GENIE v3.0.0

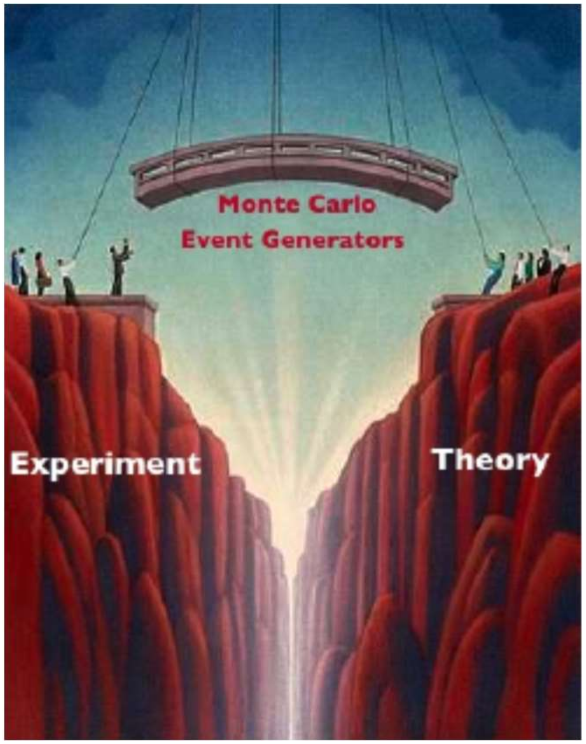
Steve Dytman, Univ. of Pittsburgh

Major physics release
1 November, 2018

- collect recent models + new models
- new structure for simpler simulation
- new tuning framework/results
- many recent plots, some same as NUINT
- look ahead to v3.2, v4.0

GENIE

- Tries to be event generator for any experiment for νA beam 10 MeV-10 TeV
- Used by almost all experiments, especially FNAL
  - Geometry
  - Reweighting – systematic errors
  - Physics models
- Service to the HEP community
- Needs have greatly increased as experiments become more advanced



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

GENIE Collaboration

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

[Faculty, Postdocs, PhD students]

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

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

Core GENIE mission - from GENIE by-law

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

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

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

GENIE contributors

- GENIE has grown as the field grows (required!!) since 2013
  - New postdocs – all 5 now in the group work at FNAL (10-50% effort)
  - New group at FNAL joins core groups in US and UK
  - New contributing groups – Dubna (Moscow)
  - New contributors – theorists more willing to work with us, experiments more willing to provide people to work with us
    - **33 contributors to code since v2.8 (see backup)**
  - Large enough? stable? Community decides
- Developers Workshop (FNAL, March, 2015) brings new models – Valencia MEC, SingleK…
- FNAL group has provided validation framework
- Liverpool group has built tuning framework (private)
- Better physics in a more professional environment

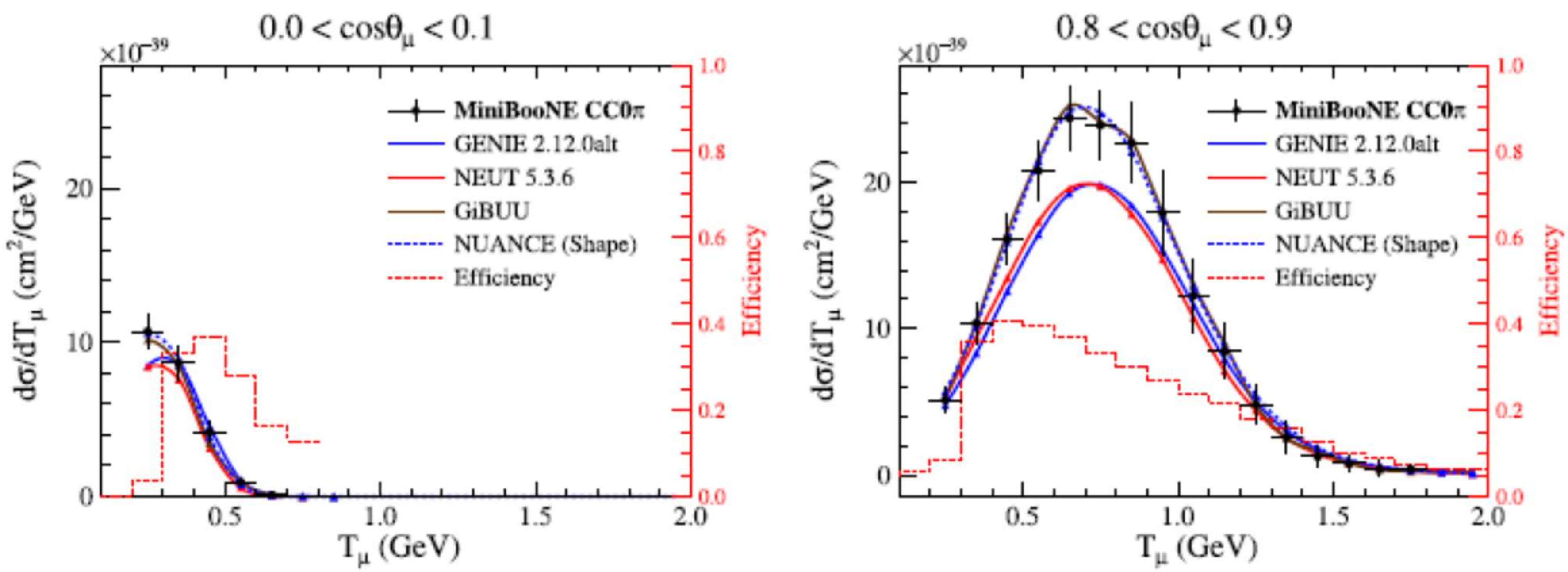
Comparison of generator models - 2017

Model/generator	GENIE	NuWro	NEUT
QE	Lwlyn-Smith Nieves, Eff MA	Lwlyn-Smith RPA	Lwlyn-Smith Eff RPA
Nuclear model	RFG, LFG, Effective spectral function	RFG, LFG, spectral function	RFG, LFG, spectral function
MEC	Valencia Empirical	Valencia Marteau	Valencia
Delta model	Rein-Sehgal (updated) Berger-Sehgal	Home-grown, great	Rein-Sehgal (update) Berger-Sehgal
Coherent	Rein-Sehgal(corrected) Berger-Sehgal	Rein-Sehgal Berger-Sehgal	Rein-Sehgal Berger-Sehgal
FSI	Schematic Cascade (med corr)	Cascade(med corr)	Cascade(med corr)

- Differences more in detail than fundamental (physics)
- GENIE has larger goals, therefore slower

Event generator world

- NEUT, NuWro, and GENIE are all significant contributors
- Physics models now very similar – similar upgrades
- Reviewed in Tensions wkshp paper – Phys Repts (2018)
  - Comparison with MiniBooNE CC0π data below
  - GENIE v2.12.0alt is in v3.0 as G18_10a



GENIE v3.0.0

- Collects models into Comprehensive Model Configurations (CMC), I prefer to call them model sets
  - Most compatible physics (too many energy scales to be truly compatible)
  - Options to match energy scale of each experiment
  - Models are as good as data, theory contained
  - Not done, new contributions essential (data, *tunes*, theory)
- Presents new tunes
  - Only deuterium data for now, more later
  - Compatible with each model set (e.g. resonant model)
  - Sometimes expanded resonance region (larger W_{cut})
  - Provide full error analysis for each

Model sets

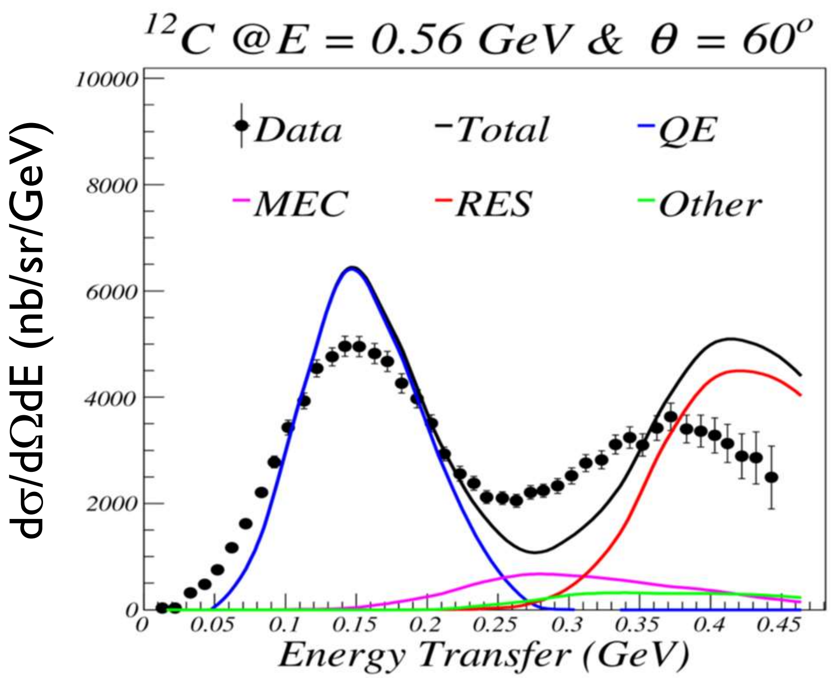
- Historical default (not supported)
  - **G00_00a** with hA, no MEC, **G00_00b** with empirical MEC
  - RFG, Llewyllen-Smith, Rein-Sehgal (not original)
- Improved historical default
  - **G18_01a/b** with hA2018/hN2018. better basic (e.g. coherent)
  - RFG, Llewyllen-Smith, Rein-Sehgal (not original), empirical MEC
- Improved pion production
  - **G18_02a/b** with hA2018/hN2018
  - Includes Berger-Sehgal resonance and coherent, updated axial FF
- Improved quasielastic/ nuclear model/ axial FF
  - All have Local Fermi Gas, Nieves QE, Valencia MEC
  - **G18_10a/b** has dipole FF, **G18_10i/j** has z-expansion FF

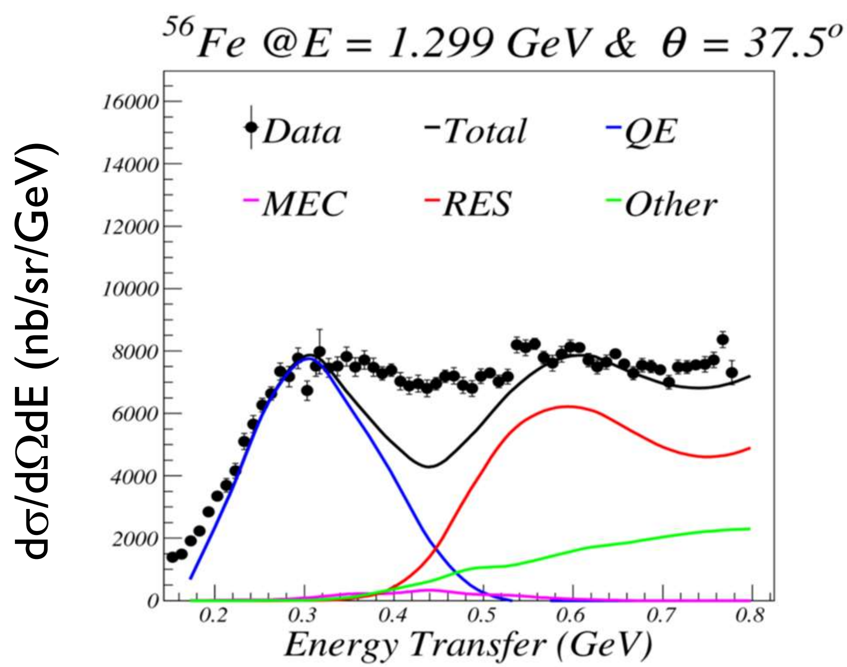
Getting code

- After many successful years on HEPForge, we migrate
- Public versions now on GitHub, can get .zip or .tar.gz file for any release at https://github.com/GENIE-MC/zzz
  - zzz=Generator/releases to get code
  - zzz=Reweight to get code
  - zzz=PhysicsAndUserManual to get instructions (private temporarily)
  - Only requirement is that you are registered with GitHub
  - http://genie-mc.org is largely updated, has most recent user manual
- Tunes will be available soon
- Comparisons results will be available soon
- Long-time users will see a re-organization of files, hopefully improved

