# Monte Carlo Generators

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- Broad overview of models
- Emphasis on GENIE
- physics models: predictions for $\nu_\mu$ carbon
- user features: validation, reweighting...

# Bigger view #1

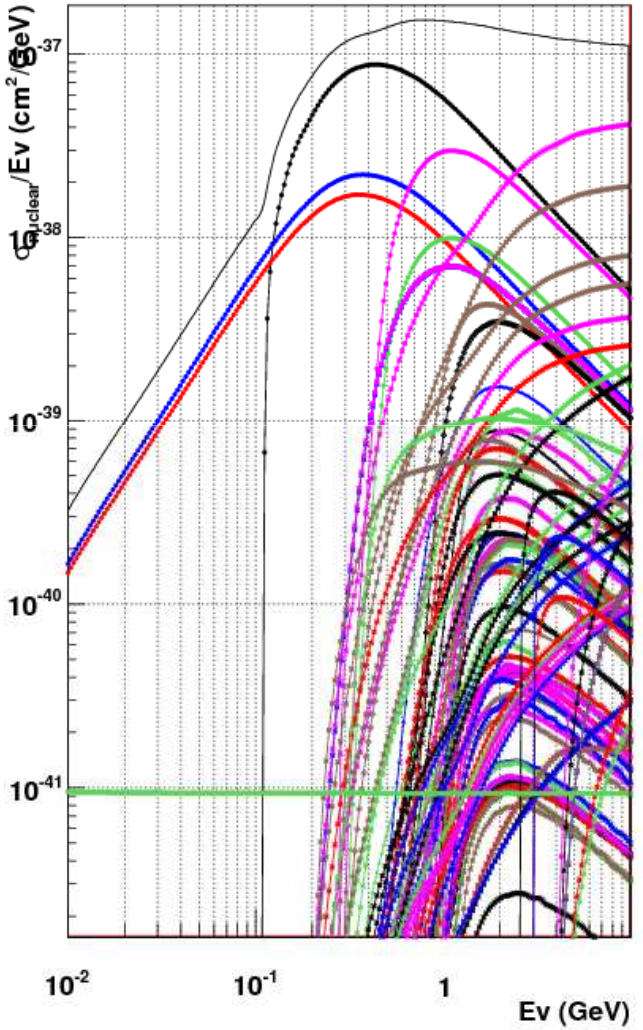
- PYTHIA (LUND) has been standard in HEP for many years. It is huge benefit to collider community, also used by neutrino community.
- There has been no universal event generator, to detriment of the field. (most generators made for single experiments)
- GENIE was created with goal of being that universal event generator. Are we succeeding?

# Bigger view #2

- Neutrino event generators have huge goal (use list from Hugh Gallagher from NUINT09)
  - plan experimental configurations
  - Detector design
  - Verify early performance before analysis develops
  - Data analysis (develop cuts, corrections)
  - Systematic errors (beam energy, topology errors)
- Thus, each program must have models for all possible neutrino interactions in many materials at a wide range of energies.

# cross sections in GENIE

- Here is what is in GENIE for $\nu_\mu$ Carbon:
  - qe
  - All resonances
  - All coherent
  - DIS of all flavors
- Input spline functions used to generate events.
- Works because models are simple.



# How we do it

- There is *very little* $\nu$A data, *models required*
- Venerable models for qe (Llewellyn-Smith) and pion production (Rein & Sehgal) on p,n - need updates? (new data even more important)
- Fit to $\nu$N Deep Inelastic Scattering data used for models.
- Nuclear model is relativistic Fermi Gas (old!) from (e,e')
- Final state interaction (FSI) comes from fits to $\pi$A , pA data [complicated!]
- How applicable are models from other probes? At the moment, no choice. Influx of new data will make interesting confrontation.

# MC event generators available

- NEUT – mainstay of SuperKamiokande, SciBoone, presently also for T2K. Maintained by Y. Hayato; Most applicable to $E_\nu$<~few GeV
- NUANCE – developed by D. Casper, mainstay of miniBoone. Recent advances only by MiniBoone. Most applicable to $E_\nu$ <~few GeV.
- NuWro – developed by J. Sobczyk and Wrocslaw. Mostly applicable at higher energies.
- GENIE – successor to Neugen (H. Gallagher ++), now Andreopoulos, Gallagher, Dytman++). Attempts to be usable for 100 MeV - 100 TeV.
- GiBUU (speed) and FLUKA (license) not generally usable despite excellent models. Focus mostly on GENIE, compare to NEUT, NuWro and NUANCE (**NUINT09**).

