DEEP UNDERGROUND NEUTRINO EXPERIMENT

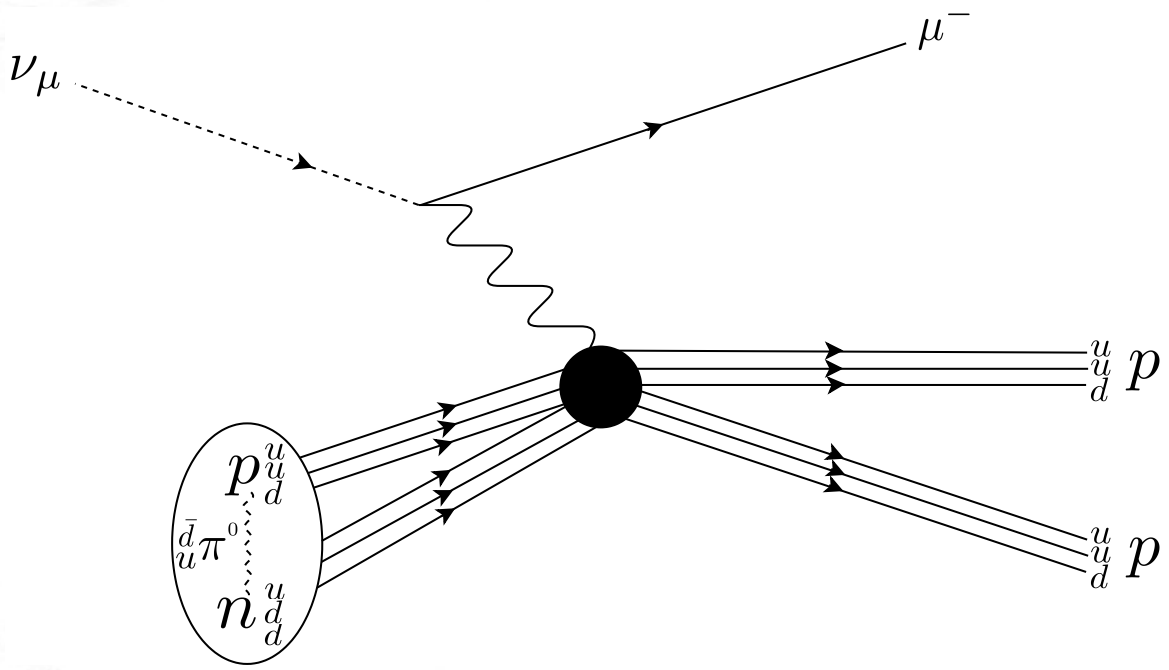
UNIVERSITY OF OXFORD

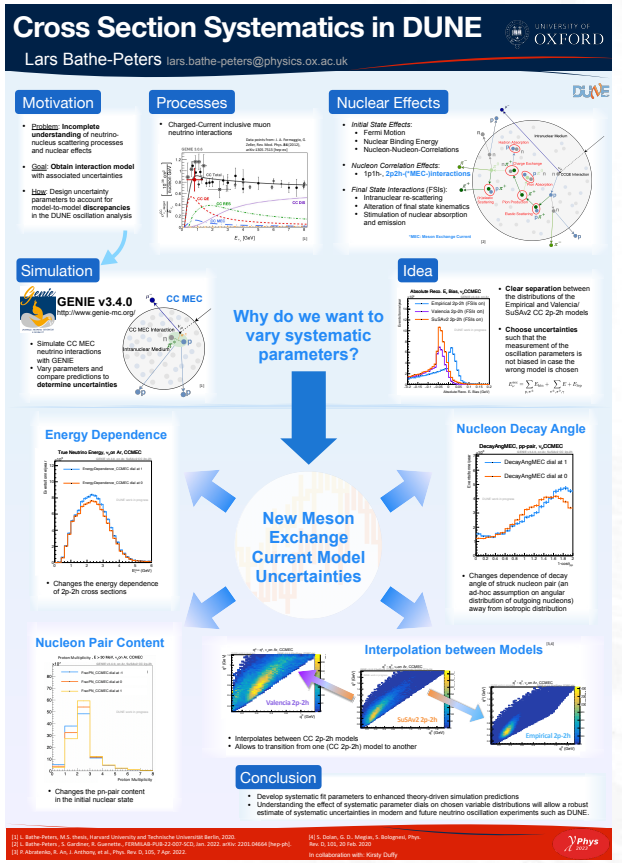
Cross Section Systematics in DUNE

2p2h dials and validations

Lars Bathe-Peters lars.bathe-peters@physics.ox.ac.uk

TH-12





Neutrino Oscillations

Neutrino Oscillations

- Neutrino *mass* and *weak* eigenstates related via PNMS-Matrix:

Usually parametrized by:

$$\begin{pmatrix} |\nu_e\rangle \\ |\nu_\mu\rangle \\ |\nu_\tau\rangle \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \begin{pmatrix} |\nu_1\rangle \\ |\nu_2\rangle \\ |\nu_3\rangle \end{pmatrix}$$

- Neutrino mixing angles: $\theta_{12}, \theta_{23}, \theta_{13}$
- CP-violating phase: δ_{CP}

Neutrino Oscillations

- Neutrino *mass* and *weak* eigenstates related via PNMS-Matrix:

Usually parametrized by:

$$\begin{pmatrix} |\nu_e\rangle \\ |\nu_\mu\rangle \\ |\nu_\tau\rangle \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \begin{pmatrix} |\nu_1\rangle \\ |\nu_2\rangle \\ |\nu_3\rangle \end{pmatrix}$$

- Neutrino mixing angles: $\theta_{12}, \theta_{23}, \theta_{13}$
- CP-violating phase: δ_{CP}

- Neutrino event rate:

$$R_{\alpha\to\beta}(p_{\text{reco}}) = \int_{E_{\text{min}}}^{E_{\text{max}}} \Phi_\alpha(E_{\text{true}}) \cdot \sum_i \sigma_\beta^i(E_{\text{true}}, p_{\text{reco}}) \cdot \sum_j N_j \cdot \varepsilon_\beta(E_{\text{true}}, p_{\text{reco}}) \cdot P_{\alpha\to\beta}(E_{\text{true}})$$

Neutrino Oscillations

- Neutrino *mass* and *weak* eigenstates related via PNMS-Matrix:

Usually parametrized by:

$$\begin{pmatrix} |\nu_e\rangle \\ |\nu_\mu\rangle \\ |\nu_\tau\rangle \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \begin{pmatrix} |\nu_1\rangle \\ |\nu_2\rangle \\ |\nu_3\rangle \end{pmatrix}$$

- Neutrino mixing angles: $\theta_{12}, \theta_{23}, \theta_{13}$
- CP-violating phase: δ_{CP}

Need to know neutrino energy

- Neutrino event rate:

$$R_{\alpha\to\beta}(p_{\text{reco}}) = \int_{E_{\text{min}}}^{E_{\text{max}}} \Phi_\alpha(E_{\text{true}}) \cdot \sum_i \sigma_\beta^i(E_{\text{true}}, p_{\text{reco}}) \cdot \sum_j N_j \cdot \varepsilon_\beta(E_{\text{true}}, p_{\text{reco}}) \cdot P_{\alpha\to\beta}(E_{\text{true}})$$

Neutrino Oscillations

- Neutrino *mass* and *weak* eigenstates related via PNMS-Matrix:

Usually parametrized by:

$$\begin{pmatrix} |\nu_e\rangle \\ |\nu_\mu\rangle \\ |\nu_\tau\rangle \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \begin{pmatrix} |\nu_1\rangle \\ |\nu_2\rangle \\ |\nu_3\rangle \end{pmatrix}$$

- Neutrino mixing angles: $\theta_{12}, \theta_{23}, \theta_{13}$
- CP-violating phase: δ_{CP}

Need to know neutrino energy

- Neutrino event rate:

Flux

$$R_{\alpha\to\beta}(p_{\text{reco}}) = \int_{E_{\min}}^{E_{\max}} \Phi_\alpha(E_{\text{true}}) \cdot \sum_i \sigma_\beta^i(E_{\text{true}}, p_{\text{reco}}) \cdot \sum_j N_j \cdot \varepsilon_\beta(E_{\text{true}}, p_{\text{reco}}) \cdot P_{\alpha\to\beta}(E_{\text{true}})$$

Neutrino Oscillations

- Neutrino *mass* and *weak* eigenstates related via PNMS-Matrix:

Usually parametrized by:

$$\begin{pmatrix} |\nu_e\rangle \\ |\nu_\mu\rangle \\ |\nu_\tau\rangle \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \begin{pmatrix} |\nu_1\rangle \\ |\nu_2\rangle \\ |\nu_3\rangle \end{pmatrix}$$

- Neutrino mixing angles: $\theta_{12}, \theta_{23}, \theta_{13}$
- CP-violating phase: δ_{CP}

Need to know neutrino energy

- Neutrino event rate:

Flux Cross Section

$$R_{\alpha\to\beta}(p_{\text{reco}}) = \int_{E_{\text{min}}}^{E_{\text{max}}} \Phi_\alpha(E_{\text{true}}) \cdot \sum_i \sigma_\beta^i(E_{\text{true}}, p_{\text{reco}}) \cdot \sum_j N_j \cdot \varepsilon_\beta(E_{\text{true}}, p_{\text{reco}}) \cdot P_{\alpha\to\beta}(E_{\text{true}})$$

Neutrino Oscillations

- Neutrino *mass* and *weak* eigenstates related via PNMS-Matrix:

Usually parametrized by:

$$\begin{pmatrix} |\nu_e\rangle \\ |\nu_\mu\rangle \\ |\nu_\tau\rangle \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \begin{pmatrix} |\nu_1\rangle \\ |\nu_2\rangle \\ |\nu_3\rangle \end{pmatrix}$$

- Neutrino mixing angles: $\theta_{12}, \theta_{23}, \theta_{13}$
- CP-violating phase: δ_{CP}

Need to know neutrino energy

- Neutrino event rate:

Flux · Cross Section · # of target nuclei

$$R_{\alpha\to\beta}(p_{\text{reco}}) = \int_{E_{\text{min}}}^{E_{\text{max}}} \Phi_\alpha(E_{\text{true}}) \cdot \sum_i \sigma_\beta^i(E_{\text{true}}, p_{\text{reco}}) \cdot \sum_j N_j \cdot \varepsilon_\beta(E_{\text{true}}, p_{\text{reco}}) \cdot P_{\alpha\to\beta}(E_{\text{true}})$$

Neutrino Oscillations

- Neutrino *mass* and *weak* eigenstates related via PNMS-Matrix:

Usually parametrized by:

$$\begin{pmatrix} |\nu_e\rangle \\ |\nu_\mu\rangle \\ |\nu_\tau\rangle \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \begin{pmatrix} |\nu_1\rangle \\ |\nu_2\rangle \\ |\nu_3\rangle \end{pmatrix}$$

- Neutrino mixing angles: $\theta_{12}, \theta_{23}, \theta_{13}$
- CP-violating phase: δ_{CP}

Need to know neutrino energy

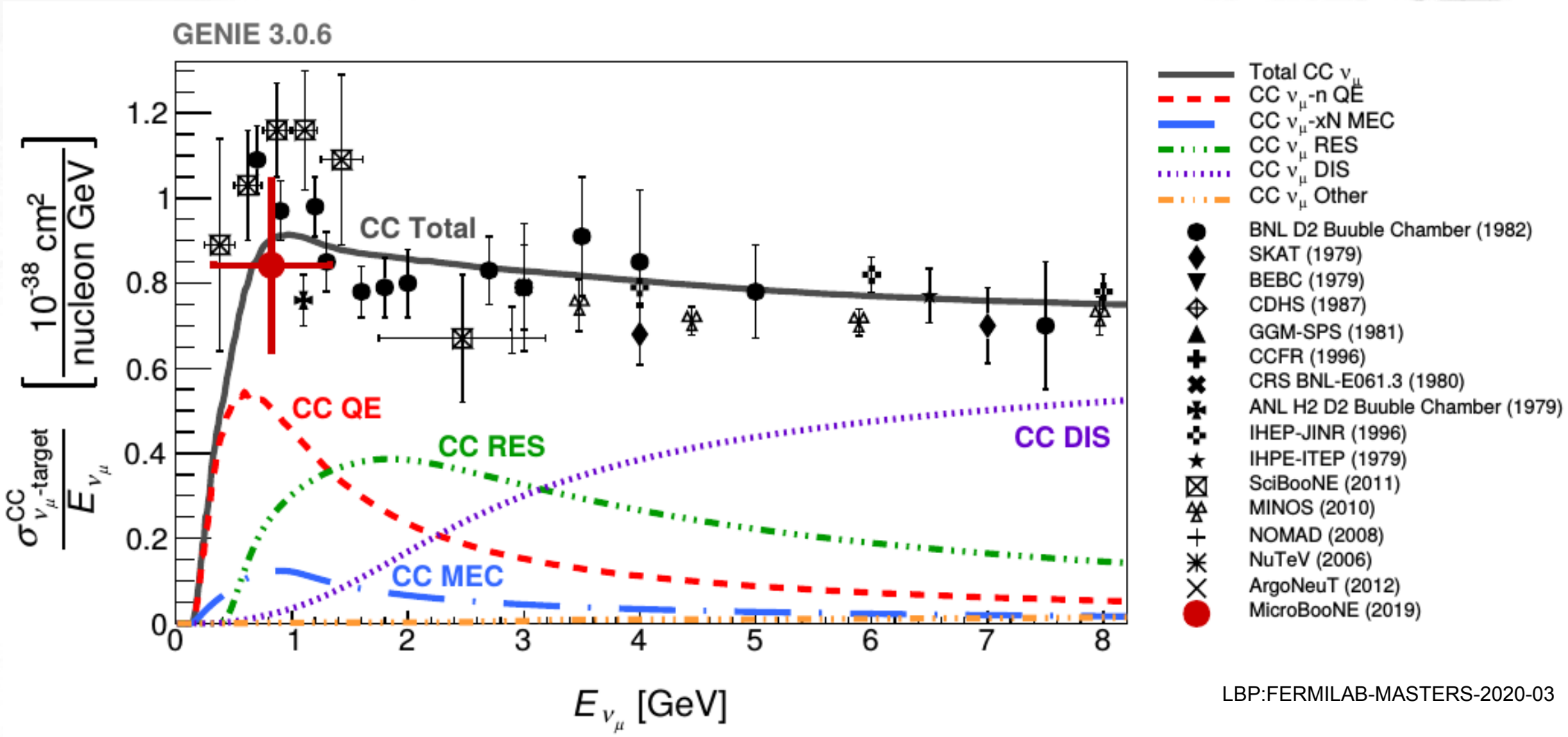
- Neutrino event rate:

Flux | Cross Section | # of target nuclei | Detector Efficiency

$$R_{\alpha\to\beta}(p_{\text{reco}}) = \int_{E_{\min}}^{E_{\max}} \Phi_\alpha(E_{\text{true}}) \cdot \sum_i \sigma_\beta^i(E_{\text{true}}, p_{\text{reco}}) \cdot \sum_j N_j \cdot \varepsilon_\beta(E_{\text{true}}, p_{\text{reco}}) \cdot P_{\alpha\to\beta}(E_{\text{true}})$$

Neutrino-Nucleus Cross Section

Interaction Modes



LBP:FERMILAB-MASTERS-2020-03

Nuclear Effects

Initial State Effects

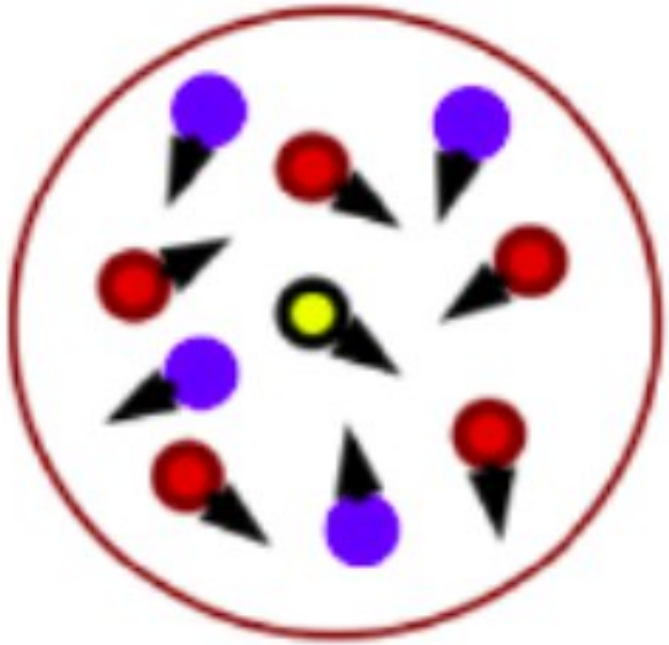
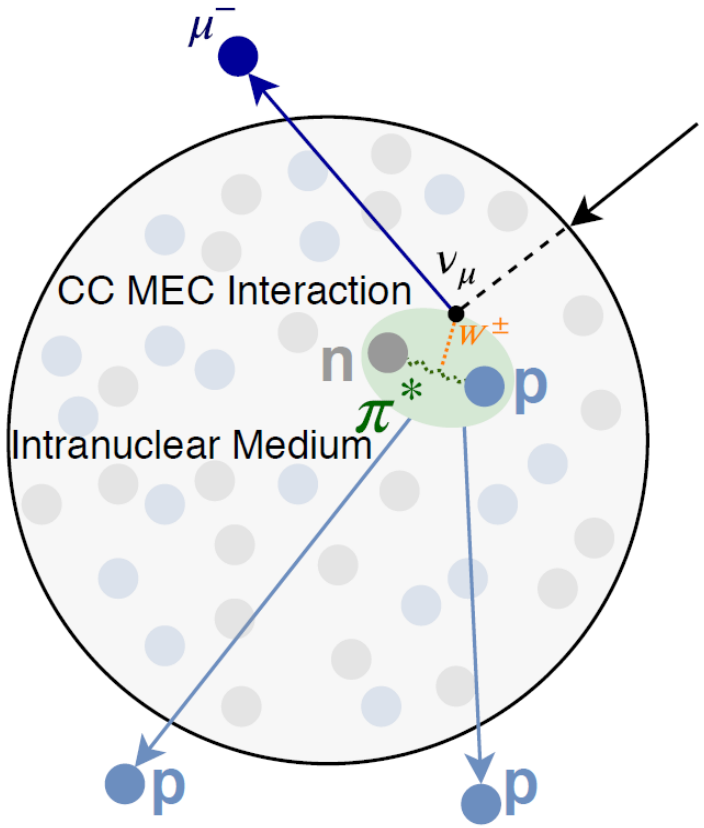


