Neutrino Cross Sections

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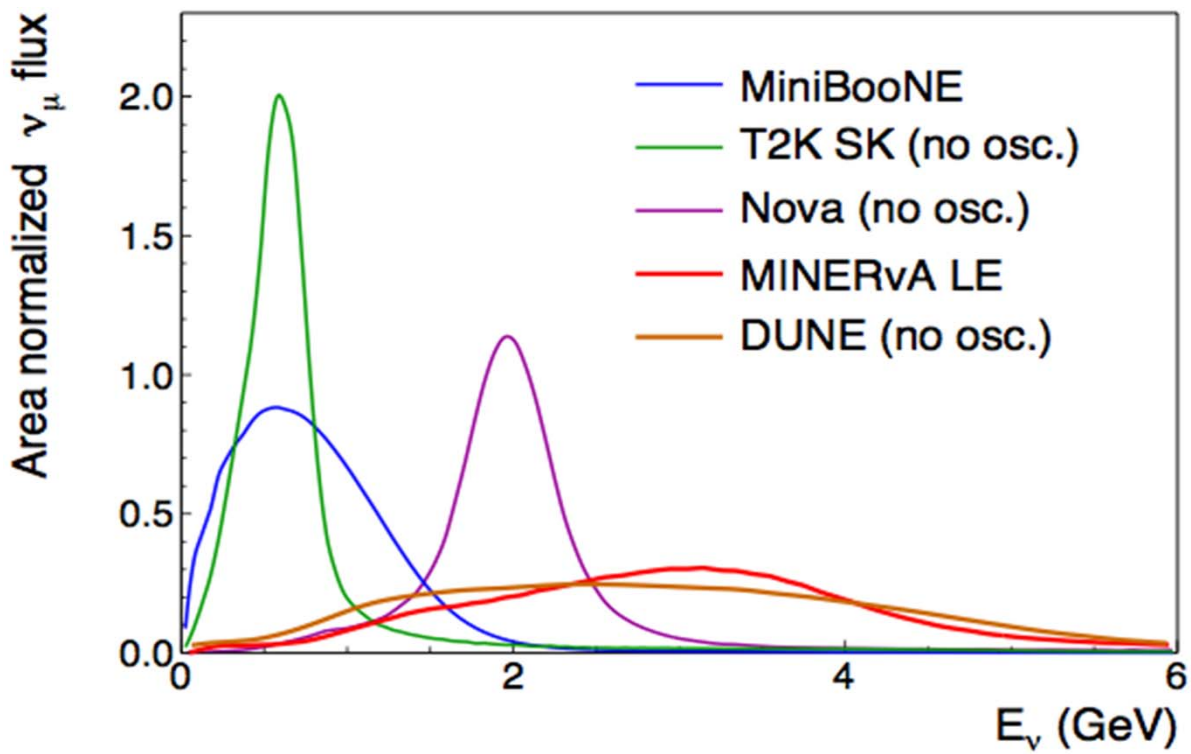
- ν-nucleus Cross sections
- Compare/contrast published data
- importance of signal
- Use models (event generators) for comparison

ν cross section experiments

- Important for evaluating background, systematics for oscillation experiments
- Wide band beams; flux is hard to monitor (must calculate)
- New experiments much improved, but easier to see problems
- Tensions workshop (July, 2016) focused on MiniBooNE, MINERvA, and T2K data sets and Monte Carlo
  - **Work**shop organized by K. Mahn, SD summer, 2016
  - Analyzers from MiniBooNE, Minerva, and T2K
  - Core people from GENIE, NuWro, NEUT, Nuance
  - Examine published data sets, focus on QE and 1π
  - Paper with many plots/conclusions to arXiv soon

Neutrino energy distribution

- Neutrino experiments all have wide-band energy spectrum which must be calculated
- MiniBoone, T2K at $<E_\nu>$~0.6 GeV, Minerva LE, Nova, DUNE at $<E_\nu>$~ 2-3 GeV.



Data in this study

Quasielastic

Katori [MiniBooNE] ν_μ QE in CH_2 PR D81:092005 (2010)
Fiorentini [Minerva] ν_μ ,$\bar{\nu}_\mu$ QE in CH PRL 111, 022502 (2013)
Bolognesi [T2K] ν_μ QE-like in CH PR D93:112012 (2016)

Pion production

Wilking [MiniBooNE] ν_μ CH_2 $1\pi^+$ PR D83: 052007 (2011)
Eberly [Minerva] ν_μ CH $1\pi^+$, $\geq 1\pi^+$ PR D92: 092008 (2015)
McGivern [Minerva] ν_μ CH $1\pi^+$, $\geq 1\pi^+$, $1\pi^0$ PR D (2016)

Monte Carlo

- Event generators (EG) have significant role in every experiment for background, systematic errors
- GENIE tries to be Universal EG, some success
- GiBUU and NuWro more theoretical, others by experimenters
- EG groups have worked hard to include these improved nuclear theory models, show some results today
- NUISANCE: T2K work (Stowell, Wret, Pickering, and Wilkinson) to provide program for matching EG with data
  - Makes plots, does reweighting, fits with MINUIT, uses all EG
  - Needs working copy of each EG program
  - Important part of Tensions workshop

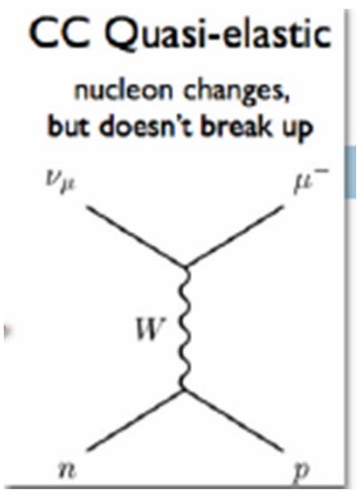
Compare to other generators (2.12 default)

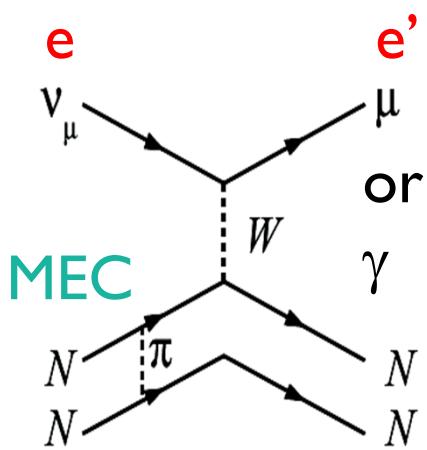
Model/generator	GENIE	NuWro	NEUT
QE	Lwlyn-Smith Nieves, Eff MA	Lwlyn-Smith RPA	Lwlyn-Smith Eff RPA
Nuclear model	RFG, LFG, Effective spectral function	RFG, LFG, spectral function	RFG, LFG, spectral function
MEC	Valencia Empirical	Valencia Marteau	Valencia
Delta model	Rein-Sehgal (updated)	Home-grown	Rein-Sehgal (update)
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)

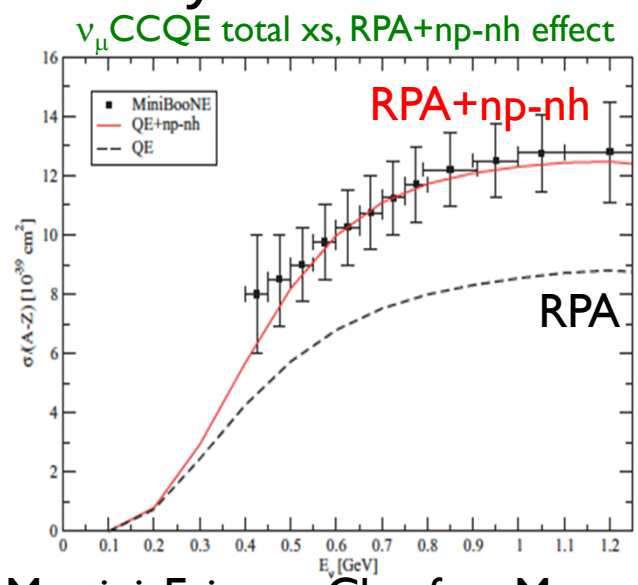
- Differences more in detail than fundamental (physics)
- GENIE default still uses old models, use theory-based models for 2.12.

CC Quasielastic data

- Get good data with well-motivated topology definition
  - CCQE from data with only muon is difficult (overlap with pions)
  - Use large acceptance to take out events with no final state pions
  - MiniBooNE (E_ν~1 GeV) published quality data (PRL 2004)
- (Re)discovery of 2p2h important, but only indirect experimental confirmation so far







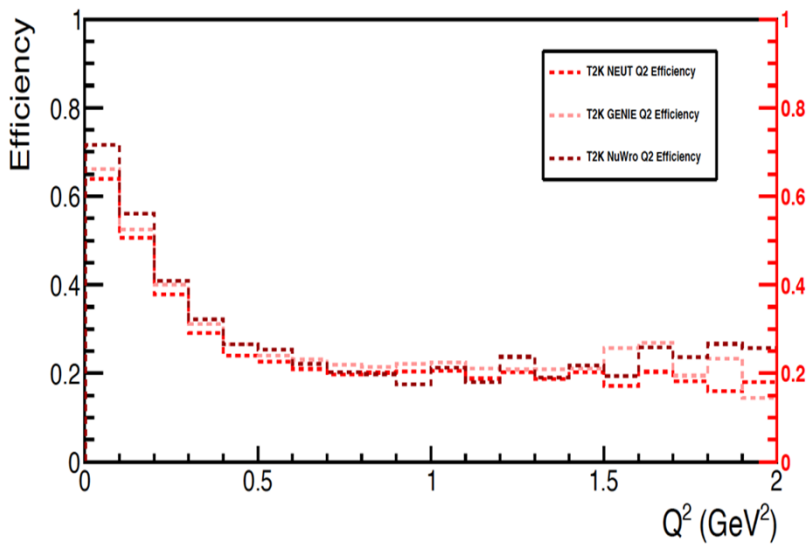
Martini, Ericson, Chanfray, Marteau
Phys Rev C80:065501 (2009)

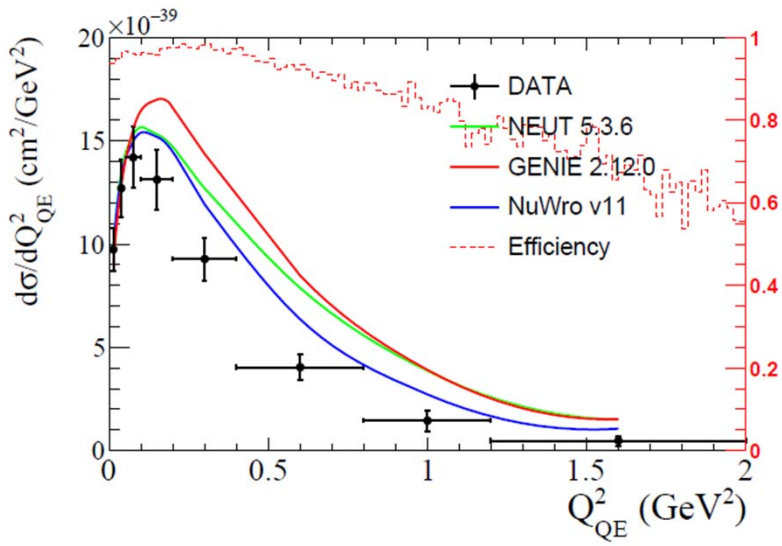
QE Experiment Signals (complicated)

