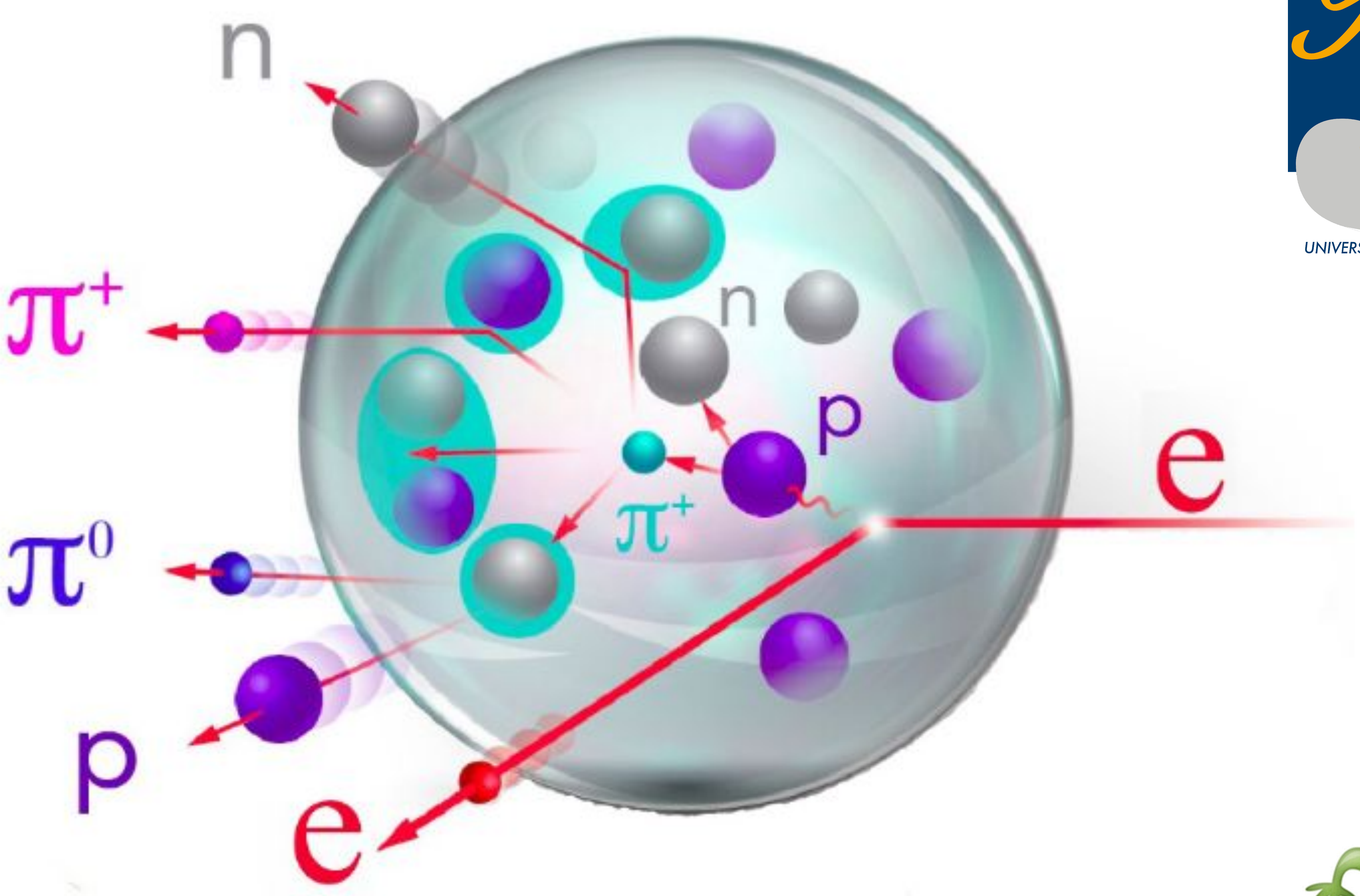
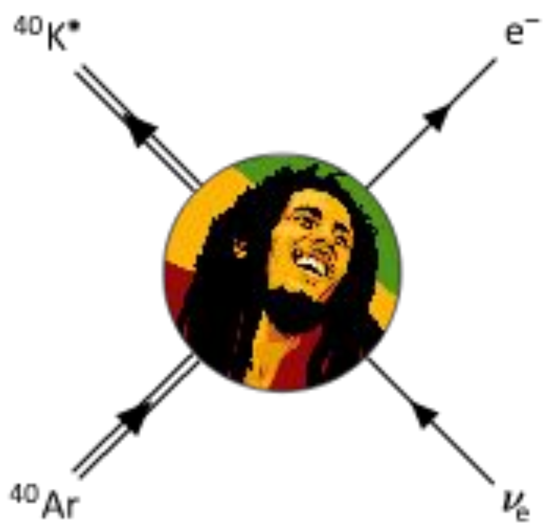
Electron scattering in neutrino event generators

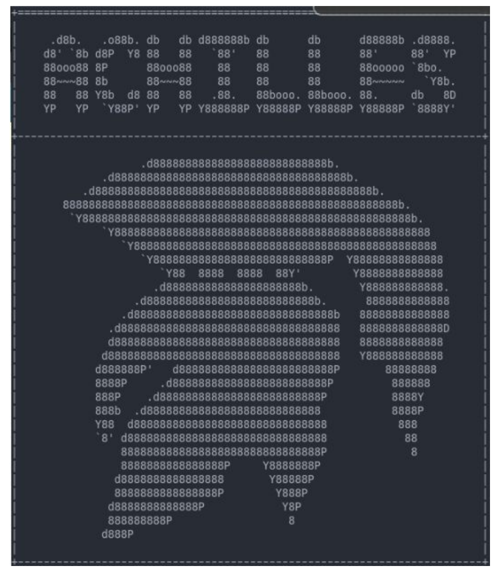


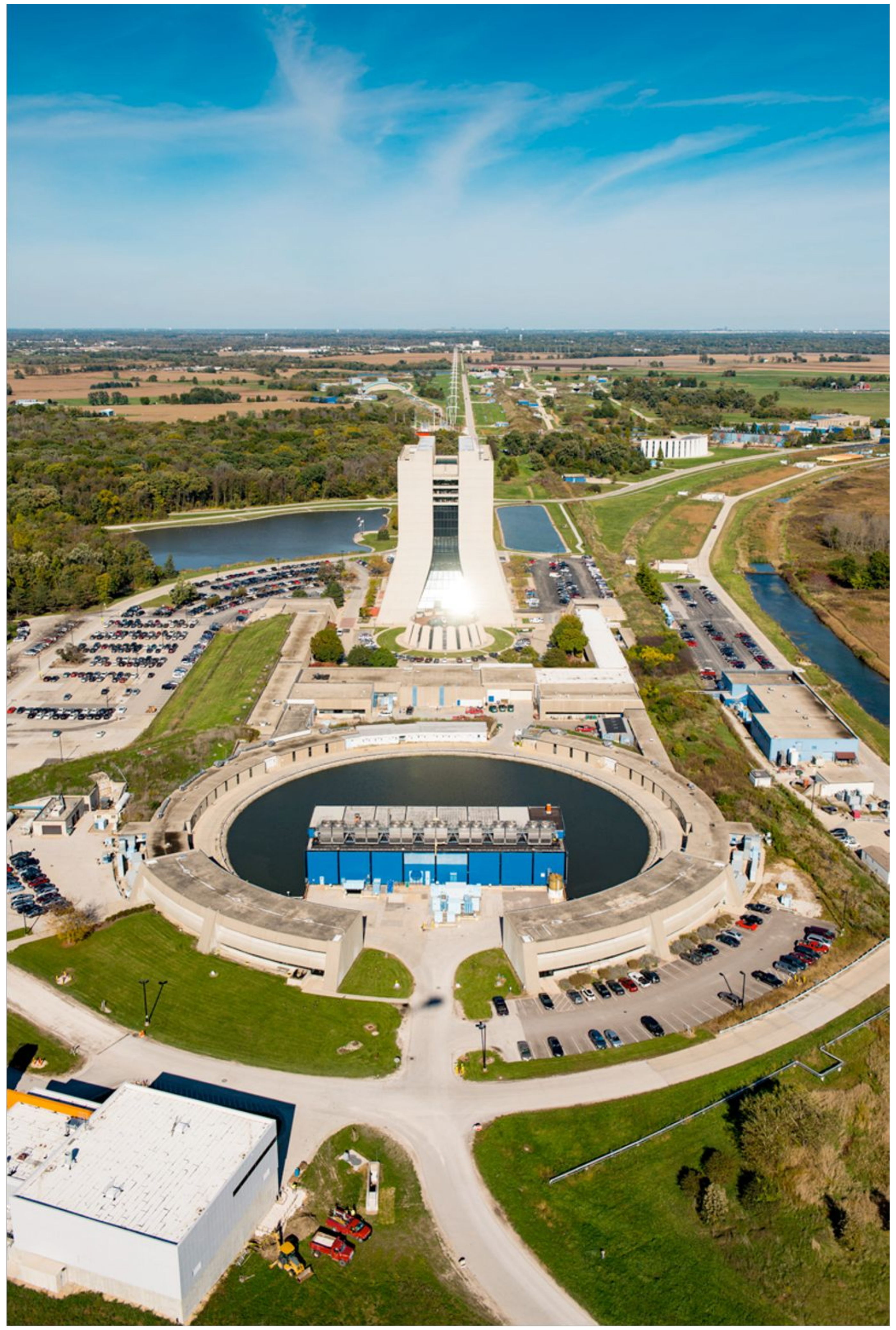
GENIE
UNIVERSAL NEUTRINO GENERATOR & GLOBAL FIT

GiBUU



NuWro
Wrocław Neutrino Event Generator





Steven Gardiner (gardiner@fnal.gov)

Event Generators Group Leader, Fermilab Physics Simulation Department

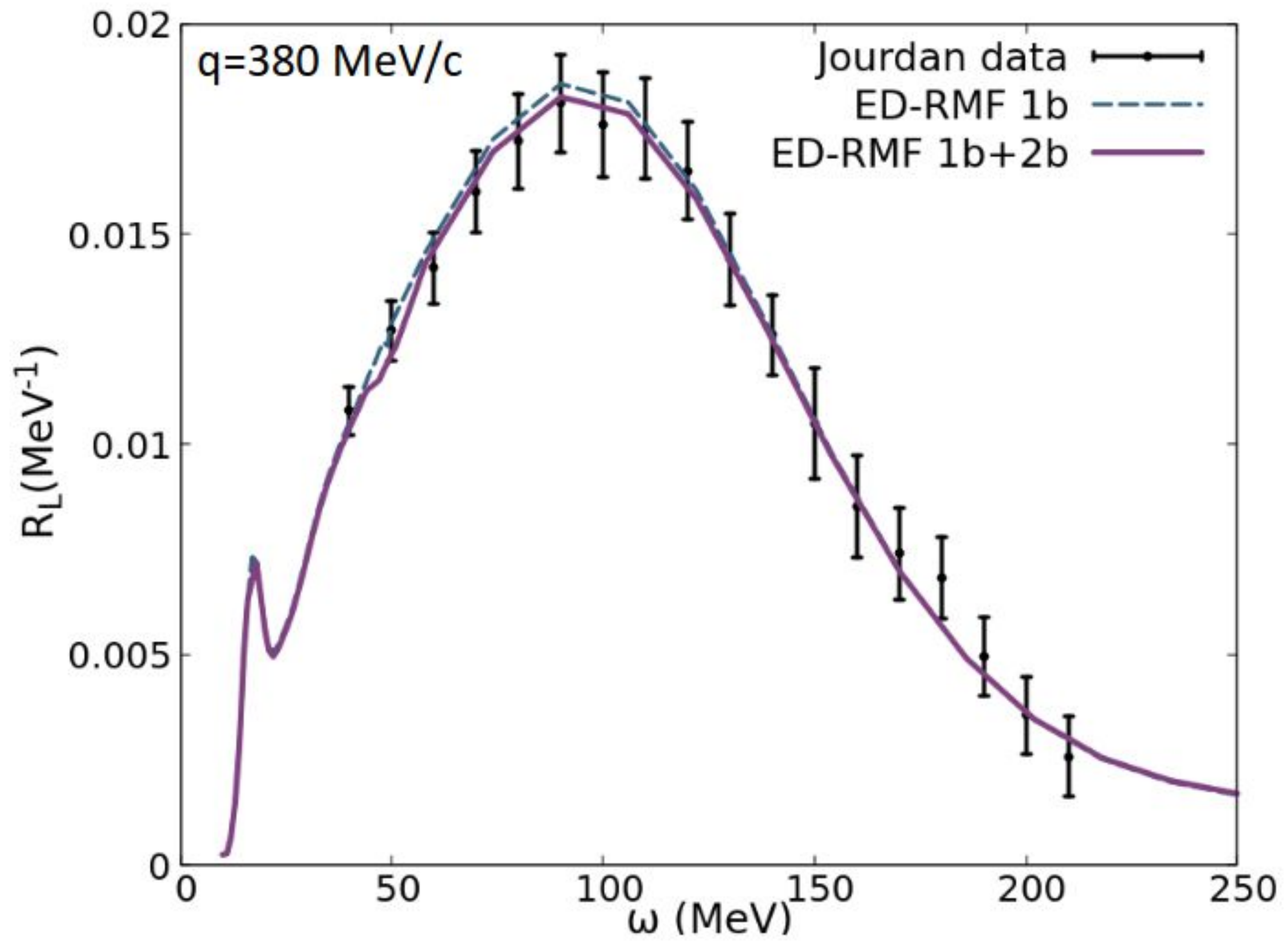
NuInt 2024, São Paulo, 18 April 2024

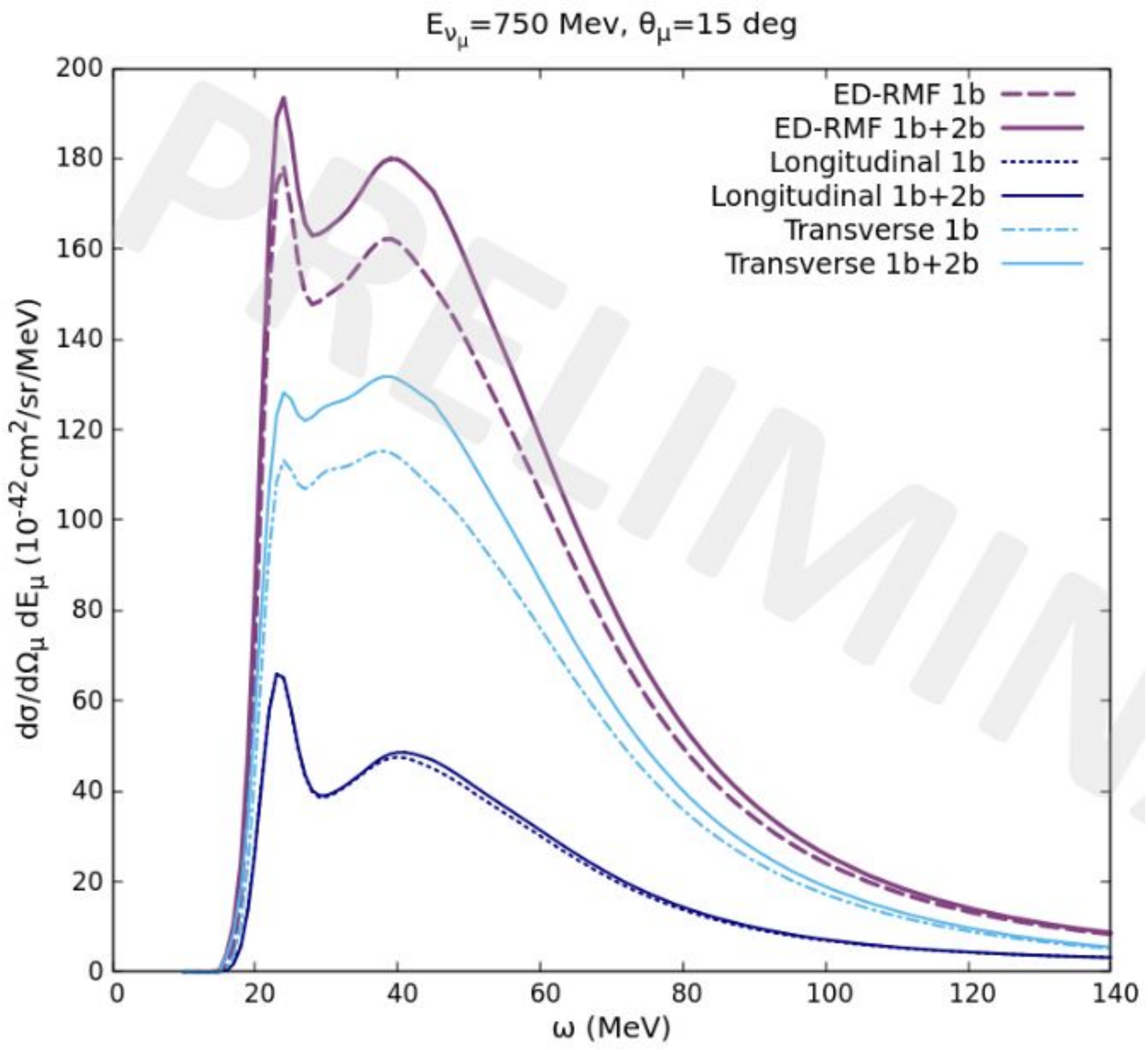
Electron data as a guide for neutrino model development

