Summary of 1pion studies
Tensions Workshop - 2016

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INT, Seattle

5 December, 2016

- informal meeting in Pittsburgh
- T2K, MINERvA, MiniBooNE data
- GENIE, NEUT, NuWro, Nuance, GiBUU event generators
- Try to compare/contrast published data

data

Wilking [MiniBooNE] Phys. Rev. D83: 052007 (2011)

ν_μ CH_2 →-> $\mu^-\pi^+X$ (only $1\pi^+$)

Nelson [MinibooNE] Phys. Rev. D83: 052009 (2011)

ν_μ CH_2 → $\mu^-\pi^0X$ (only $1\pi^0$)

Eberly [Minerva] Phys. Rev. D92: 092008 (2015)

ν_μ CH → $\mu^-\pi^+X$ (only $1\pi^+$, I or $2\pi^+$),

Le [Minerva] Phys. Lett. B749, 130 (2015)

$\overline{\nu}_\mu$ CH → $\mu^-\pi^0X$ (only $1\pi^0$)

McGivern, et al. [Minerva] Phys. Rev. D (2016)

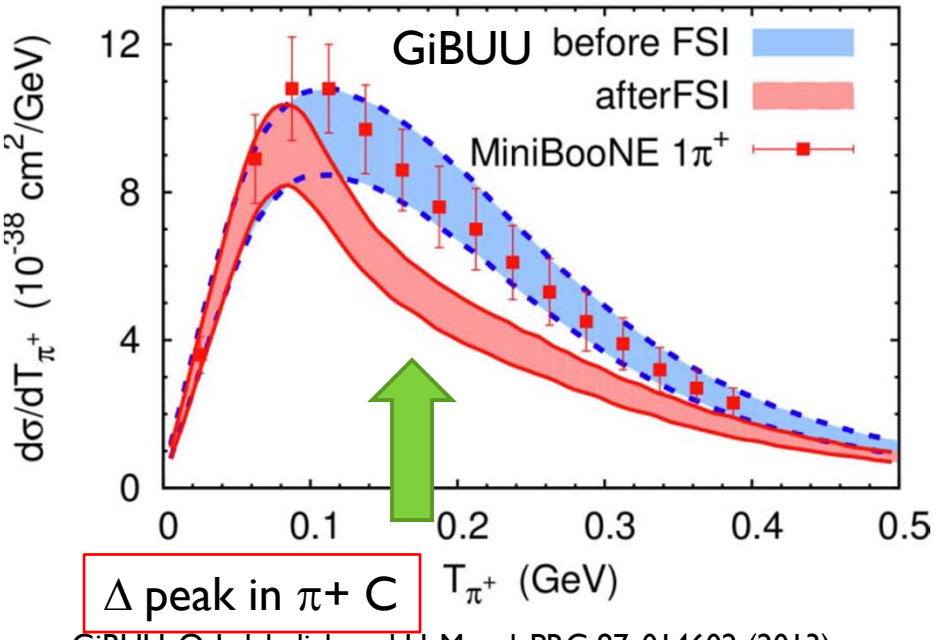
ν_μ CH → $\mu^-\pi^+X$, $\overline{\nu}_\mu$ CH → $\mu^-\pi^0X$

Castillo, et. al. [T2K] to be submitted soon

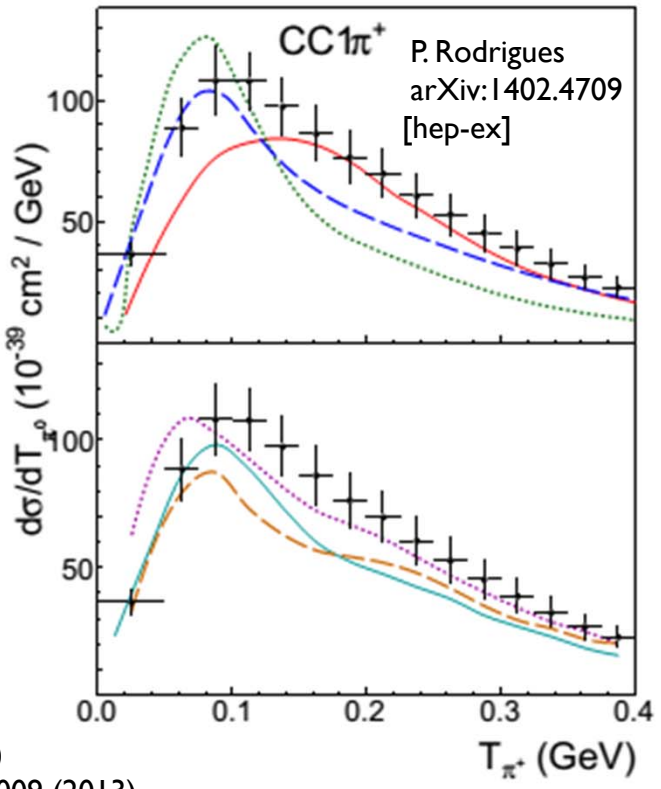
MiniBooNE problem (ν CC1π^+)

- MiniBooNE data hard to reproduce, questions FSI models?
- Very relevant to CCQE-like oscillation signal, new systematic?

Data at E_ν~1 GeV



Δ peak in π+ C



theory
- Athar *et al.*
- Nieves *et al.*
- GiBUU

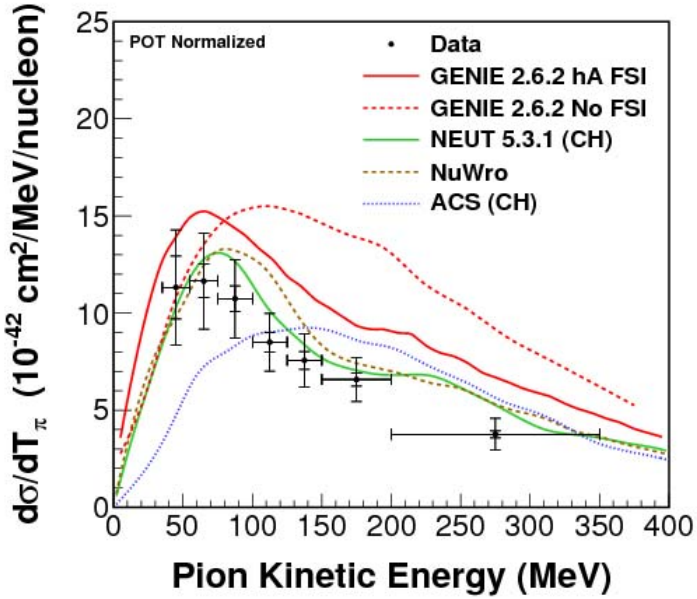
ev gen
- NuWro
- GENIE
- NEUT

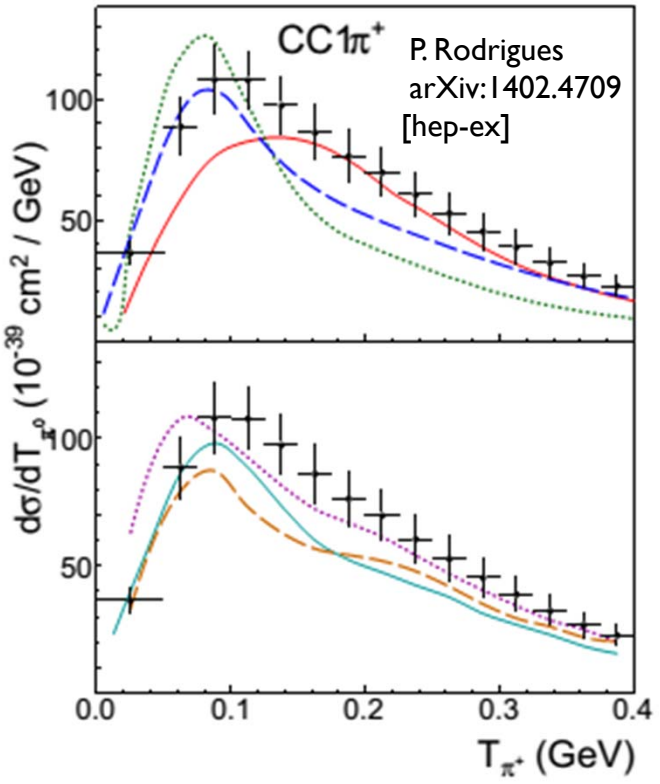
MB data

GiBUU: O. Lalakulich and U. Mosel, PRC 87, 014602 (2013)
NuWro: T. Golan, C. Juszczak, J. Sobczyk Phys Rev C80, 15505 (2012)
Nieves: E. Hernanadez, J. Nieves, M. Vicente Vacas, Phys Rev D87, 113009 (2013)

Minerva ν CH π+ data

- GiBUU unavailable, Valencia not applicable for MINERvA
- FSI strongly affects shape, generators shape close to data
- No model fits both data sets
- Improvement?



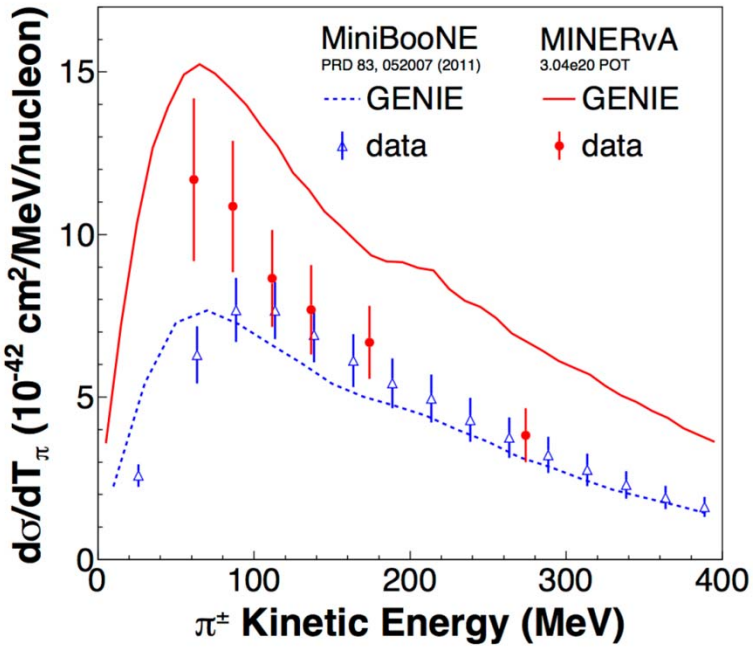


Model choices

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)

How well do MiniBooNE and MINERvA agree?

- MiniBooNE - $\langle E_\nu \rangle \sim 1$ GeV; MINERvA - $\langle E_\nu \rangle = 4$ GeV
- W cuts are different, covered in calculations
- MINERvA (Eberly and I) 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) for **direct comparison**
- Shapes are different

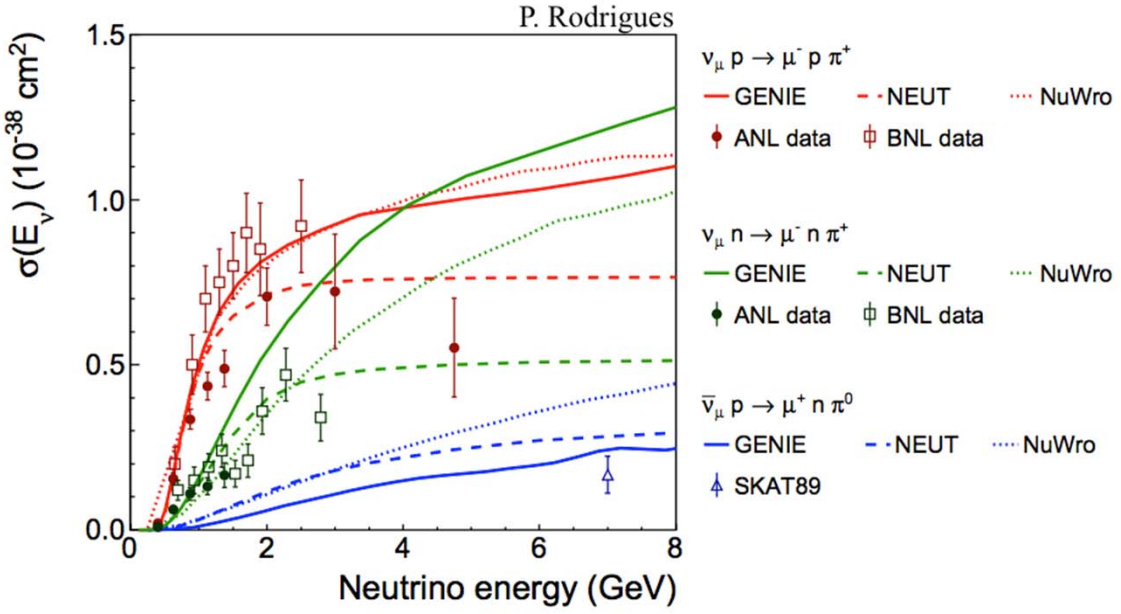


responses

- Theorists have fitted models to existing (e,e'), πA, and older νd data. Clearly better than event gen at the time.
  - What can be changed?
  - GiBUU oscillates between ANL and BNL νd data for fitting
  - Ask why no new νd data?
  - Valencia improves pion production vertex
  - Sobczyk & Zmuda question shape difference, suspect magnitude error
- New data
  - MiniBooNE publishes ν production of π^0
  - Minerva publishes ν production of π^+, νbar prod of π^0.
  - T2K coming soon
  - More Minerva data coming

Input to principal vertex (^{2}H bubble chamber data)

