Event Generator Monte Carlo programs in Neutrino Oscillation Experiments
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- oscillation results $\rightarrow$ syst errors, bkgd
- νA (neutrino-nucleus) event generators
- validation, comparisons for νA
- Final state interactions (FSI)
- Link back to oscillations

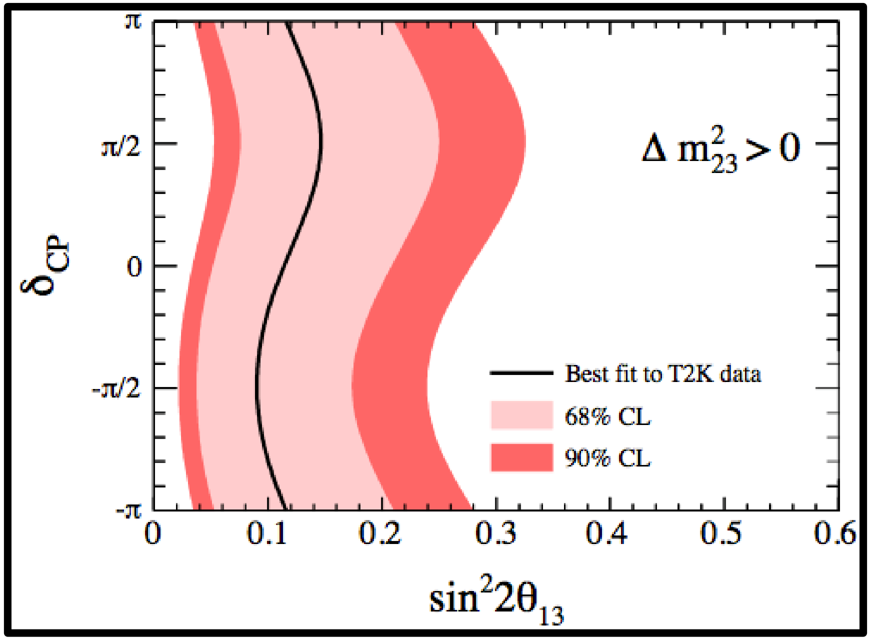
Thanks to Leverhulme Foundation

Introduction

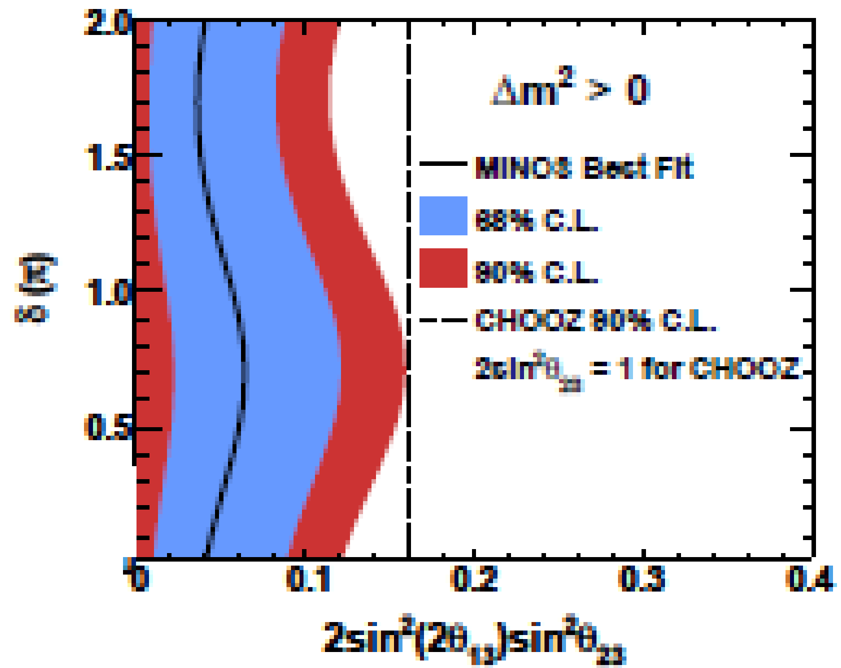
- The main result of accelerator ν experiments is oscillations
  - Fundamental information of mixing, mass differences, (CP violation)
- MINOS (major US expt, my previous expt)
  - Best value of $\Delta m_{23}^2 = 2.32^{+.12}_{-.08} \times 10^{-3}$ ev^2.
  - Recent measurement of $2\sin^2(\theta_{23}) \sin^2(2\theta_{13}) < .12$
- T2K (large Oxford, UK activity – my main reason to be here)
  - Recent measurement of $0.03 < \sin^2(2\theta_{13}) < .28$ for 6 events with 1.5 ± 0.3 estimated background events.
  - Both are 90% CL (Feldman-Cousins) for normal hierarchy and $\delta_{CP}=0$.
- Neither result is a 'discovery' ($<3\sigma$), but still very exciting.
- This talk is about major components of the background and systematic error estimation, not a simple subject.

Best representation of ν_e results with CL.

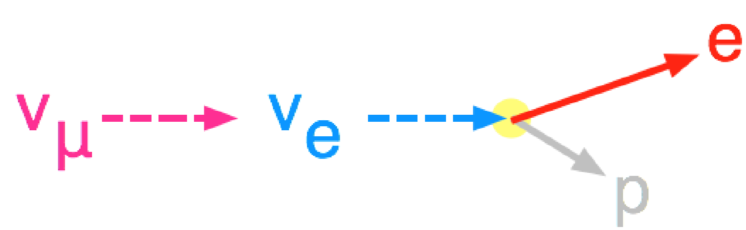
T2K (1.43 x 10^{20} POT)



MINOS (8.2 x 10^{20} POT)

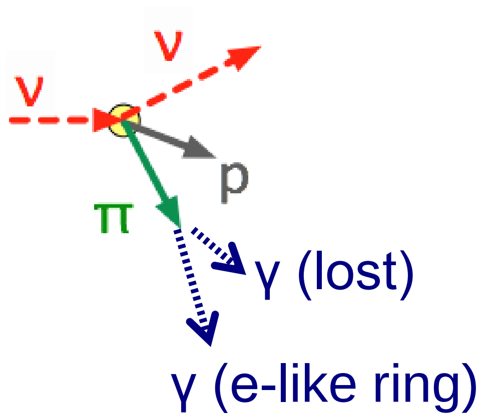


This is an *appearance* experiment, much harder than ν_μ *disappearance* expt.

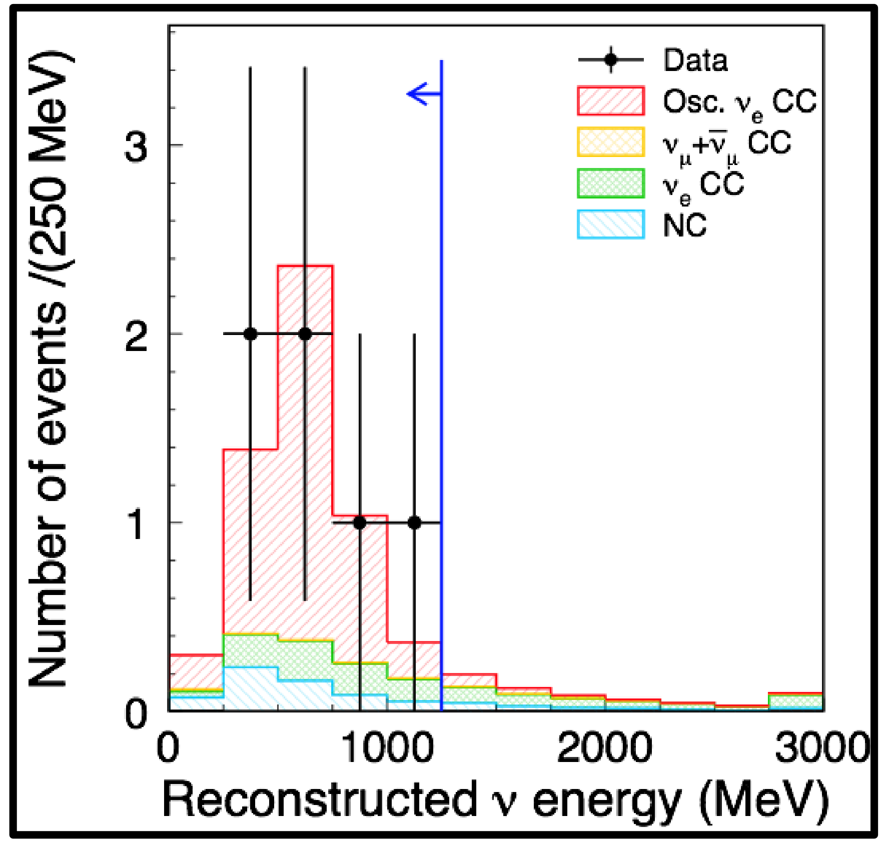


Neutral current π^0 production background

- Jargon: NC means mediated by Z^0, ν in final state, CC means mediated by $W^\pm$, μ in final state.



- 40% of bkgd in T2K ν_e. (beam ν_e is 53.3%)
- Estimate comes from **MC** and mixed data.



Systematic errors - T2K

$$N_{SK}^{exp} = R_{ND}^{\mu,\,Data} \times \frac{N_{SK}^{MC}}{R_{ND}^{\mu,\,MC}}$$

$$\frac{\int \Phi^{SK}_{\nu_\mu(\nu_e)}(E_\nu) \cdot P_{osc.}(E_\nu) \cdot \sigma(E_\nu) \cdot \epsilon_{SK}(E_\nu)\ dE_\nu}{\int \Phi^{ND}_{\nu_\mu}(E_\nu) \cdot \sigma(E_\nu) \cdot \epsilon_{ND}(E_\nu)\ dE_\nu}$$

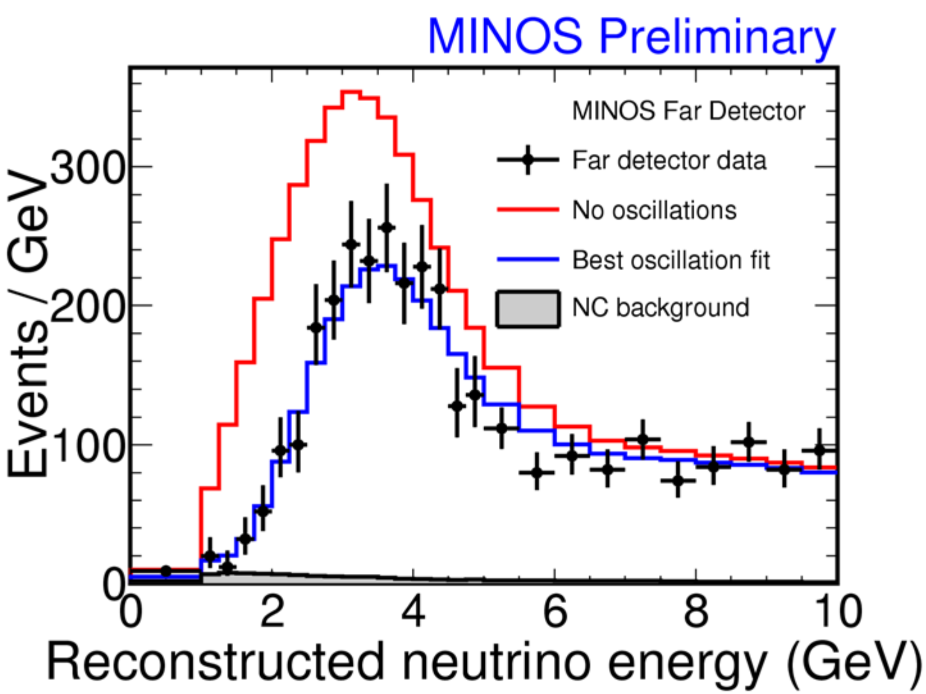
- ν cross section is important as components (QE, NCπ0, CCπ... set scale for various bkgds as they are calculated in MC.
- Jargon: QE=quasielastic: ν interacts with bound nucleon as if *almost* free. At T2K energies, matters.

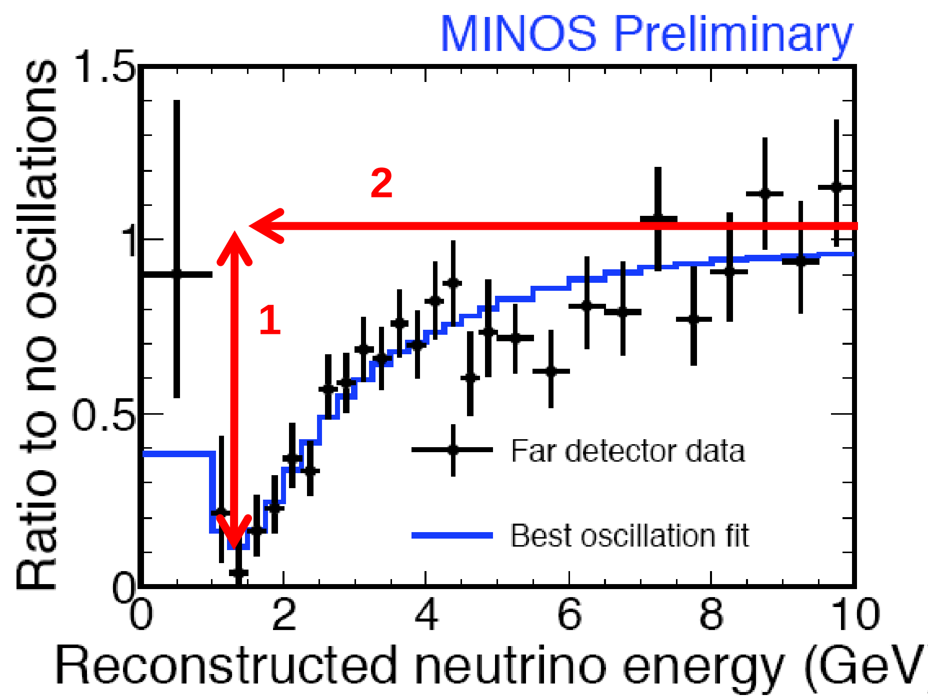
For $\sin^2(2\,\theta_{13})$ =0, smaller for real value

error source	syst. error
(1) ν flux	$\pm 8.5\%$
(2) ν cross section	$\pm 14.0\%$
(3) Near detector	${}^{+5.6}_{-5.2}\%$
(4) Far detector	$\pm 14.7\%$
(5) Near det. statistics	$\pm 2.7\%$
Total	${}^{+22.8}_{-22.7}\%$

Calculation of E_ν (disappearance)

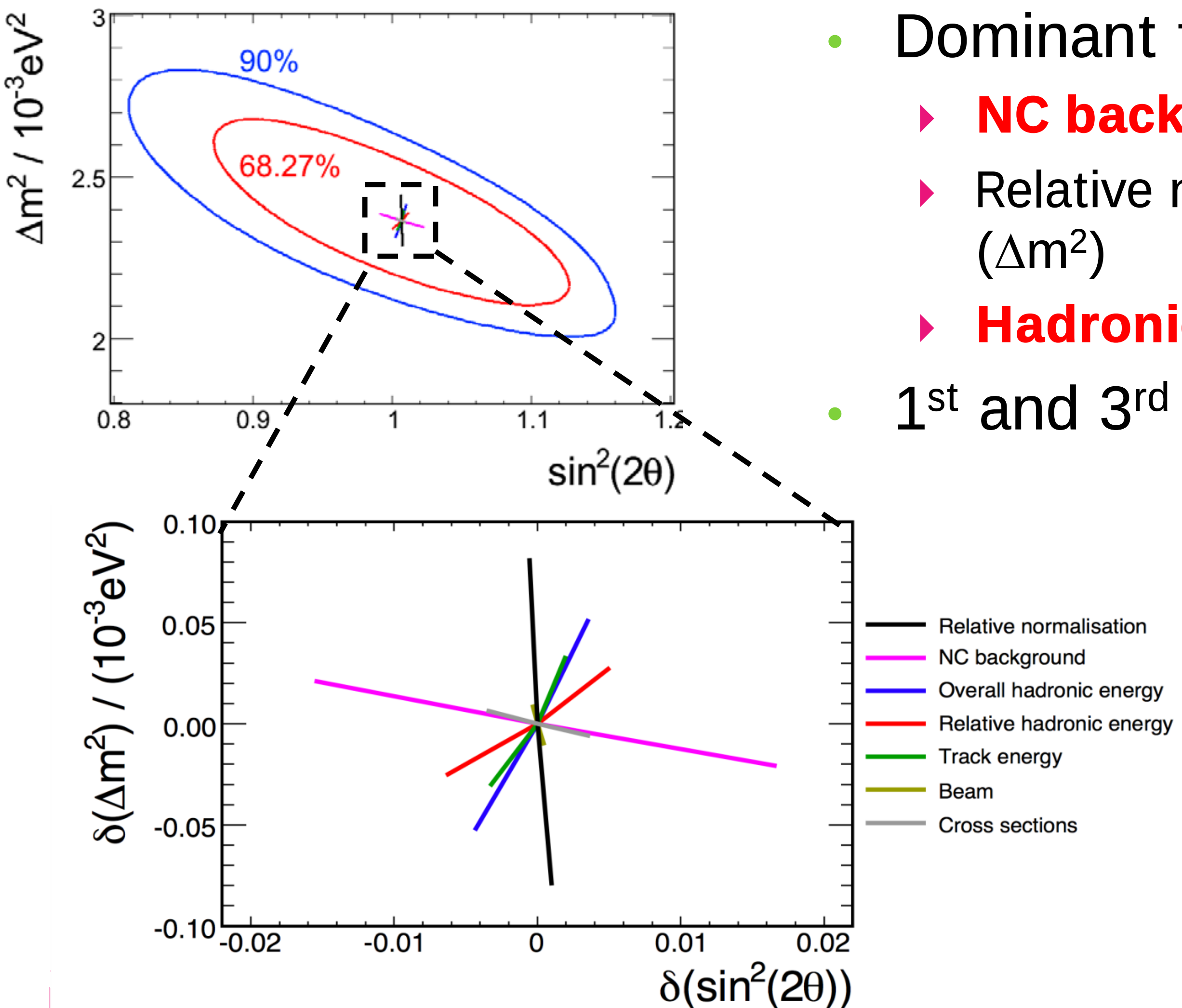
- MINOS must calculate $E_\nu = E_\mu + E_{hadrons}$ to get θ and Δm^2.
- As a sampling calorimeter (π, N), MC corrections important. They estimate syst error in E_ν of ~8%.





$$P(\nu_\mu \to \nu_\mu) = 1 - \underset{1}{\boxed{\sin^2 2\theta}} \sin^2(1.27 \underset{2}{\boxed{\Delta m^2}} L / E)$$

Systematic errors in MINOS ν_μ disappearance (2008) which I helped with.

