The challenges of tuning neutrino event generators

NuXTract at CERN

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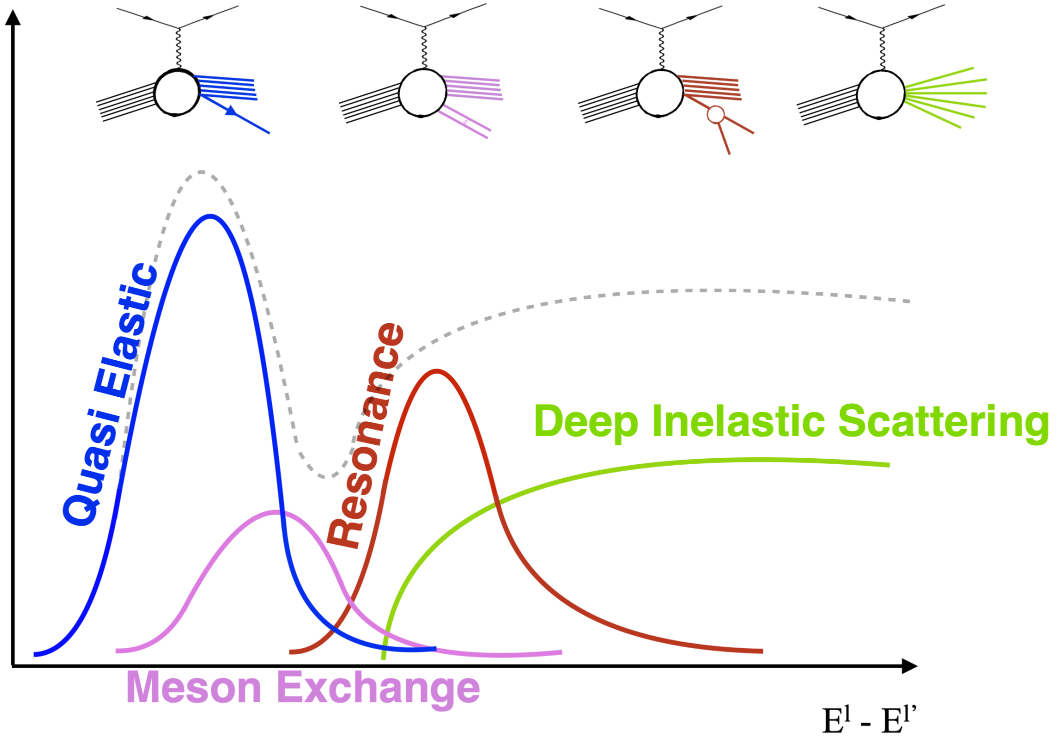
Genie

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, build model comparisons, …
- **Models are not complete – built in approximations**
  - Focus on lepton kinematics
  - Limited phase space coverage
  - Empirical transition between kinematic regions
  - Nuclear effects are factorized out
- **Model systematic uncertainties estimates**
  - Missing from current theory models



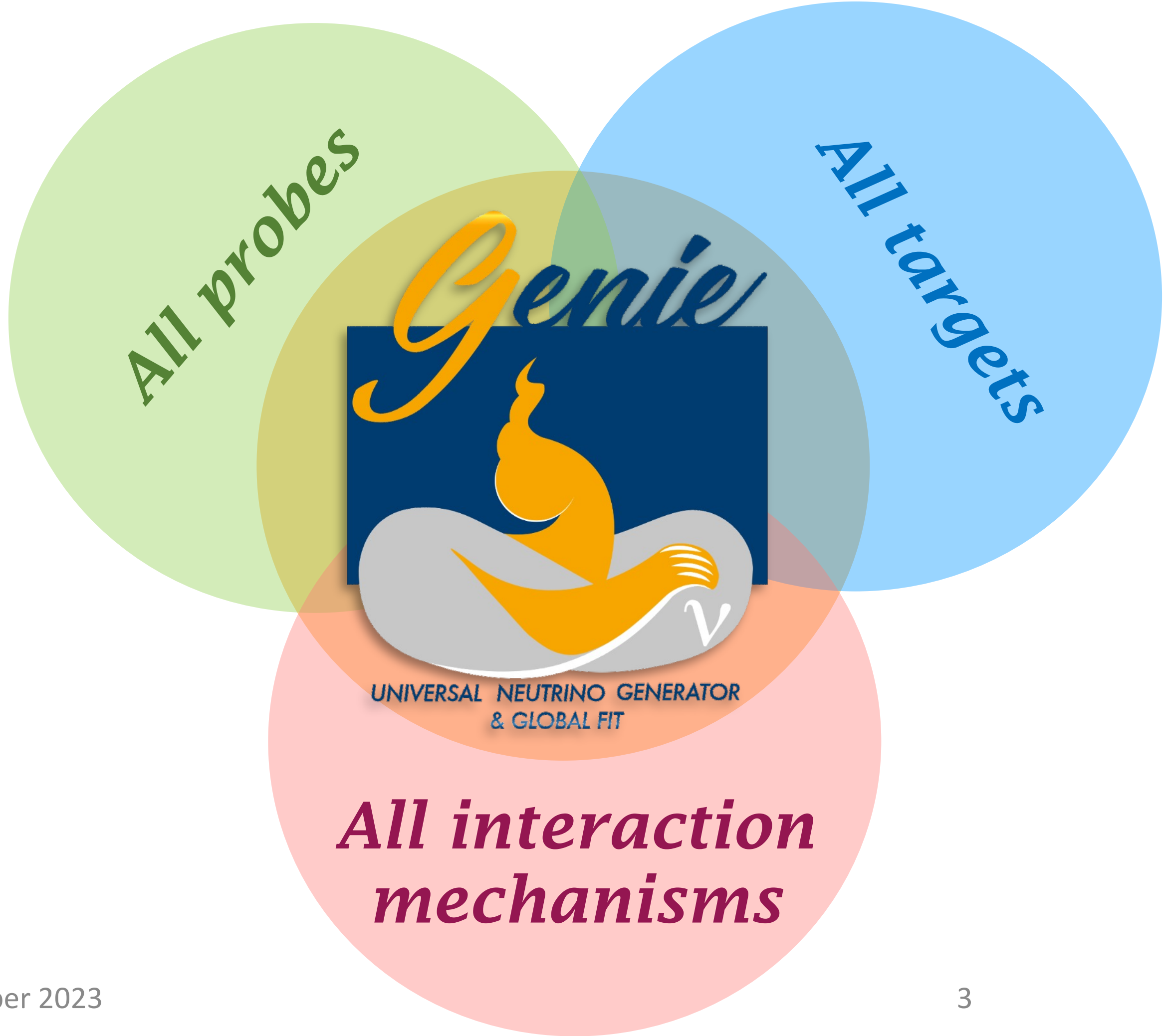
The GENIE event generator

GENIE model configurations

A configuration consists of a **set of models** which englobe all interaction mechanisms

Models, once implemented in event generators, can have two aspects:

- **Theoretical**
  - Derived from first principles
  - Limited phase-space coverage
  - Free parameters constrained by data
- **Empirical**
  - **Data-driven models**
  - Transition regions
  - Inclusive models implemented as exclusive
  - **Must be tuned to data**



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
- 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
- Professor-build response function using brute-force parameter scans
    - Parameters are defined in the event generator
- **Can tune all aspects of your event generator!**

GENIE global analysis program

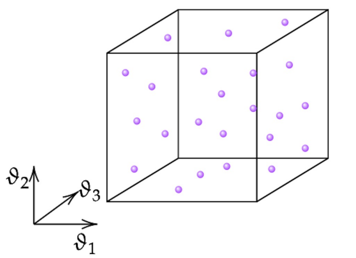
https://professor.hepforge.org

- Model fitting and data-driven uncertainty quantification with **Professor-GENIE**
  - Originally developed by the LHC community
  - Concept applied to neutrinos for the first time by the GENIE Collaboration
- **Applicable to all modelling aspects**
  - Can tune non-reweightable parameters
- Easily to replicate whenever new models are included

GENIE-Professor based tunes

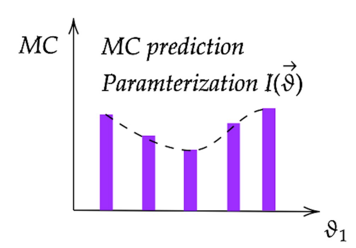
https://professor.hepforge.org

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



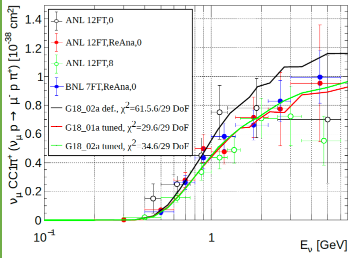
Brute-force scan of Monte Carlo response function

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



Parameterisation of response function

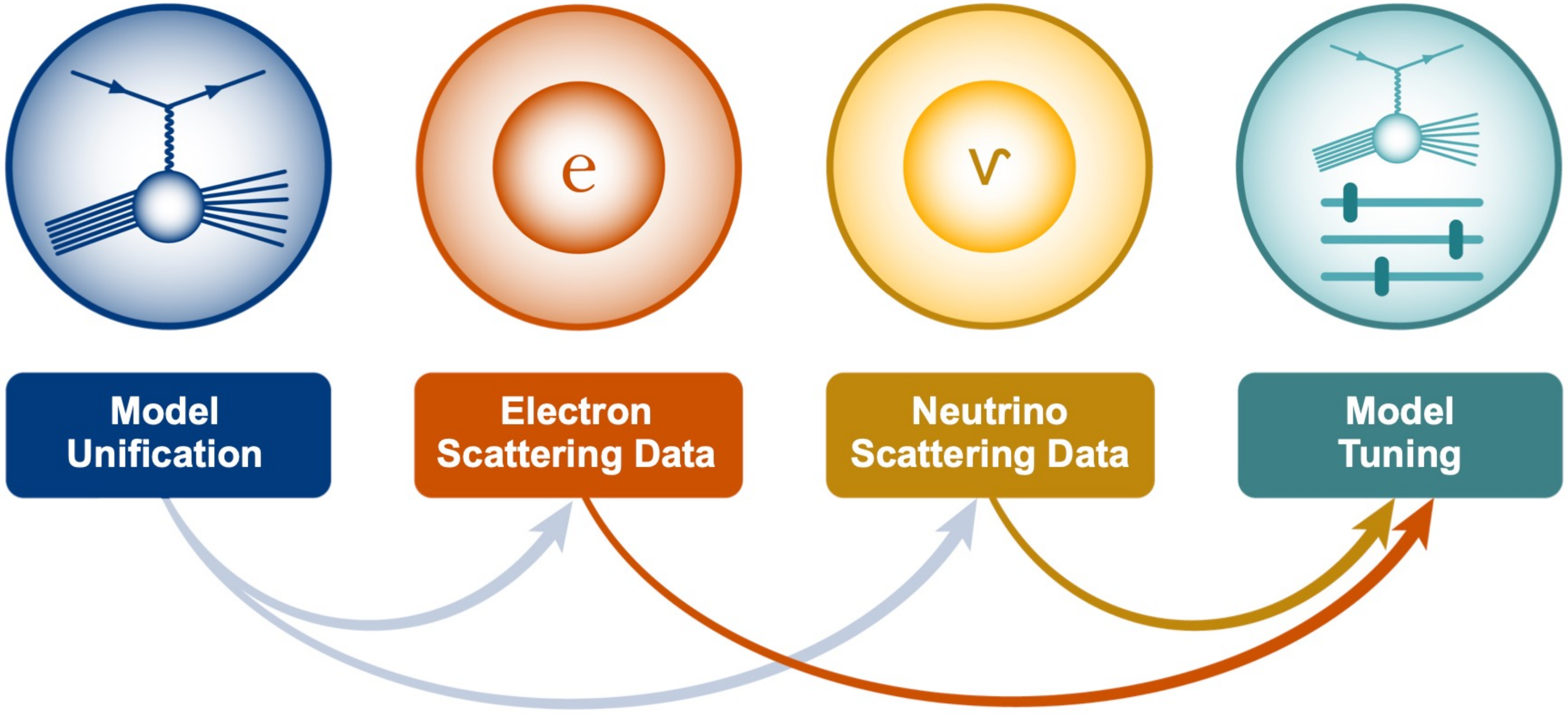
- The predictions are then interpolated using N-dimensional polynomials as a function of the parameter space
- Handled by the standard Professor software [The European Physical Journal C volume 65, 331 (2010)]
- The parameterization is not exact. Validation tools are used.



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 data releases
- Proper treatment of highly correlated datasets with Peelle's Pertinent Puzzle resolution

GENIE global tuning approach
Global tune with π-A, e-/ν-N/A data



GENIE global analysis approach

https://professor.hepforge.org

Free-nucleon model tune – global tune starting point

- Constrain nucleon cross sections – core of νA 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)**

(*) Ongoing work

Nuclear model tunes

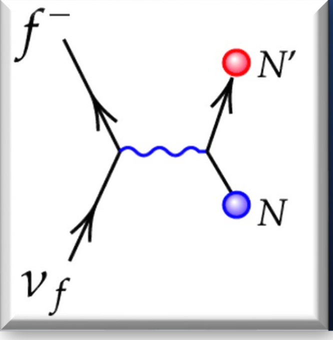
- Nuclear ground state, 1p1h+2p2h models, FSI
- Neutrino-nucleus CC0π cross-section tuning in GENIE v3 [PhysRevD.106.112001] with MINERvA, MiniBooNE and T2K data
- **(*) TKI tune with CC0π and CC1π data from MINERvA and T2K (Weijun Li, M.Roda, Xianguo Lu, C.Andreopoulos, J. Tena-Vidal)**

Hadronization tune

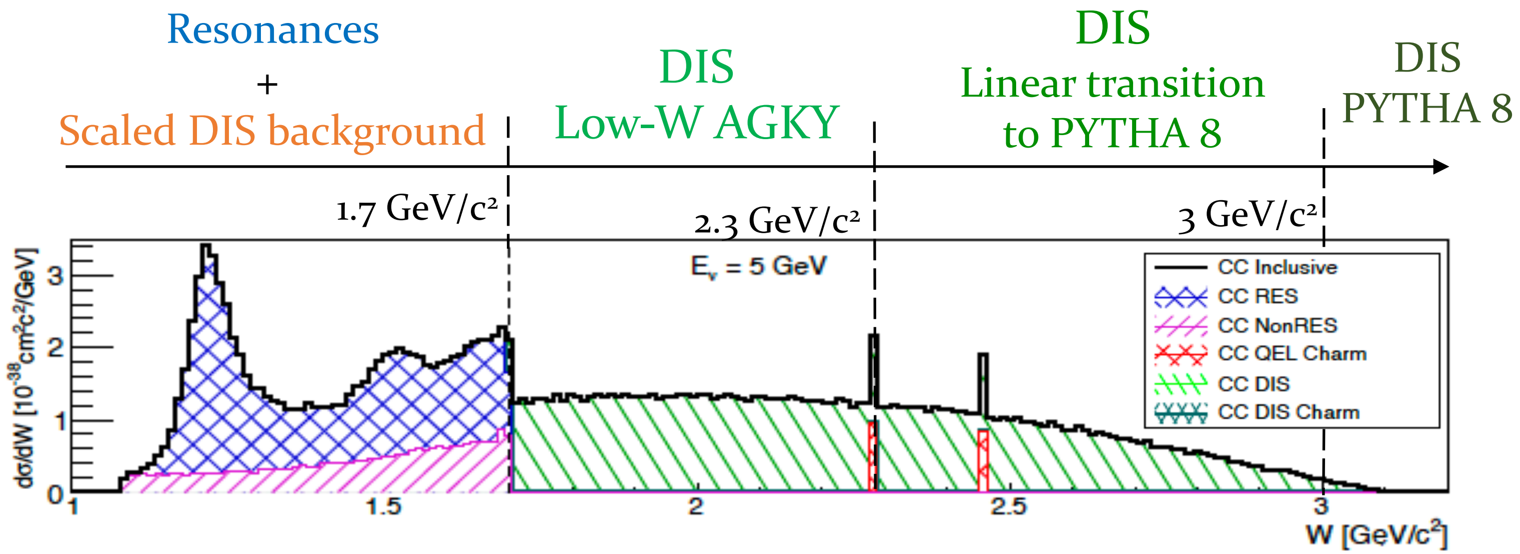
- Hadronization Model Tuning in GENIE v3 [PhysRevD.105.012009] using bubble chamber data
- First tune using neutrino data to constrain non-reweightable parameters

Uncertainty characterization and propagation

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



Tuning of the Shallow-Inelastic Scattering region



GENIE's Shallow-Inelastic Scattering model

RES

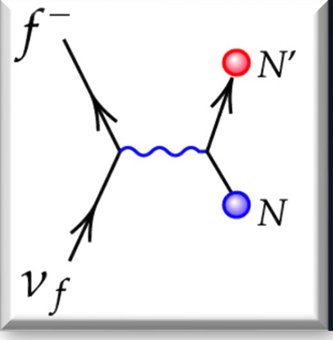
- Rein-Sehgal or Bergher-Sehgal are the starting point
- Added additional resonances
- Dipole Parameterization

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

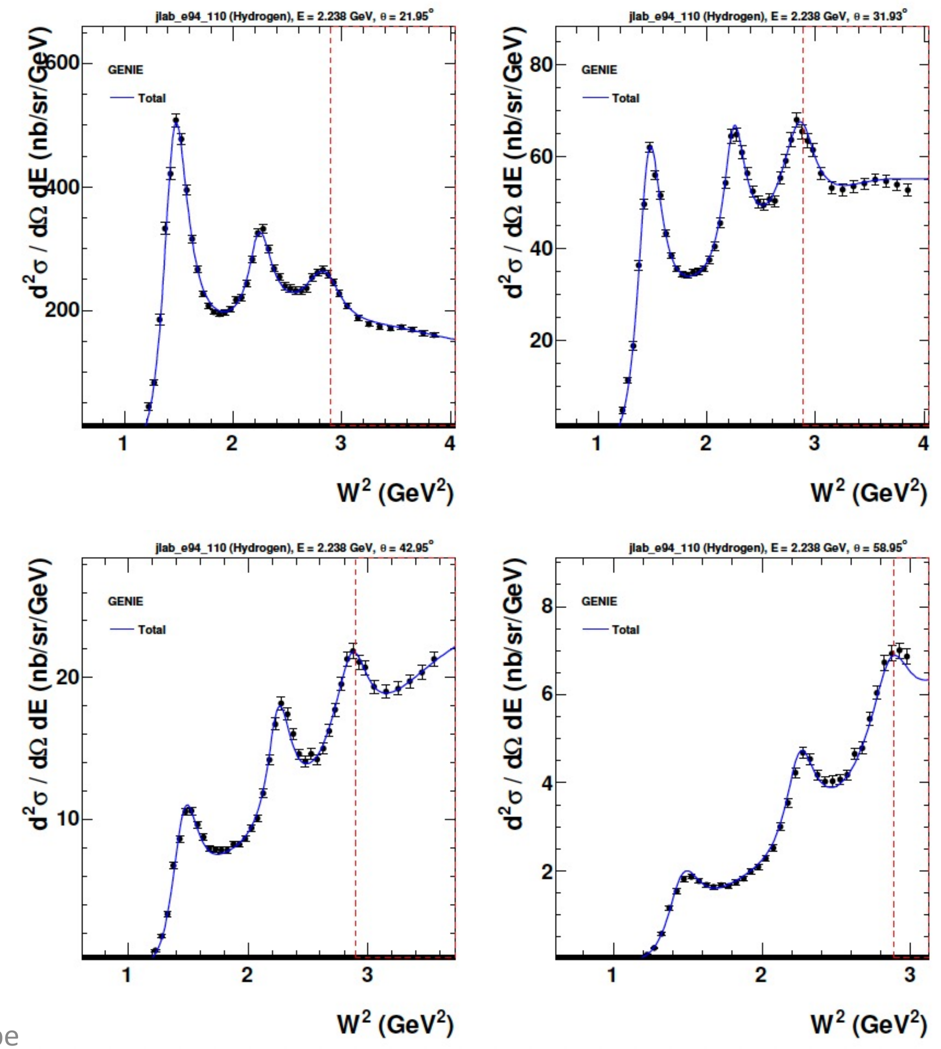


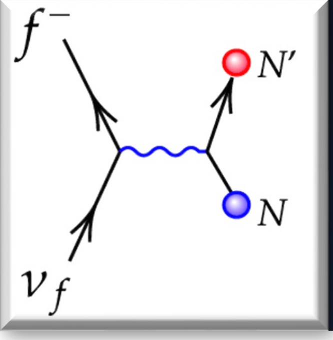
Tuning of the Shallow-Scattering Inelastic region Datasets available – electron scattering

Electron-scattering data

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

(*) Data is compared against Boosted-Christy prediction





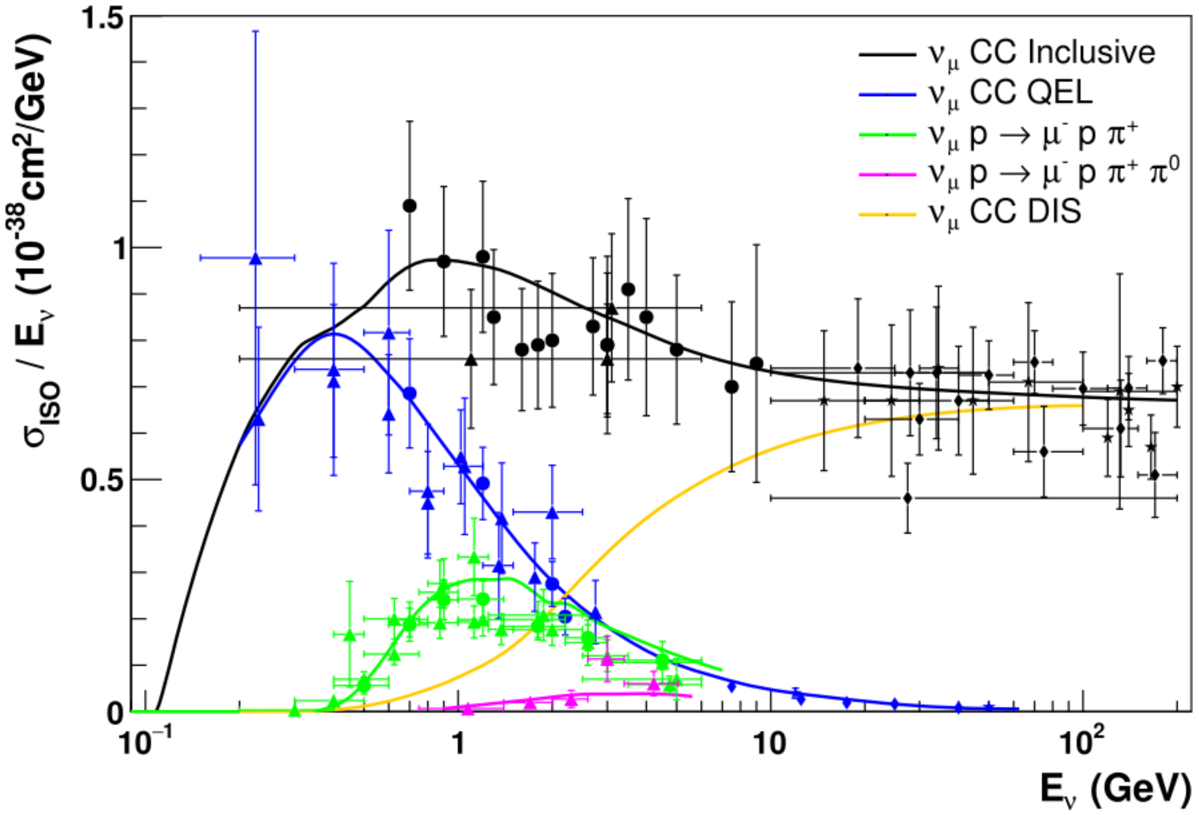
Tuning of the Shallow-Scattering Inelastic region
Datasets available – neutrino scattering

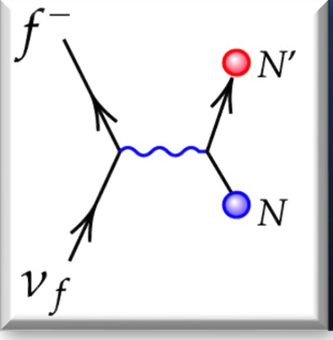
PhysRevD.104.072009

Neutrino data

- ANL, BNL, FNAL and BEBC bubble chambers
- Hydrogen and deuterium targets
- **Flux-unfolded** cross-section measurements as a function of E_ν:
  - $\boldsymbol{\nu_\mu}$ **and anti-** $\boldsymbol{\nu_\mu}$ **CC inclusive**
  - $\boldsymbol{\nu_\mu}$ **and anti-** $\boldsymbol{\nu_\mu}$ **CC single-pion**
  - $\boldsymbol{\nu_\mu}$ **and anti-** $\boldsymbol{\nu_\mu}$ **CC two-pion**

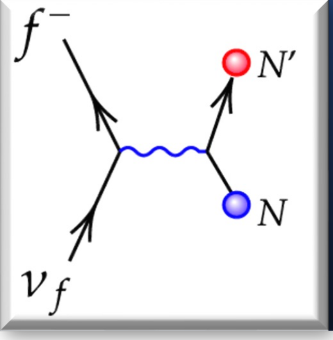
as a function of E_ν.





