Review of neutrino Data/Theory

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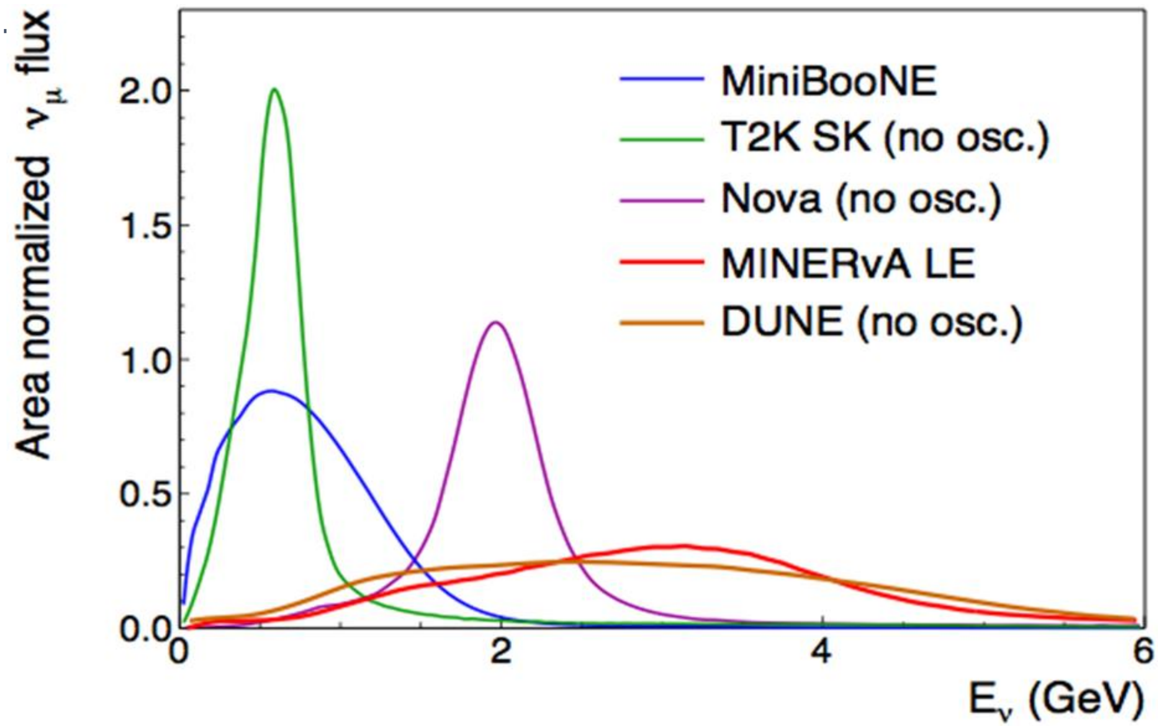
Emphasis on resonances

4 October, 2019

- Existing ν data is sparse
  - ❑ Low statistics for nucleon and nuclei
- Calculations start with electron scattering, add axial from sparse neutrino data
- Generators use simplified versions of theory

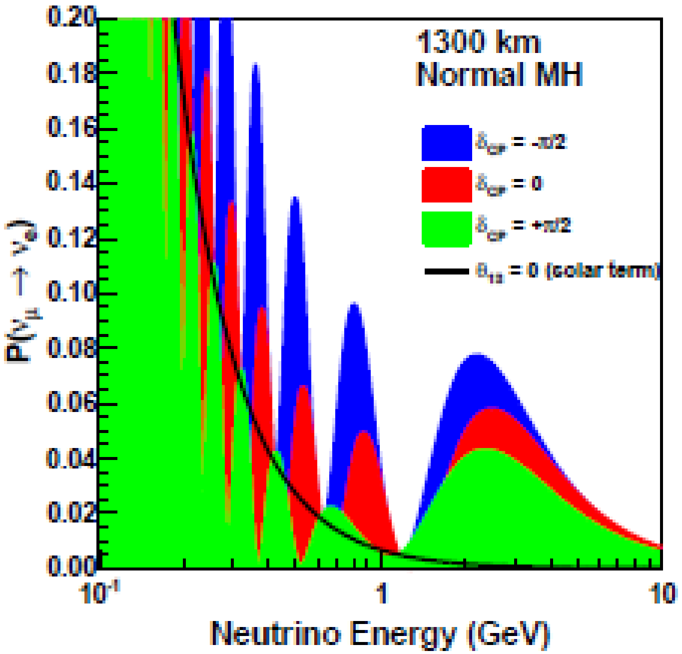
Data overview

- Effort for quasielastic data/theory significantly larger than for resonances
  - More recent experiments at low energy (T2K, MiniBooNE, MicroBooNE)
  - T2K uses QE as signal
- NOvA, MINERvA are running at higher energies
  - DUNE matches these expts better
  - Sensitive to Res/DIS signal



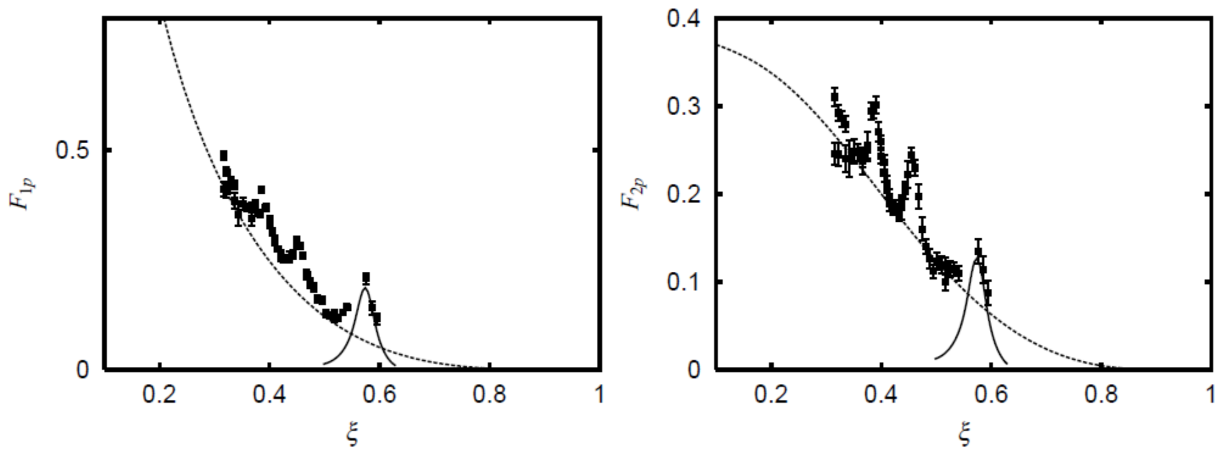
DUNE requirements

- Detect pions, protons, neutrons, etc. with enough accuracy to get neutrino energy accuracy of a few %
- Response will largely be resonances, dis processes
- Method will likely be calorimetric reconstruction



