GENIE models and global fits of neutrino scattering data

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on behalf of GENIE collaboration

University of Liverpool

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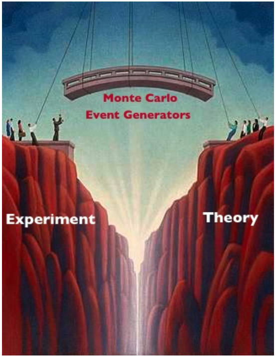
Neutrino MC Generators: A Theory/Experiment Interface



- Access the flux distorsion due to oscillation
  - Every observable is a convolution of flux, interaction physics and detector effects
- Connect truth and observables
  - Event topologies and kinematics
  - Model dependencies
- *Good Generators*
  - ⇒ Support oscillation analyses
  - uncertainty validation
  - tune the *physics* models

⇒ Tuning proved to be difficult
  - So far no results

Several MC Generators in use: **GENIE**, **GiBUU** , **NuWro**, **NEUT**

Roles of MC generators in Oscillation Physics

- Comparing data and models
  - $\Rightarrow$ You cannot study oscillations without fully understood models
  - Validity region
  - Highlight tensions
- Feedback for experiments
  - Drive the format of cross section releases
  - Hint toward key measurements

Roles of MC generators in Oscillation Physics

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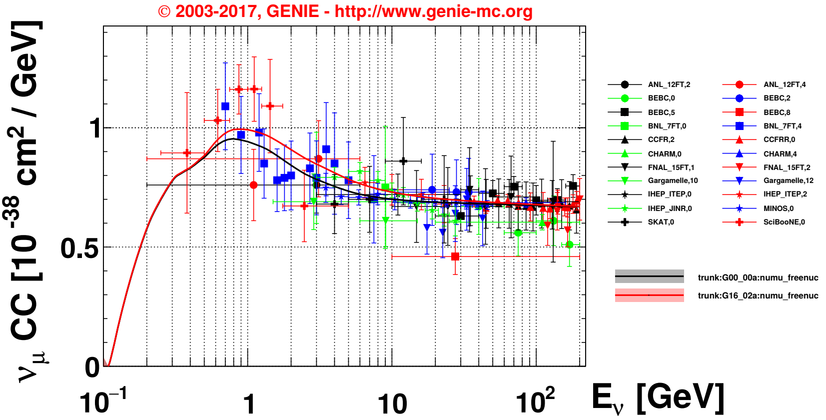
  - Hint toward key measurements
- Global fits
  - Generator is the ideal place for global fits
    - We control the model implementation
- Constraints on Cross Section for oscillation analysis
  - Neutrino Cross sections priors
  - Eventually based on data

What generators can do depends on the available datasets

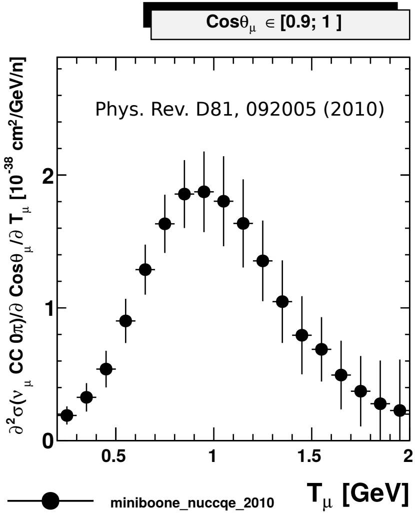
Evolving datasets - Old datasets



- Functions of E_ν
- Not flux-integrated
- “Only” statistical errors
- Ignore nuclear effects
- Poor statistical interpretation
- Poor model discrimination power

Evolving datasets - Present datasets

- Functions of experimental observables
- flux-integrated
- Usually differential cross-sections
  - 1D, 2D
- Organized by topology, not process
- Higher statistics
- More statistically robust
  - ⇒ Fermilab Neutrino seminar by Mikael Kuusela - 2017/04/13



Evolving datasets - Present datasets

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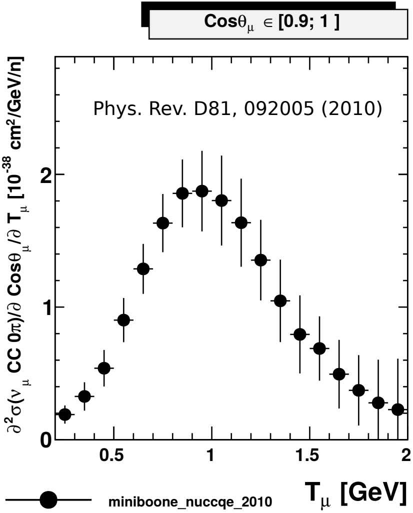
- Organized by topology, not process
- Higher statistics
- More statistically robust
  - ⇒ Fermilab Neutrino seminar by Mikael Kuusela - 2017/04/13
- Sometimes incomplete
- Helped the development of new models
  - 2p/2h

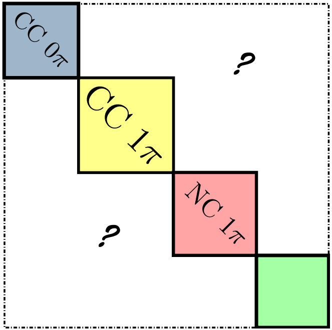


Future of datasets - a personal view

- One big covariance matrix per experiment
- Correlation between datasets
- Differential cross sections, dim > 2

- No data releases with this format
  - in SBND we are thinking about a solution

- It is usually a big effort but ...



