Genie

Sub-GeV neutrino interactions

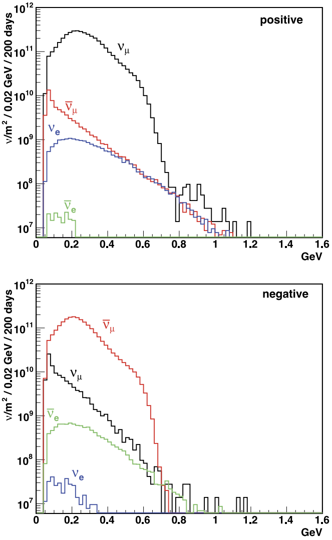
Marco Roda
mroda@liverpool.ac.uk
marco@genie-mc.org

on behalf of GENIE collaboration

University of Liverpool

7-8 November 2018
ESSnuSB meeting
Strasbourg

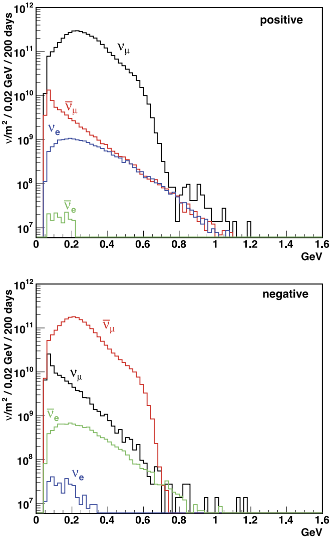
ESSnuSB beam and targets



- Neutrinos: ν_μ, $\bar{\nu}_\mu$, ν_e, $\bar{\nu}_e$
- Target: polystyrene and paraterphenyl
  - Carbon and hydrogen
  - ⇒ We already have data for these targets!
- Main topologies
  - 0π for ν_μ and $\bar{\nu}_\mu$
  - 0π and 1π for ν_e and $\bar{\nu}_e$

⇒ Relevant models
  - Main interaction types
    - Quasi-Elastic
    - 2p2h
    - Resonant
    - Diffractive
  - FSI

ESSnuSB beam and targets



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⇒ Outline

- Intro: generators, data, nuclear physics
- 0π and 1π
- Comparisons with data

Neutrino MC generators: our vision

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

⇒ Tuning is difficult - CPU time
  - ⇒ Unprecedented systematic tuning program

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

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

⇒ Dealing with errors is unavoidable

Roles of generators in oscillation physics

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

GENIE - www.genie-mc.org

GENIE Collaboration

Luis Alvarez Ruso[8], Costas Andreopoulos[2,5], Christopher Barry[2], Francis Bench[2], Steve Dennis[2], Steve Dytman[3], Hugh Gallagher[7], Steven Gardiner[1], Walter Giele[1], Robert Hatcher[1], Libo Jiang[3], Rhiannon Jones[2], Igor Kakorin[4], Konstantin Kuzmin[4], Anselmo Meregaglia[6], Donna Naples[3], Vadim Naumov[4] Gabriel Perdue[1], Marco Roda[2], Jeremy Wolcott[7], Júlia Tena Vidal[2], Julia Yarba[1]

[Faculty, Postdocs, PhD students]

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

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

Core GENIE mission - from GENIE by-law

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

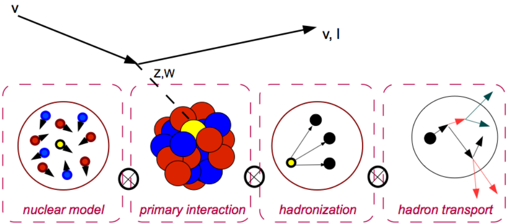
Universality "... simulate all processes for all neutrino species and nuclear targets, from MeV to PeV energy scales ..."

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

Calculation factorisation

- no complete theory of neutrino scattering on hadrons

⇒ Factorisation is required
  - the initial nuclear state dynamics
  - cross-sections at the neutrino-nucleon level
    + a model of how to sum-up the nucleon-level contributions
  - hadronization - Pythia 6
  - intranuclear hadron transport
    - GENIE-grown models



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

Status overview

- Well established generator
  - Used by many experiments around the world
  - Fermilab experiments are driving the momentum
    - Lot of interest from LAr experiments
- Two main efforts
  - Model development
    - Mostly happen during the latest releases of GENIE v2
    - growing interest from theorists wanting to supply new models
  - Tuning

    $\Rightarrow$ Entering the tuning phase
- The new release v3
  - Interface with the developments

  $\Rightarrow$ Tunes against public datasets

  $\Rightarrow$ Easy way to share configurations
    - Experiments can propose their own configuration for others to use

Models

- Steady introduction as alternate models
- Many thanks to all who contributed
  - more detailed list in backup
- List of most interesting physics introduction:
  - Valencia complete QE+MEC+LFG model
  - Berger-Sehgal resonance model+MiniBooNE form factors
  - Berger-Sehgal coherent model + updated Rein-Sehgal coherent
  - Single kaon production of *Athar et al.*
  - New cascade FSI model with medium corrections for pions and nucleons

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A complete generation needs more than a set of models

- The experimental smearing mixes all the different interaction process
- There are ad-hoc solutions in every generator that needs tuning
  - ⇒ Transition between RES and DIS interactions
  - Implications for 1π production

GENIE Version 3

Genie
UNIVERSAL NEUTRINO GENERATOR
& GLOBAL FIT

graphics by `grafiche.testi@gmail.com`

- Interface with the work behind the scenes

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

- Access to tunes against datasets
  - same interface
  - Documentation:
    - Manual
    - Dedicated web page – tunes.genie-mc.org/

