Tuning of Monte Carlo event generators

Neutrino Scattering at Low and Intermediate Energies

at Mainz Institute for Theoretical Physics (MITP)

Julia Tena Vidal at Tel Aviv University

TEL AVIV UNIVERSITY אוניברסיטת תל אביב

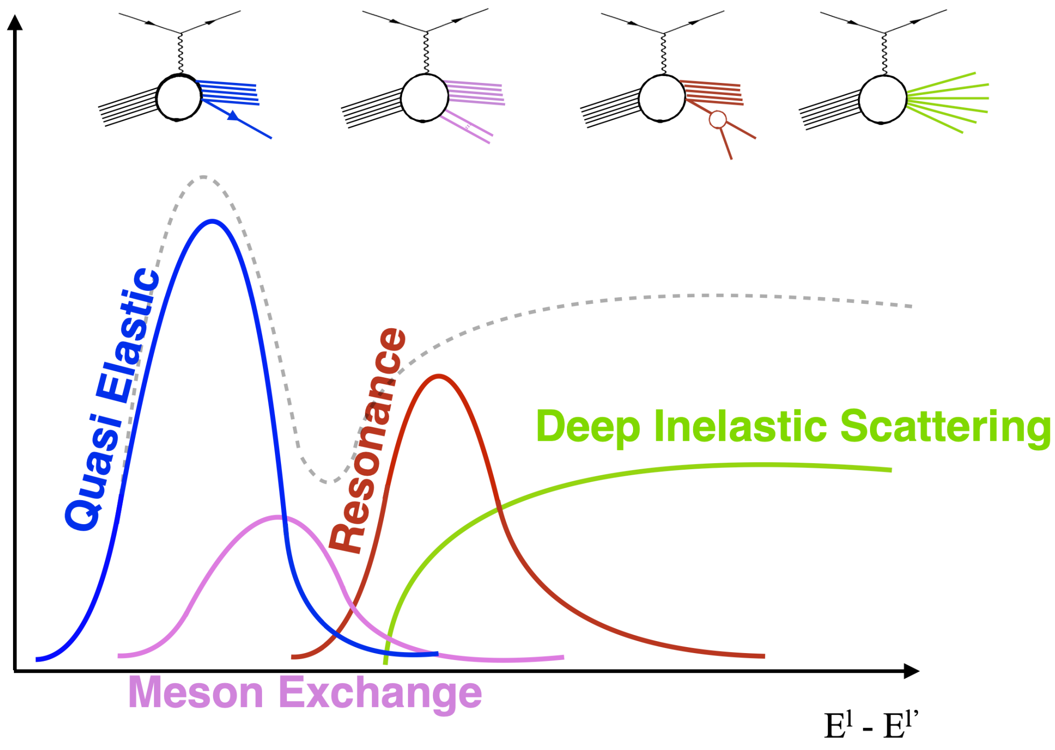
Genie

The TAU Neutrino Group

Neutrino event generators

Event generators provide with the state of the art neutrino interaction modelling

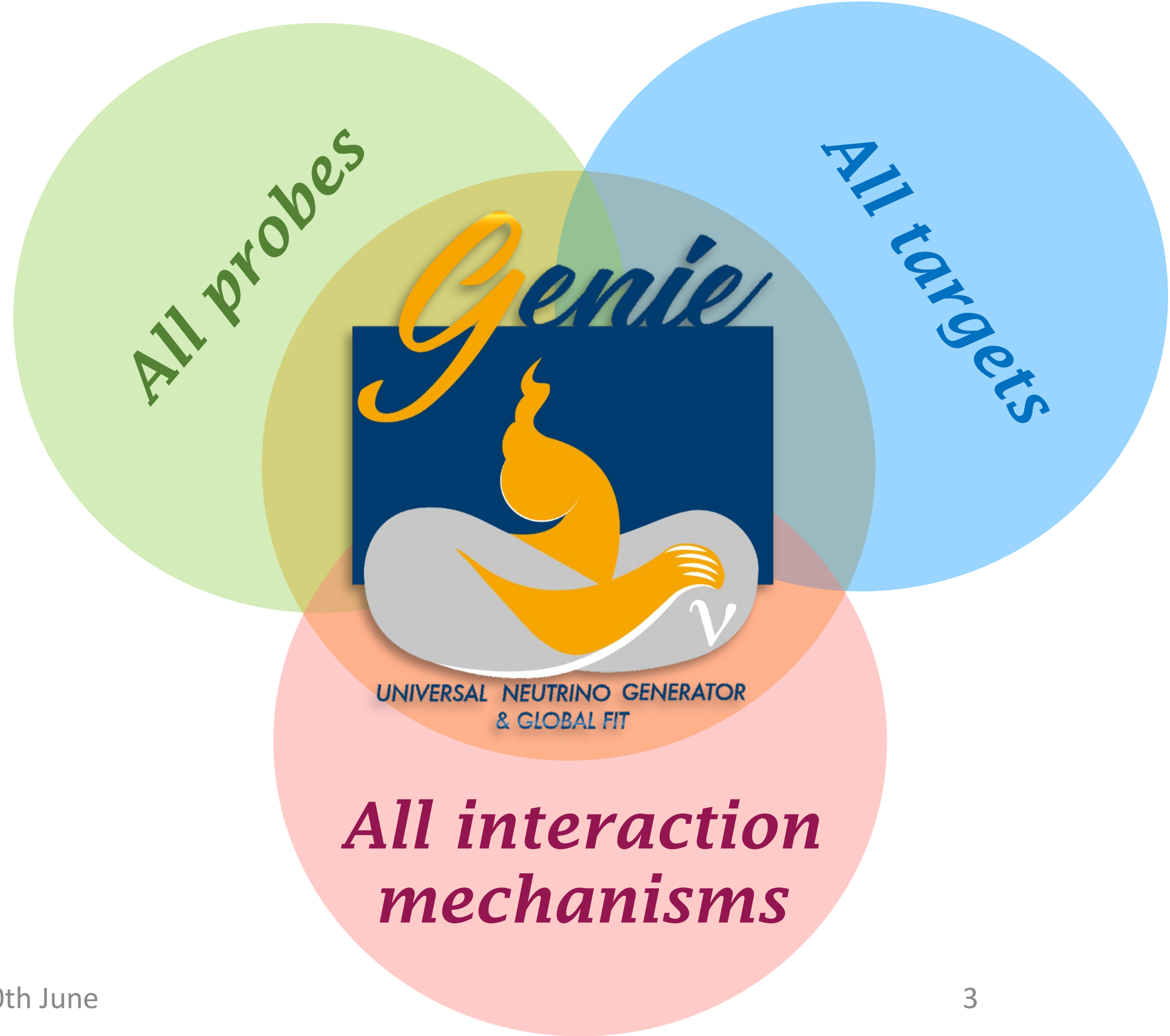
- **ν-experiments rely on simulations:**
  - To reconstruct the neutrino energy, estimate backgrounds, systematic uncertainties, …
- **Models are not complete**
  - Limited phase space coverage
  - Focus on lepton kinematics
  - Focus on lepton kinematics
  - Empirical transition between kinematic regions
  - Nuclear effects are factorized out
- **Model systematic uncertainties estimates**
  - Missing from current theory models



The GENIE event generator

GENIE model configurations

- For each interaction process, GENIE offers a **range of models**
- These are grouped into **model configurations**
  - Consistent set of interaction models
  - A configuration englobes all interaction mechanisms, for all probes and targets, at the energies of interest for neutrino experiments

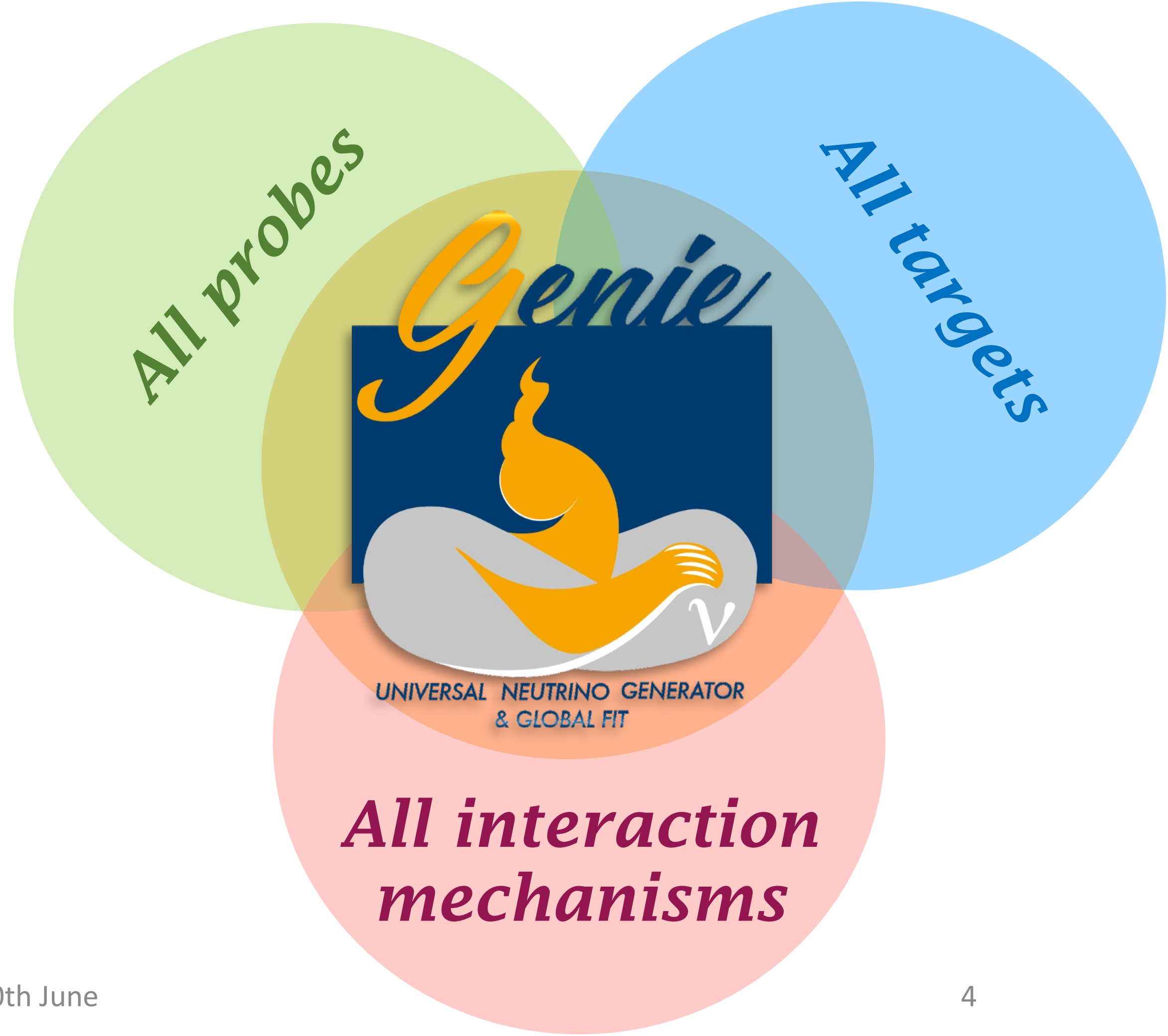


The GENIE event generator

GENIE model configurations

Models can be classified into:

- **Theoretical models** are used to simulate specific processes at specific parts of the phase space
- **Empirical models** complete the picture
  - **Data-driven models**
  - **Transition regions**
  - **Inclusive models**



Empirical aspects of the GENIE event generator

Data-driven models

- **Parameterization of vector and axial QEL and RES form factors**
  - Fits to e-N and ν-N data
- **Low-W AGKY Hadronization**
  - “Tuned” to ν-N data
- **GENIE hA 2018**
  - Fates and mean-free-path
- **Ground state model**
  - Binding-energy
  - High-momentum tail

Transition regions

- **Shallow Inelastic Scattering**
  - Simplistic RES model
  - Empirical non-resonant background (NRB)
  - Coupled to low-W AGKY
  - Tuned to ν-N data
- **AGKY Hadronization model**
  - Low-W to high-W hadronization (PYTHIA)
  - Low-W parameters extracted from H data

Inclusive cross-section models

- Lepton kinematics only
- **2p2h inclusive models:**
  - Valencia and SuSAv2
  - Theory-driven models
  - Pre-computed hadron tensors for isoscalar nuclei
  - Used in exclusive final-states
- **π kinematics:**
  - Rein-Sehgal and Berger-Sehgal RES models
  - π-kinematics after decay

Why tuning event generators?

1. Optimize baseline model with data
2. Constrain empirical models
3. Minimize double-counting in transition regions
4. Data-driven constrains and uncertainties
5. Highlight model limitations
6. Quantify/resolve tensions between experiments

Review of MC tuning methods

GENIE's interaction model parameters can be tuned using different methods:

Analytic calculations

- Tune the GENIE physics algorithms directly
- Nominal prediction is an analytical calculation
- Splines/events not needed to build the predictions
- **Restricted to analytical models**

GENIE Reweight ("RWG")

- Nominal prediction build using full event information
  - Can construct any type of prediction
- Reweight is used to emulate parameter impact on the nominal prediction
- **Limited to reweightable models**

GENIE-Professor based tunes

- Prediction is build using full event information
  - Can construct any type of prediction
- Professor-build response function using brute-force parameter scans
  - Parameters are defined in the event generator
- **Can tune all aspects of your event generator!**

Review of MC tuning methods

GENIE's interaction model parameters can be tuned using different methods:

Analytic calculations

- Tune the GENIE physics algorithms directly
- Nominal prediction is an analytical calculation
- Splines/events not needed to build the predictions

Analytical nominal prediction

Analytical response function

- **Restricted to analytical models**

GENIE Reweight ("RWG")

- Nominal prediction build using full event information
  - Can construct any type of prediction
- Reweight is used to emulate parameter impact on the nominal prediction

Monte Carlo prediction

Analytical response function

- **Limited to reweightable models**

GENIE-Professor based tunes

- Prediction is build using full event information
  - Can construct any type of prediction
- Professor build response function using brute-force parameter scans
  - Parameters are defined in the event generator

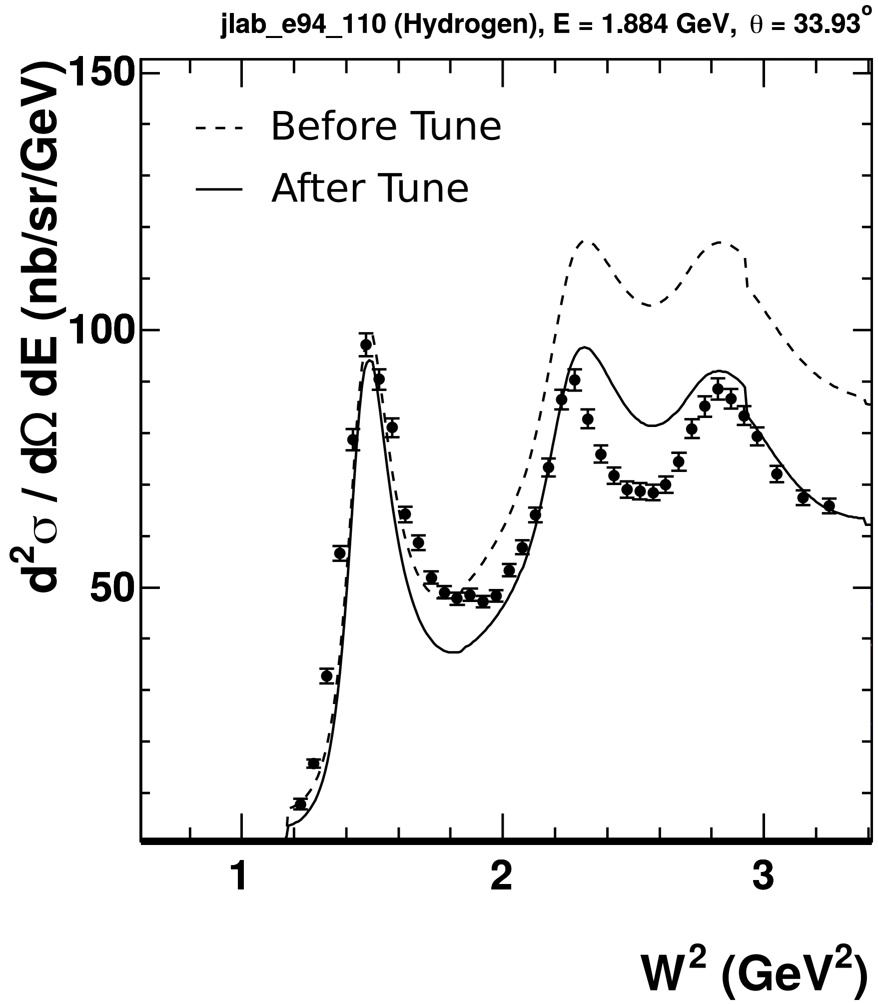
Monte Carlo prediction

Monte-Carlo parameterized response function

- **Can tune all aspects of your event generator!**

Analytical calculation

- **Possible use case:** tune of e-N inclusive data
- e-N inclusive can be calculated directly using GENIE cross-section algorithms
  - Known beam energy, probe and target type (nucleon)
  - Simplified case without stochasticity
  - No need to generate events
- **NRB tune with inclusive electron data**
  - Single scaling parameter for all NRB
  - NRB parameters depend on pion multiplicity
    - Can only be tuned with exclusive data



GENIE Reweight

https://github.com/GENIE-MC/Reweight

- Nominal prediction is reweighted to emulate parameter impact

$$w = \sigma'(\vec{p} + \Delta\vec{p}) \Big/ \sigma(\vec{p})$$

  - σ is the baseline cross-section
  - σ' is the cross section after parameter variations
- No need to re-generate the events
- Each parameter can have a ”dial” or “knob” which produces weights
  - Must be able to express the weight as a function of the dial
  - Several knobs are already available on GitHub:
    - I.e: shape and normalization parameters, resonance decay knobs, hA knobs, etc.
- Most-common technique used in neutrino experiments
  - Tunes to near-detector data

GENIE Reweight limitations

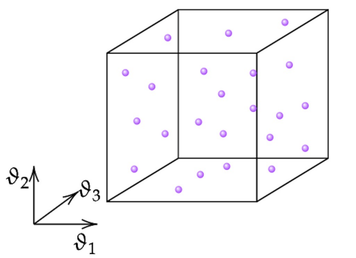
https://github.com/GENIE-MC/Reweight

- The product does not include weight calculators for several important processes
  - New knobs can be added by the user – it can be a non-trivial task
  - Several important simulation aspects are not reweightable, such as FSI cascade models or hadronization
  - This limits the physics that can be tuned with this technique
  - Approximations are not always justifiable
- It doesn't provide a comprehensive parameterization of the underlying model configuration
  - ReWeight behaviour should be specific to the configuration
  - Lack of rich parameter constraints
- The tune cannot be easily run out of the box
  - Users must run reweight packages on top of the nominal GENIE predictions

GENIE-Professor based tunes

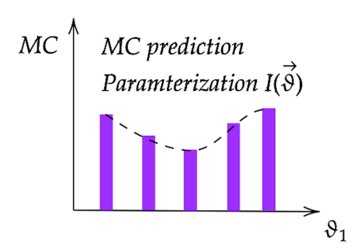
https://professor.hepforge.org

The GENIE-Professor method is based on a brute force approach



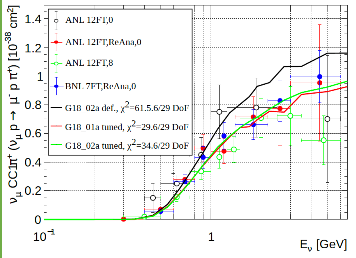
Brute-force scan of Monte Carlo response function

- Predictions are constructed in specific points of the parameter space
- No limitation on number of parameters to tune
- The response function is computed for the datasets of interest



Parameterisation of response function

- The predictions are then interpolated using N-dimensional polynomials as a function of the parameter space
- Handled by the standard Professor software [The European Physical Journal C volume 65, 331 (2010)]
- The parameterization is not exact. Validation tools are used.



Minimization of the MC response function parameterization

- Developed entirely by GENIE with emphasis on neutrino experiments demands
- Multi-dimensional parameter priors (uncorrelated and correlated), weights, nuisance parameters
- Can handle bin-to-bin correlation as well as correlation between experiments
- Proper treatment of highly correlated datasets with Peelle's Pertinent Puzzle resolution

Expected output

- Best-fit tuned parameters results
- Estimated systematic uncertainties / correlation matrix

- **Tuned configuration to run out-of-the box**
  - New parameterizations are added directly in the GENIE Generator
  - The results of the tune can be easily included in GENIE CMC's to be run by users
    - Complex configurations are handled with tune tags: Example of nuclear tune configuration (GPRD18_10a)

GENIE global analysis program

https://professor.hepforge.org

- Model fitting and data-driven uncertainty quantification
- Curated data-base
  - Neutrino-scattering
  - Electro-scattering
  - Hadro-nucleus scattering
- Applicable to all modelling aspects
  - Can tune non-reweightable models
- Easily to replicate whenever new models are included

Based on the **Professor concept**
- Developed by LHC community
- Concept applied to neutrinos for the first time by GENIE

GENIE-Professor based tunes

Hydrogen and deuterium bubble chamber data

- **Neutrino-Nucleon Cross-Section Model Tuning in GENIE v3**
  - Focus on the Shallow inelastic region
  - Global CC inclusive, 1π and 2π datasets
  - [PhysRevD.104.072009]
- **Hadronization Model Tuning in GENIE v3**
  - First neutrino-induced hadronization tune
  - Charged averaged neutrino data as a function of W
  - [PhysRevD.105.012009]

Nuclear tunes with modern neutrino data

- **Neutrino-nucleus CC0π cross-section tuning in GENIE v3**
  - Carbon data from MicroBooNE, T2K and MINERvA data
  - Focus on partial tunes to individual experiments and tensions between datasets
  - [PhysRevD.106.112001]

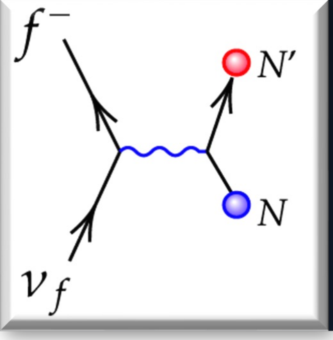
GENIE-Professor based tunes

Hydrogen and deuterium bubble chamber data

- **Neutrino-Nucleon Cross-Section Model Tuning in GENIE v3**
  - Focus on the Shallow inelastic region
  - Global CC inclusive, 1π and 2π datasets
  - [PhysRevD.104.072009]
- **Hadronization Model Tuning in GENIE v3**
  - First neutrino-induced hadronization tune
  - Charged averaged neutrino data as a function of W
  - [PhysRevD.105.012009]

