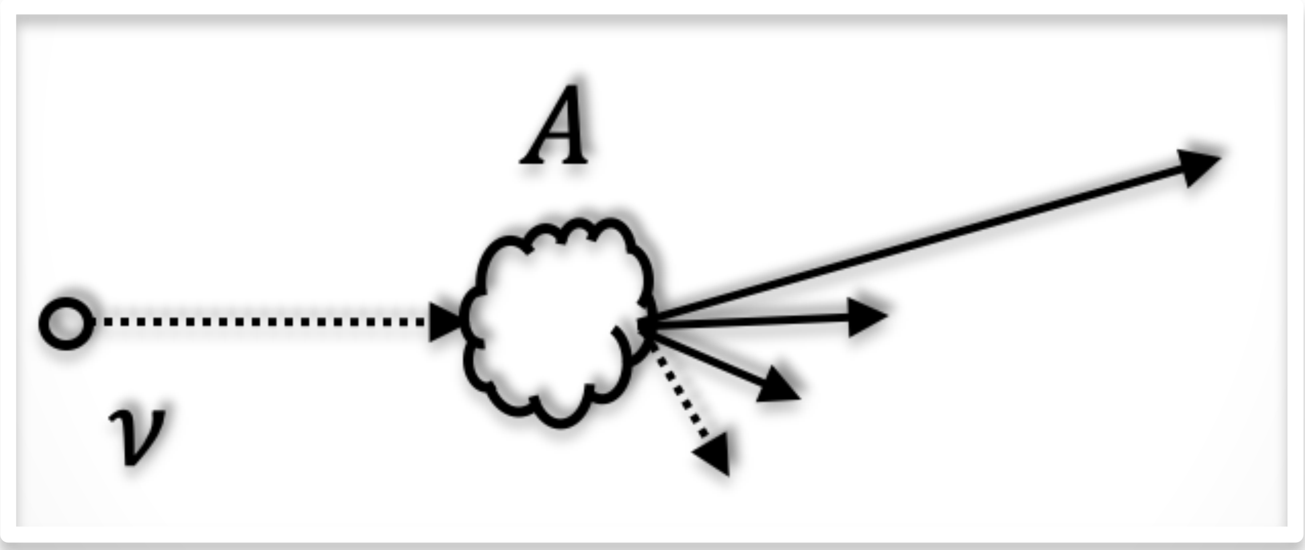
Neutrino-Nucleus Scattering in Neutrino Oscillation Experiments



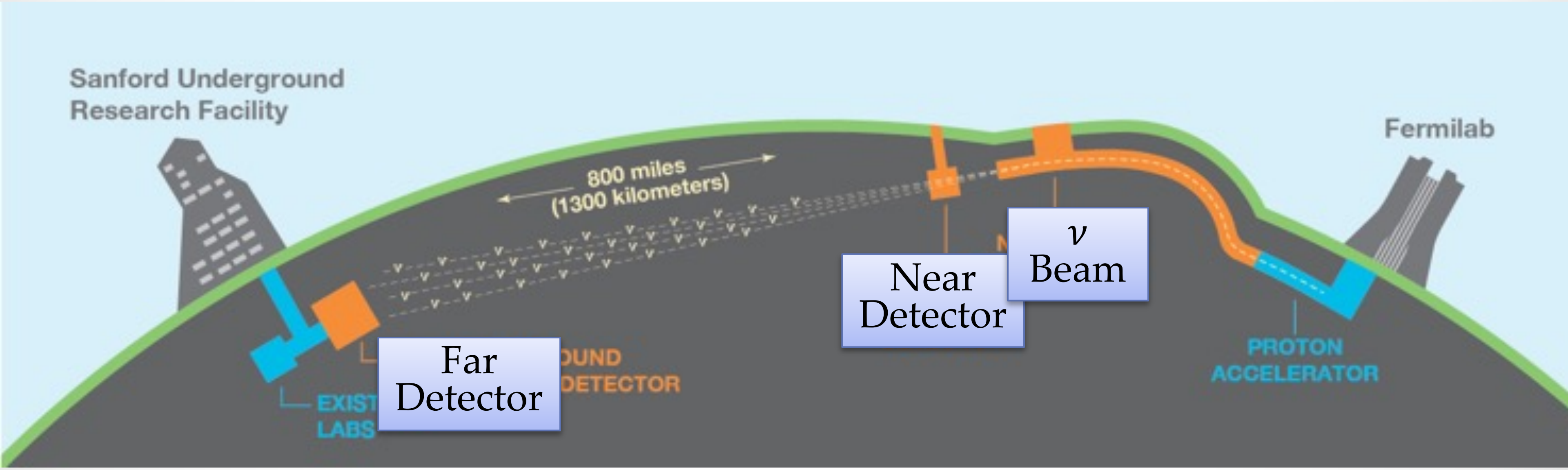
Shirley Li

NNPSS 2022, Boston

Long-Baseline Experiments

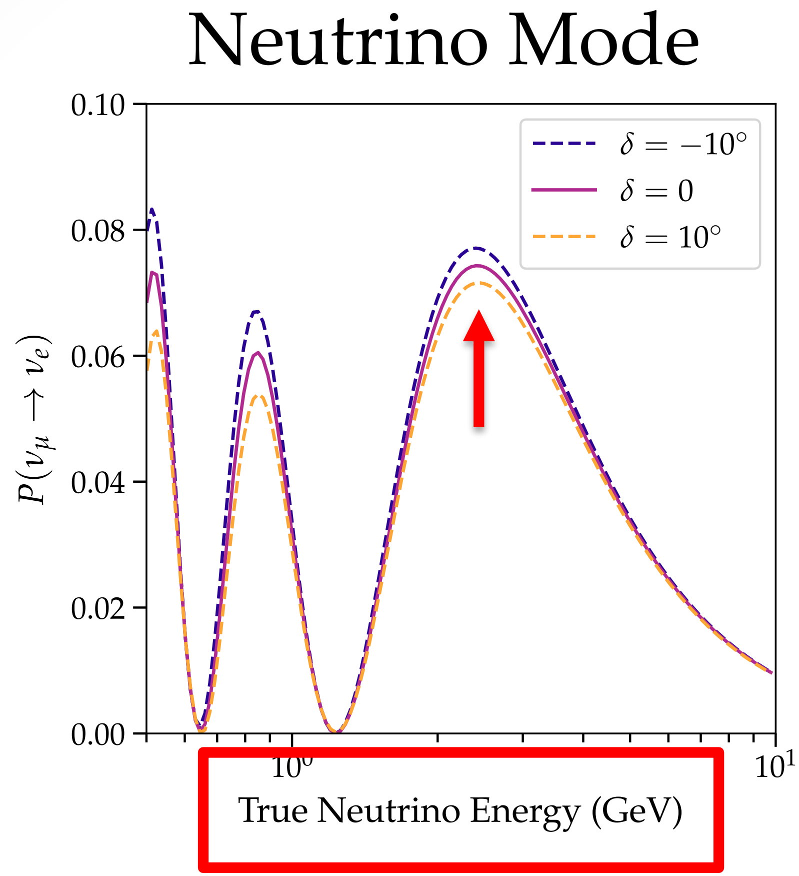
$$0.5\text{—}5\ \text{GeV}\ \nu_\mu \xrightarrow{\sim 1000\ \text{km}} \nu_e$$

DUNE 15



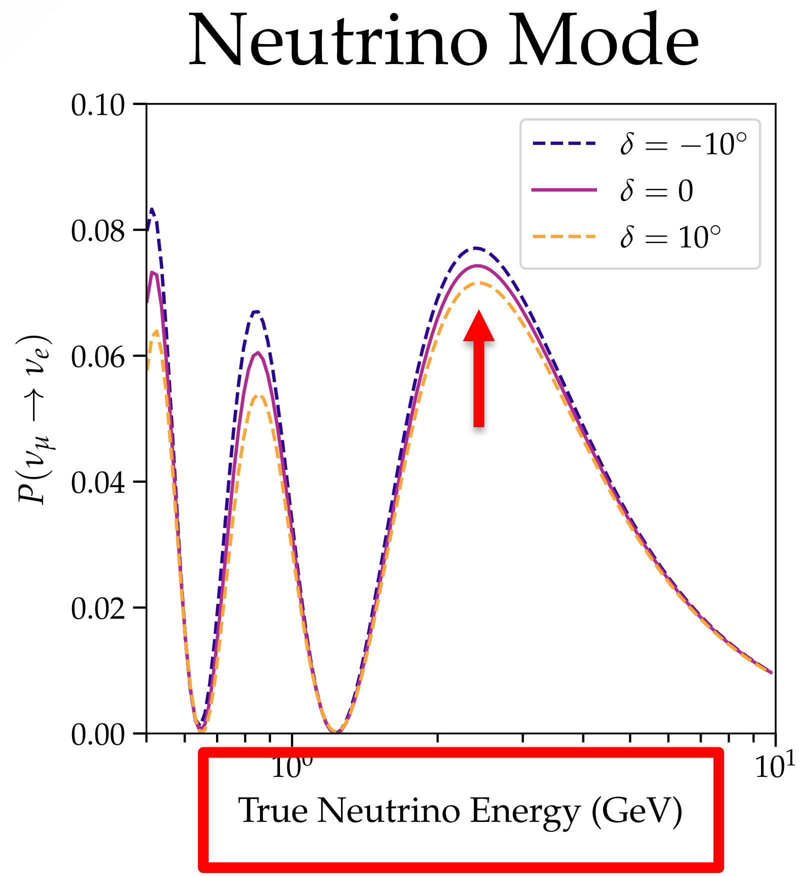
1. Discussions Focus on DUNE and NOvA
2. Details Differ for Hyper-K and T2K

Measuring δ_{CP}



1. Differences Between ν and $\bar{\nu}$ Are Important
2. Neutrino Energy Reconstruction Is Important
3. Level of Accuracy: ≃5%

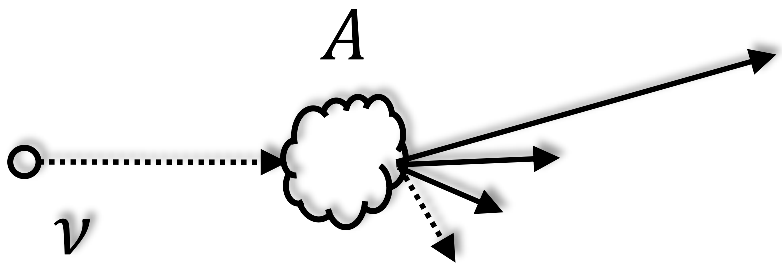
Measuring δ_{CP}



1. Differences Between ν and $\bar{\nu}$ Are Important
2. Neutrino Energy Reconstruction Is Important
3. Level of Accuracy: ≃5%

Outline

Neutrino-Nucleus Cross Sections

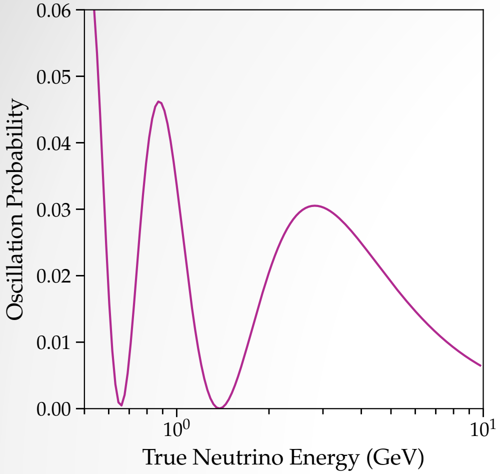


How Do They Affect Measurements

How to Improve

How Do We Compute the Cross Sections?

