Neutrino-Nucleus CC0π cross-section tuning in GENIE

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on behalf of the GENIE Collaboration

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Overview

Neutrino interaction modeling is essential to **estimate the neutrino energy and calculate backgrounds and systematic errors** in neutrino measurements

Modeling of neutrino interactions is one of the dominant systematic uncertainties

- ➢ Need to improve the models and quantify and reduce systematic uncertainties associated to neutrino cross sections modeling

There is no available model that allows us to simulate the whole region of interest for neutrino experiments

- ➢ Event generators merge models together with ad-hoc prescriptions

We rely on empirical approaches that need to be tuned

Neutrino-nucleus cross section data

Huge effort from the experimental neutrino community

Many datasets are available for different neutrino energies and targets:

- ★ Inclusive measurements ($\nu_\mu A \rightarrow \mu^- X$)
- ★ Exclusive measurements
  - ○ Topologies: CC0π, CC0p0π, CCNp0π, CC1π, …
  - ○ Single differential as well as double- and triple-differential measurements are available
  - ○ Big effort on new measurements on STKI variables and proton kinematics

These datasets are crucial to validate and tune models in neutrino MC event generators

GENIE’s global analysis with Professor

GENIE develops a global analysis of scattering data for **tuning** and **uncertainty characterization** of comprehensive neutrino interaction models

GENIE’s tuning program is based on the **Professor tool**:

- Tuning software tool from LHC community
    - Efficient implementation of complex multi-parameter brute-force scans
    - Applied to neutrinos for the first time by GENIE
    - Decoupled from event reweighting procedures

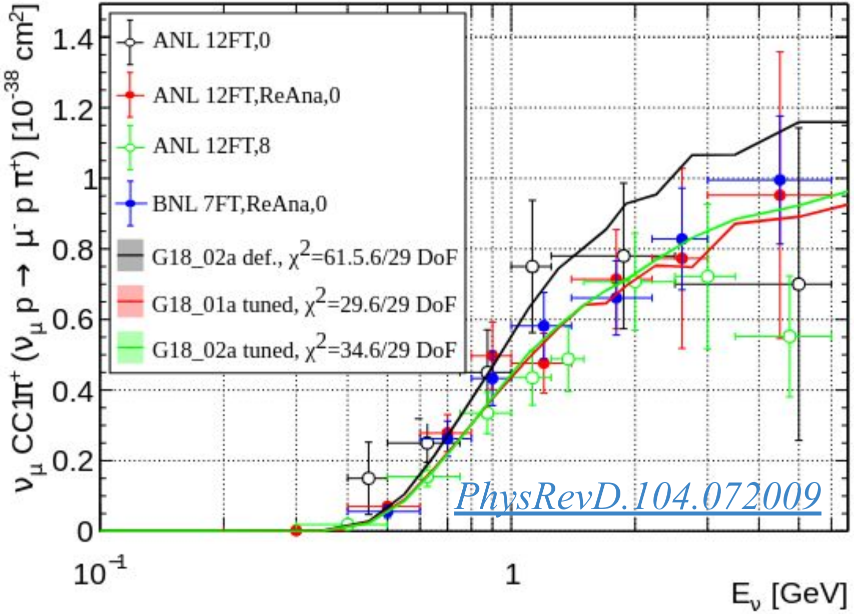
- Our goal is to perform a global tune that improves agreement with data
    a. Tune GENIE’s free nucleon models, including hadronization, with available data on hydrogen and deuterium targets
    b. Tune nuclear models with modern neutrino data
    c. Include electron-scattering data

https://professor.hepforge.org/

The GENIE global analysis effort

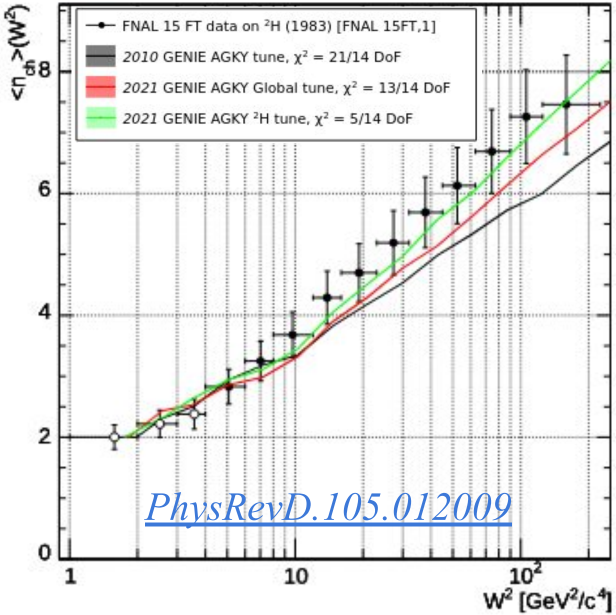
The first goal was to tune ν-N models - Core of ν-A simulations!

Global fit to CC inclusive, 1π, and 2π data sets



PhysRevD.104.072009

First neutrino-induced hadronization tune on charged averaged multiplicity data on H and D



PhysRevD.105.012009

The GENIE global analysis effort

Accepted for Publication at Phys.Rev.D

The latest effort focuses on tuning of ν-A data:

Neutrino-Nucleus CC0π cross-section tuning ArXiv:2206.11050

This analysis incorporates new challenges with respect to previous free-nucleon tunes. It

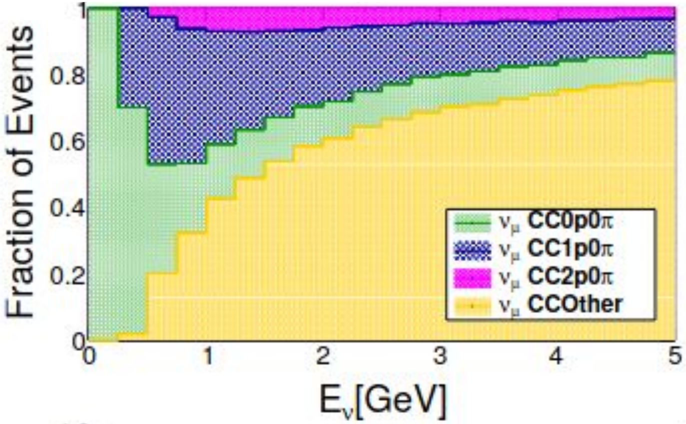
- Deals with the complexity of modeling the nuclear environment
- Consolidates the main elements of the tuning methodology with nuclear data
- Explores avenues for improving the agreement of GENIE and nuclear data
  - New parameterizations that encapsulate our lack of understanding of νA must be developed within GENIE

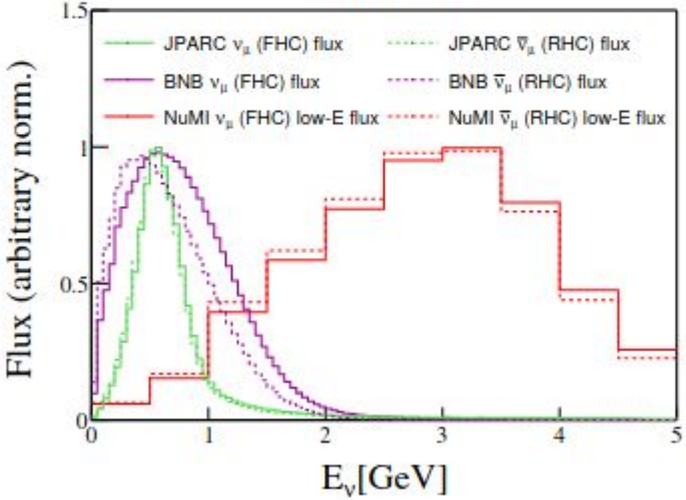
This work is the first step towards a global tune using all data on nuclei

This work focuses on the tuning of modern neutrino CC0π cross-section data on carbon

