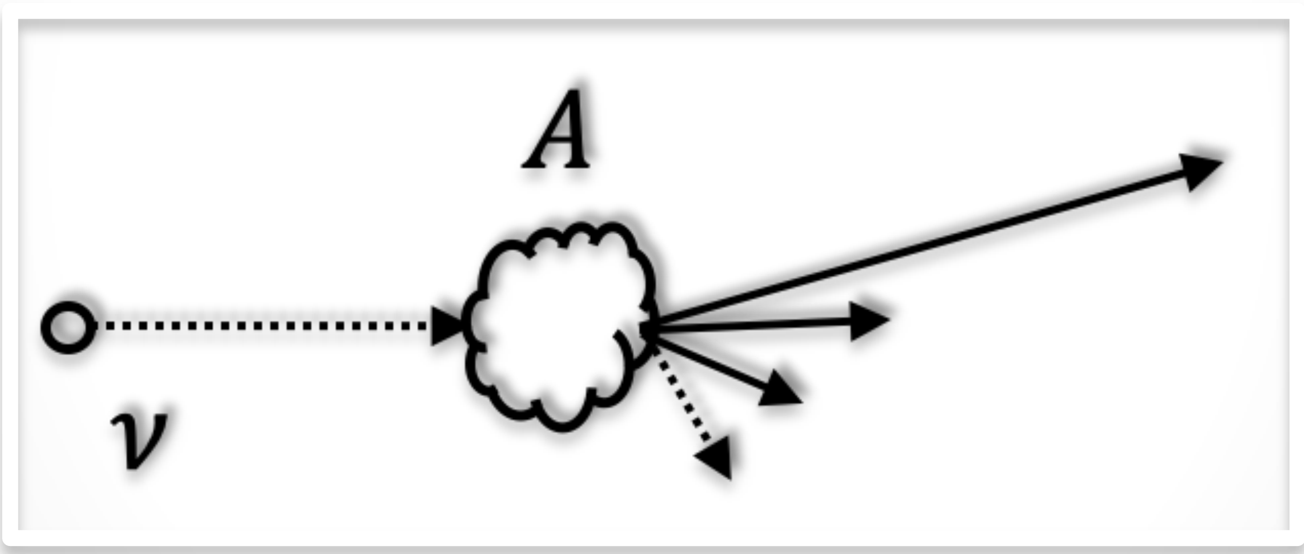
Neutrino-Nucleus Cross Sections Explained



Shirley Li (SLAC)

3-Flavor Neutrino Oscillations

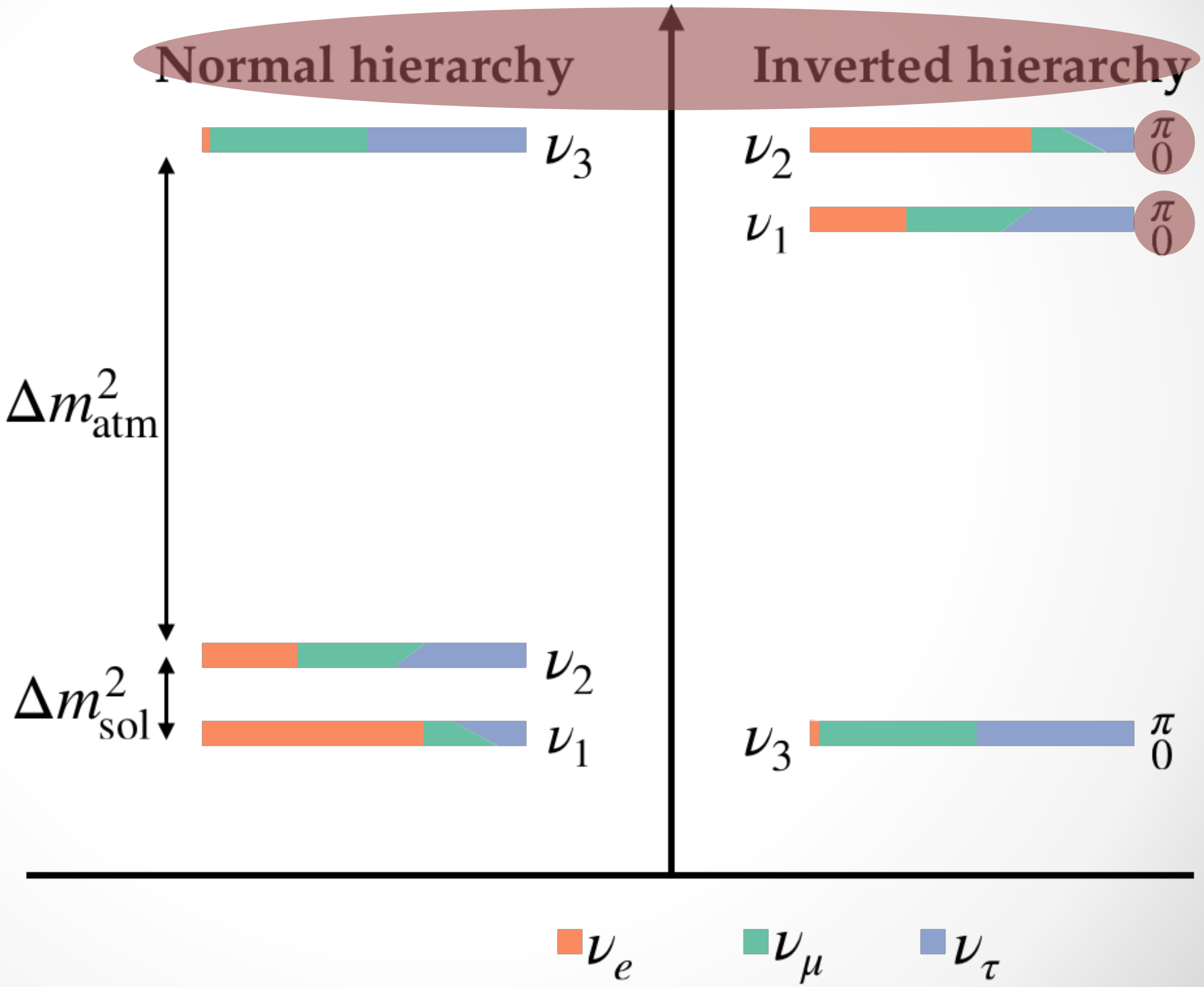
Unknown:

δ_{CP}, MH

A Few %:

$\theta_{12}, \theta_{13}, \theta_{23}$,

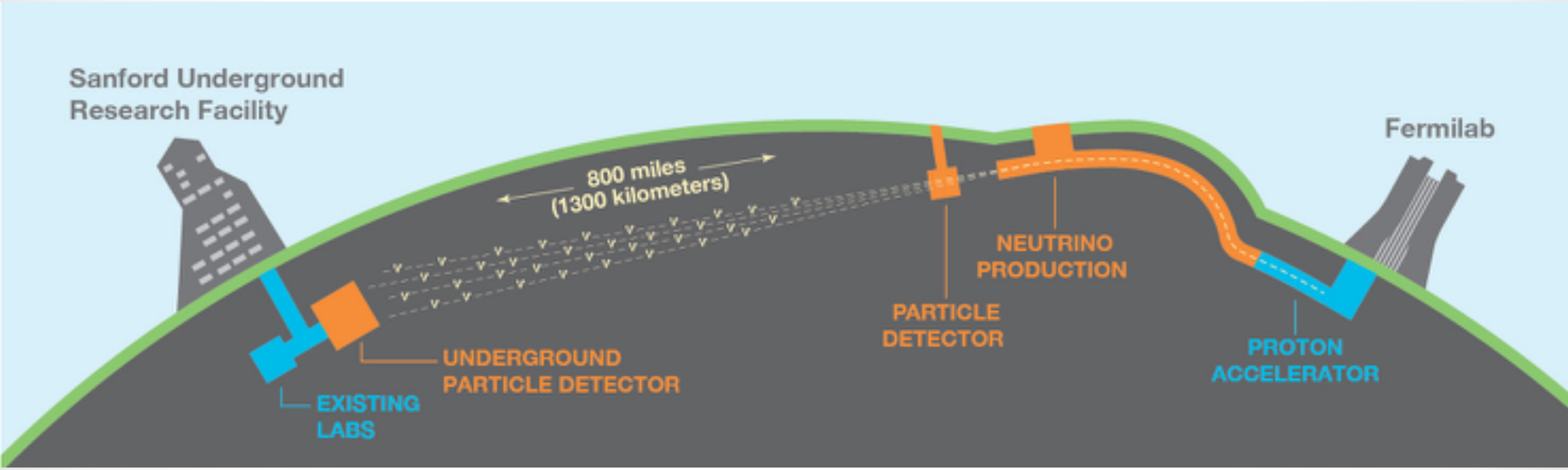
$\Delta m^2_{21}, \Delta m^2_{32}$



Long-Baseline Experiments

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

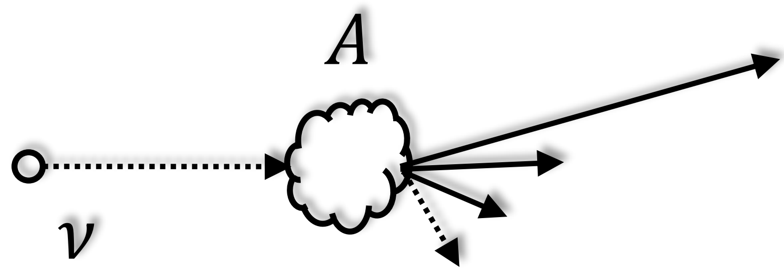
DUNE 15



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

Outline

Neutrino-Nucleus Cross Sections



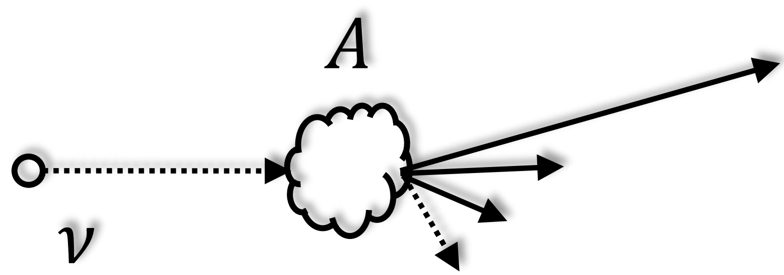
How They Affect Measurements

What Are Current Theoretical Uncertainties

Why Is the Calculation Difficult?

Outline

Neutrino-Nucleus Cross Sections



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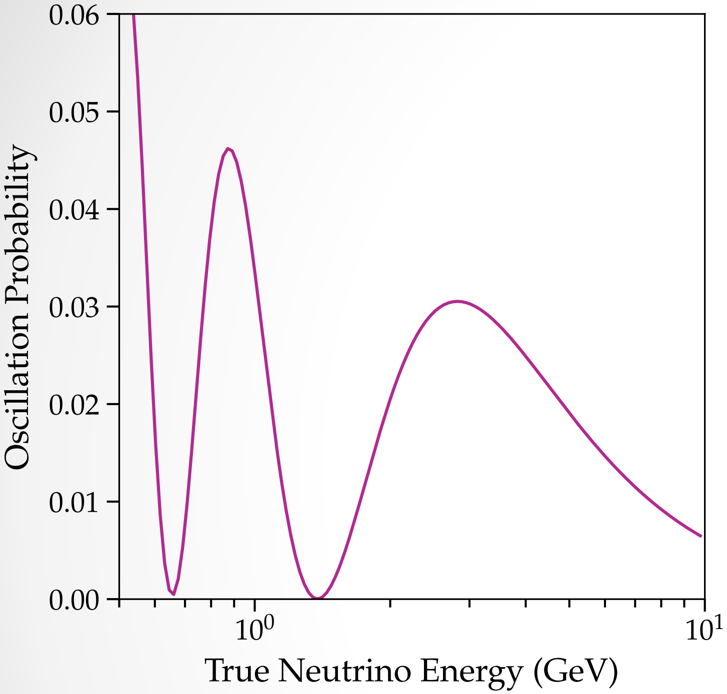
Measuring Neutrino Oscillation



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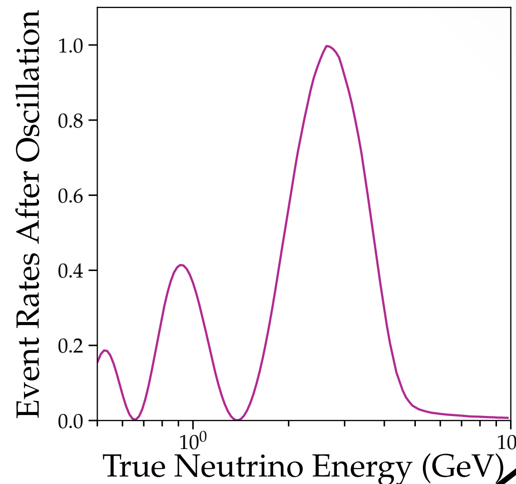
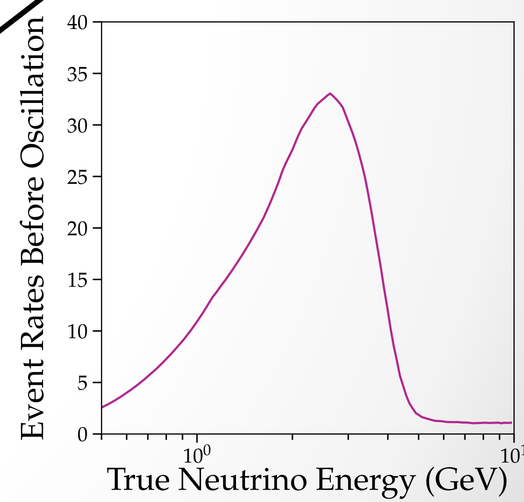


