H.A.TANAKA (SLAC/STANFORD)

NEUTRINO EXPERIMENTS

SFB 1044 Workshop on Electromagnetic Observables for Low Energy Nuclear Physics
Johannes Gutenberg University, Mainz, Germany

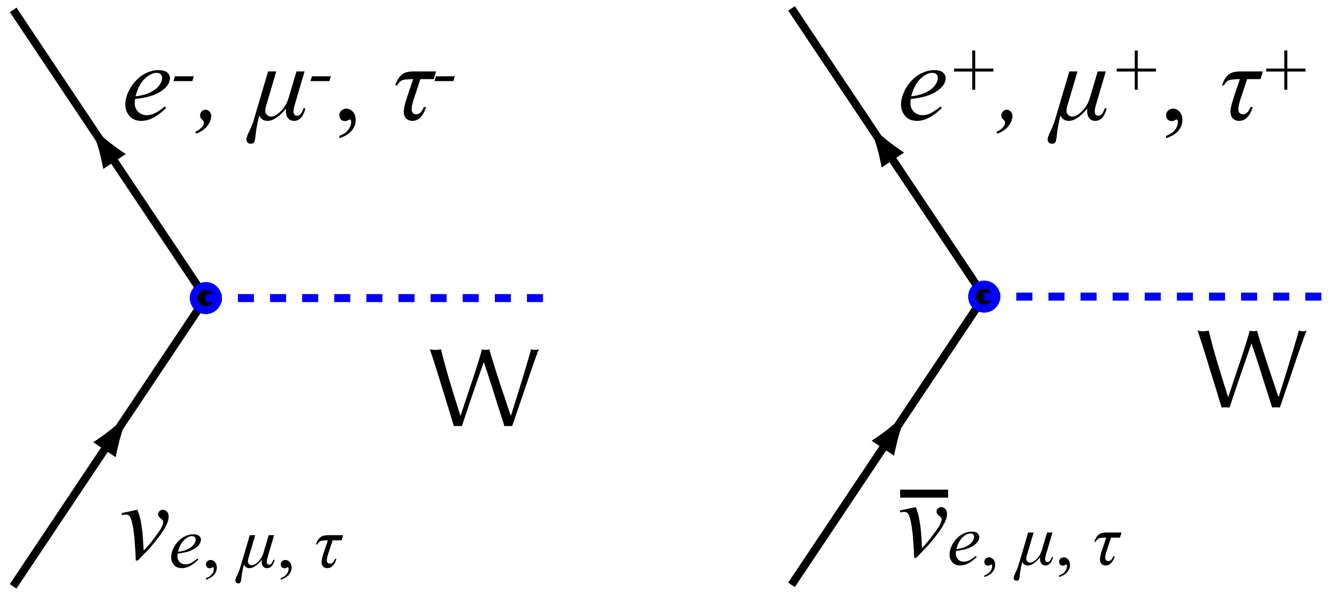
OVERVIEW:

- Introduction to neutrino oscillation experiments
  - How are neutrino oscillations measured?
  - An overview of the current program and a survey of a few problems
  - Some words about generators

- *What is the role of relativity in neutrino-nucleus collisions?*
- ***What new electron scattering measurements can be useful for this program?***
  - ***Yes!***
- ***How can better theory be implemented in neutrino generators simulations?***
  - ***Yes!***

NEUTRINO OSCILLATION

- Neutrino come in three "flavor" eigenstates (ν_e, ν_μ, ν_τ)
    - Determined by how their weak interaction properties
    - Corresponding "antineutrinos" for each
- Likewise, neutrinos come in three mass eigenstates (ν_1, ν_2, ν_3)
    - energy eigenstates which are stationary under time evolution
- The mass and flavor eigenstates "mix"
    - Neutrinos are produced in flavor eigenstates (by weak interaction)
    - Mass eigenstates evolve differently in time . . . ..
    - New flavor components appear . . . . . "neutrino oscillations"
- For a two neutrino species, a simple formula results



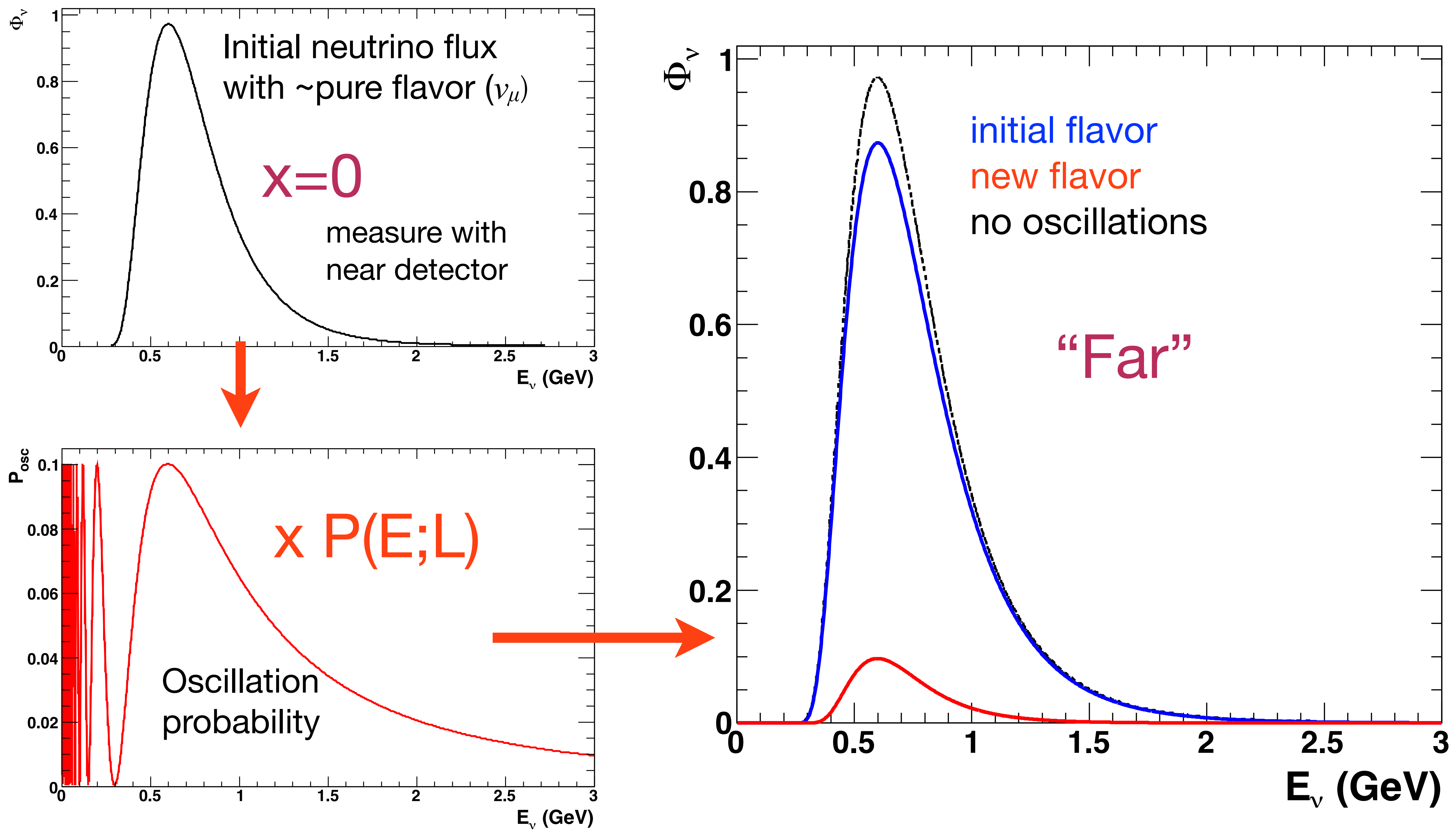
$$\underbrace{|\nu_\alpha\rangle}_{\text{flavor}} = \sum_i \overbrace{U^*_{\alpha i}}^{\text{Mixing}} \underbrace{|\nu_i\rangle}_{\text{mass}}$$

$$\underbrace{\begin{pmatrix} \nu_\alpha \\ \nu_\beta \end{pmatrix}}_{\text{flavor}} = \overbrace{\begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix}}^{\text{Mixing}} \underbrace{\begin{pmatrix} \nu_1 \\ \nu_2 \end{pmatrix}}_{\text{mass}}$$

$$P(\nu_\alpha \xrightarrow{t} \nu_\beta) = \overbrace{\sin^2 2\theta}^{\text{transformation properties}} \; \sin^2 \underbrace{1.27}_{\text{unit conversion}} \overbrace{\frac{\Delta m^2_{21}(\text{eV}^2)}{E(\text{GeV})}}^{\text{energy difference (special relativity)}} \underbrace{L(\text{km})}_{\text{“time”}}$$

Note the importance of neutrino energy

MEASURING OSCILLATIONS



- Start with a beam in a (relatively) pure flavor state
- Observe oscillations at a fixed baseline (L) by:
  - “Appearance”
    - new flavor in the beam arising from oscillations
  - “Disappearance”
    - deficit of original flavor due to oscillations into new flavors
- In each case, we want to measure as a function of neutrino energy to obtain the probability as a function of E_ν

$$P(\nu_\alpha \xrightarrow{t} \nu_\beta) = \sin^2 2\theta \ \sin^2 1.27 \frac{\Delta m^2_{21}(\mathrm{eV}^2)}{E(\mathrm{GeV})} L(\mathrm{km})$$

- More formally . . . we can predict the expected spectrum at the “far” detector (FD) as

$$N_{FD}(\nu_\alpha \to \nu_\beta, E_{rec}) = \int dE_\nu \ \Phi_{\nu_\alpha}(E_\nu) \times \boxed{\sigma_{\nu_\alpha}(E_\nu) \times R_{\nu_\alpha}(E_\nu, E_{rec})} \times P(\nu_\alpha \to \nu_\beta, E_\nu)$$

- An essential strategy is also to observe the “same” neutrino beam with a “near” detector (ND)at L~0

$$N_{ND}(\nu_\alpha, E_{rec}) = \int dE_\nu \ \Phi_{\nu_\alpha}(E_\nu) \times \boxed{\sigma_{\nu_\alpha}(E_\nu) \times R_{\nu_\alpha}(E_\nu, E_{rec})}$$

R is what takes us from physics which depend on the “true” neutrino energy to what we actually observe (N, E_{rec})

R is a combination of neutrino interaction modeling (what comes out) and what the detector sees (efficiency, resolution, etc.)

NEUTRINO ENERGY RECONSTRUCTION

- Two basic approaches:
  - Kinematic:
    - Selection events which *correspond* to a "well defined" reaction and use the inferred kinematics
    - e.g. target ν+n→μ+p interactions by selection pionless events and assume the kinematics:
    - $$E_{Rec} = \frac{m_N E_\mu - m_\mu^2/2}{m_N - E_\mu + |\vec{p}_\mu| \cos\theta_\mu}$$
  - Calorimetric:
    - Add up the energy of all the products detected in the neutrino reaction
- Issues:
  - Kinematic:
    - Reactions like "ν+n→μ+p" do not really exist on a nucleus
      - Rely on modeling to predict the **outgoing muon kinematics** for events with **targeted topology** (e.g. "pionless")
  - Calorimetric
    - Energy reconstruction depends on particle composition of outgoing particles (e.g. neutrons)
      - Rely on modeling **outgoing particles** inclusively across **all types of neutrino interactions that are selected**

Reminder: $R(E_\nu, E_{rec})$ tells us how a neutrino of energy E_ν will be reconstructed to get E_{rec}

NEUTRINO BEAMS

- With few exceptions (e.g. stopped meson beams), we are always presented with a spectrum of neutrinos
  - For any observed neutrino interaction, we do not know its energy
  - It must be inferred from the products emerging from the reaction
    - Nuclear modeling is essential not only for predicting event rates, but the energy spectrum
- Whether in the near or far detector, what we observed is inherently flux-averaged

$$N_{FD}(\nu_\alpha \to \nu_\beta, E_{rec}) = \boxed{\int dE_\nu} \, \Phi_{\nu_\alpha}(E_\nu) \times \boxed{\sigma_{\nu_\alpha}(E_\nu) \times R_{\nu_\alpha}(E_\nu, E_{rec})} \times P(\nu_\alpha \to \nu_\beta, E_\nu)$$

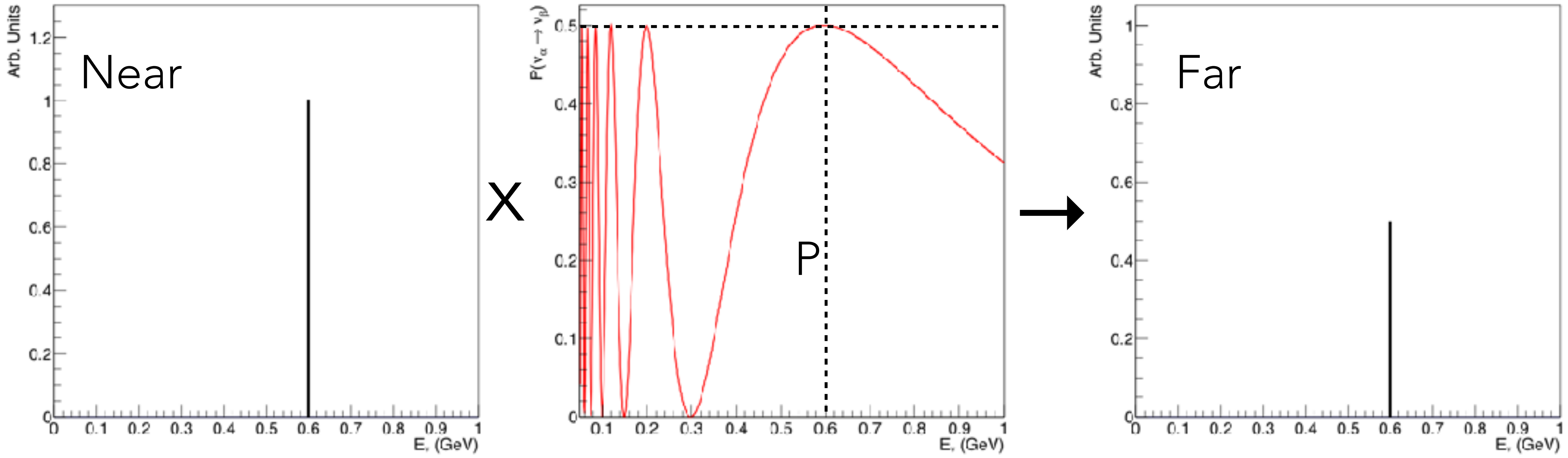
$$N_{ND}(\nu_\alpha, E_{rec}) = \boxed{\int dE_\nu} \, \Phi_{\nu_\alpha}(E_\nu) \times \boxed{\sigma_{\nu_\alpha}(E_\nu) \times R_{\nu_\alpha}(E_\nu, E_{rec})}$$