- MiniBooNE (2011)
  - CCQE+'2p2h' (no 2p2h available)
  - CC0π (preferred)
- MINERvA (2014)
  - TrueCCQE+'true2p2h' +0π (no 2p2h available)
  - CC0π1p T_p<110 MeV
- T2K (2016)
  - CCQE+'2p2h'+0π (no 2p2h available)
- Very tricky to compare directly, must do it with models
- Future signals likely to be CCQE+2p2h+0π. If proton included, better signal? Threshold required!?

experiment

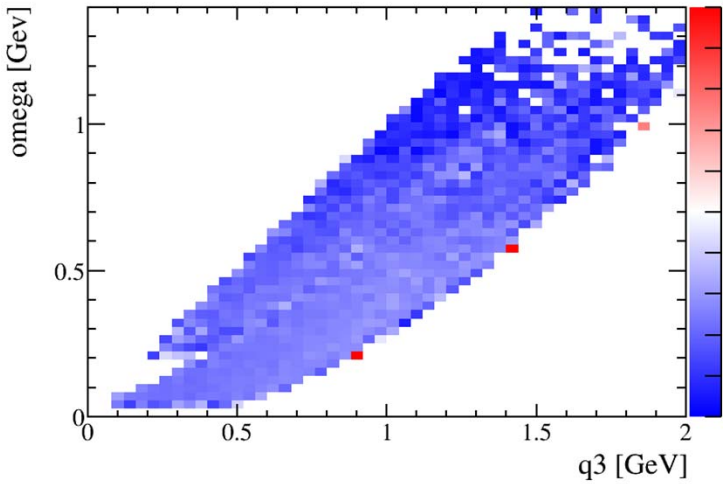
- Many high quality results published, many more near
- Signal, acceptance varies between experiments
- MiniBooNE gives CCQE, CCQE-like (NUANCE)
- Minerva gives CCQE (2 CCQE-like analyses soon) (GENIE)
- T2K gives CCQE-like (NEUT, NuWro, GENIE)

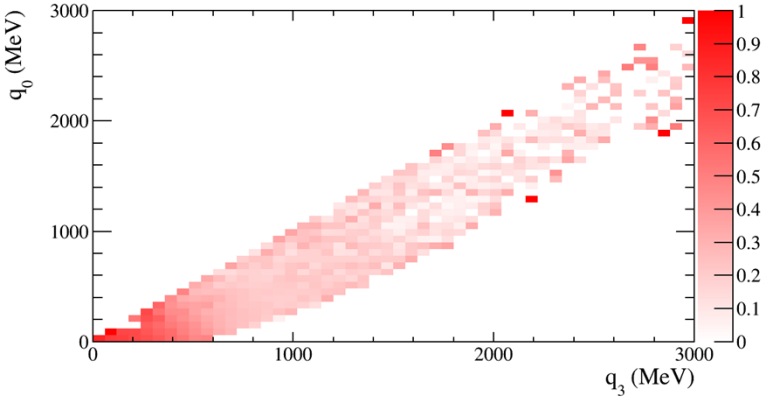


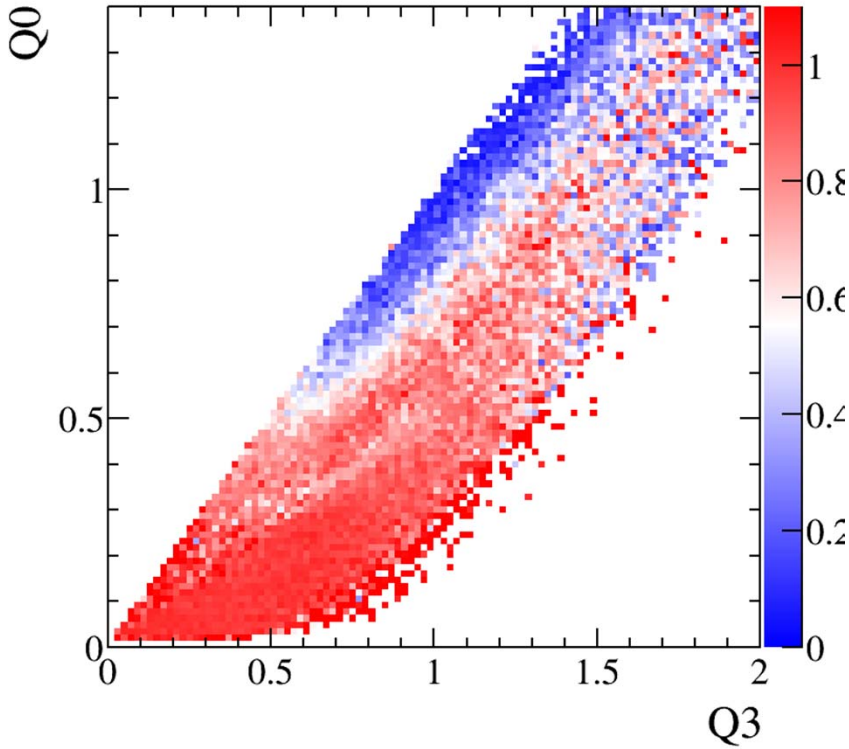


Problem is in details

- Coverage in ν, $\vec{q}$ $(Q^2 = |\vec{q}|^2 - \nu^2)$ not uniform
- MiniBooNE fairly uniform, both T2K and MINERvA vary (cutoff?)

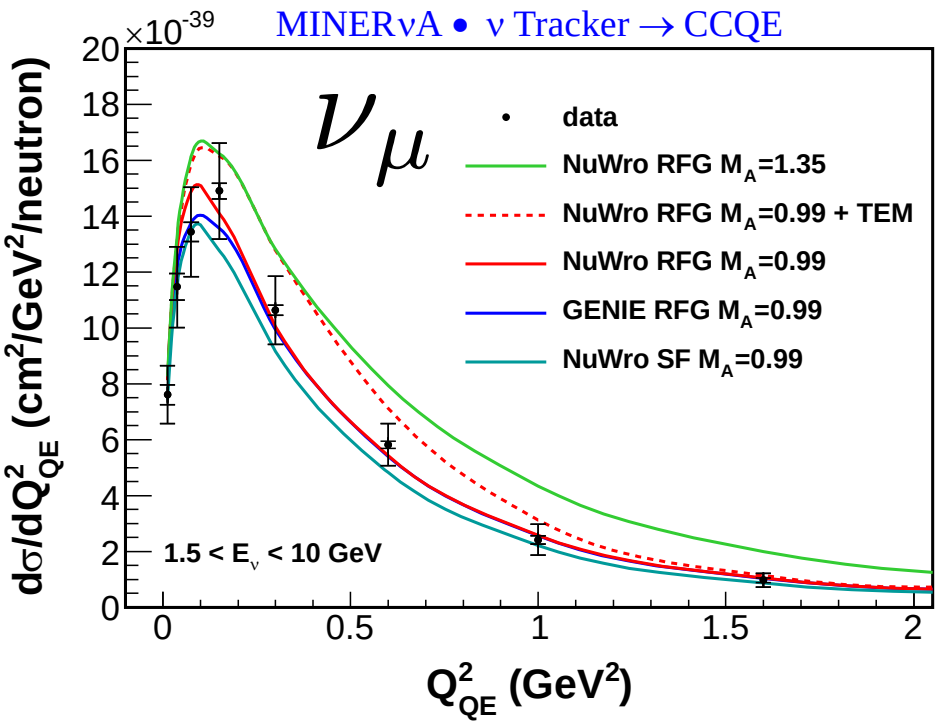


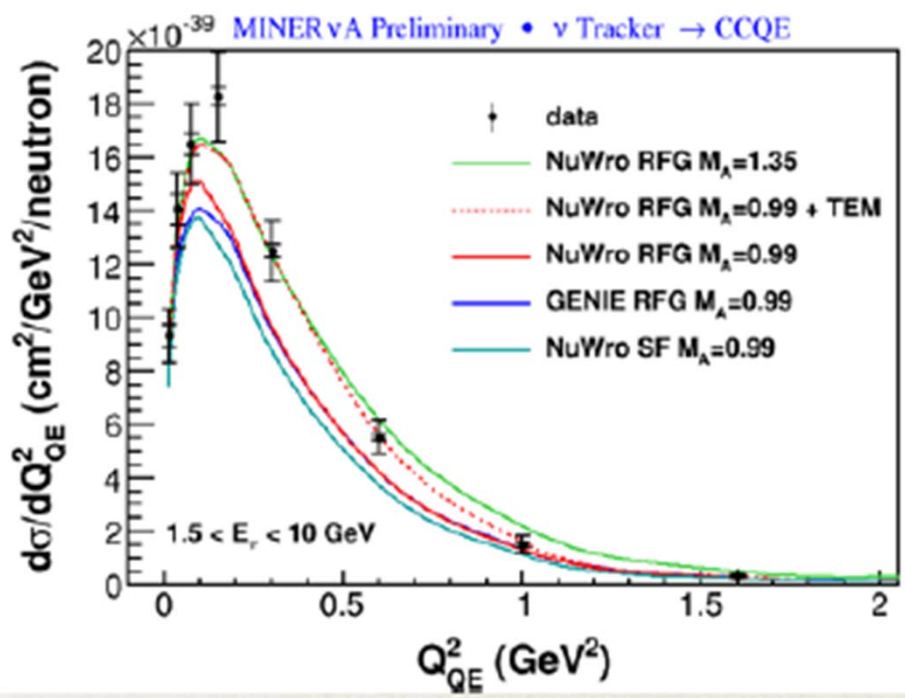




News flash – Minerva has updated flux calc

- Improved fit to hadroproduction data
- Cross sections grow, ~15% effect
- Same calculations as 2013 (older NuWro, GENIE 2.6.2)





