Extracting Model Uncertainties for Neutrino Event Generators with neutrino and electron data

Theoretical Physics Uncertainties to Empower Neutrino Experiments
An Institute for Nuclear Theory Workshop

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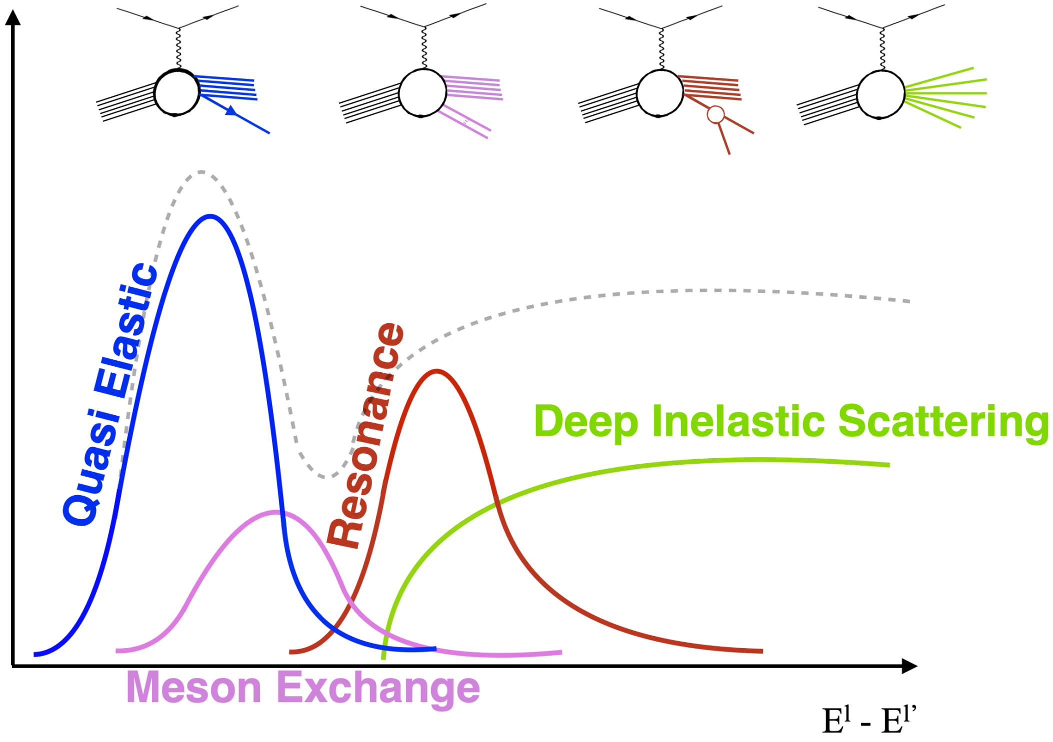
Genie

The TAU Neutrino Group

Neutrino event generators

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

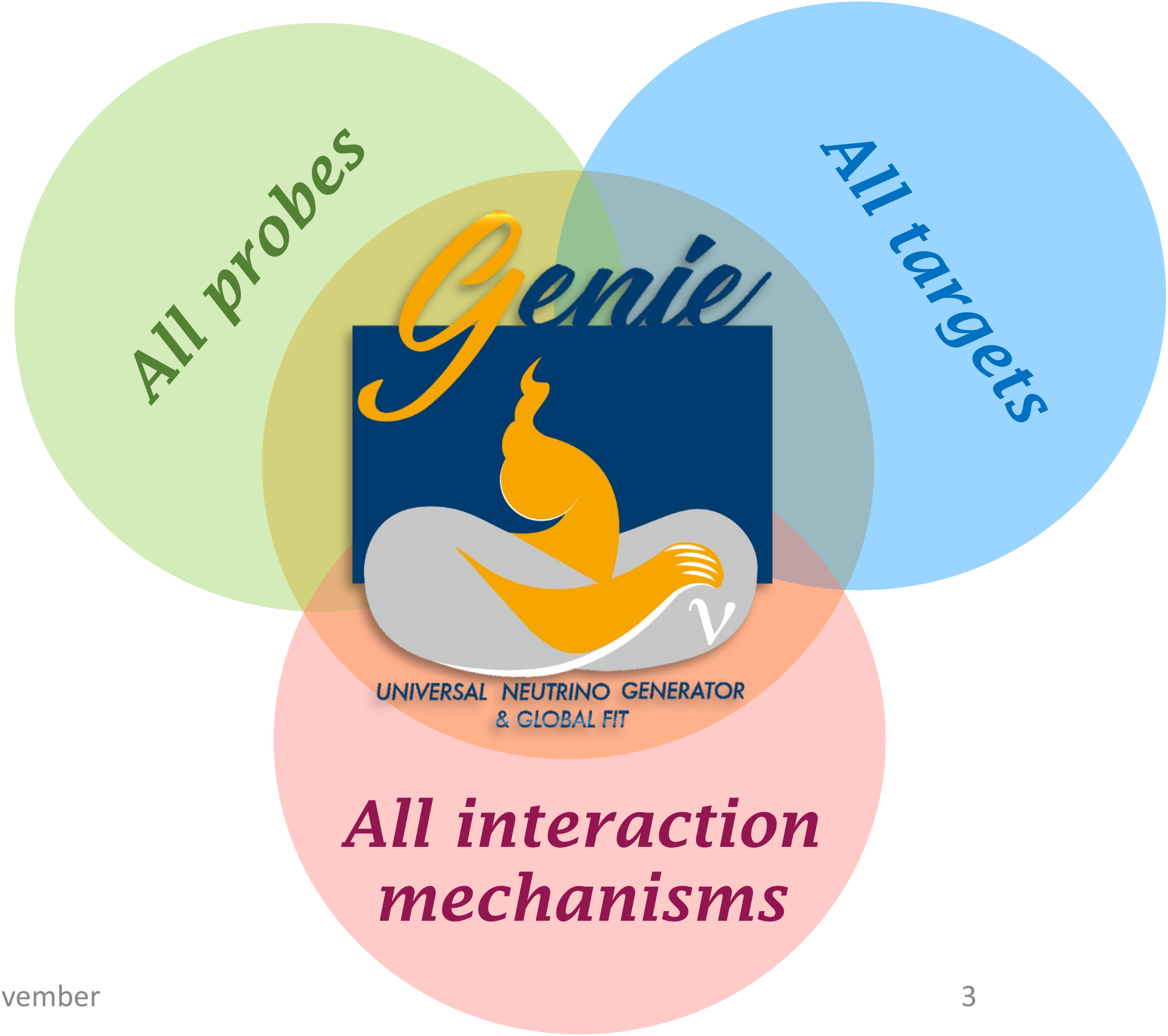
- ***ν*-experiments rely on simulations:**
  - To reconstruct the neutrino energy, estimate backgrounds, systematic uncertainties, …
- **Generator models are not complete**
  - Limited phase space coverage
  - Focus on lepton kinematics
  - Empirical transition between kinematic regions
  - Nuclear effects 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



All probes

All targets

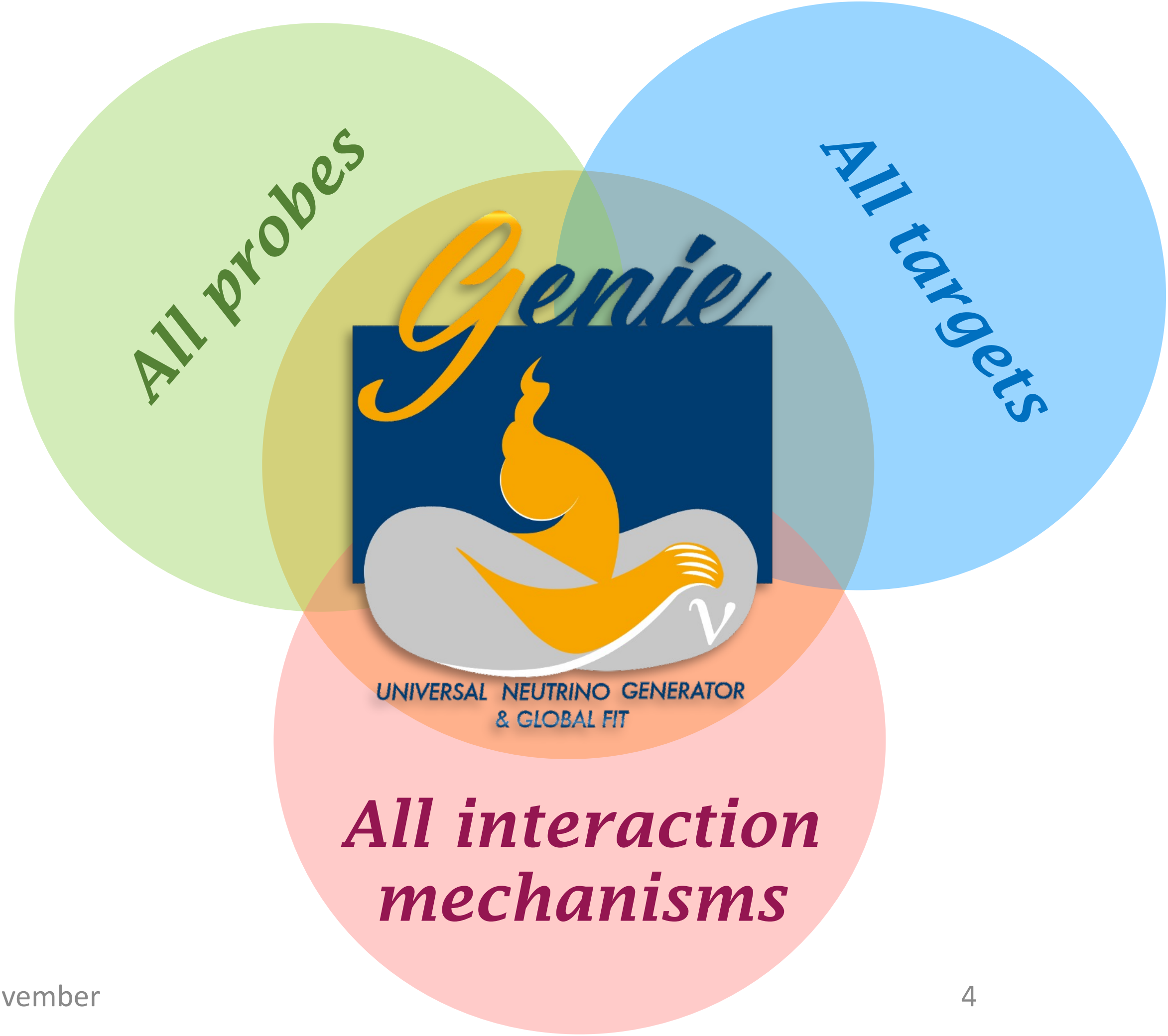
All interaction mechanisms

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 made exclusive!**



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 correlated 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:**
  - GENIE implementation of Valencia and SuSAv2 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. Minimize double-counting in transition regions
3. Highlight model limitations
4. Quantify/resolve tensions between experiments
5. **Data-driven constrains and uncertainties**

Review of MC tuning methods

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

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 parameters**

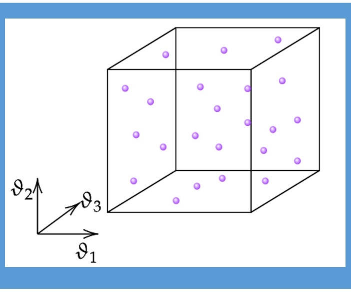
GENIE-Professor based tunes

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

GENIE-Professor based tunes

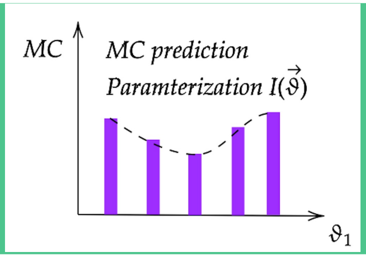
https://professor.hepforge.org

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



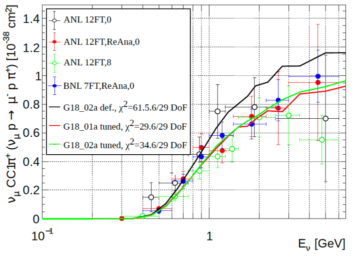
Brute-force scan of Monte Carlo response function

- 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

- Further developed by GENIE with emphasis on neutrino experiments demands (Active development)
- Multi-dimensional **parameter priors** (uncorrelated and correlated), weights, nuisance parameters
- **Input from theorists can be used as priors!**
- Can handle bin-to-bin correlation as well as correlation between experiments
- Proper treatment of highly correlated datasets with Peelle's Pertinent Puzzle resolution

GENIE-Professor based tunes

https://professor.hepforge.org

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 Tune Approach

with neutrino, electron and hadron-nucleus data

Model unification

- Have a generator with neutrino and electron scattering modes
- Ideally, implement models with clear V-A separation
- Have specific V and A parameters
- Most neutrino generators were developed for $\nu - A$ simulations

Tune your generator against electron-scattering data

- Much higher statistics than neutrino data – fix parameters before adding neutrino data
- Turn off axial components: **clear A-V separation might not be availab**le, but we aim for it
- When the separation is not available, it is still crucial to tune base-model for meaningful predictions
- Crucial input for ground state models, FSI and hadronization
- New exclusive measurements from e4nu collaboration! – See Larry's talk

Propagate tune results to neutrino tune – Iterative approach

- Neutrino based tune focus on the axial parameters
- Free nucleon tunes used to constrain $\nu - N$ parameters
- Partial tunes to explore **tensions between datasets** and **degrees of freedom**
- **Global tune** aims to improve agreement with all data
- **Data driven uncertainties** for neutrino experiments

GENIE-Professor based tunes

Free-nucleon model tune – global tune starting point

- Constrain nucleon cross sections – core of $\nu - A$ and $e - A$ models
- Neutrino-Nucleon Cross-Section Model Tuning in GENIE v3 [PhysRevD.104.072009] with νH and D data
- **(*) e-N tuning with inclusive electron scattering data (J.Tena-Vidal @ GENIE Collaboration)**

Nuclear model tunes

- Nuclear ground state, 1p1h+2p2h models, pion production, FSI
- Neutrino-nucleus CC0π cross-section tuning in GENIE v3 [PhysRevD.106.112001] with MINERvA, MiniBooNE and T2K data
- **(*) TKI tune with CC0π and CC1π data from MINERvA and T2K (Weijun Li, M.Roda, Xianguo Lu, C.Andreopoulos, J. Tena-Vidal)**

Hadronization tune

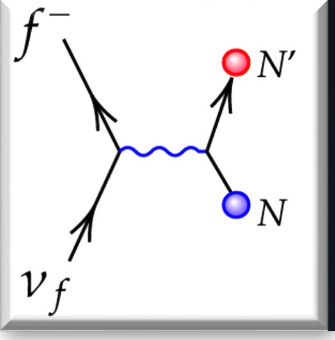
- Hadronization Model Tuning in GENIE v3 [PhysRevD.105.012009] using bubble chamber data
- First tune using neutrino data to constrain non-reweightable parameters

Uncertainty characterization and propagation

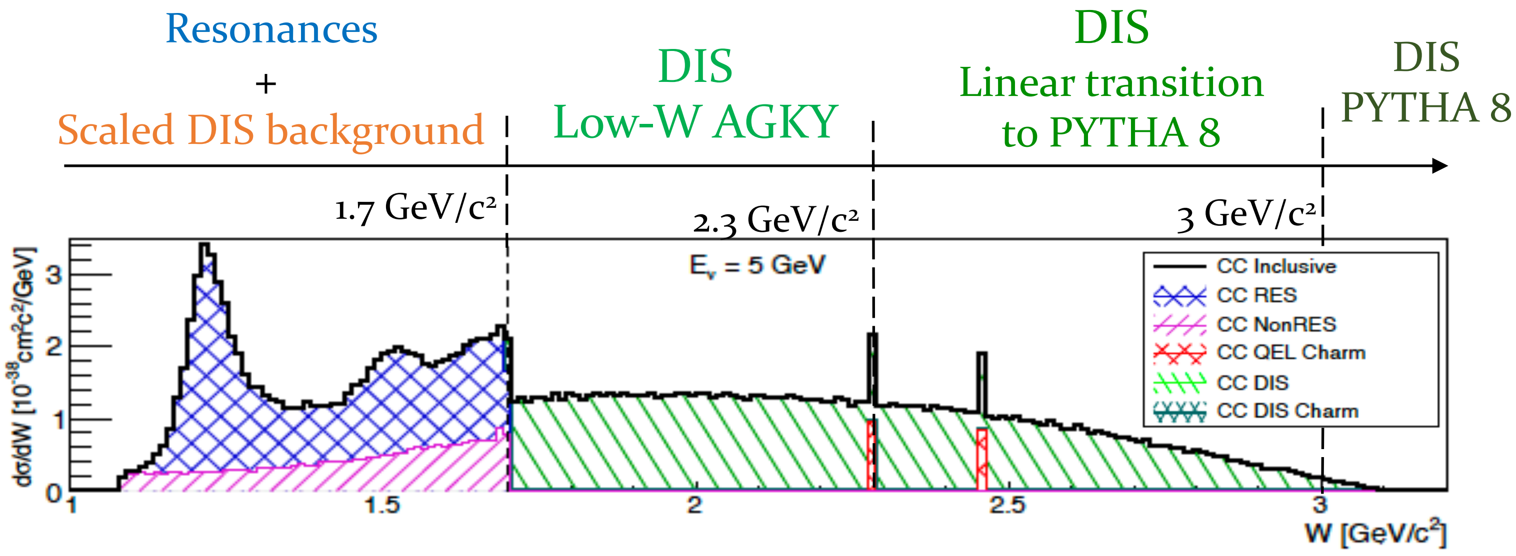
- **(*) Reweight upgrade to fully support GENIE tunes (Qiyu Yan, Marco Roda, Xianguo Lu, Costas Andreopoulos, Julia Tena-Vidal)**
  See Marco Roda's talk

Tuning with free nucleon data

- Shallow Inelastic scattering region
- Hadronization models



$\nu - N$ Shallow-Scattering Inelastic region



Resonances
+
Scaled DIS background

DIS
Low-W AGKY

DIS
Linear transition
to PYTHA 8

DIS
PYTHA 8

e-N scattering is based on the same concept

RES

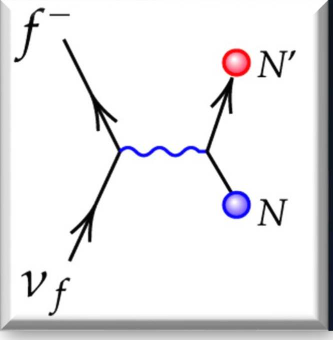
- Rein-Sehgal or Bergher-Sehgal are the starting point
- Added additional resonances
- Dipole Parameterization

Non-resonant bkg

- Duality-based approach
- Scaled Bodek-Yang model
- Scaling factors depend on initial state and hadron multiplicity
- Coupled to low-W AGKY model

DIS

- Bodek-Yang model
- Cross-section calculation at partonic level
- AGKY hadronization model



$\nu - N$ Shallow-Scattering Inelastic region

- **Lack of a theory driven NRB model in GENIE**
- 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
  - NRB modelled with Bodek and Yang extrapolated at $W < W_{cut}$
  - And still use a RES model for single resonance predictions
  - **Tuning is essential to avoid double-counting**
- f_m parameters **couple** with the AGKY hadronization model via $P_m^{had}(Q^2,W)$

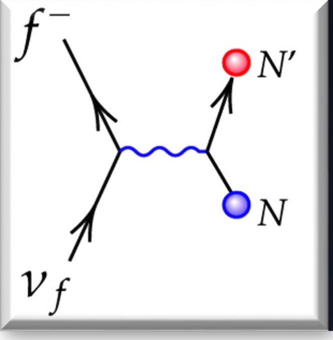
$$f_m(Q^2,W) = R_m P_m^{\mathrm{had}}(Q^2,W) \qquad P_m^{\mathrm{had}}(Q^2,W) = \frac{1}{\langle m\rangle}\psi\left(\frac{m}{\langle m\rangle}\right)$$

m: hadron multiplicity

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

Free parameters

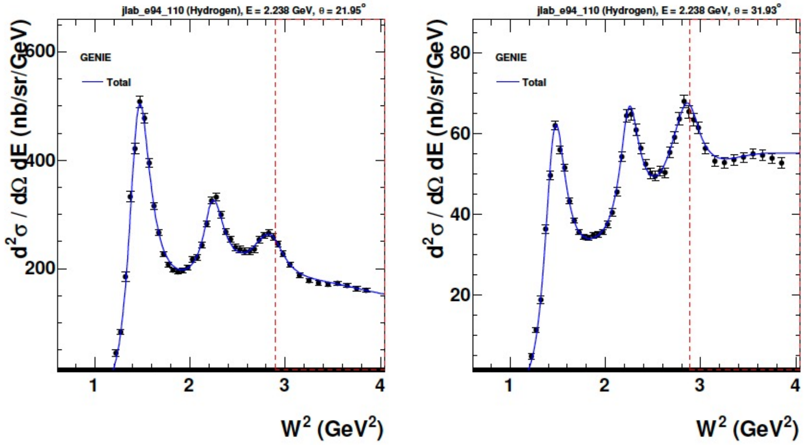
Different parameters for EM and CC/NC



Tuning the Shallow-Scattering Inelastic region
Available datasets

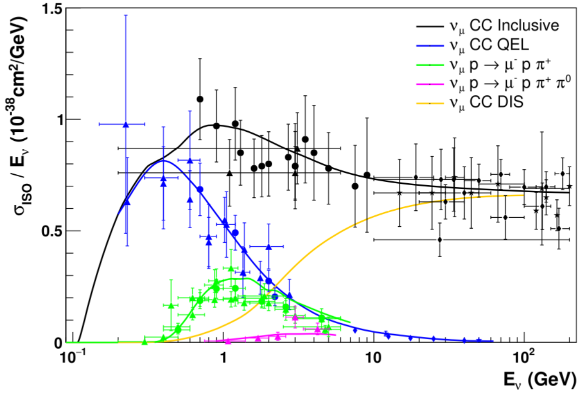
$\boldsymbol{e - H/^2H}$

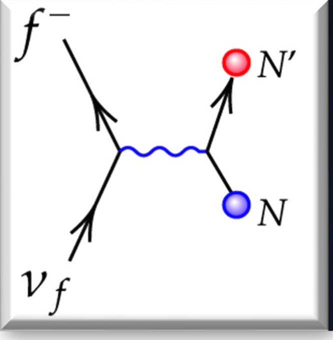
- Inclusive data from JLAB and SLAC as a function of W^2 (true!)
- For different beam energies and angles



$\boldsymbol{\nu - H/^2H}$

- ANL, BNL, FNAL and BEBC bubble chambers
  - One and two-pion production
- **Flux-unfolded** cross-section measurements as a function of reco-E_ν
  - Many reasons not to use it
  - Only data available on free nucleon





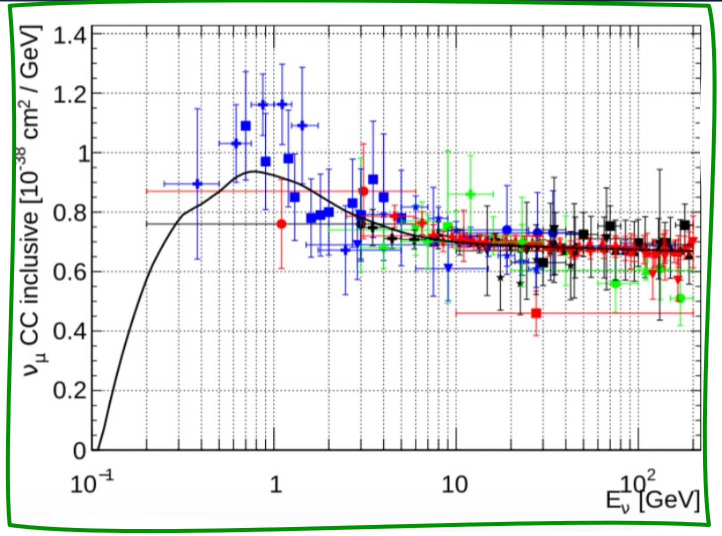
Tuning the Shallow-Scattering Inelastic region Neutrino tune

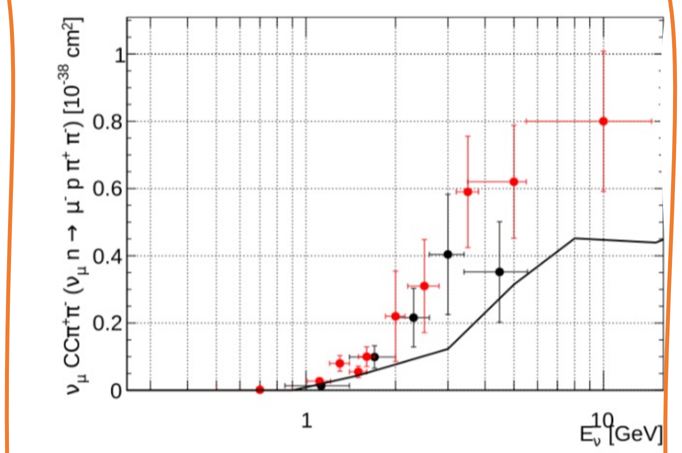
PhysRevD.104.072009

The neutrino tune took precedence:

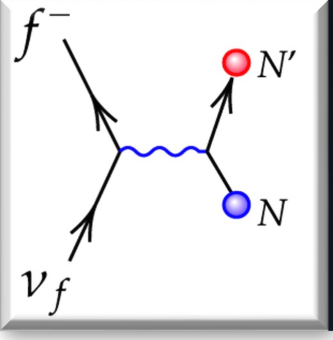
- Crucial to provide with the best description for neutrino experiments
- **Previous tune parameters (G00_00a) were tuned to inclusive only**

- **Description of exclusive channels was not satisfactory**
- Missing systematic uncertainties estimation





G00_00a default vs ν_μ CC p$\pi^+\pi^-$.



