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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IPPP/NuStec

Outline

- Introduction
- Genie status vs recent datasets
- Tuning mechanism
- Tuning results
- Conclusions

Thanks to

IPPP Associateship award

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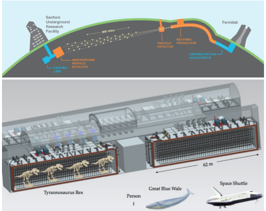
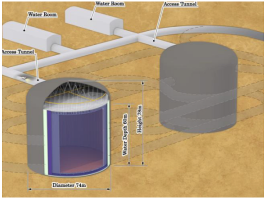
Why care about 0π?

- We want to study neutrinos
  - flavour and mixing
  - Lepton CP violation
- Oscillation experiments
  - T2k, NOvA
  - DUNE, HyperK
  - Beam energy $\sim$ few GeV
- CC 0π is the dominant reaction
- Two body reaction
  - Ideal for ν energy estimation ...
  - ...on free nucleons

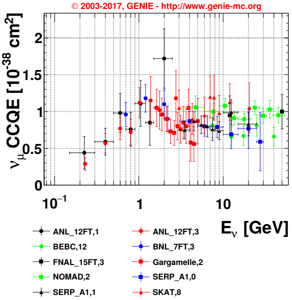




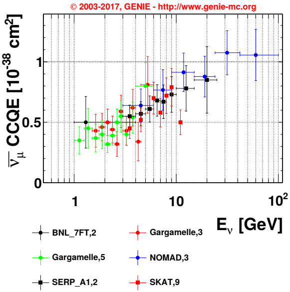
CC Quasi-Elastic - 0π on single nucleons

- Theoretically understood
- Well constrained by experimental information
- Electron scattering
- Neutron β decay
- Experiments on Hydrogen / Deuterium

Neutrinos

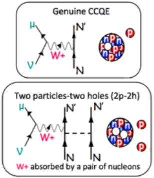


Antineutrinos

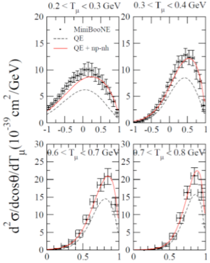


CC Meson Exchange Current - 0π on heavy nuclei

- On higher A nuclei things are complicated
- CCQE is not enough to describe data
  - MiniBooNE
- MEC is required
  - nucleons interactions
  - 2p-2h
  - *n*p-*n*h
  - $>$ 20 % effect
    - On carbon



MiniBooNE data

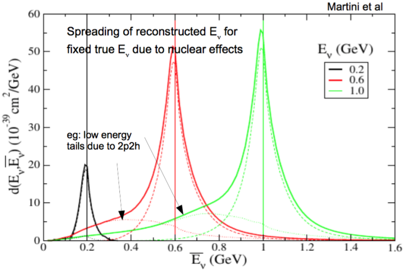


[Martini et al. PRC 84 055502 (2011)]

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

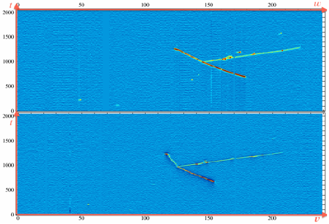


Martini et al.

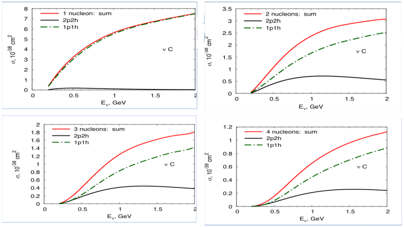
Search for 2p-2h

- 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]

MC generators

- What can we do as generator people?
- Comparing different data and models
  - Being quantitative
    - $\Rightarrow$ highlight tensions
    - Call for experiments: we need full covariance matrices
  - feedback for experiments
    - $\Rightarrow$ drive the format of cross section releases
    - $\Rightarrow$ hint toward key measurements
- Global fits
  - Model $\Rightarrow$ Cross sections is not analytic

What is the status of Genie in all of this?

