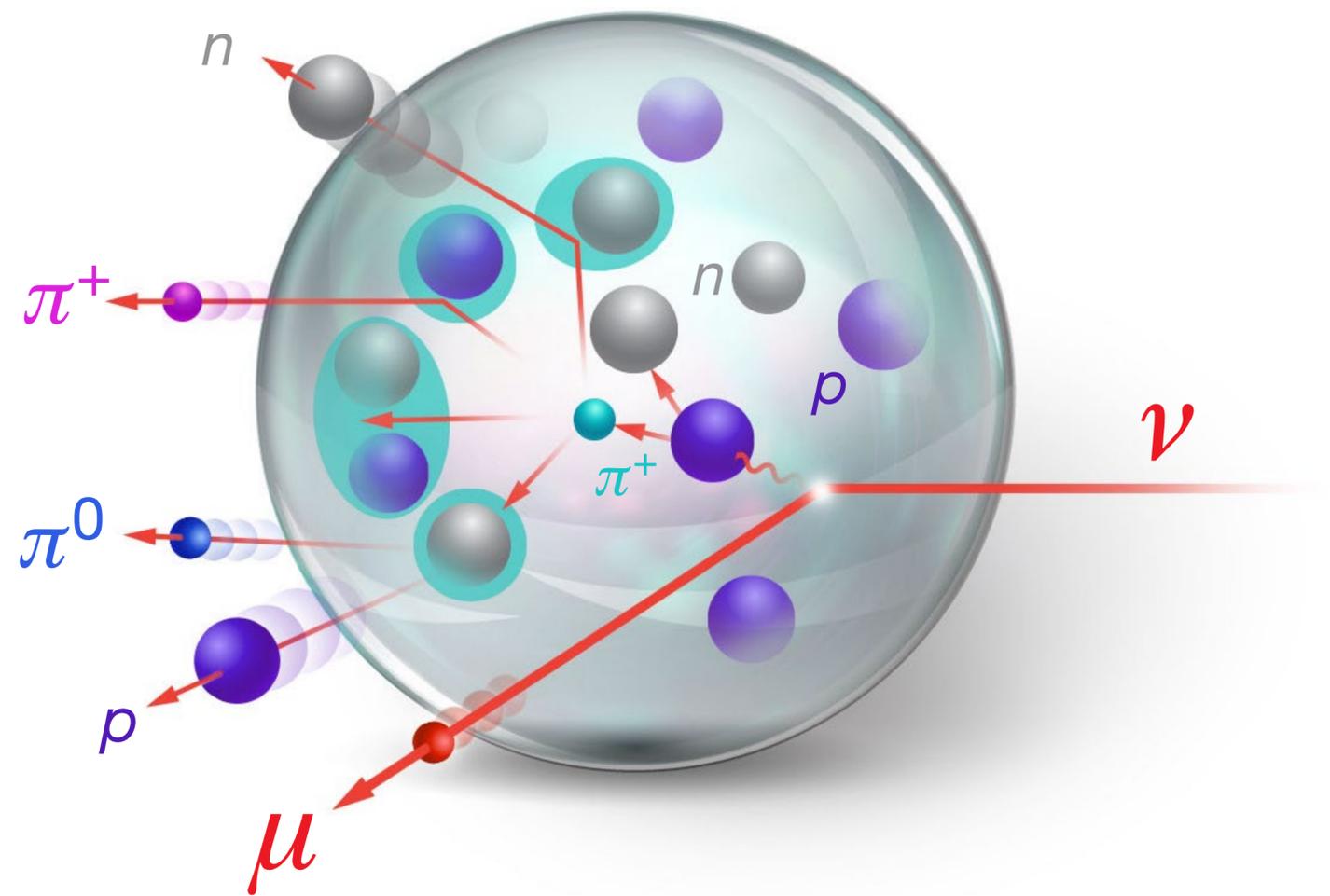


# Recent developments in the GENIE neutrino event generator

Steven Gardiner on behalf of the GENIE collaboration



4 August 2022

23rd International Workshop on Neutrinos from Accelerators

# GENIE Collaboration

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Hugh Gallagher,<sup>12</sup> Alfonso Andres Garcia Soto,<sup>3,4</sup> Steven Gardiner,<sup>2</sup> Matan Goldenberg,<sup>11</sup>  
Robert Hatcher,<sup>2</sup> Or Hen,<sup>8</sup> Timothy Hobbs,<sup>2</sup> Igor Kakorin,<sup>6</sup> Konstantin Kuzmin,<sup>5,6</sup>  
Anselmo Meregaglia,<sup>1</sup> Vadim Naumov,<sup>6</sup> Afroditi Papadopoulou,<sup>8</sup> Gabriel Perdue,<sup>2</sup> Marco Roda,<sup>7</sup>  
Beth Slater,<sup>7</sup> Alon Sportes,<sup>11</sup> Noah Steinberg,<sup>2</sup> Vladyslav Syrotenko,<sup>12</sup>  
Júlia Tena Vidal,<sup>7</sup> Jeremy Wolcott,<sup>12</sup>

(1) CENBG, Université de Bordeaux (2) Fermilab (3) Harvard University (4) Instituto de Física Corpuscular  
(5) Alikhanov Institute for Theoretical and Experimental Physics (6) Joint Institute for Nuclear Research  
(7) University of Liverpool (8) Massachusetts Institute of Technology (9) University of Pittsburgh  
(10) STFC Rutherford Appleton Laboratory (11) Tel Aviv University (12) Tufts University

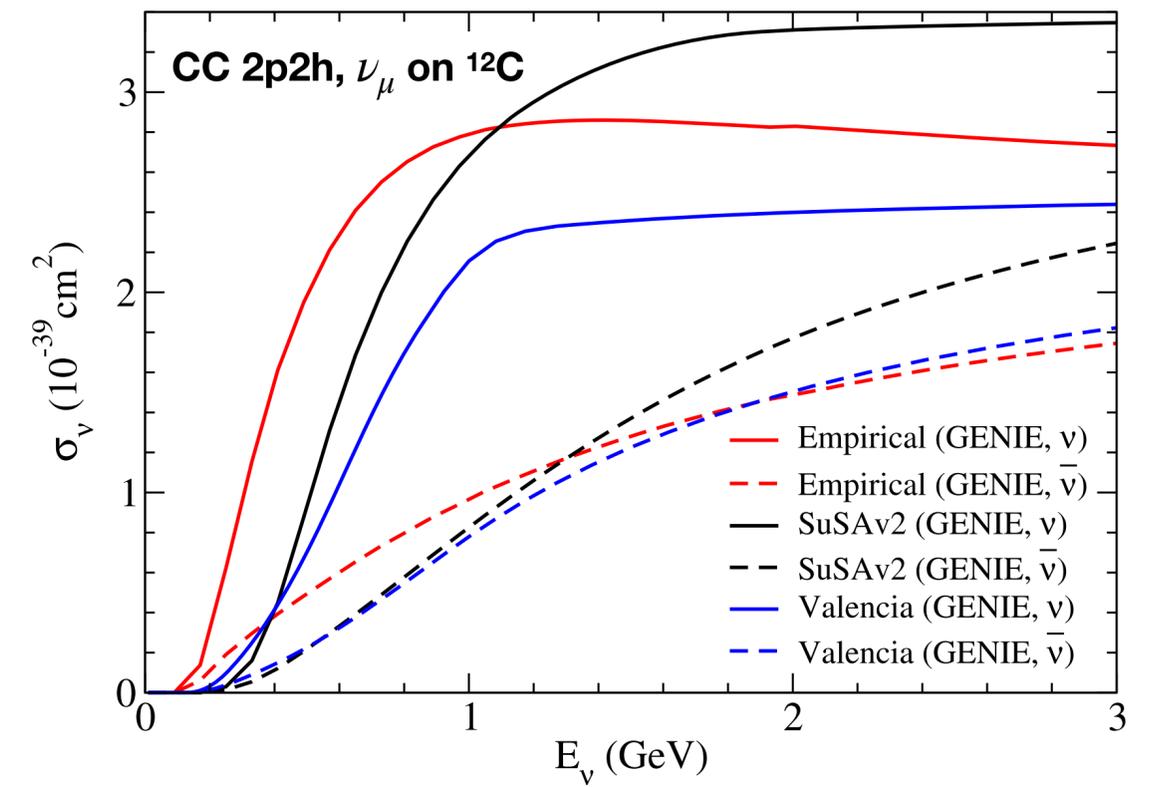
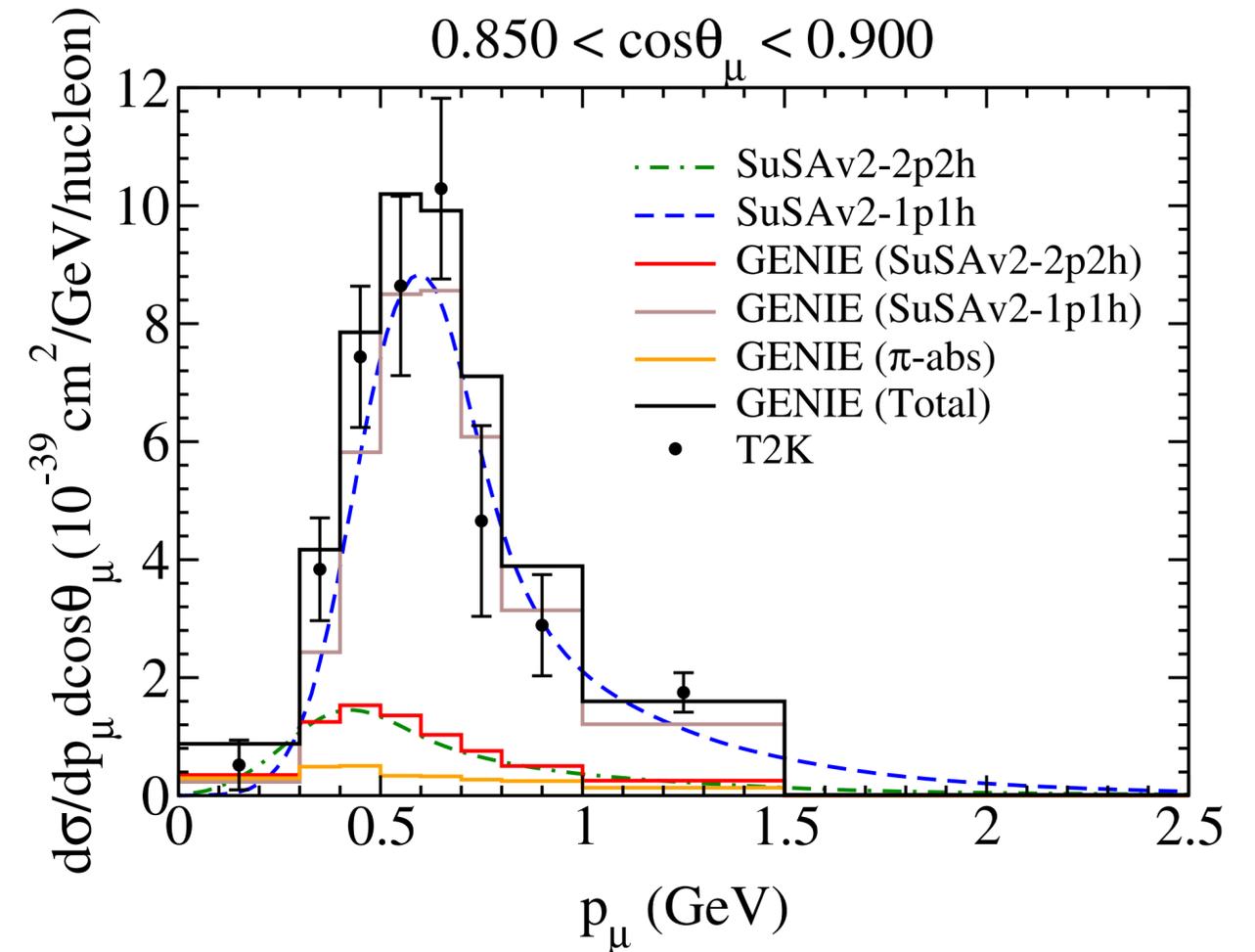
- **Mission:** “provide a state-of-the-art neutrino MC generator for the world experimental neutrino community”
- Highlights from the current release (v3.2.0) and ongoing developments
  - New theoretical model implementations
  - Technical infrastructure
  - Tuning to neutrino data



