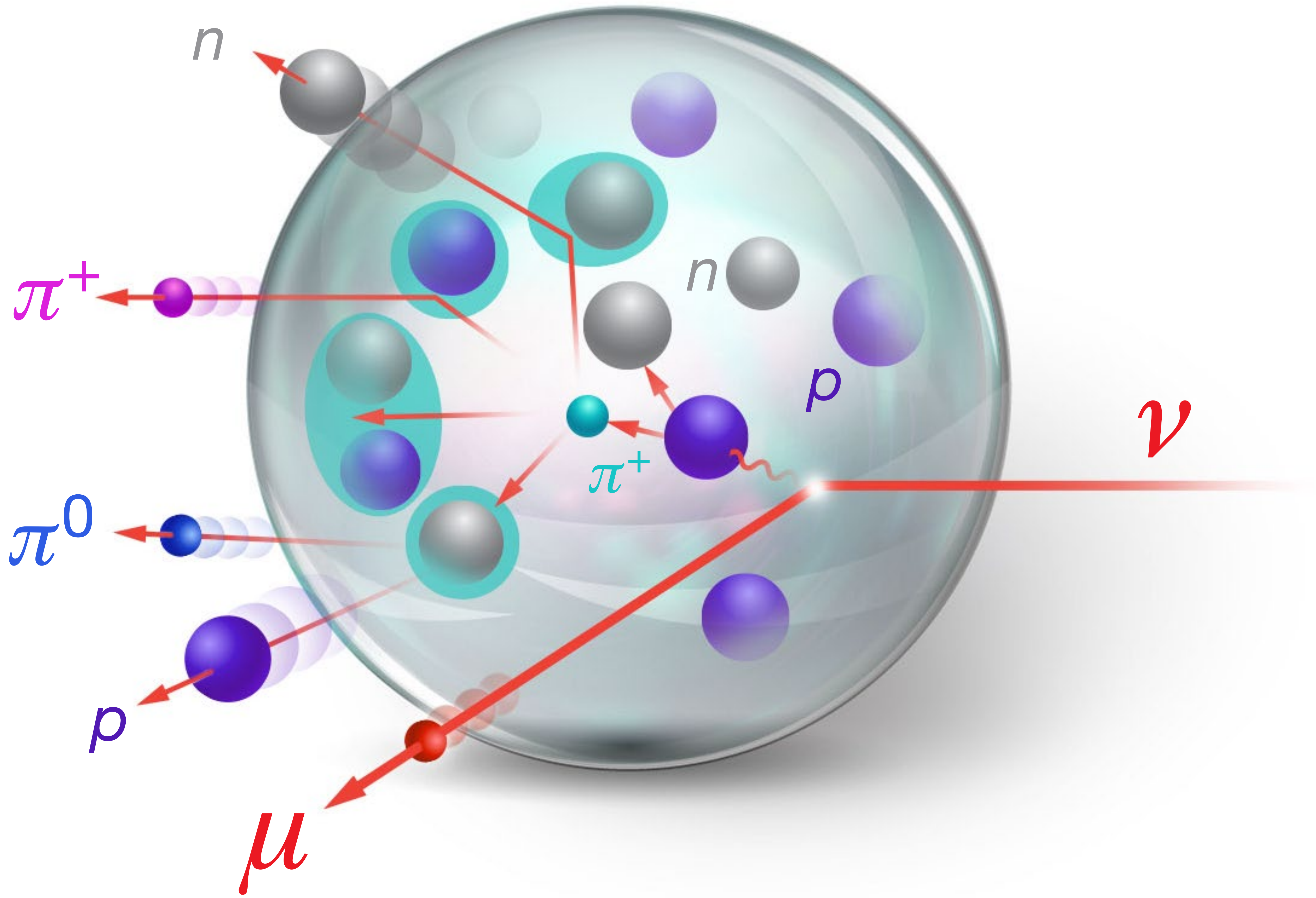
Theoretical tools for neutrino scattering: interplay between lattice QCD, EFTs, nuclear physics, phenomenology, and neutrino event generators



Steven Gardiner

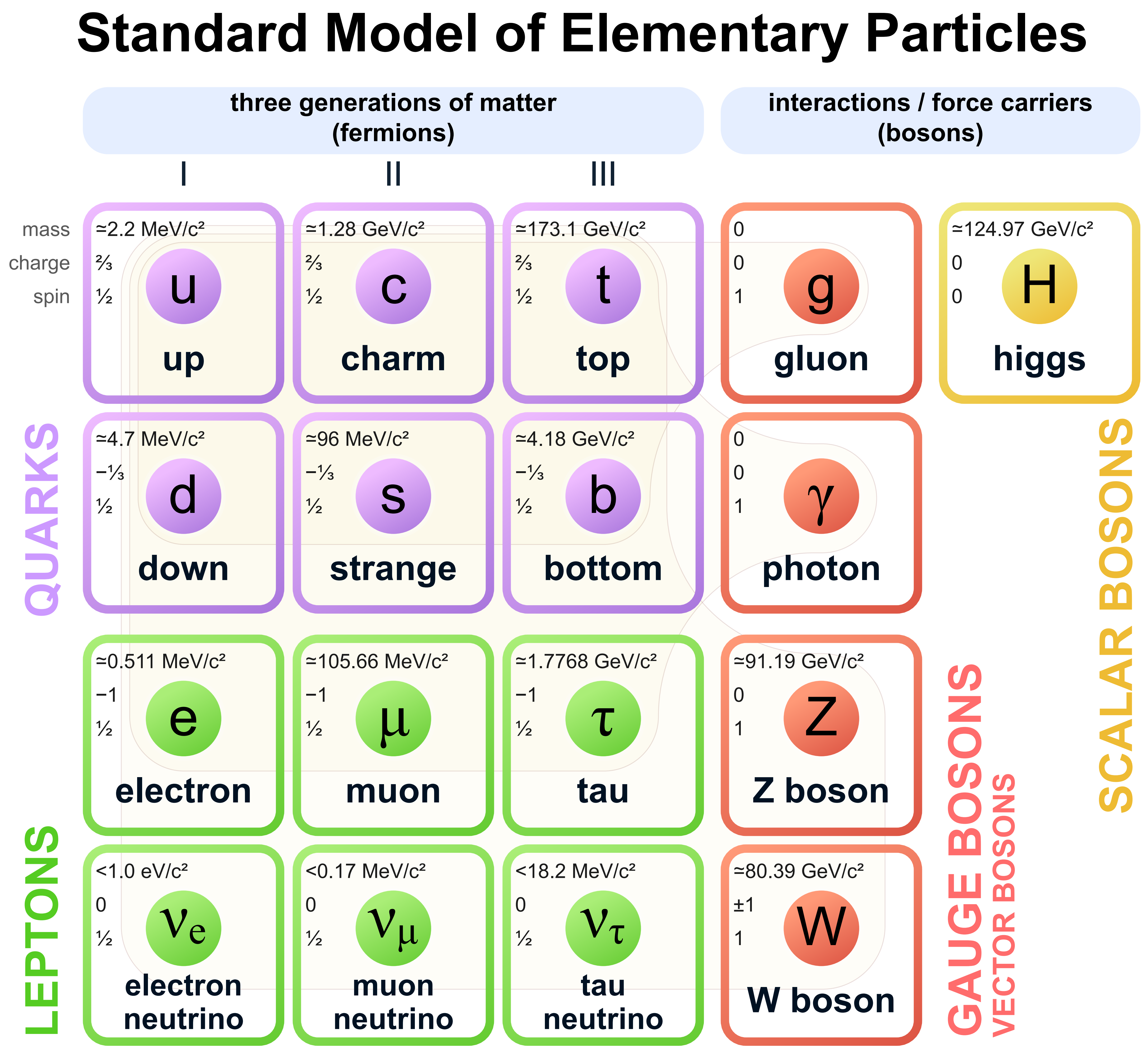
HSF Generator WG Meeting

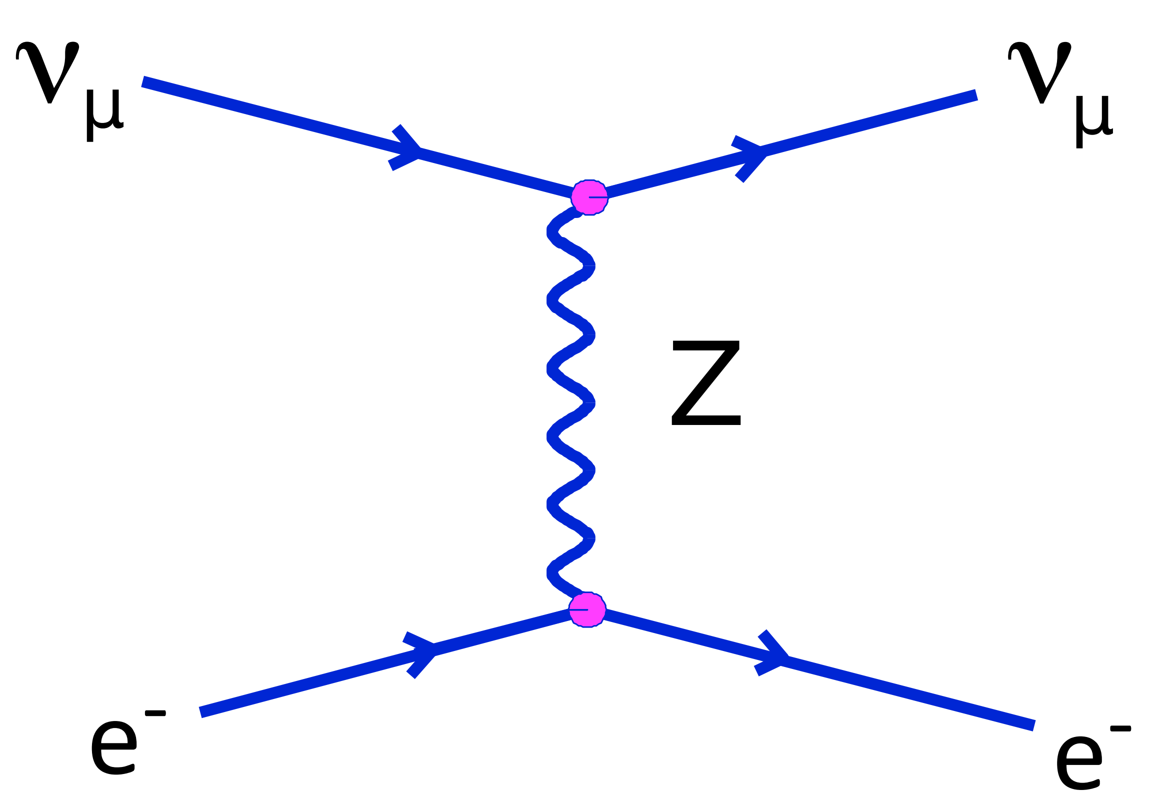
5 May 2022

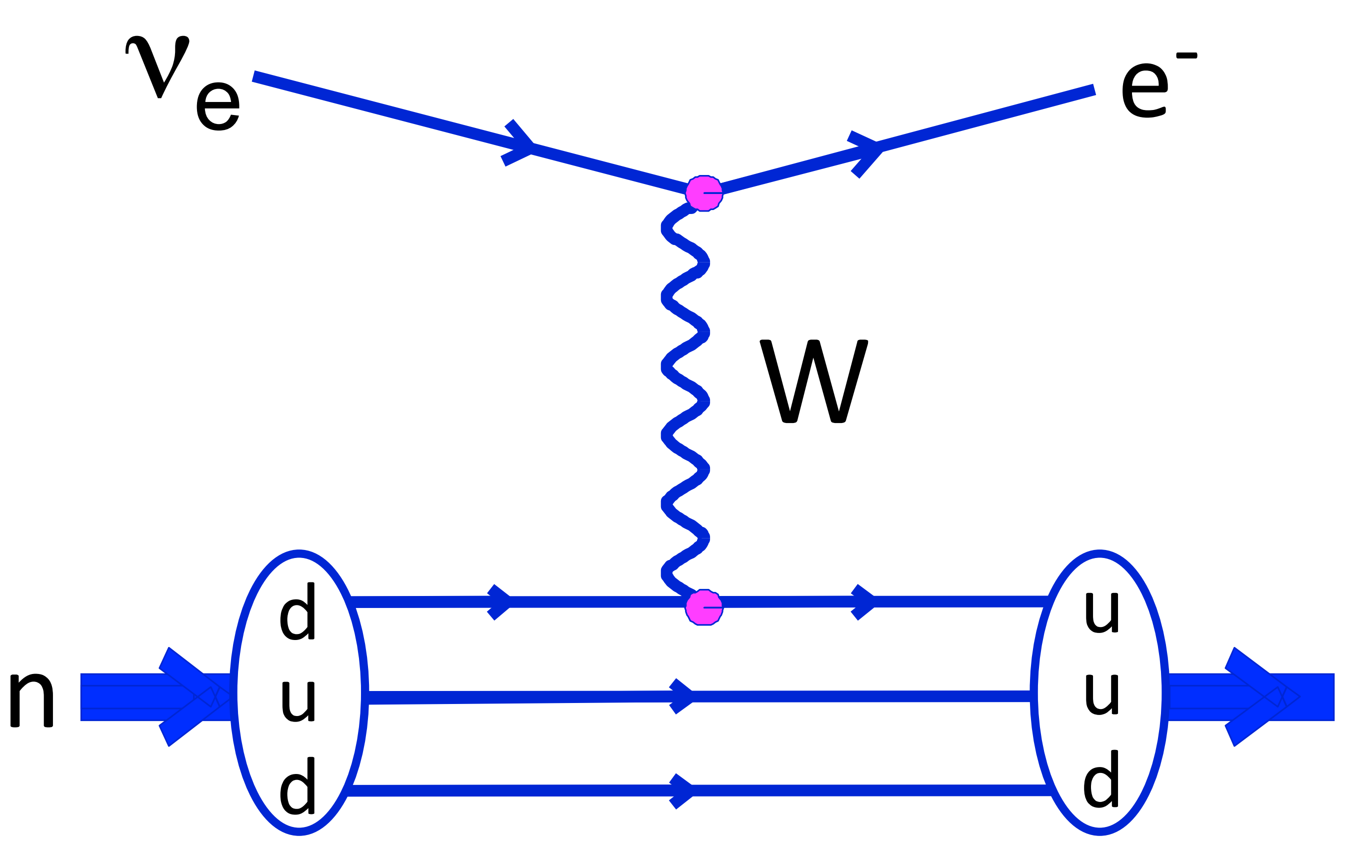
Partially based on arXiv:2203.09030

Neutrinos in the Standard Model

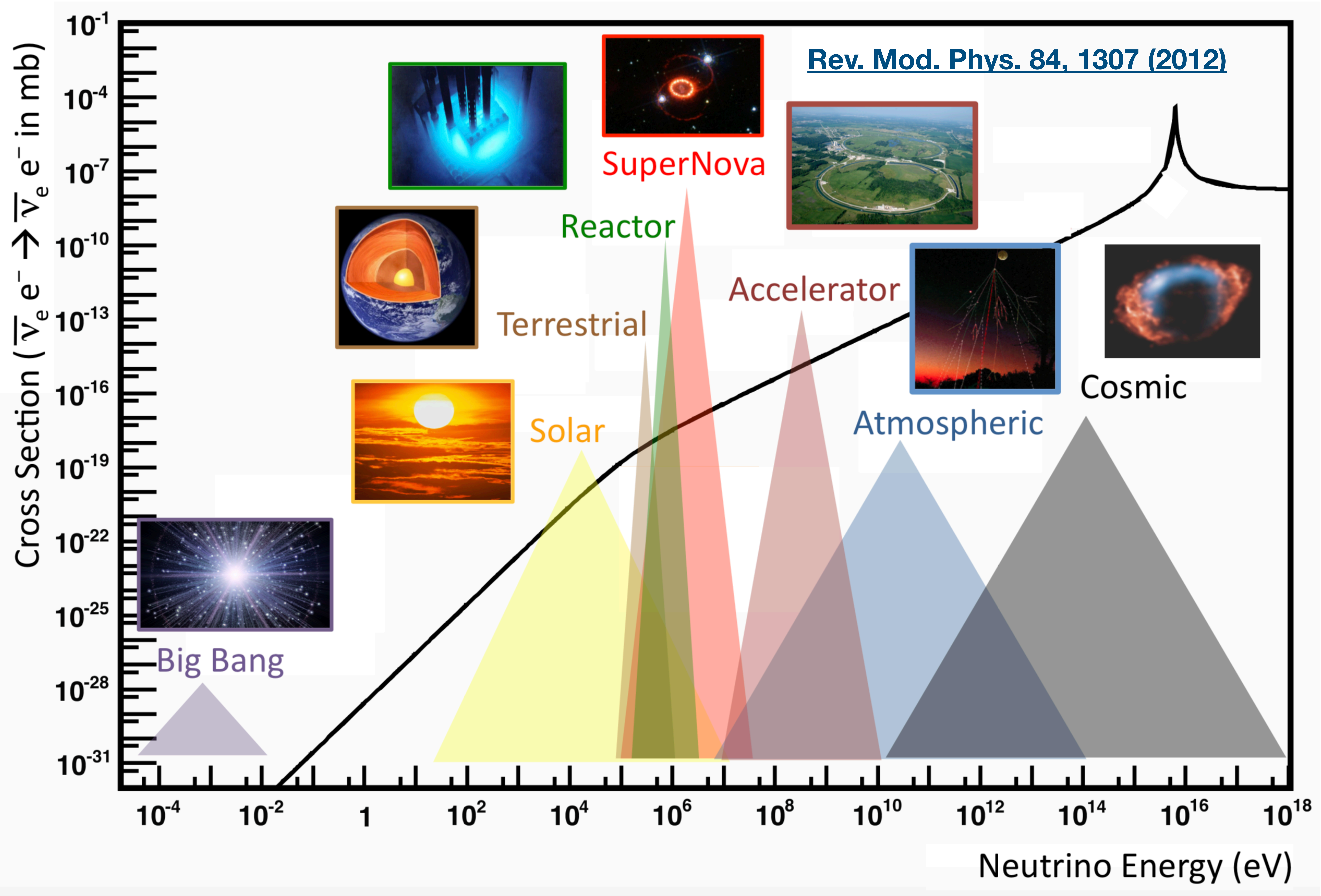
- Weakly interacting
  - W exchange = “charged current” (CC)
  - Z exchange = “neutral current” (NC)
- Detectors typically rely on **neutrino-nucleus** interactions
  - Far larger cross section than ν-e scattering
- Intense neutrino beams and massive targets still required to do the physics!







