New physics model developments in

Steven Gardiner
on behalf of the GENIE collaboration

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New Directions in Neutrino-Nucleus Scattering

GENIE Collaboration

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(1) CENBG Université de Bordeaux (2) JINR Dubna (3) Fermilab (4) Massachusetts Institute of Technology

(5) University of Liverpool (6) University of Pittsburgh (7) STFC Rutherford Appleton Laboratory (8) Tufts University

(9) University of Valencia

- Extensive recent development toward new physics capabilities
- Collaboration has benefitted from great engagement with external contributors
- This talk emphasizes new features in the upcoming v3.2 release

External contributors to featured physics models

SuSAv2: Stephen Dolan, Guillermo Megias, Sara Bolognesi

STA: Josh Barrow, Saori Pastore, Minerba Betancourt, Joe Carlson

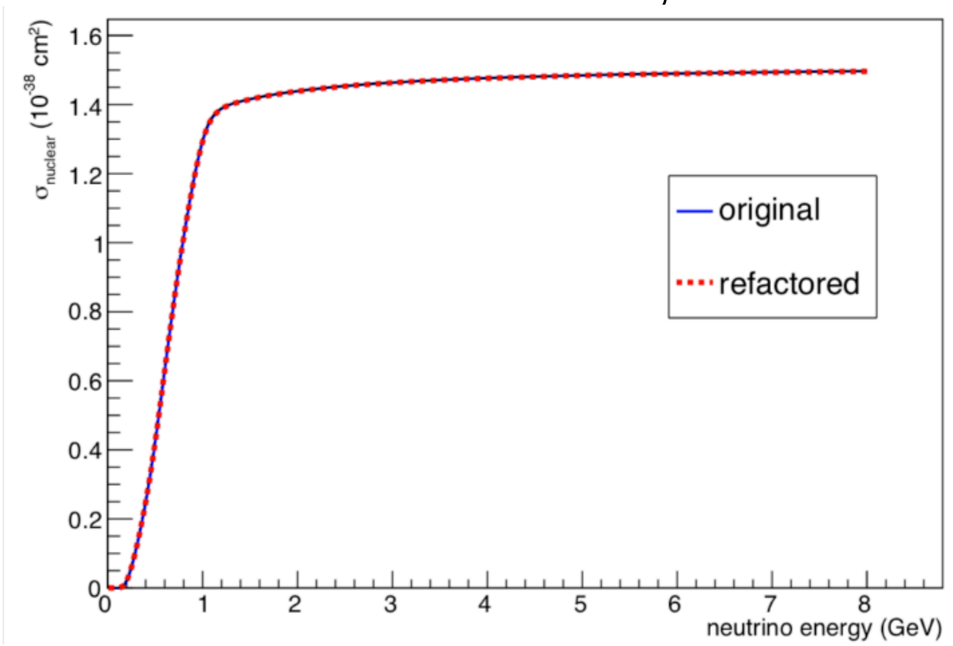
INCL++/Geant4 FSI: Marc Volonaiaina

HEDIS: Alfonso Garcia

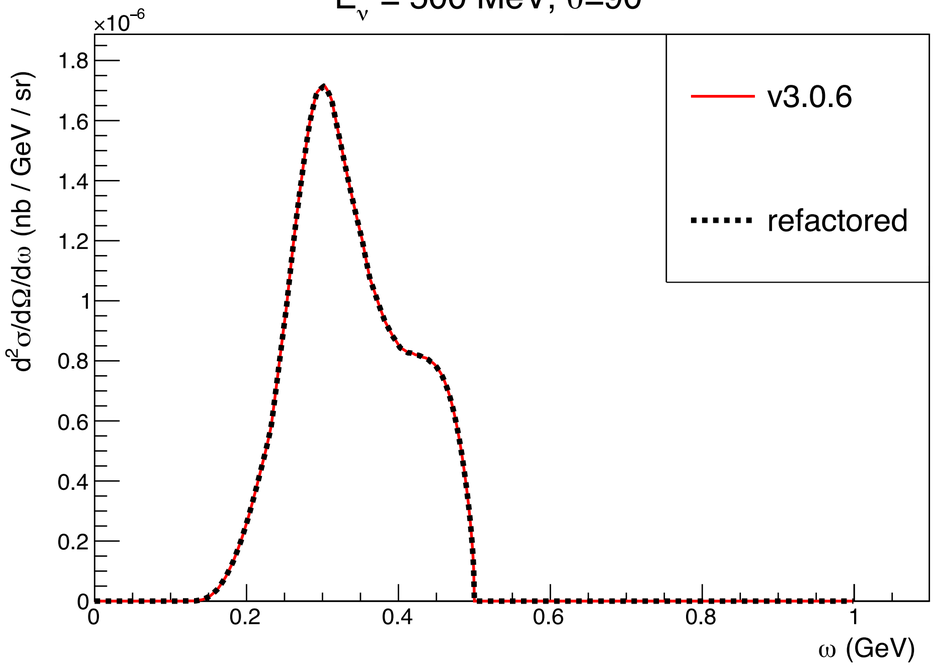
Hadronic tensor interface

- Provides flexible platform for implementations of **inclusive** CC/NC/EM cross sections
  - Hadronic final state prepared via an ad hoc factorization
- Based on IFIC Valencia CC 2p2h implementation by Jackie Schwehr, Dan Cherdack, and Rik Gran (arXiv:1601.02038)
  - Generalized to handle NC, EM channels
  - Various technical enhancements
  - See implementation tech note: GENIE docDB #137
- GENIE v3.2 will include refactored Valencia 2p2h model based on the new framework
  - **Reproduces predictions of the previous version**

IFIC Valencia CC 2p2h, ν_μ on ^{12}C



E_ν = 500 MeV, θ=90°



Hadronic tensor interface

Inclusive differential cross section

$$\frac{d^2\sigma}{dE'_\ell\, d\Omega'_\ell} = \frac{C}{\pi^2}\frac{|\mathbf{k}'|}{|\mathbf{k}|} L_{\mu\nu} W^{\mu\nu}$$