# SuSAv2: CC neutrino scattering

- Provides 1p1h and 2p2h predictions based on the SuperScaling approach
  - See, e.g., [Phys. Rev. D 94, 093004 \(2016\)](#)
- Recent paper presents **comparisons** to T2K data, alternate models
  - Limitations of the factorization strategy also discussed
- External contributors: Stephen Dolan, Guillermo Megias, and Sara Bolognesi

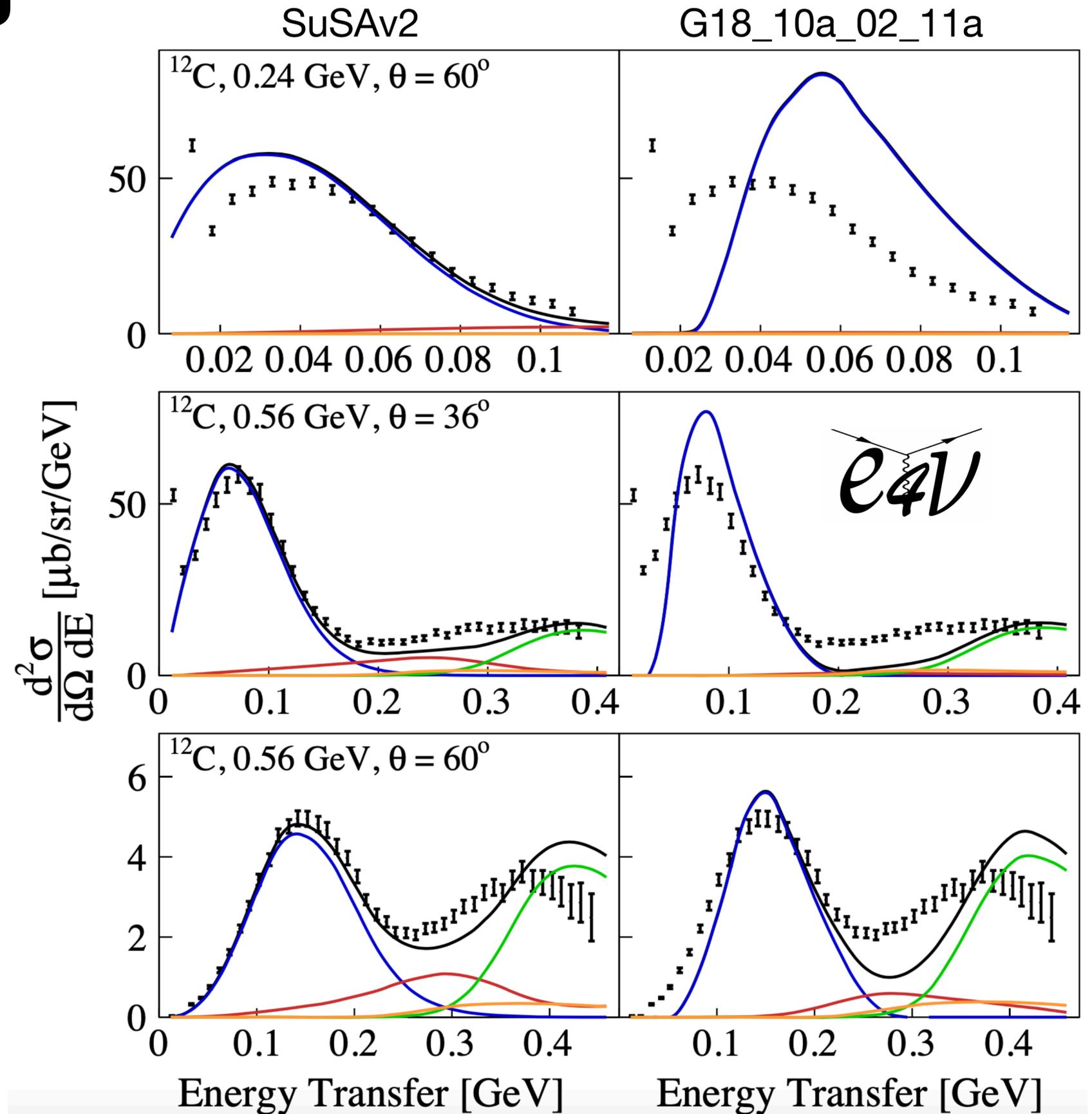
[Phys. Rev. D 101, 033003 \(2020\)](#)



# SuSAv2: electron scattering

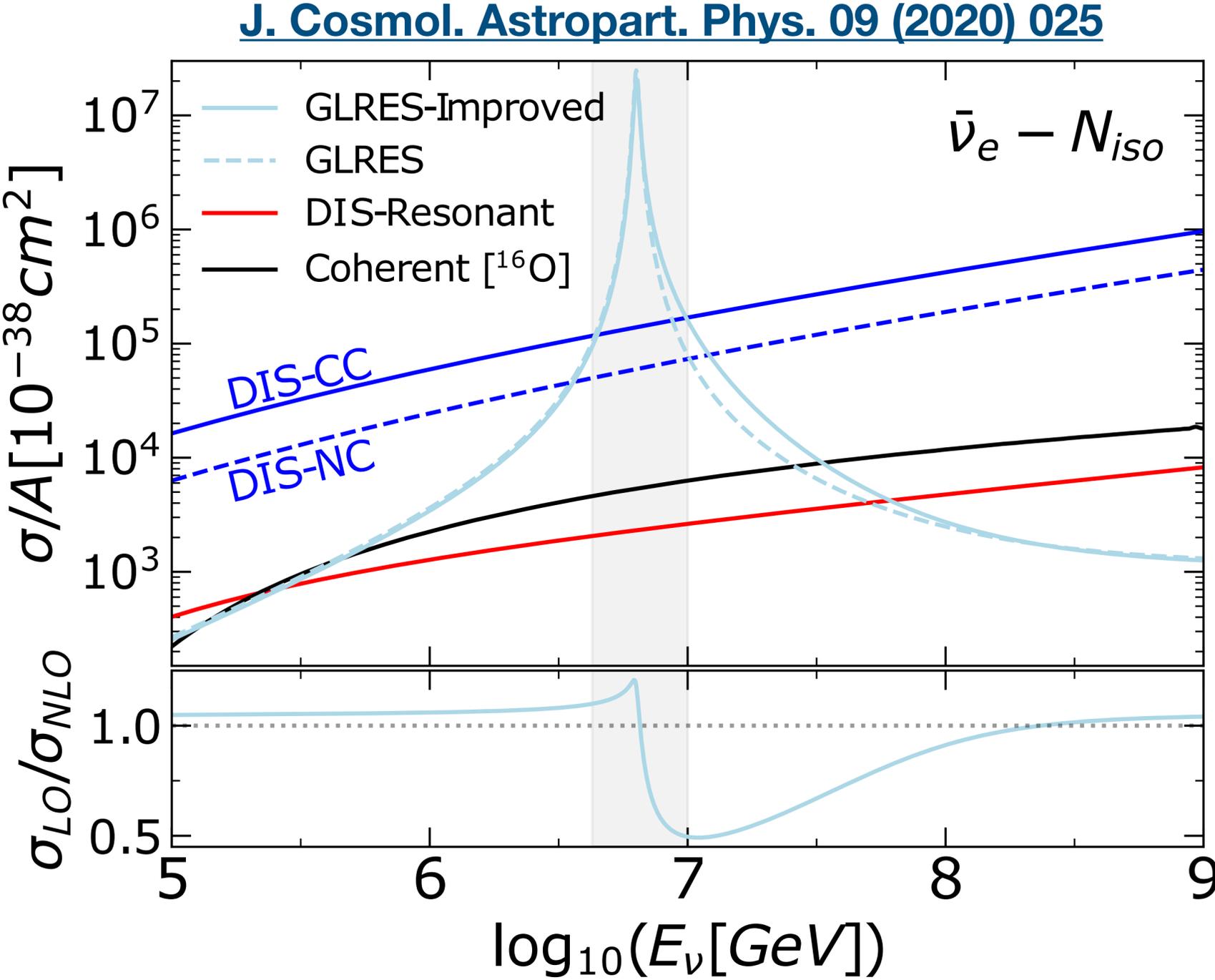
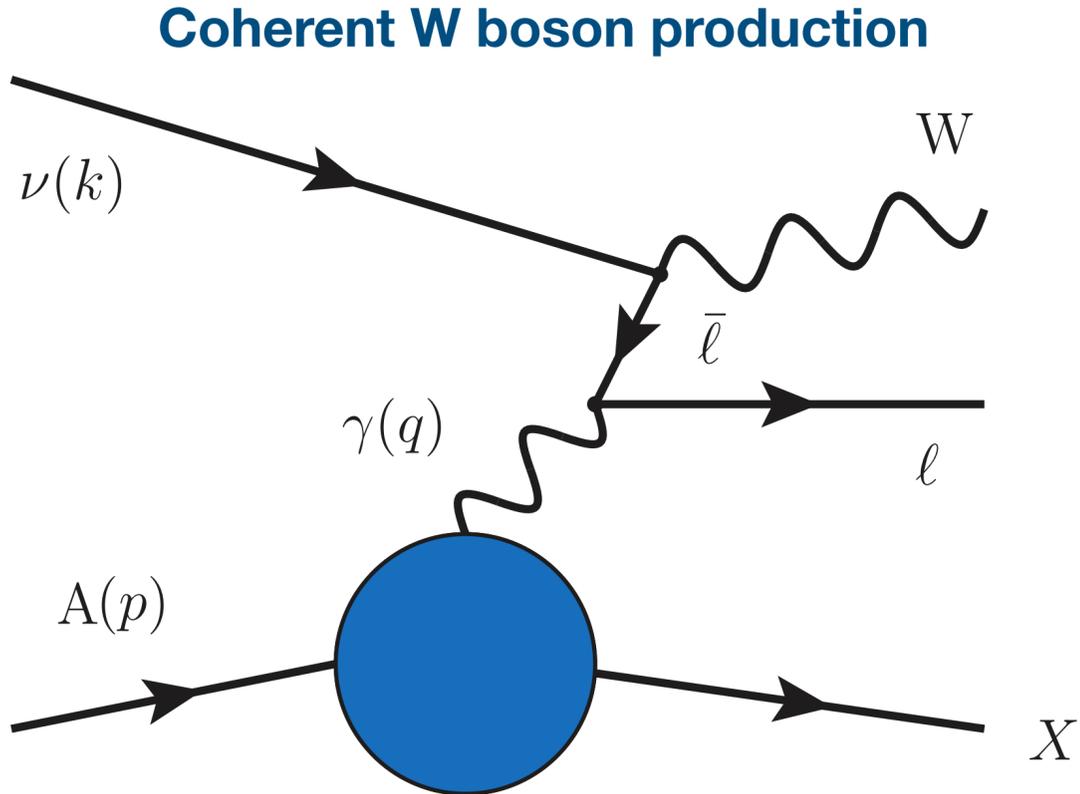
- Consistent with neutrino version
- **Benchmarked** against inclusive ( $e, e'$ ) by members of the e4v collaboration
- GENIE SuSAv2 **1p1h** and **2p2h** achieves improved agreement over the existing G18\_10a\_02\_11a model set
- See Tuesday talk by Afroditi Papadopoulou for more e4v results