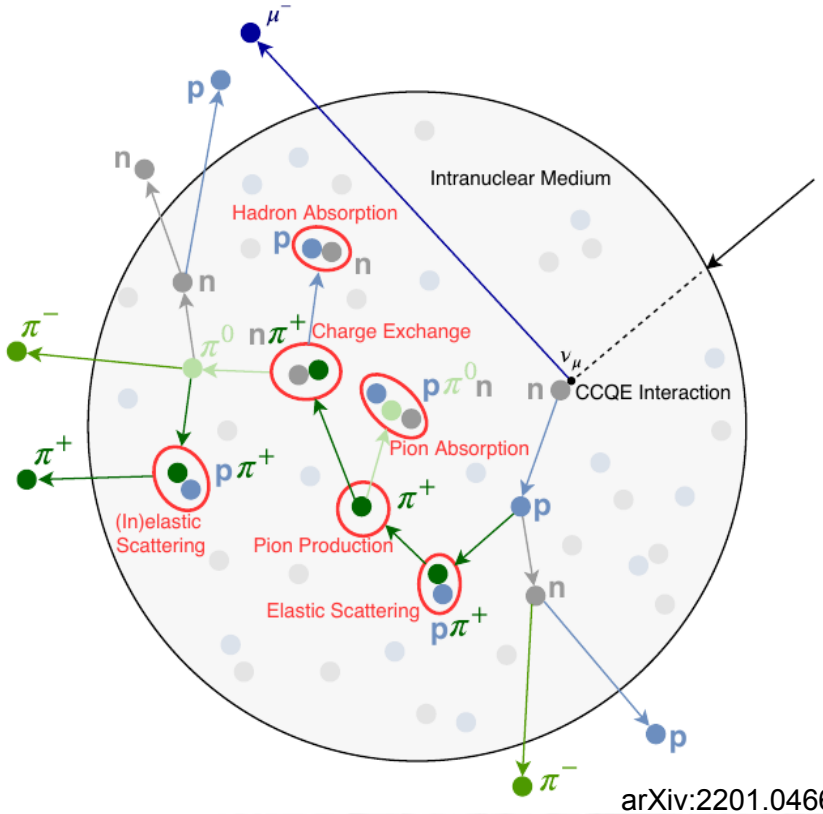
Figure by C. Andreopoulos

Meson Exchange Currents



LBP:FERMILAB-MASTERS-2020-03

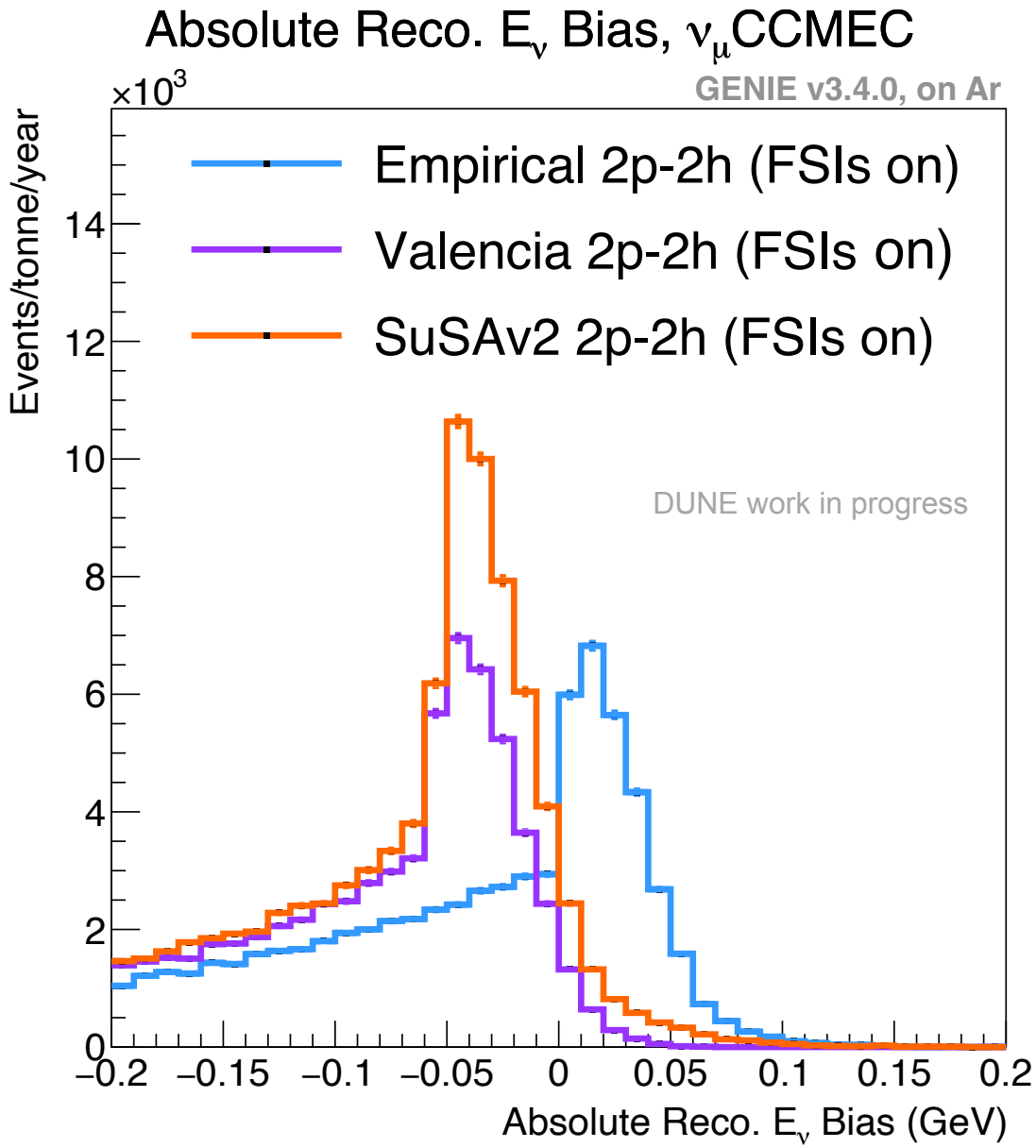
Final State Interactions



arXiv:2201.04664

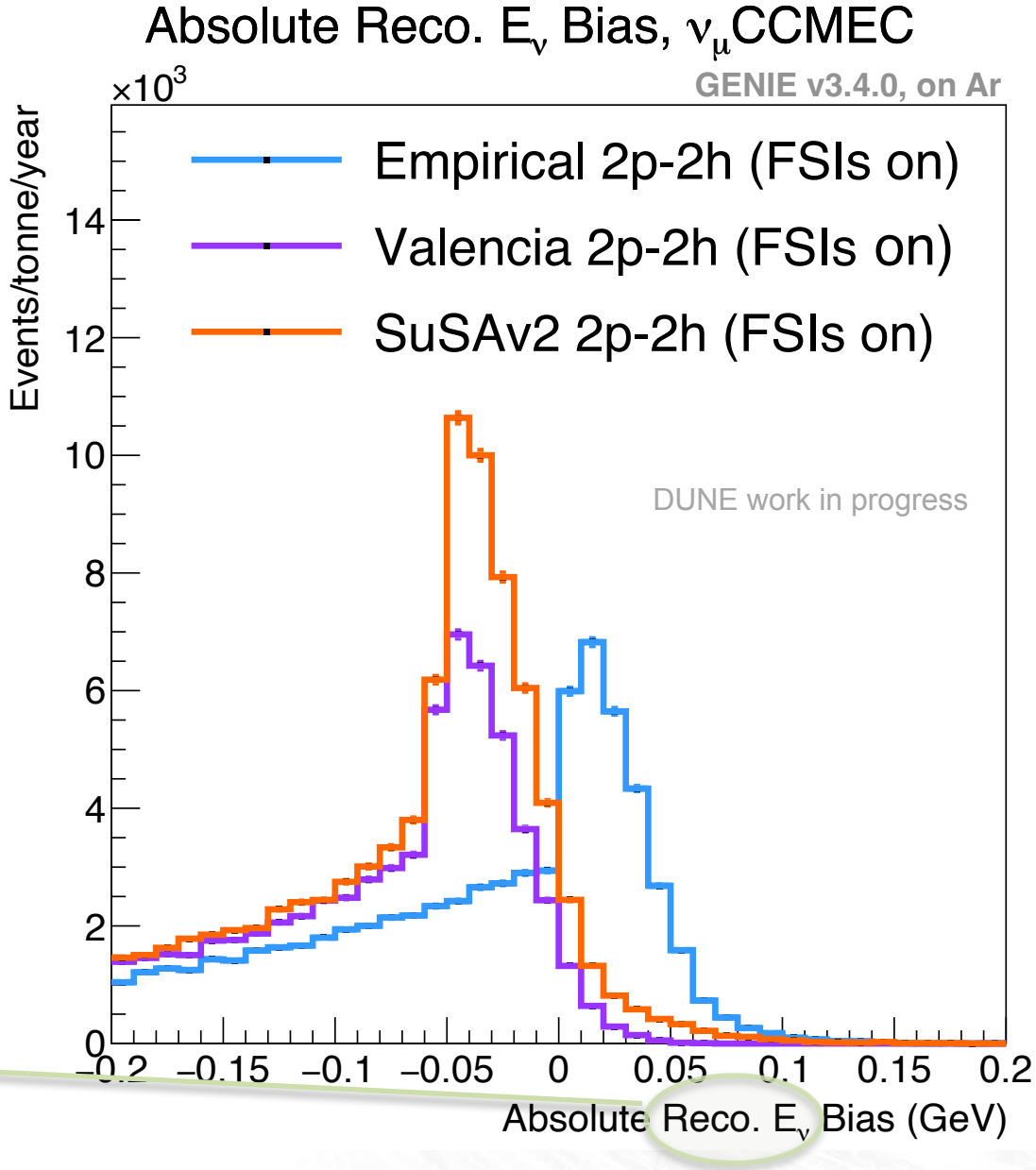
2p-2h Model Comparisons

- **Clear separation** between the Empirical and Valencia/SuSAv2 CC 2p-2h models
- **Choose uncertainties** such that the measurement of the oscillation parameters is not biased in case the wrong model is chosen



2p-2h Model Comparisons

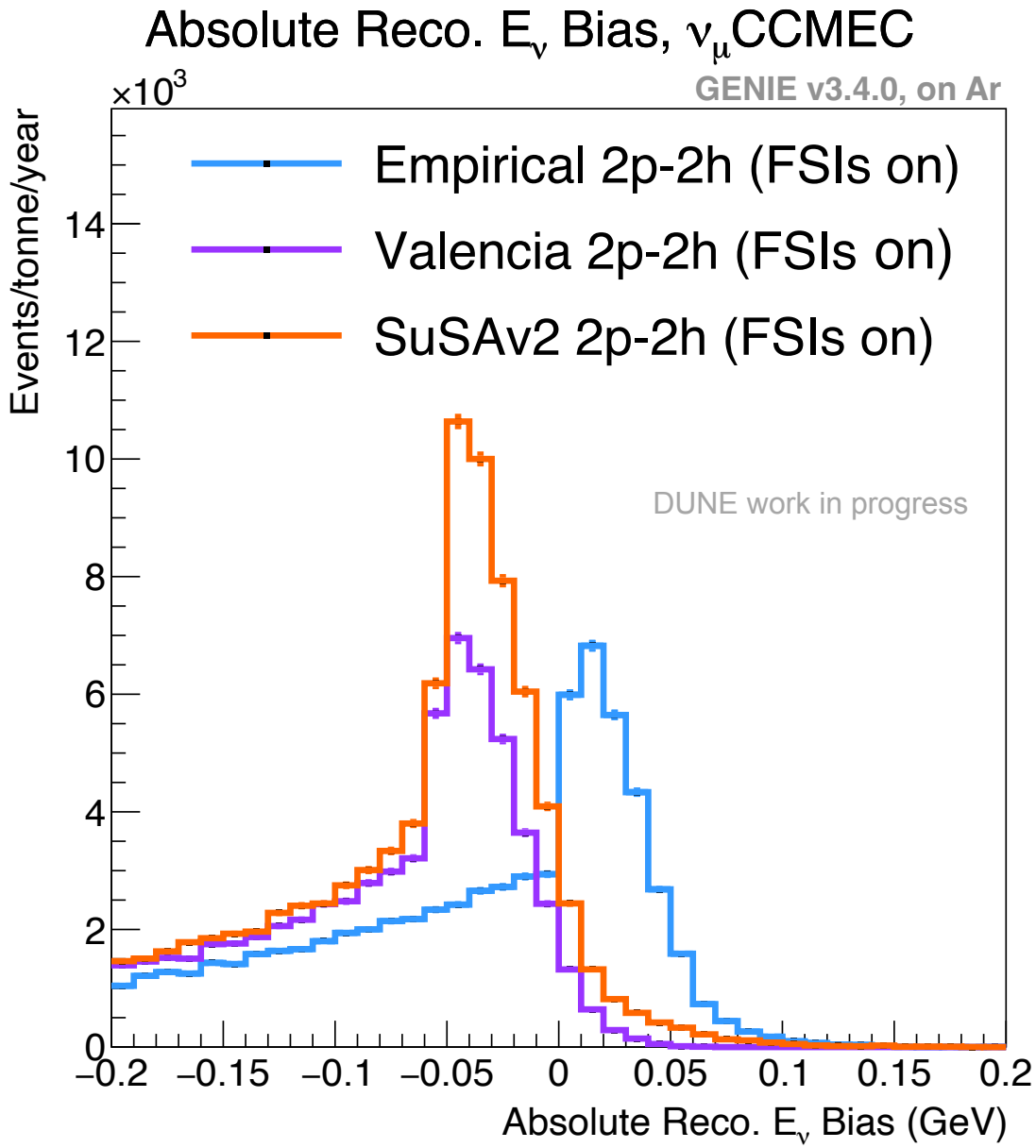
- **Clear separation** between the Empirical and Valencia/SuSAv2 CC 2p-2h models
- **Choose uncertainties** such that the measurement of the oscillation parameters is not biased in case the wrong model is chosen



$$E_\nu^{\text{rec}} = \sum_{\text{p},\pi^\pm} E_{\text{kin}} + \sum_{\text{e}^\pm,\pi^0,\gamma} E + E_{\text{lep}}$$

2p-2h Model Comparisons

- **Clear separation** between the Empirical and Valencia/SuSAv2 CC 2p-2h models
- **Choose uncertainties** such that the measurement of the oscillation parameters is not biased in case the wrong model is chosen



Propagating Uncertainties

Modify physical parameter: $$P \longrightarrow P' = P\left(1 + x_P \frac{\delta P}{P}\right)$$

Event weight: $$w_\sigma = \frac{\mathrm{d}^n\sigma}{\mathrm{d}K^n} \Big/ \frac{\mathrm{d}^n\sigma'}{\mathrm{d}K^n}$$

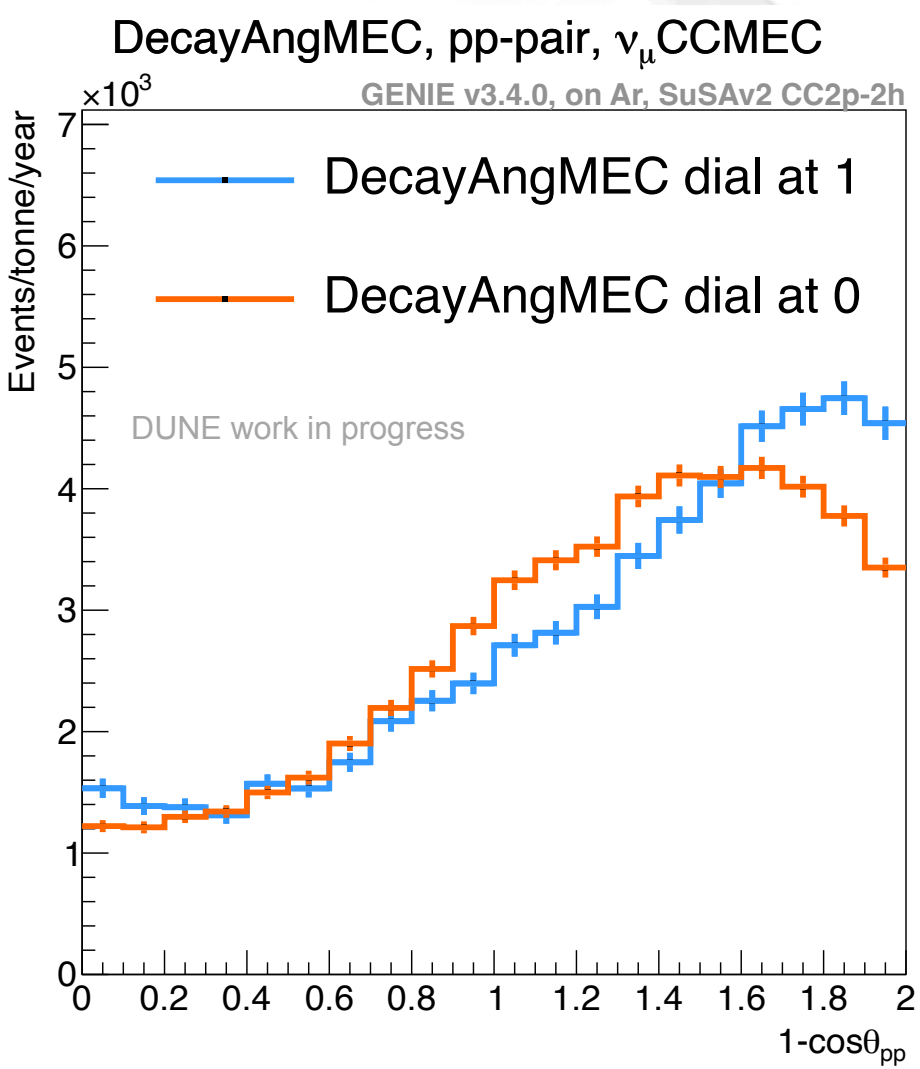
New dials:

- *NormCCMEC*
- *FracPN_CCMEC*
- *DecayAngMEC*
- *XSecShape_CCMEC*
- *DeltaNotDelta_CCMEC*
- *EnergyDependence_CCMEC*

2p-2h Model Uncertainty Dials

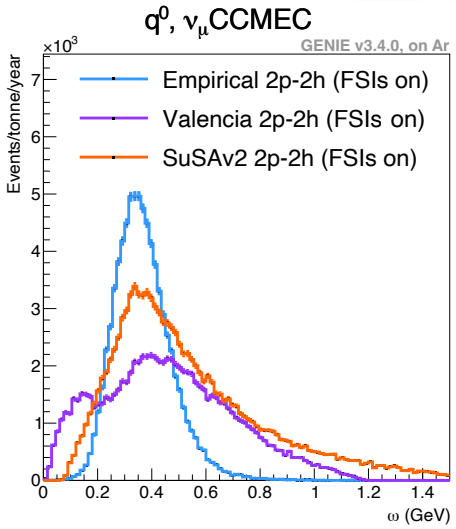
DecayAngMEC - changes angular dependence on struck nucleon pair

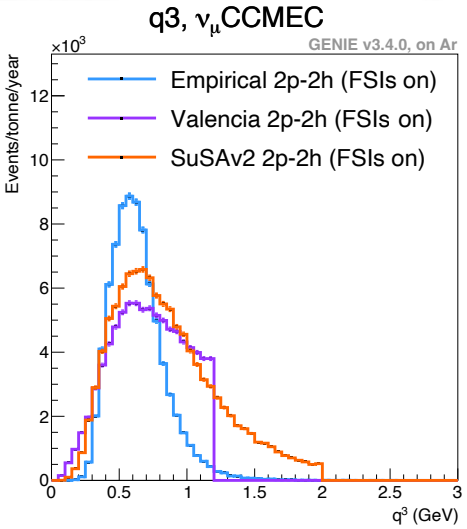
- Ad-hoc assumption on **angular distribution** of outgoing nucleons) away from isotropic distribution

