GENIE Status and Prospects

Simulations Underpinning Discovery and Precision Measurements

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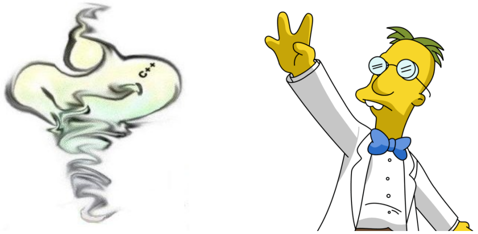
Outline

- Neutrino interaction simulations and challenges
- Baseline model in GENIE v2 series
- **New model development work** in v2.10.0 and v2.12.0
- **Towards new baseline model and tunes** - GENIE v3 and v4



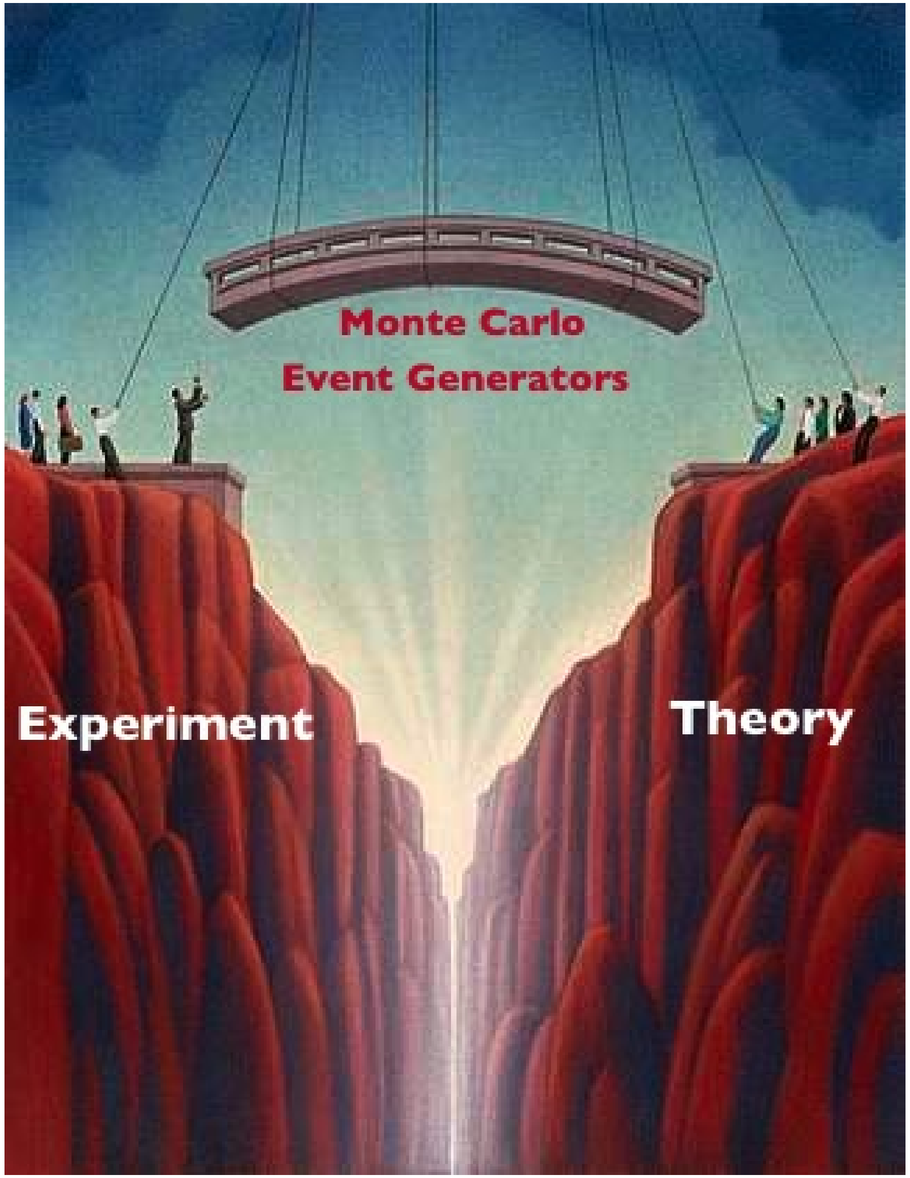
GENIE meets Professor
https://professor.hepforge.org

- **Towards a comprehensive evaluation of the effect of model uncertainties** for accelerator LBL and SBL experiments

GENIE meets VALOR
https://valor.pp.rl.ac.uk

- Summary

Neutrino MC Generators: A Theory/Experiment Interface

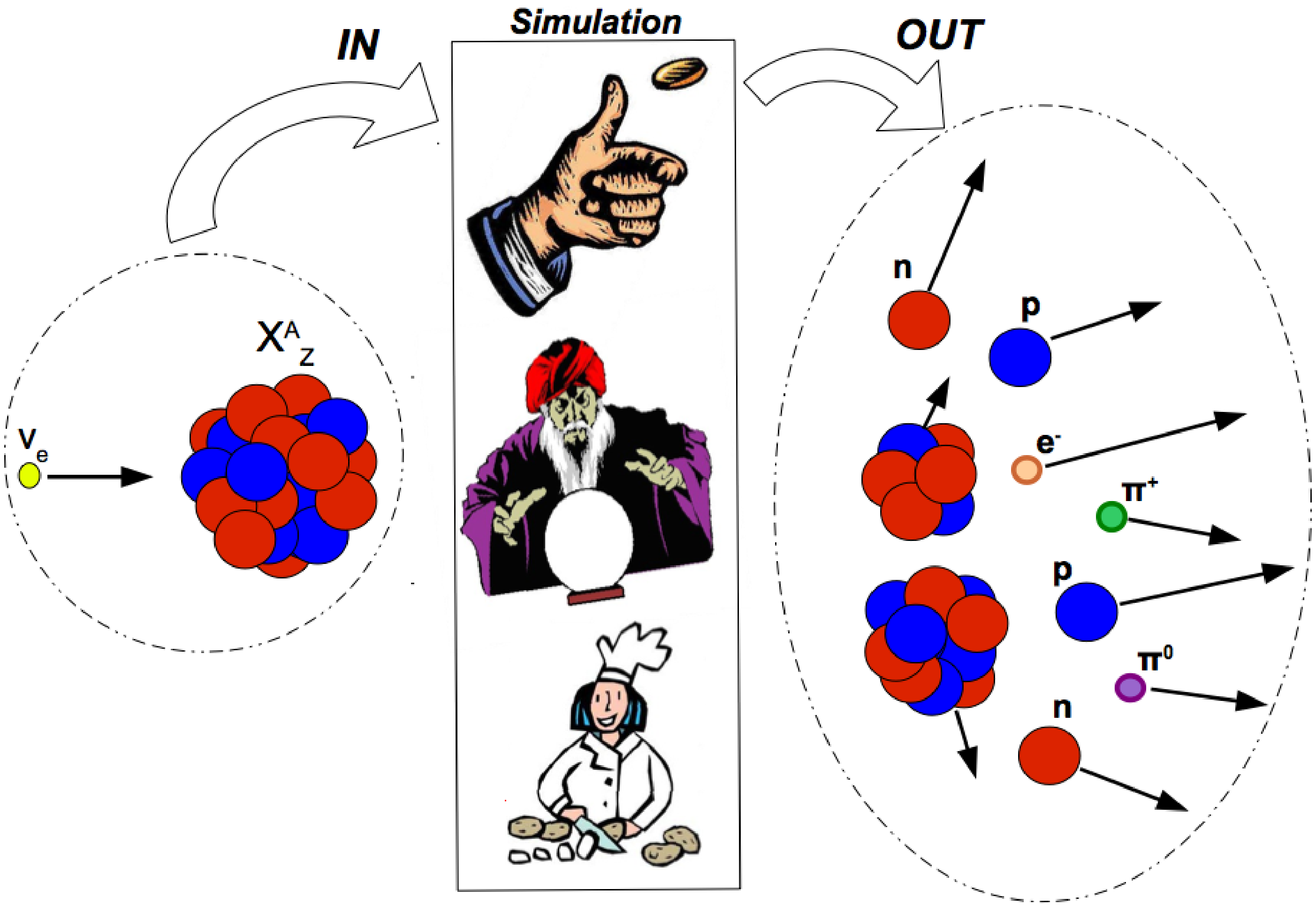


Neutrino MC Generators connect the true and observed event topologies and kinematics.

Every observable a convolution of flux, interaction physics and detector effects. Neutrino MC Generators allow experimentalists to access, improve, validate, assess the uncertainty of and tune the *physics* models that drive the result of that convolution.

What do we want to simulate?

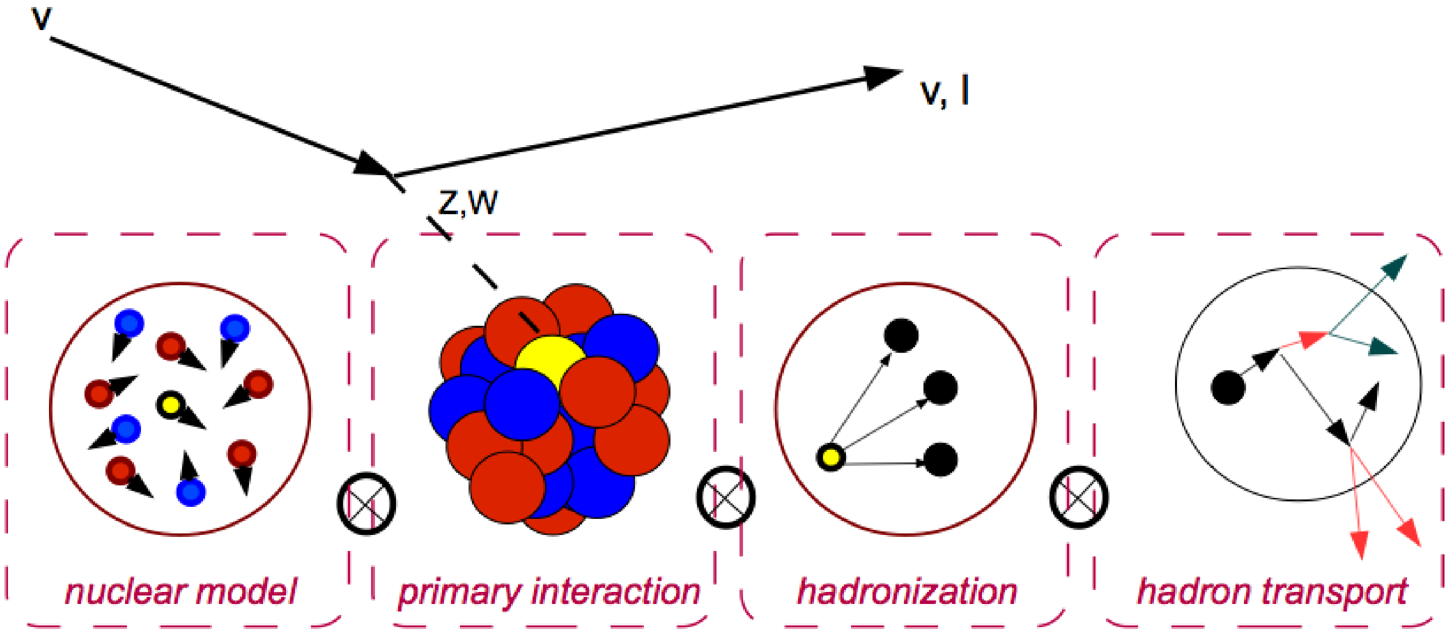
To boost the event rate, experiments use nuclear targets. Dozens of different isotopes present in our detectors, but typically the bulk of detector fiducial mass is made of C12, O16, Ar40, Fe56.
A Neutrino MC Generator needs to simulate, on an event-by-event basis, the types and 4-momenta of *all* final state particles produced in interactions of neutrinos with nuclei.



Neutrino MC Generator factorization

Since we do not have a complete theory of particle production in neutrino scattering off nuclear targets, simulation of exclusive final states proceeds in a *bottom-up fashion*, using models of:

- the initial nuclear state dynamics
- cross-sections at the neutrino-nucleon level (+ a model of how to sum-up the nucleon-level contributions)
- the process by which hadrons emerge from the primary interaction (hadronization)
- intranuclear hadron transport



GENIE (http://www.genie-mc.org)

Core GENIE mission

Extracts from: https://genie.hepforge.org/pub/policy/genie_bylaws_v1.0.pdf

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

GENIE Collaboration

Luis Alvarez Ruso[8], Costas Andreopoulos[2,5], Chris Barry[2], Francis Bench[2], Steve Dennis[2], Steve Dytman[3], Hugh Gallagher[7], Tomasz Golan[1,4], Robert Hatcher[1], Libo Jiang[3], Rhiannon Jones[2], Anselmo Meregaglia[6], Donna Naples[3], Gabriel Perdue[1], Marco Roda[2], Jeremy Wolcott[7], Julia Yarba[1]

[*Faculty*, *Postdocs*, *PhD students*]

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

GENIE development/release history & roadmap

- August 2007: Release of first public production version (v2.0.0)
- 2008 - 2010: Releases (v2.2.0, v2.4.0, v2.6.0) with technical improvements.

Effort to interface GENIE with full simulation chain of experiments and to develop tools to support generator-related analysis activities.

GENIE now used by all experiments. Main paper approaches 400 citations!

- 2011 - 2014: Only a single minor release (v2.8.0).

Period overlapped with start of T2K data-taking and analysis and a change of research focus for some GENIE authors.

Substantial re-organization and new effort after 2014

- **Nov. 2, 2015**: Release (**v2.10.0**) with several physics additions.
- **Oct 31, 2016**: Release (**v2.12.0**) with several physics additions.

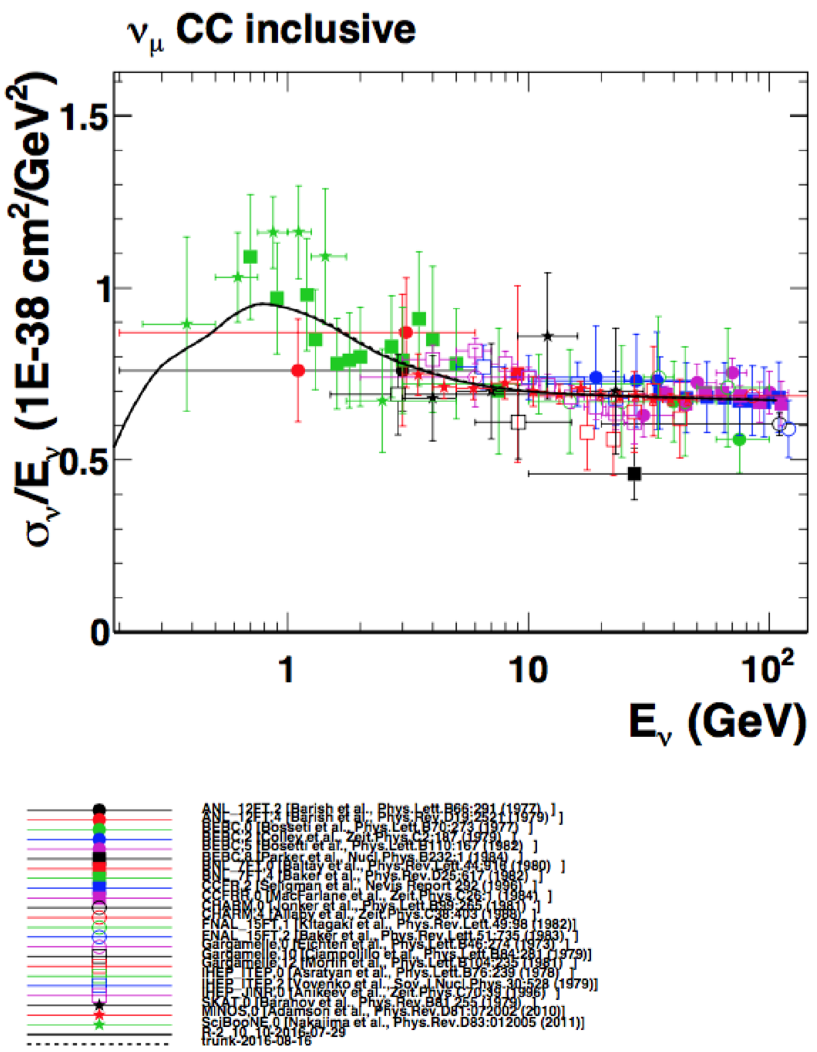
Largely caught-up with new theory. This is the **end of the v2 series**!

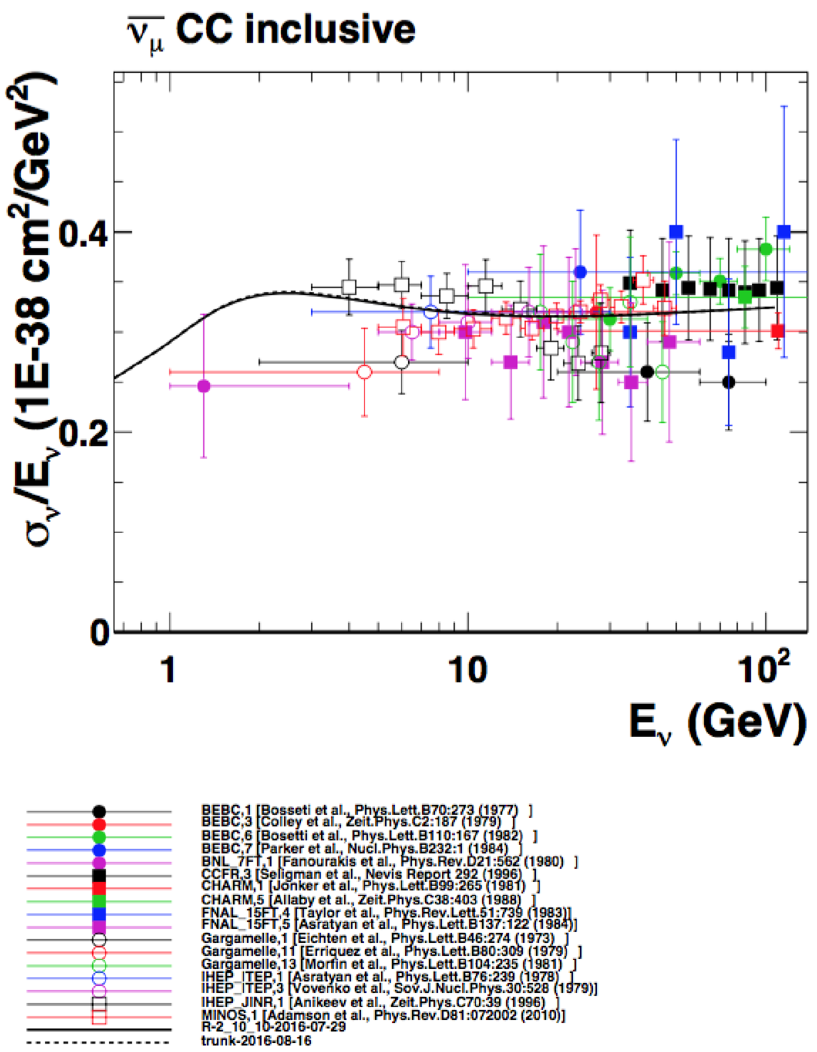
- *Early 2017*: **v3.0.0** - Several new fully-characterised comprehensive models.
  - Including a new *default* model - minimally tuned.
- *Late 2017*: **v4.0.0** - Extensive new tunes via a Professor/GENIE interface.

Default physics model in v2 series

- **Cross-section model**:
  - **NCEL**: Ahrens model; dipole axial form factor ($M_A = 0.99$ GeV/c^2); strange axial contribution η=0.12.
  - **CCQE**: Llewellyn-Smith with BBA05 elastic f/f; pseudo-scalar form factor by PCAC; dipole axial form factor ($M_A = 0.99$ GeV/c^2)
  - **RES**: Rein-Sehgal model; 16 resonances (ignoring interference) with updated parameters at W<1.7 GeV/c^2; lepton mass only in phase space boundaries; dipole vector form factor ($M_A = 0.84$ GeV/c^2); dipole axial form factor ($M_A = 1.12$ GeV/c^2).
  - **DIS**: Bodek-Yang
  - **Coherent** π: Rein-Sehgal with updated PCAC formula
  - Also: QE and DIS charm production, νe elastic, IMD, IMD annihilation
- **Nuclear modelling**: FG with high-momentum tail. Off-shell kinematics.
- **Transition region treatment**: Non-resonance background is extrapolated Bodek-Yang model at W<1.7 GeV/c^2, tuned by a fit to CC inclusive, CC 1π and CC 2π data.

Default physics model in v2 series



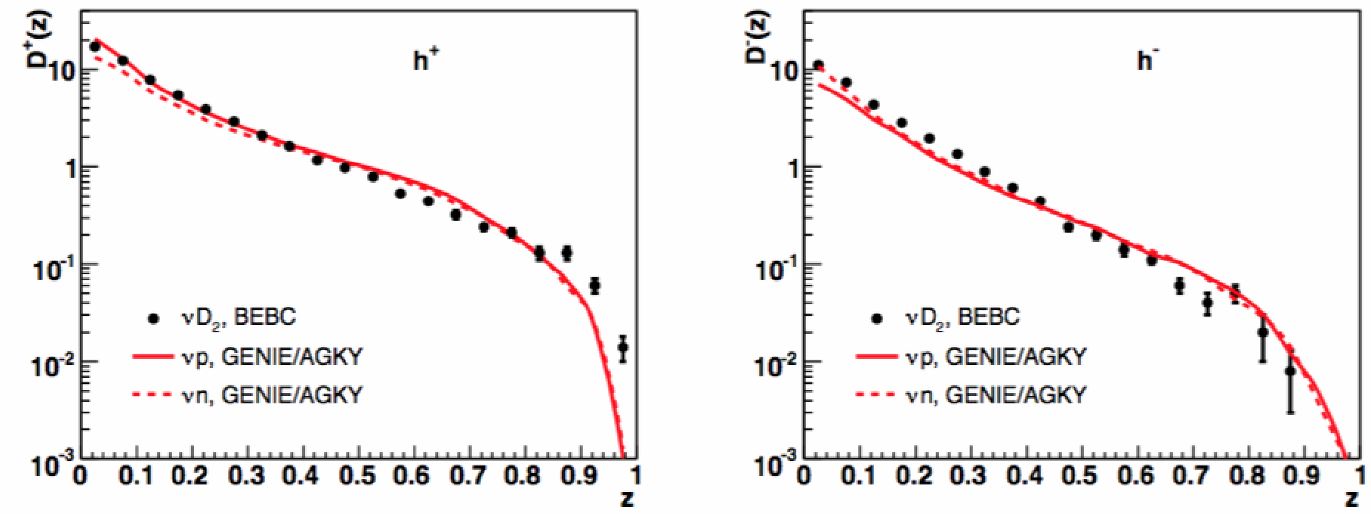


Default physics model in v2 series

Neutrino-induced hadronization

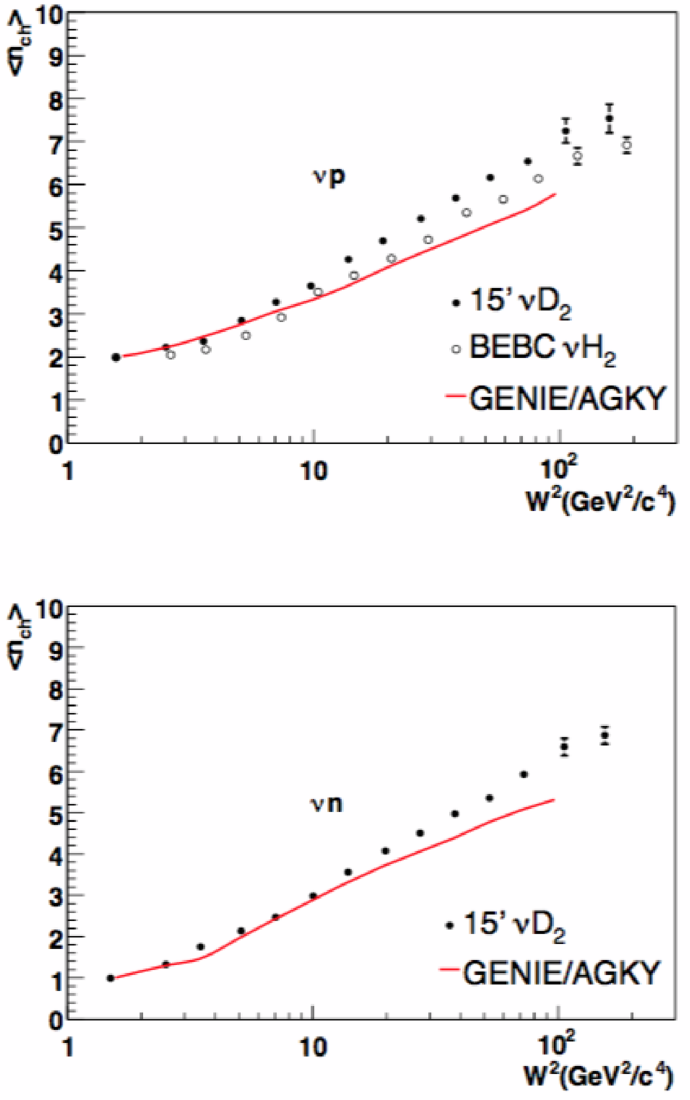
- Resonances: Phase space decay; All known decay channels included.
- DIS/SIS: Home-grown AGKY effective KNO-based "free-nucleon" hadronization at low W, anchored on many bubble chamber data; Switching gradually (W = 2.3 - 3 GeV/c^2) to (tuned) PYTHIA at higher W.
- DIS charm: Home-grown model based on charm fragmentation functions and measured charm fractions, PYTHIA for non-charm system.
- In-medium effects: SKAT-type formation zone parameterization (DIS only).

Data/model comparisons of the fragmentation function for + and - charged hadrons.

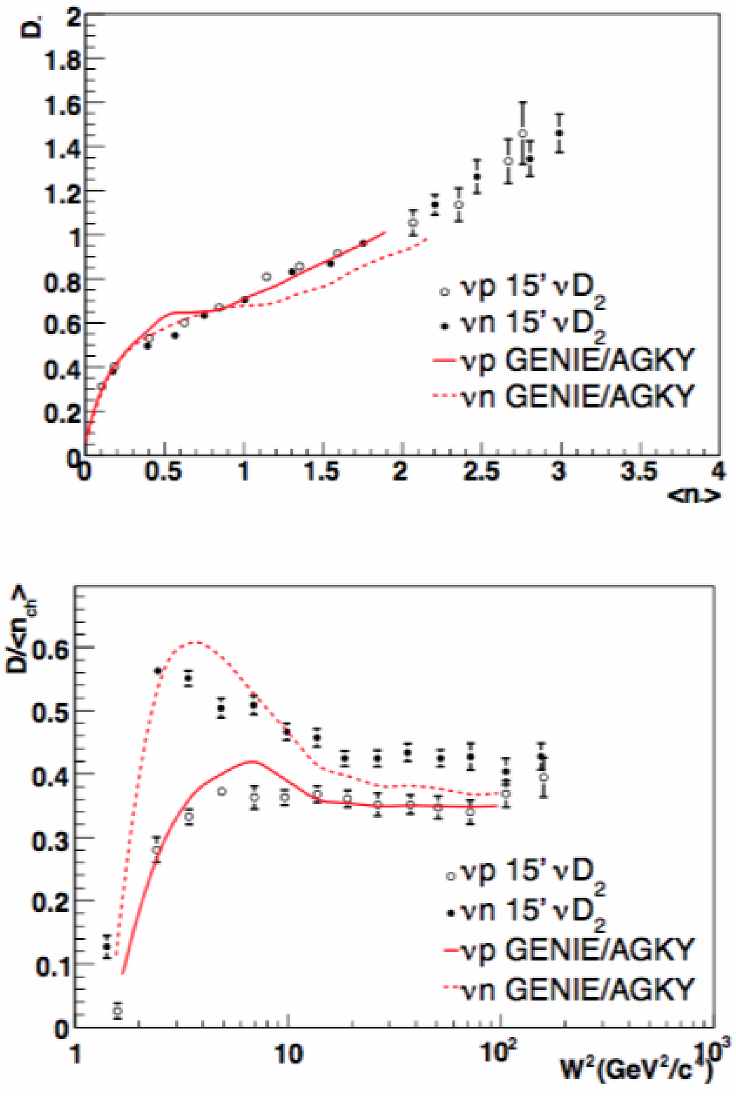


Default physics model in v2 series

Average charged hadron multiplicity.



