Search for Understanding in Pion Production with Neutrinos

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Fermilab Neutrino Seminar
1 October, 2015

- start with 3 MINERvA W&C pion prod talks
- compare and contrast with MiniBooNE
- compare with models + dig down a bit
- a look to the future

T2K Results
ν_μ disappearance

- neutrino energy spectrum shape significantly changed.
- Best-fit oscillation parameters are calculated to be

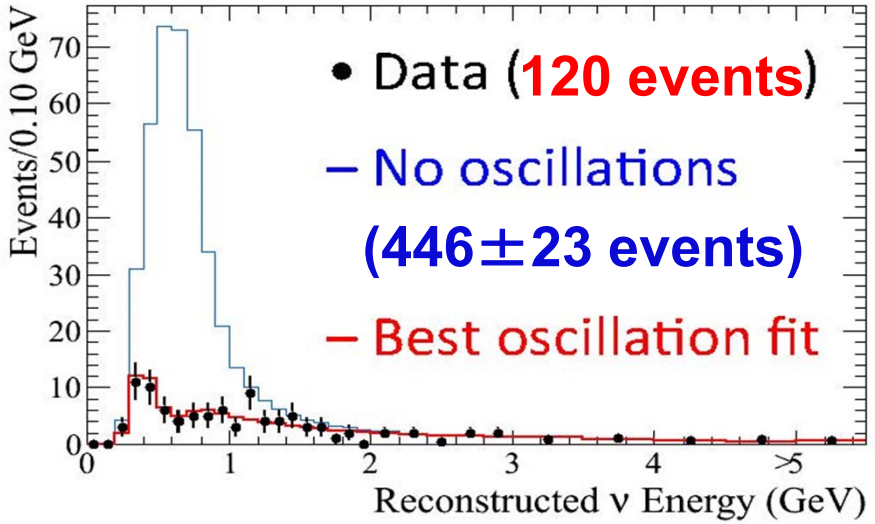
$$\Delta m^2_{32} = (2.51 \pm 0.10) \times 10^{-3} \text{eV}^2$$
$$\sin^2\theta_{23} = 0.514^{+0.055}_{-0.056}$$

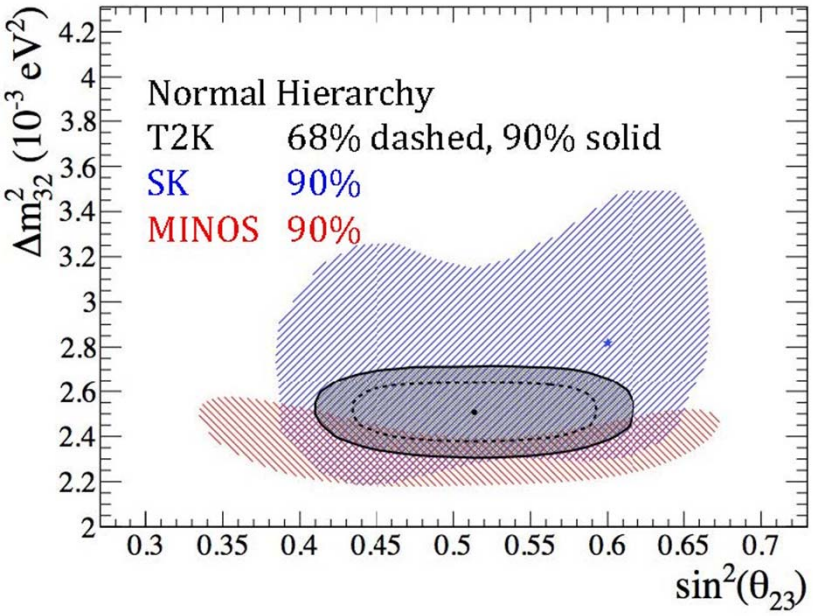
- for normal hierarchy, and

$$\Delta m^2_{13} = (2.48 \pm 0.10) \times 10^{-3} \text{eV}^2$$
$$\sin^2\theta_{23} = 0.511 \pm 0.055$$

for inverted hierarchy.

- With 8% of expected data, NOvA results are in agreement.





Problems

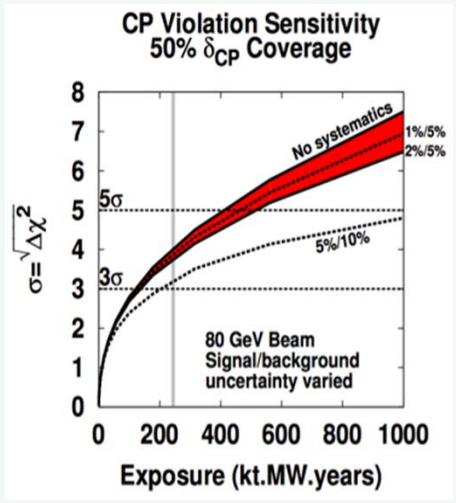
- How do you measure beam energy?
  - Choose topology that 'guarantees' interaction (e.g. CCQE) and measure energy with kinematic equations (T2K, MiniBooNE)
  - Measure all particles in final state (MINOS, DUNE?)
- How do you predict neutrino spectrum?
  - Extrapolate results from near to far detector
  - How many ν_e in beam if you are searching for $\nu_\mu \rightarrow \nu_e$?
  - Calculate with Monte Carlo.
- How do you know backgrounds?
  - Measure if possible (NCπ^0 in near det), use Monte Carlo
- Of course, Monte Carlo must be the sum of all cross section information (near detectors, dedicated expts)

Systematic errors & backgrounds

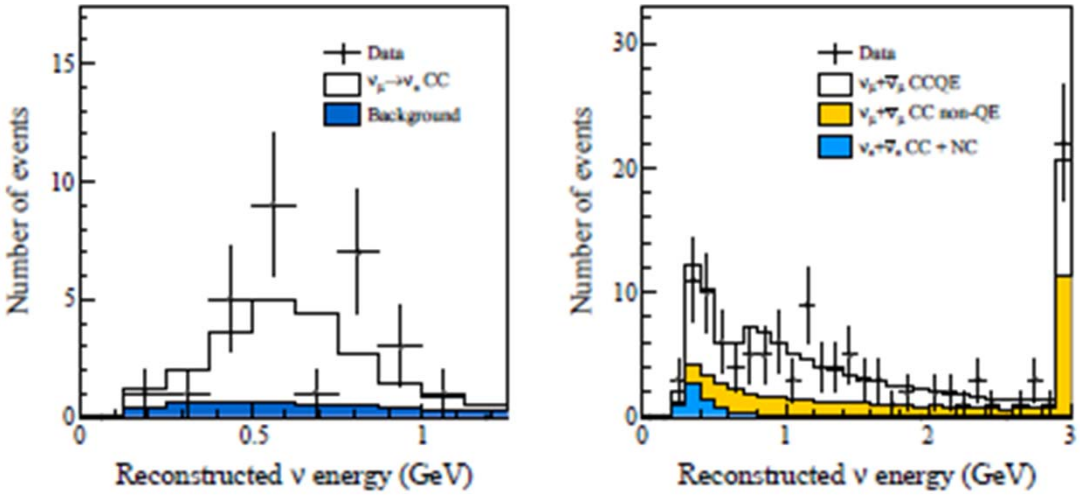
T2K syst errors for $\nu_\mu \rightarrow \nu_e$ (2014)

Source of Uncertainty	Est. stan. dev.
Cross section (MC)	**4.9%**
Cross section (ND280), Flux	2.7%
Far Det, FSI	**5.6%**
Oscillation parameters	0.2%
TOTAL	8.1%

DUNE estimated syst errors

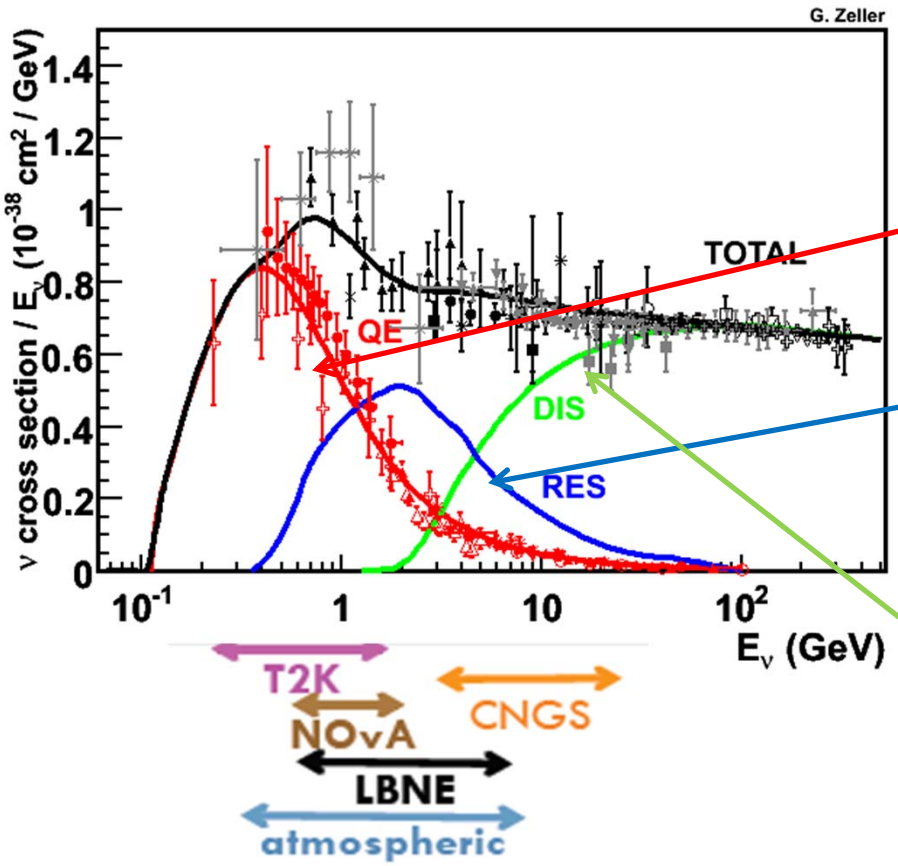


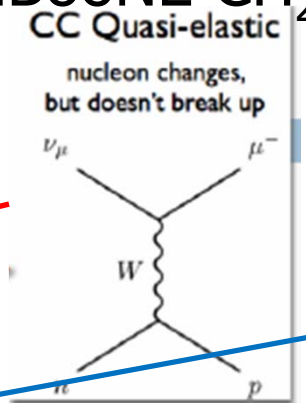
T2K data with estimated background

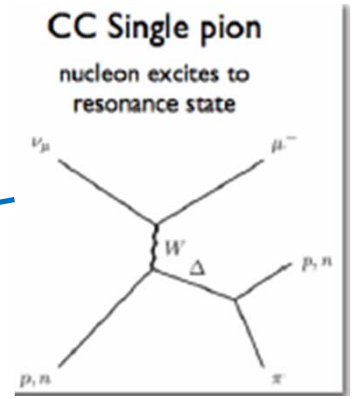


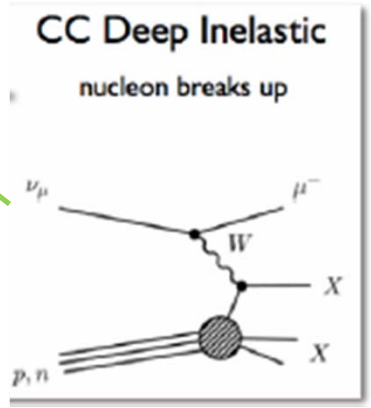
Cross section definitions
See Formaggio & Zeller RMP 2012

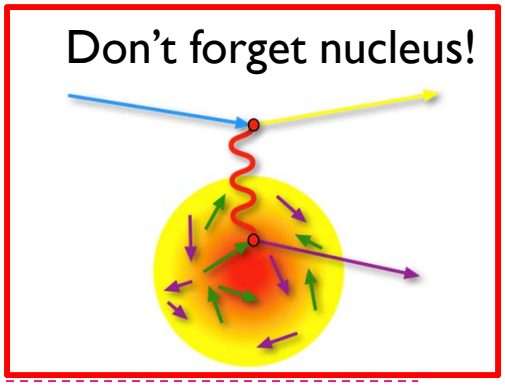
- Most nucleon data from bubble chambers (low statistics)
- MINERvA measures A dependence, MiniBooNE CH_2.









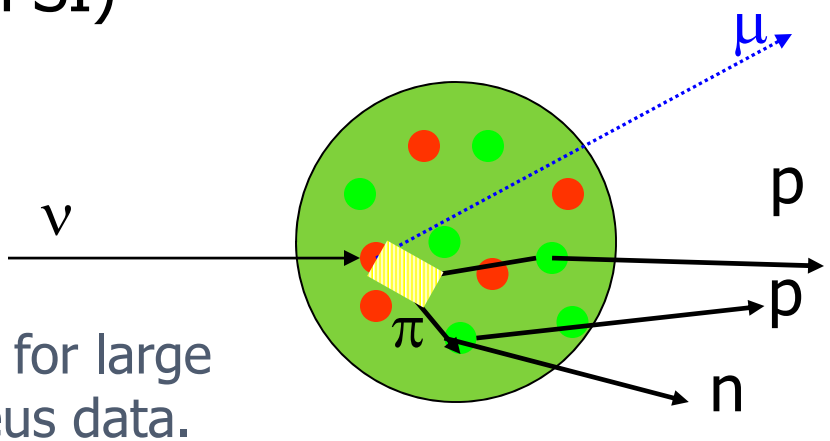


Theory/generators

- 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?

Problem is complicated

- Principal vertex
  - HEP models from 1970's & 1980's still relevant (bubble chamber expts)
  - Numerous recent improvements
- Nuclear structure
  - Momentum/energy of struck nucleon in nuclear environment
  - (e,e') experiments/interpretation very valuable
  - Corrections to principal vertex
- Hadron Final State Interactions (FSI)
  - Principal vertex particles smeared in topology, energy/charge distribution
  - Assume pion produced in medium same as beam pion
  - Numerous phenomenological studies for large body of γ-, e-, π-, K-, p-, and n-nucleus data.
- Problem: not enough young people

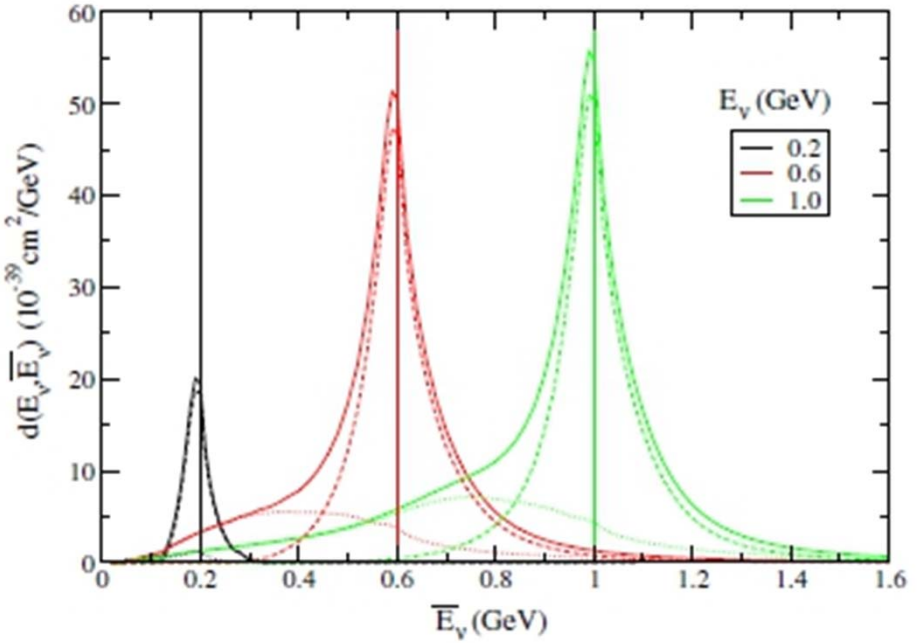


Measuring beam energy with CCQE (T2K)

- Experiments identify reaction with topology, calculate Eν assuming single nucleon at rest. *Ambiguities!*

$$E_\nu^{QE} = \frac{2\left(M_n - E_B\right)E_\ell - \left[\left(M_n - E_B\right)^2 + m_\ell^2 - M_p^2\right]}{2\left[M_n - E_B - E_\ell + p_\ell \cos(\theta_\ell)\right]}$$

- What if principal interaction was pion production and pion was absorbed?
- What if principal interaction was with correlated nucleons (MEC)? (plot from Martini, PRD **87**, 013009 (2013))
- *Nuclear model essential!*



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

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] (W&C 2/14) submitted to PRD

