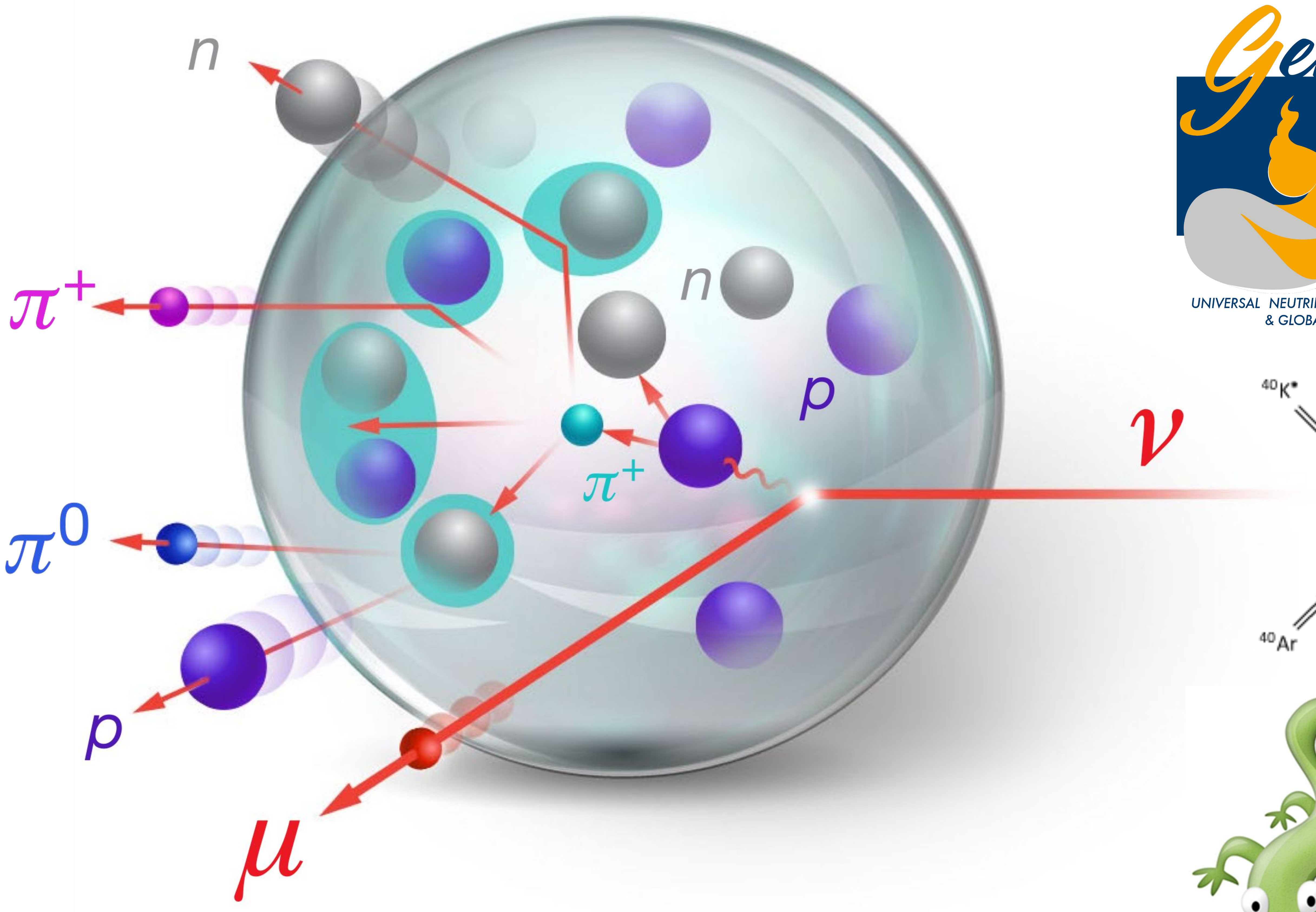
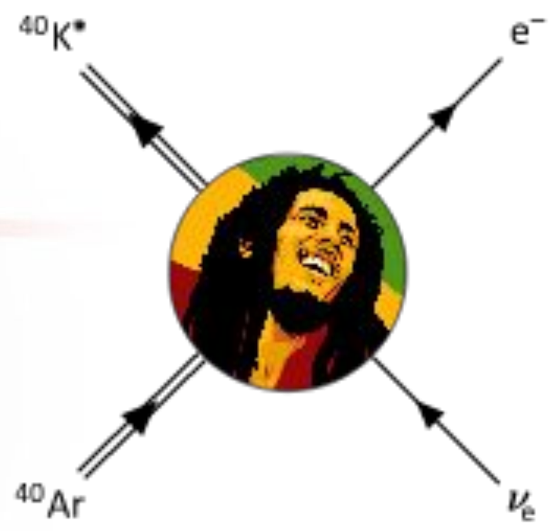
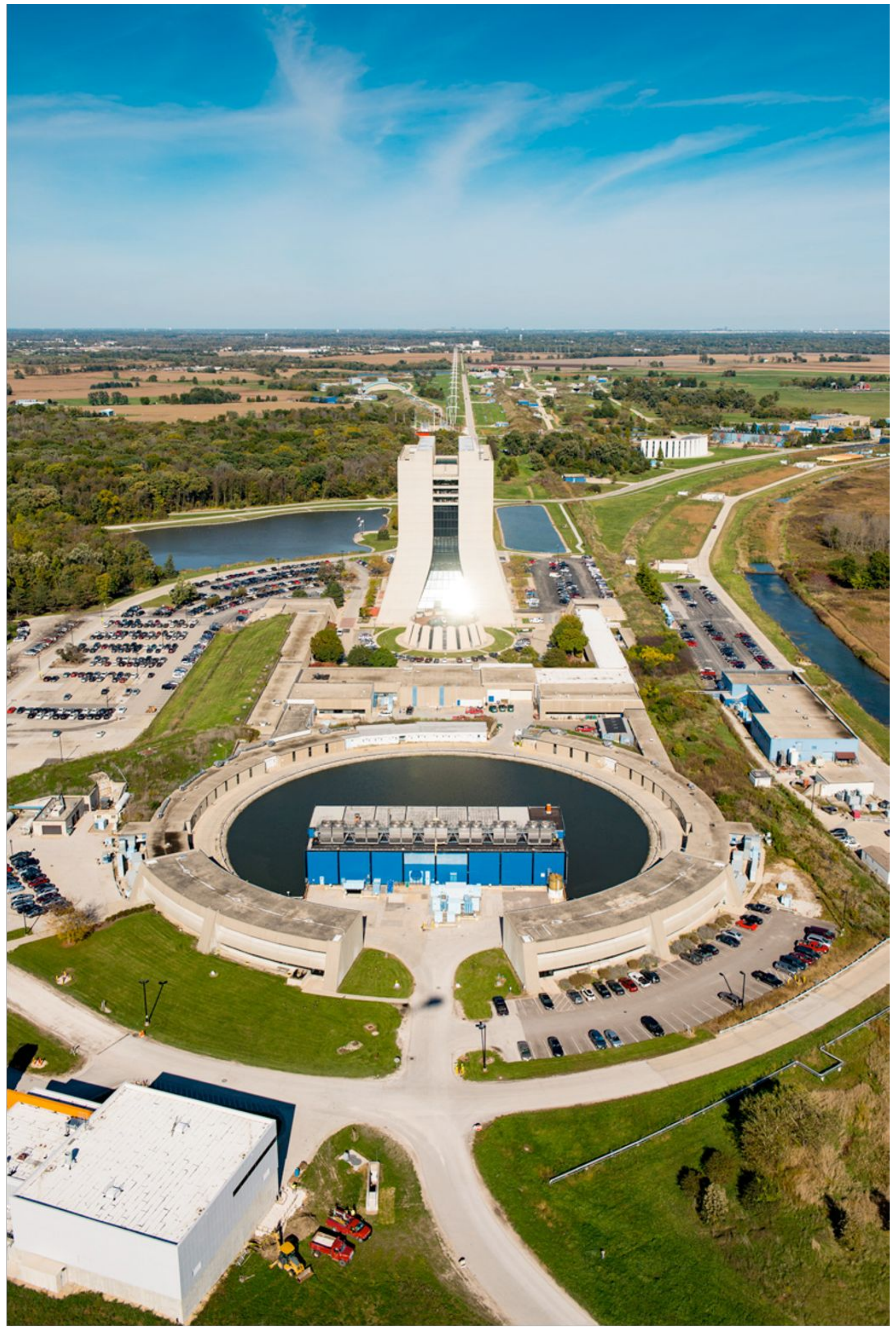
Introduction to neutrino event generators







Steven Gardiner (gardiner@fnal.gov)

Event Generators Group Leader, Fermilab Physics Simulation Department

NuSTEC School & Workshop, São Paulo, 12 April 2024

Who am I?

- Associate Scientist @ Fermilab
- Liquid argon experiments (MicroBooNE, SBND)
  - Focus on neutrino interaction physics
- Event generator development
  - Author for GENIE and MARLEY
- PhD in 2018, University of California, Davis
  - MARLEY + ANNIE Phase-I analysis
- **Falo português**
  - I'm delighted to be back in Brazil, you have the best beaches!

Praia de Cumbuco, CE, 2008

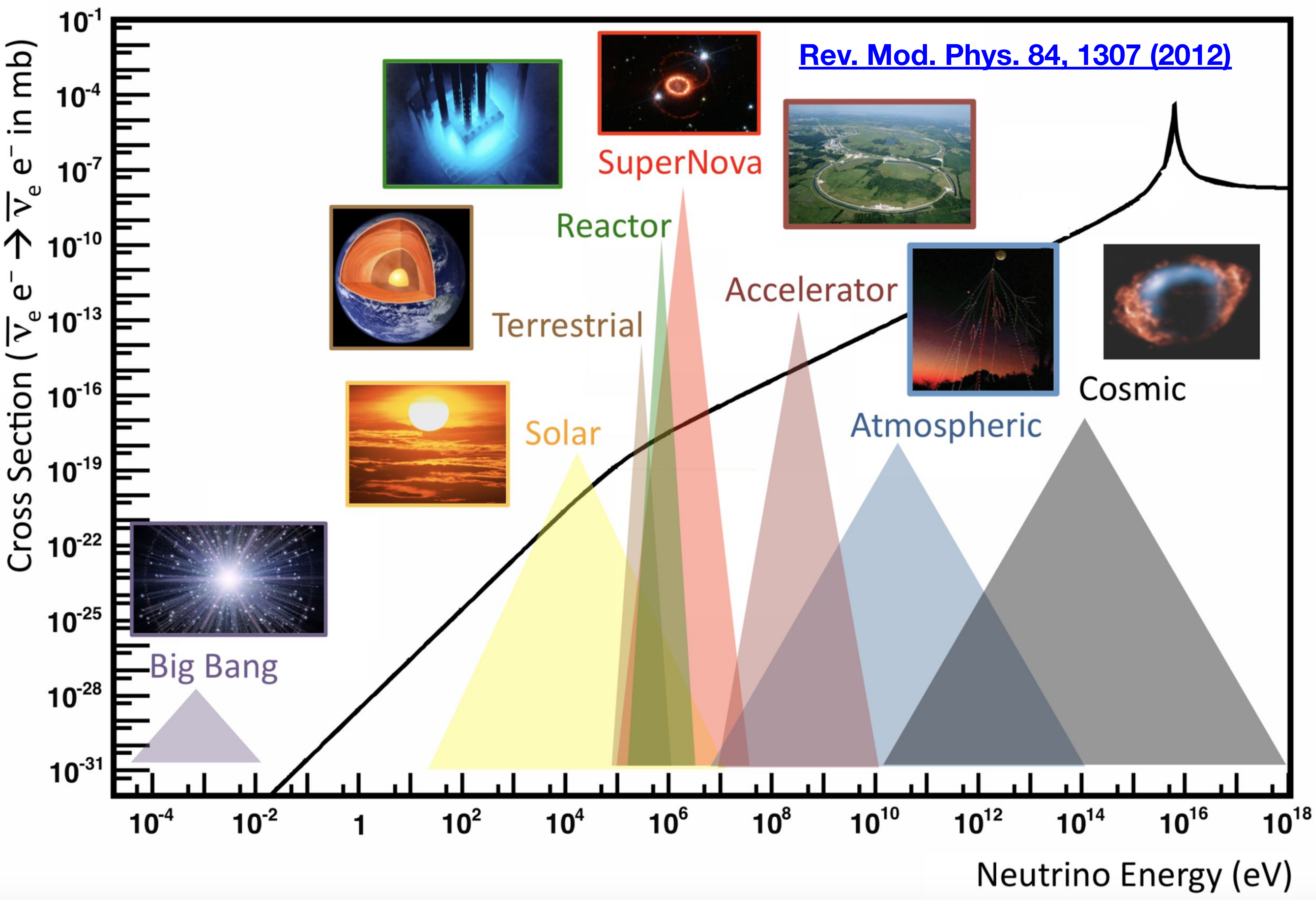
Praia de Ipanema, RJ, 2024

Plan for the lecture

- **Gentle introduction** to a complicated and highly technical field!
- Role of generators for experiments
- Software landscape and highlights from selected generators
  - **Not intended to be comprehensive**
  - See related NuInt sessions for more
- Uncertainties and model tuning
- Role of cross-section data to make generators better

Some of my prior teaching experience

Neutrino physics across energy scales

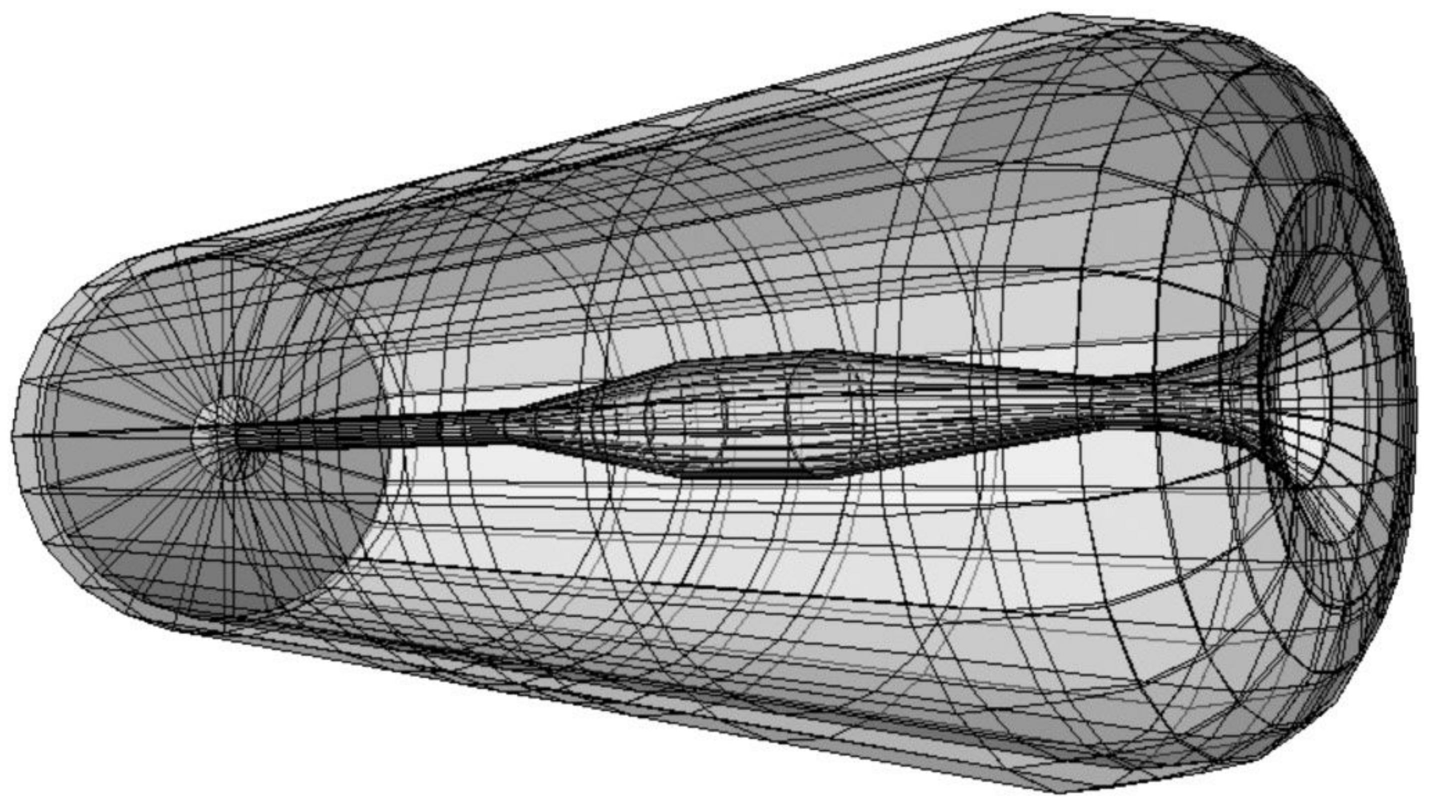


- Many orders of magnitude in energy!
- **Most of NuInt** looks at ~100 MeV to ~10 GeV region
- I'll **also talk a tiny bit** about ~1 MeV to ~10 MeV
- Enable new discoveries by better understanding neutrino interactions

Part I: Role of event generators for neutrino experiments

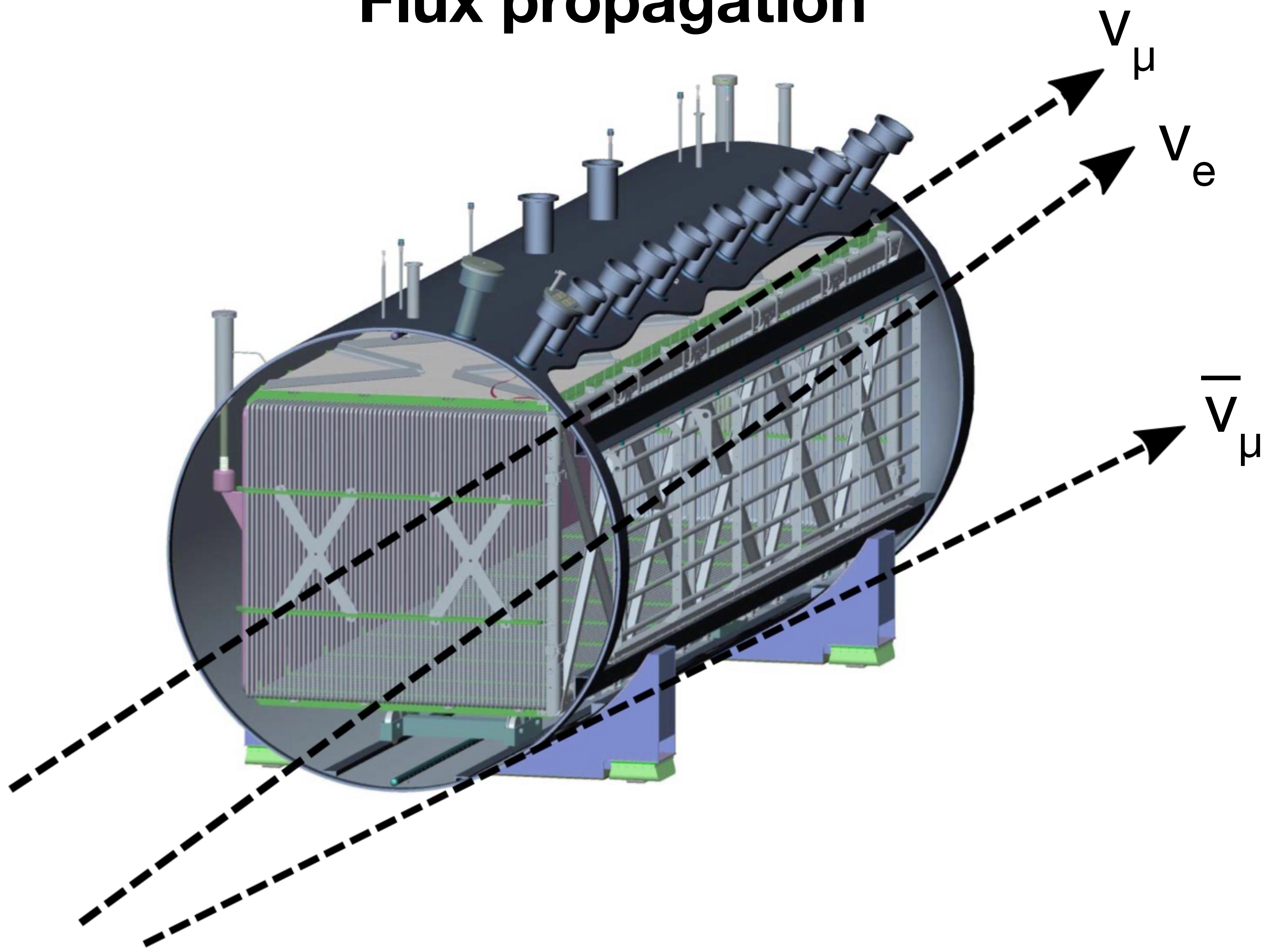
Neutrino experiments require comprehensive simulations

Beam production

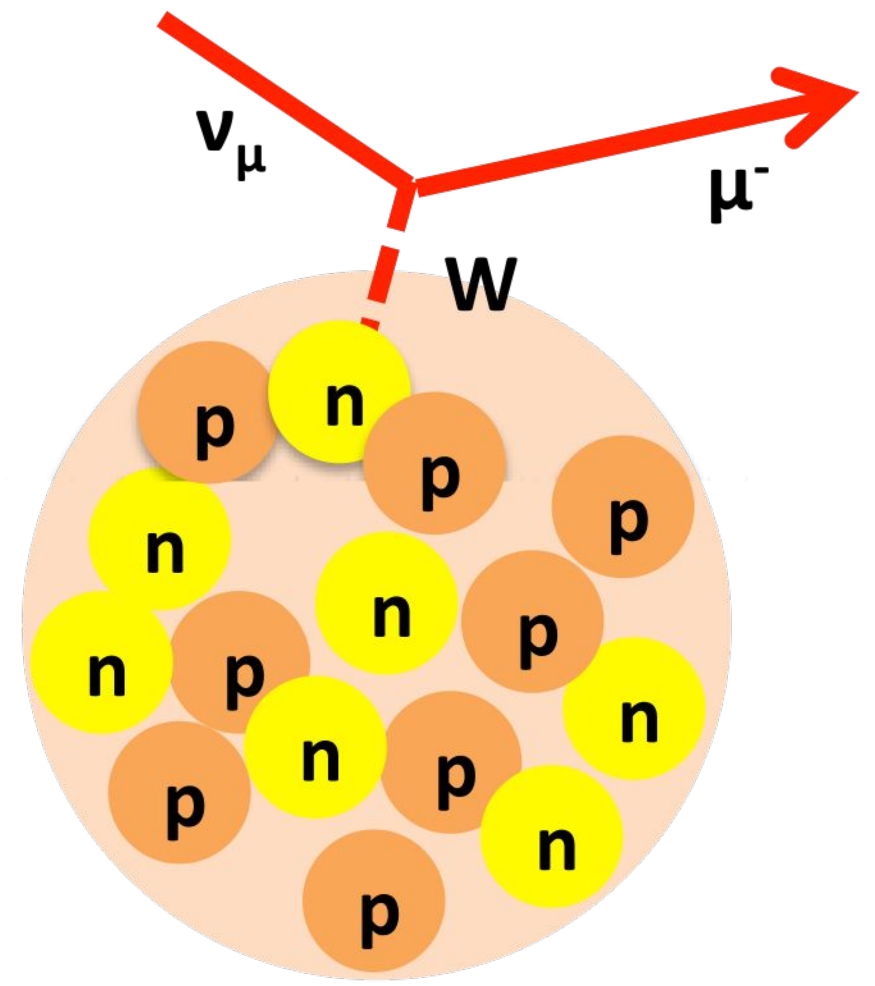


BNB horn geometry from
Phys. Rev. D 79, 072002 (2009)

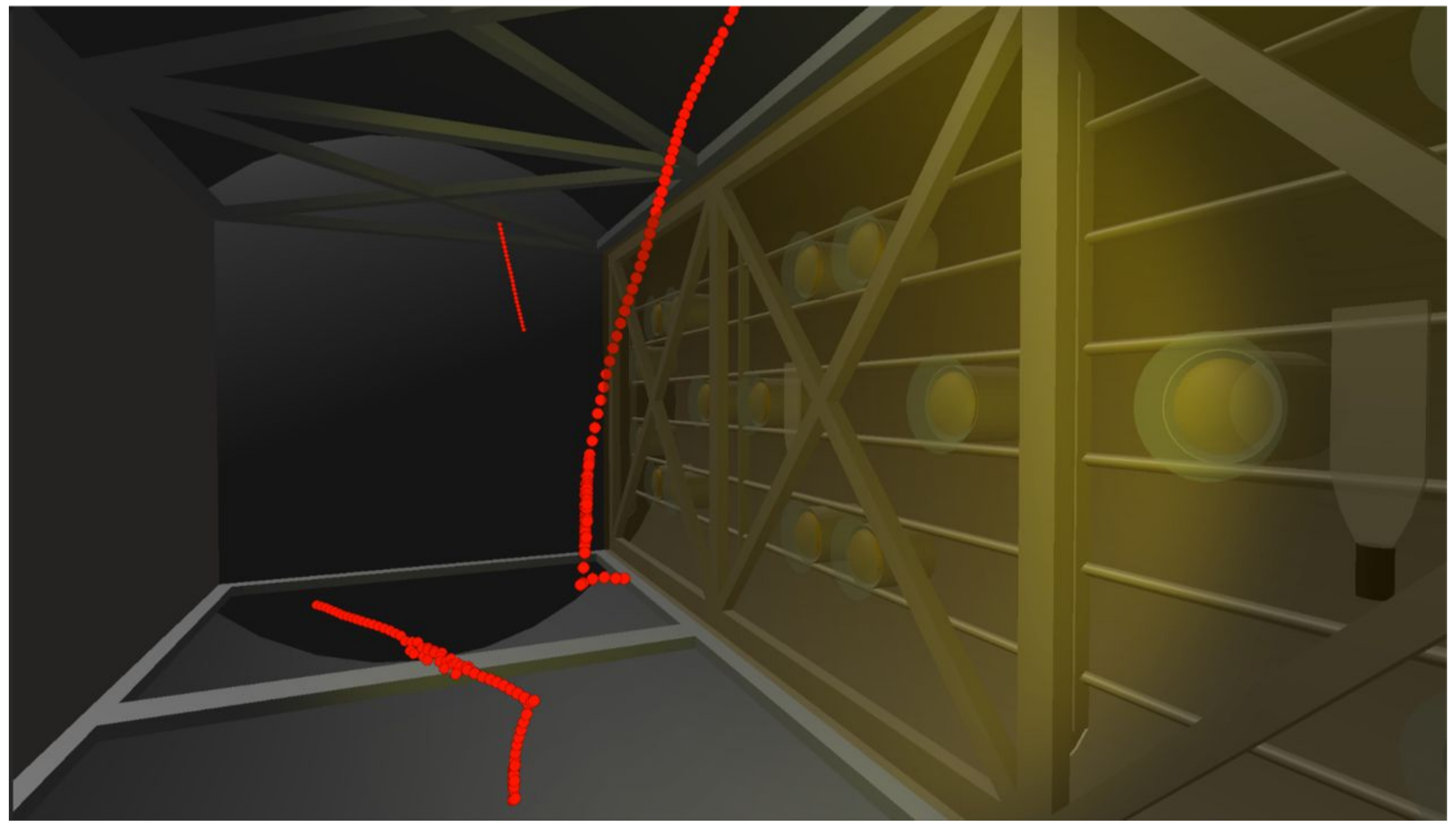
Flux propagation



Neutrino interactions

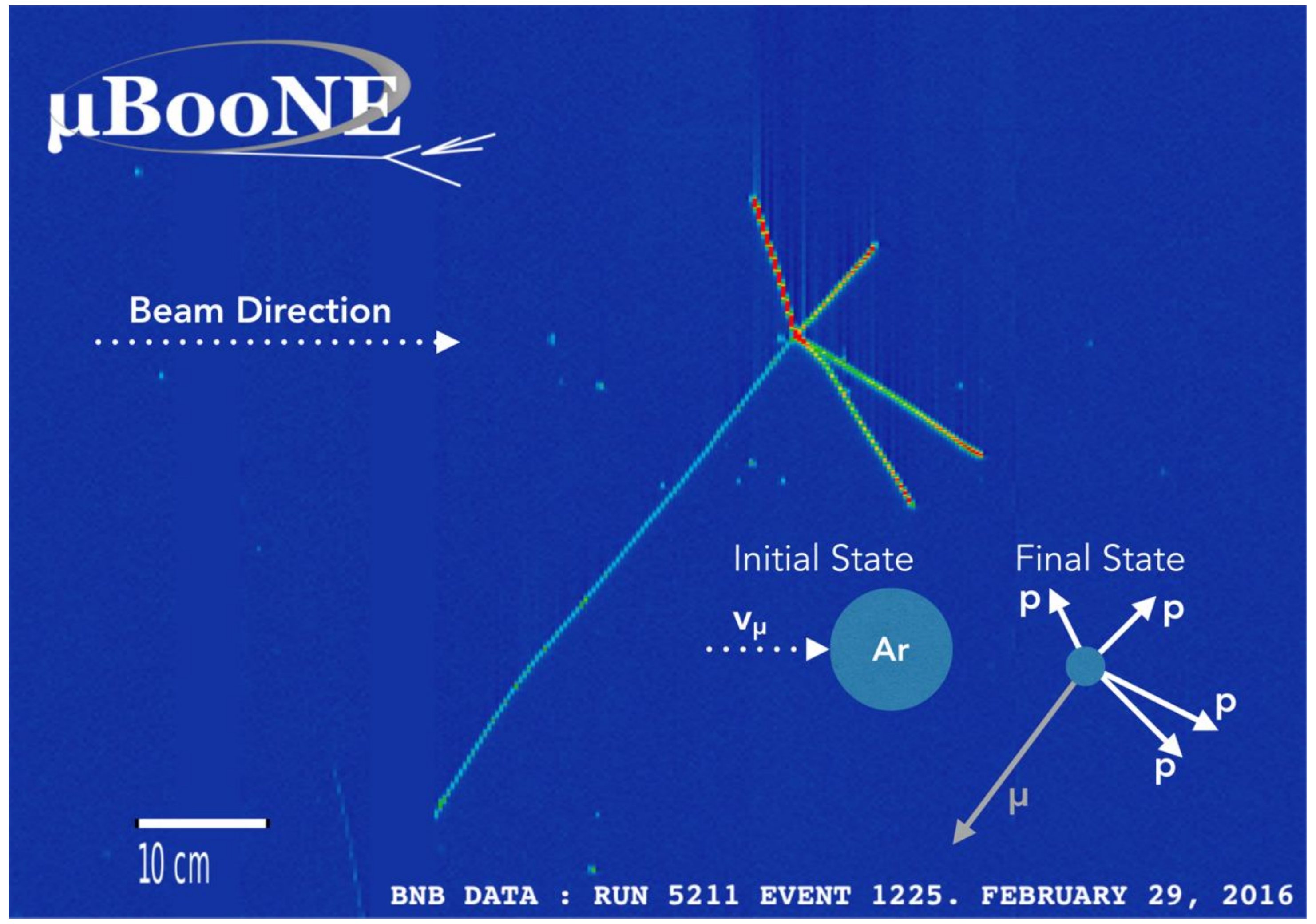


Particle transport



M. Del Tutto, JETP seminar May 2019

Detector response



GEANT4
A SIMULATION TOOLKIT

Genie
UNIVERSAL NEUTRINO GENERATOR & GLOBAL FIT

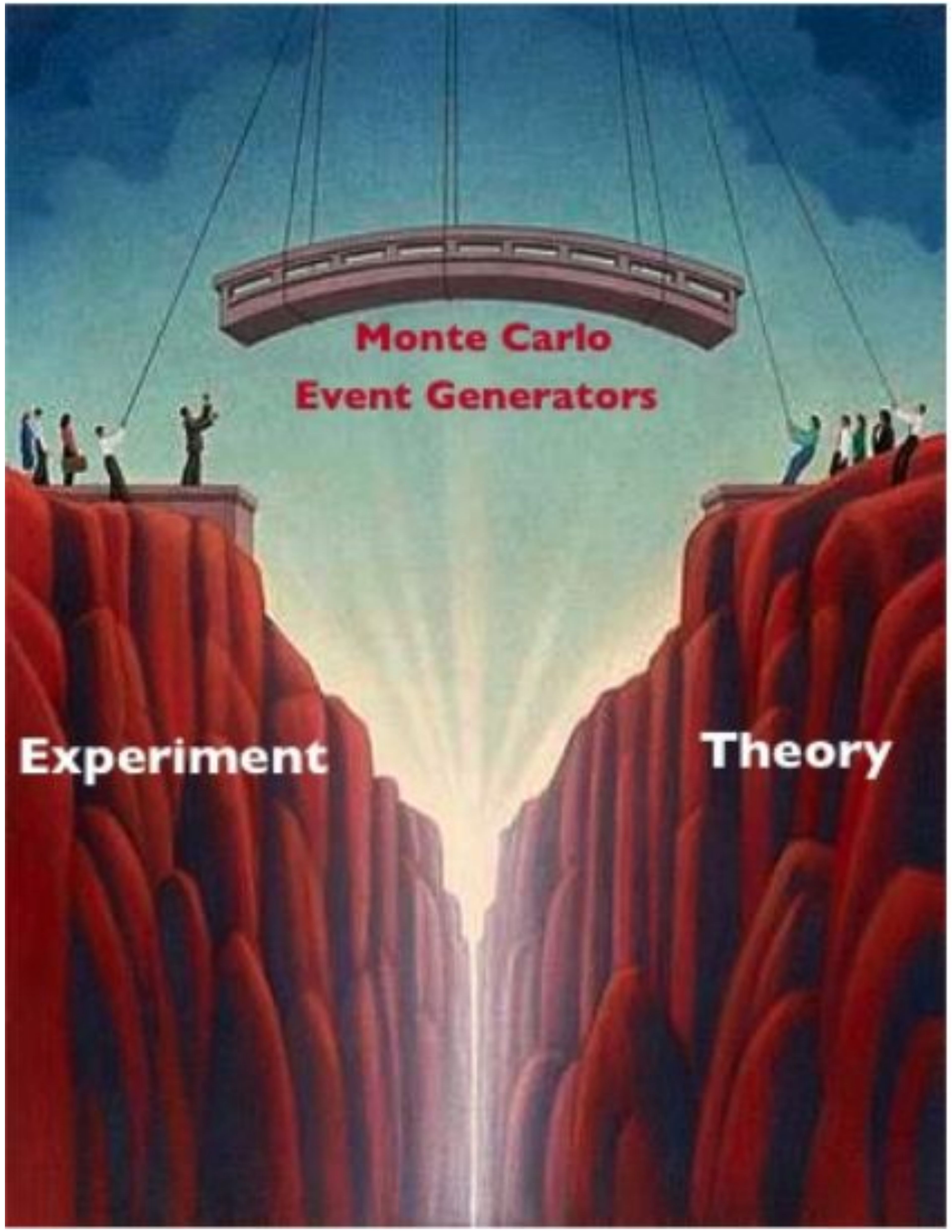
LArSoft

Role of neutrino event generators

- **“Bridge” between theory and experiment:** model predictions are made easily usable

