The Impact of Neutrino Interaction Uncertainties on MicroBooNE and SBN Physics Measurements

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On behalf of the MicroBooNE Collaboration

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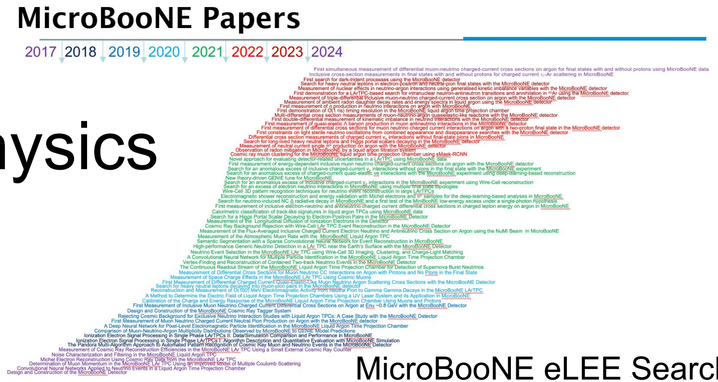
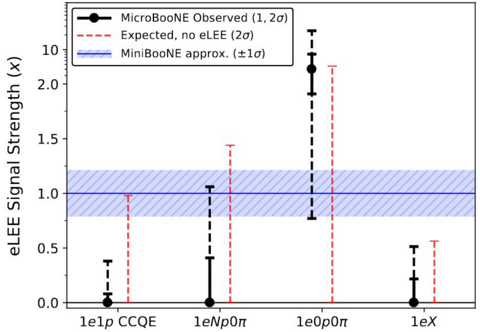
It’s an Exciting Time for Neutrino Physics

- MicroBooNE is a well established experiment with 65 published papers since 2017
  - Produced e-like and γ-like low energy excess searches
  - Cross section measurements on a diverse range of interactions and in multiple dimensions

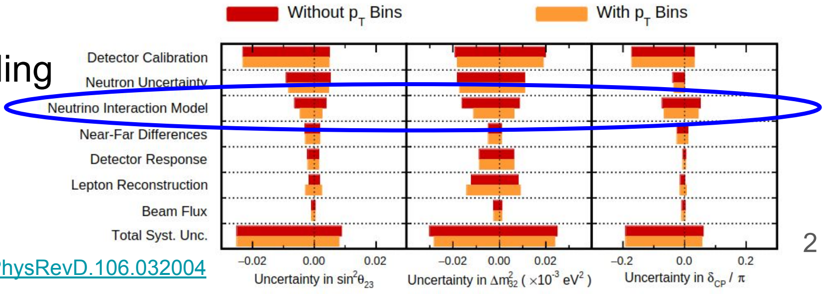
- SBN is ramping up to provide a 2-detector oscillation search and even higher statistics
  - DUNE is on the horizon with even more precise requirements
  - Neutrino interaction modeling is a potential leading source of uncertainty



MicroBooNE eLEE Search



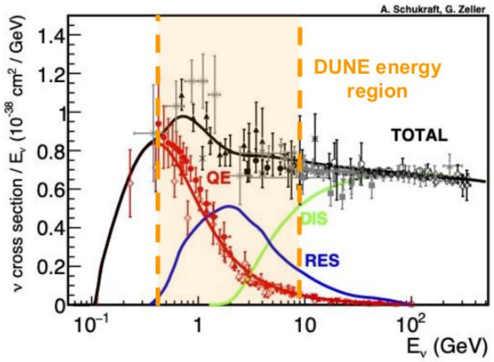
NOvA Uncertainties Breakdown



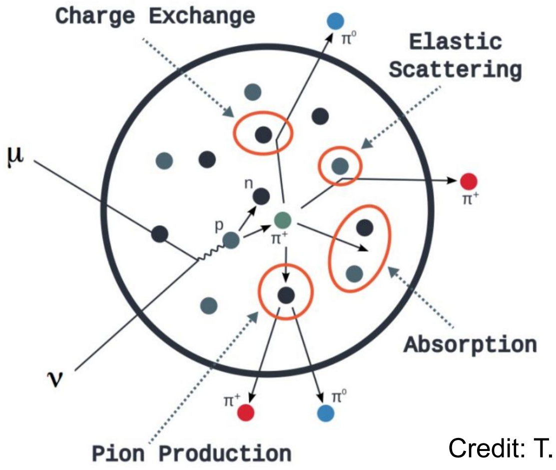
PhysRevD.106.032004

Challenges in Neutrino Interaction Modeling

RevModPhys.84.1307



- Wide range of energies
  - Spans QE, RES, DIS
- Range of nuclear targets across experiments
  - Hydrogen, Deuterium, Carbon, Argon, Iron, Lead
- Complex QCD physics inside nucleus
  - Nuclear initial state
  - Nucleon-nucleon correlations
  - Final state interactions



Credit: T. Golan

Cross Section Modeling with GENIE

- GENIE is the primary ν interaction event generator for Fermilab experiments
  - Development is huge effort, tons of knobs
  - Lots of approx/estimates - room for improvement
- GENIE v3 is the latest major release
  - Genie v2 is also in use by other experiments
  - Many configurations possible within Genie v3. Details in [Eur. Phys. J. Spec. Top. 230, 4449–4467 (2021)]
- MicroBooNE uses GENIE v3.0.6 G18_10a_02_11a
  - MicroBooNE tune discussed later
  - MicroBooNE was the first experiment to adopt GENIE v3

UNIVERSAL NEUTRINO GENERATOR & GLOBAL FIT

Historical: RFG, Llewellyn Smith CCQE, Rein-Sehgal RES, hA FSI

LFG, Valencia CCQE, Berger-Sehgal improved RES modeling

SuSAv2 CCQE, hN FSI

TABLE IX. GENIE model parameters used with default settings in the "MicroBooNE tune."

