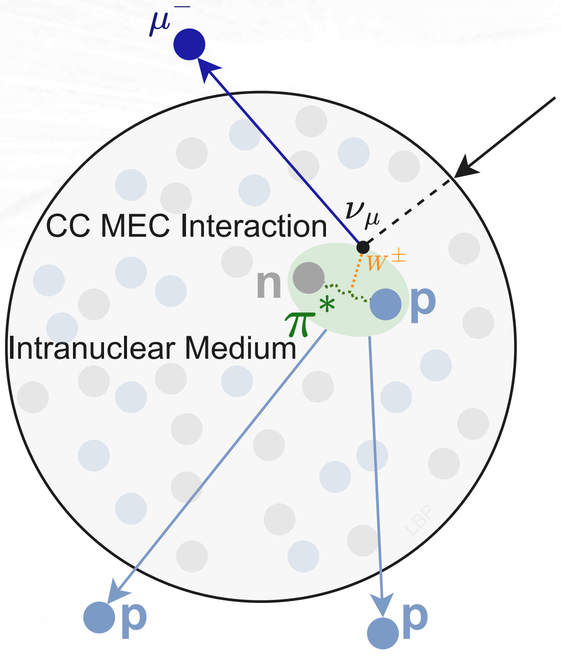
2p-2h Cross-Section Systematics in DUNE

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

for the DUNE Collaboration



Lars Bathe-Peters: FERMILAB-MASTERS-2020-03

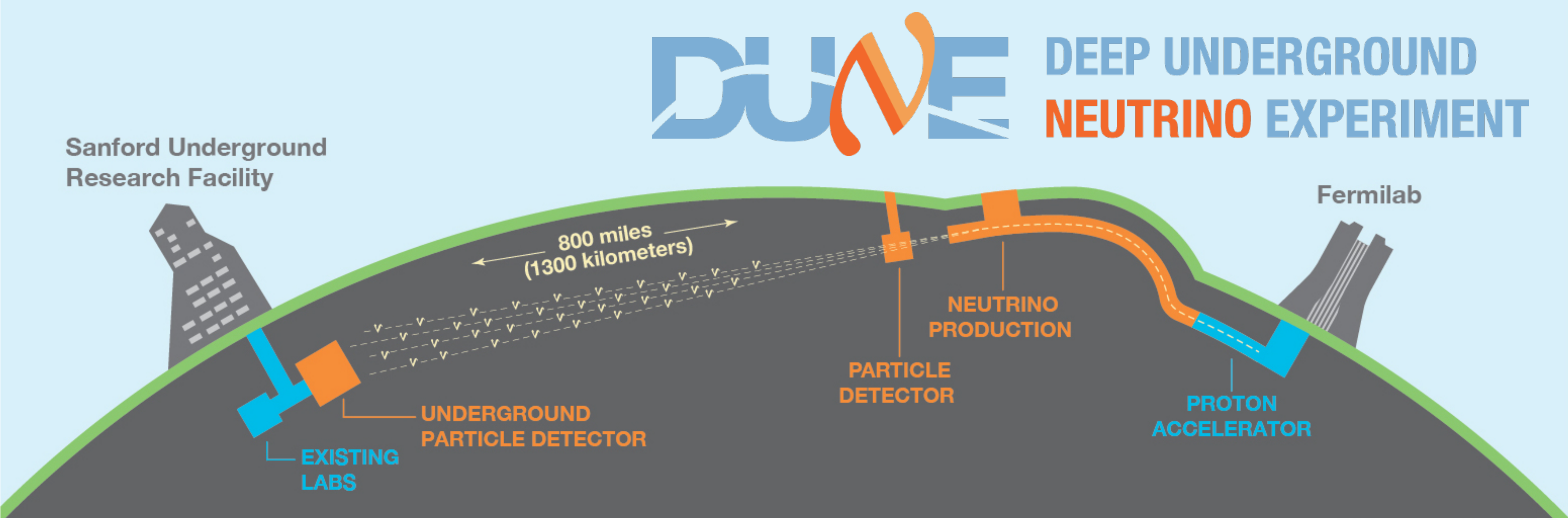
ANL

NuFact 2024

WG 1: Neutrino Oscillation Physics Parallel Session

Argonne National Laboratory, Illinois, USA

17th September, 2024

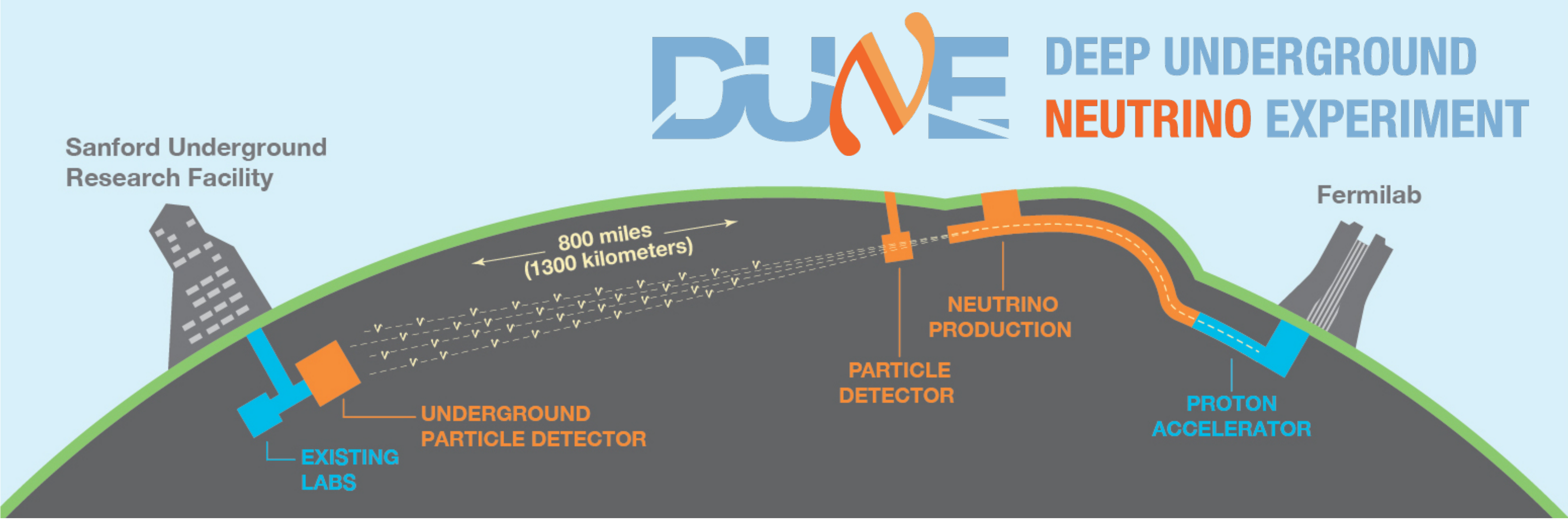


https://www.dunescience.org/

Primary Science Goals:

- Neutrino Oscillation Measurements $\left(\delta_{CP}\right.$, the sign of $\Delta m^2_{31}, \theta_{23}$ and its octant$\left.\right)$, search for CPV
- Proton Decay Search
- Detection and Measurement of ν_e flux from supernova

DUNE Far Detector Technical Design Report - Volume II: DUNE Physics



Ancillary Science Goals:

- Beyond-the-Standard-Model Physics (NSIs, LIV, CPT-violation, sterile neutrinos, large extra dimensions, heavy neutral leptons, measurements of tau neutrino appearance)
- Neutrino oscillations with atmospheric neutrinos
- Dark matter searches, neutron-antineutron oscillations
- Rich **neutrino interaction program** (cross sections, nuclear effects)

DUNE Far Detector Technical Design Report - Volume II: DUNE Physics

DUNE Near Detector

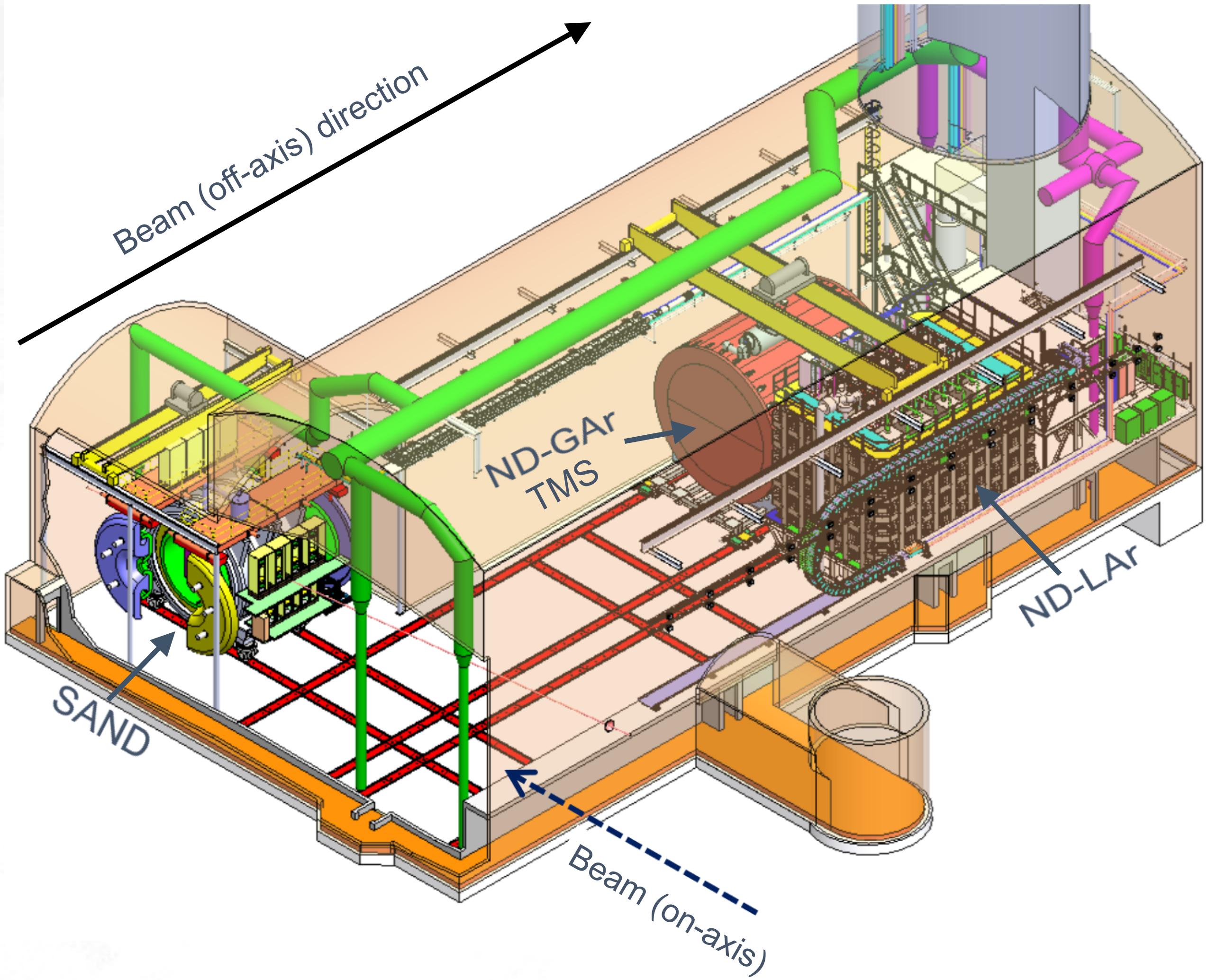


Image adapted from: The SAND detector at the DUNE near site

Roles of Near Detector:

- Characterization of beam
- Monitoring of beam
- Tuning of interaction model
- Constrain beam and cross-section models using different off-axis beam positions

DUNE Near Detector Conceptual Design Report

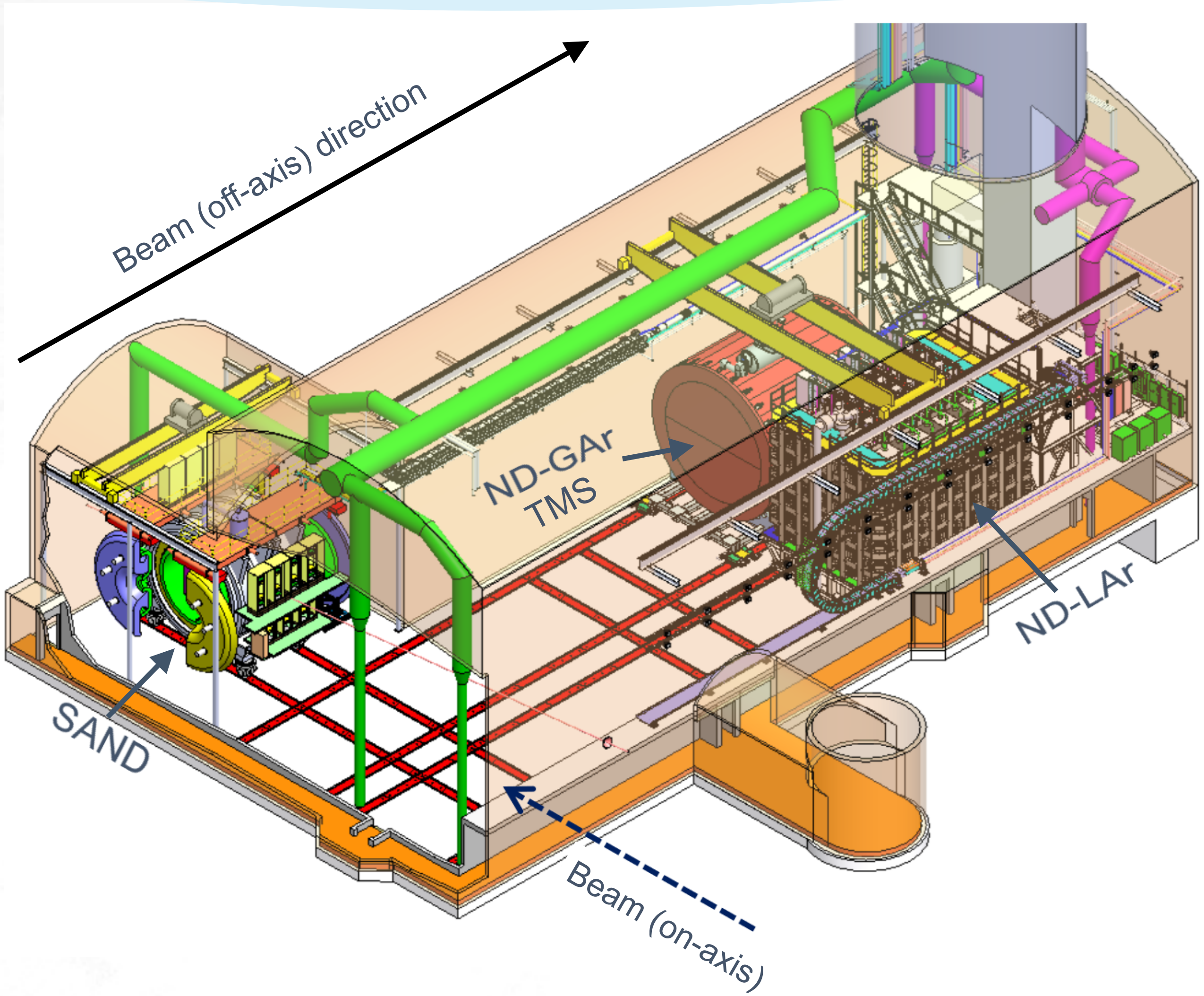


Image adapted from: [The SAND detector at the DUNE near site]

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[DUNE Near Detector Conceptual Design Report]

Neutrino Oscillations

Need Neutrino Cross Sections

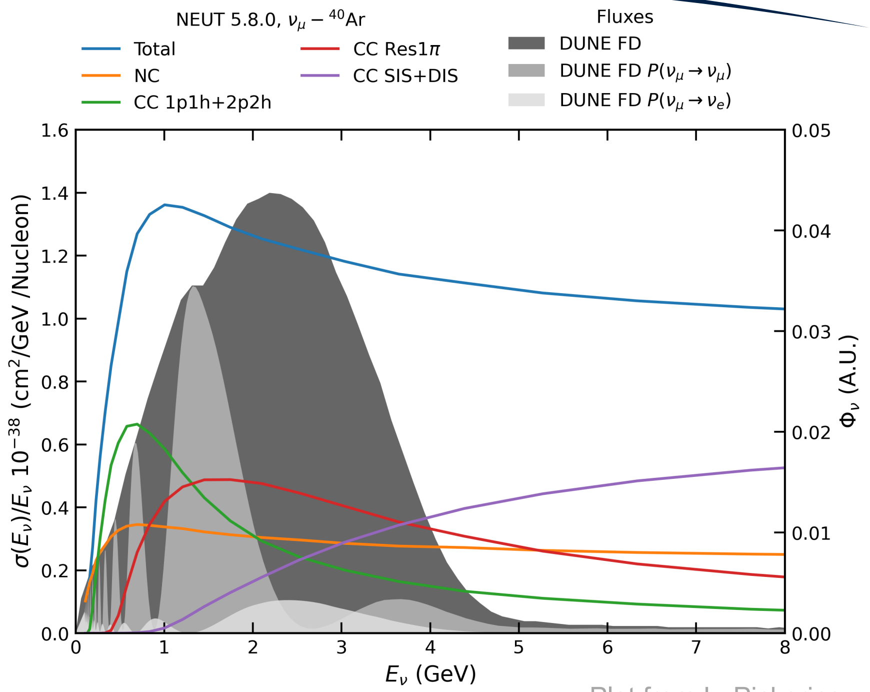
- Neutrino *flavour* and *mass* eigenstates are related via the PNMS-matrix:

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}



Plot from L. Pickering

- What we measure:

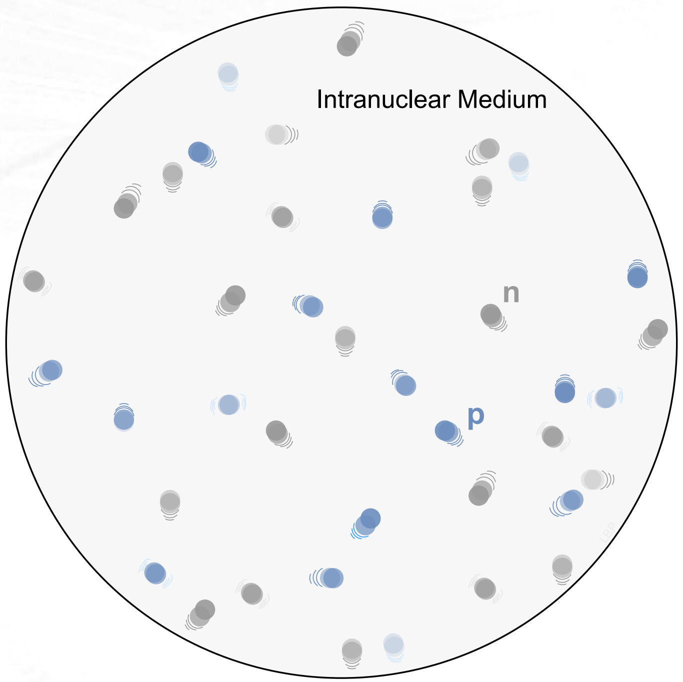
Need to know neutrino energy

ν Event Rate, Flux, Cross Section, # targets, Detector Efficiency, Osc Probability

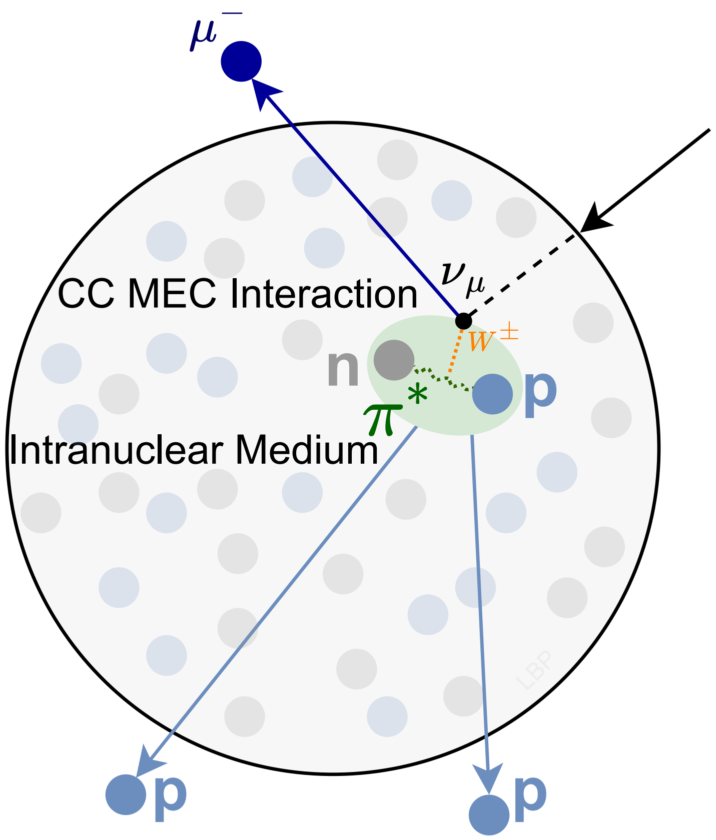
$$R^{FD}_{\alpha\to\beta}(E^{reco}_\nu) = \int_{E_{min}}^{E_{max}} \Phi_\alpha(E^{true}_\nu) \cdot \sigma^i_\beta(E^{true}_\nu, E^{reco}_\nu) \cdot \sum_j N_j \cdot \varepsilon_\beta(E^{true}_\nu, E^{reco}_\nu) \cdot P_{\alpha\to\beta}(E^{true}_\nu)$$

Nuclear Effects

Initial State Effects



Meson Exchange Currents



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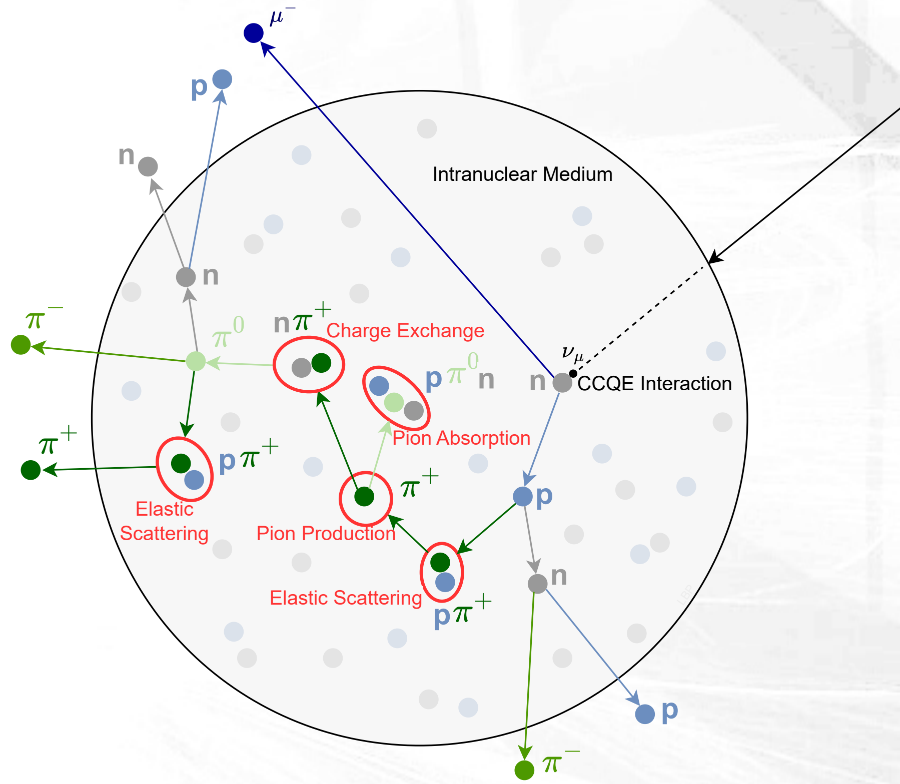
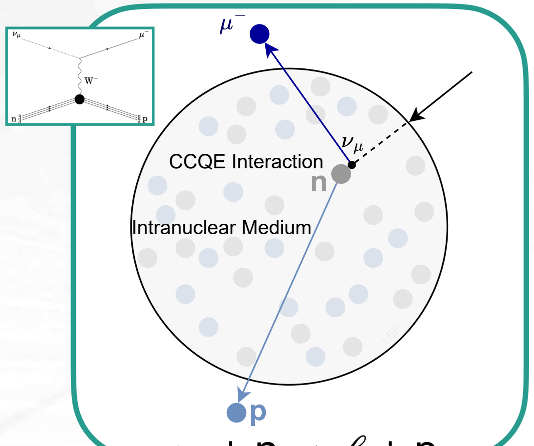
Final State Interactions



[arXiv:2201.04664]()

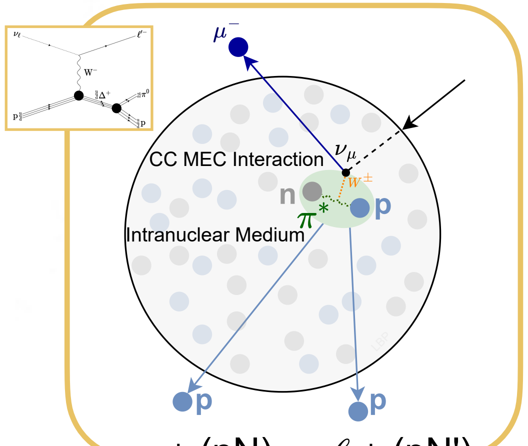
Neutrino-Nucleus Cross Section

Quasi-Elastic (QE)



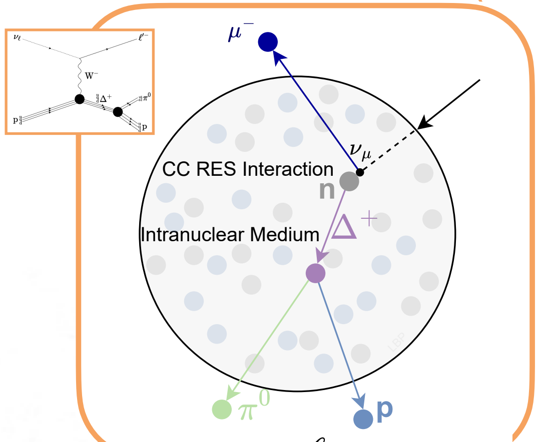
$\nu_\ell + \mathrm{n} \rightarrow \ell + \mathrm{p}$

2particle-2hole (2p-2h)



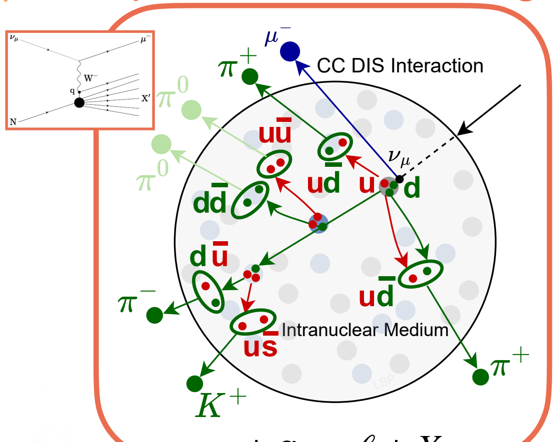
$\nu_\ell + (\mathrm{nN}) \rightarrow \ell + (\mathrm{pN'})$

RESonance excitation (RES)

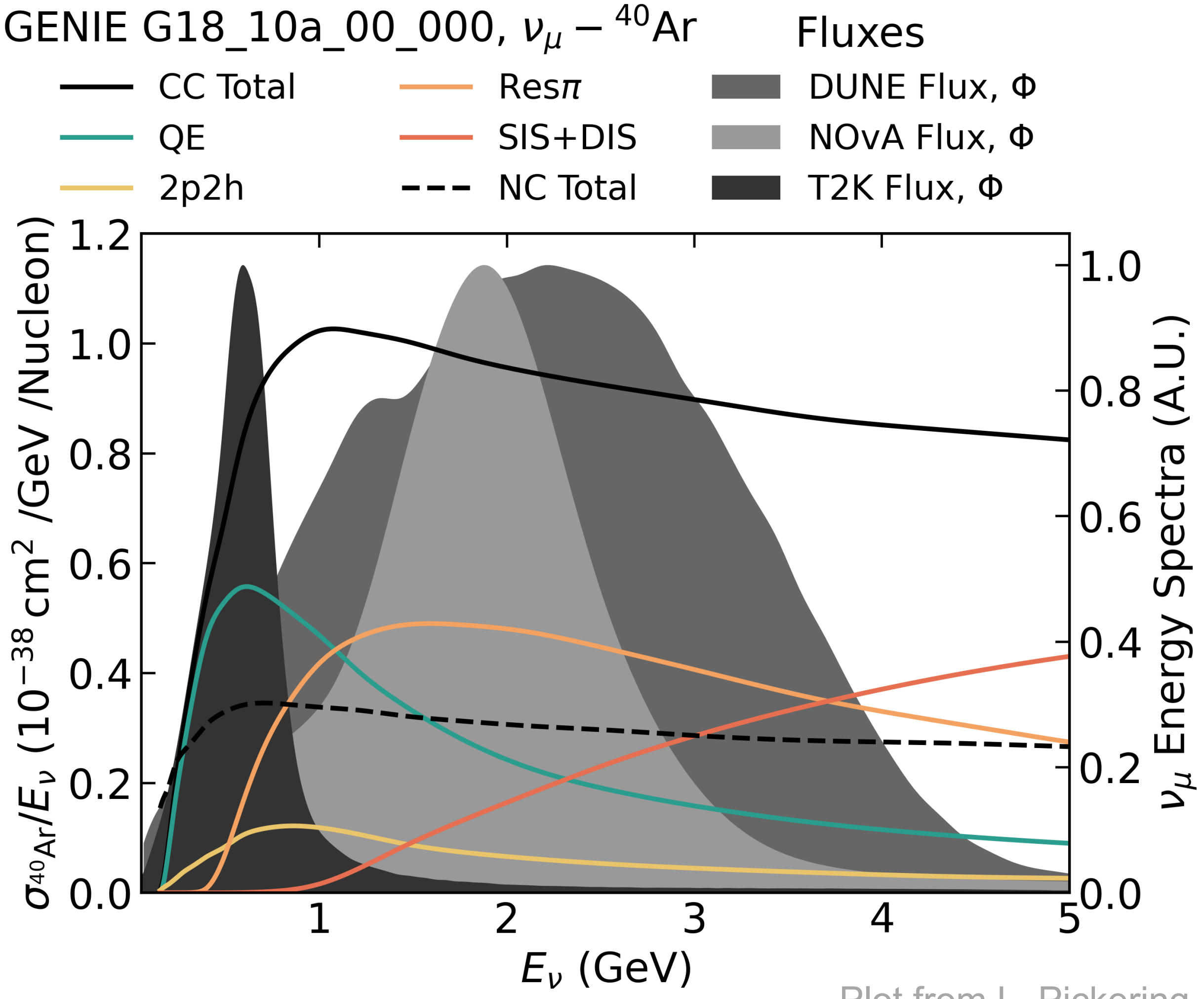


$\nu_\ell + \mathrm{p} \rightarrow \ell + \mathrm{p} + \pi$

Deep Inelastic Scattering (DIS)



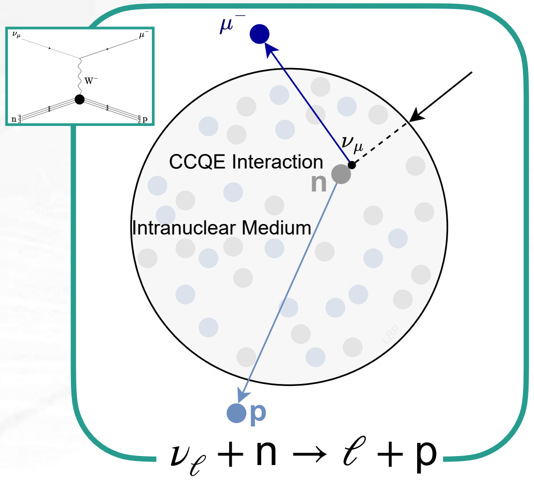
$\nu_\ell + \mathrm{q} \rightarrow \ell + X$



Plot from L. Pickering

Neutrino-Nucleus Cross Section

Quasi-Elastic (QE)



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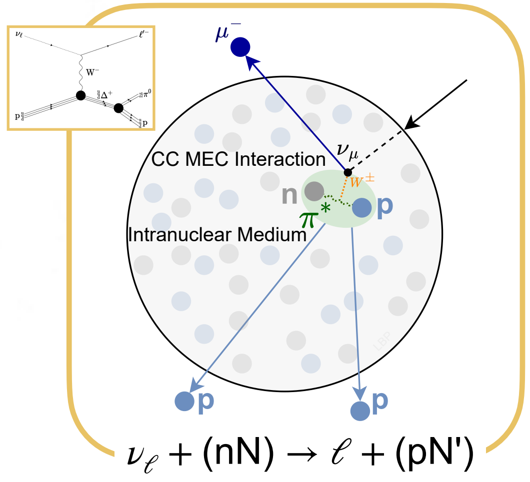

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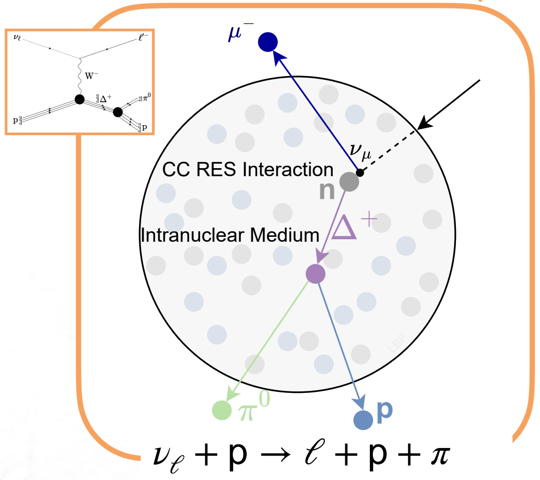