Deep Inelastic (DIS) properties

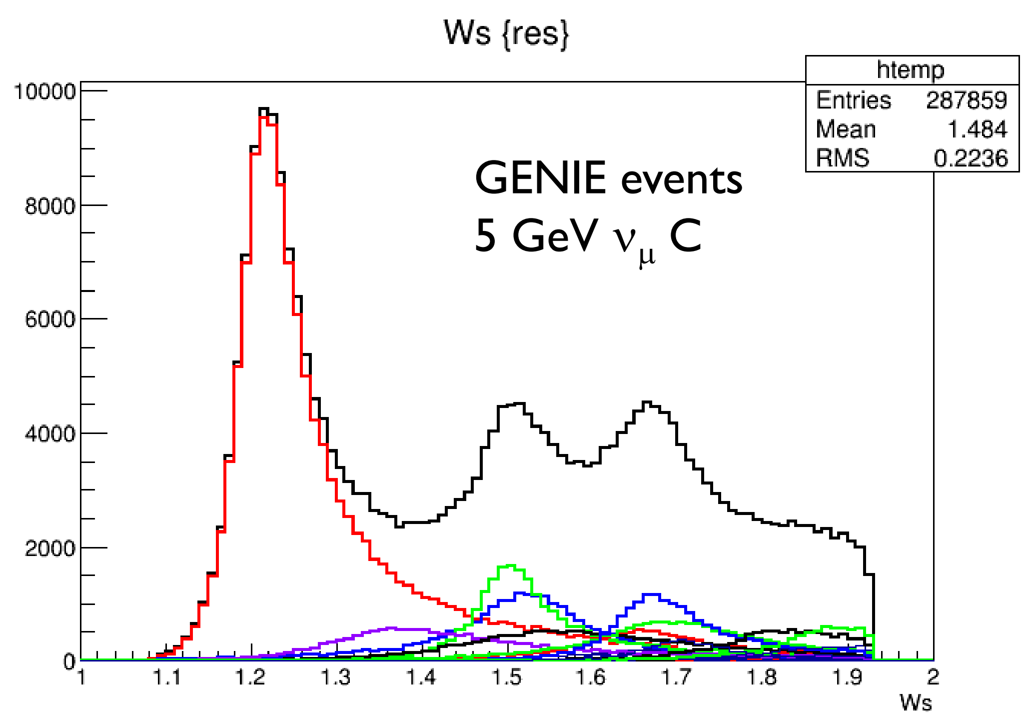
- Need neutrino PDFs and hadronization
- Subject of NusTec workshop last fall
- Very active discussions with the emphasis on understanding existing data and anticipating needs
- This workshop is the counterpart for resonances
- The separation is not well-defined



RES as we know it

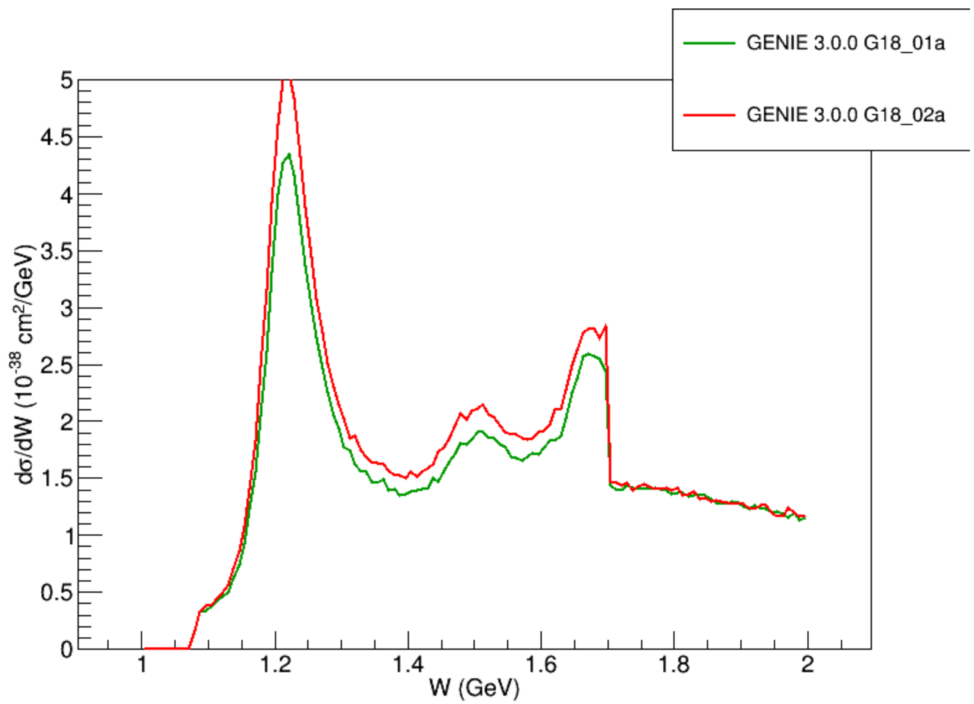
- All based on *electron scattering (modern)* and *Rein-Sehgal 1981*
- PDG summary table on left, GENIE for ν on right
- Can ν validate anything here? (need high statistics D expt.)

N^*	M_R [MeV]	Γ_R [MeV]	β_π
$P_{33}(1232)$	1232	130	1.0
$P_{11}(1440)$	1440	350	0.70
$D_{13}(1520)$	1530	130	0.60
$S_{11}(1535)$	1535	100	0.40
$S_{31}(1620)$	1620	150	0.25
$S_{11}(1650)$	1690	100	0.85
$D_{15}(1675)$	1675	150	0.45
$F_{15}(1680)$	1680	135	0.70
$D_{33}(1700)$	1740	450	0.15
$P_{13}(1720)$	1740	250	0.20
$F_{35}(1905)$	1905	350	0.10
$P_{31}(1910)$	1910	250	0.25
$F_{37}(1950)$	1945	280	0.40



RES vs. DIS

- DIS response comes from quark structure, smooth
- RES is states on top of smooth background
- Theory, e.g. Bodek-Yang, can explain smoothed spectra



