

GENIE development of comprehensive neutrino interaction model and global fit

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on behalf of GENIE collaboration



University of Liverpool

14 September 2017
Fermilab

Outline

- Introduction
 - Generators
 - Dataset
- GENIE status vs recent datasets
- Tuning mechanism
- Tuning of CC 0π datasets
- Conclusions

Why not only theory?

- Theory models are just analytical functions
 - Not everything is analytical
 - Sometimes empirical models are the only option
 - Information has to be extracted from data
 - Notable examples:
 - Final State Interactions
 - Nucleus form factors
 - Experiments do Monte Carlo simulations
 - No exceptions
 - We need **events**
- ⇒ Numerical analysis



No spherical cows

Generators are required

- Merge theory and experimental approaches
- Obvious practicality of a single machinery

Roles of MC generators in Oscillation Physics

- Interface between neutrino flux and experimental observables
 - ⇒ Calculate predictions
 - ⇐ Constraint flux

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 - Reliability
 - Validity region
 - ⇒ You cannot study oscillations without fully understood models

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 - Data quality is increasing
 - ⇒ Inconsistency
 - Highlight **tensions**

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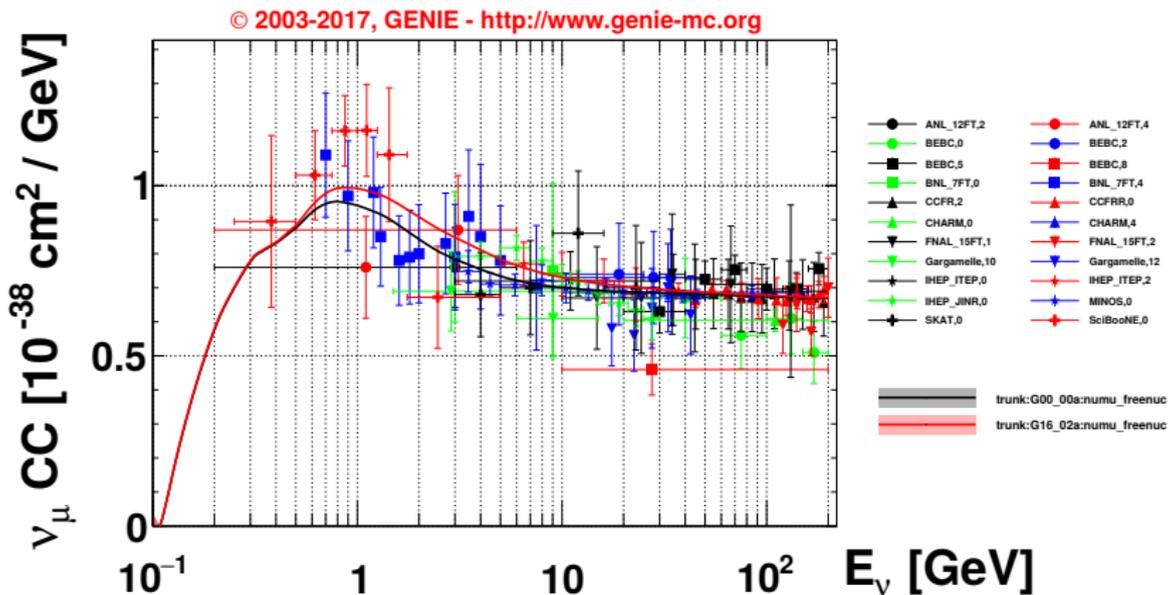
Keyword: quantitative

- Using all the information we can
 - Obvious ⇒ covariance matrix in a plot
 - Less Obvious ⇒ correlation between difference datasets

Role of MC generators in Oscillation Physics

- Feedback for experiments
 - Drive the format of cross section releases
 - Hint toward key measurements

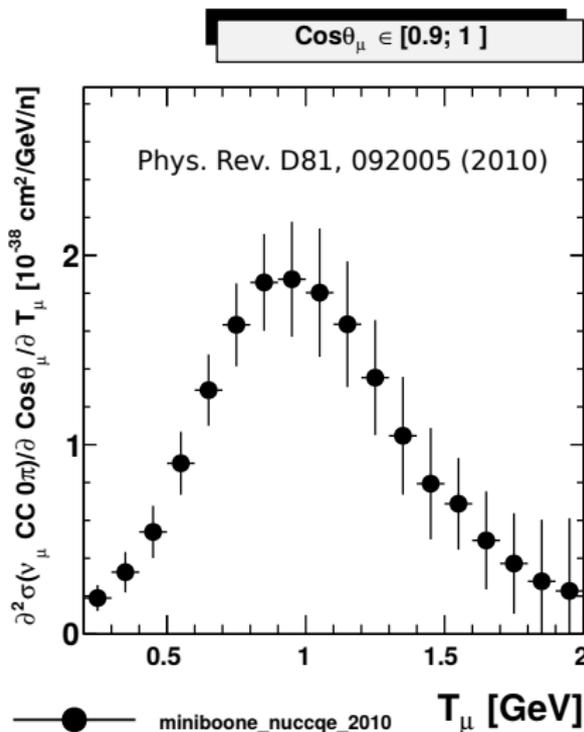
Evolving datasets - Old datasets



- Functions of E_{ν}
- Not flux-integrated
- “Only” statistical errors
- Ignore nuclear effects
- Poor statistical interpretation
- **Poor model discrimination power**

