Genie

Overview and systematic

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on behalf of GENIE collaboration

University of Liverpool

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T2K Cross section workshop
CERN

Outline

- GENIE Overview
- GENIE model implementation
  - Present
  - GENIE specifics
  - Future developments
- Systematic treatments
  - Standard Reweight approach
  - Future overview

GENIE - www.genie-mc.org

GENIE Collaboration

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[Faculty, Postdocs, PhD students]

1 - Fermi National Accelerator Laboratory, 2 - University of Liverpool, 3 - University of Pittsburgh, 4 - JINR Dubna,

5 - STFC Rutherford Appleton Laboratory, 6 - CENBG Université de Bordeaux, 7 - Tufts University, 8 - Valencia University, 9 - MIT

Core GENIE mission - from GENIE by-law

Framework "... provide a state-of-the-art neutrino MC generator for the world experimental neutrino community ..."

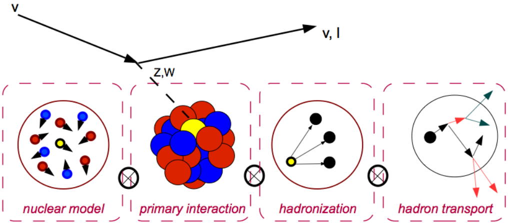
Universality "... simulate all processes for all neutrino species and nuclear targets, from MeV to PeV energy scales ..."

Global fit "... perform global fits to neutrino, charged-lepton and hadron scattering data and provide global neutrino interaction model tunes ..."

Calculation factorisation

⇒ Factorisation approach

- the initial nuclear state dynamics
- cross-sections at the neutrino-nucleon level
  + a model of how to sum-up the nucleon-level contributions
- hadronization - mainly based on external dependencies
- intranuclear hadron transport
  - GENIE-grown models



- GENIE design allows multiple combinations of models
  - Multiple choices available for each interaction as well

Status overview

- Well established generator
  - Used by many experiments / project around the world
    - Different energy ranges - from MeV to PeV
  - Fermilab experiments are driving the momentum
    - Lot of interest from LAr experiments
- Two main efforts of the collaboration
  - Model development
    - growing interest from theorists wanting to supply new models
  - Tuning

    ⇒ Entering the tuning phase
- The new release v3 - last release v3.00.06
  - Interface with the developments

  ⇒ Tunes against public datasets

  ⇒ Easy way to share configurations
    - Experiments can propose their own configuration for others to use

GENIE Version 3

UNIVERSAL NEUTRINO GENERATOR
& GLOBAL FIT

graphics by `grafiche.testi@gmail.com`

- Interface with the work behind the scenes

⇒ "Comprehensive Model Configurations"

  - Self-consistent collections of primary process models
  - Help cooperation between collaborations
    - Unified model identifications
  - single command-line flag
    - `--tune G18_02a_00_000`
  - Complete characterisation against public data
  - Possibility to host configurations provided by experiments

- Access to tunes against datasets
  - same interface
  - Impact on the systematic treatment - see later slides

Quick start

- New Git Repository - `https://github.com/GENIE-MC`
  - Contributions are welcome through this new channel
  - Thanks to HEPForge for the many years of support
- Reweight is now a detached and independent repository
- Website - `http://www.genie-mc.org/`
- Updated manual hosted on a `dedicated DocDB`
- Documentation on CMC and tunes available on manual and website
- GENIE user Forum
  - Monthly meeting - 3rd Wednesday of each month at 15:00 UK time
  - Moment of exchange between core GENIE developers, experiments and users
  - dedicated `web page`
- There is also a genie slack
  - Link from the website
  - Request invitation to Costas

Models

- Steady introduction as alternate models
  - Many thanks to all who contributed - non just GENIE authors

⇒ Usual set of models implemented by other generators

- List of most interesting physics introduction:
  - Valencia complete QE+MEC+LFG model
  - Berger-Sehgal resonance model+MiniBooNE form factors
  - Berger-Sehgal coherent model + updated Rein-Sehgal coherent
  - Single kaon production of *Athar et al.*
  - New cascade FSI model with medium corrections for pions and nucleons
  - Coherent elastic interaction
- Other physics usages
  - Dark matter simulations
  - $n - \bar{n}$ oscillations
  - Very High energy extension

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Models have to be stitched together

- There are ad-hoc solutions in every generator
- Often empirical models ⇒ need tuning

Comprehensive Model Configurations

A complete generation needs more than a set of models

- The experimental smearing mixes all the different interaction processes

$\Rightarrow$ All processes needs to be simulated without double counting

- `G18_02a_00_000` - New default in v3
  - Empirical MEC
  - CCQE process is Llewellyn Smith Model
  - Dipole Axial Form Factor - Depending on $M_A = 0.99\ GeV$
  - Nuclear model: Fermi Gas Model - Bodek, Ritchie
- `G18_02a_02_11a` - a genie supported tune
  - Started from `G18_02a_00_000`
  - Tuned to match 1π and 2π production
  - Deuterium data
- `G16_10j_00_000` - Nieves, Simo, Vacas Model - NOνA starting point
  - Z-Expansion Axial Form Factor
  - Nuclear model: Local Fermi Gas Model
  - Full nuclear cascade model for FSI
- Small variations changing FSI models

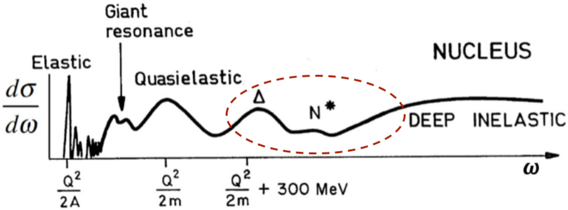
Specific of GENIE implementations

- Every model has generator related specifications / approximations
  - I'm not going to talk about all of them
  - Just mention one ⇒ that probably relevant for T2K