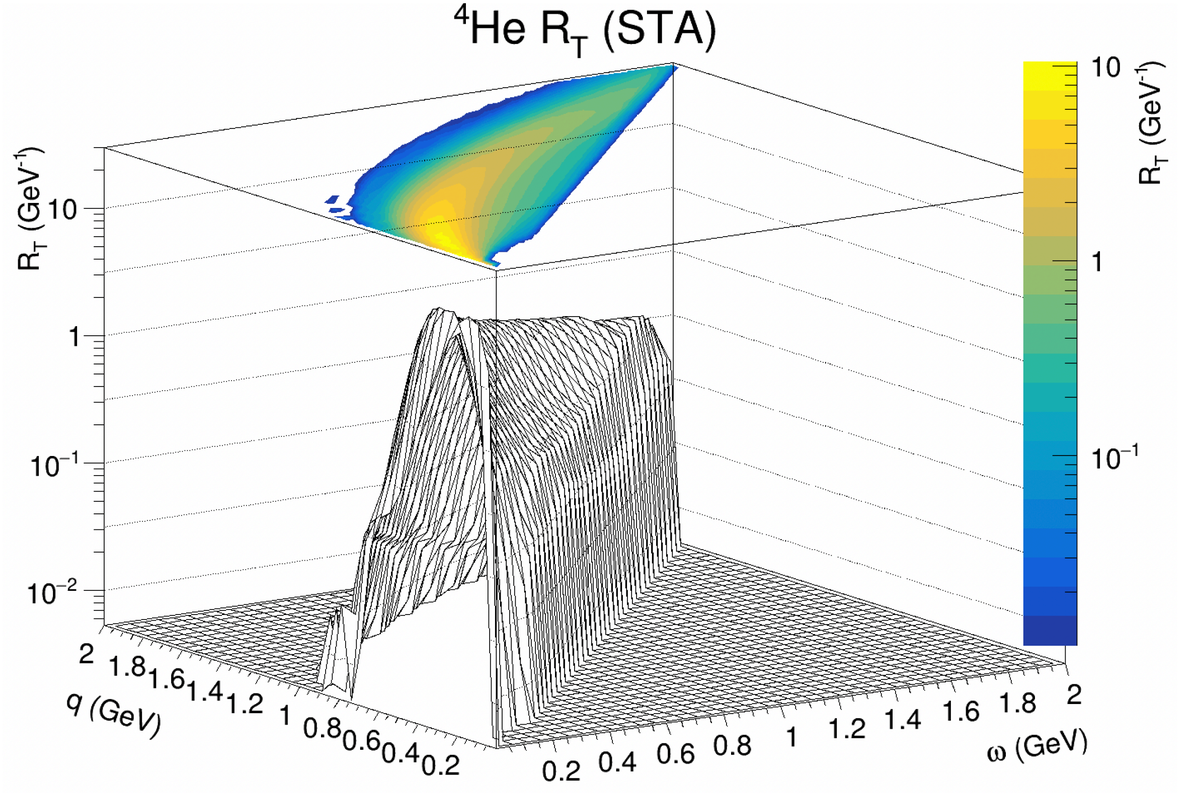
Channel-dependent "coupling factor"

$$C = \begin{cases} \frac{1}{2} G_F^2 |V_{ud}|^2 & \text{CC} \\ \frac{1}{2} G_F^2 & \text{NC} \\ \alpha^2 / Q^4 & \text{EM} \end{cases}$$

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

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

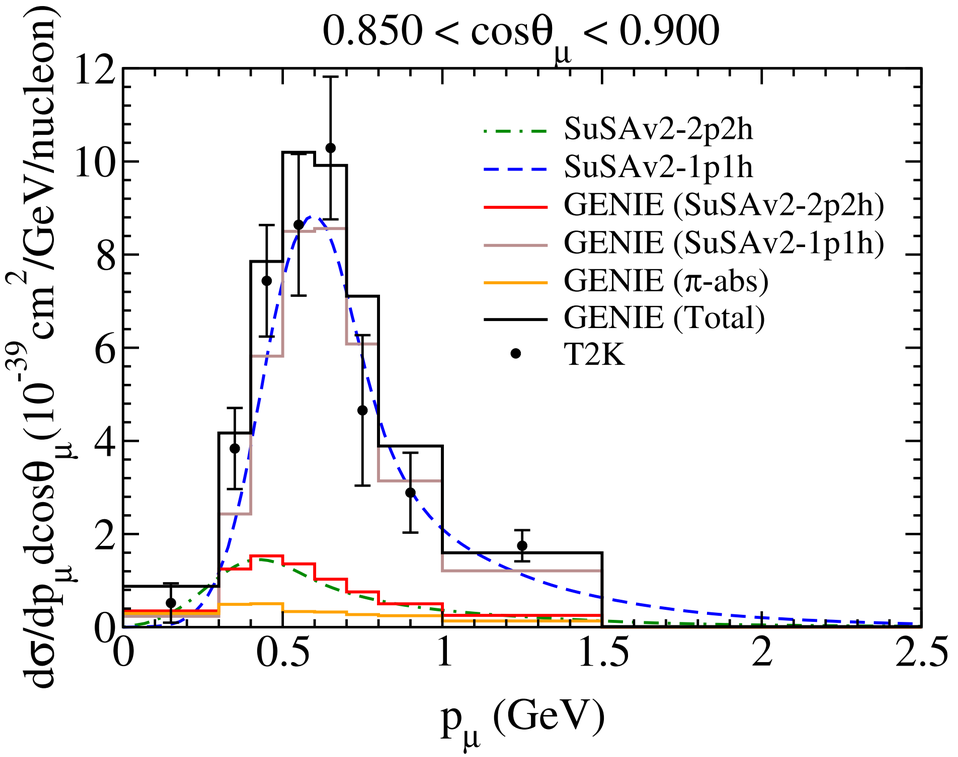
Precomputed tables of these on a $(\omega, |\mathbf{q}|)$ grid allow for **efficient interpolation**

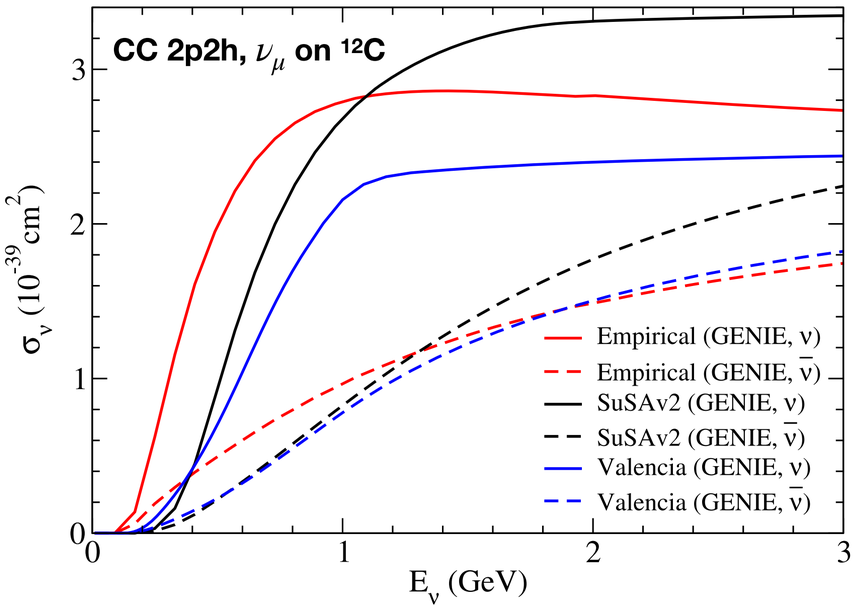


SuSAv2: CC neutrino scattering

- Provides 1p1h and 2p2h predictions based on the SuperScaling approach
  - See, e.g., **Phys. Rev. D 94, 093004 (2016)**
- GENIE implementation by Stephen Dolan, Guillermo Megias, and Sara Bolognesi
  - Leverages the hadronic tensor interface
- Recent paper presents **comparisons** to T2K data, alternate models
  - Limitations of the factorization strategy also discussed