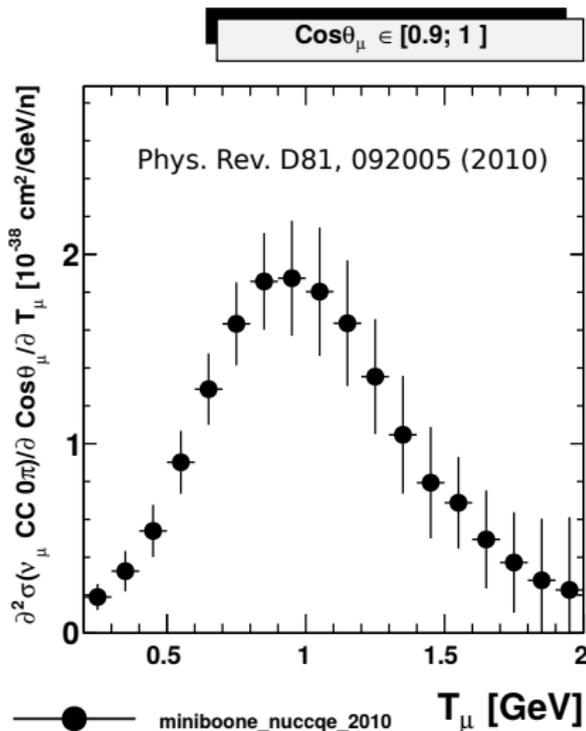
Evolving datasets - Present datasets

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

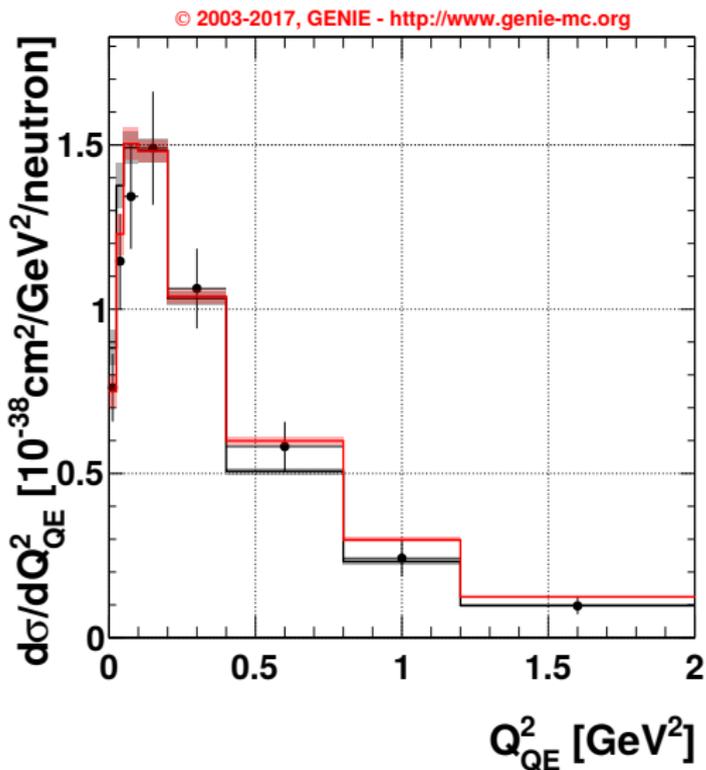


Evolving datasets - Present datasets

- Functions of experimental observables
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 - 1D, 2D
- Organized by topology, not process
- Higher statistics
- More statistically robust
 - ⇒ See seminar by Mikael Kuusela - 2017/04/13
- Sometimes incomplete
- Helped the development of new models
 - 2p/2h



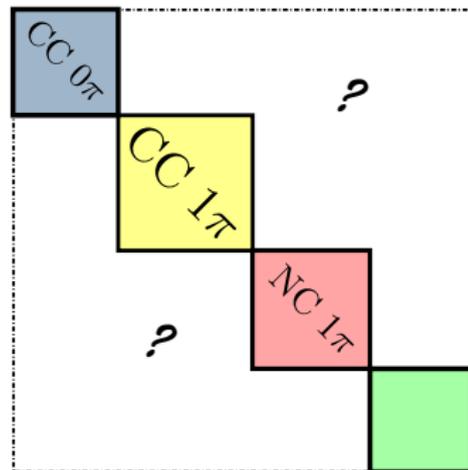
Importance of the covariance - an example



- 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
- ⇒ Almost 2σ

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 datasets

- Statistically coherent
- Complete error analysis

Call for experiments

- Generators are where data and models combines
- Planning a systematic analysis of available data
 - Which was not possible before
 - Requirements in terms of dataset completeness
- Dataset can be optimized for global analyses
 - Sometimes with small effort
 - This requires knowing how data can be used

Call for experiments

- Generators are where data and models combines
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If you plan Cross section Analysis, contact us!

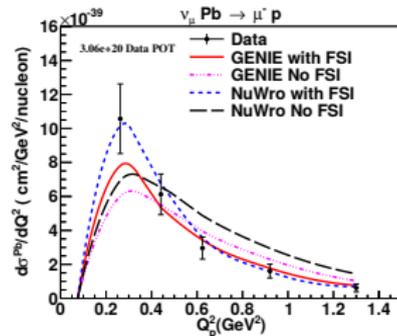
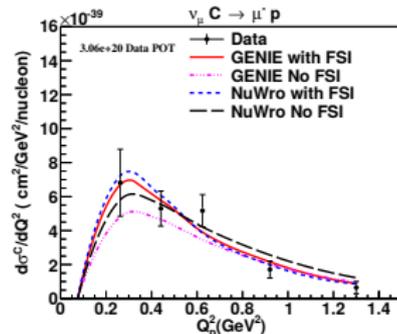
We can help you to make your data more useful

- Once data are published, it can be too late
 - especially if the main developers have already moved on

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

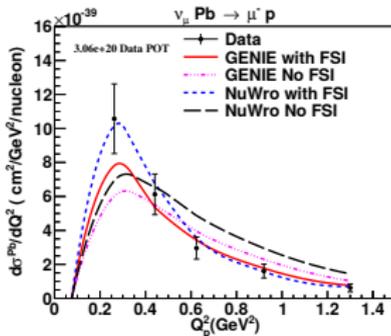
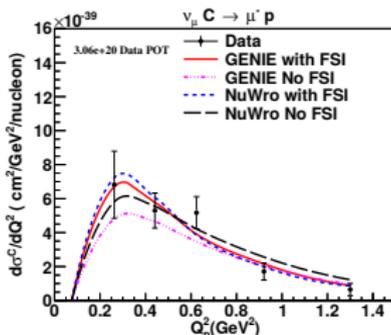
arXiv:1705.03791v1