Electron scattering – vector int, nuclear model

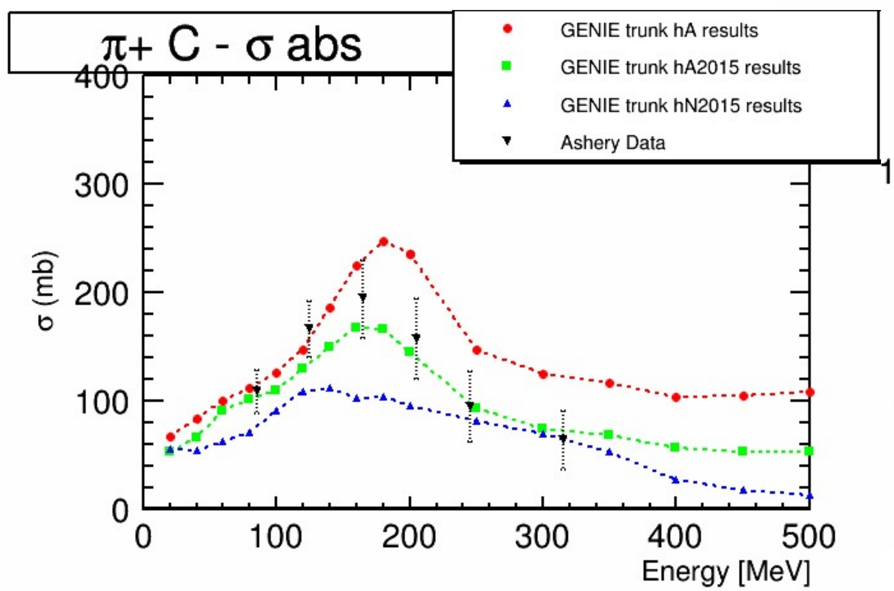
- Significant advances in v3.0
  - Bug fixes, better 2p2h, resonance models
- Comparisons with GENIE in elec scat mode **G18_10i**
  - QE has no medium corrections, Nieves model only for νA
- Good agreement, but more tuning required

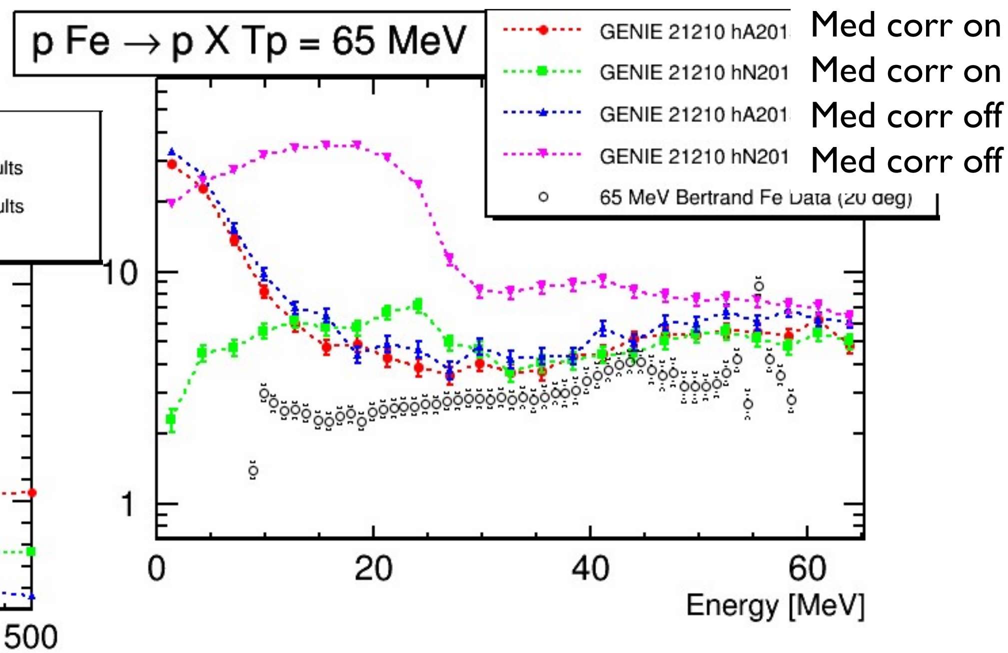




Final State Interaction (FSI) advances

- hA2018 is latest version of schematic model
- Recent emphasis on medium corr, low energy nucleons
- hN2018 is new intranuclear cascade (INC) model with same nuclear medium corrections (π, N) as NuWro





Summary of models

- Total of 10 model sets *per deuterium tune*
- Each callable via 1 new switch --tune G18_10a_00_000
- year model set param set data set
- Splines must be compatible with chosen data set
- For low energy experiments (dominated by QE) G18_02x (LS/emp MEC/RFG) vs. G18_10x (Valencia/LFG) interesting
  - Valencia QE has very good description of MiniBooNE QE
- For higher energy experiments (dominated by pion production) G18_01a (RS/hA) vs. G18_02b (BS/hN) interesting
  - Rein-Sehgal/Berger-Sehgal have updated resonance parameters
  - Berger-Sehgal coherent has improved pion scattering model

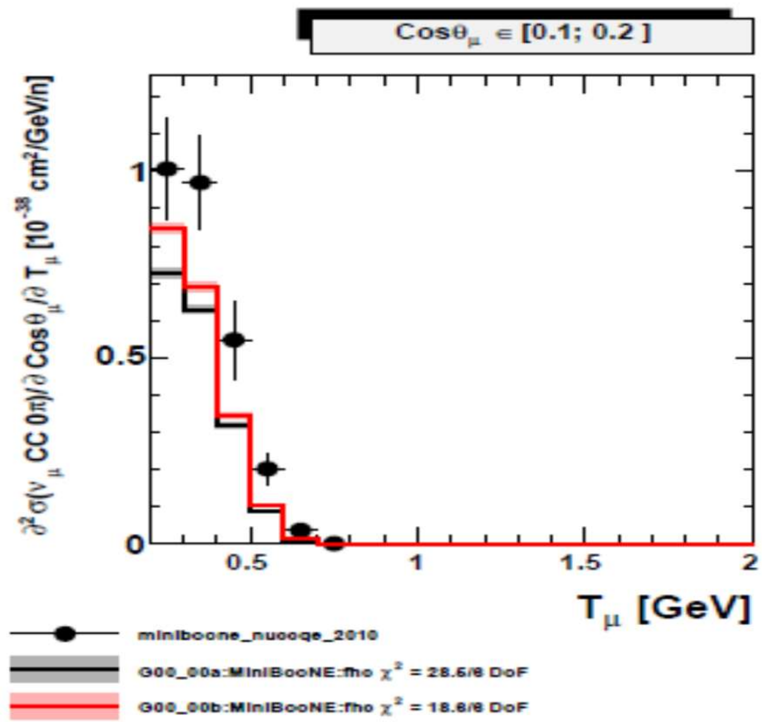
Additional new models now in v3.0.0

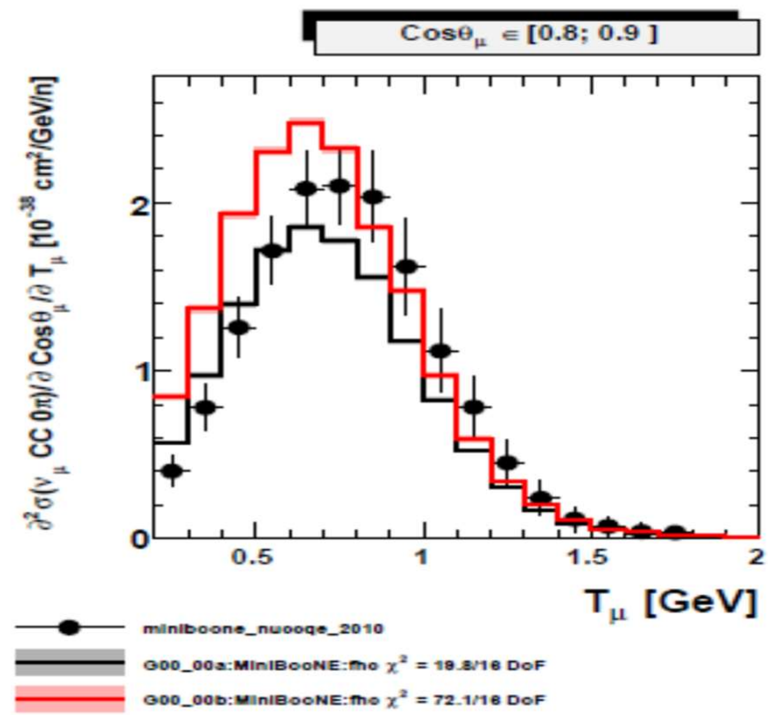
- Single K^+ production
- Diffractive pion production with neutrinos
- Boosted Dark Matter (low energy exotic particle)
- $n\bar{n}$ annihilation
- Quasielastic hyperon production (Pais)
- Alvarez-Ruso coherent model (low energy only)
- Smith-Moniz quasielastic model
- Effective-Ma QE model
- Effective spectral function (QE+2p2h)

CC ν_μ Quasielastic

MiniBooNE CC0π (2010) need for 2p2h (MEC)

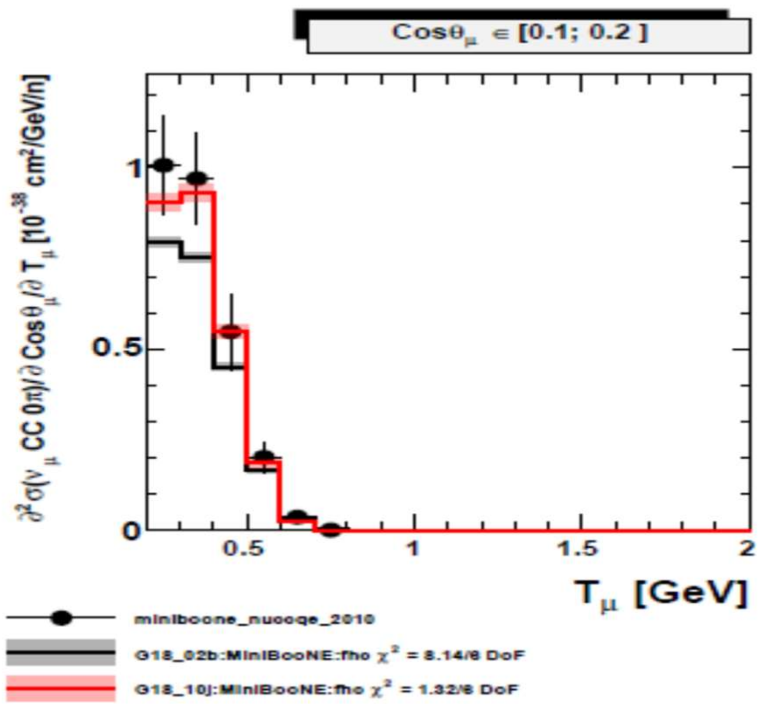
- CC0π has become standard - needs true QE, pion abs, and 2p2h
- MiniBooNE published both true CCQE and CC0π, we use latter
- GENIE has had these for a few years, 2p2h increases cross section at all angles. Here, **G00_00b** is a little better than **G00_00a**.