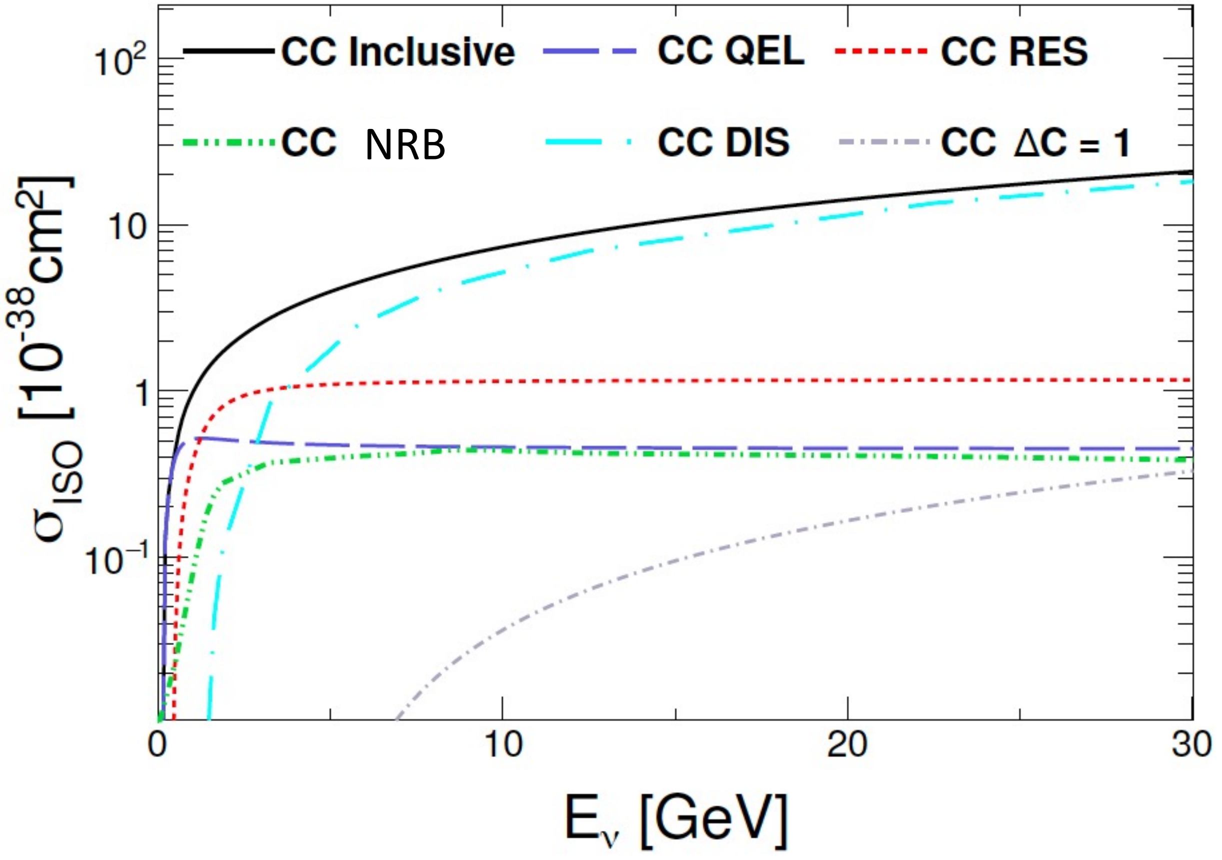
Nuclear tunes with modern neutrino data

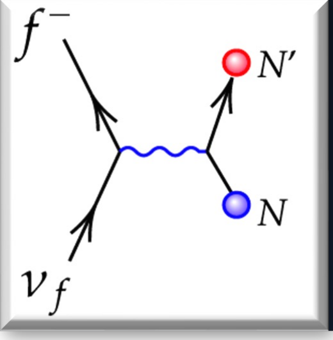
- **Neutrino-nucleus CC0π cross-section tuning in GENIE v3**
  - Carbon data from MicroBooNE, T2K and MINERvA data
  - Focus on partial tunes to individual experiments and tensions between datasets
  - [PhysRevD.106.112001]



Tuning of $\nu - N$ interaction models

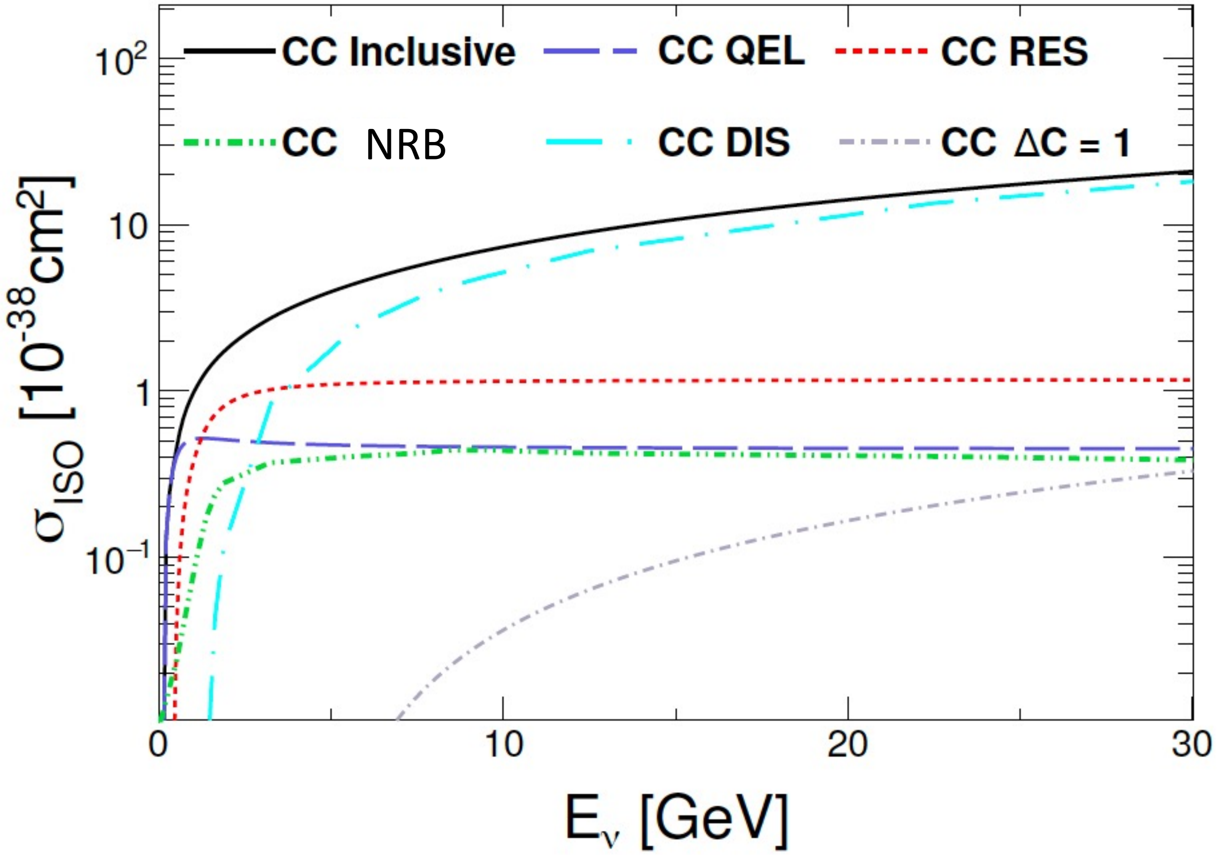
- ν-N models are crucial to describe ν-A interactions
  - Starting point for ν-A simulations
- Quasi-elastic is relatively well understood
  - Llewellyn-Smith model
  - Inputs from neutrino, electro-scattering and beta decay experiments
- Deep-Inelastic Scattering:
  - Bodek and Yang model
  - Cross-section computation at partonic level
  - Overall scaling factor of 1.032
    - Agreement with high energy ν-cross-section data
  - Hadronized with AGKY model

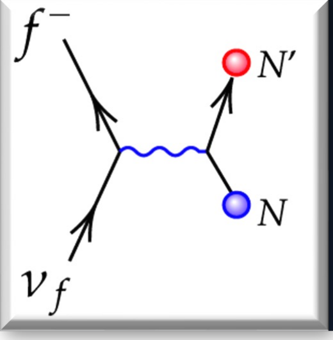




Tuning of $\nu - N$ interaction models

- Shallow inelastic Scattering:
  - Very hard to model
  - **Resonant** and **non-resonant** (NRB) contribution cannot be distinguished experimentally
  - **Interference between resonances and NRB**
  - Models should predict single- multiple-pion production mechanisms
  - 184 ν-N data points available from bubble chamber experiments
    - ANL 12FT, BNL 7FT, FNAL 15FT and BEBC
    - Hydrogen and deuterium





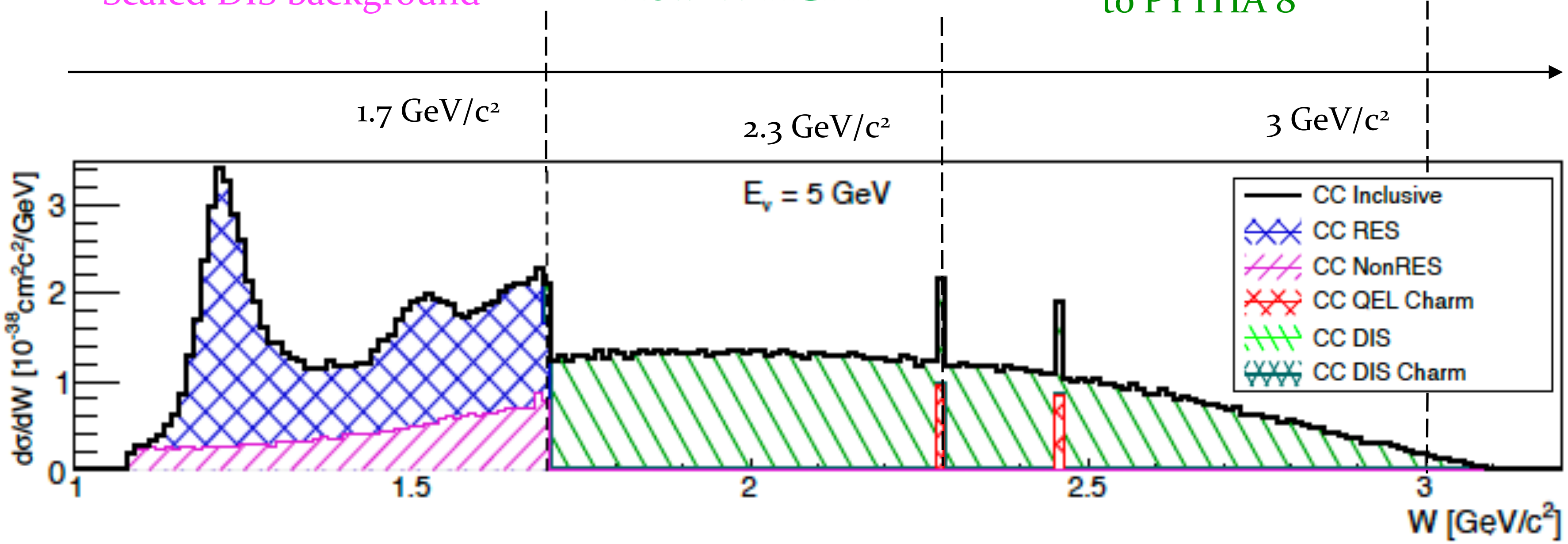
$\nu - N$ Shallow-Scattering Inelastic region

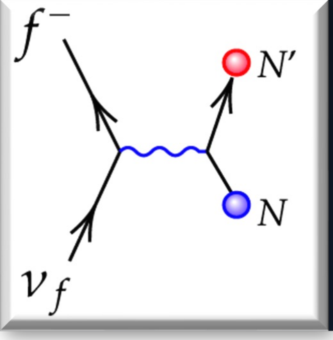
Resonances
+
Scaled DIS background

DIS
Low-W AGKY

DIS
Linear transition
to PYTHA 8

DIS
PYTHA 8





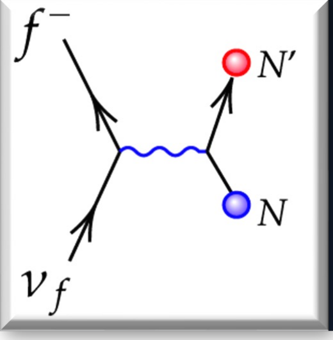
$\nu - N$ Shallow-Scattering Inelastic region

RES is modelled with Rein-Sehgal or Berger-Sehgal models

- Resonances are added coherently in GENIE
- In GENIE's implementation, additional resonances are added - 1π and 2π production
- Not full kinematical models – resonances are decayed to get full pion kinematics
- RES model does account for NRB

$$\frac{d^2\sigma^{inel}}{dQ^2dW} = \begin{cases} \frac{d^2\sigma^{RES}}{dQ^2dW} + \frac{d^2\sigma^{NRB}}{dQ^2dW} & for\ W < \boldsymbol{W_{cut}} \\ \frac{d^2\sigma^{DIS}}{dQ^2dW} & for\ W \geq \boldsymbol{W_{cut}} \end{cases}$$

Free parameters



$\nu - N$ Shallow-Scattering Inelastic region

- **Lack of a NRB model**
- Duality inspired approach:

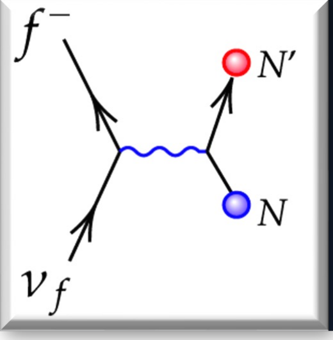
  "On average, the RES cross section is described by the DIS cross section at W<2 GeV"
- We use the DIS prediction to account for the missing NRB model
  - Tuning is essential to avoid double-counting
- NRB modelled with Bodek and Yang extrapolated at $W < W_{cut}$
- f_m parameters **couple** with the AGKY model

$$f_m(Q^2, W) = R_m P_m^{\text{had}}(Q^2, W) \qquad P_m^{\text{had}}(Q^2, W) = \frac{1}{\langle m \rangle} \psi\left(\frac{m}{\langle m \rangle}\right)$$

m: hadron multiplicity

$$\frac{d^2\sigma^{NRB}}{dQ^2 dW} = \frac{d^2\sigma^{DIS}}{dQ^2 dW} \cdot \Theta(\boldsymbol{W_{cut}} - W) \cdot \sum_m \boldsymbol{f_m}(Q^2, W)$$

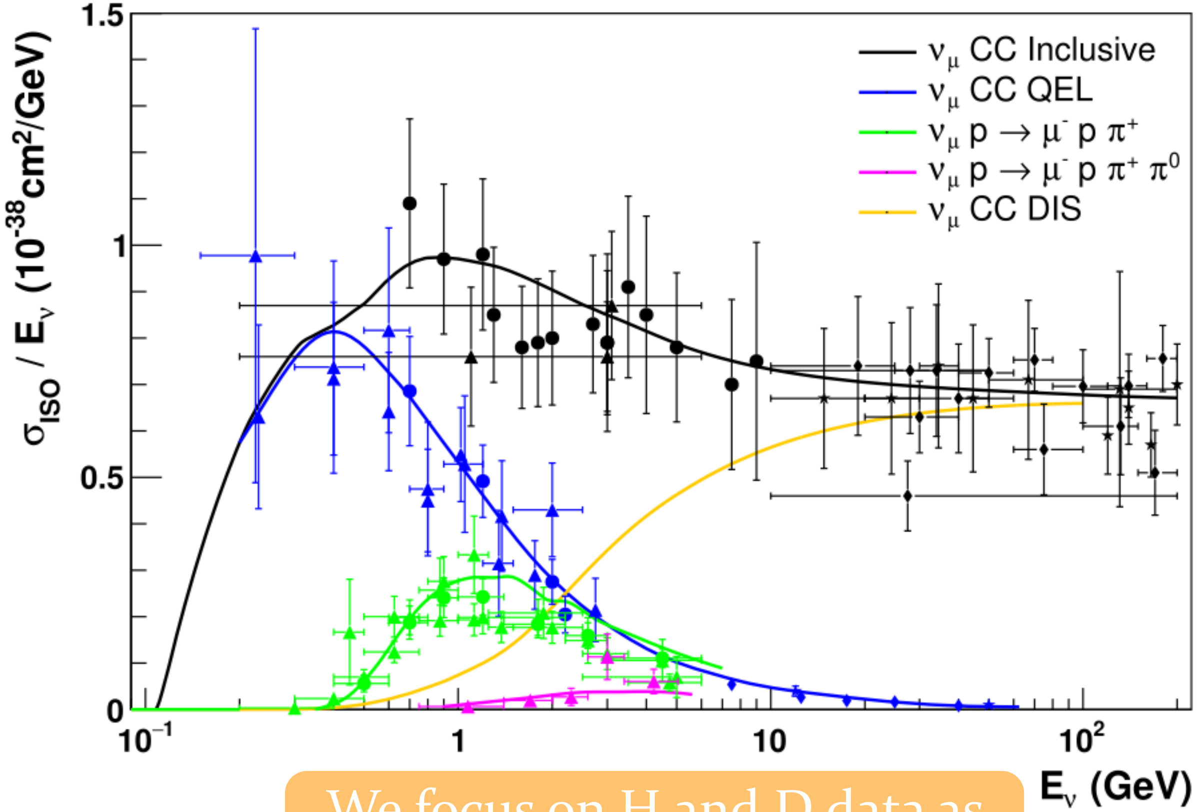
Free parameters



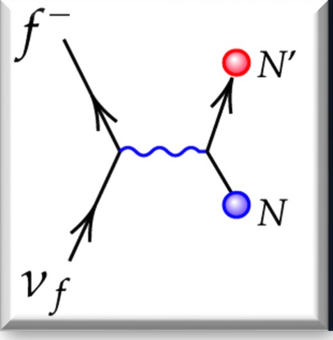
Tuning the Shallow-Scattering Inelastic region
Available datasets

PhysRevD.104.072009

- ν_μ and anti- ν_μ CC inclusive
- ν_μ and anti- ν_μ CC QEL
- ν_μ and anti- ν_μ CC single-pion
  - $\nu_\mu + n \to \mu^- + n + \pi^+$
  - $\nu_\mu + p \to \mu^- + p + \pi^+$
  - $\nu_\mu + n \to \mu^- + p + \pi^0$
  - $\bar{\nu}_\mu + p \to \mu^+ + p + \pi^-$
  - $\bar{\nu}_\mu + n \to \mu^+ + n + \pi^-$
- ν_μ and anti- ν_μ CC two-pion
  - $\nu_\mu + p \to \mu^- + n + 2\pi^+$
  - $\nu_\mu + p \to \mu^- + p + \pi^+ + \pi^0$
  - $\nu_\mu + p \to \mu^- + n + \pi^+ + \pi^-$



We focus on H and D data as a function of E_ν



Tuning the Shallow-Scattering Inelastic region
Parameters of interest

PhysRevD.104.072009

RES model parameters:

- M_A^{RES}: global fit result applied as prior - $M_A^{RES} = 1.014 \pm 0.014\ GeV$
- S_{RES}: overall scaling factor for RES cross-section

NRB model parameters:

- W_{cut} to determine the end of the SIS region
- R_m parameters for proton and neutron, multiplicity 2 and 3
- *Simplification:* we neglect the AGKY low-W parameters

DIS model parameters:

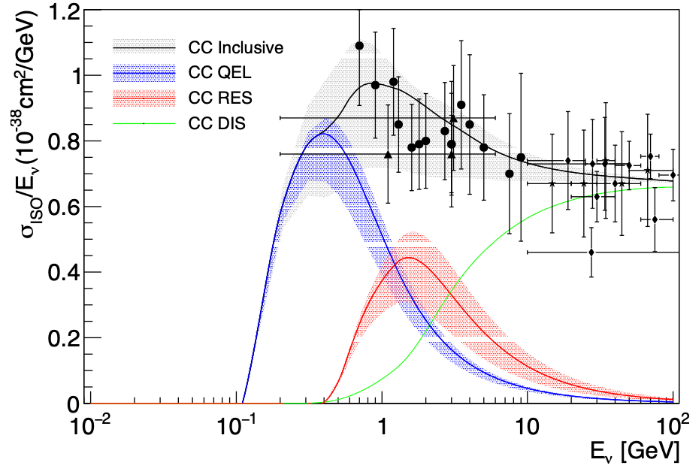
- S_{DIS}: overall scaling factor for DIS cross-section
- Prior of 1±0.5 to preserve agreement with high E data (>100GeV)

QEL model parameters:

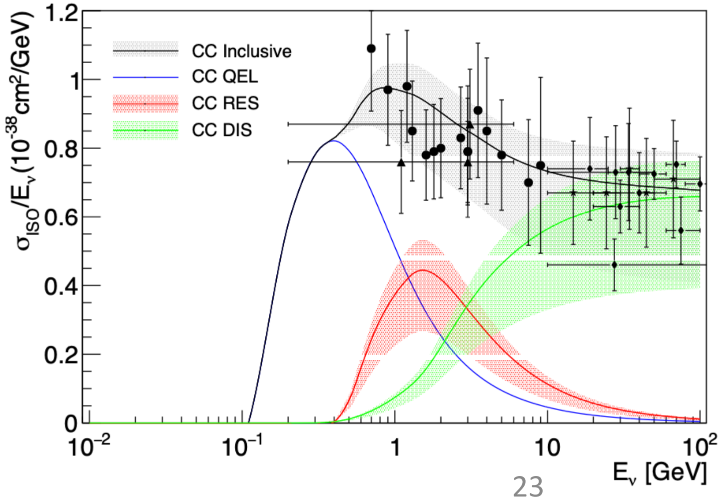
- M_A^{QEL}: global fit result applied as prior - $M_A^{RES} = 1.12 \pm 0.03\ GeV$

Normalization uncertainty:

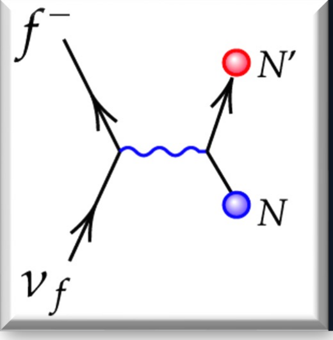
- Nuisance parameters per experiment to account for missing normalization uncertainties



(a) M_A^{RES} and M_A^{QE} impact.



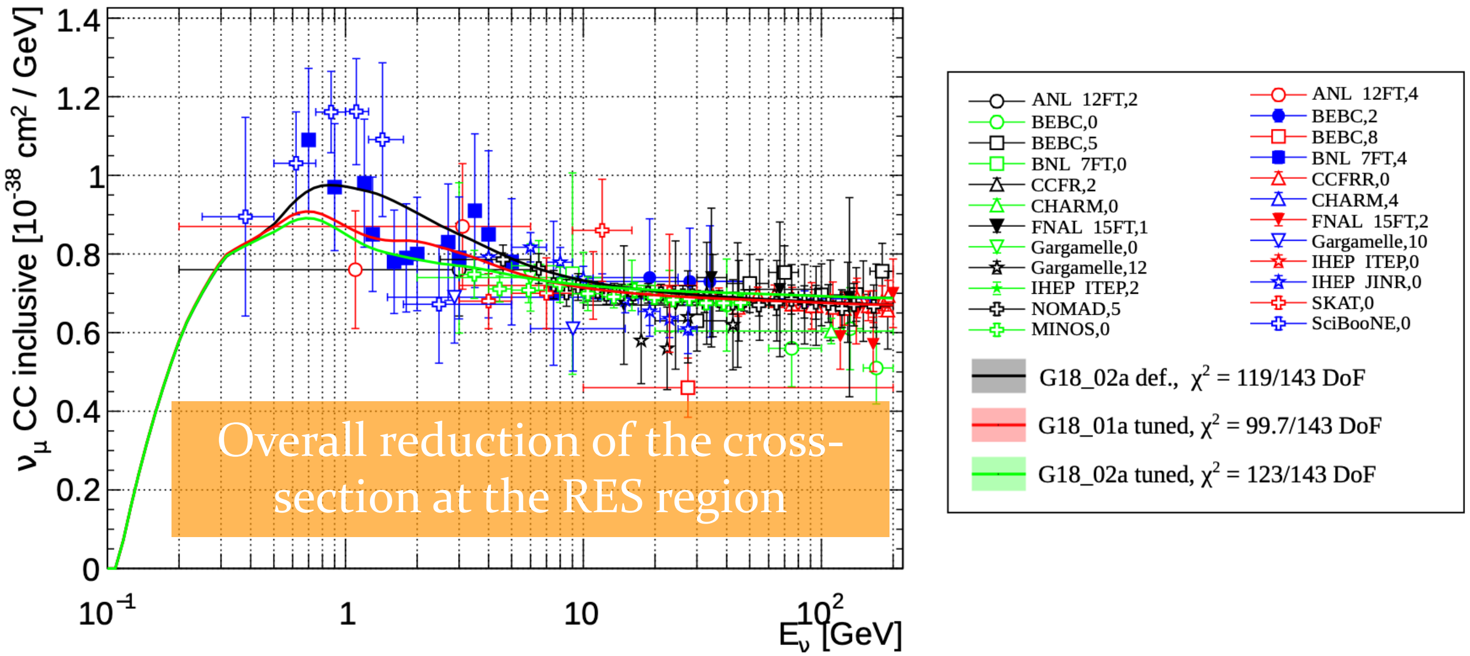
(b) S_{RES} and S_{DIS} impact.