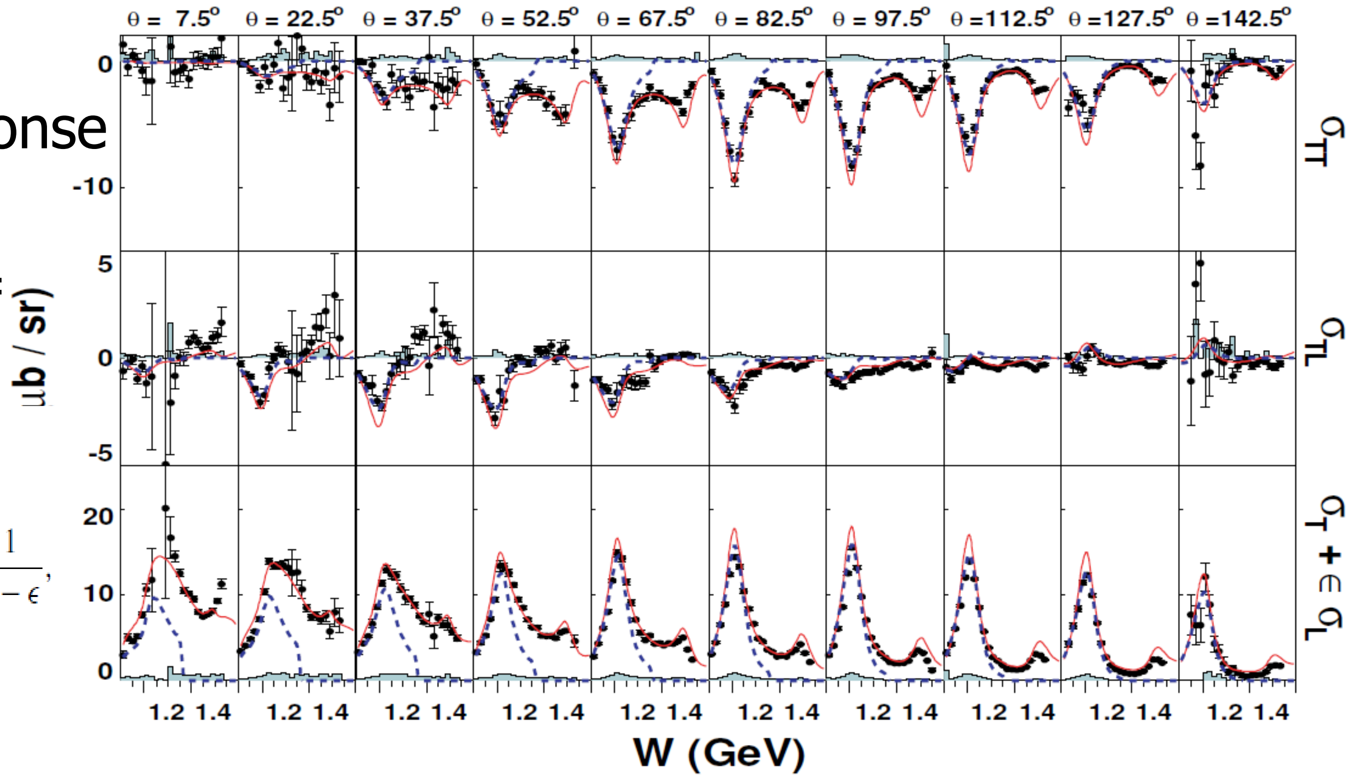
eN for resonances

- Major subject of CLAS for 2000's…
- Added polarized targets in 2010's…
- One example, Egiyan, et al. Phys. Rev. C73, 025204 (2006)
- ep → e'nπ+
- Q^2=0.4 response functions
- N.B. 1μb/sr= 10^{-30} cm^2

$$\frac{\partial^5\sigma}{\partial E_f \partial\Omega_e \partial\Omega_\pi^*} = \Gamma \frac{d\sigma}{d\Omega_\pi^*},$$

$$\Gamma = \frac{\alpha}{2\pi^2 Q^2} \frac{(W^2 - M^2)E_f}{ME_i} \frac{1}{1-\epsilon},$$

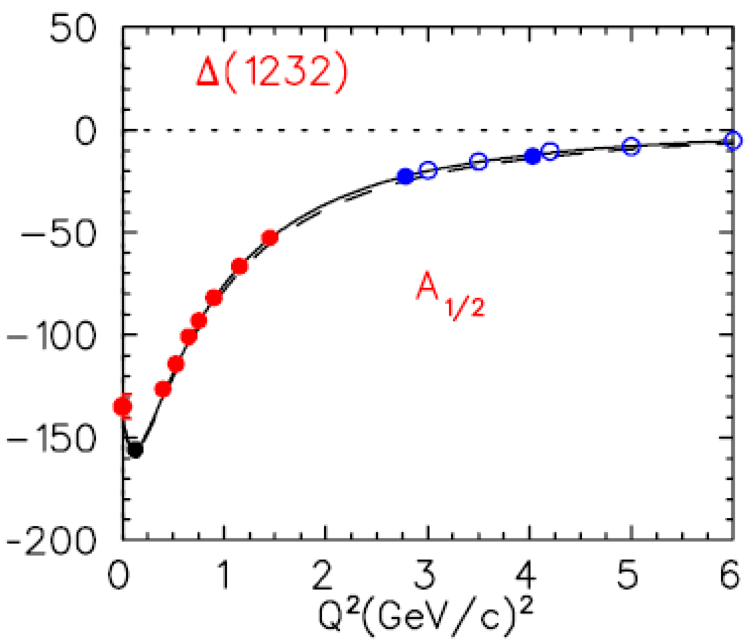
$$\frac{d\sigma}{d\Omega_\pi^*} = \sigma_T + \epsilon\sigma_L + \epsilon\sigma_{TT}\cos 2\phi + \sqrt{2\epsilon(1+\epsilon)}\sigma_{TL}\cos\phi,$$

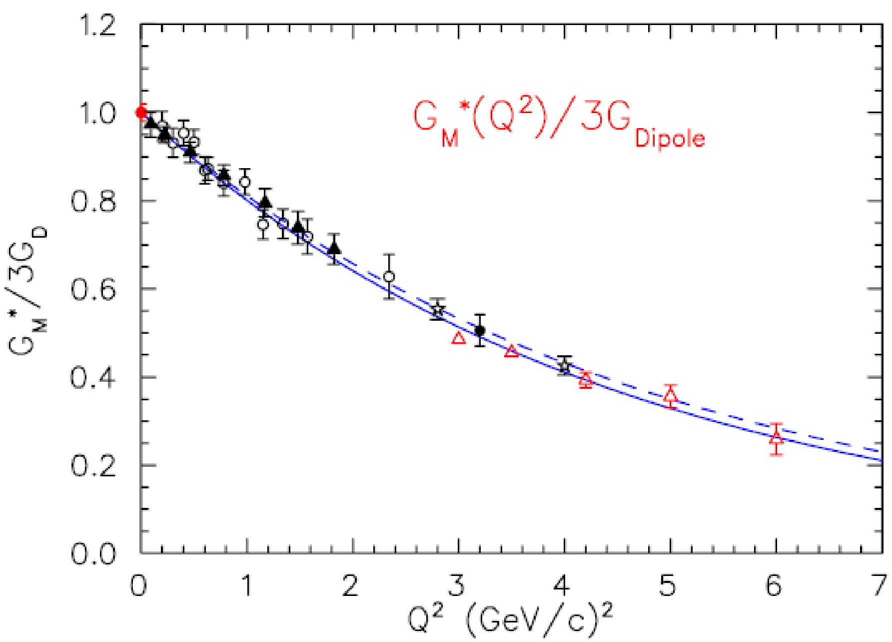


MAID- Unitary Isobar Model

Drechsel, Kamalov, Tiator - Eur. Phys. A34, 69 (2007)