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

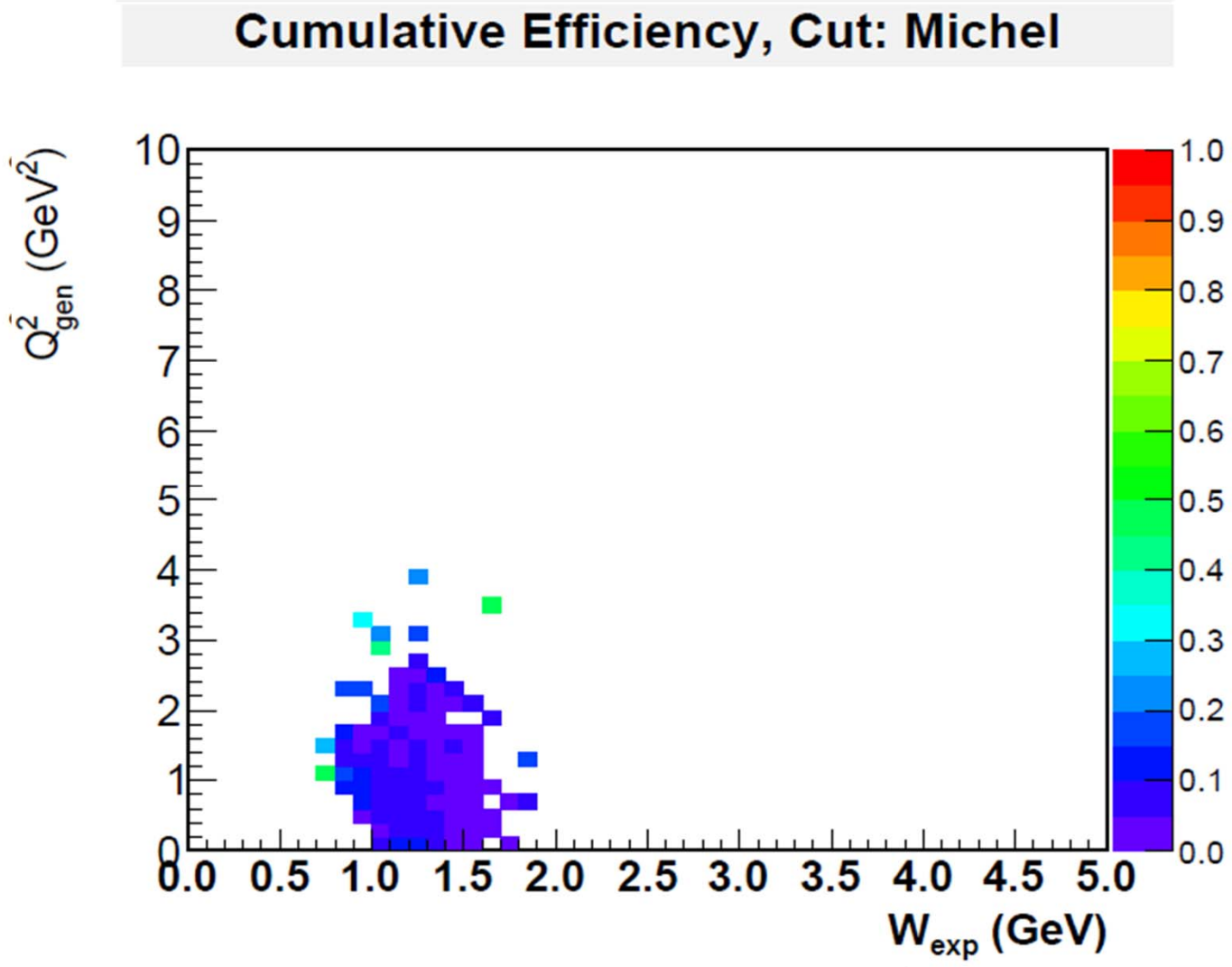


- Wide variation in use of n π^+ data
- Fortunately, p π^+ dominates in results.
- NEUT has updated fit to reanalyzed data
- Additional data not shown

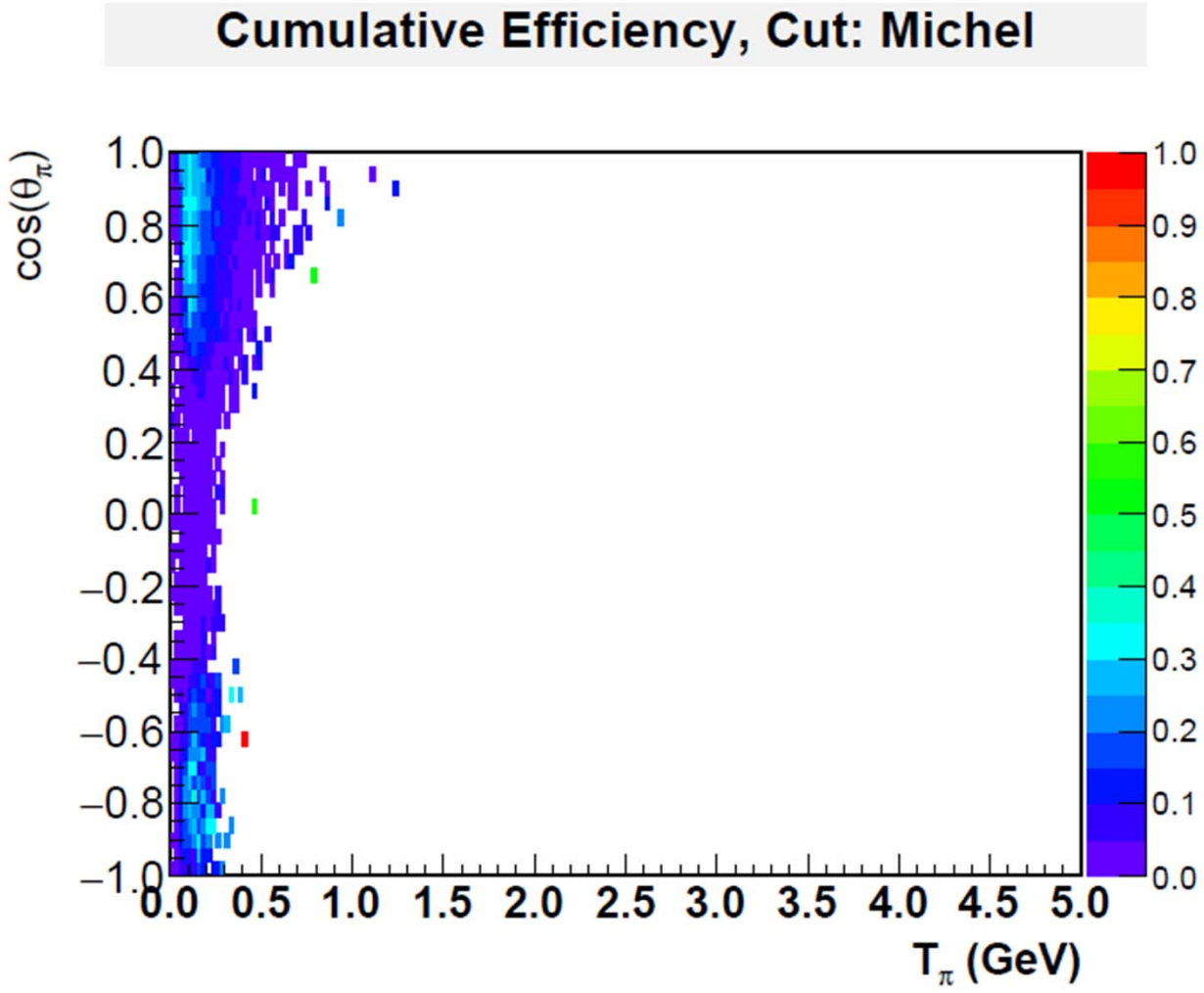
Signals

- MiniBooNE CC1π^+
  - Detected p from dE pattern in Cerenkov
  - 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; W<1.4 GeV
  - Eν~4 GeV
- T2K CC1π^+ (not available)
  - T_μ > 200 MeV/c p_π > 200 MeV/c
  - Eν~1 GeV

Cut progression – W vs. Q^2 MINERvA



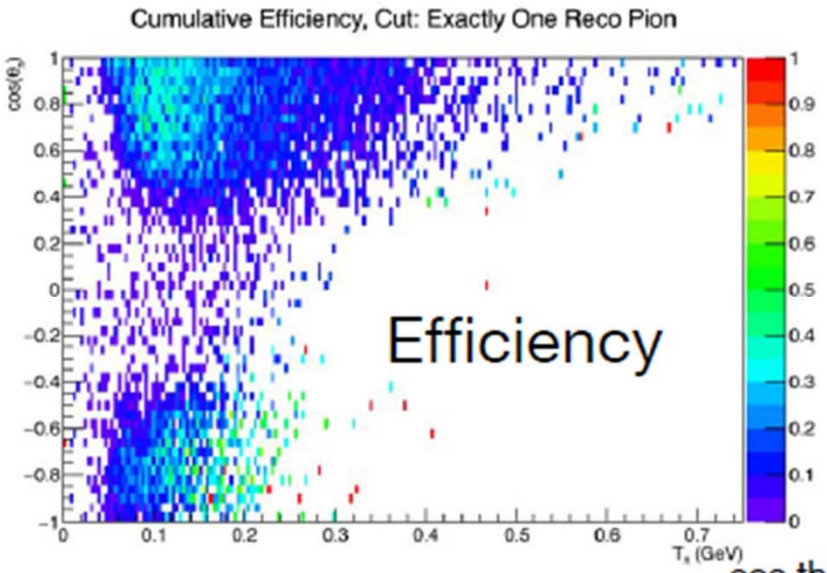
Before and after cuts – pion KE vs. cos(θ_π) MINERvA



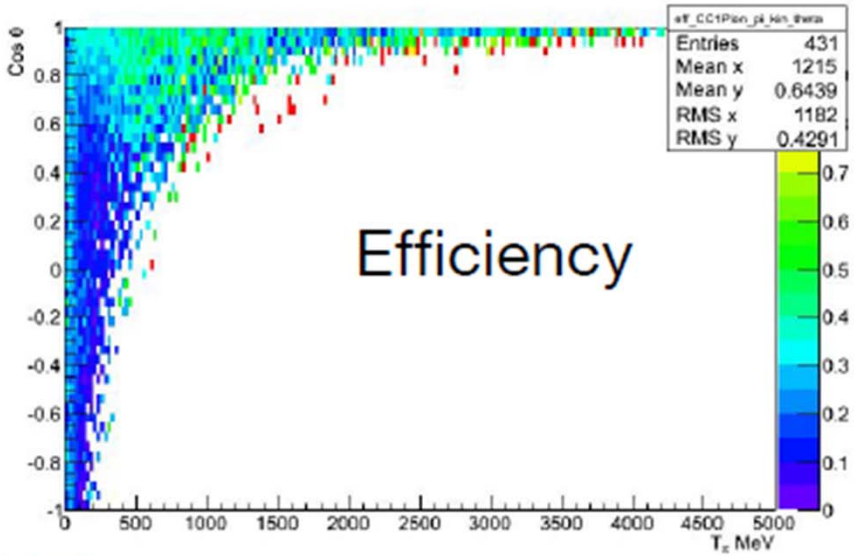
T2K vs. MINERvA – pion KE vs. cos(θ_π)

- $1\pi^+$ signal
- Similar coverage in KE_π, quite different in cos(θ_π)

MINERvA



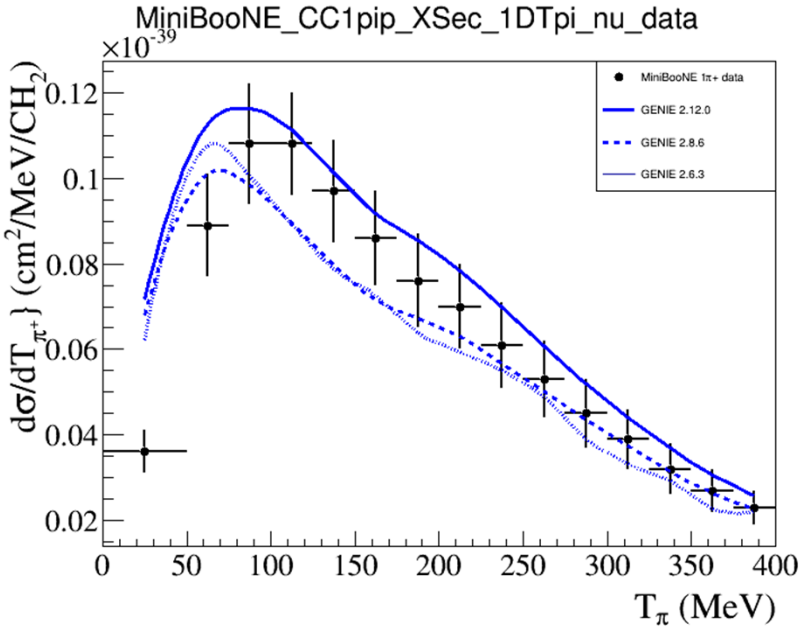
T2K



cos theta pi - Tpi

Generator comparisons

- Much easier with NUISANCE – public program from Stowall, Pickering, Wilkinson, Wret based on T2K work
- Makes plots comparing published data with generator
  - Includes signal definition for each data set
  - However, user must supply the proper generator file
  - Patrick Stowall made all the files used for comparisons in this talk



Model choices

Model	N res	Non resonant	Nucleon Momentum	Δ Medium effects	FSI
GENIE 2.12.0alt	Berger-Sehgal +	Bodek-Yang (extrap low W	Local Fermi gas	none	Improved Effective
NEUT 5.3.6	Berger-Sehgal +	Rein-Sehgal	Global (rel) Fermi gas	None	Salcedo-Oset (full)
NuWro	Adler (Δ only)	Bodek-Yang (extrap low W)	Local Fermi gas	none	Salcedo-Oset (full)
GiBUU	Leitner et al.	Lalakulich et al. - empirical	Local Fermi gas	Fit to (γ,π) Oset	Transport
GENIE 2.6.3/2.8.6	Rein-Sehgal	Bodek-Yang (extrap low W)	Global (rel) Fermi gas	none	Effective cascade
NEUT 5.1.4.2	Rein-Sehgal	Rein-Sehgal	Global (rel) Fermi gas	none	Salcedo-Oset (full)

MODERN

OLD

Models sets

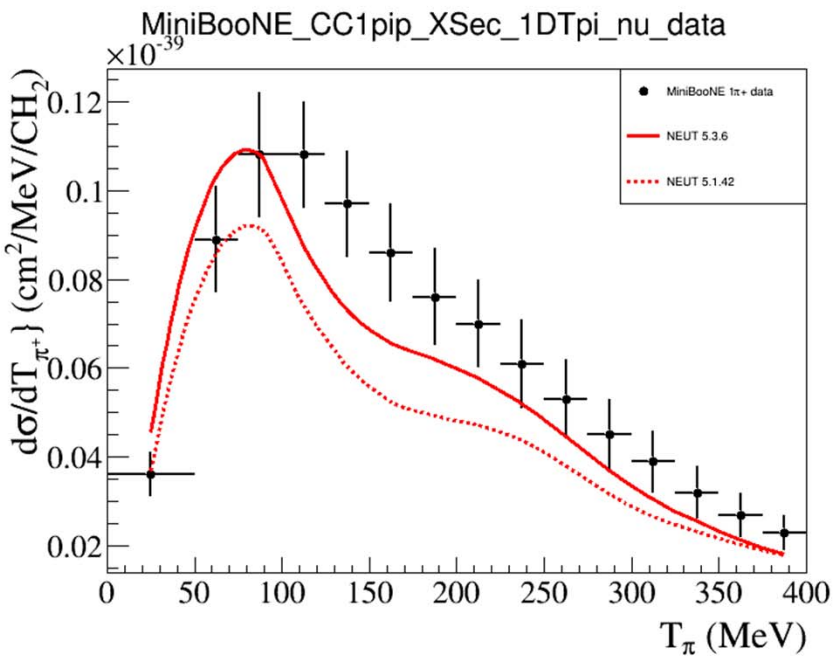
- What matters is generator release chosen by expts
- Modern
  - GENIE 2.12.0 alt (LFG, better Δ)
  - NEUT 5.3.6 (RFG, large MAres, better production for N, better Δ)
  - GiBUU BNL (medium effects, sophisticated FSI, no coherent)
  - NuWro (LFG, better Δ, RPA)
- Old
  - GENIE 2.6.3 (used for all published π) 2.8.6 (next publications)
  - NEUT 5.1.4.2 (~used for upcoming π paper)
  - GiBUU ANL (otherwise same)
  - NuWro (no RPA, otherwise same)