Model choices

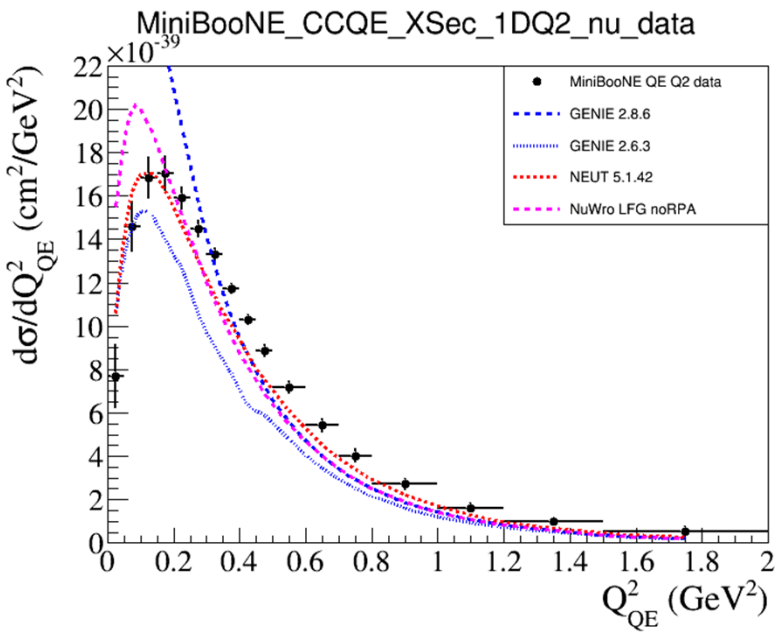
Model	N res	Non resonant	Nucleon Momentum	MEC	RPA
GENIE 2.12.0alt	Berger-Sehgal +	Bodek-Yang (extrap low W	Local Fermi gas	Valencia	Valenica
NEUT 5.3.6	Berger-Sehgal +	Rein-Sehgal	Global (rel) Fermi gas	Valencia	Valencia
NuWro	Adler (Δ only)	Bodek-Yang (extrap low W)	Local Fermi gas	Valenica	Valencia
GiBUU	Leitner et al.	Lalakulich et al. - empirical	Local Fermi gas	Home-grown	Home-grown
GENIE 2.6.3/2.8.6	Rein-Sehgal	Bodek-Yang (extrap low W)	Global (rel) Fermi gas	None	none
NEUT 5.1.4.2	Rein-Sehgal	Rein-Sehgal	Global (rel) Fermi gas	None	none

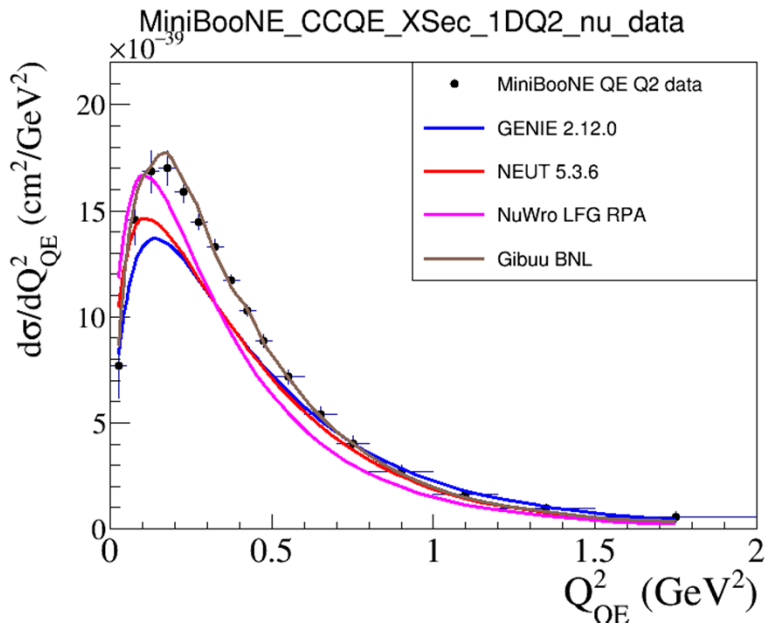
MODERN

OLD

NUISANCE Comparisons – New vs. Old

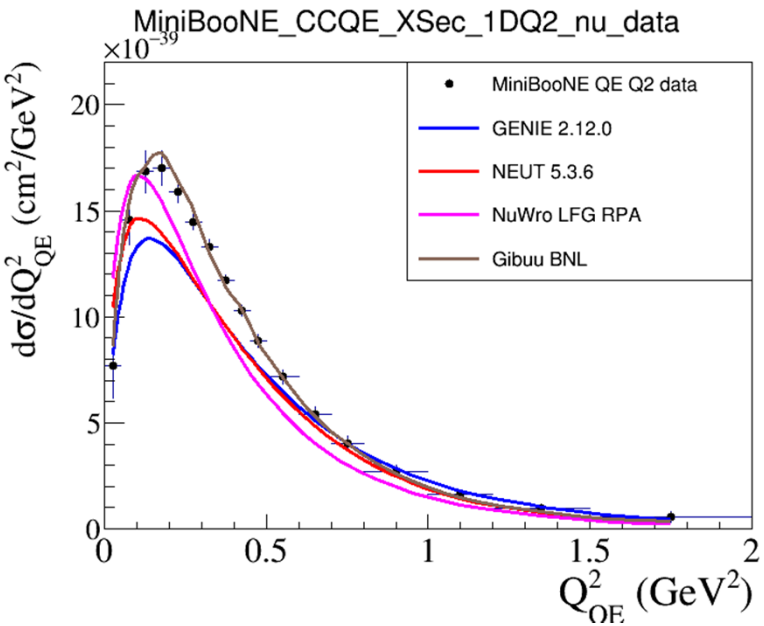
- MiniBooNE Q^2
  - Spread of models smaller for New
  - NEUT partially tuned to this
  - GENIE added improved models, no tuning yet

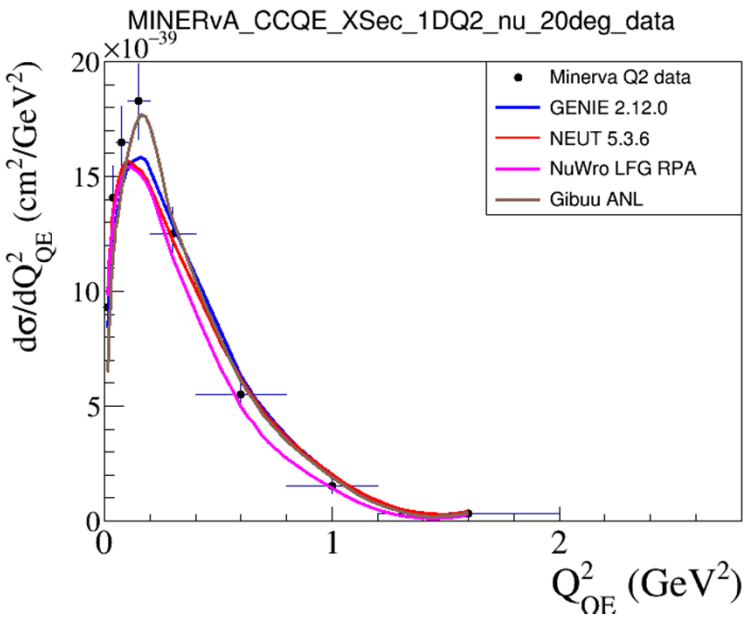




NUISANCE comparison for QE
updated Minerva flux

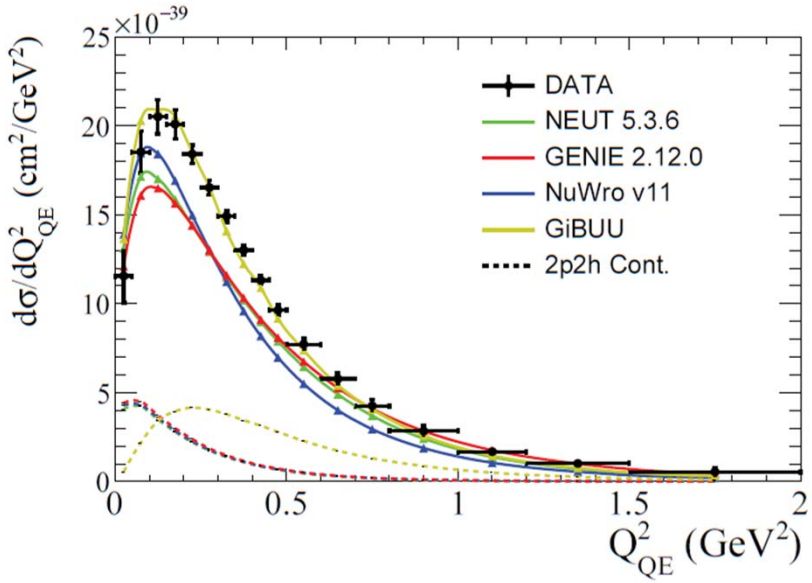
- Calculations using most recent versions of generator (user might have trouble reproducing these plots)
- normalization mismatch much reduced
- Shapes very similar, ~right for all

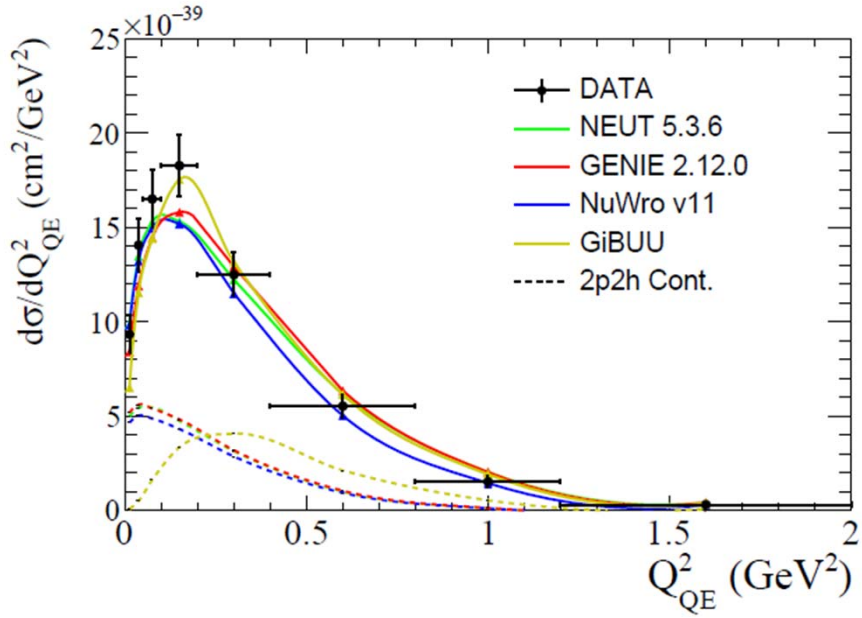




2p2h comparison interesting

- Q2QE assumes pure QE, ignores Fermi motion, constant binding energy
- NuWro, NEUT, and GENIE all use same Valencia model
- GiBUU is different