The CC0π Event topology

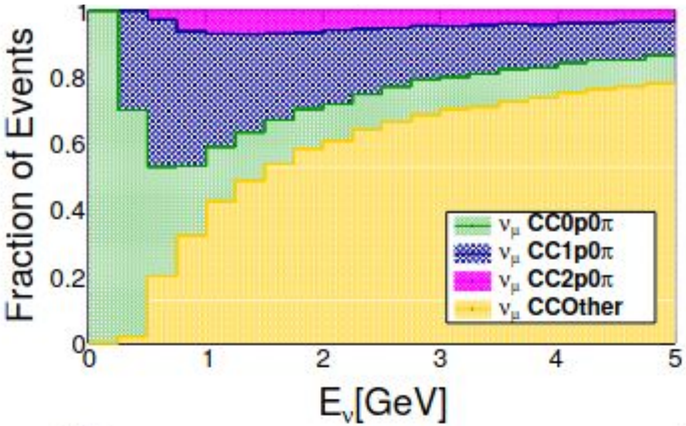
- **Dominant event topology at E_ν < 1 GeV**
- Usually defined as an event with a muon and no mesons in the final state
  - CC0π: no mesons, any number of protons
  - CC0p0π: no protons above detection threshold
  - CCNp0π: at least one proton above detection threshold

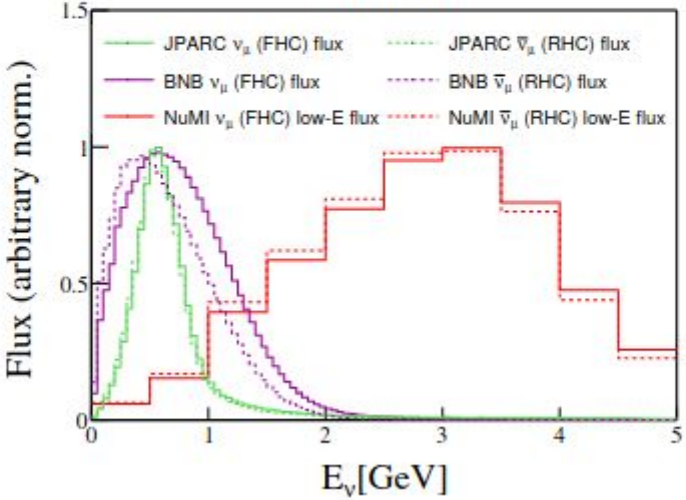




The CC0π Event topology

- The contribution from different channels depends on the neutrino flux:
    - The CC0π topology is dominated by CCQEL events
    - Inelastic channels are also important due to FSI
        - Small RES contribution for T2K and MicroBooNE with respect to MINERvA
        - For T2K CC0p0π, most 2p2h events have W~ M_N whilst for MINERvA, W~M_Δ
        - Negligible contribution of DIS events



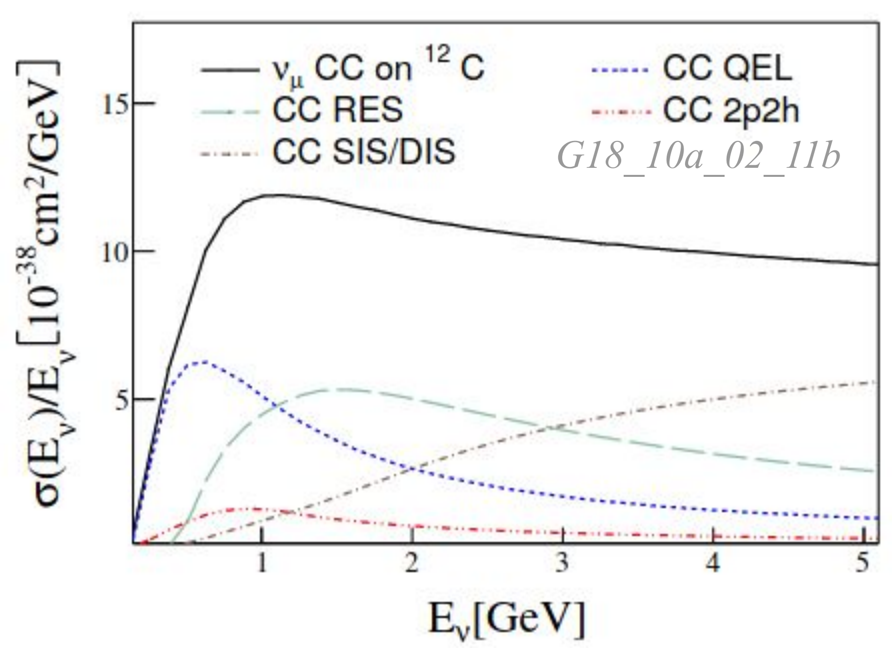


Modeling of CC0π events with GENIE

GENIE has different models available to simulate neutrino-nucleus interactions:

- **CC QEL:** Llewellyn-Smith, Valencia or SuSAv2 model
- **CC 2p2h:** Empirical, Valencia or SuSAv2 model
- **CC RES:** Rein-Sehgal or Berger-Sehgal model
- **FSI:** hA2018, hN2018, INCL++
- **Nuclear model:** Relativistic, Local or Correlated Fermi Gas model

The models are grouped into different Comprehensive Model Configurations = self-consistent collections of the primary models

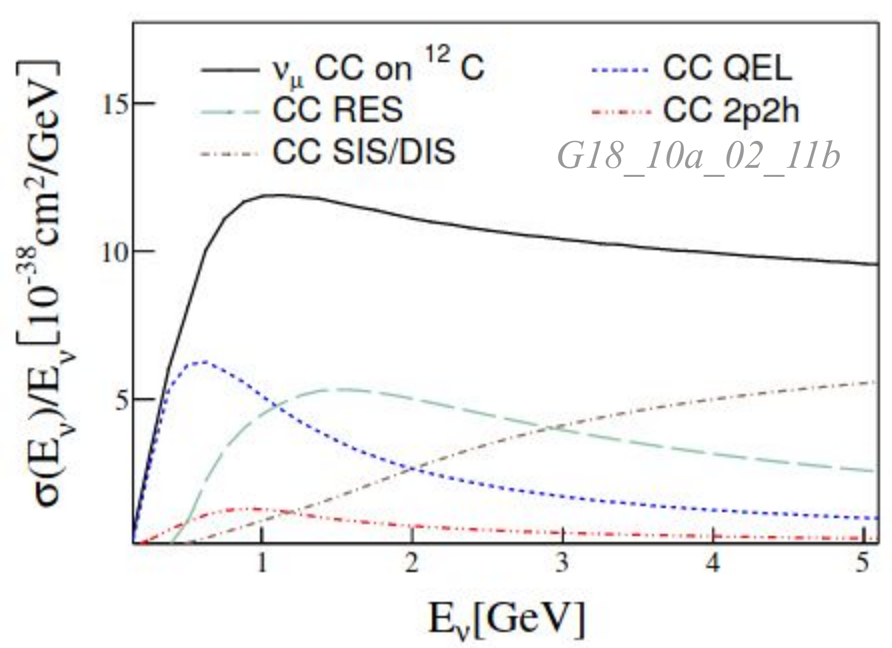


Modeling of CC0π events with GENIE

In this work we use the G18_10a_02_11b CMC:

- QEL+2p2h: Valencia model
- RES: Berger-Sehgal model
- FSI: GENIE hA2018
- Nuclear model: LFG