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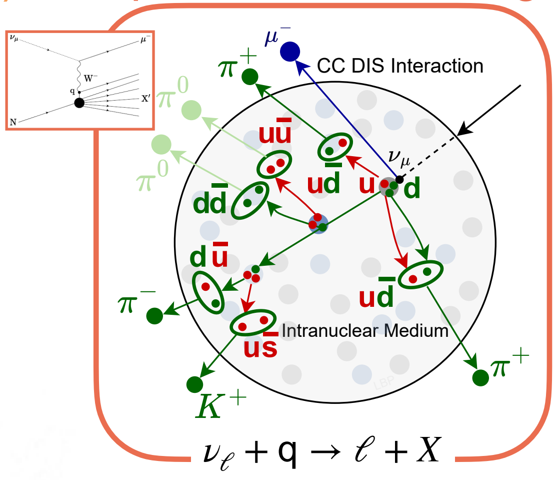
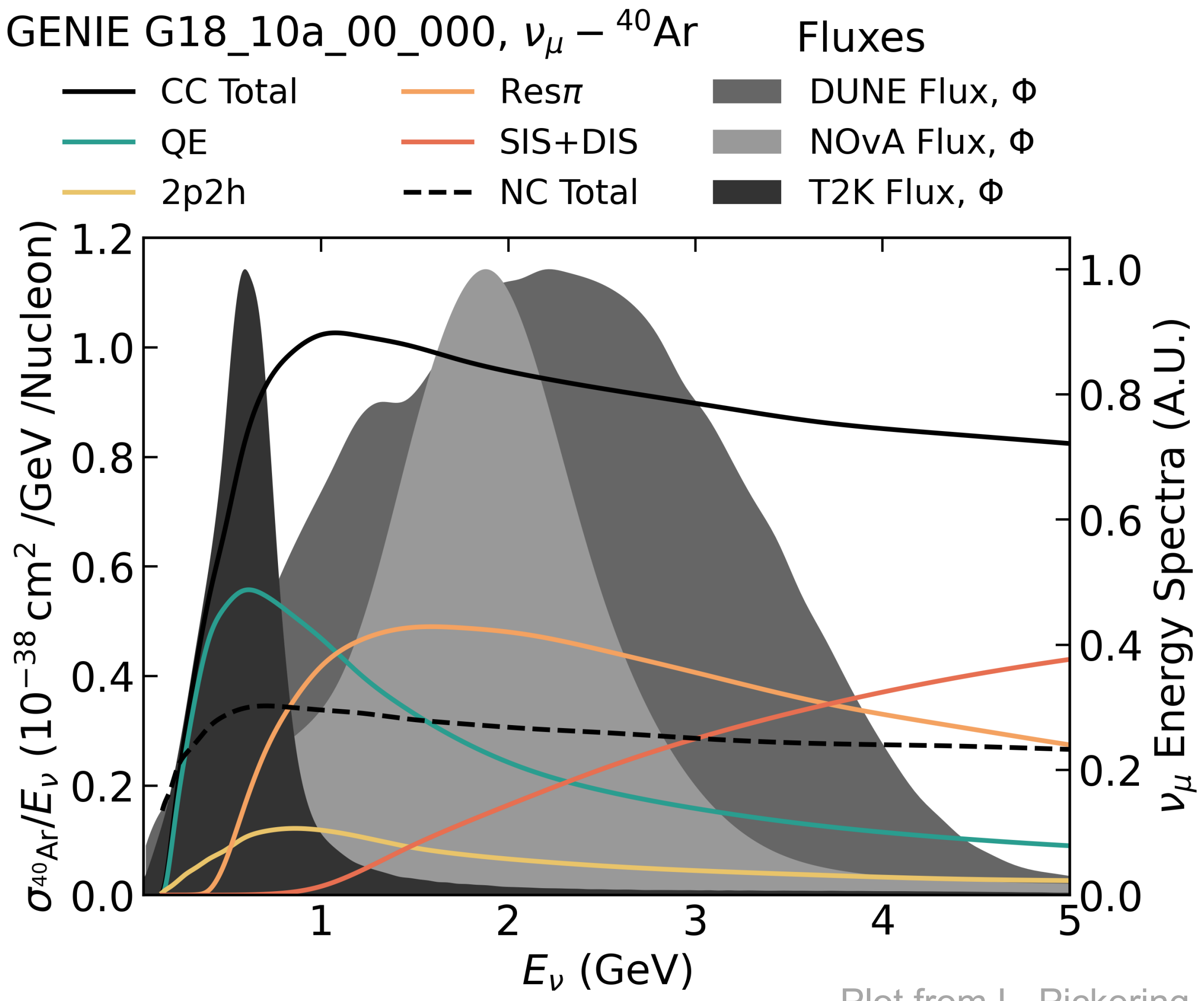
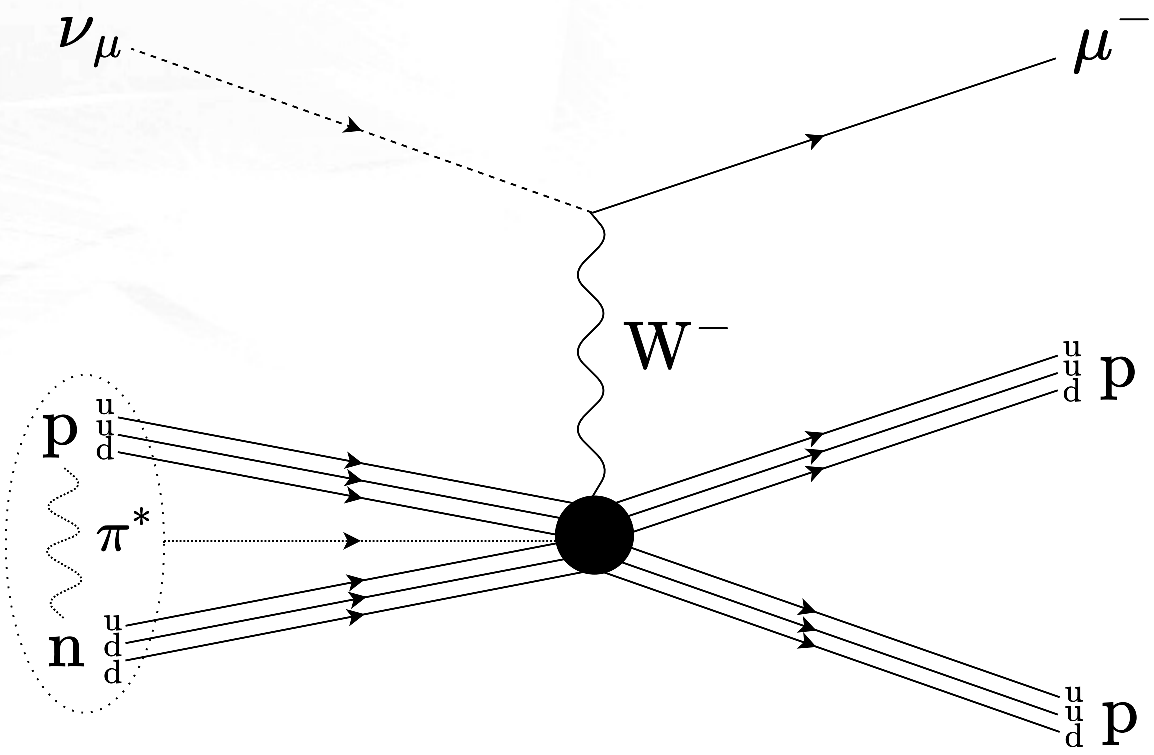
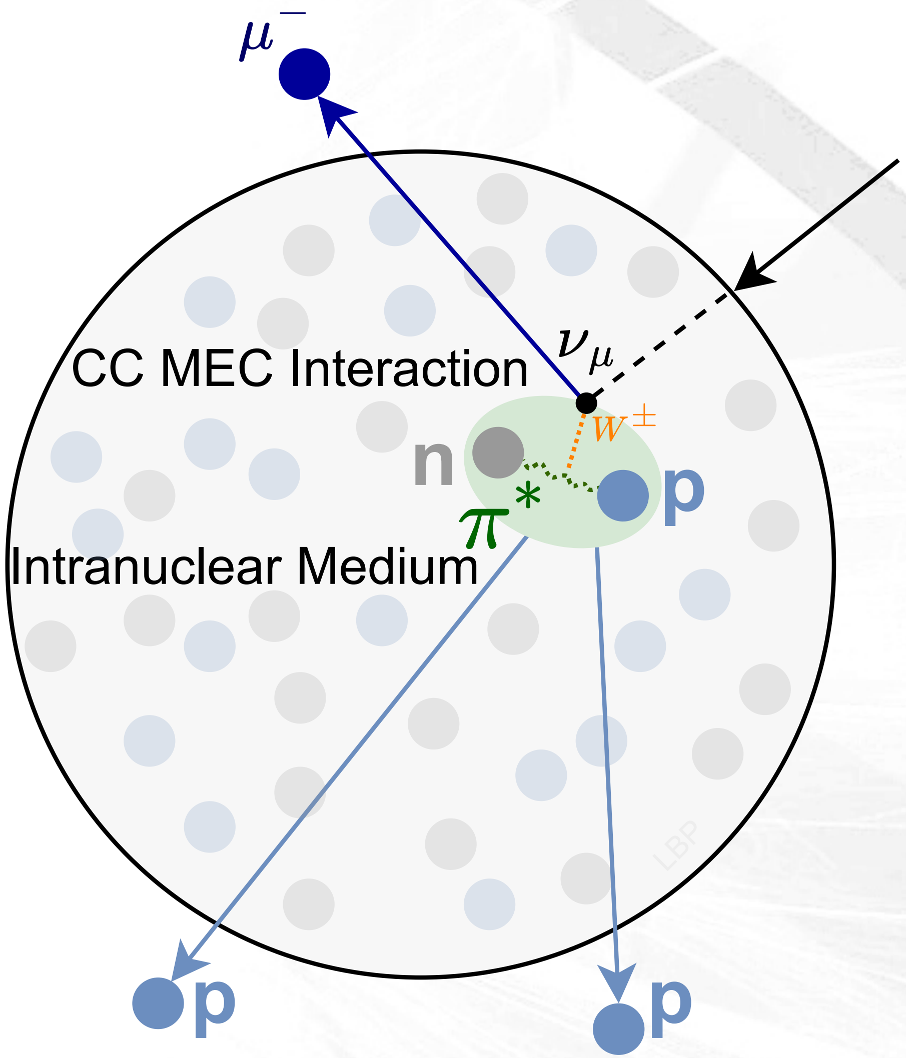




Plot from L. Pickering

CC 2p-2h Neutrino Interaction





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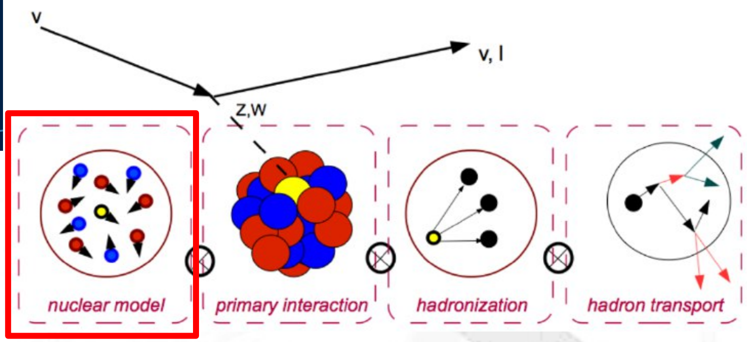
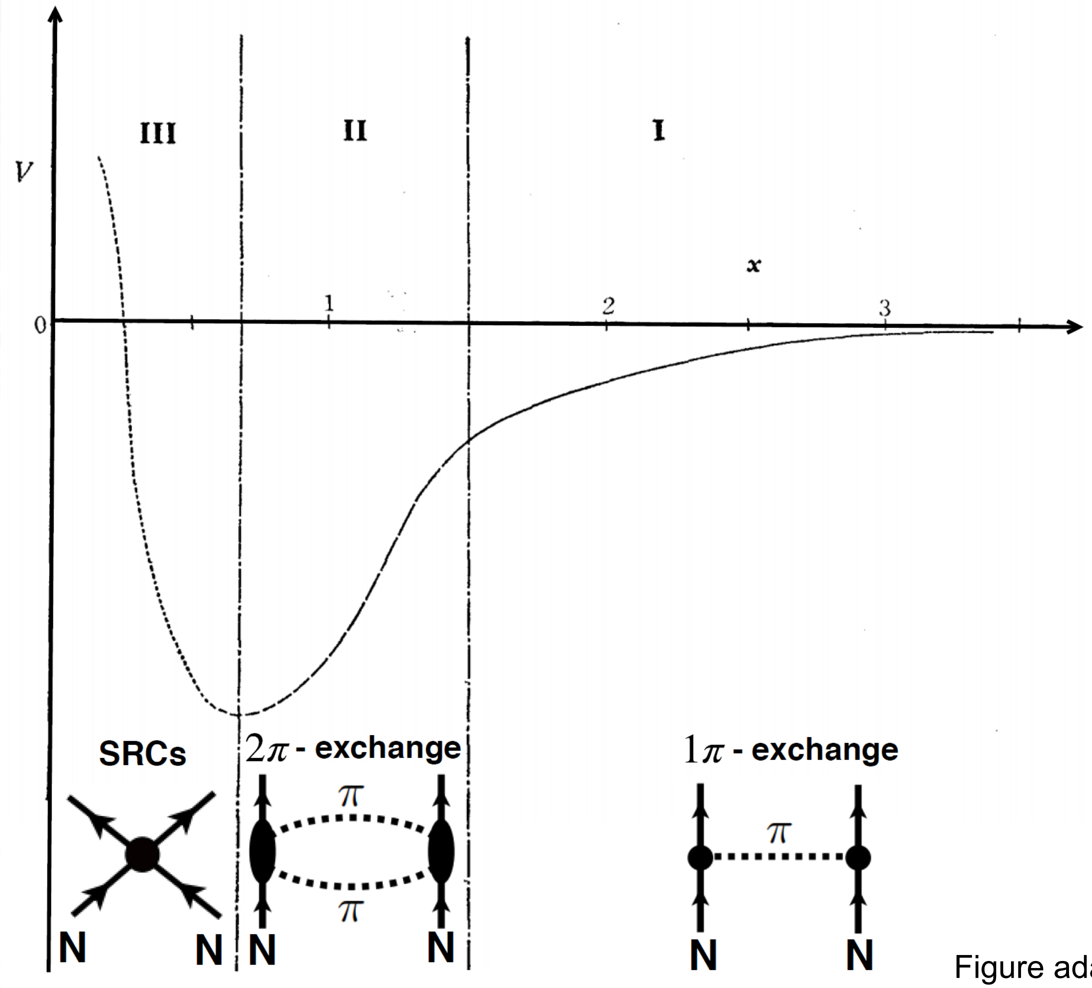
Nuclear Effects



Nucleon-Nucleon (N-N) Binding by Meson Exchange Currents



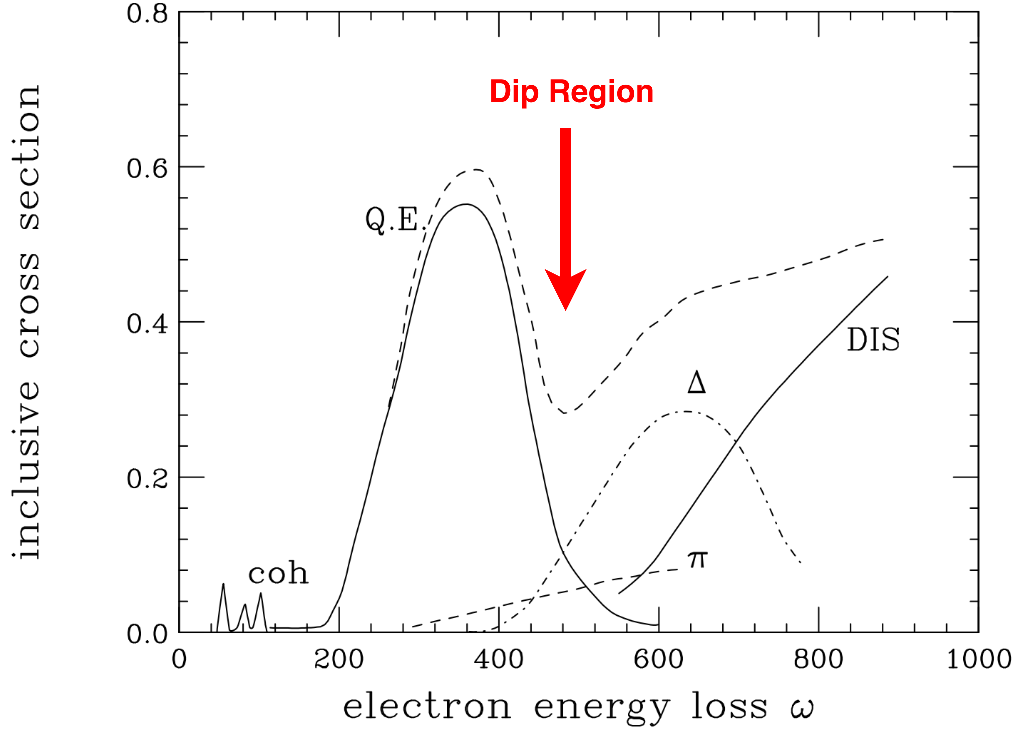
- Yukawa (1955): Proposed field between proton and neutron
- Later determined to be a virtual pion mediating a color charge exchange between nucleons
- Three N-N potential regions in dependence on inter-nucleon distance x

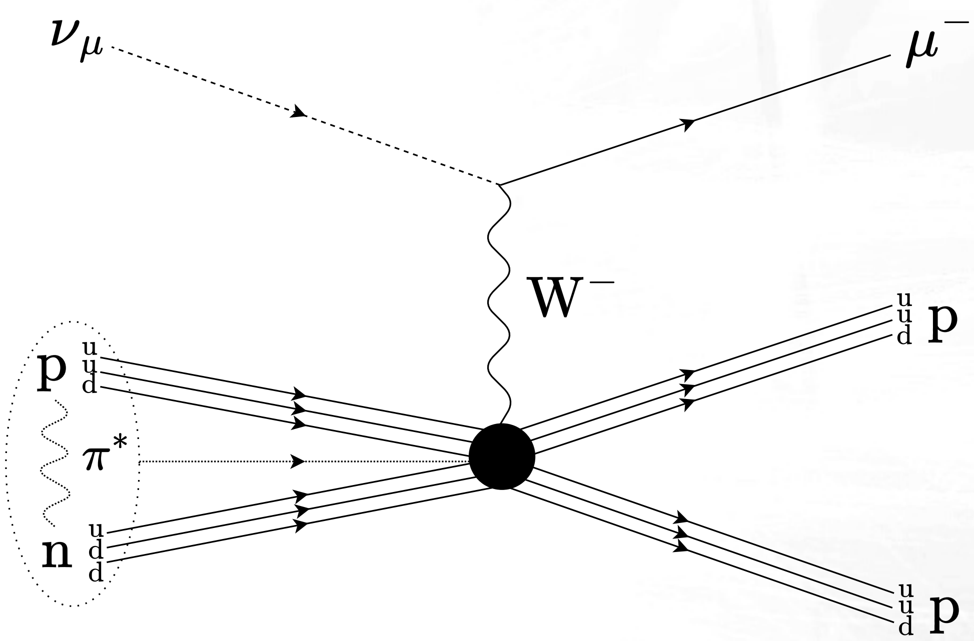
Figure adapted from Prog.Theor.Phys.Suppl.170:161-184,2007 and Prog.Theor.Phys.Suppl.3:1-12,1956.

Nuclear Effects

Meson Exchange Current Interaction Process

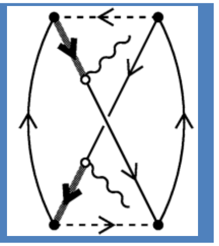
Figure adapted from Rev.Mod.Phys.80:189-224,2008.





Underestimation of inclusive cross sections (Dip Region) → Add MEC contributions to models → Successful reproduction of dip region → MEC responsible for dip region

Different Approximations for 2p-2h Calculations

Model	Approach	Vector	Axial	NN correlations	MEC	NN-MEC interference	Relativistic	
Martini	**Martini et al.**	Yes	Yes	**π,g'**	Yes (Only Δ MEC)	Yes	Some ingredients	No
Valencia	**Nieves et al.**	Yes	Yes	**π,ρ,g'**	Yes	Yes	Approximations in the WNNπ vertex	No
SuSAv2	**Amaro et al.** **Megias et al.**	Yes	Yes	**π** or already in Superscaling function	Yes	No	Fully Relativistic	Yes

- Major differences in NN correlations and NN correlation – MEC interference treatment?

Slide adapted from M. Martini and M. Ericson: Inclusion of multi-nucleon effects in RPA-based calculations for ν-nucleus scattering. Talk given at ESNT 2p-2h workshop in April 2016.

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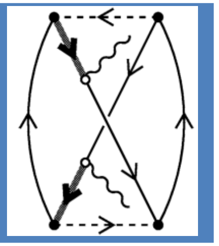
Model	Approach	Vector	Axial	NN correlations	MEC	NN-MEC interference	Relativistic	
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GENIE Model Configurations

- Collection of model elements used in the simulation of muon neutrino interactions on argon:

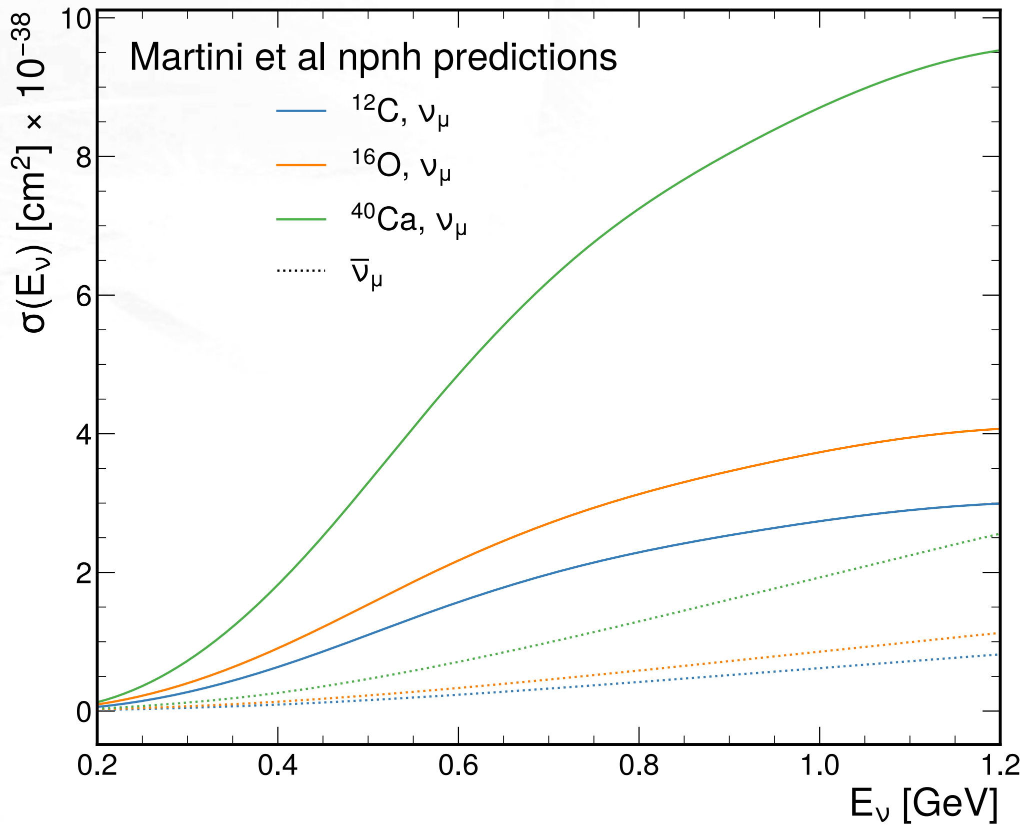
Model element \ Set name	Valencia CC 2p-2h G18_10a_00_000	SuSAv2 CC 2p-2h G18_10s_00_000	Empirical CC 2p-2h G18_10e_00_000
Nuclear (Ground-State) Model	Local Fermi Gas	Local Fermi Gas	Local Fermi Gas
Quasi-Elastic (QE) processes	Nieves	Nieves	Nieves
2p-2h (MEC)-processes	Nieves (Valencia)	SuSAv2	Empirical
Resonance (RES) production	Berger-Sehgal	Berger-Sehgal	Berger-Sehgal
Deep Inelastic Scattering (DIS)	Bodek-Yang	Bodek-Yang	Bodek-Yang
Coherent (COH) production	Berger-Sehgal	Berger-Sehgal	Berger-Sehgal
Final-State Interactions (FSI)	INTRANUKE hA 2018	INTRANUKE hA 2018	INTRANUKE hA 2018

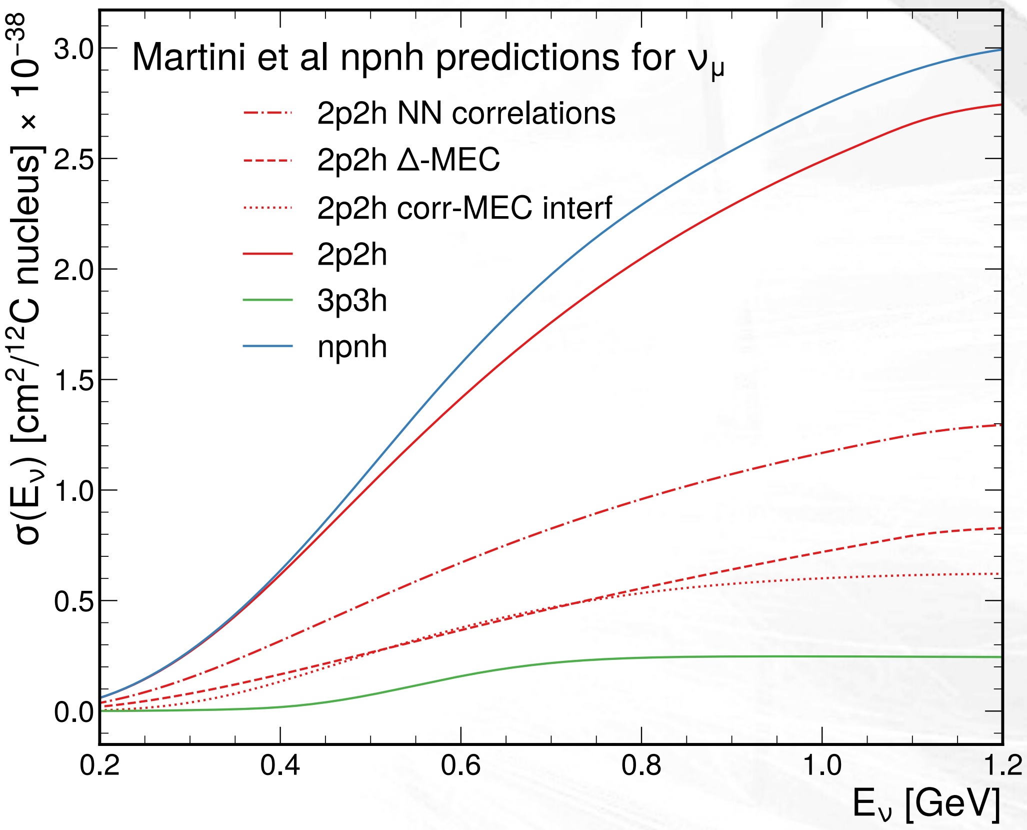
- Revisited Valencia model in arXiv:2407.21587 to be implemented in GENIE!
- Recently added Martini CC *np*-*nh* model to GENIE!

Reference: http://tunes.genie-mc.org/

CC np-nh Martini Model in GENIE

Implementation of the CC np-nh Martini model





Plots from L. Russo: Implementation of the npnh model of Martini et al in the GENIE event generator. Poster given at Neutrino2024 in June 2024.

Advertisement - NuSystematics and GENIE Reweight

Tools to Propagate Systematic Modelling Uncertainties

- NuSystematics
  - Custom systematic event reweighting as well as interface to GENIE Reweight
  - Initially developed for DUNE, also used in the SBN program
  - More information

- GENIE Reweight
  - Framework for evaluating model uncertainties via event reweighting

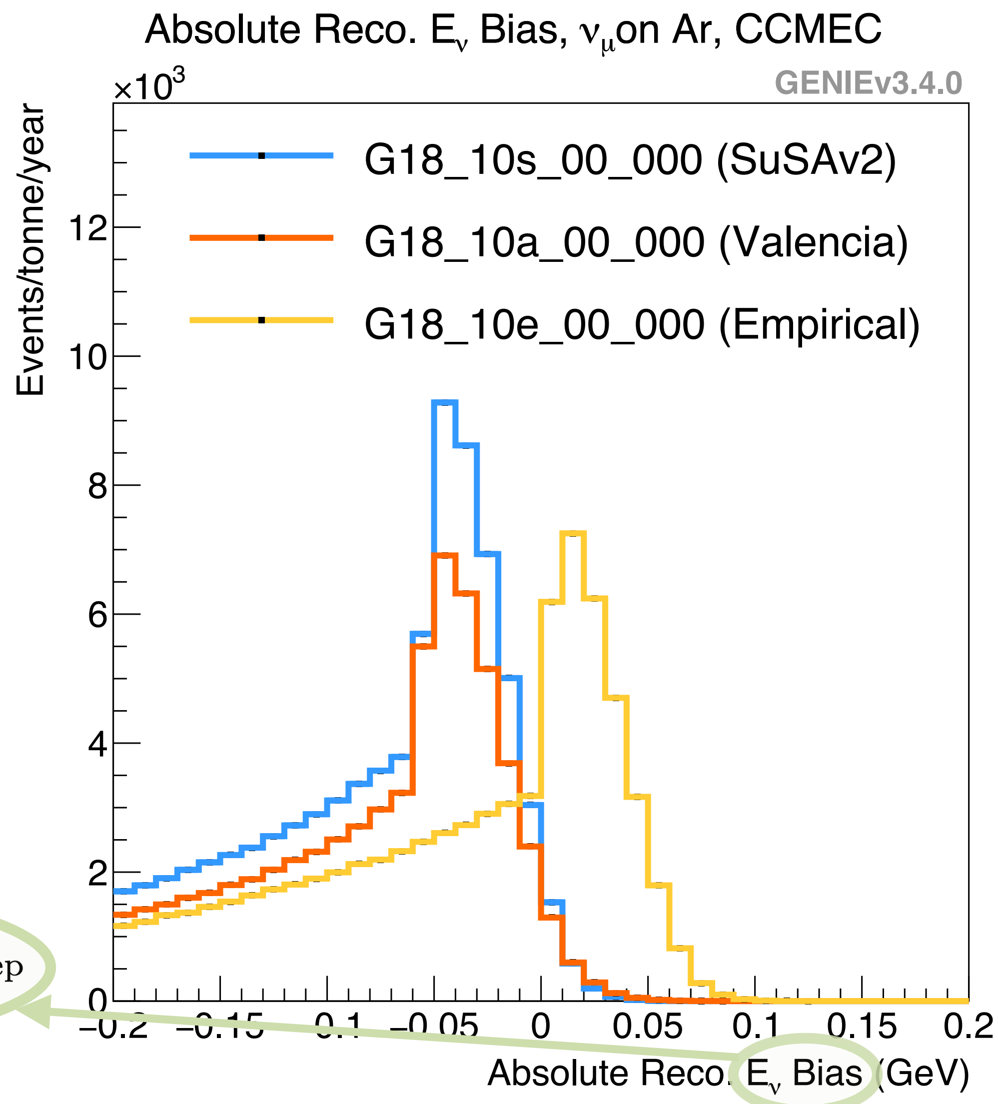
UNIVERSAL NEUTRINO GENERATOR & GLOBAL FIT

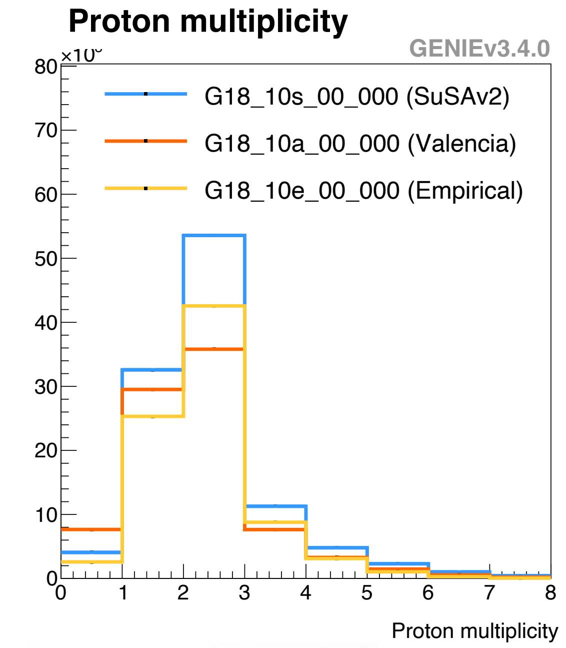
2p-2h Modeling Uncertainties

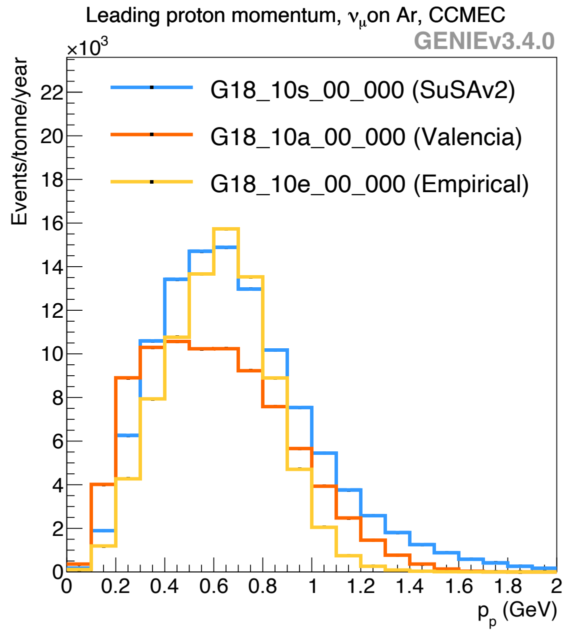
- **Clear separation** between the Empirical and Valencia/SuSAv2 CC 2p-2h models
- **Choose uncertainties** such that the measurement of the oscillation parameters is not biased in case the wrong model is chosen

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

100 000 events generated







CC 2p-2h Uncertainty Parameters

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

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

Nominal differential cross section

Differential cross section using modified input physics parameters

$\{K^n\}$: Kinematical phase space wrt n variables

Input CC 2p-2h Models:

- Valencia
- **SuSAv2** (Central-Value tune in DUNE)

New systematic parameters*:

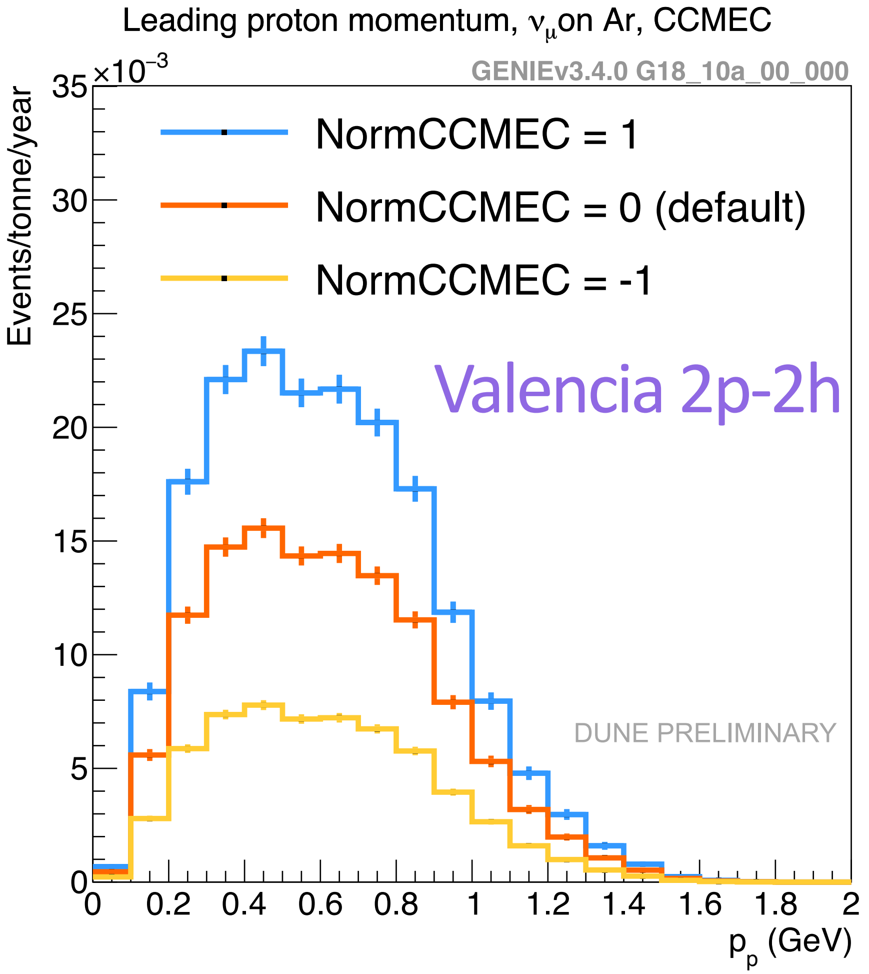
- *NormCCMEC*
- *DecayAngMEC* (two tweak dials)
- *FracPN_CCMEC*
- *DeltaNotDelta_CCMEC (Valencia only)*
- *XSecShape_CCMEC*
- *XSecShape_CCMEC_Empirical*
- *XSecShape_CCMEC_Martini*
- *EnergyDependence_CCMEC*