Comprehensive Model Configurations

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

Technical updates

- New Git Repository - `https://github.com/GENIE-MC`
  - Contributions are welcome through this new channel
  - Thanks to HEPForge for the many years of support
- Reweight is now a detached and independent repository
- Website - `http://www.genie-mc.org/`
- Updated manual hosted on a dedicated DocDB
- Code
  - System handles multiple configurations
  - Updated XML file structure $\Rightarrow$ safer and with no redundancies
  - Files re-organisation

Tuning

- Why tuning?
  - Constraint parameters
  - Provide specific tunes for experiments
    - Liquid Argon tune
- Expected Output:
  - Parameter sets from data from various experiments
  - with estimated systematic errors
    - Parameter covariance matrix
    - ⇒ No official support until v4
- Numerical methodology
  - Old problem in High Energy Physics
    - CPU demanding
  - Solution found in the Professor suite
    - `http://professor.hepforge.org`
  - Numerical assistant
    - Developed for ATLAS experiment

Database and validation

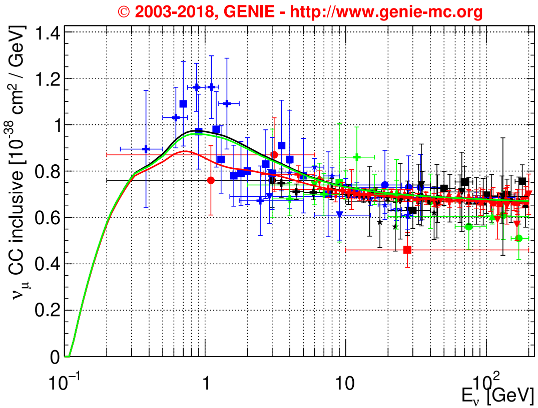
- Comparing GENIE predictions against public datasets
  - Modern Neutrino Cross Section measurement
    - nuclear targets
    - MiniBooNE, T2K, MINERvA
  - Historical Neutrino Cross Section Measurement
  - Measurements of neutrino-induced hadronic system characteristics
    - e.g. Forward/backward hadronic multiplicity distributions
  - Measurements of hadron-nucleon and hadron-nucleus event characteristics
    - 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

$\Rightarrow$ Validation based on neutrino, electron and hadron beam simulations

- We are not limited to simulate only neutrinos

What generators can do depends on the available datasets

Evolving datasets - Old datasets

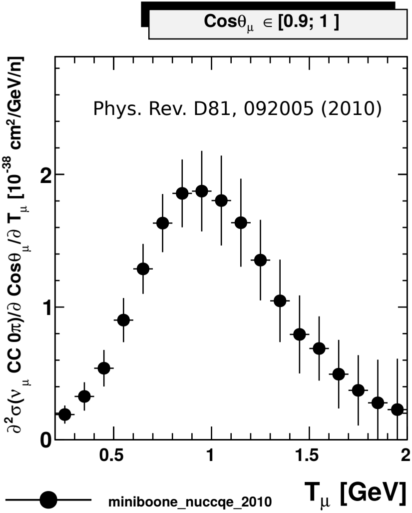


- Functions of E_ν
- "Only" statistical errors

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

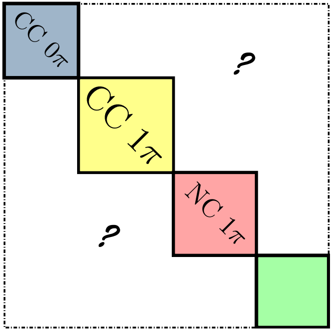


Future of datasets - a personal view

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

- No data releases with this format
  - SBND is thinking about a solution

- It is usually a big effort but ...
  - dedicated experiments



We finally have a way to use these datasets

- Statistically coherent
- Complete error analysis

Neutrino interactions at few GeV - A crash course

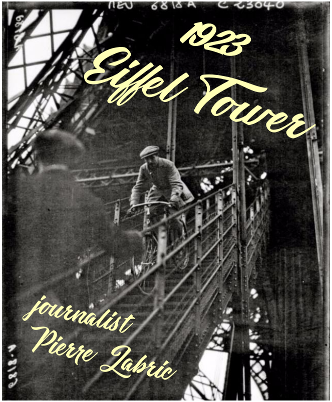
- Multiple topologies
  - 0π
  - 1π
  - ...
  - DIS

$\Rightarrow$ It might be easier if it wasn't for the nucleus

Difficult Multi-Scale problems - a metaphor

- Bicycle rider descending the Eiffel Tower
  - from the first level
  - about 350 steps

- Bicycle wheel is $\sim$1 m in diameter



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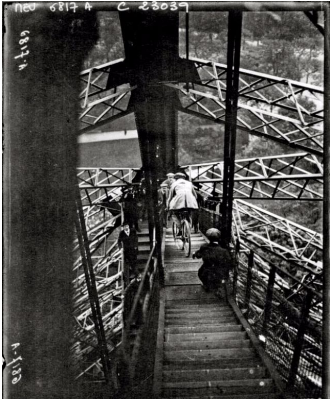

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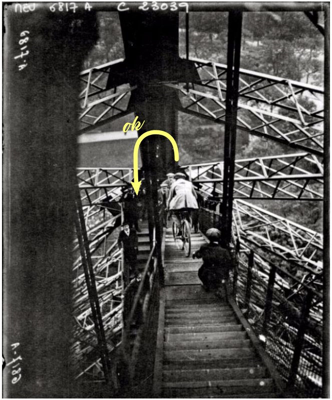