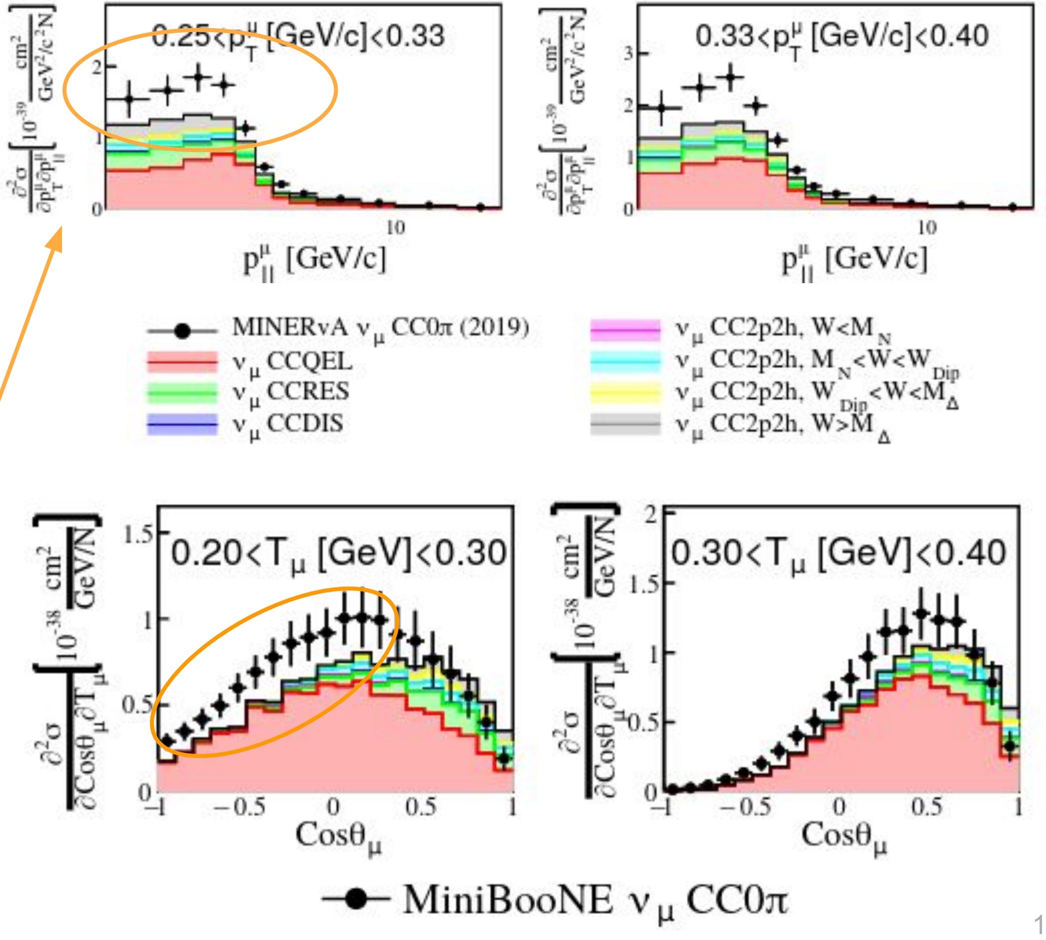
This CMC is tuned against free nucleon data on H and ^{2}H, PhysRevD.104.072009



Current description of CC0π data

The G18_10a_02_11b CMC **underpredicts all data on CC0π and CC0p0π**

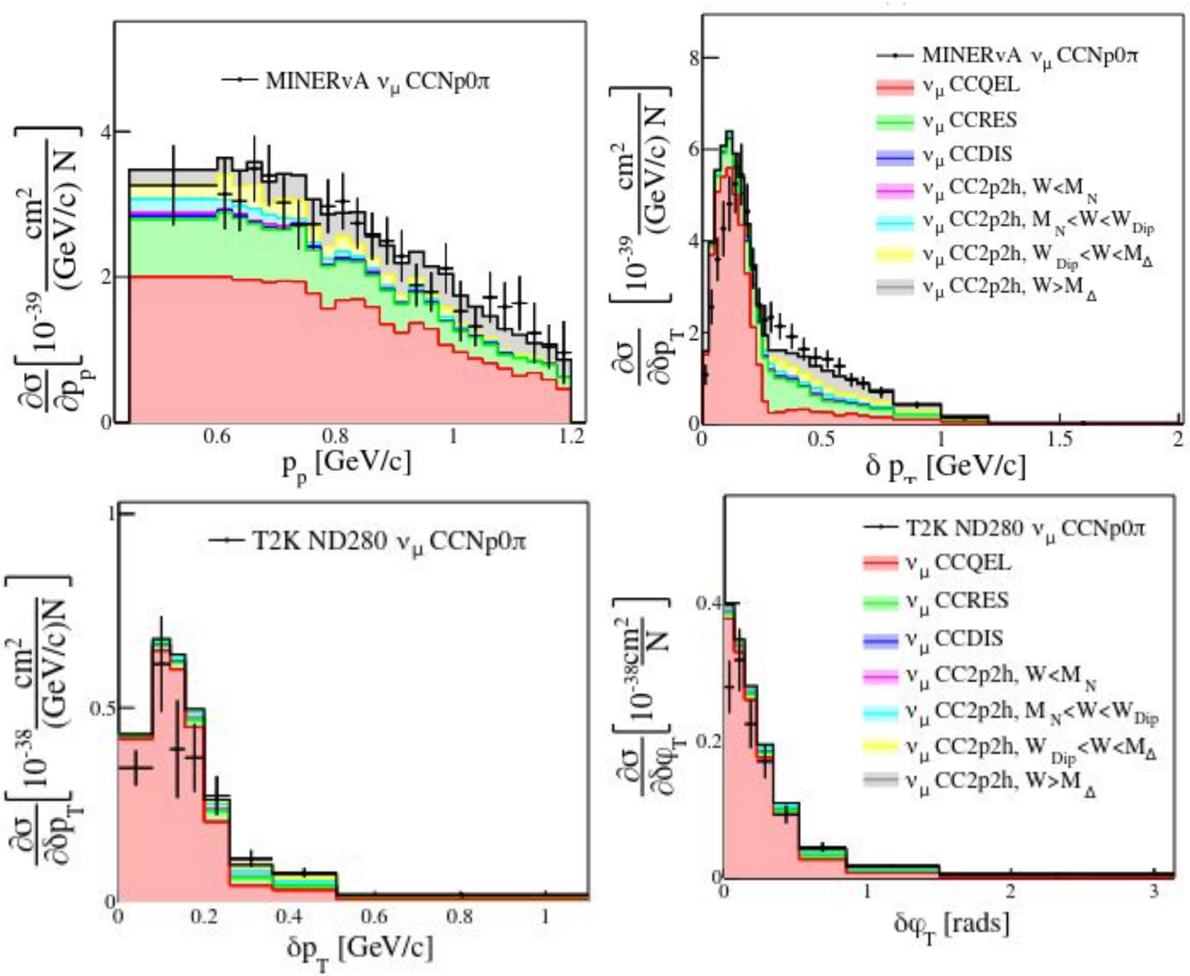
- Kinematic region where 2p2h events dominate
- But also for $\cos\theta_\mu < 0$, where QEL events dominate



Current description of CCNp0π data

The G18_10a_02_11b CMC **has better agreement with CCNp0π** data:

- It cannot describe CC0π and CCNp0π data at the same time
- CCNp0π data is not directly used in this analysis due to this tension



Tuned parameters (1)

At the free nucleon level, the QEL cross section is well understood

- Base model was tuned to hydrogen and deuterium data
- We use correlated priors from free nucleon tune to constrain the nucleon axial mass (**M_A^{QEL}**) and RES normalization factor (**S_{RES}**)

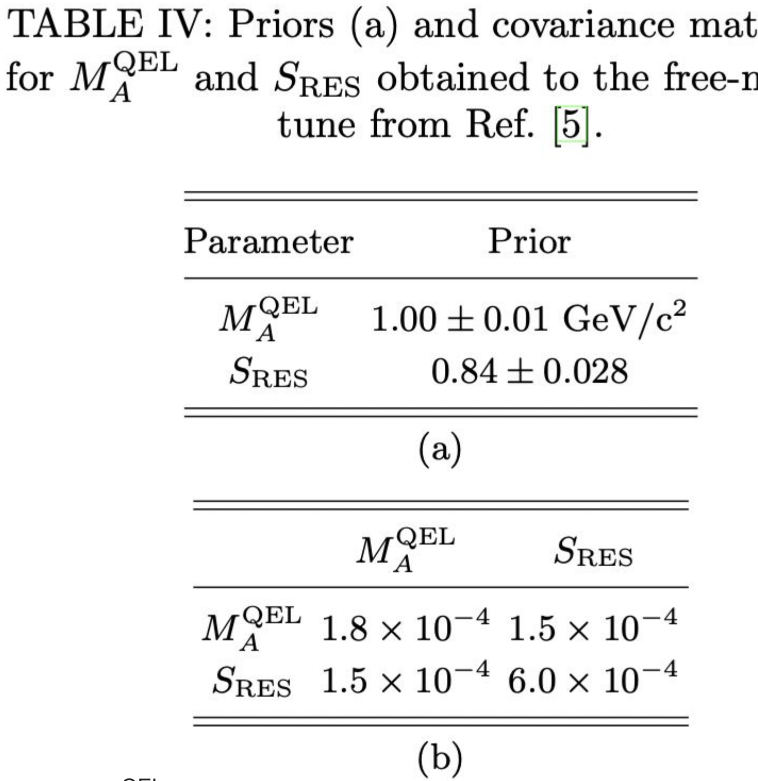


TABLE IV: Priors (a) and covariance mat
for M_A^{QEL} and S_{RES} obtained to the free-n
tune from Ref. [5].