- **Not news** to the nuclear theory community

- Commonalities have been appreciated for a long time
  - Nuclear ground state
  - Vector part of hard interaction
  - FSI (including de-excitations)

- Many talks from this meeting show **both e and ν** model predictions
  - Plots from [Tania Franco-Munoz]





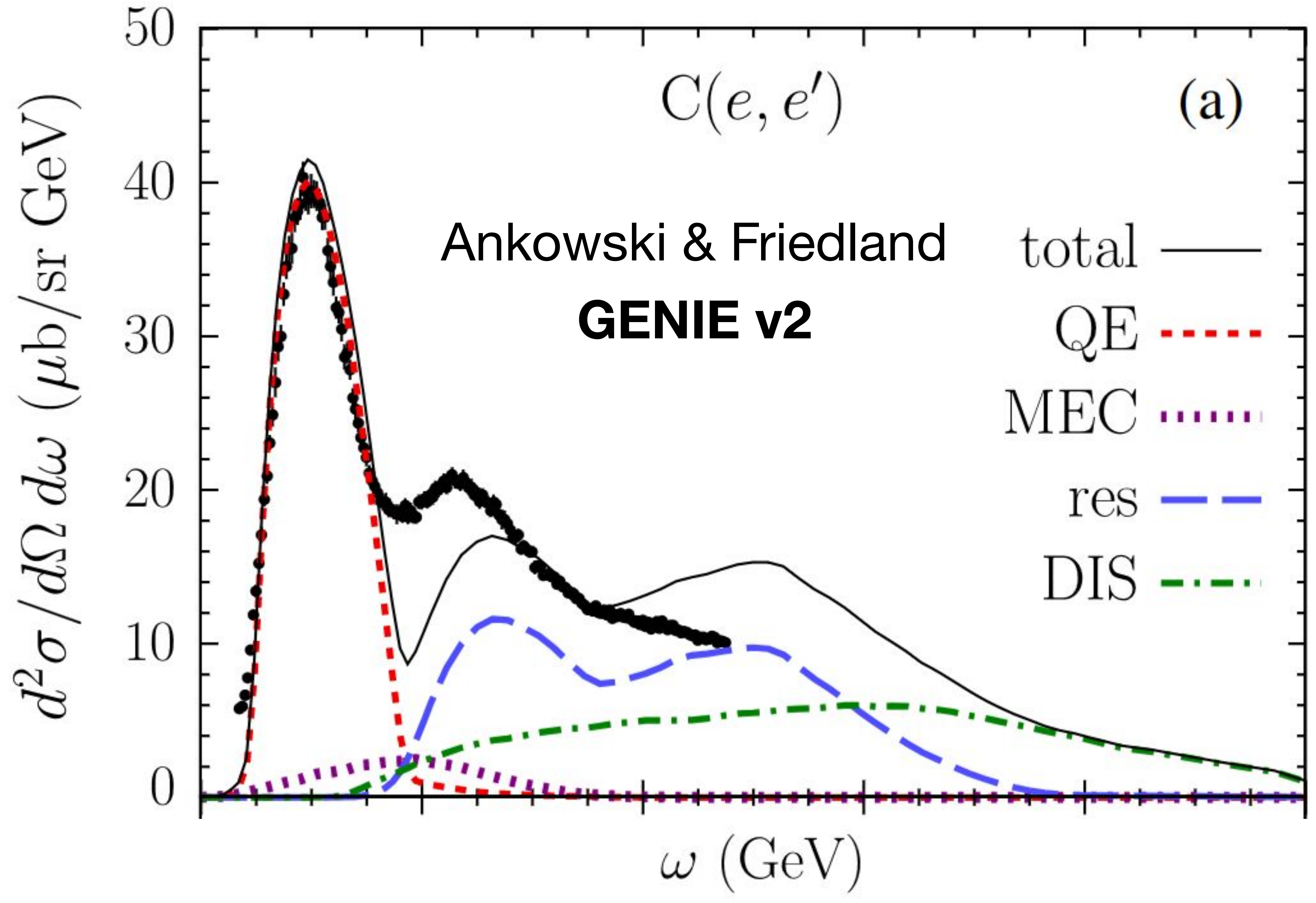
Benchmarking generators

- Increased interest in direct use of e- data
  - Most existing measurements are inclusive
  - Carbon is best-studied target

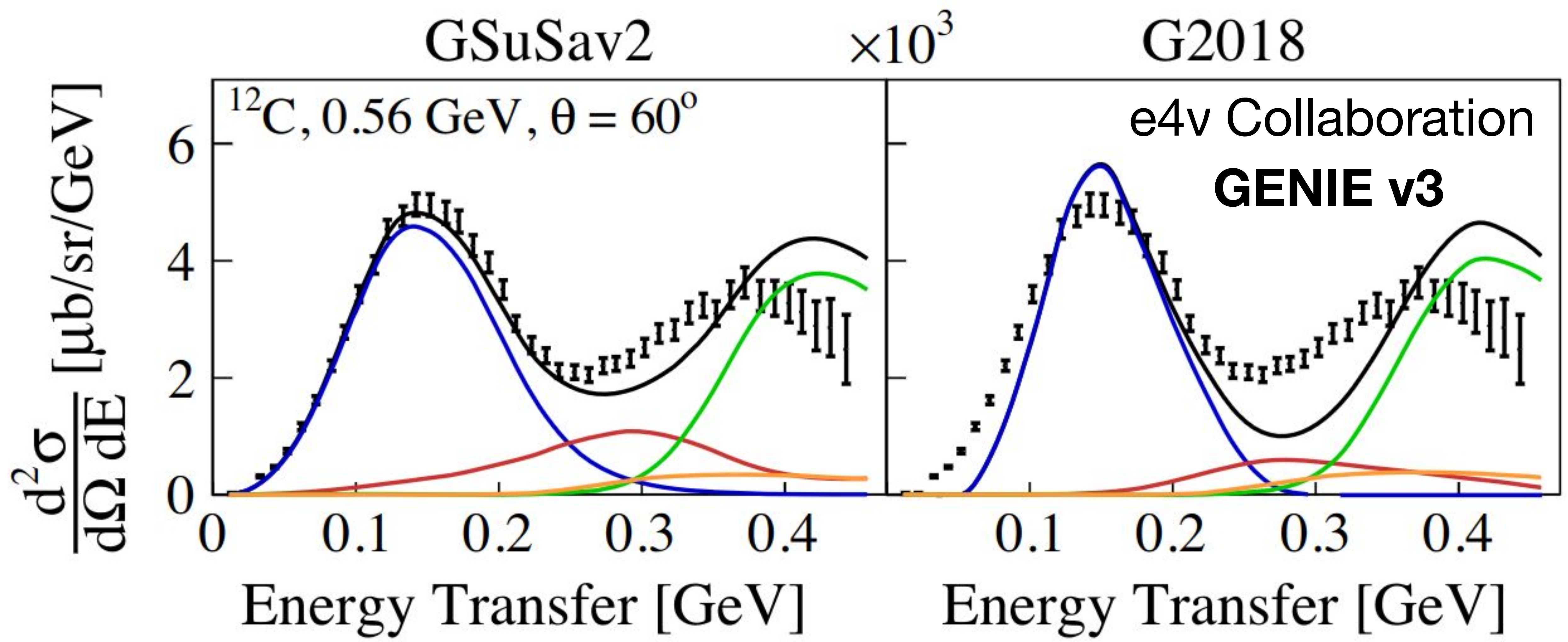
- Comparisons by MC developers as well as independent groups

- Other earlier examples available
  - e.g., Acta Phys. Polon. B46, 2329 (2015) for NuWro

Phys. Rev. D 102, 053001 (2020)



Phys. Rev. D 103, 113003 (2021)



New experimental efforts

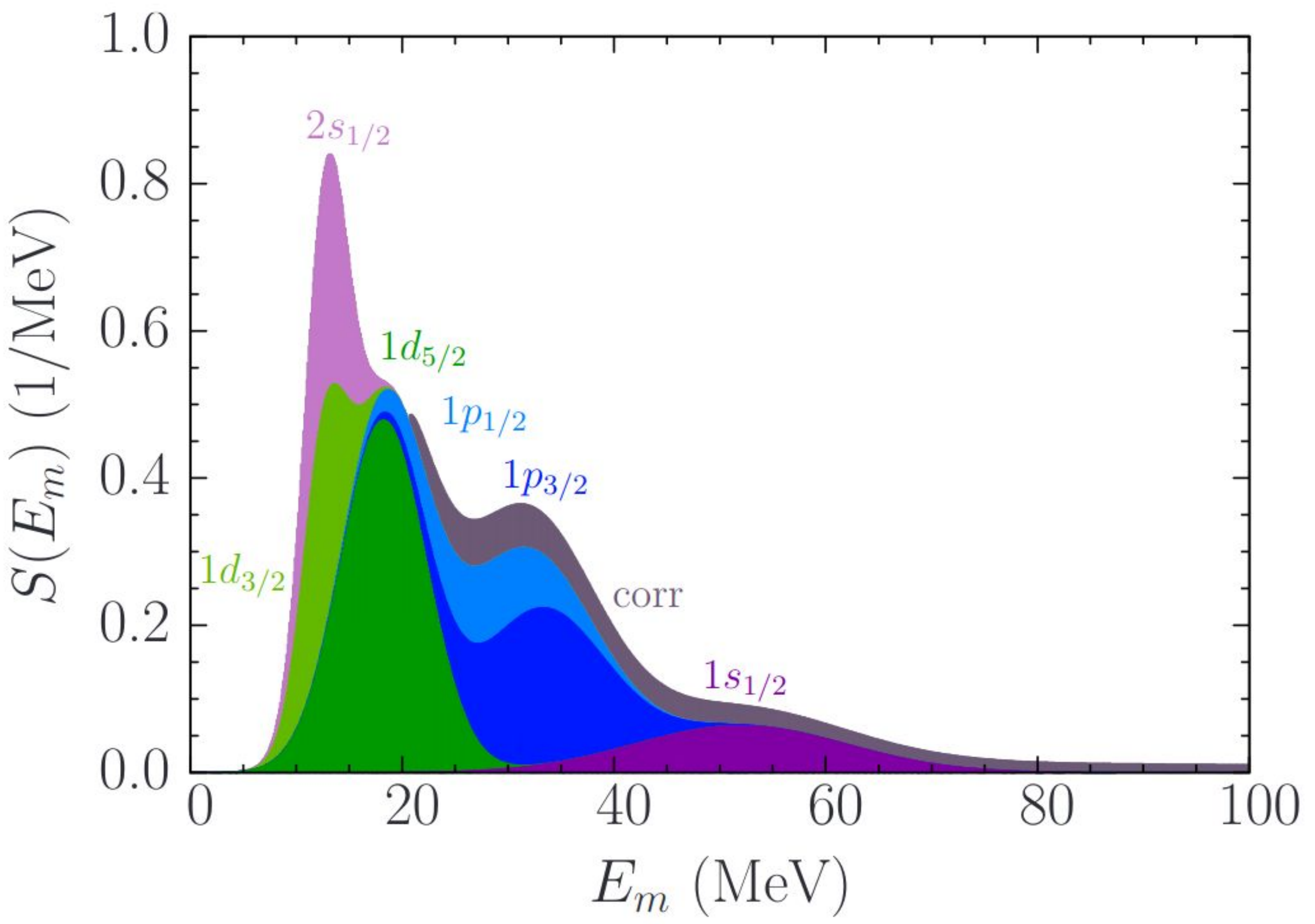
- Motivated by neutrino physics, two kinds

- **Improve nuclear inputs**
  - Argon SF via p knockout (Omar's talk)
  - Parity-violating e- scattering

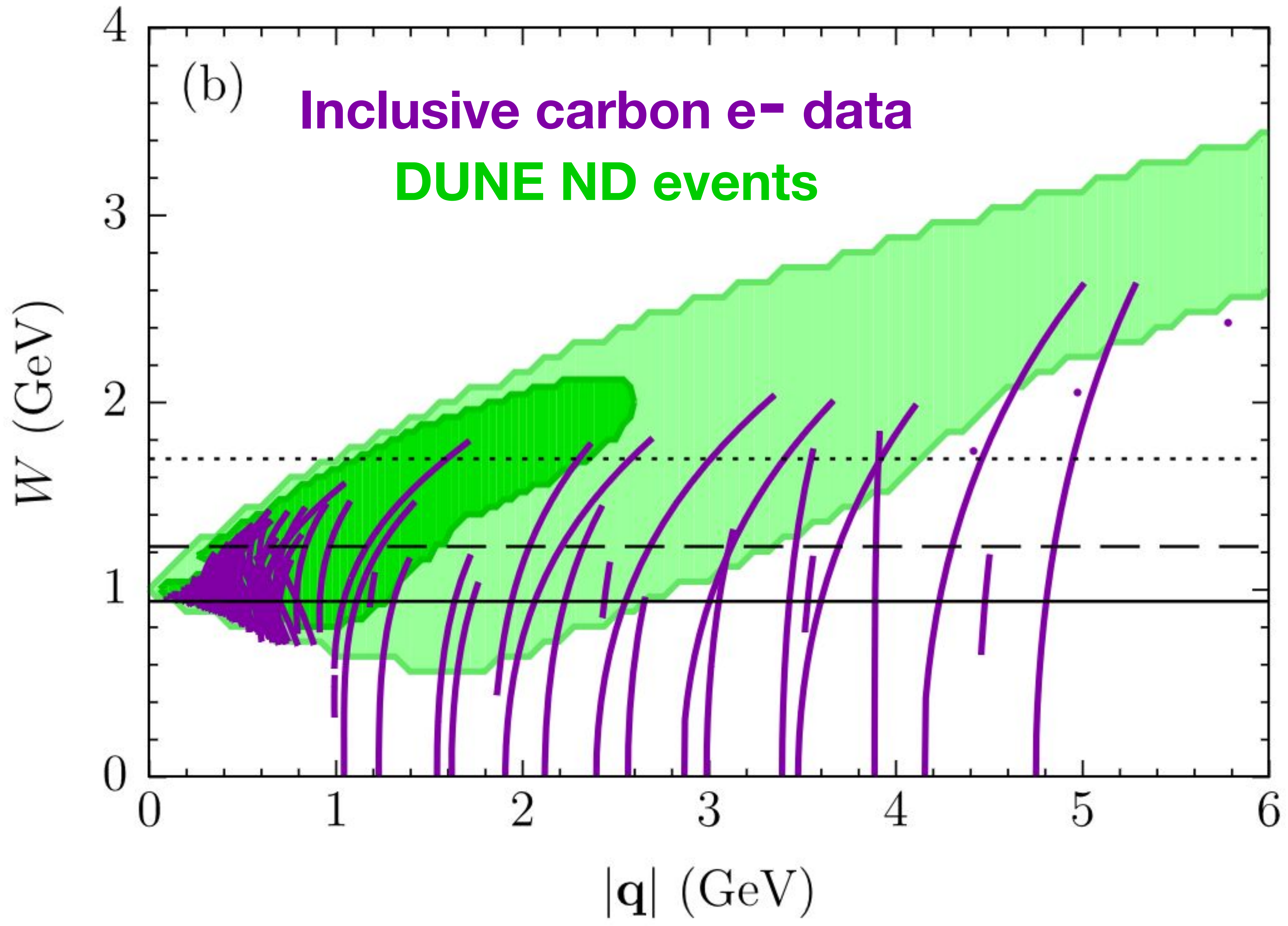
- **Directly test simulations** at relevant kinematics
  - e4v (Julia's talk)
  - LDMX
  - MAMI / MESA

- Data highly valuable at both GeV and MeV energies
  - Theory and MC efforts for planning

Phys. Rev. D 105, 112002 (2022)