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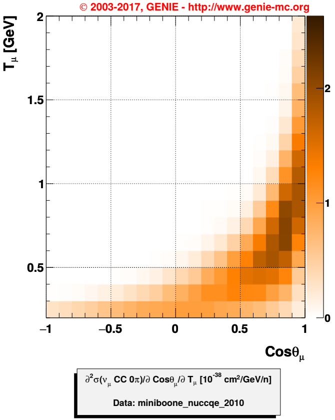
What is the status of Genie in all of this?

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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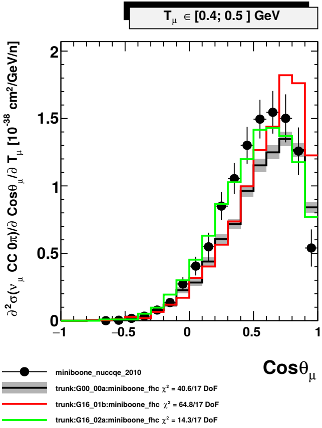
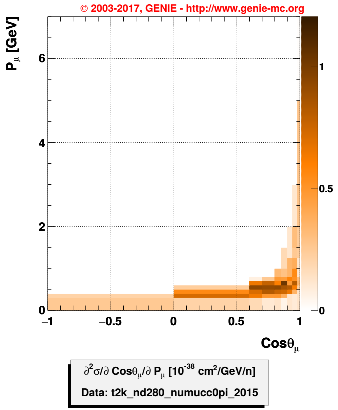


T2K ND280 0π

- 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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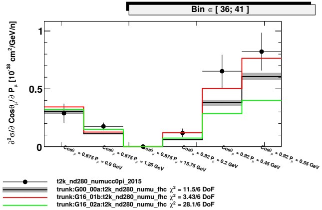

GENIE

- New Models
  - MEC models
    - Empirical
    - Nieves Simo Vacas
  - Better CCQE model
    - Nieves
    - ...
  - Nuclear models
- Multiple combinations
  - Need to check the balance between each component

will have a tuning!

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will have a tuning!

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
    - based here in Durham

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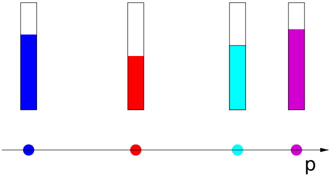

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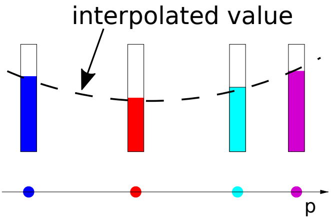

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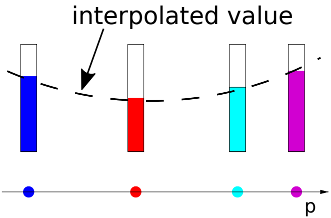

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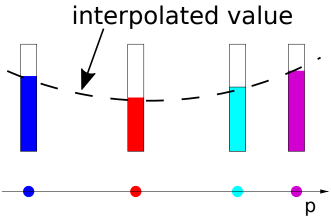
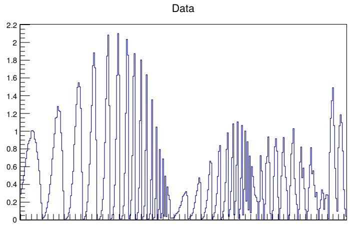


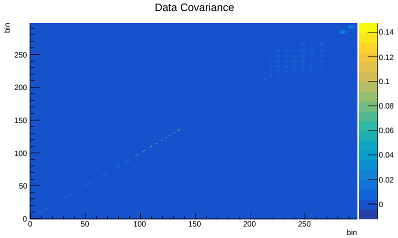
Advantages

- 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 - 298 data points

- MiniBooNE ν_μ CCQE
  - 2D histogram
  - 137 points
- MiniBooNE $\bar{\nu}_\mu$ CCQE
  - 2D histogram
  - 78 points
- T2K ND280 0π (2015)
  - irregular 2D histogram
  - 67 points
- MINERvA ν_μ CCQE
  - 1D histogram
  - 8 points
- MINERvA $\bar{\nu}_\mu$ CCQE
  - 1D histogram
  - 8 points