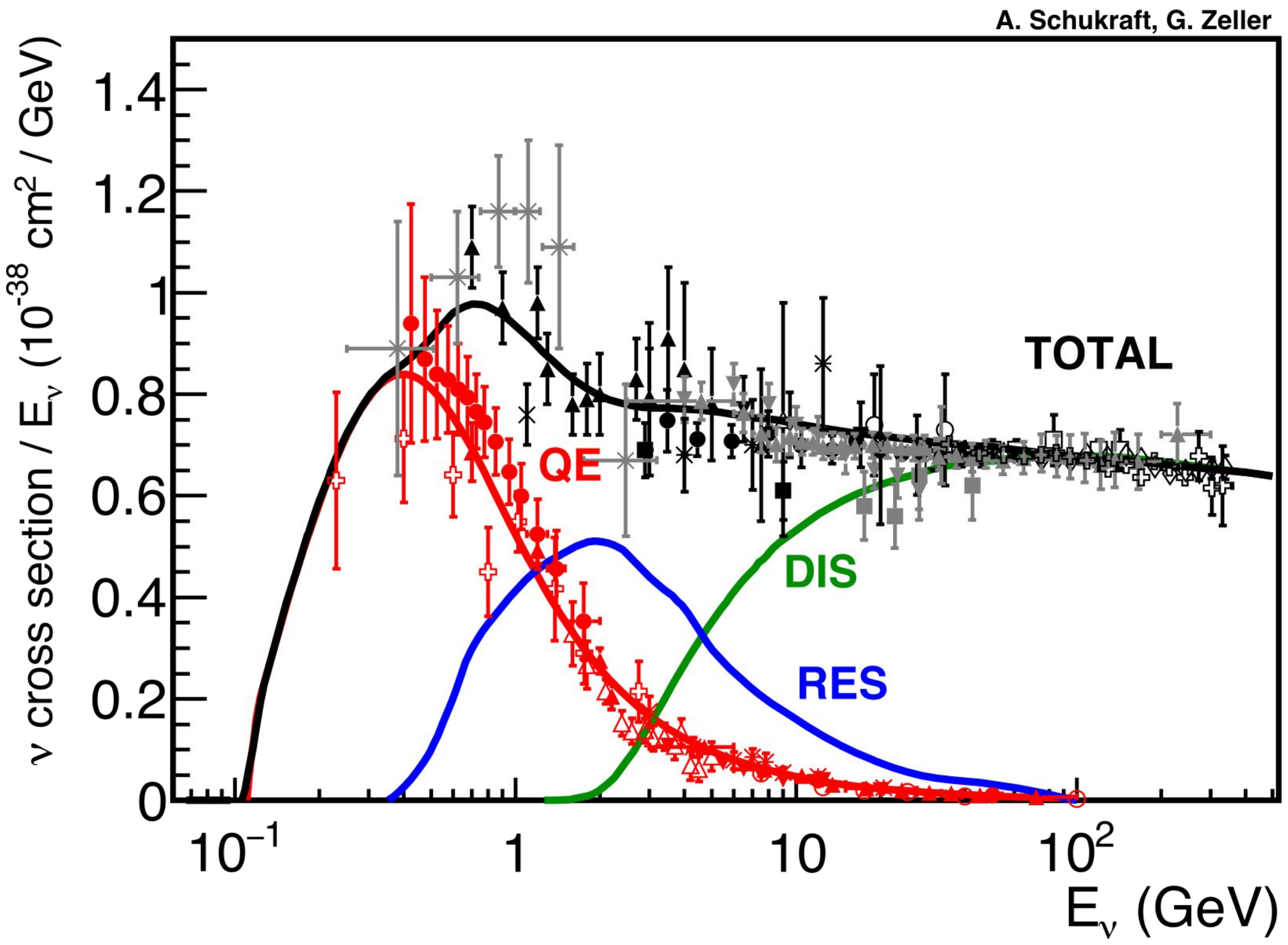
- Essential for a variety of tasks needed for experimental analyses
  - This has been mentioned repeatedly in previous lectures
  - I'll discuss some specific examples

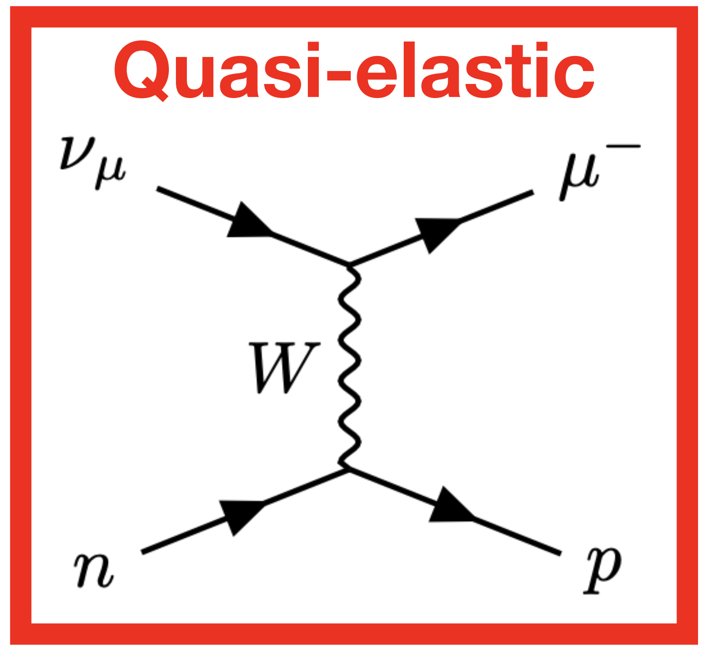
- Cross section data informs further theory improvements
  - I'll return to this point near the end of the talk



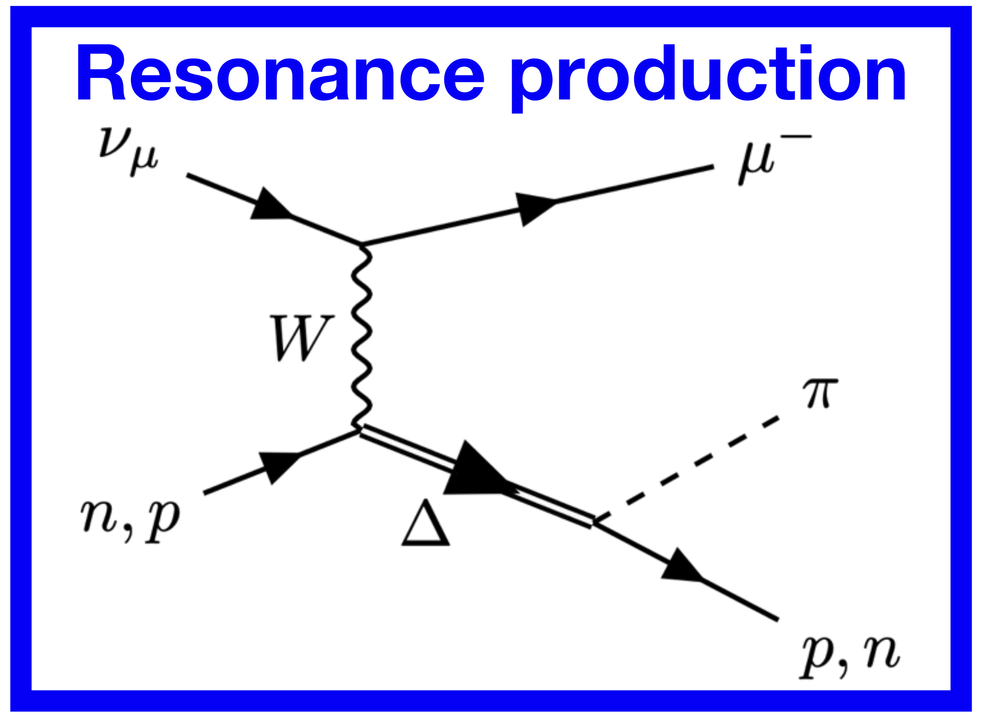
Modeling requirements

- Experiments need cross section models that predict
  - All final-state observables for
  - All important processes for
  - Many nuclear targets including inactive detector components and the surroundings ("dirt backgrounds")
  - Over a neutrino energy range spanning orders of magnitude
- Uncertainties must be well controlled for precision measurements

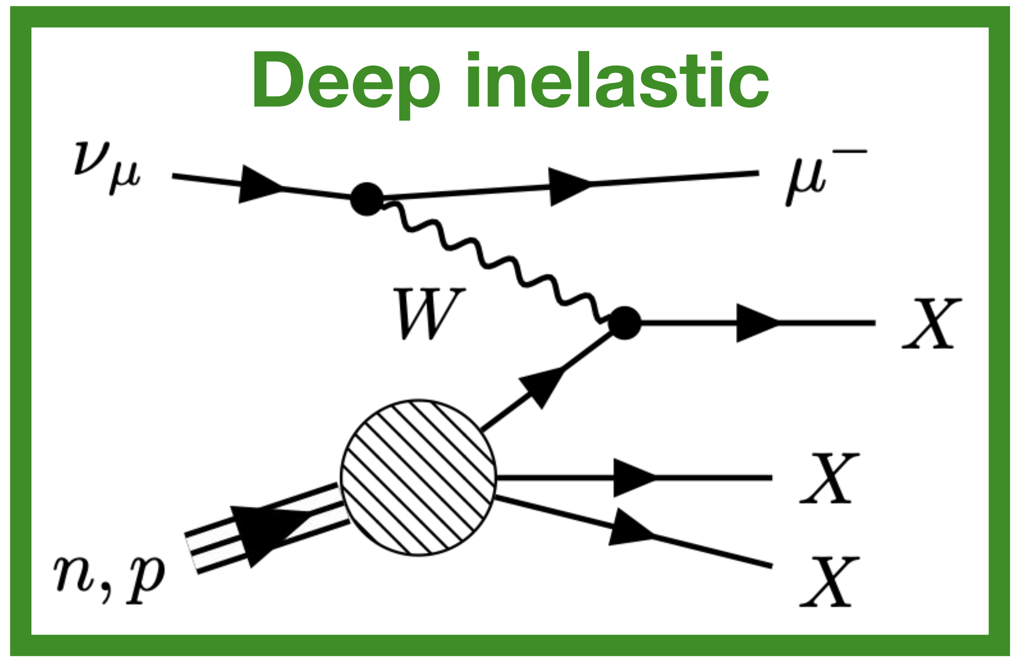




QE

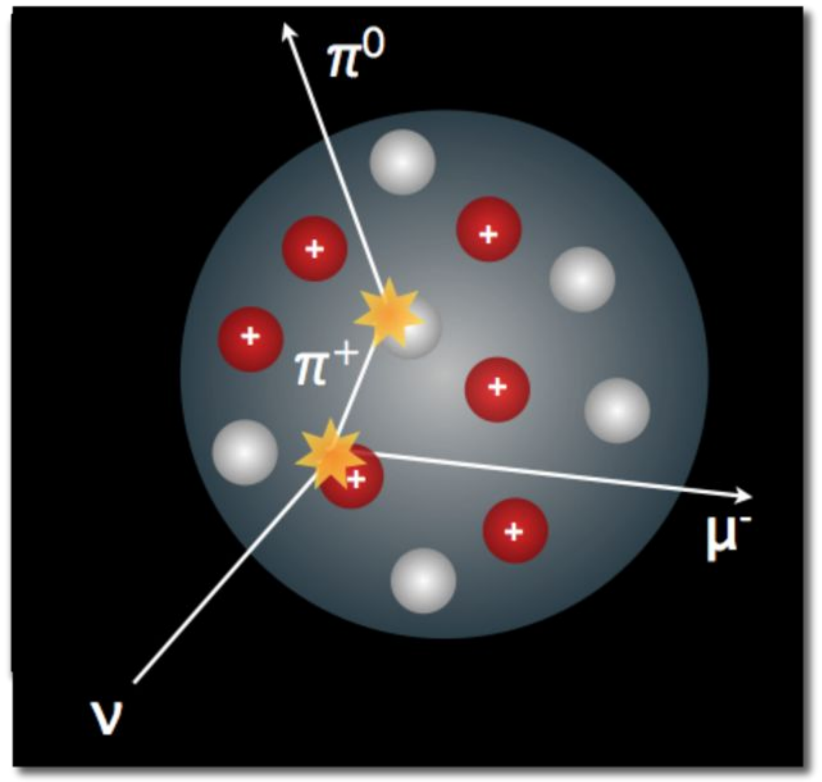


RES

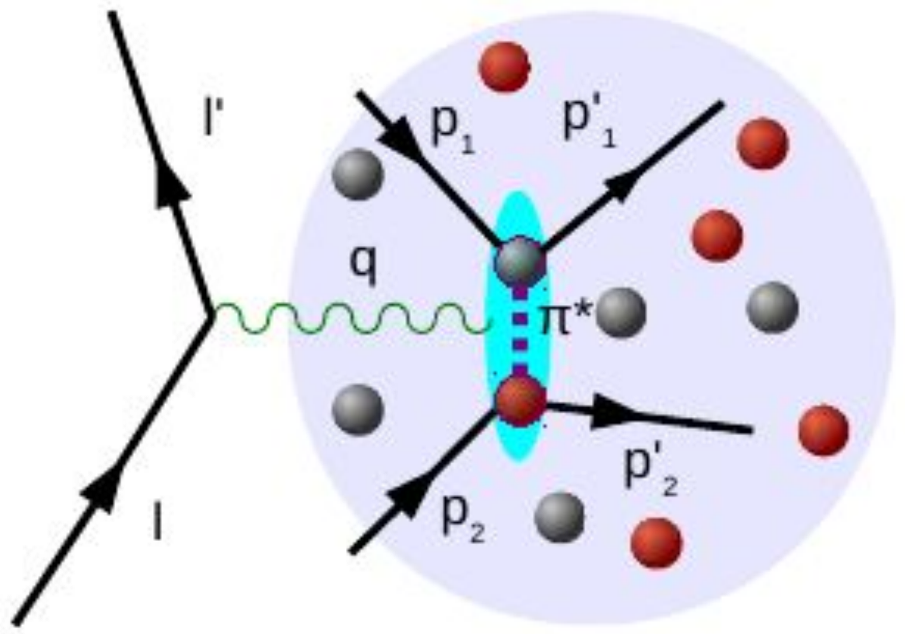


DIS

Final-state interactions (FSIs)



Two-particle two-hole (2p2h) interactions



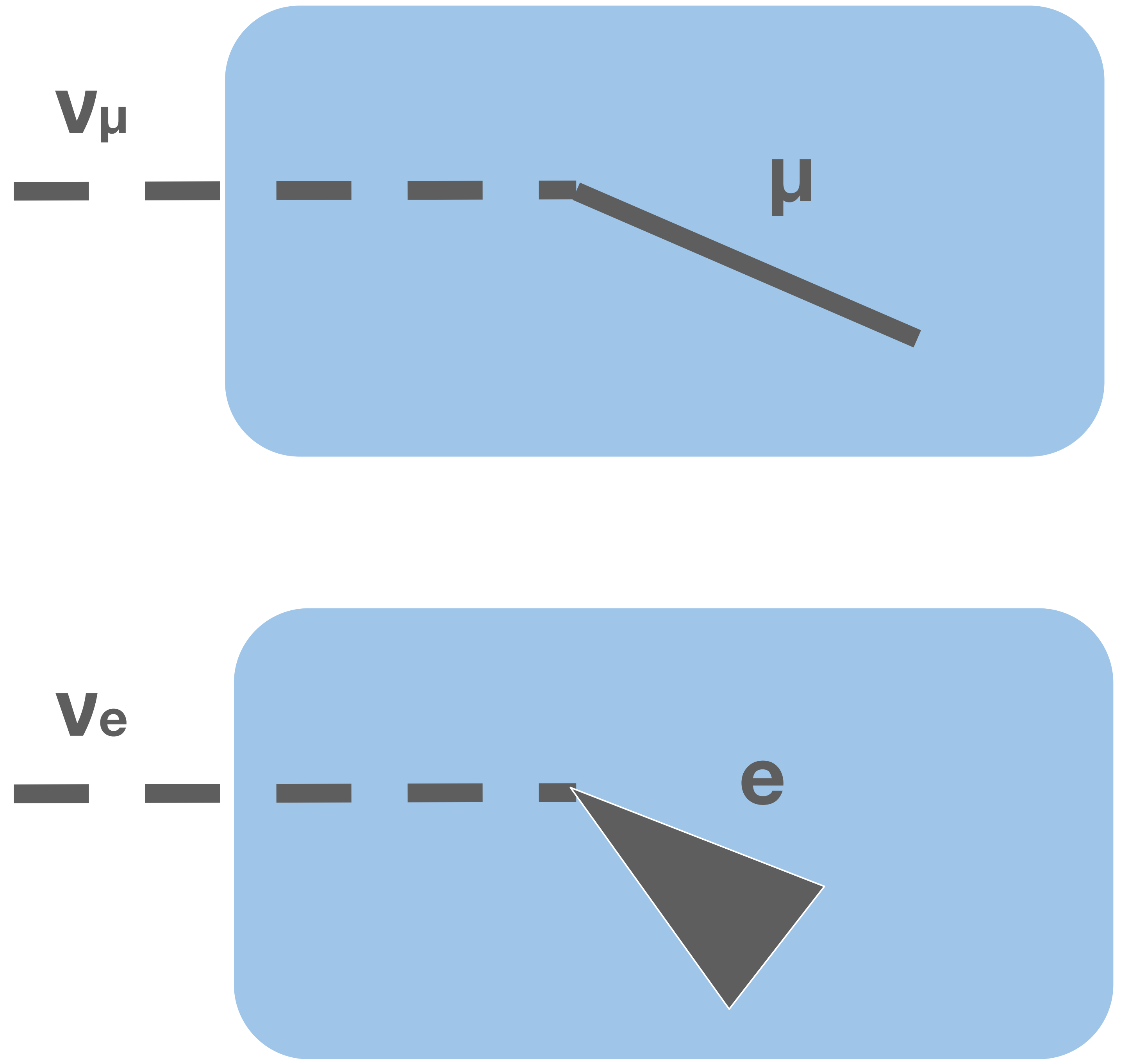
Nucleon-level processes

Nuclear effects

Structure of a neutrino oscillation measurement

- Basic task in the analysis
  - Count neutrinos at one or more locations
  - Record the flavor of each neutrino you see (requires a charged-current interaction)
  - Also estimate the neutrino energy each time
- Compare the result to what you expect
  - Vary oscillation parameters until you find the best fit for the data

Cartoon event topologies for a liquid argon neutrino detector



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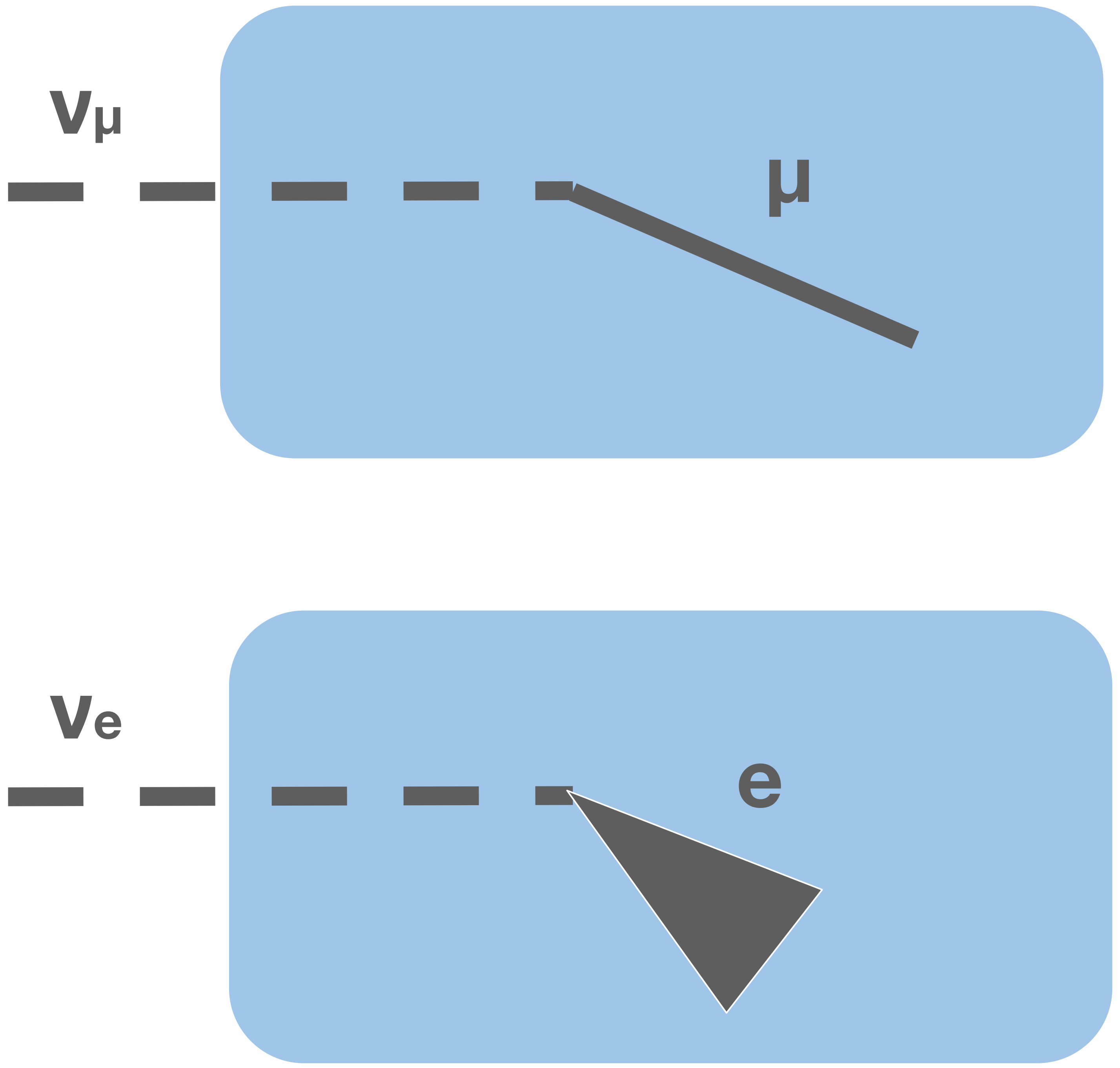
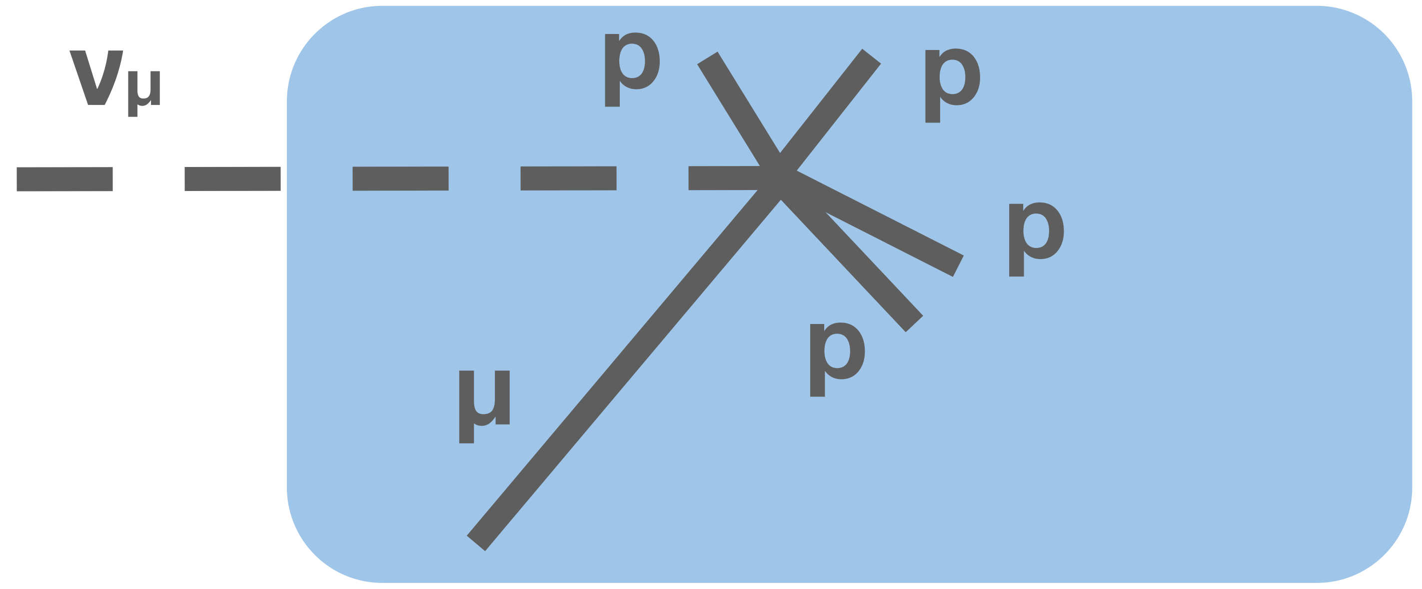
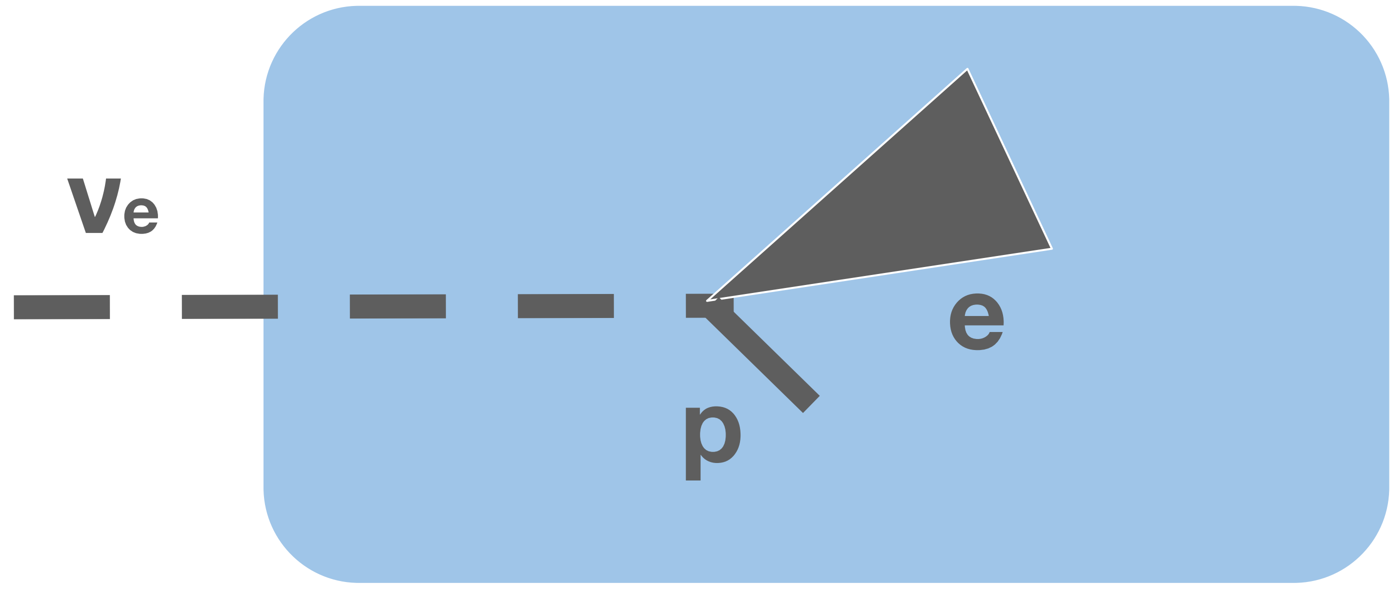
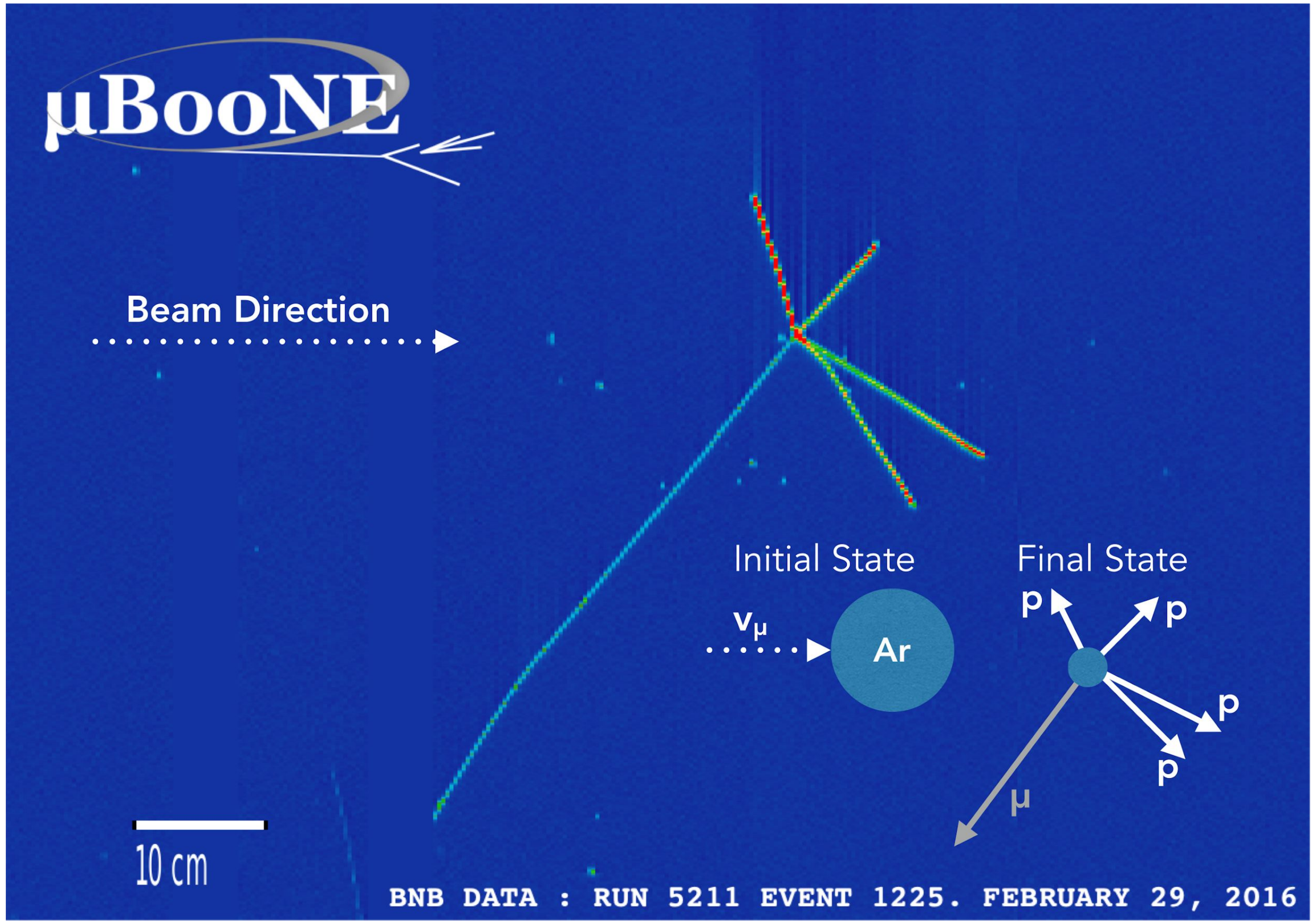
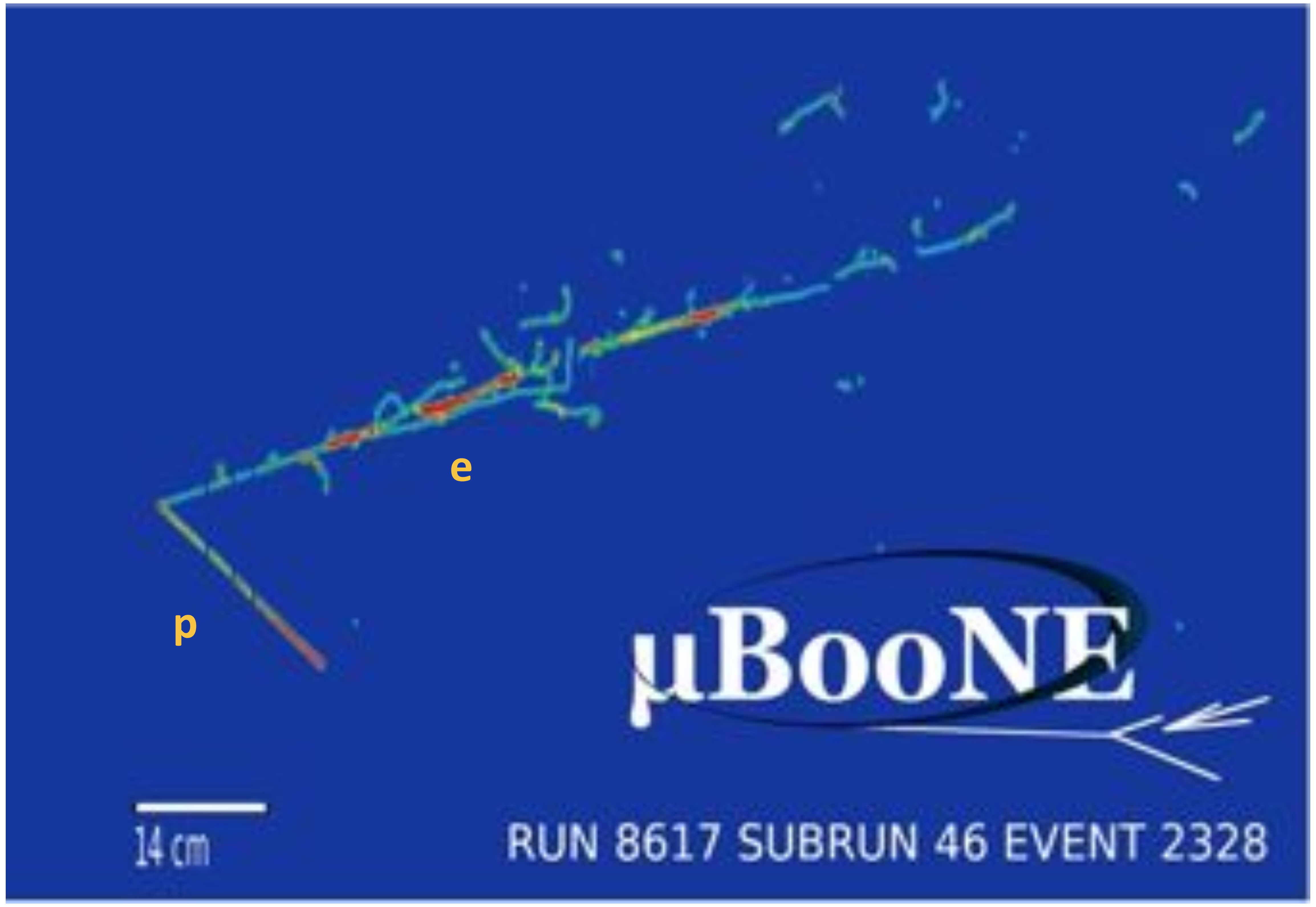


