GENIE and BSM

Steve Dytman
University of Pittsburgh

16 December, 2022

- GENIE is main event generator in ν work
- neutrino-nucleus physics is covered well, but not much BSM included
- How can we do better?

What is GENIE?

- Collaboration of a) computational experimenters with varying interests in theory and b) theorists who want to spread their models much more widely.
  - Almost every experimental collaboration (e.g. MicroBooNE) uses GENIE for simulations → efficiency, systematic uncertainties
  - It has models for all ν, e, and hadron processes for all nuclei at ~all energies (10 MeV →10 TeV). Quality varies widely.
- GENIE has a somewhat complicated structure.
  - Models are grouped into CMCs or tunes which can be easily used
  - These models are aimed at specific audiences, e.g. VHE and VLE.
    - I would recommend different CMC for MicroBooNE and MINERvA
- Like all event generators, roster of people insufficient for requirements.

Collaboration at present

Luis Alvarez-Ruso (IFIC), Costas Andreopoulos (Liverpool and STFC/RAL), Adi Ashkenazi (Tel Aviv), Joshua Barrow (Tel Aviv; MIT), Steve Dytman (Pittsburgh), Hugh Gallagher (Tufts), Alfonso Andres Garcia Soto (Harvard and IFIC), Steven Gardiner (Fermilab), Matan Goldenberg (Tel Aviv), Robert Hatcher (Fermilab), Or Hen (MIT), Timothy Hobbs (Fermilab), Igor Kakorin (JINR), Konstantin Kuzmin (ITEP and JINR), Anselmo Meregaglia (Bordeaux, CNRS/IN2P3), Vadim Naumov (JINR), Afroditi Papadopoulou (MIT), Gabriel Perdue (Fermilab), Marco Roda (Liverpool), Beth Slater (Liverpool), Alon Sportes (Tel Aviv), Noah Steinberg (Fermilab), Vladyslav Syrotenko (Tufts), Júlia Tena Vidal (Tel Aviv), Jeremy Wolcott (Tufts)

[Faculty, Postdocs, PhD Students, Master Students]

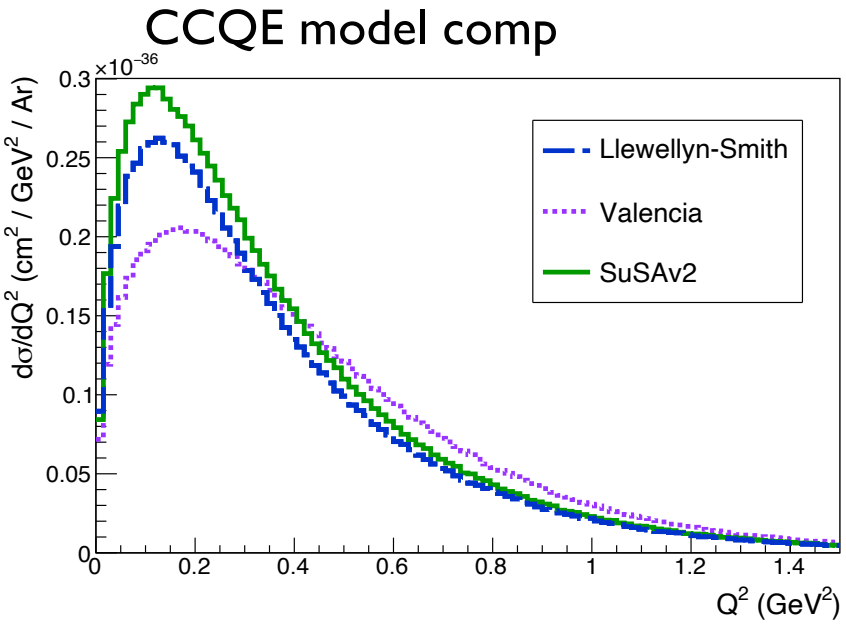
- Much larger than any other EG group, therefore many more features.
- No one is 100% on GENIE, very few >50%
- Julia Tena-Vidal (Liverpool) and Marc Vololoniaina (Madagascar) are first PhD students with primary goal of GENIE work
- 2 FNAL staff, growing this group is a primary concern

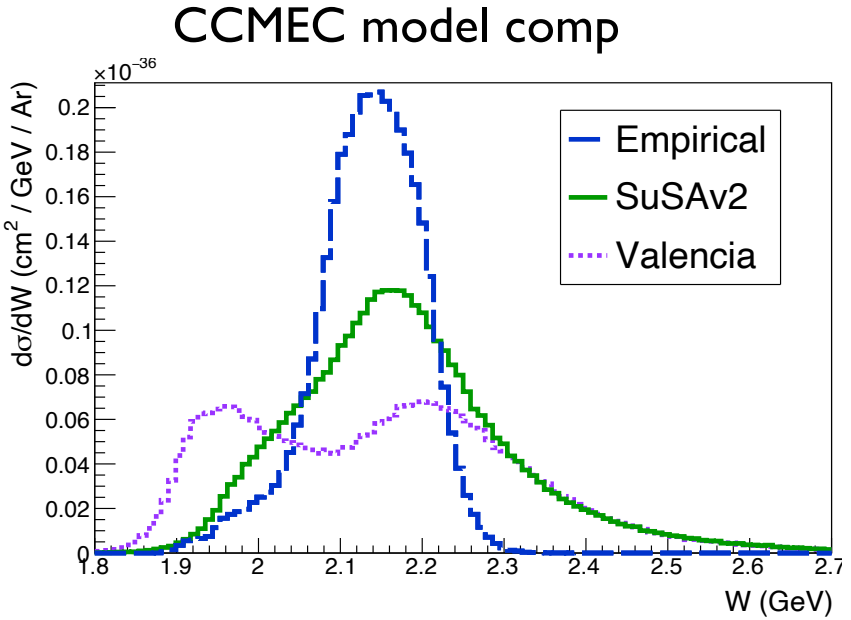
Features
See *Eur. Phys. J. ST* 230 (2021) 24, 4449