Parameter	Prior
M_A^{QEL}	1.00 ± 0.01 GeV/c^2
S_{RES}	0.84 ± 0.028

(a)

	M_A^{QEL}	S_{RES}
M_A^{QEL}	1.8×10^{-4}	1.5×10^{-4}
S_{RES}	1.5×10^{-4}	6.0×10^{-4}

(b)

Note: M_A^{QEL} was originally also constrained by a prior from ν_μd and pion electroproduction [*The European Physical Journal C* 53, 349–354 (2008)]

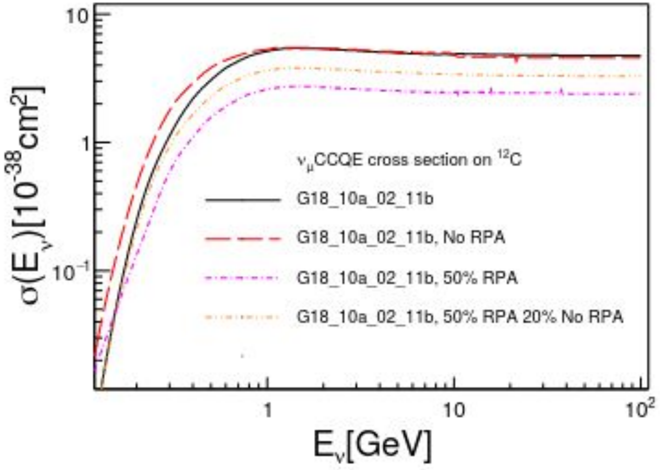
Tuned parameters (2)

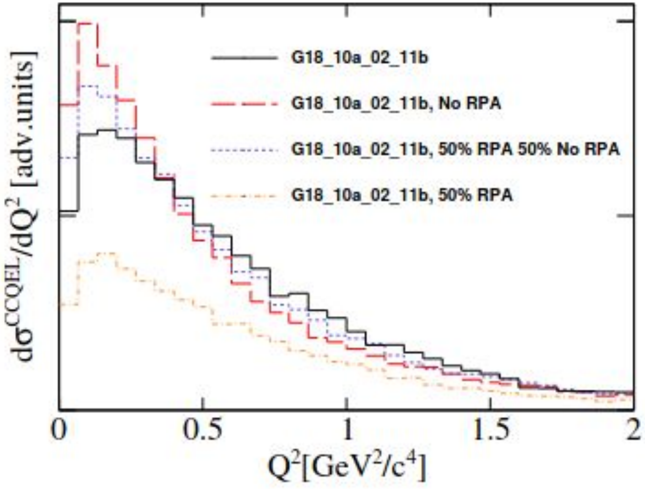
The QEL cross section is affected by the dynamics of the nuclear medium

- We include long-range NN correlations with the RPA correction
- Suppression of the QEL cross section at low Q^2
- We parameterize the RPA correction as:

$$\sigma^{\mathrm{QEL}} = \omega_{\mathrm{RPA}} \cdot \sigma^{\mathrm{QEL}}_{\mathrm{RPA}} + \omega_{\mathrm{No\,RPA}} \cdot \sigma^{\mathrm{QEL}}_{\mathrm{No\,RPA}}$$

w_{RPA}/w_{NoRPA} scales the cross section w/wo RPA (black/red line)





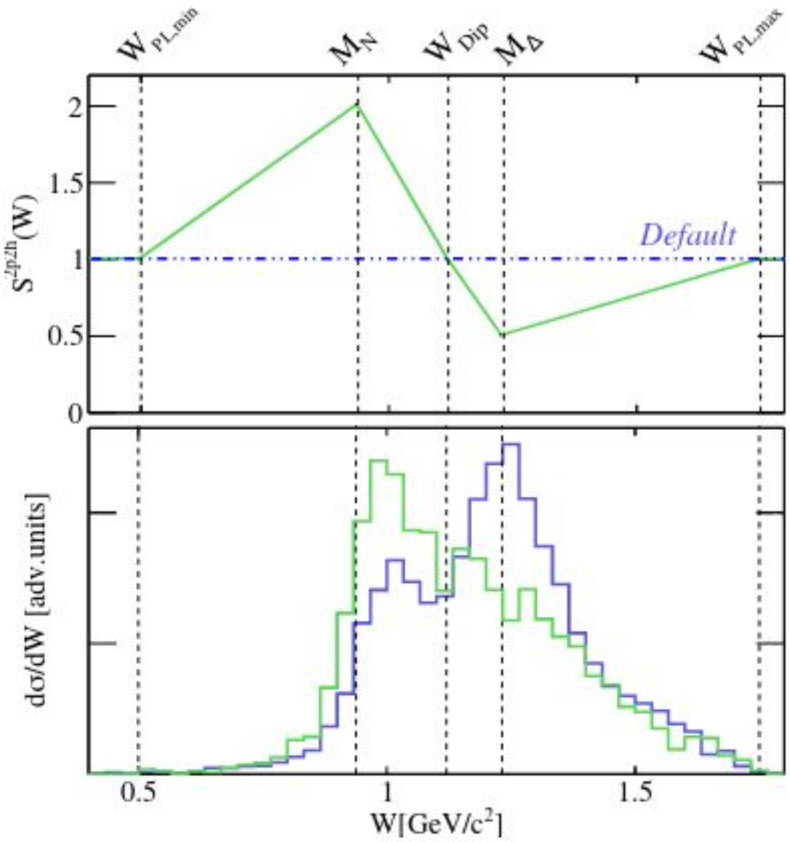
Tuned parameters (3)

- The different available 2p2h models predict a different shape and strength for the 2p2h cross section
  - The Valencia model predicts two peaks in W at M_N and M_Δ
- We scale the 2p2h cross section as:

$$\frac{d^2\sigma^{2p2h}}{dq_0 dq_3} \rightarrow S(W) \cdot \frac{d^2\sigma^{2p2h}}{dq_0 dq_3}$$

S(W) depends linearly on W between the different regions:

- **$S_N^{2p2h} = S(M_N)$**
- **$S_\Delta^{2p2h} = S(M_\Delta)$**
- **$S_{PL}^{2p2h} = S(W_{PL,Max})$**
- $S(W_{PL,Min}) = S(W_{Dip}) = 1$



This empirical parameterization can be used to change the shape and scale the 2p2h cross section

Neutrino CC0π datasets used for tuning

- All hydrocarbon targets
- Distint fluxes prove E_ν dependence
  - MiniBooNE and T2K ND280 flux's peaks below 1 GeV
  - MINERvA's low-E flux peaks at 3 GeV
- Identical base model, G18_10a_02_11b:
  - QEL+2p2h: Valencia model
  - RES: Berger-Sehgal
  - FSI: GENIE hA2018
- A total of 5 partial tunes are performed within the same framework

Experiment	**Probe**	**Event Topology**	**Partial Tune**
MiniBooNE	ν_μ	CC0π	G10a
	$\bar{\nu}_\mu$	CC0π	G11a
T2K ND280	ν_μ	CC0p0π	G20a
MINERvA	ν_μ	CC0π	G30a
	$\bar{\nu}_\mu$	CC0p0π	G31a