Measuring Neutrino Oscillation



Without Near Detector

Cross Section

Flux

$$P\left(\nu_\mu \to \nu_e, E_\nu, l = L\right) = \frac{f_e(E_\nu, L)}{f_\mu(E_\nu, 0)} = \frac{N_e(E_\nu, L)/\sigma_e(E_\nu)}{f_\mu(E_\nu, 0)}$$

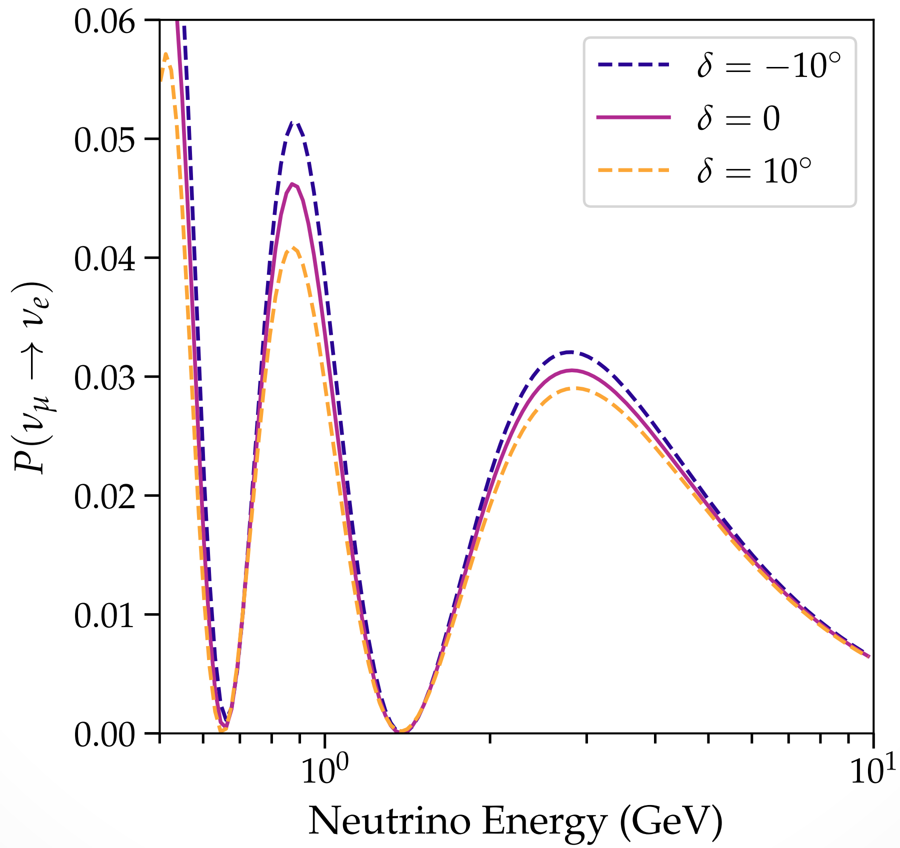
Neutrino Energy

$\sigma_e(E_\nu)$: $\nu_e + {}^{40}\mathrm{Ar} \to e^- + X$

$$\delta P/P\left(\nu_\mu \to \nu_e, E_\nu\right) \propto \delta\sigma_e/\sigma_e(E_\nu)$$

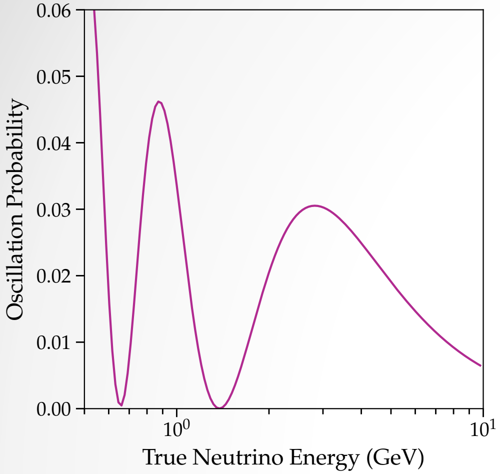
Expected Accuracy

DUNE Nominal Accuracy on δ_{CP} as An Example



Need to Measure $P(E_\nu)$/Predict $\sigma(E_\nu)$ Accurately ($\leq 5\%$)

Measuring Neutrino Oscillation



With Near Detector

Far Detector

$$P(\nu_\mu \rightarrow \nu_e, E_\nu, l = L) = \frac{f_e(E_\nu, L)}{f_\mu(E_\nu, 0)} = \frac{N_e(E_\nu, L)/\sigma_e(E_\nu)}{N_\mu(E_\nu, L)/\sigma_\mu(E_\nu)}$$

Near Detector

*Difference between σ_e and σ_μ is well appreciated

Cross Section Predictions No Longer Play A Role??*

Near/Far Cancellation?

Fluxes at Near/Far Detectors Are Different

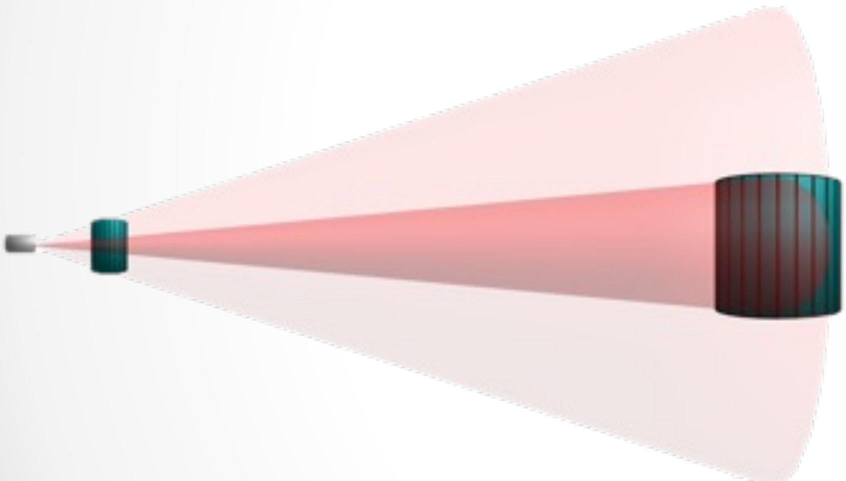
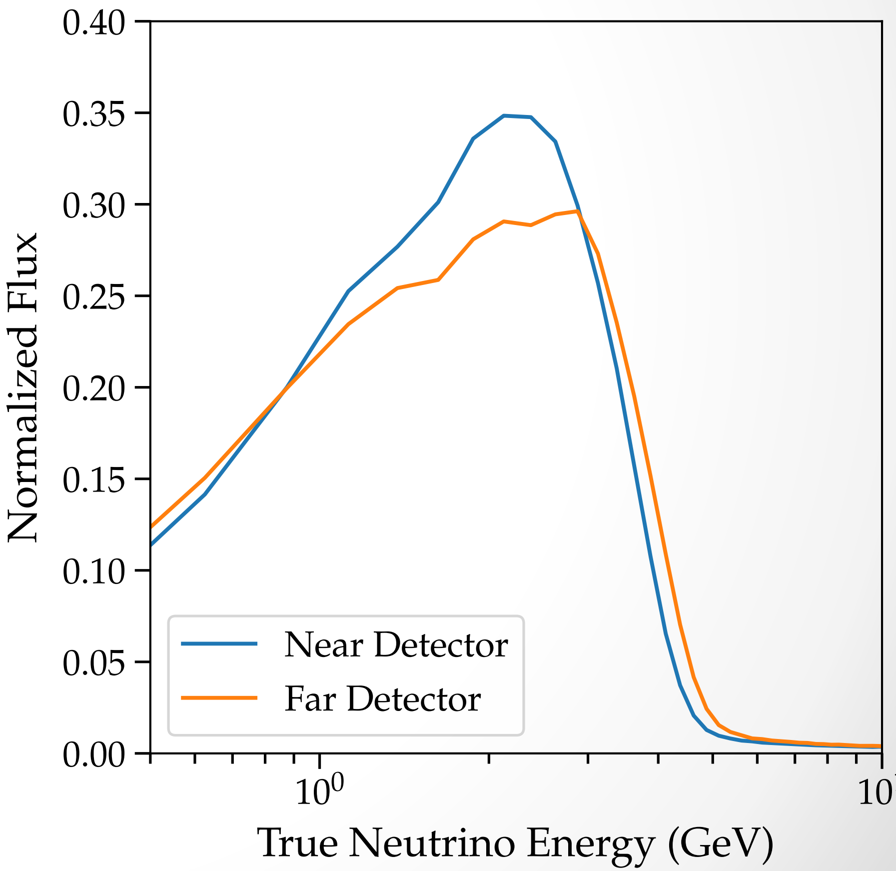


Image Stole from A. Ankowski's Talk at PINS 19



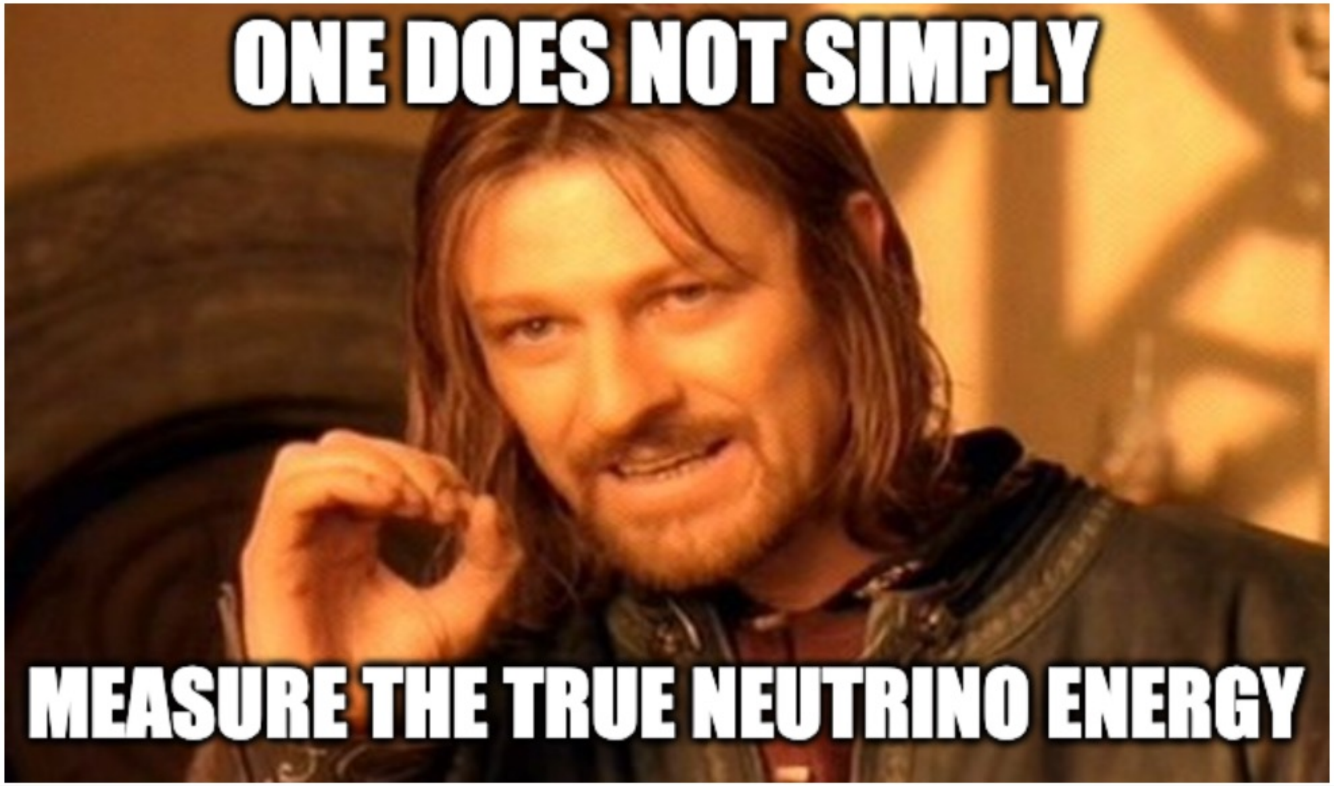
DUNE flux from
https://home.fnal.gov/~ljf26/DUNEFluxes/

Near/Far Cancellation?