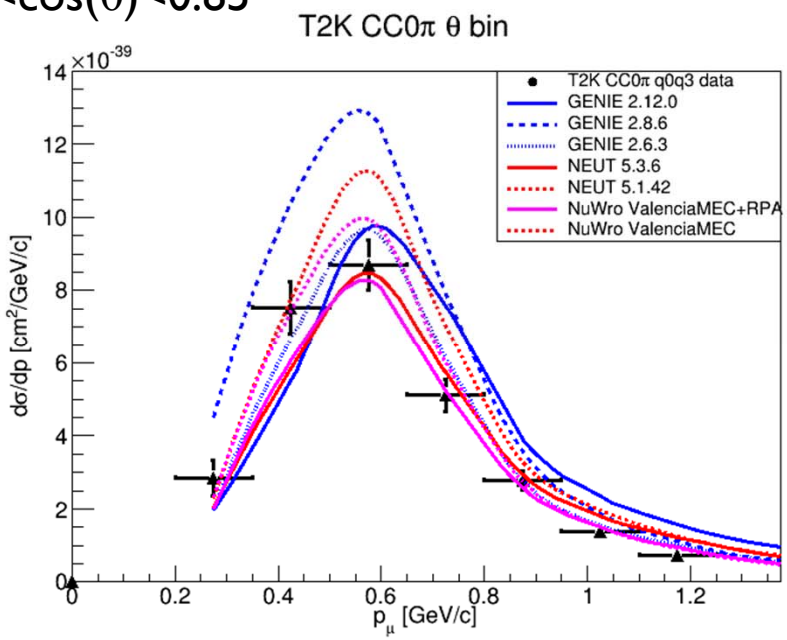




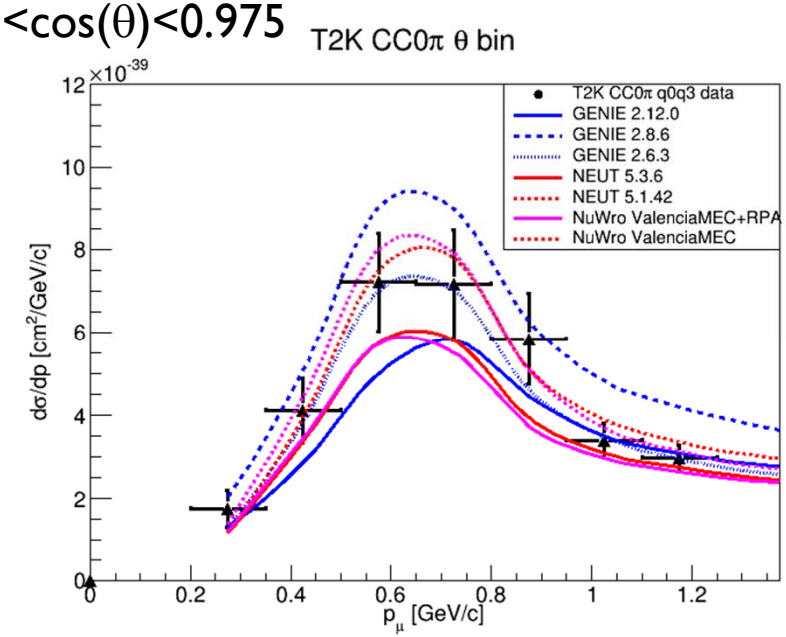
T2K becomes the third experiment

- Ok on average, but poorer agreement at forward angles
- Similar to MiniBooNE, except back angles worse there

0.8<cos(θ)<0.85



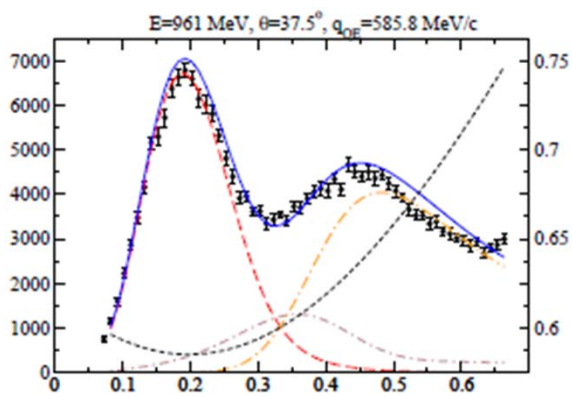
0.95<cos(θ)<0.975



Theory – Super Scaling Approach (SuSA)

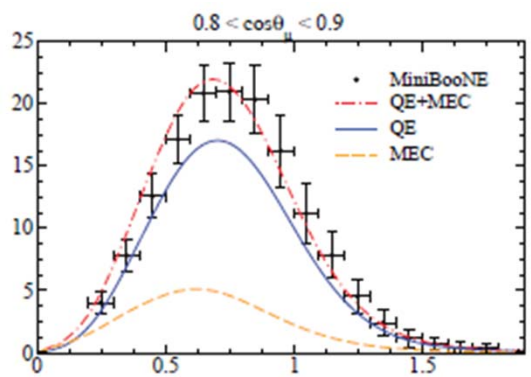
- Recent series of papers (Megias, et al.)
  - Inclusive (e,e'), (ν_μ,μ), $(\bar{\nu}_\mu,\mu)$
  - QE, Δ response from scaling fits; calculate MEC in RFG model
  - Excellent agreement with electron, neutrino inclusive data
  - Very hard to go beyond inclusive, not in any generator

e,e'



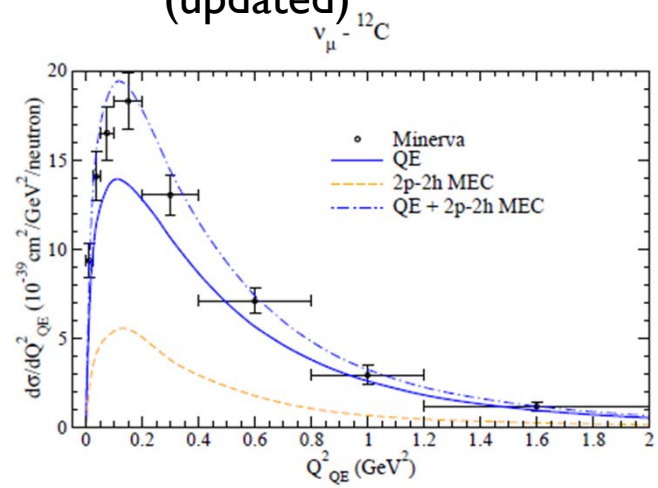
ν (GeV)

MiniBooNE CCQE



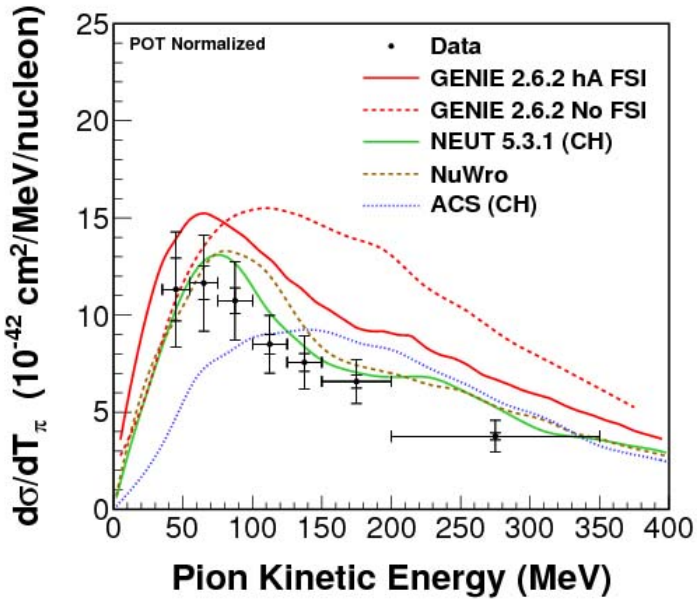
T_μ (GeV)

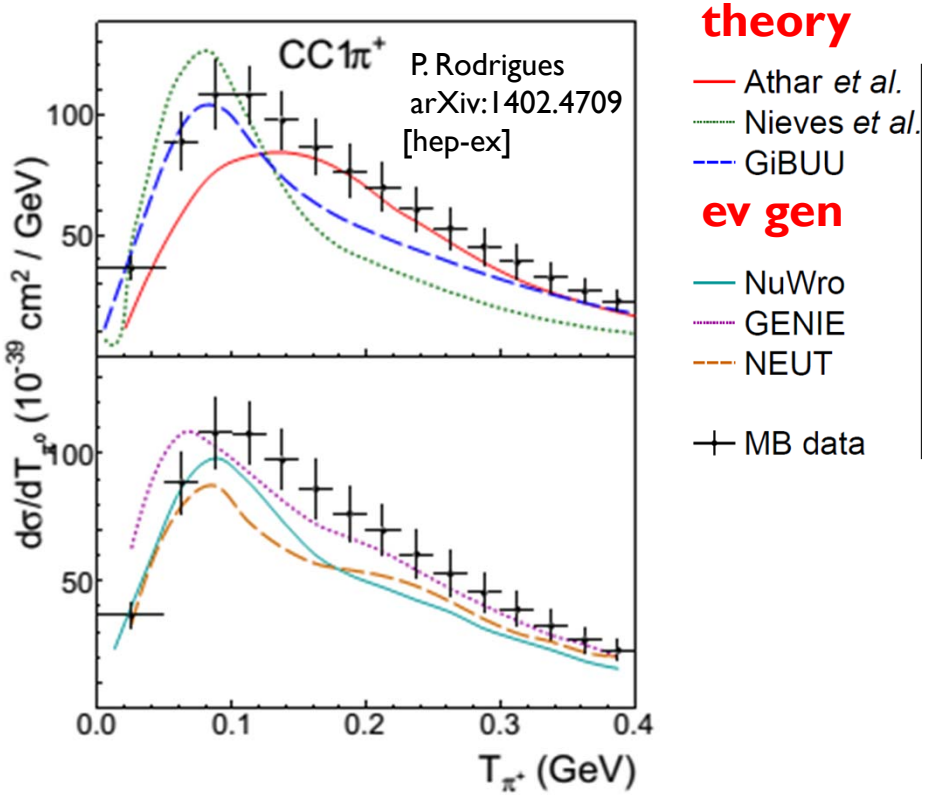
Minerva CCQE (updated)



MiniBooNE ν CH2 π+ (E_ν~ 1 GeV) vs. Minerva ν CH π+ (E_ν~ 4 GeV) data

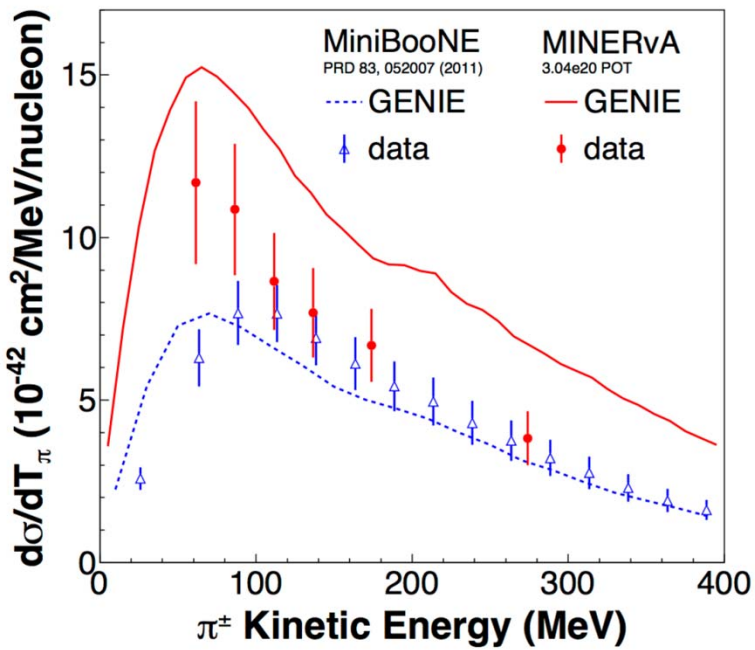
- Wide variation at first glance
- FSI strongly affects shape, generators shape close to data
- No model fits both data sets
- Improvement important for oscillation experiments?





How well do MiniBooNE and MINERvA agree?