# GENIE

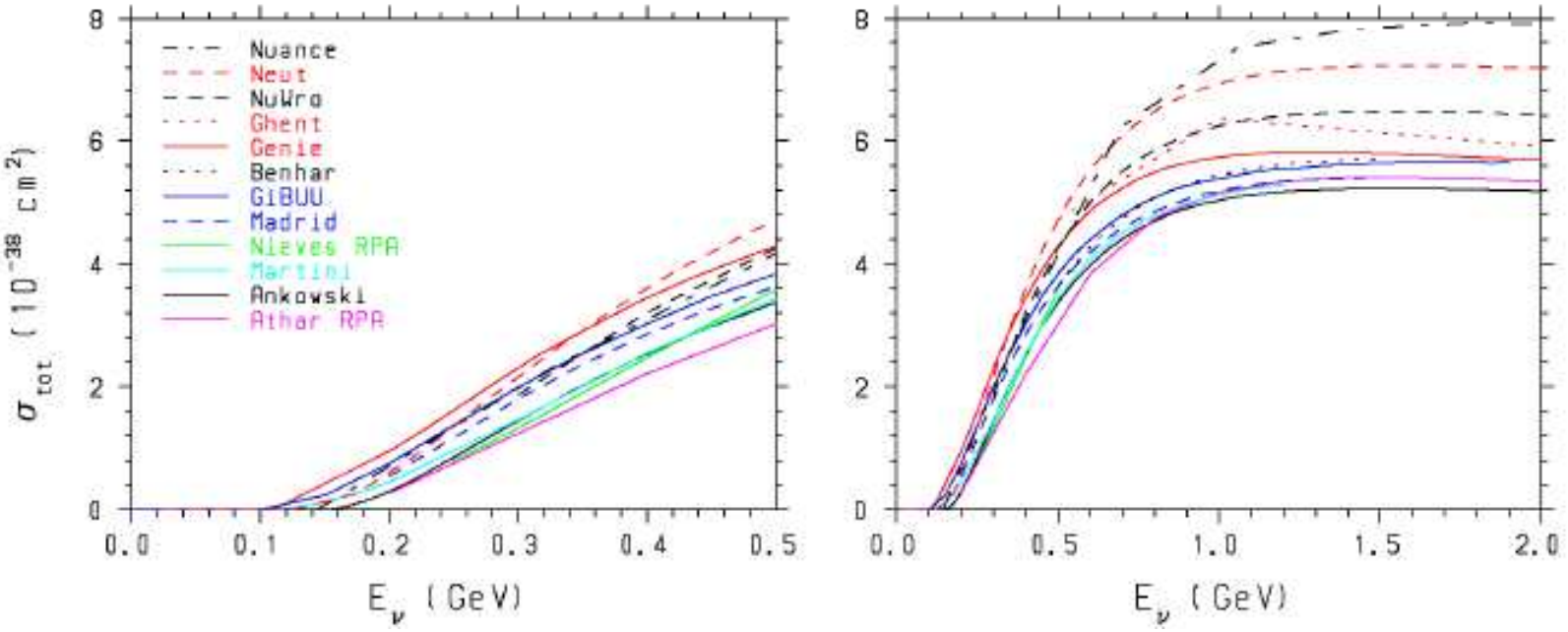
- Modern C++, object-oriented (Andreopoulos)
- Uses ROOT libraries heavily (detector geometry)
- Very modular, easy to choose different models (not many choices, but stay tuned)
- Many useful tools included, e.g. reweighting
- Active interaction with theorists, more in last year.
- NIM **A614:**87 (2010). http://www.genie-mc.org/ and http://www.hepforge.org/downloads/genie
- Authors: L. Alvarez-Ruso, C. Andreopoulos, O. Benhar, F. Cavanna, J. Dobson, S. Dytman, H. Gallagher, P. Guzowski, R. Hatcher, Y. Hayato, A. Meregaglia, A. Meyer, D. Naples, G. Pearce, C. Reed, A. Rubbia, M. Whalley

# NUINT09 theory exercise

- Steve Boyd (Warwick) and I were asked to sponsor an effort to get many theorists & modelers to calculate same quantities. NEW!!
- We suggested total, single, and double differential cross sections for $\nu_\mu$ C reactions at 0.5, 1, 1.5 GeV (qe, pi prod, and coherent). This represents about 20 distributions.
- Definition of final states very difficult.
- Response was fantastic, all known theorists -1 participated. Jan Sobczyk, Roman Tacik, and Elicier Hernandez joined organizational effort.
- See S. Boyd, et al: AIP Conf. Proc. **1189**, 60 (2009), http://regie2.phys.uregina.ca/neutrino/

# Physics comparison - qe

- Very sensitive to Nuclear structure
  - Fermi Gas or spectral functions + correlations?
  - What is $M_A$ (sets $Q^2$ dep in nucleon form factor)? (experiments set it to match their data)
- FSI important if recoil nucleon detected (better event ID)

