GENIE models and global fits of neutrino scattering data

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on behalf of GENIE collaboration

University of Liverpool

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Neutrino MC Generators: A Theory/Experiment Interface

- Access the flux distortion due to oscillation
  - Every observable is a convolution of flux, interaction physics and detector effects

- Connect truth and observables
  - Event topologies and kinematics
  - Model dependencies

- **Good Generators**
  - Support oscillation analyses
    - uncertainty validation
    - tune the *physics* models

  ⇒ Tuning proved to be difficult
  - So far no results

Several MC Generators in use: **GENIE, GiBUU, NuWro, NEUT**
Roles of MC generators in Oscillation Physics

- Comparing data and models
  - You cannot study oscillations without fully understood models
  - Validity region
  - Highlight tensions

- Feedback for experiments
  - Drive the format of cross section releases
  - Hint toward key measurements
 Roles of MC generators in Oscillation Physics

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- Global fits
  - Generator is the ideal place for global fits
    - We control the model implementation

- Constraints on Cross Section for oscillation analysis
  - Neutrino Cross sections priors
  - Eventually based on data

What generators can do depends on the available datasets
Evolving datasets - Old datasets


- Functions of $E_\nu$
- Not flux-integrated
- “Only” statistical errors

- Ignore nuclear effects
- Poor statistical interpretation
- Poor model discrimination power

Data

- GENIE
- Comparisons
- Tuning
- CC 0π tuning
- Conclusion

Introduction

Dataset

Functions of $E_\nu$

Not flux-integrated

“Only” statistical errors

Ignore nuclear effects

Poor statistical interpretation

Poor model discrimination power
Evolving datasets - Present datasets

- Functions of experimental observables
- flux-integrated
- Usually differential cross-sections
  - 1D, 2D
- Organized by topology, not process
- Higher statistics
- More statistically robust

⇒ Fermilab Neutrino seminar by Mikael Kuusela - 2017/04/13

\[ \cos \theta_{\mu} \in [0.9; 1] \]

Evolving datasets - Present datasets

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

\[ \cos \theta_{\mu} \in [0.9; 1] \]

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
GENIE Collaboration

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[ Faculty, Postdocs, PhD students]

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

Core GENIE mission

1. ... provide a state-of-the-art neutrino MC generator for the world experimental neutrino community
2. ... simulate all processes for all neutrino species and nuclear targets, from MeV to PeV energy scales
3. ... perform global fits to neutrino, charged-lepton and hadron scattering data and provide global neutrino interaction model tunes
GENIE Version 2.12.6

- **CCQE models**
  - Llewellyn Smith
  - Nieves, Amaro and Valverde

- **MEC models**
  - Empirical
  - Nieves Simo Vacas

- **Nuclear Models**
  - Relativistic Fermi Gas
  - Local Fermi Gas
  - Effective Spectral Functions
  - Single Kaon
  - \( \Lambda \) production

- **RES**
  - Rein-Sehgal
  - Berger-Sehgal
  - Kuzmin-Lyubushkin-Naumov

- **COH**
  - Rein-Sehgal
  - Berger-Sehgal
  - Alvarez Ruso

- **FSI - Intranuke**
  - Full Intra-Nuclear cascade
  - Schematic based on Hadron-nucleus data

- Only one Comprehensive Model Configuration (CMC)
- Default tune has not changed
GENIE status and prospects

GENIE Version 3

- “Comprehensive Model Configurations”
  - Self-consistent collections of primary process models
  - Tune names are supposed to become commonly used
    - Help cooperation between collaborations
  - single command-line flag
    - --tune G16_02a
  - Complete characterization against public data
  - Willing to host configuration provided by experiments

- Tunes for each CMC will also be available

- A step closer toward GENIE core mission

graphics by grafiche.testi@gmail.com
Comprehensive Model Configurations

Dedicated web page

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 configuration (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 Tuns are available.