- MiniBooNE - $<E_\nu>$~1 GeV; MINERvA - $<E_\nu>$=4 GeV
- W cuts are different, covered in calculations (GENIE 2.6.2)
- MINERvA tried to design experiment for direct comparison
- MINERvA has much larger contribution from higher W, considers it background. MiniBooNE cuts W<1.35 GeV and adds higher W strength (still Δ) from model (~28% from GENIE)
- Therefore, need to increase MINERvA data by 28% (and corresponding GENIE calc) Direct comparison not advised. MiniBooNE not able to remove model dep.
- Shapes are different in data, not calc

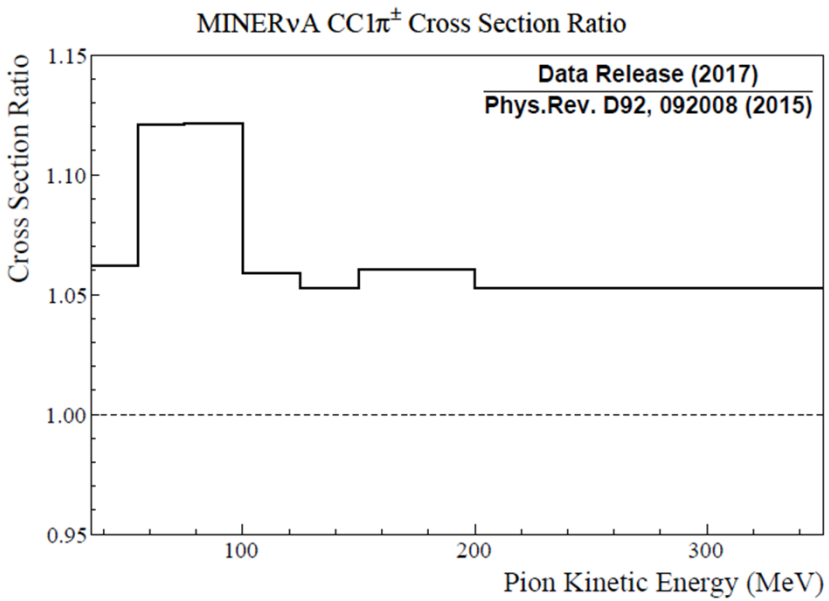


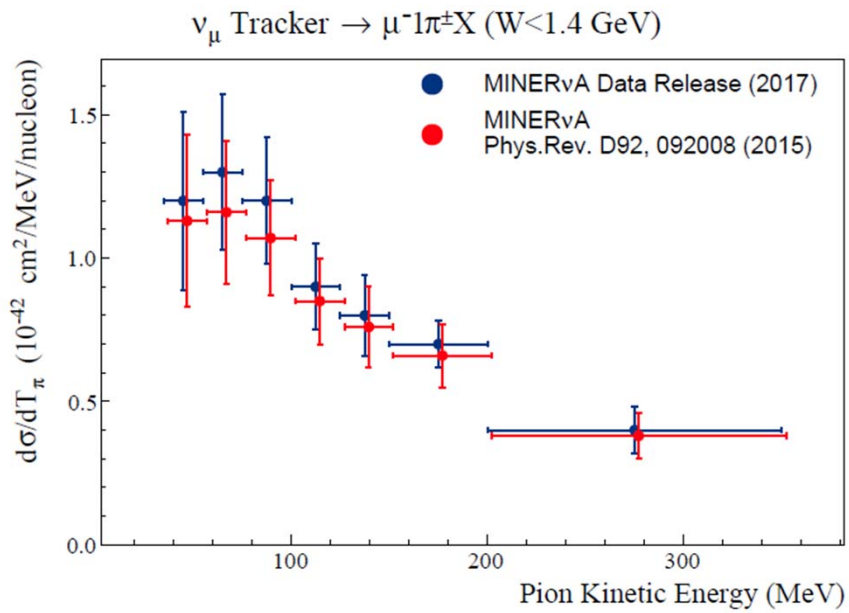
Signals

- MiniBooNE CC1π^+
  - Detected π from dE pattern in Cerenkov/scintillator
  - Interacting pions give 2 signals, valuable signature
  - Signal: 1μ^-; 1π+ at any energy, angle
  - Eν~1 GeV
- MINERvA CC1$\pi\pm$
  - Tracked pion in segmented scintillator
  - Main identification through dE/dx and Michel tag
  - Signal: 1μ^-; 1$\pi\pm$ at any energy, angle; Wtrue<1.4 GeV
  - Eν~4 GeV
- T2K CC1π^+ (not available for Tensions)
  - Signal: 1μ^-; 1π+ at any energy, angle
  - Eν~1 GeV

New analysis of Minerva $1\pi^{\pm}$ data
(really almost all π^{+})

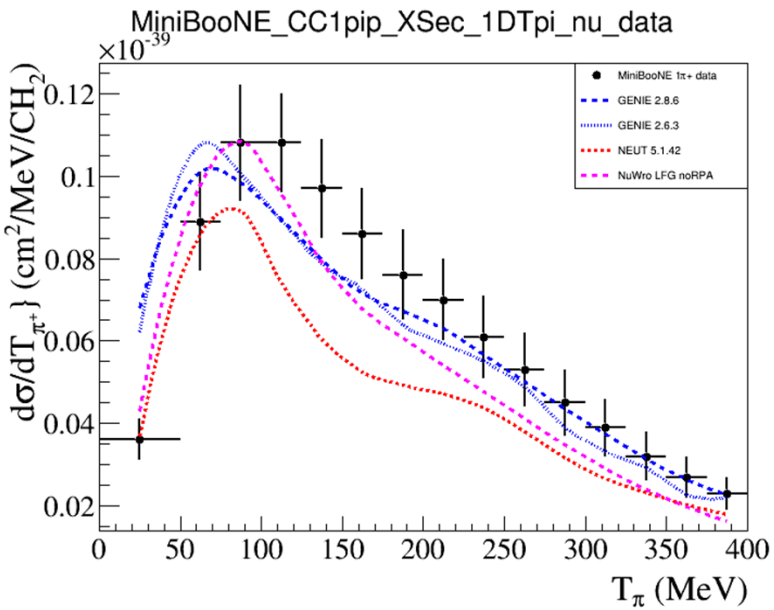
- Improved definition of W in signal – Wreco
  - Takes away fear of strong model dependence
  - ~15% increase in cross section independent of kinematics
- Improved flux (now in all Minerva LE results)
  - ~10% decrease in cross section independent of kinematics
- New data should be used in future, used in following plots

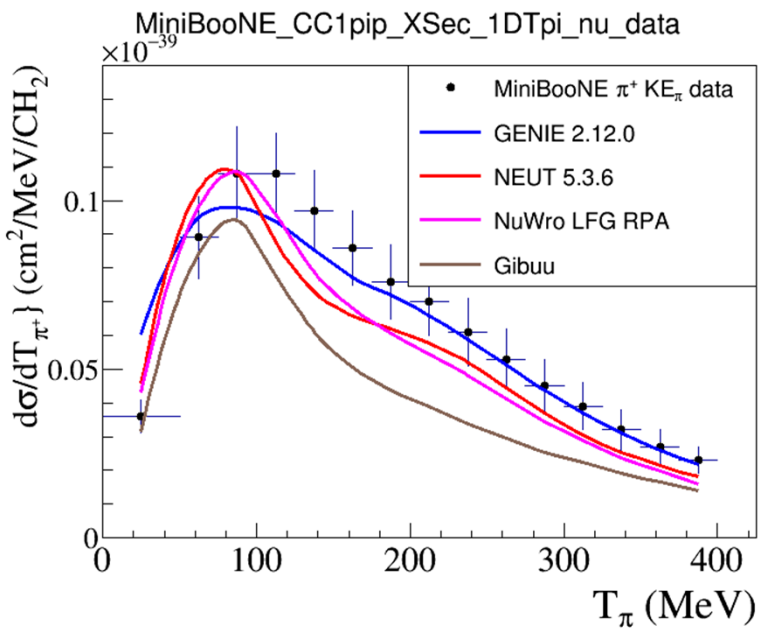




NUISANCE Comparisons – T_π OLD vs. NEW

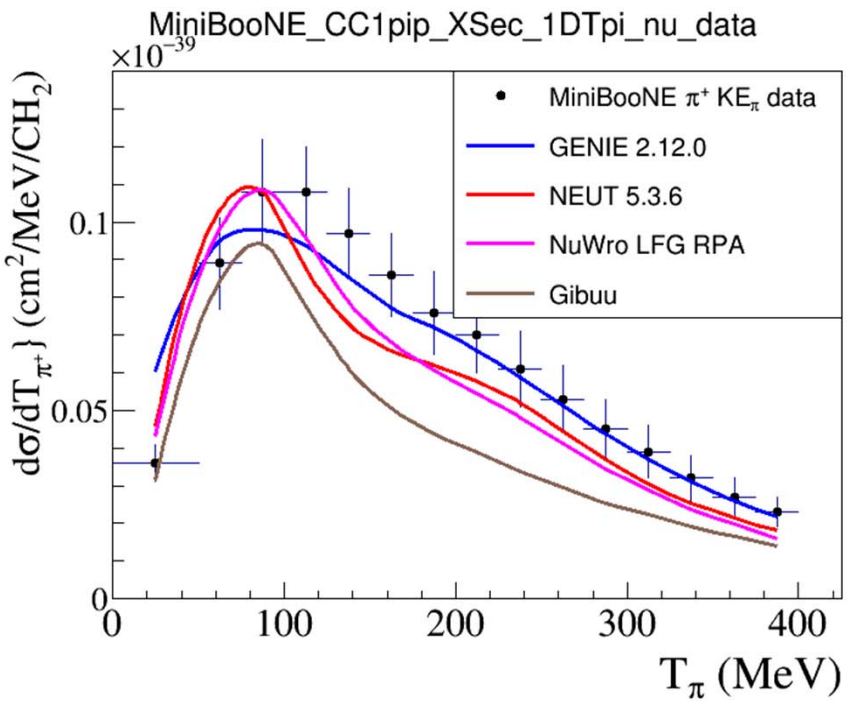
- New has significant improvements
  - NEUT has improved tune to N data
  - GENIE has improved form factors, FSI
- Better match, but discrepancies remain
- GiBUU is best theory, doesn't have coherent

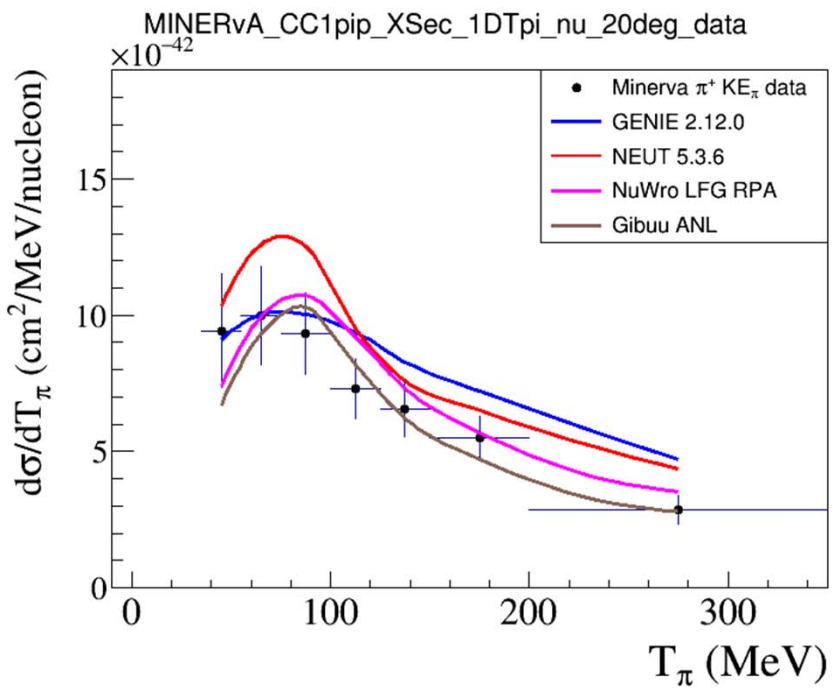




NUISANCE comparisons - T_π

- Both magnitude and shape discrepancies ~10-20%
- FSI bigger issue than nuclear structure