⇒ Non-Resonant background
  - Junction between Resonant and DIS interactions
  - AKA Shallow inelastic region

- Process relevant for single nucleons
  - Consequences for all nuclei

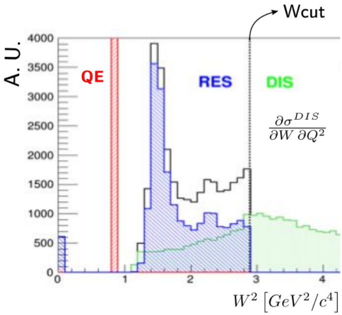
- I know this is implemented differently between NuWro and GENIE
  - No idea how this is handled in NEUT



Shallow Inelastic Region in GENIE

- Non-resonant background proportional to DIS

$$\frac{d^2\sigma^{INEL}}{dQ^2 dW} = \frac{d^2\sigma^{RES}}{dQ^2 dW} + \frac{d^2\sigma^{DIS}}{dQ^2 dW}$$



- RES contribution stops at $W = W_{cut}$

$$\frac{d^2\sigma^{RES}}{dQ^2 dW} = \sum_K \left(\frac{d^2\tilde{\sigma}^{RES}}{dQ^2 dW}\right) \cdot \Theta(W_{cut} - W)$$

- Pure DIS cross section for $W > W_{cut}$

$$\frac{d^2\sigma^{DIS}}{dQ^2 dW} = \frac{d^2\tilde{\sigma}^{DIS}}{dQ^2 dW} \cdot \Theta(W - W_{cut}) + \underbrace{\frac{d^2\tilde{\sigma}^{DIS}}{dQ^2 dW} \cdot \Theta(W_{cut} - W) \cdot \sum_m f_m}_{\text{Non-Resonant Background: Scaled DIS}}$$

- Available model combinations
  RES – Rein-Sehgal or Berger-Sehgal
  DIS – Bodek-Yang

- $\sim$ 10 parameters to be tuned to describe the mixing and the scaling

Future model developments

- General model implementation relevant for T2K
  - SuSAv2
  - Correlated Fermi Gas Model - K. S. Egiyan et al.
    - Phys. Rev. C 68 (2003) 014313
    - Phys. Rev. Lett. 96 (2006) 082501
  - NC Coherent Gamma production
    - E. Wang, L. Alvarez-Ruso, and J. Nieves Phys. Rev. C 89, 015503
  - Delta decay distribution - as measured from ANL and BNL
  - New DIS model - relevant in combination with the non-RES background
  - Nuclear de-excitation simulation
- Electron scattering developments
  - Extensive validation program with an MIT group
  - Interesting for models available for both neutrino and electron scattering
  - Radiative correction implementation
- Updates less relevant for T2K
  - Pythia 8 integration
  - Boosted Dark Matter scattering
  - Very high energy scattering
  - Other beyond standard model interaction - Dark photon and dark neutrinos
- Tuning
  - Hadronization tunes
  - With new models also new tunes are expected

Systematic treatment

- Experiments usually go for reweight
  - Full generations are not thinkable
    - Limited to small studies
  - There are tools (some inside GENIE as well) to assign a different weight to an event
    - depending on some parameters different from the one used for generation
  - All the events are then reprocessed using the different weight
  - new observable spectra are obtained
- Limitations
  - Parameters are not always reweightable
    - Cascade, Binding energies, etc
  - a dedicated reweight module is needed for each new model
    - Increase the effort necessary for implementation
  - Open question: is it possible to reweight from model to another?
    - Is it legit? Is it wise?
- Typical situation
  - Errors on the parameters are not very well defined / known
    - No priors nor covariance matrices available
    - The error assumptions are based on a vague coverage
    - Sometimes errors are $\sim$ central values $\Rightarrow$ Gaussian approximations fail

A good baseline model is a necessity

Tuning

- Why tuning?
  - Have better baseline models
  - Merge different models
    - Avoid double counting
    - Adapt empirical solutions
  - ⇔ Constraint parameters
  - Provide/distribute specific tunes for/from experiments
- Expected Output:
  - Parameter sets from data from various experiments
  - with estimated systematic errors
    - Parameter covariance matrix
    - ⇒ No official support until v4
- Numerical methodology
  - Old problem in High Energy Physics
    - CPU demanding
  - Solution found in the Professor suite
  - Numerical assistant
    - Developed for ATLAS experiment

http://professor.hepforge.org

Professor system

- Brute force approach
  - Parameterise observables
  - Not single events

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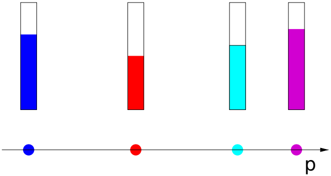
1. Select points of param space
2. Evaluate bin's behaviour with brute force



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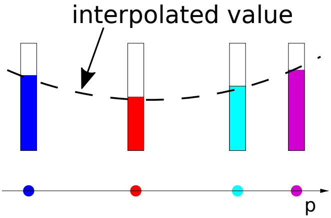

Professor system

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1. Select points of param space
2. Evaluate bin's behaviour with brute force
3. Parameterisation $I(p)$

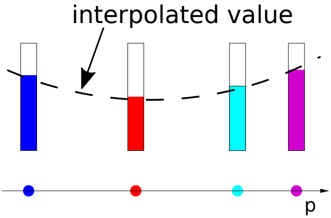
  - Repeat for each bin

- a parameterization $I_j(p)$ for each bin
  - N dimension polynomial
  - Including all the correlation terms up to the order of the polynomial

$\Rightarrow$ Minimise according to $\vec{I}(p)$

- $\sim$ 20 parameters
  - This limit is due to disk space requirements
  - It can be overcome

- Special thanks to H. Schulz



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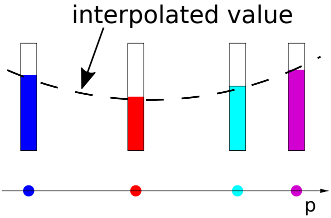

