GENIE/Professor framework for neutrino data global fit

A first application: global fit of CC 0π datasets

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on behalf of GENIE collaboration

University of Liverpool

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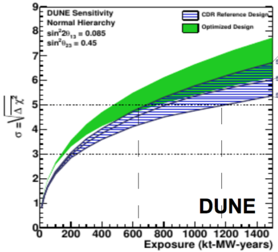
Outline

- Introduction
  - Physics of interactions
  - Generators
- Genie status vs recent datasets
- Tuning mechanism
- Tuning results
- Conclusions

Why care about 0π interactions?

- Lepton CP violation and mass hierarchy
- Oscillation experiments
  - T2k, NOvA
  - DUNE, HyperK
  - Beam energy $\sim$ few GeV
- CC 0π is the important reaction
  - for DUNE $\sim$ 40% of the interactions
- Two body reaction
  - Ideal for ν energy estimation ... ...on free nucleons



5% ± 1%

5% ± 2%

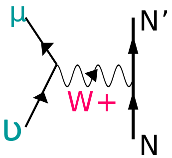
5% ± 3%

→ equivalent to factor 2 in exposure!

CC Quasi-Elastic - 0π on single nucleons

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

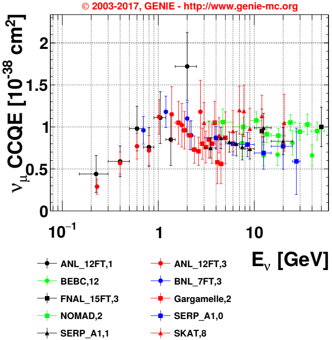
- Theoritally well understood
  - One diagram
- A, B and C are form factors
  - They have to be measured
  - B and C are known from e-N scattering
  - A to be extracted from ν data
- Axial Form factor
  - Dipole standard parameterization
  - $A(Q^2) = g_A\left(1 + \frac{Q^2}{M_A^2}\right)^{-2}$



- $g_A = 1.26$ 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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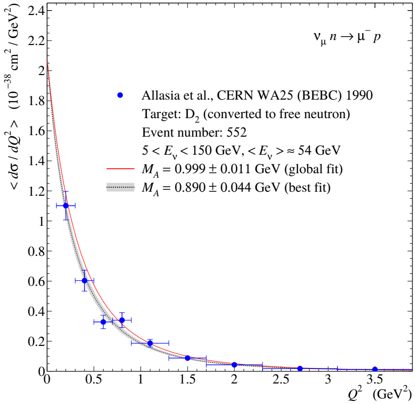
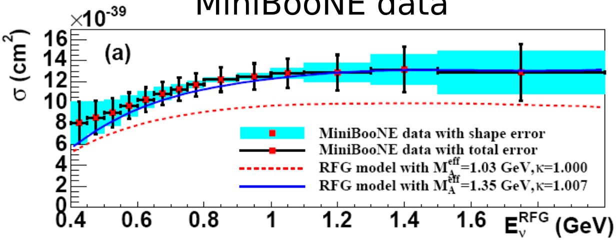


0π on heavy nuclei

MiniBooNE data



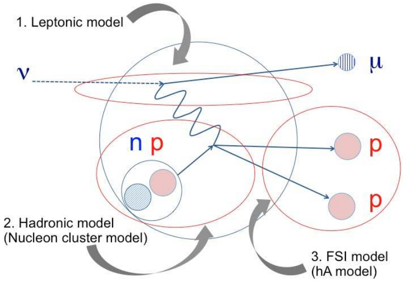
AIP Conf. Proc. 1189: 139-144 (2009); Phys. Rev. D 81, 092005 (2010)

- 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)