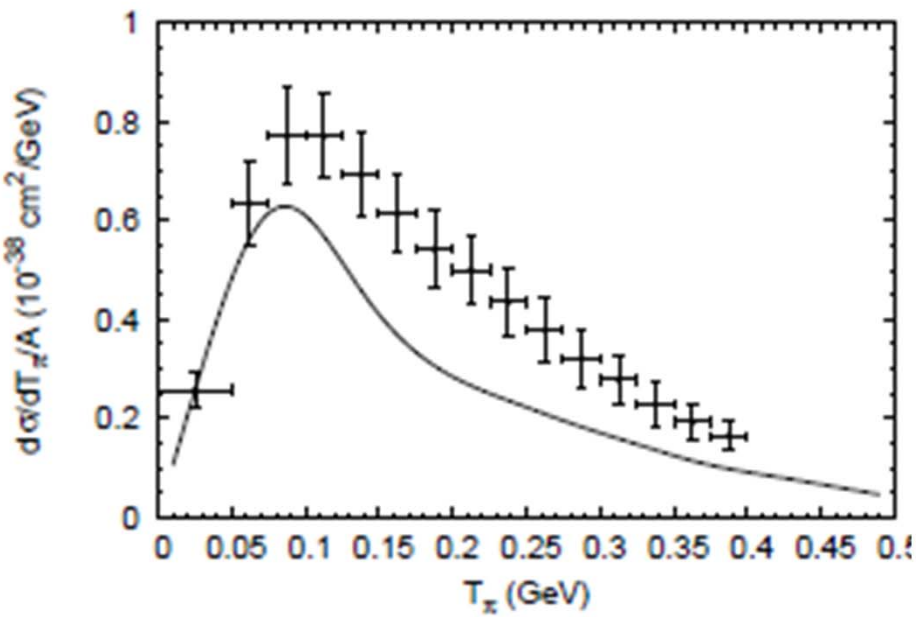


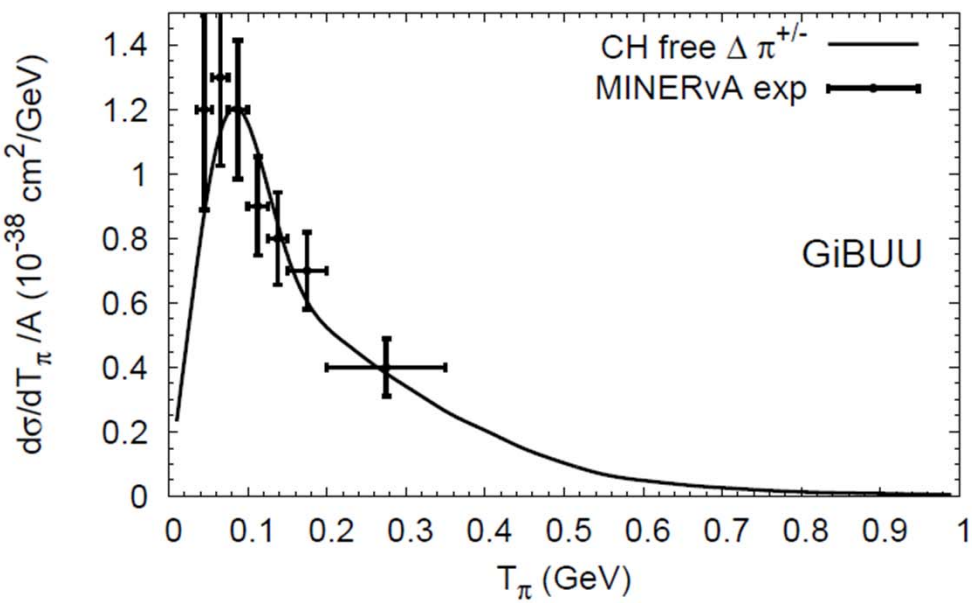
Summary

- MiniBooNE vs. MINERvA comparison more clear
  - Signals are different, no direct comparison possible
  - Magnitude problem much reduced with MINERvA flux improvement
  - Still 10-20% problems for 1π production, big issue?
- NUISANCE will be valuable tool for easier comparisons
- Tensions conclusions
  - Signals must be carefully chosen, described
  - Cuts should be on detected quantities (e.g. p_μ, T_p)
  - Avoid MC corrections from undetected kinematics (e.g. θ_μ)
  - Hard to imagine direct comparison between expts (signals)
- Need quality results for p,n targets
- Newer data to be presented in this session

GiBUU comparisons- T_π

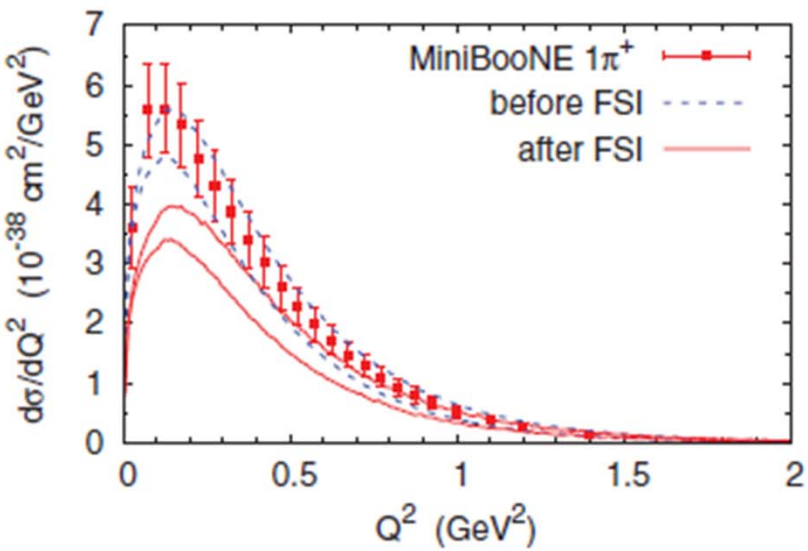
- Results from Mosel/Gallmeister arXiv:[nucl-th]1702.04932
- Calculations don't include coherent contribution (~7% for Minerva)
- Seems to be both magnitude and shape problem

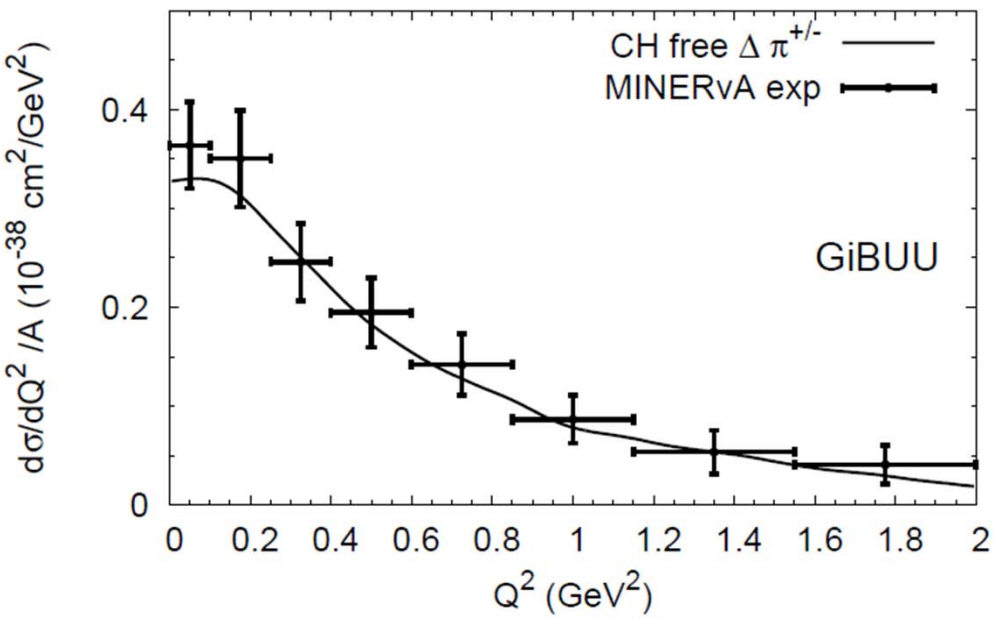




GiBUU comparisons - Q^2

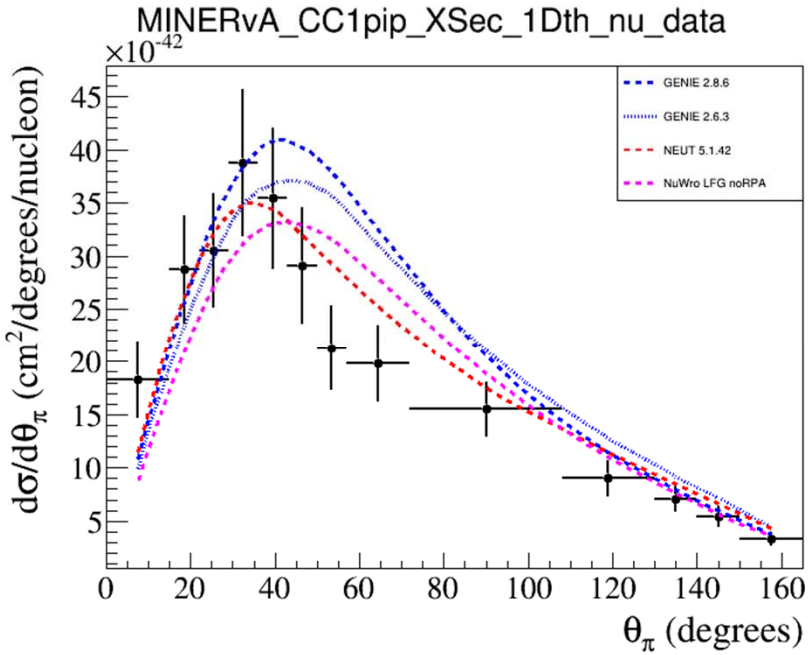
- MiniBooNE plot from PR C87, 014602 (2013)
- Minerva plot received from U. Mosel last week