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



# HEDIS module: energies up to $10^9$ GeV

- State-of-the-art NLO cross sections and event generation for all important processes
- In support of very high-energy neutrino telescopes like KM3NeT and IceCube

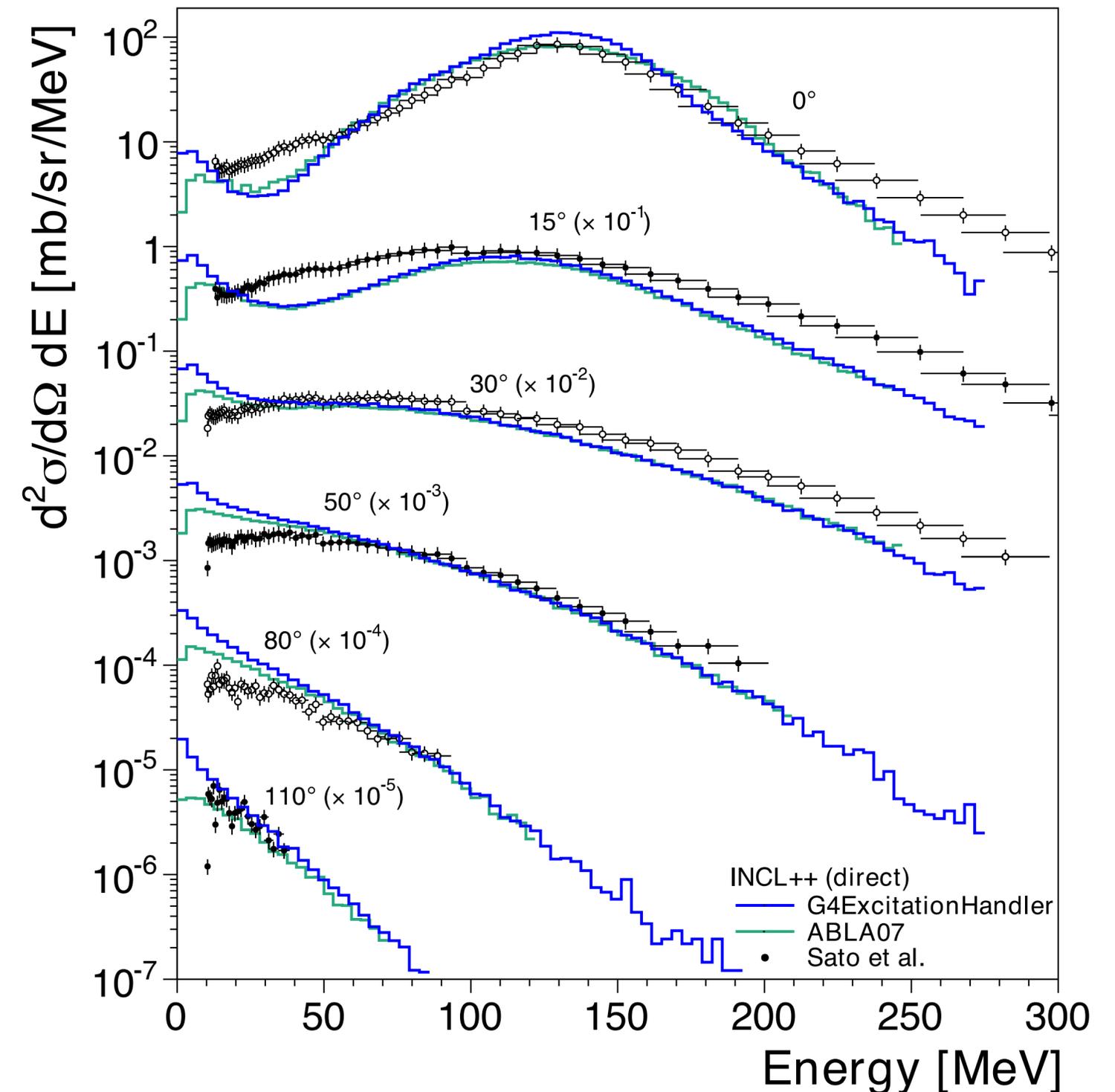


First observation of a Glashow resonance (GLRES) candidate event by IceCube: [Nature 591, 220–224 \(2021\)](#)

# New FSI models: INCL++ and Geant4 Bertini cascade

- Widely used in simulations of hadron scattering
- Low-energy effects handled via delegation to one of several de-excitation codes
  - G4ExcitationHandler, ABLA07
- **Neutron production in  $^{12}\text{C} + ^{12}\text{C}$  @ 135 MeV/nucleon**

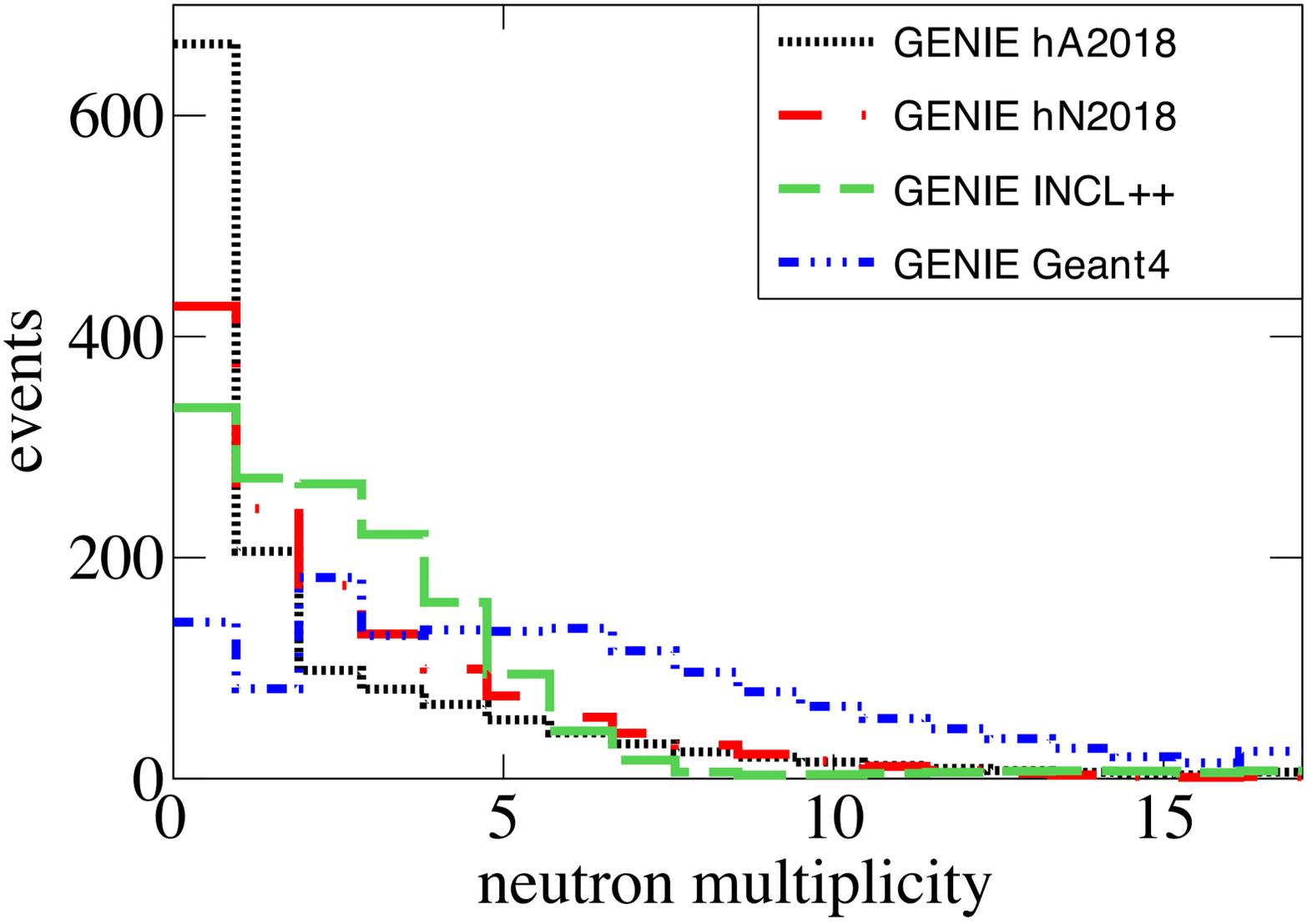
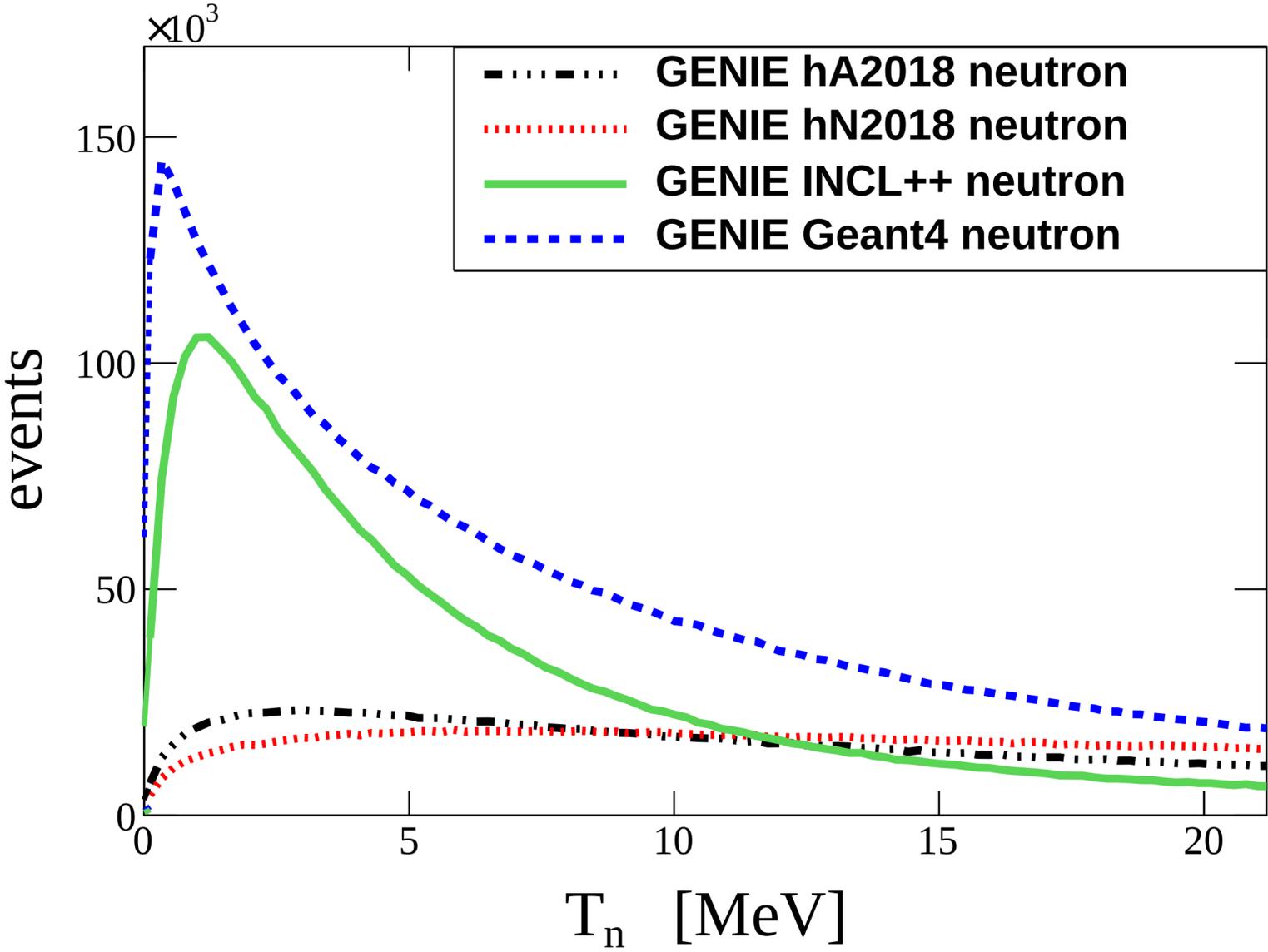
[J. Phys.: Conf. Ser. 420 012065 \(2013\)](#)