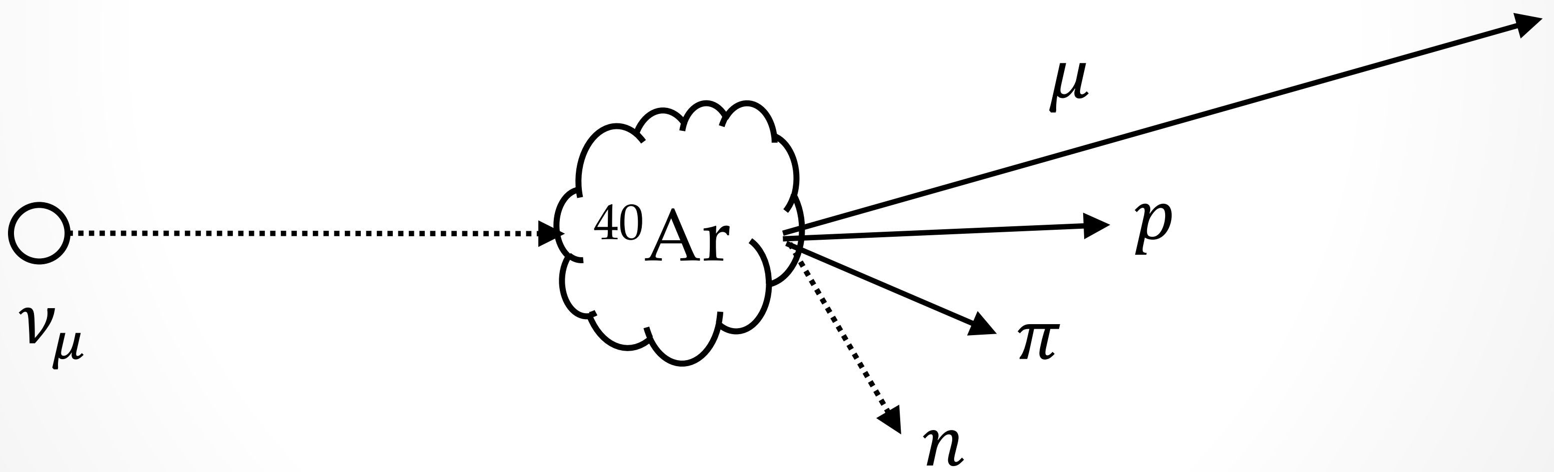
$$P(E_\nu) = \frac{N_e(E_\nu, L)/\sigma_e(E_\nu)}{N_\mu(E_\nu, L)/\sigma_\mu(E_\nu)}$$

Near/Far Cancellation?

$$P(E_\nu) = \frac{N_e(E_\nu, L)/\sigma_e(E_\nu)}{N_\mu(E_\nu, L)/\sigma_\mu(E_\nu)}$$

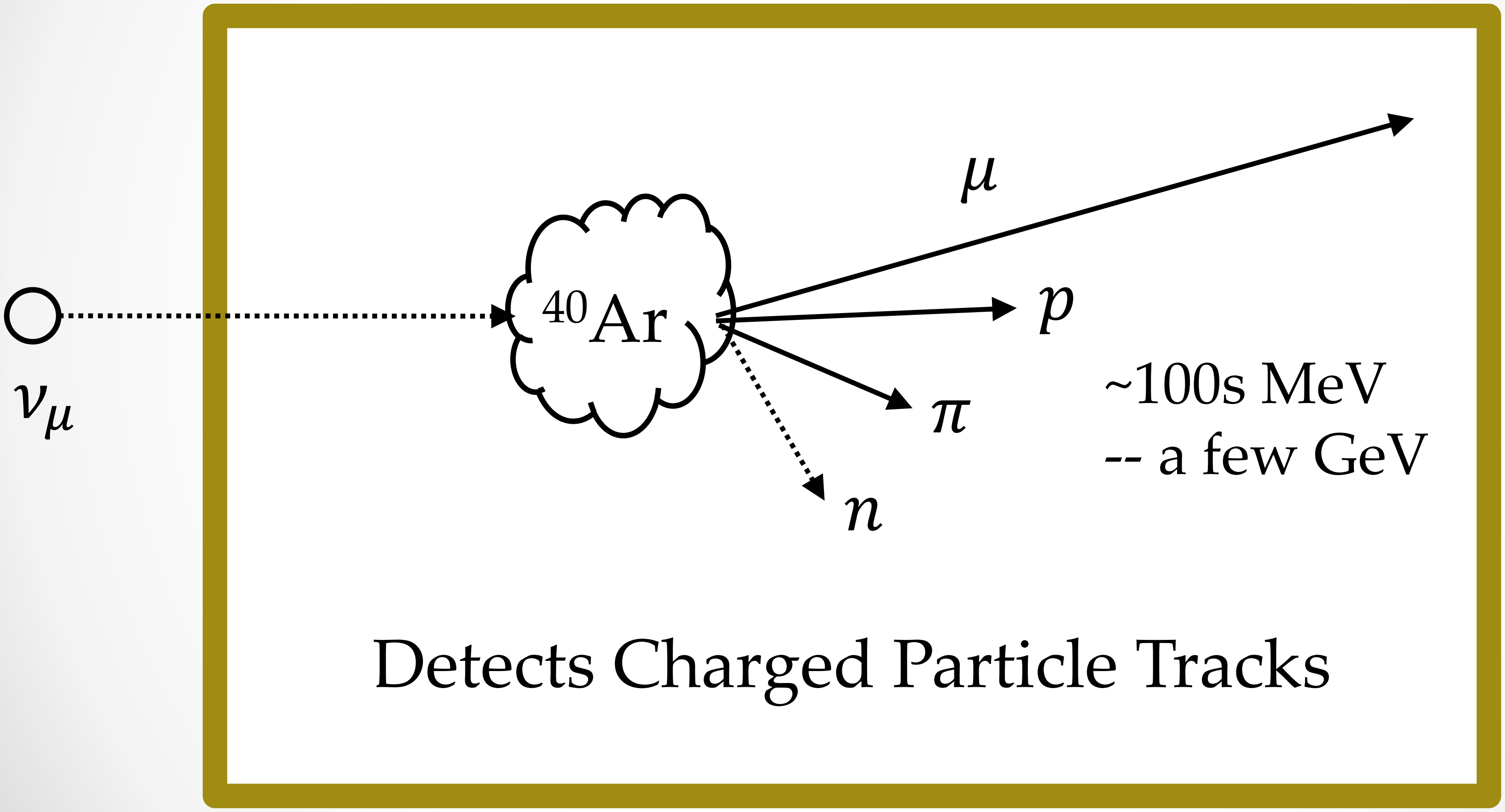


How Do Cross Section Calculations Impact Neutrino Energy Reconstruction?

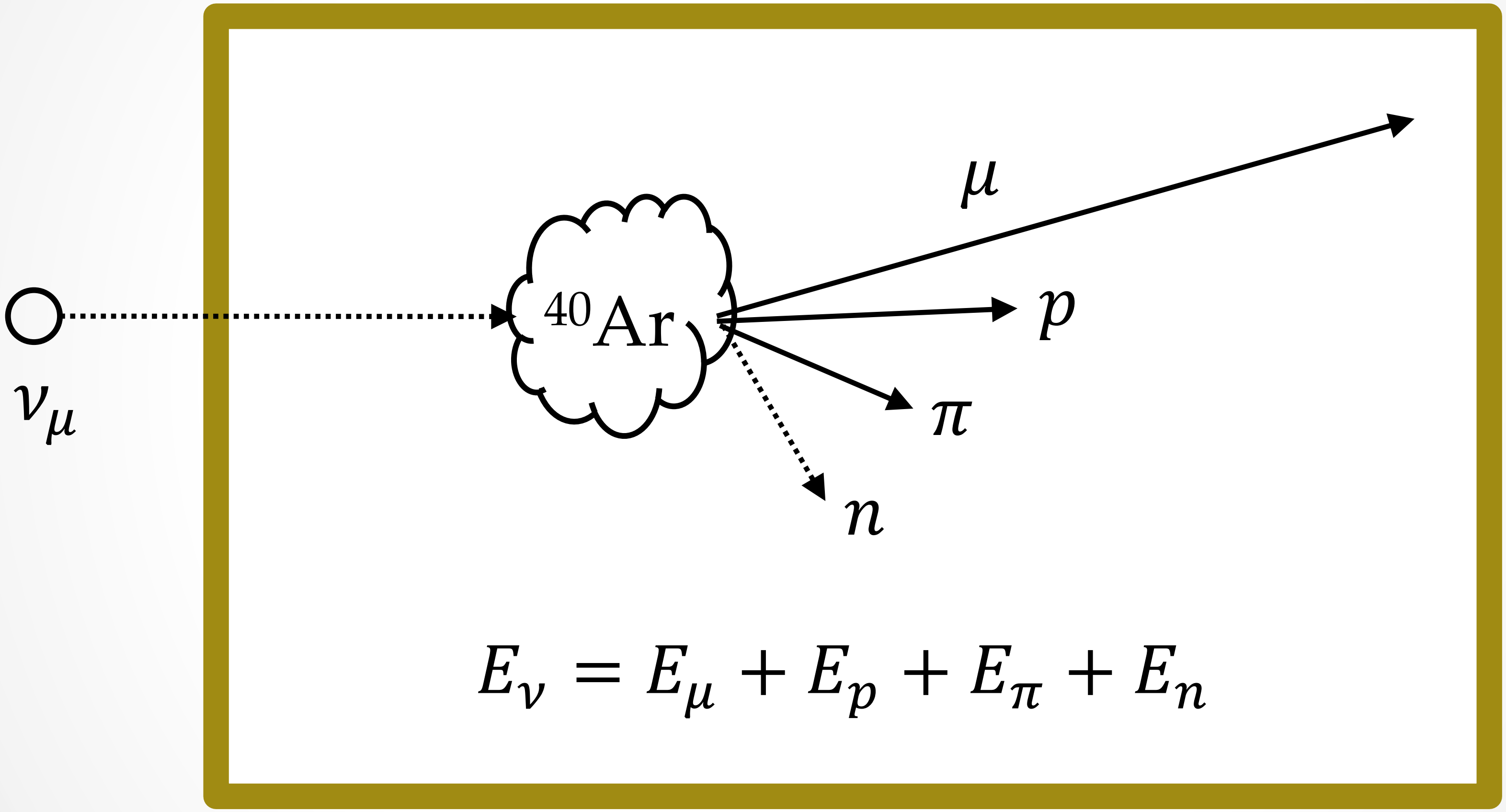


How Neutrinos Are Detected

DUNE: Liquid Argon Time-Projection Chamber



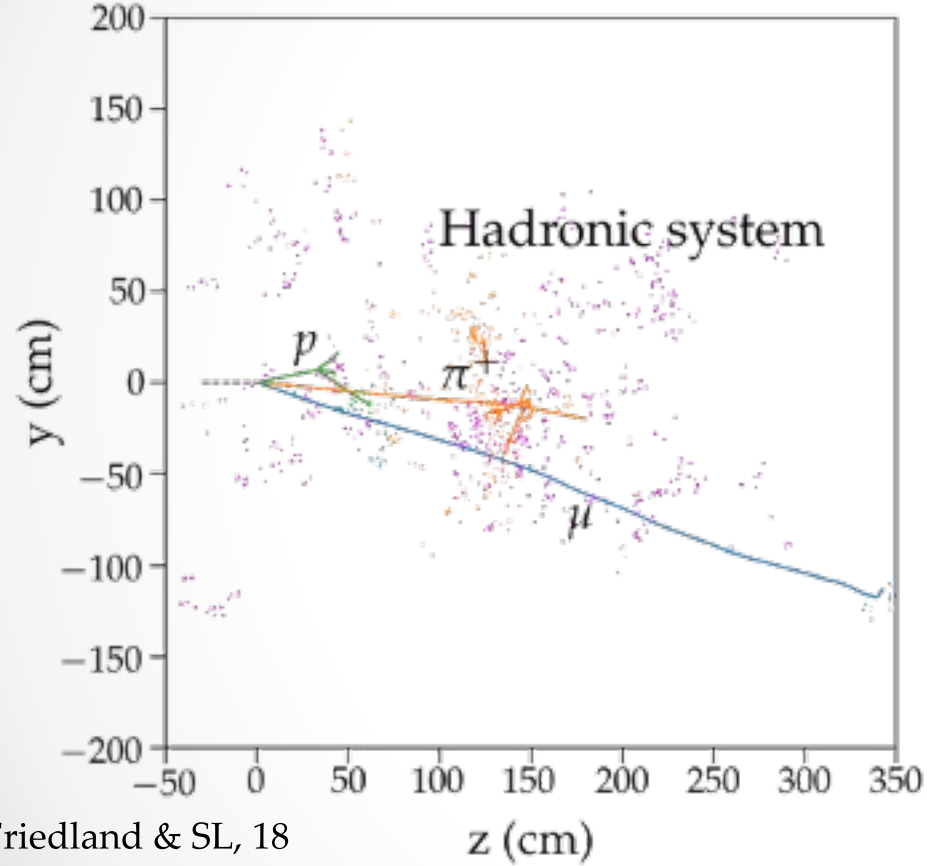
A Theorist’s View of a Neutrino Event



$$E_\nu = E_\mu + E_p + E_\pi + E_n$$

Only Predictions of Neutron Fraction Are Important

A Simulated Neutrino Event



Friedland & SL, 18

- Proton vs. Pion: Quenching
- Spectrum: Thresholds
- Number of Final-State Particles: Nuclear Breakup Energy