We finally have a way to use these datsets

- Statistically coherent
- Complete error analysis

GENIE - www.genie-mc.org

GENIE Collaboration

Luis Alvarez Ruso[8], Costas Andreopoulos[2,5], Chris Barry[2], Francis Bench[2], Steve Dennis[2], Steve Dytman[3], Hugh Gallagher[7], Tomasz Golan[1,4], Robert Hatcher[1], Libo Jiang[3], Rhiannon Jones[2], Anselmo Meregaglia[6], Donna Naples[3], Gabriel Perdue[1], Marco Roda[2], Jeremy Wolcott[7], Julia Yarba[1]

[Faculty, Postdocs, PhD students]

1 - Fermi National Accelerator Laboratory, 2 - University of Liverpool, 3 - University of Pittsburgh, 4 - University of Wroclaw, 5 - STFC Rutherford Appleton Laboratory, 6 - IPHC Strasbourg, 7 - Tufts University, 8 - Valencia University

- Core GENIE mission
  1. ... provide a state-of-the-art neutrino MC generator for the world experimental neutrino community
  2. ... simulate all processes for all neutrino species and nuclear targets, from MeV to PeV energy scales
  3. ... perform global fits to neutrino, charged-lepton and hadron scattering data and provide global neutrino interaction model tunes

GENIE Version 2.12.6

- CCQE models
  - Llewellyn Smith
  - Nieves, Amaro and Valverde
- MEC models
  - Empirical
  - Nieves Simo Vacas
- Nuclear Models
  - Relativistic Fermi Gas
  - Local Fermi Gas
  - Effective Spectral Functions

- Single Kaon
- Λ production

- RES
  - Rein-Sehgal
  - Berger-Sehgal
  - Kuzmin-Lyubushkin-Naumov
- COH
  - Rein-Sehgal
  - Berger-Sehgal
  - Alvarez Ruso
- FSI - Intranuke
  - Full Intra-Nuclear cascade
  - Schematic based on Hadron-nucleus data

- Only one Comprehensive Model Configuration (CMC)
- Default tune has not changed

GENIE Version 3

UNIVERSAL NEUTRINO GENERATOR
& GLOBAL FIT

- “Comprehensive Model Configurations”
  - Self-consistent collections of primary process models
  - Tune names are supposed to become commonly used
    - Help cooperation between collaborations
  - single command-line flag
    - `--tune G16_02a`
  - Complete characterization against public data
  - Willing to host configuration provided by experiments
- Tunes for each CMC will also be available
- A step closer toward GENIE core mission

graphics by `grafiche.testi@gmail.com`

Comprehensive Model Configurations

Dedicated web page

Home

Mission Statement
GENIE Collaboration
Policy Documents
Copyright Notices
Citing GENIE

Incubator
Public Releases

Global Tunes

Physics & User manual

Mailing lists:
→ User
→ Developer
→ Admin

Getting the code
Installation instructions

Genie Global Tunes

This section contains the description of Genie's Global configurations and of their corresponding tunings against public data.

Naming convention

A uniform naming convention is required for all Comprehensive Model configuraion (CMC) and all its derived tunes (Comphensive model Tunes, in short CMT) are identified by a single label. Although an impossibly large of information needs to be encoded in the names, they should remain reasonably short. Not only a CMC name will be a command-line argument for all GENIE applications, a CMC name will be the main vehicle for communicating GENIE model configuration and tune information, often verbally.

It is rather clear that the names of the actual physics models, or the names of the datasets, can not be a part of a uniform and compact naming scheme. Such a naming scheme can only employ "keys" that can be used by users in order to look up the corresponding model configurations, parameter lists and datasets. It is expected that all this information will be maintained in the GENIE web page, and that the subset of that information pertaining to the currently supported CMTs will be included in the GENIE Physics and Users Manual.

A CMC is identified by a 7-charachter string in the form

Gdd_MMv

where

List of available configurations

CMC definitions and charachterization

The following list contains the details of the CMCs available in GENIE. Also, for each CMC, validation plots and Tunigs are available.

Configuration	Brief description
G00_00a	Historical Genie default configuration.
G00_00b	Historical Genie default configuration, including empirical 2p/2h.
G16_01a	Update of the historical default, including new interaction processes.
G16_01b	As G16_01a, with the inclusion of empirical 2p/2h.
G16_02a	Comprehensive configuration anchored to the latest theory developments.

Comprehensive Model Configurations

Details and configuration

G16_02a

This configuration is based on the latest theorical developments. Particular emphasis is on Nieve Model for CC 0π and CC 1π interactions.

The configuration of this CMC is a bit tricky as not only the models has to be changed. So, please pay attention at the notes in the comments sections or at the end of the table.

Configuration Table

ALGORITHM	MODEL	CONFIGURATION	COMMENTS
Initial Nucleus State	Local Fermi Gas	`LocalFGM/Default`	
CC QE	J. Nieves, J. E. Amaro and M. Valverde Phys. Rev. C 70 (2004)	`NievesQELCCPXSec/Default`	BBA05 elastic nucleon FF Dipole Axial Form Factor, M_A = 0.99 GeV/c^2
CC 2p/2h	J. Nieves, I. Ruiz Simo, and M. J. Vicente Vacas PRC 83 (2011) Implementation by J. Schwehr, D. Cherdack and R. Gran arXiv:1601.02038	`NievesSimoVacasMECPXSec2016/Default`	turn *SetDiNucleonCode* to *false**
CC RES	Ch. Berger, L. M. Sehgal Phys. Rev. D76 (2007)	`BergerSehgalRESPXSec2014/Default`	dipole axial FF, M_A = 1.12 GeV/c^2 16 Resonances - No interference
CC DIS	E.A.Paschos and J.Y.Yu Phys. Rev. D65 (2002)	`QPMDISPXSec/Default`	Scaling factor = 1.032
CC COH Pion	Ch. Berger and L. M. Sehgal Phys. Rev. D 79 (2009)	`BergerSehgalCOHPiPXSec2015/Default`	
CC Diffractive Pion	D. Rein Nucl. Phys. B278 (1986) 61-77	`ReinDFRPXSec/Default`	
CC ΔS = 1 QE	A. Pais Annals Phys. 63 (1971) 361-392	`PaisQELLambdaPXSec/Default`	
CC ΔS = 1 Inelastic	M. Rafi Alam *et at.* Phys. Rev. D82 (2010) 033001	`AlamSimoAtharVacasSKPXSec2014/Default`	
CC ΔC = 1 QE	Kovalenko	`KovalenkoQELCharmPXSec/Default`	

