New electron scattering pion-production constraints for neutrino event generators

Júlia Tena Vidal at Universitat de València, IFIC

On behalf of the e4ν and CLAS Collaborations

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julia.tena-vidal@ific.uv.es

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EXCELENCIA SEVERO OCHOA

e4ν

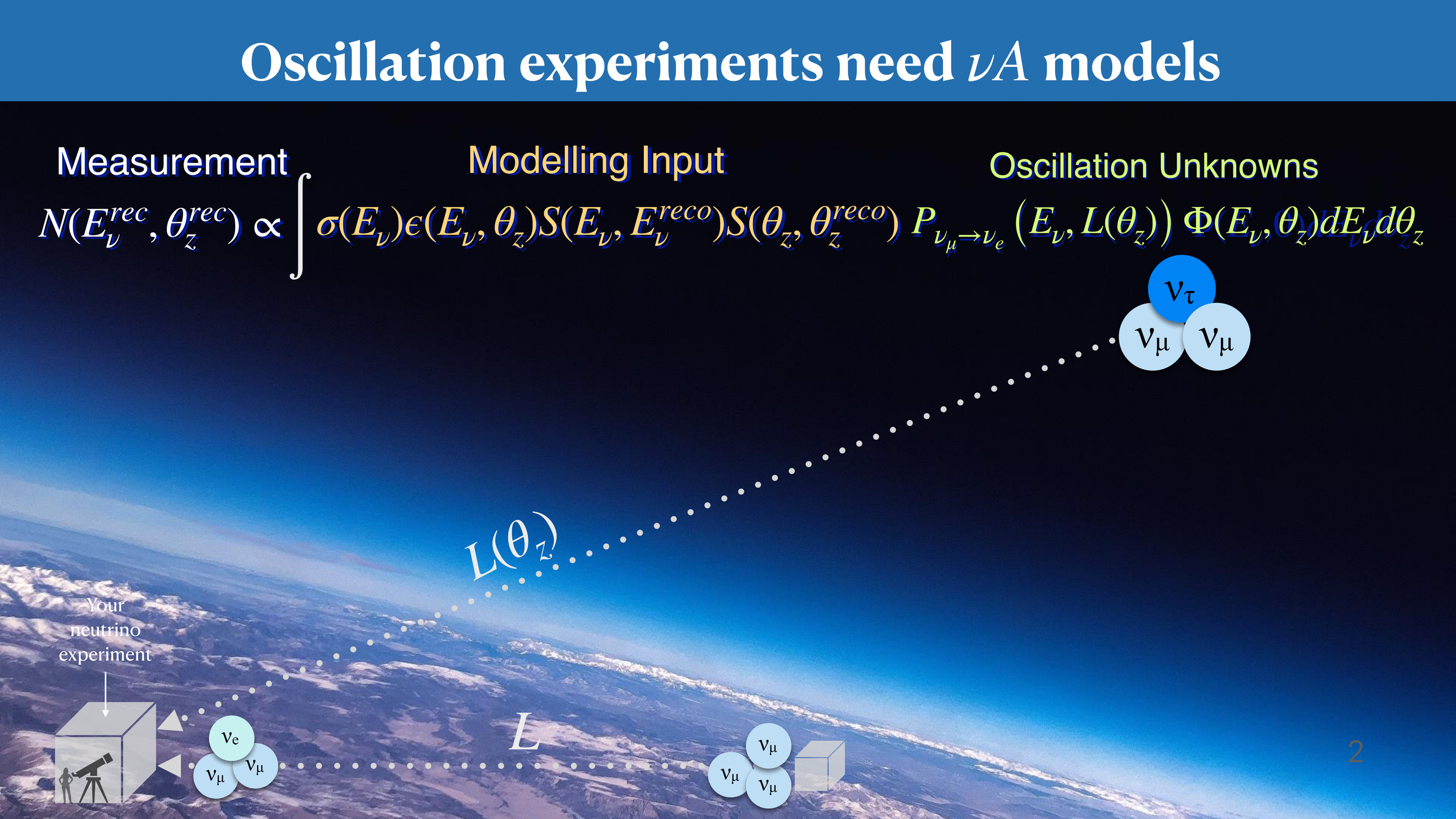
Oscillation experiments need νA models

Measurement

Modelling Input

Oscillation Unknowns

$$N(E_\nu^{rec}, \theta_z^{rec}) \propto \int \sigma(E_\nu)\epsilon(E_\nu, \theta_z)S(E_\nu, E_\nu^{reco})S(\theta_z, \theta_z^{reco})\, P_{\nu_\mu \to \nu_e}\left(E_\nu, L(\theta_z)\right) \Phi(E_\nu, \theta_z) dE_\nu d\theta_z$$



Oscillation experiments need νA models

Measurement

$$N(E_\nu^{rec}, \theta_z^{rec}) \propto \int \sigma(E_\nu)\epsilon(E_\nu, \theta_z)S(E_\nu, E_\nu^{reco})S(\theta_z, \theta_z^{reco})\, P_{\nu_\mu \to \nu_e}\left(E_\nu, L(\theta_z)\right) \Phi(E_\nu, \theta_z)$$

Modelling Input

Oscillation Unknowns

Neutrino event generators are crucial to oscillation analyses:

- Reconstruct true neutrino energy, estimate efficiencies, backgrounds, ...
- Complex nuclear physics with incomplete theories
- Many event generators: GENIE, NEUT, NuWRO, GIBUU, Achilles
  - Generators use complicated mixture of data and models

Incorrect $\nu - A$ modelling is biasing your oscillation measurement

Oscillation experiments need νA models

Measurement | Modelling Input | Oscillation Unknowns

$$N(E_\nu^{rec}, \theta_z^{rec}) \propto \int \sigma(E_\nu)\epsilon(E_\nu, \theta_z)S(E_\nu, E_\nu^{reco})S(\theta_z, \theta_z^{reco})\, P_{\nu_\mu \to \nu_e}\left(E_\nu, L(\theta_z)\right) \Phi(E_\nu, \theta_z)$$

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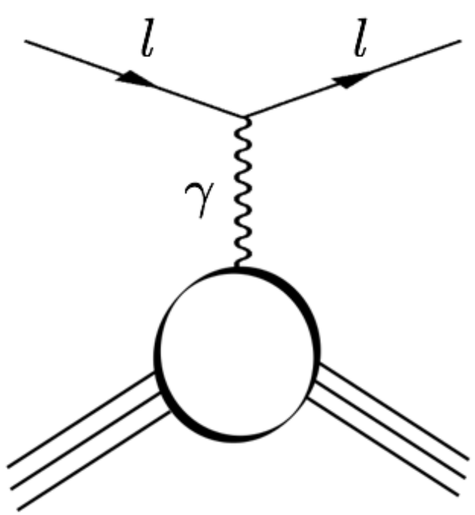
Incorrect $\nu - A$ modelling is biasing your oscillation measurement

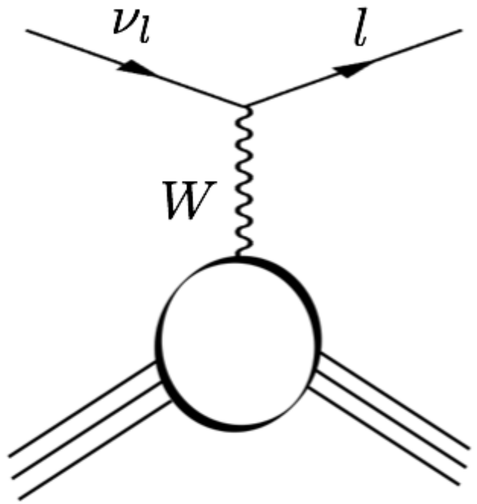
Our approach:

Use Electron Scattering data as well!