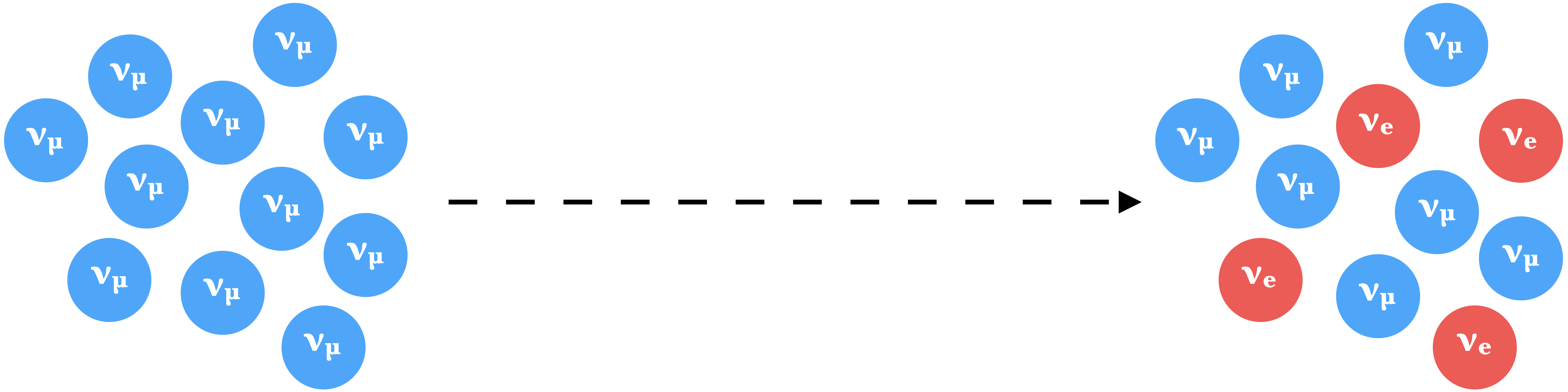
Neutrino physics across energy scales



- Many orders of magnitude in energy!
- **White paper** focuses on ~1 MeV to ~10 GeV region
- **MeV**: solar + supernova neutrinos, precision nuclear measurements
- **GeV**: oscillations, various exotic searches
- Very high energies also interesting, cross-section models sub-leading concern

Neutrino oscillations

- Flavor eigenstates (ν_e, ν_μ, ν_τ) ≠ mass eigenstates (ν_1, ν_2, ν_3) → mixing
- Leads to oscillations: flavor can change as neutrinos travel



Oscillation probability:
(two-neutrino case)

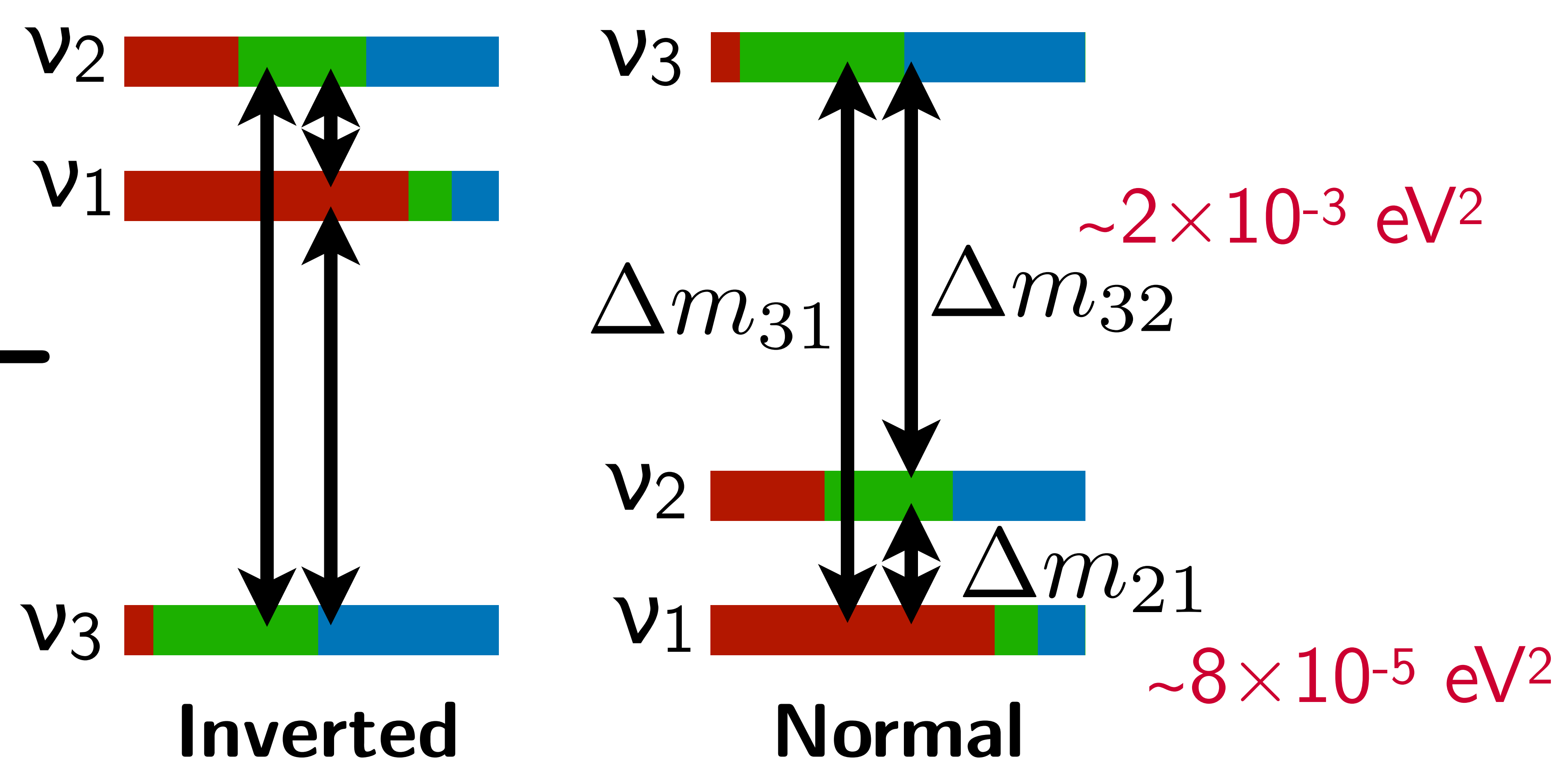
$$P(\nu_\alpha \to \nu_\beta) \approx \sin^2 2\theta \sin^2\left(\frac{\Delta m^2 L}{4E_\nu}\right)$$

Neutrino oscillations

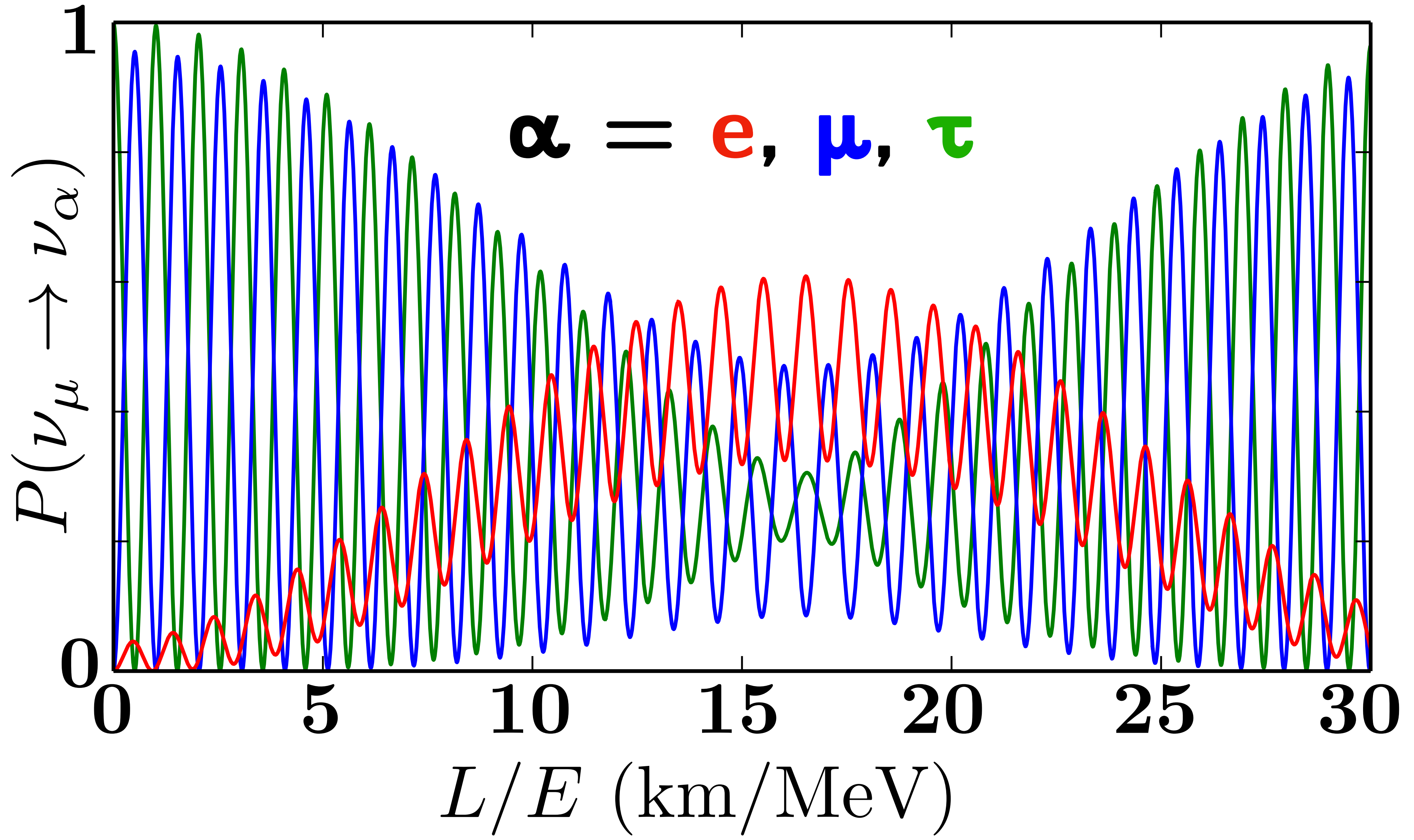
Three Neutrinos with Mixing

$$|\nu_\alpha\rangle = \sum_i U^*_{\alpha i}|\nu_i\rangle \; +$$

Mass Splittings (e μ τ)



Oscillation Probabilities



Mixing matrix

- 3 mixing angles θ_{12}, θ_{23}, θ_{13}
- CP-violating complex phase δ^{CP}
  - If $\delta^{CP} \neq 0,\pi$, then neutrinos and antineutrinos oscillate differently: $P(\nu_\alpha \to \nu_\beta) \neq P(\bar{\nu}_\alpha \to \bar{\nu}_\beta)$

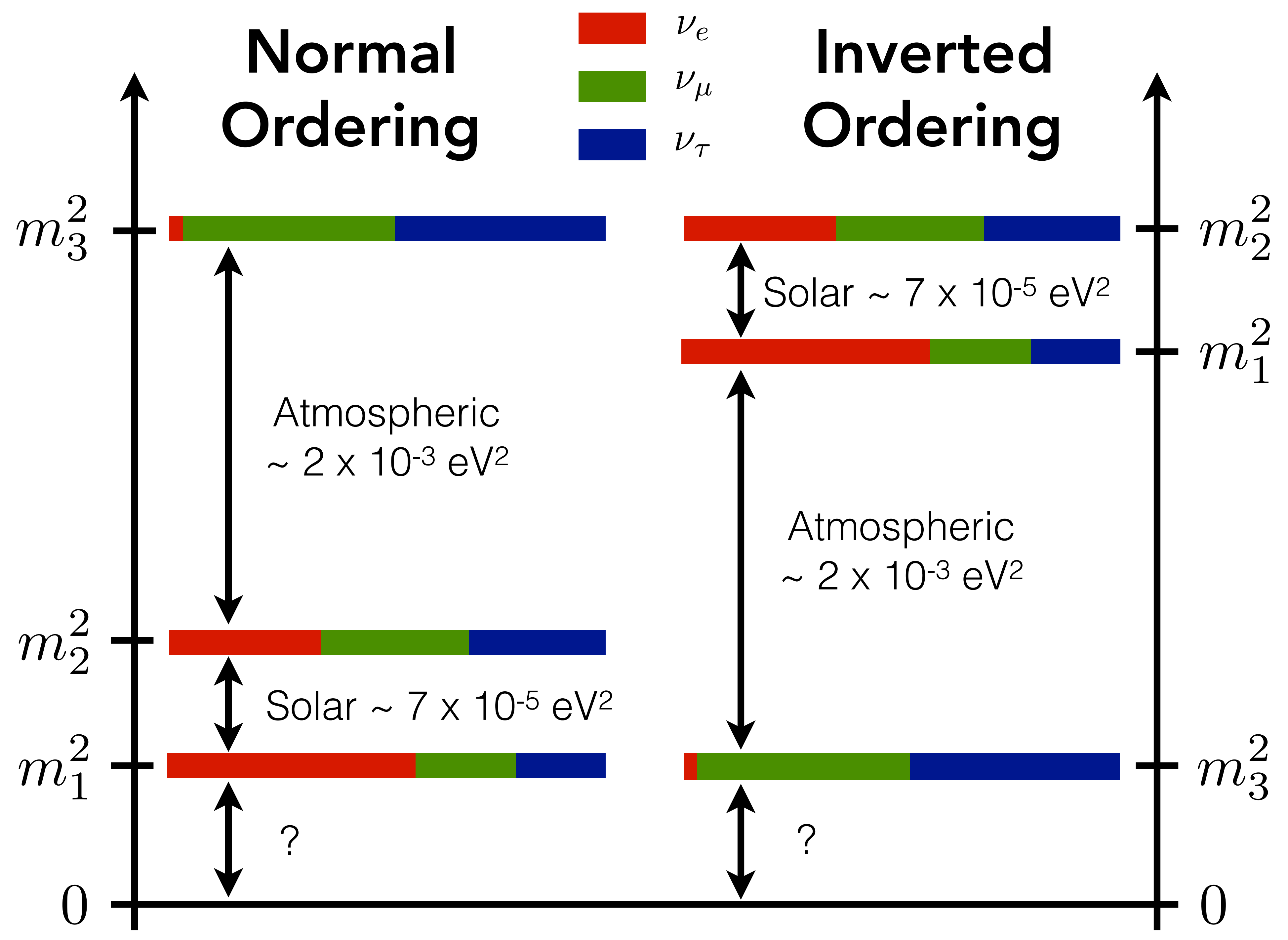
Diagrams courtesy of A. Mastbaum

Key open questions for neutrino oscillation experiments

Is there CP violation in the lepton sector?
(Is $\delta^{CP} \neq 0,\pi$?)