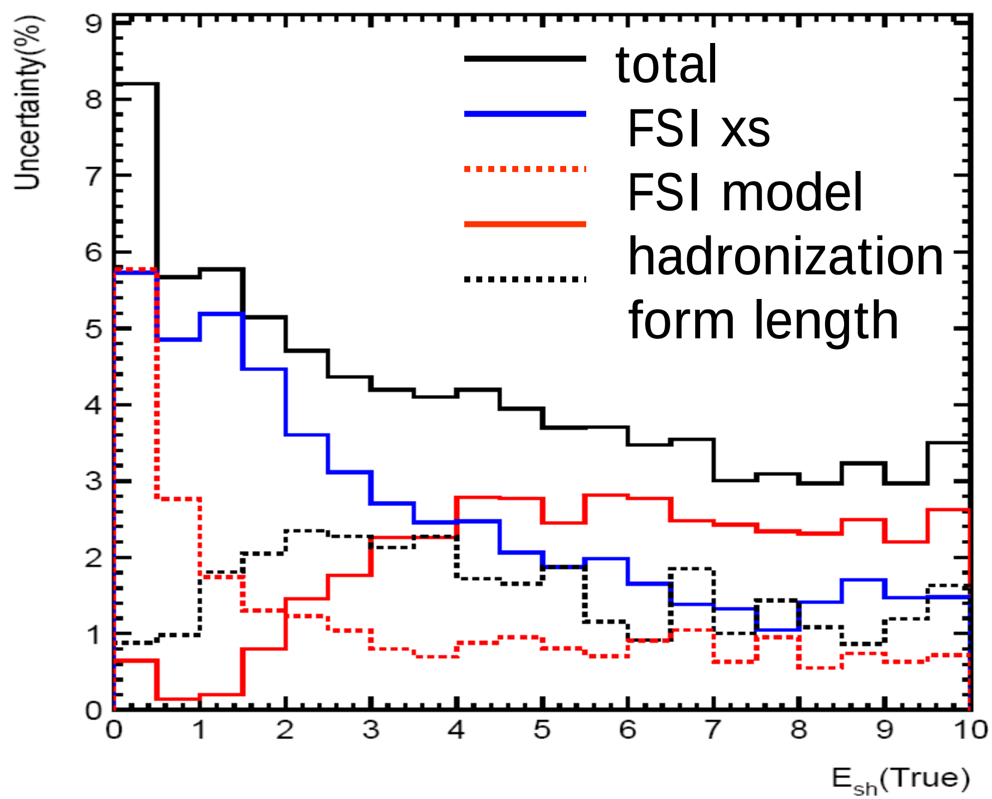


- Dominant terms
  - **NC background (θ)**
  - Relative normalization (N-F) (Δm^2)
  - **Hadronic energy (Δm^2)**
- 1st and 3rd come from MC.

Systematic errors from FSI (2008)

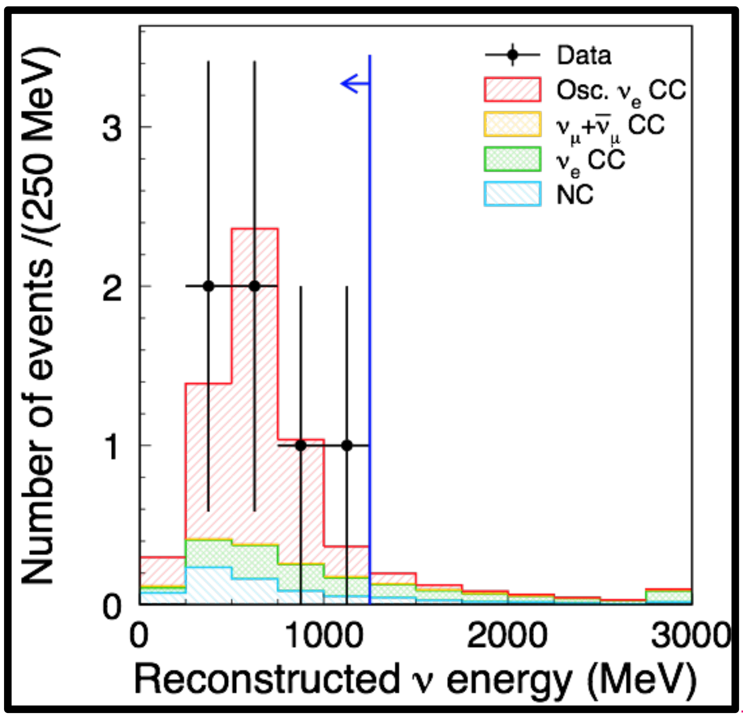
- Reweight each of these quantities according to 1σ estimates in table.
- Gives results in figure for error in total hadronic energy.

branching ratios	
parameter	1σ uncertainty (%)
π charge-exchange	50
π elastic	10
π inelastic	40
π absorption	30
π secondary π production	20
N absorption	20
N secondary π production	20
N elastic	30
cross-sections	
parameter	1σ uncertainty (%)
π total cross-section	10
N total cross-section	15

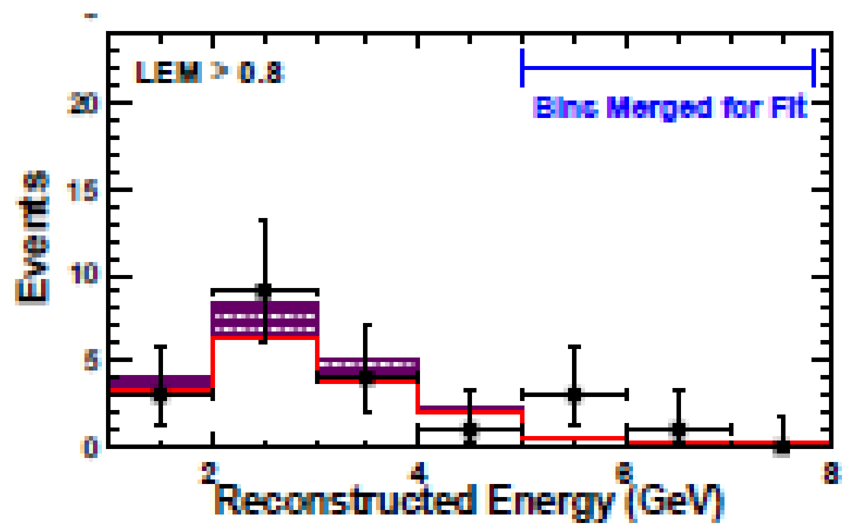


Calculation of E_ν (appearance)

- Beams are wideband, at least 1 GeV wide.
- E_ν must be calculated event by event.
  - MINOS is at few GeV and above, use calorimetry
  - T2K below 1.2 GeV, seek QE events and calculate E_ν from muon

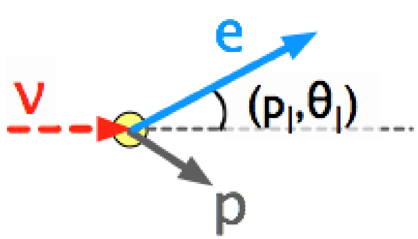


Now, just count. Need shape later.

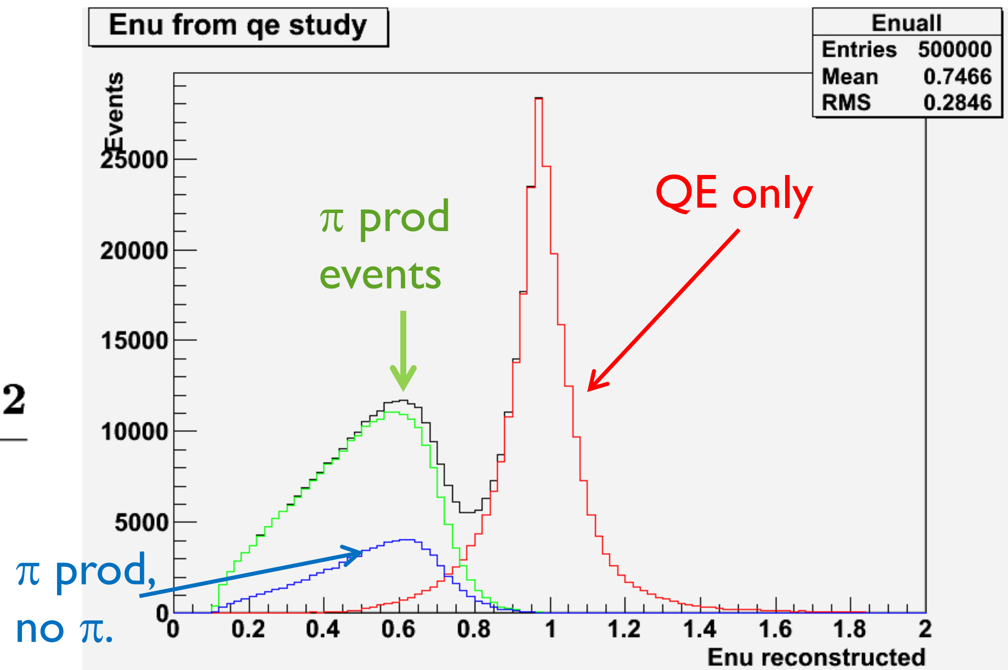


Success depends on ability to ID qe

- Nuclear corrections: assume m_n decreased by BE
- Get a width from Fermi momentum (matters for T2K)
- Real problem is pion production followed by π absorption.
- This must be simulated by MC. Fig. below is for 1 GeV ν_μ C.



$$E_{rec} = \frac{m_n E_l - m_l^2/2 - (m_n^2 - m_p^2)/2}{m_n - E_l + p_l \cos\theta_l}$$



Event Generators

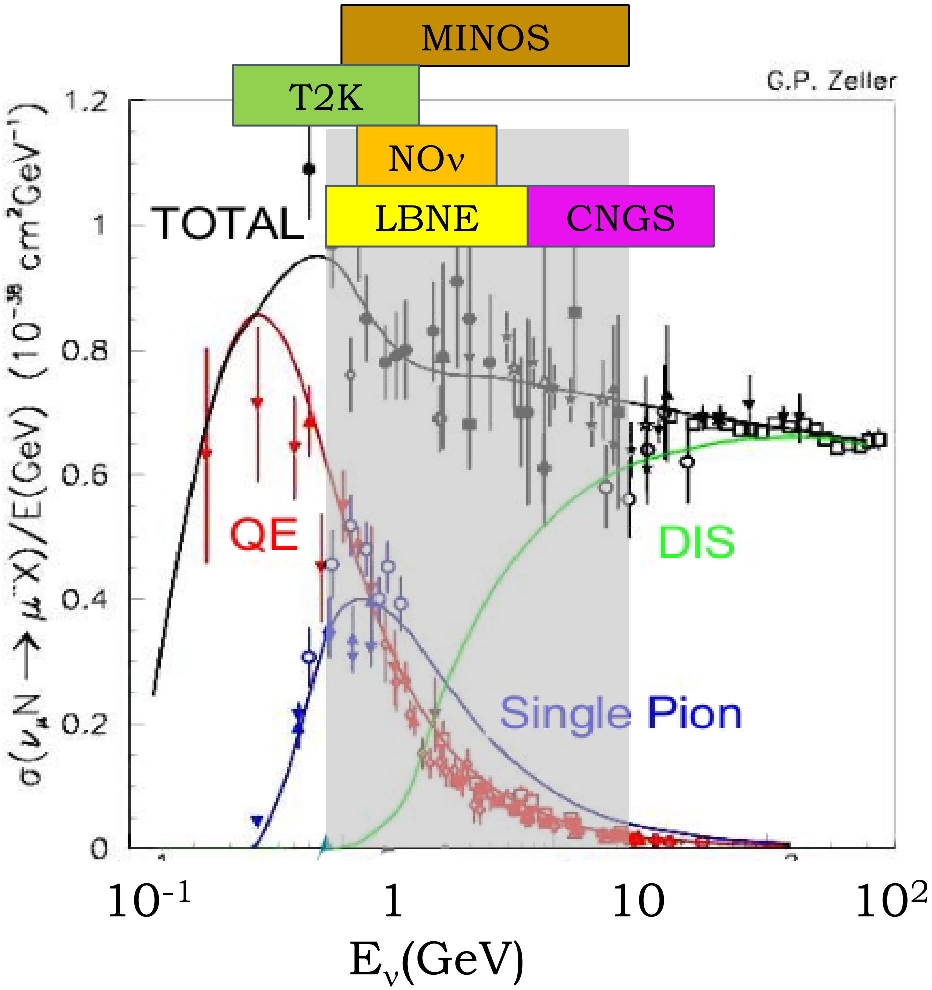
- E.g. PYTHIA (Lund model) in collider physics
- Best to have a universal method that is tried and true.
- ν experiments are smaller than collider experiments, traditionally use home-grown boutique programs.
- GENIE is the first *universal* generator
  - Root-based code
  - C++ object coding
  - Easy to switch between models
  - Root-based geometry
  - Exactly reweightable with many parameters
  - Choice of almost all modern experiments
  - MINOS uses GENIE precursor, T2K uses NEUT with GENIE as a check. (Both are largely Fortran.)

The task

- No detector technology in use is perfect.
  - Water Cerenkov misses all hadrons (π, p, n) below threshold
  - Scintillator misses many neutrals (γ, n)
  - Liquid argon would be great.
- Neutrino event generators have huge goal
  - 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.

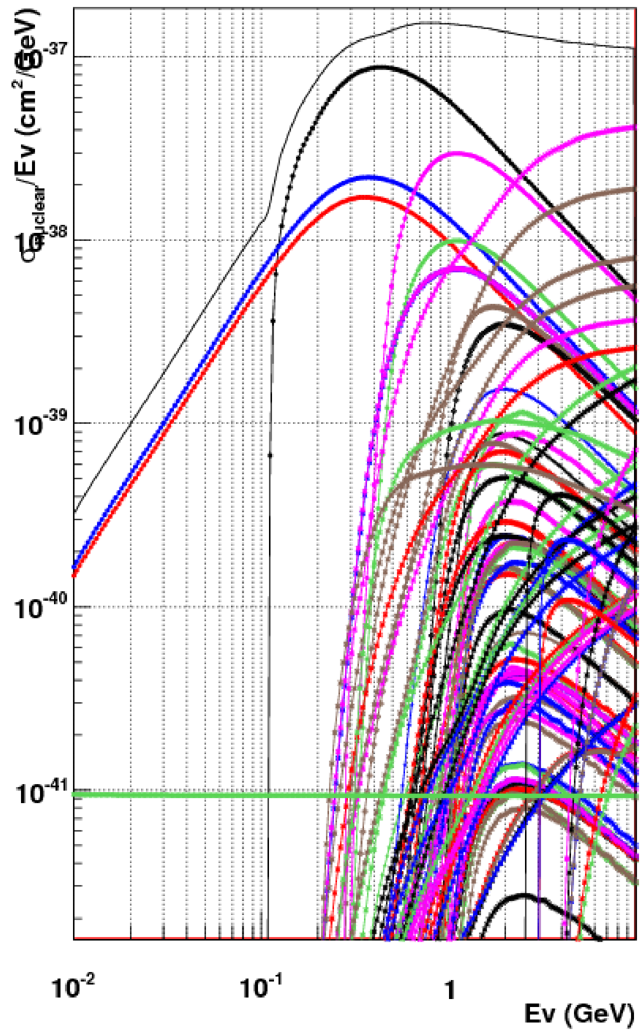
Dominant processes (CC σ_{tot}/E for N target)

- Cross section at HE rises linearly with energy.
- At low energies, quasielastic (QE) dominates. (e.g. $\nu n \rightarrow \mu^- p$)
- Single pion production (1π) (e.g. $\nu p \rightarrow \mu^- \pi^+ p$)
- Deep inelastic scattering (DIS) dominates at HE. (e.g. $\nu p \rightarrow \mu^- \pi^+ \pi^0 \pi^0 p$)
- same plot for nuclear tgt would have almost nothing.



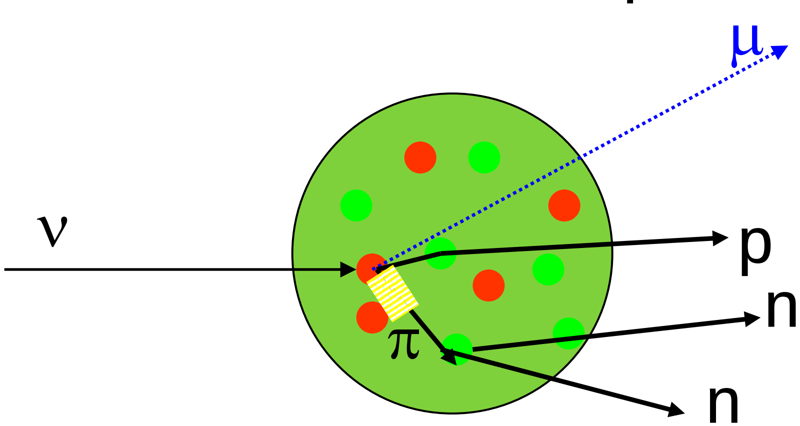
cross sections in GENIE

- GENIE has complete kinematics for all cross sections at all energies.
- Here, we show ν_μ Carbon:
  - qe
  - All resonances
  - All coherent
  - DIS of all flavors
- Input spline functions used to generate events.
- Works because models are simple.



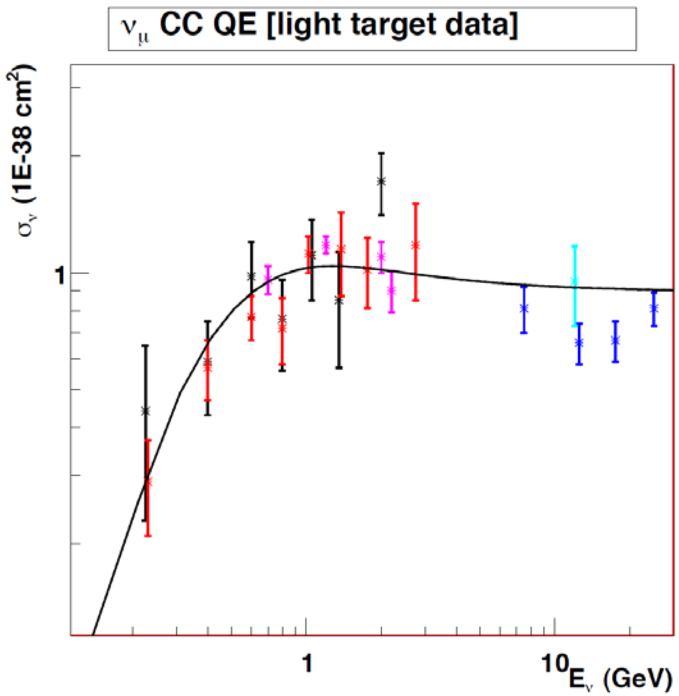
How we do it

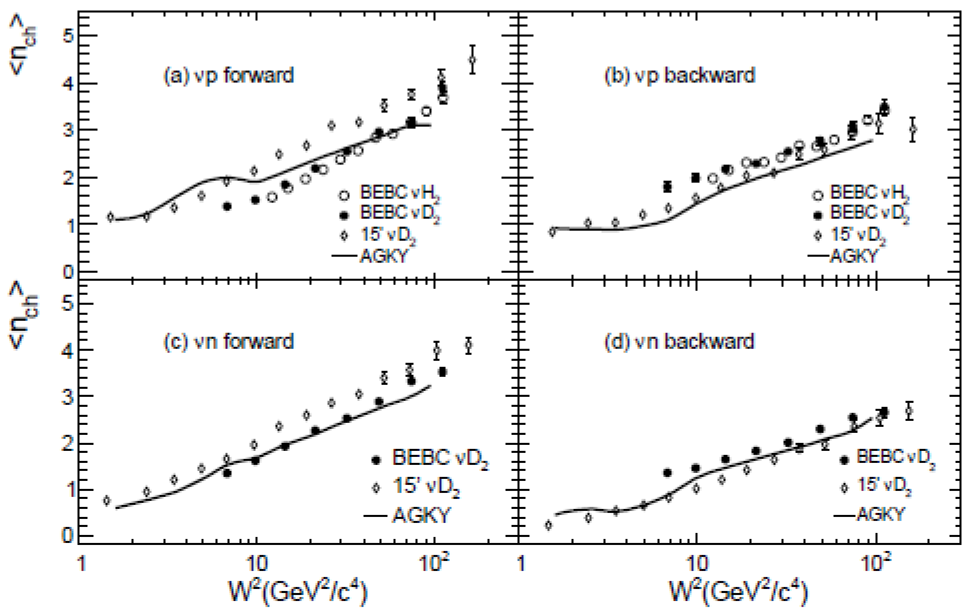
- There is *very little* νA data, *models required*
- Reaction model in Intranuclear Cascade (INC) (nucleons~free)
- Venerable models for qe (Llewellyn-Smith) and pion production (Rein & Sehgal) on p,n - updates? new data!
- Fit to νN Deep Inelastic Scattering data used for models.
- Nuclear model is relativistic Fermi Gas (old!) from (e,e')
- Final state interaction (FSI) comes from fits to πA , pA data [complicated! My work.]