Why electrons?

Same nuclear ground state, Final State Interactions (FSI), Hadronization
Similar interactions with nuclei





EM current [V]

CC weak current [V + A]

eA useful to constrain νA model uncertainties

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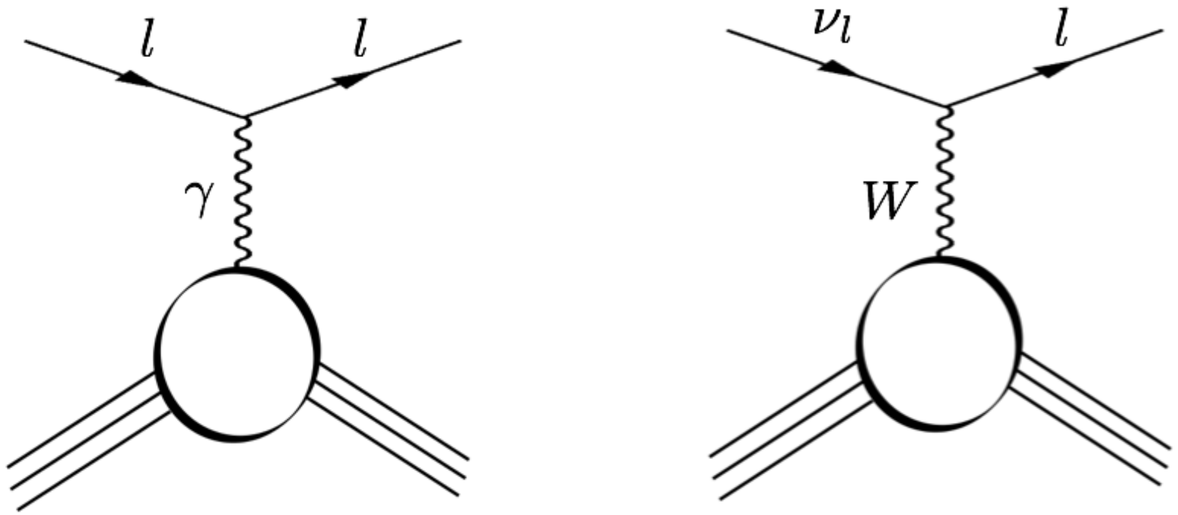


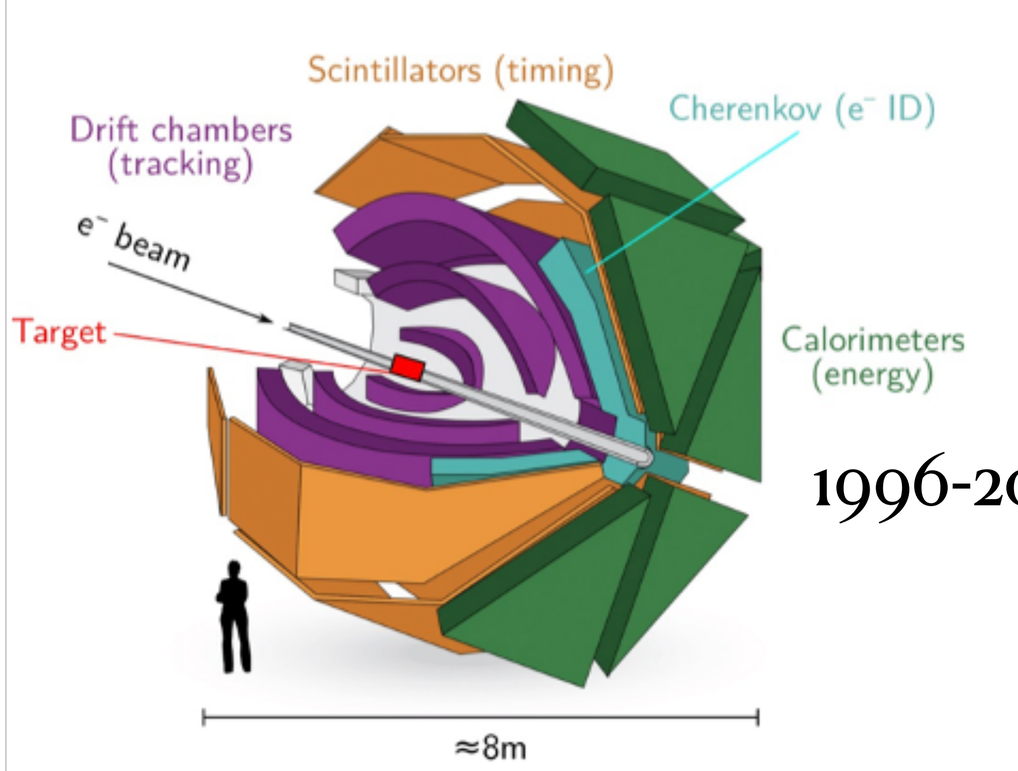
Monochromatic beam
High statistics

Wide-energy beam
Lower statistics

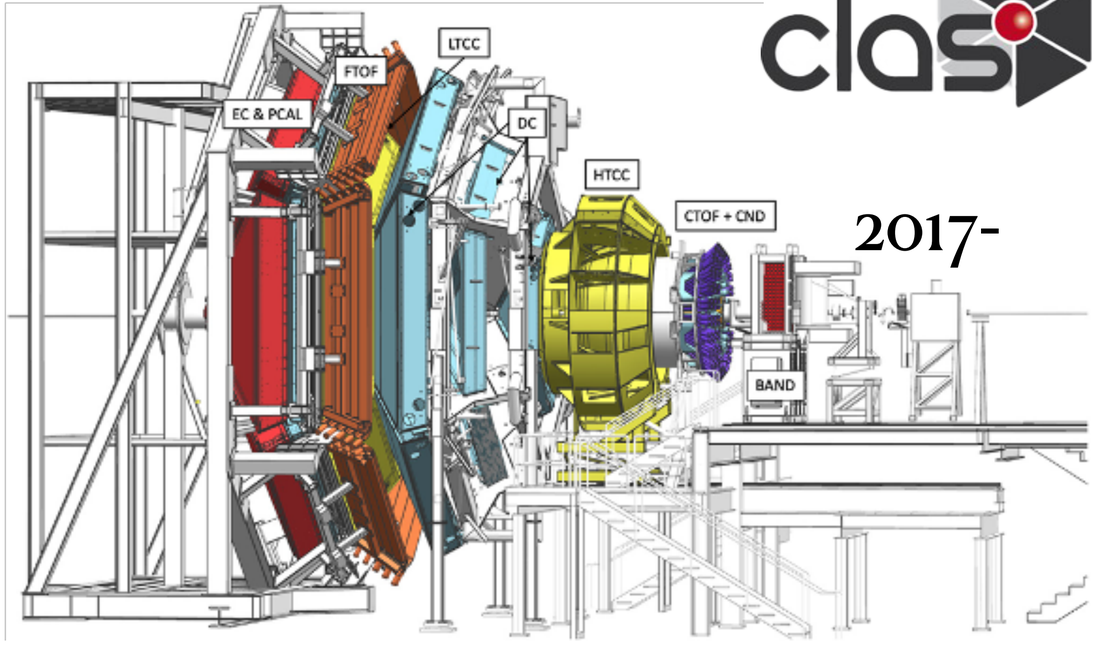
eA useful to test νA energy reconstruction methods