<table>
<thead>
<tr>
<th>Configuration</th>
<th>Brief description</th>
</tr>
</thead>
<tbody>
<tr>
<td>G00_00a</td>
<td>Historical Genie default configuration.</td>
</tr>
<tr>
<td>G00_00b</td>
<td>Historical Genie default configuration, including empirical 2p2h.</td>
</tr>
<tr>
<td>G16_01a</td>
<td>Update of the historical default, including new interaction processes.</td>
</tr>
<tr>
<td>G16_01b</td>
<td>As G16_01a, with the inclusion of empirical 2p2h.</td>
</tr>
<tr>
<td>G16_02a</td>
<td>Comprehensive configuration anchored to the latest theory developments.</td>
</tr>
</tbody>
</table>
**Details and configuration**

**G16_02a**

This configuration is based on the latest theoretical developments. Particular emphasis is on Nieves Model for CC $0\pi$ and CC $1\pi$ 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.

<table>
<thead>
<tr>
<th>ALGORITHM</th>
<th>MODEL</th>
<th>CONFIGURATION</th>
<th>COMMENTS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Initial Nucleus State</td>
<td>Local Fermi Gas</td>
<td>LocalF0M/Default</td>
<td></td>
</tr>
<tr>
<td>CC Diffractive Pion</td>
<td>D. Rein in Nucl. Phys. B278 (1986) 61-77</td>
<td>ReinDFPXPXSec/Default</td>
<td></td>
</tr>
<tr>
<td>CC $\delta$ = 1 QE</td>
<td>A. Pais in Annals Phys. 63 (1971) 361-392</td>
<td>PaisELLambdaSXPXSec/Default</td>
<td></td>
</tr>
<tr>
<td>CC $\delta$ = 1 Inelastic</td>
<td>M. Raff Almar et al. in Phys. Rev. D82 (2010) 035001</td>
<td>AlamsinoAtahrVacasaSXPXSec2014/Default</td>
<td></td>
</tr>
</tbody>
</table>
Comprehensive Model Configurations

- Configurations of interest for this talk
  - **G00_00a** - Default
    - No MEC
    - CCQE process is Llewellyn Smith Model
    - Dipole Axial Form Factor - Depending on $M_A = 0.99$ GeV
    - Nuclear model: Fermi Gas Model - Bodek, Ritchie
  
  - **G16_01b** - Default + MEC
    - with *Empirical MEC*
    - CCQE process is Llewellyn Smith Model
    - Dipole Axial Form Factor - Depending on $M_A = 0.99$ GeV
    - Nuclear model: Fermi Gas Model - Bodek, Ritchie
  
  - **G16_02a** - Nieves, Simo, Vacas Model
    - *Theory motivated MEC*
    - CCQE process is Nieves
    - Dipole Axial Form Factor - Depending on $M_A = 0.99$ GeV
    - Nuclear model: Local Fermi Gas Model

- Small variations changing FSI models
- Variation including Spectral Functions
The 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 $\nu$ and $\bar{\nu}$

- Double differential cross section
- flux integrated

- No correlations

- Preferred model is Nieves Model (G16_02a)
  - excellent agreement for $\nu$
  - $\chi^2 = 101/137$ DoF

- worse for $\bar{\nu}$
  - $\chi^2 = 176/78$ DoF

\[ \frac{d^2\sigma(\nu, CC 0\pi)}{d\theta / d T} [10^{-38} \text{ cm}^2/\text{GeV/n}] \]

Data: miniboone_nuccqe_2010
MiniBooNE CCQE

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$\nu$ and $\bar{\nu}$ double differential cross section, flux integrated.

$\chi^2$ values:
- $\chi^2 = 40.6/17$ DoF
- $\chi^2 = 64.8/17$ DoF
- $\chi^2 = 14.3/17$ DoF
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!