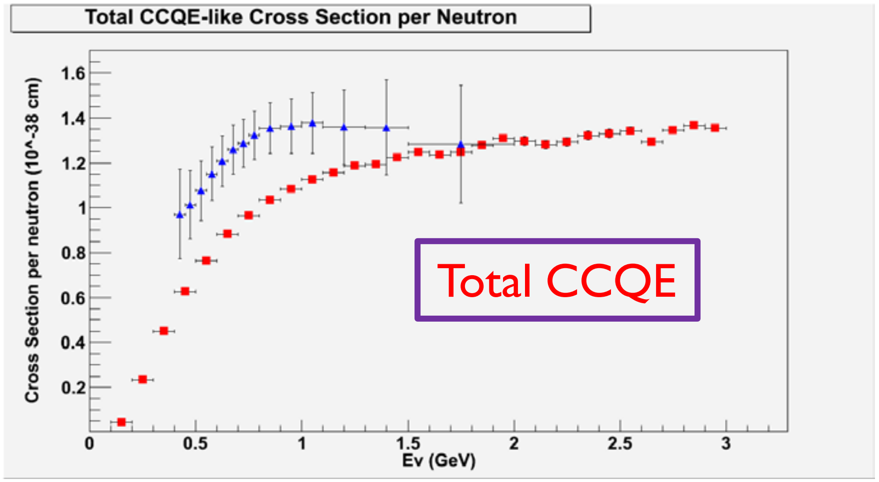
validation

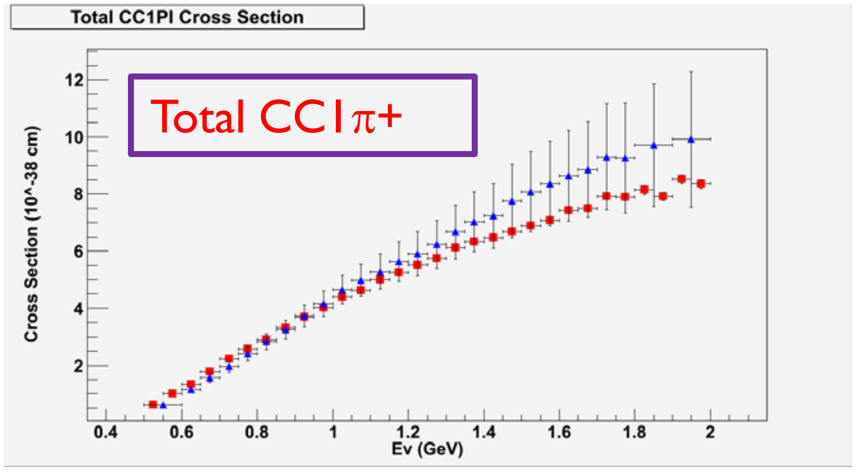
- Very little old ν data (mostly H2 and D2 targets)
- At high energies, see mainly DIS and coherent (large)
- Very little at lower energies with nuclear targets

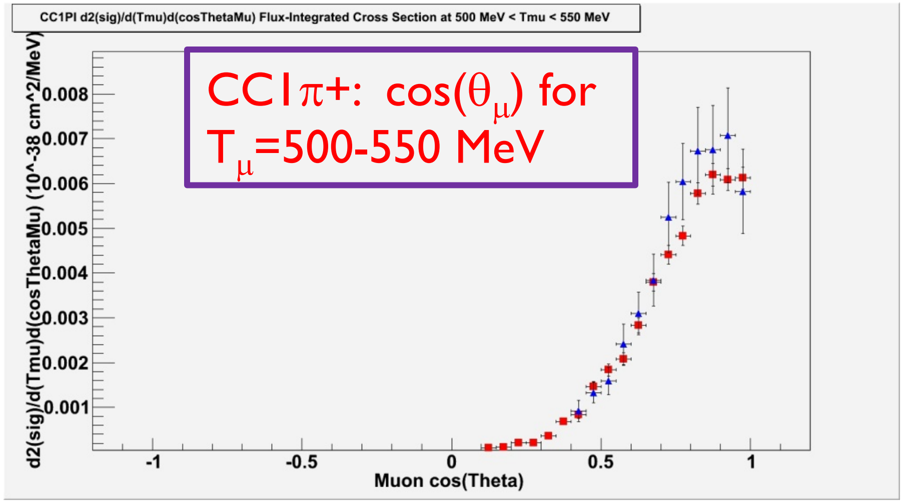


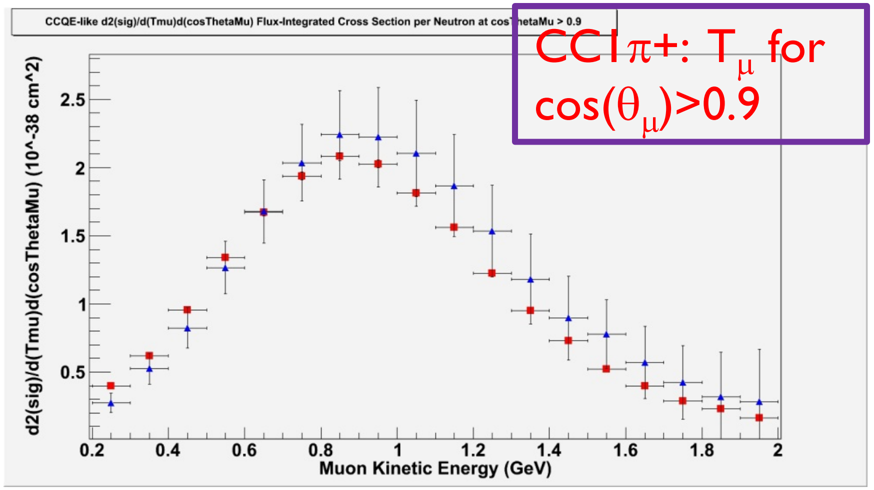


Modern validation – MiniBoone (detailed exam of CCQE and CC1π+) [no tuning]



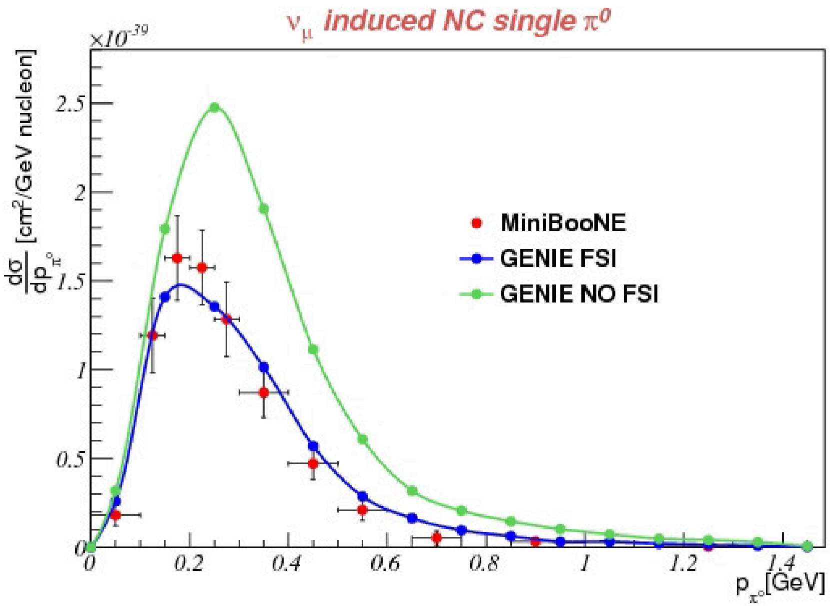


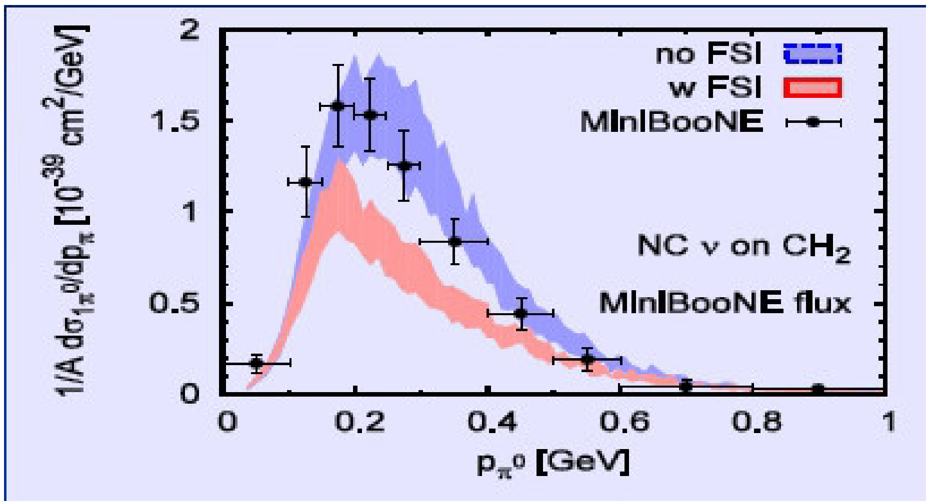




Modern validation – MiniBoone NCπ^0

- Remember, this is a cross section important for ν_e background
- Plot on right comes from leading theorist – Mosel (Giesen) has most complete model. Left plot is from GENIE.
- We agree on changes due to FSI but not on basic result.
- Nevertheless, checking with theorists and modelers matters!



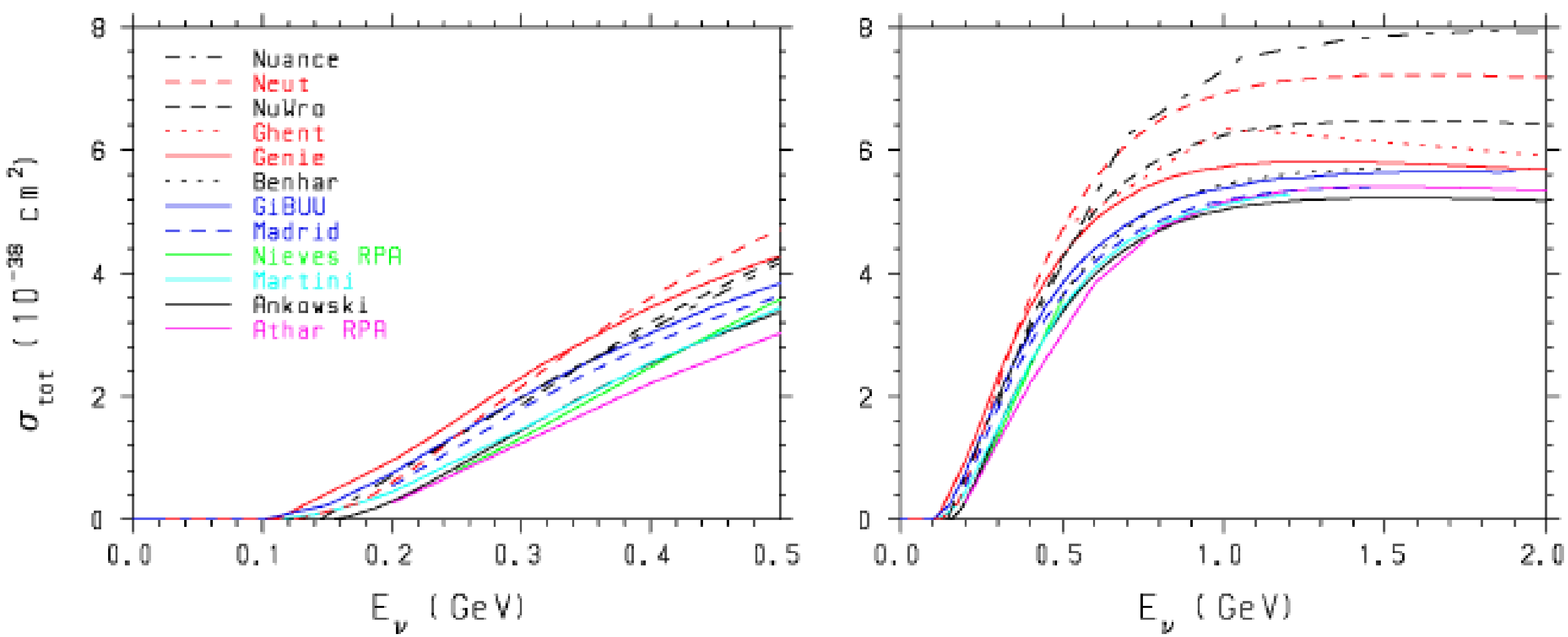


NUINT09 theory exercise

- NUINT is a series of conferences studying ν cross sections.
- 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 ν_μ C reactions at 0.5, 1, 1.5 GeV (qe, pi prod, and coherent). ~20 distributions well matched to T2K.
- 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/

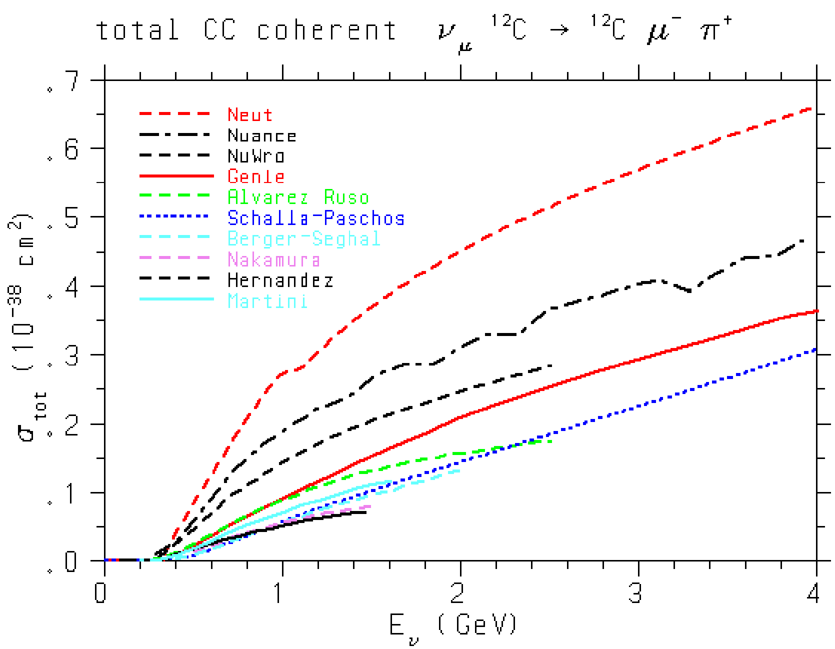
Physics comparison - qe

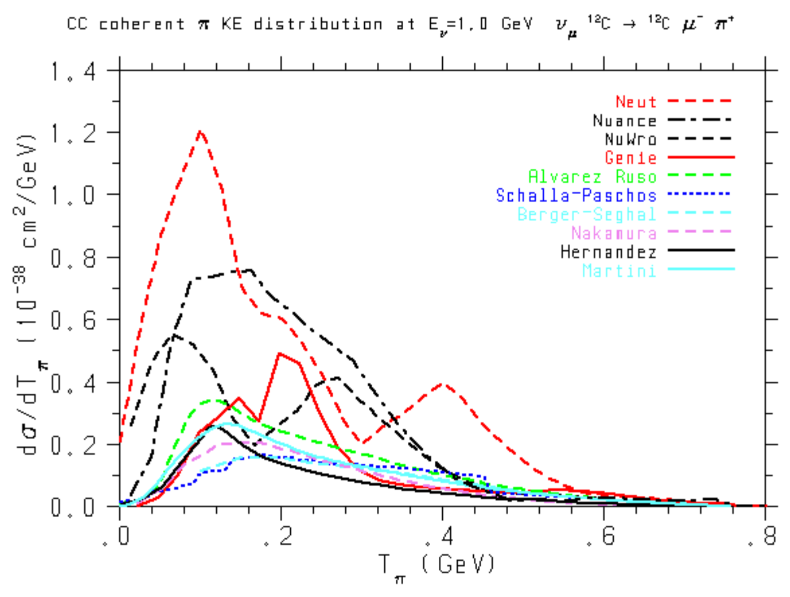
- Very sensitive to Nuclear structure
  - Fermi Gas or spectral functions + correlations?
  - What is M_A (sets Q^2 dep in nucleon form factor)? (experiments set it to match their data)
- FSI important if recoil nucleon detected (better event ID)



Coherent pion production

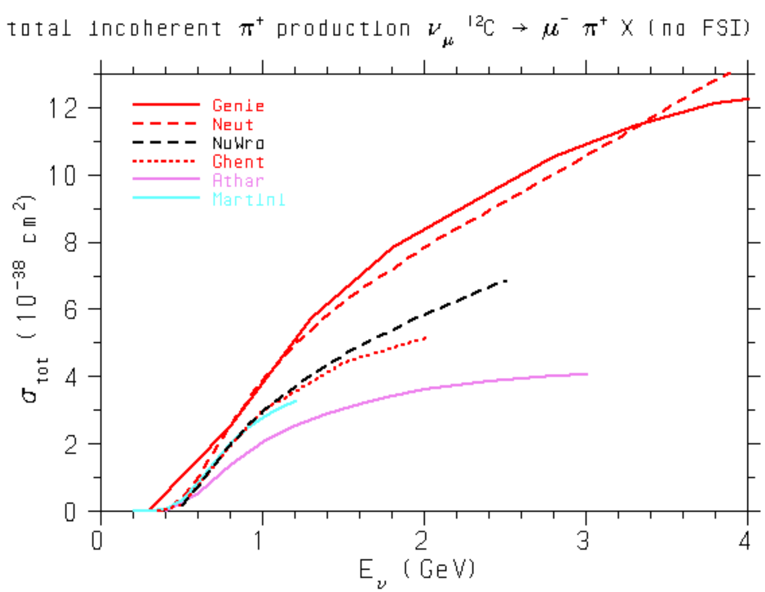
- Rein-Seghal used in all MC event generators, designed for high energy. (recently adapted for lower energies)
- More recent models from many theorists (pion prod from nucleon + pion optical potential) [best for $E_\nu < \sim 2$ GeV, limit is pion FSI]