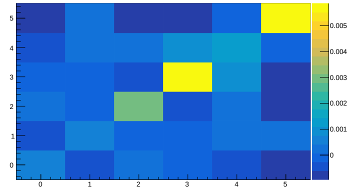
Model and parameters

- Default + Empirical MEC
- `G16_01b` in the new 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
  - MEC-FracCCQE $\in [0; 1]$ - Default value is 0.45
  - FSI-PionMFP-Scale $\in [0.6; 1.4]$ - Default value is 1
  - FSI-PionAbs-Scale $\in [0.4; 1.6]$ - Default value is 1
- No priors on the parameters
  - Considering on M_A

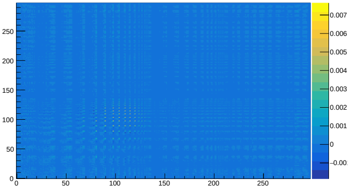
Professor Output

- Parameters best fit
  - 0 M_A
  - 1 QEL-CC-XSecScale
  - 2 RES-CC-XSecScale
  - 3 MEC-FracCCQE
  - 4 FSI-PionMFP-Scale
  - 5 FSI-PionAbs-Scale
- Prediction covariance
  - due to the propagation of the param. covariance
  - So far not used
  - Tool to propagate systematics parameters

Parameter Covariance



Prediction Covariance



Sheer results

Parameter	Best fit	Nominal
M_A (GeV/c^2)	1.21 ± 0.02	0.99
QEL-CC-XSecScale	0.95 ± 0.02	1
RES-CC-XSecScale	1.02 ± 0.05	1
MEC-FracCCQE	0.53 ± 0.08	0.45
FSI-PionMFP-Scale	0.75 ± 0.04	1
FSI-PionAbs-Scale	0.87 ± 0.07	1

- M_A is reasonably low
- Scaling factors for single processes are compatible with nominal values
- You can find the complete comparisons plots in the indico page

Single datasets

Datasets were fitted separately

Parameter	Neutrino fit	Anti-neutrino fit	Global fit
M_A (GeV/c^2)	1.17 ± 0.02	1.26 ± 0.03	1.21 ± 0.02
QEL-CC-XSecScale	0.93 ± 0.01	0.97 ± 0.02	0.95 ± 0.02
RES-CC-XSecScale	0.86 ± 0.05	0.98 ± 0.09	1.02 ± 0.05
MEC-FracCCQE	0.85 ± 0.03	0.7 ± 0.1	0.53 ± 0.08
FSI-PionMFP-Scale	0.87 ± 0.02	1.39 ± 0.03	0.75 ± 0.04
FSI-PionAbs-Scale	1.51 ± 0.03	0.7 ± 0.1	0.87 ± 0.07

Fit Results	Neutrino fit	Anti-neutrino fit	Global fit	Nominal Values
Miniboone ν_μ χ^2	152 / 137	171 / 137	138 / 137	441 / 137
MiniBooNE $\bar{\nu}_\mu$ χ^2	60 / 78	32.4 / 78	36.2 / 78	50.4 / 78
T2K χ^2	237 / 67	276 / 67	252 / 67	135 / 67
MINERvA ν_μ χ^2	6.11 / 8	8.07 / 8	7.79 / 8	17.5 / 8
MINERvA $\bar{\nu}_\mu$ χ^2	8.19 / 8	11.5 / 8	5.7 / 8	6.23 / 8
Global dataset χ^2	463 / 292	499 / 292	440 / 292	650 / 298

- M_A and cross section scale factors are in good agreement
- FSI parameters are not
- The agreement with data is reasonable
  - Better than original model