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

Le [Minerva] (W&C 1/15) Phys. Lett. B749, 130 (2015)

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

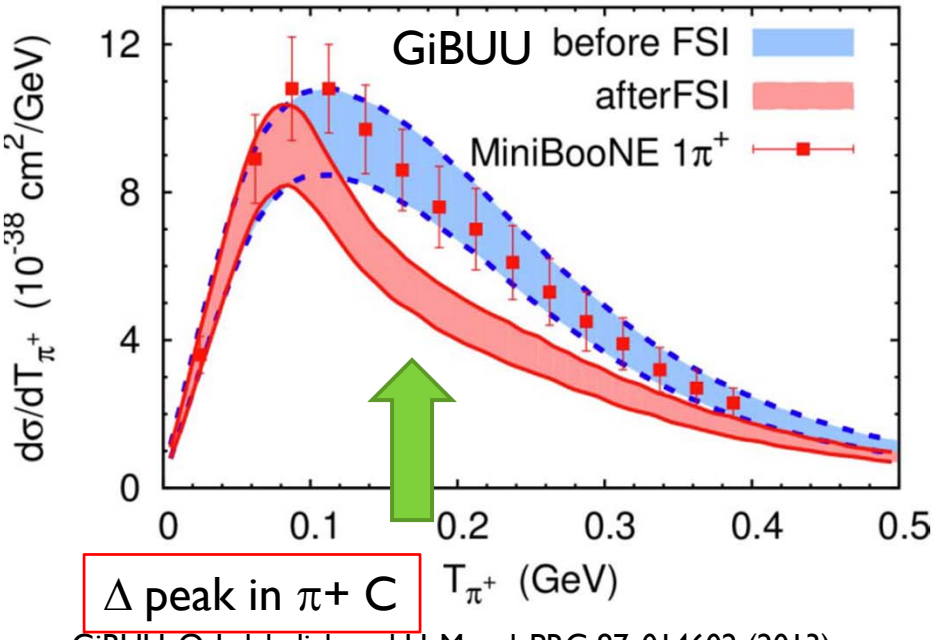
McGivern, et al. (W&C 6/15) [Minerva] to be submitted

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

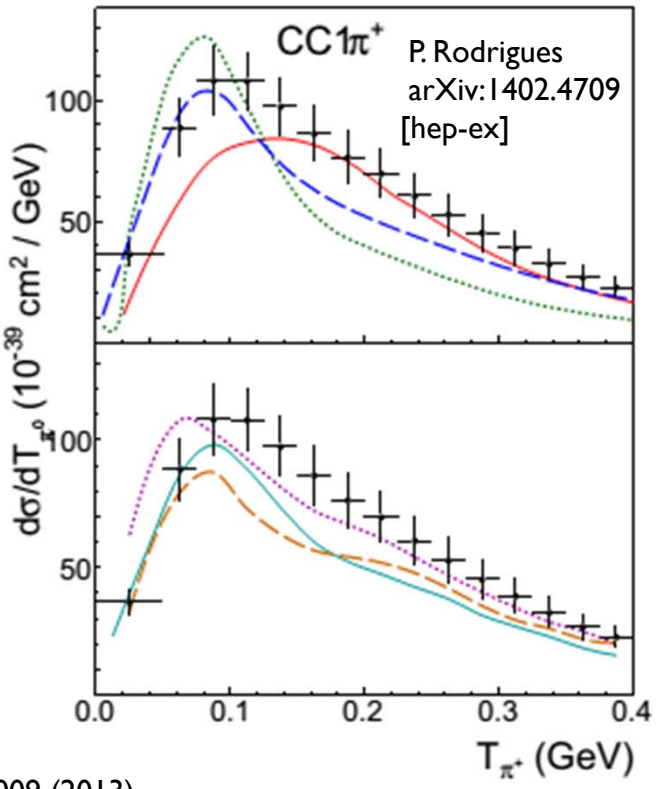
MiniBooNE problem (ν CC1π^+) 2013)

- 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)

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
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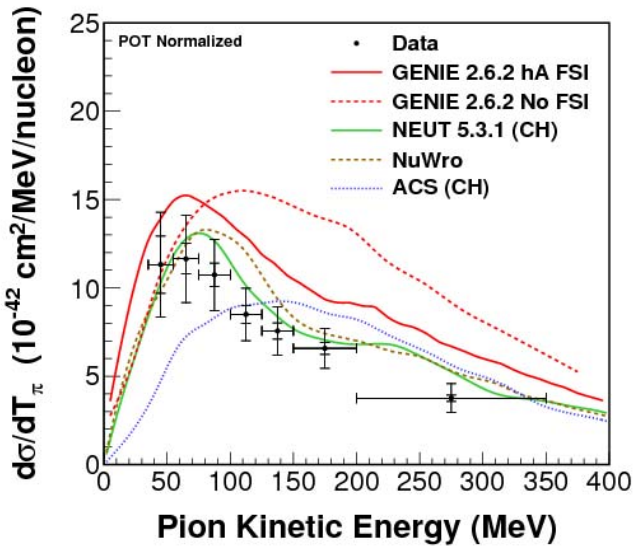
GENIE	Rein-Sehgal	Bodek-Yang (extrap low W)	Global (rel) Fermi gas	none	Effective cascade
NEUT	Rein-Sehgal	Rein-Sehgal	Global (rel) Fermi gas	Via FSI model	Salcedo-Oset (full)
NuWro	Adler (Δ only)	Bodek-Yang (extrap low W)	Global (rel) Fermi gas	Via FSI model	Salcedo-Oset (full)

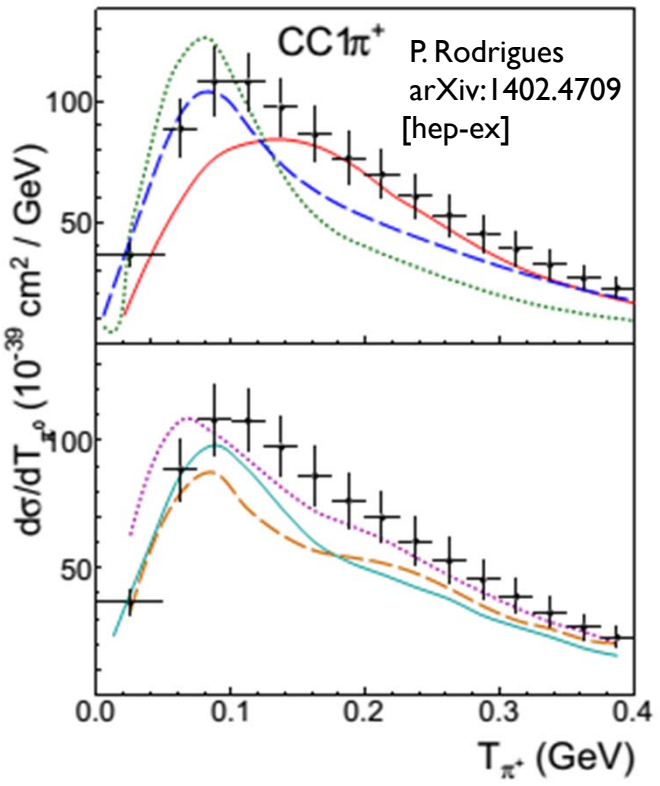
responses

- Theorists have fitted models to existing (e,e'), πA, and older νd data.
  - What can be changed?
  - GiBUU oscillates between ANL and BNL νd data for fitting
  - Valencia improves pion production vertex
  - Ask why no new νd data?
- New data
  - Minerva publishes* ν production of π^+, νbar prod of π^0.
  - T2K coming soon
  - More Minerva data coming

Minerva ν CH π+ data

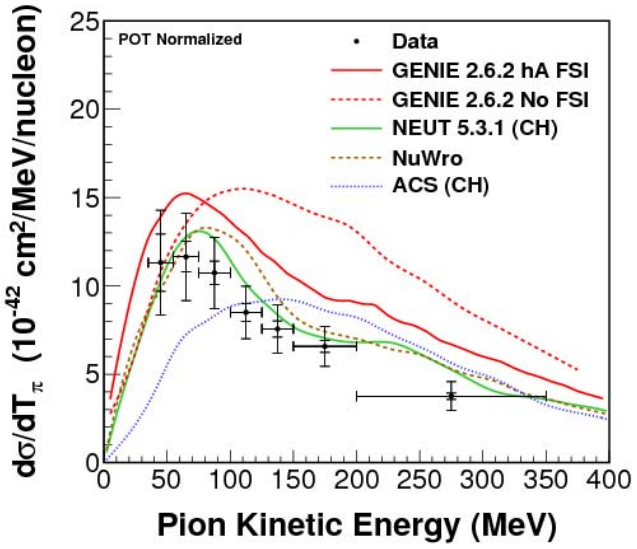
- Submitted to Phys Rev D (after PRL…)
- GiBUU unavailable, Valencia not applicable
- FSI strongly affects shape
- Generators have shape close to data

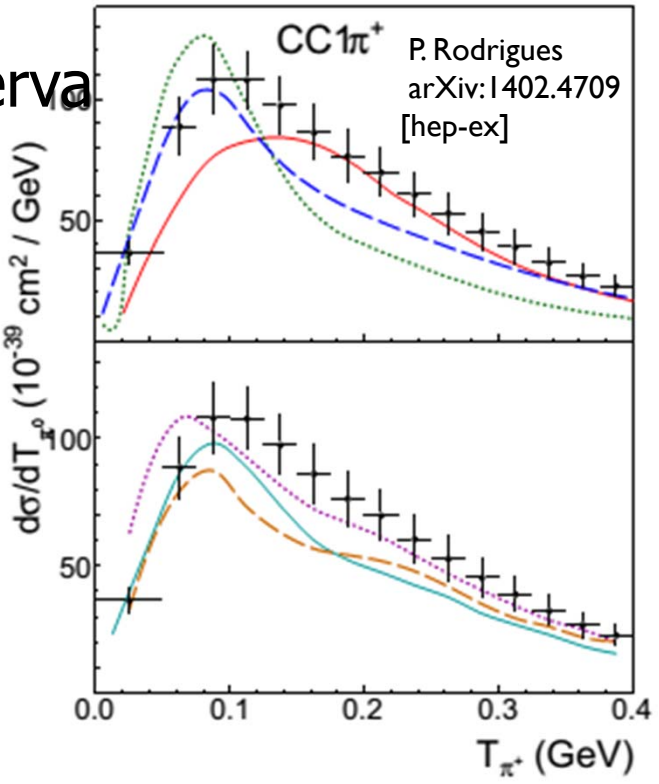




Minerva ν CH π+ data

- MiniBooNE – major issue was 'dip or no dip'
- Here, dip seems filled in (scattering + absorption)
- Event generators tend to be low for MB, right on or high for Minerva
- Athar looks like GENIE noFSI

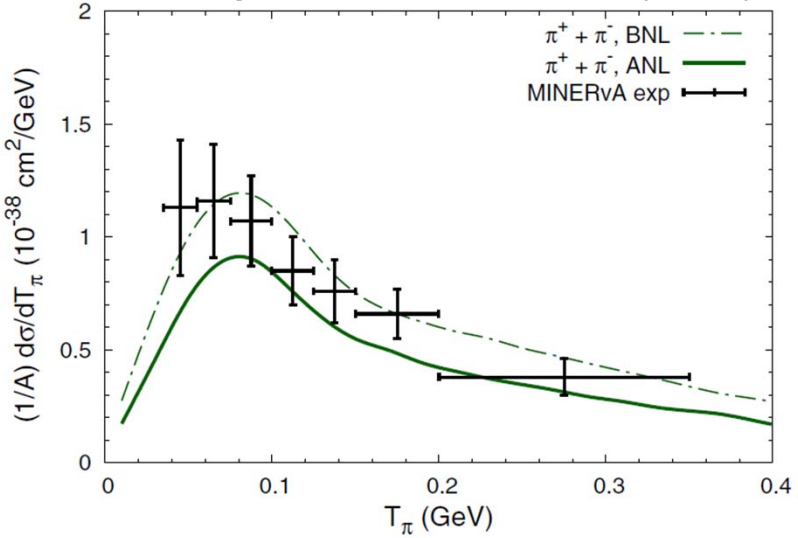


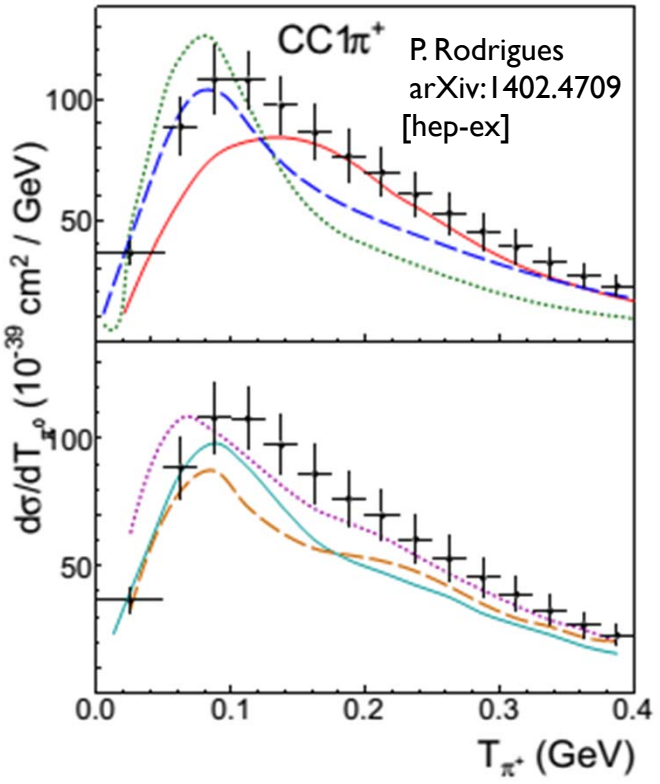


Minerva ν CH π+ data

- 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
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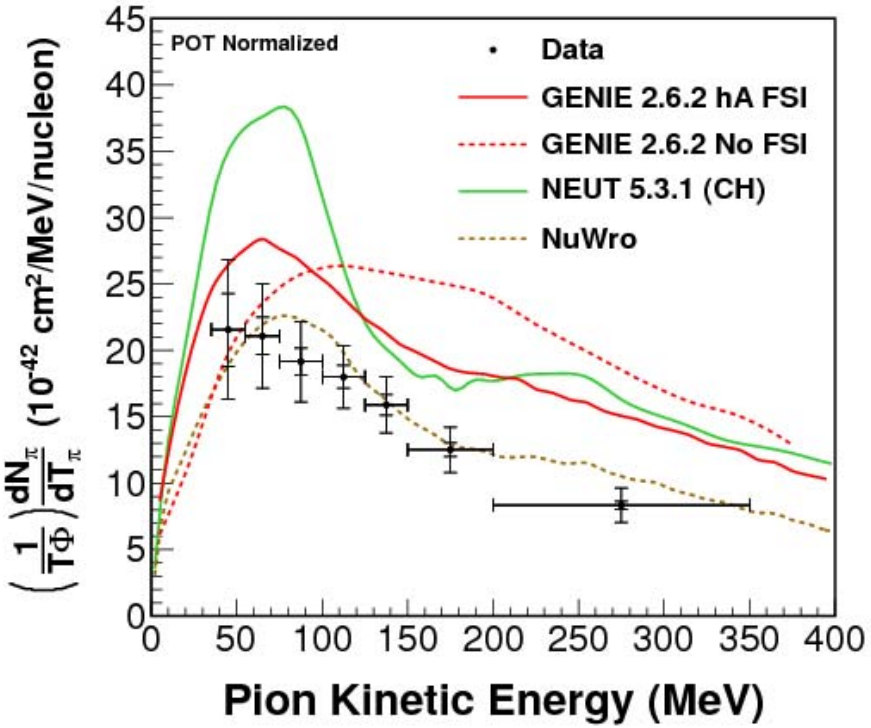
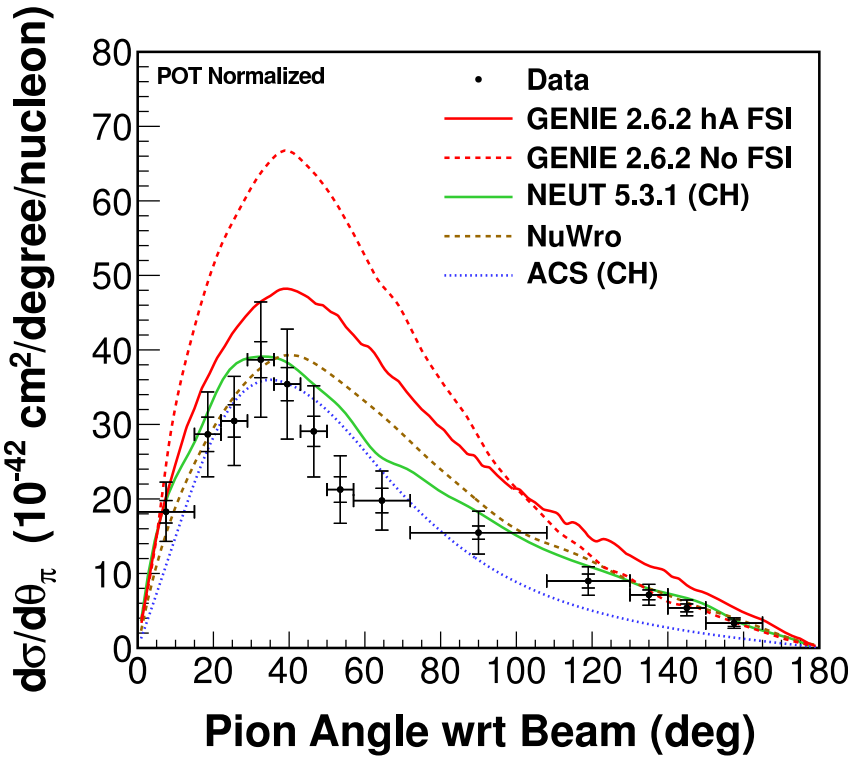
ev gen
- NuWro
- GENIE
- NEUT

