Measurement of neutron production in atmospheric ν interactions @ SK

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Seungho Han (Kyoto)

Abstract

- We report measurement of average neutron capture multiplicity from atmospheric ν events @ Super-K, as a function of Evis in [0.03, 10] GeV
- Include SK4, 5, 6 fully-contained data
- Data compared to predictions of:
  Neutrino event generators (with varied FSI models)
  + Detector simulators (with varied hadron secondary interaction (SI) models)
- Data favors model combinations that predict fewer neutrons
- We discuss model-specific features that vary predictions

1. Introduction

- “Nuclear effects” and missing neutrino energy carried by neutrons crucial in CPV and NMO studies
- Neutrons are also important for SK analyses:
  atmospheric oscillation, proton decay, DSNB
- Neutron production largely simulated using:
  - Neutrino-nucleon interaction model
  - Hadron intranuclear cascade (INC) model
  - Nuclear de-excitation model
- Past studies (T2K, SNO, MINERvA) observed neutron deficits, suggesting inaccuracies in models → Test with SK atmospherics

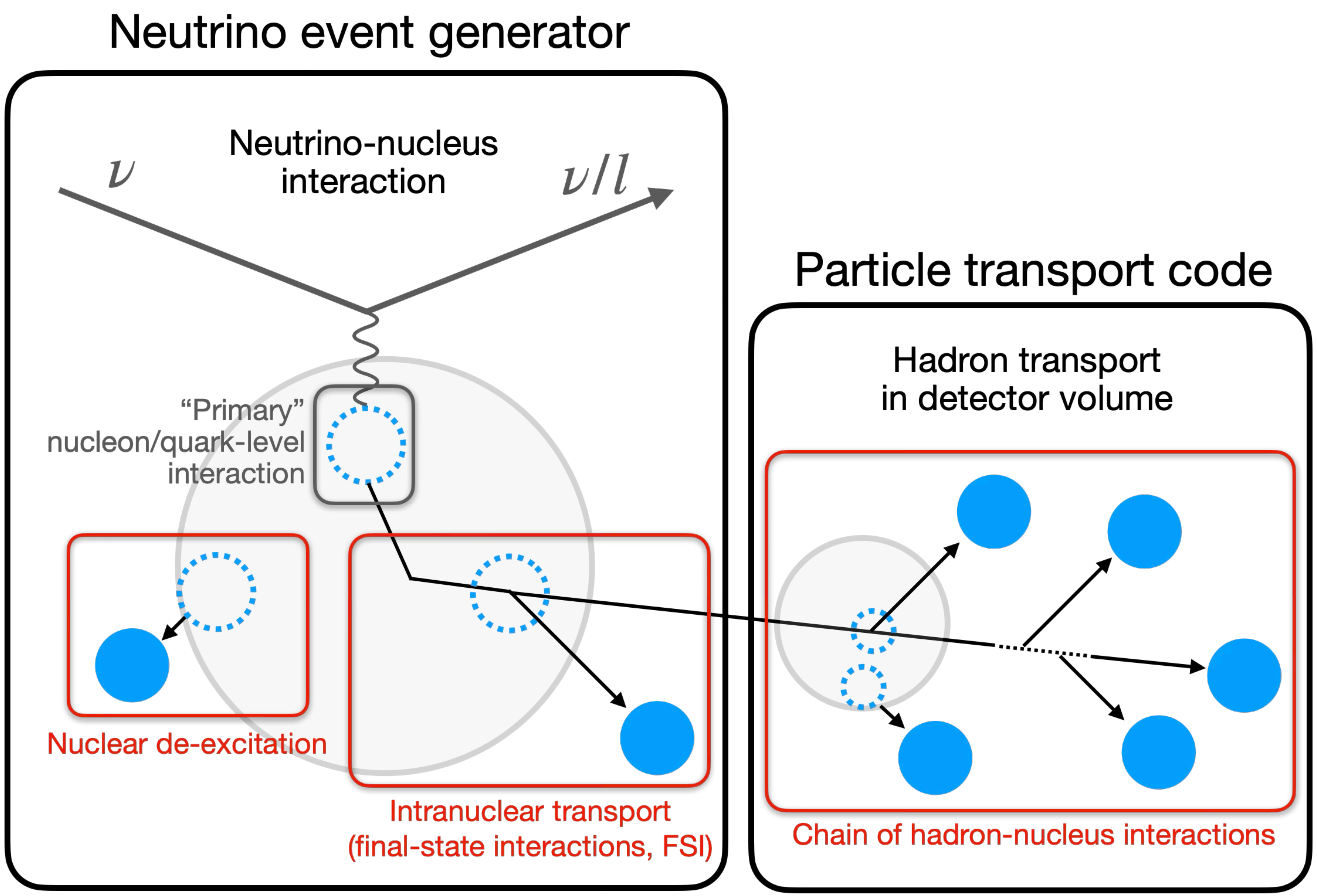


Fig 1. Schematic of neutron production sources, in typical simulation setup

2. SK detector

- SK hardware, location, event trigger system
- Lepton reconstruction with Cherenkov radiation
- Neutrons detected via scattered electrons following (n,γ) reactions
- H(n,γ): 2.2 MeV, Gd(n,γ): 8 MeV
- Detector parameters are monitored using natural/light sources
- Evis scale uncertainty is within 2%
- Description of SK phases

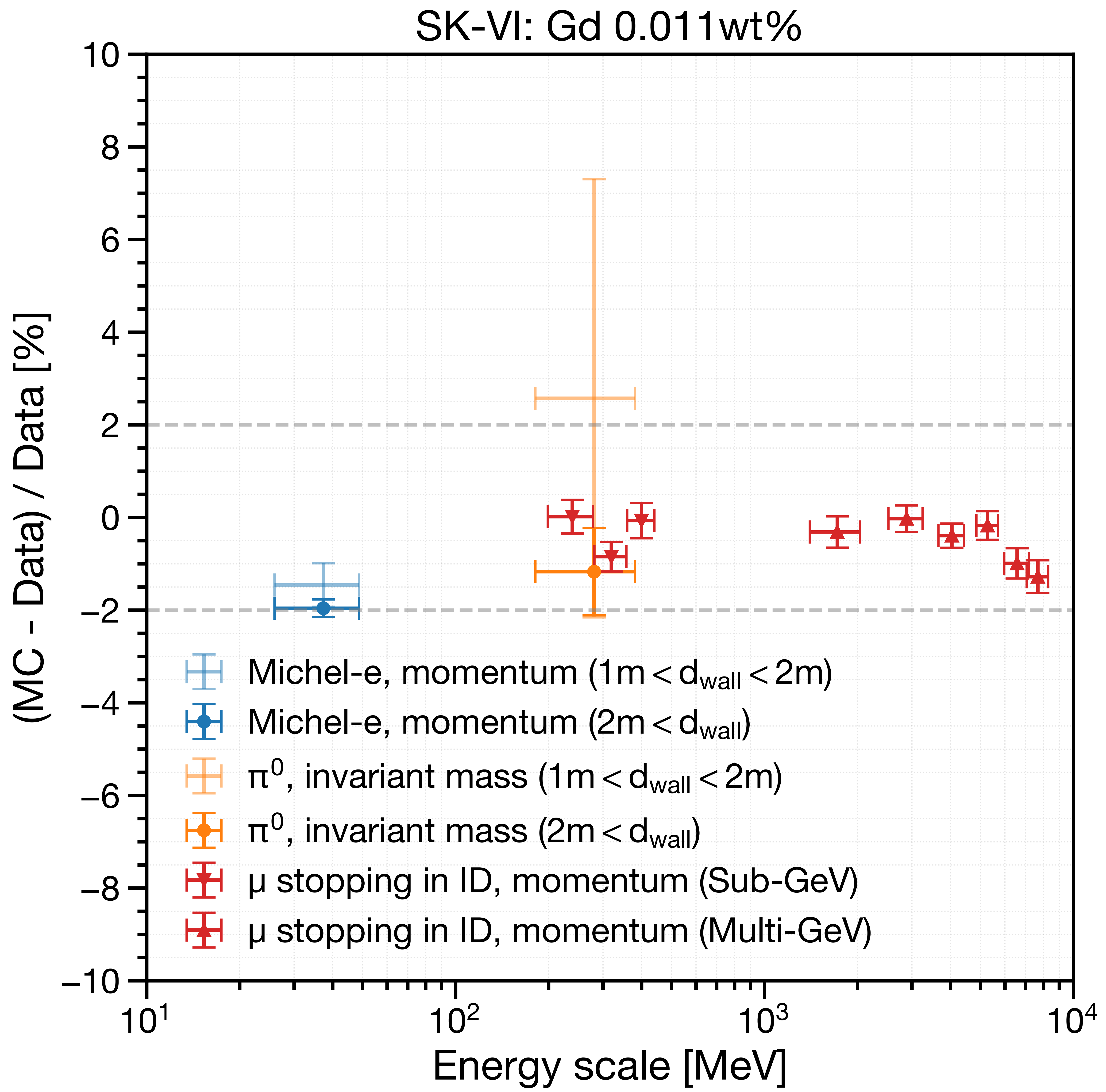


Fig 2. SK6 energy scale error (consistent with SK1-5 in citation)

TABLE I. SK operational phases and neutron-related characteristics. SK-IV, V, VI data were used in this analysis.

Phase	Dates	Livetime [days]	Gd concentration[a] [wt%]	Expected (n,γ) ratio[b] H(n,γ) [%]	Gd(n,γ) [%]	(n,γ) time constant[c] [µs]
SK-I-III	1996-2008	2805.9	-	>99.9	-	No data
SK-IV	2008-2018	3244.4	-	>99.9	-	204.8 ± 9.8
SK-V	2019-2020	461.0	-	>99.9	-	199.8 ± 10.2
SK-VI	2020-2022	564.4[d]	0.0110 ± 0.0001 [16]	56.1 ± 1.5	43.9 ∓ 1.5	116.2 ± 2.3
SK-VII-VIII	2022-present	-	0.0332 ± 0.0002 [17]	29.7 ± 0.7	70.3 ∓ 0.7	61.8 ± 0.1 [17]

[a] Based on the amount of dissolved Gd.

[b] Based on the evaluated thermal (n,γ) reaction cross sections and uncertainties of ENDF/B-VII.1 [15].

[c] Weighted mean of all Am/Be neutron source measurements, explained in Section IV B.

[d] Excludes earlier runs which showed signs of non-uniform Gd concentration, i.e., varying time constant by position.

3. Atmospheric neutrino events

A. Data reduction

- Followed FC selection process as in previous studies
- SHE trigger (N200≥58) required for AFT triggers
- FV: d_wall > 1 m
- BG contamination < 0.2% according to eye-scan

3. Atmospheric neutrino events

B. Reconstruction of prompt Cherenkov rings

- (APFit) Followed typical reconstruction as in previous analyses
- Visible energy definition, its relation to interaction Q^2

SK-VI MC: $\bar{\nu}_\mu$ CCQE, E_ν = 0.63 GeV

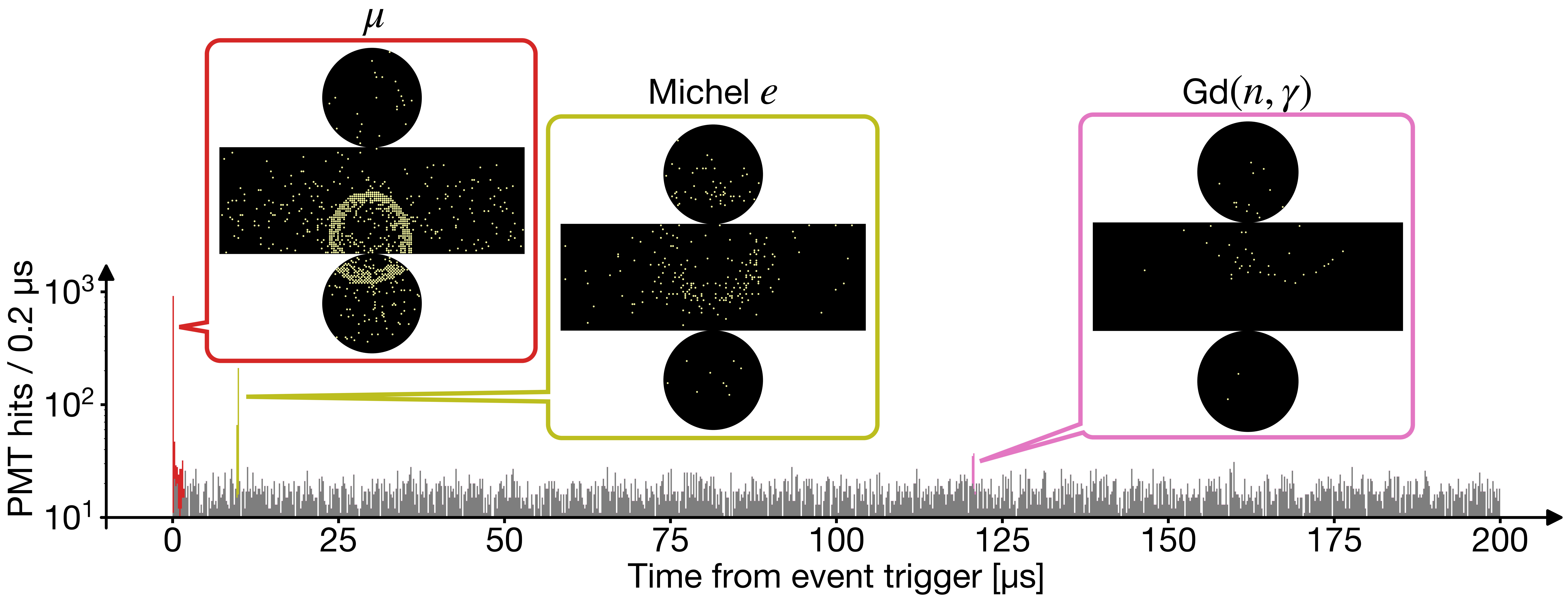


Fig 3. Typical PMT hit time distributions and signal event displays of SK6 MC: $\bar{\nu}_\mu$ CCQE interaction knocking out one neutron