CLAS and CLAS12 eA hadron production data

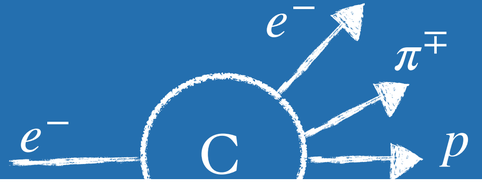
- Multi-purpose experiments, **large acceptance**
- Targets (H, D, C, Ar, etc) and energies (1-6 GeV) of interest for neutrino community
- Low-detection threshold comparable to neutrino experiments
  - 150 (300) MeV/c for $\pi^{\pm}$ (γ)



1996-2013

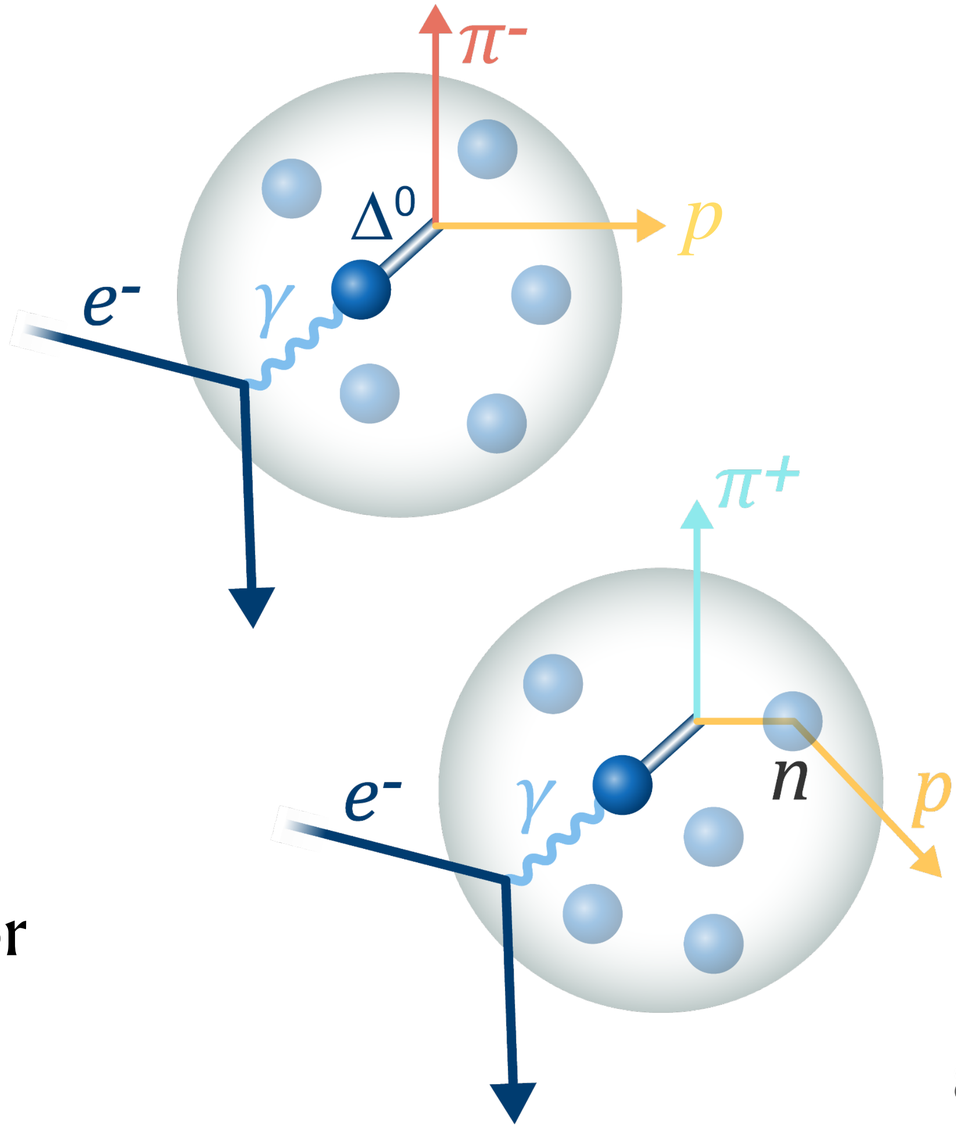


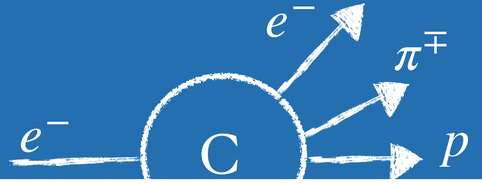
2017-