Limitations of historical neutrino bubble chamber data

- Bubble chamber experiments provided with the first flux-unfolded integrated cross-section measurements
- Mostly inclusive measurements, few exclusive (one-, two-pion, QEL..)
- Measurements as a function of E_{ν}, Q2…
  - Big bias on neutrino energy
- Statistically limited, ~ 100 events
- Poor neutrino flux knowledge
- MC-based data-corrections
  - Model dependent cuts
- Missing systematic uncertainties
  - Not quantified by experiments
  - Large normalization uncertainties lead to inconsistencies between experiments
    - Re-analysis of ANL/BNL data [PhysRevD.90.112017]



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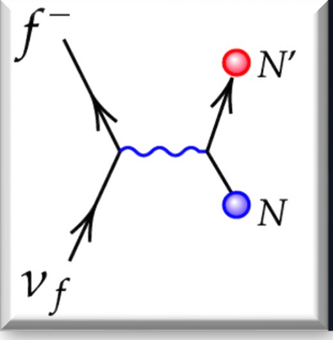
Many reasons to not use these datasets…

… only data available on hydrogen and deuterium for neutrinos!



Tuning of the Shallow-Scattering Inelastic region with ν-N data
Parameter choice challenges

PhysRevD.104.072009

RES

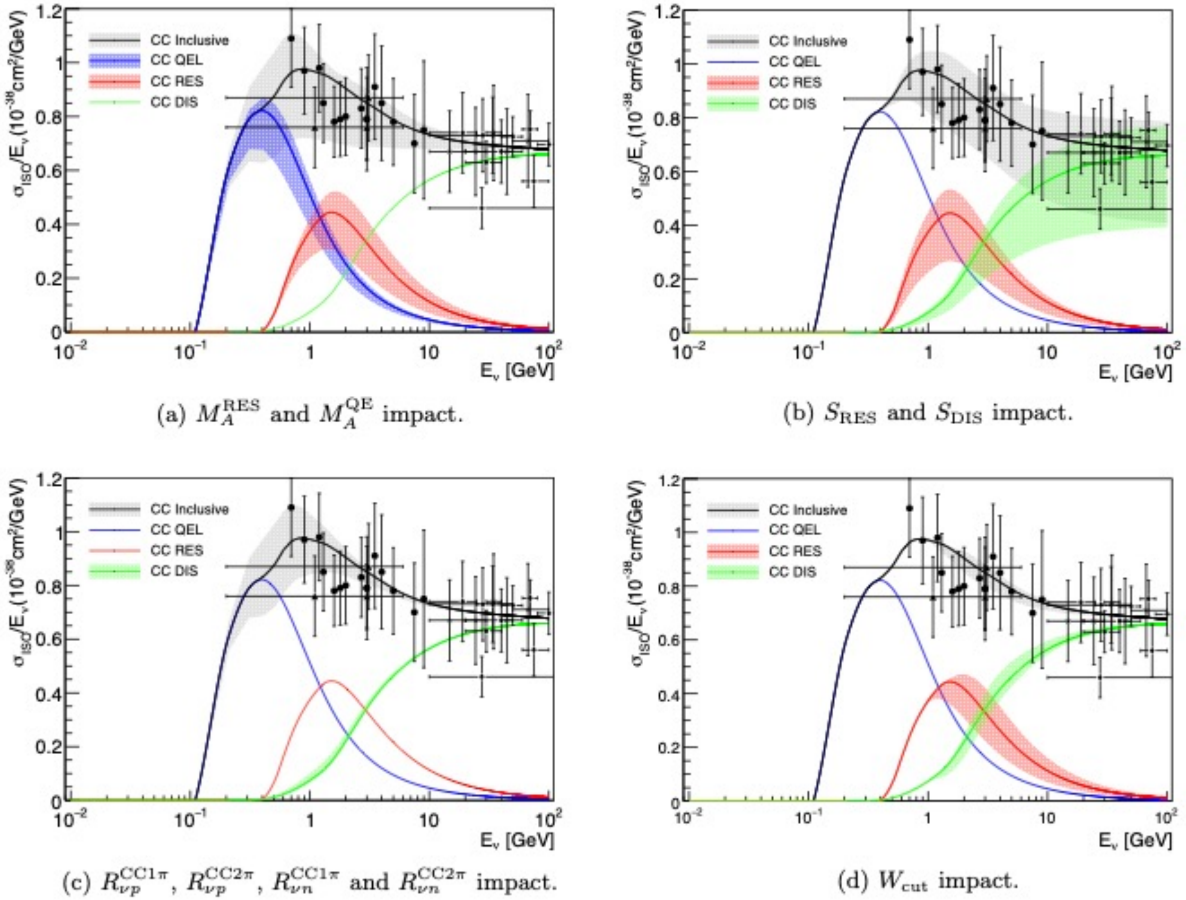
- Overall scaling parameter
- M_A^{RES}

Non-resonant bkg

- R_m parameters for proton and neutron, multiplicity 2 and 3
- *Simplification:* we neglect the AGKY low-W parameters

DIS

- W_{cut} to determine the end of the SIS region
- Overall DIS scaling

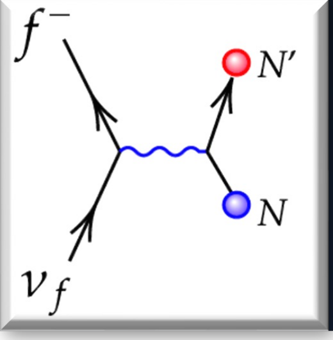


(a) M_A^{RES} and M_A^{QE} impact.

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

(c) $R_{\nu p}^{CC1\pi}$, $R_{\nu p}^{CC2\pi}$, $R_{\nu n}^{CC1\pi}$ and $R_{\nu n}^{CC2\pi}$ impact.

(d) W_{cut} impact.



Tuning of the Shallow-Scattering Inelastic region with ν-N data
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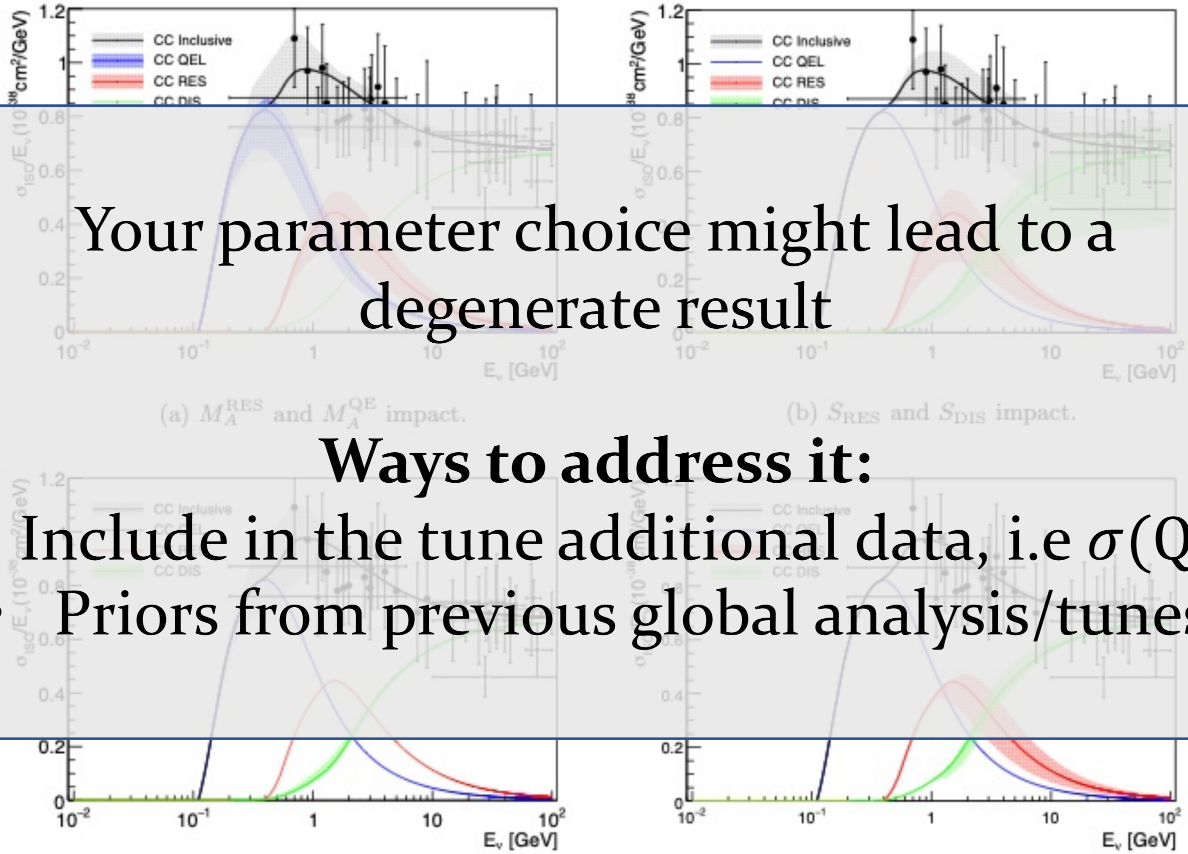
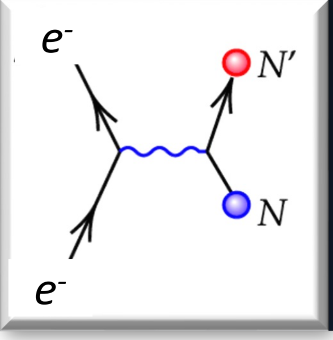


(a) M_A^{RES} and M_A^{QE} impact. (b) S_{RES} and S_{DIS} impact. (c) $R_{\nu p}^{CC1\pi}$, $R_{\nu p}^{CC2\pi}$, $R_{\nu n}^{CC1\pi}$ and $R_{\nu n}^{CC2\pi}$ impact. (d) W_{cut} impact.

Your parameter choice might lead to a degenerate result

Ways to address it:

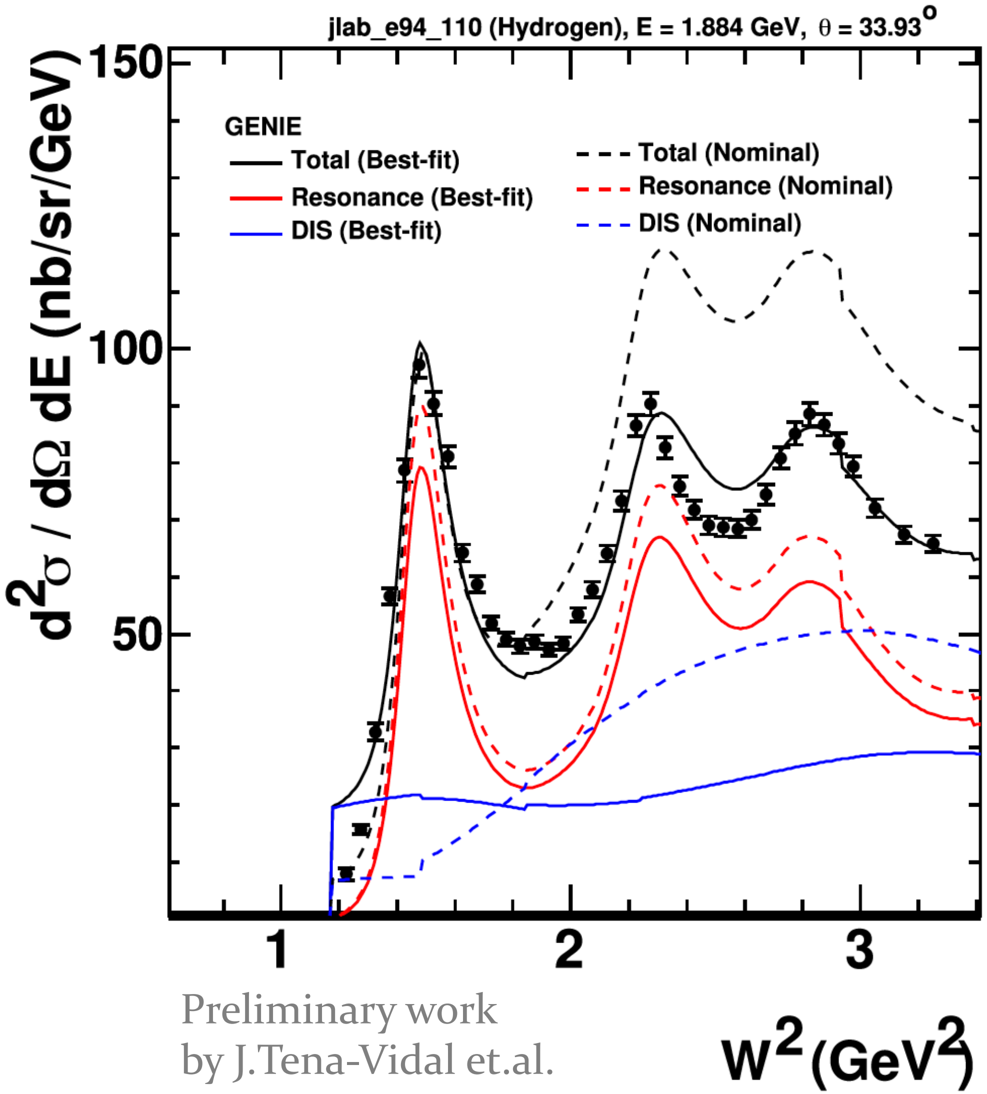
- Include in the tune additional data, i.e $\sigma(Q^2)$
- Priors from previous global analysis/tunes



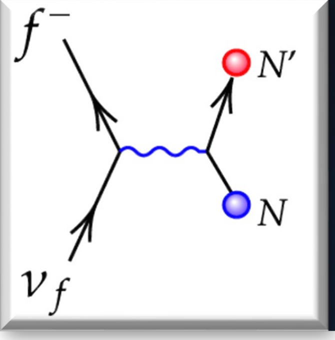
Tuning of the Shallow-Scattering Inelastic region with *e*-N data
Breaking degeneracy in the tune

e-N SIS modelling:

- Equivalent approach to neutrinos
- Non-resonant background parameters never tuned to electron data
  - Double counting is guaranteed
  - Model overpredicts data above the delta region
- Excellent inclusive data available from JLAB and SLAC
  - Fine W binning breaks most degeneracy of the free nucleon tune
  - Delta peak constrains RES Scaling
  - Multiplicity 2 and 3 non-resonant parameters can be constrained using fine W binning

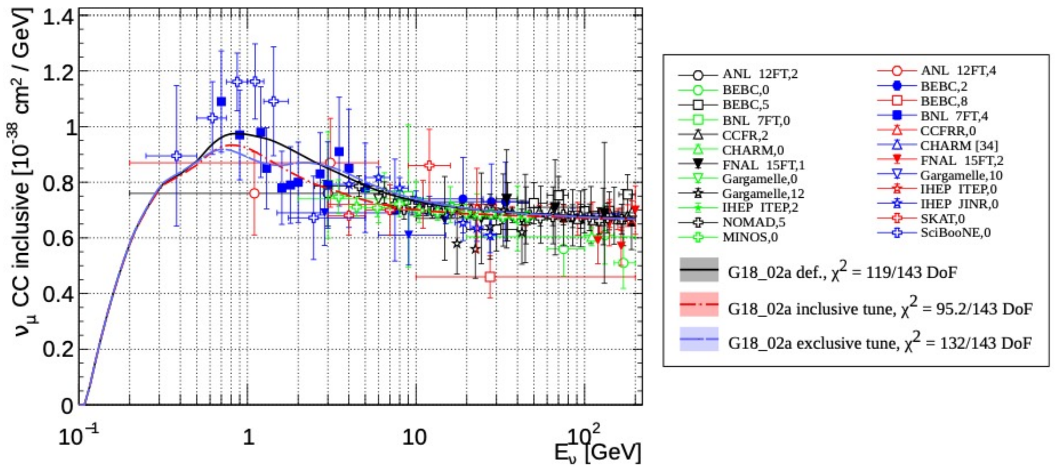


Preliminary work
by J.Tena-Vidal et.al.