All Exclusive Final States Play A Role

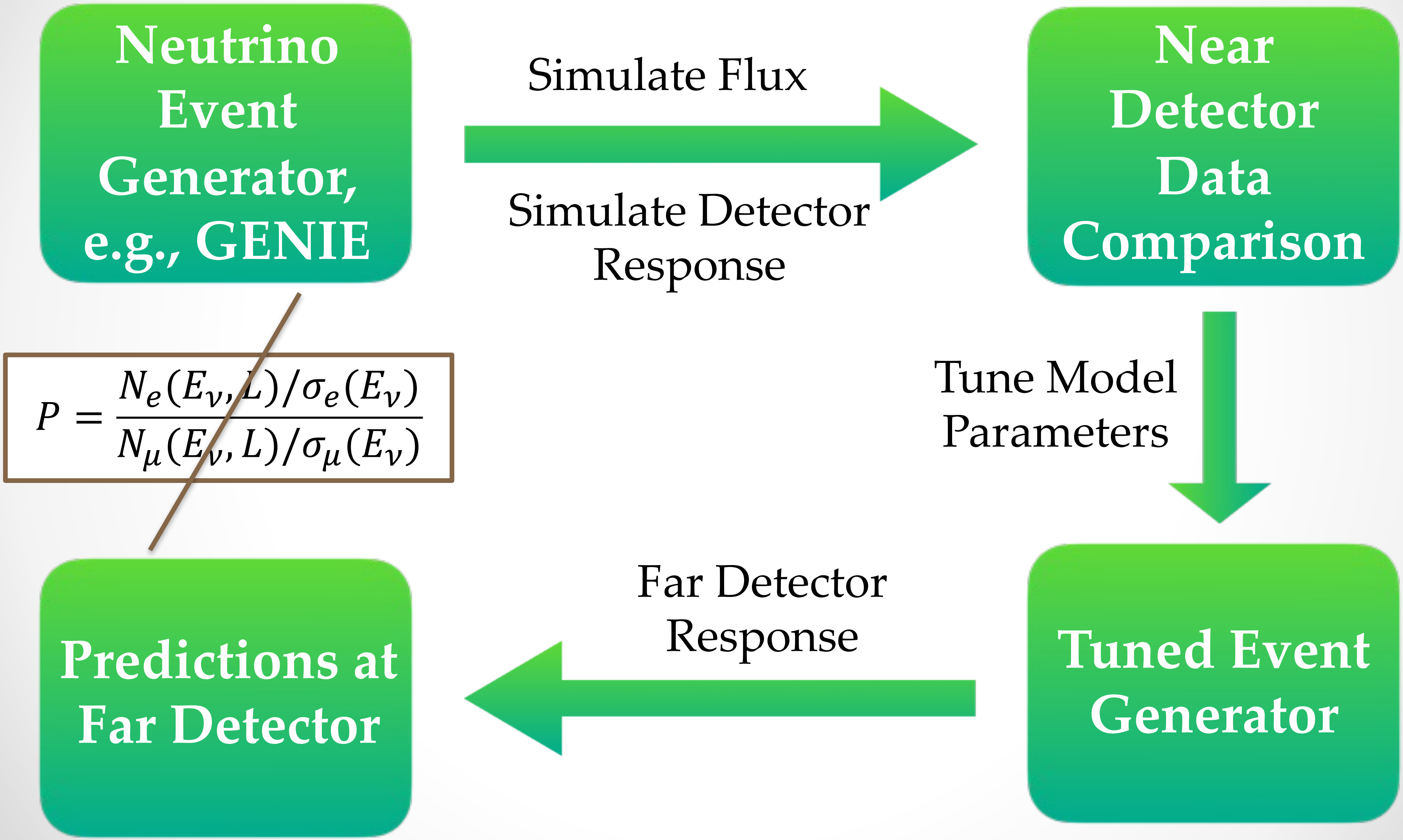
The Cross Section Predictions That We Need:

$$\frac{\mathrm{d}\sigma}{\mathrm{d}E_1 \mathrm{d}E_2 \ldots \mathrm{d}E_n}$$

Not So Much:

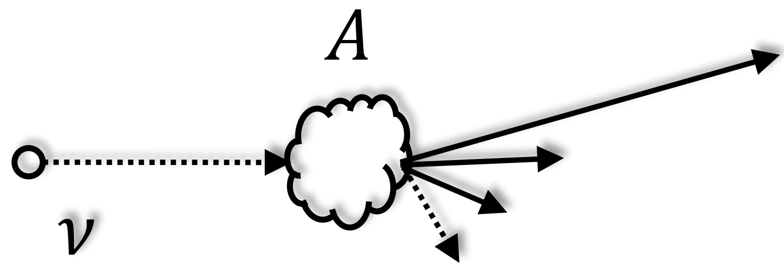
$$\sigma(E_\nu)$$

How Are Calculations Used?



Outline

Neutrino-Nucleus Cross Sections



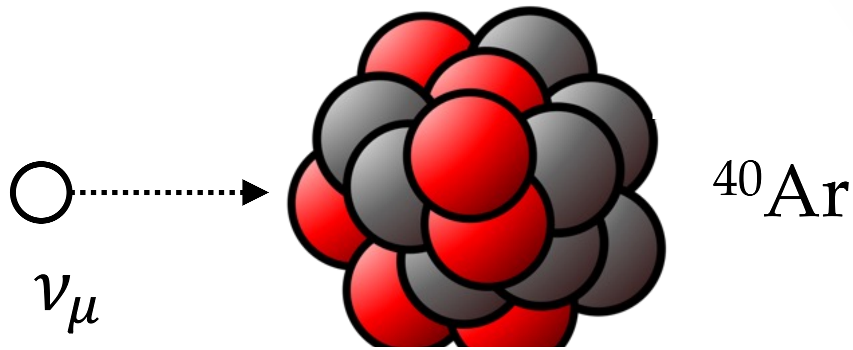
How Do They Affect Measurements

How to Improve

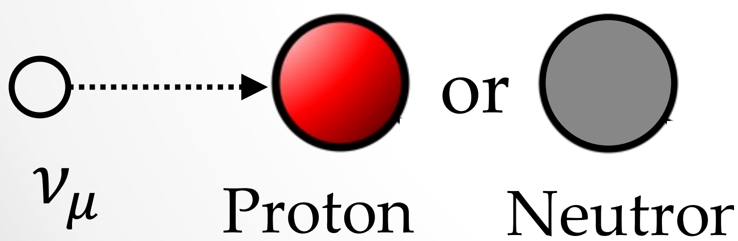
How Do We Compute the Cross Sections?

ν-Nucleus Cross Sections

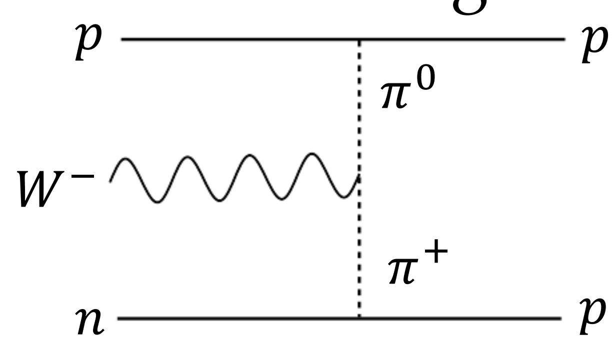
Beam Energy: 0.5 GeV – 5 GeV



- Nucleon $(m, \vec{0}) \rightarrow (E, \vec{p})$



- Meson-Exchange Current (MEC)

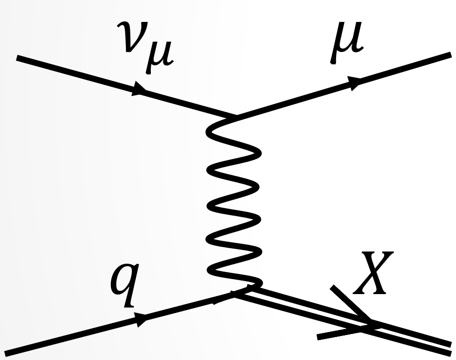


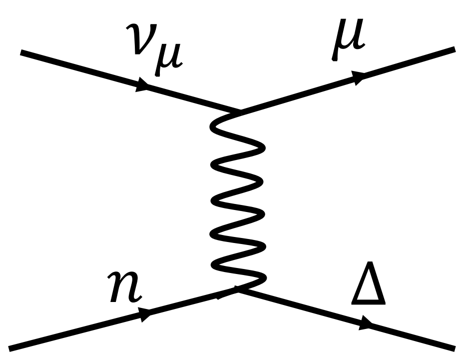
- Final-State Interactions

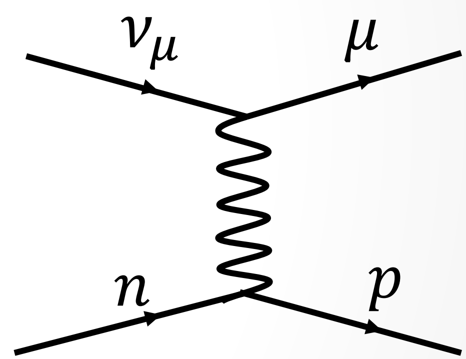
ν-Nucleon Cross Sections

Beam Energy: 0.5 GeV – 5 GeV

Deep Inelastic Scattering	Resonance Production	Quasi-Elastic Scattering







Multiple Particles	Nucleon + Meson	Single Nucleon

No Controlled Expansion

$Q^2 \cong 1\ \text{GeV}^2$

Kinematic Region

Ankowski, Friedland, SL, in prep

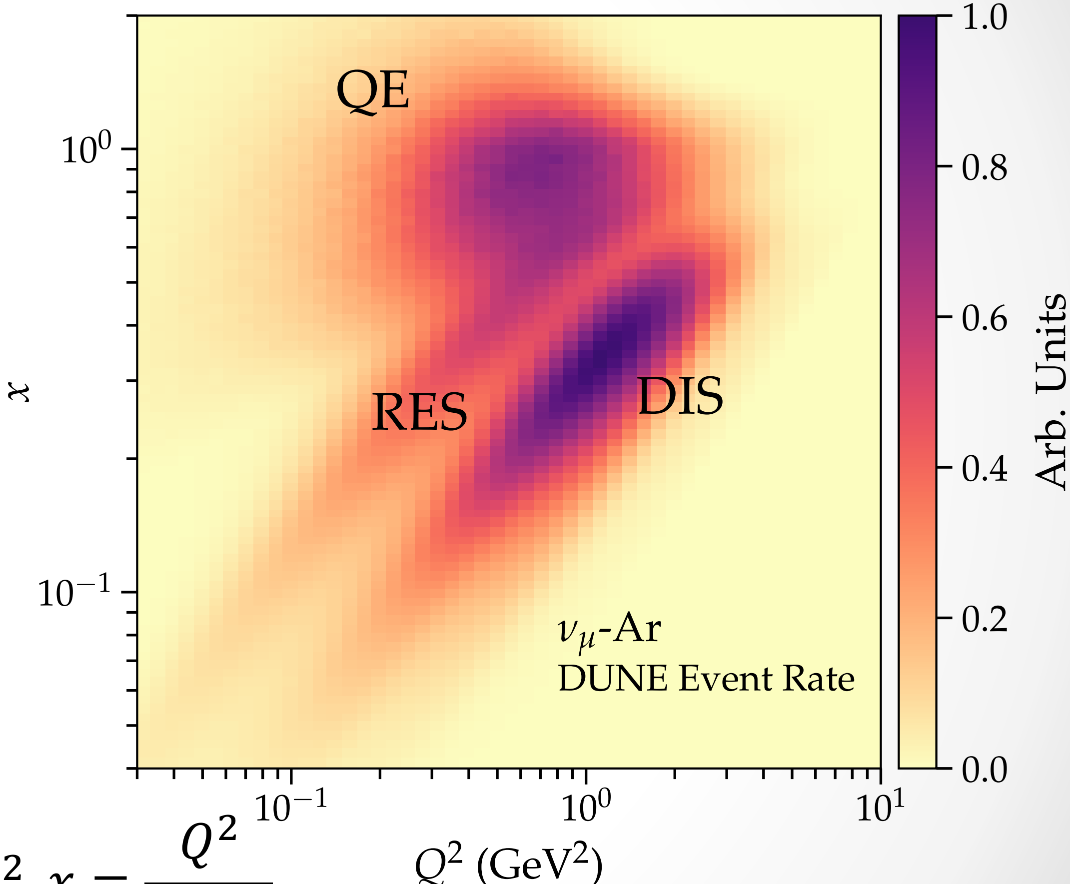
- DIS: $\nu_\mu + d \rightarrow \mu + u$