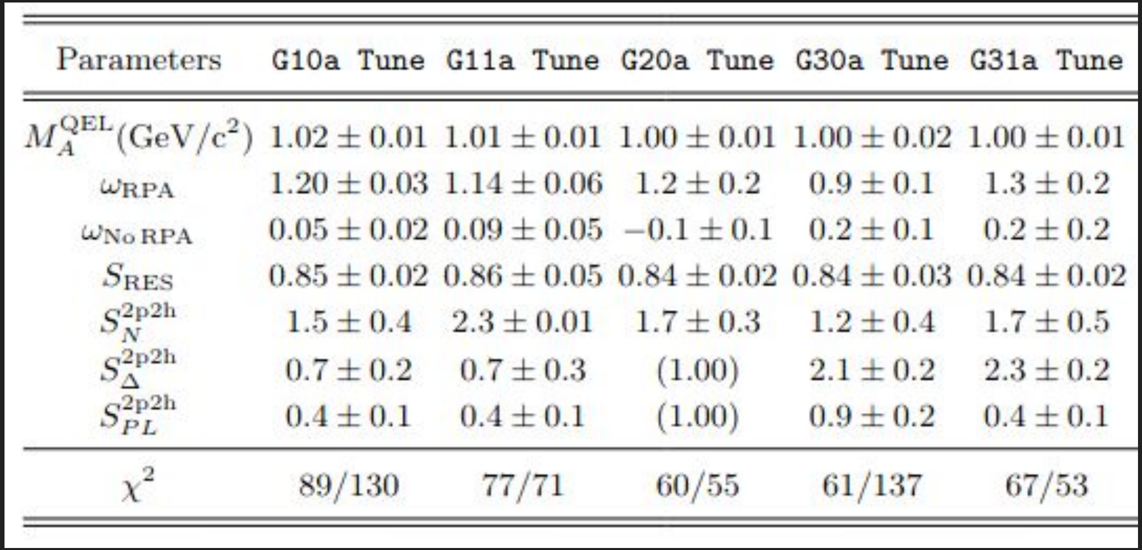
This approach provides with a common ground for the discussion of tensions between experiments

Partial tune results

- G10a: GENIE tune to MiniBooNE ν_μ CC0π data
- G11a: GENIE tune to MiniBooNE anti-ν_μ CC0π data
- G20a: GENIE tune to T2K ND280 ν_μ CC0p0π data
- G30a: GENIE tune to MINERvA ν_μ CC0π data
- G31a: GENIE tune to MINERvA anti-ν_μ CC0p0π data

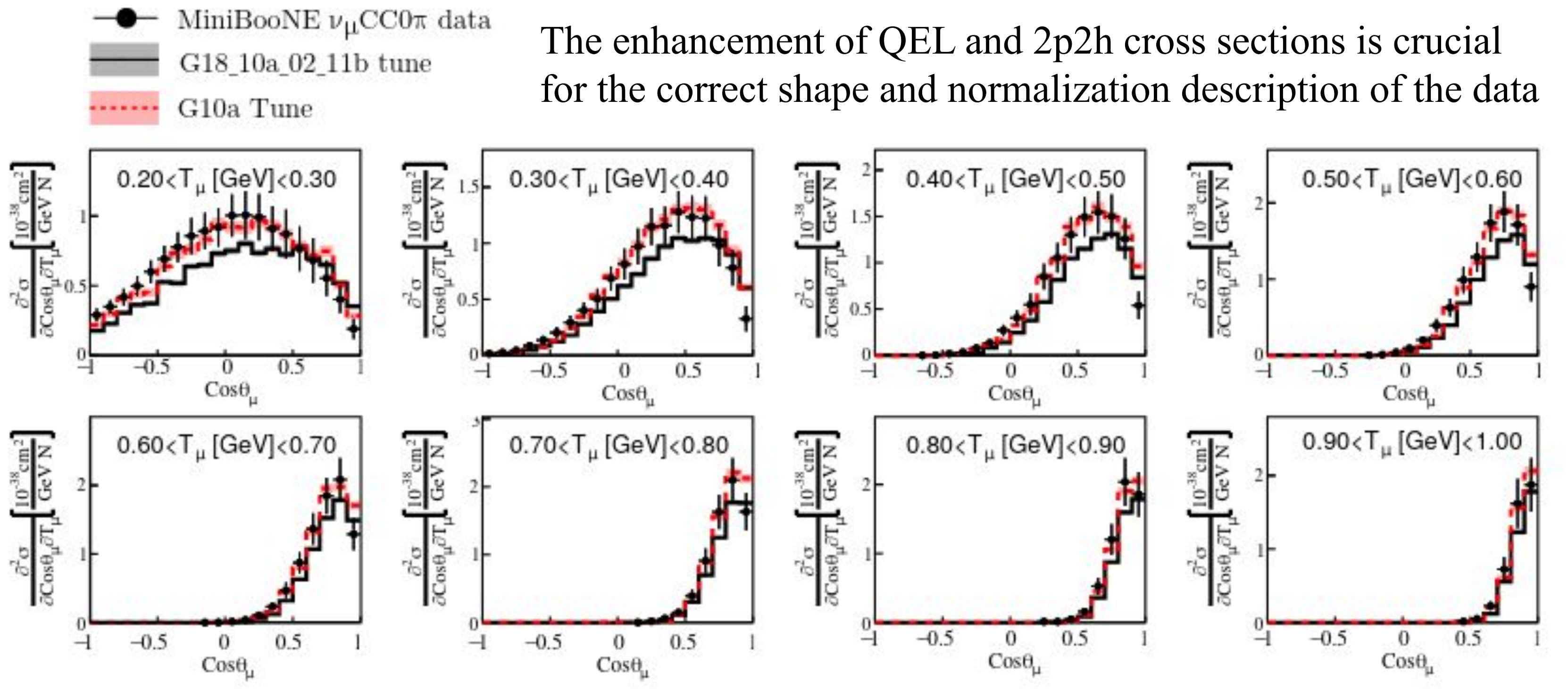
All tunes

- Respect free nucleon priors imposed on M_A^{QEL} and S_{RES}
- Have a preference for RPA corrections
- **Enhance the CCQEL and CC2p2h cross section**



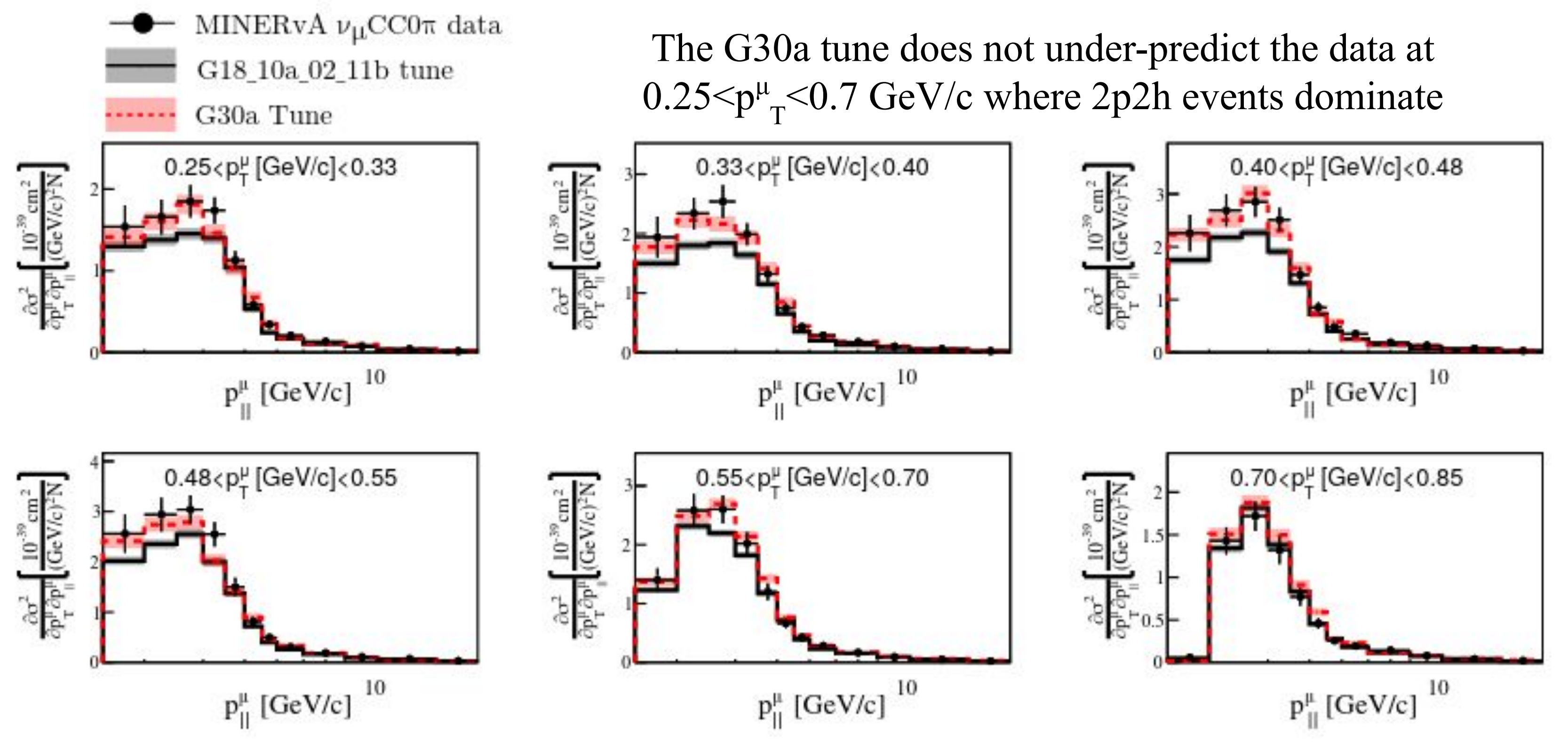
Parameters	G10a Tune	G11a Tune	G20a Tune	G30a Tune	G31a Tune
$M_A^{\mathrm{QEL}}(\mathrm{GeV/c^2})$	1.02 ± 0.01	1.01 ± 0.01	1.00 ± 0.01	1.00 ± 0.02	1.00 ± 0.01
ω_{RPA}	1.20 ± 0.03	1.14 ± 0.06	1.2 ± 0.2	0.9 ± 0.1	1.3 ± 0.2
$\omega_{\mathrm{No\,RPA}}$	0.05 ± 0.02	0.09 ± 0.05	-0.1 ± 0.1	0.2 ± 0.1	0.2 ± 0.2
S_{RES}	0.85 ± 0.02	0.86 ± 0.05	0.84 ± 0.02	0.84 ± 0.03	0.84 ± 0.02
S_N^{2p2h}	1.5 ± 0.4	2.3 ± 0.01	1.7 ± 0.3	1.2 ± 0.4	1.7 ± 0.5
S_Δ^{2p2h}	0.7 ± 0.2	0.7 ± 0.3	(1.00)	2.1 ± 0.2	2.3 ± 0.2
S_{PL}^{2p2h}	0.4 ± 0.1	0.4 ± 0.1	(1.00)	0.9 ± 0.2	0.4 ± 0.1
χ^2	89/130	77/71	60/55	61/137	67/53