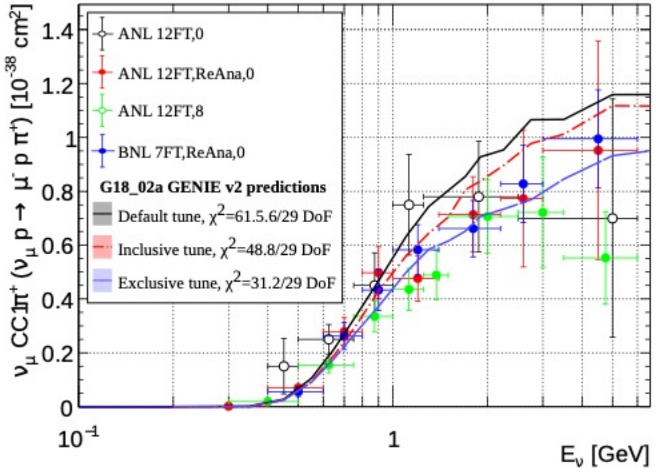
Tuning of the Shallow-Scattering Inelastic region with ν-N data Challenges – tensions between datasets

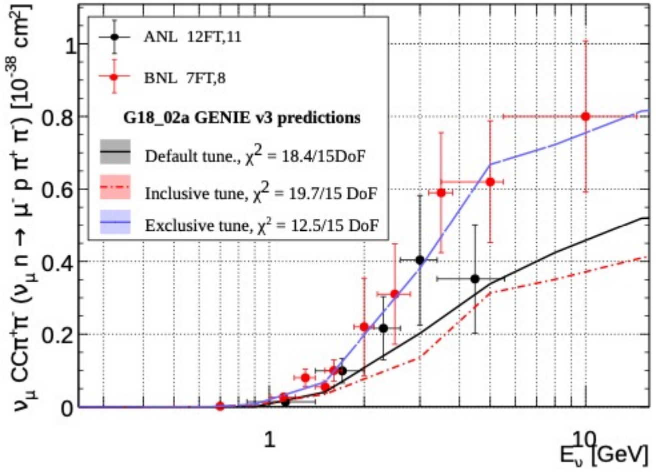
PhysRevD.104.072009



Inconsistent datasets lead into misleading tune results

Free-nucleon tune example:
Partial tune to inclusive data has opposite behavior to exclusive tune

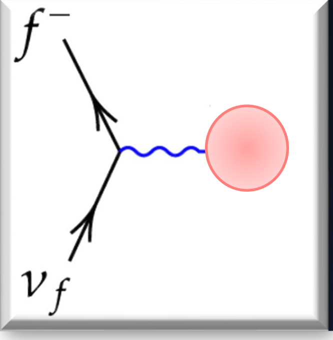




Consequence of the incorrect flux normalization used in the data analysis

Approach:

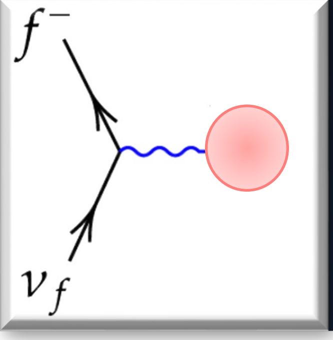
- Added QEL data
  - Well known $\sigma_{\nu N}^{QEL}(E_\nu)$
- Nuisance parameters



Tuning challenges with νA data

- The analysis of modern neutrino data defers significantly from historical bubble chamber data
  - Abundance of inclusive + exclusive measurements for different beam energies and targets
  - Flux-integrated measurements
  - Bin-to-bin correlation provided
  - Ongoing effort to release correlation between releases (see S.Gardiner talk)

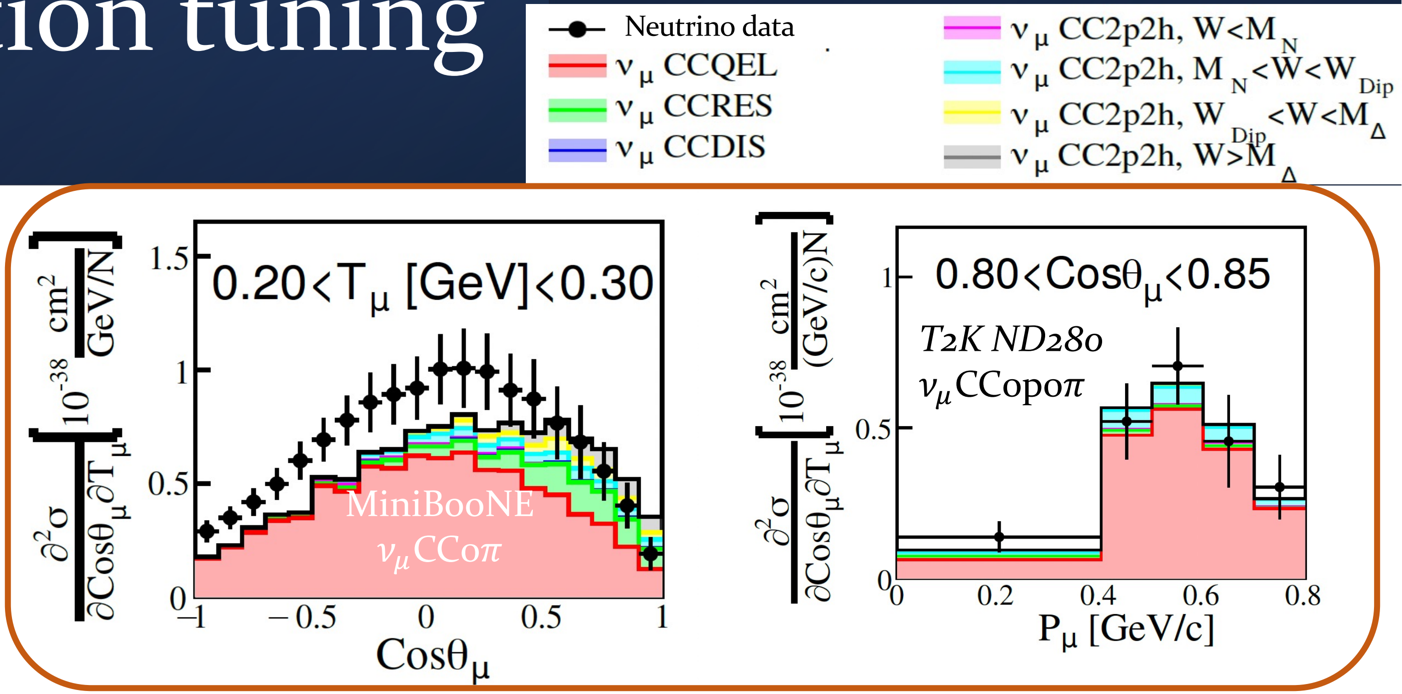
- Good news - we can accommodate all this in our tunes
  - Bin-to-bin correlation considered in likelihood minimization
  - Correlation between measurements can be easily added
    - We are excited to exploit it in future tunes



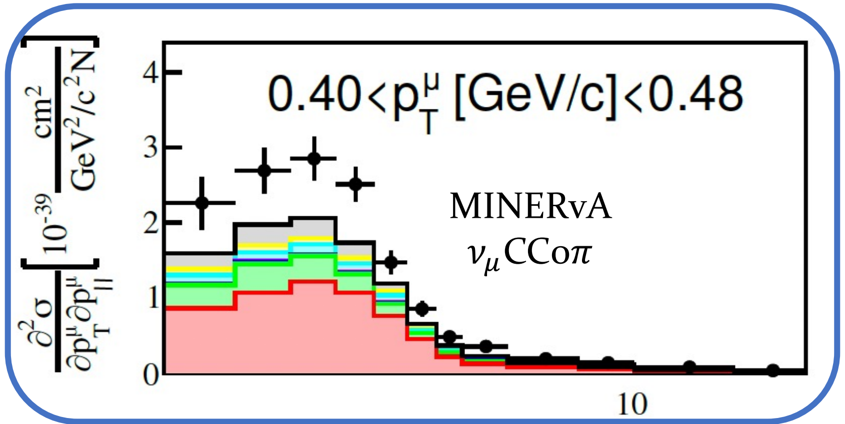
$\nu CC0\pi$ cross-section tuning

PhysRevD.104.072009

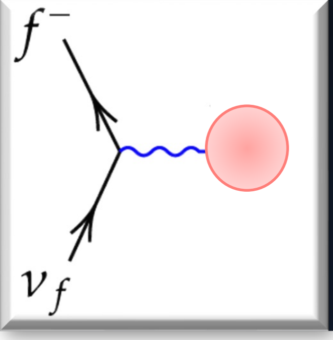
- Focus on $\nu_\mu CC0\pi$ data on hydrocarbon:
  - MINERvA (*)
  - T2K (*)
  - MiniBooNE
- Tune specifics:
  - G18_10a_02_11b: Valencia model (QEL+2p2h), LFG (ground state), BS (RES)
  - CCQE RPA , 2p2h normalization and shape, RES normalization and M_A^{QE}
  - Correlated priors from free-nucleon tune used to break degeneracy
  - Bin-to-bin correlation included (*)



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



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



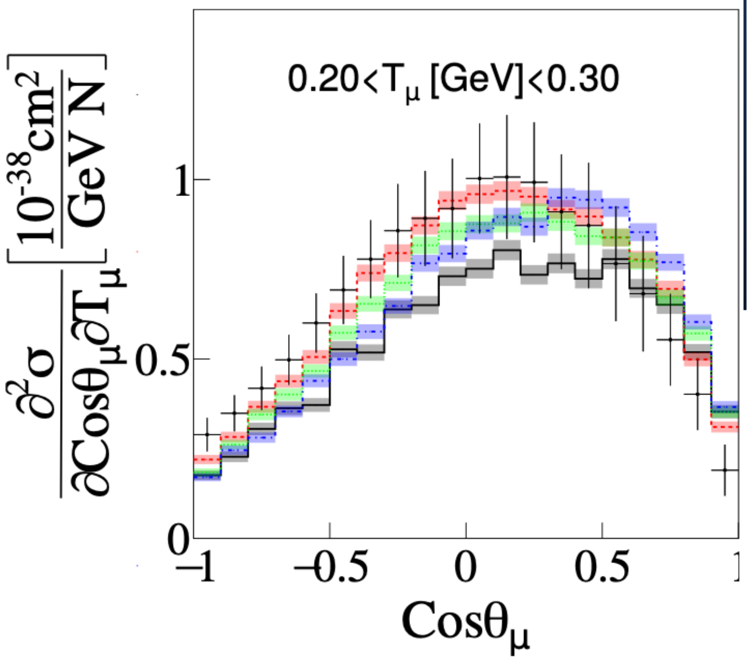
$\nu CC0\pi$ cross-section tuning

PhysRevD.104.072009

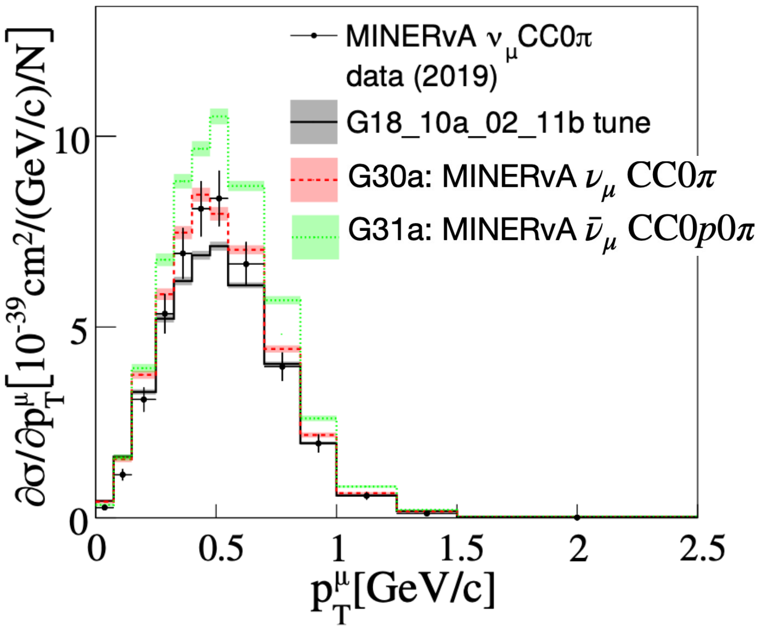
Is your model descriptive enough?

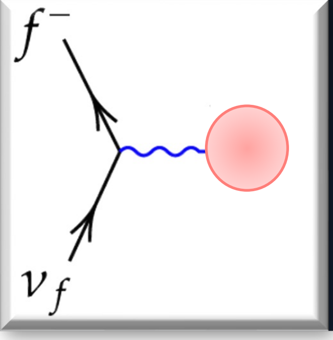
- Partial tunes highlight generator limitations
  - Distinct fluxes probe E_ν dependence
  - Tensions between ν_μ and $\bar{\nu}_\mu$ fits from the same experiment

Partial tunes highlight missing energy dependence on cross section shape



Anti-neutrino tunes predict a higher cross-section





Tuning challenges with νA data
How can we avoid more degeneration?

Free parameters **Neutrino data**

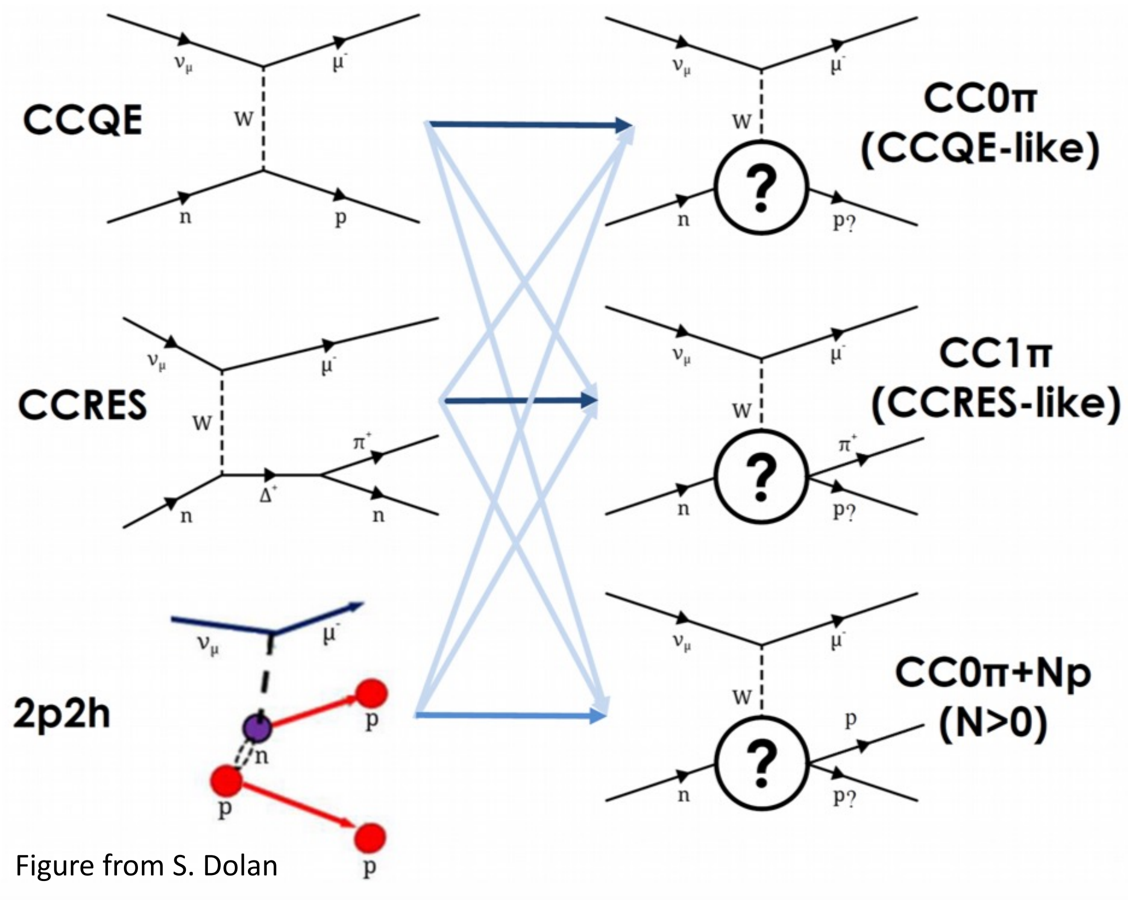
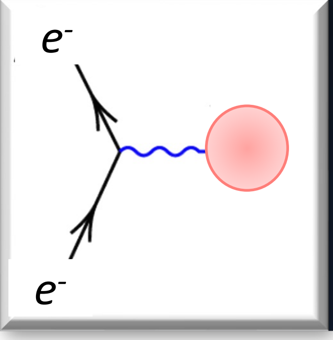


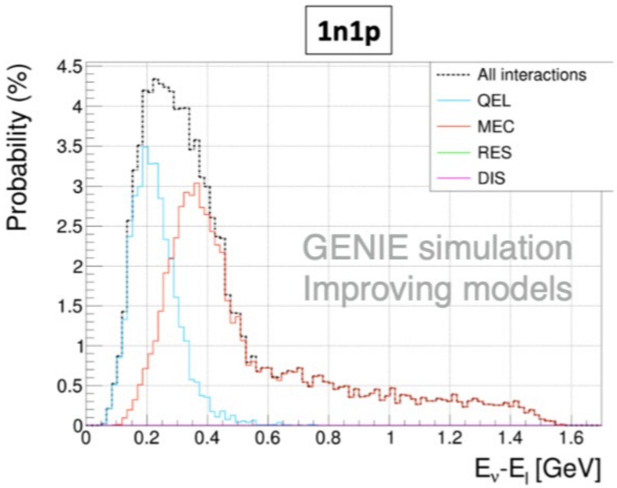
Figure from S. Dolan

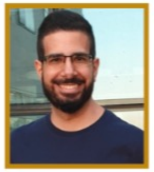
- Many modeling aspects are relevant to tune against $CC0\pi$ data
  - QE+RES+2p2h+FSI..
- Many modeling aspects to consider in nuclear tunes
  - $CC0\pi$ is affected from pion FSI – but is this the best sample to constrain this this?
  - From our experience, $CC0\pi$ data is not enough
- The parameters of interest should not be tuned to $CC0\pi$ data only
  - I.e.: correlation between $CC0\pi$ and $CCN\pi$ measurements are expected
  - Additional constrains



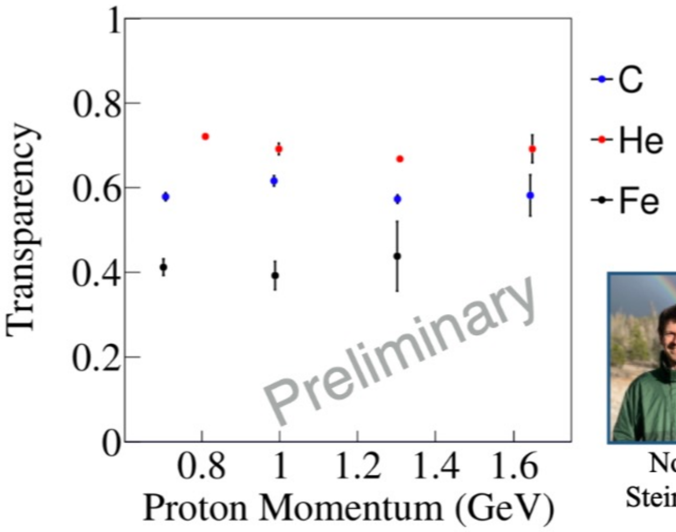
Electron-scattering
New e4nu measurements

- **New e4nu measurements on the way!**
  - Transparency on C, He, Fe (Noah Steinberg et. al.)
  - Inclusive cross-section on Argon at different Q² (Matan Goldelberg et. al)
  - Two nucleon final state (Alon Sportes et. al.)
  - Pion production (J.Tena-Vidal et. al.)
  - Re-analysis of e,e'1p0π (more kinematics, multi-dimensional) (J.Tena-Vidal et. al.)

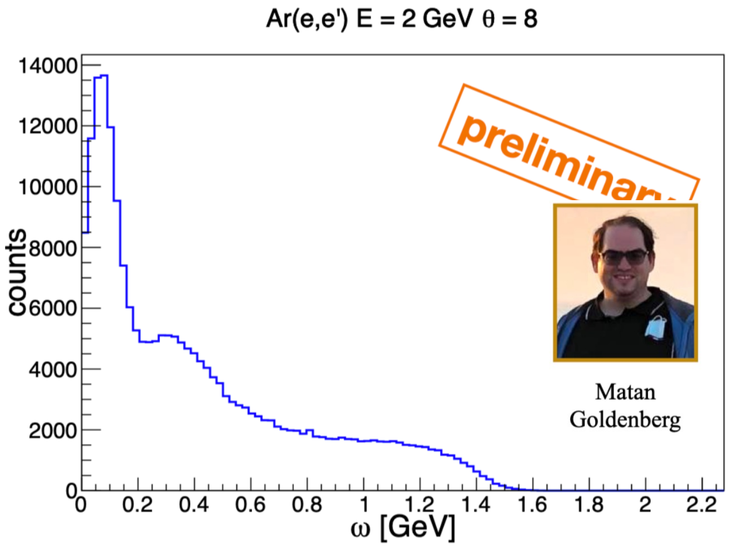




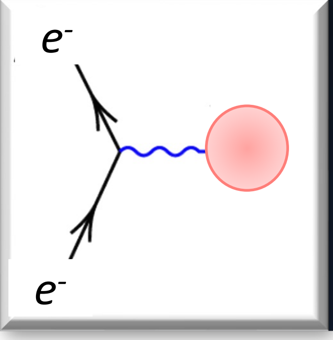
Alon Sportes



Noah Steinberg



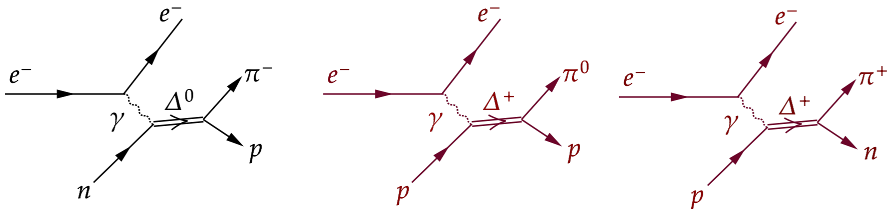
Matan Goldenberg



J.Tena-Vidal et.al

Electron-scattering Exclusive π-production

- 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

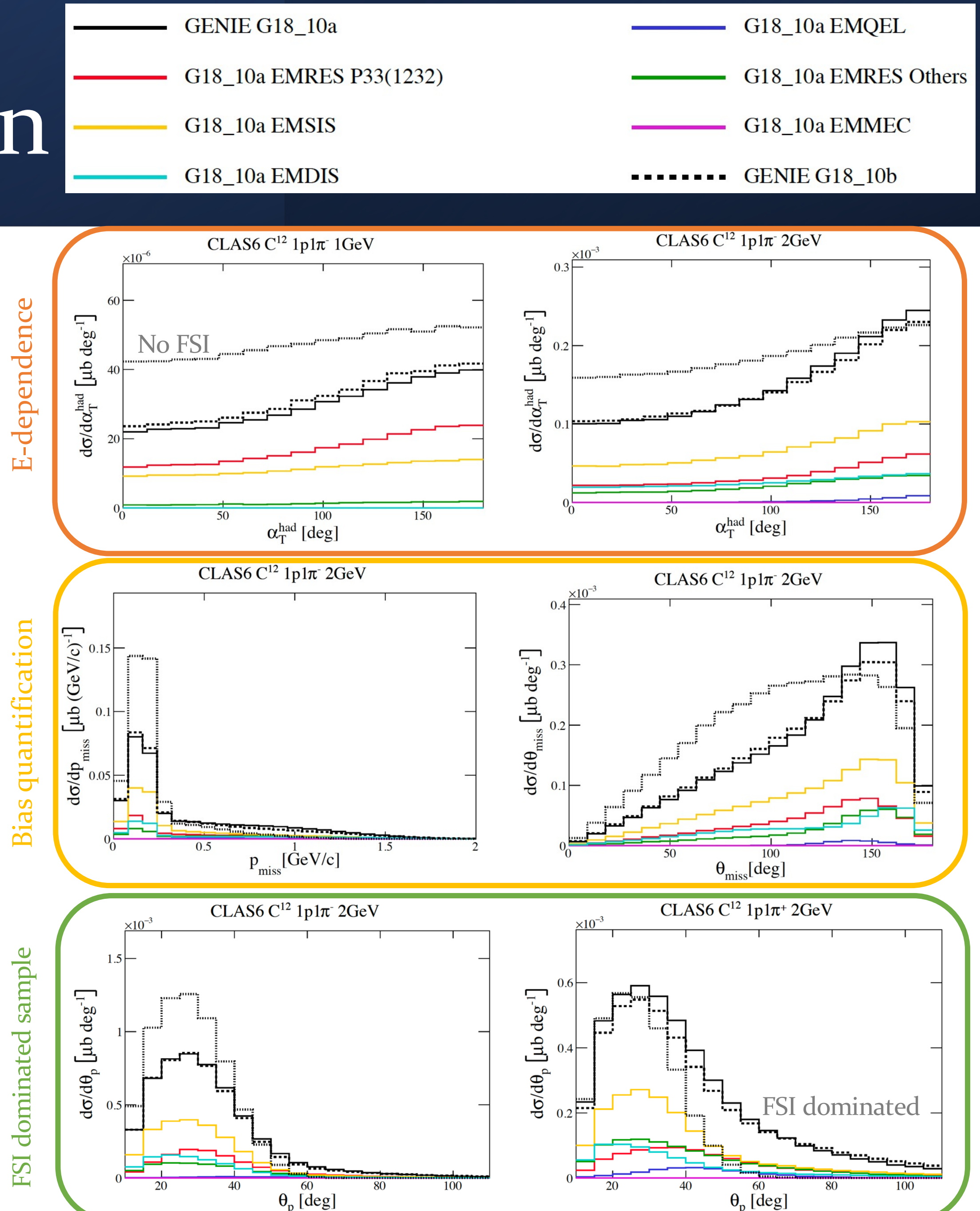


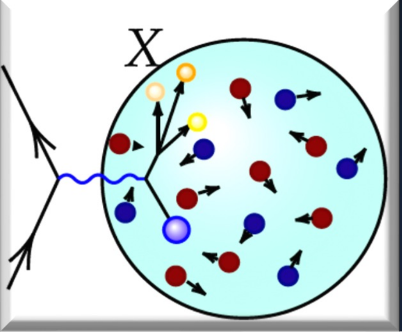
(*)