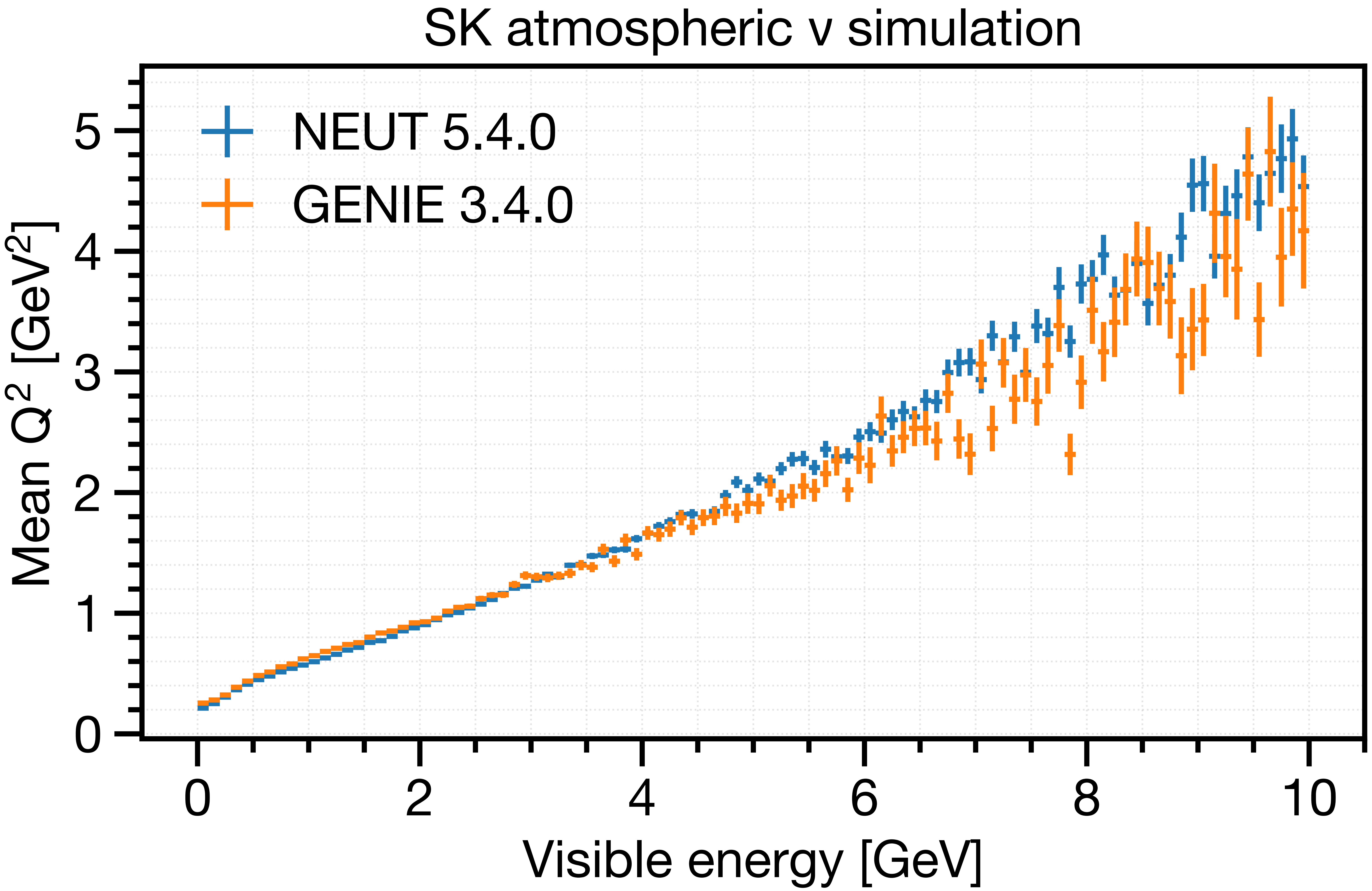


Fig 4. Evis vs. Mean Q2 has a linear relationship

3. Atmospheric neutrino events

C. Baseline simulation setup

- Honda flux, NEUT 5.4.0
- Low-E π FSI (Salcedo et al) High-E π, nucleon FSI (Bertini cascade)
- Hadron SI: GCALOR (NEUT π FSI routine for low-E π)
- For SK6:
  - ENDF/B-VII.1 for <20 MeV neutron xsec
  - ANNRI-Gd model for Gd(n,γ) cascade
- Detector noise taken from random trigger data
- 500 years simulation, Prob3++ osc probability applied

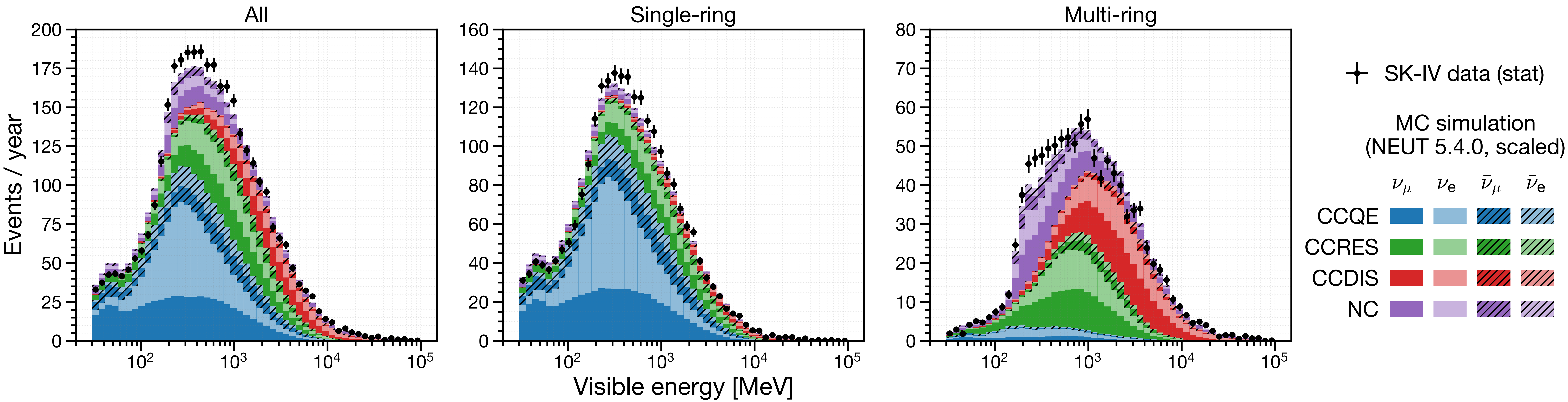


Fig 5. Simulated Evis distribution and SK4 data (reasonable agreement)
Single-ring is CCQE-rich, Multi-ring is mostly non-QE

4. Neutron signal selection

A. Signal selection algorithm

- Subtract photon TOF from neutrino vertex to PMTs, and apply PMT hit trigger (N14≥5 for SK4/5, N14≥7 for SK6)
- Apply neural network trained with thermal neutron MC
  - Network architecture, training conditions, etc.
  - Separate network trained and applied for each SK phase
- Michel electron rejection (N14<50 || Time from trigger >20 μs): reject ~98% Michel electrons when applied to stopping μ sample

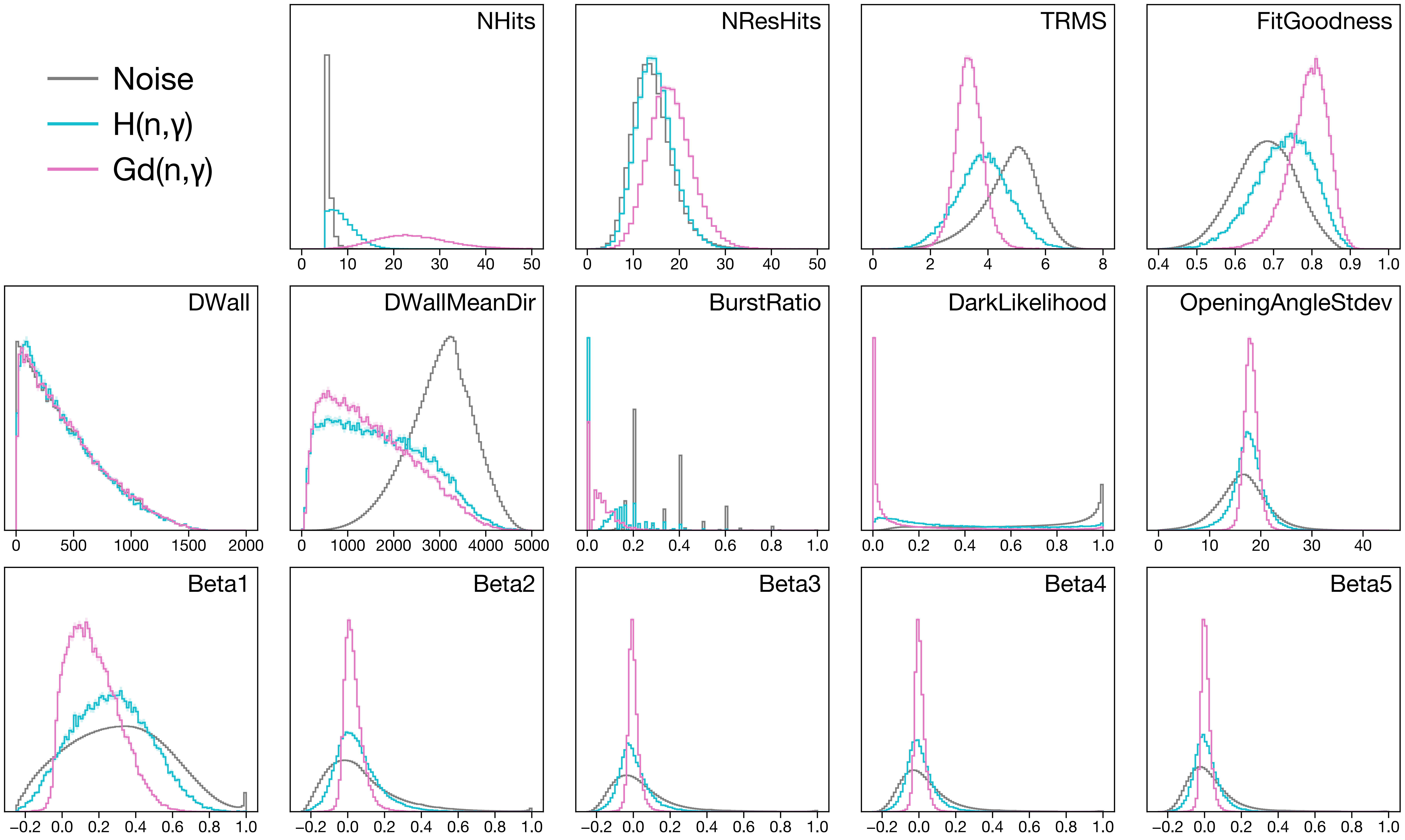
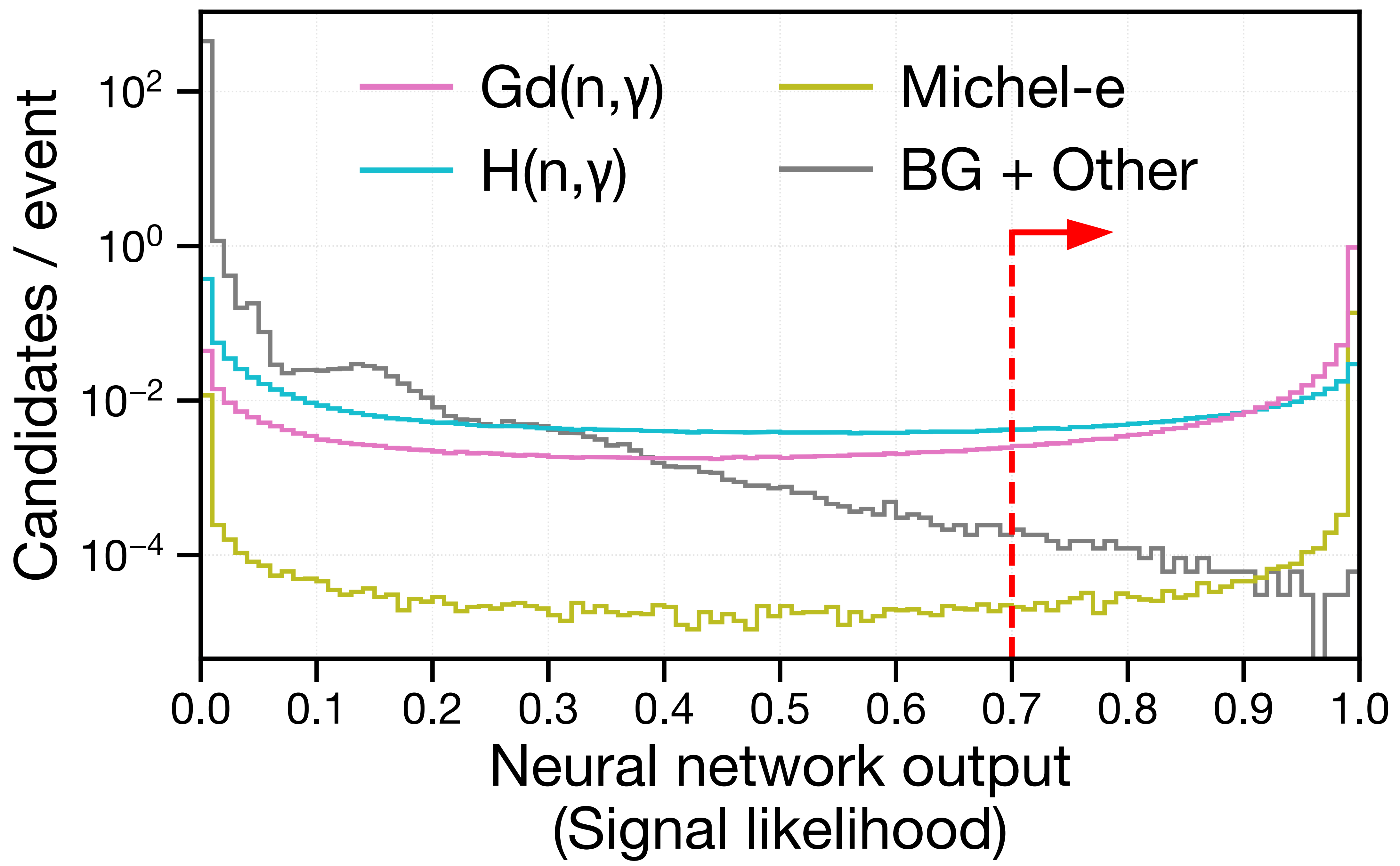


