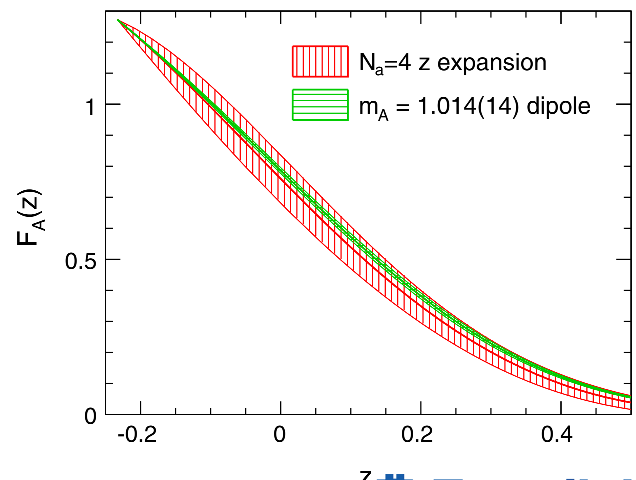

$$F_A(q^2) = \sum_{k=0}^{k_{\max}} a_k z(q^2)^k,$$

(Form factor fully specified in the paper, etc.)

Here, Minerva for **illustration** - fit was to **deuterium data**.

PHYSICAL REVIEW D **93**, 113015 (2016)



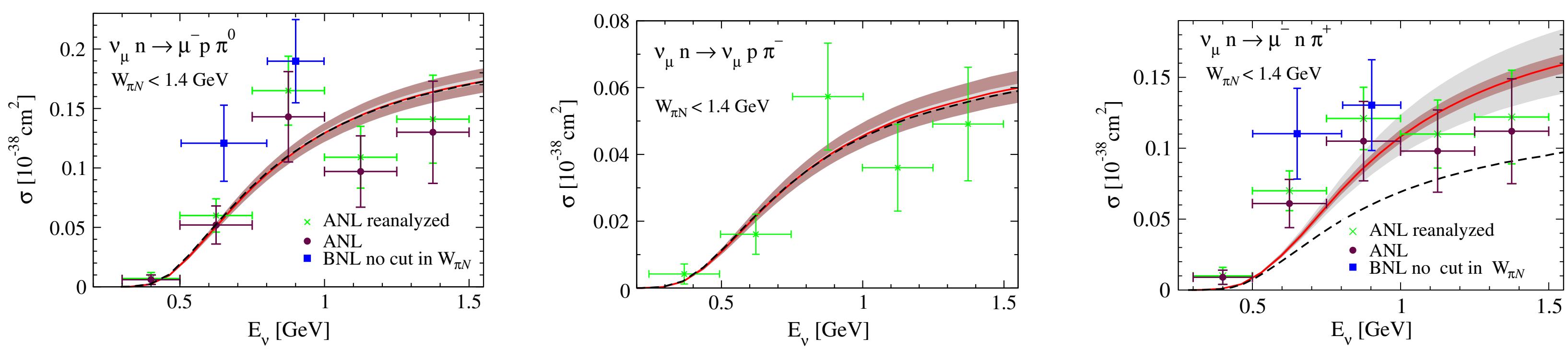




## Nucleon physics

# Single pion production on nucleons

E. Hernández[1] and J. Nieves[2]
PHYSICAL REVIEW D **95**, 053007 (2017)

- Understanding **single pion production reactions on nucleons is required to describe these processes in nuclei**.
- Reanalyze previous studies of 1-pion production on nucleons for W < 1.4 GeV to improve description of $\nu_\mu n \rightarrow \mu^- n \pi^+$ (current theoretical models give values significantly below data).
- Here **change the strength of the spin 1/2 components in the Δ propagator** and use the $\nu_\mu n \rightarrow \mu^- n \pi^+$ data to constraint its value.
- Now find good reproduction for $\nu_\mu n \rightarrow \mu^- n \pi^+$ without affecting the (good) results previously obtained for other channels.




ANL/BNL re-analysis: C. Wilkinson, P. Rodrigues, S. Cartwright, L. Thompson, and K. McFarland, Phys. Rev. D **90**, 112017 (2014). P. Rodrigues, C. Wilkinson, and K. McFarland, Eur. Phys. J. C **76**, 474 (2016).

Deuteron effects: E. Hernández, J. Nieves, M. Valverde, and M. J. Vicente Vacas, Phys. Rev. D **81**, 085046 (2010).

ANL/BNL original: G. M. Radecky *et al.*, Phys. Rev. D **25**, 1161 (1982); **26**, 3297(E) (1982). T. Kitagaki *et al.*, Phys. Rev. D **34**, 2554 (1986).

Dashed: L. Alvarez-Ruso, E. Hernández, J. Nieves, and M. J. V. Vacas, Phys. Rev. D **93**, 014016 (2016).

# Single pion production on nucleons

PHYSICAL REVIEW D **95**, 113007 (2017)

R. González-Jiménez,[1,*] N. Jachowicz,[1] K. Niewczas,[1,2] J. Nys,[1] V. Pandey,[3] T. Van Cuyck,[1] and N. Van Dessel[1]

- Low-energy models describe neutrino production of pions in the Delta region, but fail in the high-energy region (W > ~2 GeV).
- Here **developed a *single model* for electroweak pion production which is applicable to the entire energy range of interest** (DUNE, etc.).
- Start with the low-energy model of [Hernández, Nieves, and Valverde, PRD 76, 033005 (2007).], which includes resonant contributions and background terms derived from the pion-nucleon Lagrangian of chiral-perturbation theory.
- From the background contributions, build a high-energy model using a Regge approach.
- Low- and high- energy models are combined, phenomenologically, into a hybrid model. The model is then compared to a MC event generator (NuWro) and to data.

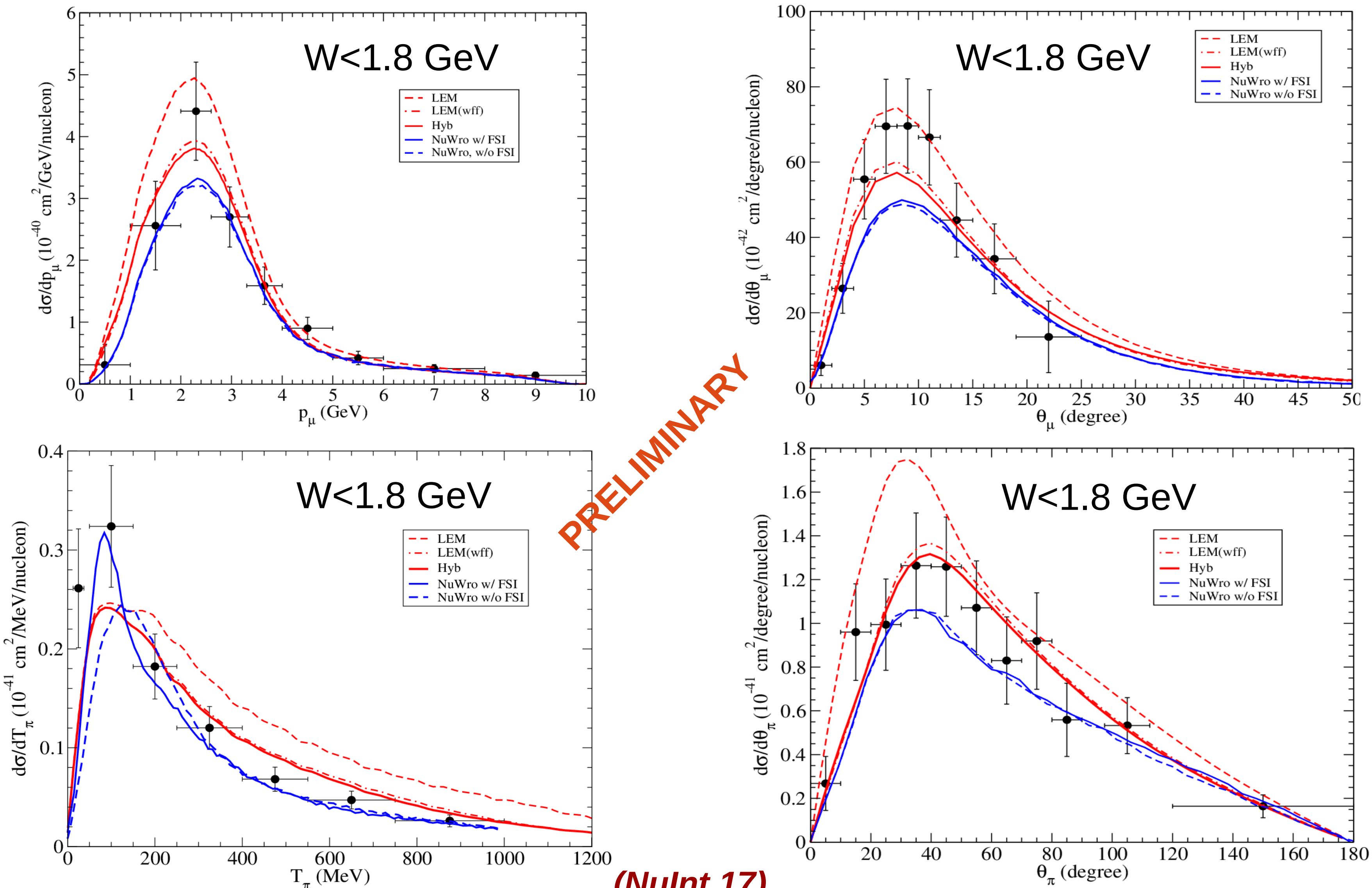
NuWro

T. Golan, C. Juszczak, and J. T. Sobczyk, Phys. Rev. C **86**, 015505 (2012).

C. Juszczak, J. A. Nowak, and J. T. Sobczyk, Nucl.Phys.Proc.Suppl. **159**, 211 (2006), hep-ph/0512365, http://borg.ift.uni.wroc.pl/nuwro/.

T. Golan, J. Sobczyk, and J. Zmuda, Nucl.Phys.Proc.Suppl. **229-232**, 499 (2012).

# MINERvA π0 data - Phys. Rev. D 94, 052005 (2016)




***(NuInt 17)***

**R. González-Jiménez** **Ghent University**

# Superscaling models with MEC

- Recent progress on the **relativistic modeling of electron-nucleus** reactions.
- Nuclear model originally based on superscaling phenomenon of electron-nucleus scattering - has been **improved by including relativistic mean field theory effects** that model the enhancement of the QE transverse scaling function compared to the longitudinal.
- Model extended to **include the complete inelastic spectrum**—resonant, nonresonant and deep inelastic scattering.
- Consider **impacts of meson-exchange currents** through two-particle two-hole (2p2h) contributions to EM response functions within the framework of the relativistic Fermi gas, examining for the first time the longitudinal channel in addition to the transverse.