  - ND inherently cannot tell you how a neutrino of E_ν appears in the detector (i.e. $R(E_\nu, E_{rec})$)
    - This requires modeling
  - The best it can do is tell you that your model of R_ν agrees or disagrees in a flux averaged sense
    - "Agrees" is necessary but not sufficient for "correct"

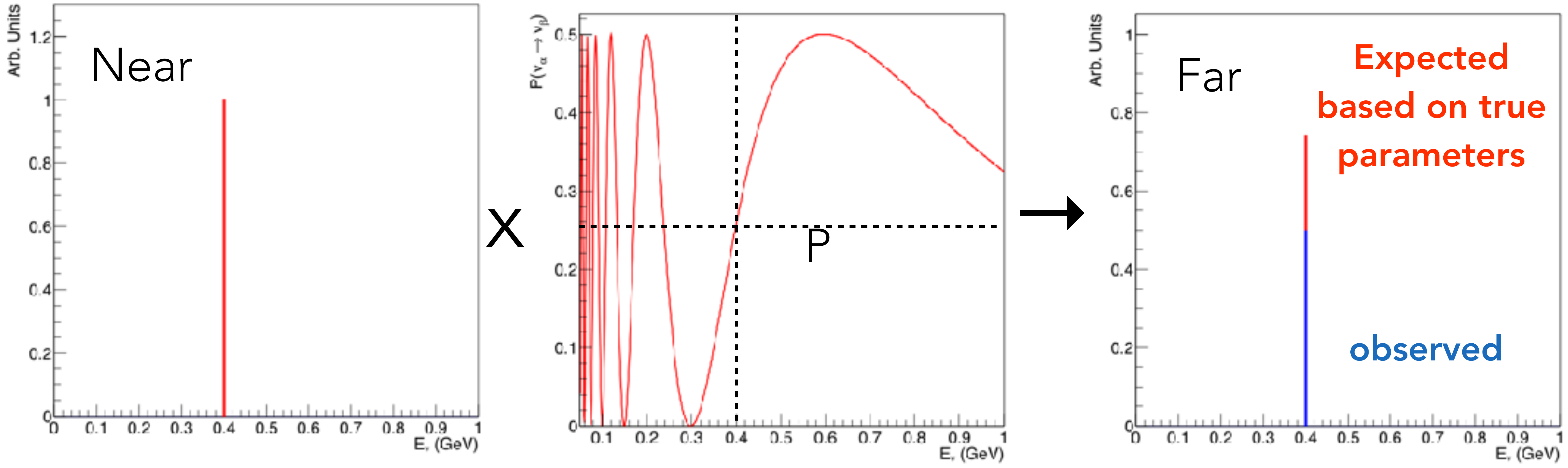
TOY EXAMPLE

$$P(\nu_\alpha \xrightarrow{t} \nu_\beta) = \sin^2 2\theta \ \sin^2 1.27\frac{\Delta m^2_{21}(\mathrm{eV}^2)}{E(\mathrm{GeV})}L(\mathrm{km})$$

True



Reconstructed



- For simplicity, assume:
  - Monoenergetic source of ν_α whose true energy is 600 MeV, but unknown to experiment
  - cross section is known to be flat: $\sigma_\nu(E_\nu) = c$
  - Δm^2 is known (2.5×10^{-3} eV^2)
  - $\sin^2 2\theta = 0.5$ but is unknown
  - Near/Far Detectors respond identically

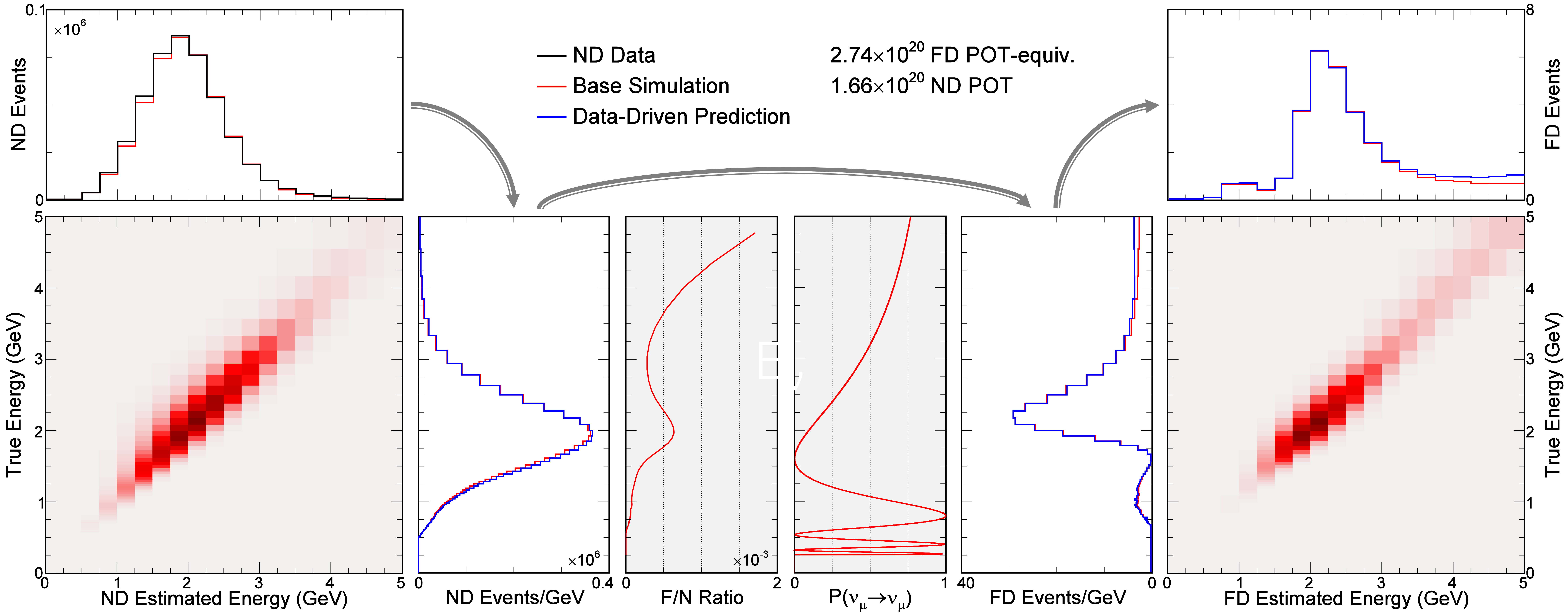
But:

- True $R(E_\nu, E_{rec})$ is "diagonal": $E_{rec}=2/3\ E_\nu$
- Incorrect modeling: assume $R(E_\nu, E_{rec})$ is $E_\nu = E_{rec}$
  - ~incorrectly assume events are QE when in fact they are Δ resonance

Two ways to look at situation:

- Based on "correct" oscillation parameters predicted FD event rate is off from what it should.
- Observed rate indicates $\sin^2 2\theta = 0.75$ (not 0.5)
- In either case, we are evaluating oscillation probability at the wrong E_ν

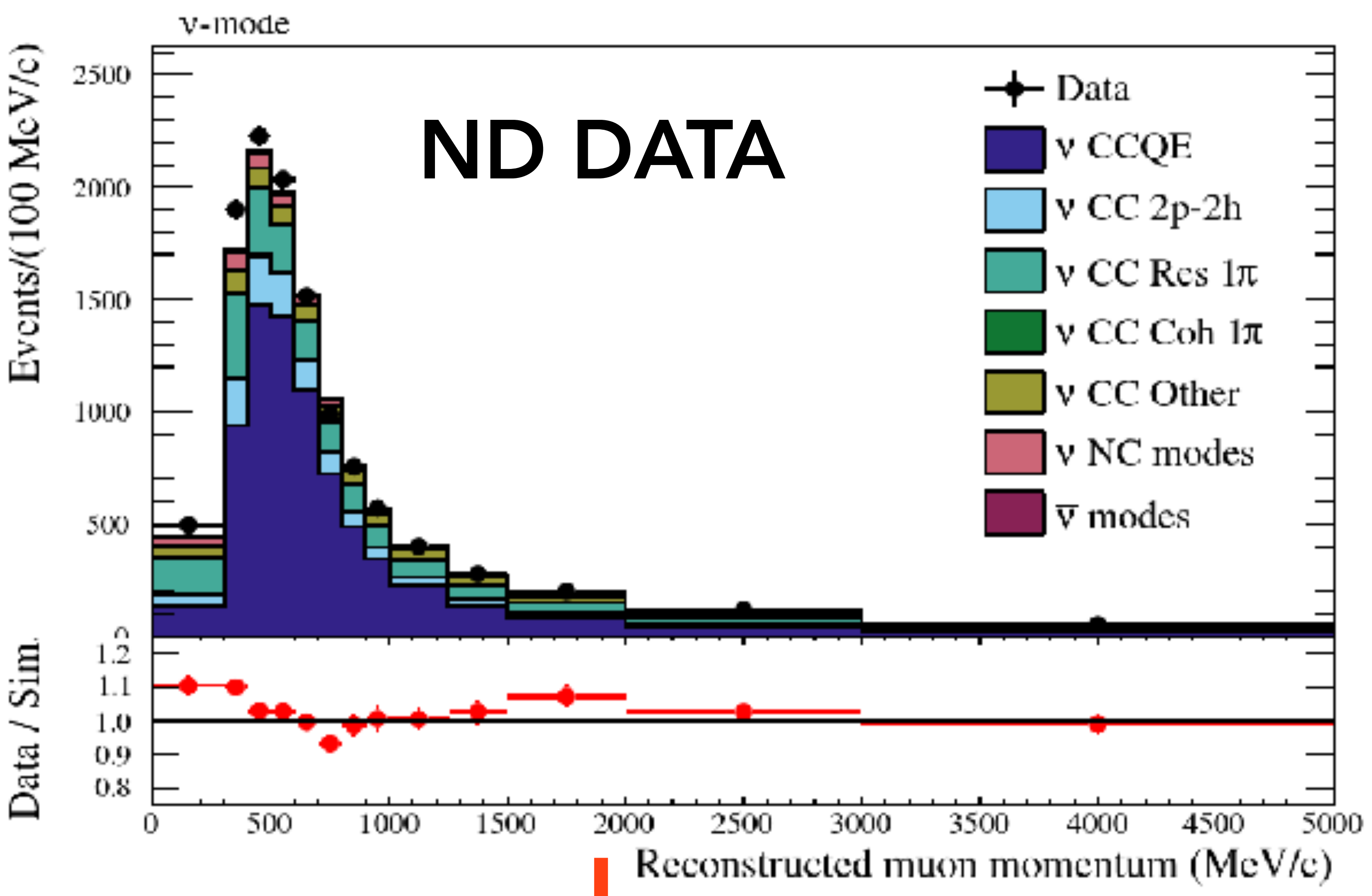
"REAL" EXAMPLE FROM NOVA



- Neutrino event rate vs. En is "corrected" by observed near detector spectrum
- Correction depends on R:
  - Incorrect model gives incorrect parameters: systematic errors propagated by varying R

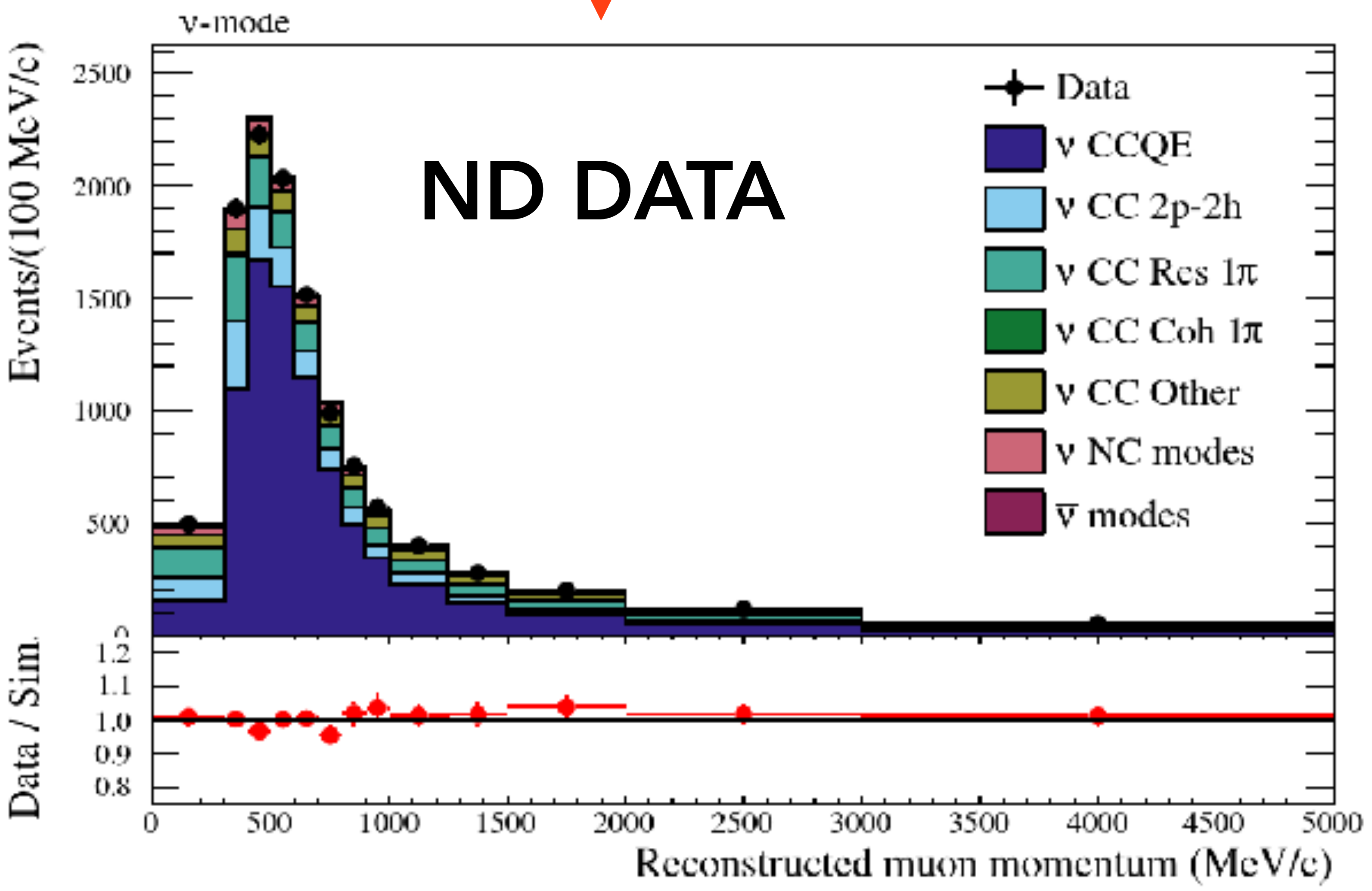
ANOTHER APPROACH (T2K)