Fig 5. SK6 training data features, from thermal neutron MC



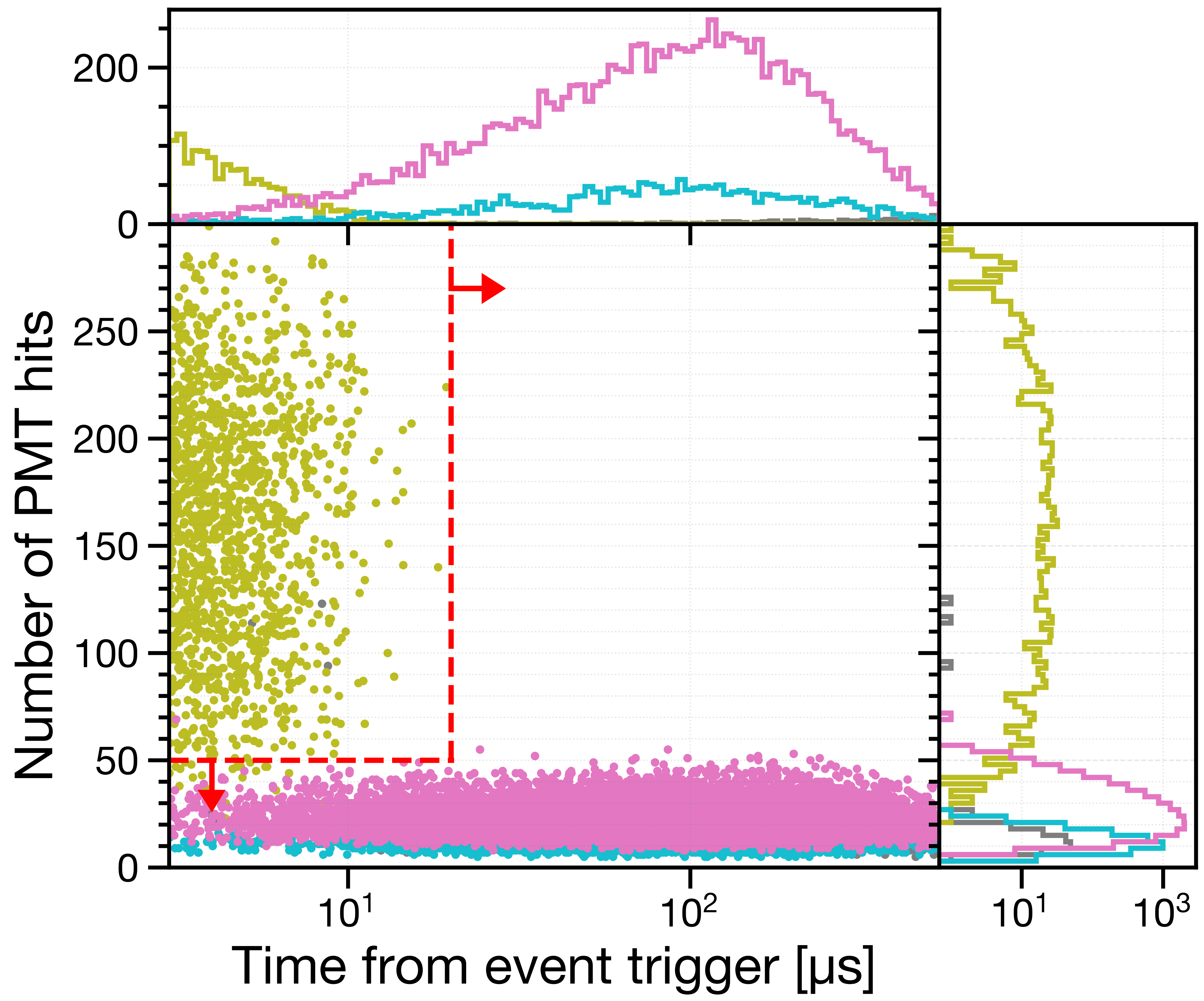


Fig 7. Neural network output (atmospheric MC) and cut,
and performance of Michel-e cut on PMT hits and time from trigger

4. Neutron signal selection

B. Signal selection performance on calibration data

- AmBe neutron source (provides 1γ1n control sample)
- Use BGO scintillator to trigger on γ scintillation
- Tuned simulation accounts for continuous source activity and pile-ups
  Successfully reproduced γ scintillation peak
- Pile-up BG without time correlation with trigger were estimated with fit
- Uncertainty in estimated efficiency: 7% (SK4), 6% (SK5), 4% (SK6)

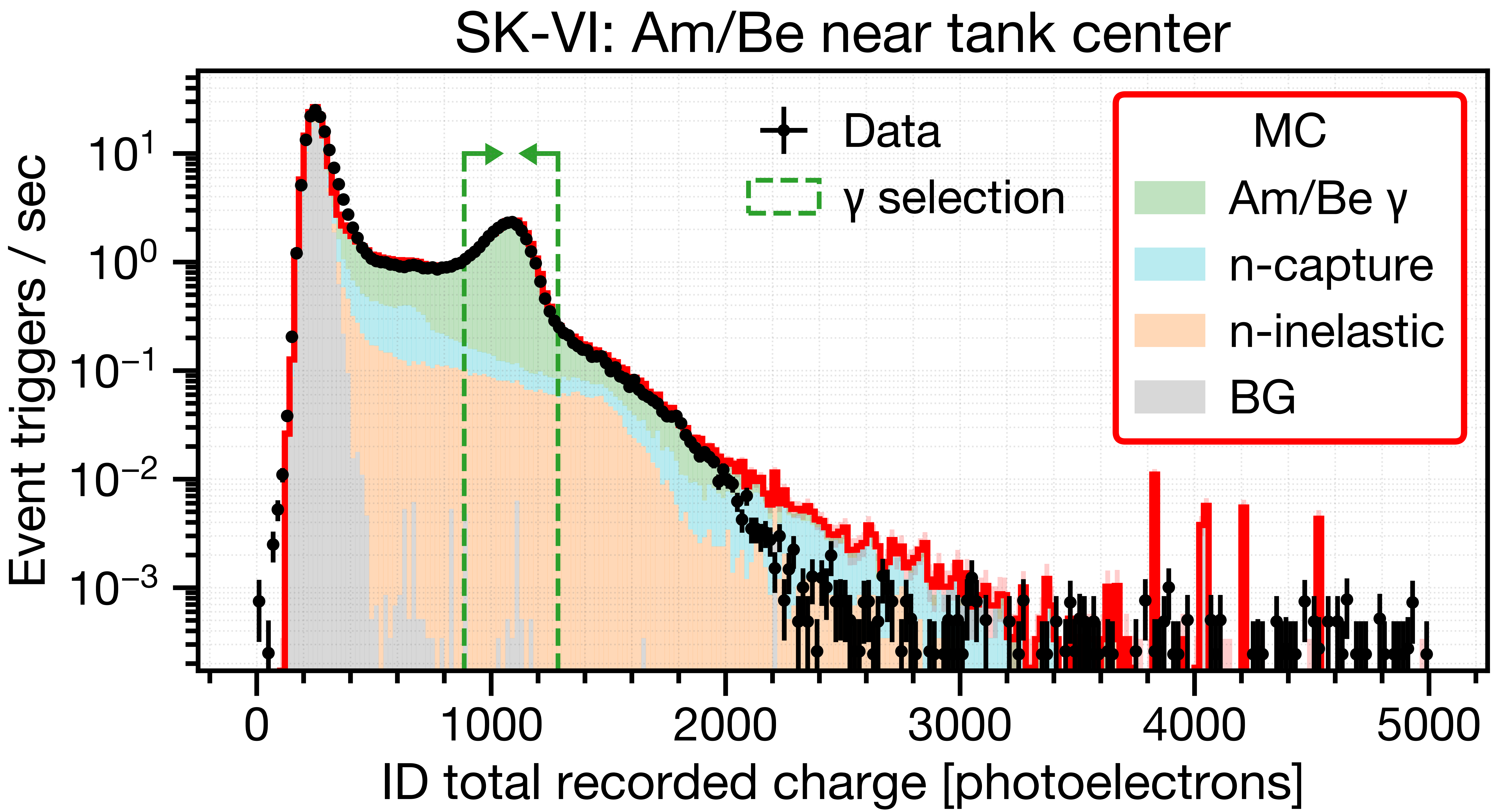


Fig 8. Recorded trigger charge (QISMSK) distribution: AmBe data vs MC
In selection: ~95% due to γ (1n events) ~5% due to BG (0n, 1n, 2n,..)

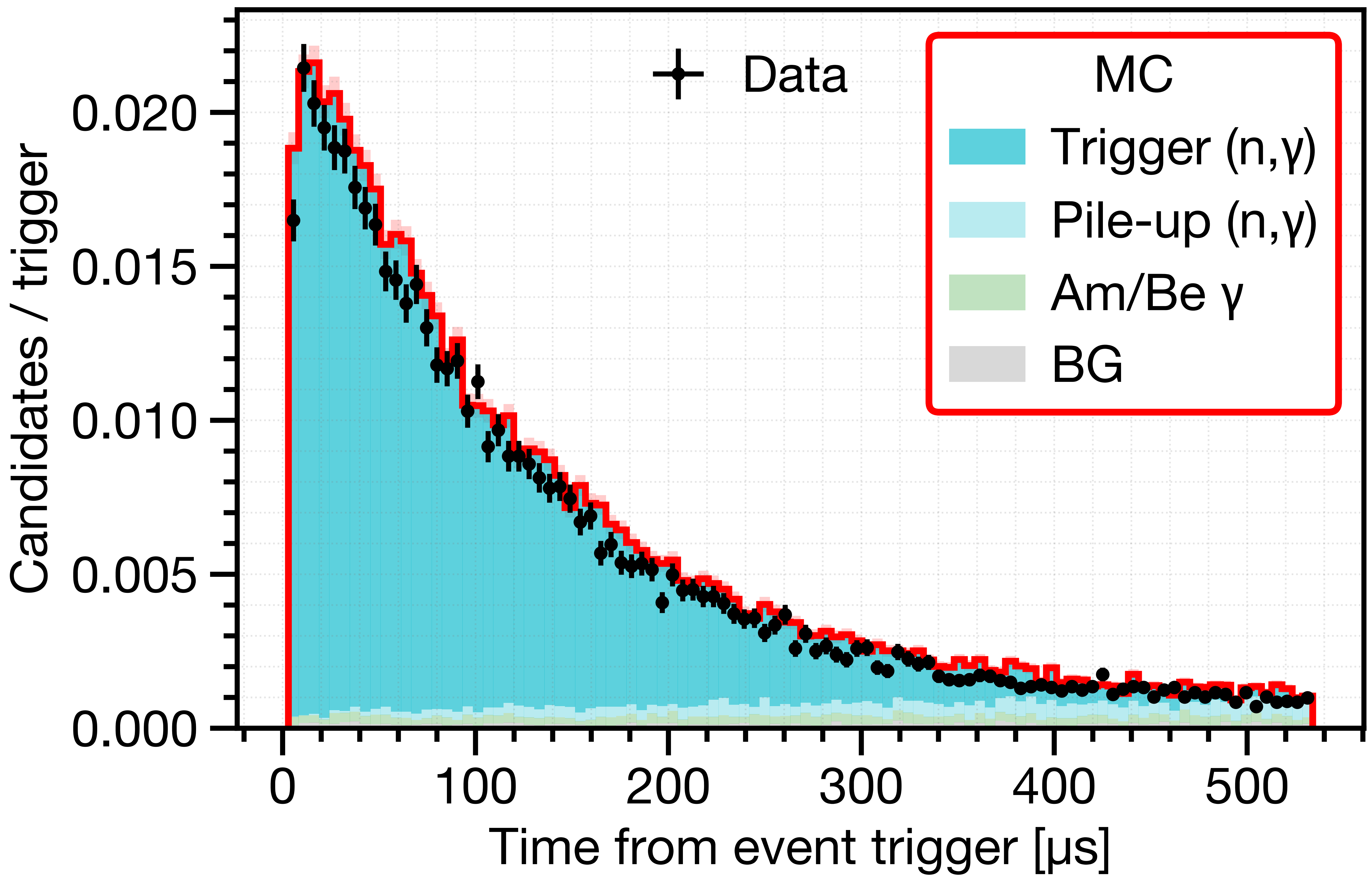


Fig 9. Neutron capture time distribution
Pile-ups and other BG estimated with fit:

$$f(t) = A(1 - e^{-t/\tau_{\mathrm{thermal}}})e^{-t/\tau_{\mathrm{capture}}} + B \quad \text{Eq (3)}$$

4. Neutron signal selection

B. Signal selection performance on calibration data

- In SK6, AmBe data and MC estimated efficiencies were off by 10%, much larger than estimated error of 4%
- This was due to Geant4 overestimating thermal motion of hydrogen bound to water molecule, resulting in ~20% higher Gd n-capture ratio
- This was corrected by applying appropriate scaling to MC efficiencies
- Neutron capture time distribution was consistent with prediction based on thermal neutron capture cross sections

TABLE II. Major sources of systematic uncertainty in the neutron detection efficiency estimated with the Am/Be neutron source.