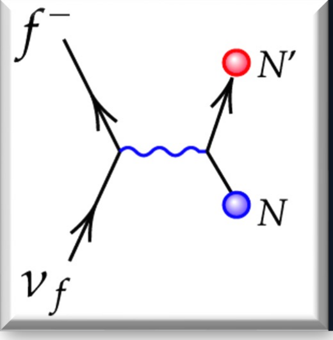
Tuning the Shallow-Scattering Inelastic region

PhysRevD.104.072009

Parameter	Default	G18_02a
$\boldsymbol{S_{RES}}$	**1.00**	**0.84±0.03**
S_{DIS}	1.032	1.06±0.01
$R_{\nu p}^{CC1\pi}$	0.10	0.008
$R_{\nu n}^{CC1\pi}$	0.30	0.03±0.01
$R_{\nu p}^{CC2\pi}$	1.00	0.94±0.08
$R_{\nu n}^{CC2\pi}$	1.00	2.3±0.1
M_A^{QEL}	0.999	1.00±0.013
M_A^{RES}	1.12	1.09±0.014
W_{cut}	1.7	1.81
$\chi^2/157DoF$		1.64



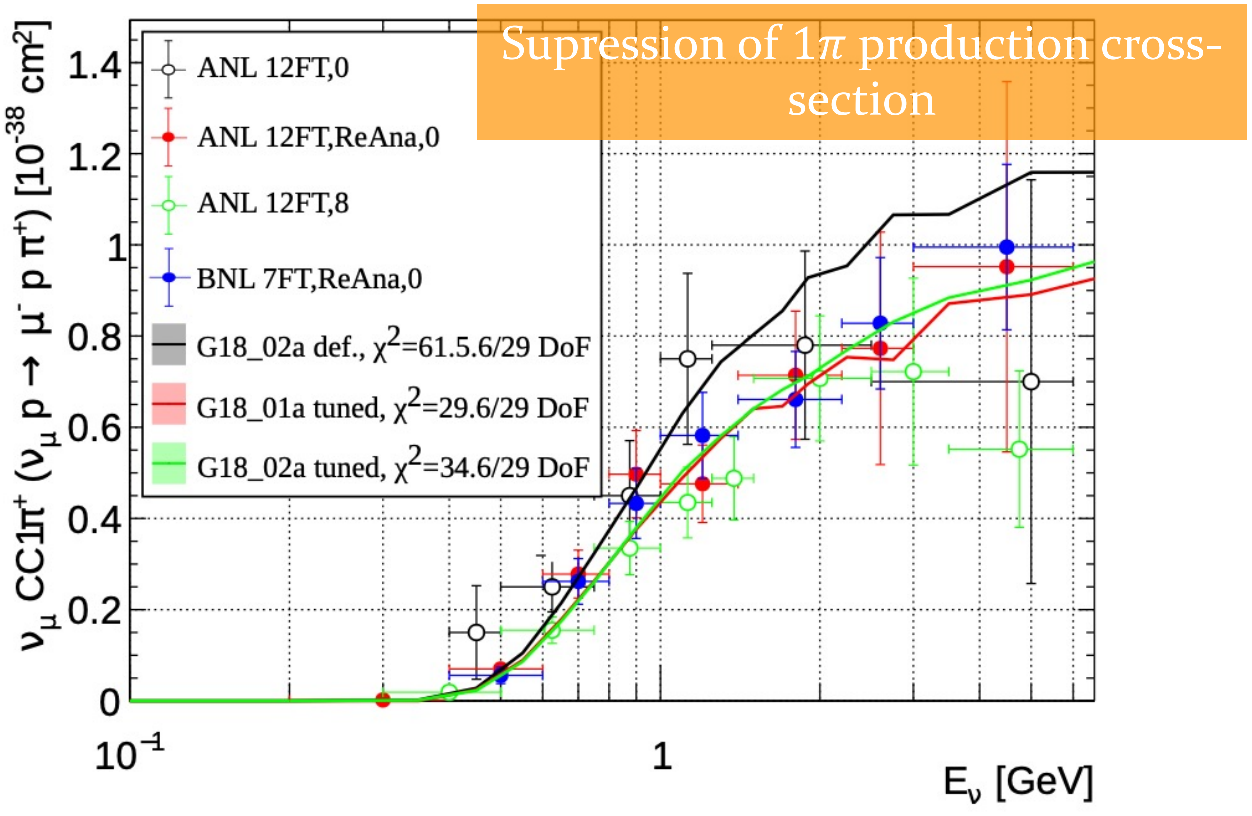
(a) Comparison of ν_μ CC Inclusive cross-section data against against the *default* and tuned CMC.



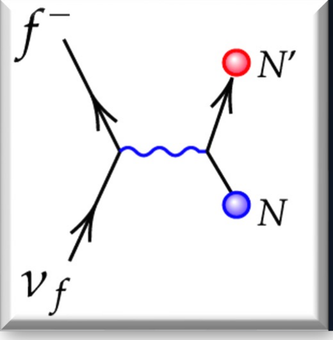
Tuning the Shallow-Scattering Inelastic region

PhysRevD.104.072009

Parameter	Default	G18_02a
S_{RES}	1.00	0.84±0.03
S_{DIS}	1.032	1.06±0.01
$\mathbf{R_{\nu p}^{CC1\pi}}$	**0.10**	**0.008**
$\boldsymbol{R_{\nu n}^{CC1\pi}}$	**0.30**	**0.03±0.01**
$R_{\nu p}^{CC2\pi}$	1.00	0.94±0.08
$R_{\nu n}^{CC2\pi}$	1.00	2.3±0.1
M_A^{QEL}	0.999	1.00±0.013
M_A^{RES}	1.12	1.09±0.014
W_{cut}	1.7	1.81
$\chi^2/157DoF$		1.64



(a) Comparison of ν_μ CC $1\pi^+$ data on proton against the *default* and tuned CMCs.

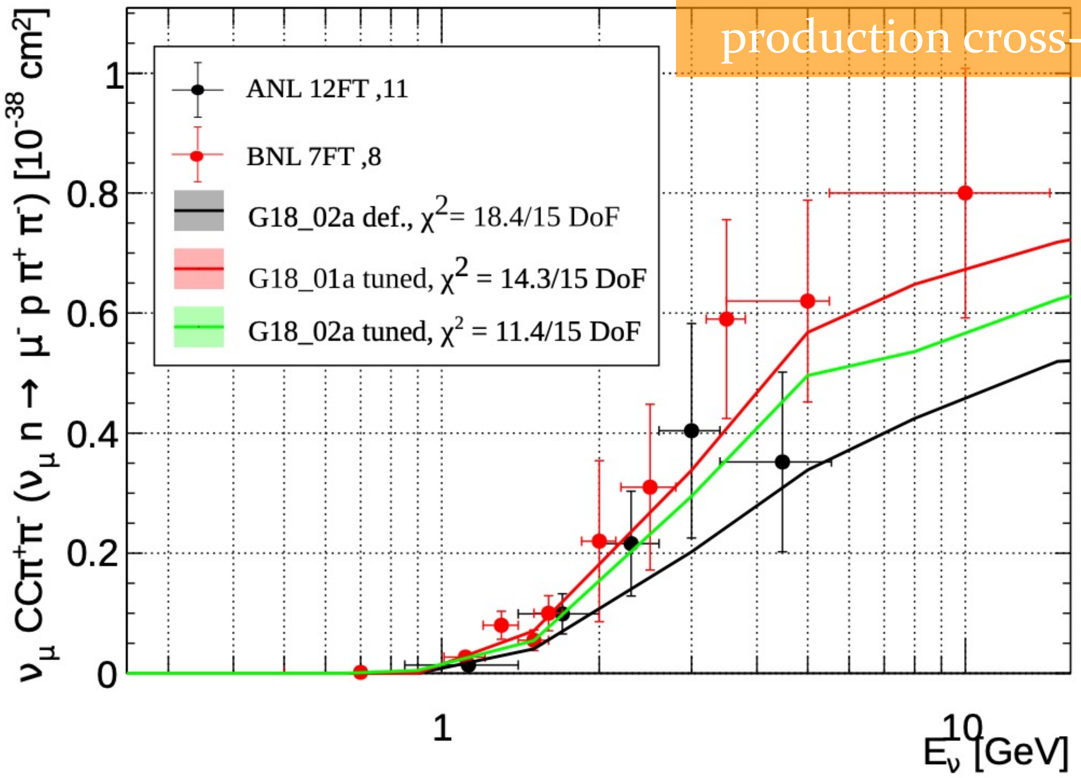


Tuning the Shallow-Scattering Inelastic region

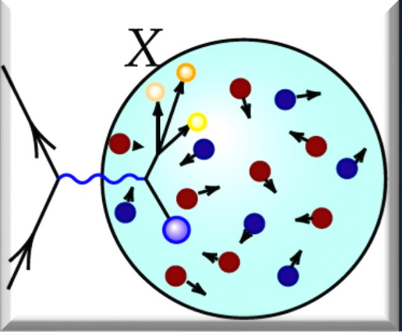
PhysRevD.104.072009

Parameter	Default	G18_02a
S_{RES}	1.00	0.84±0.03
S_{DIS}	1.032	1.06±0.01
$R_{\nu p}^{CC1\pi}$	0.10	0.008
$R_{\nu n}^{CC1\pi}$	0.30	0.03±0.01
$\boldsymbol{R_{\nu p}^{CC2\pi}}$	**1.00**	**0.94±0.08**
$\boldsymbol{R_{\nu n}^{CC2\pi}}$	**1.00**	**2.3±0.1**
M_A^{QEL}	0.999	1.00±0.013
M_A^{RES}	1.12	1.09±0.014
$\mathbf{W_{cut}}$	**1.7**	**1.81**
$\chi^2/157DoF$		1.64

Enhancement of 2π production cross-section

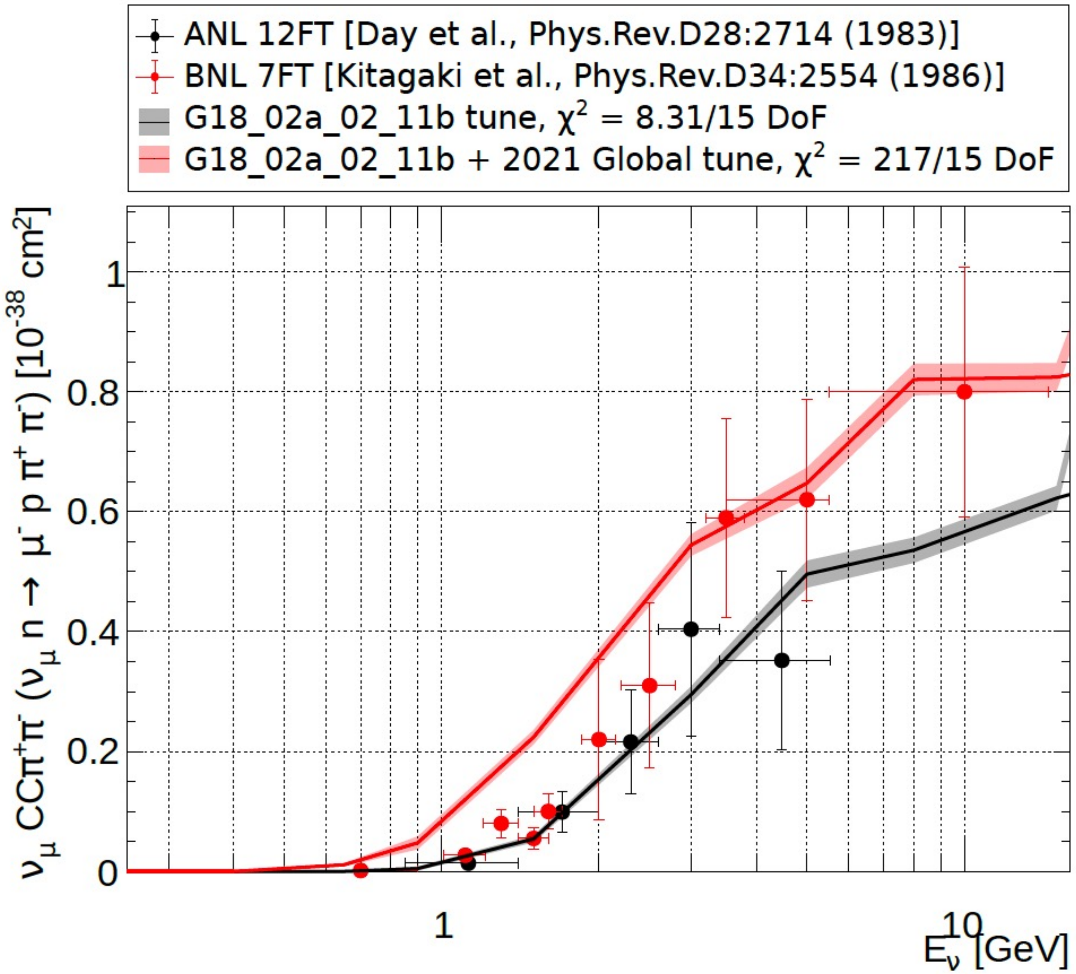


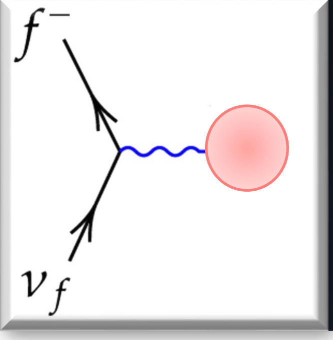
(c) Comparison of ν_μ CC $\pi^+\pi^-$ data on neutron.



Hadronization tuning impact on the Shallow Inelastic Scattering region

- The SIS region in GENIE is affected by low-W AGKY parameters
  - We simplified the problem into two separate tunes
- When the hadronization tune results are applied on the SIS region, we observe an increase of two-pion production
- The tunings are not fully independent in this configuration
  - This difference is absorbed as an increase of $R_{\nu p}^{CC2\pi}$ and $R_{\nu n}^{CC2\pi}$ in the free nucleon tune





Tuning of $\nu - A$ interaction models

PhysRevD.104.072009

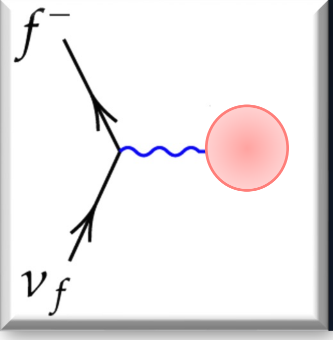
The nuclear environment further complicates the picture:

GENIE ν-A model models

Nuclear model	**Local Fermi Gas**, Bodek-Ritchie Fermi Gas, Correlated Fermi Gas
QEL model	**Valencia**, SuSAv2
RES model	**Berger-Sehgal**, Rein-Sehgal, MK model (*)
MEC model	**Valencia**, Empirical MEC, SuSAv2
DIS model	**Bodek-Yang**
FSI model	**hA**, hN, INCL++, GEANT

(*) Under internal review. Single-pion production model

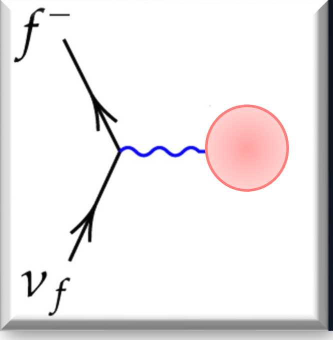
G18_10a_02_11b



Tuning of $\nu - A$ interaction models

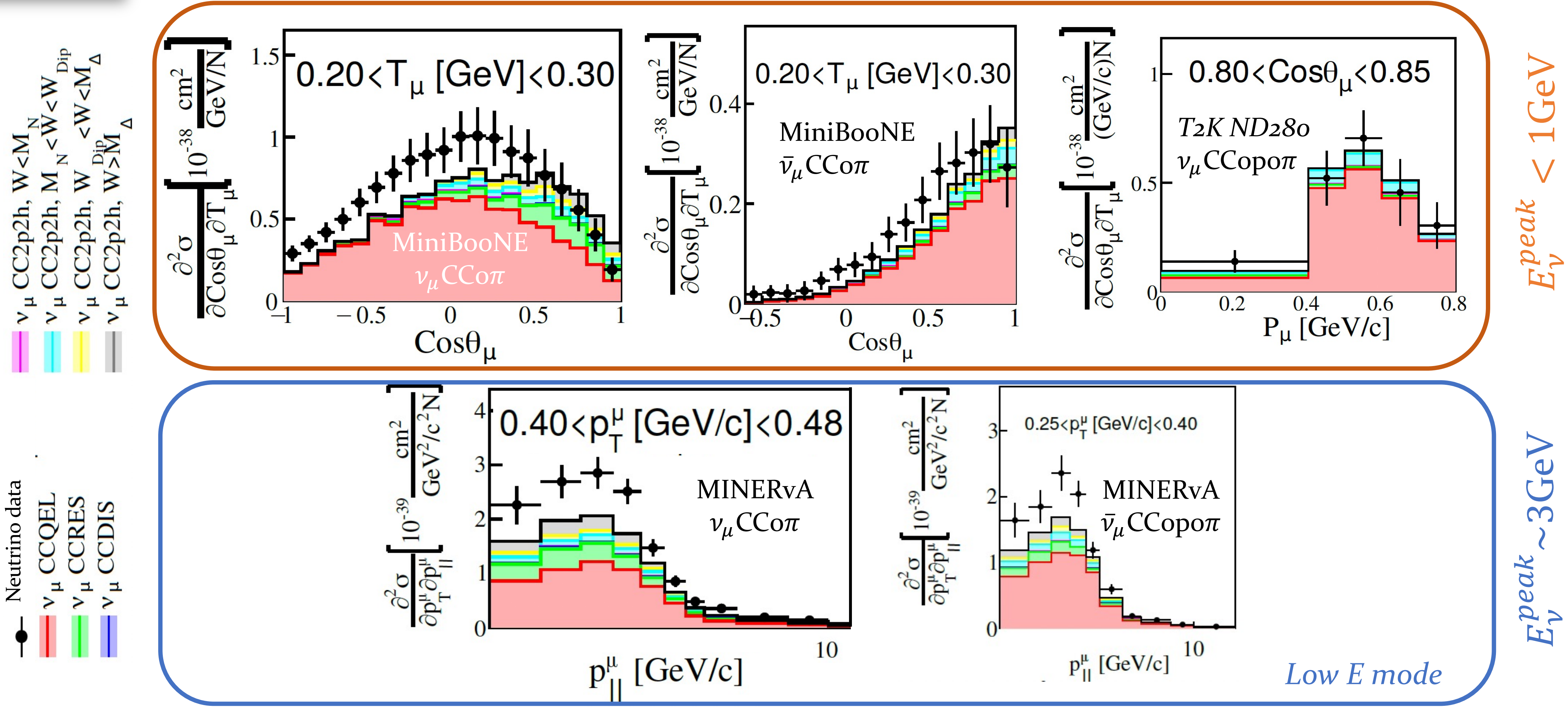
PhysRevD.104.072009

- Focus on hydrocarbon targets
- Distinct fluxes probe E_ν dependence
  - MiniBooNE and T2K ND280 flux's peak below 1GeV
  - MINERvA's low-E flux peaks at 3 GeV
- GENIE base model: G18_10a_02_11b
  - QEL+MEC: Valencia
  - RES: Berger-Sehgal
  - FSI: GENIE hA2018
  - Nuclear model: LFG
  - Free nucleon tune results



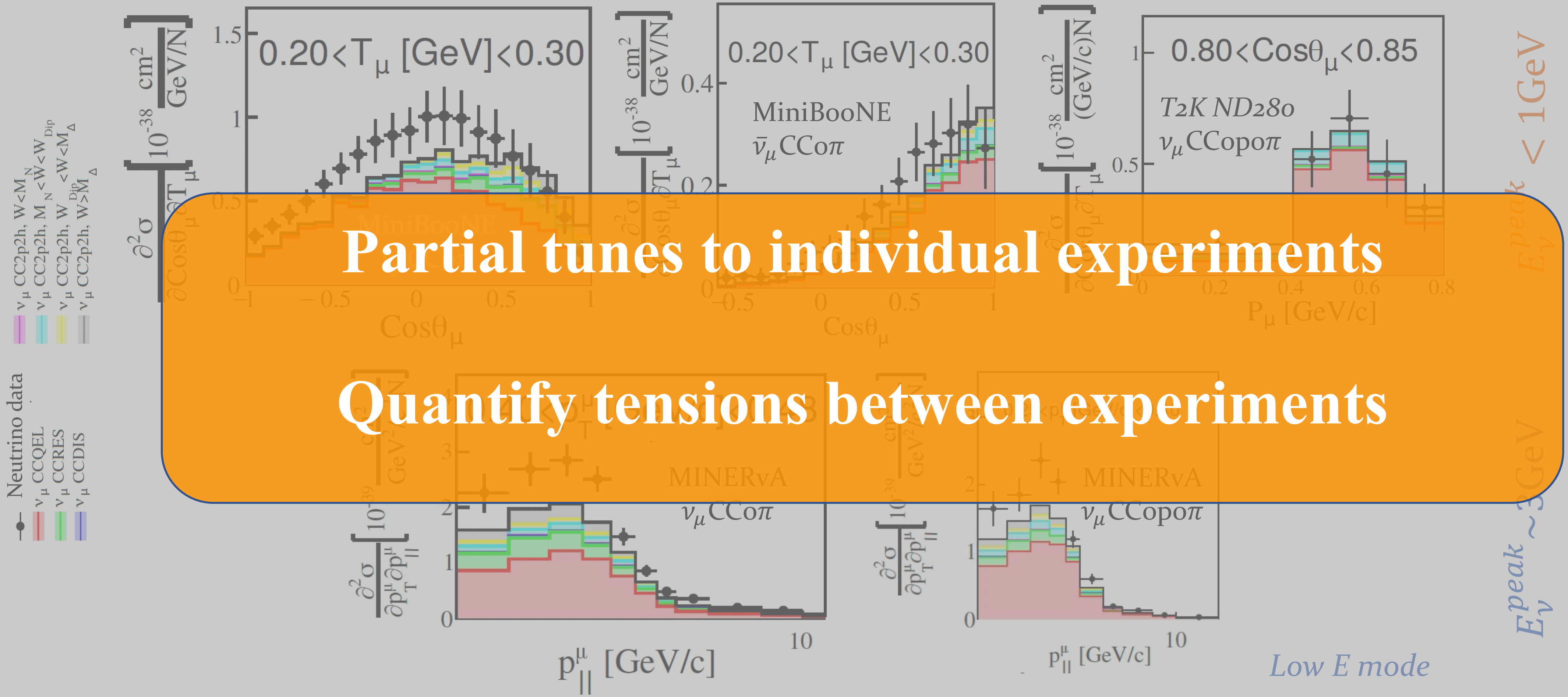
Tuning of $\nu - A$
ν_μ and $\bar{\nu}_\mu$ CC0π carbon data

PhysRevD.104.072009



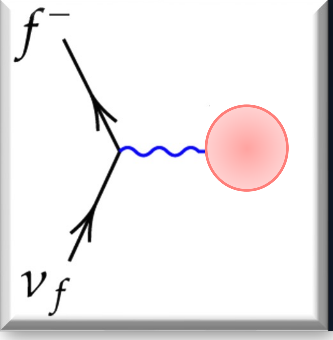
Tuning of $\nu - A$
ν_μ and $\bar{\nu}_\mu$ CC0π carbon data

PhysRevD.104.072009



Partial tunes to individual experiments

Quantify tensions between experiments

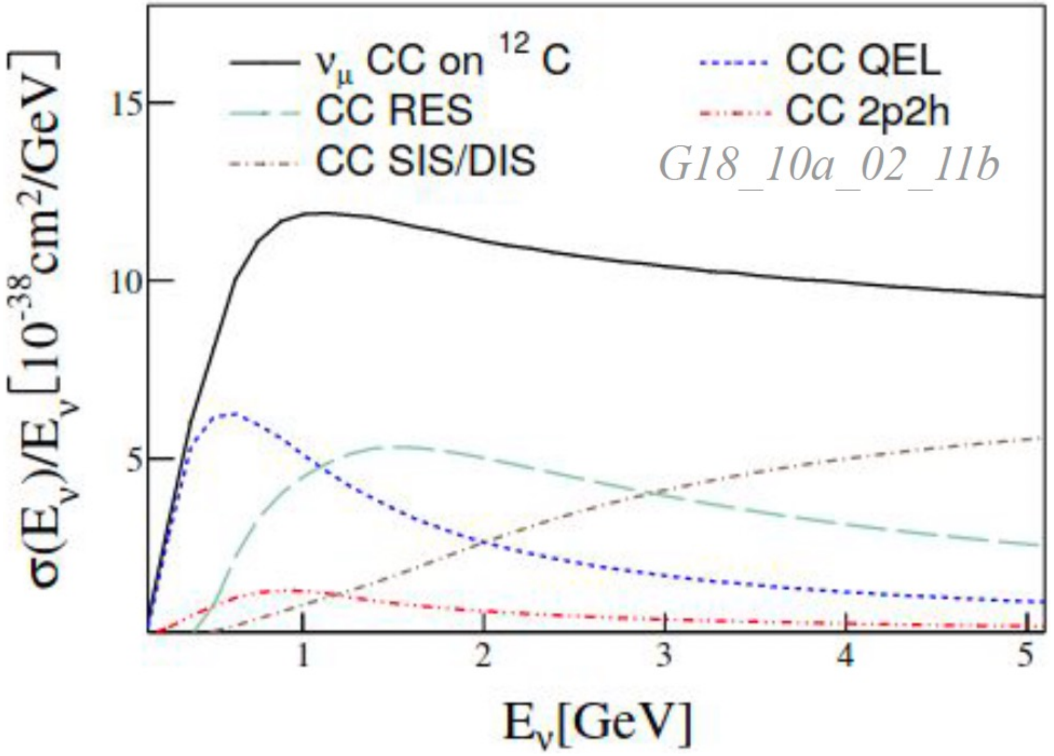


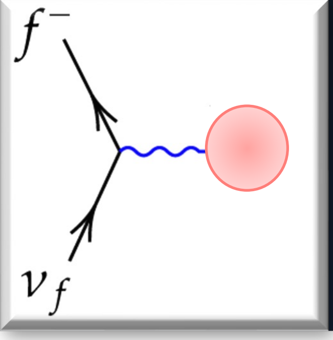
Tuning of $\nu - A$ CC0π interaction models