PHYSICAL REVIEW D **94,** 013012 (2016)

**Inclusive electron scattering within the SuSAv2 meson-exchange current approach**

G. D. Megias,[1,*] J. E. Amaro,[2] M. B. Barbaro,[3] J. A. Caballero,[1] and T. W. Donnelly[4]

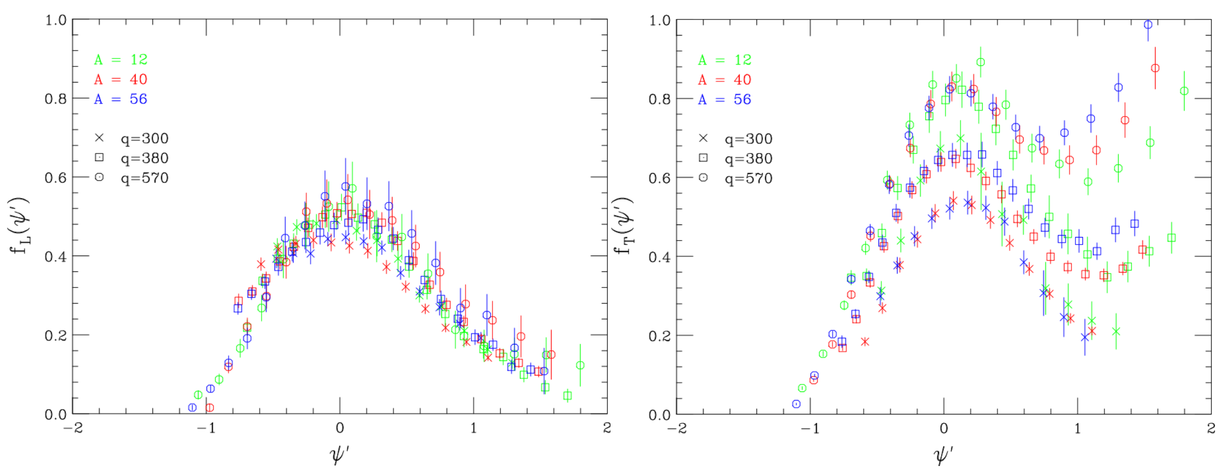
# Quick refresher - scaling

$$f(\psi) \equiv f(q,\omega) \sim \frac{\sigma_{QE}(\text{nuclear effects})}{\sigma_{\text{single nucleon}}(\text{no nuclear effects})} \quad ; \quad \psi\text{-scaling variable}$$

**In inclusive QE scattering we can observe:**

- ☆ Scaling of 1$^{st}$ kind (independence on $q$)
- ☆ Scaling of 2$^{nd}$ kind (independence on $Z$)

$\Longrightarrow$ **SuperScaling**




Scaling violations in the T channel ⇒ 2p-2h MEC, correlations

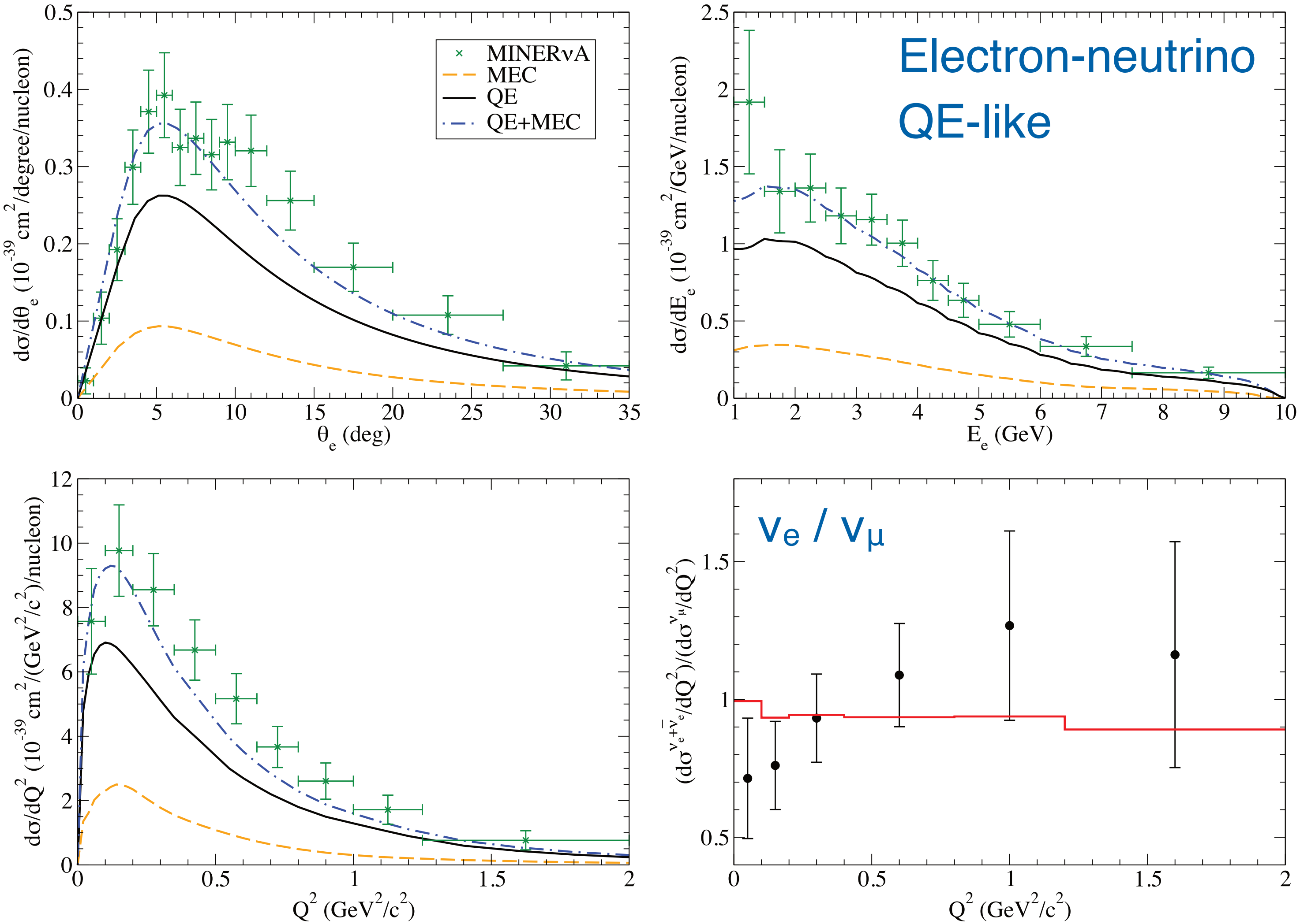
G. D. Megias[1]

[1]Dpto. de FAMN, Universidad de Sevilla, Sevilla, Spain.

*5$^{th}$ December 2016, INT-16-63W, Seattle*

Plus - 0th kind: the scaling function is the same for the transverse and longitudinal responses - assumed in original SuSA model, but SuSA v2 (based on RMF) predicts $f_T > f_L$ as a genuine relativistic effect.

# Application of the calculation to neutrinos



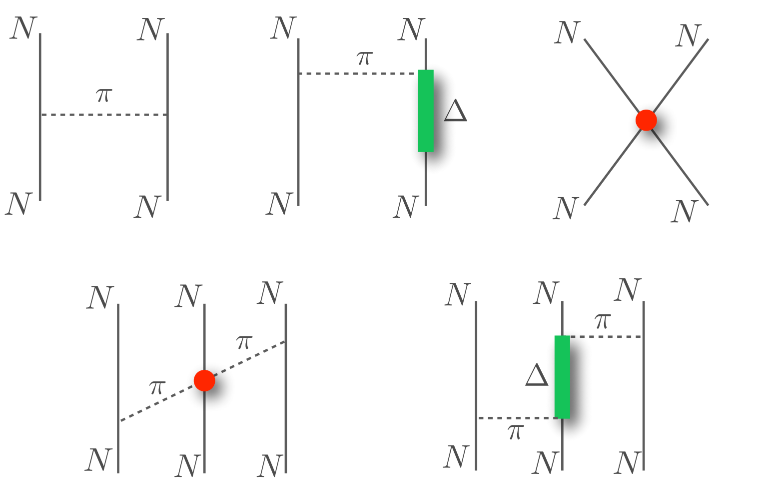

MINERvA data: PRL 116, 081802 (2016).

G. D. Megias[1]
[1]Dpto. de FAMN, Universidad de Sevilla, Sevilla, Spain.
$5^{th}$ *December 2016, INT-16-63W, Seattle*

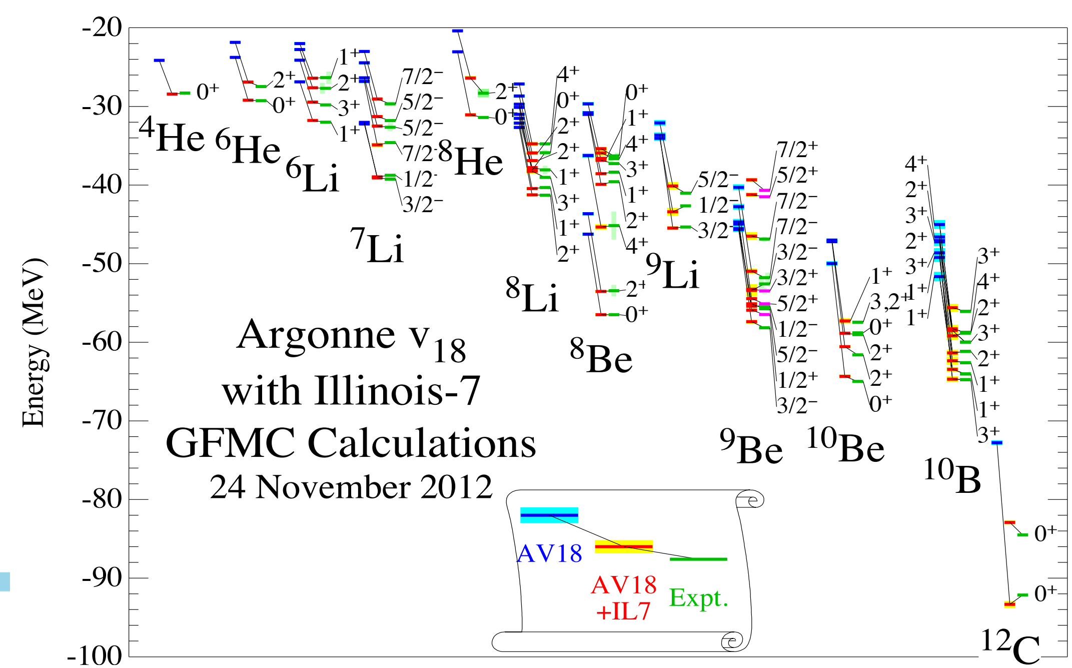
# Ab initio nuclear many body theory

- QCD is non-perturbative at large distances. Lattice QCD is our best method for handling low energy QCD, but it is limited in a nuclear physics context to small ($A < 4$) systems and restricted to a relatively large pion mass. Therefore we must employ *effective* theories.
- *Ab initio* approaches are based on a non-relativistic Hamiltonian and are able (e.g. Argonne v18) to predict the spectrum of light nuclei:

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



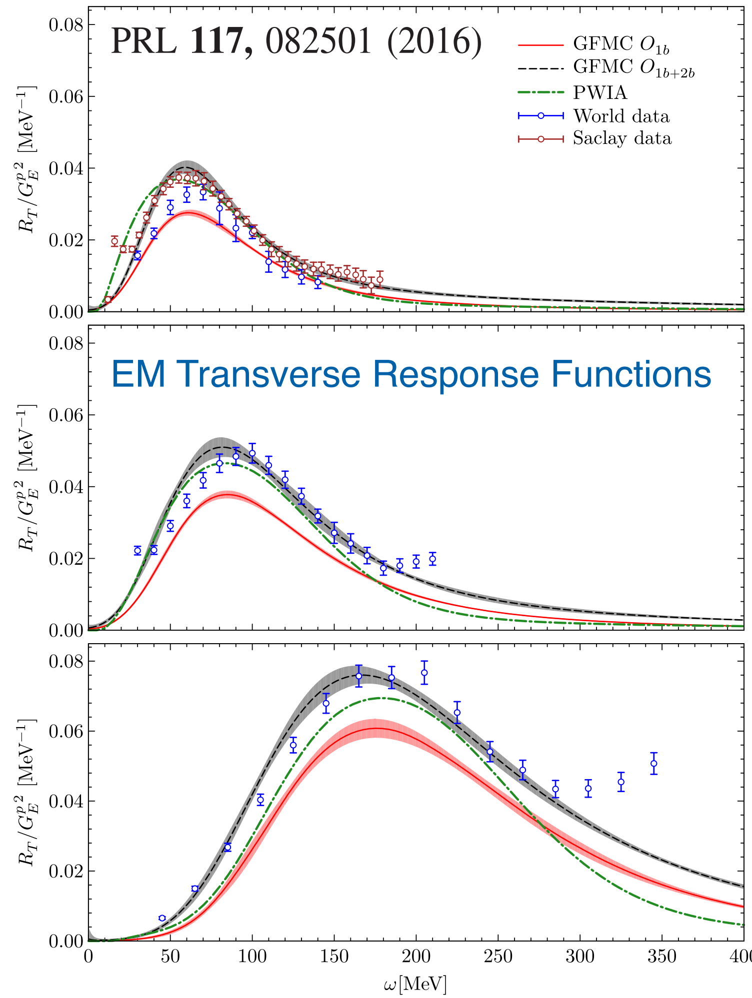

Alessandro Lovato



# NMBT response functions (here for electron scattering)

- The plan is to compute response functions (ground state, currents, propagation) for electrons and use the common pieces for neutrinos.
- Longitudinal and transverse electromagnetic response functions for Carbon-12 are computed using a "first-principles" Green's Function Monte Carlo (GFMC)
  - Calculation uses realistic 2- and 3-nucleon interactions and associated 1- and 2-body currents.
- Find good agreement with experiment and no evidence for the quenching of the measured versus calculated longitudinal response.

A. Lovato,[1] S. Gandolfi,[2] J. Carlson,[2] Steven C. Pieper,[1] and R. Schiavilla[3,4]




Data from: P. Barreau *et al.*, Nucl. Phys. **A402**, 515 (1983). J. Jourdan, Nucl. Phys. **A603**, 117 (1996).