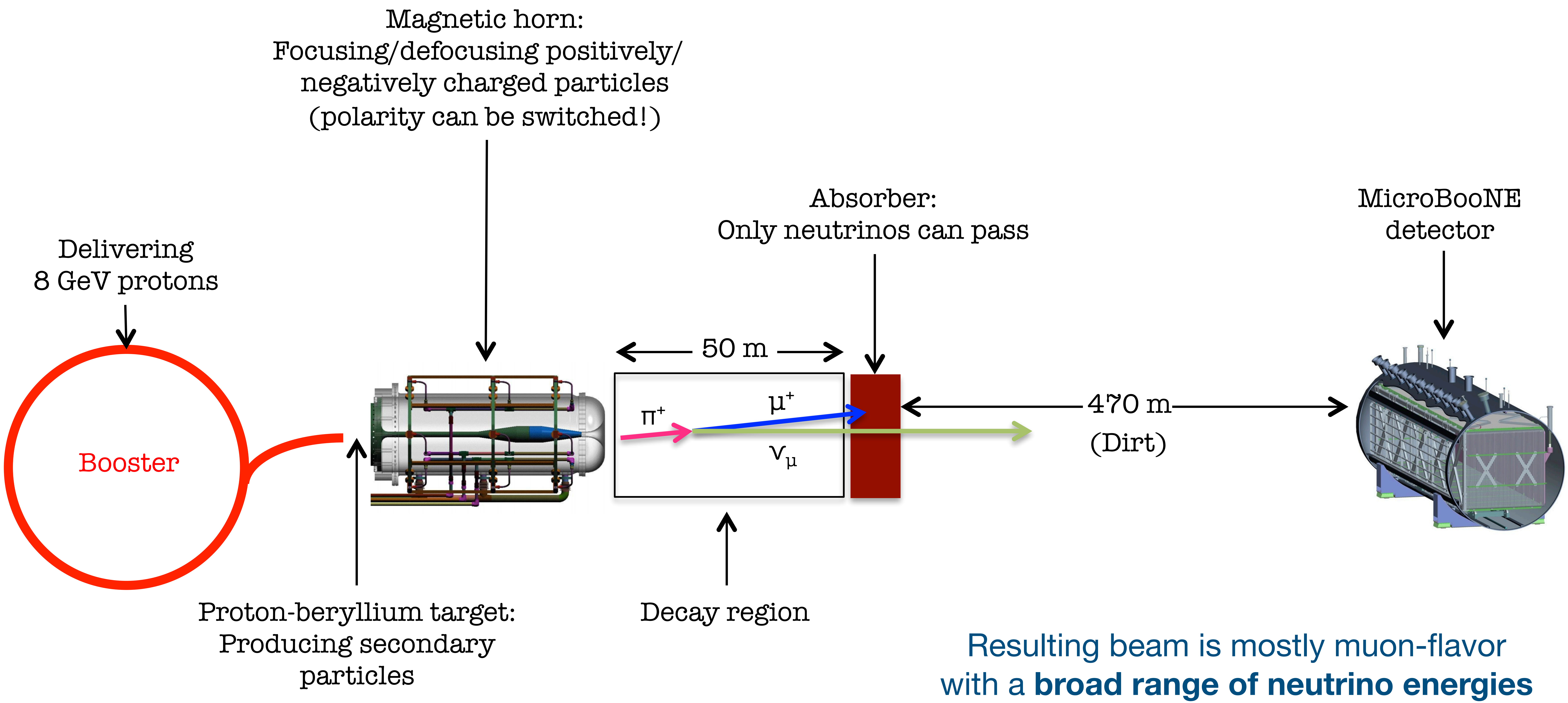
Are there more than 3 neutrinos?
(Sterile: do not participate in weak interactions)

Are there new interactions that we could discover using neutrinos?



What is the neutrino mass ordering?
(Is ν_3 the heaviest or lightest mass eigenstate?)

Neutrino production at the Booster Neutrino Beam



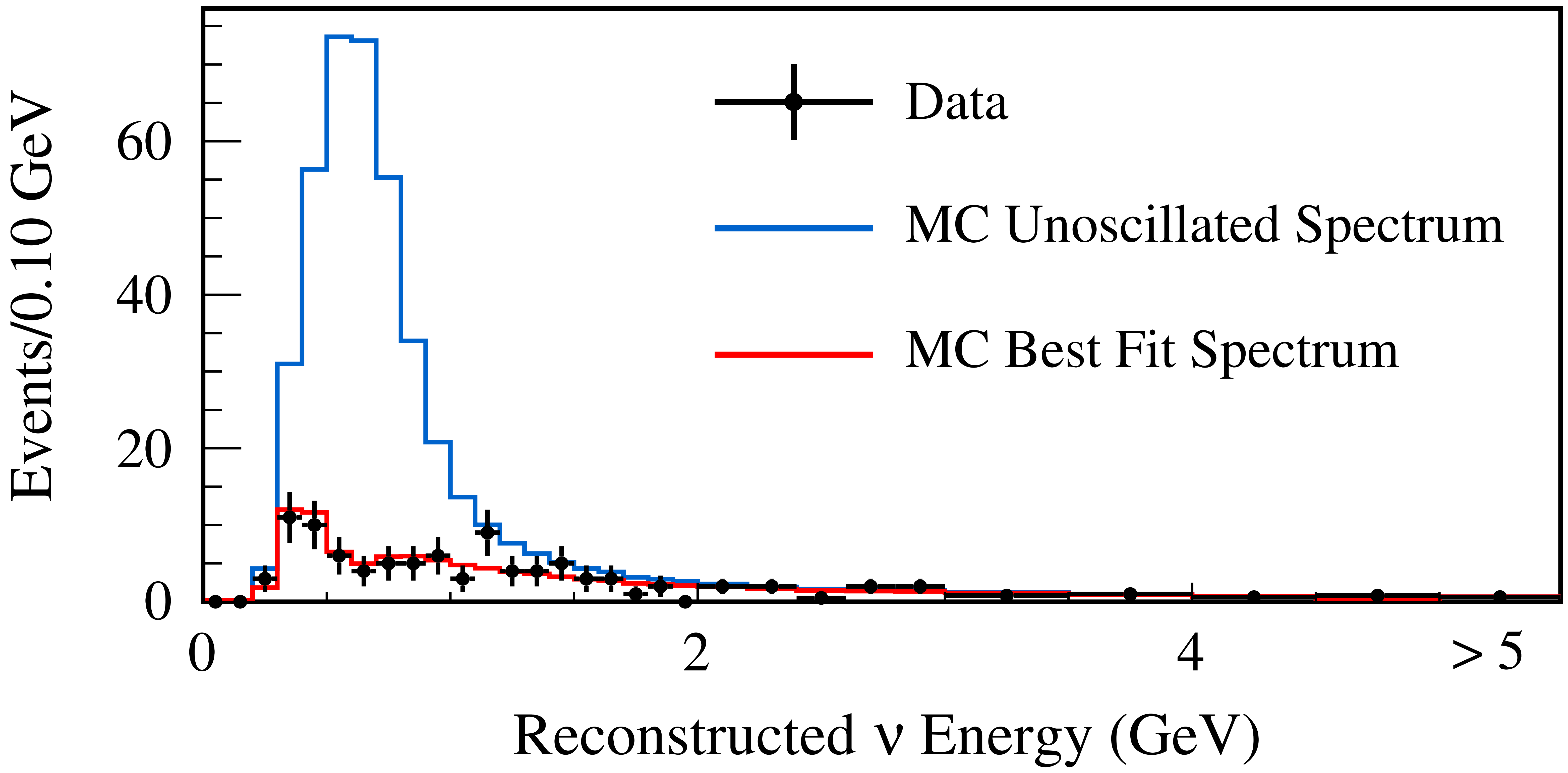
Resulting beam is mostly muon-flavor
with a **broad range of neutrino energies**

Diagram by A. Schukraft

Measuring neutrino oscillations

- Experiments typically seek to obtain $P_{\nu_\alpha \to \nu_\beta}$ from data
  - Measure parameters
  - Test non-standard scenarios
- Not directly observable
  - Compare measured event rate to a no-oscillation expectation
- **Example:** ν_μ disappearance at T2K

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



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

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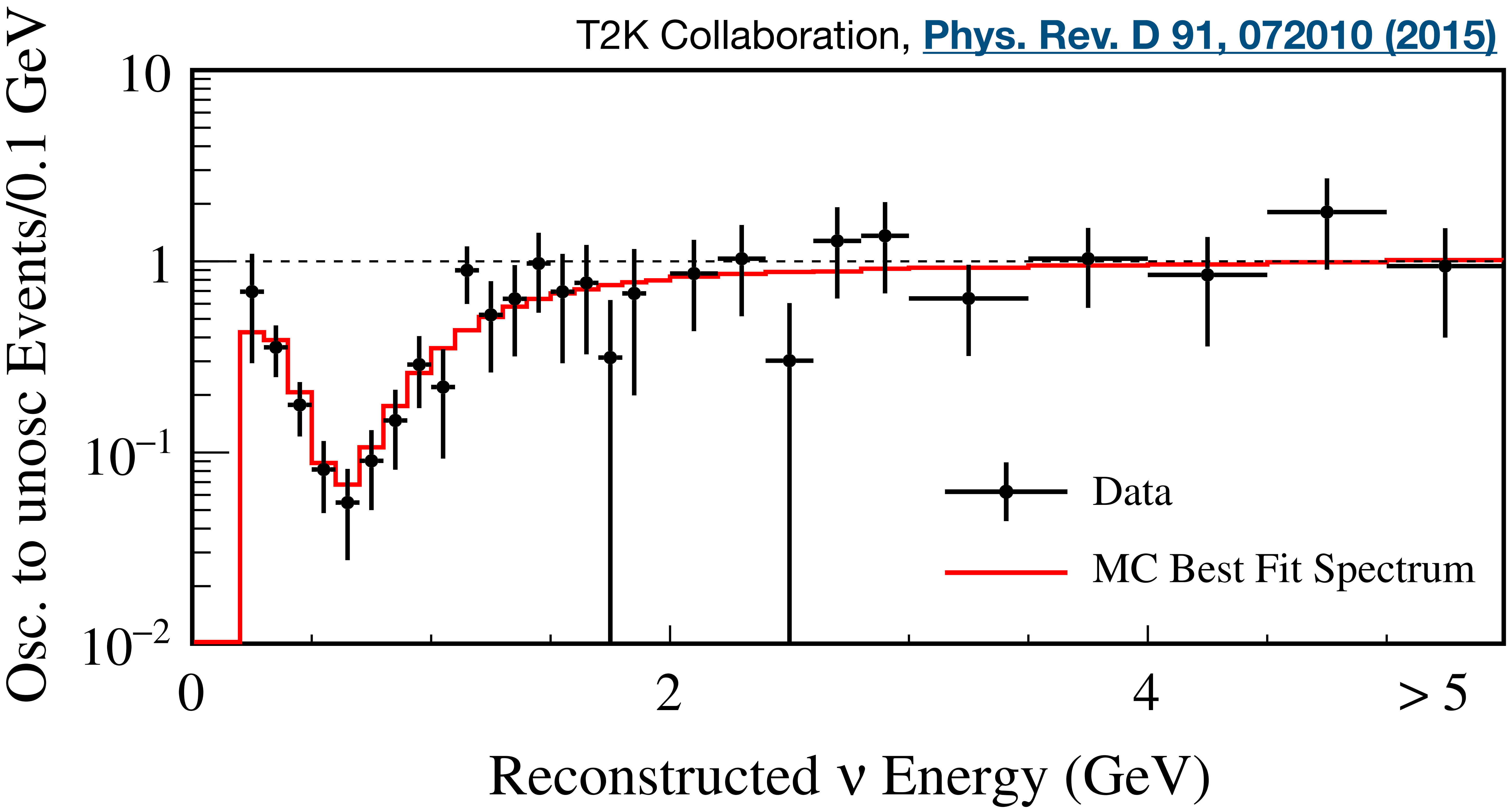
T2K Collaboration, [Phys. Rev. D 91, 072010 (2015)]



An accurate understanding of **neutrino energy reconstruction** and the **predicted event rate** is critical to success

Key open questions for neutrino oscillation experiments

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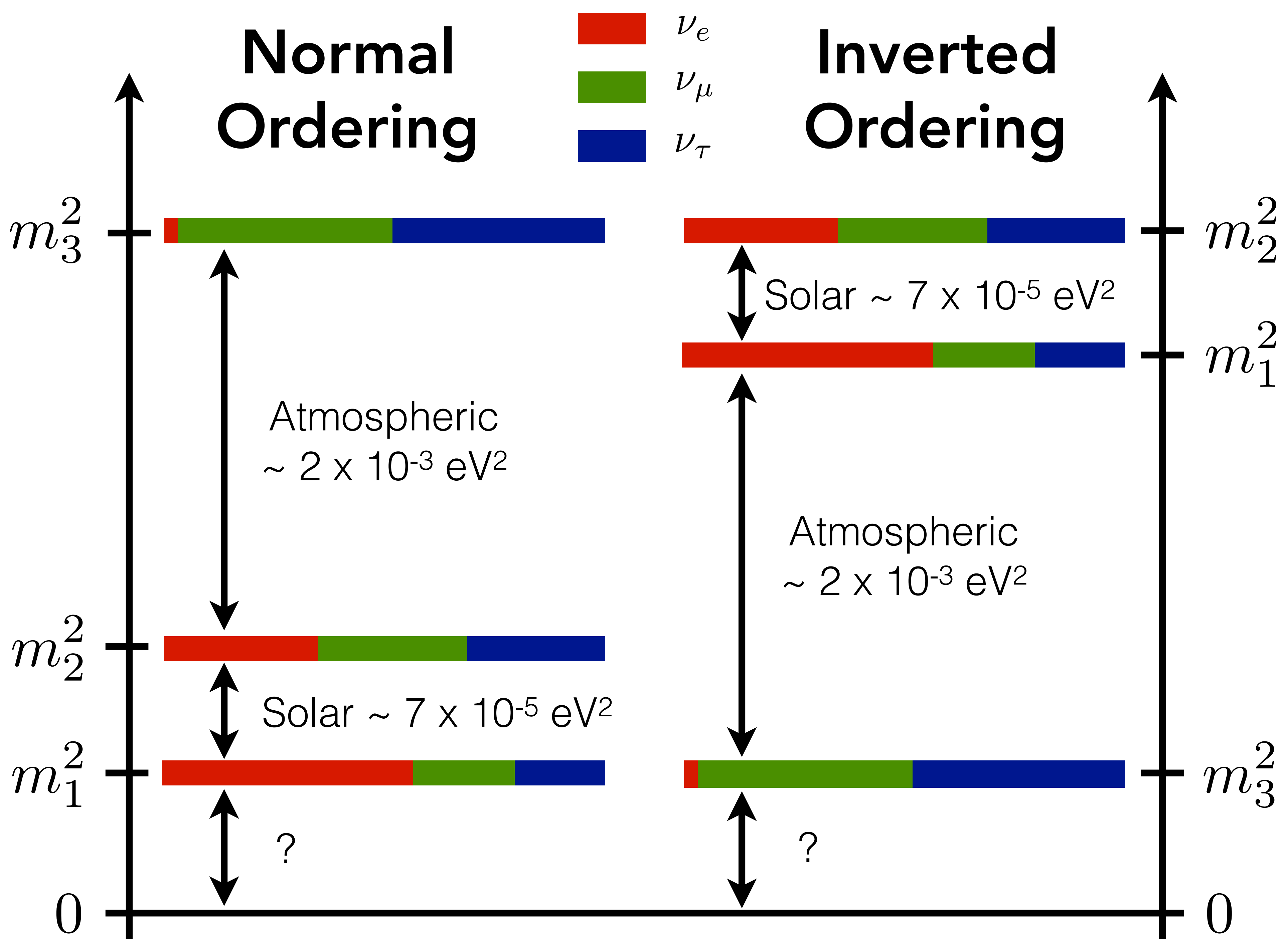

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(Is ν_3 the heaviest or lightest mass eigenstate?)

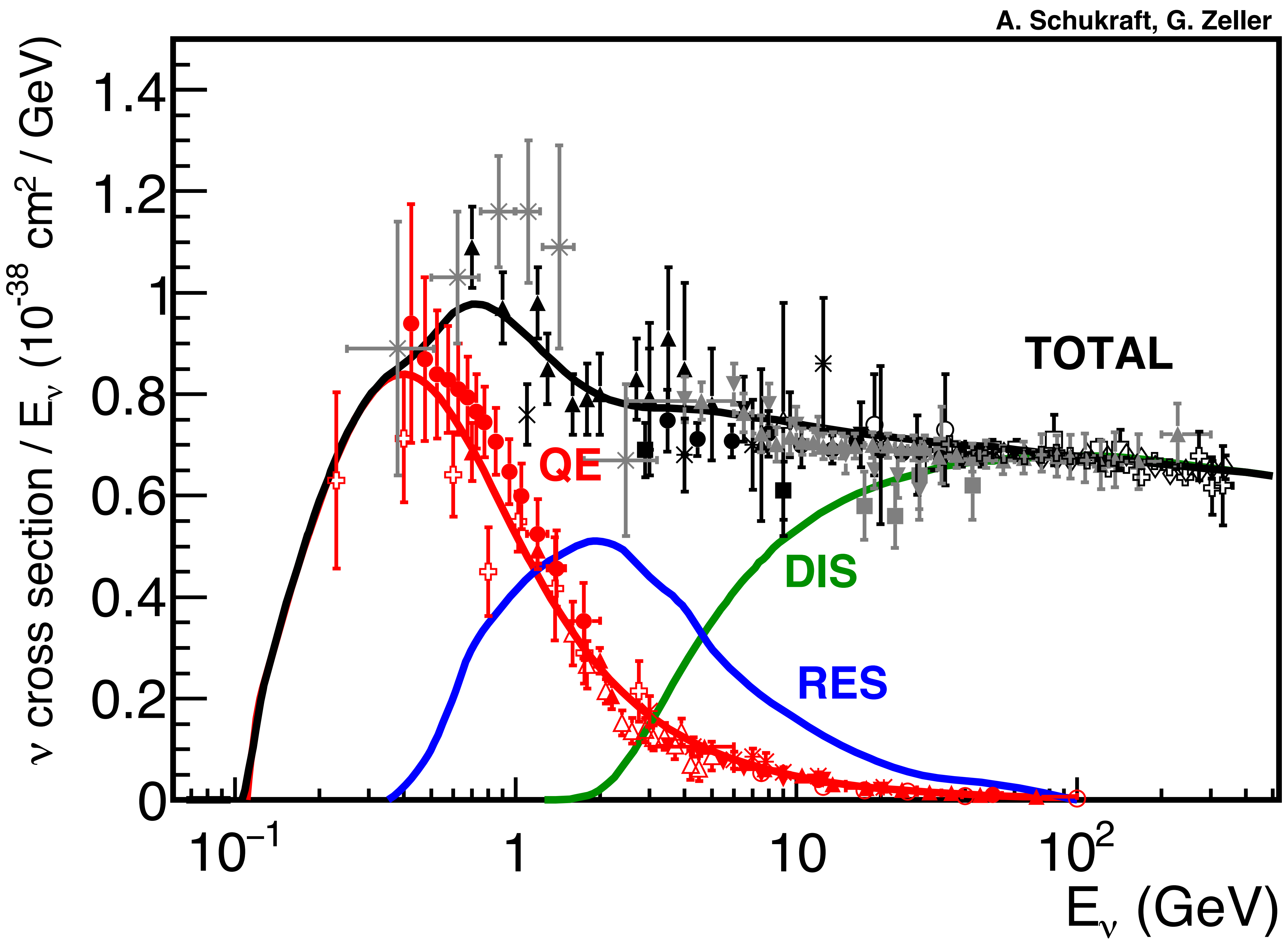
Opportunities beyond neutrino properties:

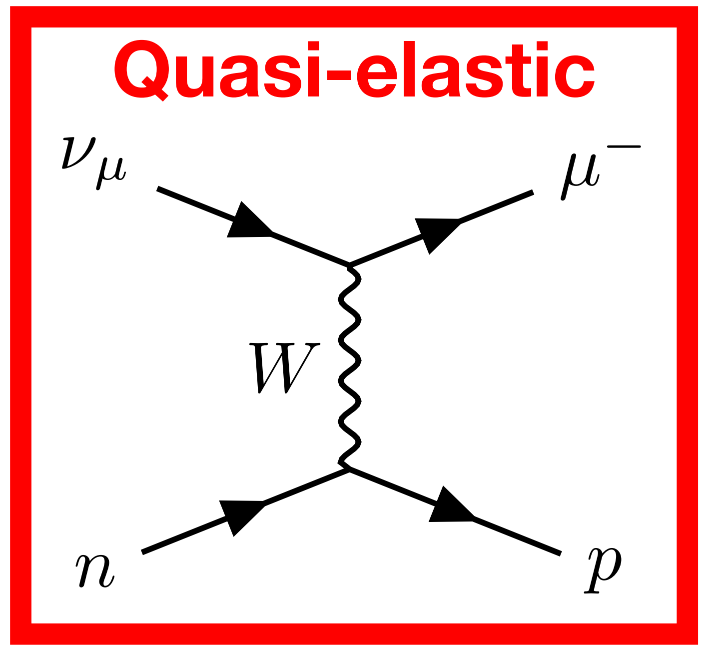
- Natural neutrino sources: solar, supernova, and atmospheric neutrinos
- Rare event searches: proton decay, dark matter, heavy neutral leptons, . . .