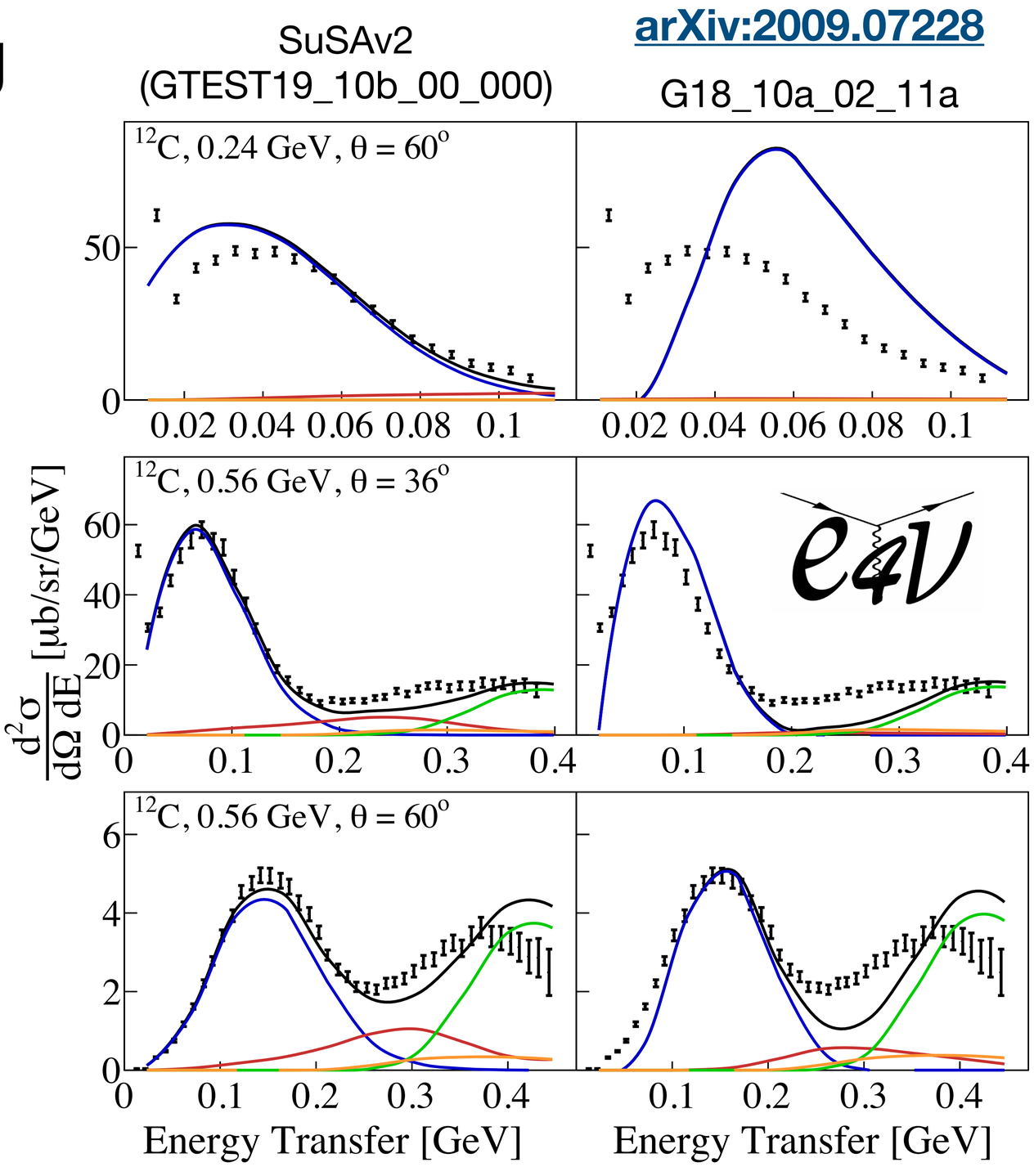
Phys. Rev. D 101, 033003 (2020)





SuSAv2: electron scattering

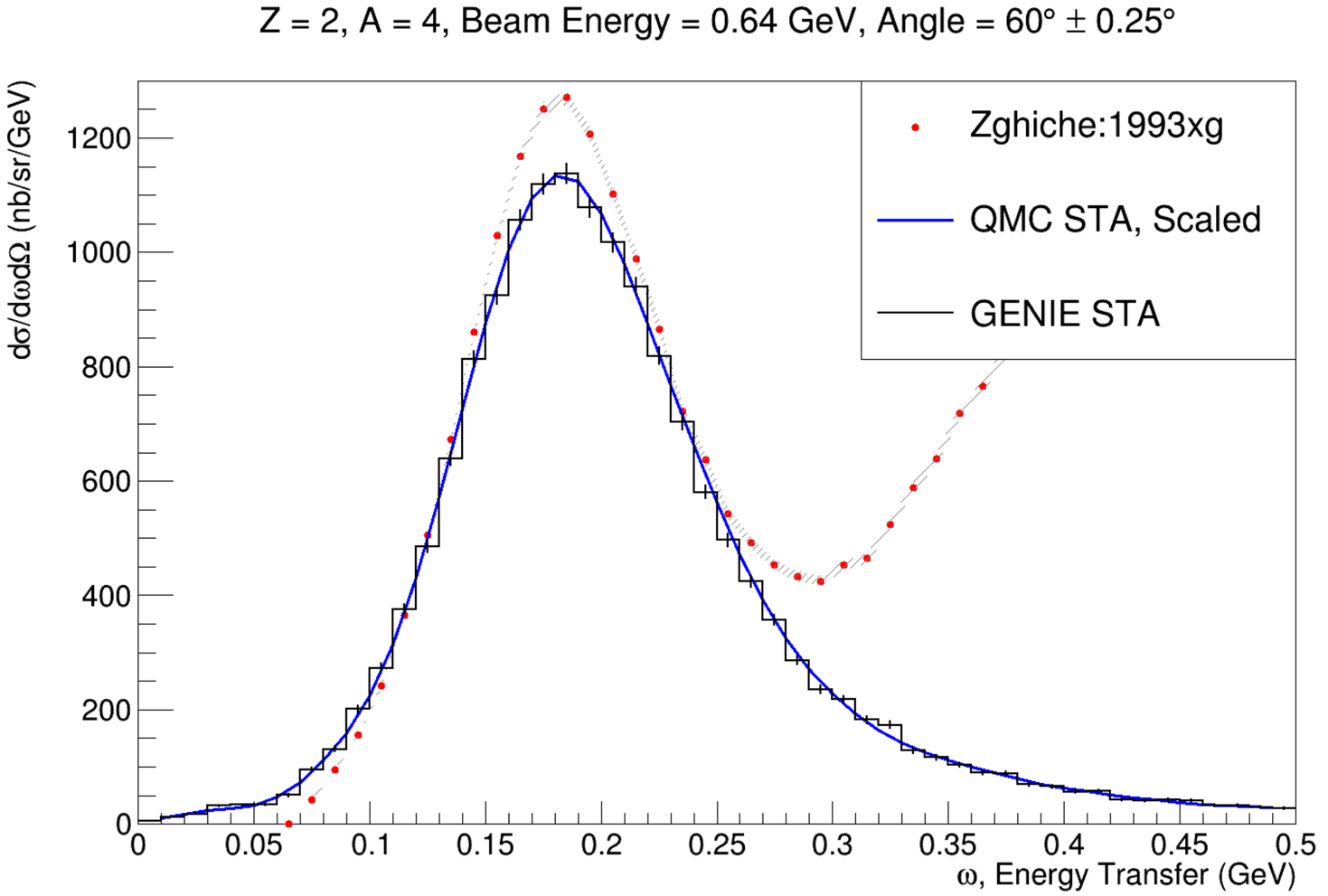
- Tables of nuclear responses consistent with neutrino version
- Recently **benchmarked** against inclusive (e, e') by members of the e4v collaboration
- GENIE SuSAv2 **1p1h** and **2p2h** achieves improved agreement over the existing G18_10a_02_11a model set