- Excellent ties to experiment – flux and geometry
- Nuclear models – Fermi Gas and Spectral Function
- QE+2p2h – Llewelyn-Smith, Valencia, SuSav2, Rocco
- Resonance – Rein-Sehgal, Berger-Sehgal, Minoo, DCC (Sato-Lee) in progress
- FSI – hA, hN (home-grown), INCL++, GEANT4, DCC in progress
- electron and hadron scattering in parallel with ν scattering. Electron scattering model incomplete, added after ν modeling well-established. Improperly linked.
- CEvNS at very low energy and HEDIS at very high energy
- Extensive tuning code (private)

Example of comparisons possible
Eur. Phys. J. ST 230 (2021) 24, 4449

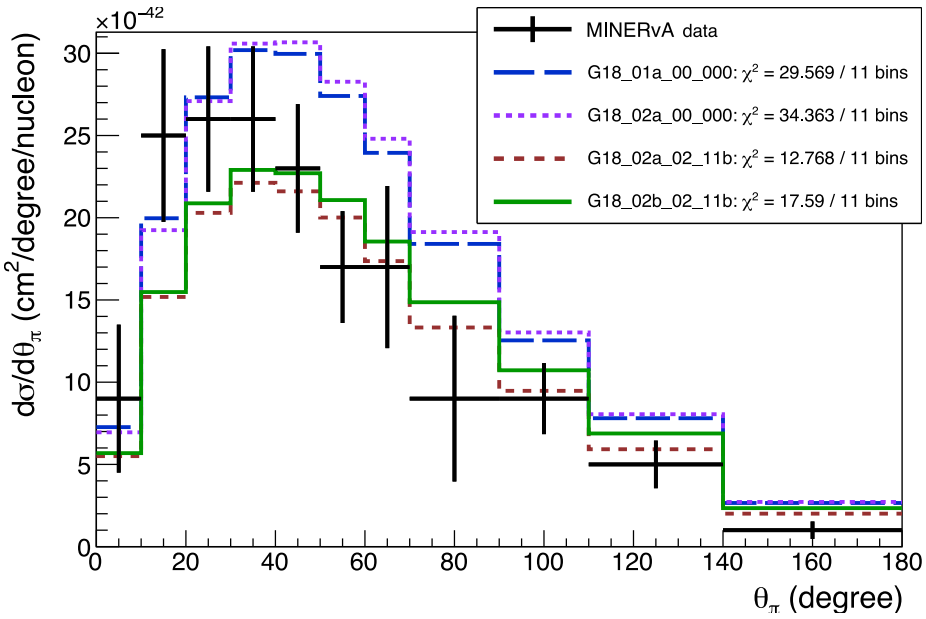
- Can confront any 2 models with identical conditions
- Here, show CCQE and CC2p2h comparisons for ν_μ Ar using MicroBooNE flux

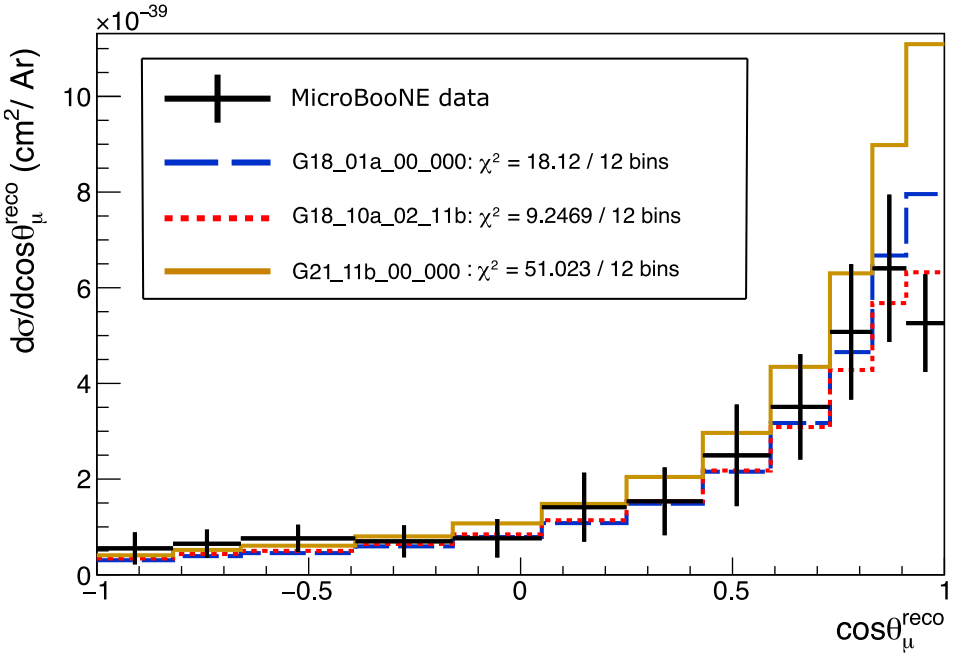




GENIE comparisons with data

- Easy to do with Comparisons section (private)
- Here, various CMCs compared to MINERvA pion and MicroBooNE inclusive data
- More modern calculations 'usually' better