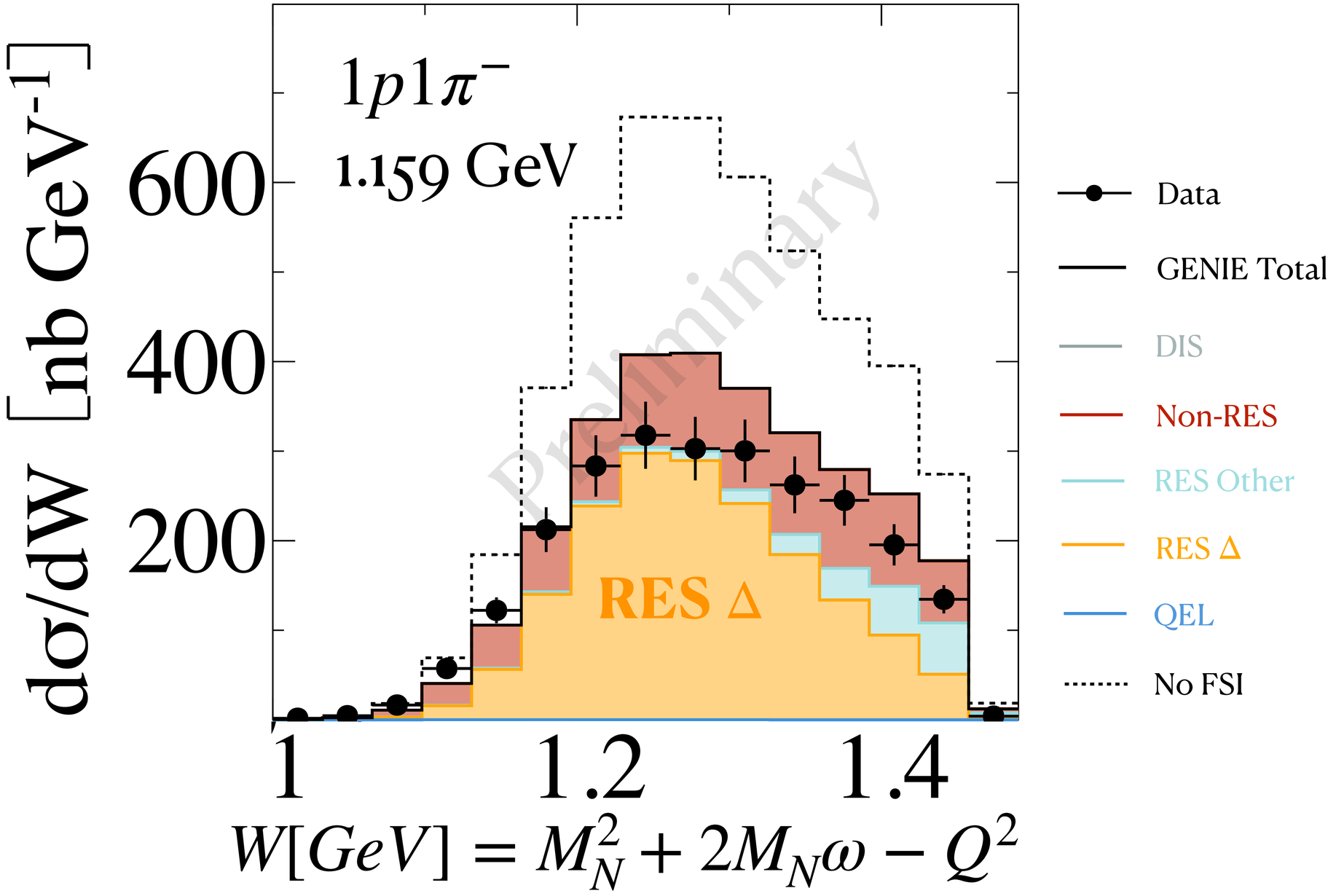
First look at C(e,e'1p1$\pi^\mp$)

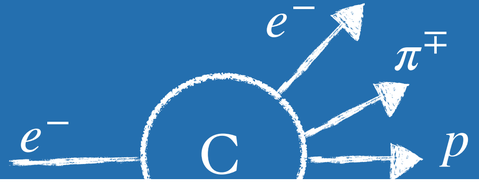
- Carbon data, 1-4 GeV
- $1p1\pi^-$ and $1p1\pi^+$, no additional hadrons or photons
  - With $\pi^\mp$ above 150 MeV
  - With γ above 300 MeV
- $1p1\pi^-$ Possible at free nucleon level
- $1p1\pi^+$ needs two or more nucleons and or undetected particles (FSI)



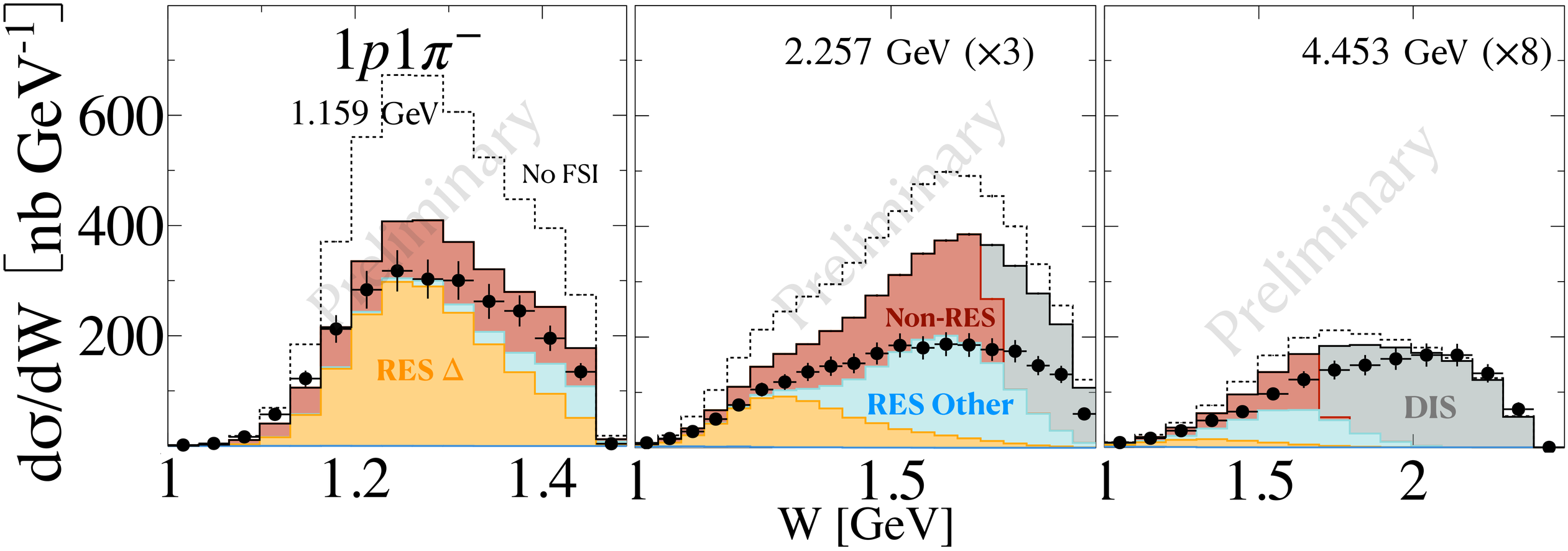


Can GENIE describe electron data?