Comprehensive Model Configurations

- Configurations of interest for this talk
  - `G00_00a` - Default
    - No 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
  - `G16_01b` - Default + MEC
    - with 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
  - `G16_02a` - Nieves, Simo, Vacas Model
    - Theory motivated MEC
    - CCQE process is Nieves
    - Dipole Axial Form Factor - Depending on $M_A = 0.99\ GeV$
    - Nuclear model: Local Fermi Gas Model
- Small variations changing FSI models
- Variation including Spectral Functions

The Comparisons

The GENIE suite contains a package devoted to comparing GENIE predictions against publicly released datasets.

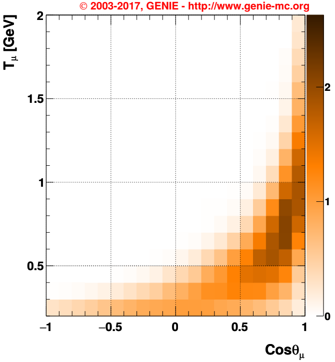
- Provides the opportunity to improve and develop GENIE models
- Crucial database for **new GENIE global fit** to neutrino scattering data
- All sorts of possible formats and dimensions
- Can store correlations, even between different datasets

The database

- **Modern Neutrino Cross Section measurement**
  - nuclear targets
  - typically flux-integrated differential cross-sections
  - MiniBooNE, T2K, MINERvA
- **Historical Neutrino Cross Section Measurement**
  - Bubble chamber experiment
- Measurements of neutrino-induced **hadronic system characteristics**
  - Forward/backward hadronic multiplicity distributions
  - Multiplicity correlations
  - ...
- Measurements of **hadron-nucleon and hadron-nucleus event** characteristics (for FSI tuning)
  - For pion, Kaons, nucleons and several nuclear targets
  - Spanning hadron kinetic energies from few tens MeV to few GeV
- Semi-inclusive **electron scattering data**
  - electron-nucleus QE data
  - electron-proton resonance data

MiniBooNE CCQE

- Both ν and $\bar{\nu}$
  - Phys. Rev. D81, 092005 (2010)
  - Phys. Rev. D88, 032001 (2013)
- Double differential cross section
- flux integrated
- No correlations
- Preferred model is Nieves Model (G16_02a)
  - excellent agreement for ν
  - $\chi^2 = 101/137$ DoF
- worse for $\bar{\nu}$
  - $\chi^2 = 176/78$ DoF



$\partial^2\sigma(\nu_\mu$ CC $0\pi)/\partial \cos\theta_\mu/\partial T_\mu$ [10^{-38} cm^2/GeV/n]

Data: miniboone_nuccqe_2010

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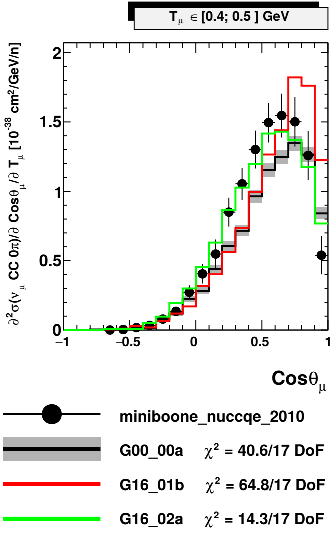
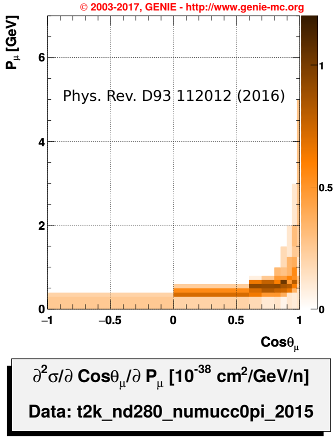


T2K ND280 0π

- Double differential cross section
- flux integrated
- Fully correlated
- Tensions between datasets
- Preferred model is G16_01b
  - $\chi^2 = 135/67$ DoF
- all models look reasonable "By eye" estimation
  - correlation is complicated
  - We can't ignore it!



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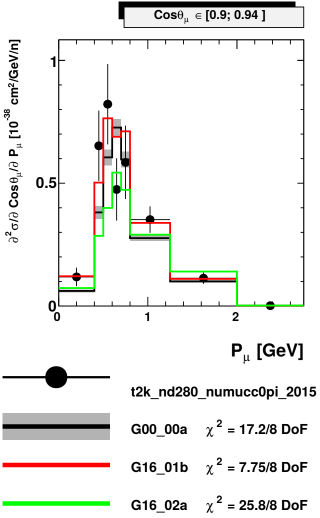

Tuning

- Why tuning?
  - Constraint parameters
  - Provide specific tuning for experiments
    - Liquid Argon tuning
- Expected Output:
  - Best parameters
  - Parameter covariance matrix
    - To be used for prior constructions