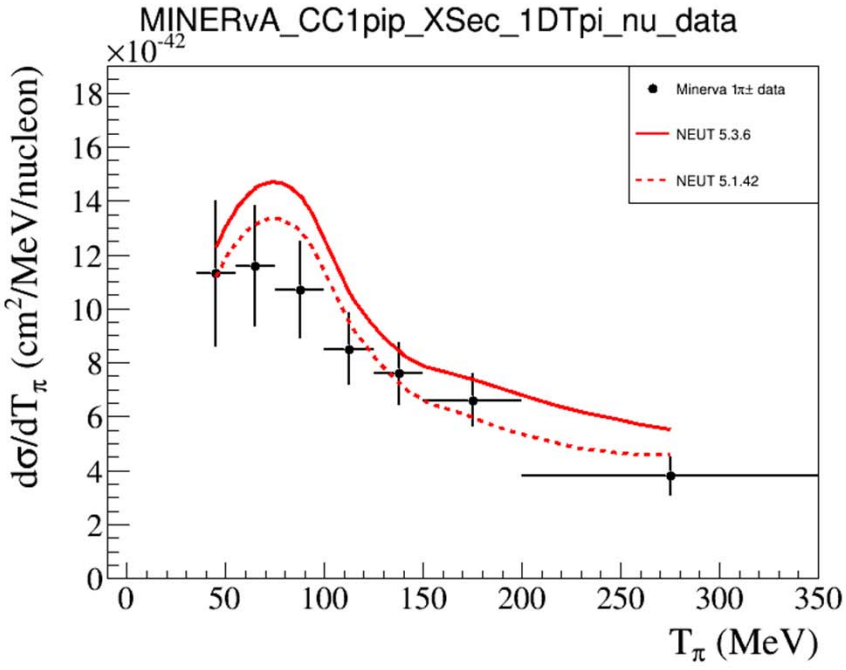
Generator advances (π prod)

- Guided in part by NuWro, GENIE and NEUT have had active programs to use better theory models
- NEUT (5.3.6 default)
  - New fit to new nucleon data (coupling, form factors)
  - Muon mass effects (Berger-Sehgal)
  - Nonisotropic Δ decay
  - Berger-Sehgal coherent
- GENIE (2.12.0 alternate model)
  - Nonisotropic Δ decay
  - Muon mass effects (Berger-Sehgal)
  - Updated form factors (MiniBooNE)
  - Berger-Sehgal coherent
  - Updated FSI

Generator advances - NEUT

- GENIE and NEUT have taken similar, but not identical paths to improve π production models





Generator advances - GENIE

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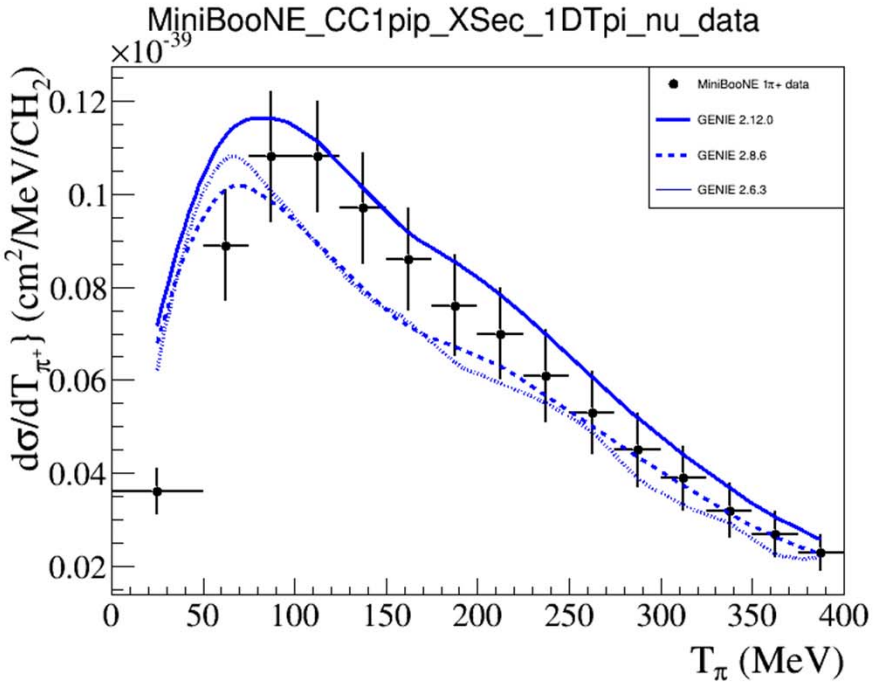
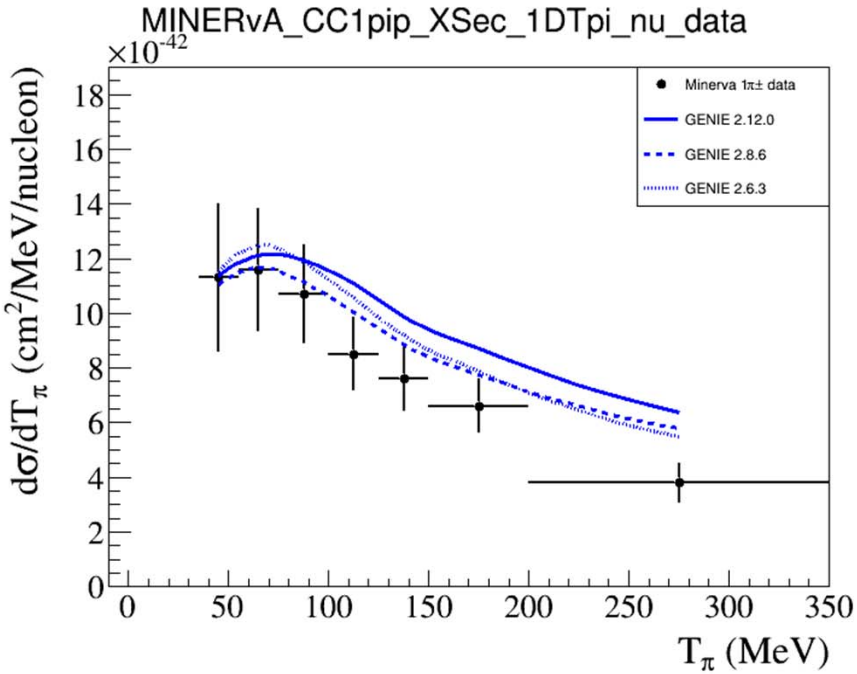


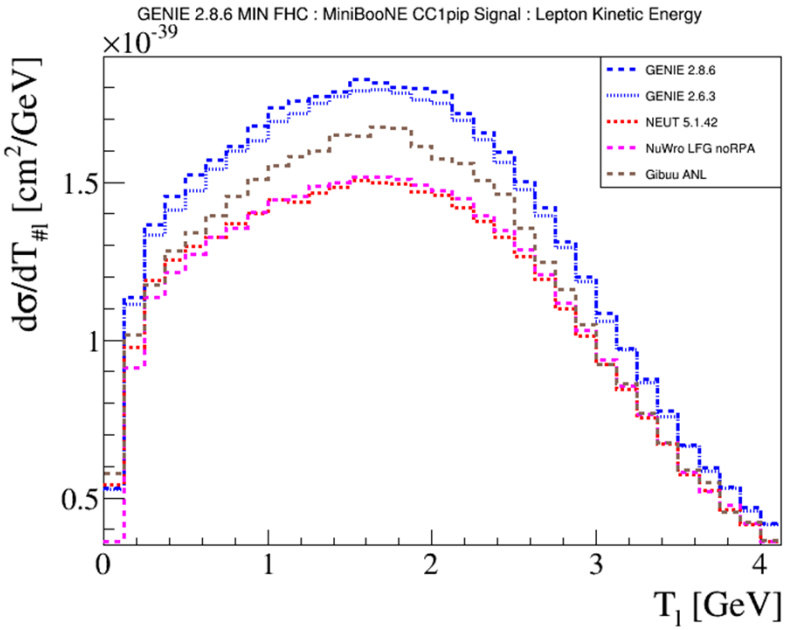


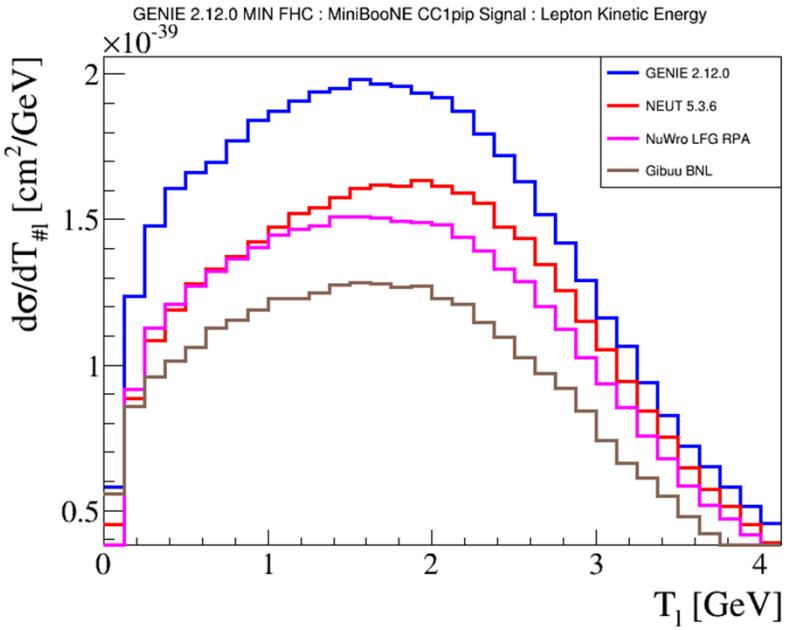
What if expt had different generator?

- Would signal have different dependence in key variables?
  - We can study this with samples available
- Would efficiency be different?
  - Since we only have NEUT tagged sample fot T2K & GENIE for Minerva, not possible now.
  - Hopefully, experiments will have this capability in future?

Muon Kinetic energy

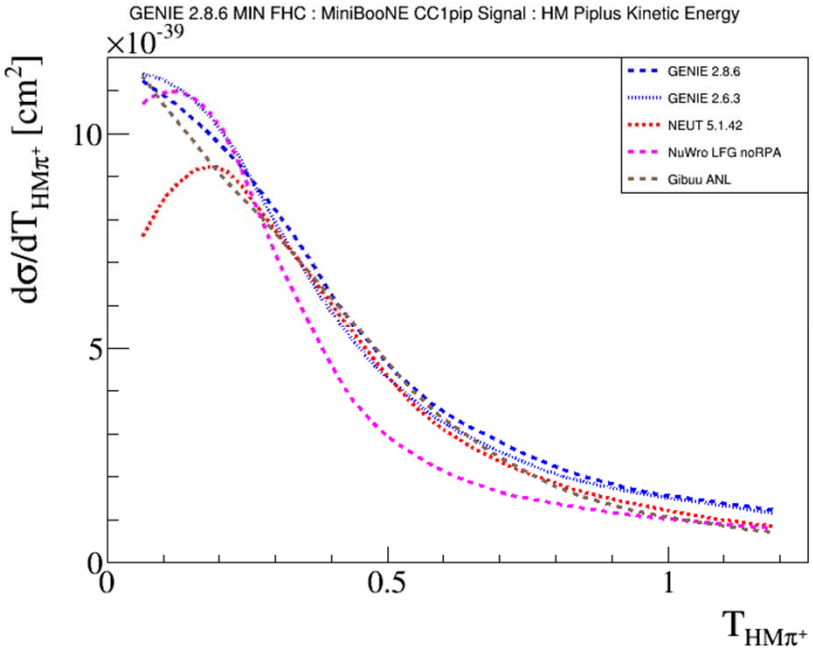
- Indicator of acceptance in key variable
- Reflects information in flux and model
- Shape changes small with model, mostly magnitude

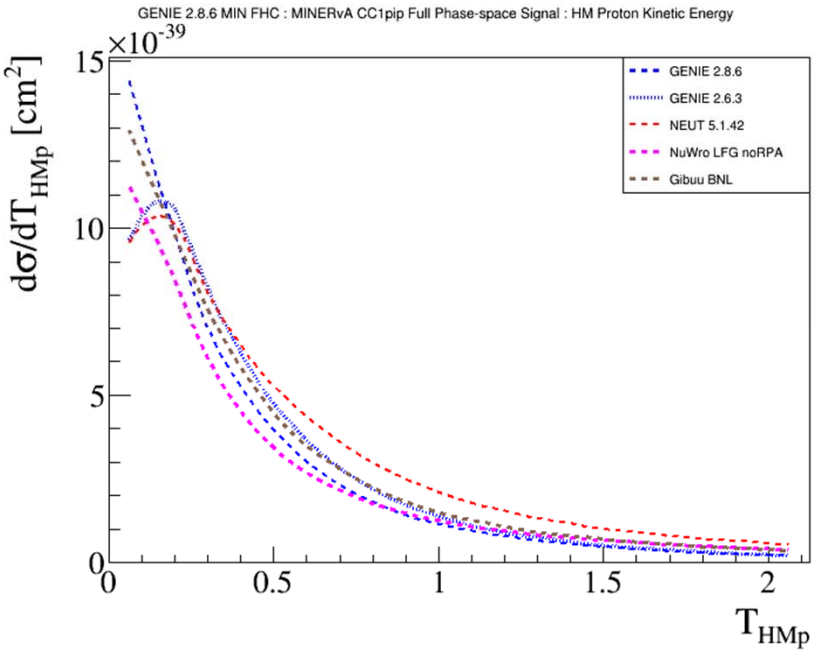




π+ Kinetic Energy – old models

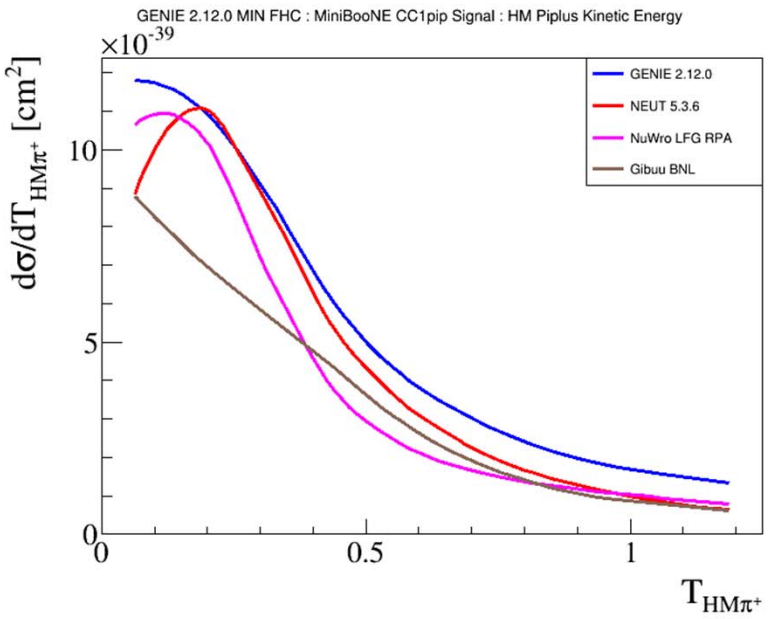
- Shows larger range than either experiment
- Disagreements at lowest energies
- Unlikely to be large problems