Parameter	Central value	$+1\sigma$	-1σ
CCQE form factor parametrization			
AxFFCCQEshape	Dipole	Z expansion	N/A
VecFFCCQEshape	BBA07	Dipole	N/A
NC elastic form factors			
MaNCEL	0.961242 GeV	+25%	−25%
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Bodek-Yang structure functions			
AhtBY	0.538 GeV^2	+25%	−25%
BhtBY	0.305 GeV^2	+25%	−25%
CV1uBY	0.291 GeV^2	+30%	−30%
CV2uBY	0.189 GeV^2	+40%	−40%
Final-state interactions			
MFP_pi	hA2018	+20%	−20%
MFP_N	hA2018	+20%	−20%
FrCEx_pi	hA2018	+50%	−50%
FrInel_pi	hA2018	+40%	−40%
FrAbs_pi	hA2018	+30%	−30%
FrPiProd_pi	hA2018	+20%	−20%
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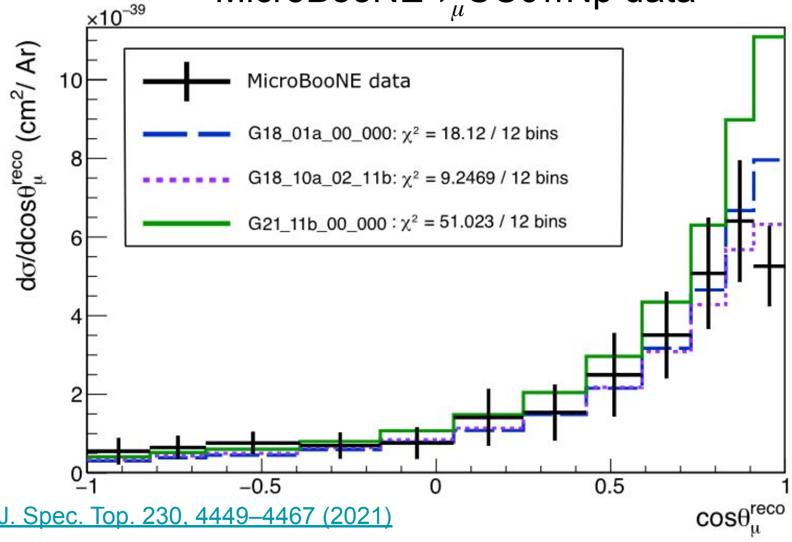
FrAbs_N	hA2018	+20%	−20%
FrPiProd_N	hA2018	+20%	−20%

See Steven Gardiner's talk for new results!

MicroBooNE ν_μ CC0πNp data



[Eur. Phys. J. Spec. Top. 230, 4449–4467 (2021)]

Underlined version is used in MicroBooNE model

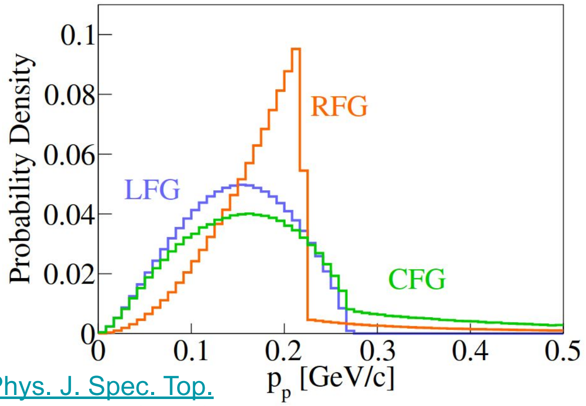
Modeling the Nuclear Initial State

- Historical model: Relativistic Fermi Gas (RFG)
  - Non-interacting nucleons with momentum up to Fermi momentum k_F
  - Non-zero momentum tail above k_F to account for short-range nucleon-nucleon correlations

- Local Fermi Gas (LFG) model
  - k_F is a function of radius, derived from nucleon density distribution
  - Underpins Valencia CCQE and CCMEC modeling with shared use of density distribution

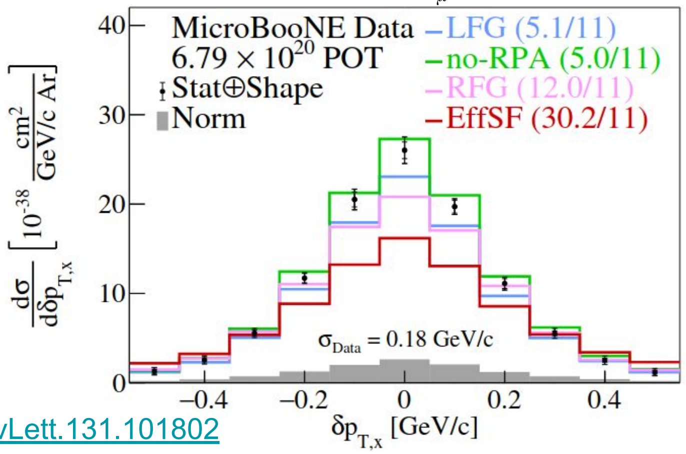
- Correlated Fermi Gas (CFG) model
  - Re-introduces non-zero momentum tail above k_F
  - Included in GENIE 3.2

Nuclear Initial State Modeling In GENIE



Eur. Phys. J. Spec. Top. 230, 4449–4467 (2021)

Impact of Initial State Modeling in MicroBooNE ν_μCC 1p0π



PhysRevLett.131.101802

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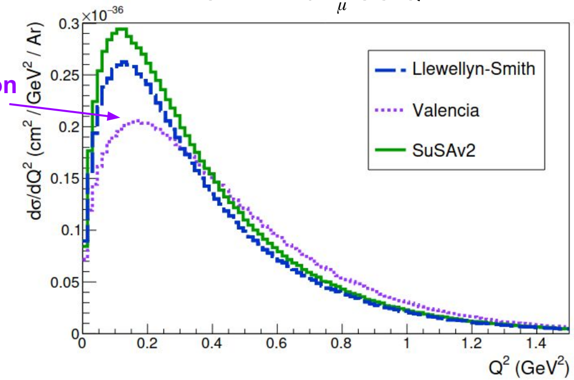
Modeling of Charged Current Quasi-Elastic (CCQE) and Meson-Exchange Current (CCMEC) interactions

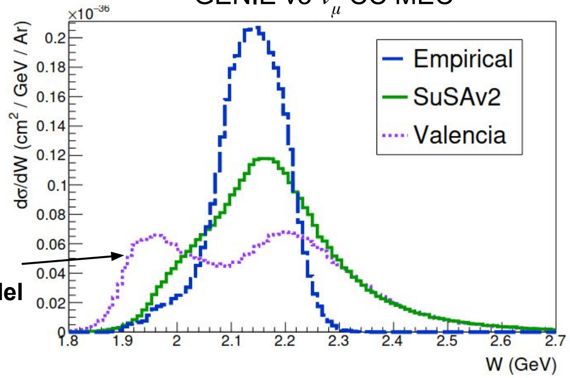
Predictions for MicroBooNE flux on argon target
Eur. Phys. J. Spec. Top. 230, 4449–4467 (2021)