Modeling neutrino-nucleus interactions

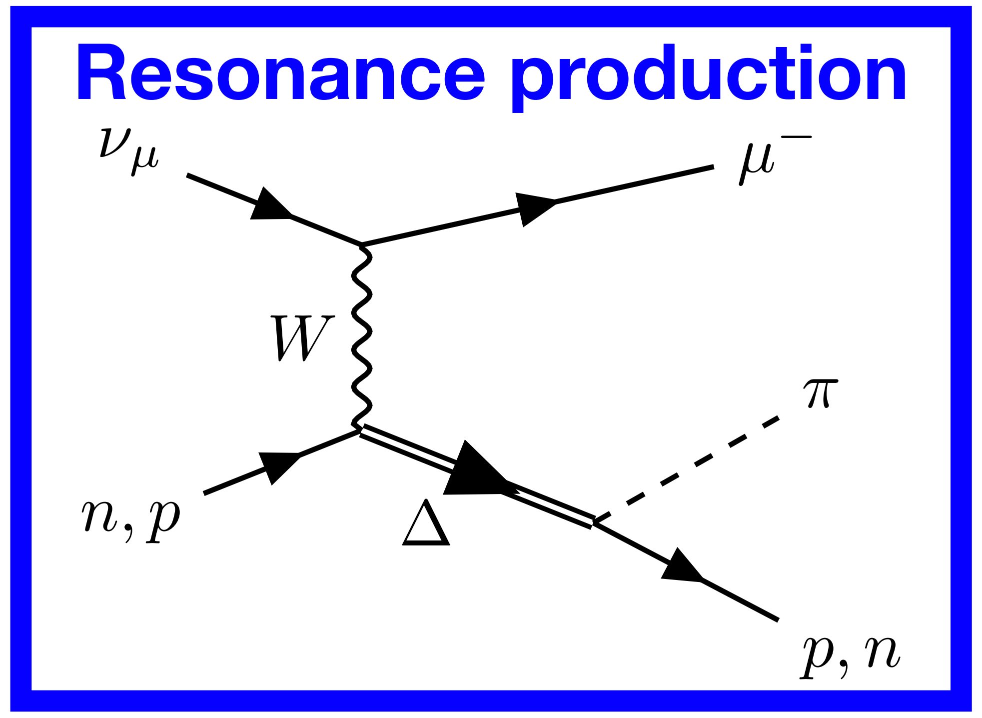
- Experiments use cross-section models for critical tasks
  - **Neutrino energy reconstruction**
  - Expected event rates
  - Efficiency and background corrections
  - Systematic uncertainty calculations

- Measurements essential to constrain and improve models

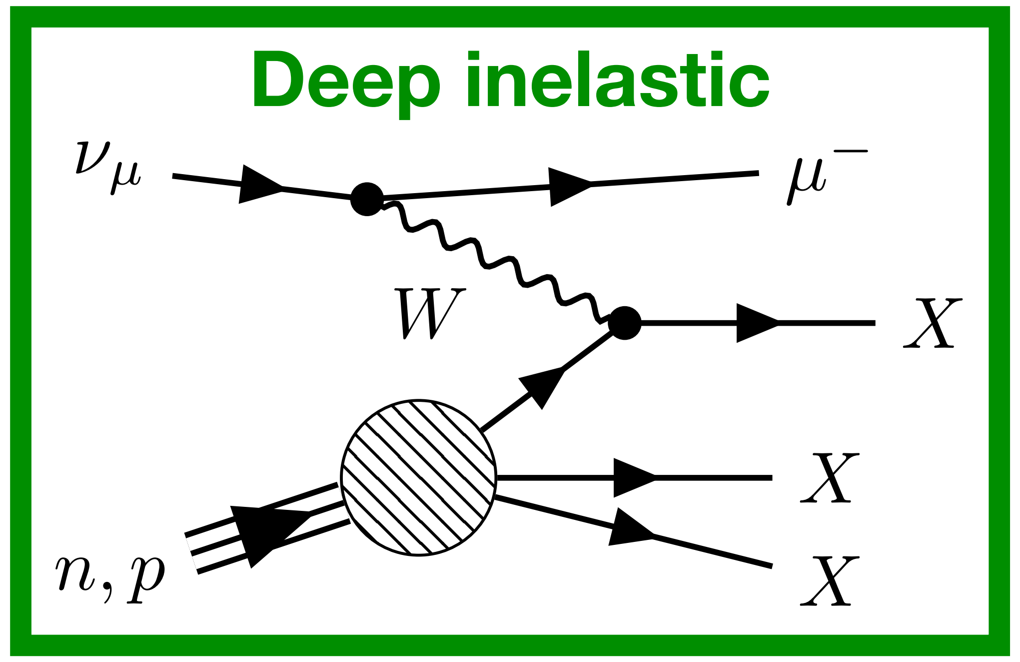




QE

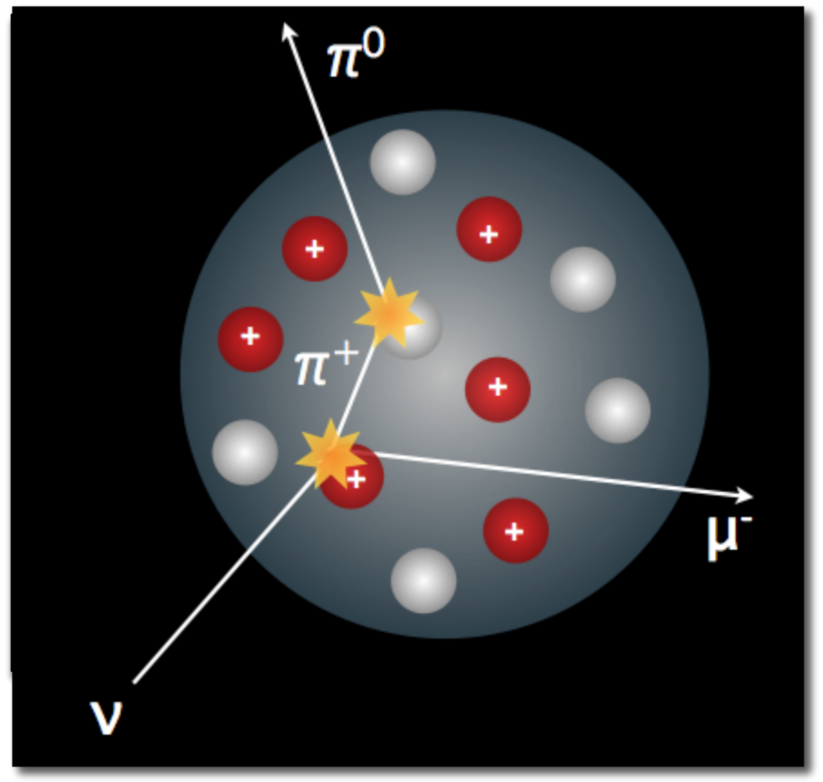


RES

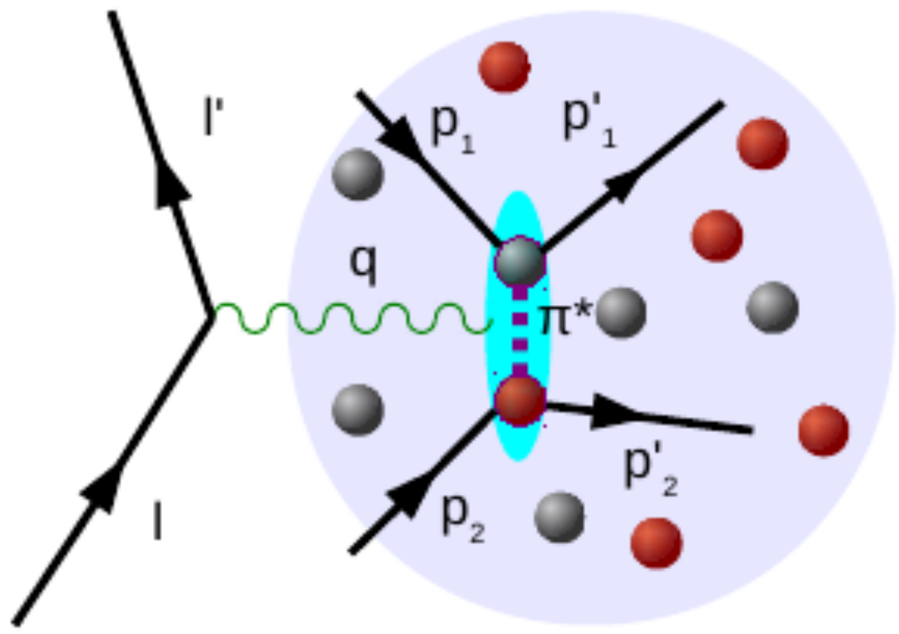


DIS

Final-state interactions (FSIs)



Two-particle two-hole (2p2h) interactions ("MEC")



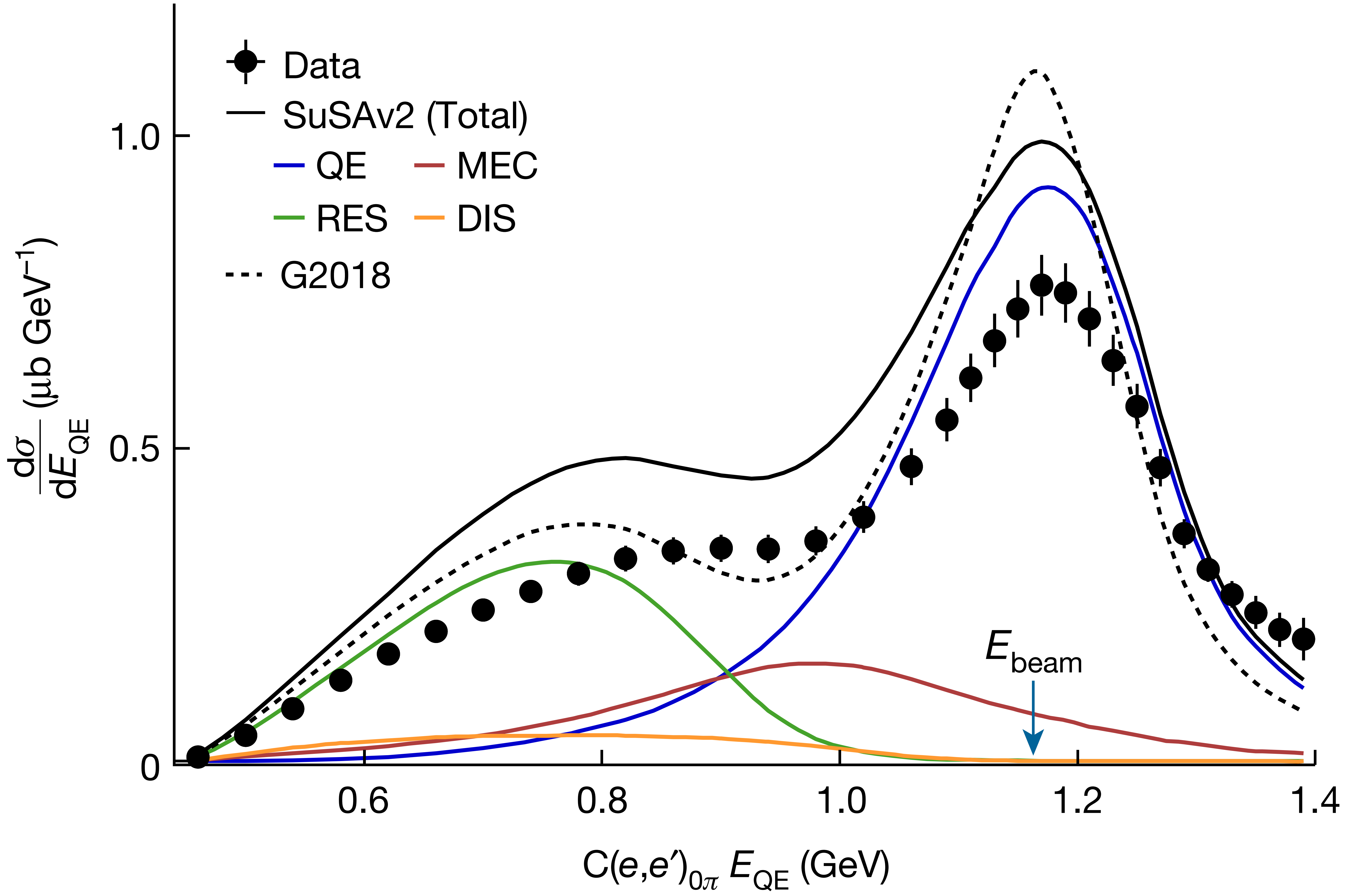
Nucleon-level processes

Nuclear effects

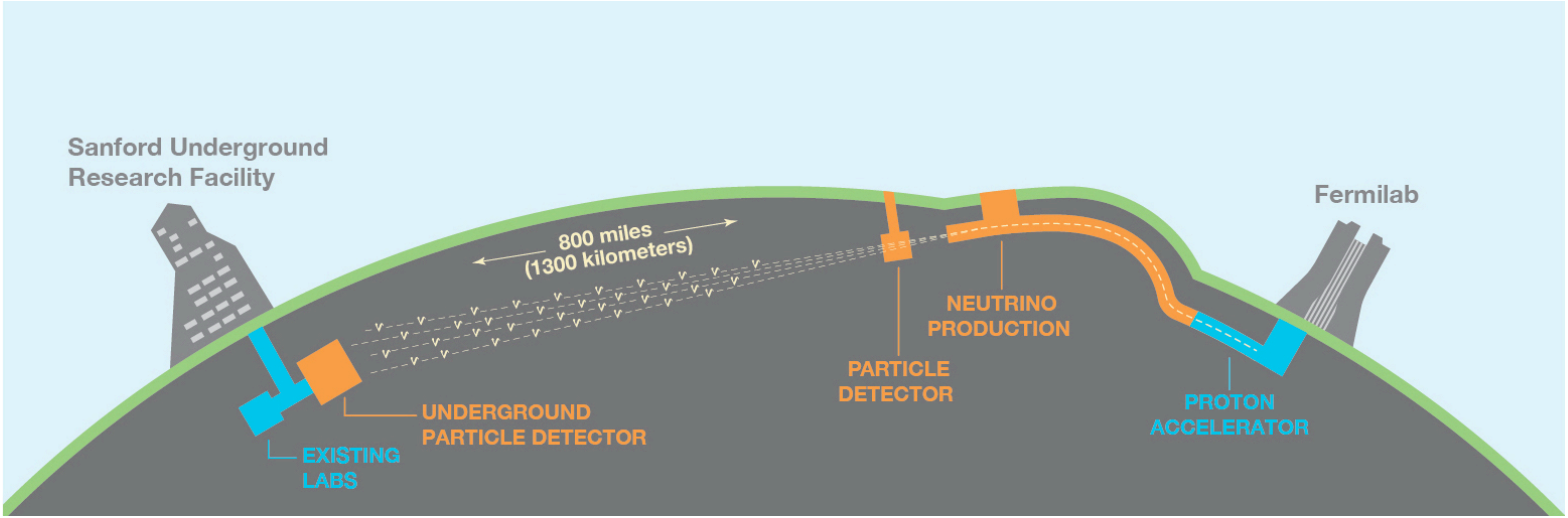
Checking neutrino energy reconstruction with electrons

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

[Nature 599, 565 (2021)]