Example event displays from MicroBooNE



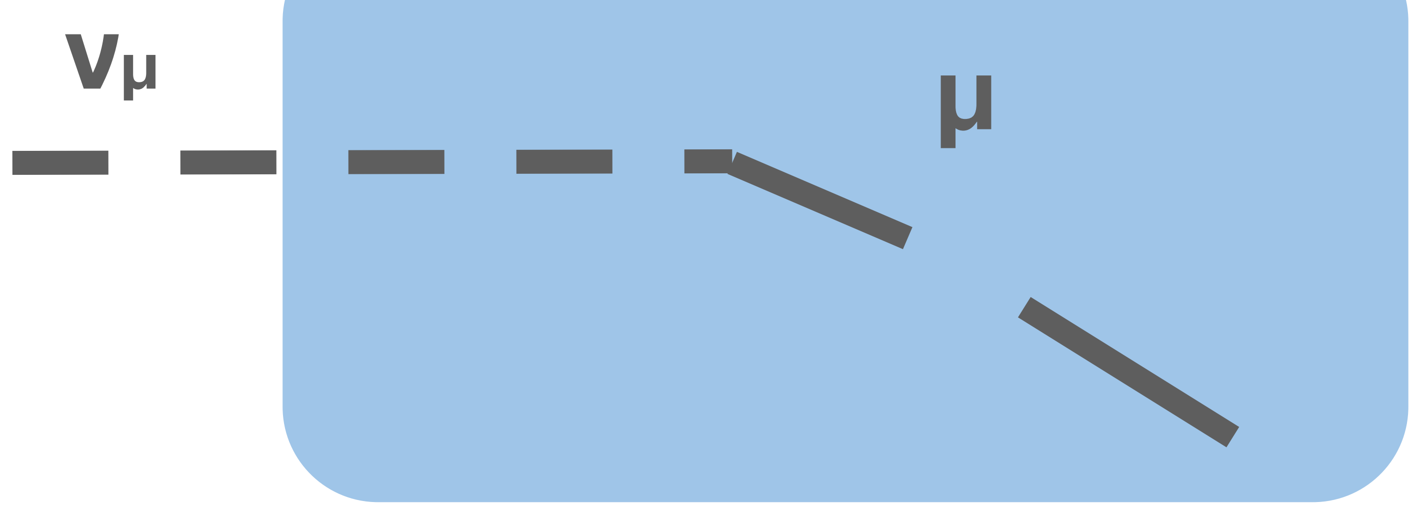




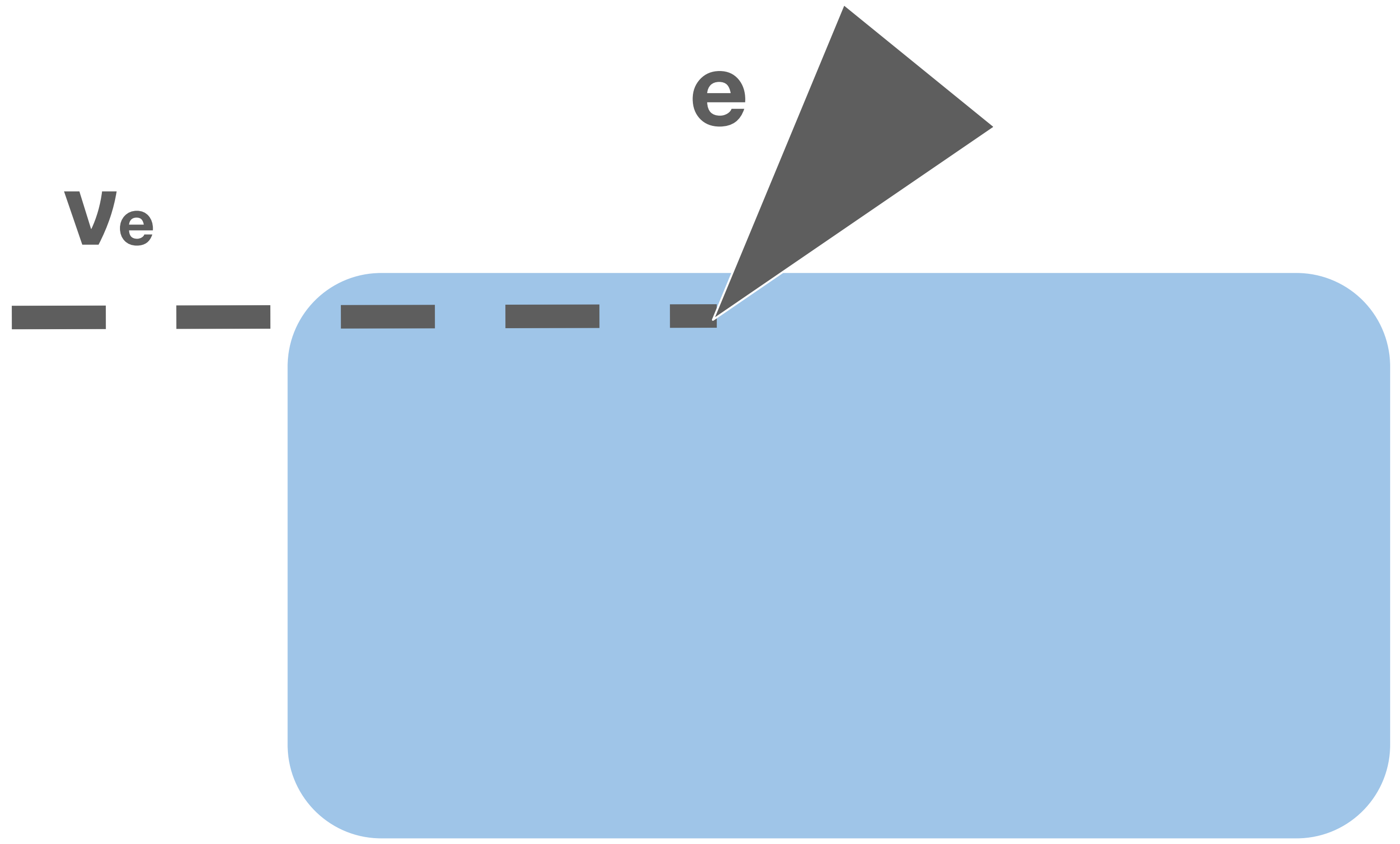


How often do we miss a neutrino? (inefficiency)

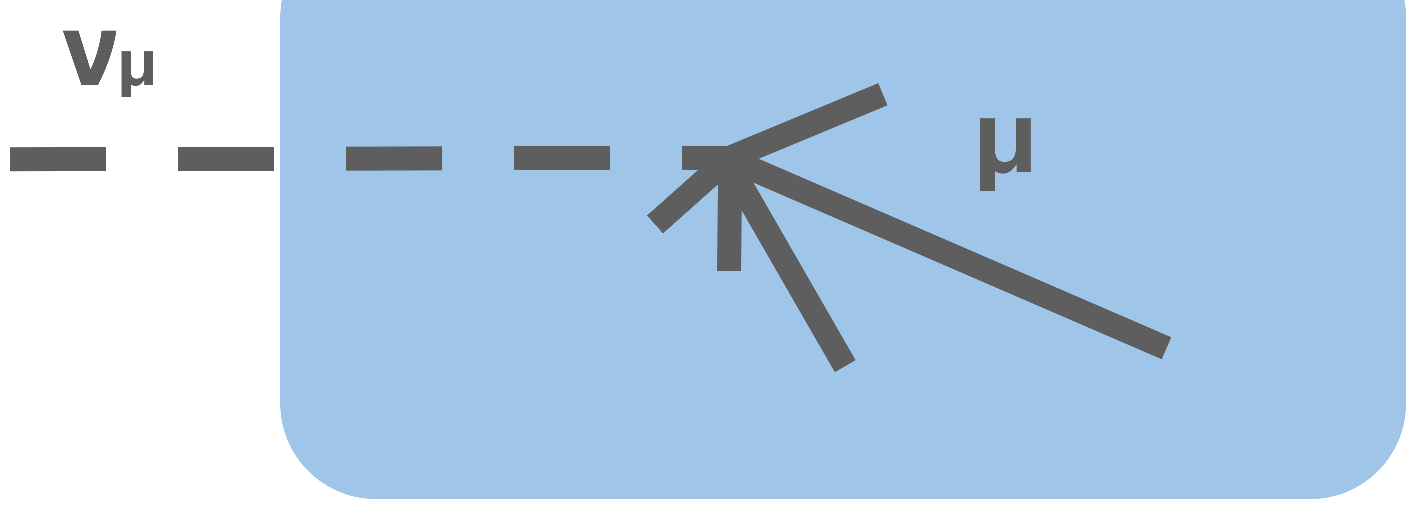
Count neutrinos at one or more locations



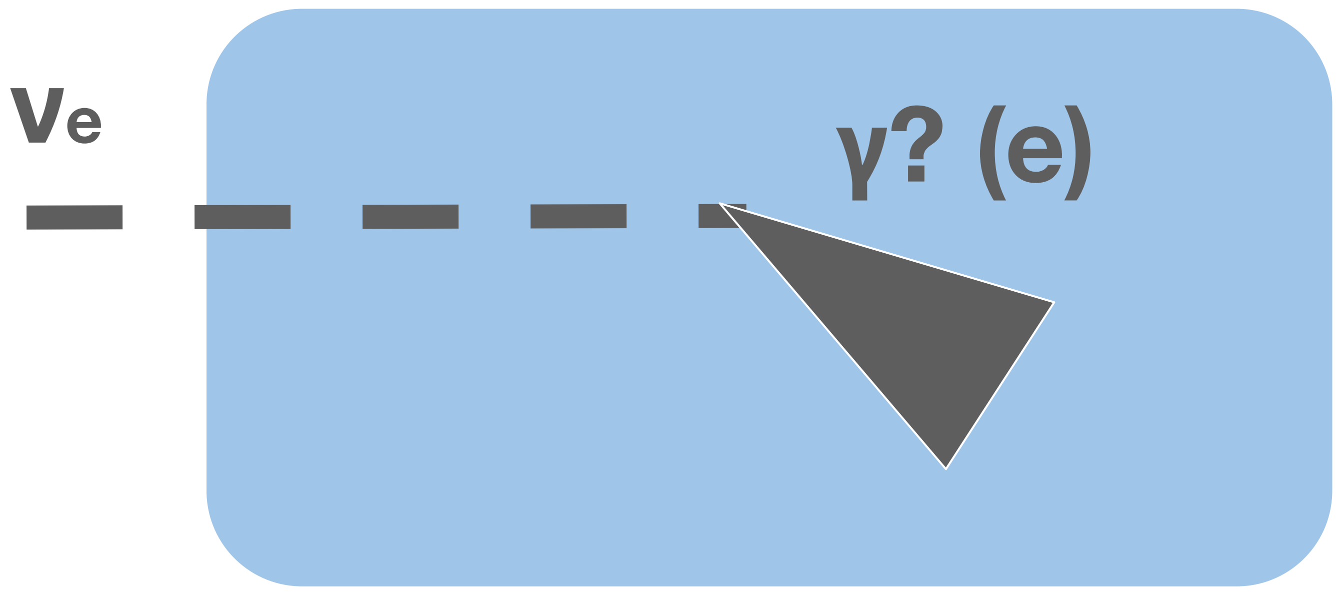
Broken muon track
(dead wires, bad reconstruction)

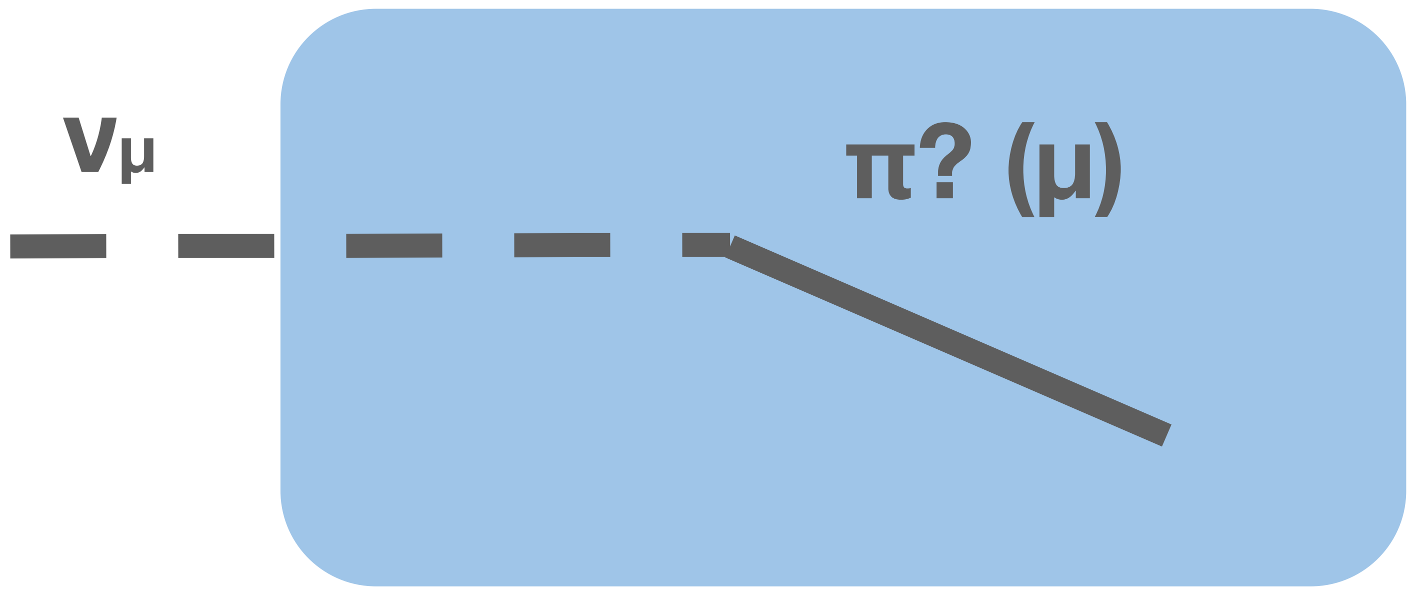


Exiting particles, edge effects



More ways to mis-reconstruct
at high multiplicities



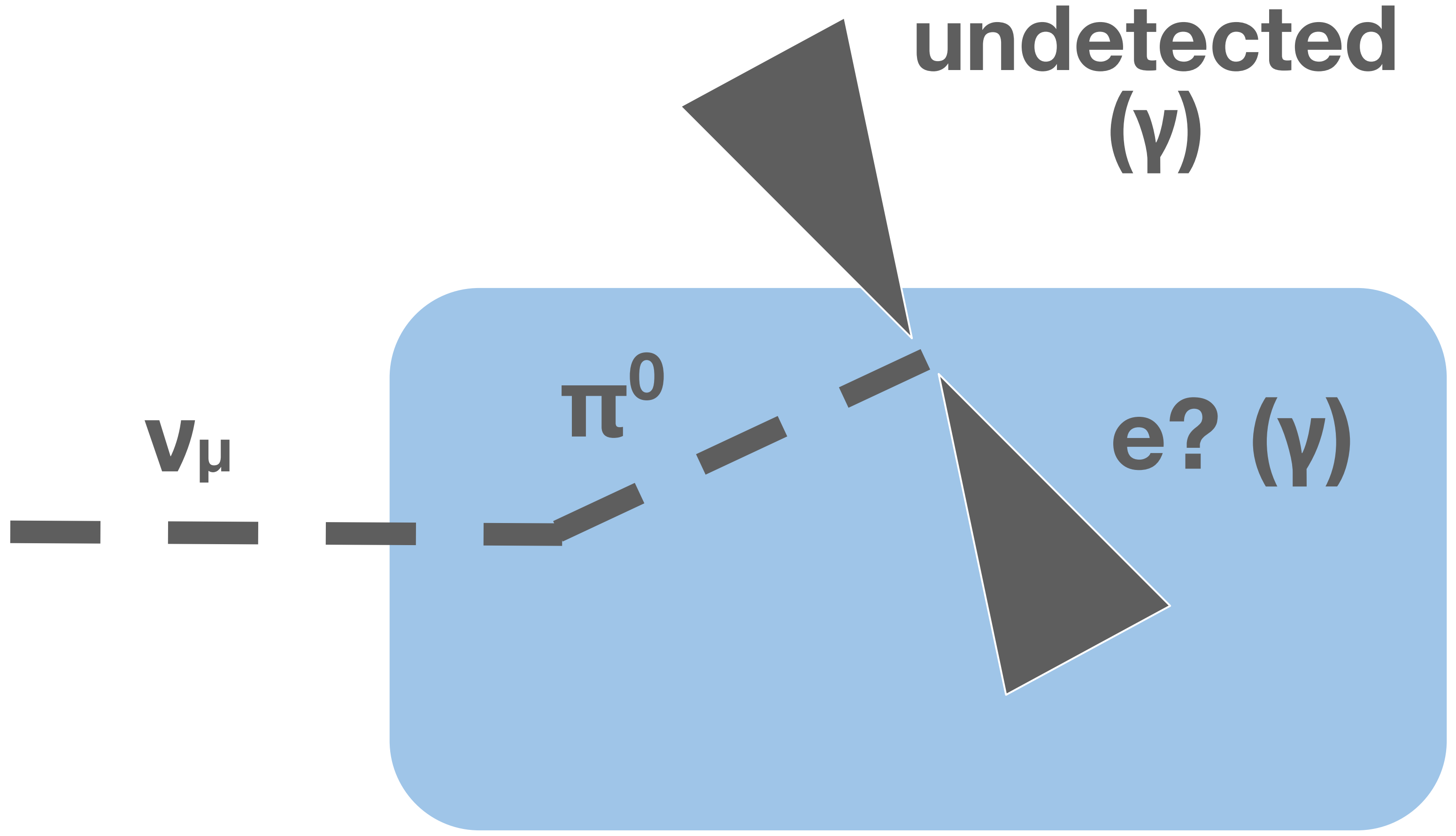


Misidentified particles

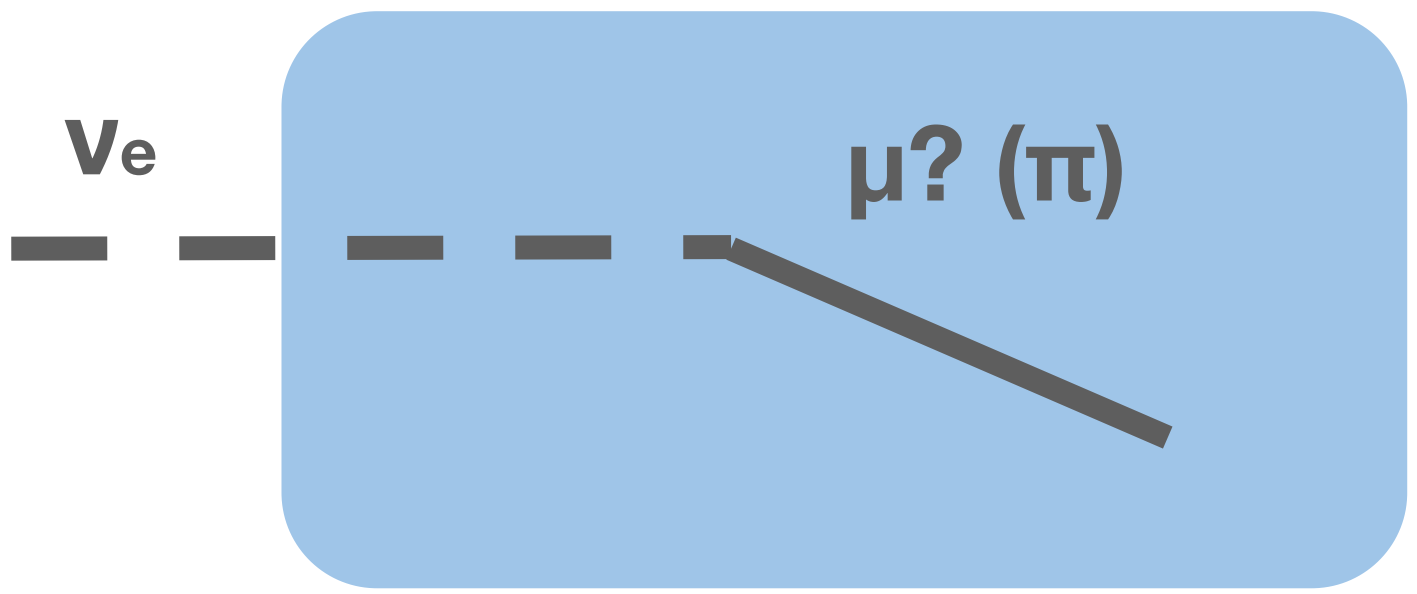
Corrections for problems like these are dependent on the geometry, neutrino energy, and all details of the interaction physics

How often do we count events that we don't want? (backgrounds)

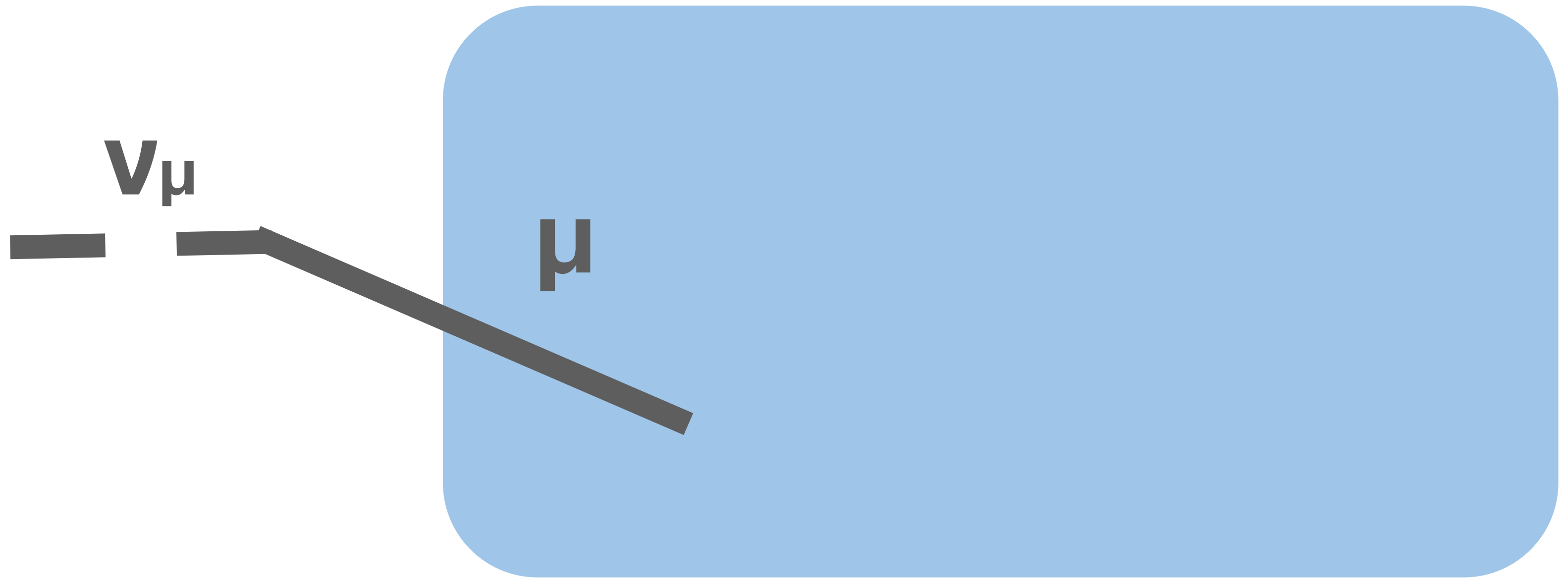
Record the flavor of each neutrino you see



Example background to ν_e counting



Example background to ν_μ counting

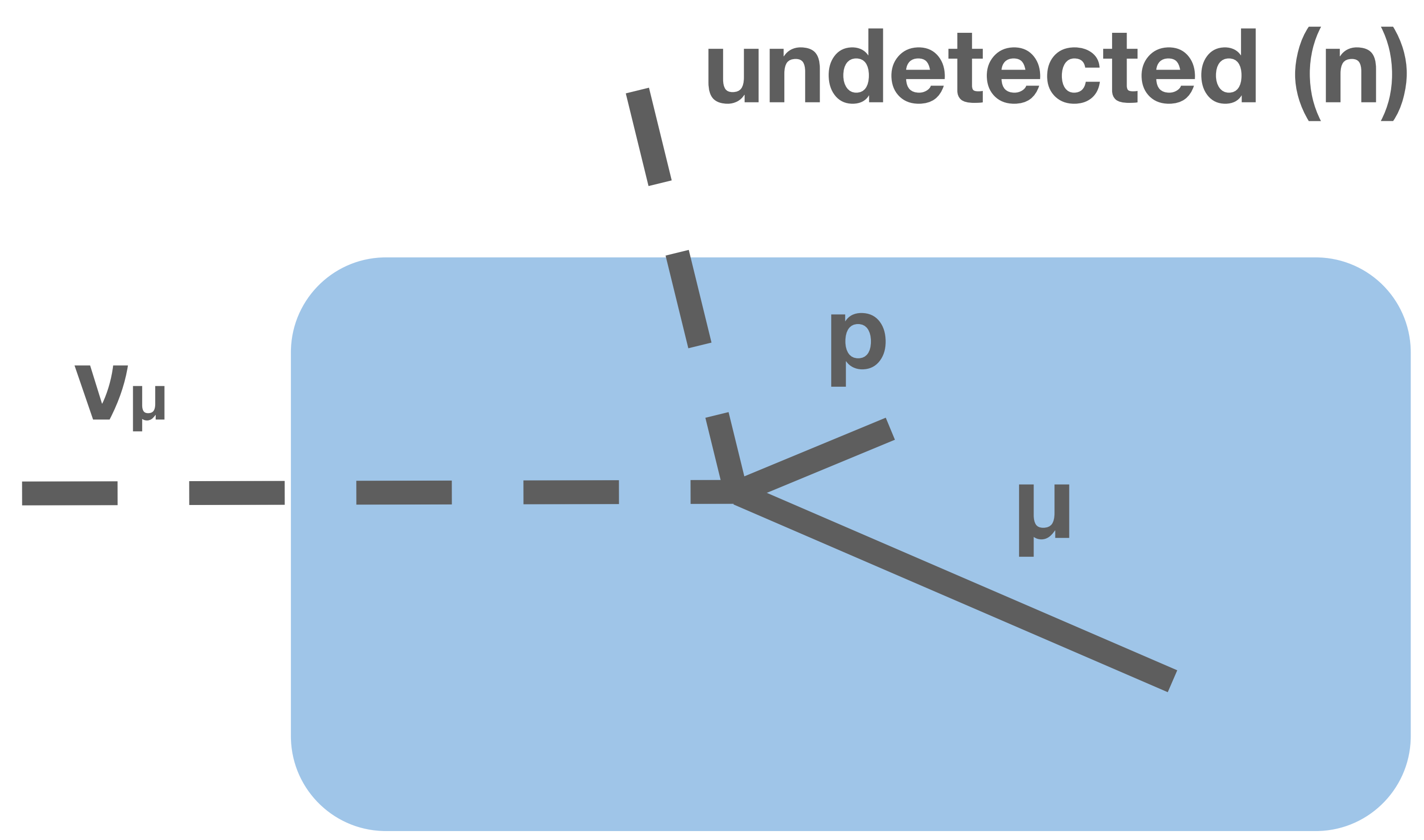


A "dirt" background event

Simulations remain crucial to account for these and other forms of background

How biased is our neutrino energy estimator? (calorimetry)

Estimate the neutrino energy each time



Quasielastic-like νμ event

$$E_{QE} = \frac{2M_N\epsilon + 2M_N E_l - m_l^2}{2(M_N - E_l + k_l \cos\theta_l)}$$

QE strategy: Assume quasielastic (wrong for this event → bias), use muon energy (E_ℓ), angle (θ_ℓ), and nucleon removal energy (ϵ)

Calorimetric strategy: Add up energies of the visible particles (but the neutron is undetected → bias)

Generators are essential to understand missing energy in neutrino events

What would our data look like under different scenarios?

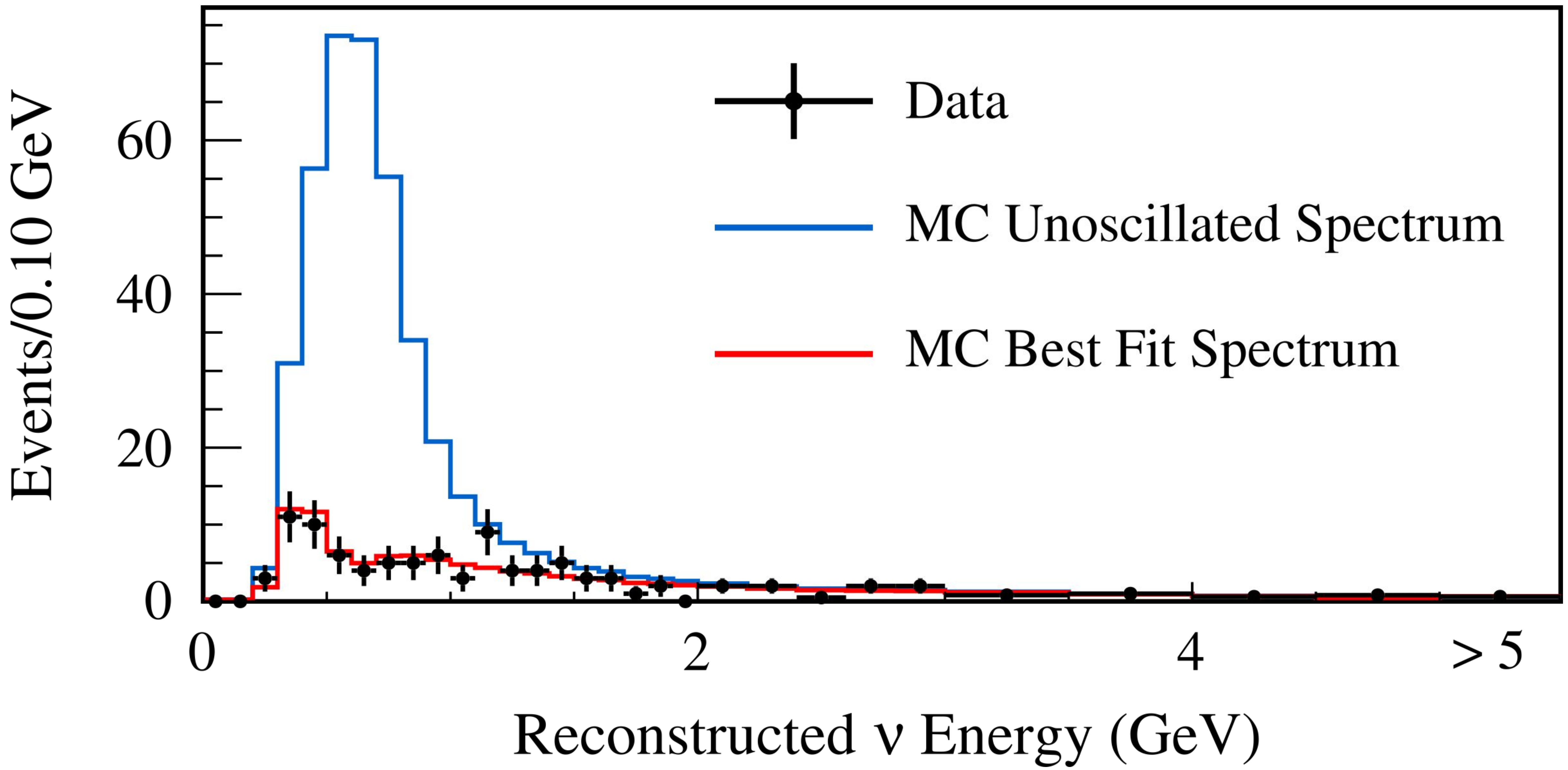
Compare the result to **what you expect**

Example: ν_μ disappearance analysis from T2K

Similar games are played for other oscillation studies (e.g., ν_e appearance in a ν_μ beam)

After we have obtained a measurement, we still need a generator to help us understand what it means

T2K Collaboration, [Phys. Rev. D 91, 072010](#) [(2015)](#)



1. Count ν_μ as a function of reconstructed energy (**black**)
2. Predict expected result without oscillations (**blue**)
3. Multiply prediction by $P_{\nu_\mu \to \nu_\mu}$ and fit oscillation parameters (**red**)

What would our data look like under different scenarios?