# New FSI models: INCL++ and Geant4 Bertini cascade

- Enhanced low-energy neutron emission (evaporation, etc.)
  - Striking differences in multiplicity distributions
- Further experimental investigation warranted!

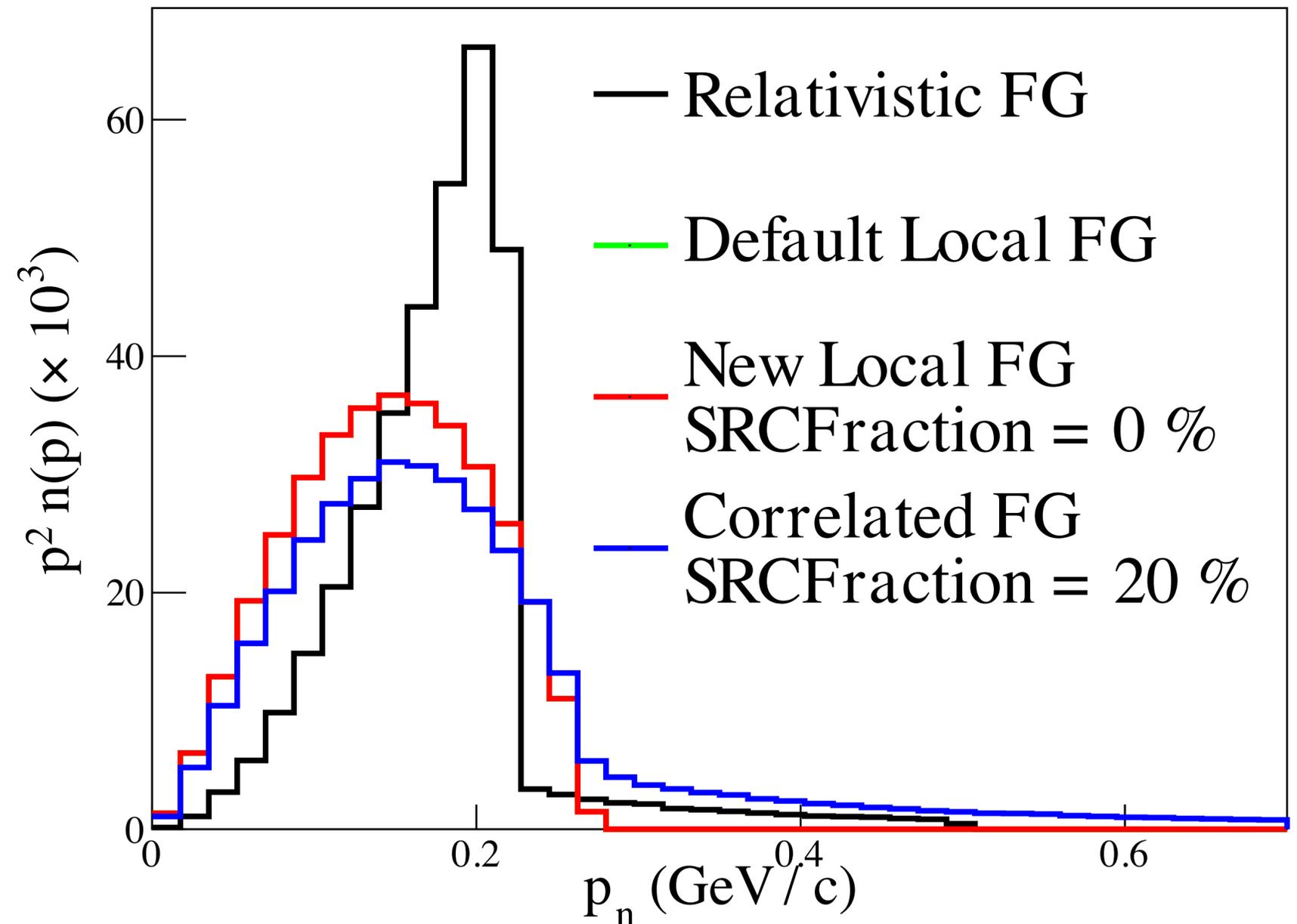
[Eur. Phys. J. Spec. Top. \(2021\)](#)



# Other new physics developments in GENIE v3.2.0

- **Correlated Fermi gas** nuclear model
- PYTHIA 8 hadronization
- Coherent elastic neutrino-nucleus scattering (CEvNS) following [Phys. Rev. C 86, 024612 \(2012\)](#)
- Boosted Dark Matter interactions by Joshua Berger: [arXiv:1812.05616](#)
- Dark neutrino BSM model: [Phys. Rev. Lett. 121, 241801 \(2018\)](#)

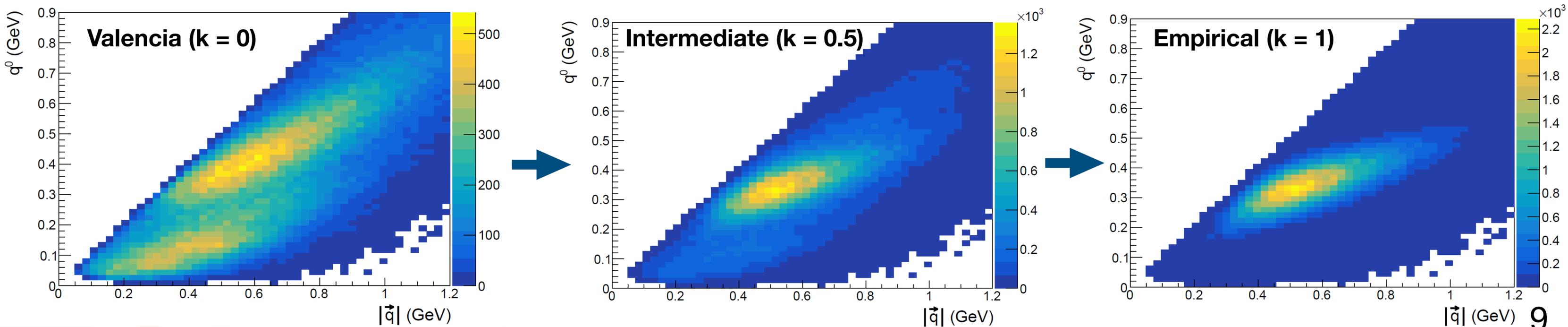
Full list of new features available at <http://releases.genie-mc.org/>



# Reweighting tools from MicroBooNE

- “MicroBooNE tune”: reweighting of CC QE+2p2h to fit T2K CC0 $\pi$  data
  - Details described in [Phys. Rev. D 105, 072001 \(2022\)](#)
  - Contribution of new calculators in GENIE Reweight
- **Now available** to the entire community as part of GENIE v3.2.0

Joint ( $q^0$ ,  $|\vec{q}|$ ) distributions across the parameter space for shape variable  $k$  (BNB  $\nu_\mu$  CC 2p2h on argon)