- MB data

More information from MINERvA

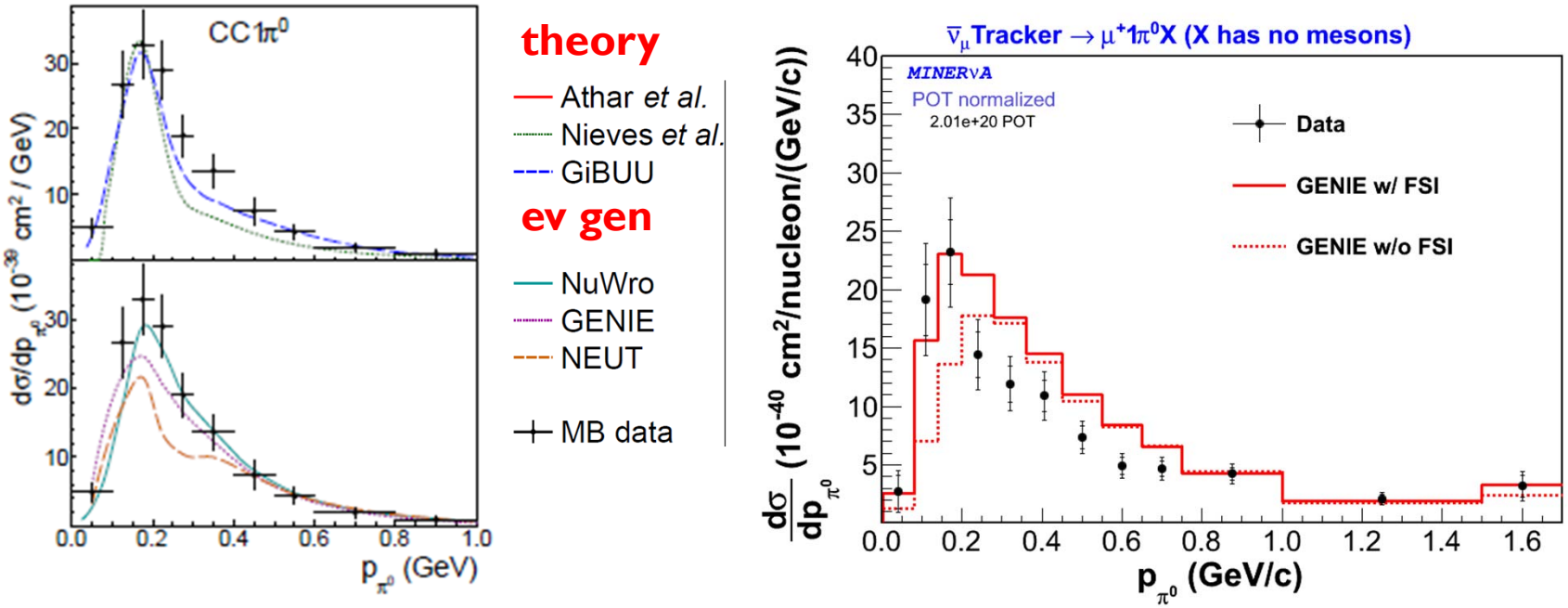
- Same analysis did W<1.8 GeV and pion polar angle.
- W<1.8 GeV verifies basic procedure, shows new sensitivity
- NEUT is now above data due to resonances 1.4<W<1.8 GeV





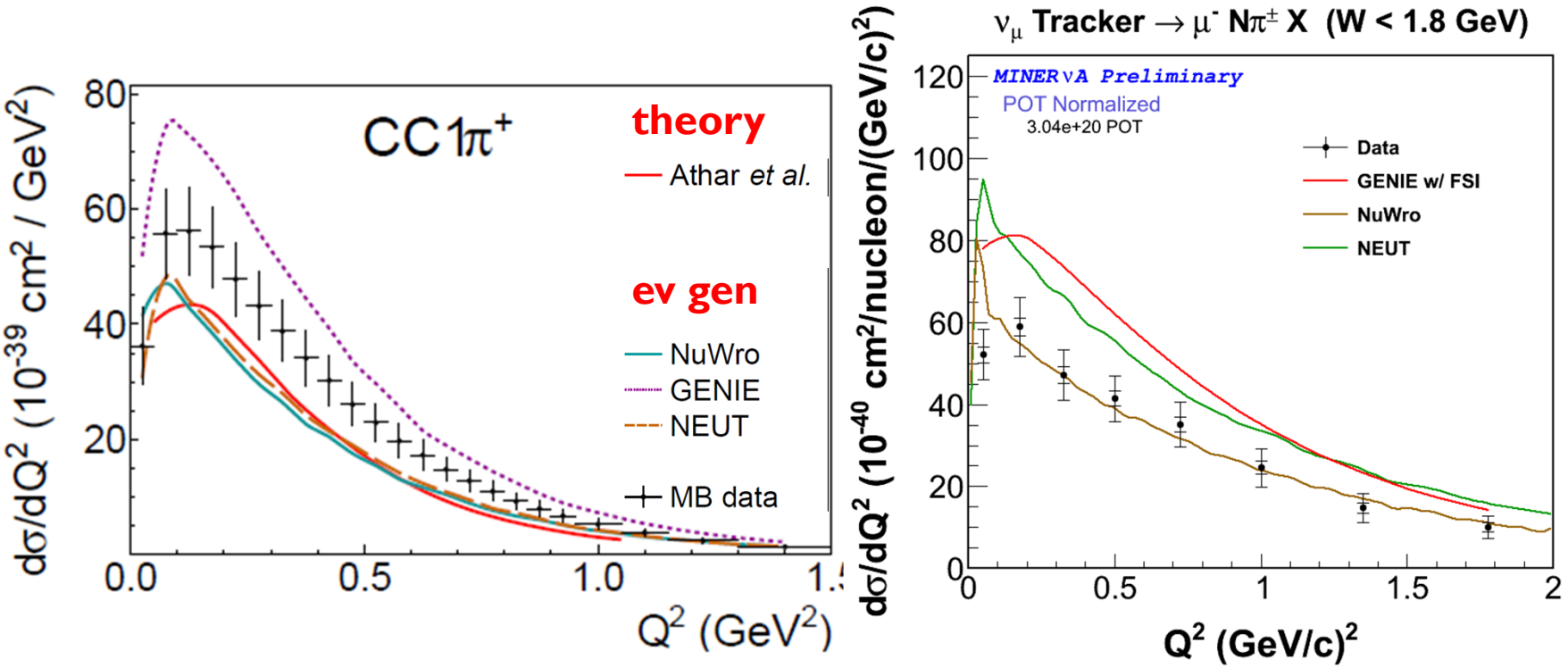
More data (π^0)

- 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



More data for μ, ν variables – Q2

- 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.



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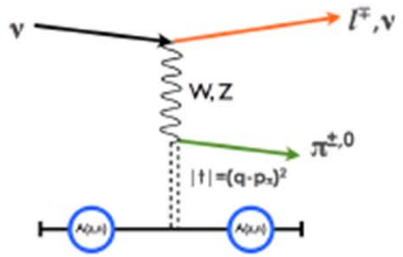
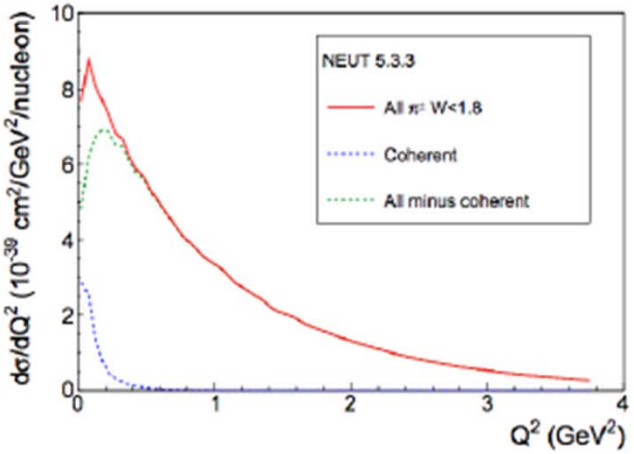
Strong contribution from coherent interactions at low Q^2

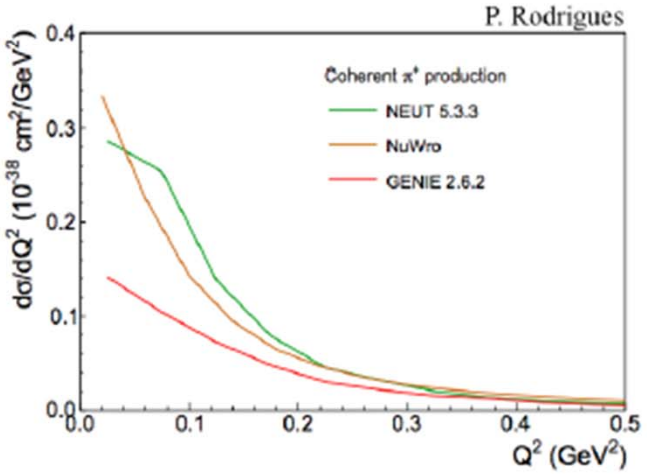
- Difference in shape between the three models at low Q^2 is largely due to coherent pion production
- No data on plots, not sure what is correct, but MINERvA does have coherent total cross section measurements

  (Phys. Rev. Lett. **113**, 261802 (2014))
  - Cross sections shows that GENIE agrees but NEUT overestimates the data



Coherent Pion Production



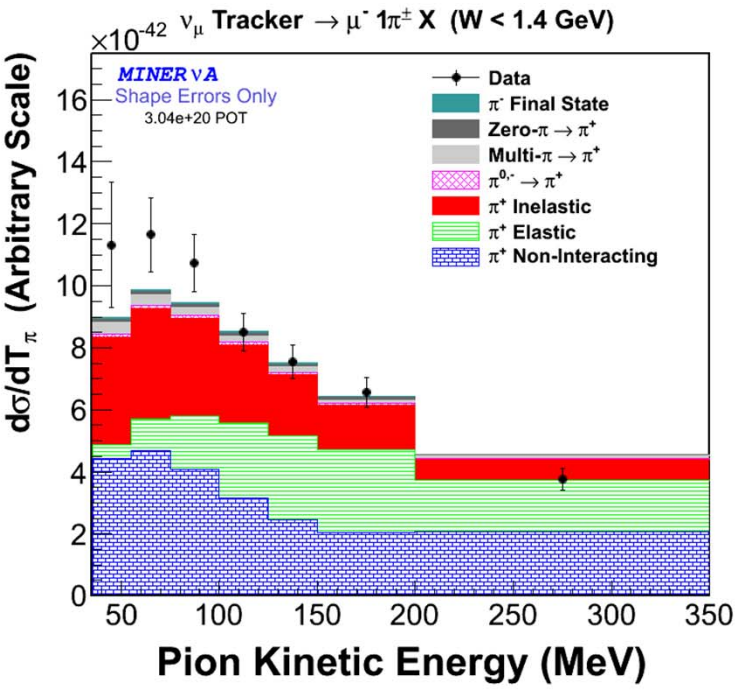


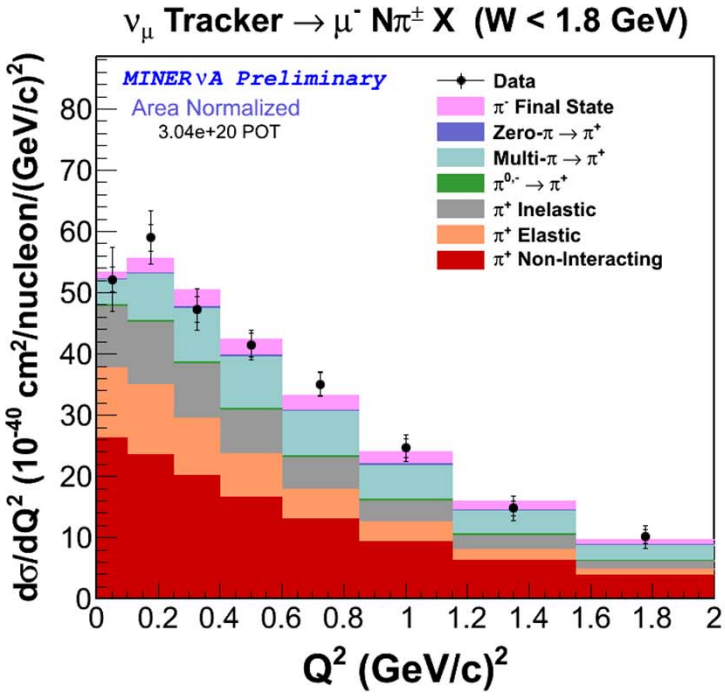
C.L. McGivern (University of Pittsburgh) | Joint Experimental-Theoretical Physics Seminar | 52/56

interpretation

FSI decompositions – focus on shape

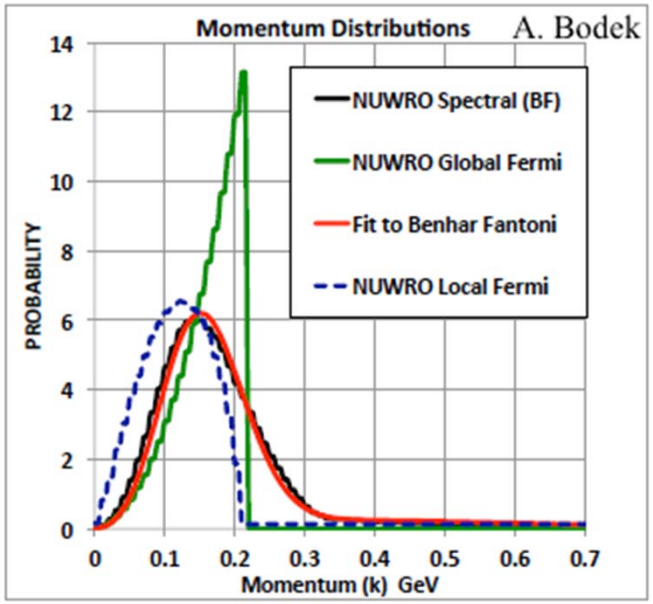
- GENIE FSI model has a single interaction
- Pion kinetic energy shows significant changes in shape
- Q^2 shape largely insensitive to FSI interaction (low Q^2)