Short-time approximation

- Quantum MC method for ab initio calculations of lepton-nucleus scattering
  - 1p1h + 2p2h + interference
  - See talk by Saori Pastore tomorrow morning
- Hadronic tensor tables used for **inclusive predictions** of e^- on ^{4}He
- Development toward use of response densities: dependent distributions of nucleon kinematics

Phys. Rev. D 103, 052001 (2021)



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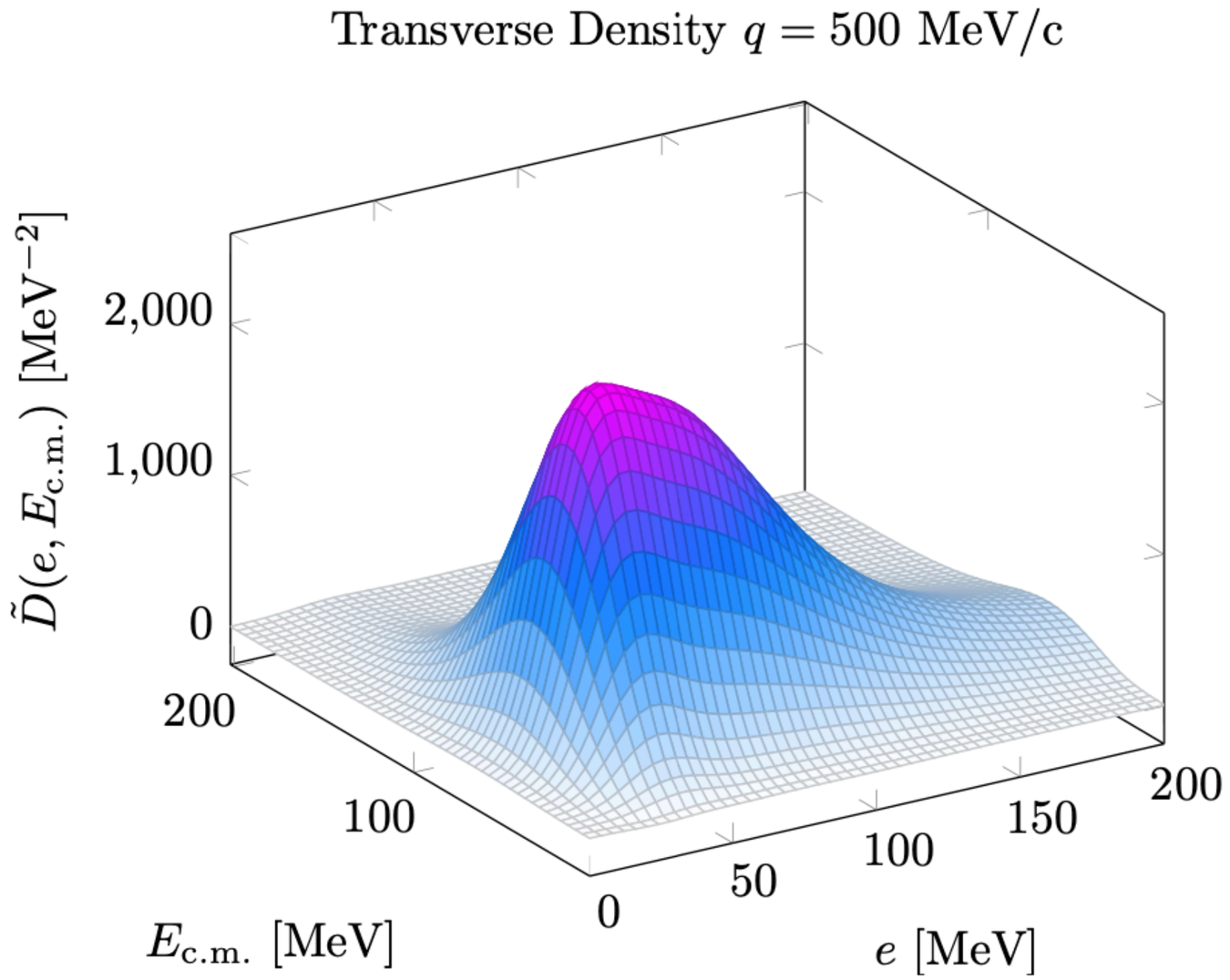
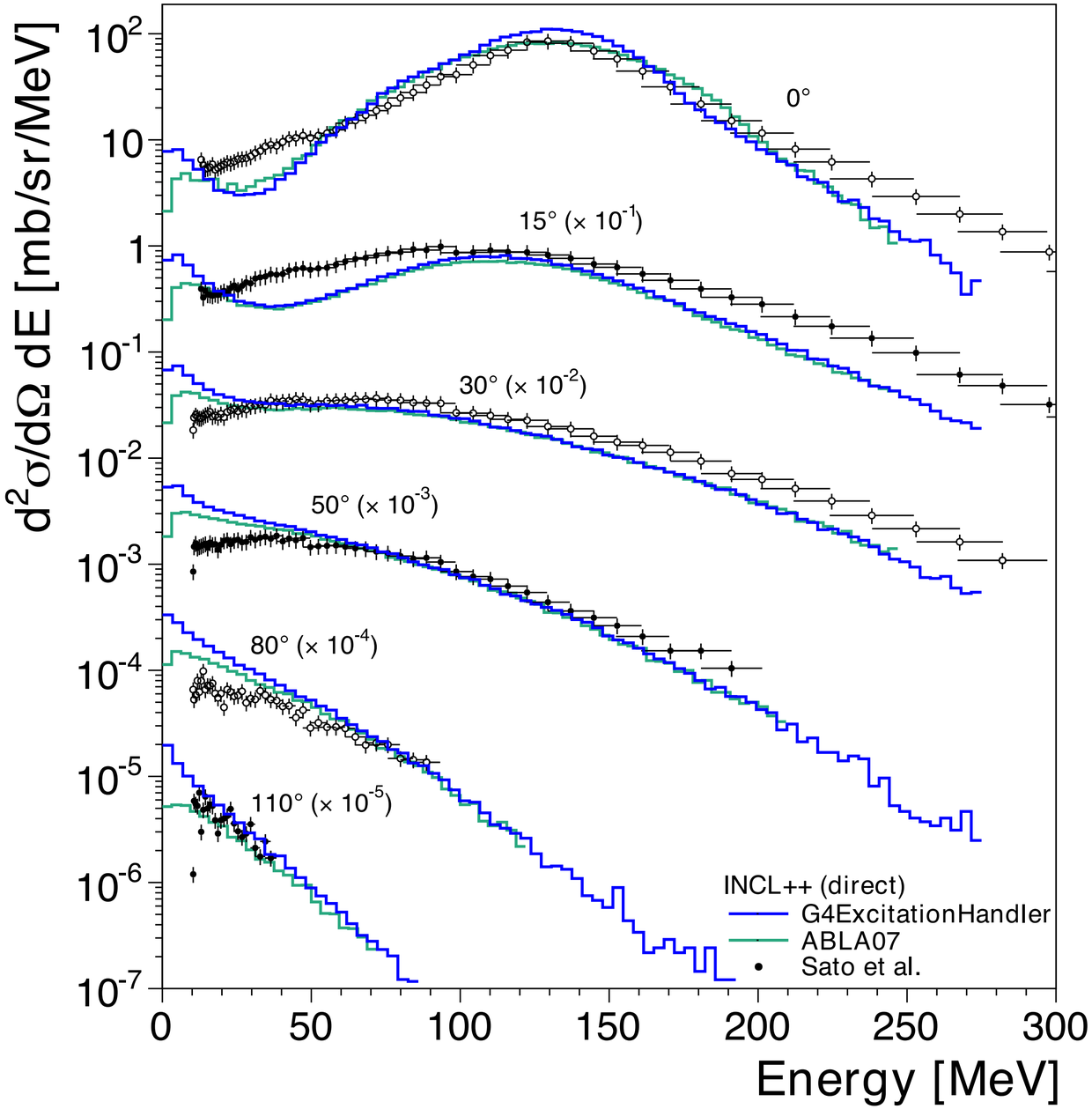
[Phys. Rev. D 103, 052001 (2021)]