- Fit model parameters to near detector
  - “model” = flux, cross section, detector
  - Updated model includes new parameter values and covariance matrix
  - New model is “transported” to far detector prediction
- Some non-parametrized model variations are considered separately



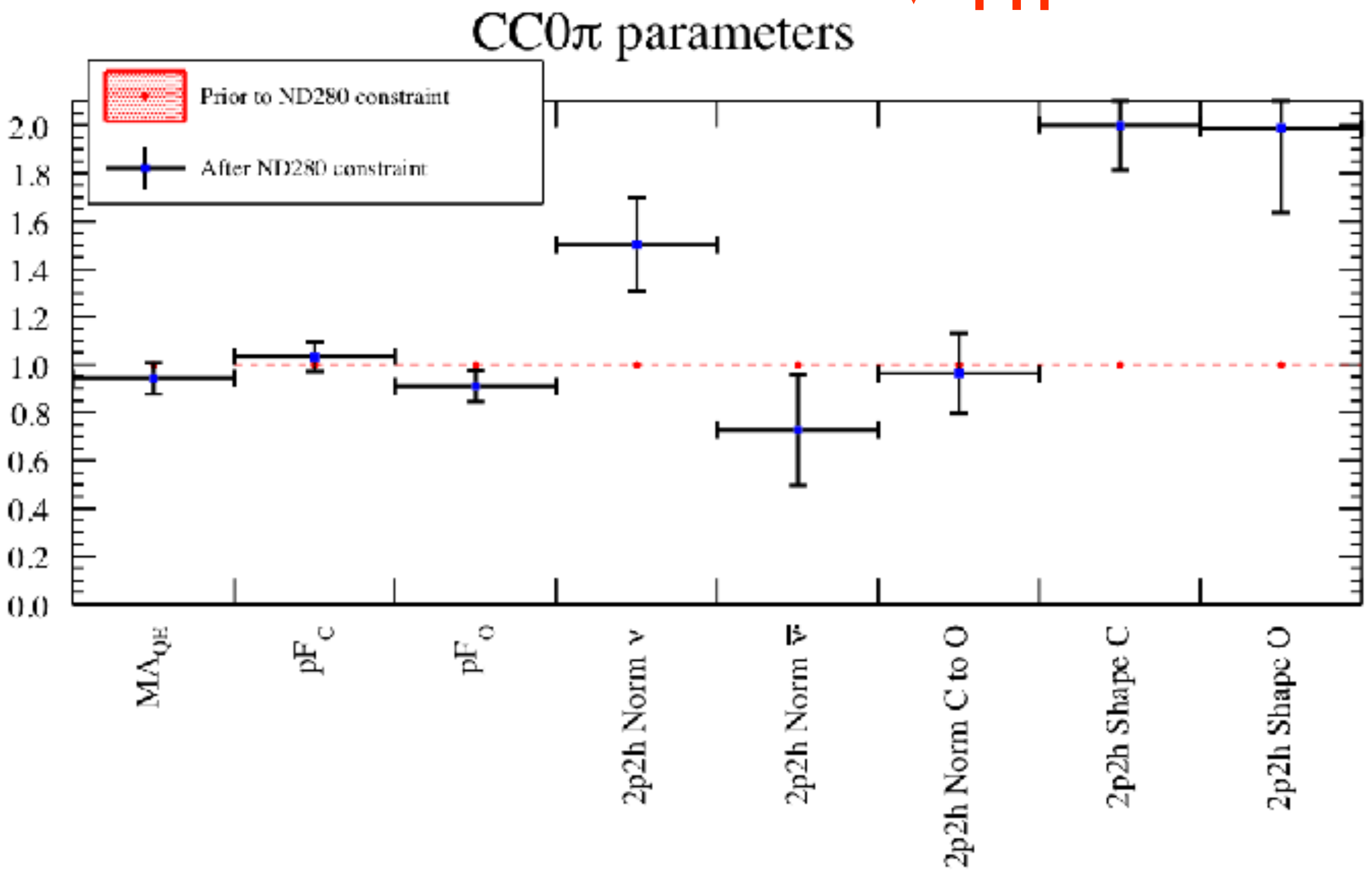
PRELIMINARY

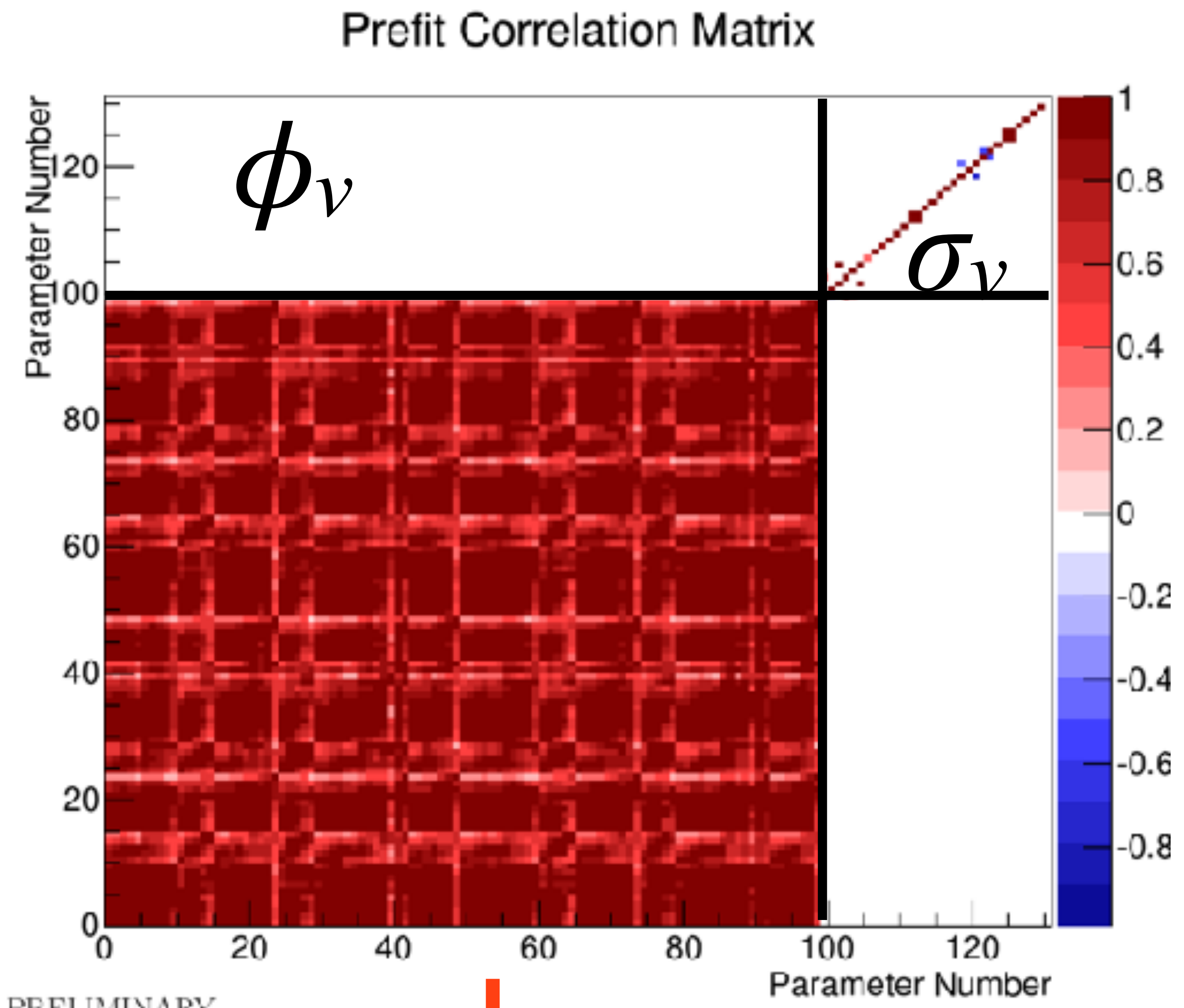
FIT



PRELIMINARY

FIT





PRELIMINARY

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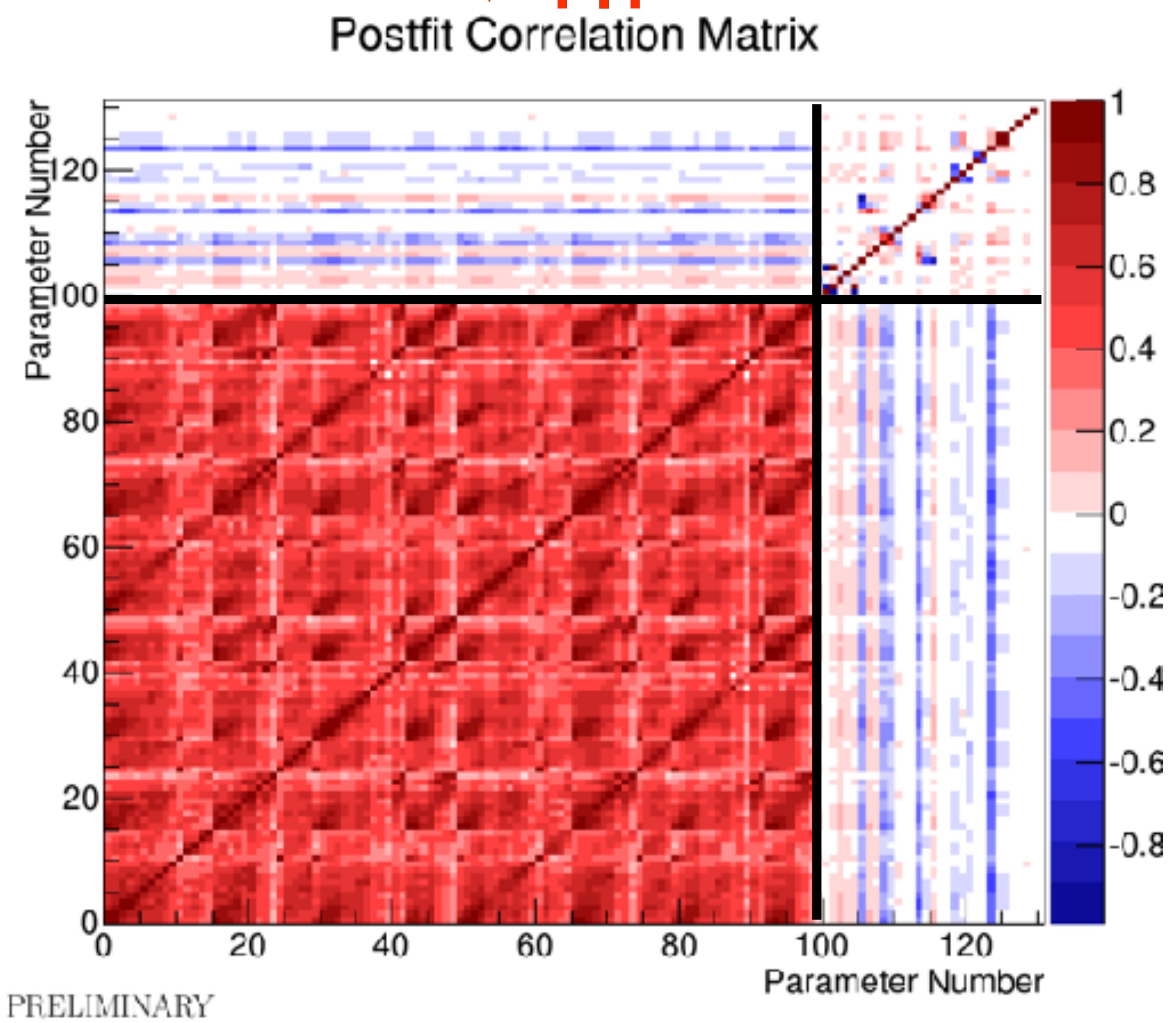


PRELIMINARY

“LONG-BASELINE” EXPERIMENTS

T2K and
T2HKK (295 km)

NOvA (812 km)