- Historical model: Llewellyn-Smith
  - Free nucleon model with corrections for Pauli blocking and binding energy
  - Accurate at higher energies (>2 GeV)
- Valencia model for CCQE and CCMEC interactions
  - **RPA corrections** for long range correlations
  - Corrections for Coulomb interactions of outgoing lepton
- SuperScaling Approach (SuSAv2) model
  - RFG model predicts lepton cross section scales ~ $\psi(q,\omega)$
  - SuSAv2 combines scaling in (e,e') data longitudinal channel with RMF prediction of significant transverse channel scaling

RPA suppression at low Q2



Significant model differences, bimodal structure in Valencia model

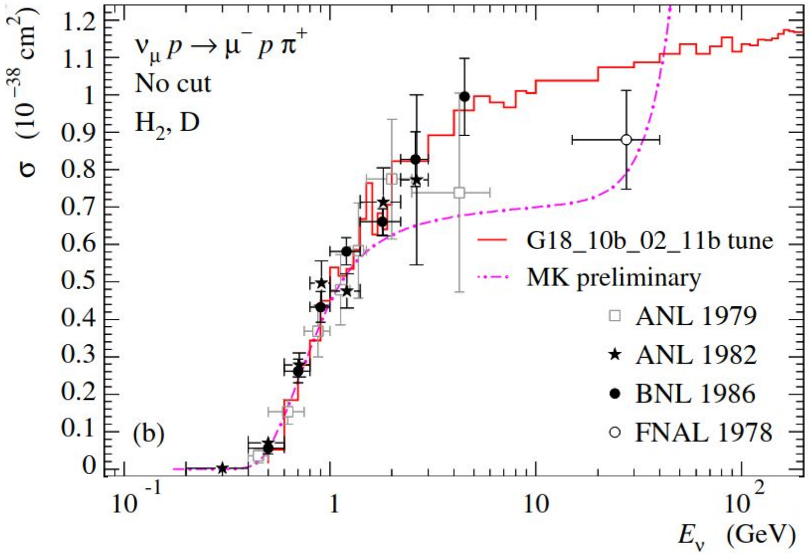


<u>Underlined</u> version is used in MicroBooNE model

Modeling of Δ-Resonance (RES) Interactions

- Historical model: Rein-Sehgal
  - Dipole expansion of axial form factor with axial-vector mass M_A^{RES} = 1.12 GeV
- <u>Berger-Sehgal model</u>
  - Includes modeling improvements of nonzero lepton mass, lepton polarization, pion pole contribution
- To first-order, bubble chamber data gives good constraints
  - Small A means fewer FSI effects
  - Multi-dimensional phase space

Bubble Chamber π^+ Cross Section Data for H_2, D

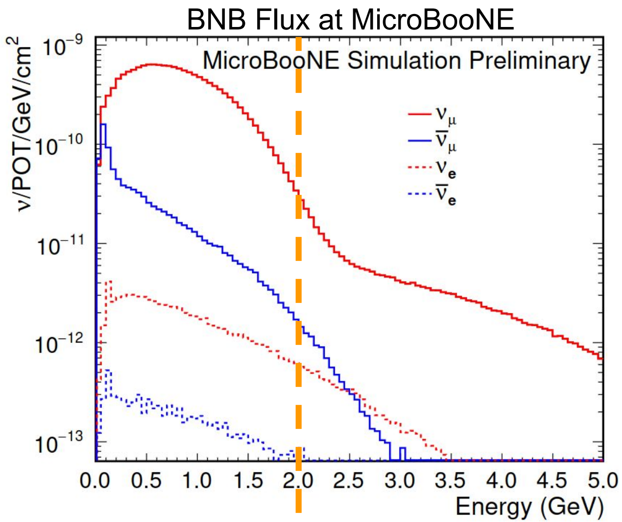


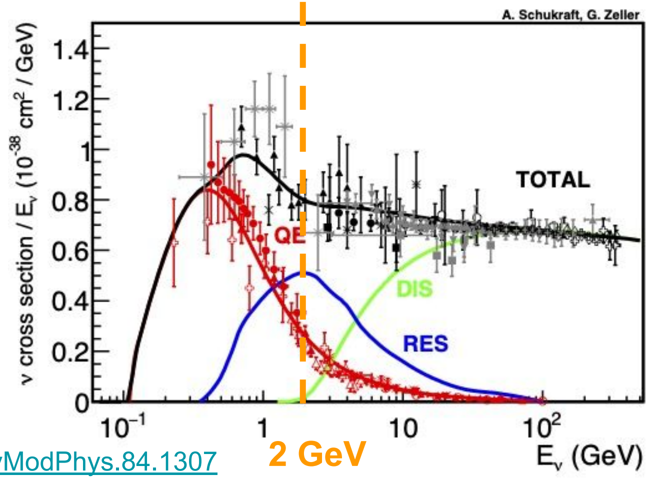
Eur. Phys. J. Spec. Top. 230, 4449–4467 (2021)

Modeling of Deep Inelastic Scattering (DIS) Interactions

- Significant for DUNE, not as much MicroBooNE / SBN
- Bodek-Yang model for CCDIS interactions
- GENIE default has large uncertainties on non-RES π (50%) and DIS (25-40%) parameters

MicroBooNE Public Note 1031





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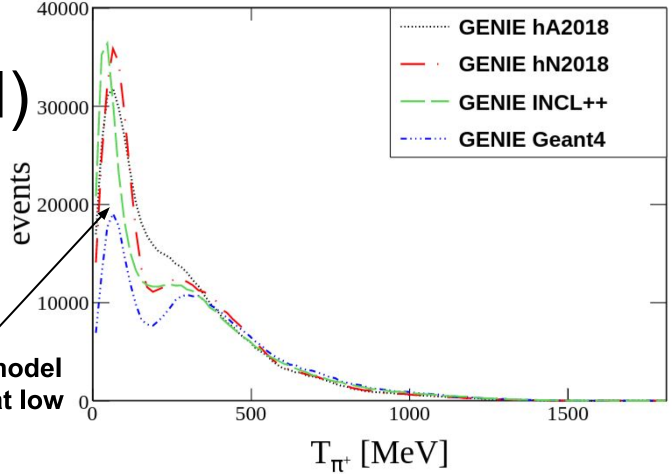
<u>Underlined</u> version is used in MicroBooNE model