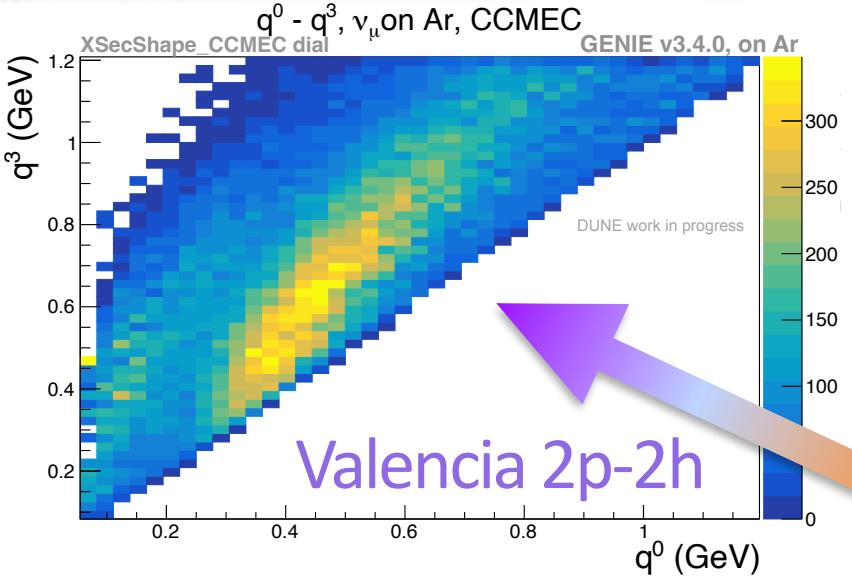


2p-2h Model Uncertainty Dials

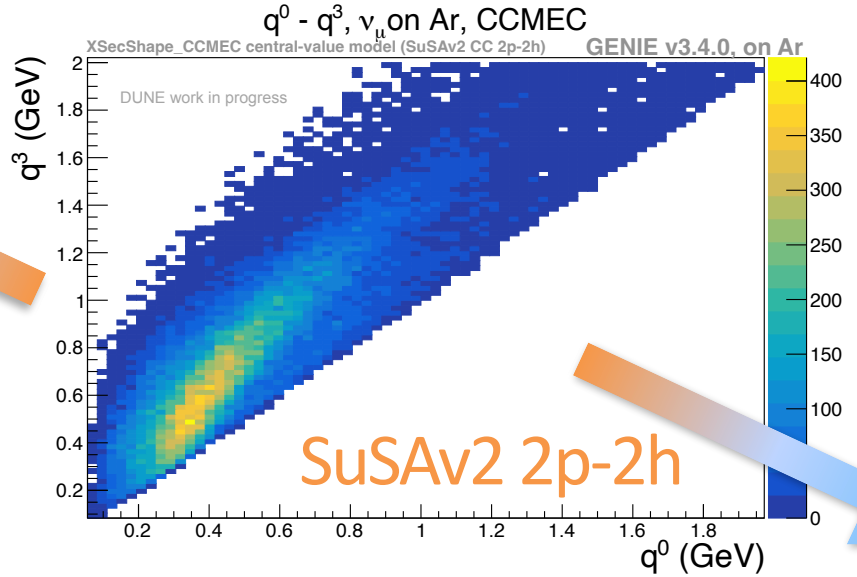
XSecShape_CCMEC - interpolates between CC 2p-2h models



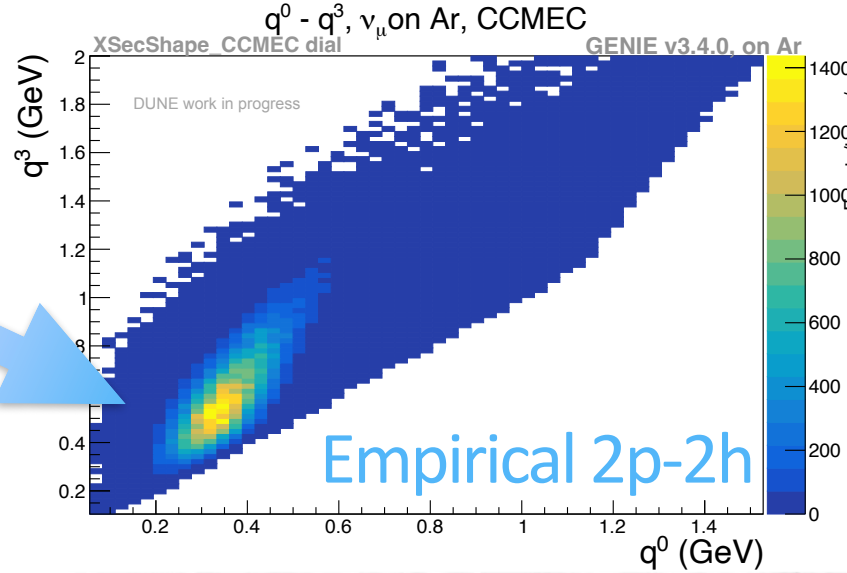




Valencia 2p-2h



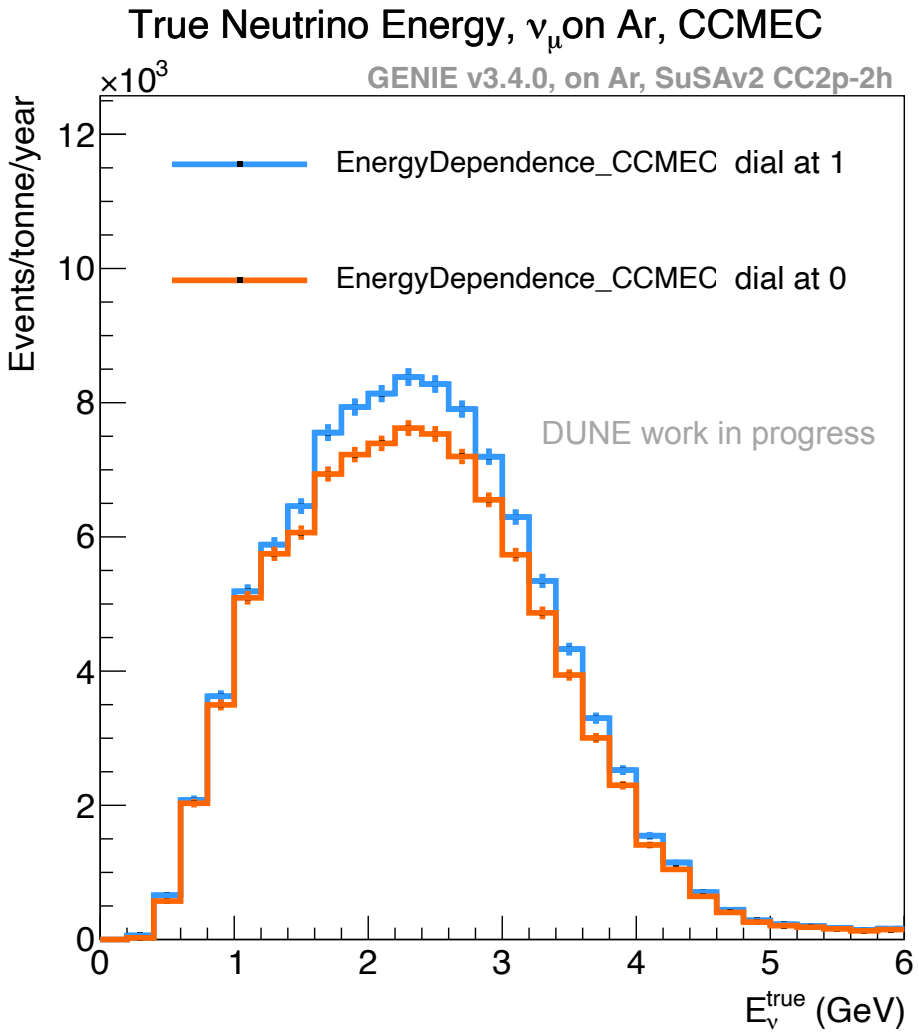
SuSAv2 2p-2h

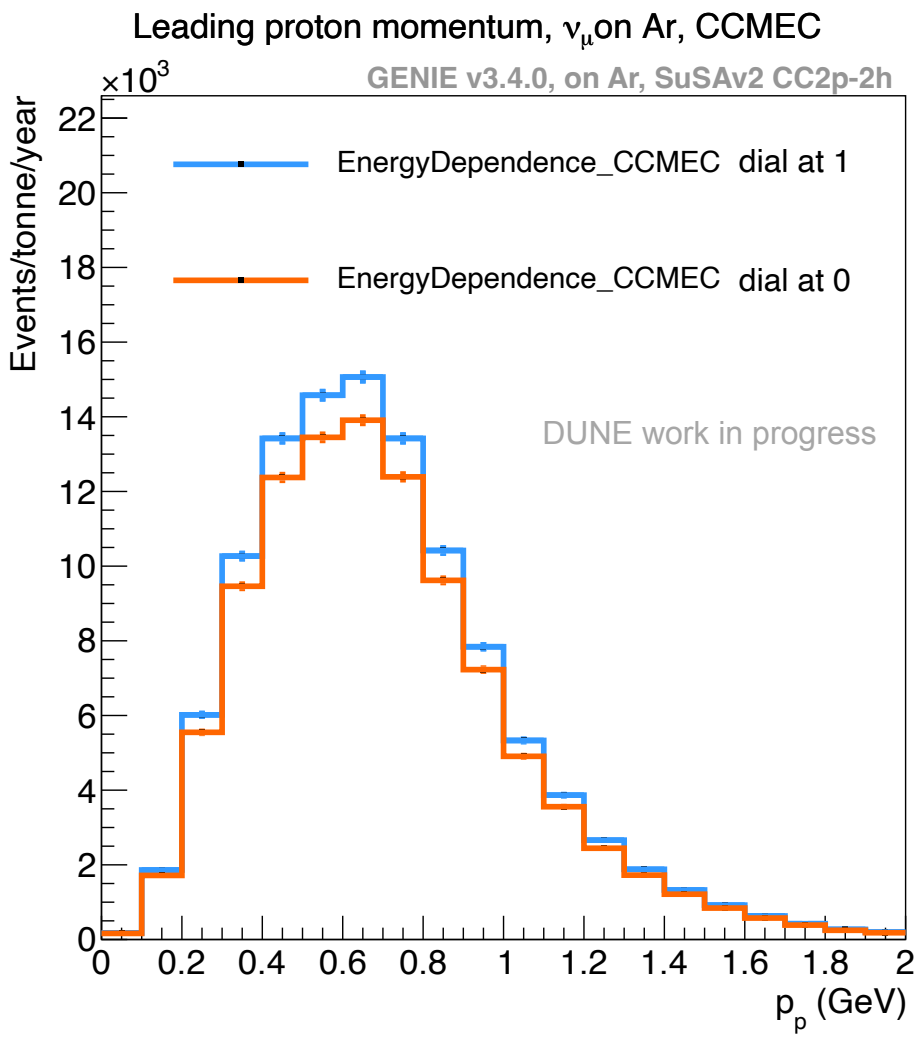


Empirical 2p-2h

2p-2h Model Uncertainty Dials

EnergyDependence_CCMEC - changes the energy dependence of 2p-2h cross sections





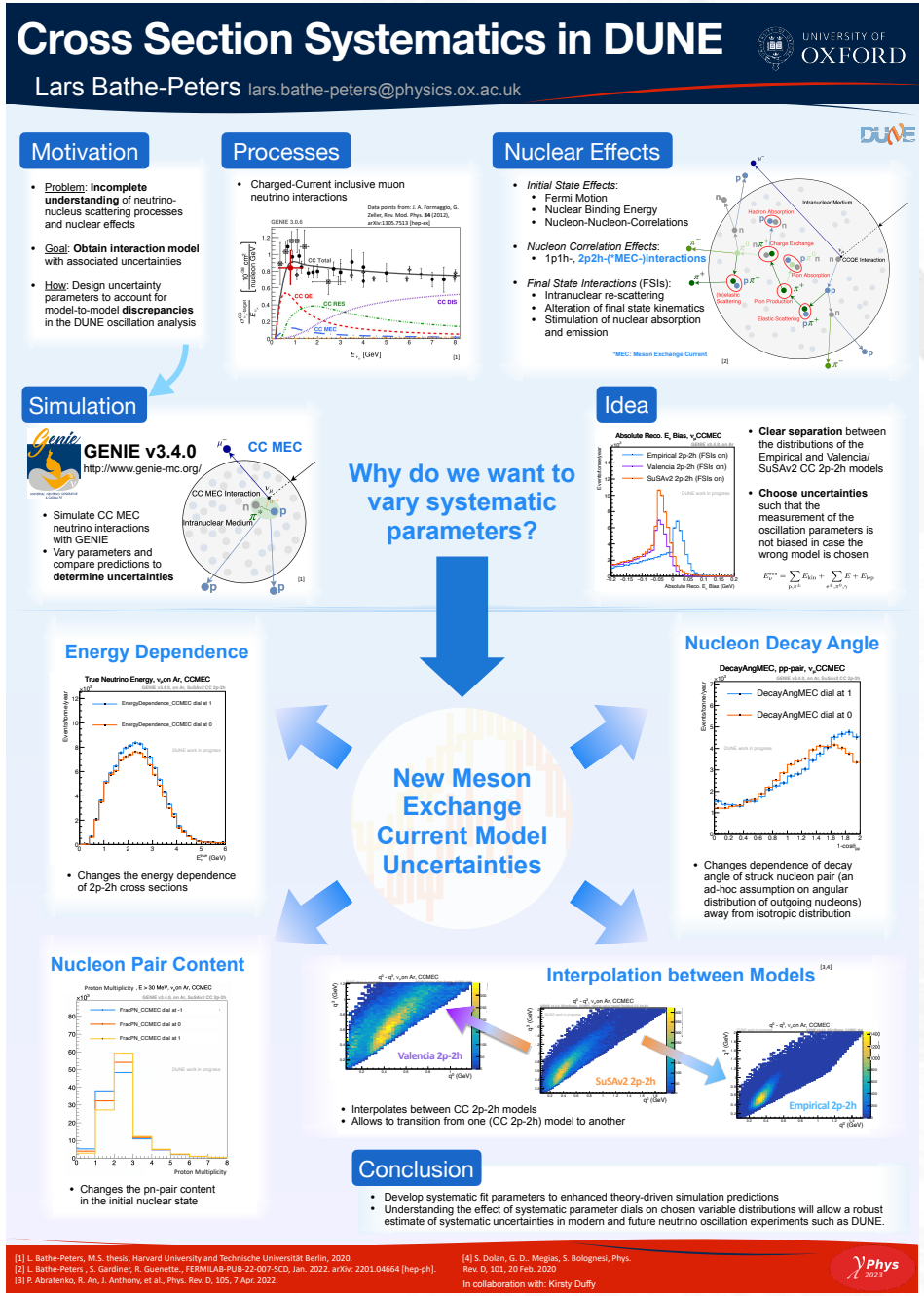
Conclusion and Outlook

- Neutrino interactions are complex and necessitate dedicated study
- **Develop systematic fit parameters** to enhanced theory-driven simulation predictions
- Understanding the effect of systematic parameter dials on chosen variable distributions will allow a robust **estimate of systematic uncertainties** in modern and future neutrino oscillation experiments such as DUNE

Thank you!

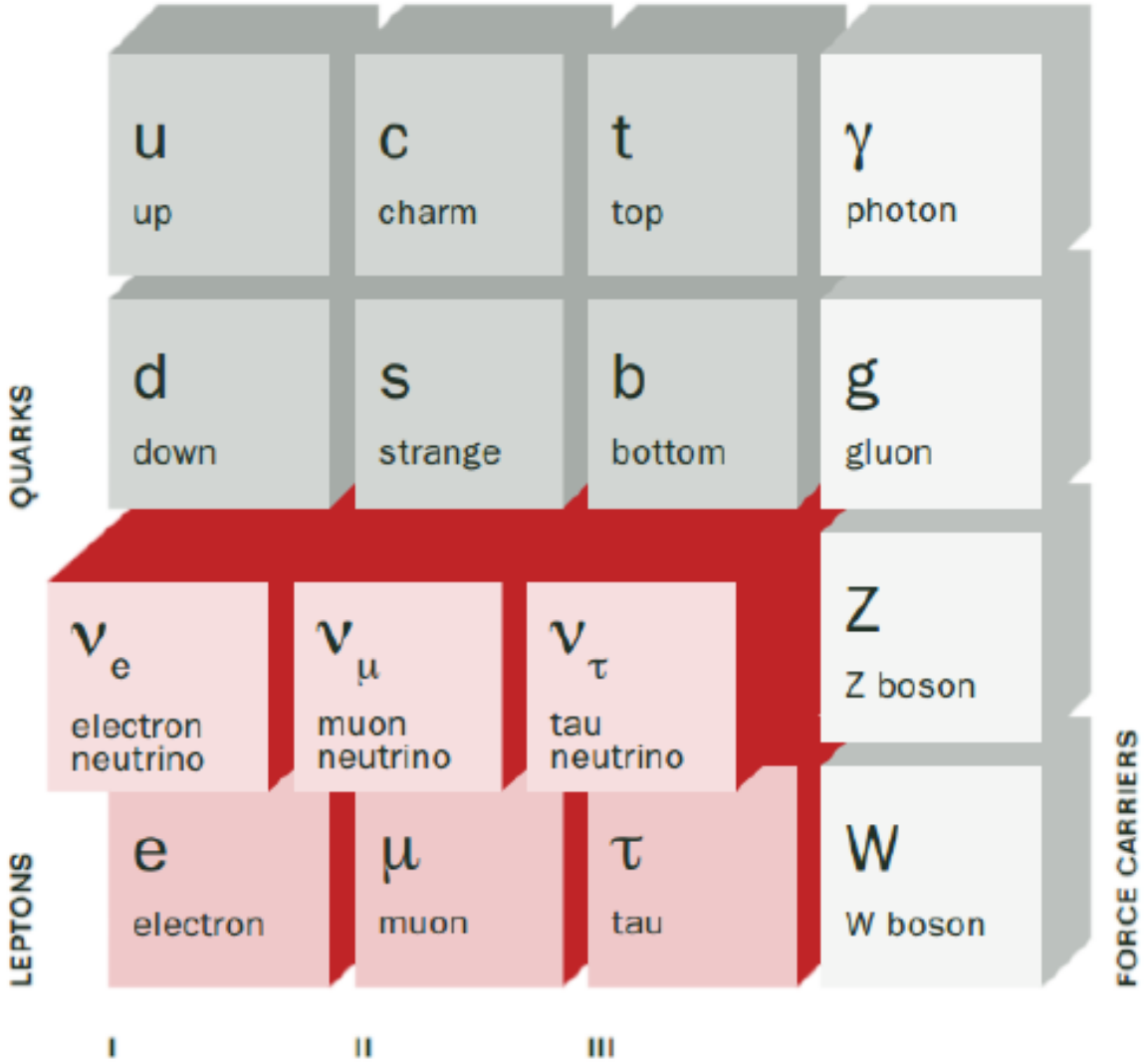
Poster:

TH-12



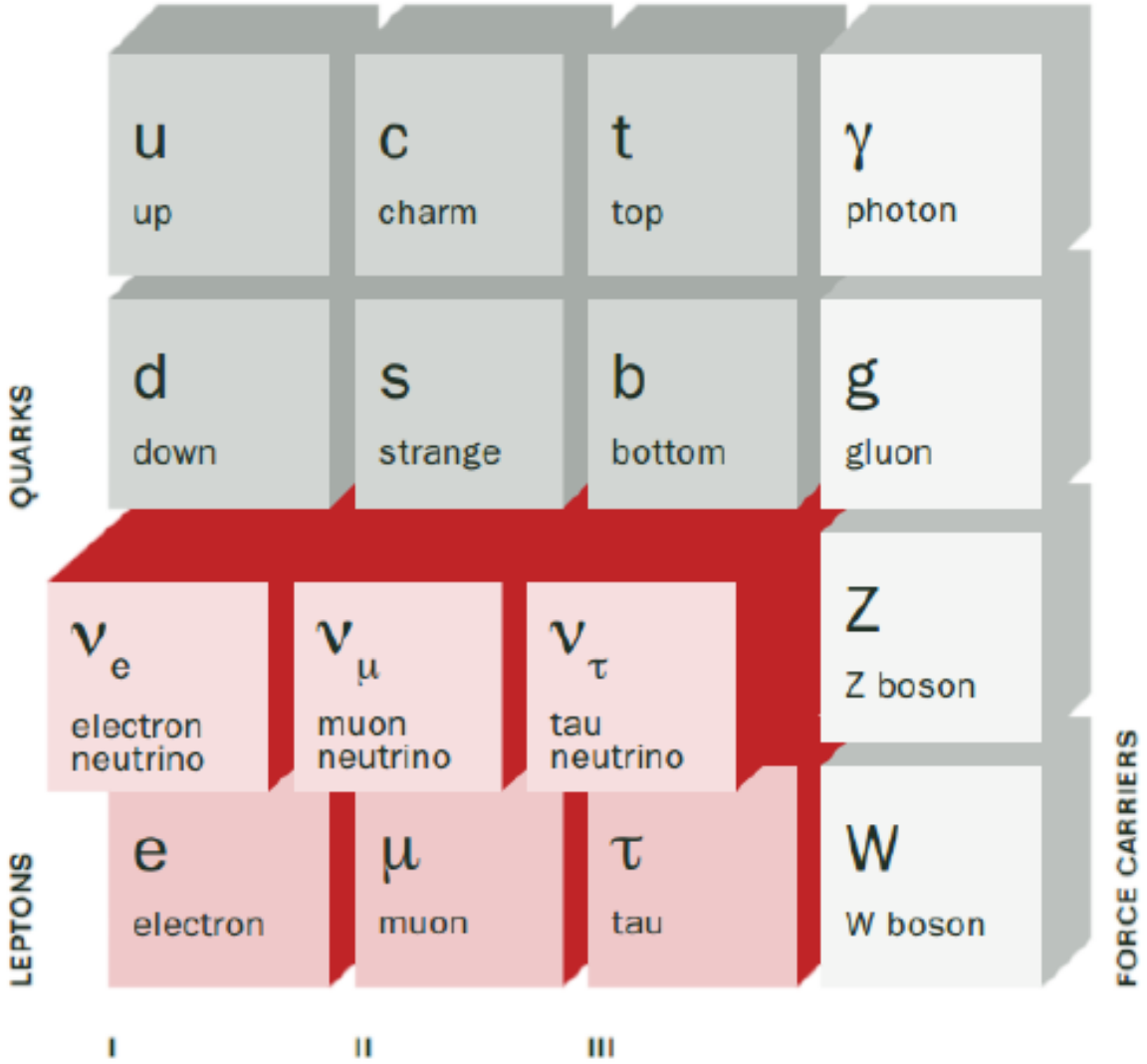
Backup

Neutrinos in the Standard Model



- Three generations (I, II, III) of fermions
- Gauge *bosons* mediate *forces*:
  - Photon ⟶ electromagnetic
  - Gluon ⟶ strong
  - $W^{\pm}$, Z ⟶ weak
- Standard Model prediction:
  - 3 *massless* neutrinos (and 3 anti-neutrinos) of 3 different flavors

