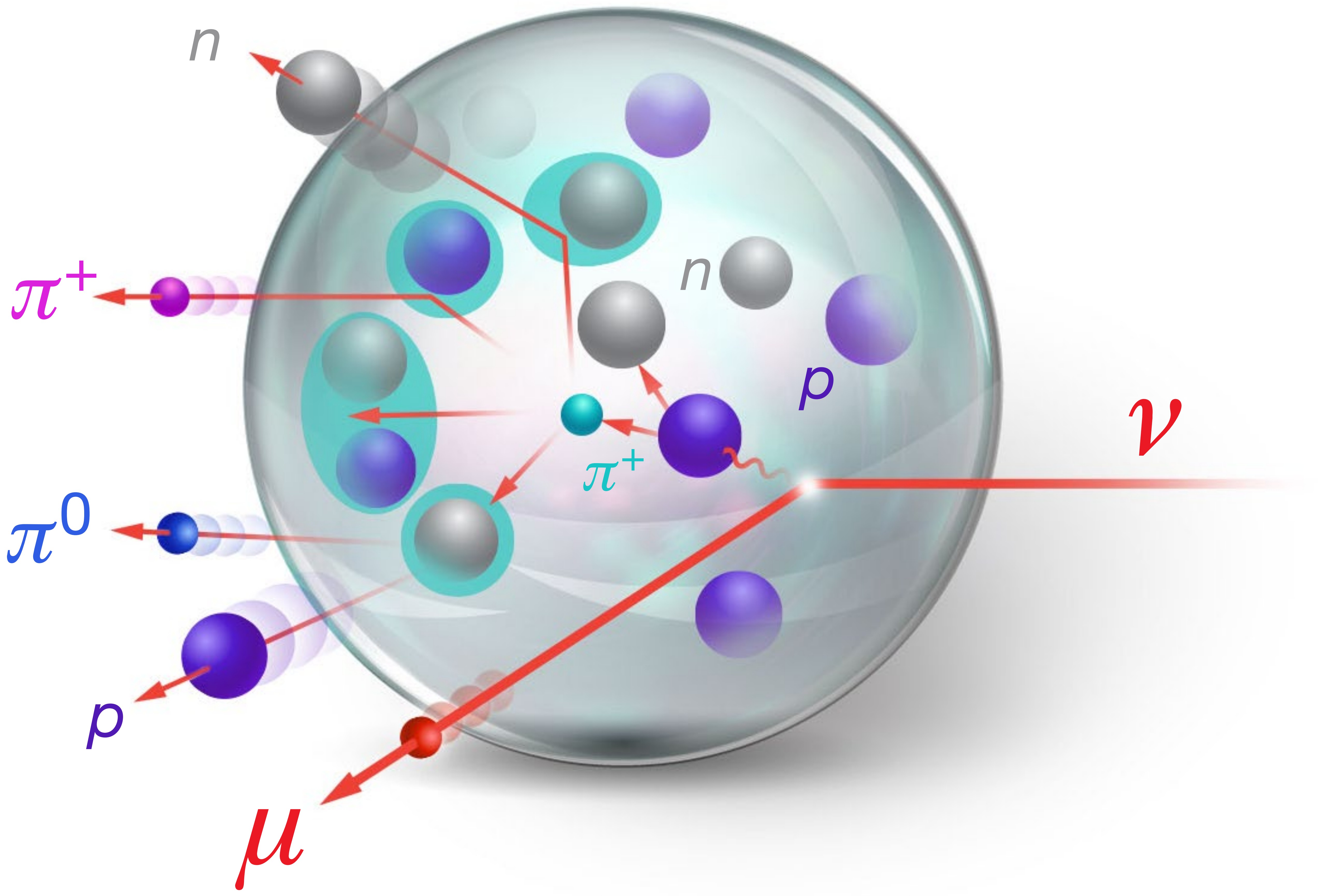
Towards precision interaction simulations for the future neutrino program



Steven Gardiner

Neutrino Oscillation Workshop

9 September 2022

Attacking The Modeling Monster

- Neutrino Cross Sections

- Event Generator Modeling
- Electron Cross Sections

See previous talk by A. Papadopoulou!

Role of generators: bridge between theory and experiment

- **Data interpretation** requires detailed theory input
  - Delivered in the form of simulations
- Key use cases for experimental analyses
  - Neutrino energy reconstruction
  - Corrections for imperfect detector performance
    - Backgrounds
    - Efficiency / acceptance / bin migrations
  - Expected event rates

Neutrino event generator landscape

Four major packages at accelerator energies (~100 MeV to ~20 GeV)

Experiment-focused generators

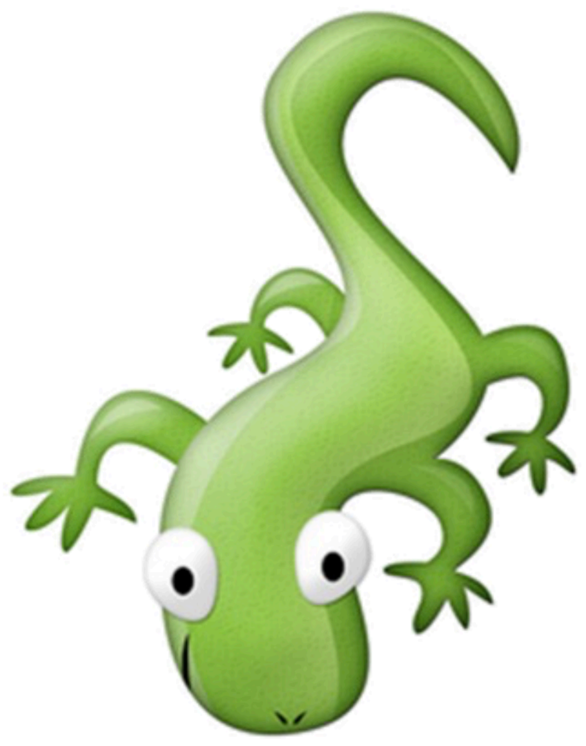
Meet the needs of current oscillation experiments

Genie
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, unweighting, etc.)

NuWro

NuWro * Wroclaw 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.

Neutrino event generator landscape

Other notable generators

Phys. Rev. D 105, 096006 (2022)

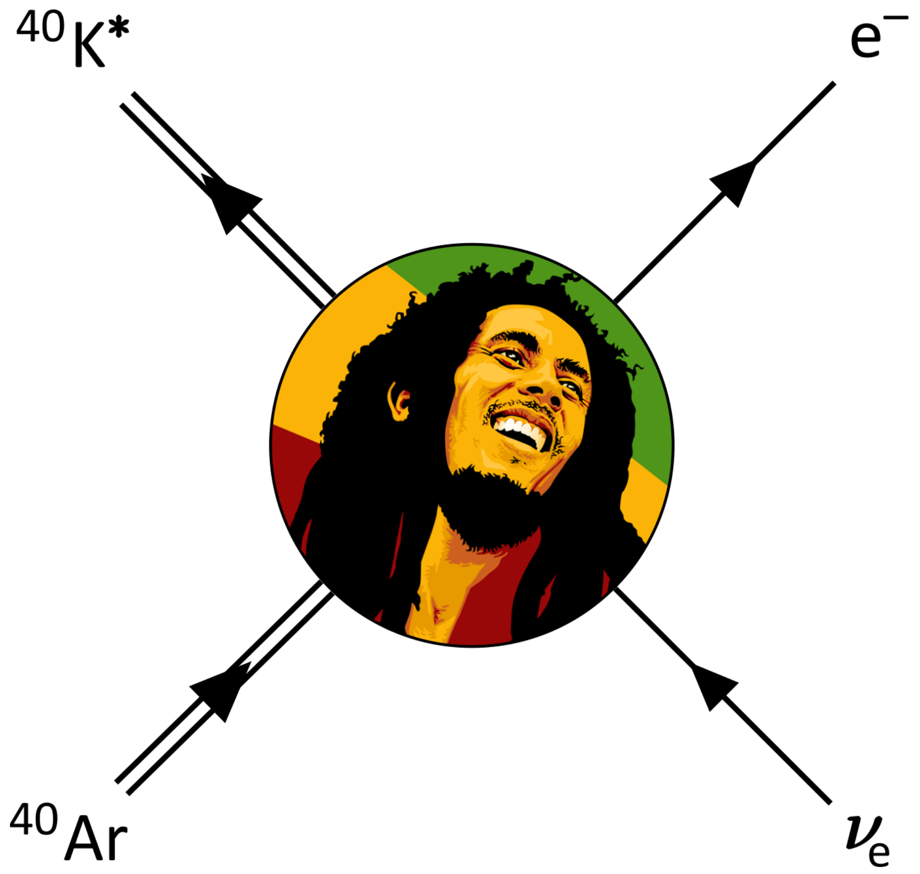
C++. In early (but very interesting!) development. Applies techniques from LHC (e.g., n-body phase space, UFO files) to neutrinos for the first time. Emphasis on BSM modeling capabilities.

LeptonInjector

Comput. Phys. Commun. 266, 108018 (2021)

C++. Generator designed for very high-energy neutrino telescopes. Created by the IceCube Collaboration.

MARLEY



Comput. Phys. Commun. 269, 108123 (2021)

C++. Focus on inelastic ν-nucleus scattering at O(10 MeV). Used by DUNE for supernova neutrino studies. Single author (for now).