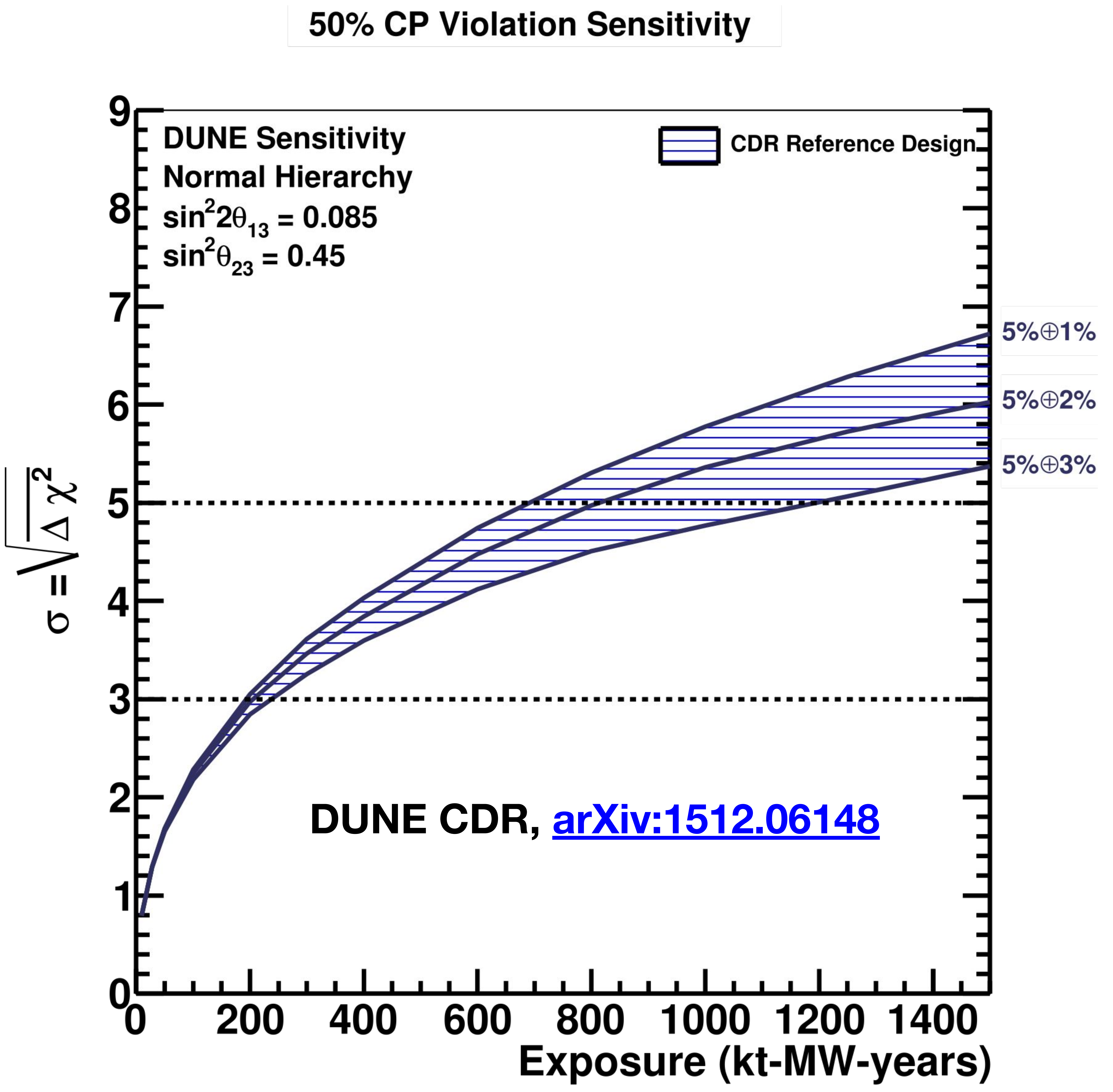


J. Phys. G: Nucl. Part. Phys. 50 120501 (2023)



Achieving high precision

- Electron data can provide powerful constraints
- Leveraging this resource requires a simulation with **consistent e/ν physics**
  - Typically not the case historically
  - Adjustments aren't mysterious, but work is non-trivial
- Efforts underway at various levels of completion, this talk will review
- Technical investment now can have strong future impact



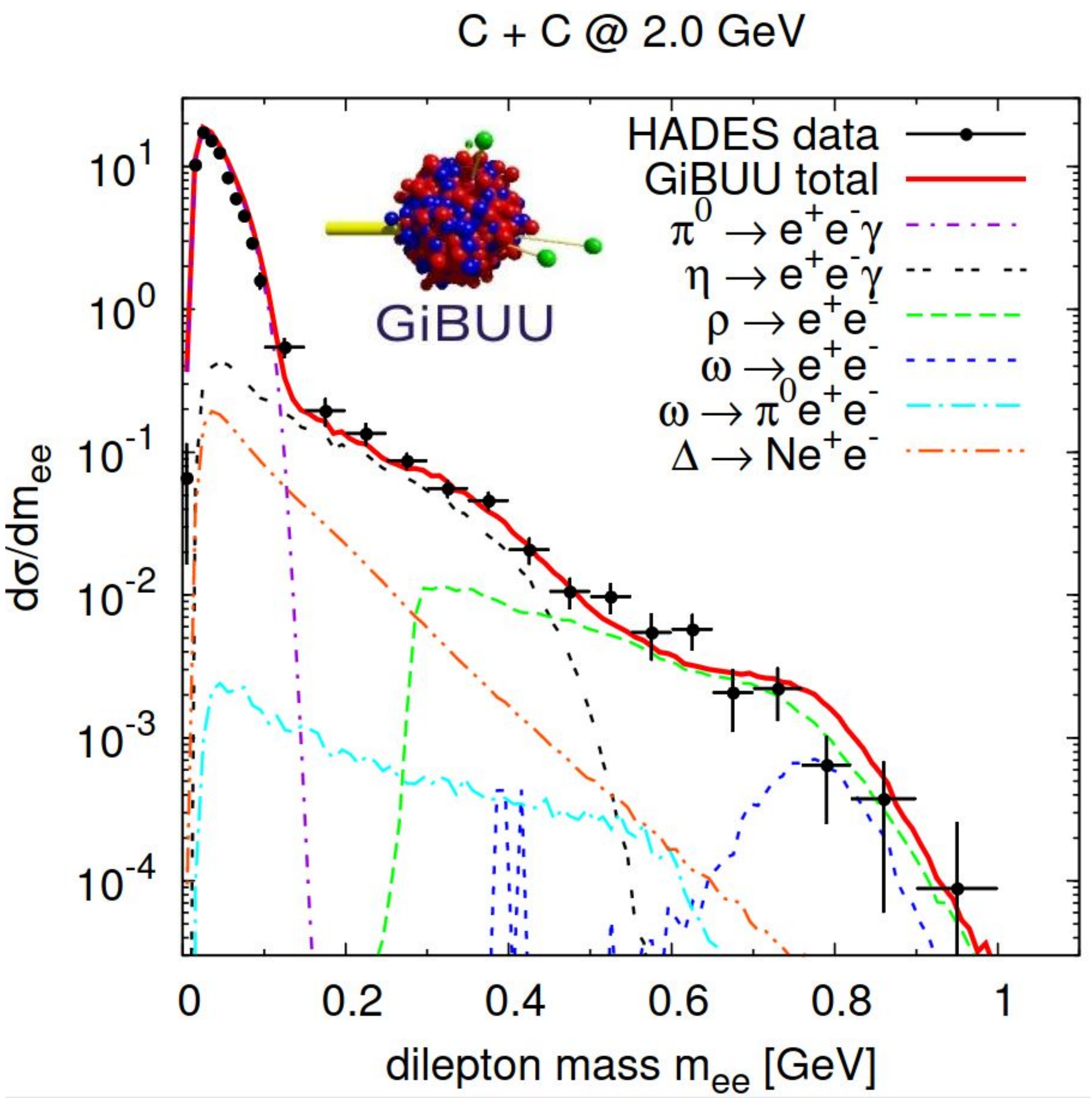
14 April "Geek Fair," Avenida Paulista, São Paulo

Impact of GiBUU history on electron and neutrino support

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

- Electron simulation thus predates neutrinos
  - Has influenced ν implementation

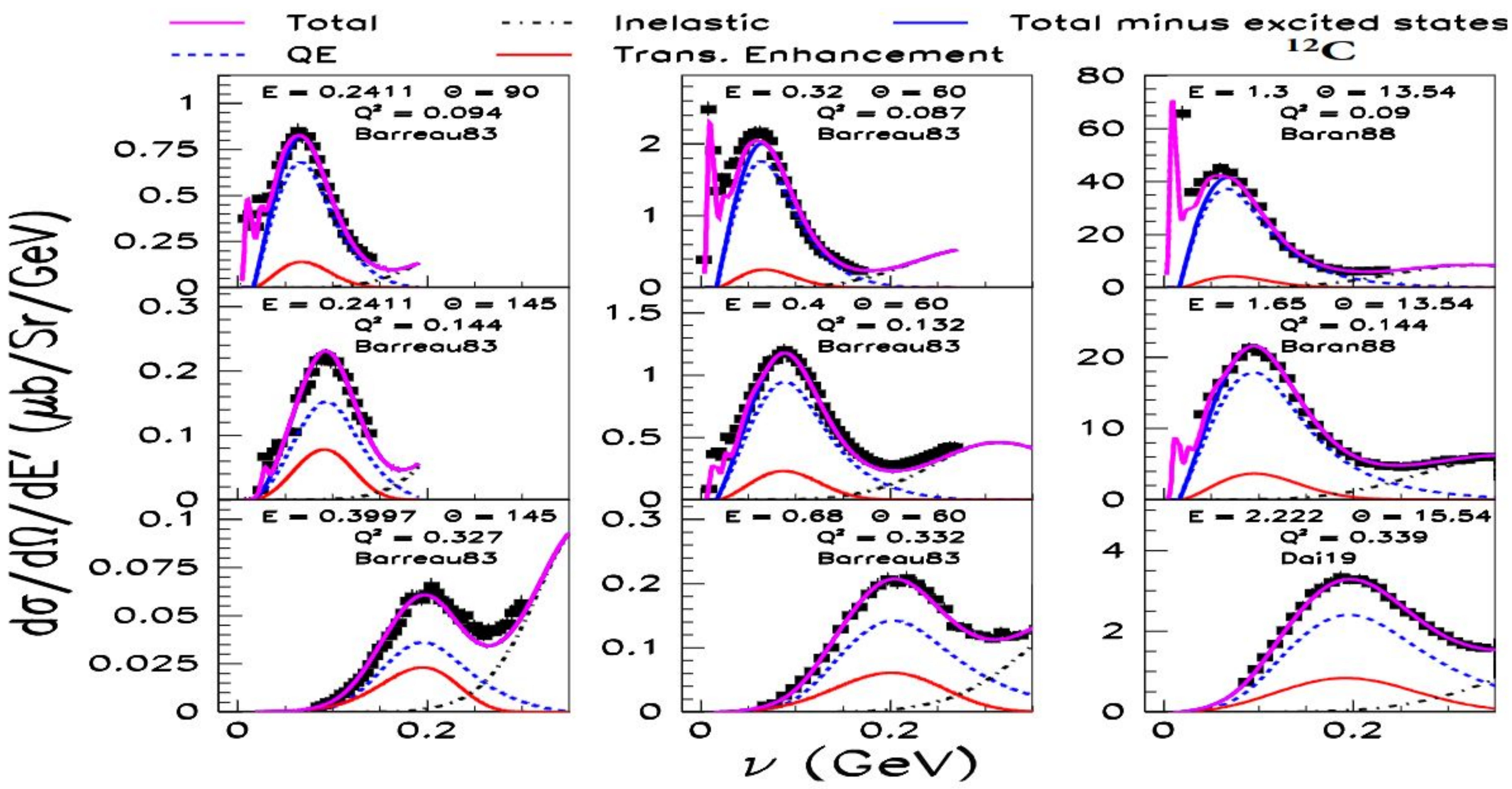
- **GiBUU 2023** includes significant electron scattering updates
  - 2p2h & RES
  - See also [Ulrich's talk]() from Monday



Bodek-Christy fits of inclusive electron data

- **Transverse enhancement** (TE) component adopted in GiBUU 2023 MEC model
- Structure function uses 2 Gaussians in W

[Phys. Rev. C 106, L061305 (2022)](#)



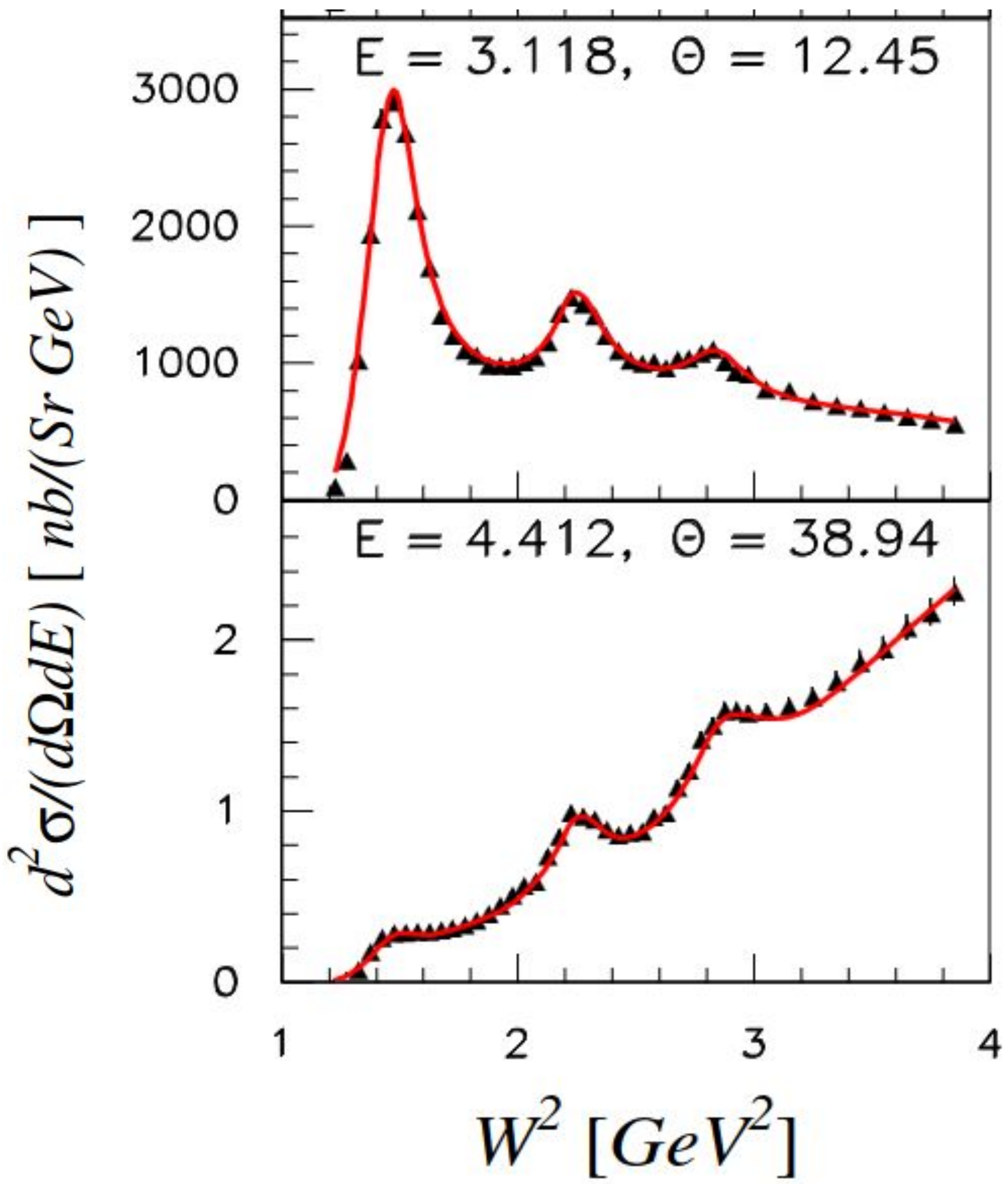
- Similar data-driven strategy used previously, but TE parameterization has been updated

Bosted-Christy fits in resonance region

- Adopted in GiBUU 2023 for e- RES and non-RES background
- Nucleon-level cross sections obtained from inclusive p and d data sets
- PYTHIA-based treatment of DIS (W > 3 GeV) preserved, low Q^2 cut removed

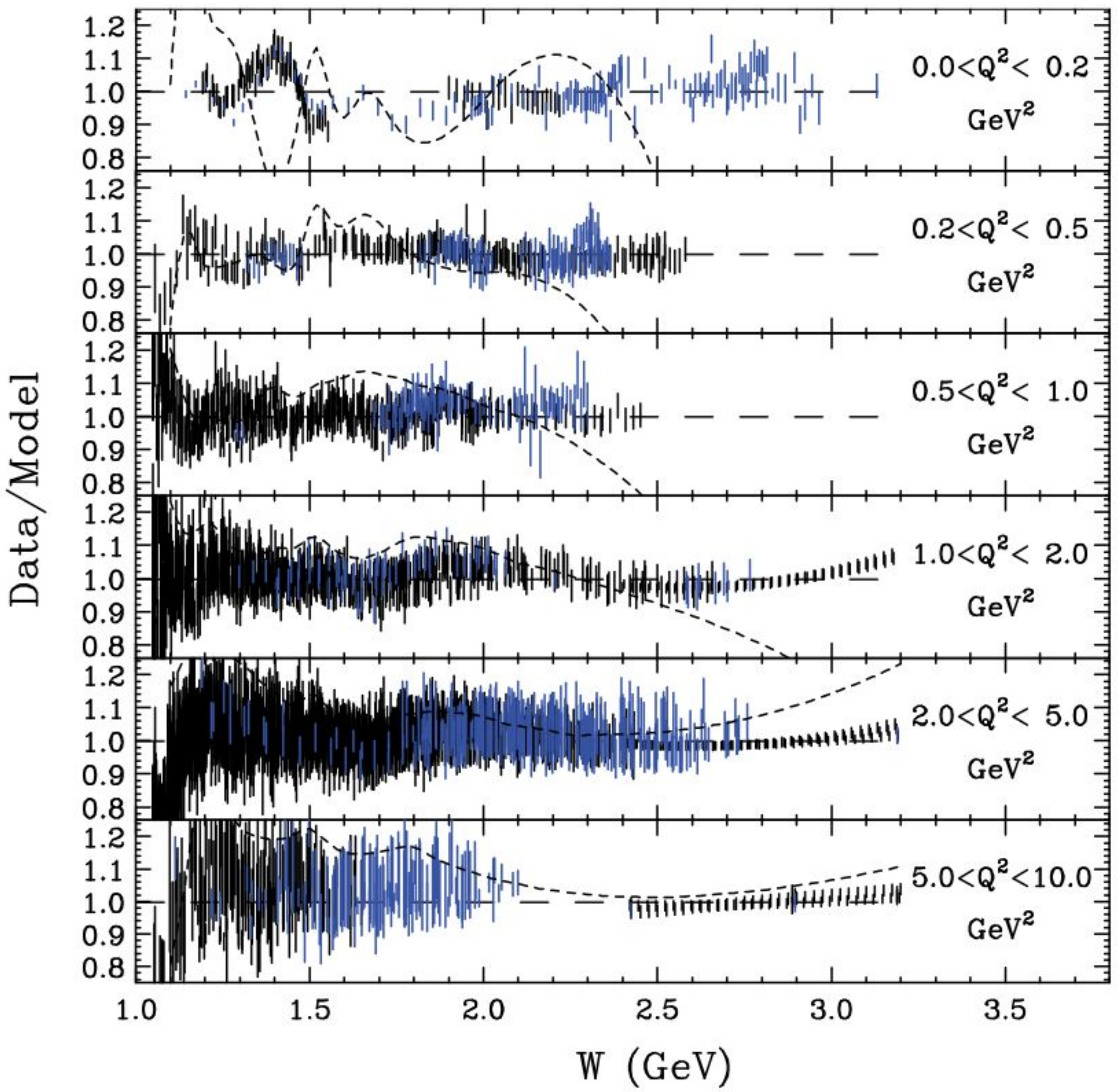
Phys. Rev. C 81, 055213 (2010)