PhysRevD.104.072009

The nuclear environment further complicates the picture:

- CC QEL
  - Free nucleon cross section is well understood
  - Nuclear effects complicate this picture
- CC MEC
  - The different GENIE models predict a different shape and strength
- CC RES
  - Most relevant for E_ν>1 GeV
- FSI
  - Pion absorption is relevant for CC0π samples
  - Hard to constrain with only CC0π data





Tuning of $\nu - A$ CC0π interaction models Parameters (1)

PhysRevD.104.072009

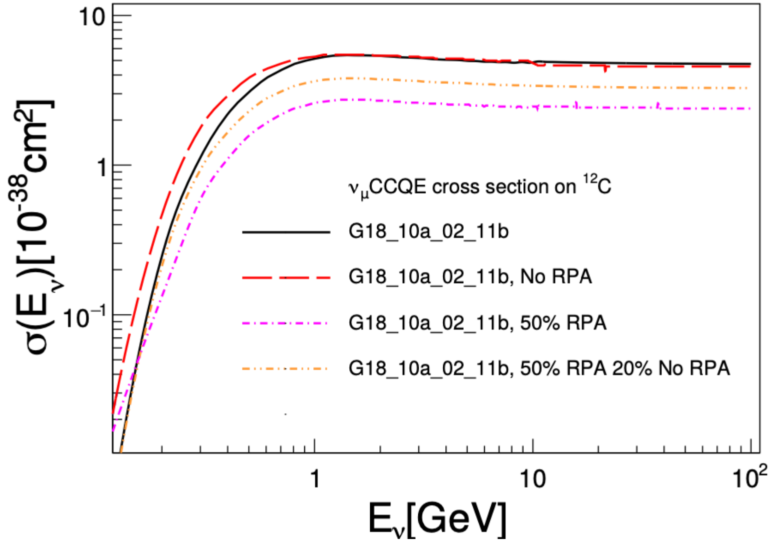
At the free nucleon level, the QEL cross section is well understood:

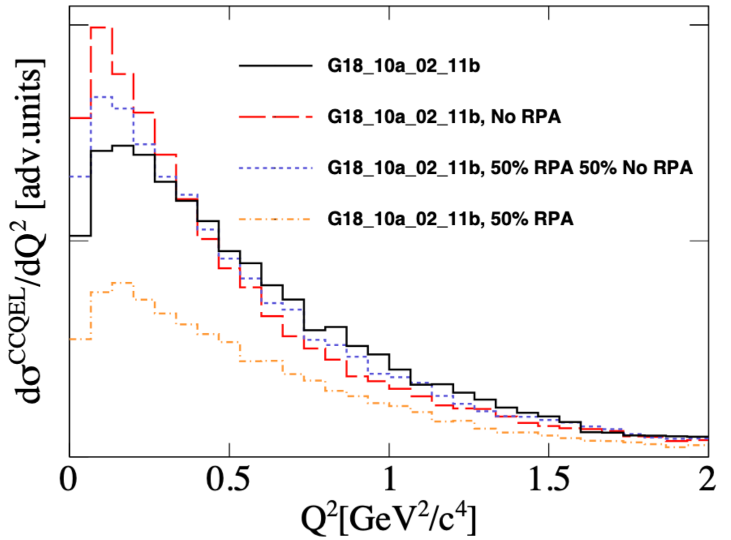
- Base model tuned to hydrogen and deuterium data
- Using correlated priors from free nucleon tune to constrain M_A^{QEL} and S_{RES}

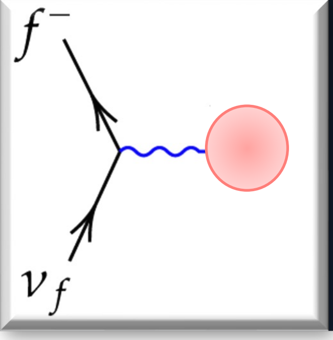
Two additional parameters:

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

- Mix on/off RPA models via separate scaling factors
- $\omega_{RPA}/\omega_{No\ RPA}$ scales the cross section w/o RPA







Tuning of $\nu - A$ CC0π interaction models Parameters (2)

PhysRevD.104.072009

Valencia model is implemented using the **table-based approach**:

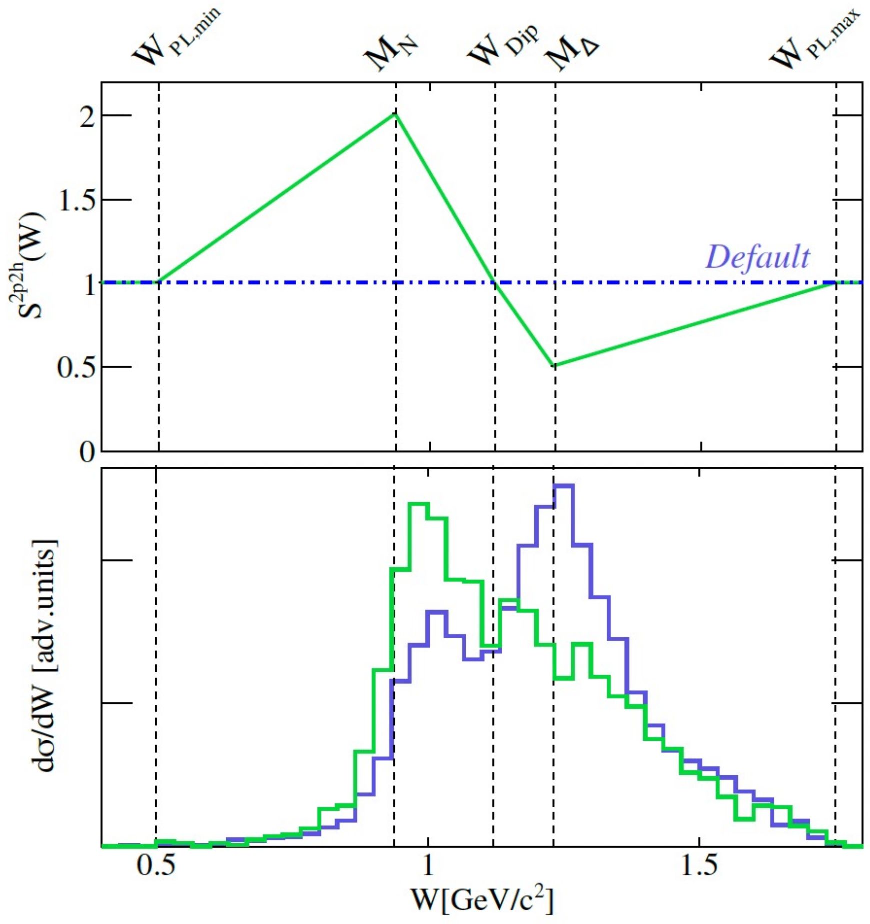
- Pre-computed hadron tensor tables on a grid of q_0-q_3
- No direct access to theory-parameters from GENIE

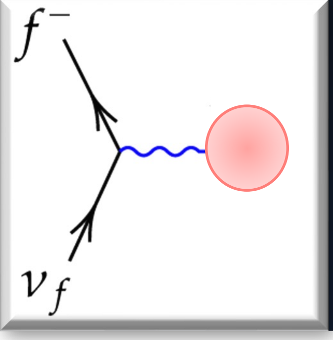
We add an **ad-hoc parameteriz**ation to add variation to the model

- Accommodate variations in shape and normalization
- The Valencia model predicts two peaks in W at M_N and M_Δ
- We scale the cross section as:

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

- $S_N^{MEC} = S(M_N)$
- $S_\Delta^{MEC} = S(M_\Delta)$
- S_{PL}^{MEC} - scaling at the end points





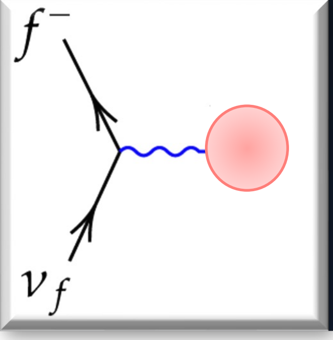
Tuning of $\nu - A$ CC0π interaction models Results

PhysRevD.104.072009

All tunes:
- Respect free nucleon priors
- Prefer RPA corrections
- Enhance the CCQEL(~20%) and CCMEC cross section

G10a: MiniBooNE ν_μ CC0π
G11a: MiniBooNE $\bar{\nu}_\mu$ CC0π
G20a: T2K ND280 ν_μ CC0p0π
G30a: MINERvA ν_μ CC0π
G31a: MINERvA $\bar{\nu}_\mu$ CC0p0π

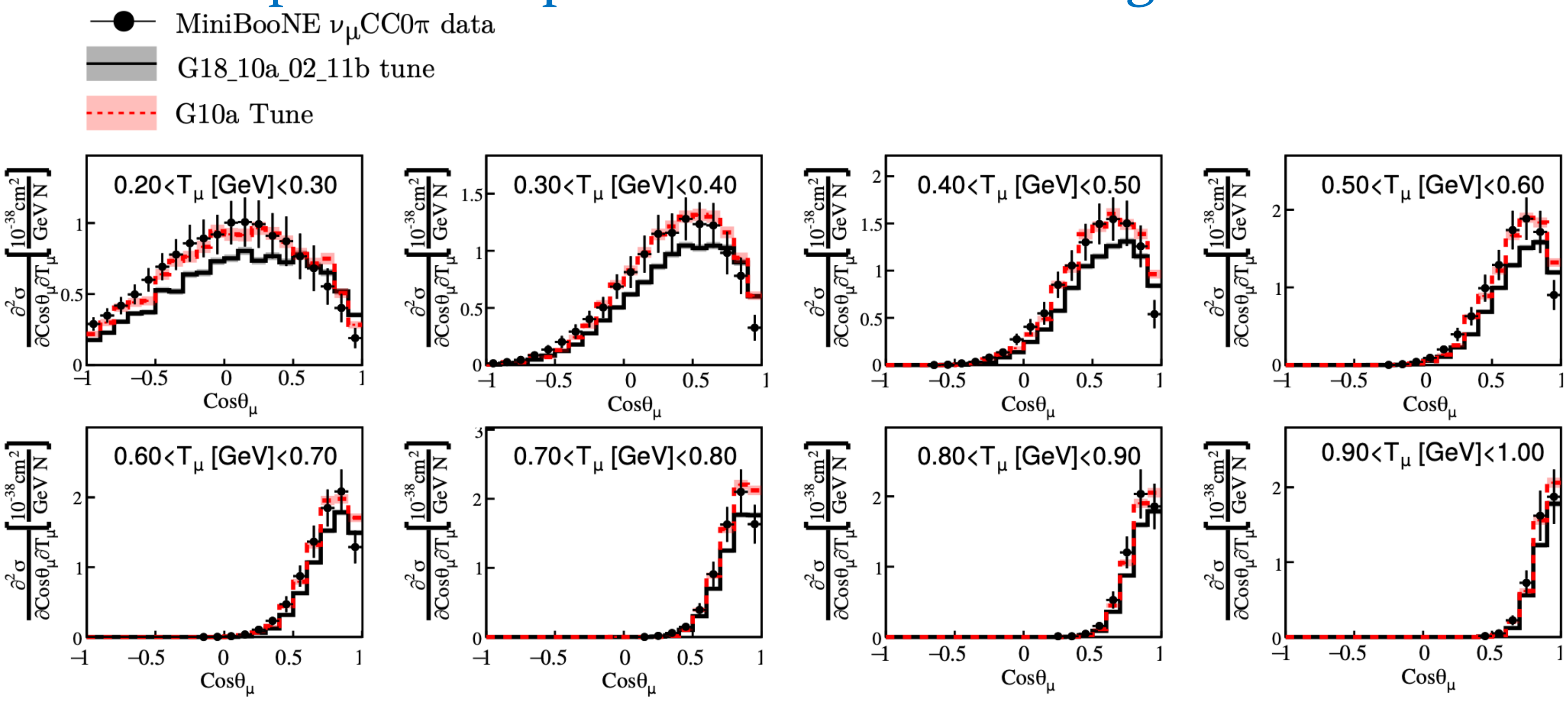
Parameters	G10a Tune	G11a Tune	G20a Tune	G30a Tune	G31a Tune
$M_A^{\mathrm{QEL}}(\mathrm{GeV/c^2})$	1.02 ± 0.01	1.01 ± 0.01	1.00 ± 0.01	1.00 ± 0.02	1.00 ± 0.01
ω_{RPA}	1.20 ± 0.03	1.14 ± 0.06	1.2 ± 0.2	0.9 ± 0.1	1.3 ± 0.2
$\omega_{\mathrm{No\,RPA}}$	0.05 ± 0.02	0.09 ± 0.05	-0.1 ± 0.1	0.2 ± 0.1	0.2 ± 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	$89/130$	$77/71$	$60/55$	$61/137$	$67/53$

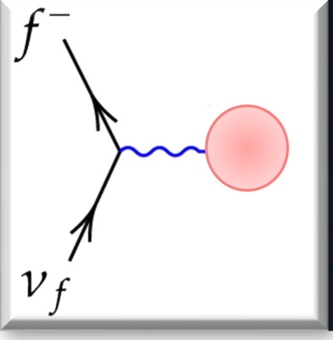


Tuning of $\nu - A$ CC0π interaction models Results

PhysRevD.104.072009

The enhancement of QEL and 2p2h cross sections lead to improved shape and normalization agreement

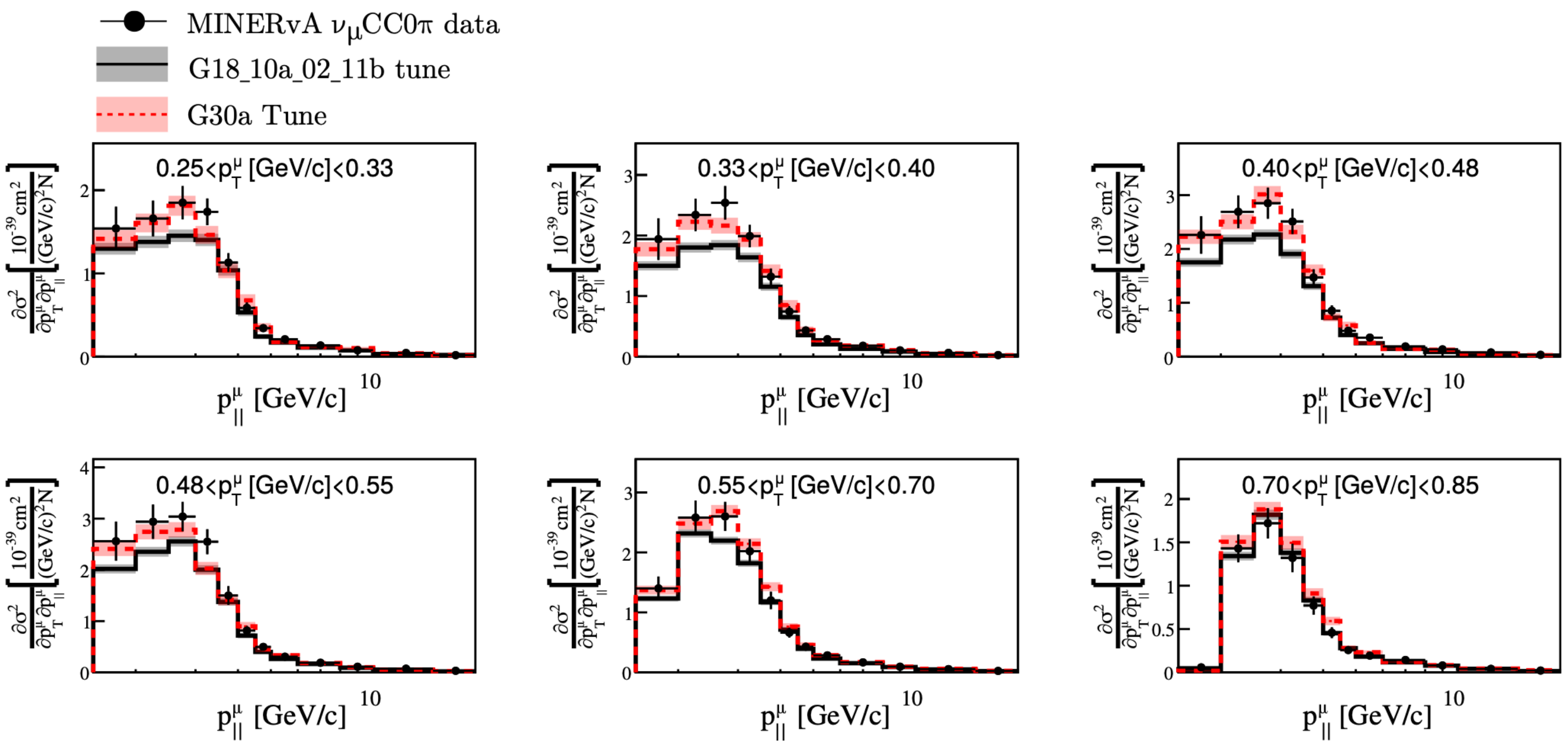


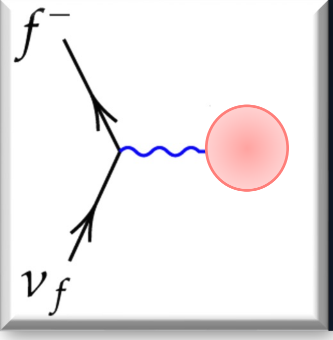


Tuning of $\nu - A$ CC0π interaction models Results

PhysRevD.104.072009

The enhancement of QEL and 2p2h cross sections lead to improved shape and normalization agreement





Tuning of $\nu - A$ CC0π interaction models Results

PhysRevD.104.072009

Differences:

- MiniBooNE + T2K enhance MEC at $W = M_N$
- MINERva's tunes enhance both MEC peaks
- **Clear energy dependence on cross section shape**
- **Anti-neutrino tunes predict a higher cross-section**
- Same observations by recent MINERvA measurements using high energy beam

G10a: MiniBooNE ν_μ CC0π

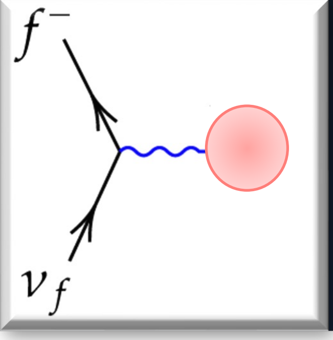
G11a: MiniBooNE $\bar{\nu}_\mu$ CC0π

G20a: T2K ND280 ν_μ CC0p0π

G30a: MINERvA ν_μ CC0π

G31a: MINERvA $\bar{\nu}_\mu$ CC0p0π

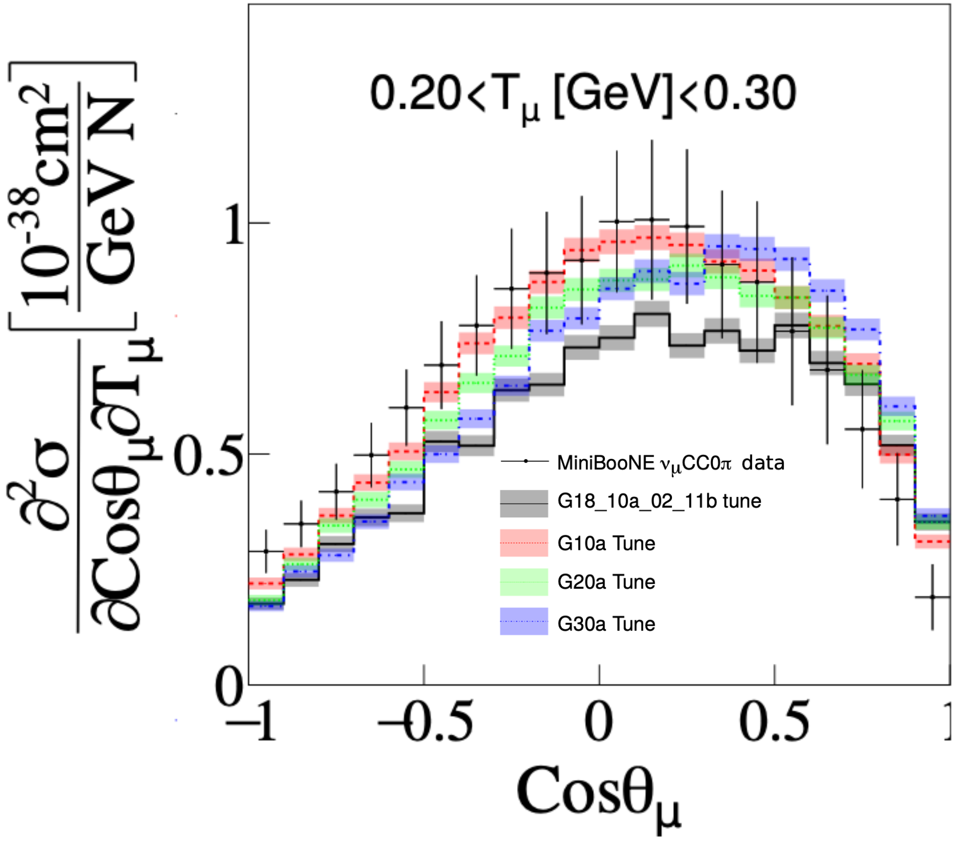
Parameters	G10a Tune	G11a Tune	G20a Tune	G30a Tune	G31a Tune
M_A^{QEL}(GeV/c^2)	1.02 ± 0.01	1.01 ± 0.01	1.00 ± 0.01	1.00 ± 0.02	1.00 ± 0.01
ω_{RPA}	1.20 ± 0.03	1.14 ± 0.06	1.2 ± 0.2	0.9 ± 0.1	1.3 ± 0.2
$\omega_{No\,RPA}$	0.05 ± 0.02	0.09 ± 0.05	-0.1 ± 0.1	0.2 ± 0.1	0.2 ± 0.2
S_{RES}	0.85 ± 0.02	0.86 ± 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