Neutrinos in the Standard Model



- Three generations (I, II, III) of fermions
- Gauge *bosons* mediate *forces*:
  - Photon ⟶ electromagnetic
  - Gluon ⟶ strong
  - $W^{\pm}$, Z ⟶ weak
- Standard Model prediction:
  - 3 *massless* neutrinos (and 3 anti-neutrinos) of 3 different flavors

Neutrino-Nucleus Interactions

Theoretical Predictions by Neutrino Event Generators

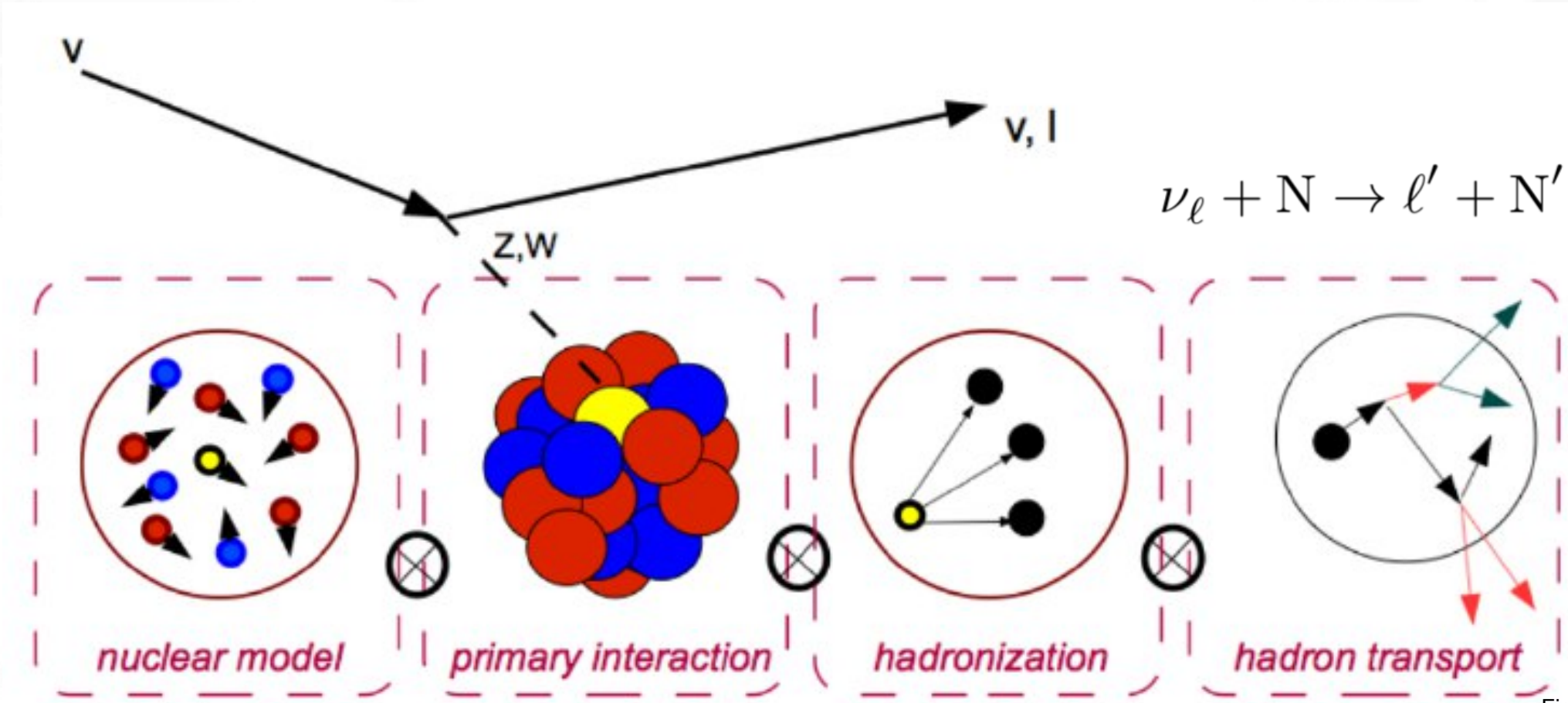


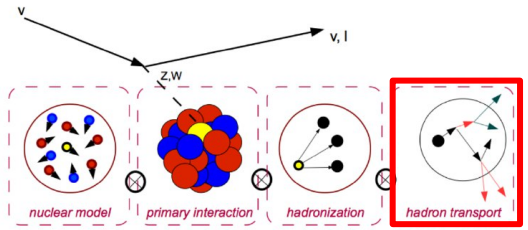
Figure by C. Andreopoulos

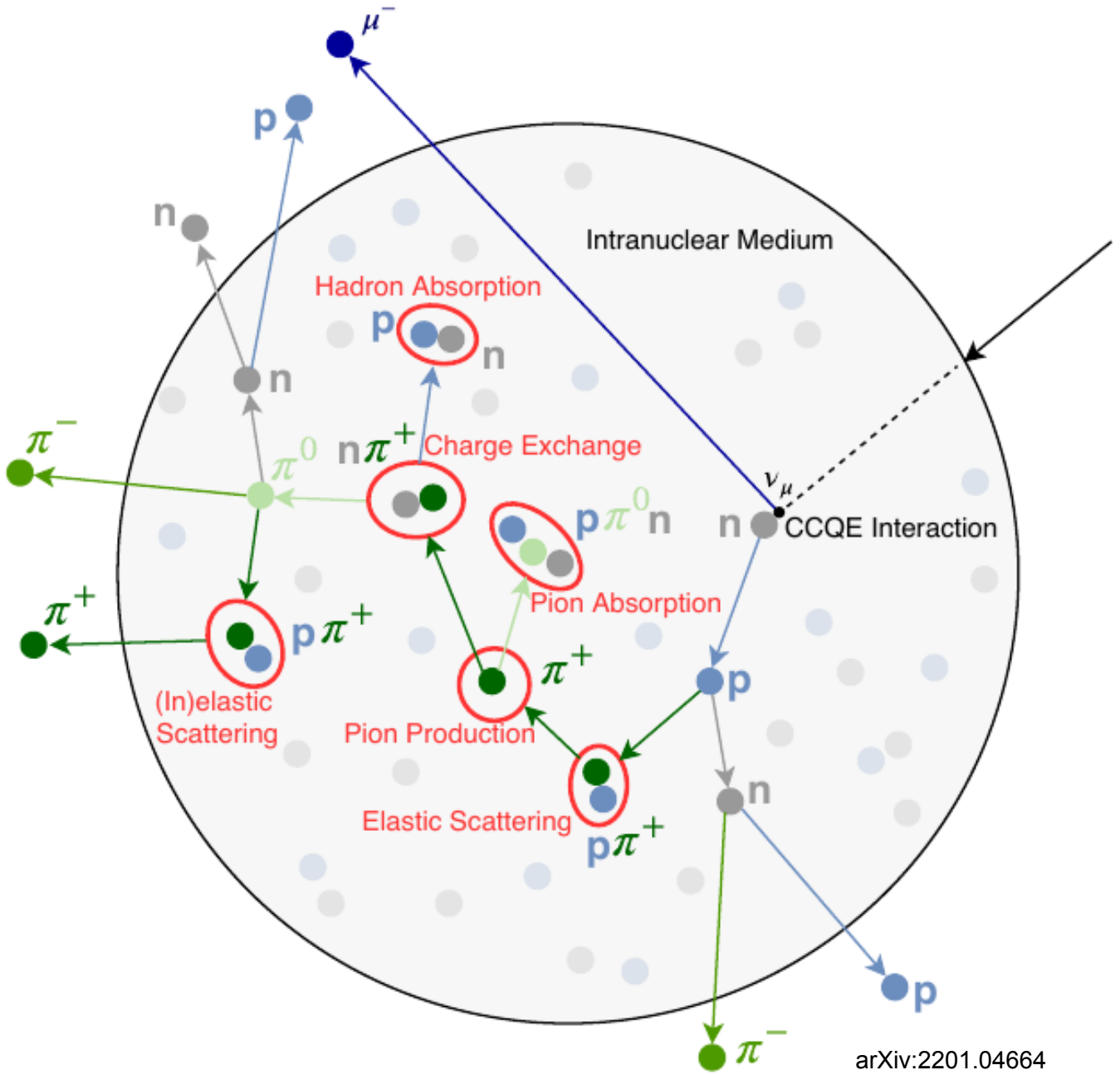
Nuclear Effects

Final **S**tate **I**nteractions (FSIs)

- FSIs inside the nucleus:
  - (In)elastic Scattering
  - Pion Production
  - Absorption
  - Charge Exchange

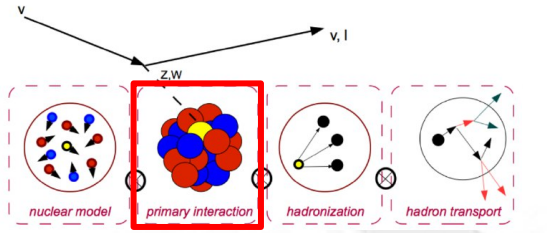
- Interaction observables, if / once hadron escapes the nucleus.



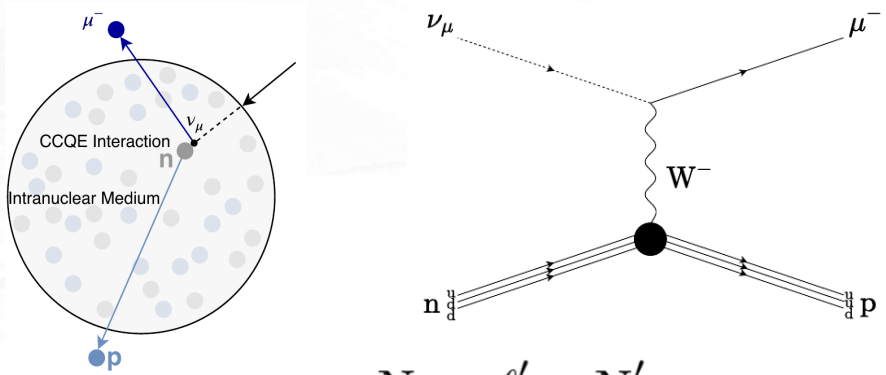


arXiv:2201.04664

Neutrino-Nucleus Interactions

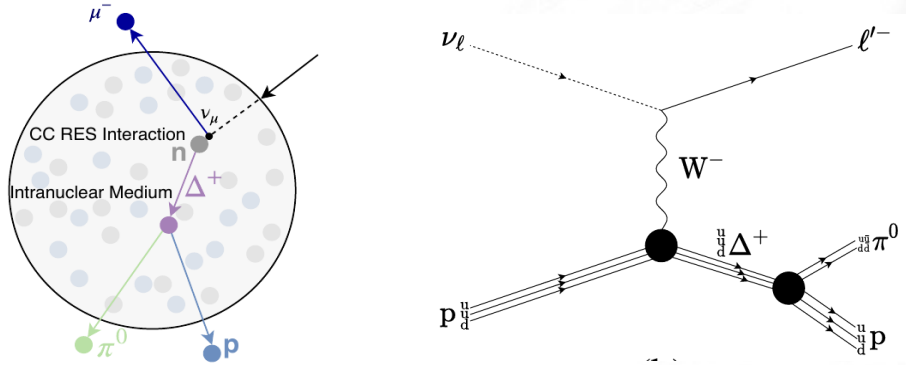


Quasi-Elastic (QE)



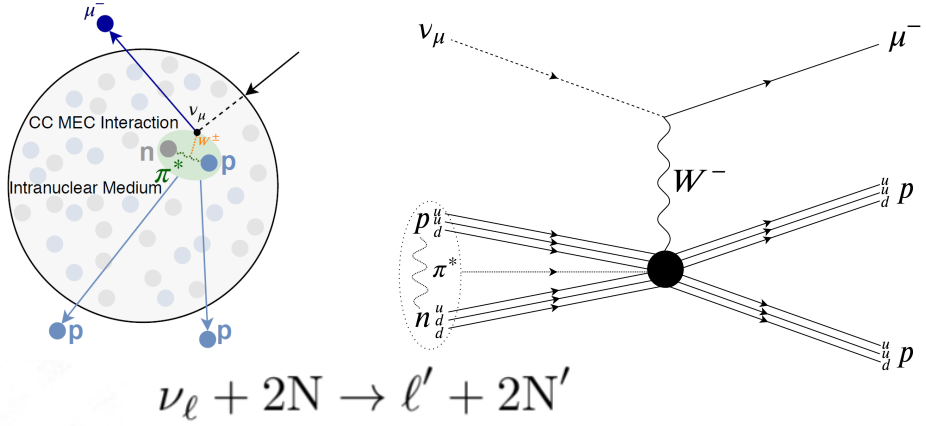
$$\nu_\ell + \mathrm{N} \rightarrow \ell' + \mathrm{N}'$$

Resonance Excitation (RES)



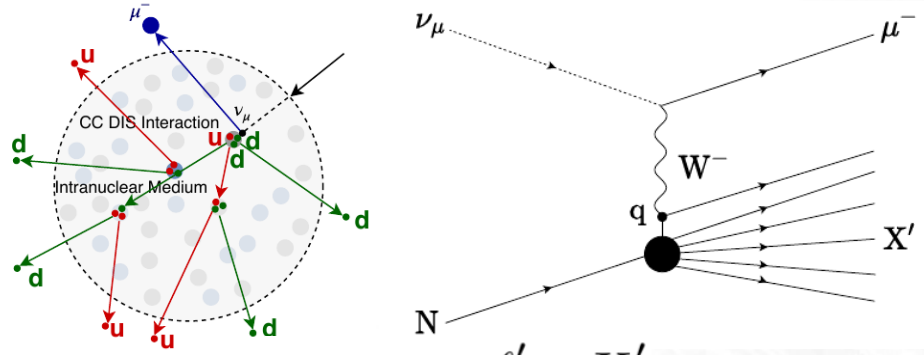
$$\nu_\ell + \mathrm{N} \rightarrow \ell' + \mathrm{N}' + \pi'$$

Multi-Nucleon Processes (*n*p-*n*h)



$$\nu_\ell + 2\mathrm{N} \rightarrow \ell' + 2\mathrm{N}'$$

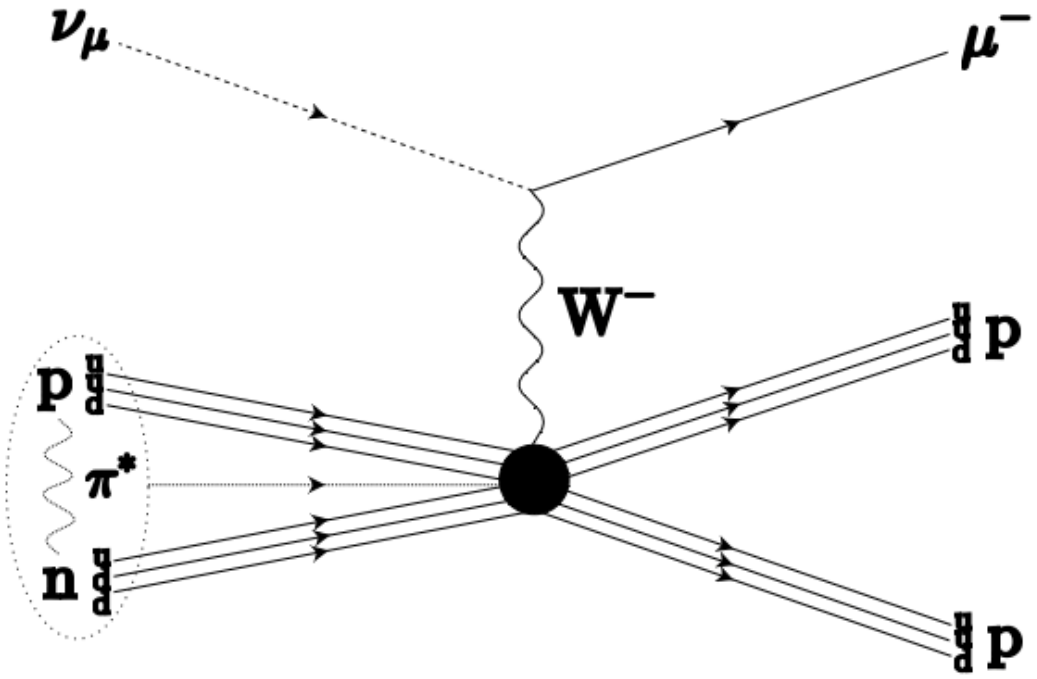
Deep Inelastic Scattering (DIS)

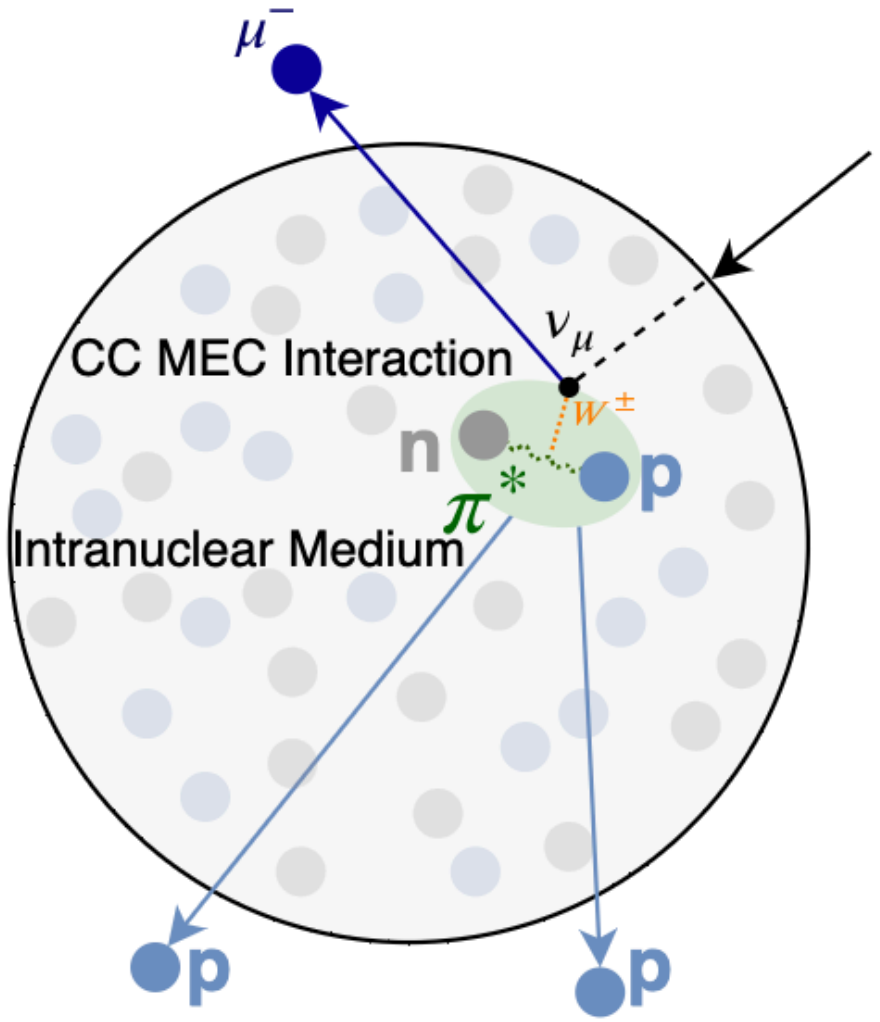


$$\nu_\ell + \mathrm{q} \rightarrow \ell' + \mathrm{X}'$$

LBP:FERMILAB-MASTERS-2020-03

CC 2p-2h Neutrino Interaction





LBP:FERMILAB-MASTERS-2020-03

Neutrino Event Generators

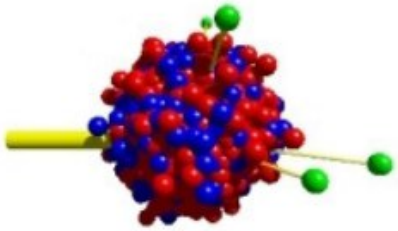
- Ambigous theoretical approach to cross-section calculation