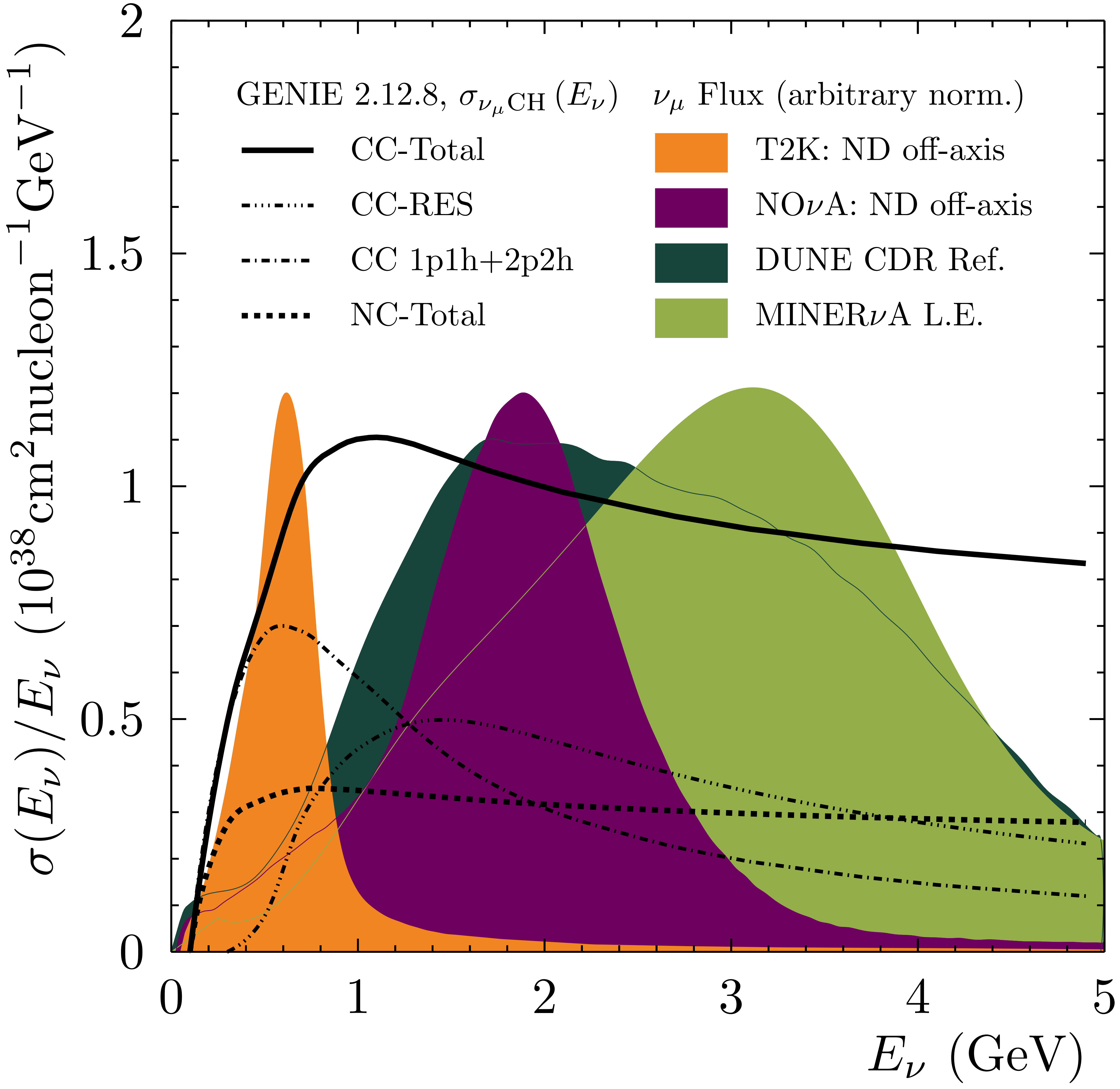
- Experiments require:
  - O(MW) proton beams to produce neutrino beams
  - O(10^{1-2} kt) detectors situated hundreds of kilometers away

DUNE/LBNF: FNAL to Homestake: 1300 km

- Accelerator-based neutrino beams have been sent to detectors hundreds of km away on three continents
- Key elements
  - Precision measurements of neutrino mixing parameters
  - CP violation, matter effects to resolve mass ordering

NEUTRINO FLUX AND INTERACTIONS

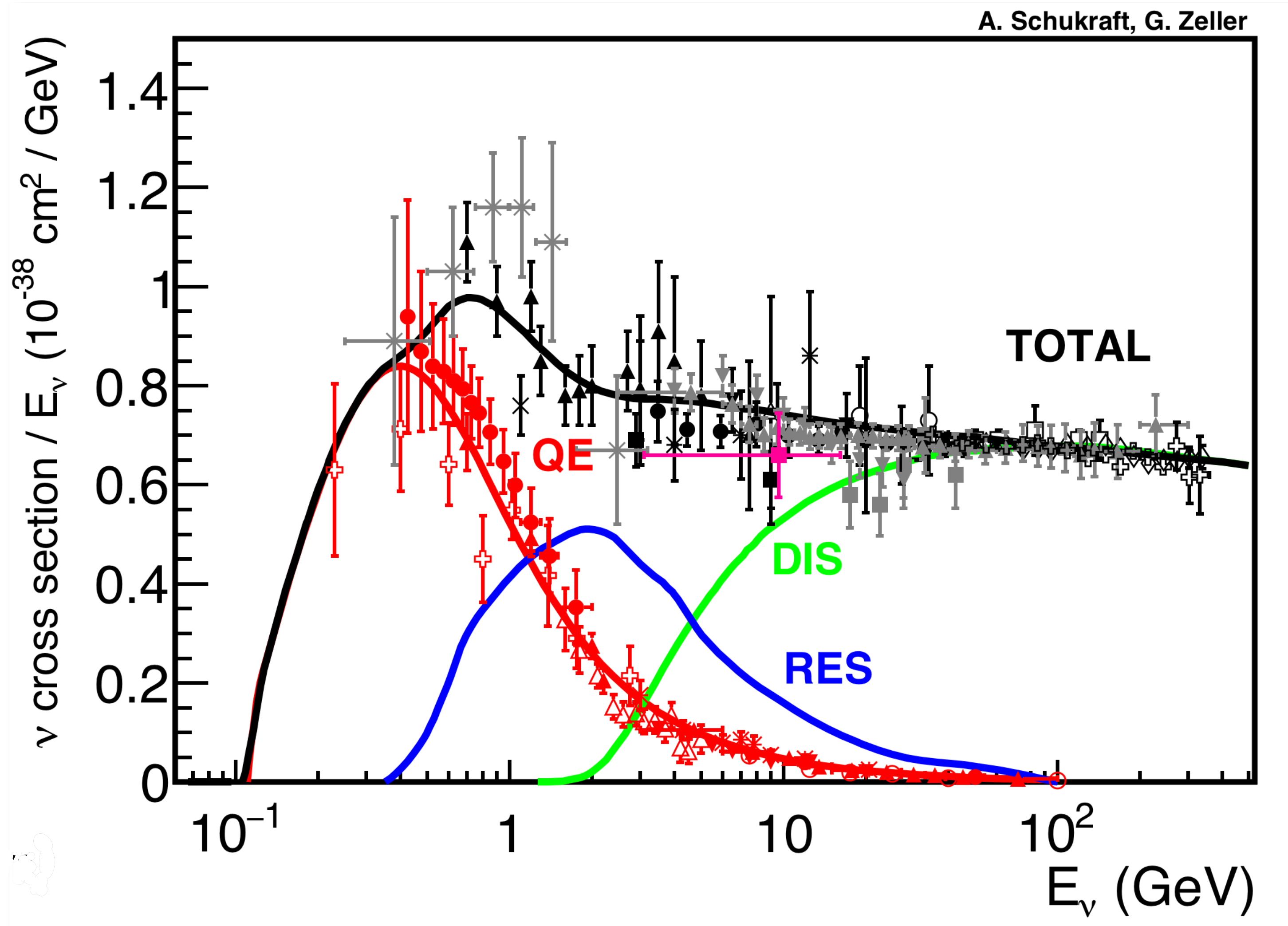
K. Mahn et al. arxiv: 1803.08848.



- Accelerator-based neutrino beams produce O(GeV) neutrinos
  - Pure ν_μ beams with O(1%) ν_e contamination from pion decays
  - Likewise ν_μ beams can be produced
- At nucleon-level, we have:
  - Quasi-elastic scattering
  - Resonant pion producition
  - Deep inelastic scattering
- Modeling relies heavily on "impulse approximation"
  - Neutrinos interactions are inherently at the nucleon (or quark) level
  - Initial state dynamics typically modeled with Relativistic Fermi Gas
  - Final state dynamics via intranuclear cascade
  - A few coherent processes considered
  - Relativistic effects important for most processes

LORE

- The issue of neutrino-nucleus modeling is intimately coupled to how we use the near detector
- Some things I have heard:
  - *The purpose of the near detector is to measure the neutrino flux*
    - This is a useful thing for the near detector to do (via leptonic processes), but it is not sufficient
    - ***n.b***. measuring the neutrino flux at ND requires you to know the cross section (observable is $\varphi \times \sigma$)
  - *What we need to know is the neutrino cross section versus energy*
    - This is a useful thing to know, but it is not sufficient in itself
    - We need our models to also predict efficiencies and response
  - *We're doing a counting experiment so shape doesn't matter*
    - Still need true neutrino spectrum to calculate overall oscillation probability
  - *The near detector data agrees with our model hence the model must be correct*
    - Disagreement with the near detector indicates mismodeling
    - But agreement does not mean the model is correct
  - *If the flux at ND/FD are the same, and the ND/FD detectors respond identically, systematic errors cancel*
    - ND/FD fluxes are not the same: we have oscillations at the FD
    - Many systematics may cancel, but we must still know E_ν (as opposed E_{rec}) in order to predict the FD events correctly



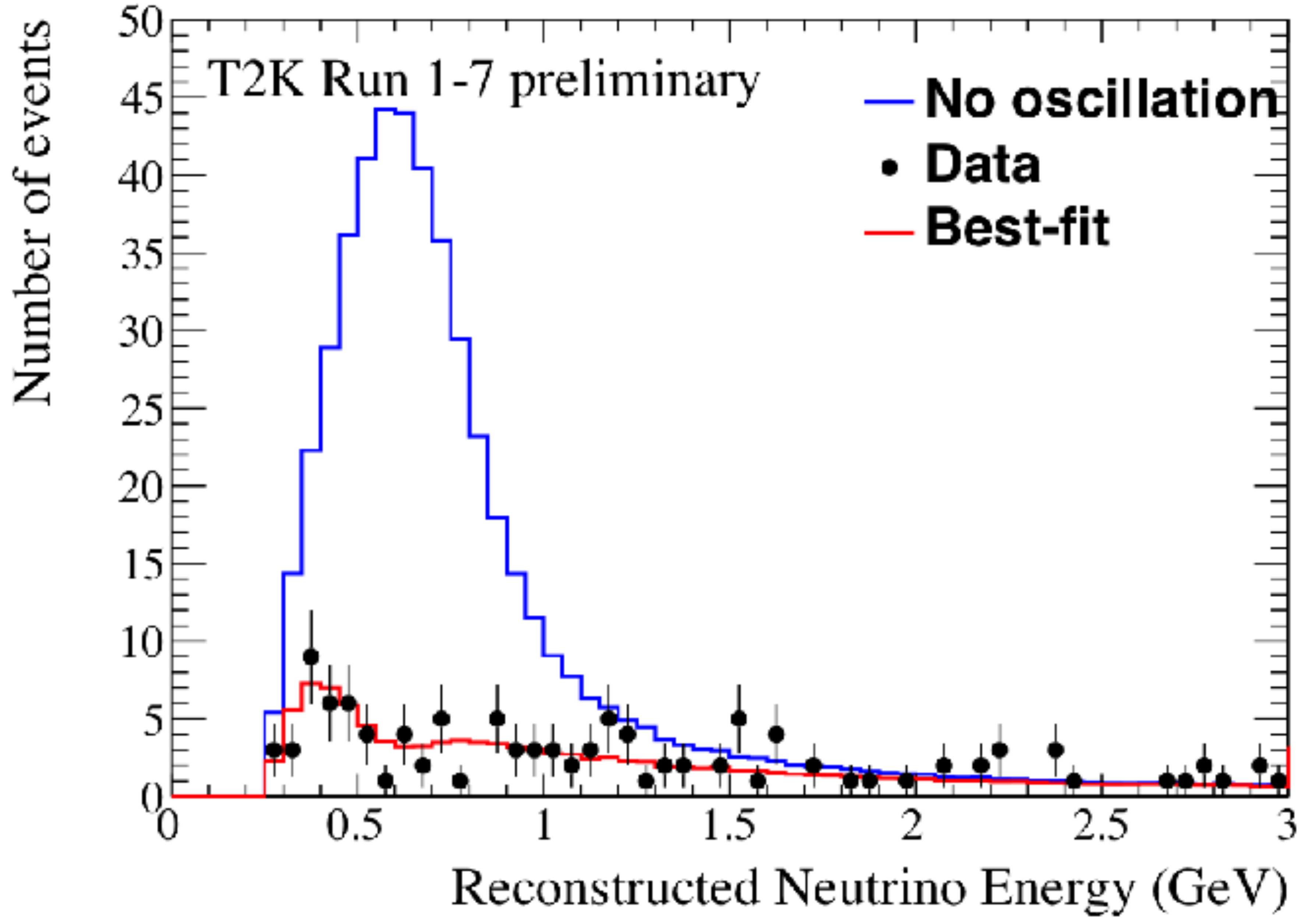
MEASUREMENTS

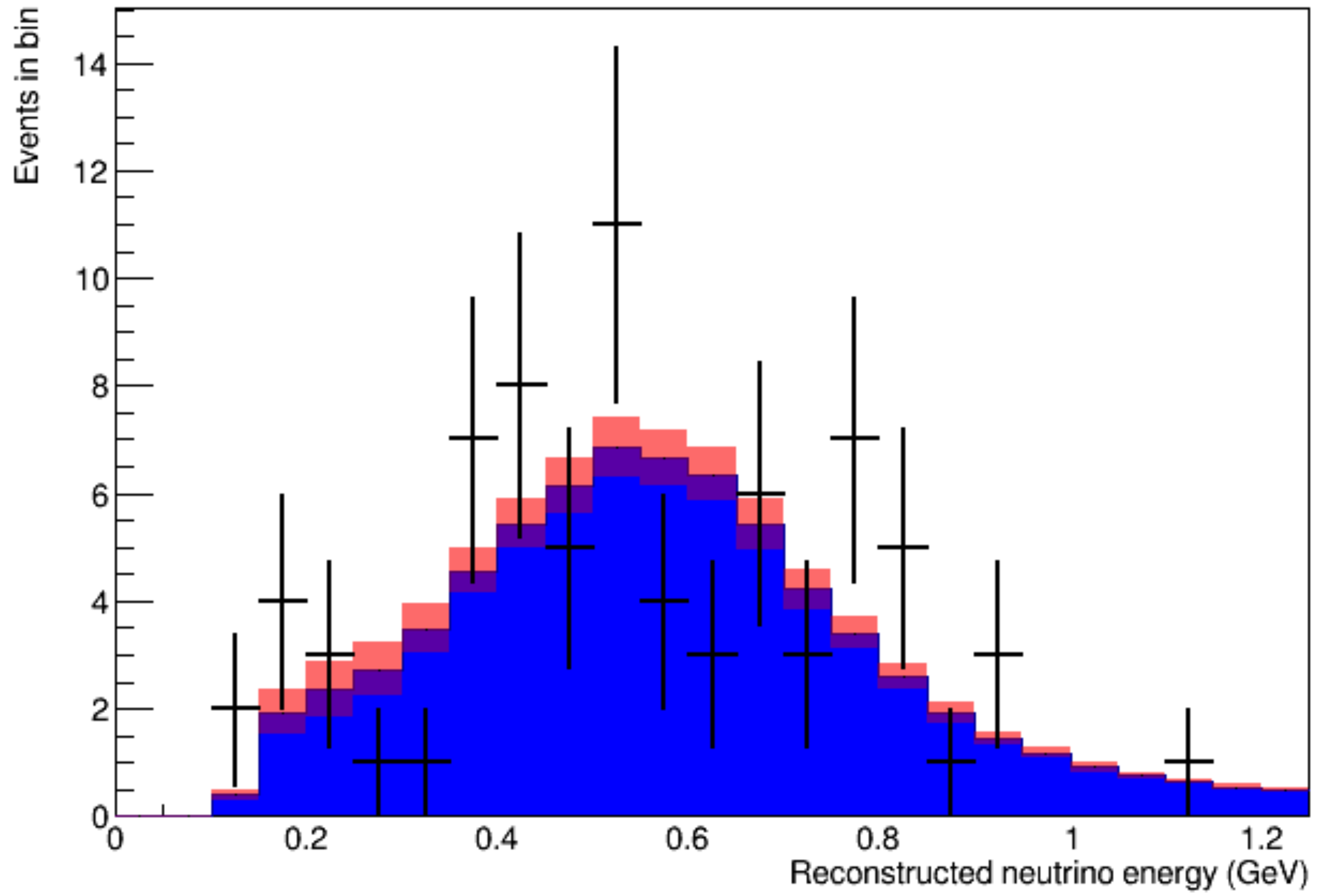
The leptonic mixing matrix U is —

$c_{ij} \equiv \cos\theta_{ij}$
$s_{ij} \equiv \sin\theta_{ij}$

$$
\begin{array}{cc}
 & \begin{array}{ccc} \quad\nu_1 \quad & \qquad\qquad \nu_2 \qquad\qquad & \quad \nu_3 \end{array} \\
U = & \begin{bmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta} & c_{23}c_{13} \end{bmatrix}
\end{array}
$$