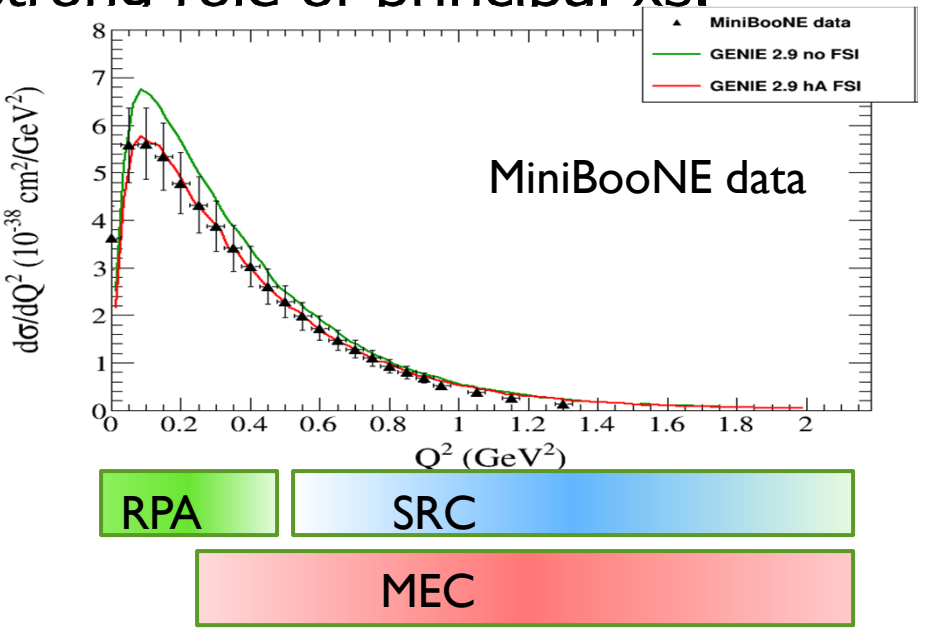




Approximate factorization of the physics

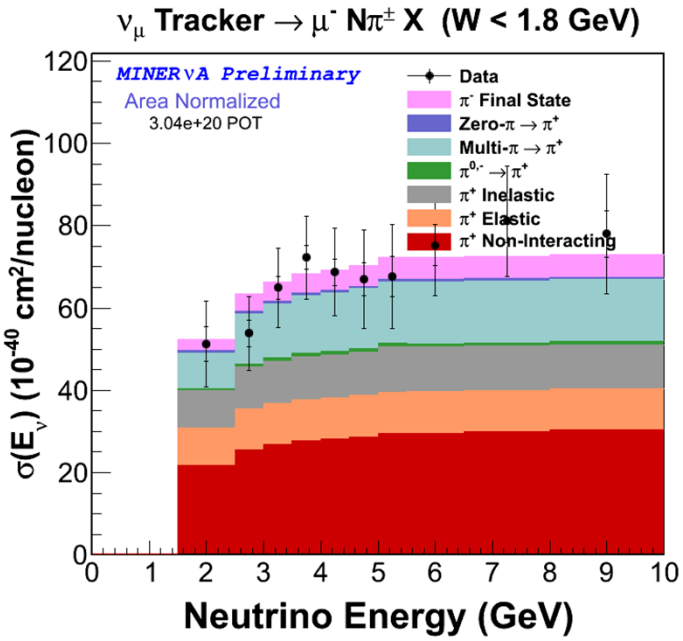
- KEπ shape very sensitive to FSI details, esp. interplay of inelastic (shift) and absorption (depletion) interactions.
- Q^2 shape largely insensitive to FSI, more sensitive to nuclear model (momentum distribution, correlations)
- Magnitude matters, expect strong role of principal xs.

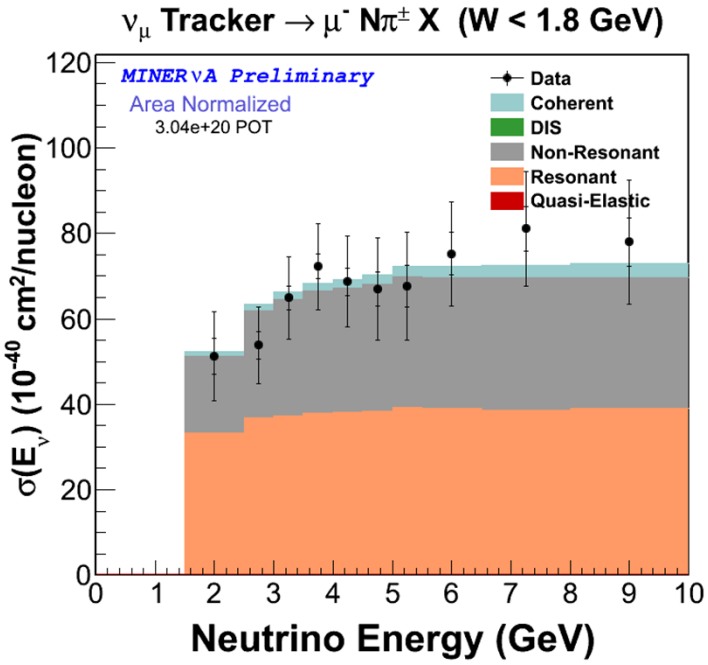




More sensitivities - Eν

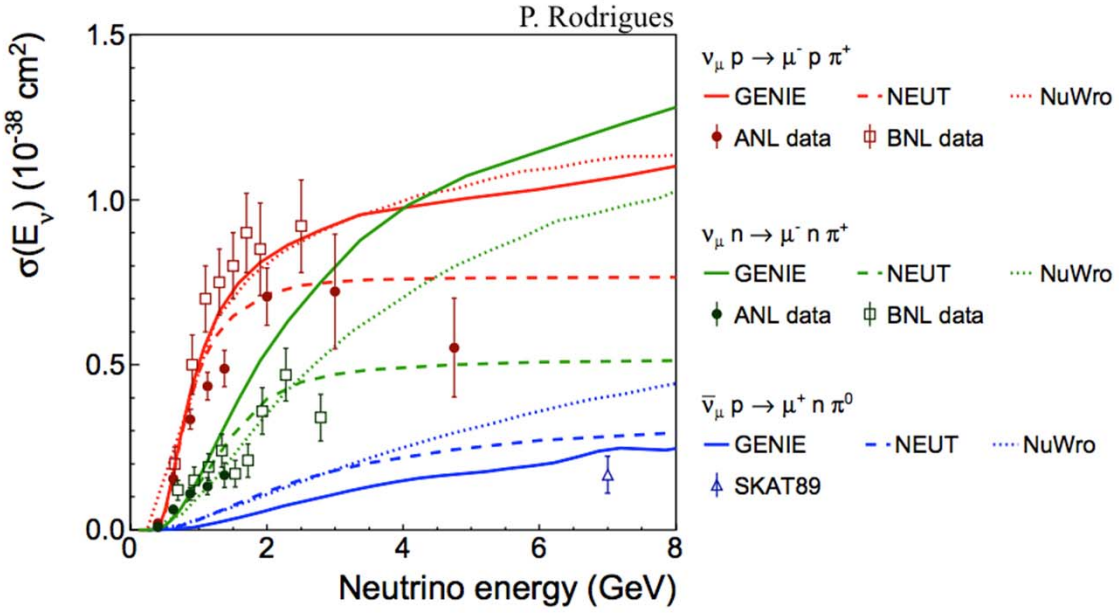
- Not much shifting in strength due to FSI
- Mix of processes has no significant dependence
- Data is largely pions from N* resonances





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

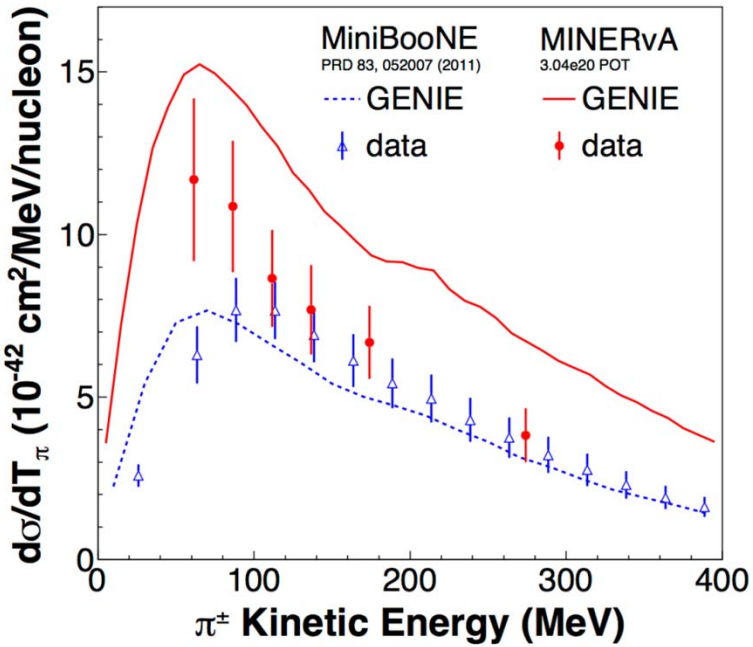
- Plot shows what GENIE, NEUT, and NuWro use
- Historical problem with BNL>ANL at low Eν
- Recent reanalysis by Wilkinson et al. favors ANL
- Most models take middle approach



- νbar π^0 production poorly constrained (isospin)
- Wide variation in use of n π^+ data
- Fortunately, p π^+ dominates in results.
- NEUT and GENIE agree, NuWro a little smaller
- Additional data not shown

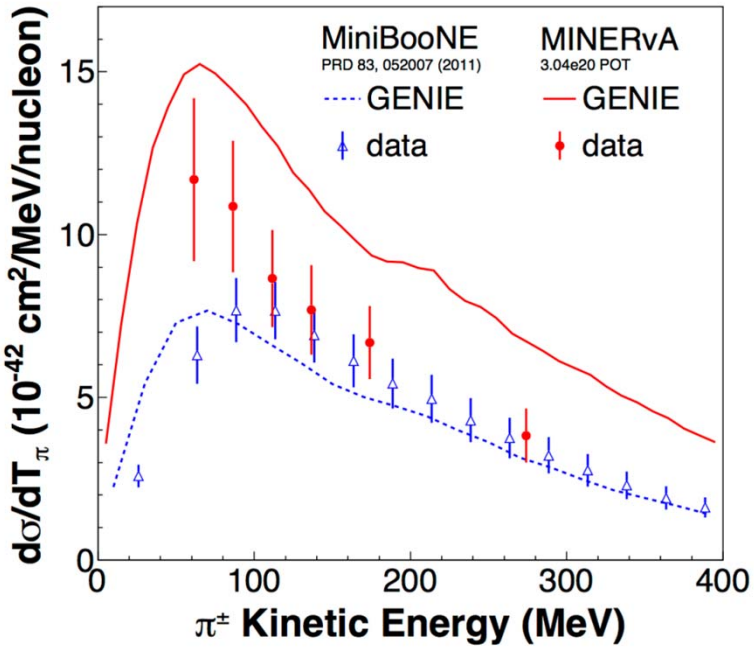
How well do MiniBooNE and MINERvA agree?

- 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**



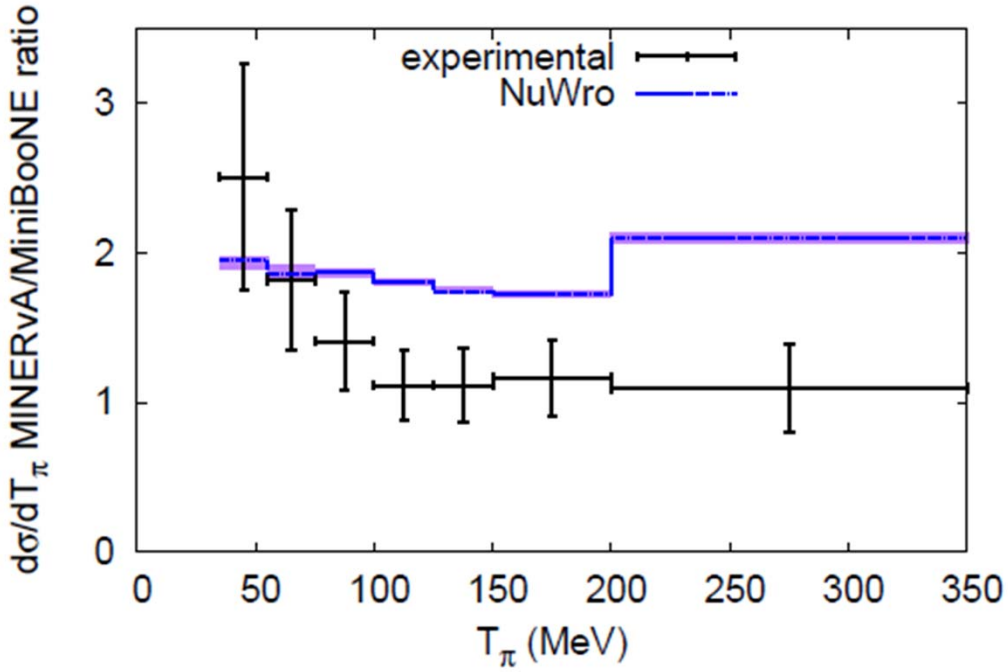
Interpretation

- Surely better for MiniBooNE to make W<1.4 GeV cut and no correction factor.
- With higher E_ν, we expect more strength in MINERvA data at high KE_π and Q^2. Don't see it.
- Shapes at low are different, expected? MINERvA errors larger (hard to reconstruct low energy pions)



Sobczyk & Zmuda (NuWro)

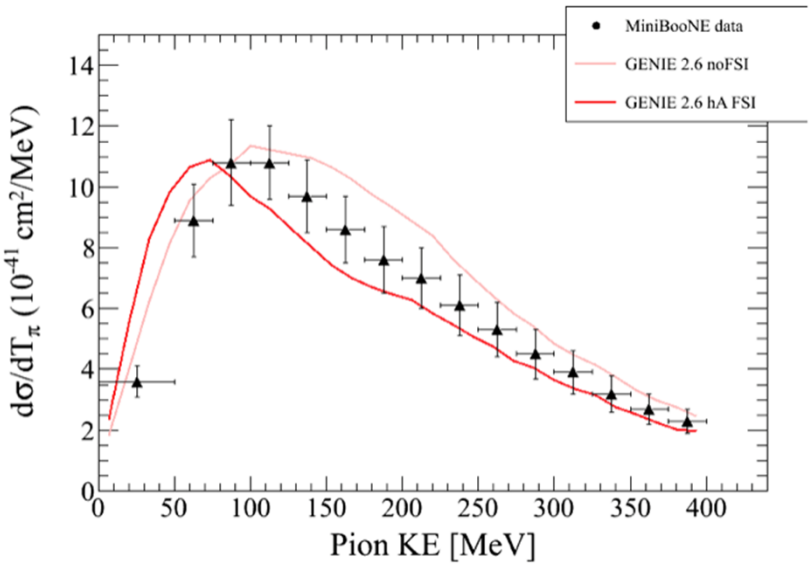
- Made ratio of experiments with proper error propagation.
- They predict factor of ~2, no large shape difference
- Question data normalization



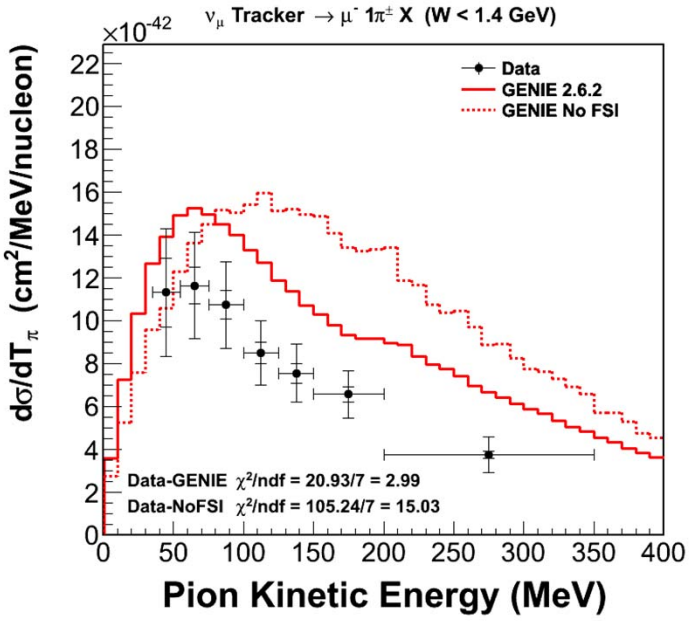
GENIE studies - energy dependence

- Results look similar to NuWro, shape change due to FSI similar for MiniBooNE and Minerva fluxes.