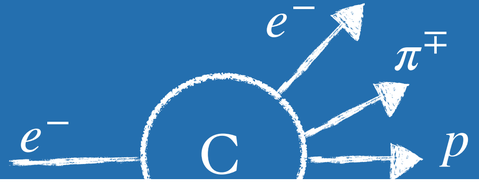




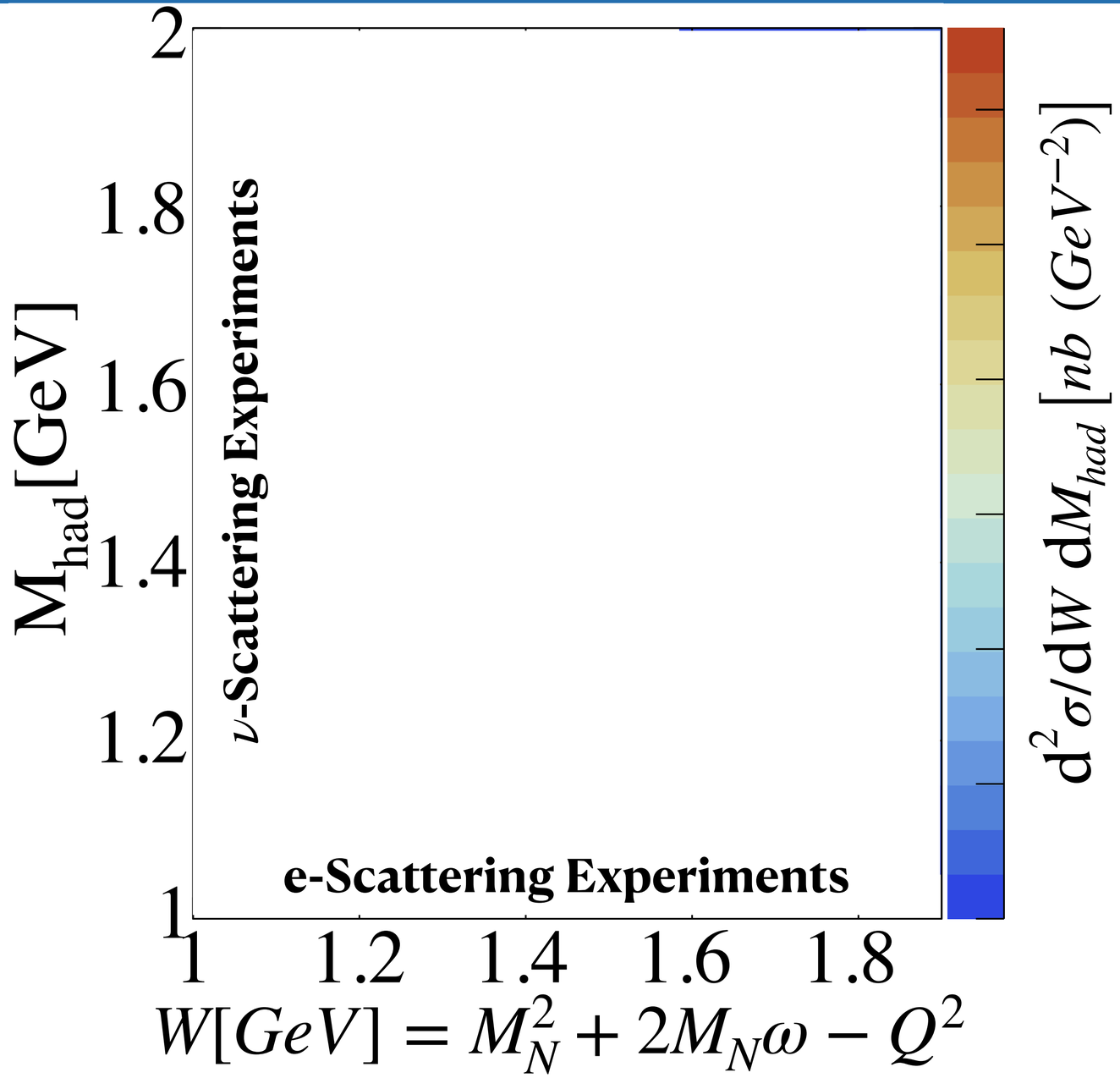
GENIE has wrong energy dependence



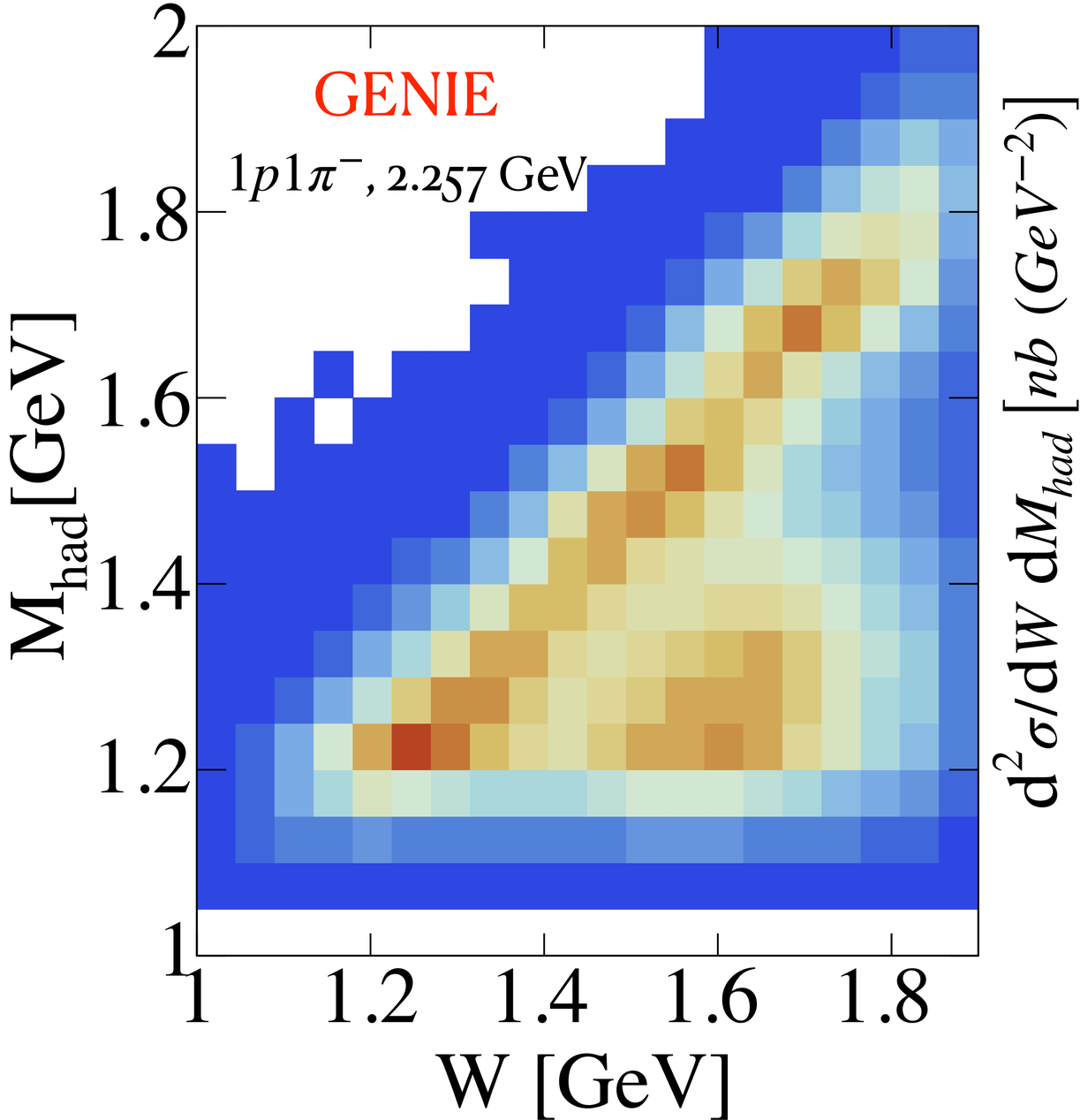
GENIE pion production fails to describe energy dependence