# GENIE's interaction model tuning program

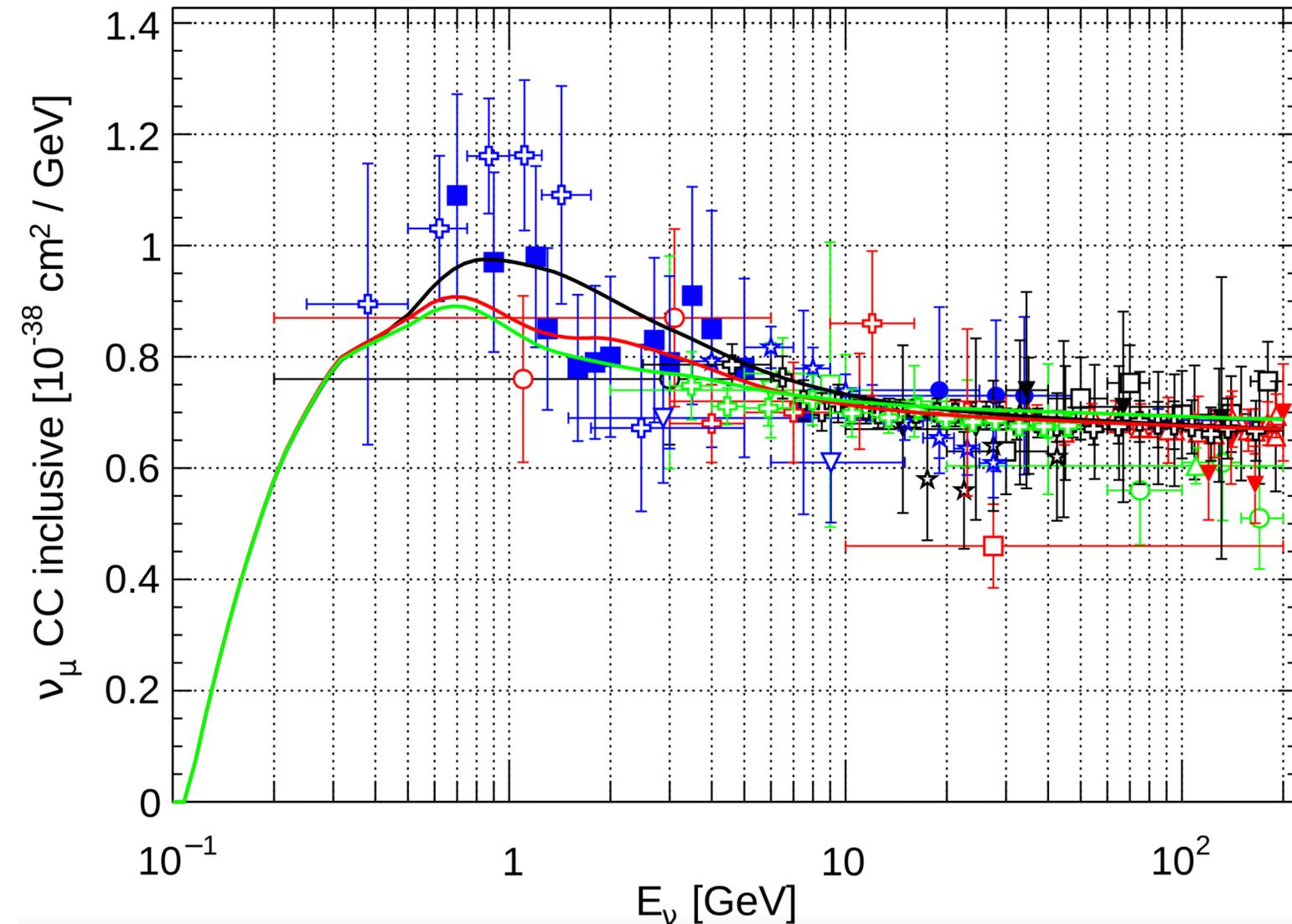
- Developing global analysis of scattering data
  - Model fitting and uncertainty quantification
- **Professor**: tuning software tool from LHC community
  - Efficiently perform brute-force scans of parameter space
  - Applied to neutrinos for the first time by GENIE
- Used together with **GENIE Comparisons**
  - Curated cross-section database



<https://professor.hepforge.org/>

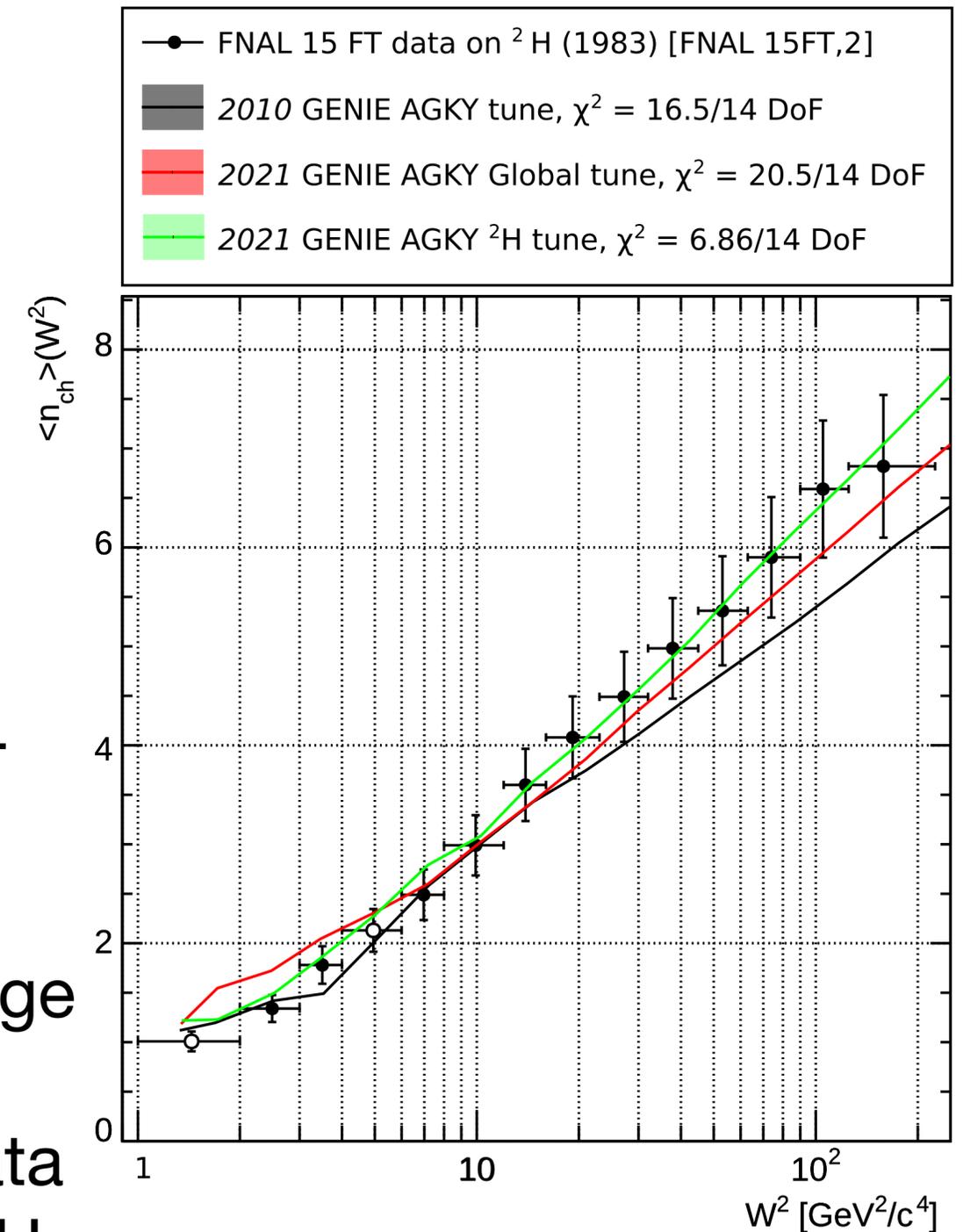
# Recent GENIE tuning papers: bubble chamber data

[Phys. Rev. D 104, 072009 \(2021\)](#)



Global fit to CC inclusive,  
 $1\pi$ , and  $2\pi$  data sets

[Phys. Rev. D 105, 012009 \(2022\)](#)



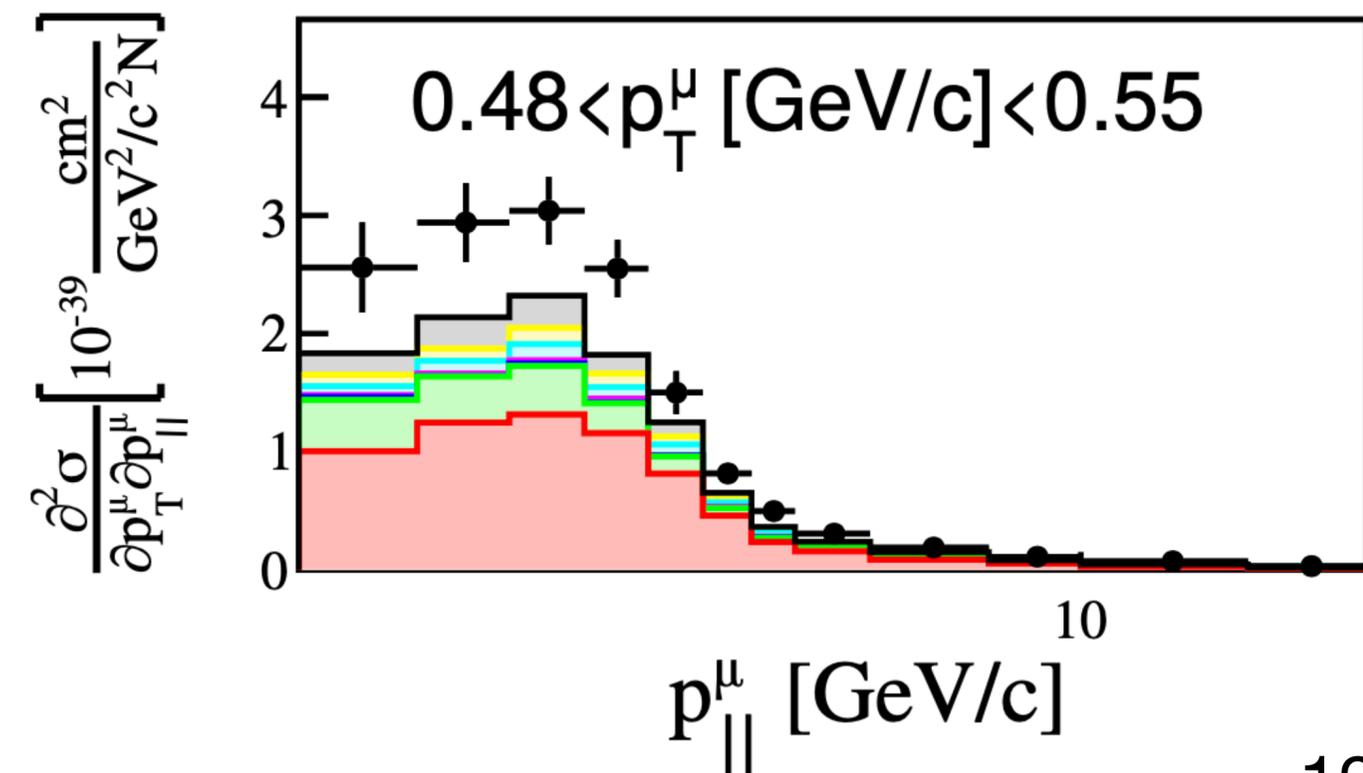
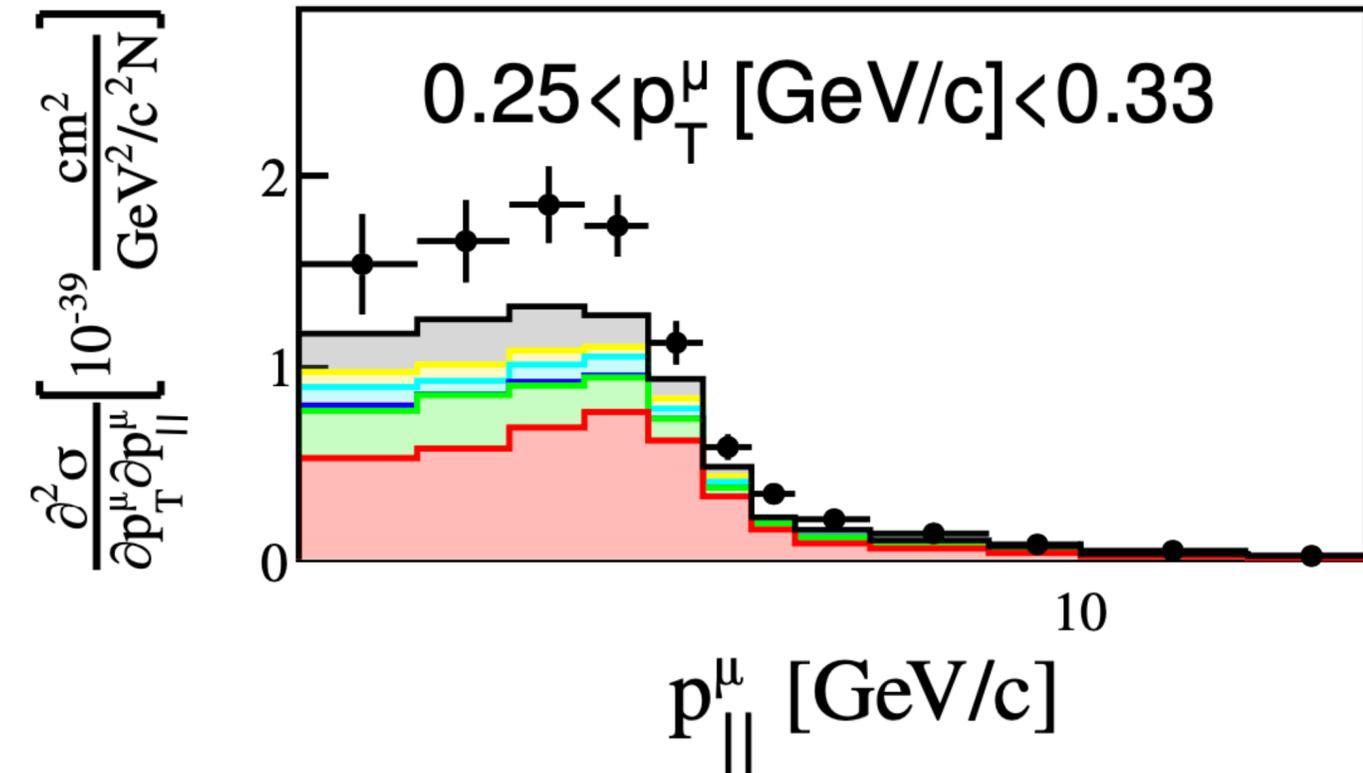
First neutrino-induced  
hadronization  
tune on average  
charged  
multiplicity data  
from  $^2\text{H}$  and  $^1\text{H}$