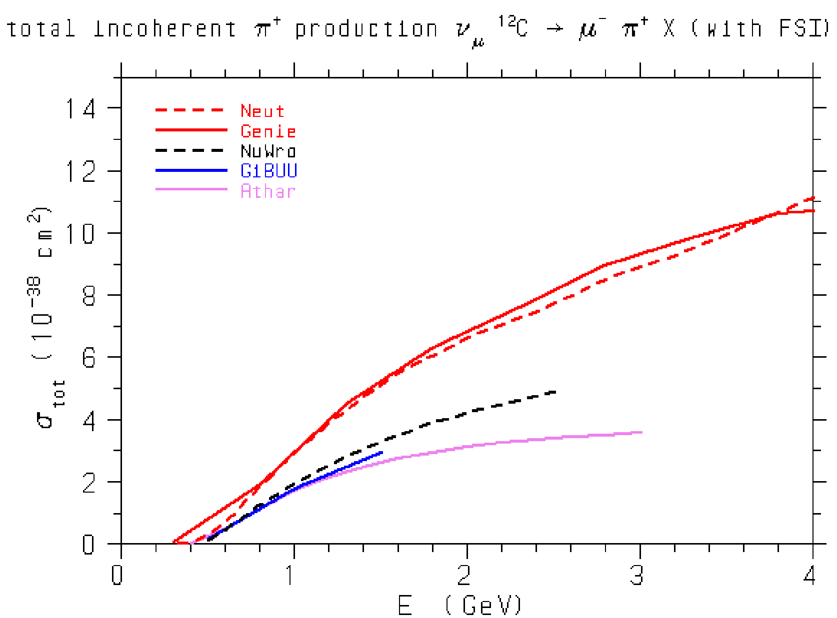




Incoherent (regular) pion production

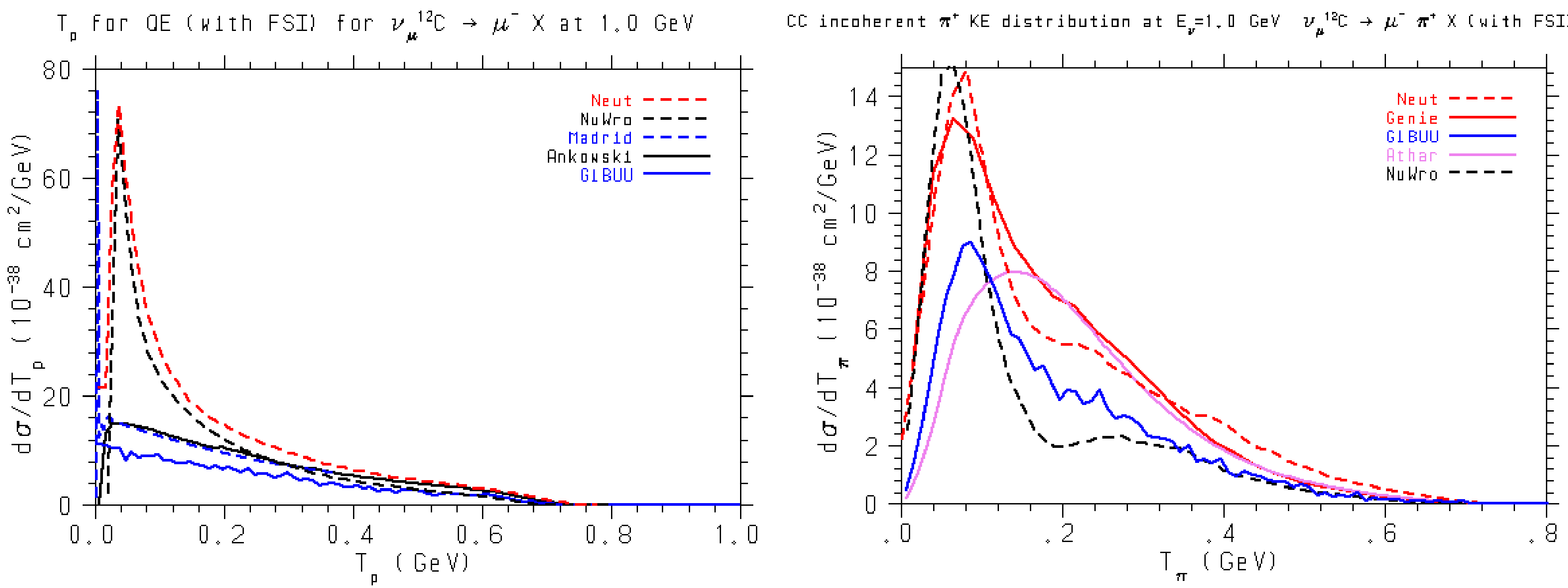
- Core is Rein & Seghal (resonance) and Bodek & Yang (non-resonant). Could be improved.
- Calculation is for CC1π.
- Form factor, nuclear structure, especially FSI matter.
- No Data, theory poor guide. (MiniBoone+Minerva+T2K)





Role of FSI is big

- ν_μ carbon at 1 GeV
- proton KE from QE (left), π KE from CC1π (right)
- Theorists have little or no FSI, EG have full FSI.
- All curves right plot except purple have full FSI.



Quick timeout for end of Introduction

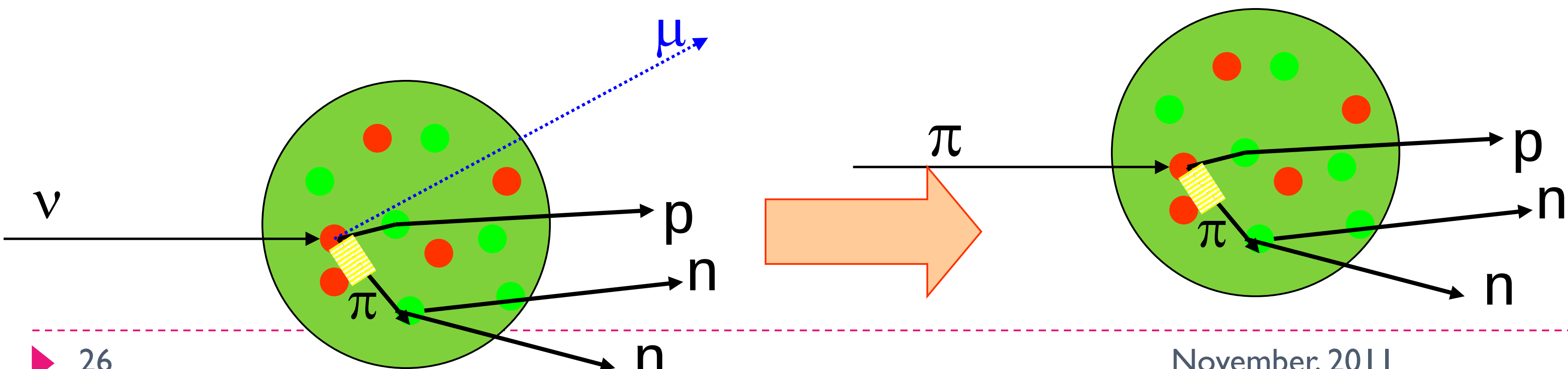
- ν oscillation experiments depend heavily on Monte Carlo.
- ν Monte Carlo simulations start with event generator.
- ν event generators are not yet universal, but we're trying.
- One of the big problems with ν event generators is FSI.
- Rest of talk is my work in FSI. This turns out to be nuclear physics, closely related to my PhD thesis.

What does FSI do to ν expts?

- ν expts want to make clean identification of physics by topology of events and **FSI masks topologies**.
- Calculate E_ν from QE events.
  - Ideally, ν interacts with single neutron and we see products. $\nu_\mu\ n \rightarrow \mu^-\ p$. In reality, n isn't free and p must get out of nucleus.
  - $\mu + p$ ID is much better, but ~35% of protons have significant FSI.
  - μ doesn't give clean ID because pion prod kinematics overlap QE.
  - Not all pion prod events have pion in final state (~25% absorption).
- Needs for π, p at kinetic energies <~1 GeV (T2K)
  - Overall interaction rates
  - Topology changing interaction rates, e.g. $p \rightarrow n$, $\pi \rightarrow p$ or n.

General Characteristics of models
Intranuclear Cascade (INC), real and inspired.

- hN is straightforward INC
  - Uses free 2- and 3-particle free cross sections + Fermi motion
  - Success comes from importance of quasielastic reaction mechanism in nuclear physics *and* existence of PWA data.
- hA is simplified INC
  - Construct models of full chain of events
  - Uses simple representations of hN code, data, and intuition.
  - Easily reweighted (exact) because **each particle has at most 1 interaction as it propagates through residual nucleus**.



Basic outline

Hadron in nucleus
produced at a principal vertex
(e.g. pion production)

Formation time = **Free step**
Step hadron through nucleus in 0.1 Fm steps. Assess probability of interaction with $\lambda(E,r)=1/\rho(r)\sigma(E)$.

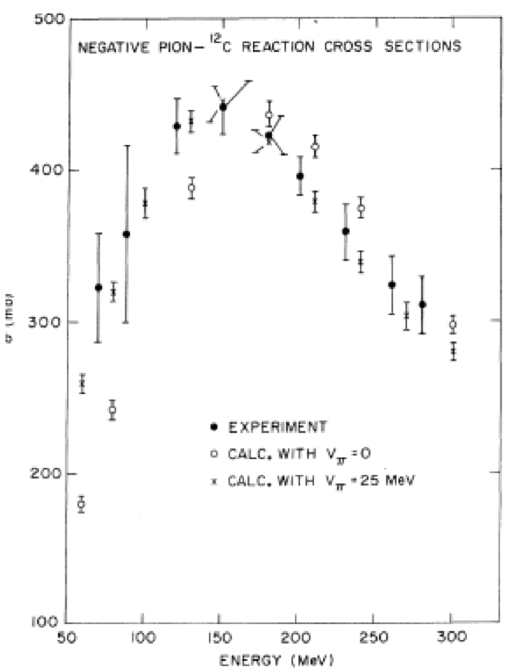
default

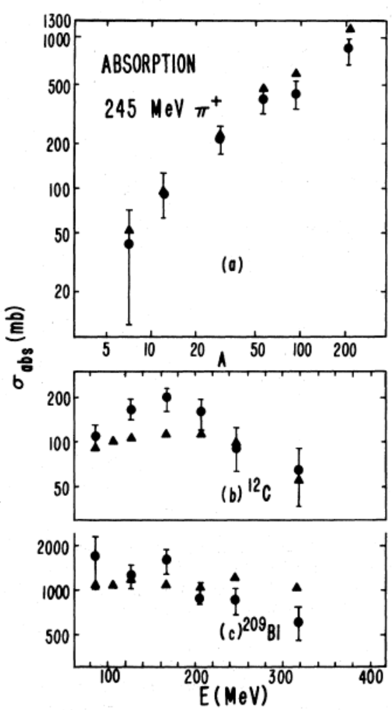
hA model
- Choose interaction from list (data, models, intuition)
- Elas, Inel, CEX, abs (KO), pi prod
- Choose kinematics by models, phase space and exit.

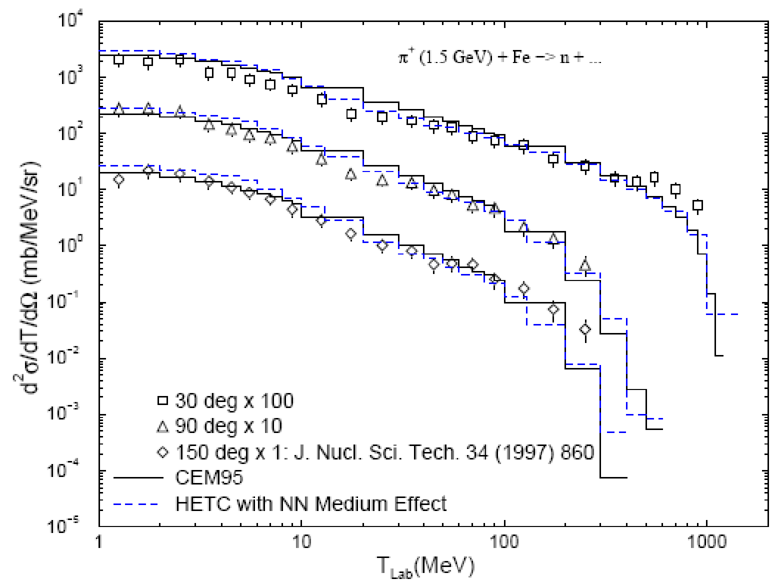
hN model
- Choose interaction according to list (data, models, intuition)
- Elas, CEX, π prod, abs, pre-eq
- Choose kinematics by PWA model
- Add particles to stack until all out.

INC models common in hadronic physics

- Inelastic reactions, esp. particle production processes.
- Only pion induced reactions shown here, but still some impressive examples. (GEANT, FLUKA...)
  Harp (74) Fraenkel (82) Mashnik (95)



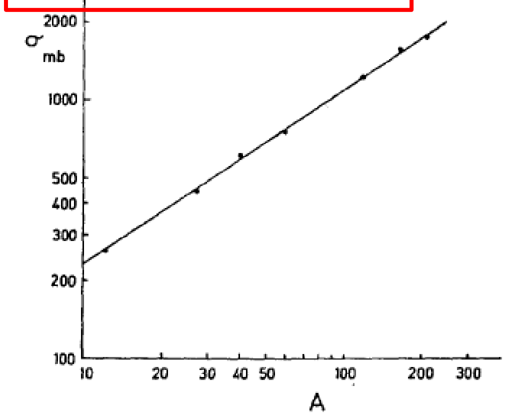


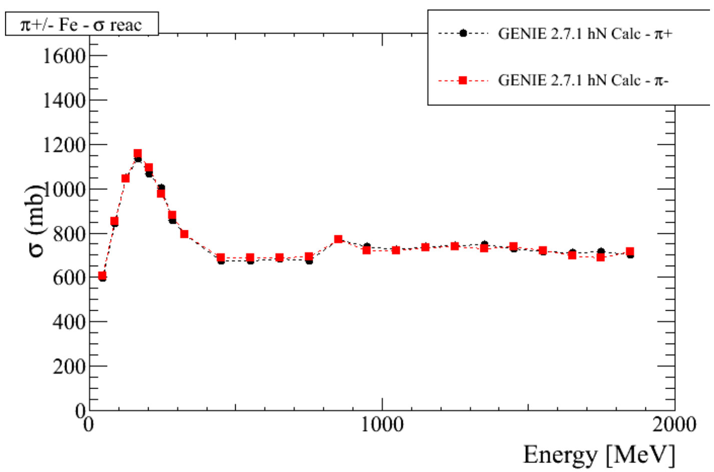


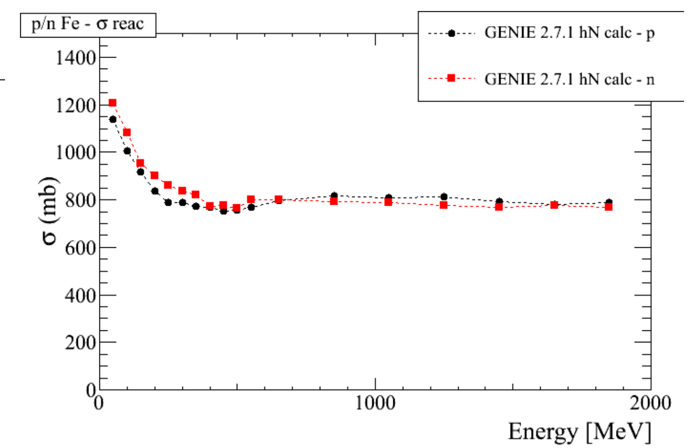
Organizing principle #1
nucleus is ~black to hadrons

- Mean free path ~ few fm, total reaction cross section ~πR^2. Jargon: σ_{reac} measures strength of all interactions other than elastic scattering. $\sigma_{reac}=\sigma_{cex}+\sigma_{inel}+\sigma_{abs}+\sigma_{\pi prod}$
- Exceptions:
  - Pions at KE~200 MeV have a strong resonance (Δ) (more than black)
  - Low energy nucleons have strong interaction and large 'size'

1 GeV/c π-
Slope=.677±.007

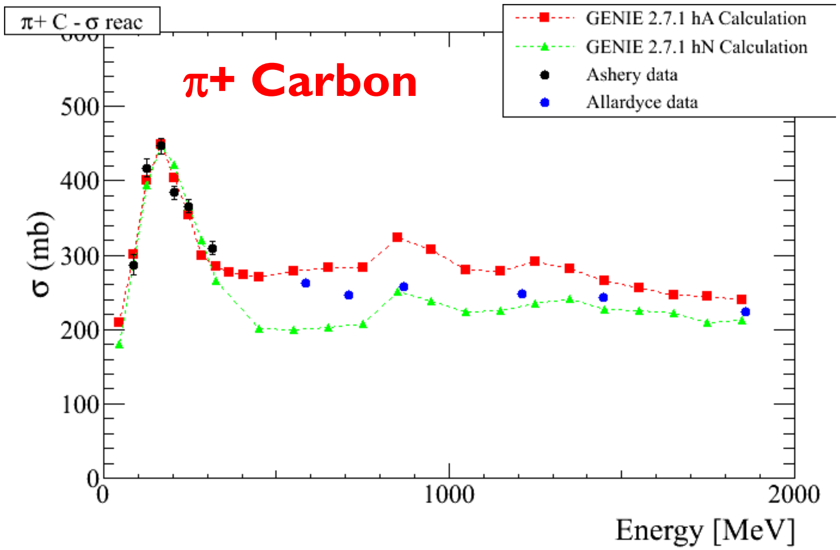


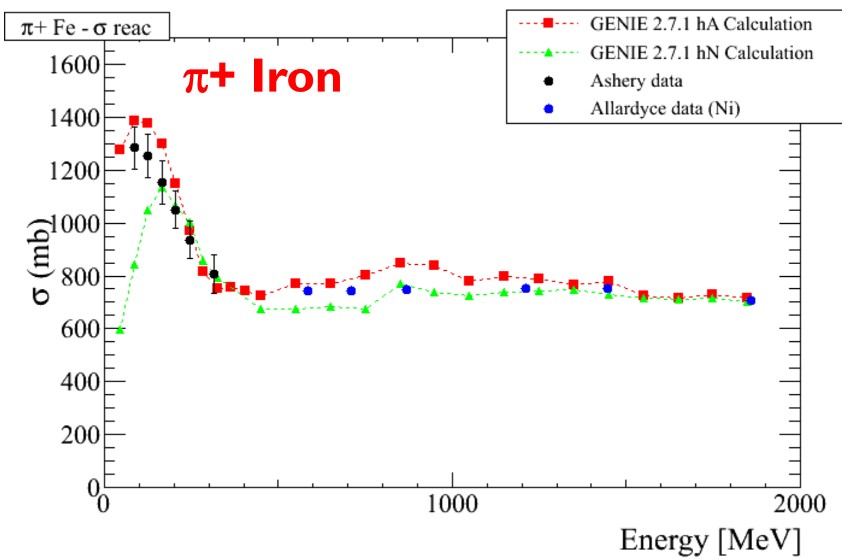


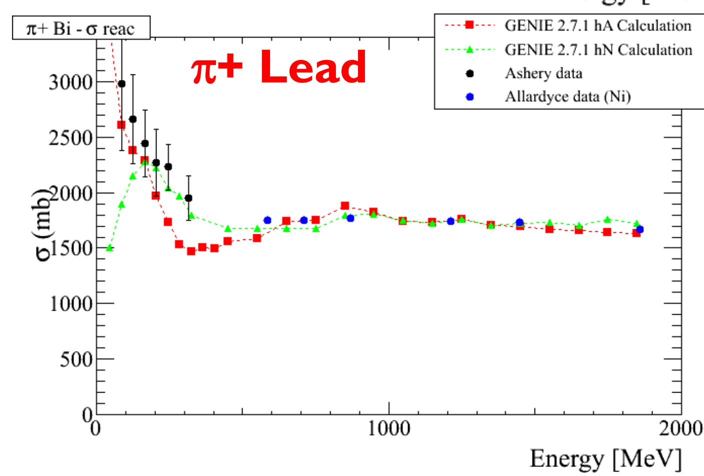


σ_{reac} (pions)

- We see same features
- GENIE is good agreement except for hN at low energies.
- π^- almost identical but data poorer quality.