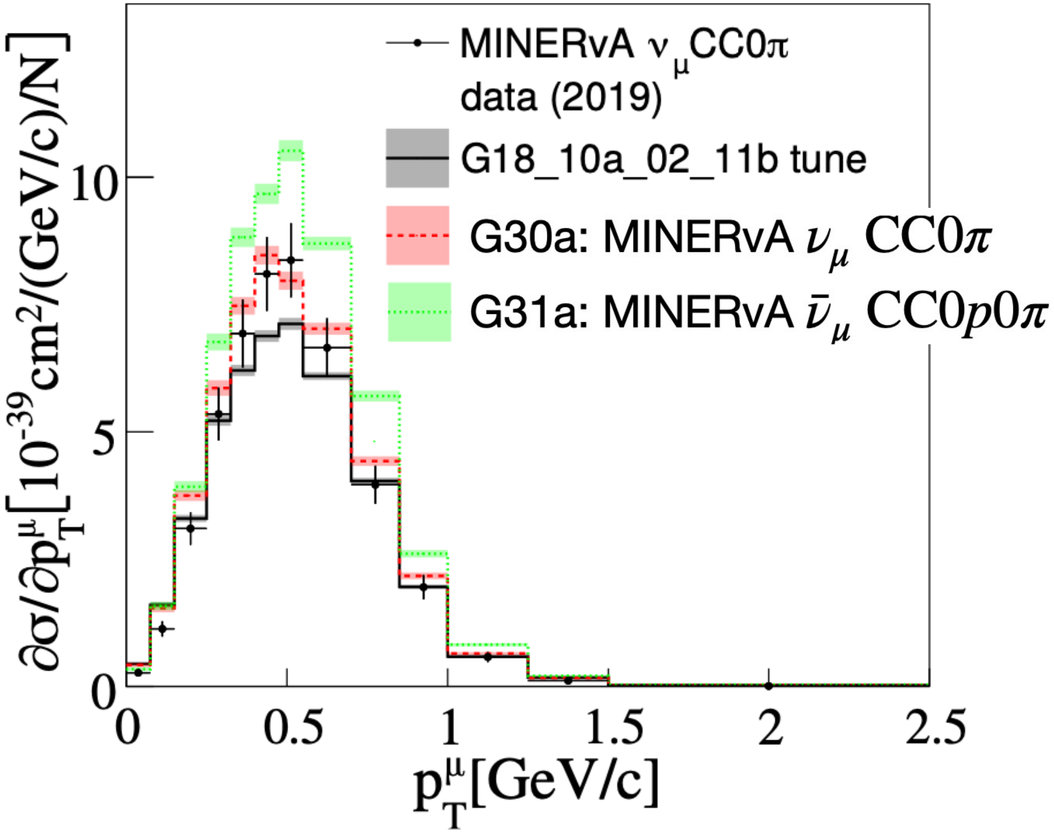
Tuning of $\nu - A$ CC0π interaction models Results

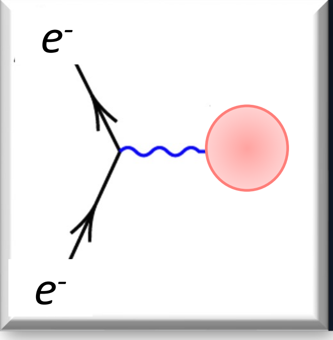
PhysRevD.104.072009

Clear energy dependence on cross section shape

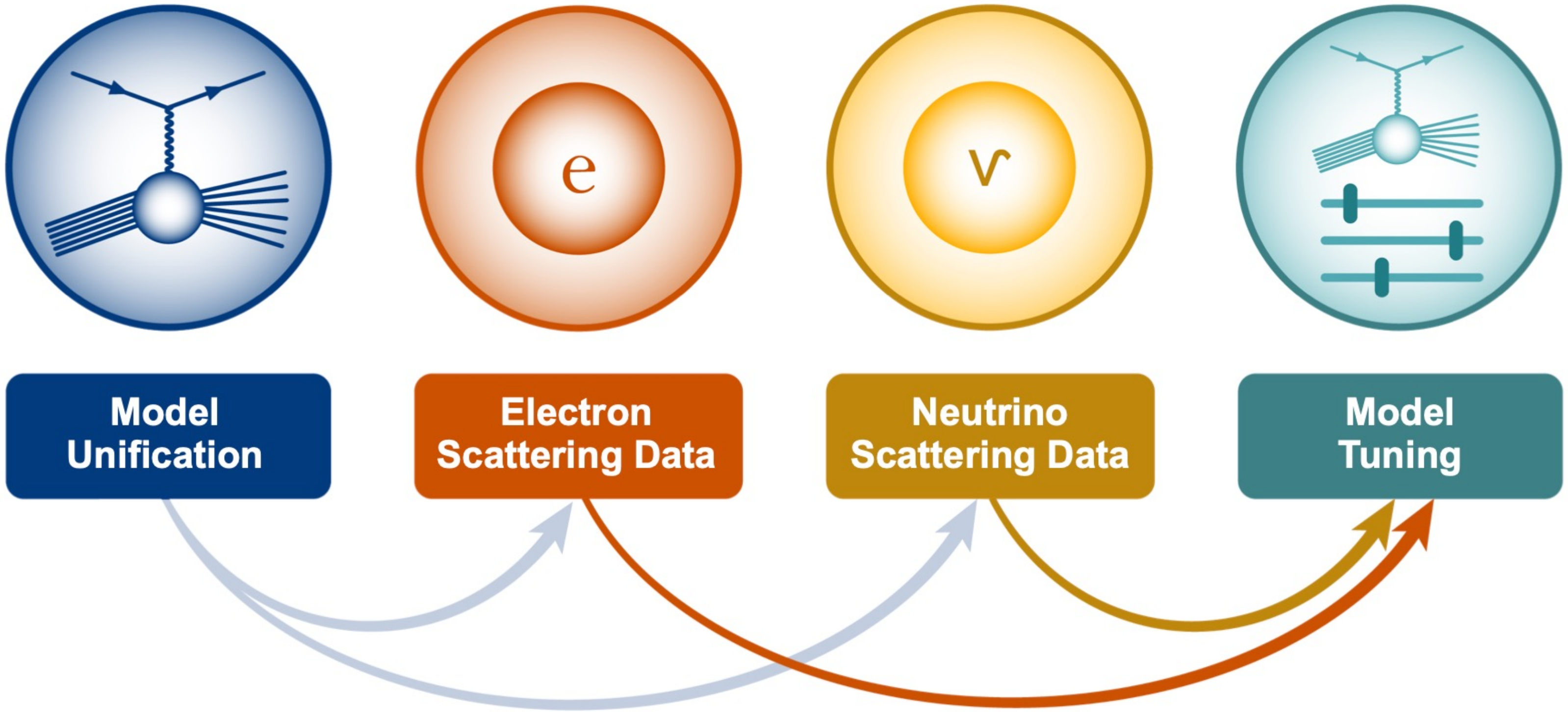


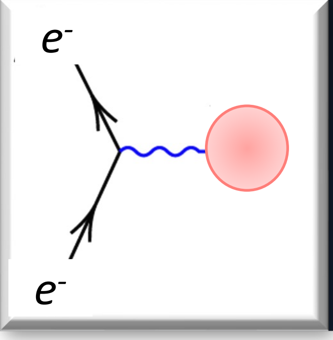
Anti-neutrino tunes predict a higher cross-section





Tuning of $\mathrm{e}-A$ interaction models

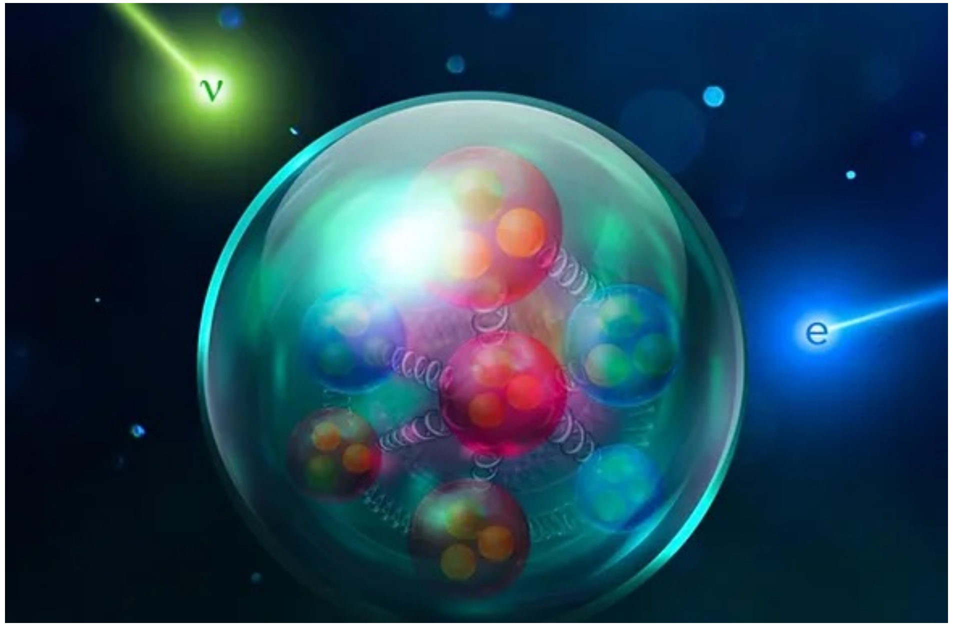


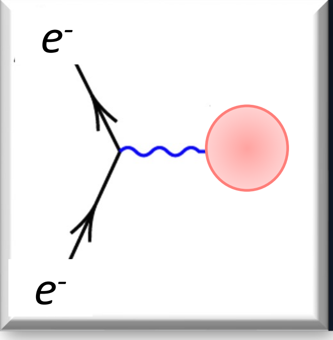


Tuning of e $-A$ interaction models

What can we constrain with electron data?

- Ground state model
- Final-State Interactions
- Vector part of the interaction

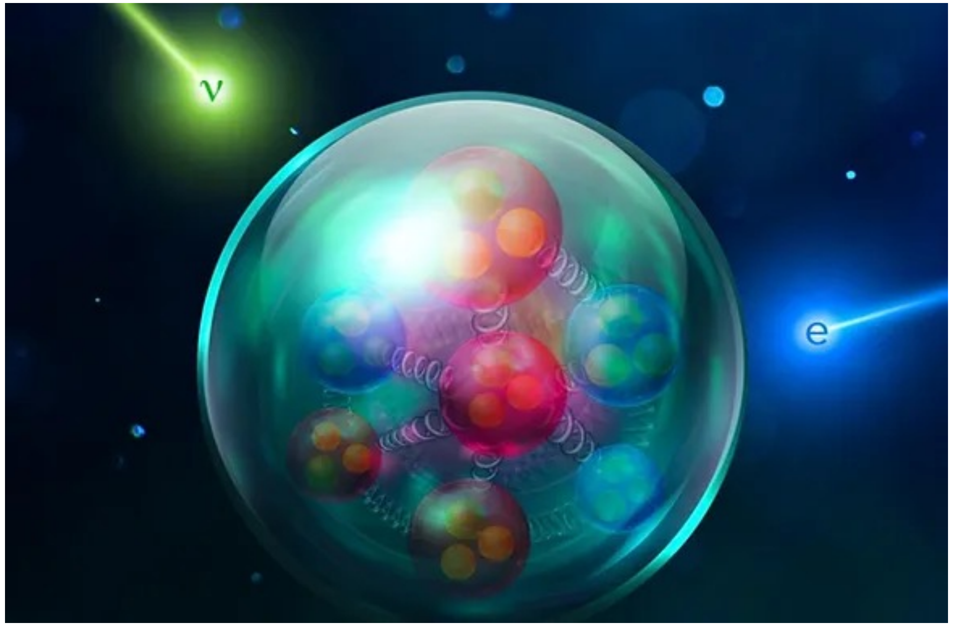


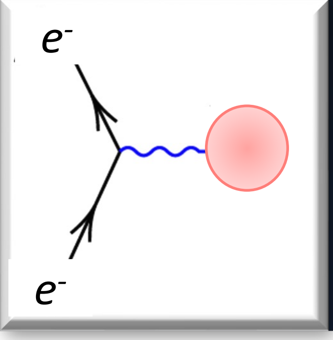


Tuning of e $-A$ interaction models

Benefits:

- High statistic measurements
- Known beam energy
- Many available inclusive measurements
- Neutrino-like exclusive measurements available by the e4nu collaboration

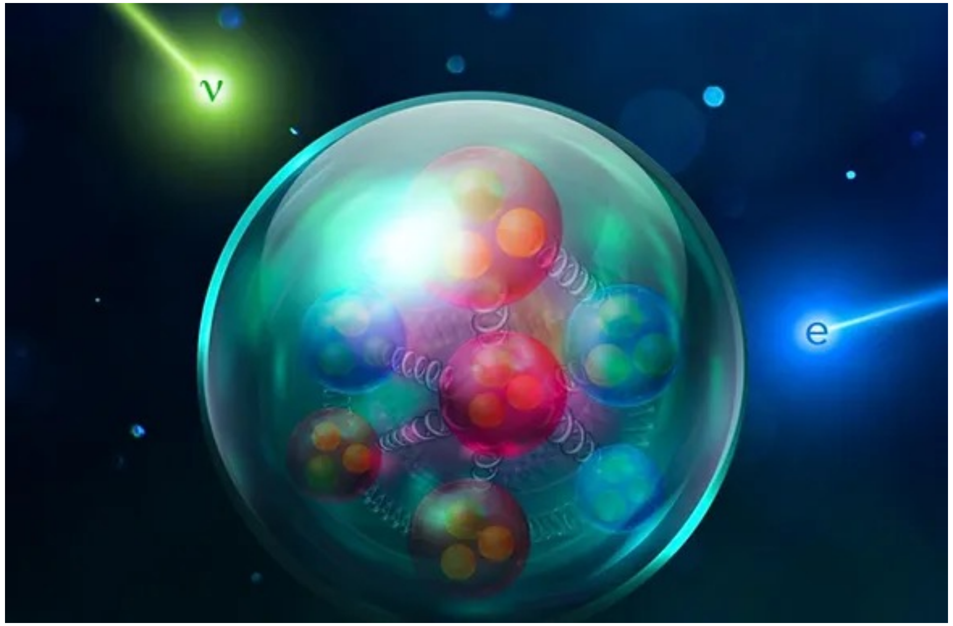


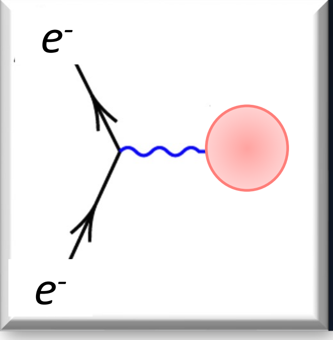


Tuning of e $-A$ interaction models

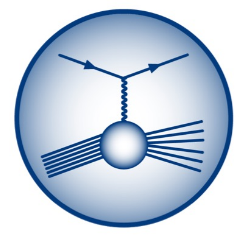
Complications:

- Much higher statistics than neutrinos!
- A common tune would bias the results in favor of electron data
- Most models don't have parameters specific to electrons
- Clear V-A separation not always easy
  - I.e: Non-resonance background model



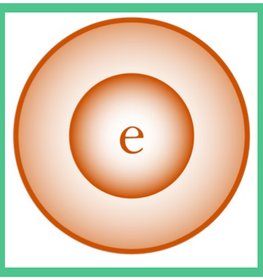


Tuning of e $-A$ interaction models Approach



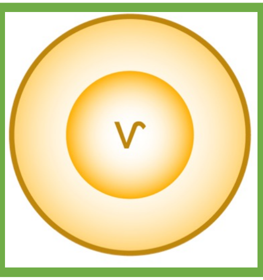
Model unification

- Ideally, implement models with clear V-A separation
- Have specific V and A parameters
- Identify modelling aspects common between e and ν



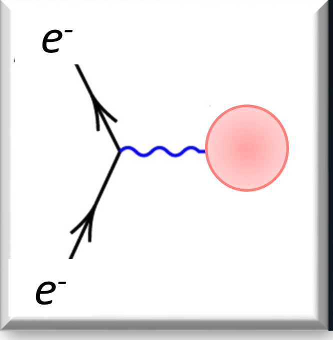
Tune your generator against electron-scattering data

- Turn off axial components
- Clear A-V separation might not be available
- Still useful to constrain base-model and focus on FSI aspects
- Exclusive data will avoid degeneracies in your tune – e4nu measurements!



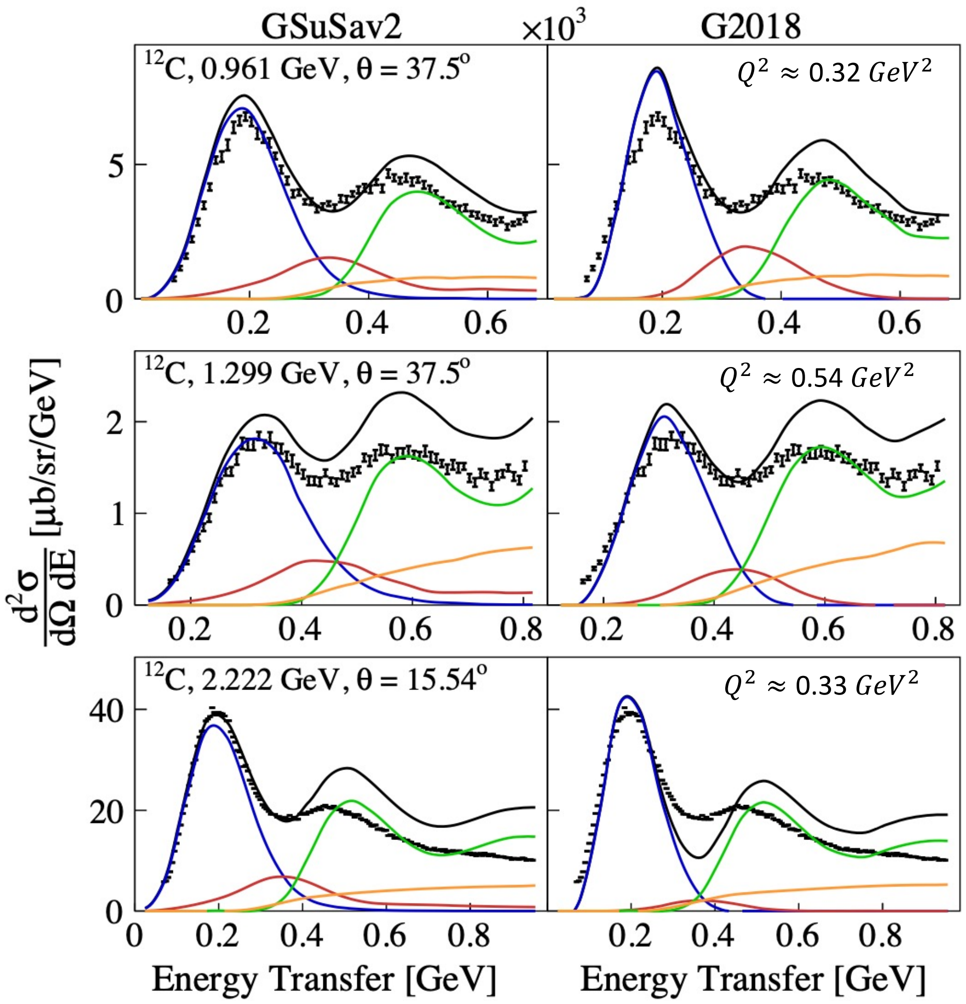
Propagate tune results to neutrino tune

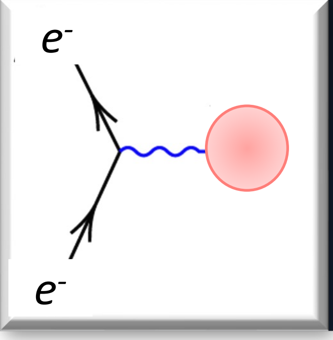
- More e-A measurements
- Results from the electron tune can be imposed as priors to avoid bias
- Constrain FSI and nuclear model with electron data
- Ideally, also axial part, but this might be tricky for some models



Tuning against $e - A$ inclusive data

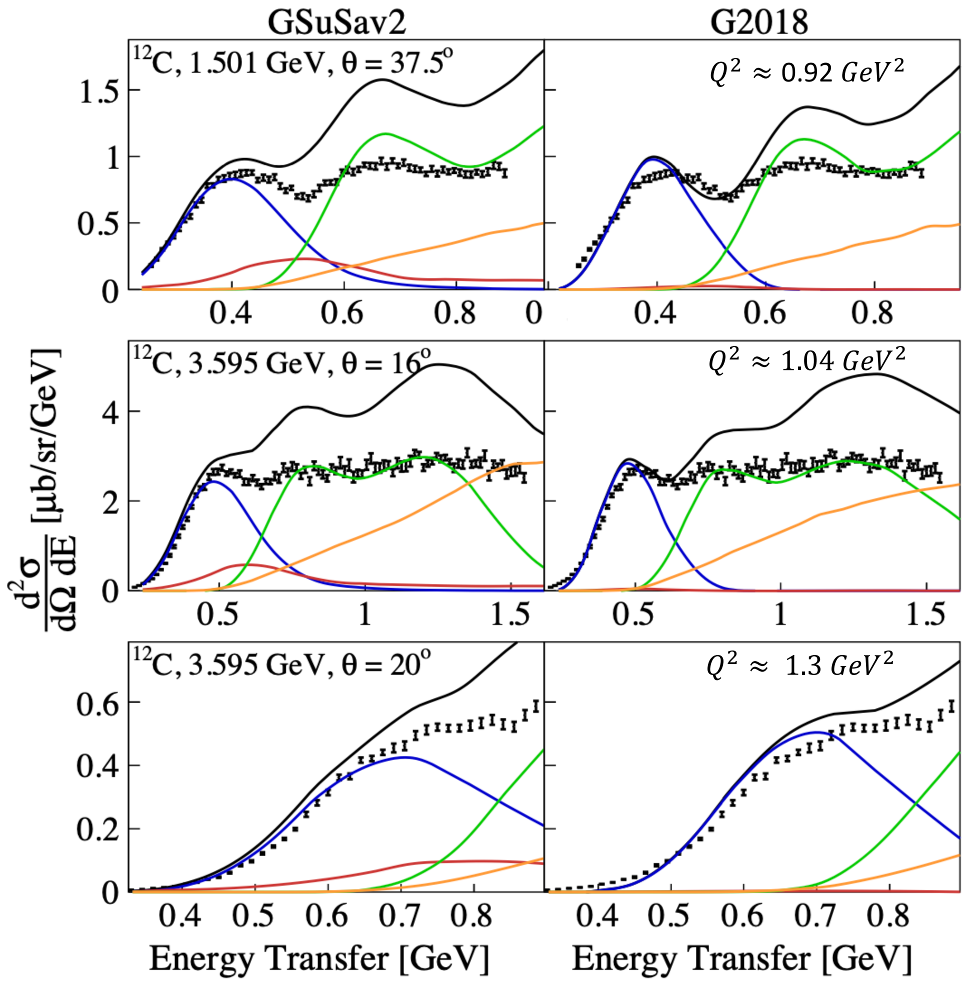
GENIE e-A models	
Nuclear model	Local Fermi Gas, Bodek-Ritchie Fermi Gas, Correlated Fermi Gas
QEL model	Rosenbluth
RES model	Berger-Sehgal, Rein-Sehgal
MEC model	Empirical, SuSAv2
DIS model	Bodek-Yang
Hadronization	AGKY

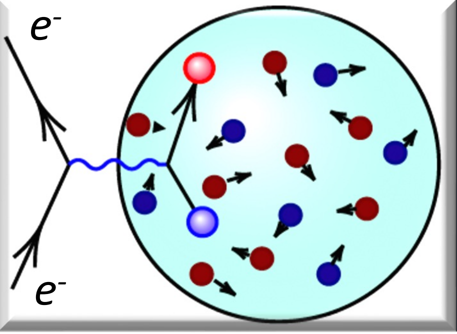




Tuning against $e - A$ inclusive data

GENIE e-A models	
Nuclear model	Local Fermi Gas, Bodek-Ritchie Fermi Gas, Correlated Fermi Gas
QEL model	Rosenbluth
RES model	Berger-Sehgal, Rein-Sehgal
MEC model	Empirical, SuSAv2
DIS model	Bodek-Yang
Hadronization	AGKY



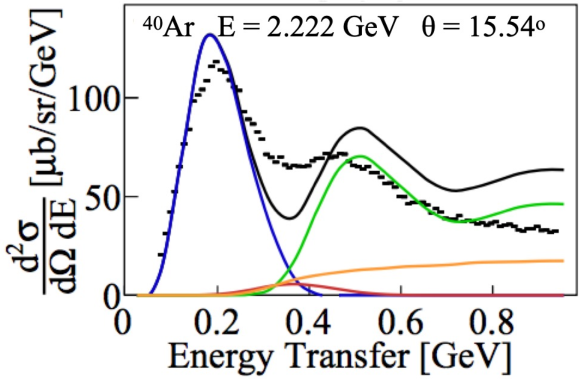


Nuclear model tuning

- The G18_10a with inclusive electron-scattering data highlight a shift with respect to the QEL-peak maximum

GENIE G18_10a_* e-A model	
Nuclear model	Local Fermi Gas
QEL model	Rosenbluth
RES model	Berger-Sehgal
2p2h model	Empirical MEC
DIS model	Bodek-Yang

