GENIE/Professor framework for neutrino data global fit
A first application: global fit of CC $0\pi$ datasets

Marco Roda - mroda@liverpool.ac.uk
on behalf of GENIE collaboration

University of Liverpool

19 April 2017
IPPP/NuStec
Outline

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

Thanks to
IPPP Associateship award
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Why care about $0\pi$?

- We want to study neutrinos
  - flavour and mixing
  - Lepton CP violation

- Oscillation experiments
  - T2k, NOvA
  - DUNE, HyperK
  - Beam energy $\sim$ few GeV

- CC $0\pi$ is the dominant reaction
- Two body reaction
  - Ideal for $\nu$ energy estimation ...
  - ...on free nucleons
CC Quasi-Elastic - $0\pi$ on single nucleons

- Theoretically understood
- Well constrained by experimental information
- Electron scattering
- Neutron $\beta$ decay
- Experiments on Hydrogen / Deuterium
On higher A nuclei things are complicated

CCQE is not enough to describe data
  - MiniBooNE

MEC is required
  - nucleons interactions
  - 2p-2h
  - np-nh
  - $> 20\%$ effect
    - On carbon

[Martini et al. PRC 84 055502 (2011)]
Effect of MEC on energy reconstruction

- CCQE is a 2-body reaction
  - $E_{\nu}$ depends 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
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 $0\pi$ samples
    - proton multiplicity

- Important dataset that will "soon" be available

ArGoNEUT

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

- **What can we do as generator people?**
  - Comparing different data and models
    - Being quantitative
      - highlight tensions
    - Call for experiments: we need full covariance matrices
  - feedback for experiments
    - drive the format of cross section releases
    - hint toward key measurements

- **Global fits**
  - Model ⇒ Cross sections is not analytic

What is the status of Genie in all of this?
What can we do as generator people?

Comparing different data and models
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Global fits
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    - drive the format of cross section releases
    - hint toward key measurements
- Global fits
  - Model \( \Rightarrow \) Cross sections is not analytic

What is the status of Genie in all of this?
Genie - Models for $0\pi$

- **Default - G00_00a**
  - No MEC
  - CCQE process is LwlynSmith Model
  - Dipole Axial Form Factor - Depending on $M_A = 0.99$ GeV
  - Nuclear model: Fermi Gas Model - Bodek, Ritchie

- **Default + MEC - G16_01b**
  - with Empirical MEC
  - CCQE process is LwlynSmith Model
  - Dipole Axial Form Factor - Depending on $M_A = 0.99$ GeV
  - Nuclear model: Fermi Gas Model - Bodek, Ritchie

- **Nieves, Simo, Vacas Model - G16_02a**
  - Theory motivated MEC
  - CCQE process is Nieves
  - Dipole Axial Form Factor - Depending on $M_A = 0.99$ GeV
  - Nuclear model: Local Fermi Gas Model

- **G17_02a (not presented in this talk) - G17_02a**
  - with Z-Expansion for Axial form factor
  - Get rid of $M_A$
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
MiniBooNE CCQE

- Both $\nu$ and $\bar{\nu}$
- Double differential cross section
- flux integrated
- No correlations
- Preferred model is Nieves Model (G16_02a)
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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
  - $\chi^2 = 135/67$ DoF
- all models look reasonable "By eye" estimation
  - correlation is complicated
  - We can’t ignore it!
• New Models
  • MEC models
    • Empirical
    • Nieves Simo Vacas
  • Better CCQE model
    • Nieves
    • ...
  • Nuclear models

• Multiple combinations
  • Need to check the balance between each component

will have a tuning!
**New Models**

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

- **Better CCQE model**
  - Nieves
  - ...

- **Nuclear models**

**Multiple combinations**

- Need to check the balance between each component

**will have a tuning!**
The GENIE suite contains a package devoted to comparing GENIE predictions against publicly released datasets.

- Crucial technology for **new GENIE global fit** to neutrino scattering data
- Provides the opportunity to improve and develop GENIE models
- All sorts of data
  - **Modern Neutrino Cross Section measurement**
    - nuclear targets
    - typically flux-integrated differential cross-sections
    - MiniBooNE, T2K, MINERvA
  - **Historical Neutrino Cross Section Measurement**
    - Bubble chamber experiment
  - Measurements of neutrino-induced **hadronic system characteristics**
http://professor.hepforge.org

Numerical assistant

Developed for ATLAS experiment

\( I(p) \) used instead of a full MC

1. MC runs subset of param space
2. Sample bin’s behaviour
3. Parametrization \( I(p) \)
   - Polynomial interpolation

Repeat for each bin

- A parameterization \( I_j(p) \) for each bin
- Minimize according to \( \tilde{I}(p) \)
- \( \sim \) 15 parameters

Special thanks to H. Schulz
- Based here in Durham
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- $I(p)$ used instead of a full MC
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A parameterization \( I_j(p) \) for each bin

Minimize according to \( \tilde{I}(p) \)

\( \sim 15 \) parameters

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\( l(p) \) used instead of a full MC

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3. Parametrization \( l(p) \)
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   - Repeat for each bin