Double differential cross section
- flux integrated
- Fully correlated
- Tensions between datasets
- Preferred model is G16_01b
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- all models look reasonable "By eye" estimation
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<table>
<thead>
<tr>
<th>Model</th>
<th>$\chi^2$</th>
<th>DoF</th>
</tr>
</thead>
<tbody>
<tr>
<td>t2k_nd280_numucc0pi_2015</td>
<td></td>
<td></td>
</tr>
<tr>
<td>G00_00a</td>
<td>17.2</td>
<td>8</td>
</tr>
<tr>
<td>G16_01b</td>
<td>7.75</td>
<td>8</td>
</tr>
<tr>
<td>G16_02a</td>
<td>25.8</td>
<td>8</td>
</tr>
</tbody>
</table>

$\cos\theta_\mu \in [0.9; 0.94]$
Tuning

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

- Expected Output:
  - Best parameters
  - Parameter covariance matrix
    - To be used for prior constructions
Tuning

- **Why tuning?**
  - Constraint parameters
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- **Expected Output:**
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- **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](http://professor.hepforge.org)
  - Numerical assistant
  - Developed for ATLAS experiment
Parametrization instead of a full MC
Parametrization instead of a full MC

1. Select points of param space
• 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
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3. Parametrization $I(p)$

- interpolated value
Parametrization instead of a full MC

1. Select points of param space
2. Evaluate bin’s behaviour with brute force
3. Parametrization $I(p)$

- Repeat for each bin

- A parameterization $l_j(p)$ for each bin
  - N dimension polynomial
  - Including all the correlation terms up to the order of the polynomial

- Minimize according to $\bar{I}(p)$

- $\sim 15$ parameters

Special thanks to H. Schulz
Advantages

- Highly parallelizable
  - independent from the minimization

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

- Priors can be included
  - Avoid unphysical result

- Nuisance rescaling parameters can be inserted
  - proper treatment for datasets without correlations
    (MiniBooNE)

- Reliable minimization algorithm
  - based on Minuit
The first tuning

Tuning against CC $0\pi$ datasets
Datasets - 311 data points

- MiniBooNE $\nu_\mu$ CCQE
  - 2D histogram
  - 137 points
  - No correlation matrix
- MiniBooNE $\bar{\nu}_\mu$ CCQE
  - 2D histogram
  - 78 points
  - No correlation matrix
- T2K ND280 $0\pi$ (2016) V2
  - 2D histogram
  - 80 points
  - full covariance matrix
- MINERvA $\nu_\mu$ 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
Models and parameters

- **Default + Empirical MEC**
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<th>Range</th>
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<tr>
<td>QEL-$M_A$ (GeV/c$^2$)</td>
<td>[0.7 ; 1.8]</td>
<td>0.99</td>
</tr>
<tr>
<td>QEL-CC-XSecScale</td>
<td>[0.8 ; 1.2]</td>
<td>1</td>
</tr>
<tr>
<td>RES-CC-XSecScale</td>
<td>[0.5 ; 1.5]</td>
<td>1</td>
</tr>
<tr>
<td>FSI-PionMFP-Scale</td>
<td>[0.6 ; 1.4]</td>
<td>1</td>
</tr>
<tr>
<td>FSI-PionAbs-Scale</td>
<td>[0.4 ; 1.6]</td>
<td>1</td>
</tr>
<tr>
<td>MEC-FracCCQE - G16_01b only</td>
<td>[0 ; 1]</td>
<td>0.45</td>
</tr>
<tr>
<td>MEC-CC-XSecScale - G16_02a only</td>
<td>[0.7 ; 1.3]</td>
<td>1</td>
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Models and parameters

- Default + Empirical MEC
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<td>[0.7; 1.3]</td>
<td>1</td>
</tr>
</tbody>
</table>