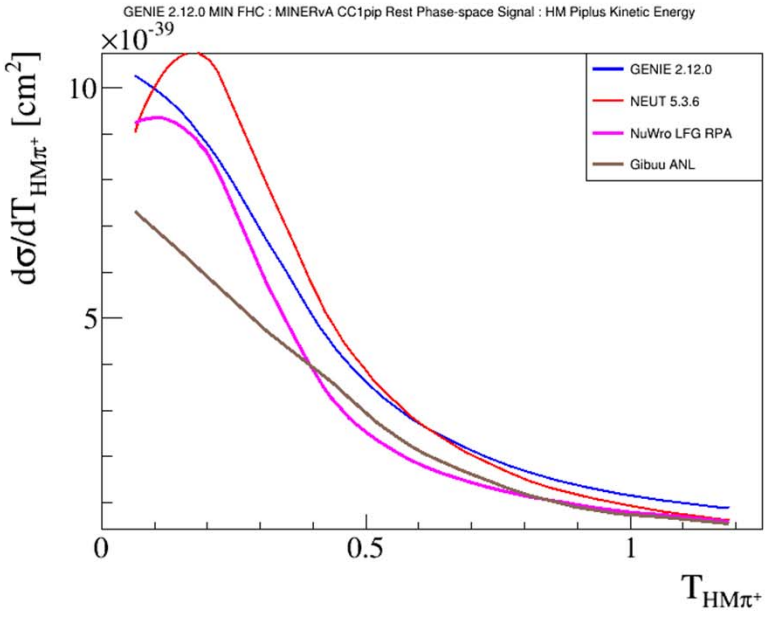




π+ Kinetic Energy - modern

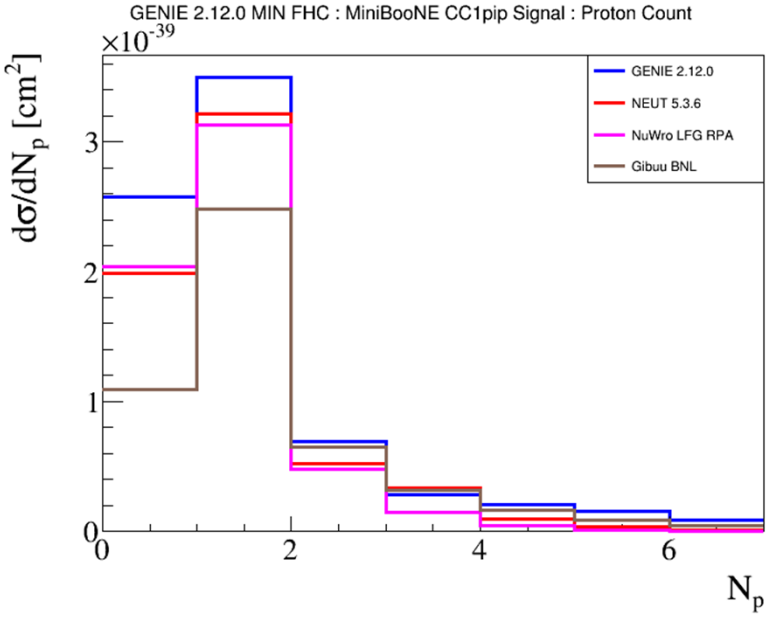
- Shows larger range than either experiment
- Disagreements at lowest energies
- Could cause problems with model dependence

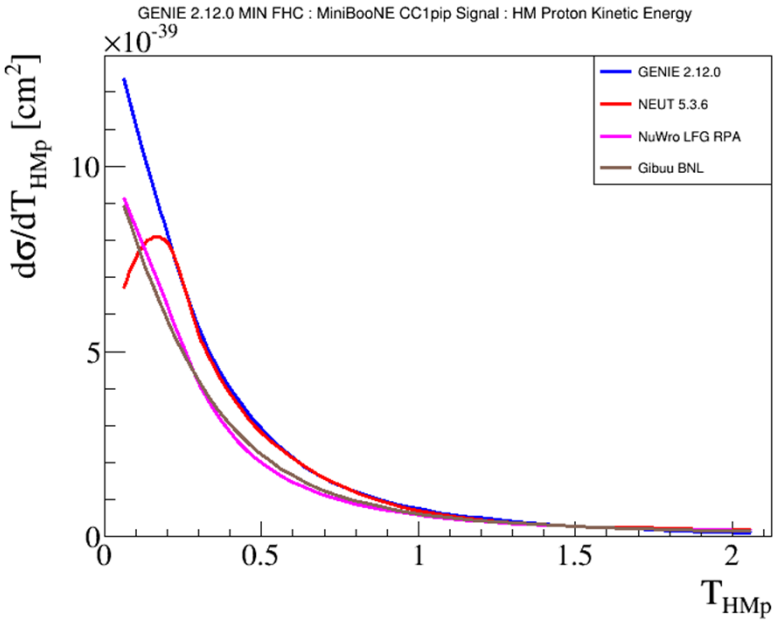




Proton multiplicity, KE

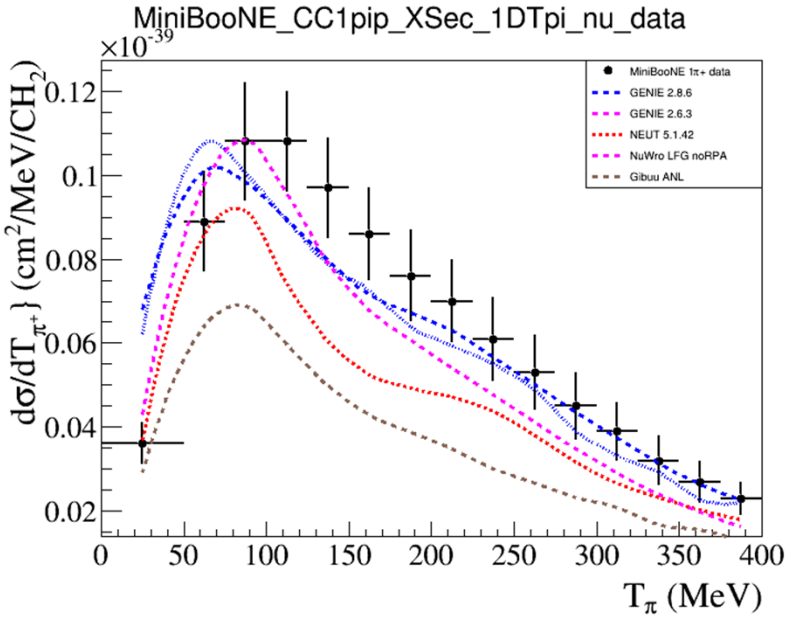
- No measurements yet, look to future
- Proton FSI is frontier subject, esp. at low energy

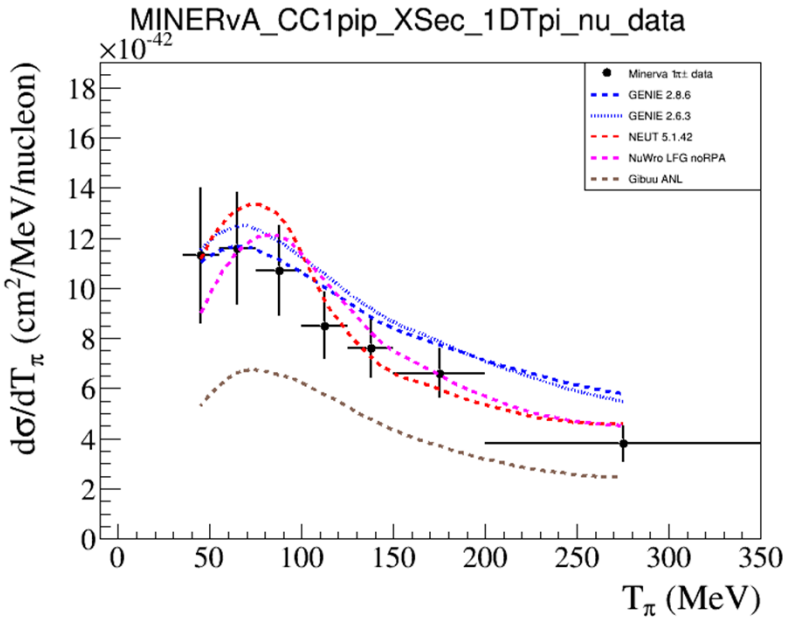




Impact of new models on data agreement (π Kinetic Energy – old - more complete)

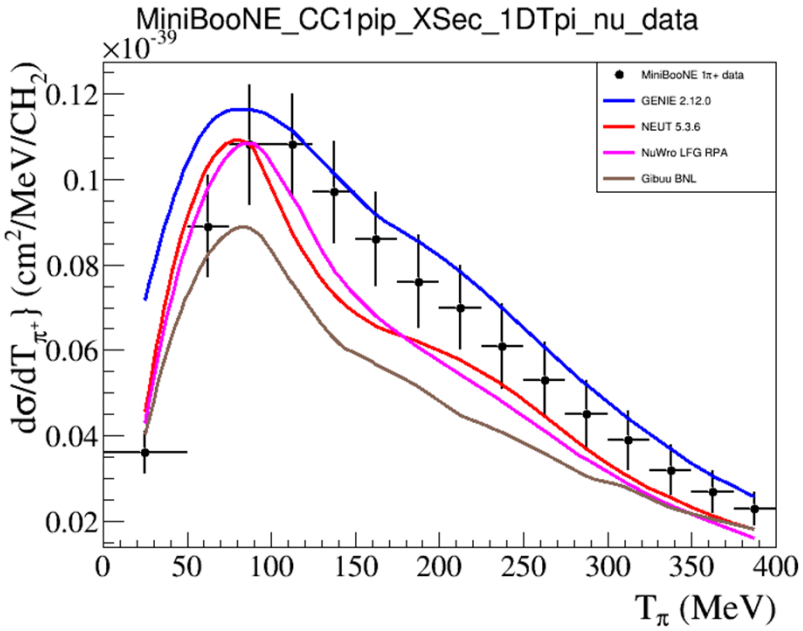
- GiBuu ANL is below data, lack of coherent?
- Generators otherwise similar
- Not much dip at peak of Δ except for NEUT

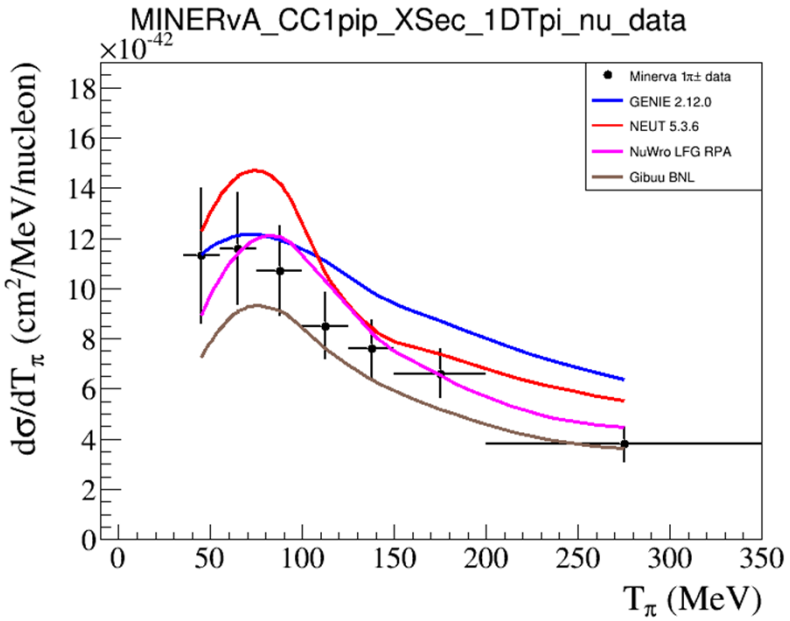




Impact of new models on data agreement (π Kinetic Energy – new – better models?)

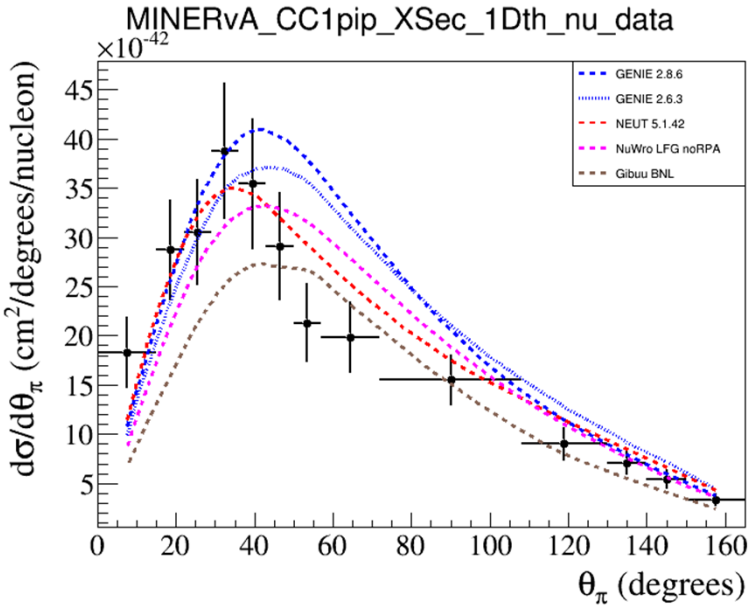
- GiBuu BNL is better, shape similar to the generators
- Moderate magnitude problem

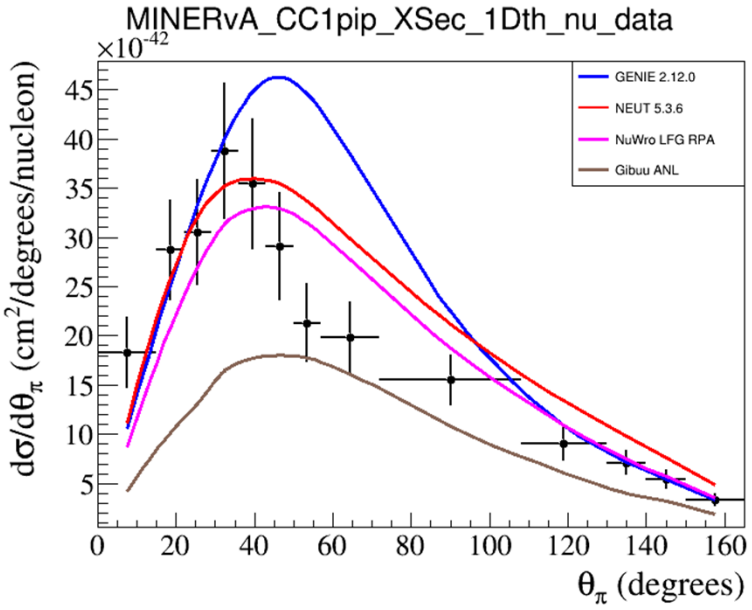




Impact of new models on data agreement (θ_π – new – better models?)