A parameterization \( l_j(p) \) for each bin

Minimize according to \( \tilde{l}(p) \)

\( \sim \) 15 parameters

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Advantages

- Highly parallelizable
  - independent from the minimization
- All kind of parameters can be tuned
  - Not only reweight-able
- Advanced system
  - Take into account correlations
  - weights specific for each bin and/or dataset
    - Proper treatment while handling multiple datasets
    - Restrict the fit to particular subsets
  - Nuisance parameters can be inserted
    - proper treatment for datasets without correlations (MiniBooNE)
- Reliable minimization algorithm
  - based on Minuit
Datasets - 298 data points

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

Model and parameters

- Default + Empirical MEC
- G16_01b in the new naming scheme

Parameters:
- QEL-$MA \in [0.7; 1.8]$ GeV - Default value is 0.99 GeV
- QEL-CC-XSecScale $\in [0.8; 1.2]$ - Default value is 1
- RES-CC-XSecScale $\in [0.5; 1.5]$ - Default value is 1
- MEC-FracCCQE $\in [0; 1]$ - Default value is 0.45
- FSI-PionMFP-Scale $\in [0.6; 1.4]$ - Default value is 1
- FSI-PionAbs-Scale $\in [0.4; 1.6]$ - Default value is 1

No priors on the parameters
- Considering on $MA$
Professor Output

- Parameters best fit
  0 $M_A$
  1 QEL-CC-XSecScale
  2 RES-CC-XSecScale
  3 MEC-FracCCQE
  4 FSI-PionMFP-Scale
  5 FSI-PionAbs-Scale

- Prediction covariance
  - due to the propagation of the param. covariance
  - So far not used
  - Tool to propagate systematics parameters
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>1.21 ± 0.02</td>
<td>0.99</td>
</tr>
<tr>
<td>QEL-CC-XSecScale</td>
<td>0.95 ± 0.02</td>
<td>1</td>
</tr>
<tr>
<td>RES-CC-XSecScale</td>
<td>1.02 ± 0.05</td>
<td>1</td>
</tr>
<tr>
<td>MEC-FracCCQE</td>
<td>0.53 ± 0.08</td>
<td>0.45</td>
</tr>
<tr>
<td>FSI-PionMFP-Scale</td>
<td>0.75 ± 0.04</td>
<td>1</td>
</tr>
<tr>
<td>FSI-PionAbs-Scale</td>
<td>0.87 ± 0.07</td>
<td>1</td>
</tr>
</tbody>
</table>

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

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Neutrino fit</th>
<th>Anti-neutrino fit</th>
<th>Global fit</th>
</tr>
</thead>
<tbody>
<tr>
<td>$M_A$ (GeV/c$^2$)</td>
<td>1.17 ± 0.02</td>
<td>1.26 ± 0.03</td>
<td>1.21 ± 0.02</td>
</tr>
<tr>
<td>QEL-CC-XSecScale</td>
<td>0.93 ± 0.01</td>
<td>0.97 ± 0.02</td>
<td>0.95 ± 0.02</td>
</tr>
<tr>
<td>RES-CC-XSecScale</td>
<td>0.86 ± 0.05</td>
<td>0.98 ± 0.09</td>
<td>1.02 ± 0.05</td>
</tr>
<tr>
<td>MEC-FracCCQE</td>
<td>0.85 ± 0.03</td>
<td>0.7 ± 0.1</td>
<td>0.53 ± 0.08</td>
</tr>
<tr>
<td>FSI-PionMFP-Scale</td>
<td>0.87 ± 0.02</td>
<td>1.39 ± 0.03</td>
<td>0.75 ± 0.04</td>
</tr>
<tr>
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Fit Results

<table>
<thead>
<tr>
<th>Dataset</th>
<th>Neutrino fit</th>
<th>Anti-neutrino fit</th>
<th>Global fit</th>
<th>Nominal Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Miniboone $\nu_\mu$ $\chi^2$</td>
<td>152 / 137</td>
<td>171 / 137</td>
<td>138 / 137</td>
<td>441 / 137</td>
</tr>
<tr>
<td>MiniBooNE $\bar{\nu}_\mu$ $\chi^2$</td>
<td>60 / 78</td>
<td>32.4 / 78</td>
<td>36.2 / 78</td>
<td>50.4 / 78</td>
</tr>
<tr>
<td>T2K $\chi^2$</td>
<td>237 / 67</td>
<td>276 / 67</td>
<td>252 / 67</td>
<td>135 / 67</td>
</tr>
<tr>
<td>MINERvA $\nu_\mu$ $\chi^2$</td>
<td>6.11 / 8</td>
<td>8.07 / 8</td>
<td>7.79 / 8</td>
<td>17.5 / 8</td>
</tr>
<tr>
<td>MINERvA $\bar{\nu}_\mu$ $\chi^2$</td>
<td>8.19 / 8</td>
<td>11.5 / 8</td>
<td>5.7 / 8</td>
<td>6.23 / 8</td>
</tr>
<tr>
<td>Global dataset $\chi^2$</td>
<td>463 / 292</td>
<td>499 / 292</td>
<td>440 / 292</td>
<td>650 / 298</td>
</tr>
</tbody>
</table>