- Breit-Wigner resonances with nonresonant amplitudes
- Resonant/nonresonant amplitude interference
- Fit all (e,e′π) N data to extract helicity amplitudes for **13 resonances** – can be matched to Rein-Sehgal formalism



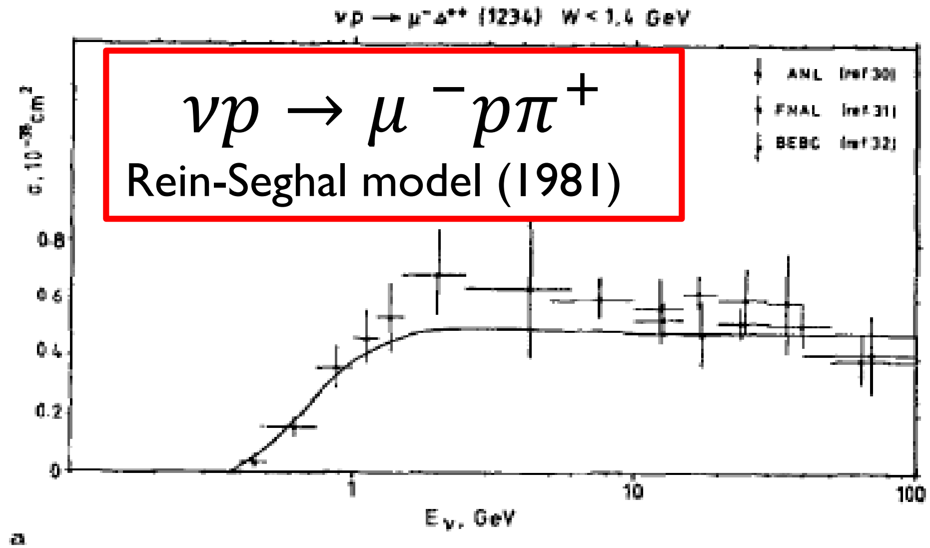


Bubble Chamber data

- Summarized nicely in Rein-Sehgal (RS) (1981)
  - π^+, π^-, and π^0
  - Basis of their model (ANL, not BNL)
- Many complaints about this – "old and out-moded"
- Knowledge about resonances/non resonant bkgd has greatly improved since 1981!!
- Electron scattering experiments (my emphasis long ago) have fantastic statistics/interpretation on many targets
  - Masses, widths, **photocoupling** (Jlab) greatly improved
- Nonrelativistic quark model is no longer important
- Dividing line between resonances/DIS remains in dispute

Bubble chamber data (Rein-Sehgal)

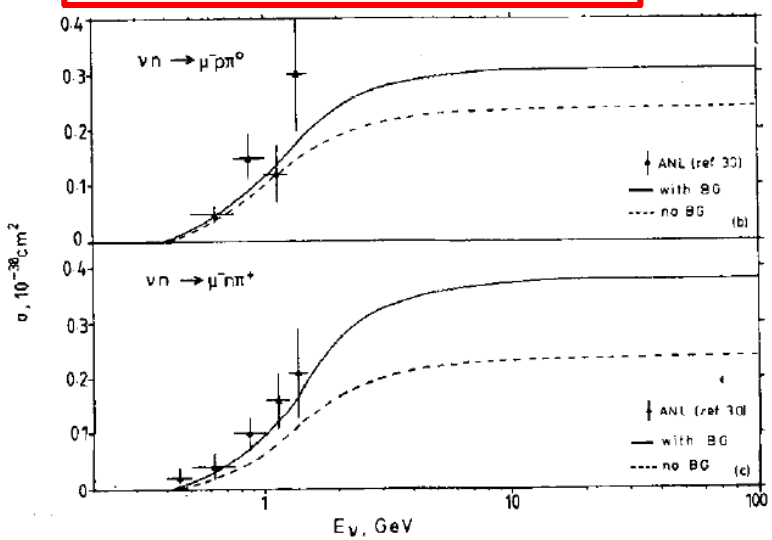
- Total cross sections still best available
- Low statistics, excellent channel identification

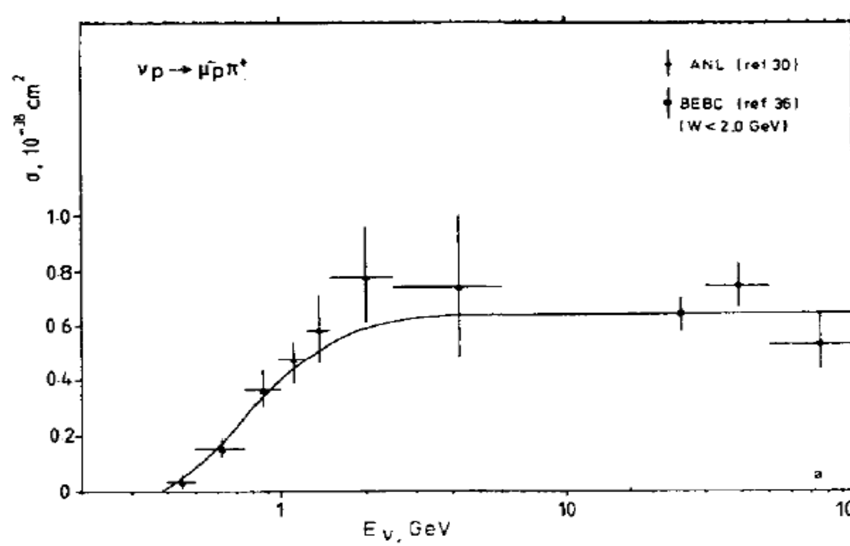


$$\nu p \rightarrow \mu^- p \pi^+$$

Rein-Seghal model (1981)