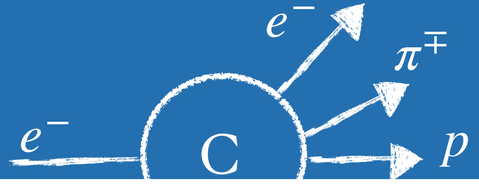


Hadronic Invariant Mass Bias

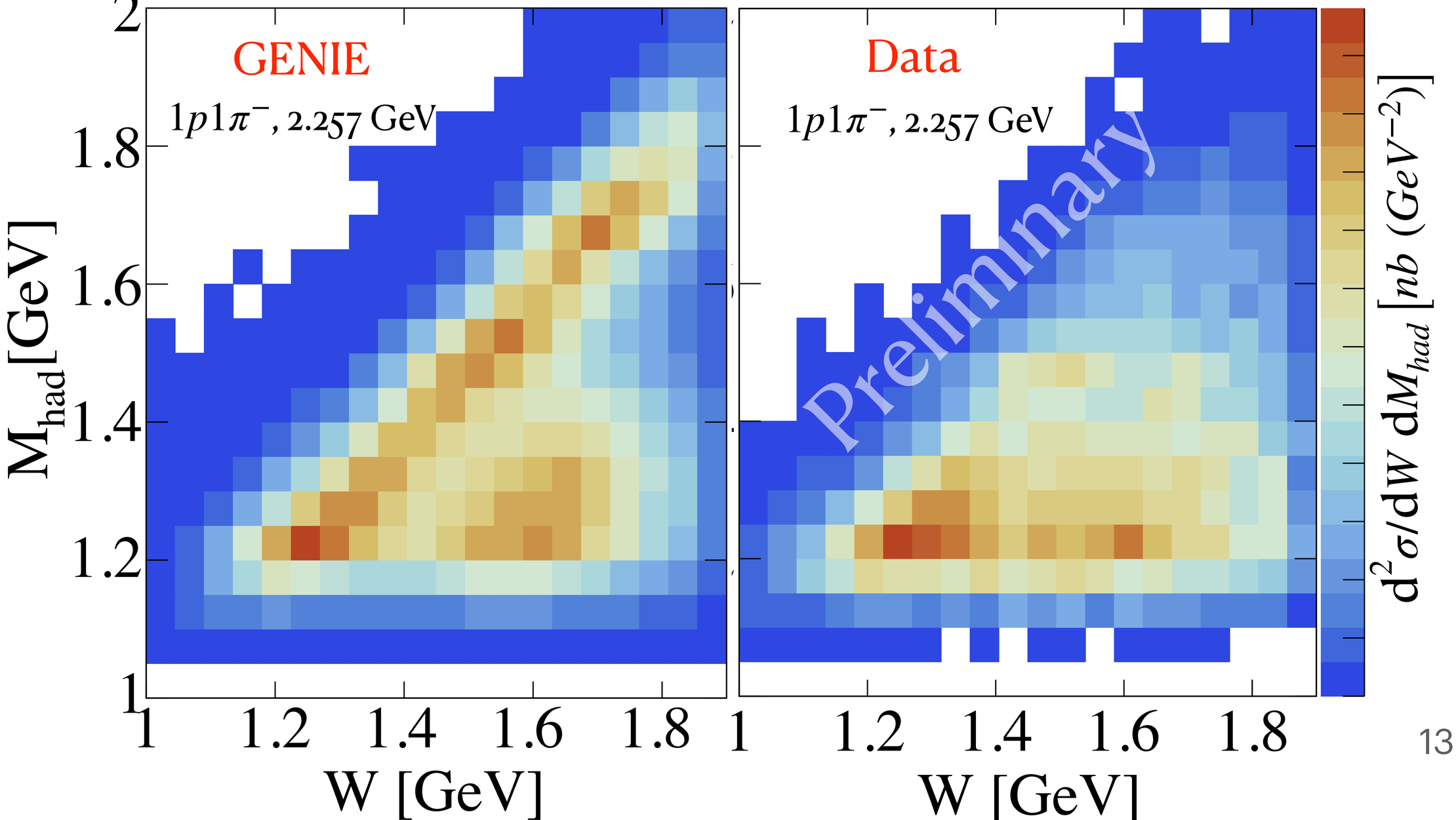


GENIE missmodels hadronization

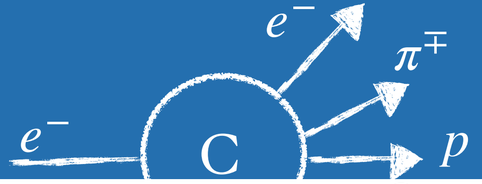


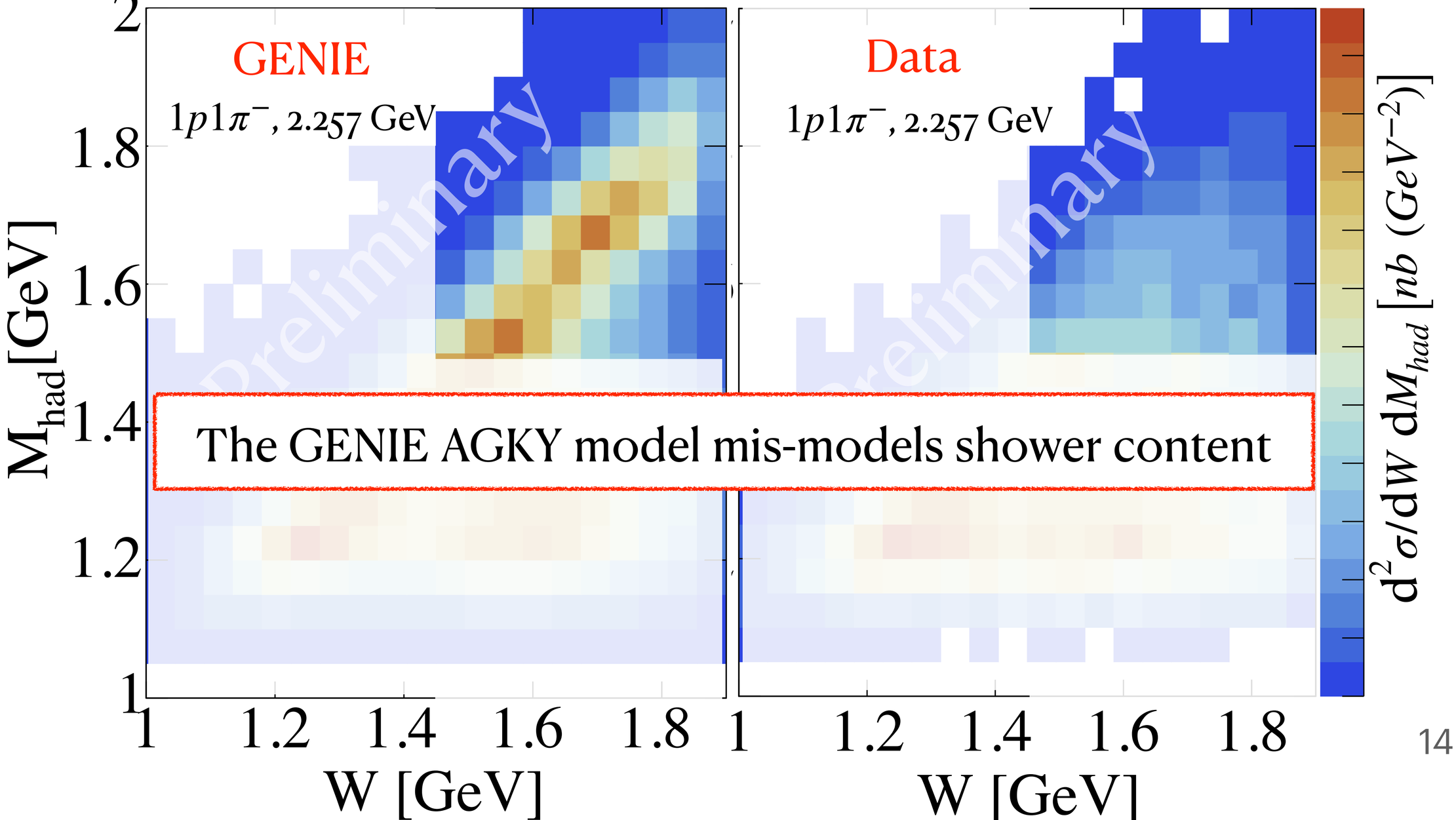


GENIE missmodels hadronization



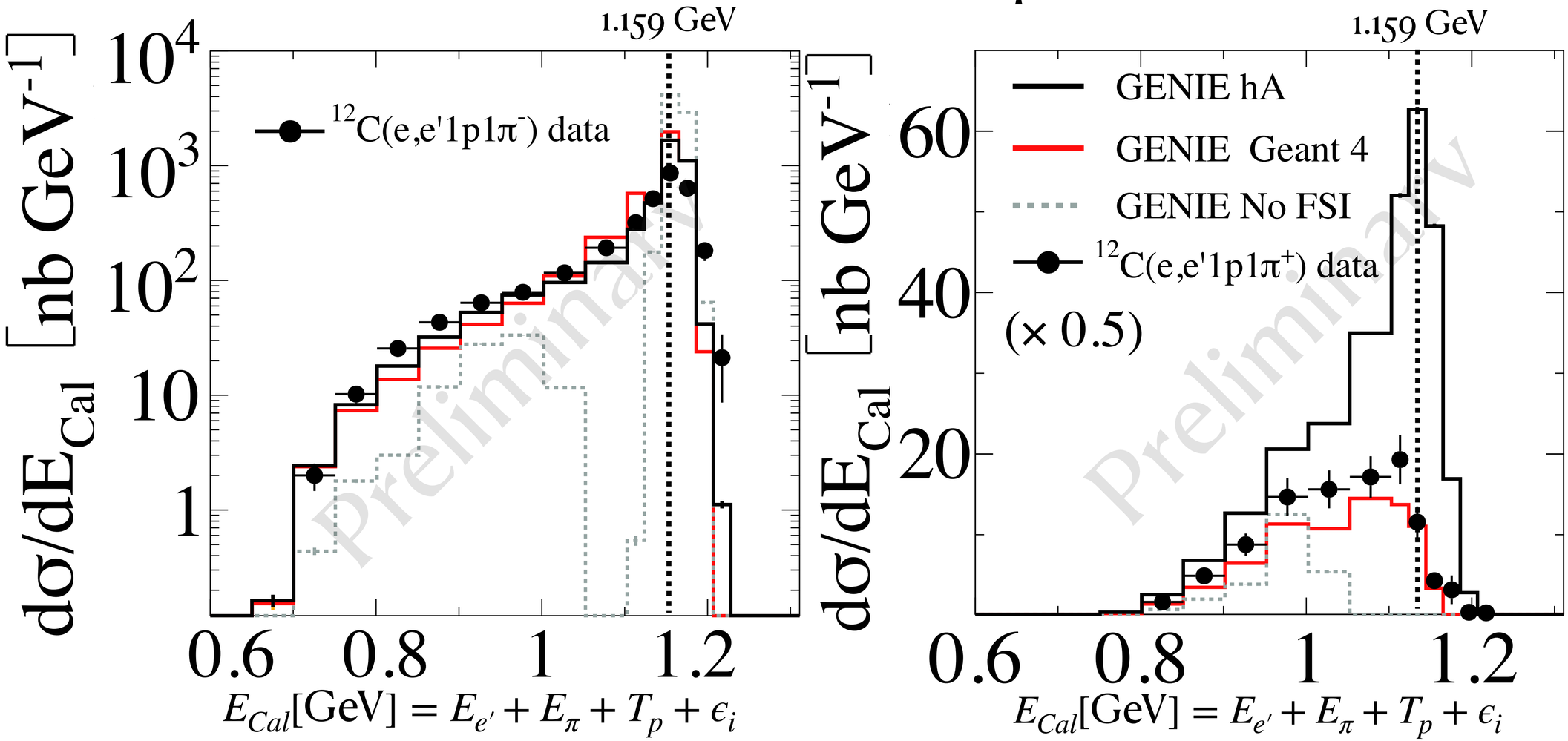
GENIE mis-models hadronization





Reconstructed incident energy

Critical for oscillation experiments

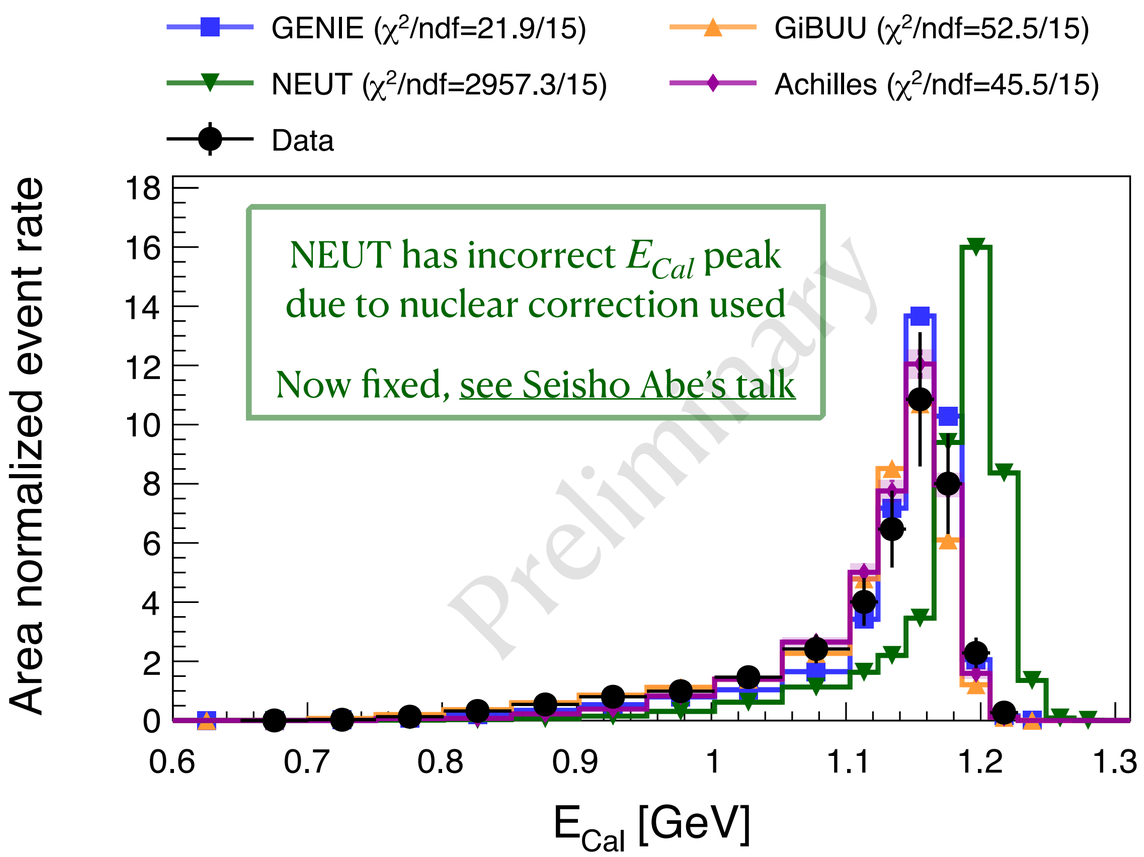


GENIE's standard FSI model fails to describe data

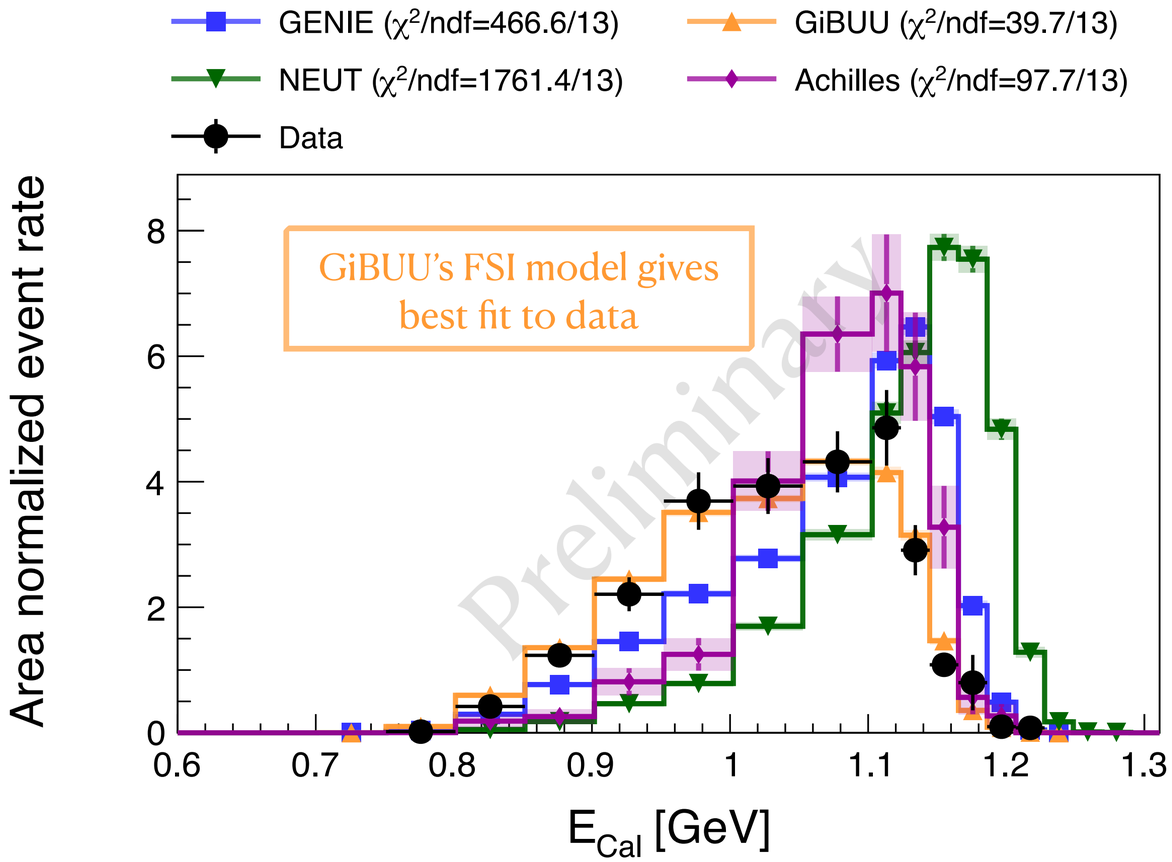
Does your generator describe e-data?

High-precision test of π- production, nuclear and FSI models in event generators

$C^{12}(e, e'1p1\pi^-)$@1.159 GeV



$C^{12}(e, e'1p1\pi^+)$@1.159 GeV



Ongoing effort between $e4\nu$ (GENIE), L. Aliaga-Soplin (GiBUU), Seisho Abe (NEUT), Noemi Rocco (Achilles)

Take aways