New FSI models: INCL++

- C++ implementation of the Liège Intranuclear Cascade model
- Widely used for calculations of hadronic cross sections
- Low-energy effects (nucleon evaporation, etc.) handled via delegation to one of several de-excitation codes
  - G4ExcitationHandler, ABLA07
- **Plot**: double-differential neutron production in ^{12}C + ^{12}C @ 135 MeV/nucleon

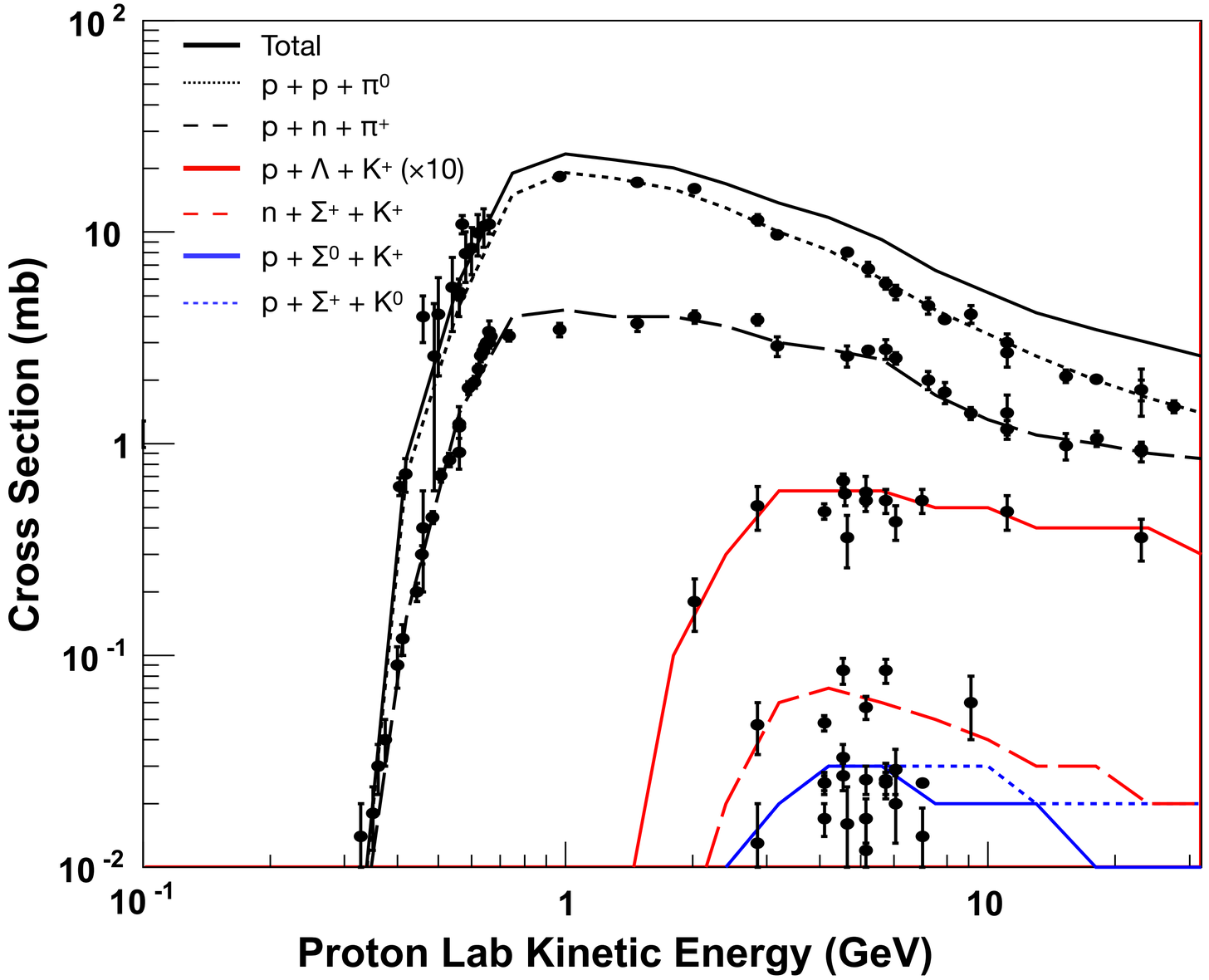
J. Phys.: Conf. Ser. 420 012065 (2013)