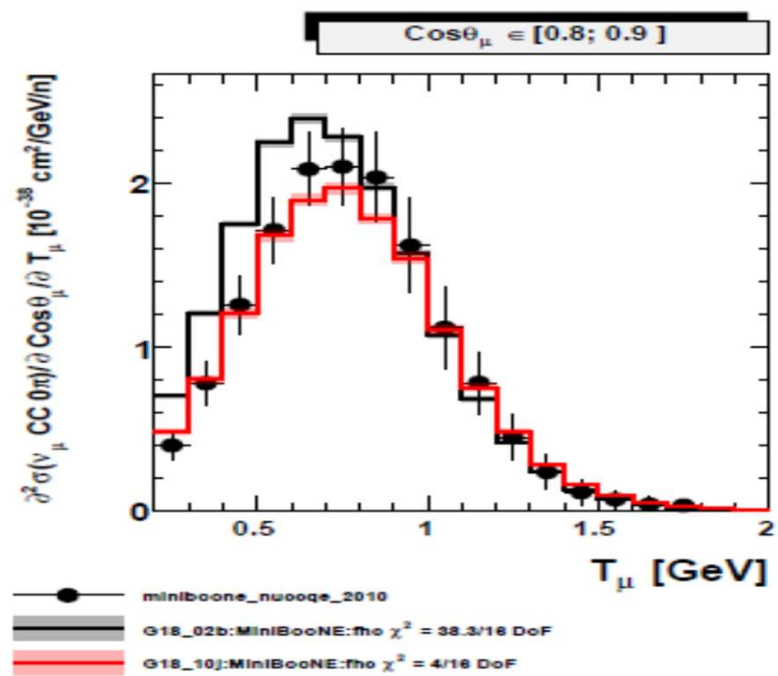




Modern calculation has better agreement

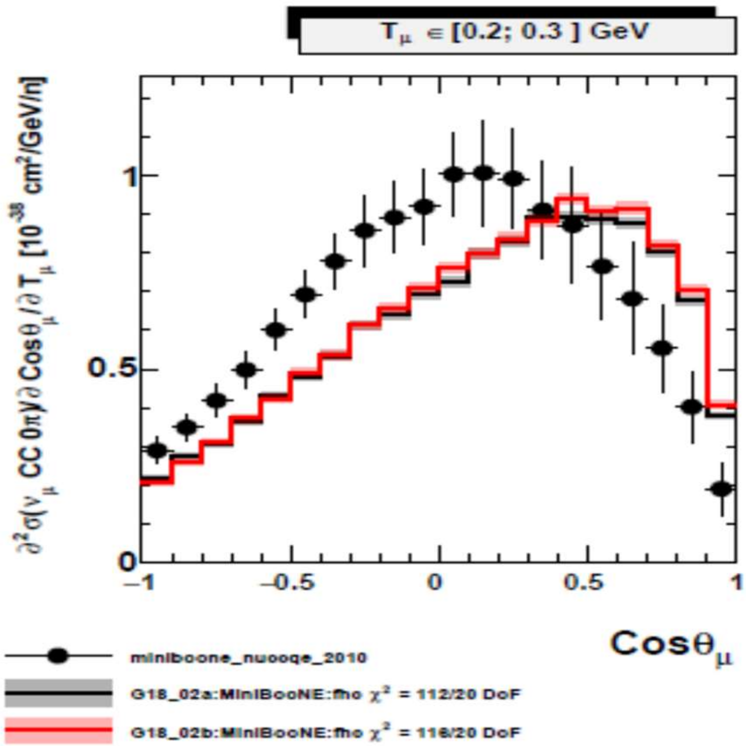
- **G18_10j** has full Valencia CCQE – QE with RPA/Coulomb, 2p2h with local Fermi gas (LFG) nuclear model
- Compared with **G18_02b** – Lwlyn-Smith, Empirical MEC

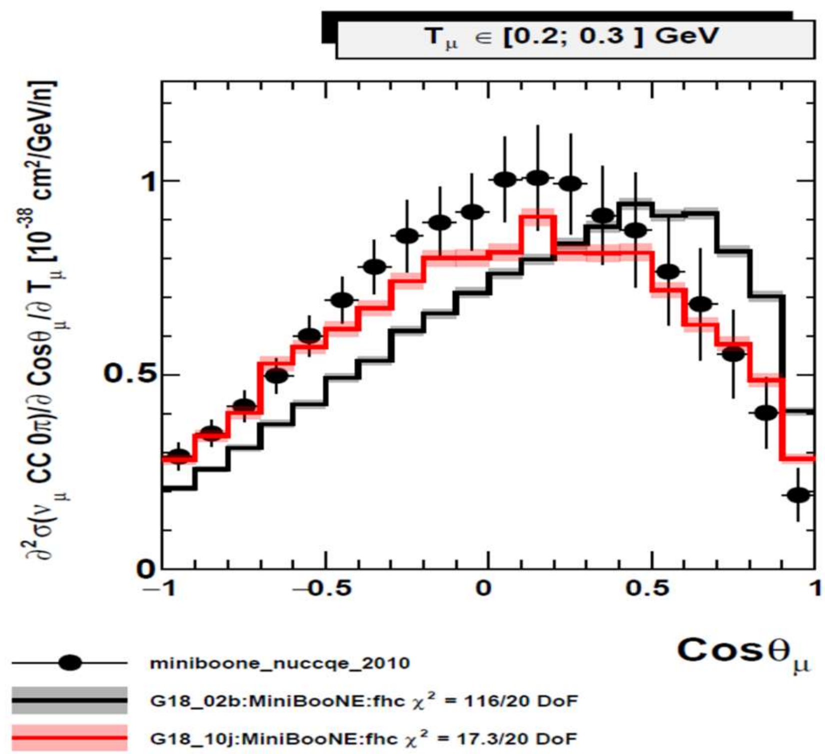




More detail for MiniBooNE CC0π

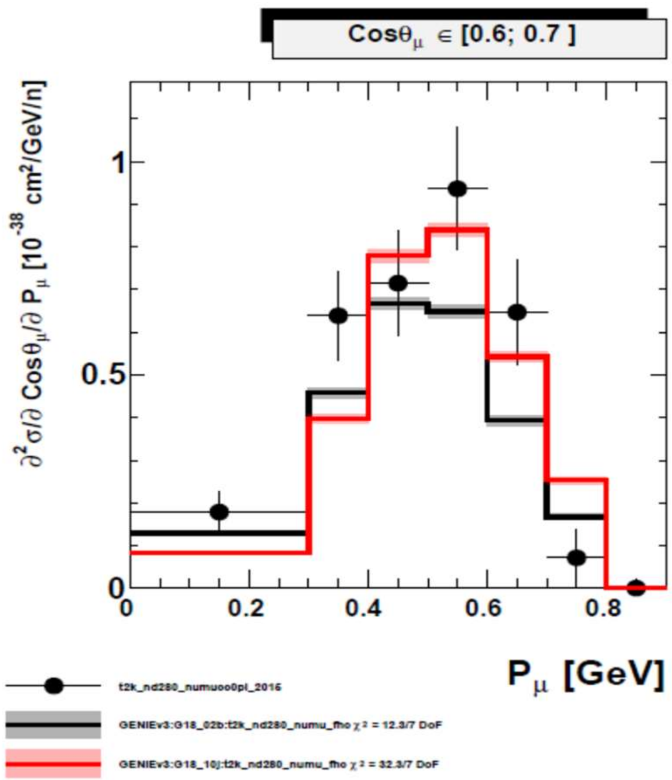
- Left compare role of FSI (hA2018 vs. hN2018) with LS
  - Angular distribution for low T_μ is not right (data or theory?)
- Right plot shows LS+Empirical MEC vs. Nieves QE+MEC
  - Looks like problem was with theory not designed for low energy

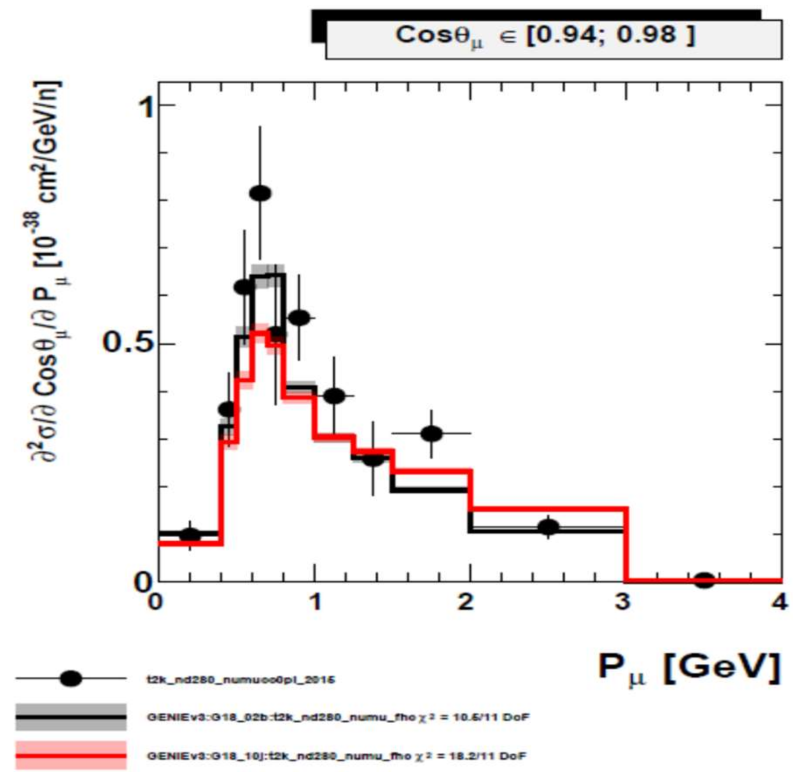




T2K CC0π (2015)

- Well understood kinematics, systematic errors
- 02b (LS/hN) vs. 10j (Nieves/hN)
- 02b has better overall χ^2, 159 vs. 332 for 67 dof