Source	SK-IV	SK-V	SK-VI
Am/Be neutron characterization	0.5%	0.9%	0.5%
Detector response	2.2%	3.3%	1.2%
Bias due to calibration setup	6.9%	4.6%	1.1%
Gd(n,γ) fraction	-	-	2.1%
Gd(n,γ) γ emission model	-	-	2.6%
Total	7.3%	5.7%	3.8%

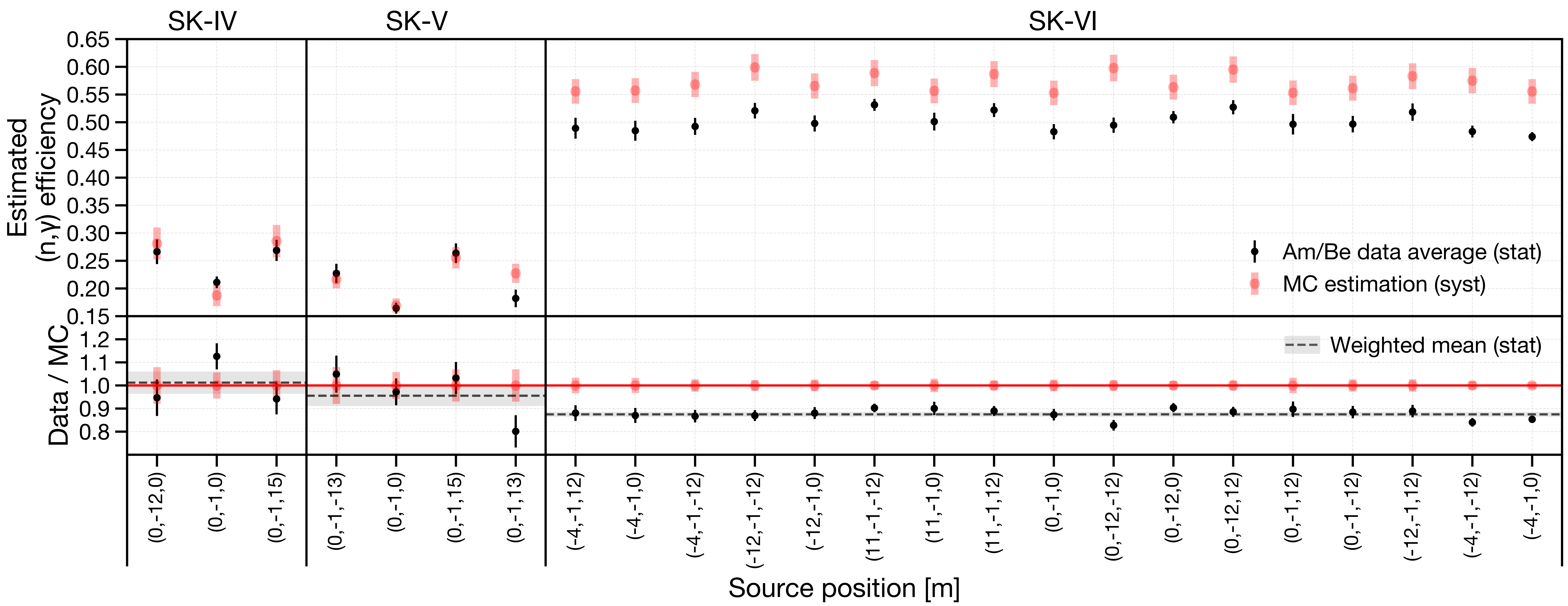


Fig 10. Estimated signal efficiency vs. AmBe source position

SK6 MC efficiencies are 10% higher than data estimates

MC correction factors: 1.01±0.04 (SK4), 0.96±0.04 (SK5), 0.88±0.01 (SK6)

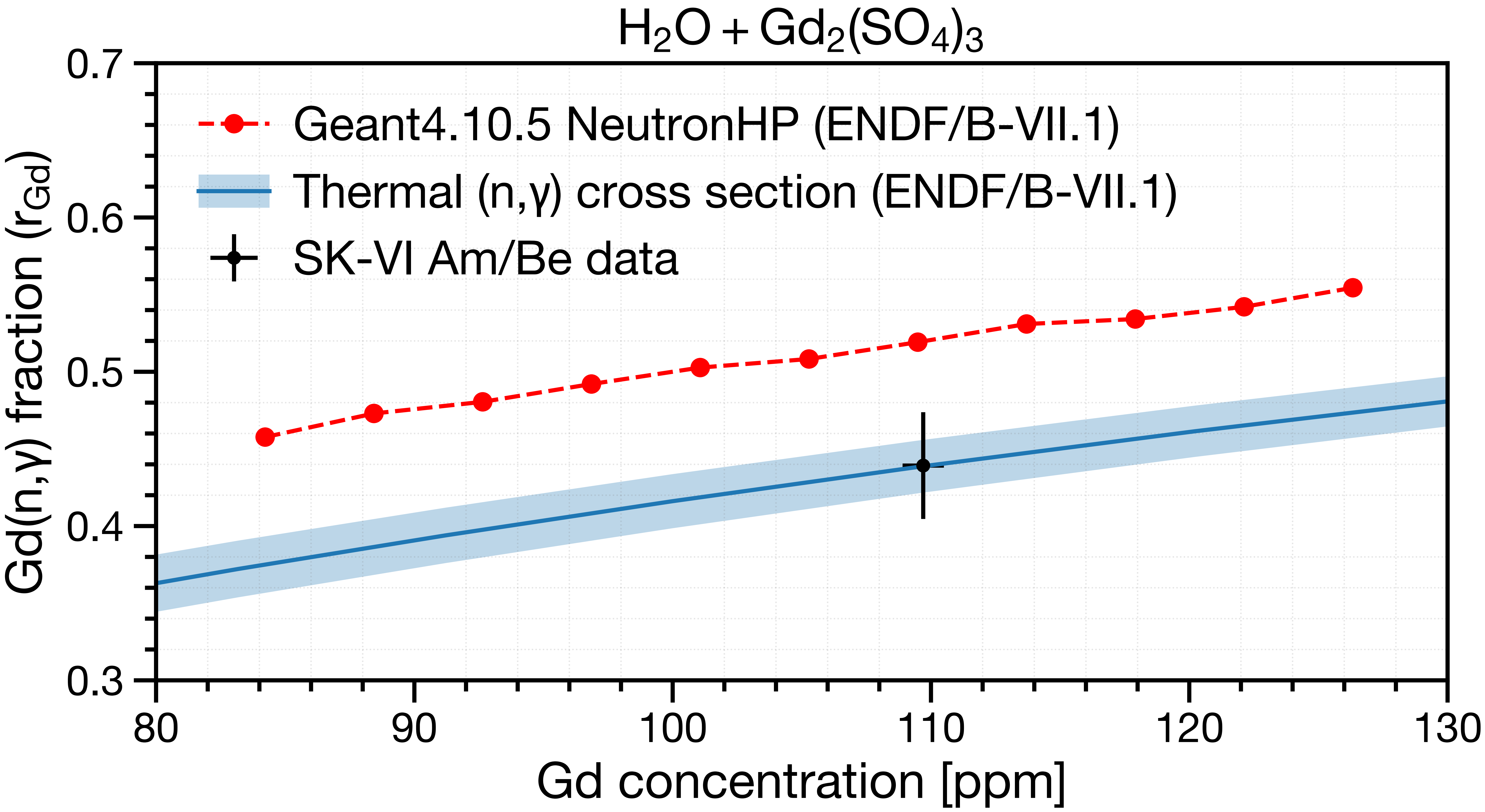


Fig 11. Gd concentration vs. Fraction of neutron captures on Gd

Geant4 prediction is 20% higher than data estimate and xsec-based prediction

5. (n,γ) multiplicity estimation

$$\langle N \rangle = \left\langle \frac{N_i^{\mathrm{detected}} - N_i^{\mathrm{BG}}}{\epsilon_i} \right\rangle$$ per Evis bin (Eq 5)

- BG contamination N^{BG} and signal efficiency ε were estimated based on non-linear regression model (called GAM) trained on atmospheric neutrino MC
- Input features: Evis, Nring, Ring PID, vertex position
- Total uncertainty 2-30% for Evis<100 MeV, otherwise ~15%

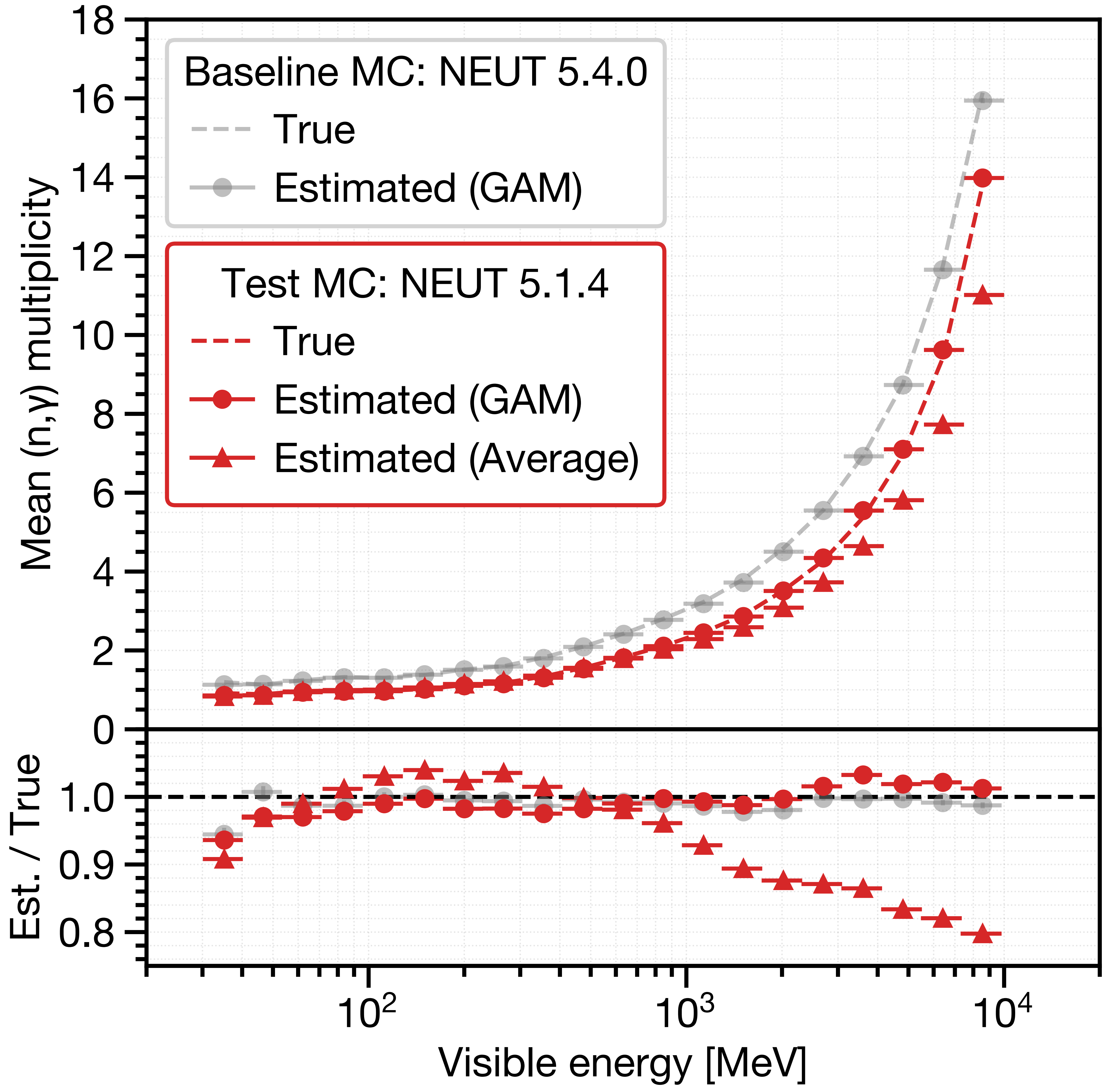


Fig 12. Performance of non-linear regression model (GAM) in estimating true (n,γ) multiplicity, compared with using average signal efficiency

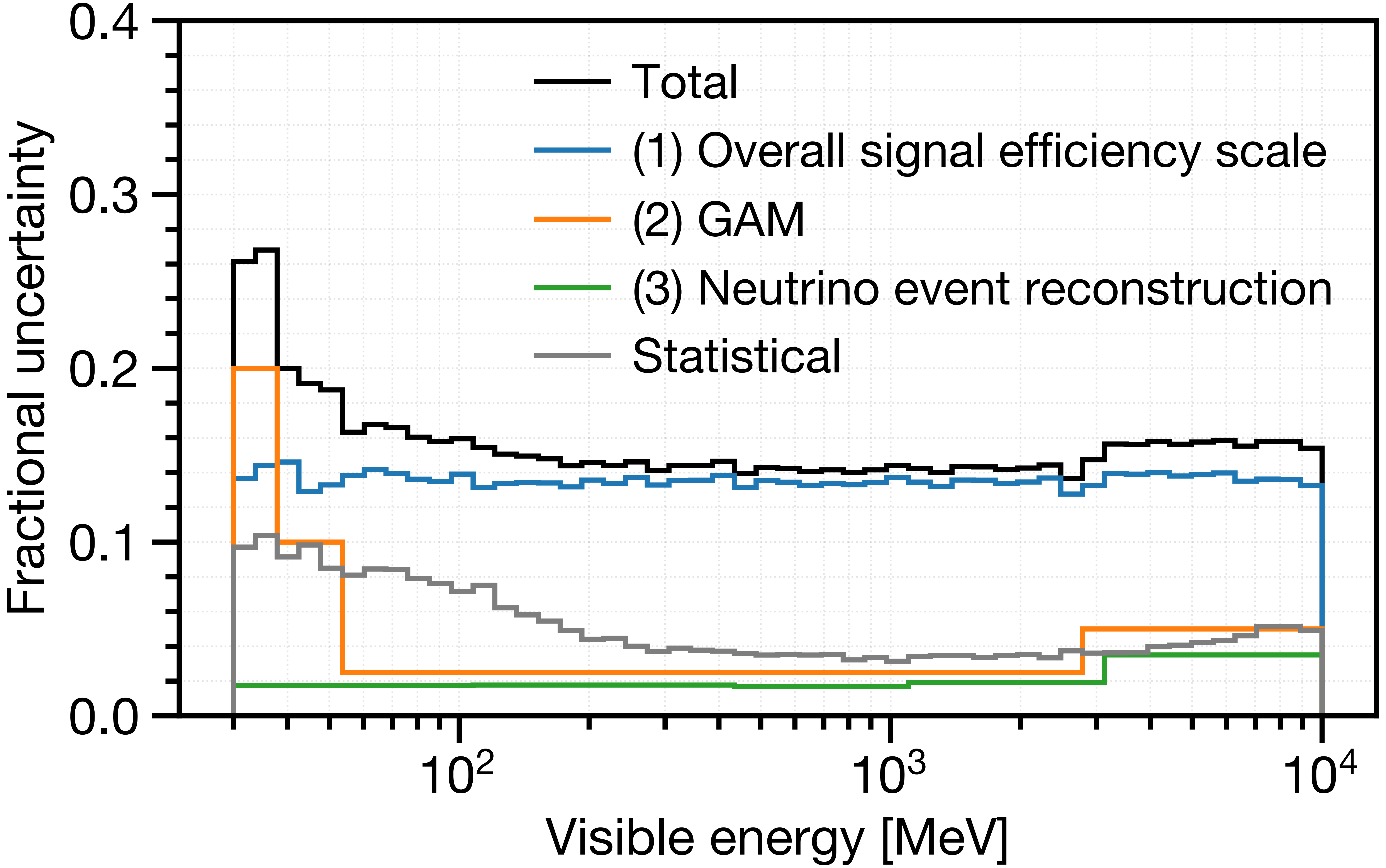


Fig 13. Fractional uncertainty per Evis bin

6. Tested interaction models

Neutrino event generators

- NEUT 5.4.0 (large QE fraction due to a bug in nuclear binding E)
- NEUT 5.6.3 (same FSI, reduced QE fraction due to binding E correction)
- GENIE 3.4.0, FSI: hA (table-based model, no Pauli blocking, de-excitation)
- GENIE 3.4.0, FSI: hN (tuned cascade model, no Pauli blocking, de-excitation)
- GENIE 3.4.0, FSI: Geant4 Bertini (cascade model with some corrections)
- GENIE 3.4.0, FSI: INCL (cascade model considering nucleon motion correlation)