e + p scattering



Phys. Rev. C 77, 065206 (2008)

e + d scattering



Application to neutrino scattering

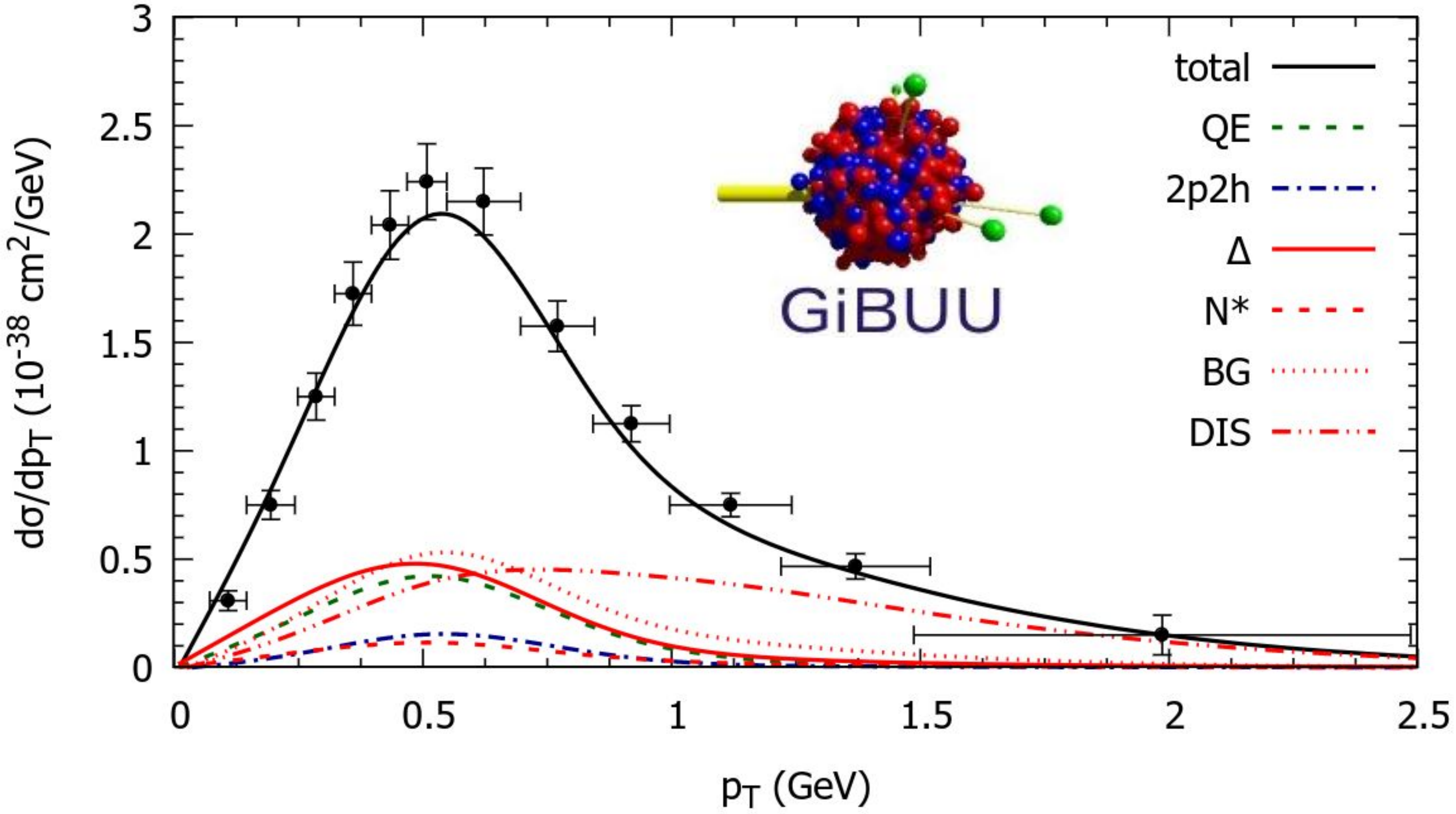
[Phys. Rev. D 109, 033008 (2024)]

$$W_1^{\nu} = \left[1 + \left(\frac{2m}{\mathbf{q}}\right)^2 \left(\frac{G_A(Q^2)}{G_M(Q^2)}\right)^2\right] 2(\mathcal{T}+1)\, W_1^e$$

$$W_3 = 2\left(\frac{2m}{\mathbf{q}}\right)^2 \frac{G_A(Q^2)}{G_M(Q^2)}\, 2(\mathcal{T}+1)\, W_1^e \, .$$

- e- structure functions used to obtain ν according to Walecka prescription
  - Assumption of isobaric analog states
  - 2p2h and non-RES only
  - Vector part of ν RES is still based on MAID 2007 analysis

- Applied to inclusive neutrino scattering cross sections in recent paper



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

GENIE: historical support for electrons

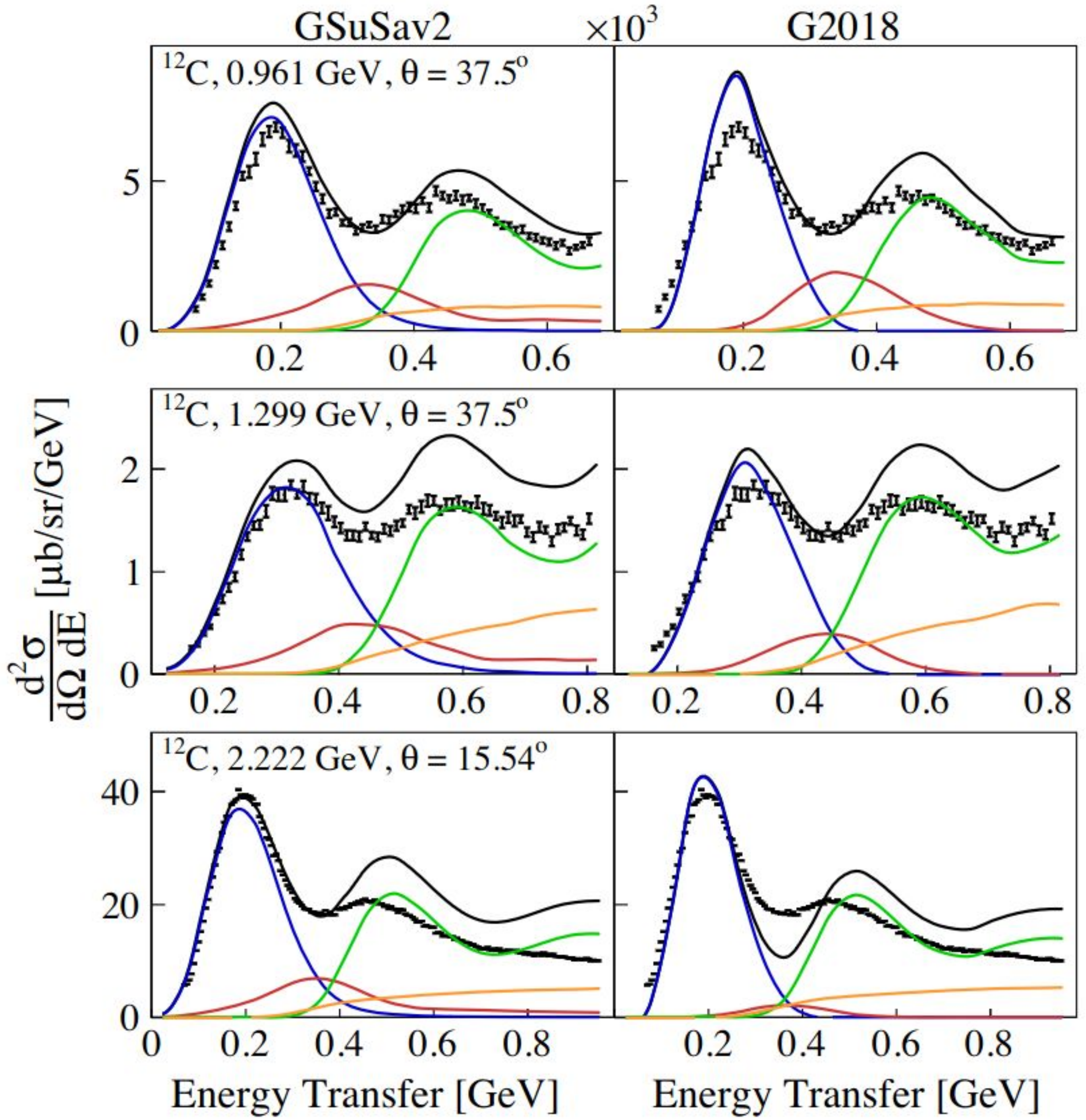
- Basic modeling for all major channels since v2 era
  - Subset of ν physics options

- Consistency not always enforced
  - Sometimes different pieces of code

- **Example:** G18_10a_02_11a model set
  - Recently popular in ν experiments
  - ν CCQE = Valencia (RPA)
  - e EMQE = Rosenbluth (no RPA)

- Modeling differences limit immediate usefulness of electron constraints

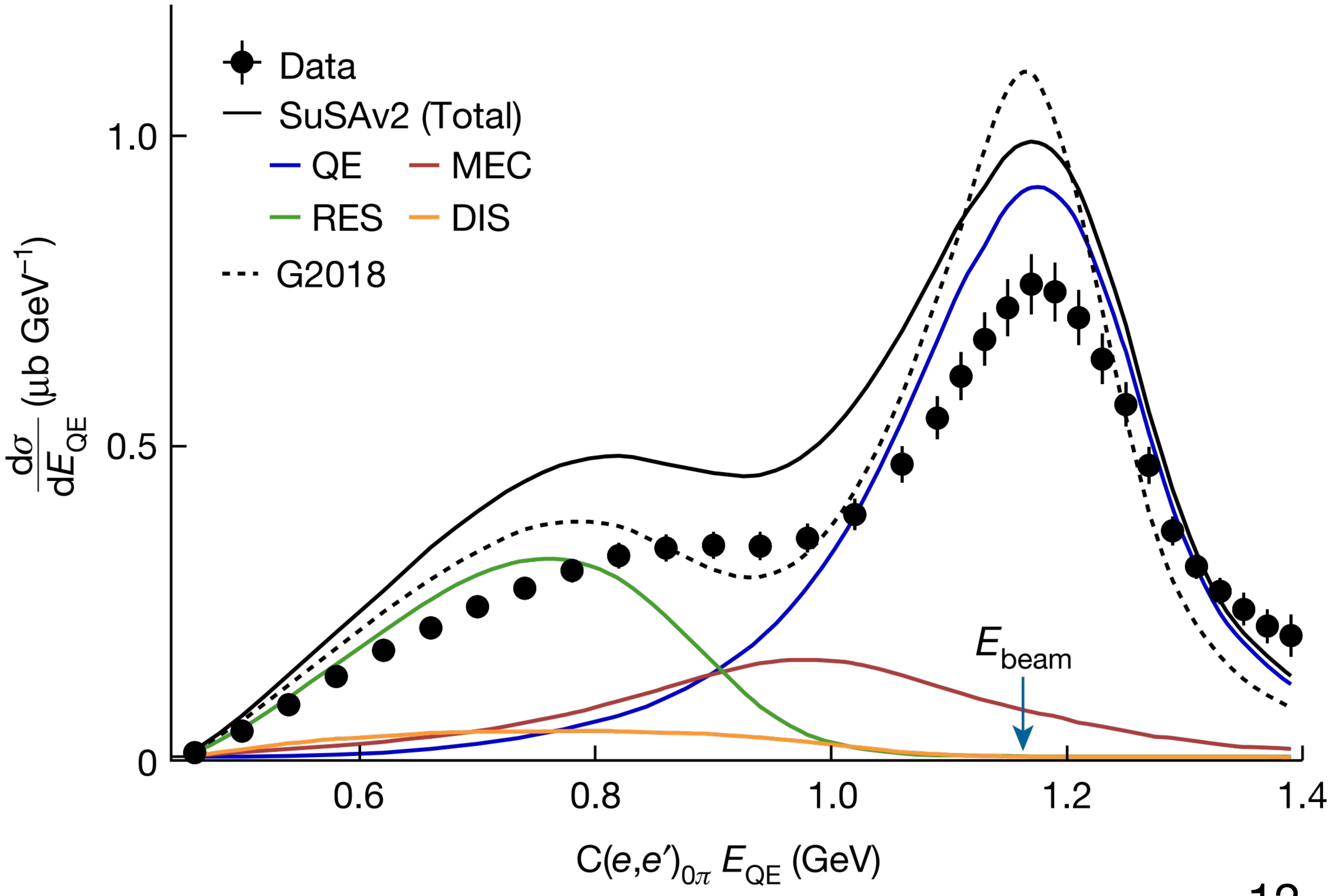
Phys. Rev. D 103, 113003 (2021)



GENIE SuSAv2 implementation and consistency

- G21 model sets use SuSAv2 for QE + 2p2h
  - Resolved e/ν discrepancies
  - EM portion driven by studies by e4ν
- Famously used in the recent **energy reconstruction** study
- Upcoming model additions to GENIE tend to treat e and ν on an equal footing
  - e.g., SuSAv2 inelastic (see Friday talk by Jesús Gonzalez-Rosa)

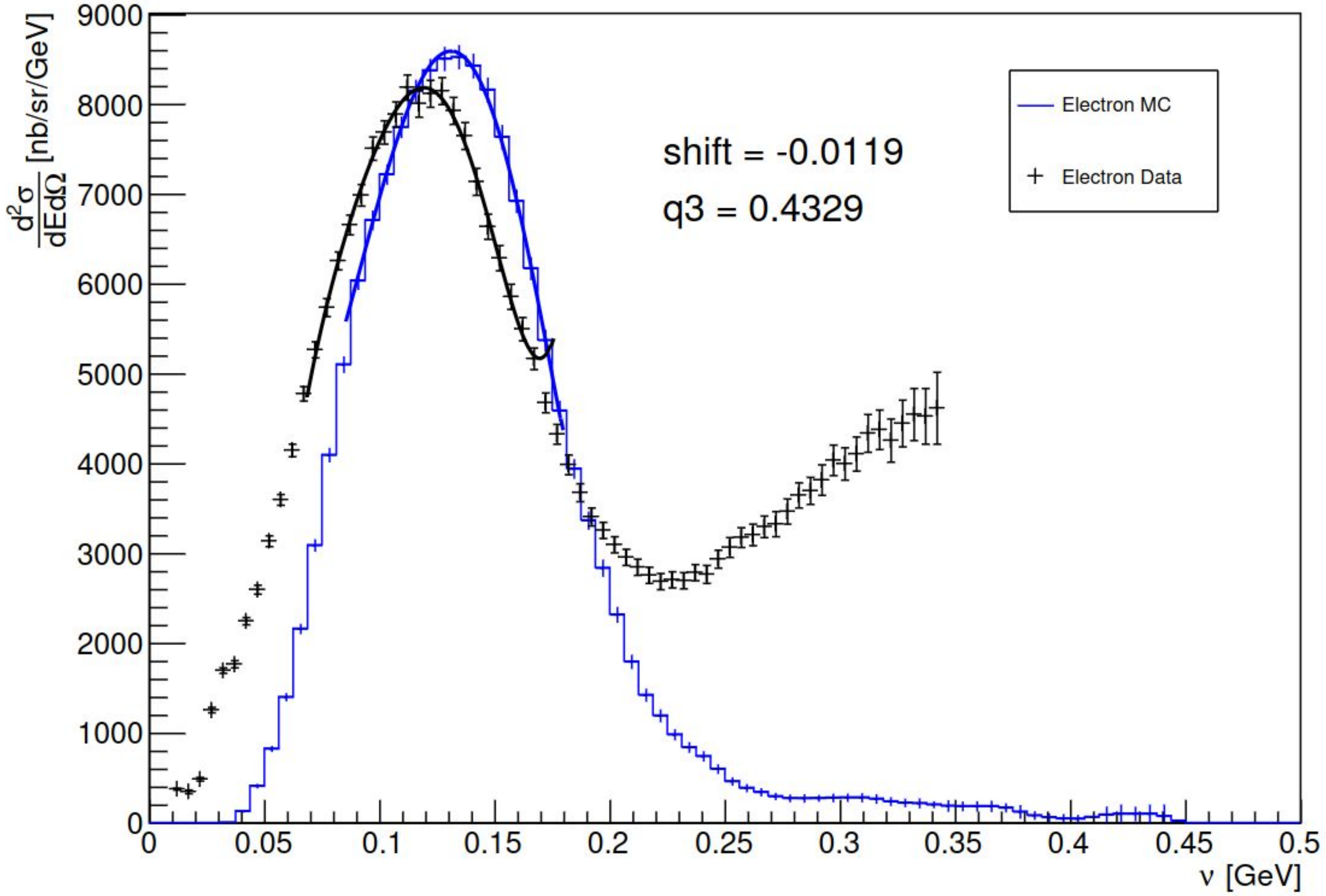
[Nature 599, 565 (2021)]