  Energy Too Low for Factorization

- RES: $\nu_\mu + n \rightarrow \mu + \Delta$

  30+ Resonance States, Not Enough Data

- QE: $\nu_\mu + n \rightarrow \mu + p$



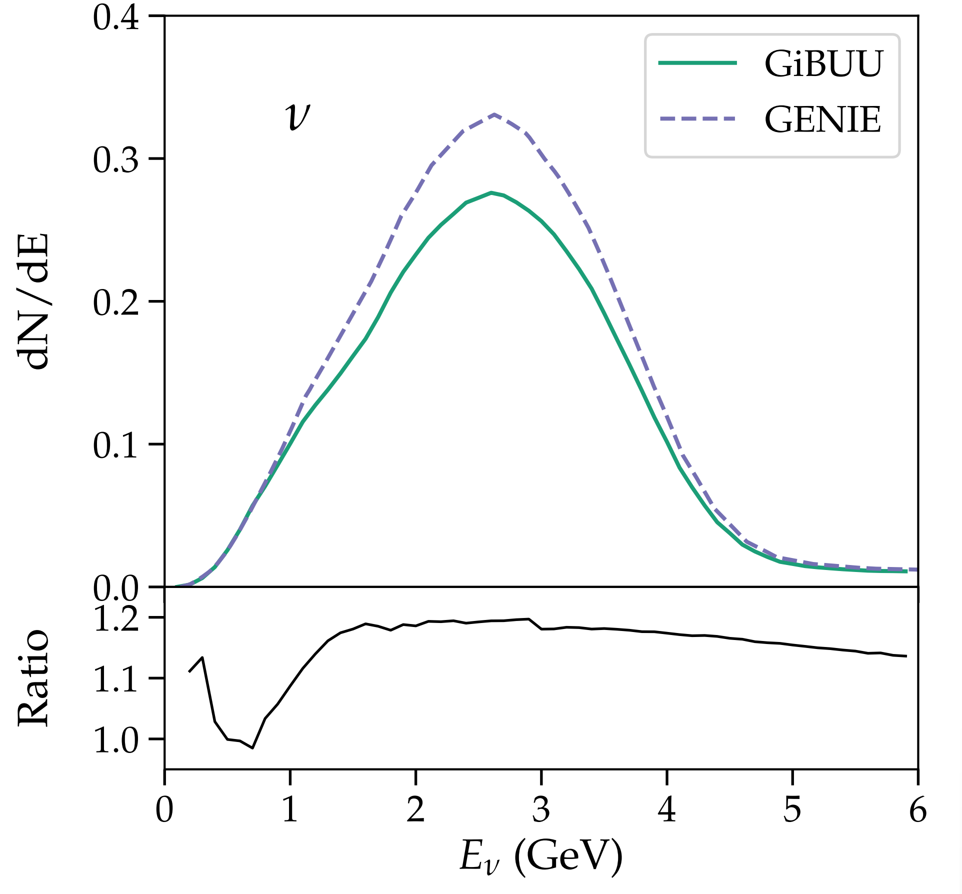
$$Q^2 = -q^2, x = \frac{Q^2}{2p \cdot q}$$

All Channels Are Important

Generator vs. Generator

Ankowski, Friedland, SL, in prep

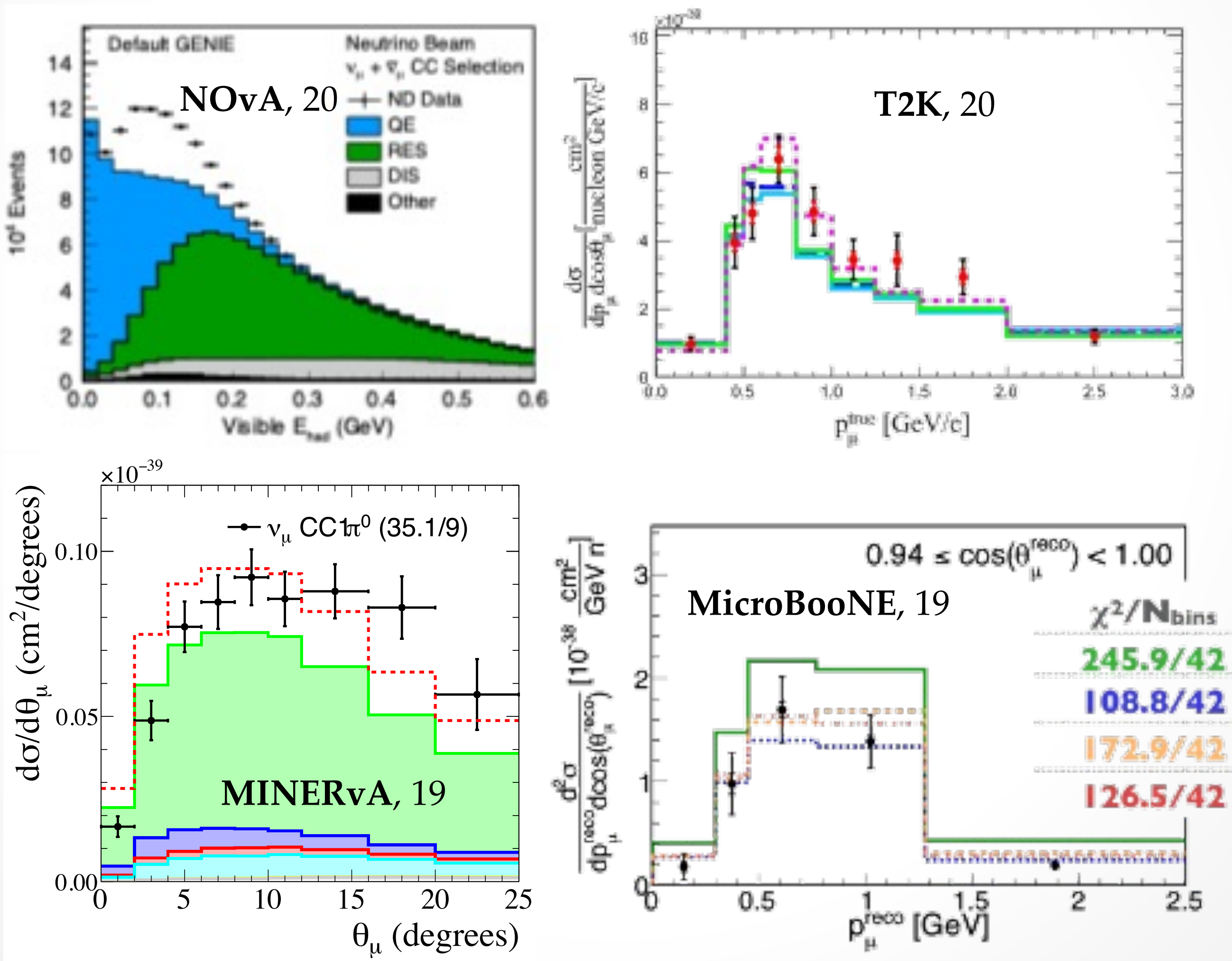
Compare $\sigma(E_\nu)$



Informative, But Not Adequate

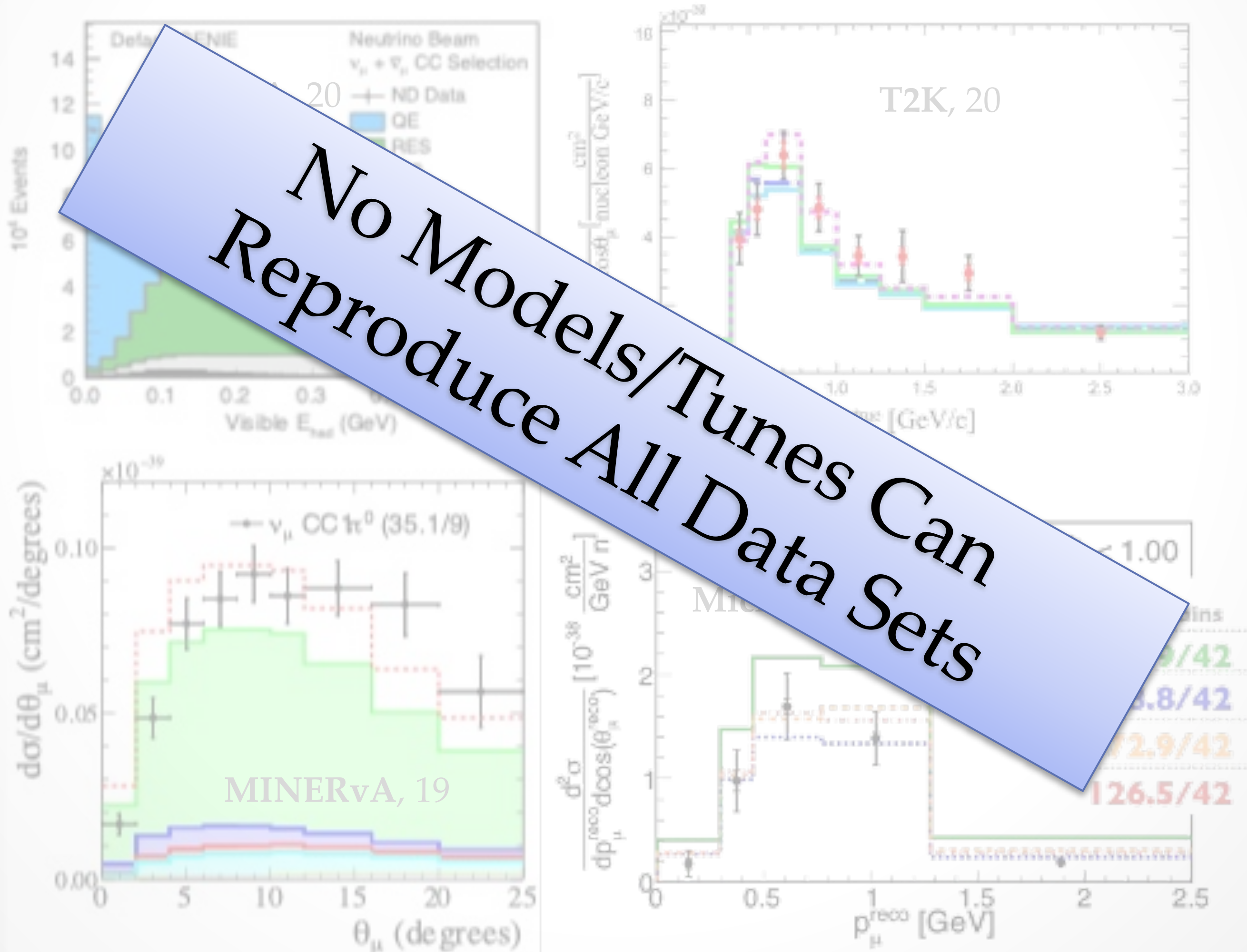
Generator vs. ν Data

Experiments Use Generators, Mostly GENIE



Generator vs. ν Data

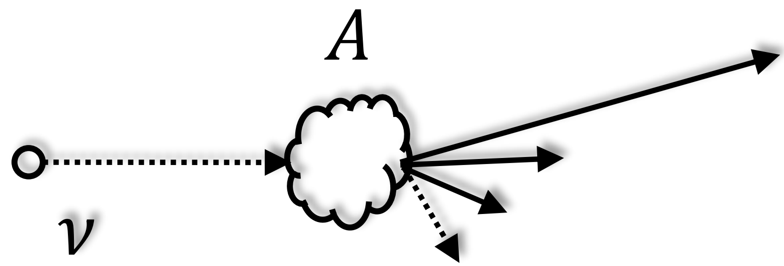
Experiments Use Generators, Mostly GENIE