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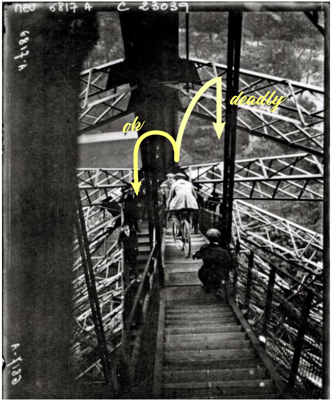

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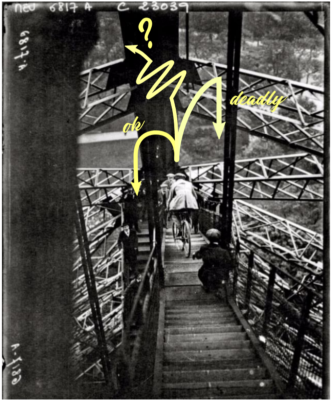
- Reality
  - wheel size is too close to the step size

  $\Rightarrow$ Not a clear trajectory
    - He could make it (luck?)
    - He could fell (how?)

    $\Rightarrow$ Information required



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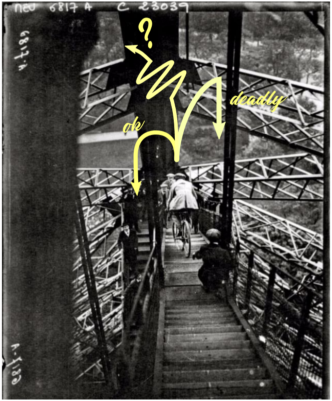

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All we know is that it is going to be painful

Difficult Multi-Scale problems - Neutrino interactions

- $E_\nu \sim 0.3 - 5.0$ GeV
- $m_\Delta - m_N \sim 250$ MeV
- Binding energy ~ 30 MeV in ^{12}C
- Different interaction types
  - Quasi-Elastic and Inelastic
  - No clean separation because of nuclear effect
- Problem ignored for the longest time
  - Charged lepton people told we were ignoring too much
- Gradually and painfully we are learning

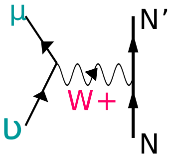
$\Rightarrow$ I'll tell you the story of 0π interactions
  - Better data
  - Relevant in the ESSnuSB case

$\Rightarrow$ Mention a bit of the 1π puzzle

CC Quasi-Elastic - 0π on single nucleons

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

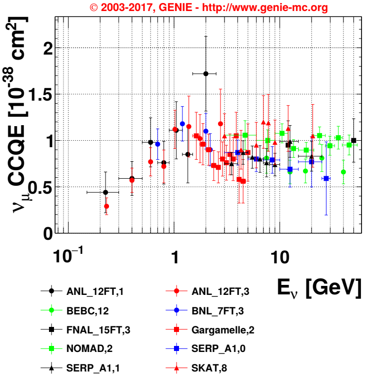
- Theoretically well understood
  - One diagram
- A, B and C are form factors
  - They have to be measured
  - B and C are known from e-N scattering
  - A to be extracted from ν data
- Axial Form factor
  - Dipole standard parameterization
  - $A(Q^2) = g_A \left(1 + \frac{Q^2}{M_A^2}\right)^{-2}$



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

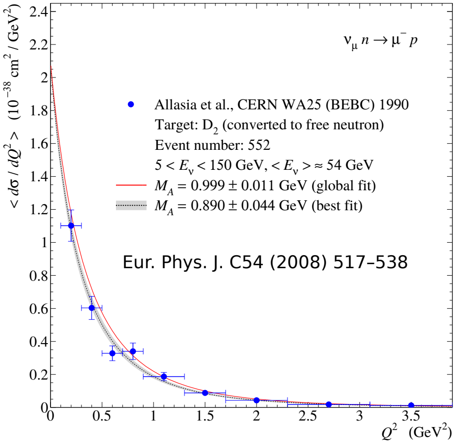
CC Quasi-Elastic - Historic datasets

- Deuterium data
  - from 0.2 GeV
  - up to ∼ 100 GeV
  - both Neutrinos and Anti-neutrinos



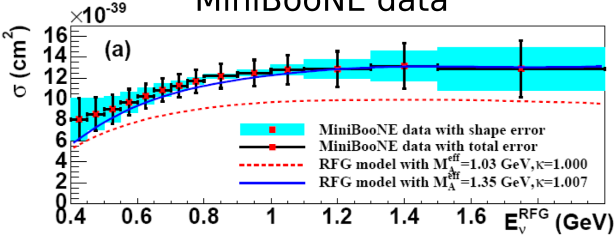
CC Quasi-Elastic - Historic datasets

- Deuterium data
  - from 0.2 GeV
  - up to ∼ 100 GeV
  - both Neutrinos and Anti-neutrinos
- Critical parameter: M_A
  - $M_A \sim 1$ GeV
- Note the energy range



0π on heavy nuclei

MiniBooNE data

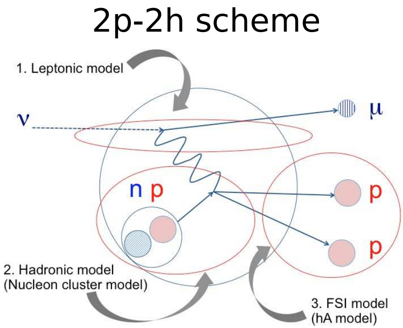


AIP Conf. Proc. 1189: 139-144 (2009); Phys. Rev. D 81, 092005 (2010)