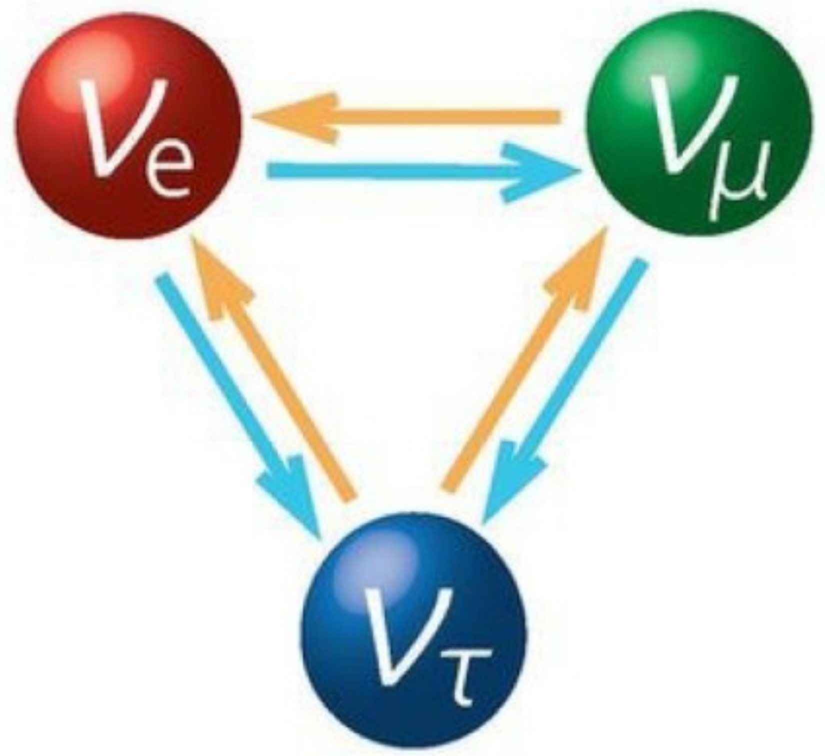


The Deep Underground Neutrino Experiment (DUNE)



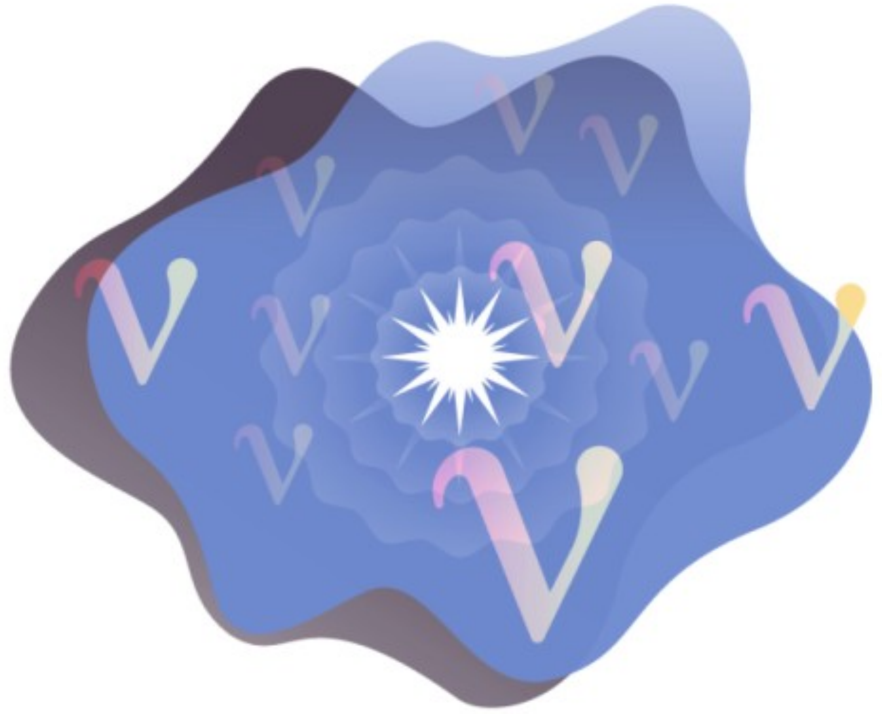
- World’s most powerful neutrino beam (1.2 MW+) and two groups of detectors
  - **Far detector**: 4 × 17 kton LArTPCs (40 kton total fiducial mass)
  - **Near detector**: Multi-component (including liquid and gaseous argon)
- Data taking to begin circa 2030

Primary science goals of DUNE



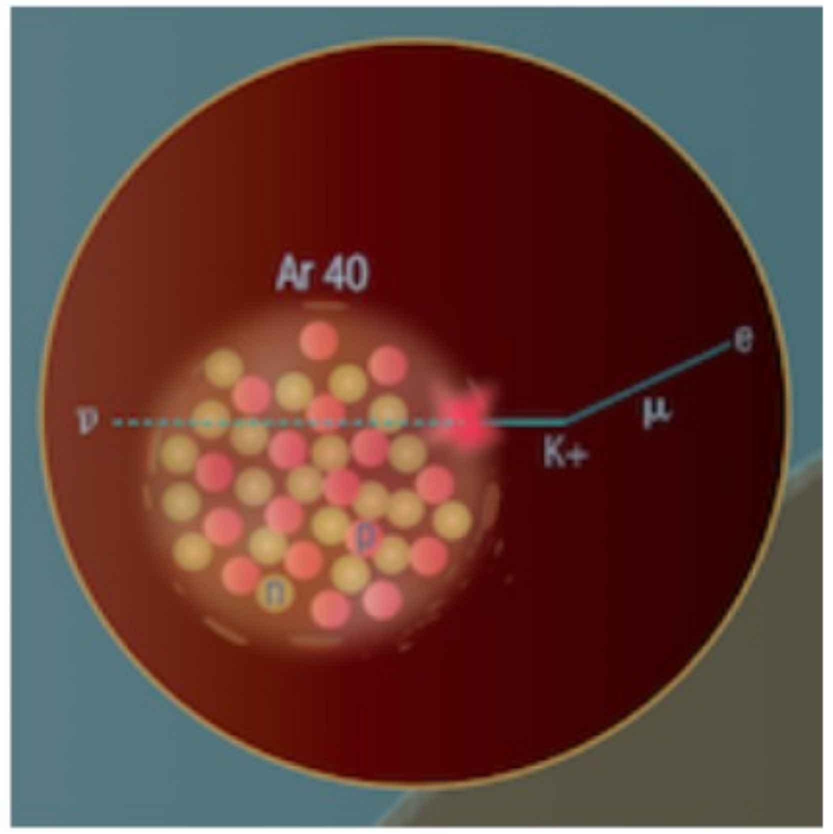
Accelerator neutrino oscillations

- Search for CP violation ($\delta^{CP} \neq 0,\pi$)
- Neutrino mass ordering
- Precision mixing parameters



Supernova physics

- Measure O(10 MeV) neutrinos from a galactic supernova
- Unique sensitivity to ν_e component, rich physics potential



Proton decay

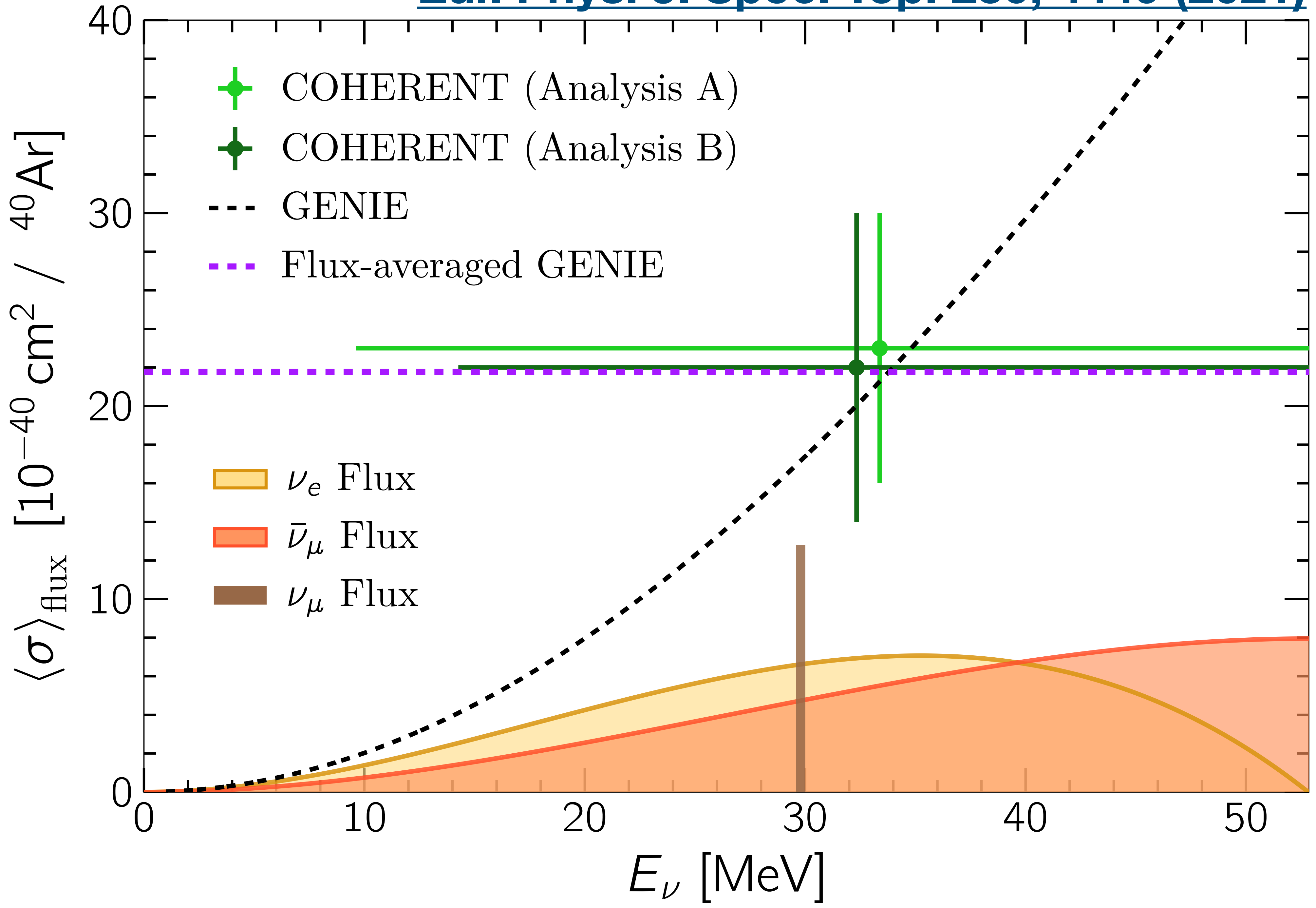
- Prediction of many BSM theories
- LArTPC well-suited to some decay modes, e.g., $p \rightarrow K^+ + \bar{\nu}$
- Potential sensitivity to other violations of baryon number ($n \rightarrow \bar{n}$)

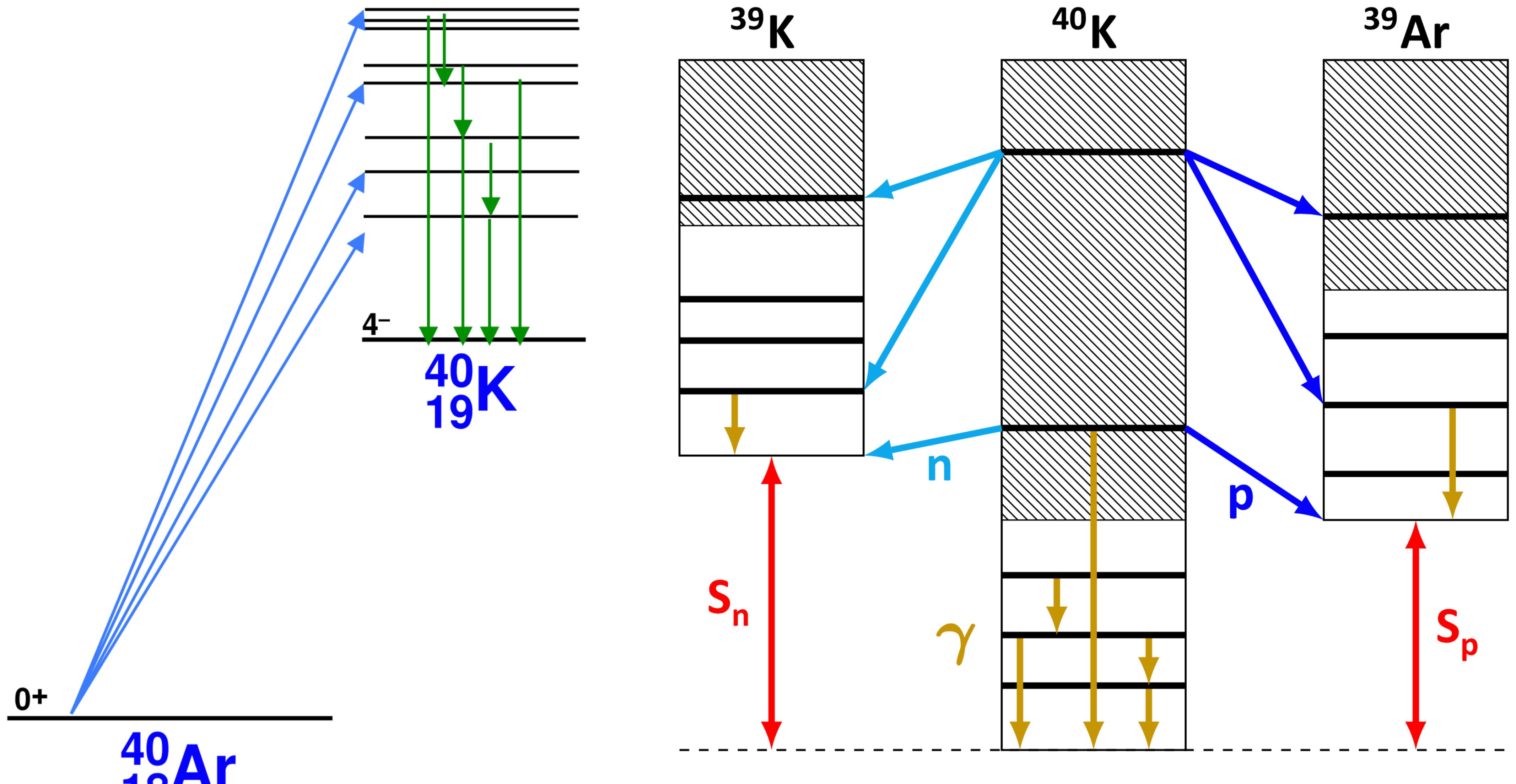
Simulating MeV-scale neutrino interactions

- ν-e, ν-p, and CEνNS are “easy” (the last up to the nuclear form factor)

- Inelastic reactions on complex nuclei are hard
  - **Example:** $\nu_e + {}^{40}\mathrm{Ar}$ for supernova detection in DUNE
  - Many competing pathways for nuclear (de-)excitation
  - Very limited direct constraints from experiment
  - More details: [Phys. Rev. C 103, 044604 (2021)]()

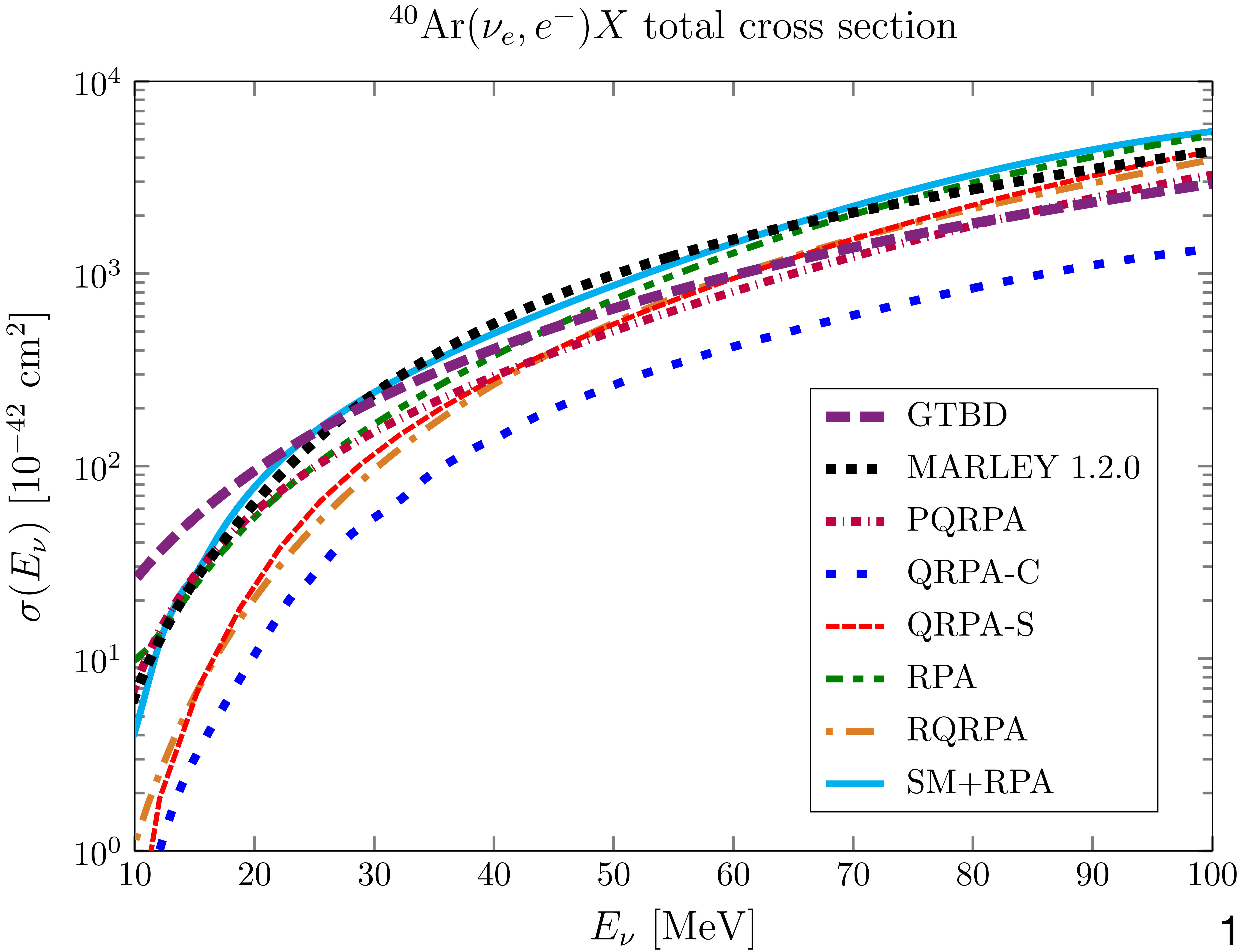
[Eur. Phys. J. Spec. Top. 230, 4449 (2021)]()