Post-fit agreement with MiniBooNE CC0π data



The enhancement of QEL and 2p2h cross sections is crucial for the correct shape and normalization description of the data

Post-fit agreement with MINERvA CC0π data



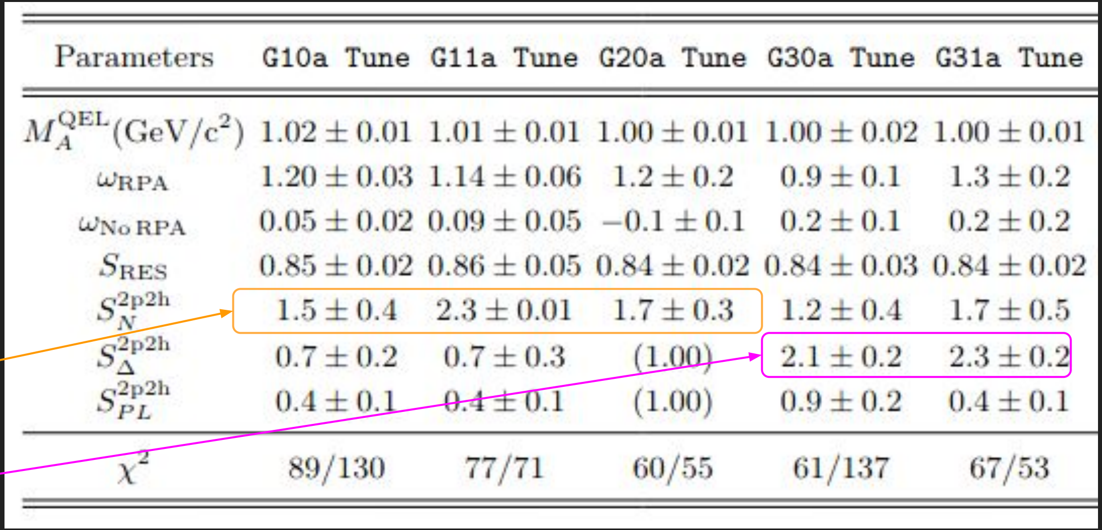
The G30a tune does not under-predict the data at $0.25<p^\mu_T<0.7$ GeV/c where 2p2h events dominate

Partial tune results
Tensions

- G10a: GENIE tune to MiniBooNE ν_μ CC0π data
- G11a: GENIE tune to MiniBooNE anti-ν_μ CC0π data
- G20a: GENIE tune to T2K ND280 ν_μ CC0p0π data
- G30a: GENIE tune to MINERvA ν_μ CC0π data
- G31a: GENIE tune to MINERvA anti-ν_μ CC0p0π data

However, differences between the partial tune results exist:

- MiniBooNE and T2K's tunes enhance the 2p2h cross section at W=M_N, whilst suppressing it at W=M_Δ
- MINERvA's tune enhances both peaks: $S_\Delta^{2p2h} > S_N^{2p2h} > 1$



Parameters	G10a Tune	G11a Tune	G20a Tune	G30a Tune	G31a Tune
M_A^{QEL} (GeV/c^2)	1.02 ± 0.01	1.01 ± 0.01	1.00 ± 0.01	1.00 ± 0.02	1.00 ± 0.01
ω_{RPA}	1.20 ± 0.03	1.14 ± 0.06	1.2 ± 0.2	0.9 ± 0.1	1.3 ± 0.2
$\omega_{\mathrm{No\ RPA}}$	0.05 ± 0.02	0.09 ± 0.05	-0.1 ± 0.1	0.2 ± 0.1	0.2 ± 0.2
S_{RES}	0.85 ± 0.02	0.86 ± 0.05	0.84 ± 0.02	0.84 ± 0.03	0.84 ± 0.02
S_N^{2p2h}	1.5 ± 0.4	2.3 ± 0.01	1.7 ± 0.3	1.2 ± 0.4	1.7 ± 0.5
S_Δ^{2p2h}	0.7 ± 0.2	0.7 ± 0.3	(1.00)	2.1 ± 0.2	2.3 ± 0.2
S_{PL}^{2p2h}	0.4 ± 0.1	0.4 ± 0.1	(1.00)	0.9 ± 0.2	0.4 ± 0.1
χ^2	89/130	77/71	60/55	61/137	67/53

There's a clear energy dependence on the cross section shape

Conclusions of the nuclear tune

Now available on ArXiv

This work is the first nuclear tune effort performed with the GENIE global analysis framework:

- The goal is to tune against CC0π data from MiniBooNE, T2K and MINERvA
- Seven parameters are included to encapsulate CC0π modelling uncertainties
  - Correlated priors from the G18_02a_02_11b tune are included
- A partial tune is performed for each experiment, providing with a common ground for the discussion of tensions
- All CC0π partial tunes increase the CCQEL and CC2p2h cross section
- Differences between the tunes exist, highlighting a clear energy dependency on the cross section shape

Thank you for your interest

The GENIE Collaboration

Luis Alvarez-Ruso [4], **Costas Andreopoulos** [7,10], **Adi Ashkenazi** [11], **Joshua Barrow** [8,11], **Steve Dytman** [9], **Hugh Gallagher** [12], **Alfonso Andres Garcia Soto** [3,4] **Steven Gardiner** [2], **Matan Goldenberg** [11], **Robert Hatcher** [2], **Or Hen** [8], **Timothy Hobbs** [2], **Igor Kakorin** [6], **Konstantin Kuzmin** [5,6], **Anselmo Meregaglia** [1], **Vadim Naumov** [6], **Afroditi Papadopoulou** [8], **Gabriel Perdue** [2], **Marco Roda** [7], **Beth Slater** [7], **Alon Sportes** [11], **Noah Steinberg** [2], **Vladyslav Syrotenko** [12], **Jeremy Wolcott** [12], **Júlia Tena Vidal** [11]

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Backup slides

GENIE’s global analysis with Professor

Advantages of GENIE’s tuning approach:

- Not limited to reweightable parameters
- Allows massive parallelisation
- Reduces exponentially expensive brute force tuning to a scaling closer to the power law.
- Advanced system which can handle
  - Correlations between data bins
  - Correlated Gaussian priors
  - Nuisance parameters
  - Weights for specific data bins

https://professor.hepforge.org/

Other nuclear uncertainties

Other parameterizations were considered initially but not used in the final analysis.