MiniBooNE data

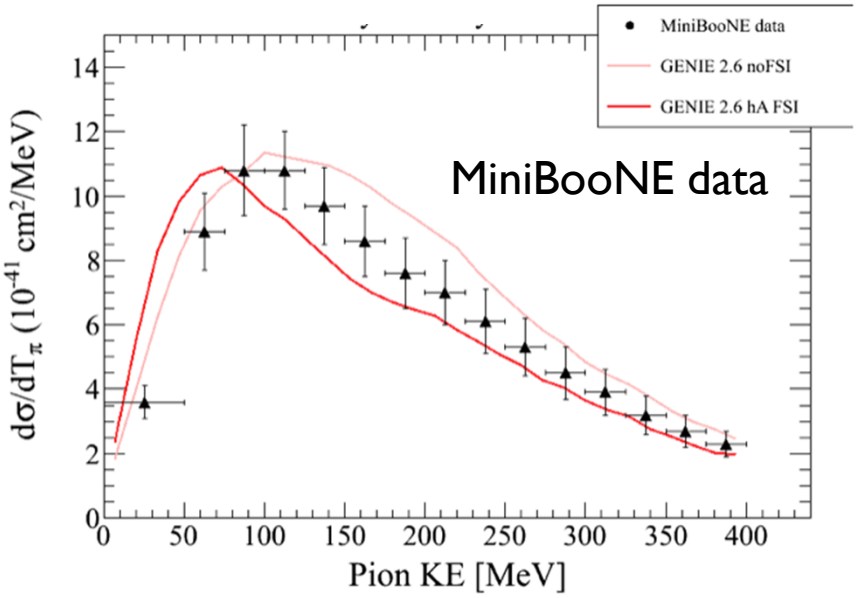


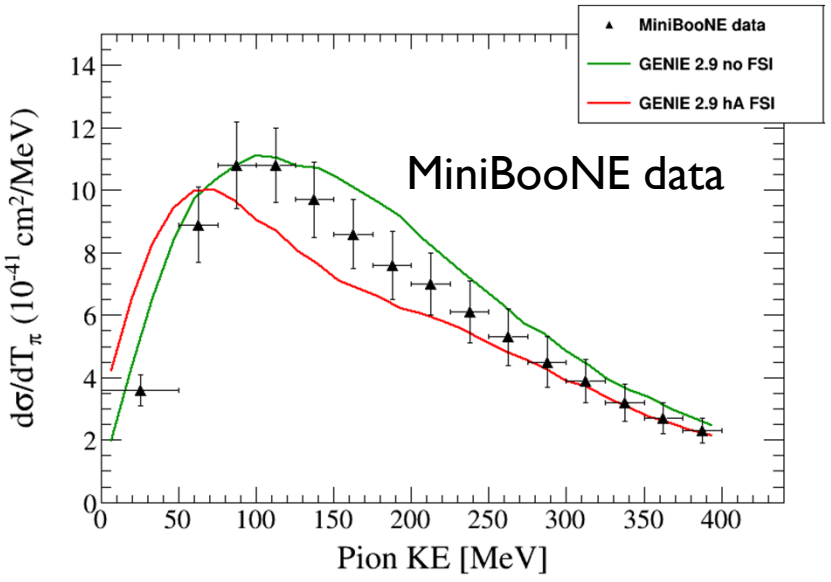
Minerva data



GENIE studies - version dependence

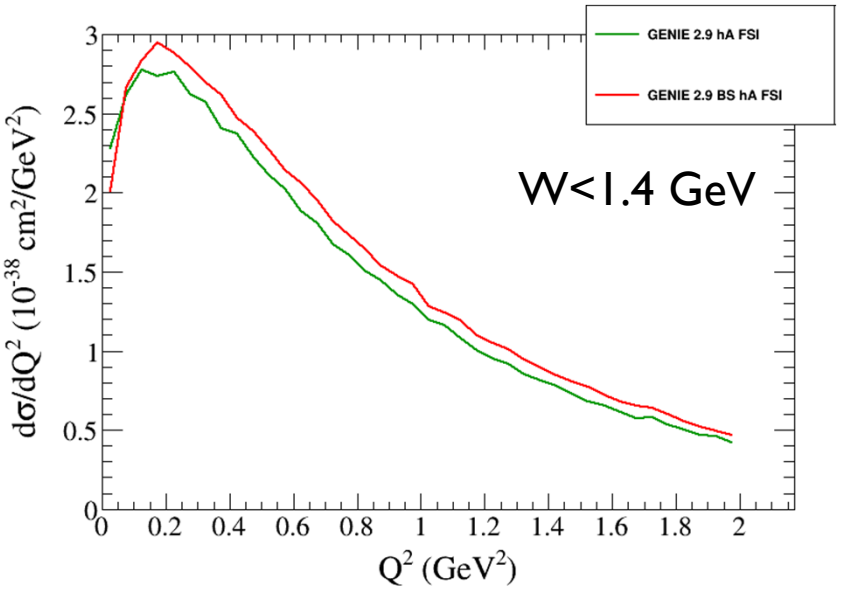
- Biggest change was in FSI for v280
  - Improved details, e.g. angular/energy distributions
  - Influence on this spectrum is not large
- v280 and v290 default are same

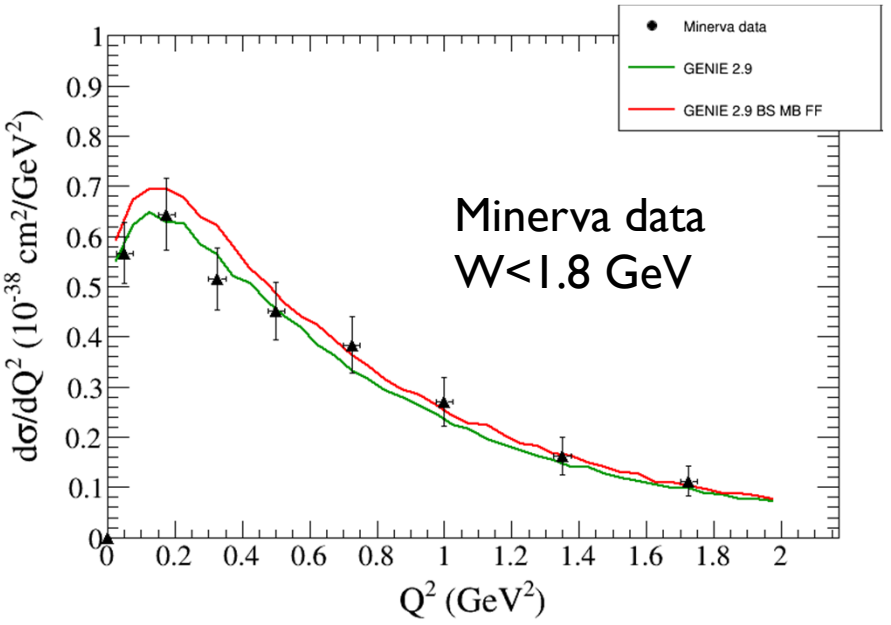




GENIE study – Q^2

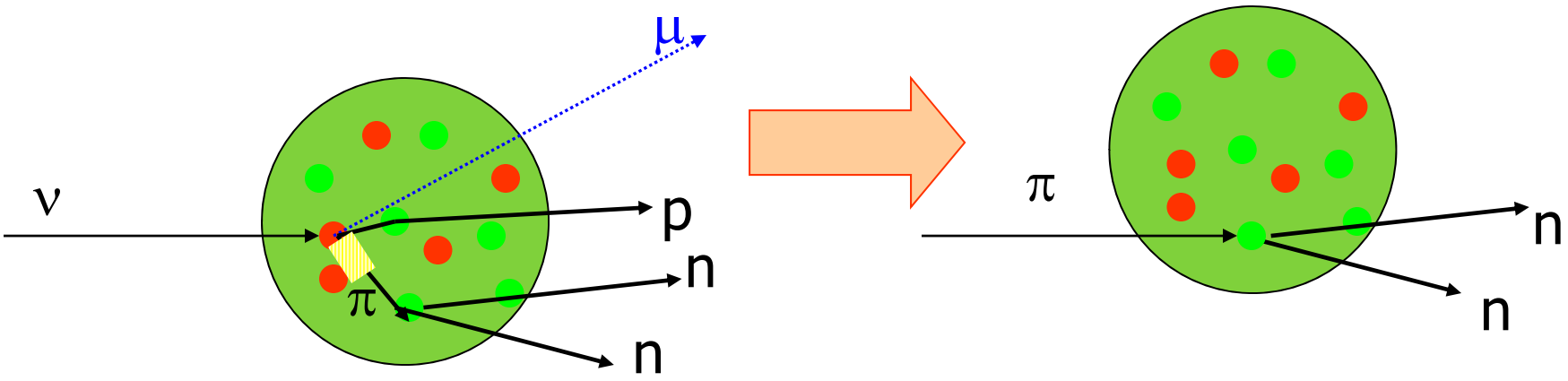
- GENIE default model unchanged in 2.9.0
- Alternate model – Berger-Sehgal, MiniBooNE GV, GA
- Changes Δ form factor, energy dependence





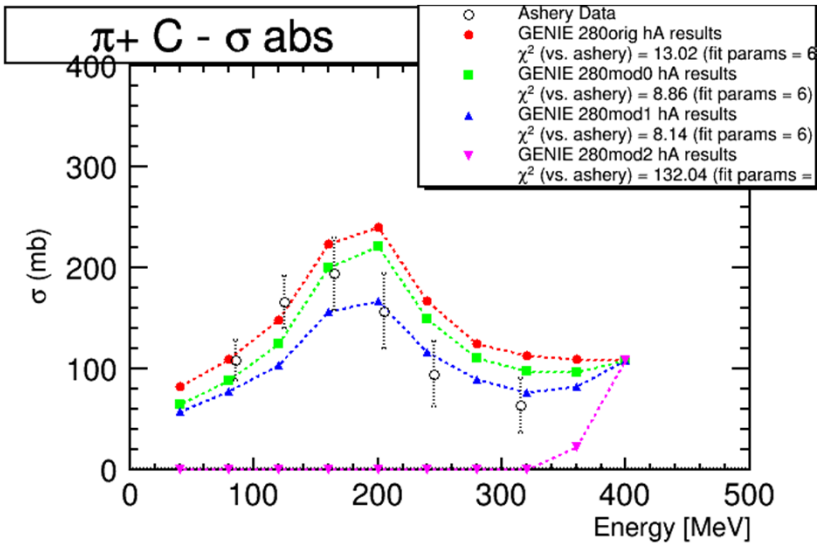
Recent work on FSI tests (Pitt undergrad)

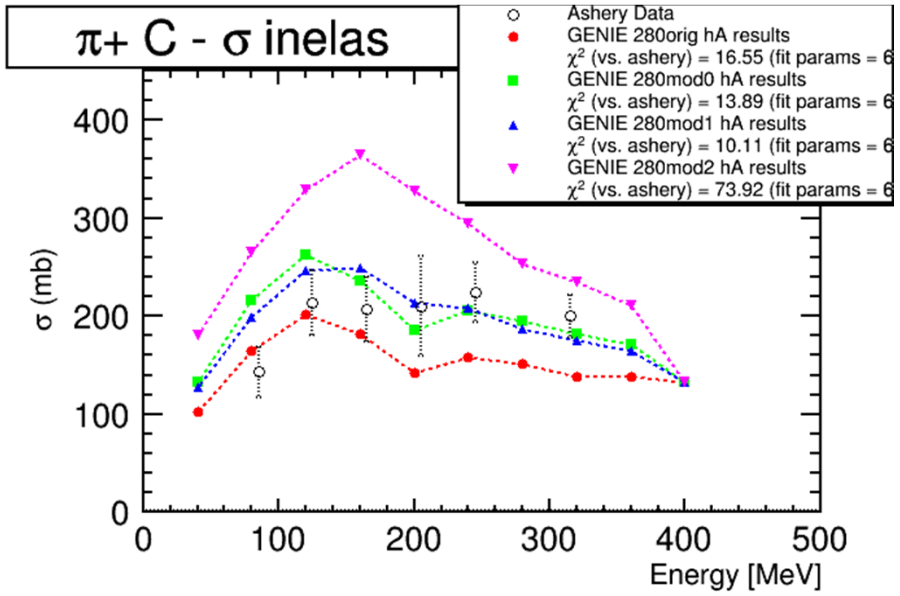
- Are shapes of MiniBooNE and MINERvA data compatible with pion scattering data?
- Is it possible to get good agreement with both kinds of data simultaneously?
- Is basic model correct?



Example plots using GENIE 2.8

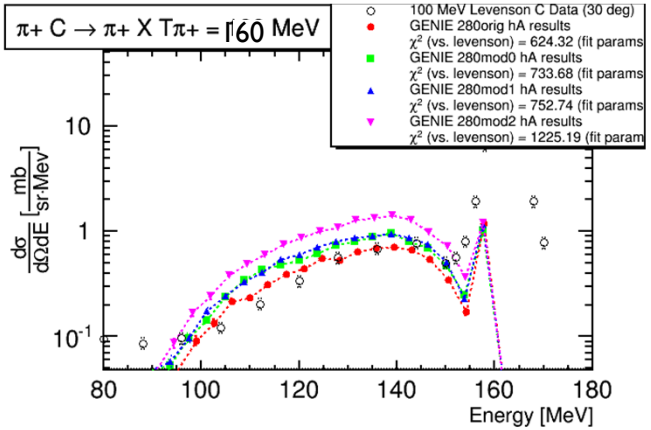
- Make changes in fates with total reaction xs constant
  - Mod 0 – increase inelastic by 40%, decrease others proportionally
  - Mod 1 – decrease absorption by 30%, increase inel proportionally
  - Mod 2 – get rid of abs, increase inel and cex (extreme!)

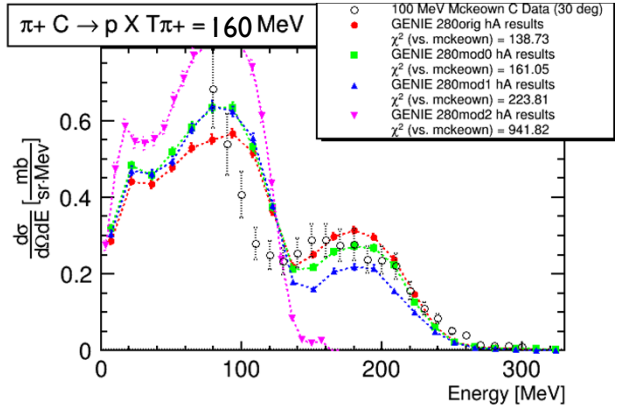


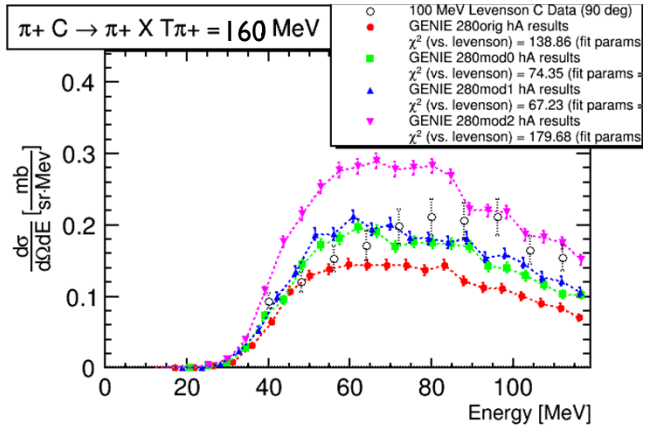


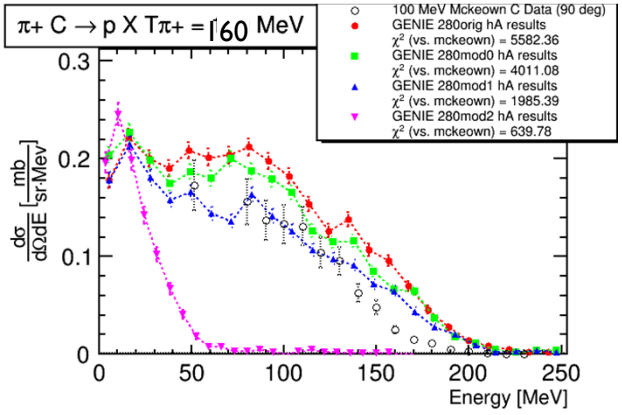
Effects on more detailed data (160 MeV π^+ C double differential xs data)

- Levenson (π,π') sensitive to inelastic
- McKeown (π,p) sensitive to inelastic at low KE and to abs at high KE.