Low-energy CC ν-Ar cross-section uncertainties

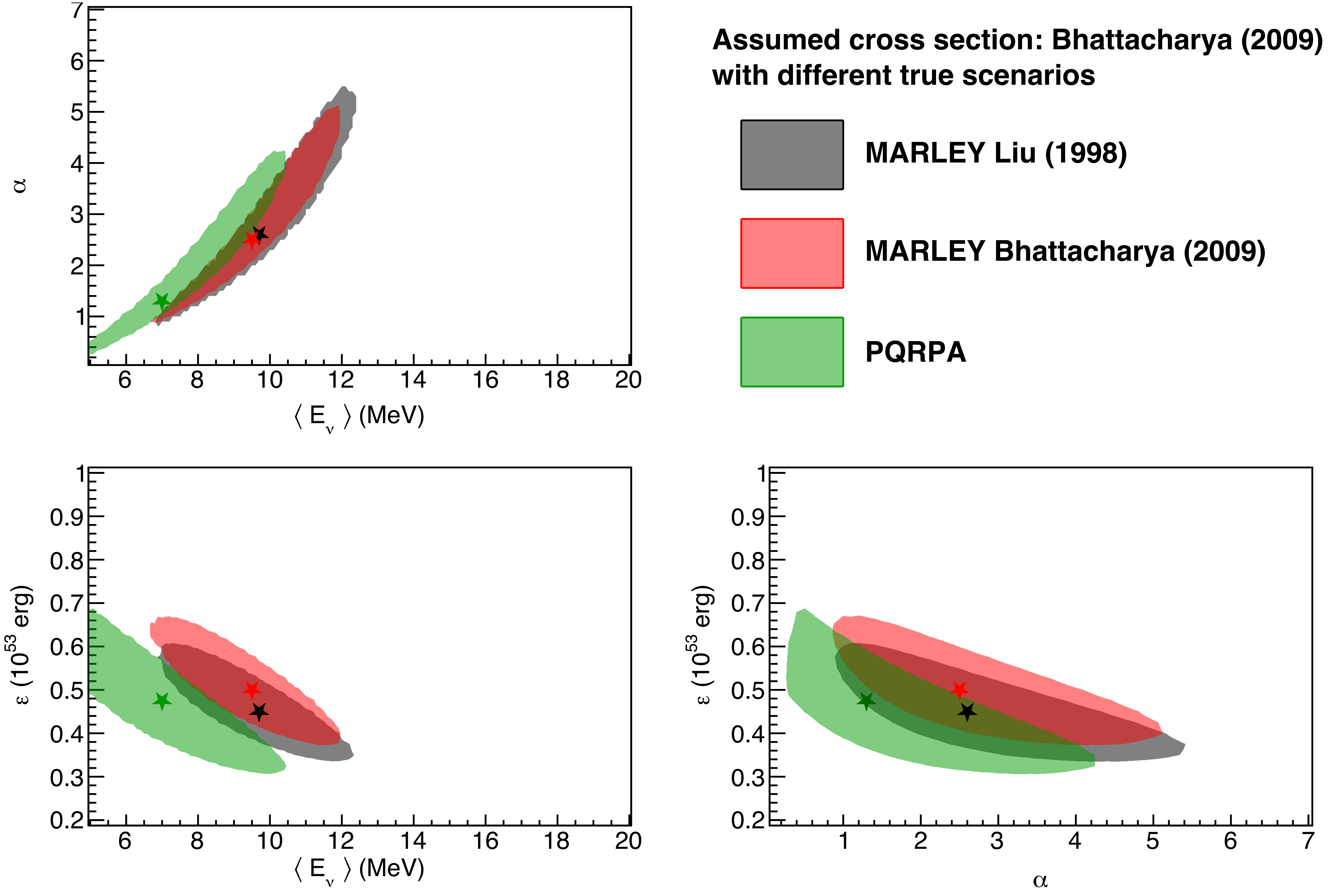
- Significant model disagreements
- No measurements this important channel below 100 MeV
- What is the impact on DUNE supernova physics?



Low-energy CC ν-Ar cross-section uncertainties

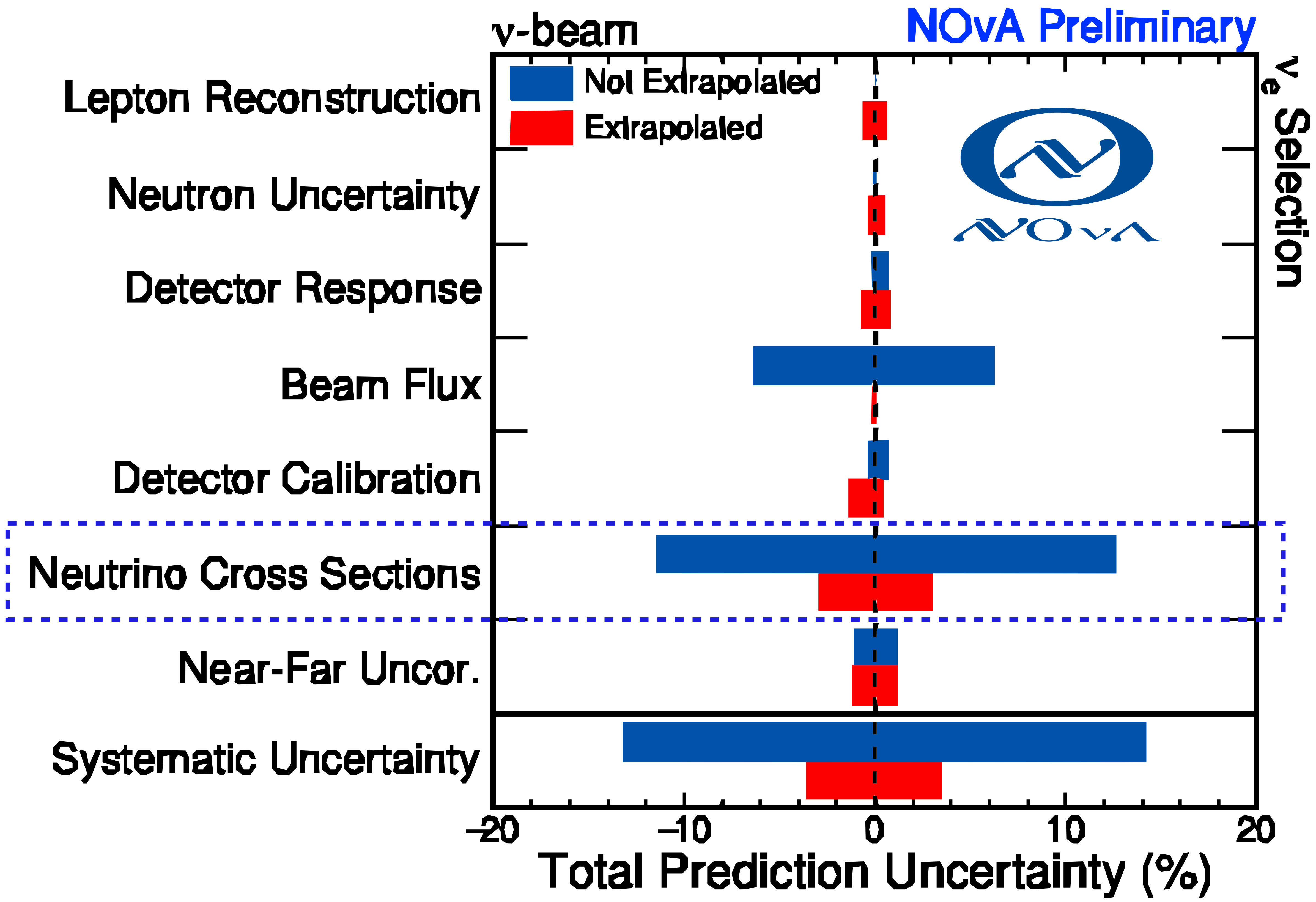
- **Toy analysis** seeks to extract flux parameters from simulated DUNE supernova neutrino data
- ε = energy release (erg)
- $\langle E_\nu \rangle$ = mean neutrino energy (MeV)
- α = shape parameter (dimensionless)

E. Conley, S. Gardiner, *et al.*, in prep.

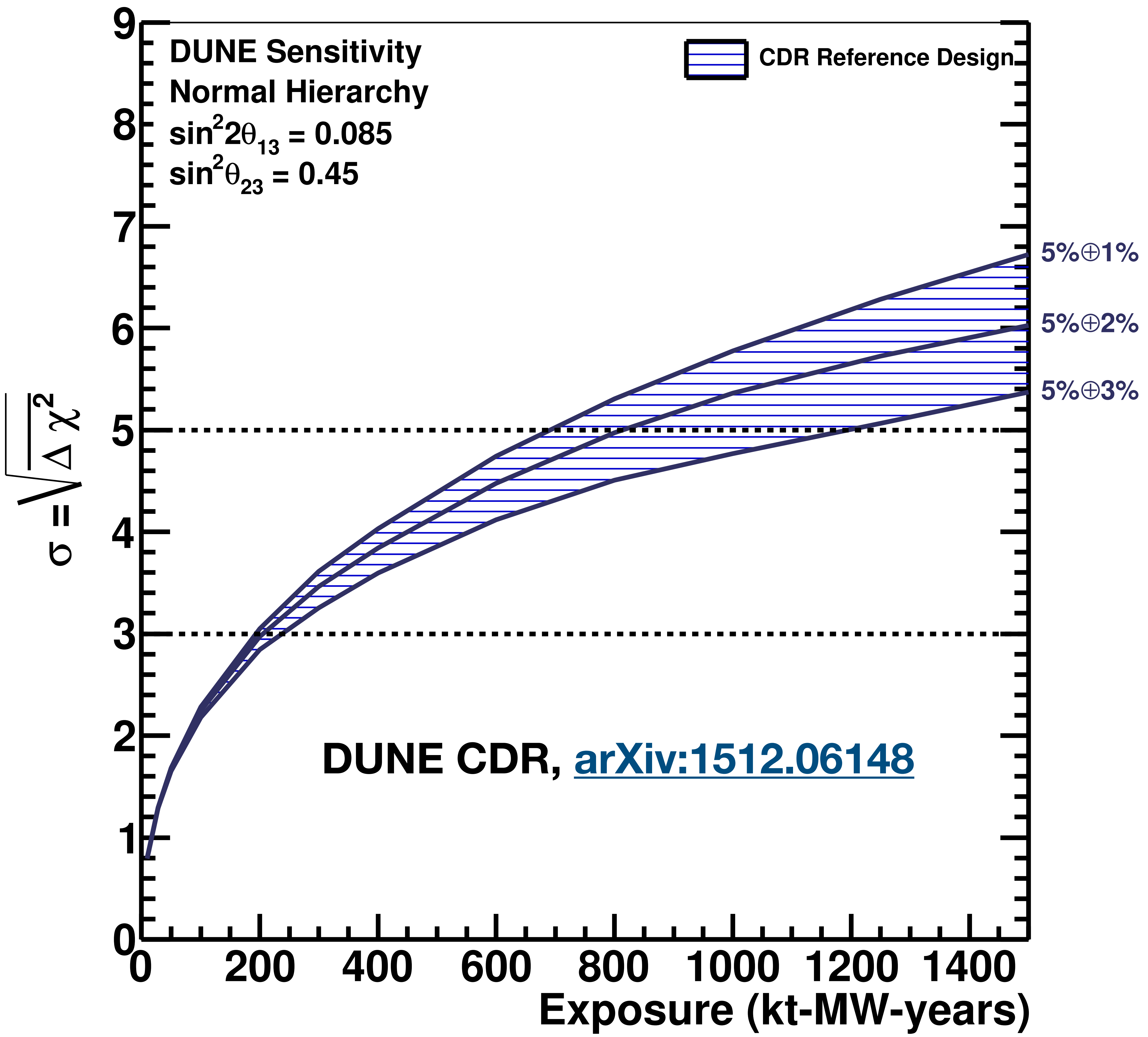


Cross-section systematic uncertainties

M. Elkins & T. Nosek (for NOvA), Neutrino 2020 poster



50% CP Violation Sensitivity



DUNE CDR, arXiv:1512.06148

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

Neutrino event generators

- **"Bridge" between theory and experiment:** model predictions are made easily usable
  - Essential for theory efforts to improve experimental precision

- Full final-state predictions needed
  - Efficiencies, backgrounds

- Systematic uncertainty quantification

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 *

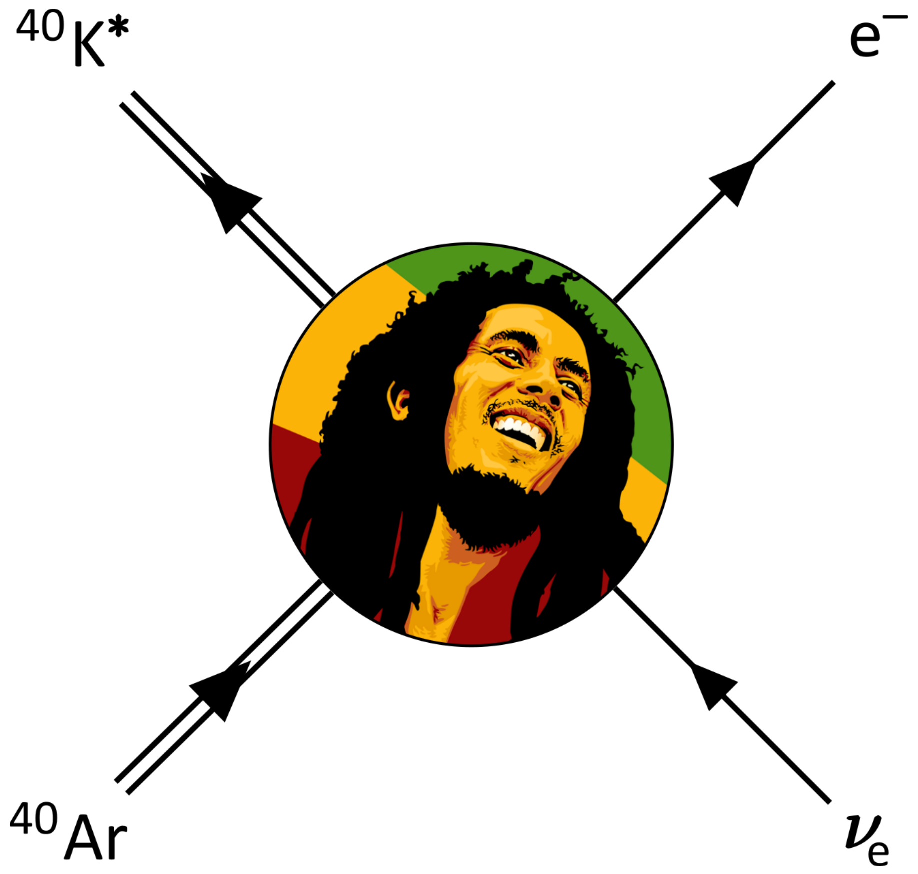
[Nucl. Phys. Proc. Suppl. 229-232, 499 (2012)]

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

Neutrino event generator landscape

Other notable generators

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).