- 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

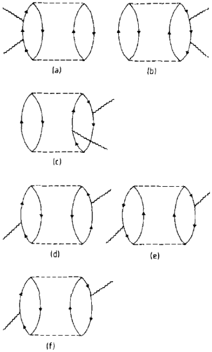
- MiniBooNE is a Cherenkov detector
  - Not able to see nucleons
- MiniBooNE dataset is a CCQE-like sample
- genuine CCQE
- Multi-nucleon Emission
  - np-nh
  - Leading contribution is 2p-2h (2 particles - 2 holes)



2 Particles - 2 Holes

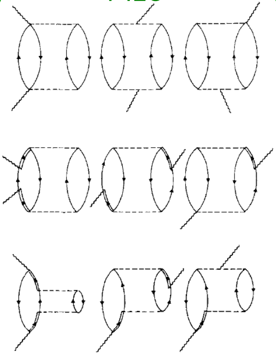
M. Martini

NN correlations



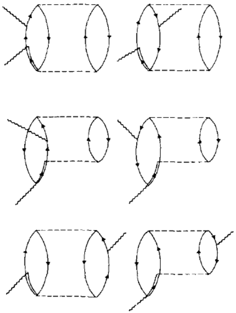
16 diagrams

MEC



49 diagrams

NN correlation-MEC interference



56 diagrams

Difficult to have a complete model

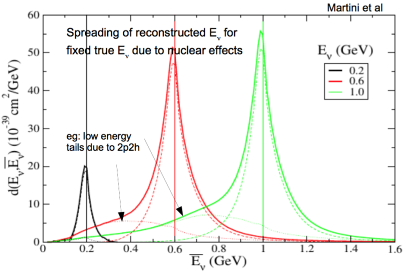
Different approaches include different diagrams

Effect of MEC on energy reconstruction

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

$\Rightarrow$ MEC is important to achieve precise measurements

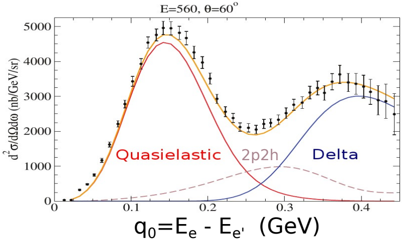
$$E_\nu = \frac{m_p^2 - (m_n - E_b)^2 - m_\ell^2 + 2(m_n - E_b)E_\ell}{2(m_n - E_b - E_\ell + p_\ell cos\theta_\ell)}$$



Martini et al.

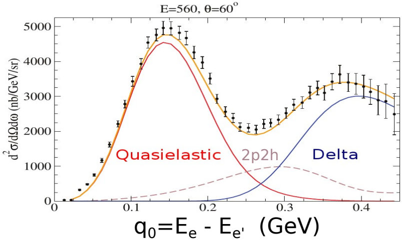
Something not entirely new

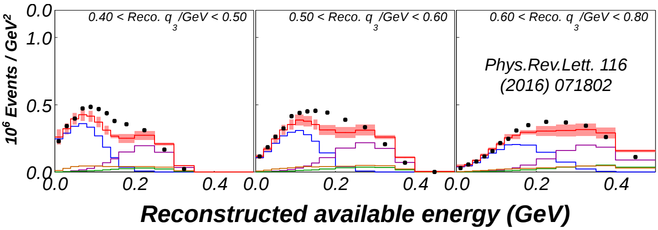
- Component well known in electron-N scattering
  - It goes under different names
- There it is easy to know q_0
  - Monochromatic electron beam



Something not entirely new

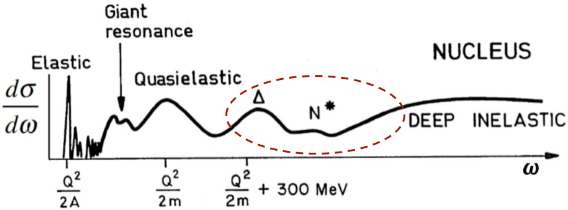
- Component well known in electron-N scattering
  - It goes under different names
- There it is easy to know q_0
  - Monochromatic electron beam
- In neutrino experiments
  - flux convoluted distributions
  - function of the visible energy
  - ⇒ MINERvA and NOvA





From Resonances to DIS

- Two resonance models:
  - Rein-Sehgal model [*D.Rein et. al., Annals Phys. 133 (1981)*]
  - Berger-Sehgal Model [*Bodek, A. et al. Nucl.Phys.Proc.Suppl. hep-ex/0308007*]
    - $\Rightarrow$ Include mass for the final state lepton



- None of the RES models includes interference

$\Rightarrow$ A non-resonant background needs to be added

- DIS also contributes to RES production after hadronization

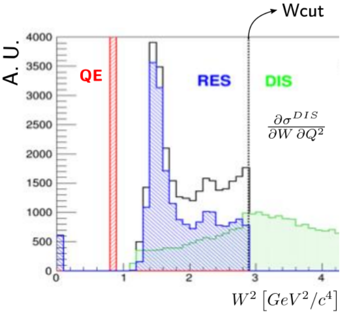
- Different models must be merged together

$\Rightarrow$ avoiding double counting

- Data only from ν_μ interactions

Shallow Inelastic Scattering region in GENIE

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



- RES contribution stops at $W = W_{cut}$
  $\rightarrow$ Rein-Sehgal or Berger-Sehgal models

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

- Pure DIS cross section for $W > W_{cut}$
  $\rightarrow$ Bodek-Yang model

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

Data below 200 MeV

That's all

Data below 200 MeV

That's all

I'm not joking!

Data below 200 MeV

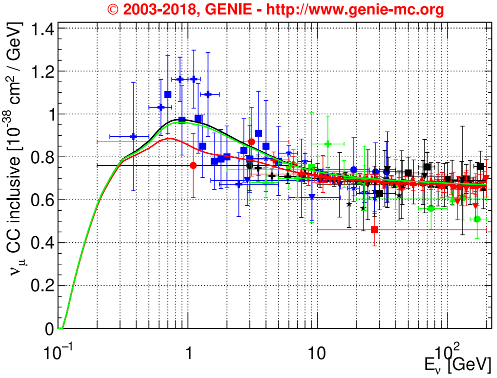
That's all

I'm not joking!