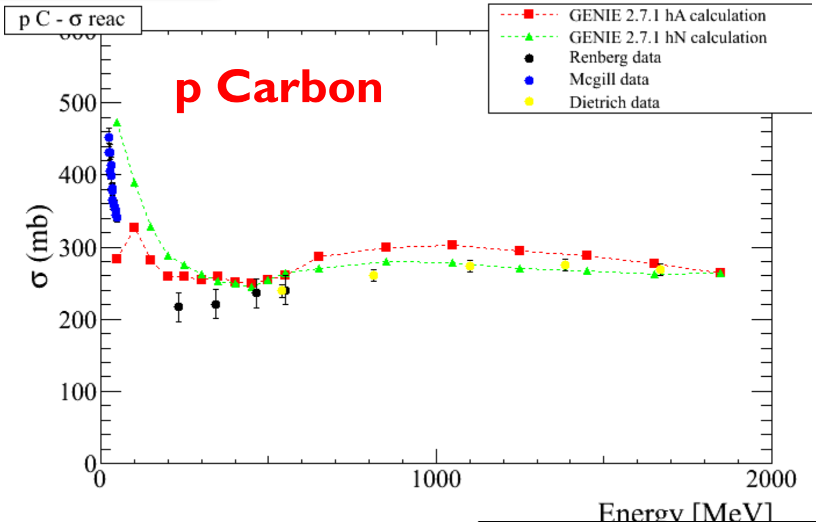


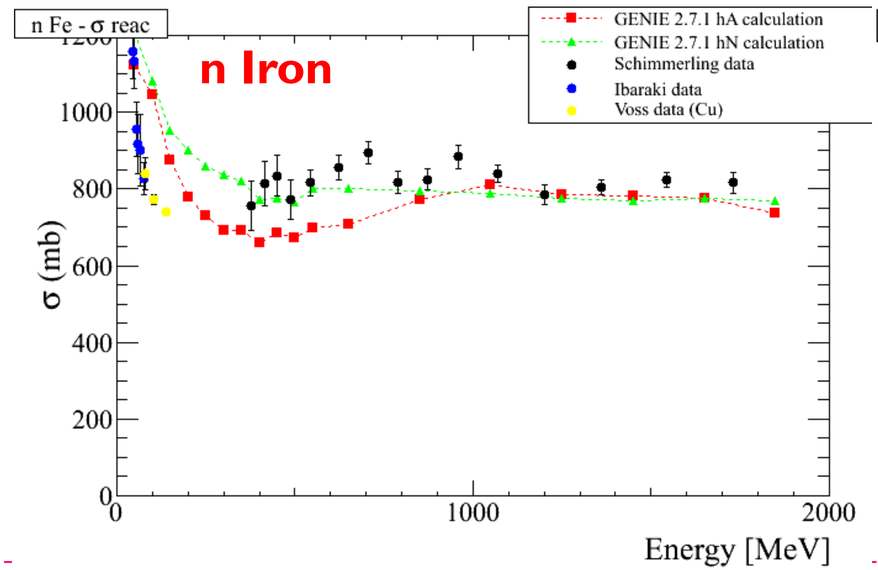


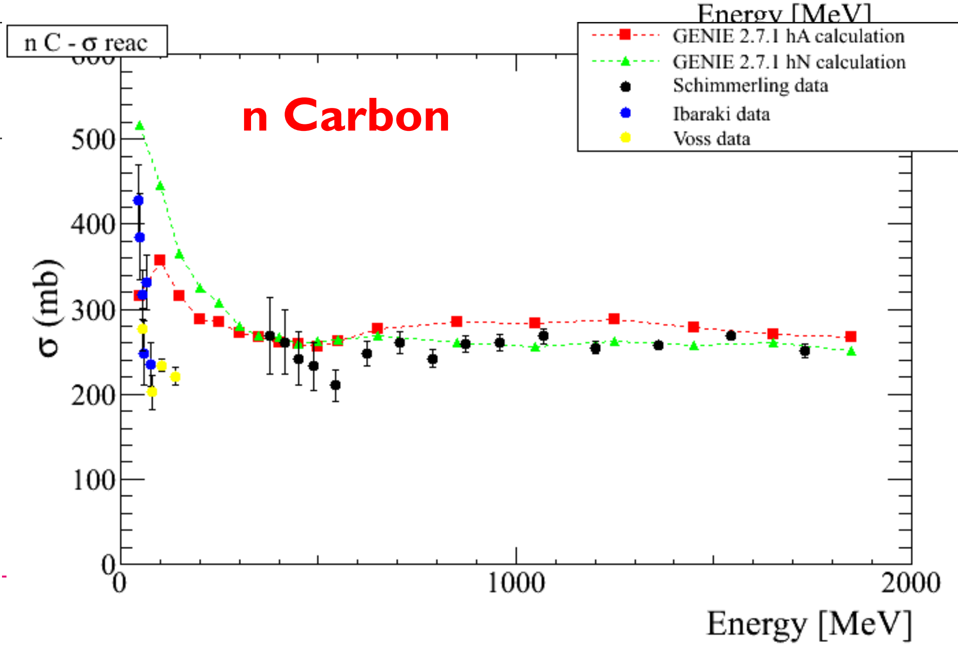


σ_{reac} (nucleons)

- Again, GENIE has right features.
- Hard to get very low energies right.

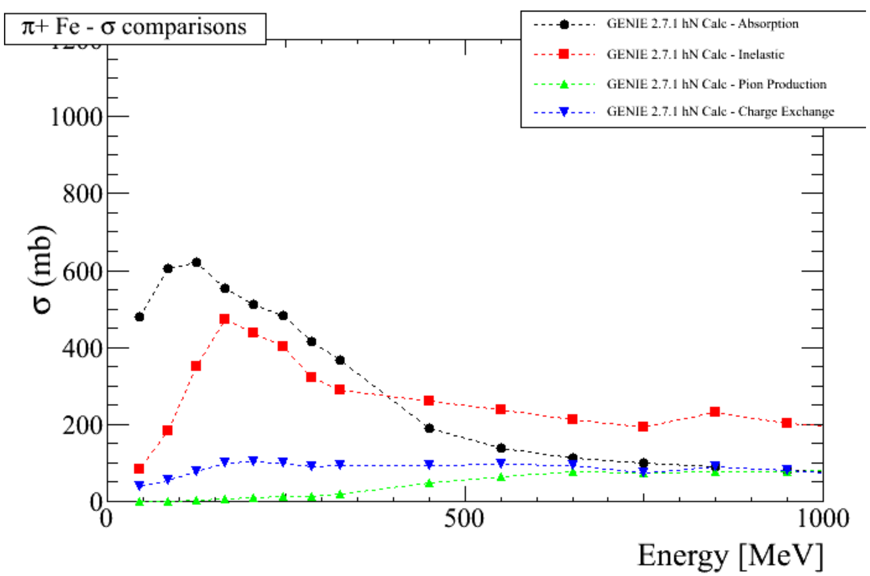




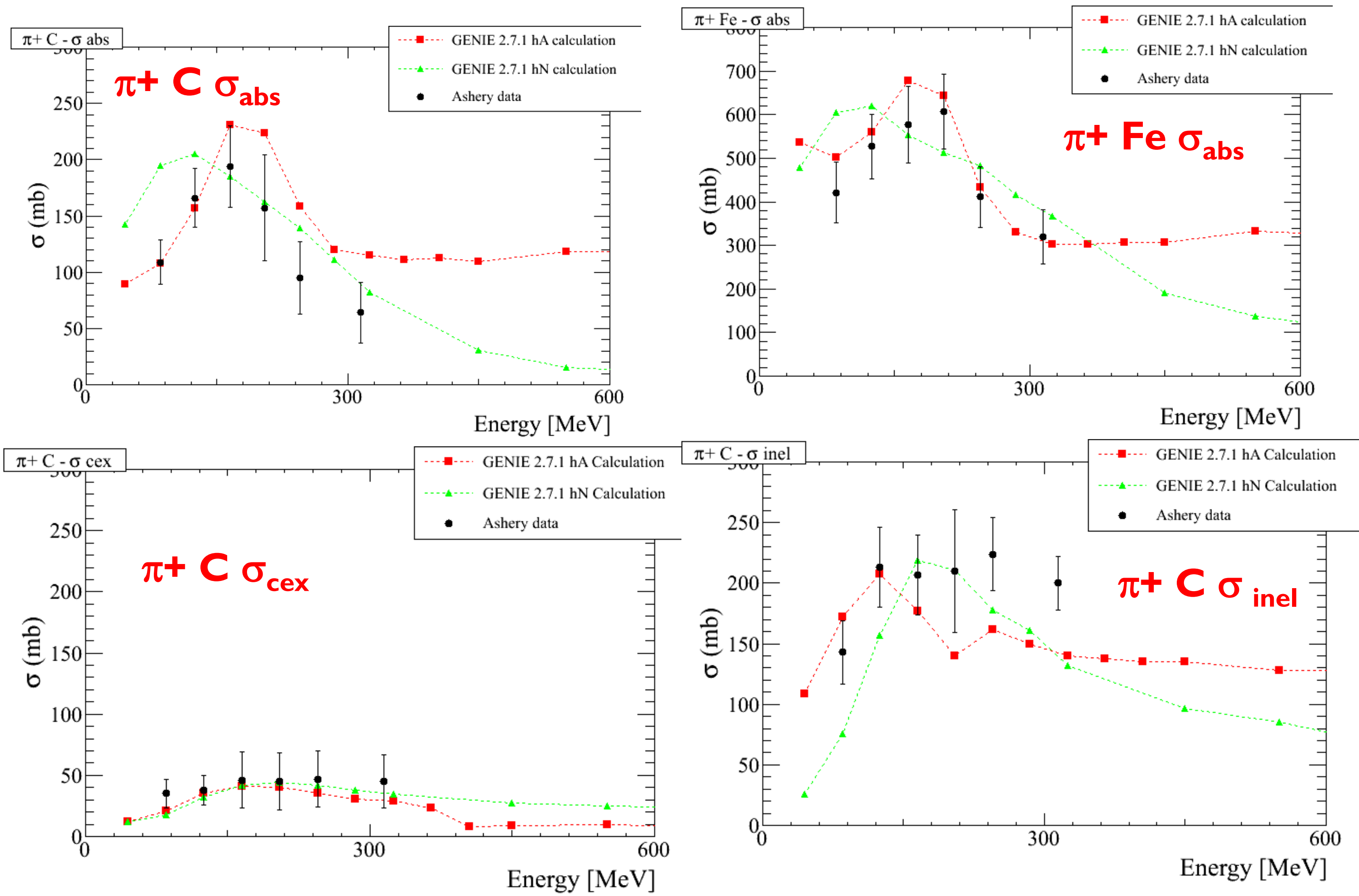


BUT, Relevant processes are very energy dependent.

- Pion processes (nucleons similar)
  - Inelasic (pion comes out with less energy, often with nucleon(s)
  - Absorption (no pion, nucleons come out)
  - Pion production (another pion comes out, can be different charge)
  - Charge exchange (pion comes out with different charge)



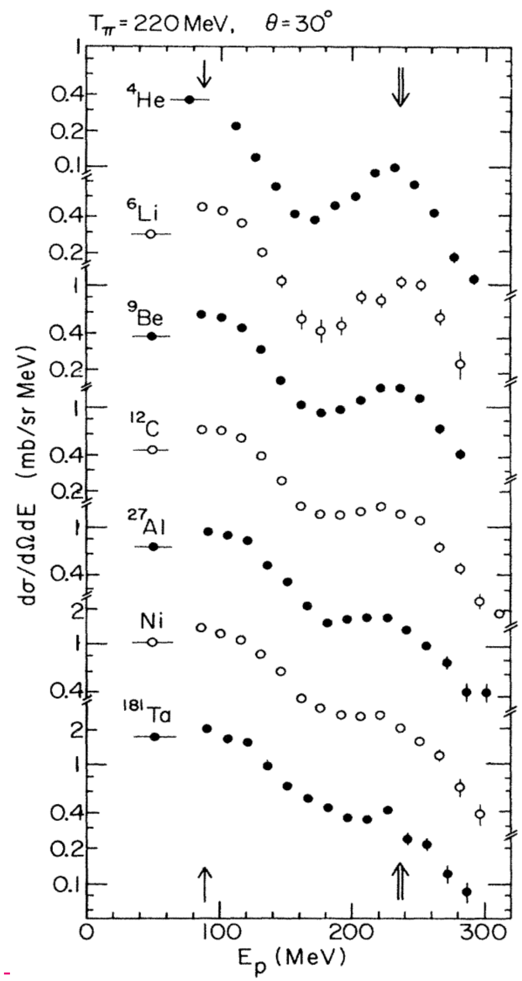
Various component total cross sections (less impressive data, ~30% est. errors common



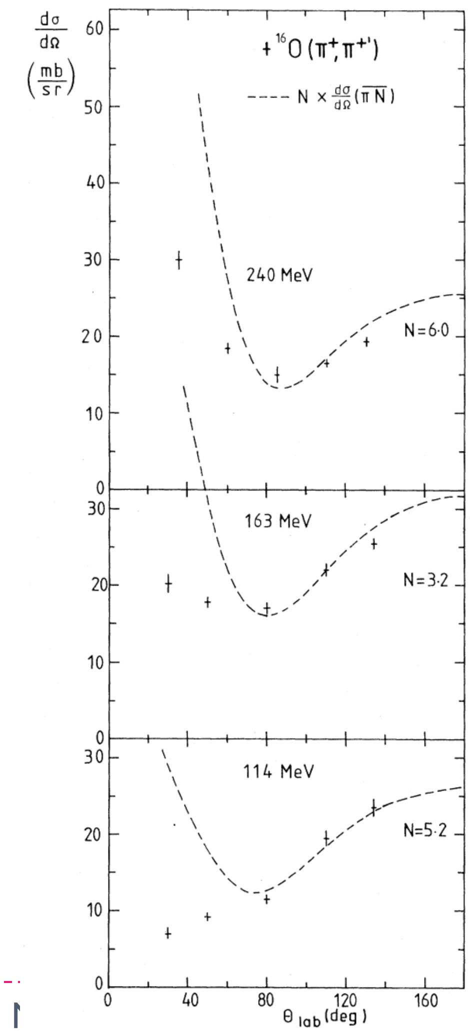
Organizing principle #2
simple processes are often important

- Quasielastic (QE, almost elastic) processes are noticeable for light nuclei even with resonance.
- Inclusive expt: map xs vs. KE at θ.
- Arrows show $\pi p \to \pi p$ and $\pi d \to pp$ kinematics.
- Right plot compares πN cross section with total inclusive xs.