$$\nu_\mu + n \rightarrow \mu^- X^+$$

# Neutrino-nucleus tune: $\nu_\mu$ CC0 $\pi$ on carbon

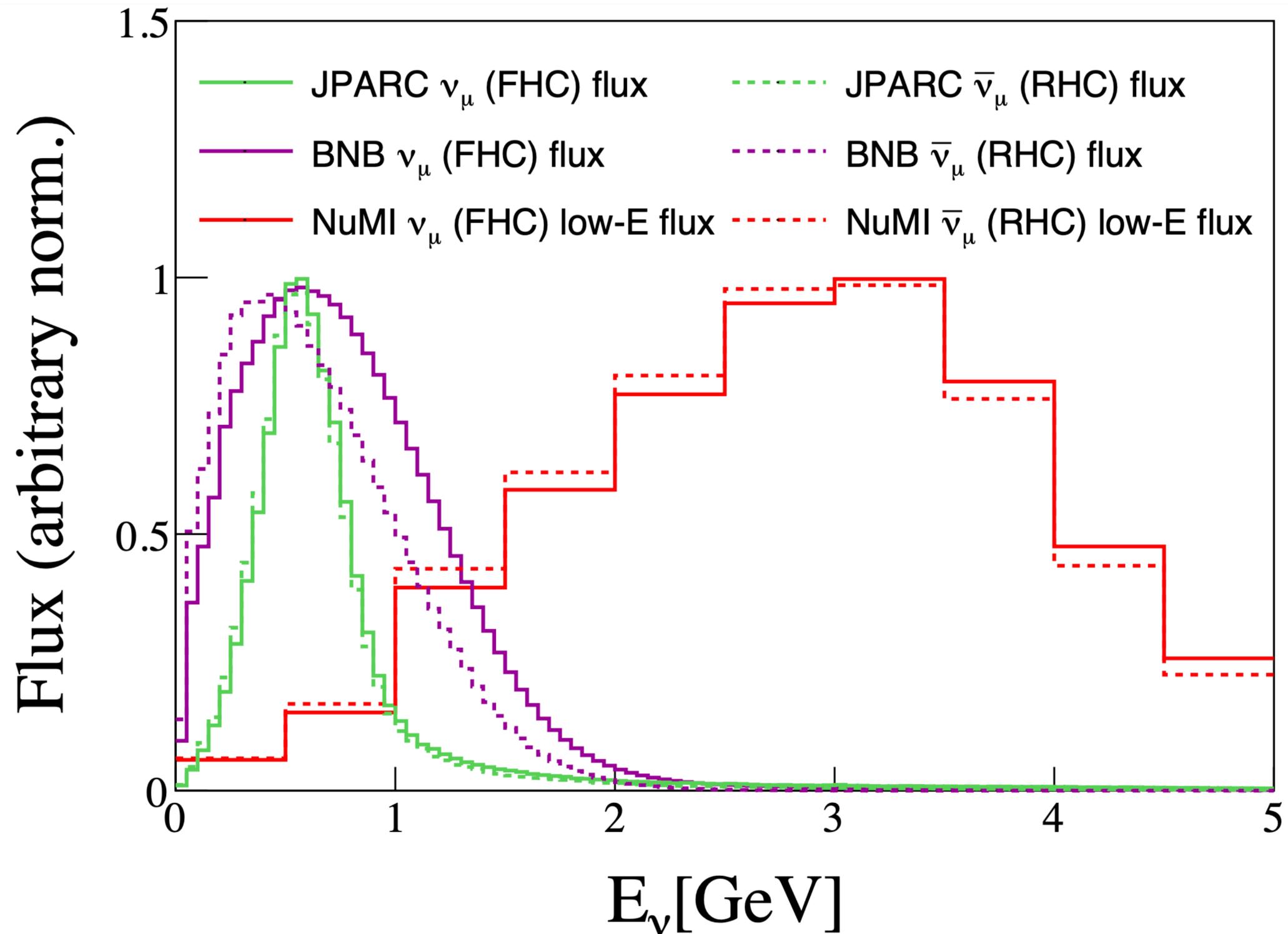
[arXiv:2206.11050](https://arxiv.org/abs/2206.11050)

- Mixture of QE, 2p2h, and inelastic + pion absorption
  - Extra complexity due to nuclear effects
  - Free nucleon results used to define priors
- Strategy: partial tunes to individual experiments, examine tensions
- **Base model:** G18\_10a\_02\_11b
  - Result of free nucleon tune
  - Similar to MicroBooNE, NOvA base models



# Data sets used for tuning

- All hydrocarbon targets
- Distinct fluxes probe  $E_\nu$  dependence
- 6 partial tunes obtained
- Identical base model
  - QE+2p2h = Valencia
  - RES = Berger-Sehgal
  - FSI = GENIE hA2018



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Experiment	Projectile	CC Topology
MiniBooNE	$\nu_\mu$	$0\pi$
	$\bar{\nu}_\mu$	
T2K ND280	$\nu_\mu$	$0p0\pi$
MINERvA	$\nu_\mu$	$0\pi$
		$Np0\pi$
	$\bar{\nu}_\mu$	$0p0\pi$

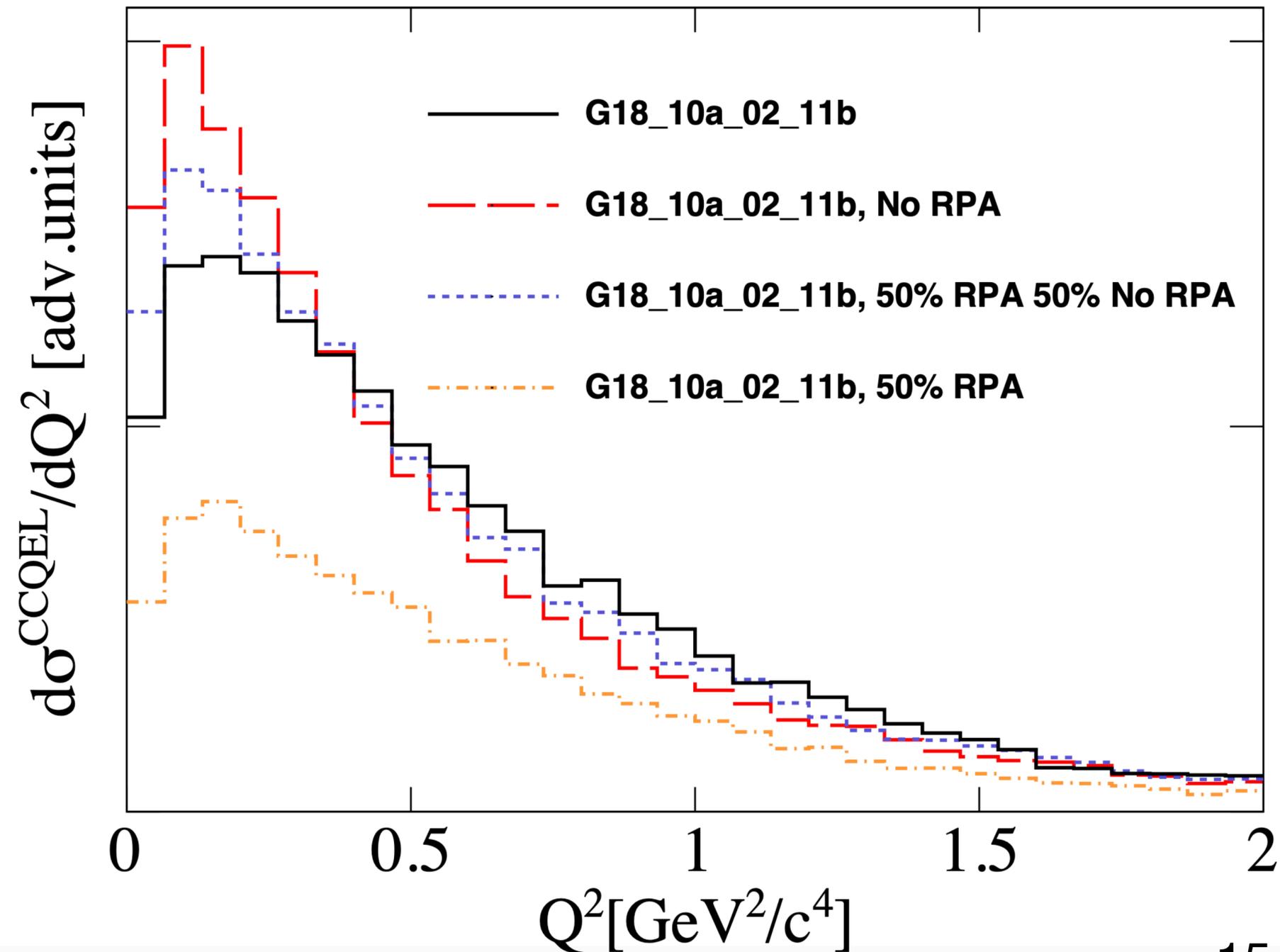
# Tuned parameters (1)