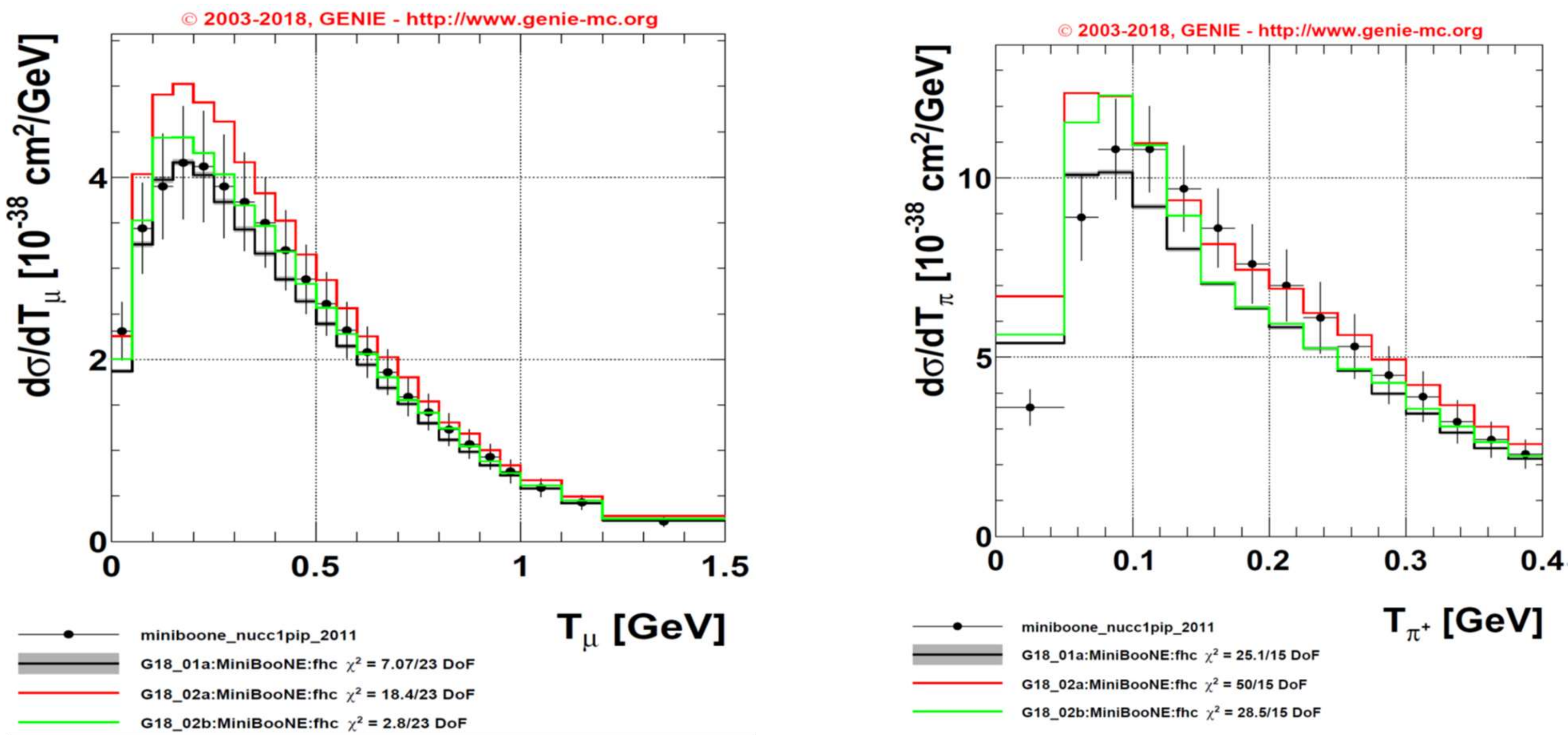




CC ν_μ Resonances

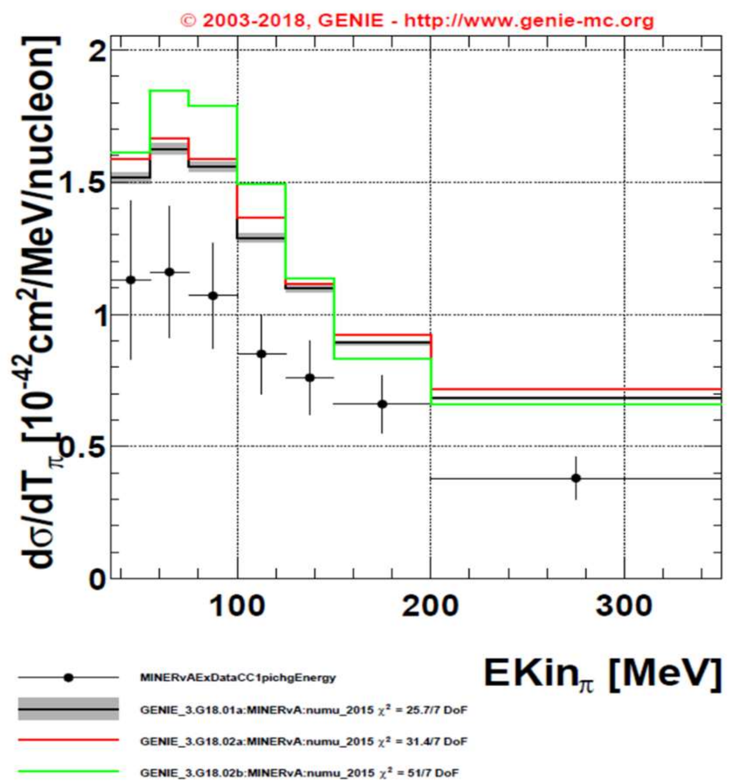
MiniBooNE ν_μ CC1π^+ <E_ν>~1 GeV

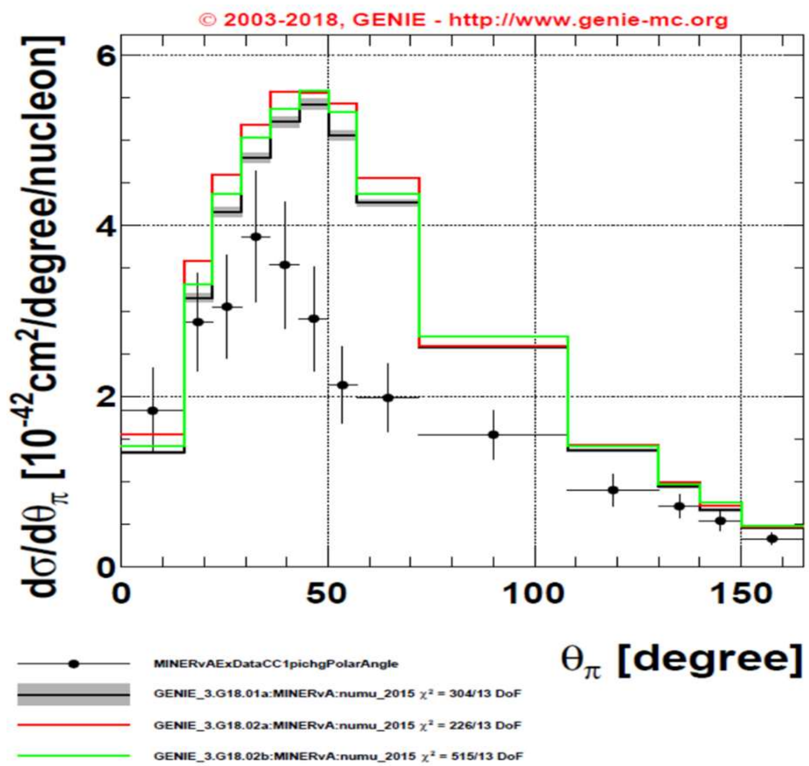
- Show 2 of many distributions
- **01a** (R-S, hA) vs. **02a** (B-S, hA) vs. **02b** (B-S, hN)
- 02b most advanced theory, gets details best



MINERvA ν_μ CC1$\pi^\pm$ <E_ν>3.6 GeV

- Energy dependence has been tricky for many (NuWro)
- Indeed, all calculations are larger than data
- 02b has different shape than others

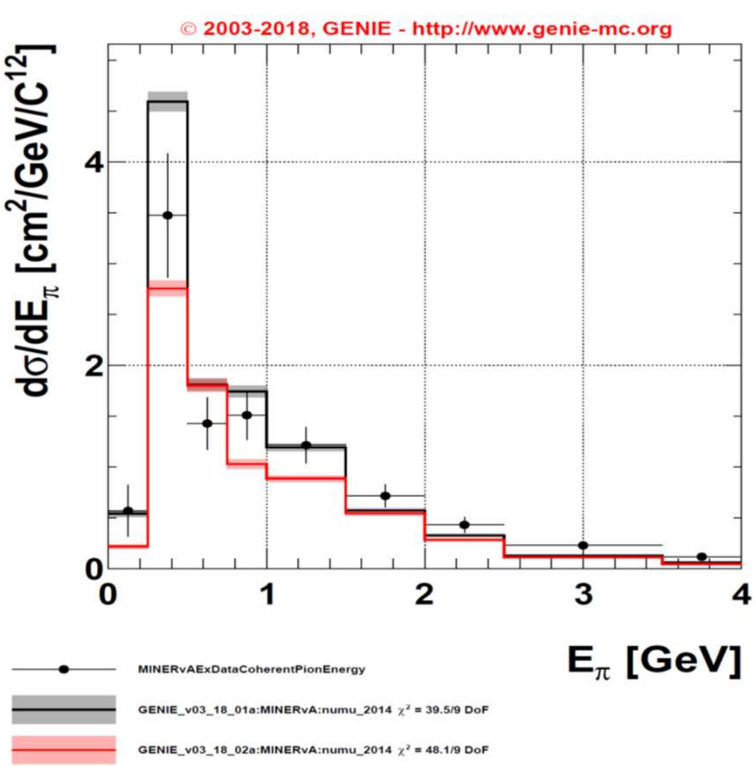


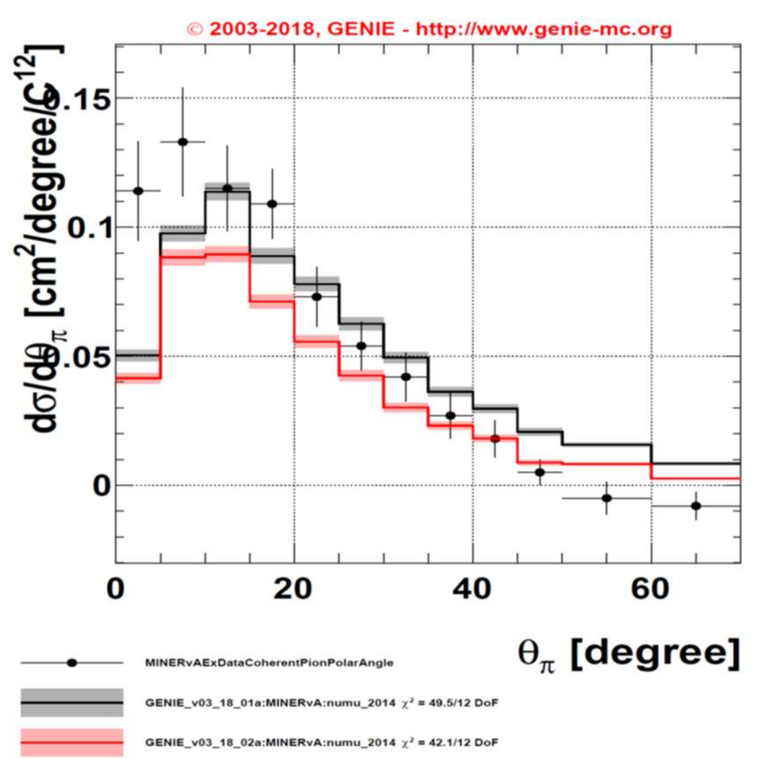


CC ν_μ Coherent pion

MINERvA ν coherent (2015)

- π^+ energy and angle with $\langle E_\nu \rangle = 4.0$ GeV
- Compares Berger-Sehgal (**G18_02a**) with updated Rein-Sehgal (**G18_01a**)