Tuning the Shallow-Scattering Inelastic region Parameters of interest for neutrinos

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:

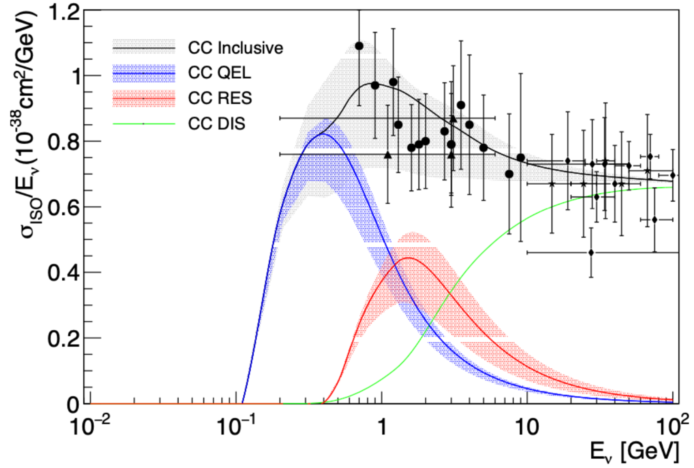
- S_{DIS}: overall scaling factor for DIS cross-section
- Prior of 1±0.5 to preserve agreement with high E data (>100GeV)

Normalization uncertainty:

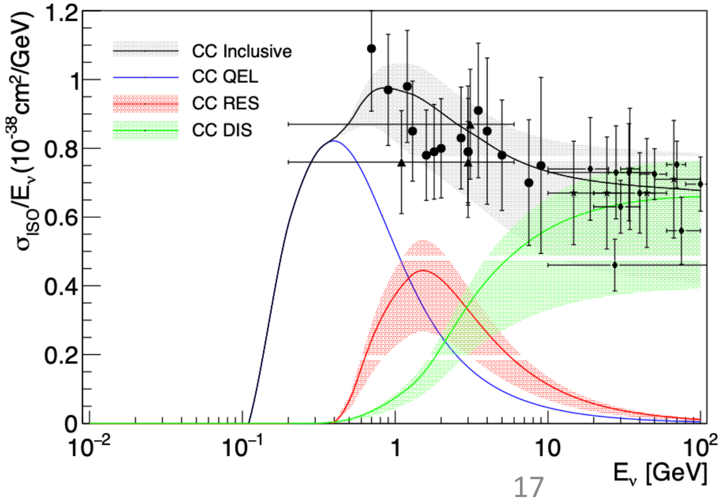
- Nuisance parameters per experiment to account for missing normalization uncertainties

QEL model parameters:

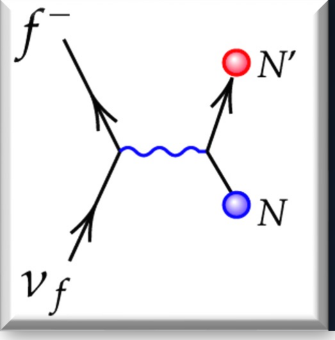
- M_A^{QEL}: global fit result applied as prior - $M_A^{RES} = 1.12 \pm 0.03\ GeV$



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



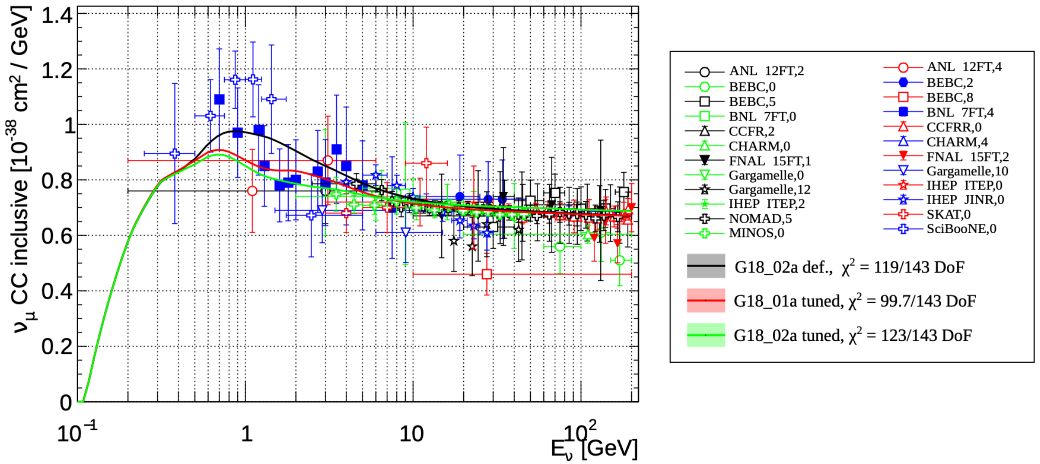
(b) $S_{\rm RES}$ and $S_{\rm DIS}$ impact.



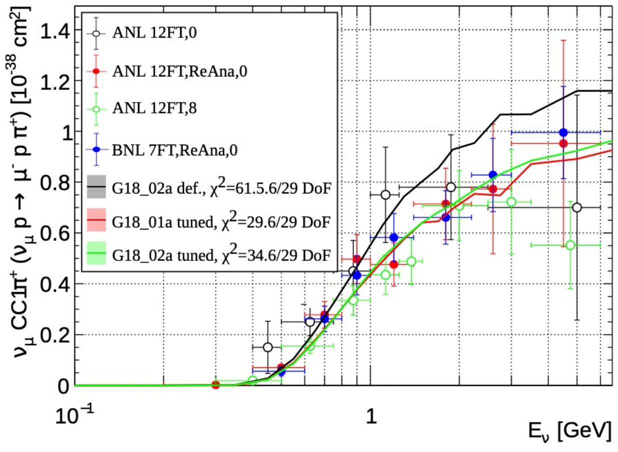
Tuning the Shallow-Scattering Inelastic Region with Neutrino Data

PhysRevD.104.072009

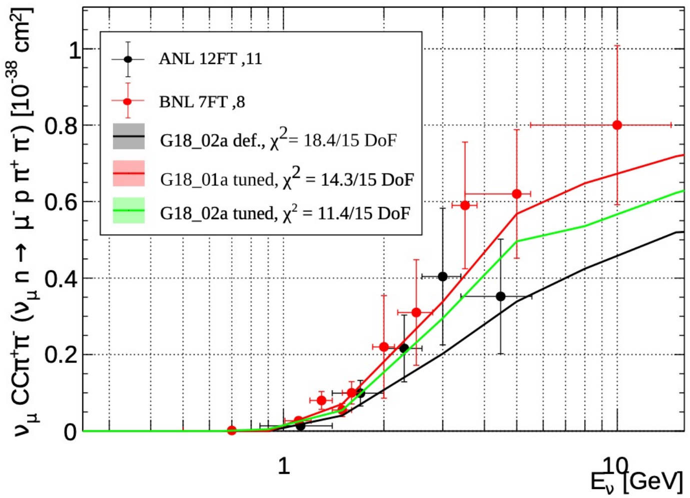
Parameter	Default	G18_02a
S_{RES}	**1.00**	**0.84±0.03**
S_{DIS}	1.032	1.06±0.01
$R_{\nu p}^{CC1\pi}$	0.10	0.008
$R_{\nu n}^{CC1\pi}$	0.30	0.03±0.01
$R_{\nu p}^{CC2\pi}$	1.00	0.94±0.08
$R_{\nu n}^{CC2\pi}$	1.00	2.3±0.1
M_A^{QEL}	0.999	1.00±0.013
M_A^{RES}	1.12	1.09±0.014
W_{cut}	1.7	1.81
$\chi^2/157DoF$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



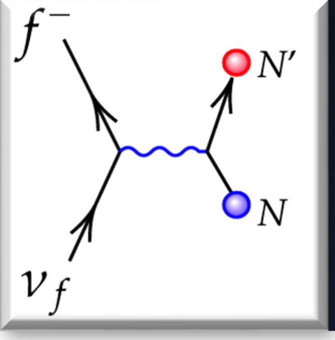
(a) Comparison of ν_μ CC Inclusive cross-section data against against the *default* and tuned CMC.



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



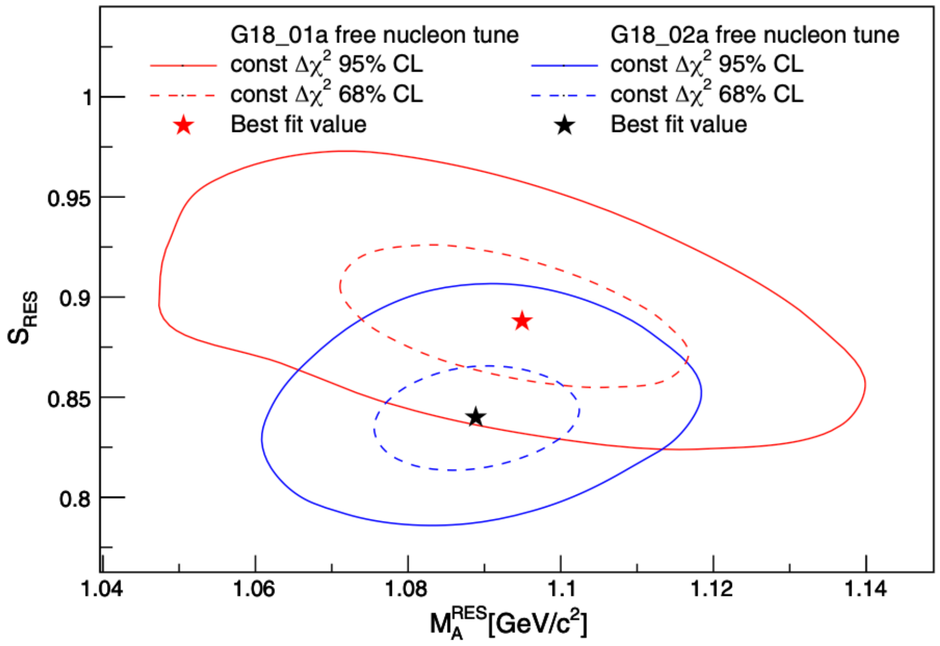
(c) Comparison of ν_μ CC $\pi^+\pi^-$ data on neutron.



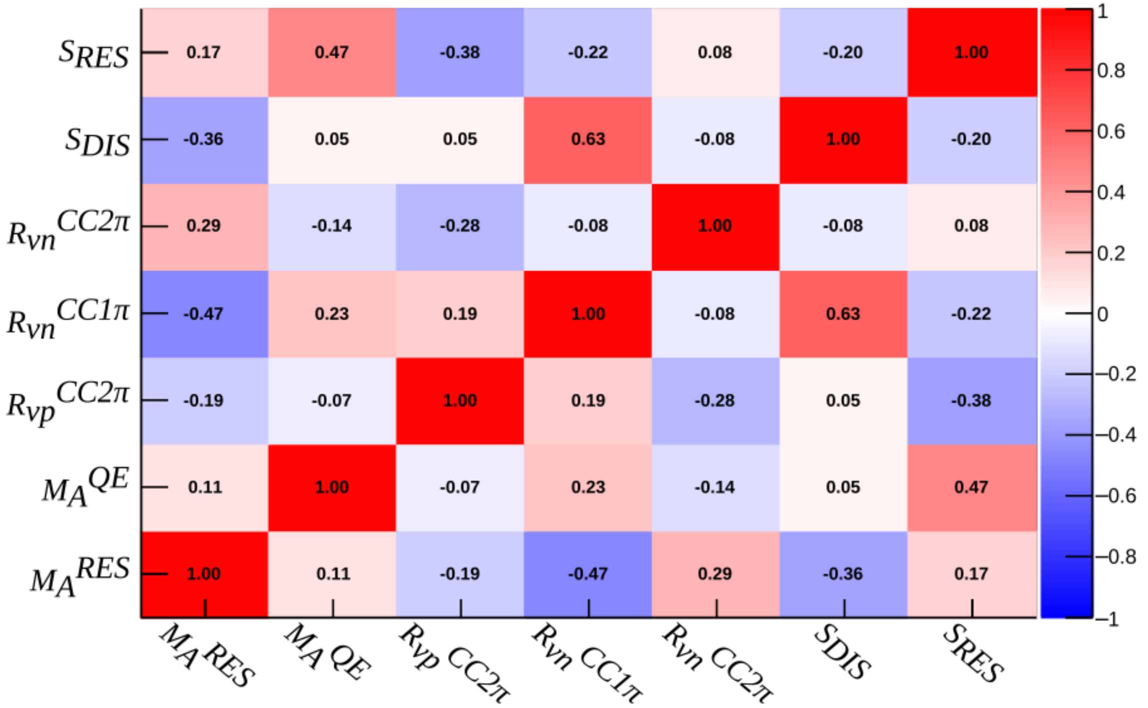
Tuning the Shallow-Scattering Inelastic Region with Neutrino Data

PhysRevD.104.072009

- The tuning machinery also provides with full correlation between parameters
- We also compute the contour and profiles to validate the tune uncertainties

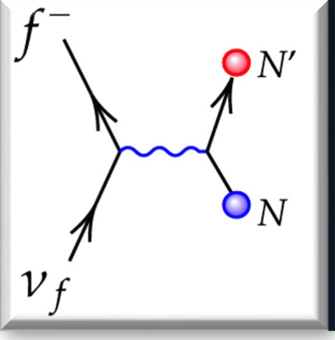


(b) Contour M_A^{RES} vs S_{RES}



	M_A RES	M_A QE	R_{vp} $CC2\pi$	R_{vn} $CC1\pi$	R_{vn} $CC2\pi$	SDIS	SRES
S_{RES}	0.17	0.47	-0.38	-0.22	0.08	-0.20	1.00
S_{DIS}	-0.36	0.05	0.05	0.63	-0.08	1.00	-0.20
$R_{vn}{}^{CC2\pi}$	0.29	-0.14	-0.28	-0.08	1.00	-0.08	0.08
$R_{vn}{}^{CC1\pi}$	-0.47	0.23	0.19	1.00	-0.08	0.63	-0.22
$R_{vp}{}^{CC2\pi}$	-0.19	-0.07	1.00	0.19	-0.28	0.05	-0.38
$M_A{}^{QE}$	0.11	1.00	-0.07	0.23	-0.14	0.05	0.47
$M_A{}^{RES}$	1.00	0.11	-0.19	-0.47	0.29	-0.36	0.17

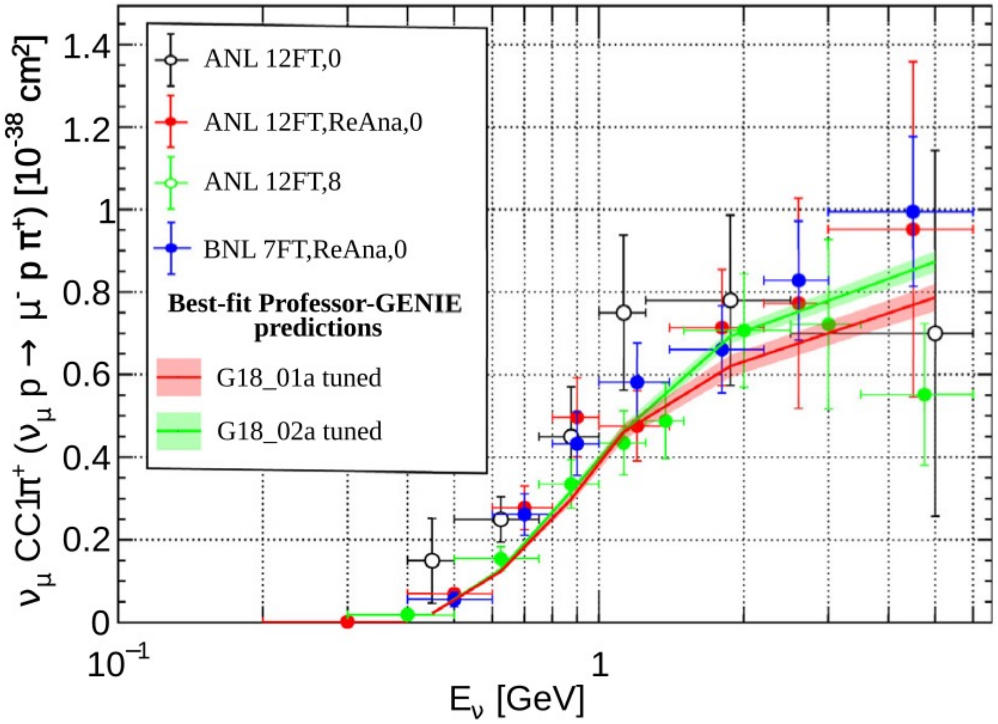
FIG. 16. Parameter correlation matrix from the GENIE fit using the G18_02a(/b) CMC correlation matrix.



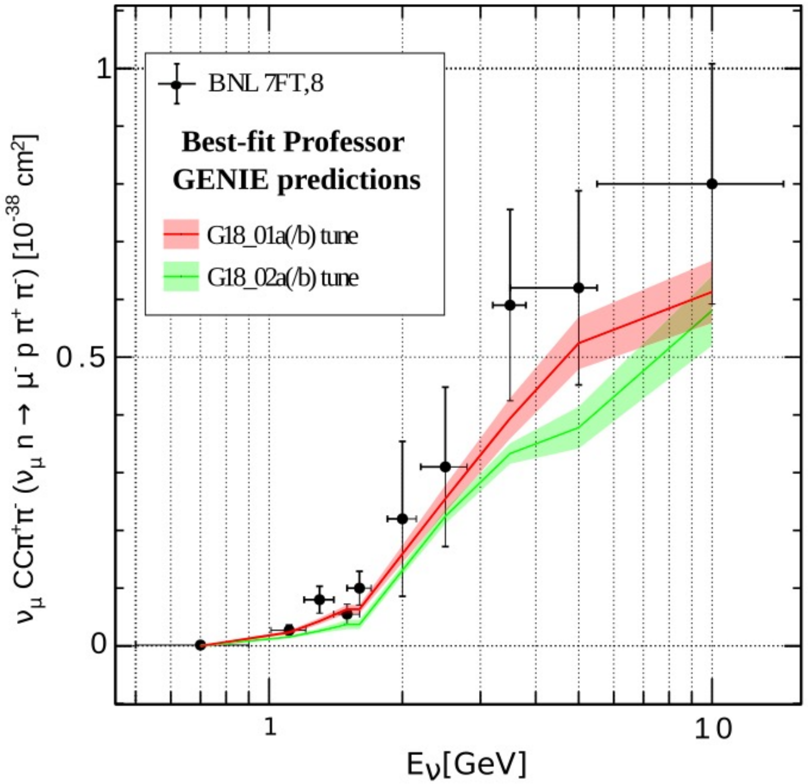
Tuning the Shallow-Scattering Inelastic Region with Neutrino Data

PhysRevD.104.072009

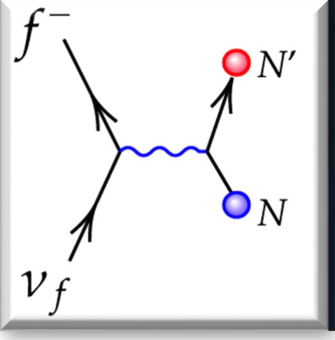
- It is possible to propagate the uncertainty to the Professor prediction
  - See Marco Roda's talk tomorrow
- 1 sigma confidence band:



(a) ν_μCC1π^+ comparison.

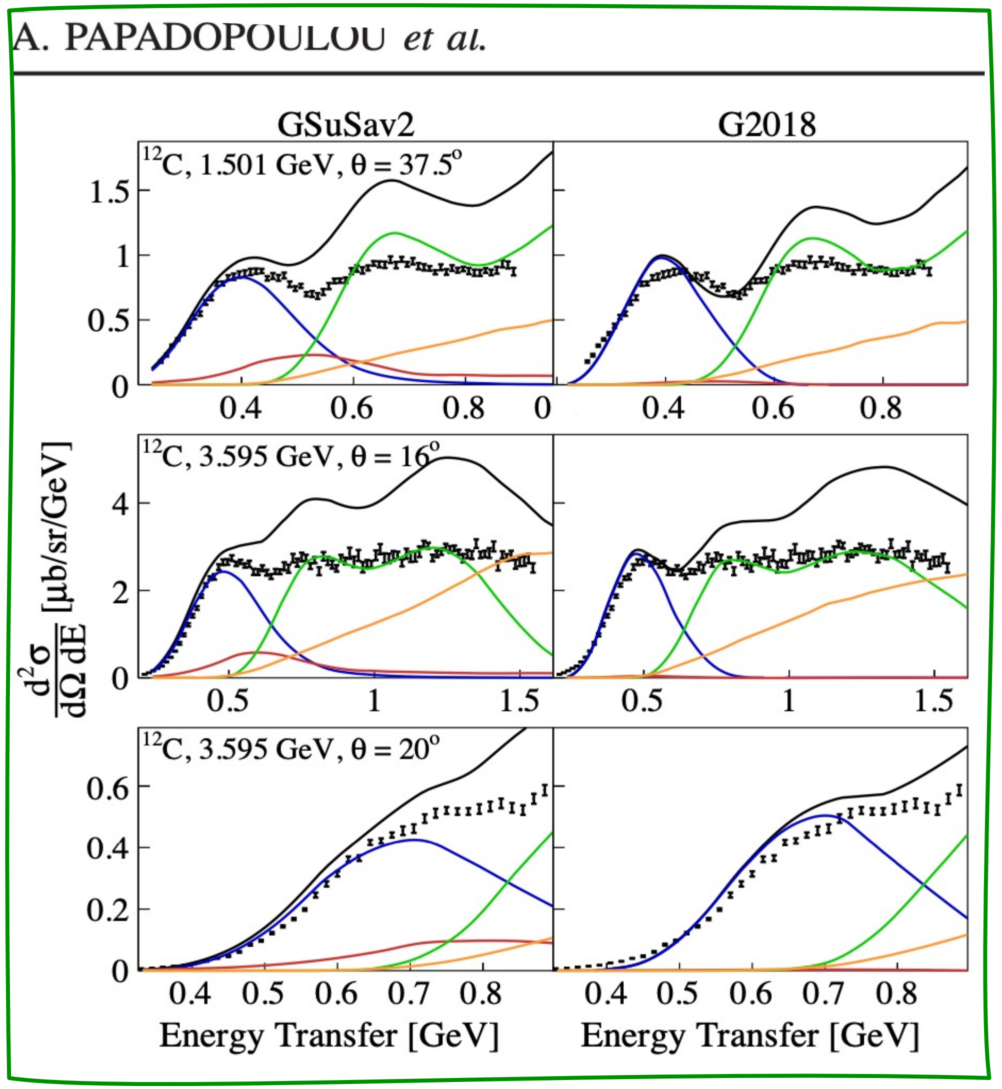


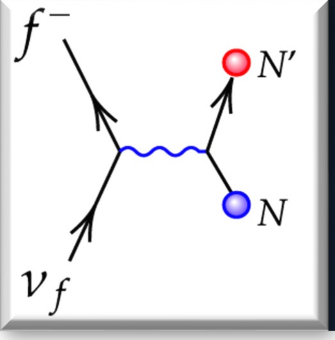
(b) ν_μCC$\pi^+\pi^-$ comparison.