No Models/Tunes Can Reproduce All Data Sets

Outline

Neutrino-Nucleus Cross Sections



How Do They Affect Measurements

How to Improve

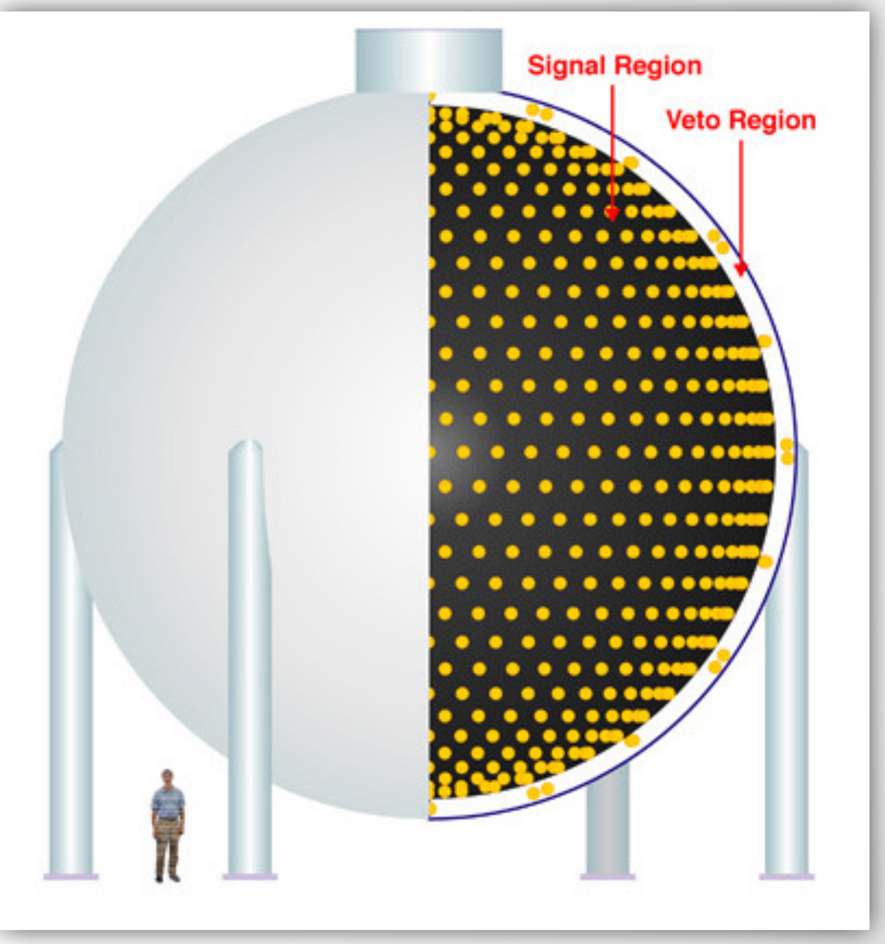
How Do We Compute the Cross Sections?

Uncovering Neutrino-Nucleus Cross Section Problems

…

MiniBooNE

- Started to Produce Results in 2007
- Designed to Test Oscillations of eV Sterile Neutrinos
- 800 MeV @ 500 m

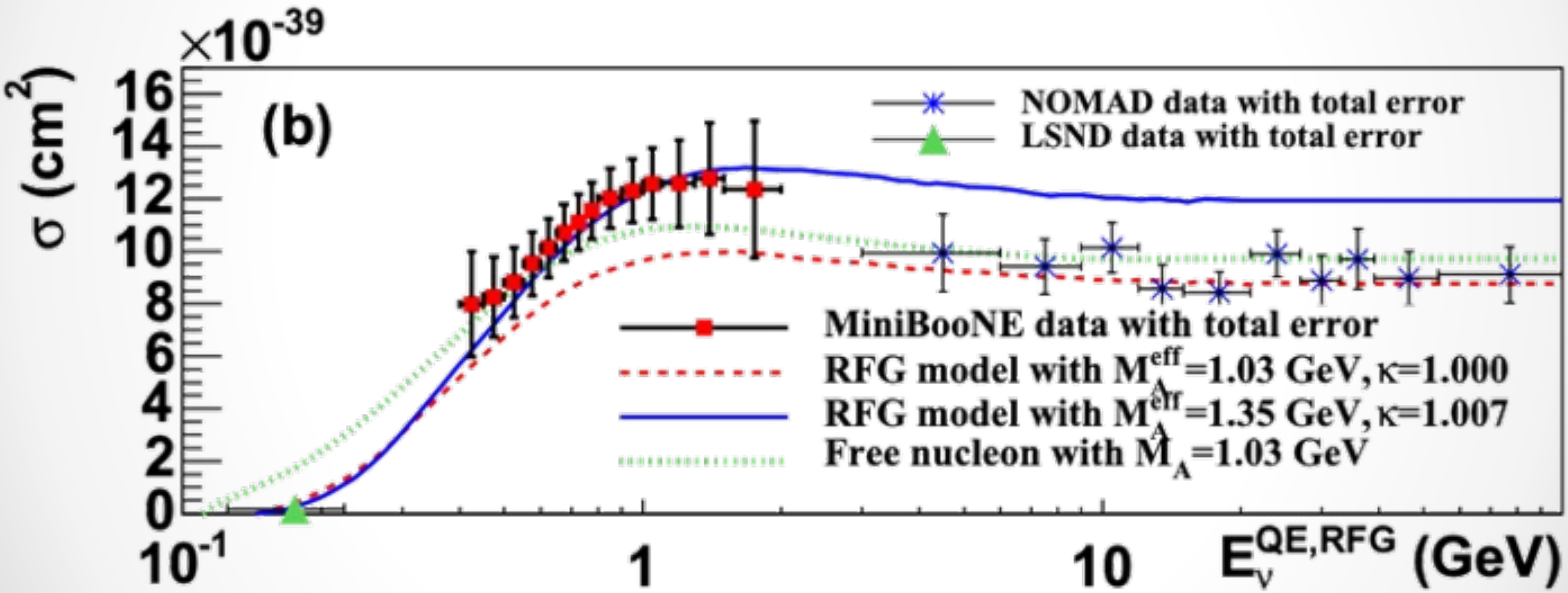


MiniBooNE, 09

Axial Mass m_A Measurement

$$\langle N' | J_W^\mu | N \rangle \supset \bar{\mu}'_N \gamma^\mu \gamma^5 F_A \mu_N, \qquad F_A(Q^2) = \frac{F_A(0)}{\left(1+\frac{Q^2}{m_A^2}\right)^2}$$