Tuning

- Why tuning?
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  - Provide specific tuning for experiments
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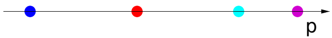
    - To be used for prior constructions
- Requirements granted by the comparisons:
  - Data
  - Metric
- Minimizer ?
  - Old problem in High Energy Physics
  - CPU demanding
  - Solution found in the Professor suite
    - `http://professor.hepforge.org`
  - Numerical assistant
  - Developed for ATLAS experiment

Professor

- Parametrization instead of a full MC

Professor

- Parametrization instead of a full MC
  1. Select points of param space



Professor

- Parametrization instead of a full MC
  1. Select points of param space
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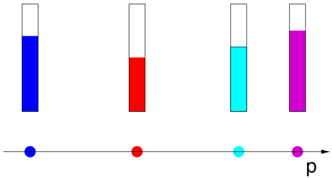

Professor

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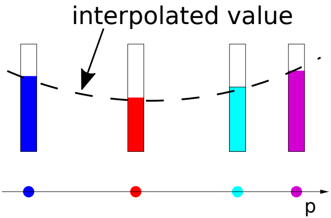
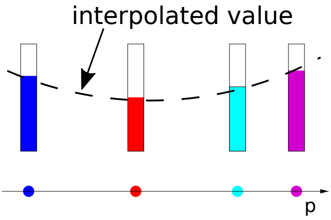


Professor

- Parametrization instead of a full MC
  1. Select points of param space
  2. Evaluate bin's behaviour with brute force
  3. Parametrization $I(p)$
  - 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
- Minimize according to $\vec{I}(p)$
- $\sim$ 15 parameters
- Special thanks to H. Schulz



Advantages

- Highly parallelizable
  - independent from the minimization
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- Highly parallelizable
  - independent from the minimization
- All kind of parameters can be tuned
  - Not only reweight-able
- Advanced system
  - 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
    - Avoid unphysical result
  - Nuisance rescaling parameters can be inserted
    - proper treatment for datasets without correlations (MiniBooNE)
- Reliable minimization algorithm
  - based on Minuit

The first tuning

Tuning against CC 0π datasets

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
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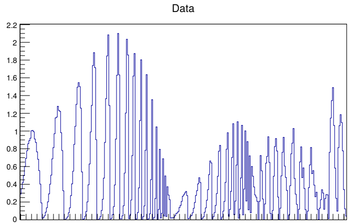

- Missing Covariance between Neutrino and antineutrino data
  - Minerva released this information!

Models and parameters

- Default + Empirical MEC
  - `G16_01b` in naming scheme
- Full Nieves Model
  - `G16_02a` in naming scheme

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Parameter	Range	Default value
QEL-M_A (GeV/c^2)	[0.7 ; 1.8]	0.99
QEL-CC-XSecScale	[0.8 ; 1.2]	1
RES-CC-XSecScale	[0.5 ; 1.5]	1
FSI-PionMFP-Scale	[0.6 ; 1.4]	1
FSI-PionAbs-Scale	[0.4 ; 1.6]	1
MEC-FracCCQE - G16_01b only	[0 ; 1]	0.45
MEC-CC-XSecScale - G16_02a only	[0.7; 1.3]	1

Models and parameters

- Default + Empirical MEC
  - `G16_01b` in naming scheme
- Full Nieves Model
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FSI-PionMFP-Scale	[0.6 ; 1.4]	1
FSI-PionAbs-Scale	[0.4 ; 1.6]	1
MEC-FracCCQE - G16_01b only	[0 ; 1]	0.45
MEC-CC-XSecScale - G16_02a only	[0.7; 1.3]	1

- Other inputs:
  - Nuisance scaling parameters 30 % for MiniBooNE Dataset
  - Priors on QEL-CC-XSecScale and RES-CC-XSecScale
    - Gaussian with sigma 0.1

Sheer results

`G16_01b` - Default + MEC

Parameter	Best fit	Nominal
M_A (GeV/c^2)	1.17 ± 0.03	0.99 ± 0.01
QEL-CC-XSecScale	0.92 ± 0.02	1
RES-CC-XSecScale	1.02 ± 0.07	1
MEC-FracCCQE	0.55 ± 0.06	0.45
FSI-PionMFP-Scale	0.86 ± 0.04	1.0 ± 0.2
FSI-PionAbs-Scale	0.76 ± 0.09	1.0 ± 0.3

`G16_02a` - Full Nieves Model

Parameter	Best fit	Nominal
M_A (GeV/c^2)	1.00 ± 0.03	0.99 ± 0.01
QEL-CC-XSecScale	0.91 ± 0.02	1
RES-CC-XSecScale	1.01 ± 0.04	1
MEC-CC-XSecScale	1.18 ± 0.02	1
FSI-PionMFP-Scale	1.17 ± 0.04	1.0 ± 0.2
FSI-PionAbs-Scale	1.02 ± 0.09	1.0 ± 0.3

- M_A is reasonably low
  - Nieve's model is compatible with free nucleons fit
  - Precision of M_A reduced
  - $\Rightarrow$ Our choice not to add a strong prior
- QEL reduced by $\sim 10\%$
- MEC increased by $\sim 20\%$
- FSI parameters strongly correlated
  - They are better constrained than the GENIE prior