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

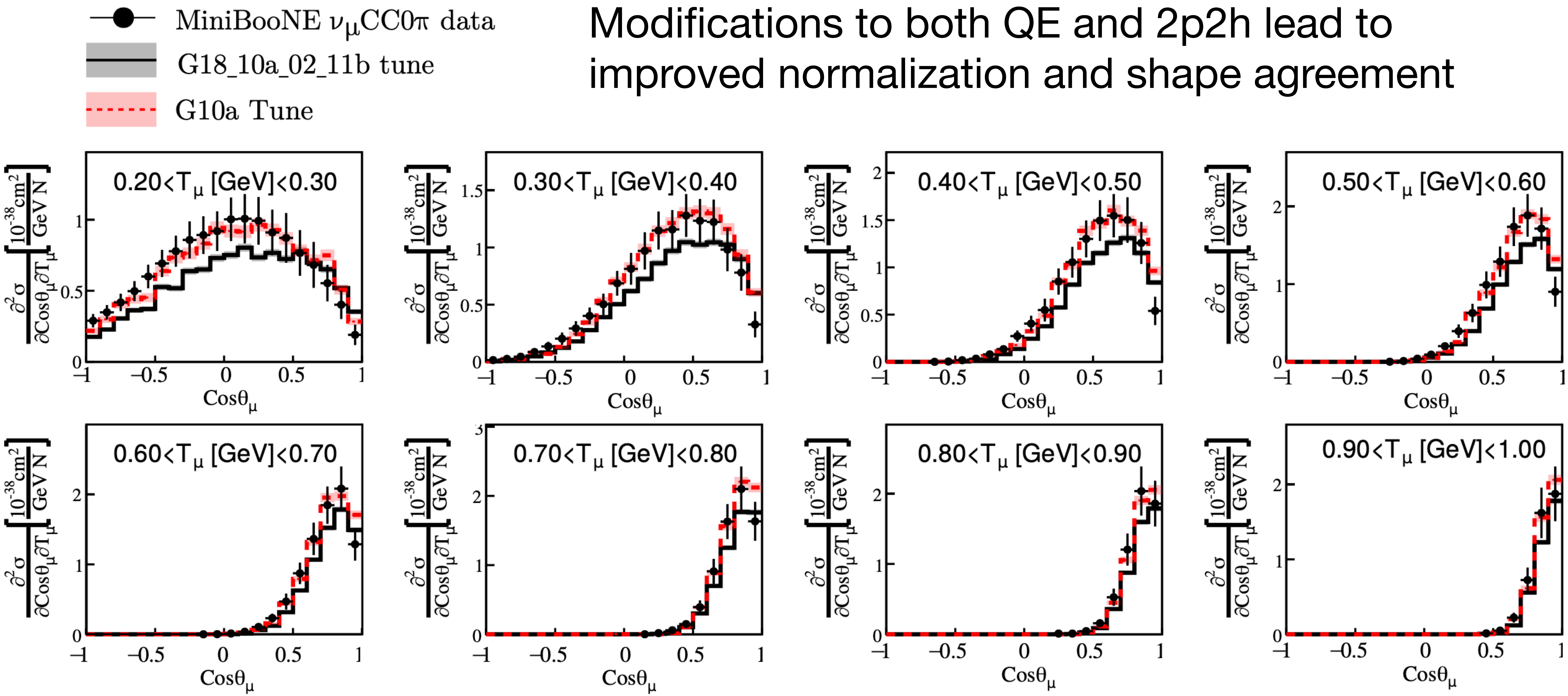
- Used together with **GENIE Comparisons**
  - Curated cross-section database

https://professor.hepforge.org/

GENIE tune results for MiniBooNE data

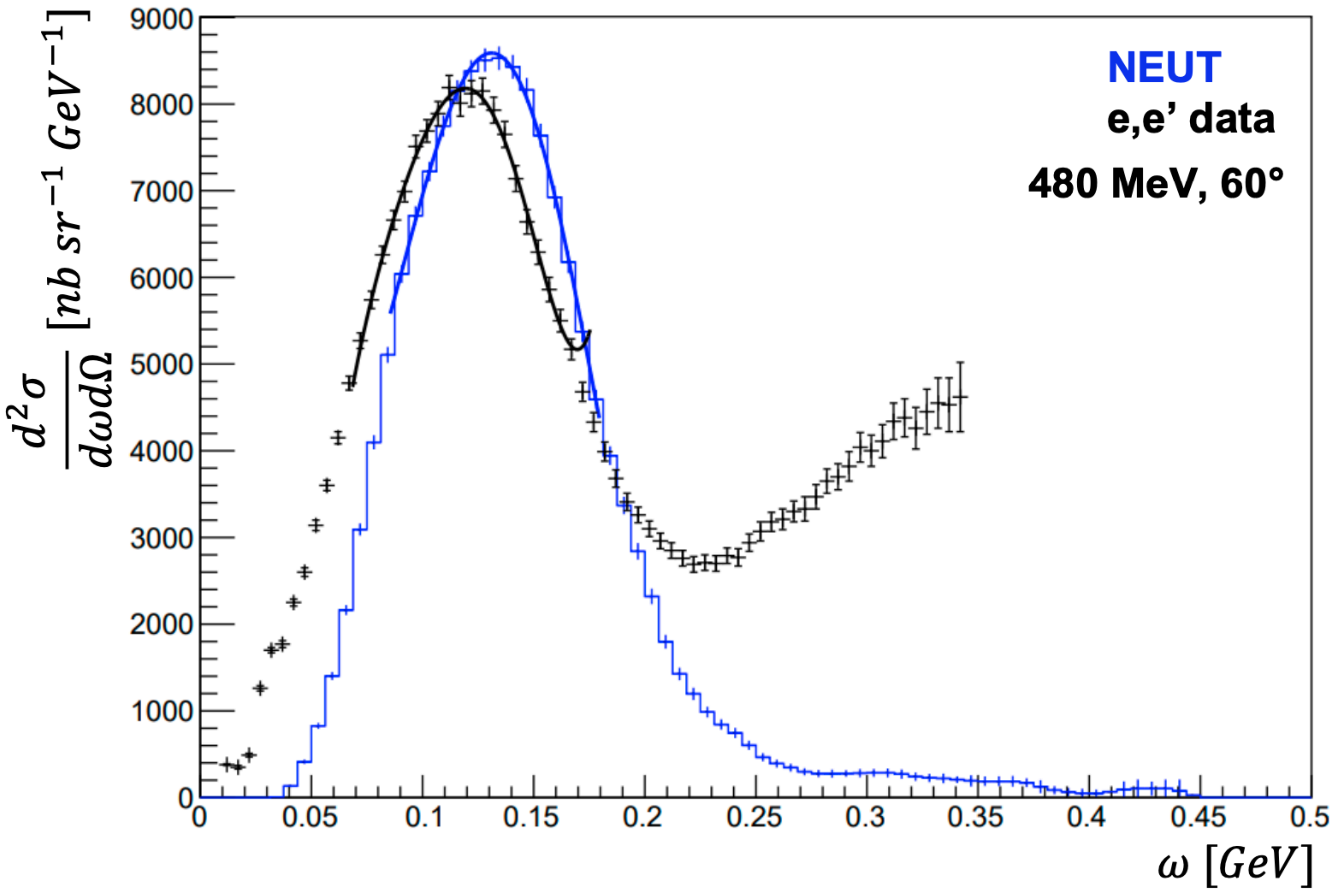
arXiv:2206.11050

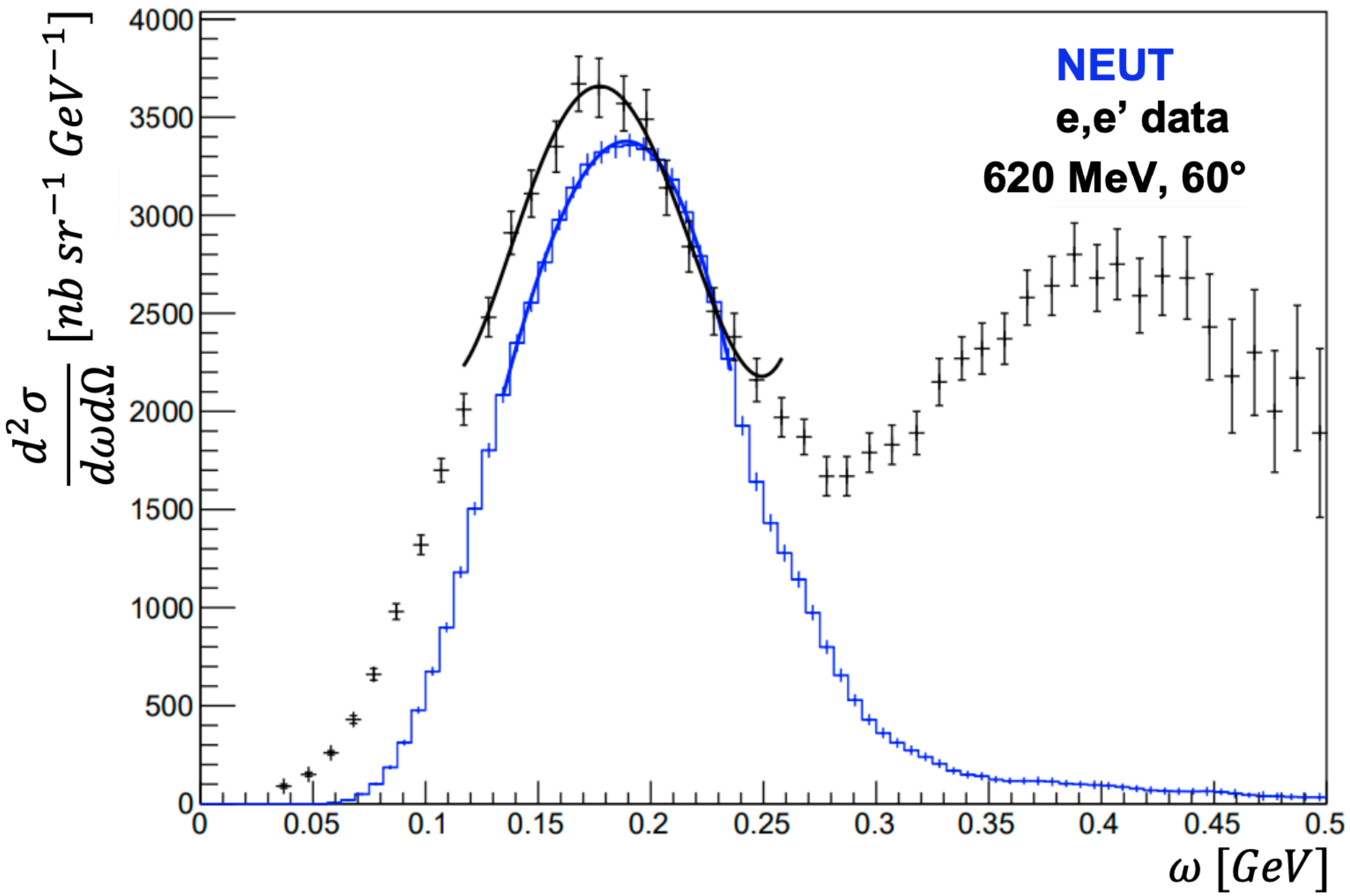
Modifications to both QE and 2p2h lead to improved normalization and shape agreement