Tuning the Shallow-Scattering Inelastic Region with Electron Data

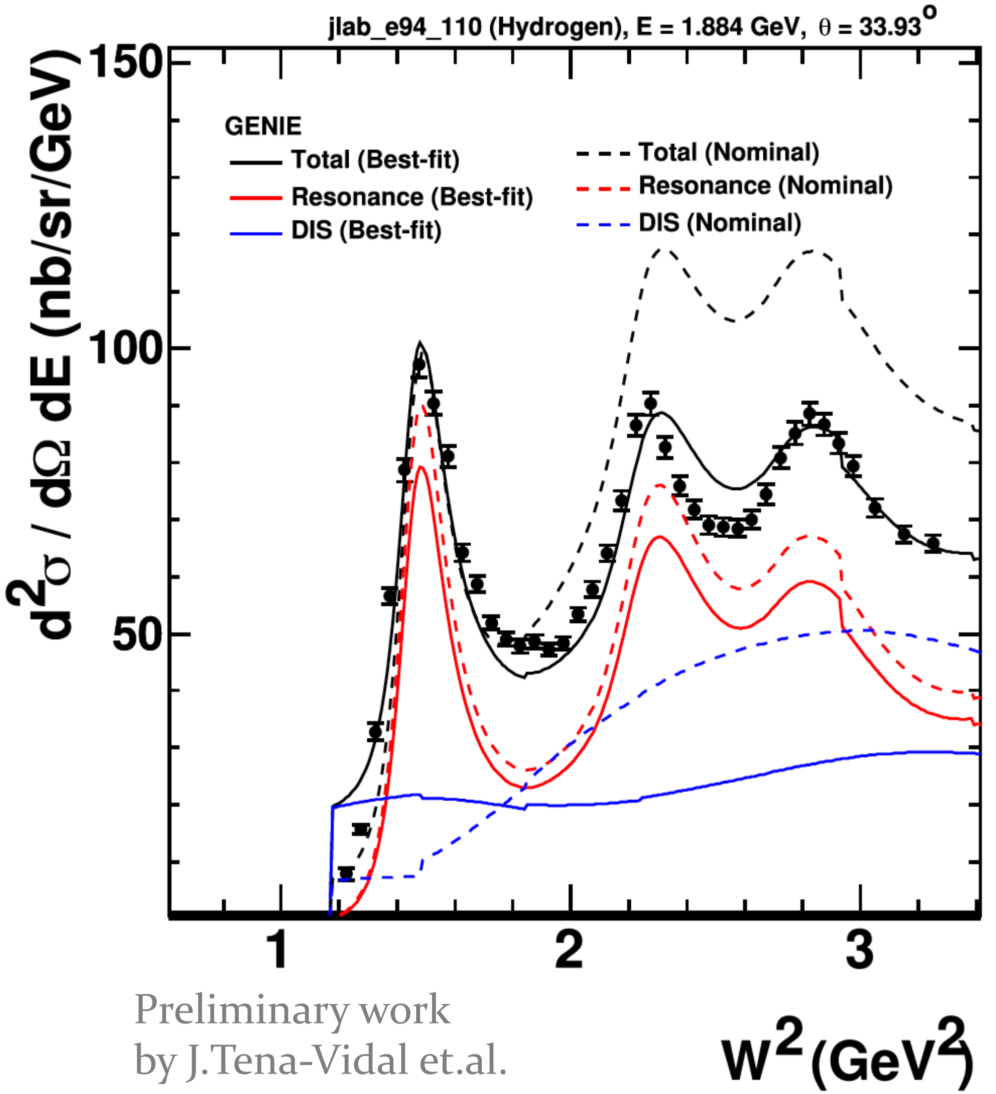
- Non-resonant background EM parameters never tuned to electron data
  - Double counting is guaranteed – overpredicting data at the SIS region
  - **The SIS region must be tuned with electron data for reliable comparisons**
  - Must get the starting point normalization correct before tuning nuclear models



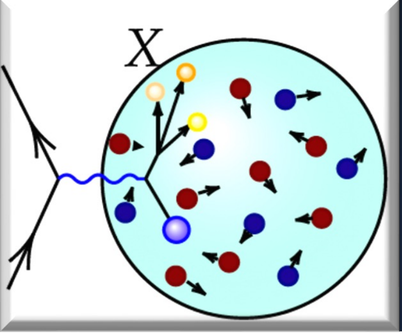


Tuning the Shallow-Scattering Inelastic Region with Electron Data

- **Excellent inclusive data available from JLAB and SLAC**
  - Different kinematic regions in GENIE are defined as a function of W - fine W binning breaks most degeneracy
- **Preliminary tune with current GENIE implementation improves overall normalization**
- **New model improvements**
  - Fully decoupled implementation from neutrino parameters
  - Review of vector form factor parameterization
  - Updated Bodek-Yang model
  - Optimized Wcut value to describe electron data
  - Improvements are directly benchmark to electron data



Preliminary work by J.Tena-Vidal et.al.

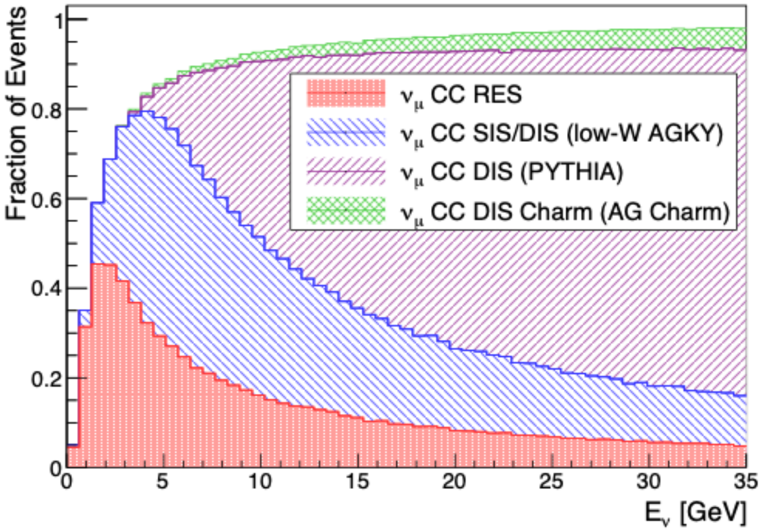


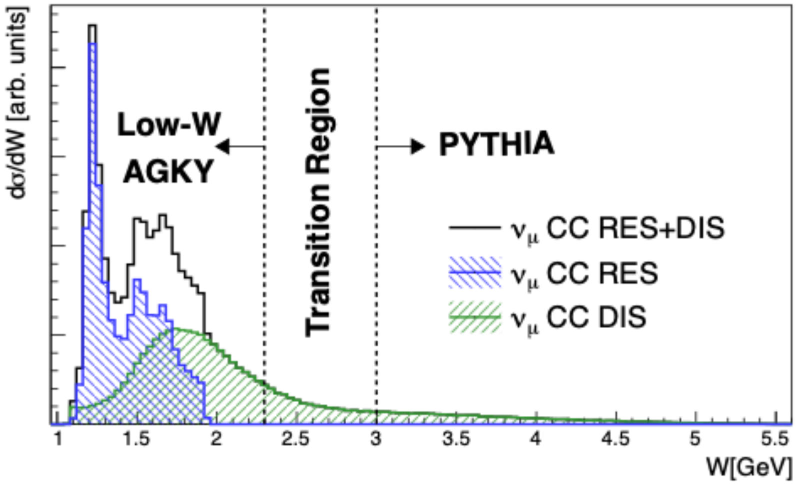
Hadronization tuning impact on the Shallow Inelastic Scattering region

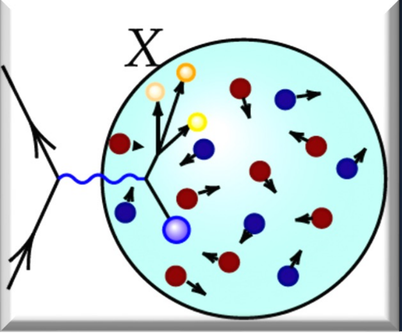
Hadronization models provide with final-state hadrons properties after a DIS interaction

Crucial for experiments:

- Experiments like DUNE expect a **large fraction of SIS and DIS events ∽ 45%**
- It determines the number of hadrons, hadronic shower shape, EM fraction of hadronic shower, hadronic shower energy reconstruction…







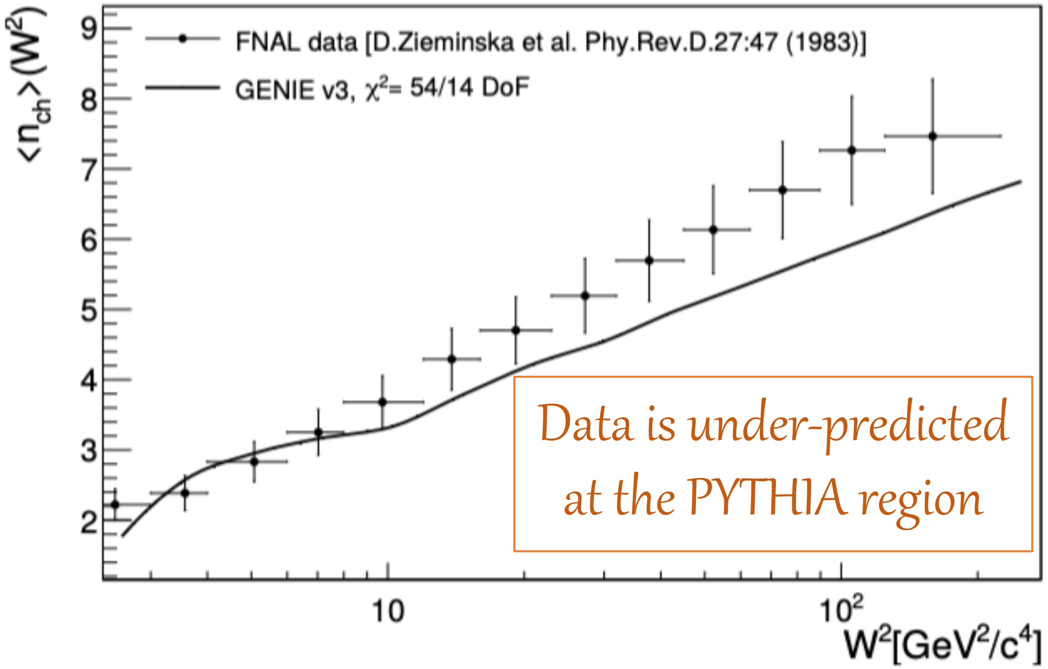
Hadronization tuning impact on the Shallow Inelastic Scattering region

- Hadronization in GENIE is handled with the AGKY model [Eur.Phys.J.C63:1-10,2009]

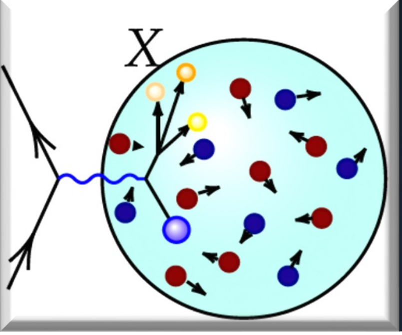
AGKY main ingredients

- Low-W empirical model for SIS/DIS events at $W < 2.3\text{GeV}/c^2$
- PYTHIA 6 for events with $W > 3\text{GeV}/c^2$
- In the $2.3 < W < 3\text{GeV}/c^2$ region, the probability of using the low-W empirical model or PYTHIA changes linearly as a function of W

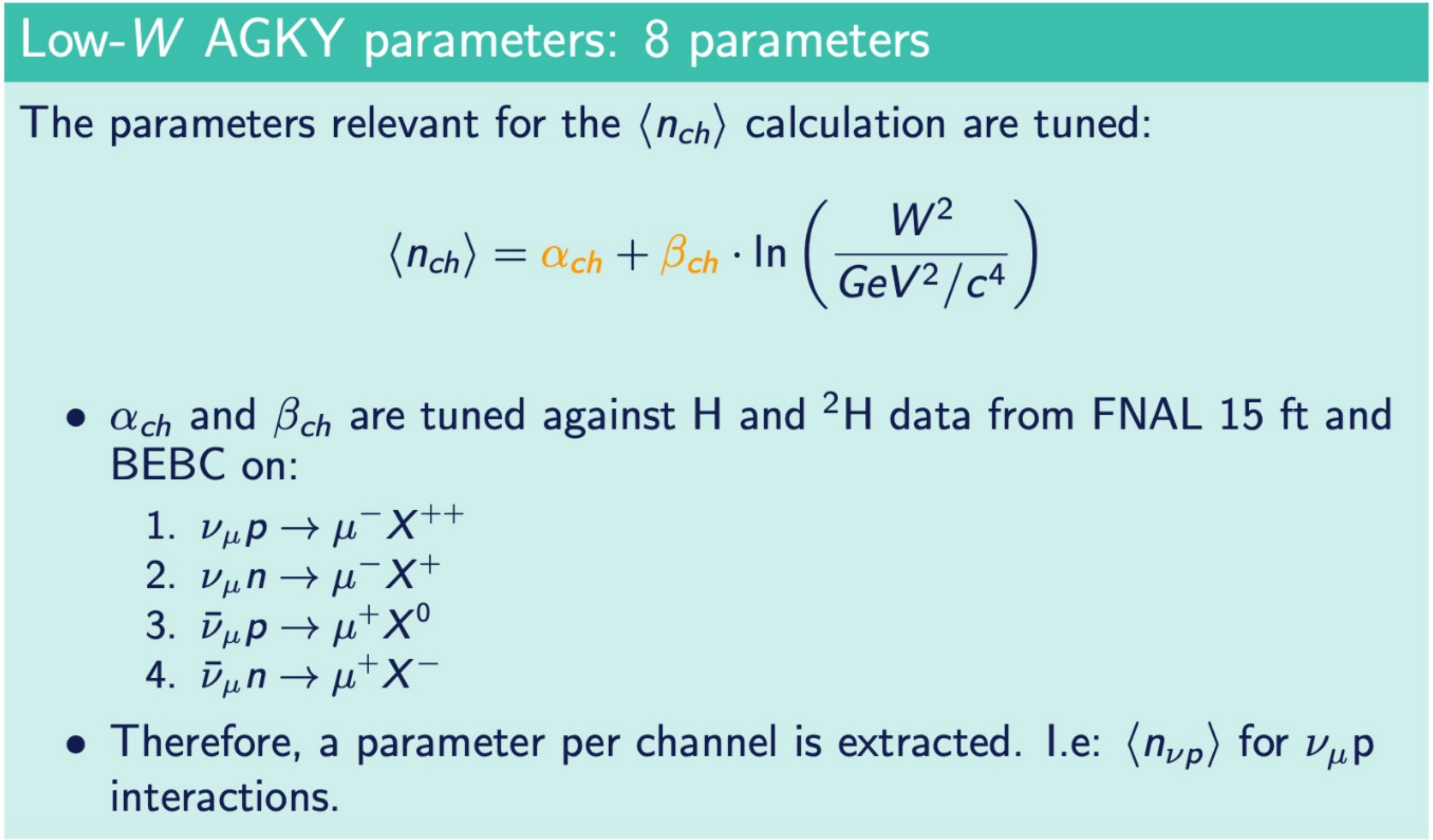
- **Missing uncertainties and correlation between low-W and PYTHIA parameters**



Data is under-predicted at the PYTHIA region



Hadronization tuning impact on the Shallow Inelastic Scattering region

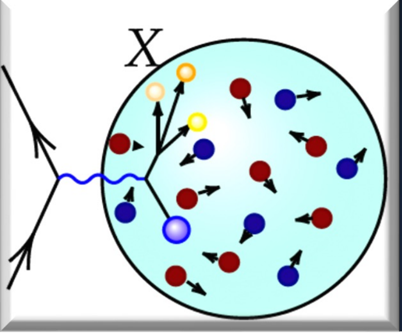


Low-W AGKY parameters: 8 parameters

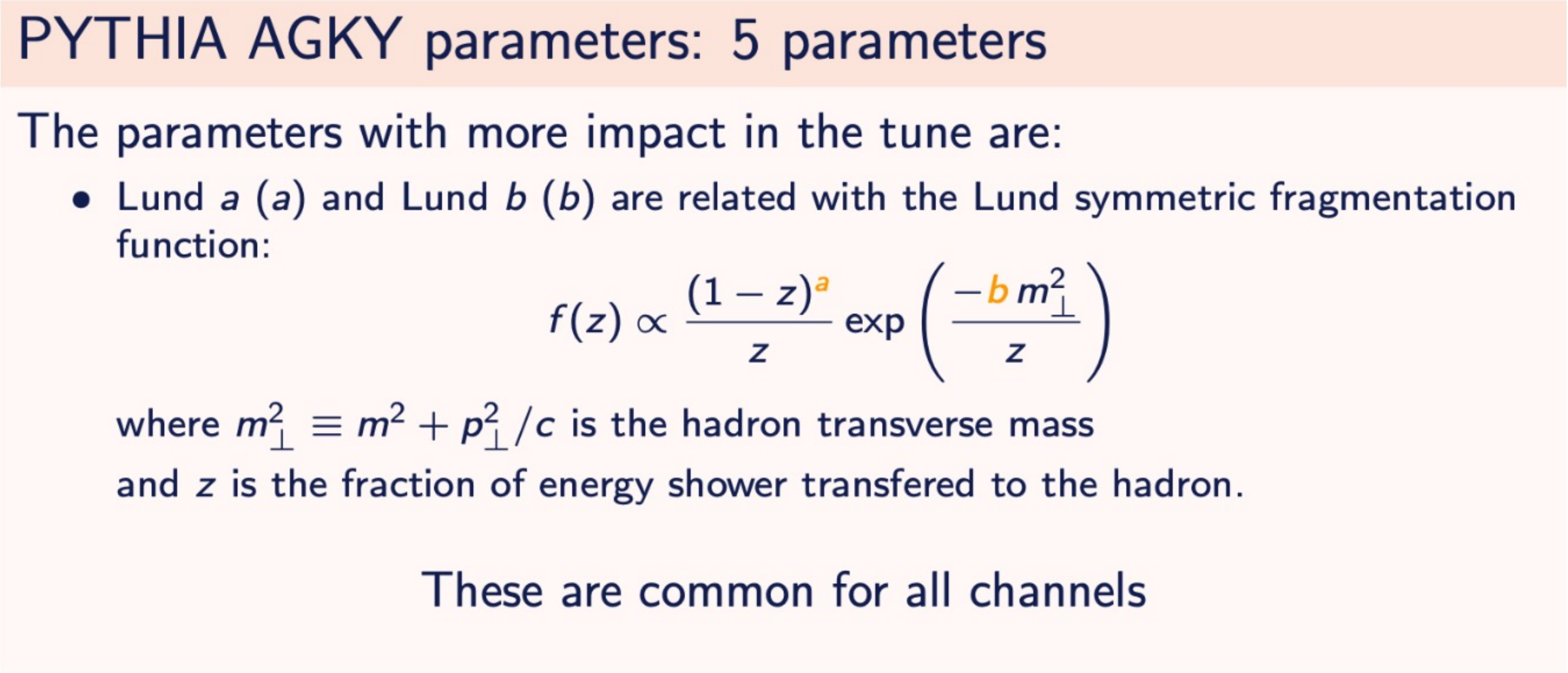
The parameters relevant for the $\langle n_{ch} \rangle$ calculation are tuned:

$$\langle n_{ch} \rangle = \alpha_{ch} + \beta_{ch} \cdot \ln \left(\frac{W^2}{GeV^2/c^4} \right)$$

- α_{ch} and β_{ch} are tuned against H and ^{2}H data from FNAL 15 ft and BEBC on:
  1. $\nu_\mu p \rightarrow \mu^- X^{++}$
  2. $\nu_\mu n \rightarrow \mu^- X^{+}$
  3. $\bar{\nu}_\mu p \rightarrow \mu^+ X^{0}$
  4. $\bar{\nu}_\mu n \rightarrow \mu^+ X^{-}$
- Therefore, a parameter per channel is extracted. I.e: $\langle n_{\nu p} \rangle$ for ν_μp interactions.



Hadronization tuning impact on the Shallow Inelastic Scattering region



PYTHIA AGKY parameters: 5 parameters

The parameters with more impact in the tune are:

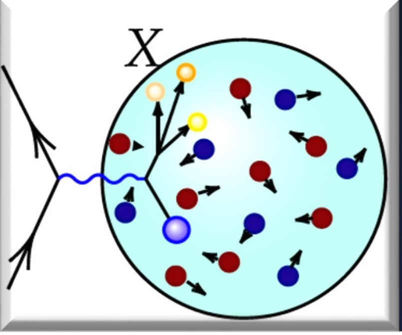
- Lund *a* (*a*) and Lund *b* (*b*) are related with the Lund symmetric fragmentation function:

$$f(z) \propto \frac{(1-z)^{a}}{z} \exp\left(\frac{-b\, m_{\perp}^{2}}{z}\right)$$

where $m_{\perp}^{2} \equiv m^{2} + p_{\perp}^{2}/c$ is the hadron transverse mass

and z is the fraction of energy shower transfered to the hadron.