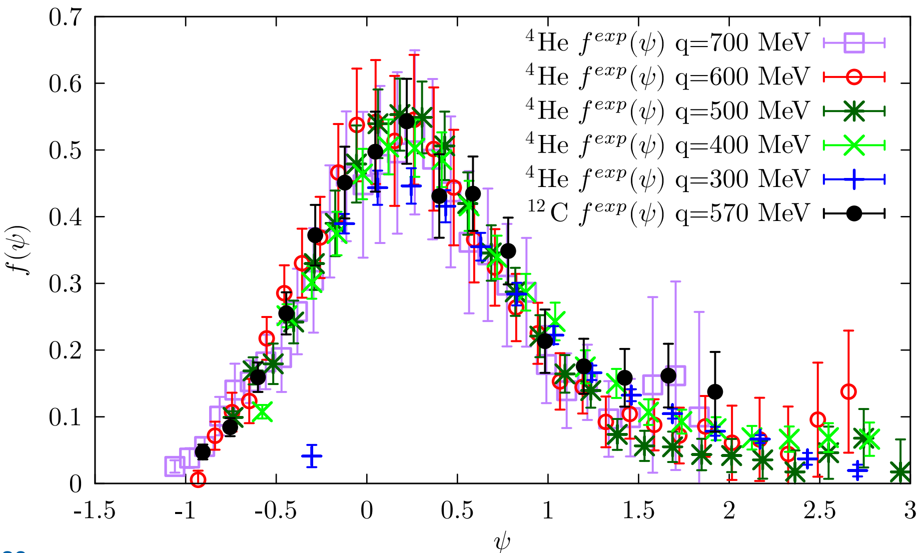
$$\frac{d^2\sigma}{d\Omega_{e'}dE_{e'}} = \left(\frac{d\sigma}{d\Omega_{e'}}\right)_M \left[\frac{Q^4}{|\mathbf{q}|^4}R_L(|\mathbf{q}|,\omega) + \left(\frac{1}{2}\frac{Q^2}{|\mathbf{q}|^2} + \tan^2\frac{\theta}{2}\right)R_T(|\mathbf{q}|,\omega)\right]$$

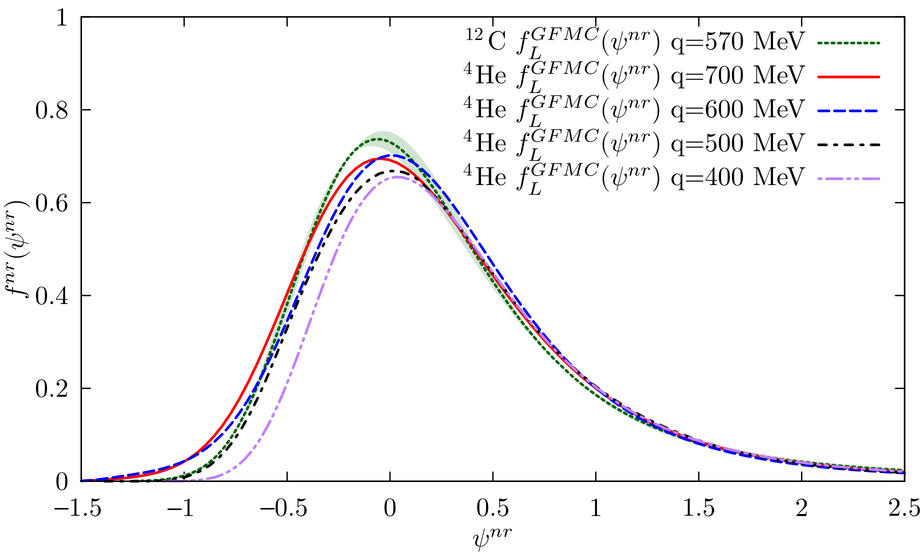
J. Carlson, LANL

# Electromagnetic scaling functions in GFMC

- Studied scaling properties of the EM response functions for 4He and 12C using GFMC, retaining only the one-body current contribution.
- Obtained longitudinal and transverse scaling functions in the relativistic and non relativistic cases and compared to experiment.
- Characteristic asymmetric shape of the scaling function seen in data is reproduced in the calculations despite a non-relativistic model.
- The results are consistent with scaling of zeroth, first and second kinds.

N. Rocco,[1] L. Alvarez-Ruso,[1] A. Lovato,[2] and J. Nieves[1] Phys. Rev. C 96, 015504 (2017)



# Conclusions

# What have we learned?

- **Theory and experiment are racing together** in neutrino interactions in an exciting way. This is a rewarding time to be working in the field - many good ideas and many fun and interesting collaborative opportunities that cut across theory/experiment and particle/nuclear bounds.
- There is **MUCH I didn't cover!**
  - **Lots** of results (running and recent experiments) and theory papers.
  - **New experiments** coming online (e.g., ANNIE, Icarus, SBND [See J. Crespo-Anadón's talk from Monday morning], etc.), vibrant **supporting program** (e.g. pion, neutron scattering measurements [See the Wednesday afternoon neutrino parallel session]), **amazing concepts and proposals** (e.g. nu-Prism [See C. Viela on Thursday morning]), and a lot of additional activity in the theory community.
  - Closely **related fields** like very-low (~MeV to 10's of MeV) energy neutrinos (e.g. COHERENT [See K. Scholberg from earlier this afternoon], supernovae [S. Locke from this morning], etc.).
  - **Implementation in MC event generators** remains a major problem. We need to dedicate more effort to helping these codes absorb new developments like those discussed here.

# Looking ahead

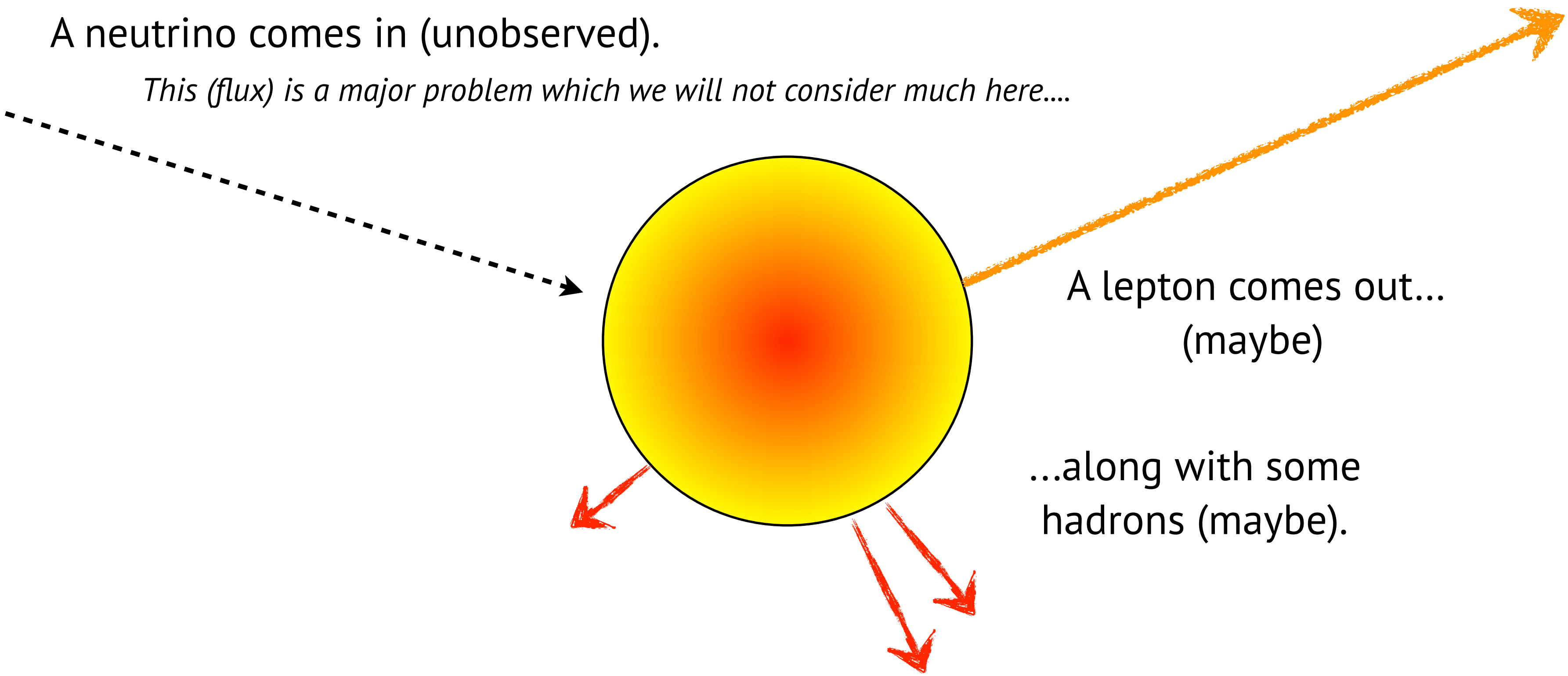
- **Vibrant cross section program** at dedicated and oscillation experiments - impressive pipeline of results to come.
- Multidisciplinary cooperation is critical:
  - Important to have **nuclear and particle theorists engaged.**
    - **Nuclear experimentalists** too! There is much we can learn from **electron scattering experiments** with regards to nuclear models and final state processes when we have better control over the probe particle.
  - **Working across the NP/HEP divide** can be tricky, but it is important!
- Major effort being invested in **cross-experiment communication** - how do we make the best, most useful measurements?
  - Excellent spirit of *cooperation over rivalry*.
  - Many recent **workshops aimed at these questions:**
    - Tensions in Neutrino-nucleus Cross Section Data (PittPACC), State of the Nu-tion (Toronto), Theoretical Developments in Neutrino-Nucleus Scattering (INT, Seattle), etc.
      - **CRITICAL** to continue to do this!


Fermilab


Thank you!


Back-up

# The Basic Problem




*What was the neutrino's **energy**?*

*We really want **flavor** too...*

# SBN Program: Three LAr TPC Detectors

| Detector | Distance from Target | Instrumented LAr Mass |
|---|---|---|
| SBND | 110 m | 112 ton |
| MicroBooNE | 470 m | 87 ton |
| ICARUS | 600 m | 476 ton |