- Tuning applications
- reweighing modules
  - independent from parameters
  - Nor model specific
  - Long term process

Impact on the cross sections for the G18_02a CMC

Global tune with respect to ν_μ CC Inclusive datasets:

- The cross section is reduced at low energies to match the low cross section of pion production
- Pion production is better described without ruining the inclusive cross section

Disclaimer: Not all of these points have been used as just a few of them are on deuterium targets

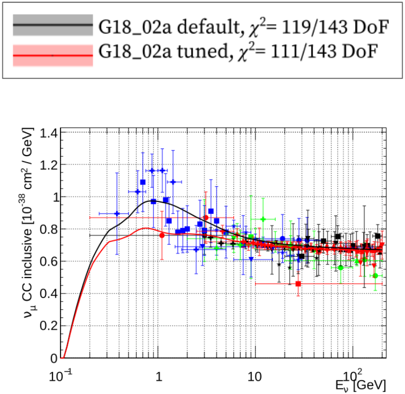

Figure: G18_02a default (black) and tuned (red) vs ν_μ CC inclusive. Just BEBC, BNL_7FT and FNAL data was used for the tune. For these datasets, $\chi^2_{default} = 18.8/26$ DoF, $\chi^2_{tuned} = 15.5/26$ DoF. References in the backup.

Impact on the cross sections for the G18_02a CMC

Global tune with respect to ν_μ CC one pion production datasets:

- The description of the data has improved
- The same effect is seen for
  - ν_μ CC $p\pi^+$
  - ν_μ CC $n\pi^+$
  - ν_μ CC $p\pi^0$

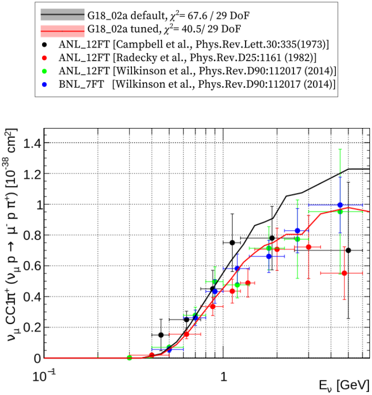

Figure: G18_02a default (black) and tuned (red) vs ν_μ CC $1\pi^+$ production data on proton. Just the ReAnalized data has been used. For these detasets, $\chi^2_{default} = 30.3/15$ DoF and $\chi^2_{default} = 16.85/15$ DoF.

Impact on the cross sections for the G18_02a CMC

Global tune with respect to ν_μ CC two pion production datasets:

- The cross section increased

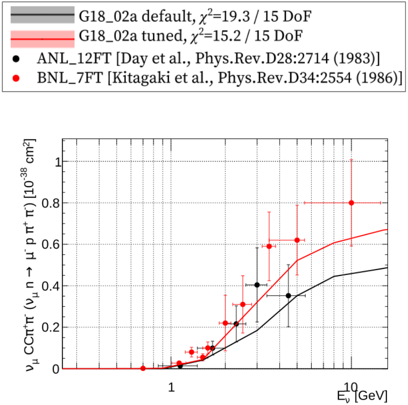

Figure: G18_02a default (black) and tuned (red) vs ν_μ CC two pion production data sets. Both datasets are included in the tune.

Personal view of present and future

- We cannot combine different generator to evaluate systematics
  - We only find bugs in the model implementations
  - Systematic requires a mapping from parameters to observables
    - Information fully available only inside the generator
  - Otherwise we can just inflate errors on parameters we have
    - Weak justification for a prior
- Experiment analyses should start considering professor-like approaches
  - Not as replacements
  - To overcome what is left out from traditional reweight
- Generators and experiments should know that these procedures are becoming standard
  - Need data releases that can be used for tuning
  - Analyzers shall expect parameter covariance matrices for selected model configurations

Next steps

- Programmed tunes
  - hadronization re-tune
    - Pythia 6 and 8 (implementation is ongoing)
  - Tune of FSI
    - Both hN and hA intranuke
  - Electron scattering development
- Data from Liquid argon experiments
  - Part of GENIE collaboration is in SBND
  - Plan for argon tunes
  - Interesting for T2K
    - Similar energy range
- Look forward to more data
  - And to a better understanding of the data we have
- Release these results
  - Papers is in preparation
  - Implementation in GENIE releases

Conclusion

- Overview of the GENIE status
  - View
  - Models
  - Tuning
  - Future expectations
- Presented a complementary way to treat systematic
  - This will require dedicated work from all sides
  - It has been proved to be extremely powerful so far
  - Dedicated reweight machinery expcted for GENIE v4
- Researchers are encouraged to contact us to start a collaboration
  - New theory models
  - New experimental collaborations

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Backup slides

Global tune with respect to $\bar{\nu}_\mu$ CC inclusive

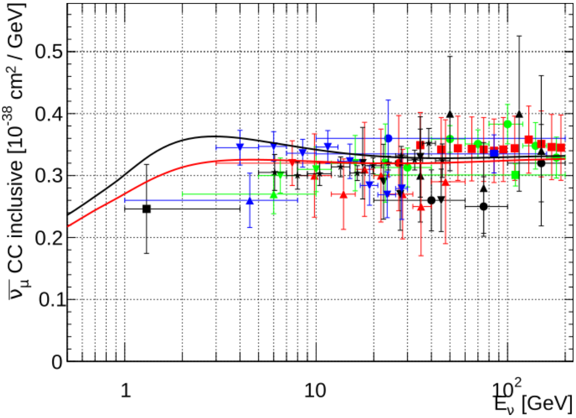


Figure: G18_02a default (black) and tuned (red) vs $\bar{\nu}_\mu$ CC inclusive data.$\chi^2_{Total,\ default} = 74.6/69$ DoF, $\chi^2_{Total,\ tuned} = 46.9/69$ DoF. Just BEBC, BNL_7FT and FNAL data used for the tune: $\chi^2_{default} = 17.48/24$ DoF, $\chi^2_{tuned} = 17.45/24$ DoF.