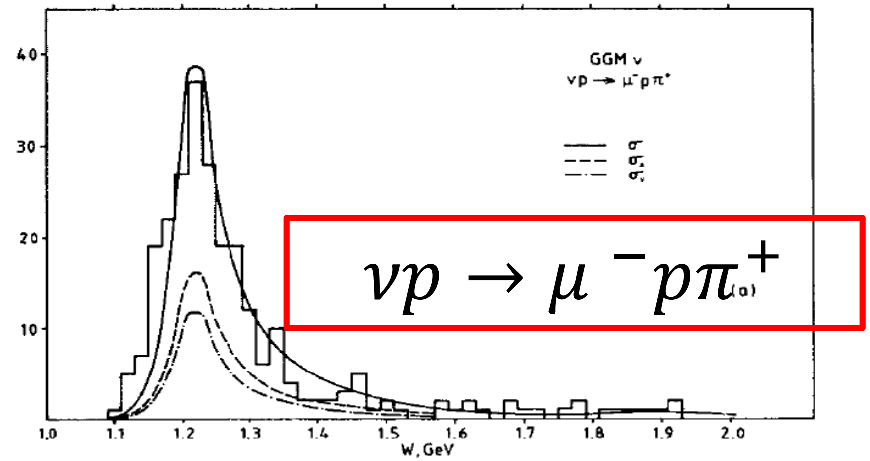
$$\nu n \rightarrow \mu^- p \pi^0$$
$$\nu n \rightarrow \mu^- n \pi^+$$

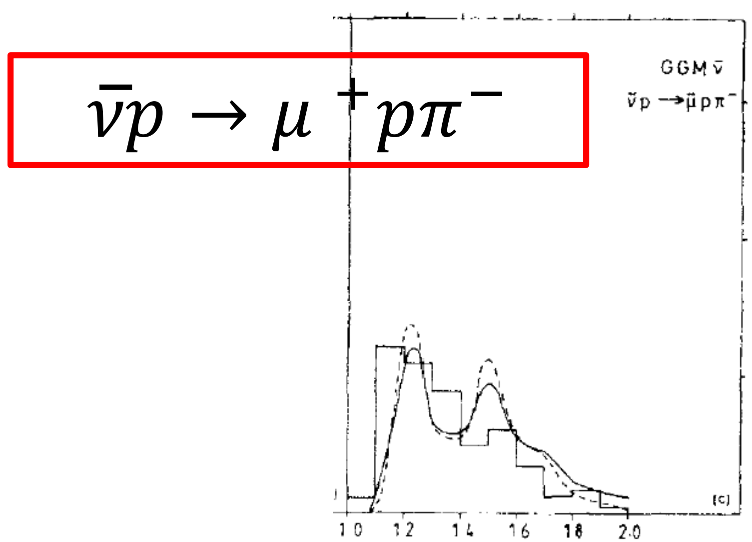


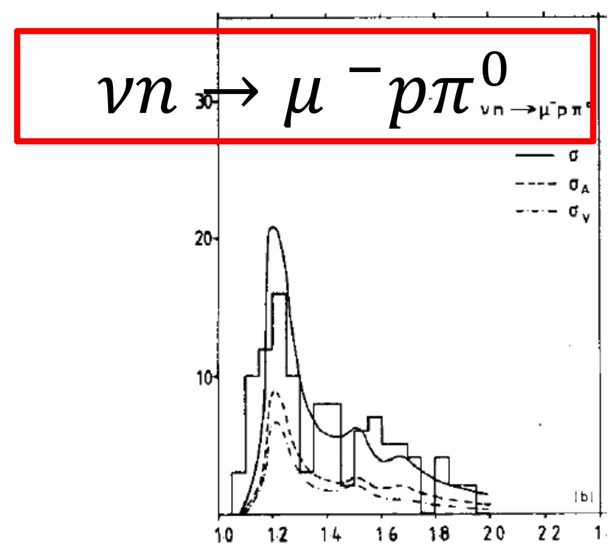


W spectra (GGM ν, ν̄)