*Implemented in GENIEReweight

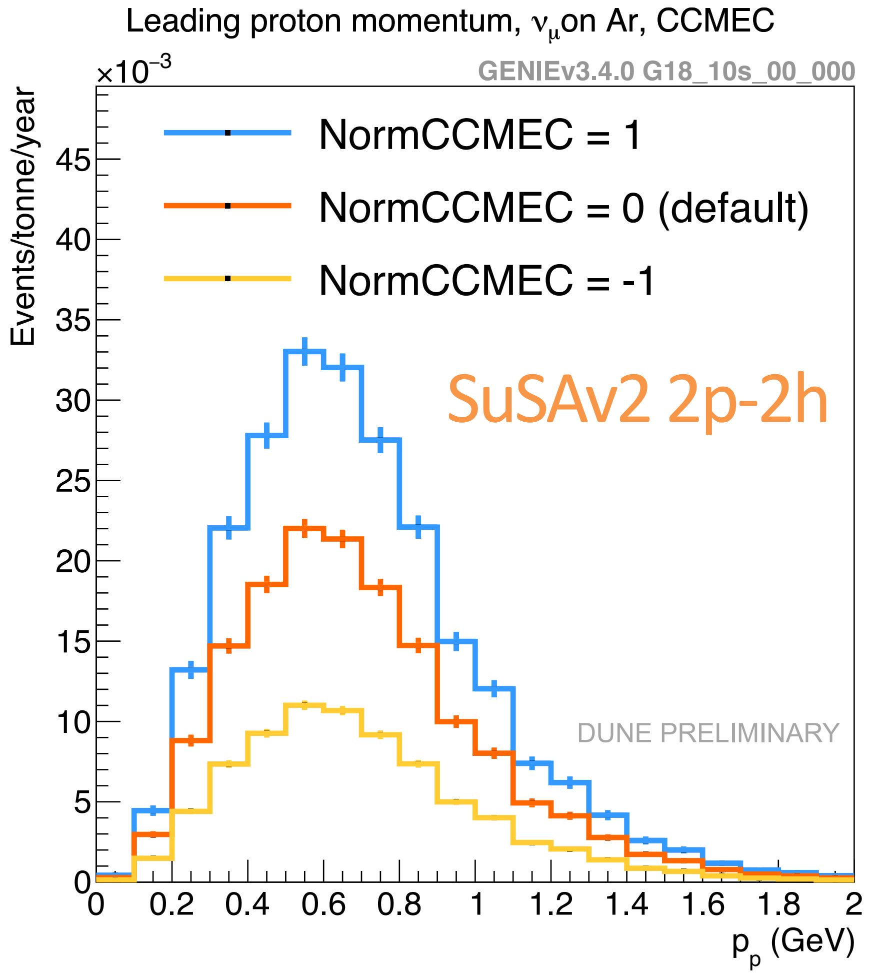
Normalisation Parameter

weight $= x_P$

NormCCMEC - changes absolute normalisation



G18_10a_00_000 (2p-2h default model: **Valencia**)

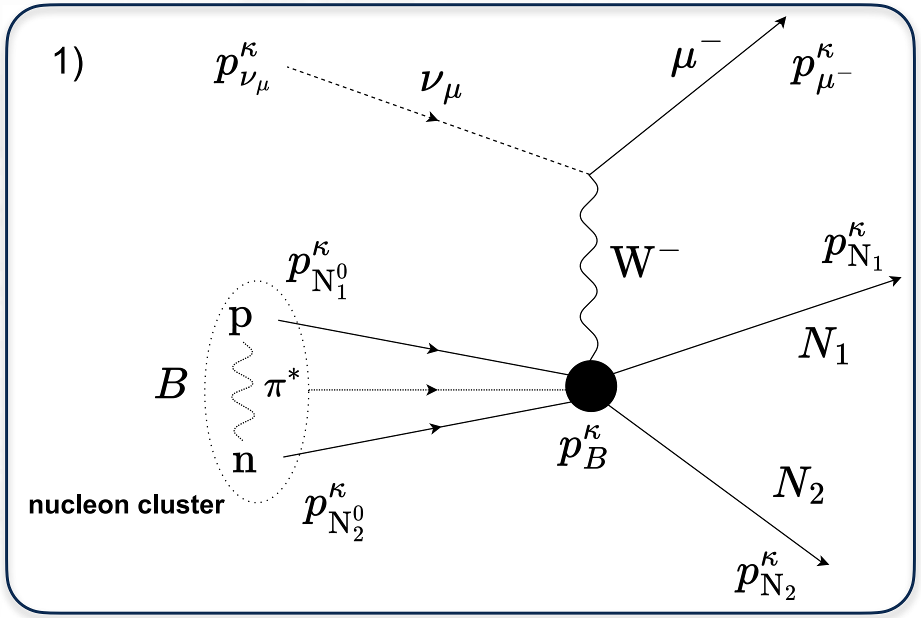


G18_10s_00_000 (2p-2h default model: **SuSAv2**)

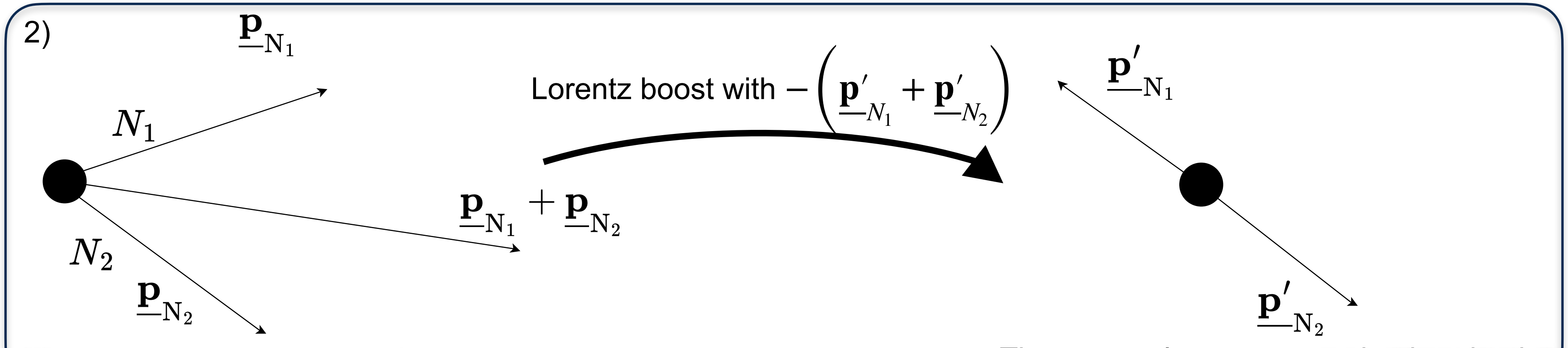
Nucleon Angular Distribution

DecayAngMEC - What is this angle?

1)



2)



The two nucleons are now back-to-back.

Nucleon Angular Distribution

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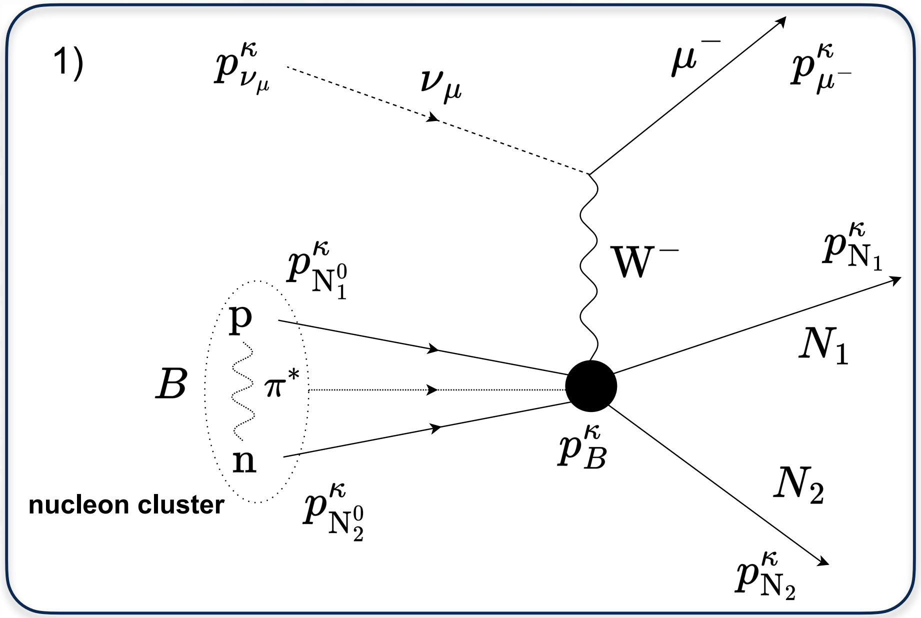
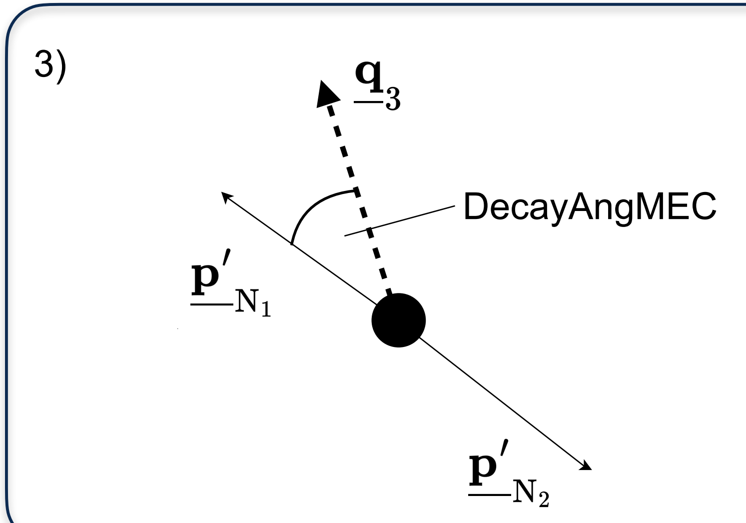
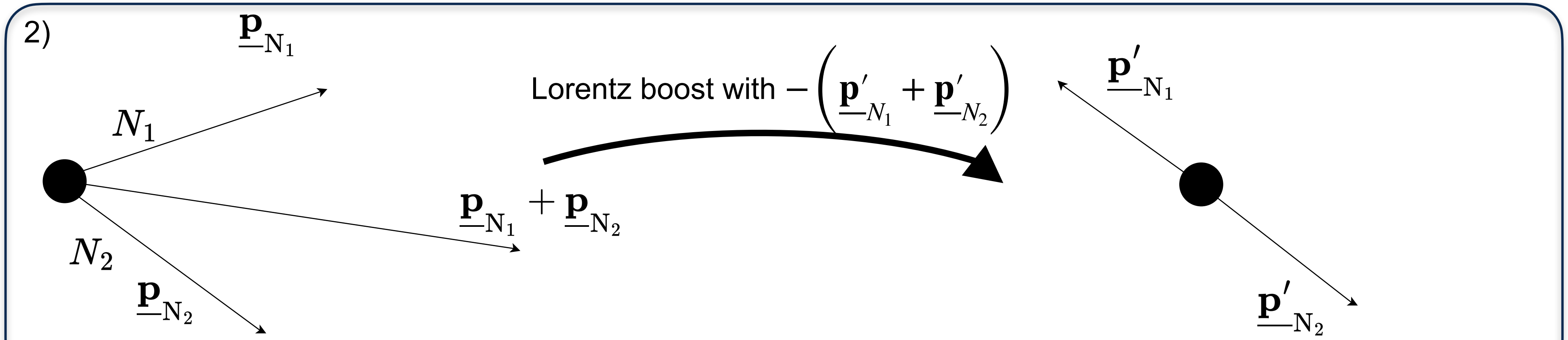




The *DecayAngMEC* is the outgoing nucleon angle wrt. to the lepton 3-momentum transfer in the 2-nucleon CM frame.



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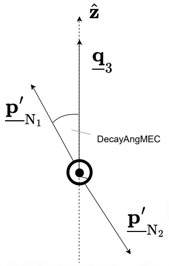
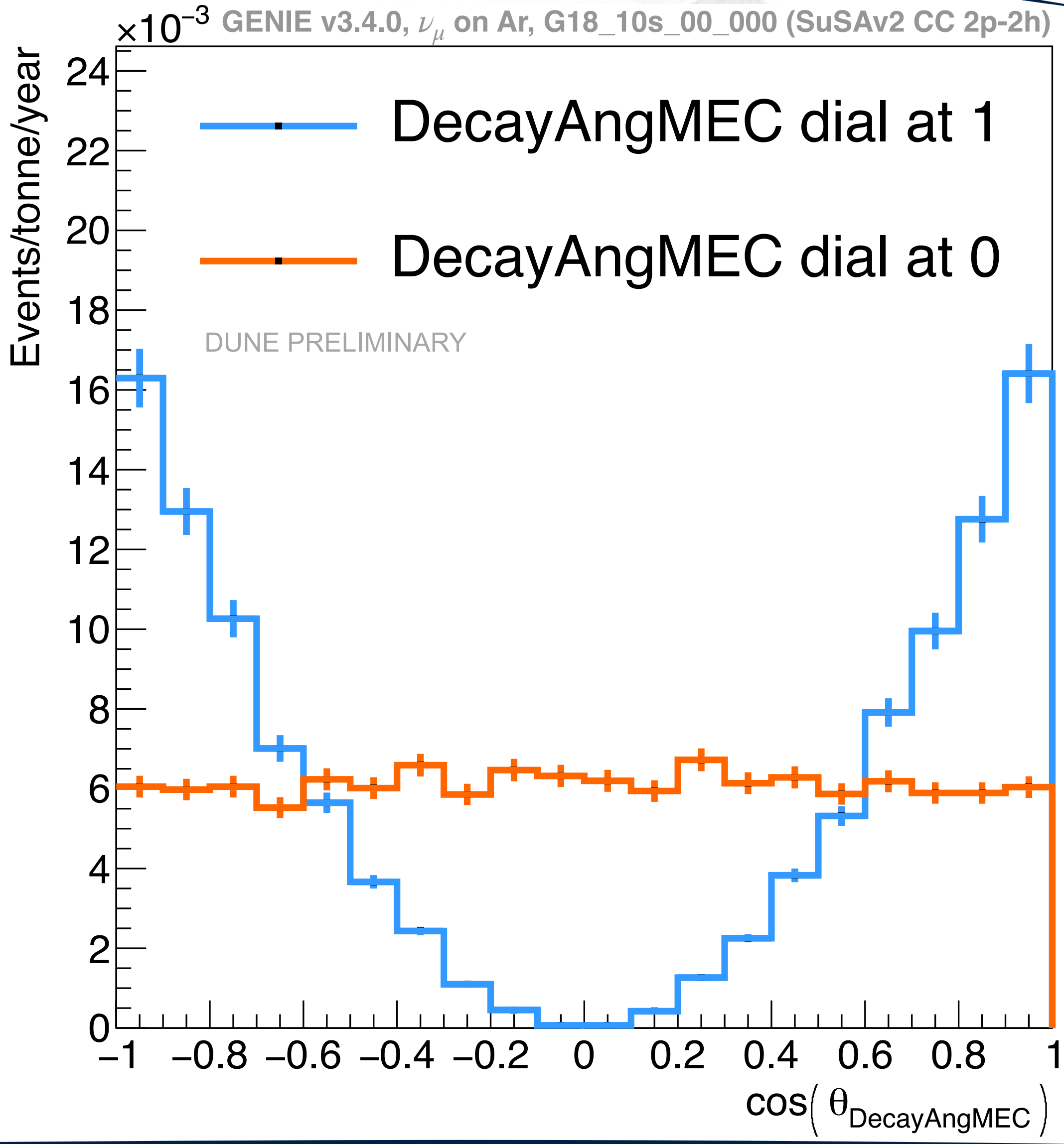
Nucleon Angular Distribution

DecayAngMEC - changes angular dependence on struck nucleon pair

- **Angular distribution** of outgoing nucleons:

$$\text{weight} = 3 \cdot x_{P_1} \cdot \cos^2(\theta_{\text{DecayAngMEC}}) + 1 - x_{P_1}$$





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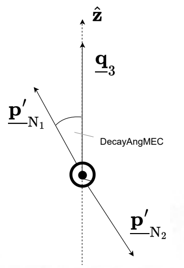

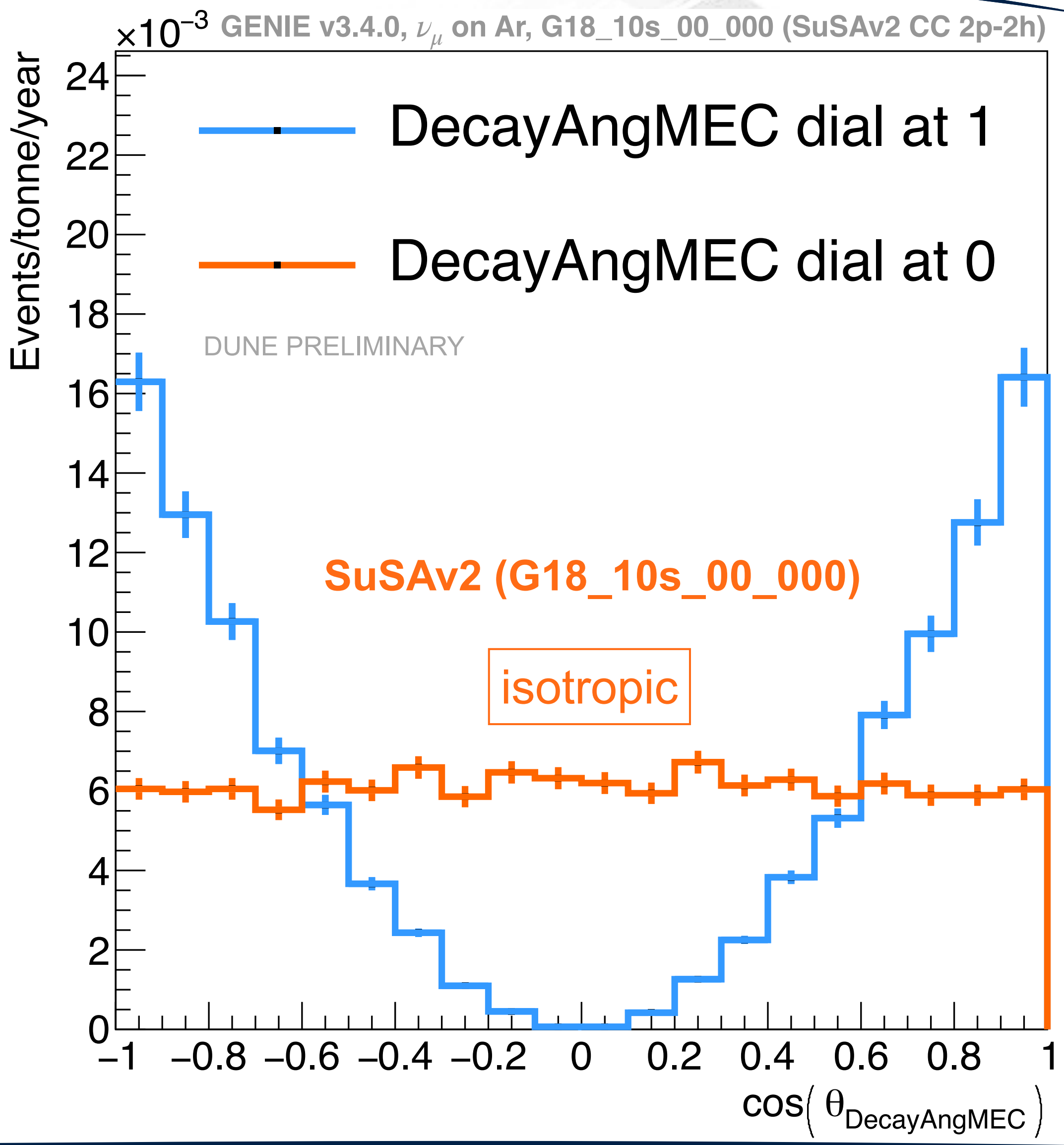

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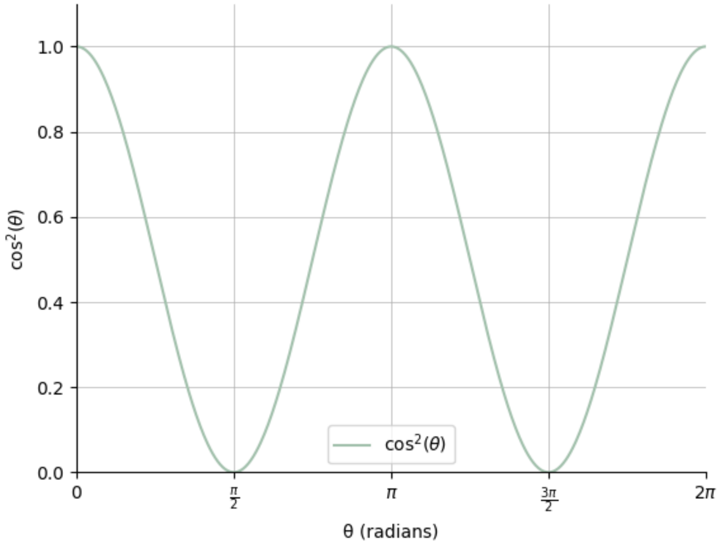

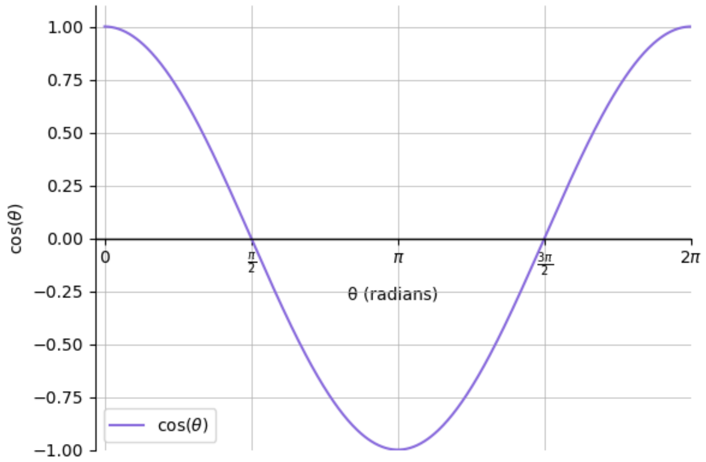

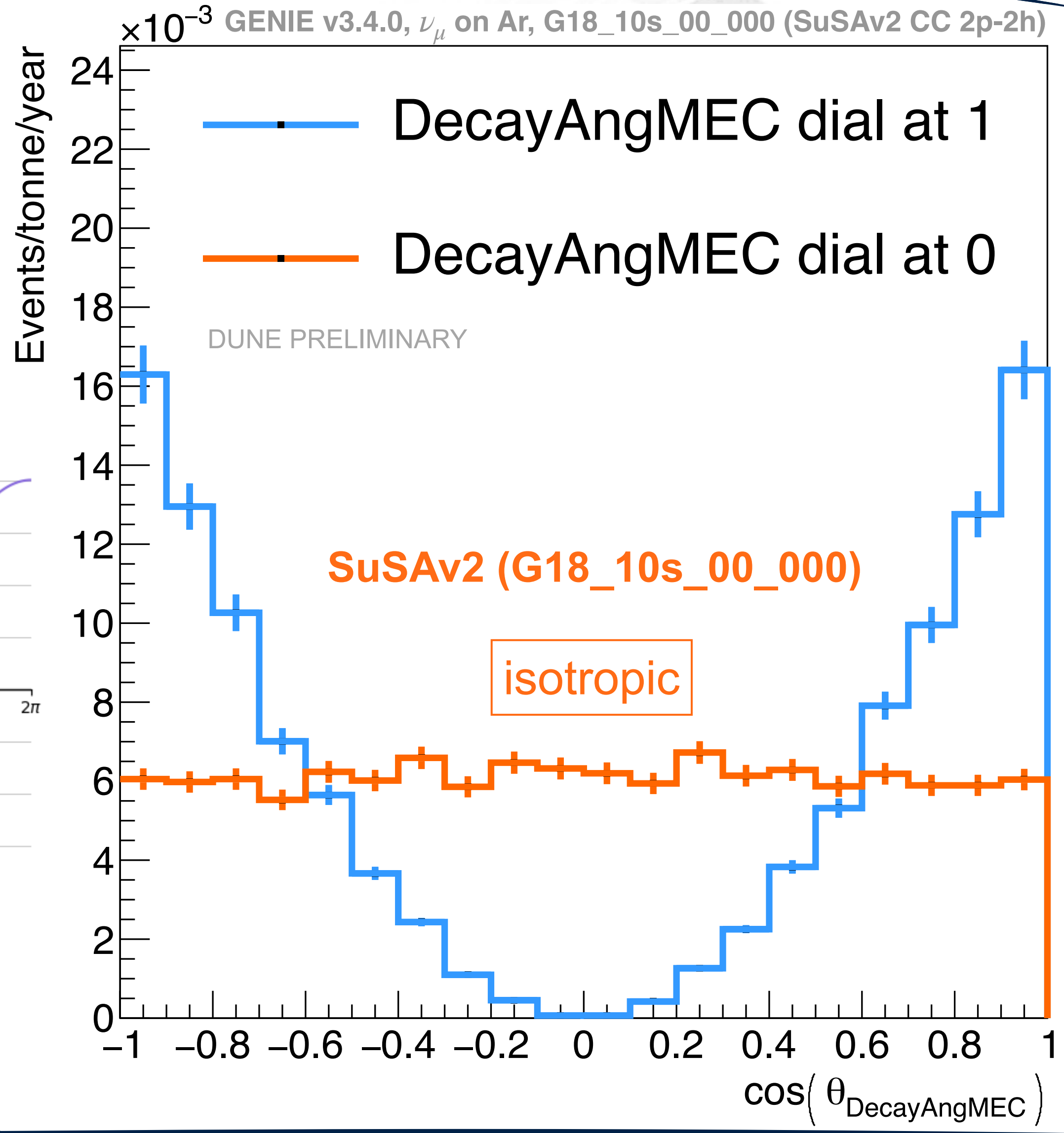

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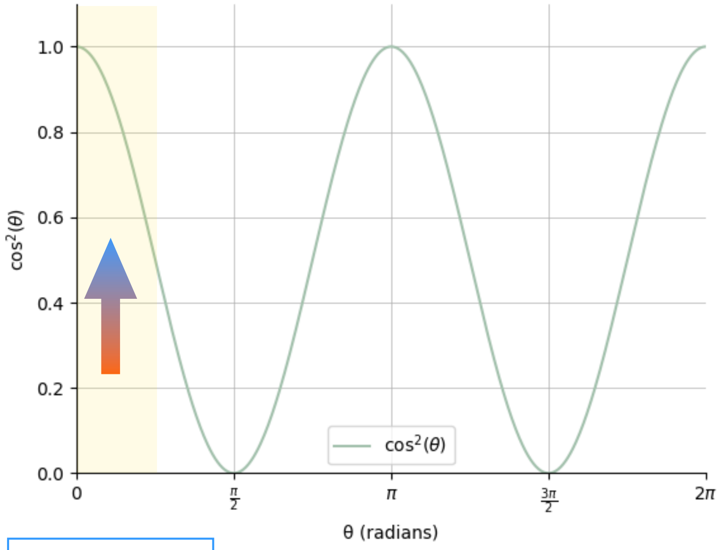
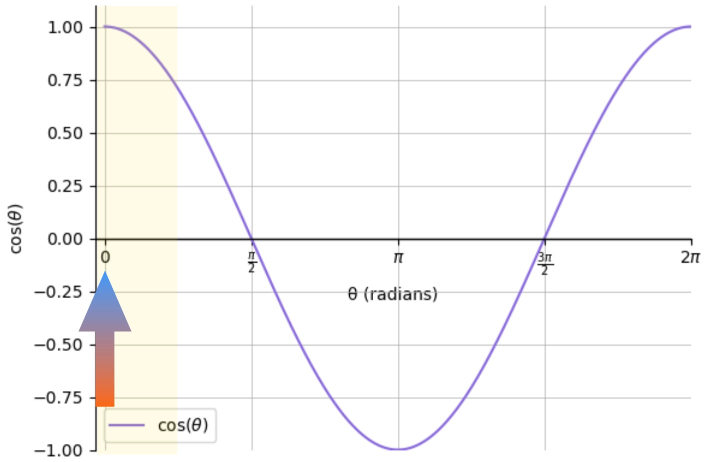
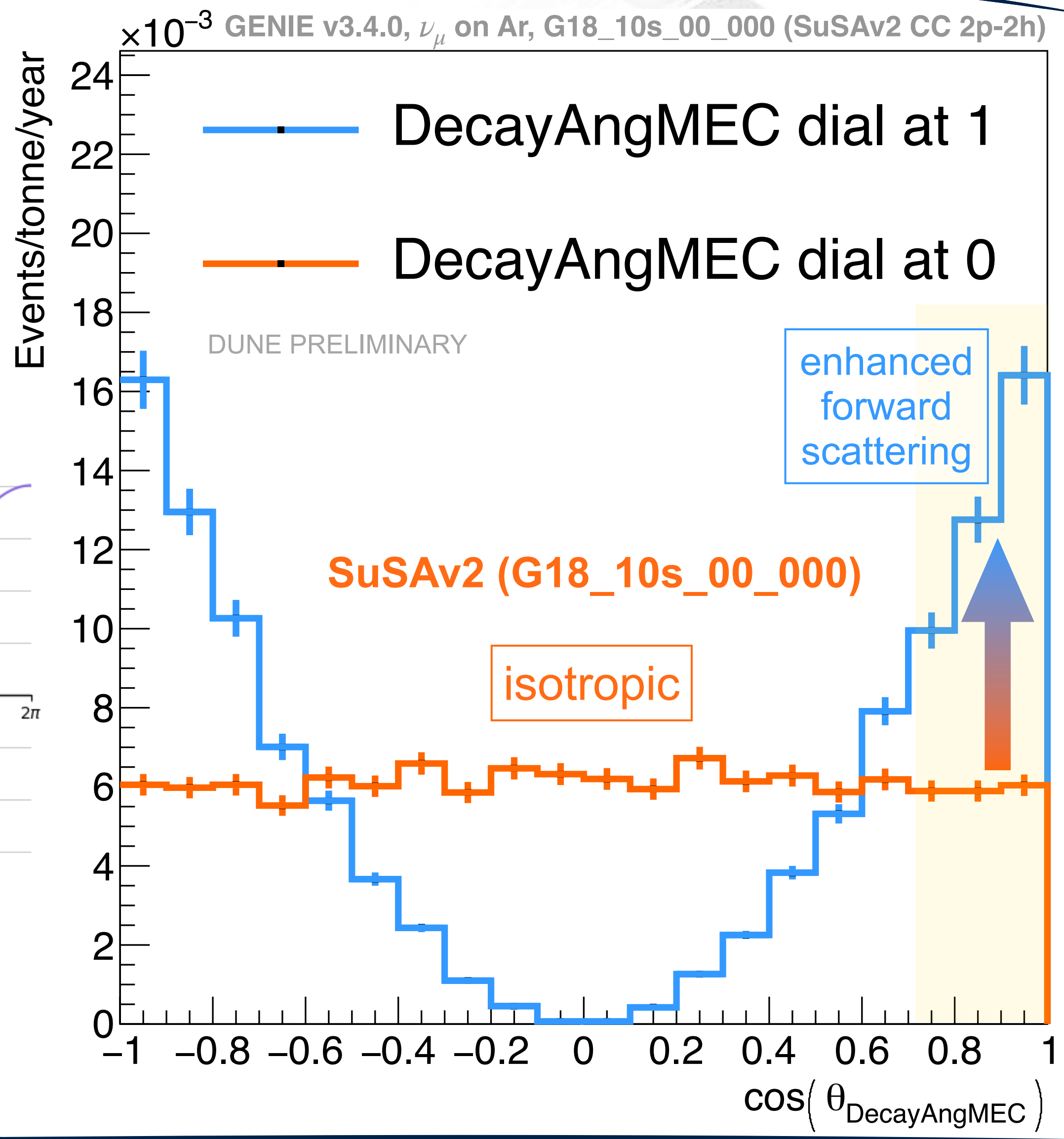
$$\text{weight} = 3 \cdot x_{P_1} \cdot \cos^2(\theta_{\text{DecayAngMEC}}) + 1 - x_{P_1}$$





enhanced forward scattering

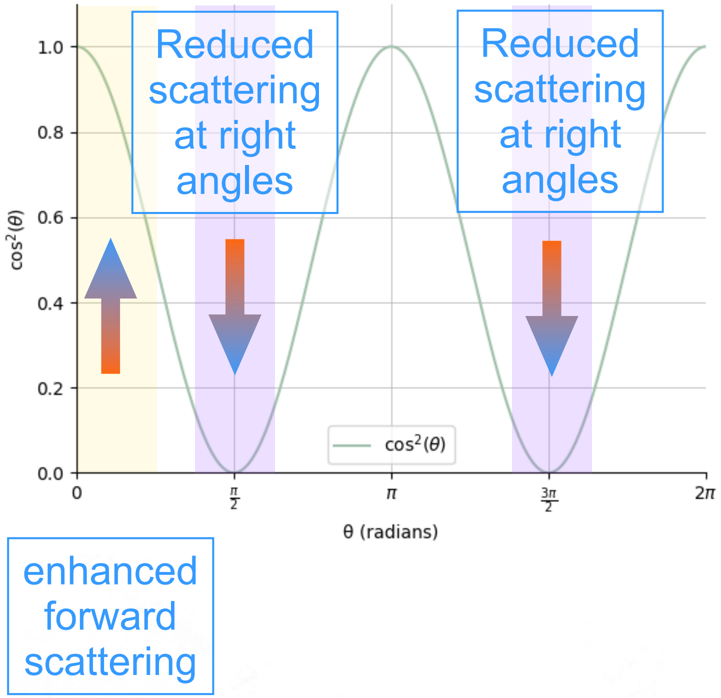


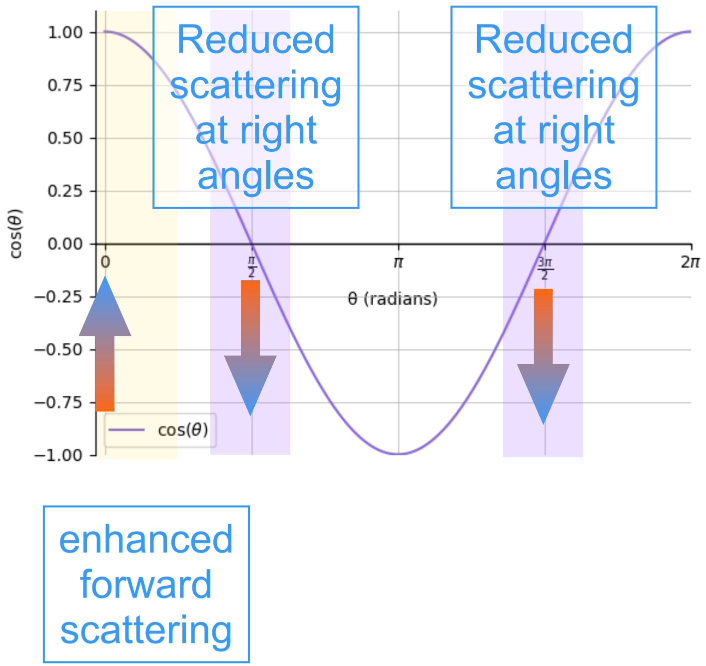
Nucleon Angular Distribution

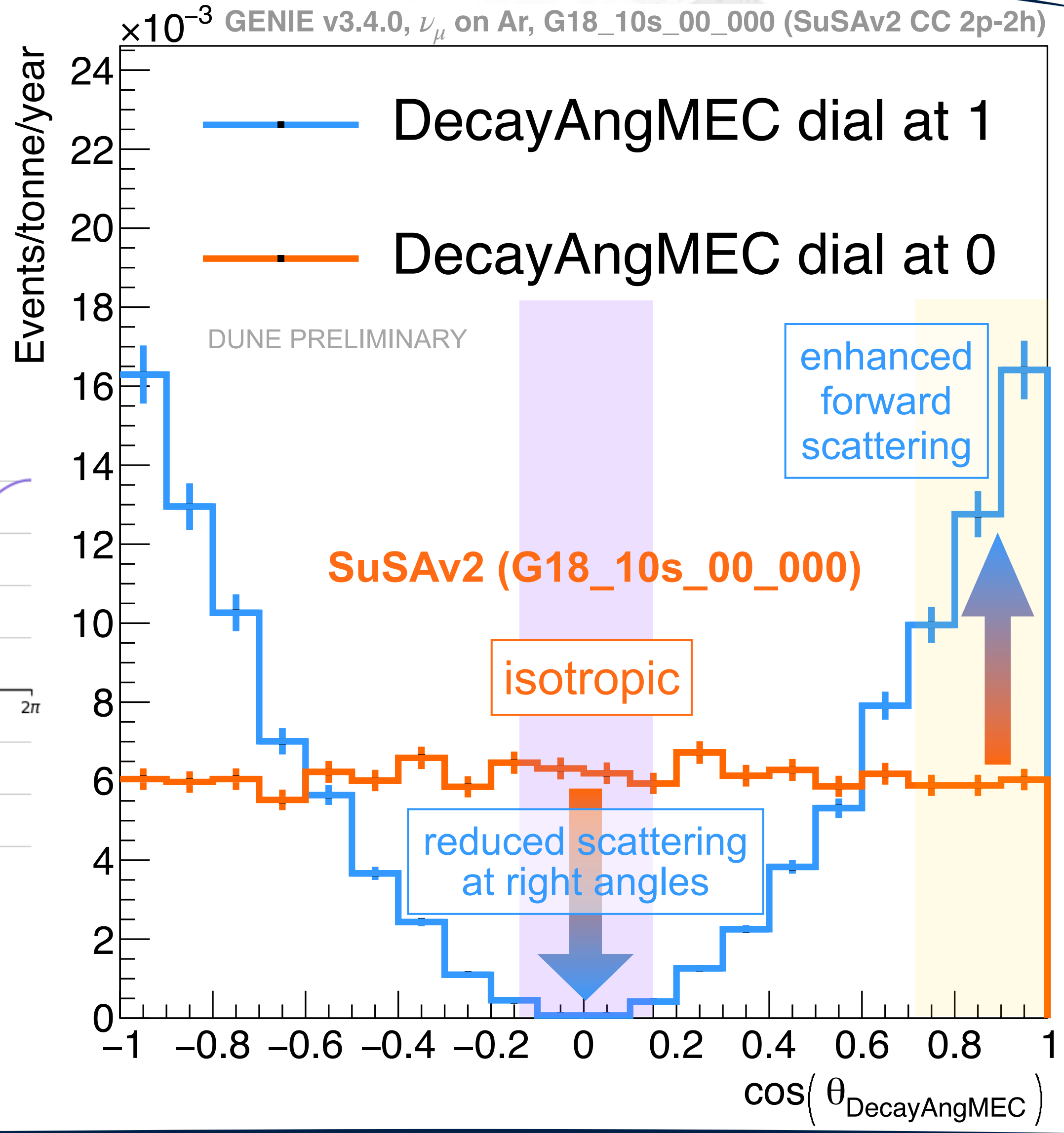
DecayAngMEC - changes angular dependence on struck nucleon pair