Modeling of Final State Interactions (FSI)

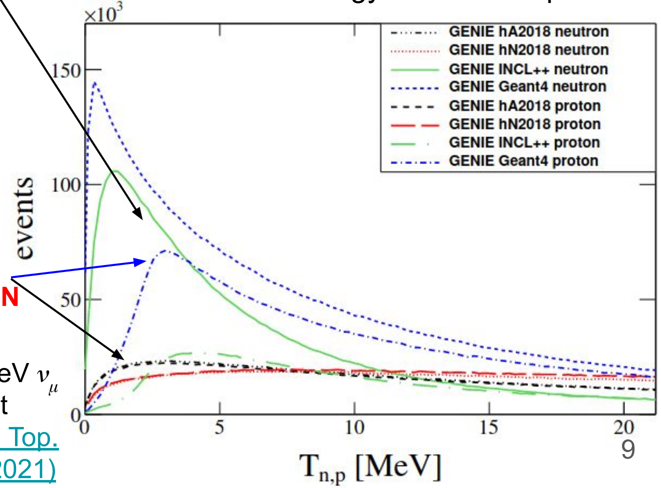
- FSI models final state particles exiting nucleus
  - Processes include charge exchange, absorption, hadron knockout
  - More important for larger nuclei such as ^{40}Ar
- **<u>MicroBooNE FSI modeled with hA approximation</u>**
  - Approximates cascade of interactions with total cross sections
  - Data-driven, gives good agreement
- GENIE v3.0 also contains hN intranuclear cascade model
  - Models multiple interactions in nuclear cascade
  - Similar to implementations in NuWro and NEUT

GENIE v3 Inclusive π^+ KE



Significant model differences at low energy

GENIE v3 Low-Energy Hadron Responses



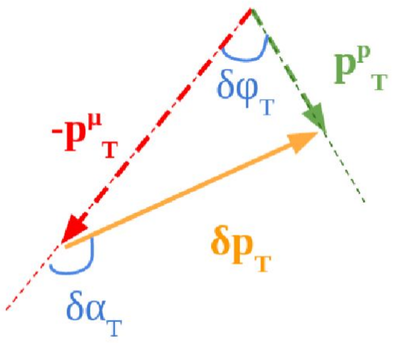
Proton suppression from Coulomb effects shown in **INCL**, **Geant4**, but not **hA**, **hN**

Predictions for 2 GeV ν_μ on argon target

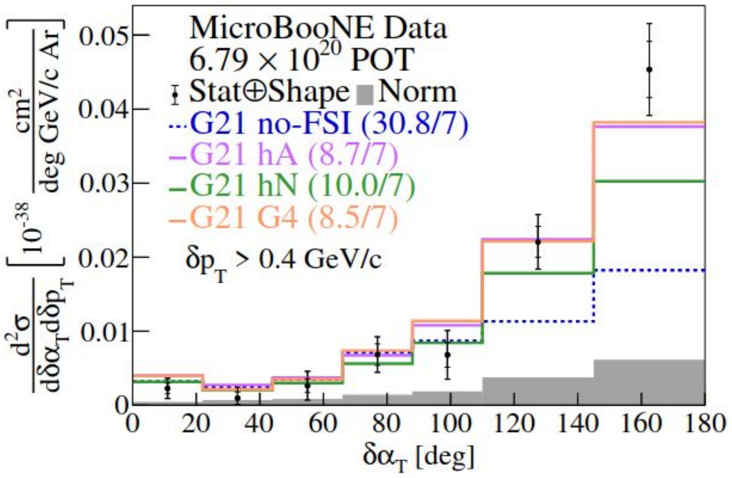
[Eur. Phys. J. Spec. Top. 230, 4449–4467 (2021)]

Modeling of Final State Interactions (FSI)

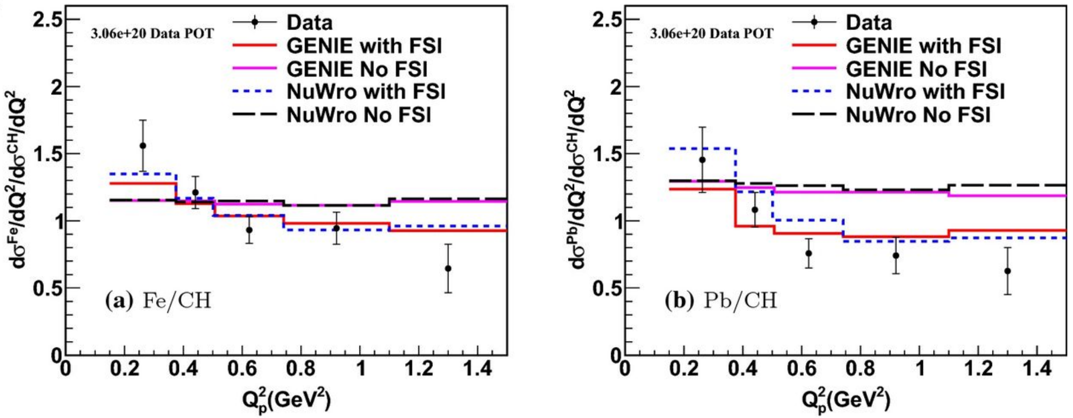
- Impact of FSI is well demonstrated in published measurements
  - FSI sensitivity varies greatly with interaction channel and across phase space
  - Large impact at high δp_T
  - FSI impact increases with nuclear size A



Impact of FSI in MicroBooNE ν_μCC 1p0π
PhysRevLett.131.101802



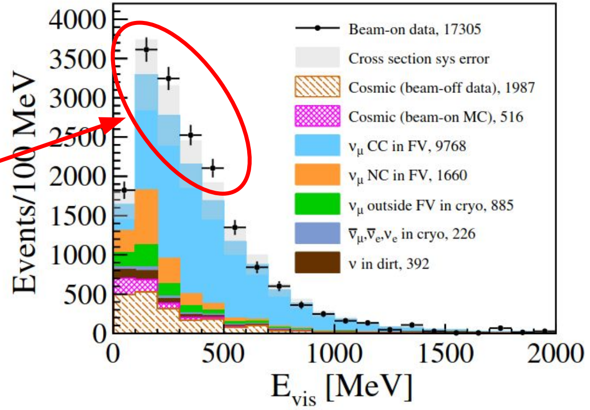
Impact of FSI in MINERνA (*Eur. Phys. J. Spec. Top.* **230**, 4243–4257)