- These are from Rein-Sehgal paper (1981)
- ANL but not BNL then

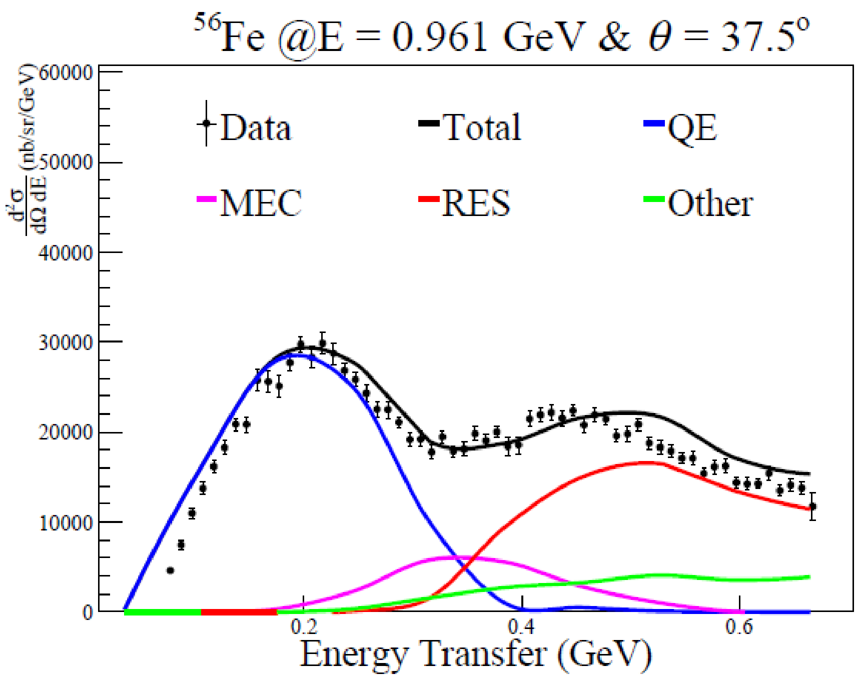


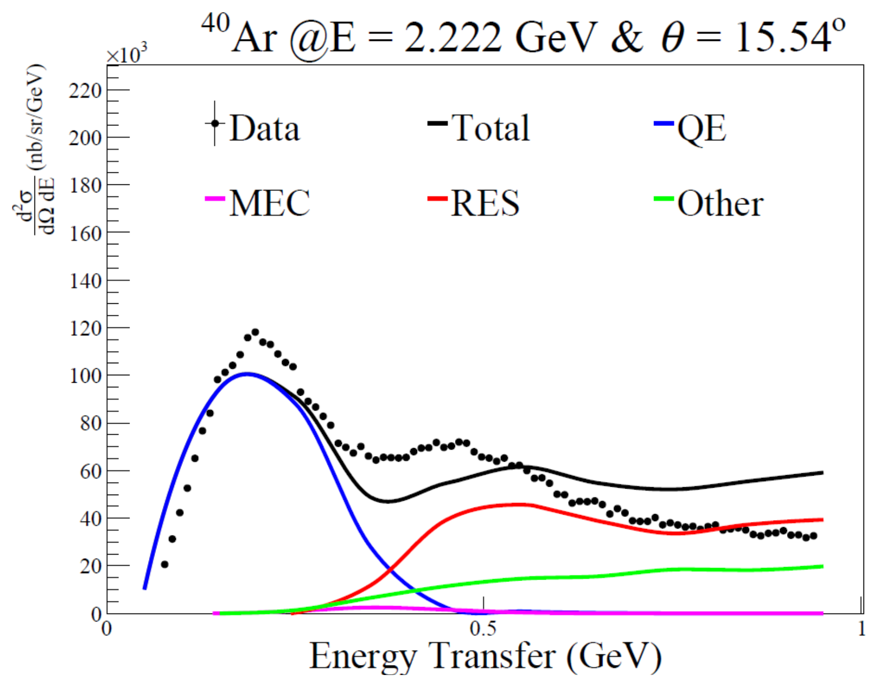




Electron scattering - nucleus

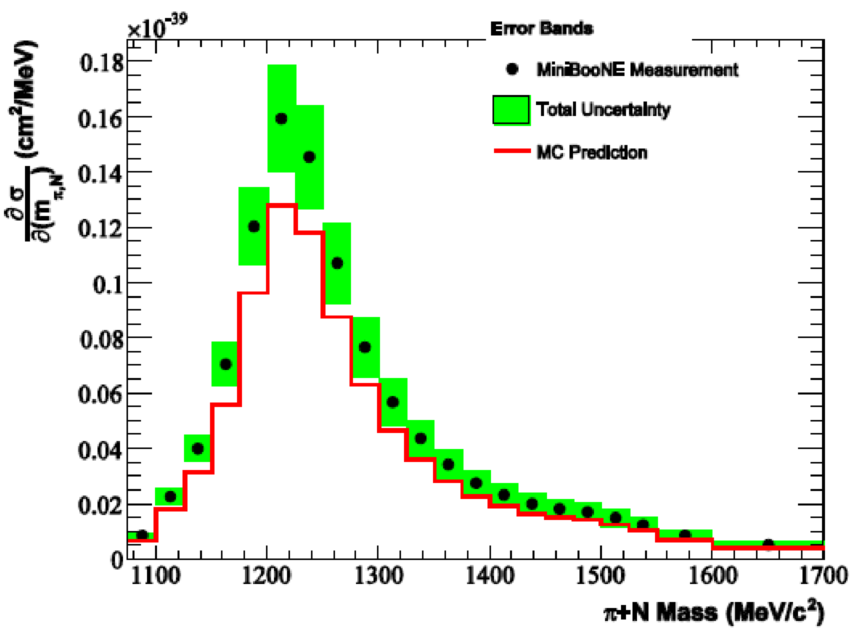
- Huge database for (e,e'), all of it in GENIE. Adi and Afro have been using it heavily. Lots for C, Ca, Fe, and Pb.
- New data from JLab for Ar target (VT group)
- Much less (e,e'p) (collect!), no (e,e'π) (important meas!)

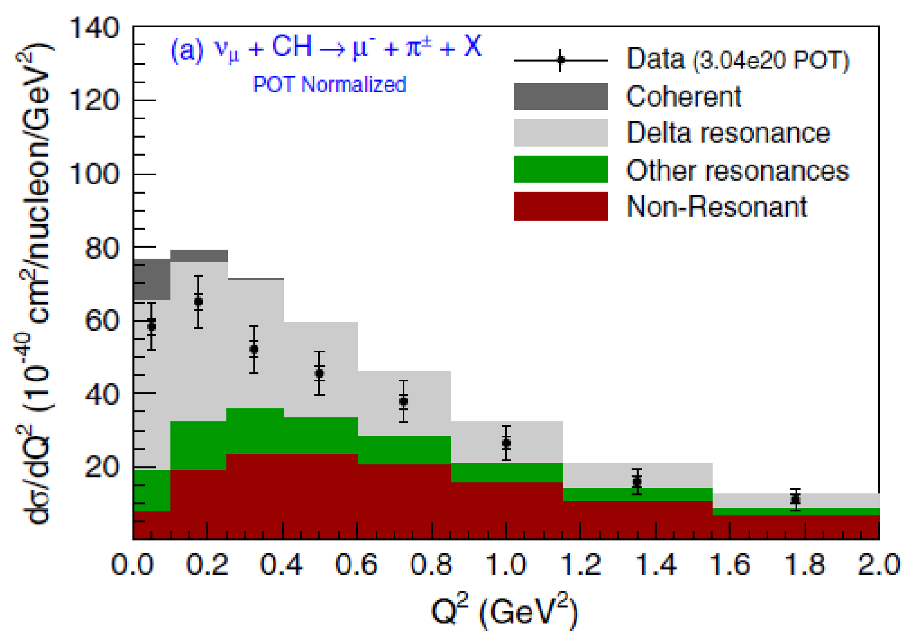




Many recent νA experiments

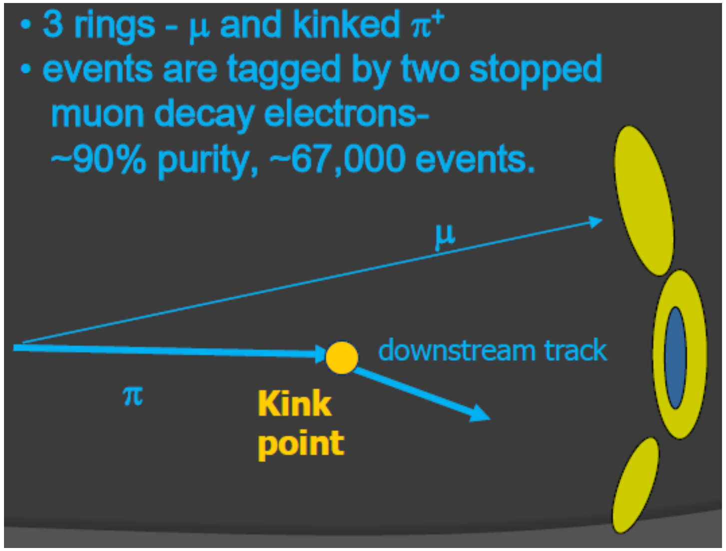
- MiniBooNE (2011) had excellent statistics, acceptance
  - Dominated by Δ(1232), distributions for muon, pion
- MINERvA (≥2015), T2K (≥2018) have fewer statistics
  - Mixture of Δ (1232) and higher resonances – also muon, pion
- Argoneut (2018) has argon target, very low statistic