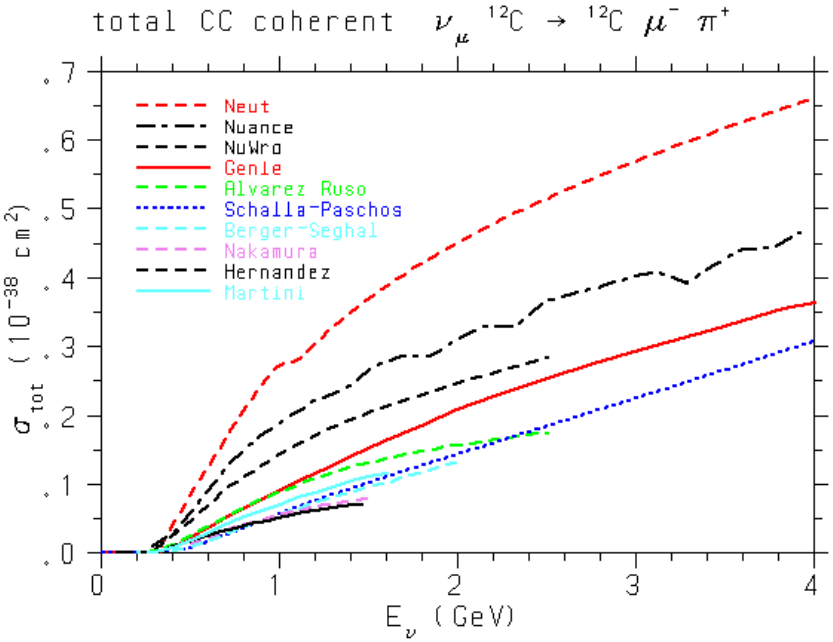


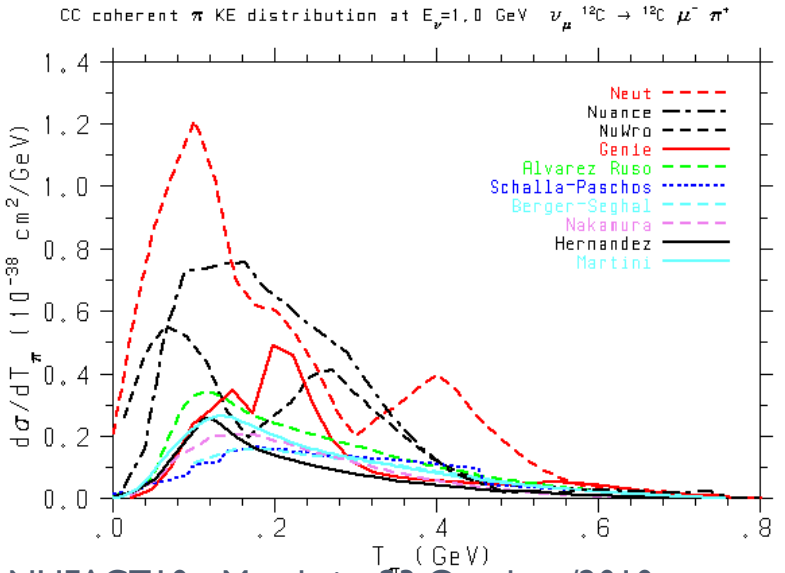
# Coherent pion production

- Rein-Seghal used in all MC event generators, designed for high energy. (recently adapted for lower energies)

$$\frac{d\sigma}{dq^2 dy dt} = \frac{G^2 f_\pi^2}{2\pi^2} \frac{E u v}{|\vec{q}|} G_A^2 \frac{d\sigma(\pi^0 \mathcal{N}_{gs} \to \pi^0 \mathcal{N}_{gs})}{dt}\bigg|_{E_\pi = q^0} \qquad \frac{d\sigma(\pi \mathcal{N}_{gs} \to \pi \mathcal{N}_{gs})}{dt} = |F_A(t)|^2 F_{\text{abs}} \frac{d\sigma(\pi N \to \pi N)}{dt}\bigg|_{t=0}$$

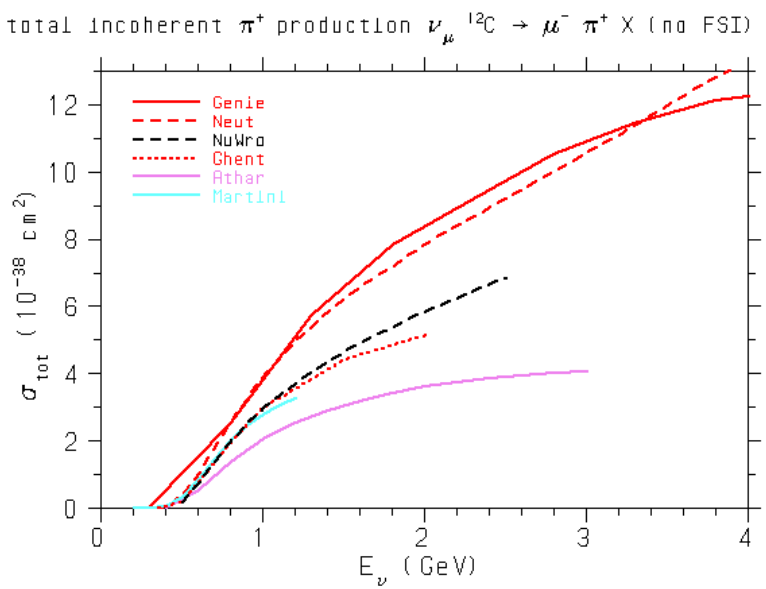
- More recent models from many theorists (pion prod from nucleon + pion optical potential) [best for $E_\nu$<~2 GeV, limit is pion FSI]