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

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

<table>
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<th>Nominal</th>
</tr>
</thead>
<tbody>
<tr>
<td>$M_A$ (GeV/c$^2$)</td>
<td>1.00 ± 0.03</td>
<td>0.99 ± 0.01</td>
</tr>
<tr>
<td>QEL-CC-XSecScale</td>
<td>0.91 ± 0.02</td>
<td>1</td>
</tr>
<tr>
<td>RES-CC-XSecScale</td>
<td>1.01 ± 0.04</td>
<td>1</td>
</tr>
<tr>
<td>MEC-CC-XSecScale</td>
<td>1.18 ± 0.02</td>
<td>1</td>
</tr>
<tr>
<td>FSI-PionMFP-Scale</td>
<td>1.17 ± 0.04</td>
<td>1.0 ± 0.2</td>
</tr>
<tr>
<td>FSI-PionAbs-Scale</td>
<td>1.02 ± 0.09</td>
<td>1.0 ± 0.3</td>
</tr>
</tbody>
</table>

- $M_A$ 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

<table>
<thead>
<tr>
<th>Dataset</th>
<th>Best fit $\chi^2$</th>
<th>Nominal $\chi^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Miniboone $\nu_\mu$ CC $0\pi$</td>
<td>177 / 137</td>
<td>441 / 137</td>
</tr>
<tr>
<td>MiniBooNE $\bar{\nu}_\mu$ CC $0\pi$</td>
<td>66.2 / 78</td>
<td>50.4 / 78</td>
</tr>
<tr>
<td>T2K ND 280 CC $0\pi$</td>
<td>94 / 80</td>
<td>56.6 / 80</td>
</tr>
<tr>
<td>Total</td>
<td>337 / 289</td>
<td>548 / 295</td>
</tr>
</tbody>
</table>

G16_02a - Full Nieves Model

<table>
<thead>
<tr>
<th>Dataset</th>
<th>Best fit $\chi^2$</th>
<th>Nominal $\chi^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Miniboone $\nu_\mu$ CC $0\pi$</td>
<td>89.3 / 137</td>
<td>101 / 137</td>
</tr>
<tr>
<td>MiniBooNE $\bar{\nu}_\mu$ CC $0\pi$</td>
<td>48.1 / 78</td>
<td>176 / 78</td>
</tr>
<tr>
<td>T2K ND 280 CC $0\pi$</td>
<td>102 / 80</td>
<td>98.9 / 80</td>
</tr>
<tr>
<td>Total</td>
<td>239 / 289</td>
<td>376 / 295</td>
</tr>
</tbody>
</table>

- Improvement possible for both models
  ⇒ The fit is working

- Fit driven by MiniBooNE datasets
  - Lowest information ⇒ No correlations
  - Room for improvement

- These T2K and Minerva datasets cannot be fit on their own
  - They cover a small phase space region
  ⇒ Parameters goes to the boundaries
Best fit plots

Best fit - G16_01b - MiniBooNE $\nu_\mu$ CCQE

$\cos\theta_\mu \in [0.8; 0.9]$

$\cos\theta_\mu \in [0.9; 1]$

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

Introducing the new model, GENIE, we compare its performance against the previous model.

**Tuning**

- **CC 0\(\pi\) tuning**
- **π tuning**

**Comparisons**

- **Best fit plots**

**Neutrinos**

- \(\chi^2 = 17.5/8\) DoF
- \(\chi^2 = 10.9/8\) DoF

**Antineutrinos**

- \(\chi^2 = 6.23/8\) DoF
- \(\chi^2 = 4.7/8\) DoF

⇒ "Eye evaluation" wouldn’t prefer a model over the other
agreement with T2K has worsened

not surprising

⇒ Tensions already highlighted

χ²: 57 → 94 / 80 DoF
Nieves’ model already works well
- Agreement is preserved

Notable improvement only w.r.t. MiniBooNE $\bar{\nu}_\mu$

Best fit plots

Best fit - G16_02a

$\chi^2 = 53.8/15$ DoF

$\chi^2 = 13.5/15$ DoF

$\cos\theta_\mu \in [0.9; 1]$
Next steps

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

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

- Data from Liquid argon experiments
  - Part of GENIE collaboration is in SBND
  - Plan for argon tunings