NEUT's new QE electron scattering mode

- Recent addition
  - Started with NC ν scattering, added in consistent way
  - Change coupling, form factors, and Coulomb corrections

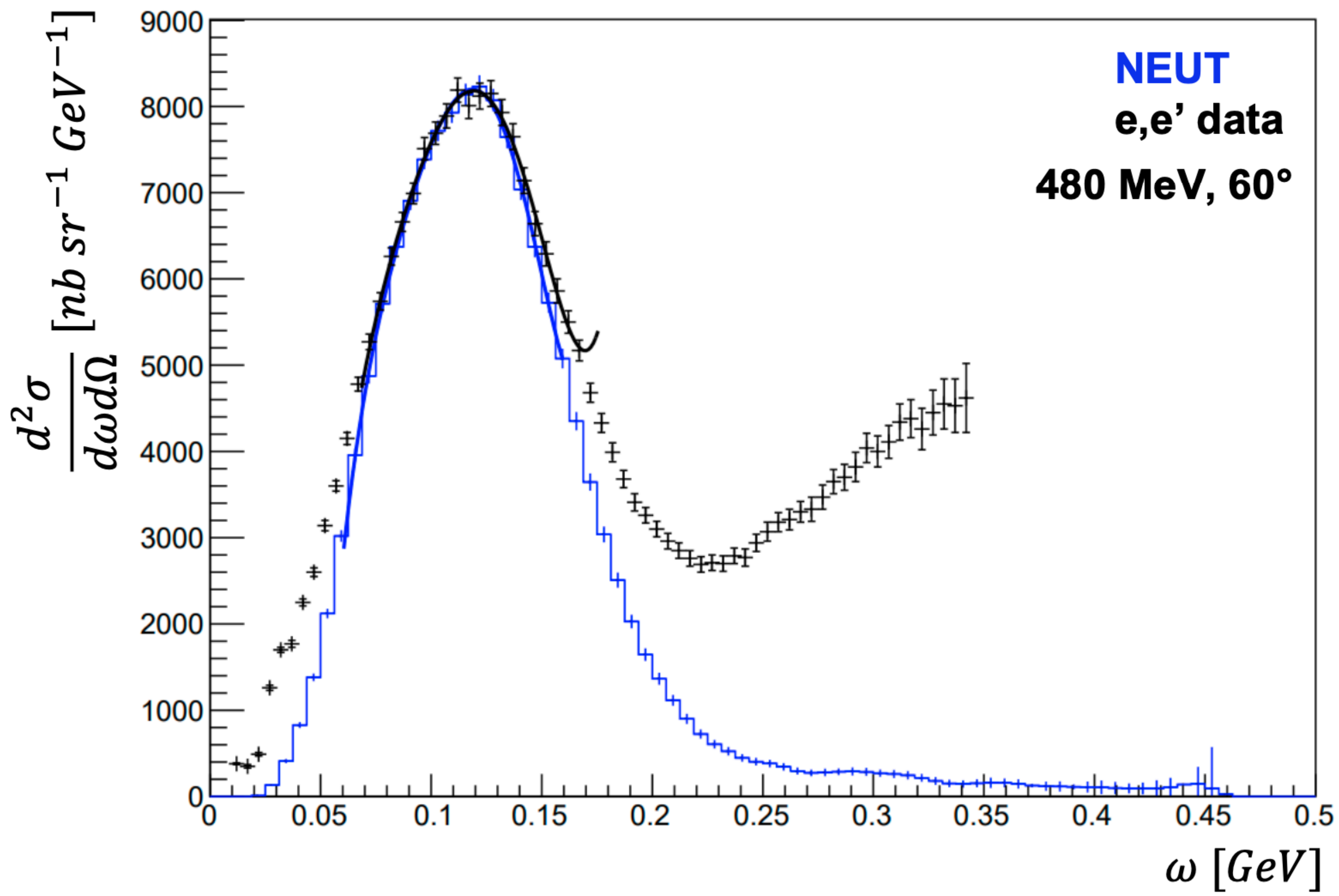


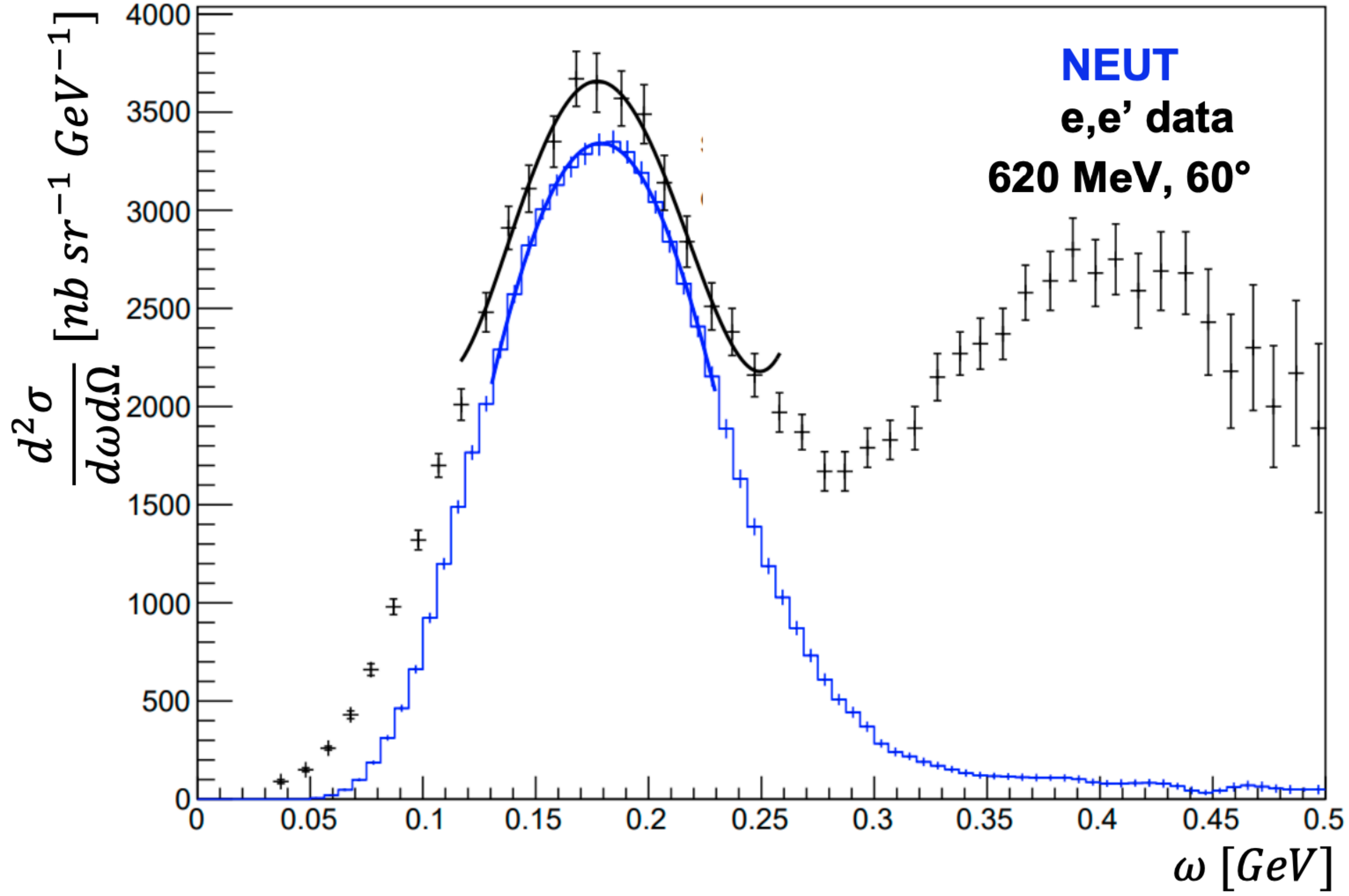


See talk by S. Dolan *et al.* at NuFact 2022

NEUT’s new QE electron scattering mode

- Empirical tune introduces $|\mathbf{q}|$-dependence similar to Relativistic Mean Field (RMF) model
  - Much improved agreement at QE peak!