- Nucleon axial mass ( $M_A^{\text{QEL}}$ ) and RES normalization factor ( $S_{\text{RES}}$ )
  - Priors from bubble chamber tune

- Two additional QE parameters:

$$\sigma^{\text{QEL}} = \omega_{\text{RPA}} \cdot \sigma_{\text{RPA}}^{\text{QEL}} + \omega_{\text{no RPA}} \cdot \sigma_{\text{no RPA}}^{\text{QEL}}$$

- Mix on/off RPA models via separate scaling factors  $\omega_{\text{RPA}}$ ,  $\omega_{\text{no RPA}}$



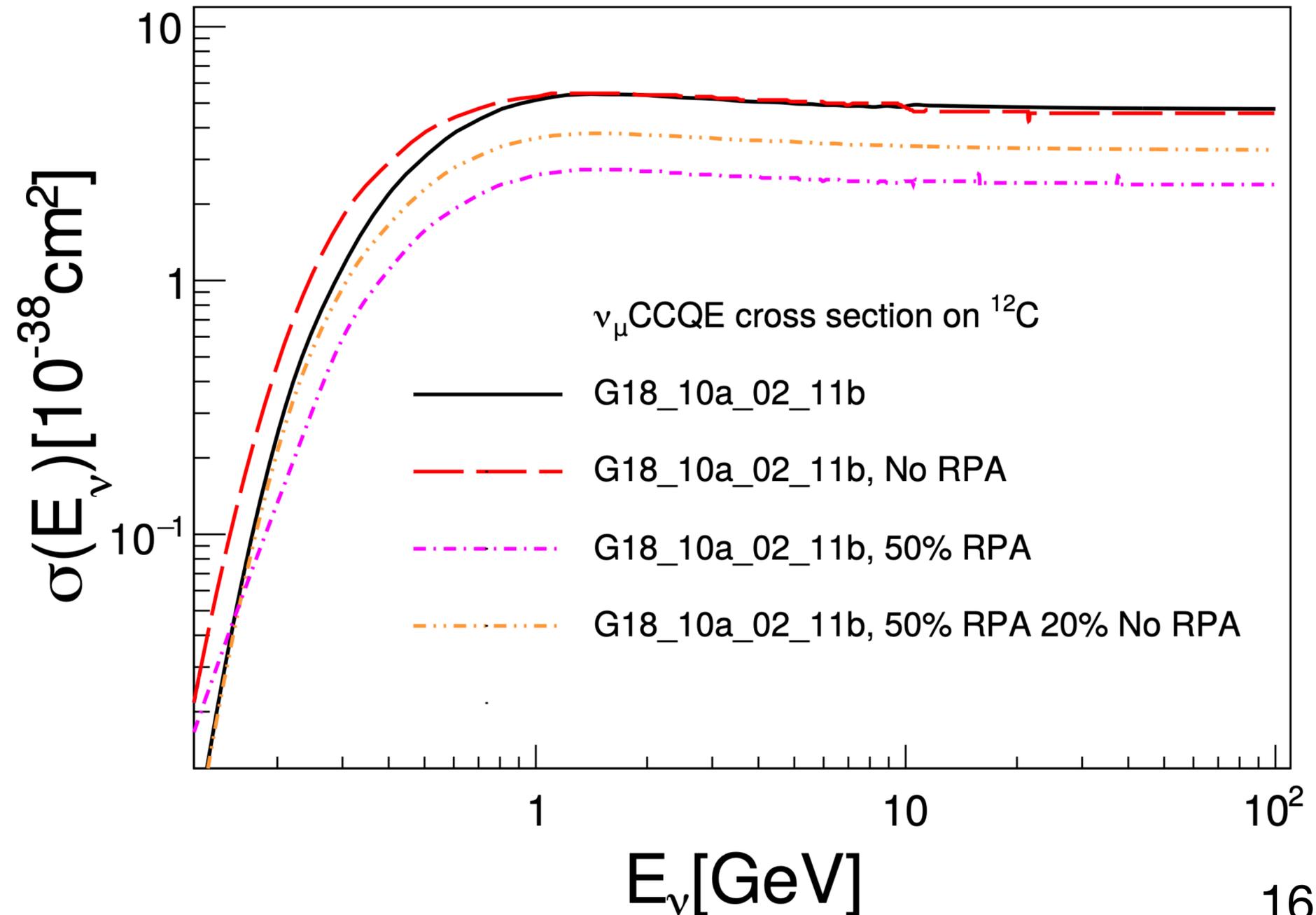
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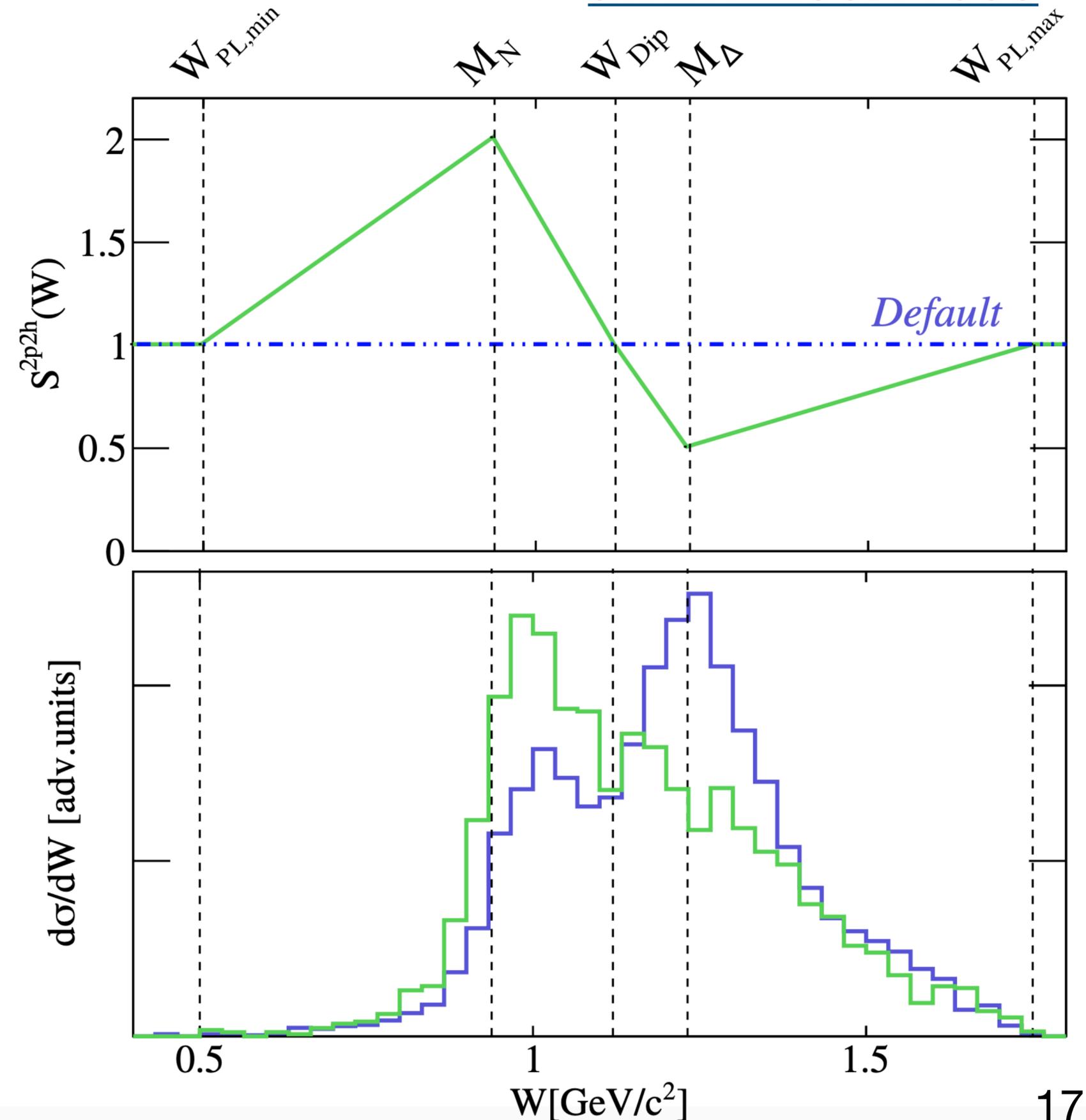
$$\sigma^{\text{QEL}} = \omega_{\text{RPA}} \cdot \sigma_{\text{RPA}}^{\text{QEL}} + \omega_{\text{no RPA}} \cdot \sigma_{\text{no RPA}}^{\text{QEL}}$$

- Mix on/off RPA models via separate scaling factors  $\omega$



# Tuned parameters (2)

- Valencia 2p2h includes two peaks in  $W$  at  $M_N$  and  $M_\Delta$
- 3 tuned scaling factors
  - $S_{PL}^{2p2h}$ : both end points
  - $S_N^{2p2h}$ :  $M_N$  peak
  - $S_\Delta^{2p2h}$ :  $M_\Delta$  peak
- Linear interpolation between  $W$  regions