ACHILLES
(no official logo)

arXiv:2110.15319

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)

ICECUBE
SOUTH POLE NEUTRINO OBSERVATORY

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

Coherent elastic neutrino-nucleus scattering (CEvNS)

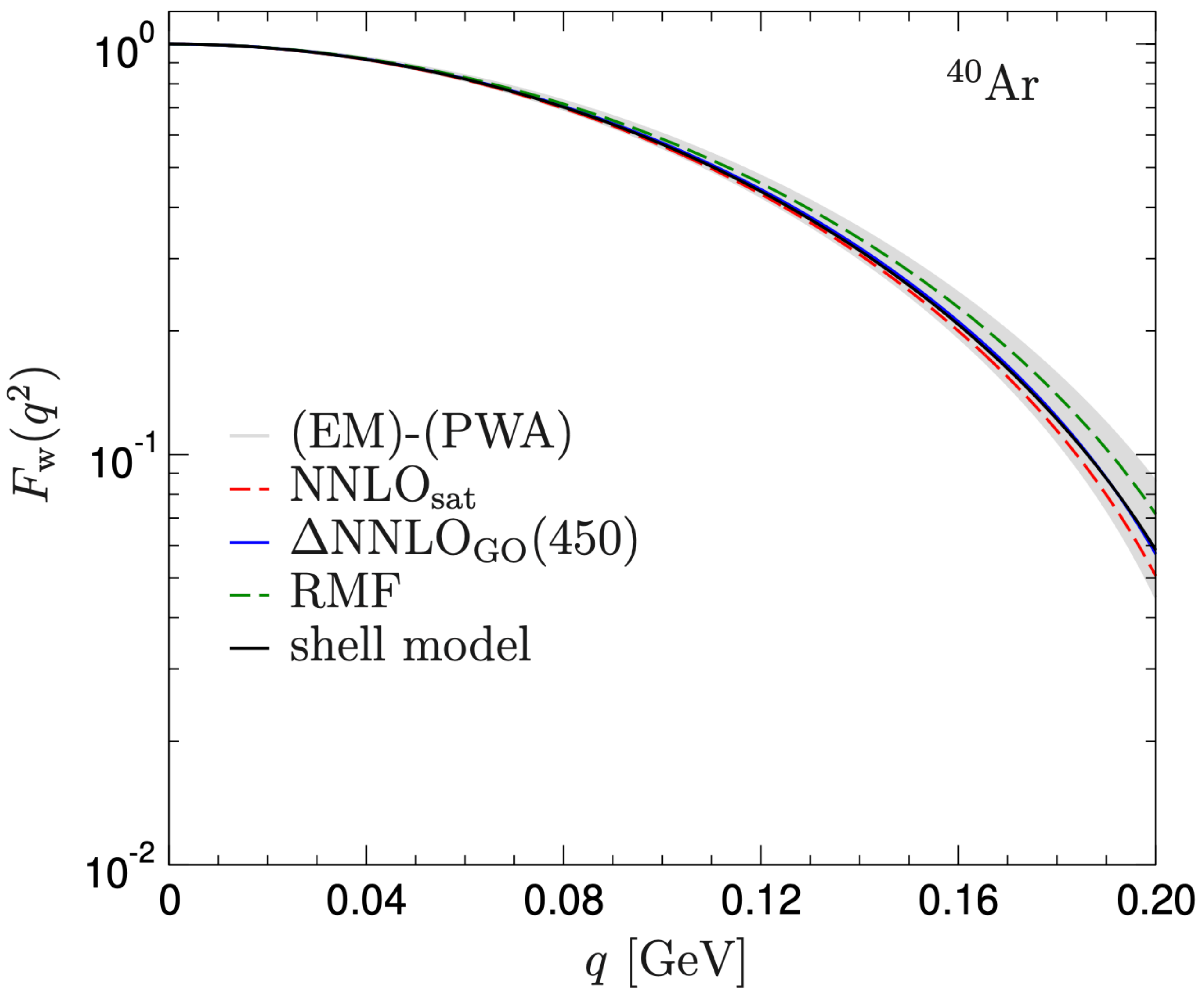
- Dominant nuclear scattering process at low neutrino energy
  - NC, leaves nucleus in ground state
  - First observed by COHERENT in 2017 at ORNL
- Nuclear form factor sensitive to proton/neutron densities
- Precise calculations will enable detailed searches for new physics

Differential cross section

$$\frac{d\sigma}{dT} = \frac{G_F^2 M}{4\pi}\left(1 - \frac{M T}{2E_\nu^2}\right) Q_w^2 [F_w(q^2)]^2$$

Weak nuclear charge

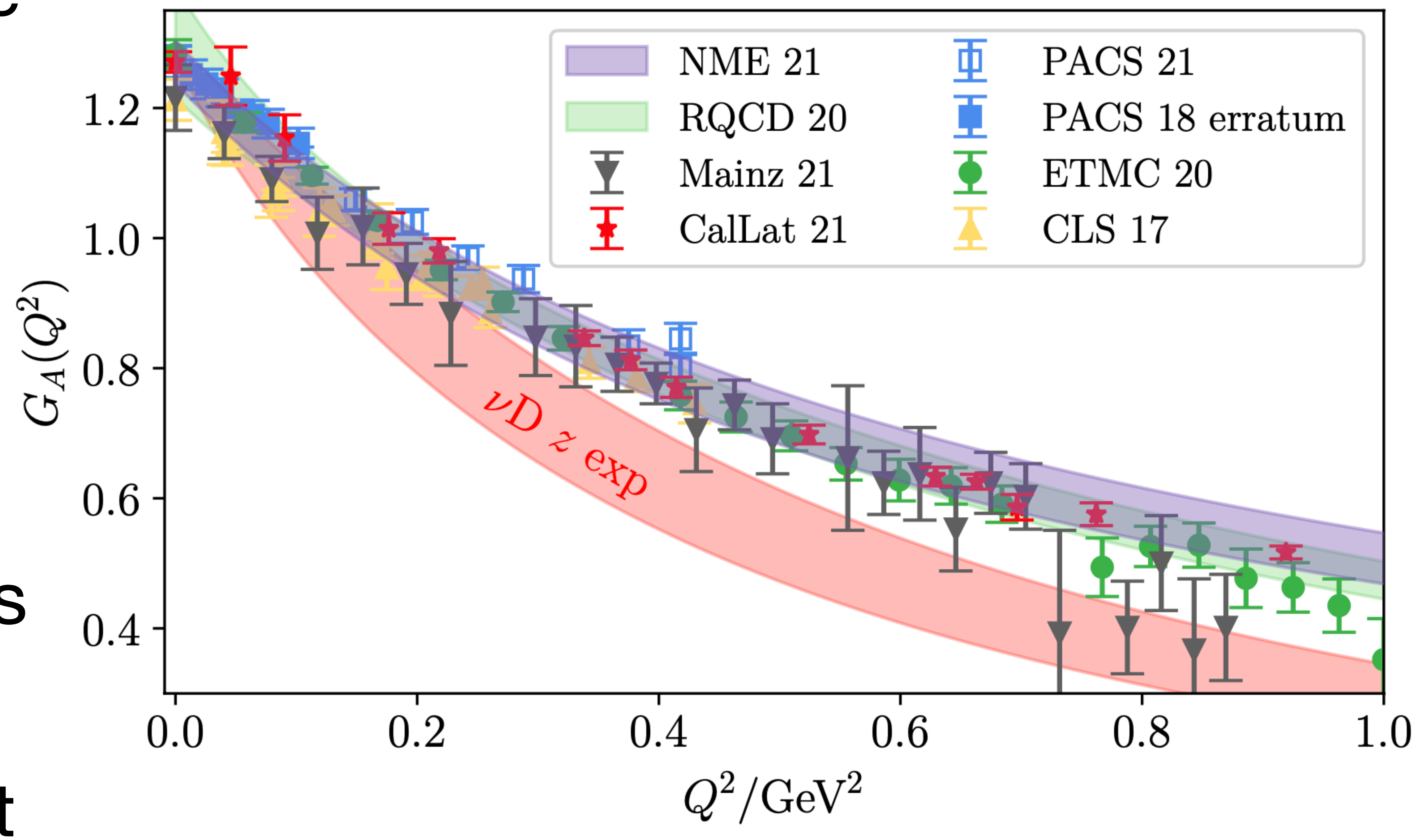
$$Q_w = Z(1 - 4\sin^2\theta_W) - N$$



Lattice QCD calculations

$$\langle N' | A_\mu^a | N \rangle = \bar{u}_{N'} \left[G_A(Q^2)\gamma_\mu + \tilde{G}_P(Q^2)\frac{q_\mu}{M_N} \right] \gamma_5 \tau^a u_N$$

- One- and few-nucleon parameters calculable now (or in the foreseeable future) via lattice techniques
  - Complementary to other approaches
- Example: nucleon axial form factor G_A
  - Key for quasielastic ν scattering
- Tension seen between recent LQCD results and νD bubble chamber data
  - Impact can be as much as a 10% effect for DUNE (arXiv:2201.01839)
  - Possible motivation for new measurements



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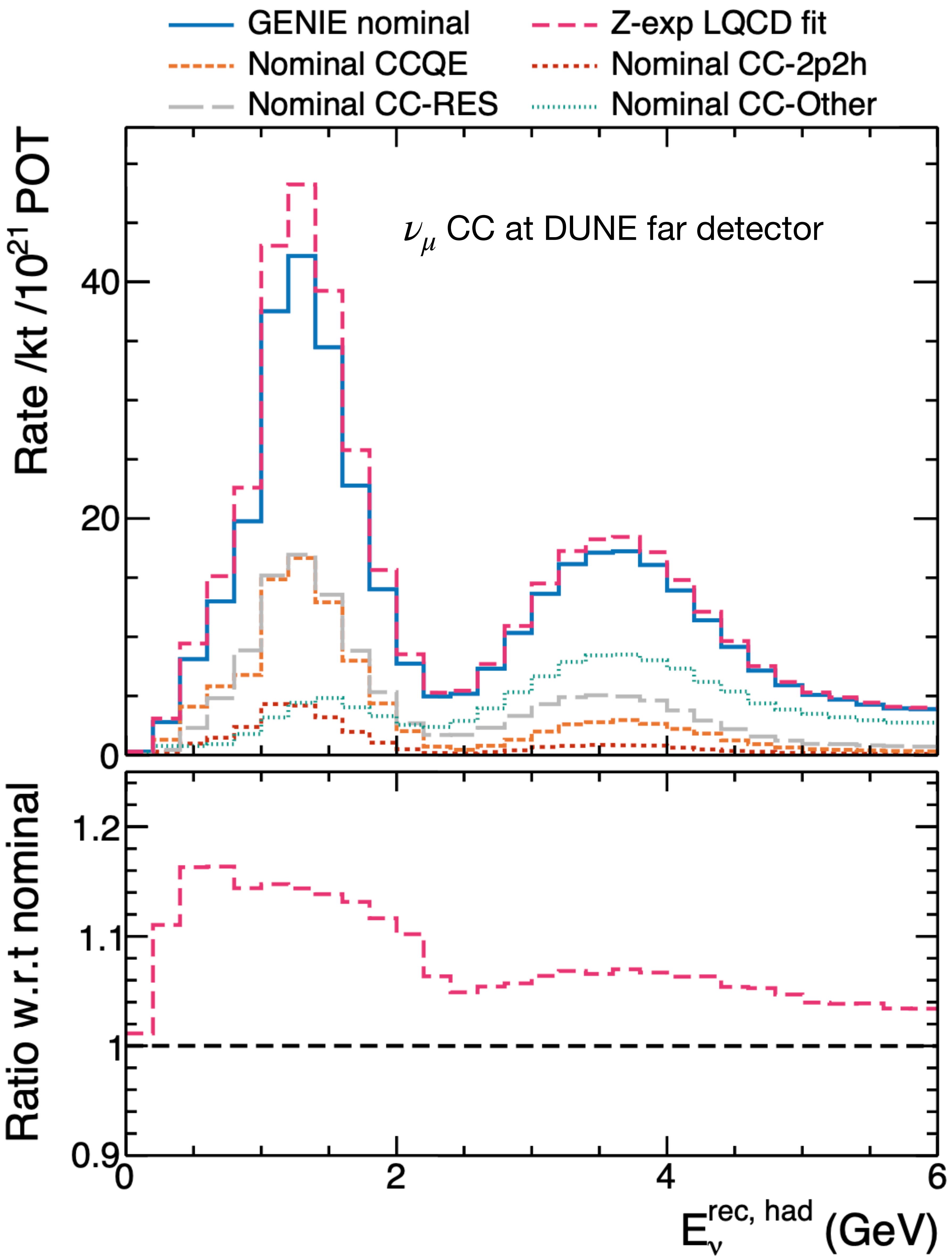
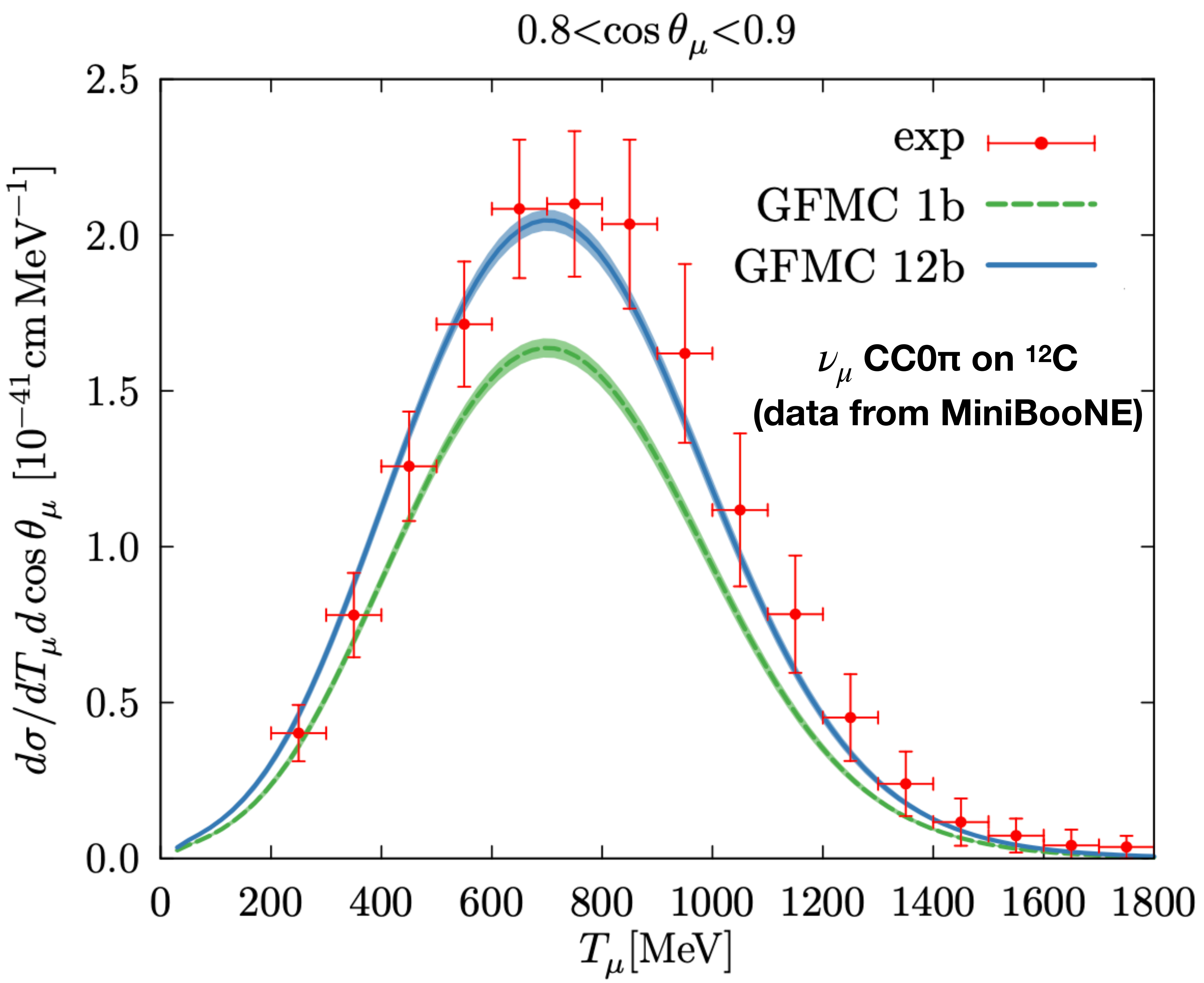


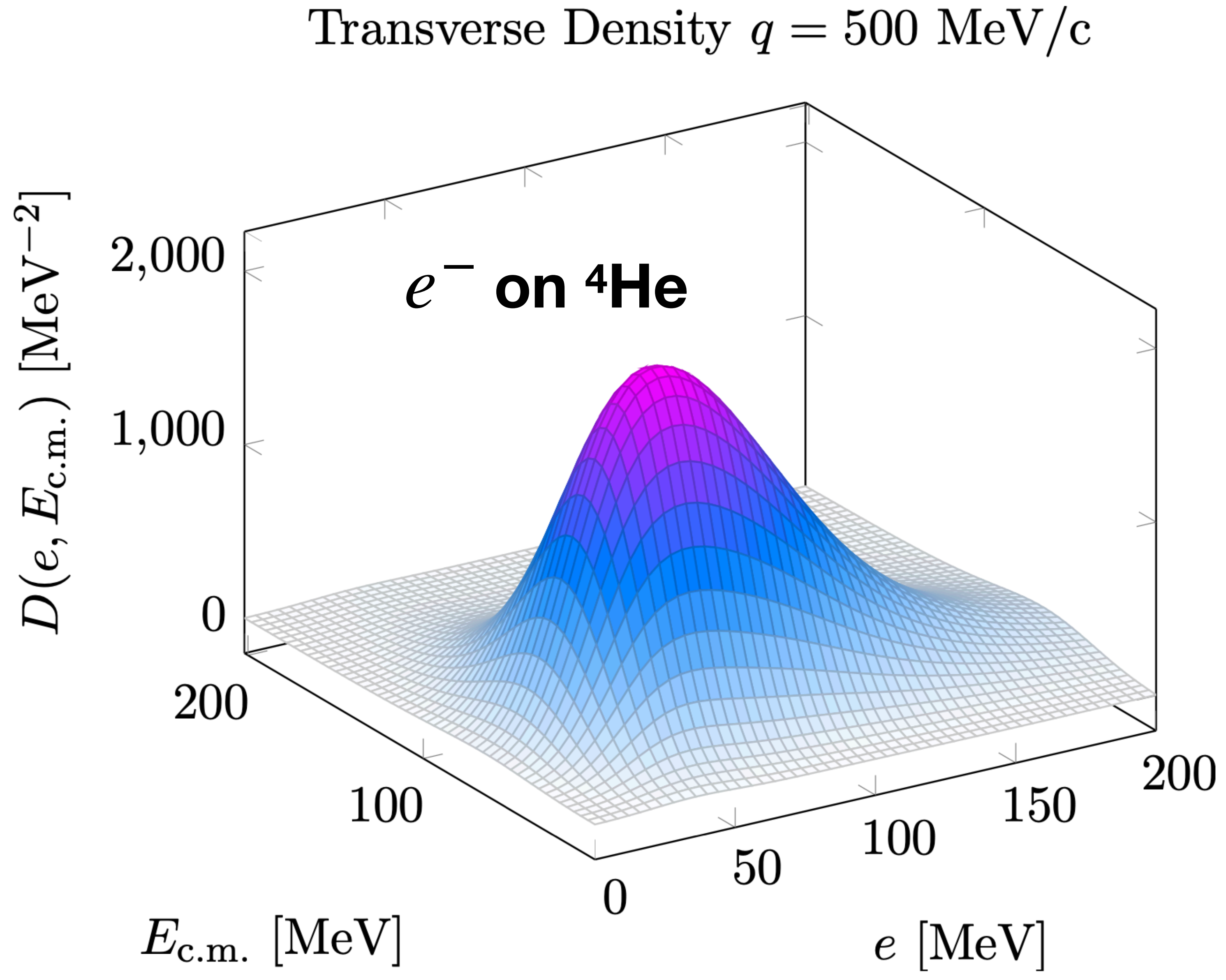
Many-body theory approaches

- Much exciting work on lepton-nucleus scattering

- Includes *ab initio* calculations performed via quantum Monte Carlo (QMC)
  - High-quality description of data
  - Computationally demanding