Negative hadron multiplicity dispersion.

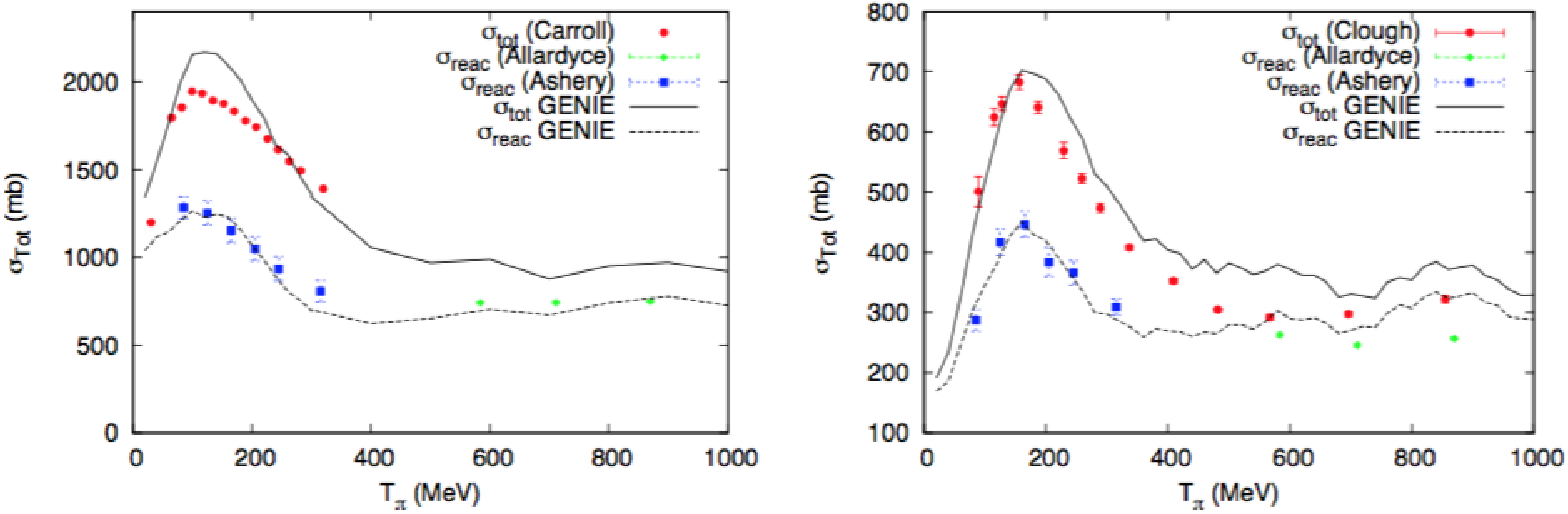


Default physics model in v2 series

Intranuclear hadron transport

- INTRANUKE/hA: Effective model anchored to selected data
- Scaled to all nuclei

Left: $\pi^+ + \text{Fe56}$. Right: $\pi^+ + \text{C12}$



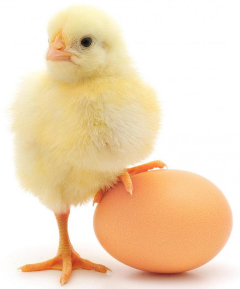
The GENIE Incubator

Incubator projects may include, but not limited to,

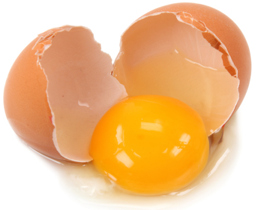
- the development of a new physics model,
- the improvement of an existing model,
- a systematic study,
- the tuning of a physics component,
- the development of new tools,
- an upgrade of the framework,
- an improvement of numerical procedure, or
- a documentation improvement.

Public tracking of incubator projects:
http://genie.hepforge.org/load.php?include=incubator

in incubator (15)



graduated (24)



retired (0)

An incubator project is the **unique route** for any physics or software development into a GENIE release.

Harnessing community contributions.

An incubator projects has **4 phases**:

1. **Launch**
2. **Research & Development**
3. **Graduation**
4. **Integration & Deployment**

The procedure is optimized for fast deployment, while maintaining GENIE standards on validation, software integration and documentation.

Production version **v2.10.0** - New physics models

- Bodek-Christy-Coopersmith eff. spectral function (EPJC 74:3091, 2014).
  B. Coopersmith and A. Bodek (Rochester)
- Very-High Energy extension (up to 5 TeV, working towards PeV scales)
  K. Hoshina (Wisconsin)
- Inclusive η production.
  J. Liu (W&M)
- Berger-Sehgal resonance model (PRD 76, 113004, 2007)
  J. Nowak (Lancaster) and S. Dytman (Pitt)
- Kuzmin-Lyubushkin-Naumov resonance model (MPL A19, 2815, 2004)
  J. Nowak (Lancaster), I. Kakorin (JINR) and S. Dytman (Pitt)
- Improved INTRANUKE/hA FSI model.
  S. Dytman and N. Geary (Pitt)
- Single K model by Alam, Simo, Athar, and Vacas (PRD 82, 033001, 2010).
  C. Marshall (Rochester) and M. Nirkko (Bern)

Production version **v2.12.0** - New physics models

- Bhattacharya, Hill, and Paz QE Z expansion model (PRD 84:073006)
  A. Meyer (Chicago)
- Local Fermi Gas & Nieves-Amaro-Valverde CCQE with RPA (Phys. Rev. C70, 055503 (2004); Phys. Rev. C72:019902, 2005)
  J. Johnston and S. Dytman (Pitt)
- Updates to the GENIE hown-grown empirical 2p-2h model
  S.Dytman (Pitt)
- Valencia 2p-2h model (Phys.Rev. D88:113007, 2013)
  J. Schwehr (CSU), D.Cherdack (CSU) and R. Gran (UMD)
- Berger-Sehgal coherent π production (PRD 79:053003, 2009)
  G. Perdue (Fermilab), H. Gallagher (Tufts), D. Cherdack (CSU)
- Alvarez Ruso, Geng, Hirenzaki and Vacas microscopic coherent pion production (PRC 75:055501, 2007; PRC 76:068501, 2007)
  D.Scully, S. Dennis and S. Boyd (Warwick)

Production version **v2.12.0** - New physics models

- Oset, Salcedo and Strottman FSI model (Phys. Lett. B 165:13, 1985; Nucl. Phys. A 468:631, 1987.)
  T. Golan (Fermilab and Rochester)
- Kaon FSI improvements
  F. de Maria Blaszczyk (LSU), S. Dytman (Pitt)
- Pais QE Hyperon production model (Ann. Phys. 63:361, 1971)
  J. Poage and H. Gallagher (Tufts)
- Updated Rein diffractive pion model (Nucl.Phys. B278:61, 1986).
  J.Wolcott (Tufts)
- Several resonance model updates.
  L.Jiang (Pittsburgh) and I.Kakorin (JINR & ITEP)
- Kuzmin, Naumov energy-dependent axial-mass model.
  I.Kakorin (JINR & ITEP)

Other notable changes in **v2.10.0** / **v2.12.0**

- Upgrade of nucleon decay generator in GENIE.
  M.Sorel (IFIC)
- Simulation of $n - \bar{n}$ oscillations.
  J. Hewes and G. Karagiorgi (Manchester)
- New Honda, Athar, Kajita, Kasahara and Midorikawa (HAKKM) atm. ν flux (PLB718:1375, 2013) driver added to existing FLUKA and BGLRS ones.
  G.Majumder, A.Ajmi (INO Collab.); T.Katori (QMUL)
- A new *unified* event generation app for all Fermilab experiments (in the NuMI, Booster and LBNF beamlines) and updates in the flux drivers.
  R.Hatcher (Fermilab)
- Event reweighting I/O
  J.Yarba (Fermilab)
- New GSL (GNU Scientific Library) dependency
  S.Dennis (Warwick/Liverpool)
- "ROOT6 and C++11"-ready!
  S.Dennis (Warwick/Liverpool)
- LHAPDFv5 dependence now optional; CERNLIB/PDFLIB discontinued.

+ Bug fixes. For a detailed list see: https://releases.genie-mc.org

v2.10.00 / v2.12.00 highlights

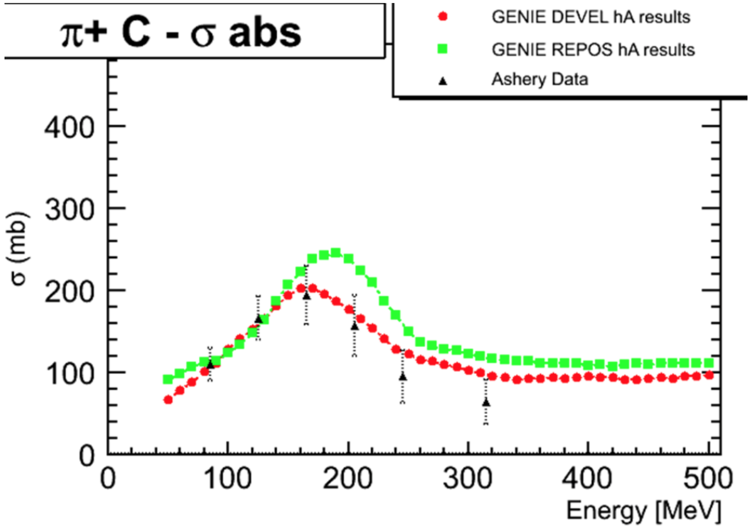
v2.10.0 highlights - Updated *hA* FSI model

Recall that the default FSI model in GENIE is **INTRANUKE/hA**:
An effective model anchored on data.

- We parameterize a cascade with one *effective* interaction.
- The model is easily re-weightable and in good agreement with data.

Previously, **hA used data on Fe^{56} and A scaling**
→ $A^{2/3}$ dependence, but this doesn't agree well with data.

- Now including π scattering data for Li^{7}, C^{12}, Al^{27}, Fe^{56}, Nb^{93} and Bi^{209} (less extrapolation needed).
- Now absorption scales as A$^{2/3+0.18}$, charge exchange as A$^{2/3}$, elastic as A$^{2/3+0.25}$, inelastic as A$^{2/3}$, and π production as A$^{2/3}$. The total cross-section scales as A$^{2/3}$.



Implemented by N. Geary and S. Dytman

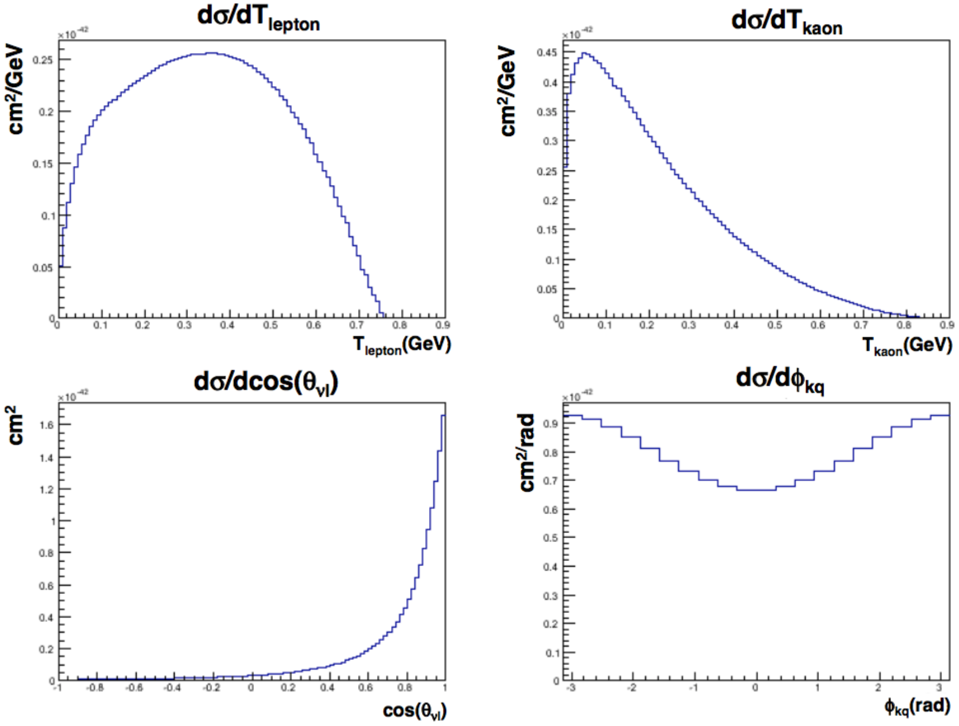
v2.10.0 highlights - Single Kaon production

New ($\Delta S = 1$) GENIE process.
Single Kaon production:

- $\nu_\ell + p \rightarrow \ell^- + K^+ + p$
- $\nu_\ell + n \rightarrow \ell^- + K^0 + p$
- $\nu_\ell + n \rightarrow \ell^- + K^+ + n$

Based on the model of Alam, Simo, Athar, and Vacas (PRD 82:033001, 2010).

Previously only associated production ($\Delta S = 0$) was simulated.

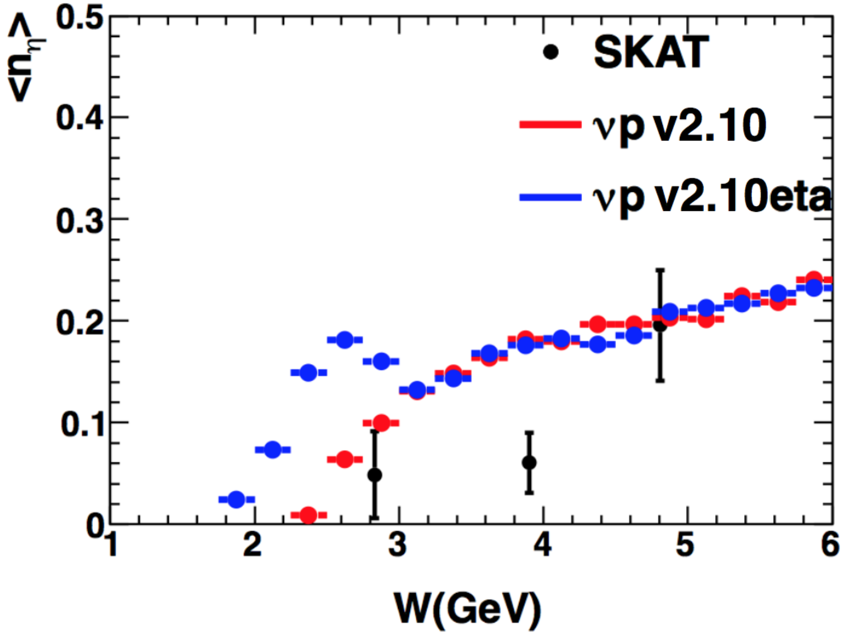


Differential distributions produced in the scattering of 1.5 GeV ν_μ in the channel $\nu_\mu + p \rightarrow \mu^- + K^+ + p$

Implemented by C. Marshall and M. Nirkko.

v2.10.0 highlights - η production

- η production important for ν_e appearance as η's have purely electromagnetic decays into photons.
- η's were produced by resonance decays and by the PYTHIA model, but not by the KNO-based part of the AGKY hadronization model.
- Kinematic gap in η production.
- Added option to generate $\eta\eta$ and $\eta\pi^0$ pairs with some probability (untuned).



η production rate measurements from the SKAT experiment, compared with the GENIE default prediction (red) and the GENIE prediction with eta production parameters set to large non-zero values (blue).

Implemented by J. Liu.

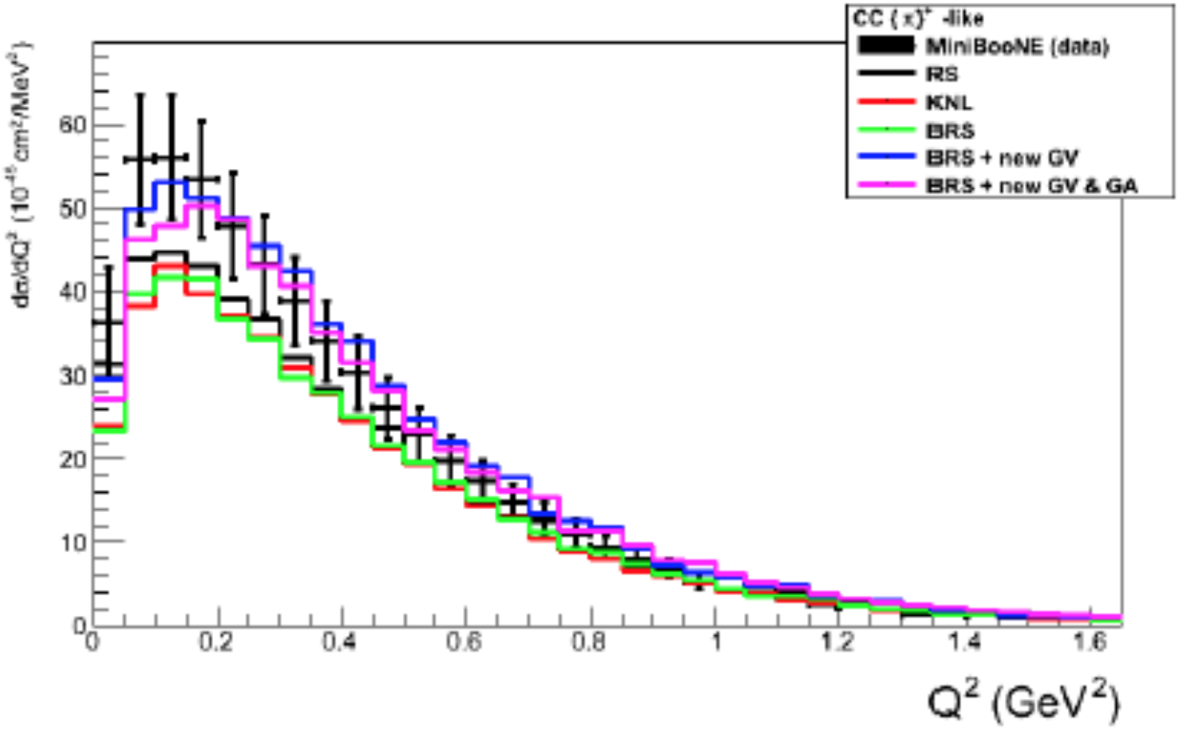
v2.10.0 highlights - New resonance models

New resonance models:

- Kuzmin-Lyubushkin-Naumov (KLN) model (MPL A19:2815, 2004). Similar to Rein-Sehgal (RS), but includes muon mass effects.
- Berger-Sehgal (BS) model (PRD 76:113004, 2007). Similar to KLN, but includes the pion pole contribution.

Both models include new vector and axial form factors by the MiniBooNE Collaboration (AIP Conf.Proc. 1189, 2009)

Right:
Comparison with MiniBooNE $CC\pi^+$ data.

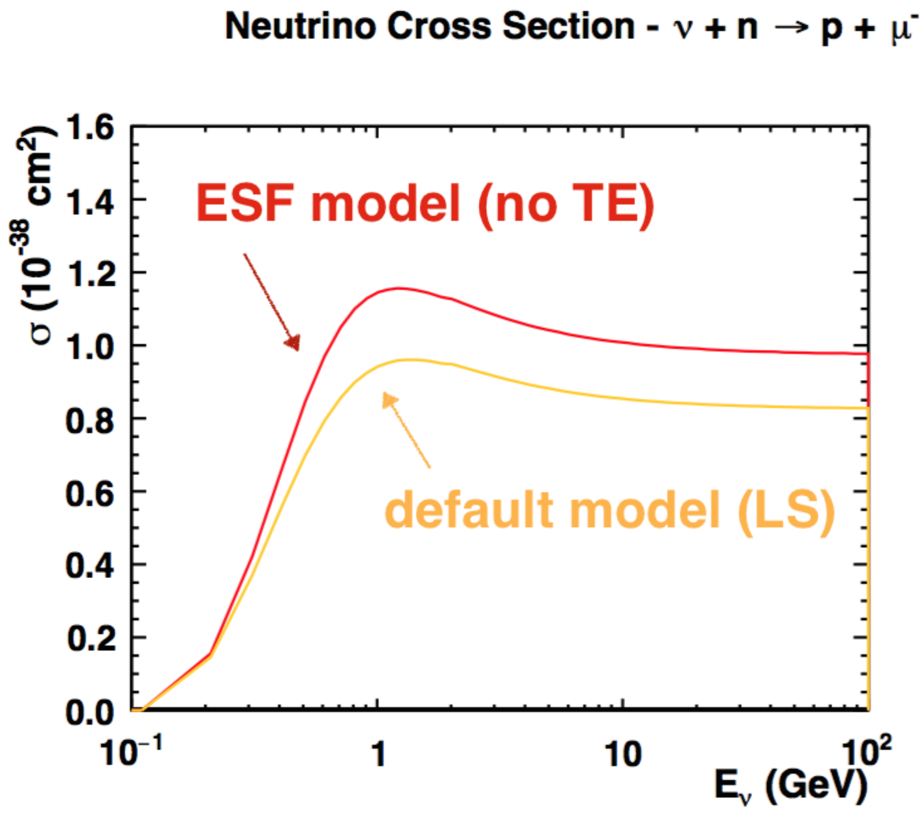


Implemented by J. Nowak, I. Kakorin and S. Dytman.

v2.10.0 highlights - ESF and TEM models

Superscaling calculations (PRC 71:015501, 2005) include FSI effects responsible for an increase of strength in the tail of the differential cross-section distribution and a decrease in the peak.

- The **Effective Spectral Function (ESF)** model (Bodek, Christy and Coopersmith, EPJC 74:3091, 2014) included in v2.10.0 is fitted to the superscaling models predictions.
- Using the Spectral Function formalism.
- v2.10.0 also includes the **Transverse Enhancement Model (TEM)** (enabled separately) where Q^2-dependent modifications to the elastic nucleon magnetic form factors emulate nuclear effects like those expected from MEC.

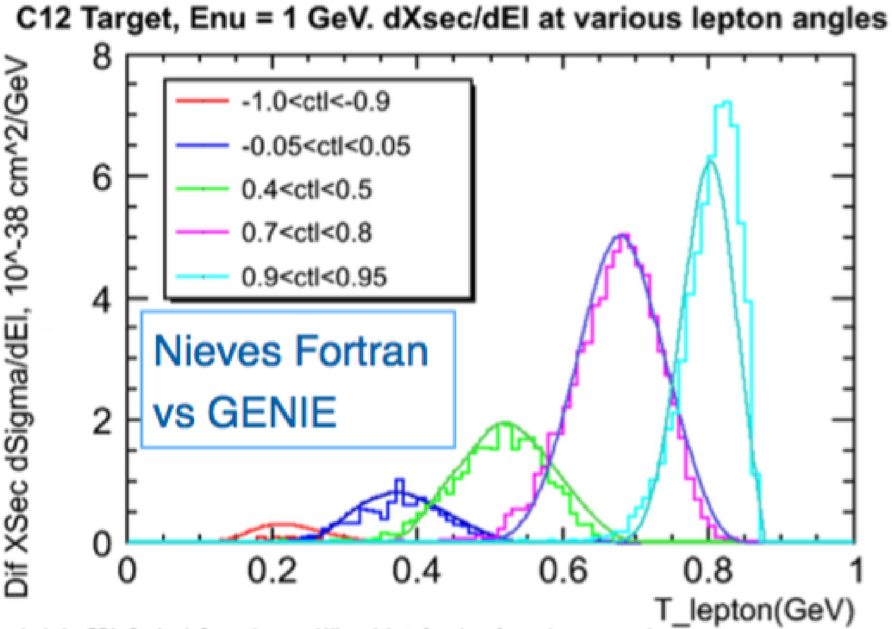


Implemented by B. Coopersmith.

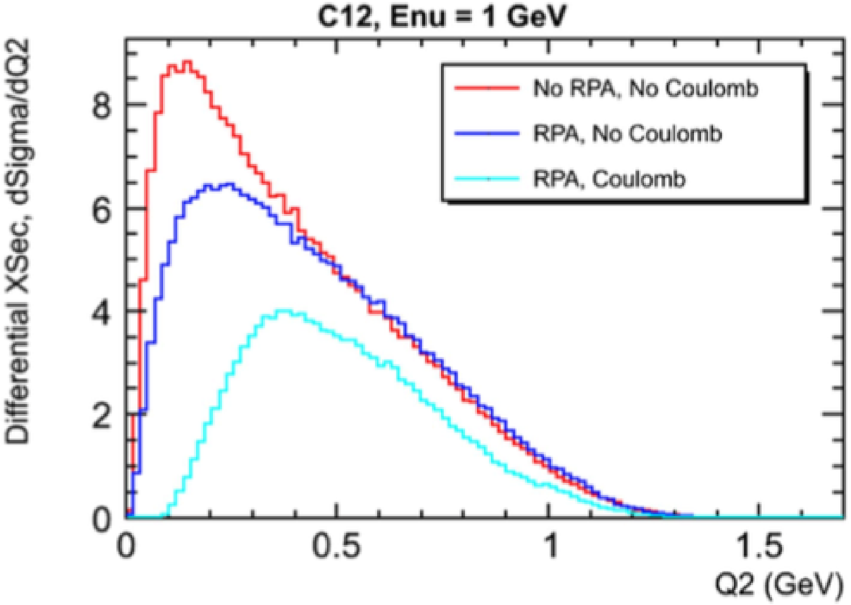
v2.12.0 highlights - LFG + Nieves et al CCQE with RPA

CCQE model by J. Nieves, J. E. Amaro, M. Valverde, PRC 79:055503, 2004.

- Requires LFG (Fermi momentum is a function of the position in the nucleus), also added in v2.12.00.
- Adds RPA long-range correlation effects and Coulomb corrections.



Includes RPA, Coulomb Corrections, and Nieves' theta functions for nuclear suppression

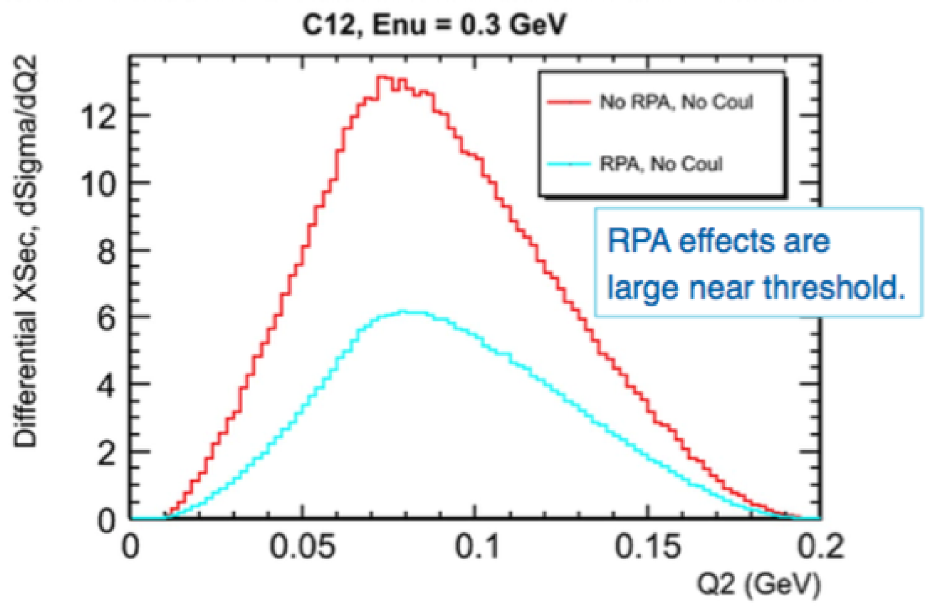


Implemented by J. Johnston and S. Dytman

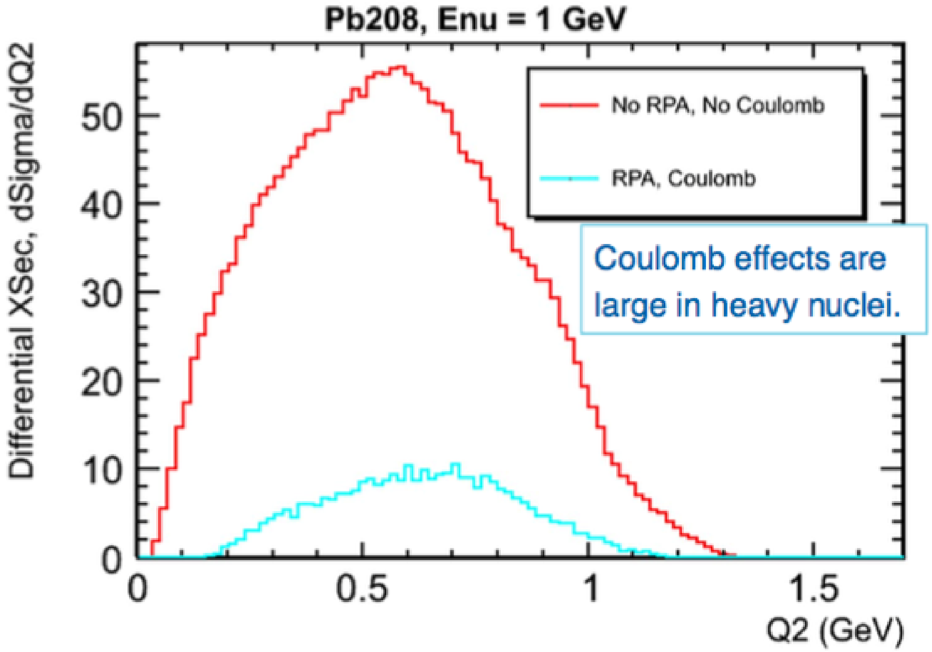
v2.12.0 highlights - LFG + Nieves et al CCQE with RPA

CCQE model by J. Nieves, J. E. Amaro, M. Valverde, PRC 79:055503, 2004.