New FSI models: Bertini Cascade

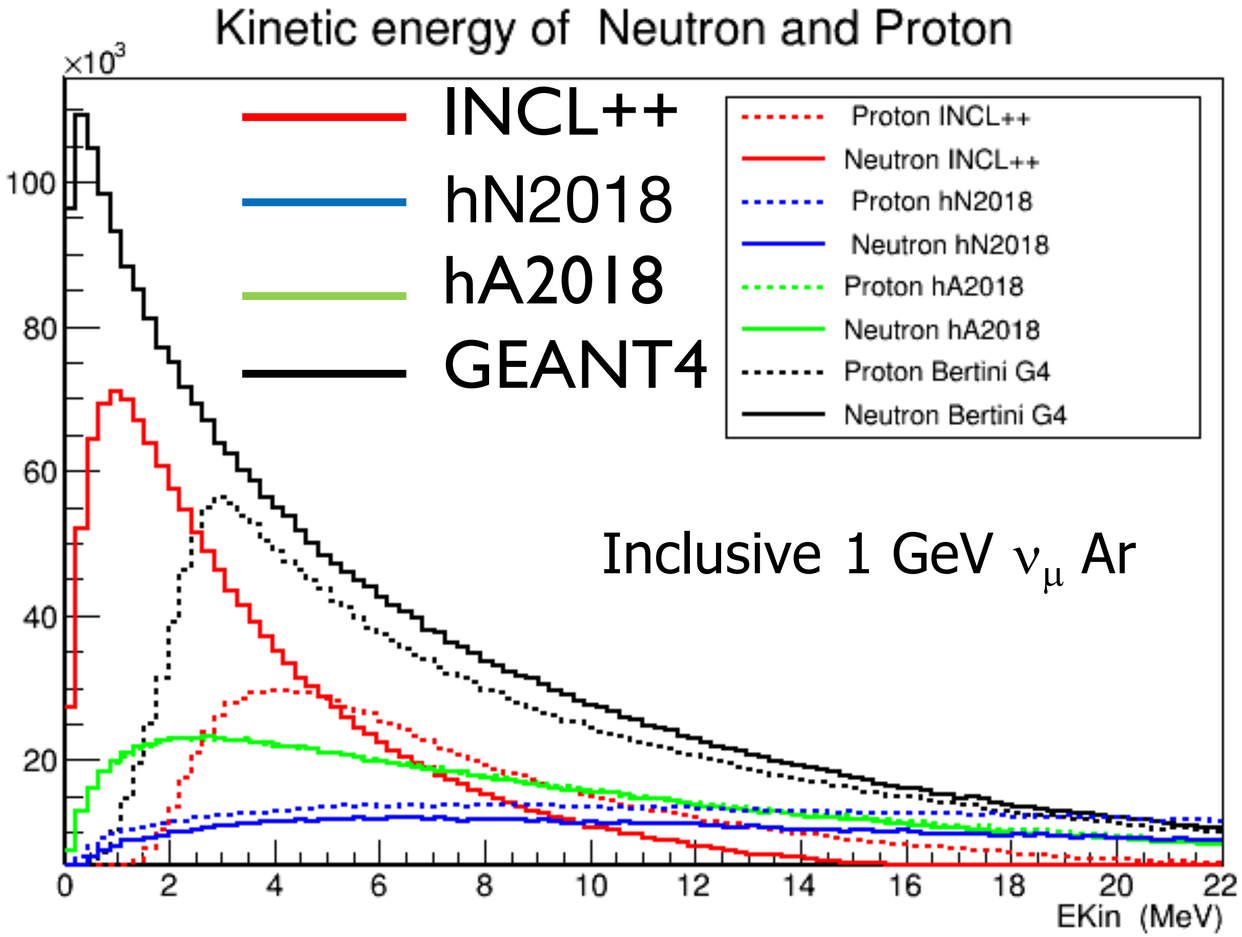
[Nucl. Instrum. Methods Phys. Res. A804 (2015) 175–188]

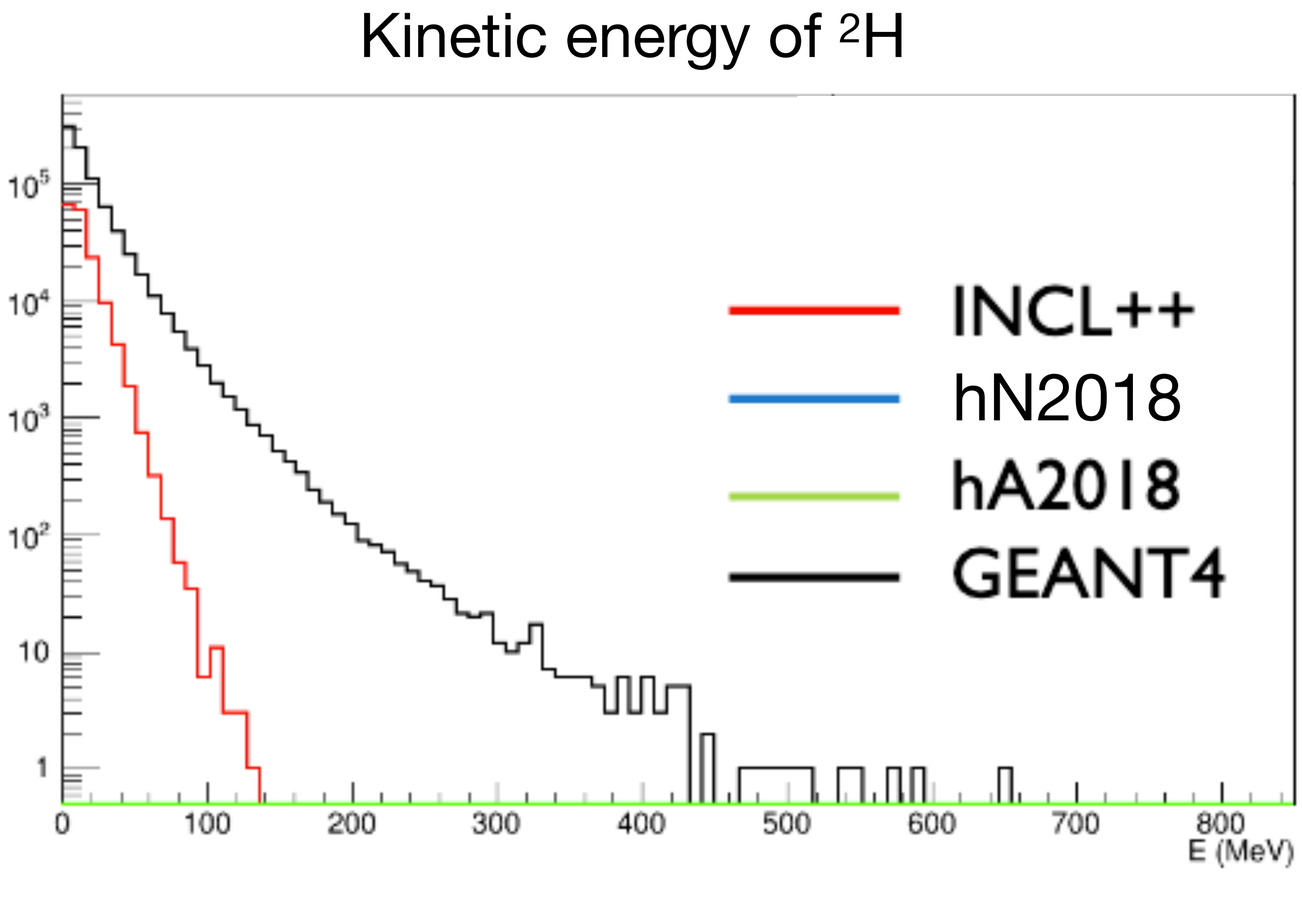
- Implemented as part of the Geant4 framework
- Conceptually similar to INCL++ but differs in many physics details
- Also includes a low-energy de-excitation treatment
- **Plot**: total cross sections for p + p → X + Y + Z
- Experimental data from [CERN-HERA-84-01]