$$\times \mathrm{diag}\Big(\underbrace{e^{i\alpha_1/2}, e^{i\alpha_2/2}}_{\text{Majorana phases}}, 1\Big)$$





- Four primary channels:
  - ν_μ disappearance: $P(\nu_\mu \rightarrow \nu_\mu)$ (measures primarily θ_{23} and Δm^2_{31})
  - ν_e appearance: $P(\nu_\mu \rightarrow \nu_e)$
  - $\bar{\nu}_\mu$ disappearance: $P(\bar{\nu}_\mu \rightarrow \bar{\nu}_\mu)$ (measures primarily θ_{23} and Δm^2_{31})
  - $\bar{\nu}_e$ appearance: $P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e)$

$\nu_\mu \rightarrow \nu_e$ OSCILLATION PROBABILITY

$$
\begin{aligned}
P(\nu_\mu \to \nu_e) \quad \sim \quad & \sin^2 2\theta_{13} && \times \boxed{\sin^2 \theta_{23}} && \times \boxed{\frac{\sin^2[(1-x)\Delta]}{(1-x)^2}} \\
& \boxed{-\alpha \sin \delta} && \times \sin 2\theta_{12} \sin 2\theta_{13} \sin 2\theta_{23} && \times \sin \Delta \frac{\sin[x\Delta]}{x} \frac{\sin[(1-x)\Delta]}{(1-x)} \\
& +\alpha \cos \delta && \times \sin 2\theta_{12} \sin 2\theta_{13} \sin 2\theta_{23} && \times \cos \Delta \frac{\sin[x\Delta]}{x} \frac{\sin[(1-x)\Delta]}{(1-x)} \\
& +\mathcal{O}(\alpha^2)
\end{aligned}
$$

M. Freund, Phys.Rev. D64 (2001) 053003

$$
\alpha = \left| \frac{\Delta m^2_{21}}{\Delta m^2_{31}} \right| \sim \frac{1}{30} \qquad \Delta \equiv \frac{\Delta m^2_{31} L}{4E} \qquad x \equiv \frac{2\sqrt{2} G_F N_e E}{\Delta m^2_{31}}
$$

- CP odd phase δ can result in
  - asymmetry of oscillation probabilities $P(\nu_\mu \to \nu_e) \neq P(\bar{\nu}_\mu \to \bar{\nu}_e)$
  - distortion of $\nu_e/\bar{\nu}_e$ appearance spectrum
- θ_{23} (as opposed to $2\theta_{23}$) dependence allows "octant" resolution if $\theta_{23} \neq 45°$
- Mass hierarchy sensitivity through $\boldsymbol{x}$: $\nu_e/\bar{\nu}_e$ enhanced in normal/inverted hierarchy

All this must be disentangled!

A FEW NOTES

- Implicit in discussion is that modeling the signal is as important as modeling the background
  - "discovery" phase of neutrino oscillations to precision phase
- CP violation in neutrinos is expected to be 30% in maximal cases
  - Much better precision in oscillated expectation needed if CPV is non-maximal
  - We also want to precisely measure the oscillation parameters, including δ_{CP}
  - "2%"
- Three major nuclear targets/detector technologies
  - H_2O: water Cherenkov detectors (Super-Kamiokande, Hyper-Kamiokande)
  - $CH_{(2)}$: plastic, liquid scintillator (NOvA, MIniBooNE)
  - Ar: Liquid and gas argon time projection chambers (MicroBooNE, ICARUS, SBND, DUNE)
- Enormous investment now and into the future
  - cf. US P5 Report
  - Ongoing momentum on DUNE/LBNF in USA
  - Recent "pre-approval" of Hyper-Kamiokande in Japan

ν-A INDUSTRY

- **NuINT:**
  - 12th Workshop since 2000
  - Vibrant and growing!
  - Also now a standard part of NuFACT and Neutrino conference series

15-19 October 2018 at Gran Sasso Science Institute!

GS SI NuInt 18 - 12th International Workshop on Neutrino-Nucleus Interactions in the Few-GeV Region

- **Review papers:** (just a sample)

NuSTEC[a] White Paper: Status and Challenges of Neutrino-Nucleus Scattering

L. Alvarez-Ruso,[1] M. Sajjad Athar,[2] M. B. Barbaro,[3] D. Cherdack,[4] M. E. Christy,[5] P. Coloma,[6] T. W. Donnelly,[7] S. Dytman,[8] A. de Gouvêa,[9] R. J. Hill,[10,6] P. Huber,[11] N. Jachowicz,[12] T. Katori,[13] A. S. Kronfeld,[6] K. Mahn,[14] M. Martini,[15] J. G. Morfín,[6] J. Nieves,[1] G. Perdue,[6] R. Petti,[16] D. G. Richards,[17] F. Sánchez,[18] T. Sato,[19,20] J. T. Sobczyk,[21] and G. P. Zeller[6]

Towards a Unified Model of Neutrino-Nucleus Reactions for Neutrino Oscillation Experiments

S.X. Nakamura[1], H. Kamano[2,3], Y. Hayato[4], M. Hirai[5], W. Horiuchi[6], S. Kumano[2,3], T. Murata[1], K. Saito[7,3], M. Sakuda[8], T. Sato[1,3], Y. Suzuki[9,10]

TOPICAL REVIEW

Neutrino-Nucleus Cross Sections for Oscillation Experiments

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Neutrino Interactions with Nucleons and Nuclei: Importance for Long-Baseline Experiments

Ulrich Mosel

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Comparisons and challenges of modern neutrino scattering experiments (TENSIONS2016 report)

M. Betancourt,[1] S. Bolognesi,[2] J. Calcutt,[3] R. Castillo,[1] A. Cudd,[3] S. Dytman,[4] B. Eberly,[5] A.P. Furmanski,[6] R. Fine,[7] J. Grange,[8] L. Jiang,[4] T. Katori,[9] J. Kleckner,[4] J. Kleyklamp,[7] K. Mahn,[3] B. Messerly,[4] G. Perdue,[1] L. Pickering,[10] J. P. Stowell,[11] J. Sobczyk,[12] N. Suarez,[4] H. Tanaka,[13] R. Tayloe,[14] R. T. Thornton,[14] M. Wilking,[15] C. Wilkinson,[16] C. Wret,[10] and G. P. Zeller[1]

From eV to EeV: Neutrino Cross-Sections Across Energy Scales

Joseph A. Formaggio*
Laboratory for Nuclear Science
Massachusetts Institute of Technology,
Cambridge, MA 02139

G. P. Zeller†
Fermi National Accelerator Laboratory
Batavia, IL 60510

(Dated: March 7, 2013)

Progress and open questions in the physics of neutrino cross sections at intermediate energies

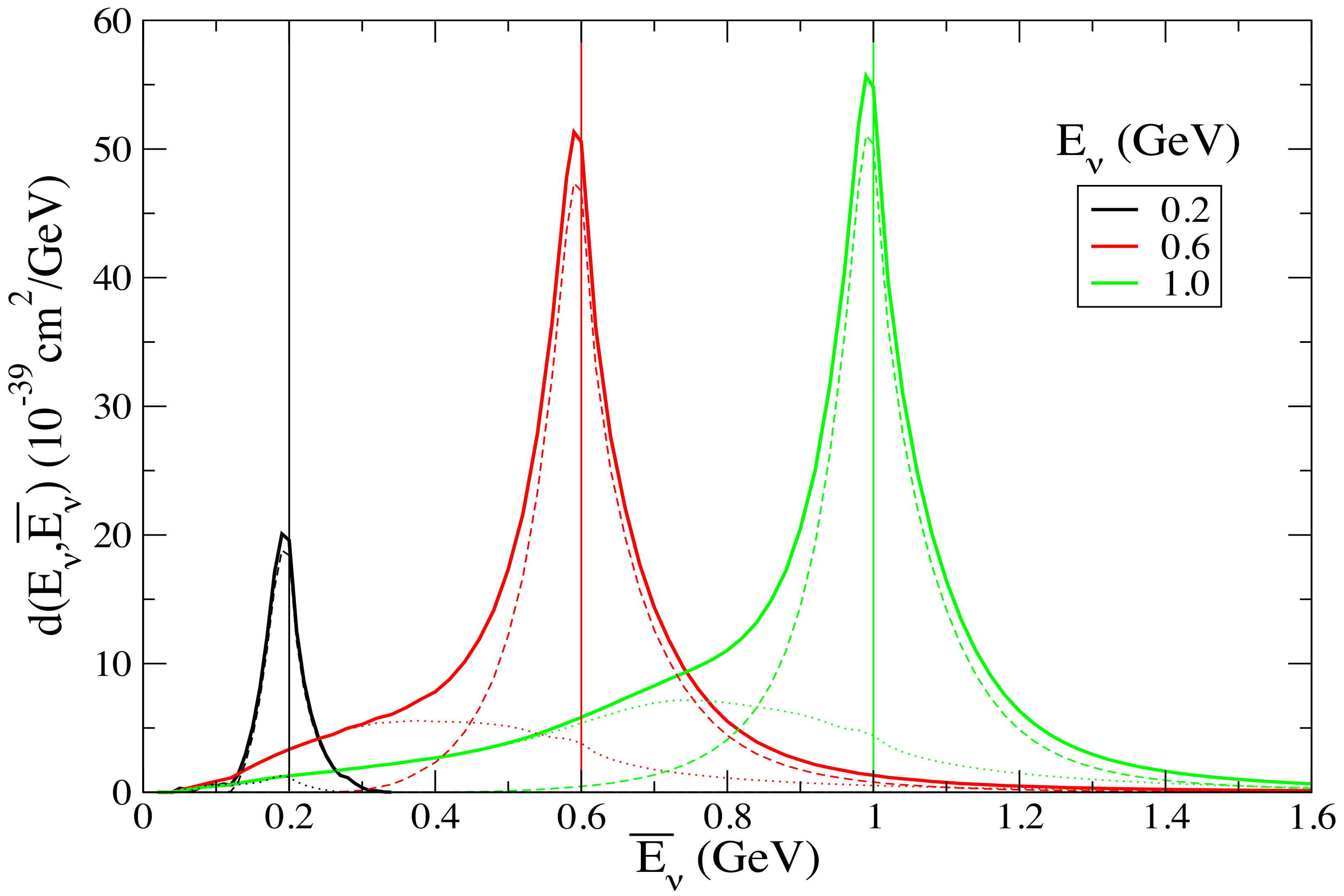
L. Alvarez-Ruso,[1] Y. Hayato,[2] and J. Nieves[1]