These are common for all channels

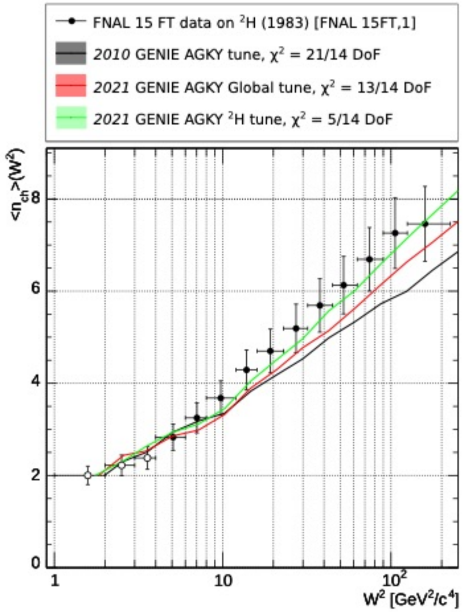


Hadronization tuning impact on the Shallow Inelastic Scattering region

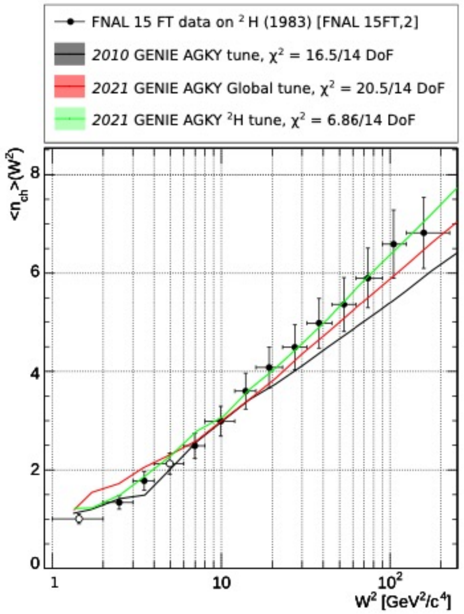
Fully exploiting the GENIE tuning machinery

- First global AGKY tune
  - Tunning the low-W AGKY + PYTHIA altogether
- Focus on averaged charged multiplicity data
- Data-driven constrains to 13 **non-reweightable parameters**
  - Improved description of H+D data
  - Best-fit parameter estimations
  - Uncertainty estimations

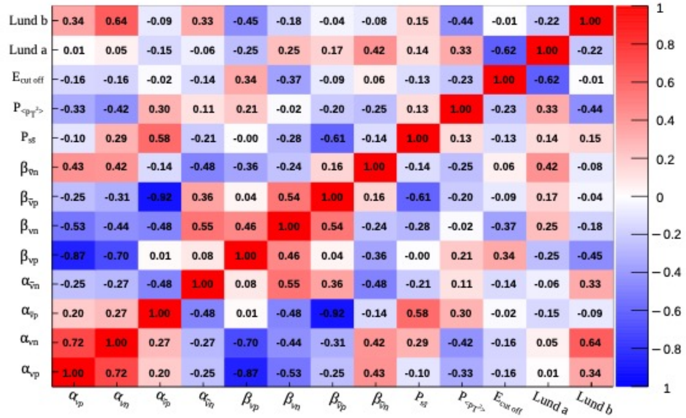
(*) How can we propagate this uncertainties?
See M.Roda's talk



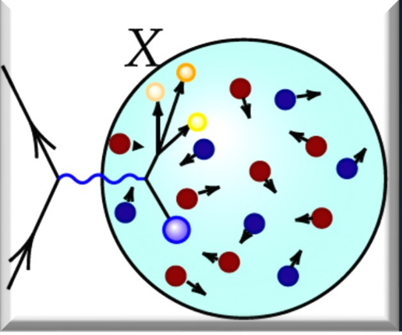
(b) $\nu_\mu + p \rightarrow \mu^- X^{++}$



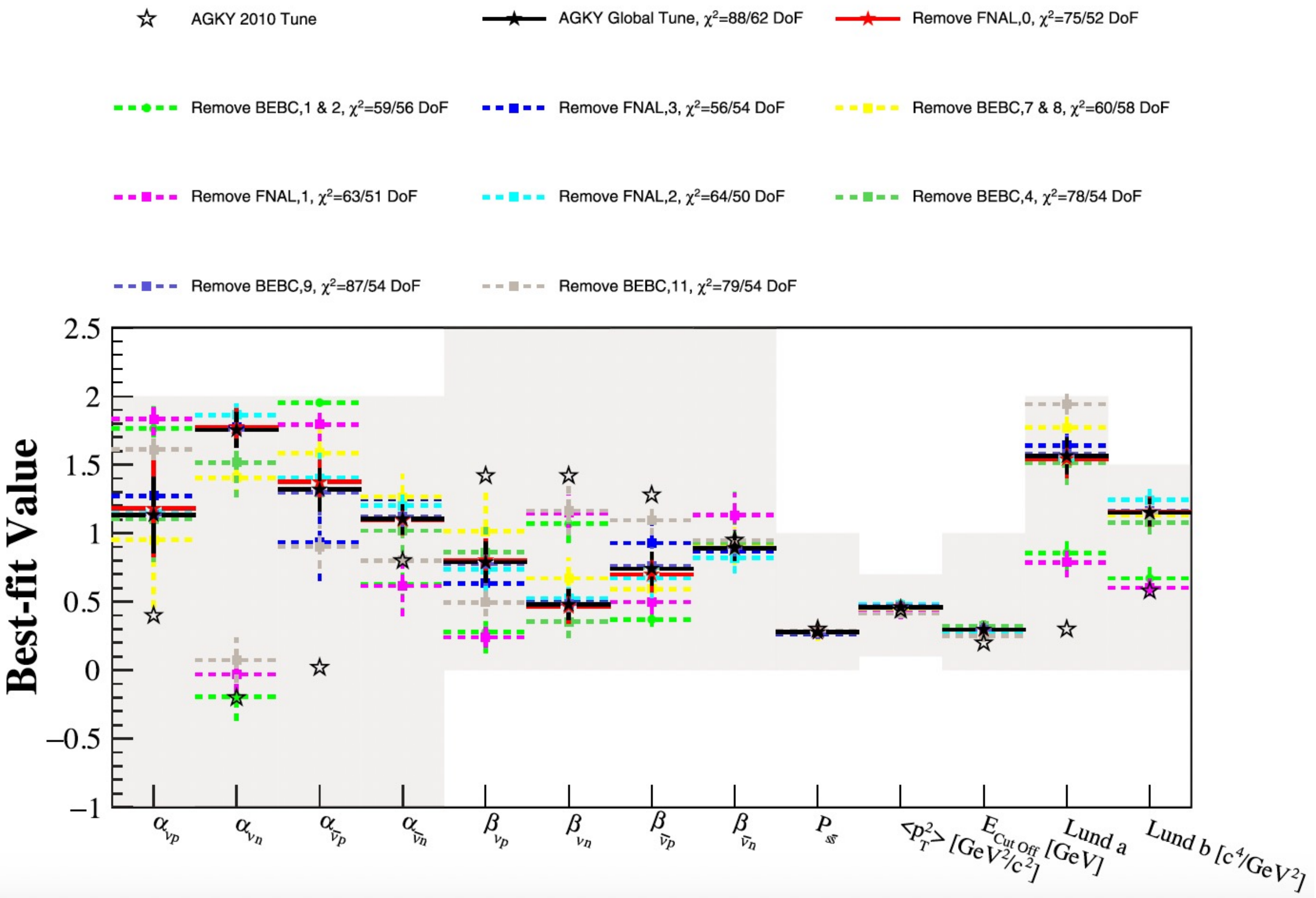
(e) $\nu_\mu + n \rightarrow \mu^- X^{+}$



	$\alpha_{\nu p}$	$\alpha_{\nu n}$	$\alpha_{\bar{\nu} p}$	$\alpha_{\bar{\nu} n}$	$\beta_{\nu p}$	$\beta_{\nu n}$	$\beta_{\bar{\nu} p}$	$\beta_{\bar{\nu} n}$	P_{ss}	$P_{<p_T^2>}$	$E_{cut\ off}$	Lund a	Lund b
Lund b	0.34	0.64	-0.09	0.33	-0.45	-0.18	-0.04	-0.08	0.15	-0.44	-0.01	-0.22	1.00
Lund a	0.01	0.05	-0.15	-0.06	-0.25	0.25	0.17	0.42	0.14	0.33	-0.62	1.00	-0.22
$E_{cut\ off}$	-0.16	-0.16	-0.02	-0.14	0.34	-0.37	-0.09	0.06	-0.13	-0.23	1.00	-0.62	-0.01
$P_{<p_T^2>}$	-0.33	-0.42	0.30	0.11	0.21	-0.02	-0.20	-0.25	0.13	1.00	-0.23	0.33	-0.44
P_{ss}	-0.10	0.29	0.58	-0.21	-0.00	-0.28	-0.61	-0.14	1.00	0.13	-0.13	0.14	0.15
$\beta_{\bar{\nu} n}$	0.43	0.42	-0.14	-0.48	-0.36	-0.24	0.16	1.00	-0.14	-0.25	0.06	0.42	-0.08
$\beta_{\bar{\nu} p}$	-0.25	-0.31	-0.92	0.36	0.04	0.54	1.00	0.16	-0.61	-0.20	-0.09	0.17	-0.04
$\beta_{\nu n}$	-0.53	-0.44	-0.48	0.55	0.46	1.00	0.54	-0.24	-0.28	-0.02	-0.37	0.25	-0.18
$\beta_{\nu p}$	-0.87	-0.70	0.01	0.08	1.00	0.46	0.04	-0.36	-0.00	0.21	0.34	-0.25	-0.45
$\alpha_{\bar{\nu} n}$	-0.25	-0.27	-0.48	1.00	0.08	0.55	0.36	-0.48	-0.21	0.11	-0.14	-0.06	0.33
$\alpha_{\bar{\nu} p}$	0.20	0.27	1.00	-0.48	0.01	-0.48	-0.92	-0.14	0.58	0.30	-0.02	-0.15	-0.09
$\alpha_{\nu n}$	0.72	1.00	0.27	-0.27	-0.70	-0.44	-0.31	0.42	0.29	-0.42	-0.16	0.05	0.64
$\alpha_{\nu p}$	1.00	0.72	0.20	-0.25	-0.87	-0.53	-0.25	0.43	-0.10	-0.33	-0.16	0.01	0.34



Hadronization tuning impact on the Shallow Inelastic Scattering region



Tuning with nuclear data

- Tuning with neutrino scattering data
- Inputs from electron scattering

Tuning of $\nu - A$ interaction models

Free parameters **Neutrino data**

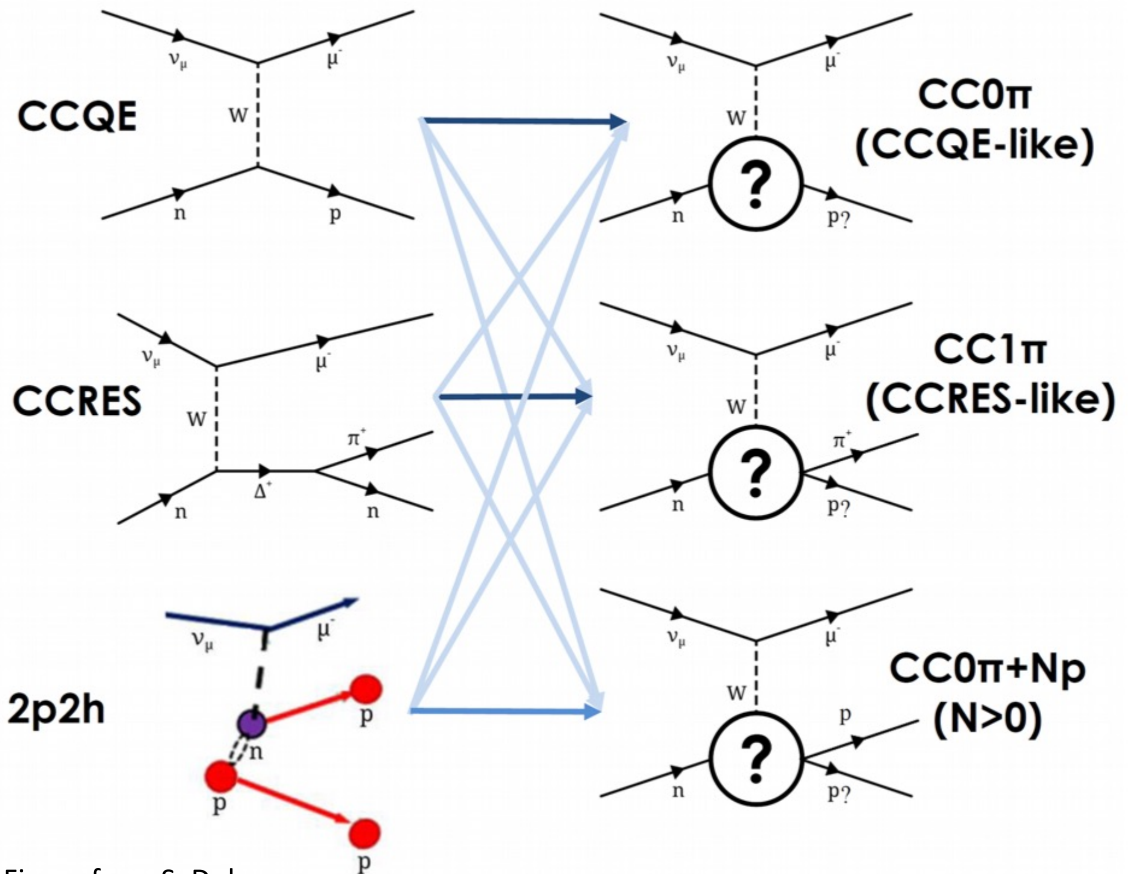
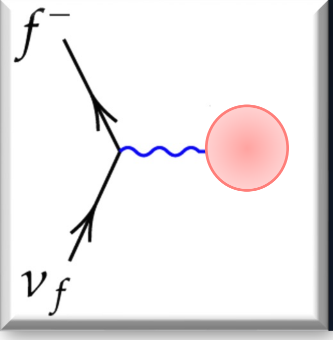


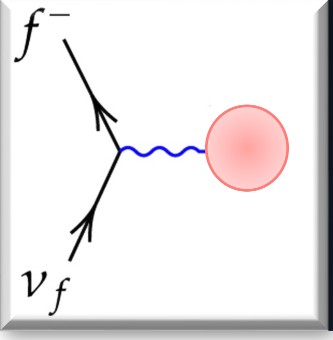
Figure from S. Dolan



Tuning of $\nu - A$ interaction models

- A lot of data available from different experiments:
  - T2K, MINERvA, MicroBooNE, MiniBooNE
  - Different targets and flux
  - Single and double differential measurements
- Many more degrees of freedom to explore
  - Additional uncertainty due of nuclear effects
  - **Complication:** many theory parameters not accessible in the GENIE implementation, which incorporate pre-computed hadron tensors
  - Degrees of freedom depend on the data you use on the tune
- Harder to interpret the results due to high tune degeneracy
  - **Tune results and associated uncertainties reflect uncertainty in kinematic region rather than process**

Figure from S. Dolan



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

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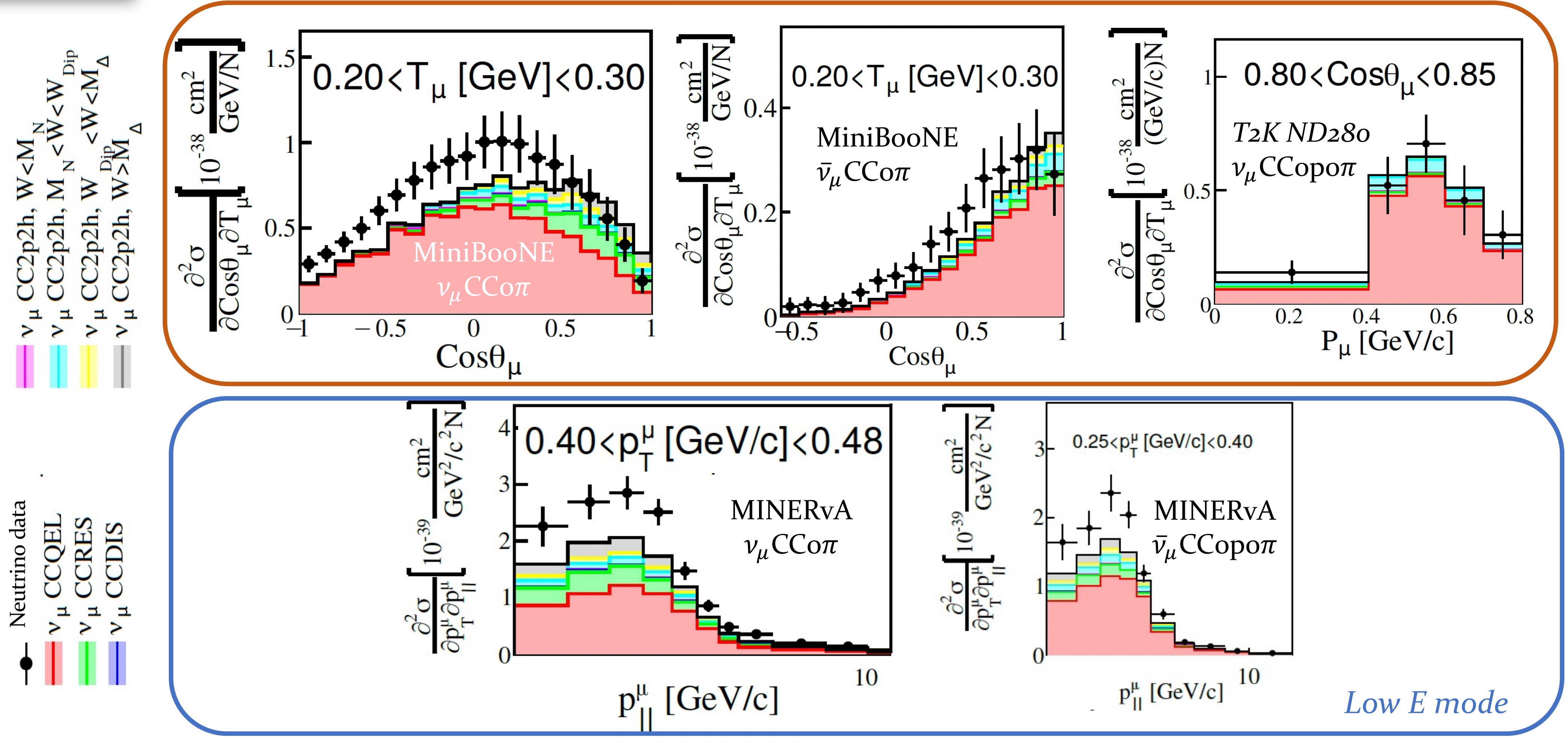
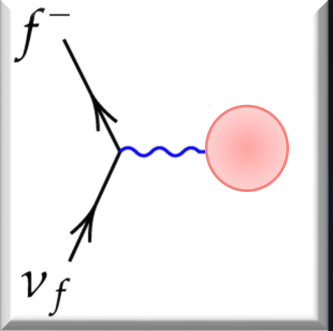


$E_\nu^{peak} < 1$GeV

$E_\nu^{peak} \sim 3$GeV



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

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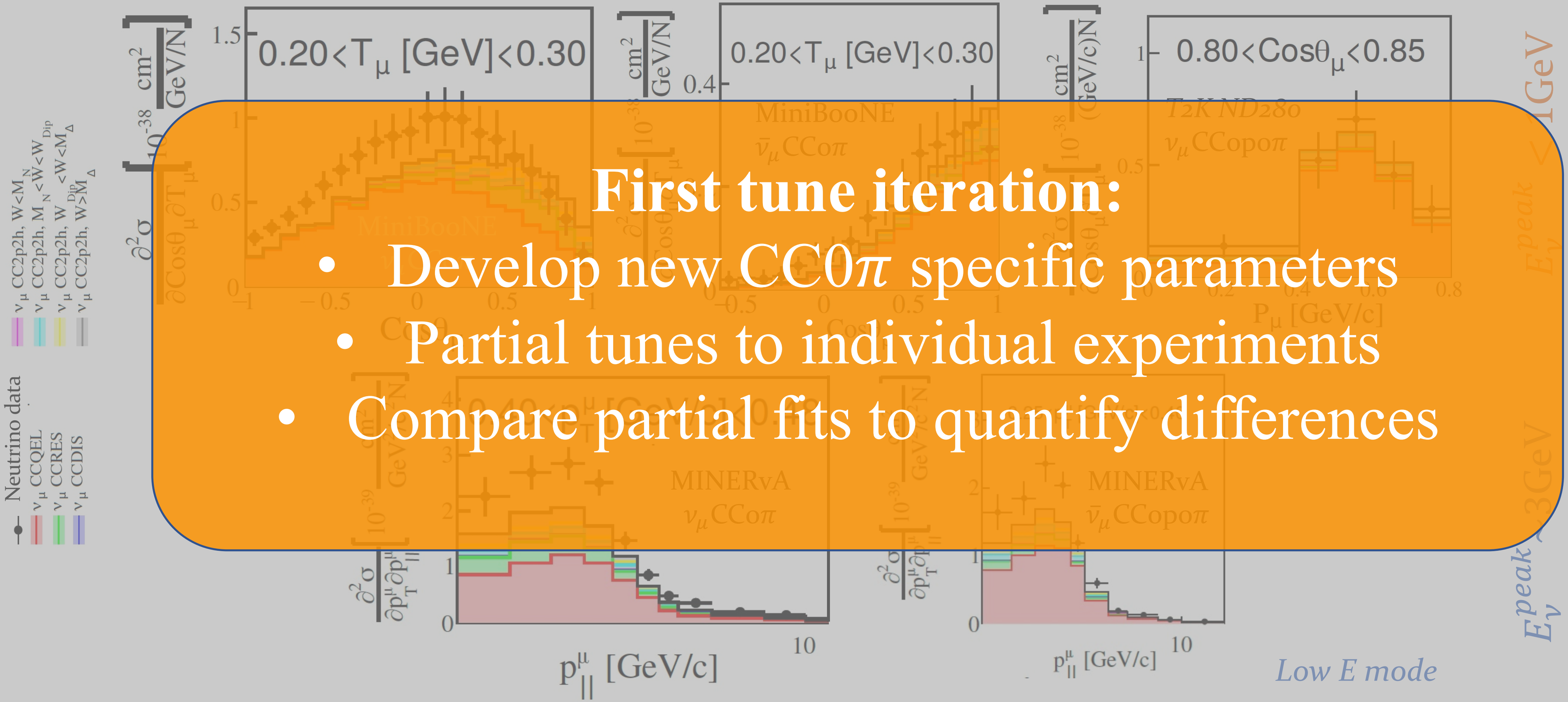
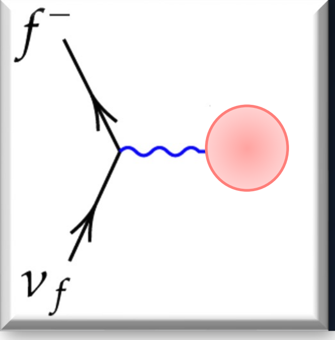


First tune iteration:

- Develop new CC0π specific parameters
- Partial tunes to individual experiments
- Compare partial fits to quantify differences



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

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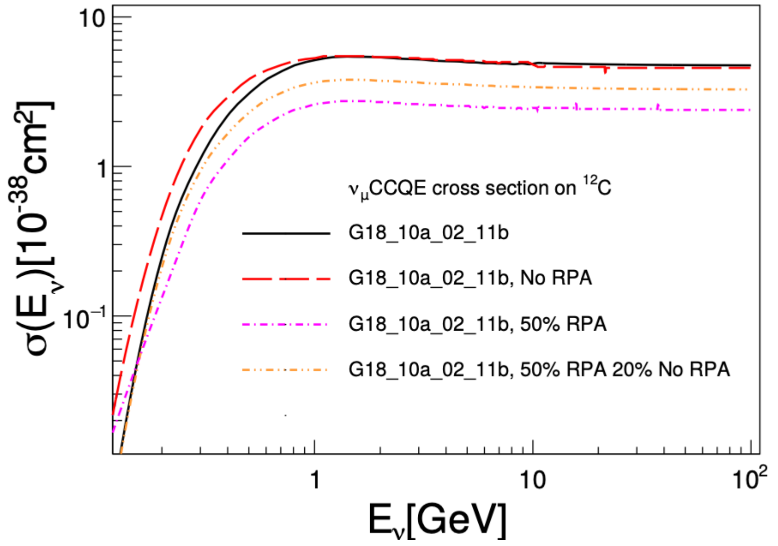
At the free nucleon level, the QEL cross section is well understood:

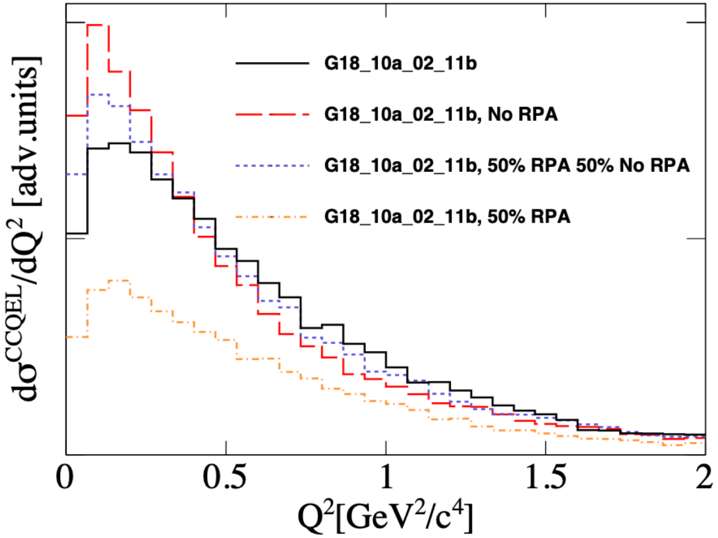
- Base model tuned to hydrogen and deuterium data
- Using correlated priors from free nucleon tune to constrain M_A^{QEL} and S_{RES}