- Various observables calculable
  - "Response densities" for outgoing nucleon kinematics





GENIE hadronic tensor interface

Differential cross section built from contraction of two tensors

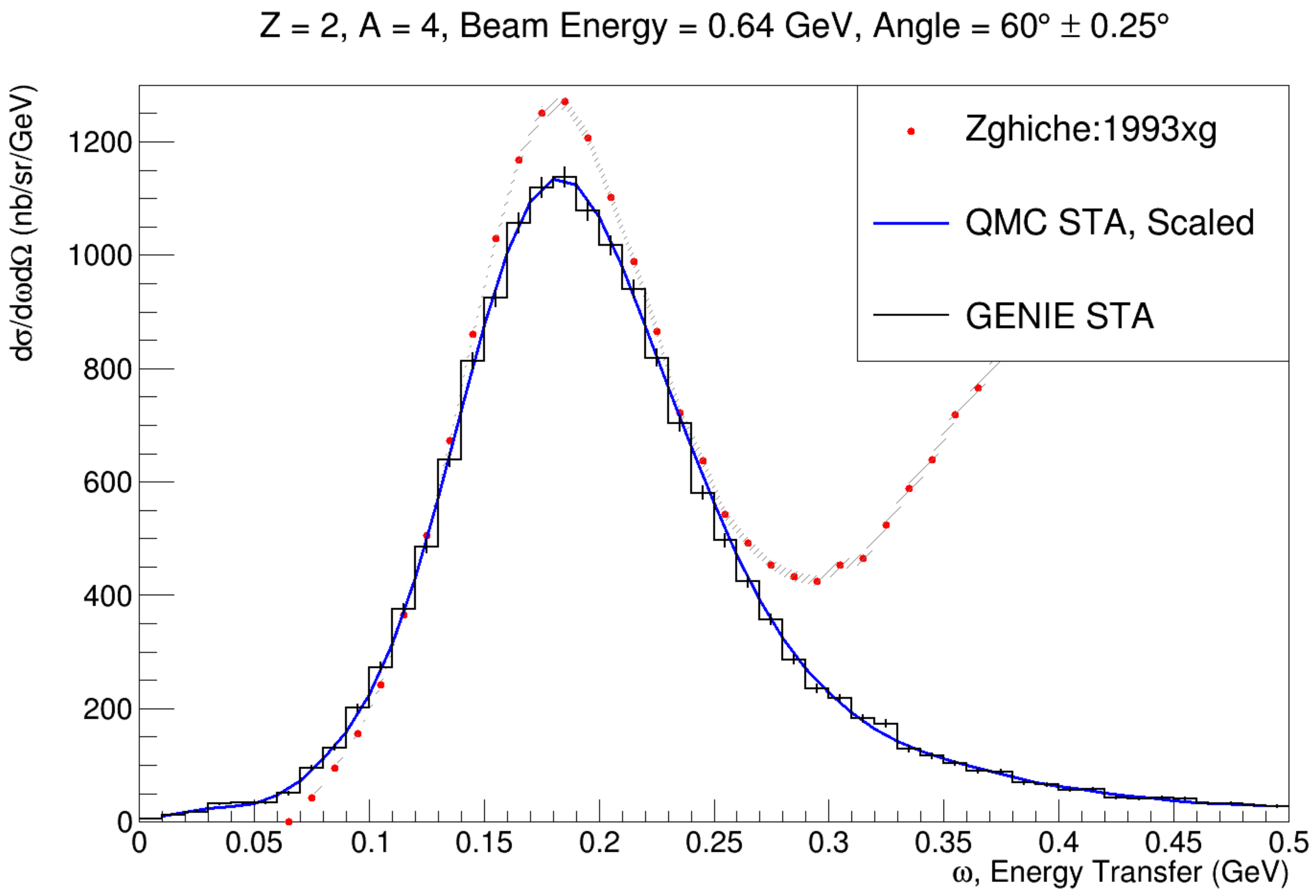
$$\frac{d^2\sigma}{dE'_\ell \, d\Omega'_\ell} \propto L_{\mu\nu} W^{\mu\nu}$$

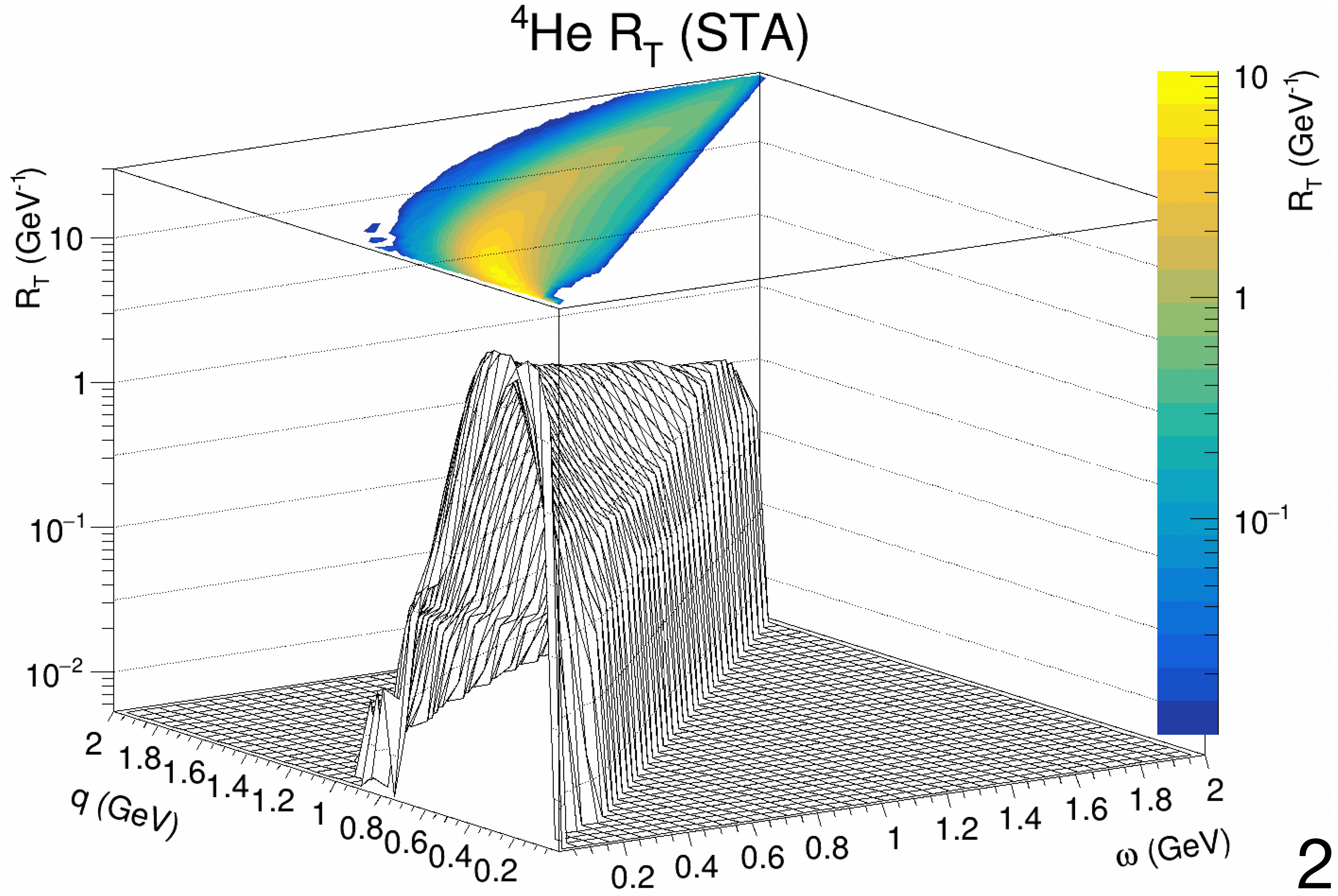
Exploit symmetries: only 5 components of $W^{\mu\nu}$ are needed for weak processes

Only two for EM: $R_L = W^{00}$ and $R_T = W^{11}$

Precomputed tables of these allow for **efficient interpolation**

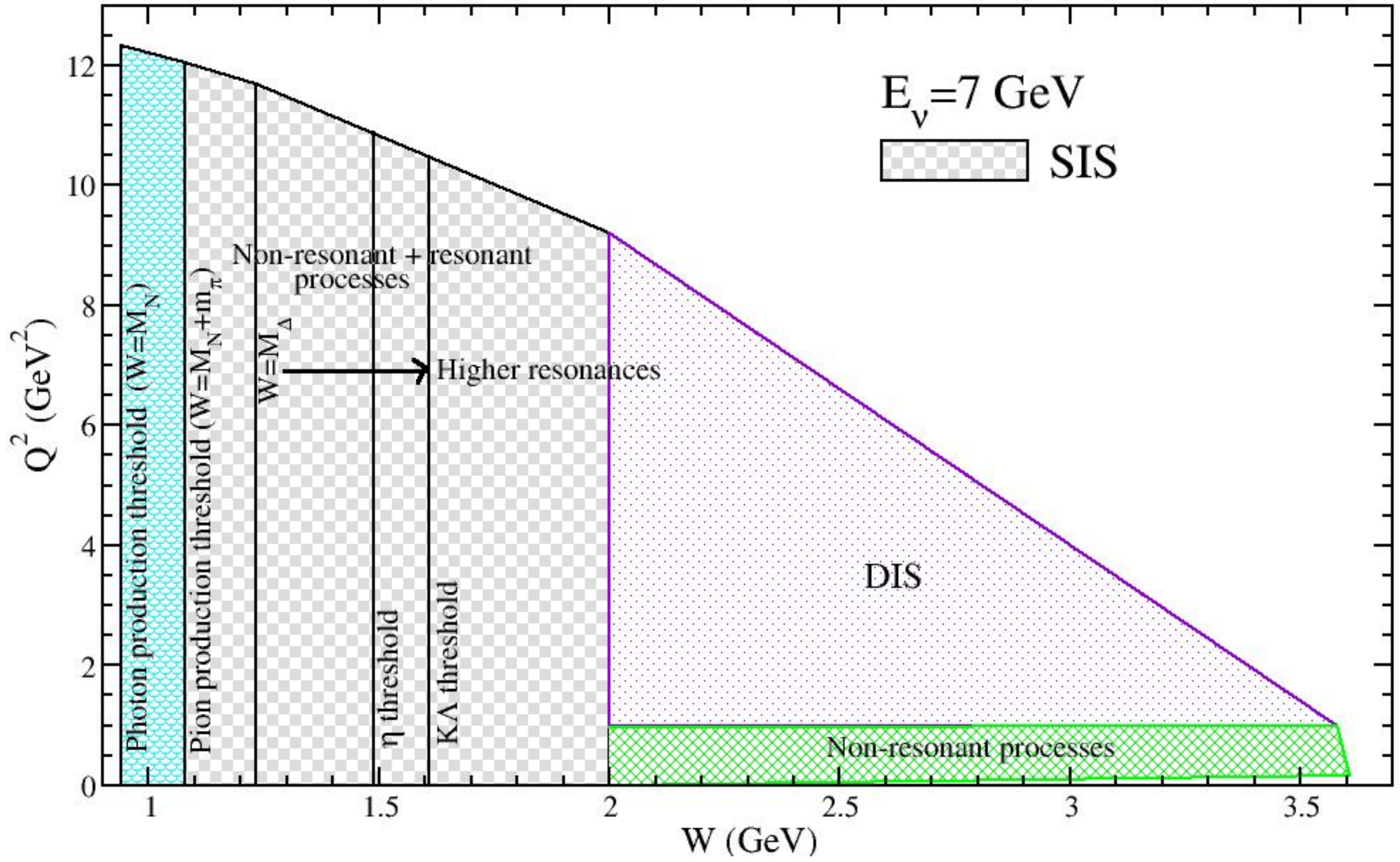
[Phys. Rev. D 103, 052001 (2021)]



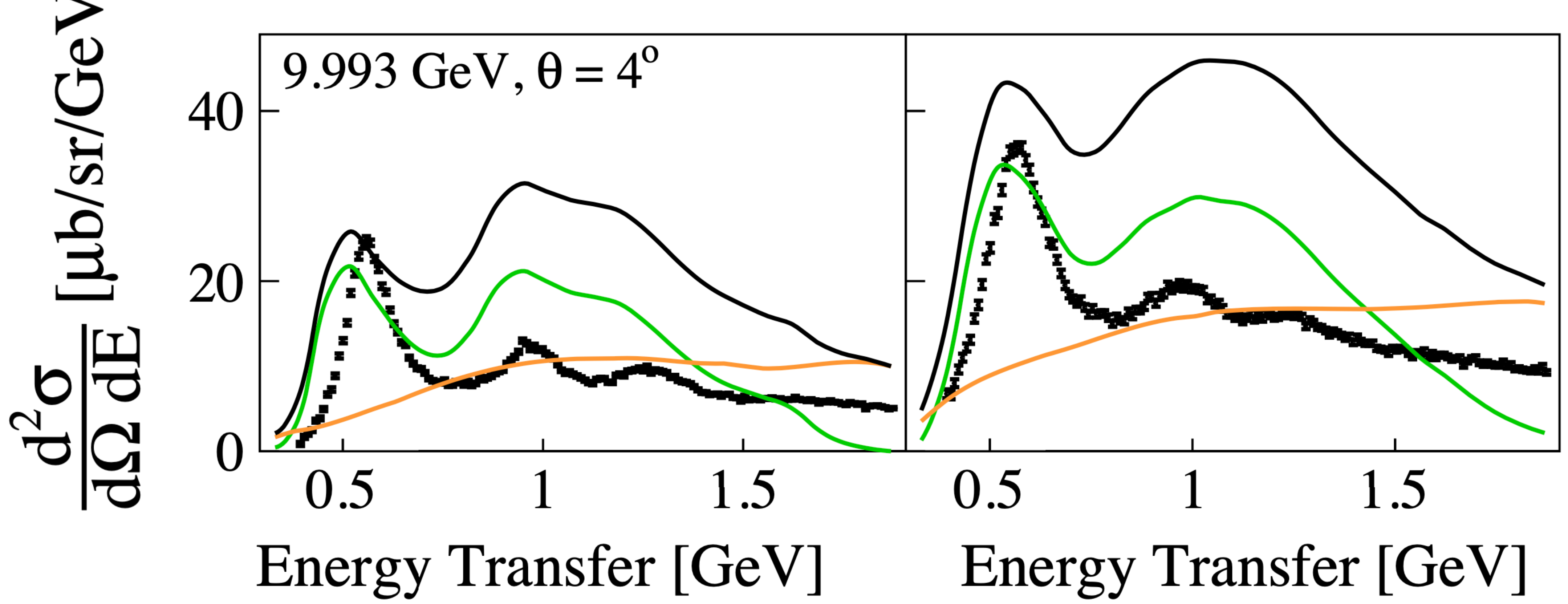


Shallow and deep inelastic scattering

- SIS = transition region between hadronic and quark + gluon representations
  - Poorly understood, but important for precision GeV-scale experiments
- Generators typically extrapolate from the DIS region
  - Checks of GENIE against electron data reveal major trouble
- Further theoretical & experimental attention to this region will be helpful!



[Phys. Rev. D 103, 113003 (2021)]



Sociological & organizational issues for neutrino generators

- Mission critical, but in a “no man’s land” between theory & experiment
  - Currently poor career incentives, motivation for short-term solutions
  - Recruiting, training, and retaining junior scientists becomes difficult
- HEP motivation, but NP expertise needed for a solution
- No clear community leadership structure
  - GENIE authors, for example, typically have other responsibilities
- Priorities hard to establish without new infrastructure investment
  - Global tunes, apply model variations to expected DUNE sensitivity, etc.
- Likely some challenges in common with comparable LHC efforts

"We're ~20 years behind the LHC folks"

- An assessment not original to me, but one that I agree with
- Many problems we're beginning to face have known LHC solutions
  - High-multiplicity events (n-body phase space generation)
  - Generator interoperability (standardization, HepMC3)
  - Tuning & systematics (Professor)
- Continued dialog with you will be very helpful
  - In return, we can offer solidarity in advocating for the importance of HEP generator work (e.g., **arXiv:2203.11110**) to the whole community
- I look forward to future opportunities to learn and collaborate!