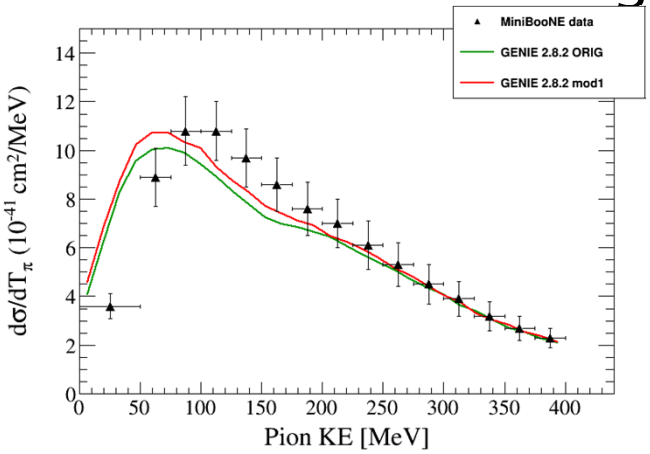
Summary – χ^2 analysis

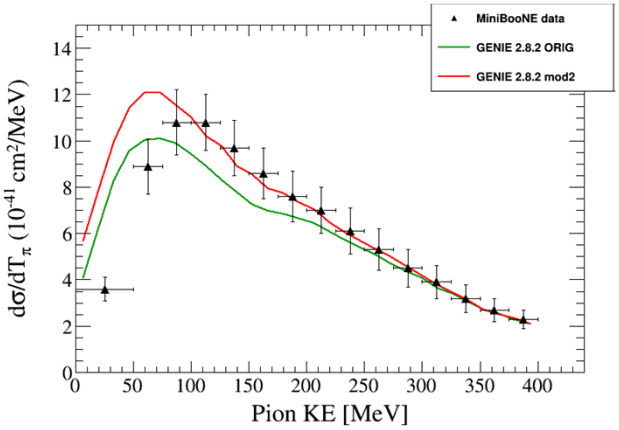
model	2.8	mod0	mod1	mod2
π+ tot abs	1.3	1.6	3.5	33.0
π+ tot inel	1.3	2.6	2.3	7.5
(π,π) Levenson	667	1079	1029	1827
MiniBooNE	3.9	5.4	4.7	7.5
Minerva (absolute)	34.4	40.9	49.2	75.2
Minerva (shape)	0.16	0.13	0.13	0.28

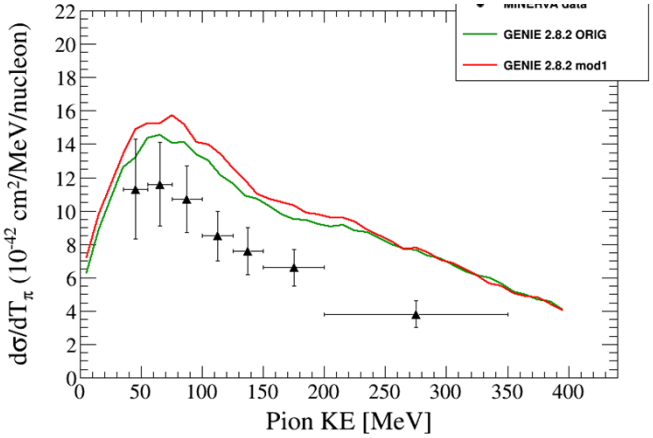
- Show χ^2/data point (no correlations) for all but Minerva
- Minerva provides correlation matrix, use it
- No obvious advantage for any modification
- model for Levenson, McKeown needs improvement

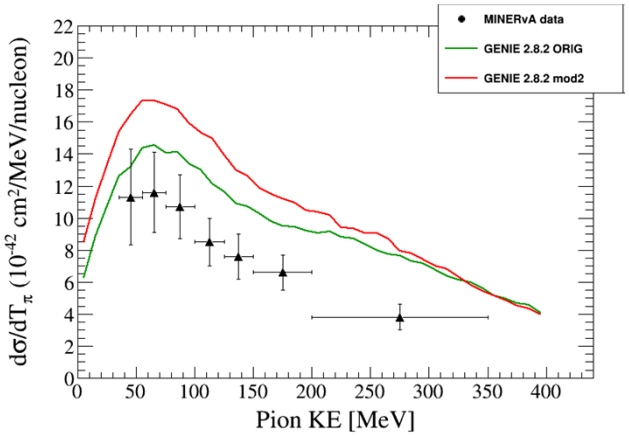
Effect on neutrino data

- Large changes in pion data have small changes for neutrino data. Changes are in right direction.



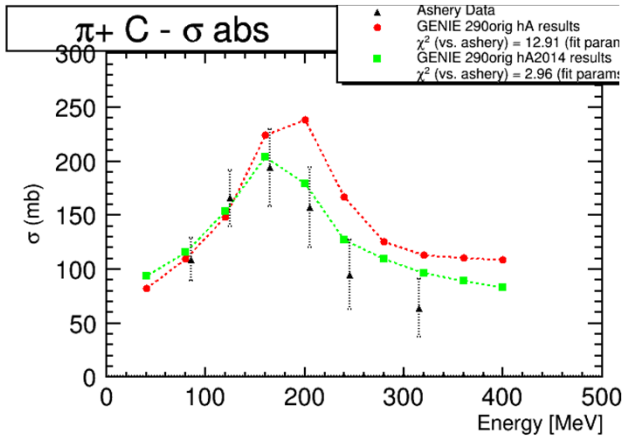


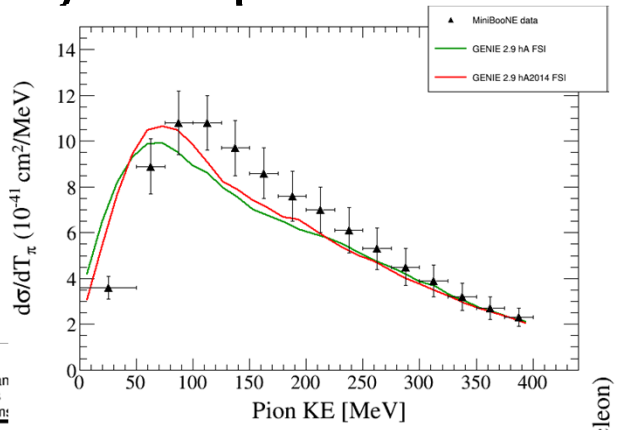


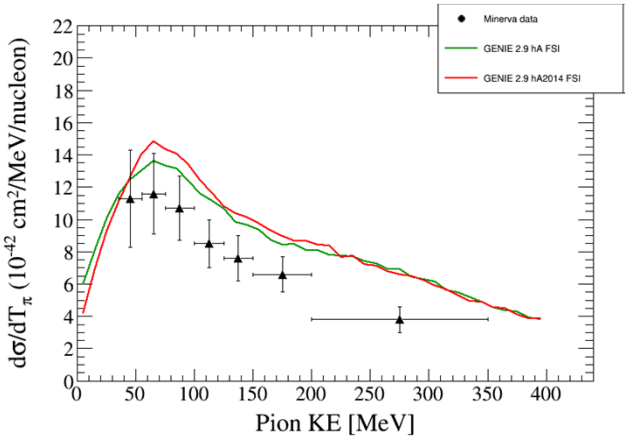


New FSI model in GENIE 2.9.0 (alternate)

- Purpose is improve A dependence, particularly for C
- Previously used Fe data, now use data for all A.
- Must change UserPhysicsOptions.xml to implement.

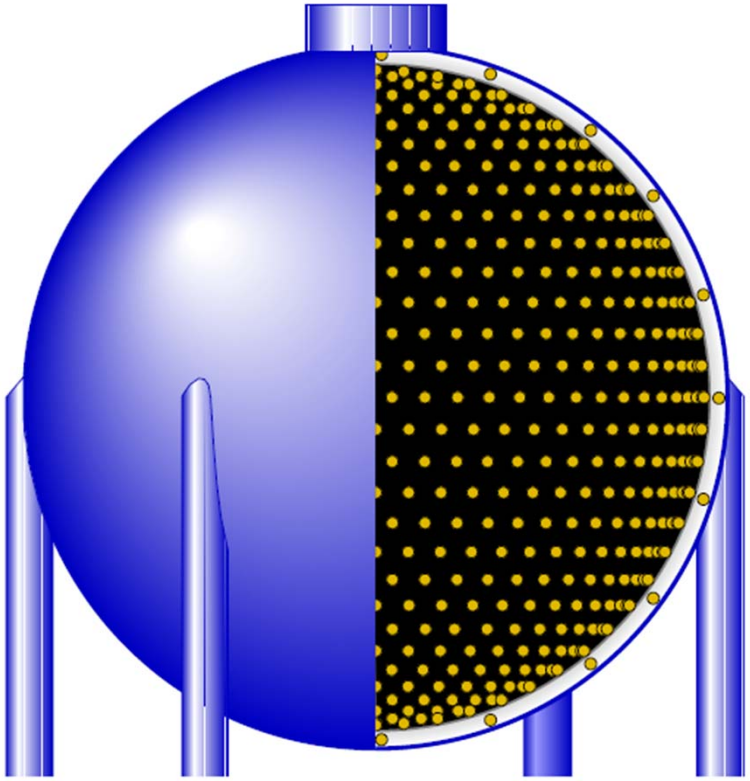


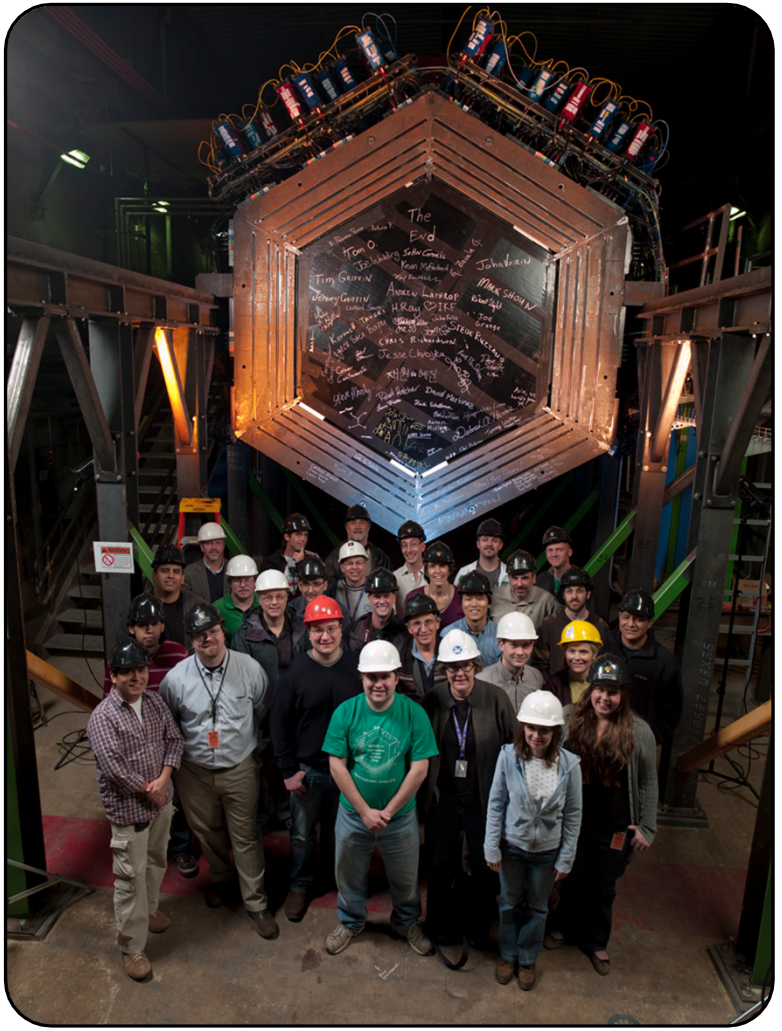




MiniBooNE (Cerenkov) vs. Minerva (Scin)

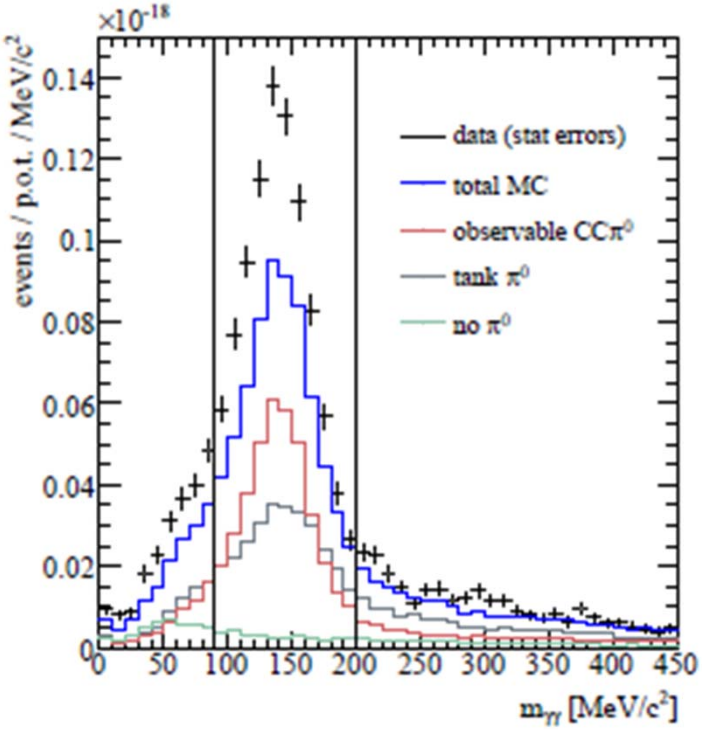
- MiniBooNE has larger data sample - longer run time

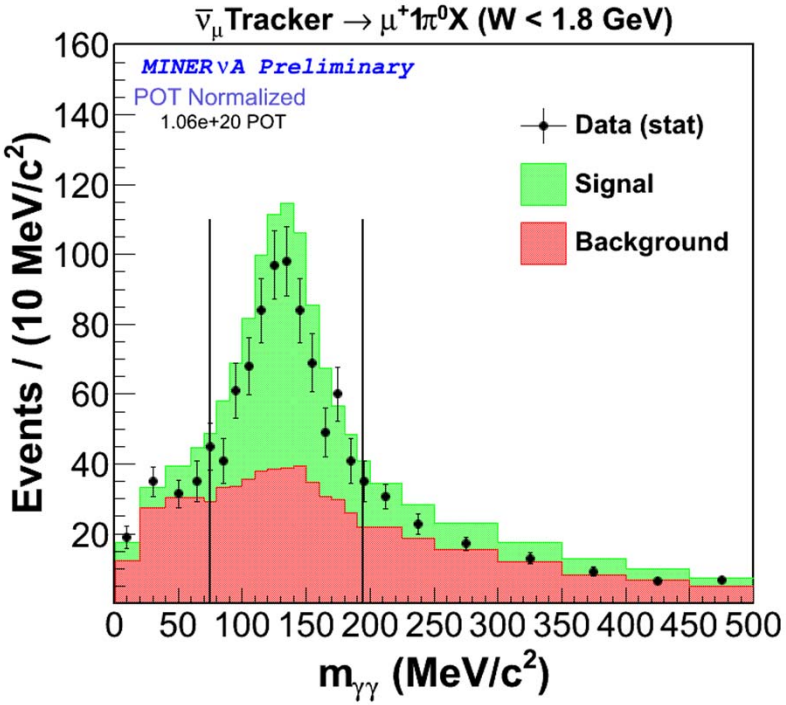




π^0 detection needs photon detector

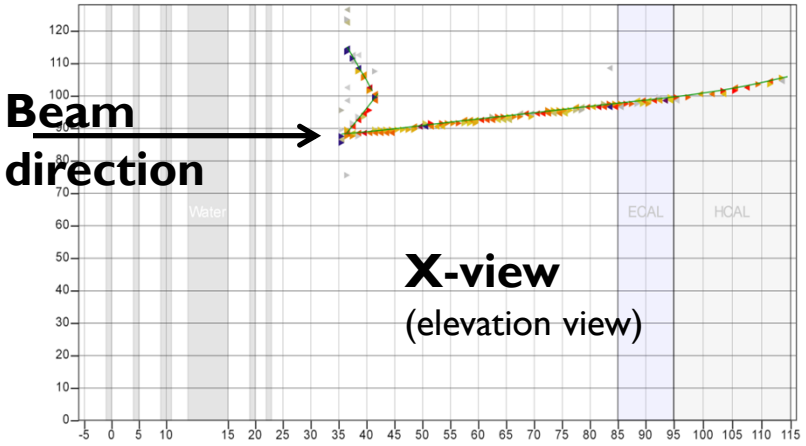
- MiniBoone (Cerenkov) does better than MINERvA (scin)
- More of an advantage
- Note MINERvA data for νbar rather than ν. (almost unique)