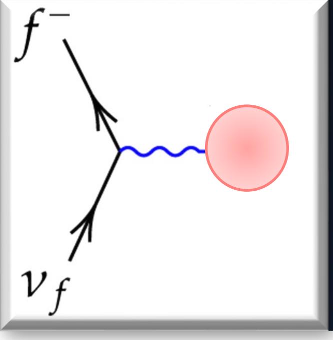
Two additional parameters:

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

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







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

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

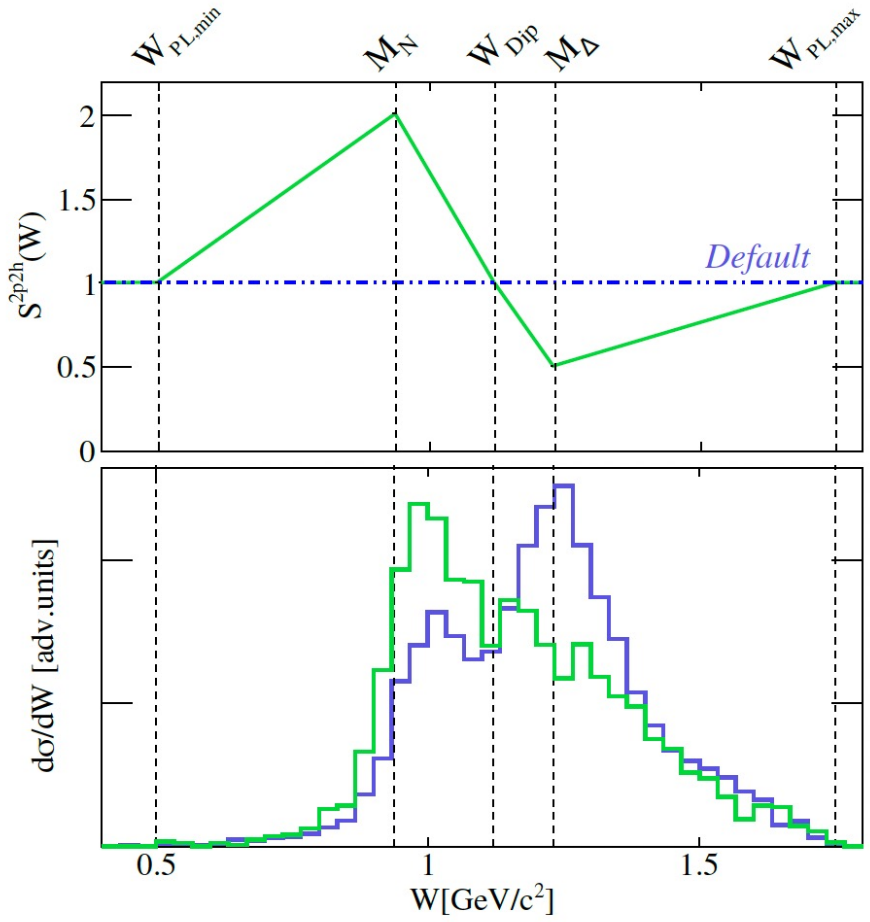
- Pre-computed hadron tensor tables on a grid of q_0-q_3
- **No direct access to theory-parameters from GENIE**

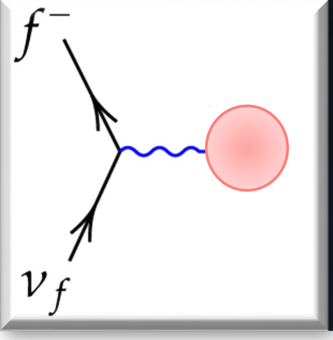
We add an **ad-hoc parameteriz**ation to add variation to the model

- 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:

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

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





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

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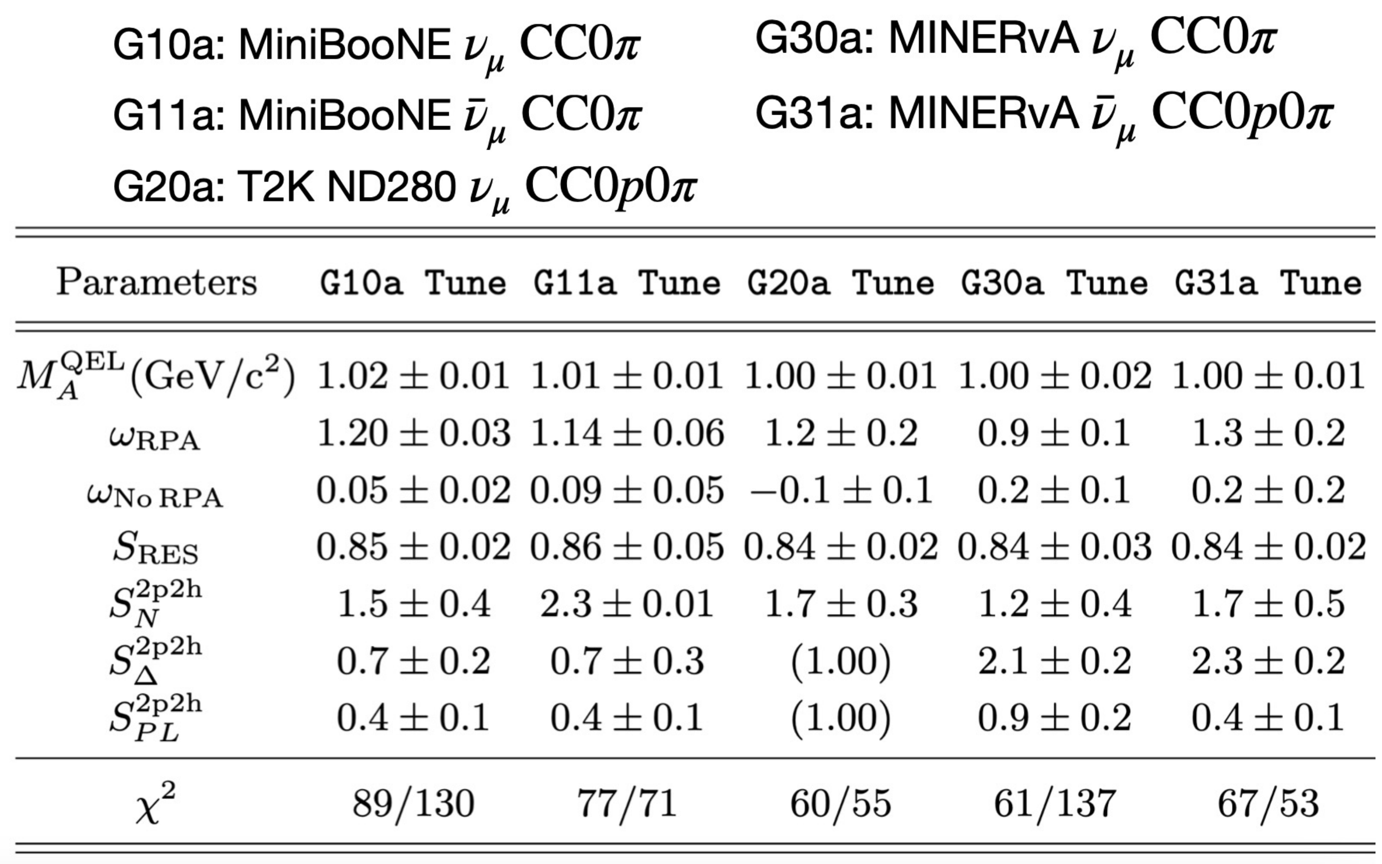
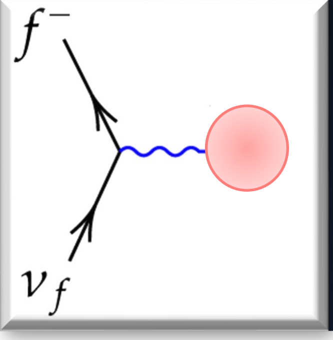
All tunes:

- 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

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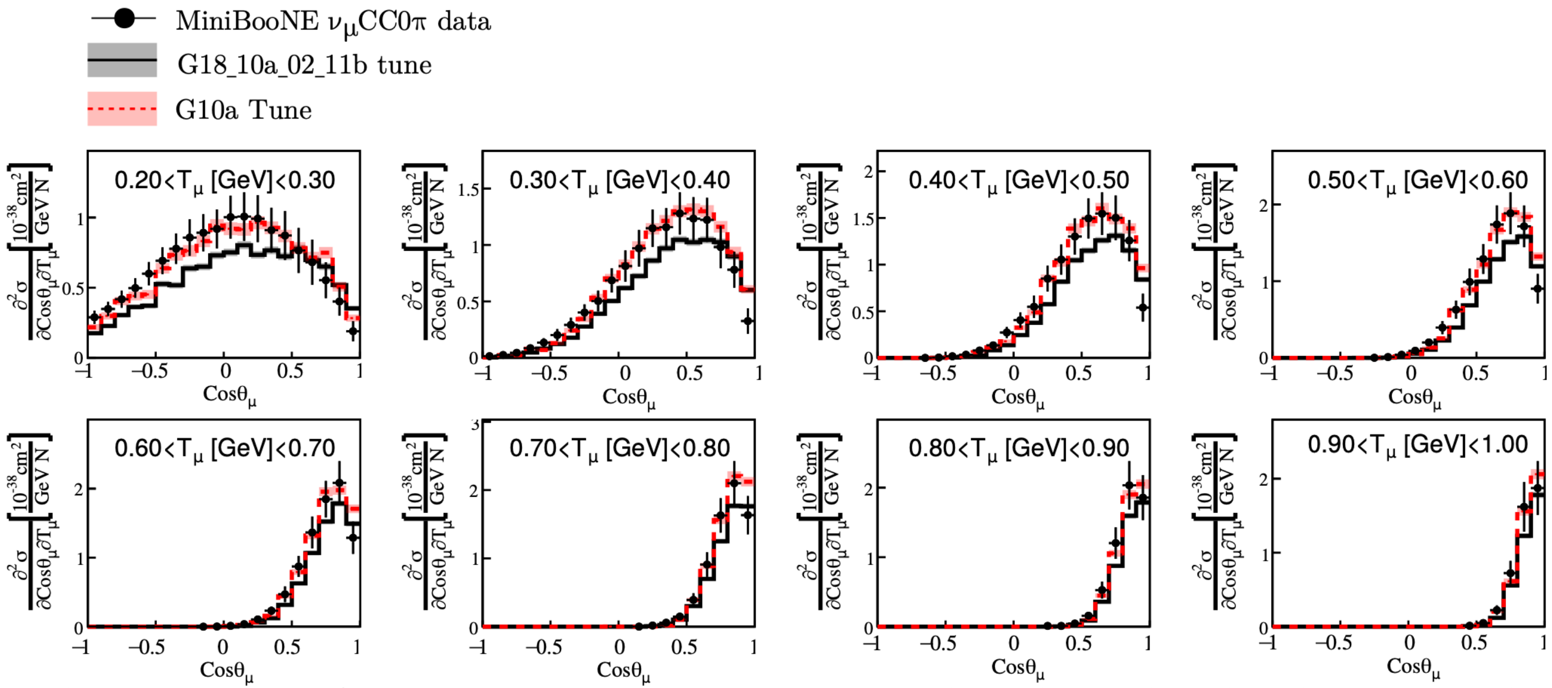
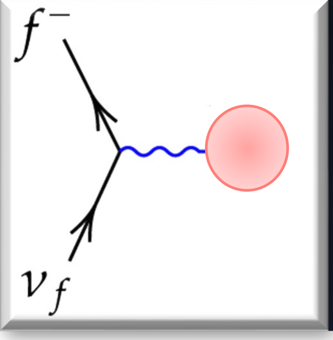
The enhancement of QEL and 2p2h cross sections lead to improved shape and normalization agreement



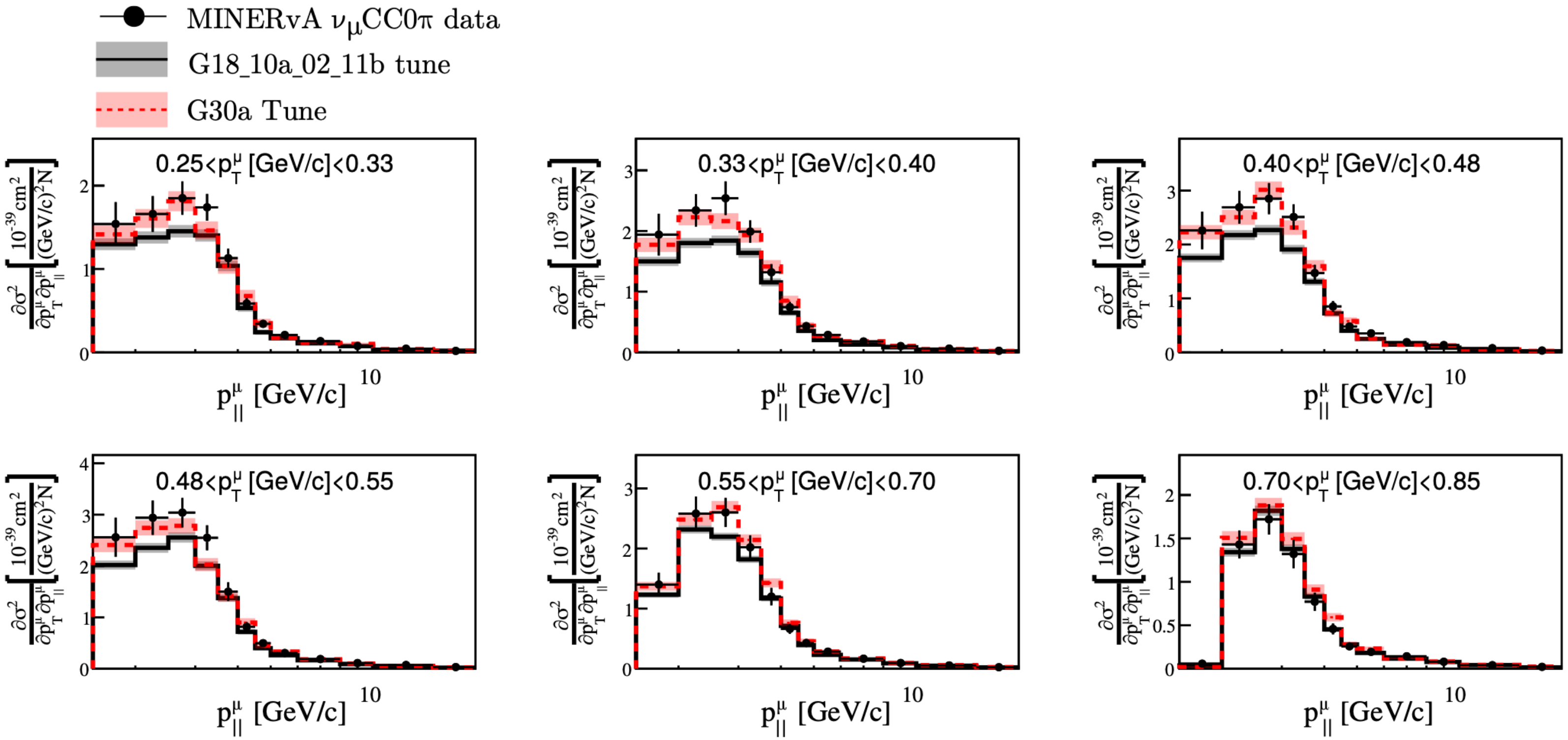
Enhancement of QEL cross section is essential to describe the data at backward angles (QEL dominated kinematic region)

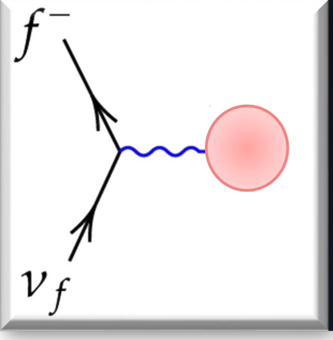


Tuning of $\nu - A$ CC0π interaction models Results

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

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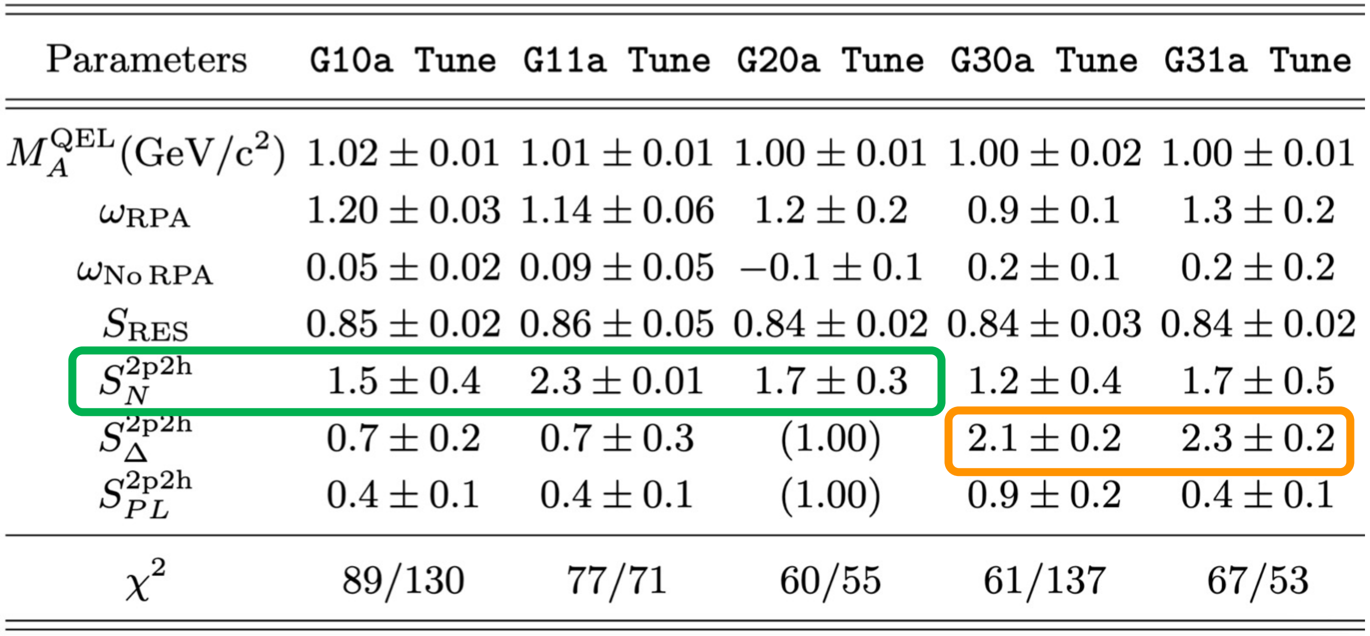
G10a: MiniBooNE ν_μ CC0π

G11a: MiniBooNE $\bar{\nu}_\mu$ CC0π

G20a: T2K ND280 ν_μ CC0p0π

G30a: MINERvA ν_μ CC0π

G31a: MINERvA $\bar{\nu}_\mu$ CC0p0π

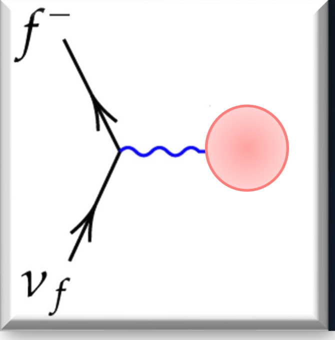


Parameters	G10a Tune	G11a Tune	G20a Tune	G30a Tune	G31a Tune
$M_A^{\mathrm{QEL}}(\mathrm{GeV/c^2})$	1.02 ± 0.01	1.01 ± 0.01	1.00 ± 0.01	1.00 ± 0.02	1.00 ± 0.01
ω_{RPA}	1.20 ± 0.03	1.14 ± 0.06	1.2 ± 0.2	0.9 ± 0.1	1.3 ± 0.2
$\omega_{\mathrm{No\,RPA}}$	0.05 ± 0.02	0.09 ± 0.05	-0.1 ± 0.1	0.2 ± 0.1	0.2 ±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

Energy dependence not captured in the current models

Differences:

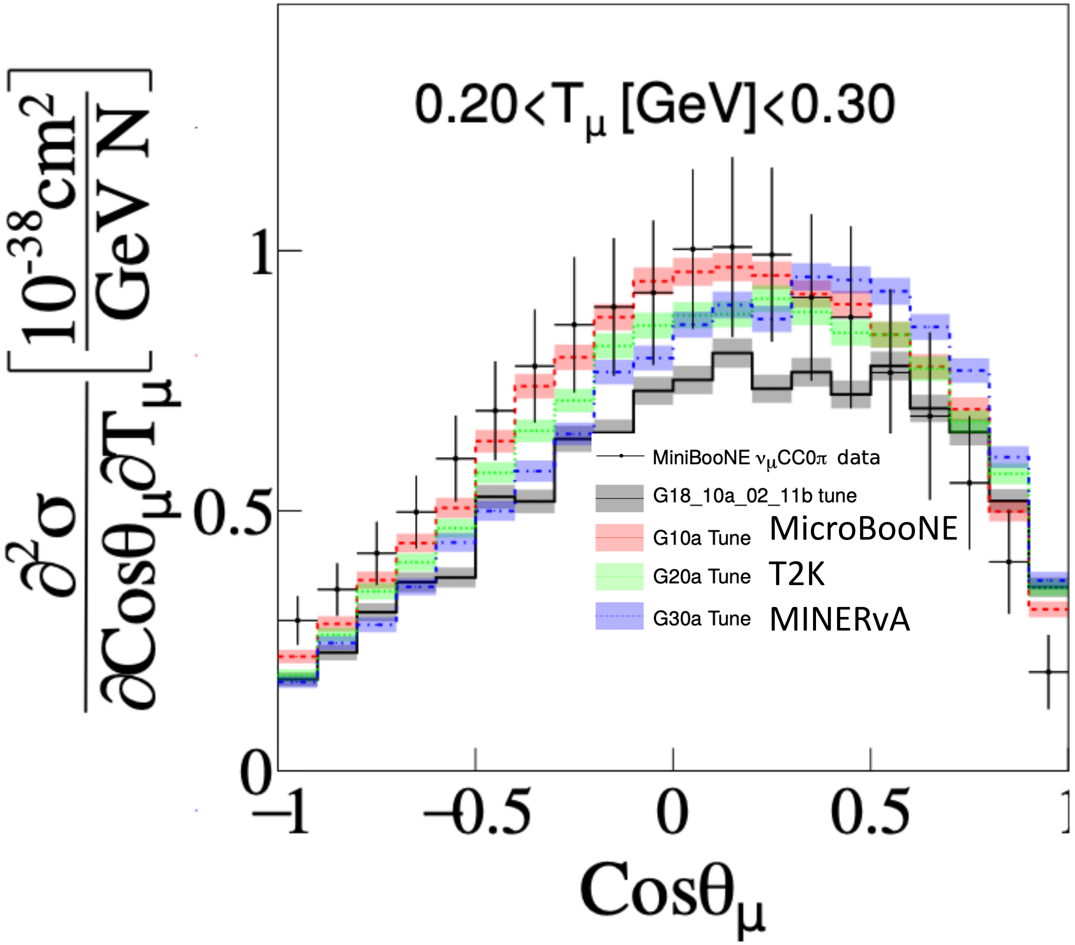
- MiniBooNE + T2K enhance MEC at $W = M_N$
- MINERva's tunes enhance both MEC peaks
- **Clear energy dependence on cross section shape**
- **Anti-neutrino tunes predict a higher CC0π cross-section**
- Same observations by recent MINERvA measurements using high energy beam