Compare the result to **what you expect**

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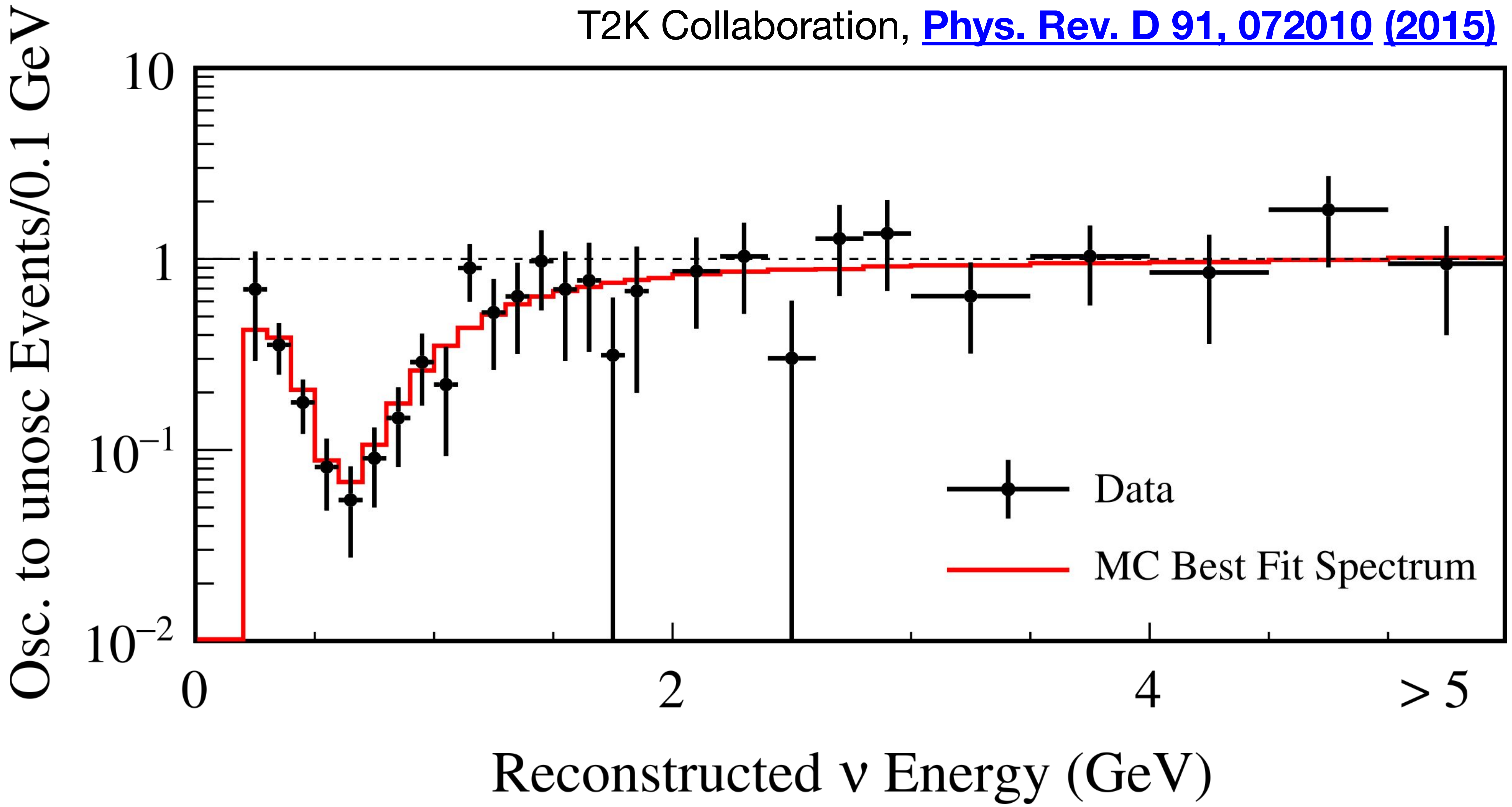
T2K Collaboration, [Phys. Rev. D 91, 072010](#) [(2015)](#)



Model comparisons also needed when searching for new physics

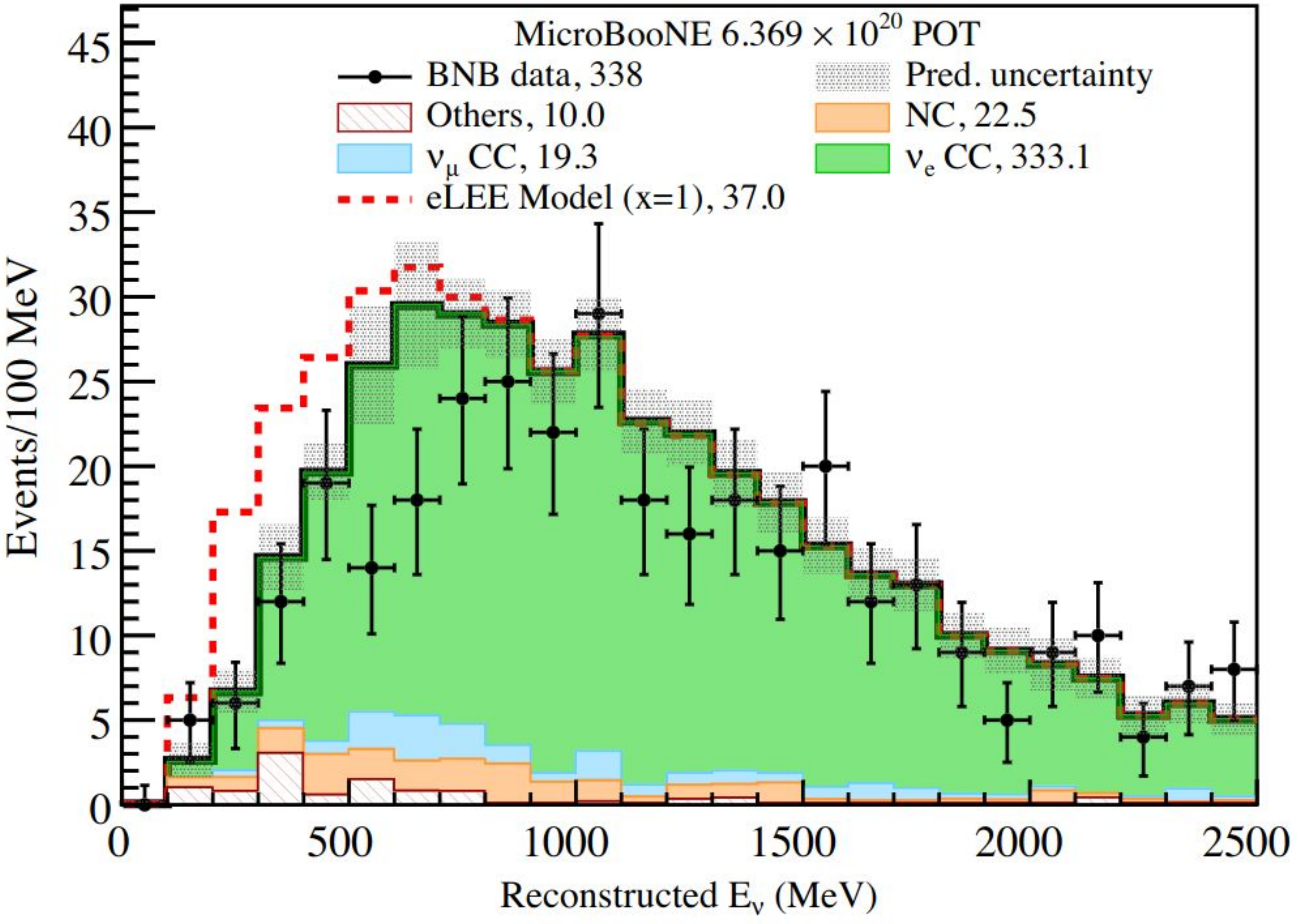
Compare the result to **what you expect**

MicroBooNE Collaboration, Phys. Rev. Lett. 128, 241801 (2022)

MicroBooNE looked for an **anomalous excess** of ν_e-like events at low energies

Comparison with **GENIE-based prediction** shows no excess (albeit an interesting deficit in a few bins)

After we have obtained a measurement, we still need a generator to help us understand what it means



Part II: Software tour and development highlights

Software landscape

Four most popular codes at accelerator energies (~100 MeV to ~20 GeV)

Experiment-focused generators

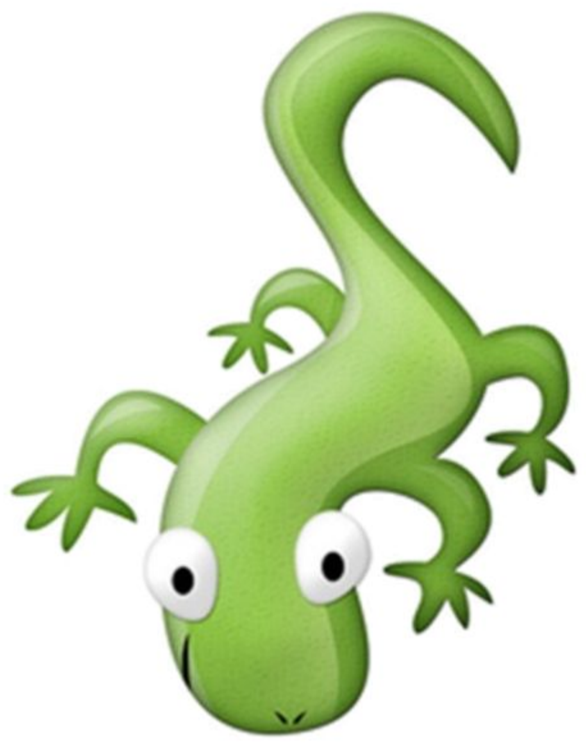
Meet the needs of current oscillation experiments

UNIVERSAL NEUTRINO GENERATOR & GLOBAL FIT

Eur. Phys. J. Spec. Top. 230, 4449 (2021)

C++. Primary generator for Fermilab experiments. Largest group (still just a handful of active developers). Ambitions to be the universal platform.

NEUT (no official logo)



Eur. Phys. J. Spec. Top. 230, 4469 (2021)

C++/Fortran. Primary generator for J-PARC experiments (T2K, Super-K, Hyper-K). Not yet fully open source.

Theory-focused generators

Aid theoretical investigations of neutrino scattering

GiBUU

J. Phys. G: Nucl. Part. Phys. 46 113001 (2019)

Fortran. Supports neutrino projectiles as part of larger framework. Most sophisticated FSI model. Limited infrastructure (no geometry handling, etc.)

NuWro

NuWro * Wrocław Neutrino Event Generator *

Nucl. Phys. Proc. Suppl. 229-232, 499 (2012)

C++. Many model options, often the first adopter of new theory developments from the literature.

GENIE's interaction model tuning program

- Developing global analysis of scattering data
  - Model fitting and uncertainty quantification

- **Professor**: tuning software tool from LHC community
  - Efficiently perform brute-force scans of parameter space
  - Applied to neutrinos for the first time by GENIE

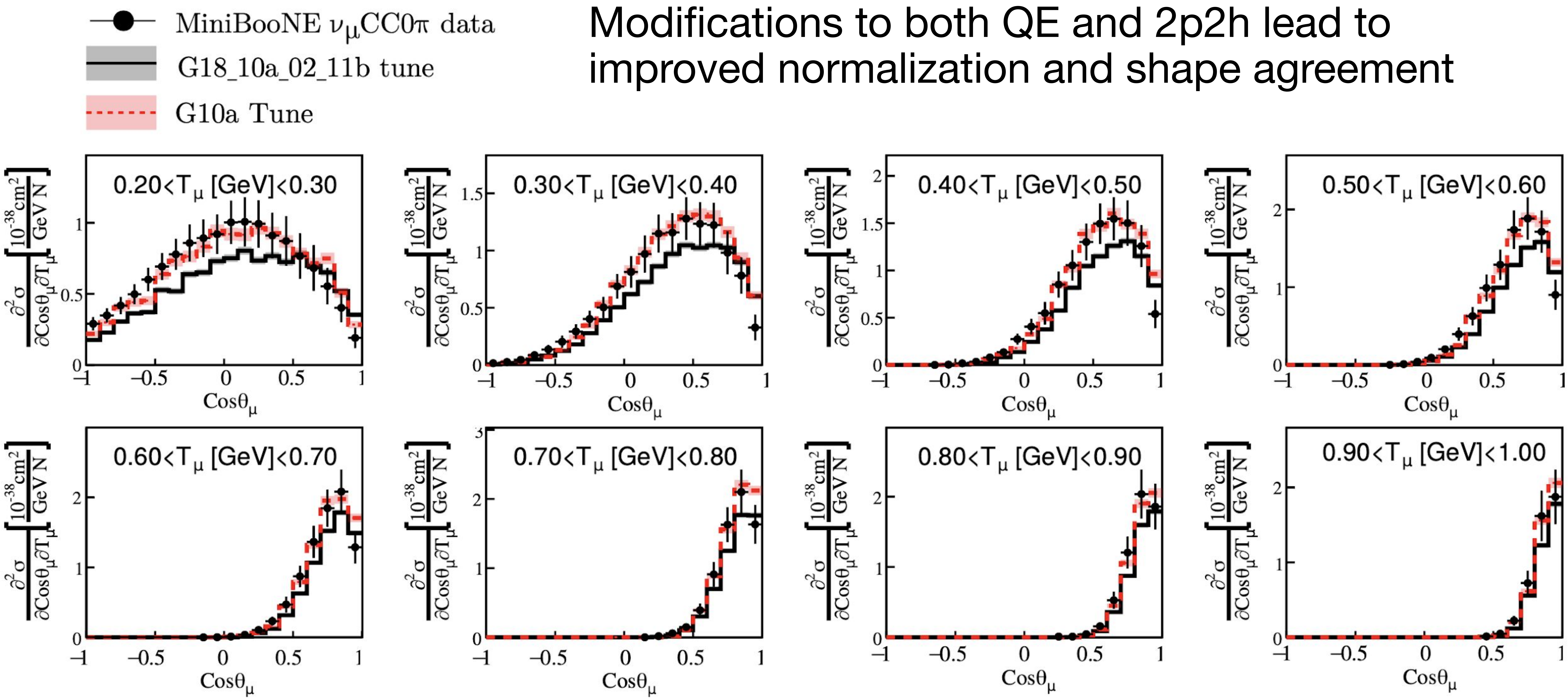
- Used together with **GENIE Comparisons**
  - Curated cross-section database
  - Proprietary to GENIE, NUISANCE is open alternative

https://professor.hepforge.org/

GENIE tune results for MiniBooNE data

Phys. Rev. D 106, 112001 (2022)

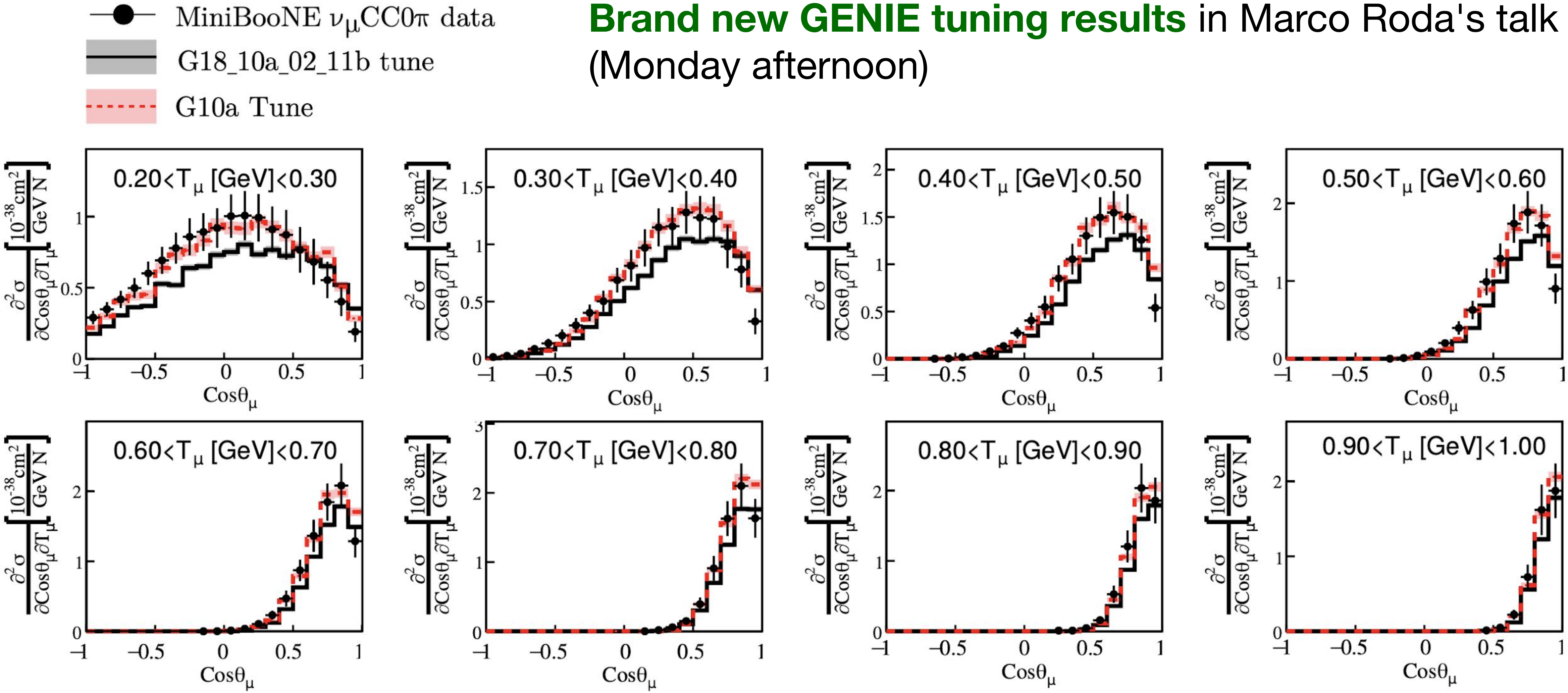
Modifications to both QE and 2p2h lead to improved normalization and shape agreement



GENIE tune results for MiniBooNE data

Phys. Rev. D 106, 112001 (2022)

Brand new GENIE tuning results in Marco Roda's talk (Monday afternoon)

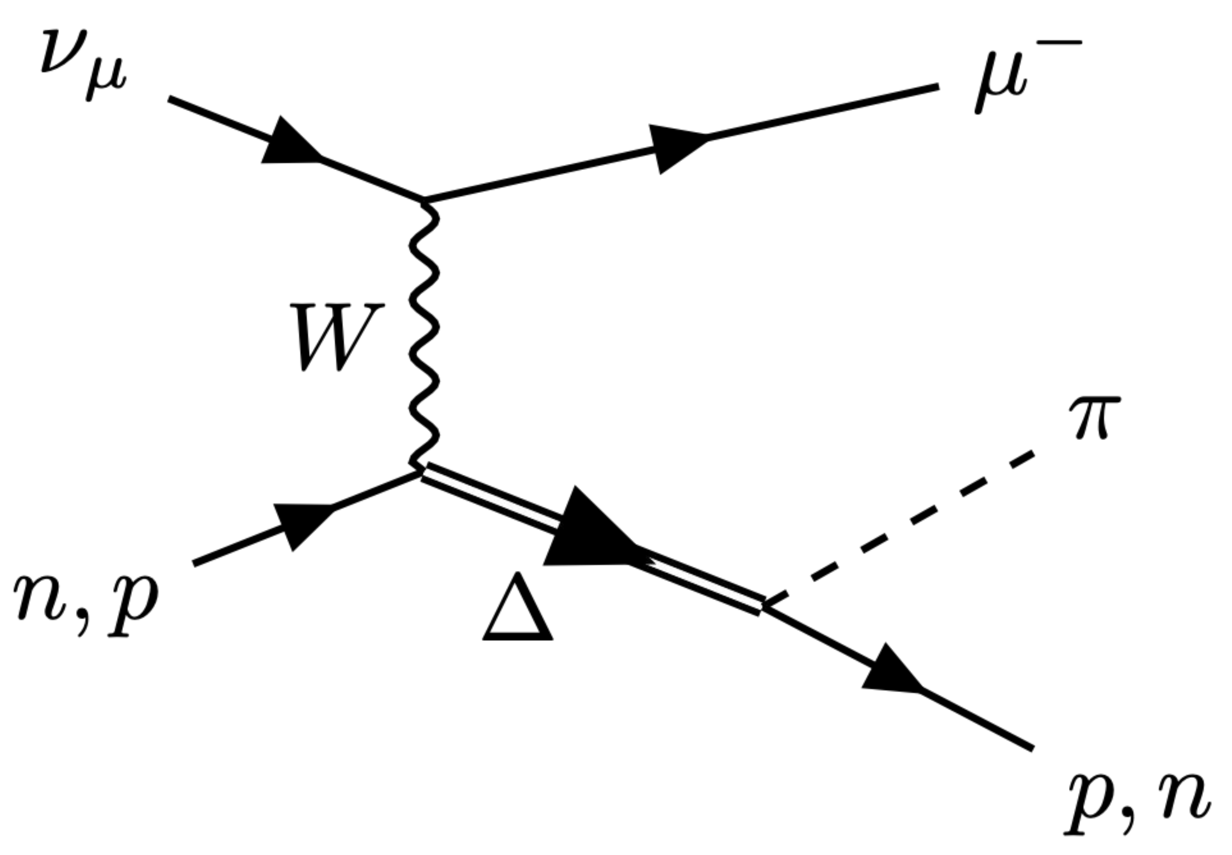


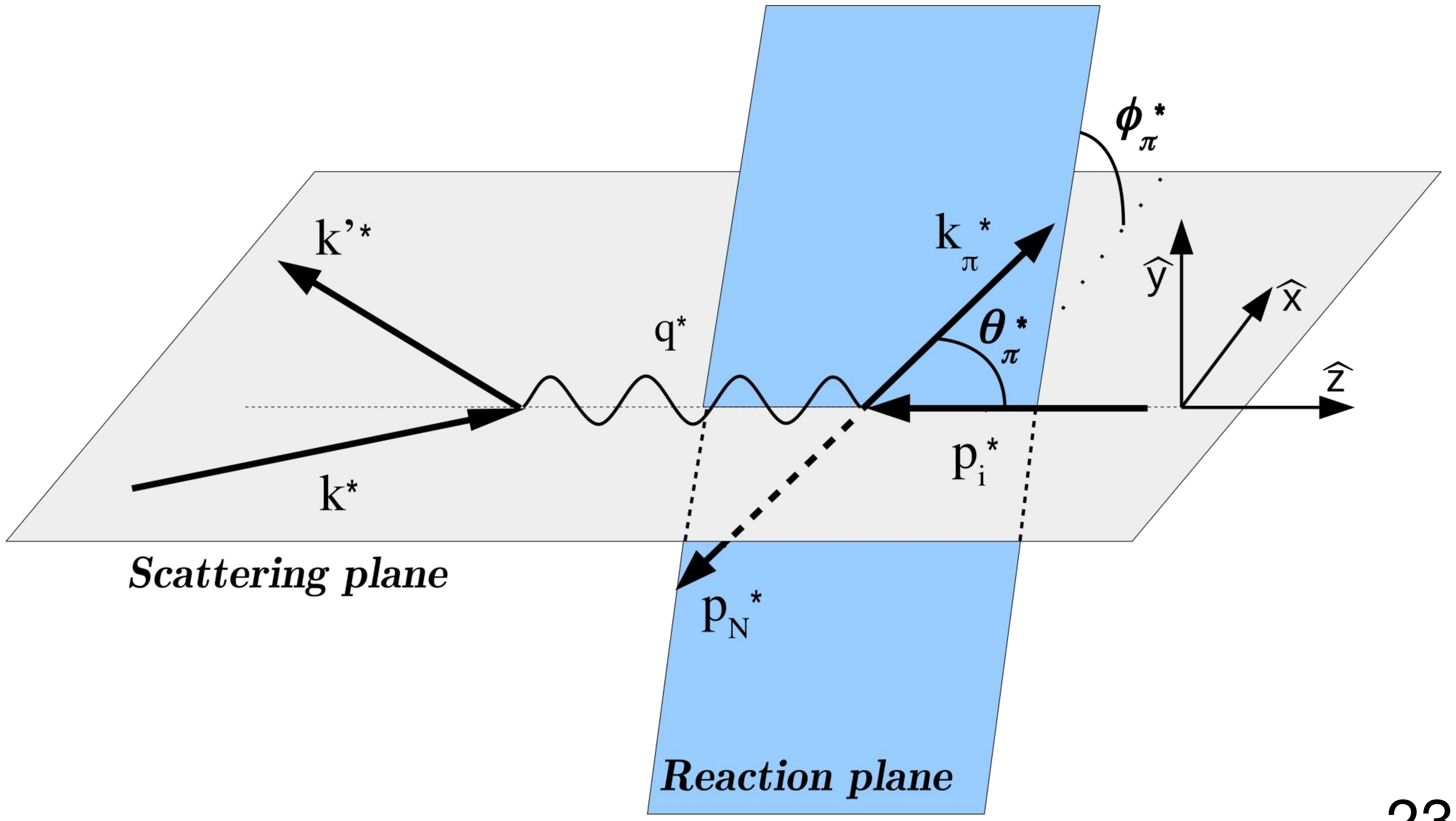
Single π production in NuWro

[Phys. Rev. D 103, 053003 (2021)](https://doi.org/)

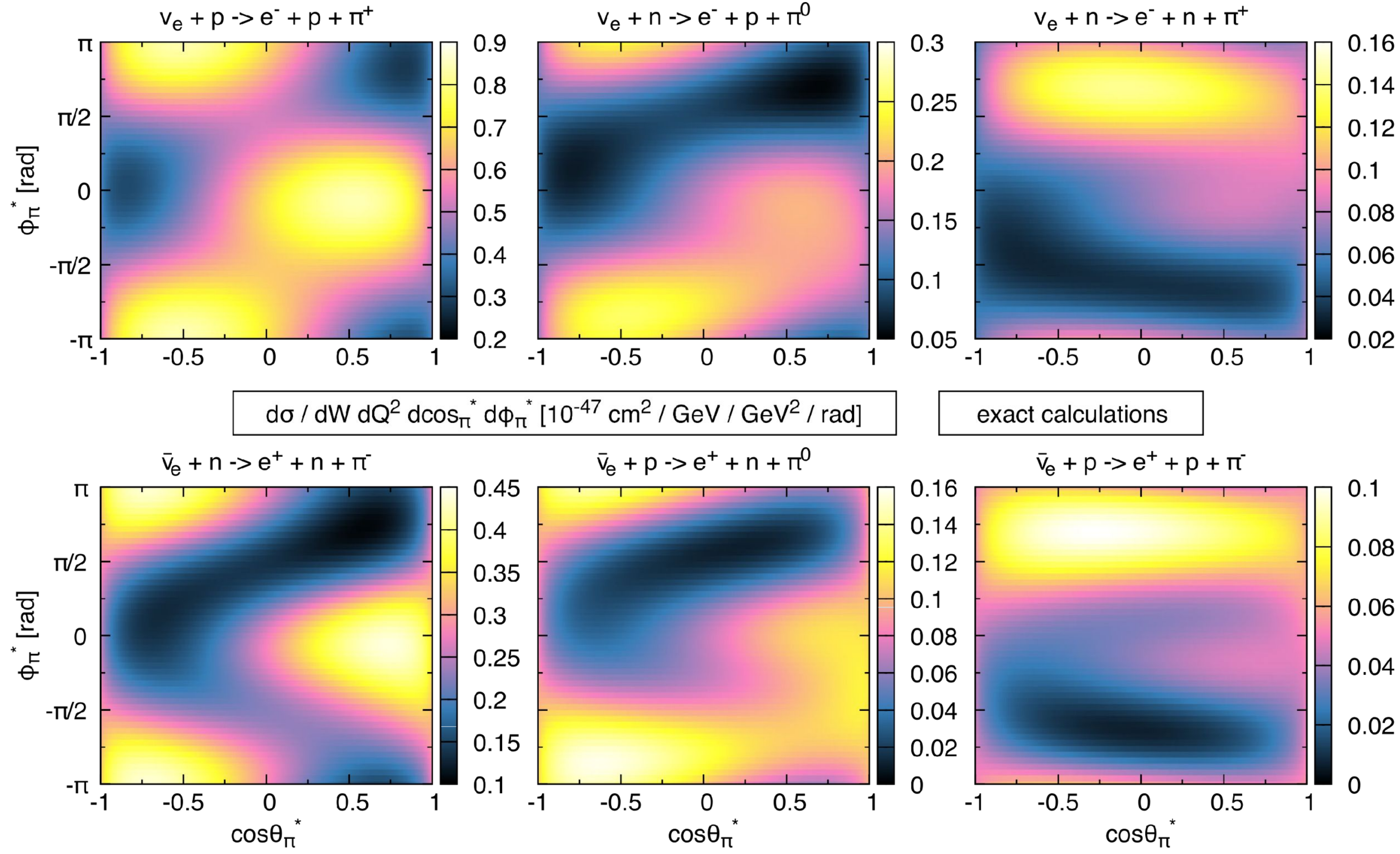
- New algorithm for event generation
  - W, Q^2, θ^*_π, and ϕ^*_π
  - Can be applied to single π production from any theory prediction

- Used to implement the Ghent low-energy model
  - Phys. Rev. D 95, 113007 (2017)





Ghent low-energy model for single-pion production



Phys. Rev. D 103, 053003 (2021)

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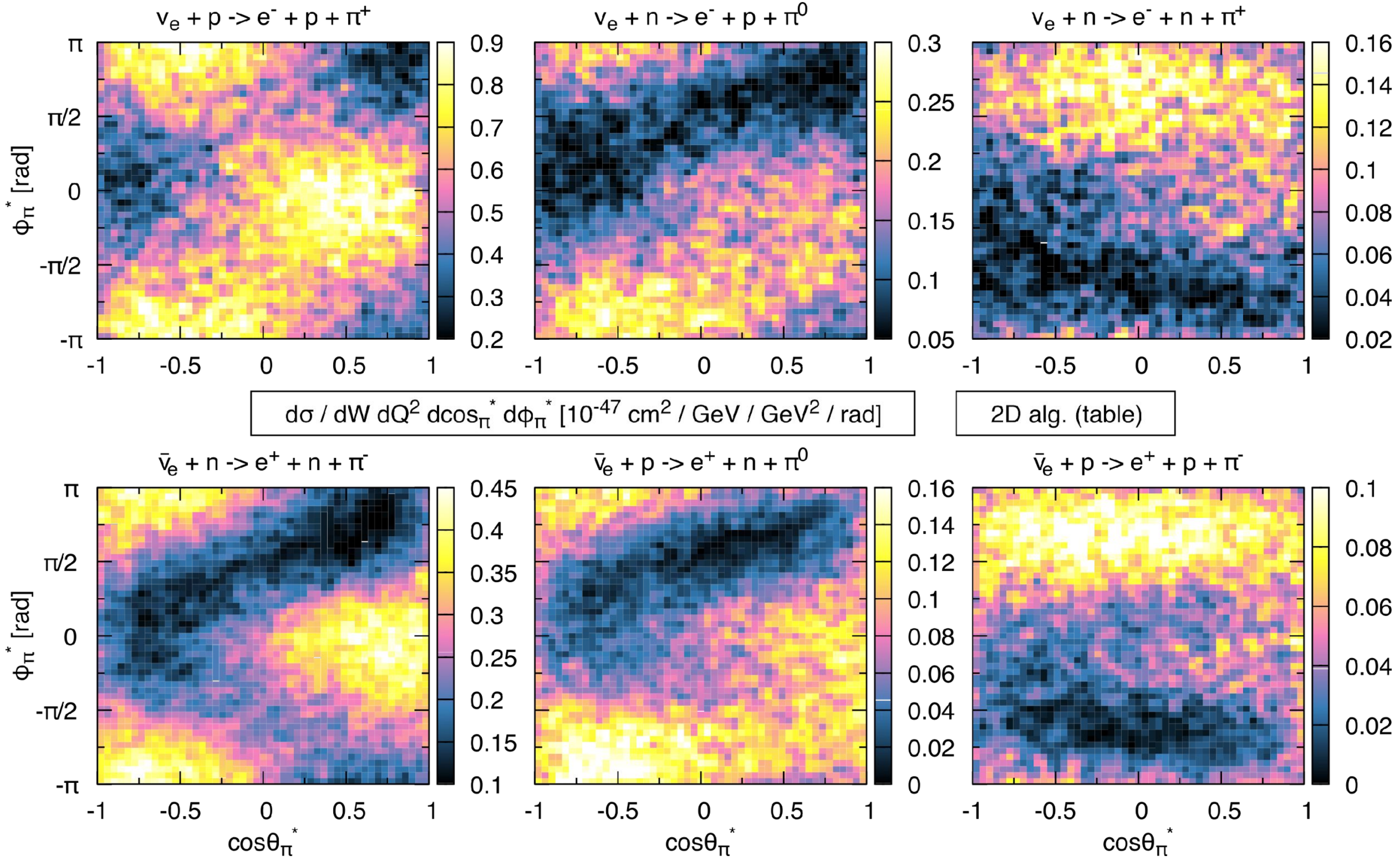


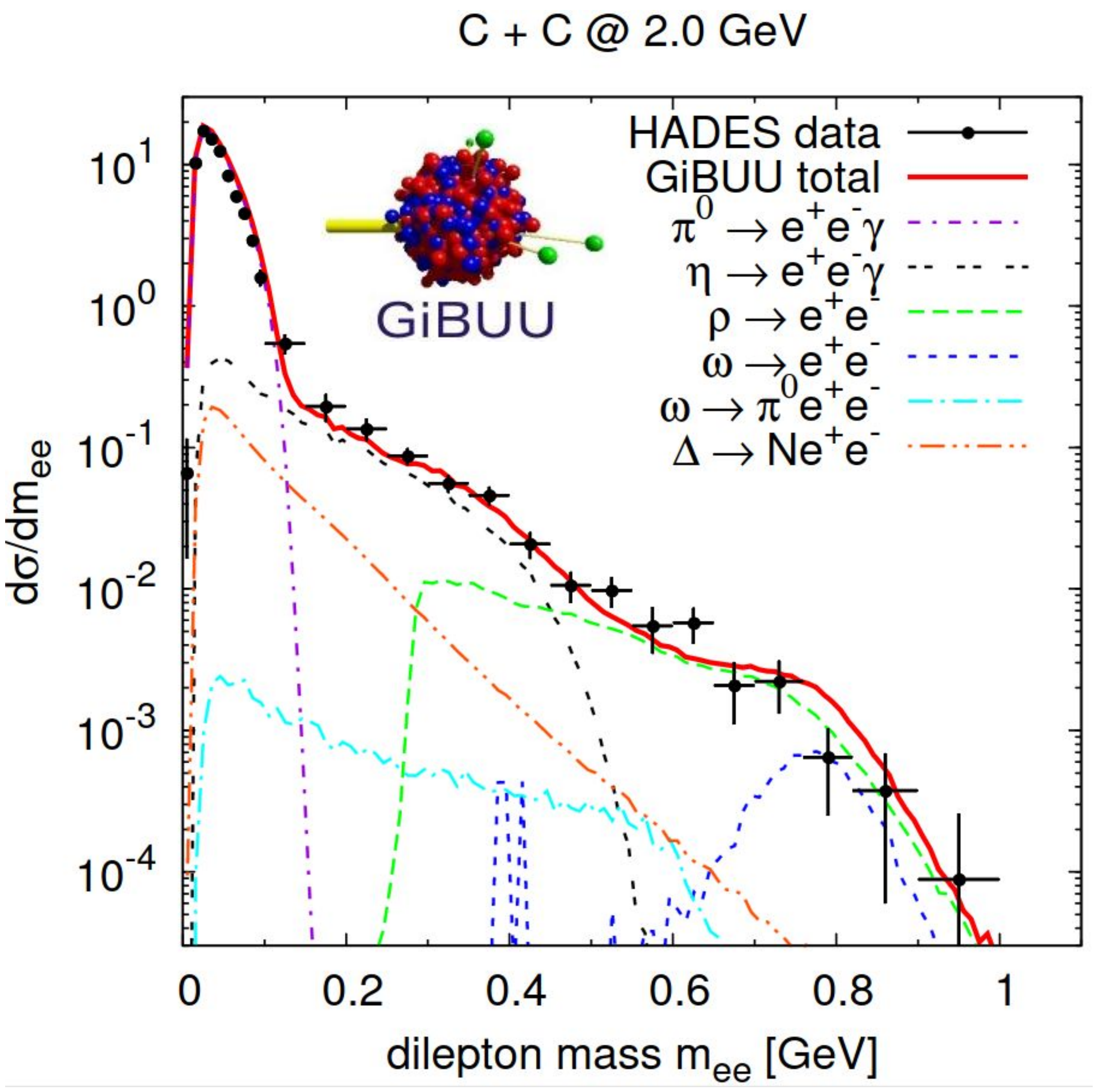
[Phys. Rev. D 103, 053003 (2021)]

Giessen Boltzmann-Uehling-Uhlenbeck Project (GiBUU)

- General nuclear reaction simulation
  - Nuclei and hadron-nucleus (early 90s)
  - γ, e, and ν added later

- Longstanding support for consistent e/ν interaction modeling
  - But other generators have been catching up!