Impact of new FSI models

GENIE docDB #188



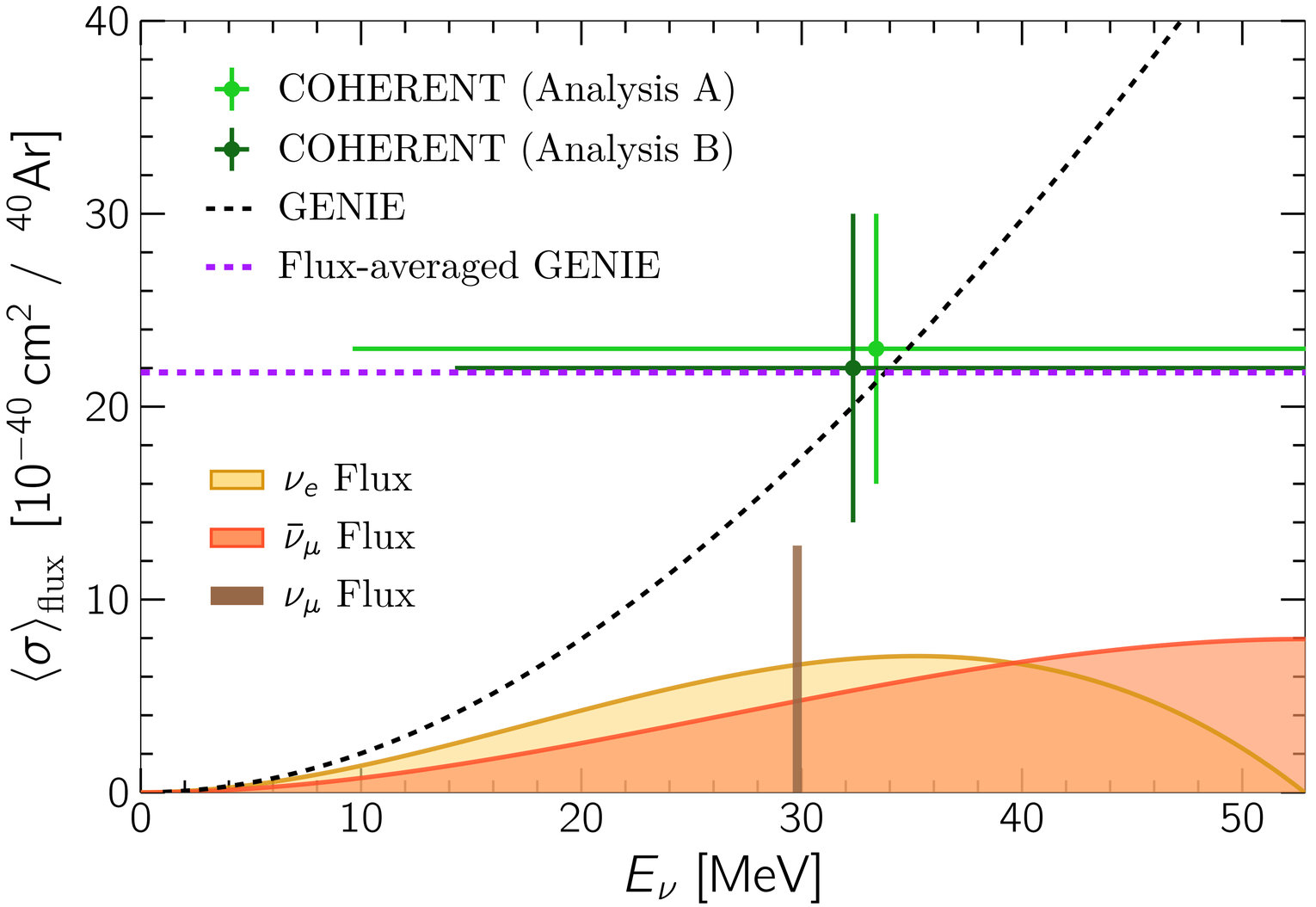


Divergence of n/p at low energies — impact of Coulomb barrier included in the new models

New physics effects included: evaporation, **coalescence**, statistical γ-ray emission

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)]

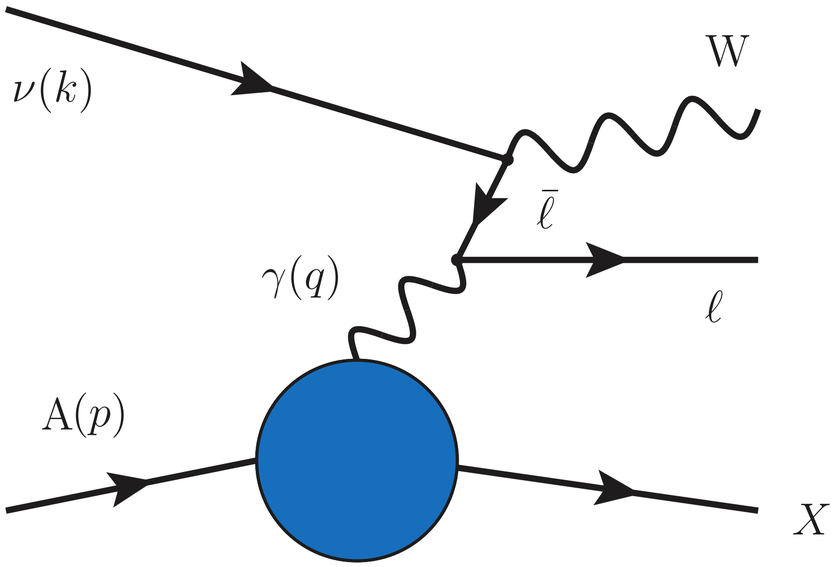


COHERENT data from [Phys. Rev. Lett. 126, 012002 (2021)]