- GiBuu BNL is better, shape similar to the generators
- modern generators all have isotropic Δ decay, not much shape difference from isotropic, perhaps less agreement



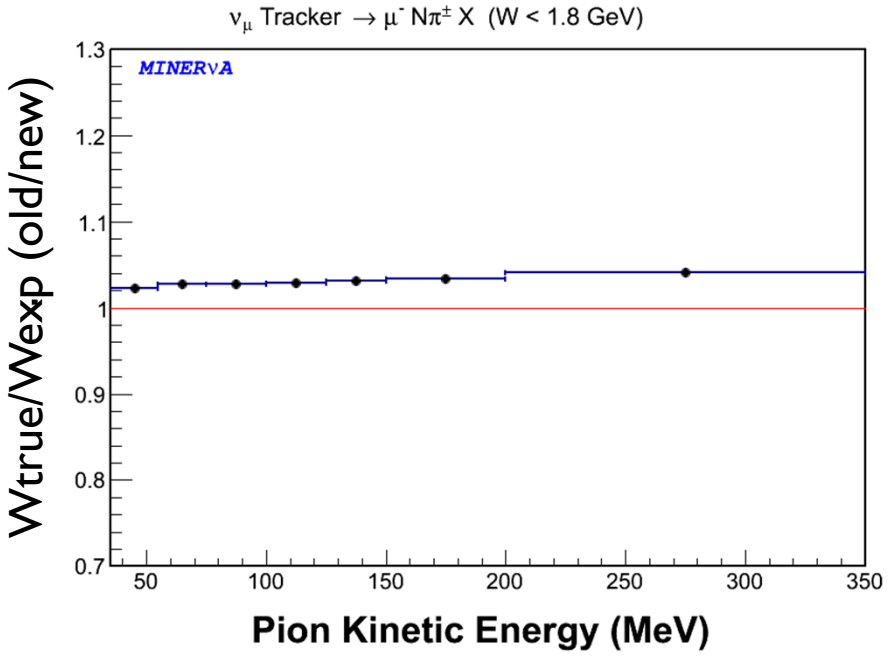


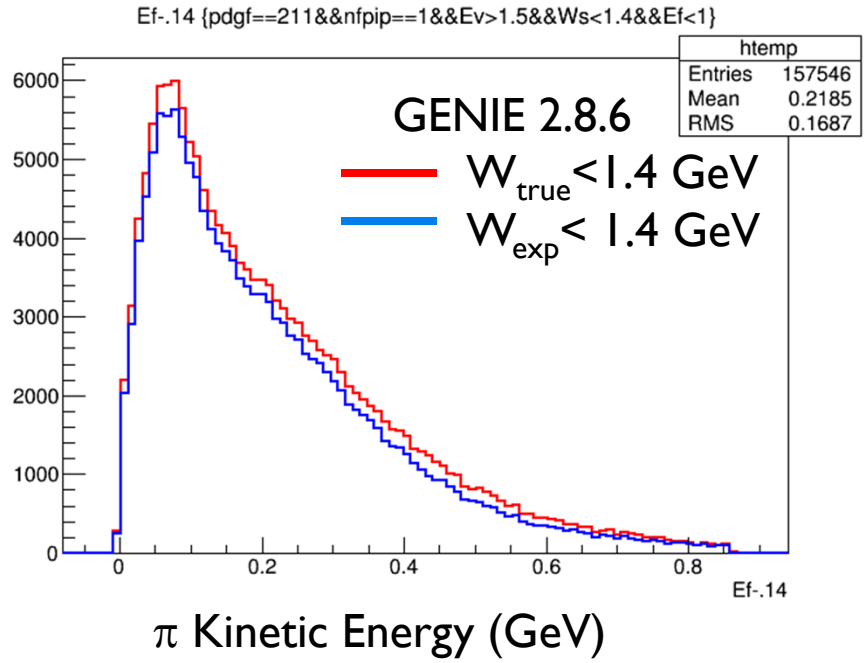
New upcoming data

- MINERvA published more complete data set (T_μ, E_ν, Q^2) for W<1.8 GeV
  - Improved signal – use Wexp instead of Wtrue (small effect)
  - Main difference from 1st paper is increase in xs, 13% due to flux
  - Sensitivity to N* states 1.4 GeV<W<1.8 GeV obvious
- MINERvA W<1.4 GeV analysis
  - Bigger effect from new signal, similar effect from flux
  - GENIE MC shows little change in shape (backup)
- T2K $1\pi^+$ measurement seen at conferences
  - Expected to be submitted for publication soon
  - Potential comparisons with theory, MiniBooNE data would be very interesting

Recent results

- Studies of W cut – complete for W<1.8 GeV – published
- Only MC for W<1.4 GeV (see effects beyond data)





Summary

- MiniBooNE and MINERvA data sets not same
  - Different flux, signal, treatment of large W
  - New MINERvA results with new signal/flux very soon
  - Direct comparison needs match in W
- Many plots seen for the first time
  - Improvements in models makes wider separation among them
- Ability for experiments to assess model dependence
  - GENIE set of alternate models allows it cleanly (reweighting coming)
  - NUISANCE can compare, fit models with data
- Is it possible to directly compare measurements from different experiments?
  - Need to have clear signal with less model dependence.
- Can theory calculations match complicated signals
  - Hadrons in final state have thresholds (less mod dep with, harder to reproduce)

Generator advances (QE like)

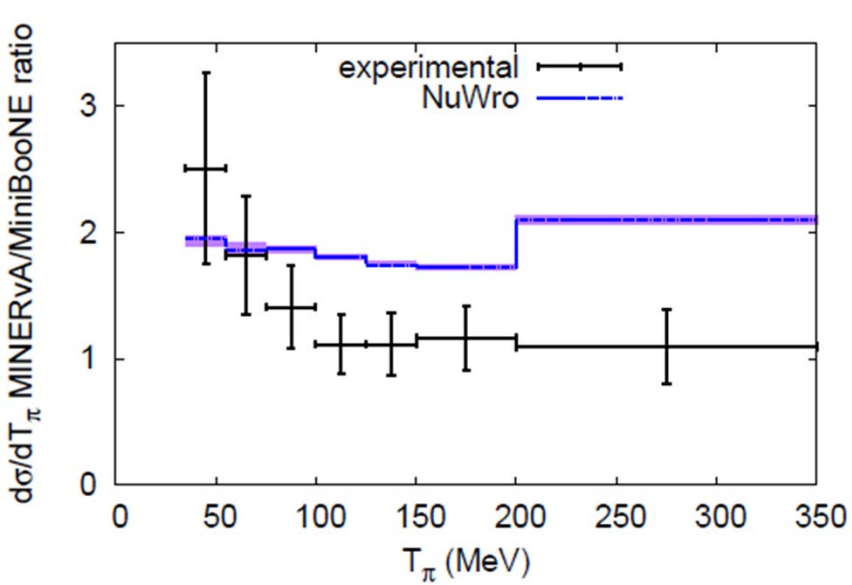
- Guided in part by NuWro, GENIE and NEUT have had active programs to use better theory models
- NEUT (5.3.6 default)
  - Local Fermi Gas
  - Llewyllen-Smith
  - Valencia MEC+RPA
  - Improved proton FSI
- GENIE (2.12.0 alternate model)
  - Local Fermi Gas
  - Nieves QE with RPA+Coulomb
  - Valencia MEC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

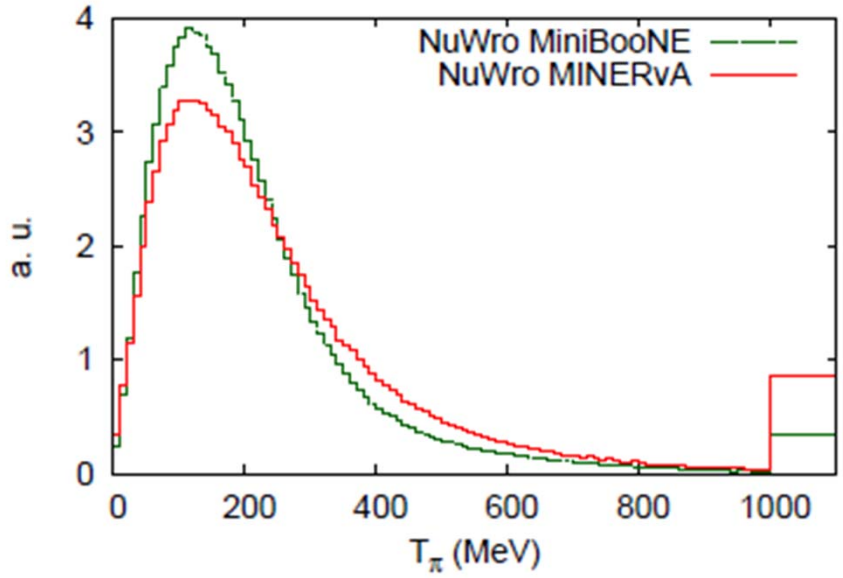
Thoughts on nubar

- Problems with N π production more severe, less data of poorer quality
- Different FSI sensitivities (QE produces n, π abs $\rightarrow$ nn)
  Less understanding of n FSI, low efficiency in most det
- Agreements of generators (GENIE, at least) with data likely to be accidental

Sobczyk & Zmuda (NuWro) PRD 2015

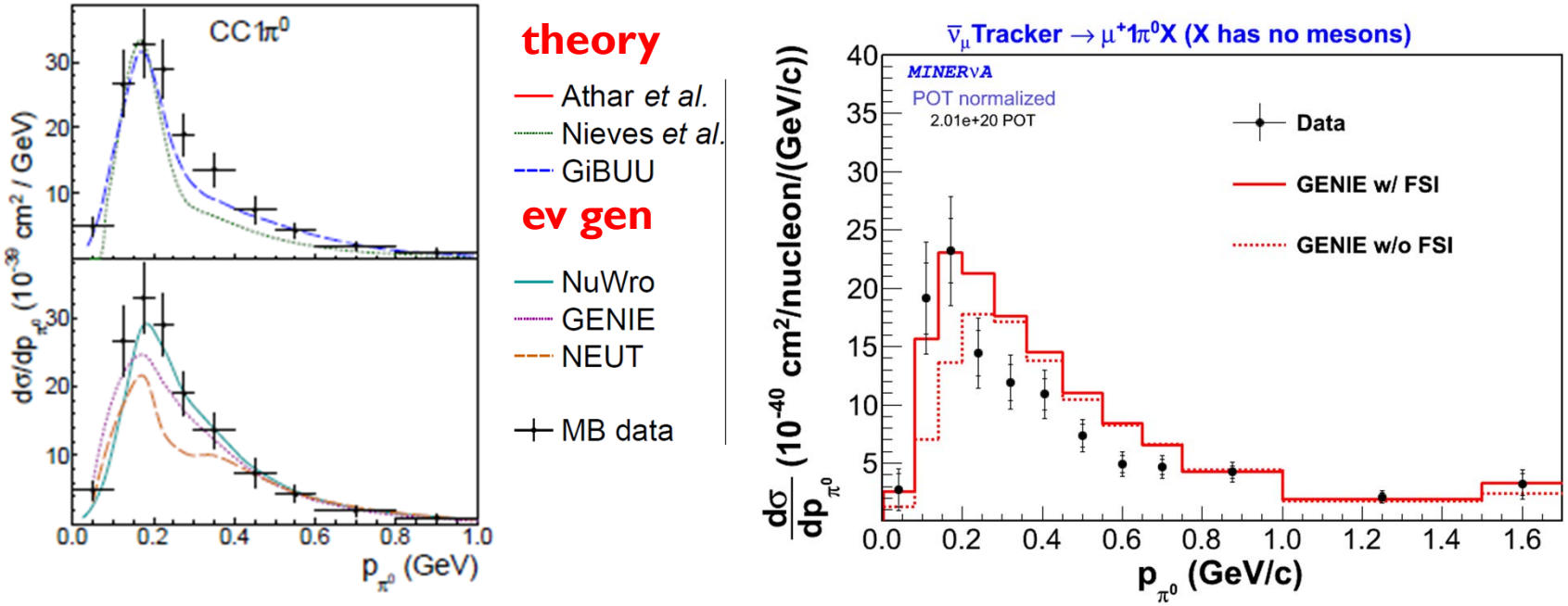
- Made ratio of experiments with proper error propagation.
- They predict factor of ~2, no large shape difference
- Question data normalization
- Predictions for *both* MiniBooNE and Minerva data have same shape for both GENIE and NuWro
- My studies with GENIE agree with these findings





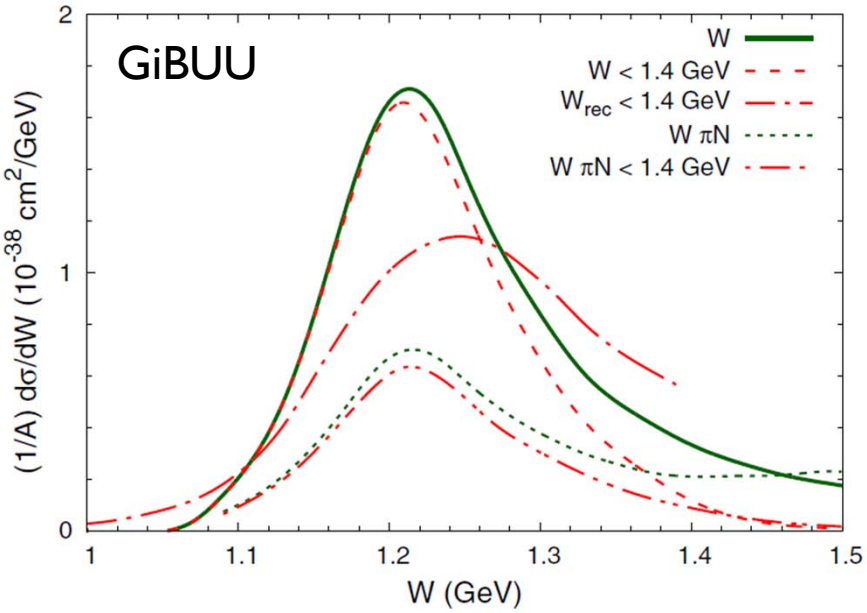
More data (π^0)

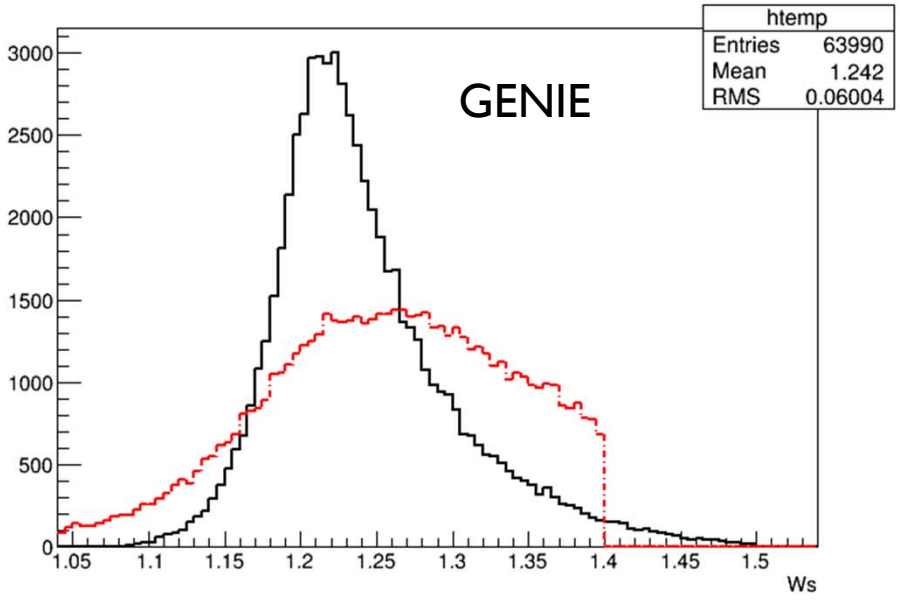
- MiniBooNE is ν and Minerva νbar (Trung Le, W&C Jan, 15).
- 'Similar' FSI, but need new production cross section
- MiniBooNE data has similar interpretation as π^+.
- Minerva data described better by GENIE



Comparison of W_{rec} (W_{exp}) and W_{true}.