Use “G18a_10x_02_11b” physics tune for GENIE 3.4.0, using similar xsec models for QE/RES models as NEUT (hadronization for DIS may be slightly different)

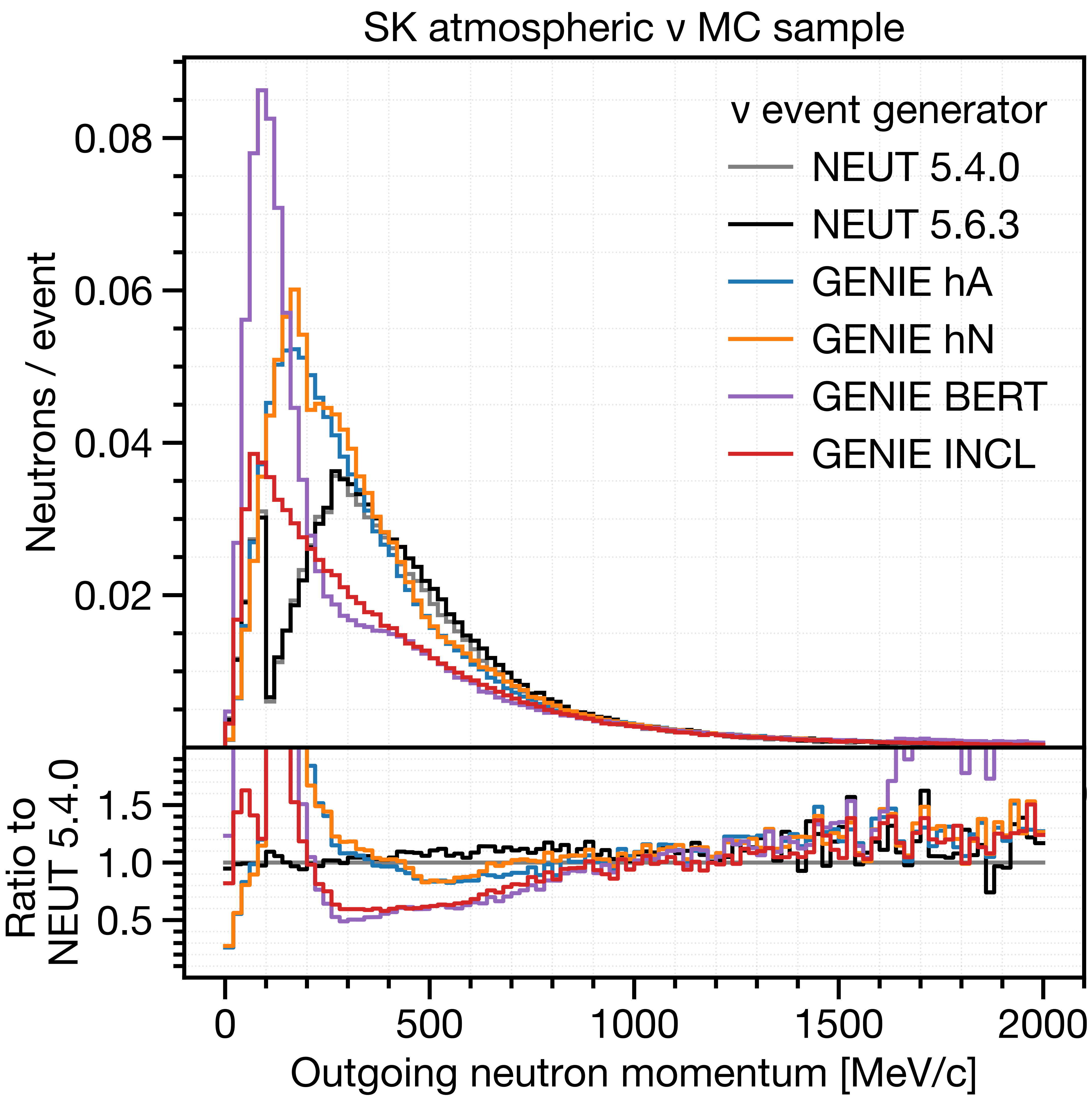


Fig 14. Predictions of outgoing neutron momentum after FSI (stark model differences below 1 GeV/c)

6. Tested interaction models

Secondary interaction (SI)

Intranuclear hadron transport	Nuclear de-excitation
SK4/5 default	Bertini native (parametrized)
SK6 default (different low-E n xsec)	Bertini native
Geant3 GCALOR (different low-E π SI)	Bertini native
Geant4 Bertini (GCALOR + corrections)	Bertini native
Geant4 Bertini	Precompound (data-driven)
Geant4 INCL	Precompound

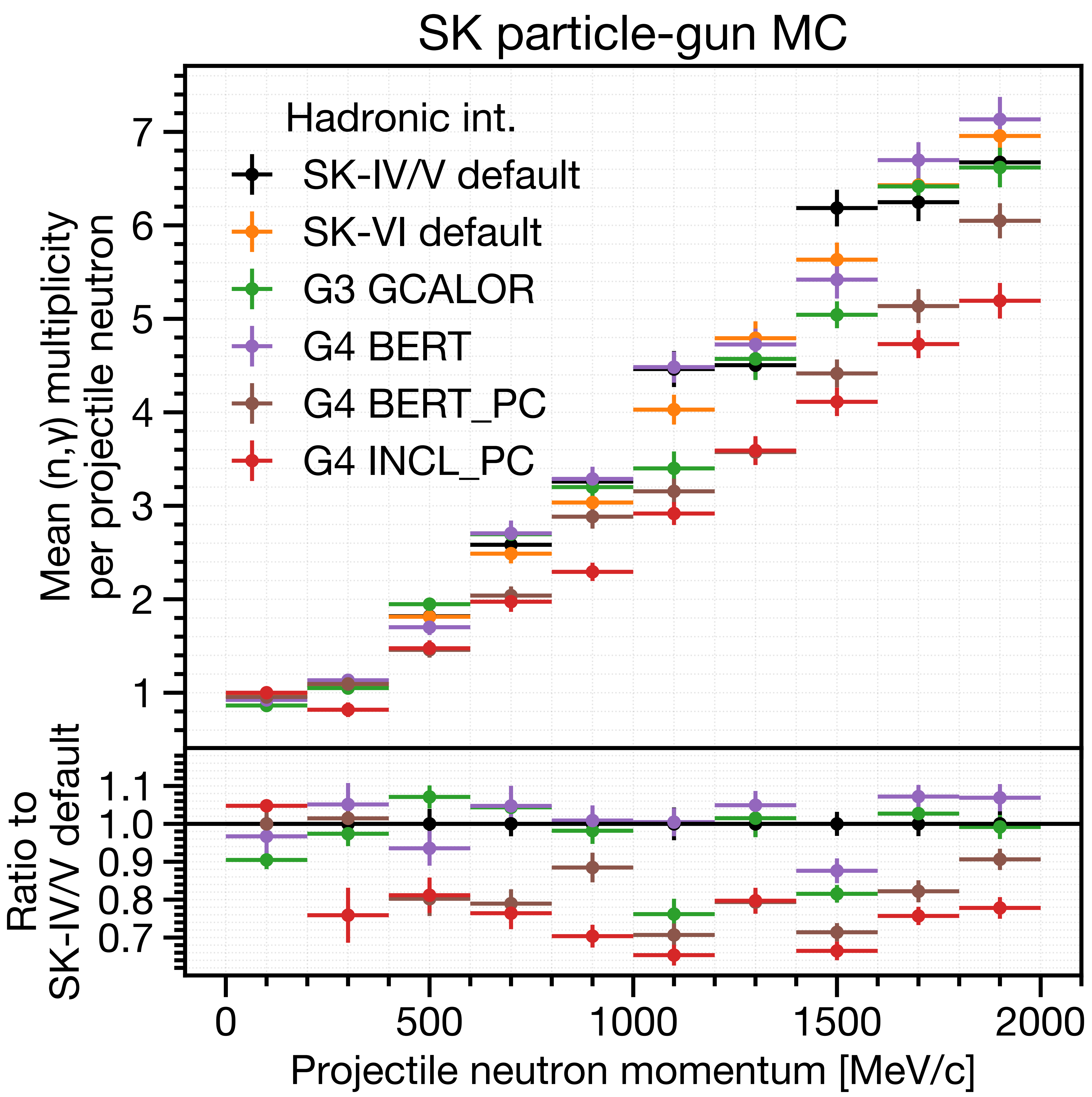


Fig 15. Mean (n,γ) reactions produced per projectile neutron (particle-gun MC with different SI models)

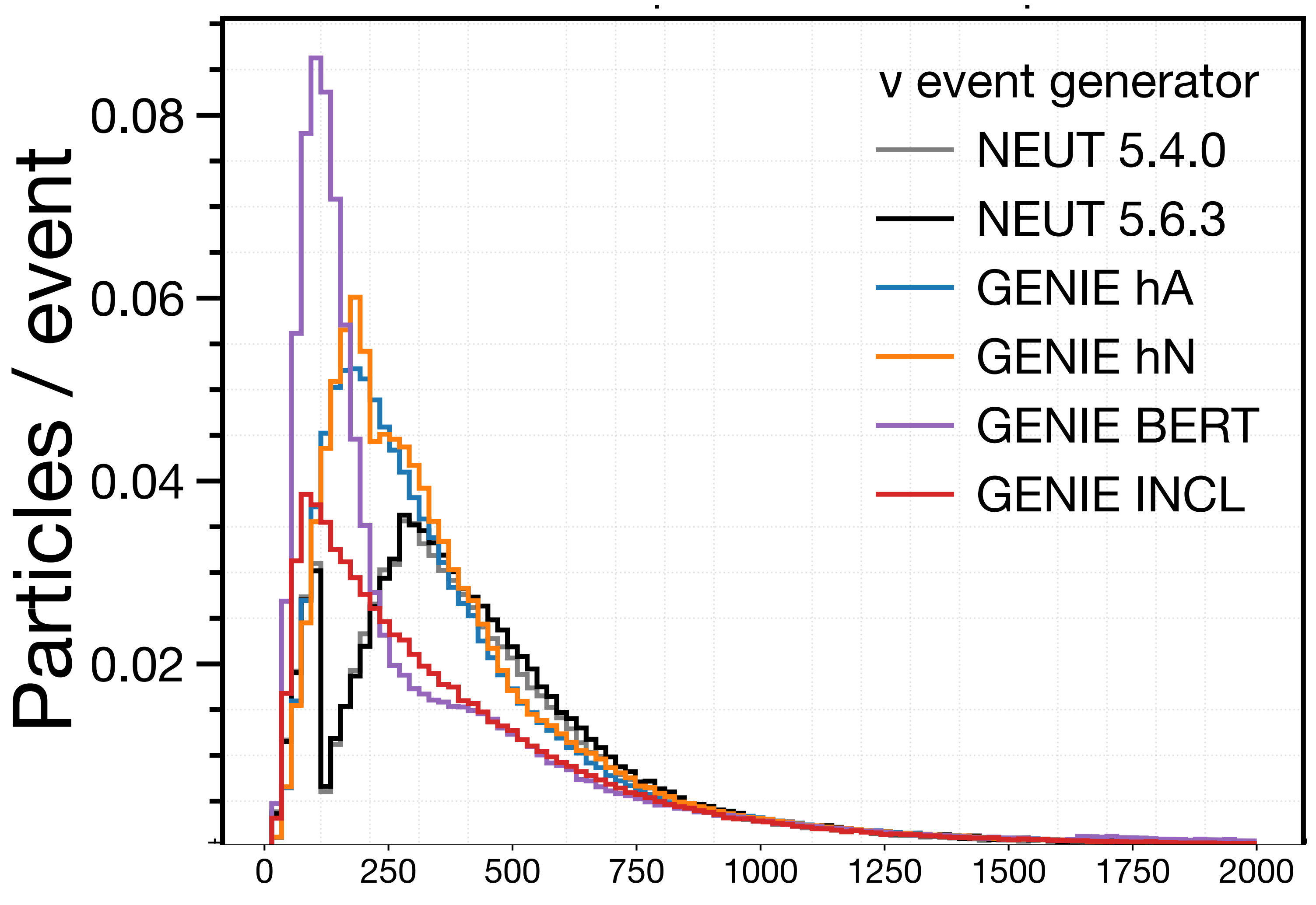
6. Tested interaction models

How to make predictions without full MC

Neutrino event generator
(neutrino target $^{1}H/^{16}O$)