# Similarities in all of the partial tunes

- Respect free nucleon priors on  $M_A^{\text{QEL}}$  and  $S_{\text{RES}}$

G10a: MiniBooNE  $\nu_\mu$  CC0 $\pi$

G30a: MINERvA  $\nu_\mu$  CC0 $\pi$

G11a: MiniBooNE  $\bar{\nu}_\mu$  CC0 $\pi$

G31a: MINERvA  $\bar{\nu}_\mu$  CC0 $p0\pi$

G20a: T2K ND280  $\nu_\mu$  CC0 $p0\pi$

G35a: MINERvA  $\nu_\mu$  CCN $p0\pi$

- Raise the QE and 2p2h cross sections

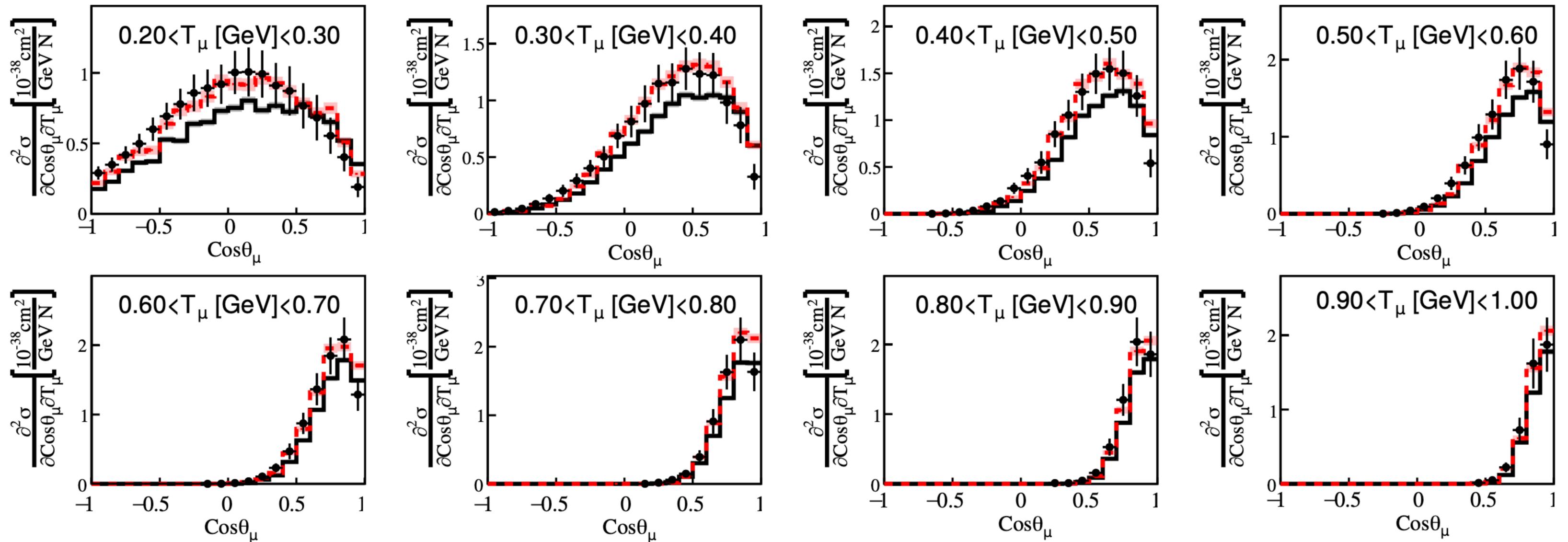
- Prefer RPA corrections

Parameters	G10a Tune	G11a Tune	G20a Tune	G30a Tune	G31a Tune	G35a Tune
$M_A^{\text{QEL}}$ (GeV/ $c^2$ )	$1.02 \pm 0.01$	$1.01 \pm 0.01$	$1.00 \pm 0.01$	$1.00 \pm 0.02$	$1.00 \pm 0.01$	$0.99 \pm 0.01$
$\omega_{\text{RPA}}$	$1.20 \pm 0.03$	$1.14 \pm 0.06$	$1.2 \pm 0.2$	$0.9 \pm 0.1$	$1.3 \pm 0.2$	$0.75 \pm 0.3$
$\omega_{\text{No RPA}}$	$0.05 \pm 0.02$	$0.09 \pm 0.05$	$-0.1 \pm 0.1$	$0.2 \pm 0.1$	$0.2 \pm 0.2$	$0.09 \pm 0.3$
$S_{\text{RES}}$	$0.85 \pm 0.02$	$0.86 \pm 0.05$	$0.84 \pm 0.02$	$0.84 \pm 0.03$	$0.84 \pm 0.02$	$0.84 \pm 0.02$
$S_N^{2p2h}$	$1.5 \pm 0.4$	$2.3 \pm 0.01$	$1.7 \pm 0.3$	$1.2 \pm 0.4$	$1.7 \pm 0.5$	$0.33 \pm 0.2$
$S_\Delta^{2p2h}$	$0.7 \pm 0.2$	$0.7 \pm 0.3$	(1.00)	$2.1 \pm 0.2$	$2.3 \pm 0.2$	$0.5 \pm 0.4$
$S_{PL}^{2p2h}$	$0.4 \pm 0.1$	$0.4 \pm 0.1$	(1.00)	$0.9 \pm 0.2$	$0.4 \pm 0.1$	$1.5 \pm 0.4$
$\chi^2$	89/130	77/71	60/55	61/137	67/53	17/19

# Tune results for MiniBooNE data

- MiniBooNE  $\nu_\mu$ CC0 $\pi$  data
- G18\_10a\_02\_11b tune
- - - G10a Tune

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



# Tensions: 2p2h cross section shape

- MiniBooNE + T2K**

- Enhance at  $W = M_N$
- Suppress at  $W = M_\Delta$

G10a: MiniBooNE  $\nu_\mu$  CC0 $\pi$

G30a: MINERvA  $\nu_\mu$  CC0 $\pi$

G11a: MiniBooNE  $\bar{\nu}_\mu$  CC0 $\pi$

G31a: MINERvA  $\bar{\nu}_\mu$  CC0p0 $\pi$

G20a: T2K ND280  $\nu_\mu$  CC0p0 $\pi$

G35a: MINERvA  $\nu_\mu$  CCNp0 $\pi$

Parameters	G10a Tune	G11a Tune	G20a Tune	G30a Tune	G31a Tune	G35a Tune
$M_A^{\text{QEL}}$ (GeV/c <sup>2</sup> )	1.02 ± 0.01	1.01 ± 0.01	1.00 ± 0.01	1.00 ± 0.02	1.00 ± 0.01	0.99 ± 0.01
$\omega_{\text{RPA}}$	1.20 ± 0.03	1.14 ± 0.06	1.2 ± 0.2	0.9 ± 0.1	1.3 ± 0.2	0.75 ± 0.3
$\omega_{\text{No RPA}}$	0.05 ± 0.02	0.09 ± 0.05	-0.1 ± 0.1	0.2 ± 0.1	0.2 ± 0.2	0.09 ± 0.3
$S_{\text{RES}}$	0.85 ± 0.02	0.86 ± 0.05	0.84 ± 0.02	0.84 ± 0.03	0.84 ± 0.02	0.84 ± 0.02
$S_N^{2p2h}$	1.5 ± 0.4	2.3 ± 0.01	1.7 ± 0.3	1.2 ± 0.4	1.7 ± 0.5	0.33 ± 0.2
$S_\Delta^{2p2h}$	0.7 ± 0.2	0.7 ± 0.3	(1.00)	2.1 ± 0.2	2.3 ± 0.2	0.5 ± 0.4
$S_{PL}^{2p2h}$	0.4 ± 0.1	0.4 ± 0.1	(1.00)	0.9 ± 0.2	0.4 ± 0.1	1.5 ± 0.4
$\chi^2$	89/130	77/71	60/55	61/137	67/53	17/19

- MINERvA**

- Enhance both peaks, especially  $W = M_\Delta$

- Clear energy dependence in the  $W$  shape

Other tensions between 0 $\pi$  and 0 $\pi$  + 0p/Np are observed across all experiments

# Summary

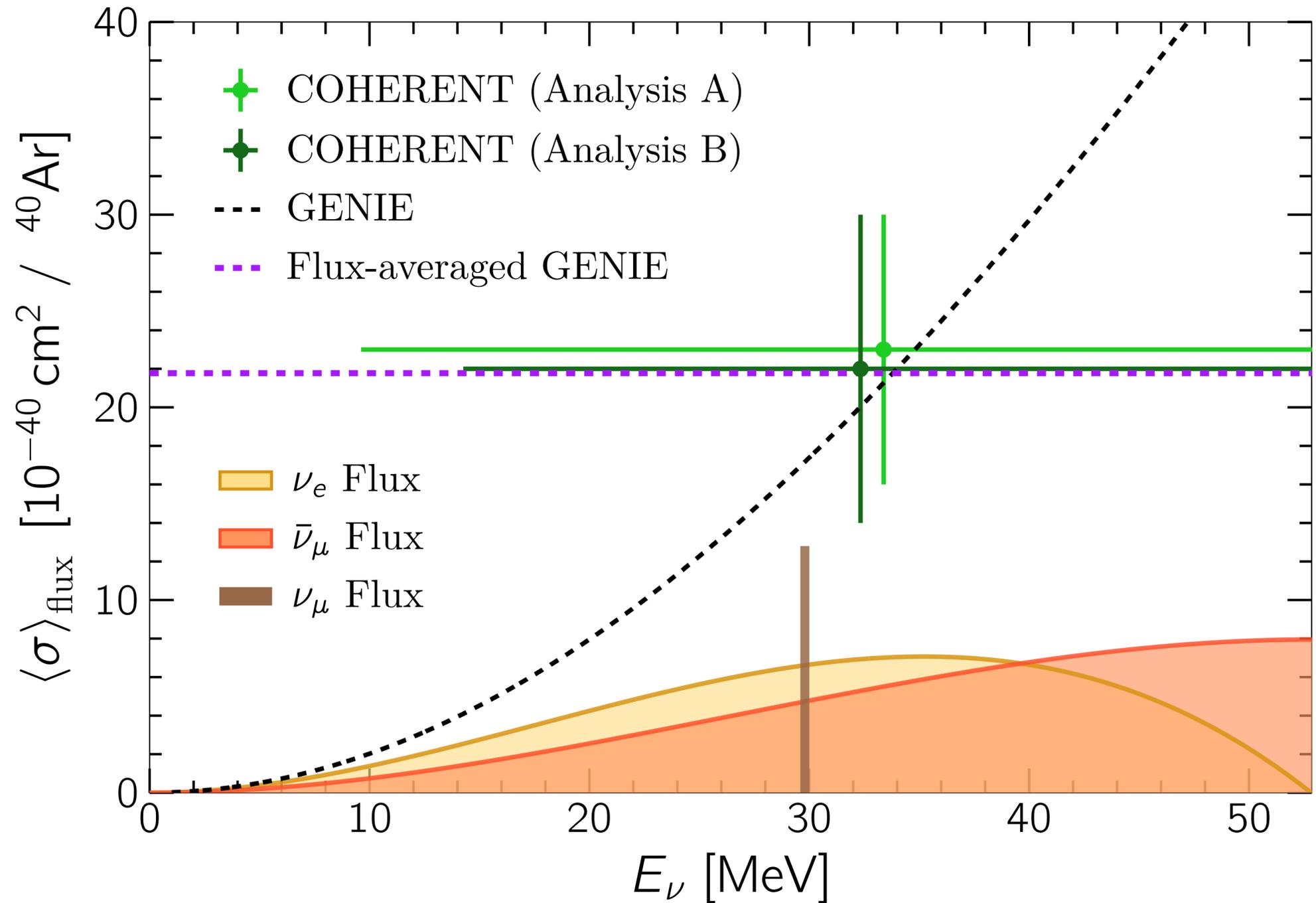
- A broad program of physics model enhancements is being pursued by GENIE and community contributors
- A first tune to  $CC0\pi$  data has been performed using the GENIE global analysis framework
- Many new features are available in the recent v3.2.0 release, with more coming soon!



# Backup

# Coherent elastic neutrino-nucleus scattering (CEvNS)

- Dominant interaction mode for O(10 MeV) neutrinos
- NC process which leaves the struck nucleus in its ground state
  - Detection via recoil
- GENIE implementation based on Patton *et al.*, [Phys. Rev. C 86, 024612 \(2012\)](#)



COHERENT data from [Phys. Rev. Lett. 126, 012002 \(2021\)](#)