- Adds RPA long-range correlation effects and Coulomb corrections.
    - RPA effects are large near the threshold
    - Coulomb effects are large in heavy nuclei



RPA effects are large near threshold.



Coulomb effects are large in heavy nuclei.

Implemented by J. Johnston and S. Dytman

v2.12.0 highlights - Z-expansion of axial form factor

Model-independent parameterization of the axial form factor by Bhattacharya, Hill, and Paz QE (PRD 84:073006)

- Constraints the axial form factor using requirements from complex analysis.
- Q^2 replaced by a small expansion parameter z (interesting kinematical region mapped within $|z| < 1$)
- Form factor F_A is written as a power series of z

$$z(t; t_0, t_c) = \frac{\sqrt{t_c - t} - \sqrt{t_c - t_0}}{\sqrt{t_c - t} + \sqrt{t_c - t_0}} \qquad F_A(z) = \sum_{k=0}^{\infty} a_k z^k \qquad t_c = 9m_\pi^2$$

- Current parameterization (initial values of coefficients) derived from fits to deuterium bubble chamber data by A.Meyer, M.Betancourt, R.Gran and R.Hill (arXiv:1603.03048)
- Lattice QCD can provide coefficients and errors from first principles.
- Implementation incudes relevant reweighting routines.

Implemented by A. Meyer.

v2.12.0 highlights - Updates to the Empirical 2p2h model

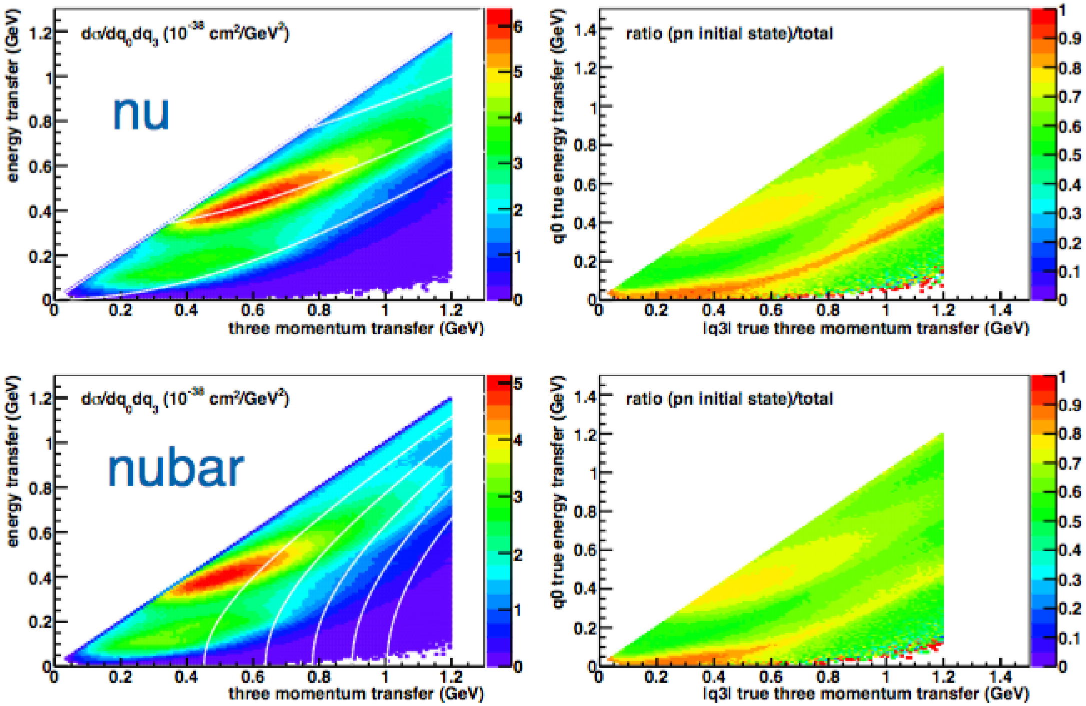
Several updates to GENIE's Empirical 2p2h model:

- Added NC mode.
    - Previously only CC and EM.
- Several parameters were made configurable (for tuning)
    - Mass and width for pseudo-response peak.
    - Form factor mass.
    - Magnitude of cross section.
    - pn vs pp fraction.
- Model no longer forced to die out at ~ 5 GeV

v2.12.0 highlights - Valencia 2p2h model

New implementation of the 2p2h model by Nieves, Simo and Vicente Vacas (PRC 83:045501, 2011; PRD 88:113007, 2013)

The differential cross section from the GENIE implementation of the QE-like 2p2h model (right) and the fraction of the total cross section with a pn initial state (left). The top plots are νC12 while the lower plots are $\bar{\nu}$C12, both at 3 GeV.



The neutrino figure has lines of constant W = 938, 1232, 1520 MeV emphasizing the dip region, and the antineutrino figure has lines of constant Q^2 from 0.2 to 1.0 GeV^2 emphasizing the low Q^2 nature of the cross-section.

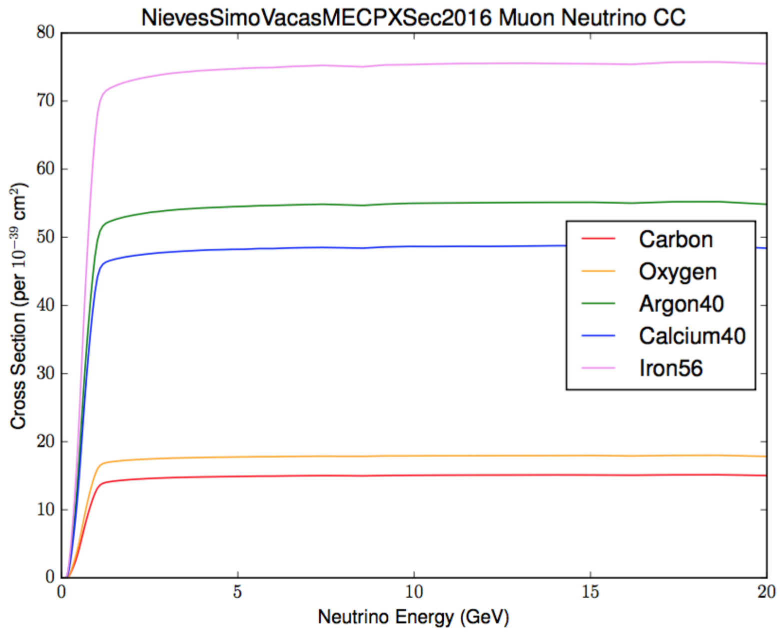
Implemented by J. Schwehr, D.Cherdack and R. Gran

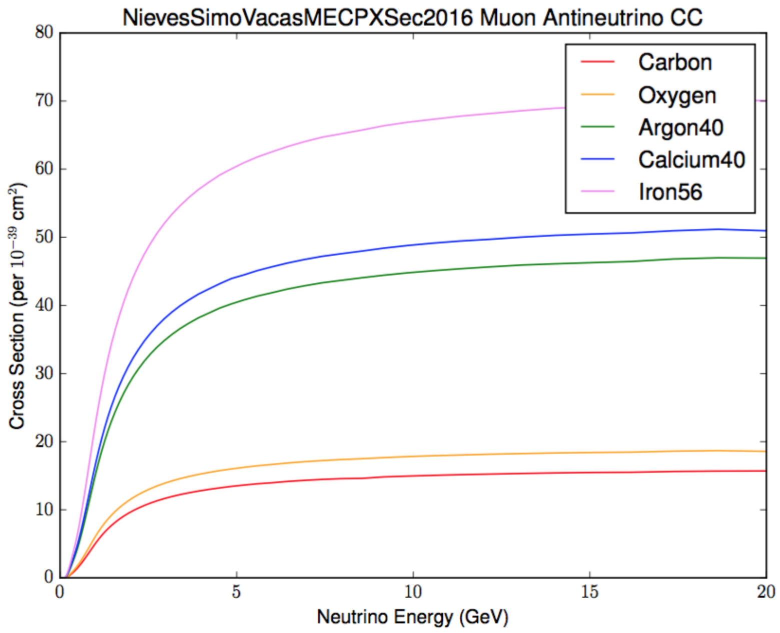
Implementation discussed in arXiv:1601.02038

v2.12.0 highlights - Valencia 2p2h model extension

Model extension to **non-isoscalar nuclei**.

- Original model worked for C12, O16, Ca40.
- Extension by Gran and Vicente Vacas includes most nuclei.
- Covers a) effects of nuclear size, b) non-isoscalar features and c) Q-value.





Implemented by R. Gran

Implementation discussed in arXiv:1601.02038

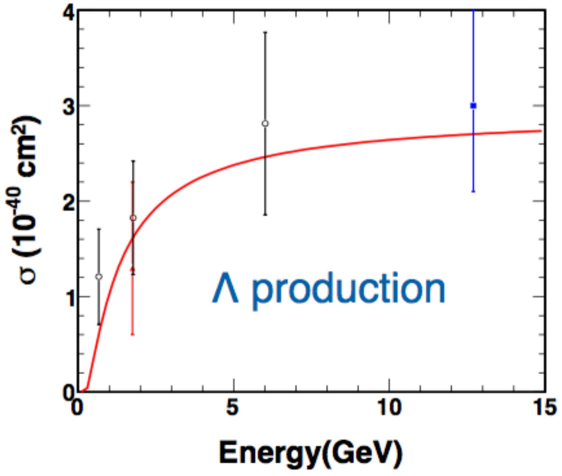
v2.12.0 highlights - QE Hyperon production

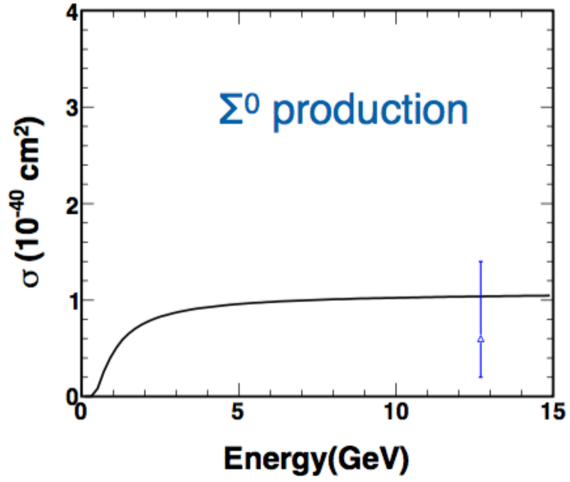
Simulation of three new ΔS=1 channels:

- $\bar{\nu}_\ell + p \rightarrow \ell^+ + \Lambda^0$
- $\bar{\nu}_\ell + p \rightarrow \ell^+ + \Sigma^0$
- $\bar{\nu}_\ell + n \rightarrow \ell^+ + \Sigma^-$

Using Pais, Ann. Phys. 63:361, 1971;
Cabibo and Chilton, v136, N6B, 1965

$$\sigma_{\Delta S} \approx tan^2\theta_C \cdot \sigma_{QE} = 0.05\sigma_{QE}$$

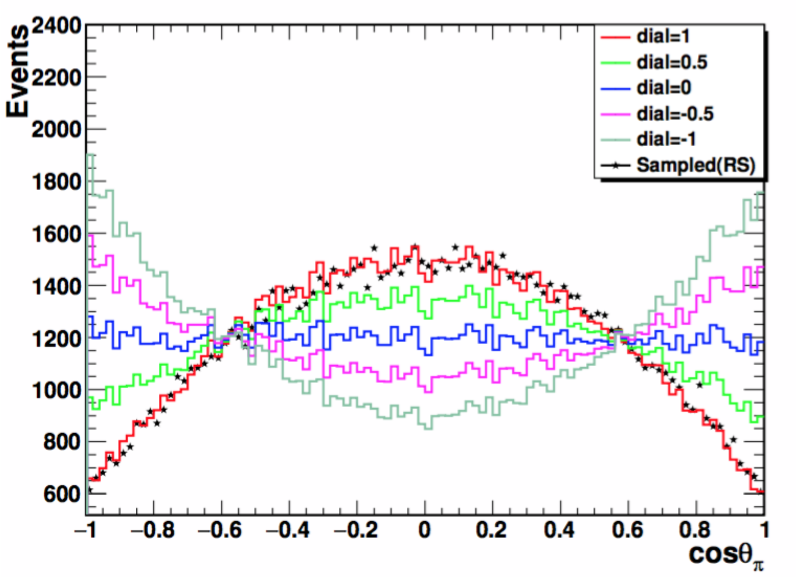




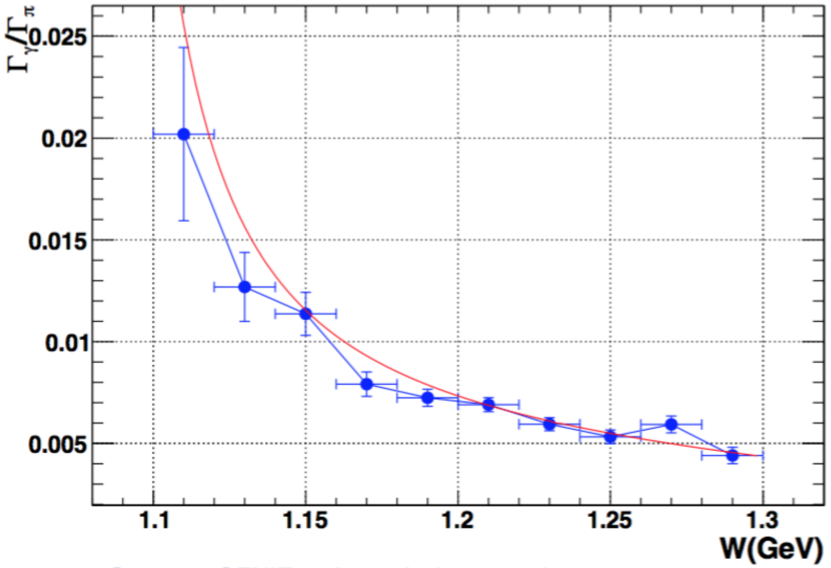
Implemented by E. Poage, E. Morissey and H. Gallagher.

v2.12.0 highlights - Resonance model updates

- Option to simulate a non-isotropic angular distribution of pions from Δ decays (πN final states).
  - Previously, only a reweighting option
- Improved the cross-section for $\Delta \rightarrow N\gamma$ in neutrino reactions.
  - Previously, no resonance production below the pion prod. threshold.
  - Previously, ratio of $\Delta \rightarrow N\gamma$ to $\Delta \rightarrow N\pi$ widths fixed to 0.006.



Comparing generated (new) to re-weighted isotropic (old)



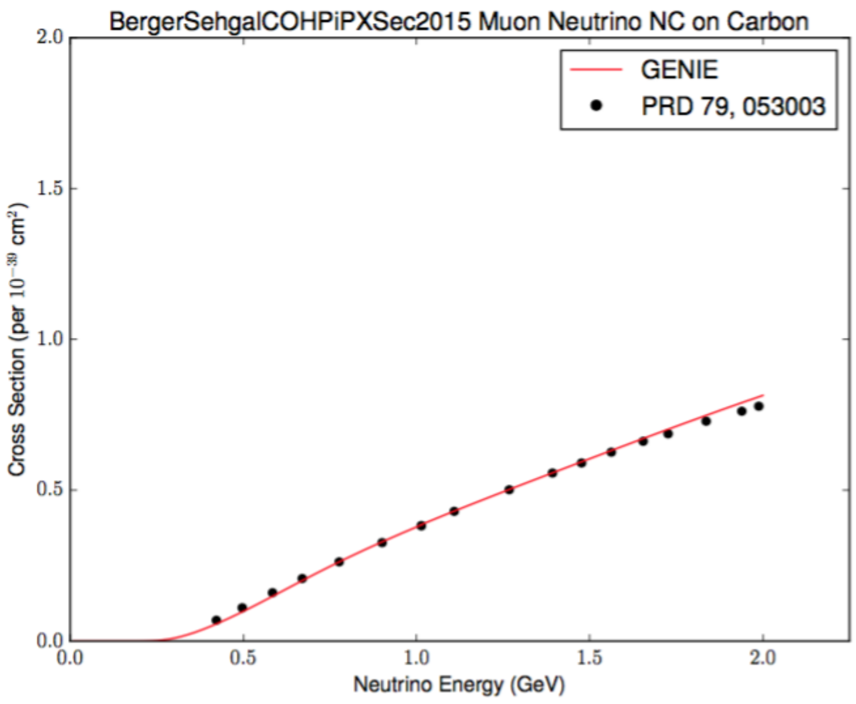
Compare GENIE to theoretical expectation.

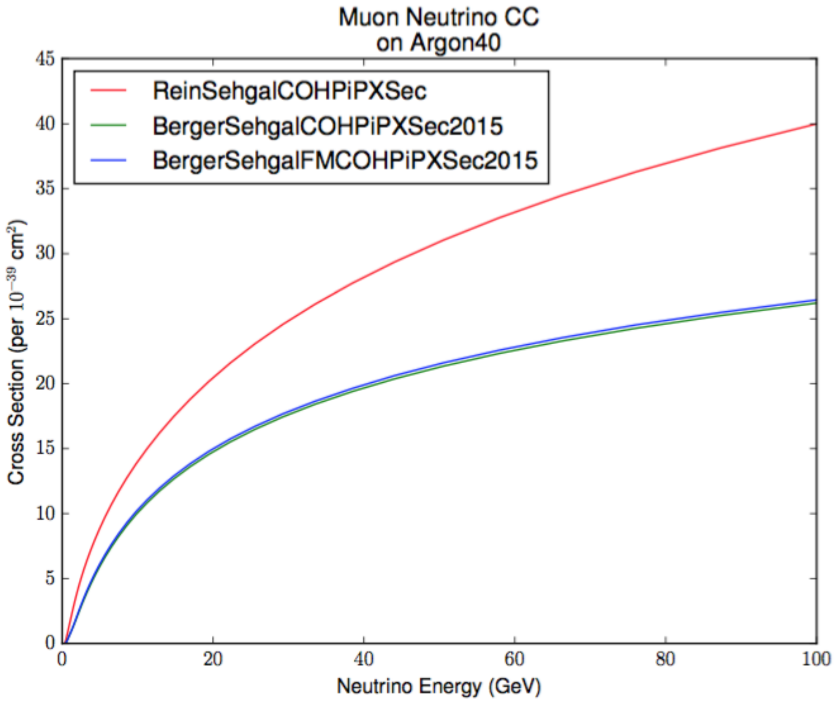
Implemented by L.Jiang.

v2.12.0 highlights - Berger-Sehgal coherent model

New implementation of the coherent pion production model of Berger and Sehgal (PRD 79:053003, 2009).

- In addition to original model, implemented a custom modification relaxing the "infinite target mass" assumptions.



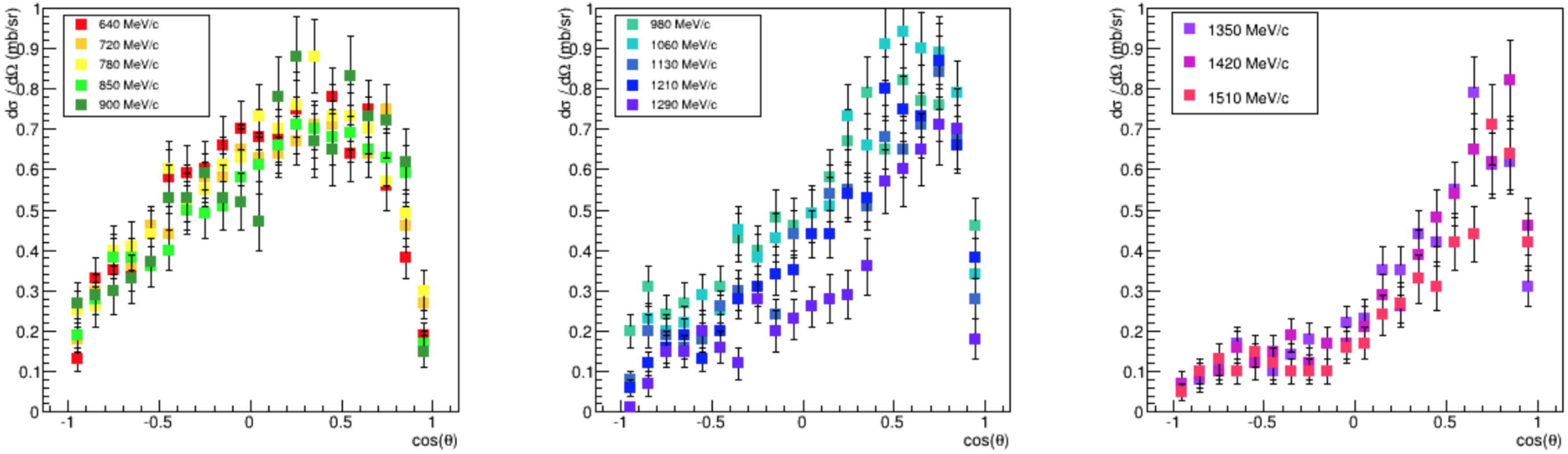


Implemented by G. Perdue, D.Cherdack and H. Gallagher.

v2.12.0 highlights - Kaon FSI

- Improvements to the Kaon FSI model, of interest to single-K production and p $\rightarrow \bar{\nu} K^+$ analyses.
- A data-driven extension to INTRANUKE.
- K^+n charge exchange (K^+n $\rightarrow$ K^0p) data built into the simulation:

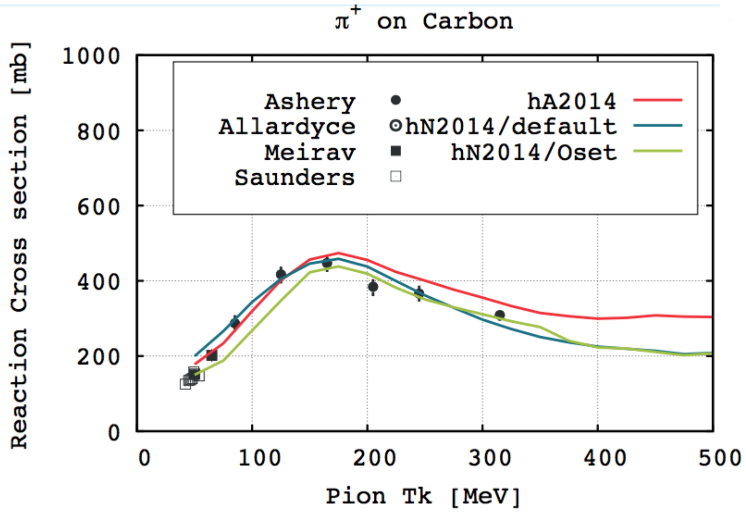
K^+n charge exchange data built into the simulation:



Implemented by F. de Maria Blaszczyk

v2.12.0 highlights - Oset FSI

π reaction cross-section:

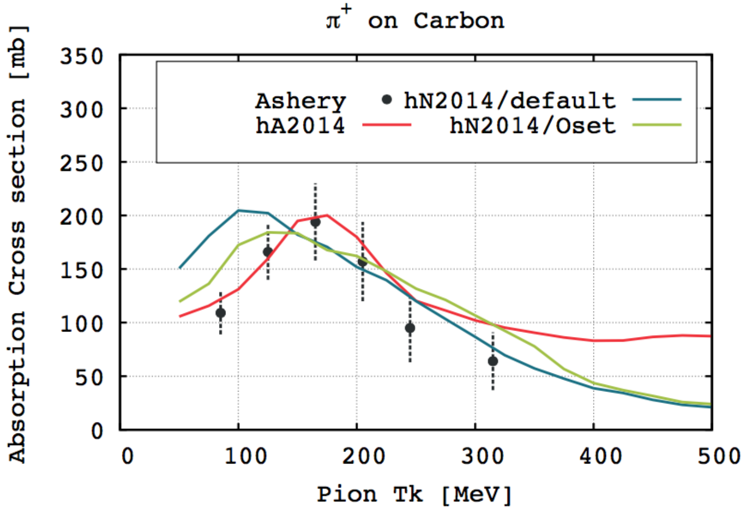


Implementing E. Oset et al, Nucl. Phys. A484:557, 1998; E. Oset et al, Nucl. Phys. A468:631, 1987 within the INTRANUKE/hN framework.

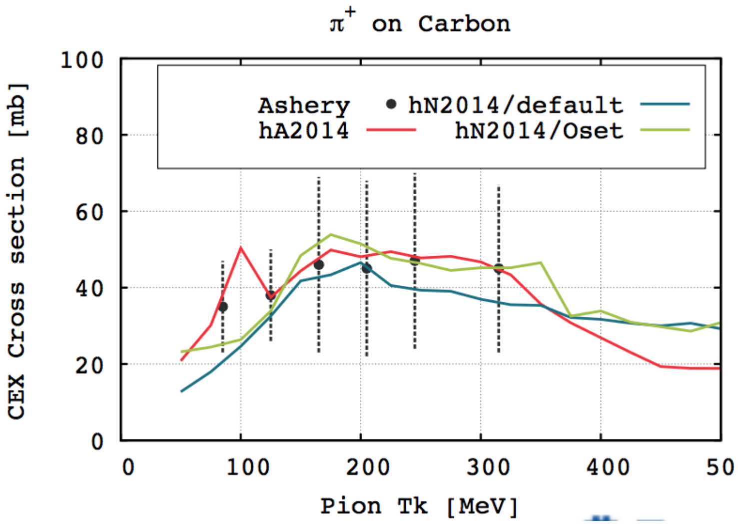
Describes low energy pion interactions.

A 3rd FSI model in GENIE which matches model used in NEUT, NuWro.

π absorption cross-section:



π CEx cross-section:



Towards a new / retuned default physics model

A longer-term goal of the GENIE Collaboration is to synthesize its models, tools and large collections of curated data archives to provide

- **global analyses of scattering data**, and
- **tunes implemented and distributed through its generator platform**.

Status of the GENIE/Comparisons package

Agreement with data would be the main consideration.
→ MINERvA, T2K, MiniBooNE data (not used for old tune) would be crucial.

GENIE includes a large collection of **data acrhives** and **comparisons**.