- Mosel's paper makes incorrect claim that Minerva data uses W_{rec} for establishing Δ dominance.
- Our discussions with him failed to change his mind.

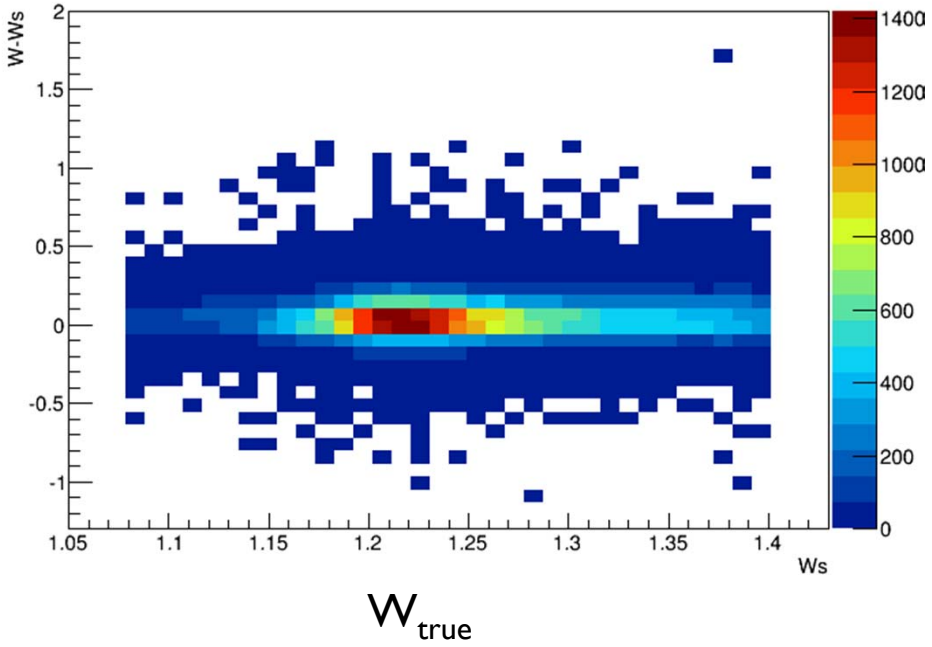


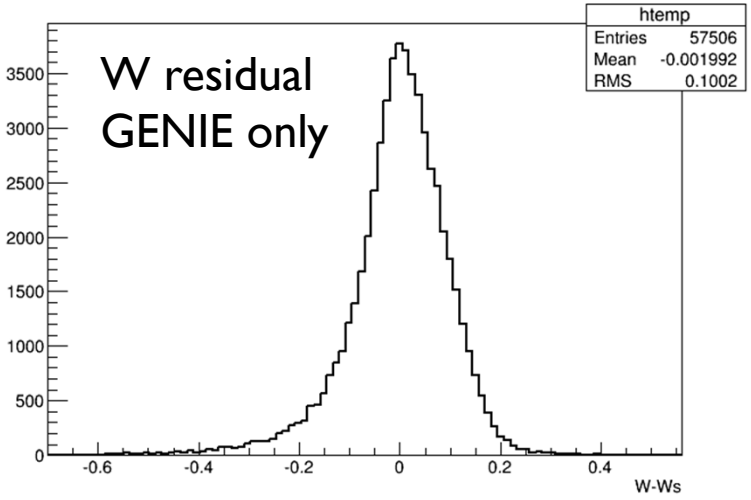


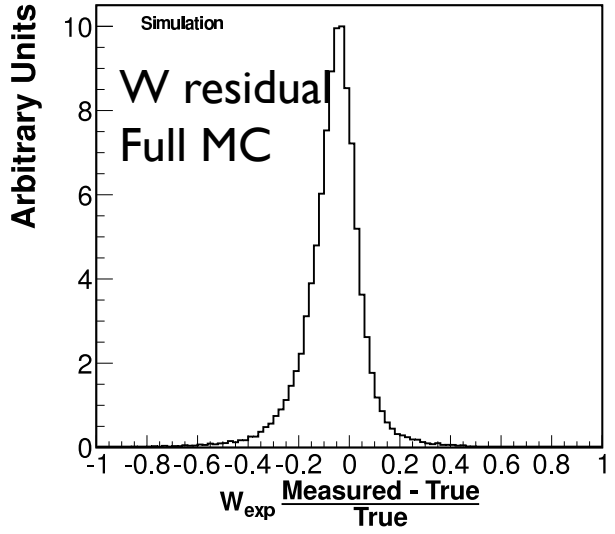
Study of MINERvA W cut

- W_{rec} is not same as W_{true}, but we can adjust with MC
- It seems to work

$(W_{rec}-W_{true})/W_{true}$ (GENIE)







Sensitivities other than FSI

- Nucleon production
  - ~10% difference between NEUT and GENIE for nucleon
  - GiBUU chose BNL for a while, they are ~15% high (abs, not shape)
- Lalakulich&Mosel paper nuclear medium corrections don't affect shape, ~10% in magnitude.

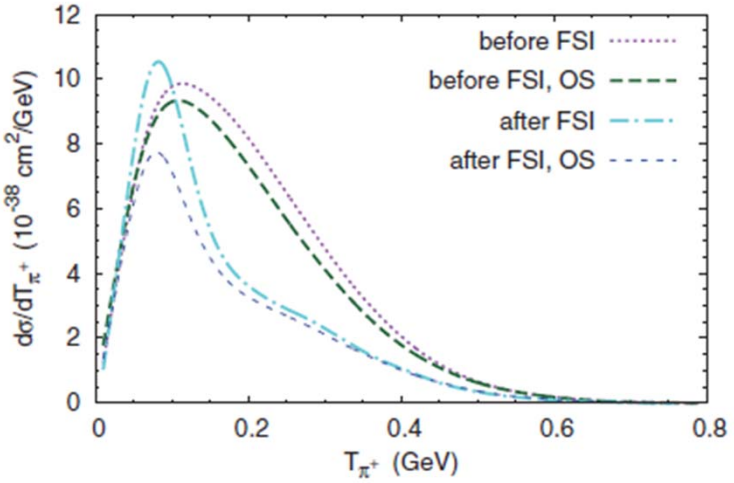
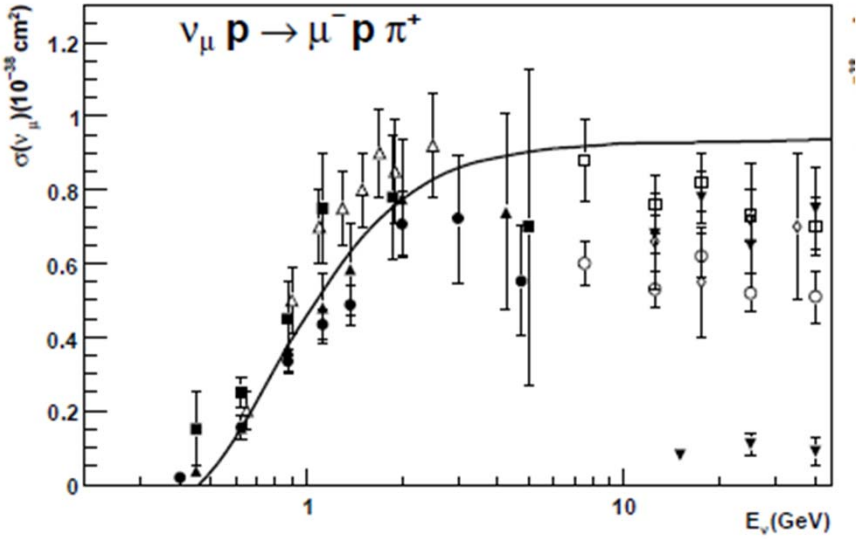


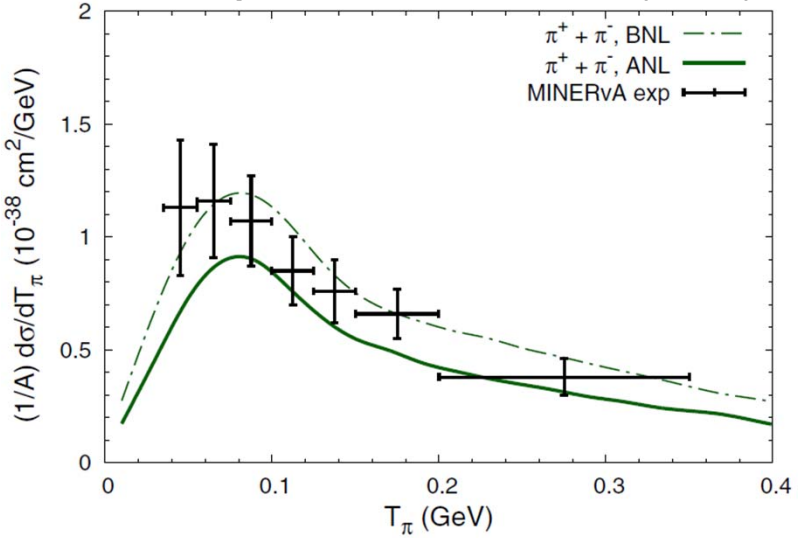
FIG. 13. (Color online) Kinetic energy distribution of π^+ produced in neutrino scattering off carbon through the weak production of the Δ resonance and its following decay. The neutrino energy is $E_\nu = 1$ GeV. The curves labeled OS were obtained using the in-medium collisional width of the Δ from [28].

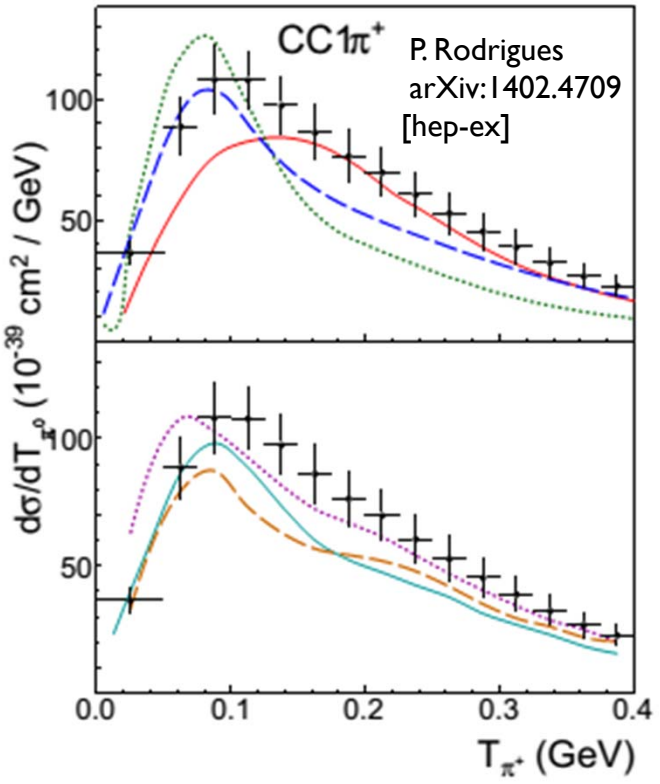


Minerva ν CH π+ data

- MiniBooNE – major issue was 'dip or no dip' for GiBUU (shape)
- GiBUU prefers νd ANL π^+ data to get magnitude right for MB
- Suggests coherent responsible for mostly magnitude error
- Chose W_{rec}<1.4, not what was measured

Mosel, Phys Rev C91, 065501 (2015)



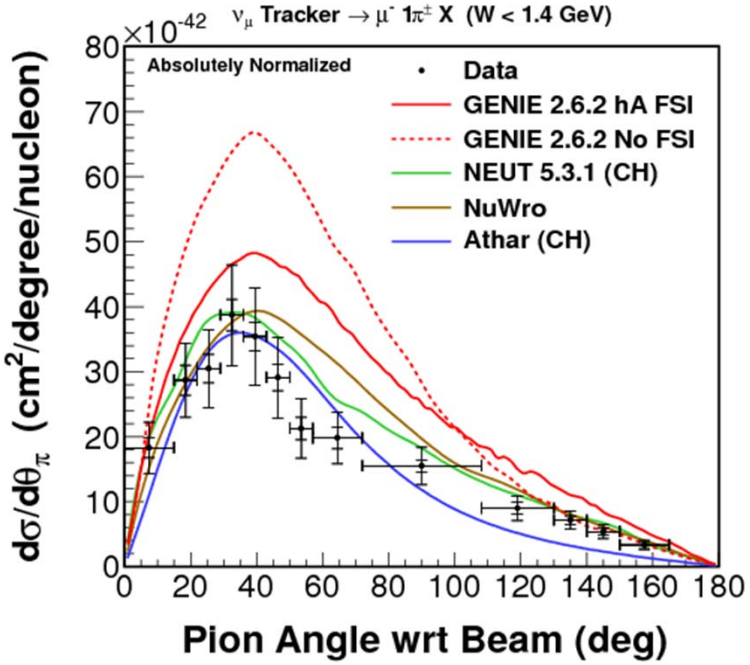


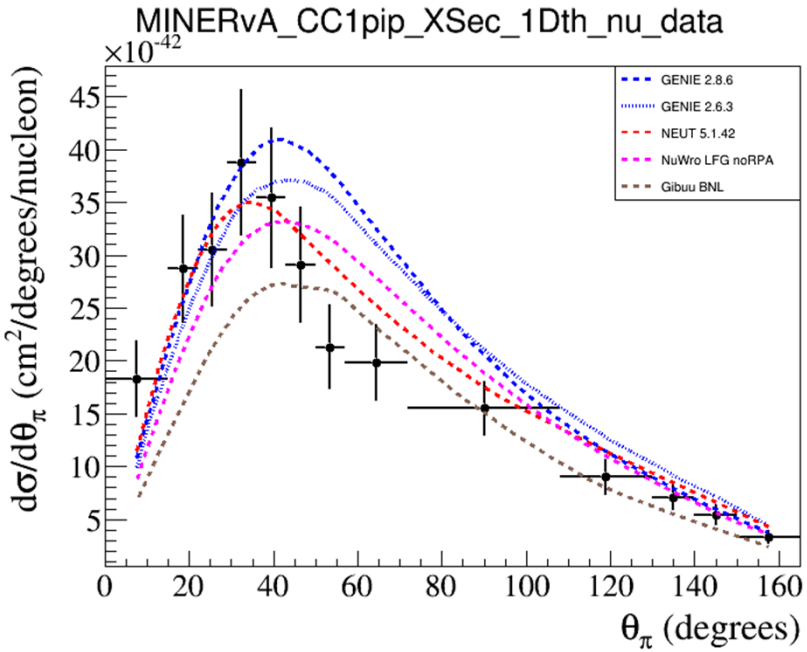
theory
- Athar *et al.*
- Nieves *et al.*
- GiBUU