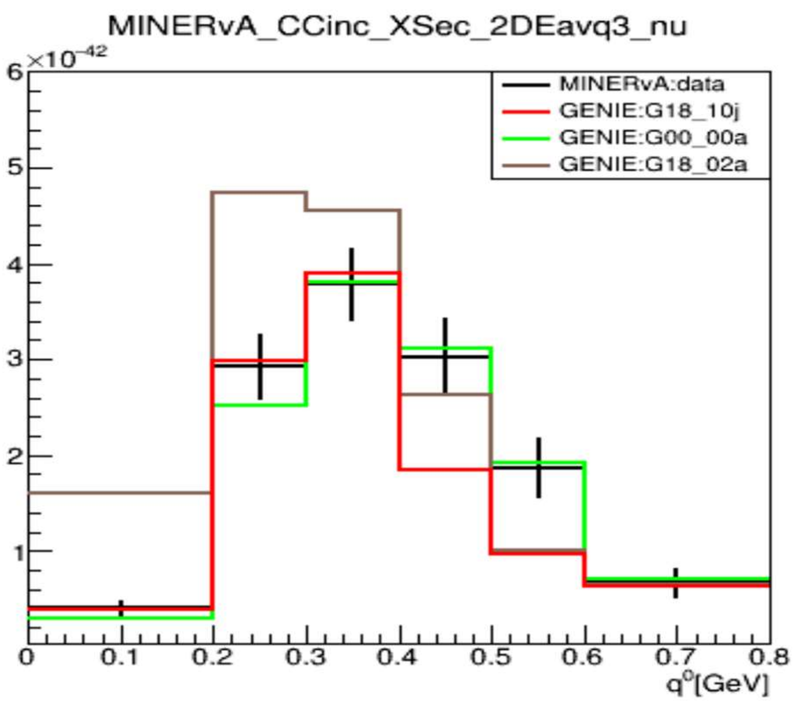


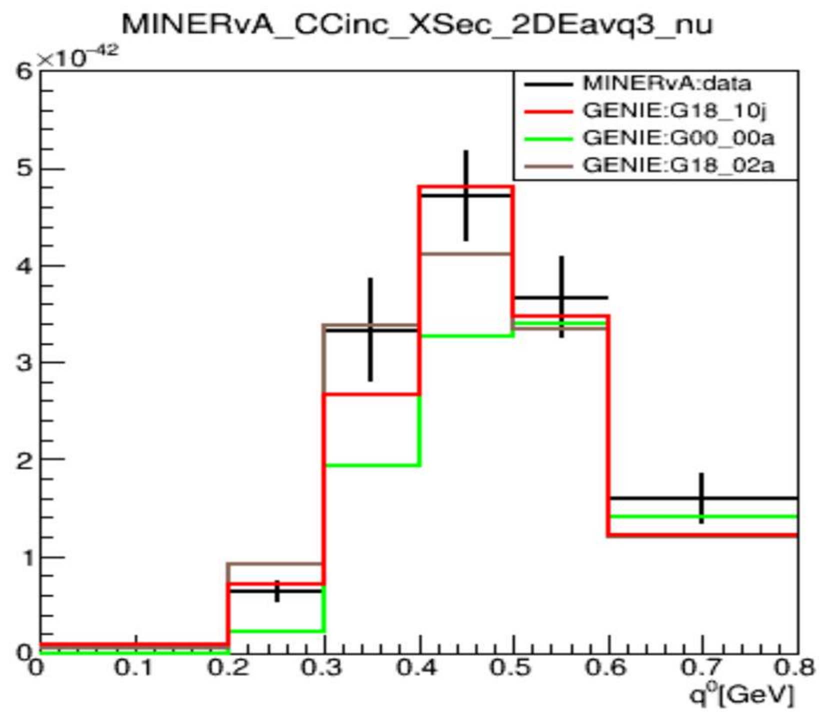


CC ν_μ Inclusive

MINERvA CC Inclusive (2016) *[NUISANCE]*

- q0 (ν) dependence in 8 q3 ($|\vec{q}|$) bins 0.2→0.3, 0.5→0.6 GeV/c
- If single beam energy, would see separate QE and Δ peaks
- "Evidence for enhanced 2p2h", no obvious need seen here
- G18_10j (Valencia QE, Berger-Sehgal) has best agreement





Tuning details - Professor

- Professor is used in many places, e.g. Pythia, for *multi-parameter tuning* (~20 params, improved use of *Minuit*)
- Uses brute force, build solutions for all variations of selected parameter within given bounds on a finite grid
- Find chisquare minima in each parameter
- *Use stored solutions to estimate errors on each parameter*
- Can report full correlation matrix
- *Fit parameters not connected to reweighting in our version*
- Can include priors, nuisance parameters
- Nuisance remains an excellent public option

Details of deuterium tune (e.g. G18_02a)

- Use only ν & $\bar{\nu}$ deuterium data, including Wilkinson et al. improvements (BNL now close to ANL)
- Goal is to maintain CCQE fit and emphasize CCRES exclusive data

Parameter	Default value	Best tune value	
M_A^{RES} [GeV/c^2]	1.12	1.065 ± 0.025	
M_A^{QE} [GeV/c^2]	0.99	0.961 ± 0.031	
R-vp-m2	0.1	0.008 ± 0.00	Multiplicity parameters, e,g, R-vp-m2 is for νp, 2 pions
R-vp-m3	1	0.788 ± 0.20	
R-vn-m2	0.3	0.128 ± 0.021	
R-vn-m3	1	2.115 ± 0.57	
RES-XSecScale	1	0.878 ± 0.031	Relative normalization, RES vs. NONRES
DIS-XSecScale	1.032	1.019 ± 0.055	
W_{cut} [GeV]	1.7	1.928 ± 0.091	Boundary – RES vs. DIS

Priors applied

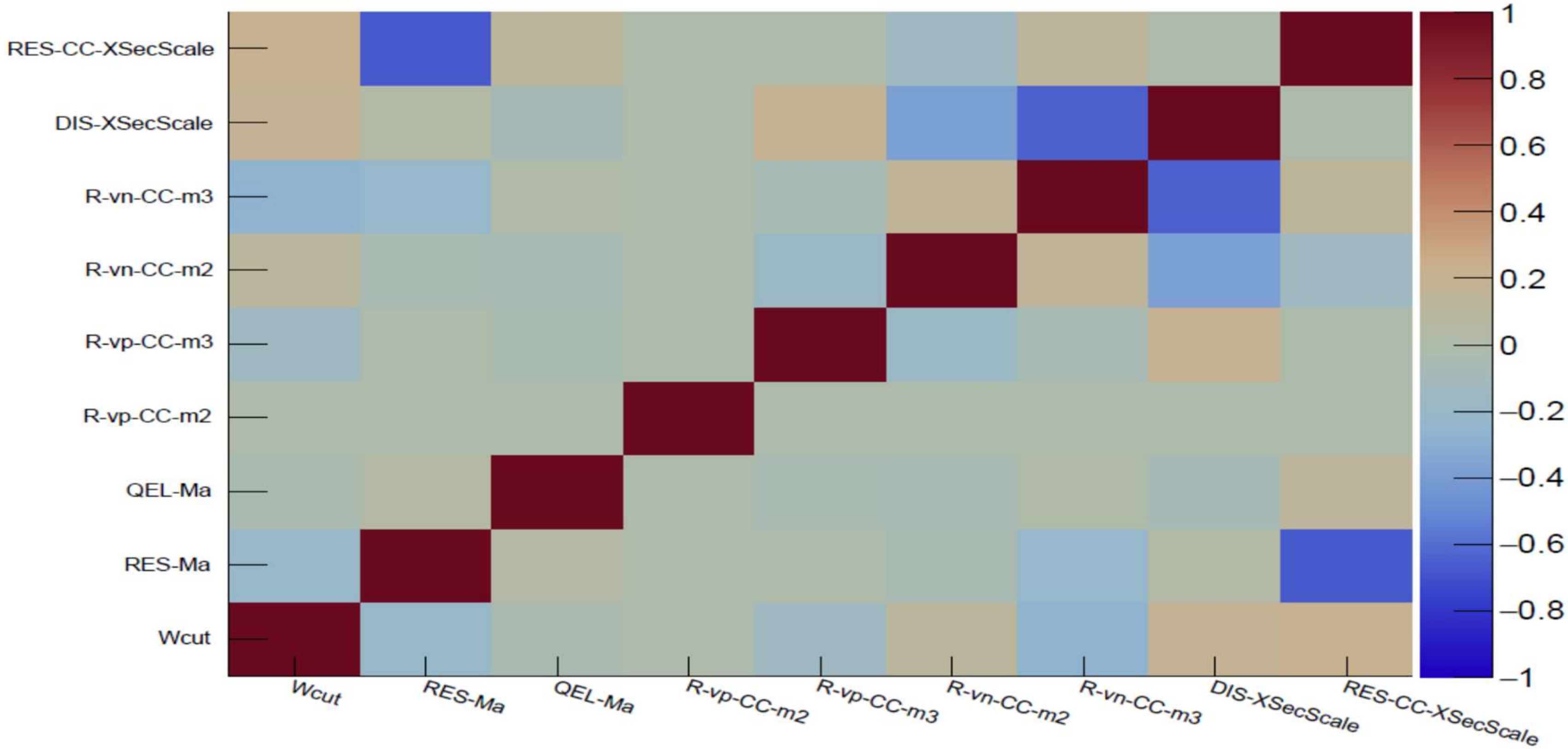
$M_A^{QE} = 0.89 \pm 0.044$ GeV/c^2, fit to just BEBC data [Eur. Phys. J. C (2008) 54]

$M_A^{RES} = 1.12 \pm 0.03$ GeV/c^2, [ArXiv:0606184]

DIS-XSecScale$= 1 \pm 0.05 \rightarrow$ Motivated by DIS high energy cross section values

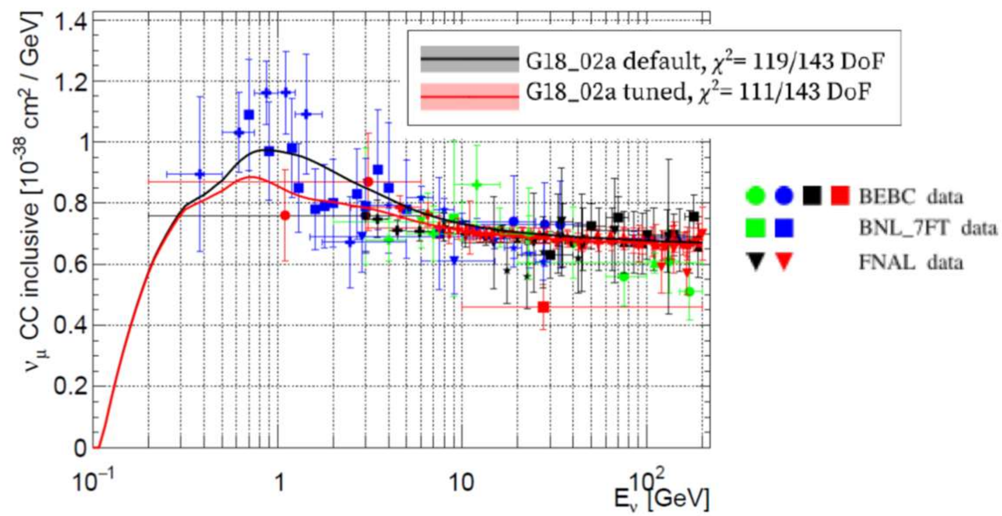
Correlation matrix

- Well understood
- Correlations mainly come from cross-section scale (e.g. RES-CC-XsecScale) vs. detailed param linked to scale (e.g. RES-Ma)

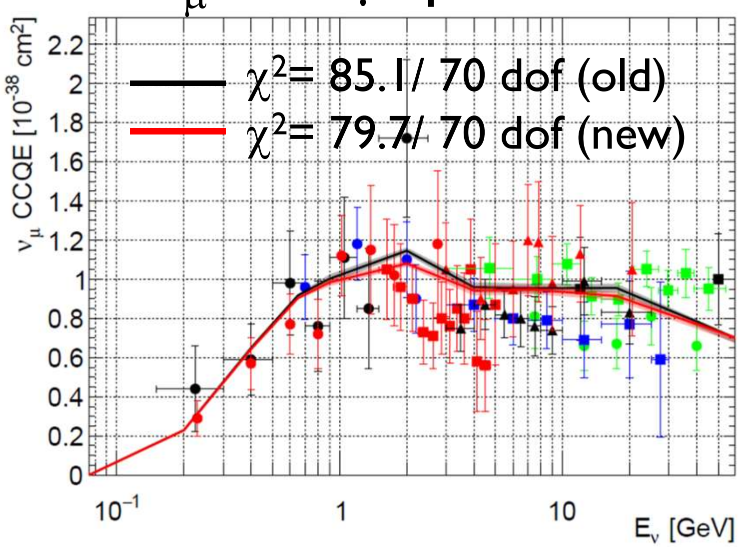


Compare previous and new fits - inclusive

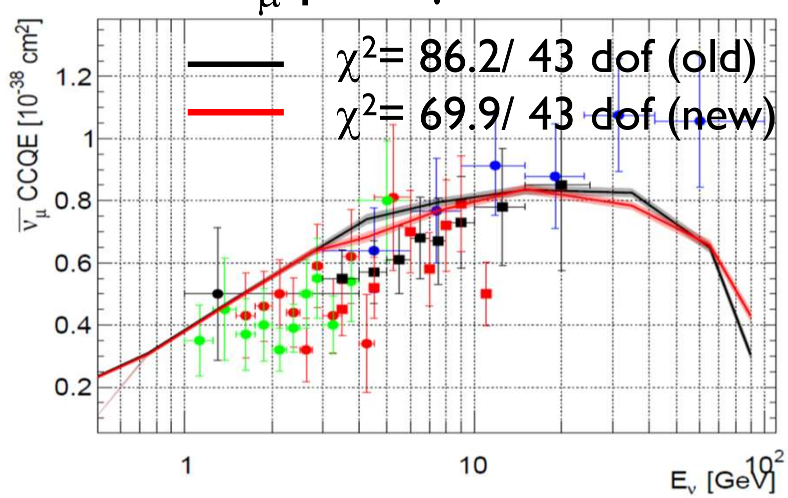
- Data has excellent PID, poor statistics, uncertain normalization
- Poor underpinning for an entire field