- Commonly used as a reference model
  - Not yet a primary generator for experiments
  - Similar situation for NuWro



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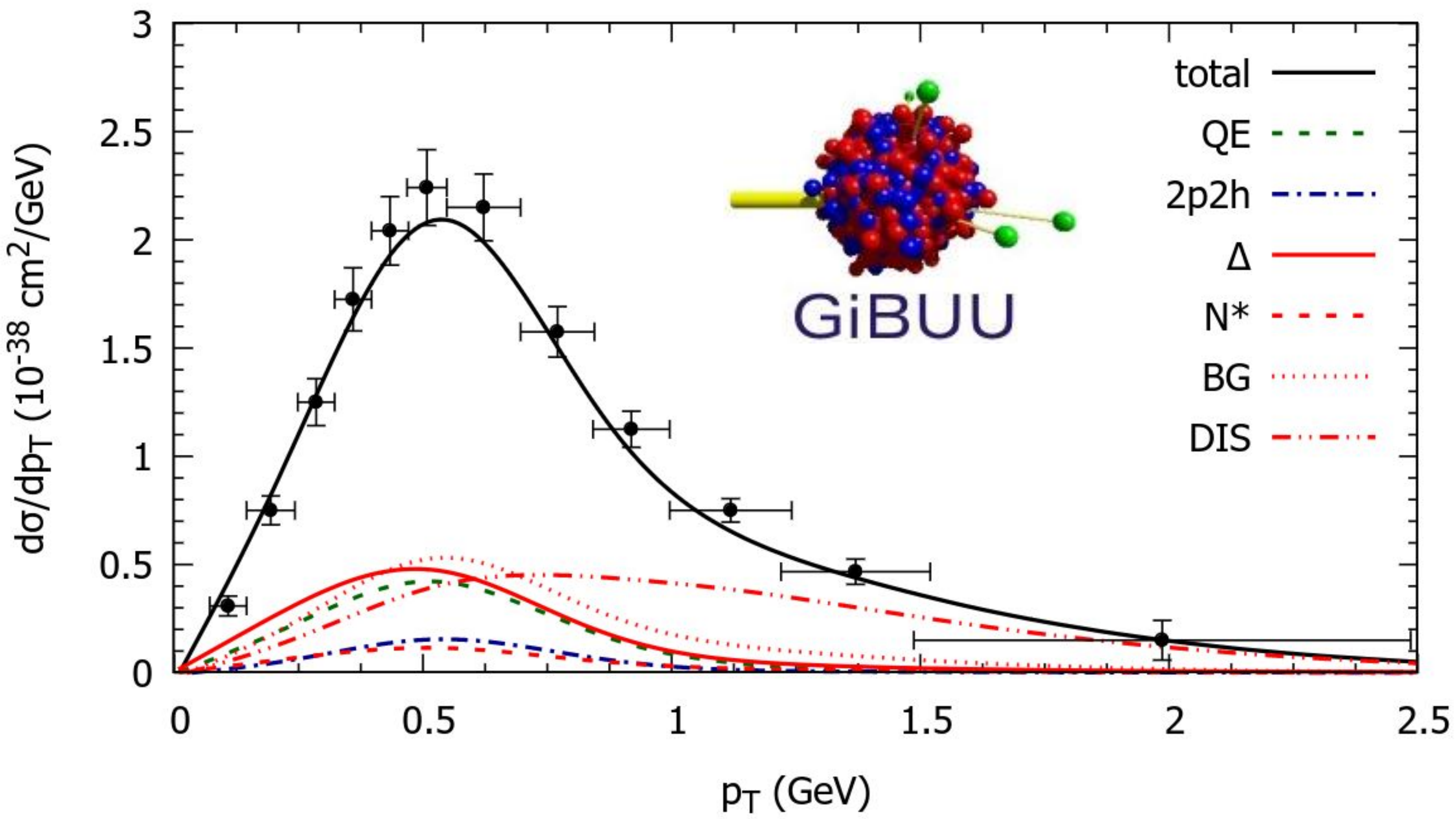
arXiv:2308.16161

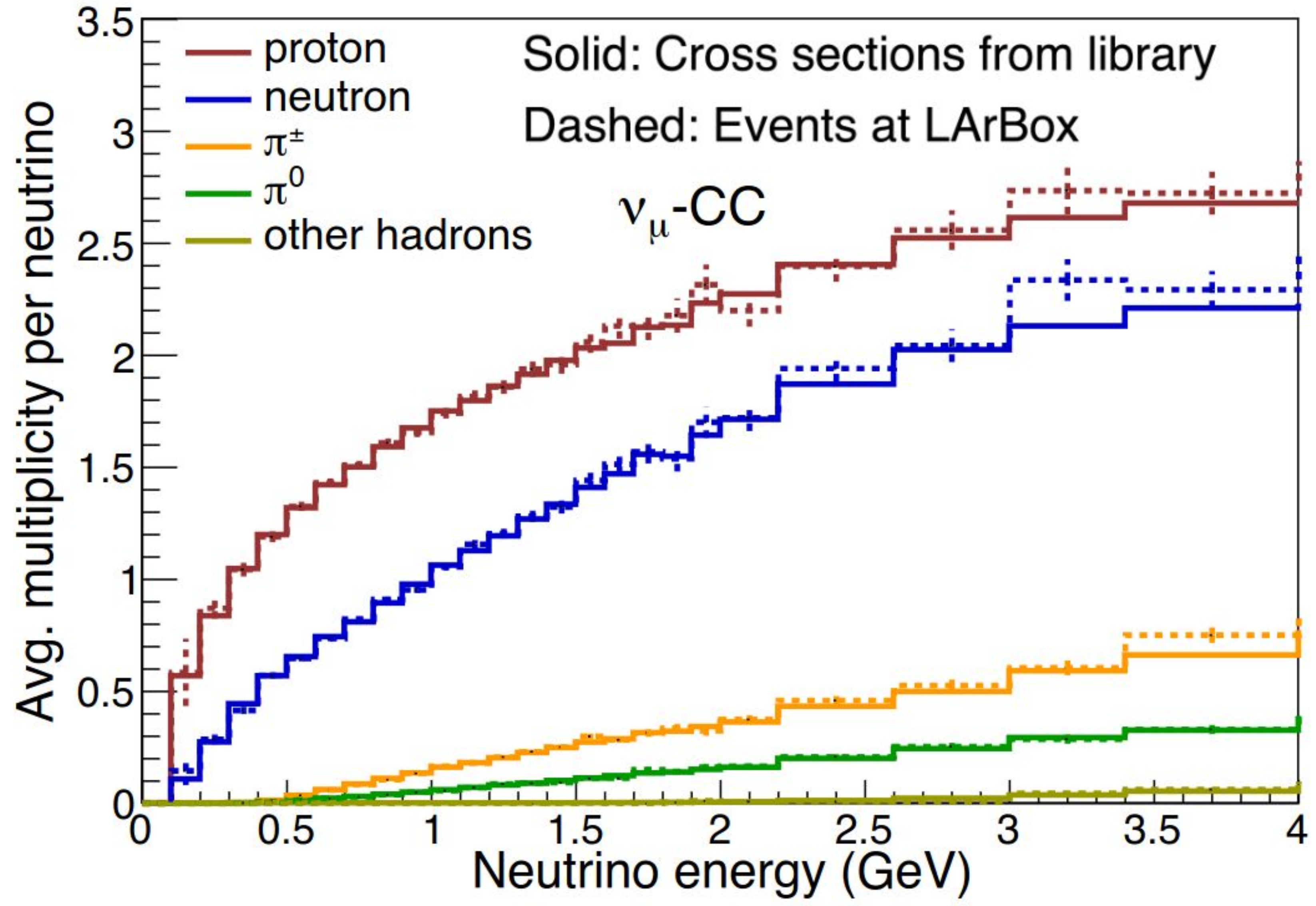


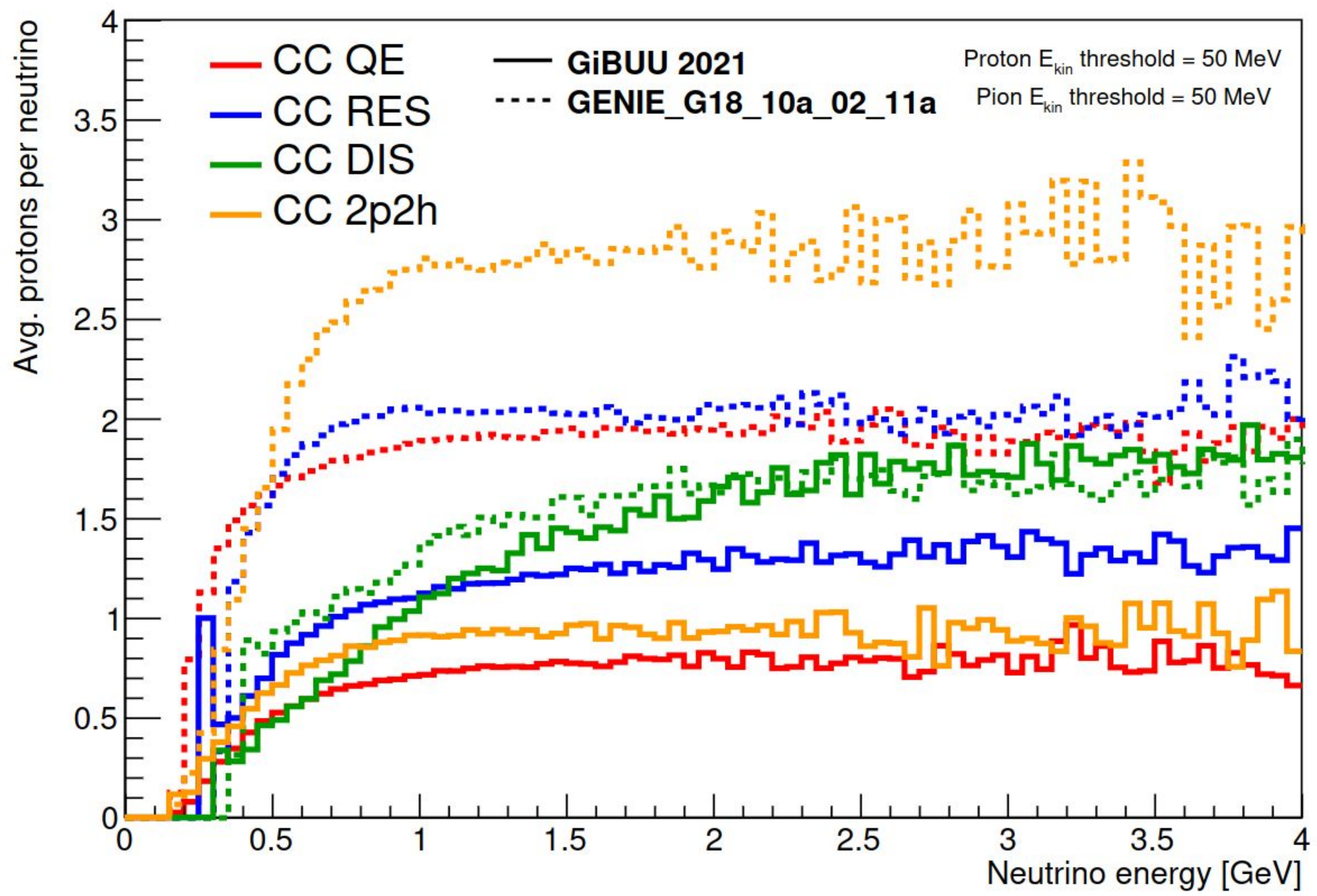
MINERvA inclusive charged-current ν_μ data from Phys. Rev. D 101, 112007 (2020)

GiBUU integration for experimental production

arXiv:2311.14286

- Ongoing effort by University of Texas at Arlington group
  - First "customer" is SBND
- Pre-generate a large library of GiBUU events
- Inject these into a GENIE-based workflow using the evtLib tool
  - Modifications to evtLib for non-unit weights, GiBUU channel labels, etc.
- Early stages of designing a related systematic uncertainty treatment

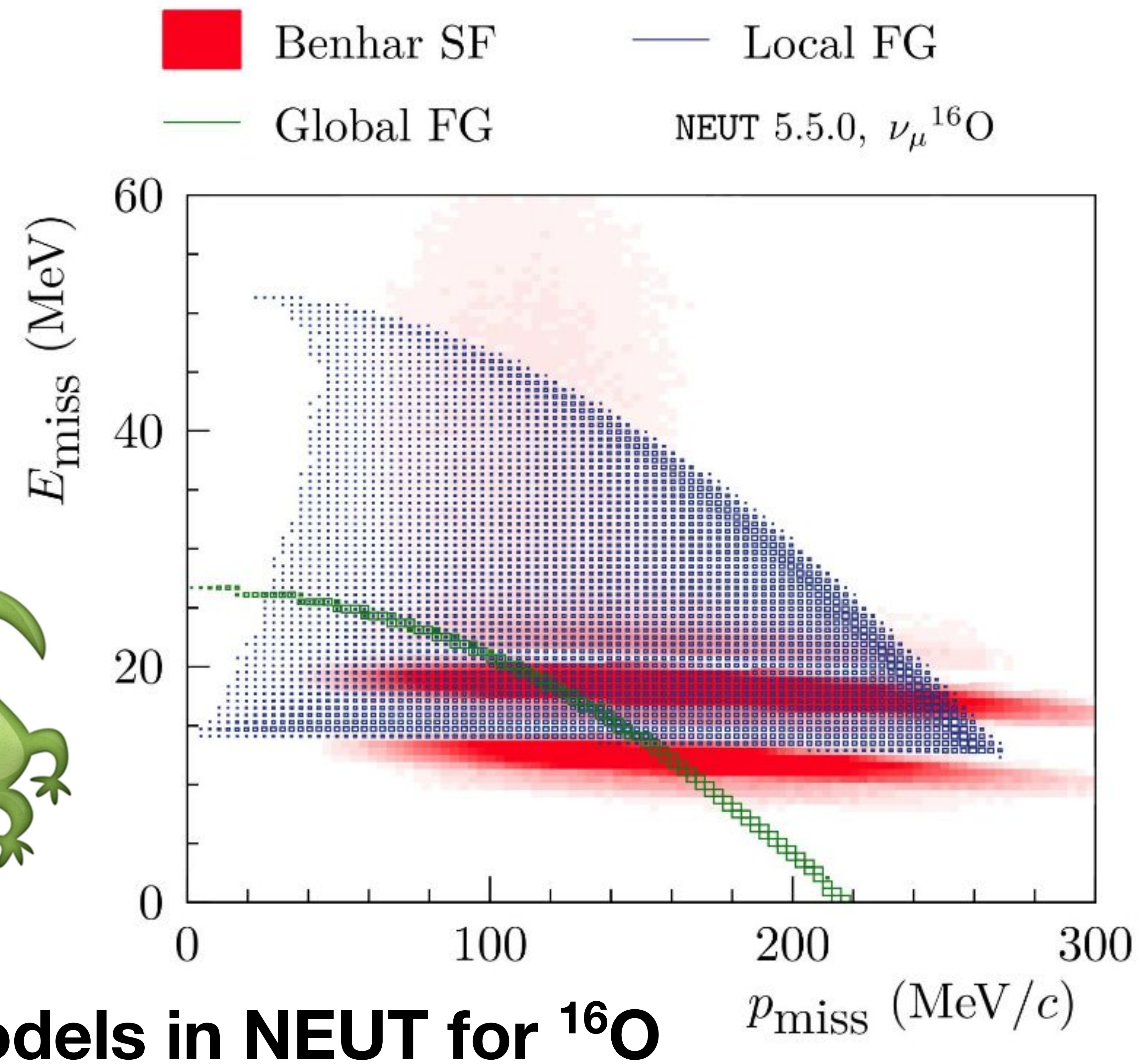




The NEUT event generator

```
**********************************************************************
*     ----------------------
      SUBROUTINE RNAZI(C,S)
*     ----------------------
*
*     (Purpose)
*       Give cosine and sine of random direction
*
*     (Input)
*       NONE
*
*     (Output)
*       C      : COSINE OF RANDOM DIRECTION
*       S      : SINE OF RANDOM DIRECTION
*
*     (Creation Date and Author)
*       1978.09.08 ; S.Yamada, A.Sato
*       1995.02.03 ; K. KANEYUKI  FOR S.K.
*                    RANAZI -> RNAZI
*
**********************************************************************
```

- History stretches back several decades
  - Original application: neutrino backgrounds for nucleon decay in Kamiokande
- Primary generator for T2K & Super-K
  - Plays a similar role for them as GENIE does for Fermilab experiments
- Open-source release planned for upcoming v6
  - Only major generator without an official logo
  - I've opted to use a cartoon of a **newt** (stolen from past talks by other speakers)



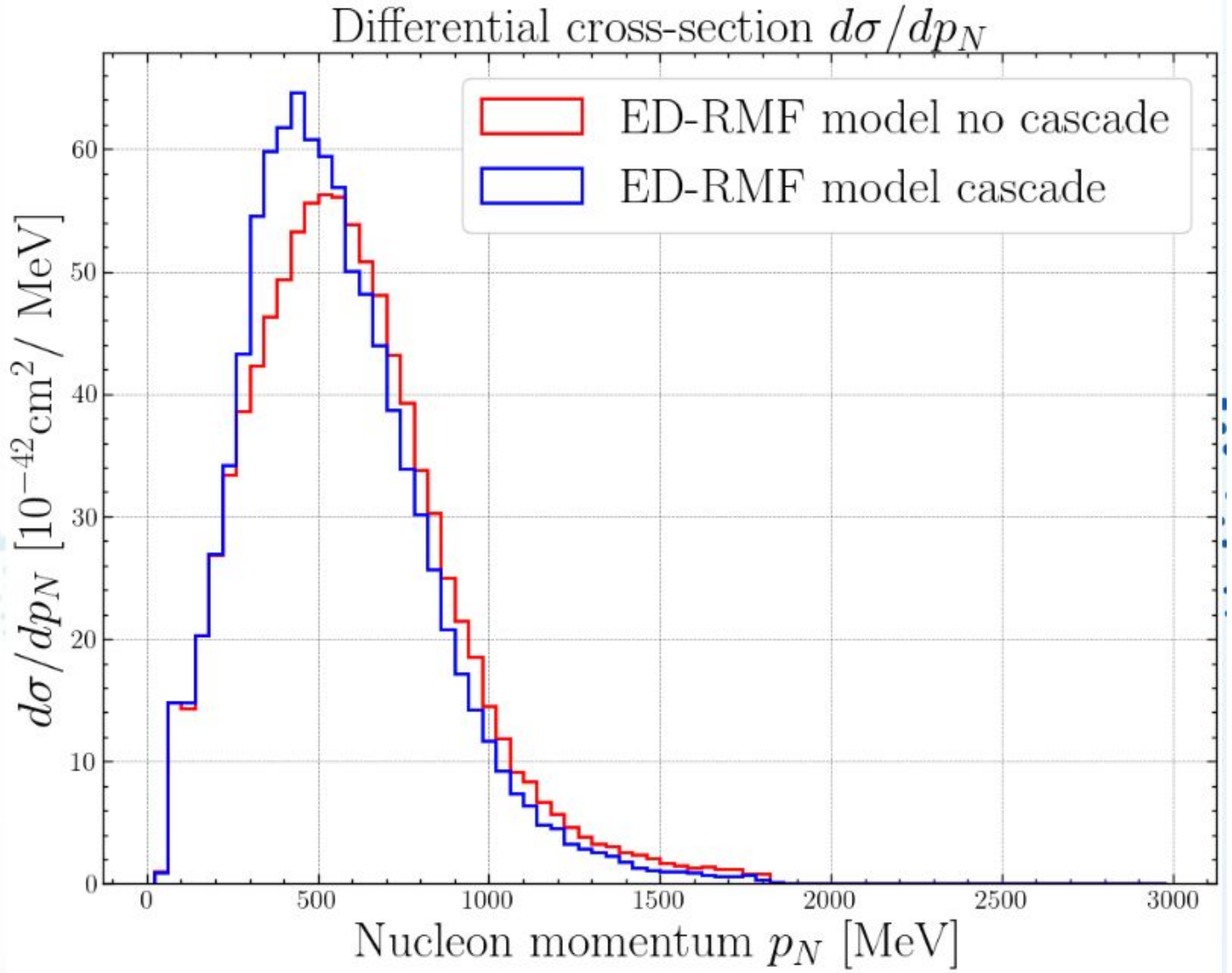
Nuclear models in NEUT for ^{16}O

RMF nuclear model in NEUT

- Cooperation between experimentalists & theorists in NEUT development
  - This is one of multiple recent success stories

- Work is ongoing to incorporate a Relativistic Mean Field nuclear model
  - See recent talk by Jake McKean on progress

- Basic validation done, work ongoing to address double-counting of elastic FSI



CCQE differential cross section **with** and **without** FSI cascade

Towards standardized neutrino community tools

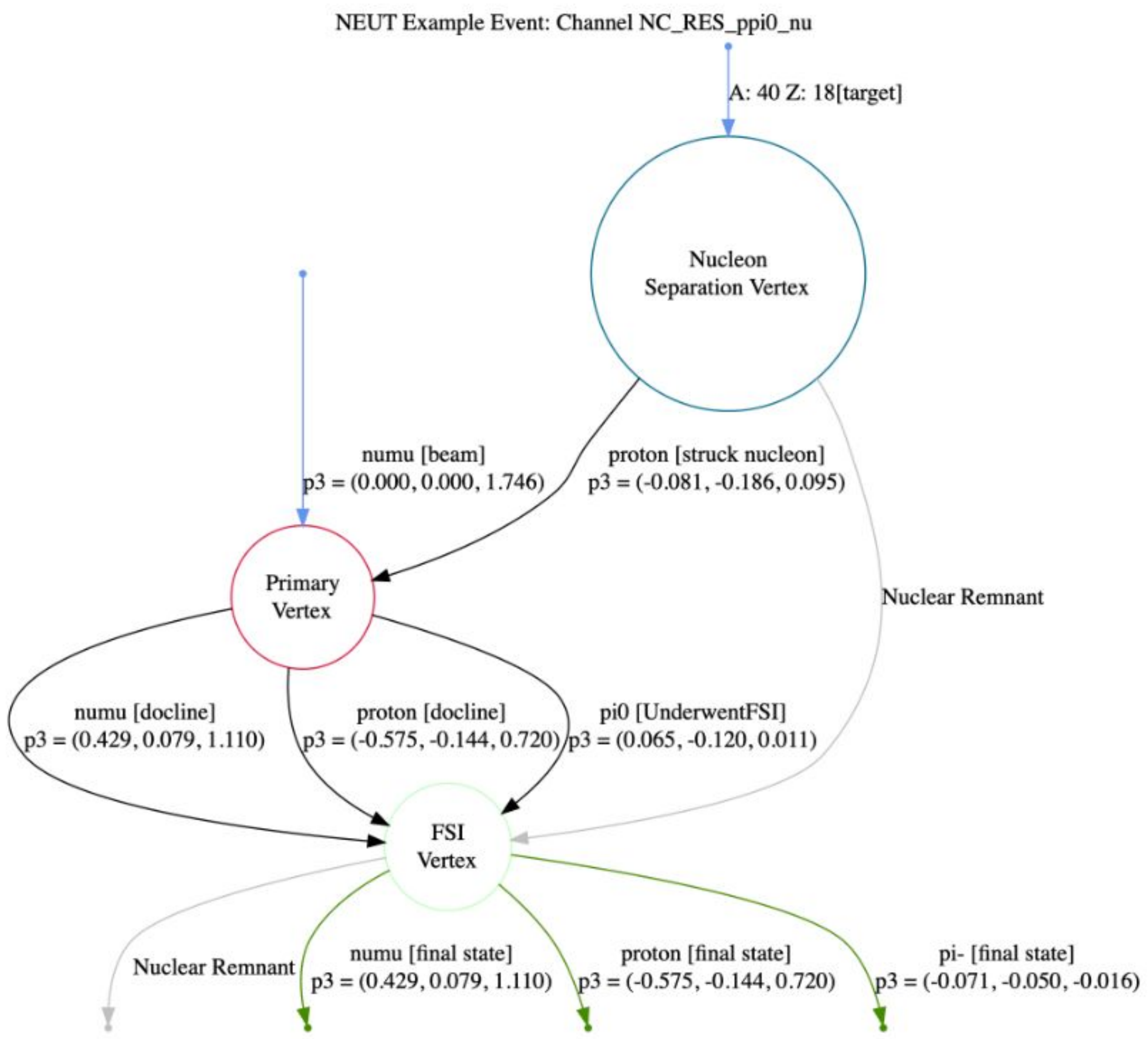
- NEUT developers have played an important role in this area
- No universal way of interfacing generators with beam/detector simulations, no official common format
  - Technical barrier for experiments to have the best variety of models
  - LHC solved this problem and continues to reap the benefits
- Proposed **"NuHepMC" standard** co-developed by NEUT developer Luke Pickering

arXiv:2310.13211

NuHepMC: A standardized event record format for neutrino event generators

S. Gardiner[a], J. Isaacson[a], L. Pickering[b]

[a] *Fermi National Accelerator Laboratory, P.O. Box 500, Batavia, IL 60510, USA*
[b] *STFC, Rutherford Appleton Laboratory, Harwell Oxford, United Kingdom*



Towards standardized neutrino community tools

- NEUT developers have played an important role in this area

- No universal way of interfacing generators with beam/detector simulations, no official common format
  - **Technical barrier** for experiments to have the best variety of models
  - LHC solved this problem and continues to reap the benefits

- Proposed **"NuHepMC" standard** co-developed by NEUT developer Luke Pickering

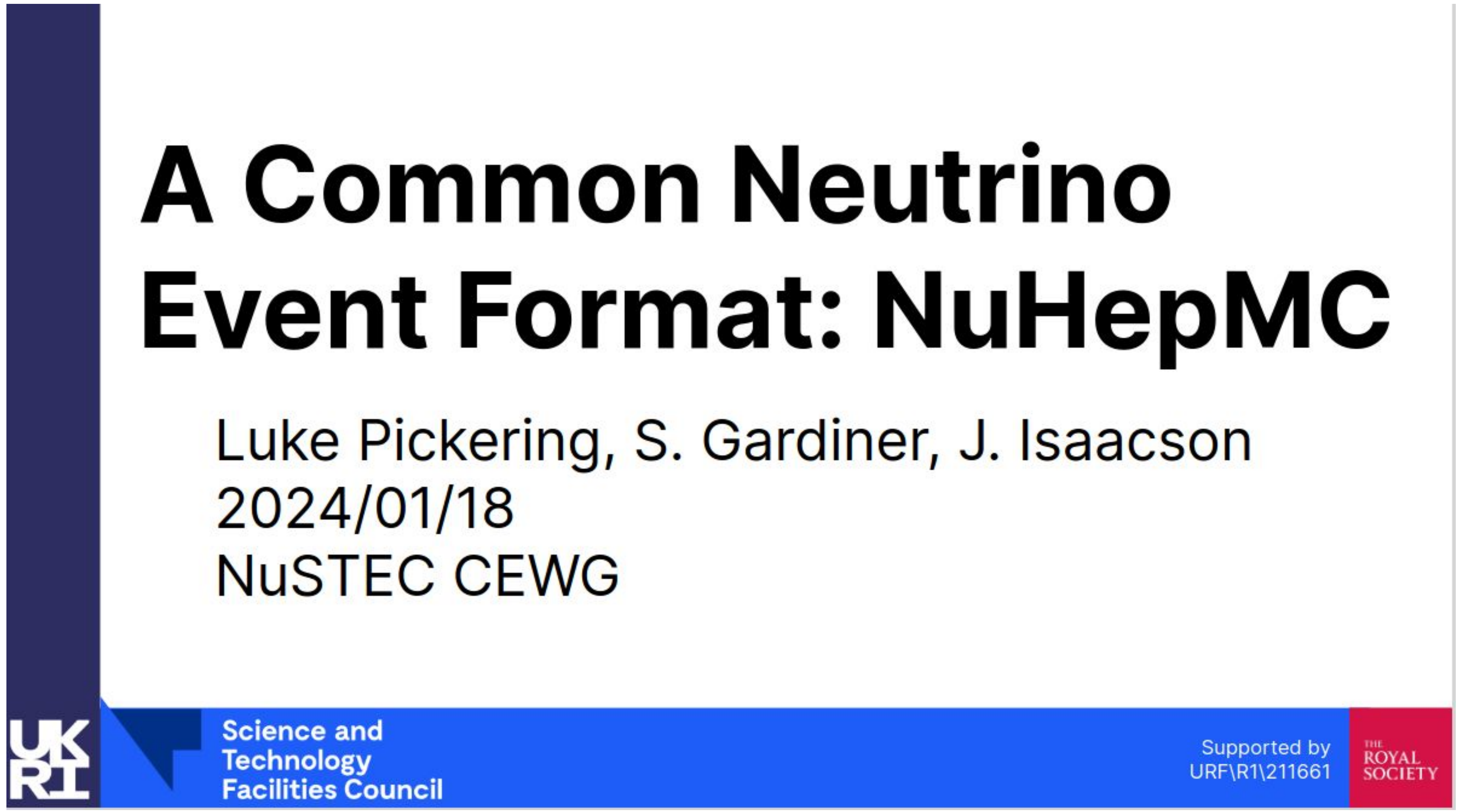
[arXiv:2310.13211]