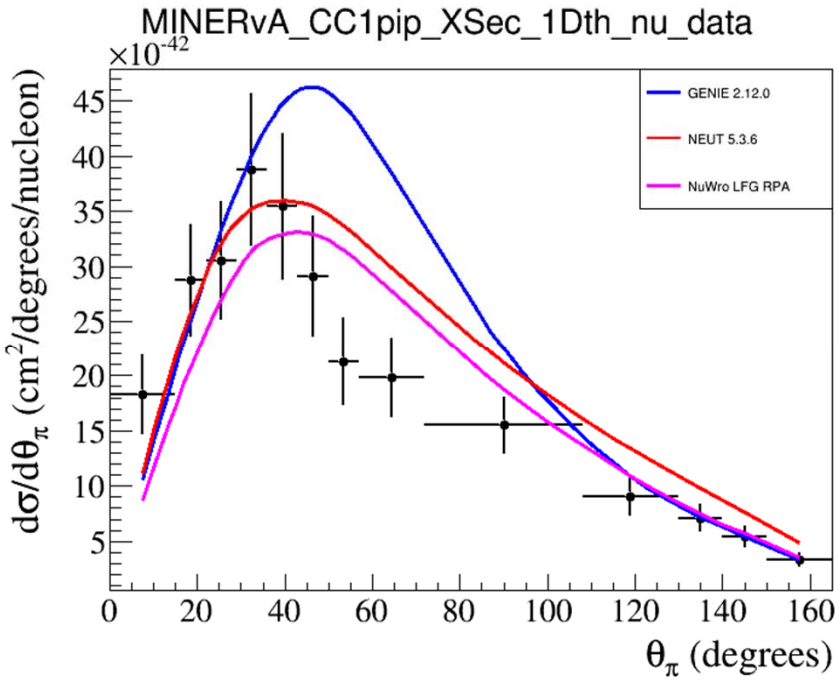




NUISANCE comparisons – θ_π New vs. Old

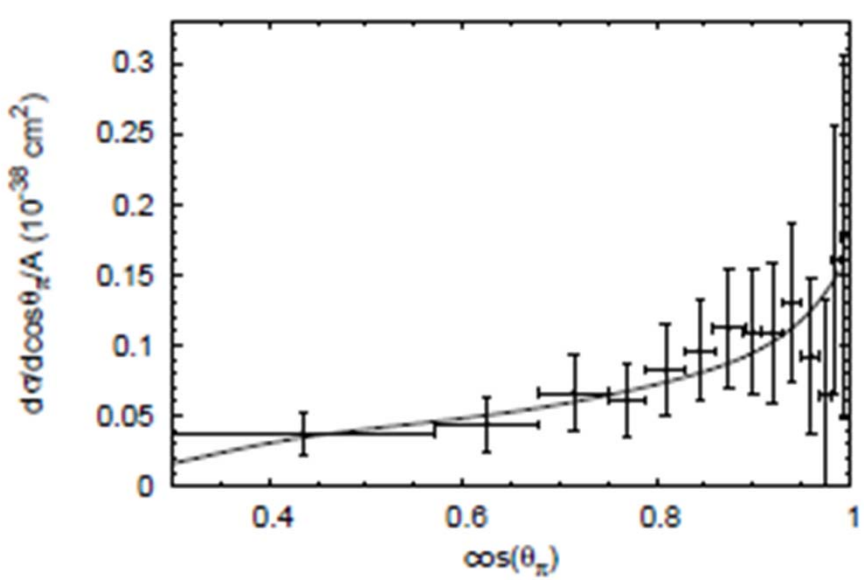
- Hardest to describe for generators
- New GENIE model does worse (T_π also)

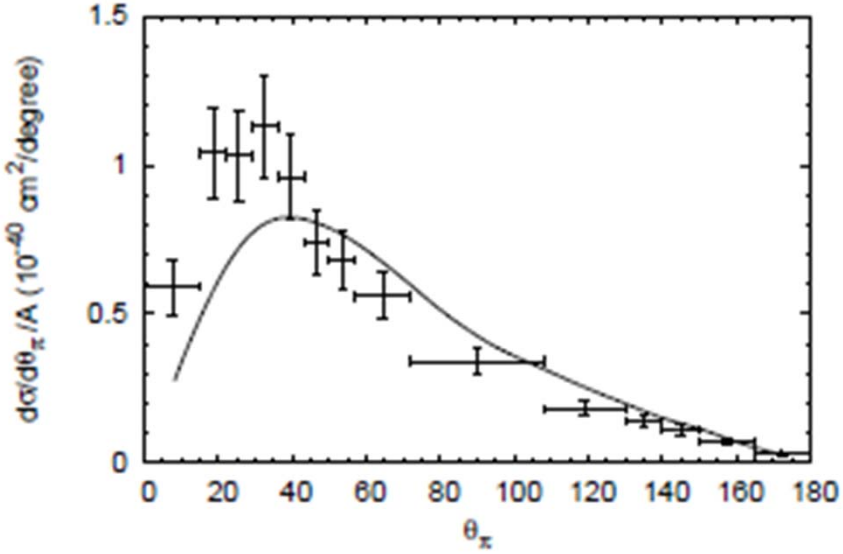




GiBUU comparison - θ_π

- (Left) T2K (new) data (cos θ_π)
- (Right) Minerva W<1.8 GeV data
- Minerva data has coherent, GiBUU doesn't





Looking ahead - experiment

- New CCQE-like results for Minerva very soon (W&C talks by Betancourt (ν_μ,μp A dep), Patrick ($\bar{\nu}_\mu$,μ $p_\mu^{T,L}$), Ruterbories (ν_μ,μp $p_\mu^{T,L}$))
- Minerva now at higher energy (5 GeV), T2K still active
- MicroBooNE (LAr), NOvA (CH) starting to produce
- Tensions conclusions
  - Signals must be carefully chosen, described
  - Cuts should be on raw quantities (e.g. p_μ, T_p)
  - Avoid MC corrections from undetected kinematics (e.g. θ_μ)
  - Hard to imagine direct comparison between expts (signals)
- Need quality results for p,n targets
- Need cross section experiment at DUNE energy

Looking ahead – Monte Carlo

- NUISANCE should be important tool (growing)
- Slow progress in electron scattering code (only GENIE)
- New models tend not to have (e,e') or reweighting
- GENIE projects underway
  - GEANT, INCL++, GiBUU alternate FSI models
    - Crosscheck between event gen (GENIE) and detector propagation (GEANT)
    - Alternate models that do better at lower energies
  - New energy in electron scattering (MIT)
  - Searching for new default model (v3.0 summer)
  - Installing new fitting code – Professor (v4.0 ~1 year)
- Proposed projects with US theorists
  - Inclusive (e,e') and (ν_μ,μ) (QE, MEC, Δ) from SuSA model, full wave func
  - Both need significant effort, collaboration

summary

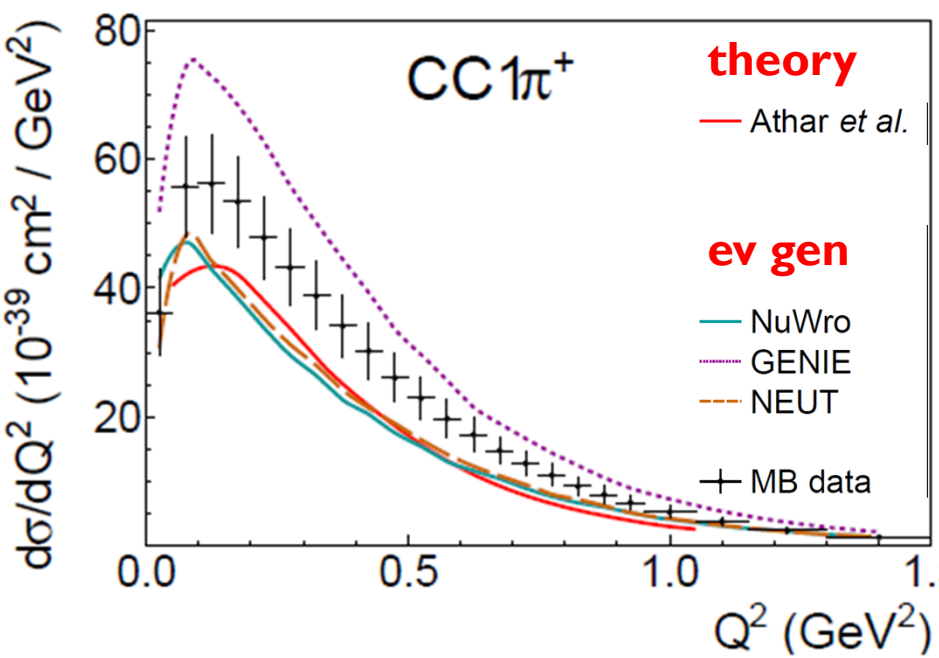
- Improved agreement with MiniBooNE, Minerva QE nuclear models, new Minerva flux
- Some improvement for 1π, ~10-20% discrepancies remain
- When is agreement with experiment good enough?
  - Are we there now?
  - We need to work harder on both event generators and signal definitions in experiment!
- All GENIE activities manpower limited
  - Much better interaction with theory, experimental communities in last few years, could still be better; funding issue complex
  - GENIE is still slow in advances (manpower, complexity)
  - Both NEUT and GENIE have adopted modern theory in last 2 years, improvement positive but limited

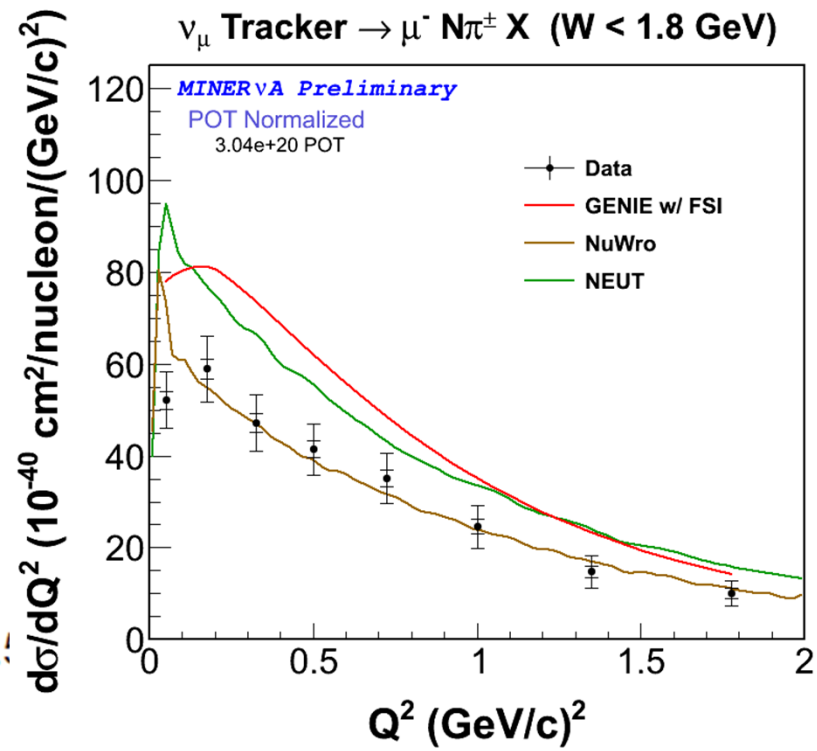
Generator advances (QE like)

- Guided in part by NuWro, GENIE and NEUT have had active programs to use better theory models
- NEUT (5.3.6 default)
  - Local Fermi Gas
  - Llewyllen-Smith
  - Valencia MEC+RPA
  - Improved proton FSI
- GENIE (2.12.0 alternate model)
  - Local Fermi Gas
  - Nieves QE with RPA+Coulomb
  - Valencia MEC
  - Improved proton FSI

More data for μ, ν variables – Q^2

- Minerva (Carrie McGivern, W&C June, 15) for W<1.8 GeV
- Data from 2 expts have similar shapes, calcs ~agree.
- Predictions for Minerva have a spike at low Q^2.