- **Angular distribution** of outgoing nucleons:

$$\text{weight} = 3 \cdot x_{P_1} \cdot \cos^2\left(\theta_{\text{DecayAngMEC}}\right) + 1 - x_{P_1}$$





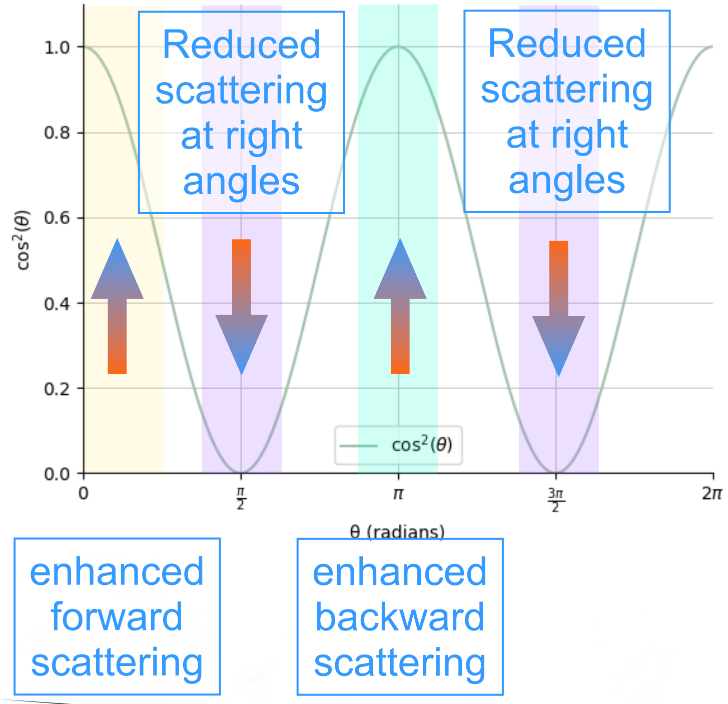


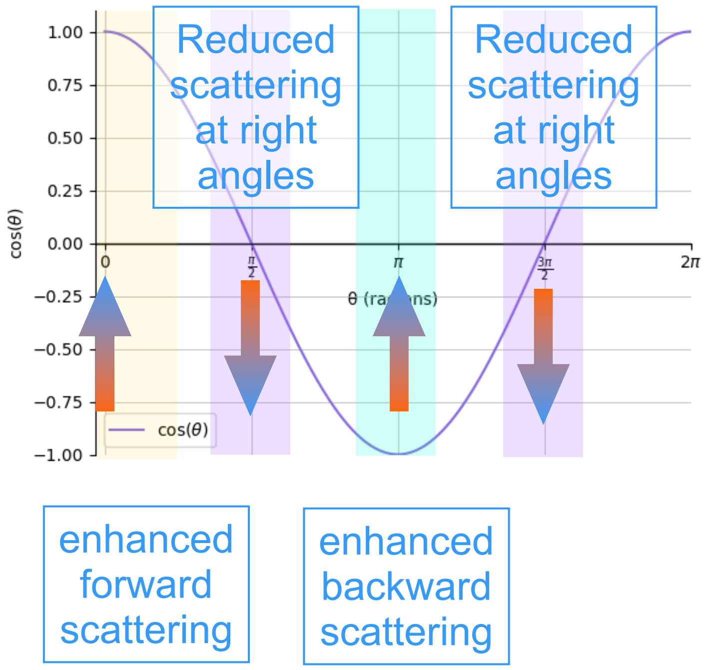
Nucleon Angular Distribution

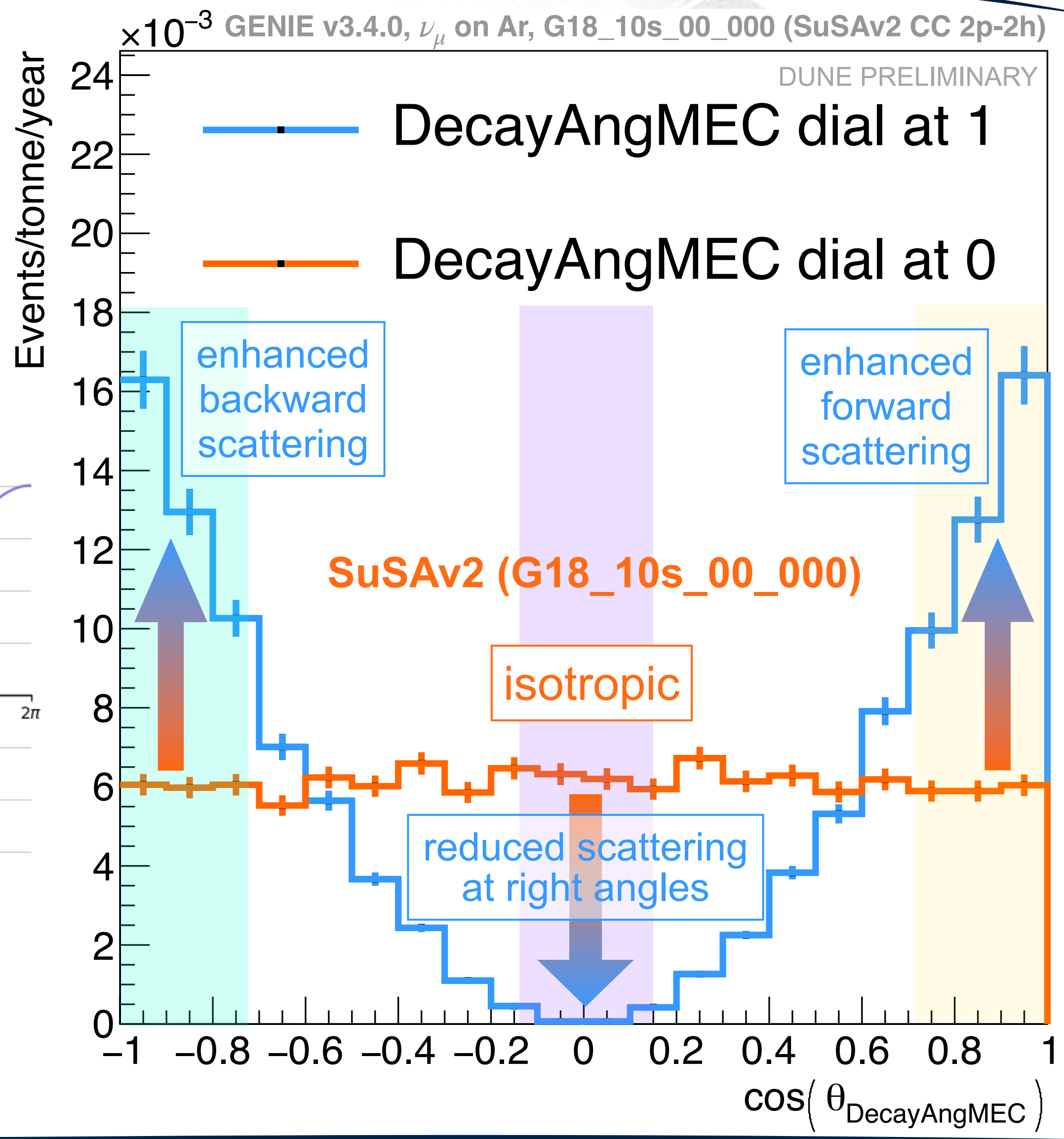
DecayAngMEC - changes angular dependence on struck nucleon pair

- **Angular distribution** of outgoing nucleons:

$$\text{weight} = 3 \cdot x_{P_1} \cdot \cos^2(\theta_{\text{DecayAngMEC}}) + 1 - x_{P_1}$$







Nucleon Angular Distribution

DecayAngMEC - changes angular dependence on struck nucleon pair

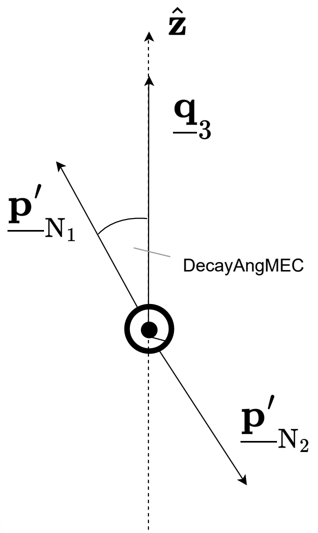
- **Angular distribution** of outgoing nucleons:

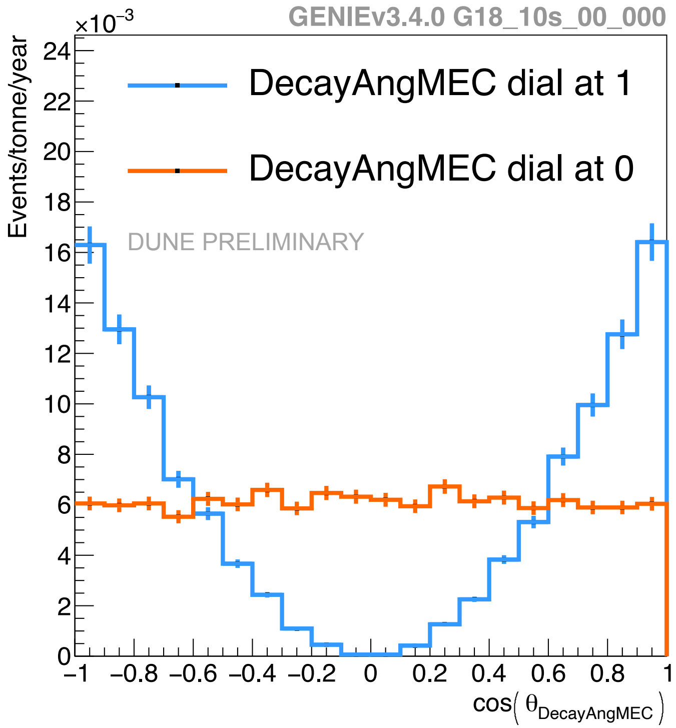
isotropic →
- enhanced forward- and backward-scattering
- reduced scattering at right angles

SuSAv2 (G18_10s_00_000)

$$\text{weight} = 3 \cdot x_{P_1} \cdot \cos^2(1 \cdot \theta_{\text{DecayAngMEC}}) + 1 - x_{P_1}$$

$$x_{P_1} \in [-1,1]$$





Ad-hoc assumption on angular distribution!

Nucleon Angular Distribution

DecayAngMEC - changes angular dependence on struck nucleon pair

- **Angular distribution** of outgoing nucleons:

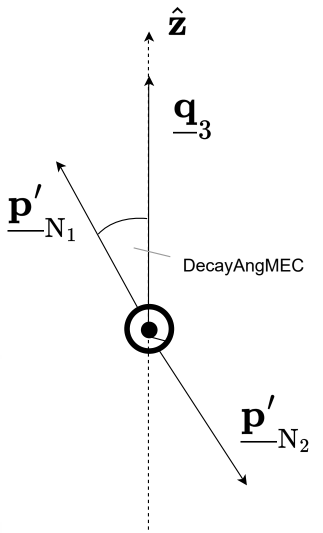
isotropic (ad-hoc assumption) → Other angular dependence (Physics motivation?)

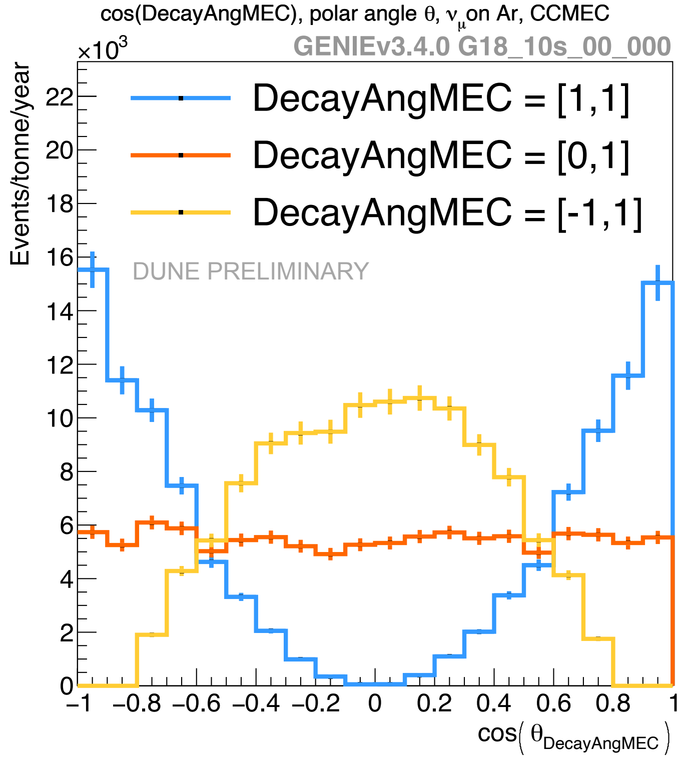
SuSAv2 (G18_10s_00_000)

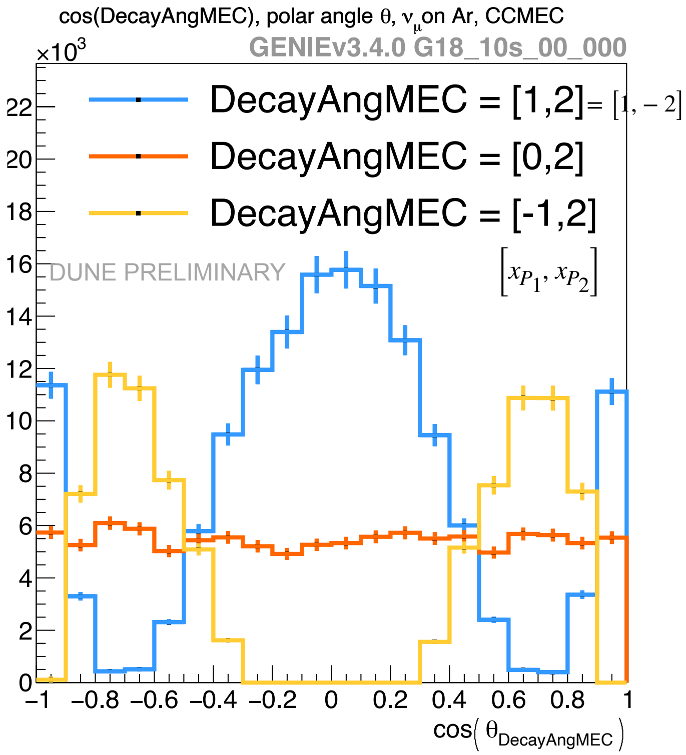
$$\text{weight} = 3 \cdot x_{P_1} \cdot \cos^2\left(x_{P_2} \cdot \theta_{\text{DecayAngMEC}}\right) + 1 - x_{P_1}$$

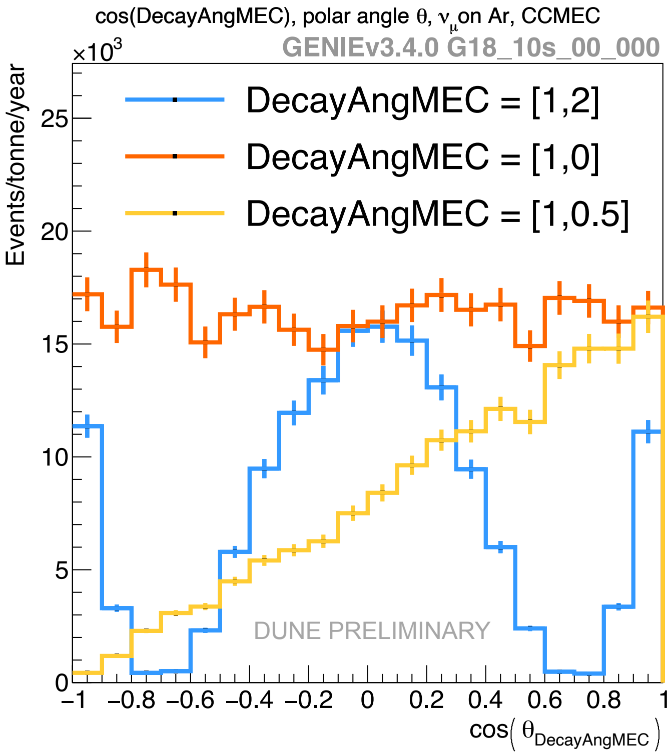
$x_{P_1} \in [-1,1]$

$x_{P_2} \in \mathscr{R}$



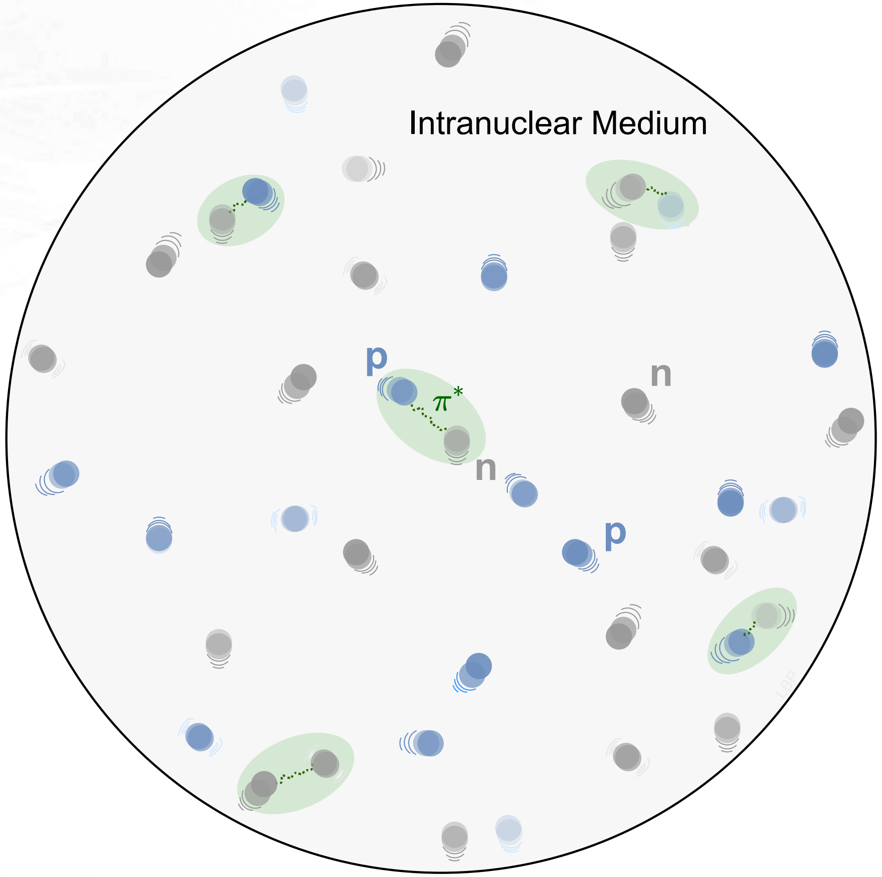


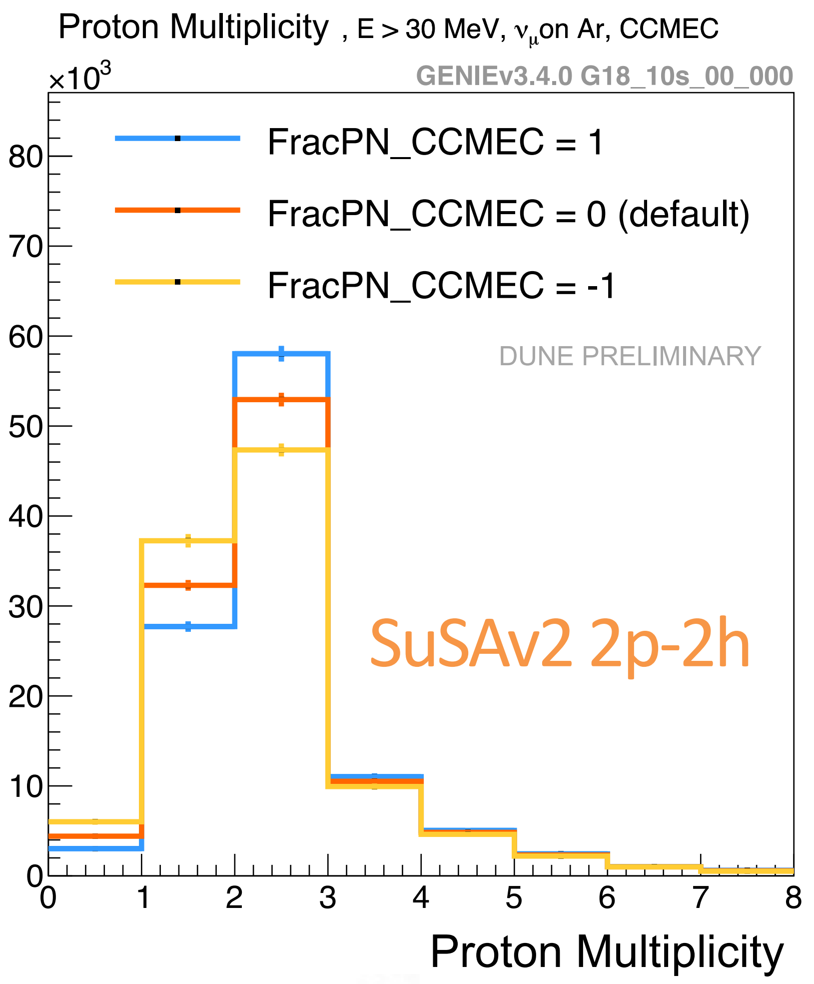




Nucleon Pair Content

FracPN_CCMEC - changes default prediction of initial pair content of nucleons

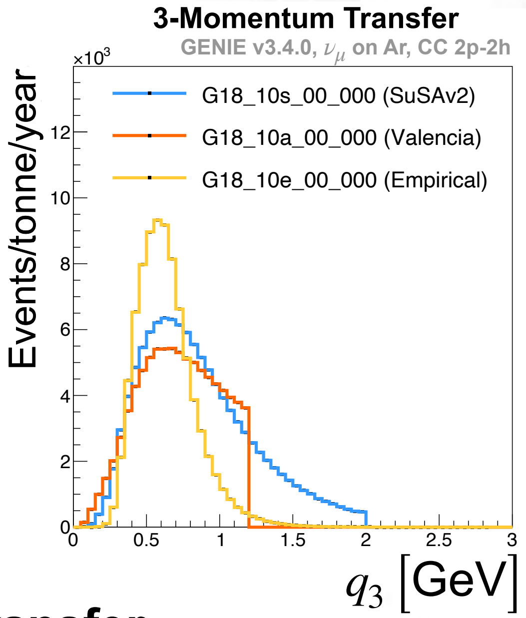


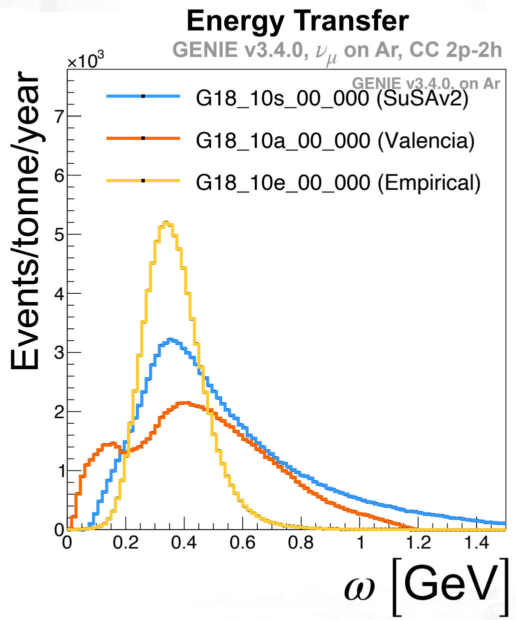


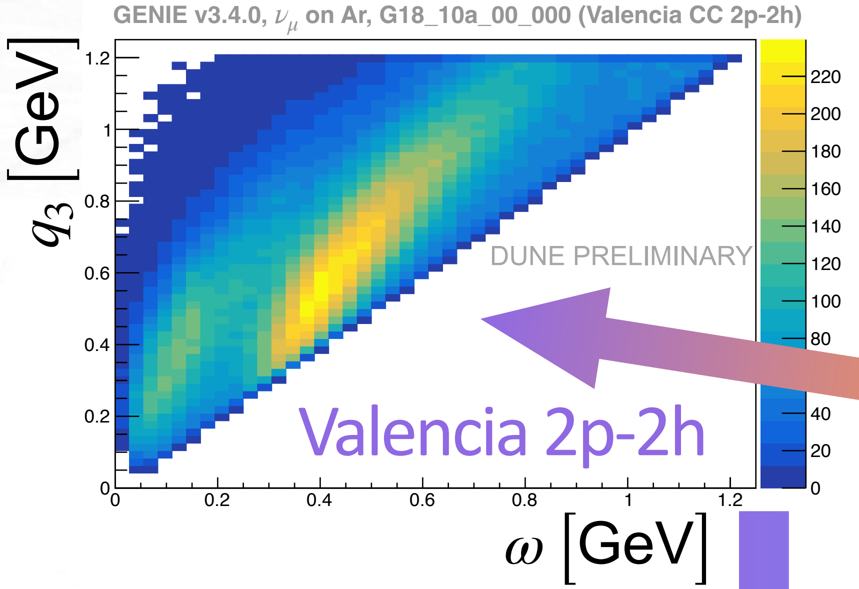
2p-2h Model Shape Differences

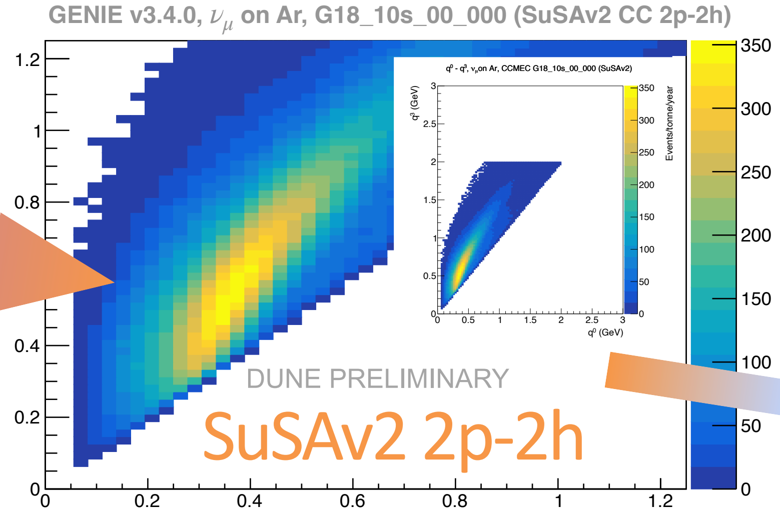
XSecShape_CCMEC parameter interpolates between CC 2p-2h models:

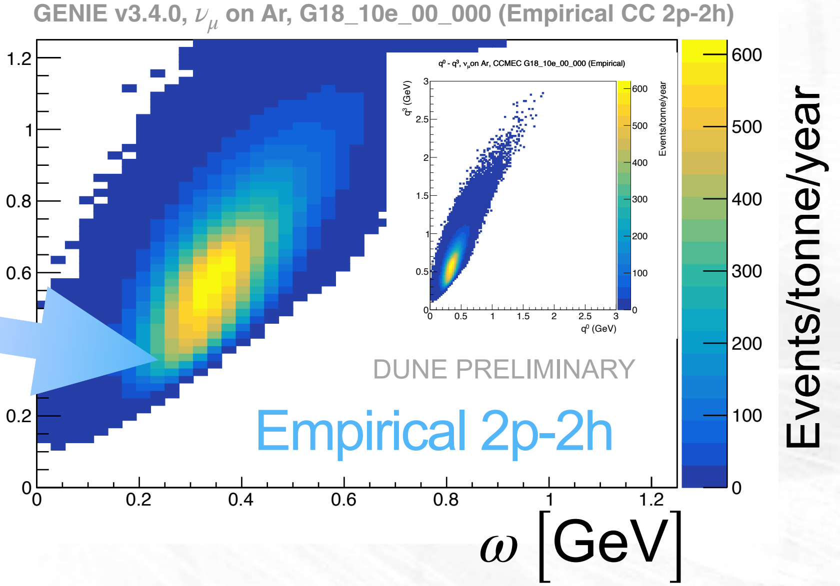
$$weight = \frac{(1-x_P)\cdot\frac{d^2\sigma^{def}}{dT_l d\cos(\theta_l)} + x_P\cdot\frac{d^2\sigma^{alt}}{dT_l d\cos(\theta_l)}}{\frac{d^2\sigma^{def}}{dT_l d\cos(\theta_l)}}$$











Nominal 2p-2h model phase-spaces

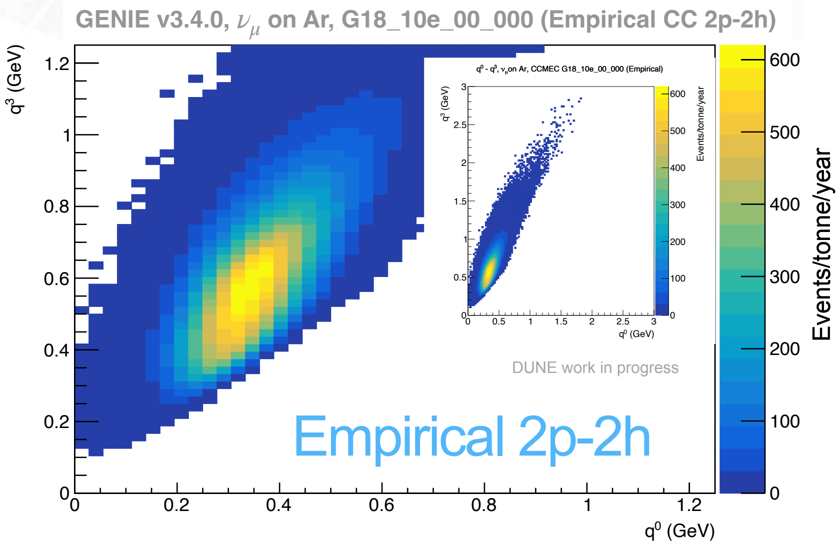
100 000 events generated

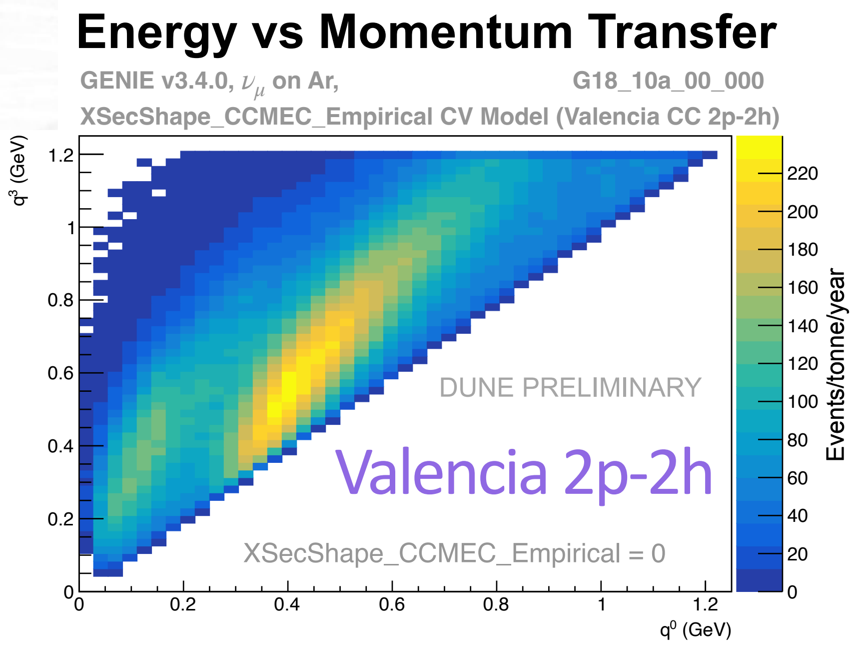
2p-2h Model Shape Differences

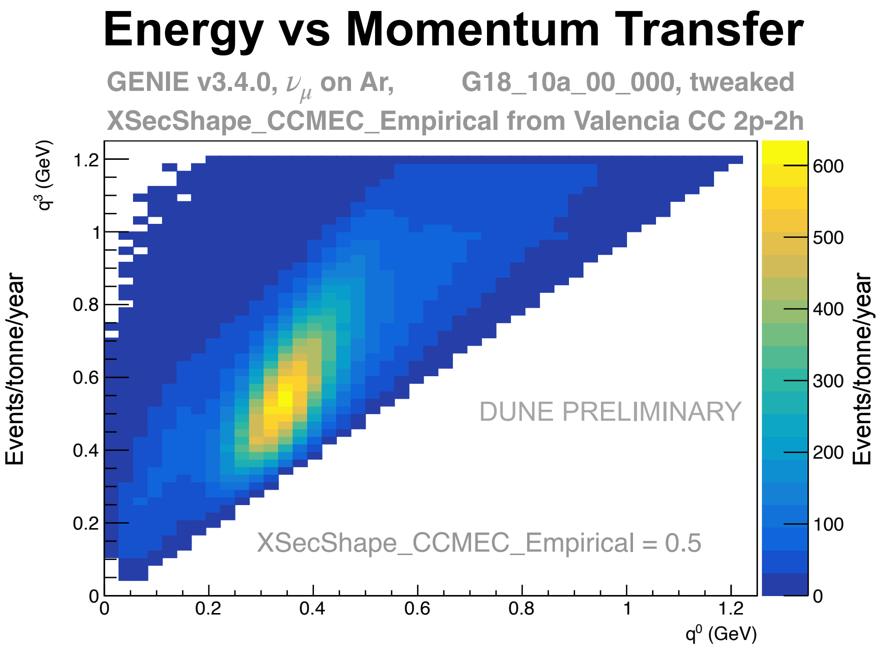
Energy vs Momentum Transfer

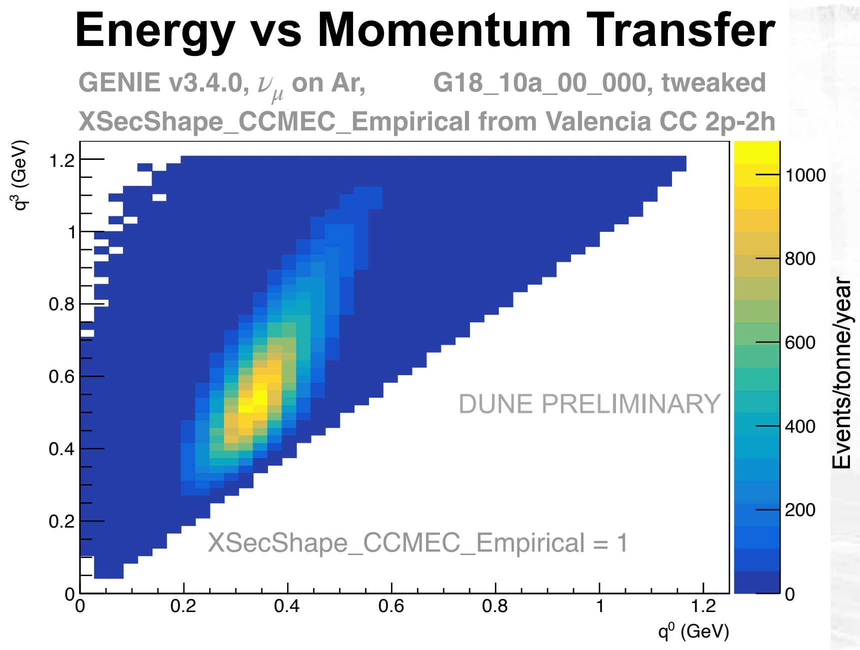
Valencia → *Empirical*

- *XSecShape_CCMEC_Empirical* parameter allows transition from (CC 2p-2h) **Valencia** or SuSAv2 to the **Empirical** model