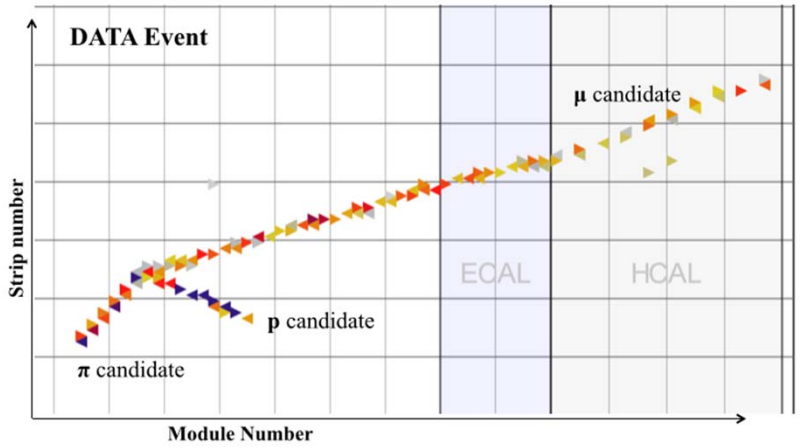


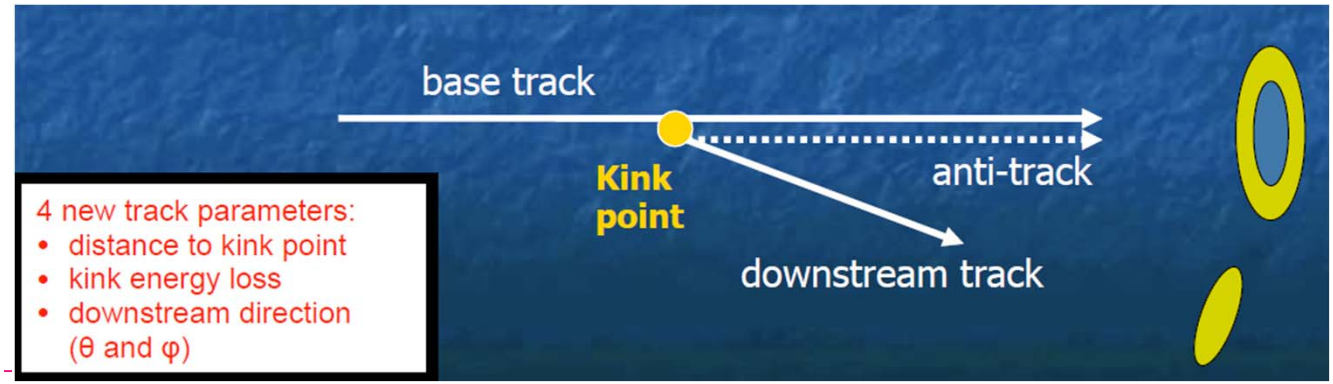


Event comparison – MiniBooNE and MINERvA

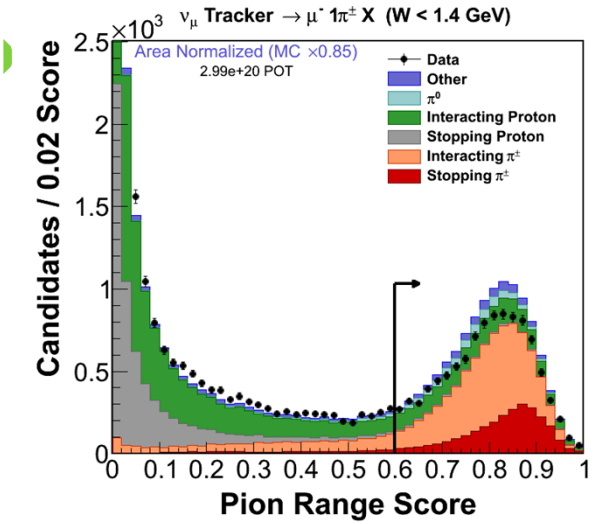
- MINERvA is a tracking detector (CH)
- MineBooNE is a Cerenkov detector (CH2)/some scintillator

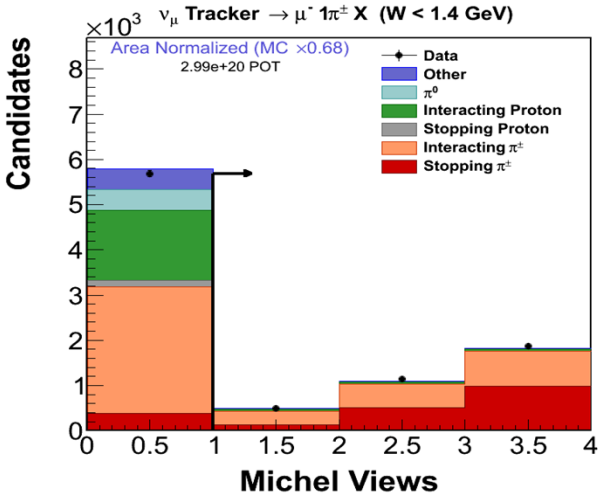


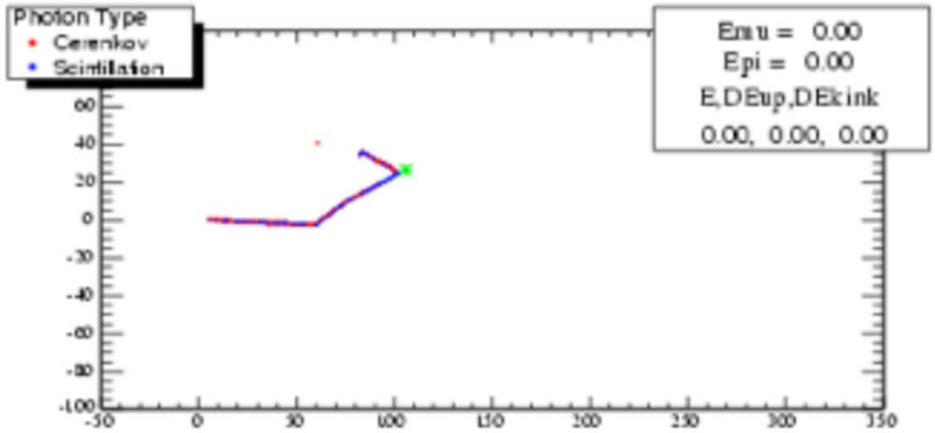


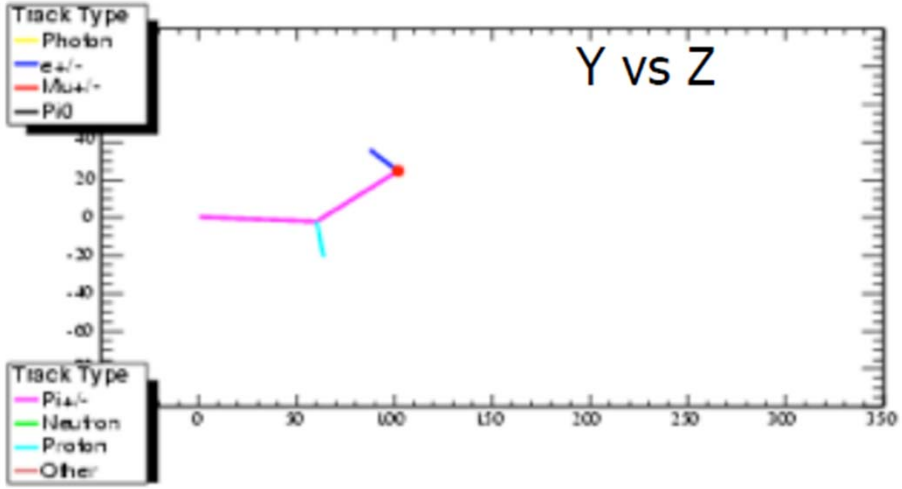


A little detail – pion identification



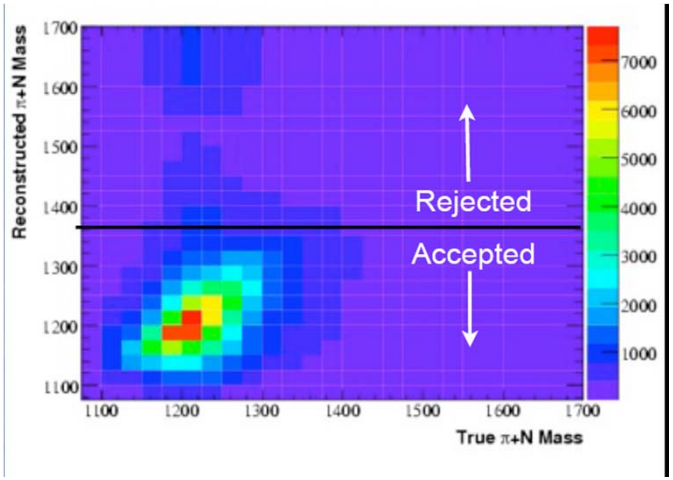


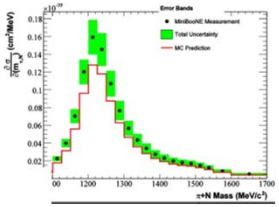


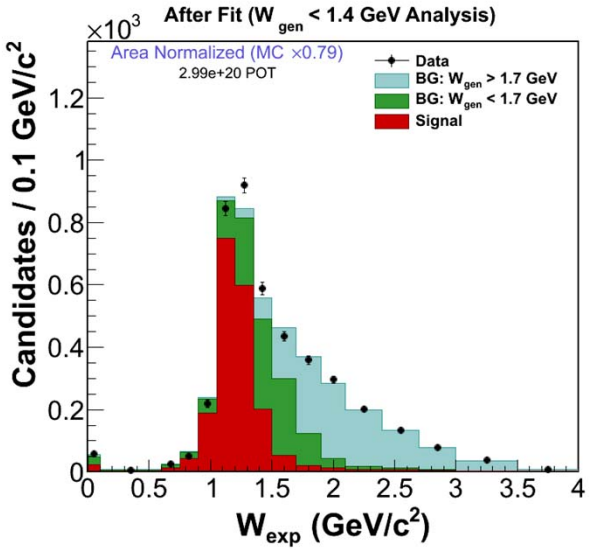


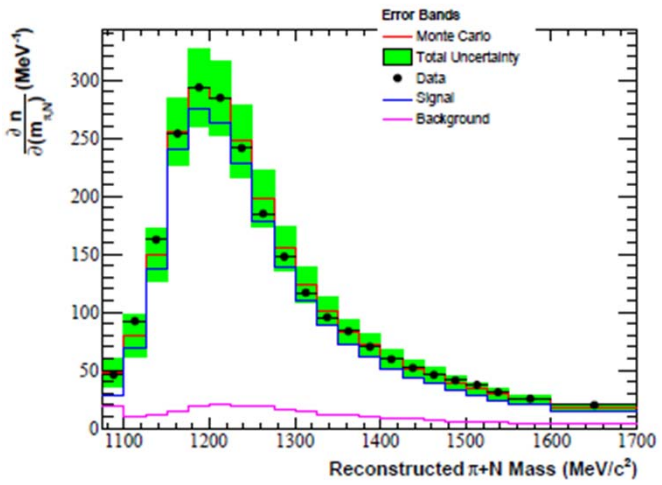
A little detail – W cuts

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



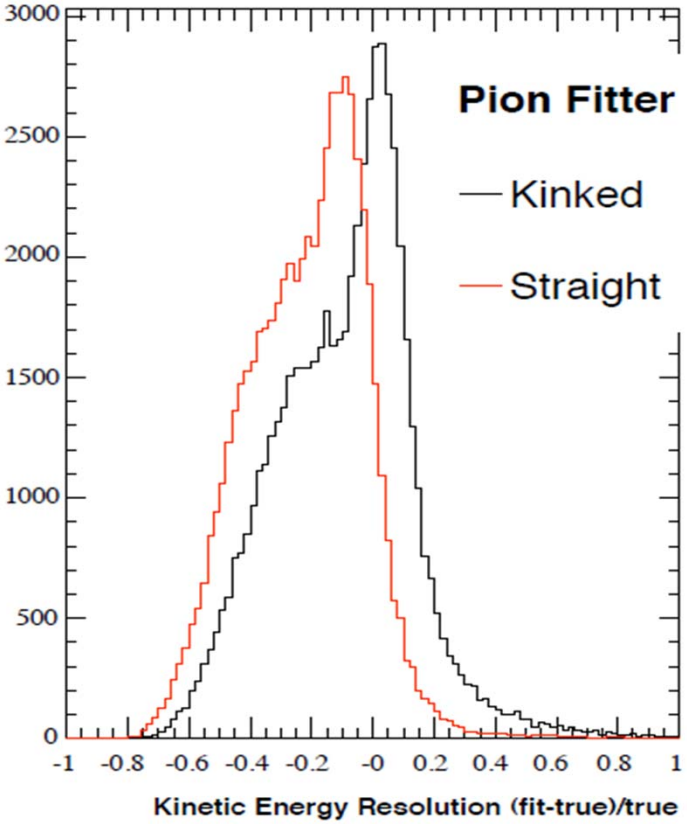


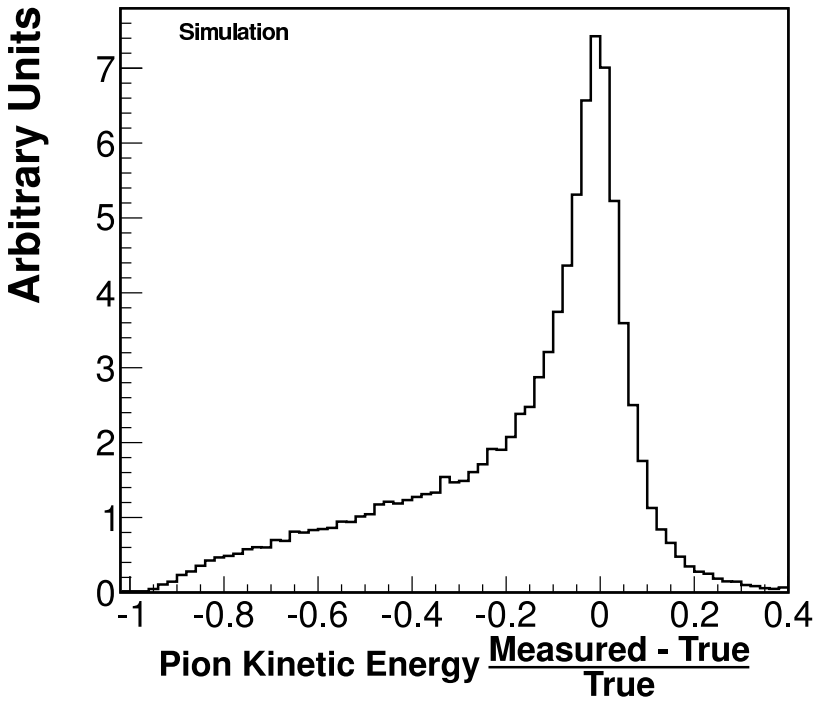




Pion energy reconstruction

- This is hard with either method





ν flux

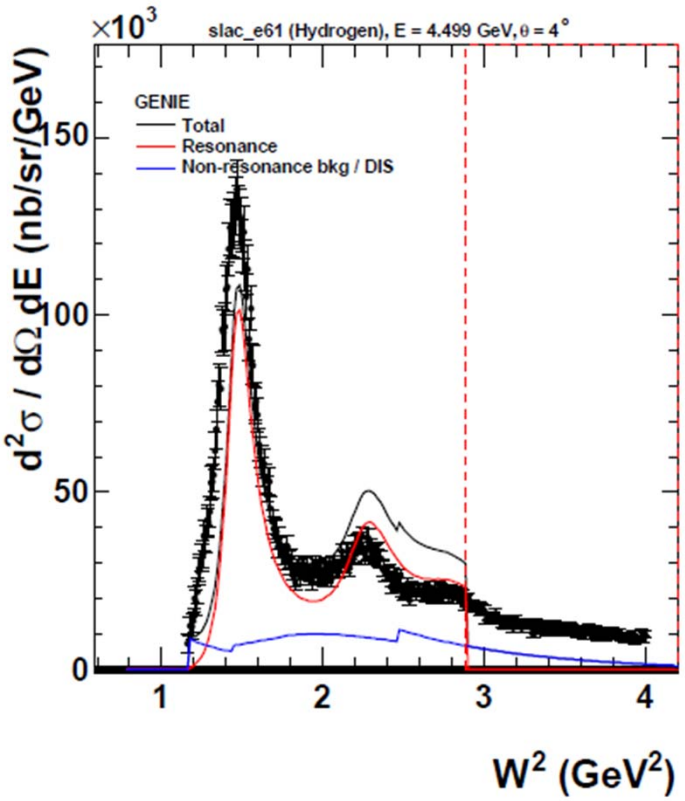
- MiniBooNE flux based on thin target HARP data (8 GeV Be).
  - Reanalysis of HARP data with 30, 40 cm targets
  - New flux established, effect on data being evaluated
- Minerva flux based on NA49 pC data
  - New flux constraint from νe data, increases ν π^+ xs by ~8%
  - Improved analysis with better model, constraints, new MIPP data
  - Results will be presented at NUINT15 (Osaka, Nov, 2015)