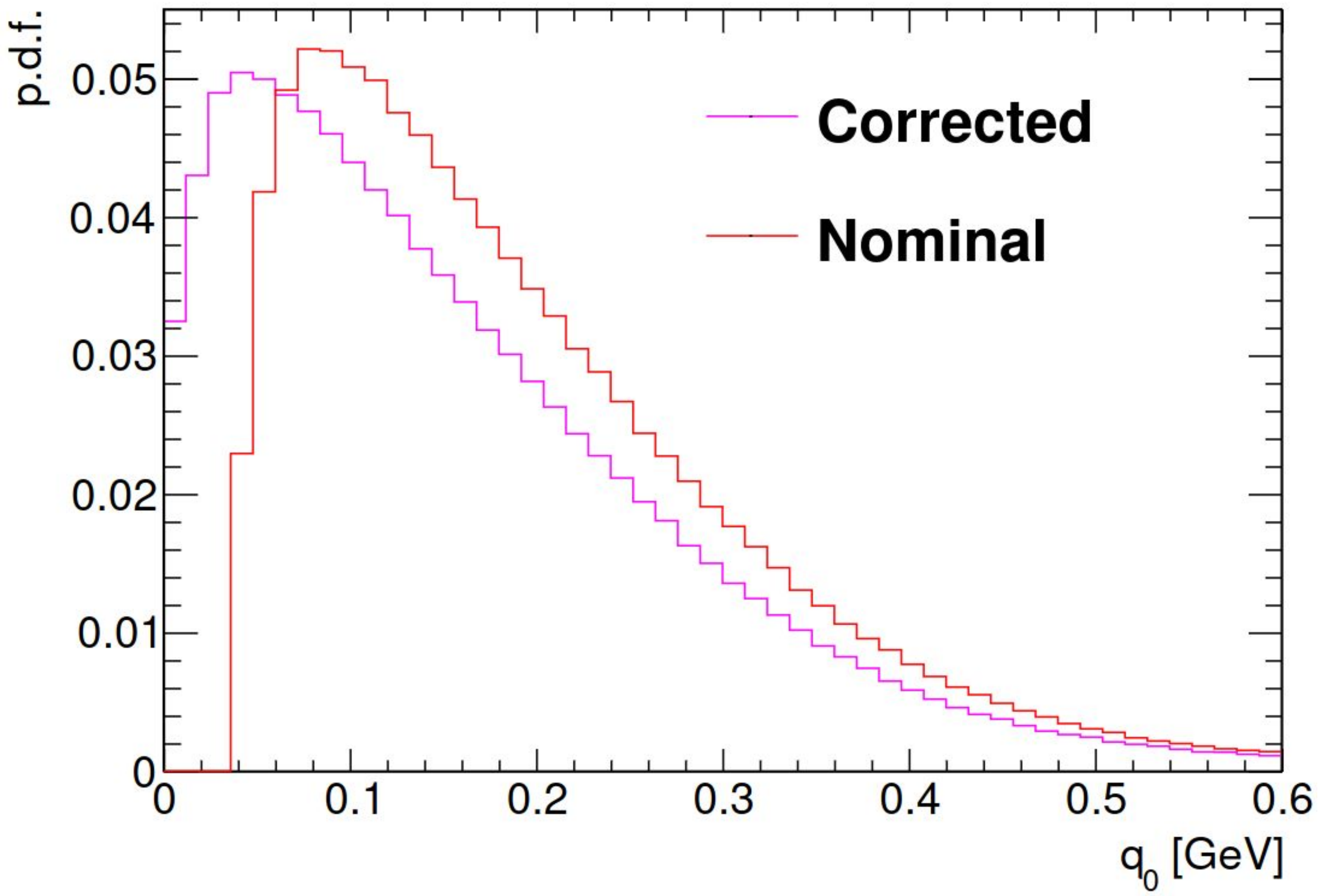


NEUT: currently QE only

- Electron support is recent addition
  - Adaptation of existing NC code
- Recent tests against data using SF nuclear model
- PWIA = shift in QE peak location relative to data
- Adjustment to removal energy
  - Empirical correction dependent on **q**
  - Applied consistently to ν simulations

arXiv:2301.09195

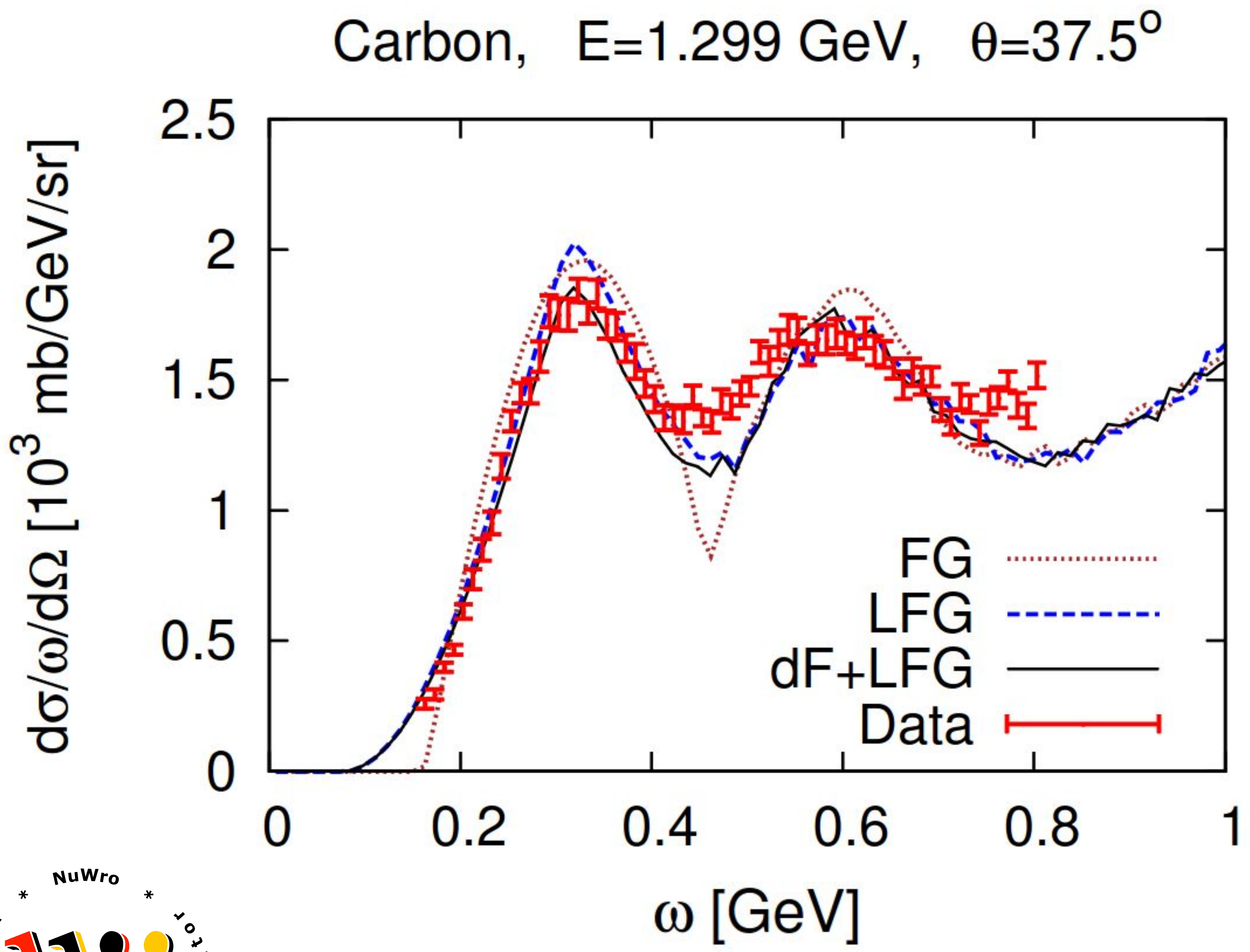




eWro: adapting NuWro for electrons

- Support for QE and single π production
    - **2015 model** has different non-RES background between e/ν
    - QE and Δ(1232) consistent
- FG and LFG nuclear models used in these comparisons

Acta Phys. Polon. B46, 2329 (2015)



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Acta Phys. Polon. B46, 2329 (2015)

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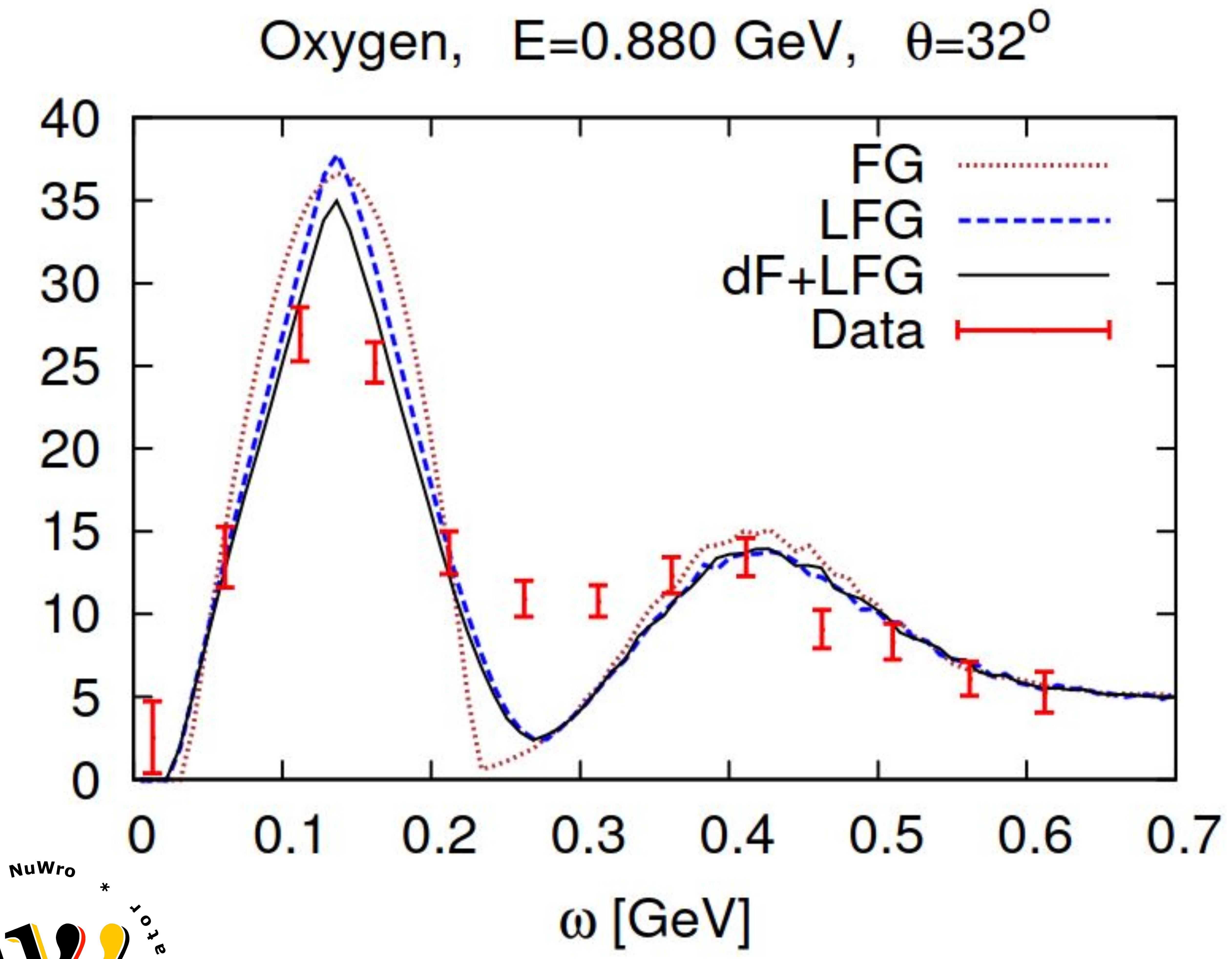
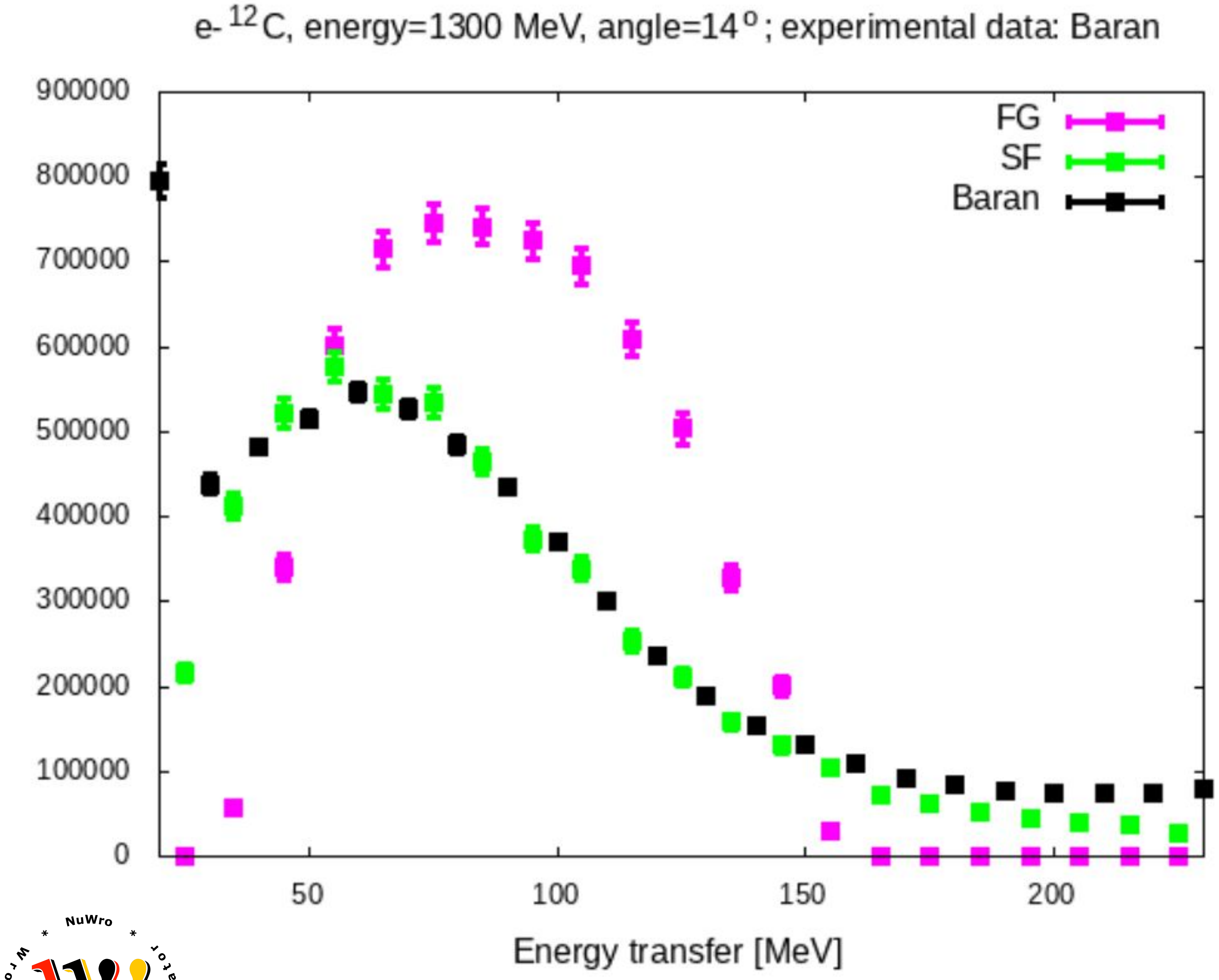


Current status

- eWro is still mainly focused on QE
    - Ongoing effort to add consistent treatments of other channels
- Available for use with more up-to-date nuclear models
    - Benhar SF for carbon
- Argon SF in upcoming software release will be an exciting addition!