Dataset	Dataset implemented	Prediction implemented
$\sigma_\nu, d\sigma_\nu$ (all MiniBooNE)	★★★★★	★★★★★
$\sigma_\nu, d\sigma_\nu$ (all MINERvA)	★★★	★★★
$\sigma_\nu, d\sigma_\nu$ (all T2K)	★★★★★	★★★★★
$\sigma_\nu, d\sigma_\nu$ (other recent / NOMAD,...)	★★★	★★★
$\sigma_\nu, d\sigma_\nu$ (bubble chamber)	★★★★★	★★★★
F_2, xF_3 world data	★★★★★	★★★★★
$\ell N, \ell A$ hadronics (ν expts.)	★★★★	★★★★
$\ell N, \ell A$ hadronics (e, μ expts)	★★	★
e^- QE (D.Day's dbase)	★★★★★	★★★★★
$e^- p$ resonance (S.Wood's dbase)	★★★★★	★★★★★
pA (various observables)	★★★★	★★★★
πA (various observables)	★★★★	★★★★
KA (various observables)	★★★★	★★★★

On-going technical upgrade to include any given (or assumed) **correlection between different data releases**.

Examples of alternative GENIE configurations (wrt v2.12)

Example: “Updated empirical model” 1:

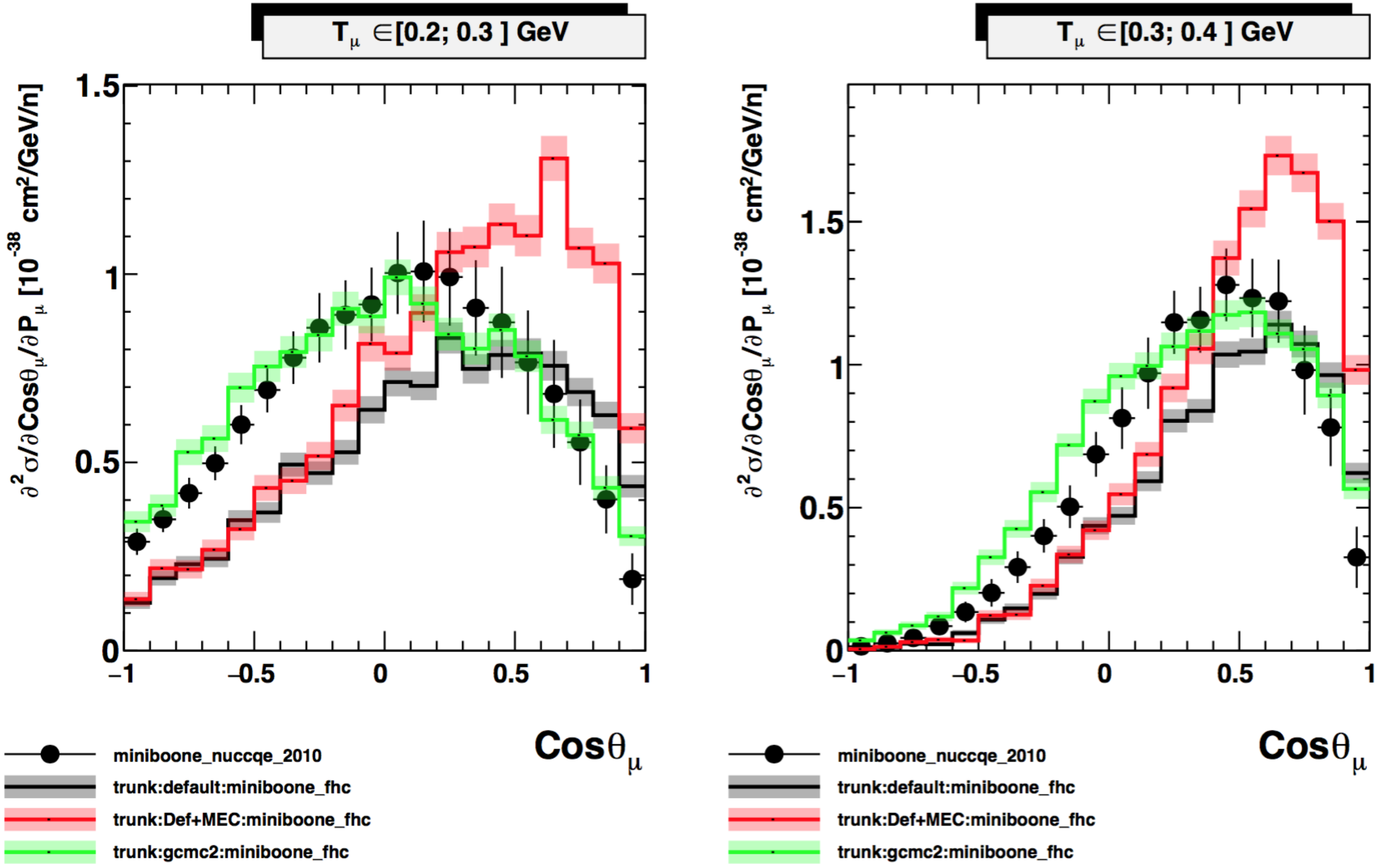
- Nuclear model: RFG (*unchanged*)
- Quasi-elastic: Llewellyn Smith with dipole axial f/f (*unchanged*)
- MEC: none → **Empirical MEC**
- Resonance: Rein-Sehgal (*unchanged*)
- Coherent: Rein-Sehgal → **Berger-Sehgal**
- QEL Hyperon: none → **Pais SU(3)**
- Diffractive: none → **Rein**
- FSI: INTRANUKE/hA → **INTRANUKE/hA2015**

Example: “Theory-driven model” 1:

- Nuclear model: RFG → **LFG**
- Quasi-elastic: Llewellyn Smith → **Nieves (incl. RPA)**
- MEC: none → **Valencia MEC**
- Resonance: Rein-Sehgal → **Berger-Sehgal**
- Coherent: Rein-Sehgal → **Alvarez Ruso**
- QEL Hyperon: none → **Pais SU(3)**
- Diffractive: none → **Rein**
- FSI: INTRANUKE/hA → **INTRANUKE/hA2015**

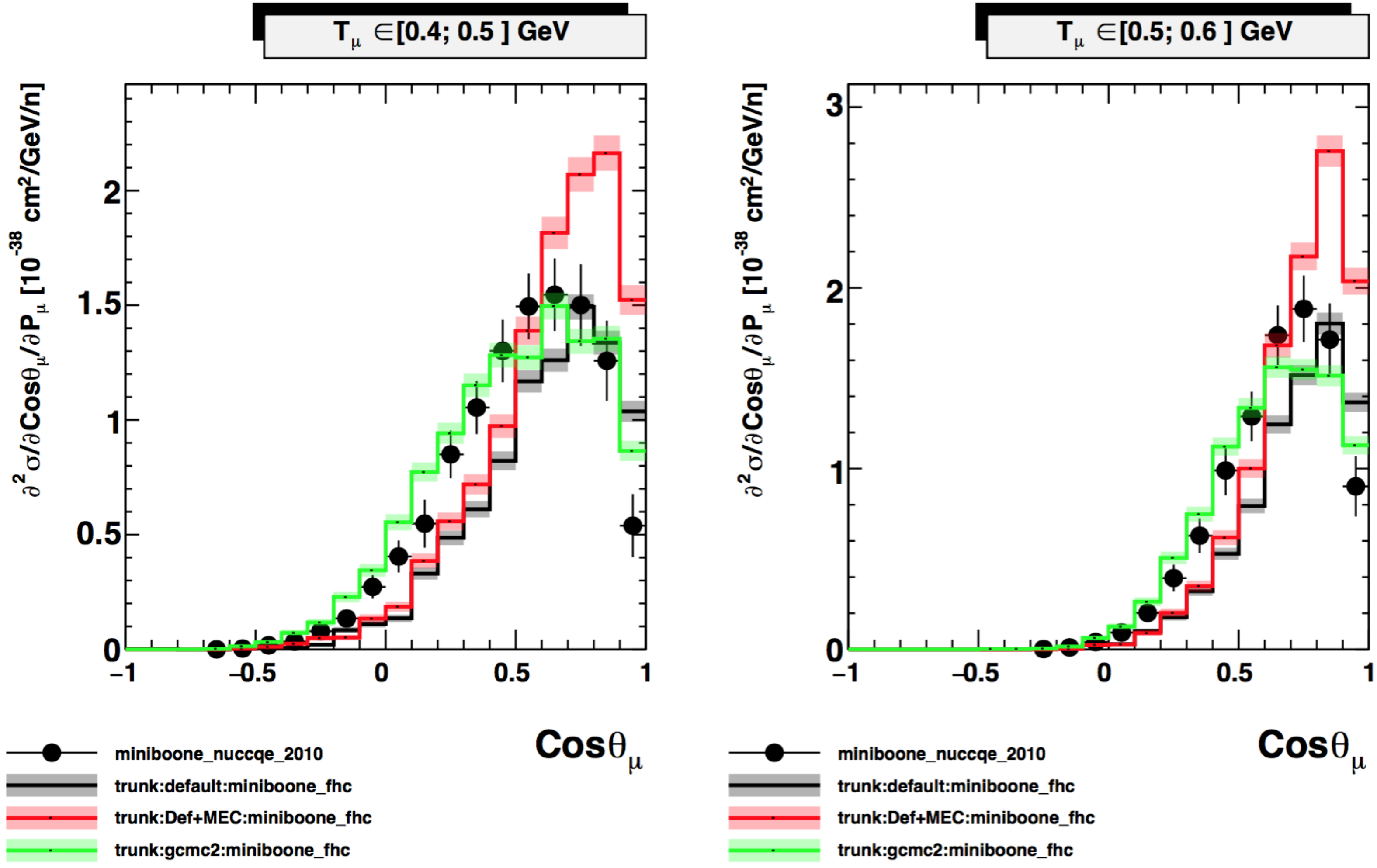
Example comparisons of alternative model configurations

Comparisons against MiniBooNE CC0π data:



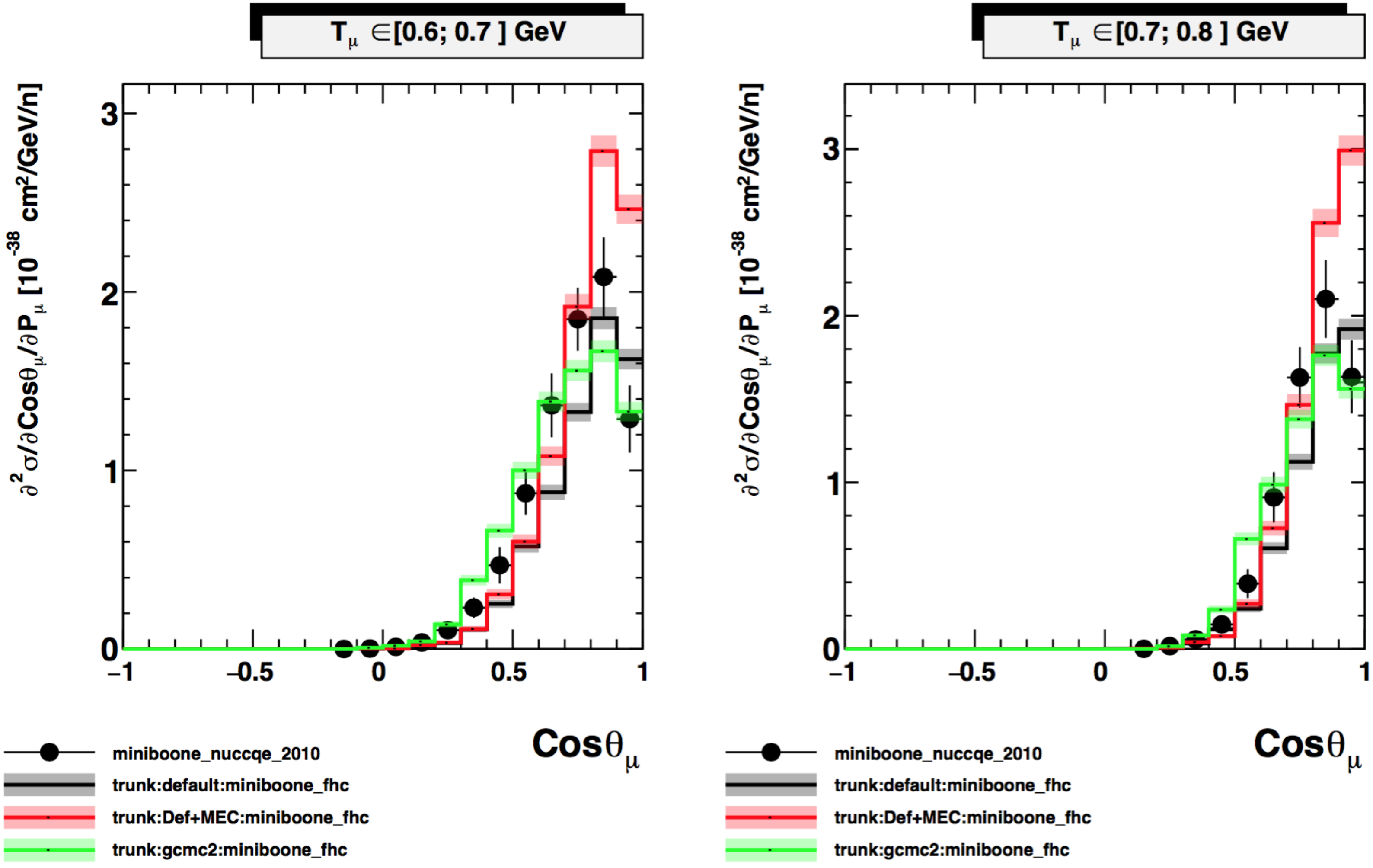
Example comparisons of alternative model configurations

Comparisons against MiniBooNE CC0π data:



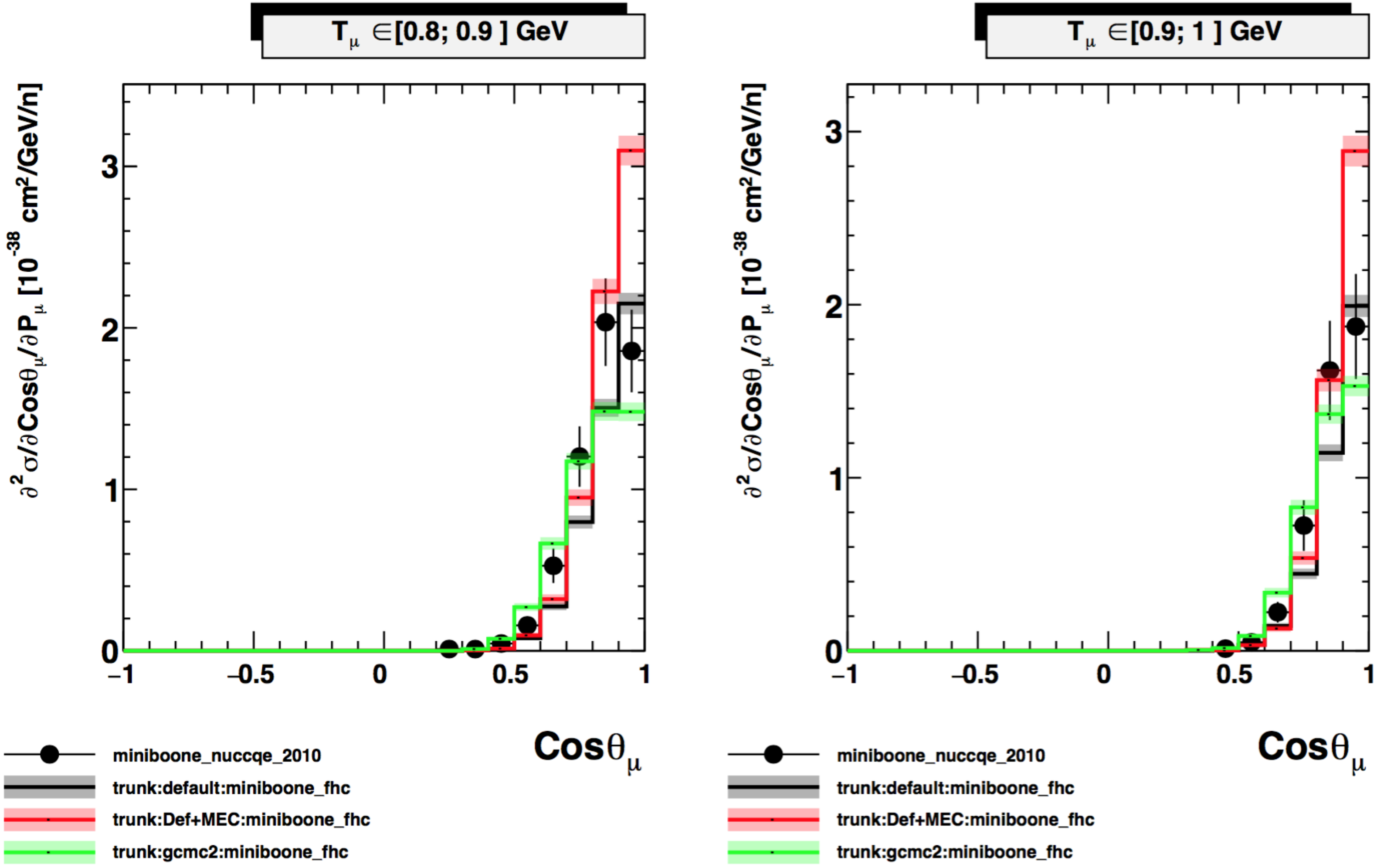
Example comparisons of alternative model configurations

Comparisons against MiniBooNE CC0π data:



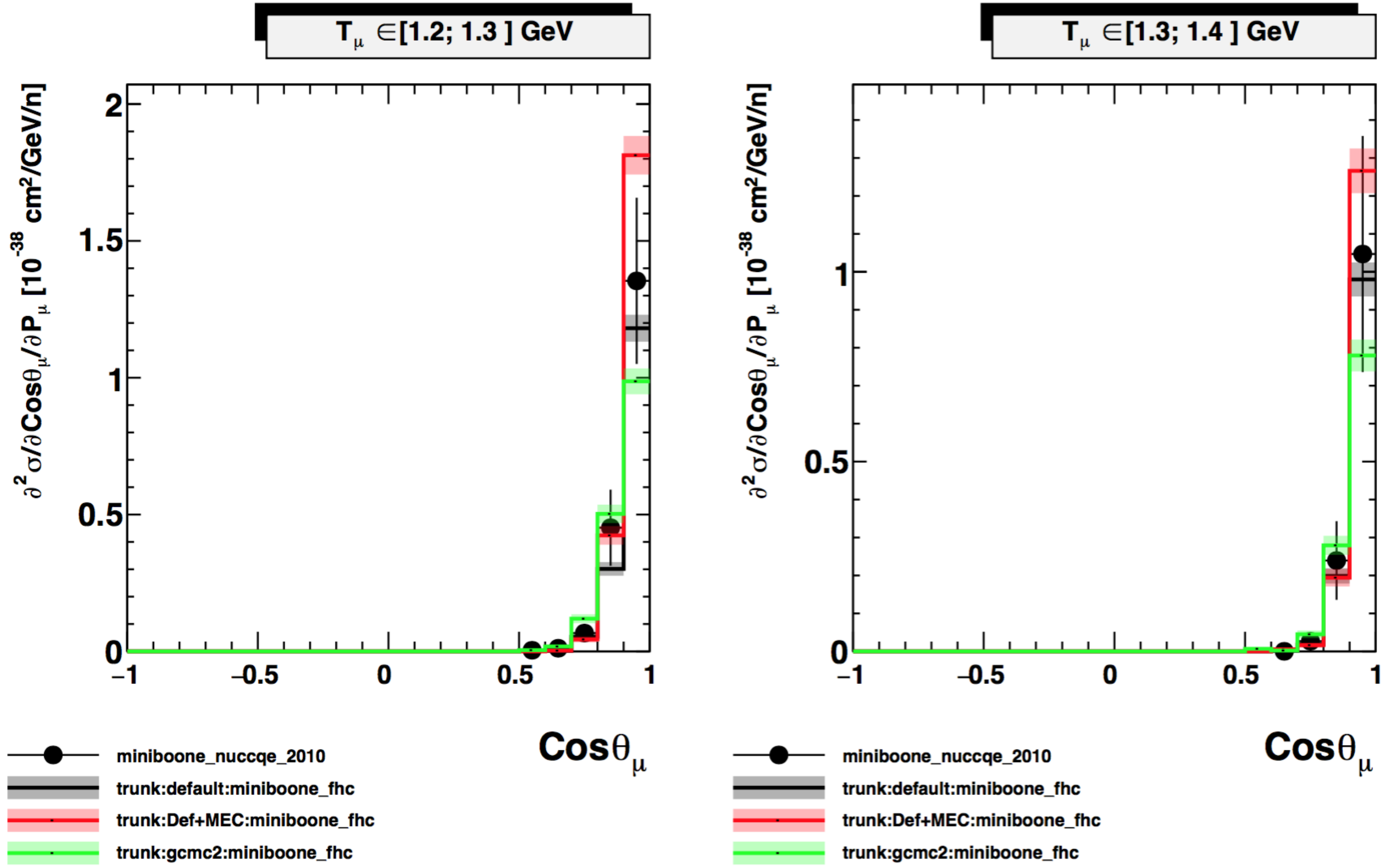
Example comparisons of alternative model configurations

Comparisons against MiniBooNE CC0π data:



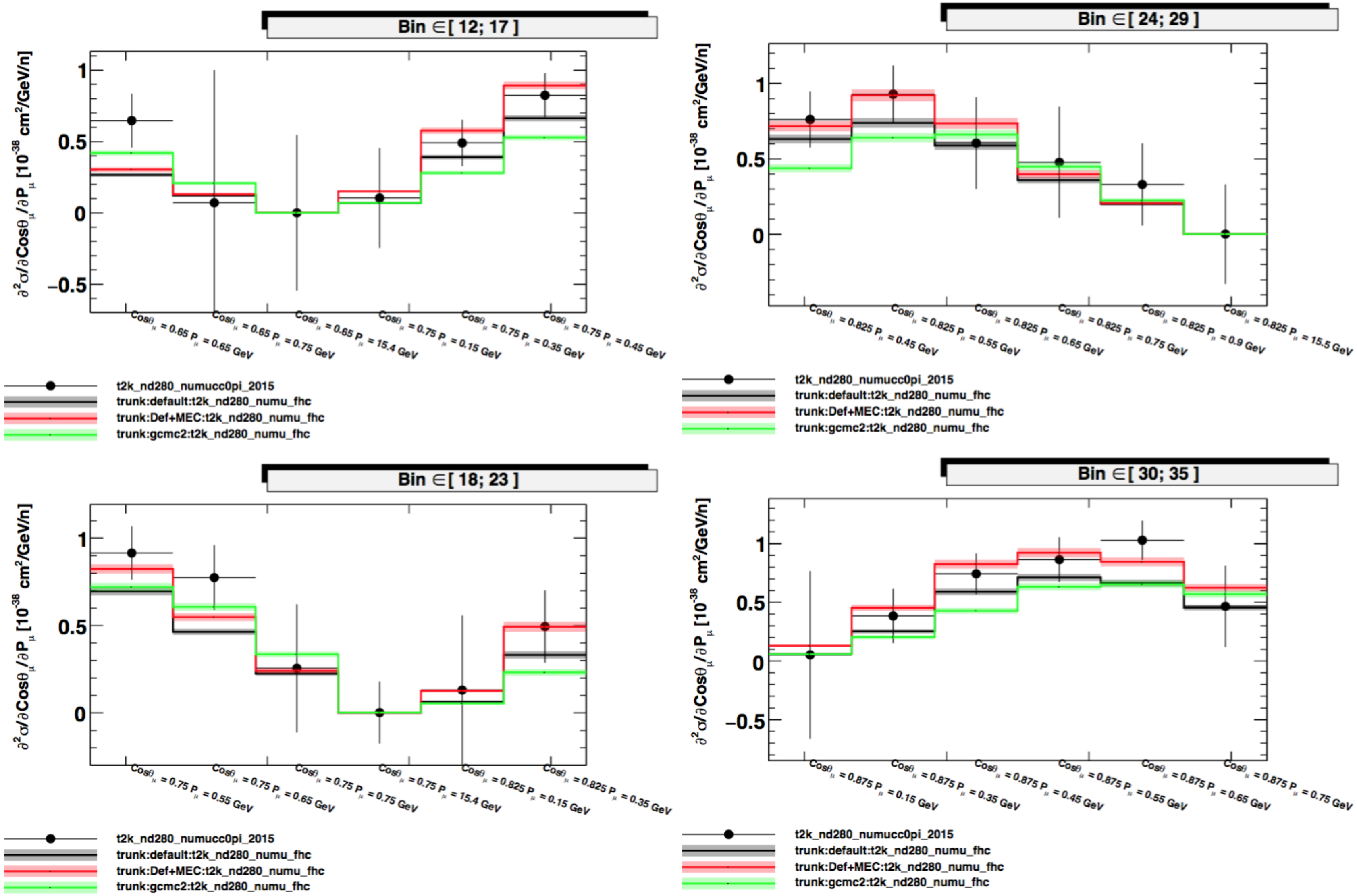
Example comparisons of alternative model configurations

Comparisons against MiniBooNE CC0π data:



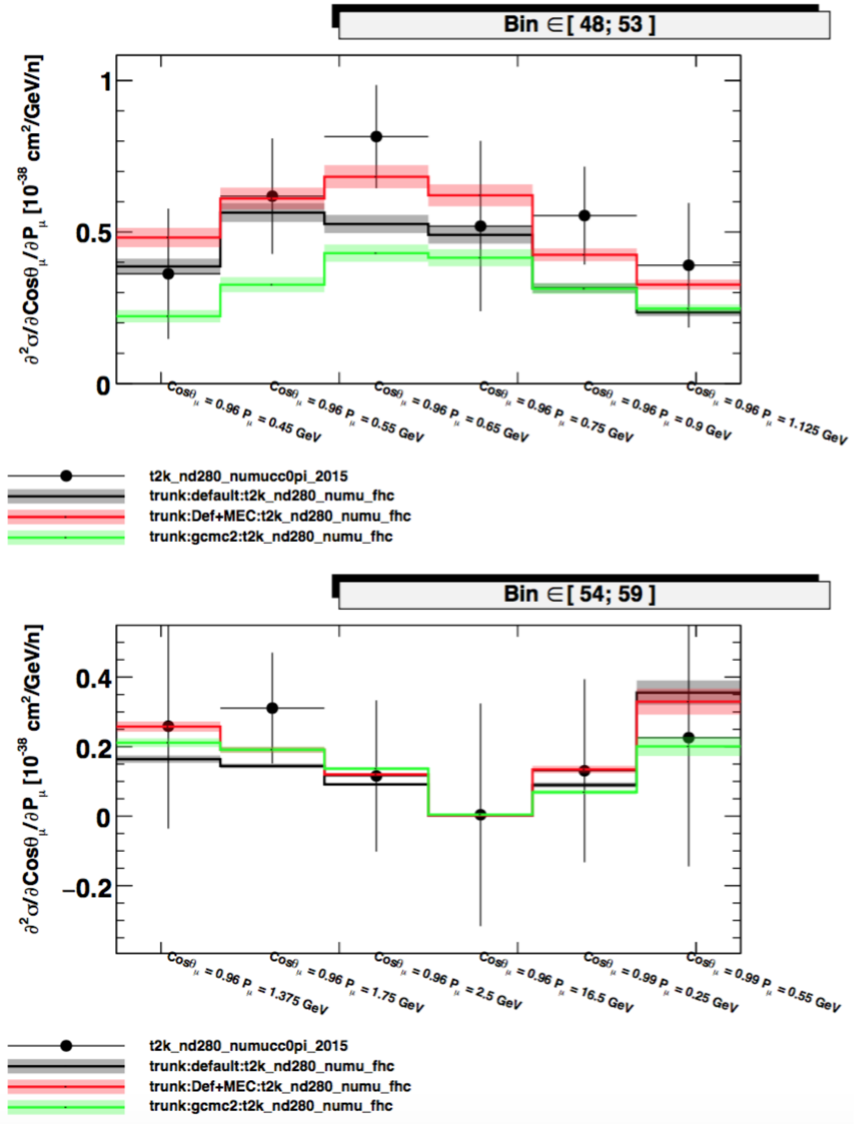
Example comparisons of alternative model configurations

Comparisons against T2K/ND280 CC0π data provides a contradictory view:



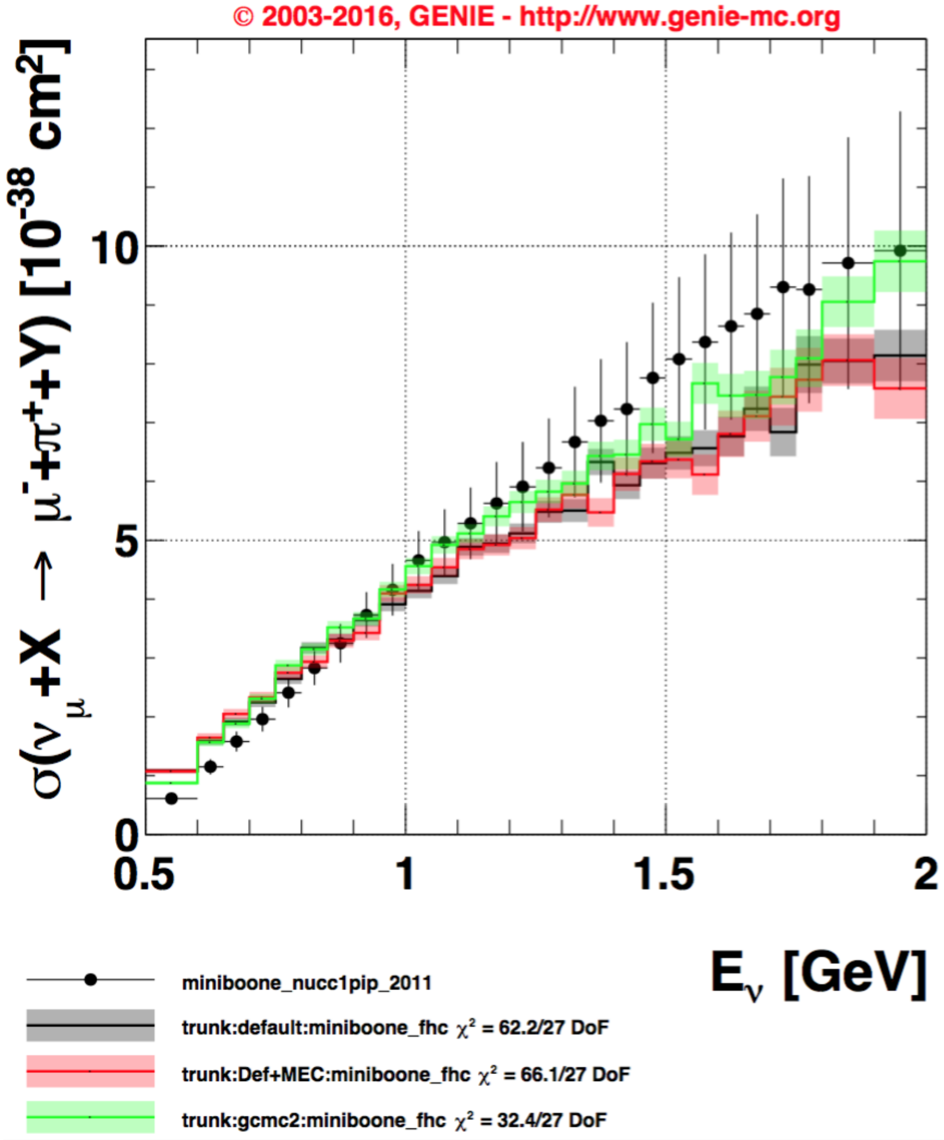
Example comparisons of alternative model configurations

Comparisons against T2K/ND280 CC0π data provides a contradictory view:



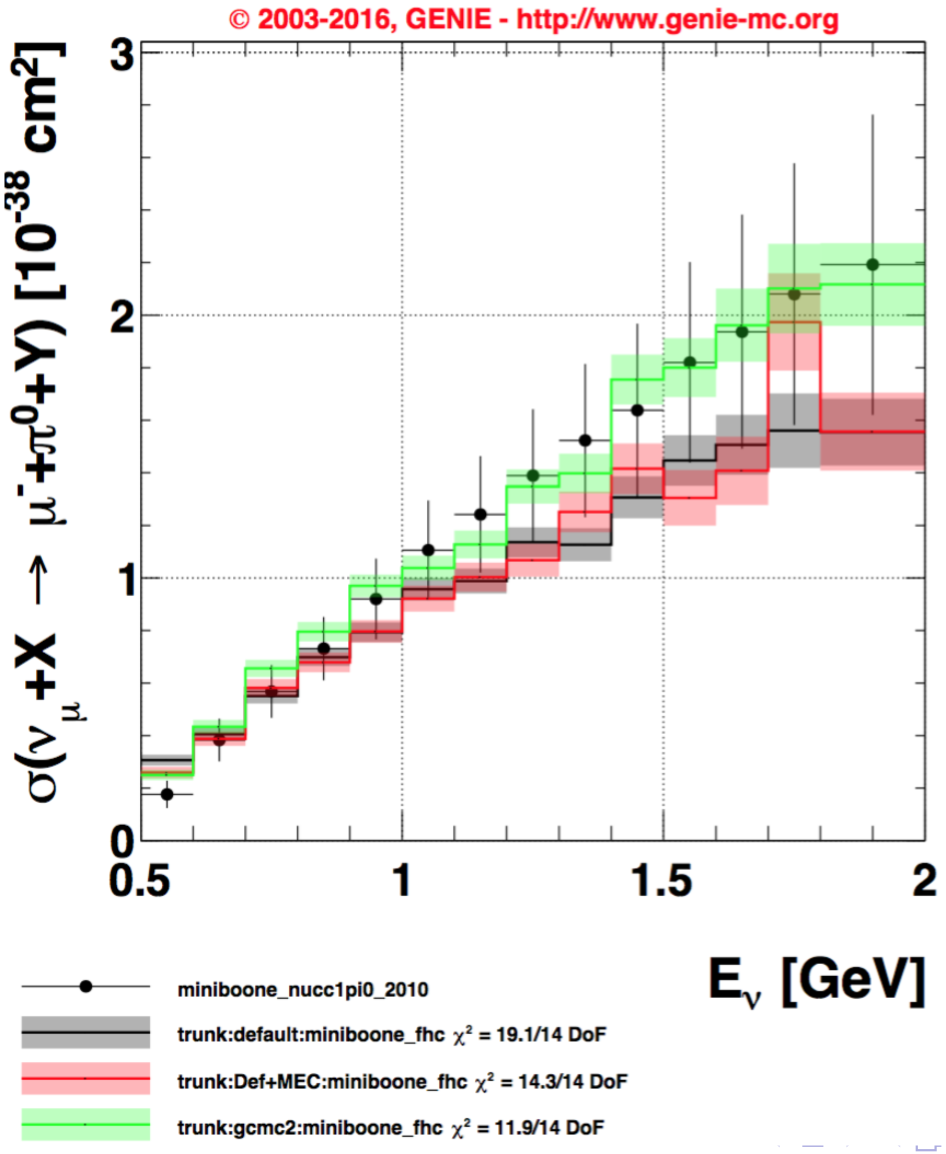
Example comparisons of alternative model configurations

Comparisons against MiniBooNE CC$1\pi^+$ data:



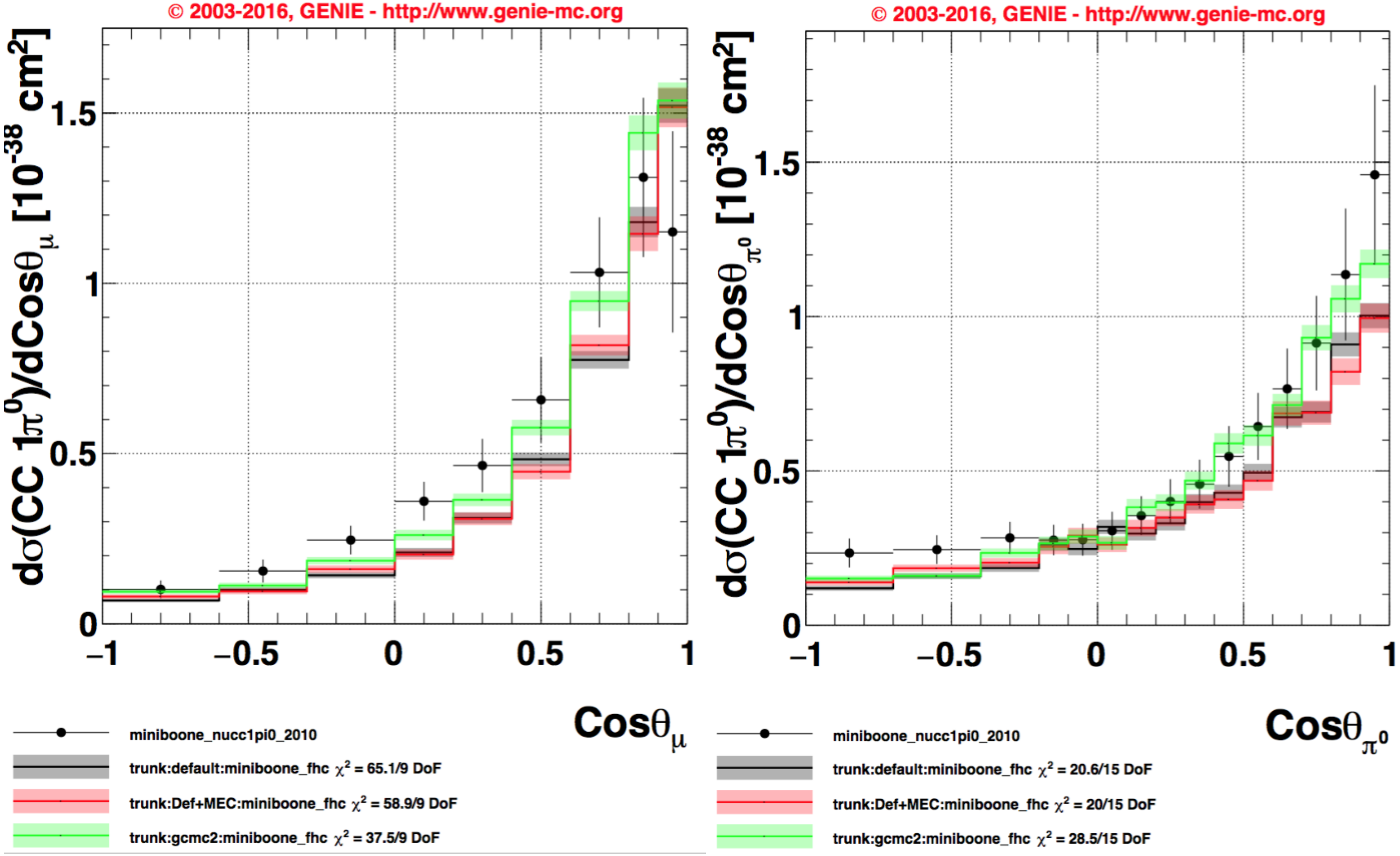
Example comparisons of alternative model configurations

Comparisons against MiniBooNE CC1π^0 data:



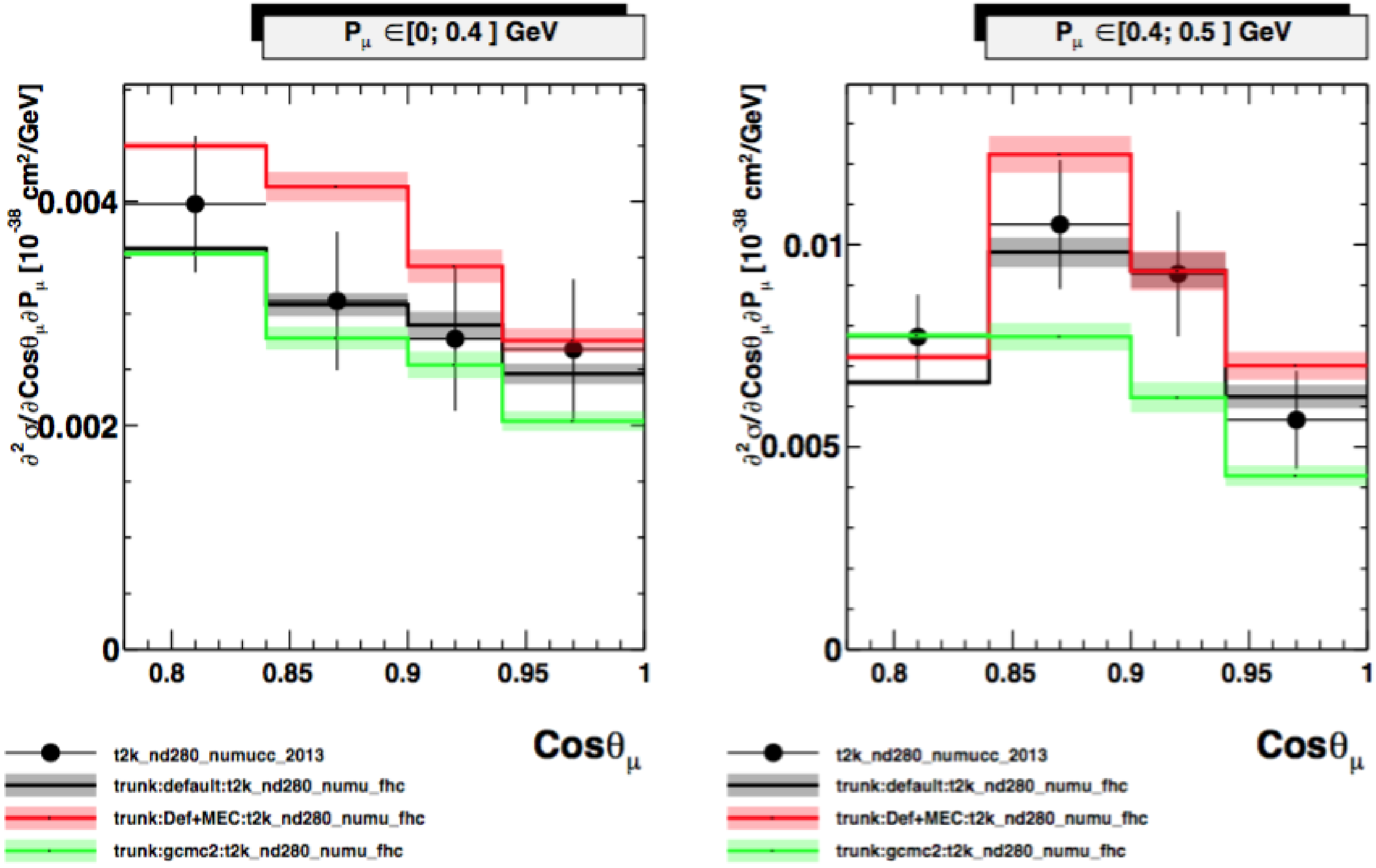
Example comparisons of alternative model configurations

Comparisons against MiniBooNE CC1π^0 data:



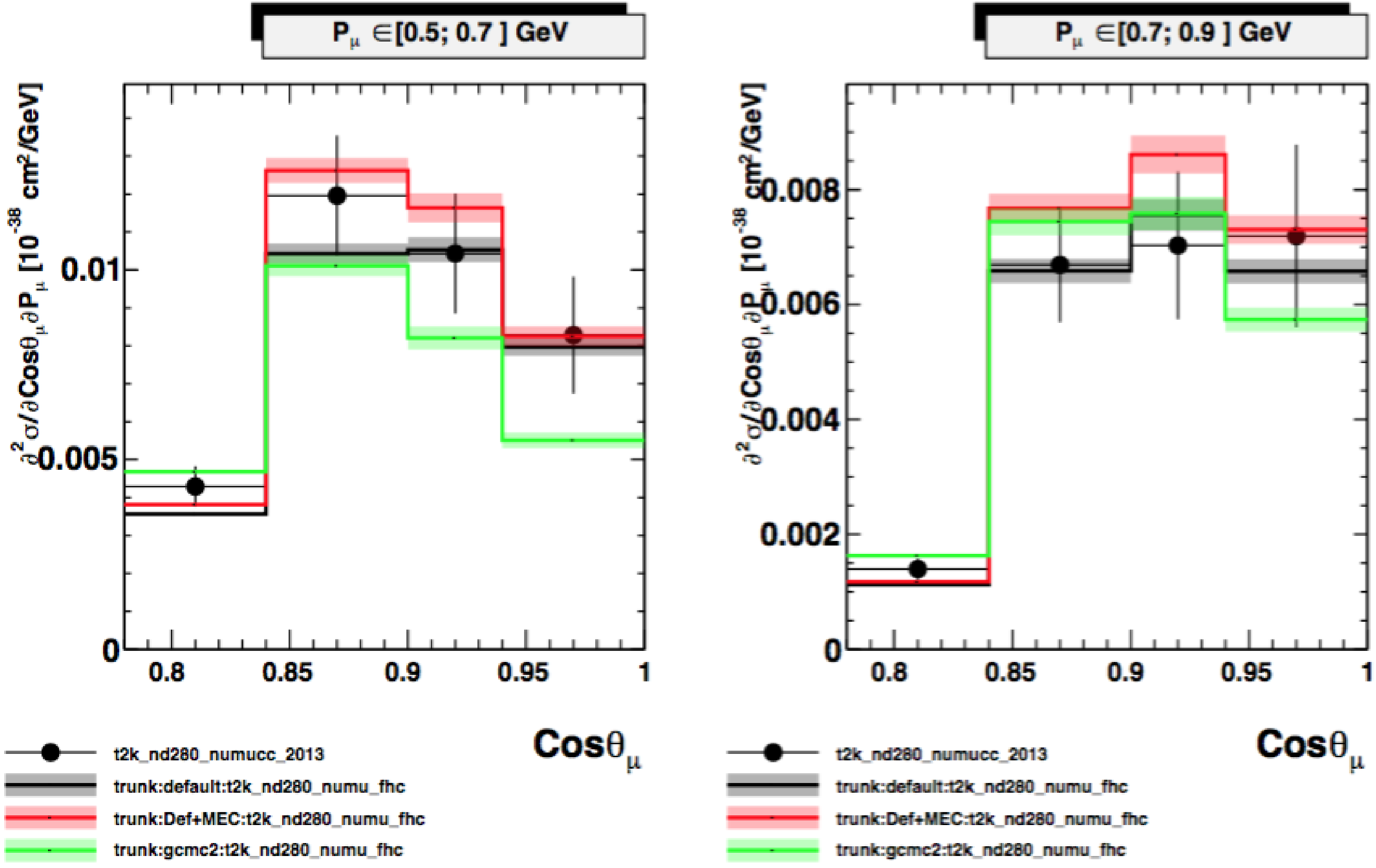
Example comparisons of alternative model configurations

Comparisons against T2K CC inclusive data provides a contradictory view:



Example comparisons of alternative model configurations

Comparisons against T2K CC inclusive data provides a contradictory view:



Strategy and plans for v3

- With v2.12.00 released earlier this week, processing for v3.0.0 has begun.
- Accumulating a **large collection of data/MC comparisons** (could only show the first few generated) and quantitative estimates of agreement to **characterise a series of new comprehensive model configurations**.
- Minor issues with alternative configurations will be addressed at this stage.
- Minimal parameter tuning for promising candidate configurations an option.
- **Plan to release all reasonable configurations in v3.0** and **document the comprehensive physics characterization** in a (hopefully influential) journal paper.
- Add configurations will be concurrently available within GENIE and would be easy to switch from one tune to another:

  Via a `'--tune'` command-line option for all GENIE apps.

- Will make an executive decision for the next *default* tune.

Subsequent releases in v3 series

The v3 series would be **a short-lived** one.

Expect

- code refactorizations (e.g. to help enable PYTHIA8),
- a needed package re-organization in GENIE/Generator,
- urgent bug fixes and tool features,
- some model development (completions of ongoing projects).

Main effort will be on parameter tuning & systematics of new comprehensive model configurations.

Strategy and plans for v4

Parameter tuning for **new comprehensive model configurations** of v3.

- To be released as v4.0.0

Models not predictive enough, and data not perfect:
Adopting a **pragmatic approach** to parameter and error estimation.

Aim to investigate model variations over **large parameter spaces**.

- Both “reweightable” and “non-reweightable”
- Ability to handle “non-reweightable” parameters is **mandatory**
  - Such “non-reweightable” parameters (nuclear, FSI, hadronization) influence important aspects of the physics model.

Task would require **substantial** new software infrastructure.

Such infrastructure **exists for generator tuning at the LHC**!

GENIE meets Professor

http://www.genie-mc.org

https://professor.hepforge.org

Professor

https://professor.hepforge.org

Current authors:
- Andy Buckley (Glasgow)
- Holger Schulz (IPPP)

Former members:
- Hendrik Hoeth
- Heiko Lacker
- Jan Eike von Seggern
- Daniel Weyh
- Simone Amoroso

Professor is a **tuning tool for Monte Carlo event generators**, based on the ideas described in "Tuning and Test of Fragmentation Models Based on Identified Particles and Precision Event Shape Data" (Z. Phys., C73 (1996) 11-60).

Professor has been successfully used to produce **most of the established "tunings"** of the general purpose MC event generators.

A collaboration between Professor and GENIE authors to produce a **Professor/GENIE interface** and **Professor-based GENIE tunes** was supported by Inst. of Particle Physics Phenomelogy via an IPPP Associateship Award.

→ **Active ongoing work!**

Professor

https://professor.hepforge.org

Current authors:
- Andy Buckley (Glasgow)
- Holger Schulz (IPPP)

Former members:
- Hendrik Hoeth
- Heiko Lacker
- Jan Eike von Seggern
- Daniel Weyh
- Simone Amoroso

Fundamentally, the idea of Professor is to

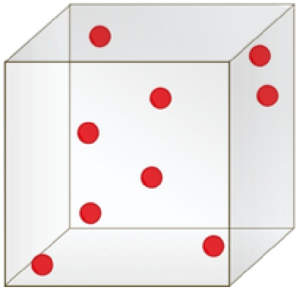
- **reduce the exponentially expensive process of brute-force tuning** to a scaling closer to a power law in the number of parameters.
- **Allow for massive parallelisation** and systematically improve the scan results by use of a deterministic parameterisation of the generator's response to changes in the steering parameters.

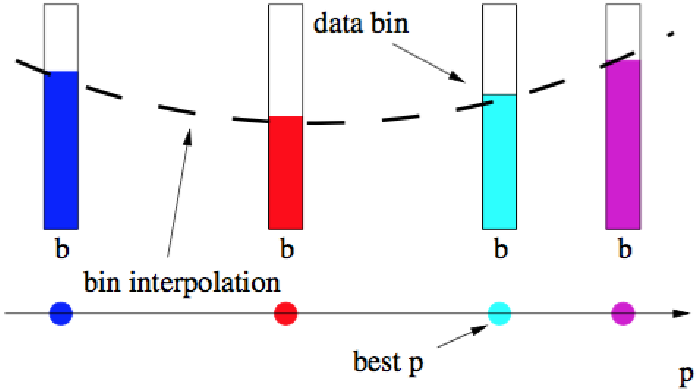
Professor

slide from Holger Schulz (IPPP Durham)

TUNING WITH PROFESSOR

- Random sampling: N parameter points in n-dimensional space
- Run generator and fill histograms (e.g. Rivet)
- For each bin:
  - Don't care about actual dependence on parameters
  - Polynomial approximation
- Construct overall (now trivial) $\chi^2(\vec{p}) \approx \sum_{bins} \frac{(D_b - I_b(\vec{p}))^2}{error^2}$
- and numerically *minimise* with `iminuit`





Professor

slide from Holger Schulz (IPPP Durham)

PROFESSOR APPROACH

- Replace exakt $f(\vec{p})$ by **analytic** approximation $I(\vec{p})$
- Thus replace CPU time for evaluation from hours . . . days to milliseconds

BASIC WORK CYCLE

1. Define and sample M-times from d-dimensional parameter space $\mathcal{P}$
2. For each of the M points $\vec{p}_i$: evaluate exact $f(\vec{p}_i)$

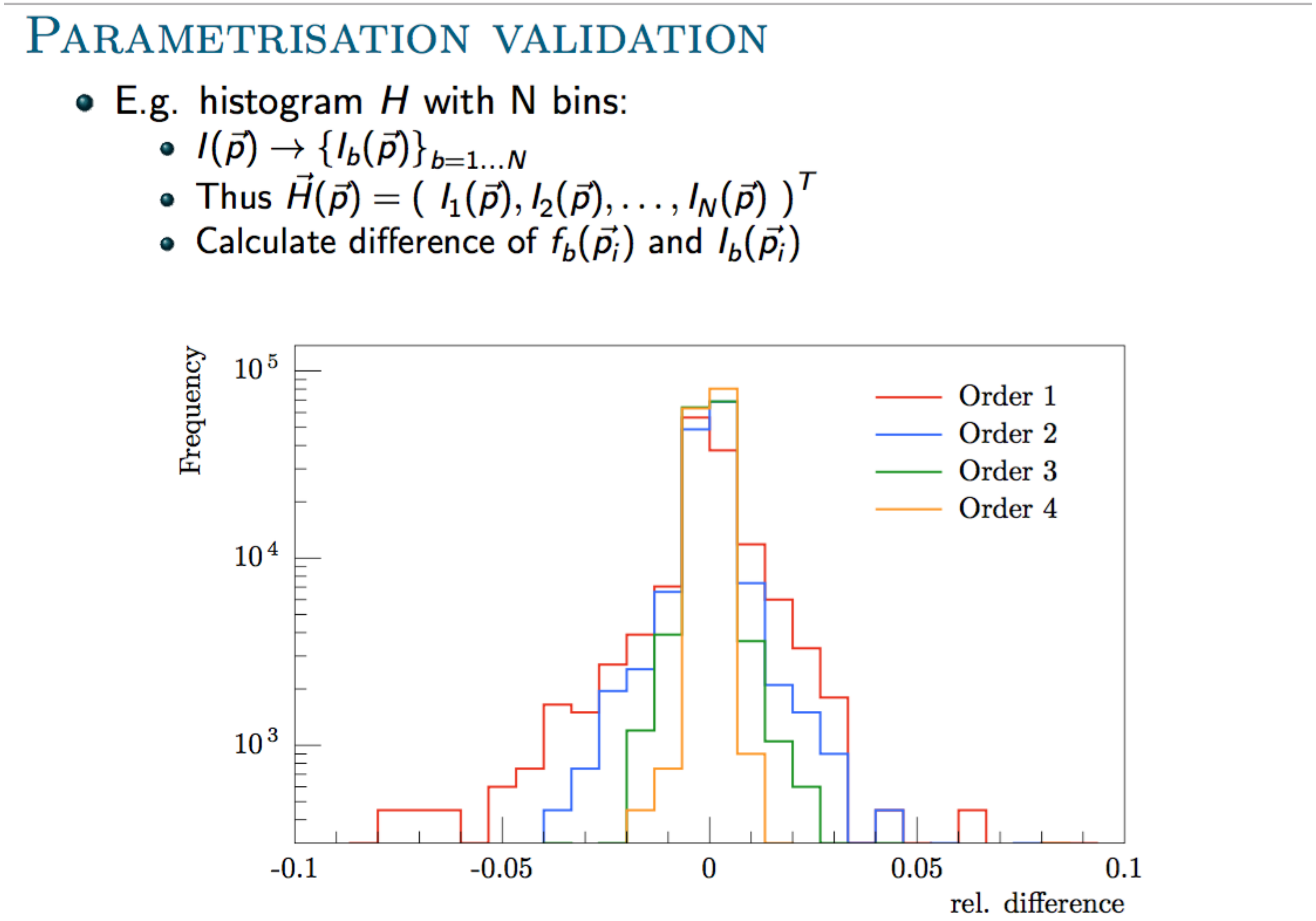
   N.b. this step is trivially parallelisable
3. Fit **polynomial** $I(\vec{p})$ through $[(\vec{p}_1, f(\vec{p}_1)), (\vec{p}_2, f(\vec{p}_2)), \cdots, (\vec{p}_M, f(\vec{p}_M))\ ]$

   e.g. $\boxed{I(p_1, p_2) = \alpha_0 + \beta_1 p_1 + \beta_2 p_2 + \gamma_{11} p_1^2 + \gamma_{12} p_1 \cdot p_2 + \gamma_{22} p_2^2}$

   Store coefficients in text file

Professor

slide from Holger Schulz (IPPP Durham)



PARAMETRISATION VALIDATION

- E.g. histogram *H* with N bins:
  - $I(\vec{p}) \rightarrow \{I_b(\vec{p})\}_{b=1\ldots N}$
  - Thus $\vec{H}(\vec{p}) = (\ I_1(\vec{p}), I_2(\vec{p}), \ldots, I_N(\vec{p})\ )^T$
  - Calculate difference of $f_b(\vec{p}_i)$ and $I_b(\vec{p}_i)$

Prof GENIE interface devel through tuning exercises

The Prof GENIE interface is currently being developed and exercised in a series of staged tuning exercises.