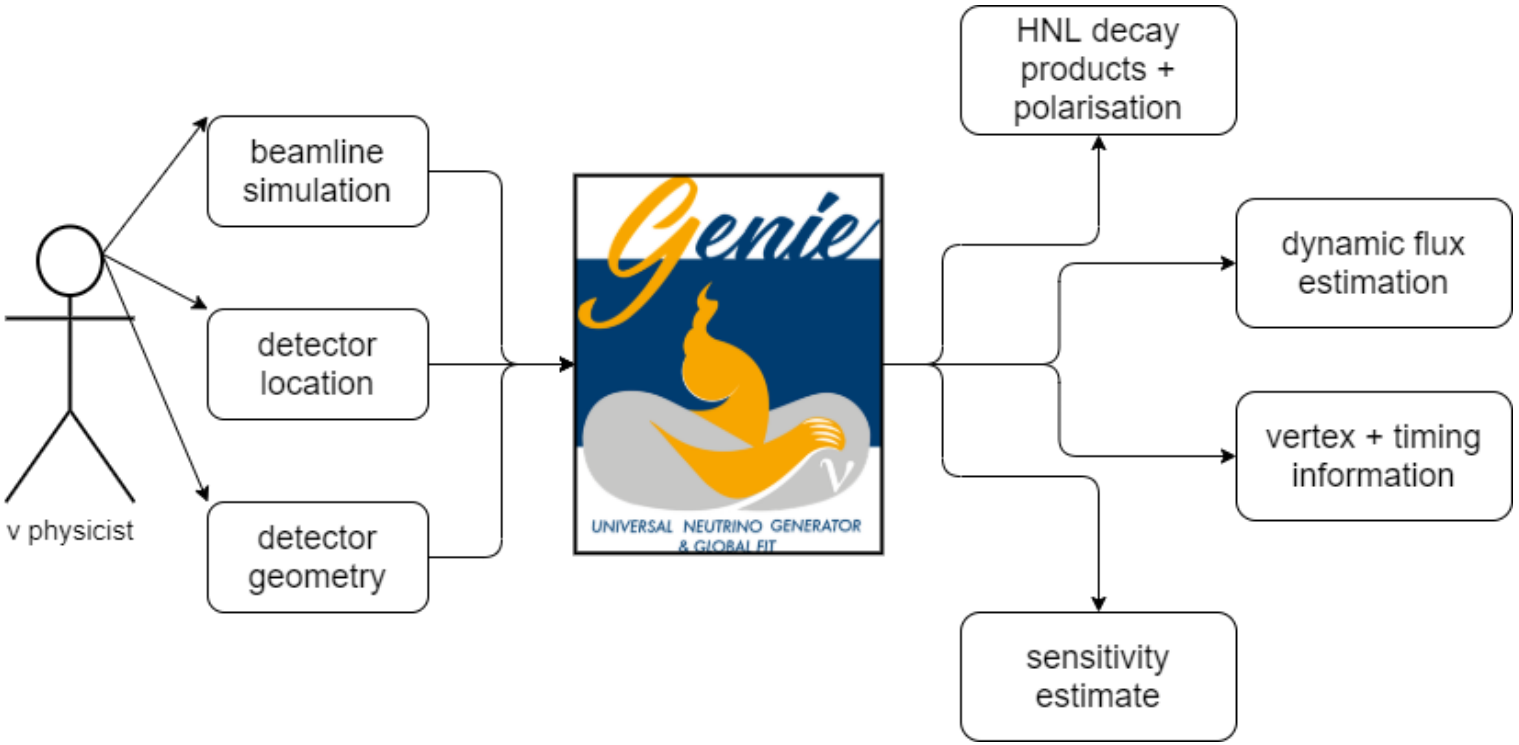


Links to BSM models

- Hooks for other generator events (Event Library Interface)
  - Built for GiBUU. Plows, Lu recently put NHL in this way
  - This allows use of many GENIE tools
  - Interesting exercise would be to try to use it for other BSM models
- P decay, nnbar models from interested experimenters
- Dark Neutrino Model (Bertuzzo et al.) available now
- Dark matter scattering (Berger et al.) mostly complete
  - Need many processes (QE, RES…) which isn't simple
- These are all incoherent with existing models, but able to use all GENIE flux, geometry, and FSI code.
  - Allowing interference between normal and BSM models complicated
  - Modern QE models written as $\Sigma L_{\mu\nu} H_{\mu\nu}$, so linkage is feasible

BeamHNL mentioned on Wed.
Great use of Event Library Interface in GENIE

- Sketch of what Plows, Lu did (DUNE talk)



GENIE and Theory

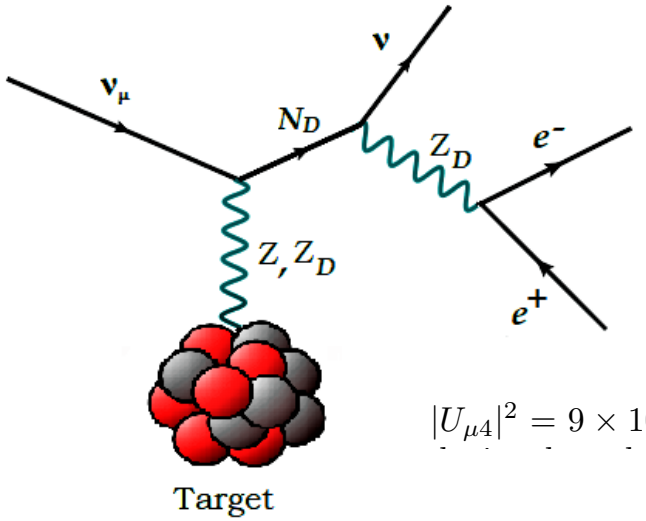
- GENIE is a bridge between theory and experiment
  - Any theory model in GENIE can be used, e.g. Valencia QE+2p2h is now standard for low energy neutrino experiments (e.g. uB)
  - GENIE is as good as its models and ability to describe data.
  - Inability to describe data → tuning and/or constraints to internal data. Good and bad!?!
- Models for theory participation
  - Papers with formulas – least successful
  - Provide C or C++ code - most successful
  - Theorist collaborating with GENIE author is very beneficial, e.g. SD and Valencia group
- GENIE has 2 BSM models, not much expertise within our group.