Have a near detector
And a dedicated tuning program

Integrated cross sections - ν_μ Inclusive

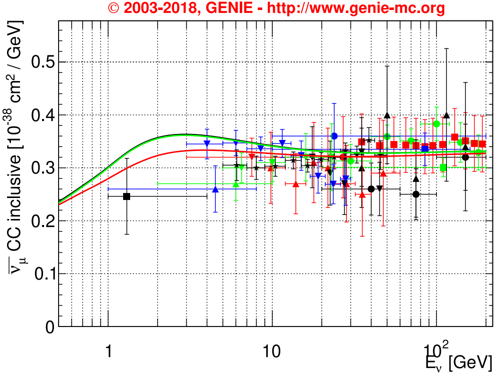
- Poor data at low energy
- Minimum energy 200 MeV
- known tensions between inclusive and 1π data
  - ⇒ Discrepancy at 1 GeV
  - Not statistically significant
- Details available in separate files



- G18_02a - untuned
- G18_02a tuned with π CC data
- G18_10j untuned

Integrated cross sections - $\bar{\nu}_\mu$ Inclusive

- Poor data at low energy
- Minimum energy 1 GeV
- known tensions between inclusive and 1π data
  - ⇒ Discrepancy at 1 GeV
  - Not statistically significant
- Details available in separate files



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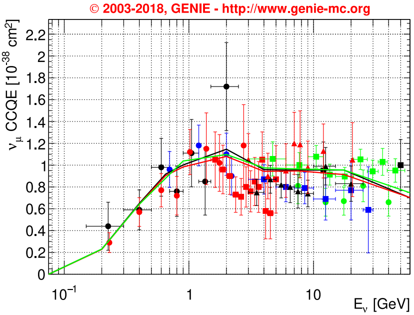
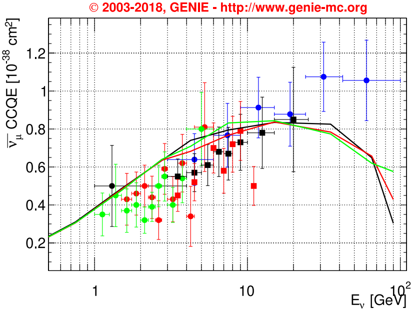
Integrated cross sections - CCQE(-like)

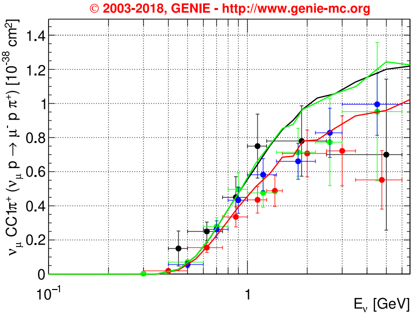


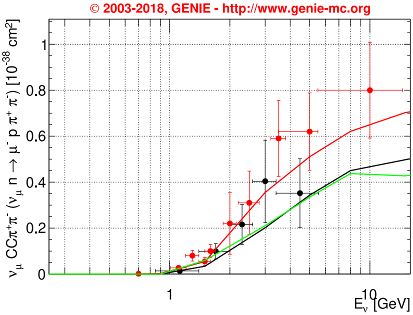


- G18_02a - untuned
- G18_02a tuned with π CC data
- G18_10j untuned

- Same model - Llewellyn Smith
  - small difference in M_A
  - tune result
- Limited low energy data

Integrated cross sections - Pion production



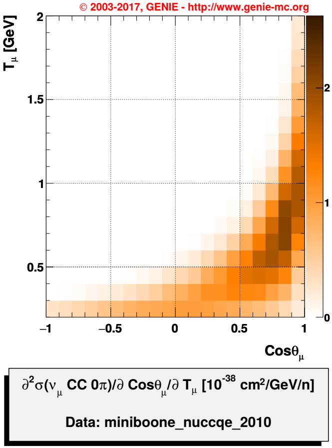


- G18_02a - untuned
- G18_02a tuned with π CC data
- G18_10j untuned

- Same model - Berger-Sehgal
  + GENIE SIS
  - Huge effect due to tune
- Data only for ν_μ

MiniBooNE CCQE (0π)

- Both ν and $\bar{\nu}$
  - Phys. Rev. D81, 092005 (2010)
  - Phys. Rev. D88, 032001 (2013)
- Double differential cross section
- flux integrated
- No correlations
- Nieves Model (G18_10j) strongly preferred
  - $\chi^2 = 68.4/137$ DoF
  - w.r.t. to $\sim$ 350 of G18_02a



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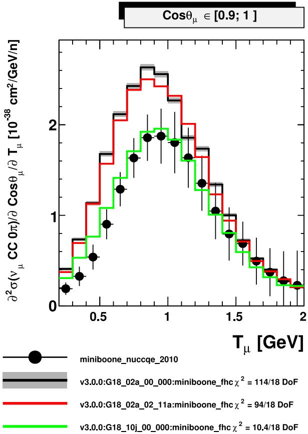