Goal: **Full 0π and 1π tunes reported at NuINT17.**

- Using multiple datasets both jointly and individually.
- Considering several baseline models.
- Considering large parameter spaces (nuclear, bare cross-section, hadronization, and FSI model parameters)

Substantial computing resources secured at CNRS and RAL to produce the tunes.

A.Buckley, H.Schulz, A.Meregaglia,
R.Jones, S.Dennis, M.Roda, C.A.

Model development and tuning effort prioritization

- **Many avenues for model improvement and tuning**.
    - But GENIE manpower-limited.
    - *GENIE only an evening job for most authors.*
- **Consider the needs of future accelerator LBL and SBL experiments.**
    - For CPV, mass ordering determination, sterile neutrino searches.
    - Focus on the Fermilab LAr programme (DUNE and SBN).
- Easy to misjudge the effect of interaction systematics without a **realistic analysis of a multi-detector experiment**.
    - A tall order!
    - *Luckily, our day job is to perform such analyses.*

GENIE meets VALOR

2010
VALOR
NEUTRINO FITS

http://www.genie-mc.org https://valor.pp.rl.ac.uk

VALOR is an **advanced neutrino oscillation data analysis**.

- Has produced several of the flagship T2K oscillation measurements.
- Is used for design optimization in HyperK and DUNE.

Goal: Use the complete VALOR oscillation analysis procedure to **characterise the effect of GENIE model uncertainties** on future precision accelerator LBL and SBL experiments and **inform GENIE development efforts**.

The VALOR group

VALOR is a well-established neutrino fitting group.

(2010 - present); https://valor.pp.rl.ac.uk

Costas Andreopoulos[1,2], Chris Barry[1], Francis Bench[1], Andy Chappell[3], Thomas Dealtry[4], Steve Dennis[1], Lorena Escudero[5], Rhiannon Jones[1], Nick Grant[3], Marco Roda[1], Davide Sgalaberna[6], Raj Shah[2,7]

[*Faculty, Postdocs (former PhD students with VALOR T2K PhD theses), Postdocs, Current PhD students*]

[1] University of Liverpool, [2] STFC Rutherford Appleton Laboratory, [3] University of Warwick, [4] Lancaster University, [5] University of Cambridge, [6] University of Geneva, [7] University of Oxford

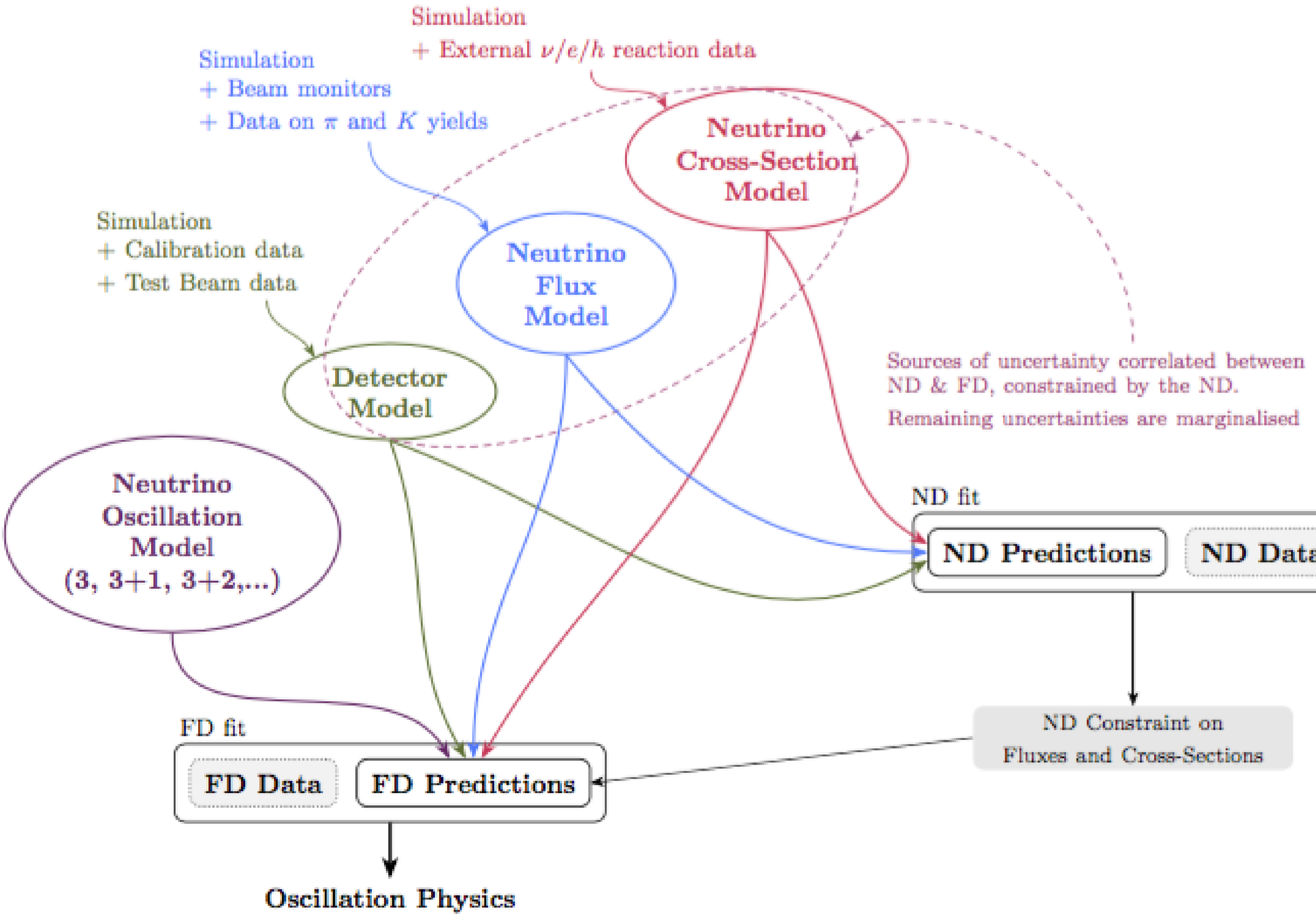
Contributions

T2K: 13 completed and reviewed analyses since 2010; Contributions to nearly all published T2K oscillation papers; 4 completed PhD theses; 4 PhDs in progress.

HyperK / DUNE / SBN: Most realistic sensitivity calculations to date.

Oscillation analysis strategy implemented in VALOR

A two-step procedure used in **T2K**: ND constraint followed by FD oscillation fit



Simulation
+ External $\nu/e/h$ reaction data

Neutrino Cross-Section Model

Simulation
+ Beam monitors
+ Data on π and K yields

Neutrino Flux Model

Simulation
+ Calibration data
+ Test Beam data

Detector Model

Neutrino Oscillation Model (3, 3+1, 3+2,...)

Sources of uncertainty correlated between ND & FD, constrained by the ND.
Remaining uncertainties are marginalised

ND fit

ND Predictions | ND Data

ND Constraint on Fluxes and Cross-Sections

FD fit

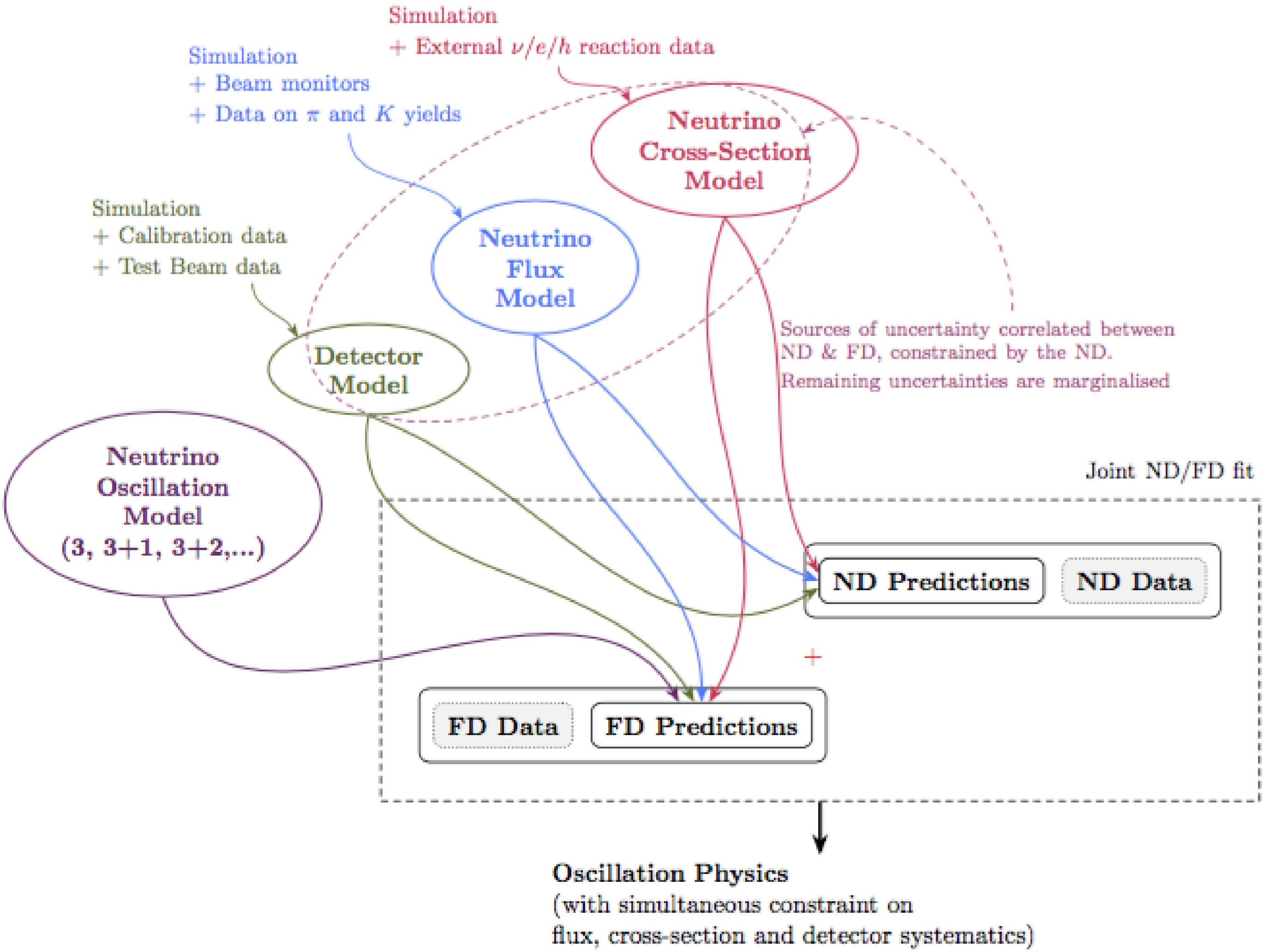
FD Data | FD Predictions

Oscillation Physics

In T2K, the ND fit is performed by a different group

Oscillation analysis strategy implemented in VALOR

VALOR analysis for **DUNE**: In the DUNE systematic error regime, a 2-step fit is unwarranted. A joint oscillation and systematics constraint fit was implemented.



Simulation
+ External $\nu/e/h$ reaction data

Simulation
+ Beam monitors
+ Data on π and K yields

Simulation
+ Calibration data
+ Test Beam data

Neutrino Cross-Section Model

Neutrino Flux Model

Detector Model

Neutrino Oscillation Model (3, 3+1, 3+2,...)

Sources of uncertainty correlated between ND & FD, constrained by the ND. Remaining uncertainties are marginalised

Joint ND/FD fit

ND Predictions **ND Data**

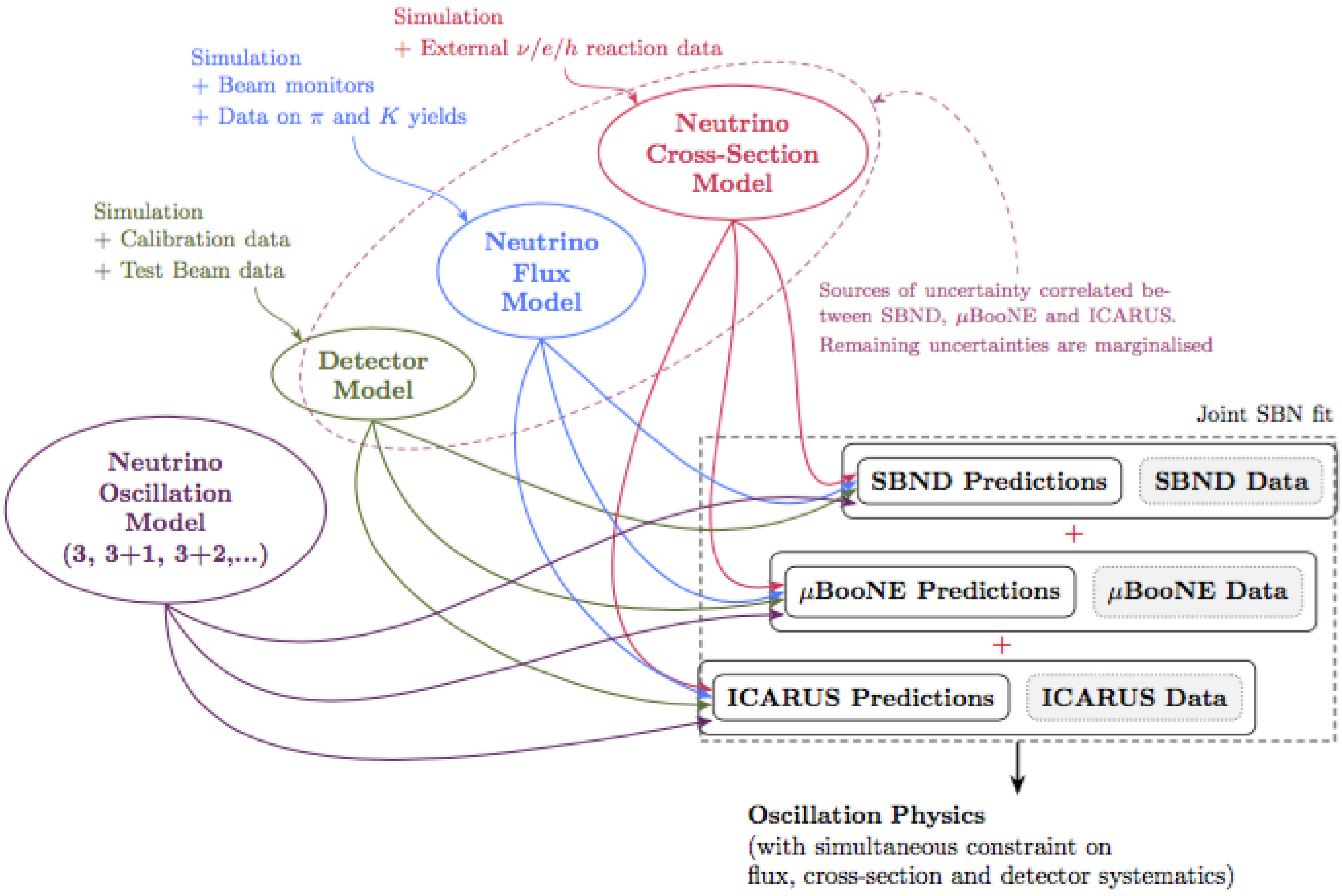
+

FD Data **FD Predictions**

Oscillation Physics
(with simultaneous constraint on flux, cross-section and detector systematics)

Oscillation analysis strategy implemented in VALOR

VALOR analysis for **SBN**: A joint oscillation and systematics constraint fit using multiple event samples from all 3 LArTPCs (SBND, μBooNE, ICARUS)



A simultaneous oscillation and systematics constraint fit

VALOR is a **multi-channel** analysis: Presently, for DUNE & SBN considers 46 samples/detector.

The following 23 samples for the FHC (neutrino) beam configuration:

- **ν_μ CC**
  1. 1-track 0π (μ^- only)
  2. 2-track 0π (μ^- + nucleon)
  3. N-track 0π (μ^- + (>1) nucleons)
  4. 3-track Δ-enhanced ($\mu^- + \pi^+ + p$, $W_{reco} \approx 1.2$ GeV)
  5. $1\pi^\pm$ ($\mu^- + 1\pi^\pm + X$)
  6. $1\pi^0$ ($\mu^- + 1\pi^0 + X$)
  7. $1\pi^\pm + 1\pi^0$ ($\mu^- + 1\pi^\pm + 1\pi^0 + X$)
  8. Other
- **Wrong-sign ν_μ CC**
  9. 0π ($\mu^+ + X$)
  10. $1\pi^\pm$ ($\mu^+ + \pi^\pm + X$)
  11. $1\pi^0$ ($\mu^+ + \pi^0 + X$)
  12. Other
- **ν_e CC**
  13. 0π ($e^- + X$)
  14. $1\pi^\pm$ ($e^- + \pi^\pm + X$)
  15. $1\pi^0$ ($e^- + \pi^0 + X$)
  16. Other

- **Wrong-sign ν_e CC**
  17. Inclusive
- **NC**
  18. 0π (nucleon(s))
  19. $1\pi^\pm$ ($\pi^\pm + X$)
  20. $1\pi^0$ ($\pi^0 + X$)
  21. Other
- **ν-e**
  22. $\nu_e + e^-$ elastic
  23. Inverse μ decay $\nu_\mu + e^- \rightarrow \mu^- + \nu_e$ and annihilation channel $\bar{\nu}_e + e^- \rightarrow \mu^- + \bar{\nu}_\mu$

and a similar set of 23 samples for the RHC (antineutrino enhanced) beam configuration.

The utility of additional samples in reducing systematic uncertainties is being investigated in tandem with the development of improved systematic error / physics parameterizations.

A simultaneous oscillation and systematics constraint fit

Different samples “*speak*” to different physics.

A simultaneous fit of all 46 (currently) event samples per SBN detector **maximizes physics sensitivity** by

- breaking flux, cross-section and efficiency degeneracies, and
- providing in-situ constrain of systematic uncertainties

The method is statistically robust and provides **correlations between physics parameters**.

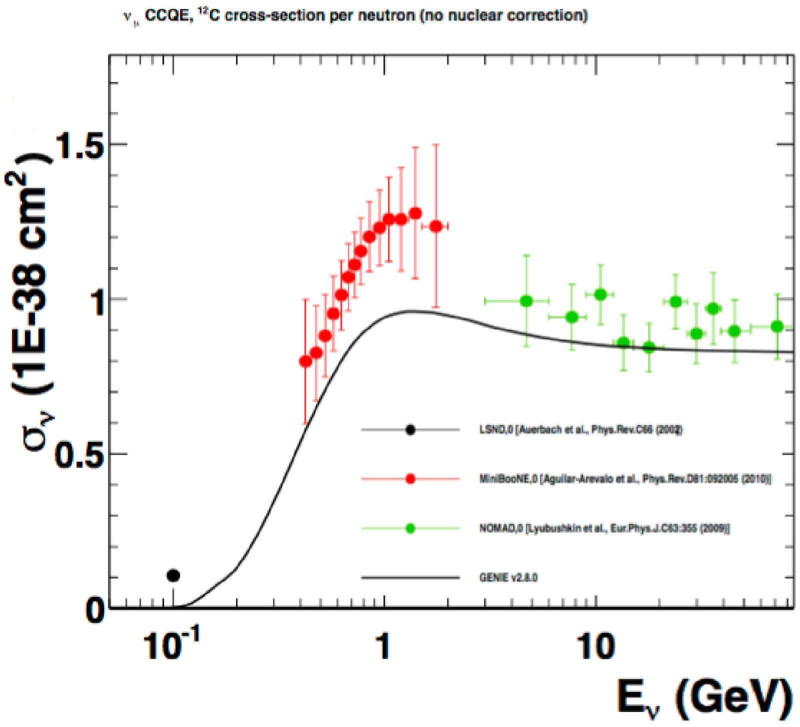
It exploits the **complementarity and redundancy of information** that is brought about by the novel LArTPC technology.

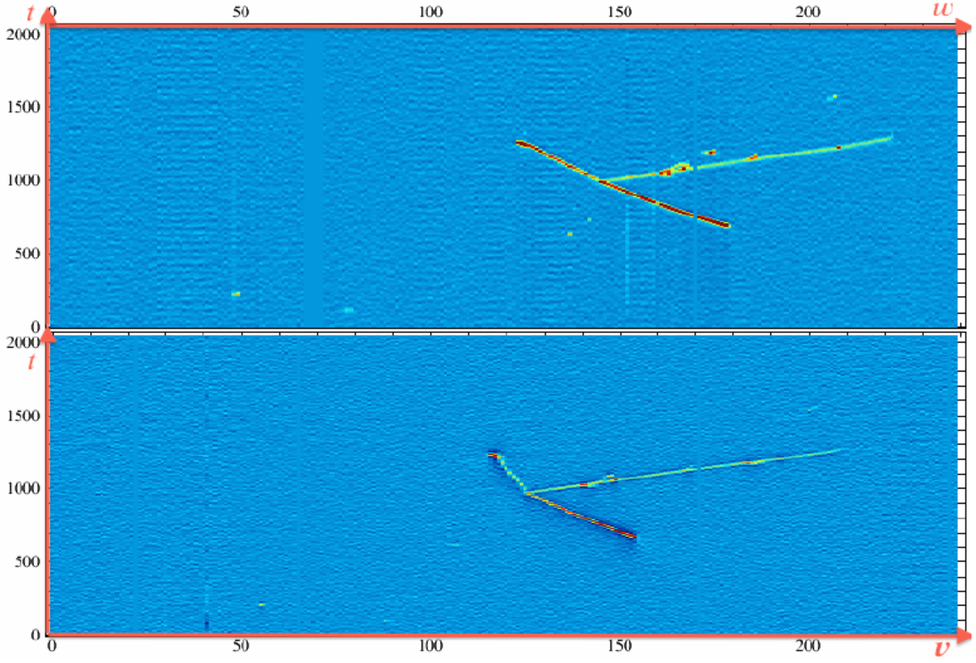
Joint multi-channel analysis is a “necessity”

The need for such a joint analysis is dictated by the physics we need to study.

Example

A particular concern at the SBN energy range would be the tuning of QE/2p2h modelling and the in-situ reduction of the corresponding theoretical uncertainty.

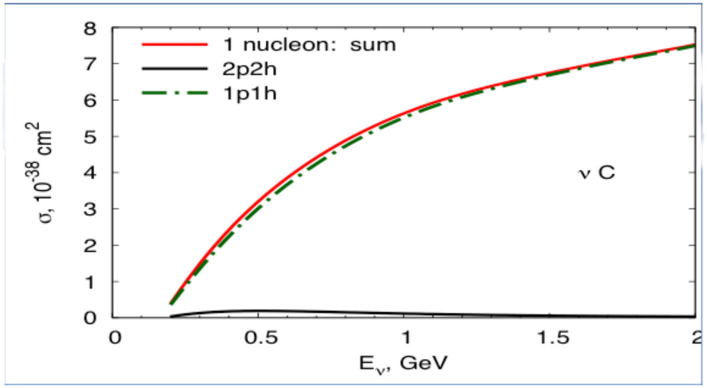


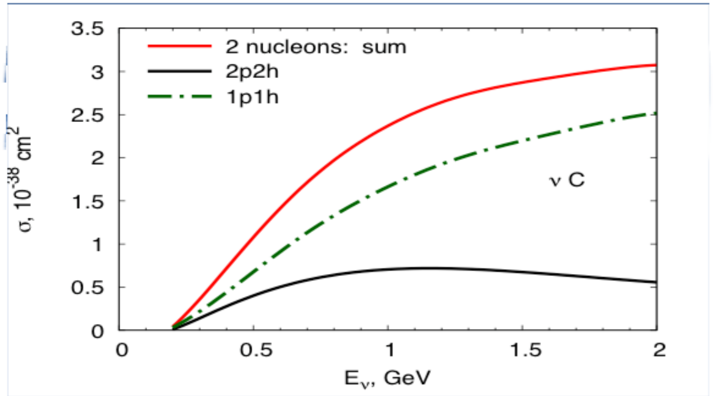


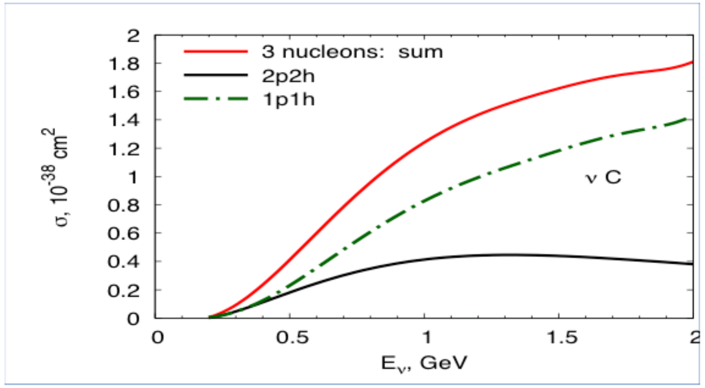
[O.Palamara, F.Cavanna et al.]

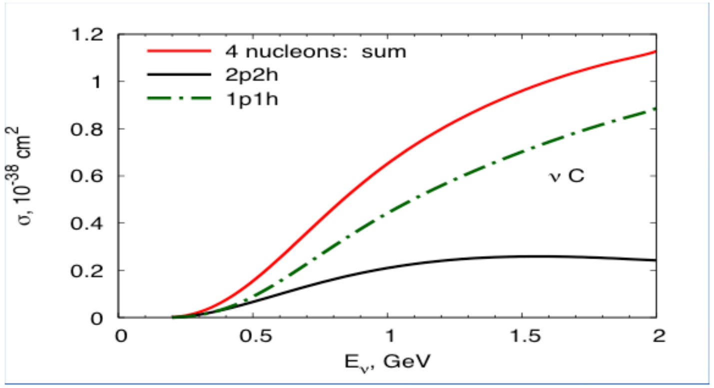
Joint multi-channel analysis is a “necessity”

But there is **no smoking gun signature for 2p2h!** *“Avalanching shadows the initial reaction”* [Mosel].