NuHepMC: A standardized event record format for neutrino event generators

S. Gardiner[a], J. Isaacson[a], L. Pickering[b]

[a]*Fermi National Accelerator Laboratory, P.O. Box 500, Batavia, IL 60510, USA*
[b]*STFC, Rutherford Appleton Laboratory, Harwell Oxford, United Kingdom*

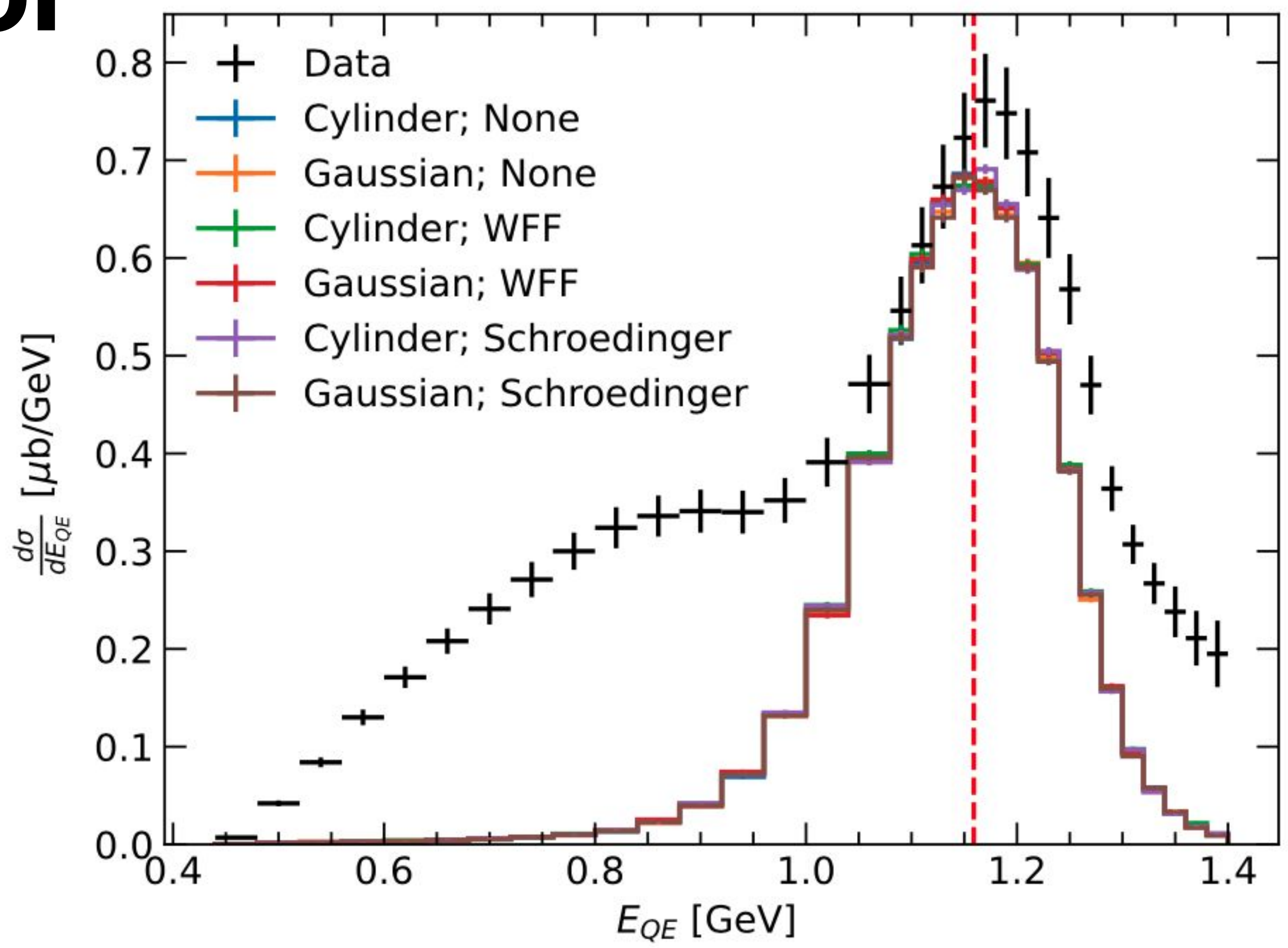
[NuSTEC seminar by Luke]



The ACHILLES event generator

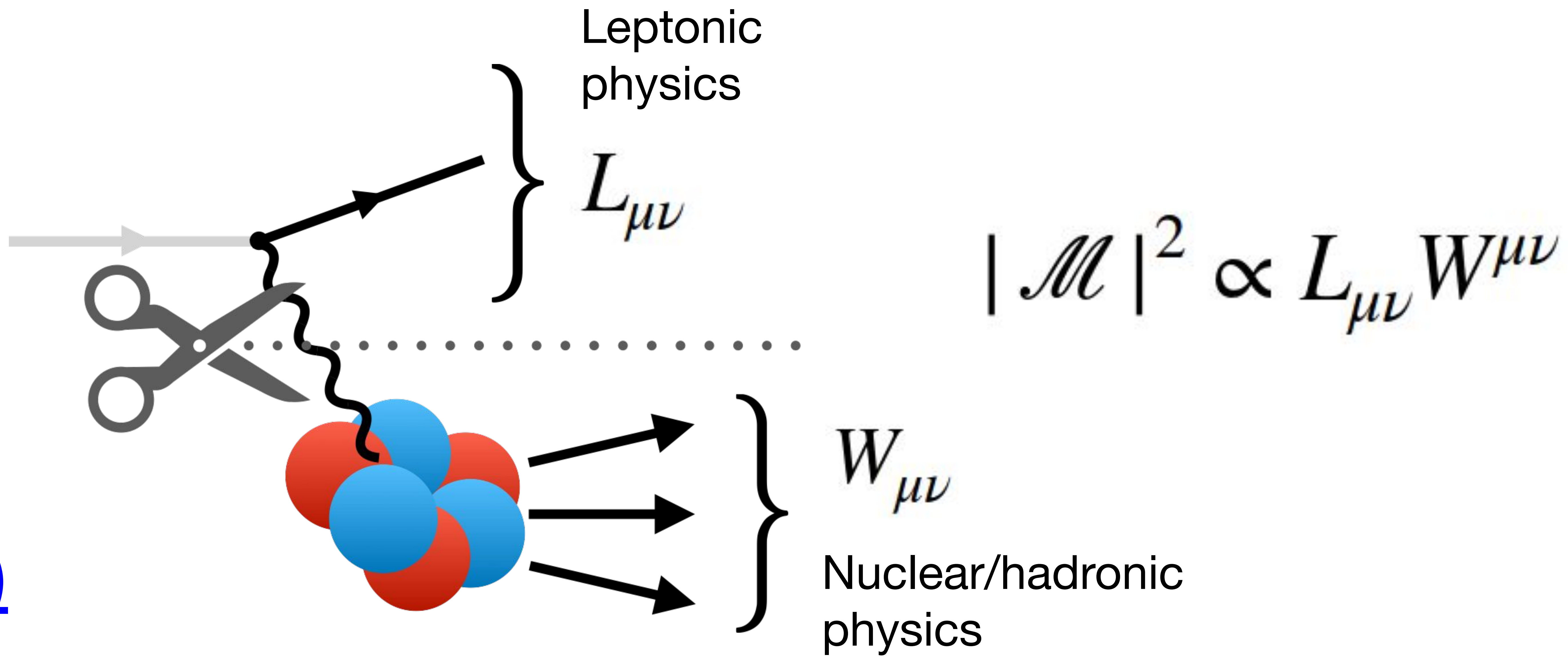
Phys. Rev. D 107, 033007 (2023)

A CHIcagoLand Lepton Event Simulator

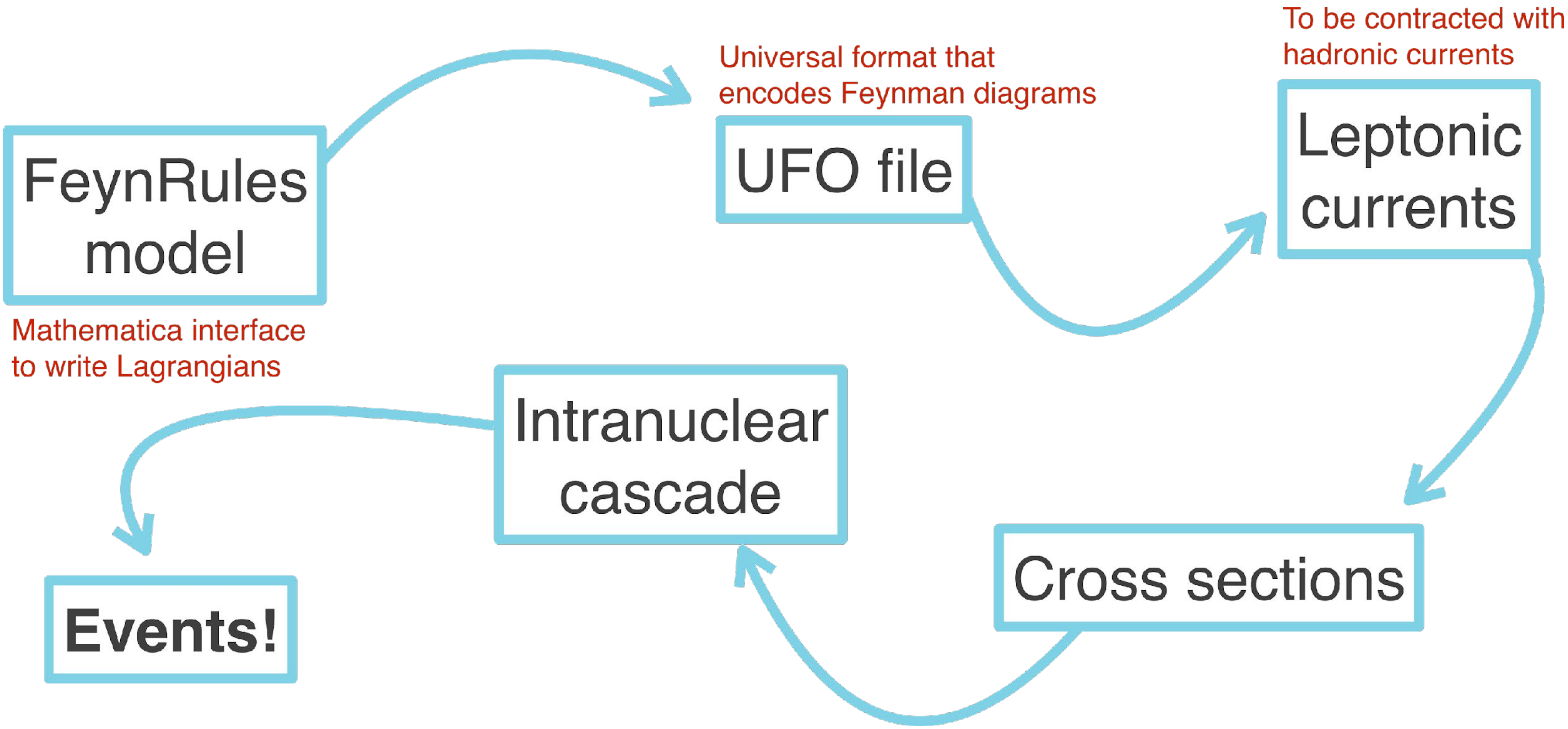


- New theory-driven event generator, Fermilab-led
  - Quasielastic-only so far, but development continues

- Innovations
  - New approach to FSI: Phys. Rev. C 103, 015502 (2021)
  - **Automated leptonic tensor:** Phys. Rev. D 105, 096006 (2022)



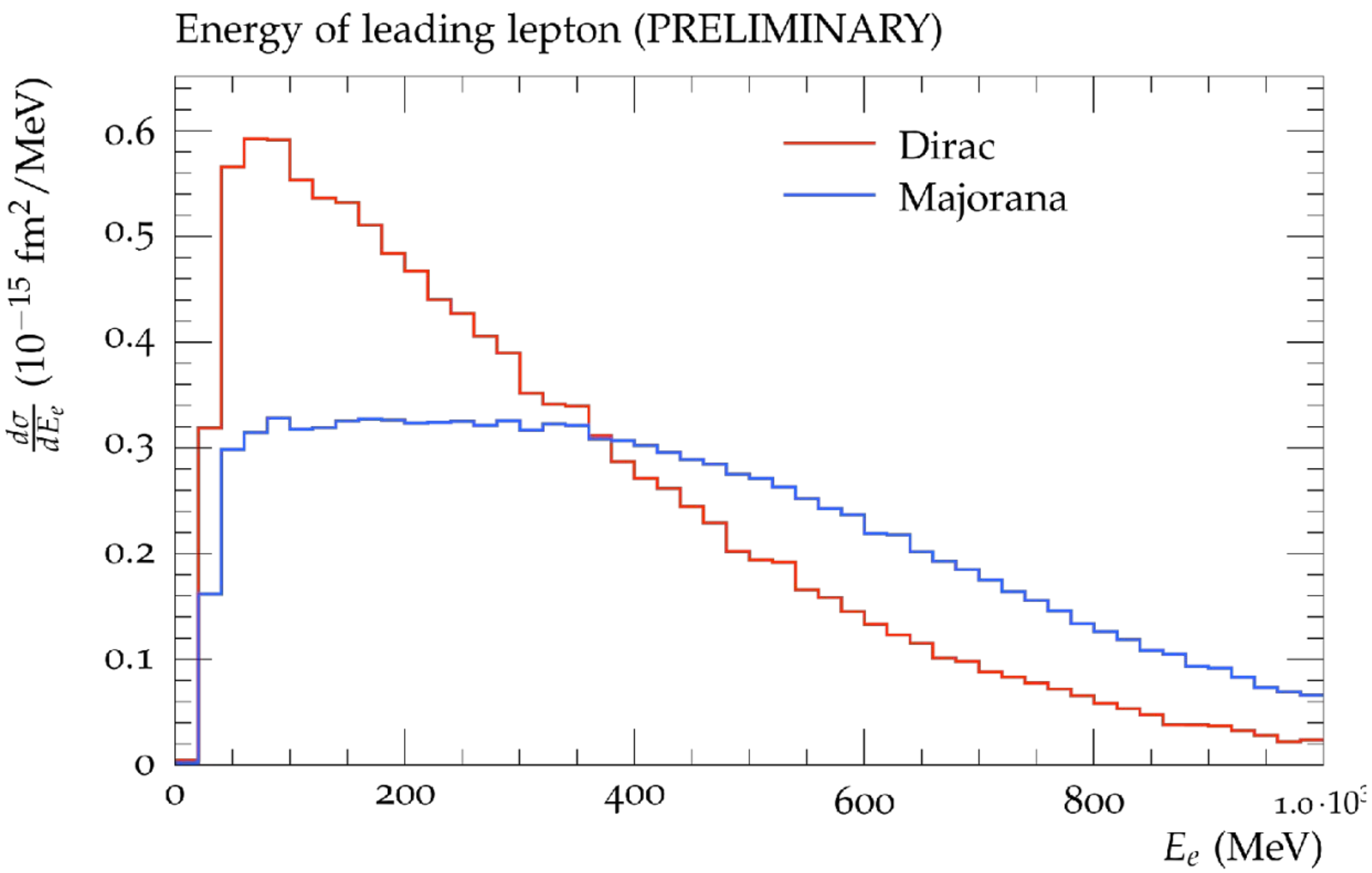
ACHILLES approach to automating the leptonic tensor

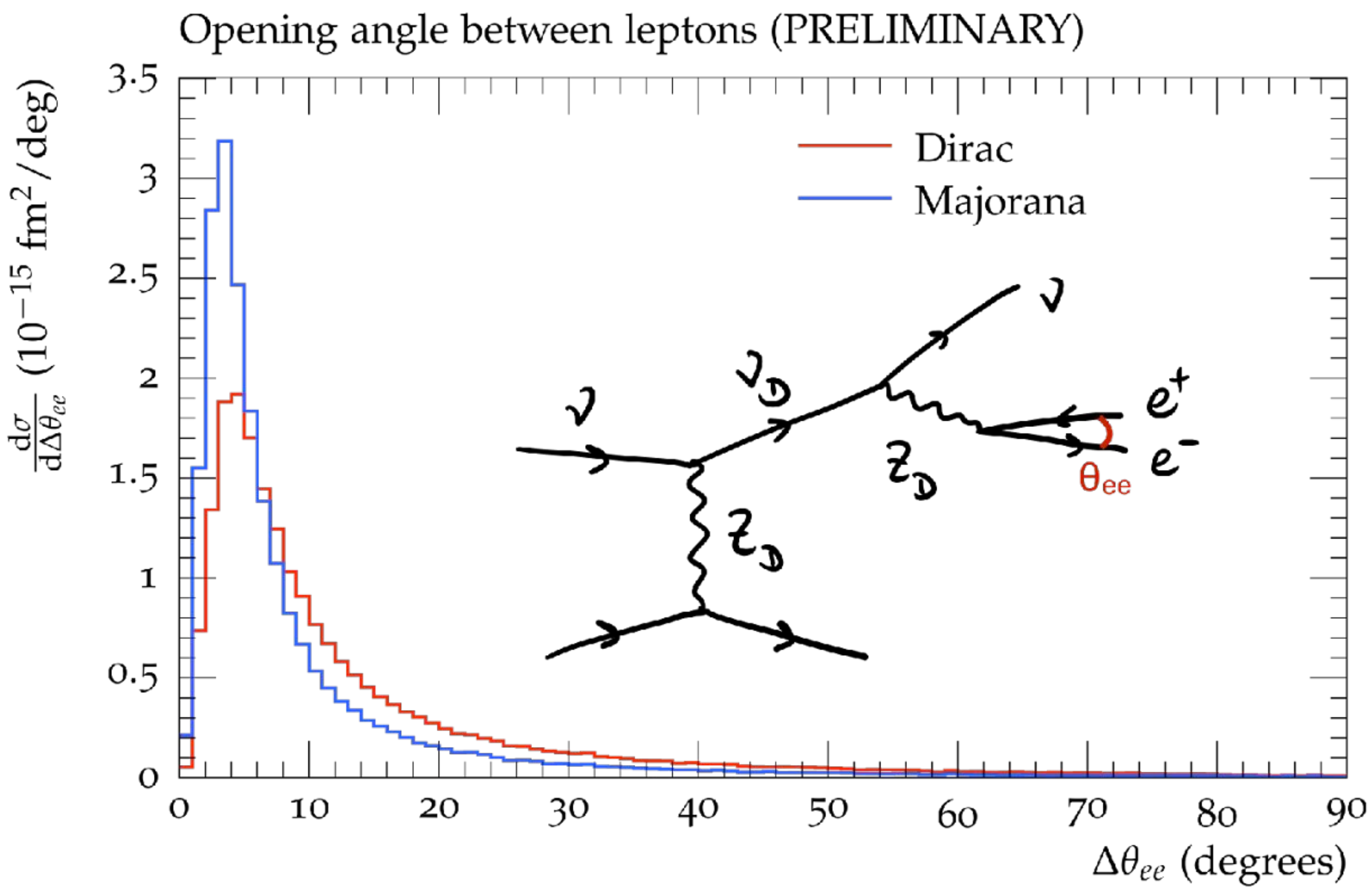


Slide credit: P. Machado

Example application to exotic physics

Full calculation of scattering amplitude can account for relevant effects, such as spin-correlations, which may end up having an O(1) effect on final state kinematics

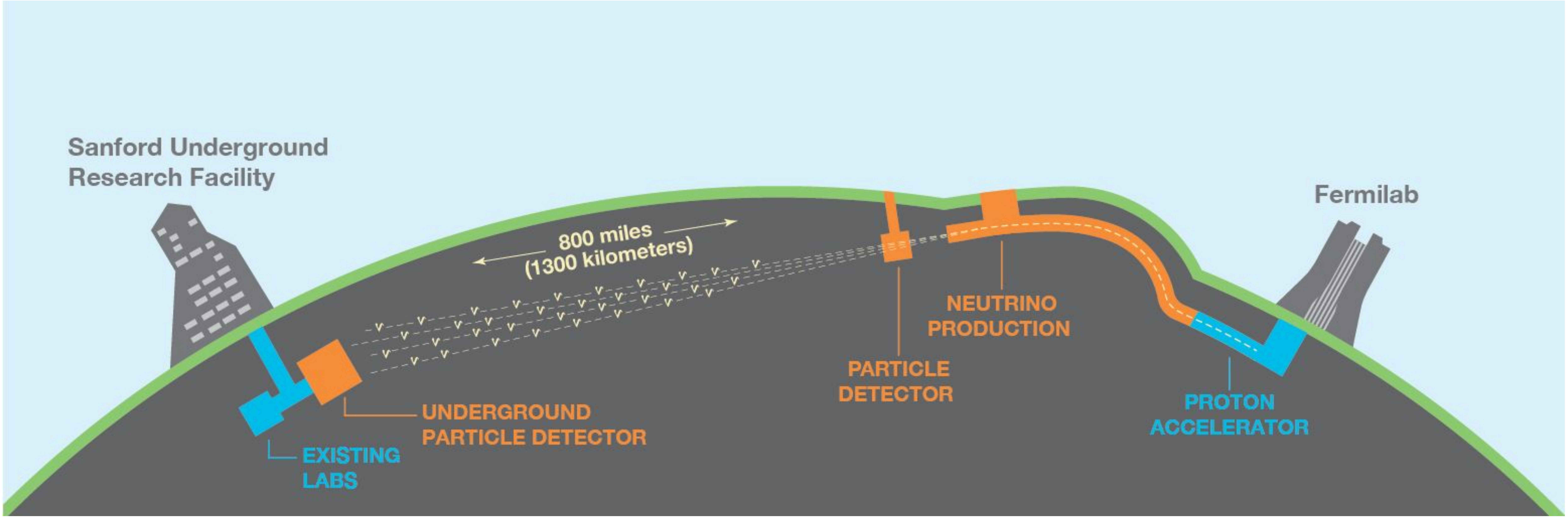




Dark neutrino observables folded against MiniBooNE ν_μ flux

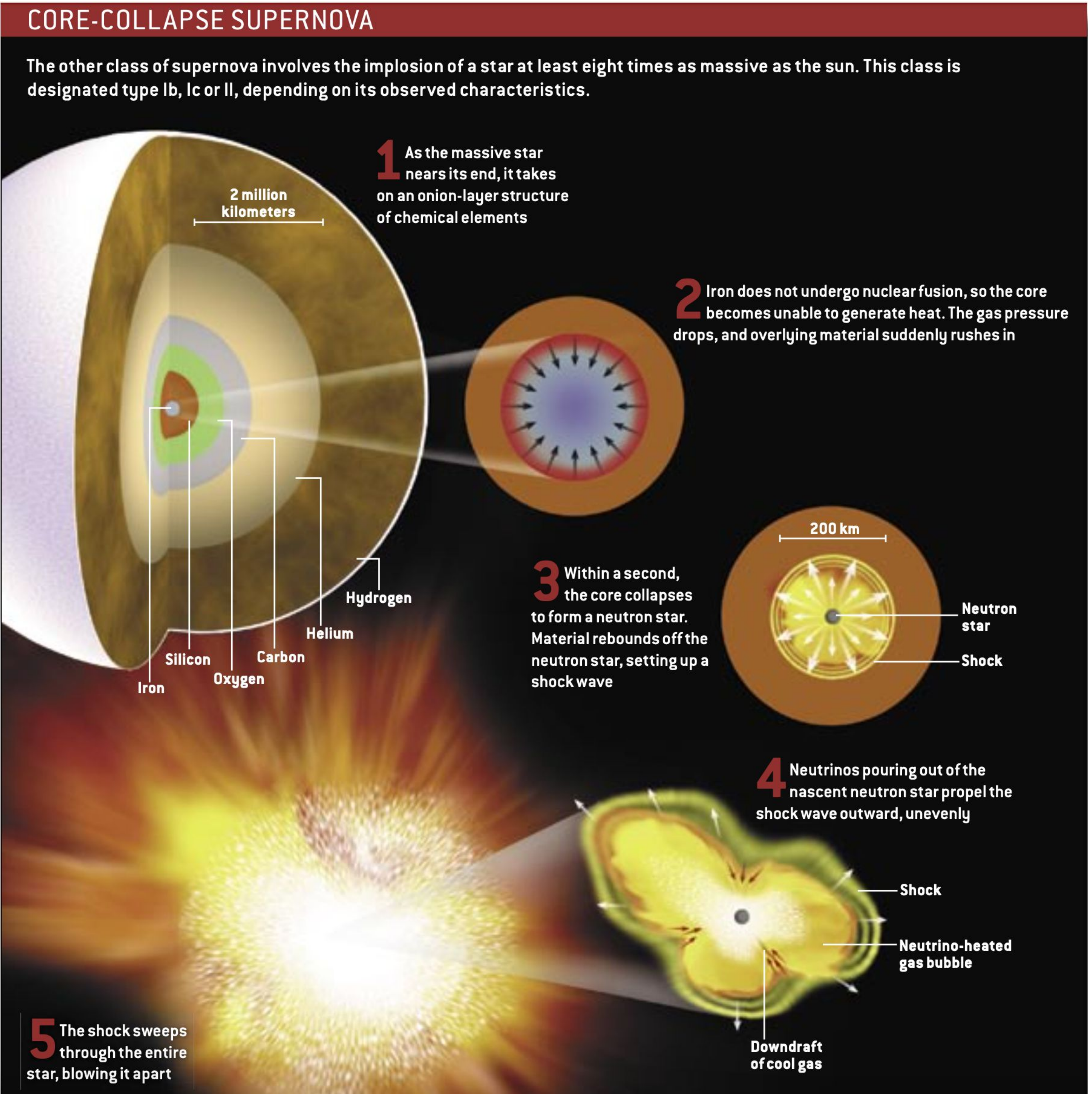
Slide credit: P. Machado

The Deep Underground Neutrino Experiment (DUNE)



- World's most powerful neutrino beam (1.2 MW+) and two groups of detectors
  - **Far detector**: Initially 2 × 10 kton (active volume) liquid argon detectors
  - **Near detector**: Multi-component (including liquid and gaseous argon)
- Data taking to begin circa 2029

Core-collapse supernovae: nearly-perfect neutrino bombs



- Deaths of stars > 10 $M_\odot$
- 99% of gravitational binding energy converted to ~10^{58} neutrinos
- Many ν_e produced in initial neutronization burst (~10 ms)
- Core cools via all-flavor neutrino radiation in ~10 s
- Momentarily outshines visible universe (in neutrinos)

[Scientific American 295, 42-49 (2006)]

MARLEY: Model of Argon Reaction Low Energy Yields

- Event generator focused specifically on neutrino energies below ~100 MeV
- Emphasizes ν_e CC on ^{40}Ar, extensible to other channels
- Two dedicated publications so far:
  - Physics models: [Phys. Rev. C 103, 044604 (2021)]()
  - Numerical implementation: [Comput. Phys. Commun. 269, 108123 (2021)]()
- Written in C++14, few dependencies

Nuclear de-excitations in low-energy charged-current ν_e scattering on ^{40}Ar

Steven Gardiner[1,2,*]

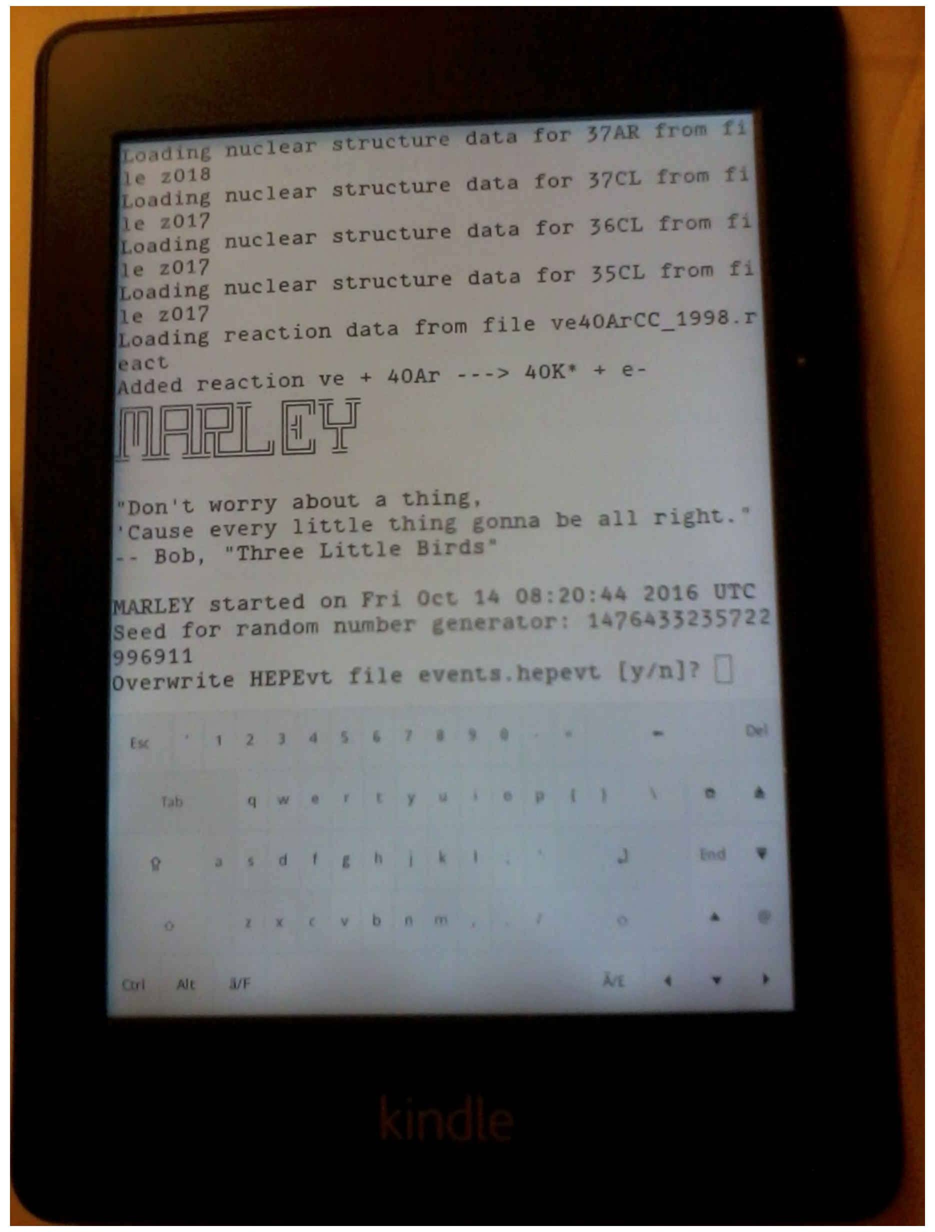
[1] *Fermi National Accelerator Laboratory, P.O. Box 500, Batavia, Illinois 60510 USA*
[2] *Department of Physics, University of California, Davis, One Shields Avenue, Davis, California 95616 USA*

(Dated: September 15, 2020)

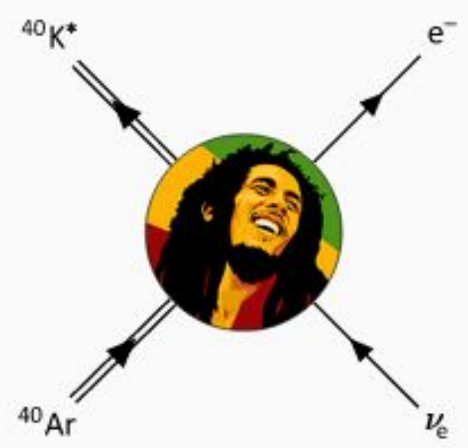
Background: Large argon-based neutrino detectors, such as those planned for the Deep Underground Neutrino Experiment (DUNE), have the potential to provide unique sensitivity to low-energy (~10 MeV) electron neutrinos produced by core-collapse supernovae. Despite their importance for neutrino energy reconstruction, nuclear de-excitations following charged-current ν_e absorption on ^{40}Ar have never been studied in detail at supernova energies.

Purpose: I develop a model of nuclear de-excitations that occur following the $^{40}\mathrm{Ar}(\nu_e, e^-)^{40}\mathrm{K}^*$ reaction. This model is applied to the calculation of exclusive cross sections.

Methods: A simple expression for the inclusive differential cross section is derived under the allowed approximation. Nuclear de-excitations are described using a combination of measured γ-ray decay schemes and the Hauser-Feshbach statistical model. All calculations are carried out using a novel Monte Carlo event generator called MARLEY (Model of Argon Reaction Low Energy Yields).



MARLEY User Guide



Model of Argon Reaction Low Energy Yields

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Docs / Overview

Overview

MARLEY (Model of Argon Reaction Low Energy Yields) is a Monte Carlo event generator for neutrino-nucleus interactions at energies of tens-of-MeV and below. The current version computes inclusive neutrino-nucleus cross sections employing the *allowed approximation*: the nuclear matrix elements are evaluated while neglecting Fermi motion and applying the long-wavelength (zero momentum transfer) limit. De-excitations of the final-state nucleus emerging from the primary interaction are simulated using a combination of tabulated γ-ray decay schemes and an original implementation of the Hauser-Feshbach statistical model.

Input files are provided with the code that are suitable for simulating the charged-current process

$$\nu_e + {}^{40}\mathrm{Ar} \rightarrow e^- + {}^{40}\mathrm{K}^*,$$

coherent elastic neutrino-nucleus scattering (CEvNS) on spin-zero target nuclei, and neutrino-electron elastic scattering on any atomic target. Inclusion of additional reactions and targets is planned for the future.

The material presented here focuses on the practical aspects of MARLEY: installing the code, configuring and running simulations, and analyzing the output events. For more details on the MARLEY physics models, please see the references in the online bibliography.