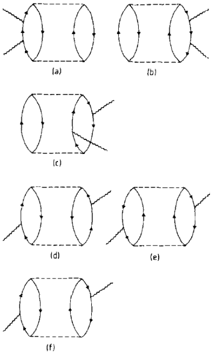
2p-2h scheme



2 Particles - 2 Holes

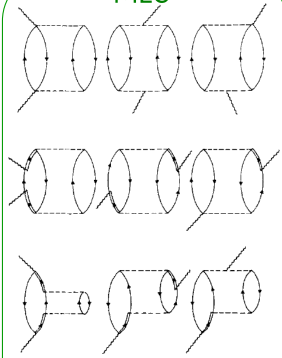
M. Martini

NN correlations



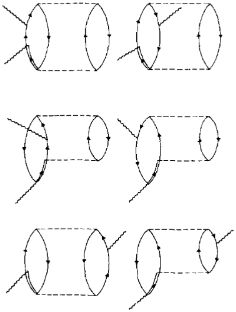
16 diagrams

MEC



49 diagrams

NN correlation-MEC interference



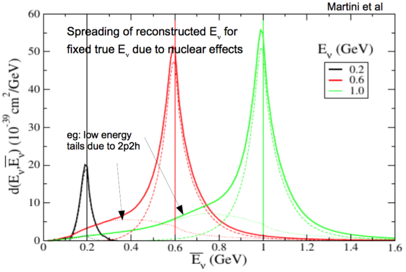
56 diagrams

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

Effect of MEC on energy reconstruction

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

$\Rightarrow$ MEC is important to achieve precise measurements

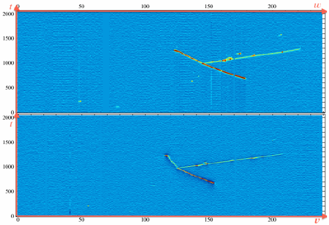


Martini et al.

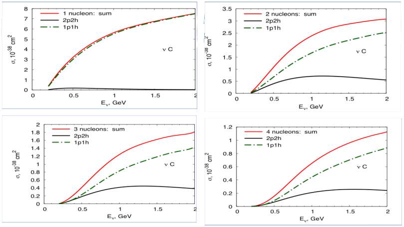
Search for 2p-2h

- 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

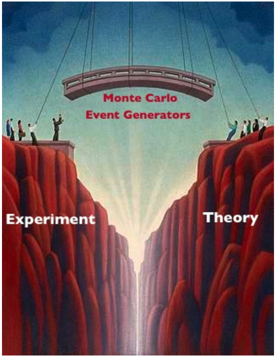


[Phys.Rev. D90 (2014) 1, 012008]



[Ulrich Mosel]

Neutrino MC Generators: A Theory/Experiment Interface



- Connect truth and observables
  - event topologies and kinematics
- Neutrino MC Generators allow access the flux distorsion due to oscillation
  - Every observable is a convolution of flux, interaction physics and detector effects
- *Good Generators*
  - uncertainty validation
  - tune the *physics* models that drive the result of that convolution

$\Rightarrow$ Tuning proved to be difficult
  - So far no results

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

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 Rochester, 5 - STFC Rutherford Appleton Laboratory, 6 - IPHC Strasbourg, 7 - Tufts University, 8 - Valencia University

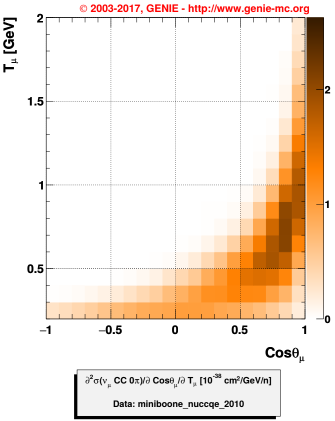
- Core GENIE mission
  1. ... provide a state-of-the-art neutrino MC generator for the world experimental neutrino community
  2. ... simulate all processes for all neutrino species and nuclear targets, from MeV to PeV energy scales
  3. ... perform global fits to neutrino, charged-lepton and hadron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

Genie - Models for 0π

- Default - `G00_00a`
  - No MEC
  - CCQE process is LwlynSmith Model
  - Dipole Axial Form Factor - Depending on $M_A = 0.99\ GeV$
  - Nuclear model: Fermi Gas Model - Bodek, Ritchie
- Default + MEC - `G16_01b`
  - with Empirical MEC
  - CCQE process is LwlynSmith Model
  - Dipole Axial Form Factor - Depending on $M_A = 0.99\ GeV$
  - Nuclear model: Fermi Gas Model - Bodek, Ritchie
- Nieves, Simo, Vacas Model - `G16_02a`
  - Theory motivated MEC
  - CCQE process is Nieves
  - Dipole Axial Form Factor - Depending on $M_A = 0.99\ GeV$
  - Nuclear model: Local Fermi Gas Model
- G17_02a (not presented in this talk) - `G17_02a`
  - with Z-Expansion for Axial form factor
  - Get rid of M_A