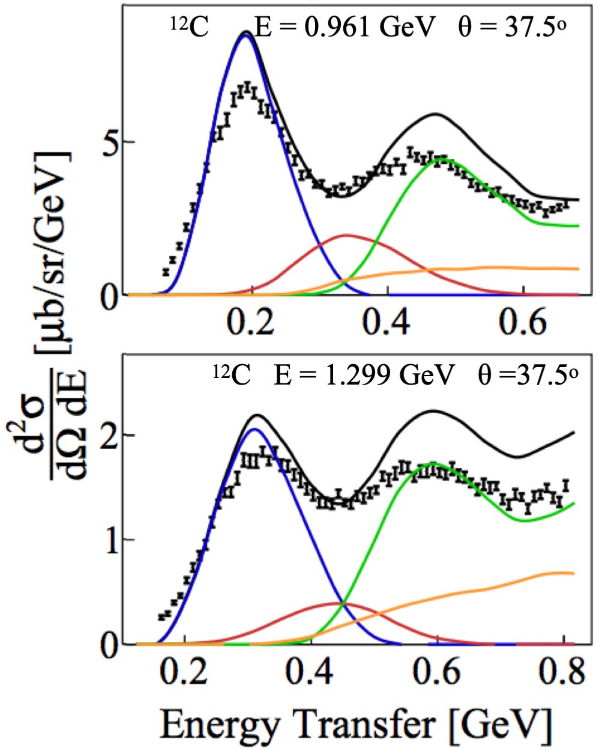
- The shift is correlated with the binding energy

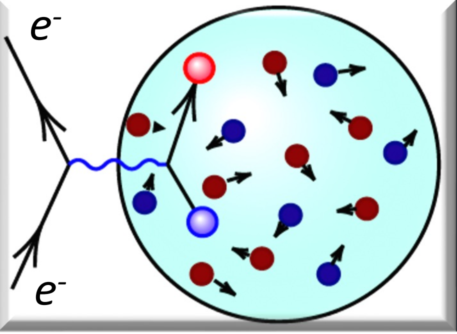


Genie

— v3.0.6 tune G18_10a_02_11a

Phys.Rev.D 103 (2021) 113003



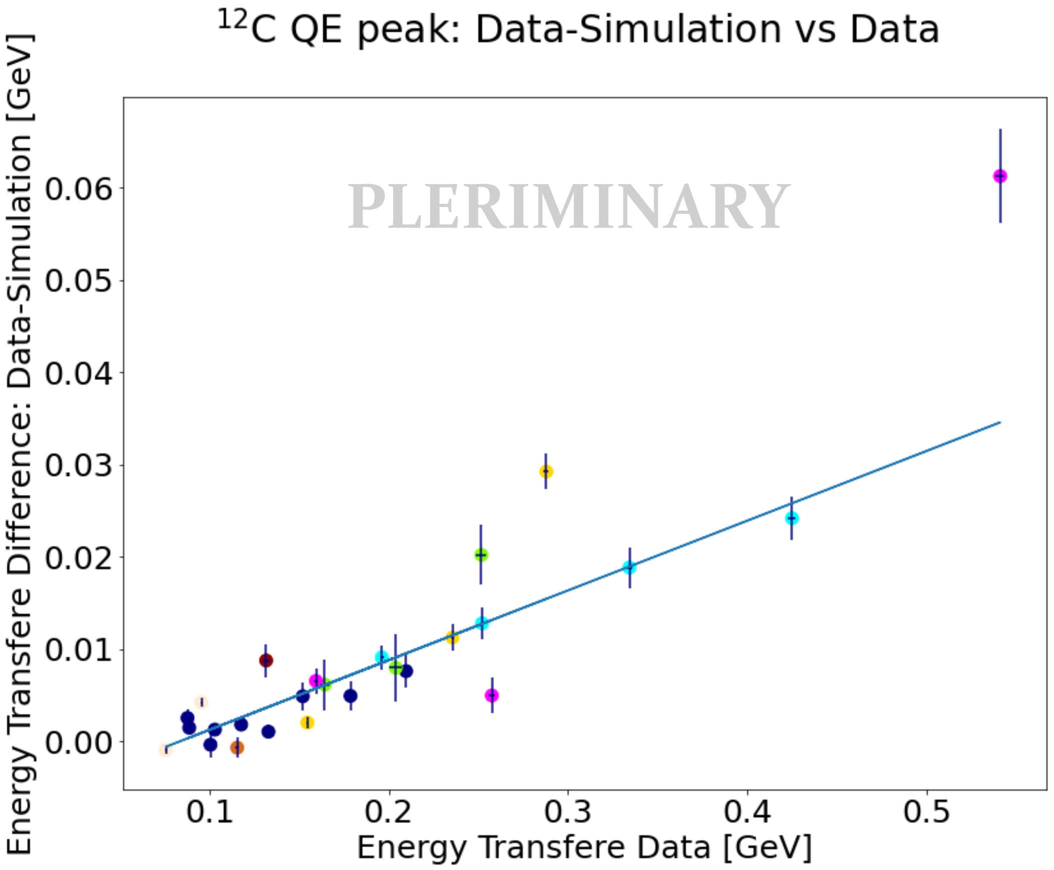


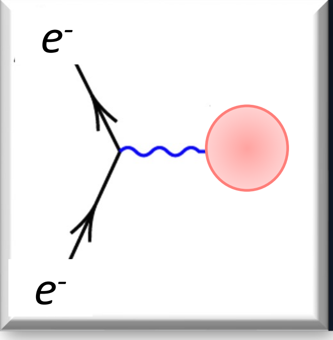
Nuclear model tuning

Matan Goldenberg

Approach:

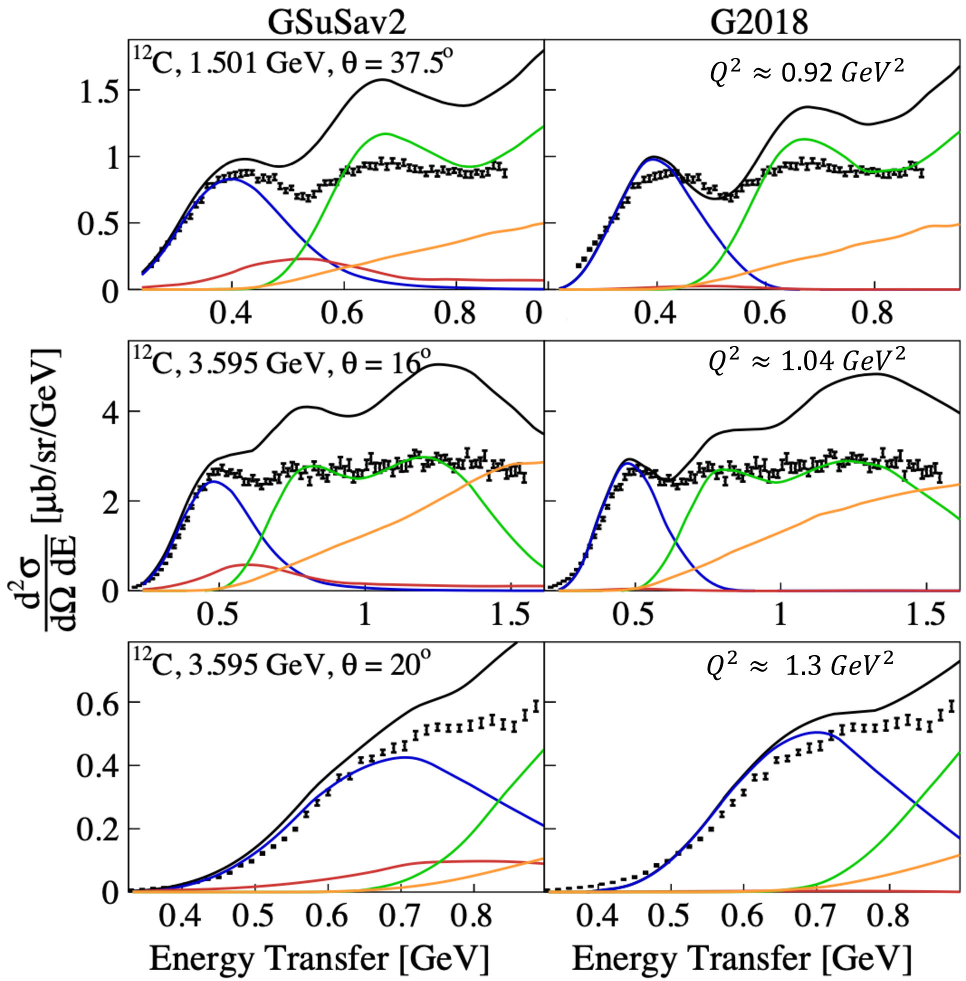
- MC predictions for each dataset using G18_10a CMC
- Same binning as inclusive data
- Opening angle: 1.14 deg
- Fit data and MC separately with same approach
- Calculate difference in peak position
- Peak shift increases with the energy transfer

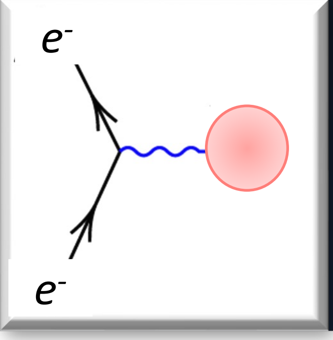




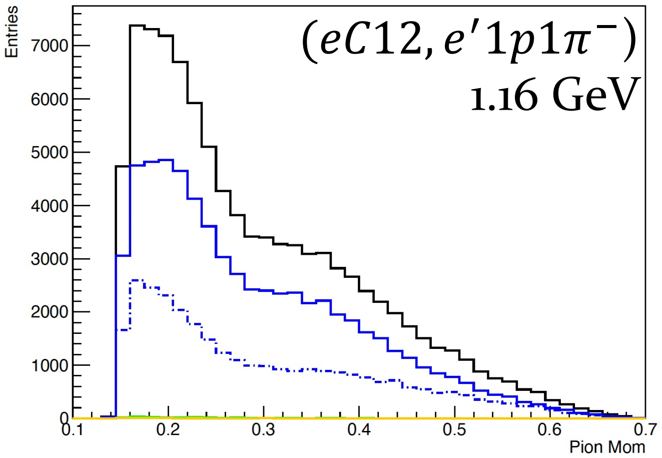
Tuning against e $-A$ inclusive data
Next focus

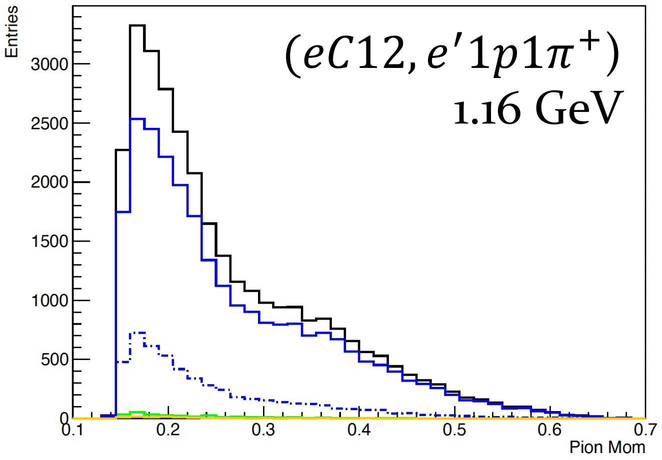
- SIS region is not well described
  - As it is, the NRB background has never been tuned against e-N data – disagreement not surprising
- Inclusive data is not enough
  - We need to go exclusive
- Working towards the first $(e, e' 1p1\pi^{\pm})$ cross-section measurement with CLAS6 data
  - $1p1\pi^-$: test RES model and FSI
  - $1p1\pi^+$: mostly affected by FSI
  - Focus on hadron kinematics
  - For now, focus is on Carbon (He4, Fe56 to come)
  - $E_\nu = 1, 2$ *and* 4 GeV
- In parallel we are working on improving SIS models



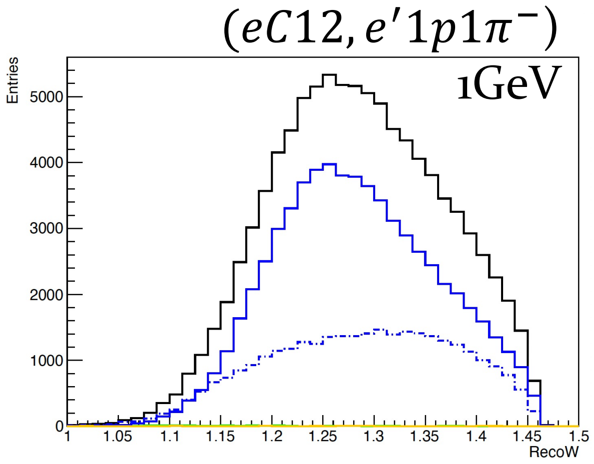


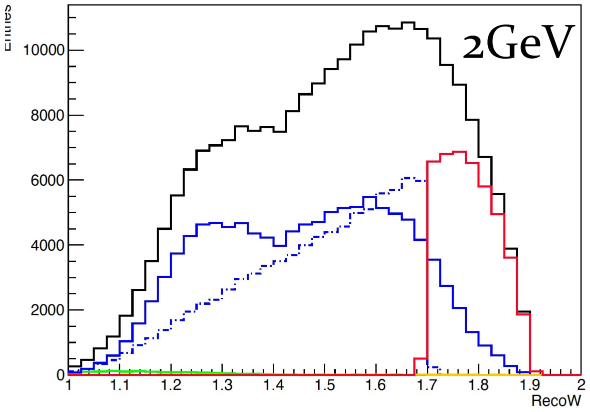
Tuning against e $-A$ inclusive data
Next focus

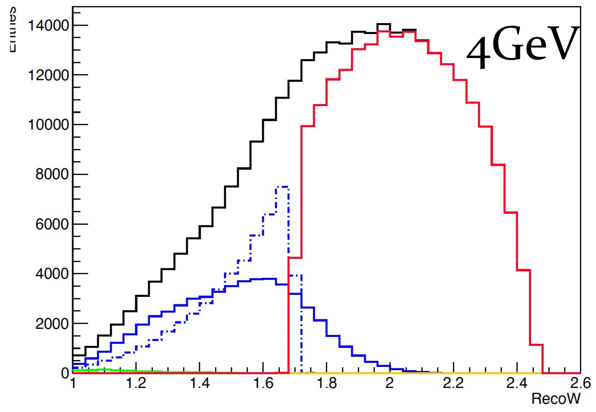


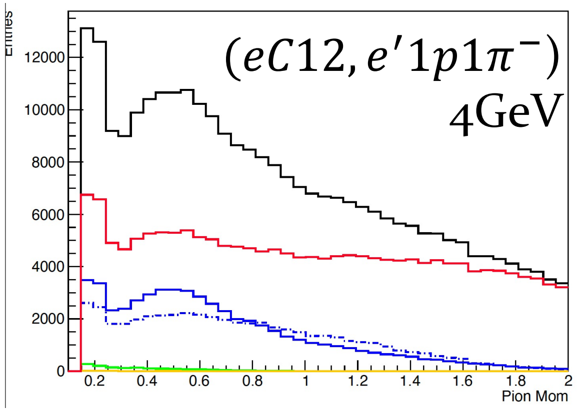


Exhaustive test of SIS and FSI models









Conclusions

- Tuning event generators is essential due to the empirical nature of most modeling aspects
  - Also used to estimate model uncertainties, quantify disagreements…
- Different methods available
  - Analytic calculations, ReWeight, GENIE-Professor
  - The GENIE Collaboration is building a Global analysis framework based on the Professor concept
- Global tunes are complex
  - Parameter and data choice essential to over-come degeneracies
- We are working to include electron-scattering data
  - Inclusive data shown to be useful for binding energy corrections
  - Next focus on pion-production measurements

Thank you!

TEL AVIV UNIVERSITY אוניברסיטת תל אביב

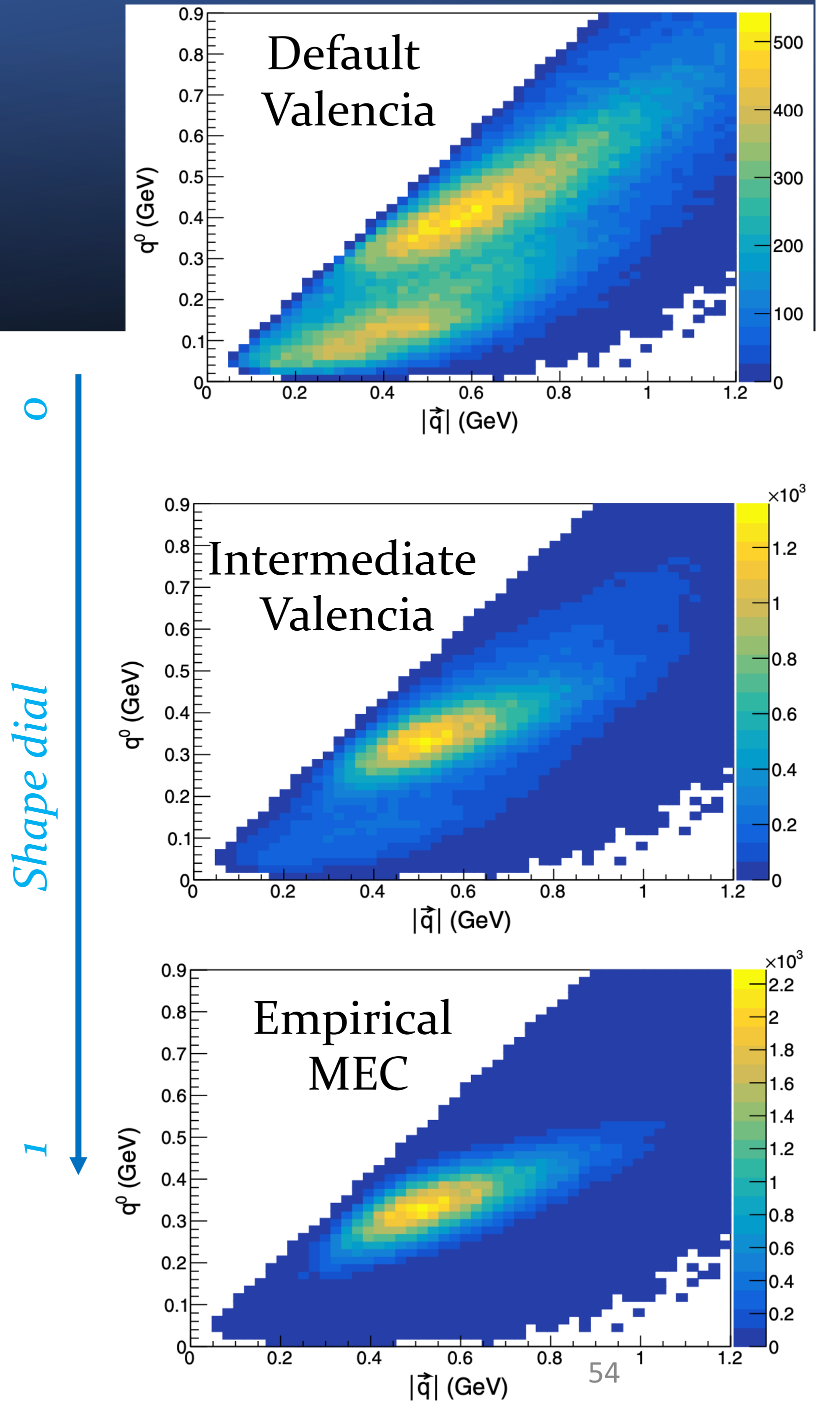
Genie

The TAU Neutrino Group

Backup slides

GENIE Reweight

- [MicroBooNE Tune [PhysRevD.105.072001]]()
  - Tuned to T2K data to avoid bias
  - Base configuration: G18_10a_02_11b (Valencia)
  - MaCCQE, CCQE RPA, 2p2h normalization and shape
  - New dials available in GENIE-Reweight



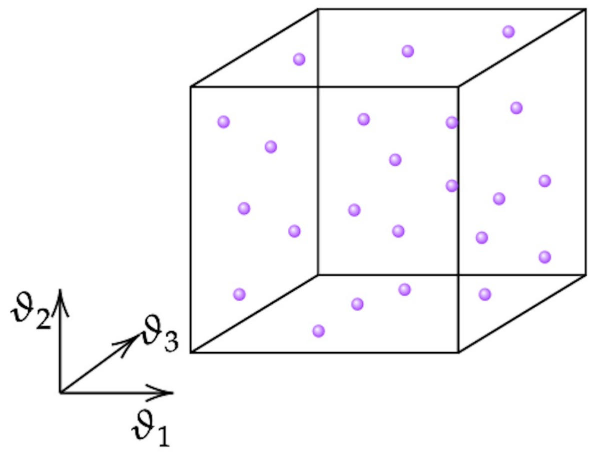
Sampling of the phase-space GENIE-Professor

- Once the set of parameters is selected $(\vartheta_1, \vartheta_2, \dots, \vartheta_{N_\vartheta})$, the next step is to define the parameters phase-space
  - Ideally, the best-fit result should lie around the middle of the phase-space
- In order to parameterize the response-function with an N-dimensional polynomial, we uniformly sample the phase space with

$$N_{MC\ Samples} = \frac{(N_\vartheta + N)!}{N_\vartheta!\, N!} \cdot 1.5$$

N_ϑ	4th order polynomial	5th order polynomial
2	22	31
5	189	378
10	1500	4500
13	3570	12852

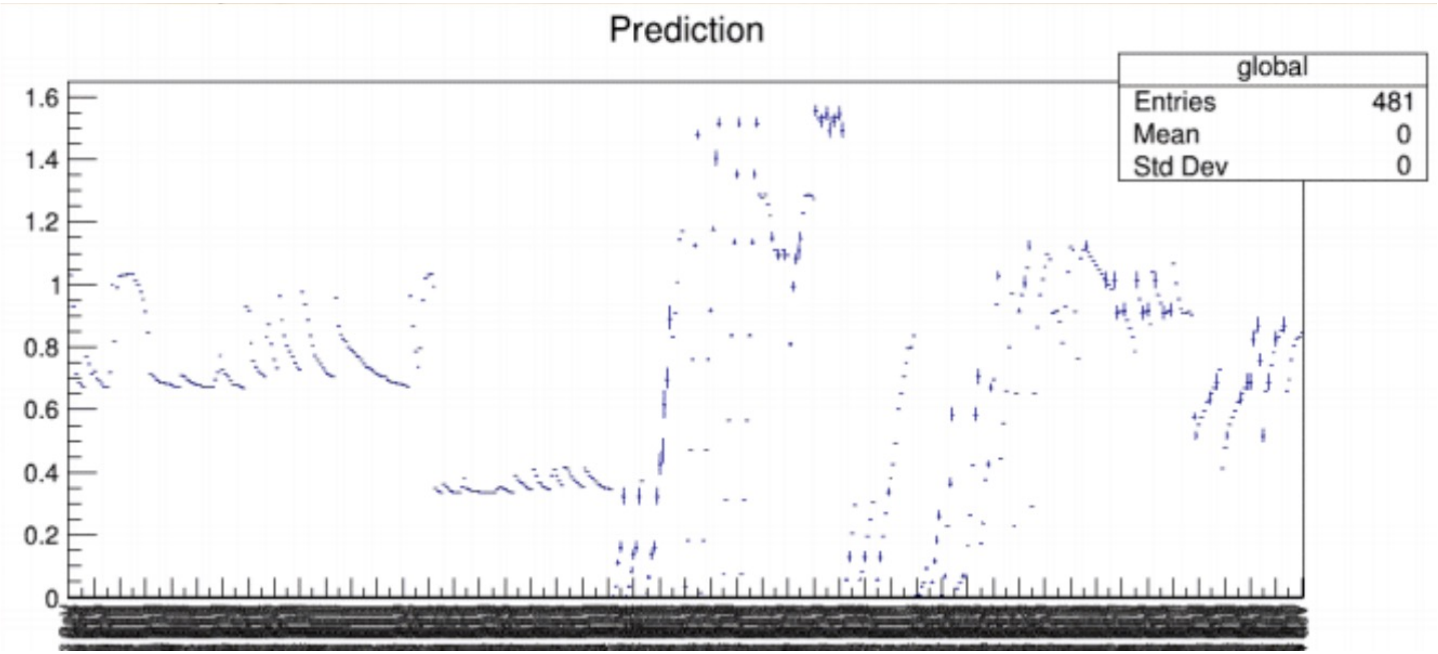
N_ϑ dimensions phase-space



The generation of all the samples is the most expensive CPU expensive step
It can be easily parallelized to minimize computing time
It happens before the actual fit (which takes few minutes to run)