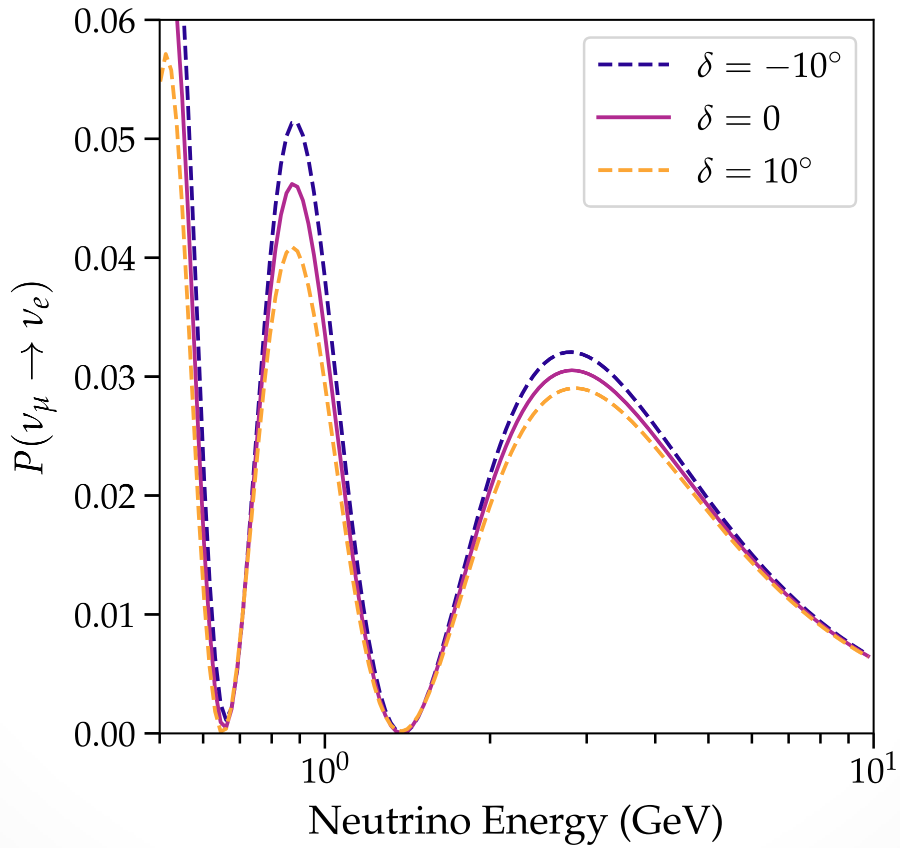


DUNE flux from https://home.fnal.gov/~ljf26/DUNEFluxes/

1. Predict Flux*<u>Cross Section</u> as a Function of Neutrino Energy
2. Measure Event Rates as a Function of <u>True Neutrino Energy</u>

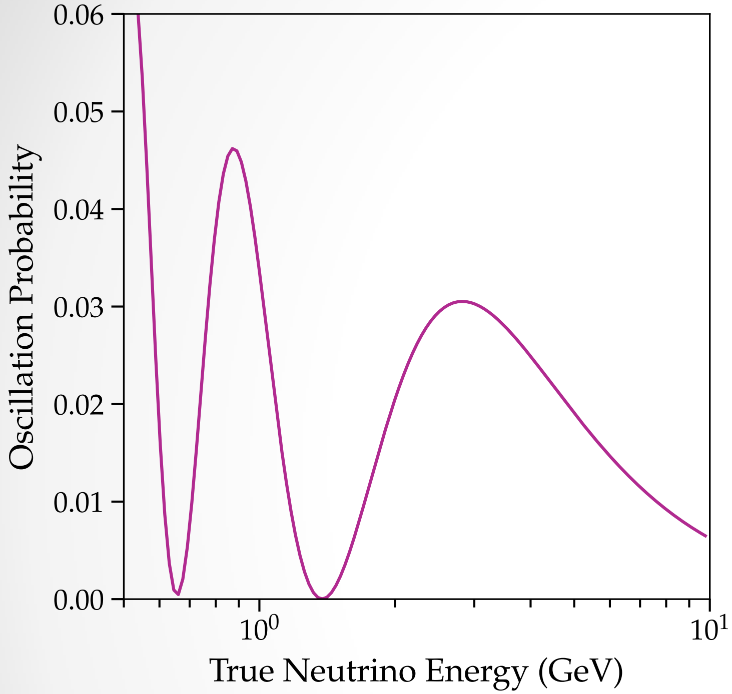
Expected Accuracy

DUNE Nominal Accuracy on δ_{CP} as An Example



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

Measuring Neutrino Oscillation



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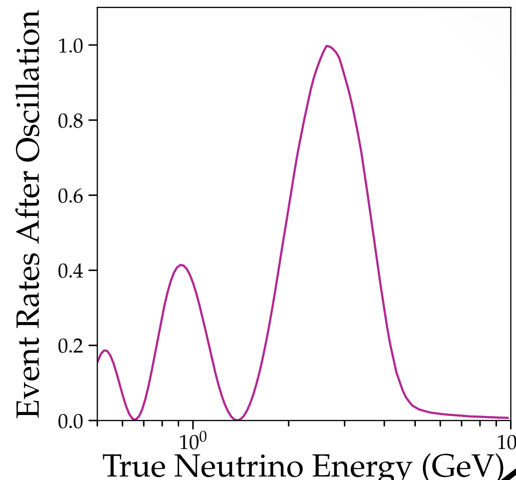
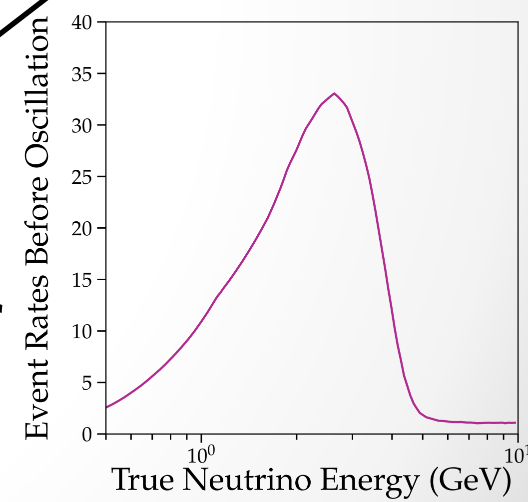


Far Detector

Near Detector

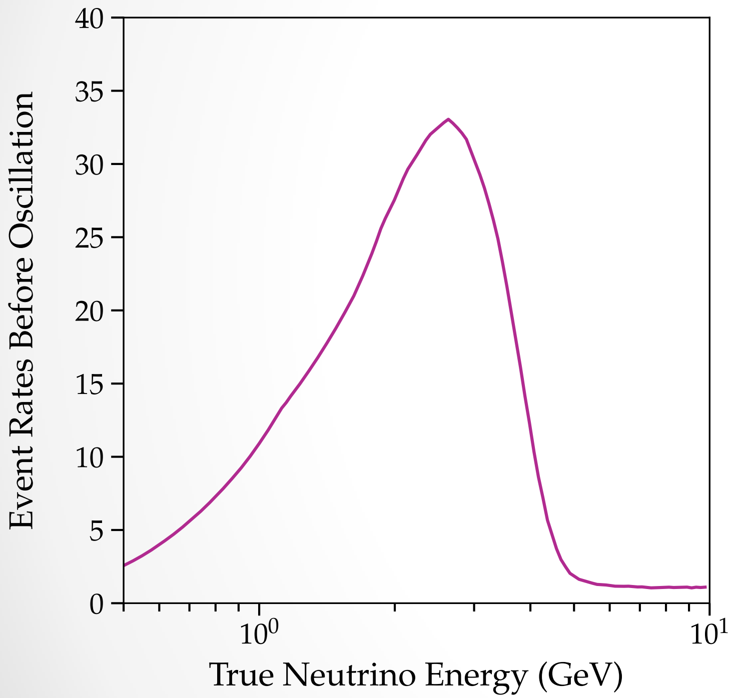


DUNE flux from https://home.fnal.gov/~ljf26/DUNEFluxes/

1. Predict Flux*Cross Section as a Function of Neutrino Energy
2. Measure Event Rates as a Function of True Neutrino Energy

A Near Detector

~~Predict~~ *Measure* Flux*Cross Section



It Does NOT Work Perfectly:

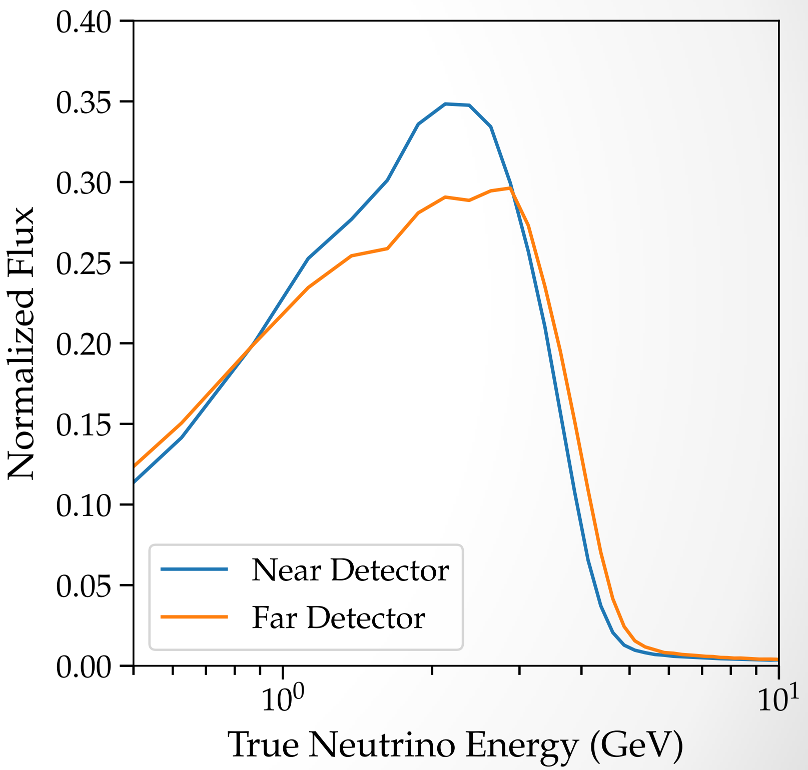
1. The Fluxes at Near Detector and Far Detector Are Different

Flux Difference

Near/Far Detectors See Different Parts of the Beam

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

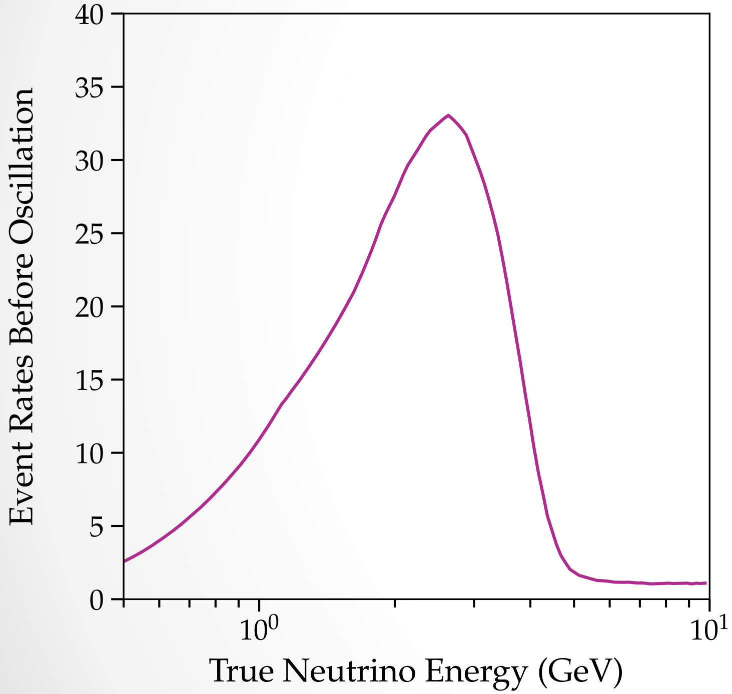
Image Stole from A. Ankowski's Talk at PINS 19



Difference Larger Than Experimental Target Accuracy

A Near Detector

~~Predict~~ *Measure* Flux*Cross Section



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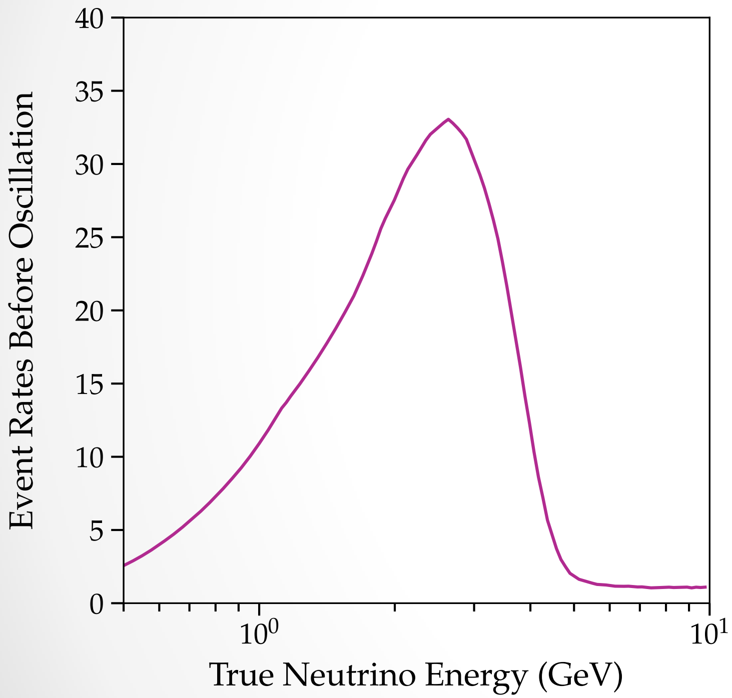
A Near Detector