- 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



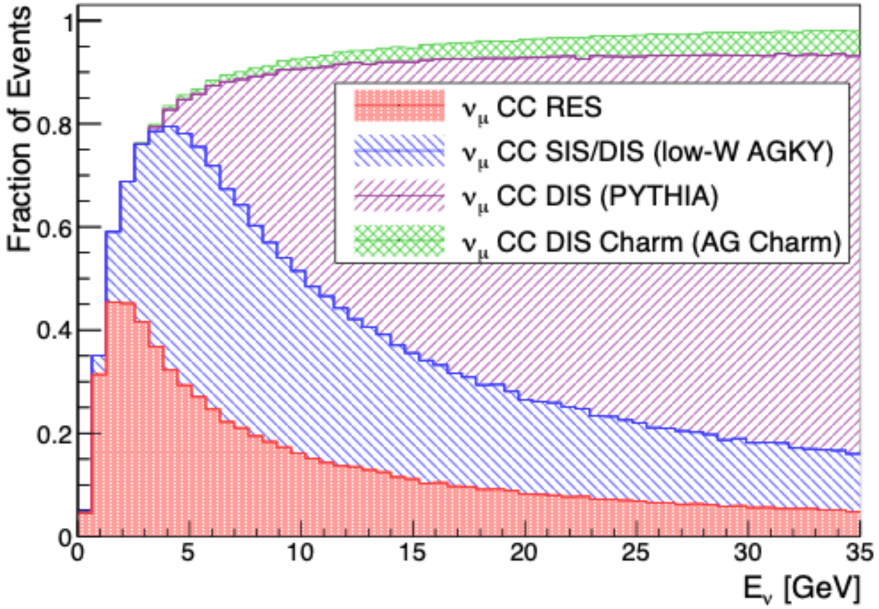


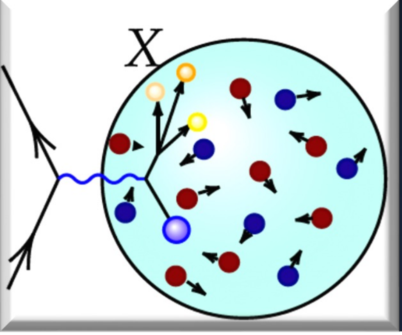
Tuning the AGKY Hadronization tune
Tuning non-reweightable models

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…





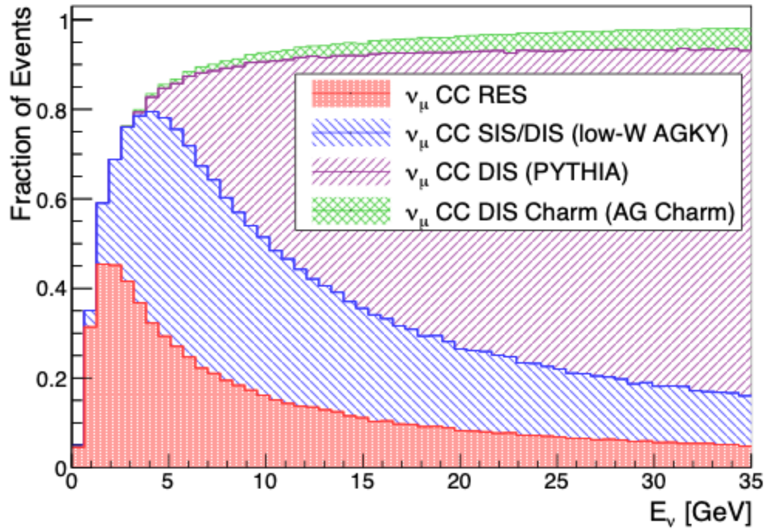
Tuning the AGKY Hadronization tune
Tuning non-reweightable models

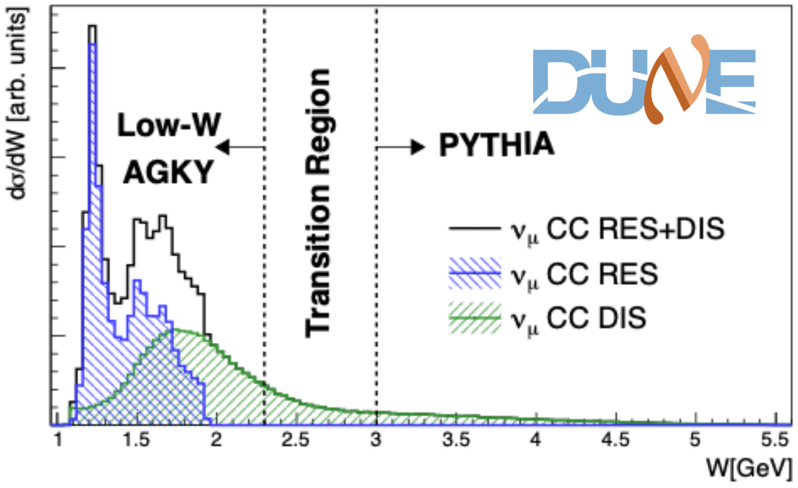
Modeling:

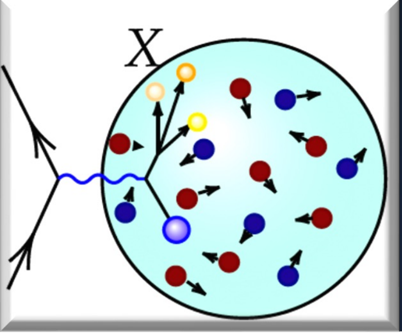
- At low-W, model is anchored to bubble chamber data
- PYTHIA for W>3 GeV doesn't describe neutrino data
- In GENIE it is also used to determine pion multiplicity at the SIS region

Limitations:

- Missing global tune of low-W AGKY + PYTHIA
    - Most parameters are non-reweightable
- Missing uncertainties





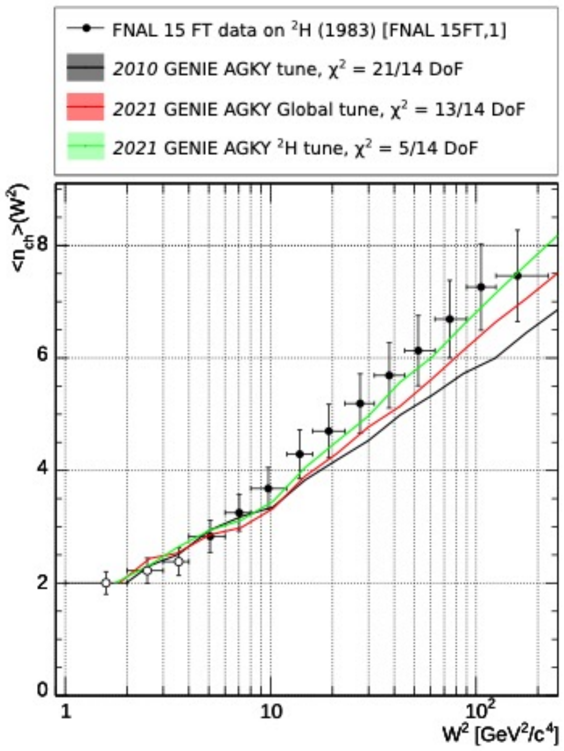


Tuning the AGKY Hadronization tune

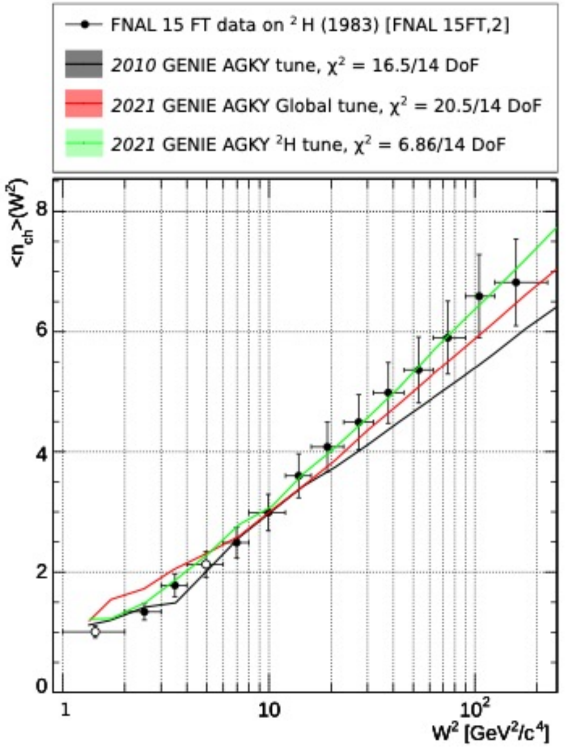
Fully exploiting the GENIE tuning machinery

- 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

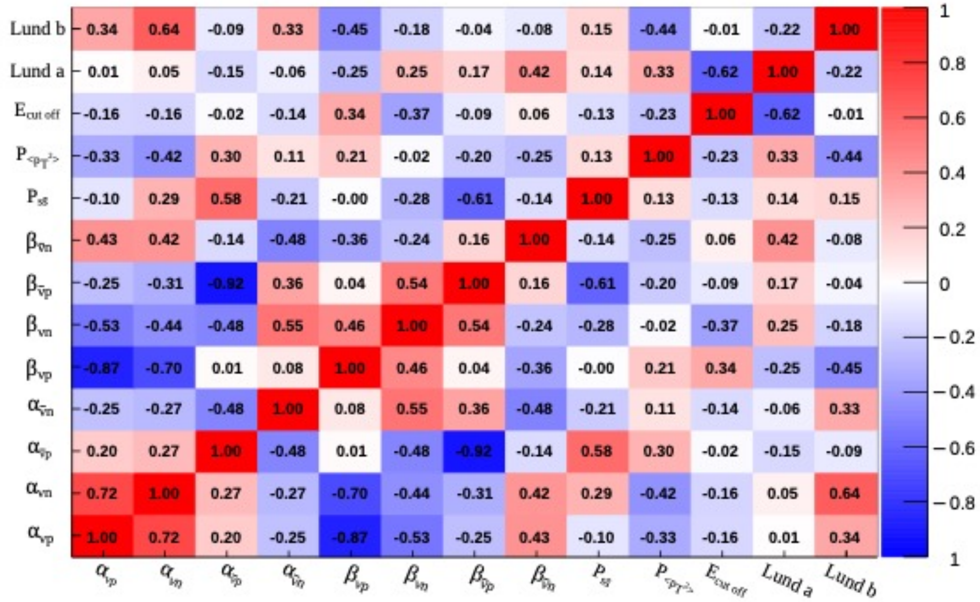
(*) How can we propagate this uncertainties?

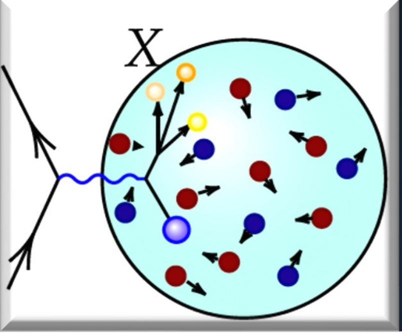


(b) $\nu_\mu + p \rightarrow \mu^- X^{++}$



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



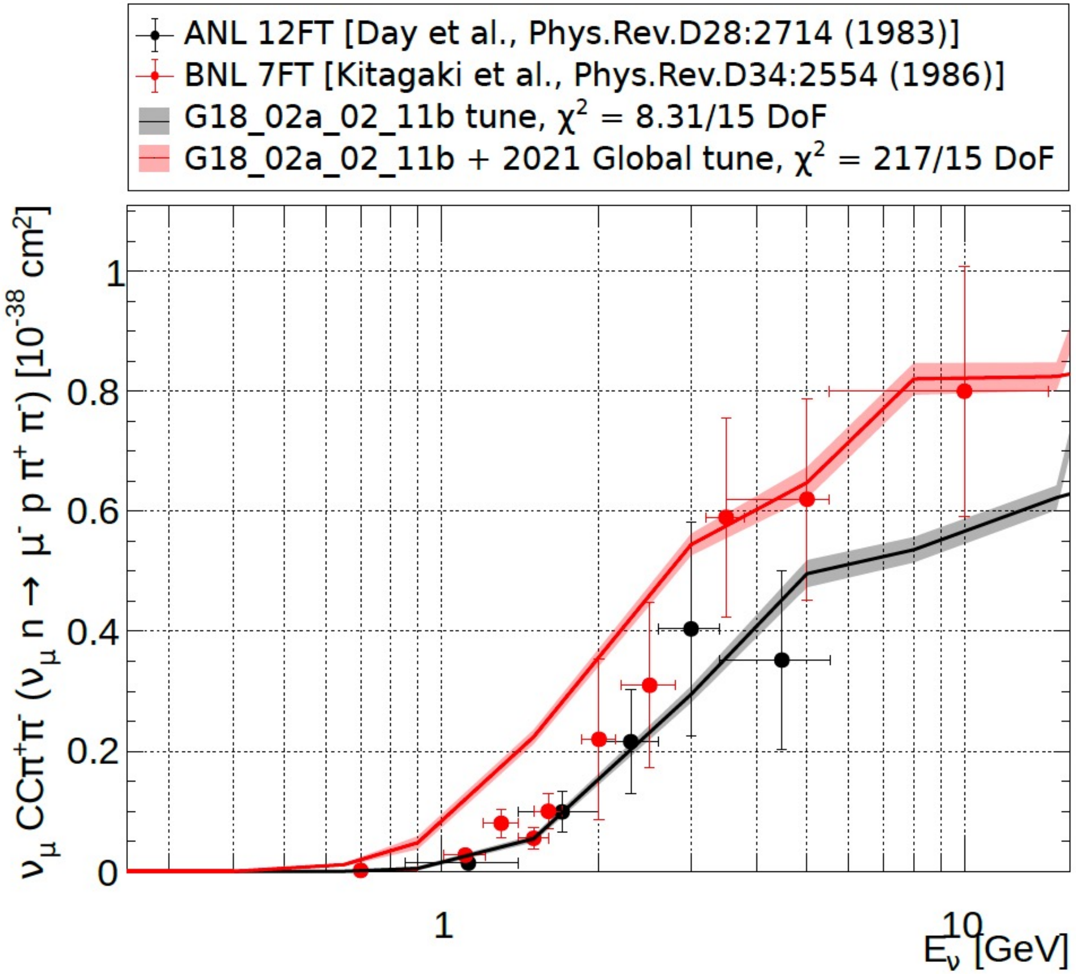


Tuning the AGKY Hadronization tune Factorization challenges

- The SIS region in GENIE is affected by low-W AGKY parameters
  - We simplified the problem into two separate tunes

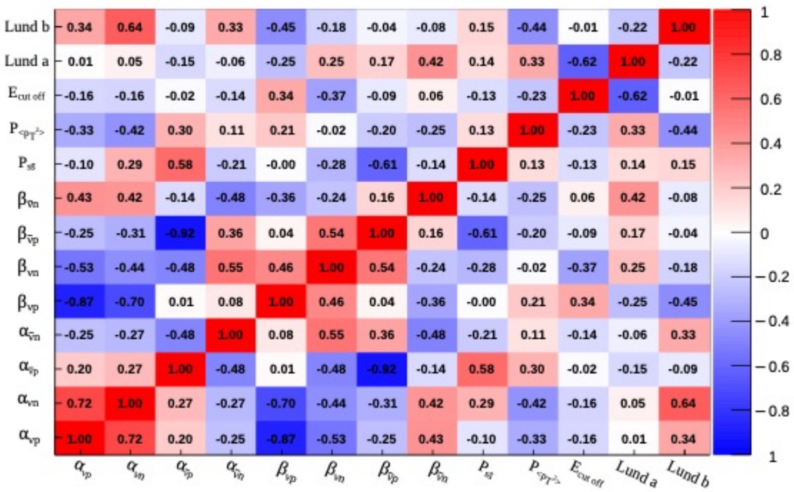
- The hadronization tune breaks the agreement at the SIS region!
  - The results suggest a SIS+hadronization tune would describe all νN data

- **Note:** Some models must be tuned altogether



Reweight & Professor

How can experiments further exploit the GENIE data-driven systematics in their analysis?



i.e. hadronization uncertainties

YOUR

ANALYSIS

Reweight & Professor

New effort to incorporate a Professor-based reweight scheme

- **Incorporates GENIE/Professor MC-response into the ReWeight framework**
  - Efficient brute-force MC scans of parameter phase-space are used to build the N-dimensional response function
  - MC-response function used for the weight calculation
- **Supports weights in multi-dimensional parameter spaces**
  - Various parameters can be tweaked simultaneously
- **Reweighting works for all MC parameters**
- **No need to write new reweight modules**
  - User and developer friendly
- **It will be built in existing GENIE-ReWeight package**
  - Neutrino experiments will be directly benefited from this tool
- This effort is lead by **Qiyu Yan** (UCAS & U.Warwick), **Marco Roda** (University of Liverpool) et. al.

Final Remarks

- **Tuning MC event generators with neutrino data is a complicated task**
  - Parameter choice might lead to tune degeneracies if the incorrect approach is used
  - Using data with “questionable” cross-section analysis will bias your results
    - You must consider missing systematic uncertainties
  - Correlation between data releases often ignored but key for the global tuning effort
- **Electron-scattering data is crucial for global tunes**
  - High statistics and well-known beam - same nuclear effects
  - Excellent on hydrogen and deuterium data to tune the SIS region
  - New E4Nu measurements will be crucial to tune e-A models
    - New pion-production measurements by the e4ν collaboration are coming up soon!
- **New Professor-based Reweight tool**
  - Neutrino experiments will be able to propagate GENIE’s data-driven uncertainties to their oscillation analysis

Thank you!