➡ Different attempts in cross section predictions

➡ Various neutrino event generators to simulate neutrino-nucleus scattering

- Large gap between theory and experiment

➡ Need data from experiment



GiBUU

The Giessen Boltzmann-Uehling-Uhlenbeck Project

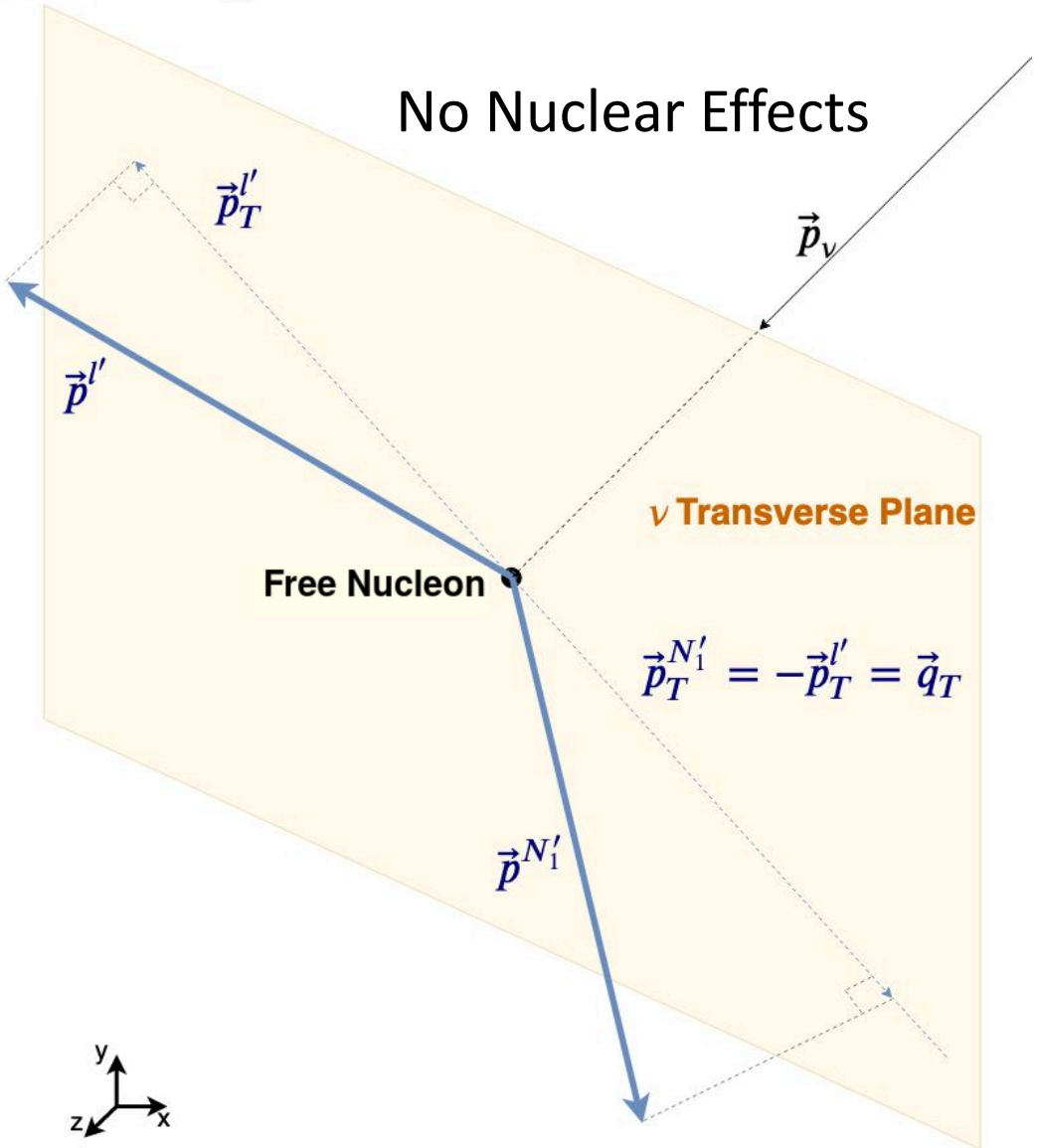
Genie

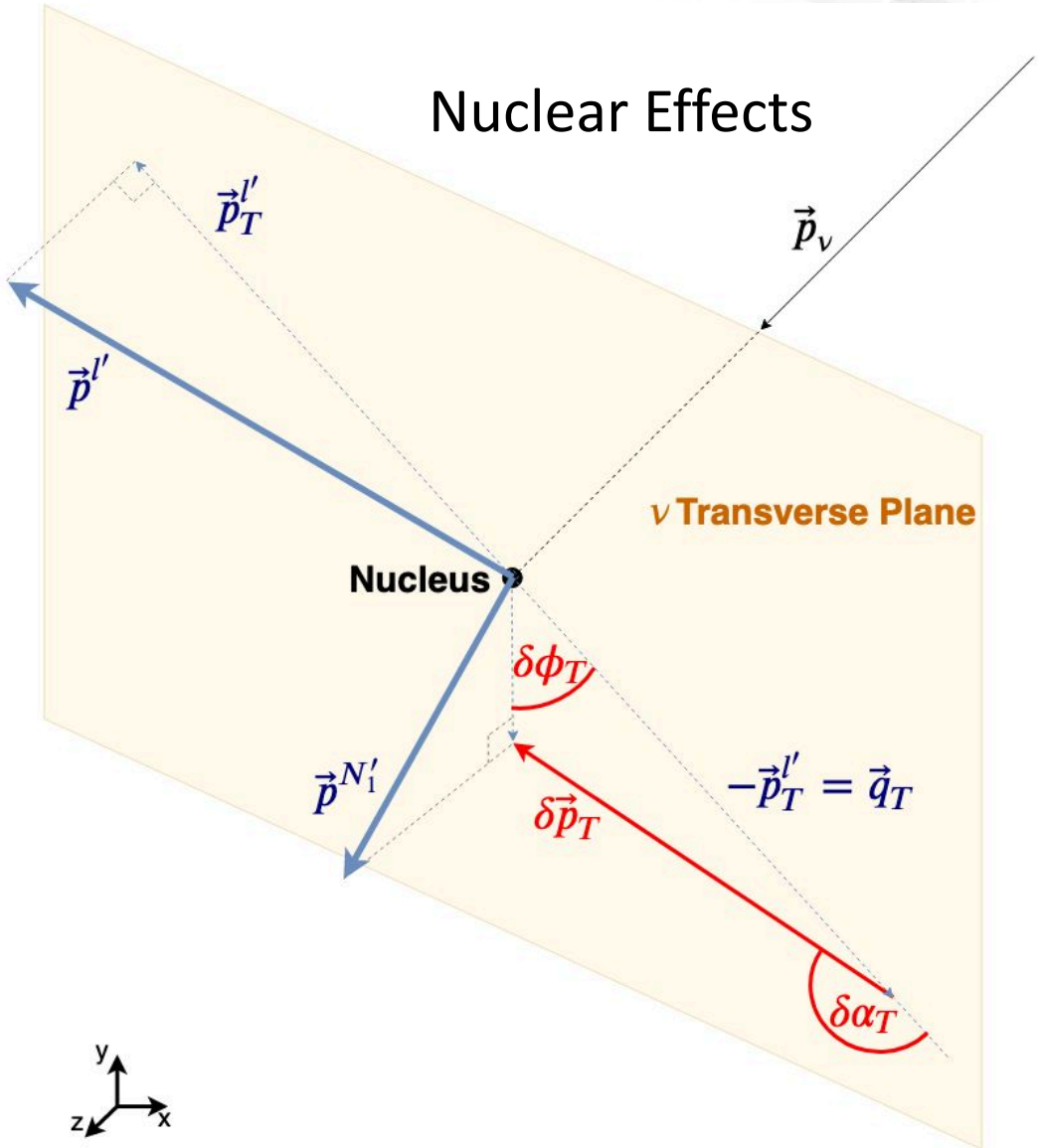
UNIVERSAL NEUTRINO GENERATOR & GLOBAL FIT

NuWro

Wrocław Neutrino Event Generator

Transverse Kinematic Imbalance (TKI)

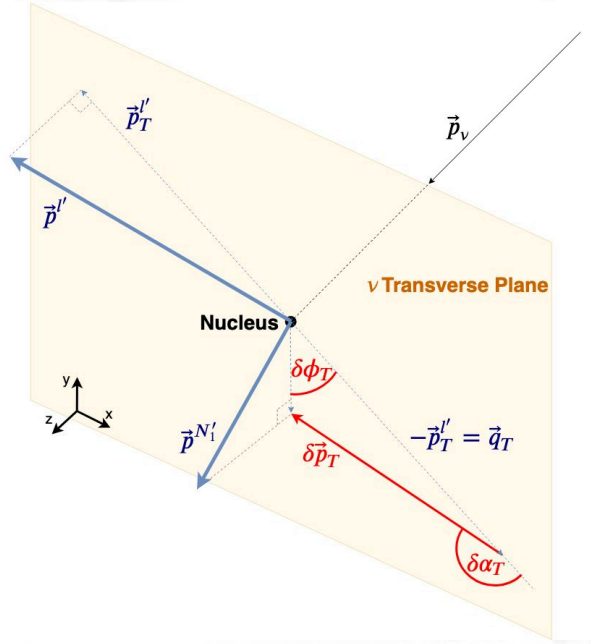




Transverse Kinematic Imbalance Variables

- Any imbalance observed for CCQE interactions between lepton and hadron kinematics is a direct consequence of nuclear effects

- This imbalance (STKI) can be fully characterised by a set of three **S**ingle-**T**ransverse **V**ariables (STVs)

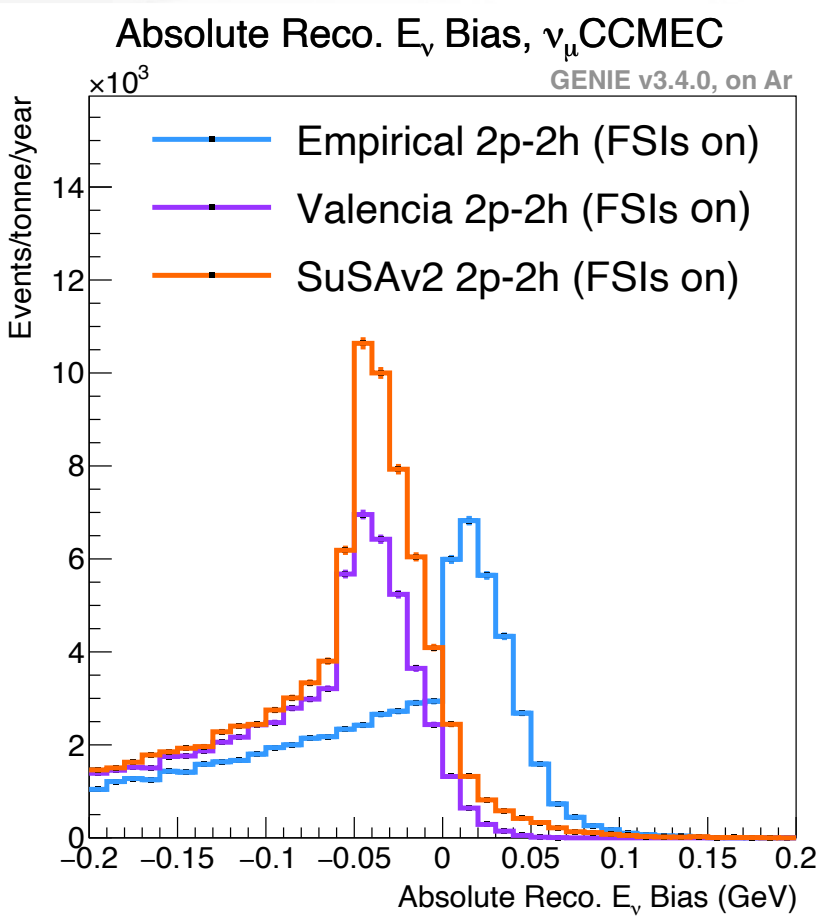


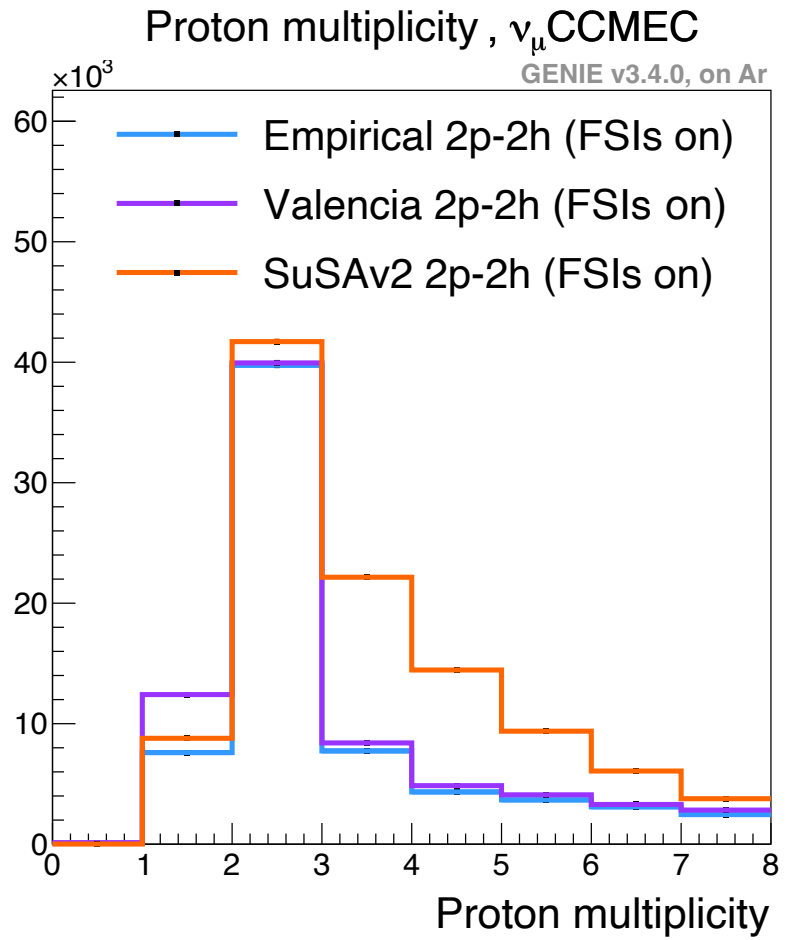
$$\delta\vec{p}_{\mathrm{T}} \equiv \vec{p}_{\mathrm{T}}^{\,\ell'} + \vec{p}_{\mathrm{T}}^{\,\mathrm{N}}$$

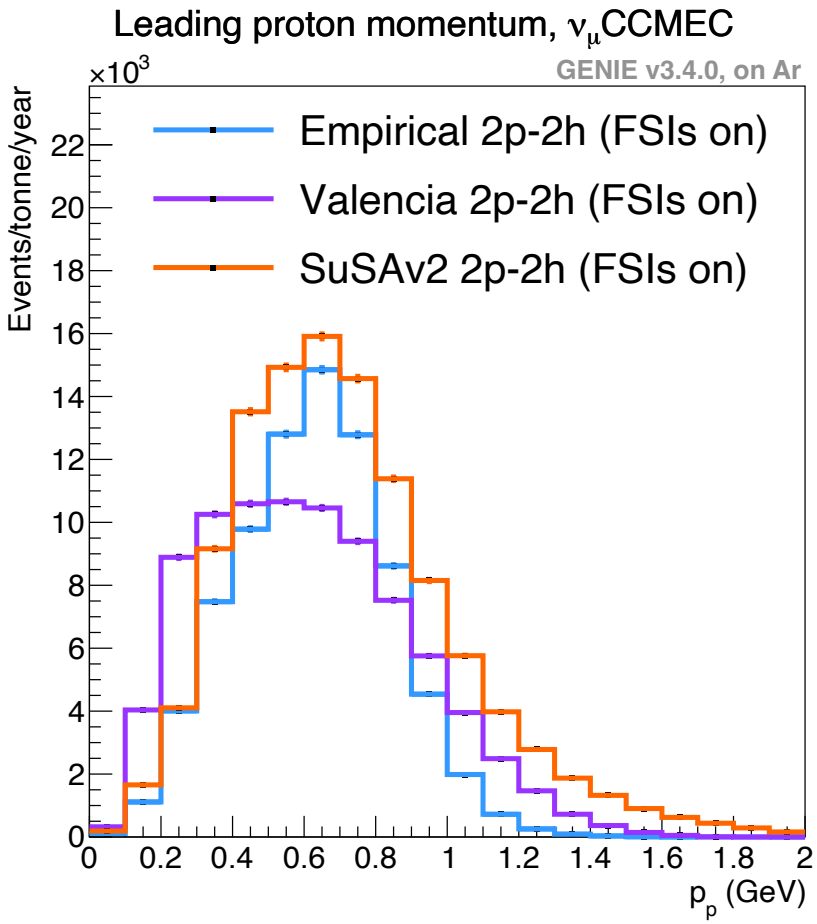
$$\delta\alpha_{\mathrm{T}} \equiv \arccos\frac{-\vec{p}_{\mathrm{T}}^{\,\ell'} \cdot \delta\vec{p}_{\mathrm{T}}}{p_{\mathrm{T}}^{\ell'}\,\delta p_{\mathrm{T}}}$$

$$\delta\phi_T \equiv \arccos\frac{-\vec{p}_T^{\,l'} \cdot \vec{p}_T^{\,N'}}{p_T^{\,l'}\,p_T^{N'}}$$