Global tune with respect to $\bar{\nu}_\mu$ CC inclusive

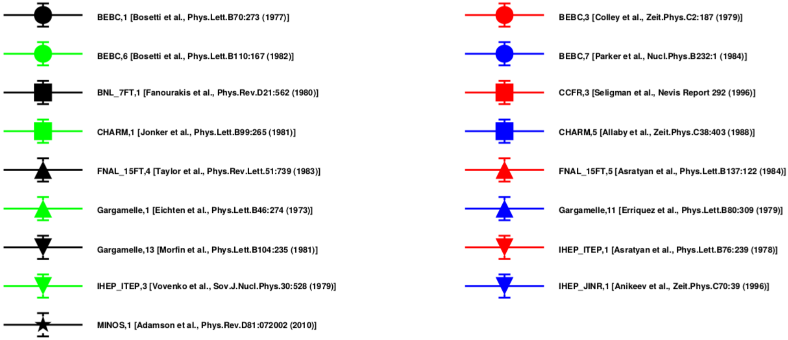


Figure: References for $\bar{\nu}_\mu$ CC inclusive datasets.

Global tune with respect to $\nu_\mu n \to \mu^- n \pi^+$

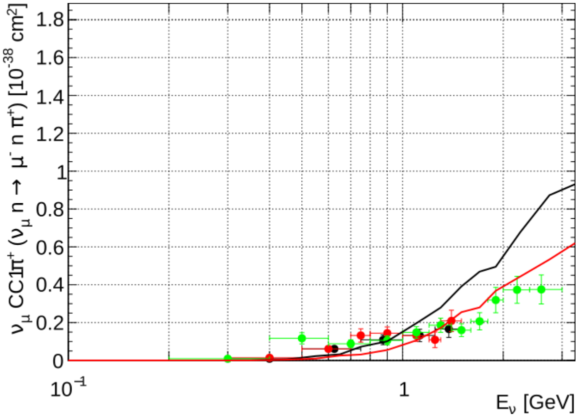


Figure: G18_02a default (black) and tuned (red) vs $\nu_\mu n \to \mu^- n\pi^+$ data. All the datasets have been used for the tune. $\chi^2_{Total,default} = 187/23$ DoF, $\chi^2_{Total,tuned} = 98.7/23$ DoF.

Global tune with respect to $\nu_\mu n \to \mu^- n\pi^+$

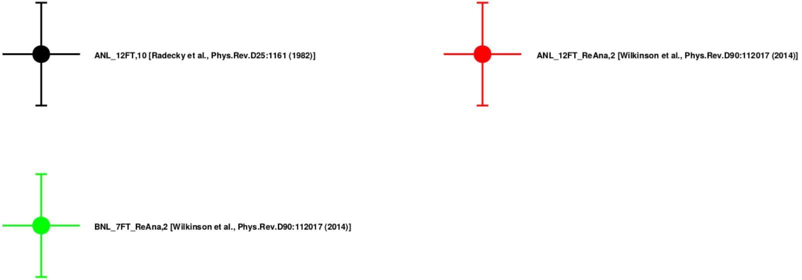


Figure: Datasets references for $\nu_\mu n \to \mu^- n\pi^+$.

Global tune with respect to $\nu_\mu p \to \mu^- p \pi^+$ with 1.4 GeV cut on W

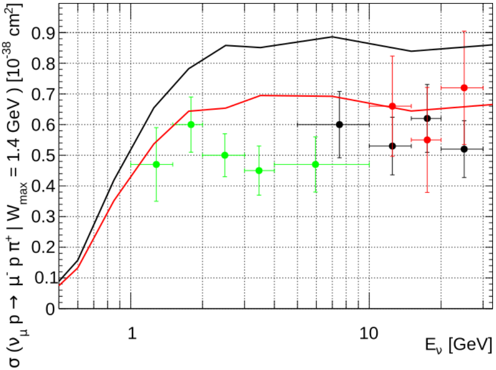


Figure: G18_02a default (black) and tuned (red) vs $\nu_\mu p \to \mu^- p \pi^+$ data. In the analysis of these datasets they applied a cut on W at 1.4 GeV. $\chi^2_{Total,\ default} = 94.5/12$ DoF, $\chi^2_{Total,\ tuned} = 25/12$ DoF. Just BEBC and FNAL data used for the tune: $\chi^2_{default} = 19.65/8$ DoF and $\chi^2_{tuned} = 5.054/8$ DoF.

Global tune with respect to $\nu_\mu p \to \mu^- p \pi^+$

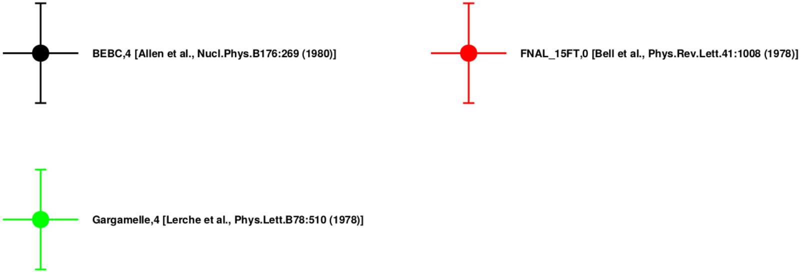


Figure: Datasets references for $\nu_\mu p \to \mu^- p \pi^+$ with a cut on W at 1.4 GeV.