T2K effect on the fit

- T2K ND280 data are complicated
  - Tensions
  - Correlations $\Rightarrow$ anti-intuitive
- T2K ND280 data can not even be fitted by their own with the current model

$\Rightarrow$ $\chi^2 = 127/61$

- T2K fit results are not compatible with other dataset

$\Rightarrow$ $\chi^2 = 1023/137$ vs MiniBooNE ν_μ CCQE

$\Rightarrow$ $\chi^2 = 1567/292$ vs whole fitted dataset

- global fit can suffer from this
- Effect is clear
- discrepancy in low momentum muons
  - $T_\mu < 400$ MeV
- No reason to remove this dataset from the fit
  - Their effort on the error estimation should be praised

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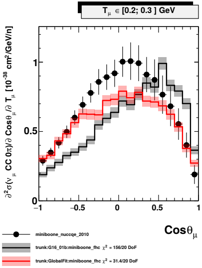
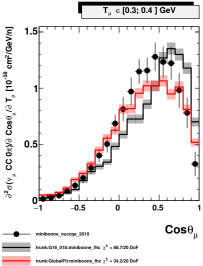
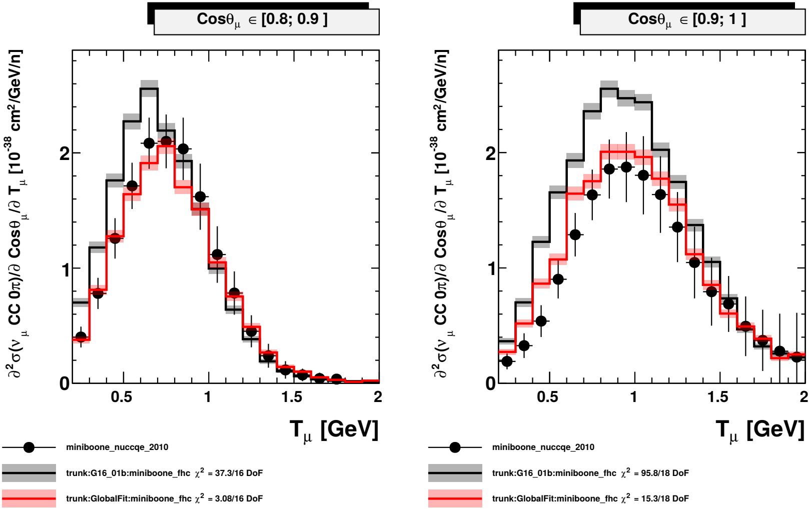