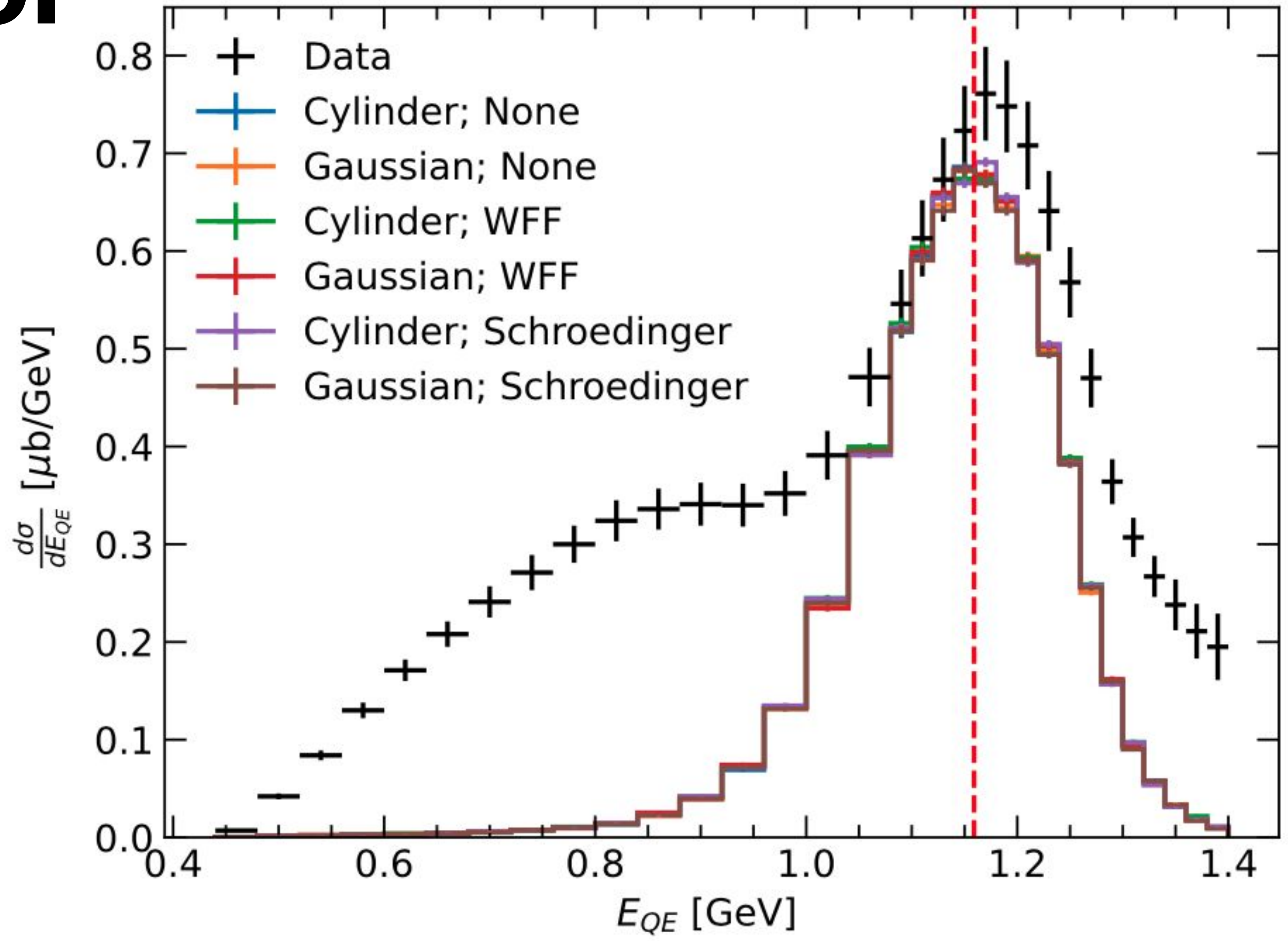
[Jan's talk on Monday](#)



The ACHILLES event generator

[Phys. Rev. D 107, 033007 (2023)](#)

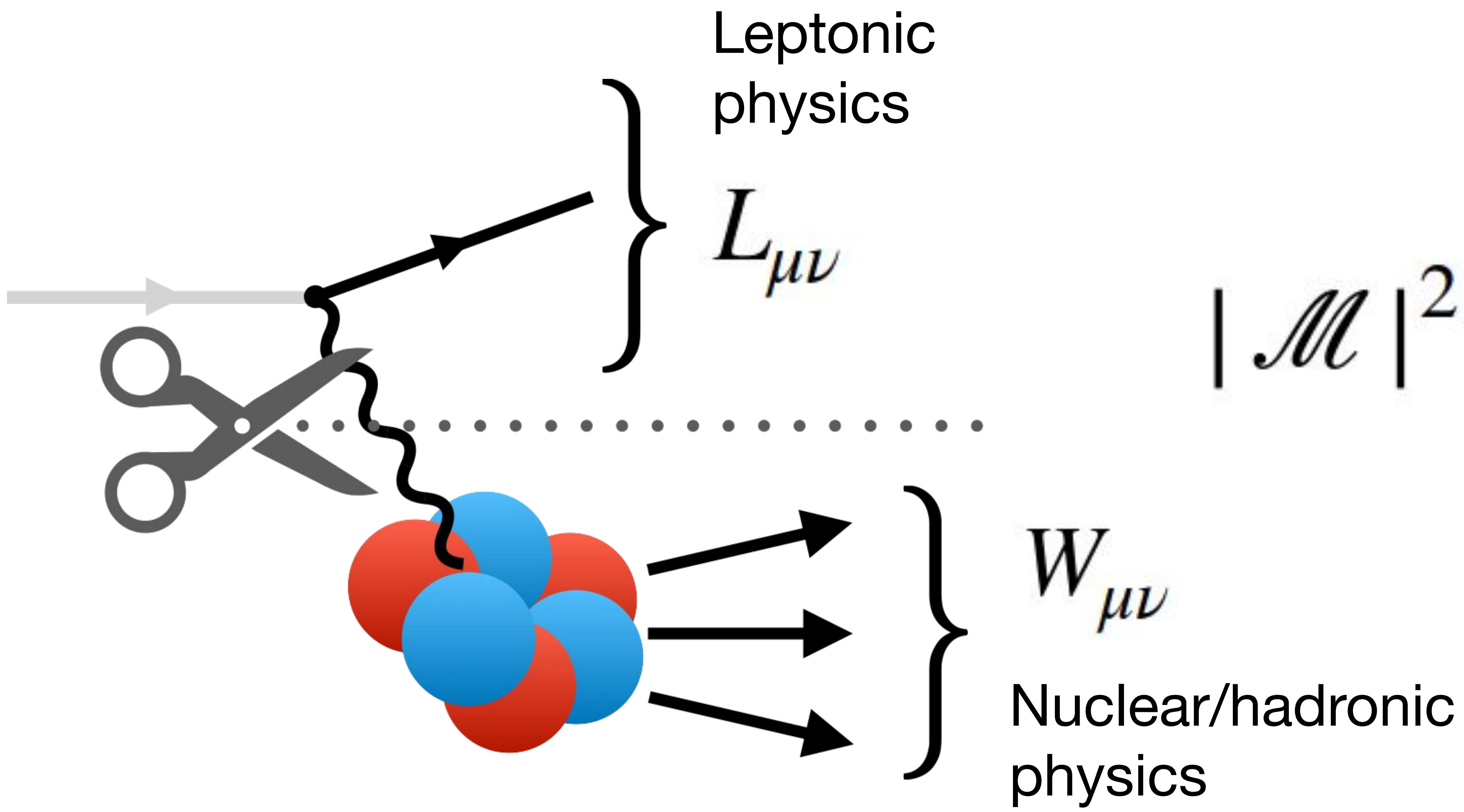
A CHIcagoLand Lepton Event Simulator



- New theory-driven event generator, Fermilab-led
  - QE only until recently, active development of other channels

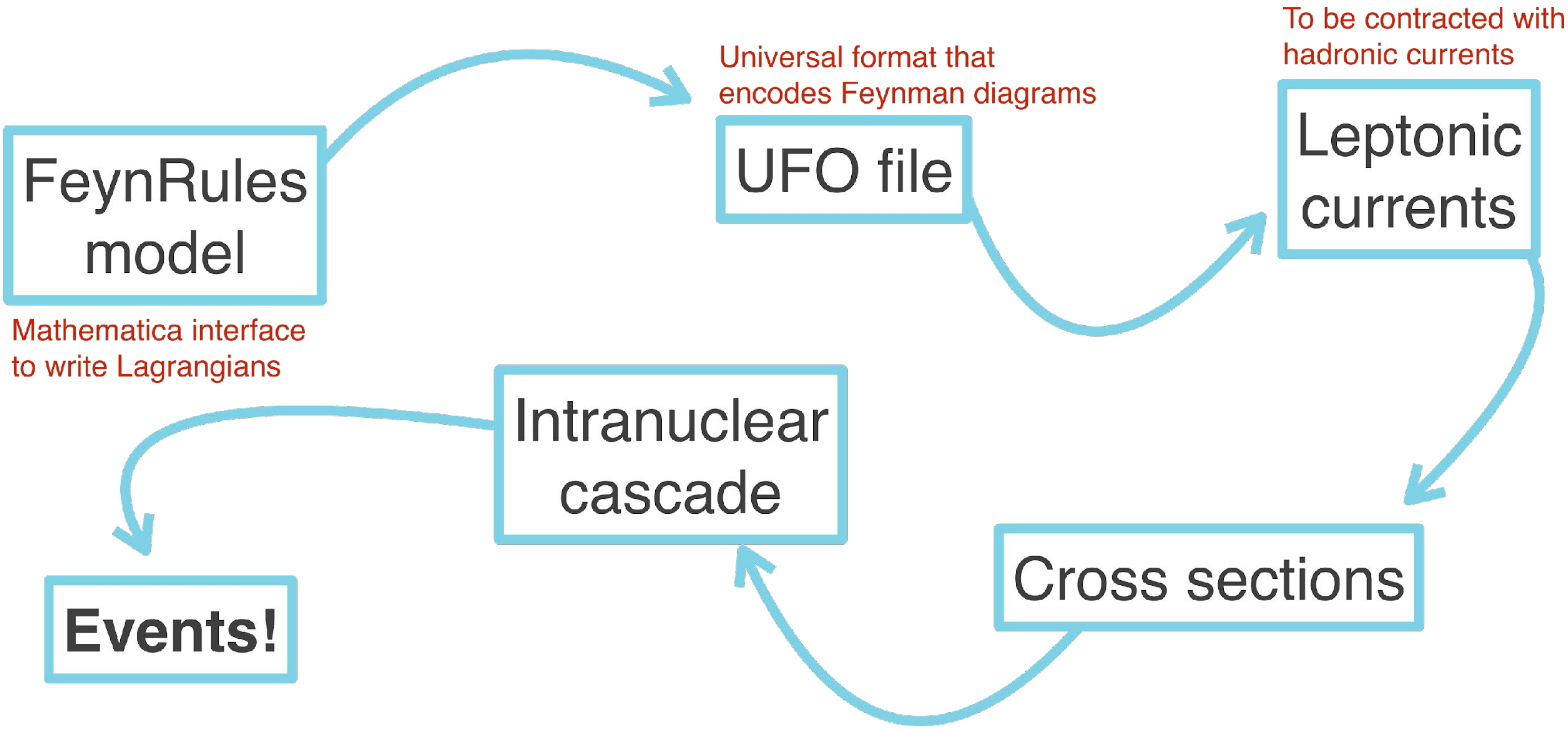
- Built from the ground up with e/ν/BSM consistency in mind

- Enabling technology = automated leptonic tensor
  - [Phys. Rev. D 105, 096006 (2022)](#)