BSM in GENIE – theory paper

- Dark Neutrino Portal Model – Bertuzzo et al. *Phys. Rev. Lett.* 121 (2018) 24, 241801

$$\nu_\alpha = \sum_{i=1}^{3} U_{\alpha i}\,\nu_i + U_{\alpha 4}\,N_{\mathcal{D}}\,, \quad \alpha = e, \mu, \tau, \mathcal{D},$$

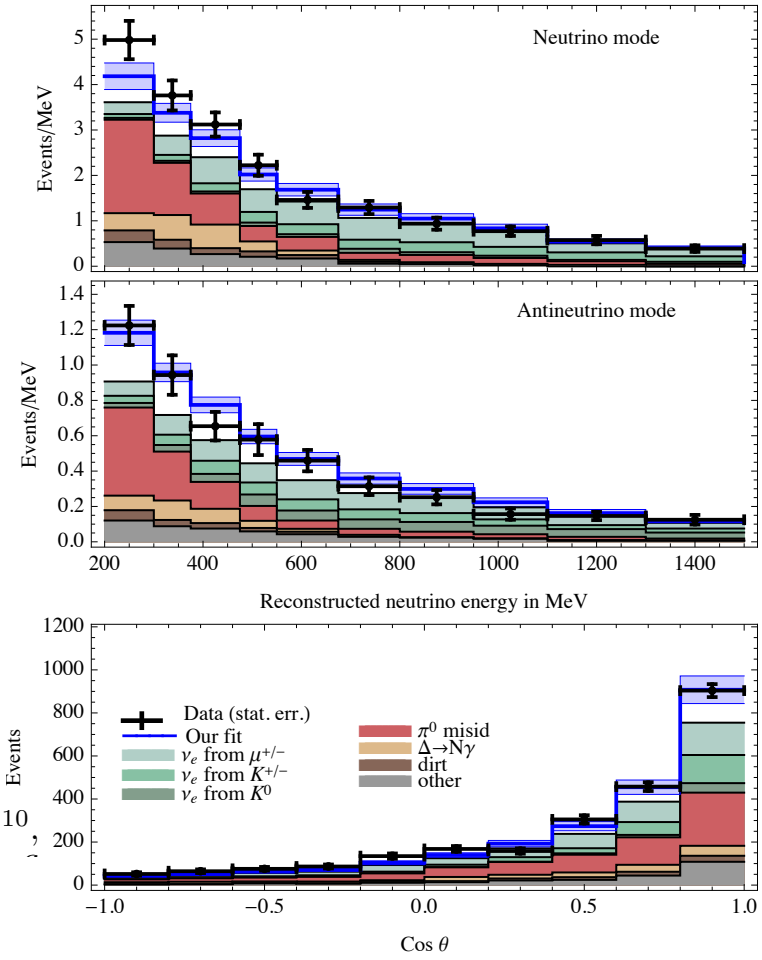
$$\mathcal{L}_{\mathcal{D}} \supset \frac{m_{Z_{\mathcal{D}}}^2}{2} Z_{\mathcal{D}\mu} Z_{\mathcal{D}}^{\mu} + g_{\mathcal{D}} Z_{\mathcal{D}}^{\mu}\, \overline{\nu}_{\mathcal{D}} \gamma_\mu \nu_{\mathcal{D}} + e\epsilon\, Z_{\mathcal{D}}^{\mu}\, J_{\mu}^{\mathrm{em}} + \frac{g}{c_W}\epsilon'\, Z_{\mathcal{D}}^{\mu}\, J_{\mu}^{\mathrm{Z}}$$



- Needs new light ND, ZD
- Fit to MiniBooNE excess gives

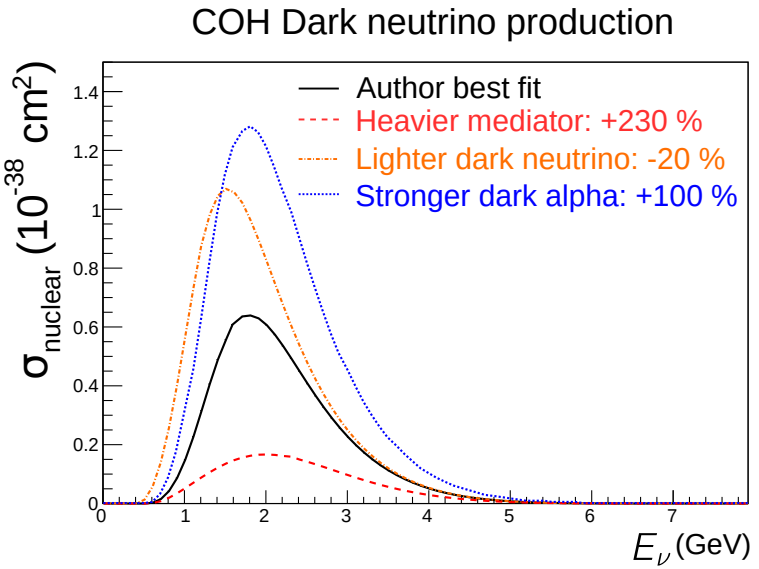
$m_{N_{\mathcal{D}}} = 420$ MeV, $m_{Z_{\mathcal{D}}} = 30$ MeV,

$|U_{\mu 4}|^2 = 9 \times 10^{-7}$, $\alpha_{\mathcal{D}} = 0.25$ and $\alpha\epsilon^2 = 2 \times 10^{-10}$,