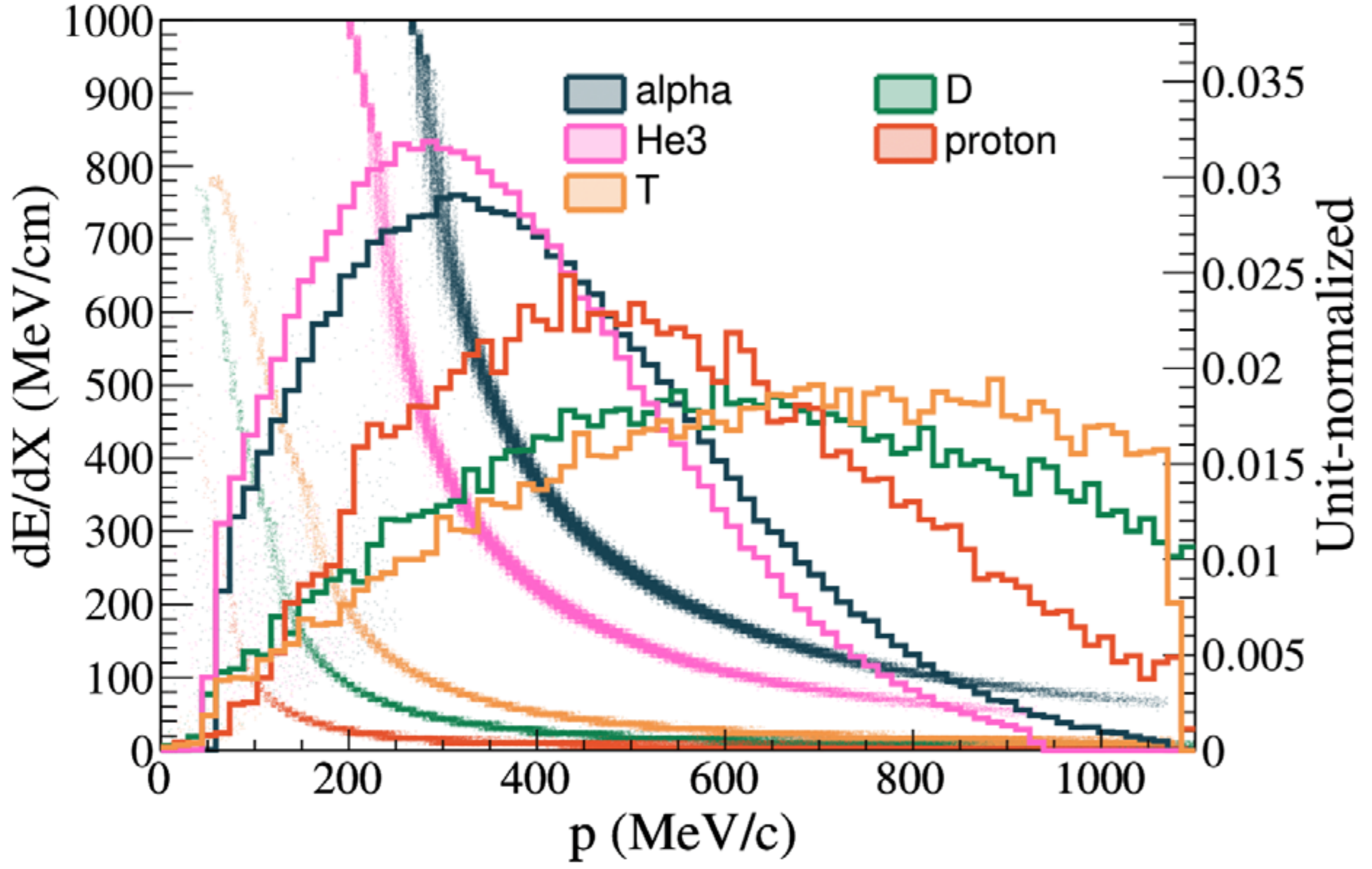




See talk by S. Dolan *et al.* at NuFact 2022

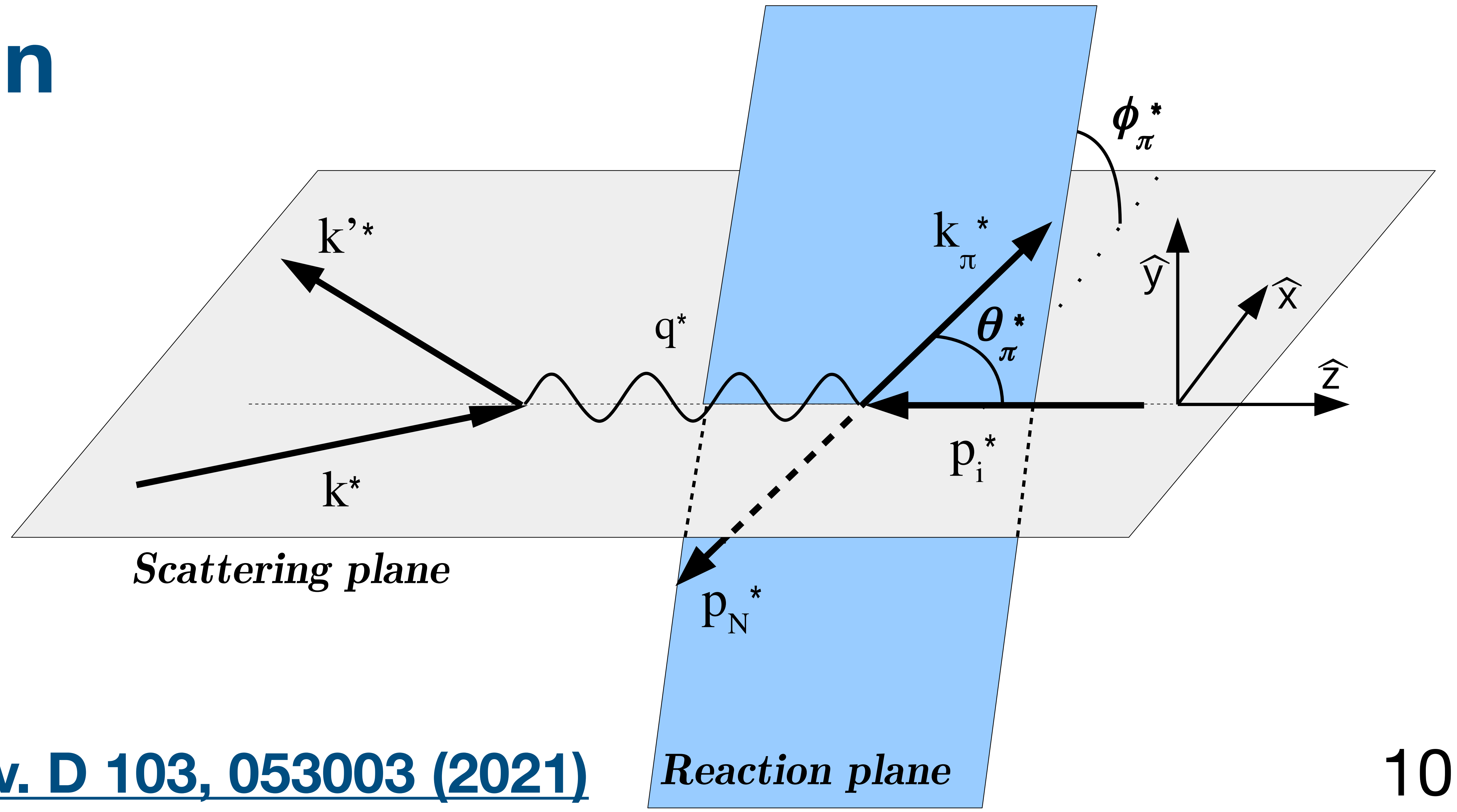
Recent NuWro developments

Phys. Rev. D 106, 032009 (2022)



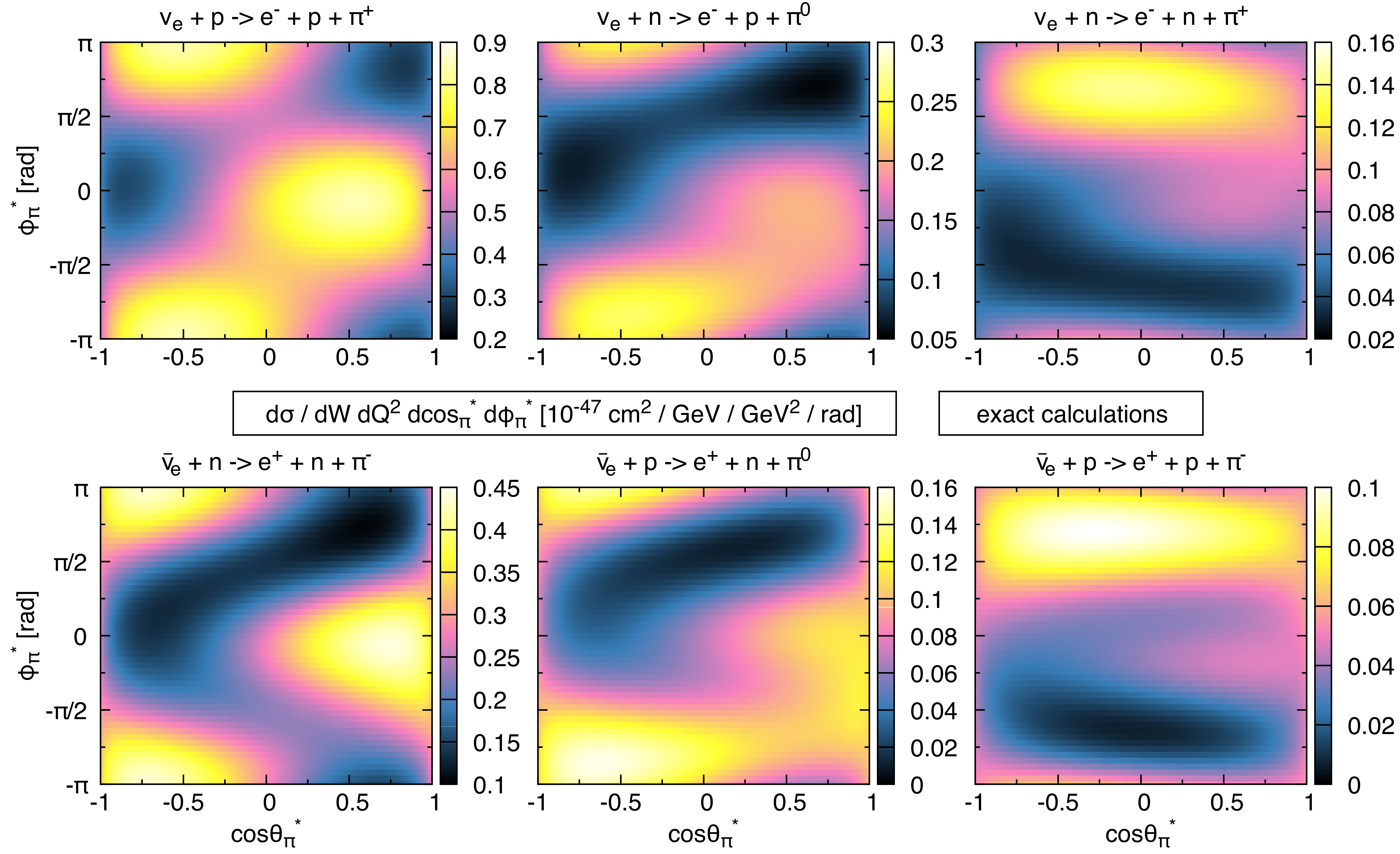
- Interface to Liège Intranuclear Cascade model (INCL)
  - **Nucleon cluster emission**
  - See talk by S. Dolan