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- 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



GENIE Collaboration

Luis Alvarez Ruso⁸, Costas Andreopoulos^{2,5}, **Chris Barry**², **Francis Bench**²,
Steve Dennis², Steve Dytman³, Hugh Gallagher⁷, Tomasz Golan^{1,4}, Robert Hatcher¹,
Libo Jiang³, **Rhiannon Jones**², Anselmo Meregaglia⁶, Donna Naples³,
 Gabriel Perdue¹, **Marco Roda**², **Jeremy Wolcott**⁷, Julia Yarba¹

[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

- Models
 - MEC models
 - Empirical
 - Nieves Simo Vacas
 - CCQE models
 - Llewellyn Smith
 - Nieves, Amaro and Valverde
 - Nuclear Models
 - Relativistic Fermi Gas
 - Local Fermi Gas
 - Effective Spectral Functions
 - RES, COH, ...
- Only one Comprehensive Model Configuration (CMC)
- Default tune has not changed



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GENIE Version 3

Things are going to change

GENIE Version 3



graphics by grafiche.testi@gmail.com

- “Comprehensive Model Configurations”
 - Self-consistent collections of primary process models
 - single command-line flag
 - Complete characterization against public data

- Tunes for each CMC will also be available

- We finally fulfilled the GENIE core missions

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 configurations (CMC) and all its derived tunes (Comprehensive 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-character string in the form

Gdd_MMv

List of available configurations

CMC definitions and characterization

The following list contains the details of the CMCs available in GENIE. Also, for each CMC, validation plots and Tunings 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 theoretical developments. Particular emphasis is on Nieve Model for CC 0 π and CC 1 π 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, $M_A = 0.99 \text{ GeV}/c^2$
CC 2p2h	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	NievesSinoVacasMECPXSec2016/Default	turn SetDNucleonCode to false*
CC RES	Ch. Berger, L. M. Sehgal Phys. Rev. D76 (2007)	BergerSehgalRESPXSec2014/Default	dipole axial FF, $M_A = 1.12 \text{ GeV}/c^2$ 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)	BergerSehgalCHPIPXSec2015/Default	
CC Diffractive Pion	D. Rein Nucl. Phys. B278 (1986) 61-77	ReinDFRPXSec/Default	
CC $\Delta S = 1$ QE	A. Pais Annals Phys. 63 (1971) 361-392	PaisQELambdaPXSec/Default	
CC $\Delta S = 1$ Inelastic	M. Rafi Alam et al. Phys. Rev. D82 (2010) 033001	AlanSinoAtharVacasSKPXSec2014/Default	

Comprehensive Model Configurations

- Tune names are supposed to become commonly used
- Usage: `--tune G16_02a` available from version 3
- Models:
 - G00_00a - Default
 - No MEC
 - CCQE process is Llewellyn Smith Model
 - Dipole Axial Form Factor - Depending on $M_A = 0.99 \text{ GeV}$
 - 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 $M_A = 0.99 \text{ GeV}$
 - 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 $M_A = 0.99 \text{ GeV}$
 - Nuclear model: Local Fermi Gas Model
 - Small variations changing FSI models

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

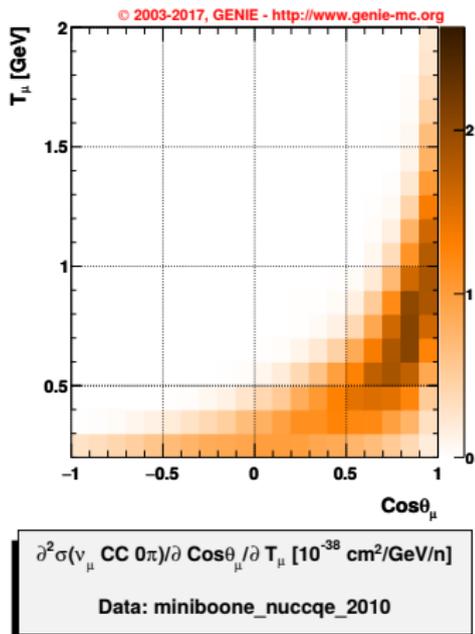
- Measurements of neutrino-induced **hadronic system characteristics**
 - Forward/backward hadronic multiplicity distributions
 - Multiplicity correlations
 - ...

- 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

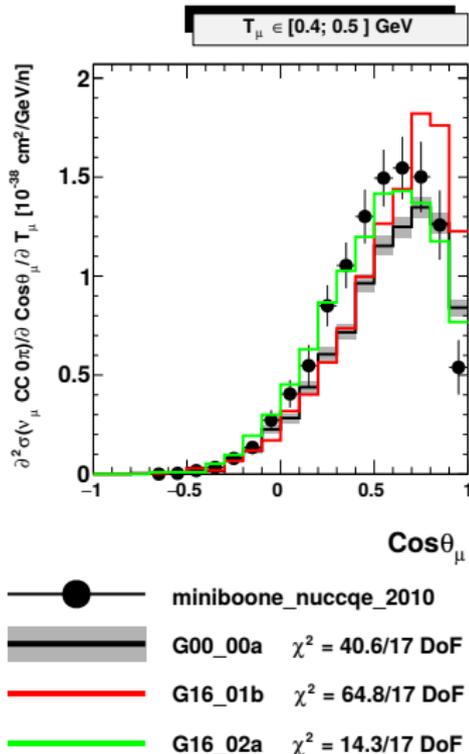
MiniBooNE CCQE

- 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



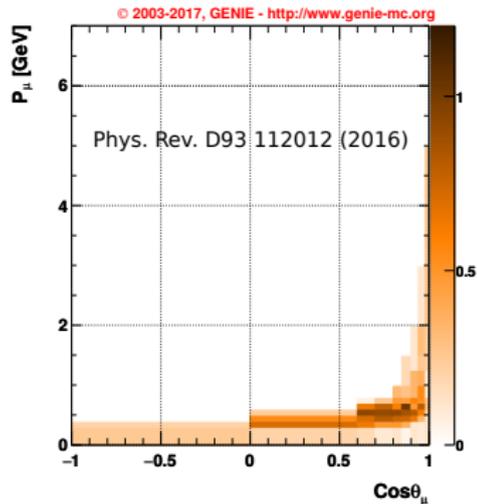
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T2K ND280 0 π

- 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!