~~Predict~~ *Measure* Flux*Cross Section



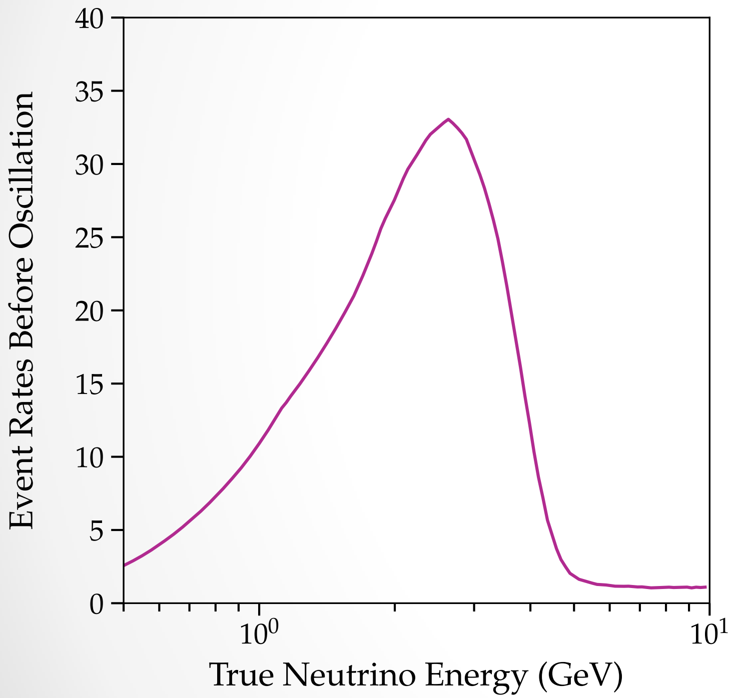
It Does NOT Work Perfectly:

1. The Fluxes at Near Detector and Far Detector Are Different

2. One Cannot Measure True Neutrino Energy

A Near Detector

~~Predict~~ *Measure* Flux*Cross Section



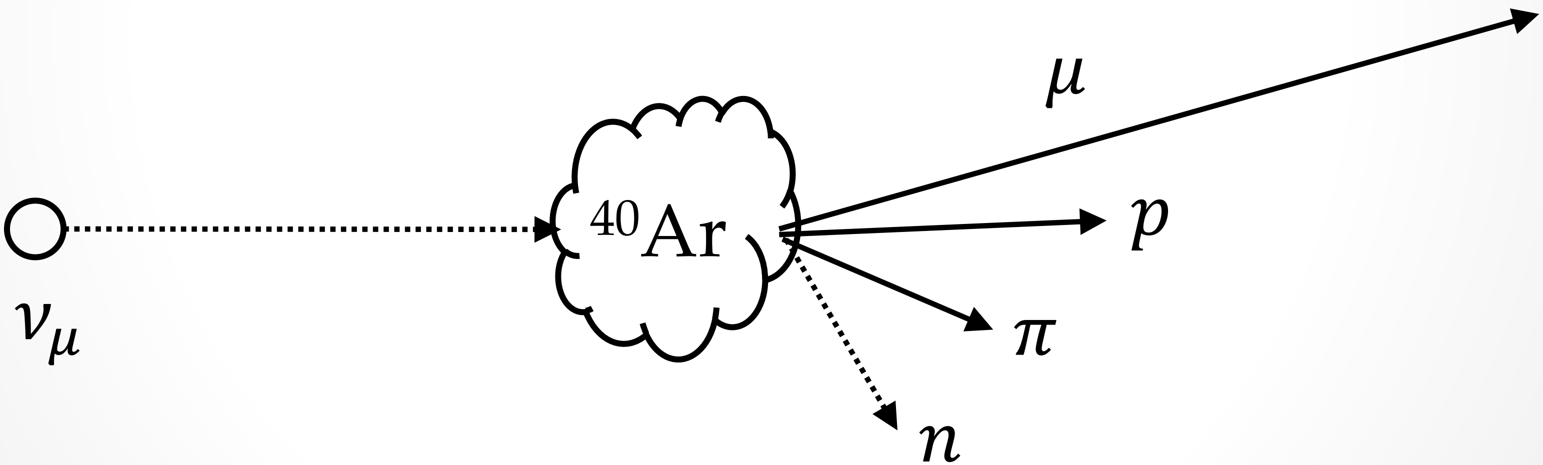
It Does NOT Work Perfectly:

1. The Fluxes at Near Detector and Far Detector Are Different

2. One Cannot Measure True Neutrino Energy

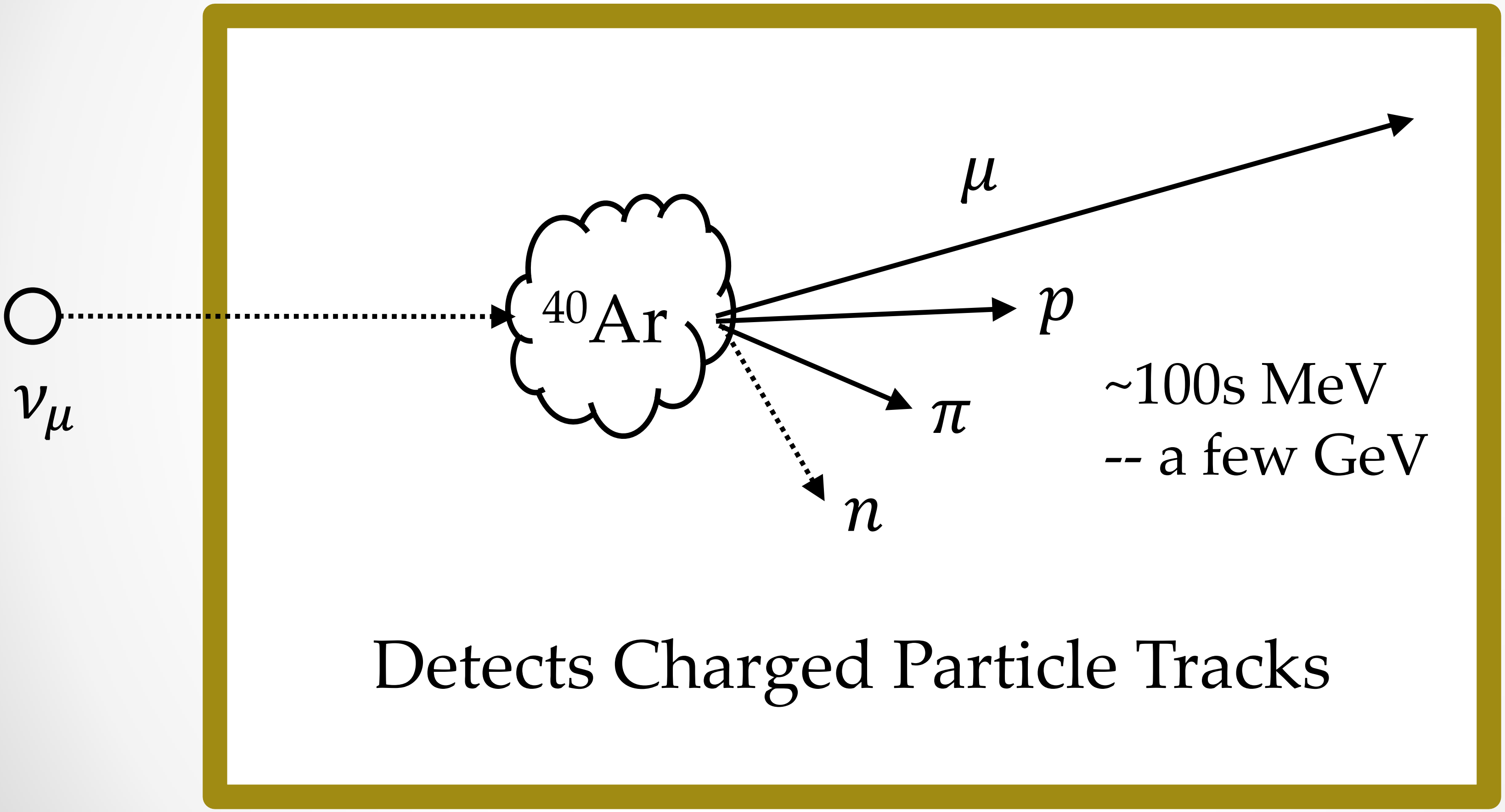
1. Predict Flux*Cross Section as a Function of Neutrino Energy
2. Measure Event Rates as a Function of True Neutrino Energy

How Do Cross Section Calculations Impact Neutrino Energy Reconstruction?

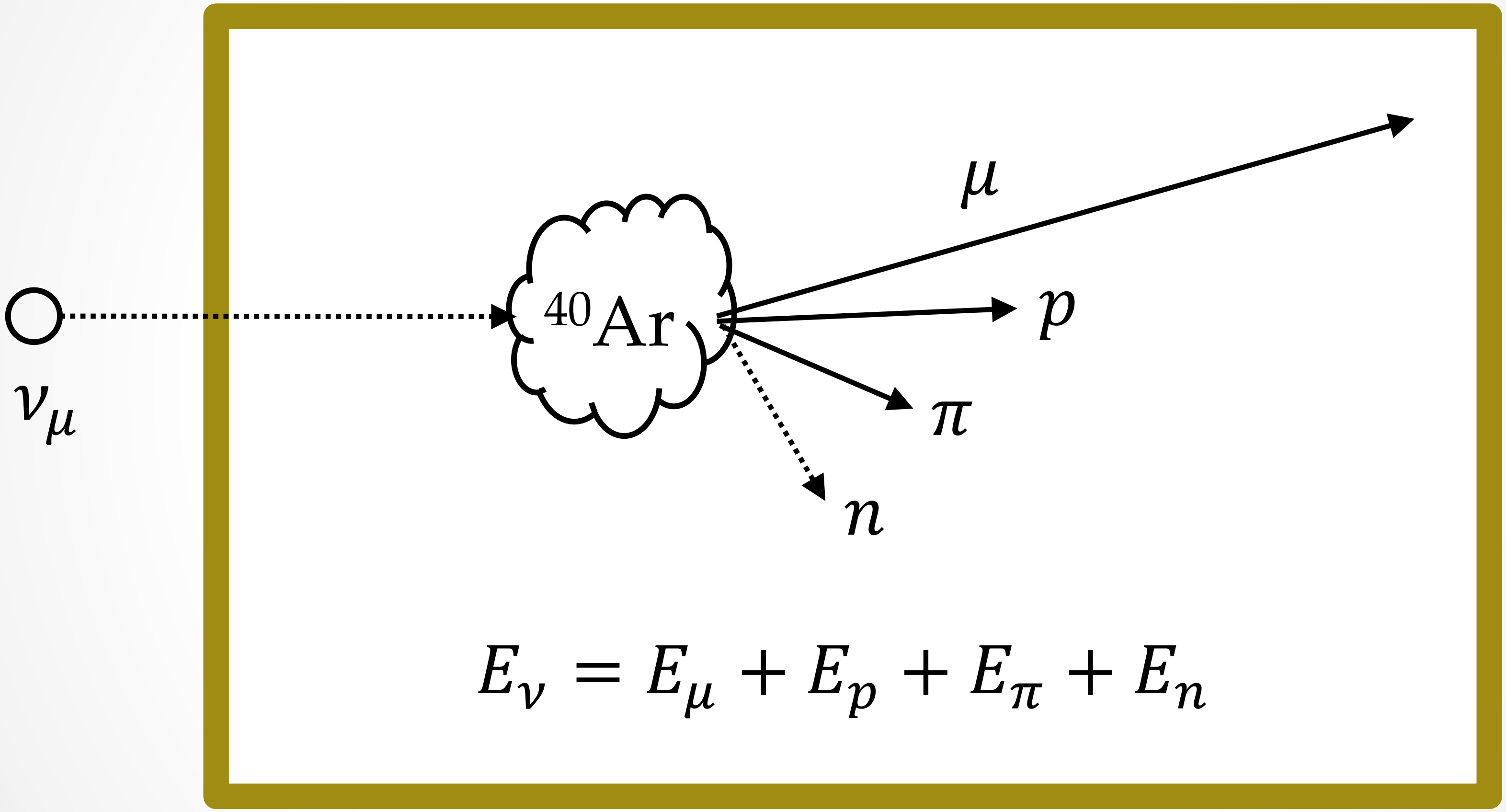


How Neutrinos Are Detected

DUNE: Liquid Argon Time-Projection Chamber



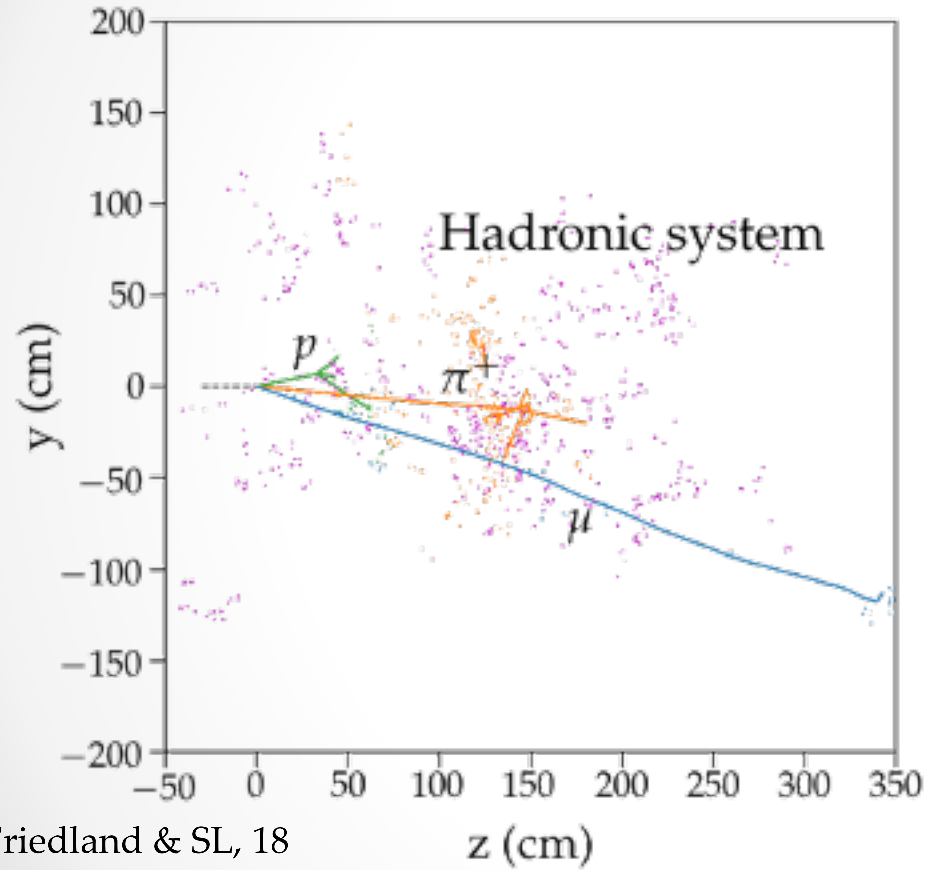
A Theorist’s View of a Neutrino Event



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

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:

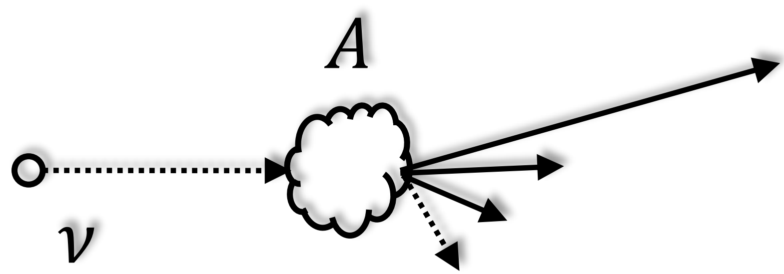
$$\frac{\mathrm{d}\sigma}{\mathrm{d}E_1 \mathrm{d}E_2 \ldots \mathrm{d}E_n}$$

Not So Much:

$$\sigma(E_\nu)$$

Outline

Neutrino-Nucleus Cross Sections



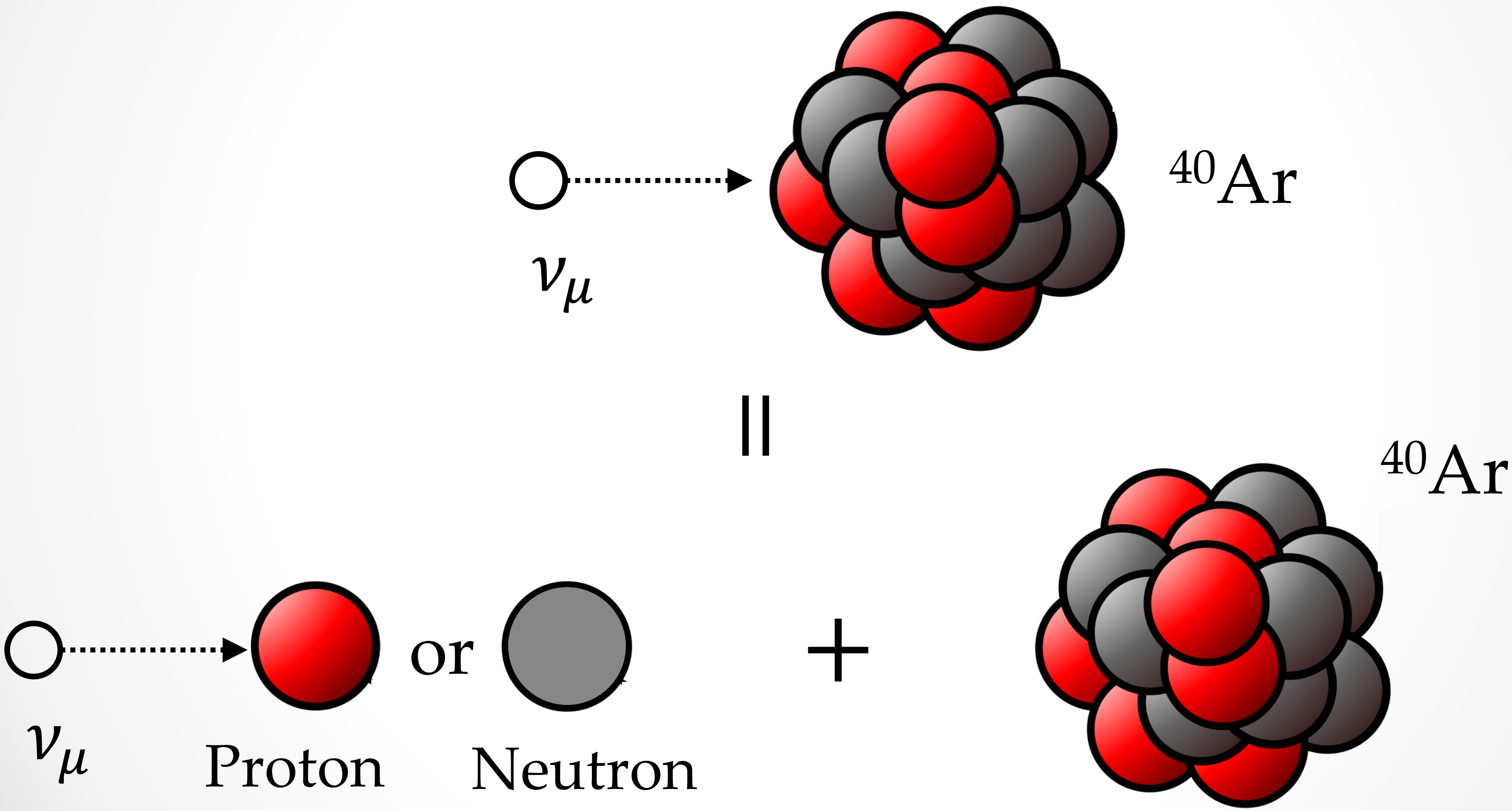
How They Affect Measurements

What Are Current Theoretical Uncertainties

Why Is the Calculation Difficult?

ν-Nucleus Cross Sections

Beam Energy: 0.5 GeV – 5 GeV



^{12}C, ^{16}O for Other Experiments

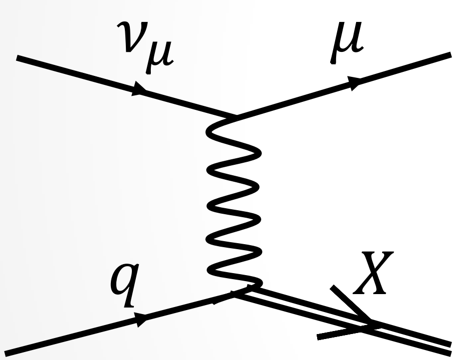
ν-Nucleon Cross Sections

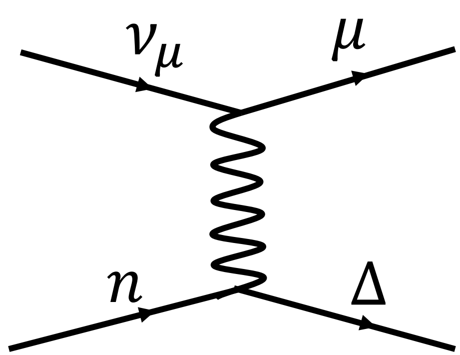
Beam Energy: 0.5 GeV – 5 GeV

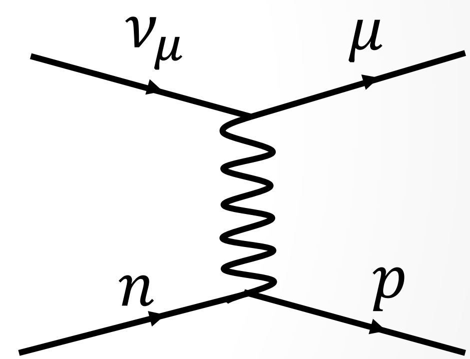
Deep Inelastic Scattering

Resonance Production

Quasi-Elastic Scattering







Multiple Particles

Nucleon + Meson

Single Nucleon

Complete Theoretical Description Is Difficult

Kinematic Region

Ankowski, Friedland, SL, in prep

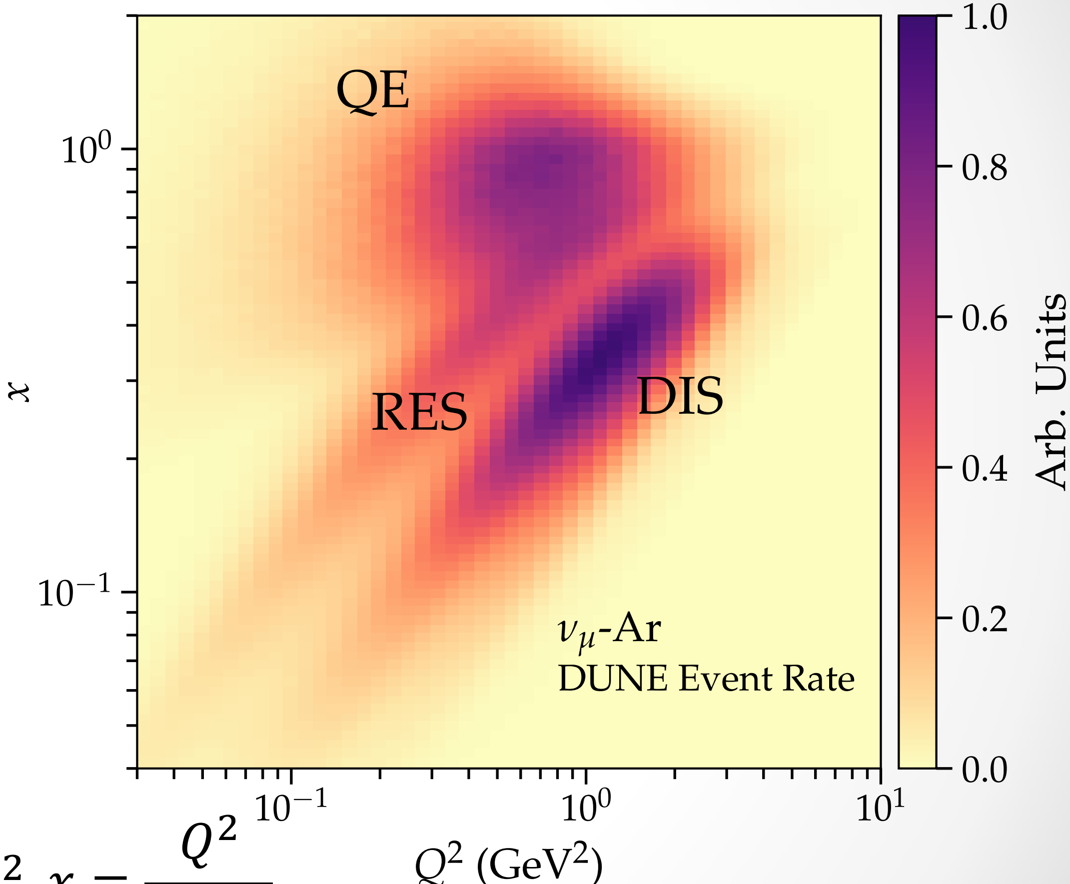
- DIS: $\nu_\mu + d \rightarrow \mu + u$

  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

Cross Section Calculations

No Controlled Expansion

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

Calculations Broken Into Many Distinct Pieces

QE $(\nu_\mu + n \rightarrow \mu + p)$

RES: $(\nu_\mu + n \rightarrow \mu + \Delta)$

DIS: $(\nu_\mu + d \rightarrow \mu + u)$

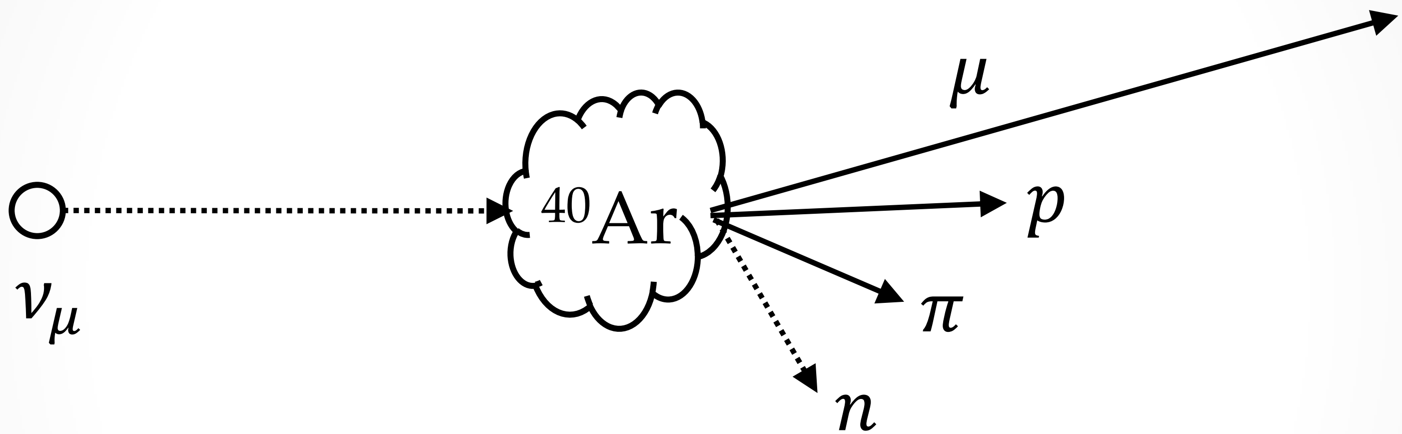
Existing Models Do Not Include All Physics

e.g., How to Transition from RES to DIS?