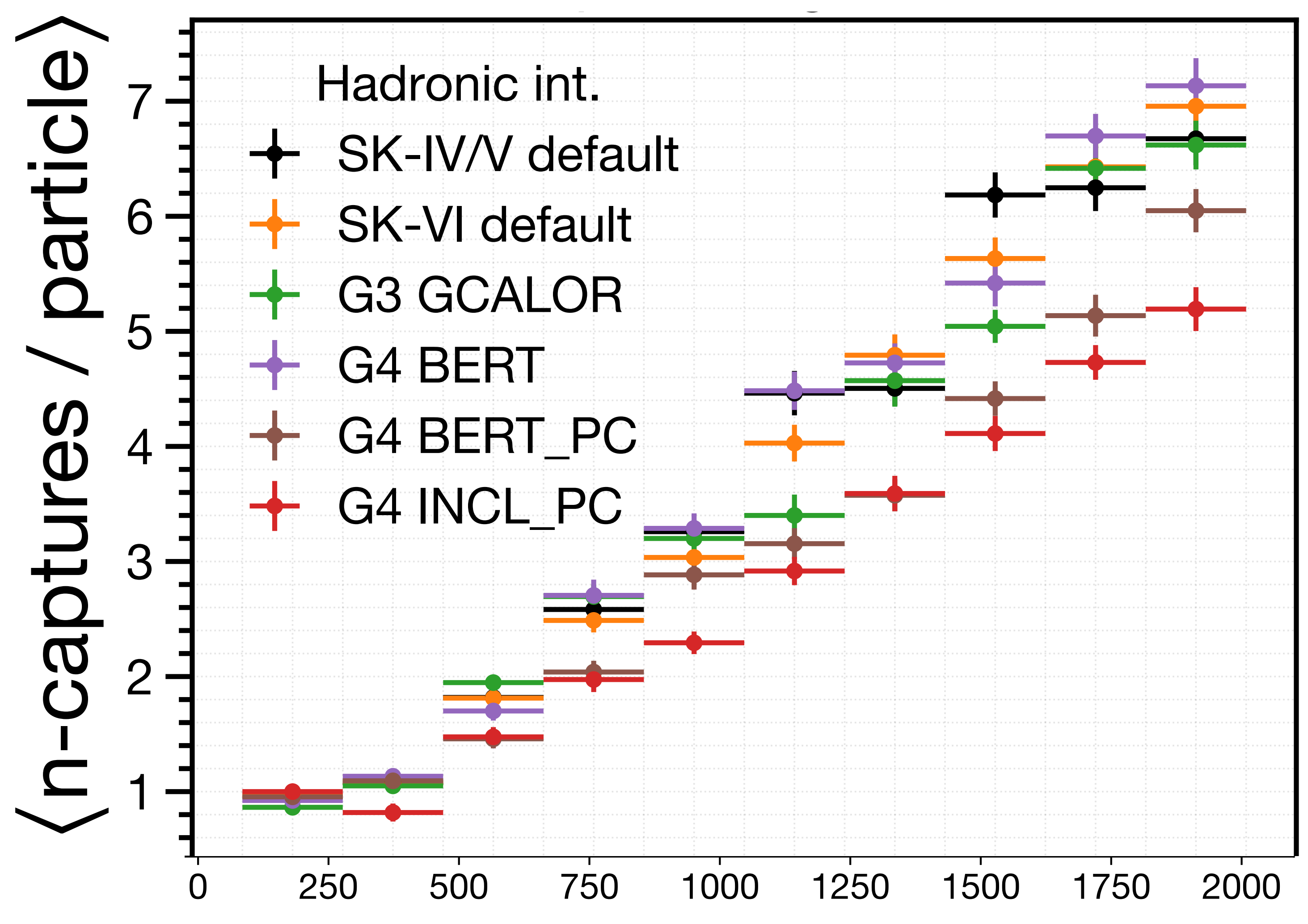
Detector simulator
(water volume)

$\sum_{\in \{n,\, p,\, \pi^{\pm},\, \mu^{-}\}}$ (



Outgoing particle momentum
(after FSI) [MeV/c]

x



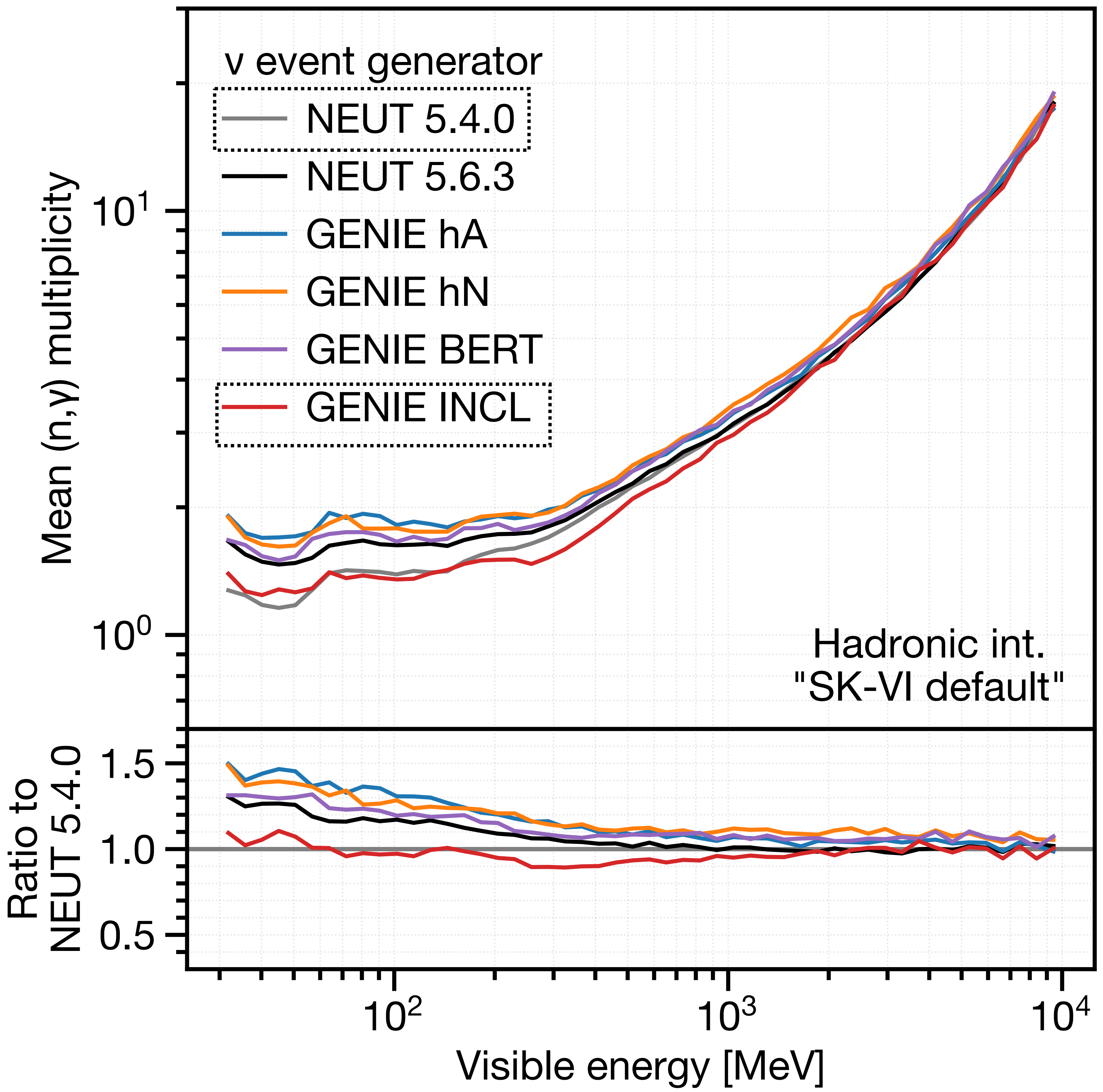
Incoming particle momentum
[MeV/c]

) $= \left\langle \dfrac{\#n}{\nu \text{ event}} \right\rangle$

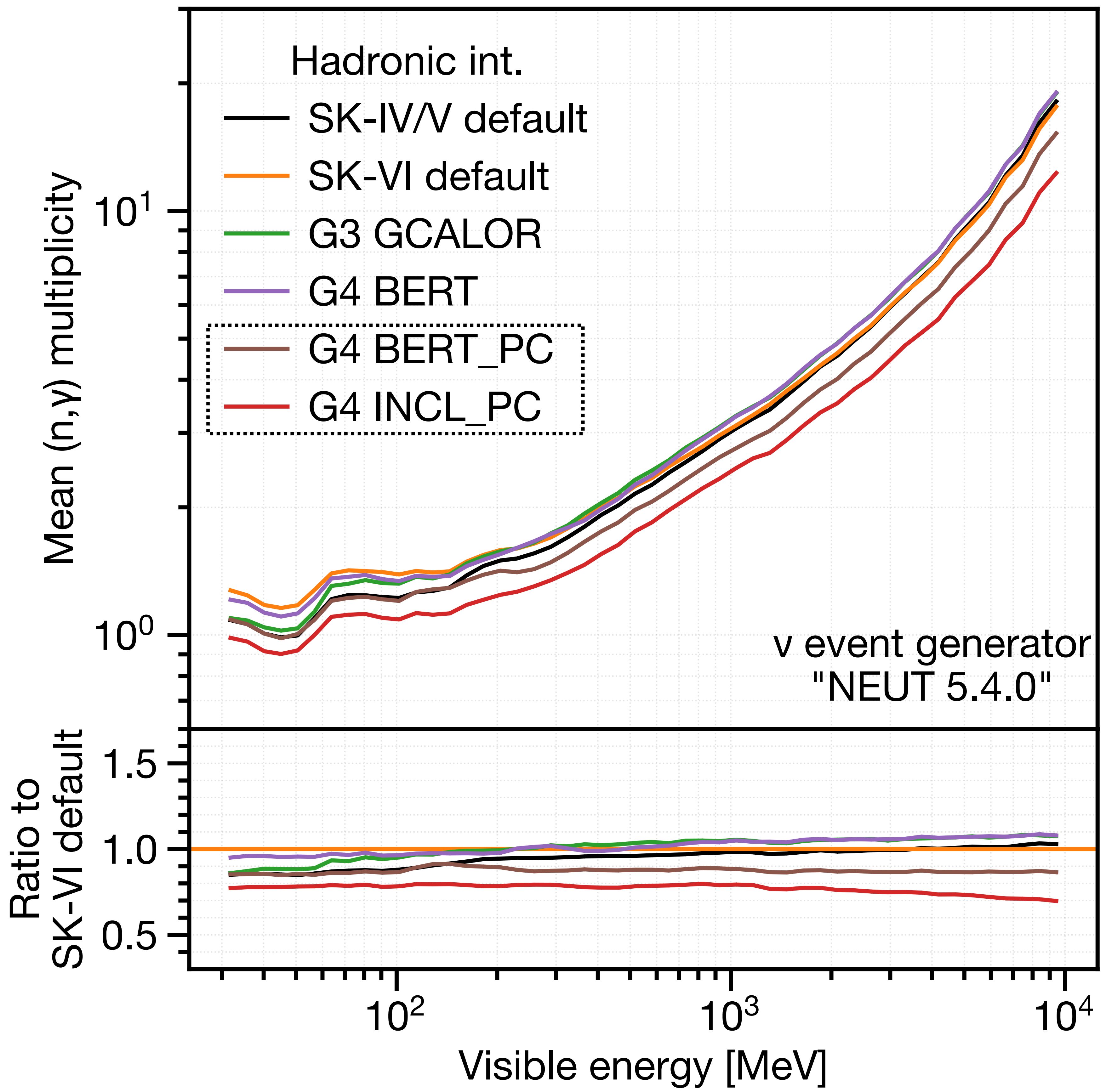
Models that predict lower neutron production

Fig 16. Differences in model predictions

Varying FSI models



Varying SI models



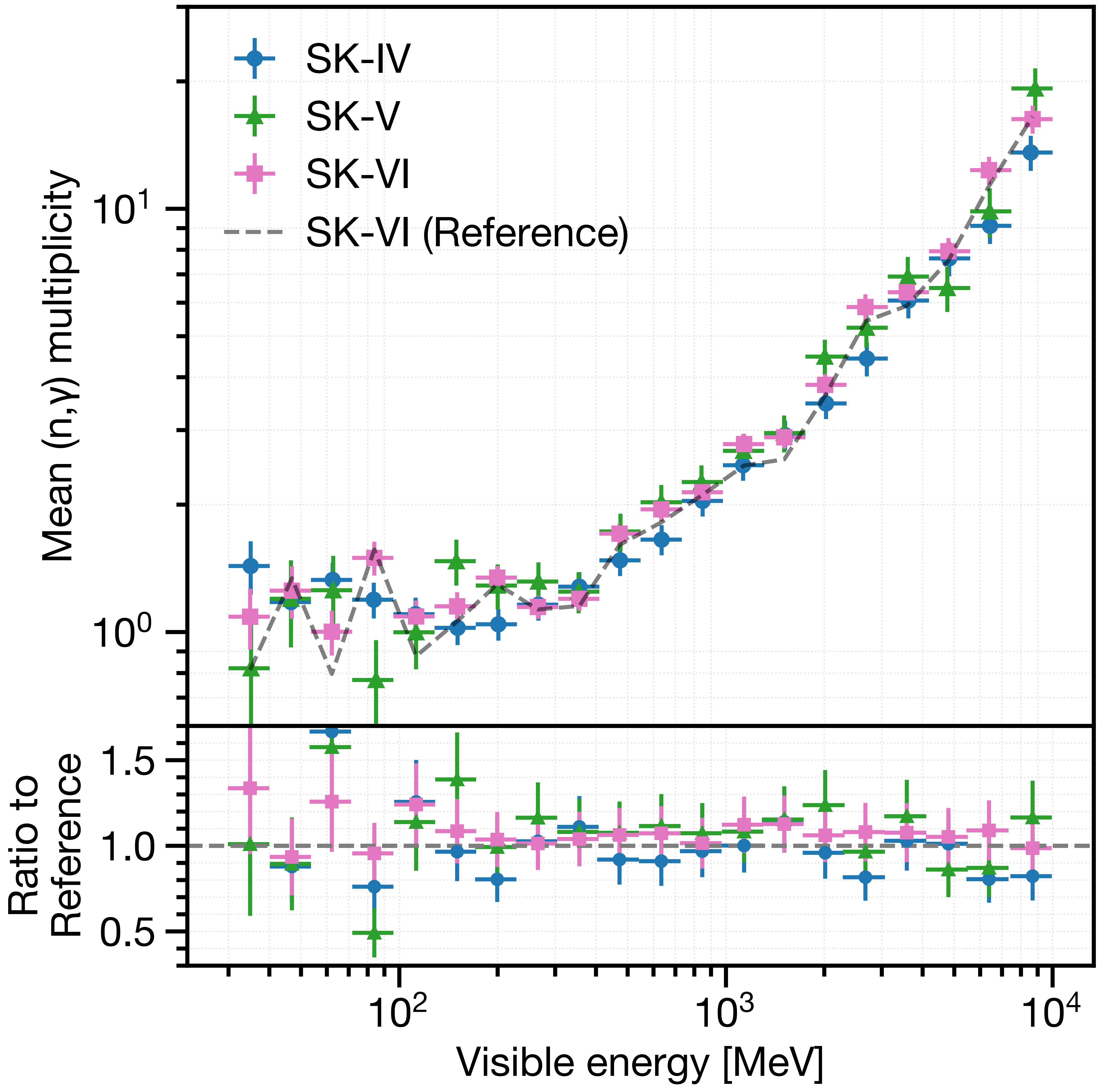
Sub-GeV: FSI impact large (3-50%) SI impact small (2-30%)

Multi-GeV: FSI impact small (1-20%) SI impact large (3-40%)

7. Results

TABLE III. Summary of atmospheric neutrino events and detected neutron signals in the final data sample. $\langle N \rangle_{\text{total}}$ denotes the average (n, γ) multiplicity and its systematic uncertainty. Other errors shown are purely statistical.