- e-data is key to **reduce large systematic uncertainties** in oscillation experiments
  - CLAS has large acceptance and magnetic field allowing for high-statistics hadron production data with monochromatic electron beams
- First $^{12}C(e, e'1p1\pi^{\mp})$ analysis unveils **new limitations of event generators**
  - GENIE fails to describe cross-section energy dependence
  - Commonly used GENIE FSI model fail to describe new data
  - Already helping generators improve their underlying physics!

Stay tuned!

More data, newer GENIE models and comparisons to more generators coming soon

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ID 100010434, LCF/BQ/PI25/12100025

More data on the way!

e4v

Thank you for your attention!

The GENIE Event Generator

https://genie-mc.github.io/

Tune name in GENIE: GEM21_11a_00_000

Process	Model
Quasi-ELastic and Two-Particle Two-	SUSAv2 model
RESonance Production	Berger-Sehgal model
Non-RESonance (SIS)	Bodek-Yang model, scaled with multiplicity dependent parameters
Deep Inelastic Scattering	Bodek-Yang model
Final State Interaction model	hA model
Hadronization model	AGKY model (KNO+Pythia)
Nuclear Model	Local Fermi Gas

(*) This is the GENIE model used in the talk

Pion production dominates DUNE's event-rate

GENIE models e^- and $\nu - A$ pion production events in the same way:

Resonant (RES)

Deep Inelastic Scattering

Bodek-Yang model

$W > 1.7$ GeV

Non-Resonant (SIS)

DIS tuned to ν-data

$W < 1.7$ GeV

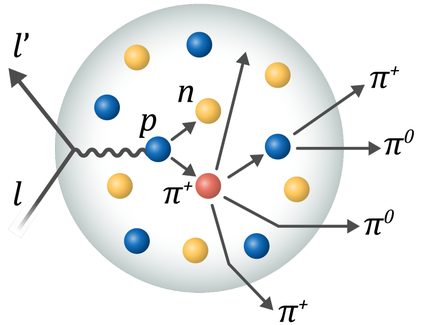
+ Hadronization

AGKY empirical model (tuned to $\nu-$data) + PYTHIA 8

+ Final State Interactions:

Describes hadron-nucleus re-interactions

Several models available (hA, hN, G4)



Can GENIE pass the electron test?