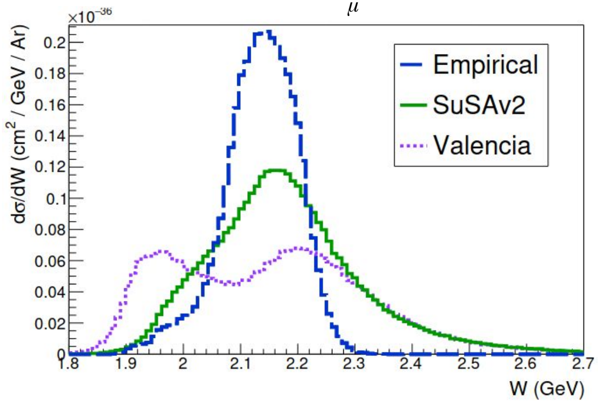
MicroBooNE tune of GENIE v3

- Out-of-box GENIE v3.0.6 G18_10a_02_11a under-predicted data
  - Particularly prevalent at low energy (<600 MeV)
- Tuned to T2K CC0π data (CH target)
  - Independent detector and beam
  - CCQE physics at a similar energy range
- Tuned 2 CCQE and 2 CCMEC parameters
  - Reflect known uncertainties in models of CC0π cross sections
  - Cannot easily be constrained by electron scattering data
  - Can be constrained by T2K data

Genie v3 Untuned vs MicroBooNE Data



GENIE v3 ν_μ CC MEC

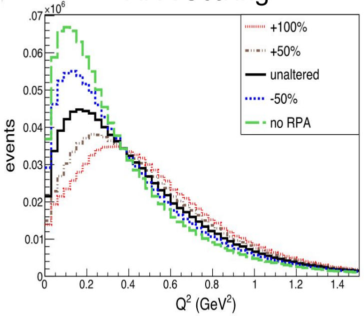


PhysRevD.105.072001

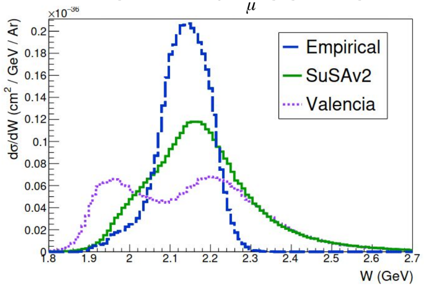
MicroBooNE tune of GENIE v3

- CCQE tuned parameters
  - CCQE M_A - low nominal value of ~0.96 GeV contributes to underpredicting data
  - RPA strength - implemented by interpolating between Valencia model and no RPA correction
- CCMEC tuned parameters
  - CCMEC normalization - proportionally scales CCMEC contribution
  - CCMEC shape - implemented by interpolating between Valencia model and GENIE empirical model

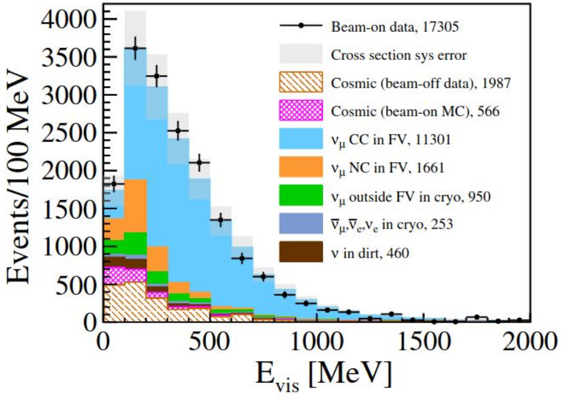
RPA Scaling



GENIE v3 ν_μ CC MEC



Genie v3 Tuned vs MicroBooNE Data



Fitted Parameters

	CCQE M_A	RPA Strength	CCMEC Norm	CCMEC Shape
Nominal	**0.961242 GeV**	**1**	**1**	**0 (Valencia)**
Fitted	**1.1 ± 0.1 GeV**	**0.85 ± 0.4**	**1.66 ± 0.50**	**1 (Empirical) $^{+0}_{-1}$**

All Non-Default Parameters

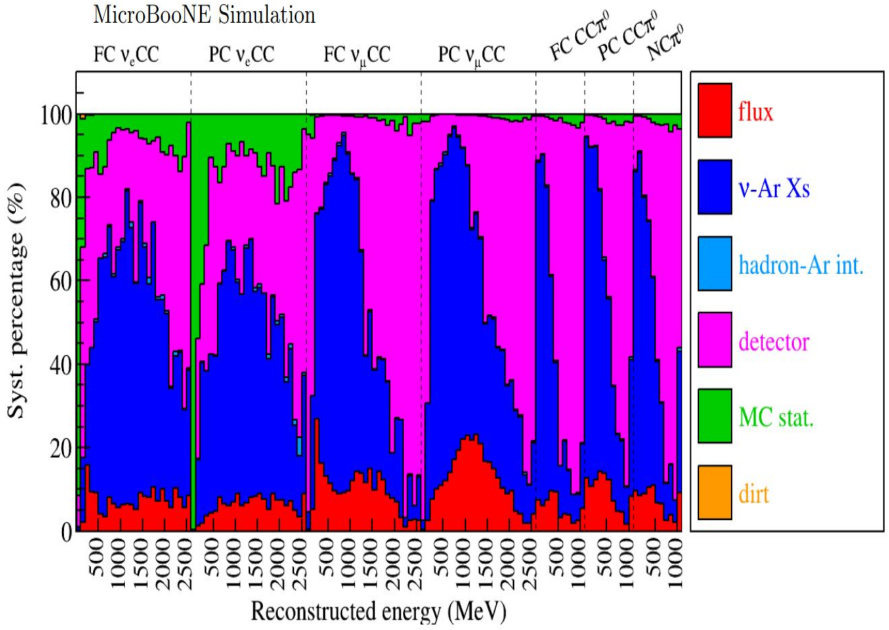
Parameter	Central value	$+1\sigma$	-1σ
MaCCQE[a]	1.10 GeV	+0.1 GeV	−0.1 GeV
RPA_CCQE[b]	85%	+40%	−40%
Normccmec	166%	+50%	−50%
XSecShape_CCMEC	Empirical[c]	N/A	Valencia[d]
Coulomb_CCQE	Nominal	+30%	−30%
DecayAngMEC	Isotropic	Alternative[e]	N/A
FracPN_CCMEC	Valencia	+20%	−20%
FracDelta_CCMEC	Valencia	+30%	−30%
NormNCMEC	Nominal	+100%	−100%
ThetaDelta2NRad	Isotropic	Alternative[e]	N/A
NormCCCOH	Nominal	+100%	−100%
NormNCCOH	Nominal	+100%	−100%