$\nu_\mu\, n \rightarrow \mu^-\, p$



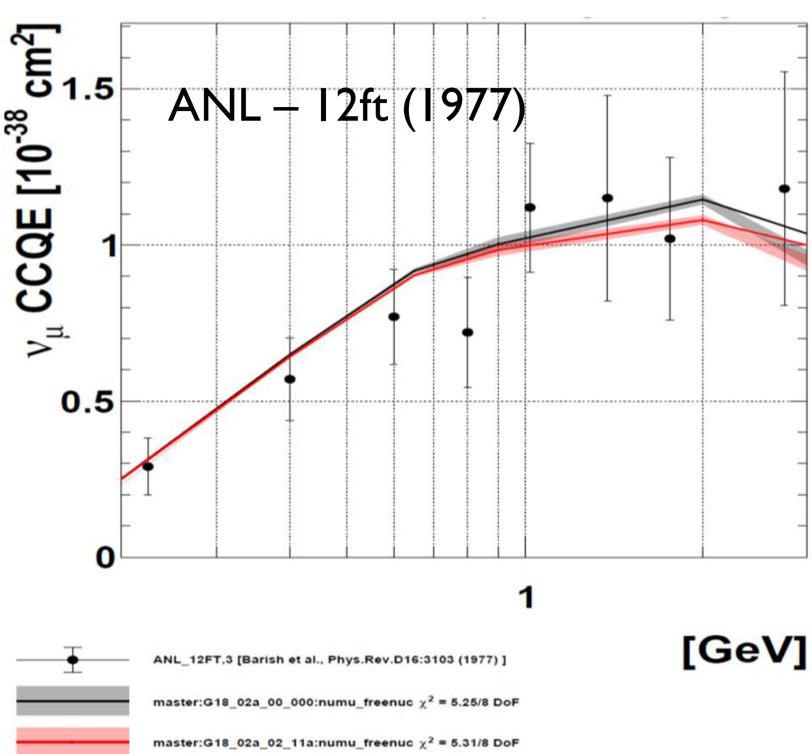
$\bar{\nu}_\mu\, p \rightarrow \mu^+\, n$



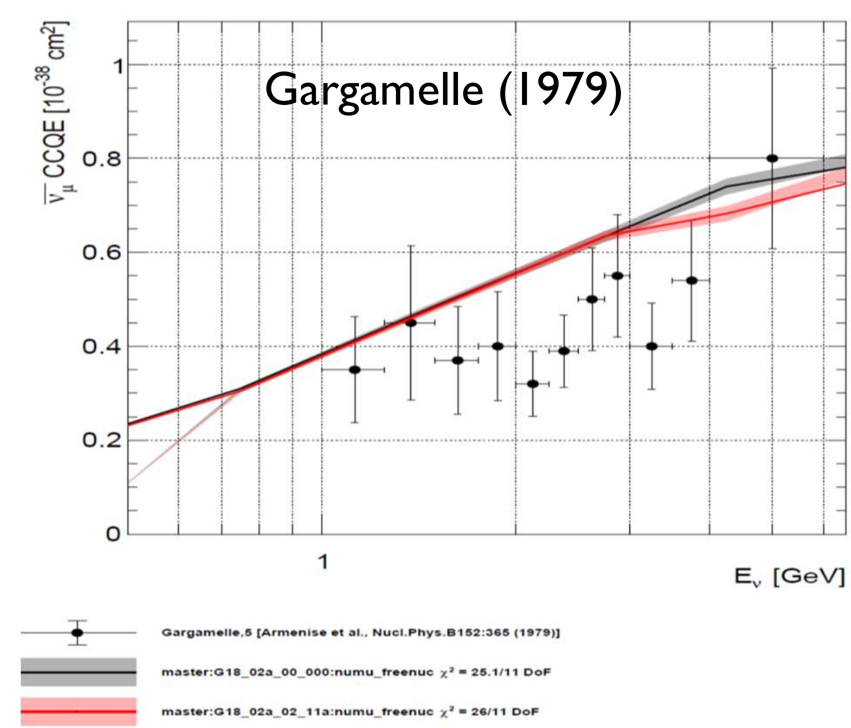
CCQE detail

- Representation of the CCQE data is unchanged

$\nu_\mu\, n \rightarrow \mu^-\, p$



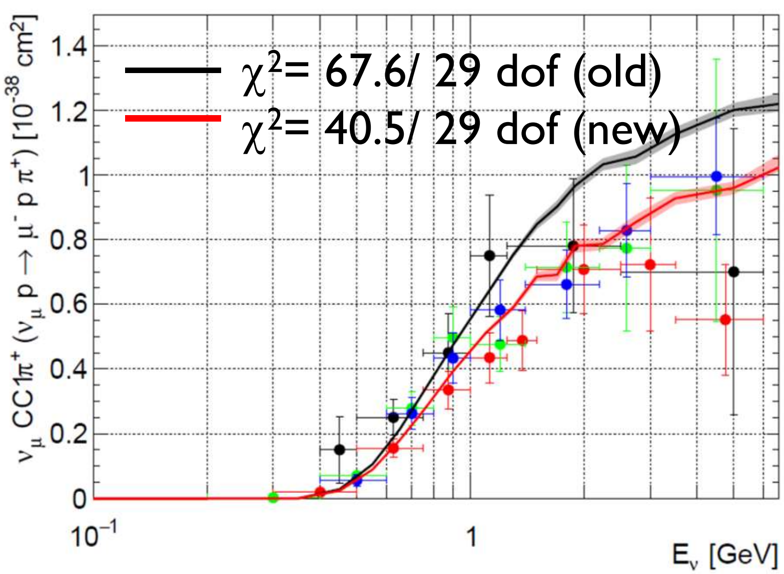
$\bar{\nu}_\mu\, p \rightarrow \mu^+\, n$



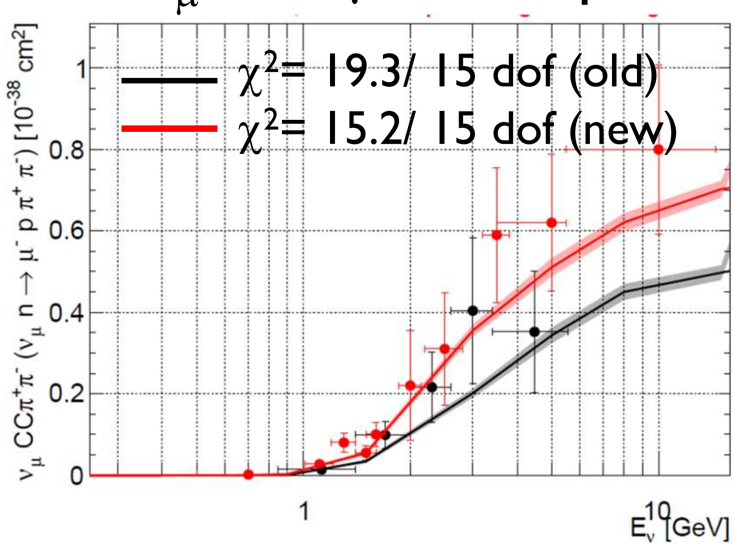
Compare previous and new fits - exclusive

- 1π production decreases (due to smaller BNL in part), 2π production increases
- Overall, result is ν_μ CCQE few% smaller, CCπ ~30% smaller

ν_μ p $\rightarrow$ μ^- π^+ p

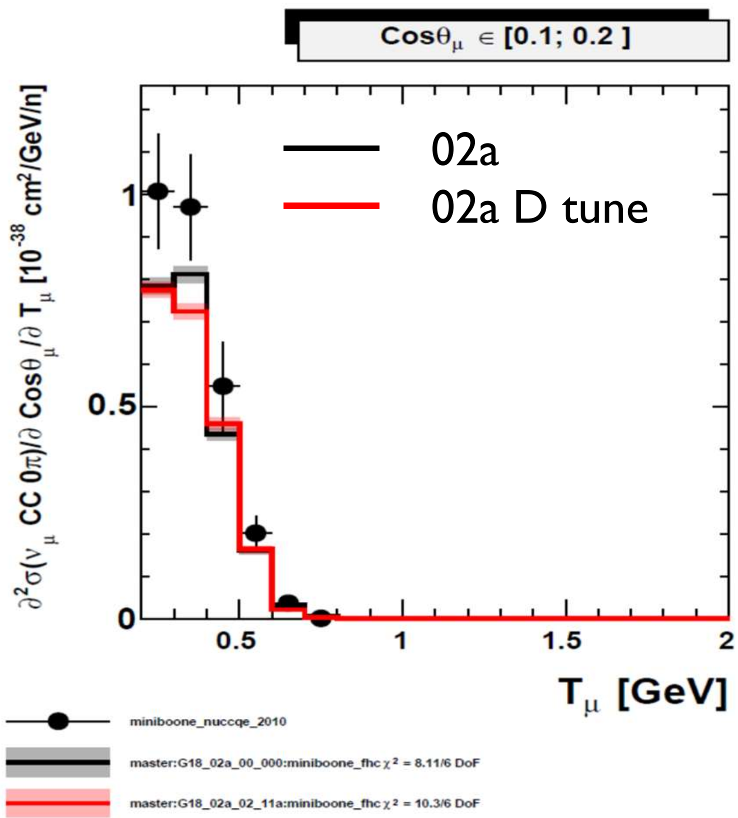


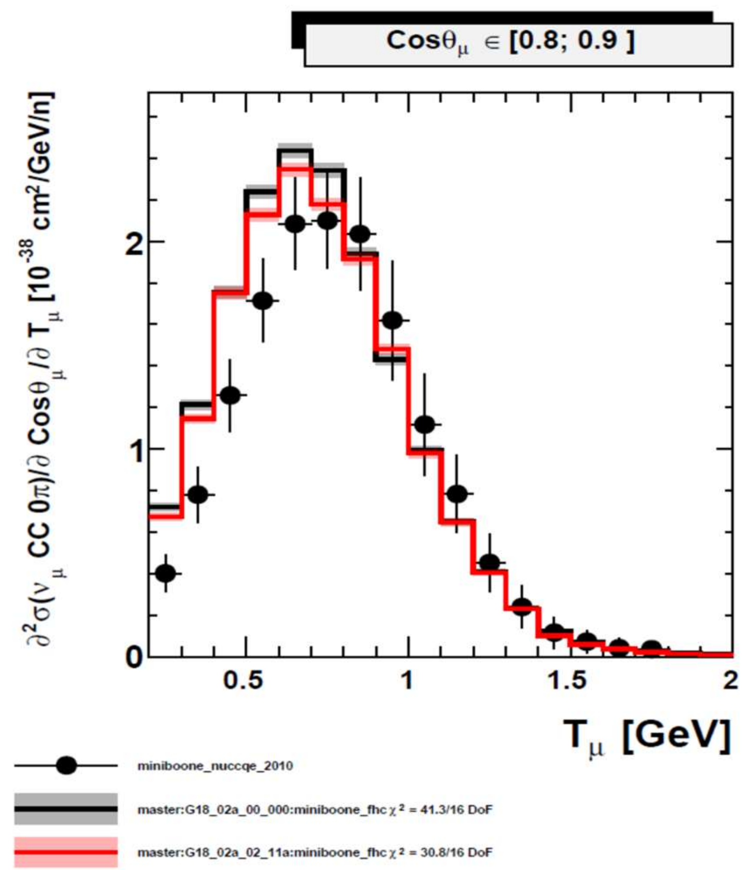
ν_μ n $\rightarrow$ μ^- π^+ π^- p



Results - 02a vs. 02a_tune

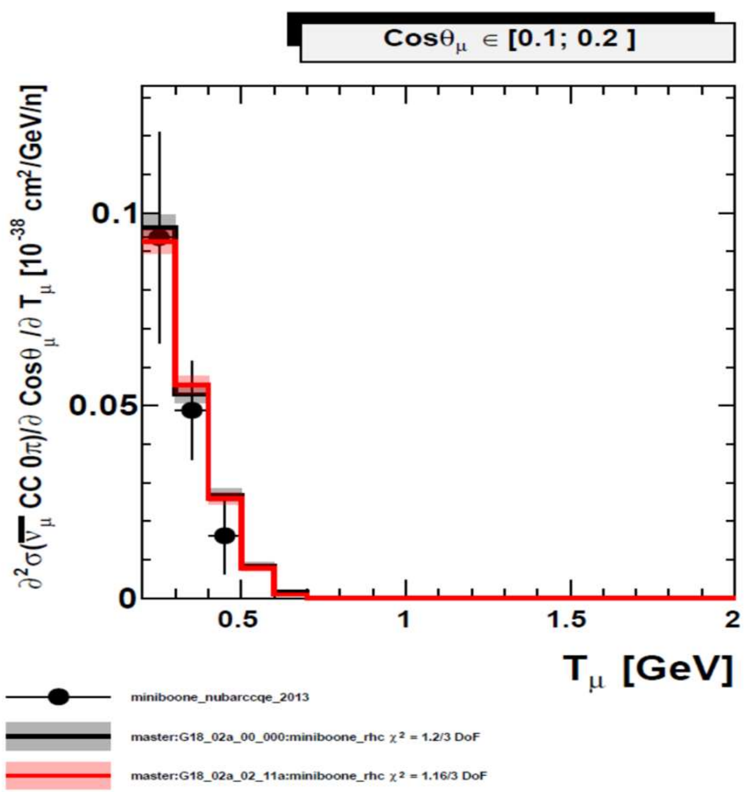
- MiniBooNE CC0π (2010) LS+Empirical MEC
- Very little difference between tuned and untuned
  - χ^2 = 71.5 (untuned), 75 (tuned) 78 dof for full data set