MARLEY follows an open-source development model and welcomes contributions of new input files and code improvements from the community. A partial list of potential projects for future MARLEY development is available on the developer documentation webpage.

https://www.marleygen.org

MARLEY: Model of Argon Reaction Low Energy Yields

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- Written in C++14, few dependencies

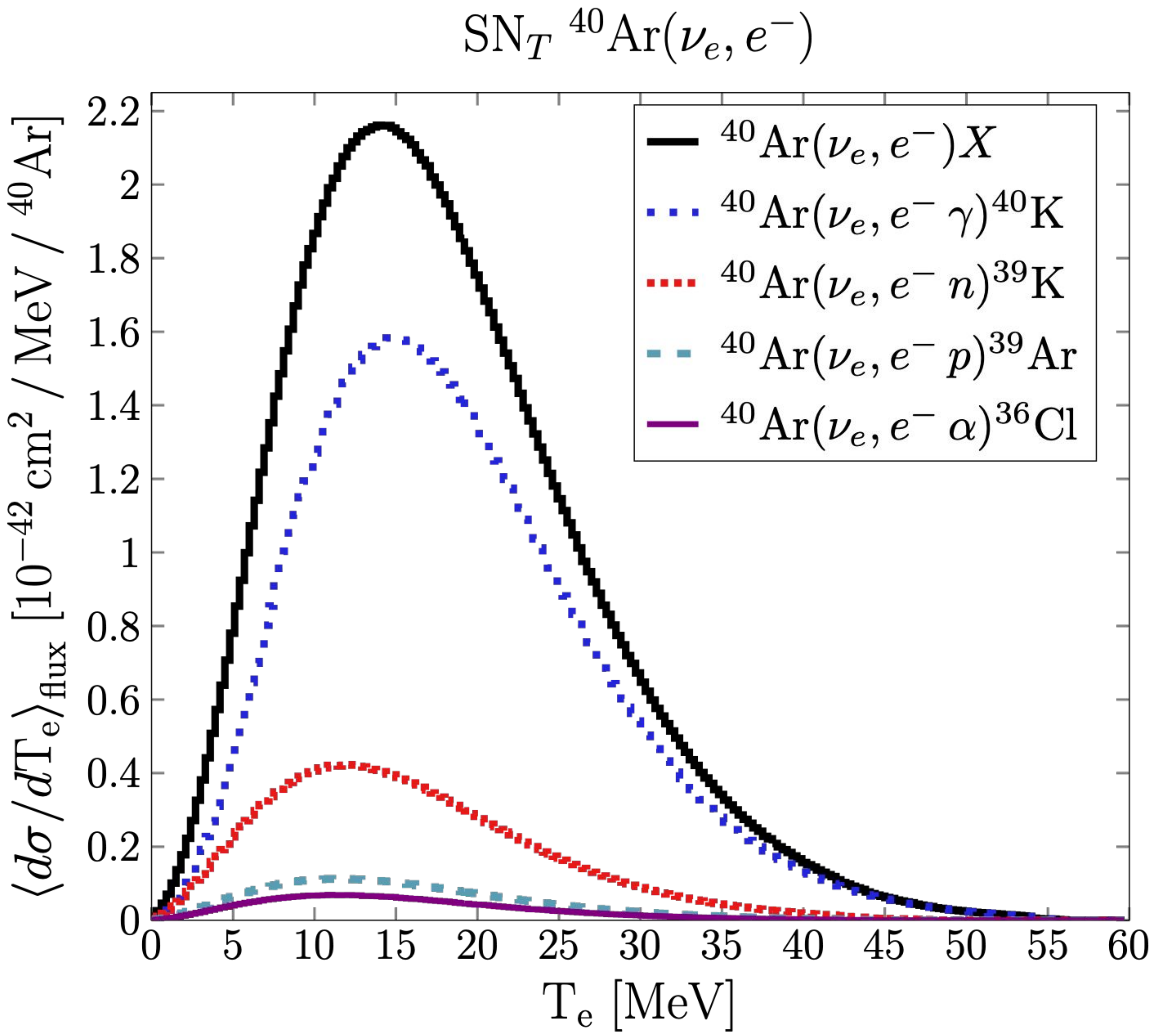
Garage near Escadaria Selarón, Rio de Janeiro

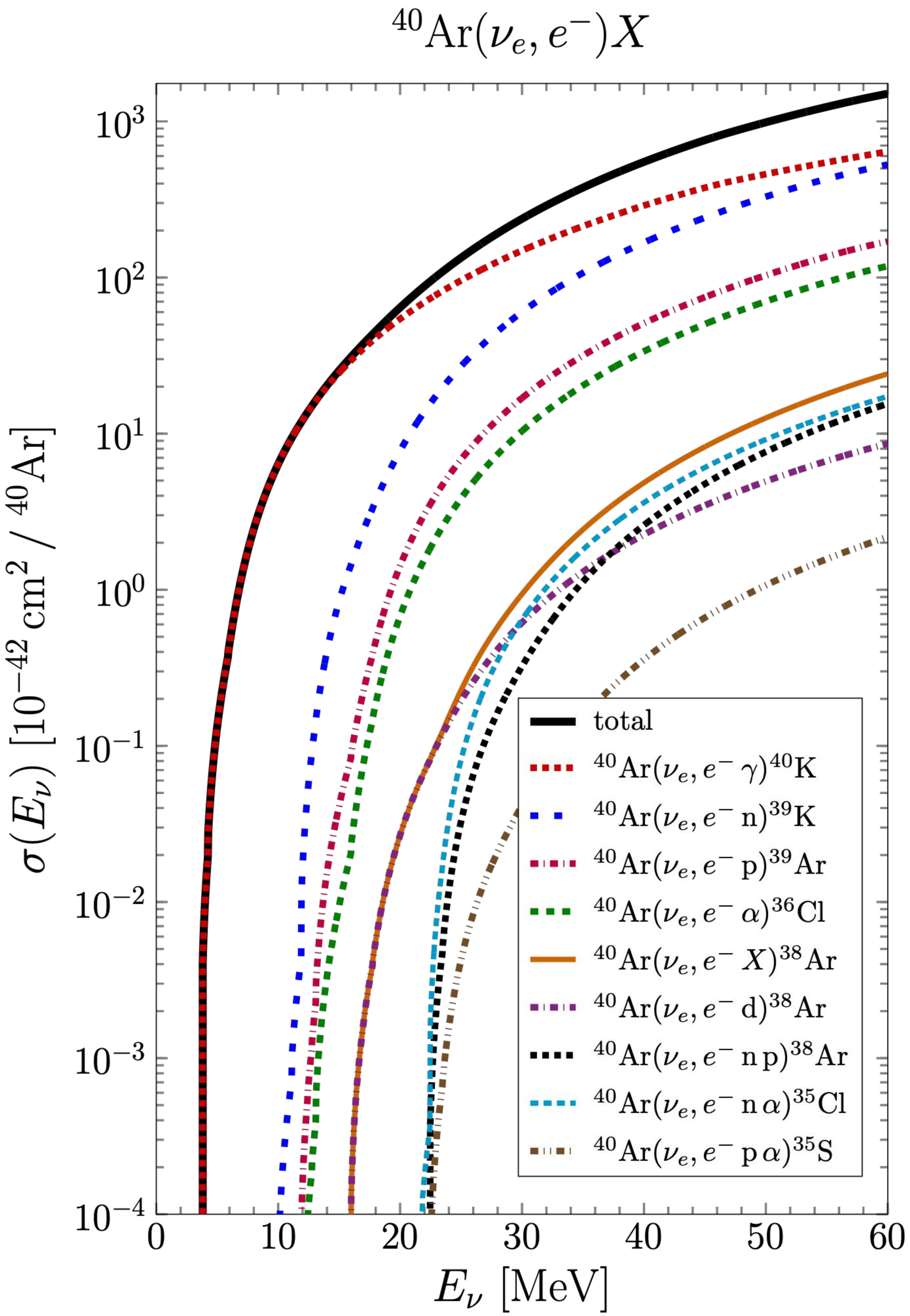
MARLEY v1.2.0 predictions for ^{40}Ar

[Phys. Rev. C 103, 044604 (2021)]

- First calculation of cross sections for **exclusive final states** of the CC ve reaction at O(10 MeV)

- Flux-averaged differential cross sections shown here are for the supernova model described in [Phys. Rev. D 97, 023019 (2018)].

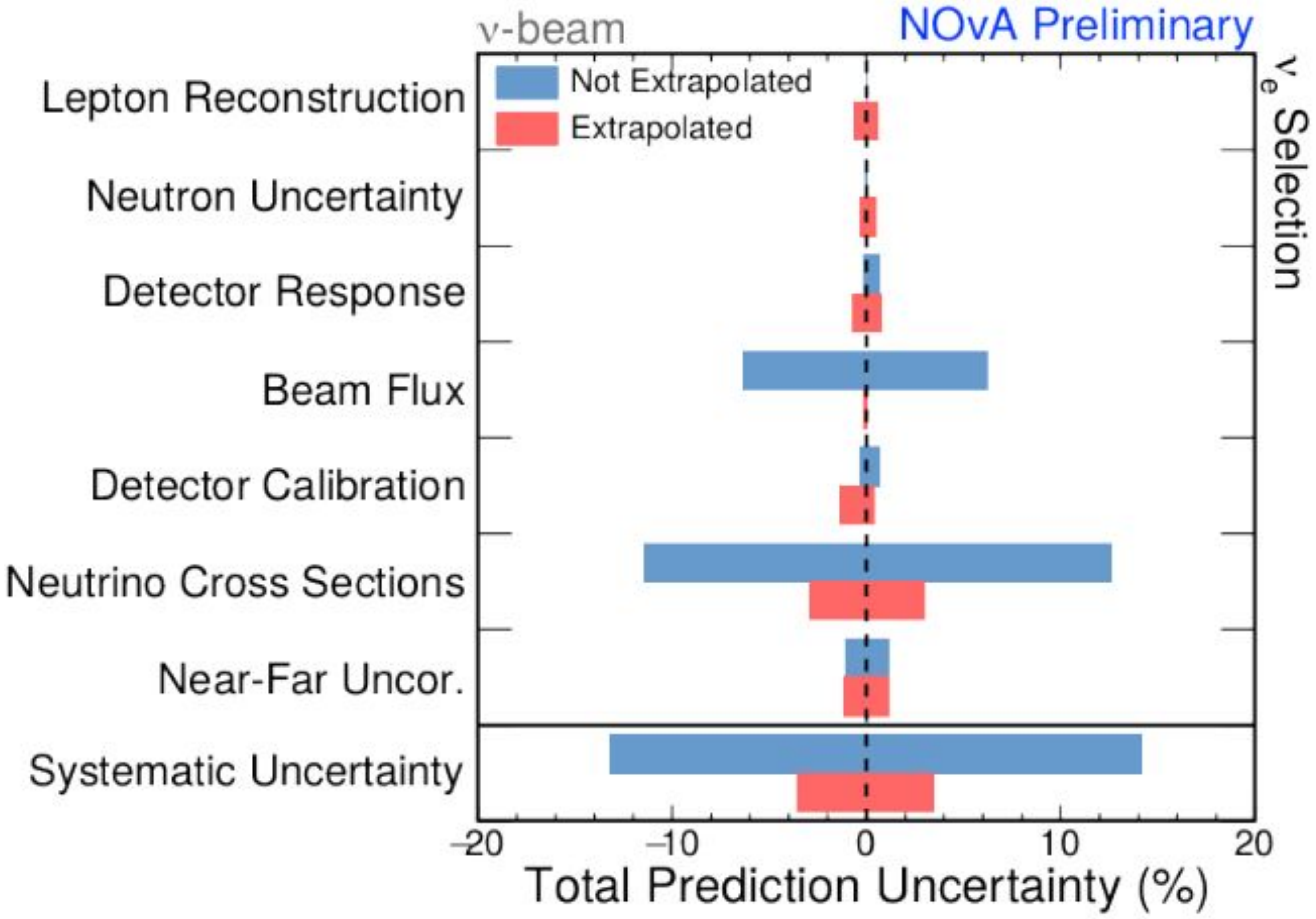


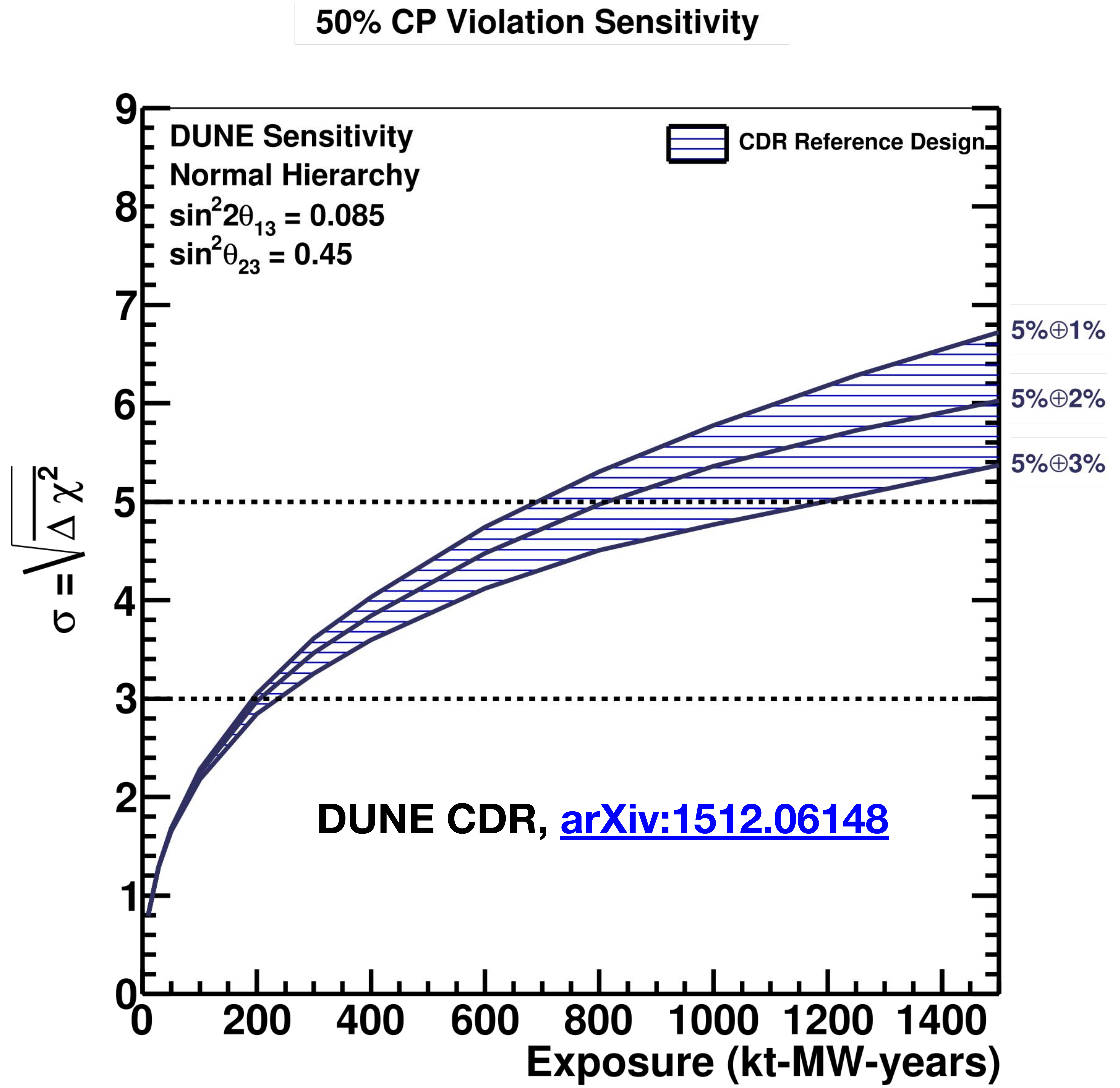


Part III: Uncertainties & Interaction Data

Need for high-precision simulations

M. Elkins & T. Nosek (for NOvA), **[Neutrino 2020](#) [poster](#)**





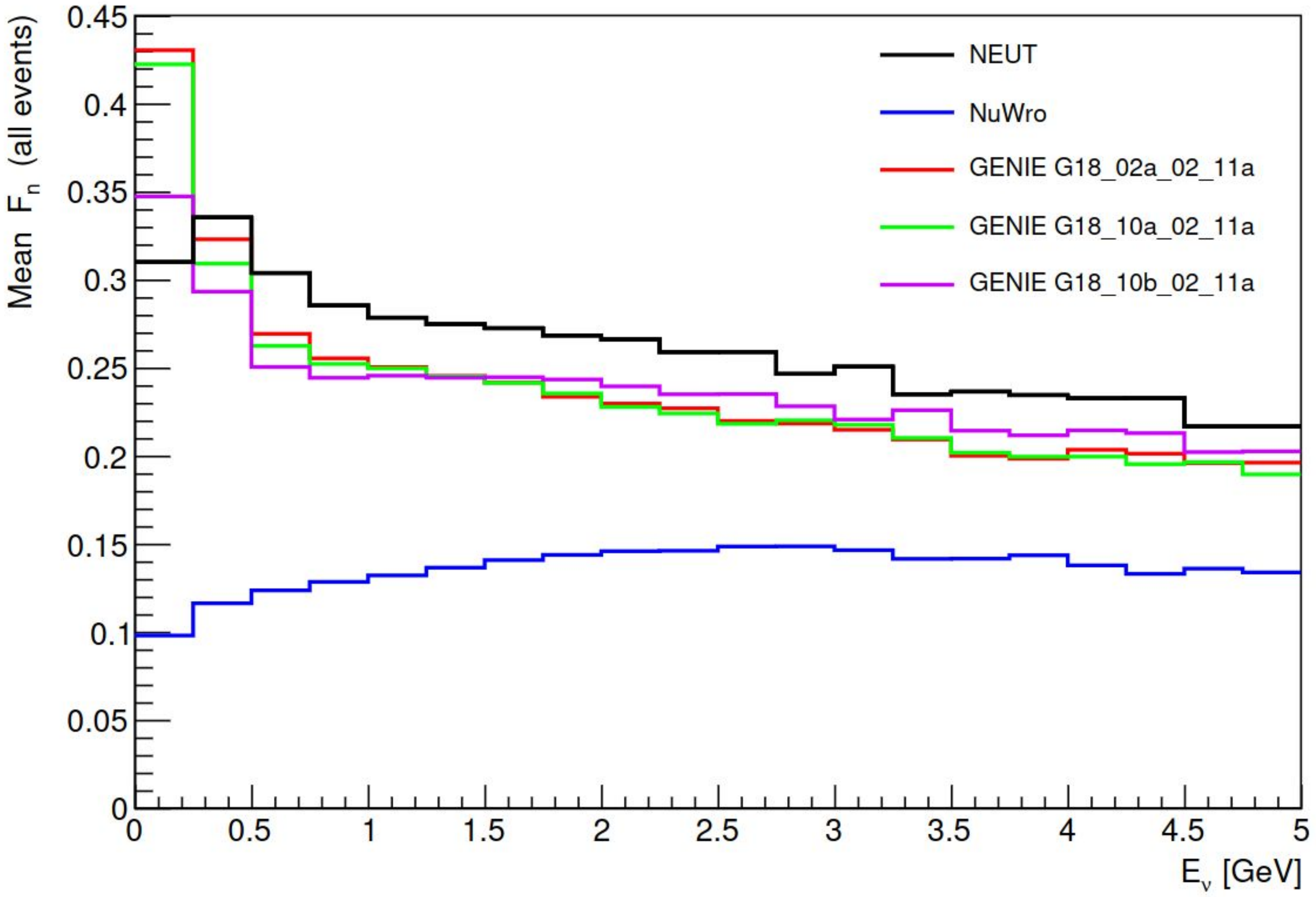
DUNE CDR, [arXiv:1512.06148](#)

Typically among the leading uncertainties, and percent-level improvements matter!

Where do the modeling uncertainties come from?

- Many sources, some are easier to quantify than others
- Model ingredients with a standard parameterization
  - "Easy" (nucleon form factors)
- **Competing models, no preference from data**
  - Harder (take the spread between them?)
- Approximations whose impact is hard to quantify
  - Very hard (how wrong is using a cascade for FSI?)
- Observed data/simulation differences
  - Tricky (which part of the model?)

[Phys. Rev. D 105, 092004 (2022)]



Mean fraction of energy transfer imparted to neutrons (all CC ν_μ events)

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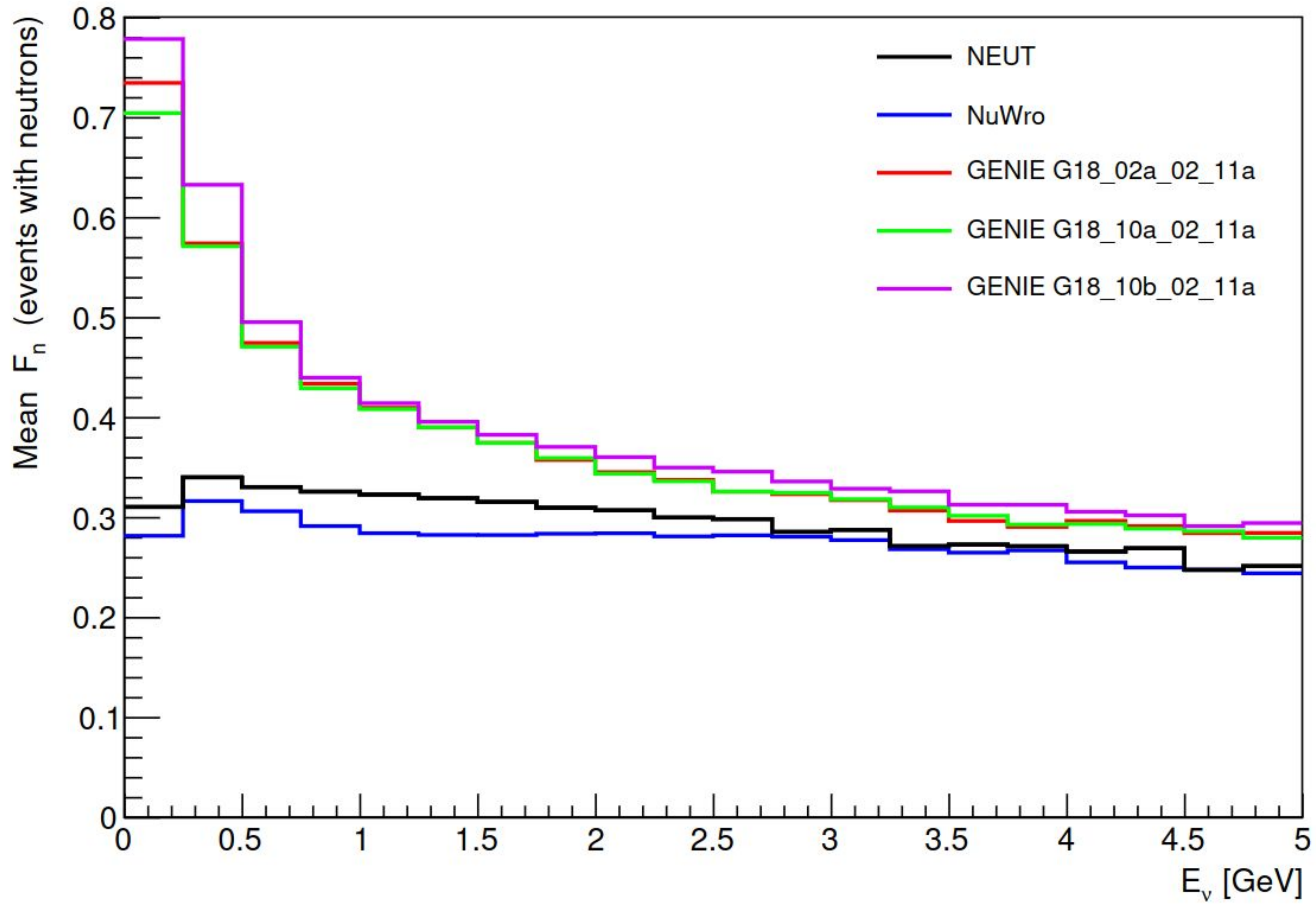
[Phys. Rev. D 105, 092004 (2022)]



Mean fraction of energy transfer imparted to neutrons (CC ν_μ events with n)

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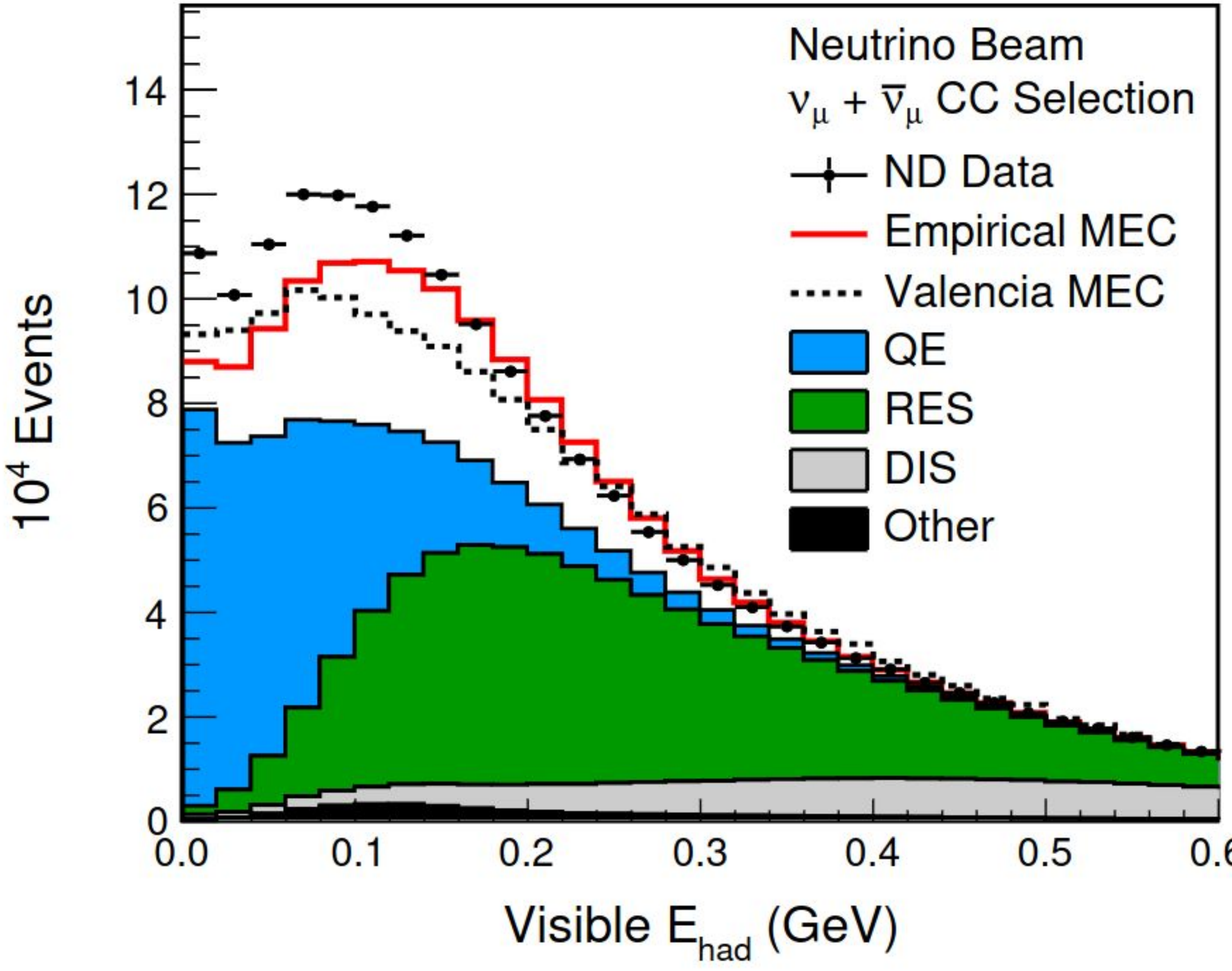
NOvA Collaboration, [Eur. Phys. J. C 80, 1119 (2020)]



Where do the modeling uncertainties come from?

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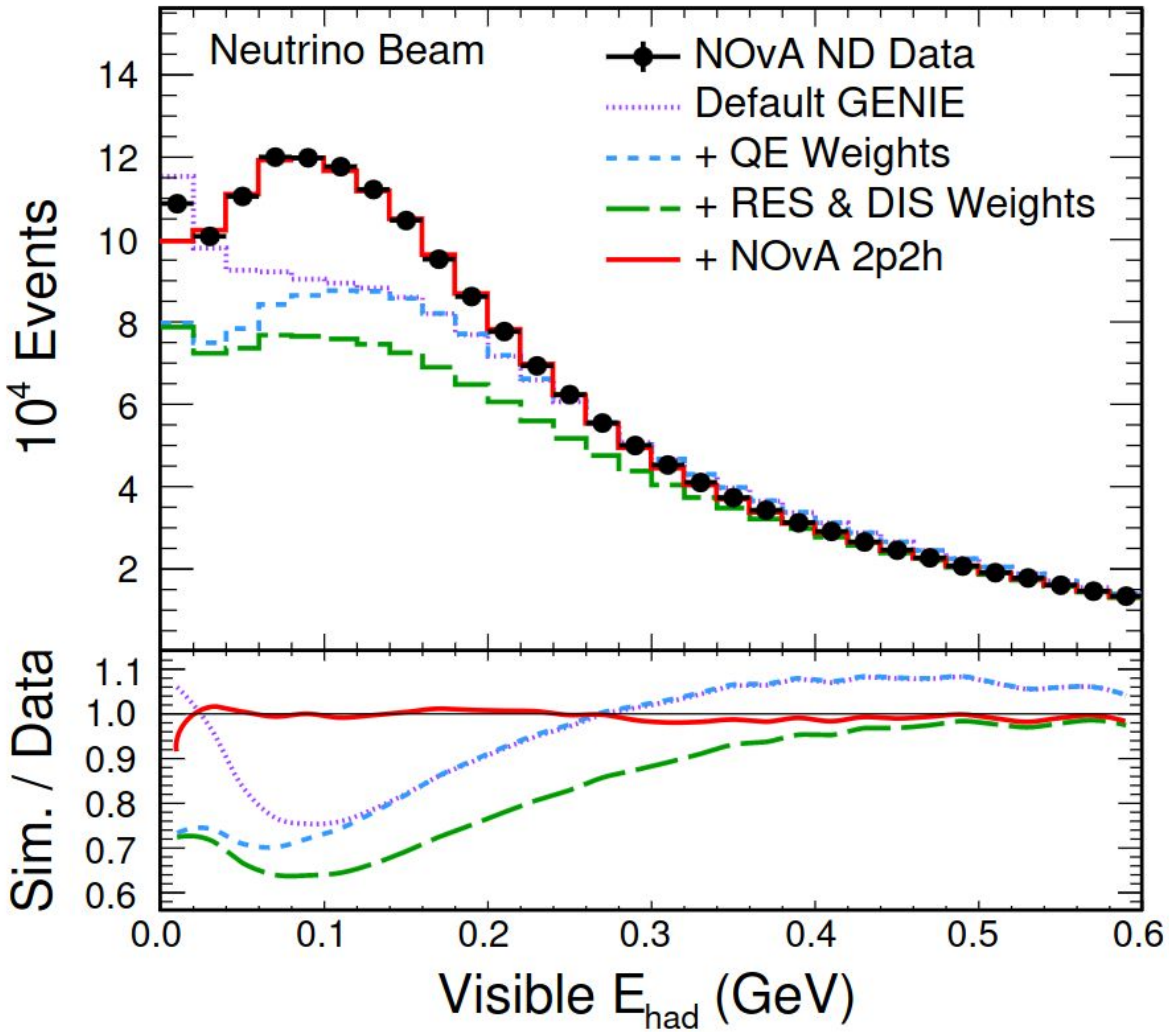
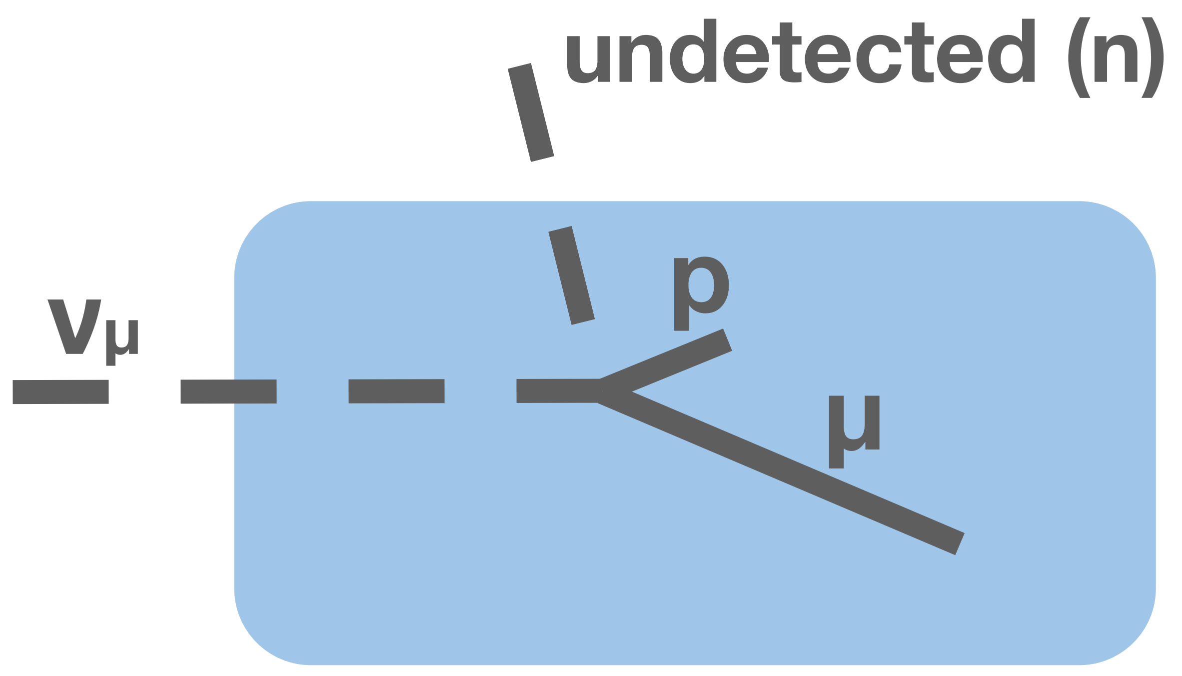
NOvA Collaboration, [Eur. Phys. J. C 80, 1119 (2020)]