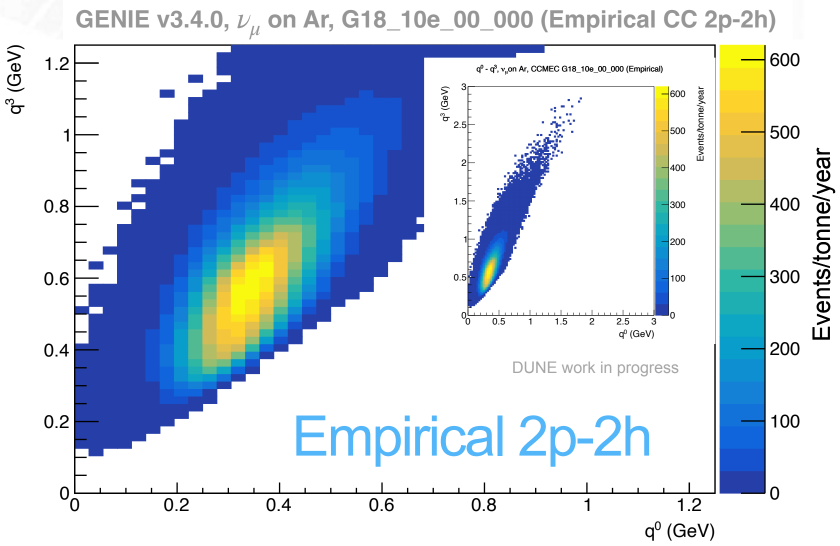




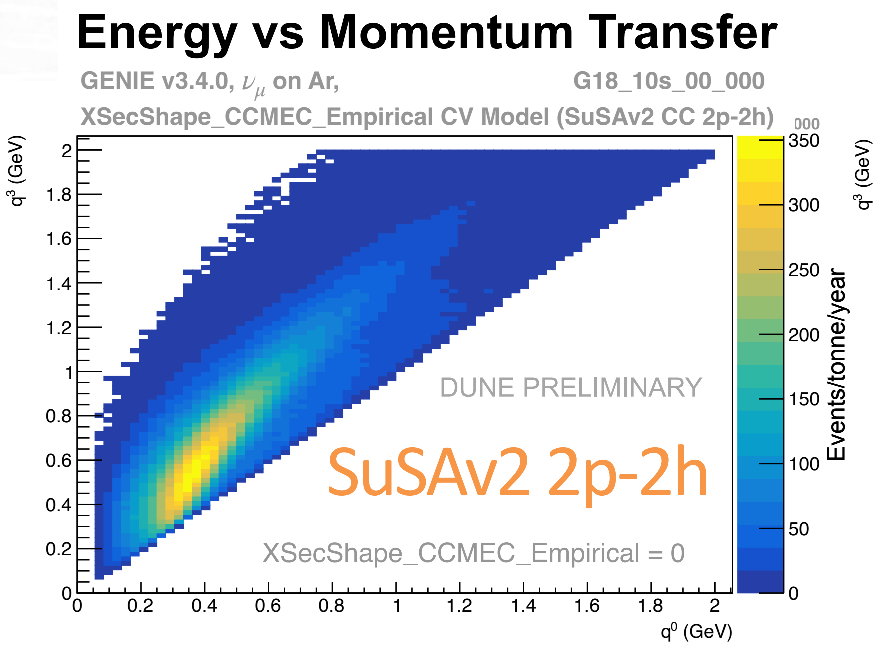
2p-2h Model Shape Differences

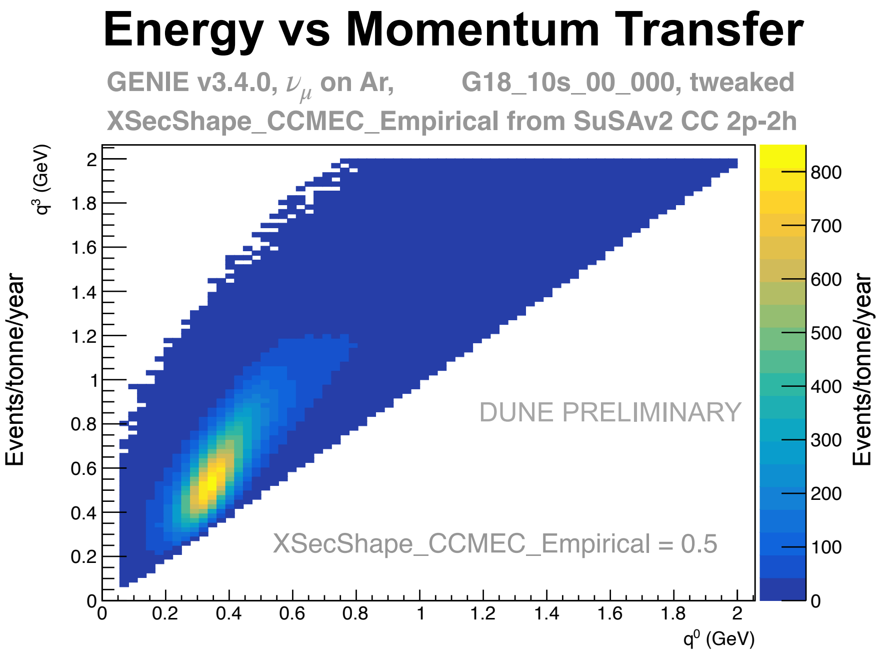
Energy vs Momentum Transfer

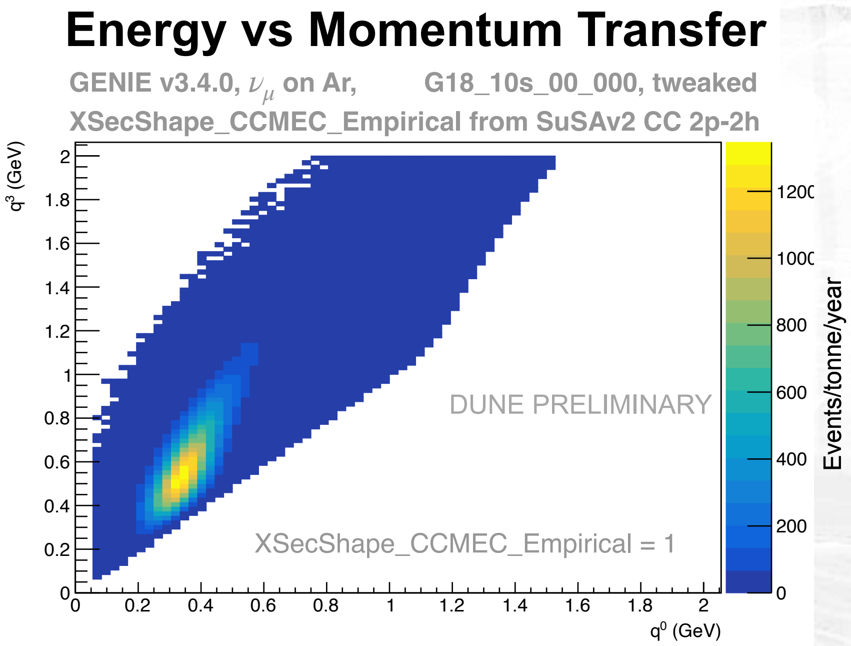
SuSAv2 → **Empirical**



- *XSecShape_CCMEC_Empirical* parameter allows transition from (CC 2p-2h) Valencia or **SuSAv2** to the **Empirical** model



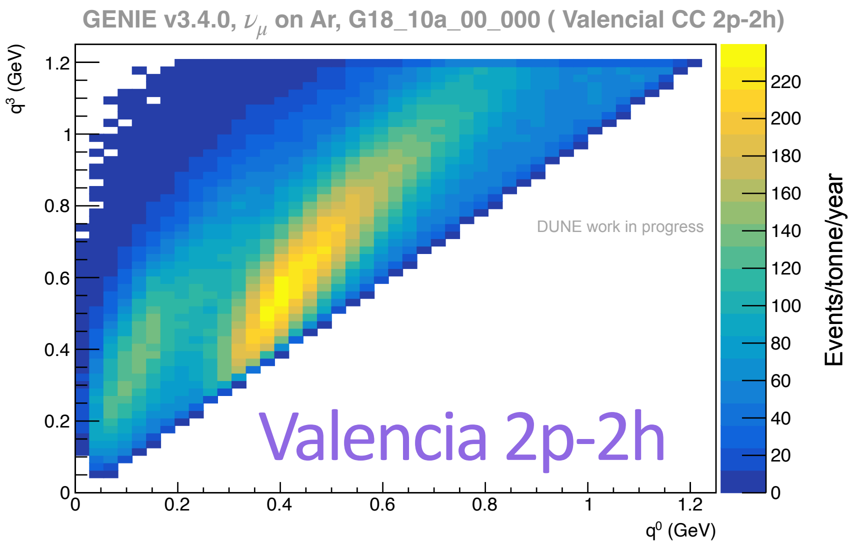




2p-2h Model Shape Differences

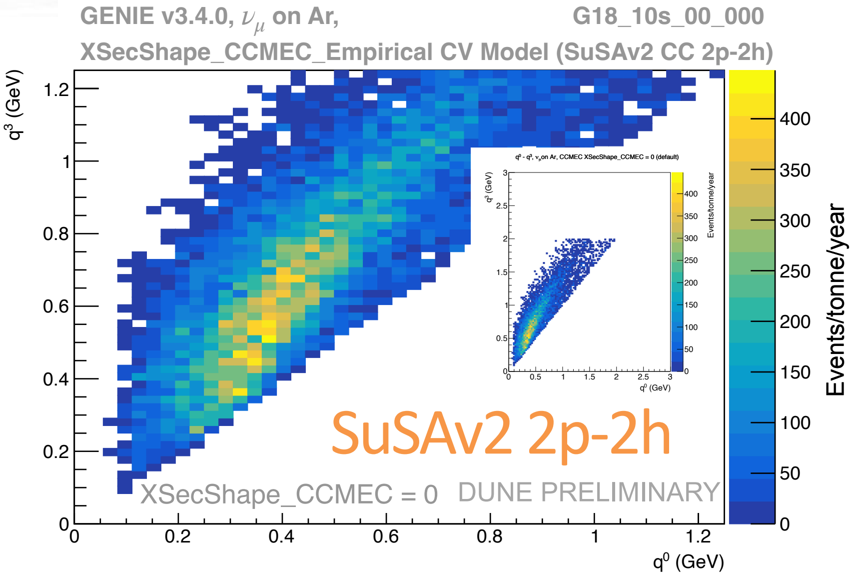
Energy vs Momentum Transfer

SuSAv2 → **Valencia**



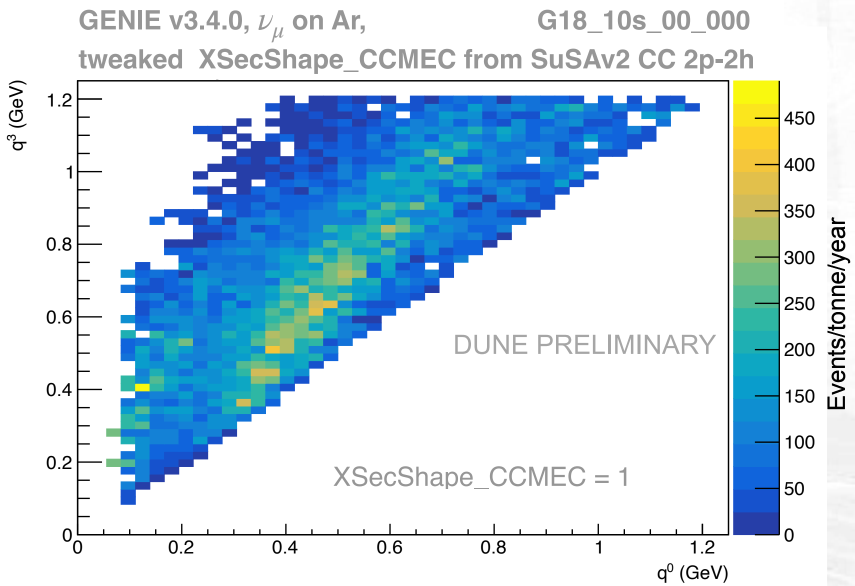
- *XSecShape_CCMEC* parameter allows transition from (CC 2p-2h) **SuSAv2** to the **Valencia** or the Empirical model

Energy vs Momentum Transfer



- Note:
  - *Long processing time* to produce the XSecShape_CCMEC reweighted distributions
  - May boil down to GENIE generation of 2p-2h events using the Valencia model

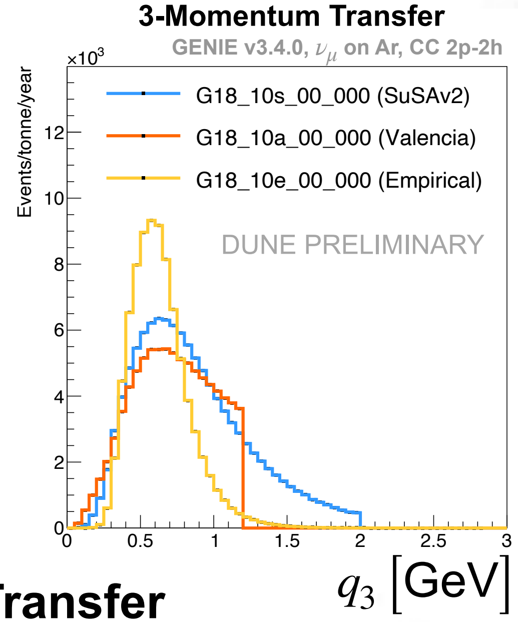
Energy vs Momentum Transfer

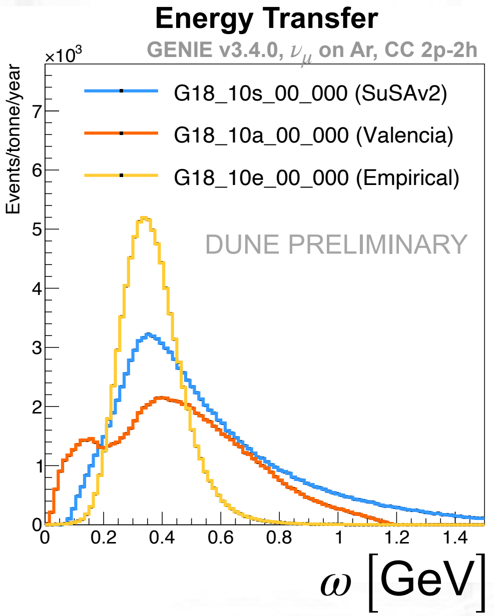


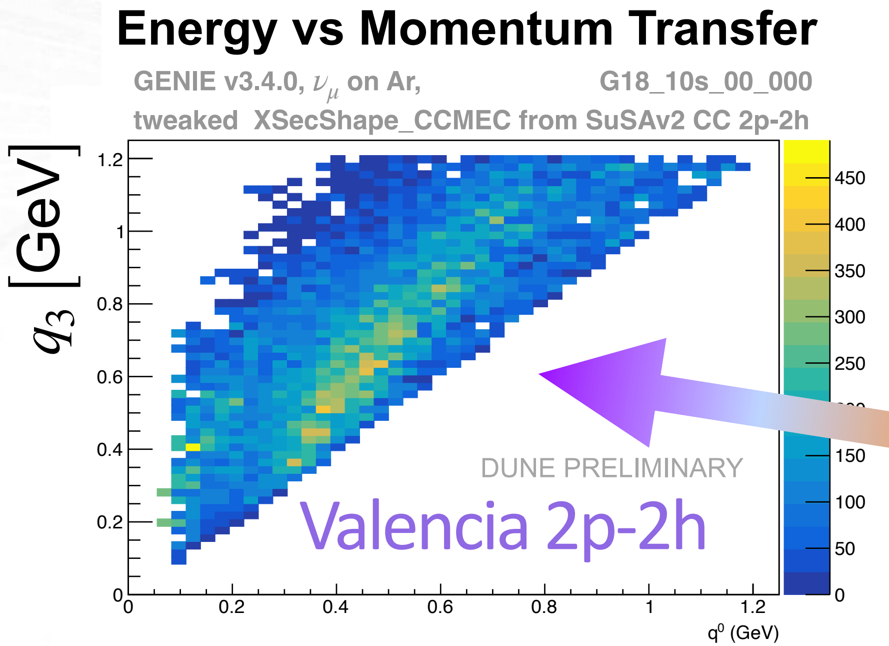
2p-2h Model Shape Differences

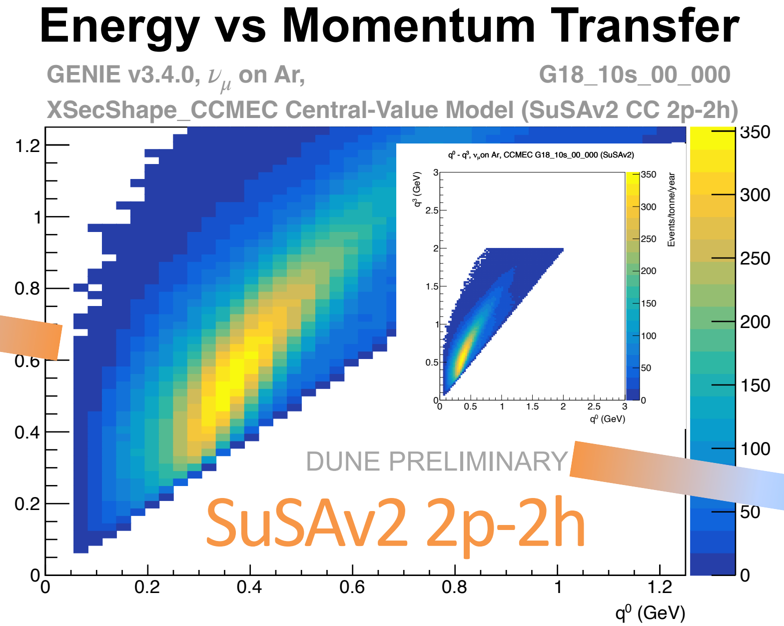
XSecShape_CCMEC parameter interpolates between CC 2p-2h models:

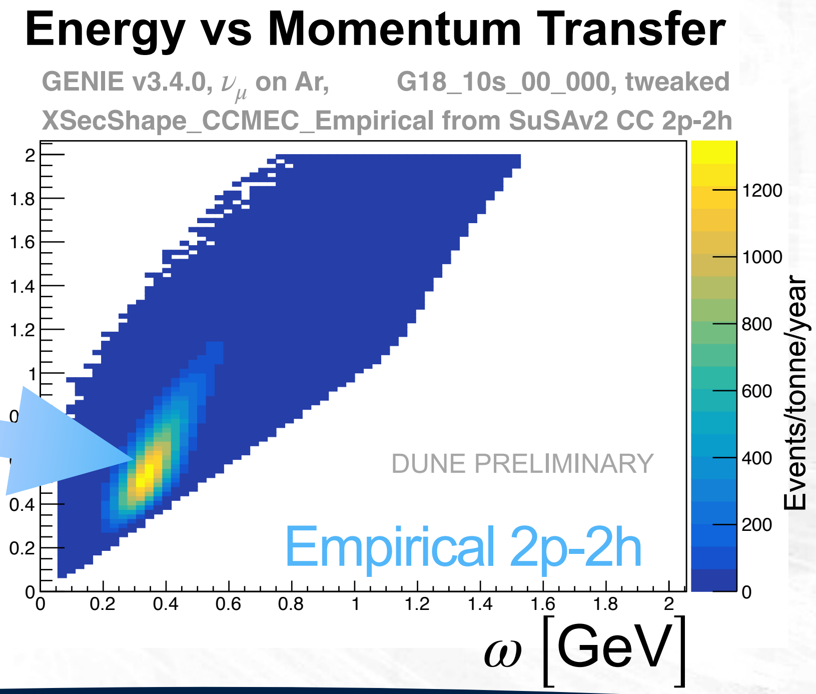
$$weight = \frac{(1 - x_P) \cdot \frac{d^2\sigma^{def}}{dT_l d\cos(\theta_l)} + x_P \cdot \frac{d^2\sigma^{alt}}{dT_l d\cos(\theta_l)}}{\frac{d^2\sigma^{def}}{dT_l d\cos(\theta_l)}}$$











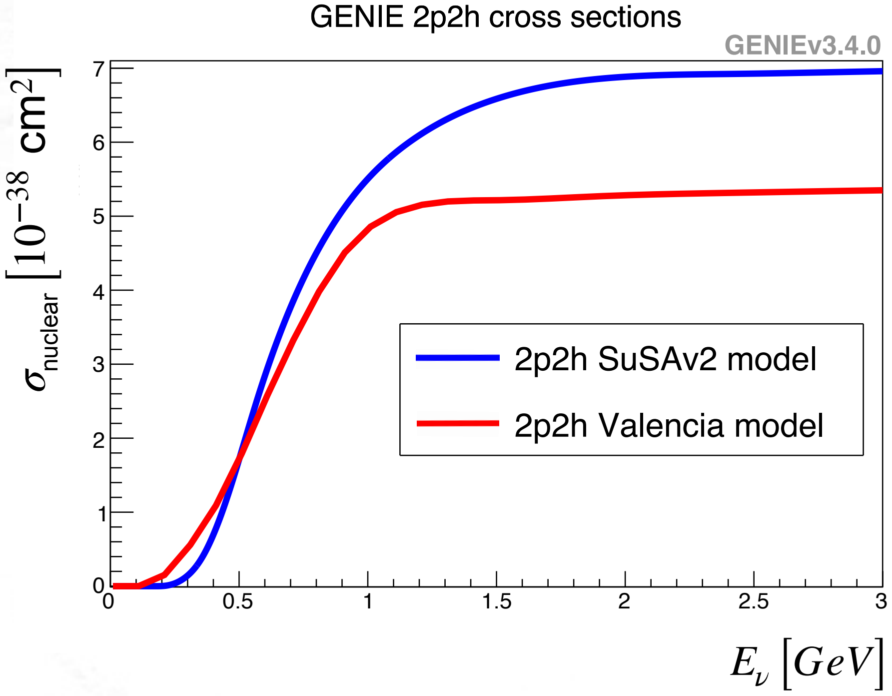
- However, *XSecShape_CCMEC* parameter works and allows to transition from **SuSAv2** to both the Valencia and the Empirical model

Energy Dependence

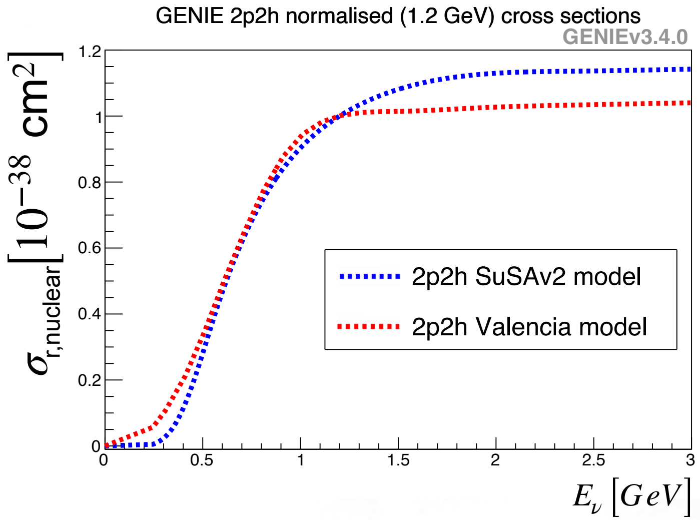
EnergyDependence_CCMEC - changes the energy dependence of 2p-2h cross sections

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

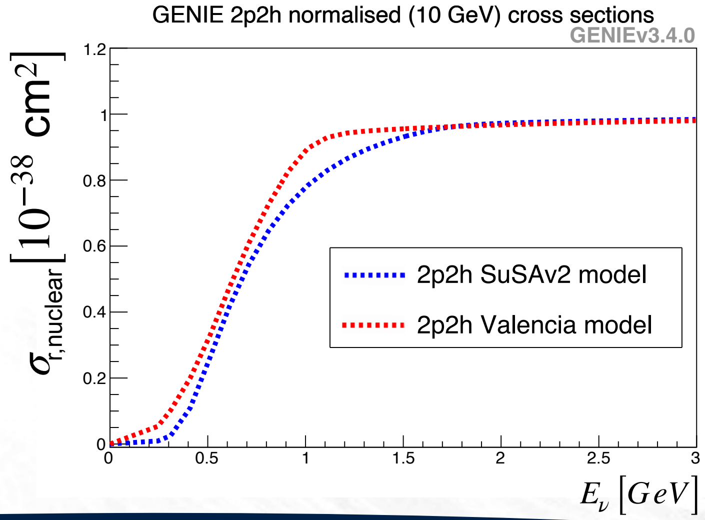
weight



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



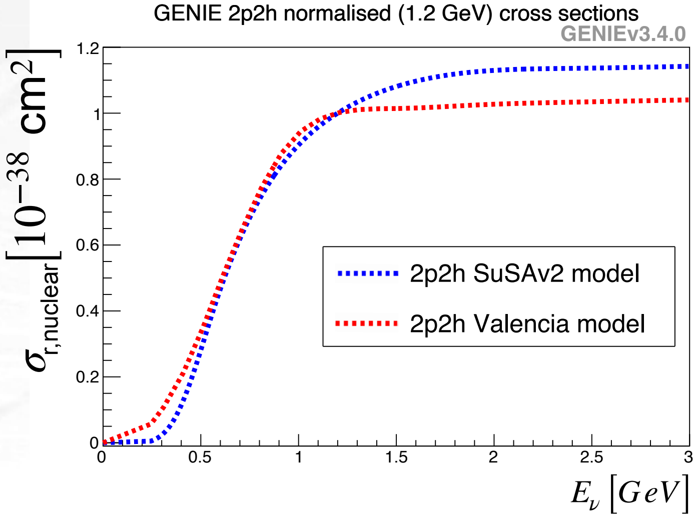
$$\sigma_r(E_\nu) = \frac{\sigma(E_\nu)}{\sigma(10\ \text{GeV})}$$

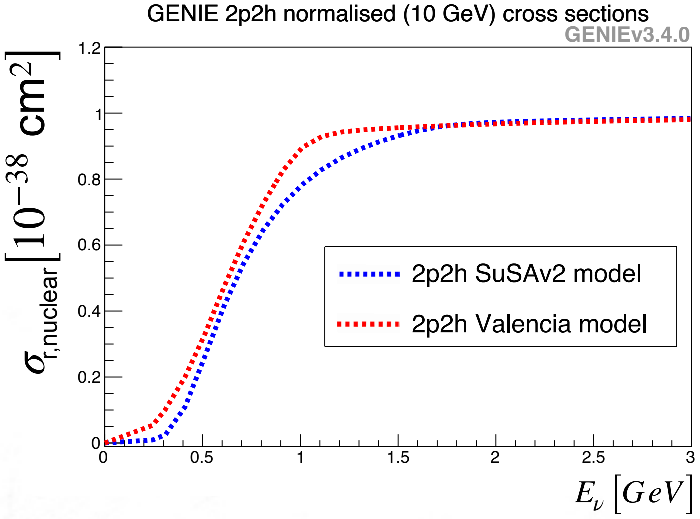


Approach inspired by T2K's implementation.

Energy Dependence

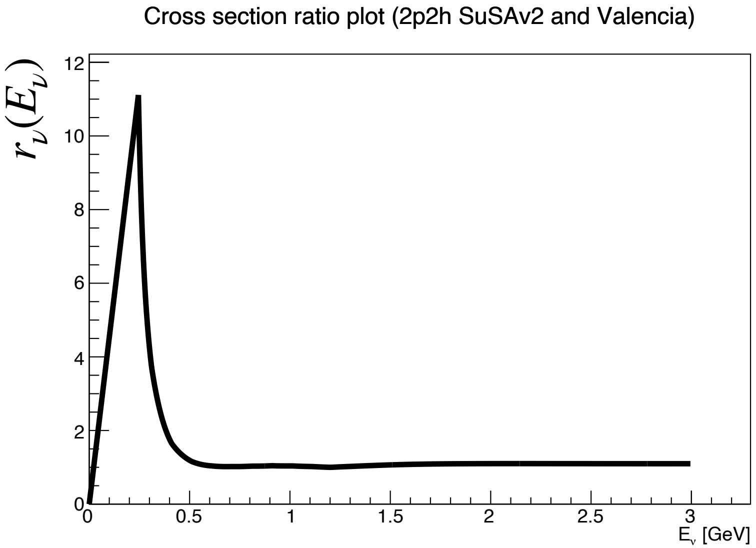
EnergyDependence_CCMEC - changes the energy dependence of 2p-2h cross sections

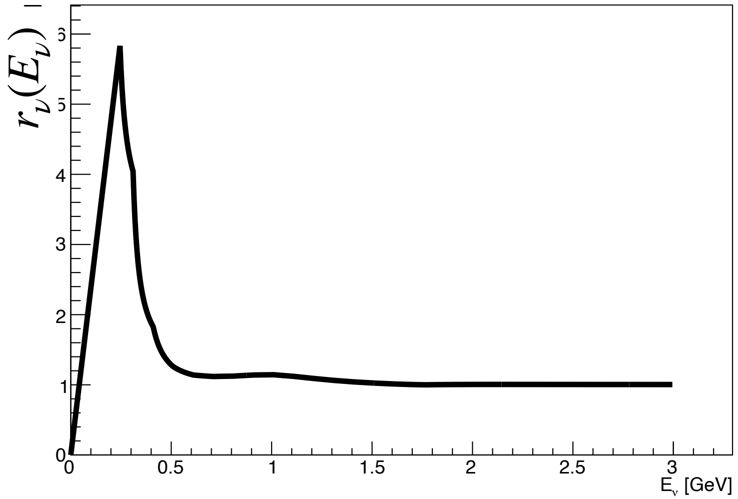




$$r_\nu(E_\nu) = \frac{\sigma_r^{max}(E_\nu)}{\sigma_r^{min}(E_\nu)}$$

$$r_\nu(E_\nu) = \frac{\sigma_r^{alt}(E_\nu)}{\sigma_r^{nom}(E_\nu)}$$

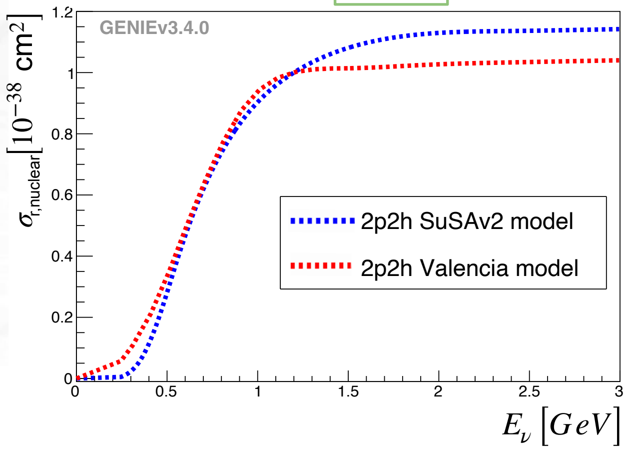




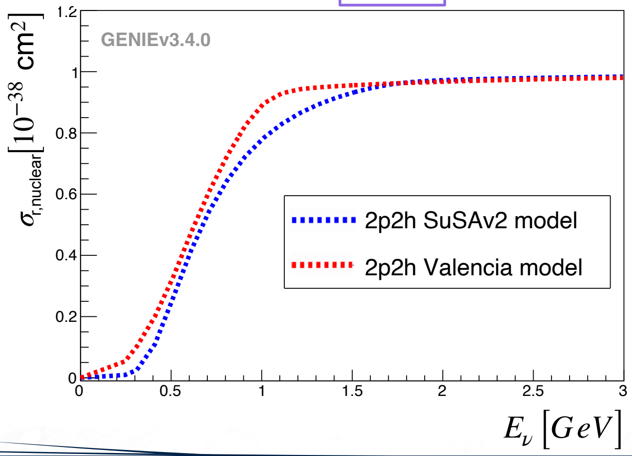
Energy Dependence

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

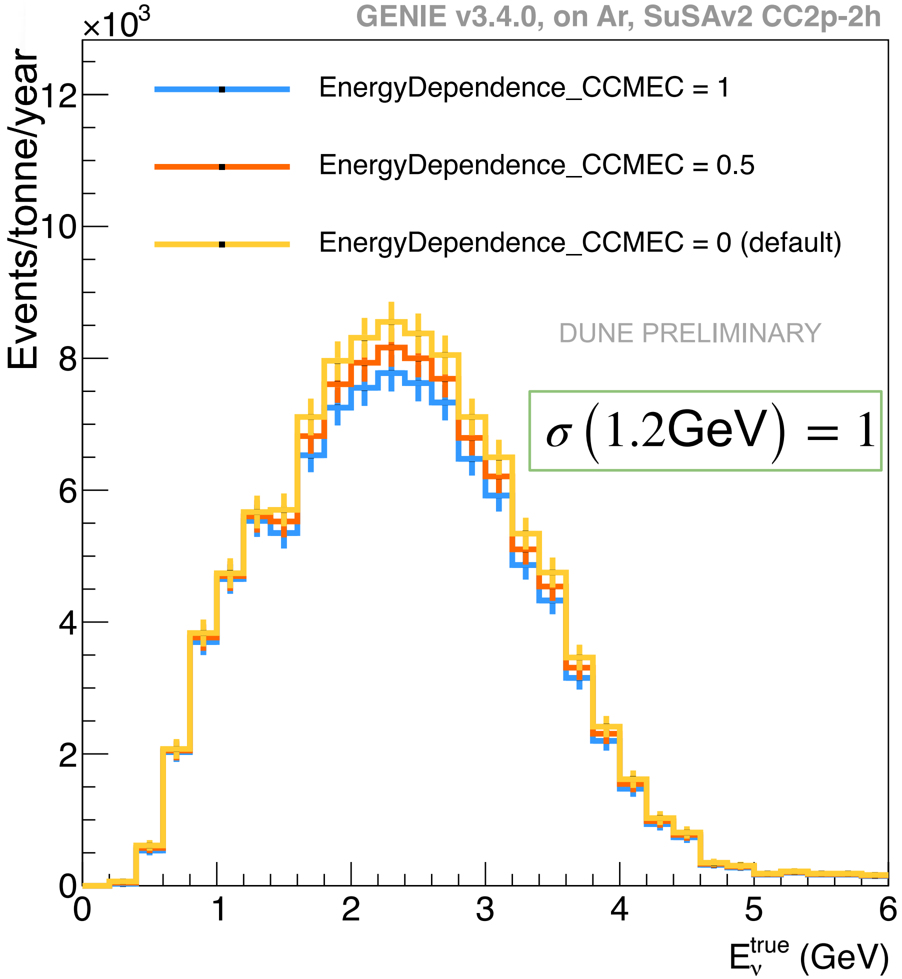
CC 2p-2h normalised (1.2GeV) cross sections



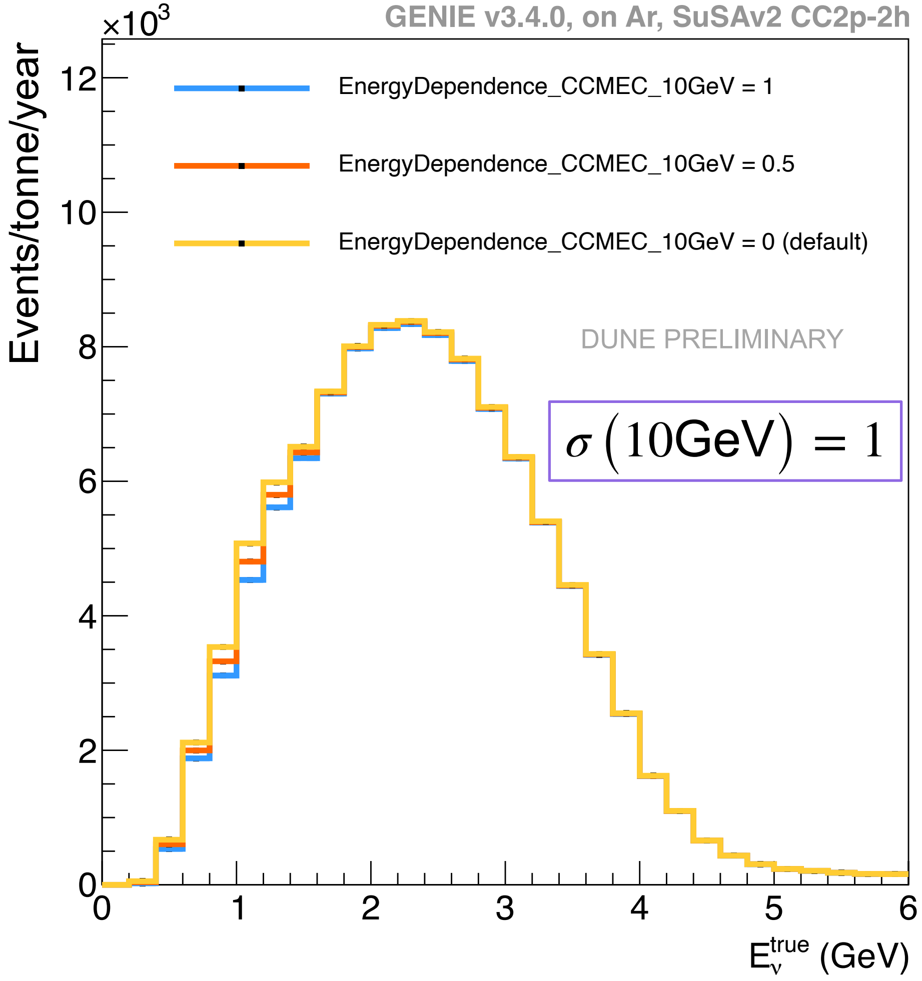
CC 2p-2h normalised (10GeV) cross sections



True Neutrino Energy, ν_μ on Ar, CCMEC



True Neutrino Energy, ν_μ on Ar, CCMEC



2p-2h Model Uncertainty Parameters

Summary of CC 2p-2h parameters in GENIEReweight.