Agreement with respect to datasets

G16_01b - Default + MEC

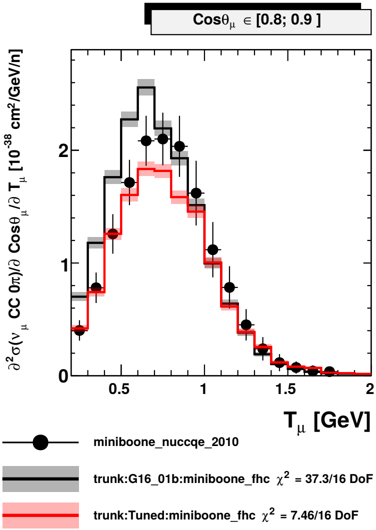
Dataset	Best fit χ^2	Nominal χ^2
Miniboone ν_μ CC 0π	177 / 137	441 / 137
MiniBooNE $\bar{\nu}_\mu$ CC 0π	66.2 / 78	50.4 / 78
T2K ND 280 CC 0π	94 / 80	56.6 / 80
Total	337 / 289	548 / 295

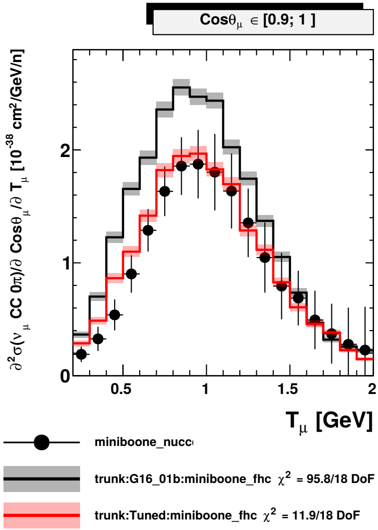
G16_02a - Full Nieves Model

Dataset	Best fit χ^2	Nominal χ^2
Miniboone ν_μ CC 0π	89.3 / 137	101 / 137
MiniBooNE $\bar{\nu}_\mu$ CC 0π	48.1 / 78	176 / 78
T2K ND 280 CC 0π	102 / 80	98.9 / 80
Total	239 / 289	376 / 295

- Improvement possible for both models
  - $\Rightarrow$ The fit is working
- Fit driven by MiniBooNE datasets
  - Lowest information $\Rightarrow$ No correlations
  - Room for improvement
- These T2K and Minerva datasets cannot be fit on their own
  - They cover a small phase space region
  - $\Rightarrow$ Parameters goes to the boundaries

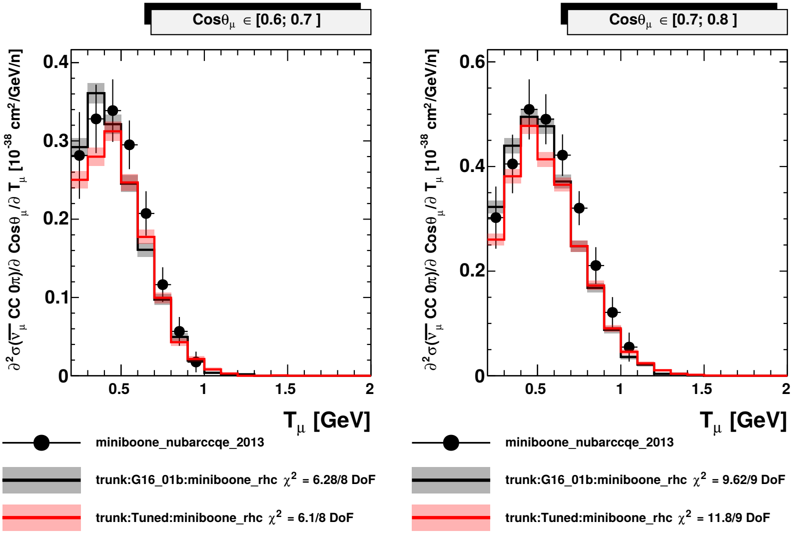
Best fit - G16_01b - MiniBooNE ν_μ CCQE





Fit has a big impact

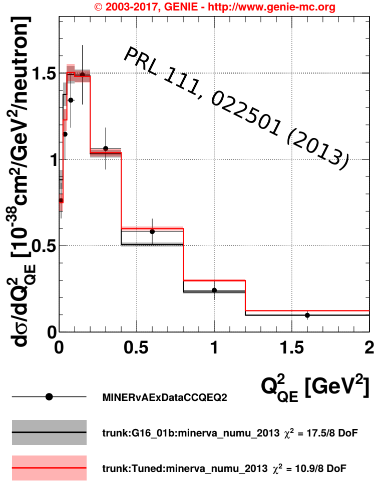
Best fit - G16_01b - MiniBooNE $\bar{\nu}_\mu$ CCQE



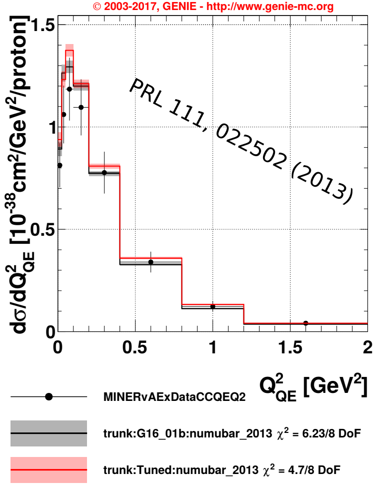
Improvement not really necessary in this case

Best fit - G16_01b - MINERvA

Neutrinos



Antineutrinos



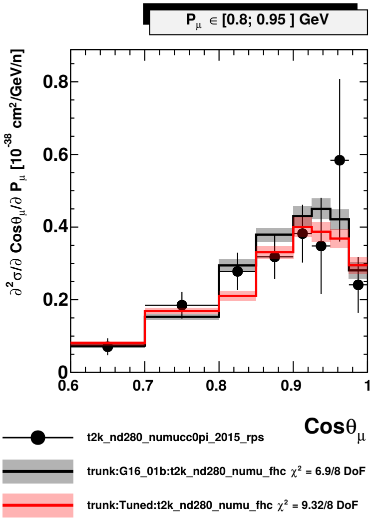
$\Rightarrow$ "Eye evaluation" wouldn't prefer a model over the other