PhysRevD.105.072001

Impact of Cross Section Uncertainties on Oscillation Measurements

- Inclusive signal
  - Not concerned with final state composition (eg: particle multiplicity, charge exchange)
- Requires E_ν measurement
  - Transfer energy contains invisible portion in LArTPC (eg: neutrons)
  - Potential source of model dependence
- **Cross section uncertainties** dominant at low E_ν for both ν_e and ν_μ
  - MicroBooNE uses sideband constraints in place of 2-detector setup

ν_eCC Inclusive eLEE Search Uncertainty



PhysRevD.105.112005

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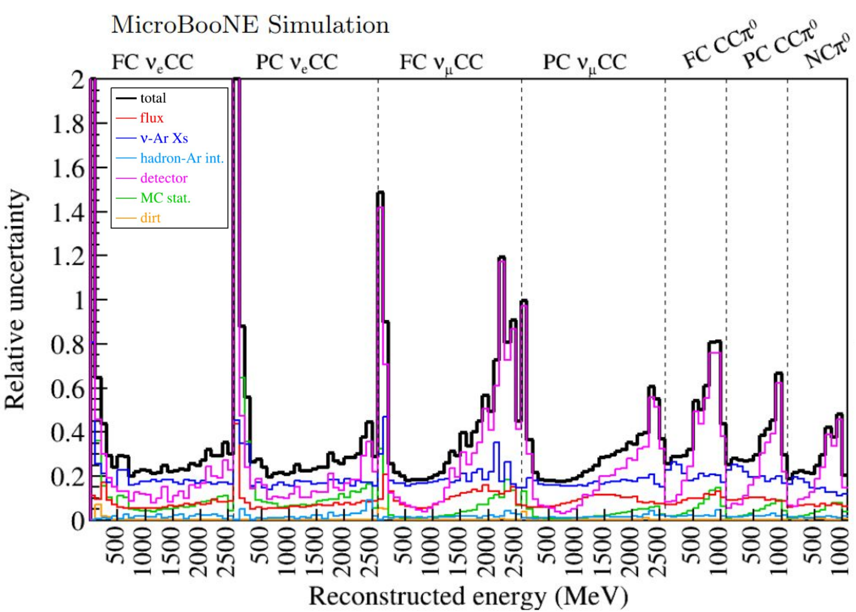
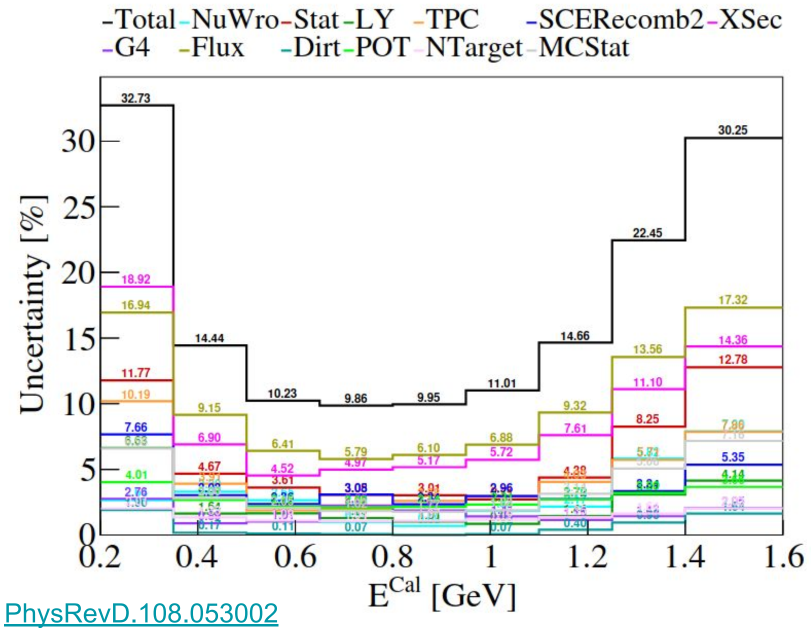


PhysRevD.105.112005

Impact of Cross Section Uncertainties on Cross Section Measurements

- Often exclusive signal
  - Backgrounds from interaction channels such as MEC
  - Impact varies between signal definitions
- Unfolding naturally suppresses **cross section uncertainties**
- Impact of **cross section uncertainties** depends on kinematic distribution
  - Sub-dominant across E_{Cal}
  - Dominant at high δp_T

ν_μCC 1p0π Cross Section Uncertainty



[PhysRevD.108.053002 Supplemental Material](PhysRevD.108.053002)

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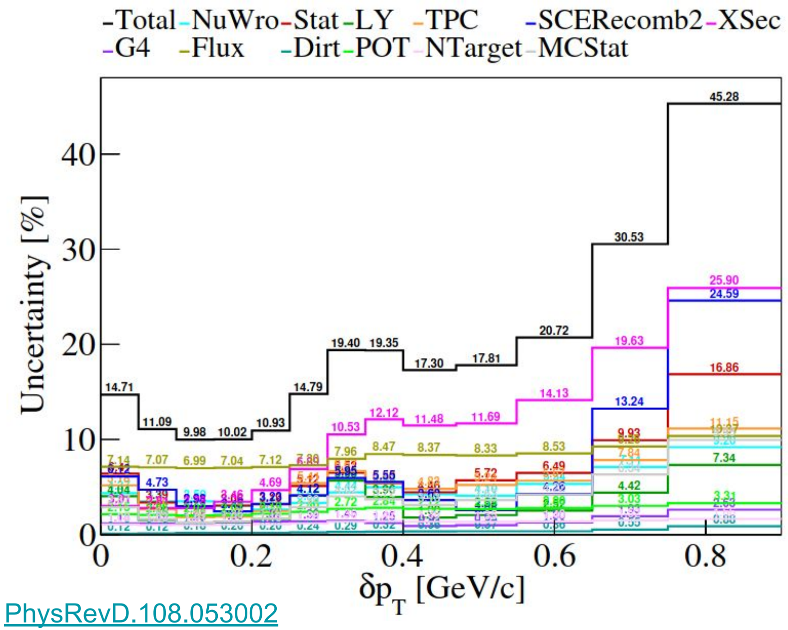