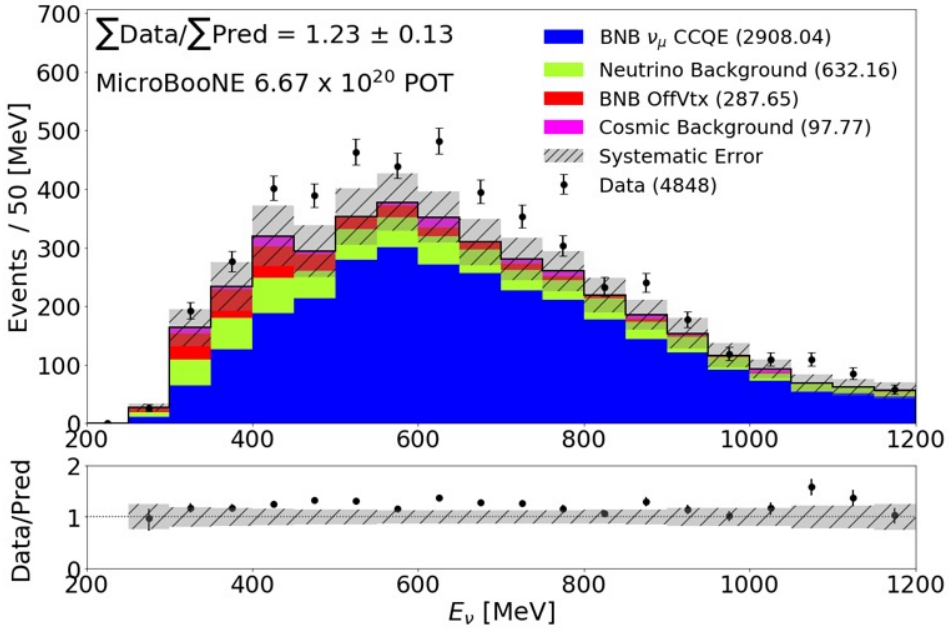
BSM in GENIE - implementation

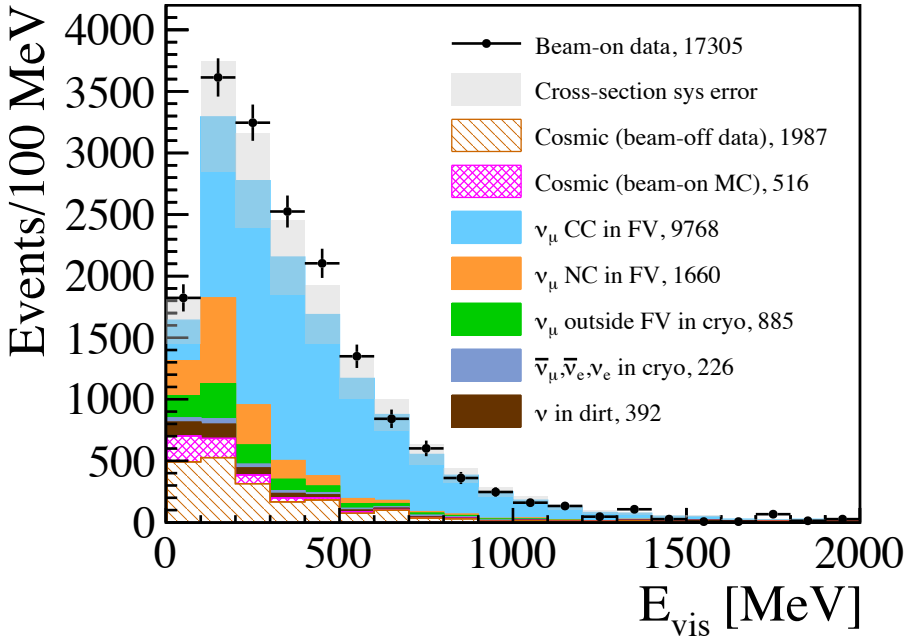
- SBND wanted BSM inside GENIE, assigned a student (Iker de Icaza) who worked with GENIE (Marco Roda)
  - It is well-integrated into GENIE as a separate model, 'easy' to add to existing models without conflict.
  - IMHO This integration style isn't ideal, need more buy-in from theorists
    - Time was slow because experimenters had to figure out model
    - Discussion with theorist (Pedro Machado) was helpful, but not ideal
  - It is in GENIE v3.2 and anyone can use it.
- GENIE needs a cross section. Plot shows what we used.



MicroBooNE tune - *Phys. Rev. D* 105 (2022) 7, 072001
how we provided nonBSM 'background'

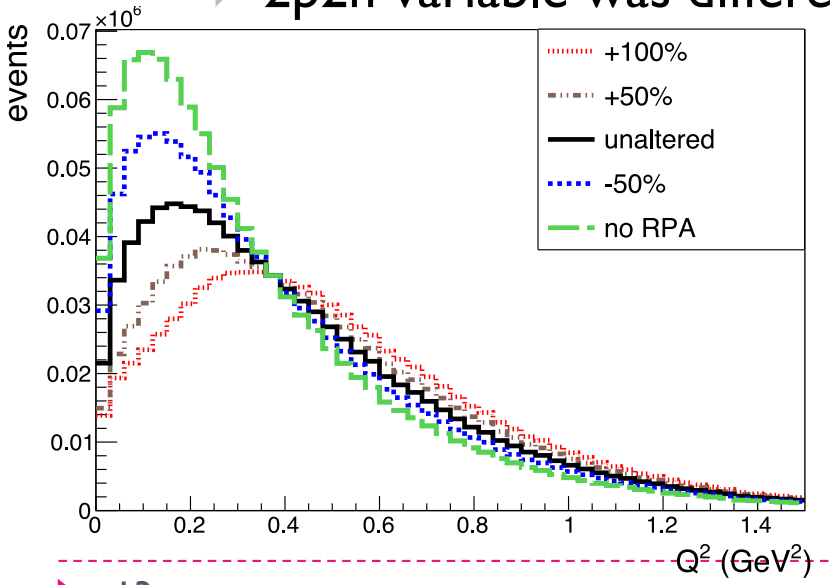
- A few of us (4 in the end) were asked to provide this tune on somewhat short notice. True tune takes >1 yr.
  - Goal was to use outside data to make up the shortfall (~30%) seen in uB internal data vs GENIE v3 (G18_10a_02_11a)
  - Use of outside data alleviates issue of double-counting