- $M_A$ and cross section scale factors are in good agreement
- FSI parameters are not
- The agreement with data is reasonable
  - Better than original model
T2K effect on the fit

- T2K ND280 data are complicated
  - Tensions
  - Correlations $\Rightarrow$ anti-intuitive

- T2K ND280 data can not even be fitted by their own with the current model
  $\Rightarrow \chi^2 = 127/61$

- T2K fit results are not compatible with other dataset
  $\Rightarrow \chi^2 = 1023/137$ vs MiniBooNE $\nu_\mu$ CCQE
  $\Rightarrow \chi^2 = 1567/292$ vs whole fitted dataset

- global fit can suffer from this
- Effect is clear
  - discrepancy in low momentum muons
    - $T_\mu < 400$ MeV

- No reason to remove this dataset from the fit
  - Their effort on the error estimation should be praised
T2K effect on the fit

- T2K ND280 data are complicated
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Best fit plots

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

Fit has a big impact.
Best fit - MiniBooNE $\bar{\nu}_\mu$ CCQE

Improvement not really necessary in this case
Best fit plots

Best fit - MINERvA

Neutrinos

Antineutrinos

⇒ "Eye evaluation" would prefer default model
• agreement with t2k has worsened
• not surprising
⇒ it happened also with models
• \( \chi^2: 135 \rightarrow 252 / 67 \text{ DoF} \)
Next steps

- More datasets:
  - Bubble chamber CCQE data
    - Why not fitting $M_A$ all together?
    - Data are in our database (see introduction)
  - inclusive cross sections
    - avoid fit results to go in not physical regions

- Fit of new models
  - Full Nieves Model - g16_02b
  - ...

- Find a way to estimate correlations for MiniBooNE
  - Nuisance parameters
Conclusion

- We are renewing Genie
  - new models
  - Easy comparisons with Cross section Data
  - Deployed in Genie v3 and v4

- We have a very powerful fitting machinery
  - Proved to work
  - This is not an exercise

- We hope that these tools will improve theory / experiments collaboration
New Position in Liverpool
Join a big neutrino group

Position has to be filled in 10 days

Big data science
SBND
Argon Tune for GENIE
Backup slides
## Single datasets - MiniBooNE

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Miniboone $\nu_\mu$ fit</th>
<th>MiniBooNE $\bar{\nu}_\mu$ fit</th>
<th>MiniBooNE Global fit</th>
</tr>
</thead>
<tbody>
<tr>
<td>$M_A$ (GeV/c$^2$)</td>
<td>$1.10 \pm 0.03$</td>
<td>$1.25 \pm 0.03$</td>
<td>$1.17 \pm 0.02$</td>
</tr>
<tr>
<td>QEL-CC-XSecScale</td>
<td>$1.12 \pm 0.02$</td>
<td>$0.99 \pm 0.03$</td>
<td>$1.05 \pm 0.02$</td>
</tr>
<tr>
<td>RES-CC-XSecScale</td>
<td>$0.69 \pm 0.06$</td>
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<tr>
<td>MEC-FracCCQE</td>
<td>$0.43 \pm 0.07$</td>
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<td>$0.33 \pm 0.08$</td>
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<td>FSI-PionMFP-Scale</td>
<td>$0.95 \pm 0.03$</td>
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<td>$0.99 \pm 0.06$</td>
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<tr>
<td>FSI-PionAbs-Scale</td>
<td>$1.17 \pm 0.07$</td>
<td>$0.8 \pm 0.2$</td>
<td>$1.08 \pm 0.09$</td>
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### Fit Results

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<td>Miniboone $\nu_\mu$ $\chi^2$</td>
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<td>Miniboone $\bar{\nu}_\mu$ $\chi^2$</td>
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<td>$29 / 72$</td>
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<td>T2K $\chi^2$</td>
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<td>$11.4 / 8$</td>
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<td>Global dataset $\chi^2$</td>
<td>$507 / 292$</td>
<td>$483 / 292$</td>
<td>$455 / 292$</td>
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Single datasets - T2K ND280 $\nu_\mu$ 0$\pi$

<table>
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<tr>
<th>Parameter</th>
<th>T2K fit</th>
<th>T2K fit - no corr</th>
<th>T2K fit with priors</th>
</tr>
</thead>
<tbody>
<tr>
<td>$M_A$ (GeV/$c^2$)</td>
<td>0.75 ± 0.04</td>
<td>1.03 ± 0.13</td>
<td></td>
</tr>
<tr>
<td>QEL-CC-XSecScale</td>
<td>0.90 ± 0.02</td>
<td>1.11 ± 0.04</td>
<td></td>
</tr>
<tr>
<td>RES-CC-XSecScale</td>
<td>1.2 ± 0.1</td>
<td>1.500 ± 0.001</td>
<td></td>
</tr>
<tr>
<td>MEC-FracCCQE</td>
<td>0.36 ± 0.09</td>
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<tr>
<td>FSI-PionMFP-Scale</td>
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<td>/ 8</td>
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<td>/ 131</td>
<td>/ 137</td>
<td>220 / 137</td>
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