$\pi^+ A \to pX$

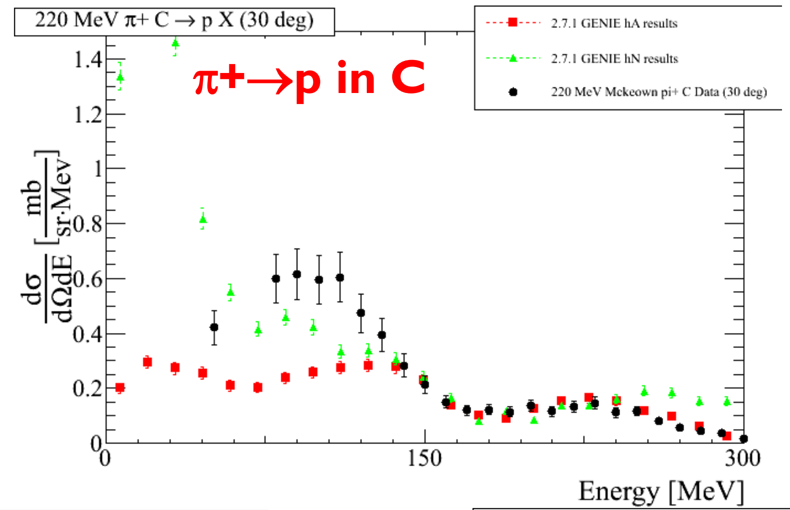


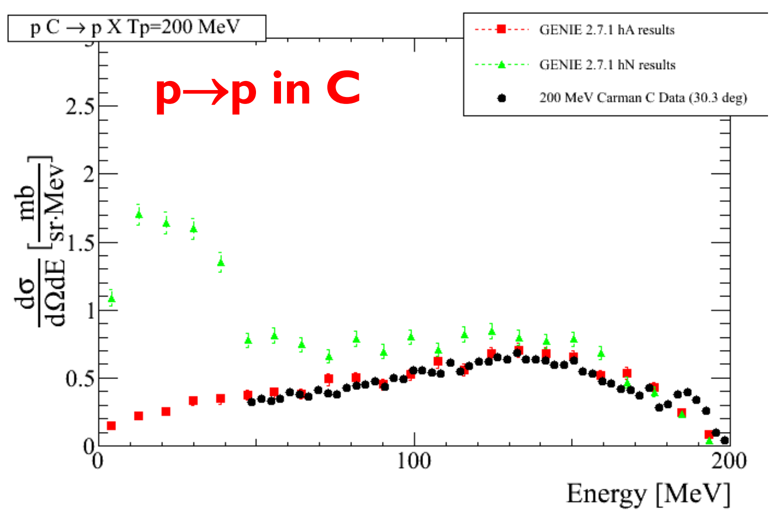
$\pi^+ O \to \pi^+ X$

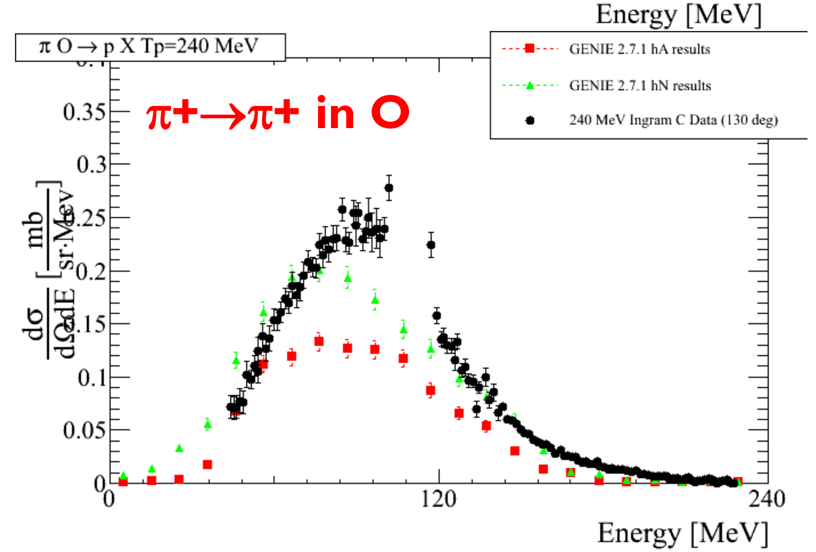


Look for QE processes

- Both hA and hN have it about right.
- QE peak is shifted (BE) and broadened (Fermi motion)

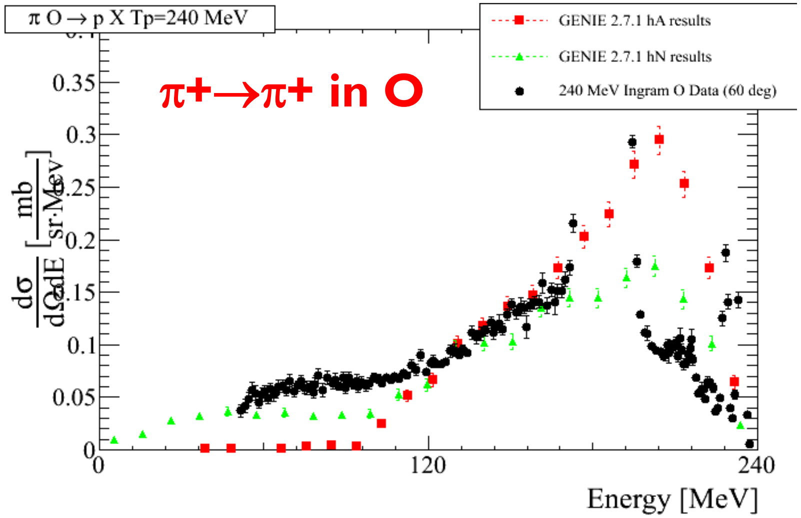


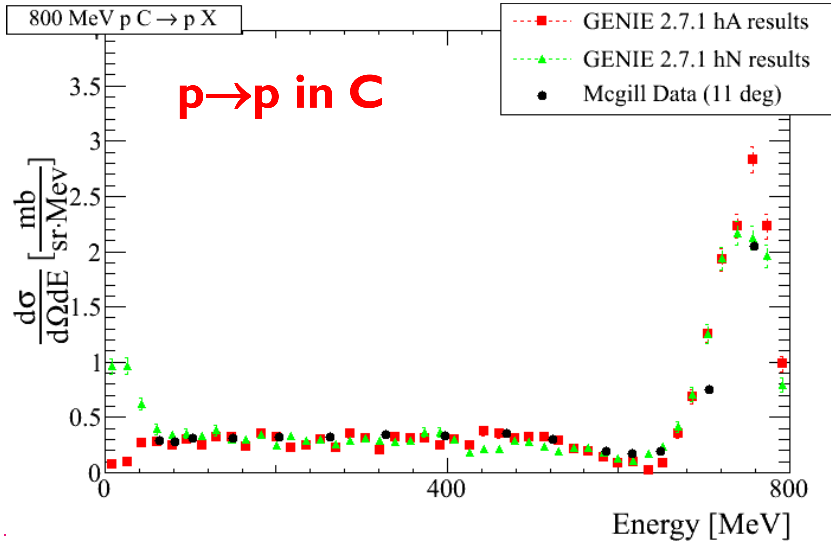




BUT there are other processes….

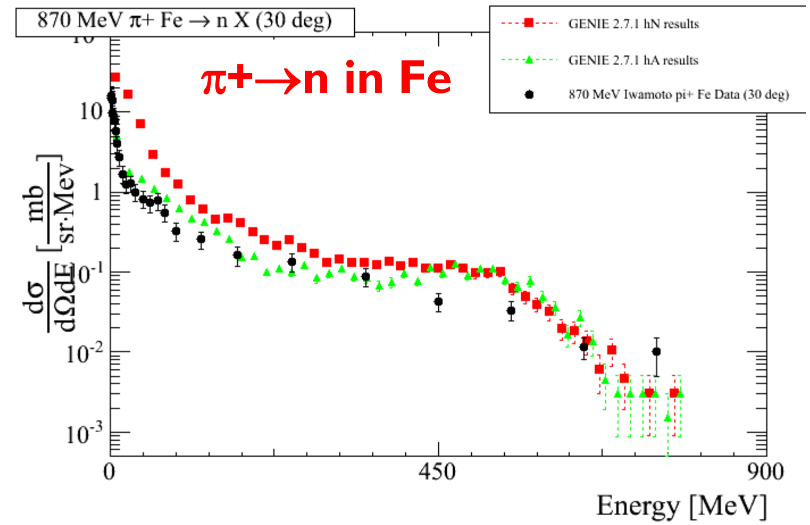
- At forward angles, get QE peak at low energy loss.
- Also see long tail due to additional scattering.
- hN has this, hA doesn't have it.
- Perhaps, this is a detail?

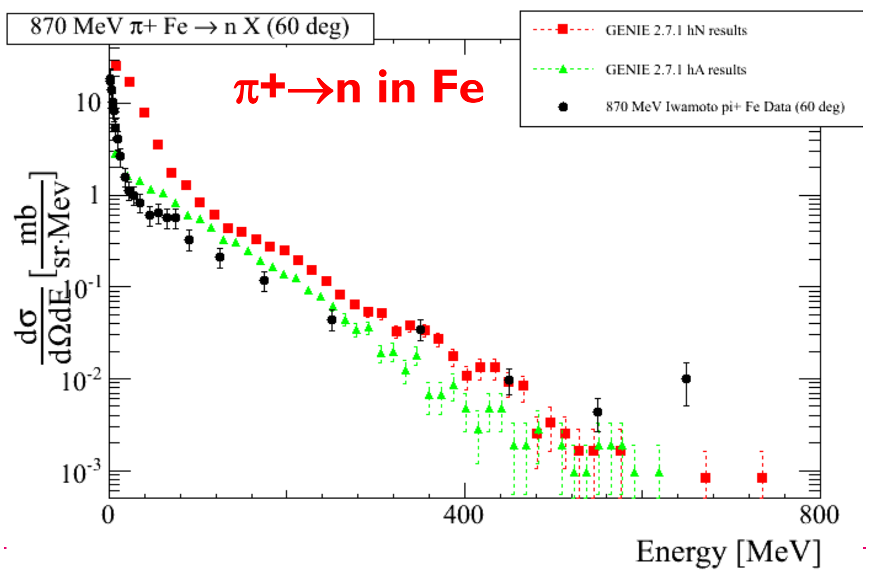


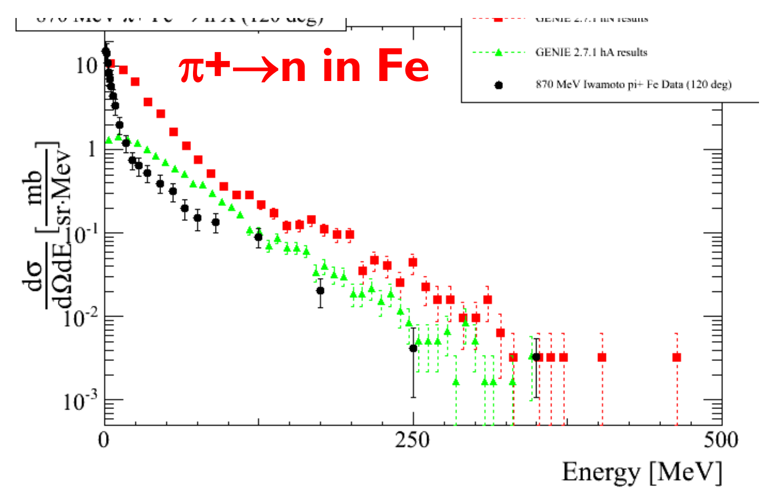


…BUT QE processes not always obvious *phase space matters. (also important example)*

- 870 MeV π^+ in Fe, look for n (1-800 MeV) at various angles
- See various processes, but not much separation.
- Large peak at few MeV constant with angle (compound nuclear processes)

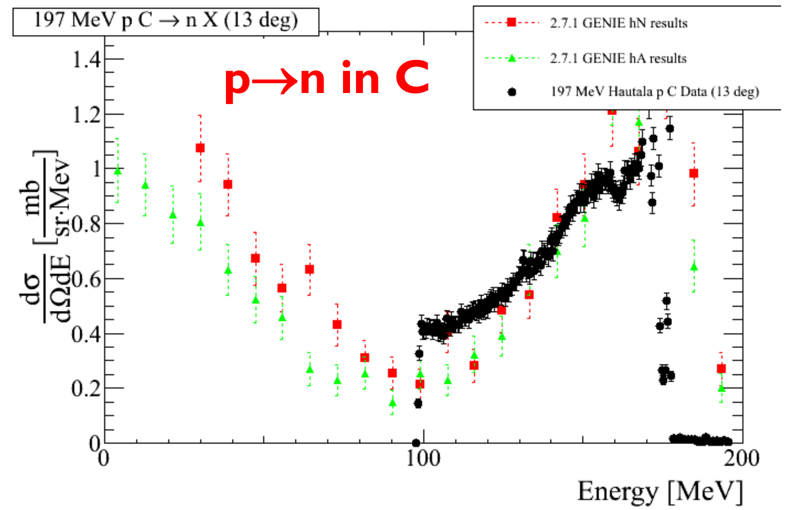


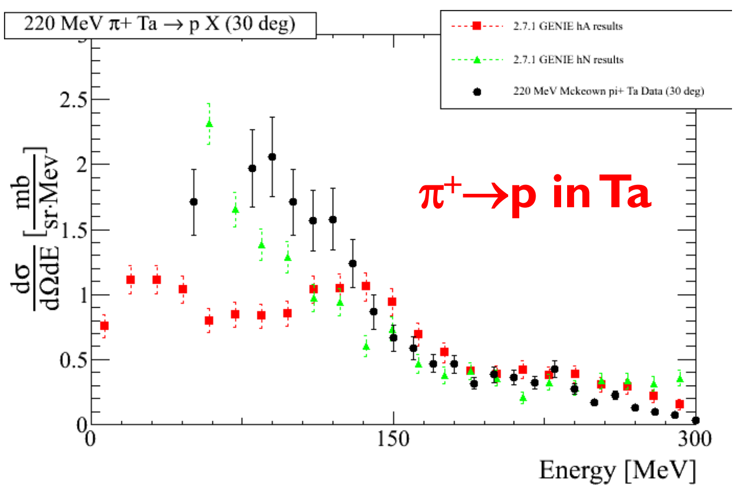


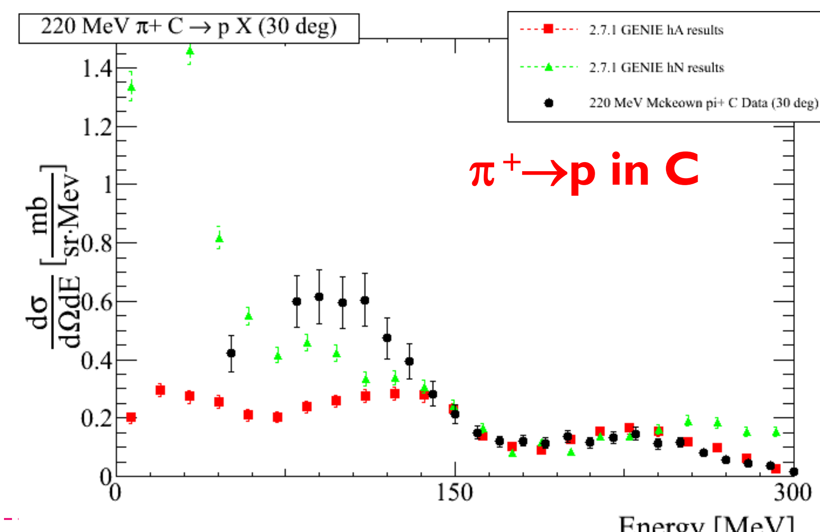


More topology changing interactions

- $\pi^{\pm}$, p, and n all have different responses in scintillator.
- Features all done well, differences in detail.

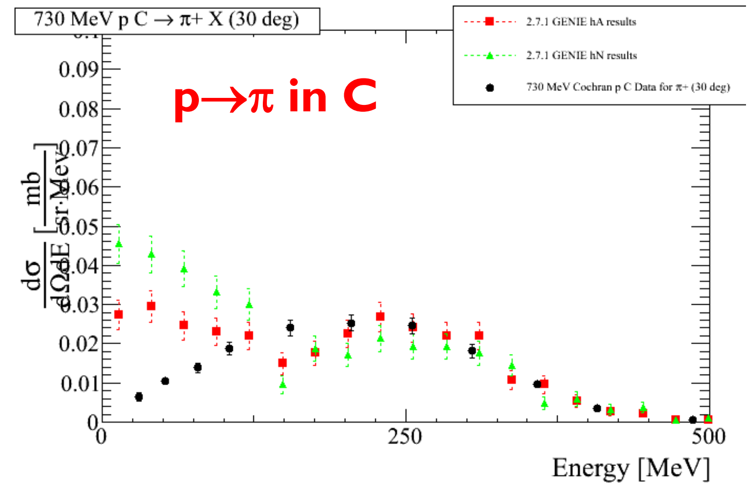


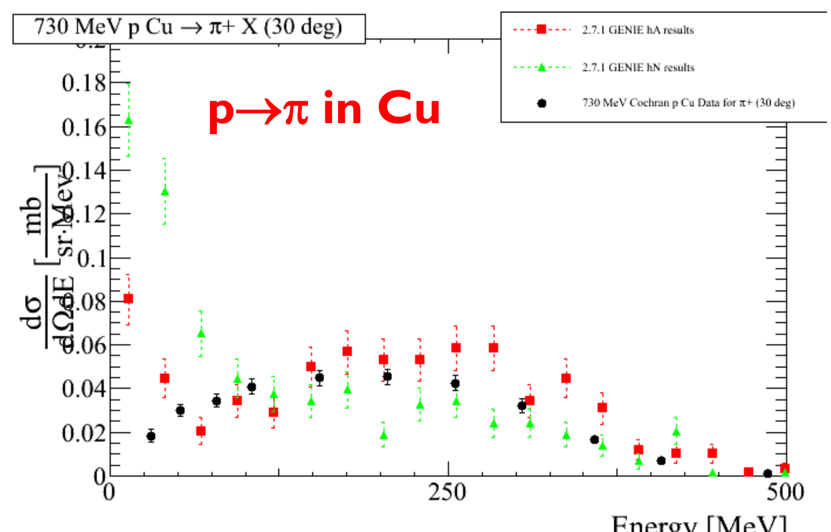




And more topology changing interactions

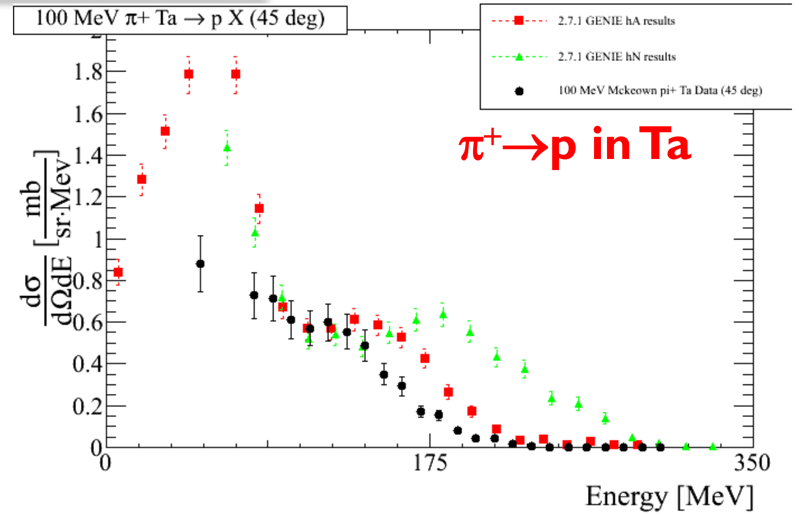
- At higher energies (NOMAD), pion production from p, n is important.
- As with most experiments shown here, representative of many dozens of spectra.
- (If you're confused, perhaps because we sample probe, target, probe energy, process, FS angle, FS energy.)