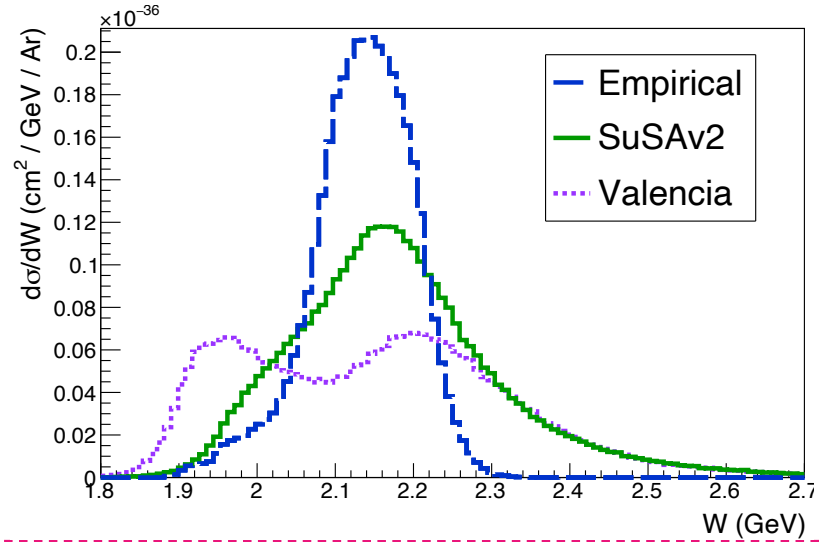




Fit parameters

- We decided on T2K 2016 CC0π inclusive data
  - Similar ν energy flux (~0.8 GeV) but lighter target (CH vs. Ar)
  - Focus on QE and 2p2h (not FSI, RES!)
  - Invented shape systematic knobs (normalization already included)
    - Based on theory deficiencies
    - QE shape variable was strength of Valencia RPA
    - 2p2h variable was difference between GENIE Empirical and Valencia