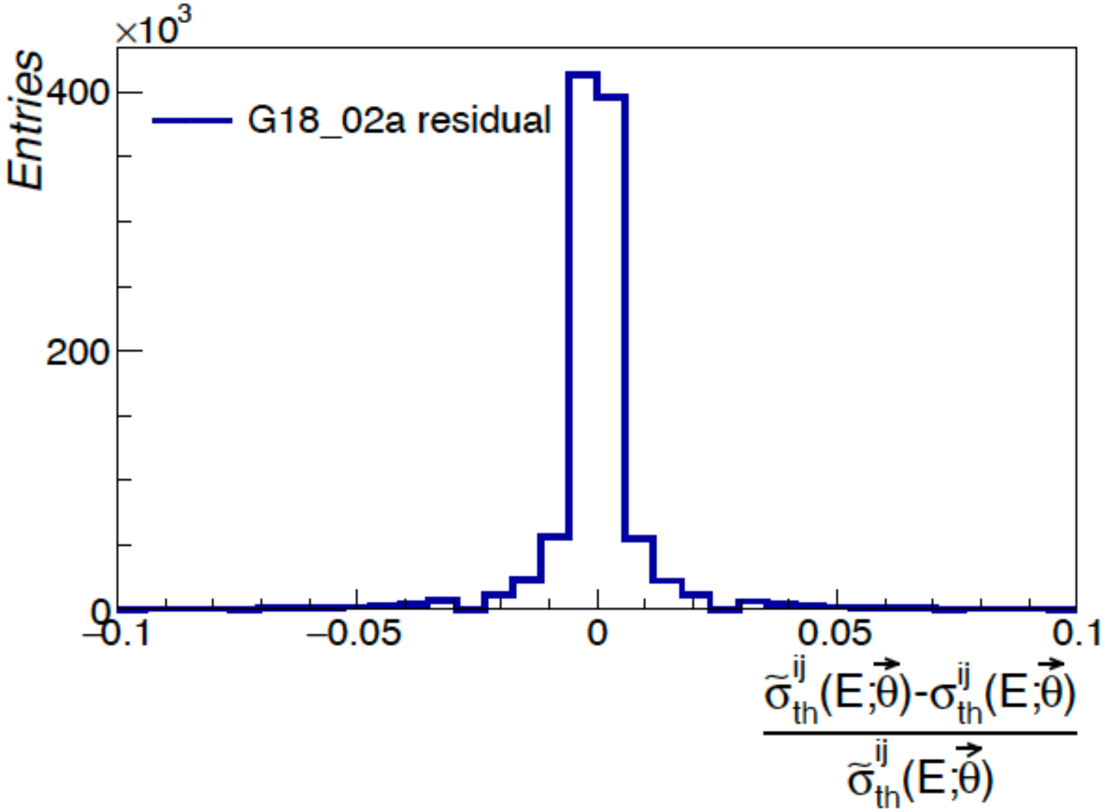
Definition of Observable GENIE-Professor

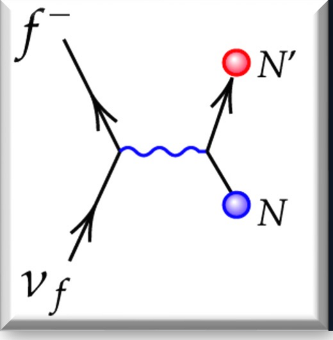
- Prediction histogram associated to thirty-three datasets [PhysRevD.104.072009]
  - The observable corresponds to a series of GENIE Predictions for ν_μ and anti- ν_μ CC inclusive, QEL, single-pion and two-pion production associated to ANL 12 ft, BNL 7ft, BEBC and FNAL bubble chamber data
- This prediction is computed with a single parameter set of our sampled phase space



Parameterization of response function GENIE-Professor

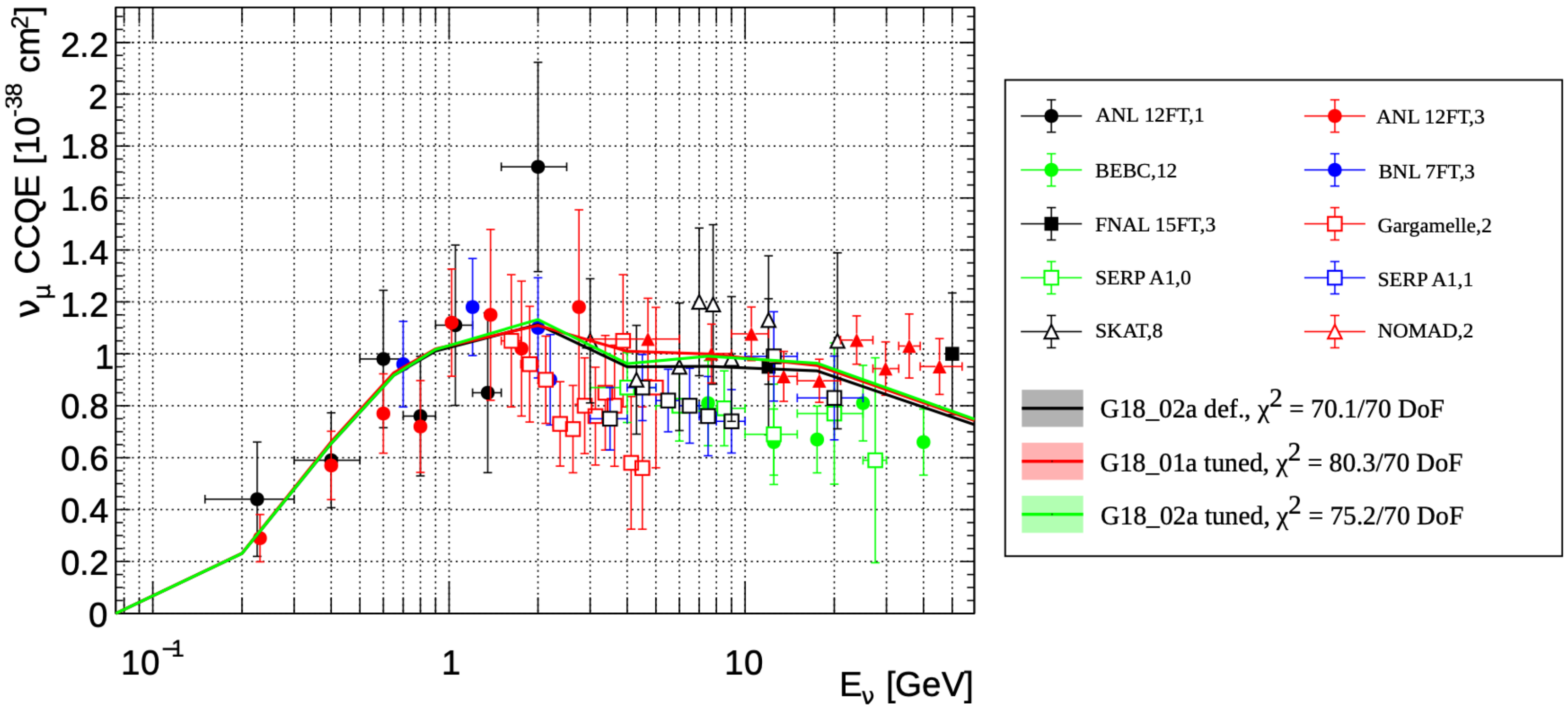
- For each bin, we parameterize the observable mean value and error dependency on the parameters
- The parameterization is fit against the brute force scan
- The parameterization is an **approximation**
- It is possible to quantify its accuracy with the residual:
  - True prediction - parameterization bin-by-bin



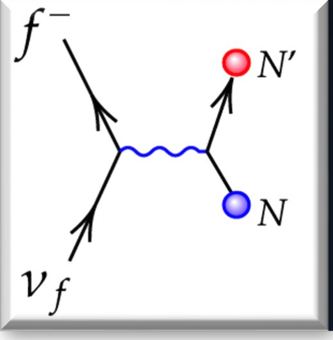


Tuning the Shallow-Scattering Inelastic region

PhysRevD.104.072009

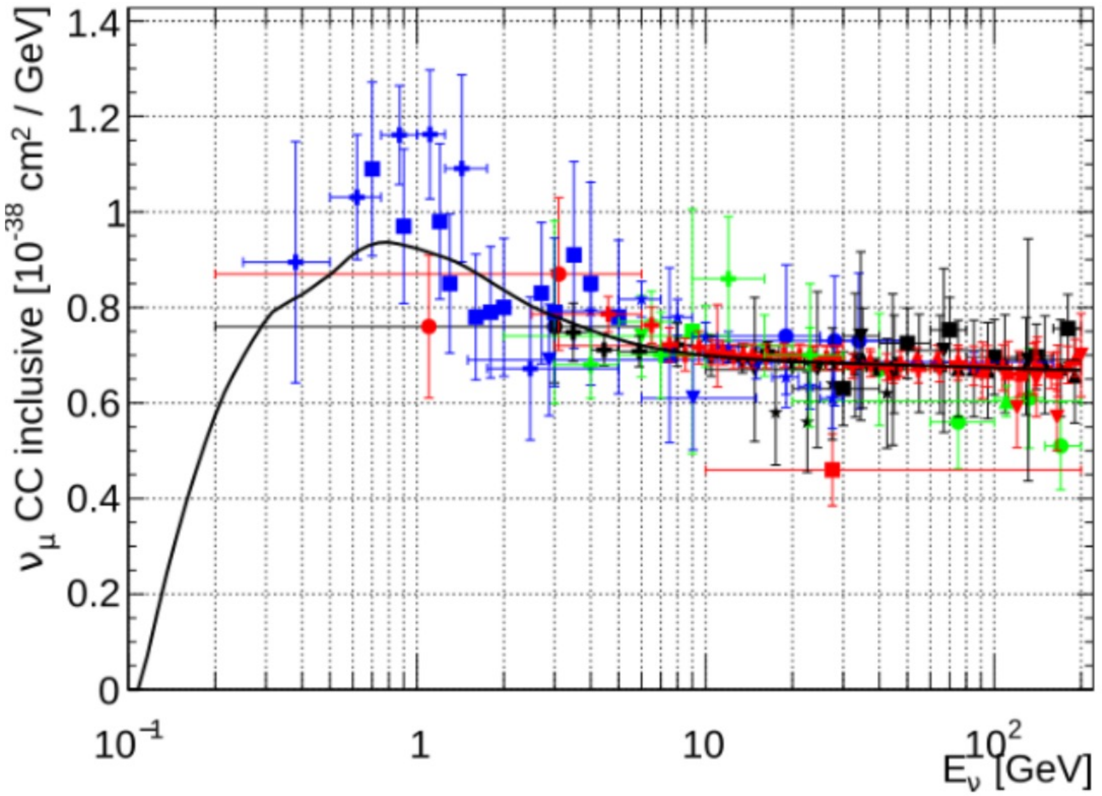


(a) Comparison of ν_μ CC quasi-elastic cross-section data against the *default* and tuned CMCs.

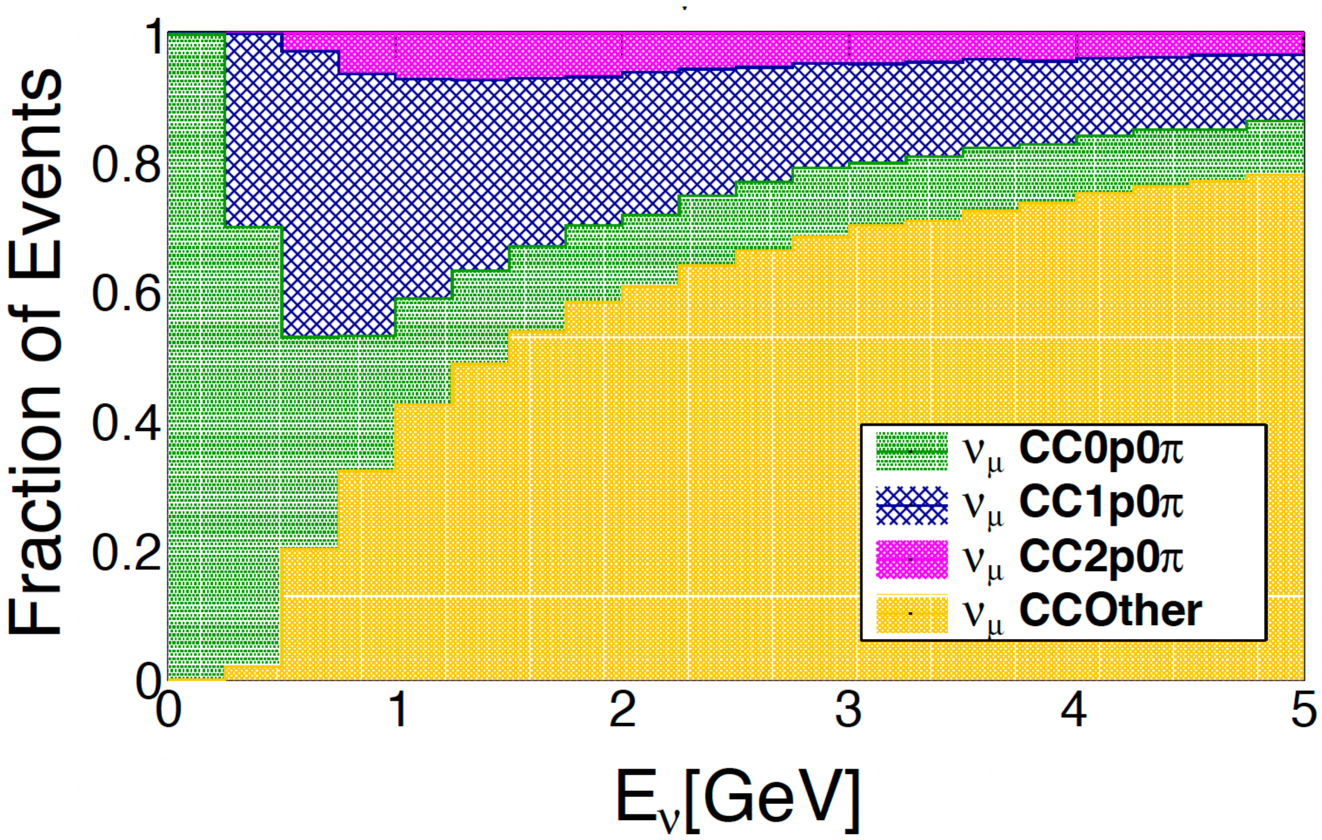


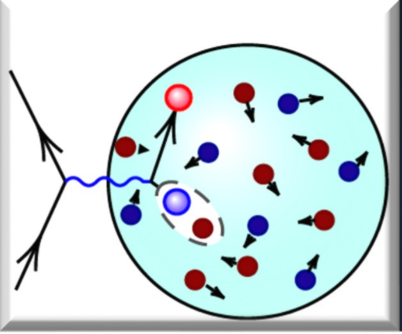
Tuning the Shallow-Scattering Inelastic region

- **The G18_02a_00_000 configuration corresponds to the untuned model**
  - Originally tuned to describe inclusive data
  - Tensions with exclusive data couldn't be resolved
    - Overprediction of 1π production
    - Underprediction of 2π production
- **Resolving the tensions between inclusive and exclusive data is the key**



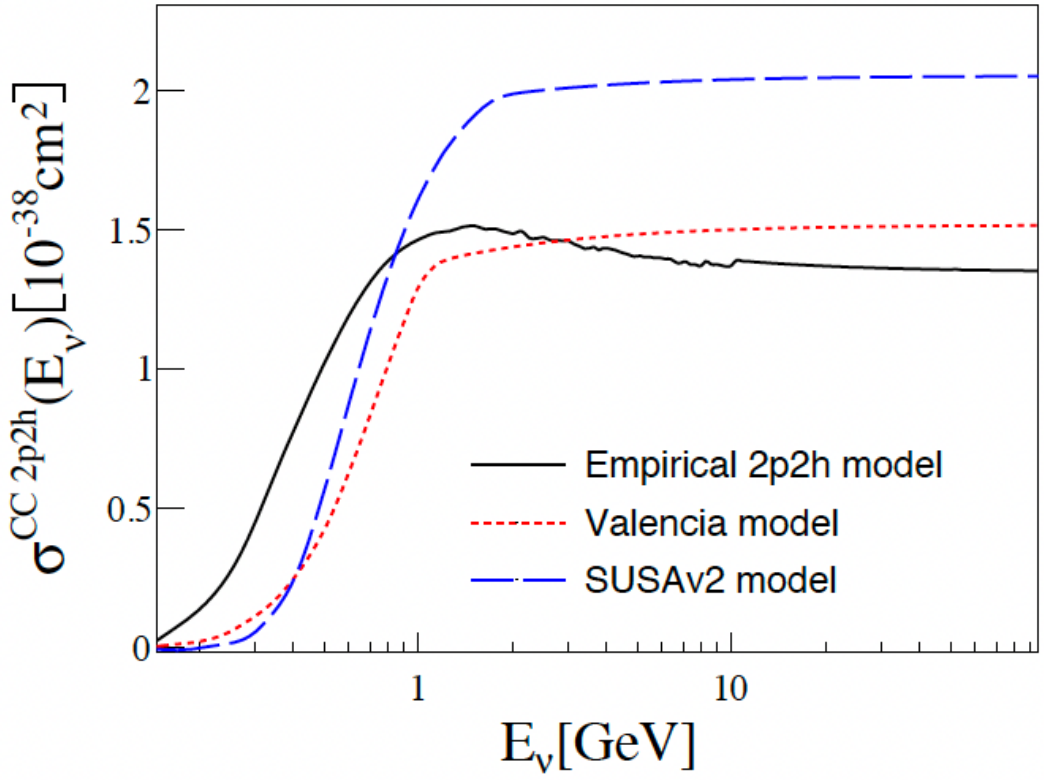
Neutrino-nuclei interactions



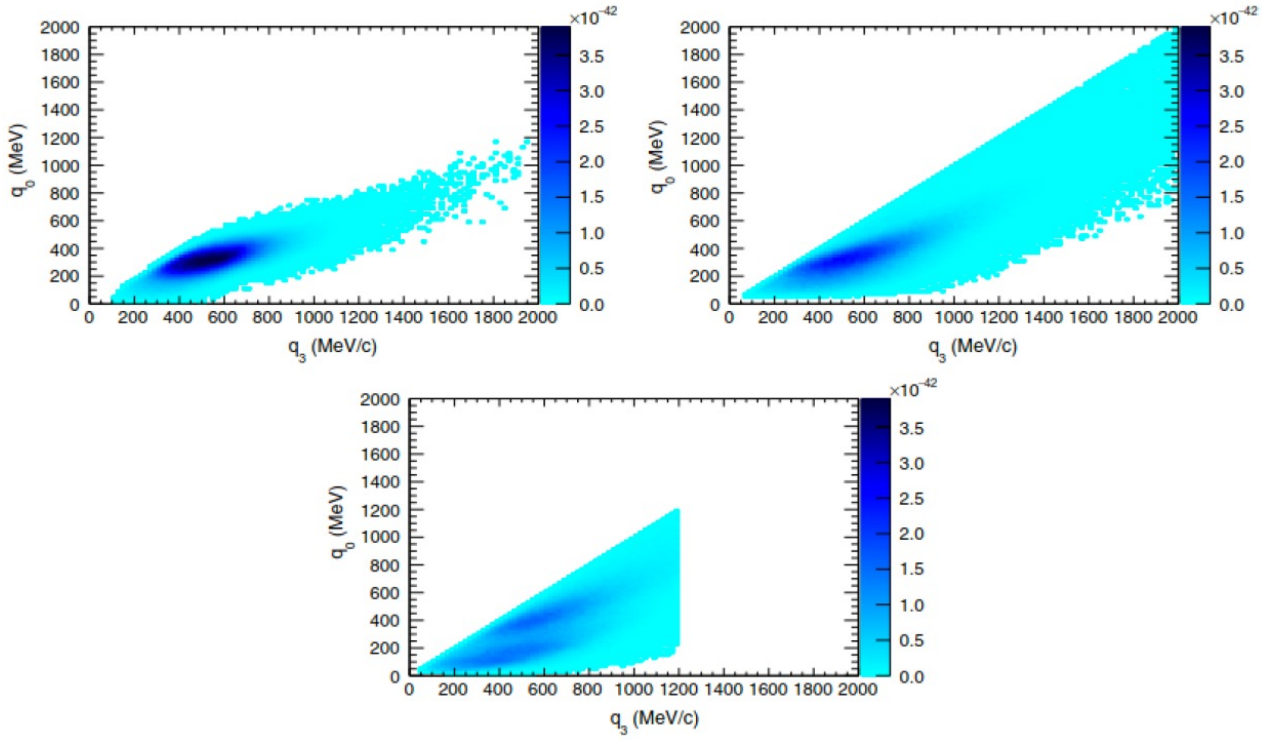


Multi-nucleon mechanisms tuning

Models differ in normalization



and shape

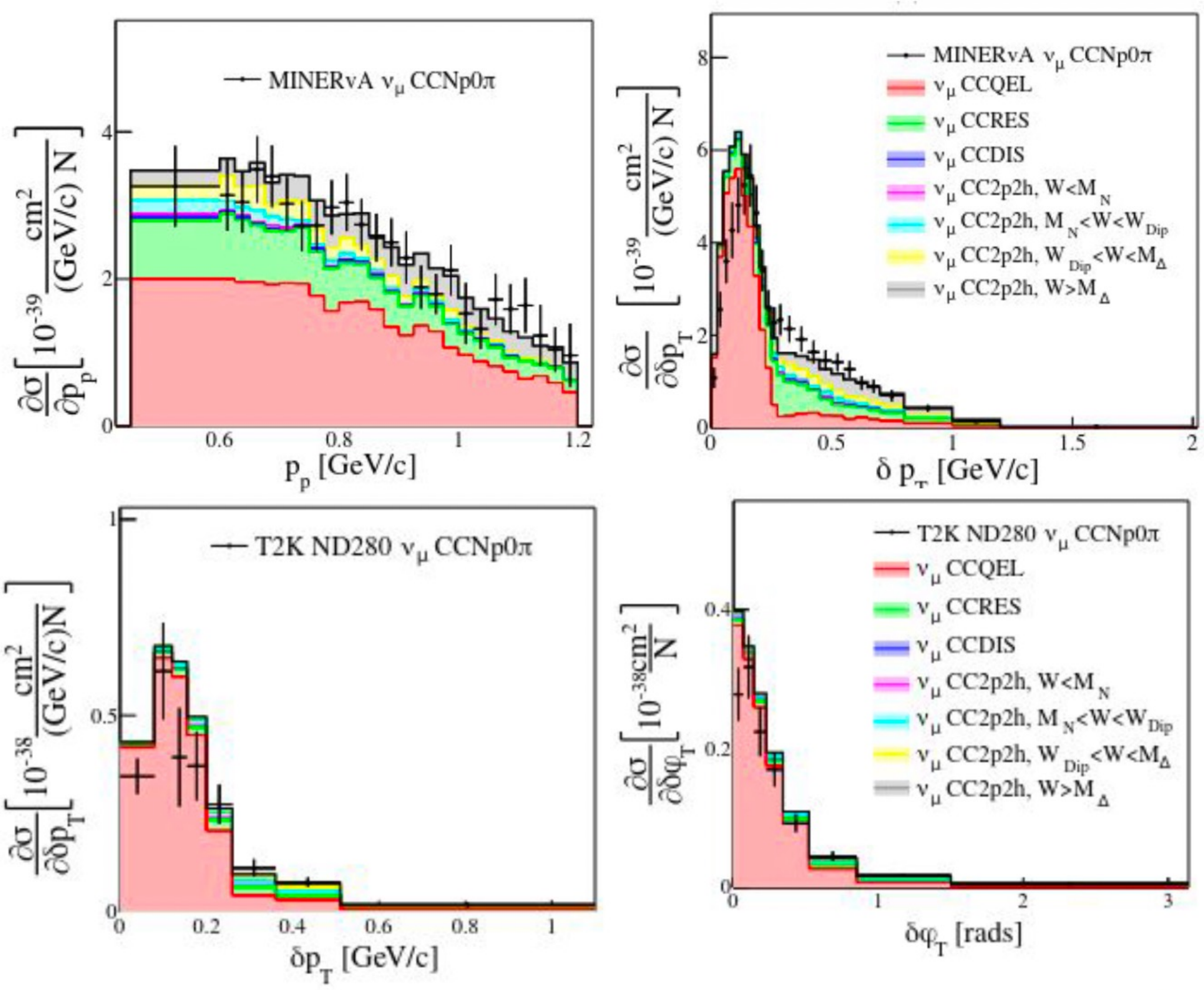


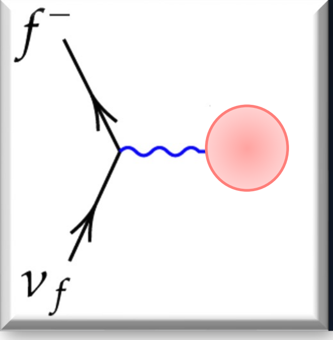
(b)