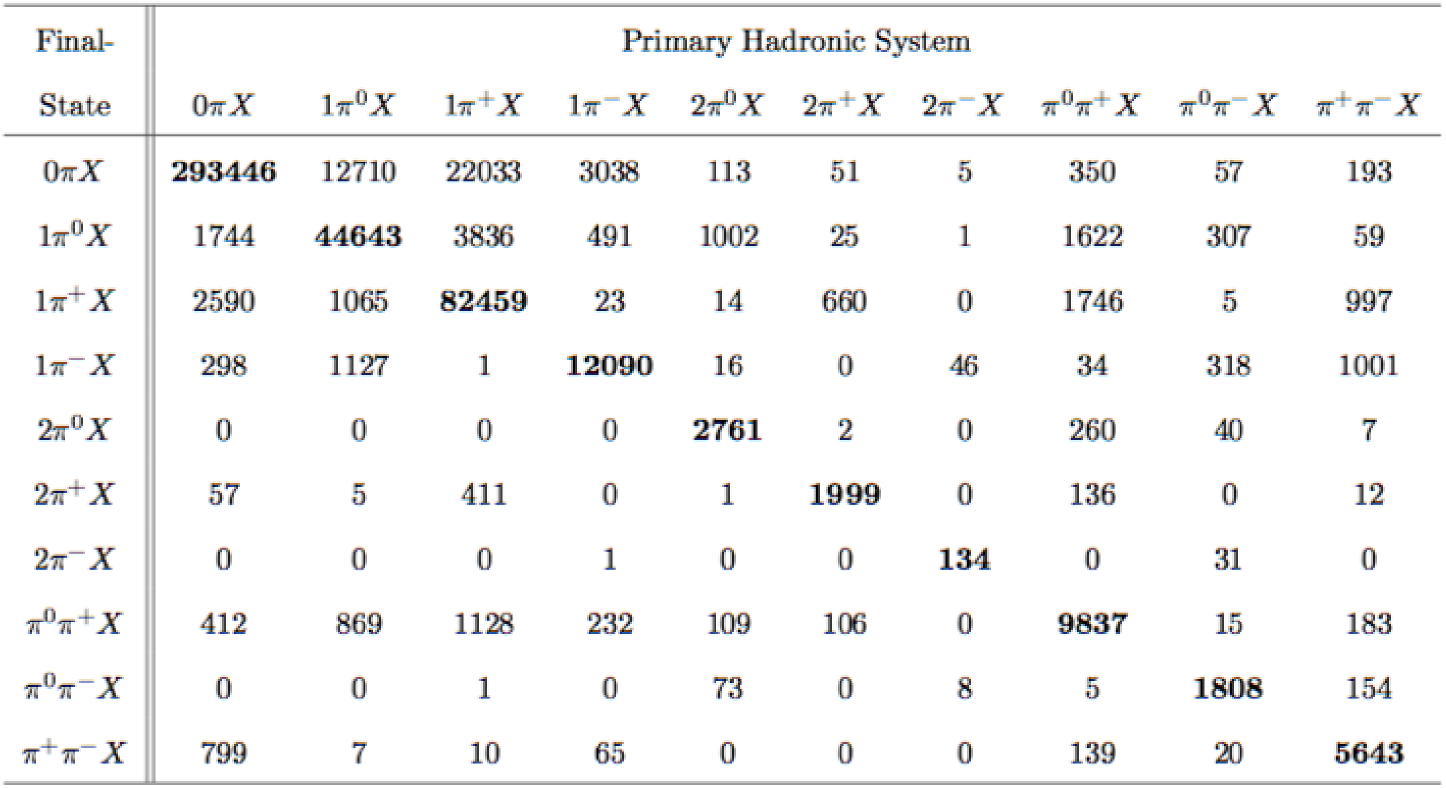


How to constrain 2p2h?

Need to look at multiple samples to disentangle the 2p2h contribution.

Joint multi-channel analysis is a “necessity”

The primary interaction processes that we want to study and constrain are **mingled** together due to the presence of the nucleus.



Final-State	Primary Hadronic System									
	$0\pi X$	$1\pi^0 X$	$1\pi^+ X$	$1\pi^- X$	$2\pi^0 X$	$2\pi^+ X$	$2\pi^- X$	$\pi^0\pi^+ X$	$\pi^0\pi^- X$	$\pi^+\pi^- X$
$0\pi X$	**293446**	12710	22033	3038	113	51	5	350	57	193
$1\pi^0 X$	1744	**44643**	3836	491	1002	25	1	1622	307	59
$1\pi^+ X$	2590	1065	**82459**	23	14	660	0	1746	5	997
$1\pi^- X$	298	1127	1	**12090**	16	0	46	34	318	1001
$2\pi^0 X$	0	0	0	0	**2761**	2	0	260	40	7
$2\pi^+ X$	57	5	411	0	1	**1999**	0	136	0	12
$2\pi^- X$	0	0	0	1	0	0	**134**	0	31	0
$\pi^0\pi^+ X$	412	869	1128	232	109	106	0	**9837**	15	183
$\pi^0\pi^- X$	0	0	1	0	73	0	8	5	**1808**	154
$\pi^+\pi^- X$	799	7	10	65	0	0	0	139	20	**5643**

Left: Migration from “primary” (before FSI) to final-state / observed topologies ($\nu_\mu O^{16}$, 1 GeV)

For example, the 0π, $1\pi^+$, $\pi^+\pi^0$, $2\pi^+$ and other datasets are connected via the *same pion FSI physics*: In a joint multi-channel analysis, one would not be allowed to pull FSI parameters to “fix” an unrelated problem manifesting in one of the channels.

Joint multi-channel oscillation analysis

A multi-channel analysis lifts oscillation parameter degeneracies and can embed in it the relations between appearance and disappearance channels.

For example, in SBN: $\underline{\overset{(-)}{\nu}_\mu \rightarrow \overset{(-)}{\nu}_e \text{ appearance } \textbf{requires } \overset{(-)}{\nu}_\mu \text{ and } \overset{(-)}{\nu}_e \text{ disappearance.}}$

- **$\overset{(-)}{\nu}_e$ disappearance**

$$P(\overset{(-)}{\nu}_e \nrightarrow \overset{(-)}{\nu}_e) = 1 - sin^2(2\theta_{ee}) \cdot sin^2(\frac{\Delta m^2_{41}}{4E_\nu}), \; sin^2(2\theta_{ee}) = |U_{e4}|^2 \cdot (1 - |U_{e4}|^2)$$

- **$\overset{(-)}{\nu}_\mu$ disappearance**

$$P(\overset{(-)}{\nu}_\mu \nrightarrow \overset{(-)}{\nu}_\mu) = 1 - sin^2(2\theta_{\mu\mu}) \cdot sin^2(\frac{\Delta m^2_{41}}{4E_\nu}), \; sin^2(2\theta_{\mu\mu}) = |U_{e4}|^2 \cdot (1 - |U_{\mu 4}|^2)$$

- **$\overset{(-)}{\nu}_e$ appearance in $\overset{(-)}{\nu}_\mu$ beam**

$$P(\overset{(-)}{\nu}_\mu \nrightarrow \overset{(-)}{\nu}_e) = 1 - sin^2(2\theta_{\mu e}) \cdot sin^2(\frac{\Delta m^2_{41}}{4E_\nu}), \; sin^2(2\theta_{\mu e}) = \frac{1}{4} sin^2(2\theta_{ee}) \cdot sin^2(2\theta_{\mu\mu})$$

VALOR fit
Physics parameterization

VALOR fit: Construction of likelihood

A joint VALOR fit considers simultaneously:

- A flexibly-defined **set of detectors d**. *E.g.* $d \in \{SBND, \mu BooNE, ICARUS\}$.
- A flexibly-defined **set of beam configurations b** (for each d). *E.g.* $b \in \{FHC, RHC, ...\}$
- A flexibly-defined **set of event selections s** (for each d and b). *E.g. see page 11.*

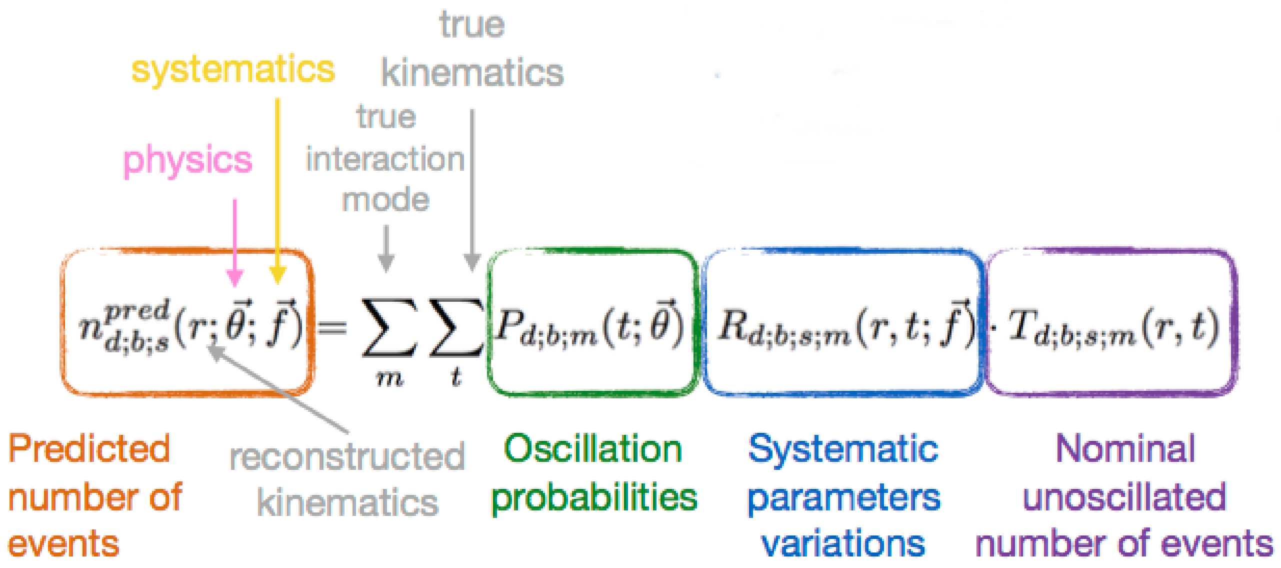
For each (d,b,s):

- Experimental information is recorded in a number of **multi-dim. reco. kinematical bins r** *E.g.* $r \equiv \{ E_{\nu;reco} \}, \{E_{\nu;reco}, y_{reco} \}, \{ p_{\ell;reco}, \theta_{\ell;reco} \}, \{ E_{vis;reco} \}, ...$

Our predictions for

- a set of **interesting physics params $\vec{\theta}$** (*e.g.* $\{\theta_{23}, \delta_{CP}, \Delta m^2_{31}\}$ *or* $\{\theta_{\mu e}, \theta_{\mu\mu}, \Delta m^2_{41}\}$), and
- a set of O(10^2)-O(10^3) **systematic (nuisance) params $\vec{f}$**

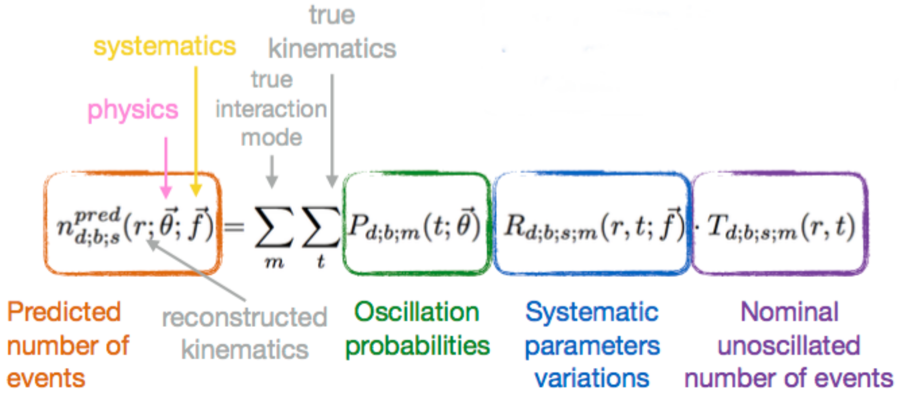
are constructed as follows:



$$n^{pred}_{d;b;s}(r;\vec{\theta};\vec{f}) = \sum_m \sum_t P_{d;b;m}(t;\vec{\theta}) \, R_{d;b;s;m}(r,t;\vec{f}) \cdot T_{d;b;s;m}(r,t)$$

VALOR fit: Construction of likelihood

Predictions are built using **MC templates $T_{d;b;s;m}(r,t)$** constructed by applying event selection code to the output of a full event simulation and reconstruction chain.



$$n^{pred}_{d;b;s}(r;\vec{\theta};\vec{f}) = \sum_{m} \sum_{t} P_{d;b;m}(t;\vec{\theta}) \, R_{d;b;s;m}(r,t;\vec{f}) \cdot T_{d;b;s;m}(r,t)$$

For each (d,b,s), MC templates are constructed for a set of **true reaction modes m**.

- Currently, templates are constructed for the 52 true reaction modes shown on the right.

The templates store the mapping between reconstructed and truth information (as derived from full simulation and reconstruction).

- E.g. $\{ E_{\nu;true}, Q^2_{true}, W_{true} \} \leftrightarrow \{ p_{\ell;reco}, \theta_{\ell;reco} \}$

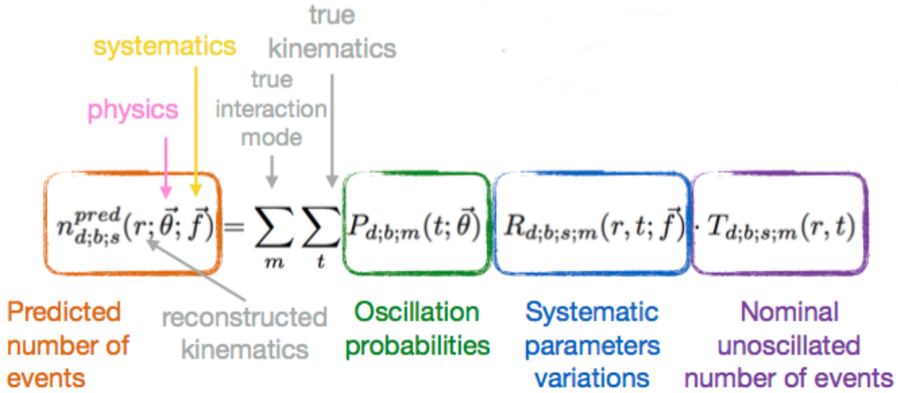
The choice of true kinematical space { t } and true reaction modes m is **highly configurable** for each (d,b,s) independently.

- Main consideration: **Sufficient granularity to apply desired physics and systematic effects** (function of truth quantities).

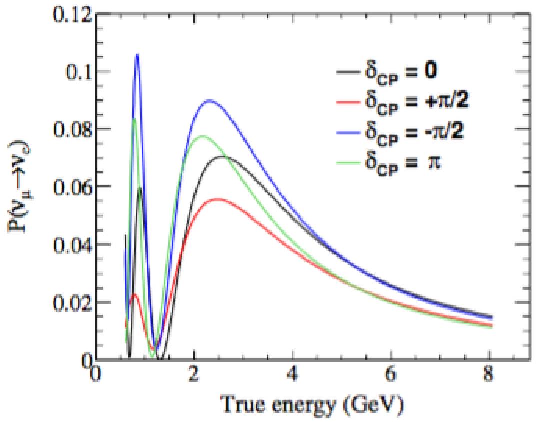
- ν_μ CC QE
- ν_μ CC MEC
- ν_μ CC $1\pi^\pm$
- ν_μ CC $1\pi^0$
- ν_μ CC $2\pi^\pm$
- ν_μ CC $2\pi^0$
- ν_μ CC $1\pi^\pm + 1\pi^0$
- ν_μ CC coherent
- ν_μ CC other
- ν_μ NC $1\pi^\pm$
- ν_μ NC $1\pi^0$
- ν_μ NC coherent
- ν_μ NC other
- **similarly for** $\bar{\nu}_\mu$
- **similarly for** ν_e
- **similarly for** $\bar{\nu}_e$

VALOR fit: Construction of likelihood

Finally, the effect of **neutrino oscillations** is included in $P_{d;b;m}(t;\vec{\theta})$.



$$n^{pred}_{d;b;s}(r;\vec{\theta};\vec{f}) = \sum_{m}\sum_{t} P_{d;b;m}(t;\vec{\theta})\, R_{d;b;s;m}(r,t;\vec{f}) \cdot T_{d;b;s;m}(r,t)$$

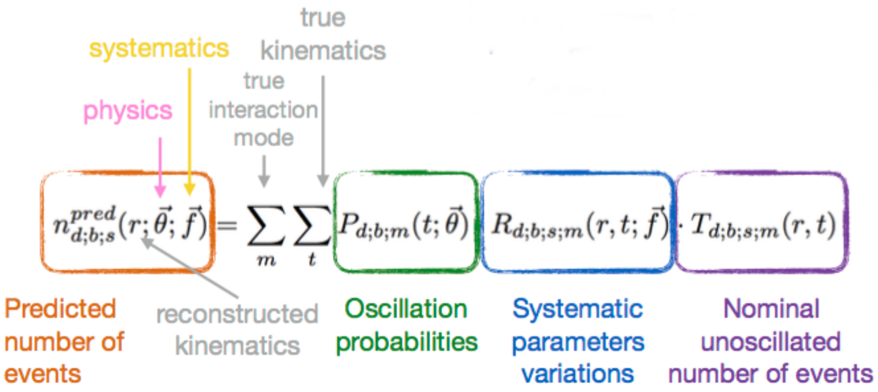


- Using bespoke library for calculation of osc. probabilities.
- **Very fast!**
- **Extensively validated** against GloBES and Prob3++.
- Supports 3-flavour calculations (incl. standard matter / NSI effects) and, also, calculations in 3+1, 3+2, 1+3+1 schemes.
- **Flexibility** provided by bespoke library is immensely useful (tuning performance, moving between different parameter conventions, trying out different oscillation frameworks).

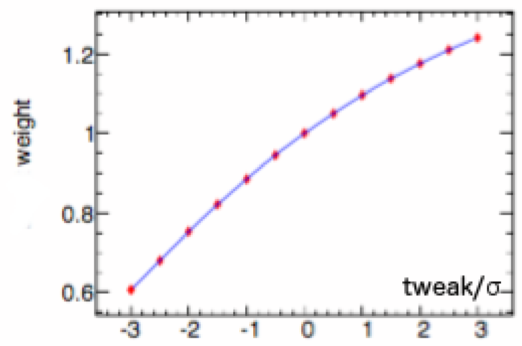
- $\sin^2(\theta_{12}) = 0.3$
- $\sin^2(\theta_{13}) = 0.025$
- $\sin^2(\theta_{23}) = 0.5$
- $\Delta m^2_{21} = 7.5\times10^{-5}$ eV^2/c^4
- $\Delta m^2_{32} = 2.5\times10^{-3}$ eV^2/c^4
- Normal ordering
- Earth matter density = 2.7 g/cm^3
- Baseline = 1300 km

VALOR fit: Construction of likelihood

Systematic variations are applied using the **response functions** $\boldsymbol{R_{d;b;s;m}(r,t;\vec{f})}$.



Example of a non-linear response function.



Typically, but not always, the response $R_{d;b;s;m}(r,t;\vec{f})$ factorises and it can be written as

$$R_{d;b;s;m}(r,t;\vec{f}) = \prod_{i=0}^{N-1} R^{i}_{d;b;s;m}(r,t;f_i)$$

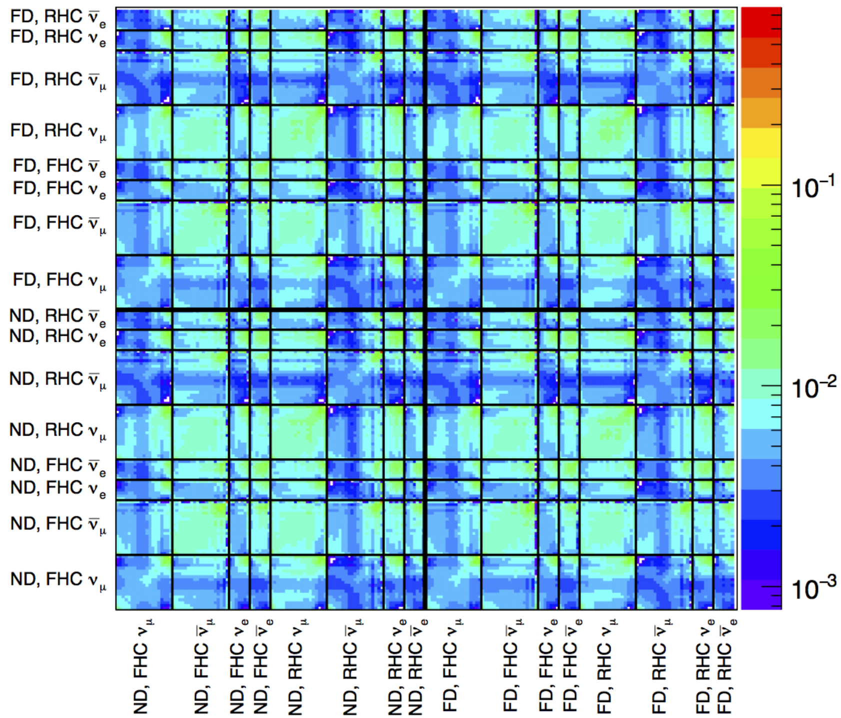
For several systematics the response is linear and, therefore,

$$R^{i}_{d;b;s;m}(r,t;f_i) \propto f_i$$

For non linear systematics, the response function $R^{i}_{d;b;s;m}(r,t;f_i)$ is pre-computed (for every detector, beam, sample, mode, true kinematical bin and reconstructed kinematical bin) using event reweighting libraries in the [-5σ, +5σ] range of the parameter f_i and it is represented internally using an Akima spline.

Flux systematics in the VALOR fit

In the current version of the VALOR/DUNE 3-flavour oscillation analysis, we consider **208 (104 ND and 104 FD) neutrino flux systematics**.



Each parameter is a normalization factor for a particular

- detector (ND, FD),
- beam configuration (FHC, RHC),
- neutrino flavour (ν_μ, ν_e, $\bar{\nu}_\mu$, $\bar{\nu}_e$), and
- true neutrino energy bin.

The **prior (pre-fit) constraints** on the flux systematics and their pre-fit covariances is described by the matrix shown on the left (provided by the DUNE and SBN Beam Simulation groups).

DUNE flux covariance matrix from:

https://indico.fnal.gov/getFile.py/access?contribId=67&sessionId=21&resId=0&materialId=slides&confId=10613

Neutrino interaction systematics in the VALOR fit

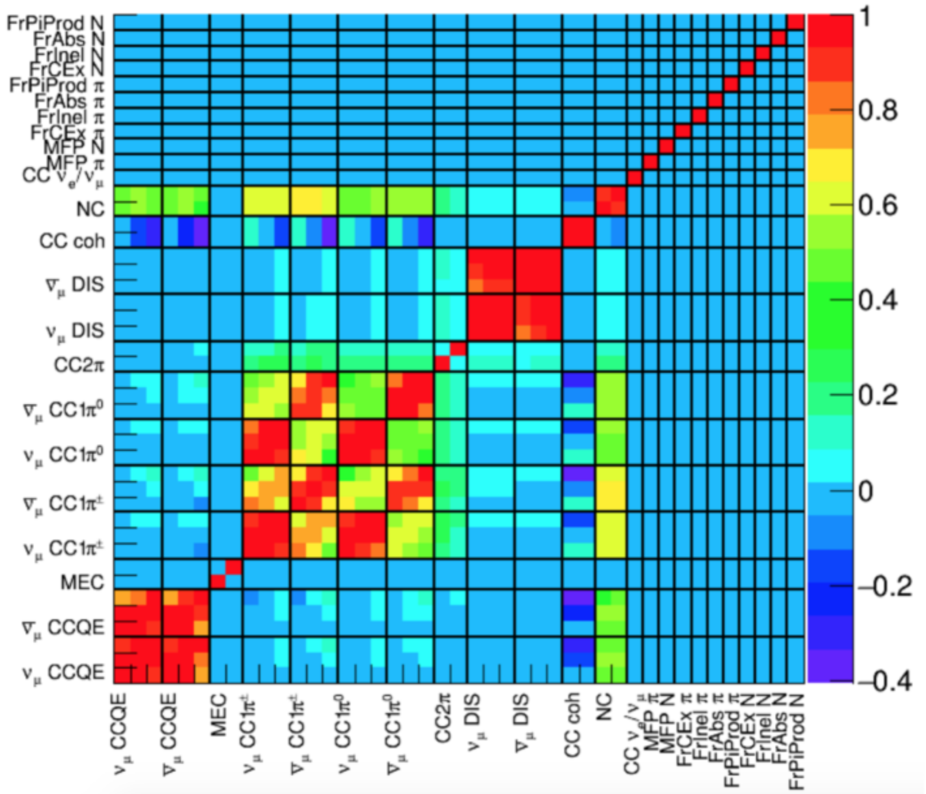
In the current version of the VALOR/DUNE 3-flavour oscillation analysis, we consider **43 neutrino interaction systematics**.

- 33 cross-section linear systematics
  - CCQE normalization in 3 Q^2 bins, separately for ν and $\bar{\nu}$ (6)
  - CCMEC normalization in 2 Q^2 bins, separately for ν and $\bar{\nu}$ (4)
  - CC1$\pi^{\pm}$ normalization in 3 Q^2 bins, separately for ν and $\bar{\nu}$ (6)
  - CC1π^0 normalization in 3 Q^2 bins, separately for ν and $\bar{\nu}$ (6)
  - CC2π normalization, separately for ν and $\bar{\nu}$ (2)
  - CCDIS normalization in 3 E_ν bins, separately for ν and $\bar{\nu}$ (6)
  - CC coherent normalization, separately for ν and $\bar{\nu}$ (2)
  - NC normalization, separately for ν and $\bar{\nu}$ (2)
  - ν_e/ν_μ normalization (1)
- 10 FSI non-linear systematics (require pre-computed response functions)
  - π and nucleon mean free paths (2)
  - probabilities for an interacting π or nucleon to participate in charge exchange, inelastic, absorption or π-production interaction (8)

Neutrino interaction systematics in the VALOR fit

Using predominantly **linear** and **model-independent** parameters.

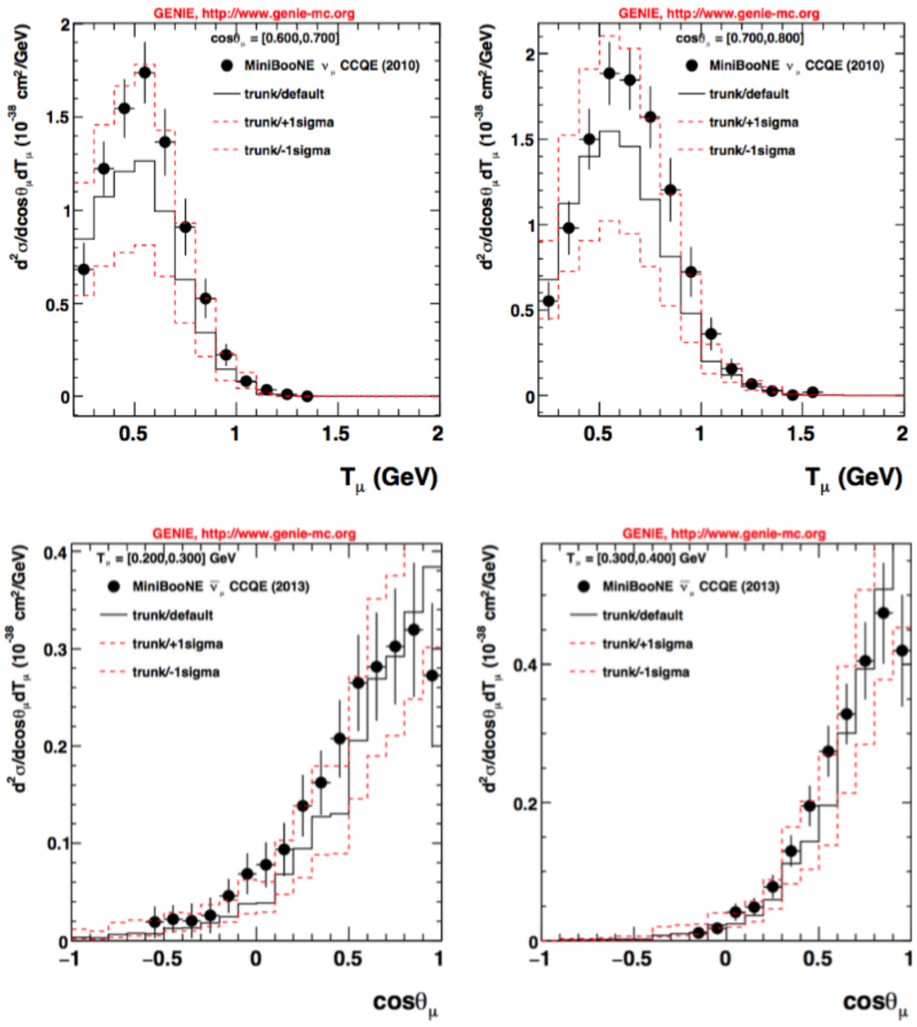
- Any set of GENIE model parameters can be mapped onto it..
- Parameterization used in the fit remains stable.
- Flexibility to move to new GENIE tunes / model configurations, using identical VALOR fitting code.