Unknown Effects Make Uncertainty Estimation Difficult

Cross Section Calculations

Observables Are High-Dimensional

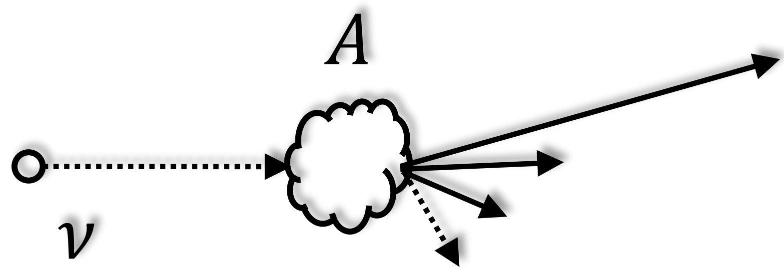


$$\frac{\mathrm{d}\sigma}{\mathrm{d}E_1\,\mathrm{d}E_2\ldots\mathrm{d}E_n}\ \text{(Exclusive), not}\ \frac{\mathrm{d}\sigma}{\mathrm{d}E}\ \text{(Inclusive)}$$

Difficult to Match to Experimental Observables

Outline

Neutrino-Nucleus Cross Sections



How They Affect Measurements

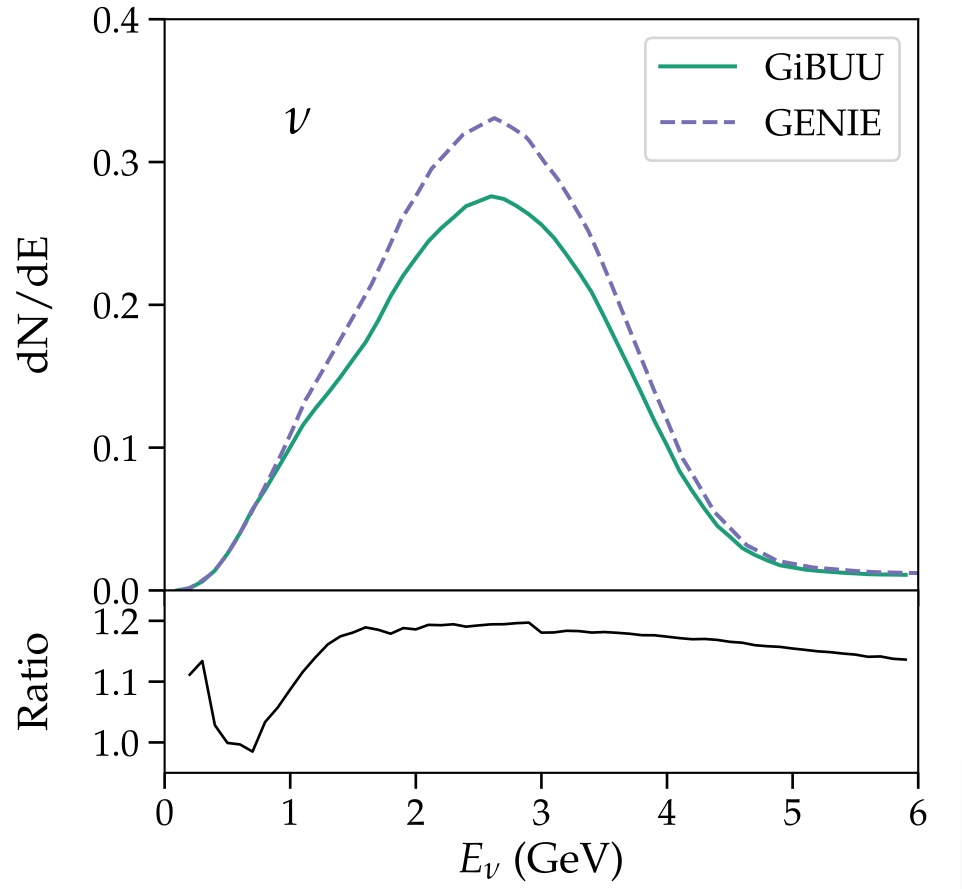
What Are Current Theoretical Uncertainties

Why Is the Calculation Difficult?

Generator vs. Generator

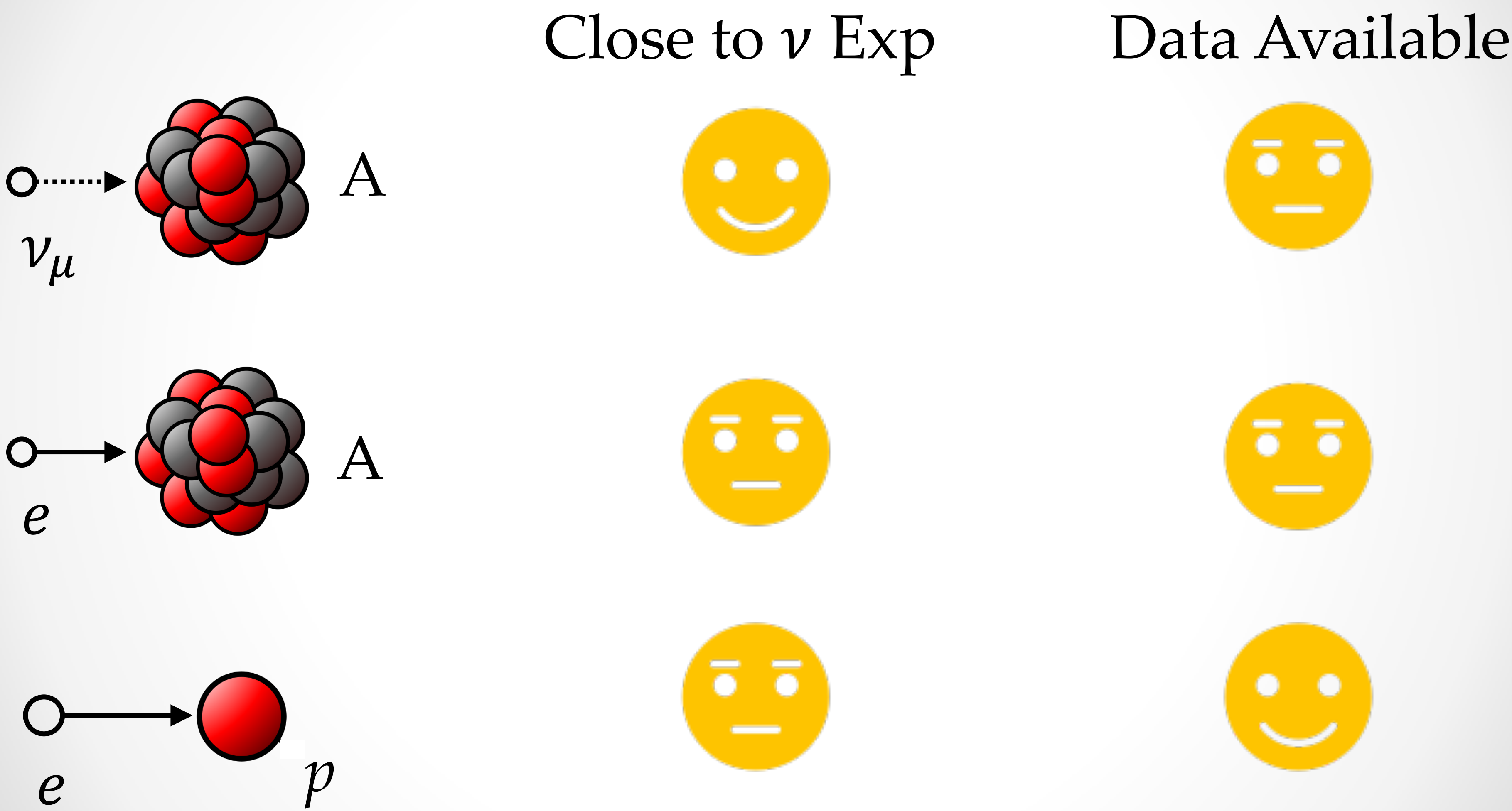
Ankowski, Friedland, SL, in prep

Compare $\sigma(E_\nu)$



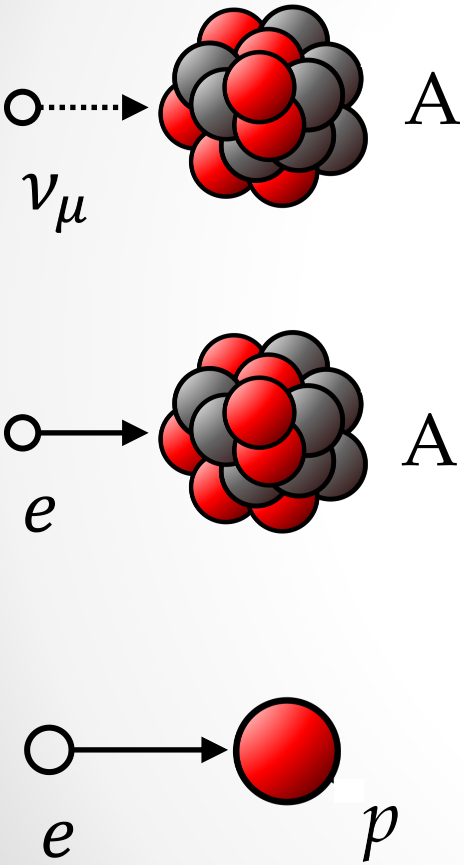
Informative, But Not Adequate

ν-A Generators vs. e-A Data



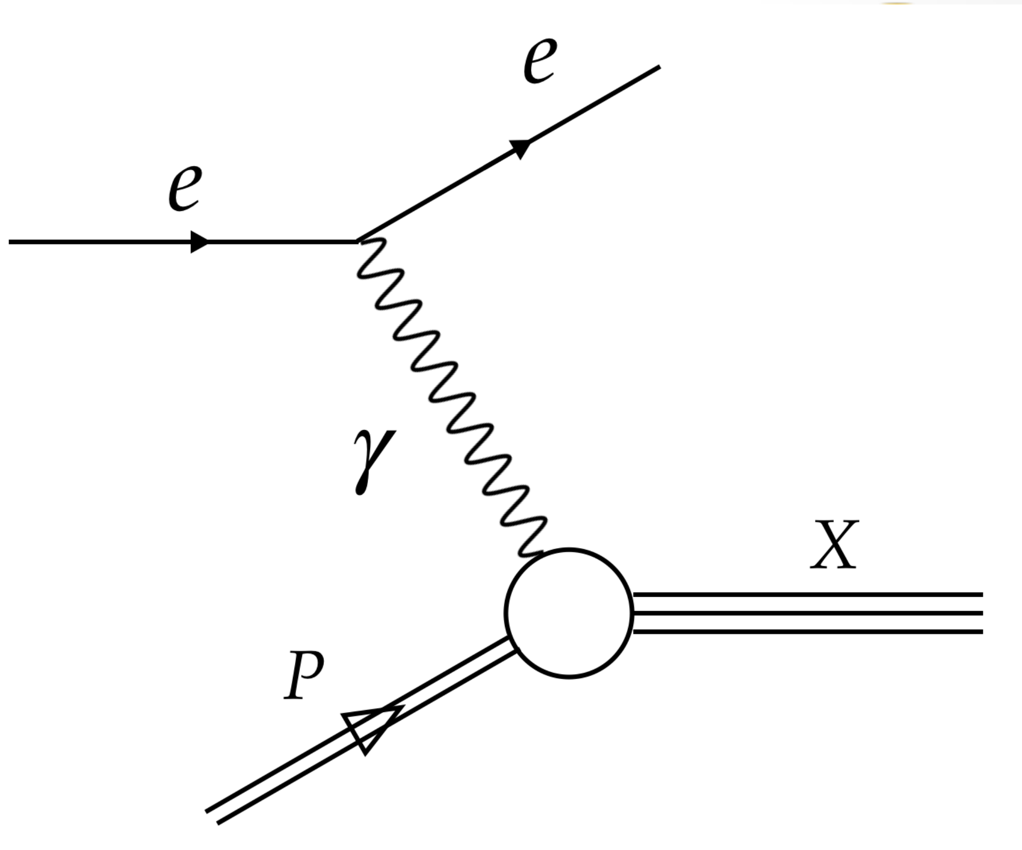
Ankowski, Friedland, SL, in prep
Data from Niculescu et al., 00