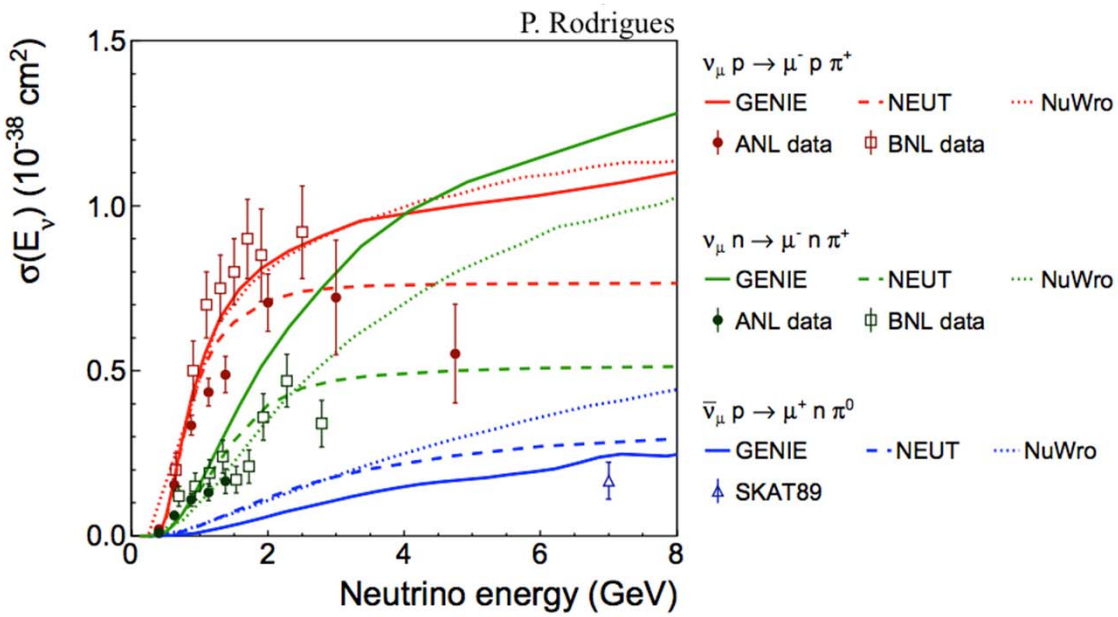


GiBUU (Mosel) vs. GENIE default

- Local Fermi Gas momentum distribution [global FG]
  - Smearing from local potential well [no]
- Principal vertices
  - Fit to old bubble chamber data with modern models [same]
  - Simple MEC (constant matrix element) [none]
- FSI
  - Transport equations allow some medium corrections [empirical]
    [no medium corr.]
  - Slow, but very accurate and well-tested [fast, well-tested]
- Best nuclear physics available today
- GENIE is (slowly? surprisingly quickly?) catching up

ν_μ p,n data, interpretation
The nucleon problem - low statistics BC expts

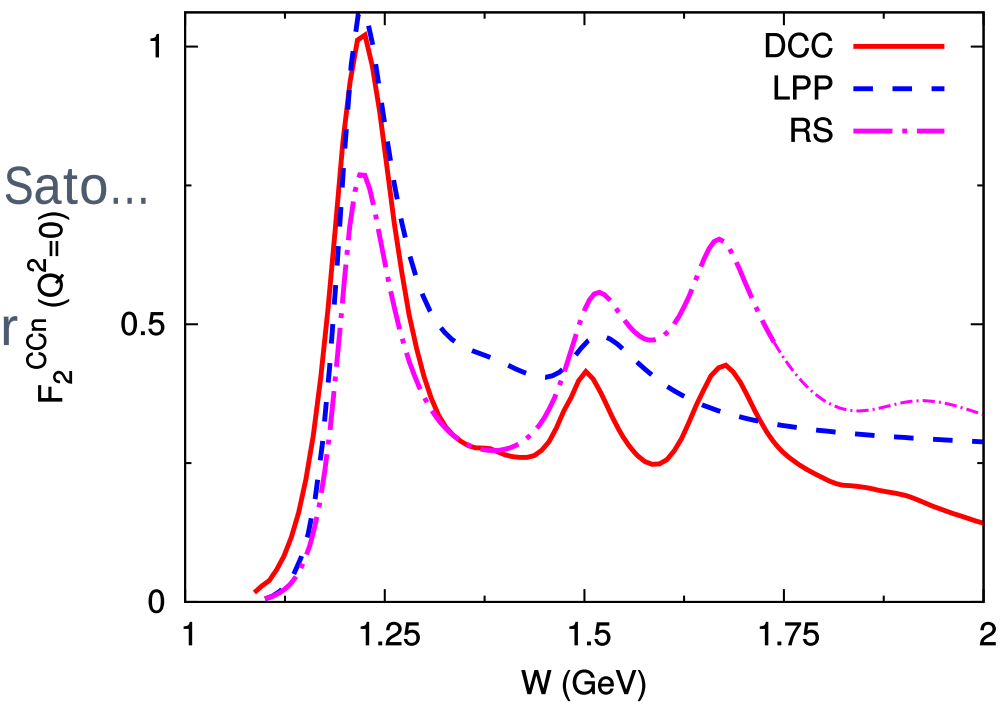
- Plot shows what GENIE, NEUT, and NuWro use (pion prod)
- Historical problem with BNL>ANL at low Eν for all calculation
- Recent reanalysis by Wilkinson et al. favors ANL
- Most models take middle approach



- Wide variation in use of n π^+ data
- Fortunately, p π^+ dominates in results
- NEUT has updated fit to reanalyzed data
- Additional data not shown

Solutions?

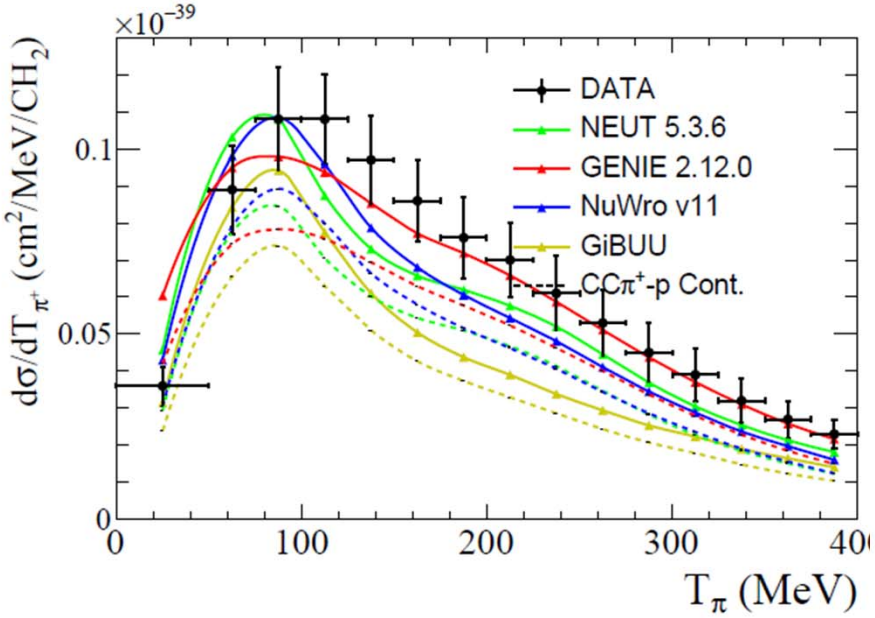
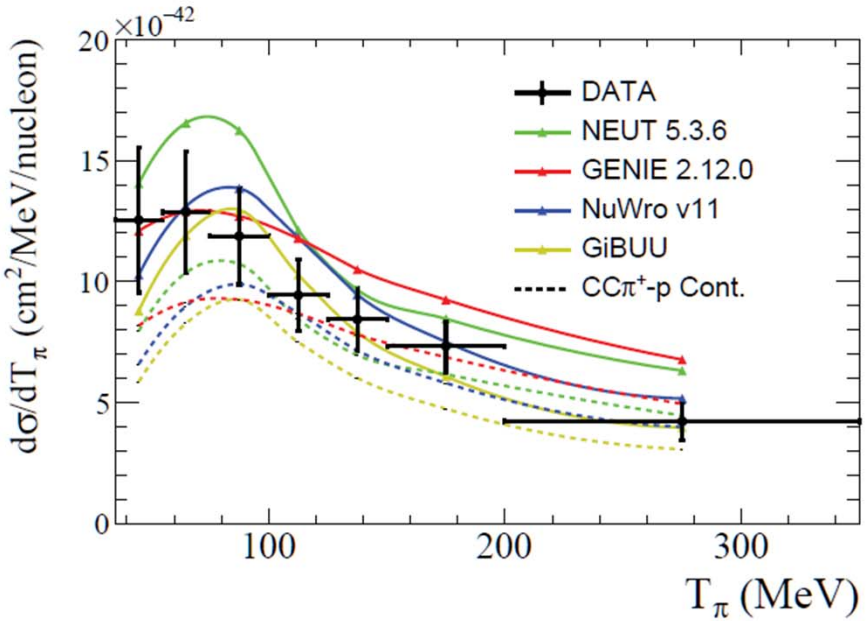
- Data
  - Reanalysis of old data
  - New analyses of CH data (T2K, Minerva)
  - New experiment
- Theory
  - Coupled channel
    work of Nakayama, Sato...
    very interesting
  - Not in any generator



Model choices

Model	N res	Non resonant	Nucleon Momentum	Δ mods	FSI
Athar	Schreiner-Von Hippel	none	Local Fermi gas	Fit to (γ,π)	Attenuation only
GiBUU	Leitner et al.	Lalakulich et al. - empirical	Local Fermi gas	Fit to (γ,π) Oset	Transport
Valencia	Hernandez et al.	Chiral model	Local Fermi gas	Fit to (γ,π)	Salcedo-Oset (full)
GENIE	Rein-Sehgal	Bodek-Yang (extrap low W)	Global (rel) Fermi gas	none	Effective cascade
NEUT	Rein-Sehgal	Rein-Sehgal	Global (rel) Fermi gas	Via FSI model	Salcedo-Oset (full)
NuWro	Adler (Δ only)	Bodek-Yang (extrap low W)	Global (rel) Fermi gas	Via FSI model	Salcedo-Oset (full)

Nuisance – Monte Carlo comparator

- Grew out of tuning efforts in T2K
- P. Stowell (Sheffield), L. Pickering (Oxford), C. Wilkinson (Bern), C. Wret (Imperial)
- Single program makes predictions for various data sets
  - Plots with generator files
  - Reweighting from generator
  - Fitting using Minuit
  - Working copy of each generator required
- They got fit to MiniBooNE data, important for T2K oscillations
- Important contribution to Tensions workshop

- Importance of Δ^{++}