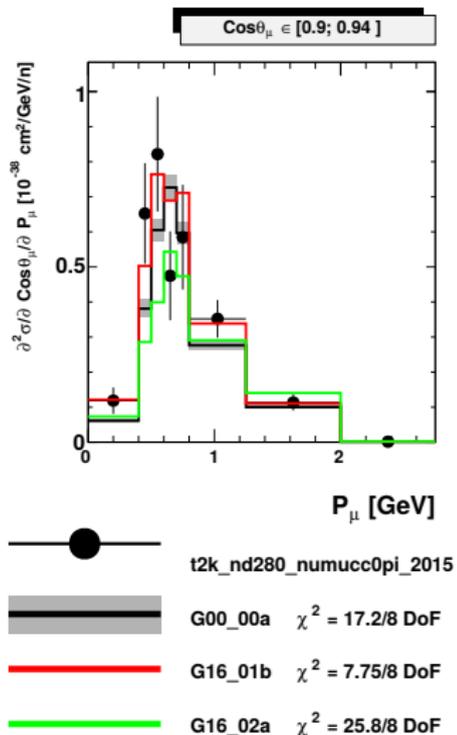


$$\frac{\partial^2 \sigma}{\partial \text{Cos}\theta_\mu \partial P_\mu} [10^{-38} \text{ cm}^2/\text{GeV/n}]$$

Data: t2k_nd280_numucc0pi_2015

T2K ND280 0 π

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Tuning

- Why tuning?
 - Constraint parameters
 - Provide specific tuning for experiments
 - Liquid Argon tuning
- 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

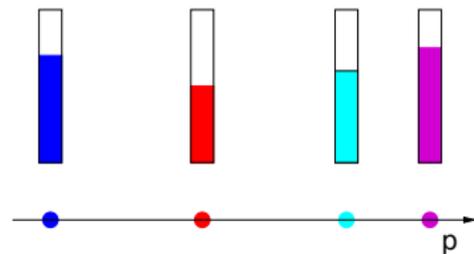
- Parametrization instead of a full MC

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 - ① Select points of param space

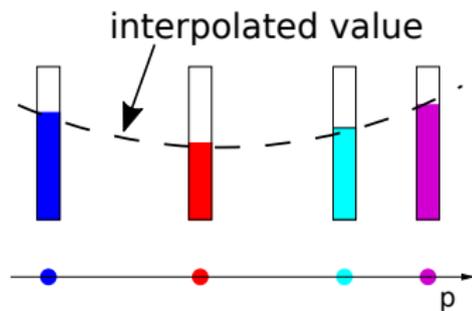


Professor

- Parametrization instead of a full MC
 - 1 Select points of param space
 - 2 Evaluate bin's behaviour with brute force



- Parametrization instead of a full MC
 - 1 Select points of param space
 - 2 Evaluate bin's behaviour with brute force
 - 3 Parametrization $I(p)$



Advantages

- Highly parallelizable
 - independent from the minimization
- All kind of parameters can be tuned
 - Not only reweight-able

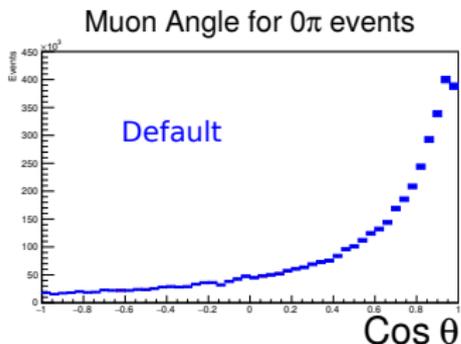


Tuning Output

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

Tuning Output

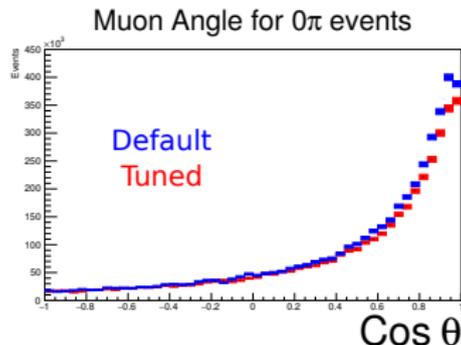
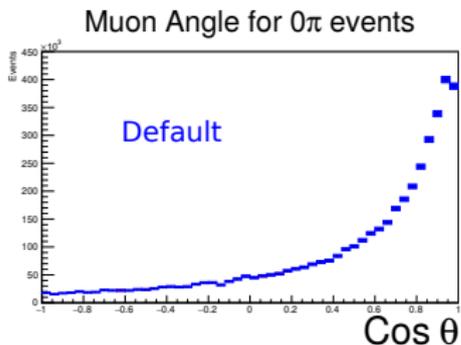
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- Data Constraints for Oscillation analyses



Tuning Output

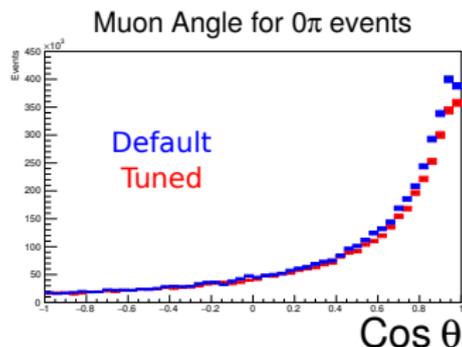
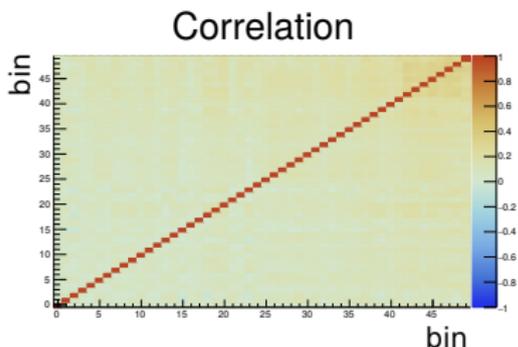
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- Data Constraints for Oscillation analyses
 - Propagate the result to other observables