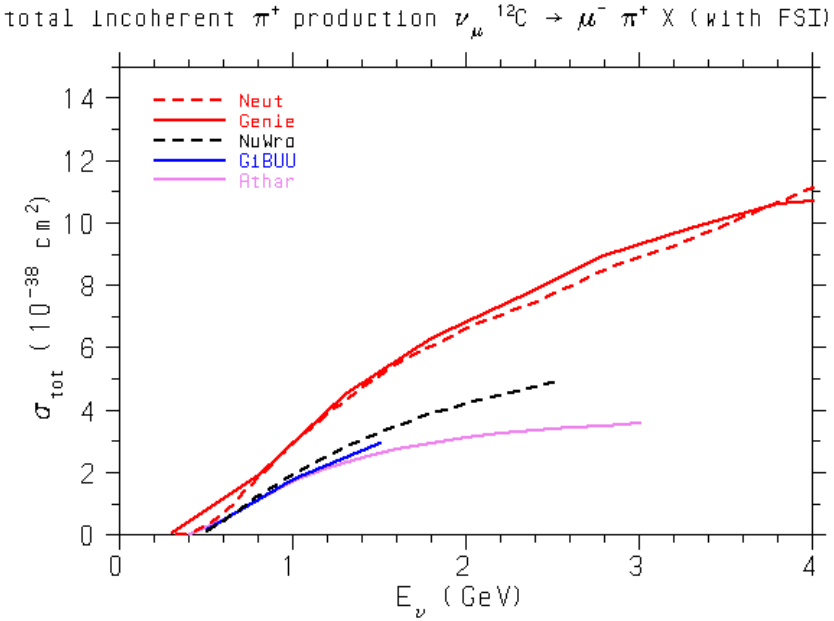


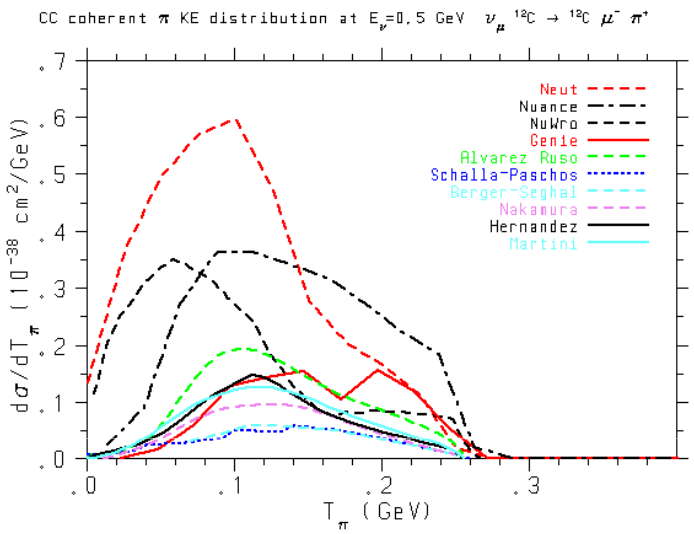
# Incoherent (regular) pion production

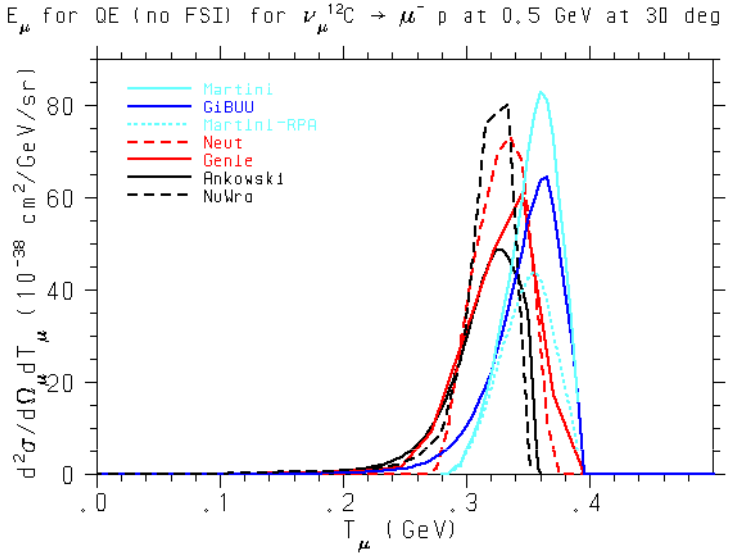
- Core is Rein & Seghal (resonance) and Bodek & Yang (non-resonant). Could be improved.
- Calculation is for CC1$\pi$.
- Form factor, nuclear structure, FSI all matter.
- Data, theory poor guide.