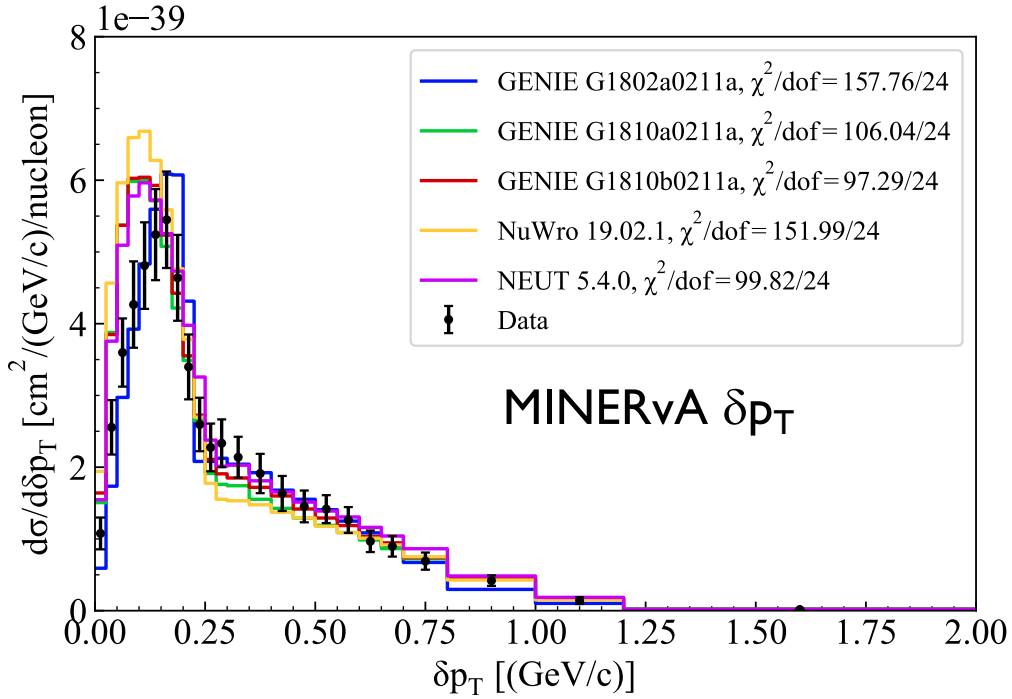


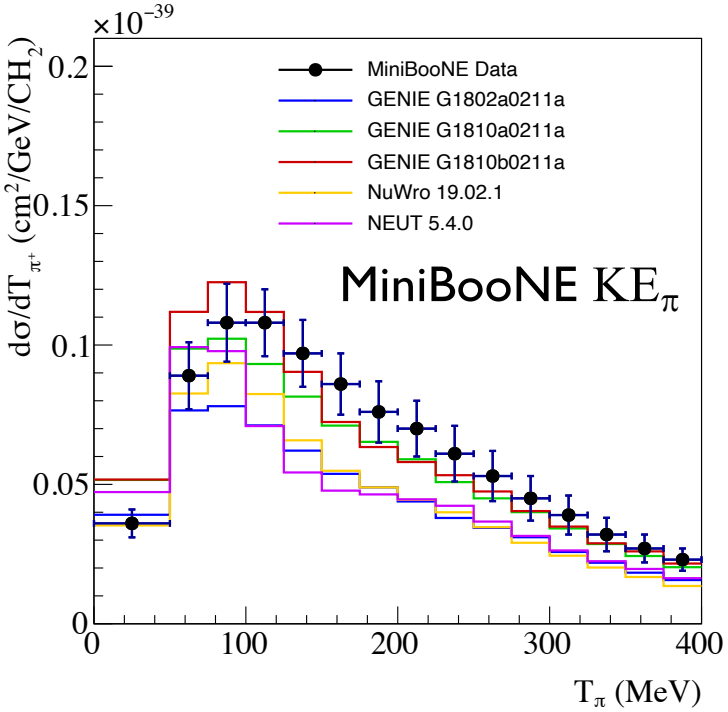


Tensions workshop output

M. Buizza Avanzini et al., Phys. Rev. D 105 (2022) 9, 092004

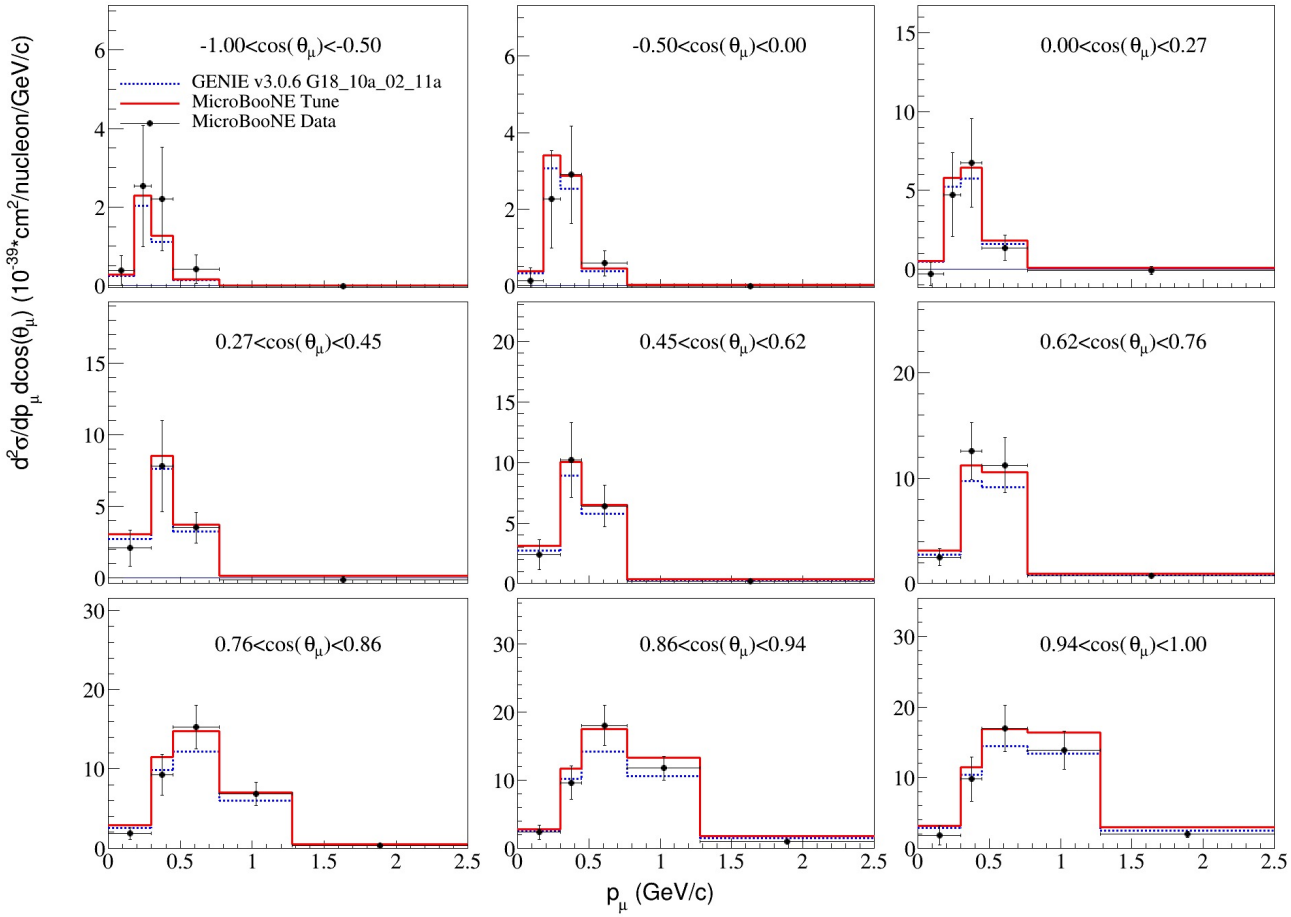
- Goal is to examine data sets in detail, make recommendations.
- MiniBooNE data (right) is less reliable, use with care
- Pion production (right) is much harder than QE
- Transverse imbalance variables (left) give new insight into underlying physics





Fit results

- χ^2 wasn't horrible at beginning but shortfall similar to what we saw w/r uB data.
- Definite improvement in χ^2!
- Fit was done with Minuit inside Nuisance (4 params)