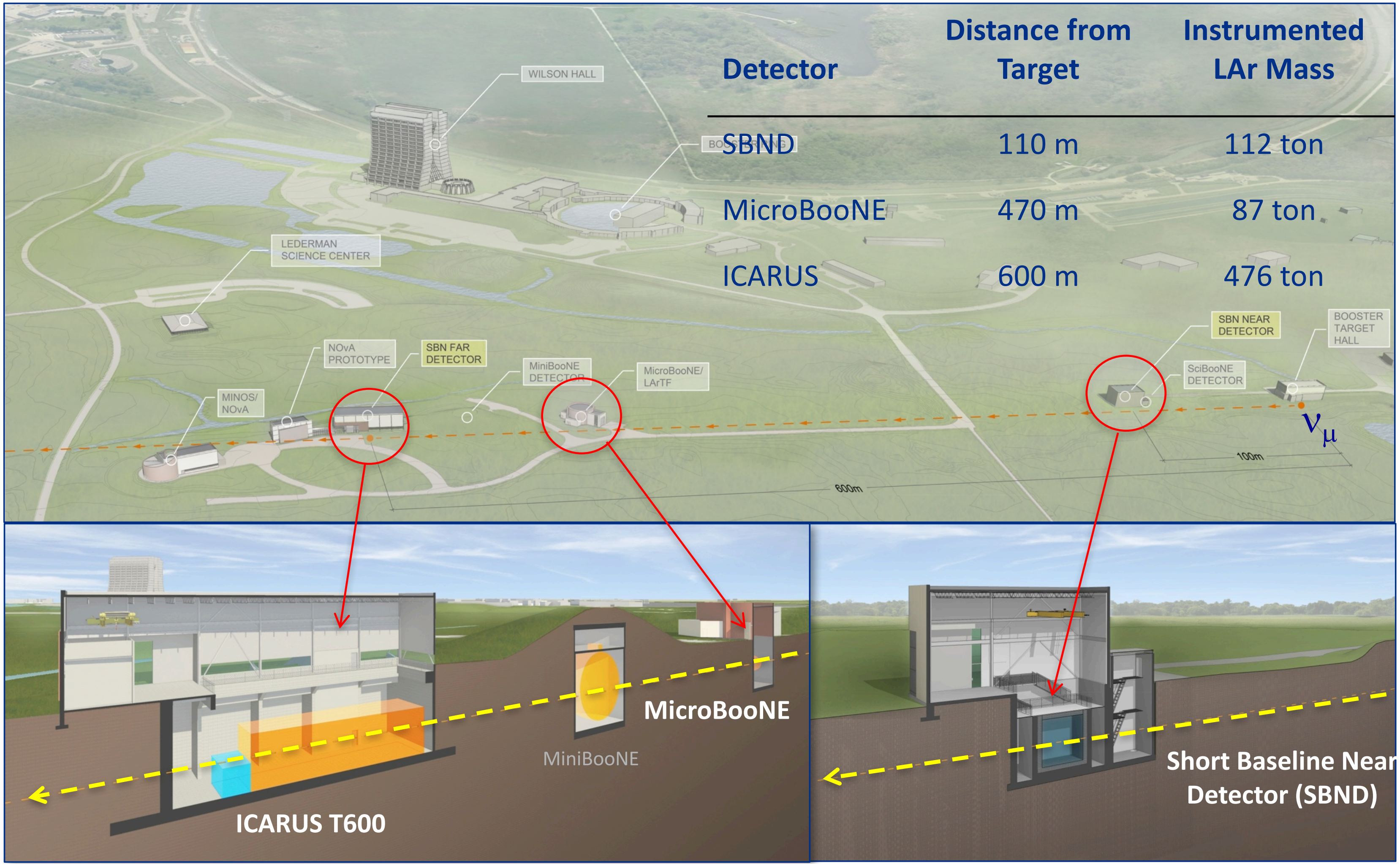


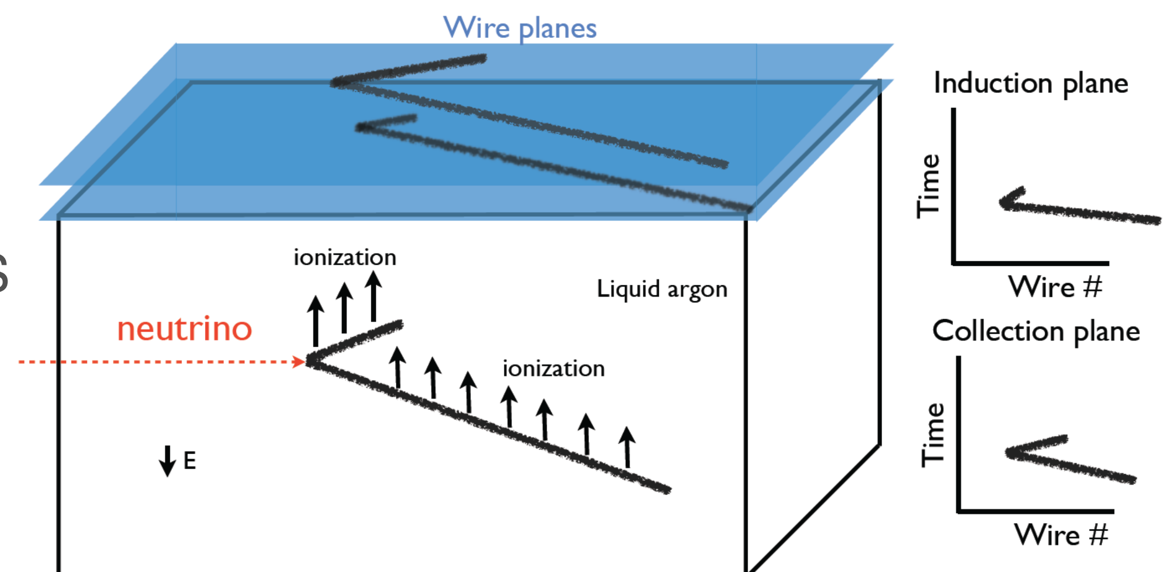

Figure by M. Kirby

# ArgoNeuT

- 175L **Liquid Argon Time Projection Chamber** (TPC).
- **First step** in the US liquid argon program (MicroBooNE, LBNE) & first LArTPC in a low-energy neutrino beam.
- Physics run in the **NuMI Beam** June '09 ⊕ Sept. '09 - Feb. '10.
    - Located between MINOS ND and MINERvA & utilized MINOS for muon momentum and charge sign. (NuMI "LE" beam.)

| | |
|---|---|
| TPC / Cryostat Volume | 175 / 500 L |
| # of Electronics Channels* | 480 |
| Wire Pitch | 4 mm |
| Max Drift Length | 0.5 m (330 μs) |
| Electric Field | 500 V/cm |

*Two readout planes: Induction & Collection
Each Channel: 2048 Samples / 400 μs

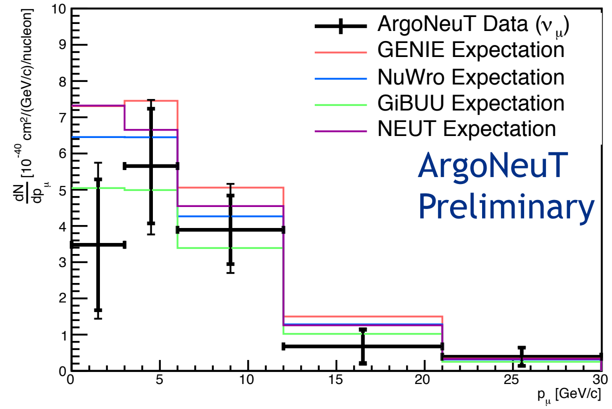



J. Spitz, arXiv: 1009.2515v1

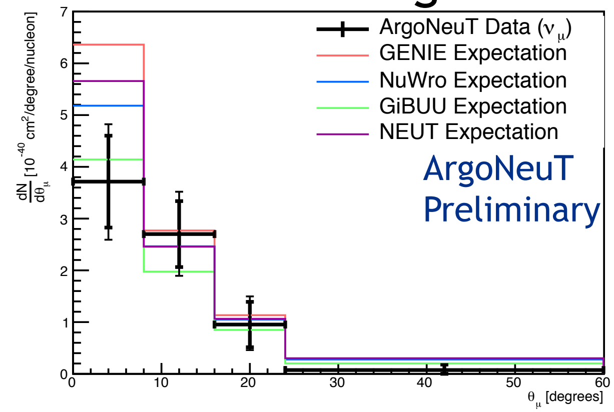
$$\nu_\mu + \mathrm{Ar} \rightarrow \mu^- + 1\pi^\pm + X$$

- **Exactly one charged pion** with momentum over 100 MeV/c.
- No neutral pions or charged or neutral kaons.
- No restriction on the number of nucleons, or on other mesons.

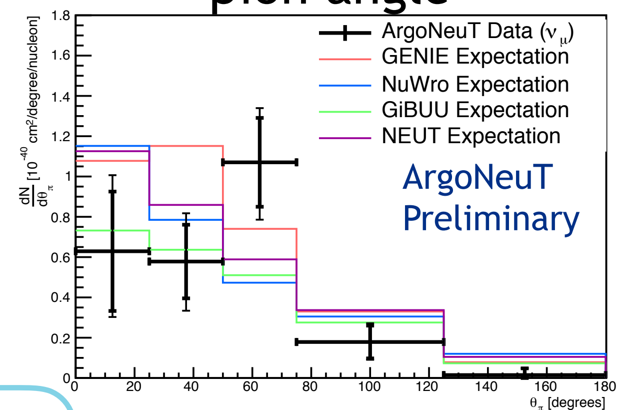
### muon momentum



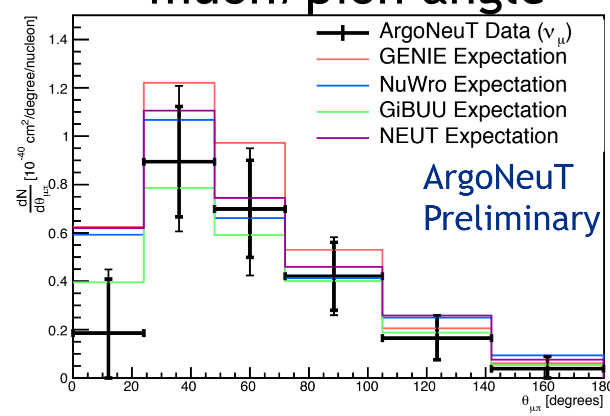

### muon angle




### pion angle




### muon/pion angle

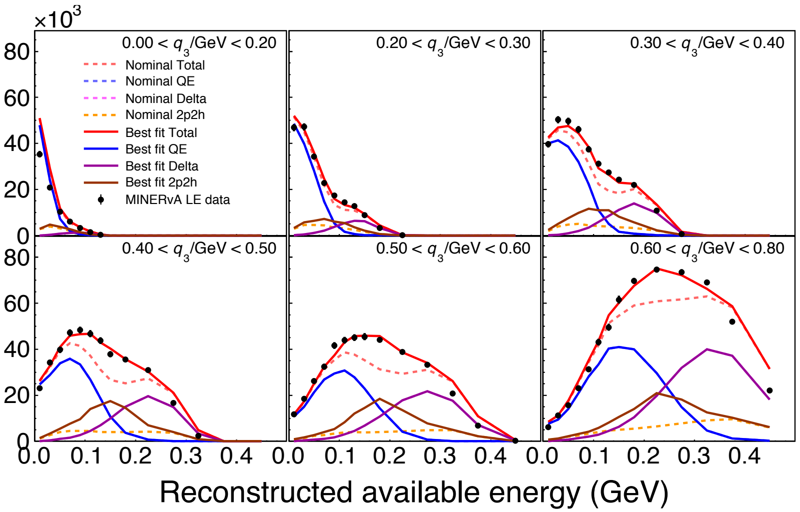



Tingjun Yang (Fermilab)
NuINT 2017

Antineutrino also new!

# MINERvA Event Generator Development and Evolution

- We have made considerable progress in modeling neutrino interactions lately, thanks to GENIE collaboration!
- We use GENIE (2.8.4) Monte Carlo generator
- We are using one of the theoretical predictions and latest GENIE implementation of Valencia model for QE-like 2p2h, arXiv:1601.02038, PRC 83, 045501 (2011)



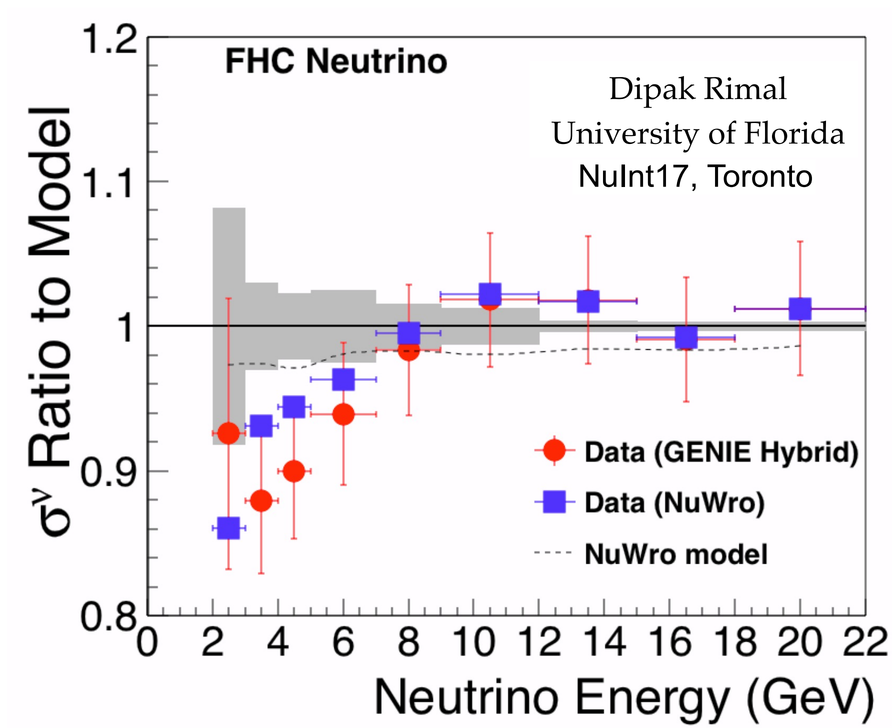

- We use a 2d Gaussian in true variables ($q_3$,$q_0$) as a reweighting function applied to the 2p2h events, and fits its parameters to get the best agreement between data and MC (QE and RES are unchanged)