- Look forward to more data

- Release these results
  - Paper is in preparation
  - Implementation in GENIE v3
Conclusion

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

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

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

Good

Bad

/gLOBAL
Data Covariance
A simple ratio between Near and Far spectra is not enough
- Detectors exposed to different flux
- “functionally identical” detectors do not exist

Near flux has to be fitted at the near detector and then propagated
⇒ Models required
CCQE is a 2-body reaction
- $E_\nu$ depends is just a function of lepton momentum and angle

2p/2h is not a 2-body reaction
- low energy tails in reconstructed energy distributions

2p/2h also relevant for CP searches
- np-nh is different for $\nu/\bar{\nu}$

⇒ 2p/2h modelling is important to achieve required precision

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

Martini et al.
Model comparison
Model comparison

\[ \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 R_T + \frac{\omega^2}{q^2} G_A^2 R_{\sigma_T(L)} + \right. \\
+ 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_T(T)} \pm 2 \frac{\epsilon + \epsilon'}{M_N} \tan^2 \frac{\theta}{2} G_A G_M R_{\sigma_T(T)} \right] \\

[M. Martini, FUNFACT J Lab workshop]
Importance of Covariance

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 $\sigma$
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

Data Genie with FSI
Genie No FSI
NuWro with FSI
NuWro No FSI
3.06e+20 Data POT

$\nu_\mu C \rightarrow \mu^- p$

$\nu_\mu Pb \rightarrow \mu^- p$
Importance of Covariance

Example of easy improvement

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

arXiv:1705.03791v1

![Graph](image_url)
CC Quasi-Elastic - $0\pi$ on single nucleons

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

- 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 $\nu$ 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 $\beta$ decay
- fitted based on $\partial\sigma/\partial Q^2$ data
CC Quasi-Elastic - Data

- Hydrogen / Deuterium data
  - from 0.1 GeV to \( \sim \) 100 GeV
  - For both Neutrinos and Anti-neutrinos

- Critical parameter: \( M_A \)
  - \( M_A \sim 1 \text{ GeV} \)
CC Quasi-Elastic - Data

- Hydrogen / Deuterium data
  - from 0.1 GeV to \(\sim 100\) GeV
  - For both Neutrinos and Anti-neutrinos

- Critical parameter: \(M_A\)
  - \(M_A \sim 1\) GeV

\[\frac{d\sigma}{dQ^2} (10^{-38} \text{ cm}^2 / \text{GeV}^2)\]

\(\nu_n \rightarrow \mu^- p\)

- Allasia et al., CERN WA25 (BEBC) 1990
- Target: \(D_2\) (converted to free neutron)
- Event number: 552
- \(5 < E_\nu < 150\) GeV, \(<E_\nu> \approx 54\) GeV

\(M_A = 0.999 \pm 0.011\) GeV (global fit)
\(M_A = 0.890 \pm 0.044\) GeV (best fit)
On heavy nuclei things got complicated

MiniBooNE ⇒ first evidence
  • Carbon target

Possible explanation from enhanced $M_A$
  ⇒ incompatibility with "historical" datasets
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

1. Leptonic model
2. Hadronic model (Nucleon cluster model)
3. FSI model (hA model)
2 Particles - 2 Holes

**NN correlations**

(a) 

(b) 

(c) 

(d) 

(e) 

(f) 

16 diagrams

**MEC**

**NN correlation-MEC interference**

49 diagrams

56 diagrams

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

Data from comparisons

**Hadronization example**

![Graph](image-url)
Backup

Systematic propagation

Tuning Output

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

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

Data Constraints for Oscillation analyses

Muon Angle for 0π events

Default
- 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

Muon Angle for $0\pi$ events

**Default**

**Tuned**
Systematic propagation

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

Correlation

Muon Angle for 0π events

Default
Tuned