Parameter	Central Value	+1σ	-1σ	Comment
NormCCMEC	166%	+50%	-50%	Adopted implementation for MicroBooNE*
DecayAngMEC	Isotropic	Alternative [a]	Alternative [a]	Adopted implementation for MicroBooNE*
FracPN_CCMEC	Valencia or SuSAv2	+20%	-20%	Adopted implementation for MicroBooNE*
FracDelta_CCMEC	Valencia	+30%	-30%	Adopted implementation for MicroBooNE*
XSecShape_CCMEC	Empirical [b] or Valencia [c]	N/A	SuSAv2 [d]	Adopted implementation for MicroBooNE* Changed default input model from Valencia to SuSAv2
XSecShape_CCMEC_Empirical	Empirical	N/A	SuSAv2 or Valencia	Based on XSecShape_CCMEC implementation for reweighting to Empirical
XSecShape_CCMEC_Martini [e]	Martini	N/A	SuSAv2 or Valencia	Based on XSecShape_CCMEC implementation for reweighting to Martini
EnergyDependence_CCMEC	SuSAv2 or Valencia	+100%	N/A	Implementation inspired by T2K's approach

[a] An angular distribution proportional to $\cos^2(\theta_{\mathrm{DecayAngMEC}})$ with two tweak dials, one interpolating from an isotropic angular distribution to $\cos^2(\theta_{\mathrm{DecayAngMEC}})$ and one to change its argument.
[b] Nominal prediction of the GENIE Empirical CC 2p-2h model, here GENIE tune G18_10e_00_000.
[c] Nominal prediction of the Valencia CC 2p-2h model, here GENIE tune G18_10a_00_000.
[d] Nominal prediction of the SuSAv2 CC 2p-2h model, here GENIE tune G18_10s_00_000.
[e] For future nominal prediction of the Martini CC 2p-2h model.

*For central values and uncertainties in MicroBooNE, see Phys. Rev. D **105**, 072001. Table adopted from Table VIII in there.

GENIE-MC/Generator/config/GSystUncertaintyTable.xml

Outlook

What is missing?

- Nucleon decay angle:
  - Implement dependence of hadron kinematics on 4-momentum transfer (Phys. Rev. C 109, 015502)
  - Design weight mimicking Fourier modes for more freedom
  - Reweighting between imbalanced and back-to-back nucleons (arXiv:2201.04664)
- Consider parameter to address uncertainty on removal energy
- Implement reweighing for $\bar{\nu}$-CC2p-2h on Ar (especially *XSecShape_CCMEC* and *EnergyDependence_CCMEC* parameters)

- Energy dependence: reweight strength of structure functions:

$$\frac{\overline{L}_{\mu\nu}\overline{W}^{\mu\nu}}{E_\nu^2} = \frac{1}{E_\nu^2}\left[W_1\left(Q^2+m_l^2\right) - \frac{W_2}{2}\left(m_l^2+Q^2\right) \mp \frac{q_0 W_3}{2M}\left(m_l^2+Q^2\right) + \frac{W_4}{M^2}\frac{Q^2 m_l^2 + m_l^4}{2}\right] + \frac{1}{E_\nu}\left[-2q_0 W_2 \pm \frac{W_3 Q^2}{M} - \frac{W_5 m_l^2}{M}\right] + W_2$$

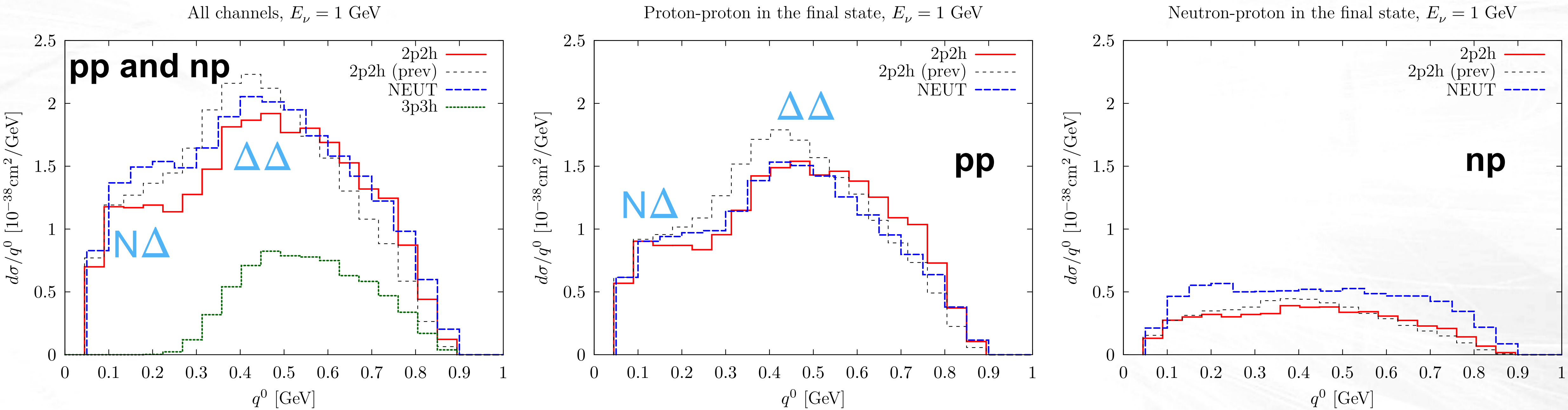
Srivastava, Asit: FERMILAB-MASTERS-2023-01

Outlook

What is missing?

↓

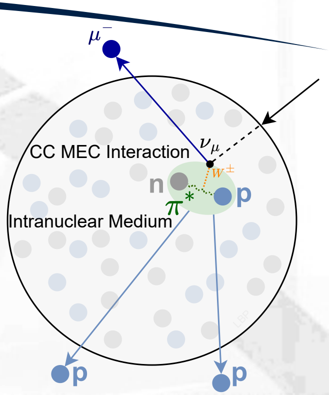
- Better agreement between theoretical predictions and implementations in MC event generators



- Tensions between generator predictions of hadron kinematics in 2p-2h and theory!

Reference: Phys. Rev. C 102, 024601

Summary and Outlook

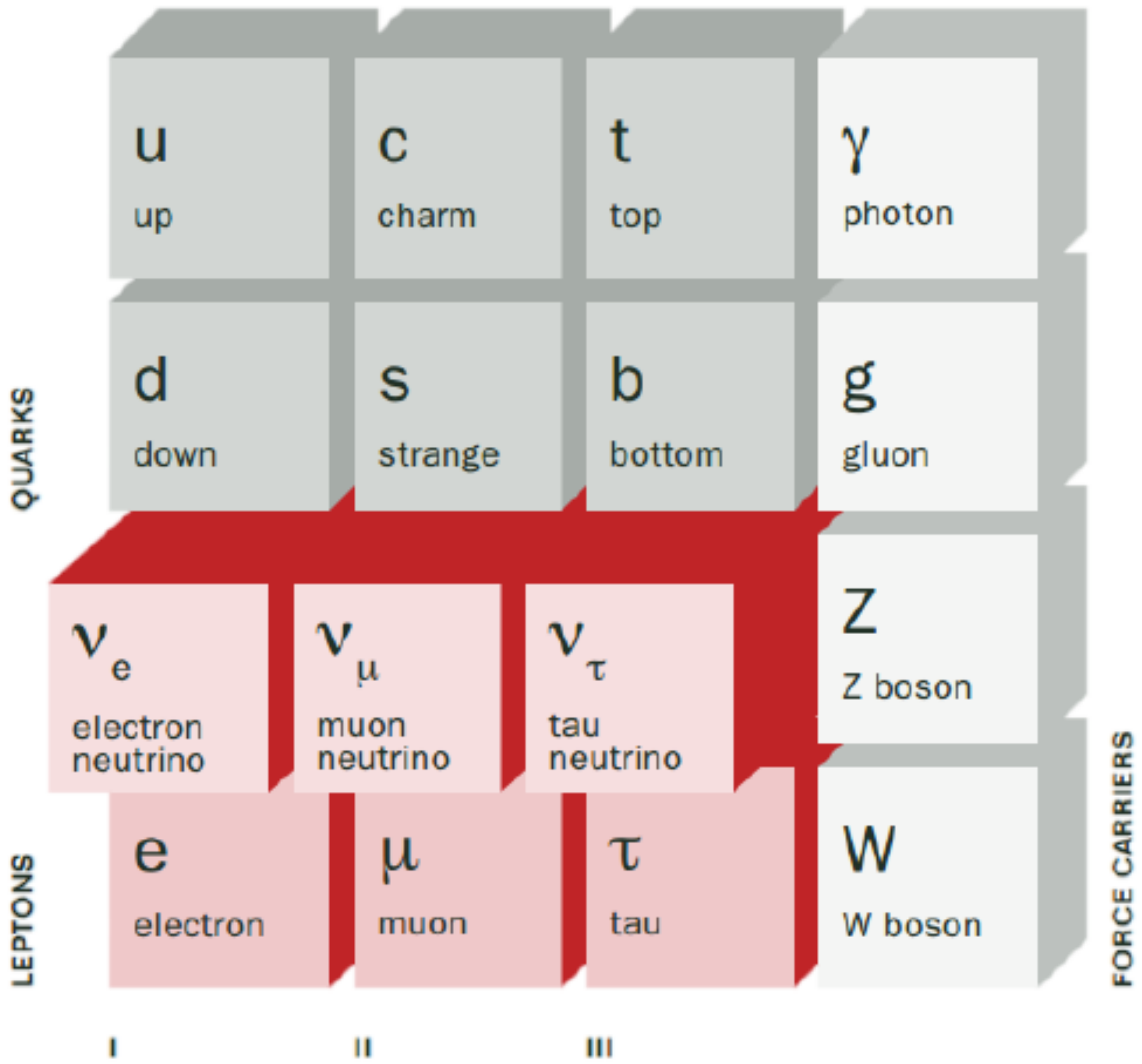


- CC 2p-2h neutrino interactions are **complex** and necessitate dedicated study
- **Develop fit parameters** to estimate systematic uncertainties
- **Choose uncertainties** such that the measurement of the oscillation parameters is not biased
- Development of novel CC 2p-2h systematic parameters in progress
- Finish and make my GENIEReweight/larsbp_feature_2p2h branch publicly available
- Understanding the effect of systematic parameters on chosen variable distributions will allow a robust **estimate of systematic uncertainties** in modern and future neutrino oscillation experiments such as DUNE

Thank you!

Backup

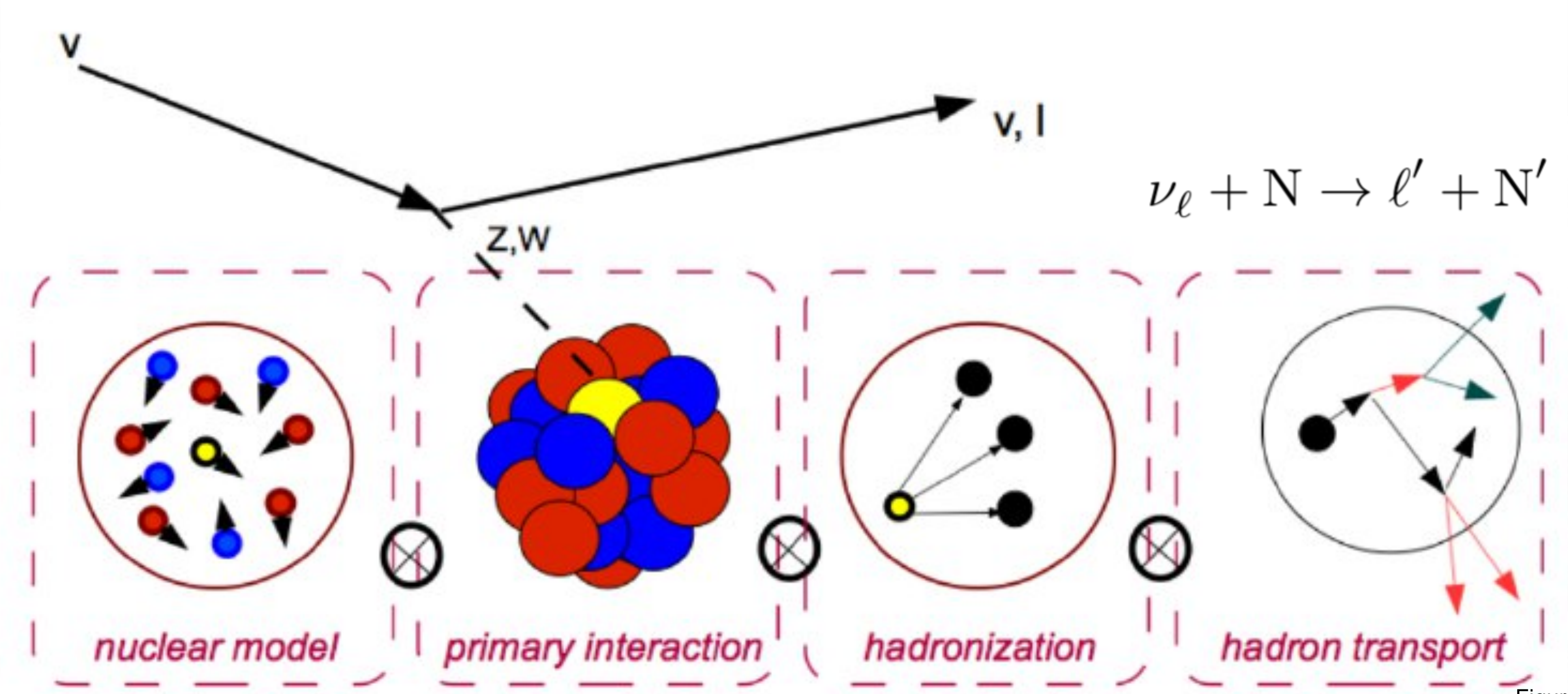
Neutrinos in the Standard Model



- 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

Neutrino-Nucleus Interactions

Theoretical Predictions by Neutrino Event Generators



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

Figure by C. Andreopoulos

Neutrino-Nucleus Interactions

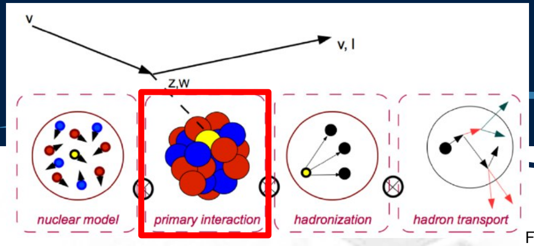
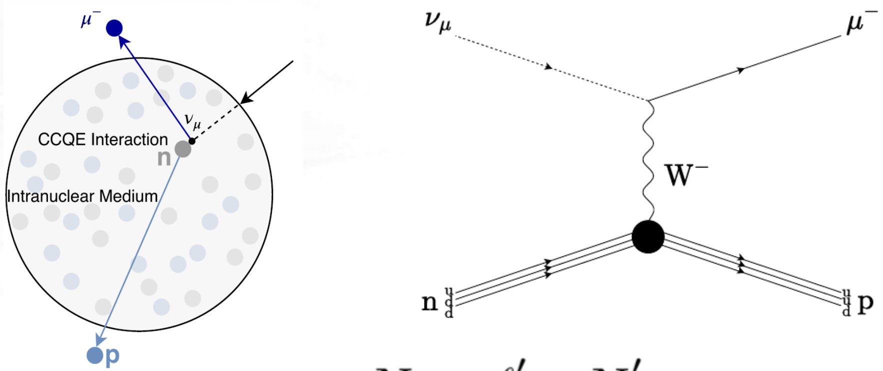


Figure by C. Andreopoulos

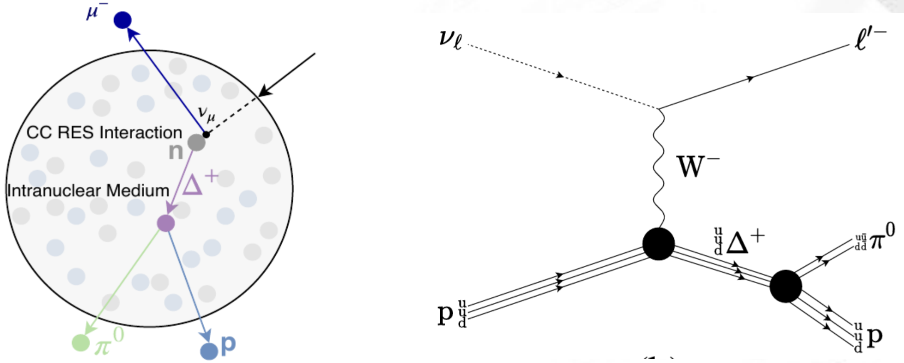
Lars Bathe-Peters: FERMILAB-MASTERS-2020-03

Quasi-Elastic (QE)



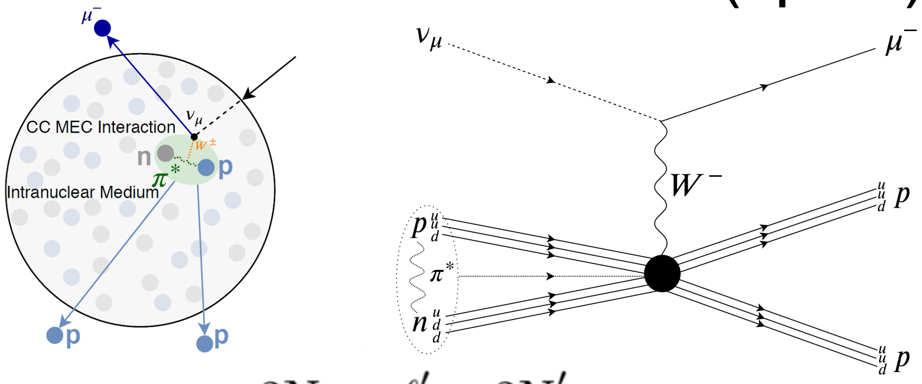
$$\nu_\ell + \mathrm{N} \rightarrow \ell' + \mathrm{N}'$$

Resonance Excitation (RES)



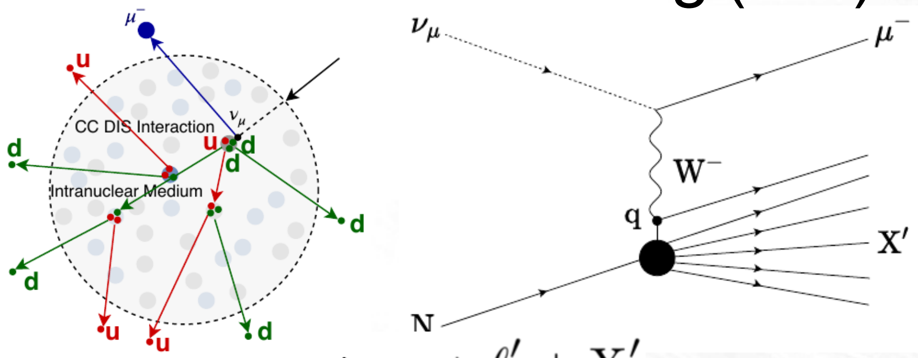
$$\nu_\ell + \mathrm{N} \rightarrow \ell' + \mathrm{N}' + \pi'$$

Multi-Nucleon Processes (*np*-*nh*)



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

Deep Inelastic Scattering (DIS)



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

Nuclear Effects

Final State Interactions (FSIs)

- FSIs inside the nucleus:
  - (In)elastic Scattering
  - Pion Production
  - Absorption
  - Charge Exchange
- Hadron that escape the nucleus are measurable

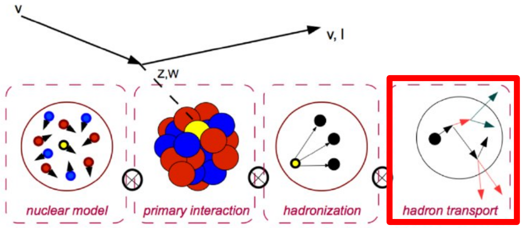
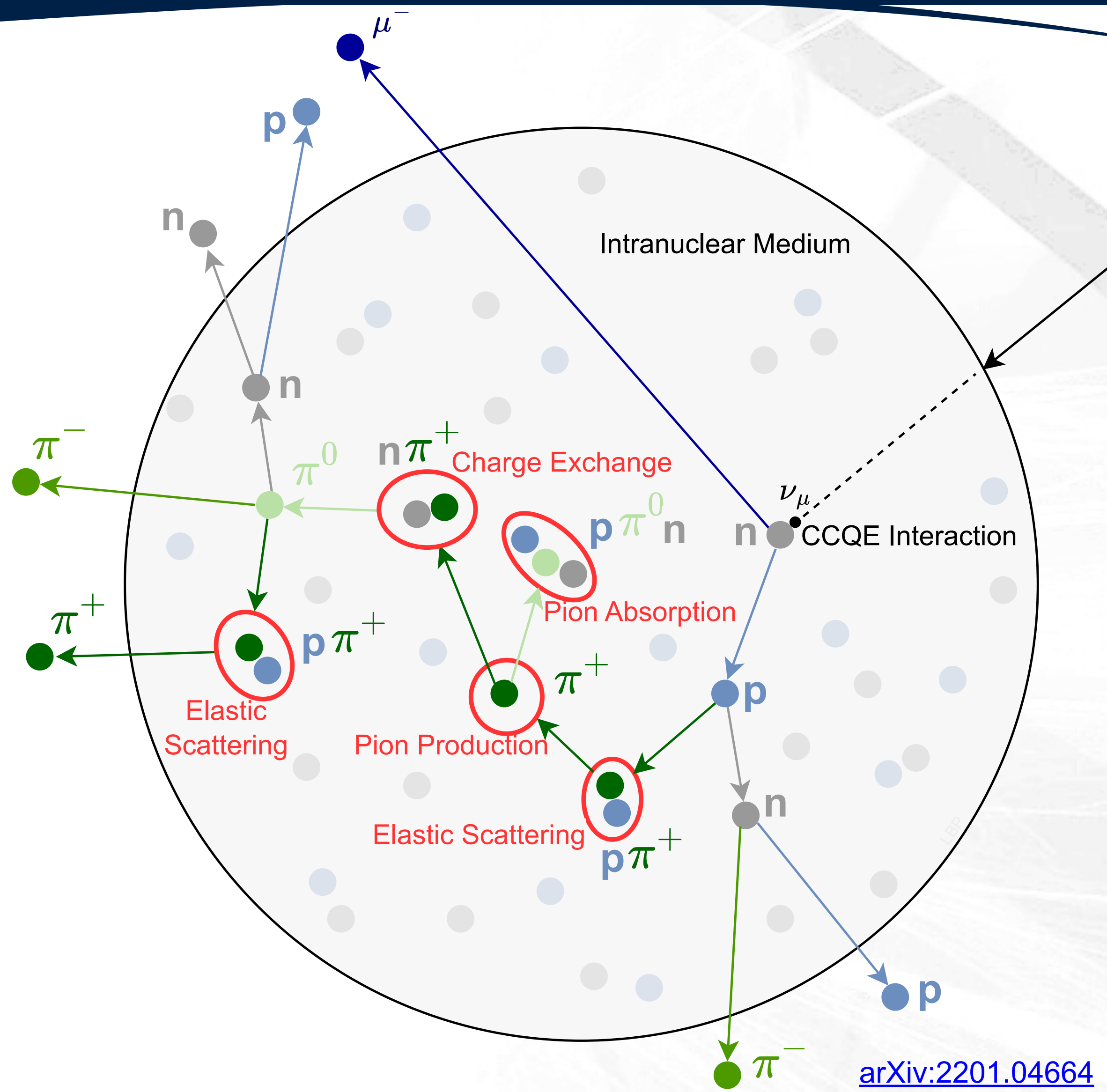


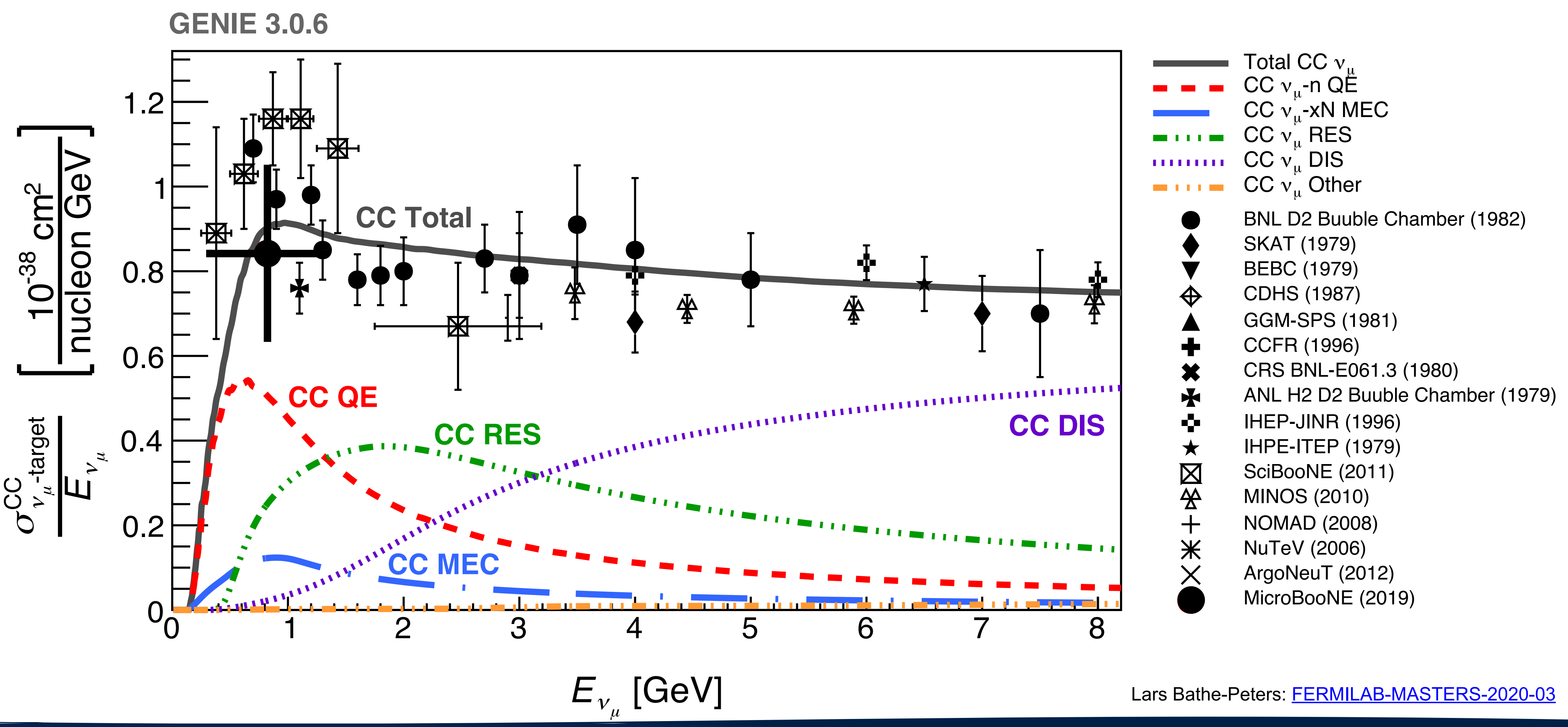
Figure by C. Andreopoulos



arXiv:2201.04664

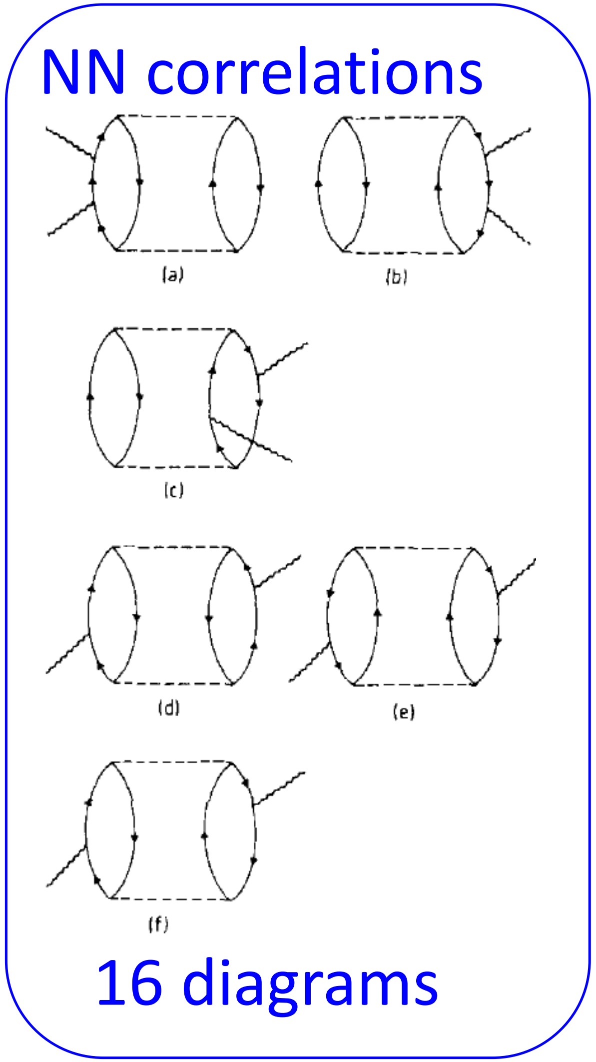
Neutrino-Nucleus Cross Section

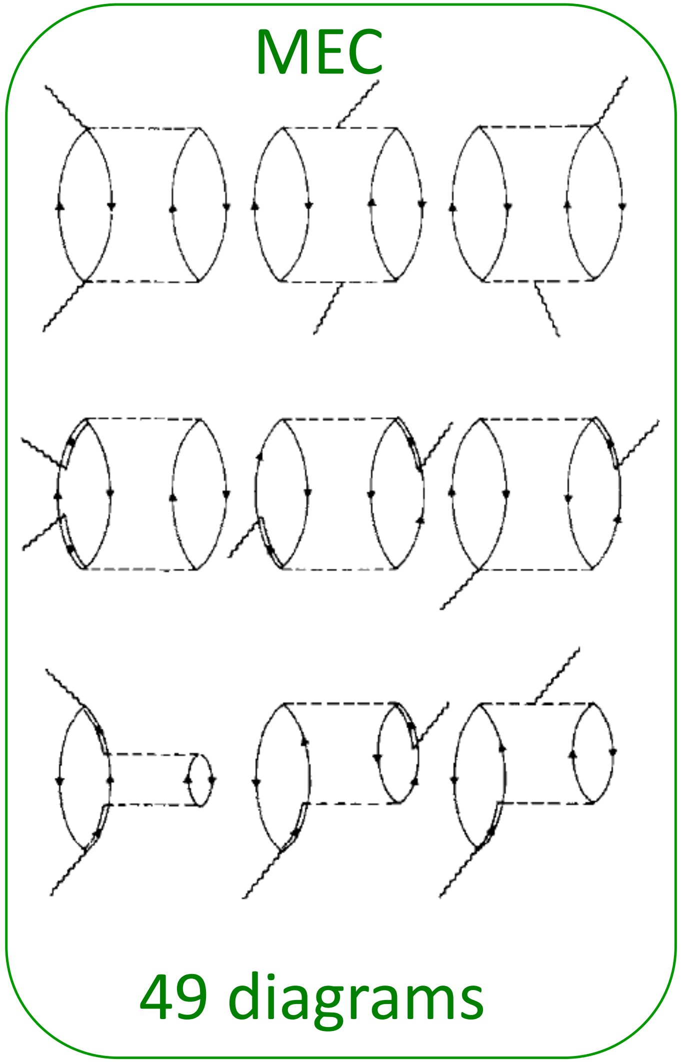
Interaction Modes

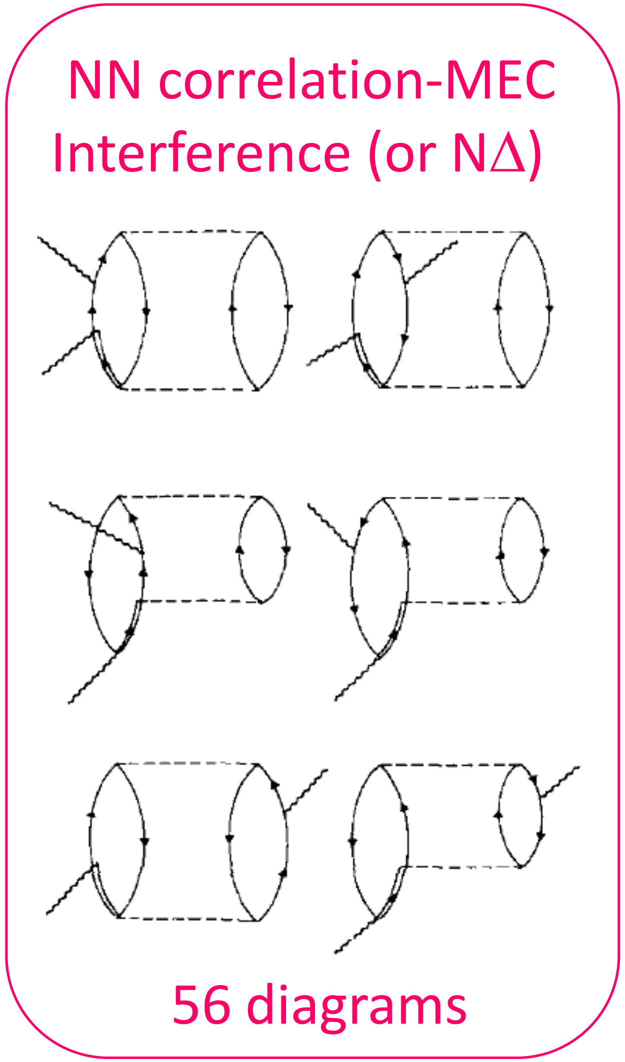


Lars Bathe-Peters: FERMILAB-MASTERS-2020-03

Diagrams for 2p-2h Responses







Slide adapted from M. Martini and M. Ericson: Inclusion of multi-nucleon effects in RPA-based calculations for ν-nucleus scattering. Talk given at [ESNT 2p-2h workshop] in April 2016.