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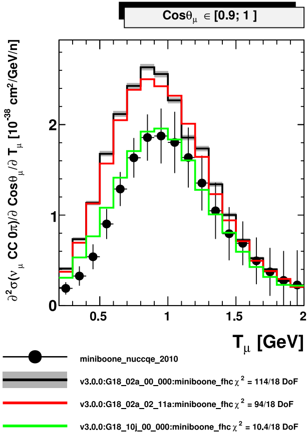
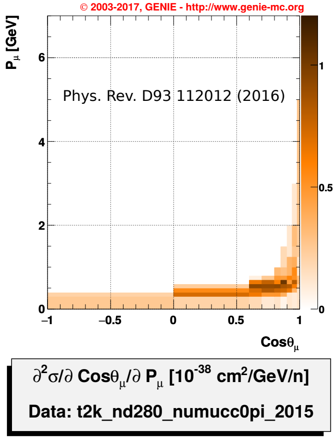
  - $\chi^2 = 68.4/137$ DoF
  - w.r.t. to ~ 350 of G18_02a
- Difference in the forward μ region
- The same goes for $\bar{\nu}_\mu$
  - $\chi^2 = 43/78$ DoF
  - w.r.t. ~ 80 of G18_02a



T2K ND280 0π

- Double differential cross section
- flux integrated
- Fully correlated
- No strongly preferred model
- All not completely satisfactory
  - $\chi^2 \sim 180/67$ DoF

$\Rightarrow$ Tensions between datasets

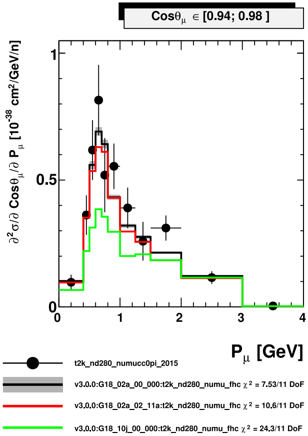


T2K ND280 0π

- Double differential cross section
- flux integrated
- Fully correlated
- No strongly preferred model
- All not completely satisfactory
  - $\chi^2 \sim 180/67$ DoF

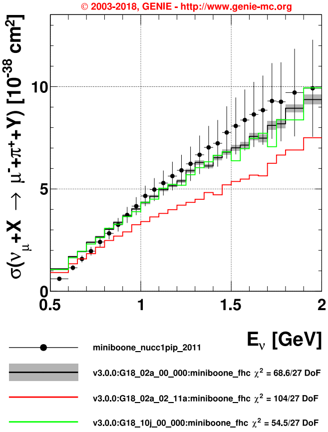
$\Rightarrow$ Tensions between datasets

- all models look reasonable "By eye" estimation
  - correlation is complicated
  - We can't ignore it!



MiniBooNE 1π

- Loads of different observables
- Missing correlations between different observables
- Untuned models seem favoured
- Complete disagreement with what MINERvA sees
  - $\Rightarrow$ 1π puzzle
- Only ν_μ data
  - $\Rightarrow$ You should not care about ν_μ pion production



Next steps

- More tunes can be done
  - hadronization re-tune
    - Pythia 6 and 8 (implementation is ongoing)
  - Tune of FSI
    - Both hN and hA intranuke
- Data from Liquid argon experiments
  - Part of GENIE collaboration is in SBND
  - Plan for argon tunes
- Look forward to more data
  - ESSnuSB will be a unique source of low energy data
- Release these results
  - Papers is in preparation
  - Implementation in GENIE v3

Conclusion

- GENIE shall serve the ESSnuSB case
  - Some models are designed for low energy regions
  - Future tunes and developments will be helpful
- Lack of data is serious
  - This will require dedicated work
  - Source of interesting physics data
  - $\Rightarrow$ you better have a good near detector
- Researchers are encouraged to contact us to start a collaboration
  - New theory models
  - New experimental collaborations

Genie
UNIVERSAL NEUTRINO GENERATOR
& GLOBAL FIT

Backup slides

Why care about ν interactions in the few-GeV region?

- Precision era in ν experiments
  - Lepton CP violation
  - Mass hierarchy

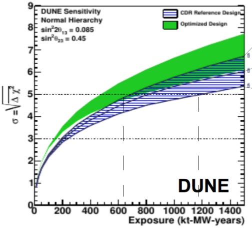
$\Rightarrow$ Oscillation measurements
  - Appearance mode

- Relevant experiments
  - T2k, NOvA
  - DUNE, HyperK

  $\Rightarrow$ Beam energy $\sim$ few GeV

- Total systematic at few-percent level

- CC 0π is the important reaction
  - for DUNE $\sim$ 40% of the interactions



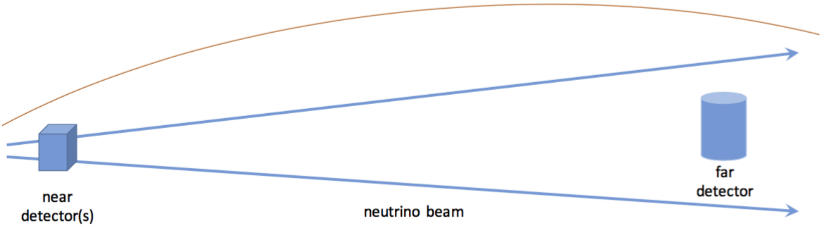
5% ± 1%

5% ± 2%

5% ± 3%

$\rightarrow$ equivalent to factor 2 in exposure!

Model Dependencies



- A simple ratio between Near and Far spectra is not enough
  - Detectors exposed to different flux
  - “functionally identical” detectors do not exists

⇒ No cancellations of model dependencies

- Near flux has to be fitted at the near detector and then propagated
  - ⇒ Models required

Is theory enough?