- **MC sampling for single π production**
  - Model-independent algorithm
  - W, Q^2, θ_π^*, and ϕ_π^*
  - Used to implement the Ghent low-energy model



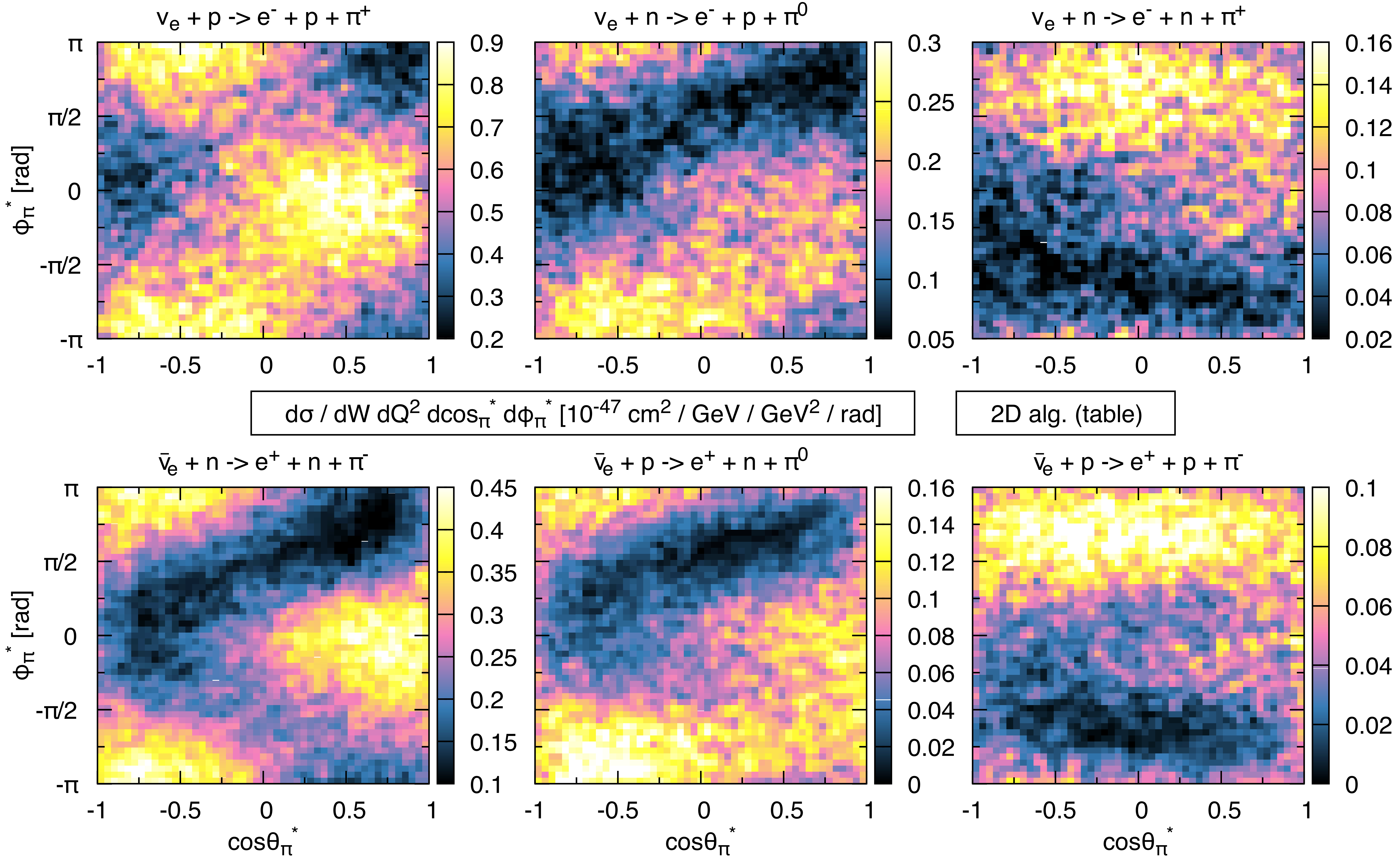
Phys. Rev. D 103, 053003 (2021)

Ghent low-energy model for single-pion production



Phys. Rev. D 103, 053003 (2021)

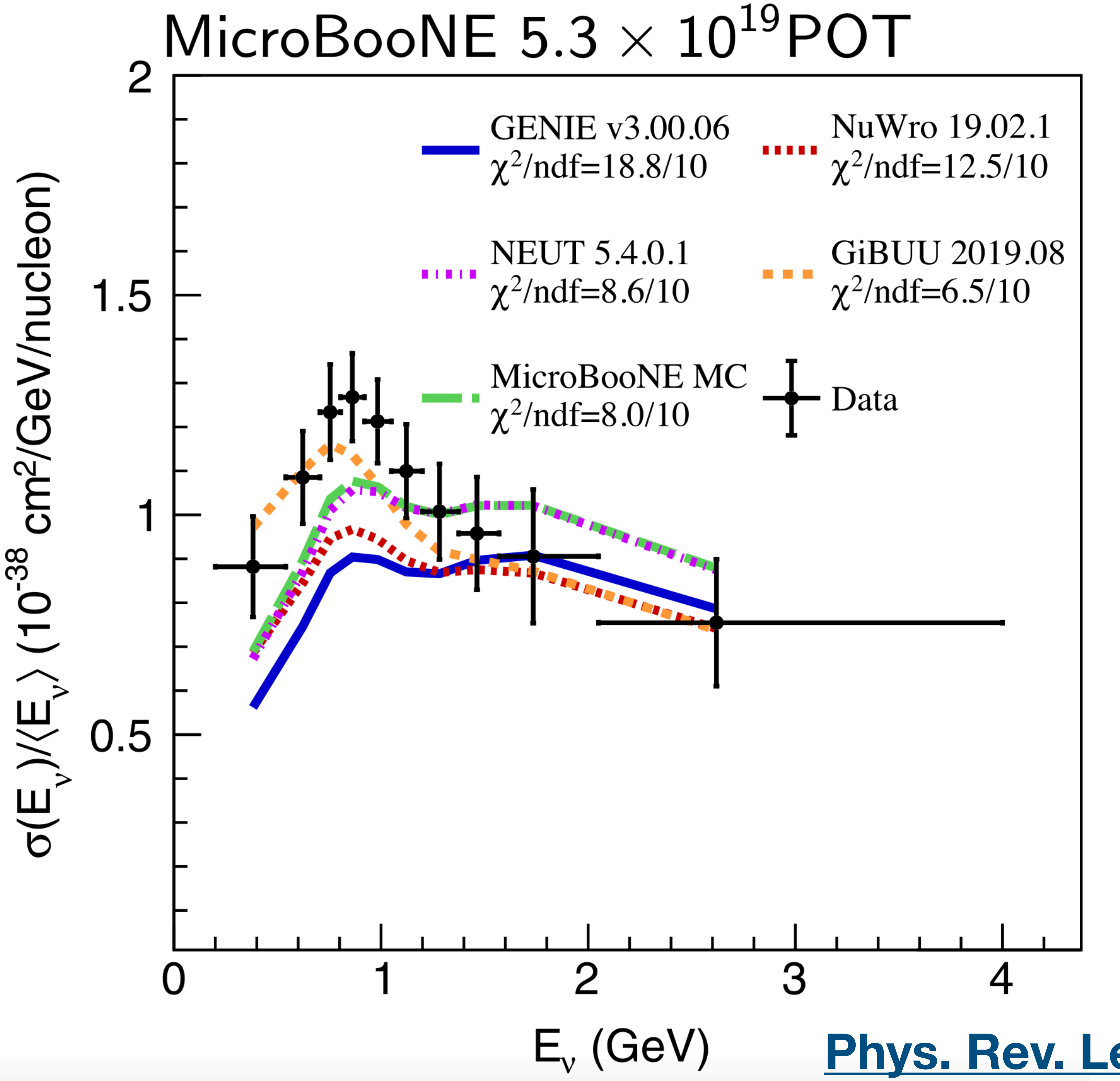
Ghent low-energy model for single-pion production