Best fit - G16_01b - T2K ND280

- agreement with T2K has worsened
- not surprising

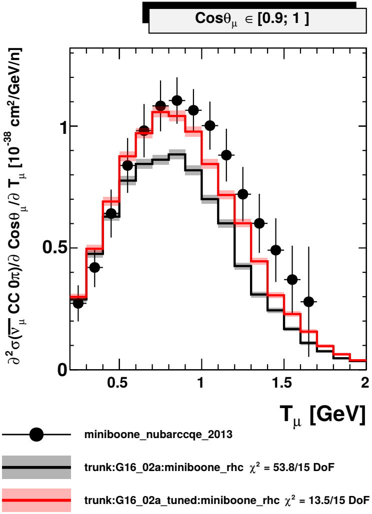
$\Rightarrow$ Tensions already highlighted

- χ^2: 57 $\rightarrow$ 94 / 80 DoF



Best fit - G16_02a

- Nieves' model already works well
  - Agreement is preserved
- Notable improvement only w.r.t. MiniBooNE $\bar{\nu}_\mu$



Next steps

- More tunings can be done
  - hadronization retune
    - Pythia 6 and 8 (implementation is ongoing)
  - Tune of FSI
    - Both hN and hA intranuke
  - Free nucleon cross section model
    - including $d\sigma/dQ^2$ data

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  - Tune of FSI
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  - Free nucleon cross section model
    - including $d\sigma/dQ^2$ data
- Data from Liquid argon experiments
  - Part of GENIE collaboration is in SBND
  - Plan for argon tunings
- Look forward to more data
- Release these results
  - Paper is in preparation
  - Implementation in GENIE v3

Conclusion

- We are renewing GENIE
  - New models
  - Systematic validation against Cross section data
  - Maintained and rich database

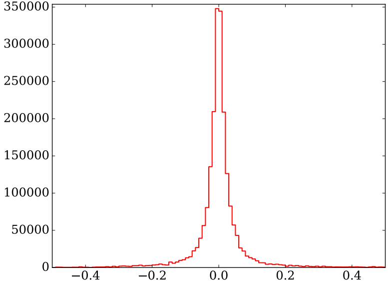
- We have a very powerful fitting machinery
  - Validated
  - A new branch of analyses
  - Alternative tool to propagate systematic uncertainties

- What we can do depends on data quality
  - Look forward a promising collaboration between generators, experiments and theorists

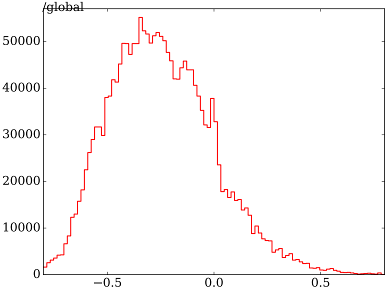
Genie
UNIVERSAL NEUTRINO GENERATOR & GLOBAL FIT

Backup slides

Parametrization residuals

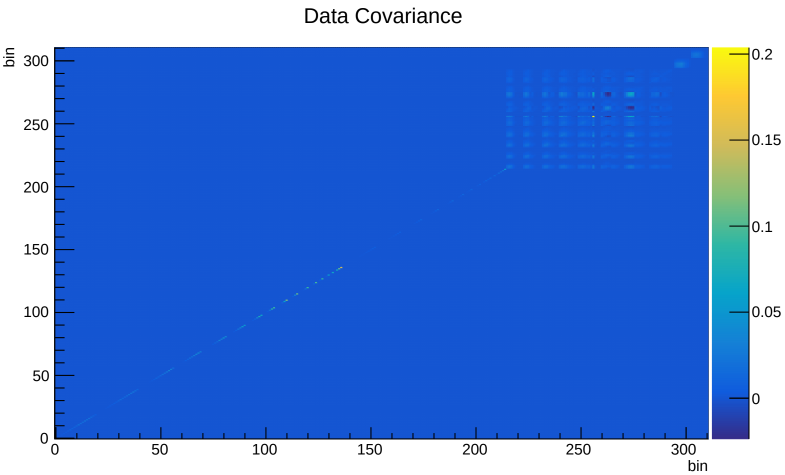


Good

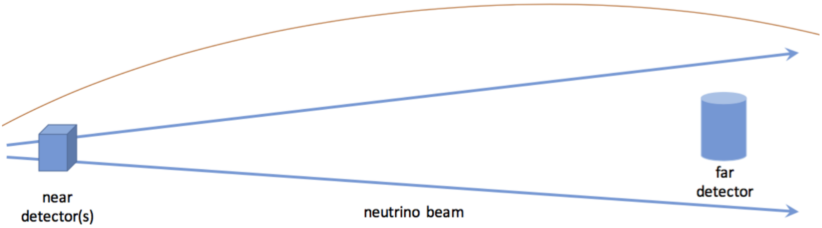


Bad

Data covariance



Model dependencies in Oscillation Analyses



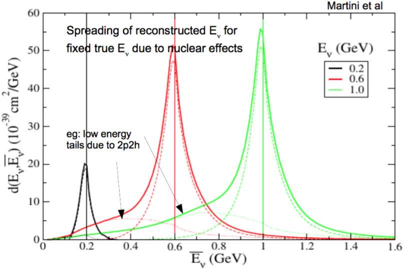
- A simple ratio between Near and Far spectra is not enough
  - Detectors exposed to different flux
  - “functionally identical” detectors do not exists
- Near flux has to be fitted at the near detector and then propagated
  - $\Rightarrow$ Models required

Model dependencies in Oscillation Analyses (2)

- CCQE is a 2-body reaction
  - E_ν depends is just a function of lepton momentum and angle
- 2p/2h is not a 2-body reaction
  - low energy tails in reconstructed energy distributions
- 2p/2h also relevant for CP searches
  - np-nh is different for $\nu/\bar{\nu}$

$\Rightarrow$ 2p/2h modelling is important to achieve required precision

$$E_\nu = \frac{m_p^2 - (m_n - E_b)^2 - m_\ell^2 + 2(m_n - E_b)E_\ell}{2(m_n - E_b - E_\ell + p_\ell cos\theta_\ell)}$$



Martini et al.