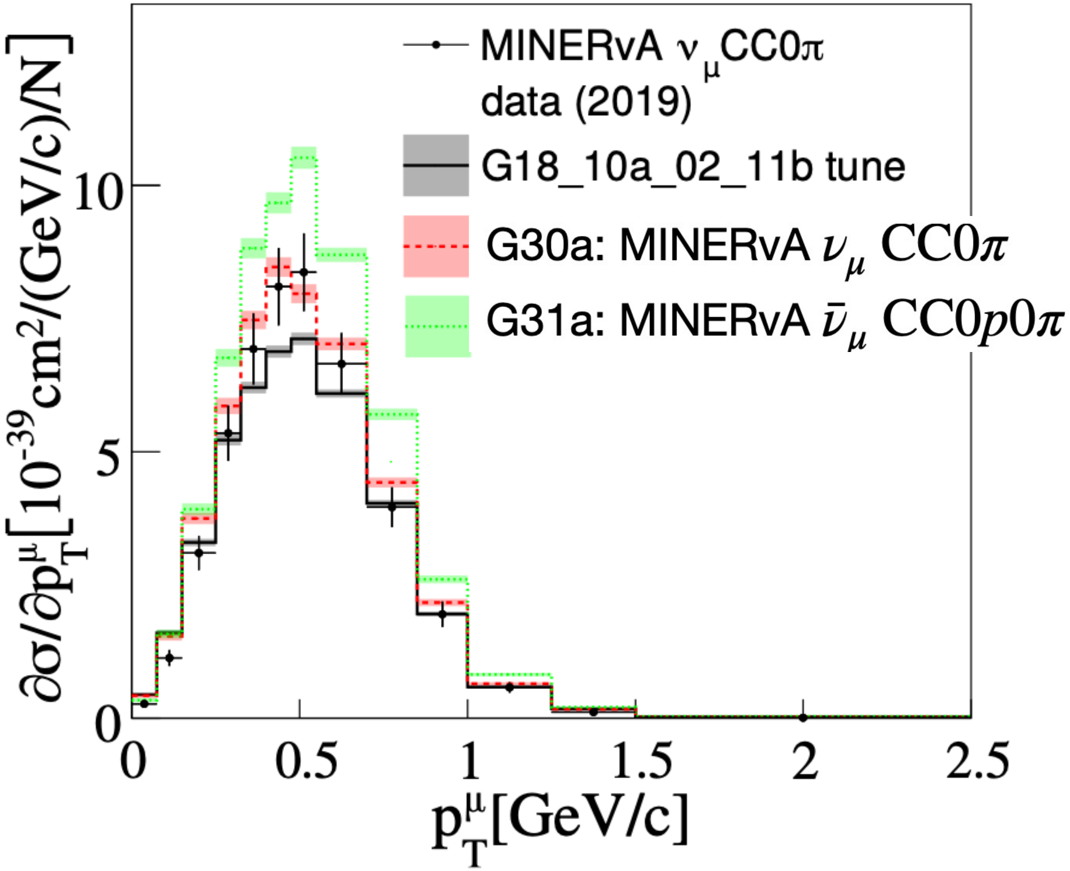
Tuning of $\nu - A$ CC0π interaction models Results

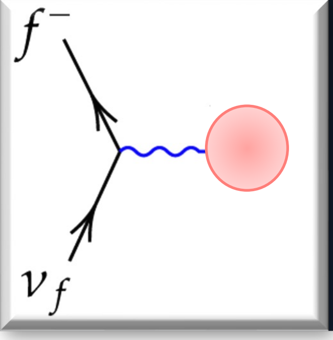
PhysRevD.104.072009

Clear energy dependence on cross section shape



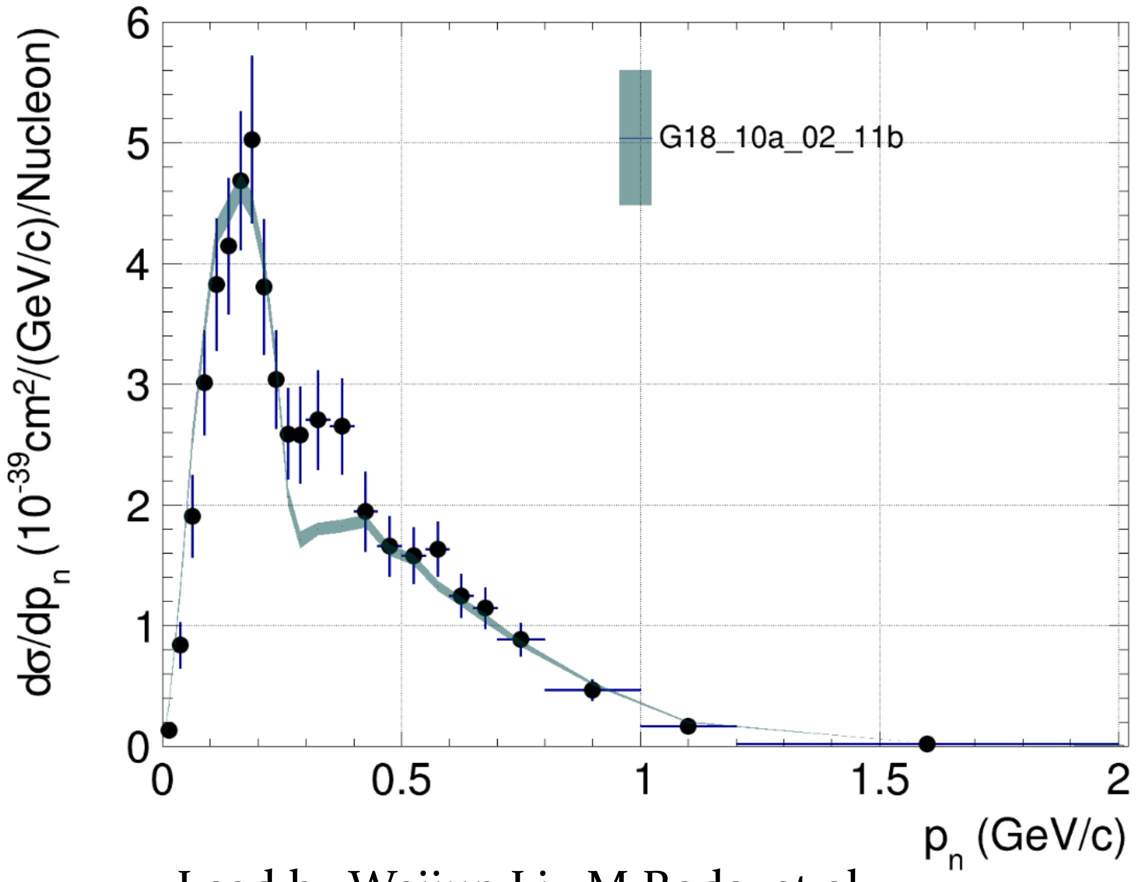
Anti-neutrino tunes predict a higher cross-section



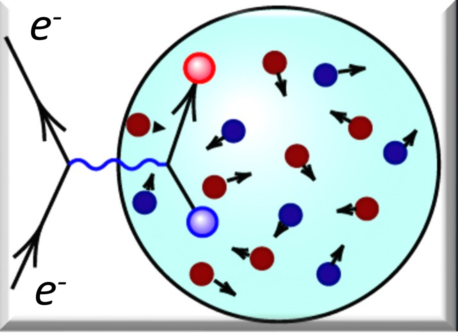


Tuning of $\nu - A$ CC0π interaction models
Next steps

- The first tune iteration focused on T2K, MINERvA, MiniBooNE CC0π double-differential data as a function of muon kinematics
- **New tune** will focus on TKI datasets:
  - MINERvA $\nu_\mu CC0\pi$ TKI data
  - MINERvA $\nu_\mu CC\pi0$ TKI data
  - T2K $\nu_\mu CC0\pi$ TKI data
  - MINERvA $\nu_\mu CC1\pi$ TKI data
- **Focus on nuclear model and FSI**
  - New data will offer new insights to nuclear model uncertainty



Lead by Weijun Li, M.Roda, et.al

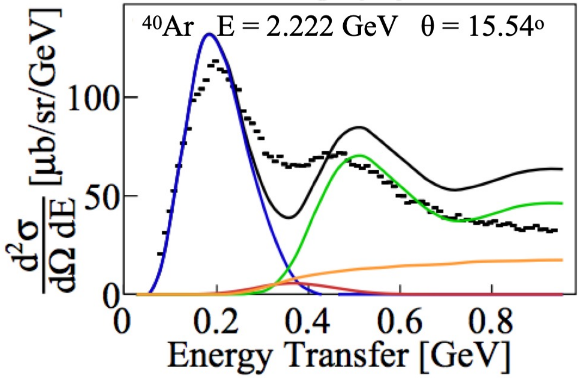


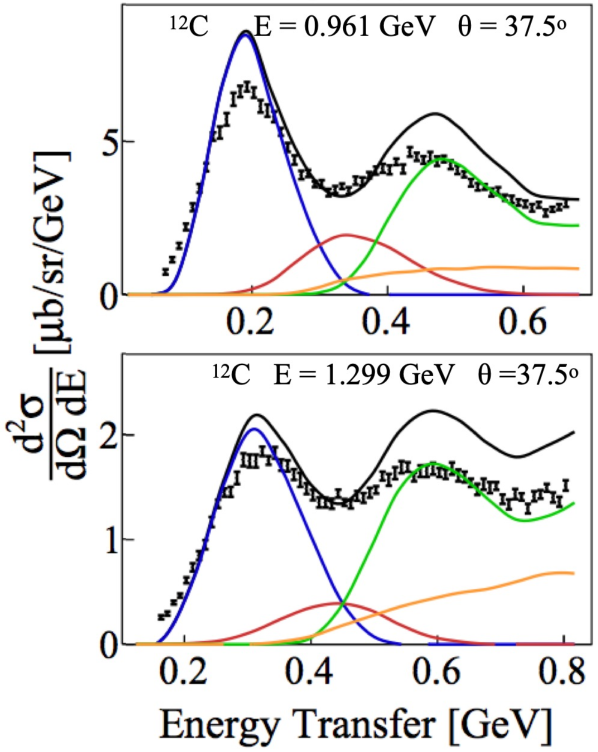
Nuclear model tuning with electron-scattering data

- 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





— v3.0.6 tune G18_10a_02_11a

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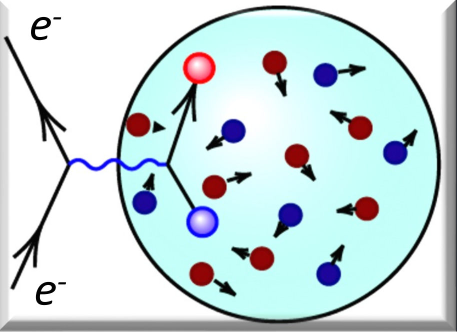
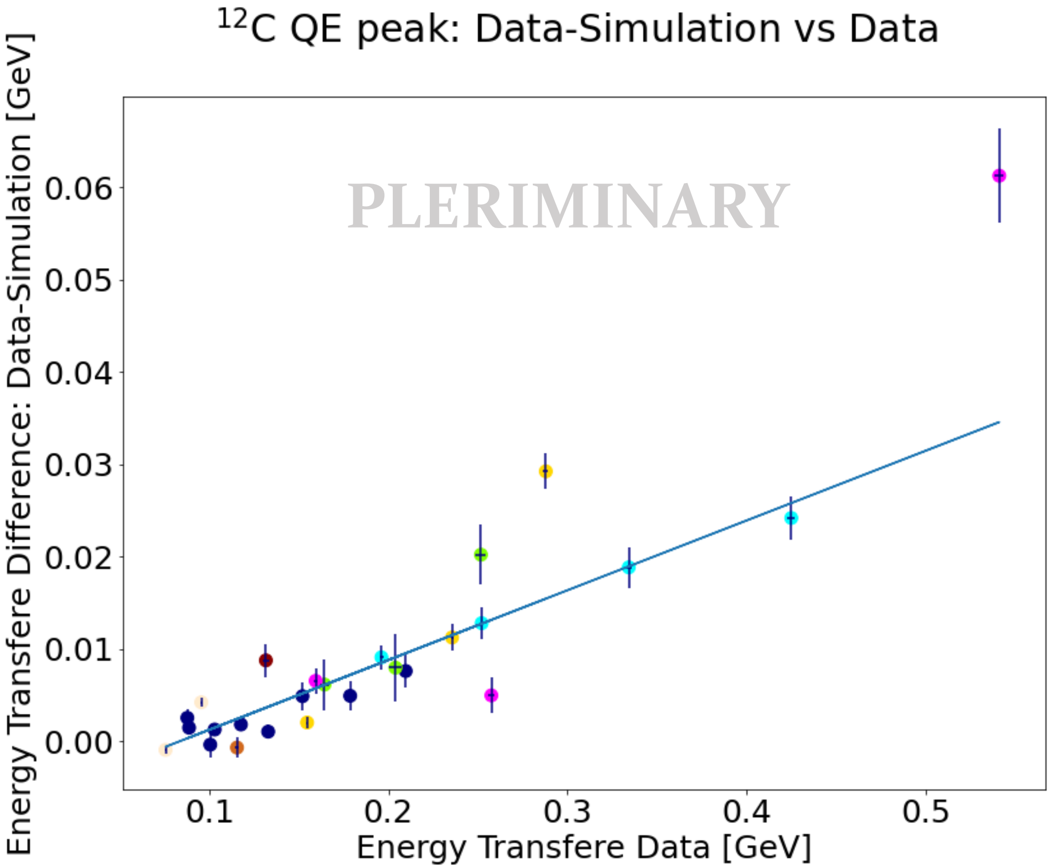


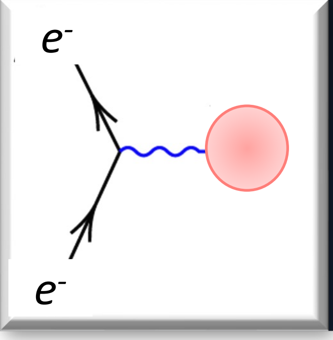
Nuclear model tuning with electron-scattering data

Matan
Goldenberg

Approach:

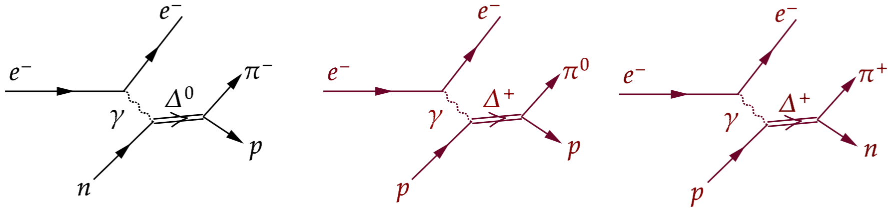
- MC predictions for each dataset using G18_10a CMC
- Same binning as inclusive data
- Opening angle: 1.14 deg
- Fit data and MC separately with same approach
- Calculate difference in peak position
- Peak shift increases with the energy transfer





Tuning against e – A exclusive data
Next focus

- CLAS6 data on ^{12}C, ^{4}He and ^{56}Fe
- Beam energies 1, 2 and 4 GeV
- Topology definition:
  - $1\pi^{\mp}$, $1p1\pi^{-}$: possible final sate from Δ decay and FSI
  - $1p1\pi^{+}$: only possible from higher W resonances and FSI

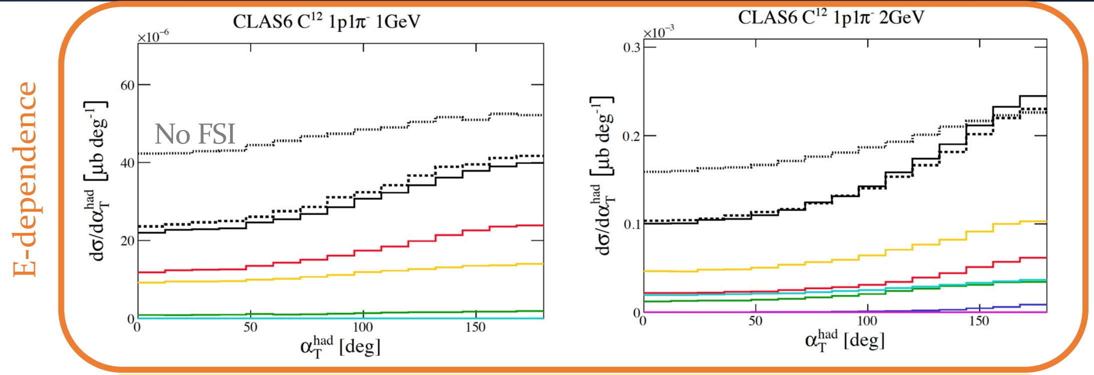


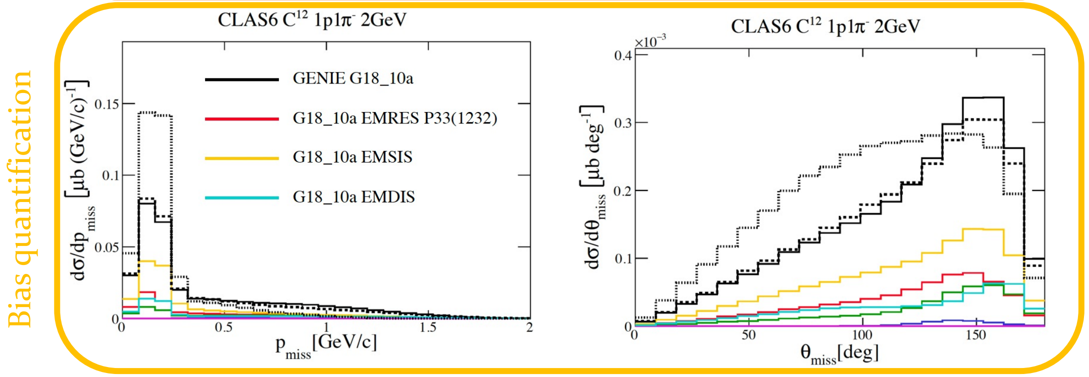
(*)

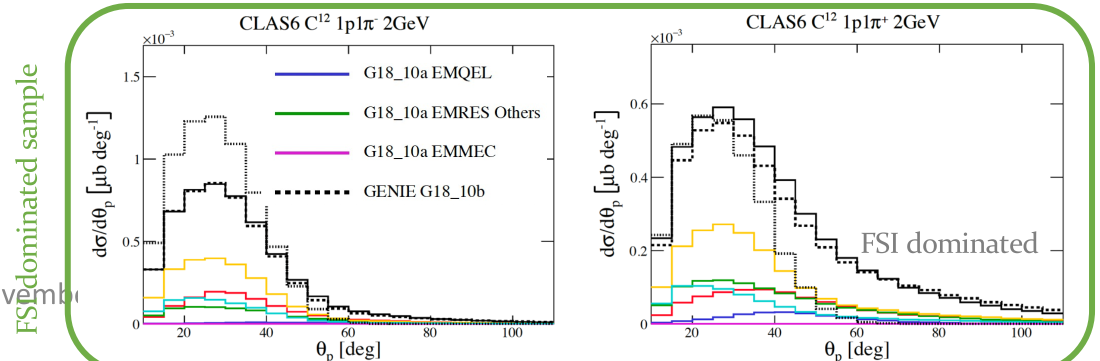
- Many observables relevant for neutrino experiments:
  - Pion and proton kinematics
  - TKI observables
  - 4-missing momentum

This data will be crucial to constrain event generators

(*) Cannot detect in CLAS6







Conclusions

- The GENIE Collaboration is building a **global analysis** framework based on the Professor concept
- Tuning event generators is essential due to the empirical nature of most modeling aspects
- It is also key to:
  - Quantify data-driven uncertainties
  - Explore tensions between theory and data
- GENIE is working towards a global tune:
  - Neutrino, electron-scattering and hadron-nucleus data
  - First tune iterations focused on neutrino data
  - Working towards the first electron-based tunes and TKI based tune

Thank you!

TEL AVIV UNIVERSITY
אוניברסיטת תל אביב

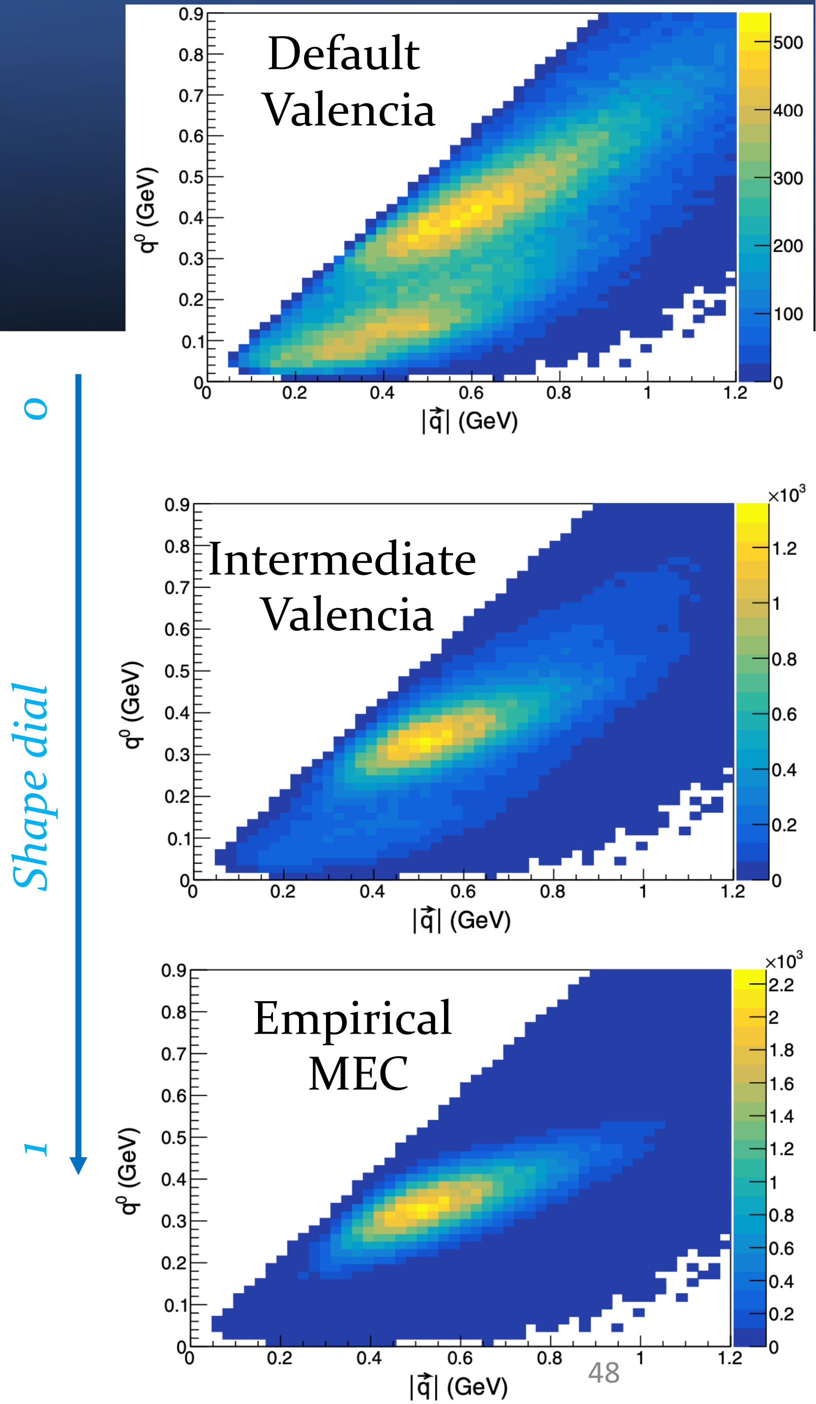
Genie

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



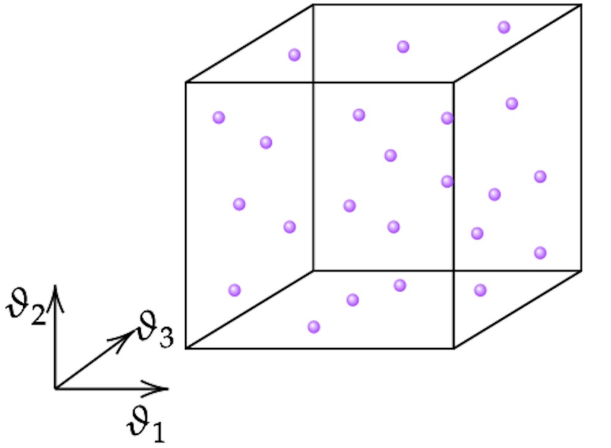
Sampling of the phase-space GENIE-Professor