	SK-IV	SK-V	SK-VI
ν events	29,942	4,231	5,203
Events/day	9.23 ± 0.05	9.18 ± 0.14	9.22 ± 0.13
n signals	15,705	2,035	5,752
n signals/event	0.525 ± 0.004	0.481 ± 0.011	1.106 ± 0.015
$\langle N \rangle_{\text{total}}$	2.04 ± 0.34	2.33 ± 0.27	2.36 ± 0.21

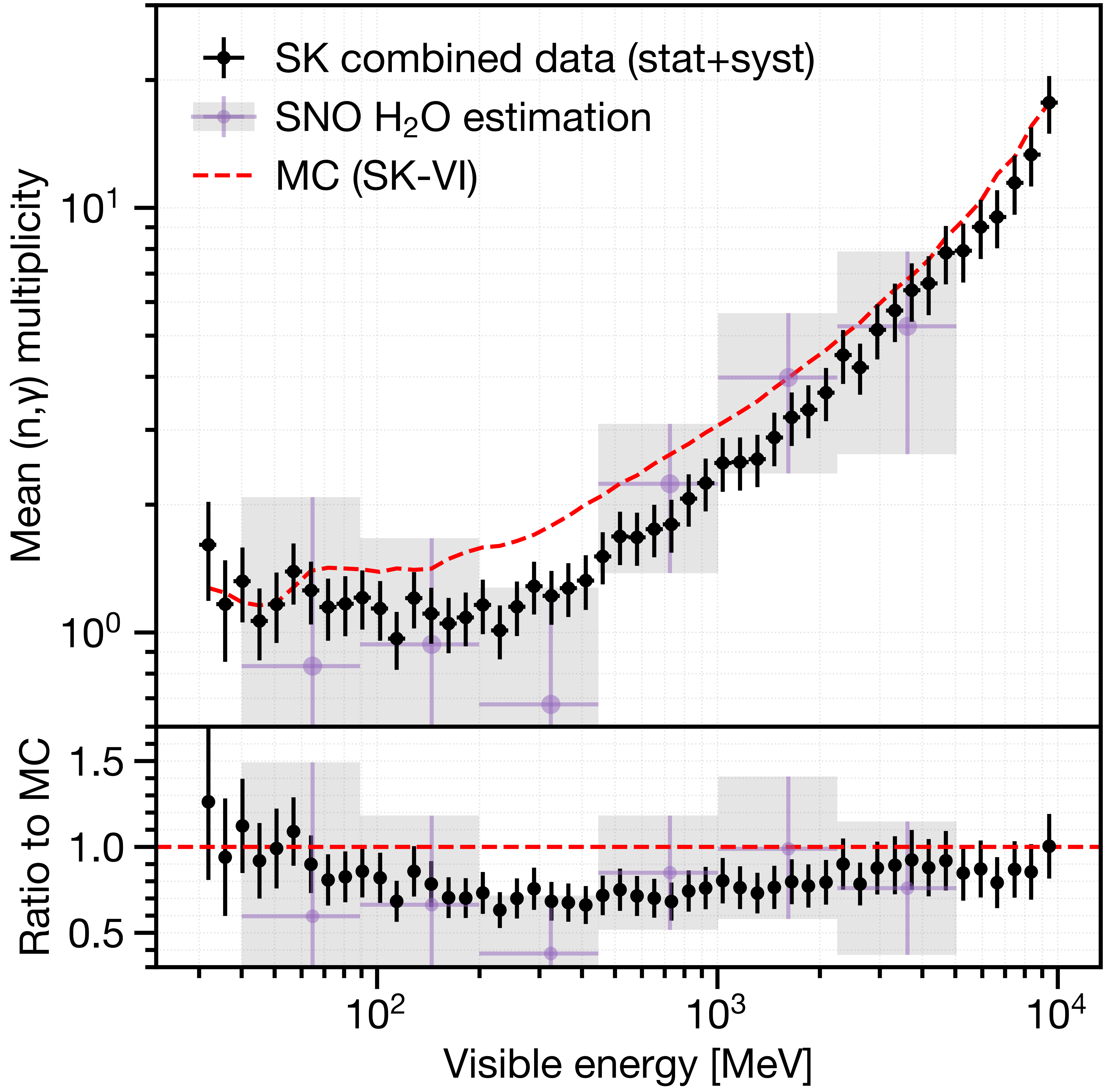


“SK6 (Reference)” uses
neutron detection algorithm that applies
BONSAI for Gd(n,γ) vertex reconstruction
so efficiency less dependent on FSI/SI models

whereas the nominal results
assume all n-captures near ν vertex (APFit),
so efficiency varies with FSI/SI models

Scale difference with “SK6 reference”
taken as syst uncertainty in efficiency scale

Fig 17. SK phase consistency of the results



A. Effective metrics for model evaluation

1. Linear increase in [0.3,10] GeV
→ Fit "slope"
(since slope is not affected by scale, consider stat errors only)

2. Large dip in [0.1, 0.3] GeV
→ Measure multiplicity in this bin: "Low-E multiplicity"

Off by 3-40% in sub-GeV

Fig 18. Combined data results vs. SNO "water" estimation vs. SK6 MC

consistent

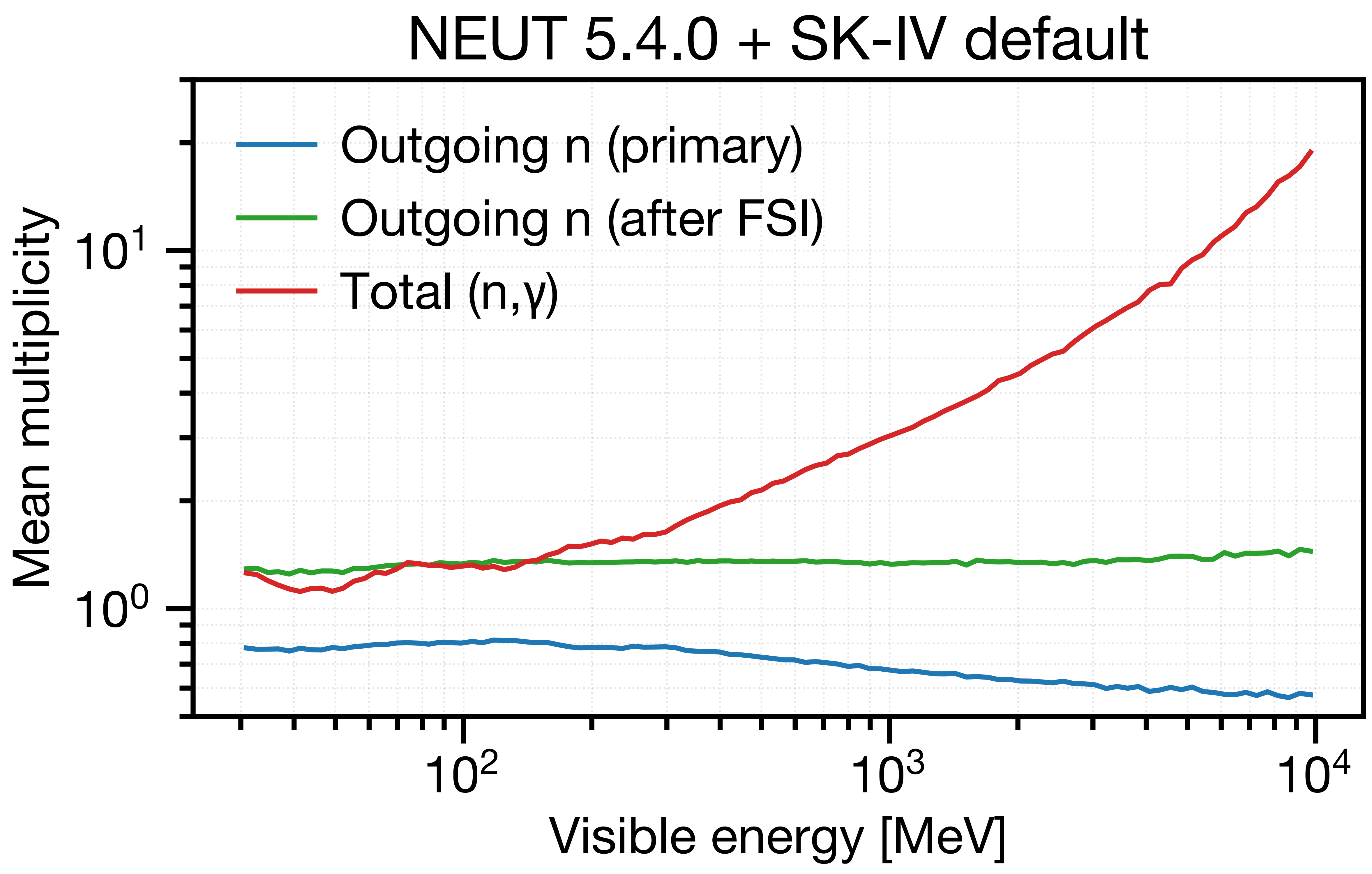


Fig 19: Neutron production source vs. visible energy

- Outgoing neutrons from neutrino-nucleus interaction mostly constant in visible energy
- Slope should be determined mostly by the SI model
- Low-E multiplicity should be relatively sensitive to FSI models

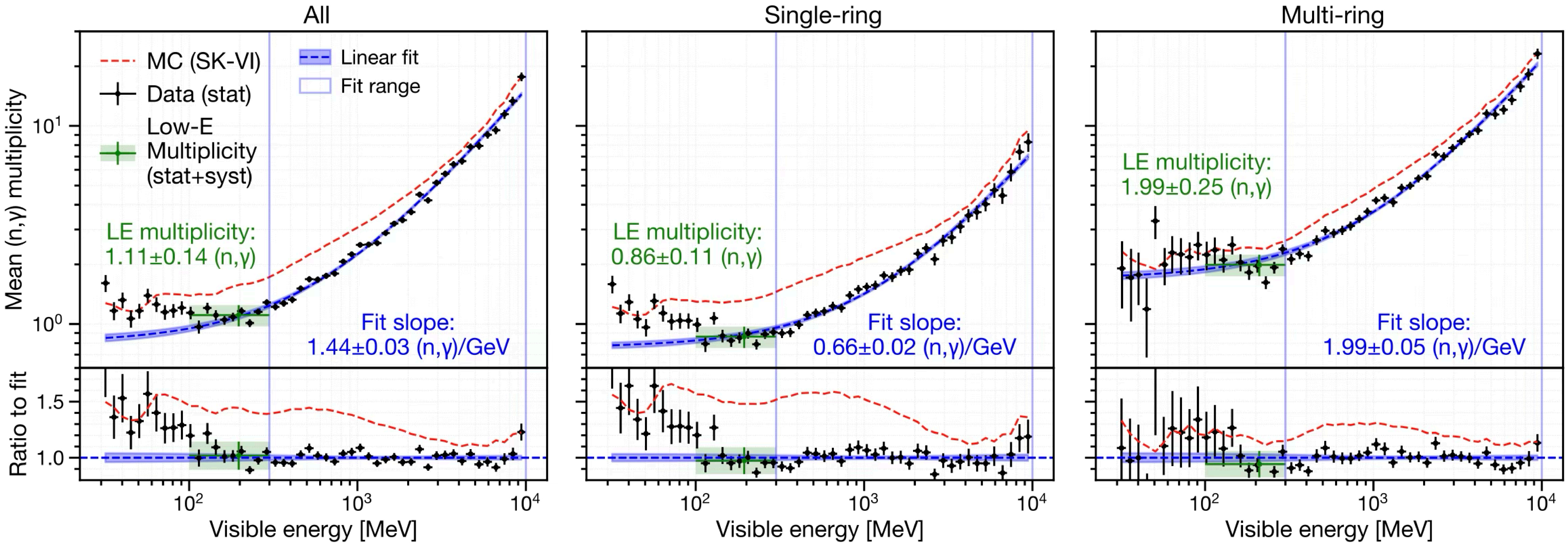


Fig 20. Results of slope fit + Low-E multiplicity

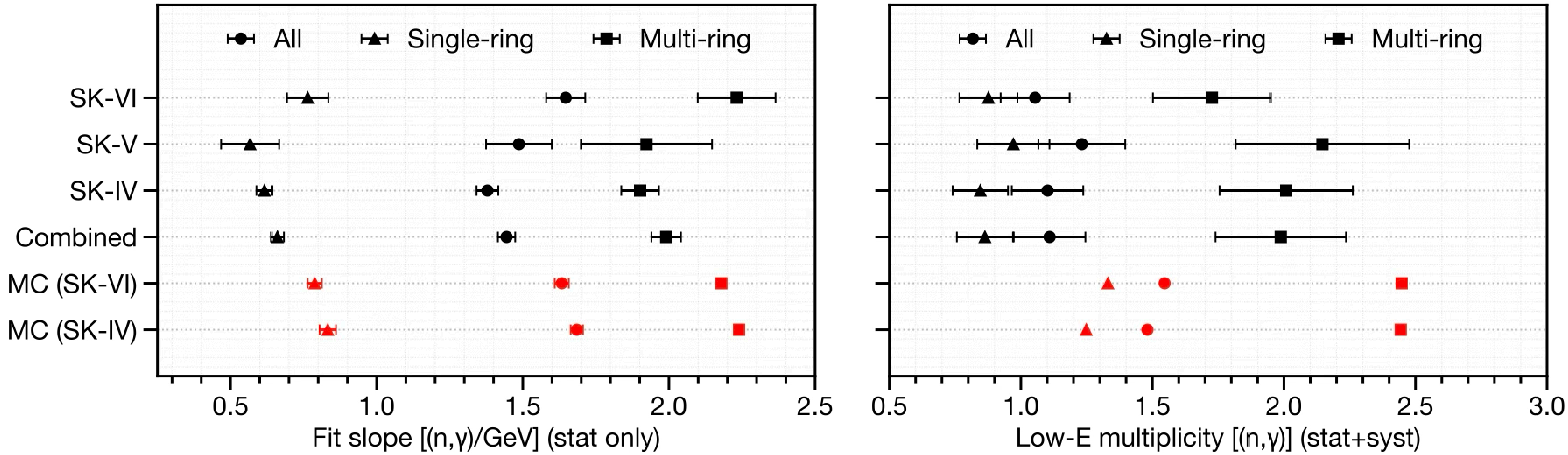


Fig 21. SK phase consistency: Slope and low-E multiplicity

- Both slope and LE multiplicity larger in multi-ring due to larger DIS fraction
- Both were smaller in data than MC
- SK6 slope is a little larger than SK4, which is not so with MC?