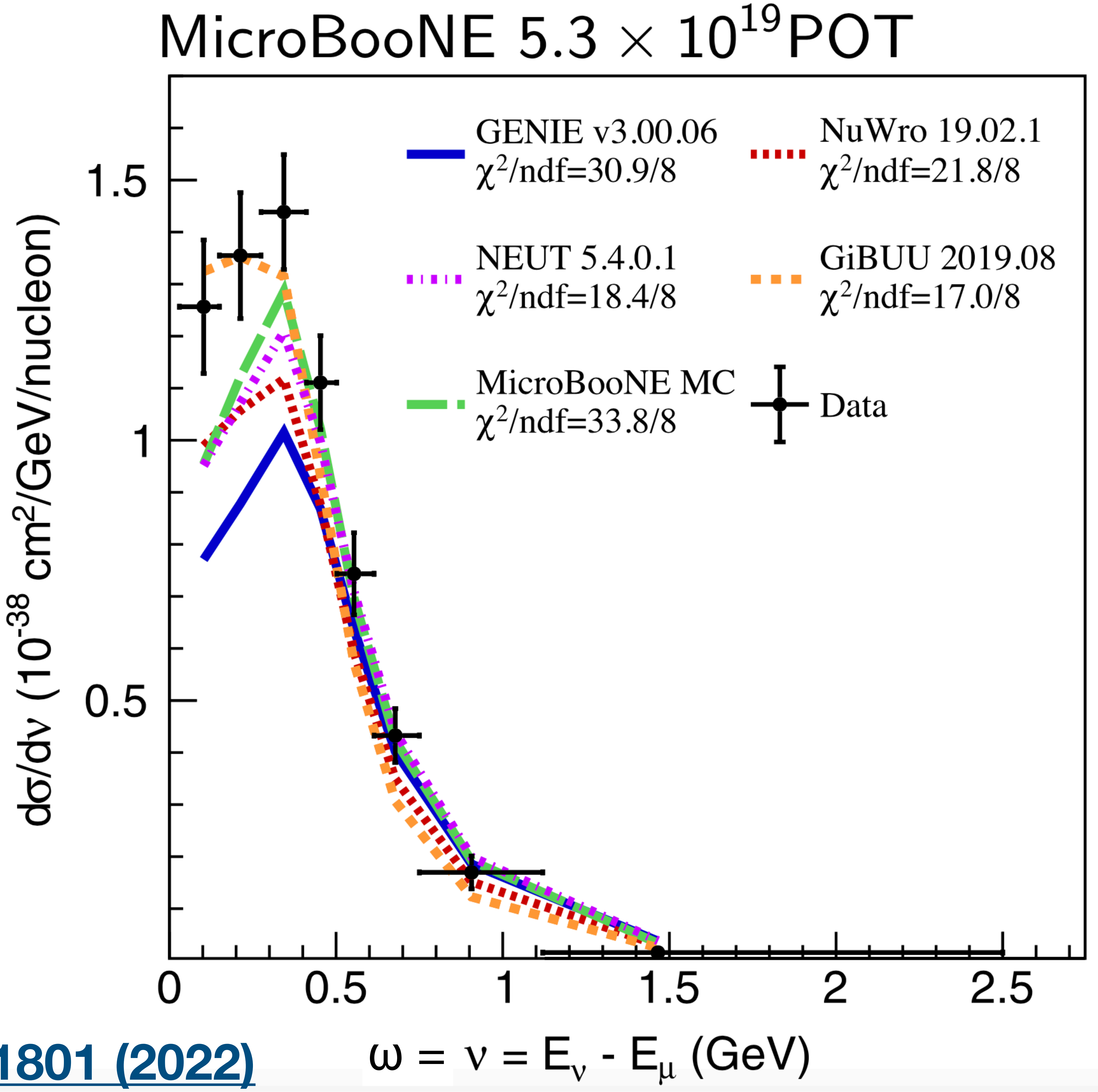


Phys. Rev. D 103, 053003 (2021)

GiBUU comparisons to new MicroBooNE data

- Small recent improvements, but “no fundamentally new physics involved”
- MicroBooNE analysis shows preference for GiBUU 2019 model at low E_ν and ω

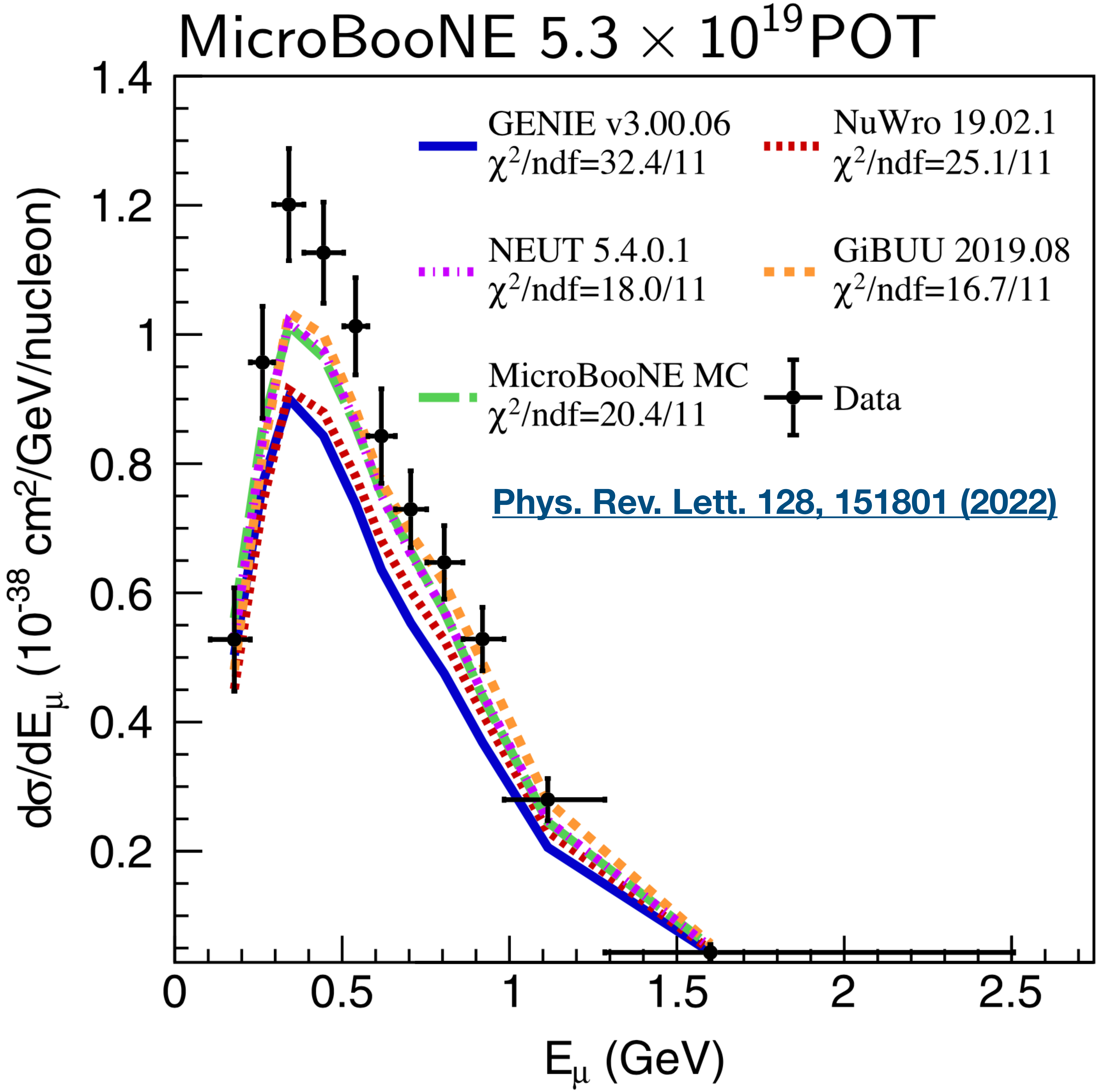


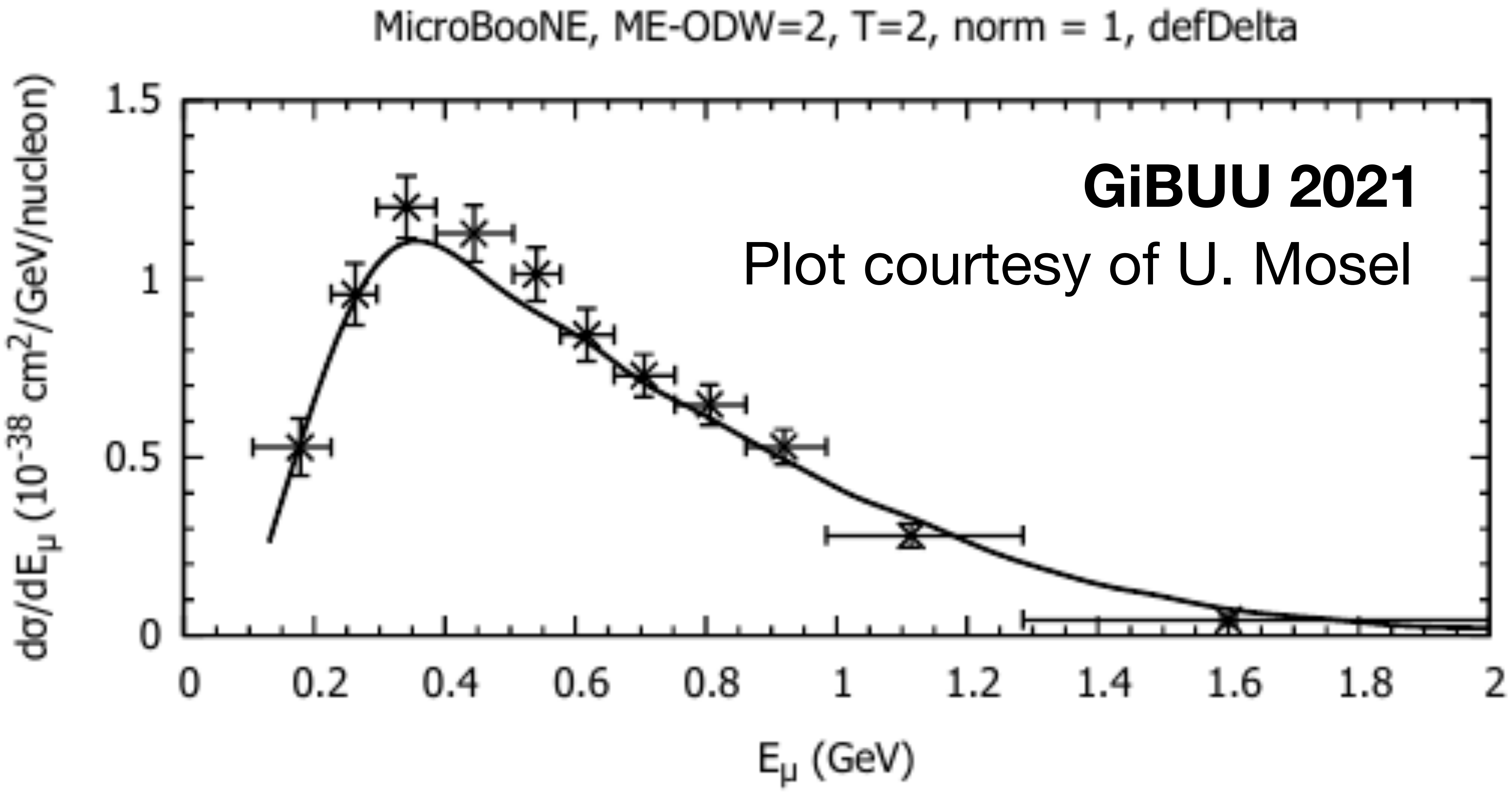


Phys. Rev. Lett. 128, 151801 (2022)