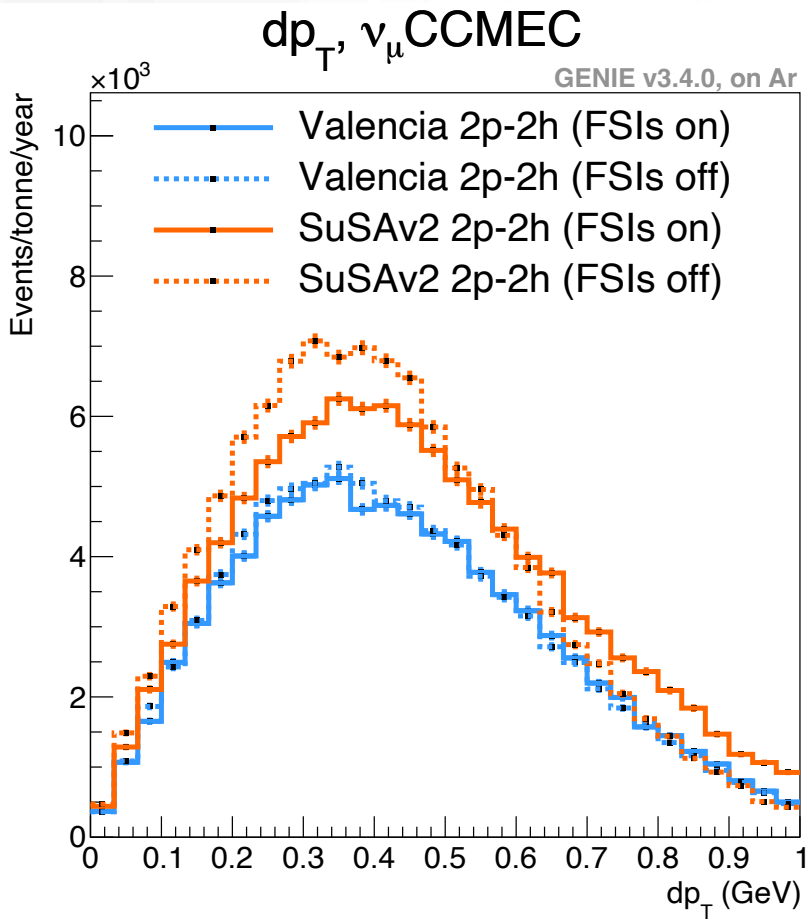
2p-2h Model Comparisons (FSIs on)

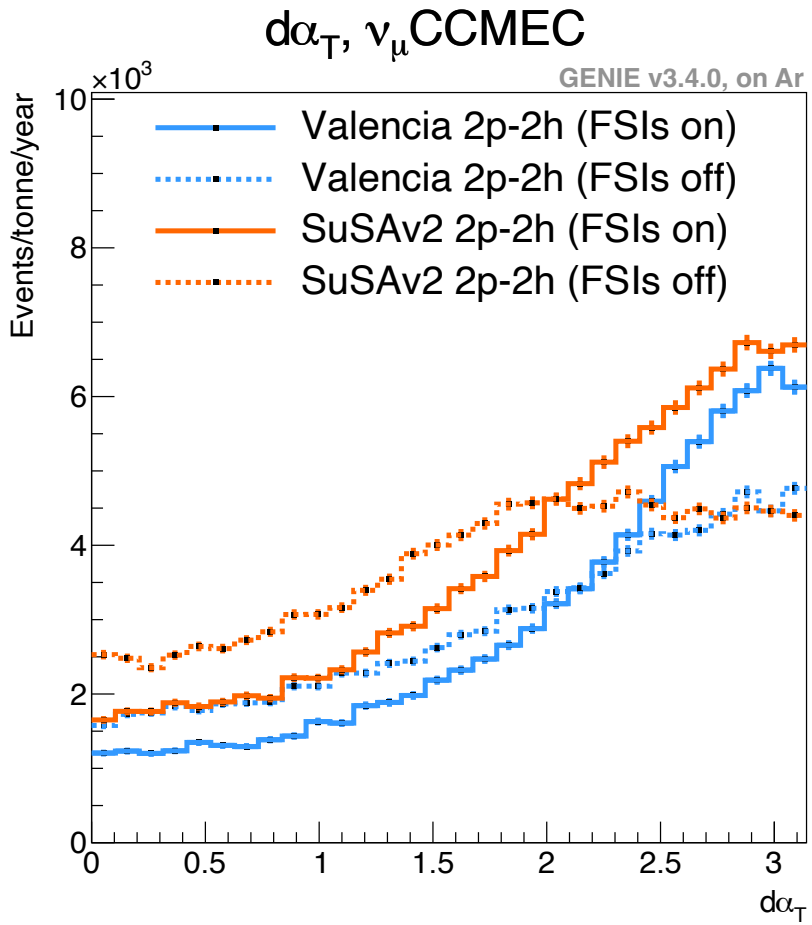


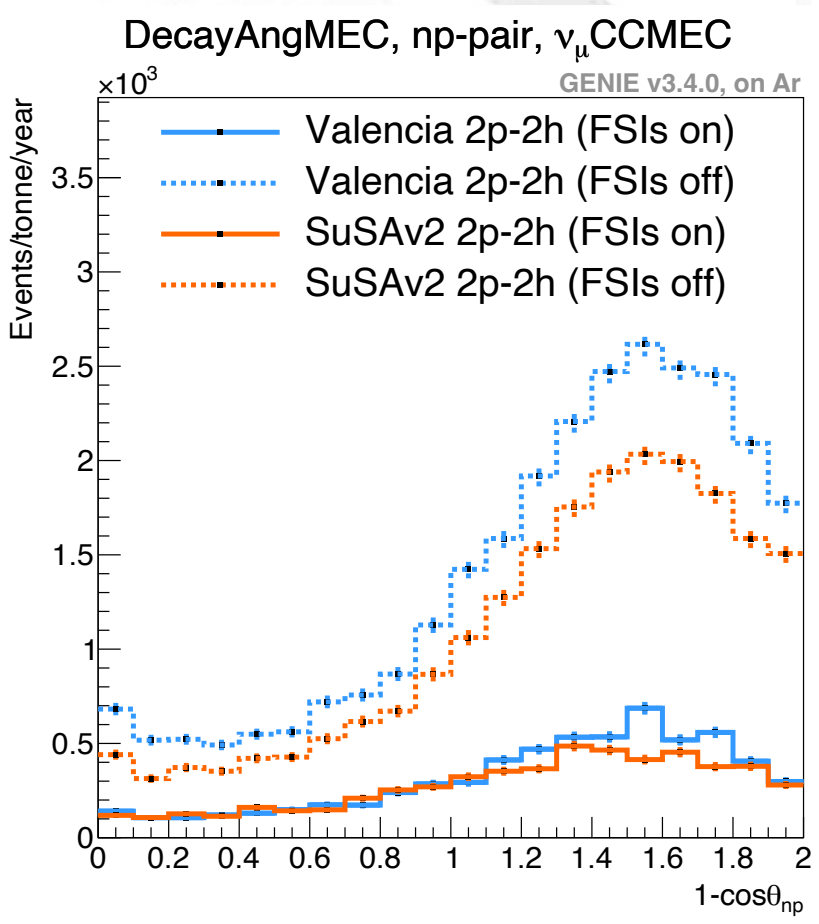




2p-2h Model Comparisons (preFSI vs. postFSI)

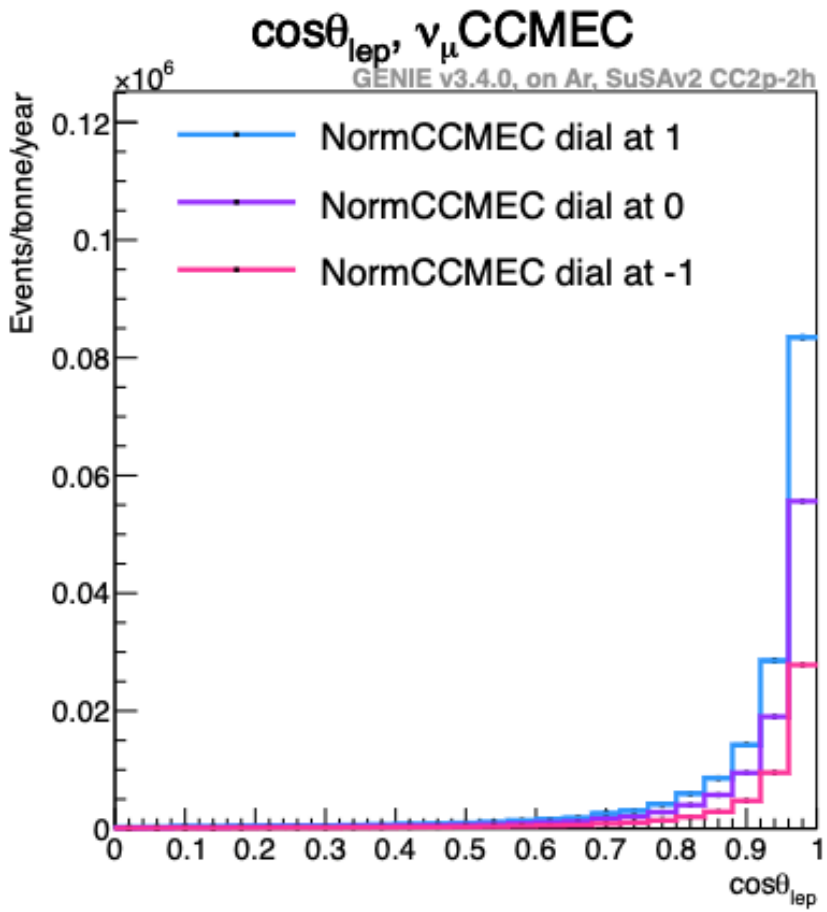


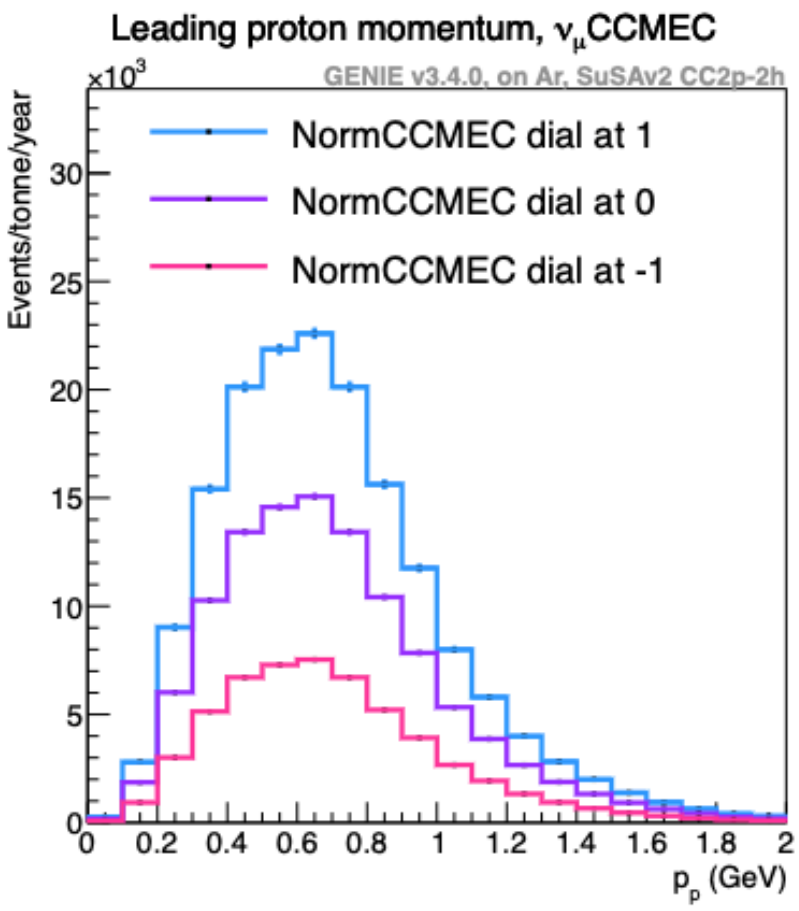


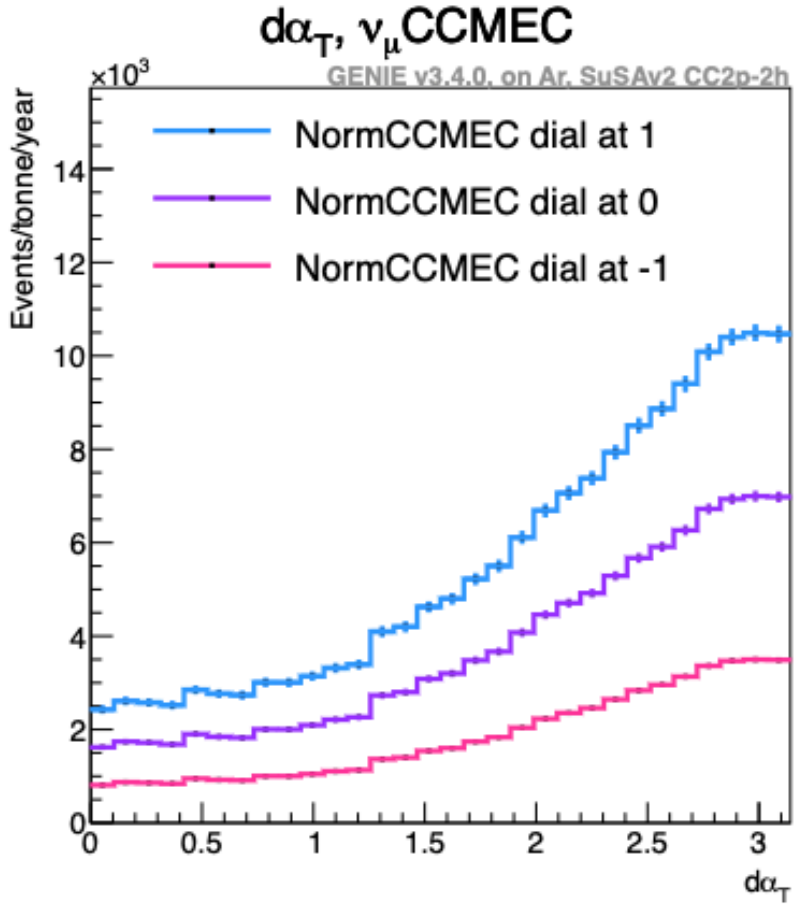


2p-2h Model Uncertainty Dials

NormCCMEC - changes absolute normalisation

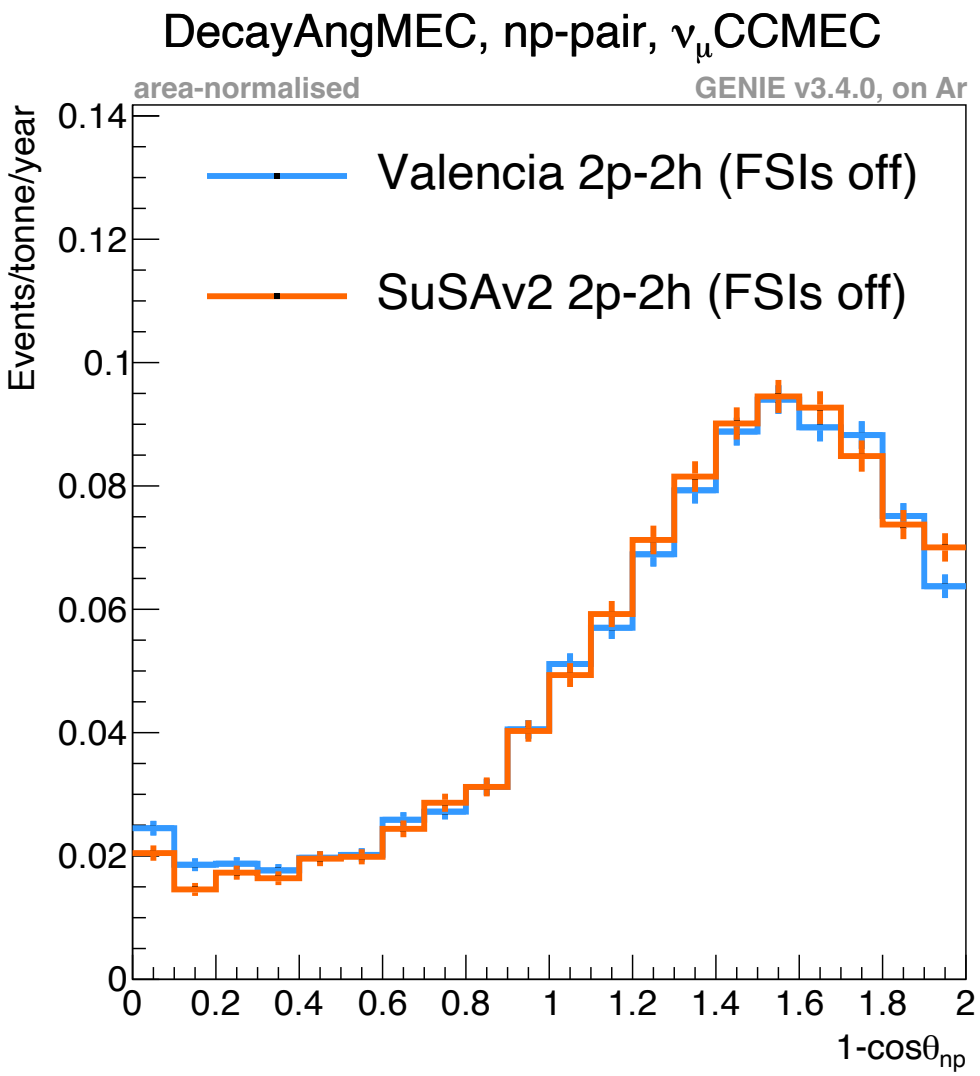


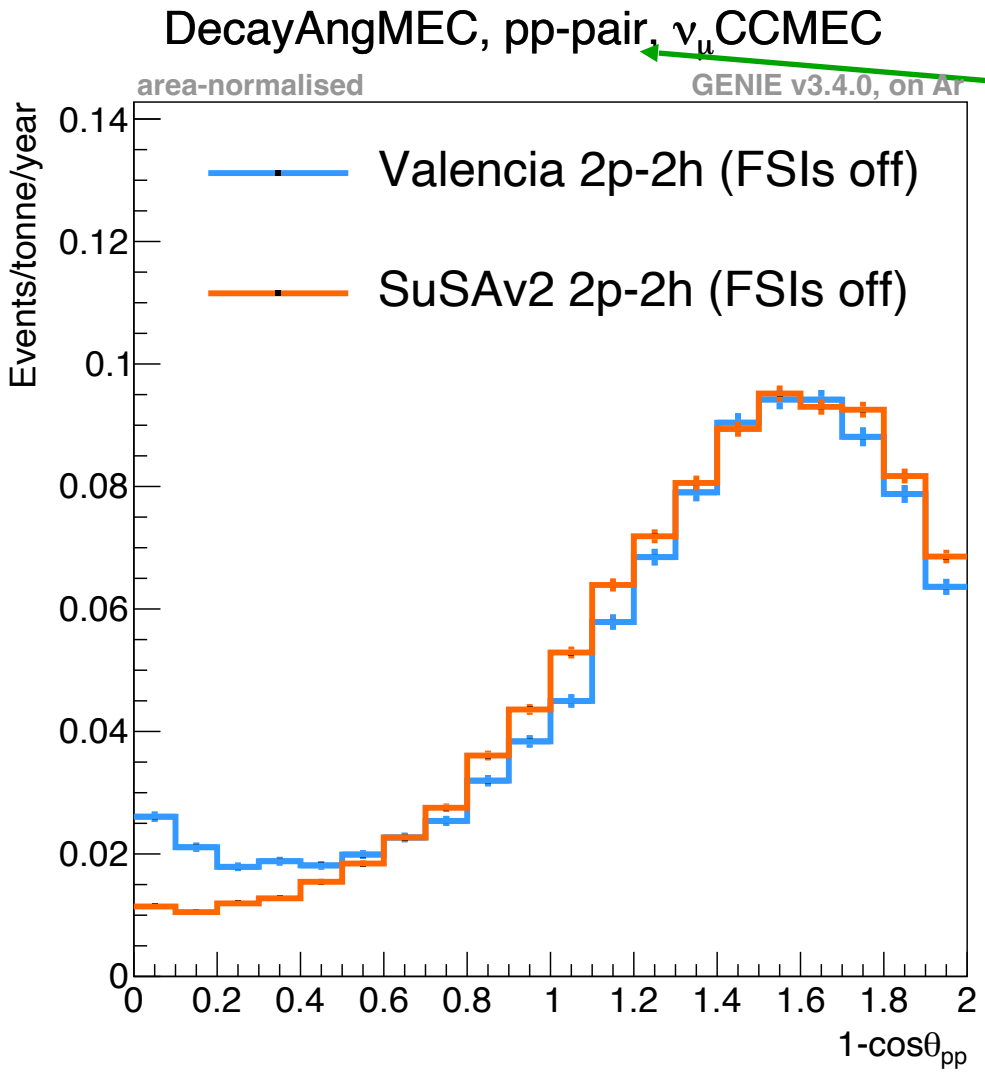




2p-2h Model Comparisons (FSIs off)