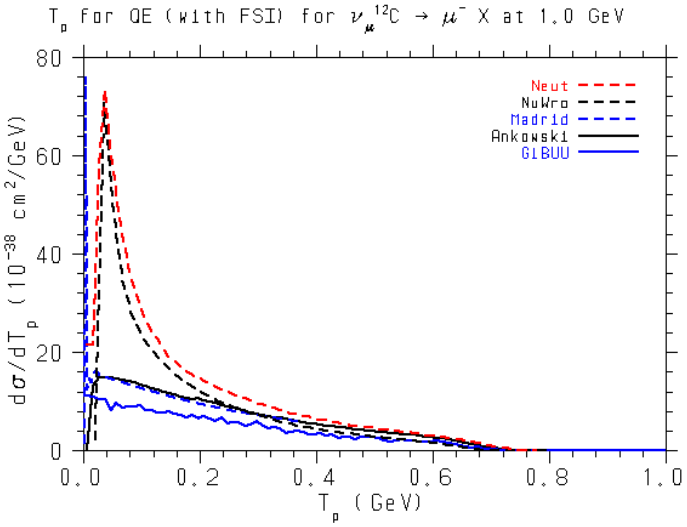


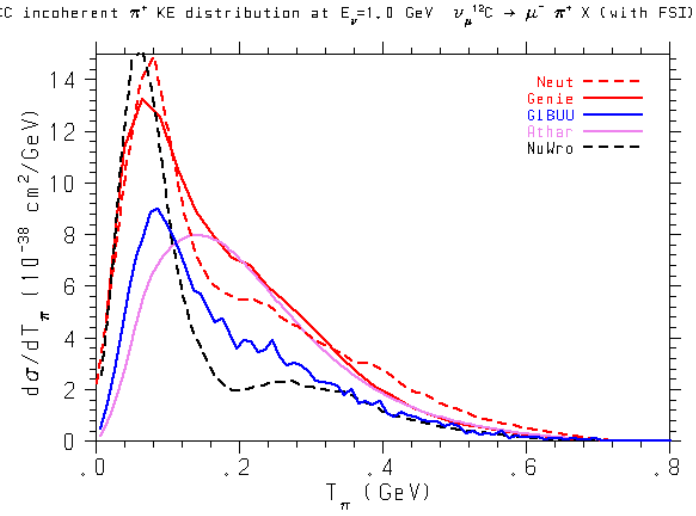



# More detailed distributions



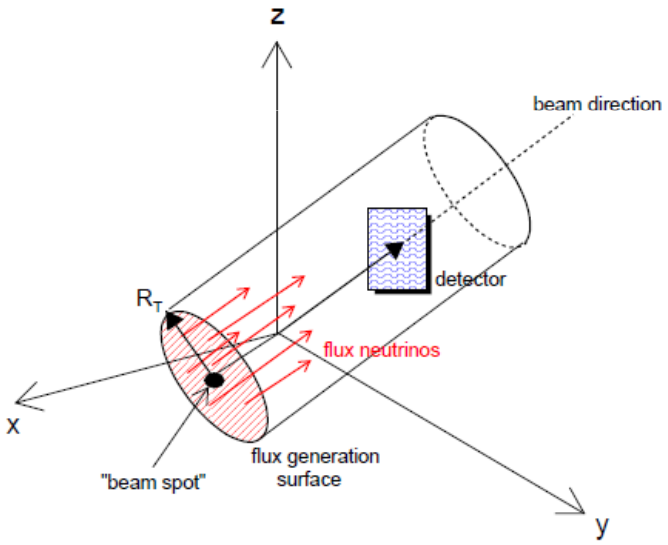



# GENIE features

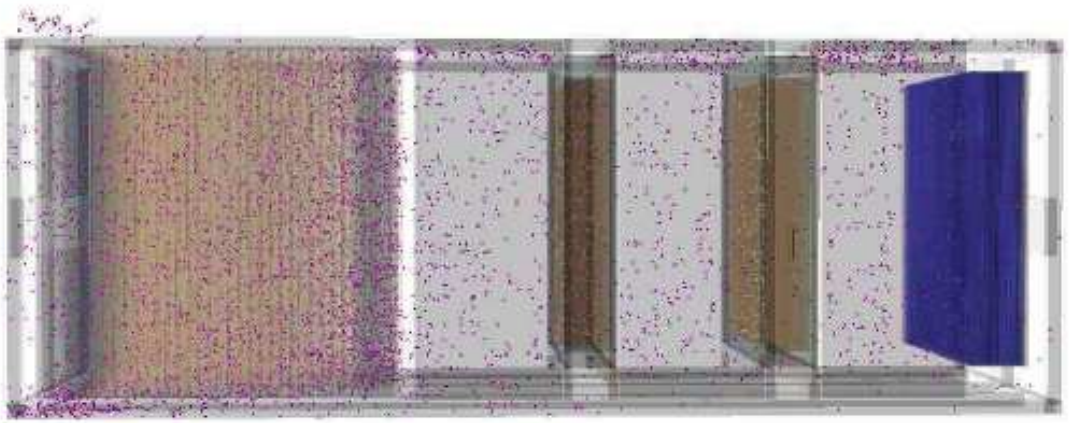
- Previous codes all designed around specific experiment, GENIE is adaptable to different situations
- Geometry
- Reweighting
- Validation
- E.g. Minerva adopted GENIE ~1.5 yrs ago
  - Fully integrated into Monte Carlo
  - Gallagher and I are mainly advisors, young people do the work

# Geometry

- Detector geometry in Root format
- Each element can have variety of nuclei
- Flux files as histogram, in ascii or as full Ntuple.