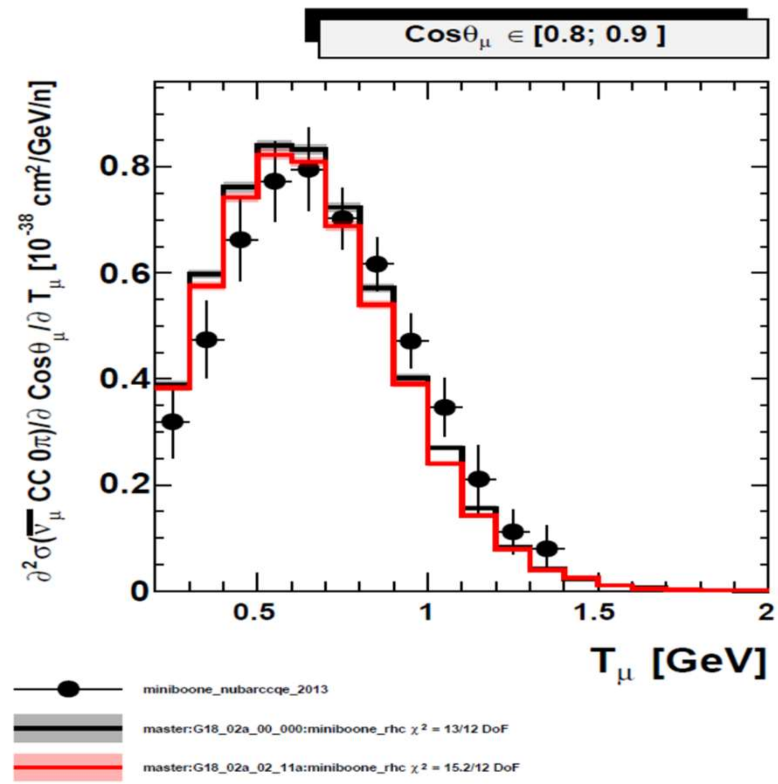




Results - 02a vs. 02a_tune

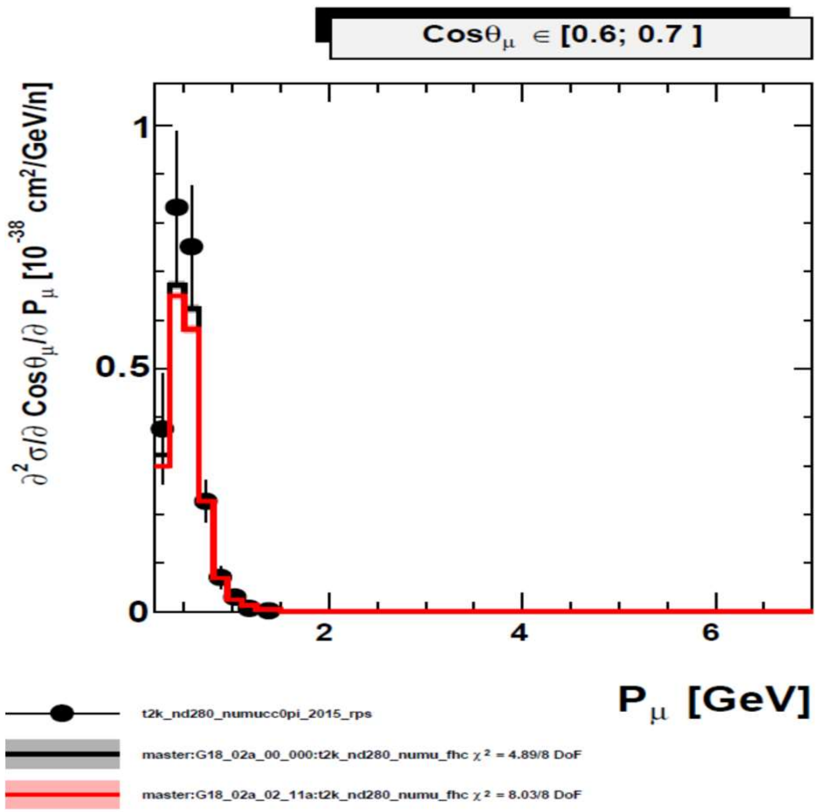
- MiniBooNE CC0π ($\bar{\nu}_\mu$) (2013)
- Good agreement with LS!
  - χ^2 = 352 (untuned), 374 (tuned) 137 dof for full data set

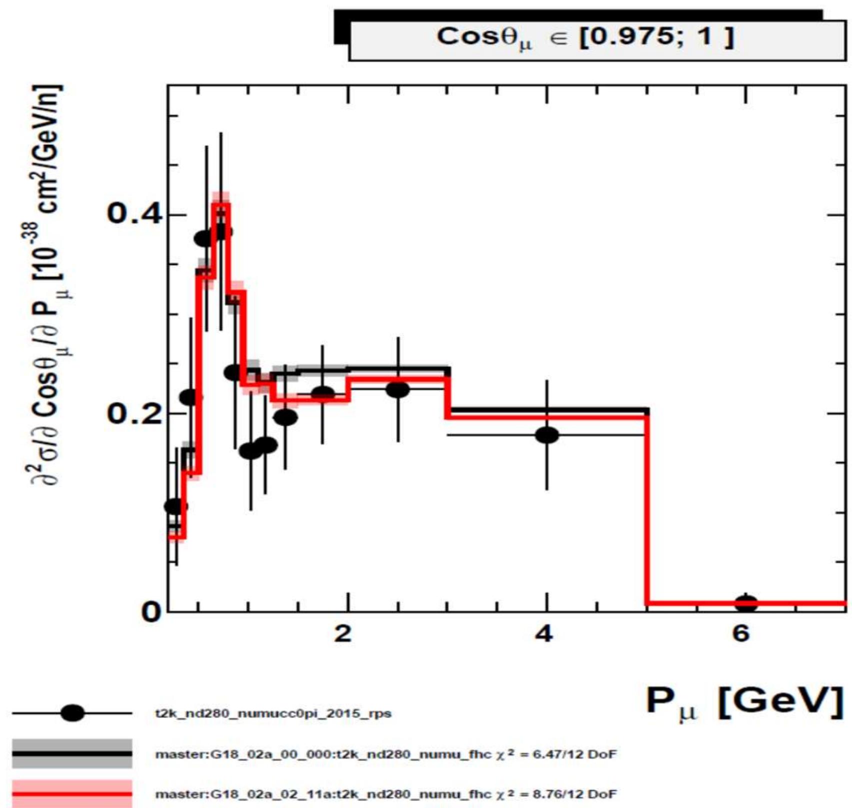




T2K CC0π (2015)

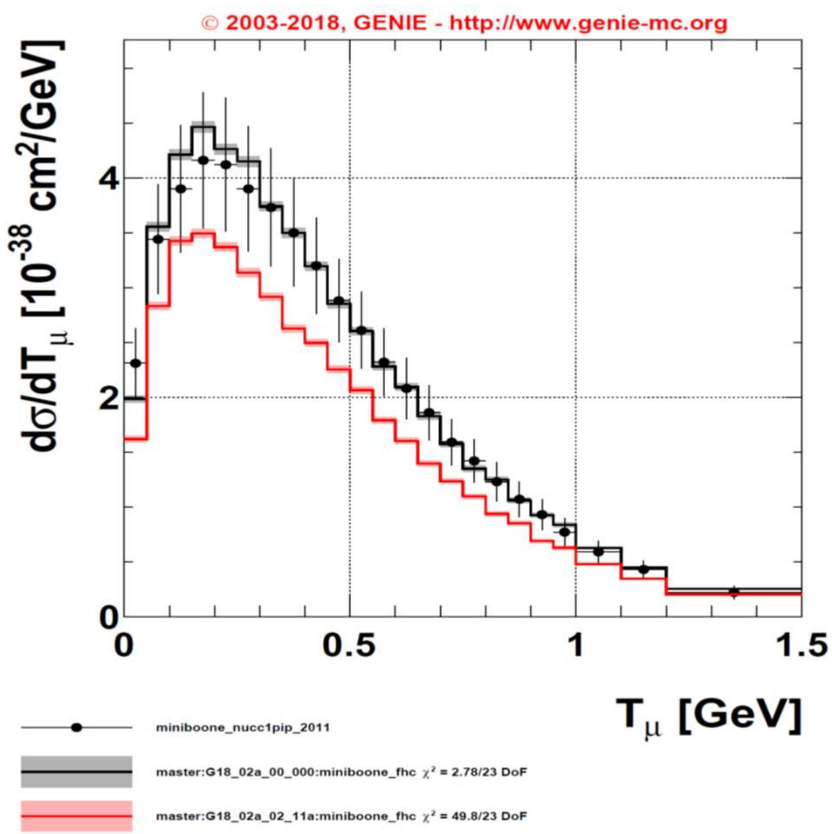
- μ^- momentum at most backward and most forward angles
- Very little difference between tuned and untuned
- Moderate agreement – χ^2 = 179 (untuned), 183 (tuned)