Model comparison

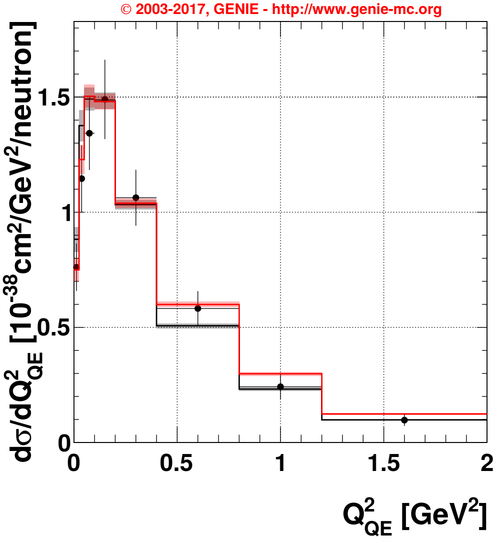
Model comparison

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]

Importance of the covariance - an example



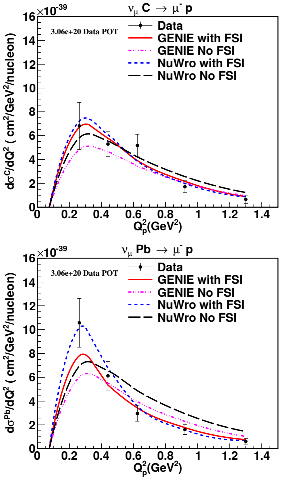
- Real dataset
- 8 points
- Which is the best agreeing curve?
  - Black
  - Red
- Difference in terms of sigma?
  - < 1
  - > 1
- Black $\chi^2 = 17.5/8$ DoF
- Red $\chi^2 = 10.9/8$ DoF

$\Rightarrow$ Almost 2 σ

Example of easy improvement

- Minerva experiment
- Cross sections of CC 1-proton on different targets
  - C, Fe, Pb
- Wonderful dataset
  - 2p/2h and FSI tuning
- Covariance matrices for each target
  - Best format among present data releases

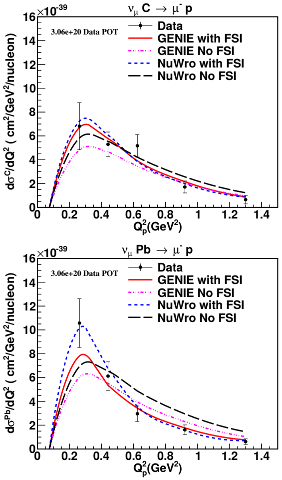
arXiv:1705.03791v1



Example of easy improvement

- Minerva experiment
- Cross sections of CC 1-proton on different targets
  - C, Fe, Pb
- Wonderful dataset
  - 2p/2h and FSI tuning
- Covariance matrices for each target
  - Best format among present data releases
- Not a full covariance matrix
  - Neglecting the same flux
  - Same detector/reconstruction
- We can check agreement
- we can not fit these data
  - without neglecting a correlation

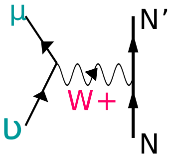
arXiv:1705.03791v1



CC Quasi-Elastic - 0π on single nucleons

$$\frac{d\sigma^{QES}}{dQ^2} = \frac{G_F^2 \cos^2\theta_C M^2 \kappa^2}{2\pi E_\nu^2} \left[A\left(q^2\right) + \left(\frac{s-u}{4M^2}\right) B\left(q^2\right) + \left(\frac{s-u}{4M^2}\right)^2 C\left(q^2\right) \right]$$

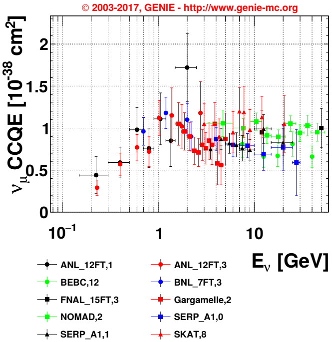
- Theoretically well understood
  - One diagram
- A, B and C are form factors
  - They have to be measured
  - B and C are known from e-N scattering
  - A to be extracted from ν data
- Axial Form factor
  - Dipole standard parameterization
  - $A(Q^2) = g_A \left(1 + \frac{Q^2}{M_A^2}\right)^{-2}$



- $g_A = 1.26$ from neutron β decay
- fitted based on $\partial\sigma/\partial Q^2$ data

CC Quasi-Elastic - Data

- Hydrogen / Deuterium data
  - from 0.1 GeV to ∼ 100 GeV
  - For both Neutrinos and Anti-neutrinos
- Critical parameter: M_A
  - $M_A \sim 1$ GeV