PhysRevD.108.053002 Supplemental Material

Impact of Cross Section Parameter Uncertainties on ν_μCC 1p0π **1-Bin** Cross Section Measurement

PhysRevD.108.053002
Supplemental Material

*Largest uncertainties shown here; full list in backup slides

CCQE Parameters

	1σ Genie Uncertainty	Fractional Contribution to Meas
RPA Strength	40 %	2.1 %

CCMEC Parameters

	1σ Genie Uncertainty	Fractional Contribution to Meas
CCMEC Norm	50 %	1.832 %
MEC Decay Angle	Isotropic vs $\cos^2\theta$	0.693 %

RES Parameters

	1σ Genie Uncertainty	Fractional Contribution to Meas
M_A CCRES	20%	0.986 %
M_ν CCRES	10%	0.775 %
M_A NCRES	20%	0.969 %
$\Delta \rightarrow N+\pi$ Angle	Rein-Sehgal vs Isotropic	1.533 %

FSI Parameters

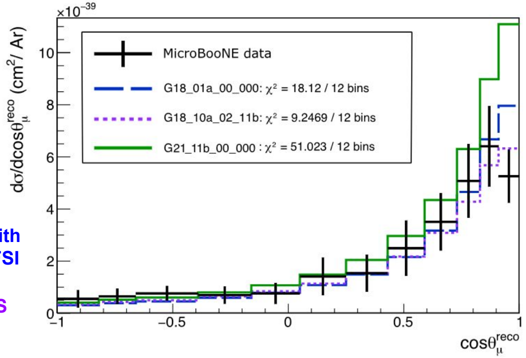
	1σ Genie Uncertainty	Fractional Contribution to Meas
Nucleon Mean Free Path	20 %	1.212 %
π Absorption	30 %	0.906 %
Nucleon Charge Exchange	20 %	0.953 %
Nucleon Absorption	40 %	0.906 %

Summary

- Neutrino interaction modeling is important for precision oscillation measurements
  - Modeling is adequate for MicroBooNE, must do better for future experiments
- Many new model developments in recent years
  - Initial state models, CCQE models (SuSAv2, RPA correction), FSI models, …
- Areas of significant model disagreement
  - RPA corrections, MEC contribution, FSI, …
- Cross section measurements can continue to guide model development
  - Multi-dimensional phase spaces, high statistics, new detectors and unfolding methods, new kinematics being measured

See Steven Gardiner's talk for new results!

MicroBooNE ν_μ CC0πNp Data
Phys. Rev. D 102, 112013 (2020)



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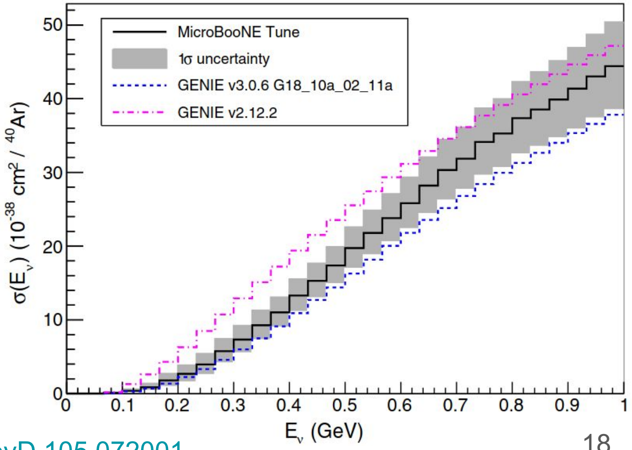
LFG, Valencia CCQE, Berger-Sehgal improved RES modeling
SuSAv2 CCQE, hN FSI

MicroBooNE Tune ν_e CC Inclusive Cross Section



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Backup

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NonRESBGvpNC1pi	0.1	+50%	−50%
NonRESBGvpNC2pi	1	+50%	−50%
NonRESBGvnNC1pi	0.3	+50%	−50%
NonRESBGvnNC2pi	1	+50%	−50%
NonRESBGvbarpNC1pi	0.3	+50%	−50%
NonRESBGvbarpNC2pi	1	+50%	−50%
NonRESBGvbarnNC1pi	0.1	+50%	−50%
NonRESBGvbarnNC2pi	1	+50%	−50%
Bodek-Yang structure functions			
AhtBY	0.538 GeV^2	+25%	−25%
BhtBY	0.305 GeV^2	+25%	−25%
CV1uBY	0.291 GeV^2	+30%	−30%
CV2uBY	0.189 GeV^2	+40%	−40%
Final-state interactions			
MFP_pi	hA2018	+20%	−20%
MFP_N	hA2018	+20%	−20%
FrCEx_pi	hA2018	+50%	−50%
FrInel_pi	hA2018	+40%	−40%
FrAbs_pi	hA2018	+30%	−30%
FrPiProd_pi	hA2018	+20%	−20%
FrCEx_N	hA2018	+50%	−50%
FrInel_N	hA2018	+40%	−40%
FrAbs_N	hA2018	+20%	−20%
FrPiProd_N	hA2018	+20%	−20%