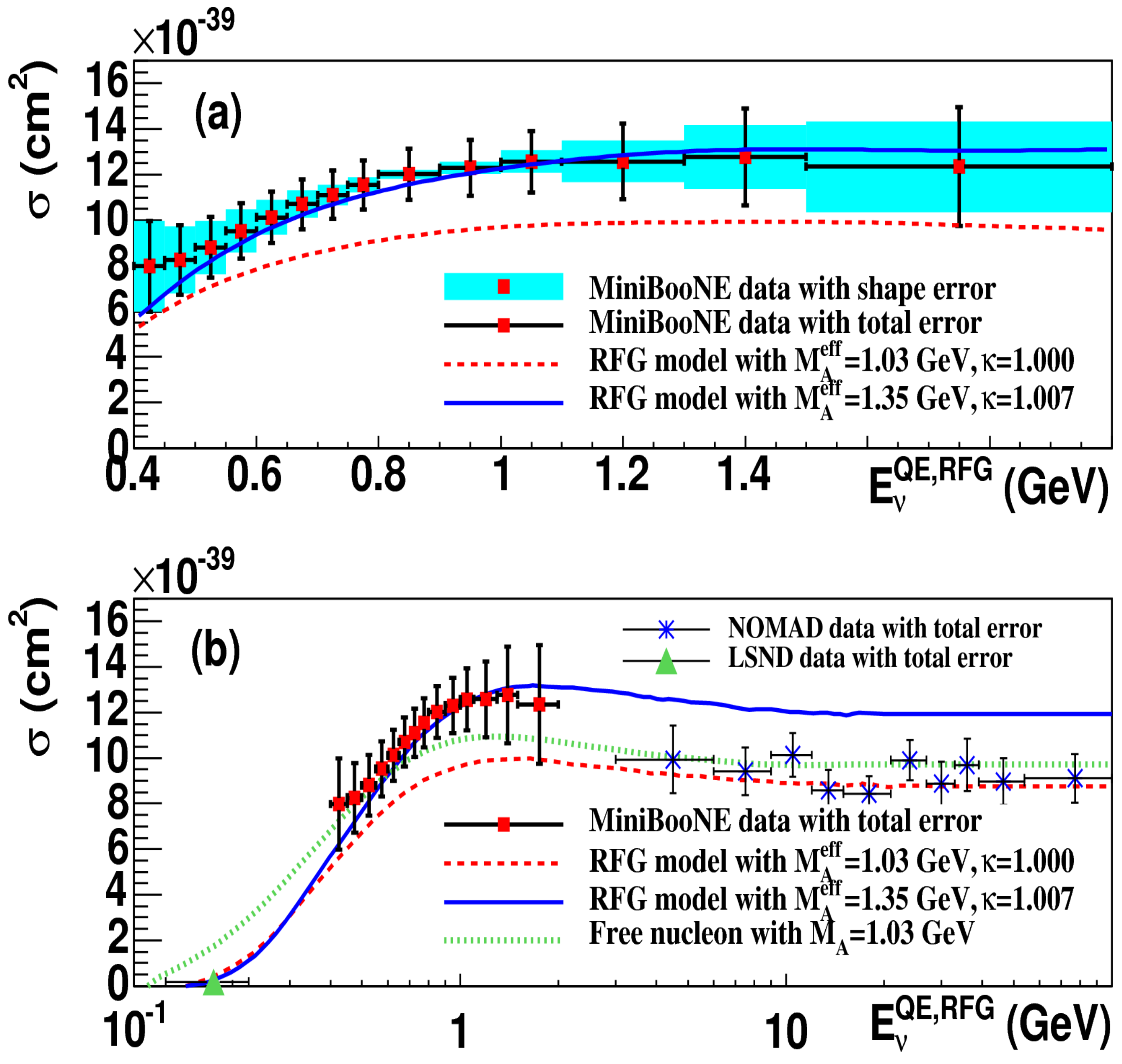
[1]*Instituto de Física Corpuscular (IFIC), Centro Mixto CSIC-Universidad de Valencia, E-46071 Valencia, Spain*
[2]*University of Tokyo, Institute for Cosmic Ray Research, Kamioka Observatory, Kamioka, Japan*

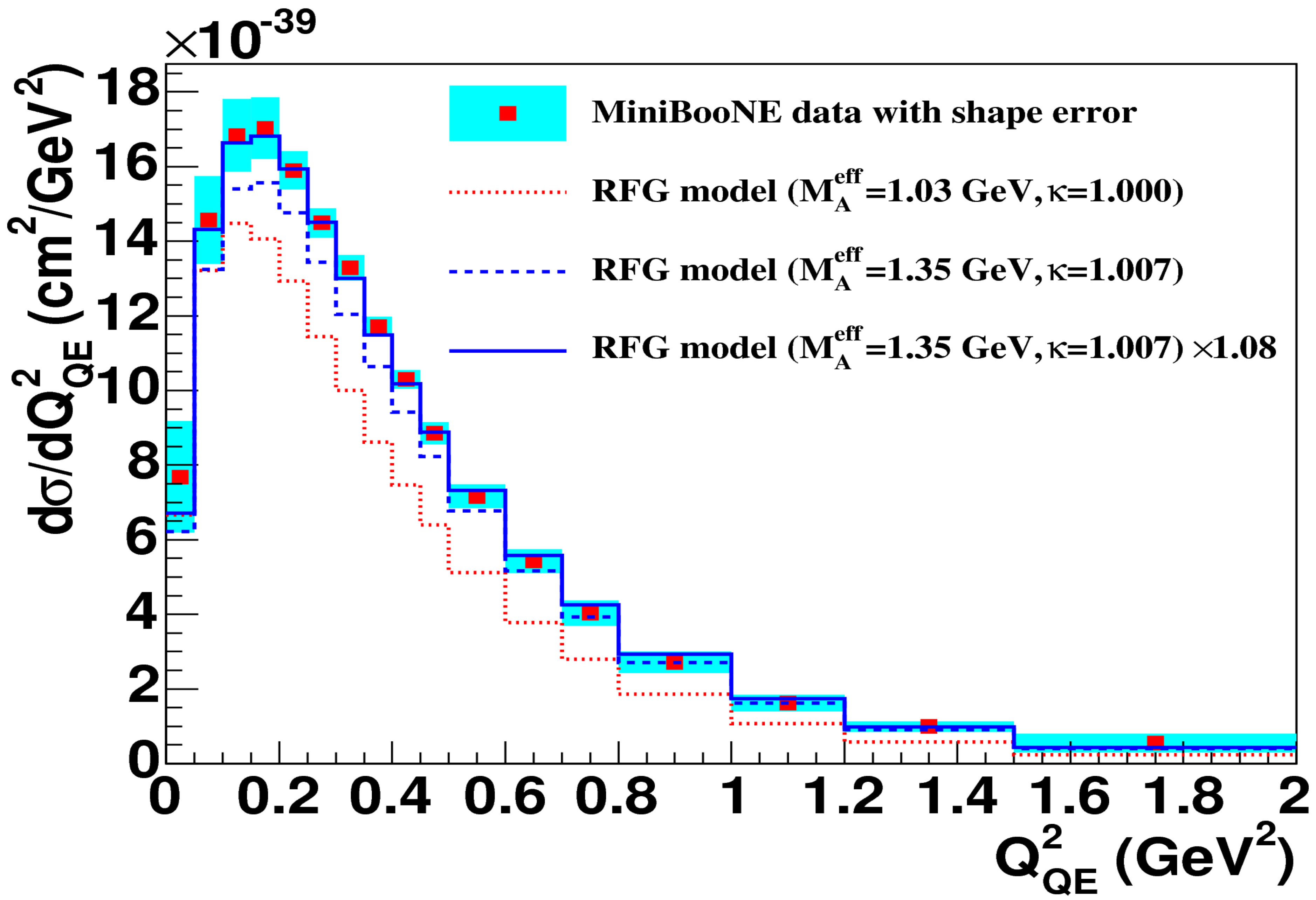
ISSUES IN KINEMATIC RECONSTRUCTION

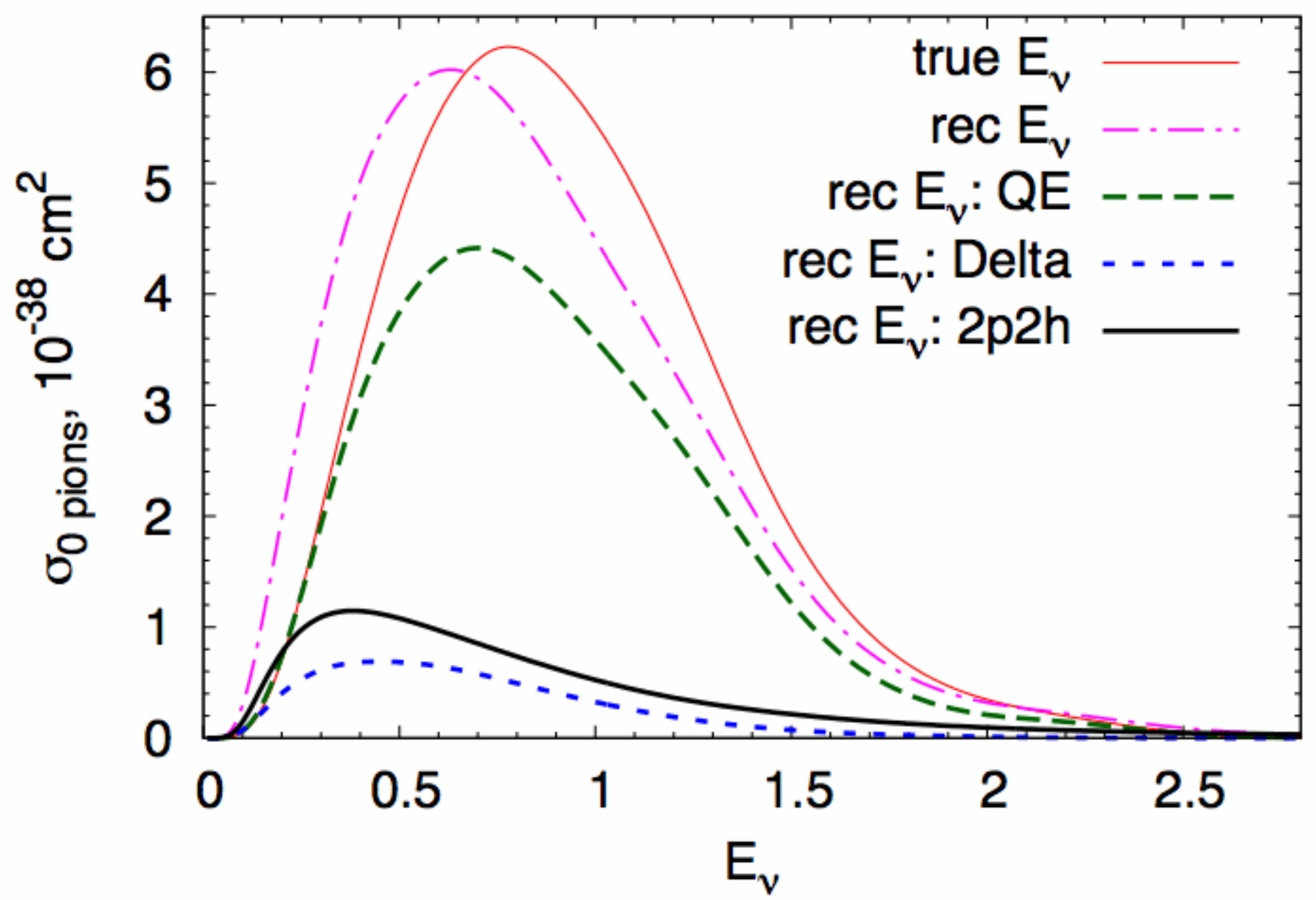
- Kinematic reconstruction:
    - Observed as an "excess" of pionless ν-^{12}C interactions at MiniBooNE
    - Fits well with M_A ~1.35 GeV CCQE interactions!
  - Our understanding now is that these are ~3 things going on
    - CCQE, MEC, pionless Δ excitation
    - Kinematically different from single nucleon "quasi-elastic" interactions
- Modeling of these interactions is one of the biggest issues in T2K
  - New kinematic handles, but still need modeling guidance