- 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

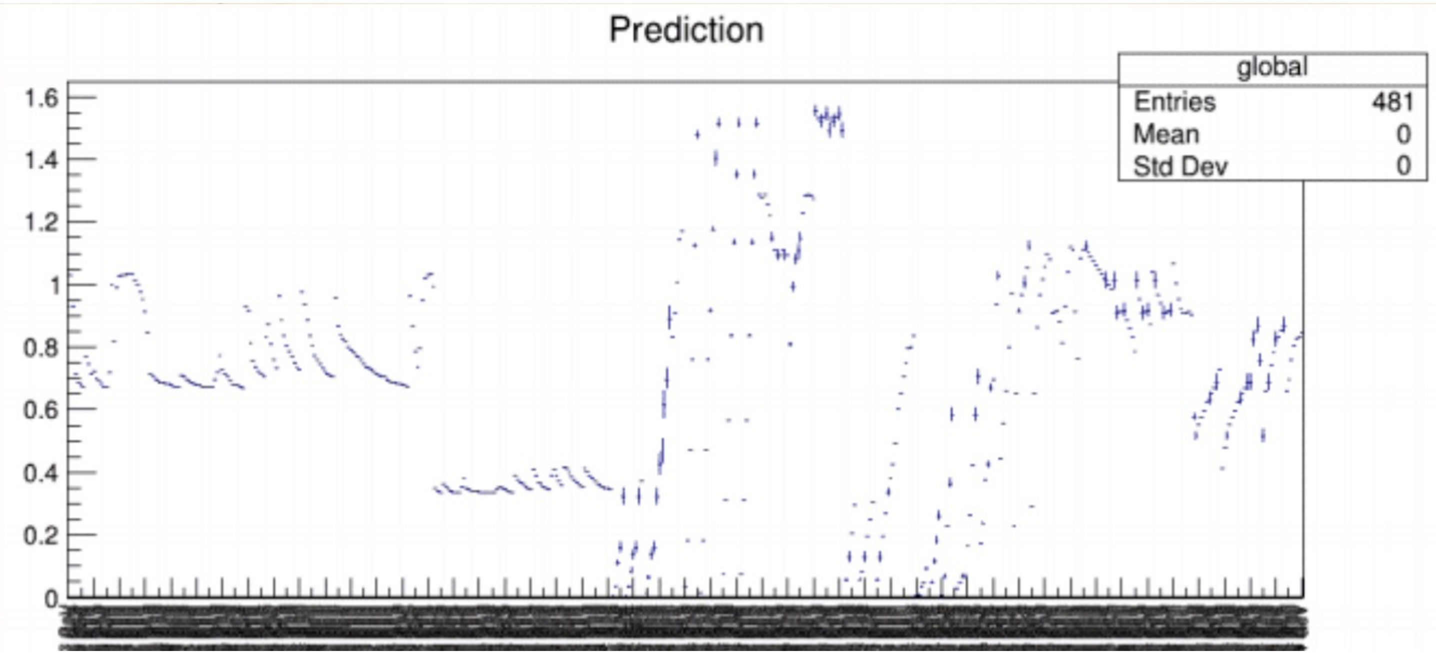
N_ϑ dimensions phase-space



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)

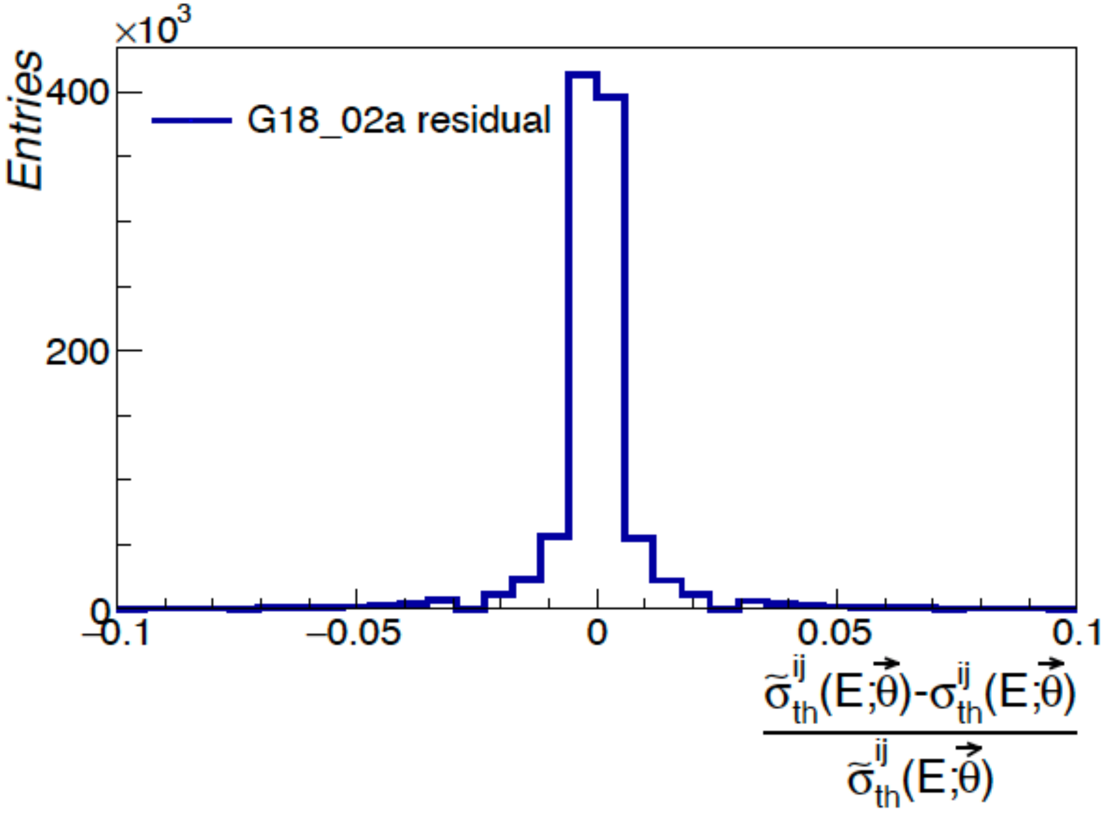
Definition of Observable GENIE-Professor

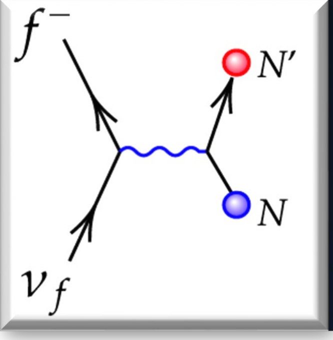
- Prediction histogram associated to thirty-three datasets [PhysRevD.104.072009]
  - The observable corresponds to a series of GENIE Predictions for ν_μ and anti- ν_μ CC inclusive, QEL, single-pion and two-pion production associated to ANL 12 ft, BNL 7ft, BEBC and FNAL bubble chamber data
- This prediction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



Parameterization of response function GENIE-Professor

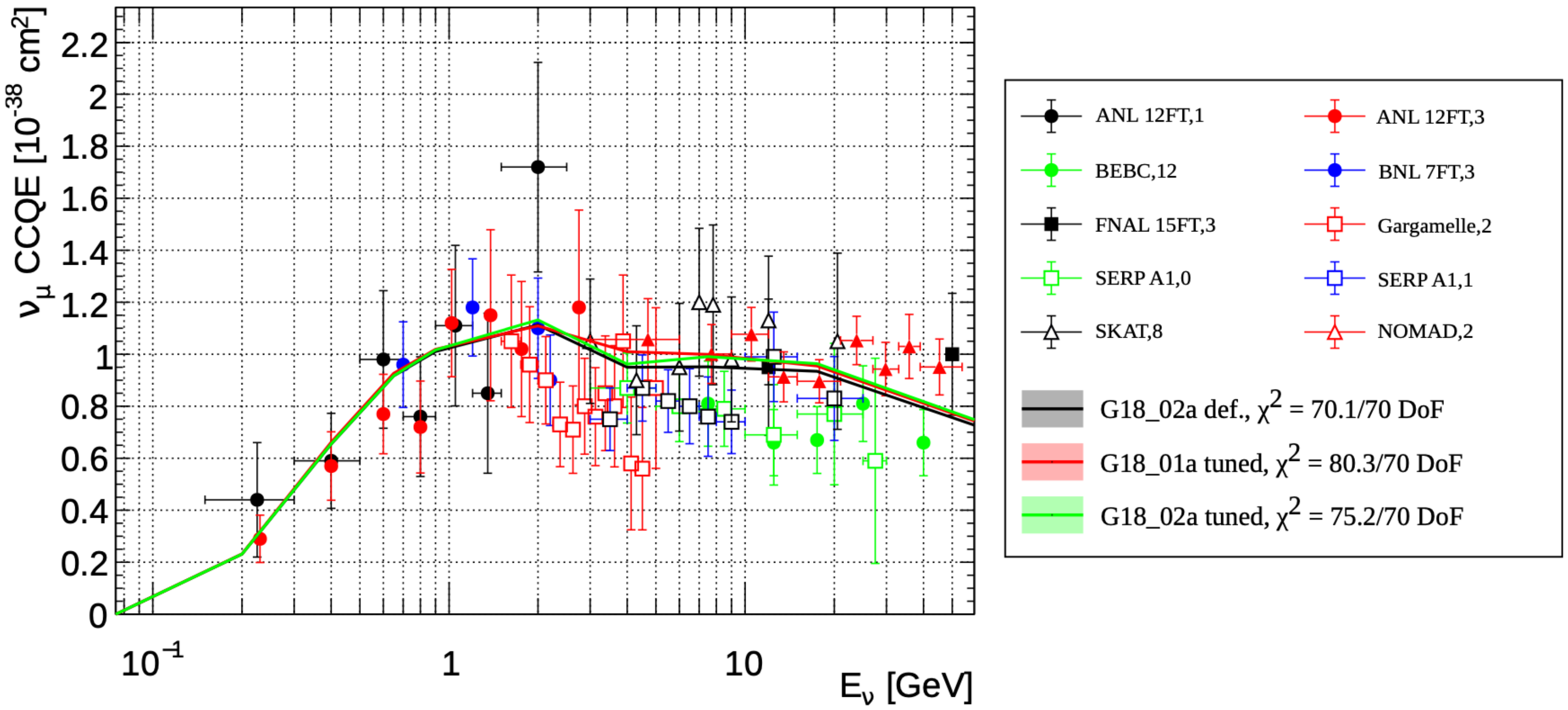
- For each bin, we parameterize the observable mean value and error dependency on the parameters
- The parameterization is fit against the brute force scan
- The parameterization is an **approximation**
- It is possible to quantify its accuracy with the residual:
  - True prediction - parameterization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



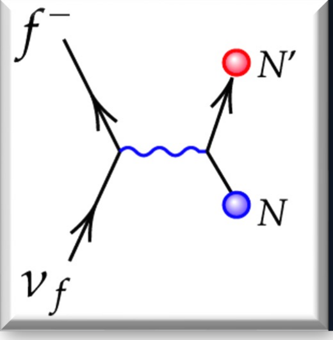


Tuning the Shallow-Scattering Inelastic region

PhysRevD.104.072009

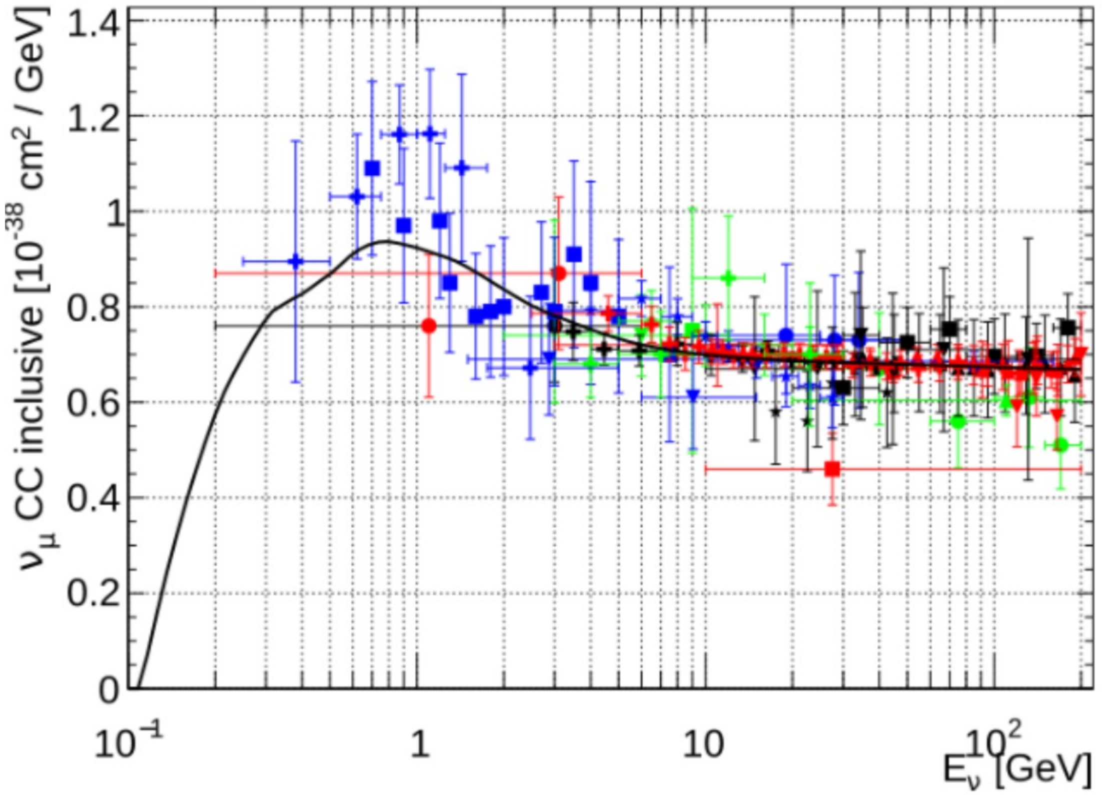


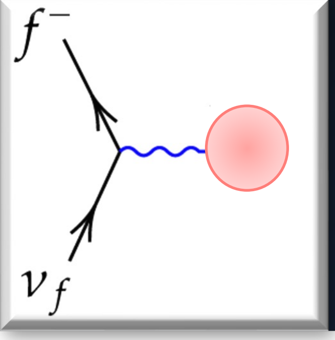
(a) Comparison of ν_μ CC quasi-elastic cross-section data against the *default* and tuned CMCs.



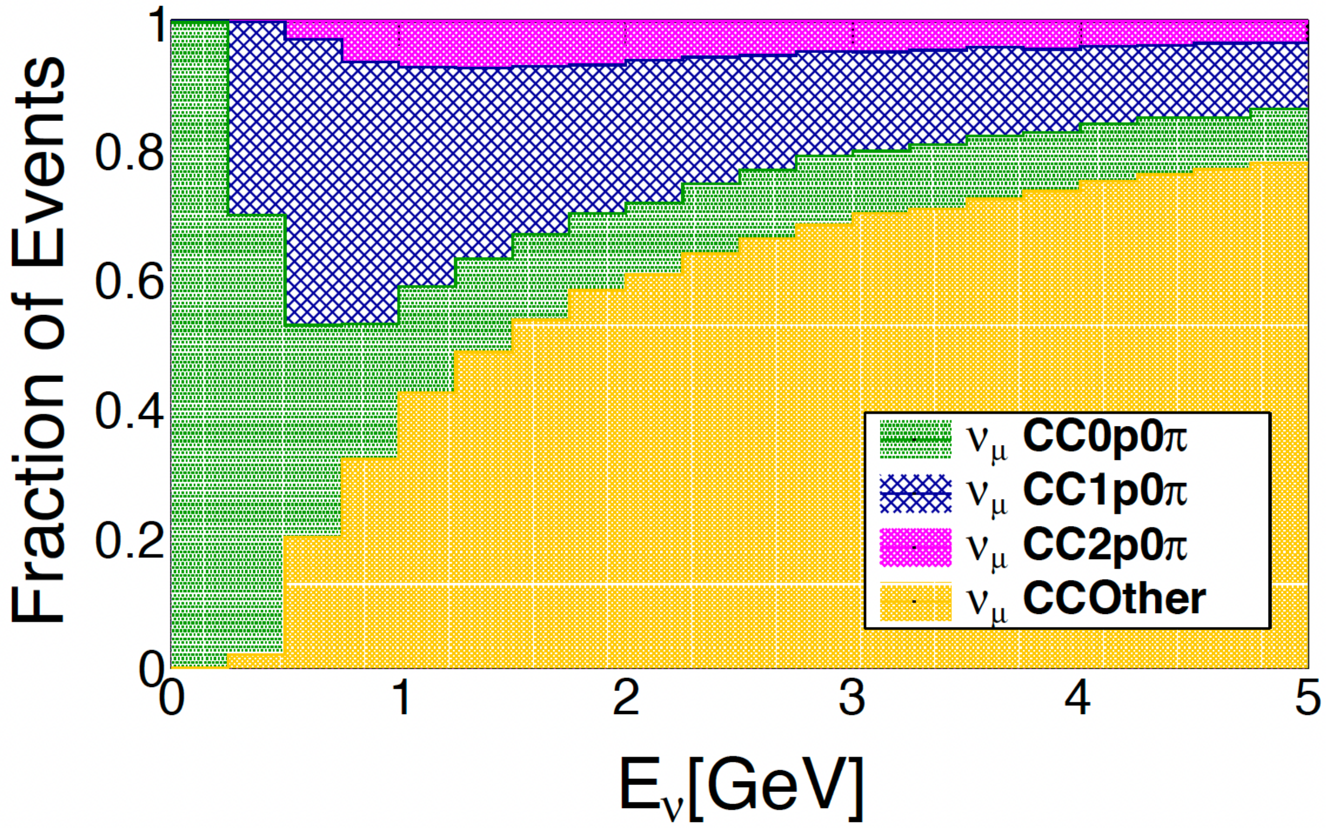
Tuning the Shallow-Scattering Inelastic region

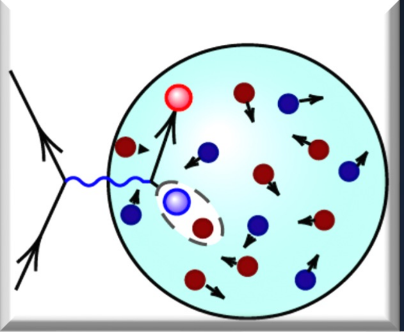
- **The G18_02a_00_000 configuration corresponds to the untuned model**
  - Originally tuned to describe inclusive data
  - Tensions with exclusive data couldn't be resolved
    - Overprediction of 1π production
    - Underprediction of 2π production
- **Resolving the tensions between inclusive and exclusive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