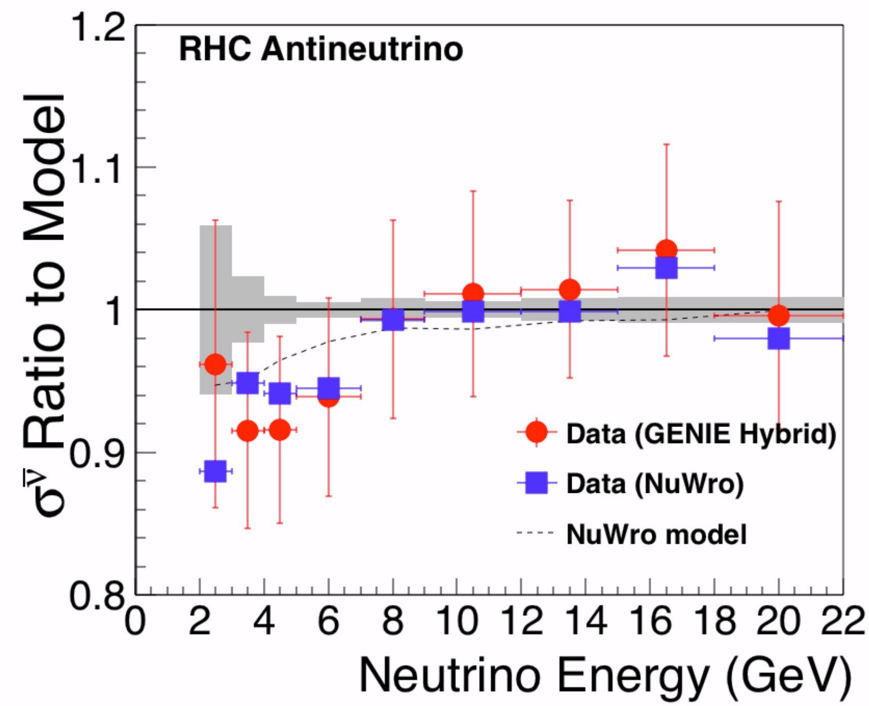
- We add the Valencia RPA to GENIE by reweighting the QE events, Valverde, Amaro, Nieves PLB 638 (2006) 325
- We modify the GENIE non-resonance pion production to agree with deuterium data, Rodrigues P., Wilkinson C. & McFarland K. Eur. Phys. C (2016) 76:474

Minerba Betancourt
NuInt 2017

# Charged current inclusive cross sections

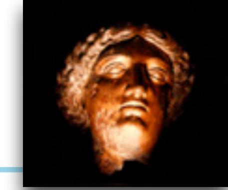
- Use the “low-nu” to extract a flux; then use that flux to measure the inclusive cross sections.
- Here we normalize to the reference model (GENIE) and look at data extracted using that model (low-nu correction) and data extracted with an alternate model (nuWro), plus the behavior of that alternate model.



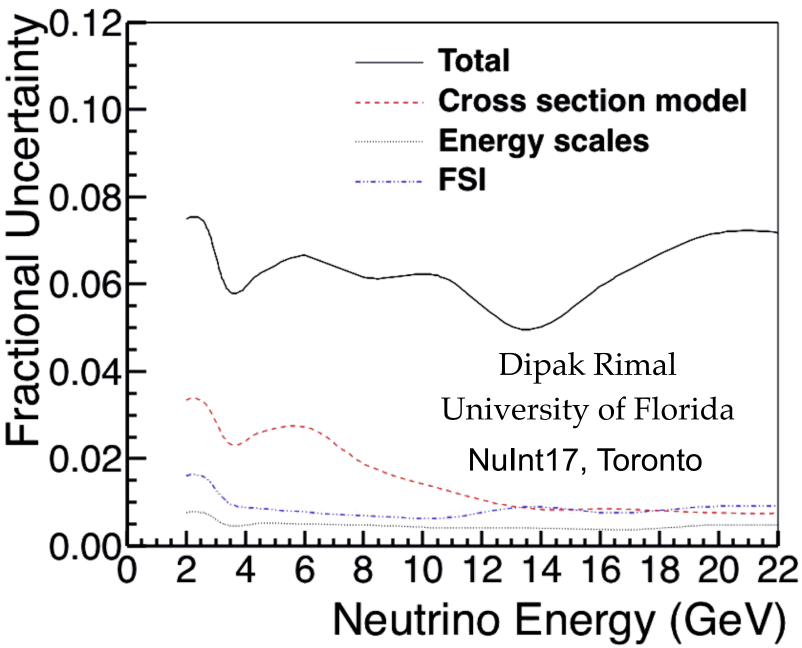

L. Ren et al., PRD 95 (2017) no.7, 072009

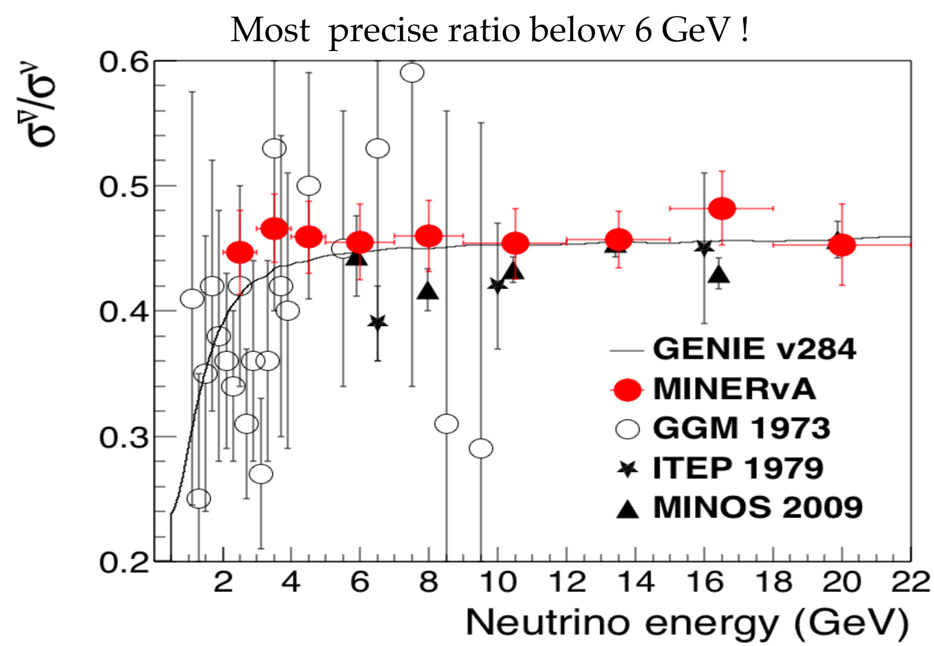
GENIE: Nucl.Instrum.Meth.A614 (2010) 87-104



# Charged current $\bar{\nu}$ / $\nu$ cross section ratios

- Extract fluxes with "low-nu" method, then extract cross sections.
- The muon-antineutrino/neutrino cross section is the **most precise in the world below 6 GeV** and uncertainties are dominated by statistics.




L. Ren et al., PRD 95 (2017) no.7, 072009

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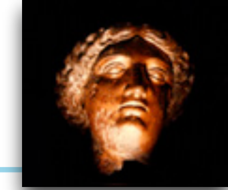
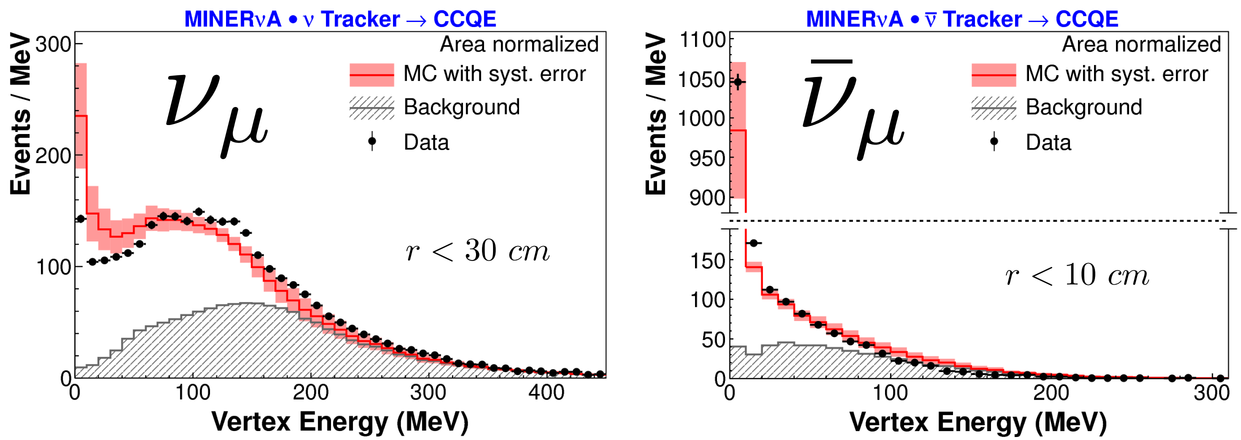
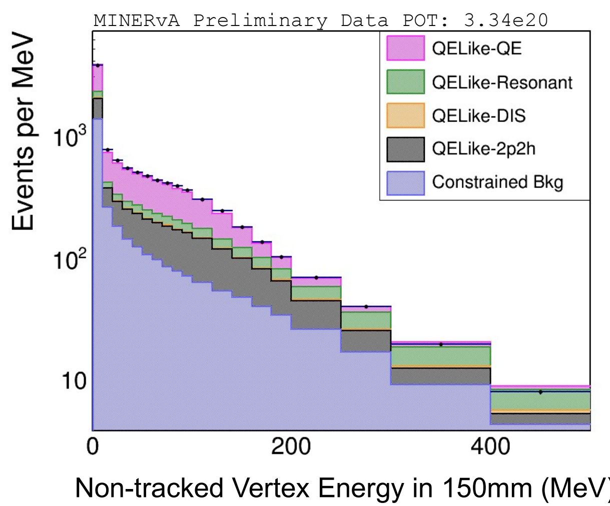
# Double-differential CCQE-like vertex energy

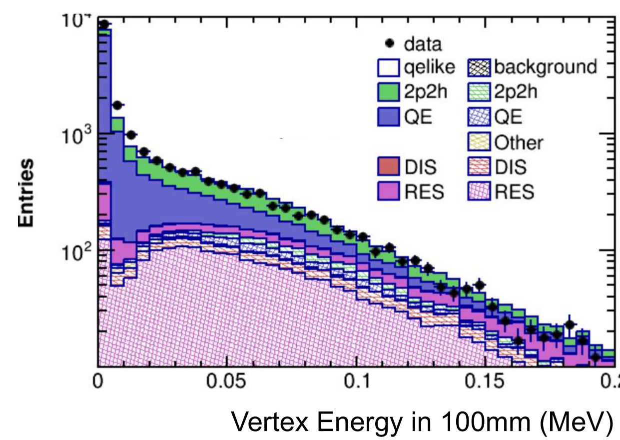


D. Schmitz, FNAL JETP, May 2013

- These measurements are NOT of exactly the same quantity.
- Improvements in MINERvA reconstruction mean **much more of the energy is tracked in 2017**, and so not part of the same "non-vertex recoil" distribution (where the vertex region is very tight around the event vertex).
- What IS interesting about these distributions is the **data-MC agreement!**