Different Approaches to 2p-2h Contributions

Martini et al. — Nieves et al. — Amaro et al. (only vector MEC) — Lovato et al. — Bodek et al.

[Follow the color and the style of the lines:]

different notations

$$\frac{\partial^2\sigma}{\partial\Omega\ \partial\epsilon'} = \sigma_0 \left[L_{CC}(R^V_{CC} + R^A_{CC}) + L_{CL}(R^V_{CL} + R^A_{CL}) + L_{LL}(R^V_{LL} + R^A_{LL}) + L_T(R^V_T + R^A_T) \pm L_{T'VA}R^{VA}_{T'}\right]$$

$$\frac{\partial^2\sigma}{\partial\Omega\ \partial\epsilon'} = \sigma_0 \left[L_{00}R_{00} + L_{0z}R_{0z} + L_{zz}R_{zz} + L_{xx}R_{xx} \pm L_{xy}R_{xy}\right]$$

$$\frac{\partial^2\sigma}{\partial\Omega\,\partial\epsilon'} = \frac{G_F^2\ \cos^2\theta_c}{2\,\pi^2} k'\epsilon'\ \cos^2\frac{\theta}{2}\left[\frac{(q^2-\omega^2)^2}{q^4} G_E^2\, R_\tau + \frac{\omega^2}{q^2} G_A^2\, R_{\sigma\tau(L)} + 2\left(\tan^2\frac{\theta}{2} + \frac{q^2-\omega^2}{2q^2}\right)\left(G_M^2\frac{\omega^2}{q^2} + G_A^2\right) R_{\sigma\tau(T)} \pm 2\,\frac{\epsilon+\epsilon'}{M_N}\ \tan^2\frac{\theta}{2}\, G_A\, G_M\, R_{\sigma\tau(T)}\right]$$

Slide adapted from M. Martini and M. Ericson: Inclusion of multi-nucleon effects in RPA-based calculations for ν-nucleus scattering. Talk given at ESNT 2p-2h workshop in April 2016.

Theoretical Calculations on np-nh Contributions to ν-nucleus Cross Sections

M. Martini, M. Ericson, G. Chanfray, J. Marteau (Lyon, IPNL)

Phys. Rev. C 80 065501 (2009) ν σtotal
Phys. Rev. C 81 045502 (2010) ν vs antiν (σtotal)
Phys. Rev. C 84 055502 (2011) ν $d^2\sigma$, $d\sigma/dQ^2$
Phys. Rev. D 85 093012 (2012) impact of np-nh on ν energy reconstruction
Phys. Rev. D 87 013009 (2013) impact of np-nh on ν energy reconstruction and ν oscillation
Phys. Rev. C 87 065501 (2013) antiν $d^2\sigma$, $d\sigma/dQ^2$
Phys. Rev. C 90 025501 (2014) inclusive ν $d^2\sigma$
Phys. Rev. C 91 035501 (2015) combining ν and antiν $d^2\sigma$, $d\sigma/dQ^2$

J. Nieves, I. Ruiz Simo, M.J. Vicente Vacas, F. Sanchez, R. Gran (Valencia, IFIC)

Phys. Rev. C 83 045501 (2011) ν, antiν σtotal
Phys. Lett. B 707 72-75 (2012) ν $d^2\sigma$
Phys. Rev. D 85 113008 (2012) impact of np-nh on ν energy reconstruction
Phys. Lett. B 721 90-93 (2013) antiν $d^2\sigma$
Phys. Rev. D 88 113007 (2013) extension of np-nh up to 10 GeV

J.E. Amaro, M.B. Barbaro, T.W. Donnelly, I. Ruiz Simo, G. Megias et al. (Superscaling)

Phys. Lett. B 696 151-155 (2011) ν $d^2\sigma$
Phys. Rev. D 84 033004 (2011) ν $d^2\sigma$, σtotal
Phys. Rev. Lett. 108 152501 (2012) antiν $d^2\sigma$, σtotal
Phys. Rev. D 90 033012 (2014) 2p-2h phase space
Phys. Rev. D 90 053010 (2014) angular distribution
Phys. Rev. D 91 073004 (2015) parametrization of vector MEC

Slide adapted from M. Martini and M. Ericson: Inclusion of multi-nucleon effects in RPA-based calculations for ν-nucleus scattering. Talk given at ESNT 2p-2h workshop in April 2016.

Neutrino-Nucleus Interactions

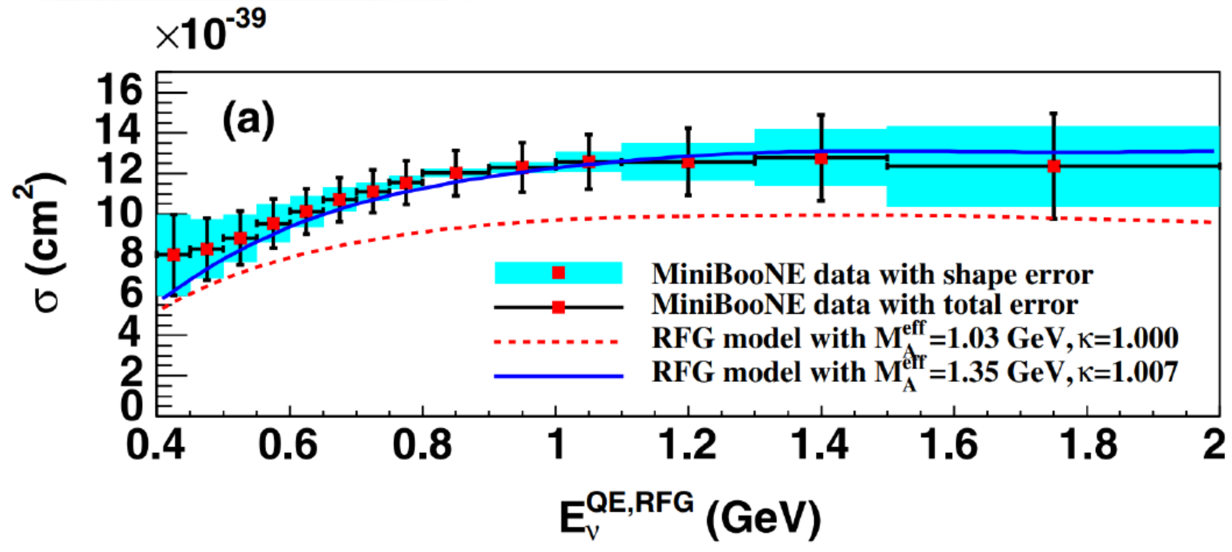


Figure adapted from Phys.Rev.D81:092005,2010.

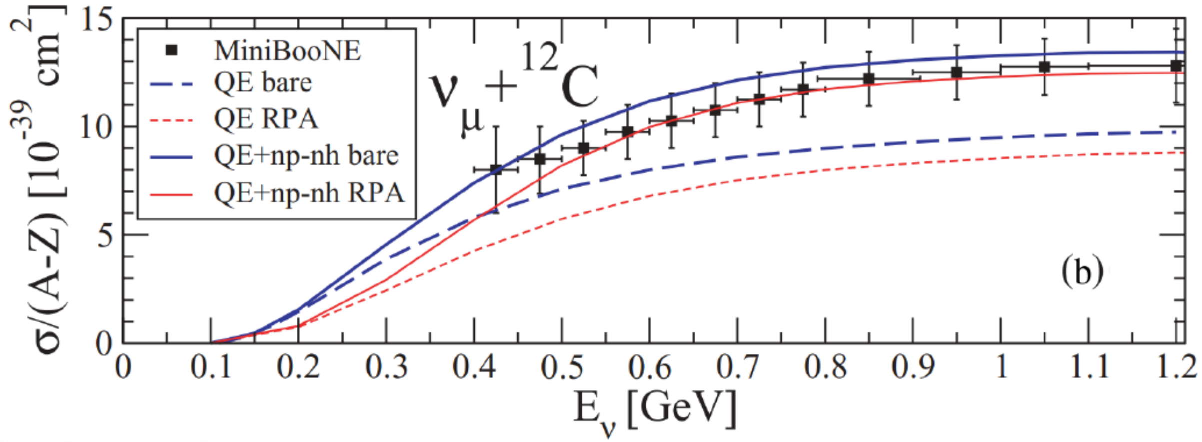


Figure adapted from Physical Review C 81 (2010) 045502.

- Data excess in ν_μ-CCQE cross section in MiniBooNE
- Possible explanations:
  - Increasing the axial mass M_A
  - Inclusion of np-nh and Random-Phase Approximation (RPA) model

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

NEUT

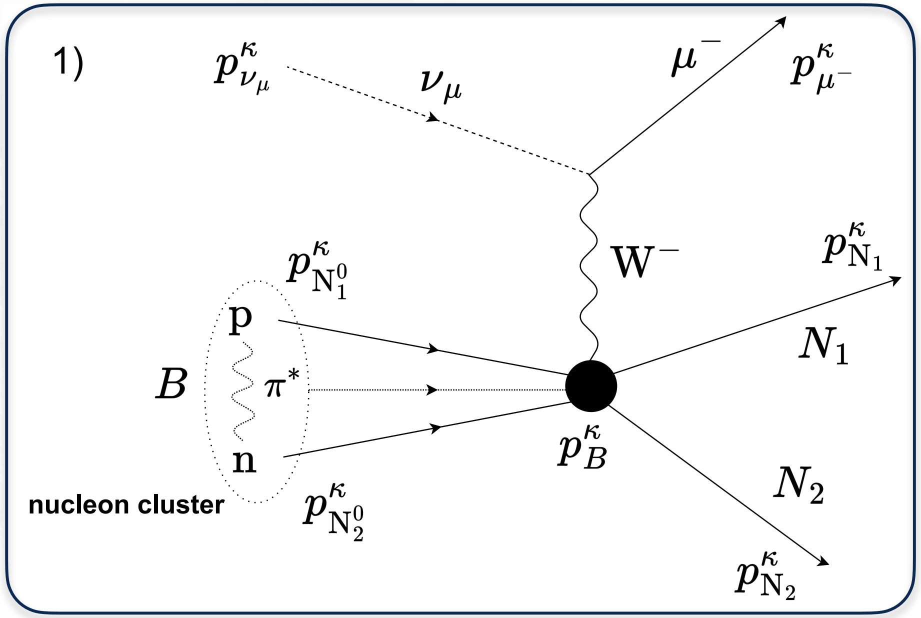
NuWro – Wrocław Neutrino Event Generator

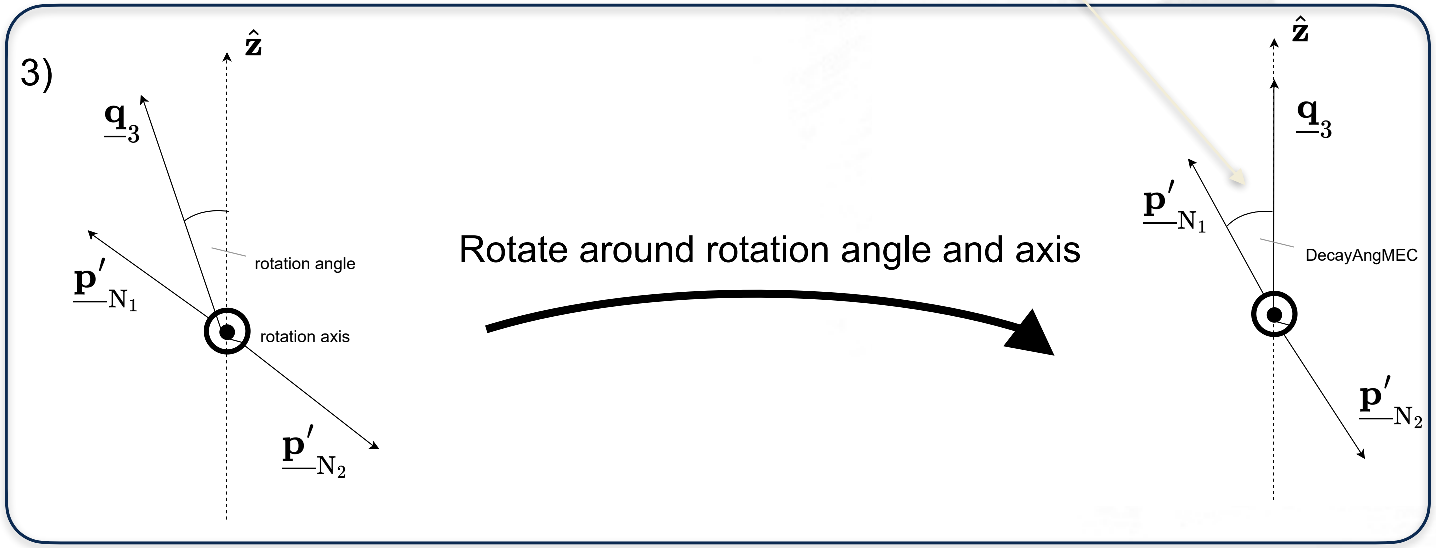
Genie – UNIVERSAL NEUTRINO GENERATOR & GLOBAL FIT

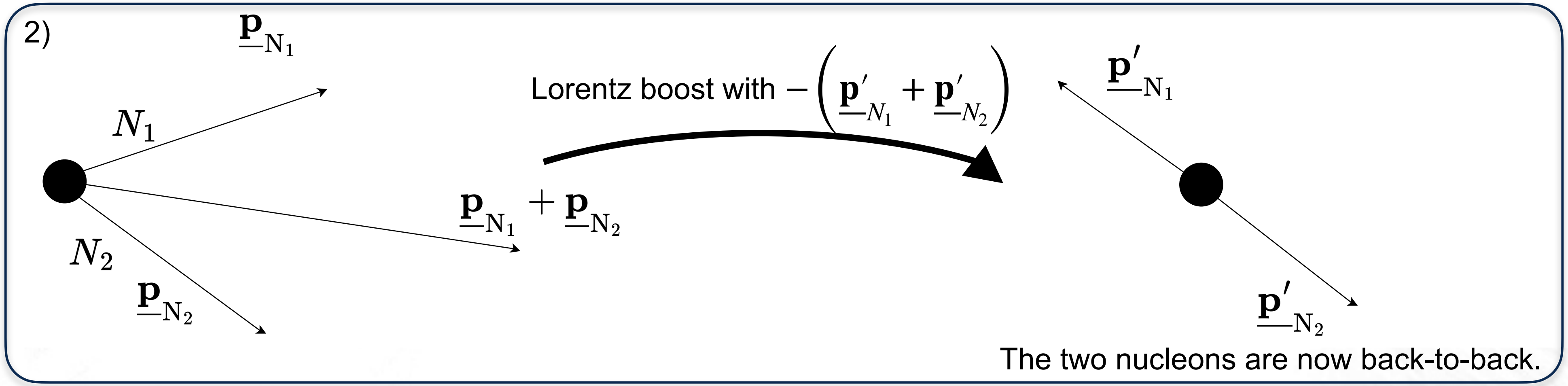
GiBUU – The Giessen Boltzmann-Uehling-Uhlenbeck Project

Nucleon Angular Distribution

DecayAngMEC - What is this angle?







DecayAngMEC is outgoing nucleon angle wrt to lepton 3-momentum transfer in 2-nucleon CM frame

Nucleon Angular Distribution

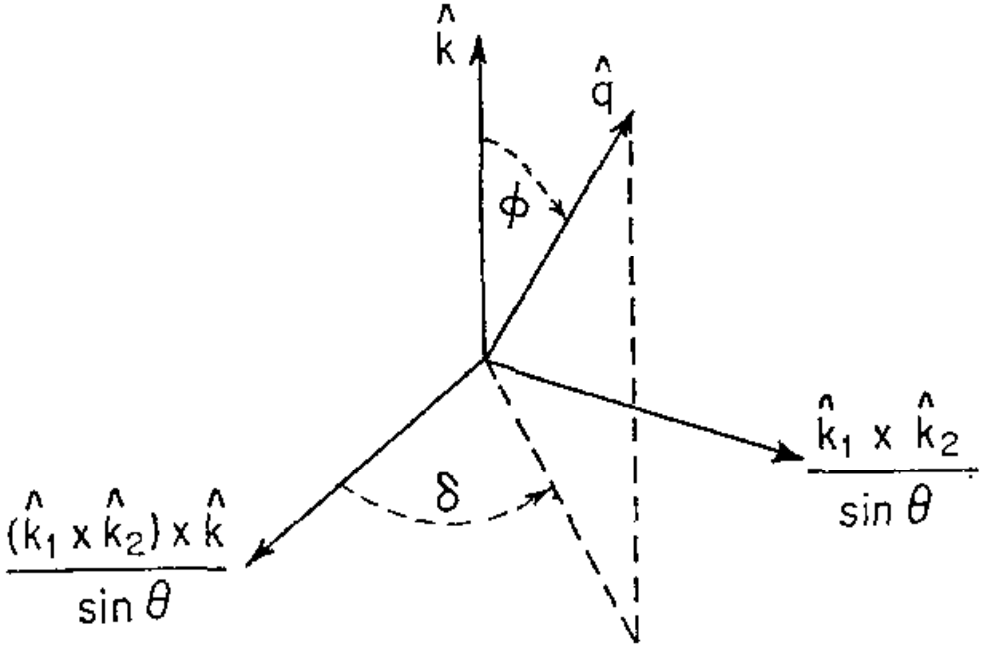


FIG. 2. Axes and angles which specify the final pion direction $\hat{q}$ in the isobaric frame. $\hat{k}$ is the direction of the momentum transfer between the leptons.

Figure taken from S. L. Adler: Photo-, Electro-, and Weak Single-Pion Production in the (3,3) Resonance Region published in 1968.

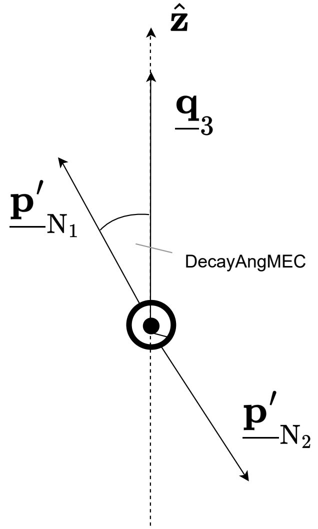
2p-2h Model Uncertainty Parameters

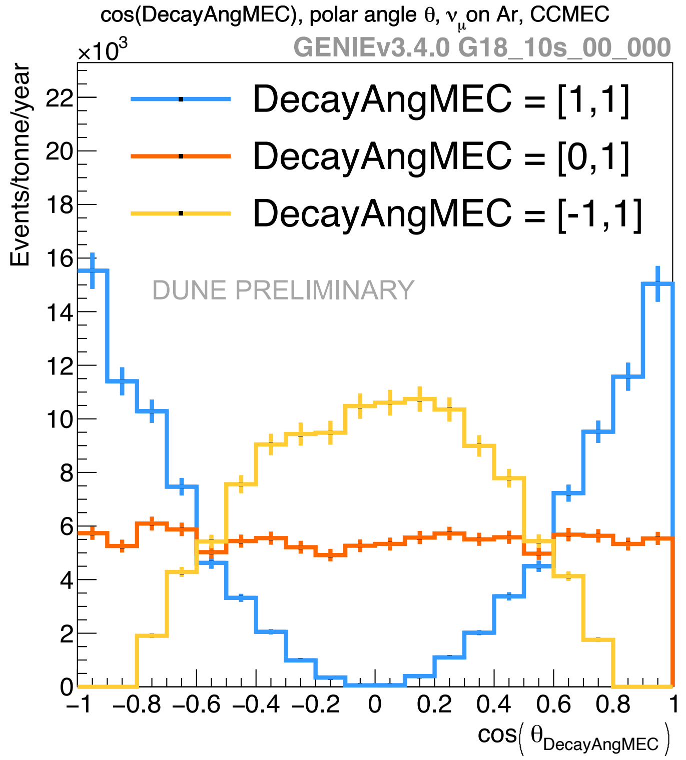
DecayAngMEC - changes angular dependence on struck nucleon pair

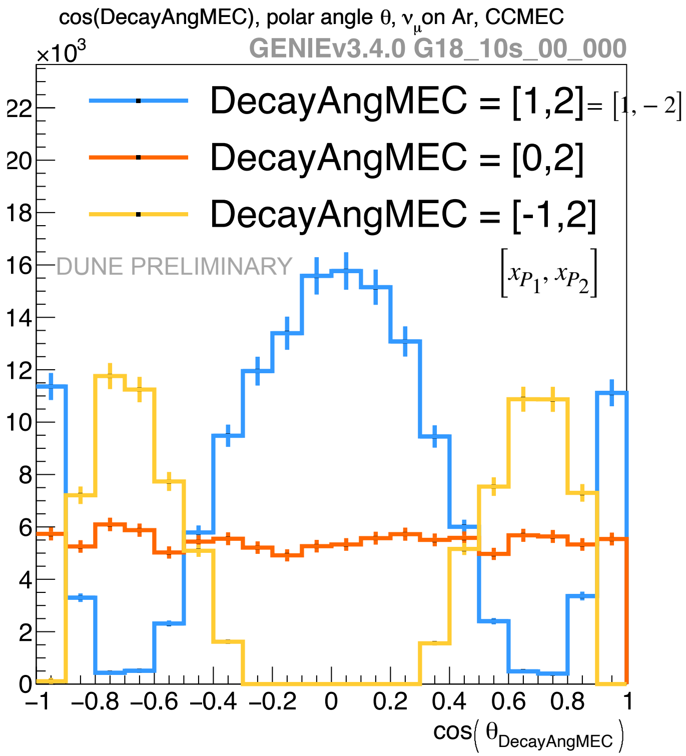
- Ad-hoc assumption on **angular distribution** of outgoing nucleons) away from isotropic distribution to a $\cos^2(\theta_{\text{DecayAngMEC}})$ dependence

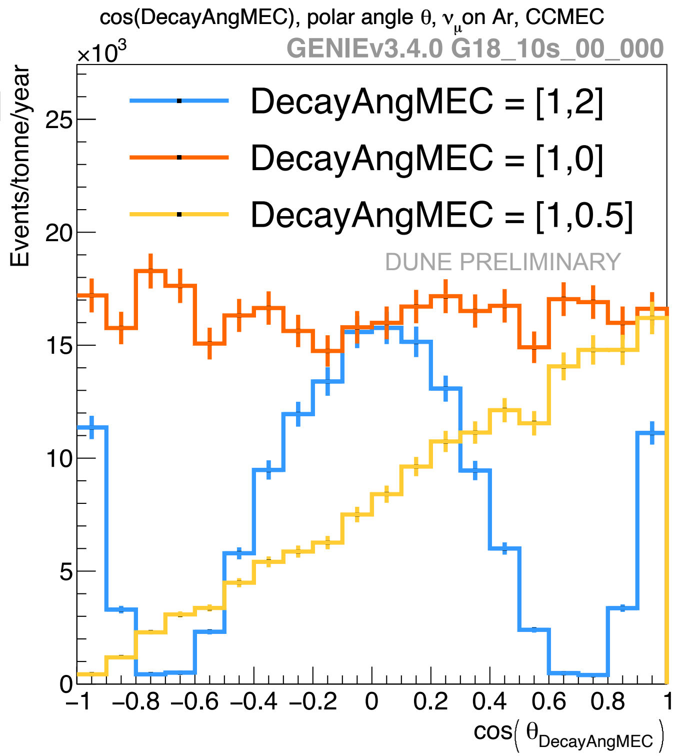
$$\text{weight} = 3 \cdot x_{P_1} \cdot \cos^2\left(x_{P_2} \cdot \theta_{N_1}\right) + 1 - x_{P_1}$$

twk_dial$_i = x_{P_i}$









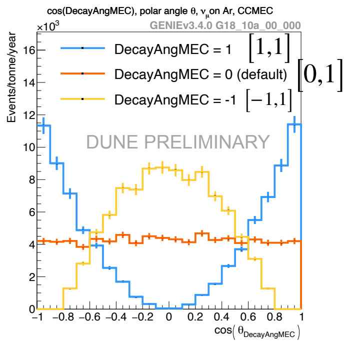
2p-2h Model Uncertainty Parameters

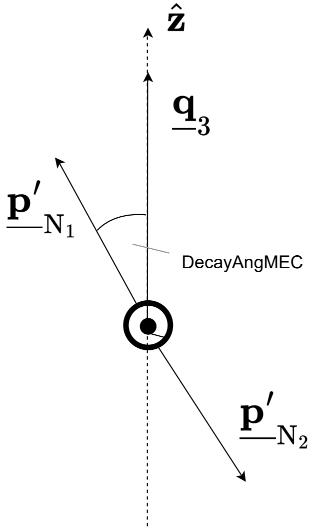
DecayAngMEC - changes angular dependence on struck nucleon pair

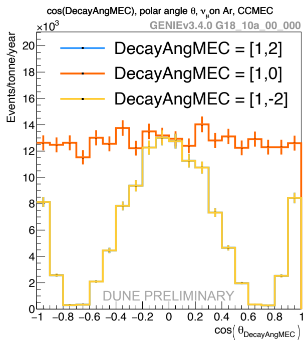
- Ad-hoc assumption on **angular distribution** of outgoing nucleons) away from isotropic distribution to a $\cos^2(\theta_{\text{DecayAngMEC}})$ dependence

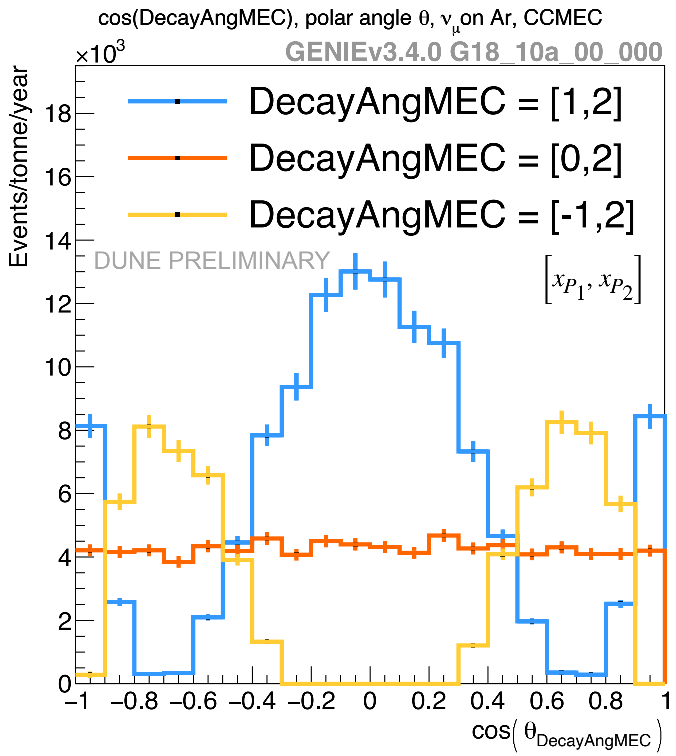
$$weight = 3 \cdot x_{P_1} \cdot \cos^2\left(x_{P_2} \cdot \theta_{N_1}\right) + 1 - x_{P_1}$$

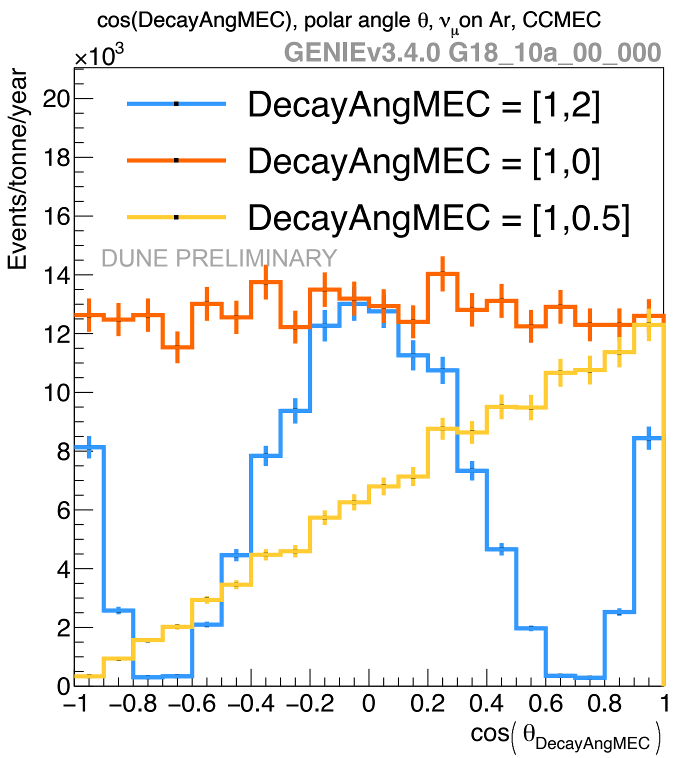
twk_dial$_i$ = x_{P_i}











Nucleon Angular Distribution

DecayAngMEC - changes angular dependence on struck nucleon pair

- **Angular distribution** of outgoing nucleons:

isotropic
(ad-hoc assumption)

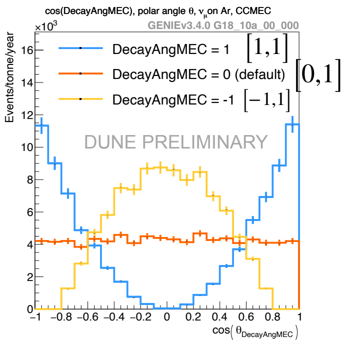
Other angular dependence
(Physics motivation?)