ν-A Generators vs. e-A Data



Close to ν Exp

Data Available



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

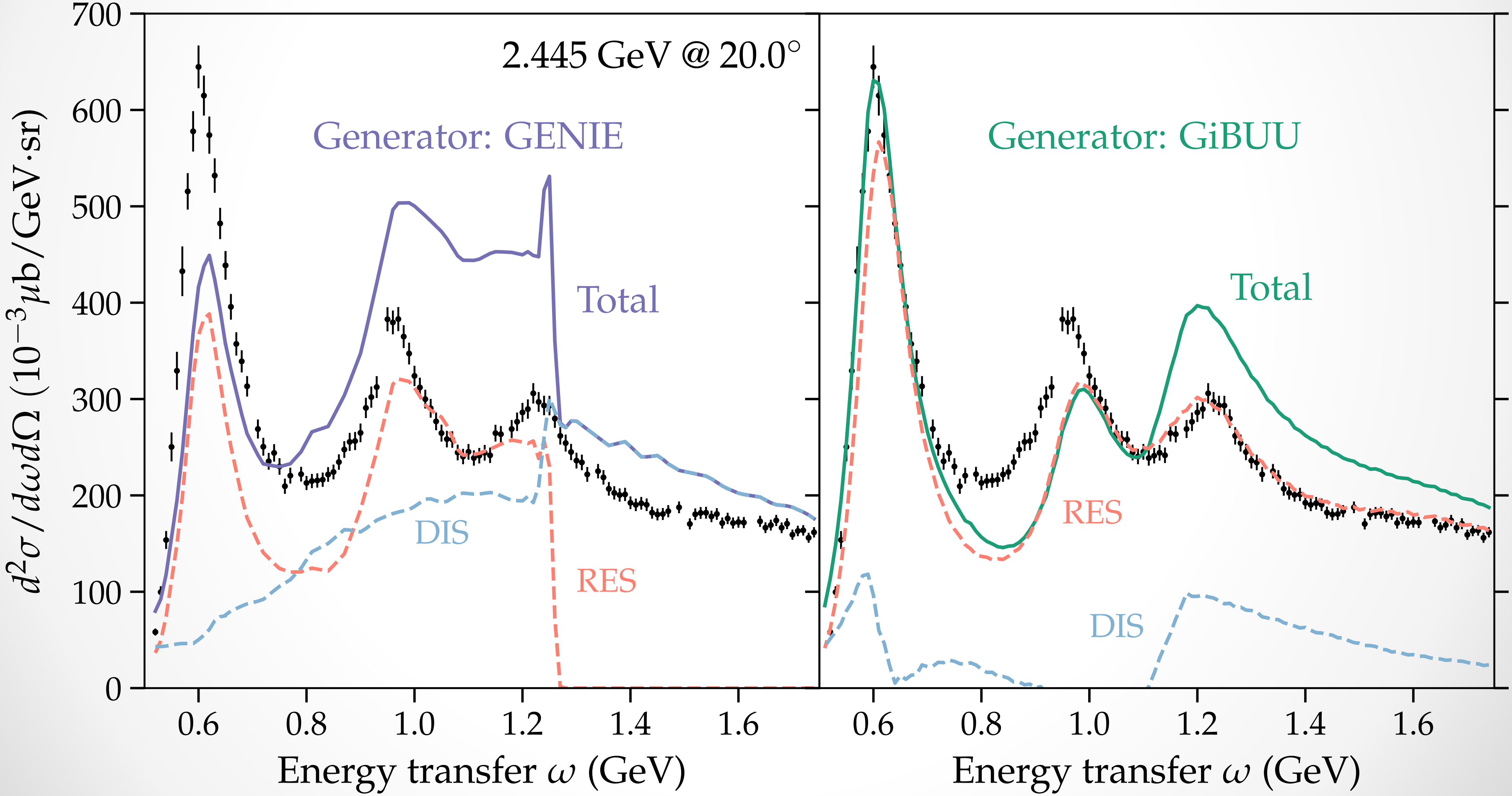
ν-A Generators vs. e-A Data

Close to ν Exp | Data Available

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

e-p Scattering

Neutrino Generators vs. Data



Ankowski, Friedland, SL, in prep
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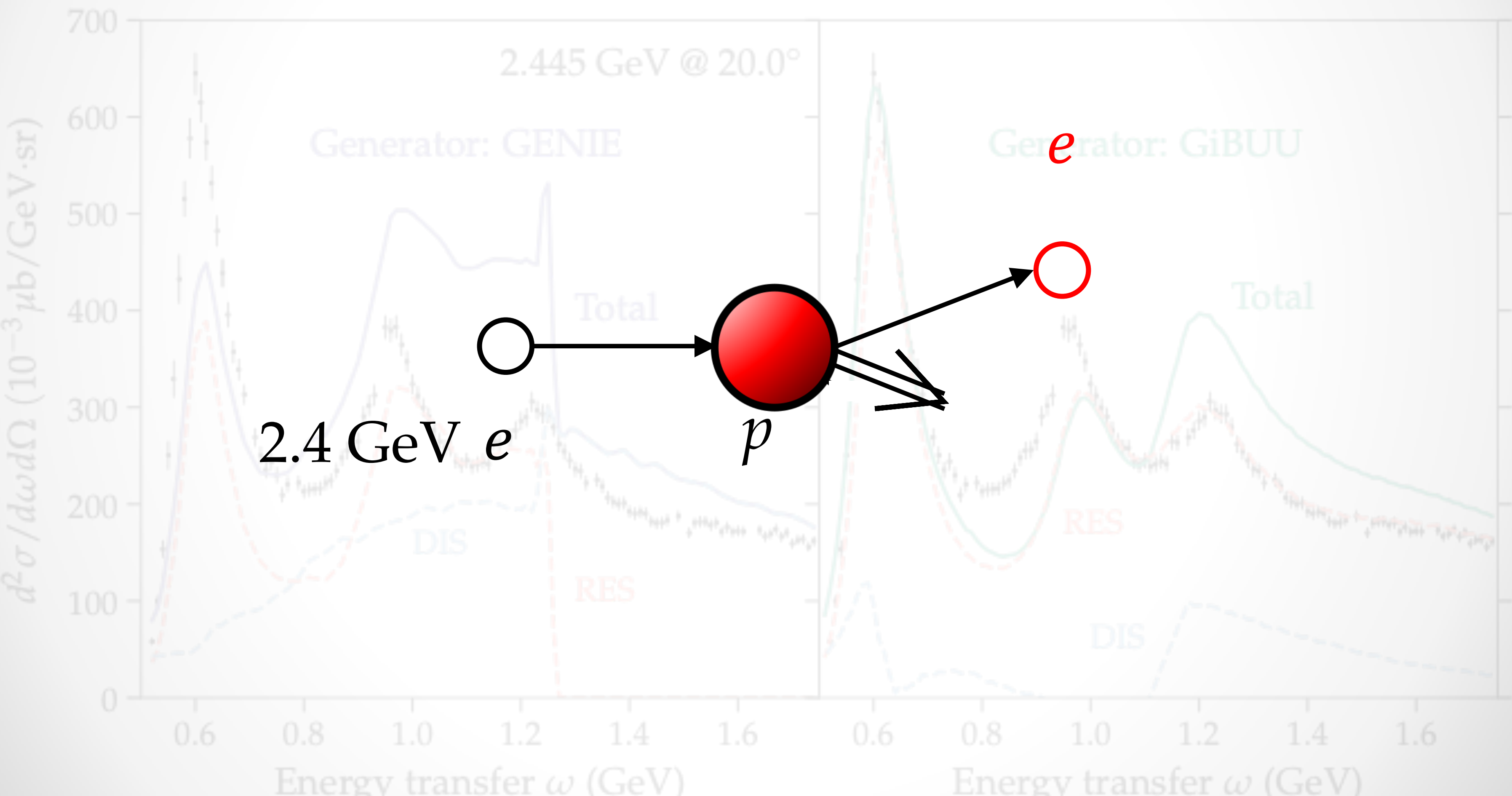

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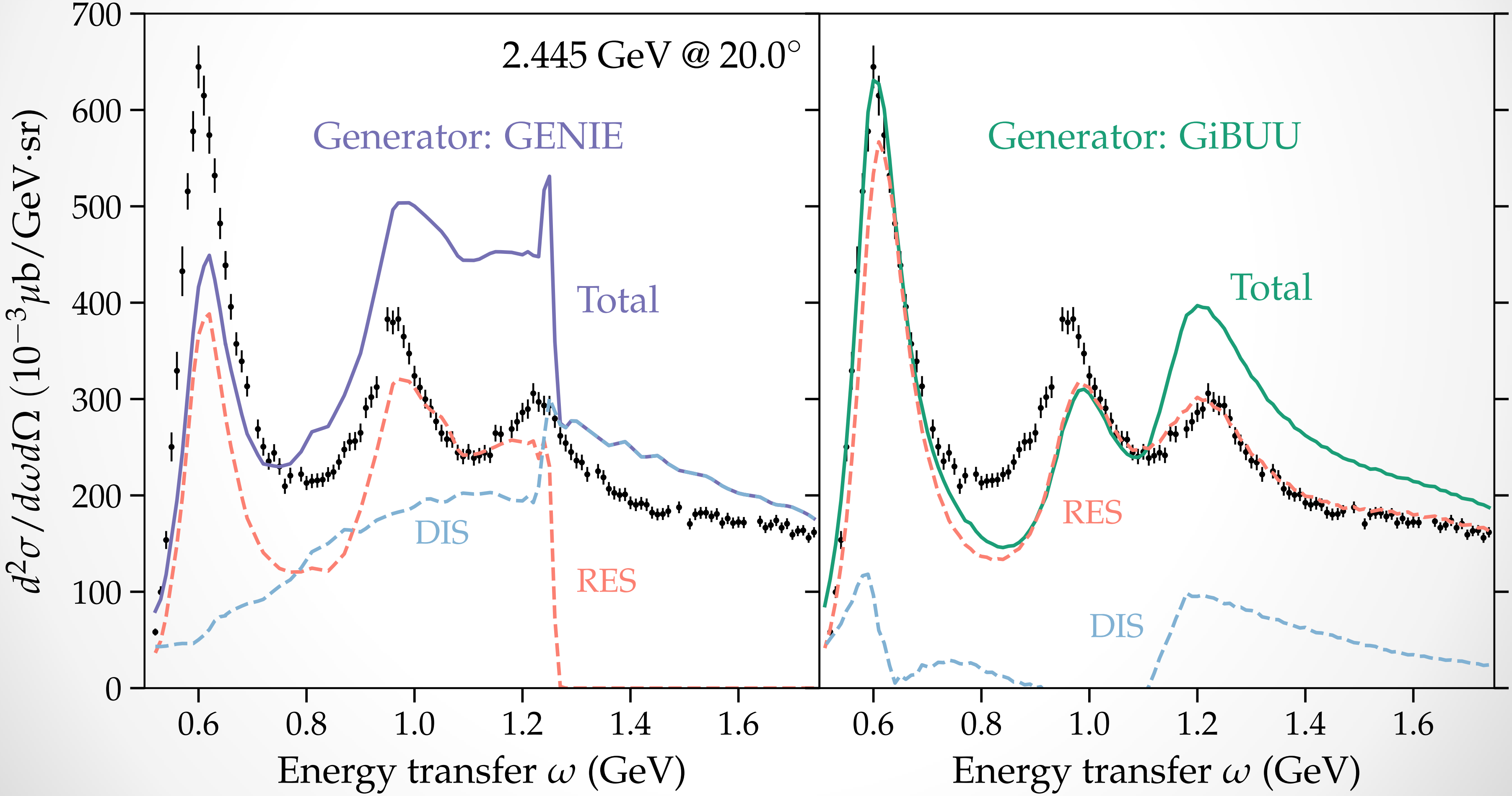

Ankowski, Friedland, SL, in prep
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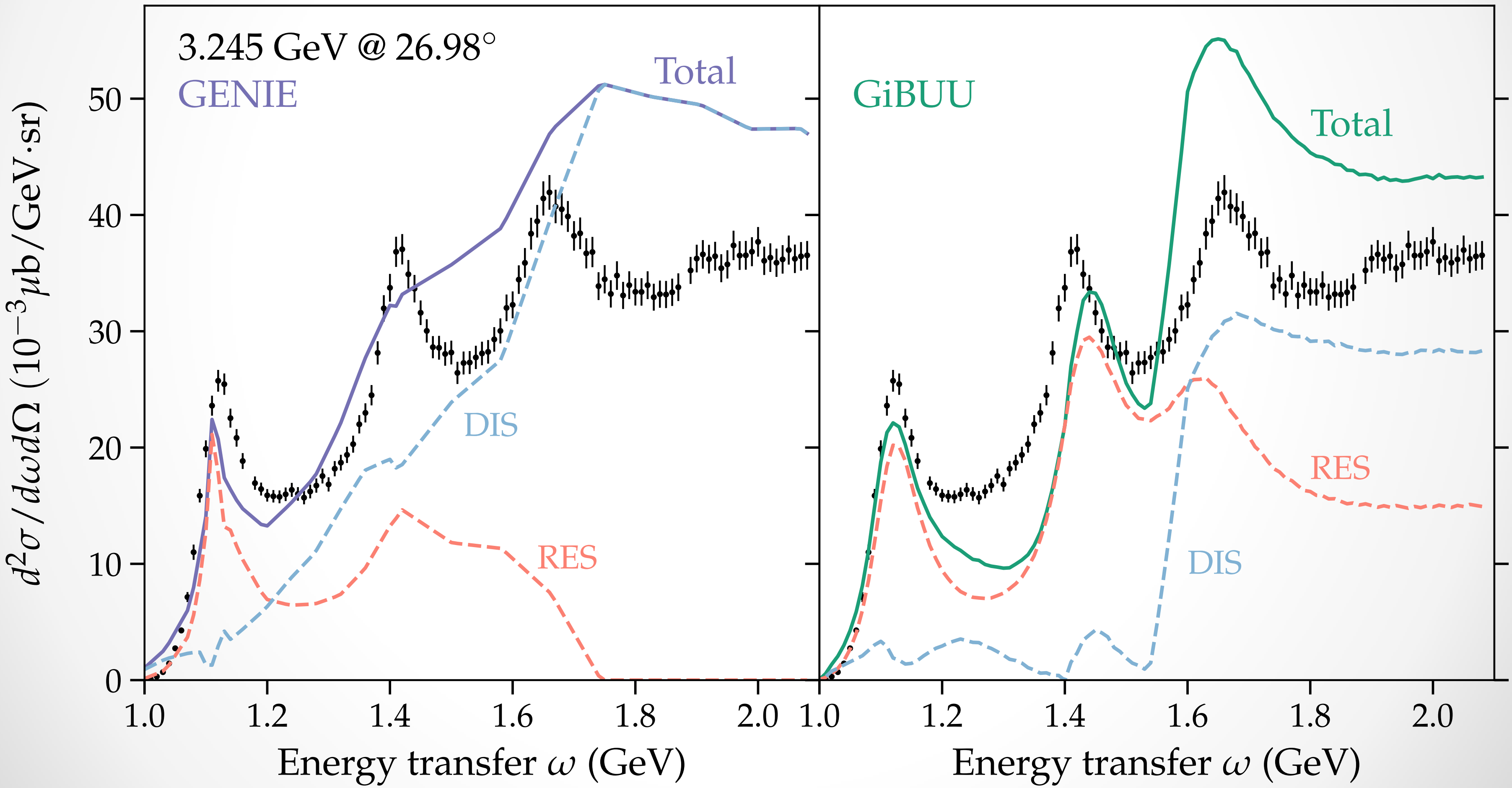
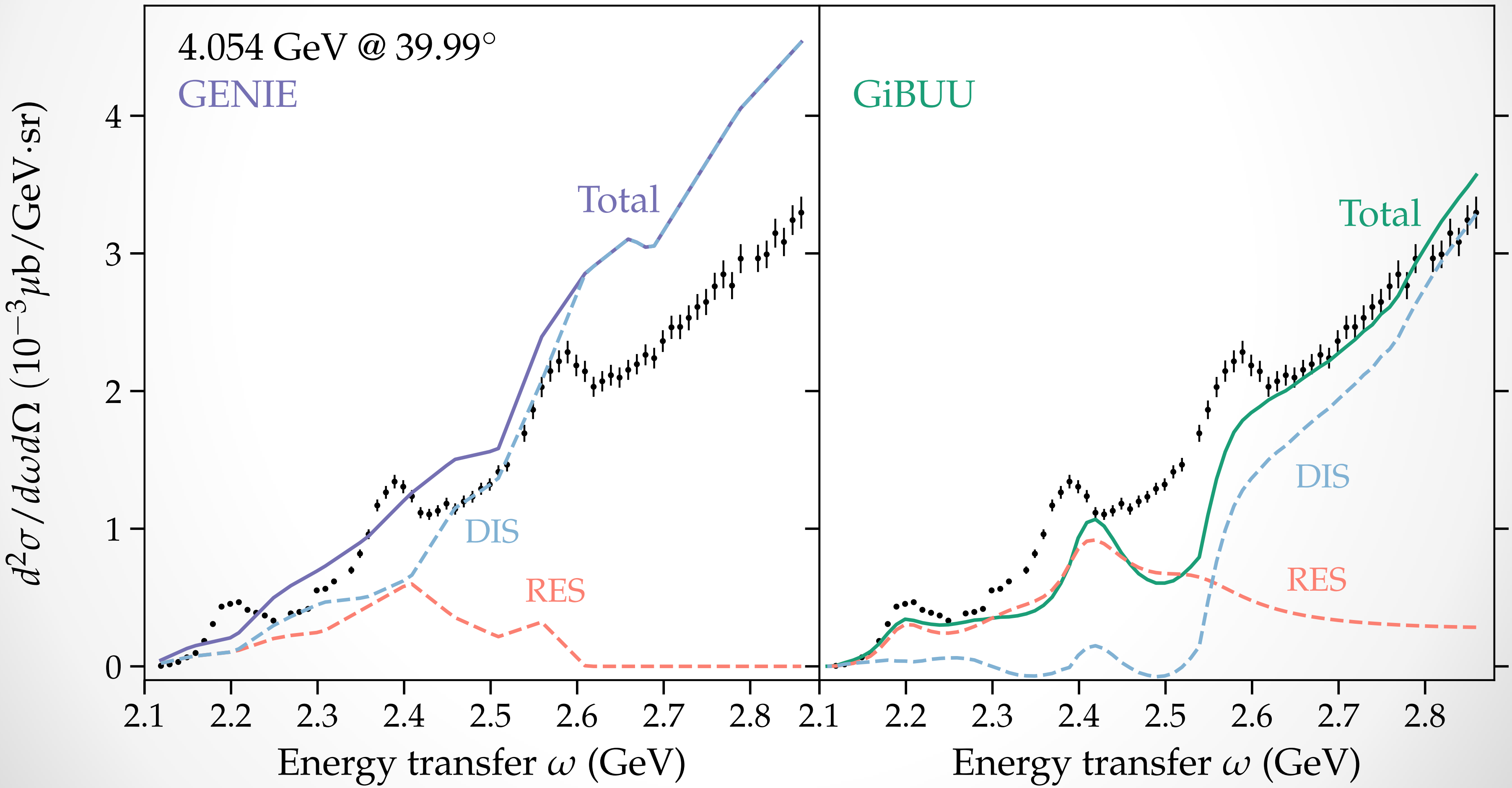
Neutrino Generators vs. Data