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

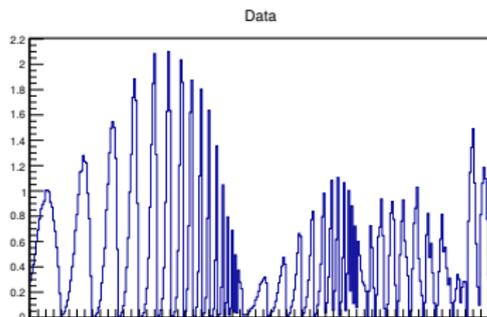


The first tuning

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
 - full covariance matrix



- 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
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Parameter	Range	Default value
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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
 ⇒ 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

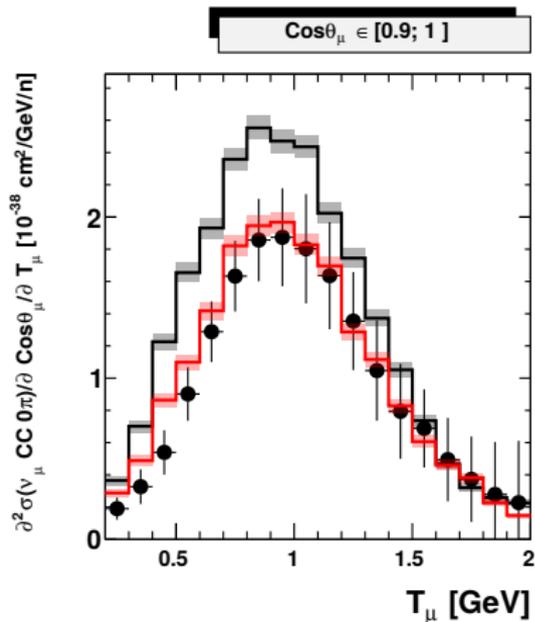
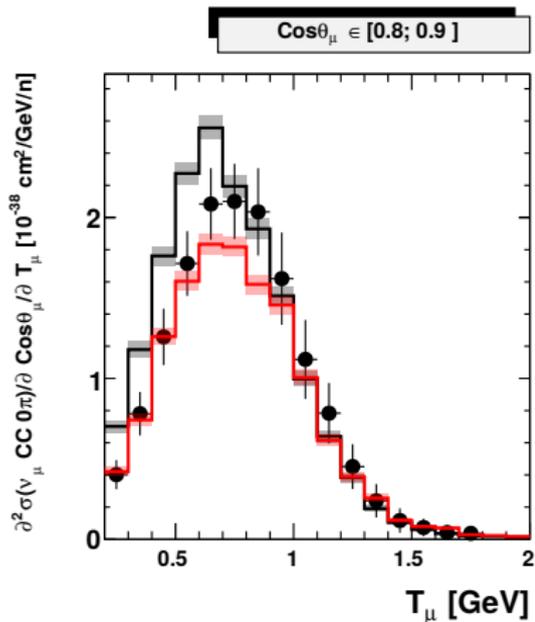
Dataset	Best fit χ^2	Nominal χ^2
Miniboone ν_μ CC 0 π	177 / 137	441 / 137
MiniBooNE $\bar{\nu}_\mu$ CC 0 π	66.2 / 78	50.4 / 78
T2K ND 280 CC 0 π	94 / 80	56.6 / 80
Total	337 / 289	548 / 295

G16_02a - Full Nieves Model

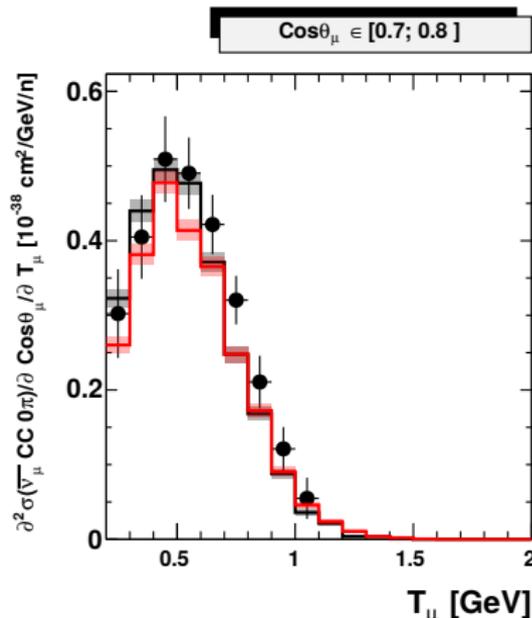
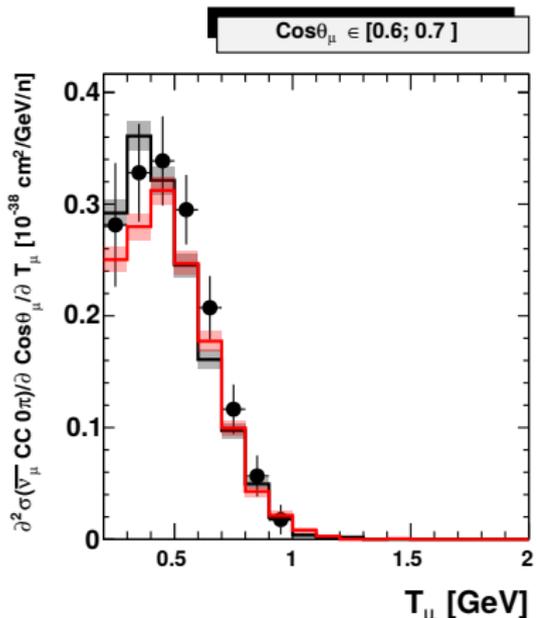
Dataset	Best fit χ^2	Nominal χ^2
Miniboone ν_μ CC 0 π	89.3 / 137	101 / 137
MiniBooNE $\bar{\nu}_\mu$ CC 0 π	48.1 / 78	176 / 78
T2K ND 280 CC 0 π	102 / 80	98.9 / 80
Total	239 / 289	376 / 295