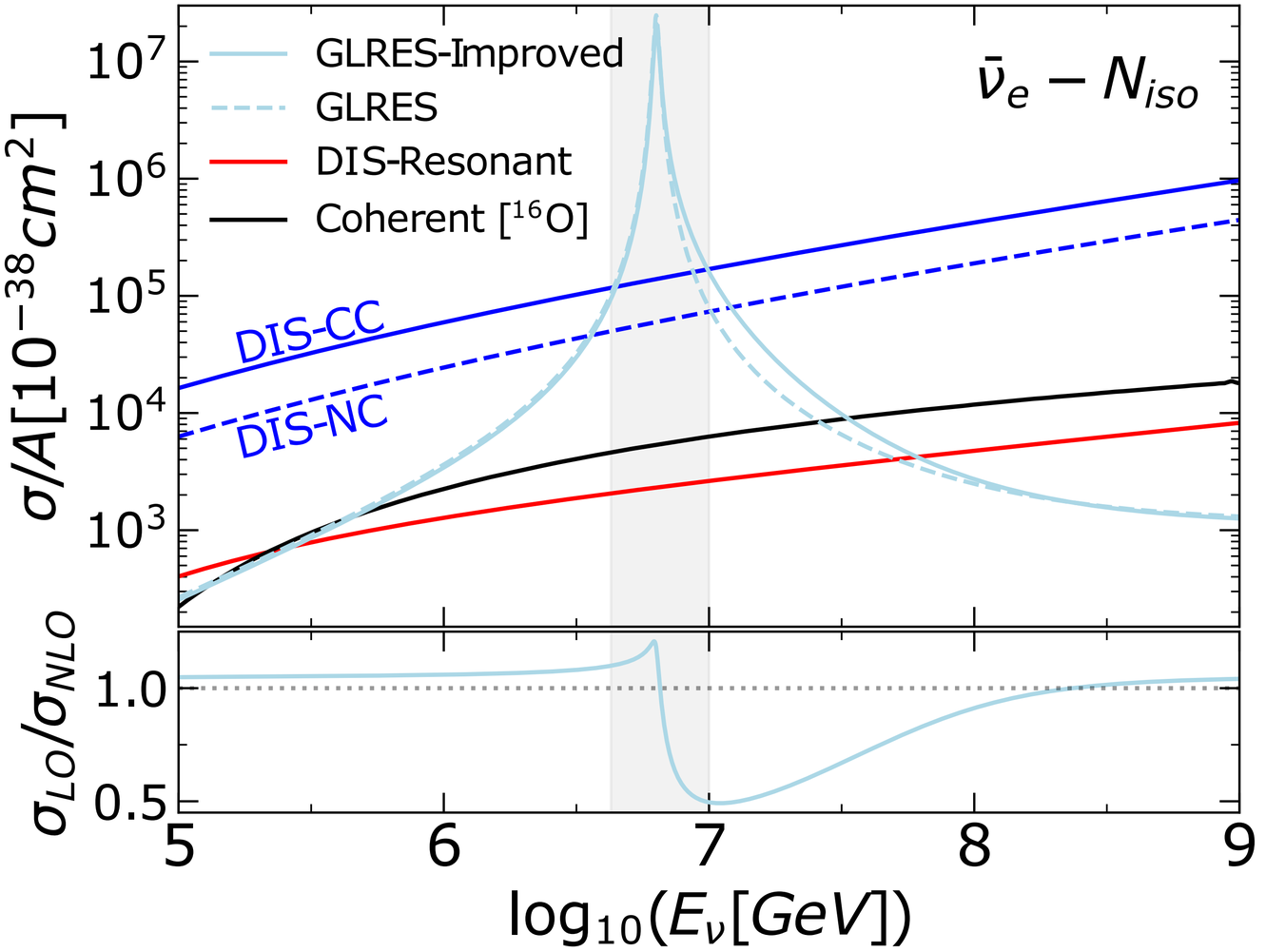
HEDIS module: energies up to 10^9 GeV

- 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

Coherent W boson production



J. Cosmol. Astropart. Phys. 09 (2020) 025

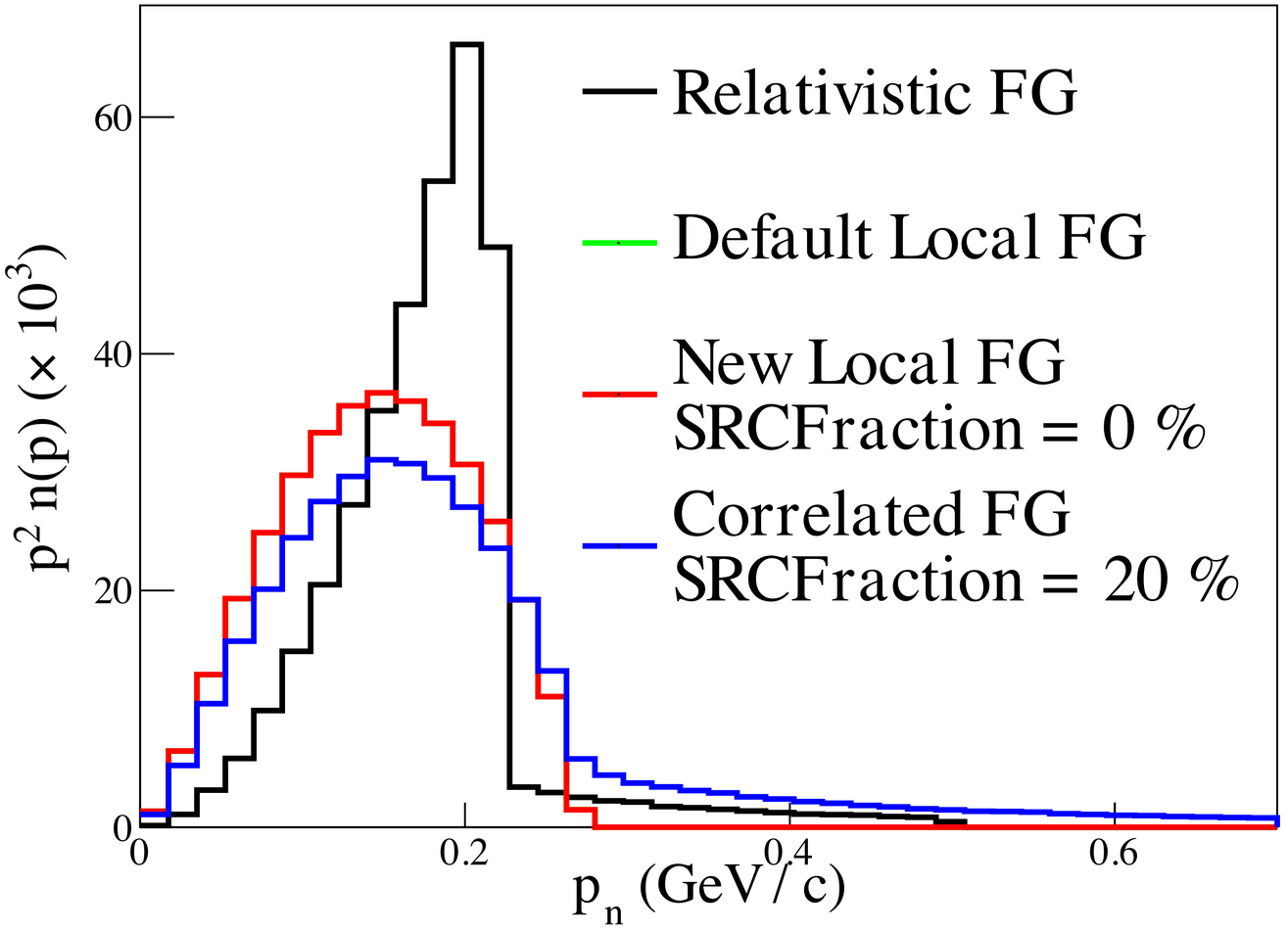


First observation of a Glashow resonance (GLRES) candidate event by IceCube: Nature 591, 220–224 (2021)

Other new physics developments for GENIE v3.2

- Single pion production model by Minoo Kabirnezhad: **Phys. Rev. D 97, 013002 (2018)**
- PYTHIA 8 hadronization
- **Correlated Fermi gas** nuclear model
- Boosted Dark Matter interactions by Joshua Berger: **arXiv:1812.05616**
- Dark neutrino BSM model: **Phys. Rev. Lett. 121, 241801 (2018)**
  - Flash talk by Iker de Icaza
- Event Library interface to external generators
  - Flash talk by Chris Backhouse

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



Summary

- A broad program of physics enhancements is being pursued by GENIE and community contributors

- Many new features will soon be available in the upcoming v3.2 release

- Exploration of new ways to streamline model development continues
  - Hadronic tensor tables
  - Interfacing to external codes