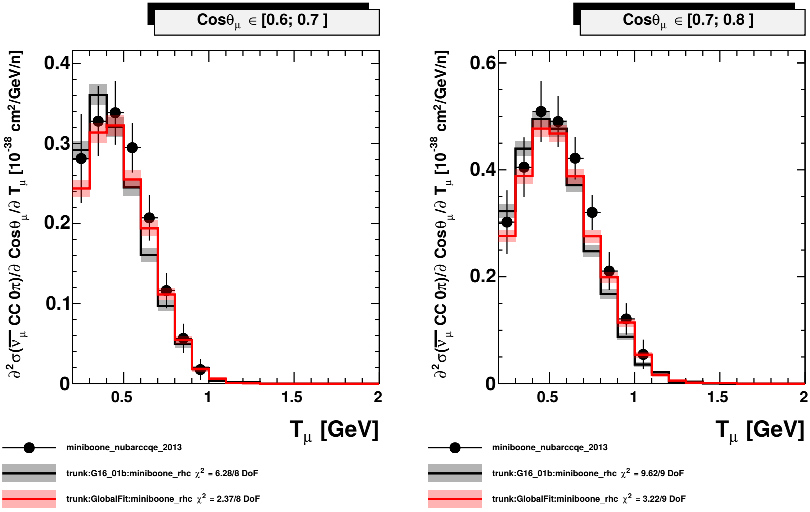


Best fit - MiniBooNE ν_μ CCQE



Fit has a big impact

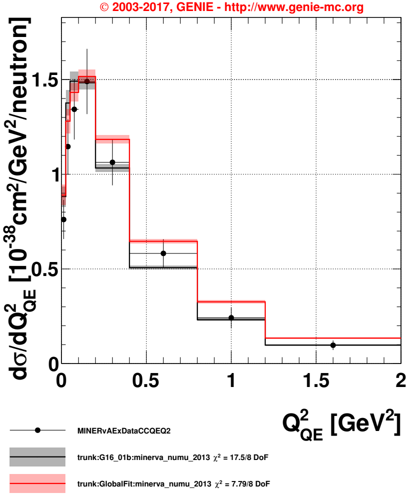
Best fit - MiniBooNE $\bar{\nu}_\mu$ CCQE



Improvement not really necessary in this case

Best fit - MINERvA

Neutrinos



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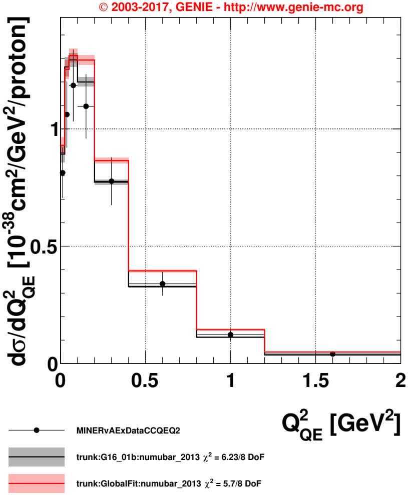


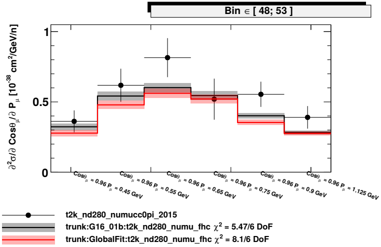
$\Rightarrow$ "Eye evaluation" would prefer default model

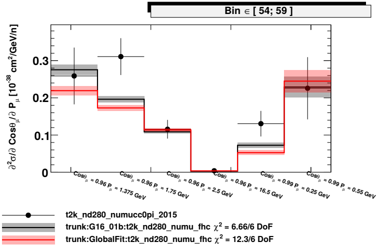
Best fit - T2K ND280

- agreement with t2k has worsened
- not surprising

$\Rightarrow$ it happened also with models

- χ^2: 135 $\rightarrow$ 252 / 67 DoF





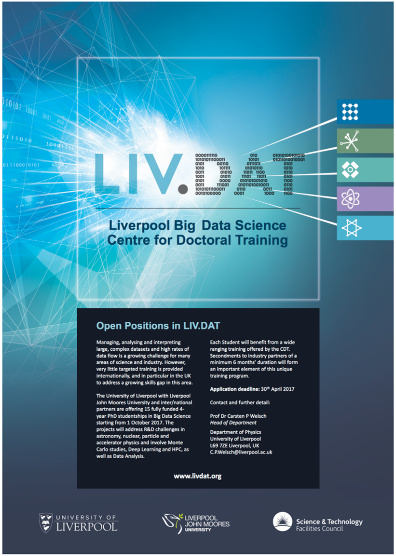
Next steps

- More datasets:
  - Bubble chamber CCQE data
    - Why not fitting M_A all together?
    - Data are in our database (see introduction)
  - inclusive cross sections
    - avoid fit results to go in not physical regions
- Fit of new models
  - Full Nieves Model - `G16_02b`
  - ...
- Find a way to estimate correlations for MiniBooNE
  - Nuisance parameters

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

Advertisment



- New Position in Liverpool
  - Join a big neutrino group
- Position has to be filled in 10 days
- Big data science
  - SBND
  - Argon Tune for GENIE