- Improvement possible for both models
 - ⇒ The fit is working
- Fit driven by MiniBooNE datasets
 - Lowest information ⇒ No correlations
 - Room for improvement
- T2K ND280 data are complicated
 - Tensions
 - Correlations ⇒ anti-intuitive

Best fit plots

Best fit - G16_01b - MiniBooNE ν_μ CCQE

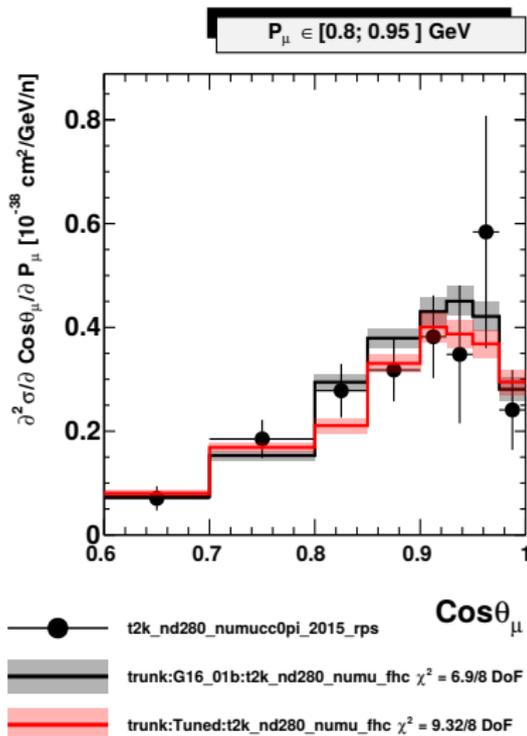
Fit has a big impact

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

Improvement not really necessary in this case

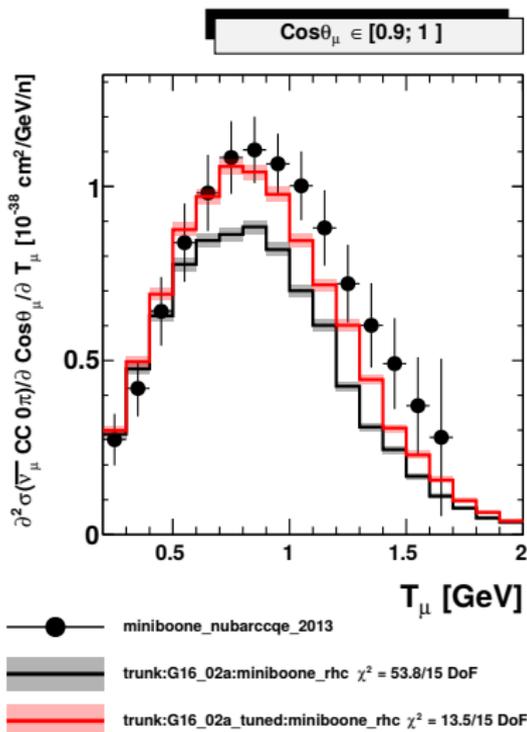
Best fit - G16_01b - T2K ND280

- agreement with T2K has worsened
- not surprising
- ⇒ 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

- This is just the beginning
- 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



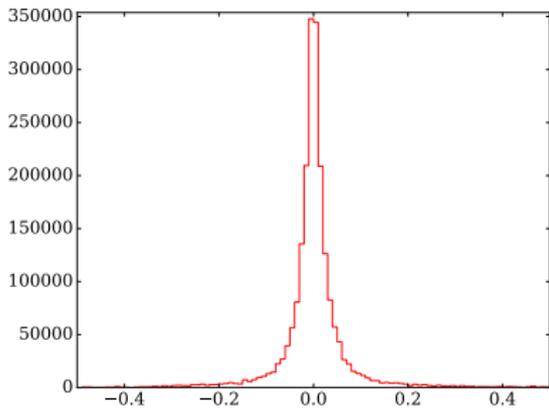
Conclusion

- 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

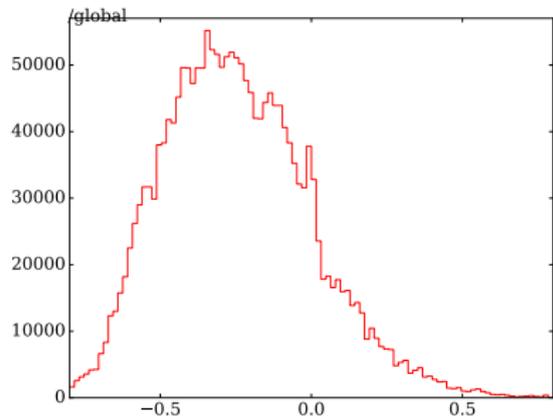


Backup slides

Parametrization residuals



Good

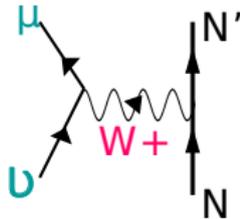


Bad

CC Quasi-Elastic - 0 π on single nucleons

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

- 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
 - $A(Q^2) = g_A \left(1 + \frac{Q^2}{M_A^2} \right)^{-2}$