These were affecting:

- FSI pion absorption
- Binding energy correction for QEL and 2p2h events

They were found to be highly correlated with other aspects of this tune

These can be used in future global tunes where we include additional data such as:

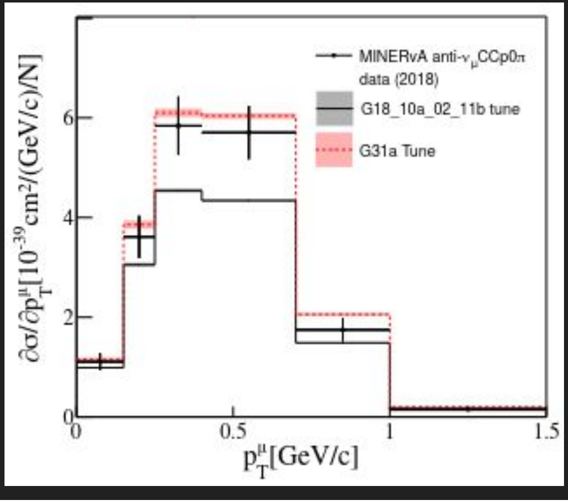
- ❖ CCNp0π
- ❖ CC1π …

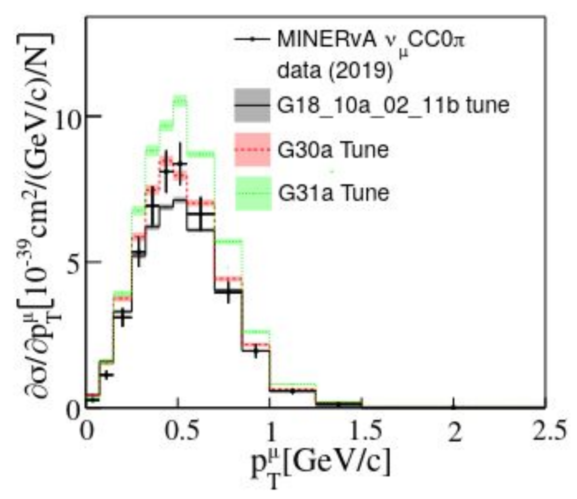
Tensions

The G31a tune (MINERvA anti-ν_μCC0p0π) overpredicts all the other datasets

- MINERvA's ν_μCC0π topology does not impose conditions on the proton multiplicity
- MINERvA's anti-ν_μCC0p0π topology requires no protons with T_p > 120 MeV

This tension can be due to the different event topology definition and the neutrino type

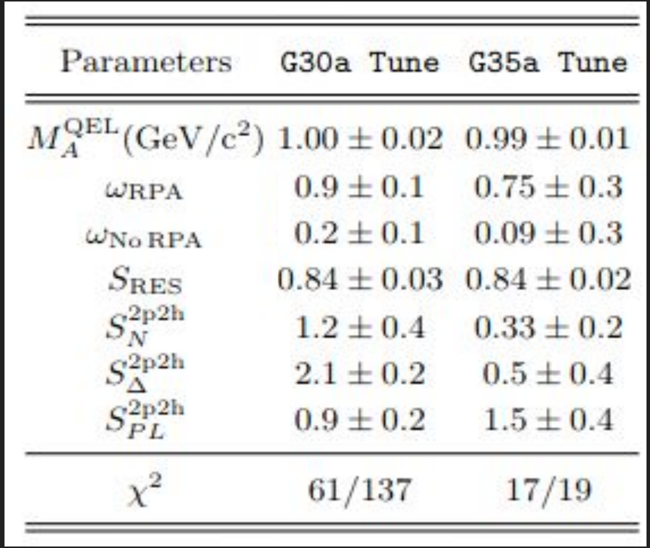




Tension between CC0π and CCNp0π datasets

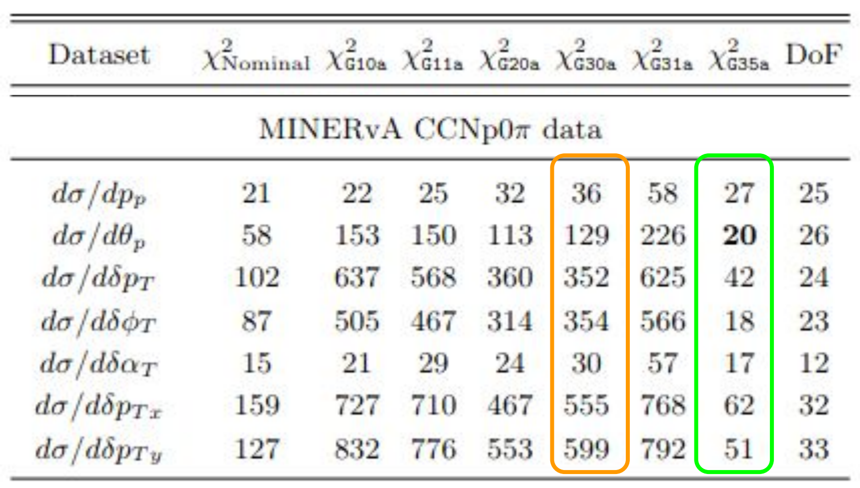
Tune to MINERvA ν_μ CCNp0π data:

- The G30a and G35a best-fit values are contradictory
- G35a suppresses the QEL and 2p2h cross sections to better describe the data
- **It highlights the need to improve the nuclear model**



Parameters	G30a Tune	G35a Tune
$M_A^{\rm QEL}(\rm GeV/c^2)$	1.00 ± 0.02	0.99 ± 0.01
$\omega_{\rm RPA}$	0.9 ± 0.1	0.75 ± 0.3
$\omega_{\rm No\,RPA}$	0.2 ± 0.1	0.09 ± 0.3
$S_{\rm RES}$	0.84 ± 0.03	0.84 ± 0.02
$S_N^{\rm 2p2h}$	1.2 ± 0.4	0.33 ± 0.2
$S_\Delta^{\rm 2p2h}$	2.1 ± 0.2	0.5 ± 0.4
$S_{PL}^{\rm 2p2h}$	0.9 ± 0.2	1.5 ± 0.4
χ^2	61/137	17/19

- ❖ G30a: GENIE tune to MINERvA ν_μ CC0π
- ❖ G35a: GENIE tune to MINERvA ν_μ CCNp0π



Dataset	$\chi^2_{\rm Nominal}$	$\chi^2_{\rm G10a}$	$\chi^2_{\rm G11a}$	$\chi^2_{\rm G20a}$	$\chi^2_{\rm G30a}$	$\chi^2_{\rm G31a}$	$\chi^2_{\rm G35a}$	DoF
MINERvA CCNp0π data								
$d\sigma/dp_p$	21	22	25	32	36	58	27	25
$d\sigma/d\theta_p$	58	153	150	113	129	226	**20**	26
$d\sigma/d\delta p_T$	102	637	568	360	352	625	42	24
$d\sigma/d\delta\phi_T$	87	505	467	314	354	566	18	23
$d\sigma/d\delta\alpha_T$	15	21	29	24	30	57	17	12
$d\sigma/d\delta p_{Tx}$	159	727	710	467	555	768	62	32
$d\sigma/d\delta p_{Ty}$	127	832	776	553	599	792	51	33

Neutrino CC0π cross-section data

This analysis focuses on:

MiniBooNE: ν_μ-^{12}C CC0π and anti-ν_μ-^{12}C CC0π

T2K ND280: ν_μ-^{12}C CC0p0π

MINERvA: ν_μ-^{12}C CC0π and anti-ν_μ-^{12}C CC0p0π

T2K and MINERvA’s data releases provide with information on the bin-to-bin correlation due to systematic uncertainties

➢ This information is included in our analysis

MiniBooNE does **not** provide with such information - Instead they quote a 10.7% normalization uncertainty for the neutrino case, which we add to our database.