ev gen
- NuWro
- GENIE
- NEUT

- MB data

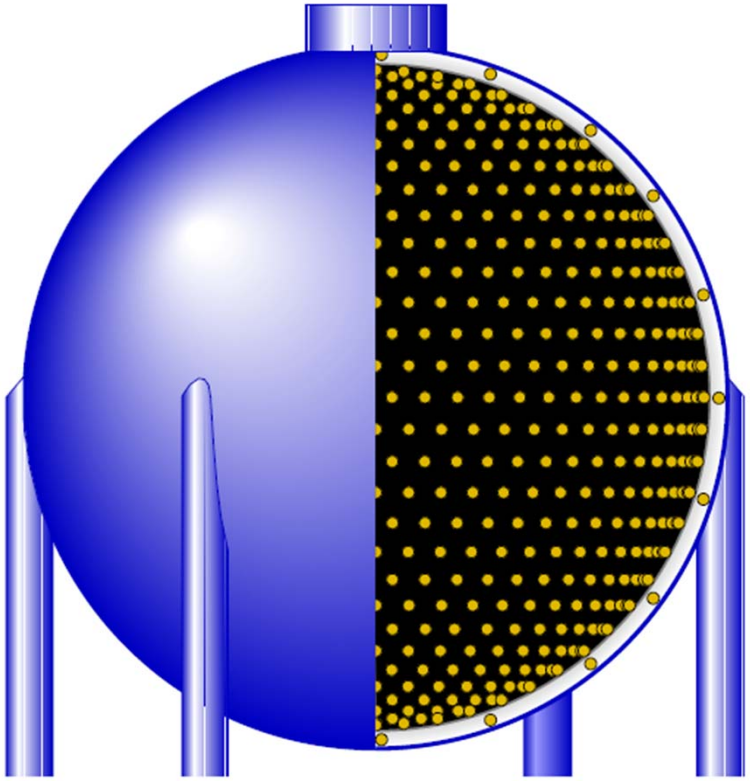
- dd

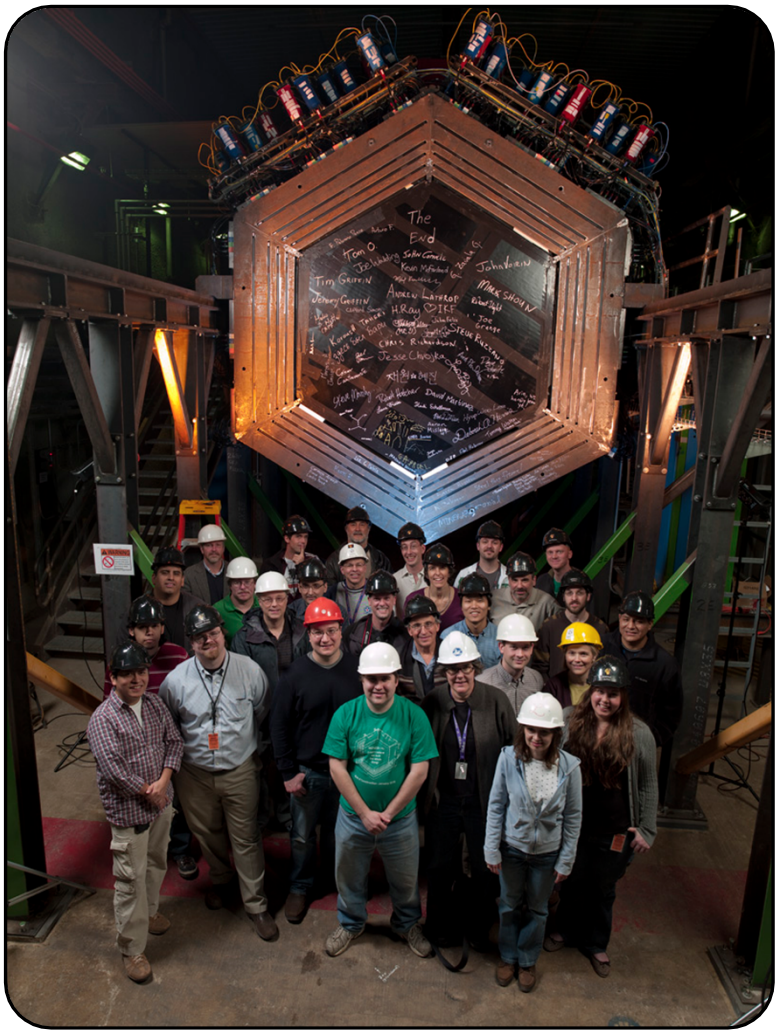

ν_μ Tracker $\rightarrow \mu^- 1\pi^\pm$ X (W < 1.4 GeV)
$\times 10^{-42}$
Absolutely Normalized
Data
GENIE 2.6.2 hA FSI
GENIE 2.6.2 No FSI
NEUT 5.3.1 (CH)
NuWro
Athar (CH)
$d\sigma/d\theta_\pi$ (cm^2/degree/nucleon)
Pion Angle wrt Beam (deg)


MINERvA_CC1pip_XSec_1Dth_nu_data
$\times 10^{-42}$
GENIE 2.8.6
GENIE 2.6.3
NEUT 5.1.42
NuWro LFG noRPA
Gibuu BNL
$d\sigma/d\theta_\pi$ (cm^2/degrees/nucleon)
θ_π (degrees)

MiniBooNE (Cerenkov) vs. Minerva (Scin)

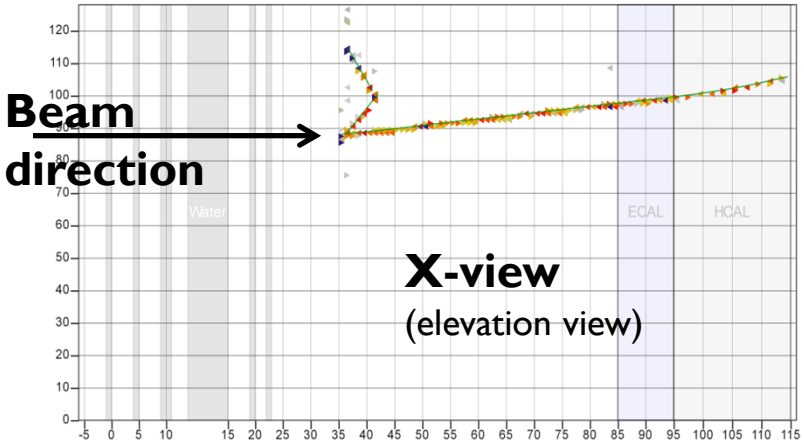
- MiniBooNE has larger data sample - longer run time

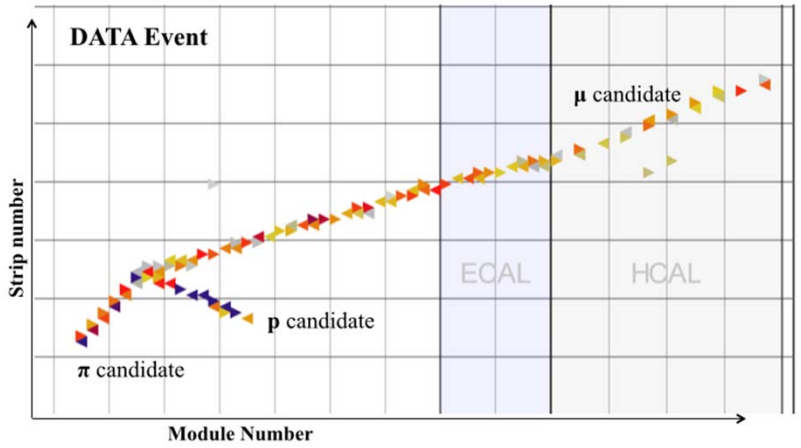


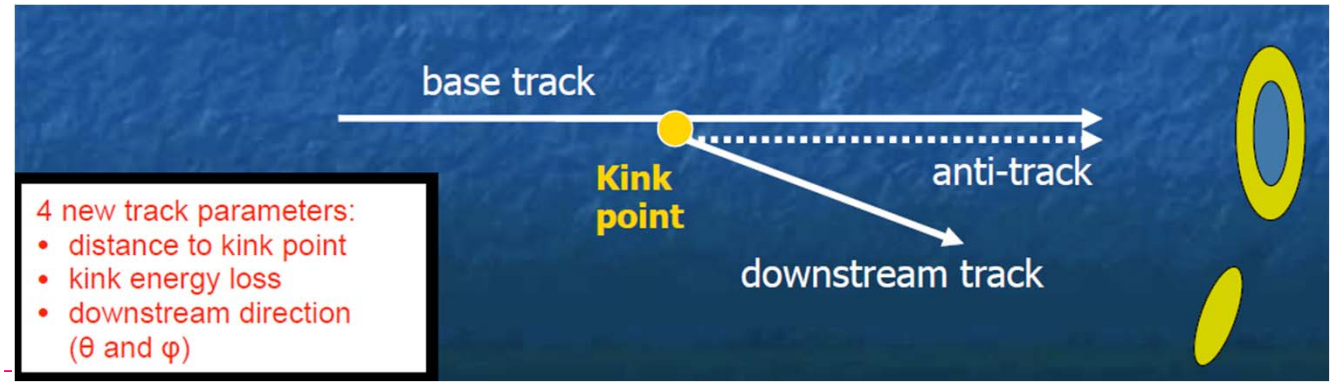


Event comparison – MiniBooNE and MINERvA

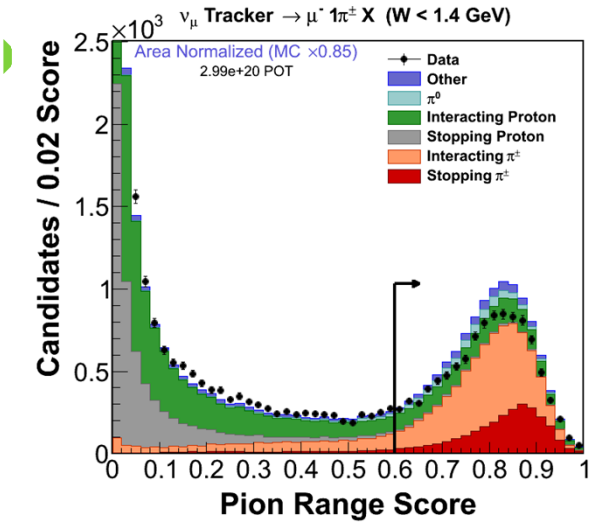
- MINERvA is a tracking detector (CH)
- MineBooNE is a Cerenkov detector (CH2)/some scintillator