Global tune with respect to $\nu_\mu p \to \mu^- p \pi^+$ with 2 GeV cut on W

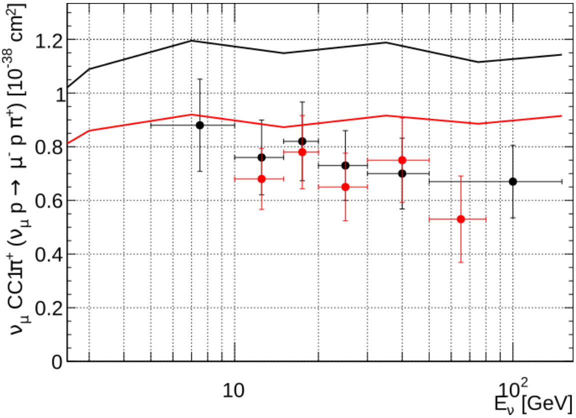


Figure: G18_02a default (black) and tuned (red) vs $\nu_\mu p \to \mu^- p\pi^+$ data. All data was used for the tune. In the analysis of these datasets they applied a cut on W at 2 GeV. $\chi^2_{Total,\ default} = 44.9/11$ DoF, $\chi^2_{Total,\ tuned} = 15.3/11$ DoF.

Global tune with respect to $\nu_\mu p \to \mu^- p \pi^+$

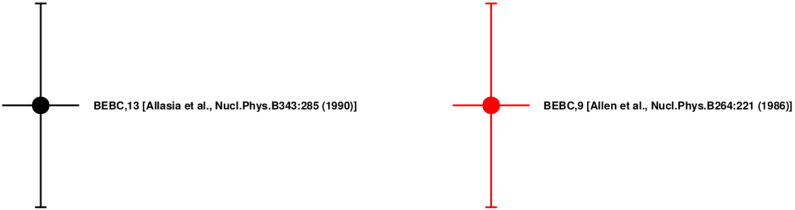


Figure: Datasets references for $\nu_\mu p \to \mu^- p \pi^+$ with a cut on W at 2 GeV.

Global tune with respect to $\nu_\mu p \to \mu^- n\pi^0$

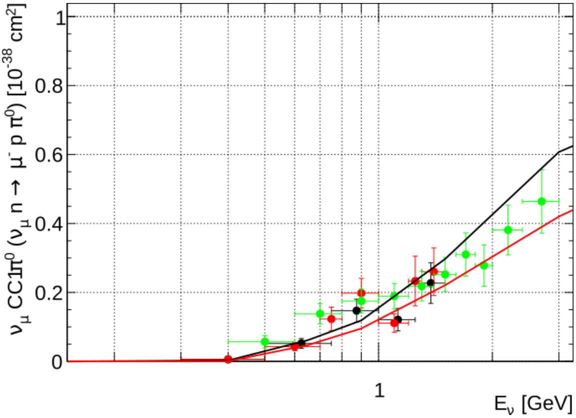


Figure: G18_02a default (black) and tuned (red) vs $\nu_\mu p \to \mu^- n\pi^0$ data. All data was used for the tune. $\chi^2_{Total,\ default} = 66.7/22$ DoF, $\chi^2_{Total,\ tuned} = 42.1/22$ DoF.

Global tune with respect to $\nu_\mu p \to \mu^- n \pi^0$

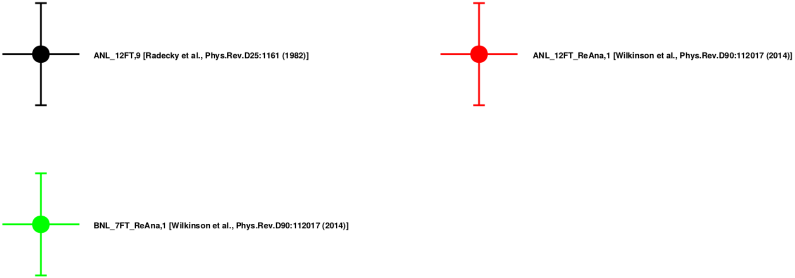


Figure: Datasets references for $\nu_\mu p \to \mu^- n \pi^0$.

Global tune with respect to $\nu_\mu p \to \mu^- n\pi^+\pi^-$

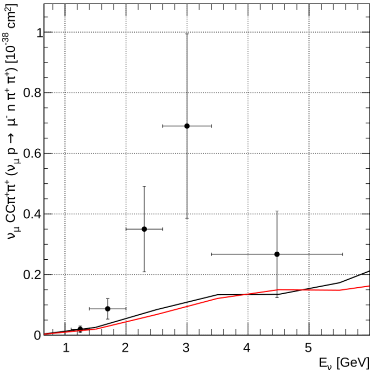


Figure: G18_02a default (black) and tuned (red) vs $\nu_\mu p \to \mu^- n\pi^+\pi^-$ data. ANL_12FT,13 [Day et al., Phys.Rev.D28:2714 (1983)] used in the tune. $\chi^2_{Total,\ default} = 8.61/5$ DoF, $\chi^2_{Total,\ tuned} = 9.54/5$ DoF.

Global tune with respect to $\nu_\mu p \to \mu^- p \pi^+ \pi^0$

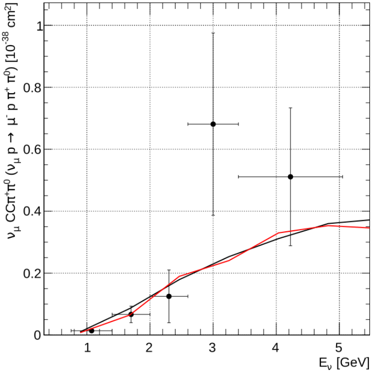


Figure: G18_02a default (black) and tuned (red) vs $\nu_\mu p \to \mu^- p\pi^+\pi^0$ data. ANL_12FT,12 [Day et al., Phys.Rev.D28:2714 (1983)] used in the tune. $\chi^2_{Total,\ default} = 4.21/5$ DoF, $\chi^2_{Total,\ tuned} = 4.4/5$ DoF.