M. Martini et al. Phys.Rev. D87 (2013) no.1, 013009





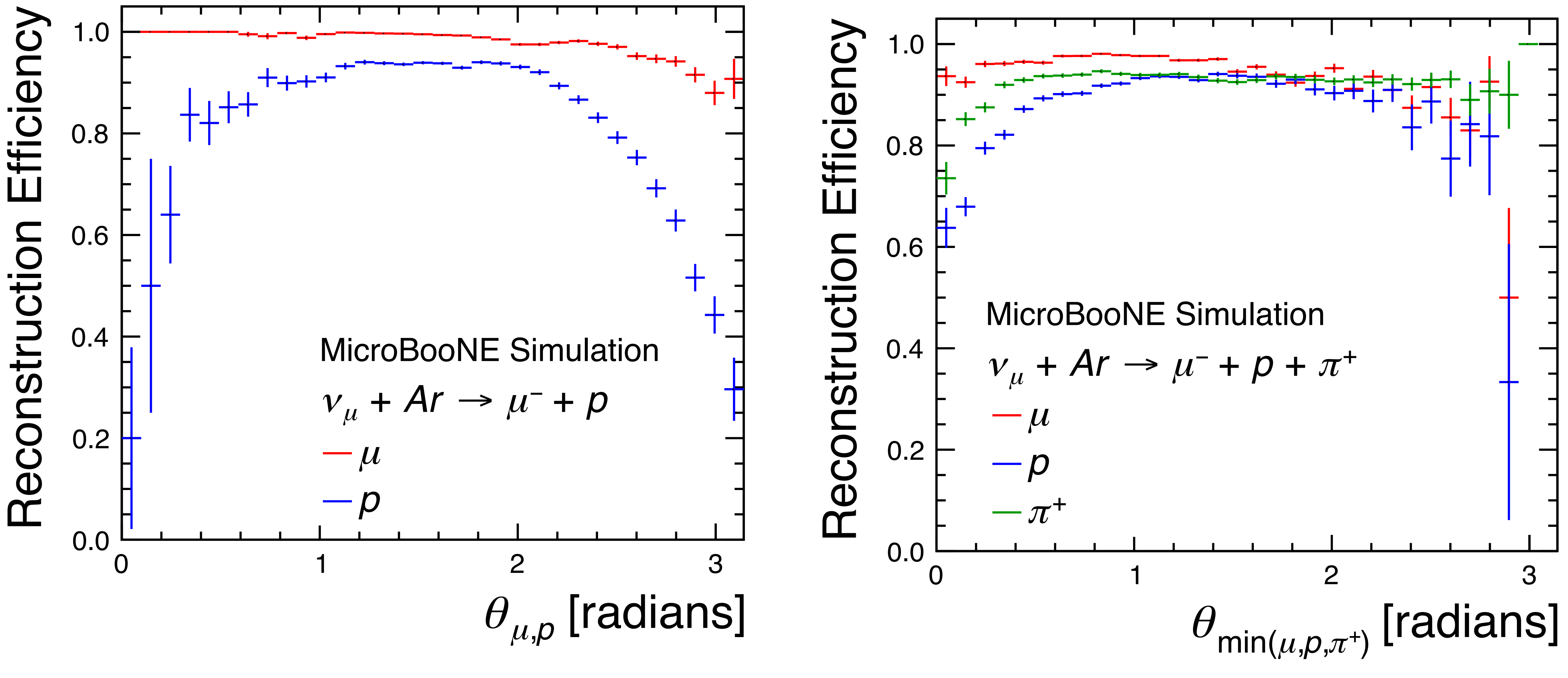




ISSUES IN CALORIMETRIC RECONSTRUCTION

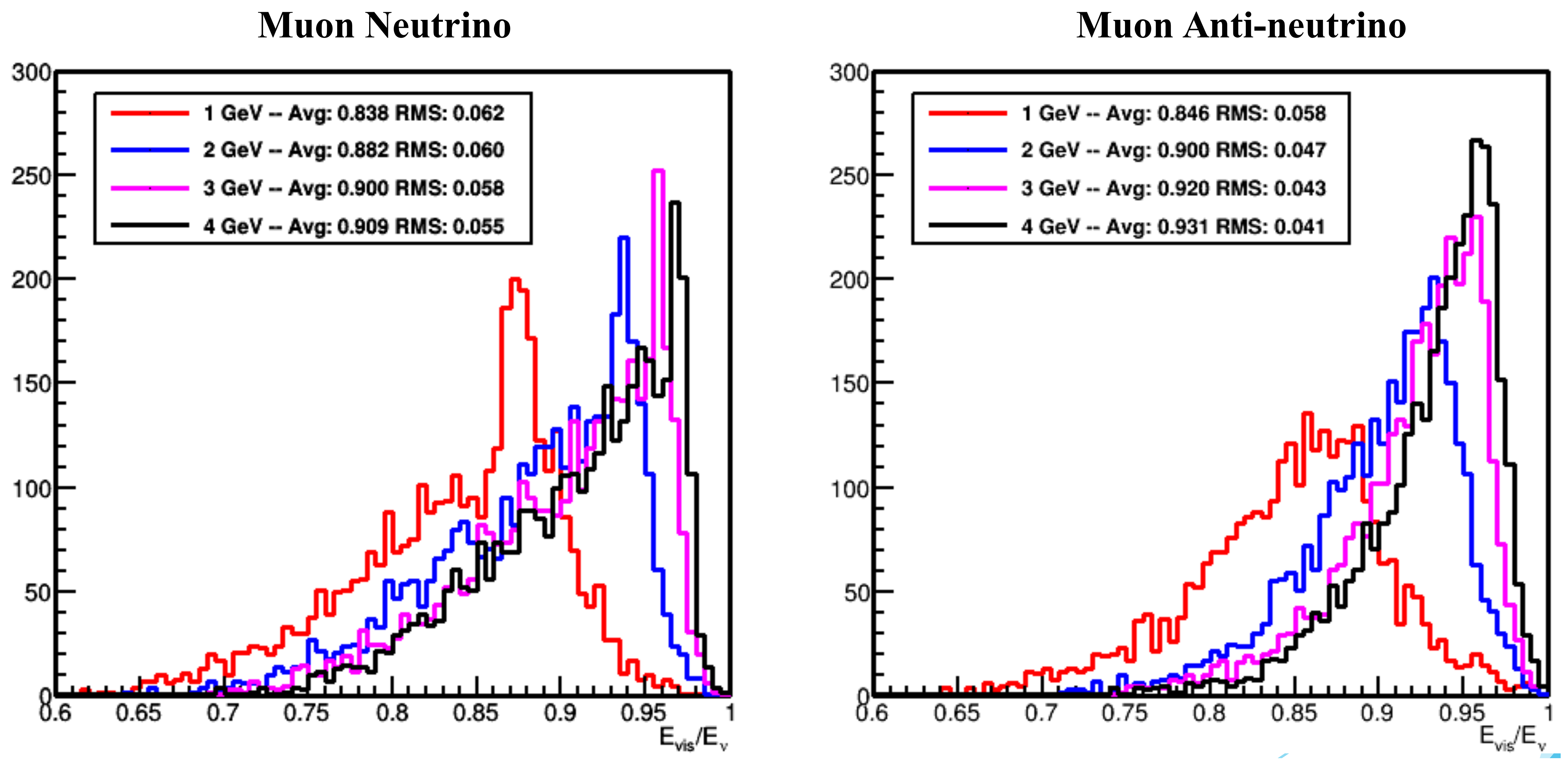
- Detectors react differently to different particles:
  - Detection thresholds (tracking or particles below Cherenkov threshold
  - neutrons (not detected or just "tagged" without energy reconstruction)
  - Misidentified particles (e.g. π ↔ p)
  - Electromagnetic showers (incomplete shower reconstruction)
- Particle content matters!

- Large effect even for LAr
  - "low thresholds"
  - Fully active calorimetric target



μBooNE Eur.Phys.J. C78 (2018) no.1, 82
arxiv:1708.03135

L. Whitehead: CAPTAIN proposal to FNAL



THOUGHTS ON GENERATORS

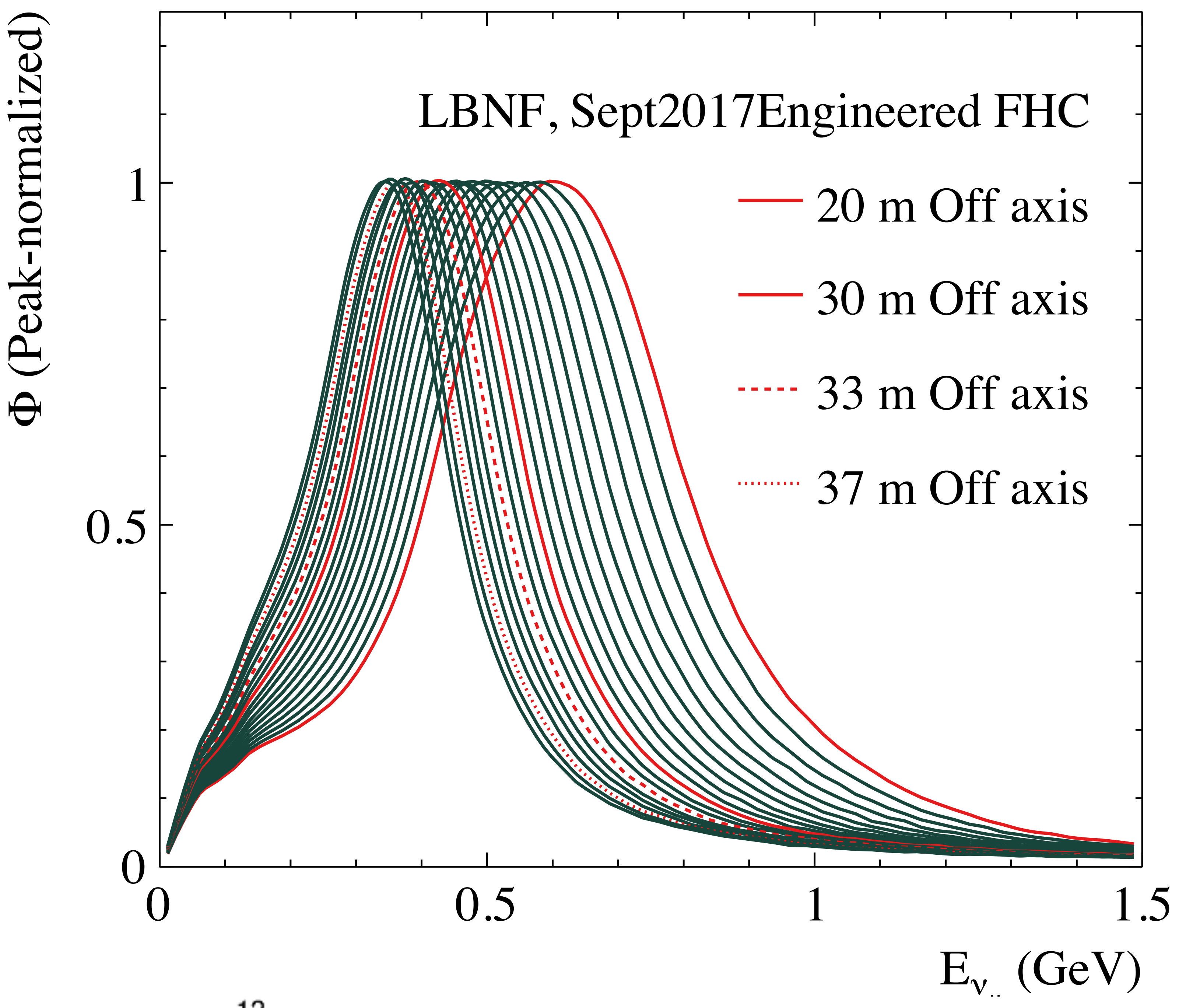
- *How can better theory be implemented in neutrino generators simulations?*
- "Event generator":
  - Event generators do much more than calculate cross sections
  - They must generate complete interactions
    - We rely on them to evaluate detection efficiencies, misidentification of particles, etc.
    - We can tailor analyses to focus on particular aspects (lepton kinematics) but we still need to model everything else
- "Frankenmodel":
  - We need to combine different models to give the "inclusive" model
    - We have to ensure that the models are combined as consistently as possible (can be ugly!)
    - Left and right hands can be different, but we can't have two left hands
  - New models need to find their place
    - Because of topological migrations, etc. we cannot consider a model "in vacuo" to make contact with measurements
- Systematic Errors
  - New models are as important for evaluating potential errors as they are for "improving" models
  - A more realistic model may increase uncertainties!

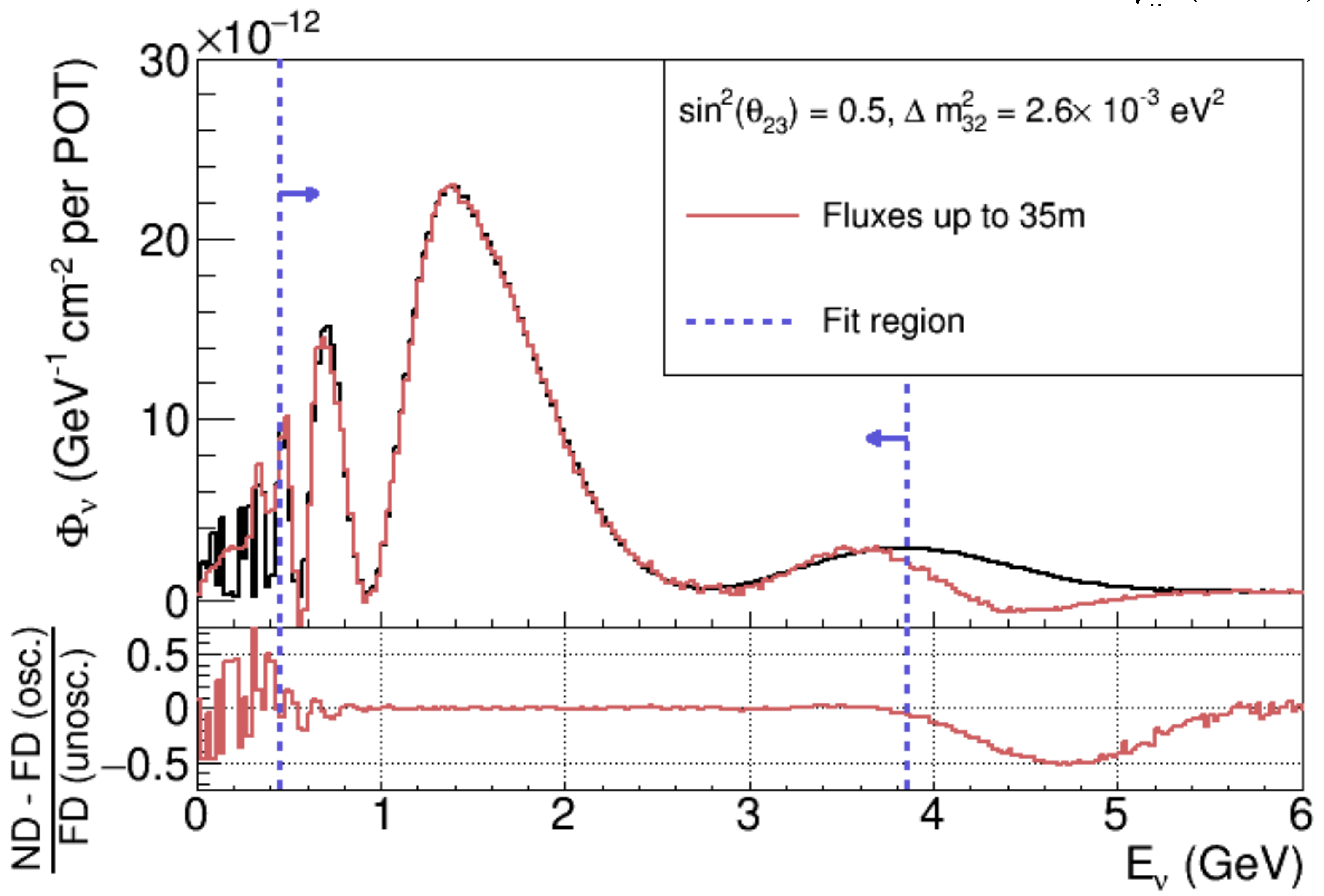
WHAT GOES IN THE GENERATOR

- Physics is not important
  - traditionally, generators contain physics and calculate relevant cross sections
  - It is not essential that they do this . . . .
    - Some physics can be captured numerically (e.g. lookup table) or parametrized
    - Some differential cross sections and other “corrections” can be reweighed
  - the physics does not need to “live” in the generator
    - Additionally, we need to be able to match data (particularly ND), not just new models
    - If a new model is within reach of reweighting, etc. we can “incorporate” it this way.
- Physics is important
  - We need a clear understanding of how a given model relates to everything else in the generator
    - If we don’t, we need to account for that in the systematic error
  - Physics guides systematic/modelling uncertainties
    - How do we generate and propagate model variations through the generator?