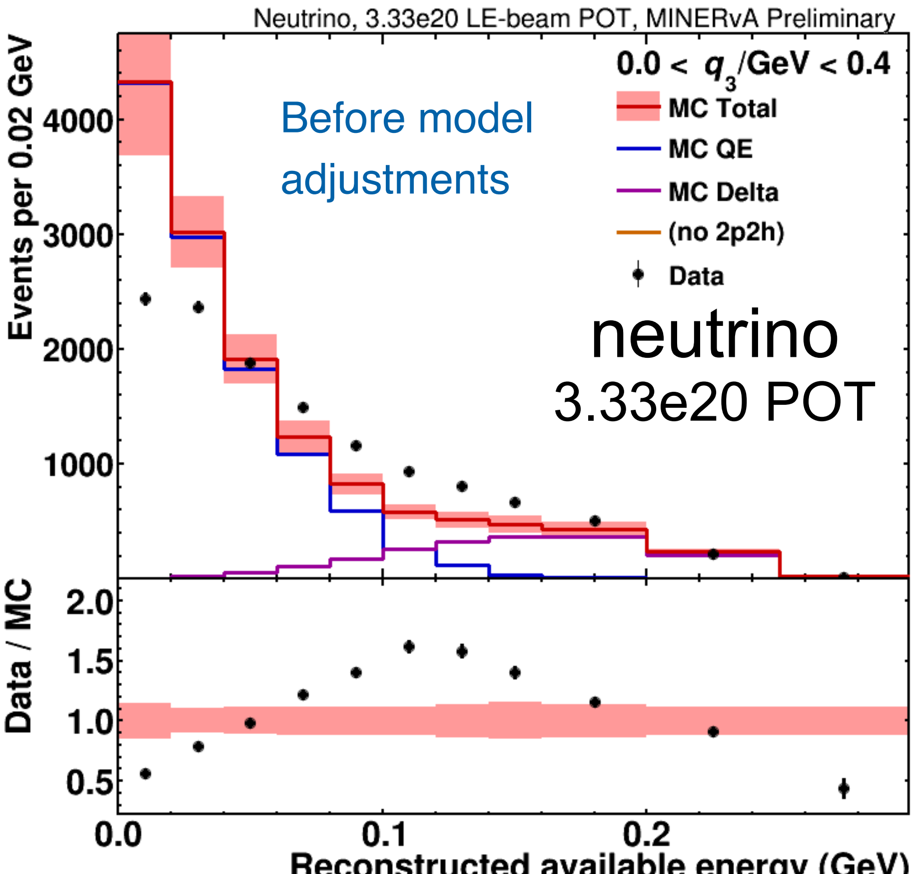


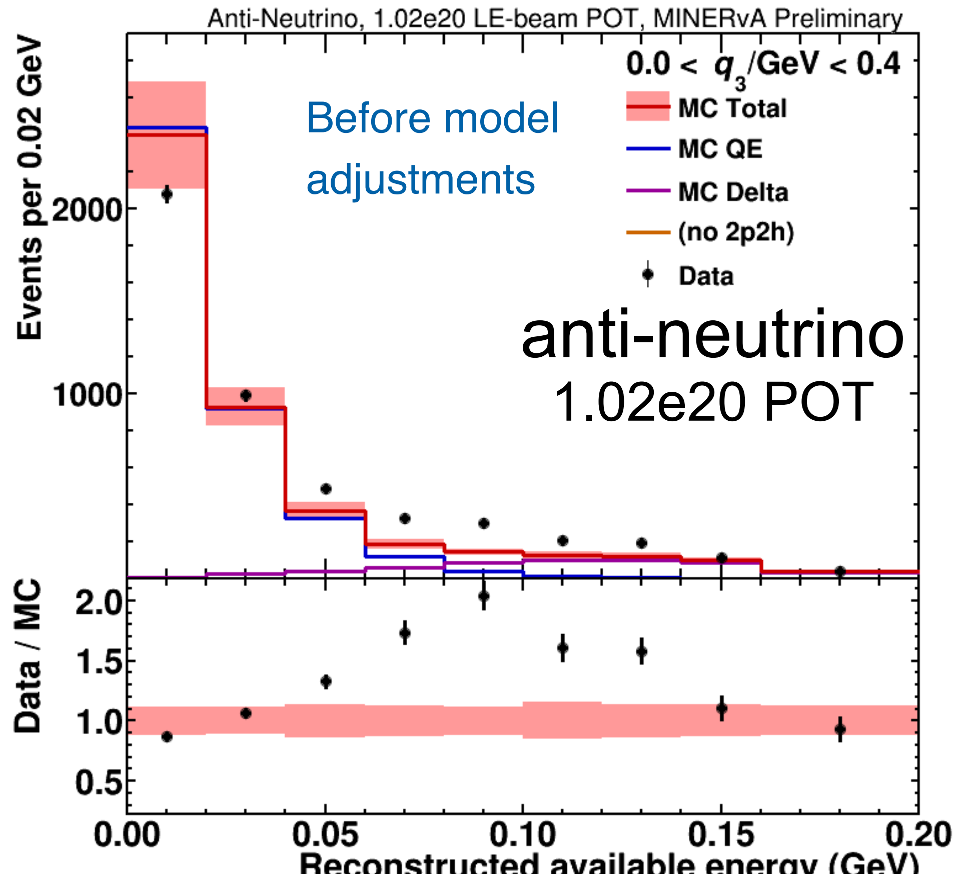




D. Ruterbories, NuInt, June 2017

MINERvA adds weak charge screening model ("RPA"), a 2p2h model (Valencia (below)), and re-weighting the 2p2h using hadronic energy for *neutrinos*…



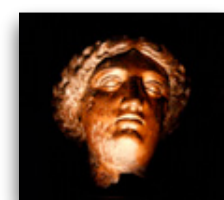




Rodrigues, Demgen, Miltenberger et al. [MINERvA] PRL 116 071802

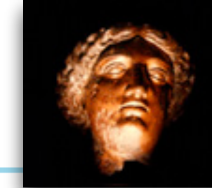
Rik Gran

NuInt17, Toronto

Valverde, Amaro, Nieves PLB 638 (2006) 325 with unpub. followup by F. Sanchez plus muon capture uncertainty and implementation R. Gran, arXiv:1705.02932



# Neutral pion production in MINERvA



$$\nu_\mu + \mathrm{CH} \rightarrow \mu^- + \pi^0 + \text{nucleon(s)}$$

**Neutrino and Antineutrino induced CC Single Pion Production Cross Sections**

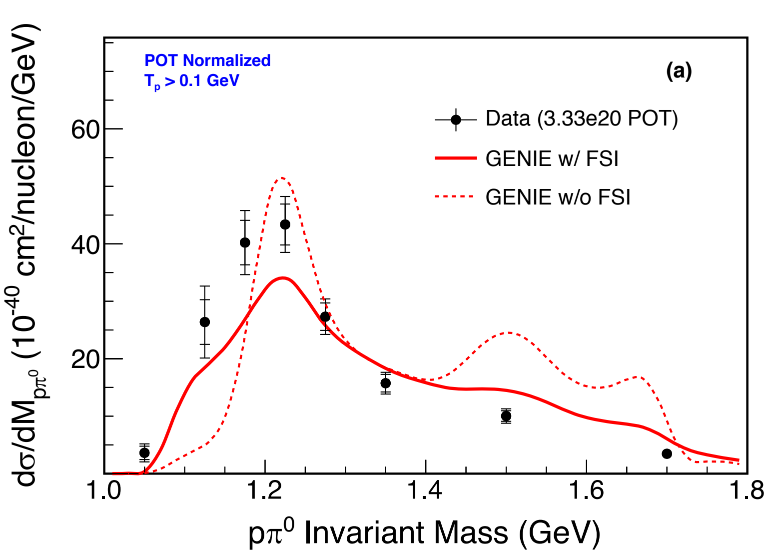
- PRD **94**, 052005 (2016), PRD **92**, 092008 (2015), PLB **749,** 130-136 (2015)

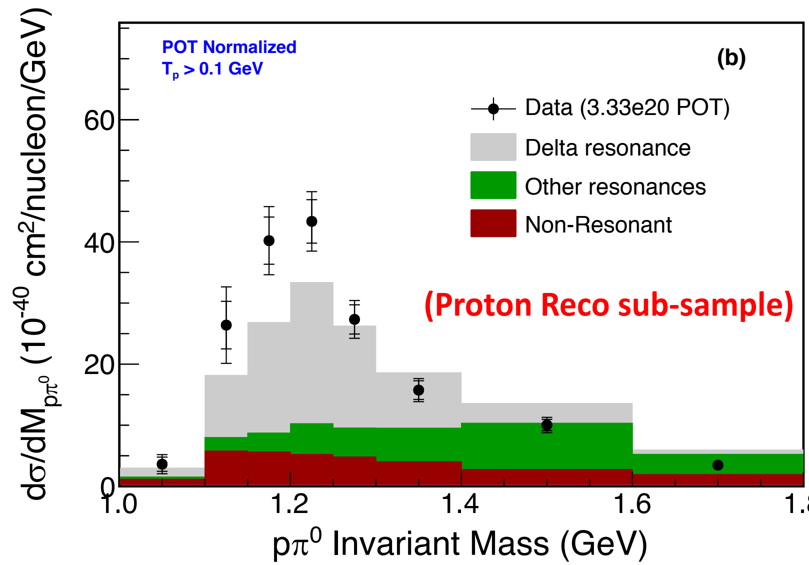
**Coming soon!**

**New!**

| | | |
|---|---|---|
| **Published** $\nu_\mu$–CC($\pi^+$) | $\bar{\nu}_\mu$–CC($\pi^-$) | **In Progress** |
| **This Work** $\nu_\mu$–CC($\pi^0$) | $\bar{\nu}_\mu$–CC($\pi^0$) | **Published** |

**Aim is to complete the set of dominant CC($1\pi$) channels.**



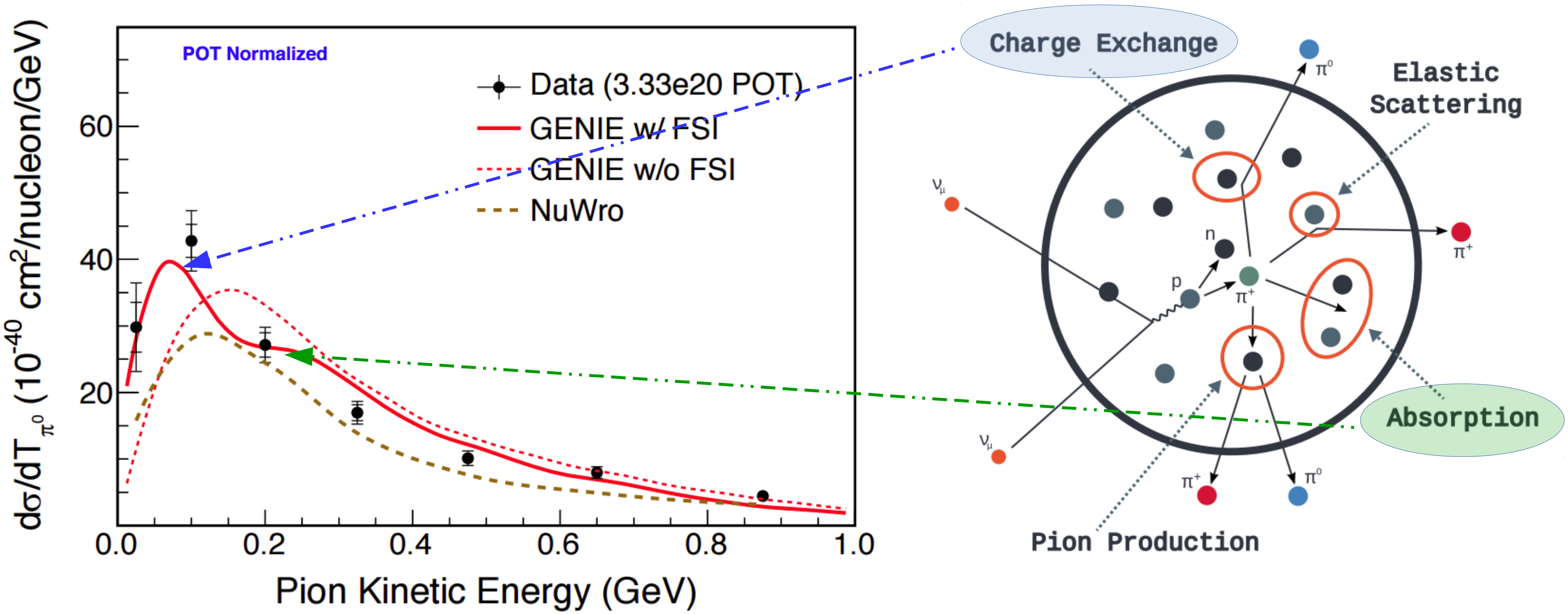




**Ozgur Altinok**

**FNAL JETP Seminar, July 2017**

# Neutral pion production in MINERvA

## Pion Kinetic Energy




- Enhancement at ~ 100 MeV due to $\pi^+ \rightarrow \pi^0$ feed-in events.
- Depletion at ~240 MeV from $\pi^0$ absorption feed-out events.