DecayAngMEC





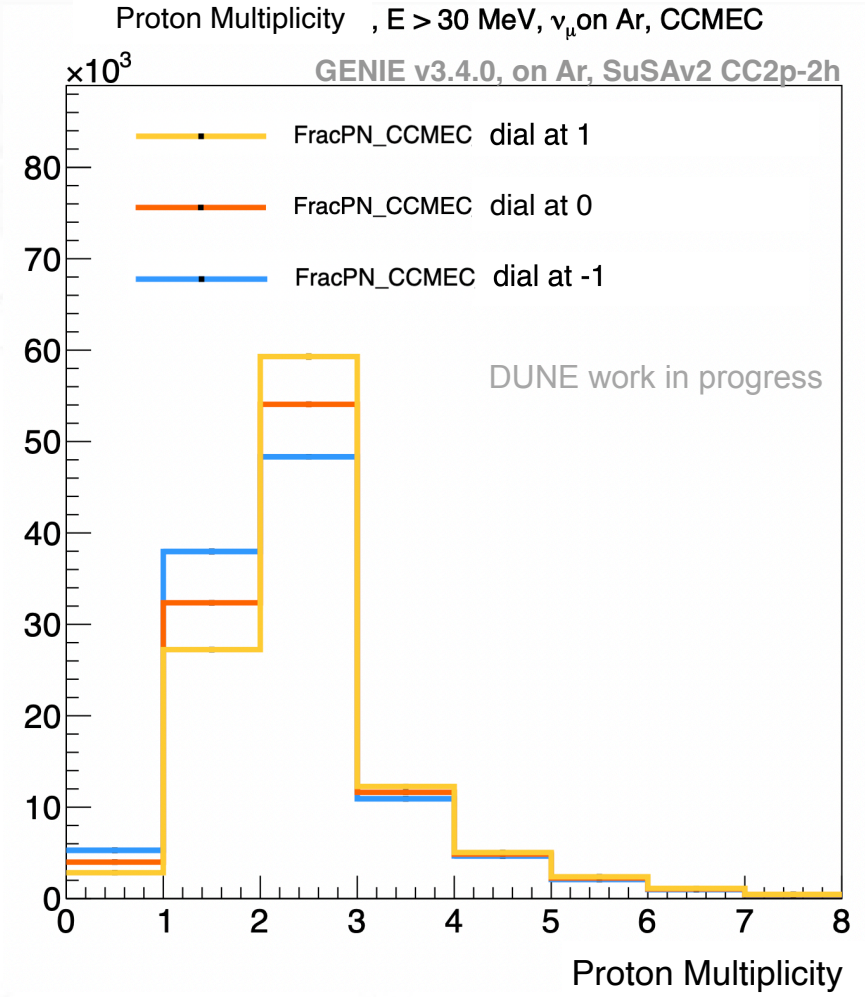
final-state pair!

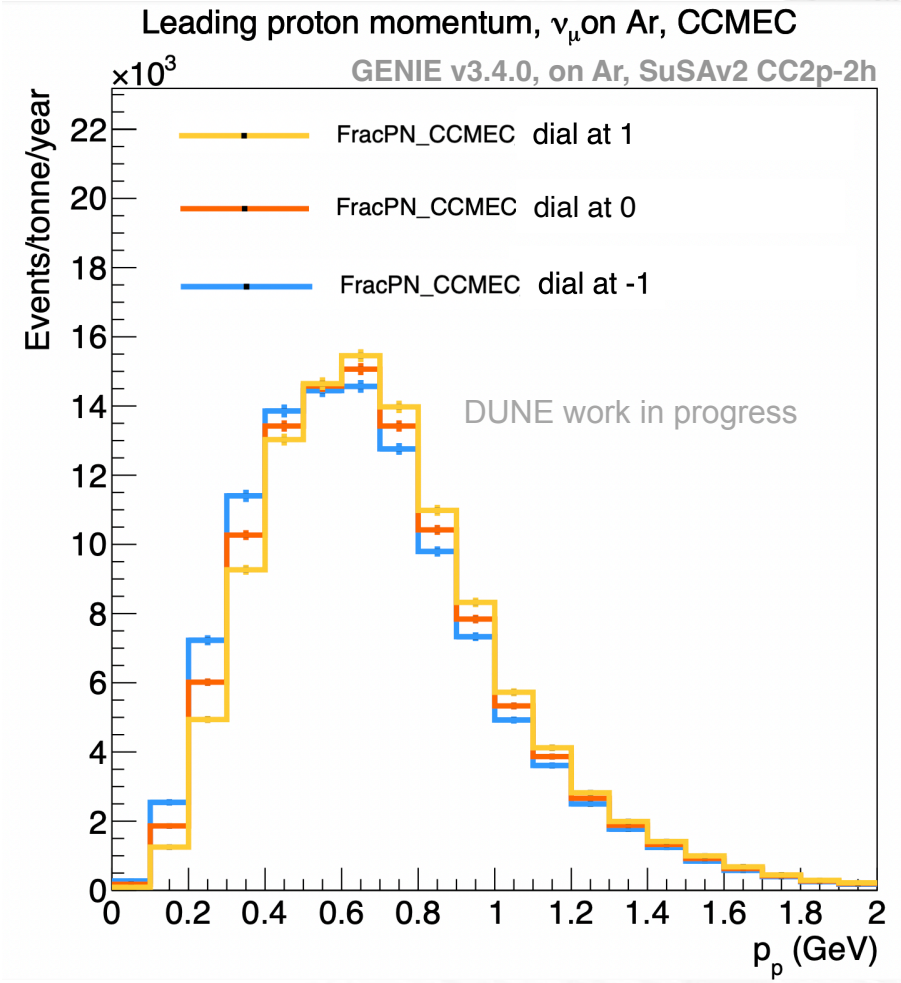
Muon Neutrino interaction on bound states:

- nn -> np
- np -> pp

2p-2h Model Uncertainty Dials

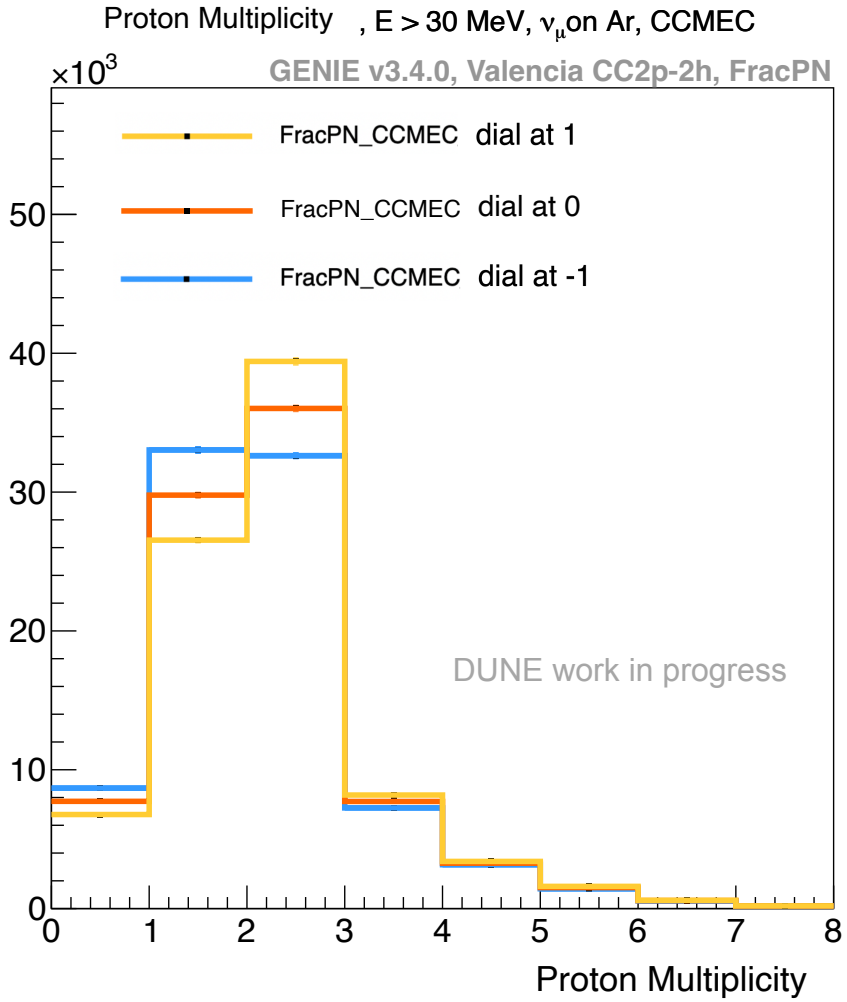
FracPN_CCMEC - changes default prediction of initial pair content of nucleons

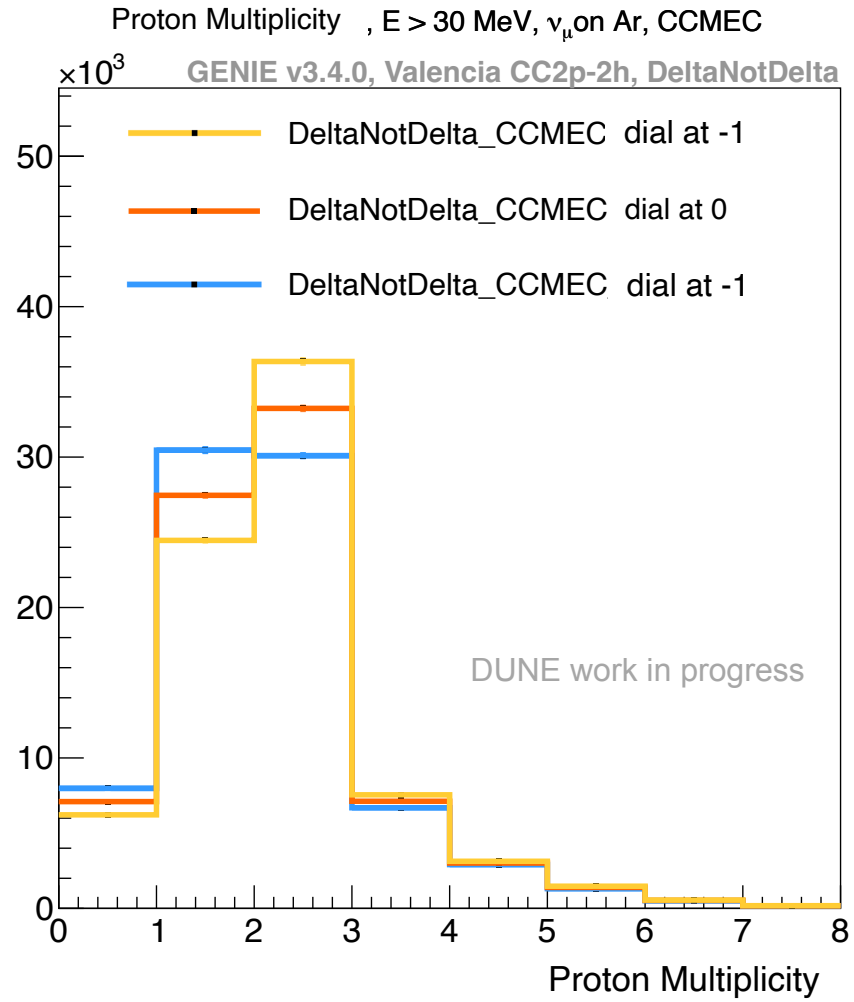




2p-2h Model Uncertainty Dials

FracPN_CCMEC vs. *DeltaNotDelta_CCMEC* - the effect of Δ-resonances





- *DeltaNotDelta_CCMEC* dial: adjusts relative strength of Δ-resonance contributions to 2p-2h cross sections
- Distinguish four cases
  - !is_pn_event & !is_delta_event
  - !is_pn_event & is_delta_event
  - is_pn_event & !is_delta_event
  - is_pn_event & is_delta_event
- Implemented flagispnevent and flagisdeltaevent variables in NUISANCE

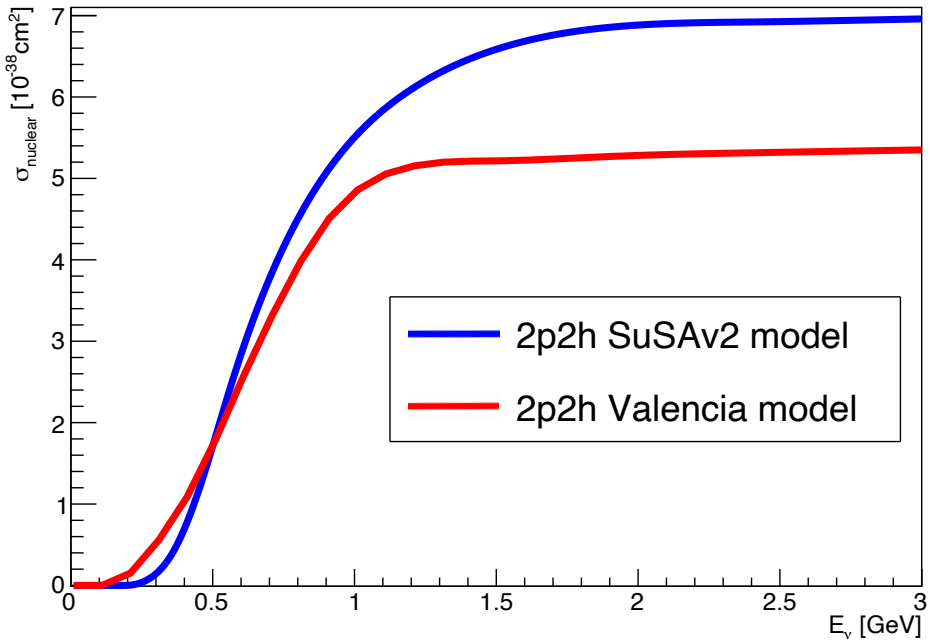
2p-2h Model Uncertainty Dials

EnergyDependence_CCMEC - changes the energy dependence of 2p-2h cross sections

[T2K-TN-344-v4]

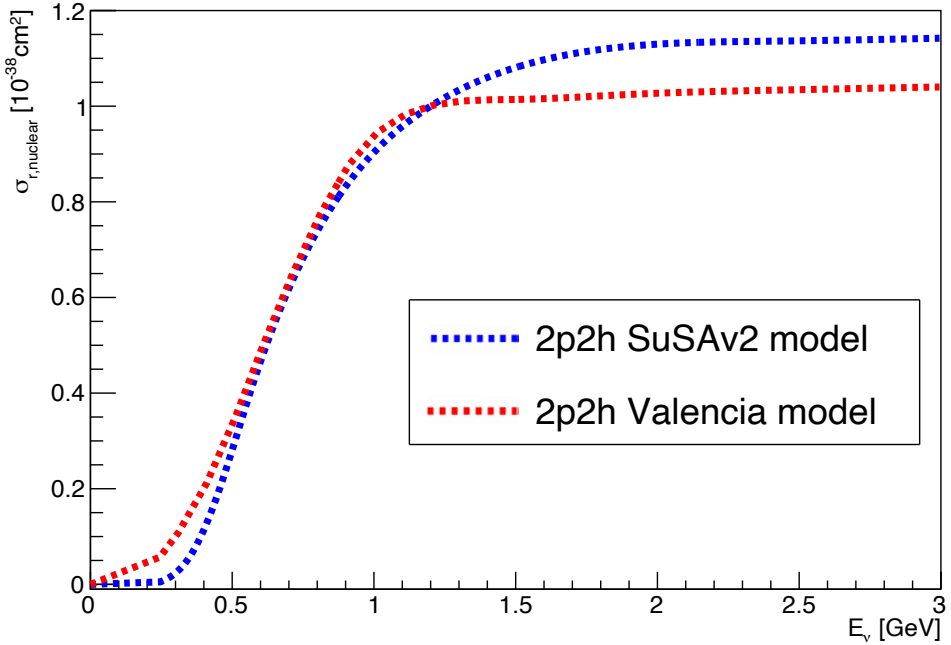
- Parametrise 2p-2h cross section by $\sigma_\nu(E_\nu) = \sigma_\nu^{\mathrm{MC}}(E_\nu) \cdot N_\nu \cdot \left(1 + \frac{1 - a_h}{r_\nu(E_\nu)}\right)$

GENIE 2p2h cross sections



$$\sigma_r(E_\nu) = \frac{\sigma(E_\nu)}{\sigma(1.2\ \mathrm{GeV})}$$

GENIE 2p2h normalised (1.2 GeV) cross sections



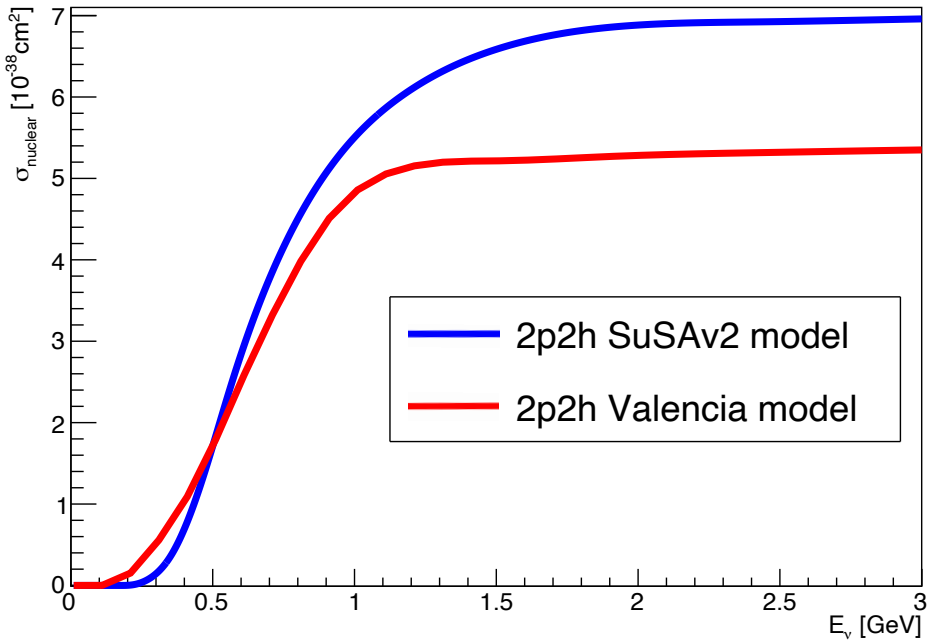
2p-2h Model Uncertainty Dials

EnergyDependence_CCMEC - changes the energy dependence of 2p-2h cross sections

[T2K-TN-344-v4]