Current description of CCNp0π data

The G18_10a_02_11b CMC **has good agreement with all CCNp0π** data

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

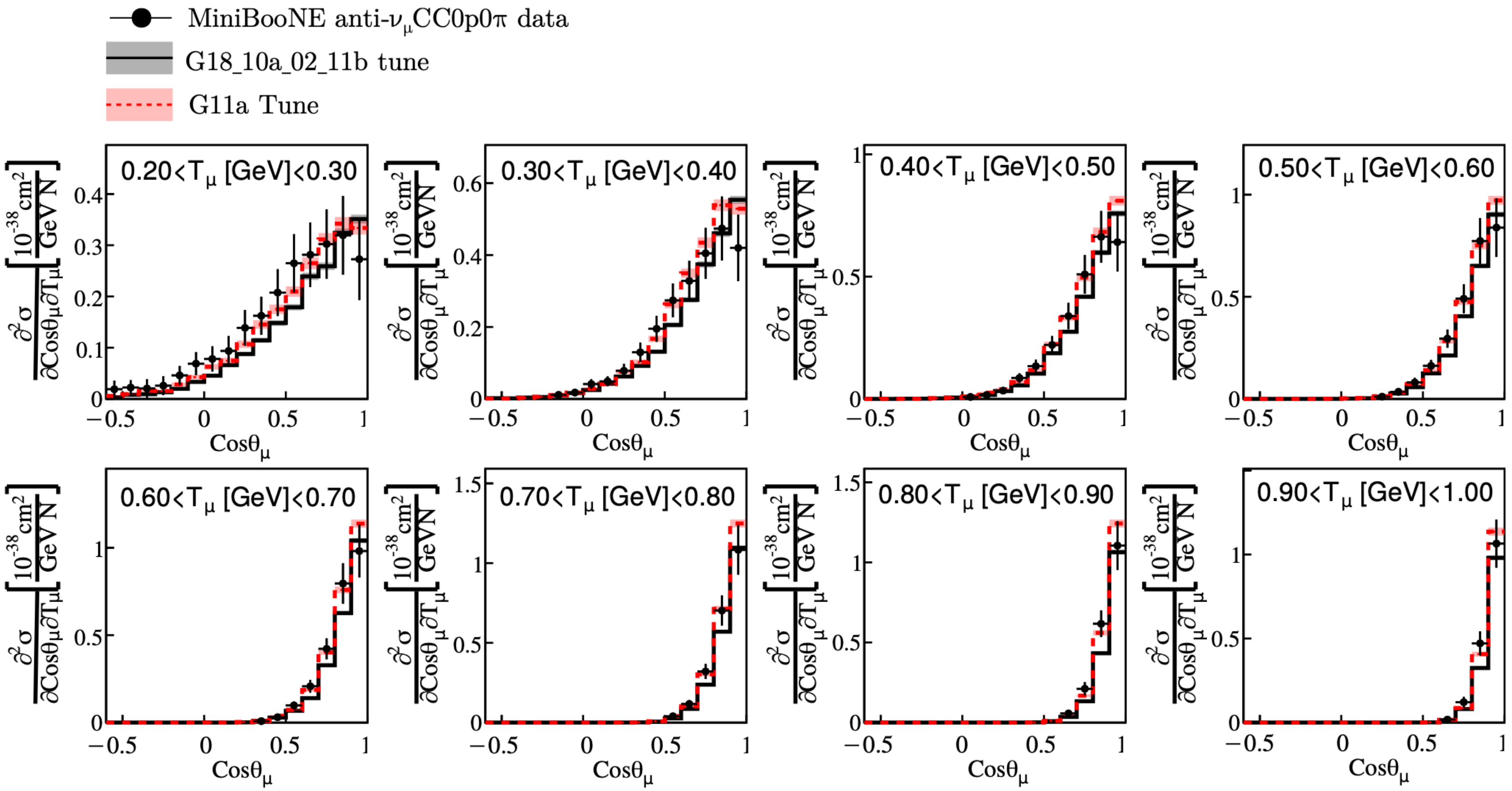




Tuning of $\nu - A$ CC0π interaction models Results

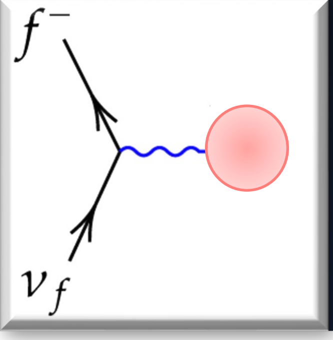
PhysRevD.104.072009

The enhancement of QEL and 2p2h cross sections lead to improved shape and normalization agreement

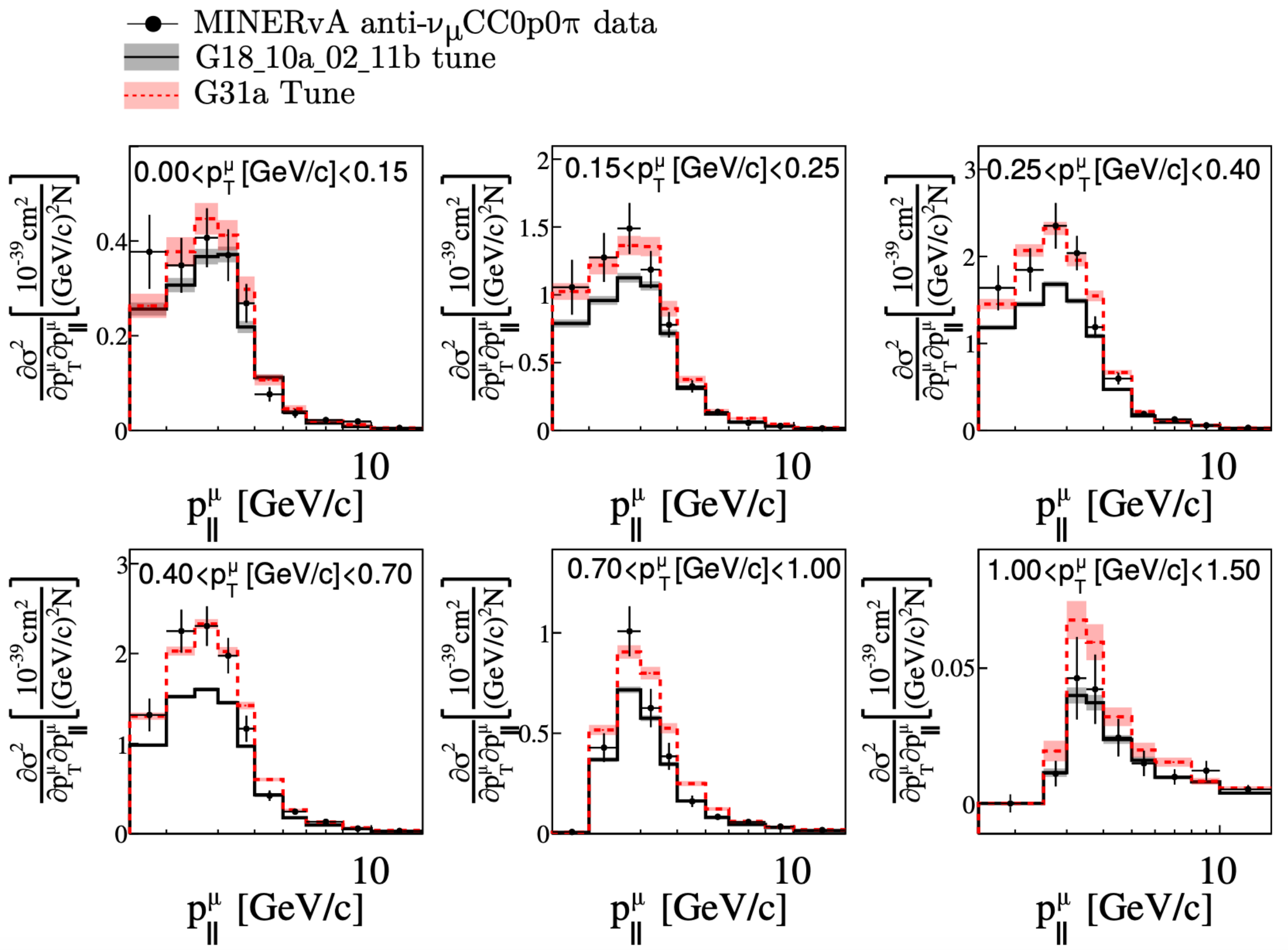


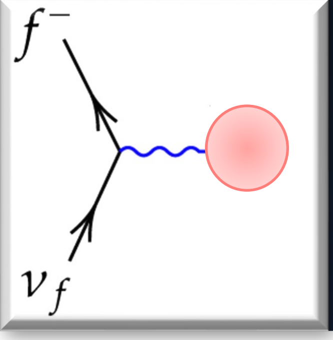
Tuning of $\nu - A$ CC0π interaction models Results

PhysRevD.104.072009



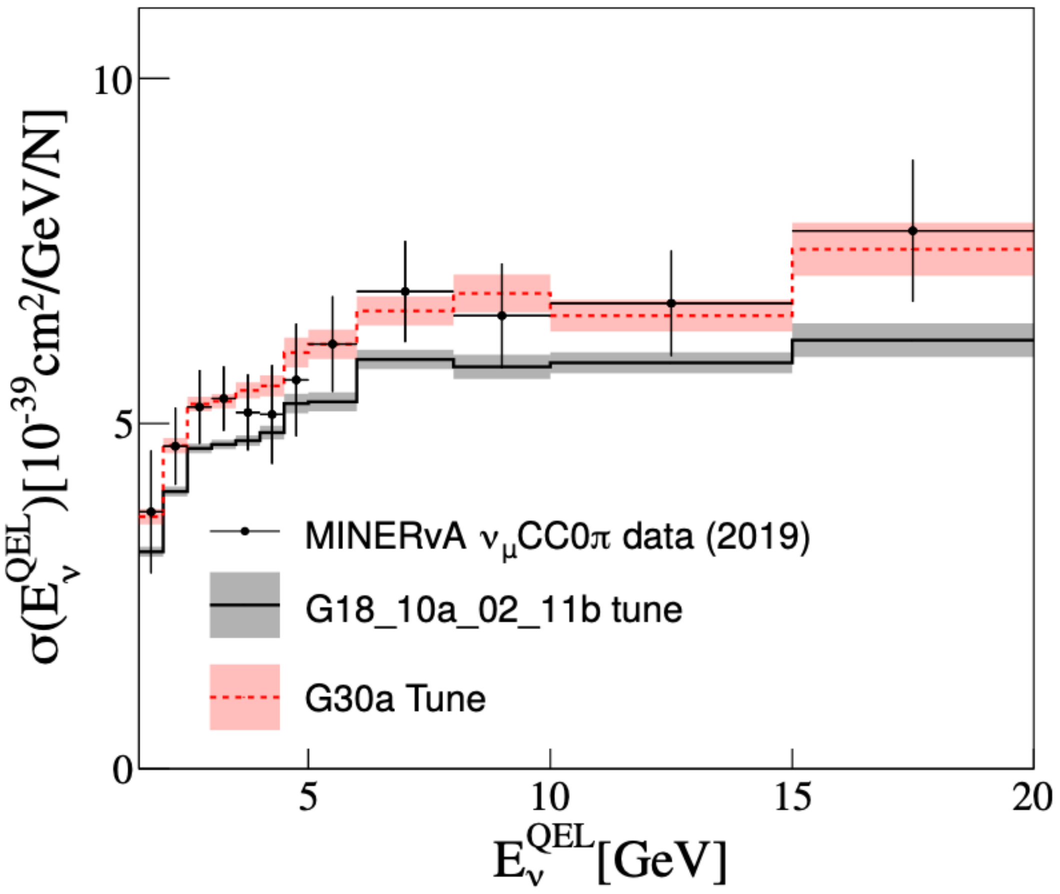
The enhancement of QEL and 2p2h cross sections lead to improved shape and normalization agreement

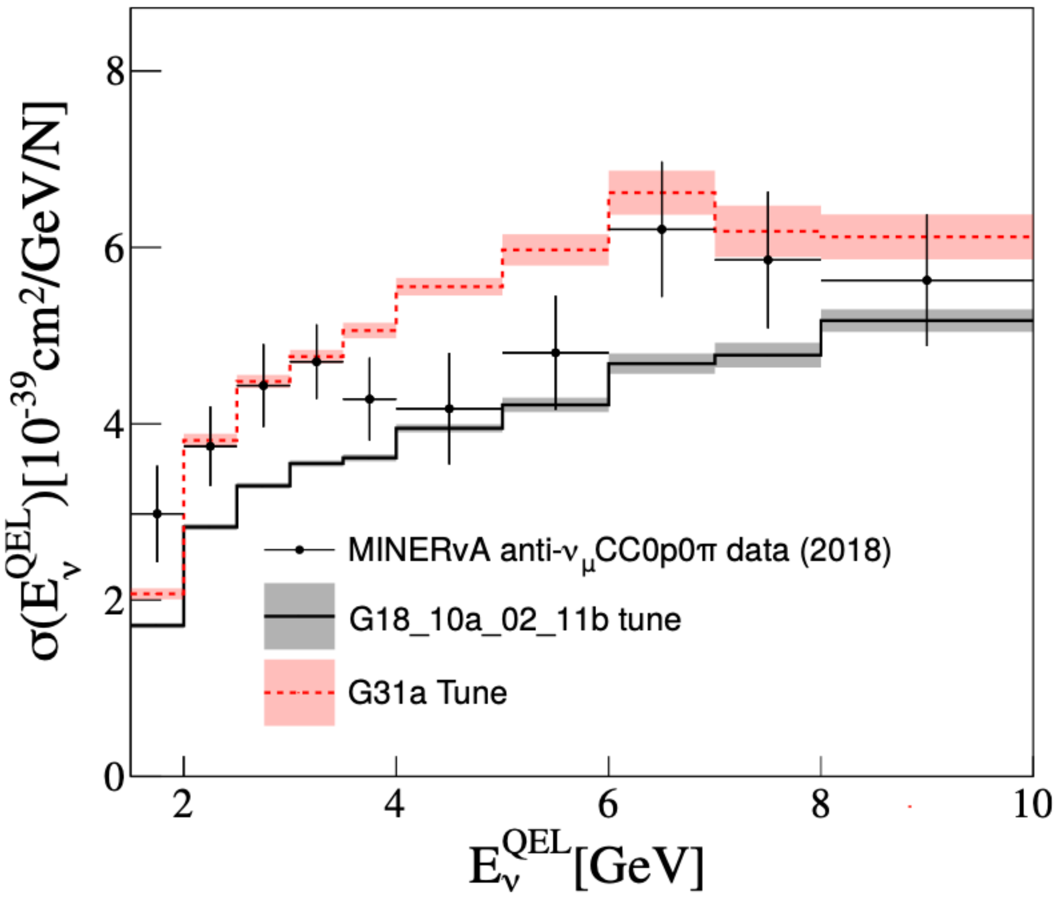


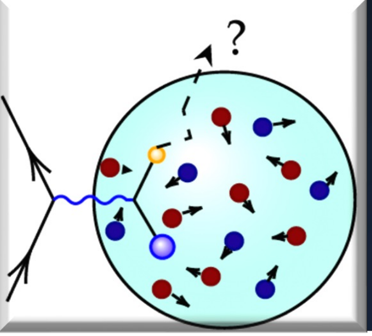


Tuning of $\nu - A$ CC0π interaction models Results

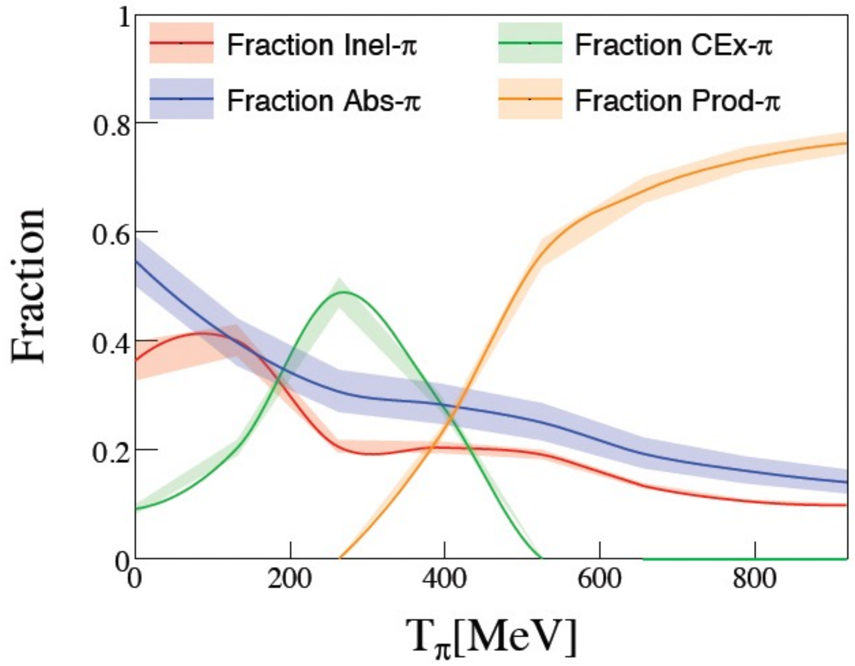
PhysRevD.104.072009



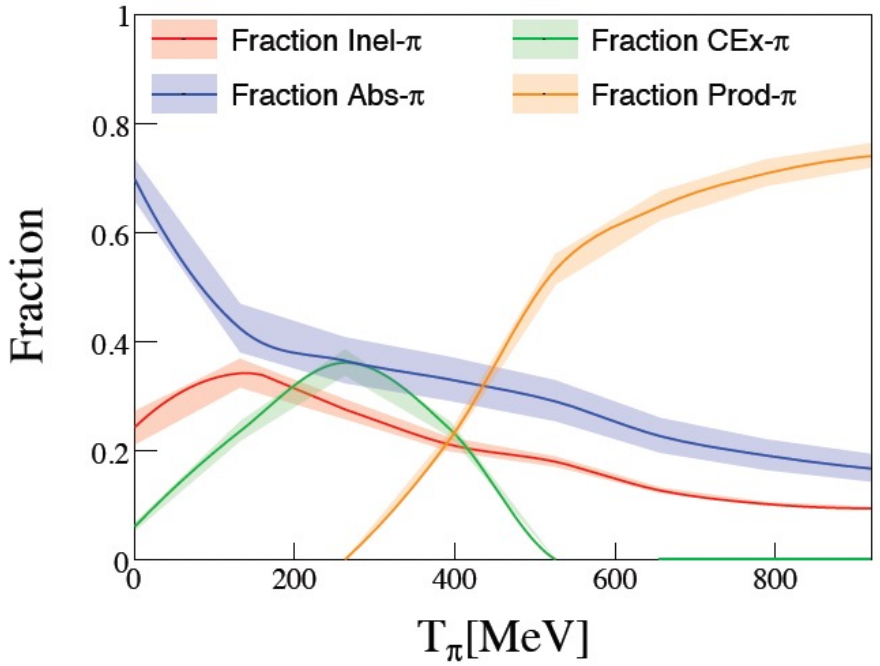




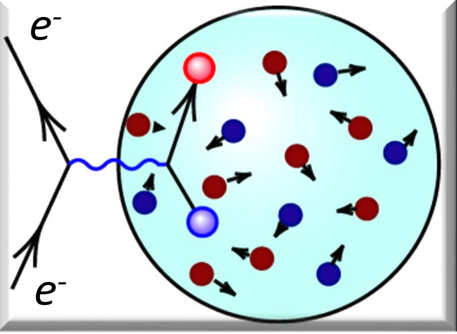
Final-State Interactions tuning



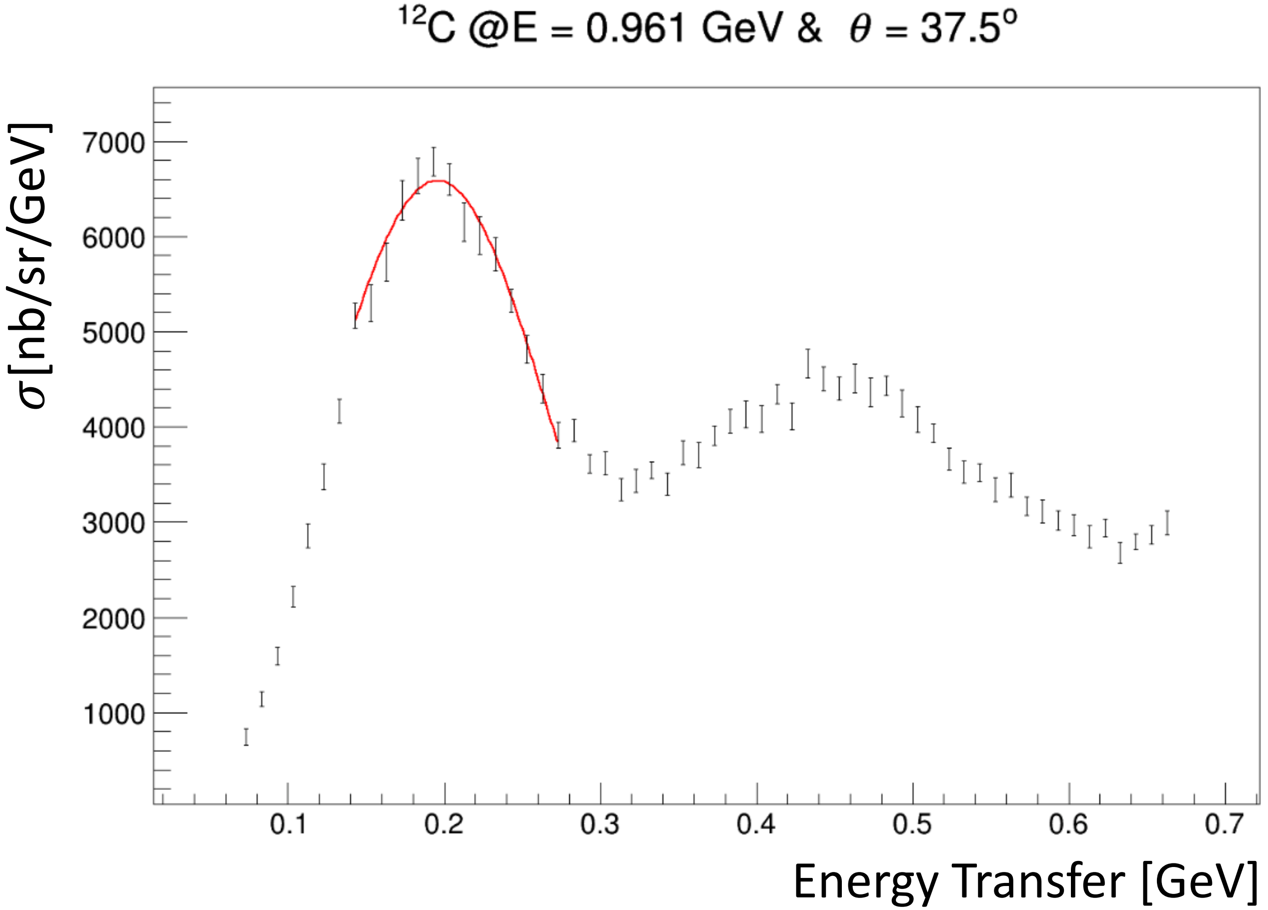
(a) hA2018 pion fractions for ^{12}C.

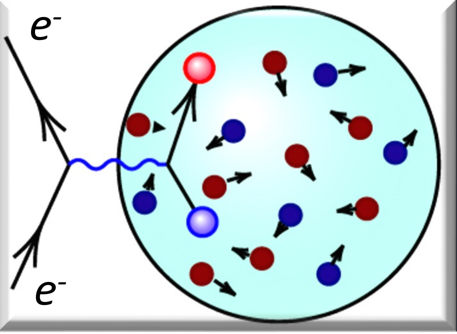


(b) hA2018 pion fractions for ^{40}Ar.



Nuclear model tuning





Nuclear model tuning

Matan Goldenberg