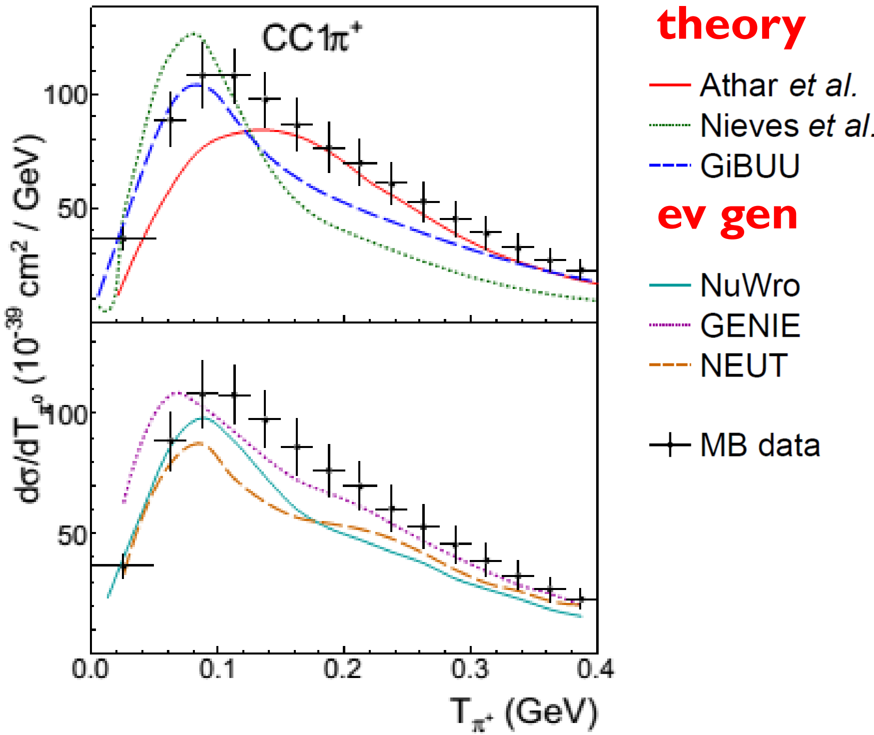




Modern experiments – MiniBooNE <Eν>~1 GeV

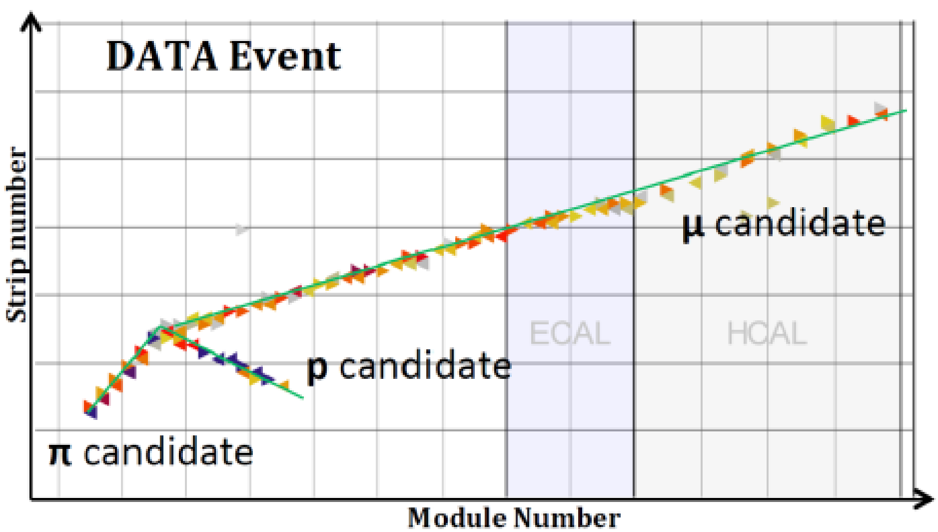
- High statistics, excellent acceptance (CH_2 target)
- Muons via Cerenkov, also pions via π inelastic reactions
- Fine binning, results for both π and μ, π^+ and π^0.
- Lots of theory interest

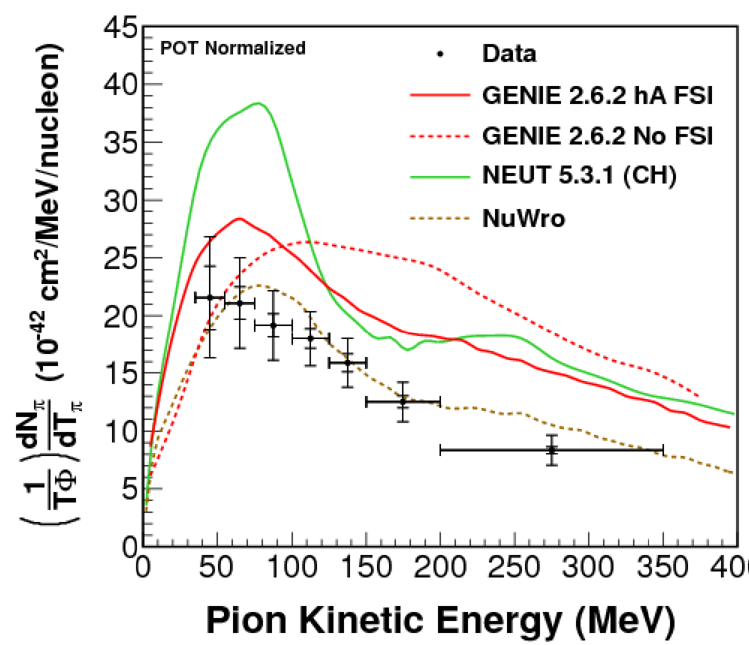




MINERvA LE results ‹Eν›~3.5 GeV

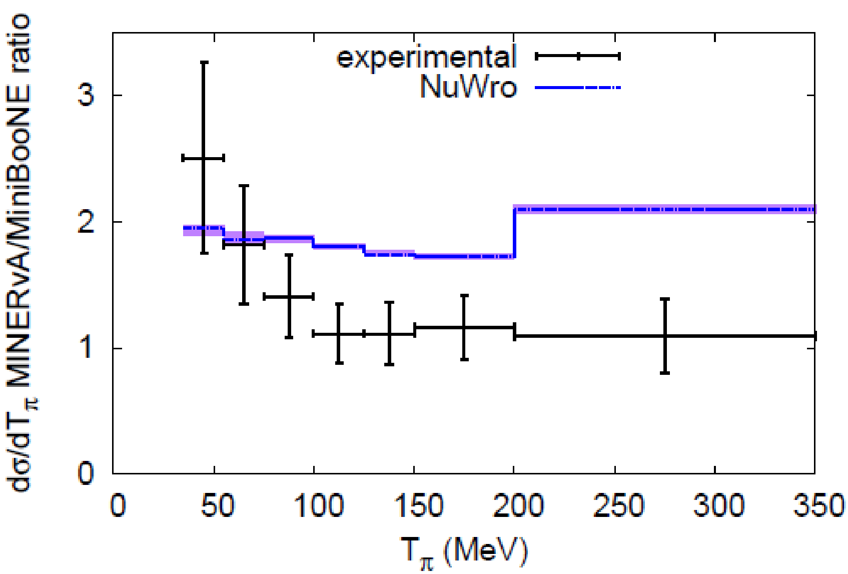
- Finely segmented (~1.2 cm) scintillator tracker (38k bars) CH target (Signal is $\mu^-\pi^\pm$, but π^+ dominates)
- Moderate statistics, very good acceptance
- Michel electron from $\pi\rightarrow\mu\rightarrow e$ decay gives excellent purity