MiniBooNE CCQE

- Both ν and $\bar{\nu}$
- 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



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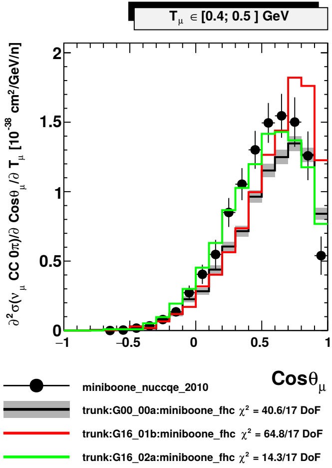
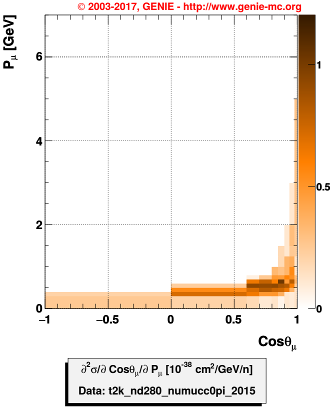


T2K ND280 0π

- 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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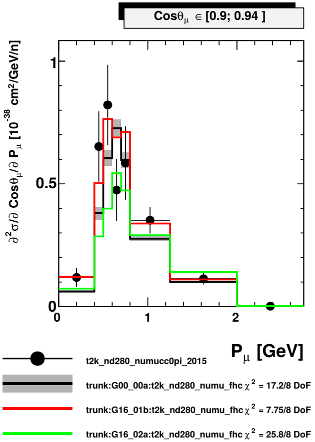

Role of MC generators

- Comparing different data and models
  - Being quantitative ⇒ highlight tensions
    - Call for experiments: we need full covariance matrices
  - feedback for experiments
    - ⇒ drive the format of cross section releases
    - ⇒ hint toward key measurements
    - ⇒ If you plan Cross section Analysis first call us!!
- Global fits
  - Provide the constraints on Cross Section for oscillation analysis

- Neutrino Cross sections priors
- Based on Neutrino data fit!

Example of VALOR Cross Section
Correlation matrix

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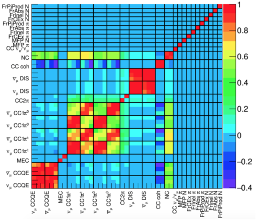

Example of VALOR Cross Section Correlation matrix

- Neutrino Cross sections priors
- Based on Neutrino data fit!

Role of Generators - Global Fits

- Natural environment to perform global fits
  - Model $\Rightarrow$ Cross sections is not analytic
  - Tuning requires tweaking the code
- Notable attempt - Nuisance
  - “aims to provide a coherent framework for comparing neutrino generators to external data”
  - “can also tune cross-section parameters to available data”
- Limitations
  - Models treated like black boxes
  - Limited acces to the code
    - Tweaking the code is important for tuning

GENIE

- New Models
  - MEC models
    - Empirical
    - Nieves Simo Vacas
  - Better CCQE model
    - Nieves
    - ...
  - Nuclear models
  - Dedicated codes
    - Starting from GENIE v3
    - `--tune G16_01a`
- Multiple combinations
  - Need to check the balance between each component

will have a tuning!

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The Comparisons

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

- Crucial technology for **new GENIE global fit** to neutrino scattering data
- Provides the opportunity to improve and develop GENIE models
- All sorts of data
  - **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**

Professor

- `http://professor.hepforge.org`
- Numerical assistant
- Developed for ATLAS experiment
- $I(p)$ used instead of a full MC
  1. MC runs subset of param space
  2. sample bin's behaviour
  3. Parametrization $I(p)$
     - Polinomial interpolation
  - Repeat for each bin
- a parameterization $I_i(p)$ for each bin
- Minimize according to $\vec{I}(p)$
- $\sim$ 15 parameters
- Special thanks to H. Schulz

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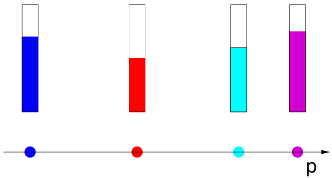

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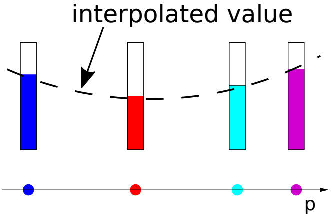

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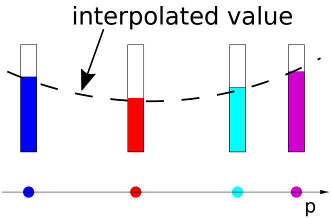

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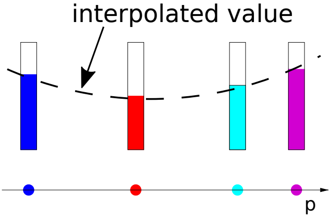

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Advantages

- 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
  - Nuisance parameters can be inserted
    - proper treatment for datasets without correlations (MiniBooNE)
- Reliable minimization algorithm
  - based on Minuit