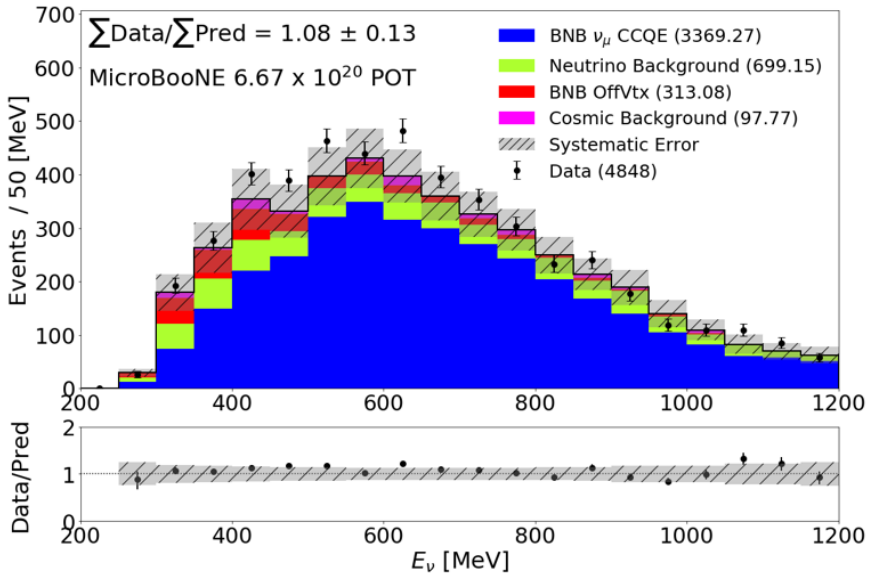
Aside on correlations

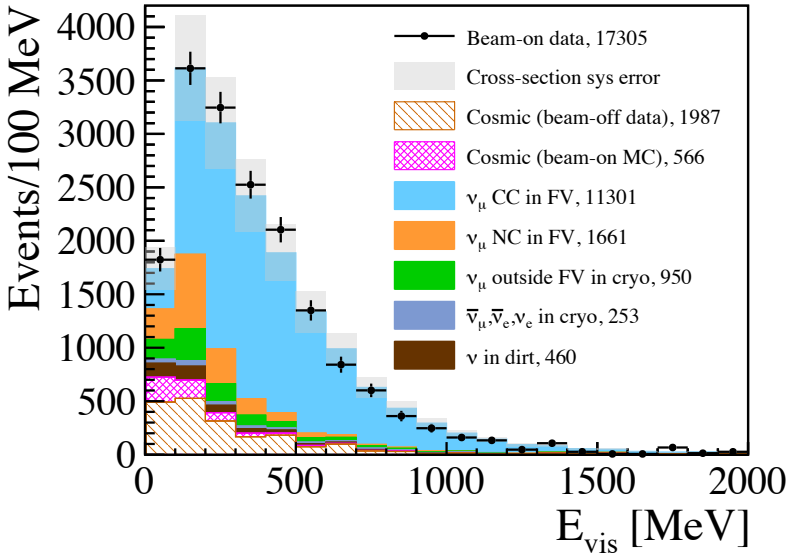
- Experiments quote a variety of systematic uncertainties, many of them (esp. flux) strongly correlated
- This can confuse fitting programs (Peele's pertinent paradox)
- Main fit was with diagonal uncertainties. We used T2K fix for PPP, keep normalization separate. That's the alternate fit.
- Results are almost identical (couldn't change because uB oscillation work was well underway)

	MaCCQE fitted value	CC2p2h Norm. fitted value	CCQE RPA Strength fitted value	CC2p2h Shape fitted value	T2K $\chi^2_{diag}/\mathrm{N}_{bins}$	T2K $\chi^2_{Koch}/\mathrm{N}_{bins}$	T2K $\chi^2_{full}/\mathrm{N}_{bins}$
Nominal (untuned)	0.961242 GeV	1	100%	0	106.7/58	149.83/58	97.56/58
"MicroBooNE Tune"	1.10±0.07 GeV	1.66±0.19	(85±20)%	$1^{+0}_{-0.74}$	52.5/58	110.58/58	103.84/58
"Alternate fit"	1.04±0.10 GeV	1.44±0.42	(67±16)%	$0.91^{+0.09}_{-0.18}$	55.51/58	100.59/58	91.68/58

Effect on MicroBooNE data

- Very positive, much better agreement and oscillation people were happy! (they could then forget us)
- See slide 10 for 'before' plots





Effect on physics interpretation

- Oscillation folks don't care.
- Result only makes sense for the GENIE model used!
- Needs enhanced QE and 2p2h. Shape prefers Gaussian shape for 2p2h mildly. (traditional finding!)
- Interesting aside: GENIE tune was more complete (more data, more parameters). They saw same result.

Problems I have heard

- Implementation too slow/cumbersome
  - GENIE requirements to maintain configuration structure
  - Not enough hooks (FSI, event input)
  - Too few theorists in GENIE
- Improper citation
  - Need more GENIE papers
  - Need a way to access full bibliography (Josh Isaacson)
- Work in event simulation tough way to build a career
  - Young people need to be theorist or experimenter to get a job

Achilles

- Alternate event generator started by Josh Isaacson (FNAL) and collaborators recently
- Goal is to have a platform for BSM models more welcoming than GENIE
  - To do this, they need to have similar capability as GENIE?
- Multiple models for a variety of processes possible?
  - Nuclear model, QE, 2p2h, FSI…!
  - GENIE group is large and took years of effort to get where we are
- What do people at this workshop think?

Summary+outlook

- GENIE tries hard to service the broad neutrino community
  - All targets, broad range of energies with many kinds of physics
  - Dozens of models included
  - Even with recent additions of people, needs still outweigh capabilities
  - Experiments devote very few resources to event generators
- BSM still new to us
  - no expertise in our group
  - Willing to work with you if you are willing to work with us
  - Problems with theorist interactions remain, I consider this as my personal challenge
- Need better hooks for models
  - Event Library Interface is excellent start
  - Including BSM models that can interfere with nonBSM models is special challenge