TEL AVIV UNIVERSITY אוניברסיטת תל אביב

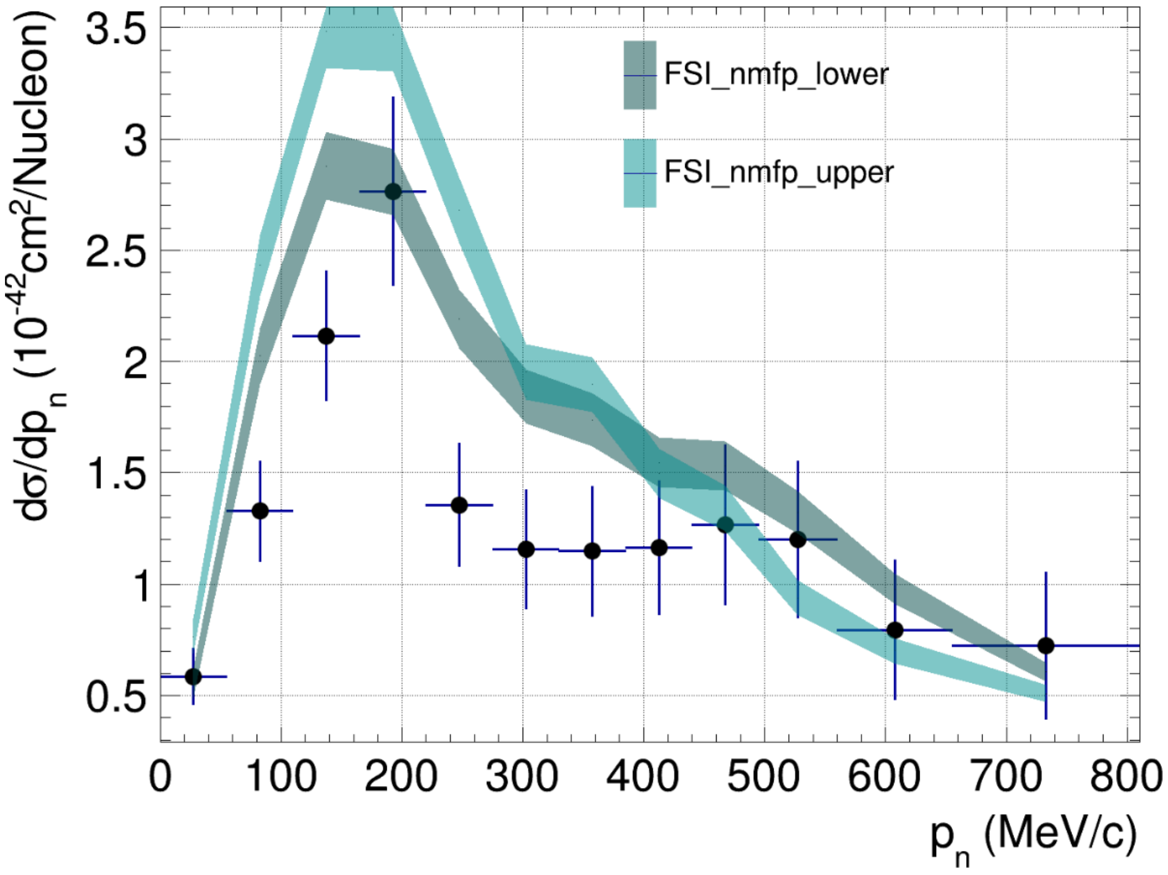
Genie

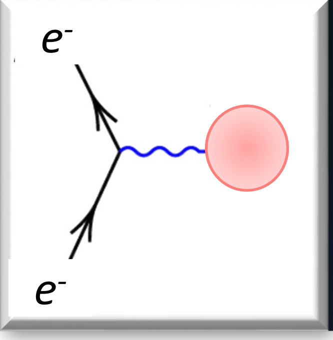
The TAU Neutrino Group

Complementary Slides

TKI tune with CC0π and CC1π data from MINERvA and T2K (Weijun Li, M.Roda, Xianguo Lu, C.Andreopoulos, J. Tena-Vidal)

- MINERvA $\nu_\mu CCNp0\pi$ (2020) [https://doi.org/10.1103/PhysRevD.101.092001]
- MINERvA $\nu_\mu CC\pi0$ (2020) [10.1103/PhysRevD.102.072007]
- T2K $\nu_\mu CC0\pi$ (2018) [10.1103/PhysRevD.98.032003]
- T2K $\nu_\mu CCNp1\pi$ [10.1103/PhysRevD.103.112009]





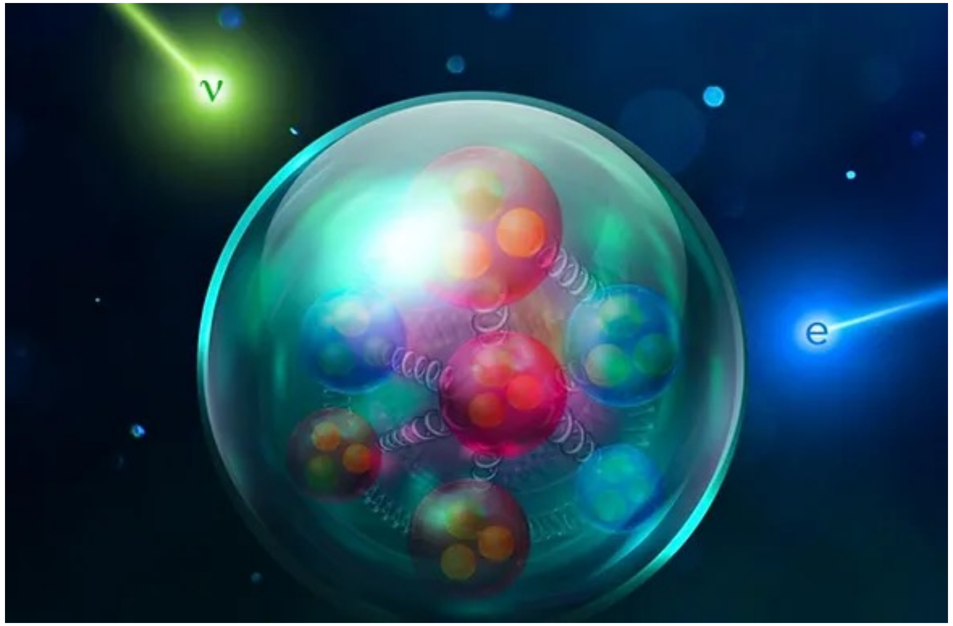
GENIE global tuning approach
Importance of electron-scattering data

Benefits:

- Known beam energy
- High statistic measurements
- Many available inclusive measurements
- Neutrino-like exclusive measurements available by the e4ν collaboration

Can constrain:

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



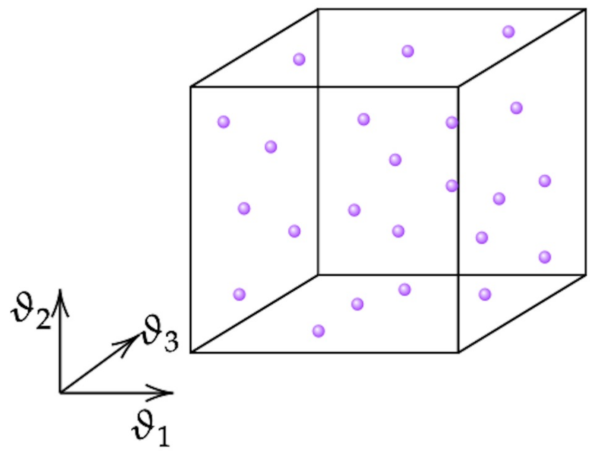
Sampling of the phase-space GENIE-Professor

- 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

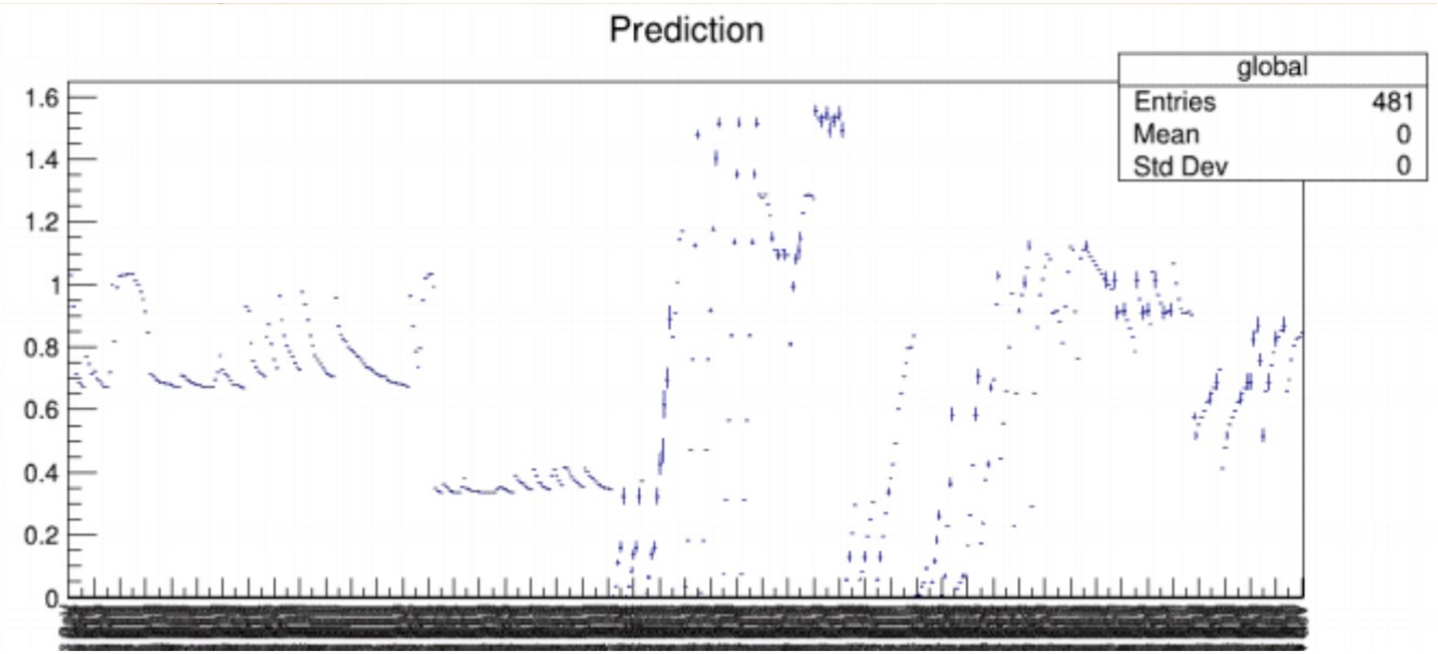
N_ϑ dimensions phase-space



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)

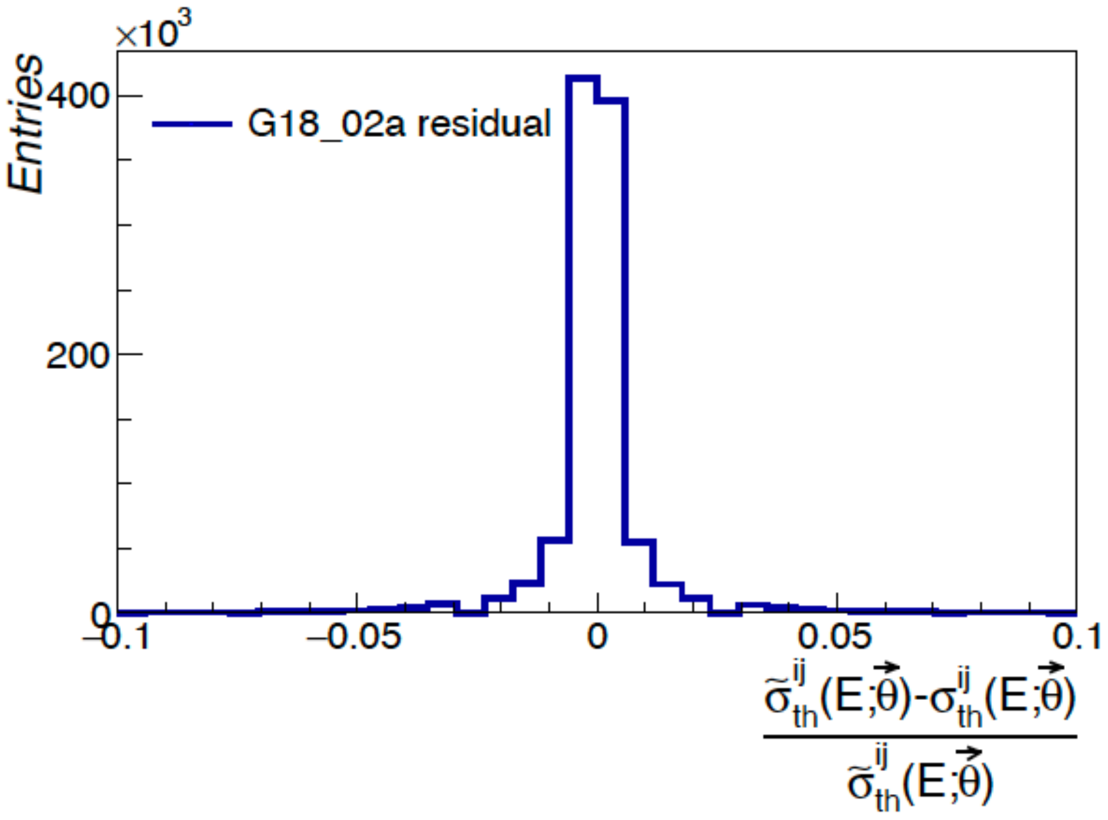
Definition of Observable GENIE-Professor

- 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



Empirical aspects of the GENIE event generator

Data-driven models

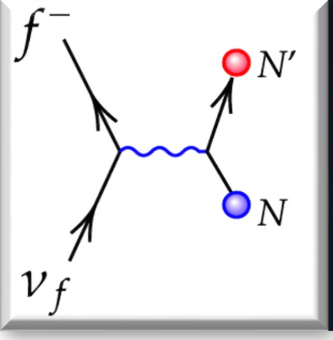
- **Parameterization of vector and axial QEL and RES form factors**
  - Fits to e-N and ν-N data
- **Low-W AGKY Hadronization**
  - "Tuned" to ν-N data
- **GENIE hA 2018**
  - Fates and mean-free-path
- **Ground state model**
  - Binding-energy
  - High-momentum tail fraction

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

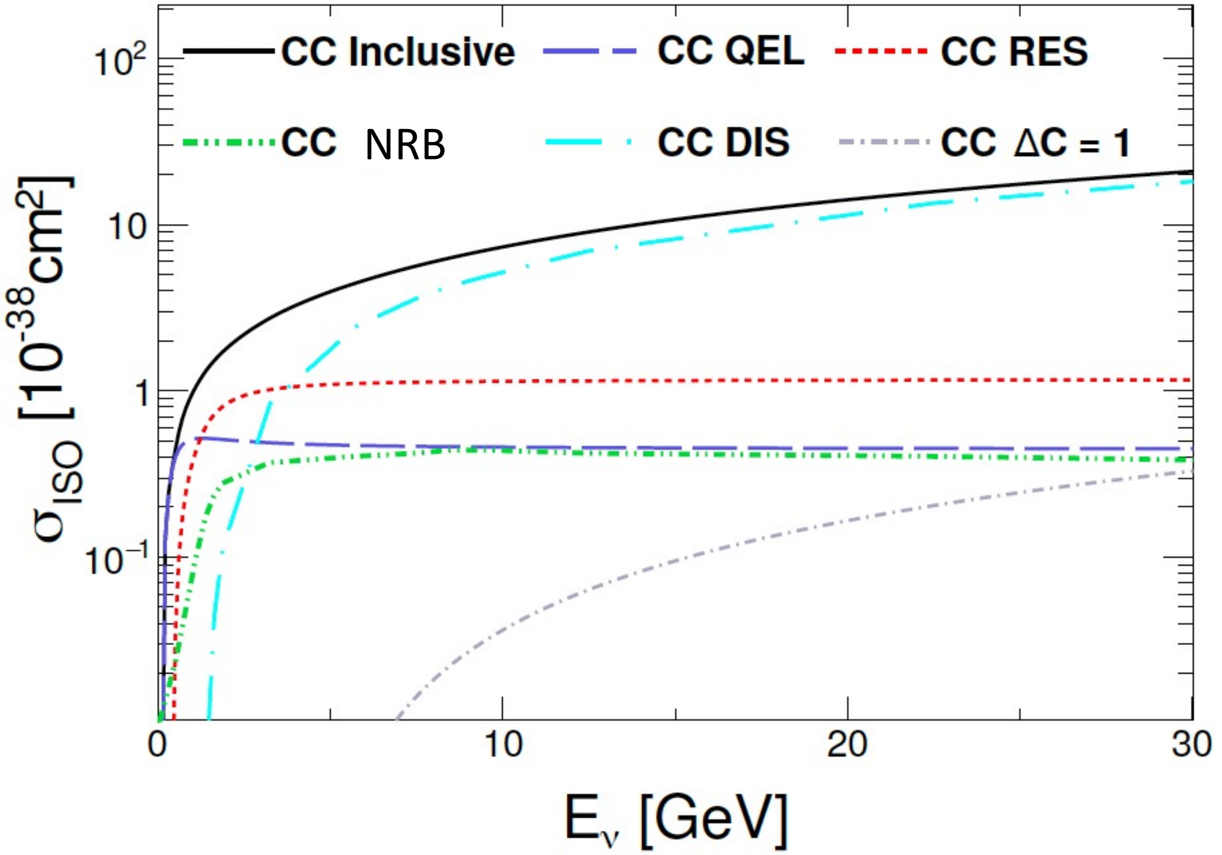
Inclusive cross-section models

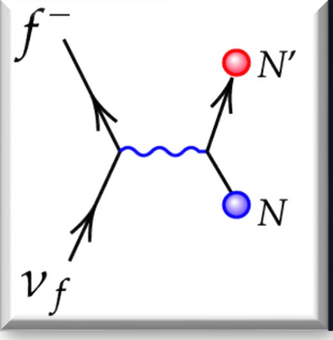
- Lepton kinematics only
- **2p2h inclusive models:**
  - Valencia and SuSAv2
  - Theory-driven models
  - Pre-computed hadron tensors for isoscalar nuclei
  - Used in exclusive final-states
- **π kinematics:**
  - Rein-Sehgal and Berger-Sehgal RES models
  - π-kinematics after decay



Tuning of $\nu - N$ interaction models

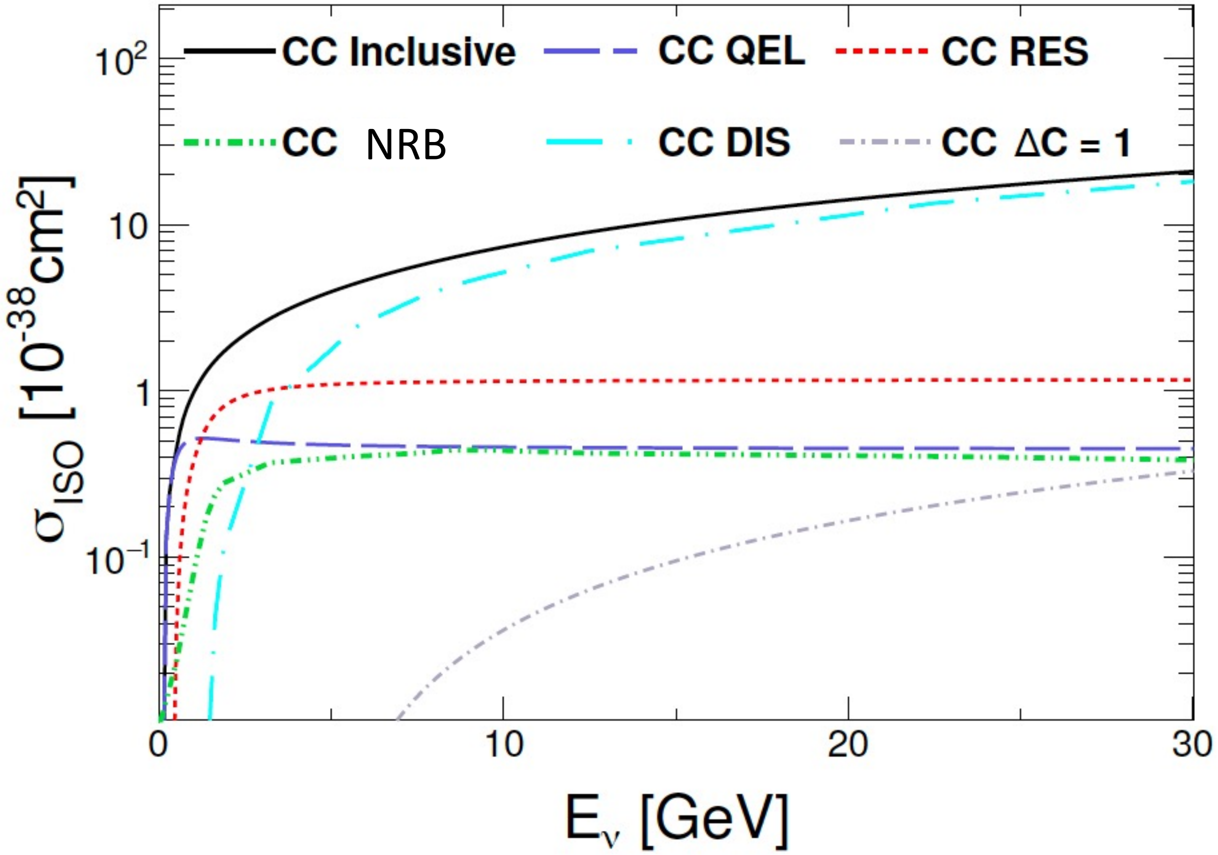
- ν-N models are crucial to describe ν-A interactions
  - Starting point for ν-A simulations
- Quasi-elastic is relatively well understood
  - Llewellyn-Smith model
  - Inputs from neutrino, electro-scattering and beta decay experiments
- Deep-Inelastic Scattering:
  - Bodek and Yang model
  - Cross-section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

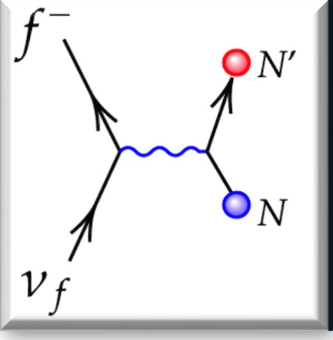




Tuning of $\nu - N$ interaction models

- 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





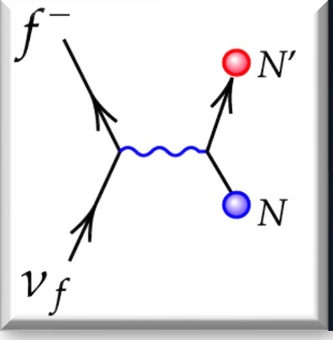
$\nu - N$ Shallow-Scattering Inelastic region

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

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

Free parameters



$\nu - N$ Shallow-Scattering Inelastic region

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

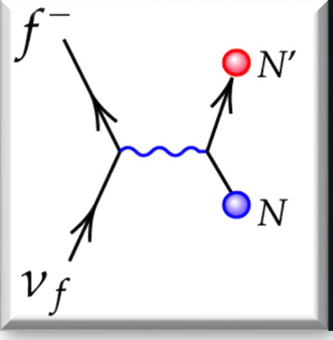
  "On average, the RES cross section is described by the DIS cross section at W<2 GeV"
- We use the DIS prediction to account for the missing NRB model
  - Tuning is essential to avoid double-counting
- NRB modelled with Bodek and Yang extrapolated at $W < W_{cut}$
- f_m parameters **couple** with the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

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

Free parameters



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:

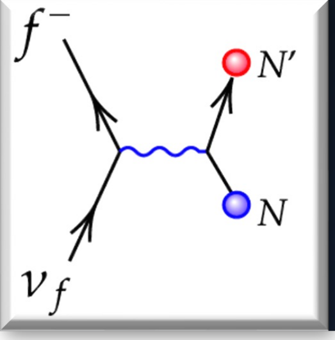
- S_{DIS}: overall scaling factor for DIS cross-section
- Prior of 1±0.5 to preserve agreement with high E data (>100GeV)

QEL model parameters:

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

Normalization uncertainty:

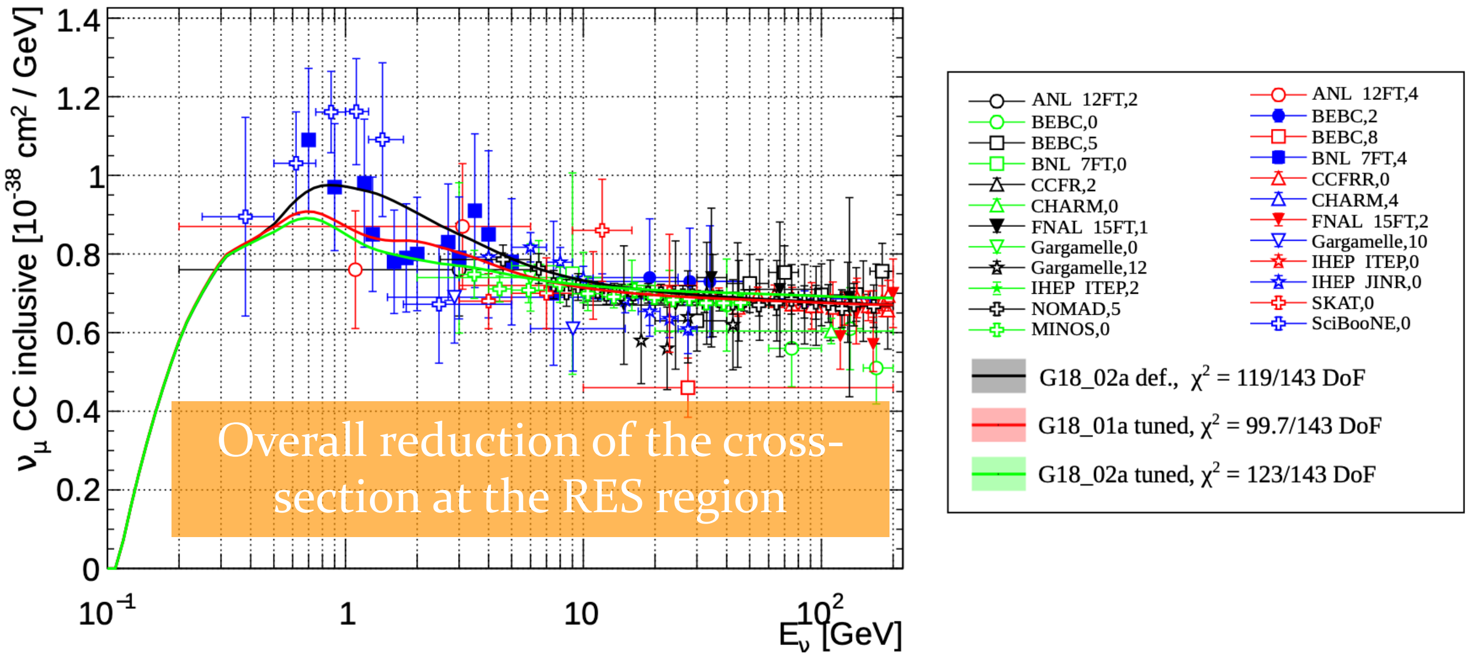
- Nuisance parameters per experiment to account for missing normalization uncertainties



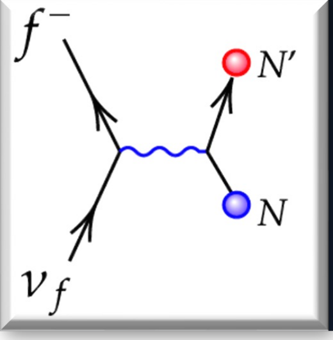
Tuning the Shallow-Scattering Inelastic region

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
$R_{\nu p}^{CC2\pi}$	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.