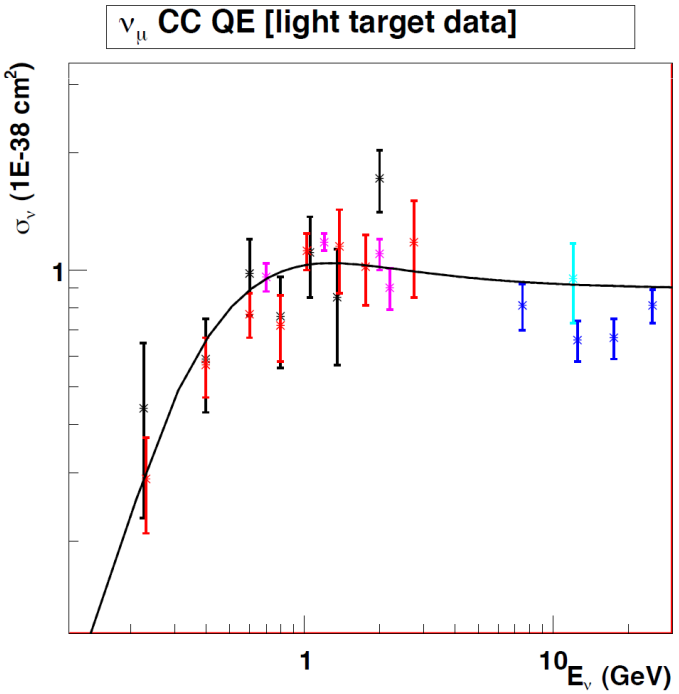


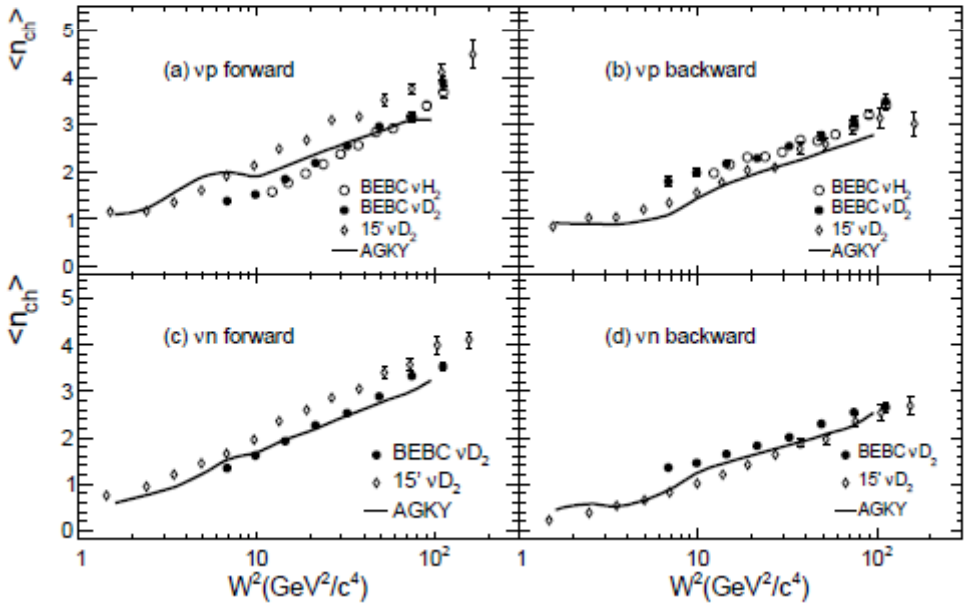

ND280 simulation- shows vertex location



# validation

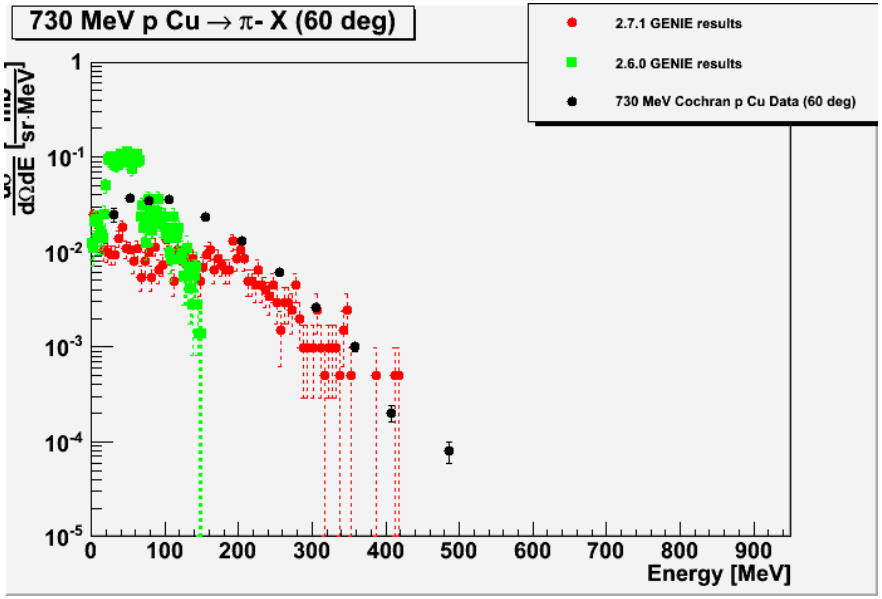
- Coming with new GENIE releases
- ν cross sections
- DIS cross sections
- Hadron-nucleus cross sections