Parameter	Description	CV	1σ Uncertainty	Contributing Uncertainty (%) Total (Sig/Bkg)
Quasi-Elastic Parameters				
`MaCCQE`	CCQE axial mass	1.10 GeV	±0.1 GeV	0.038 (0.256, 0.218)
`RPA CCQE`	Strength of the RPA correction	0.151	±0.4	2.094 (1.989, 0.104)
`MaNCEL`	Axial mass for NCEL	0.961242 GeV	±25%	0.348 (0.010, 0.348)
`EtaNCEL`	Empirical parameter used to account for sea quark contribution to NCEL form factor	0.12	±30%	0.010 (0.010, 0.010)
`AxFFCCQEshape`	Parametrisation of the nucleon axial form factor	Dipole	z-expansion	0.022 (0.016, 0.031)
`VecFFCCQEshape`	Parametrisation of the nucleon vector form factors	BBA07	Dipole	0.051 (0.186, 0.137)
MEC Parameters				
`NormCCMEC`	Energy-independent normalization for CCMEC	1.66	±0.5	1.832 (0.514, 1.319)
`NormNCMEC`	Energy-independent normalization for NCMEC	1	±20%	0.129 (0.010, 0.129)
`FracPNCCMEC`	Fraction of initial nucleon pairs that are pn (0 = Valencia)	0	±20%	0.041 (0.333, 0.293)
`FracDeltaCCMEC`	Relative contribution of Δ diagrams to total MEC cross section (0 = Valencia)	0	±30%	0.124 (0.124, 0.158)
`XSecShape CCMEC`	Changes shape of differential cross section	1.0	0.0	2.273 (1.762, 0.511)
`DecayAngMEC`	Changes angular distribution of nucleon cluster	Isotropic	$\cos^2\vartheta$ in rest frame	0.693 (0.290, 0.404)
Resonant Parameters				
`MaCCRES`	CCRES axial mass	1.120 GeV	±0.2	0.986 (0.119, 1.103)
`MvCCRES`	Shape-only CCRES axial mass	0.840 GeV	±0.1	0.775 (0.121, 0.896)
`MaNCRES`	NCRES axial mass	1.120 GeV	±0.2	0.969 (0.010, 0.969)
`MvNCRES`	NCRES vector mass.	0.840 GeV	±0.1	0.395 (0.010, 0.395)
`ThetaDelta2Npi`	Interpolates angular distribution for $\Delta \rightarrow N + \pi$	Rein-Sehgal	Isotropic	1.533 (0.142, 1.392)
`ThetaDelta2NRad`	Interpolates angular distribution for $\Delta \rightarrow N + \gamma$	Rein-Sehgal	$\cos^2\vartheta$	0.016 (0.016, 0.016)

Parameter	Description	CV	1σ Uncertainty	Contributing Uncertainty (%) Total (Sig/Bkg)
Non-Resonant Parameters				
NonRESBGvpNC1pi	Non-resonant background normalization for νp NC1π	0.1	±0.5	0.041 (0.010, 0.041)
NonRESBGvpNC2pi	Non-resonant background normalization for νp NC2π	1	±0.5	0.096 (0.010, 0.096)
NonRESBGvnNC1pi	Non-resonant background normalization for νn NC1π	0.3	±0.5	0.390 (0.010, 0.390)
NonRESBGvnNC2pi	Non-resonant background normalization for νn NC2π	1	±0.5	0.022 (0.010, 0.022)
NonRESBGvbarpNC1pi	Non-resonant background normalization for ν̄p NC1π	0.3	±0.5	0.010 (0.010, 0.010)
NonRESBGvbarpNC2pi	Non-resonant background normalization for ν̄p NC2π	1	±0.5	0.010 (0.010, 0.010)
NonRESBGvbarnNC1pi	Non-resonant background normalization for ν̄n NC1π	0.1	±0.5	0.010 (0.010, 0.010)
NonRESBGvbarnNC2pi	Non-resonant background normalization for ν̄n NC2π	1	±0.5	0.010 (0.010, 0.010)
NonRESBGvpCC1pi	Non-resonant background normalization for νp CC1π	0.007713	±0.5	0.014 (0.010, 0.019)
NonRESBGvpCC2pi	Non-resonant background normalization for νp CC2π	0.787999	±0.5	0.059 (0.010, 0.063)
NonRESBGvnCC1pi	Non-resonant background normalization for νn CC1π	0.127858	±0.5	0.217 (0.034, 0.250)
NonRESBGvnCC2pi	Non-resonant background normalization for νn CC2π	2.11523	±0.5	0.079 (0.010, 0.077)
NonRESBGvbarpCC1pi	Non-resonant background normalization for ν̄p CC1π	0.127858	±0.5	0.013 (0.010, 0.013)
NonRESBGvbarpCC2pi	Non-resonant background normalization for ν̄p CC2π	2.11523	±0.5	0.010 (0.010, 0.010)
NonRESBGvbarnCC1pi	Non-resonant background normalization for ν̄n CC1π	0.007713	±0.5	0.010 (0.010, 0.010)
NonRESBGvbarnCC2pi	Non-resonant background normalization for ν̄n CC2π	0.787999	±0.5	0.010 (0.010, 0.010)
AhtBY	A_{HT} higher-twist parameter in the Bodek-Yang model scaling variable ξ_w	0.538	±0.25	0.010 (0.010, 0.010)
BhtBY	BHT higher-twist parameter in the Bodek-Yang model scaling variable ξ_w	0.305	±0.25	0.010 (0.010, 0.010)
CV1uBY	CV1u valence GRV98 PDF correction parameter in the Bodek-Yang model	0.291	±0.3	0.010 (0.010, 0.010)
CV2uBY	CV2u valence GRV98 PDF correction parameter in the Bodek-Yang model	0.189	±0.4	0.010 (0.010, 0.010)
Hadronisation Parameters				
AGKYxF1pi	Hadronization parameter, applicable to true DIS interactions only	-0.385	±0.2	0.108 (0.013, 0.120)
AGKYpT1pi	Hadronization parameter, applicable to true DIS interactions only	1/6.625	±0.03	0.034 (0.014, 0.046)
Final State Interaction Parameters				
MFP_π	π mean free path	0	±0.2	0.032 (0.010, 0.028)
MFP_N	Nucleon mean free path	0	±0.2	1.212 (1.067, 0.147)
$FrCEx_\pi$	Fractional cross section for π charge exchange	0	±0.5	0.159 (0.025, 0.184)
$FrInel_\pi$	Fractional cross section for π inelastic scattering	0	±0.4	0.133 (0.042, 0.091)
$FrAbs_\pi$	Fractional cross section for π absorption	0	±0.3	0.906 (0.066, 0.019)
$FrCEx_N$	Fractional cross section for nucleon charge exchange	0	±0.2	0.953 (0.411, 0.542)
$FrInel_N$	Fractional cross section for nucleon inelastic scattering	0	±0.5	0.289 (0.228, 0.061)
$FrAbs_N$	Fractional cross section for nucleon absorption	0	±0.4	0.906 (0.526, 0.380)
Delta Resonant Decay Parameters				
RDecBR1gamma	Normalization for $\Delta \to \gamma$ decays	Nominal BR	±0.5	0.042 (0.017, 0.025)
RDecBR1eta	Normalization for $\Delta \to \eta$ decays	Nominal BR	±0.5	0.513 (0.198, 0.324)
Coherent Parameters				
NormCCCOH	Scaling factor for CCCOH π production total cross section	Nominal	100% increase	0.027 (0.016, 0.027)
NormNCCOH	Scaling factor for NCCOH π production total cross section	Nominal	100% increase	0.016 (0.016, 0.016)

https://arxiv.org/abs/2403.19574