Global tune with respect to ν_μ CC QEL

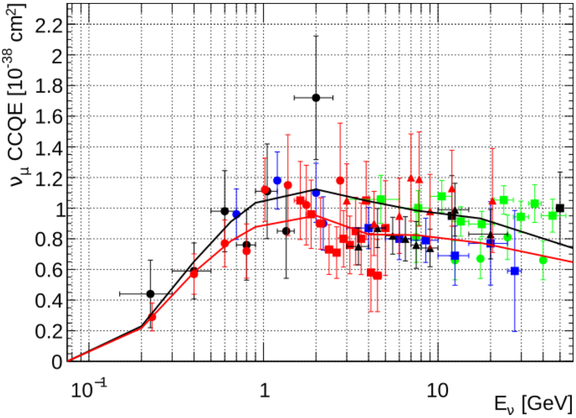


Figure: G18_02a default (black) and tuned (red) vs ν_μ CC QEL data. $\chi^2_{Total,\ default} = 85.1/70$ DoF, $\chi^2_{Total,\ tuned} = 79.7/70$ DoF. Only ANL_12FT, BEBC, BNL_7FT and FNAL data used for the fit: $\chi^2_{default} = 28.85/26$ DoF, $\chi^2_{tuned} = 22.84/26$ DoF.

Global tune with respect to ν_μ CC QEL

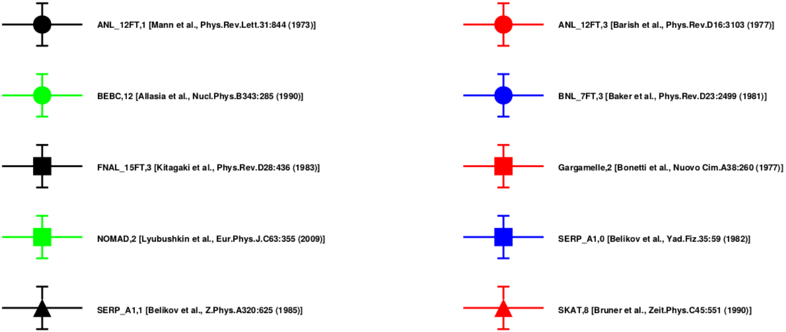


Figure: Datasets references for ν_μ CC QEL.

Global tune with respect to $\bar{\nu}_\mu$ CC QEL

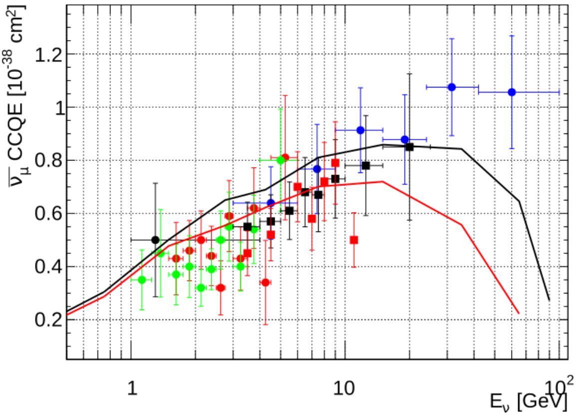


Figure: G18_02a default (black) and tuned (red) vs $\bar{\nu}$ CC QEL data. $\chi^2_{Total,\,default} = 86.2/43$ DoF, $\chi^2_{Total,\,tuned} = 69.9/43$ DoF. Only BNL_7FT data used for the fit: $\chi^2_{default} = 0.125/1$ DoF, $\chi^2_{tuned} = 0.00566/1$ DoF.

Global tune with respect to $\bar{\nu}_\mu$ CC QEL

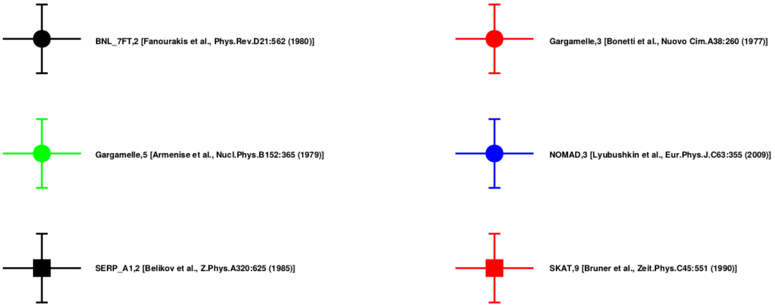
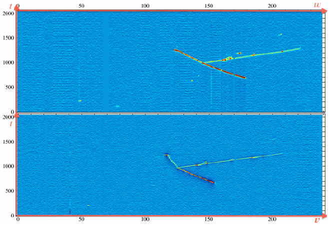


Figure: Datasets references for $\bar{\nu}$ CC QEL.

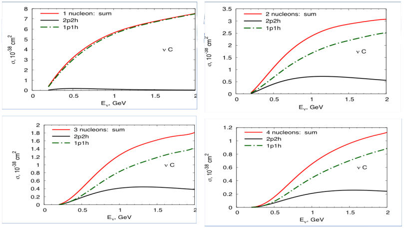
Search for 2p-2h

- Characteristic events
  - 2 back-to-back nucleons
- Nuclear effect can change observed topology
  - migrations in the number of observed protons
- future LarTPCs (or gas TPCs) important role
  - Disentangle FSI from MEC
  - CC 0π samples proton multiplicity
- Important dataset that will "soon" be available

ArgoNEUT



[Phys.Rev. D90 (2014) 1, 012008]



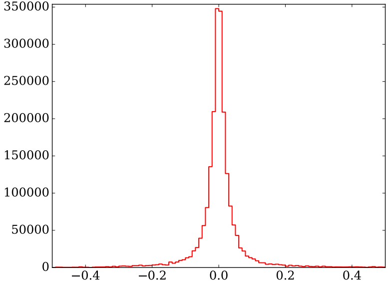
[Ulrich Mosel]