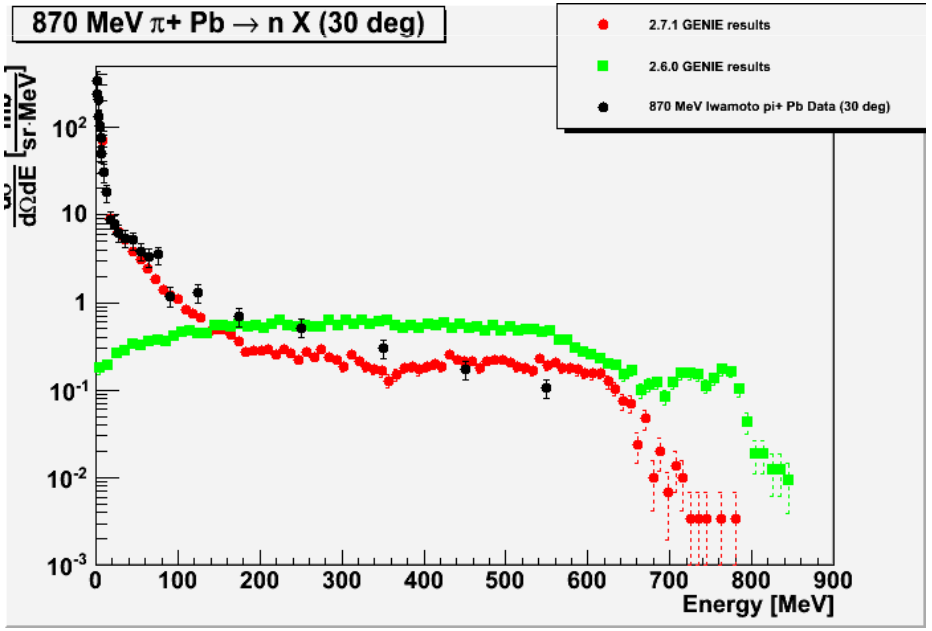


# Validation - hadrons

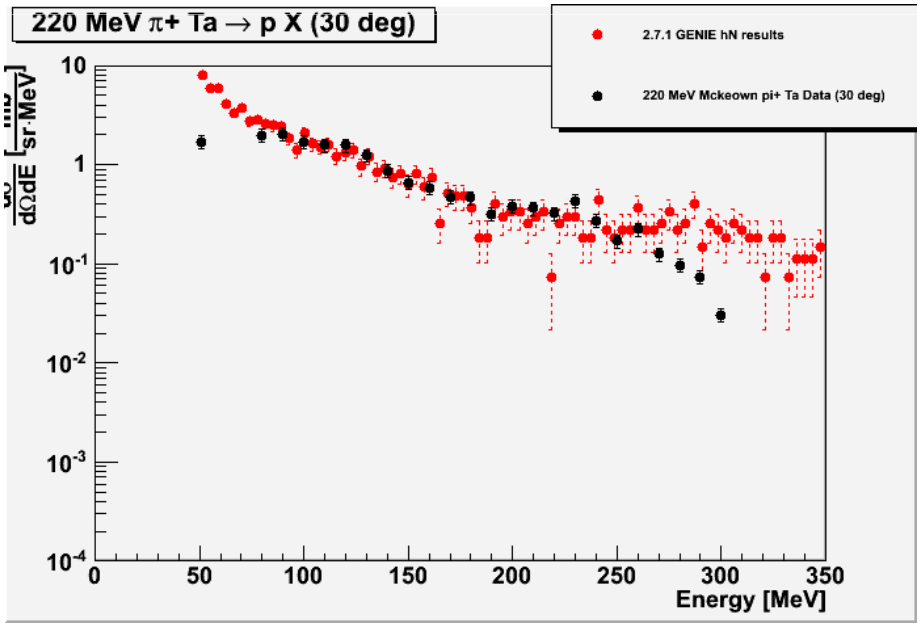
- Separate program – gevgen_hadron
- Run cases with script (probe, tgt, no. of events)
- Run scripts to compare with hundreds of data sets
- Compare 2.6.0 (existing) vs. 2.7.1 (new)
- Show most complicated, detailed distributions

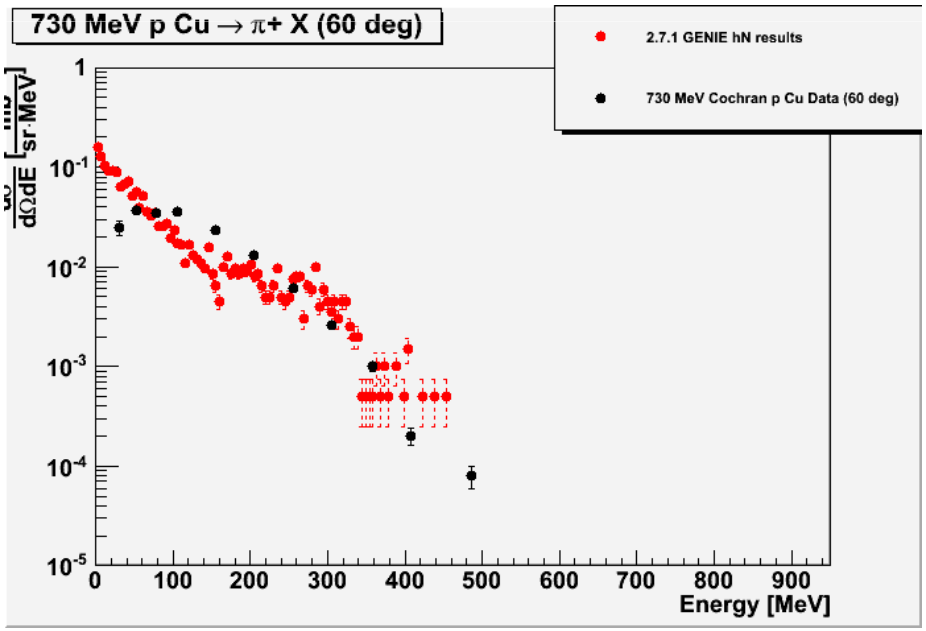


# Validation - hadrons

- This is hN, microscopic Intranuclear Cascade (2.7.1).