- 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

$\Rightarrow$ Numerical analysis

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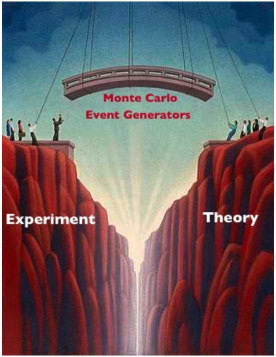
$\Rightarrow$ Numerical analysis

No spherical cows

Generators are required for a complete prediction

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

Neutrino MC Generators: A Theory/Experiment Interface



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

⇒ 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

- Compare data and models
  - Reliability
  - Validity region
  - $\Rightarrow$ You cannot study oscillations without fully understood models

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  - Data quality is increasing
    - ⇒ Inconsistency
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  - Generator is the ideal place for global fits
    - We control the model implementation
    - Have access to empirical models
  - Finding the best parameters
  - Cross Section priors based on data

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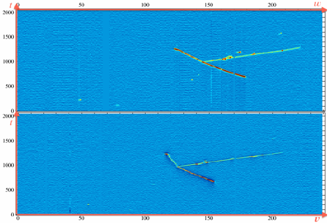
  - Cross Section priors based on data
- Feedback for experiments
  - Drive the format of cross section releases
  - Hint toward key measurements

What generators can do depends on the available datasets

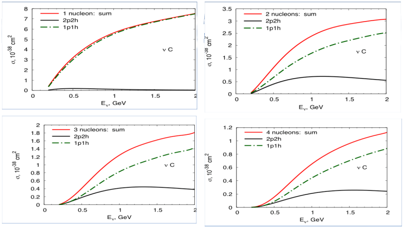
Search for 2p-2h

- 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]

Professor

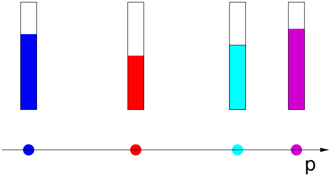
- Parameterisation instead of a full MC

Professor

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

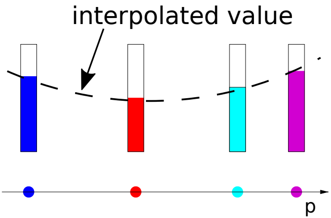
Professor

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



Professor

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

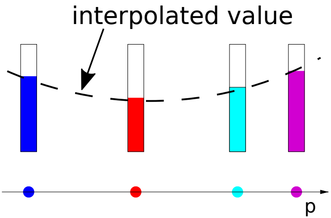


Professor

- Parameterisation instead of a full MC
  1. Select points of param space
  2. Evaluate bin's behaviour with brute force
  3. Parameterisation $I(p)$
  - Repeat for each bin
- a parameterization $I_j(p)$ for each bin
  - N dimension polynomial
  - Including all the correlation terms up to the order of the polynomial

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

- $\sim$ 20 parameters
  - This limit is due to disk space requirements
  - It can be overcome
- Special thanks to H. Schulz



Advantages and expectations

- All parameters can be tuned
  - Not only reweight-able

  ⇒ no dedicated machinery to develop

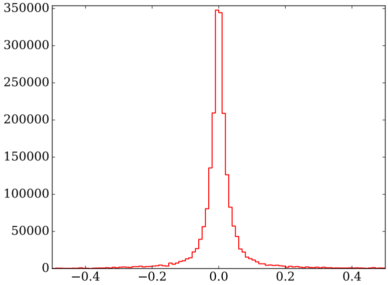
- Advanced features
  - Take into account correlations
  - weights specific for each bin and/or dataset
    - Proper treatment while handling multiple datasets
    - Restrict the fit to particular subsets
  - Priors can be included
  - Nuisance parameters can be inserted
    - proper treatment for datasets without correlations

    ⇒ MiniBooNE, old bubble chamber datasets

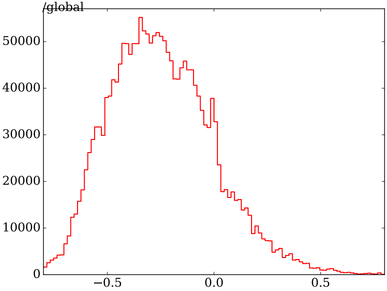
- Professor based Reweight package in development
  - Reweight hard to maintain: each model requires a specific reweight module
  - Better interface with the errors produced by a global fit
  - Allow non-reweightable parameters - e.g. HN FSI

  ⇒ version 4

Parameterization residuals



Good



Bad

RES Models: the Rein-Sehgal Model

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

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

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

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

RES Models: the Berger-Sehgal Model

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

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

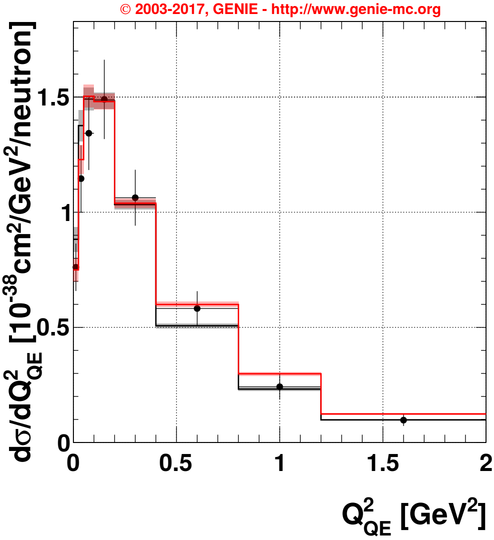
Depends on:

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

Shallow Inelastic Scattering region

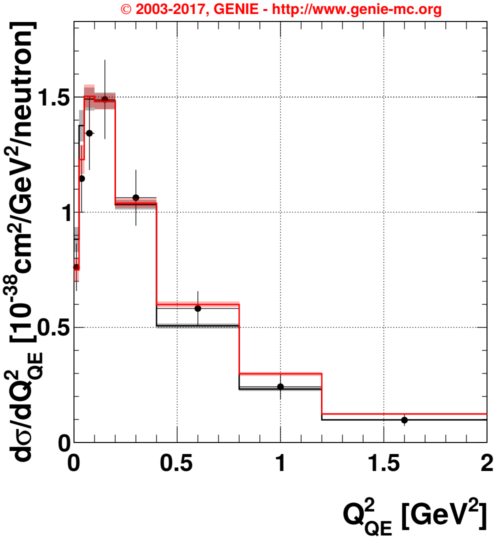
- In the RS model the non-resonant background is computed by introducing incoherently an extra amplitude with I=1/2
  $\rightarrow$ not completely satisfactory approach
- **Quark-Hadron duality** can give an alternative model to describe the non-resonant background
  - The average over resonances behaves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

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

Importance of the covariance - an example

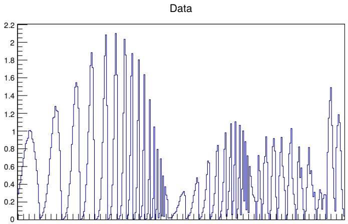


- Real dataset
- 8 points
- Which is the best agreeing curve?
  - Black
  - Red
- Difference in terms of sigma?
  - < 1
  - > 1
- Black $\chi^2 = 17.5/8$ DoF
- Red $\chi^2 = 10.9/8$ DoF

$\Rightarrow$ Almost 2 σ

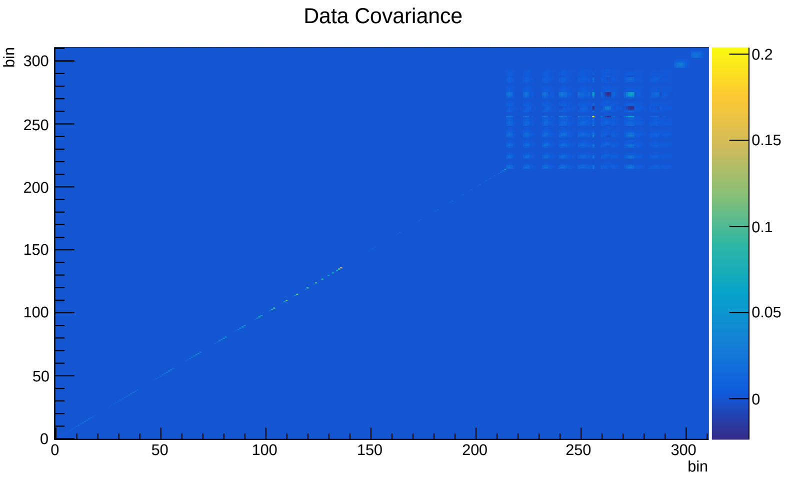
Datasets - 311 data points

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



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

Data covariance



Tuning Output

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

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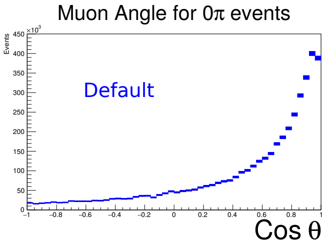

- Data Constraints for Oscillation analyses

Tuning Output

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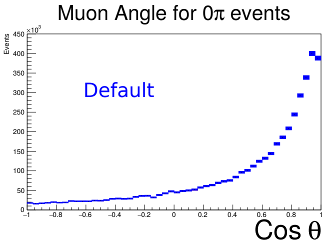
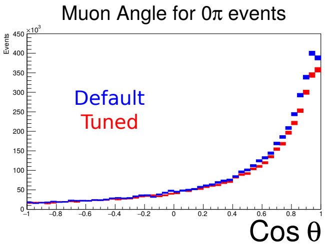
- Prediction covariance
  - due to the propagation of parameter covariance

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

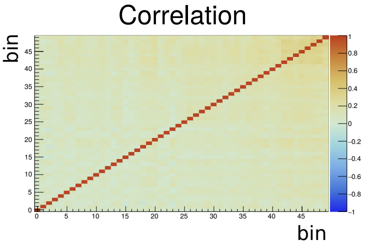


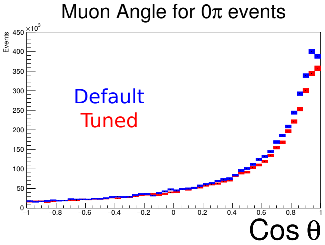


Tuning Output

- 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





Model comparison

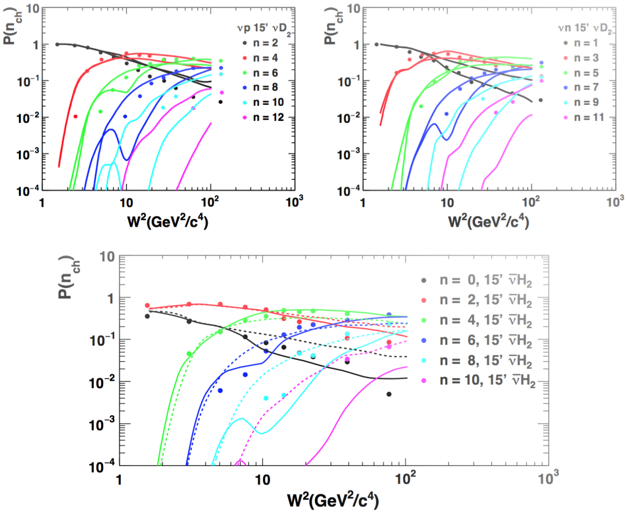
Model comparison

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

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

[M.Martini, FUNFACT JLab workshop]

Hadronization example



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