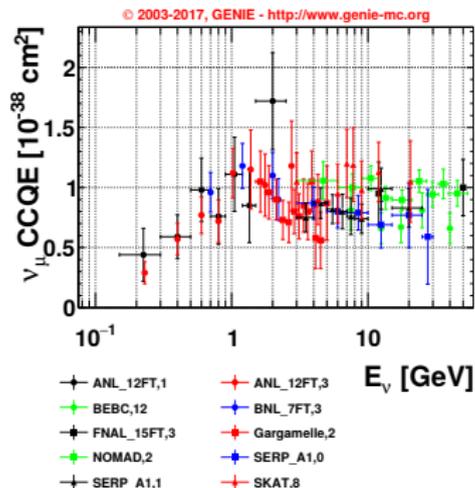


- $g_A = 1.26$ from neutron β decay
- fitted based on $\partial\sigma/\partial Q^2$ data

CC Quasi-Elastic - Data

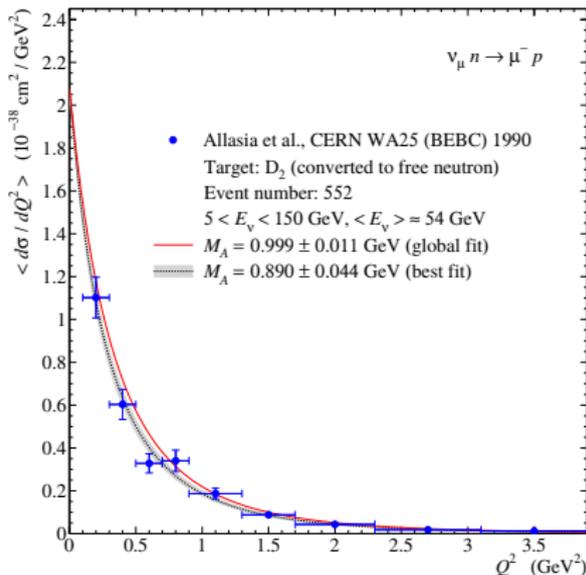
- Hydrogen / Deuterium data
 - from 0.1 GeV to ~ 100 GeV
 - For both Neutrinos and Anti-neutrinos

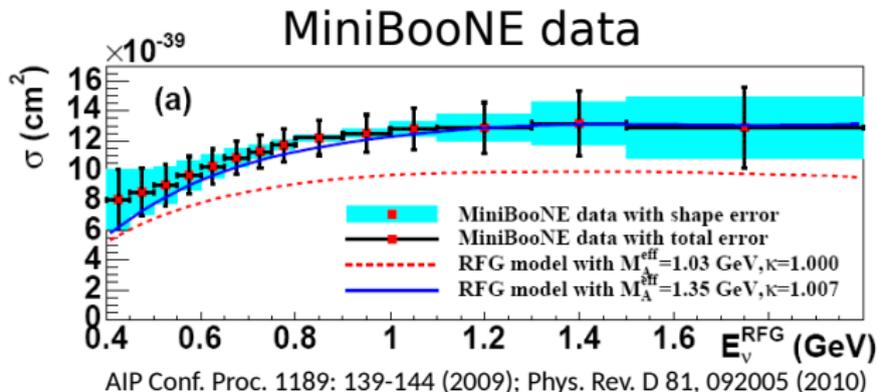
- Critical parameter: M_A
 - $M_A \sim 1$ GeV



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



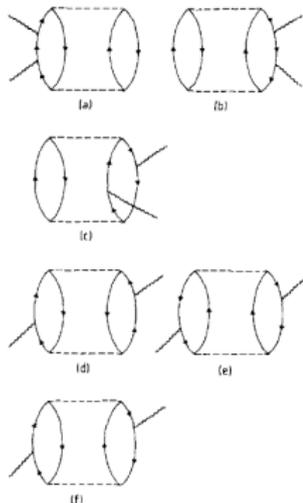
0 π on heavy nuclei

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

2 Particles - 2 Holes

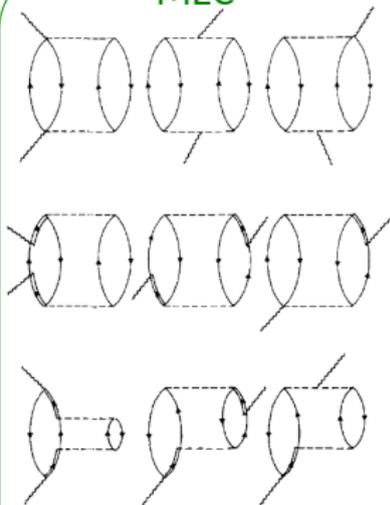
M. Martini

NN correlations

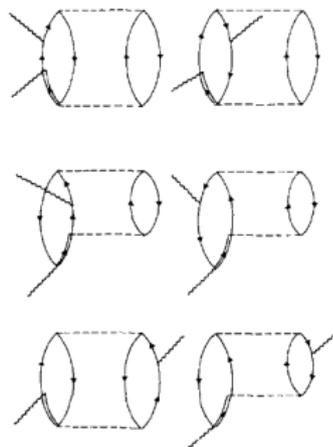


16 diagrams

MEC



49 diagrams

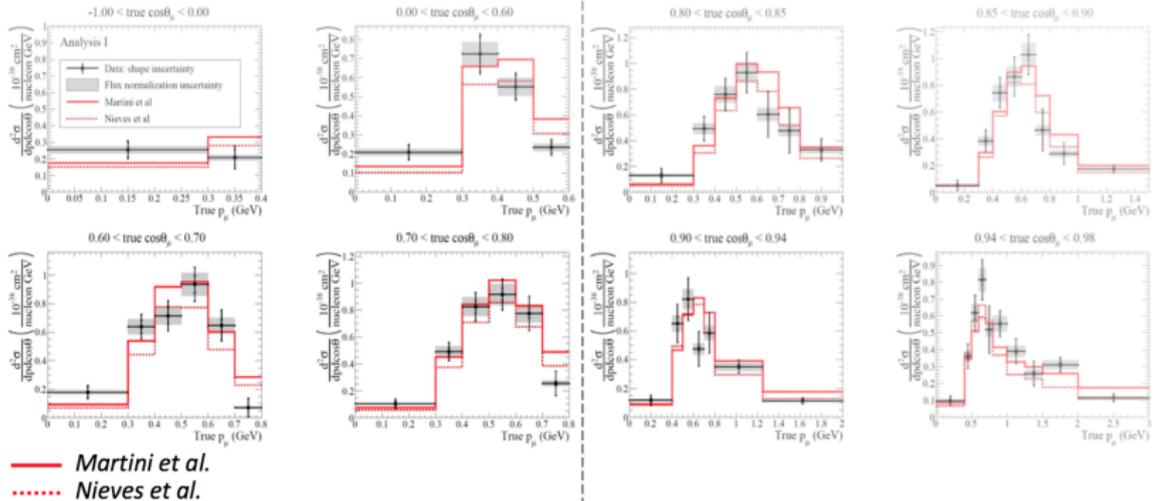
NN correlation-MEC
interference

56 diagrams

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

Model comparison

T2K collaboration: Abe et al. Phys. Rev. D 93 11012 (2016)