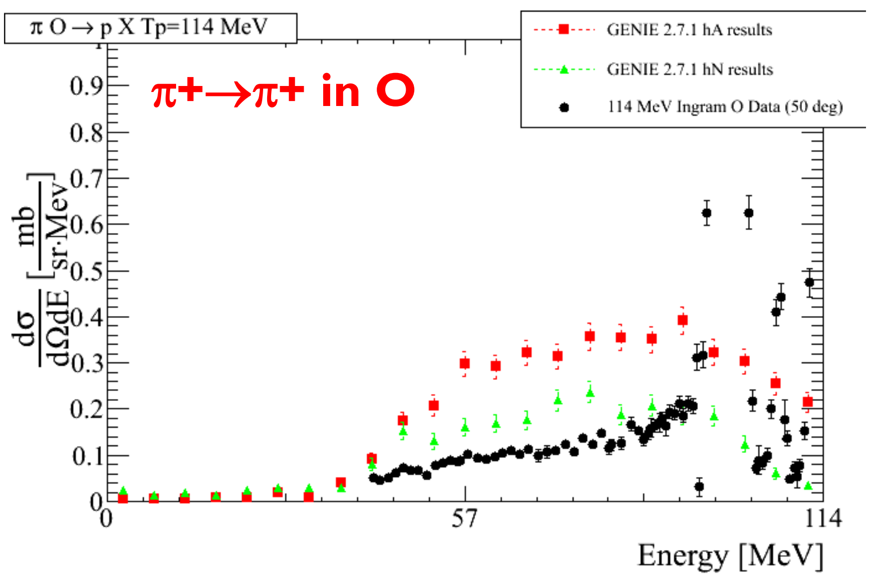


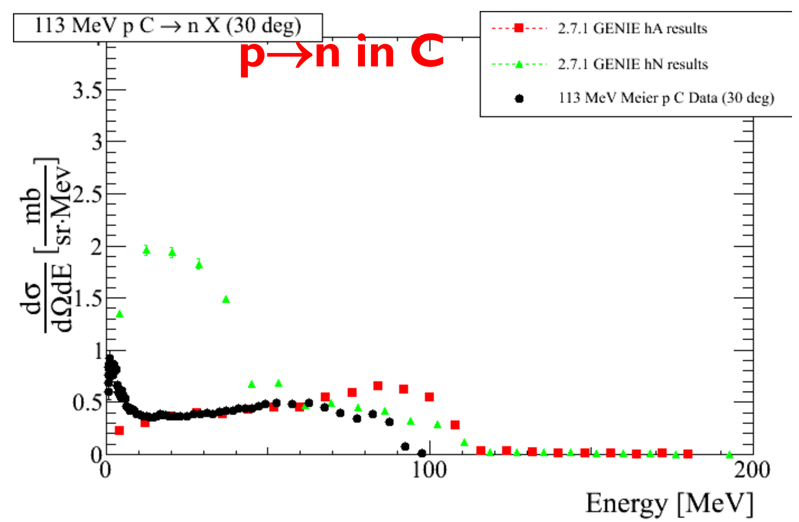


Trouble around KE<~100 MeV

- INC model less accurate.
- FLUKA (peanut) introduces many quantum corrections)
- hA model (schematic) tends to do better than hN (INC)

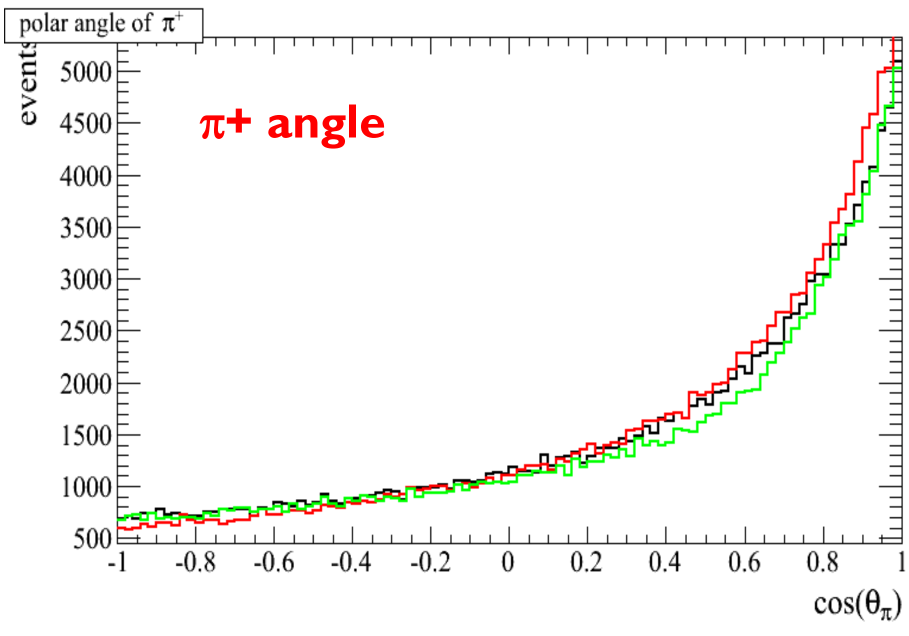


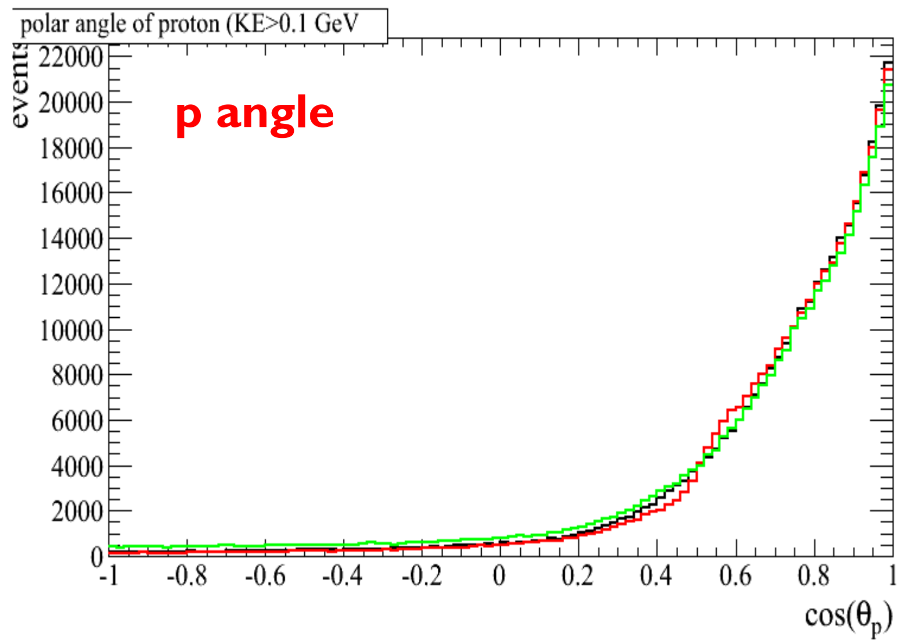




Inclusive spectra from νA valuable check

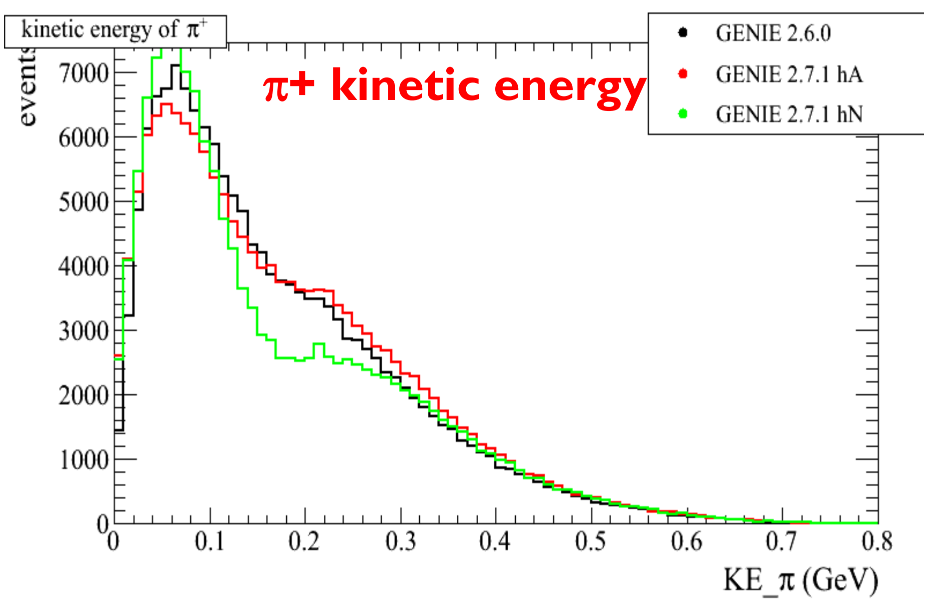
- Example is 1 GeV ν_μ C (all CC processes).
- Compare different GENIE FSI models (hA vs. hN)
- Here, show θ_π and θ_p.
- Details in FSI (change in angle) don't seem to matter.

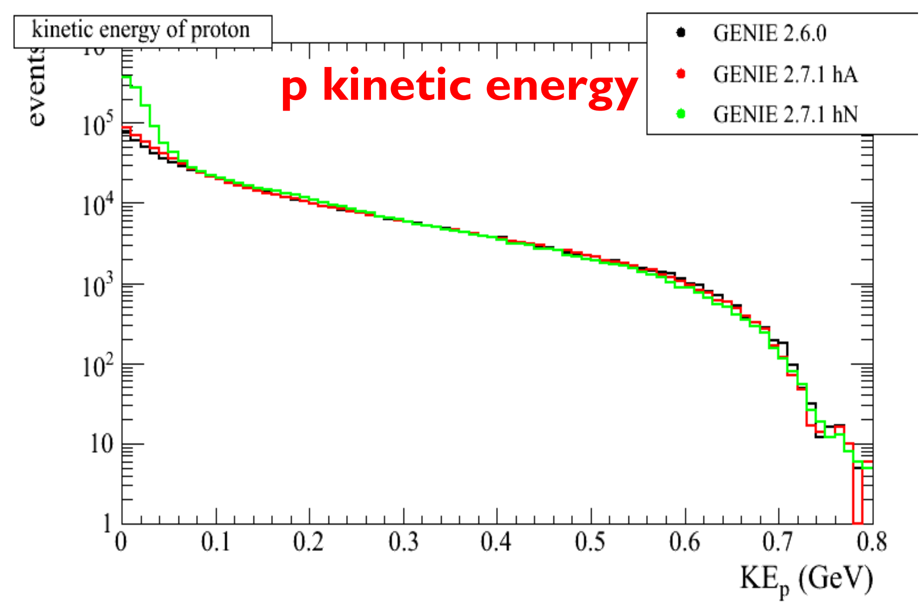




Inclusive spectra - 1 GeV ν_μ C (CC).

- Proton and pion KE show interesting sensitivity.
- New pre-eq/compound reaction produces low energy p,n
- Pions at Δ resonance energy have different suppression.
- This is due to absorption, likely problem seen in σ_{tot}^{abs}



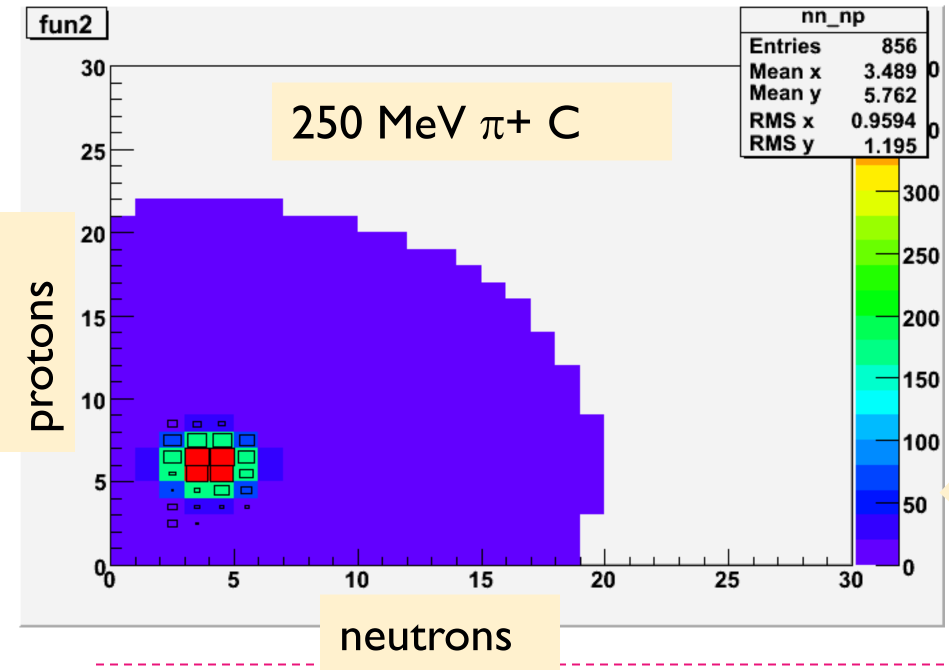


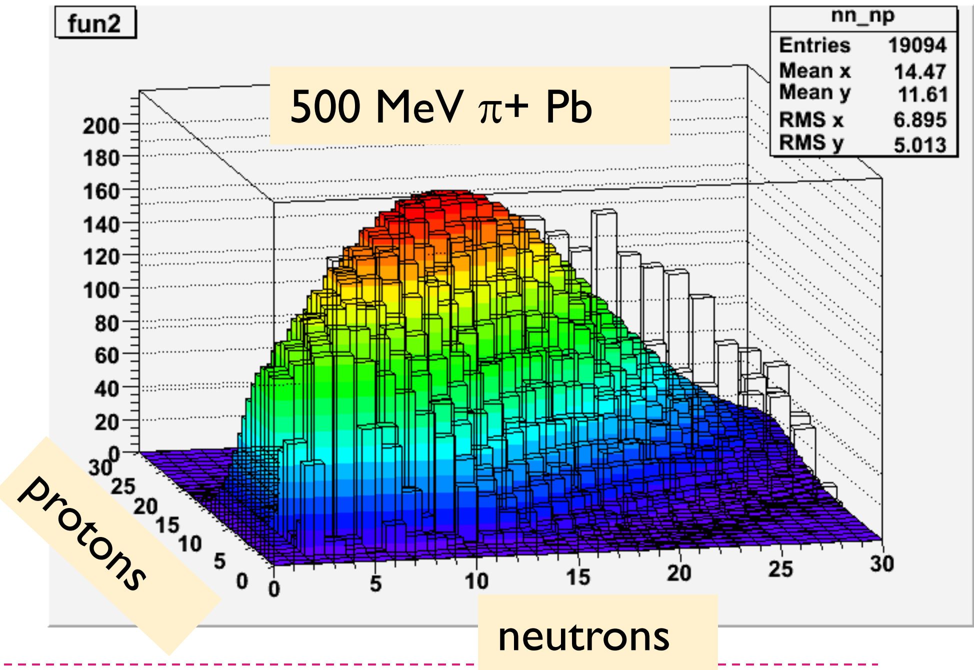
conclusions

- ν oscillation expts depend on MC
- GENIE is most modern, highest quality νA event generator
- Excellent agreement with existing ν xs data (meagre).
- Need more ν cross section data for nuclei
  - MiniBoone now, Minerva (FNAL) and T2K in near future
- FSI code is a critical component of any event gen code.
- Here, show examples of many phenomena, overall agreement good$\rightarrow$excellent for GENIE FSI models.
- Intranuclear cascade (INC) model is high energy approximation, low energy processes more quantum.
- ν oscillation error estimates largely seem justified.

hA development

- Fit no. of neutrons/protons from N & π absorption
- NO data available for this quantity, validate with inclusive
- Fit A, E dependence
- Finite probability to knock out all nucleons





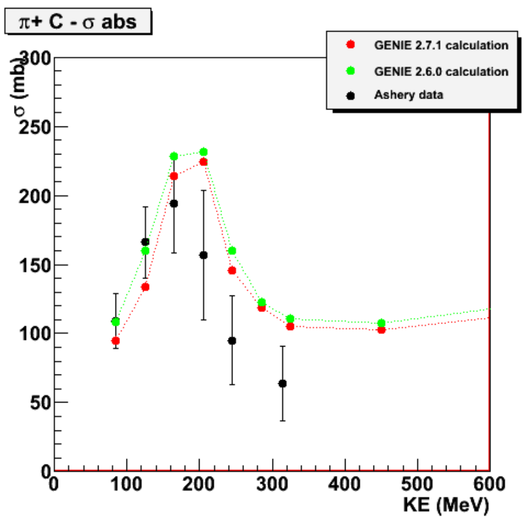
notes

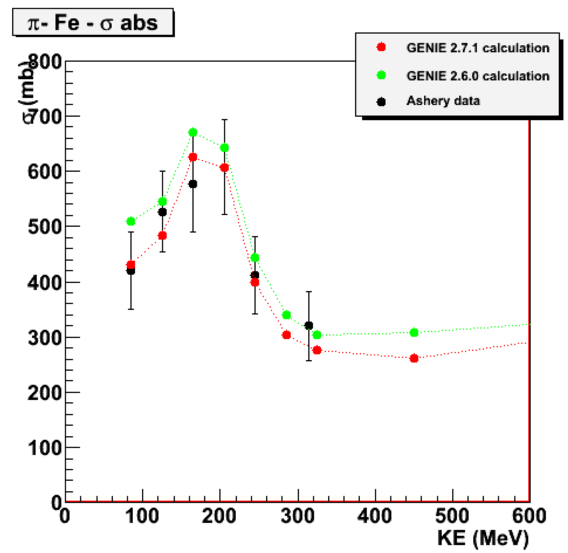
- Goal is to describe pions, nucleons, (and kaons) in nuclei up to 2 GeV kinetic energy
- Only hA in v2.6, same code since NEUGEN.
- v2.7.1 has updated hA (default) and first hN, will become v2.8 soon.
- Main validation is comparison to hadron-nucleus data
  - Hundreds of distributions in use, will be included in v2.8.
- Features
  - Same Fermi Gas nuclear model as neutrino section
  - Very little experience with nuclei A<12.
  - Conserve energy, baryon no., charge at every step

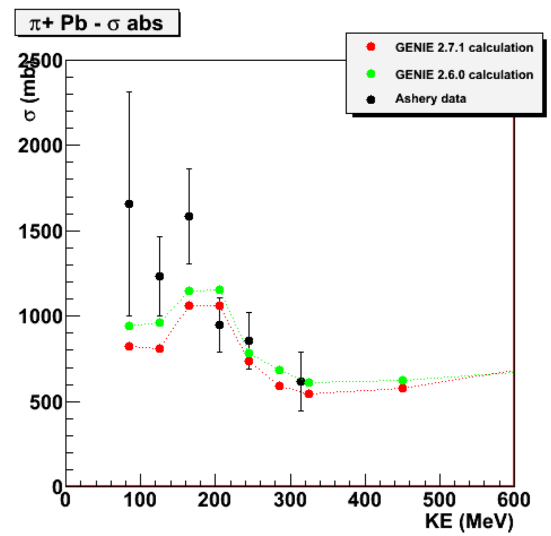
Sources

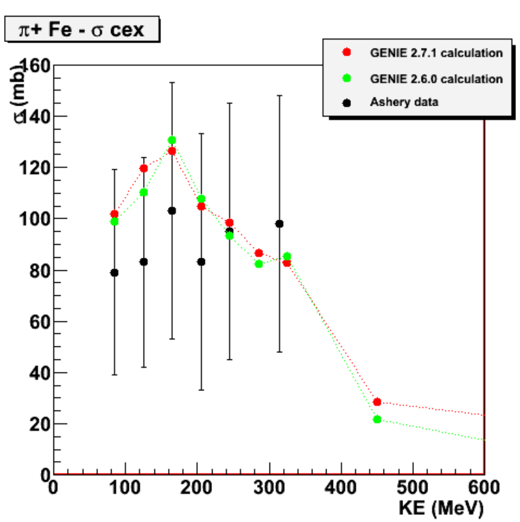
- Mean free path info from (e,e) data, SAID
- papers, www.nndc.bnl.gov, pacs (APS), private
- Total cross sections
  - Reaction xs up to 2 GeV for nucleons and pions
  - Component xs up to ~400 MeV
- Angular distributions
  - Integrate over all energies at specific angle
  - Limited supply of data
- Energy distributions
  - Most detailed info, shows flow of energy vs. angle
  - Many distributions available at a wide range of kinematics