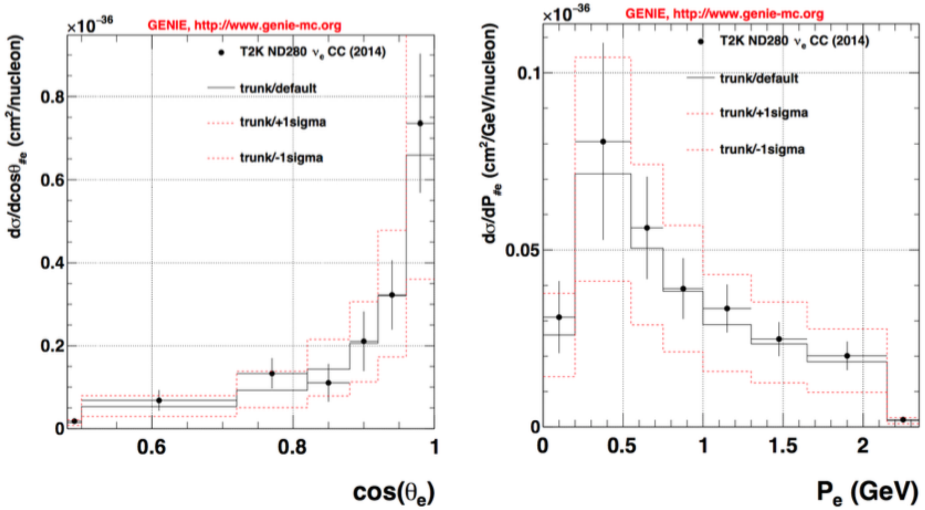


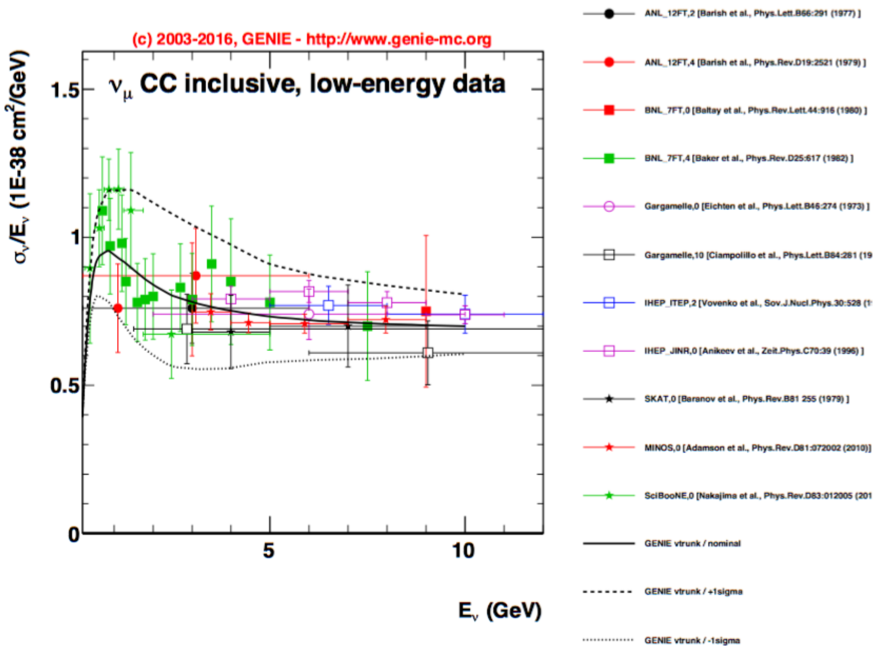
A prior (pre-fit) correlation matrix for our neutrino interaction systematic parameters (see on the left) was computed by tweaking the parameters of the default GENIE model.

Neutrino interaction systematics in the VALOR fit

The **prior** neutrino interaction systematics assignments were supported by a series of data/MC comparisons (see DUNE-docdb-1291). More studies are in progress.







VALOR/SBN fit: Construction of likelihood

Once we have estimates of $n^{pred}_{d;b;s}(r;\vec{\theta};\vec{f})$, VALOR computes a **likelihood ratio**:

$$ln\ \lambda_{d;b;s}(\vec{\theta};\vec{f}) = -\sum_{r}\left\{\left(n^{pred}_{d;b;s}(r;\vec{\theta};\vec{f}) - n^{obs}_{d;b;s}(r)\right) + n^{obs}_{d;b;s}(r)\cdot ln\frac{n^{obs}_{d;b;s}(r)}{n^{pred}_{d;b;s}(r;\vec{\theta};\vec{f})}\right\}$$

$$\lambda_{SBN}(\vec{\theta};\vec{f}) = \prod_{d}\prod_{b}\prod_{s}\lambda_{d;b;s}(\vec{\theta};\vec{f})$$

Most parameters in the fit come with prior constraints from external data. Where needed, the following Gaussian penalty term is computed:

$$ln\ \lambda_{prior}(\vec{\theta};\vec{f}) = -\frac{1}{2}\left\{(\vec{\theta}-\vec{\theta}_0)^T C_{\theta}^{-1}(\vec{\theta}-\vec{\theta}_0) + (\vec{f}-\vec{f}_0)^T C_{f}^{-1}(\vec{f}-\vec{f}_0)\right\}$$

and combined likelihood ratio is given by:

$$\lambda(\vec{\theta};\vec{f}) = \lambda_{SBN}(\vec{\theta};\vec{f})\cdot\lambda_{prior}(\vec{\theta};\vec{f})$$

In the large-sample limit, the quantity $-2\lambda(\vec{\theta};\vec{f})$ has a χ^2 distribution and it can therefore be used as a goodness-of-fit test.

Statistical treatment in VALOR LBL and SBL fits

All physics is included in the definition of $\lambda(\vec{\theta}; \vec{f})$ (see previous page).

Several statistical procedures are built on top $\lambda(\vec{\theta}; \vec{f})$ for nuisance parameter elimination, point and interval estimation, and hypothesis testing.

VALOR draws in a pragmatic way on both Bayesian and Frequentist methods. The methodology follows best HEP traditions and it was exercised repeatedly by the group in precision neutrino measurements (T2K).

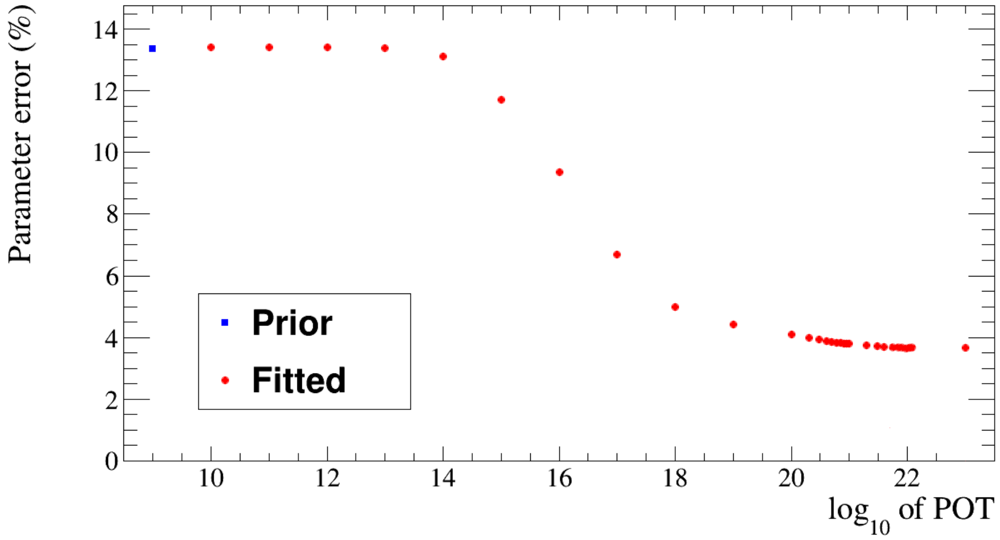
See several talks and posters by group members during PHYSTAT-ν at IPMU and FNAL.

Some information is also included at the end of the talk

Reduction of systematic uncertainties

Using the VALOR joint oscillation and systematics constraint fit, the expected **in-situ error reduction** can be computed:

- Limiting value (for large exposure) depends critically upon the detector assumptions and event reconstruction.



Example of CC1π^0 cross-section error reduction in DUNE.

Constraint systematic improves oscillation physics reach.

Moving backwards (*oscillation physics target sensitivity* → *systematic constraint* → *detector characteristics*) allows us to optimise the detector design.

(This is how VALOR is used in DUNE)

Metrics for effect of interaction uncertainties on CP

Here we want to

- relax dependence on detector performance and reconstruction, and
- ignore the actual post-fit constraint.

Instead, study a series of 'what-if' scenarios for interaction systematics: E.g. what is the effect:
- of failing to improve on the prior, or
- of constraining a systematic to 50% or 10% of the prior (*).

Possible metrics:

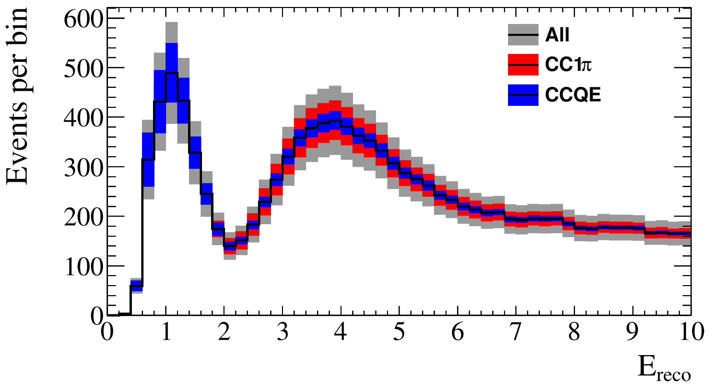
- Effect on observed event spectra and on energy reconstruction.
- Effect on CP discovery sensitivity (DUNE).
- δ_{CP}, θ_{23}, Δm^2_{32} best-fit biases (DUNE).
- Effect on δ_{CP}, θ_{23}, Δm^2_{32} measurement resolution (DUNE).
- Effect on θ_{ee}, $\theta_{e\mu}$ limits (SBN).

(*) Parameter correlations make this tricky. Running tests to establish the most robust statistical procedure.

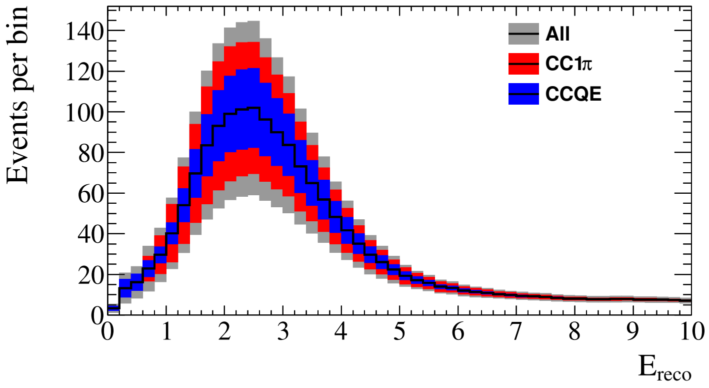
Effects of uncertainties on FD event spectra

Effect of CC0π and CC1π (focus of current GENIE tuning exercises) full prior error on the FD oscillation analysis samples:

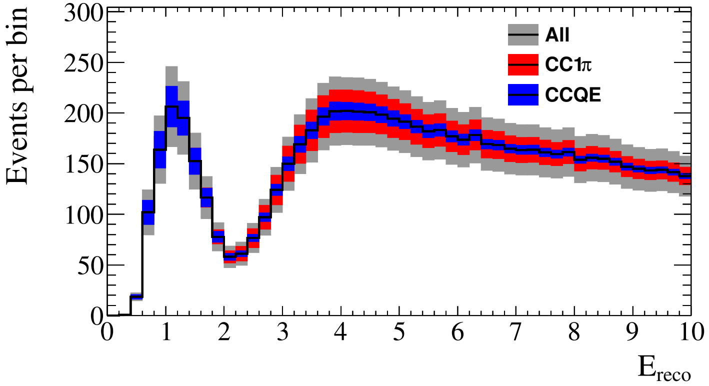
FHC, ν_μ CC-like



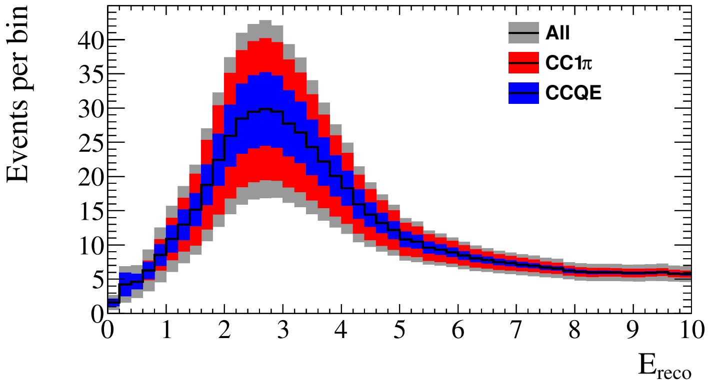
FHC, ν_e CC-like



RHC, $\bar{\nu}_\mu$ CC-like



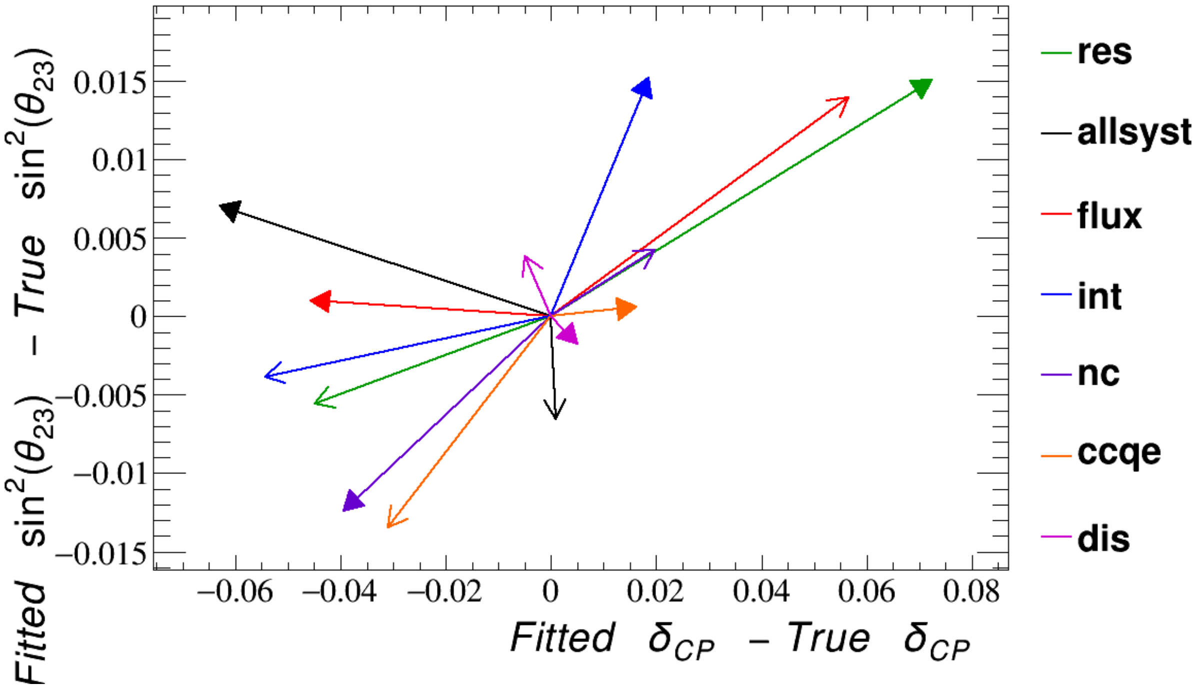
RHC, $\bar{\nu}_e$ CC-like



Oscillation parameter bias

What is the effect of a group of syst. parameters on $(\delta_{CP}, \theta_{23})$ determination?

- Fit an Asimov toy-expt using the nominal MC.
- Fit two Asimov toy-expts using MC with a systematic parameter tweaked by $\pm 1\sigma$.
- Let all systematic parameters can to float in the fit to try to compensate.
- Study shifts in $(\delta_{CP}, \theta_{23})$ best-fit values.



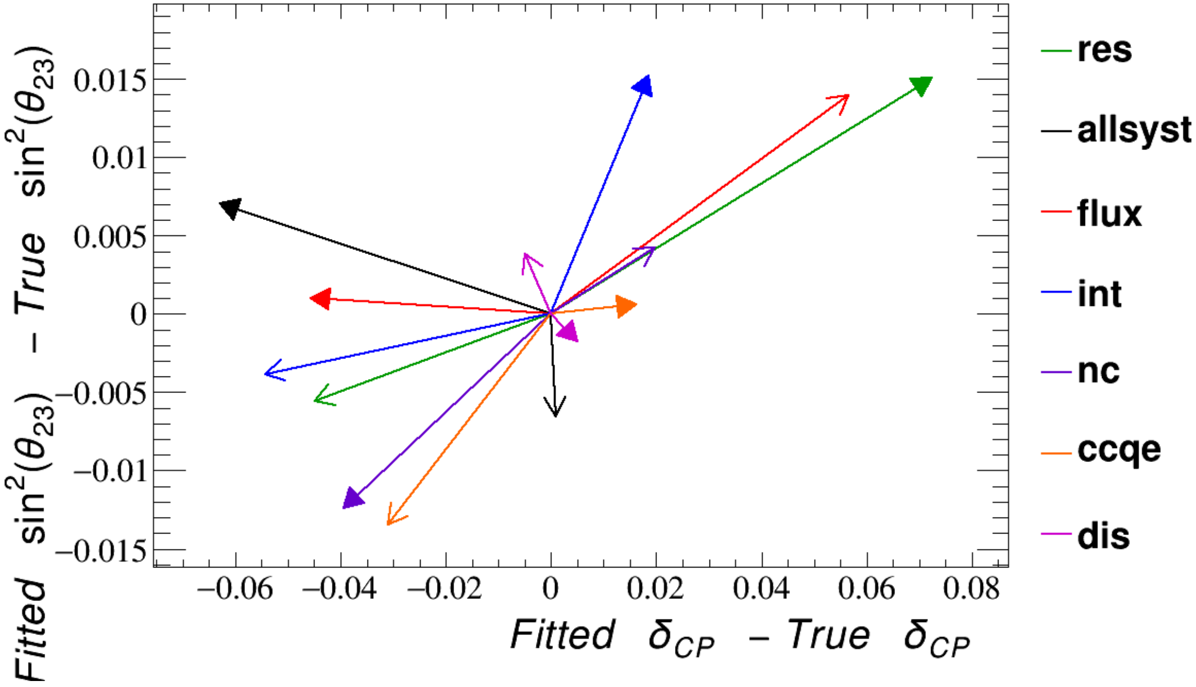
- True $d_{CP} = 0$
- True $sin^2\theta_{23} = 0.514$

- Full arrow: $+1\ \sigma$
- Line arrow: -1 σ

DUNE-like expt.

890 kt·MW·yr

Oscillation parameter bias



- True $d_{CP} = -\frac{\pi}{2}$
- True $sin^2\theta_{23} = 0.514$

- Full arrow: $+1\ \sigma$
- Line arrow: $-1\ \sigma$

DUNE-like expt.

890 kt·MW·yr

Summary

- A lot of interesting ongoing work!
- Recent GENIE releases with several new model implementations.
  - v2.12 released this week
- Ongoing work to characterize new comprehensive GENIE model configurations using a vast array of data.
  - v3.0.0 with new default model to be relesed in the next few months.
- Fruitful collaborations (GENIE/Professor and GENIE/VALOR)
  - Parameter tuning for GENIE v4 (using Professor)
  - Comprehensive characterization of the effects of GENIE uncertainties on accelerator LBL and SBL experiments (using VALOR)
- We're aiming to show several new results at NuINT17.

Supplementary slides

The GENIE **suite of products**

- **Generator**:
  1. a modern framework for implementing neutrino event generators,
  2. a well-understood and known comprehensive physics model,
  3. tools to support a systematic analysis of the GENIE physics model, and
  4. tools to support neutrino interaction simulation for realistic experimental setups (flux and geometry drivers, event generation apps)
- **Comparisons**:
  1. extensive curated data archives
     - neutrino, charged-lepton and hadron scattering data
  2. software to produce a data/MC comparisons,
  3. a common framework that facilitates error analysis and tuning, and
  4. event reweighting and tuning hooks
- **Tuning**:
  1. an event generator tuning framework, and
  2. several apps implementing the GENIE tuning strategy.

VALOR fit: Parameter elimination

The likelihood ratio $\lambda(\vec{\theta}; \vec{f})$ built for the **VALOR/SBN** **multi-detector**, **multi-channel**, **joint oscillation and systematics constraint fit** will be a function of $\mathbf{O(2 \times 10^3)}$ interesting physics and nuisance parameters!

Both **marginalization** and **profiling** are used for parameter elimination.

- Most parameters $\vec{f'}$ (any subset of $(\vec{\theta}; \vec{f})$) would have a **well-established prior** $\pi(\vec{f'})$ (from hadron-production measurements, external neutrino cross-section measurements, electron scattering data, calibration data etc.).
  - Eliminated by marginalization. The **marginal likelihood** $\lambda_{marg}(\vec{\theta'})$ is:

$$\lambda_{marg}(\vec{\theta'}) = \int \lambda(\vec{\theta'}; \vec{f'}) \pi(\vec{f'}) d\vec{f'}$$

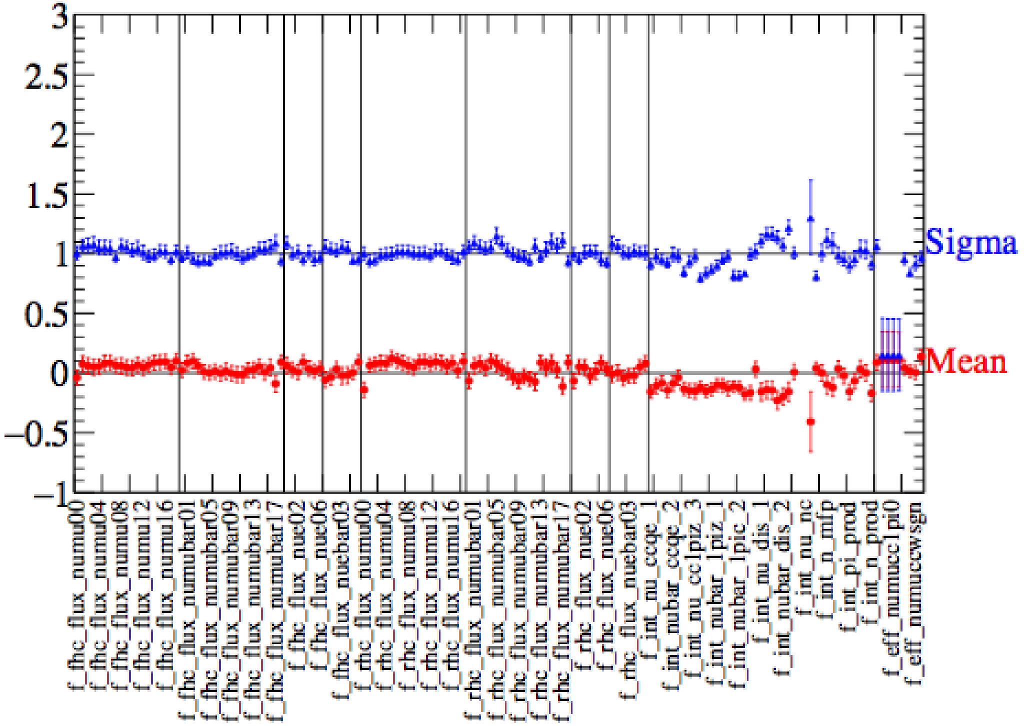
- For other parameters ($\theta_{\mu e}$, $\theta_{\mu\mu}$, Δm^2_{41}) use of a prior may be undesirable and an uninformative prior may be problematic: Flat priors in $\theta_{\mu e}$, $sin\theta_{\mu e}$, $sin^2\theta_{\mu e}$, $sin^2 2\theta_{\mu e}$, would yield different results!
  - Eliminated by profiling (free-floating parameters included in the fit).

VALOR fit: Parameter estimation

To extremize the test-statistic VALOR uses the **MINUIT/MIGRAD** algorithm.

Several other methods available within VALOR via a **VALOR/GSL** interface:
Simulated annealing, Levemberg-Marquardt, Fletcher-Reeves conjugate gradient, Polak-Ribiere conjugate gradient and Vector Broyden-Fletcher-Goldfarb-Shanno.

Pulls from a O(150) parameter fit.



$$pull = \frac{f_{bf} - f_0}{\sqrt{\sigma^2_{prior} - \sigma^2_{post-fit}}}$$

- f_{bf}: best-fit value of systematic parameter f
- f_0: nominal value
- σ_{prior}: prior error on f
- $\sigma_{post-fit}$: fit (MIGRAD) error on f

VALOR fit: Interval estimation

After the fit is completed, the full χ^2 $(= -2\lambda(\vec{\theta'}))$ distribution is shifted with respect to $\chi^2(\vec{\theta'}_{bf})$:

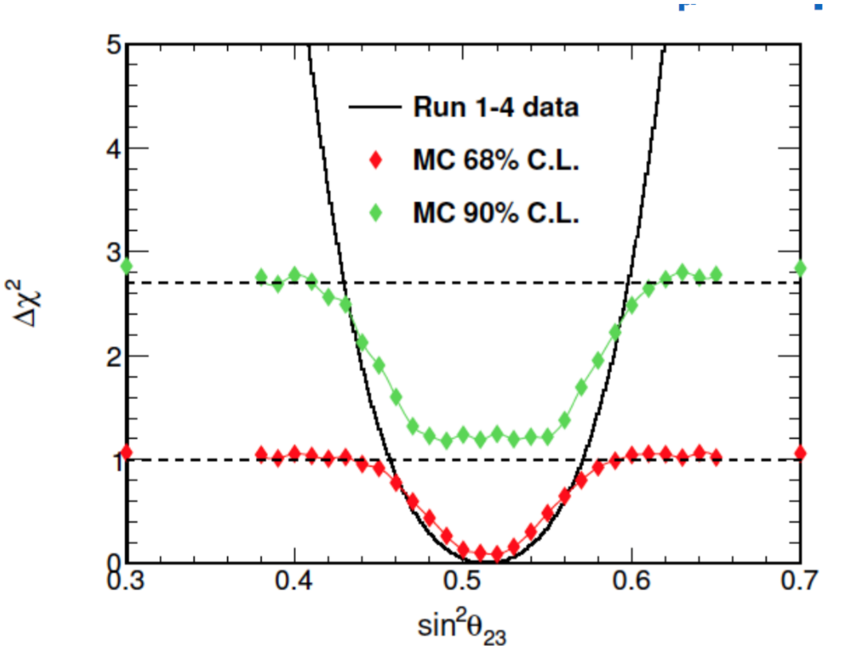
$$\Delta\chi^2(\vec{\theta'}) = \chi^2(\vec{\theta'}) - \chi^2(\vec{\theta'}_{bf})$$

Confidence intervals at X% C.L. are set on $\Delta\chi^2(\vec{\theta'})$.

$$\Delta\chi^2(\vec{\theta'}) < \Delta\chi^2_{crit;X}$$

where $\Delta\chi^2_{crit;X}$ the corresponding critical value.

In the Gaussian approximation constant values of $\Delta\chi^2_{crit}$ can be used. Usually this approximation is not reliable and the Feldman - Cousins / Cousins - Highland method is used instead.



Example from T2K Run 1-4 disappearance analysis. Comparison of $\Delta\chi^2_{crit;X}$ values from the FC method with the ones obtained under the Gaussian approximation.

The VALOR group has developed several tools to probe the severity of coverage problems. If needed, it has the CPU muscle and efficient methods to compute corrections.

- O(0.5 million CPU*days) were spent since 2010 on oscillation analyses, mainly at RAL.

Detector systematics in the VALOR DUNE & SBN fits

- Allow **one detector systematic parameter for each multi-dimensional reconstructed kinematical bin of each sample** (corresponding to any given detector, beam configuration and topological selection).
- **Correlations between parameters also taken into account.**
- **Likely that O(10^3) detector systematics shall be considered** (with a corresponding O($10^3 \times 10^3$ input covariance matrix).
- We expect this to be reasonably well-manageable within VALOR
  - Parameter elimination via **marginalization** (MCMC integration)
- Leptonic and hadronic energy scale errors causing migration of events between bins will be treated on their own.