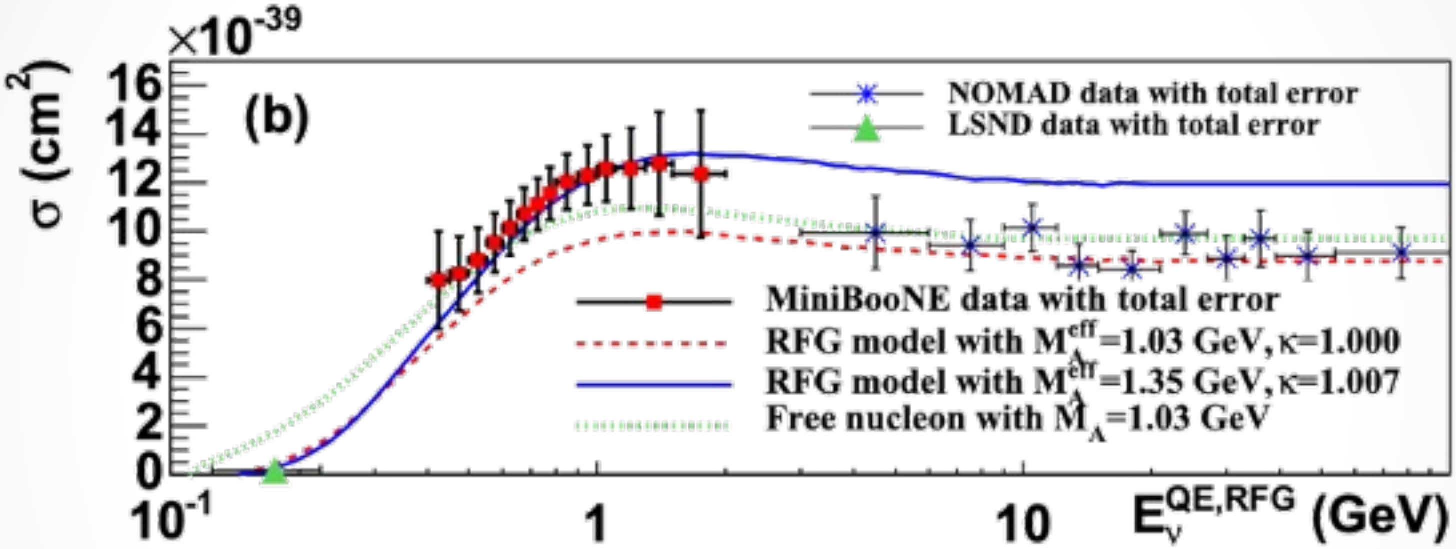
MiniBooNE, 10



Results Disagree with Previous Experiments

MiniBooNE Setting the Tone

MiniBooNE, 10

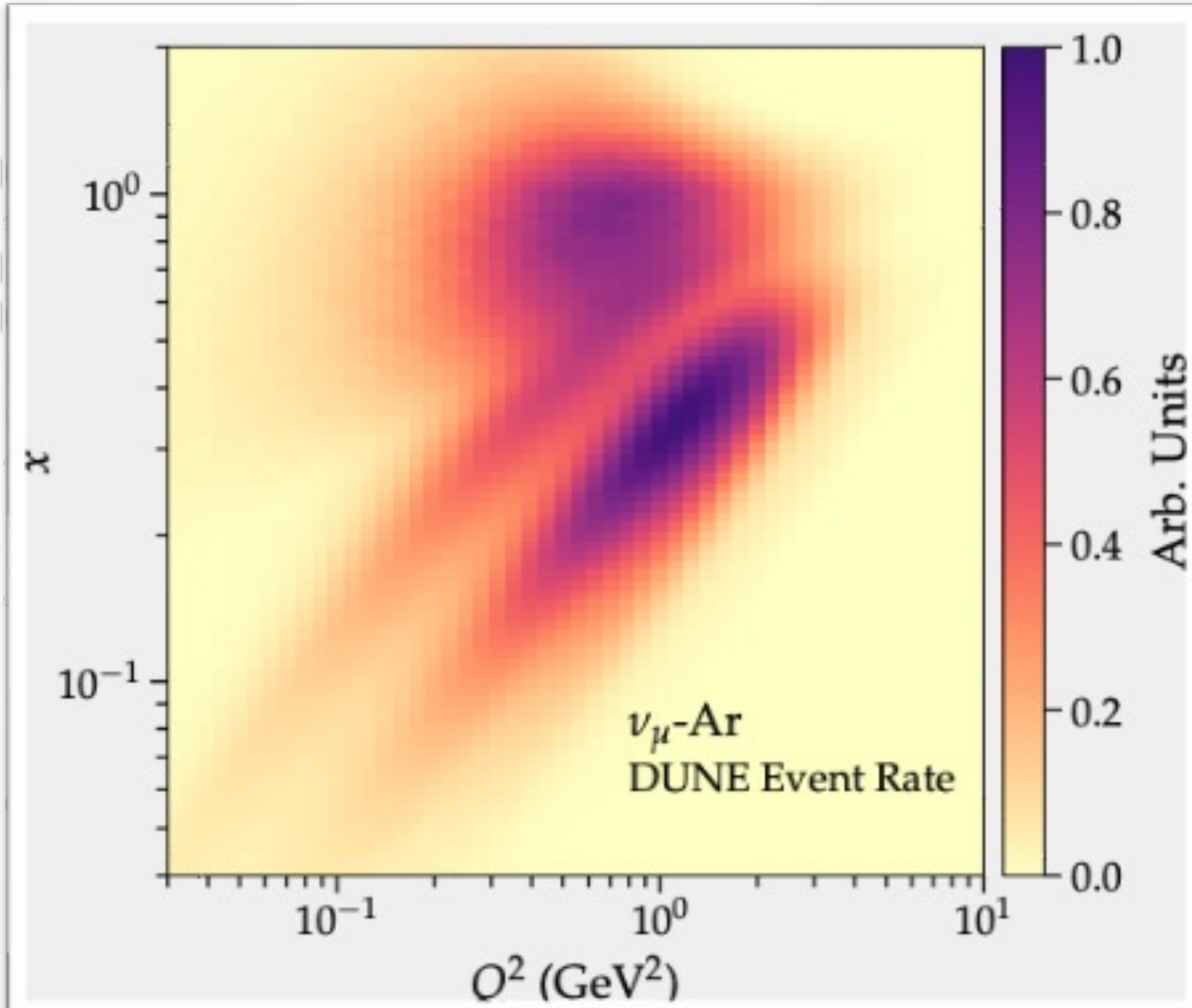


Quasi-Elastic And Meson-Exchange Current Channels Are Important

What About Resonance Production and DIS?

MiniBooNE Setting the Tone

MiniBooNE, 10

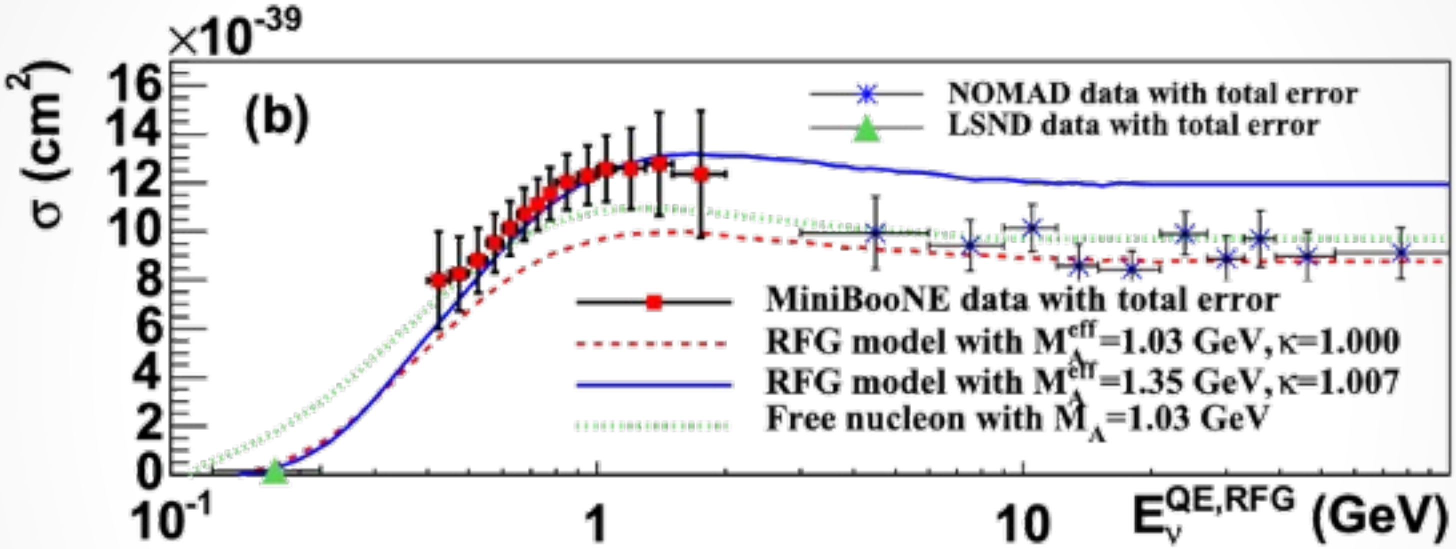


Quasi-El... Channels

What About Resonance Production and DIS?

MiniBooNE Setting the Tone

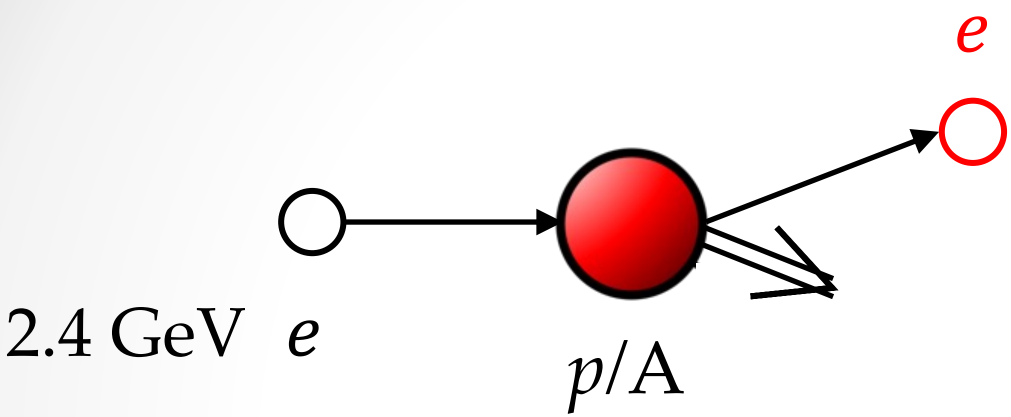
MiniBooNE, 10

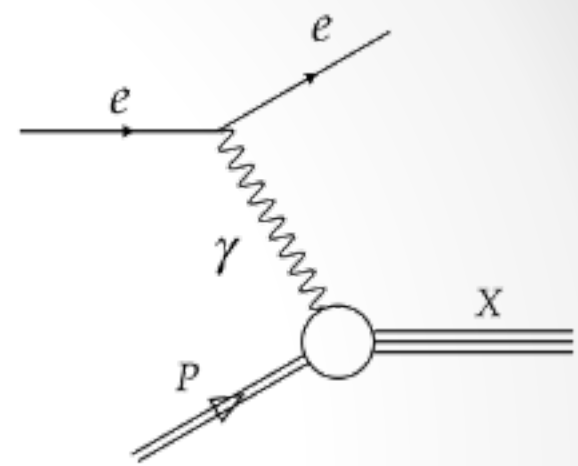


Quasi-Elastic And Meson-Exchange Current Channels Are Important

What About Resonance Production and DIS?

ν-A Generators vs. e-A Data





- Same Primary Vertex Models, Only Vector Couplings
- Same Final-State Interactions / Nucleon Distributions

E.g., Elastic Scattering:

$e-p$

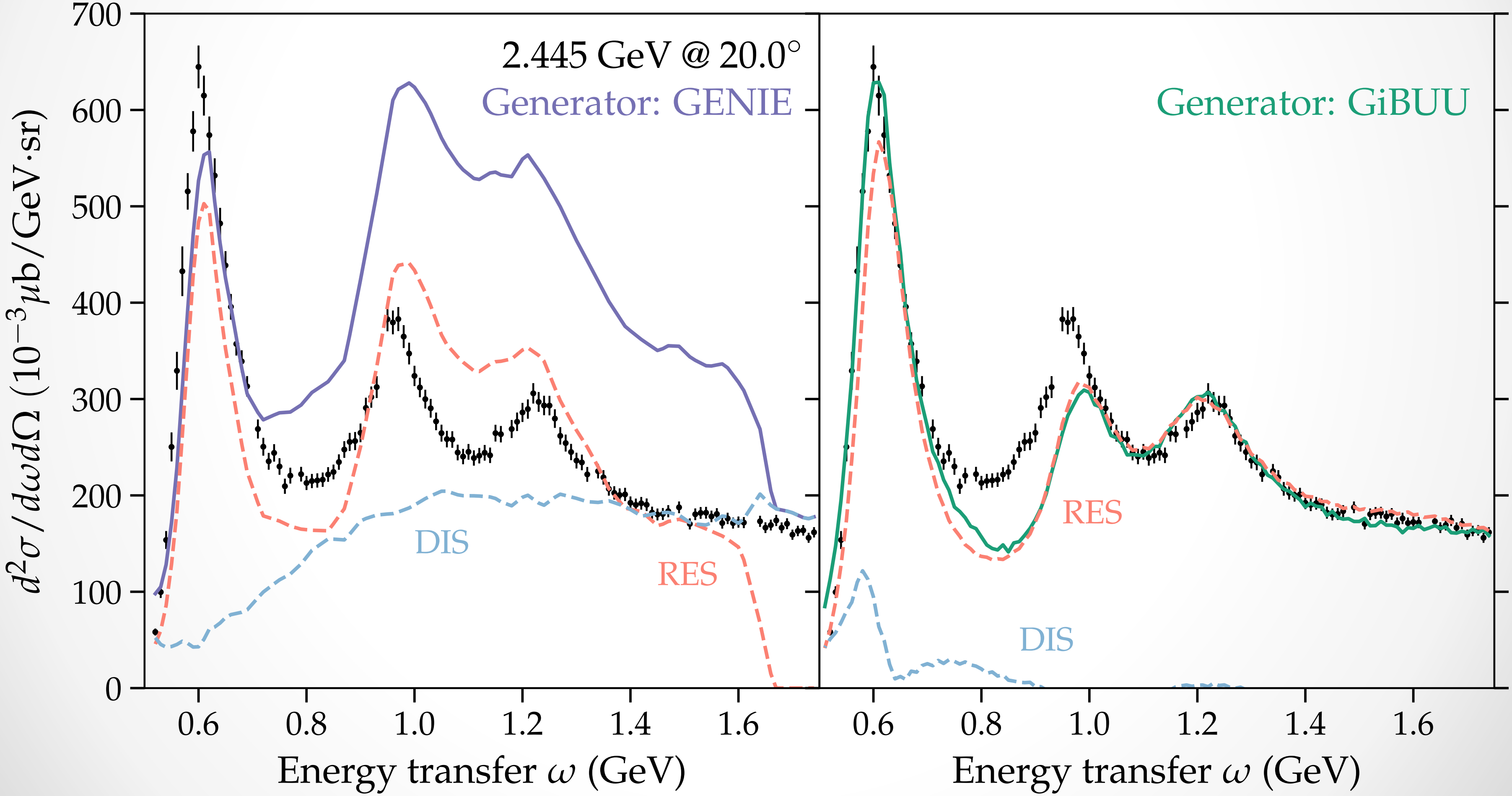
$$\langle N'|J^{\mu}_{\gamma}|N\rangle = \bar{\mu}'_N \left\{ \gamma^{\mu} F_1 + \frac{i\sigma^{\mu\nu} q_{\nu}}{2M} F_2 \right\} \mu_N$$