$$|\mathscr{M}|^2 \propto L_{\mu\nu} W^{\mu\nu}$$

ACHILLES approach to automating the leptonic tensor



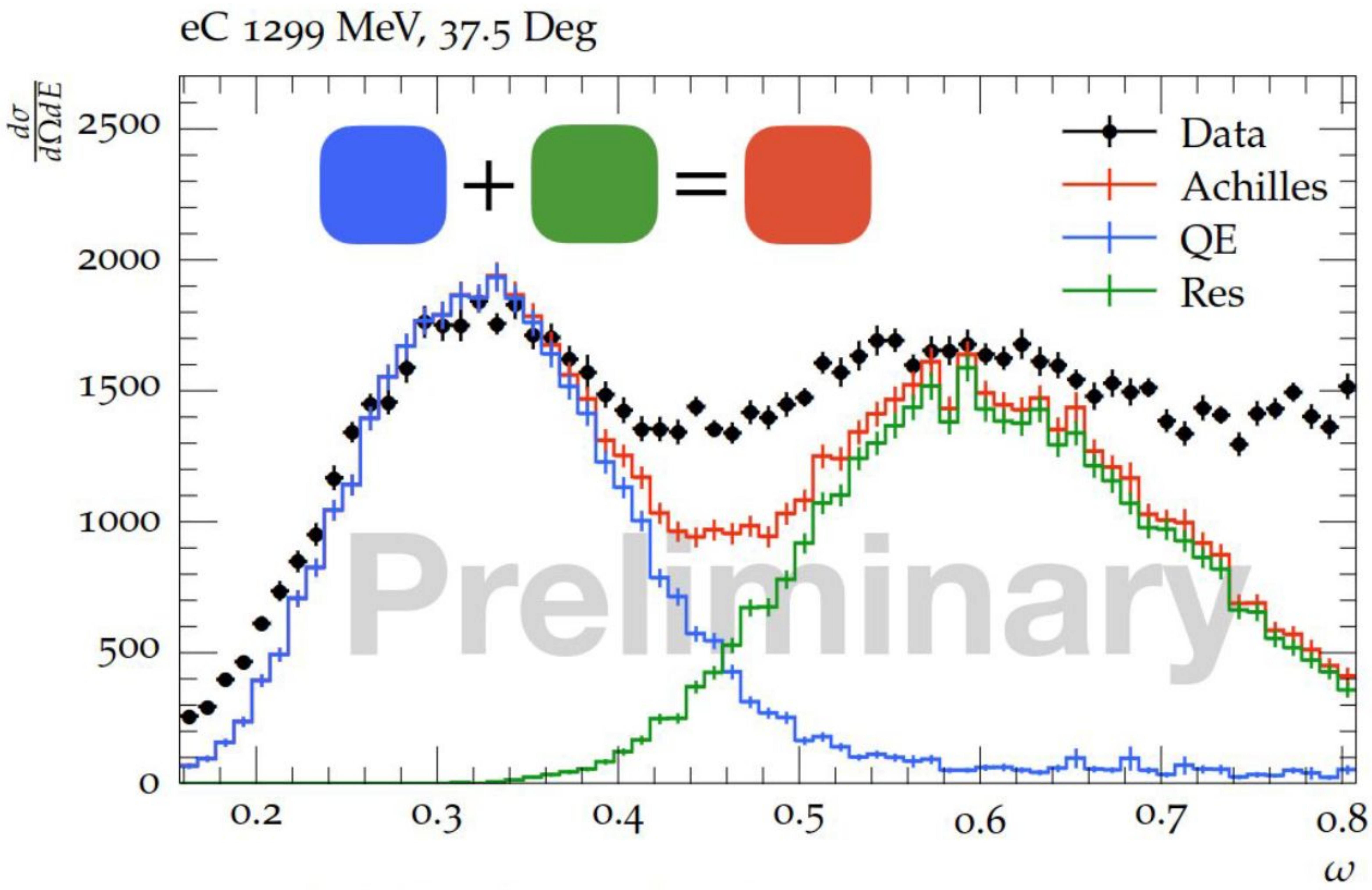
Slide credit: P. Machado

Latest ACHILLES comparison

- Preliminary results show RES is up and running

- Goal to have support for all major channels in the near future

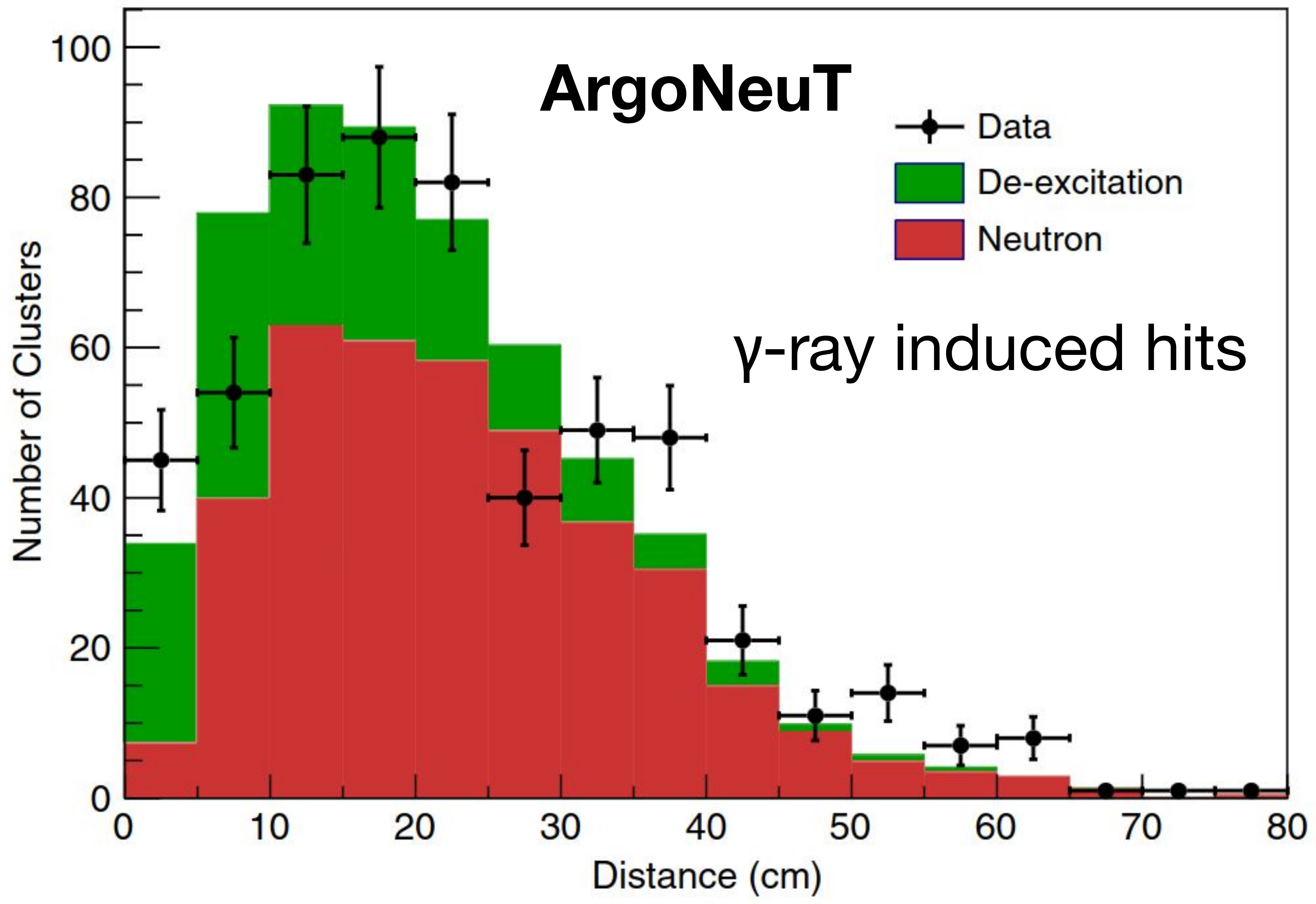
Josh's talk on Monday



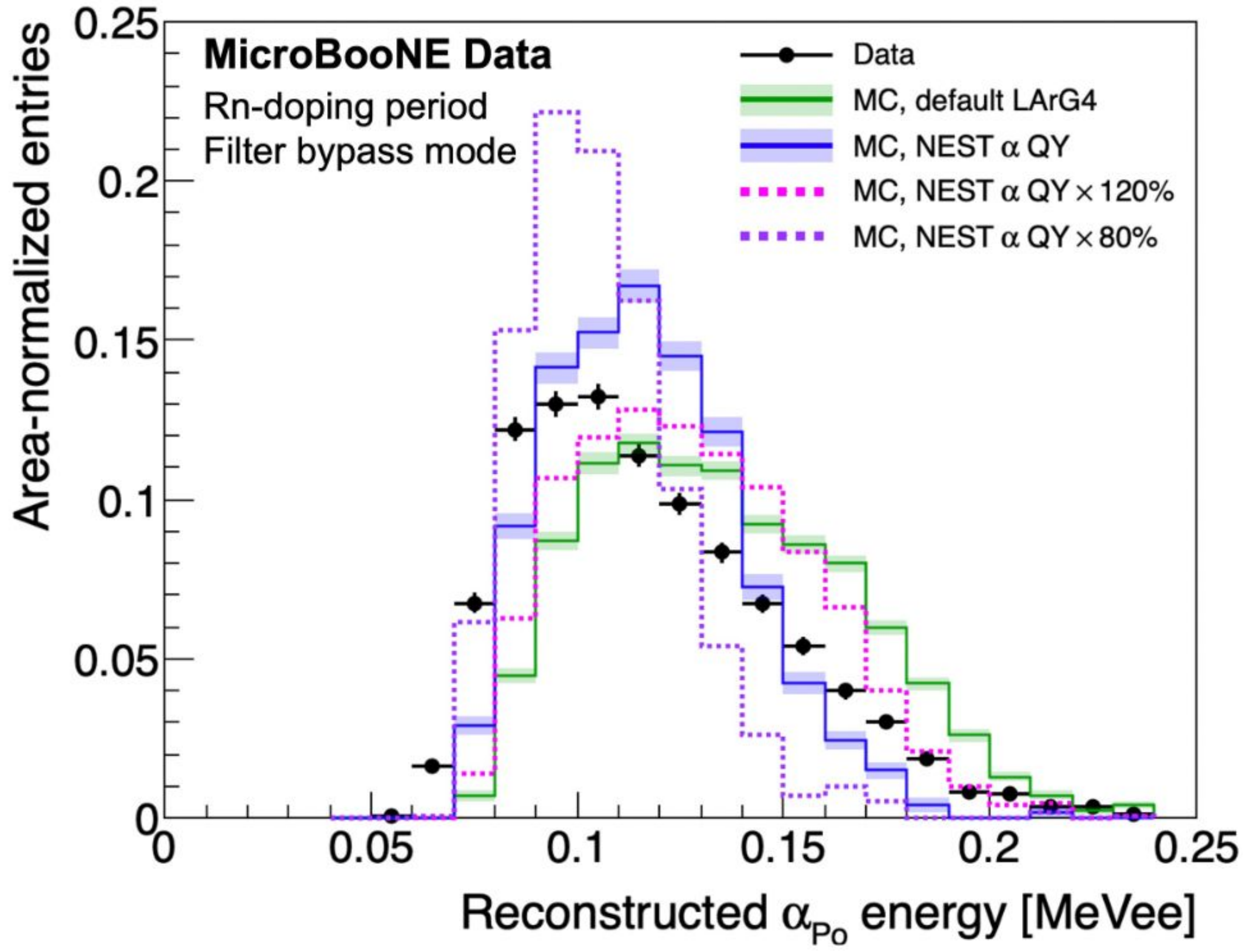
Nuclear de-excitation modeling

- Increased community interest on this topic
- Variety of interesting applications
  - NC backgrounds in JUNO (Jie's talk)
  - ν calorimetry (Anna's talk)
  - See also Abe-san's poster!
- **LArTPCs can also participate**
- Like cascade FSI, dynamics expected to be the same for e/ν

Phys. Rev. D 99, 012002 (2019)



Phys. Rev. D 109, 052007 (2024)



Hauser-Feshbach formalism

- De-excitation treatment used in TALYS, very similar to ABLA, PEANUT, and other codes
- Quantum-mechanical, but relies on **lots** of empirical input from hadron- and γ-nucleus data

Differential decay width for emission of a nuclear fragment α (A ≤ 4 considered)

$$\frac{d\Gamma_\alpha}{dE'_x} = \frac{1}{2\,\pi\,\rho_i(E_x, J, \Pi)} \sum_{\ell=0}^{\ell_{\max}} \sum_{j=|\ell-s|}^{\ell+s} \sum_{J'=|J-j|}^{J+j} T_{\ell j}(\varepsilon)\, \rho_f(E'_x, J', \Pi')$$

Differential decay width for emission of a γ-ray

$$\frac{d\Gamma_\gamma}{dE'_x} = \frac{1}{2\,\pi\,\rho_i(E_x, J, \Pi)} \sum_{\lambda=1}^{\lambda_{\max}} \sum_{J'=|J-\lambda|}^{J+\lambda} \sum_{\Pi'\in\{-1,1\}} T_{X\lambda}(E_\gamma)\, \rho_f(E'_x, J', \Pi')$$

Level density model: Back-shifted Fermi gas (RIPL-3), Nucl. Data Sheets 110, 3107–3214 (2009)

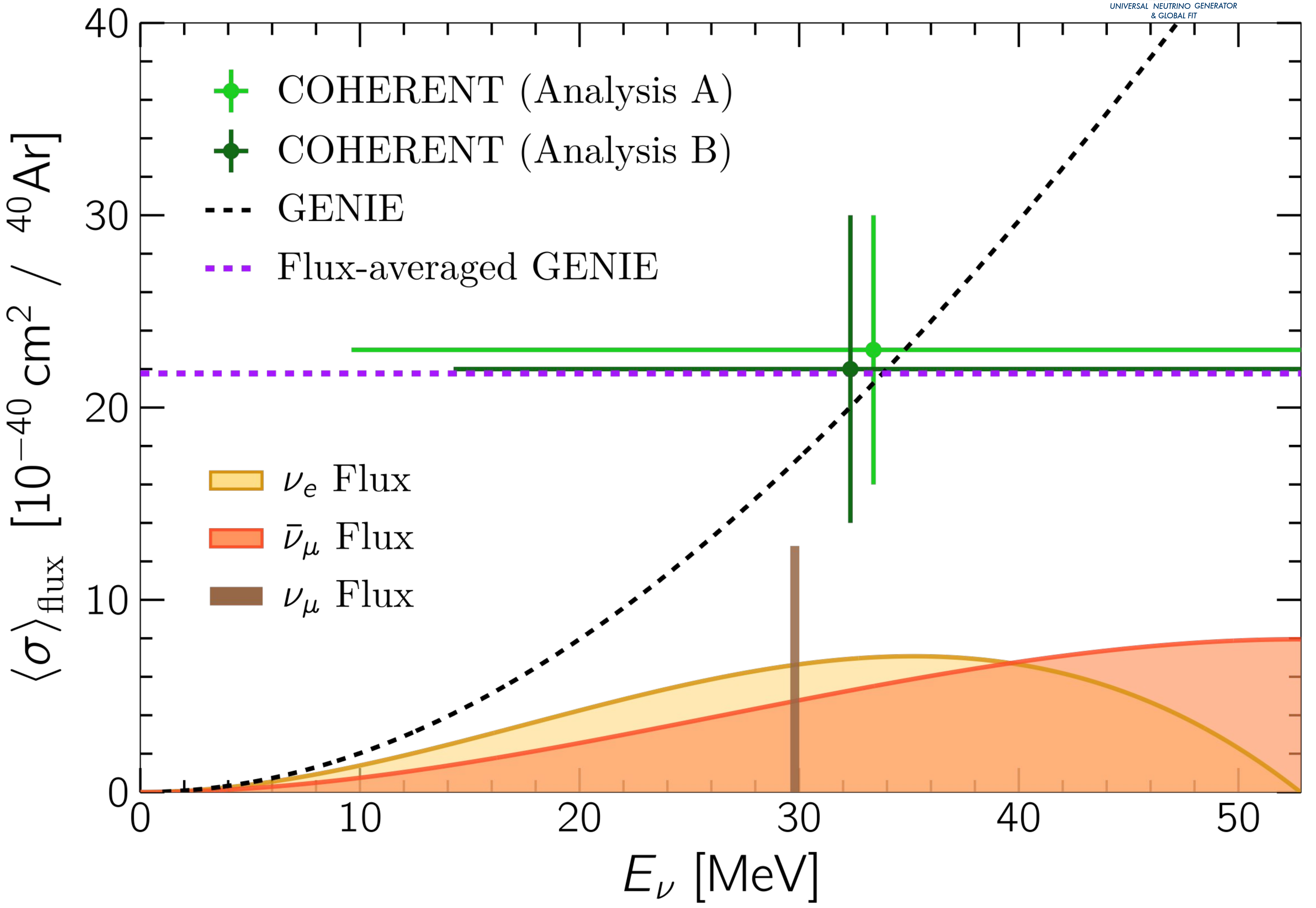
Nuclear optical model: Koning & Delaroche, Nucl. Phys. A 713, 231–310 (2003) (**45 parameters!**)

Gamma-ray strength function model: Standard Lorentzian (RIPL-3), Nucl. Data Sheets 110, 3107–3214 (2009)

- Data-driven, but **subtleties exist** in applying this to the e/ν-nucleus case
- Electron experiments could help us verify that we haven't missed something important

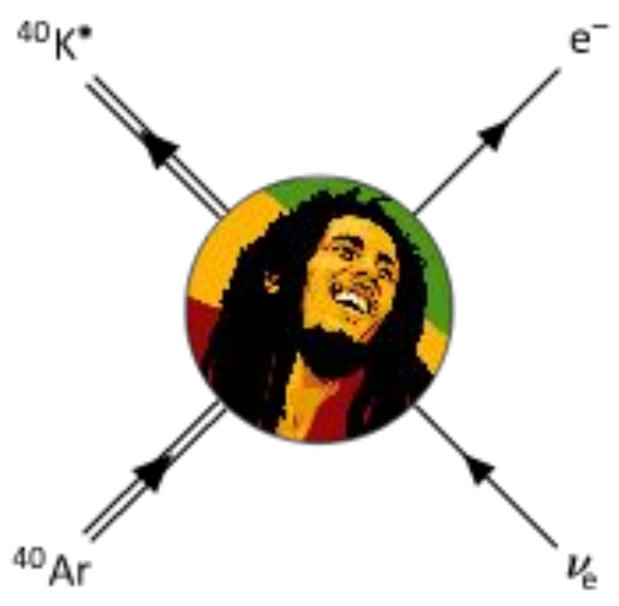
Coherent elastic neutrino-nucleus scattering (CEvNS)

- NC process which leaves the struck nucleus in its ground state
  - Detection via recoil
  - Dominant for O(10 MeV) ν
- Easy to simulate
- **Main uncertainty** is weak nuclear form factor
  - Polarized electron beams allow precise constraints via **parity-violating electron scattering**



COHERENT data from Phys. Rev. Lett. 126, 012002 (2021)

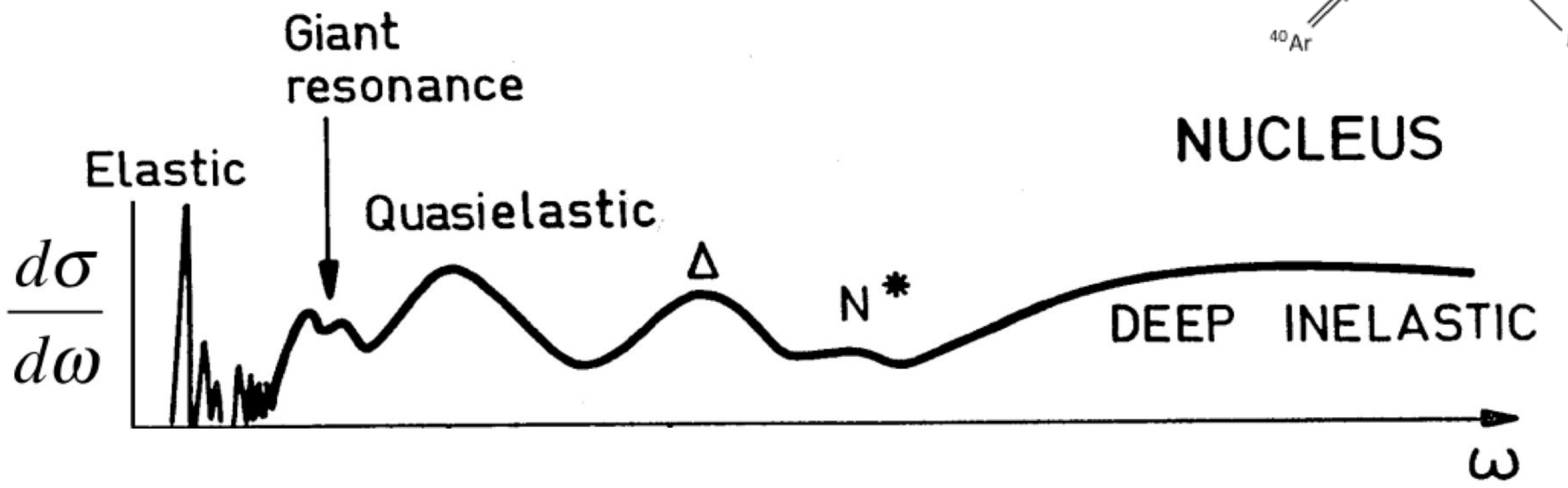
MeV-scale inelastic neutrino-nucleus scattering

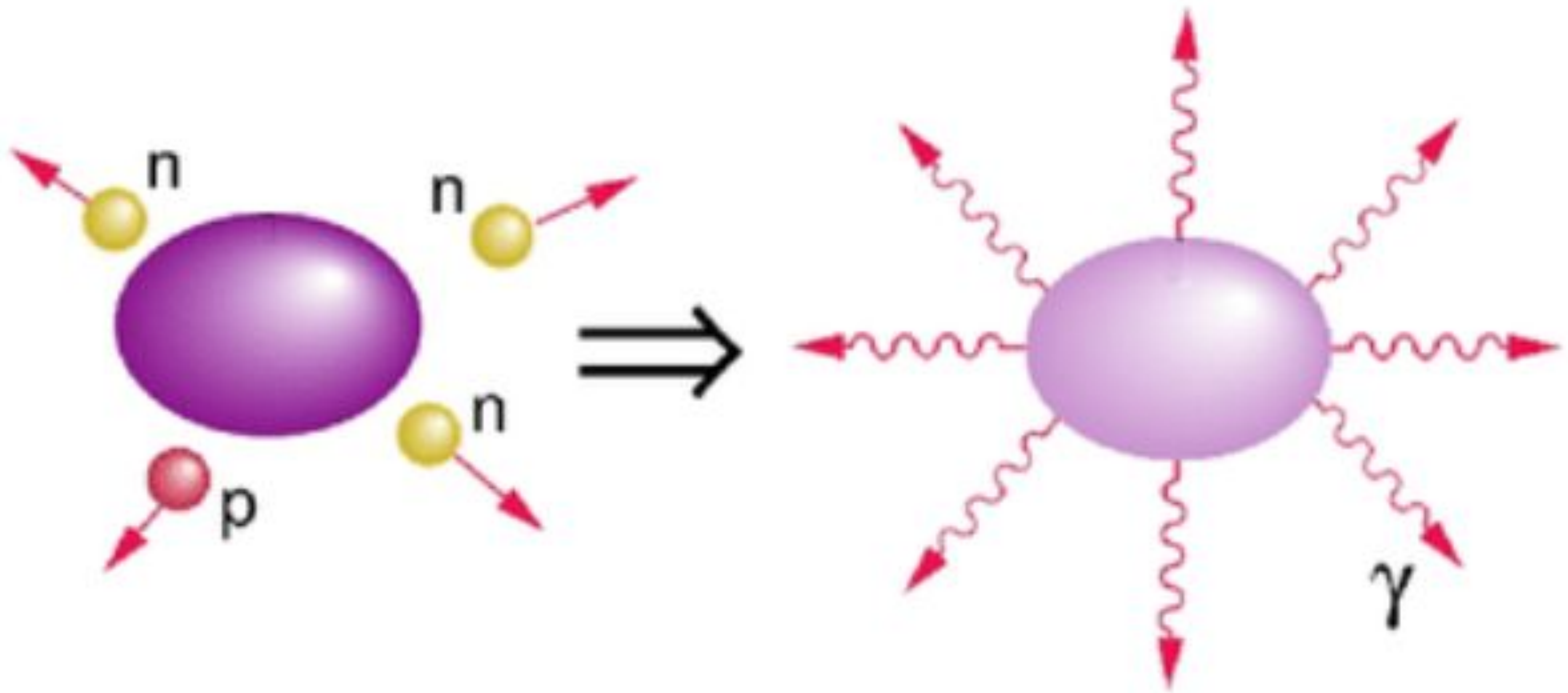


- Of interest for supernova and solar neutrino physics, BSM searches, etc.