B. Comparison with model predictions

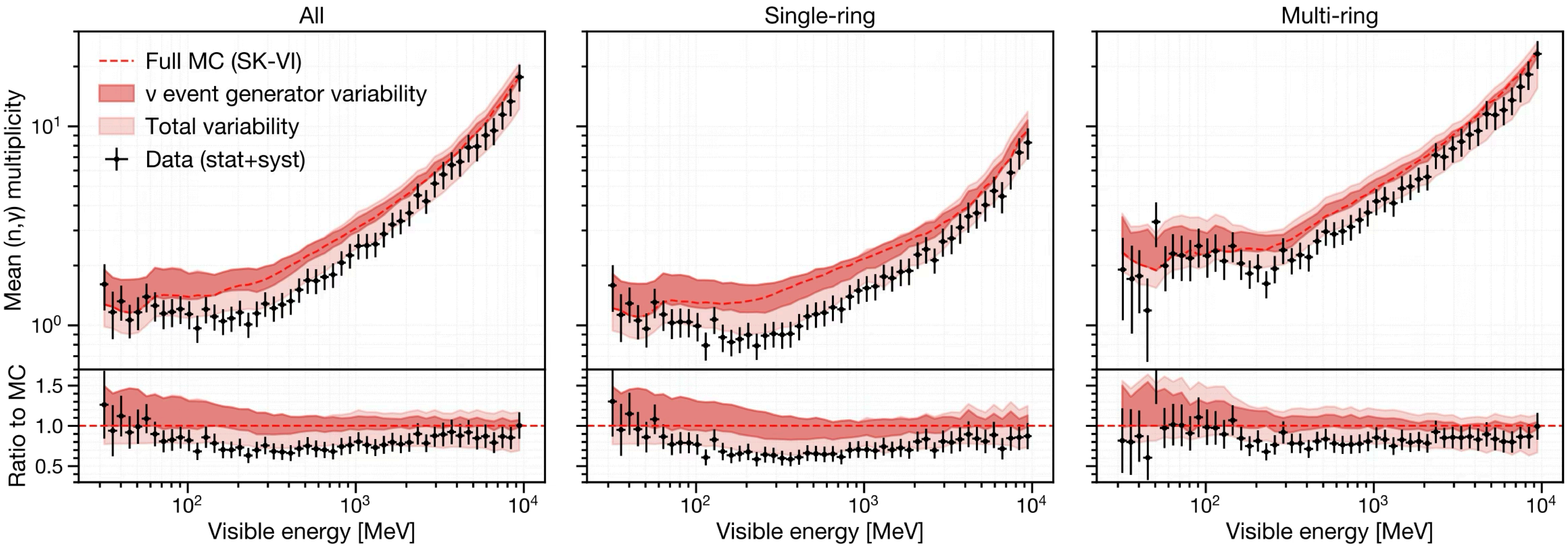


Fig 22 (top): Data vs. Model predictions (only min-max ranges are shown)

Sub-GeV dip more prominent in single-ring, which is only explained if both FSI and SI models with lower neutron production are used

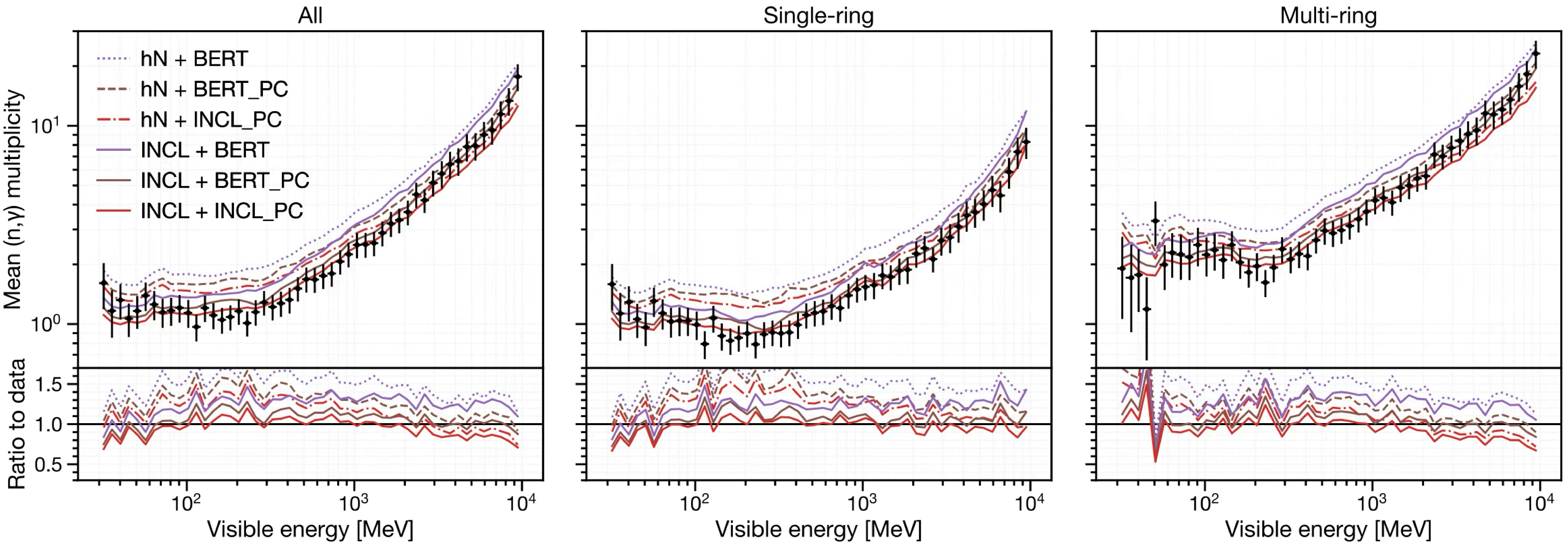


Fig 22 (bottom): Data vs. Selected models (FSI: hN/INCL, SI: BERT/BERT_PC/INCL_PC)

- Using “hN” FSI model (dashed) does not explain the sub-GeV dip
- Using “INCL” for both FSI and SI works well, while at mult-GeV it overshoots the slope prediction
- At multi-GeV, using BERT_PC for SI matches better with data

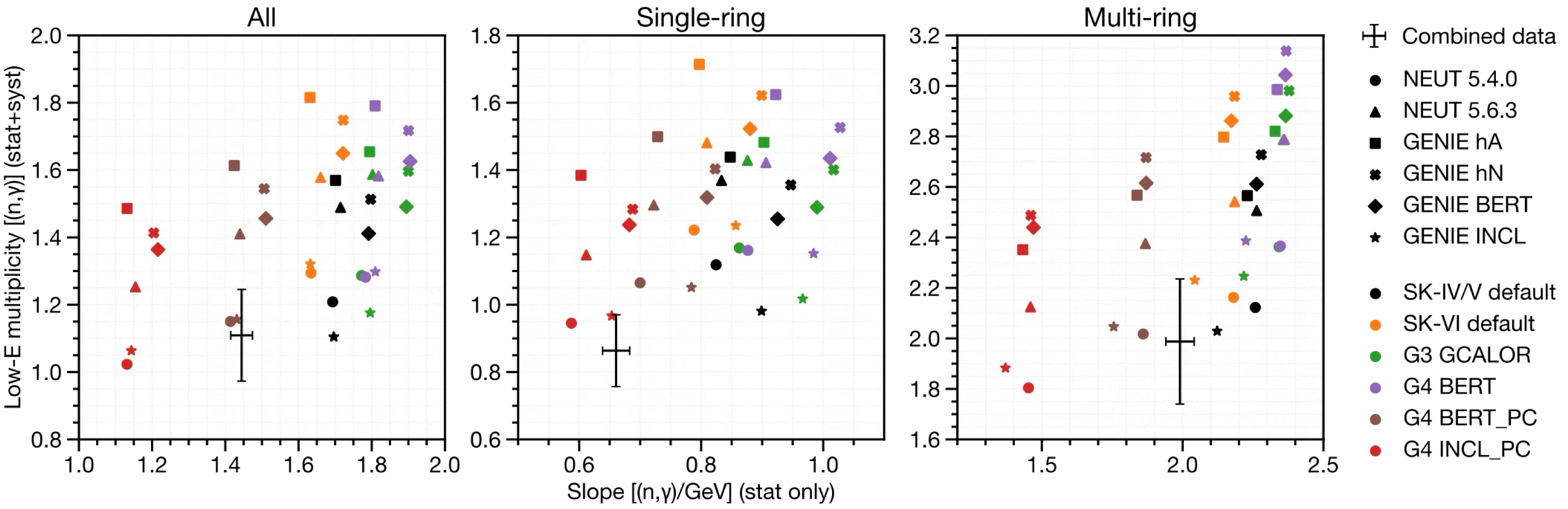


Fig 23: Data vs model predictions: Slope and Low-E multiplicity

- 3 distinct groups in slope prediction: INCL < BERT_PC < BERT variants (GCALOR, SK defaults)
- Slope: INCL better at Sub-GeV and BERT/BERT_PC better at Multi-GeV
- GENIE hA, hN, BERT overpredict LE multiplicity regardless of SI model used

8. Discussion

- Our data favors models with lower neutron production
- We discuss features in models that affect neutron production

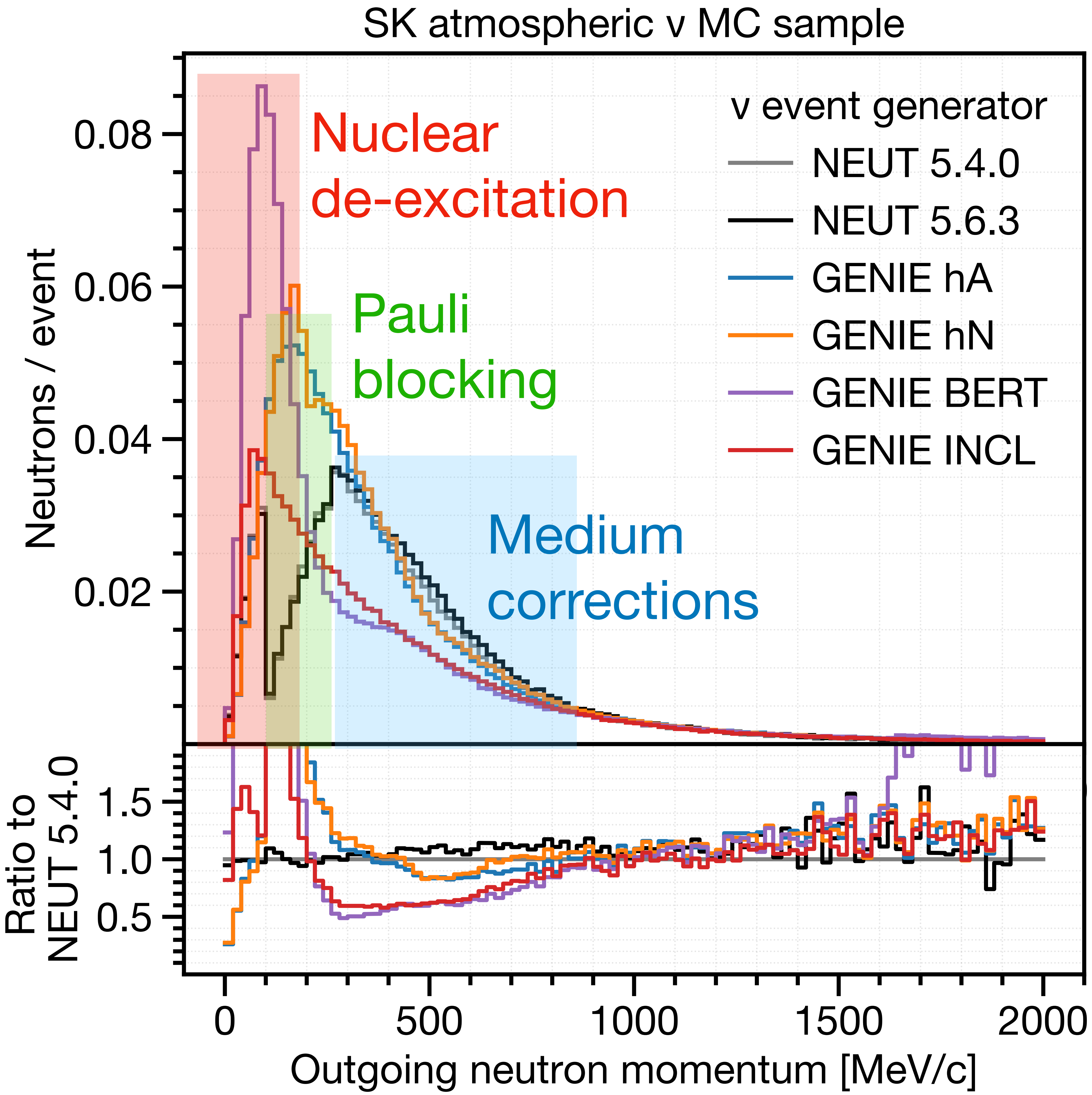


Fig 14 revisited: Outgoing neutron momentum predictions
with different neutrino event generator options

8. Discussion

A. Nuclear de-excitation

- “Bertini native” de-excitation model predicts very large peak
- This model is based on crude parametrization of
  “nucleon absorption (inverse reaction)” cross sections in 1959
- Geant4 Precompound (PC) model (as used in GENIE INCL)
  is more recent and data-driven,
  predicting much lower neutron emission in the process of evaporation

8. Discussion

A. Nuclear de-excitation

- GENIE hA and hN have no consideration of de-excitation
- NEUT shows similar peak size to GENIE INCL using G4 PC model
- De-excitation model largely decides (n,γ) reactions per secondary interaction hence very important

8. Discussion

B. Pauli blocking

- Bertini, NEUT applies “strict” Pauli blocking:
  all nucleon scatterings below Fermi momentum 225 MeV/c are rejected
  → Large dip in this momentum range,
  main reason why NEUT predicts lower neutron multiplicity than GENIE
- GENIE hA, hN do not consider Pauli blocking
- INCL considers “probabilistic” Pauli blocking:
  scatterings below Fermi momentum may be allowed,
  if there is a hole created in previous cascade steps

8. Discussion

C. Other considerations

- INCL and Geant4 Bertini cascade considers nucleon-nucleon repulsion and lower cross section due to holes created by previous cascade steps
  → Major distinction btw these models and “original” Bertini model, predicting lower neutron production in (0.25-1 GeV/c)
- Impact of the difference in π FSI/SI modeling (e.g., Salcedo/Oset vs. Bertini) or low-energy neutron xsec (e.g., ENDF/B-V vs. ENDF/B-VII.1) was relatively minor

9. Summary

- Accurate modeling of neutron production in neutrino interaction is crucial in neutrino oscillation measurements and rare event searches
- We measured neutron production in atmospheric ν events at SK, as a function of electron-equivalent visible energy
- Our data favors FSI/SI models that predict lower neutron production