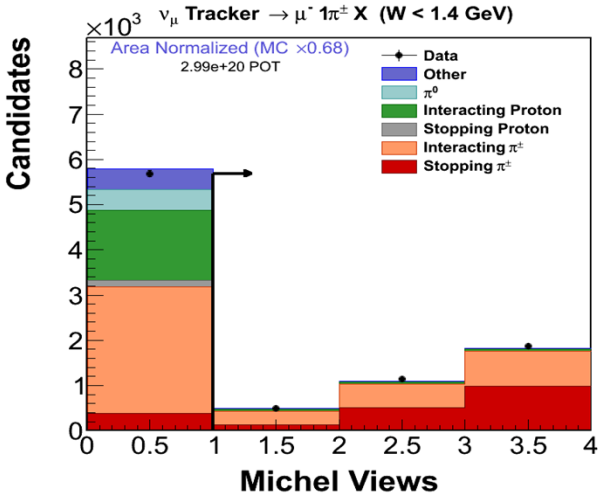


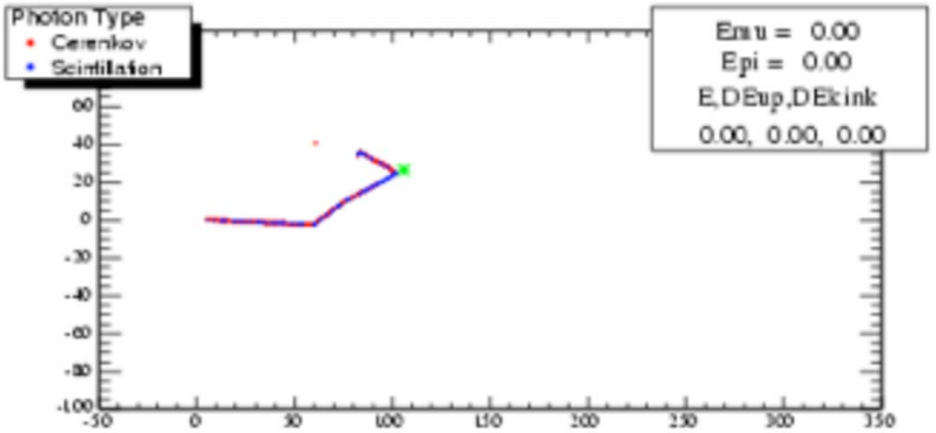


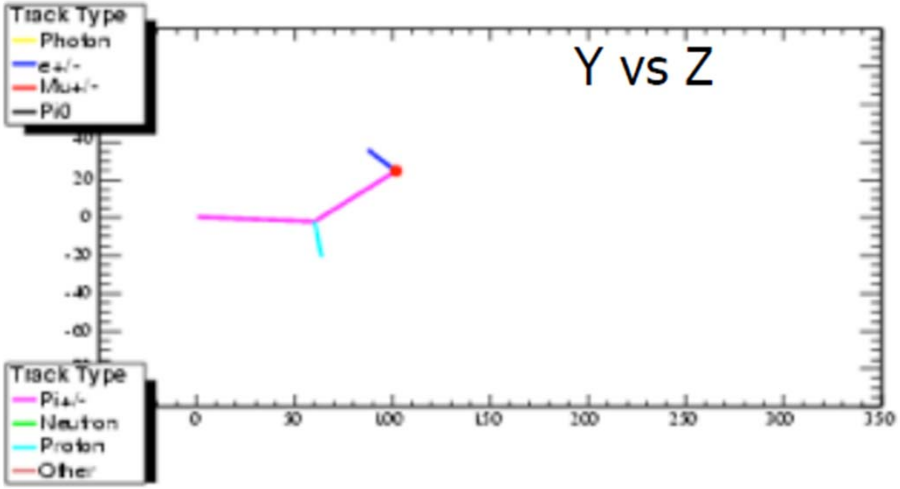


A little detail – pion identification



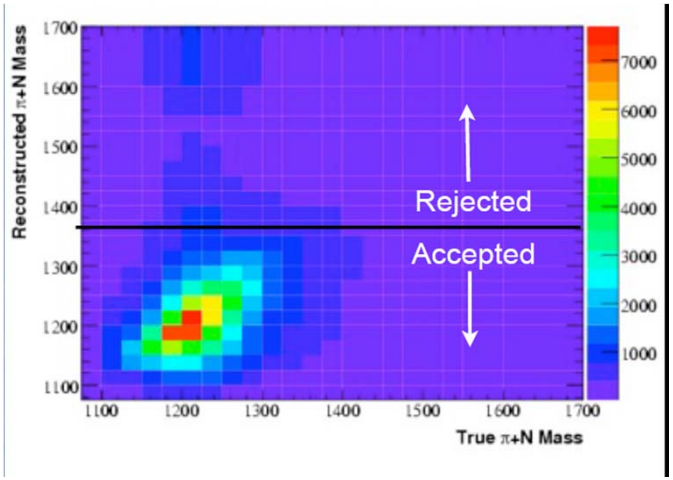


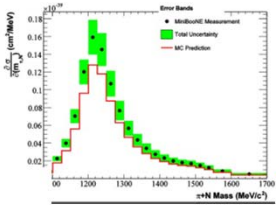


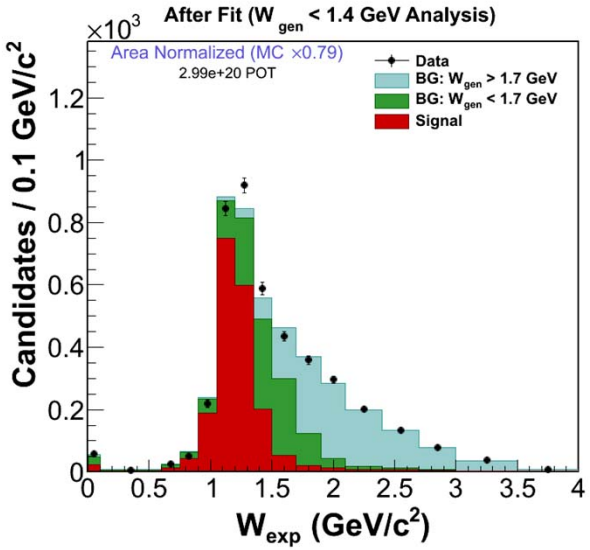


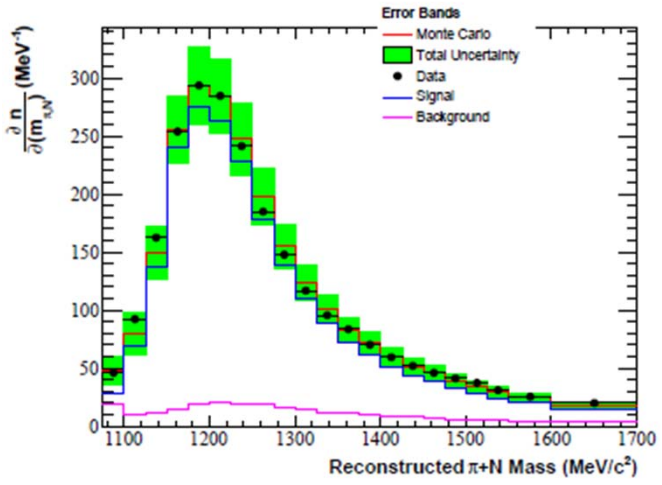
A little detail – W cuts

- MiniBooNE MπN normalized **up** by ~1.25
- MINERvA background mainly higher res smeared (~17%)



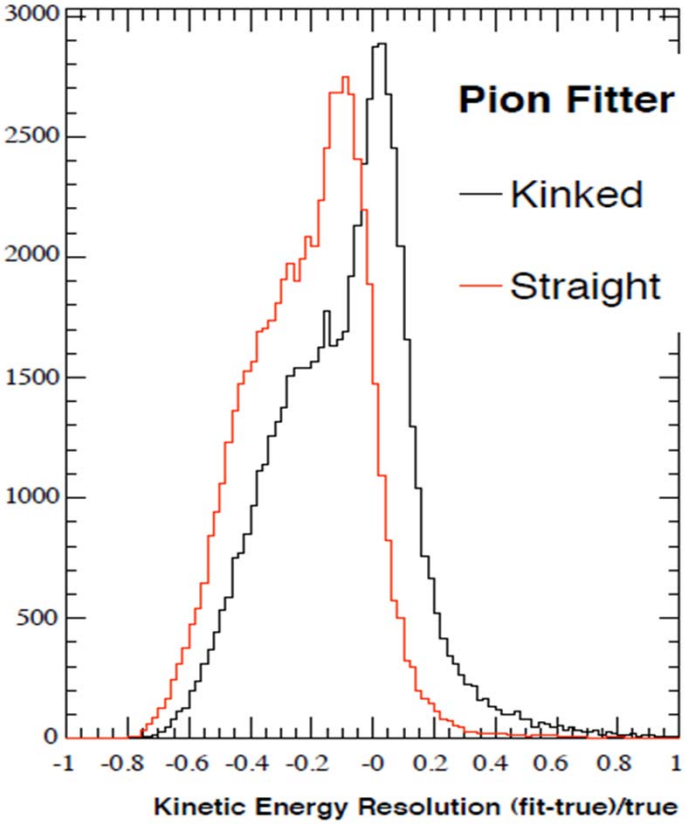


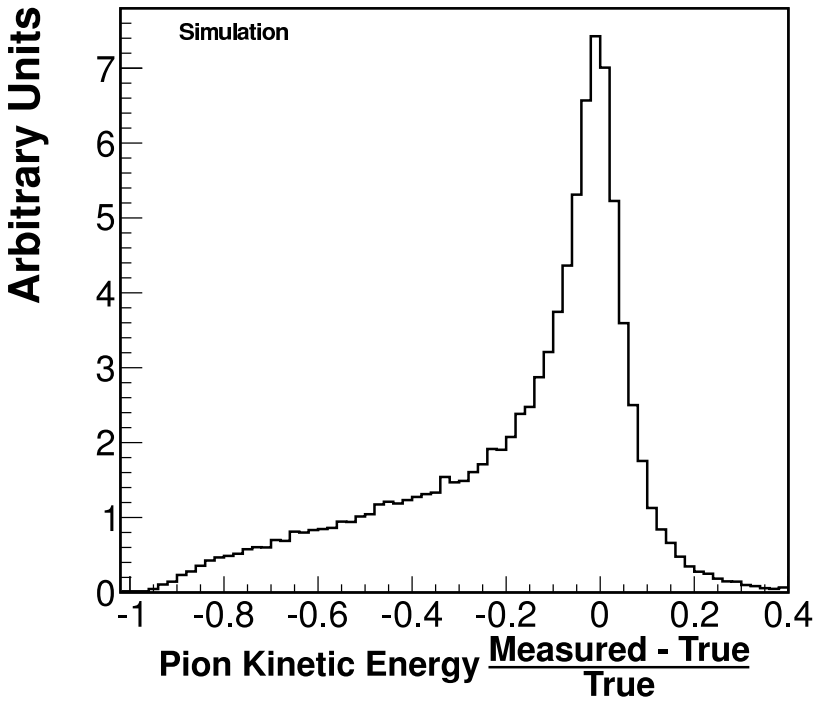




Pion energy reconstruction

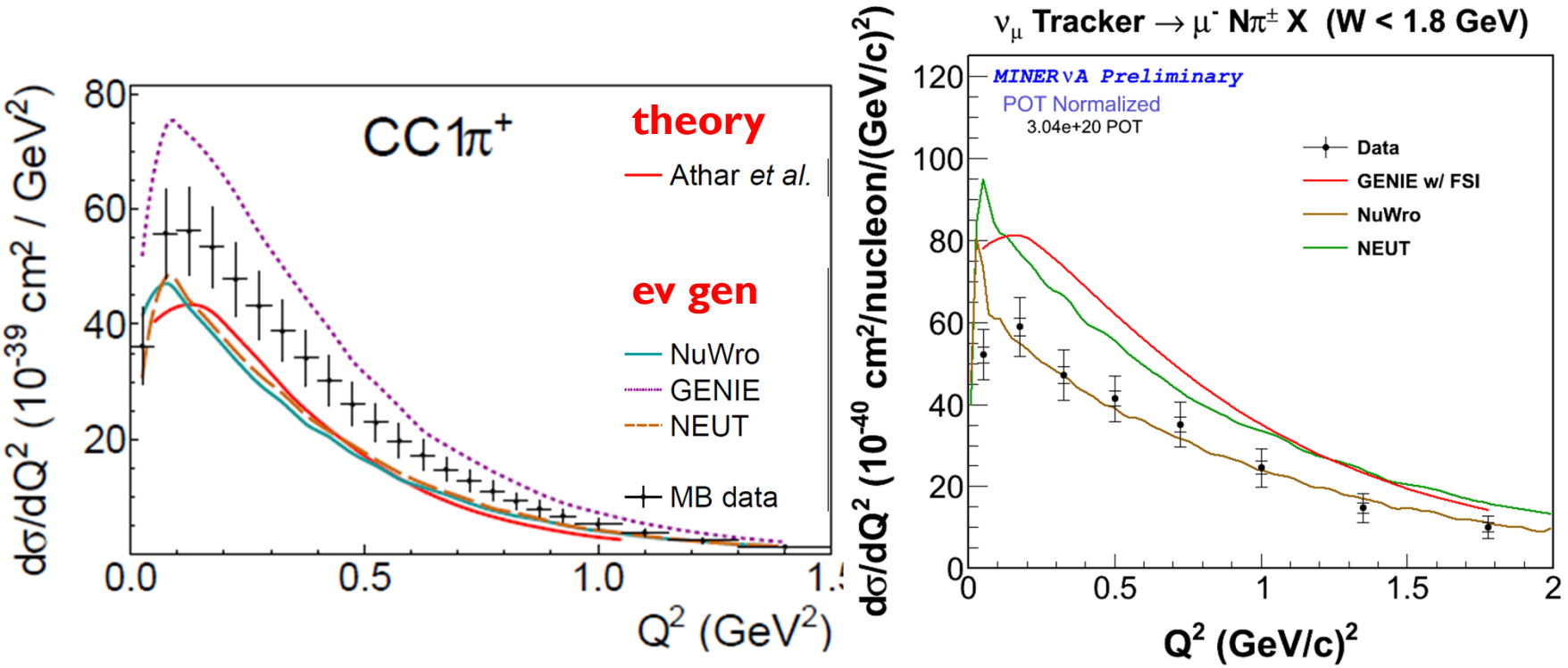
- This is hard with either method





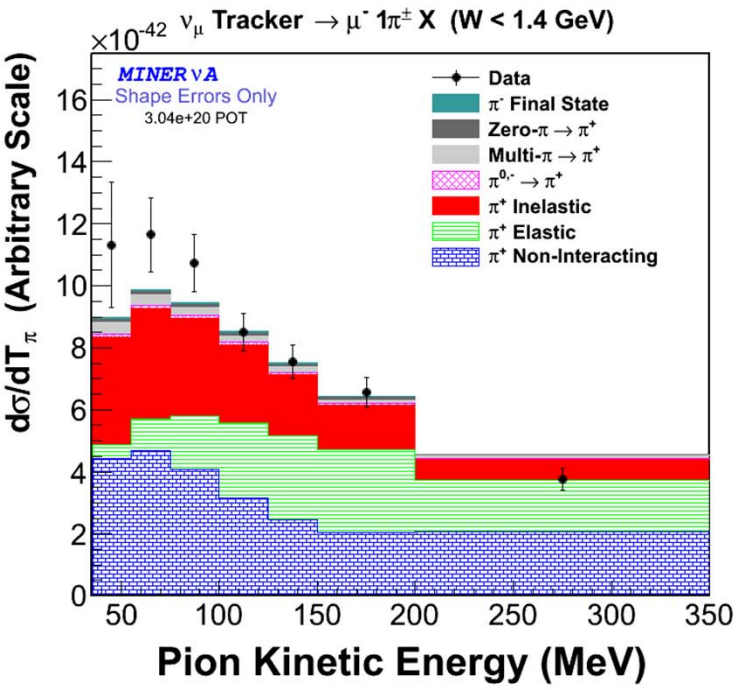
More data for μ, ν variables – Q^2

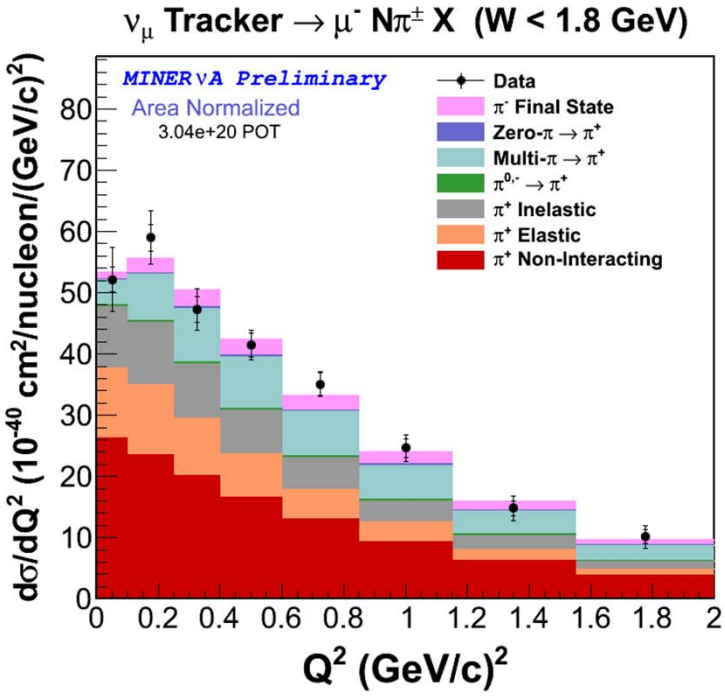
- Minerva (Carrie McGivern, W&C June, 15) for W<1.8 GeV
- Data from 2 expts have similar shapes, calcs ~agree.
- Predictions for Minerva have a spike at low Q^2.



FSI decompositions – focus on shape

- GENIE FSI model has a single interaction
- Pion kinetic energy shows significant changes in shape
- Q^2 shape largely insensitive to FSI interaction (low Q^2)





Theory/generators

- Theory typically from nuclear theorists
  - GiBUU (Mosel and collaborators)
  - Valencia (Nieves, Alvarez-Ruso, Vicente-Vacas, Hernandez+ students)
  - Athar (Athar, Singh and collaborators)
  - Weak ties to experiment, but improving
- Generators typically from high energy experimentalists
  - GENIE (Andreopoulos, SD, Gallagher, Perdue...)
  - NuWro (Sobczyk, Golan ...)
  - NEUT (Hayato and numerous T2K students/postdocs)
  - Fully integrated into experiments
  - Actively including improved nuclear theory, catch up in 2 years?

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