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
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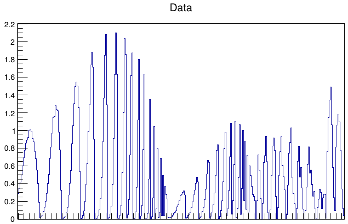

- Missing Covariance between Neutrino and antineutrino data
- Expected from next generation of experiments
  - SBND

Models and parameters

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

Parameters

- QEL-$M_A \in [0.7; 1.8]$ GeV - Default value is 0.99 GeV
- QEL-CC-XSecScale $\in [0.8; 1.2]$ - Default value is 1
- RES-CC-XSecScale $\in [0.5; 1.5]$ - Default value is 1
- FSI-PionMFP-Scale $\in [0.6; 1.4]$ - Default value is 1
- FSI-PionAbs-Scale $\in [0.4; 1.6]$ - Default value is 1

- MEC-FracCCQE $\in [0; 1]$
  - Default value is 0.45
- MEC-CC-XSecScale $\in [0.7; 1.3]$
  - Default value is 1

Other Inputs

- nuisance scaling parameters 30 % for MiniBooNE Dataset
- Priors on QEL-CC-XSecScale and QEL-CC-XSecScale
  - Gaussian with sigma 0.1

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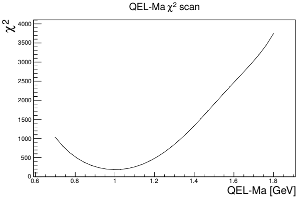
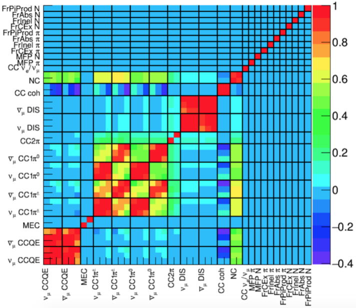
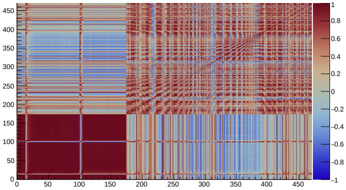
Tuning Output

- Parameters best fit
- Parameters covariance
- Prediction covariance
  - due to the propagation of parameter covariance
- Data dependent Constraints for Oscillation analyses







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 contrainted than the GENIE prior

Agreement with respect to datasets

G16_01b - Default + MEC

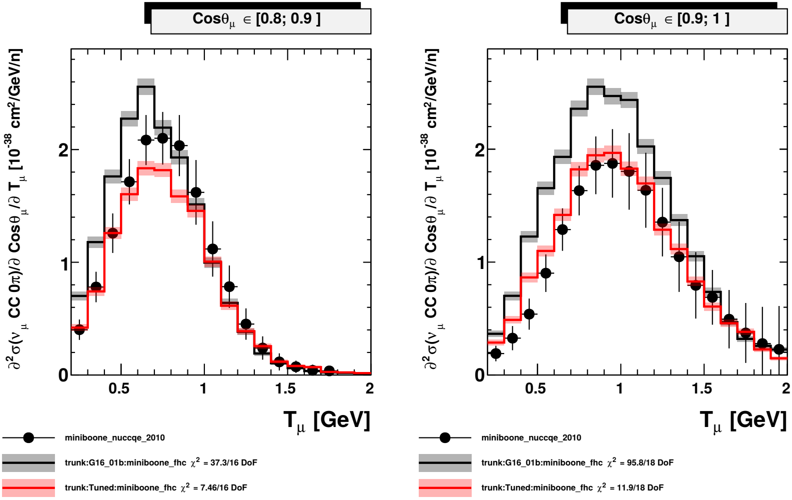
Dataset	Best fit χ^2	Nominal χ^2
Miniboone ν_μ CC 0π	177 / 137	441 / 137
MiniBooNE $\bar{\nu}_\mu$ CC 0π	66.2 / 78	50.4 / 78
T2K ND 280 CC 0π	94 / 80	56.6 / 80
Total	337 / 289	548 / 295