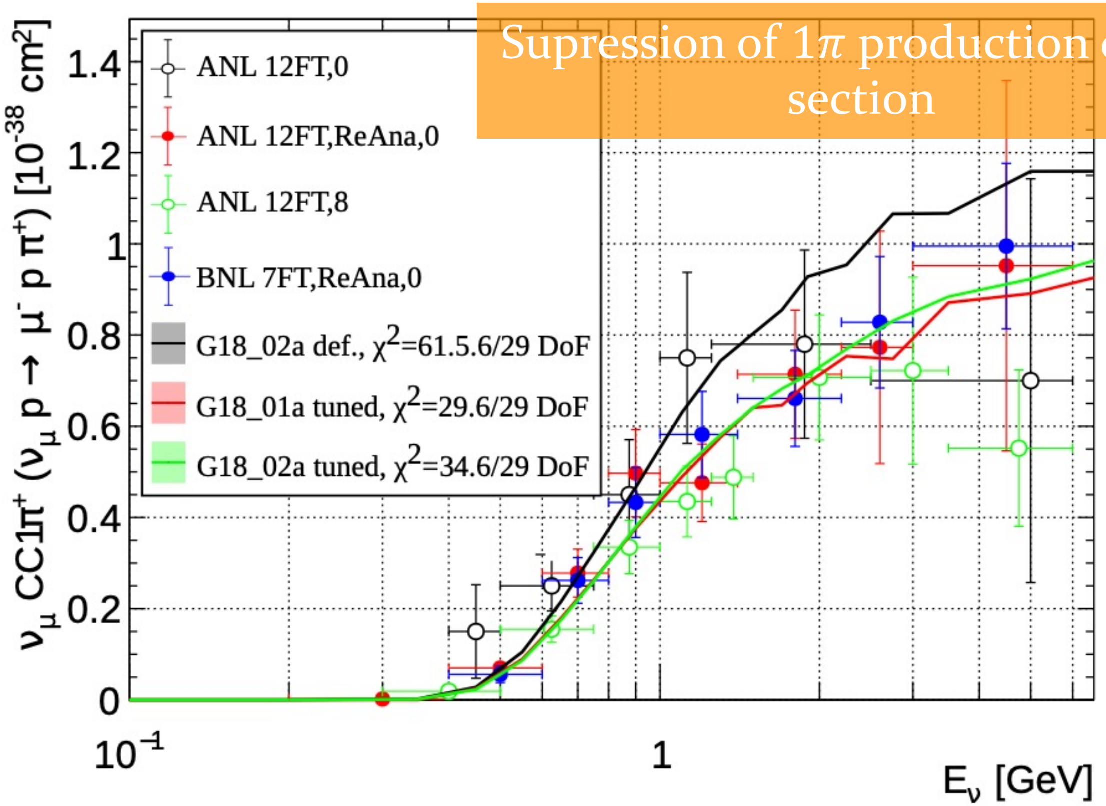


Tuning the Shallow-Scattering Inelastic region

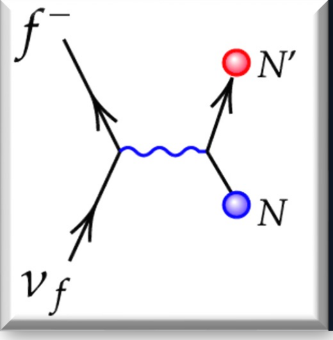
PhysRevD.104.072009

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

Supression of 1π production cross-section



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

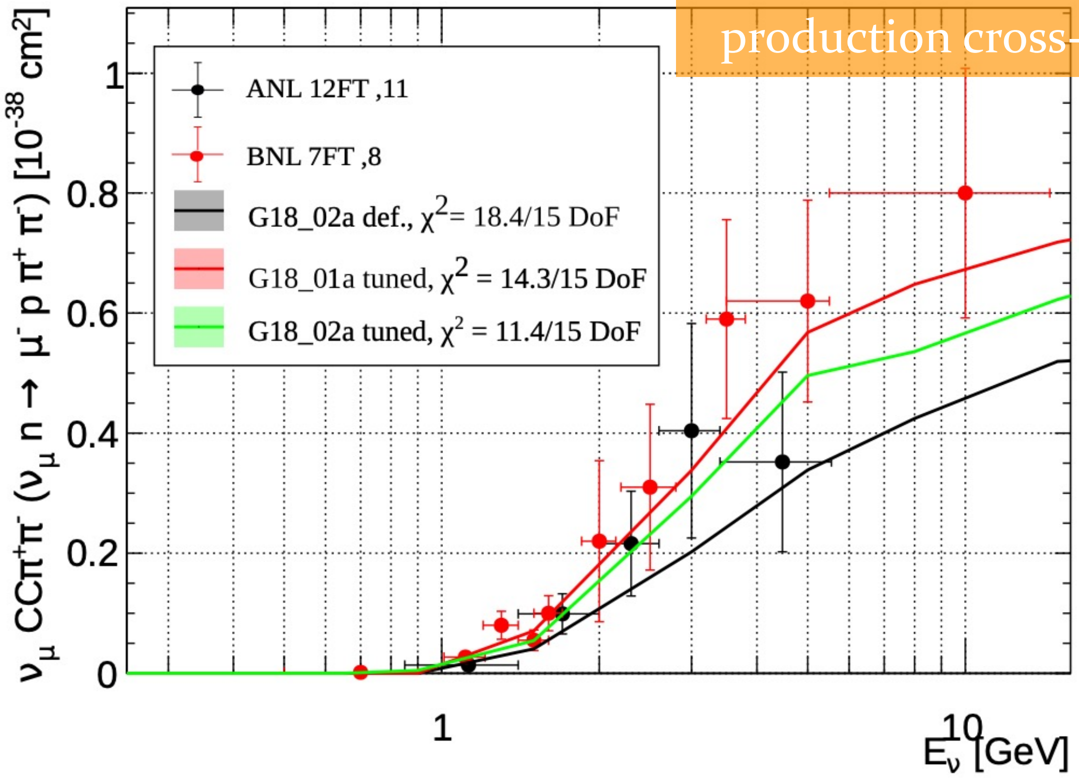


Tuning the Shallow-Scattering Inelastic region

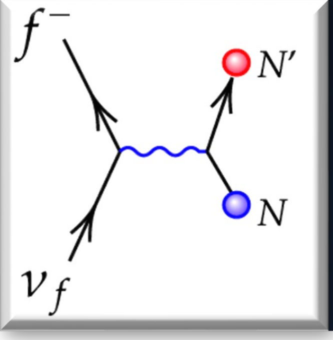
PhysRevD.104.072009

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
W_{cut}	**1.7**	**1.81**
$\chi^2/157DoF$		1.64

Enhancement of 2π production cross-section

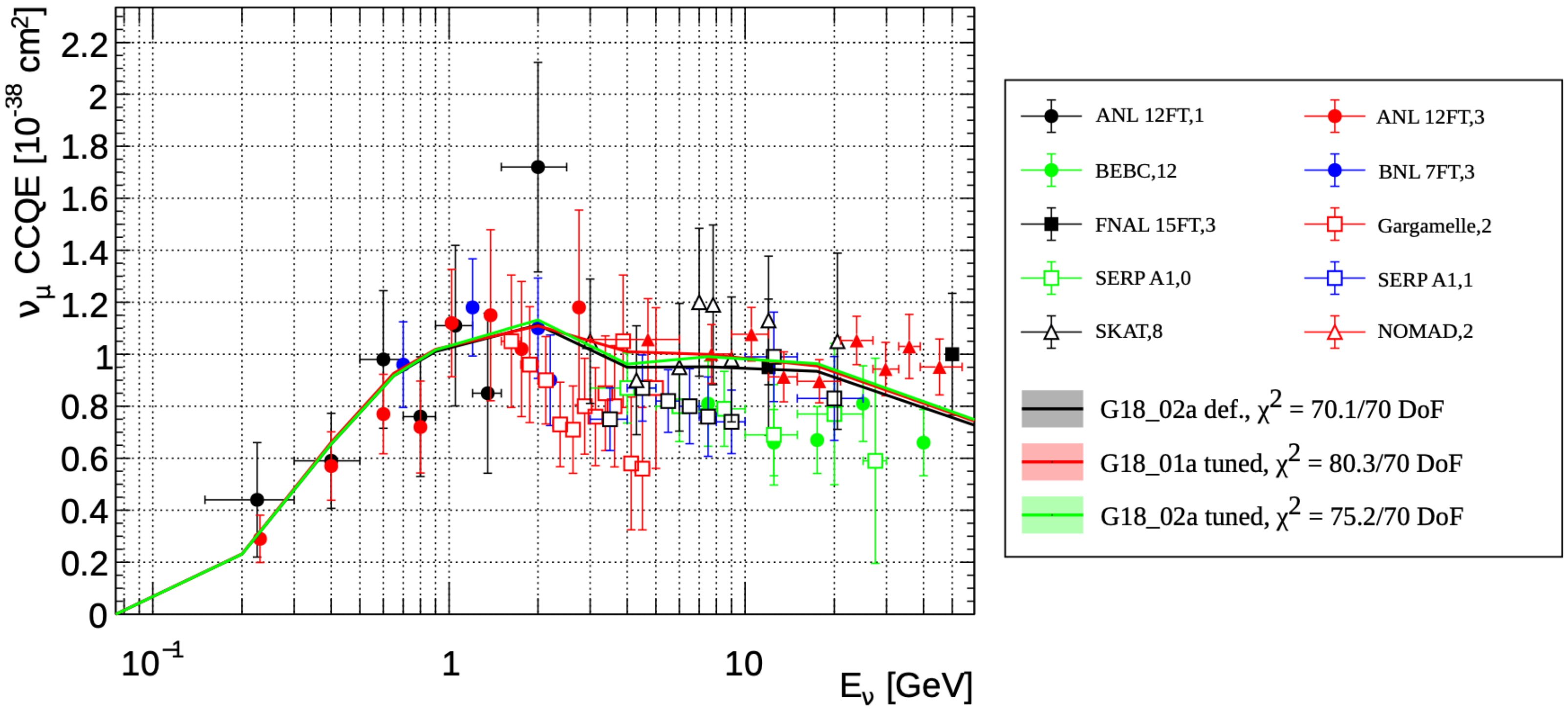


(c) Comparison of ν_μ CC $\pi^+\pi^-$ data on neutron.

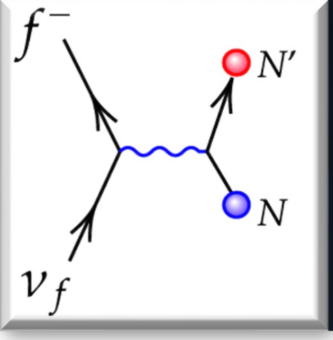


Tuning the Shallow-Scattering Inelastic region

PhysRevD.104.072009

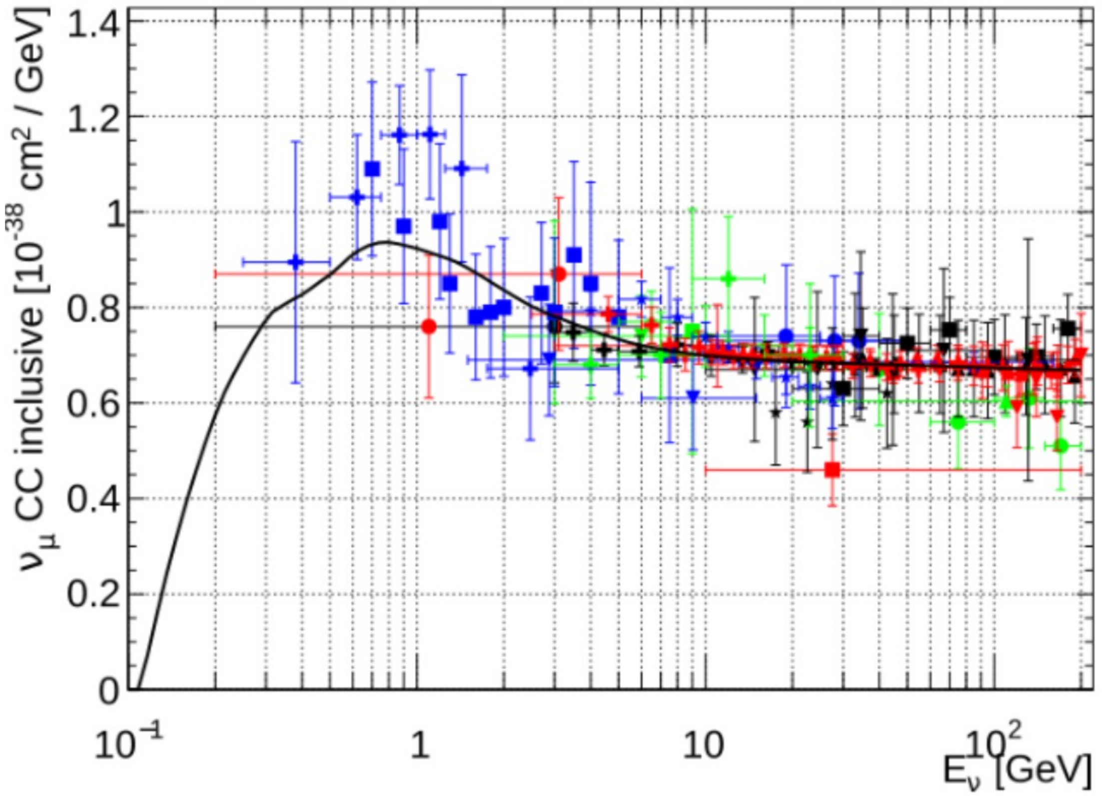


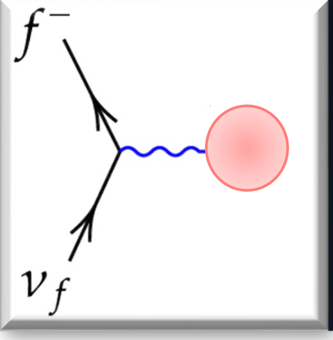
(a) Comparison of ν_μ CC quasi-elastic cross-section data against the *default* and tuned CMCs.



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**





Tuning of $\nu - A$ interaction models

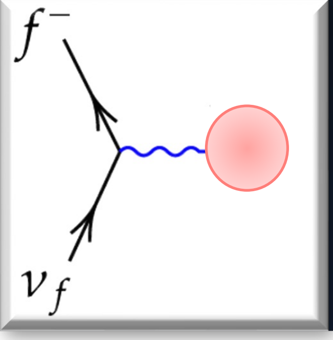
PhysRevD.104.072009

The nuclear environment further complicates the picture:

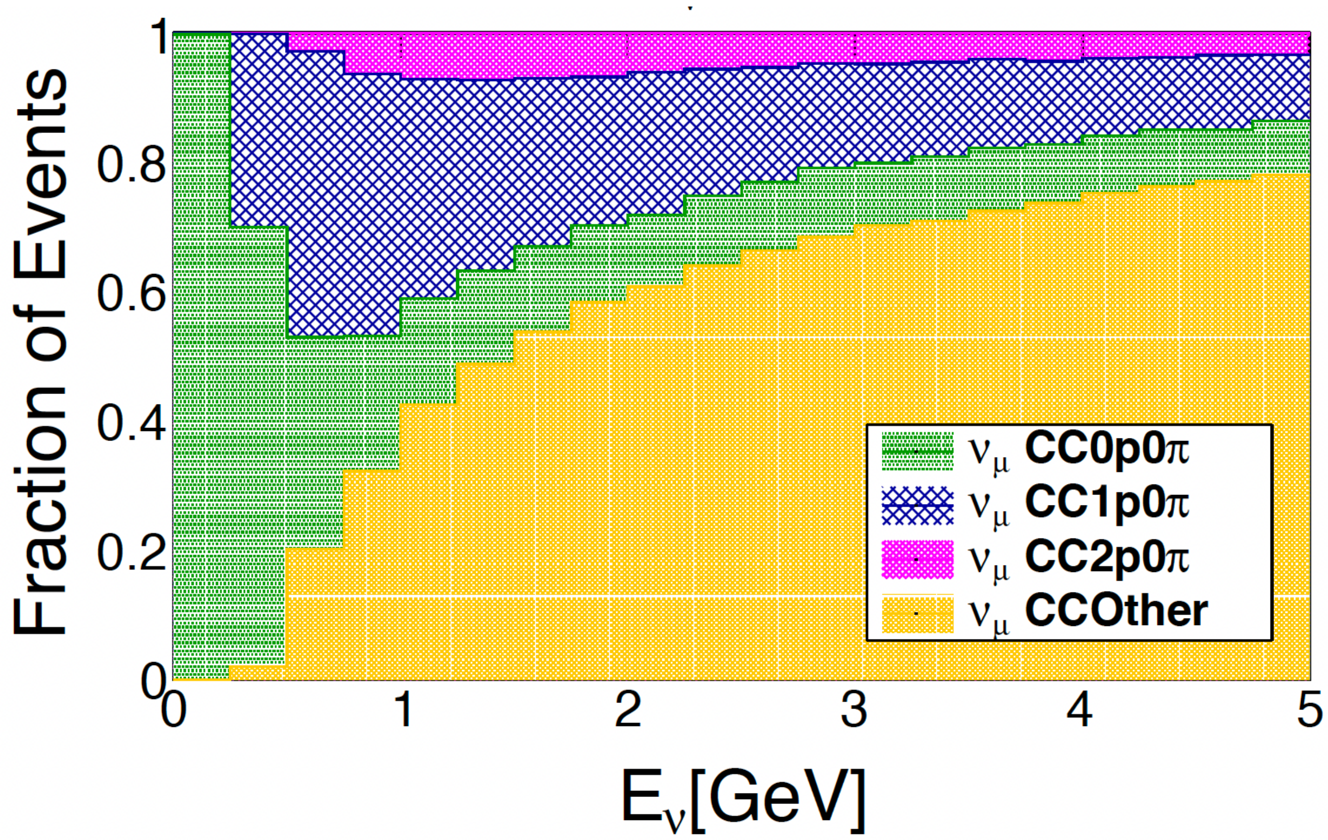
GENIE ν-A model models	
Nuclear model	**Local Fermi Gas**, Bodek-Ritchie Fermi Gas, Correlated Fermi Gas
QEL model	**Valencia**, SuSAv2
RES model	**Berger-Sehgal**, Rein-Sehgal, MK model (*)
MEC model	**Valencia**, Empirical MEC, SuSAv2
DIS model	**Bodek-Yang**
FSI model	**hA**, hN, INCL++, GEANT

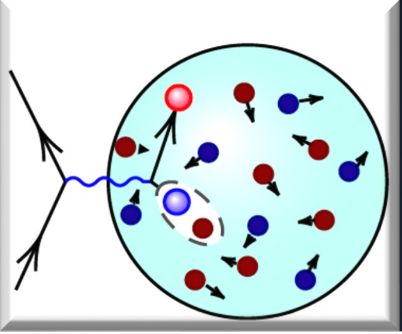
(*) Under internal review. Single-pion production model