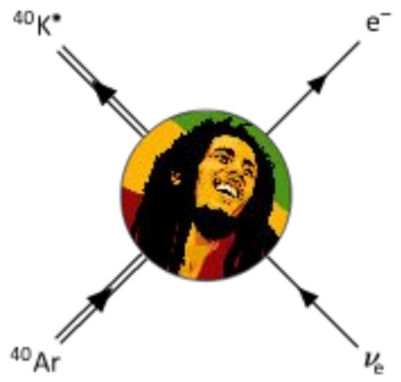
- **Modeling differences**
  - Discrete excitations and giant resonances
  - De-excitation FSI

- **MARLEY generator** attempts to simulate this physics
  - Primary interaction model is very rough





MARLEY cross-section model



[Phys. Rev. C 103, 044604 (2021)](https://doi.org/10.1103/PhysRevC.103.044604)

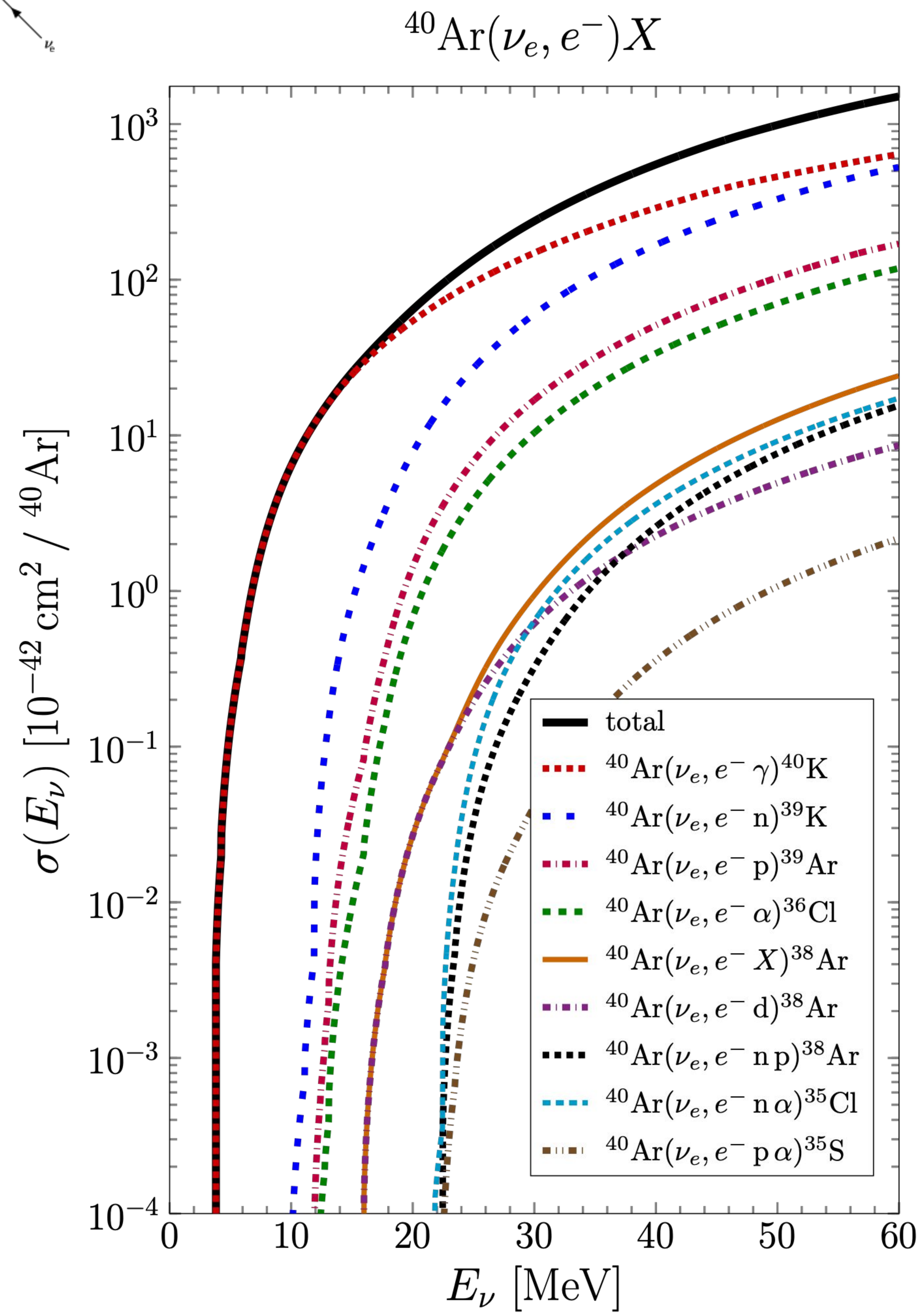
- Inclusive prediction uses B(F) and B(GT) matrix elements that survive "allowed approximation"
  - Slow nucleon and long-wavelength limits

- Exclusive obtained via HF de-excitation model

- NC implemented, B(F) = CEvNS

- EM uninteresting under this treatment
  - B(F) = elastic e-A scattering
  - B(GT) = 0 (comes from axial current)

- Limitation removed in ongoing improvements
  - MESA e-A facility could provide valuable model constraints



Conclusion

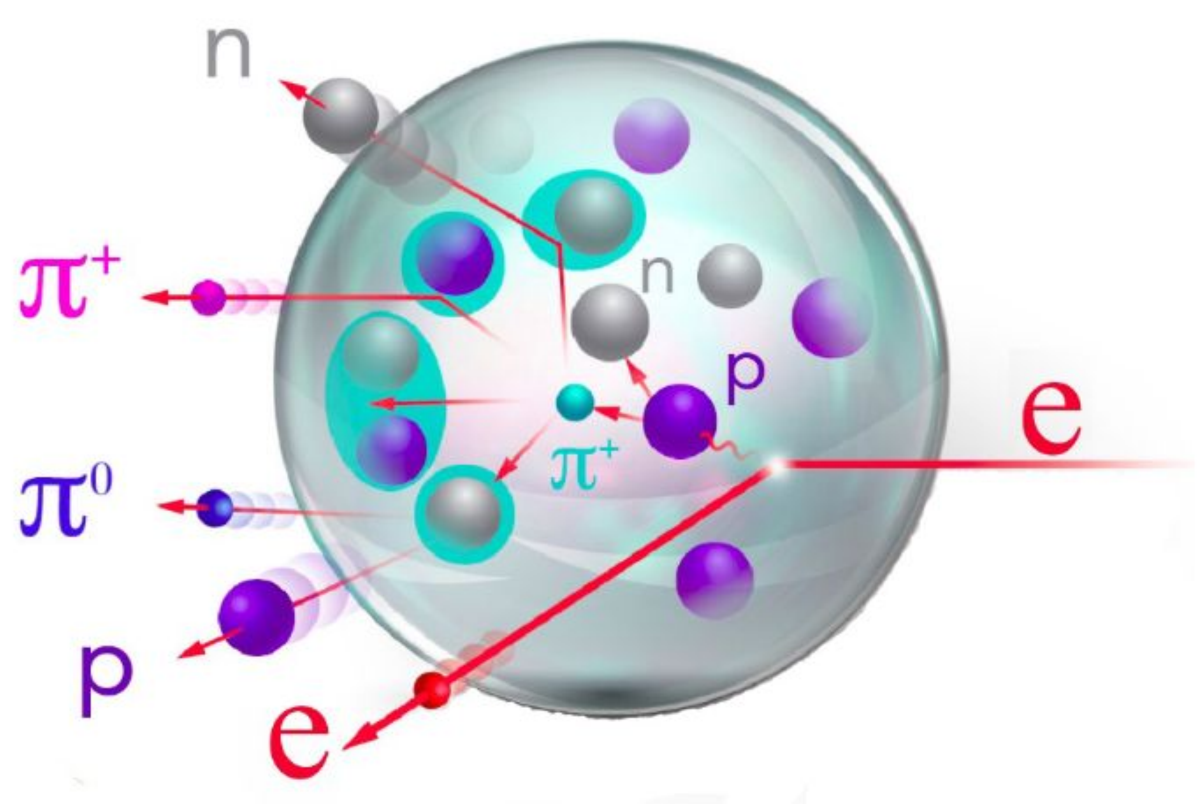
- Electron data are an incredibly valuable resource for constraining generator predictions

- Consistent e/ν physics implementations allow the data to be used most effectively

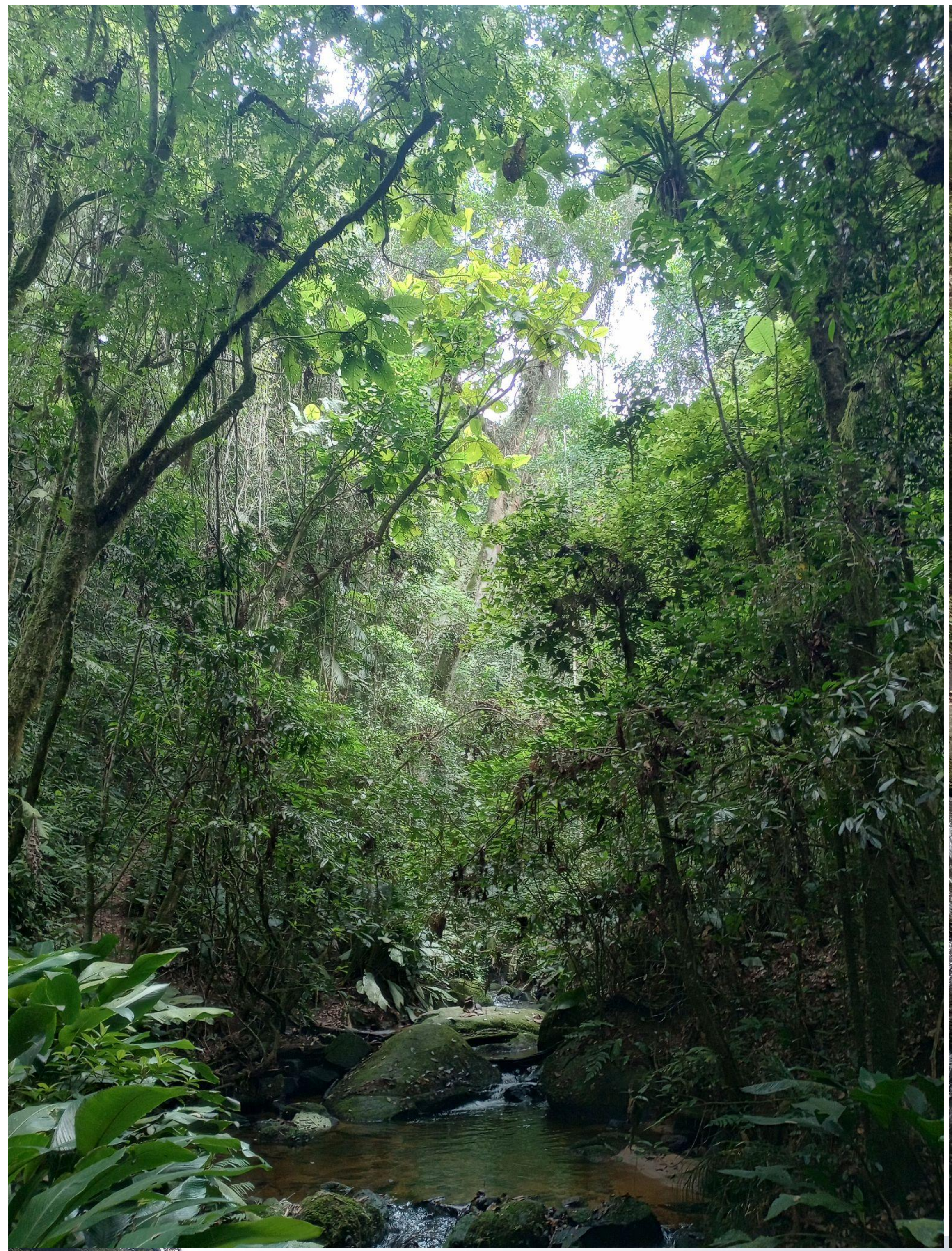
  - The community is making progress on the necessary technical work

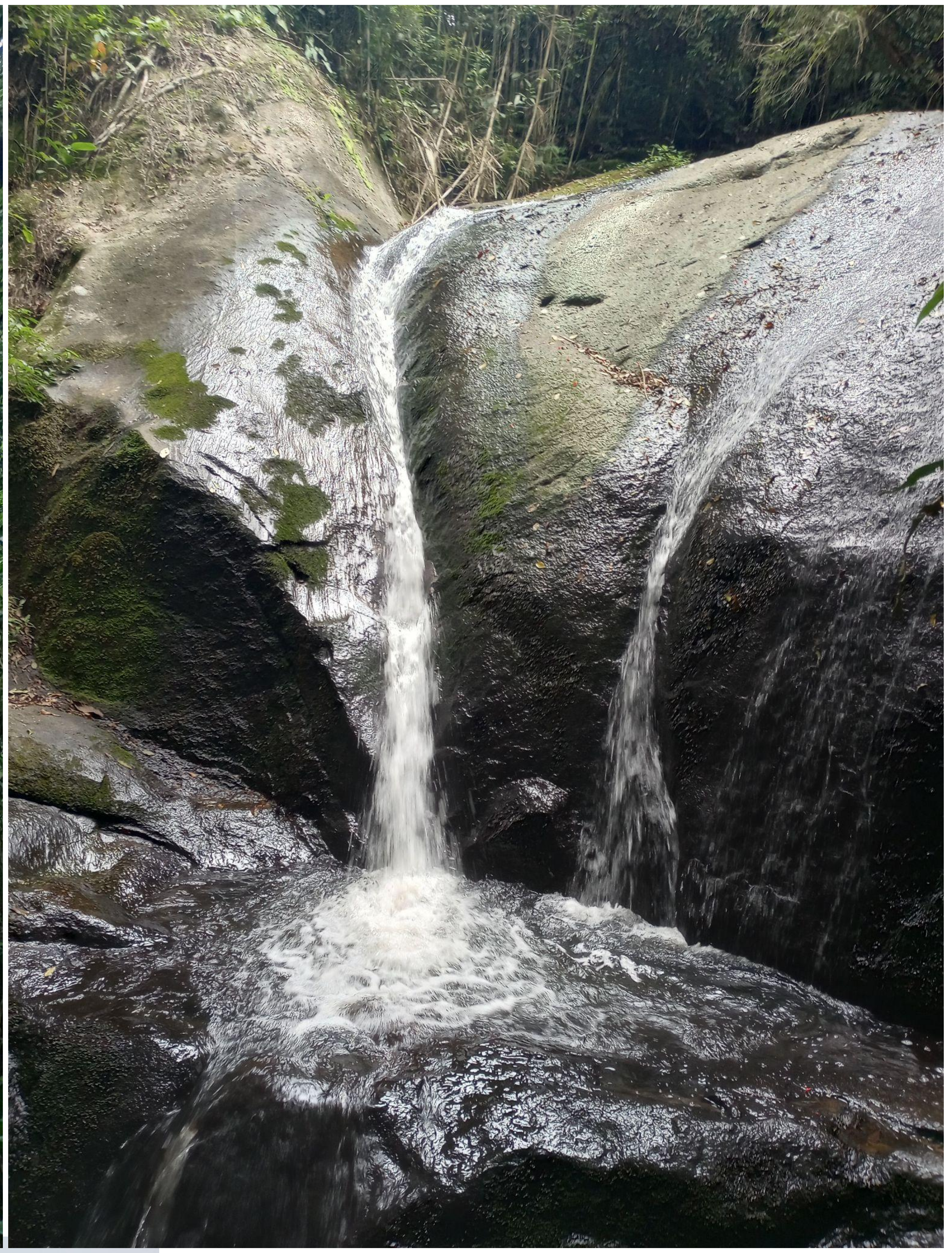
- Relevance extends to GeV and MeV energies
  - Includes previously neglected processes like nuclear de-excitations

- Watch this space for exciting new work as we pursue our precision goals



Thank you Instituto Principia & São Paulo!





Cantareira State Park

Pelé Museum

Coffee Museum

View from Monte Serrat

Backup

- A local favorite event generator
  (the açaí is good too)

- Note the "no smoking" sign!