Model comparison

Martini et al.

Nieves et al.

Amaro et al.

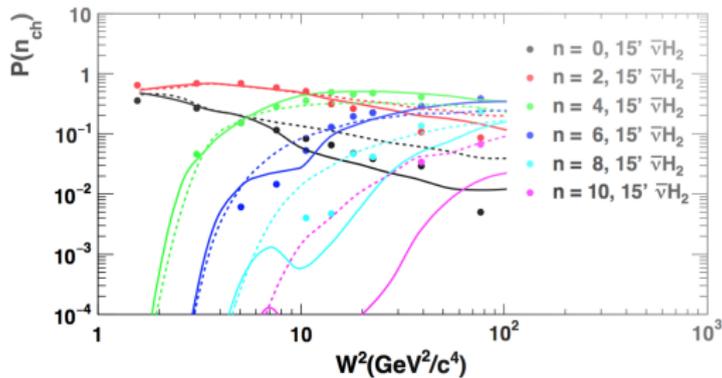
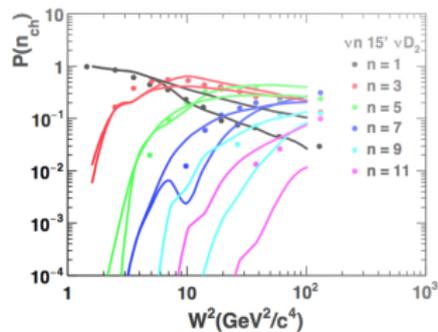
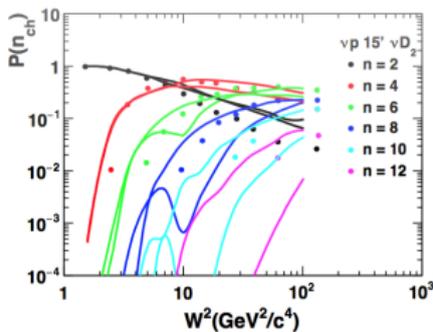
Lovato et al.

Bodek et al.

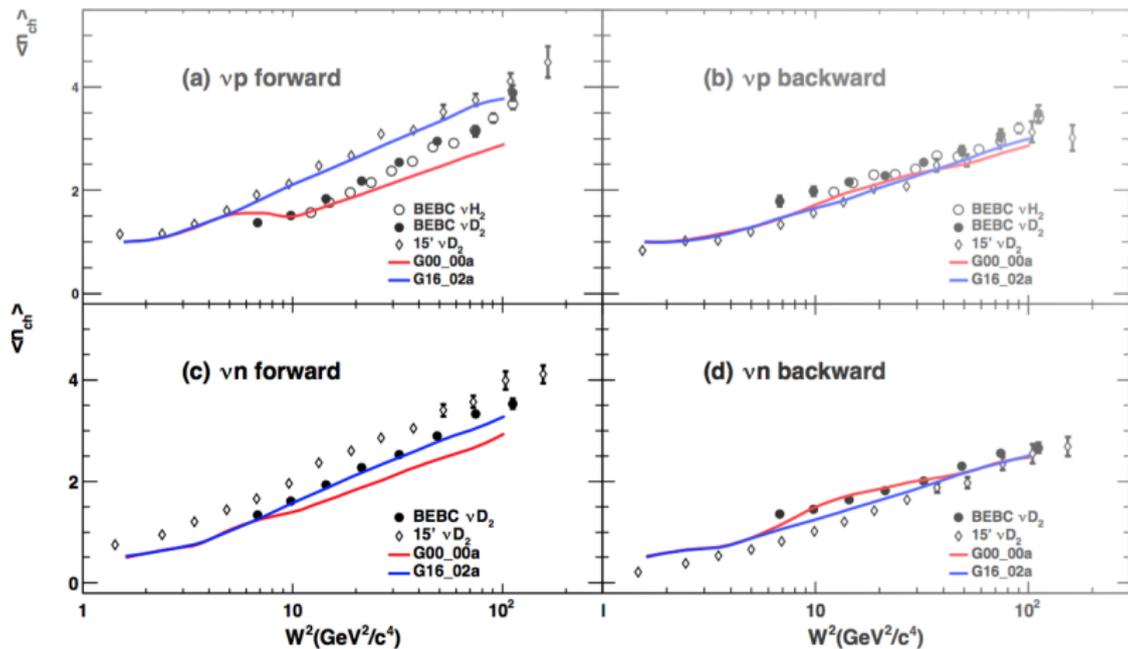
$$\frac{\partial^2 \sigma}{\partial \Omega \partial \epsilon'} = \frac{G_F^2 \cos^2 \theta_c k' \epsilon' \cos^2 \frac{\theta}{2}}{2 \pi^2} \left[\frac{(q^2 - \omega^2)^2}{q^4} G_E^2 \underline{R_\tau} + \frac{\omega^2}{q^2} G_A^2 \underline{\underline{R_{\sigma\tau(L)}}} + \right. \\ \left. + 2 \left(\tan^2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

[M.Martini, FUNFACT J Lab workshop]

Hadronization example



Hadronization example



Hadronization example