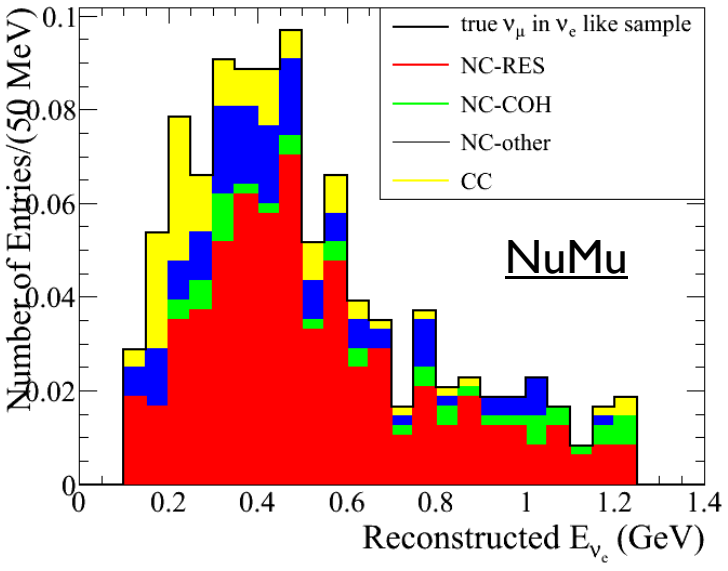


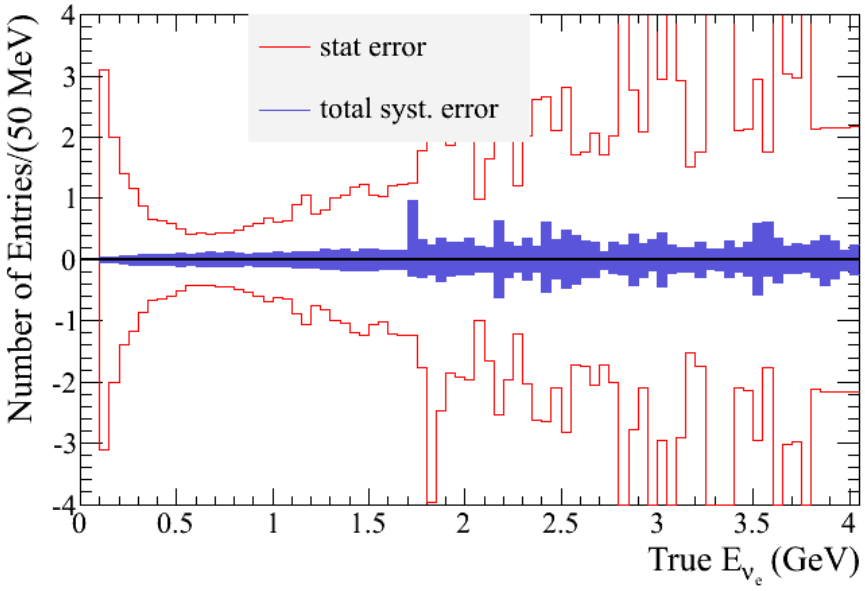
# reweighting

- Developed first for T2K , extended to MINOS and Minerva.
- Cross sections, form factors, and FSI parameters now.
- Examples (2.7.1) from T2K for $\nu_e$ measurement (RAL/Oxford).

SK Background from other channels
Total=9.2% from $\nu_e$, 0.25% from $\nu_\mu$




Systematic error in $\nu_e$ energy



# Model outlook

- Updates to NUANCE only through experiments
- NEUT is being adapted to ND280
  - Extend to heavier nuclei
  - Extend FSI to higher energies
- GENIE (now 2.6.0, future releases)
  - Spectral functions (C, O, Fe) from Benhar
  - Updated hA FSI model, new hN FSI model
  - New coherent model from Hernandez et al.
  - New coherent model from Alvarez-Ruso
  - Costas got funding to bring many of us to RAL last July. Great discussions, but slow progress since then.

# Future

- GENIE used by MINOS(*), NOvA (*), Minerva(*), T2K, MicroBoone(*), INO(*), and LBNE(*). Many developments underway with theorists.
- NEUT used by T2K(*), SuperK(*), and SciBoone(*).
- NUANCE used by MiniBoone(*), SciBoone, SuperK, KamLand, SNO, and T2K.
- We need a standard so that experimental results can be compared. Perhaps, that is GENIE.
- Better theoretical models will be required, but also theory needs improvement.
- New data should drive the field rapidly.