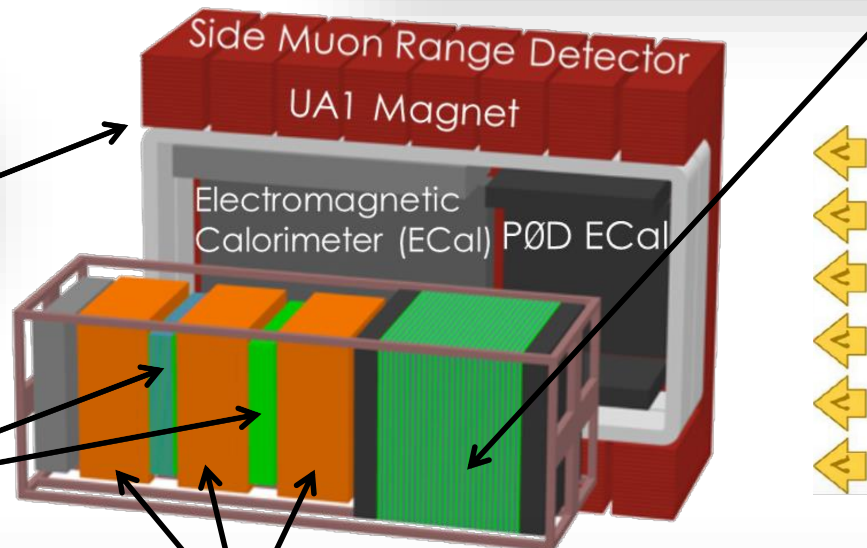
**NuInt 2017 Alejandro Ramírez**

# ND280 (off axis)

Peak $E_\nu$
On Axis ~ 1.1 GeV
Off Axis ~ 0.6 GeV

**$\pi^0$ detector (PØD):**
- CH scintillator tracker
- Target for $\nu$
- Interwoven heavy targets + drainable water bags

**Former UA1 Magnet:**
- Provides 0.2 T field




**Fine-Grained Detectors (FGD 1/2):**
- CH scintillator tracker
- Target for $\nu$
- FGD2 contains water

**Time Projection Chambers (TPC):**
- High-res tracking
- Precise particle ID
- Accurate charged-particle momenta

Stephen Dolan NuInt 2017, Toronto, Canada

# Inclusive muon neutrino CC $\pi^0$ production on CH

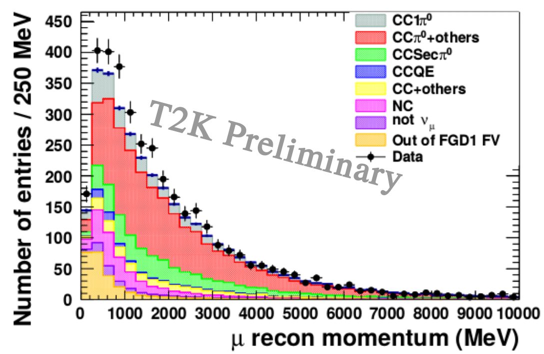
- Dominant production channels are resonance, DIS.
- Results are consistent with cross section model exceptions - discrepancies are likely due to secondary interactions.
- Systematics are still being finalized but the result is nearly ready.

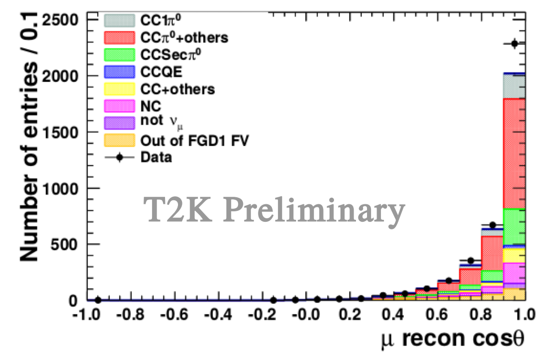
$$\sigma^{data} = \left(1.239 \pm 0.034(stat)^{+0.157}_{-0.158}(syst)^{+0.175}_{-0.149}(flux)\right) \cdot 10^{-39}\, cm^2/nucleon$$

- Cross section expected by the NEUT generator is

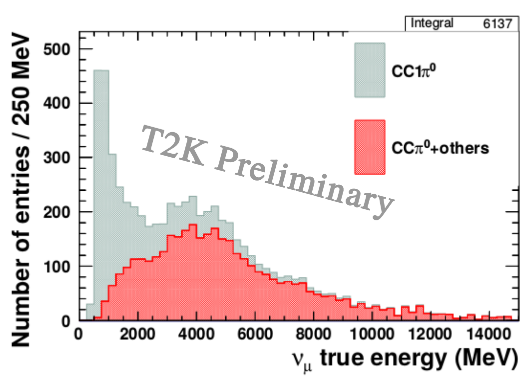
$$\sigma^{NEUT} = \left(1.0522 \pm 0.0028(stat)\right) \cdot 10^{-39}\, cm^2/nucleon$$

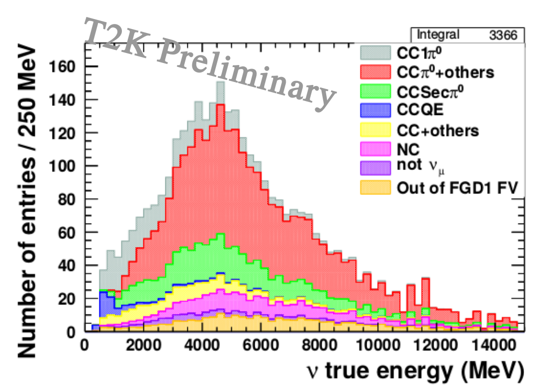
Momentum and cosθ of a muon candidate after all cuts



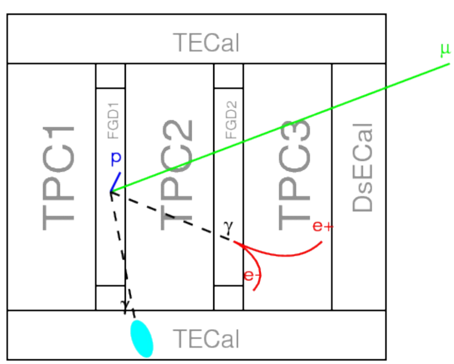

Neutrino energy for signal events before cuts and for events selected after all cuts





M.Batkiewicz
NuInt 2017


Tracker part + Tracker ECal

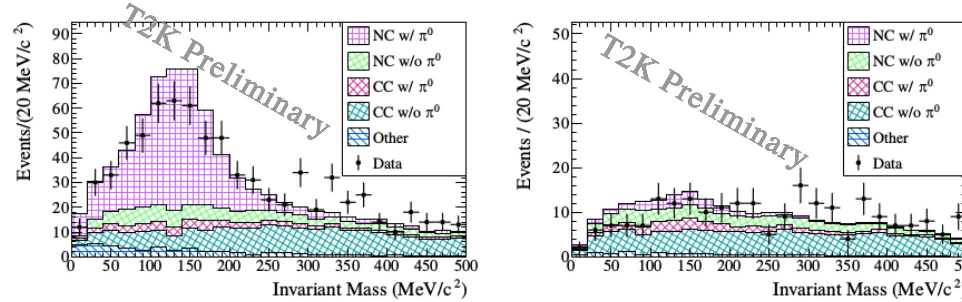
# Single $\pi^0$ production in water

- Resonance and coherent production dominate the signal.
- Statistical subtraction method (events in target with water vs events in target without).
- Results are consistent with MC expectations, leading to confidence that backgrounds are not grossly mis-predicted for oscillation measurements.

$$\nu + H_2O \rightarrow \nu + \pi^0 + X$$

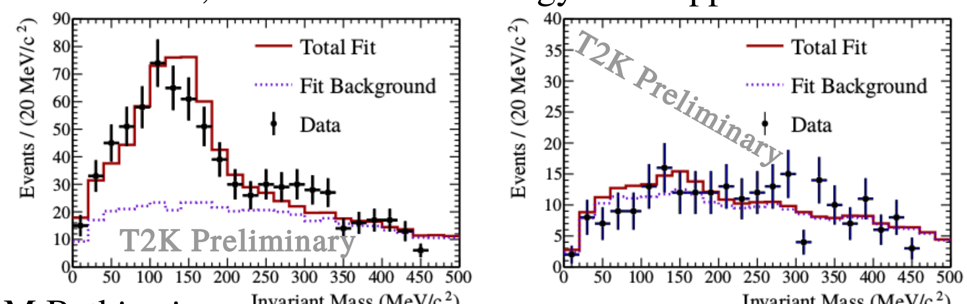
$$data/MC\,ratio = 0.68 \pm 0.26(stat) \pm 0.44(syst) \pm 0.12(flux)$$

Reconstructed invariant mass in signal-enriched and background-enriched sample




(a) Water-In configuration

Comparison of the data to the best fit invariant mass distribution, with the best fit energy scale applied to the data

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(a) Water-In configuration

arXiv:1704.074672

A neutrino interaction simulation program library NEUT – Y.Hayato, Acta Phys.Polon. B40 (2009) 2477-2489

Neut - Y.Hayato, Nucl.Phys.Proc.Suppl. 112 (2002) 171-176

# Final State Interactions

- Hadrons produced at the hard-scattering vertex must propagate out of the nucleus - very complex process (everything is an off-shell, many-bodied, non-perturbative, strongly coupled mess).
- Three ways of handling it on the market: transport theory (GiBUU - http://gibuu.hepforge.org - , best theory), intranuclear cascade ("billiard balls"), parameterized cascade.

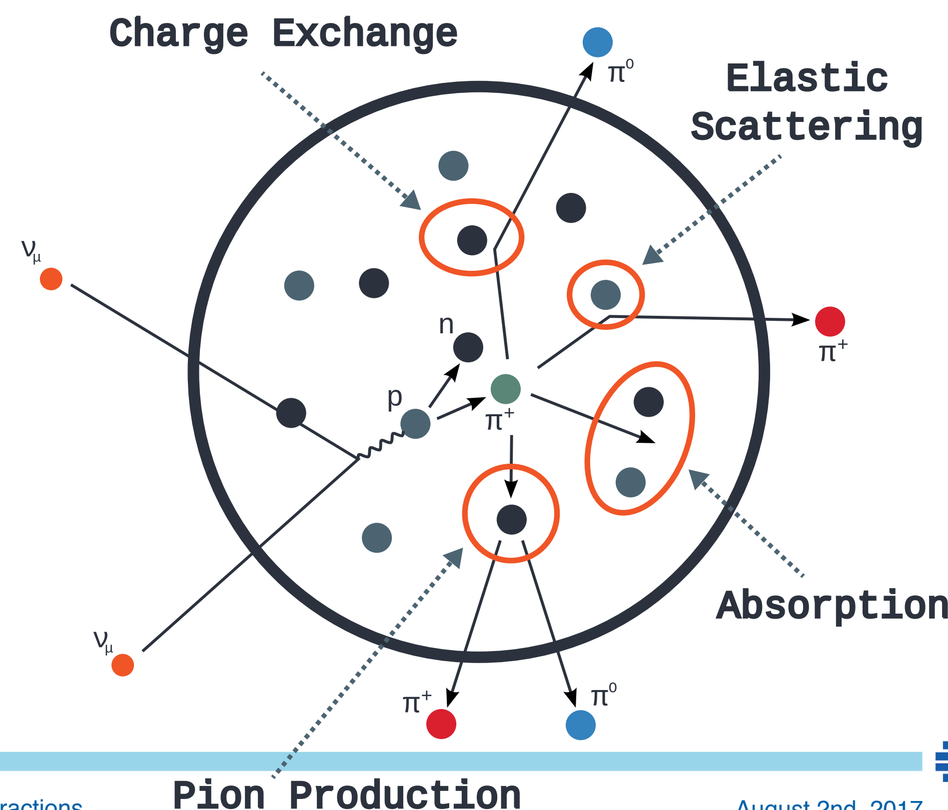
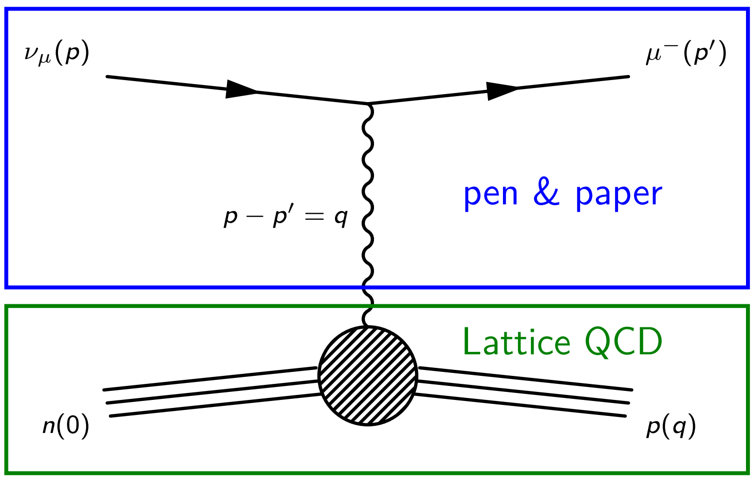