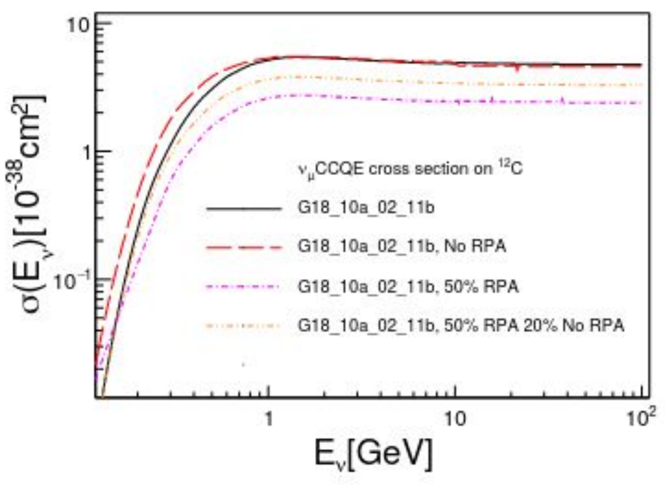
Goals of the Neutrino-Nucleus CC0π cross-section analysis

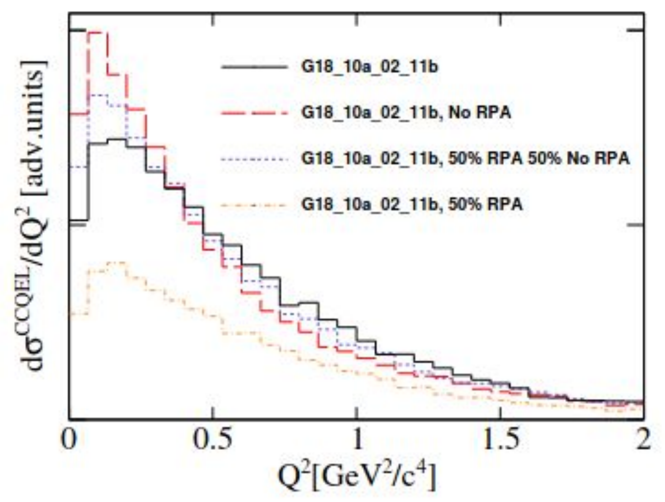
- Consolidate the main elements of the CC0π tuning methodology
- Explore avenues for improving the agreement of GENIE and nuclear data
- Provide with a common ground for the discussion of tensions between experiments

Parameterization of nuclear uncertainties of the CCQEL cross section

- At the free nucleon level, the CCQEL cross section is well understood
    - We impose a prior on the sum: $w_{RPA}+w_{No\ RPA} = 1\pm\sigma_S$
    - Nuclear effects might include some uncertainty on the scaling: $\sigma_S=0.2$
- We also need to impose a prior to the difference:
    - $w_{RPA}-w_{No\ RPA} = 1\pm\sigma_\Delta$
    - $\sigma_\Delta=5$
- This information is included in our tune using correlated priors

$$\Sigma_{\mathrm{RPA}} = \frac{1}{4}\begin{pmatrix} \sigma_S^2+\sigma_\Delta^2 & \sigma_S^2-\sigma_\Delta^2 \\ \sigma_S^2-\sigma_\Delta^2 & \sigma_S^2+\sigma_\Delta^2 \end{pmatrix}$$

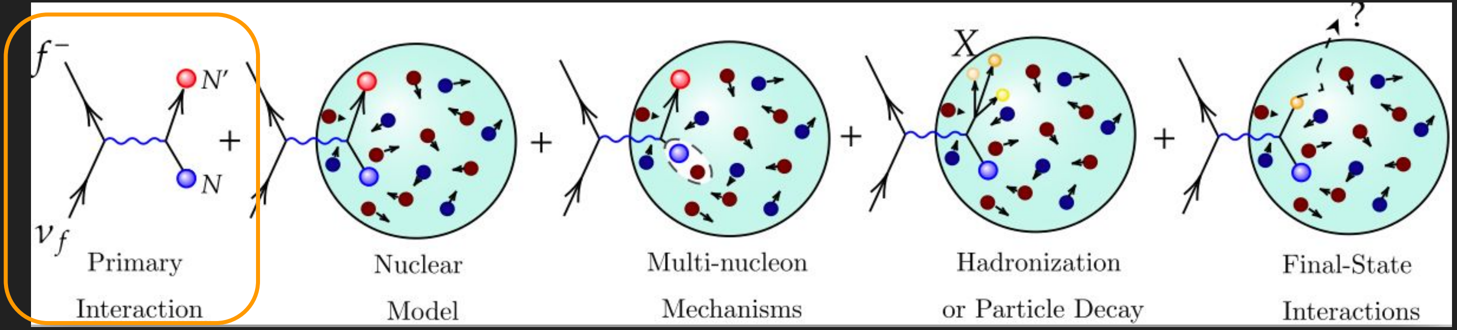




Uncertainties related to the free nucleon modeling

We model vA interactions by adding additional layers to the vN modeling

Key piece of this analysis

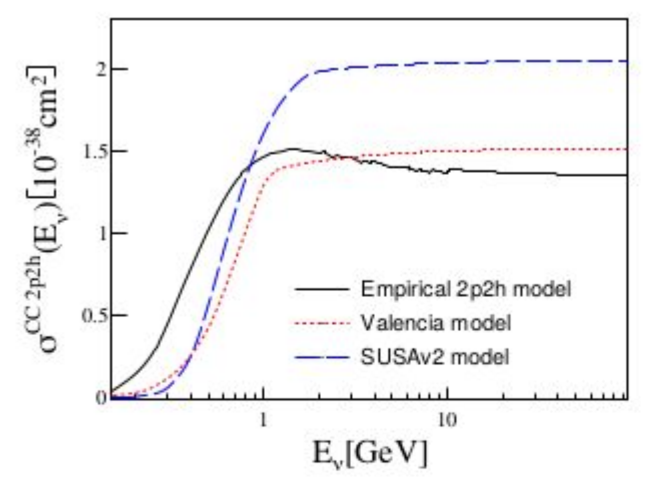


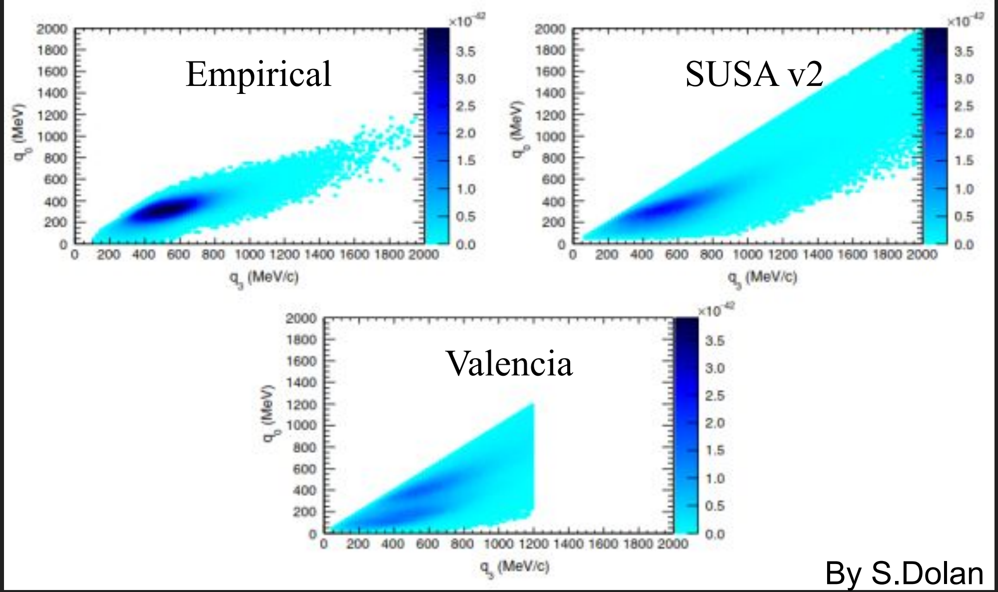
The **free nucleon tune** provides with data-driven constraints for the free-nucleon parameters

- Tuned against exclusive 1π and 2π data from ANL, BNL, BEBC and FNAL
- This information is included using correlated priors for M_A^{QEL} and S_{RES}

Parameterization of the CC2p2h cross section

- GENIE has three 2p2h models available
- Each model predicts a different shape and strength for the 2p2h cross section





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