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

e-p Scattering

Neutrino Generators vs. Data



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

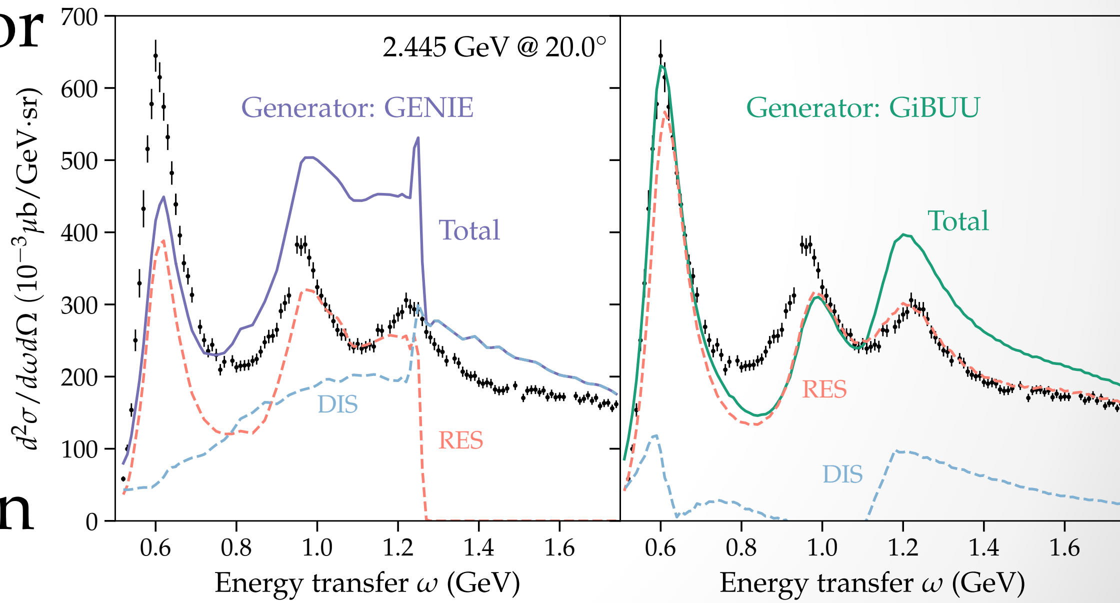
e-p Scattering

Neutrino Generators vs. Data

- GENIE: 50—80% error
  GiBUU: 20—30% error

- RES vs. DIS: Not a Good Separation

- Major Implementation Errors

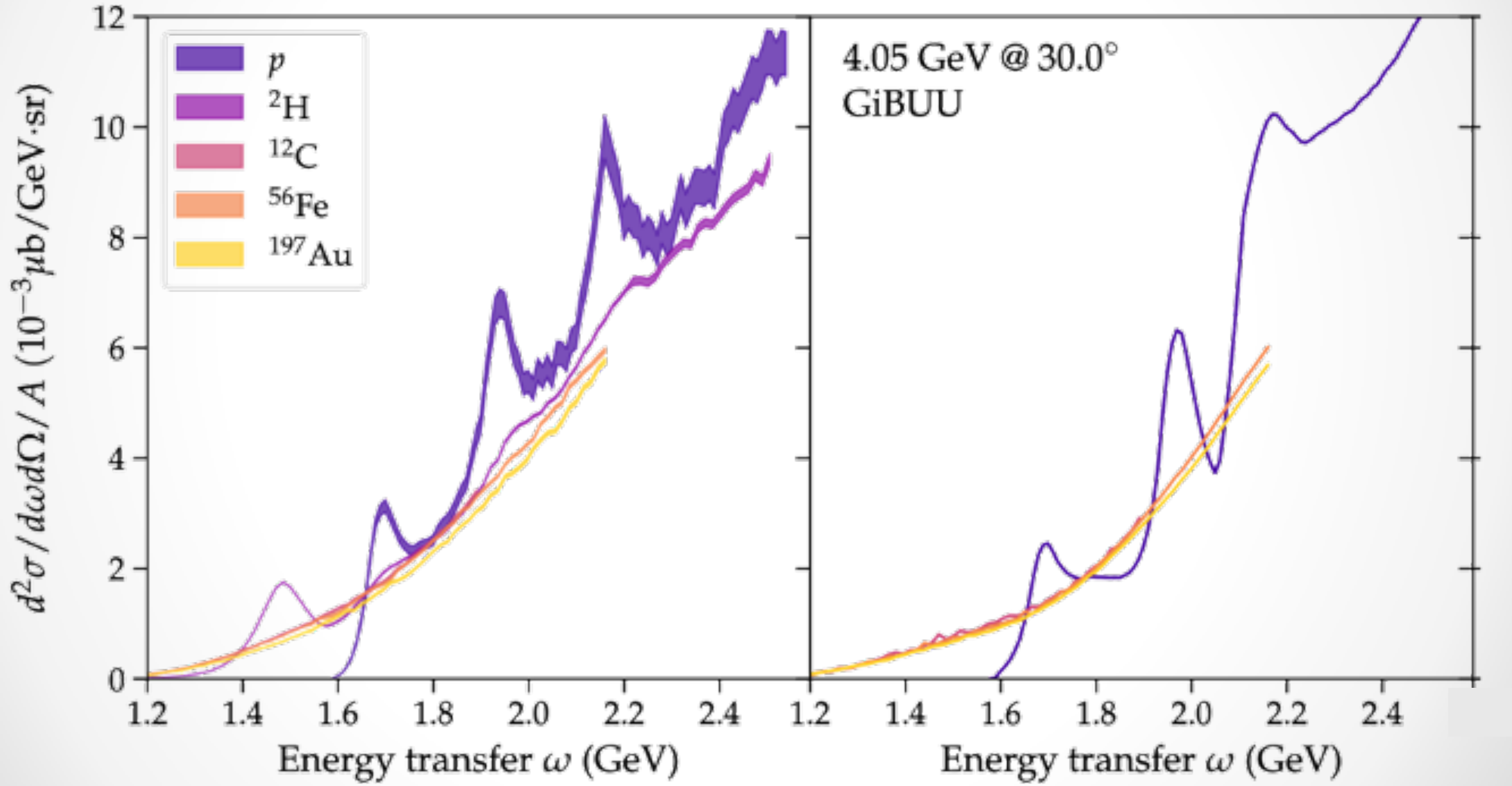


Ankowski, Friedland, SL, in prep
Data from Niculescu et al., 00

Different nuclei

Ankowski, Friedland, SL, in prep

Scale Electron-Nucleus Scattering Data

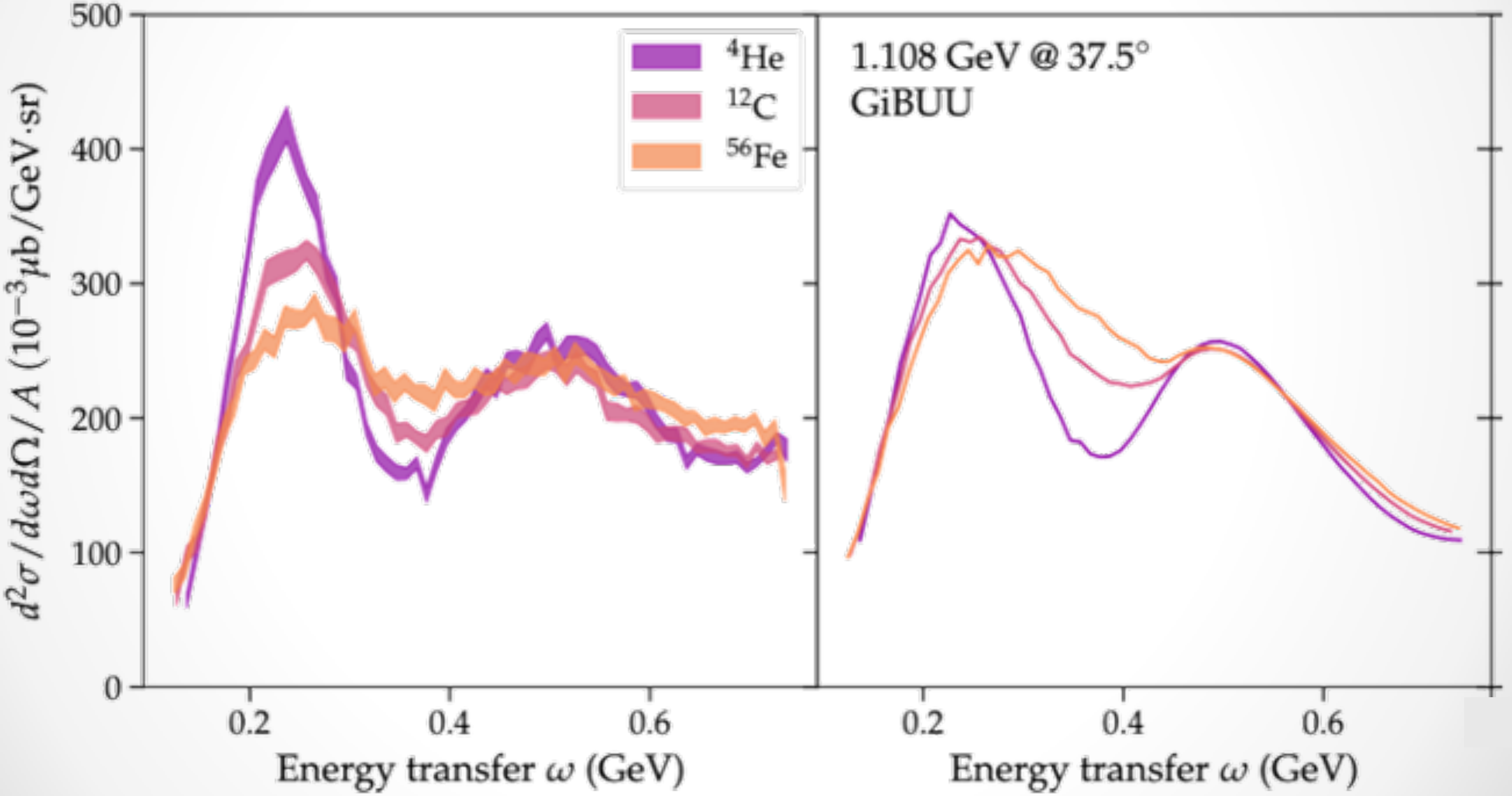


Features Are Smeared

Different nuclei

Ankowski, Friedland, SL, in prep

Scale Electron-Nucleus Scattering Data

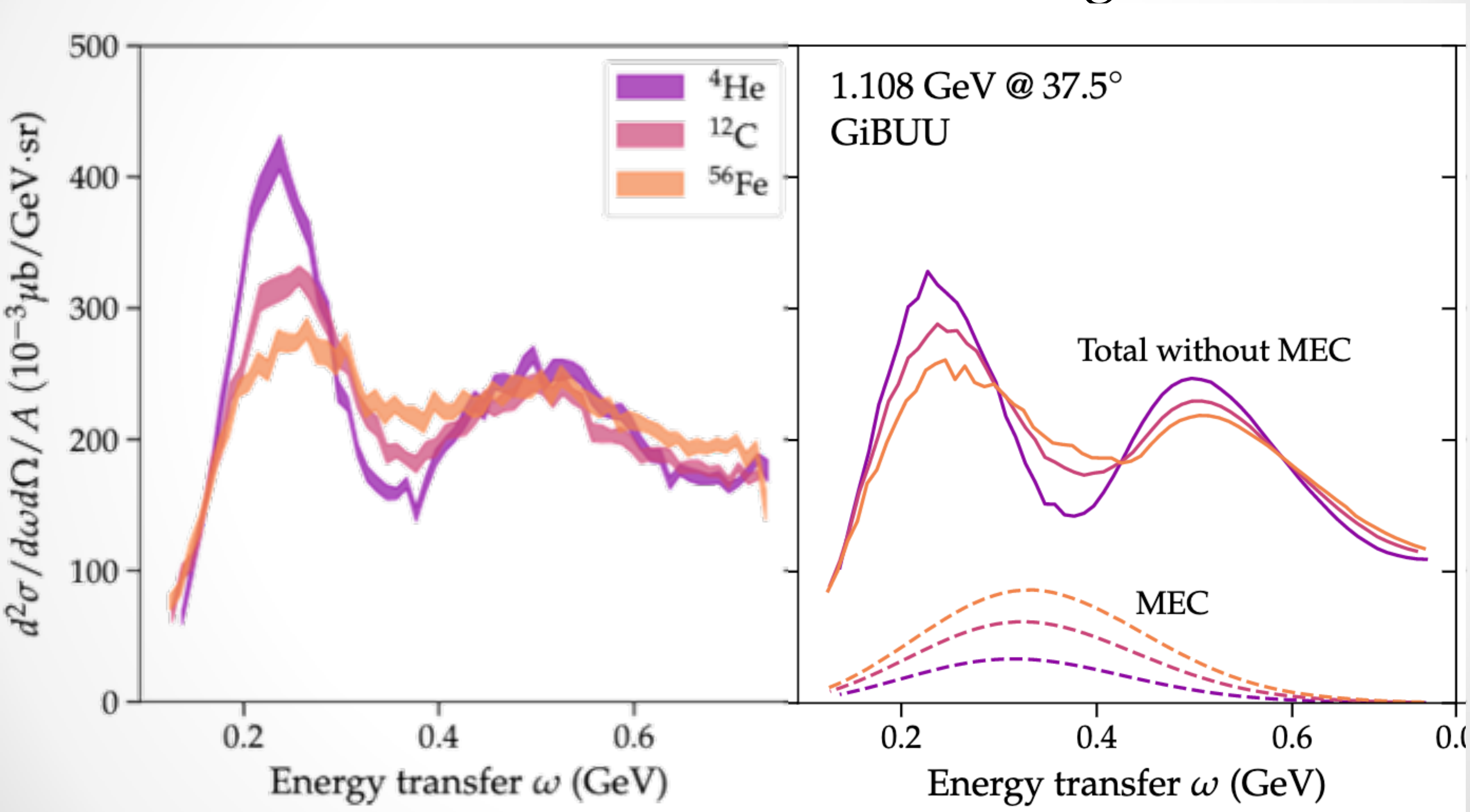


Over-estimate MEC

Different nuclei

Ankowski, Friedland, SL, in prep

Scale Electron-Nucleus Scattering Data



Over-estimate MEC

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?

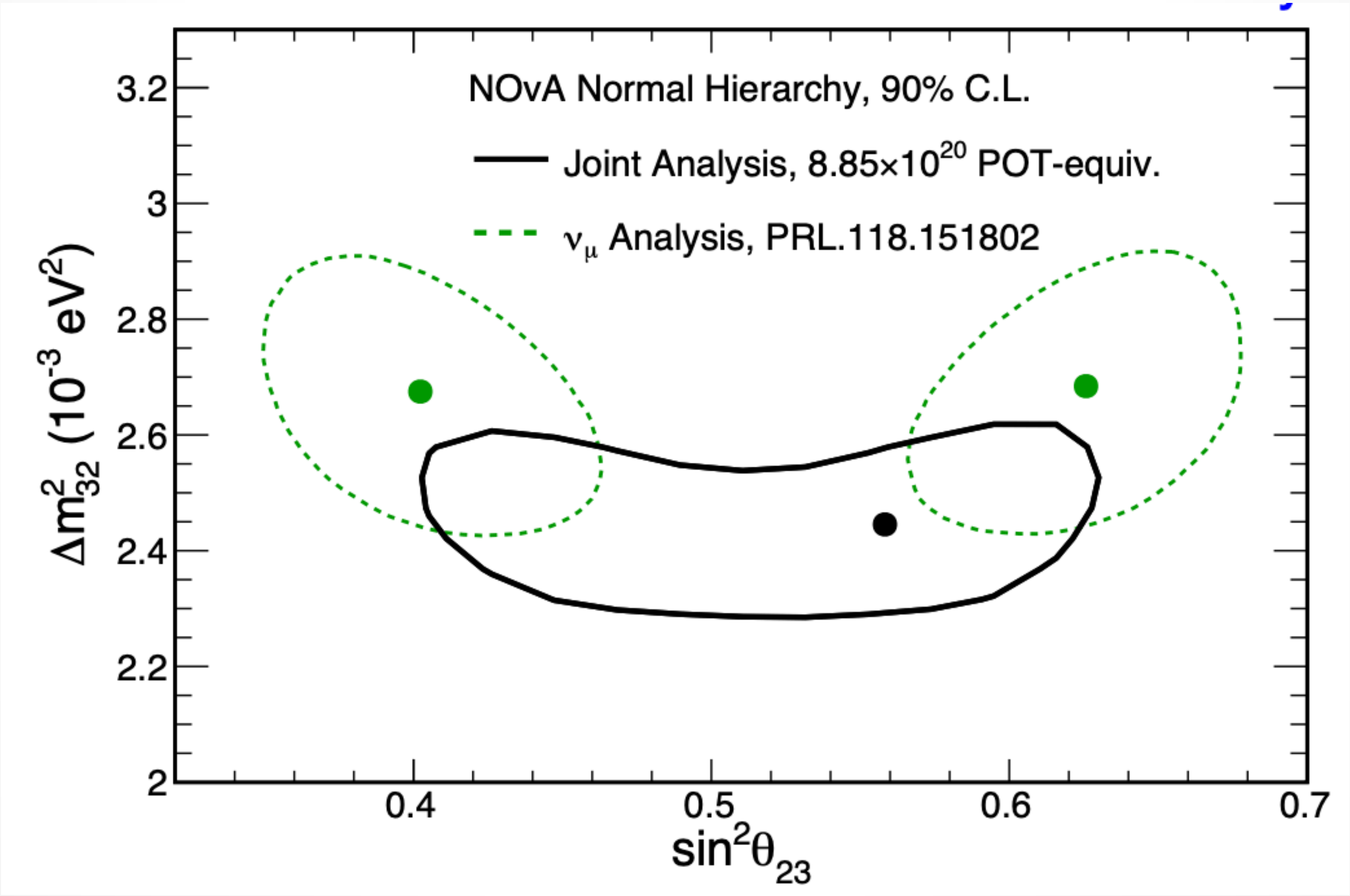
Thank you

…

Bonus Slides

Impact of Cross Sections

NOvA Analysis



A. Radovic, JETP 2018

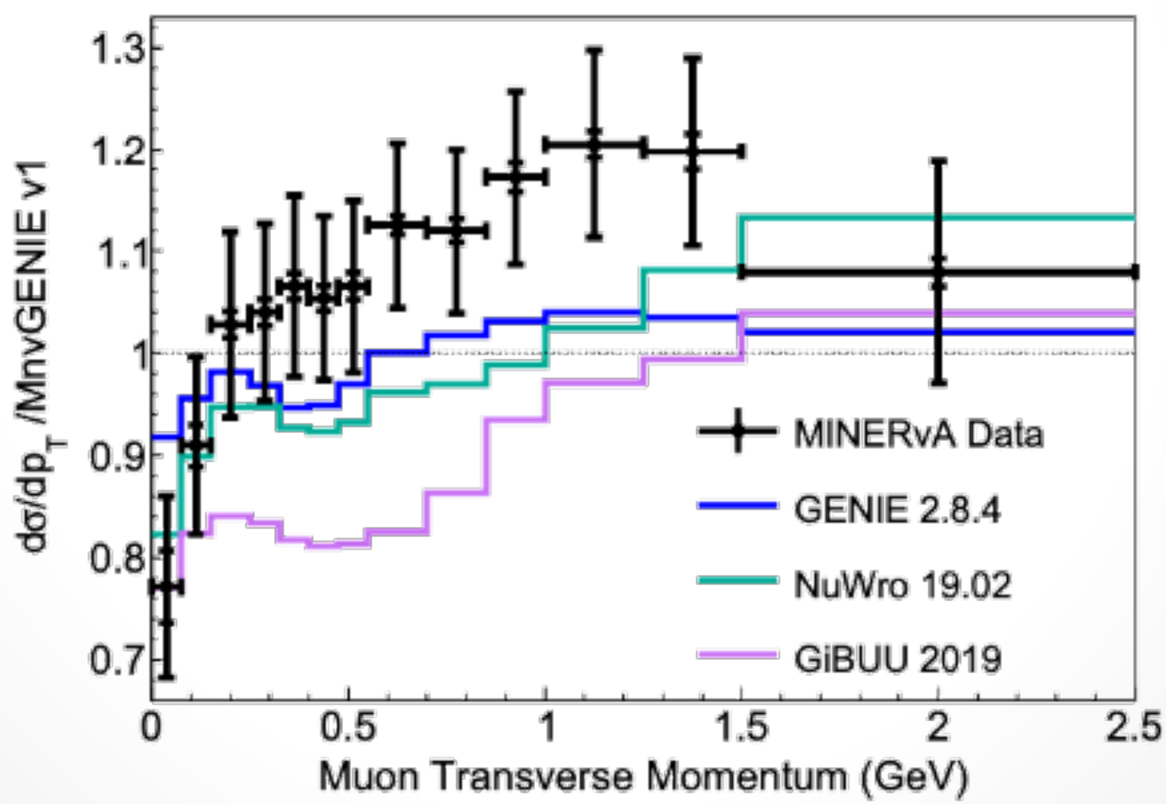
ν-A Scattering Measurements