GiBUU comparisons to new MicroBooNE data

- Agreement with E_μ distribution better in 2021 release
  - Improvements to treatment of shallow inelastic scattering (SIS) regime

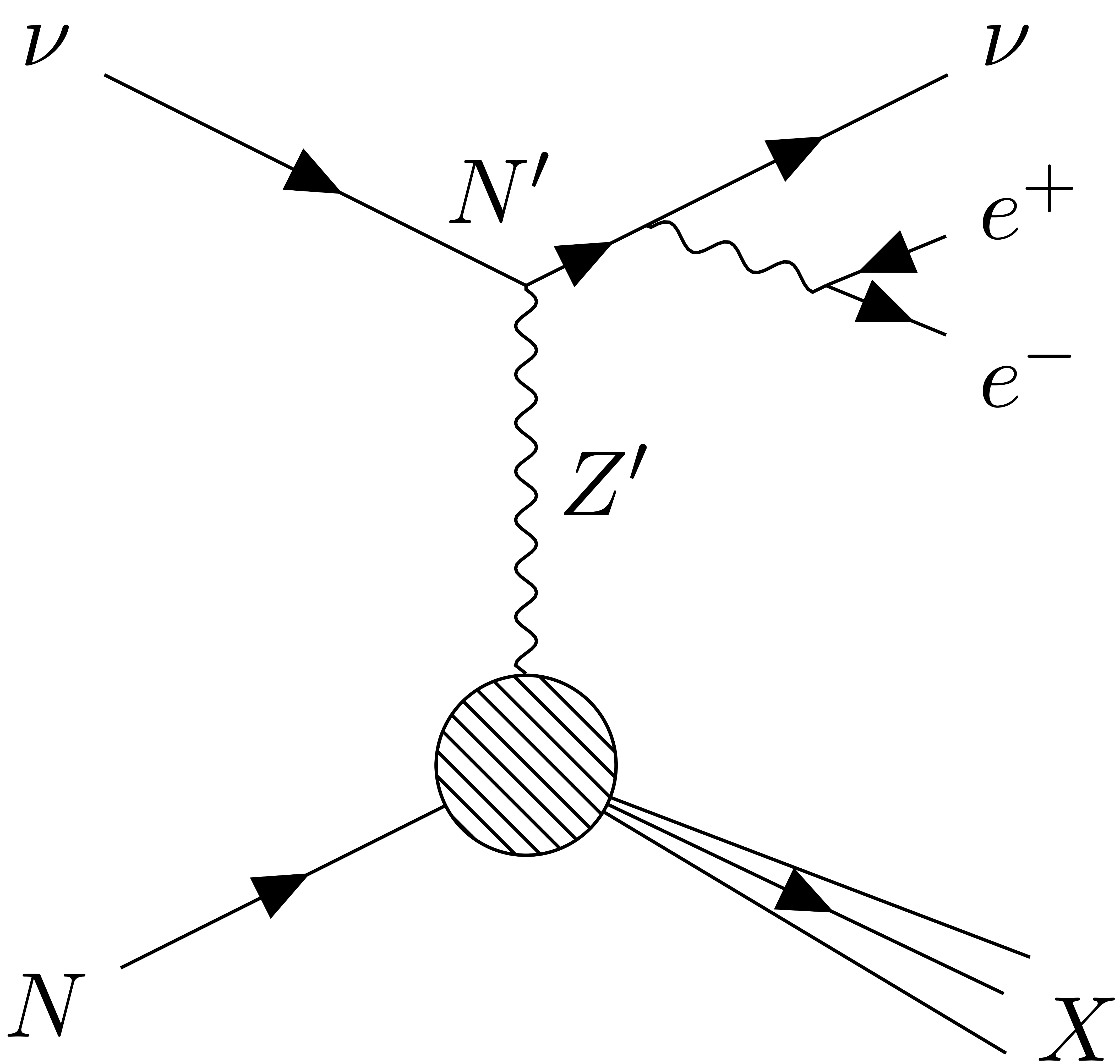




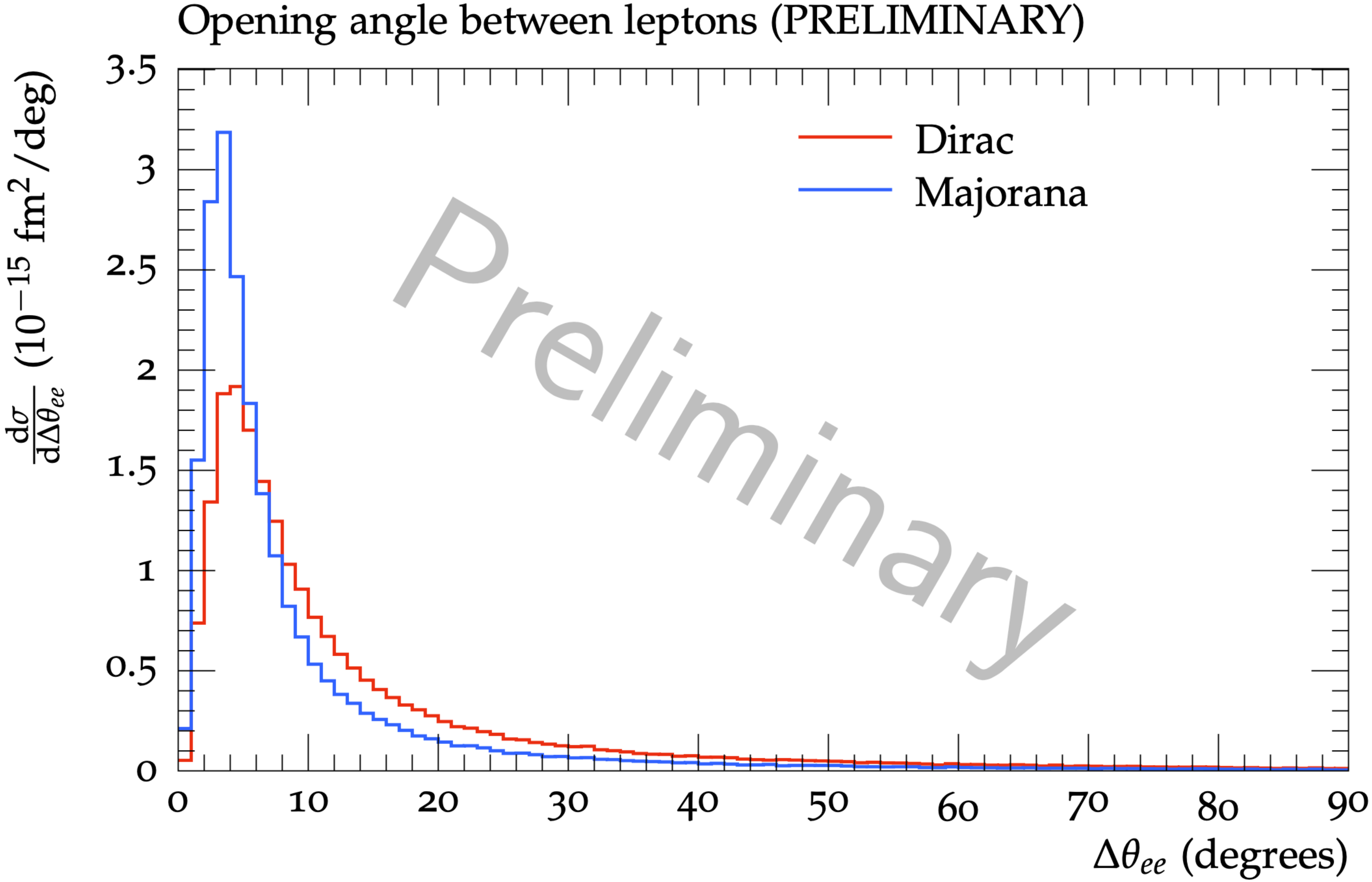
Developing ACHILLES capabilities

- First comparisons to electron scattering data
  - See previous talk by A. Papadopoulou
- **Automation of leptonic BSM**
  - Lagrangian → events
  - Tools originally developed for LHC (Comix, UFO file format, etc.)

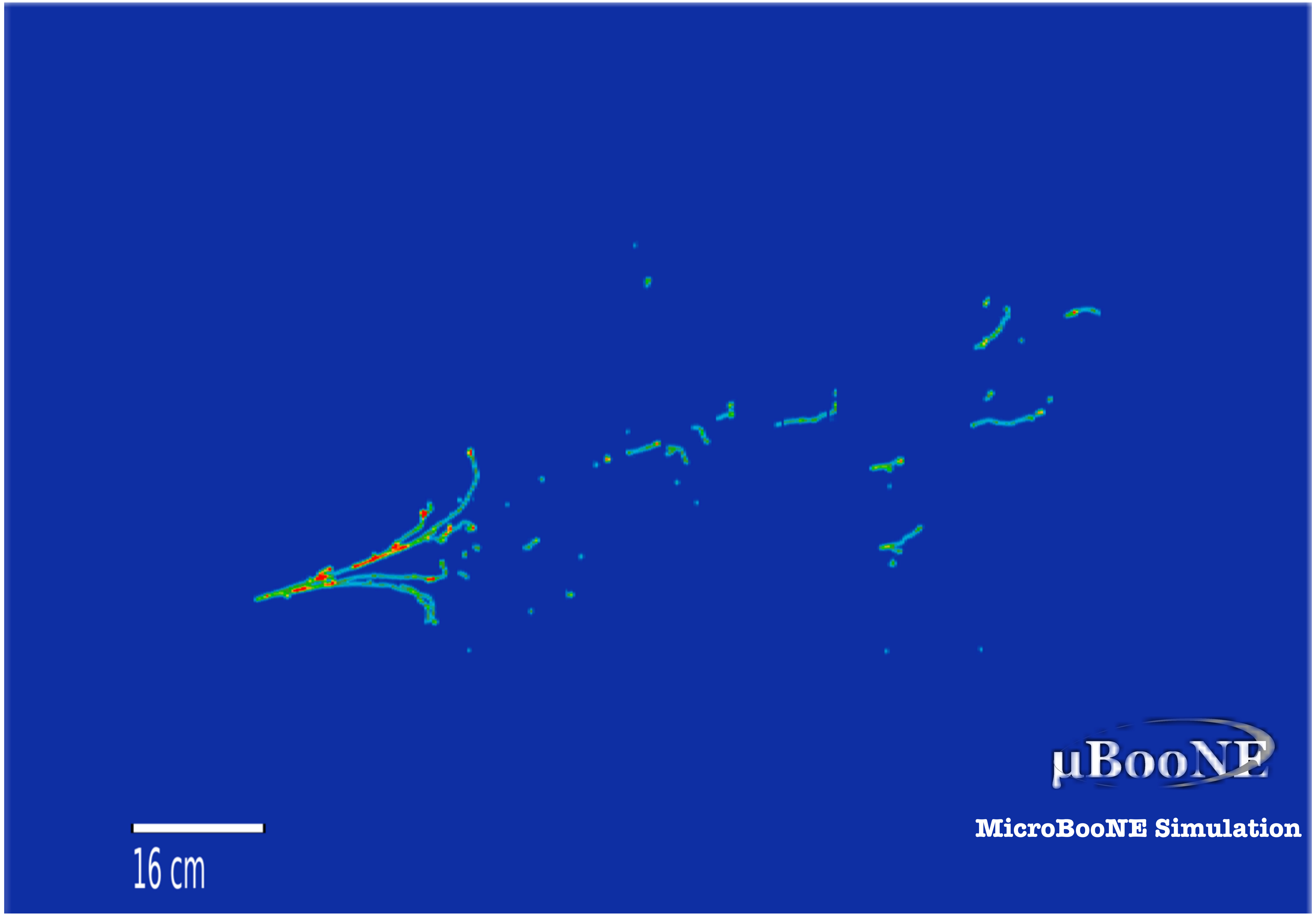
Test case: dark neutrino model from [Phys. Rev. Lett. 121, 241801 (2018)]