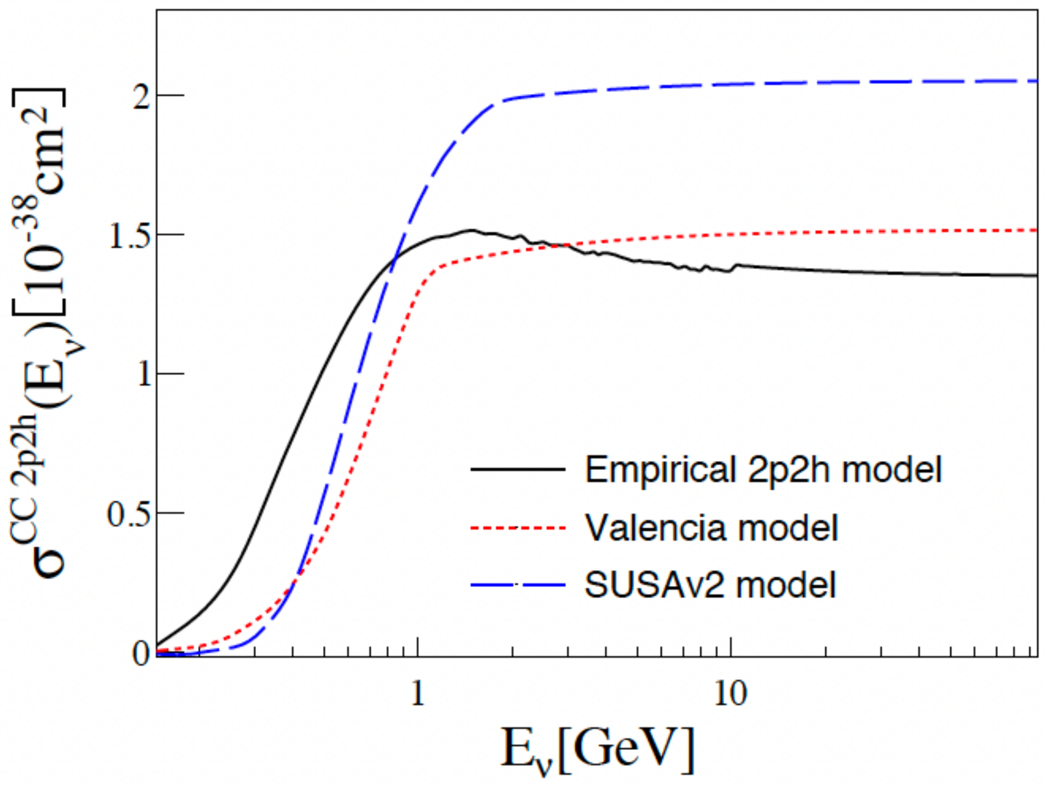
Neutrino-nuclei interactions



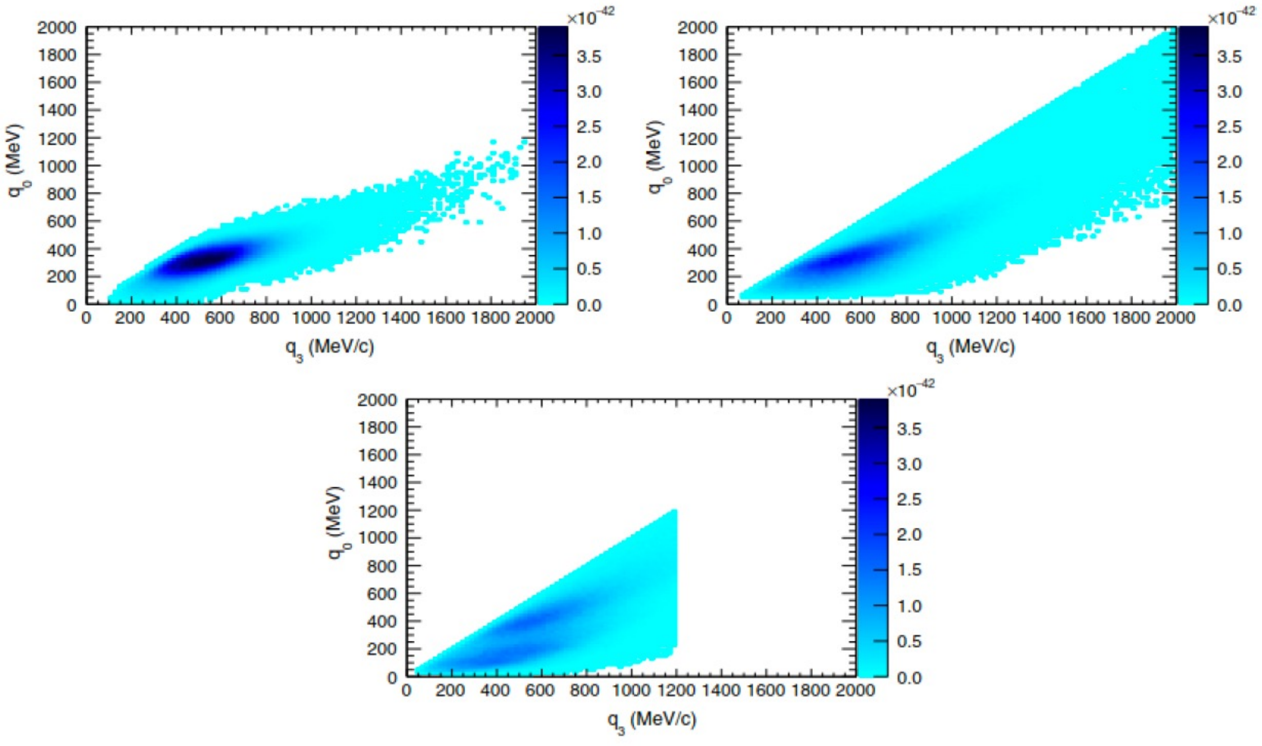


Multi-nucleon mechanisms tuning

Models differ in normalization



and shape

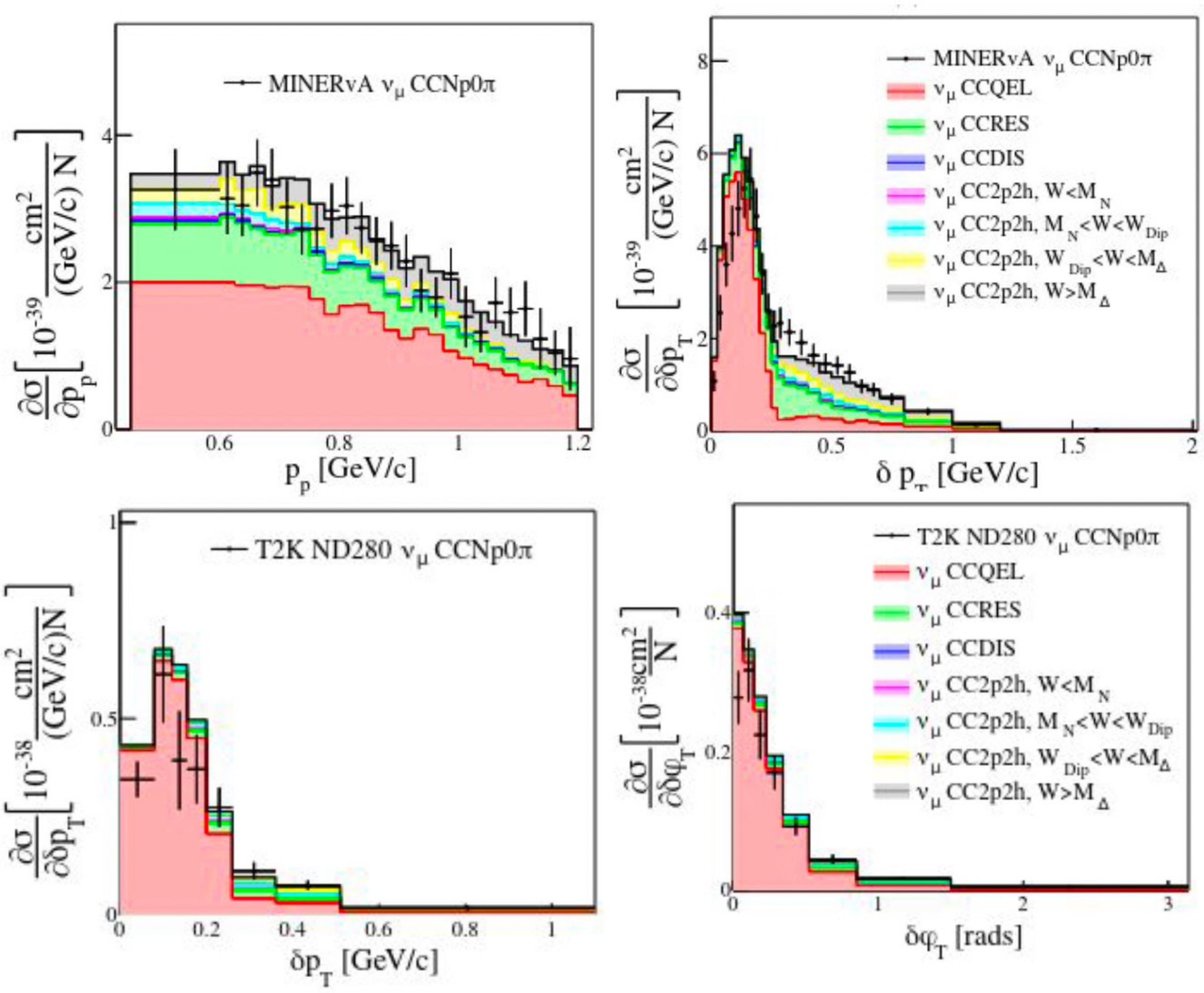


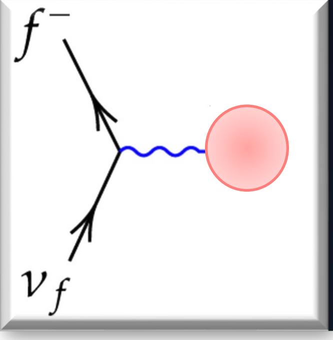
(b)

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

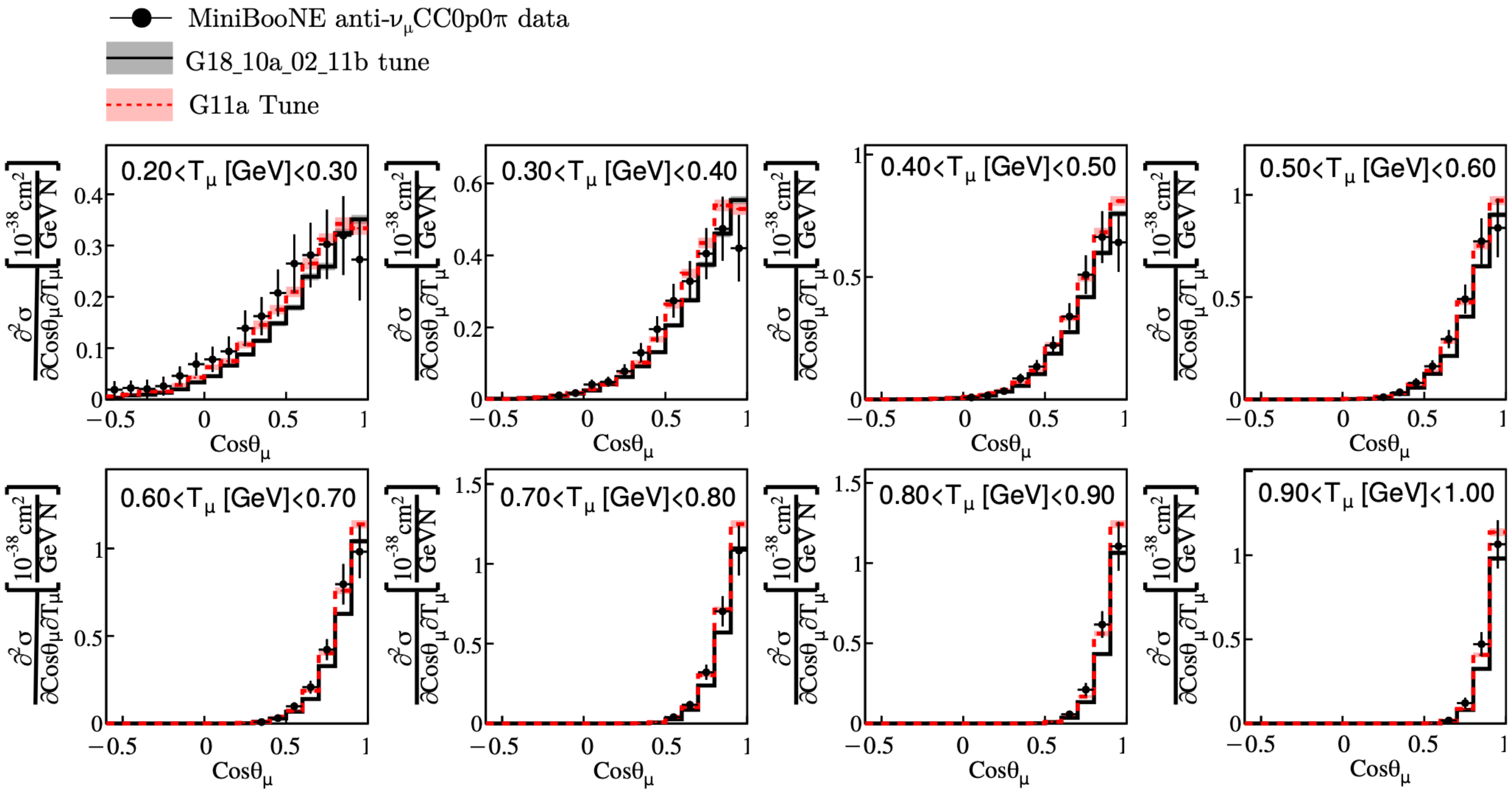


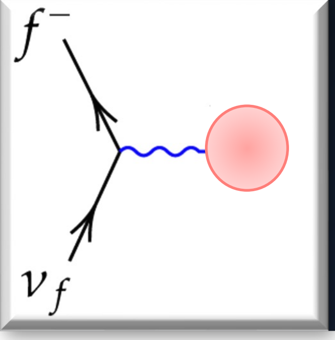


Tuning of $\nu - A$ CC0π interaction models Results

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

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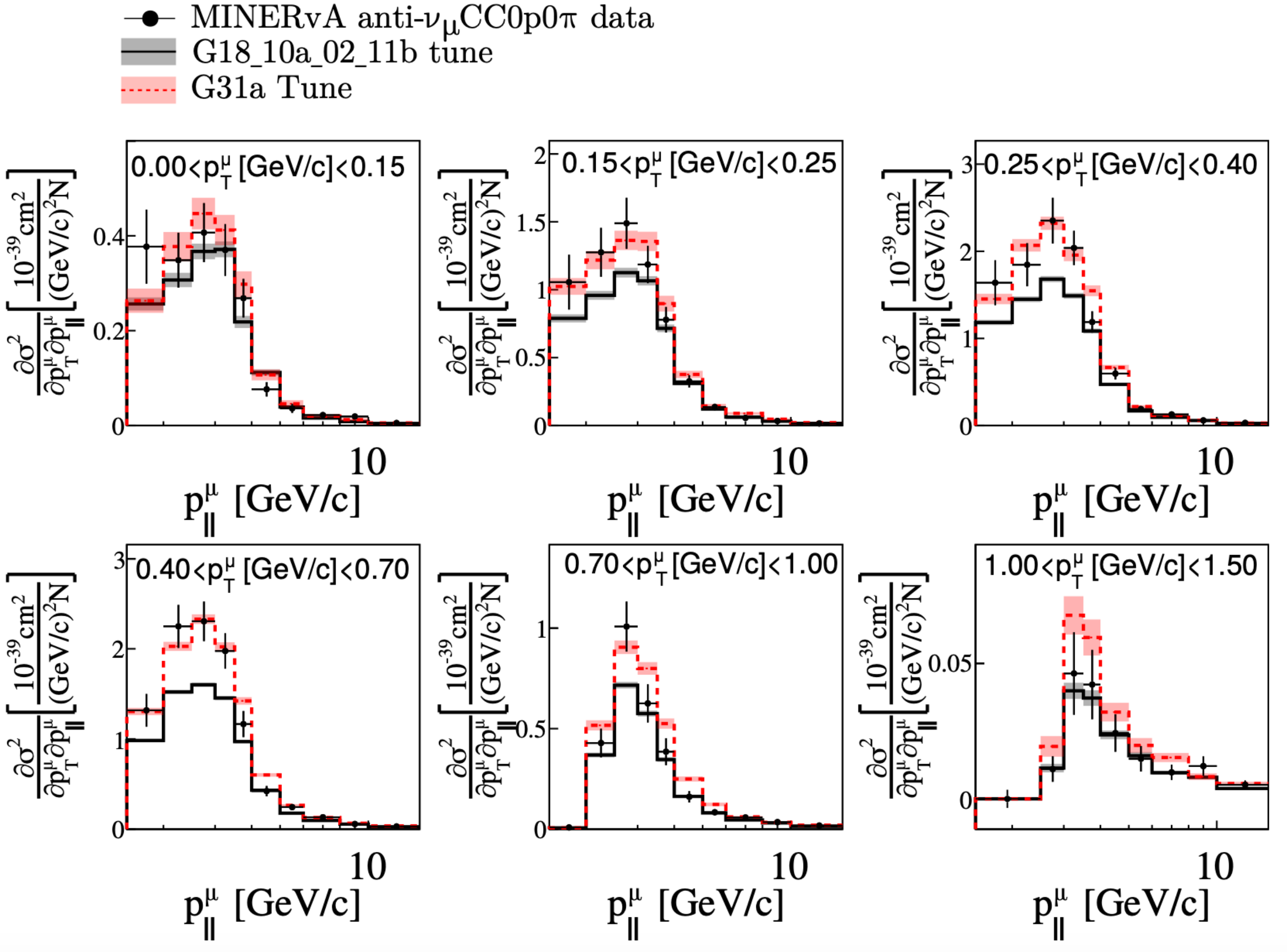
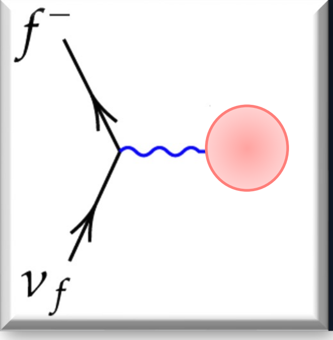
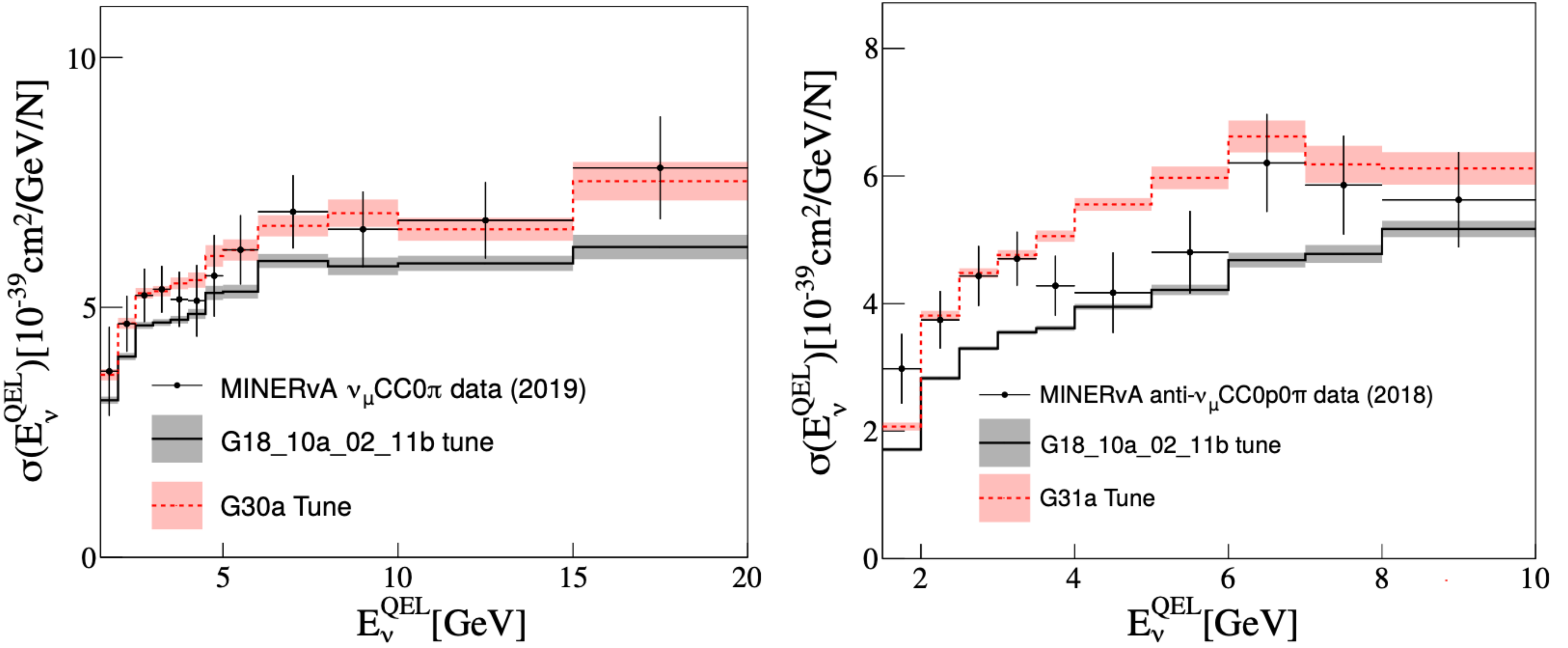
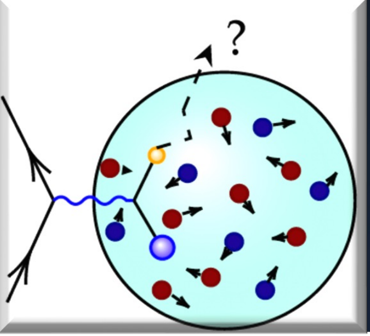




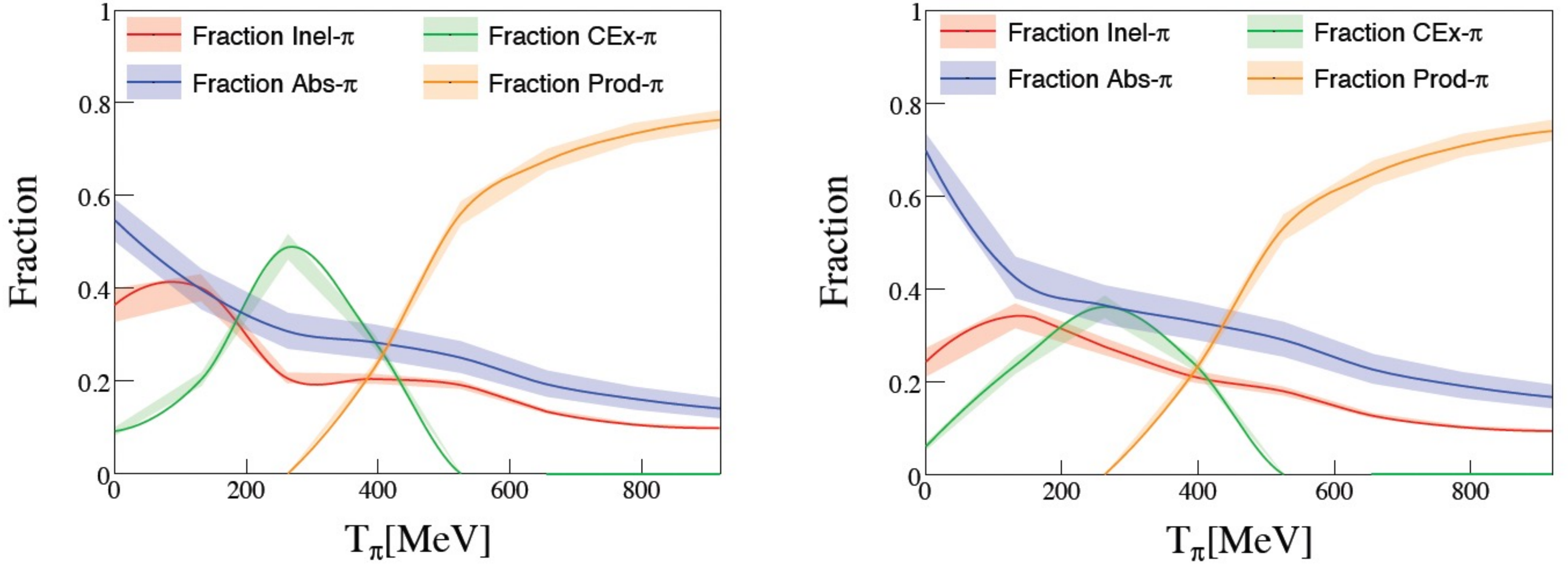
Tuning of $\nu - A$ CC0π interaction models Results

PhysRevD.104.072009

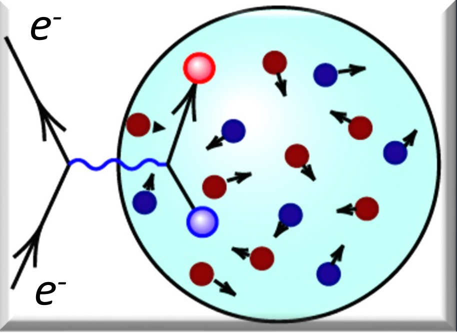




Final-State Interactions tuning



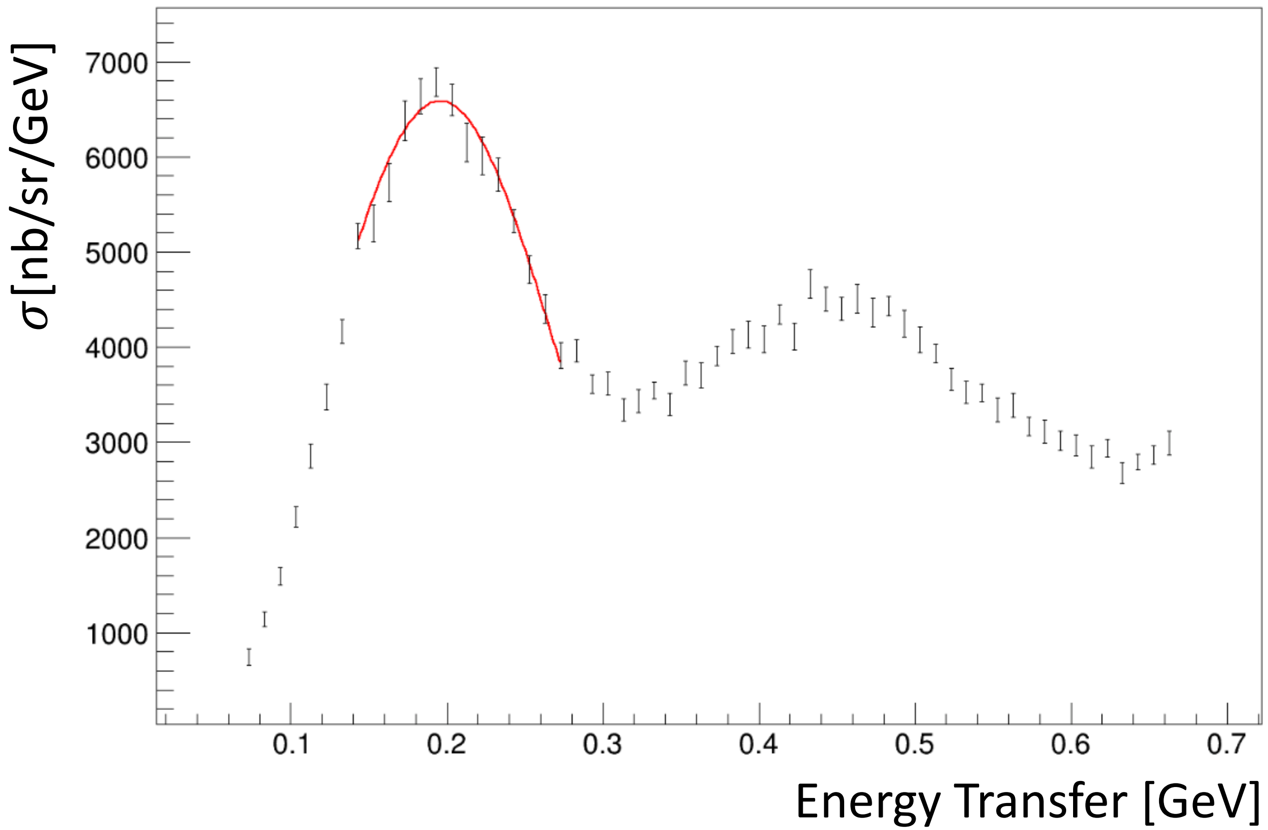
(a) hA2018 pion fractions for ^{12}C. (b) hA2018 pion fractions for ^{40}Ar.

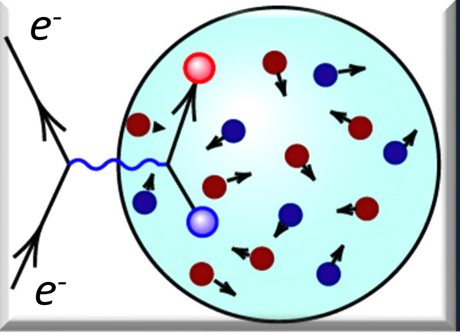


Nuclear model tuning

Matan
Goldenberg

^{12}C @E = 0.961 GeV & θ = 37.5°





Nuclear model tuning

Matan Goldenberg