G18_10a_02_11b



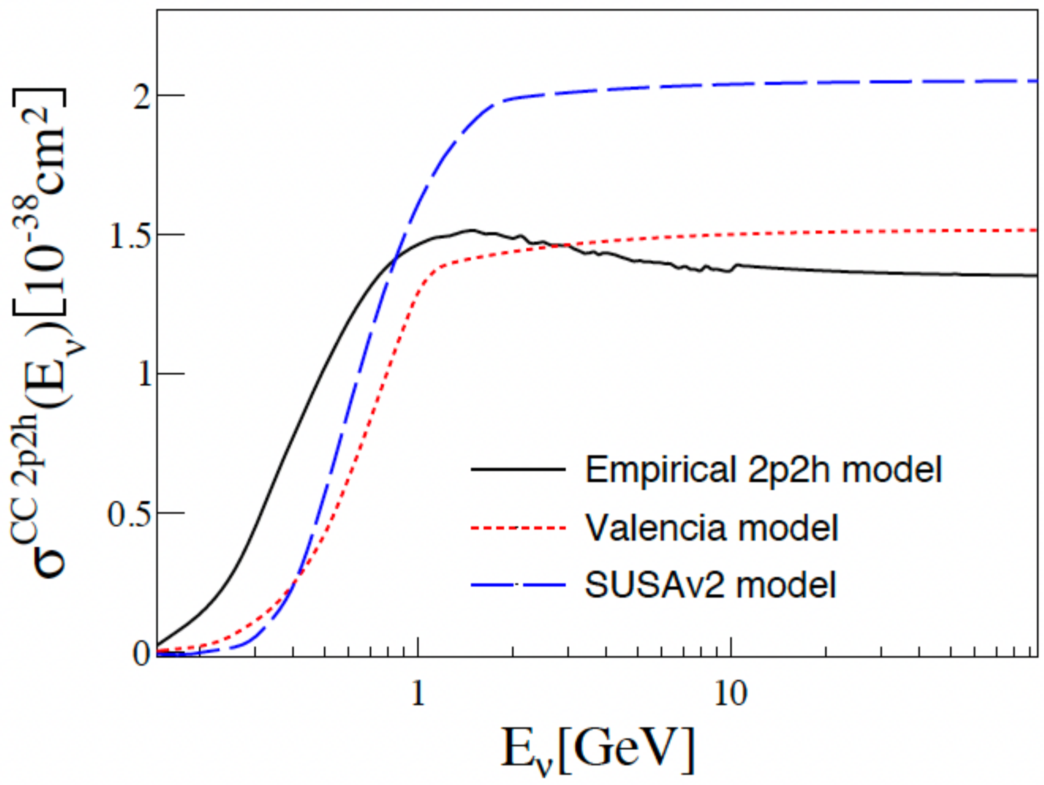
Neutrino-nuclei interactions



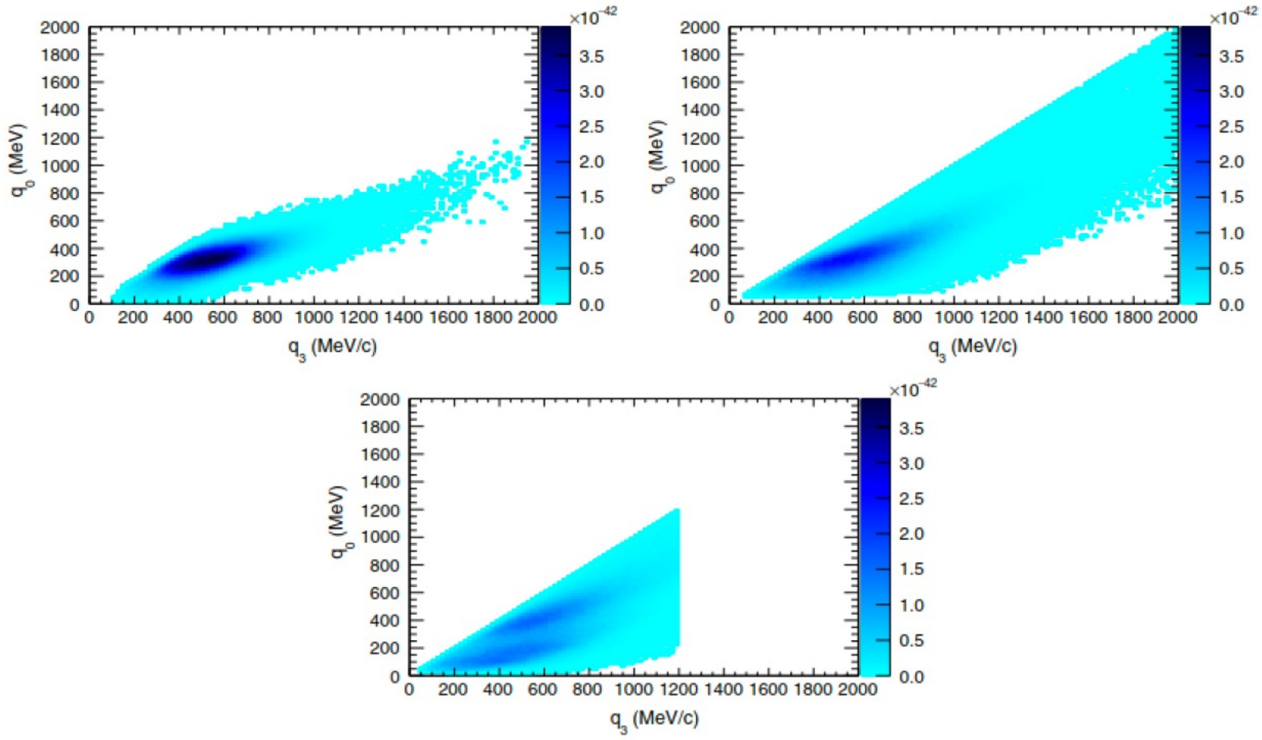


Multi-nucleon mechanisms tuning

Models differ in normalization



and shape

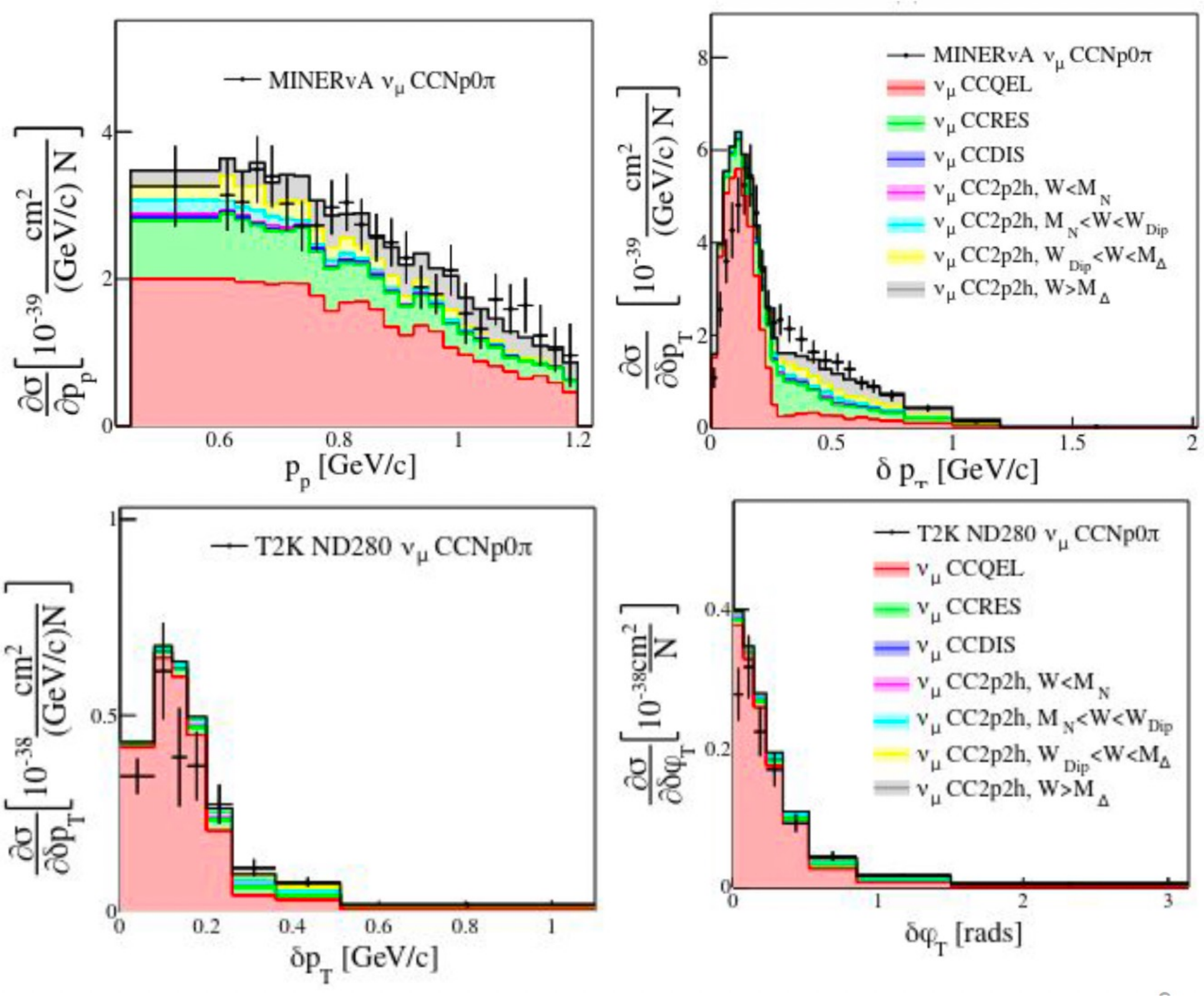


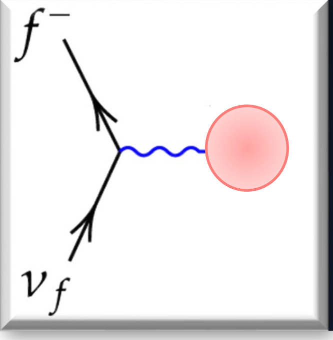
(b)

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

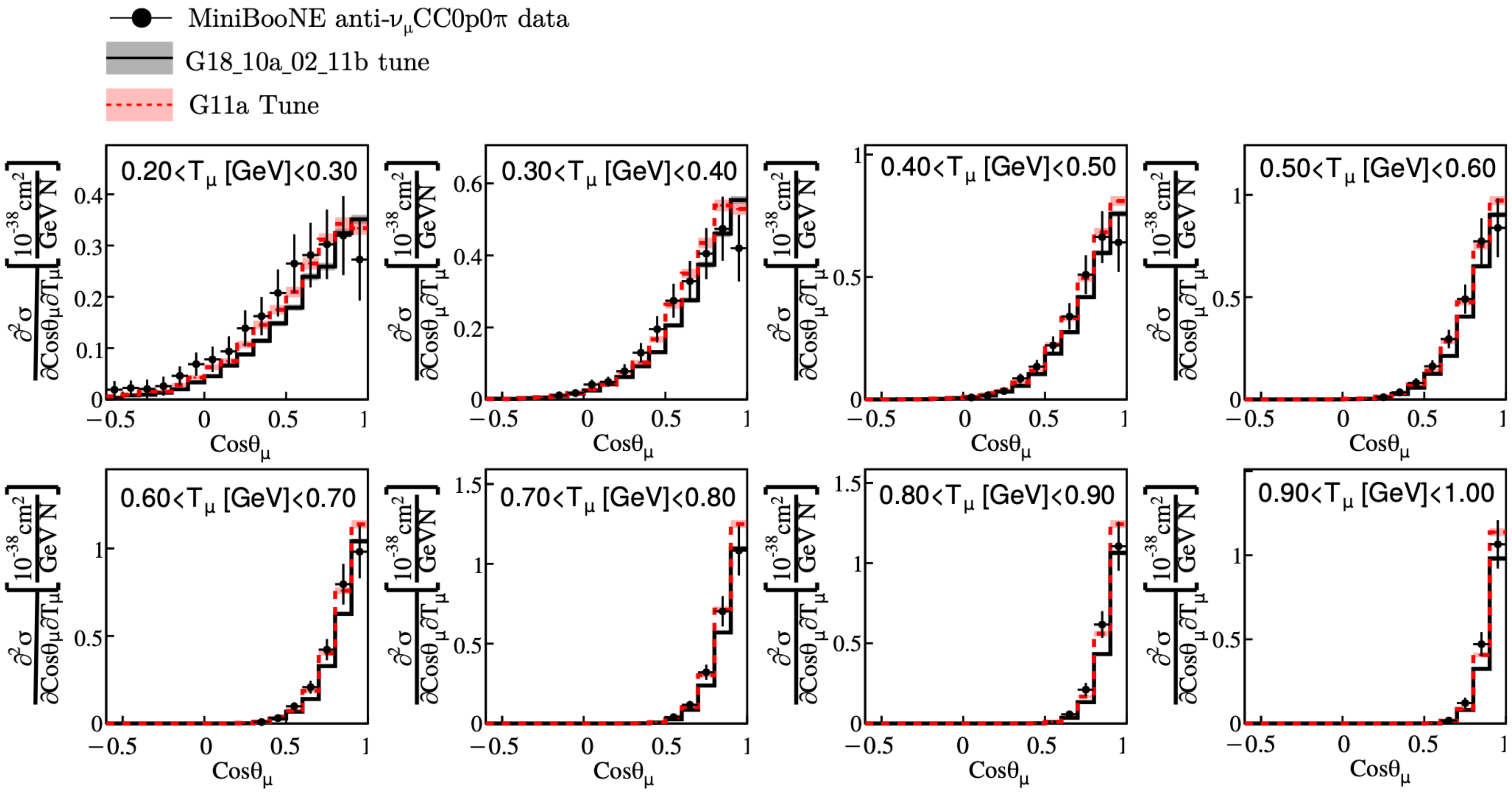


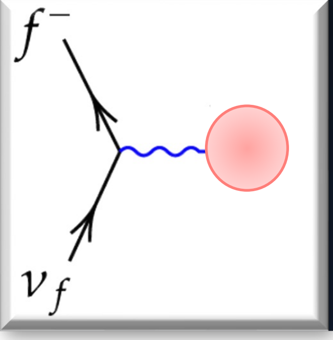


Tuning of $\nu - A$ CC0π interaction models Results

PhysRevD.104.072009

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

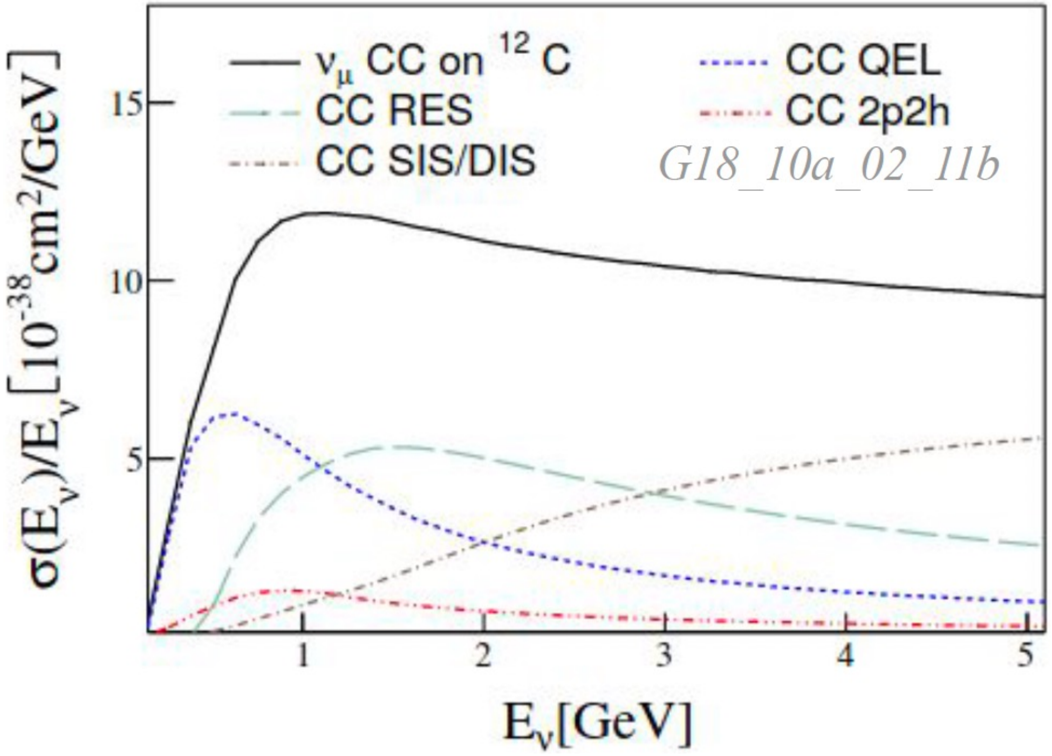


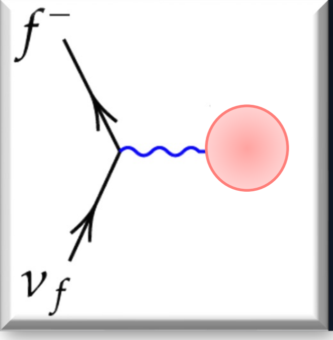


Tuning of $\nu - A$ CC$o\pi$ interaction models

PhysRevD.104.072009

- 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 CC$o\pi$ samples
  - Hard to constrain with only CC$o\pi$ data





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

PhysRevD.104.072009

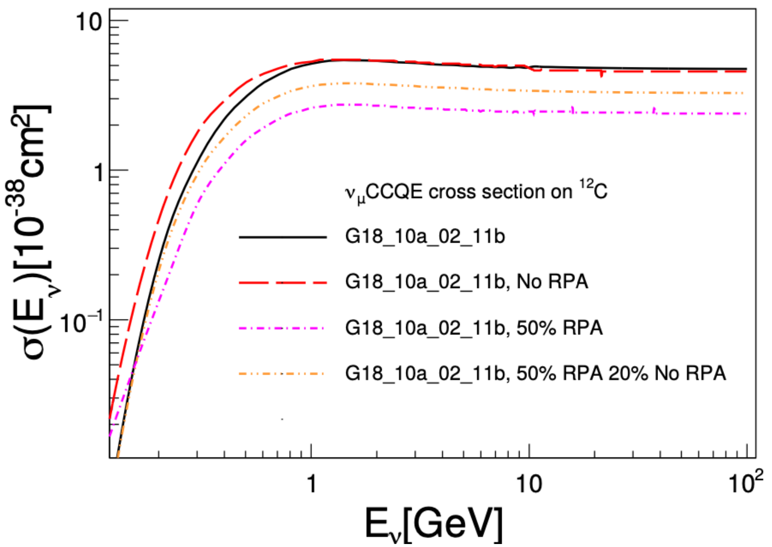
At the free nucleon level, the QEL cross section is well understood:

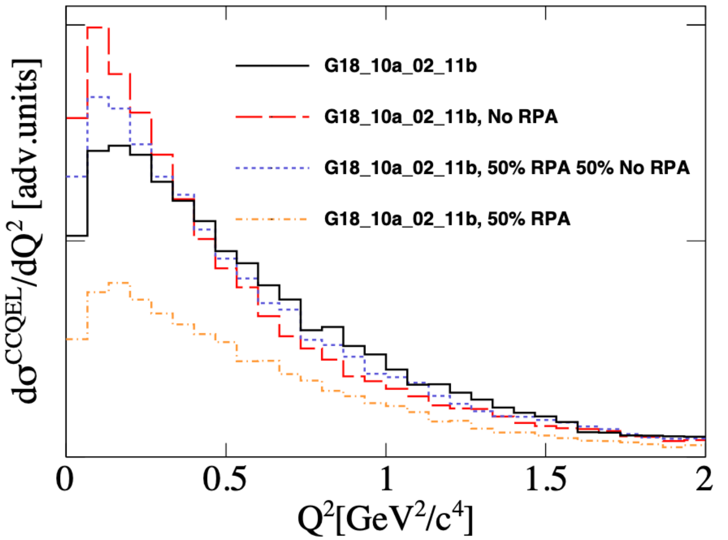
- Base model tuned to hydrogen and deuterium data
- Using correlated priors from free nucleon tune to constrain $\boldsymbol{M_A^{QEL}}$ and $\boldsymbol{S_{RES}}$

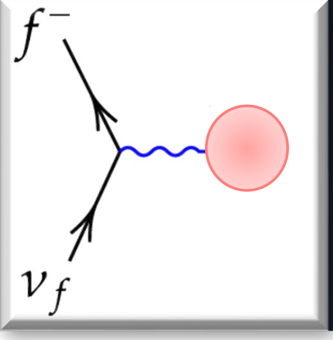
Two additional parameters:

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

- 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)

PhysRevD.104.072009

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

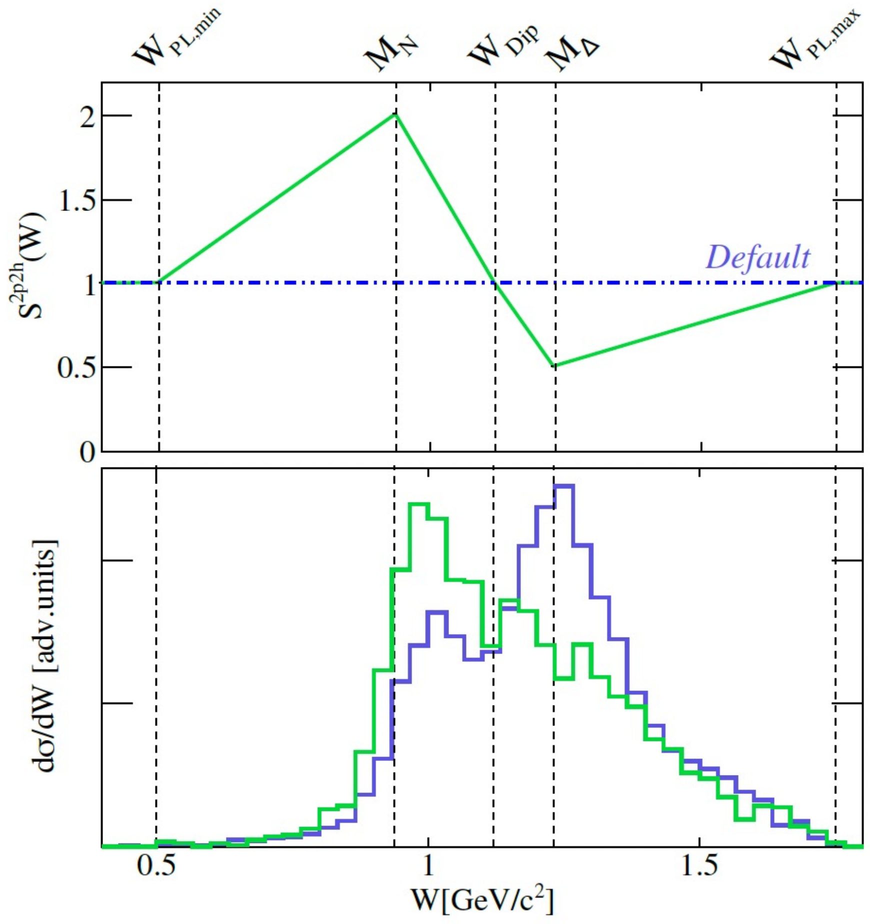
- Pre-computed hadron tensor tables on a grid of q_0-q_3
- No direct access to theory-parameters from GENIE