ACHILLES dark neutrino event generation



ACHILLES dark neutrino event generation



First events run through a full detector simulation

Getting better physics into our simulations (1)

- **How much better?**
- Precision requirements driven by physics program of SBN, DUNE, Hyper-K, *et al*.
    - δ_{CP} , BSM, supernovae, …

Current uncertainties

Source (NOvA)	$N(\nu_e)$
$\sigma_{\nu N}$ and FSI	7.7%
Total Syst.	**9.2%**

Phys. Rev. D **98**, 032012

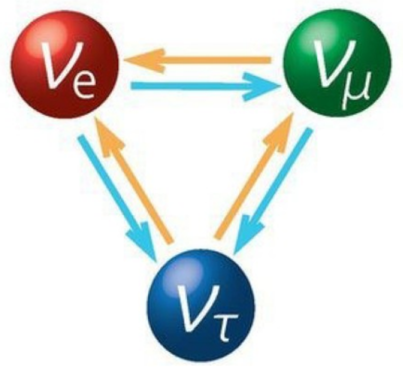
From talk by S. Dolan

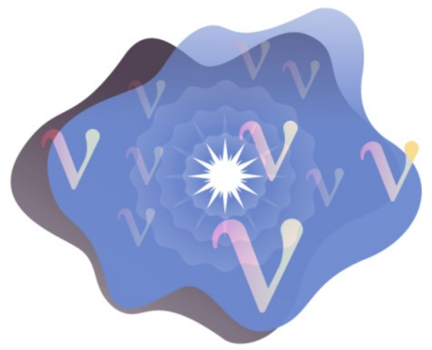
Source (T2K)	$N(\nu_e)$
$\sigma_{\nu N}$ and FSI	3.8%
Total Syst.	**5.2%**

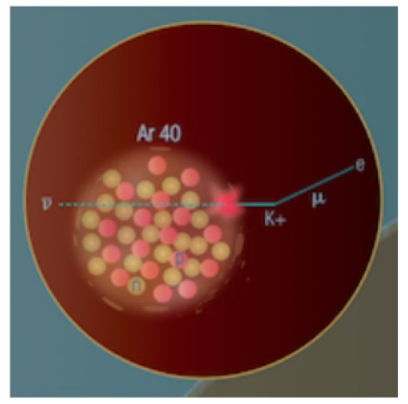
NEUTRINO 2022
XXX International Conference on Neutrino Physics and Astrophysics

- **Which improvements matter?**
- Data-driven constraints in oscillation analyses
    - A posteriori uncertainties non-trivial
- Guidance from experiments can help theory/simulation efforts ultimately be most impactful

DEEP UNDERGROUND NEUTRINO EXPERIMENT







Getting better physics into our simulations (2)

- **Better ≠ Perfect**
- Robust uncertainty quantification will remain essential
  - Traditional event reweighting may need to be supplemented
  - Must remain computationally feasible!

- Multi-generator experimental workflows
  - “Fake data,” cross-checks, etc.
  - Considered essential in collider community, we can catch up
  - Requires **infrastructure investment**: common event format, interfaces
  - See **arXiv:2008.06566** and **arXiv:2203.11110** for much more discussion

Getting better physics into our simulations (3)

- **A generator is only (at best) as good as the underlying theory**
- Support for further investigation is critical: exclusive final states, SIS/DIS, …

- **Informed by experimental data**
- Growing cross-section literature requires curation
  - Tools for model benchmarking increasingly important
  - Non-neutrino probes (electrons, hadrons, …) have much to teach us
  - “**Neutrino Scattering Center**” akin to NNDC in the US?

nuisance.hepforge.org

NUISANCE

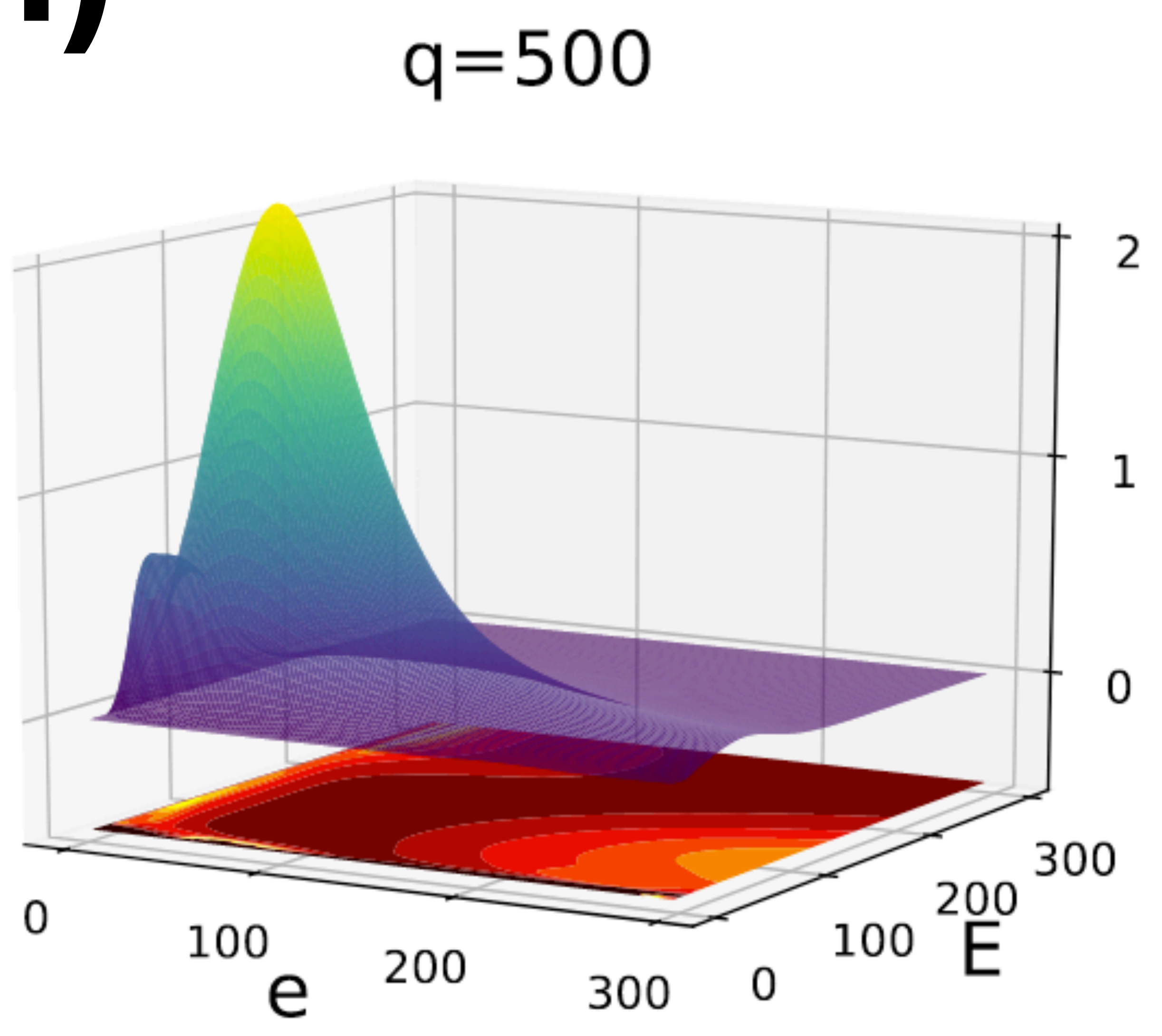
National Nuclear Data Center

Getting better physics into our simulations (4)

- **Correct and timely implementation of new models**

- Technical solutions
  - LHC-style automation as in ACHILLES
  - Direct interfacing to theory codes or their outputs

- Sociological solutions
  - Career incentives for “strengthening the bridge”
  - Why should my postdoc do this instead of analysis / model building?



Phys. Rev. C 101, 044612 (2020)

Conclusion

- Our discovery science goals require high-quality neutrino scattering simulations

- Interesting innovations are happening across the generator community

- Challenges remain for precision, but this is achievable with sufficient investment

Genie
UNIVERSAL NEUTRINO GENERATOR & GLOBAL FIT

NuWro
Wrocław Neutrino Event Generator

GiBUU