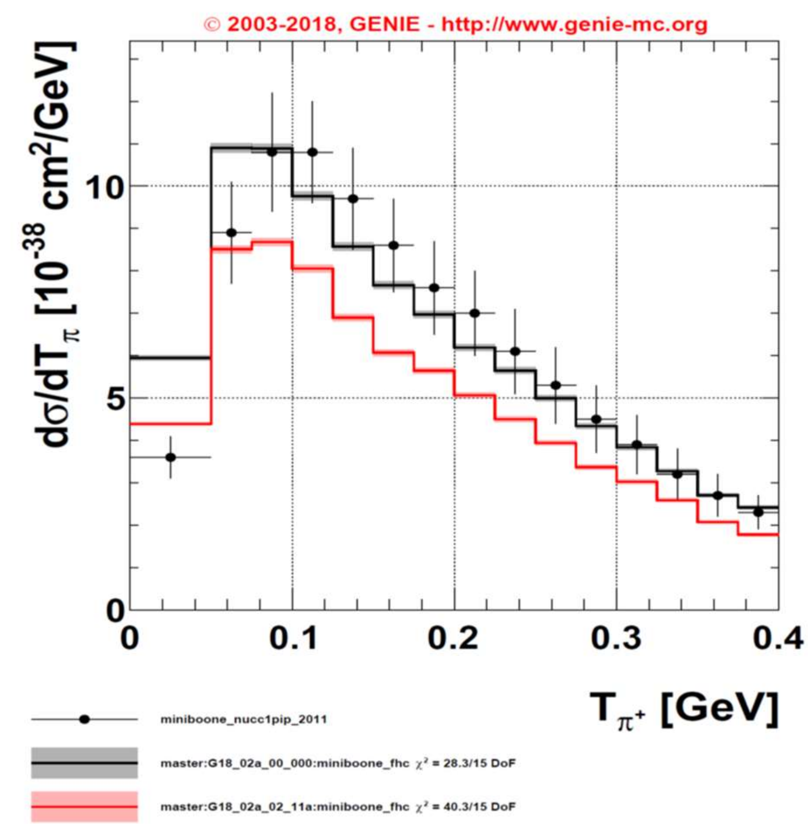




Results - 02a vs. 02a_tune

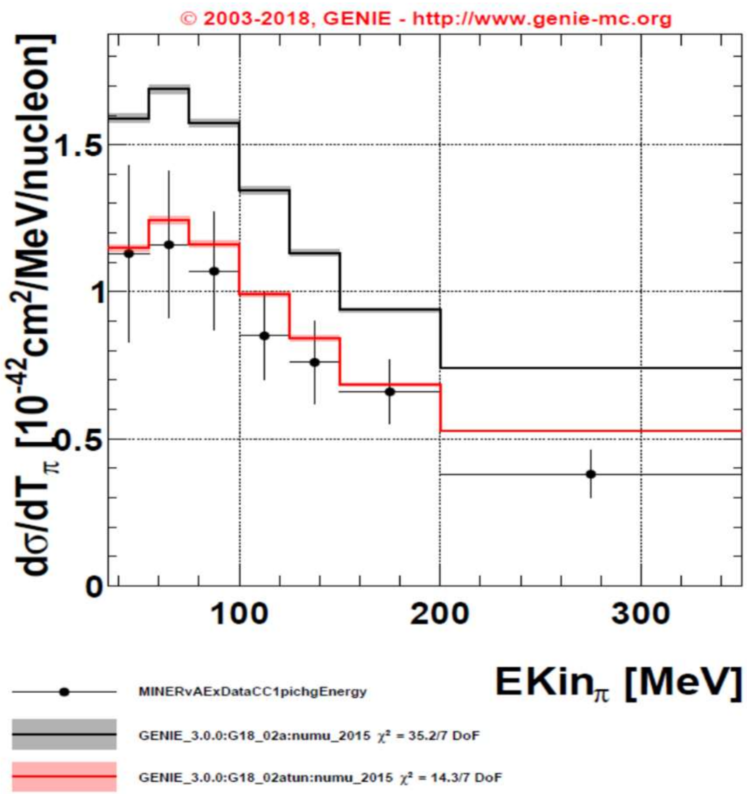
- MiniBooNE ν_μ CC1π^+
- New tune has poorer agreement in magnitude, shape ok

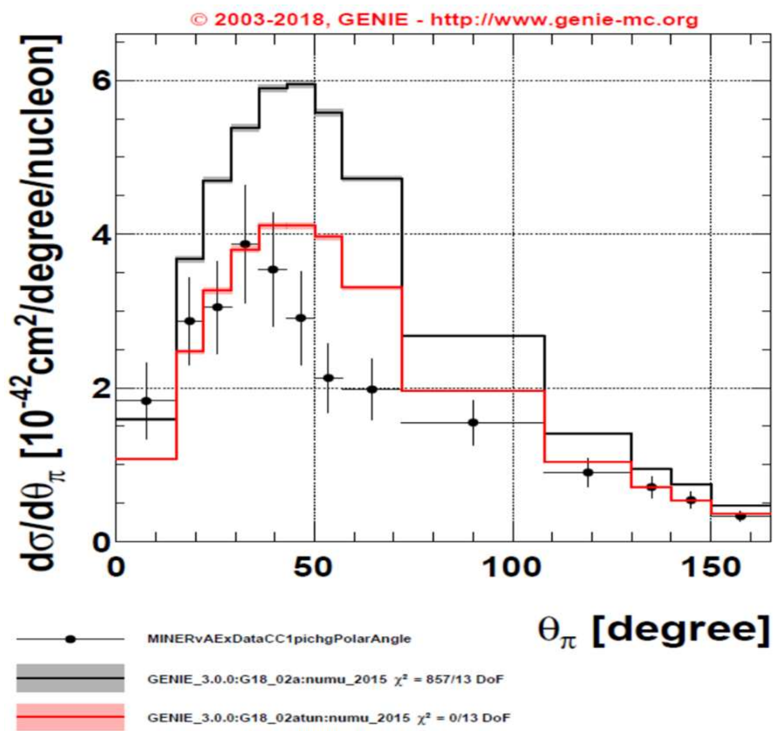




Results - 02a vs. 02a_tune

- MINERvA ν_μ CC1$\pi^\pm$
- New tune produces correct magnitude
- Angle still not easy to match





observations

- Tuned 02a produces lower pion production cross sections than untuned 02a
  - 02a in better agreement with MiniBooNE CC1π^+
  - 02a_tune in better agreement with MINERvA CC1$\pi^\pm$
  - Tension is independent of model, experiments must make choices
- 10a/b/i/j series all have good agreement with MiniBooNE data, using new deuterium tune reduces that agreement
  - best choice for BNB experiments
- Existing neutrino data mostly ν_μ CC
  - Many kinds of experiment, mostly C target (MINERvA Fe, Pb)
  - Except MiniBooNE, data has low statistics so far
  - Modern experiments have good error treatment, not MiniBooNE
- New, improved data is essential for GENIE progress

Role of experiments

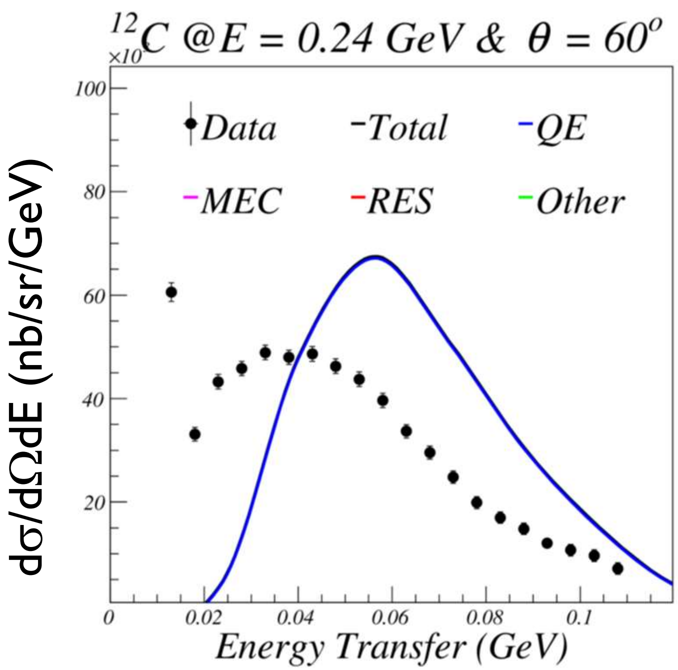
- Producing *useful* cross section results – signal!
- GENIE collaboration is no longer tiny, but still small compared to the needs of the community
- A constructive relationship with the experiments has always been desired, but doesn't happen naturally
- FNAL has a large user base, I am open to discussion
- We will do what we can, but support from experiments remains crucial
  - Testing
  - Help constructing models
  - Help upgrading error estimates

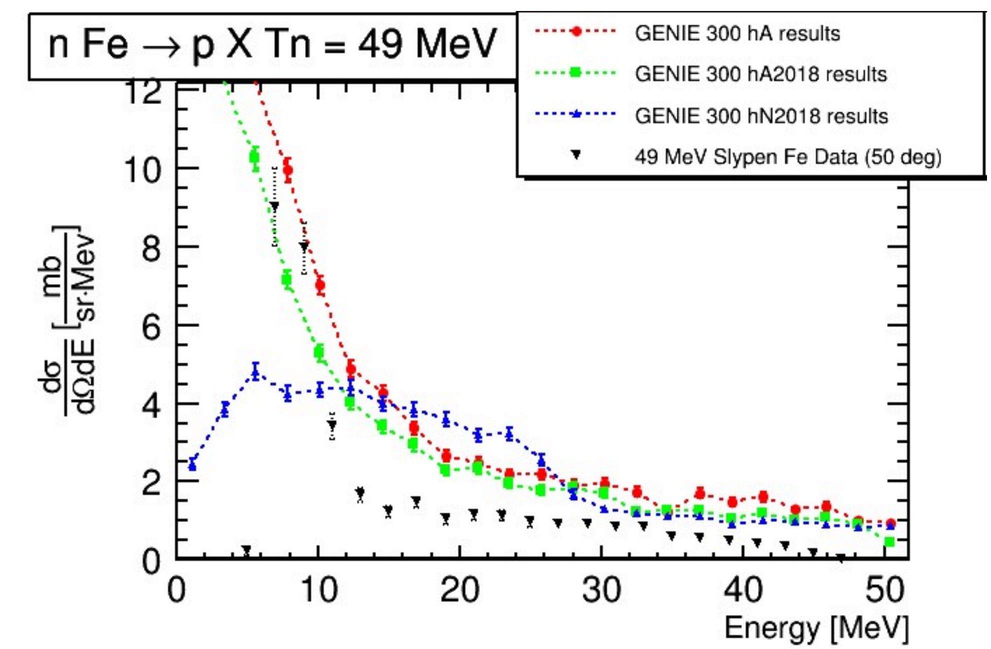
Model issues - reweighting

- Reweighting is now separate from Generator because reweighting task is based on model changes in Generator
- Short term – we realize experiments depend heavily on reweighting, keep us aware of your needs.
- Longer term improvements (with v4)
  - Fully support all tunes
  - Report tuned parameter values with covariance matrix
  - Reconstruct model sets in each tune as needed
  - Include tune parameters that don't have to be reweightable quantities (a feature of GENIE implementation of Professor)

Model issues – low neutrino energies

- (e,e') at beam energies <~300 MeV
  - No electron scattering model for Valencia, use LS+Empirical 2p2h
  - Physics emphasis changes (coherent, giant resonances, decay γ's)
- FSI for proton, neutron KE<~80 MeV
  - Still more suppression needed, shape?





v3.2 models ready to be part of a release

- Improve Delta [P_{33}(1232)] simulation
  - Upgrade decay angular distributions (NuWro)
  - *Later* – include alternate Δ models
- Coherent rho production
- Improve FSI
  - INCL++ as alternate FSI model
  - GEANT4 as alternate FSI model
  - *Later* - Update existing FSI or use alternate model
- Use links to (e,e') most advantageously
  - Resonance vector decay form factors from MAID
  - Radiative effects on all final state electrons?
  - *Later* - add tuned axial form factor, better nonresonant
  - Improved empirical MEC model - first (e,e'), then νA *later*
- Correlated Fermi Gas (CFG) nuclear model
- Pythia8 replacing Pythia6?

summary

- GENIE v3.0.0 is ready for users
  - **Many thanks to all who contributed! (see backup)**
  - LarSoft integration started in summer, thanks to them!
  - Reweight package still being modified for compatibility, expected soon
  - *We are already finding new errors, users should tell us what they learn*
- New structure makes introduction of new tunes easier
  - Experiments can put in their own tunes, easy if based on v3, harder if based on older releases
  - GENIE goal - supply nuclear tunes in roughly 1 year (v4)
- New models should be included
  - Recent theory efforts encouraging
  - New models backed up, waiting for v3.2 (few months?)
- Future
  - v4 promises to have nuclear tunes, much more realistic estimated errors
  - More rapid releases?
  - Better physics models vs. better tunes will make interesting times

Backup

GENIE 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)

GENIE 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)

GENIE 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 - v2.10 and v2.12

- 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.
  S.Dennis (Warwick/Liverpool)

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