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

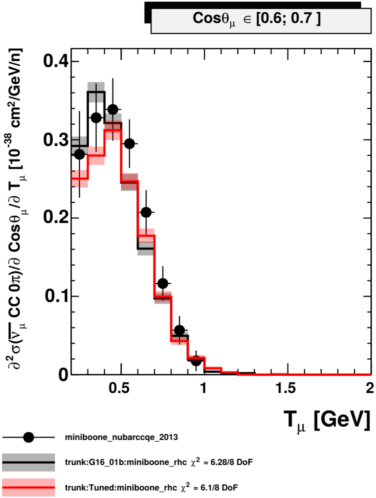
- Improvement possible for both Models
  - $\Rightarrow$ The fit is working
- Fit driven by MiniBooNE datasets
  - using MiniBooNE data is debatable
  - poor data quality
    - No correlations
- T2K ND280 data are complicated
  - Tensions
  - Correlations $\Rightarrow$ anti-intuitive

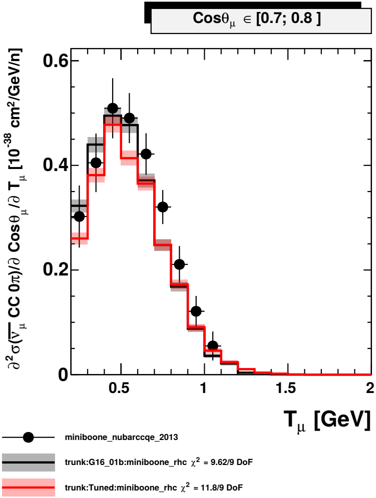
Best fit - G16_01b - MiniBooNE ν_μ CCQE



Fit has a big impact

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

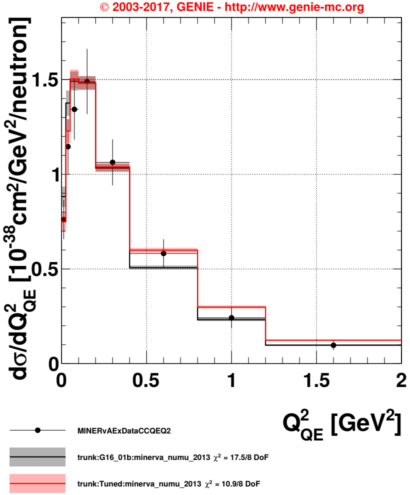




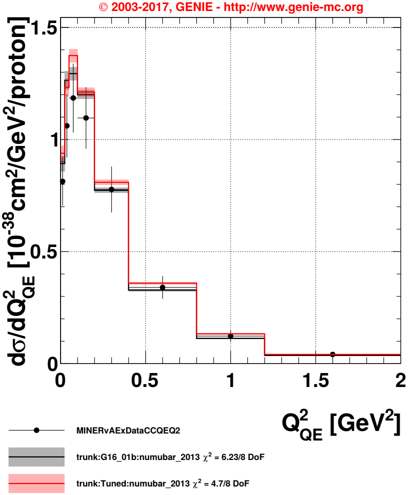
Improvement not really necessary in this case

Best fit - G16_01b - MINERvA

Neutrinos

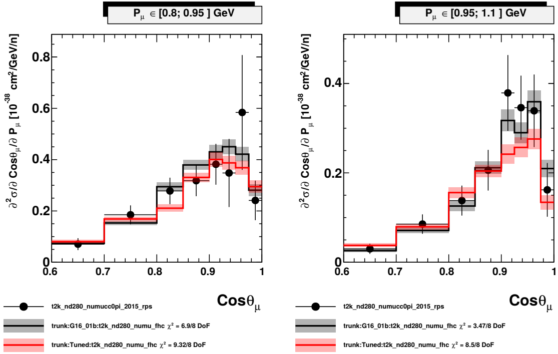


Antineutrinos



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

Best fit - G16_01b - T2K ND280



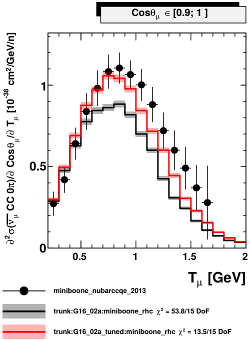
- agreement with T2K has worsened
- not surprising

⇒ Tensions already highlighted

- χ^2: 57 → 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 datasets to be included:
  - Bubble chamber CCQE data
    - Why not fitting M_A all together?
    - require database $\partial\sigma/\partial Q^2$
  - MINERvA data on differenent target nuclei
- Release these results
  - papers late summer
  - Implementation in GENIE v3

Conclusion

- We are renewing Genie
  - new models
  - Easy comparisons with Cross section Data
    - $\Rightarrow$ Quantitative
  - Deployed in Genie v3 and v4
- We have a very powerful fitting machinery
  - Proved to work
  - This is not an exercise
- We hope that these tools will improve
  - theory / experiments collaboration
  - Search for CP violation

Backup slides