Experiment	beam	$\langle E_\nu \rangle$, $\langle E_{\overline{\nu}} \rangle$ GeV	neutrino target(s)	run period
ArgoNeuT	$\nu, \overline{\nu}$	4.3, 3.6	Ar	2009 – 2010
ICARUS (at CNGS)	ν	20.0	Ar	2010 – 2012
K2K	ν	1.3	CH, H_2O	2003 – 2004
MicroBooNE	ν	0.8	Ar	2015 –
MINERvA	$\nu, \overline{\nu}$	3.5 (LE), 5.5 (ME)	He, C, CH, H_2O, Fe, Pb	2009 – 2019
MiniBooNE	$\nu, \overline{\nu}$	0.8, 0.7	CH_2	2002 – 2019
MINOS	$\nu, \overline{\nu}$	3.5, 6.1	Fe	2004 – 2016
NOMAD	$\nu, \overline{\nu}$	23.4, 19.7	C–based	1995 – 1998
NOvA	$\nu, \overline{\nu}$	2.0, 2.0	CH_2	2010 –
SciBooNE	$\nu, \overline{\nu}$	0.8, 0.7	CH	2007 – 2008
T2K	$\nu, \overline{\nu}$	0.6, 0.6	CH, H_2O, Fe	2010 –

PDG 19

An Example

Double-Differential Inclusive Charged-Current ν_μ Cross Sections on Hydrocarbon in MINERvA at $\langle E_\nu \rangle \sim 3.5\,\mathrm{GeV}$



2002.124969

T2K Kinematic Region

Ankowski, Friedland, SL, in prep

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

  30+ Resonance States, Not Enough Data

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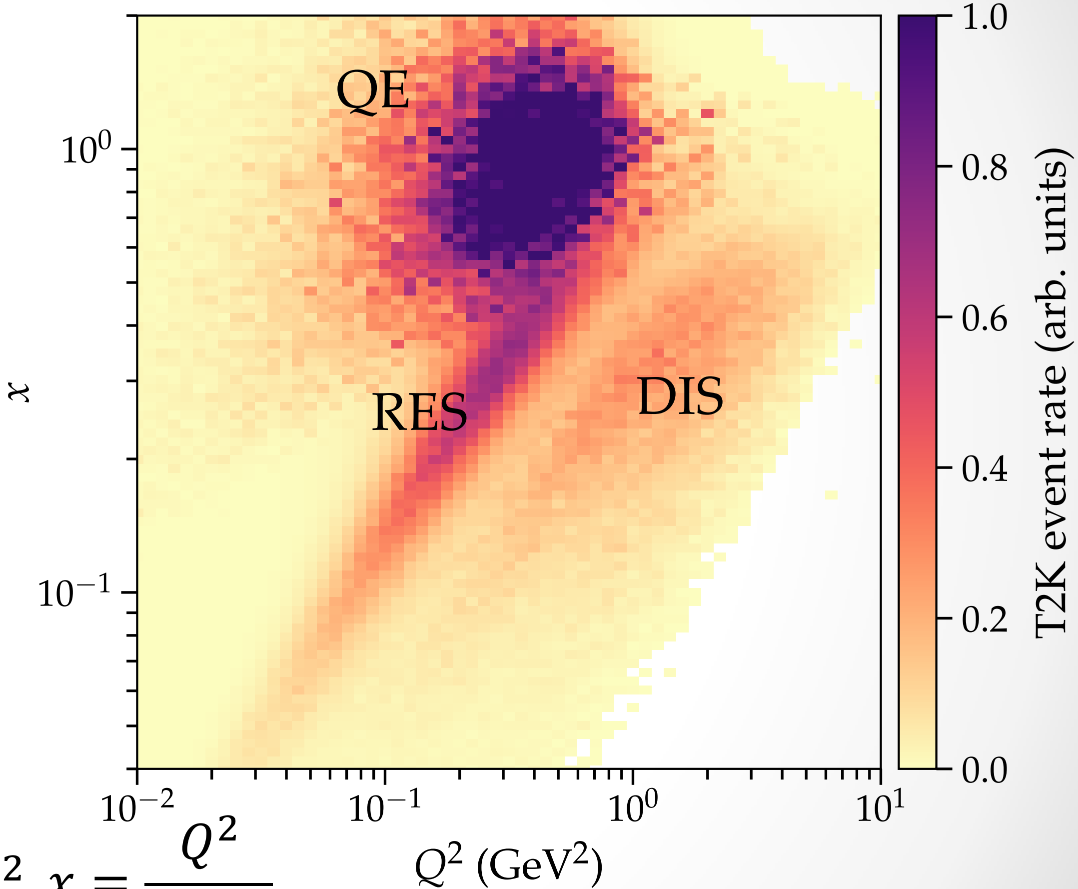

$$Q^2 = -q^2, x = \frac{Q^2}{2p \cdot q}$$

Kinematic Region

SL, Toro et al., 19