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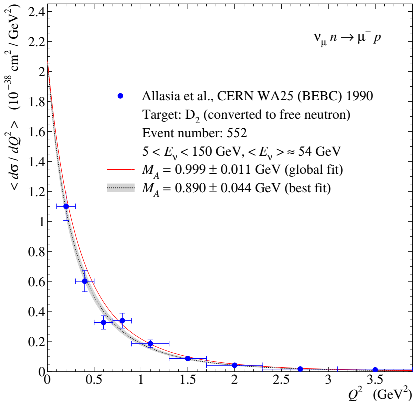
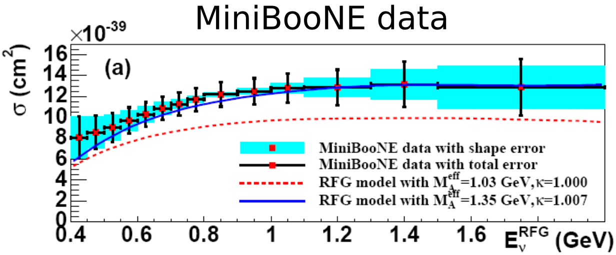


0π on heavy nuclei



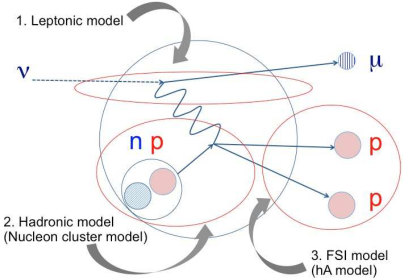
AIP Conf. Proc. 1189: 139-144 (2009); Phys. Rev. D 81, 092005 (2010)

- On heavy nuclei things got complicated
- MiniBooNE $\Rightarrow$ first evidence
  - Carbon target
- Possible explanation from enhanced M_A
  $\Rightarrow$ incompatibility with "historical" datasets

0π on heavy nuclei - Solution

- MoniBooNE is Cherenkov detector
  - Not able to see nucleons
- miniBooNE dataset is a CCQE-like sample
- genuine CCQE
- Multinucleon Emission
  - np-nh
  - Leading contribution is 2p-2h (2 particles - 2 holes)

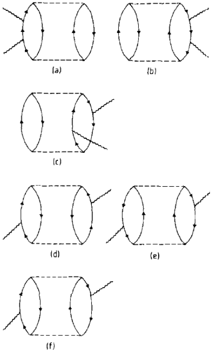
2p-2h scheme



2 Particles - 2 Holes

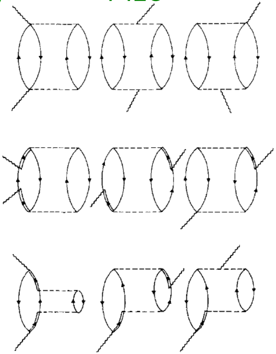
M. Martini

NN correlations



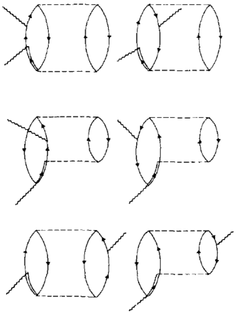
16 diagrams

MEC



49 diagrams

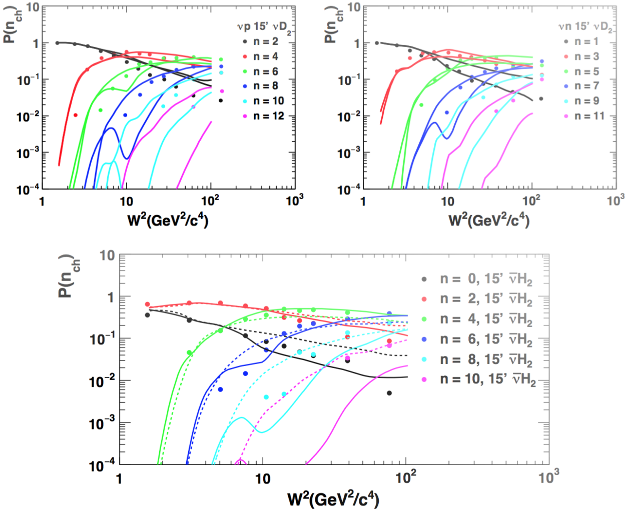
NN correlation-MEC interference



56 diagrams

Not easy to have a complete model
Different approaches include different diagrams

Hadronization example



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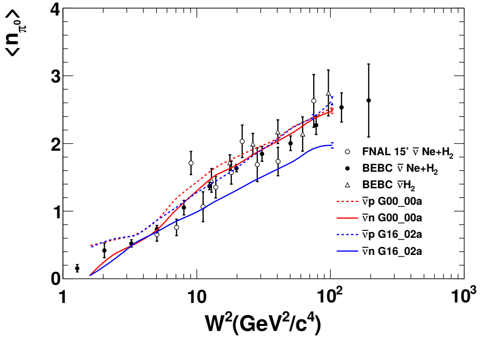

Tuning Output

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

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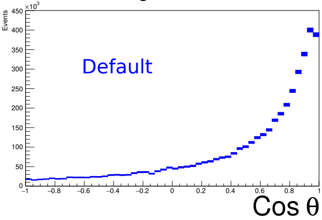
Muon Angle for 0π events



- Data Constraints for Oscillation analyses

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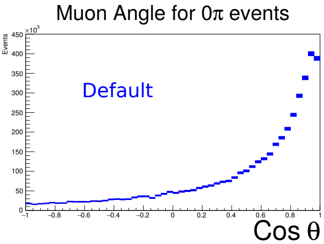
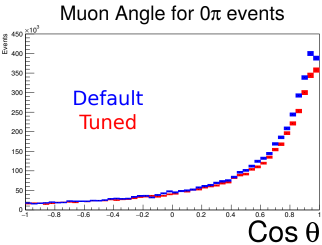
- Data Constraints for Oscillation analyses
  - Propagate the result to other observables





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