$\nu-p$

$$\langle N'|J^{\mu}_{W}|N\rangle = \bar{\mu}'_N \left\{ \gamma^{\mu} F_1 + \frac{i\sigma^{\mu\nu} q_{\nu}}{2M} F_2 + \gamma^{\mu} \gamma^{5} F_A + \frac{q^{\mu} \gamma^{5}}{M} F_P \right\} \mu_N$$

e-p Scattering

Neutrino Generators vs. Data

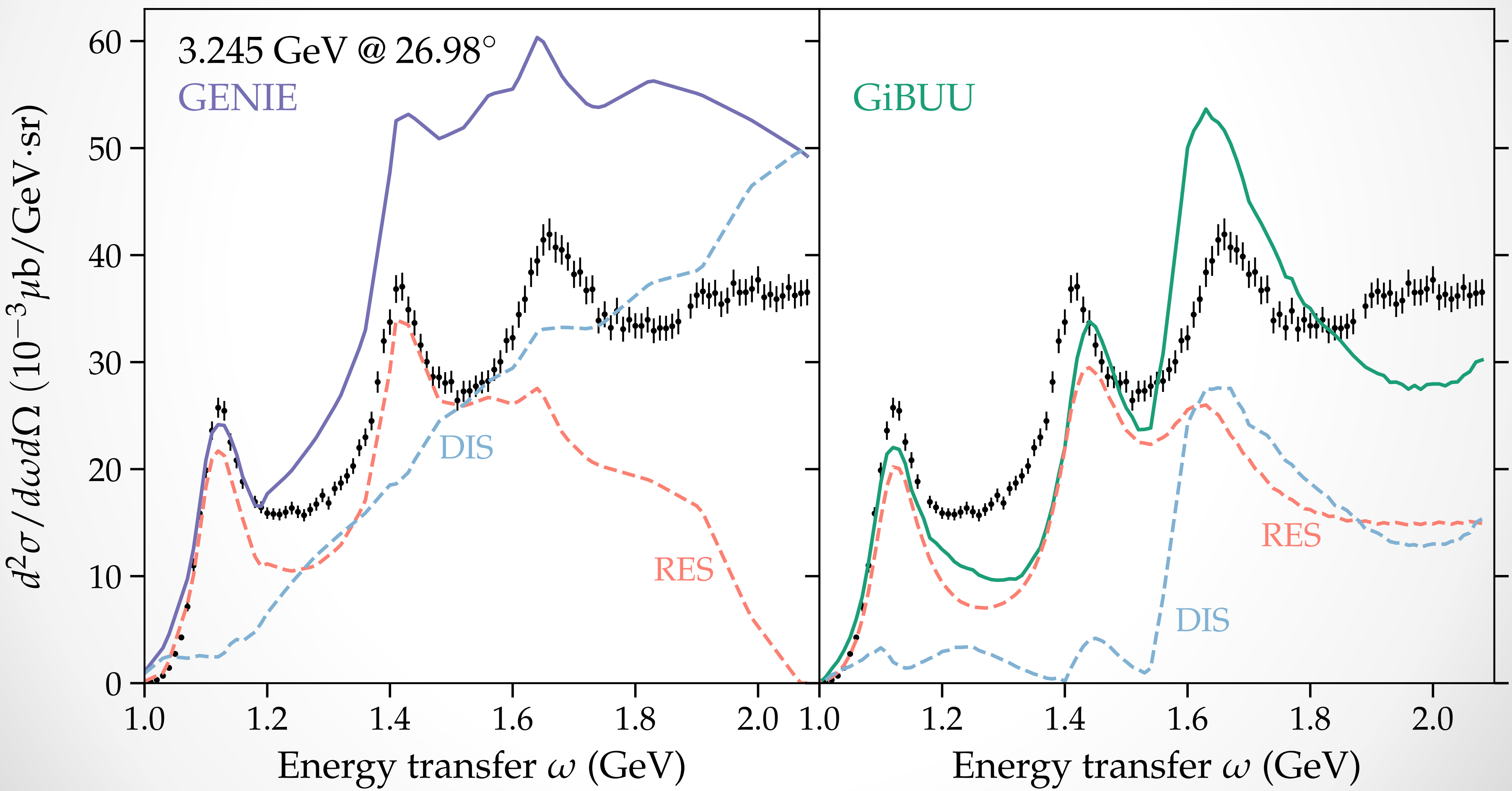


Ankowski, Friedland, SL, in prep
Data from Niculescu et al., 00

$$\omega = E_e - E_{e'}$$

e-p Scattering

Neutrino Generators vs. Data

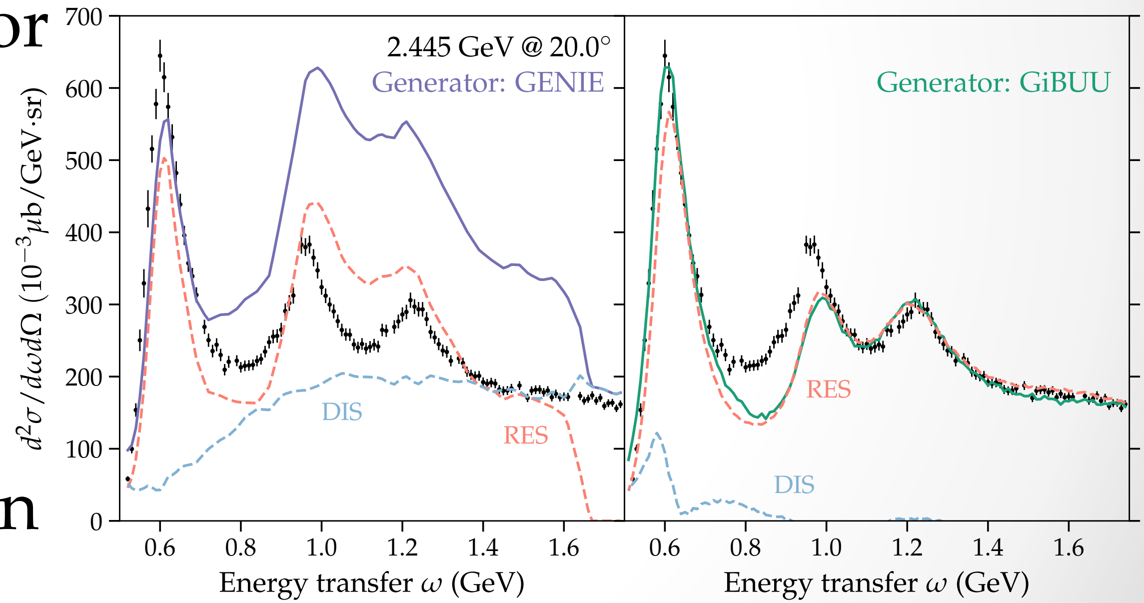


Ankowski, Friedland, SL, in prep
Data from Niculescu et al., 00

e-p Scattering

Neutrino Generators vs. Data

- GENIE: 50—80% error
  GiBUU: 20—30% error
- RES vs. DIS: Not a Good Separation
- Major Implementation Errors

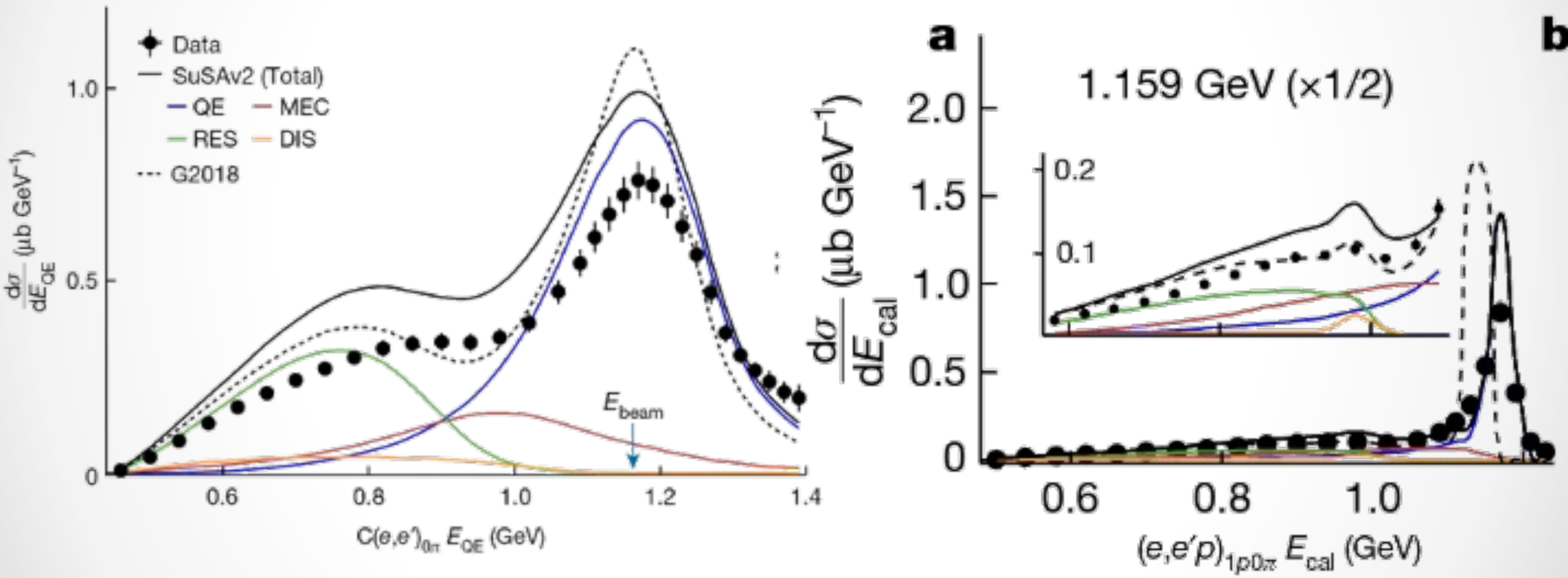


Ankowski, Friedland, SL, in prep
Data from Niculescu et al., 00

e-A Scattering

Neutrino Generators vs. Data

CLAS & e4v, Nature, 21

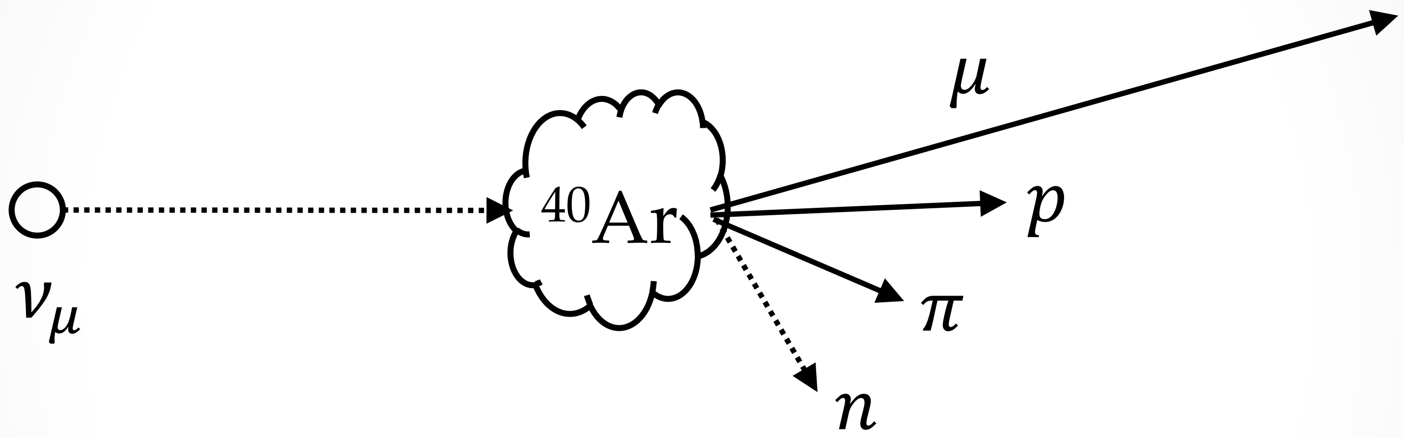


Tests Energy Reconstruction Used in Neutrino Oscillation Measurements

CLAS & e4v, Nature, 21

Cross Section Calculations

Observables Are High-Dimensional



$$\frac{\mathrm{d}\sigma}{\mathrm{d}E_1\,\mathrm{d}E_2\,\ldots\,\mathrm{d}E_n} \text{ (Exclusive), not } \frac{\mathrm{d}\sigma}{\mathrm{d}E} \text{ (Inclusive)}$$

Much Harder to Compute Exclusive Cross Sections

But the story doesn't end here …

Conclusions

1. GeV Neutrino-Nucleus Scattering is Crucial to the Success of Long-Baseline Neutrino Experiments

2. No Complete Theoretical Framework Available; Difficult to Assess Uncertainties

3. More Scattering Data is Needed

4. New Theoretical Ideas Are Needed