*Precision Reaction Independent Spectrum Measurement

PRISM*:

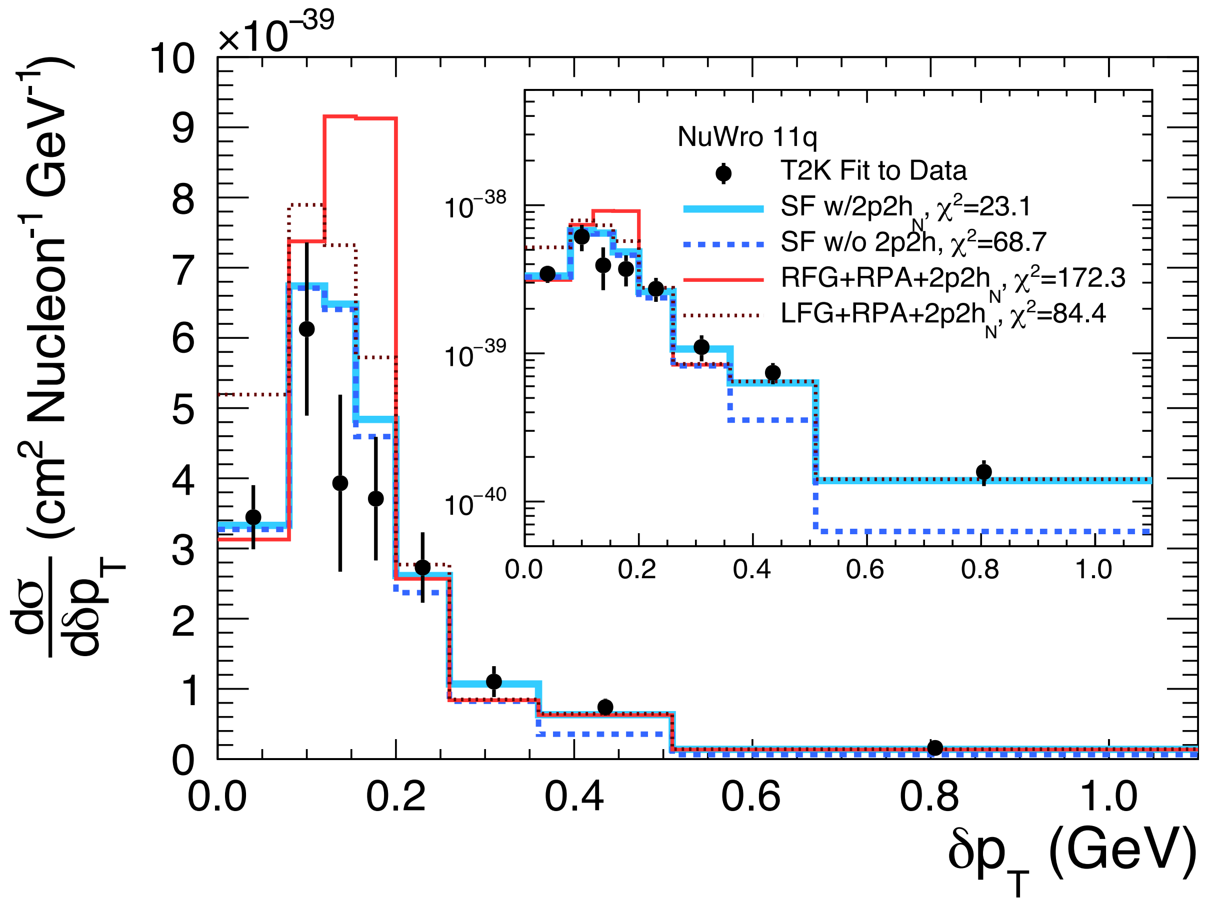


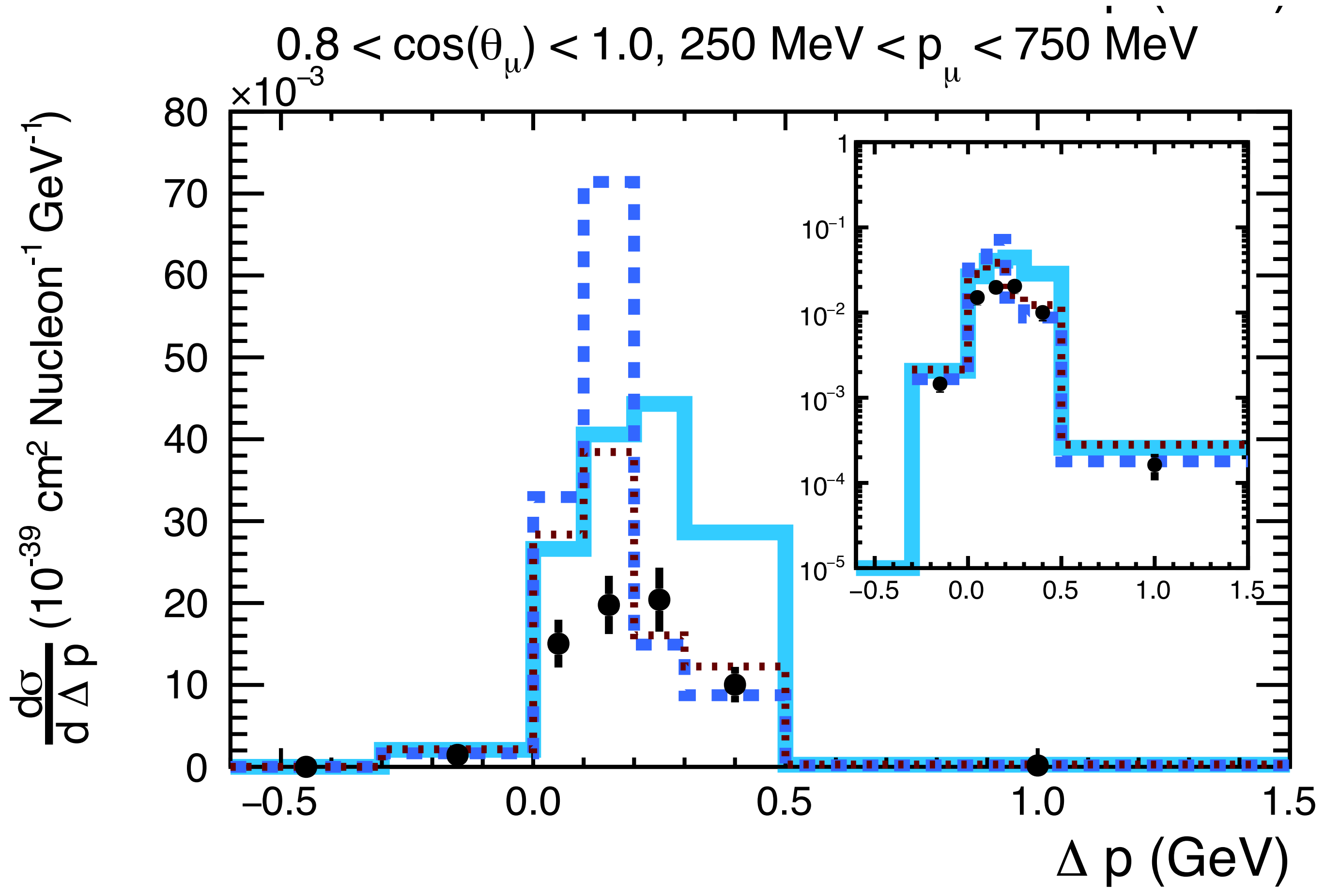


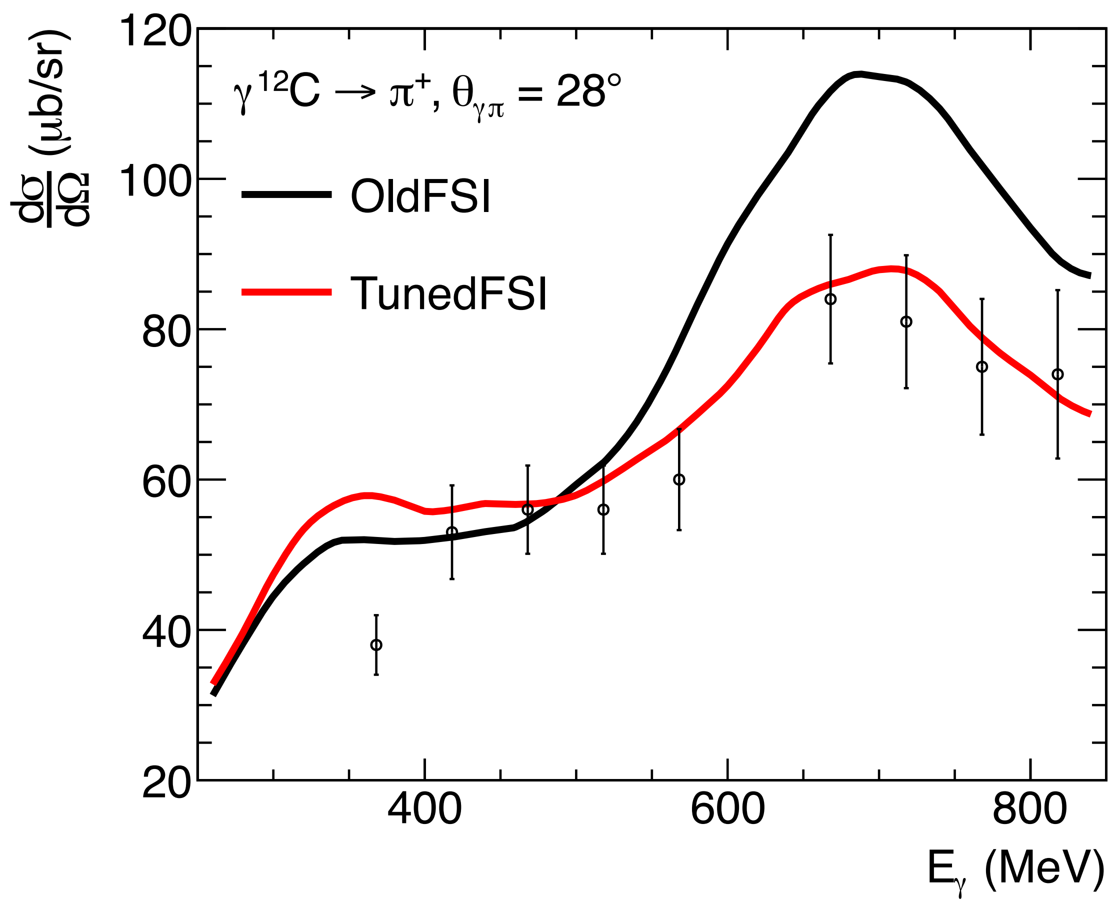
- Neutrino energy spectrum steadily marches downs and narrows as we go “off-axis” from the neutrino beam
- This variation gives us an independent handle on neutrino energy
  - Data taken at different positions (spectra) can be combined (weighted and added, with oscillation probability!) to match far detector expectation
  - Directly measured expected event properties (e.g. E_{rec})
- Pursued both from DUNE and Hyper-Kamiokande
- Pushes modeling uncertainties to higher order
- Need theoretical help:
  - Keeping now “higher order” corrections small enough
  - Probing robustness of method of this method and “traditional” approach

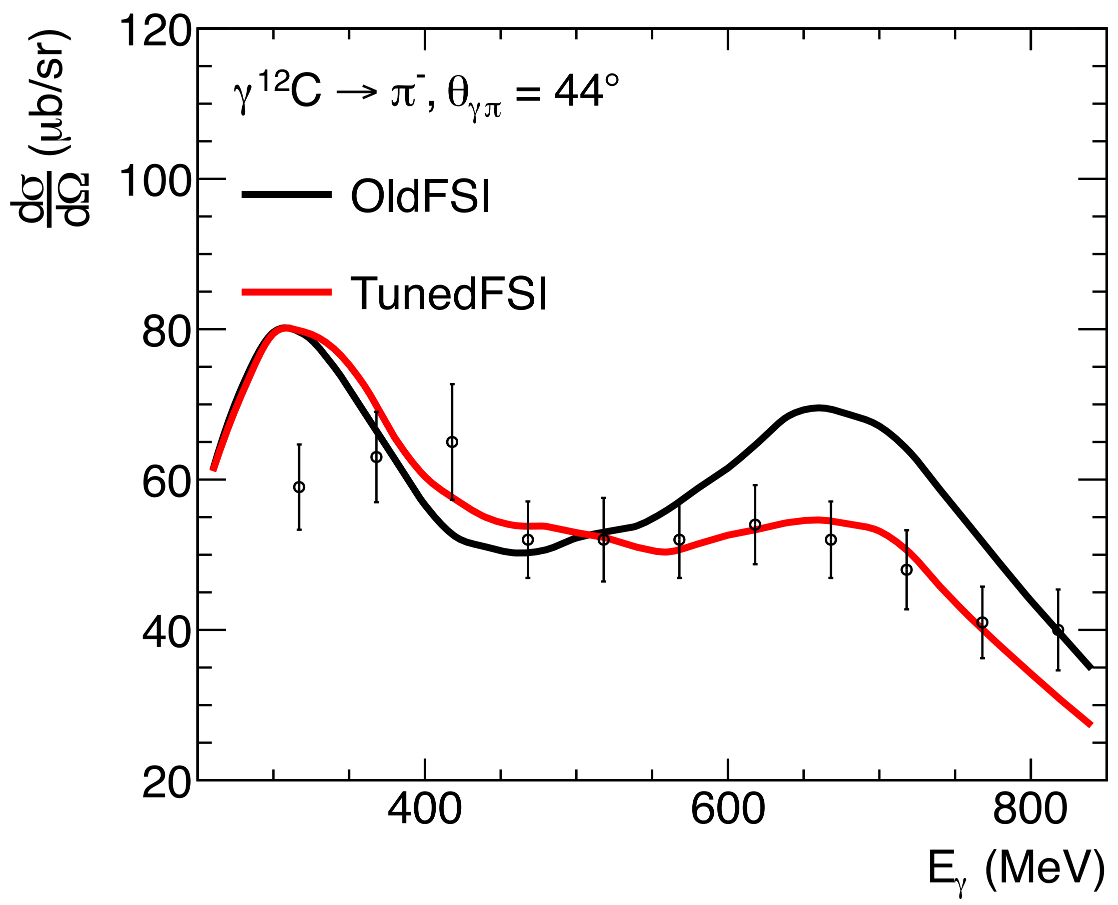
ELECTRON SCATTERING

- e-A scattering is an ***essential*** test of models
- A few specific tests beyond the "general" program
  - Tests of energy reconstruction
  - Lepton-hadron (proton) Kinematics
  - Outgoing hadron kinematics
  - Final state interactions
- In each case, the techniques and tests should be performed with the generator in "e-A mode"
  - Some generators fully support this
  - Others may allow specific parts to be tested (e.g. FSI)
- 4 π spectrometer/detector
  - It would be good to have a handle generally on all outgoing particles
  - Matches closely the situation with neutrino detectors
  - Comprehensive test of the model









CONCLUSIONS:

- Current and upcoming neutrino oscillation continue to require better nuclear theory
- Numbers like “2%” are mentioned, but it is difficult to translate what that means
    - Intimately coupled to near detector measurement strategy of at an oscillation experiment
    - Strategy continues to evolve from past experiments . . . . ..
- Impressions:
    - It’s great that theorists can engage both with e-A and ν-A calculations!
    - ν-A:
        - Community is still evolving how to report measurements, and this will continue to improve/evolve
    - e-A:
        - This is a very important area for more development
            - specifically measurements that may be more directly applied towards ν-A issues
        - Needless to say, the tightly controlled kinematics of e-A provide a much better probe for many nuclear effects
        - A wide acceptance spectrometer can provide comprehensive tests of a model
        - This kind of activity requires a convergence of particle and nuclear physicists . . . this seems like a good place!