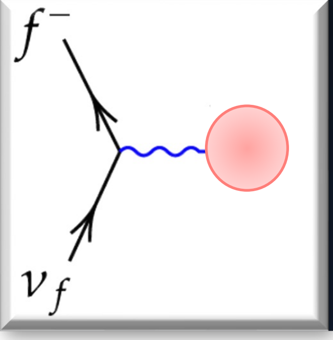
We add an **ad-hoc parameteriz**ation to add variation to the model

- 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:

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

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





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

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

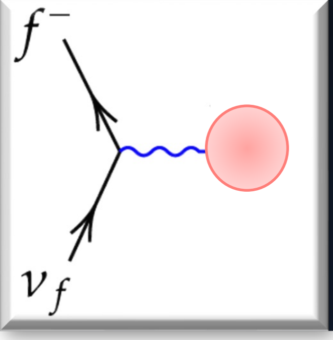
G11a: MiniBooNE $\bar{\nu}_\mu$ CC0π

G20a: T2K ND280 ν_μ CC0p0π

G30a: MINERvA ν_μ CC0π

G31a: MINERvA $\bar{\nu}_\mu$ CC0p0π

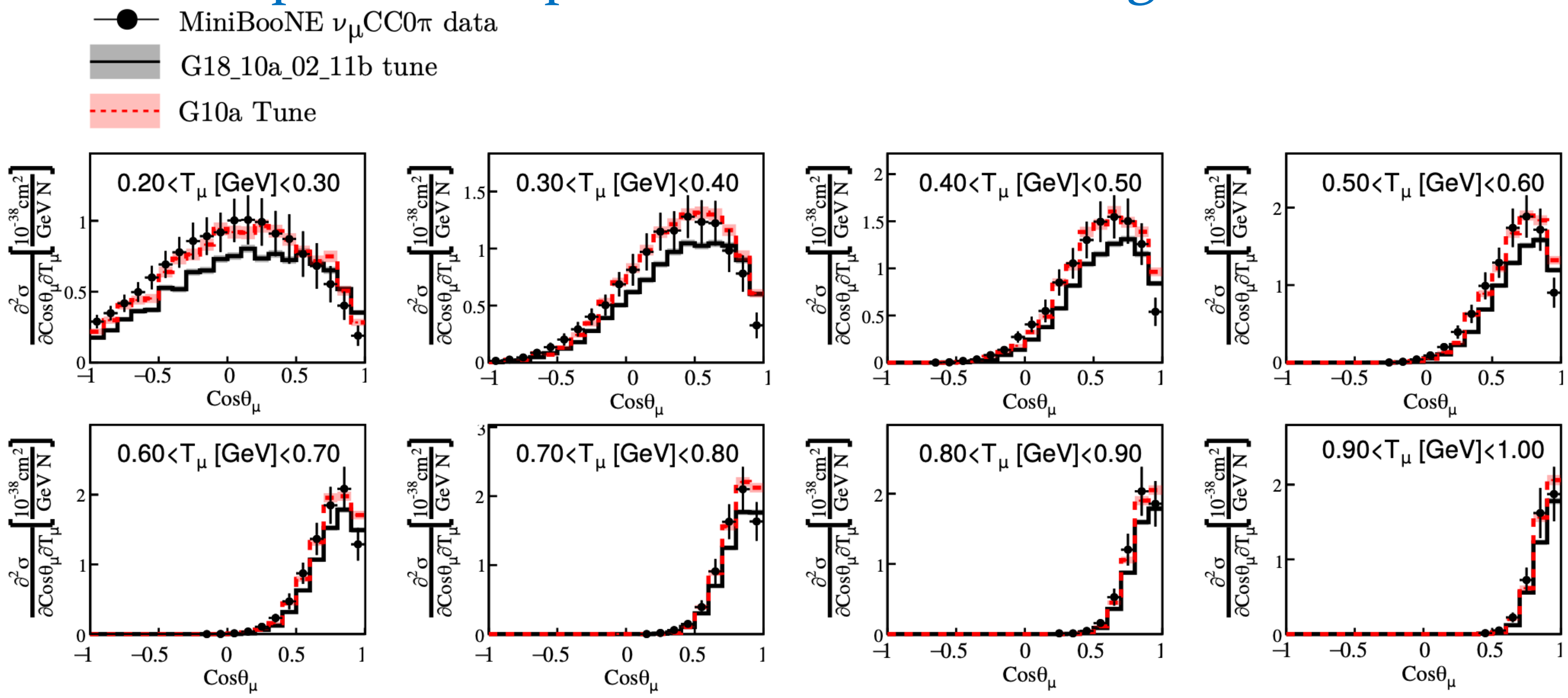
Parameters	G10a Tune	G11a Tune	G20a Tune	G30a Tune	G31a Tune
$M_A^{\mathrm{QEL}}(\mathrm{GeV/c^2})$	1.02 ± 0.01	1.01 ± 0.01	1.00 ± 0.01	1.00 ± 0.02	1.00 ± 0.01
ω_{RPA}	1.20 ± 0.03	1.14 ± 0.06	1.2 ± 0.2	0.9 ± 0.1	1.3 ± 0.2
$\omega_{\mathrm{No\,RPA}}$	0.05 ± 0.02	0.09 ± 0.05	-0.1 ± 0.1	0.2 ± 0.1	0.2 ±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

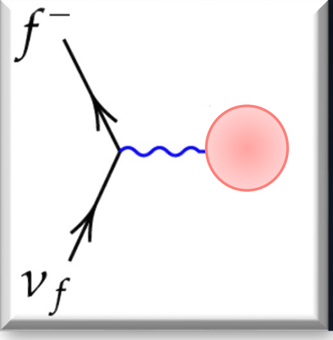


Tuning of $\nu - A$ CC0π interaction models Results

PhysRevD.104.072009

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





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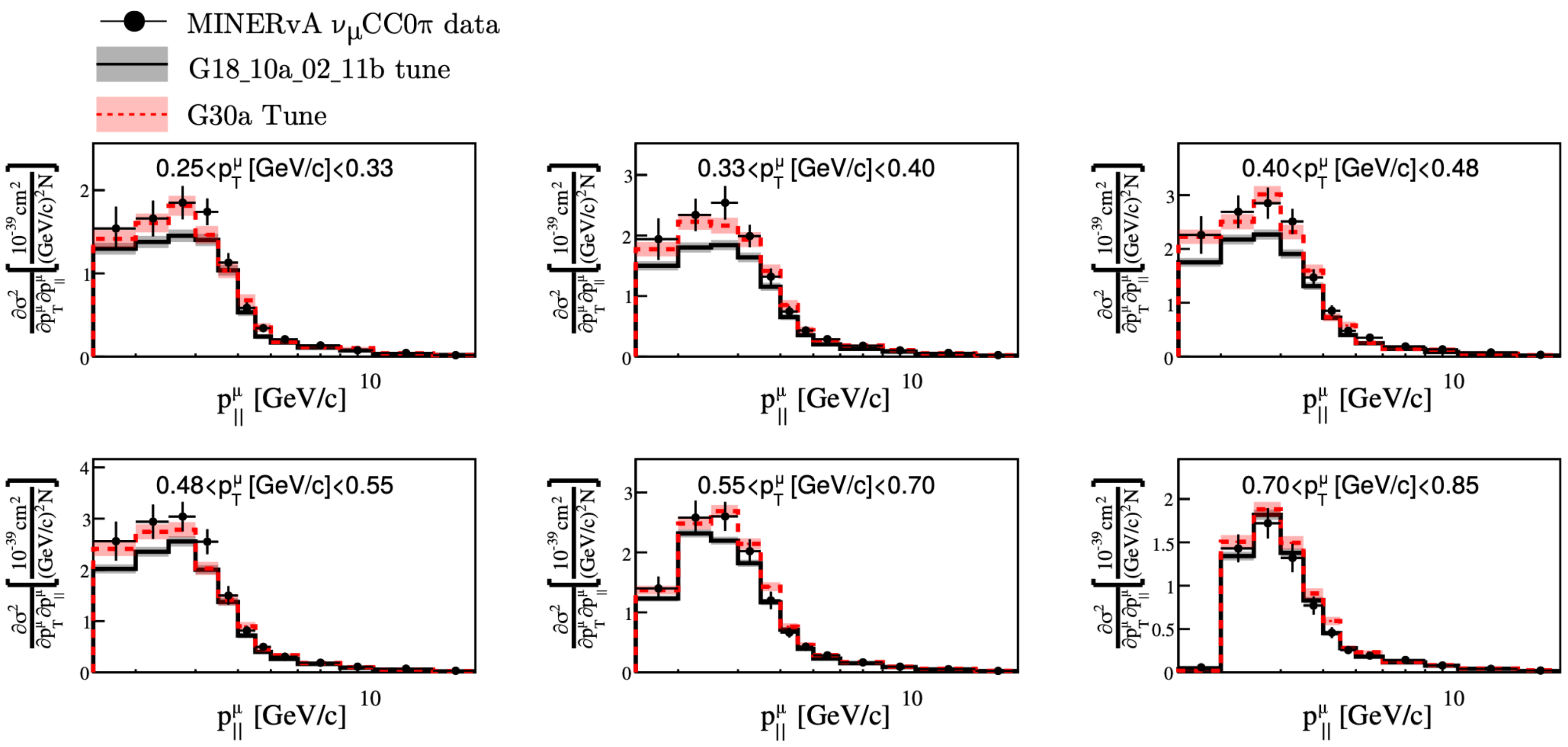

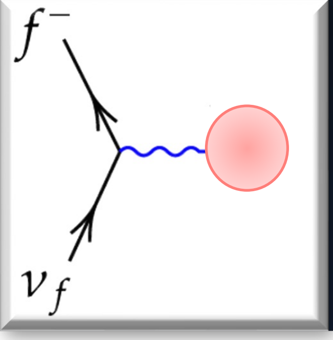

Tuning of $\nu - A$ CC0π interaction models Results

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G10a: MiniBooNE ν_μ CC0π

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G20a: T2K ND280 ν_μ CC0p0π

G30a: MINERvA ν_μ CC0π

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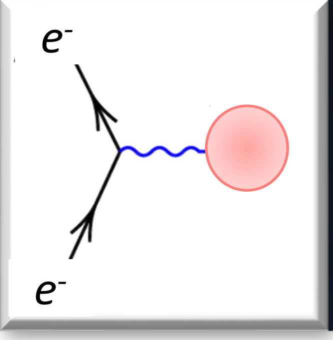
Parameters	G10a Tune	G11a Tune	G20a Tune	G30a Tune	G31a Tune
$M_A^{\rm QEL}$(GeV/c^2)	1.02 ± 0.01	1.01 ± 0.01	1.00 ± 0.01	1.00 ± 0.02	1.00 ± 0.01
$\omega_{\rm RPA}$	1.20 ± 0.03	1.14 ± 0.06	1.2 ± 0.2	0.9 ± 0.1	1.3 ± 0.2
$\omega_{\rm No\,RPA}$	0.05 ± 0.02	0.09 ± 0.05	-0.1 ± 0.1	0.2 ± 0.1	0.2 ± 0.2
$S_{\rm RES}$	0.85 ± 0.02	0.86 ± 0.05	0.84 ± 0.02	0.84 ± 0.03	0.84 ± 0.02
$S_N^{\rm 2p2h}$	1.5 ± 0.4	2.3 ± 0.01	1.7 ± 0.3	1.2 ± 0.4	1.7 ± 0.5
$S_\Delta^{\rm 2p2h}$	0.7 ± 0.2	0.7 ± 0.3	(1.00)	2.1 ± 0.2	2.3 ± 0.2
$S_{PL}^{\rm 2p2h}$	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

Differences:

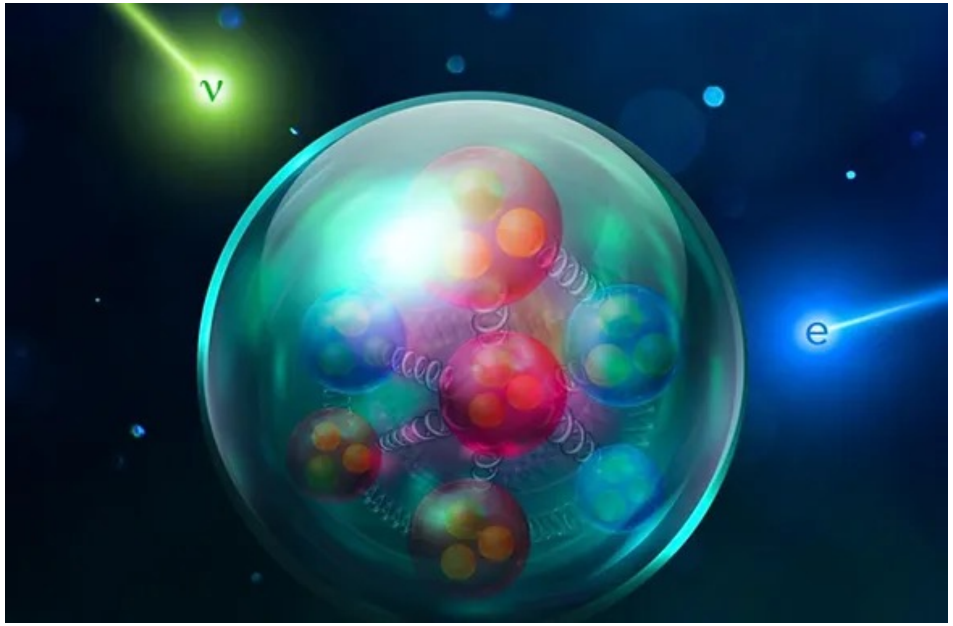
- MiniBooNE + T2K enhance MEC at $W = M_N$
- MINERva's tunes enhance both MEC peaks
- **Clear energy dependence on cross section shape**
- **Anti-neutrino tunes predict a higher cross-section**
- Same observations by recent MINERvA measurements using high energy beam



Tuning of e $-A$ interaction models

Complications:

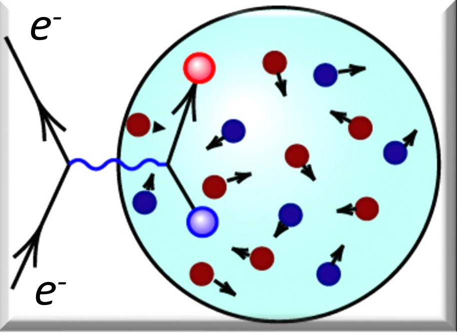
- Much higher statistics than neutrinos!
- A common tune would bias the results in favor of electron data
- Most models don't have parameters specific to electrons
- Clear V-A separation not always easy
  - I.e: Non-resonance background model



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

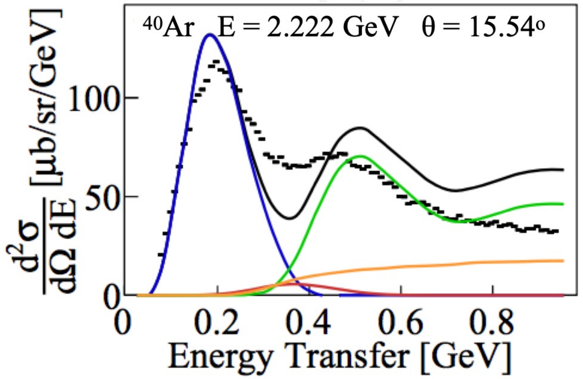


Nuclear model tuning

- 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

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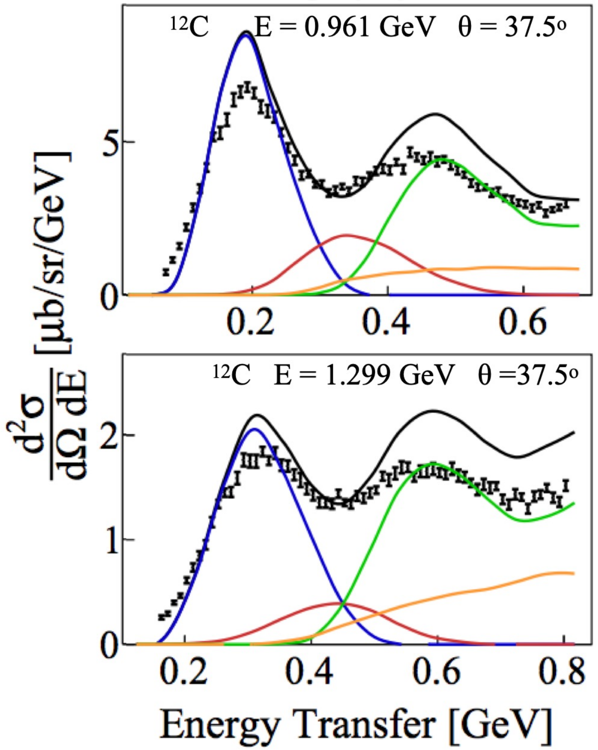
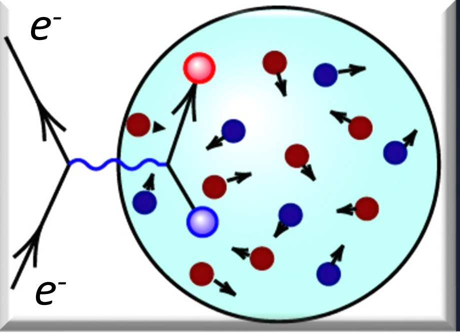


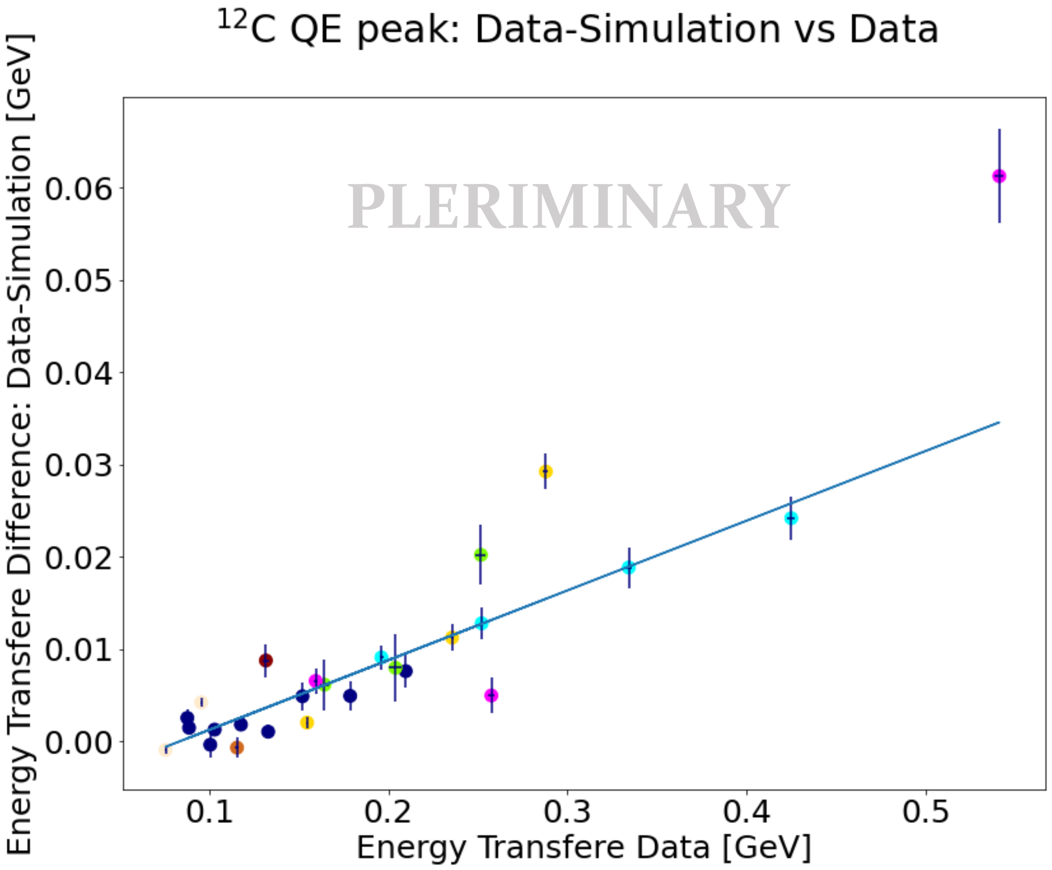


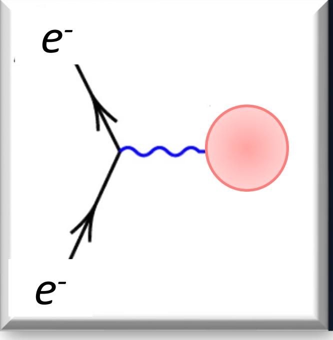
Nuclear model tuning

Matan Goldenberg

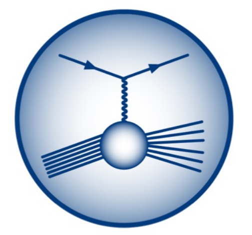
Approach:

- 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



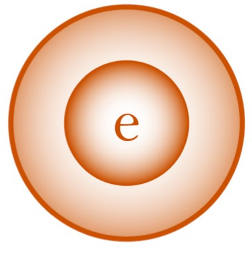


Tuning of $e-A$ interaction models Approach



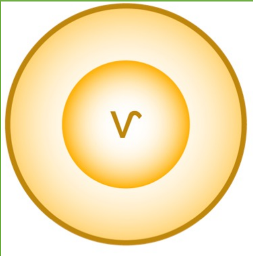
Model unification

- 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