Advantages and expectations

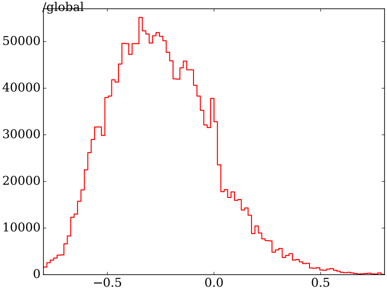
- All parameters can be tuned
  - Not only reweight-able
  - ⇒ no dedicated machinery to develop
- Advanced features
  - Take into account correlations
  - weights specific for each bin and/or dataset
    - Proper treatment while handling multiple datasets
    - Restrict the fit to particular subsets
  - Priors can be included
  - Nuisance parameters can be inserted
    - proper treatment for datasets without correlations
    - ⇒ MiniBooNE, old bubble chamber datasets

- Professor based Reweight package in development
  - Reweight hard to maintain: each model requires a specific reweight module
  - Better interface with the errors produced by a global fit
  - Allow non-reweightable parameters - e.g. HN FSI
  - ⇒ version 4

Parameterization residuals



Good



Bad

RES Models: the Rein-Sehgal Model

- Most widely used model for resonance neutrino production
  [*D.Rein et. al., Annals Phys. 133 (1981)*]
- Only contains resonances up to $W = 2GeV$
- Limit $m_\mu = 0$
- Non-resonant background of $I = 1/2$ added incoherently

$$\frac{d\sigma}{dQ^2 dW^2} \propto \left[u^2\sigma_L + v^2\sigma_R + 2uv\sigma_s\right]$$

u and v are kinematic factors
σ_L, σ_R and $\sigma_s \to$ Helicity cross sections
Depend on:

- $F_\pm$ and F_0 dynamical form factors
- Axial and vector transition form factors, $G^{V,A}(q^2) \propto \left(\frac{1}{1-q^2/M^2_{V,A}}\right)^2$
- Original paper values $M_V = 0.84GeV$ and $M_A = 0.95GeV$

RES Models: the Berger-Sehgal Model

- Improved version of the RS model
  [*Bodek, A. et al. Nucl.Phys.Proc.Suppl. hep-ex/0308007*]
- Non zero m_μ $\Rightarrow$ Final state lepton can have + or - helicity
- Gives a suppressed cross section at small angles

$$\frac{d\sigma}{dQ^2 dW^2} \propto \sum_{\lambda=+,-} \left[\left(c_L^{(\lambda)} \right)^2 \sigma_L^{(\lambda)} + \left(c_R^{(\lambda)} \right)^2 \sigma_R^{(\lambda)} + \left(c_S^{(\lambda)} \right)^2 \sigma_s^{(\lambda)} \right]$$

Depends on:

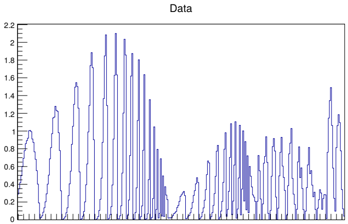
- $c_L^{(\lambda)}$, $c_R^{(\lambda)}$ and $c_s^{(\lambda)}$ are the new kinematic factors
- Six helicity cross sections that depend on dynamical form factors
- Axial and vector transition form factors also calculated using the dipole approximation

Shallow Inelastic Scattering region

- In the RS model the non-resonant background is computed by introducing incoherently an extra amplitude with I=1/2
  $\rightarrow$ not completely satisfactory approach
- **Quark-Hadron duality** can give an alternative model to describe the non-resonant background
  - The average over resonances behaves similarly to the valence quark contribution to DIS scaling curve
  - Harari and Freund conjecture suggests the existence of a relationship between non-resonant and sea-quark contributions to structure functions [*Phys. Rev. Lett. 20 (1969) 1395*]
- **If duality is satisfied, the total resonance distribution can be described by an extrapolated DIS.**

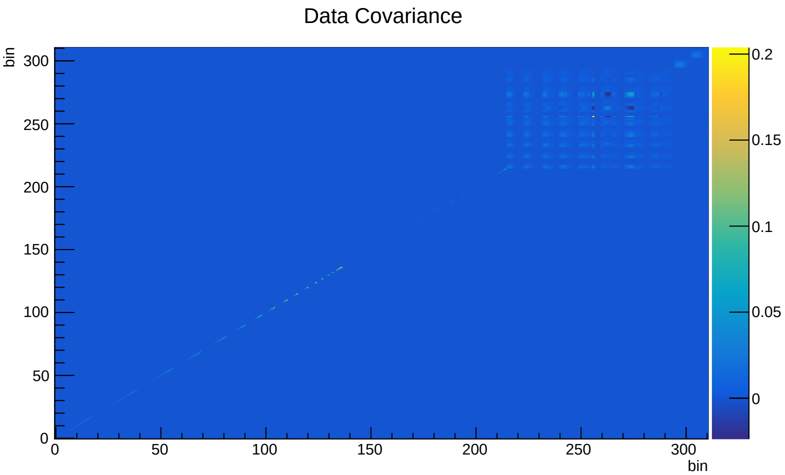
Datasets - 311 data points

- MiniBooNE ν_μ CCQE
  - 2D histogram
  - 137 points
  - No correlation matrix
- MiniBooNE $\bar{\nu}_\mu$ CCQE
  - 2D histogram
  - 78 points
  - No correlation matrix
- T2K ND280 0π (2016) V2
  - 2D histogram
  - 80 points
  - full covariance matrix
- MINERvA ν_μ CCQE
  - 1D histogram
  - 8 points
  - full covariance matrix
- MINERvA $\bar{\nu}_\mu$ CCQE
  - 1D histogram
  - 8 points
  - full covariance matrix



- Missing Covariance between Neutrino and antineutrino data
  - Minerva released this information!