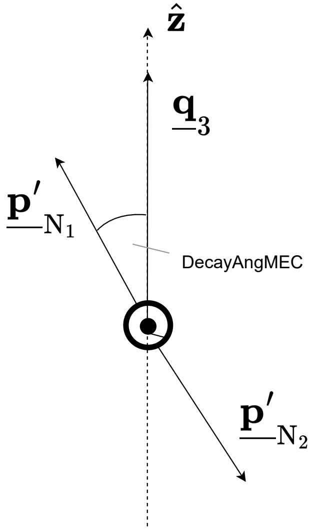
Valencia (G18_10a_00_000)

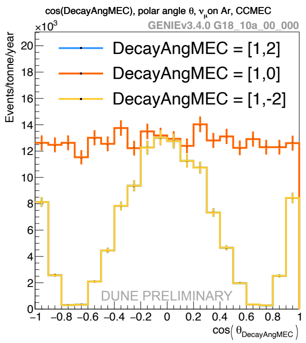
$$\text{weight} = 3 \cdot x_{P_1} \cdot \cos^2\left(x_{P_2} \cdot \theta_{\text{DecayAngMEC}}\right) + 1 - x_{P_1}$$

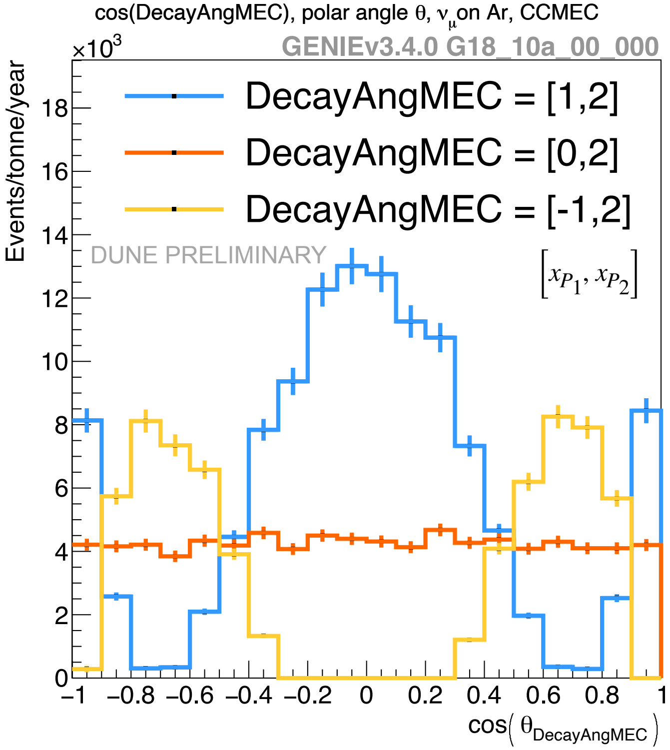
$x_{P_1} \in [-1,1]$

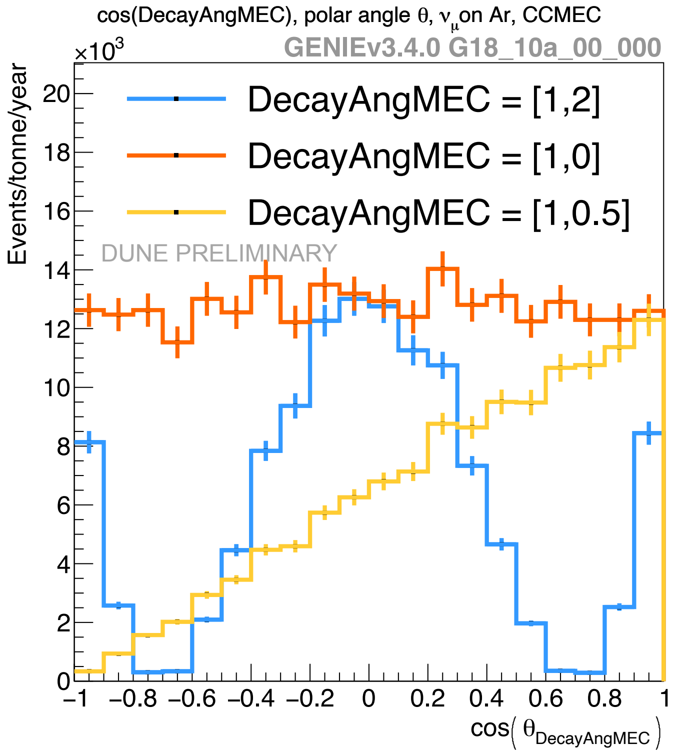
$x_{P_2} \geq 0$





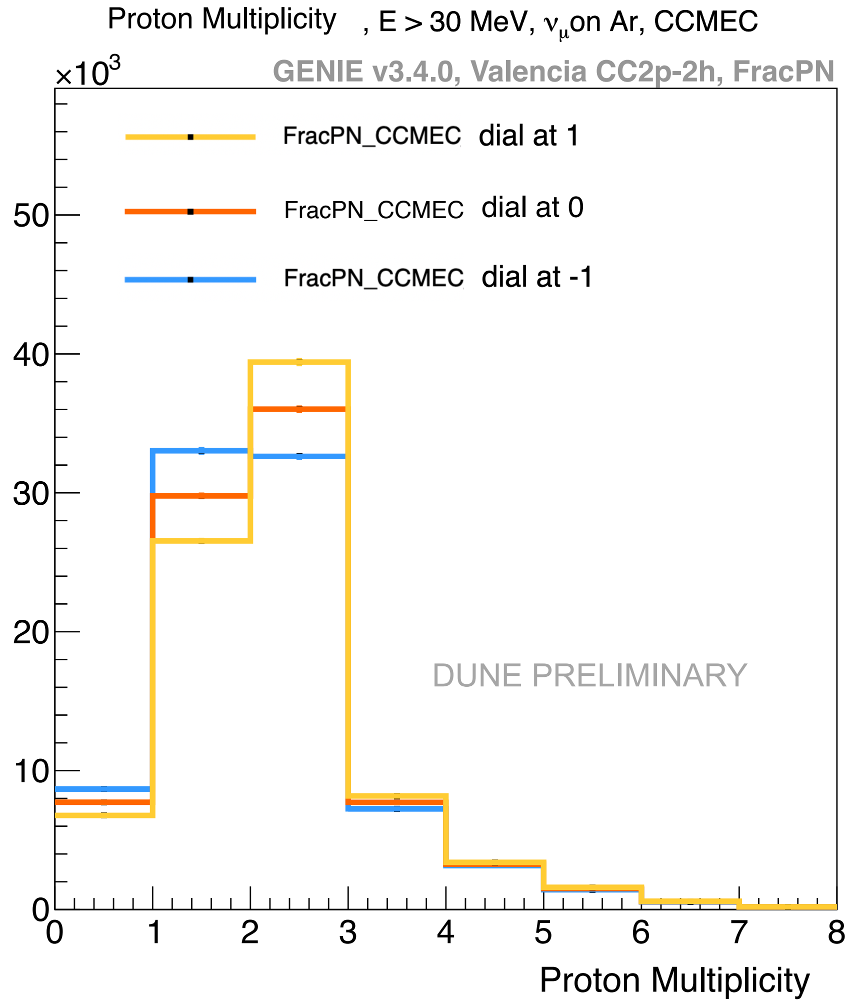


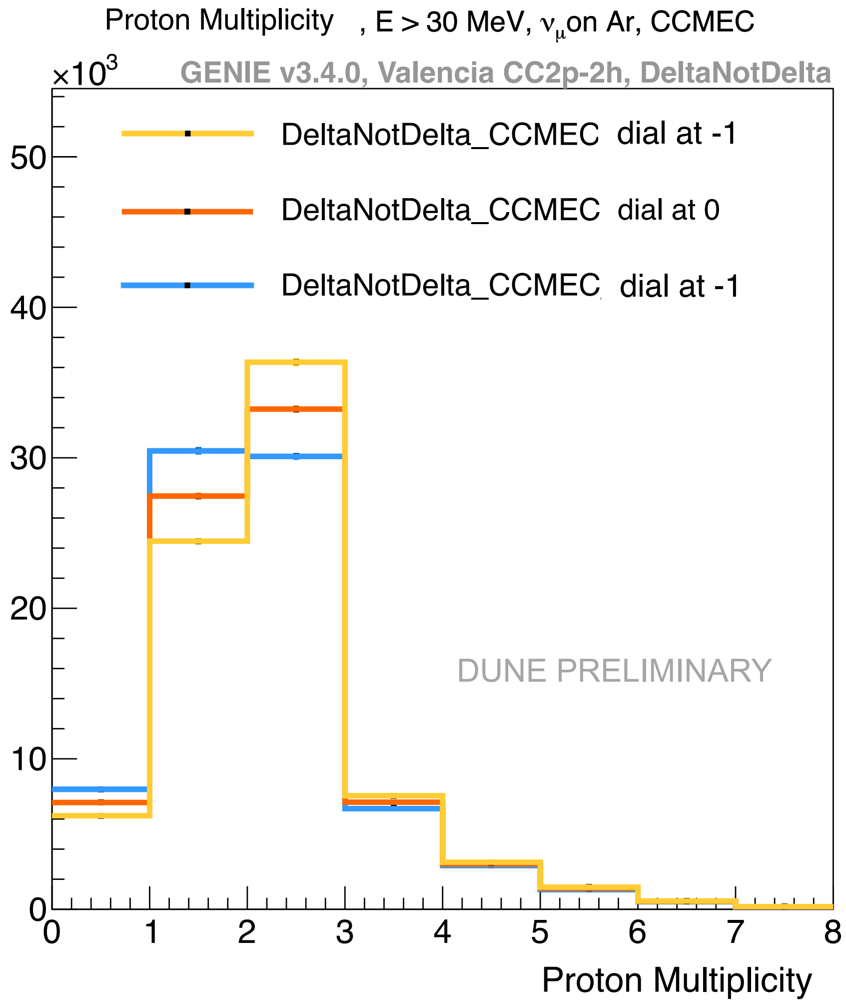




Delta Resonances

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

GENIE CC2p-2h Valencia Model Event Generation

- Generated 9950 events using each of the G18_10*_00_000 tunes
- Compared processing time
- Generation of events using the tune G18_10a_00_000 using *CC 2p-2h Valencia model* to simulate CC 2p-2h neutrino interactions on argon take *significantly longer* compared to the other tunes G18_10s_00_000 with the CC 2p-2h SuSAv2 or G18_10e_00_000 with the CC 2p-2h Empirical model implemented

G18_10a_00_000

```
Current Event Number: 9950
Approximate total processing time: 3243.64 s
Approximate processing time/event: 0.325961 s
```

Valencia

G18_10s_00_000

```
Current Event Number: 9950
Approximate total processing time: 47.34 s
Approximate processing time/event: 0.00475731 s
```

SuSAv2

G18_10e_00_000

```
Current Event Number: 9950
Approximate total processing time: 38.17 s
Approximate processing time/event: 0.0038358 s
```

Empirical

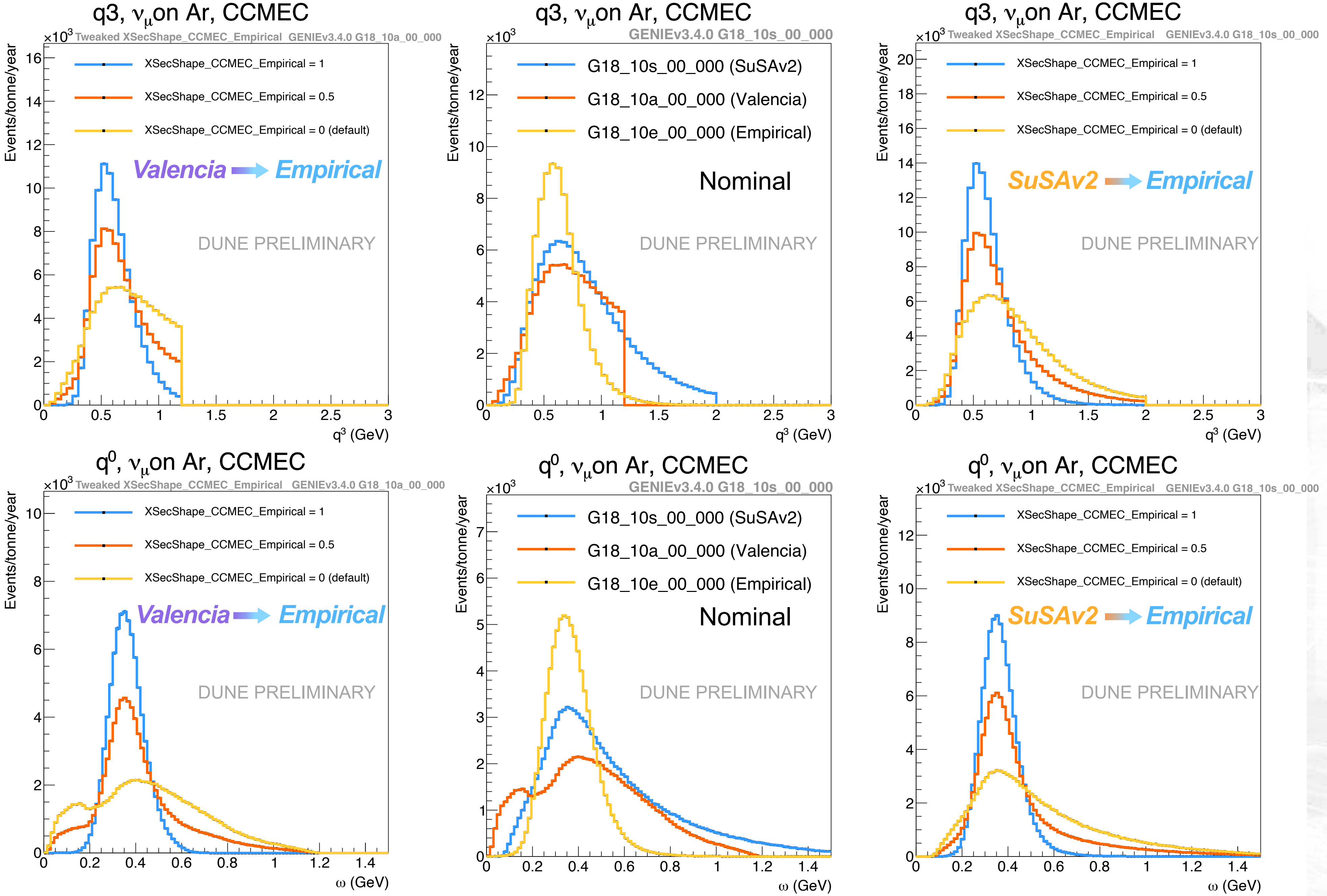
2p-2h Model Shape Differences

- *XSecShape_CCMEC_Empirical* parameter allows transition from (CC 2p-2h) Valencia or **SuSAv2** to the **Empirical** model

- Reweighted distributions *overshoot* the nominal distributions

q_3

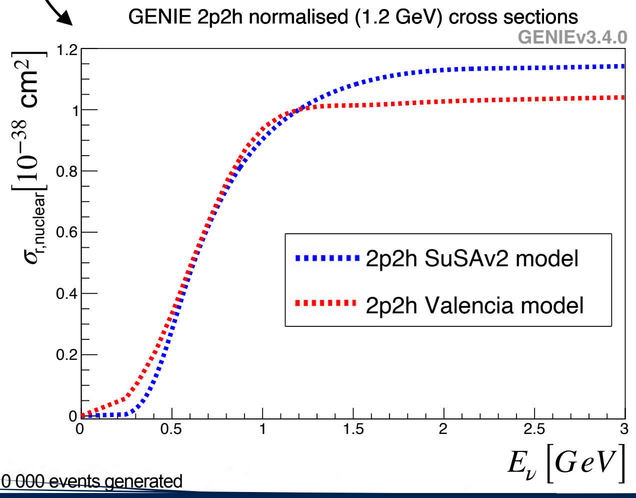
q_0

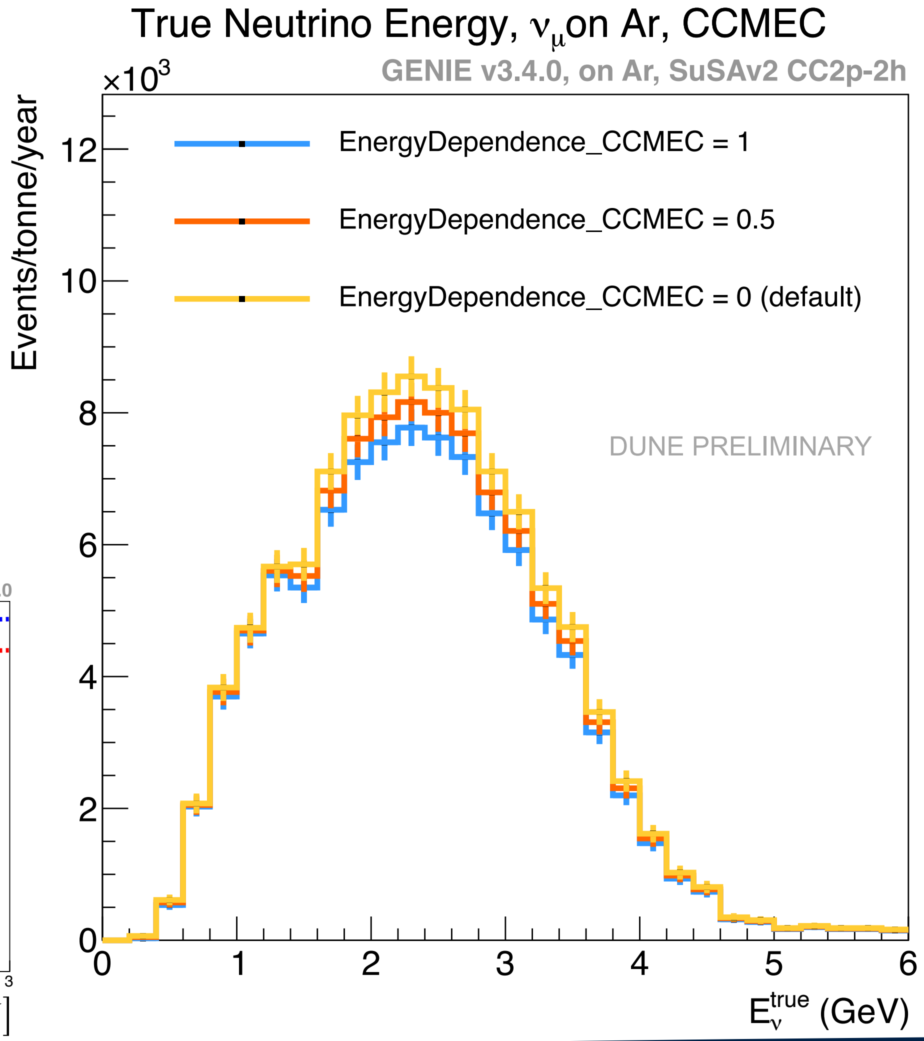


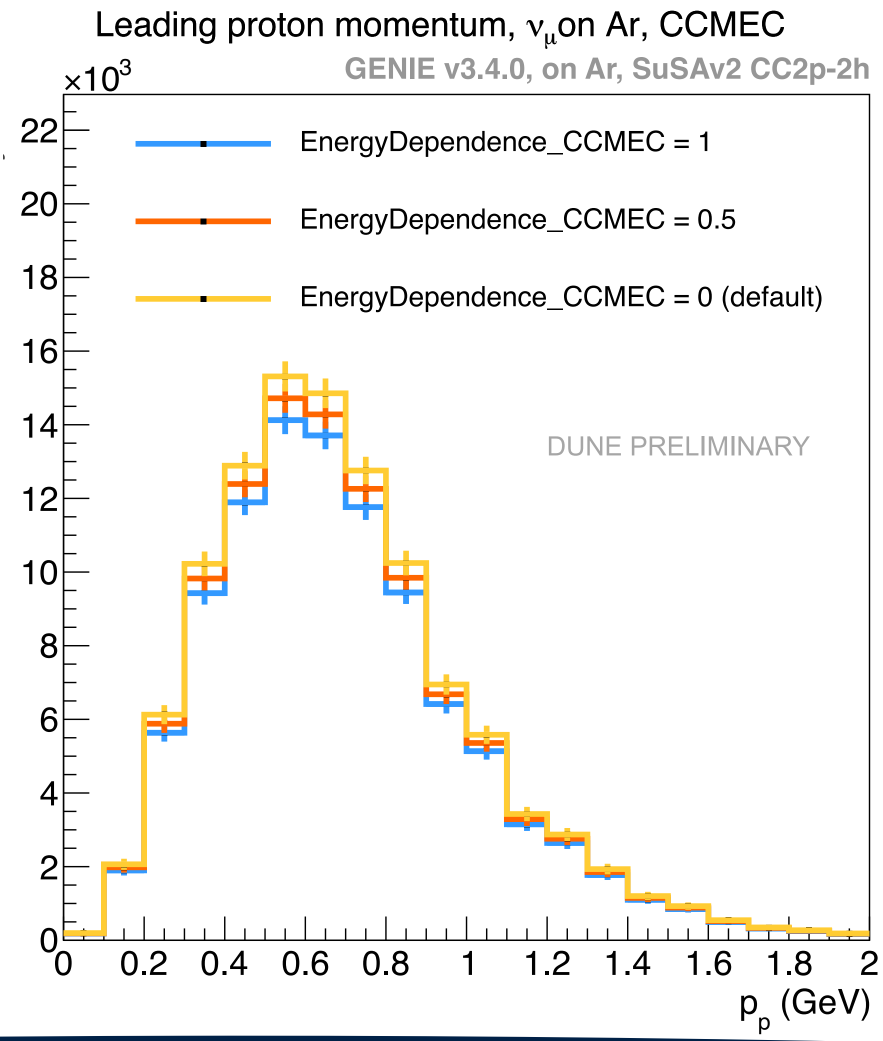
Energy Dependence

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

- Using the SuSAv2 and Valencia models
- Normalised cross-sections such that $\sigma\,(1.2\mathrm{GeV}) = 1$



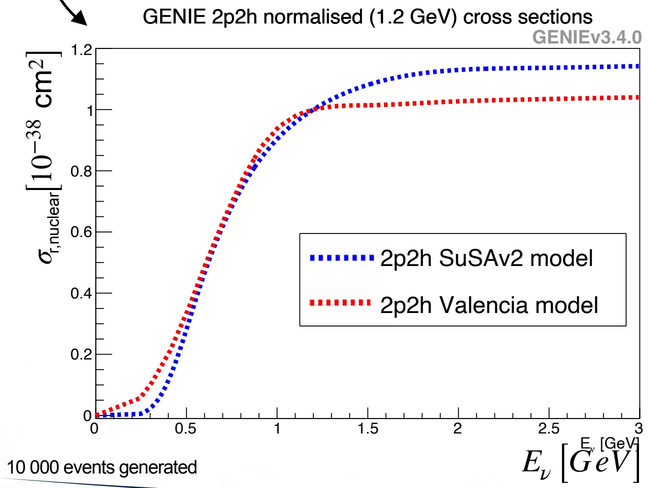


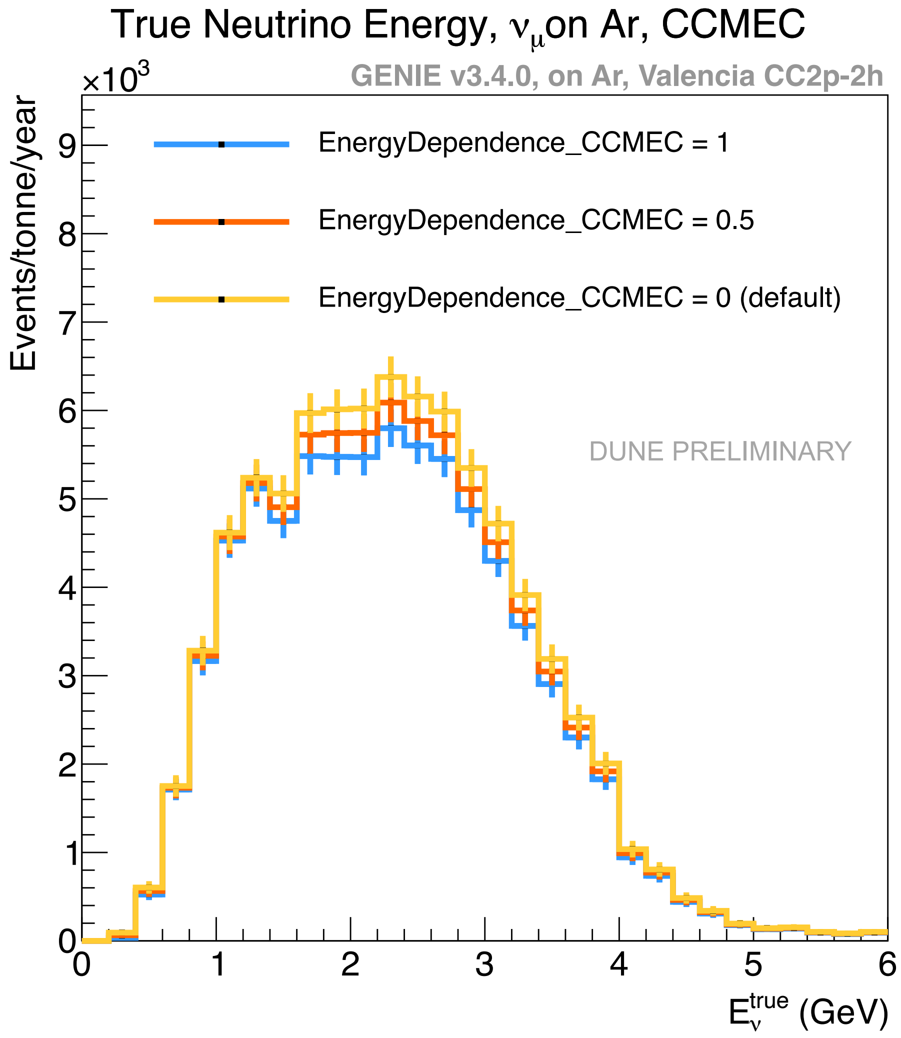


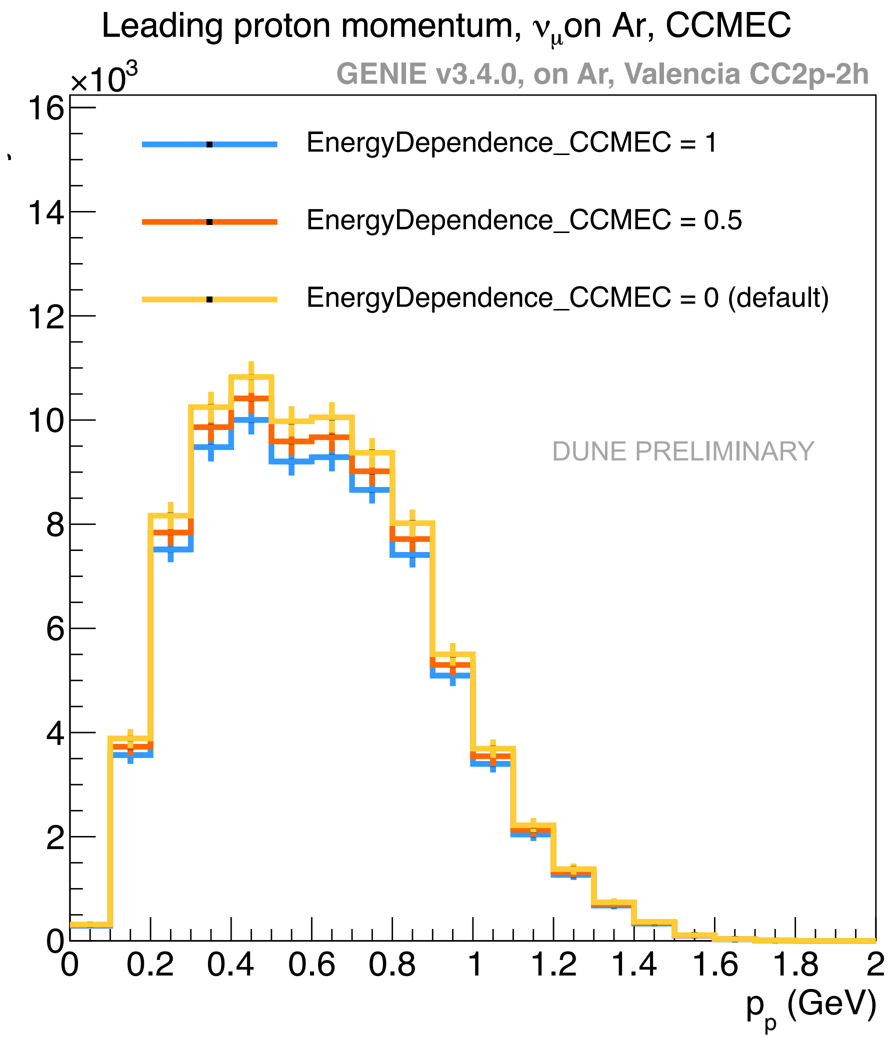
Energy Dependence

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

- Using the SuSAv2 and Valencia models
- Normalised cross-sections such that $\sigma\,(1.2\text{GeV}) = 1$





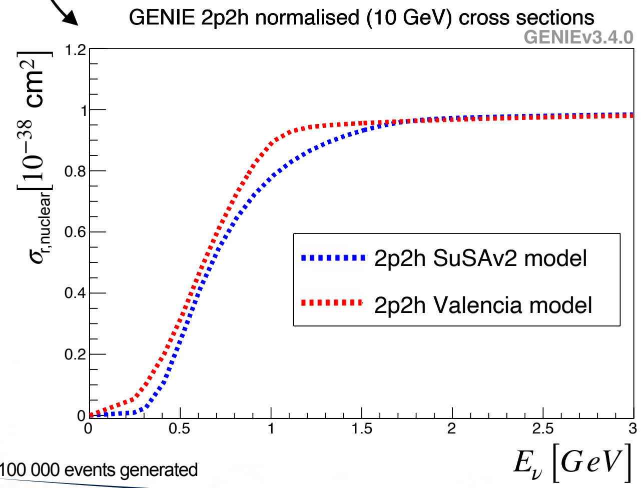


Energy Dependence

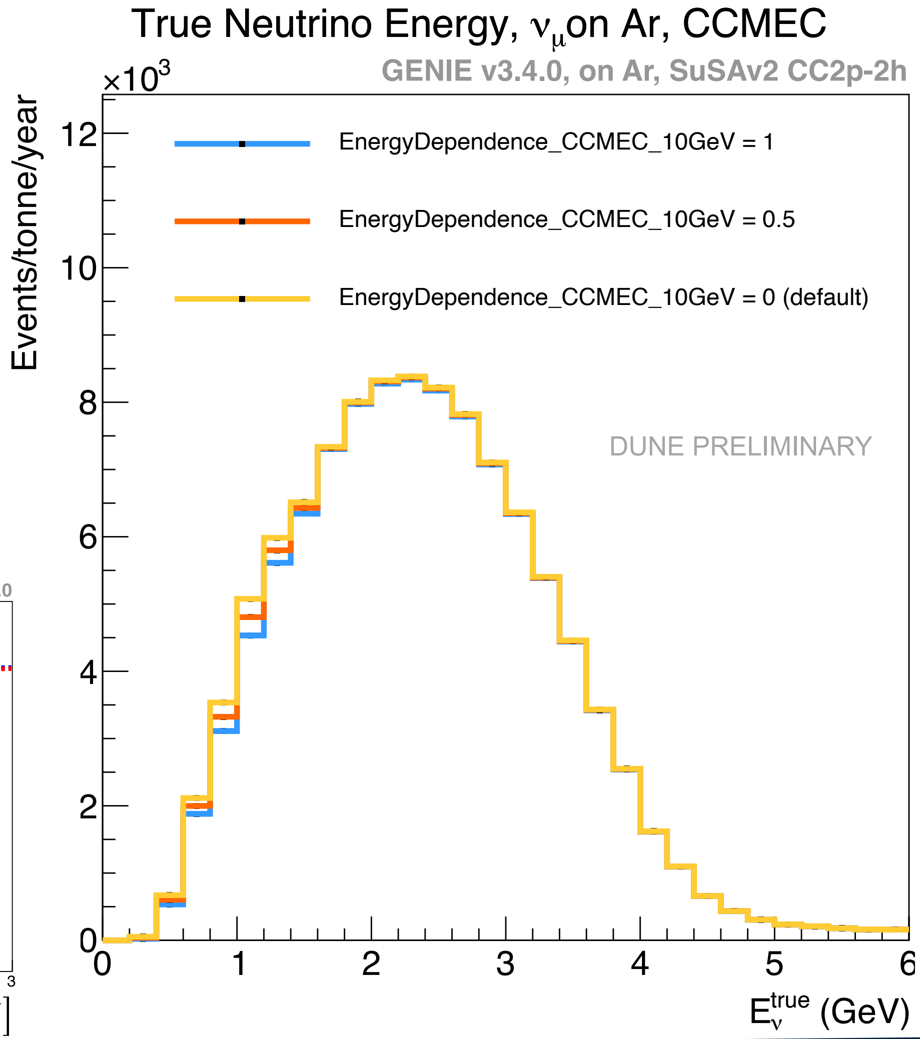
EnergyDependence_CCMEC - changes the energy dependence of 2p-2h cross sections

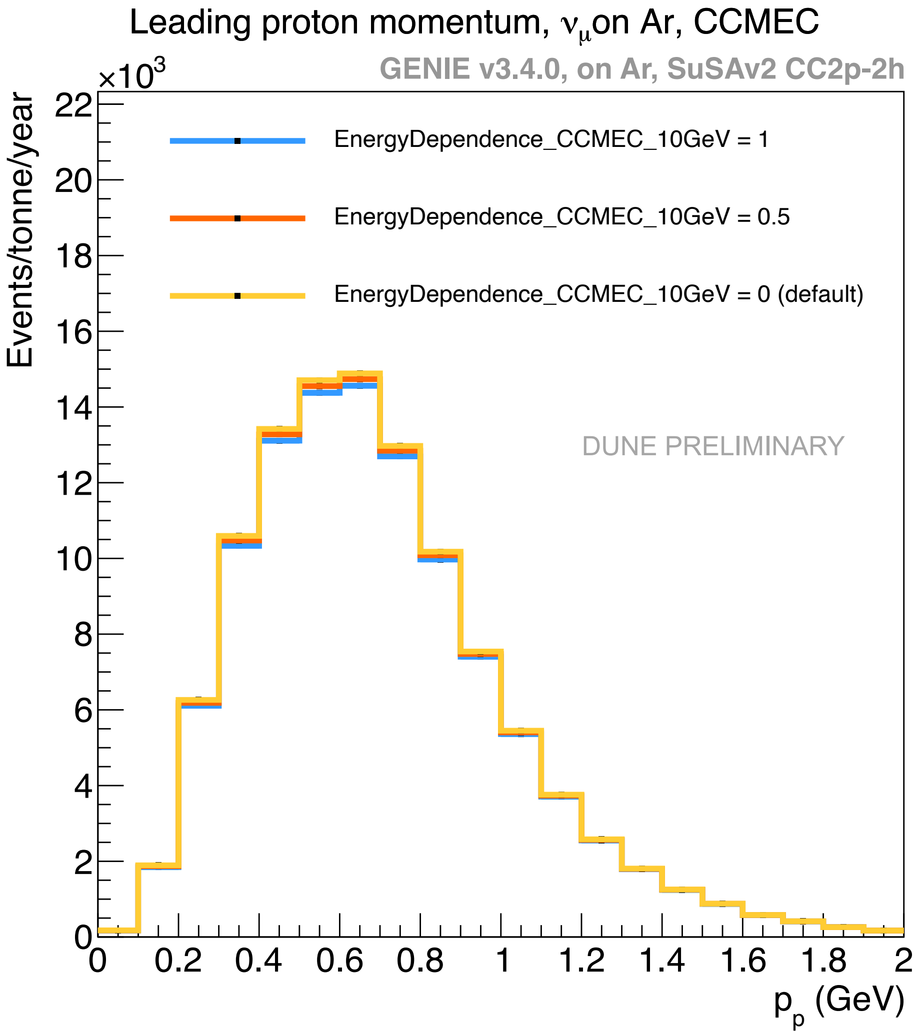
- Using the SuSAv2 and Valencia models
- Normalised cross-sections such that

$$\sigma(10\text{GeV}) = 1$$



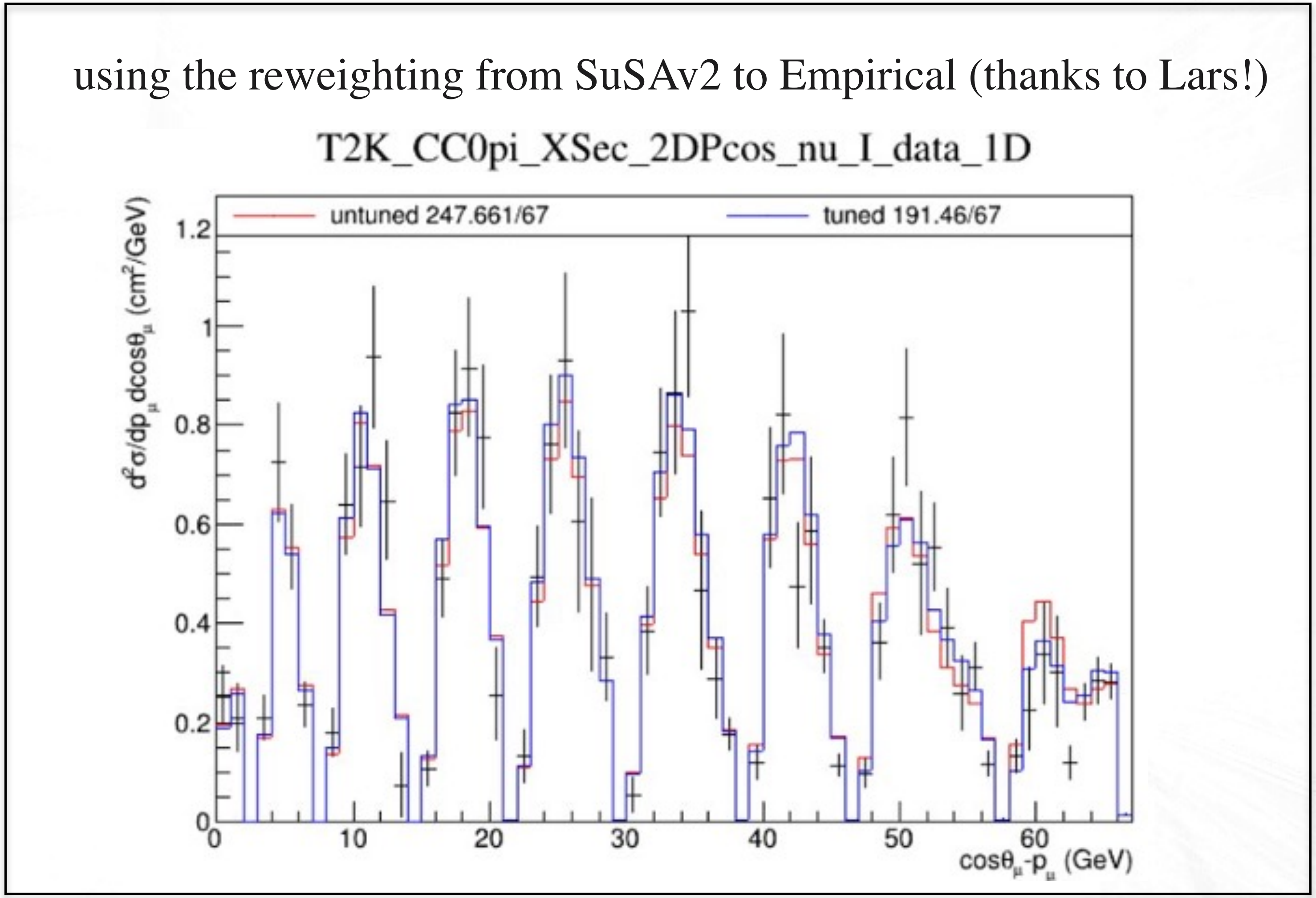
100 000 events generated





Tests and Validations

GENIEReweight XSecShapeCCMEC_Empicial parameter



Taken from: Goals of Tuning/Systematics Working Group slides and final presentation at PittPACC Neutrino Generator Workshop from 8th-11th July 2024.

2p-2h Model Uncertainty Parameters

MicroBooNE

TABLE VIII. Summary of parameters for which MicroBooNE analyses adopt a different central value and/or uncertainty than recommended in the GENIE v3.0.6 G18_10a_02_11a model set.

	"MicroBooNE Tune"		
Parameter	Central value	$+1\sigma$	-1σ
NormCCMEC	166%	+50%	-50%
XSecShape_CCMEC	Empirical[c]	N/A	Valencia[d]
DecayAngMEC	Isotropic	Alternative[e]	N/A
FracPN_CCMEC	Valencia	+20%	-20%
FracDelta_CCMEC	Valencia	+30%	-30%

[c] Nominal prediction of the GENIE Empirical CC 2p2h model
[d] Nominal prediction of the Valencia CC 2p2h model
[e] An angular distribution proportional to $\cos^2\theta$. See the description of this parameter in Sec. V A

Reference: Phys. Rev. D **105**, 072001

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.