Backup slides

Single datasets - MiniBooNE

Parameter	Miniboone ν_μ fit	MiniBooNE $\bar{\nu}_\mu$	MiniBooNE Global fit
M_A (GeV/c^2)	1.10 ± 0.03	1.25 ± 0.03	1.17 ± 0.02
QEL-CC-XSecScale	1.12 ± 0.02	0.99 ± 0.03	1.05 ± 0.02
RES-CC-XSecScale	0.69 ± 0.06	0.9 ± 0.1	0.68 ± 0.06
MEC-FracCCQE	0.43 ± 0.07	0.63 ± 0.03	0.33 ± 0.08
FSI-PionMFP-Scale	0.95 ± 0.03	1.39 ± 0.04	0.99 ± 0.06
FSI-PionAbs-Scale	1.17 ± 0.07	0.8 ± 0.2	1.08 ± 0.09

Fit Results	Miniboone ν_μ fit	MiniBooNE $\bar{\nu}_\mu$ fit	MiniBooNE Global fitGlobal χ^2
Miniboone ν_μ χ^2	121 / 131	153 / 137	124 / 137
MiniBooNE $\bar{\nu}_\mu$ χ^2	60.4 / 78	29 / 72	40.3 / 78
T2K χ^2	298 / 67	279 / 67	271 / 67
MINERvA ν_μ χ^2	11.4 / 8	10.6 / 8	9.17 / 8
MINERvA $\bar{\nu}_\mu$ χ^2	16.3 / 8	11.7 / 8	10.4 / 8
Global dataset χ^2	507 / 292	483 / 292	455 / 292

Single datasets - T2K ND280 ν_μ 0π

Parameter	T2K fit	T2K fit - no corr	T2K fit with priors
M_A (GeV/c^2)	0.75 ± 0.04	1.03 ± 0.13	
QEL-CC-XSecScale	0.90 ± 0.02	1.11 ± 0.04	
RES-CC-XSecScale	1.2 ± 0.1	1.500 ± 0.001	
MEC-FracCCQE	0.36 ± 0.09	0.3 ± 0.1	
FSI-PionMFP-Scale	0.81 ± 0.05	1.1 ± 0.1	
FSI-PionAbs-Scale	1.1 ± 0.1	1.54 ± 0.08	

Fit Results	T2K fit	T2K fit - no corr
Miniboone ν_μ χ^2	1023 / 137	/ 137
MiniBooNE $\bar{\nu}_\mu$ χ^2	367 / 78	/ 72
T2K χ^2	127 / 61	/ 61
MINERvA ν_μ χ^2	26.1 / 8	/ 8
MINERvA $\bar{\nu}_\mu$ χ^2	23.5 / 8	/ 8
Global dataset χ^2	1567 / 292	/ 292

Single datasets - MINERvA

Parameter	MINERvA ν_μ fit	MINERvA $\bar{\nu}_\mu$	MINERvA Global fit
M_A (GeV/c^2)	1.16 ± 0.10	1.2 ± 0.1	1.20 ± 0.08
QEL-CC-XSecScale	0.81 ± 0.04	0.83 ± 0.03	0.84 ± 0.04
RES-CC-XSecScale	1.2 ± 0.2	0.7 ± 0.3	1.1 ± 0.1
MEC-FracCCQE	0.7 ± 0.2	0.07 ± 0.08	0.6 ± 0.1
FSI-PionMFP-Scale	1.3 ± 0.1	0.9 ± 0.3	1.2 ± 0.2
FSI-PionAbs-Scale	0.8 ± 0.2	1.2 ± 0.3	0.8 ± 0.3

Fit Results	MINERvA ν_μ fit	MINERvA $\bar{\nu}_\mu$ fit	MINERvA Global fit
Miniboone ν_μ χ^2	/ 131	/ 137	220 / 137
MiniBooNE $\bar{\nu}_\mu$ χ^2	/ 78	/ 72	97.2 / 78
T2K χ^2	/ 67	/ 67	184 / 67
MINERvA ν_μ χ^2	/ 2	/ 8	6.49 / 8
MINERvA $\bar{\nu}_\mu$ χ^2	/ 8	/ 2	3.26 / 8
Global dataset χ^2	/ 292	/ 292	511 / 292