Data covariance



Tuning Output

- Parameters best fit
- Parameters covariance
- Prediction covariance
  - due to the propagation of parameter covariance

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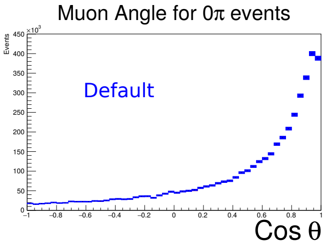

- Data Constraints for Oscillation analyses

Tuning Output

- Parameters best fit
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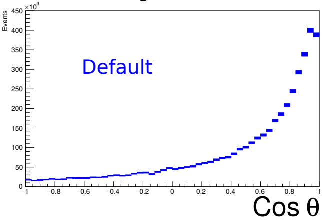
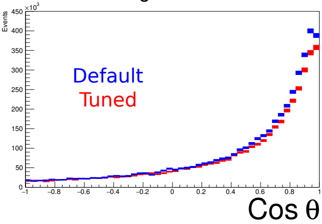
- Data Constraints for Oscillation analyses
  - Propagate the result to other observables

Muon Angle for 0π events

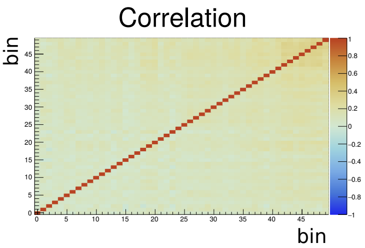


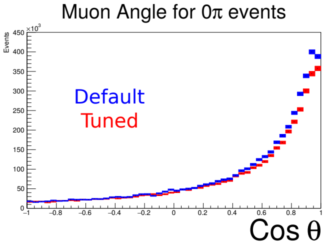
Muon Angle for 0π events



Tuning Output

- Parameters best fit
- Parameters covariance
- Prediction covariance
  - due to the propagation of parameter covariance
- Data Constraints for Oscillation analyses
  - Propagate the result to other observables
- Propagate parameters uncertainty through the parameterization





Model comparison

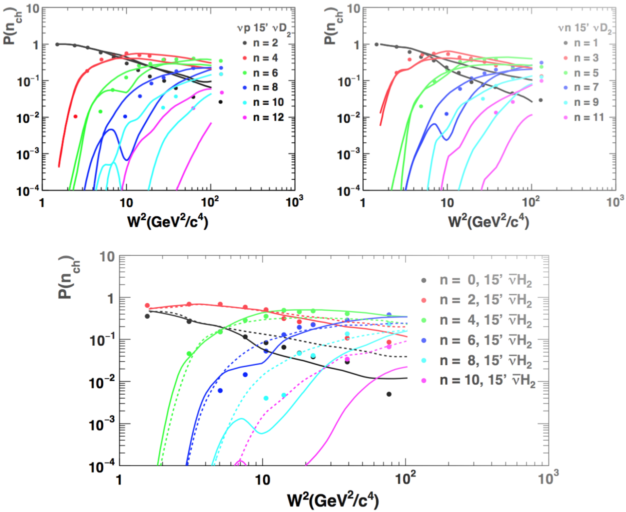
Model comparison

Martini et al. Nieves et al. Amaro et al. Lovato et al. Bodek et al.

$$\frac{\partial^2\sigma}{\partial\Omega\,\partial\epsilon'} = \frac{G_F^2\,\cos^2\theta_c}{2\,\pi^2} k'\epsilon'\,\cos^2\frac{\theta}{2}\left[\frac{(q^2-\omega^2)^2}{q^4}\,G_E^2\,R_\tau + \frac{\omega^2}{q^2}\,G_A^2\,R_{\sigma\tau(L)} + \right.$$
$$\left. +\;2\left(\tan^2\frac{\theta}{2}+\frac{q^2-\omega^2}{2q^2}\right)\left(G_M^2\,\frac{\omega^2}{q^2}+G_A^2\right)R_{\sigma\tau(T)} \pm 2\,\frac{\epsilon+\epsilon'}{M_N}\,\tan^2\frac{\theta}{2}\,G_A\,G_M\,R_{\sigma\tau(T)}\right]$$

[M.Martini, FUNFACT JLab workshop]

Hadronization example



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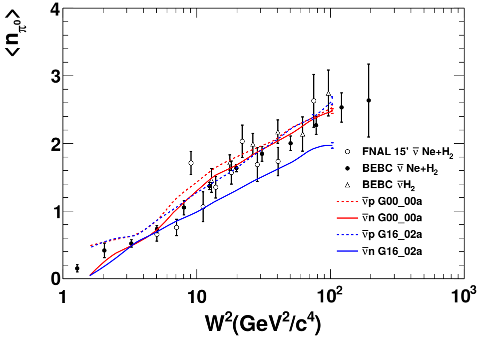

Neutrino MC generators: our vision

- Connect neutrino fluxes and observables
  - event topologies and kinematics
- *Good* generators
  - optimal coverage of physics processes
  - Uncertainty validation
  - Tune the *physics* models
- Specific requirements for *experiments*
  - fast enough for MC analyses
  - being able to prove the validity of a configuration
  - ⇒ Simple models can be perfectly acceptable

⇒ Tuning is difficult - CPU time

- ⇒ Unprecedented systematic tuning program

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We don't believe in a *perfect theory* approach

- There are always things that need to be derived from measurements

⇒ Dealing with errors is unavoidable

Roles of generators in oscillation physics

- Compare data and models
  - Reliability and validity region
  - $\Rightarrow$ You cannot study oscillations without fully understood models
- Compare dataset against dataset
  - Data quality and data sources are increasing $\Rightarrow$ tensions
  - $\Rightarrow$ joint analyses
  - $\Rightarrow$ comparing results from different experiments
- Global fits
  - A generator is the ideal place for global fits
    - Controls the model implementation
  - Finding the best parameters
  - Cross Section priors based on data
- Feedback for experiments
  - Drive the format of cross section releases
  - Hint toward key measurements