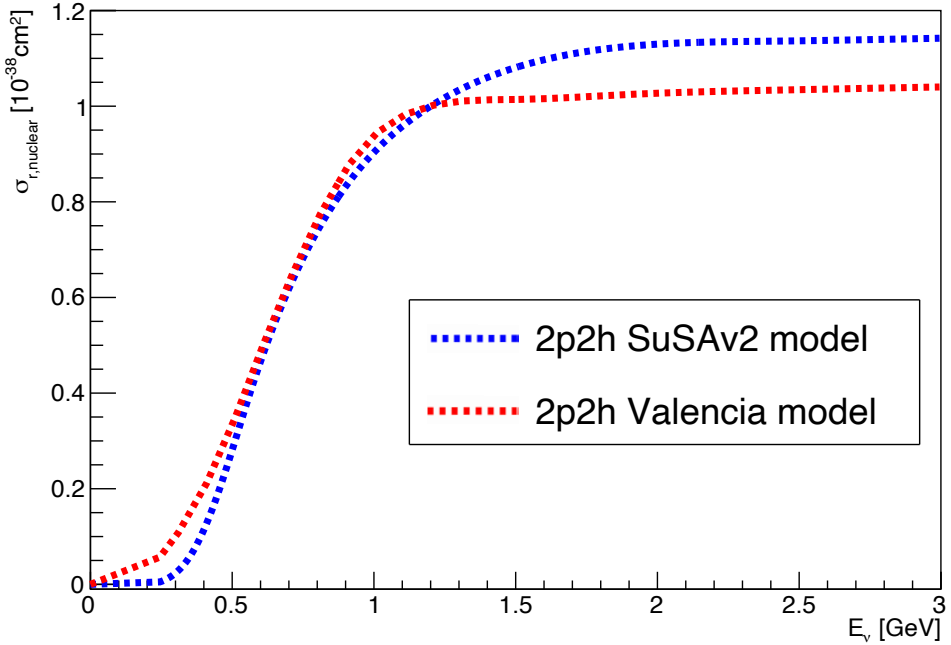
- Parametrise 2p-2h cross section by $\sigma_\nu(E_\nu) = \sigma_\nu^{\mathrm{MC}}(E_\nu) \cdot N_\nu \cdot \left(1 + \frac{1 - a_h}{r_\nu(E_\nu)}\right)$ $r_\nu(E_\nu) = \frac{\sigma_r^{max}(E_\nu)}{\sigma_r^{min}(E_\nu)}$

GENIE 2p2h cross sections



$\sigma_r(E_\nu) = \frac{\sigma(E_\nu)}{\sigma(1.2\ \mathrm{GeV})}$

GENIE 2p2h normalised (1.2 GeV) cross sections



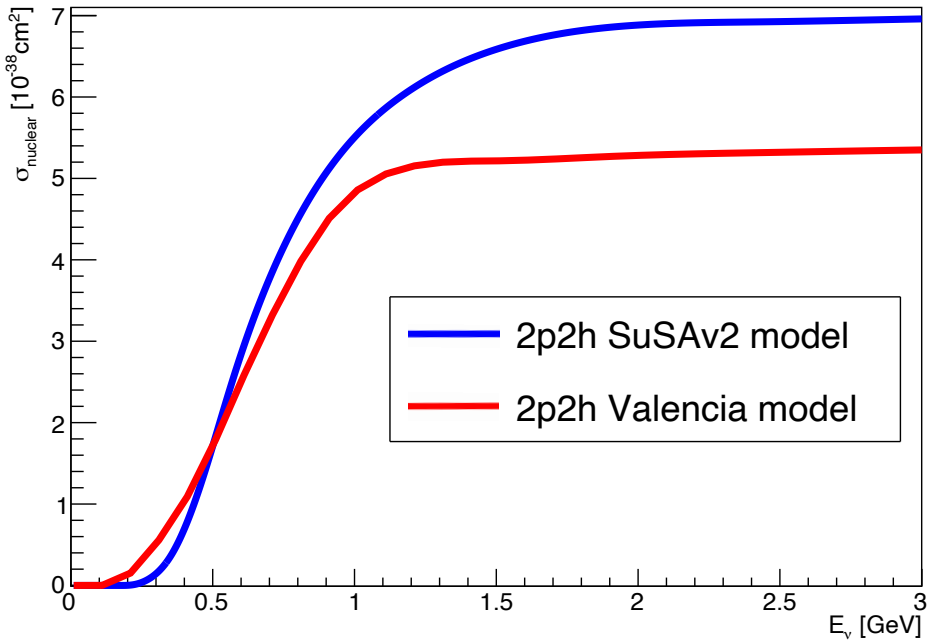
2p-2h Model Uncertainty Dials

EnergyDependence_CCMEC - changes the energy dependence of 2p-2h cross sections

[T2K-TN-344-v4]

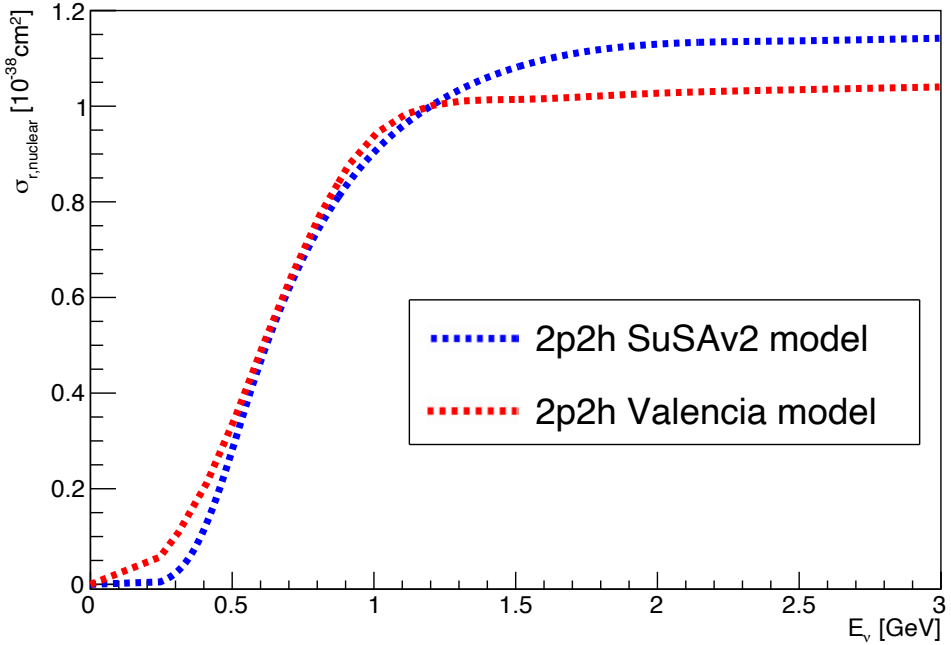
- Parametrise 2p-2h cross section by $\sigma_\nu(E_\nu) = \sigma_\nu^{\mathrm{MC}}(E_\nu) \cdot N_\nu \cdot \left(1 + \frac{1 - a_h}{r_\nu(E_\nu)}\right)$

GENIE 2p2h cross sections



$$\sigma_r(E_\nu) = \frac{\sigma(E_\nu)}{\sigma(1.2\ \mathrm{GeV})}$$

GENIE 2p2h normalised (1.2 GeV) cross sections



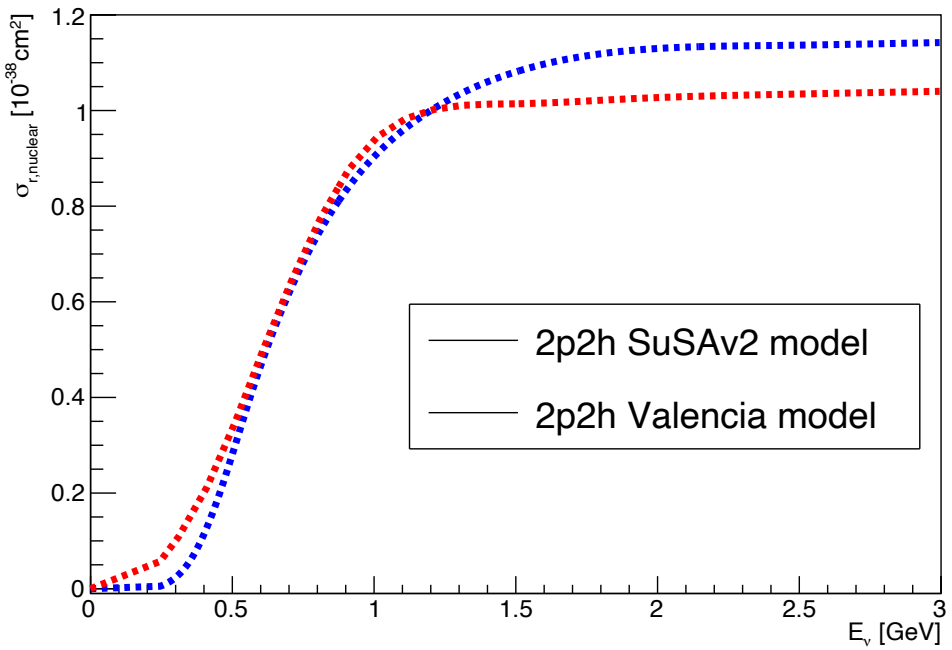
2p-2h Model Uncertainty Dials

EnergyDependence_CCMEC - changes the energy dependence of 2p-2h cross sections

[T2K-TN-344-v4]

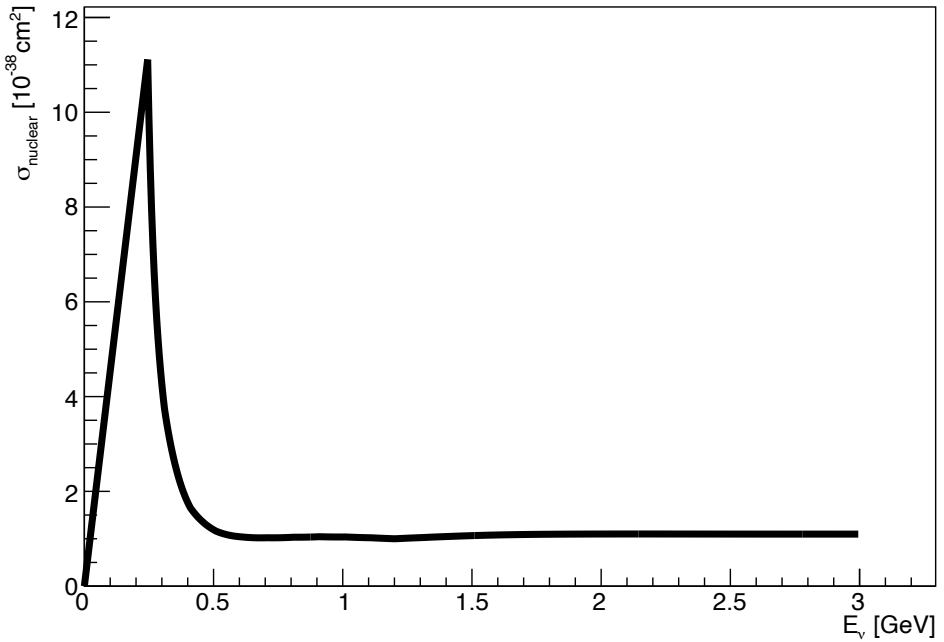
- Parametrise 2p-2h cross section by $\sigma_\nu(E_\nu) = \sigma_\nu^{\mathrm{MC}}(E_\nu) \cdot N_\nu \cdot \left(1 + \frac{1 - a_h}{r_\nu(E_\nu)}\right)$

GENIE 2p2h normalised (1.2 GeV) cross sections



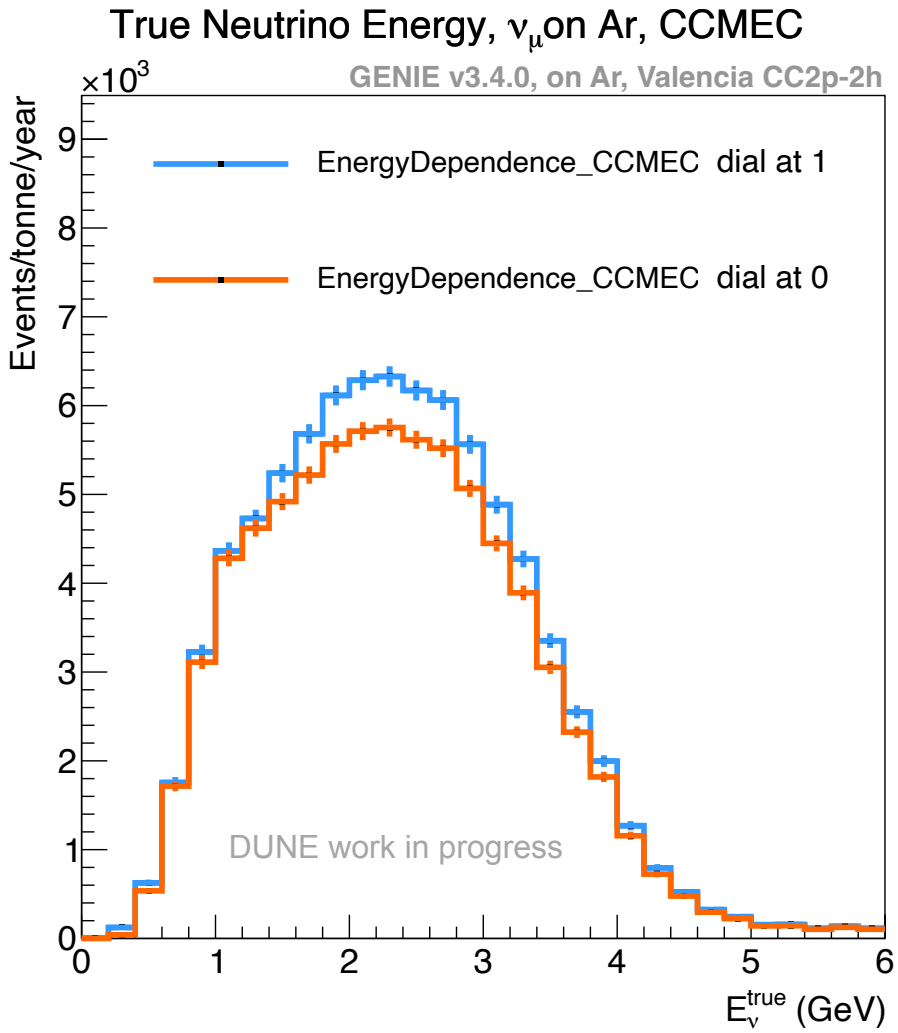
$$r_\nu(E_\nu) = \frac{\sigma_r^{max}(E_\nu)}{\sigma_r^{min}(E_\nu)}$$

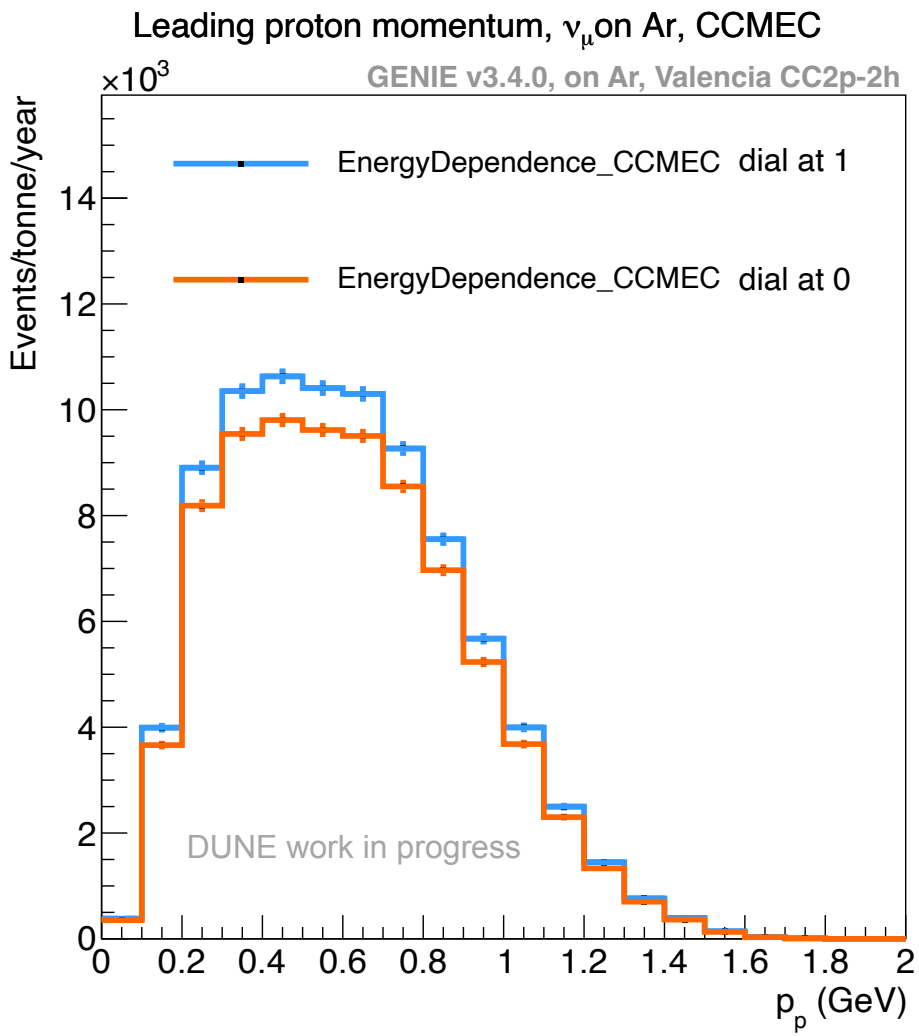
Cross section ratio plot (2p2h SuSAv2 and Valencia)



2p-2h Model Uncertainty Dials

EnergyDependence_CCMEC - changes the neutrino energy dependence





References and Further Reading

[1] L. Alvarez-Ruso, M. Sajjad Athar, M. Barbaro, *et al.*, *Prog. Part. Nucl. Phys.*, **100**, May 2018,
[2] O. Benhar *et al.*, *Adv. High Energy Phys.*, **2013**, 2013. arXiv: 1310.3869 [nucl-th].
[3] G. D. Megias *et al.*, *Springer Proc. Phys.*, **225**, 2019. arXiv: 1901.11022 [hep-ph].
[4] X.-G. Lu, D. Coplowe, R. Shah, G. Barr, D. Wark, and A. Weber, *Phys. Rev. D*, **92**, 5 Sep. 2015.
[5] X. G. Lu *et al.*, *Phys. Rev. Lett.*, **121**, (2), 2018. arXiv: 1805.05486 [hep-ex].
[6] L. Munteanu *et al.*, *Phys. Rev. D*, **101**, (9), 2020. arXiv: 1912.01511 [physics.ins-det].
[7] S. Dolan, *arXiv*, 2018. arXiv: 1810.06043 [hep-ex].
[8] J. A. Formaggio *et al.*, *Rev. Mod. Phys.*, **84**, 2012. arXiv: 1305.7513 [hep-ex].
[9] X.-G. Lu, L. Pickering, S. Dolan, *et al.*, *Phys. Rev. C*, **94**, 1 Jul. 2016.
[10] A. P. Furmanski *et al.*, *Phys. Rev.*, **C95**, (6), 2017. arXiv: 1609.03530 [hep-ex].
[11] T. Katori and M. Martini, *J. Phys. G*, **45**, (1), 2018. arXiv: 1611.07770 [hep-ph].
[12] B. Kayser, *eConf*, **C040802**, 2004. arXiv: hep-ph/0506165.
[13] K. Mahn *et al.*, *Annual Review of Nuclear and Particle Science*, **68**, (1), 2018.
[14] L. Alvarez-Ruso, M. S. Athar, M. Barbaro, *et al.*, *Progress in Particle and Nuclear Physics*, **100**, 2018,
[15] M. Del Tutto, Ph.D. dissertation, Oxford U., 2019.
[16] L. Bathe-Peters *et al.*, *FERMILAB-PUB-22-007-SCD*, Jan. 2022. arXiv: 2201.04664 [hep-ph].
[17] L. Bathe-Peters, M.S. thesis, Harvard University and Technische Universität Berlin, 2020.
[18] B. Abi *et al.*, *FERMILAB-PUB-20-025-ND*, Feb. 2020. arXiv: 2002.03005 [hep-ex].
[19] S. Dolan, U. Mosel, K. Gallmeister, L. Pickering, and S. Bolognesi, *Phys. Rev. C*, **98**, 4 Oct. 2018.
[20] P. Abratenko, R. An, J. Anthony, *et al.*, *Phys. Rev. D*, **105**, 7 Apr. 2022.
[21] C. Andreopoulos *et al.*, *Nucl. Instrum. Meth.*, **A614**, 2018. arXiv: 0905.2517 [hep-ph].
[22] T. Katori, *AIP Conference Proceedings*, **1663**, (1), May 2015, 030001,
[23] R. Gran, J. Nieves, F. Sanchez, and M. J. V. Vacas, *Phys. Rev. D*, **88**, 11 Dec. 2013.
[24] J. E. Amaro *et al.*, *Journal of Physics G: Nuclear and Particle Physics*, **47**, (12), 2020.