Updates to GENIE

- v2.6.2 – used in all Minerva results shown today
- v2.8.6 – present production release
  - Improved FSI
  - Will be used for Minerva ME results
- v2.10.0 – imminent – same default (new alternate models)
  - Effective spectral function
  - Improved pion production form factors
  - Improved FSI (better A dependence)
- v2.12.0 – in progress
  - Spectral function nuclear model
  - Valencia MEC
  - Oset-Salcedo FSI model
  - Nieves QE/ local Fermi Gas nuclear model

GENIE perspective

- Nuclear models
  - Spectral Function models
  - Complete Valencia QE model (local FG)
  - Improvements from (e,e') comparisons (?)
- π production
  - Improve nucleon cross section fits
  - Updated vector, axial form factors
  - Improved FSI
  - Medium corrections (?)
- Can GENIE catch up to nuclear theory of 2013 by 2017? (Manpower limited)



Minerva π production (in progress)

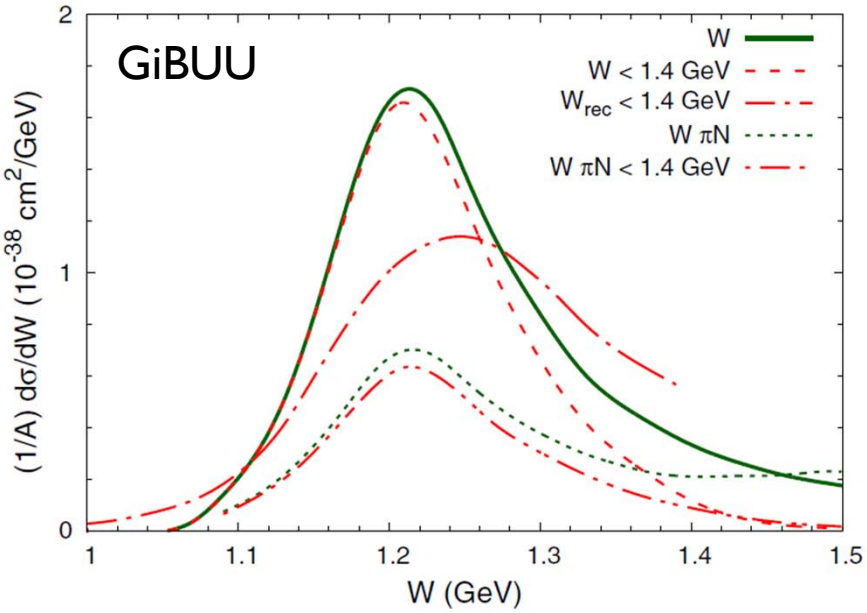
- Low energy flux
  - ν_μ CC π^0 production (CH)
  - ν_μ CC π^+ production (Fe, Pb)
- Medium energy flux
  - <Eν>~5-6 GeV more POTs, high cross section
  - ν_μ CC π^+ production (CH)
  - ν_μ CC π^+ production (Fe, Pb)
- Published $\overline{\nu}_\mu$ (ν_μ) CC π^+ (π^-) coherent production (CH)

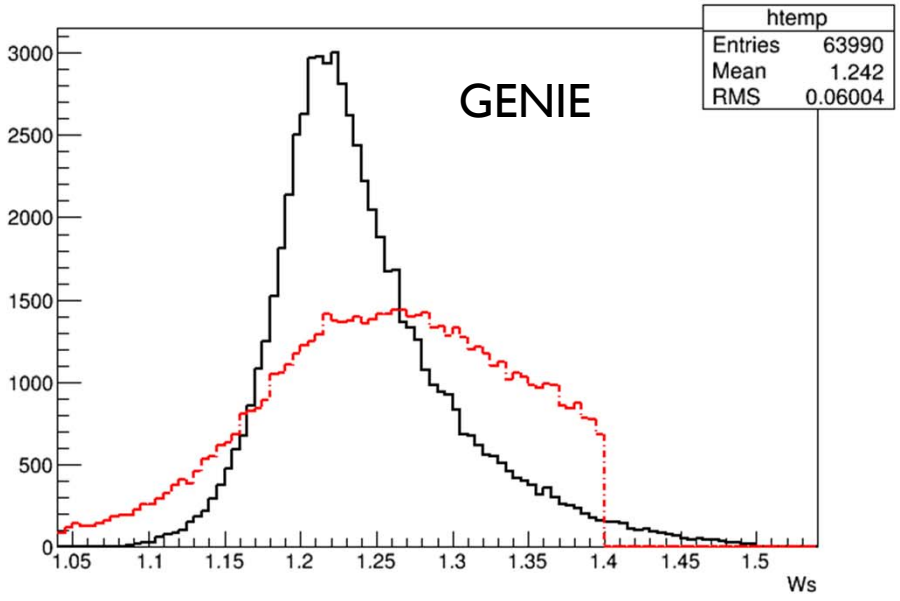
Conclusions

- νA cross section data is very valuable
  - Discrepancies are a necessary evil
  - MiniBooNE and Minerva data give different messages
    - Why are shapes so different? Are they that different?
    - Why is energy dependence wrong? Is there a problem with normalization?
  - Without more understanding, oscillation expts will need new systematic.
  - Work is planned to better integrate MiniBooNE and Minerva data
- New π production cross section data (A dependence!)
  - Minerva (CH, Ar, Fe, Pb)
  - T2K (CH, O)
  - MicroBooNE (Ar)

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.

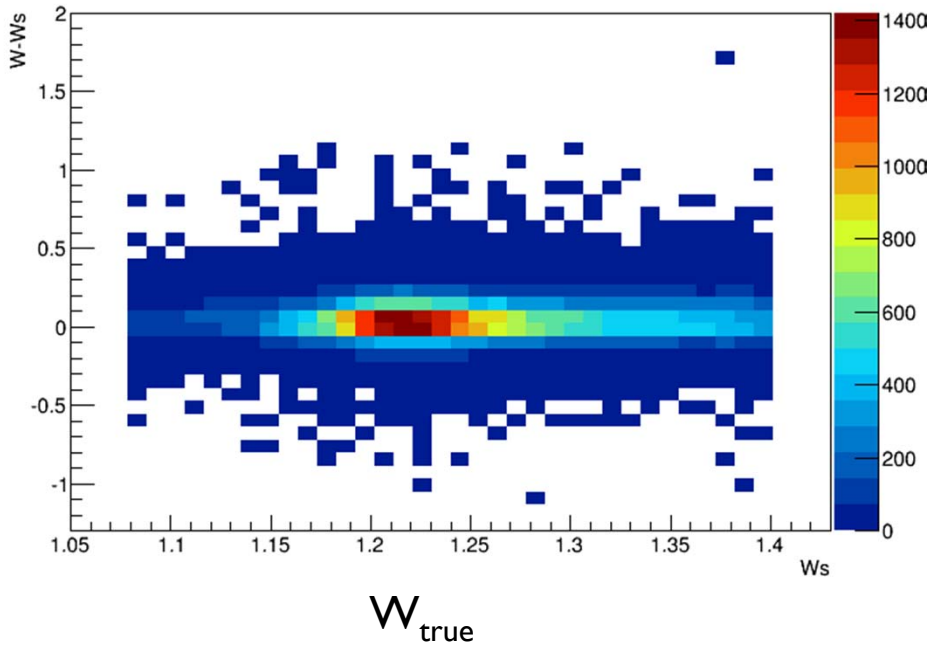


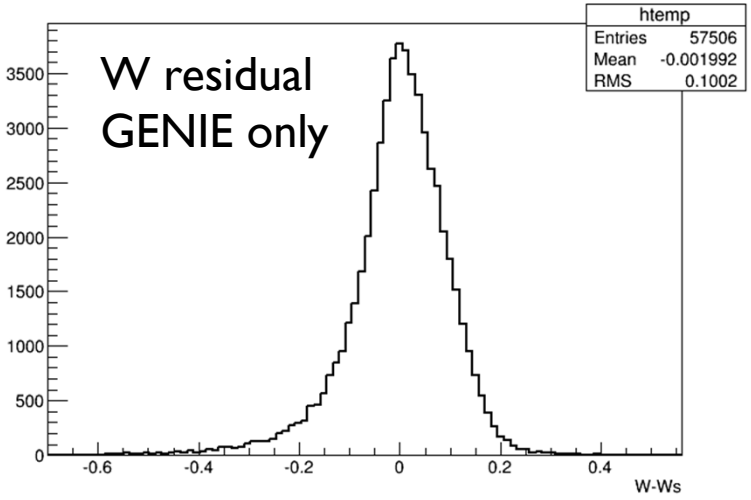


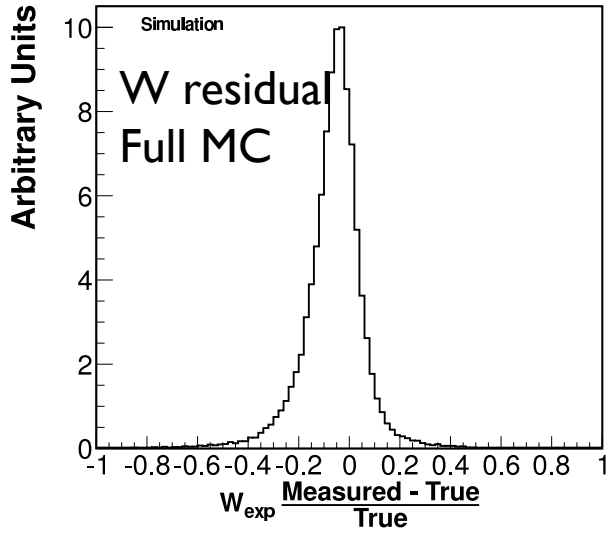
Study of MINERvA W cut

- 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.

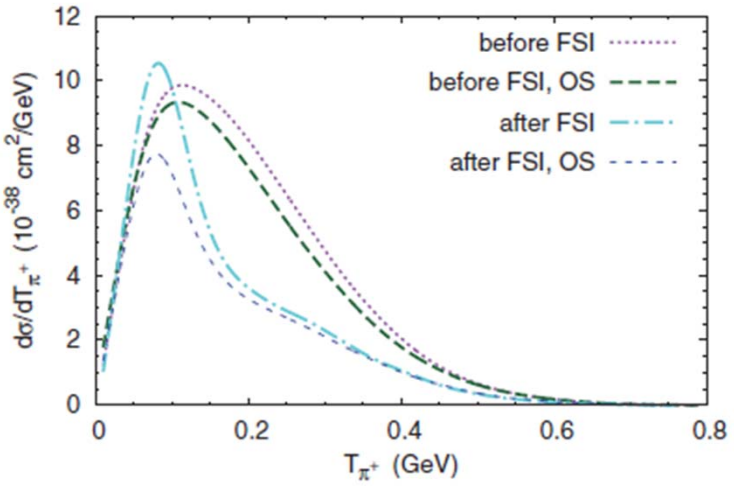
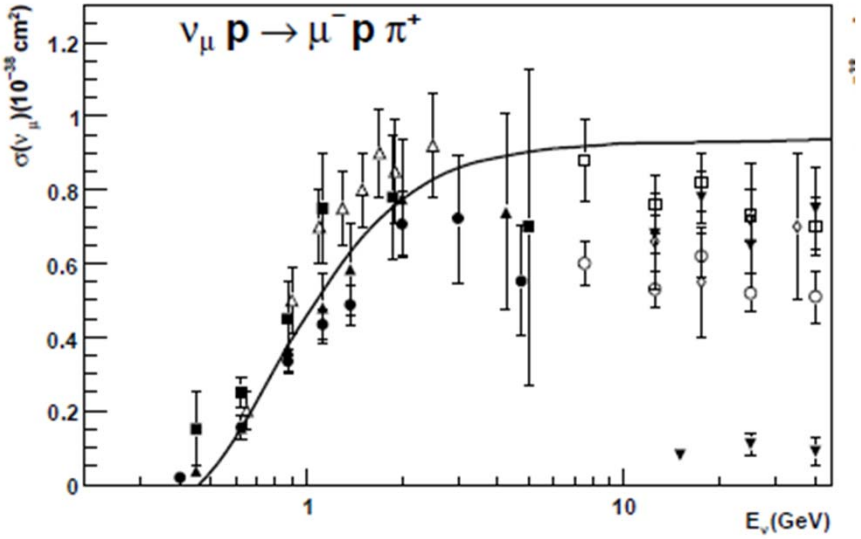
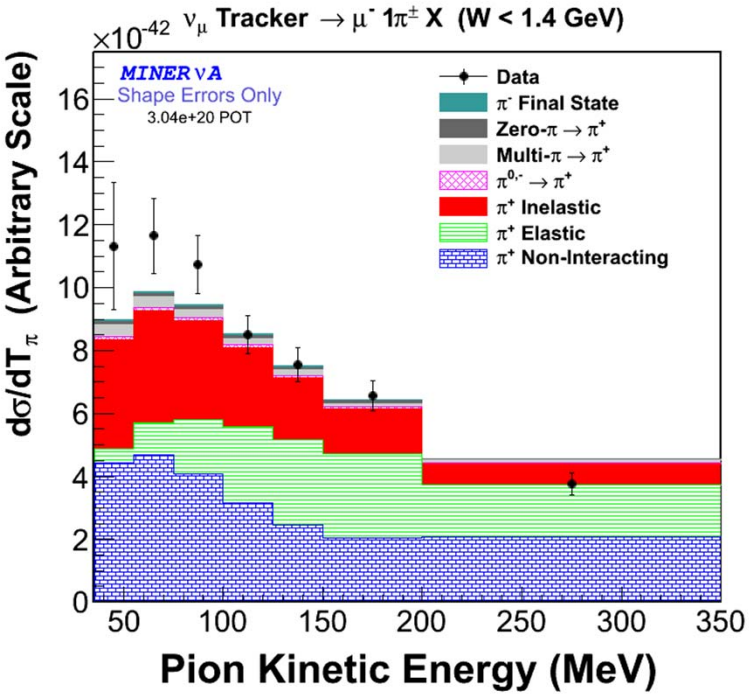


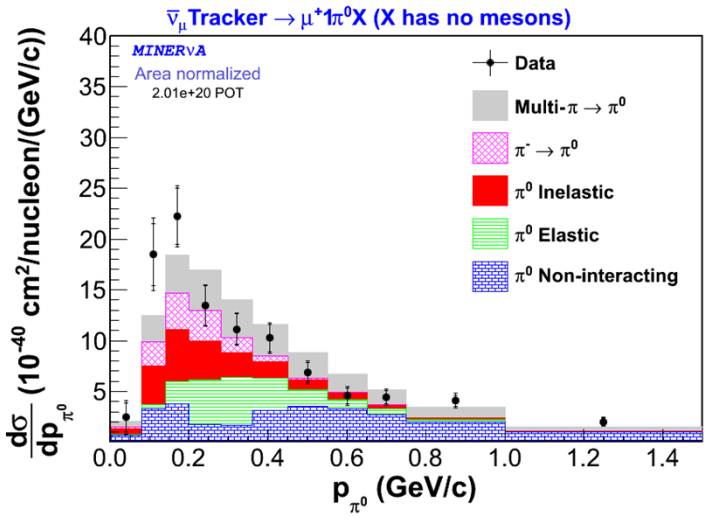
FIG. 13. (Color online) Kinetic energy distribution of π^+ produced in neutrino scattering off carbon through the weak production of the Δ resonance and its following decay. The neutrino energy is $E_\nu = 1$ GeV. The curves labeled OS were obtained using the in-medium collisional width of the Δ from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



Dig deeper into FSI (MINERvA)

- Data are sensitive to pion prod xs, medium effects; however, FSI is largest effect.
- Data for π^+ dominated by Δ, less so for π^0.





Role in experiments

- Every MC run is event generator + detector simulation
  - Design experiments – establish ability to get to goals
  - Design cuts to get close to final spectra
  - Provide estimates of background, means for subtraction
  - Provide estimate of important sources of systematic error

- *Many neutrino experiments have incomplete coverage of final state, so Monte Carlo is very important.*
- *Serious problem when event generator prediction doesn't match data.*

Comparison of event generators
(apologies for errors in fact, judgment)

- NEUT
  - Good - Excellent job for T2K through NIWG, systematic evaluation against MiniBooNE data, very good use of collaborators
  - Room for improvement – tied to T2K, how do we use their work?
- NuWro
  - Good – close attention to theory, great advice to expts
  - Room for improvement – code linkage to expt (e.g. releases)
- GENIE
  - Good – excellent code for expts, excellent organization in development, good ties to theory/FNAL.
  - Room for improvement – ties to theory and expt should be improved, need more dedicated workers
- Unexpected surprise – we are all training young people