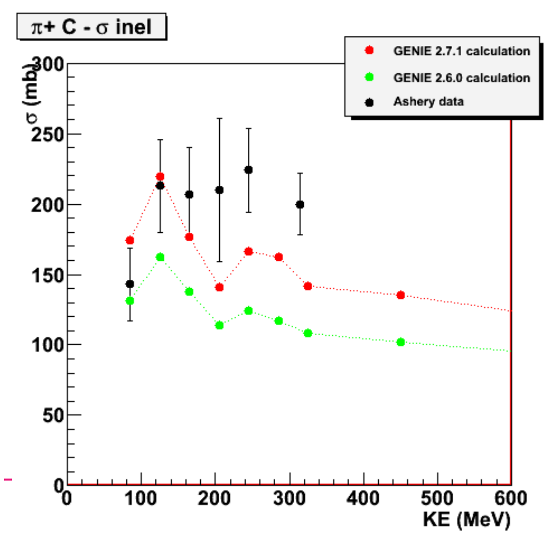
Total abs, inel, cex for various targts

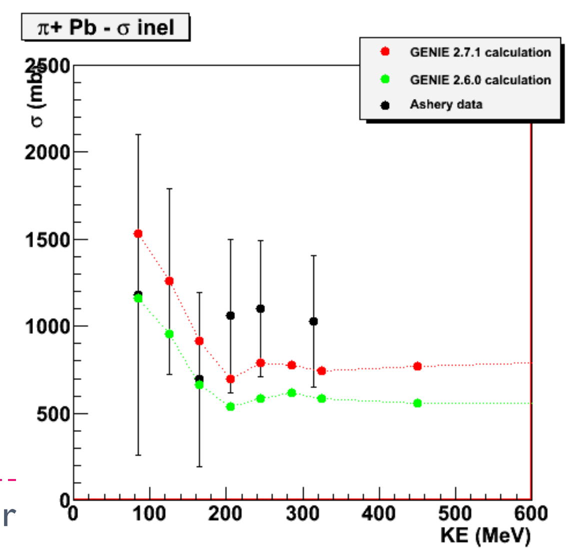




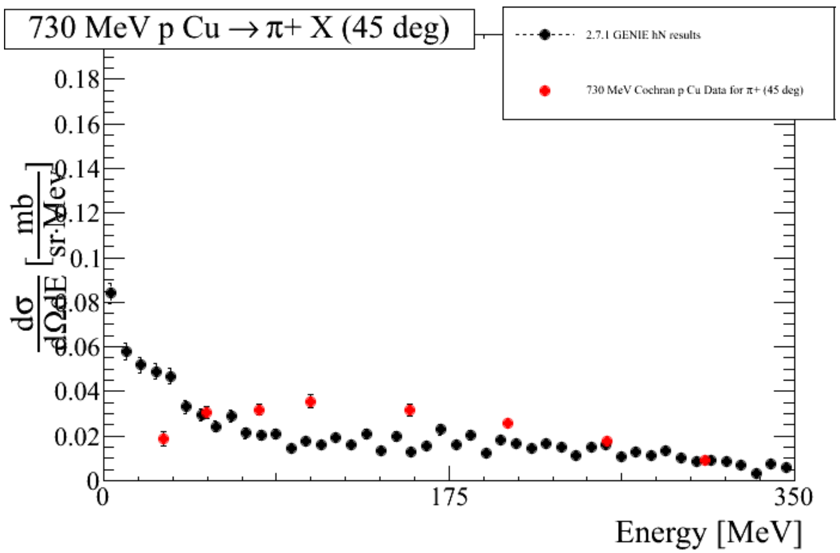


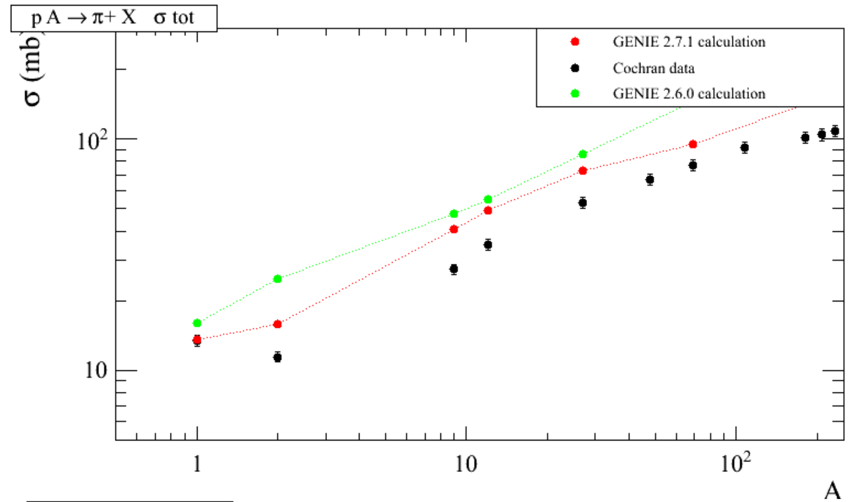


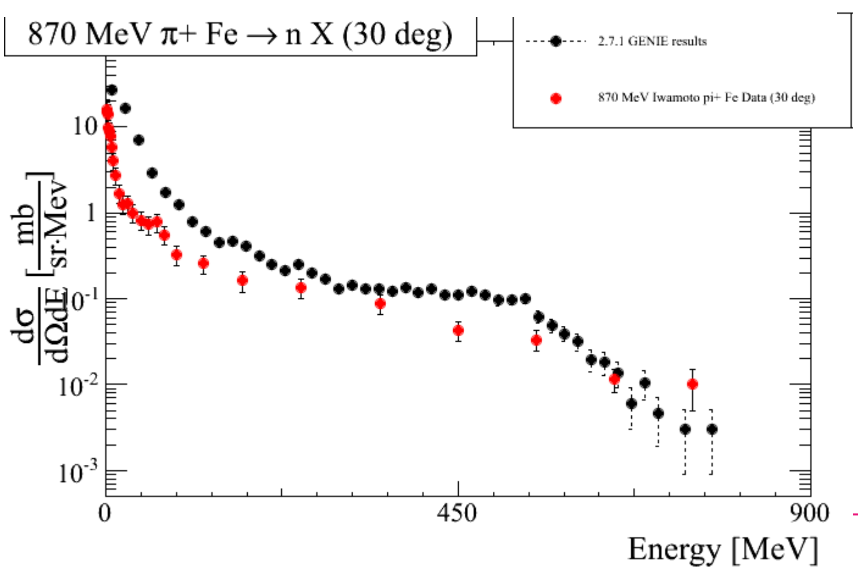


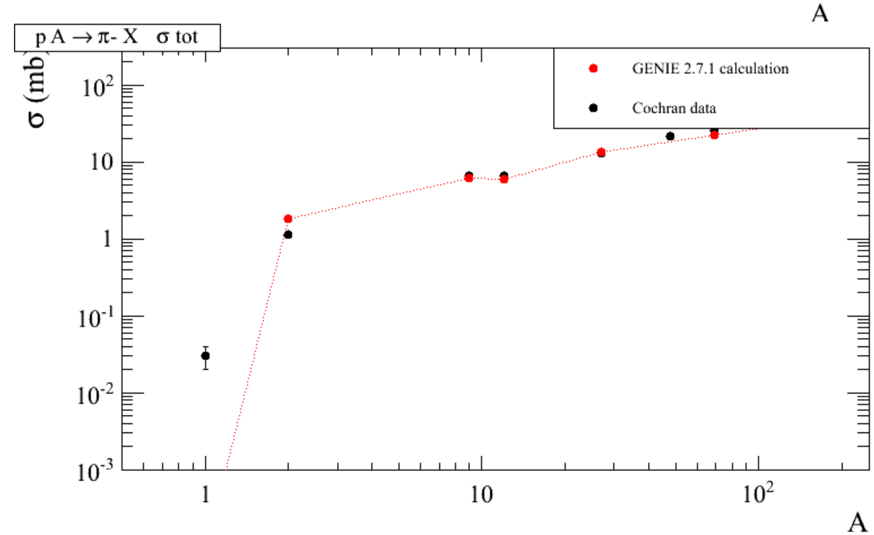


Other examples - N→π.









Tendencies of FSI

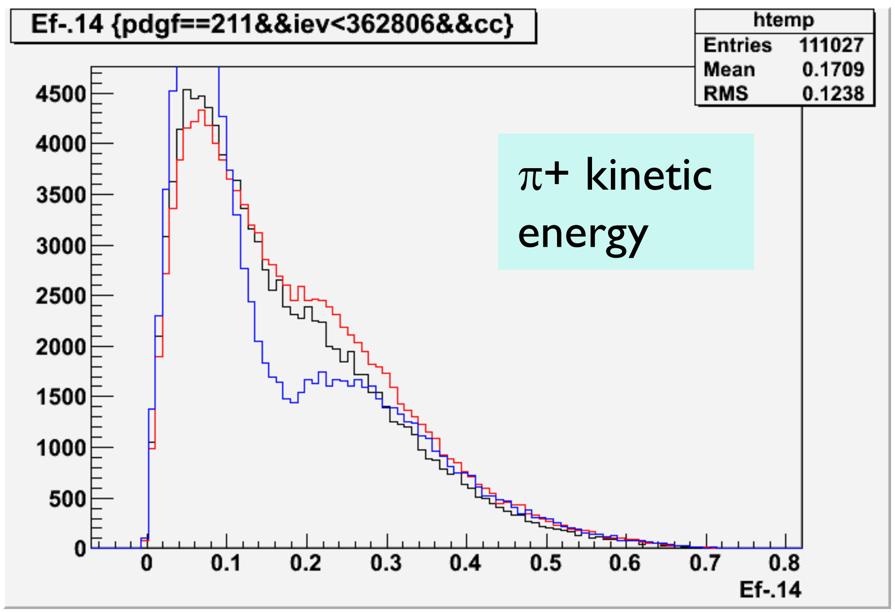
- Energy is distributed to more particles sharing energy
  - Sometimes, many more particles
- Most common FSI is same particle at different angle
- Roughly 1/3 of energy goes to neutral particles
- Many very low energy p&n are emitted (vertex activity)
- Rules of thumb to remember
  - Roughly 35% of protons produced interact before exiting
  - Roughly 25% of pions are absorbed before exiting

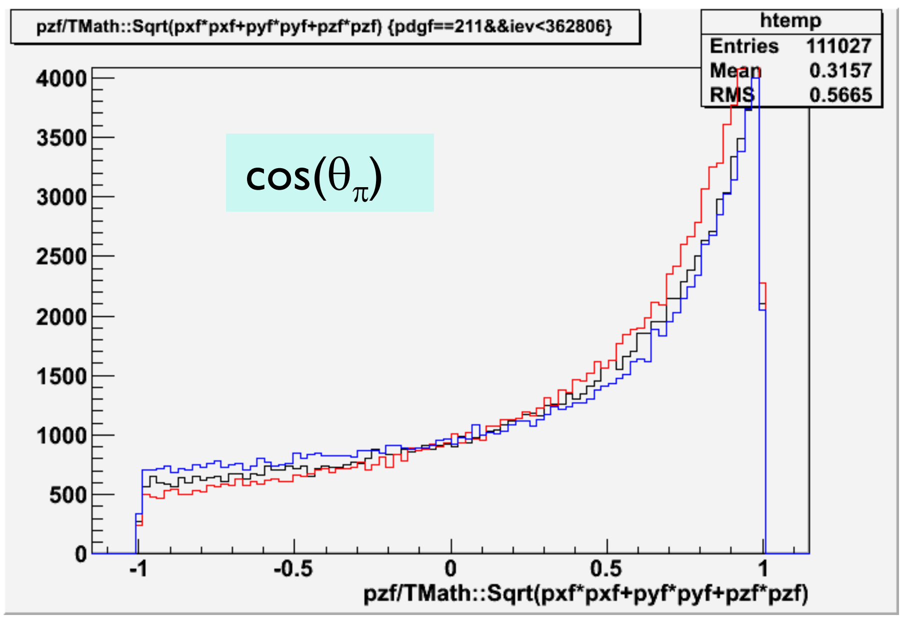
Impact on neutrino interactions

- We have 3 models with approximately same validity, but different qualities.
- hA is fast, reweightable
- hN is slow, more accurate
- Comparison is an attempt at systematic error due to FSI modeling.
- Make comparisons of simple quantities for ν_μ C at 1 GeV (~equal QE, RES)

Pion energy, angle

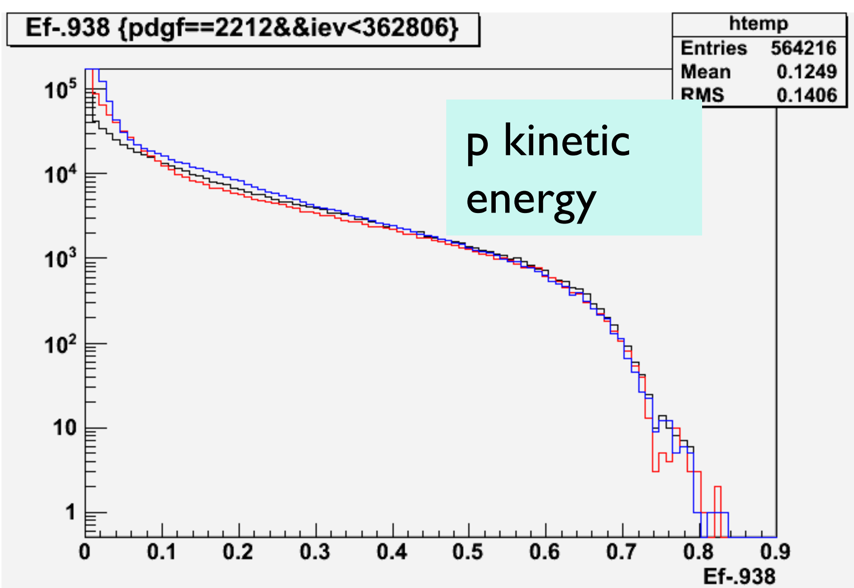
- Same legend for all cases
  - Old hA (black), new hA (red), hN (blue)
- Total of 111k pions in 263k events

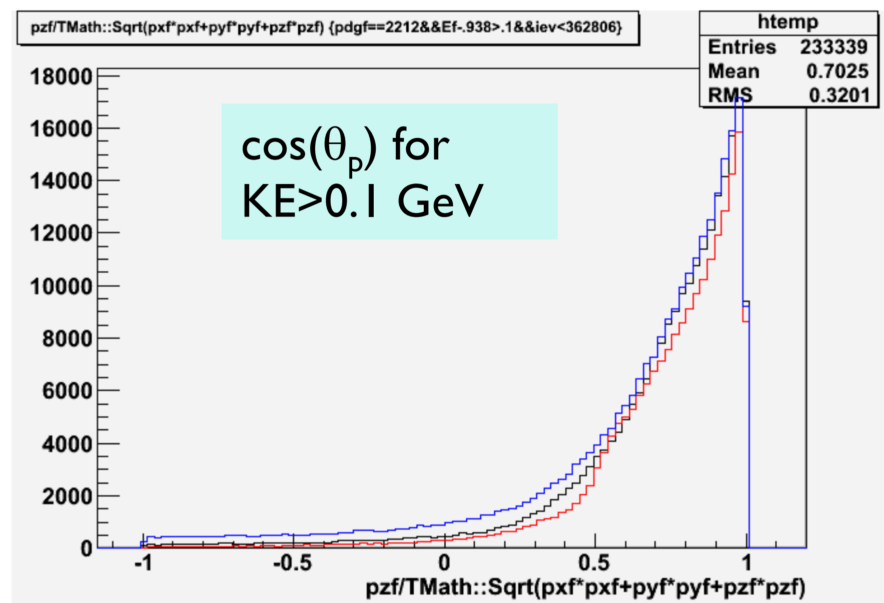




Proton energy, angle

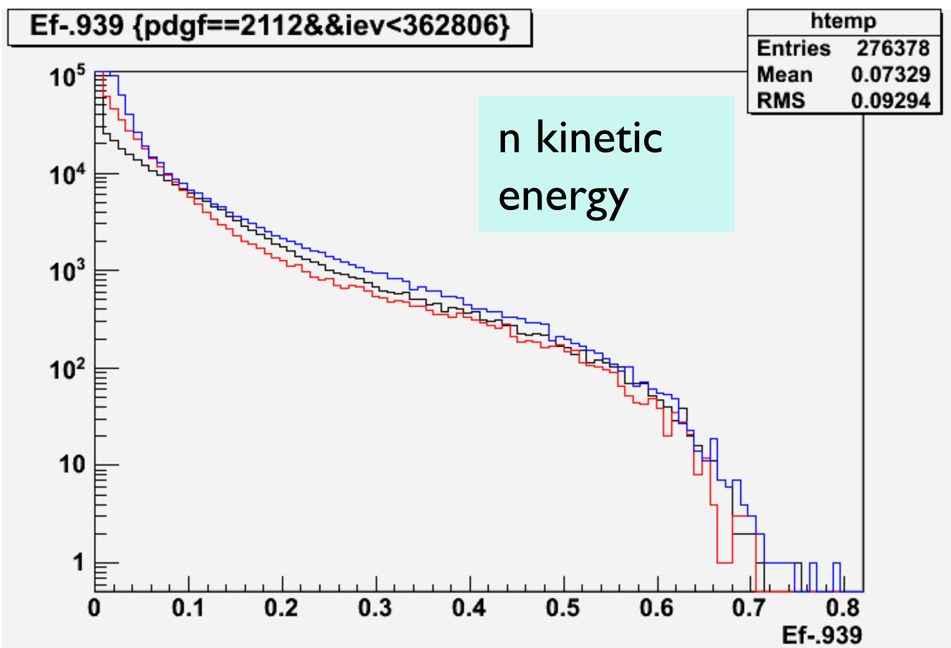
- Not much change
- Old hA (black), new hA (red), hN (blue)
- Total of 564k, 831k, 1237k protons in 362k events,
- Total 233k, 266k, and 266k protons with KE>0.1 GeV





neutron energy

- Old hA (black), new hA (red), hN (blue)
- Total of 277k, 490k, and 609k neutrons in 362k events,
- Total of 68k, 53k, and 80k neutrons with KE>0.1 GeV (~1/2 resonance events, rest is background)



summary

- Next GENIE (v2.8) will have new hA and hN FSI models.
- Small number of parameters, all physically motivated
- Each model is extensively validated against wide range of hadron-nucleus data.
- Goal is to match the features of data
- This provides a useful starting point for comparisons with neutrino cross section data.
- Distributions from ν_μ C at 1 GeV show differences due to model assumptions (first?)
- *New ν cross section data extremely important!*