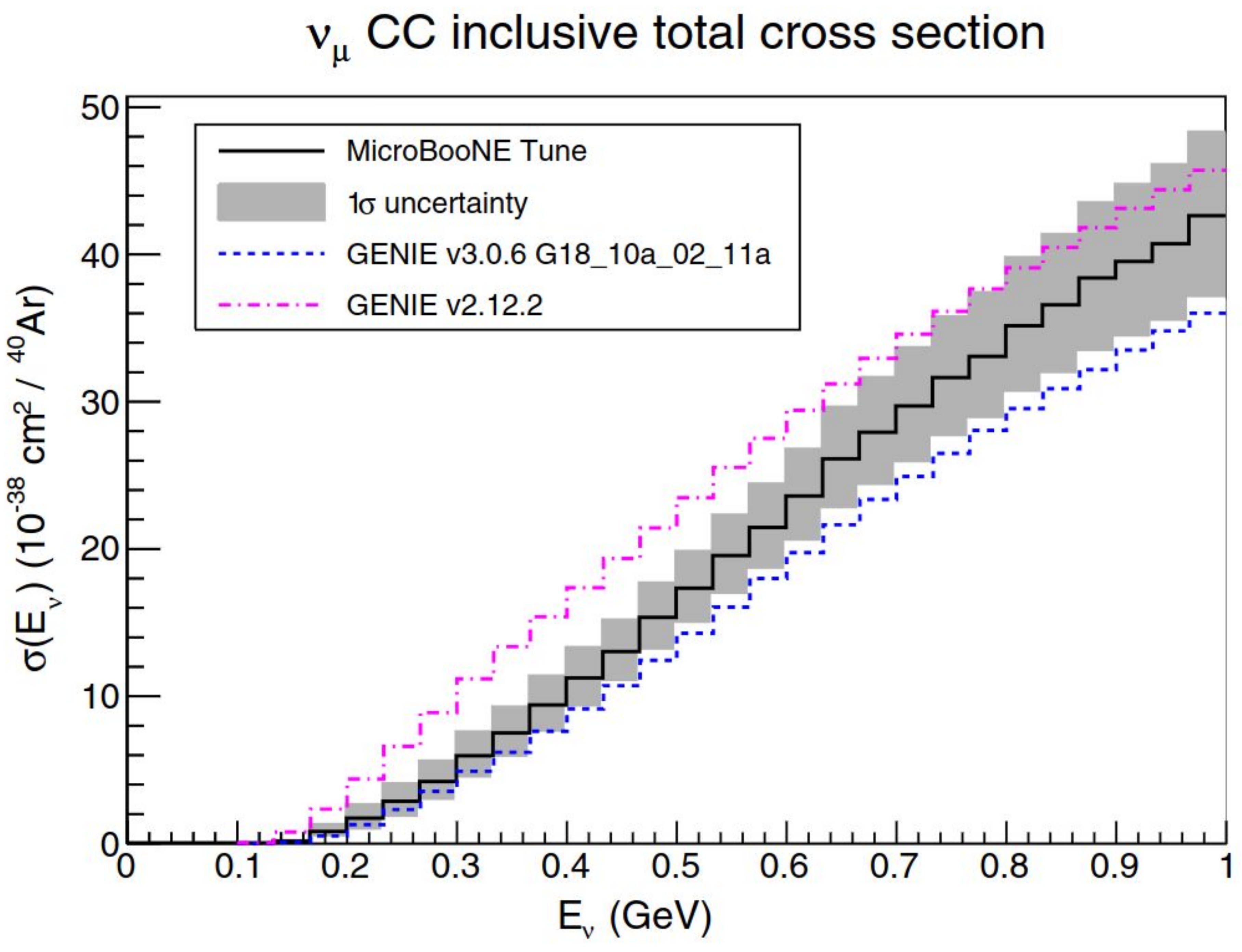
Uncertainty propagation

- How do uncertainties on the inputs impact quantities we care most about?
  - Efficiencies / purities / energy estimation
  - Cross-section predictions

- For experiments, generators must provide tools for assessing these uncertainties
  - NEUT + GENIE: large toolkits
  - NuWro: some infrastructure
  - Others mentioned in the talk: nothing official yet

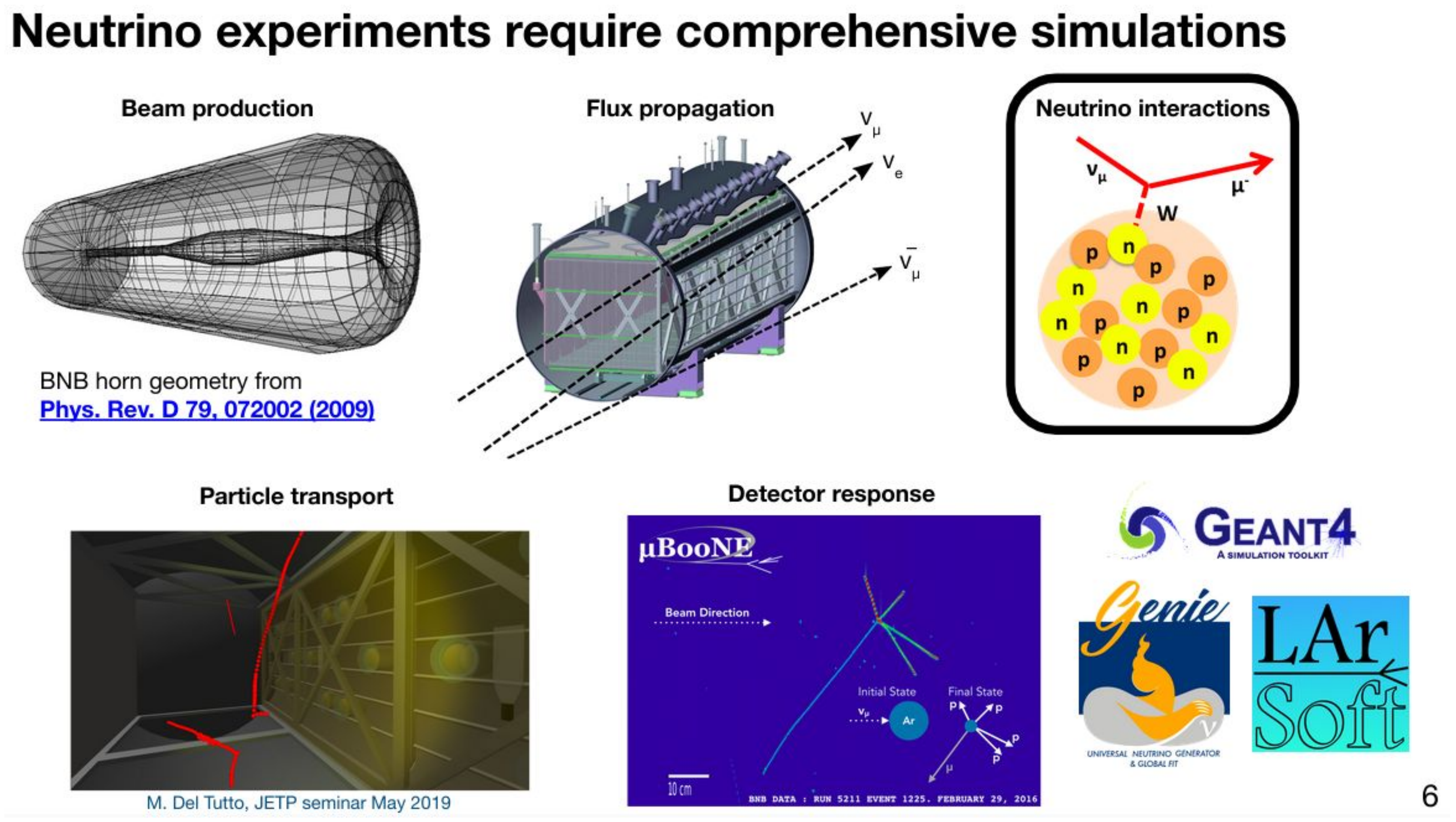


Quasielastic-like νμ event



MicroBooNE Collaboration, [Phys. Rev. D 105, 092004 (2022)]

Reweighting for uncertainty propagation



- Full experimental simulations are computationally very expensive
  - Change a form factor, and rerun everything? (nope, takes too long 😢)
  - Brute force is the only way to handle some uncertainties
- Where possible, experiments use **reweighting**
  - Use the *same* events, assign them statistical weights based on model adjustments
  - **Likelihood ratio** approach

$$w = \frac{P(\text{event}|\mathbf{p}')}{P(\text{event}|\mathbf{p})}$$

Reweighting for uncertainty propagation

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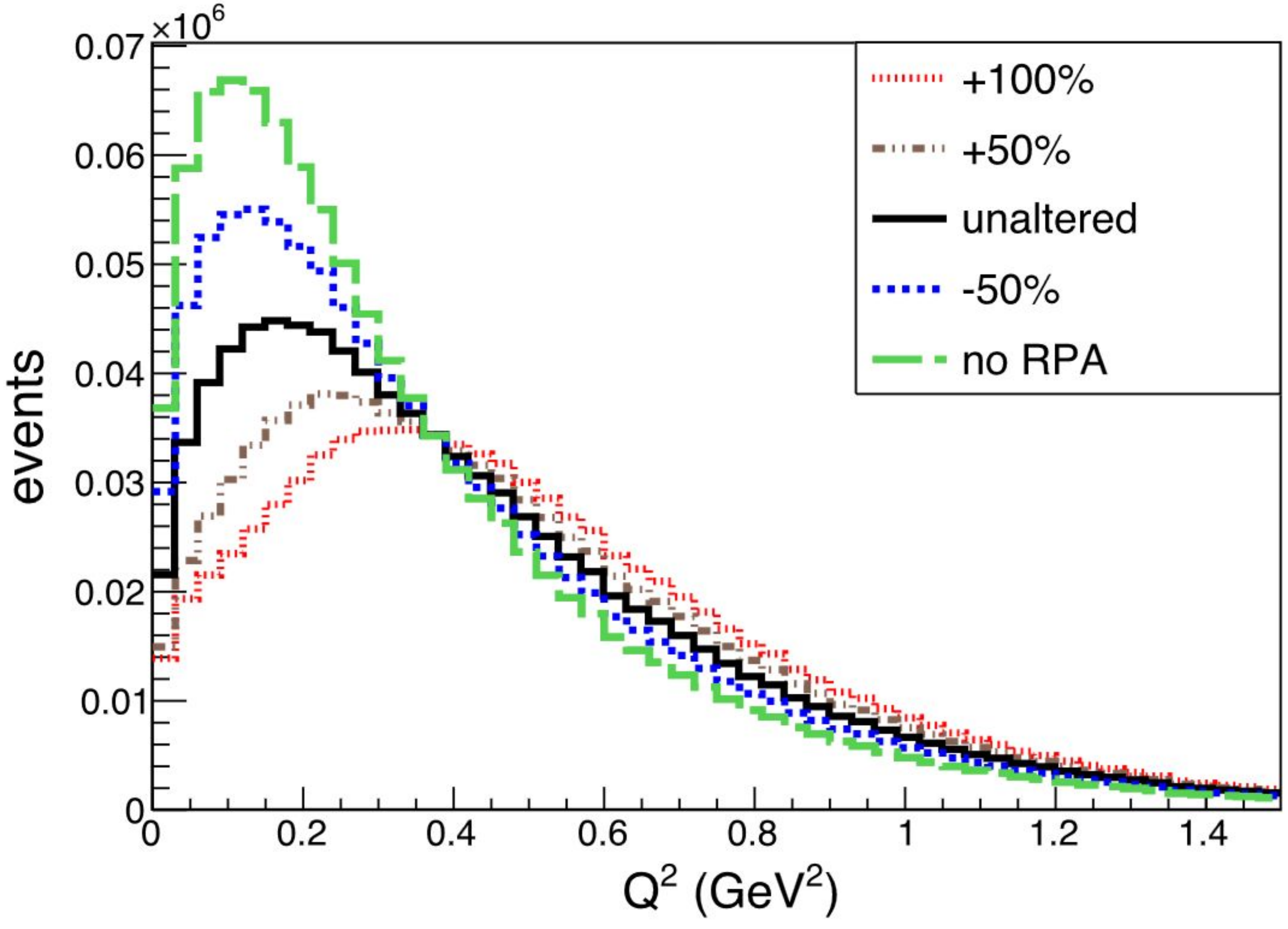
MicroBooNE Collaboration,
[Phys. Rev. D 105, 092004 (2022)]

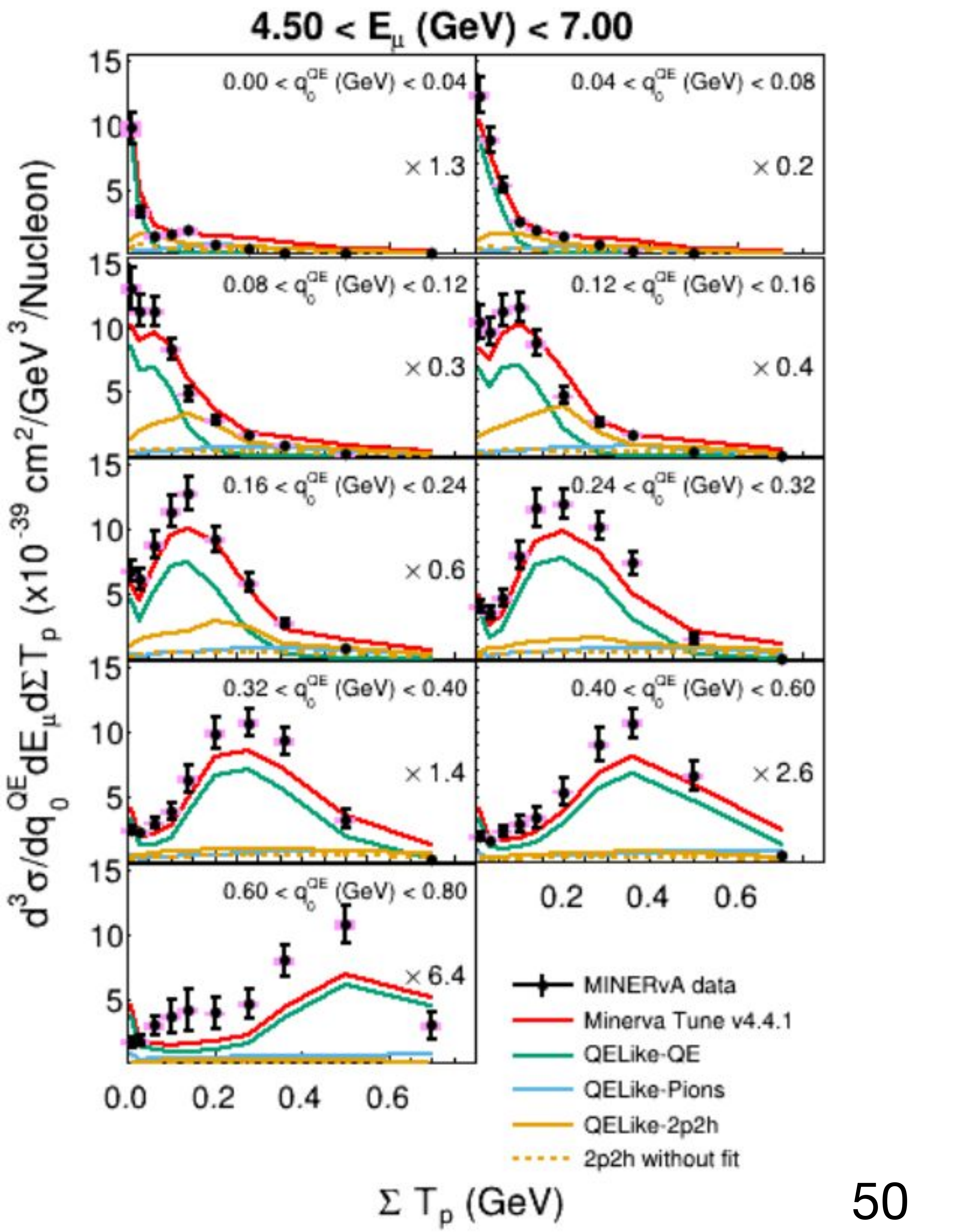


CCQE variations of RPA effect implemented via reweighting

Strengths and limitations of neutrino data

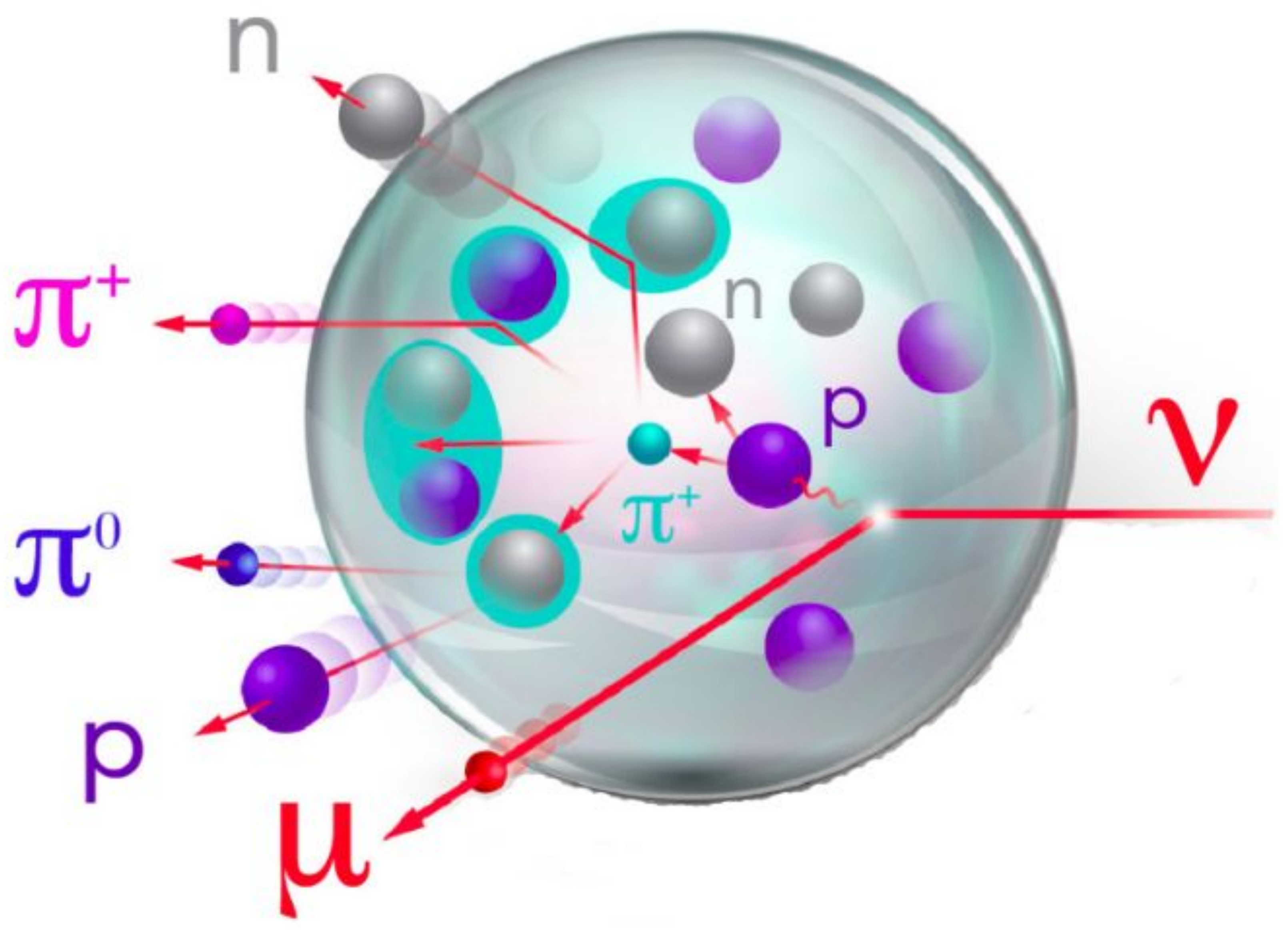
MINERvA Collaboration,
[Phys. Rev. Lett. 129, 021803 (2022)]

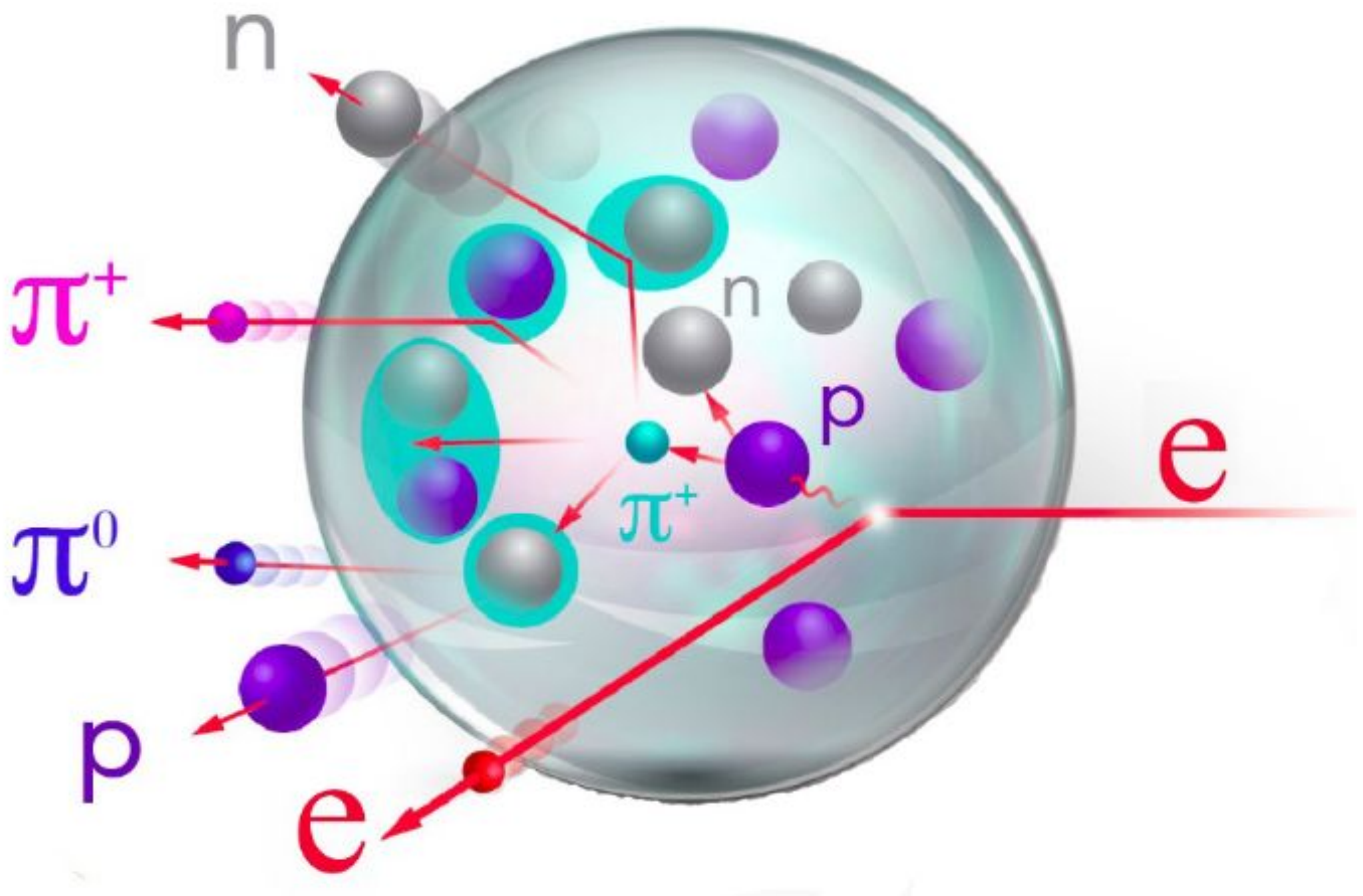
- Neutrino cross-section data are essential to benchmark generators
  - Weak probe of the nucleus, some unique features (e.g., axial-vector coupling)
- **Growing library** from many experiments
  - Introduction tomorrow by Dan, many talks next week
- There are nevertheless **drawbacks**
  - *Weak* interaction: relatively low statistics
  - Results are typically *flux-averaged*: isolating energy-dependent effects difficult!



Complementary use of electron beam data

- **Valuable resource** already mentioned in theory talks yesterday
- Much higher cross section = drastically larger statistics
- Monoenergetic beam = negligible uncertainty on incident energy
- These advantages offer a powerful constraint on shared modeling ingredients
  - Vector part of primary interaction
  - Many nuclear effects
- But you need a **consistent simulation!**
  - Not necessarily true in generators

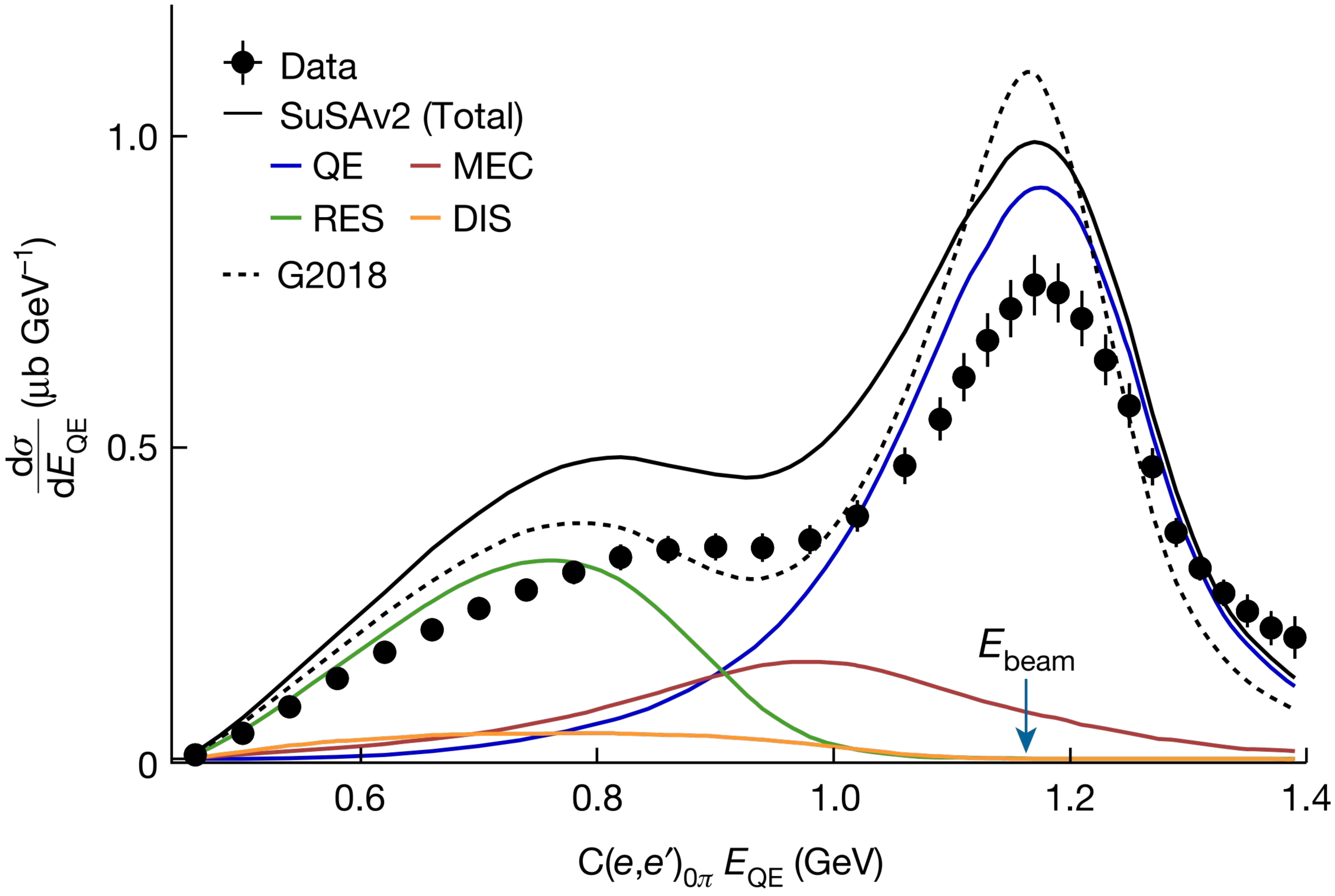




Checking neutrino energy reconstruction with electrons

- Apply neutrino energy estimation methods to electron-nucleus data
  - Monoenergetic beam
  - “Simple” 0π case
- Large fraction of events are misreconstructed
- Current GENIE-based models describe the bias poorly
  - Clear need (and path) for improvements!

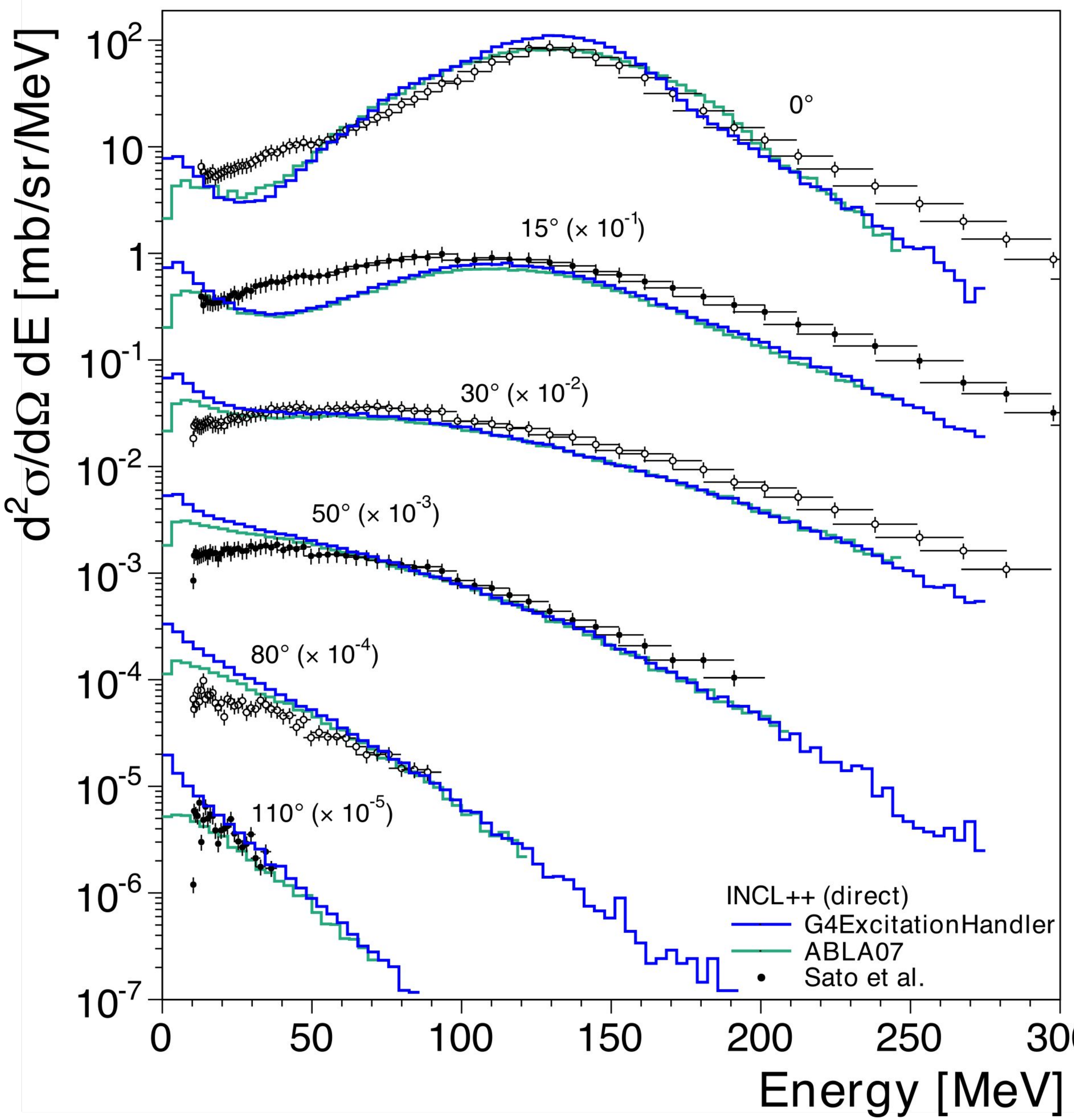
CLAS & e4v Collaborations, **Nature 599, 565 (2021)**



Hadron scattering data

- Also highly useful for FSI in neutrino generators
  - Still need measurements of hadronic final state for neutrinos
  - How well can we apply hadronic projectile case to our own?
- Liège Intranuclear Cascade model (INCL++) now available for FSI in NuWro, GENIE
  - Widely used for calculations of hadronic cross sections
- **Plot**: double-differential neutron production in $^{12}C + ^{12}C$ @ 135 MeV/nucleon

J. Phys.: Conf. Ser. 420 012065 (2013)



And finally, an invitation

Fermi National Accelerator Laboratory ("Fermilab")

- Main lab in USA for particle physics research
  - Worldwide collaboration, including with CERN
- Other focus areas:
  - Accelerator engineering
  - Astrophysics & cosmology
  - Quantum computing

Opportunities for visting students, please get in touch if you are interested