Figure by T. Golan

## How Does Lattice Help?

Lattice is well suited to compute matrix elements:

$$\mathcal{M}_{\nu_\mu n \to \mu p}(p, p') = \langle \mu(p') | \left(V_\mu - A_\mu\right) | \nu(p) \rangle \langle p(q) | \left(V_\mu - A_\mu\right) | n(0) \rangle$$





Aaron S. Meyer (asmeyer2012@uchicago.edu)

University of Chicago/Fermilab


Radiative Corrections at the
Intensity Frontier of Particle Physics

# Nucleon Axial FFs

$$\frac{d\sigma}{dQ^2} = \frac{G_f^2 M^2 \cos^2\theta_C}{8\pi E_\nu^2}\left[A \mp \frac{(s-u)}{M^2}B + \frac{(s-u)^2}{M^4}C\right]$$

$$A = \frac{(m^2+Q^2)}{M^2}\Big[(1+\tau)G_A^2 - (1-\tau)F_1^2 + \tau(1-\tau)F_2^2 + 4\tau F_1 F_2 - \frac{m^2}{4M^2}\left((F_1+F_2)^2 + (G_A + 2G_P)^2 - \left(\frac{Q^2}{M^2}+4\right)G_P^2\right)\Big]$$

$$B = \frac{Q^2}{M^2} G_A (F_1 + F_2)$$

$$C = \frac{1}{4}(G_A^2 + F_1^2 + \tau F_2^2)$$

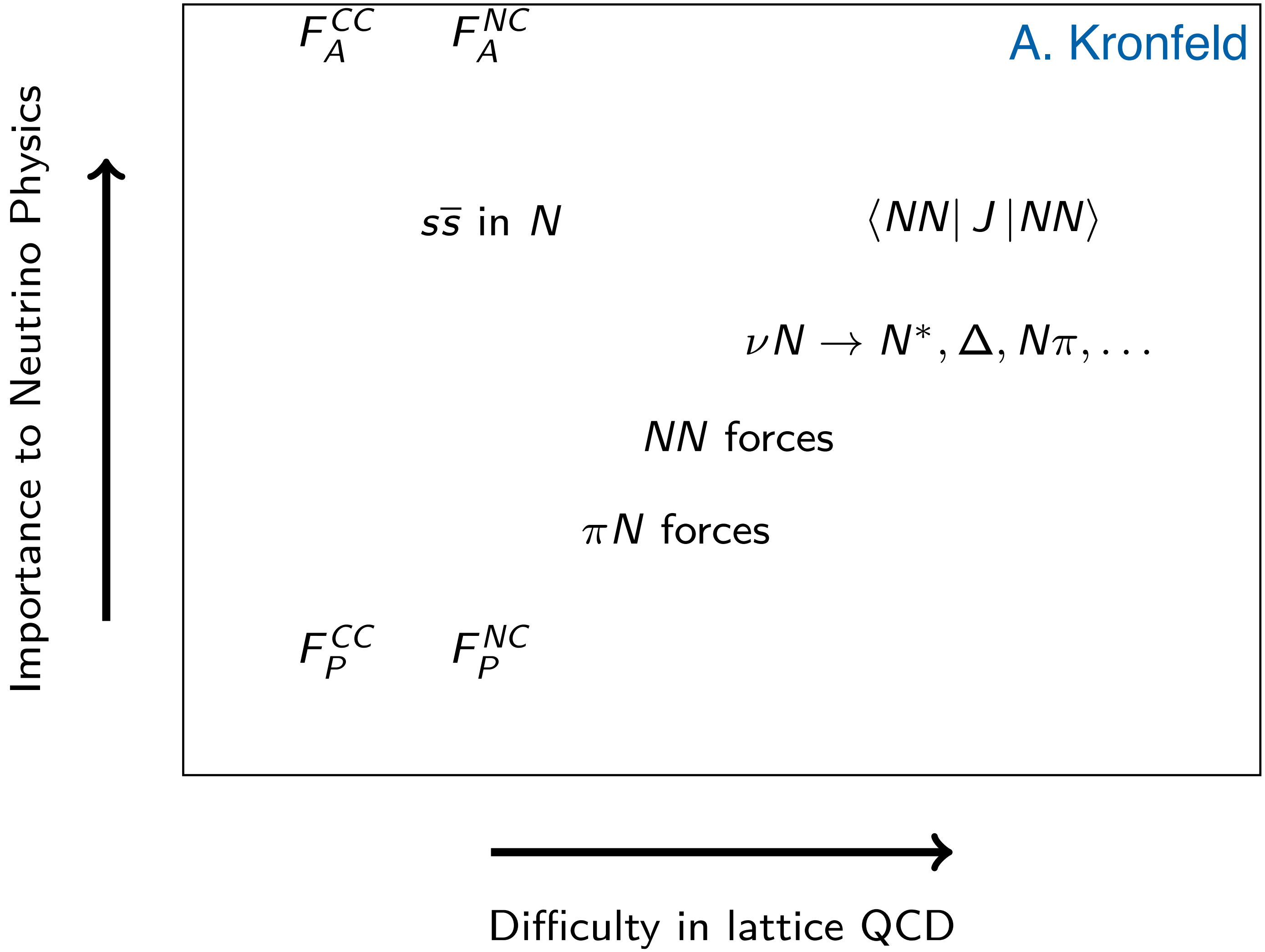
$G_A$
- dominant contribution
- largest uncertainty

$F_{1,2}$ Well-determined from electron scattering expts

$G_P$ can be related to $G_A$ by pion pole dominance


Phiala Shanahan
MIT

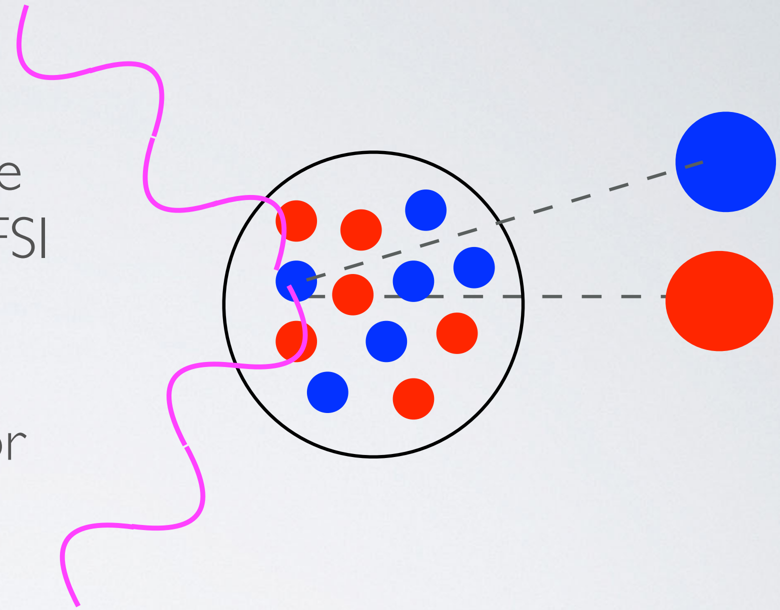
- Lattice prospects



# NMBT

J. Carlson, LANL
NuInt 2017

## Putting into Generators:



Quantum at the vertex:
- full 1- and 2-body interference
- inclusion of full two-nucleon FSI
- sum of positive contributions

Can match to classical generator
after the vertex

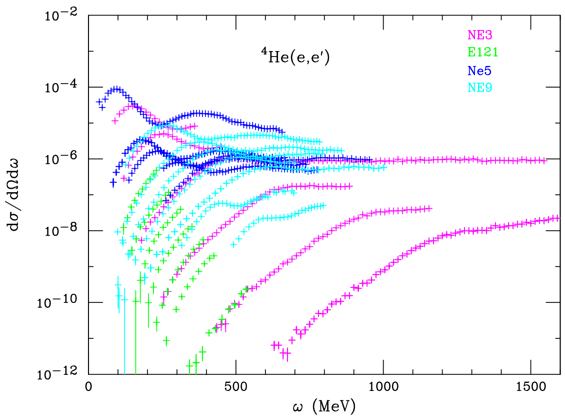
Need to include
- full weak currents (at 2N level)
- relativistic effects
- pion/delta production

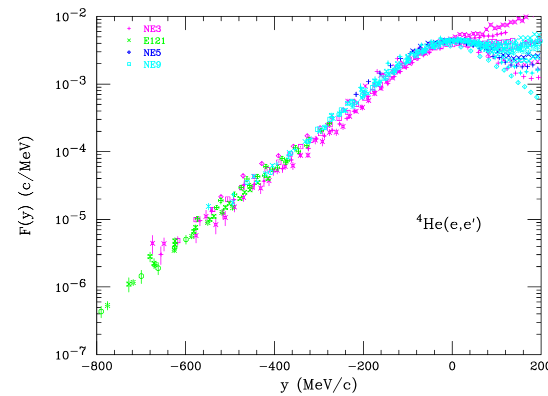
….

Experimental scaling function:

$$F(q,y) = \frac{[d\sigma/d\omega d\Omega']_{exp}}{\overline{\sigma}_{eN}(q,\omega;p=-y,\varepsilon=0)}$$

$$\overline{\sigma}_{eN}(q,\omega;p,\varepsilon) \equiv \frac{1}{2\pi}\int d\phi_N \frac{E_N}{q}\left[Z\sigma_{ep}(q,\omega;p,\varepsilon,\phi_N) + N\sigma_{en}(q,\omega;p,\varepsilon,\phi_N)\right]$$




Scaling of the first kind: $q \to \infty \Longrightarrow$ $F(q,y) \longrightarrow F(y) \equiv F(\infty, y)$

$$f(q,\psi) \equiv k_F \frac{[d\sigma/d\omega d\Omega_e]}{\sigma_M\,[v_L G^L + v_T G^T]}, \quad f^L(q,\psi) \equiv k_F \frac{R^L(q,\omega)}{G^L}, \quad f^T(q,\psi) \equiv k_F \frac{R^T(q,\omega)}{G^T}$$

- Scaling of the first kind: $f_{exp}(q,\psi) \xrightarrow{q\to\infty} f_{exp}(\psi)$; $\psi \approx y/k_F$ – *superscaling variable*
- Scaling of the second kind: $f_{exp}(\psi)$ – *independence on the nuclear system*

**SUPERSCALING**

- Scaling of the zeroth kind: $f_{exp}(q,\psi) = f^L_{exp}(q,\psi) = f^T_{exp}(q,\psi)$

J. Caballero, Seville
NuInt 2017

# Quick refresher - scaling

- Scaling of the first kind occurs when the electron-nucleus cross section or longitudinal/transverse response functions (divided by a function describing free nucleon physics) no longer depend on two variables (e.g. energy transfer and the absolute value of the 3-momentum transfer), but only on a specific function of them, which defines the *scaling variable*.
- Scaling of the second kind takes place when there is no dependence on the nuclear species.
- The simultaneous occurrence of both kinds of scaling is called *superscaling*.
- Scaling of the zeroth kind occurs when the scaling function is the same for the longitudinal and transverse responses.

# SuSA models

**Original SuSA model:**

- Fit of the $(e, e')$ longitudinal scaling data
- Assumption $f_L(\psi) = f_T(\psi)$

**SuSAv2** *PRC90, 035501, 2014*

- An improved SuperScaling model based on RMF calculations (FSI).
- Decomposition into isoscalar and isovector components which is of interest for CC neutrino reactions.
- RMF & RPWIA models are employed to get a set of scaling functions valid for all lepton-nucleus scattering processes

**RMF/RPWIA transition:** *PRD 94, 013012 (2016)*

- RMF $\Rightarrow$ FSI between the outgoing nucleon and the residual nucleus $\Rightarrow$ low-intermediate $q$
- RPWIA $\Rightarrow$ outgoing nucleon as a relativistic plane wave $\Rightarrow$ higher $q$ values

➥ SuperScaling Approach as a combination of RMF and RPWIA scaling functions:

$$\mathcal{F}_L^{T=0,1} \equiv \cos^2\chi(q,q_0)\tilde{f}_L^{T=0,1} + \sin^2\chi(q,q_0)\tilde{f}_L^{RPWIA}$$

$$\mathcal{F}_T \equiv \cos^2\chi(q,q_0)\tilde{f}_T + \sin^2\chi(q,q_0)\tilde{f}_T^{RPWIA}$$

➢ $q_0(q)$: RMF/RPWIA transition parameter, determined by performing a $\chi^2$ analysis of the $(e, e')$ data in a wide kinematical region.

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*5th December 2016, INT-16-63W, Seattle*