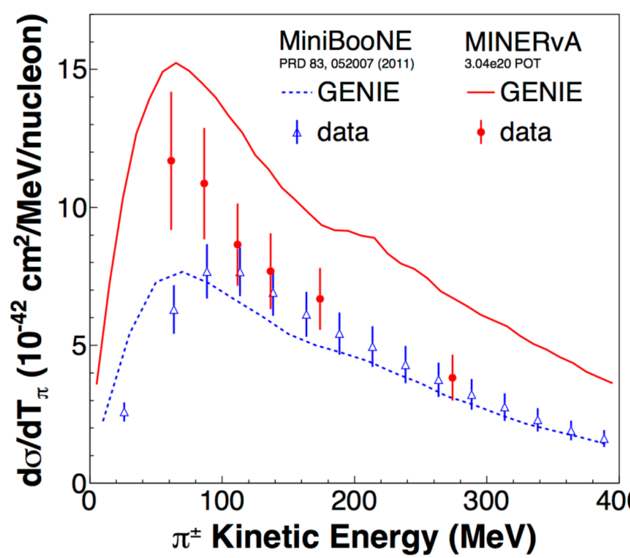




The π^+ puzzle

- Energy dependence not according to theory
  - Dangerous to have 2 measurements
- NuWro and GENIE agree on energy dependence in 2015, not on shape of kinetic energy distribution
- Sobczyk and Zmuda (PRD 2015) see same problem

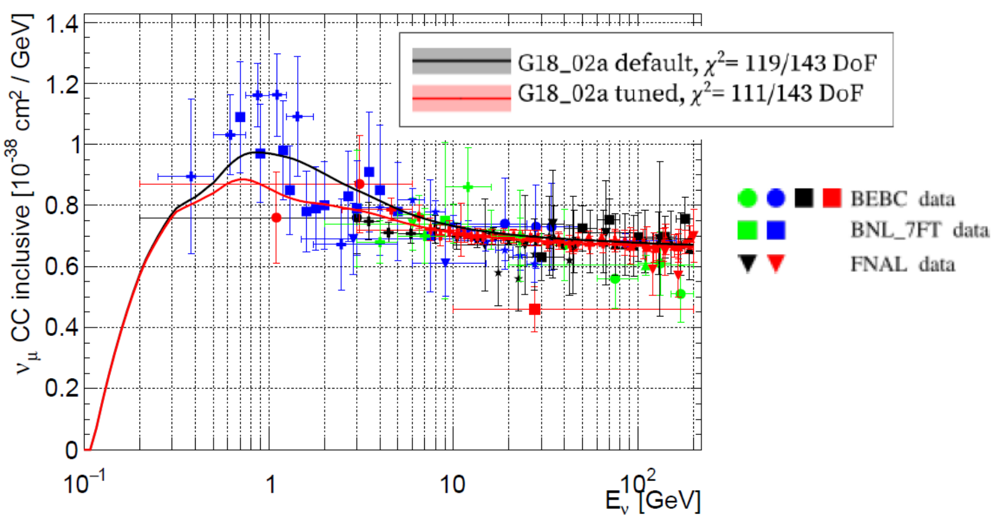




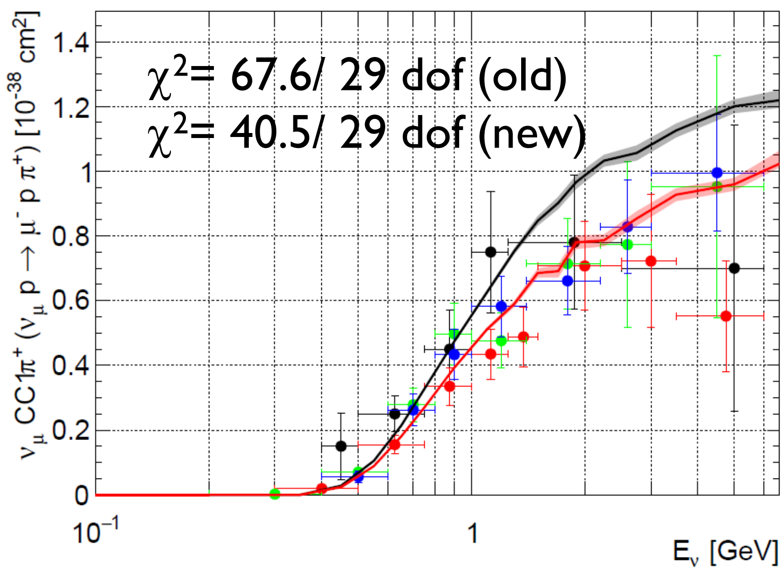
New GENIE deuterium tune

- Old tune emphasized inclusive data, new tune uses both inclusive and exclusive data [tension!]
- Similar to Rodrigues, McFarland, Wilkinson fit, decrease π production
- Data quality shows poor underpinning for the entire field

ν_μ p total cross section

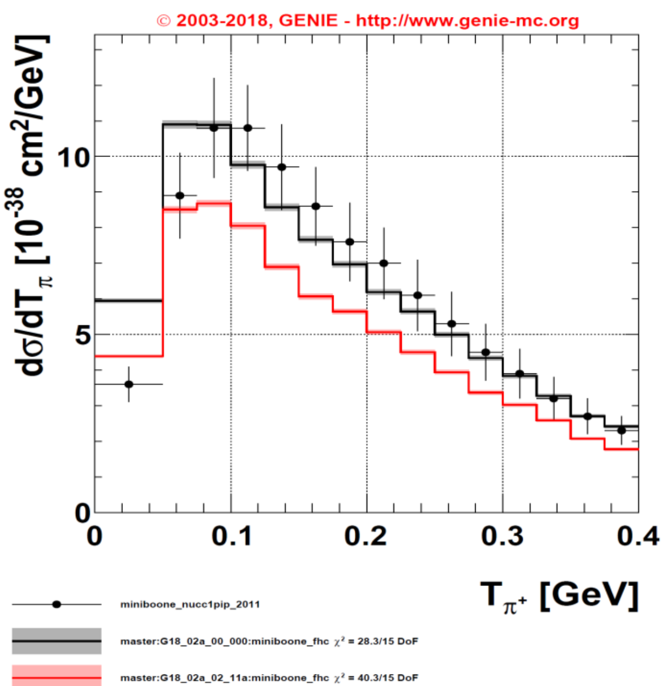


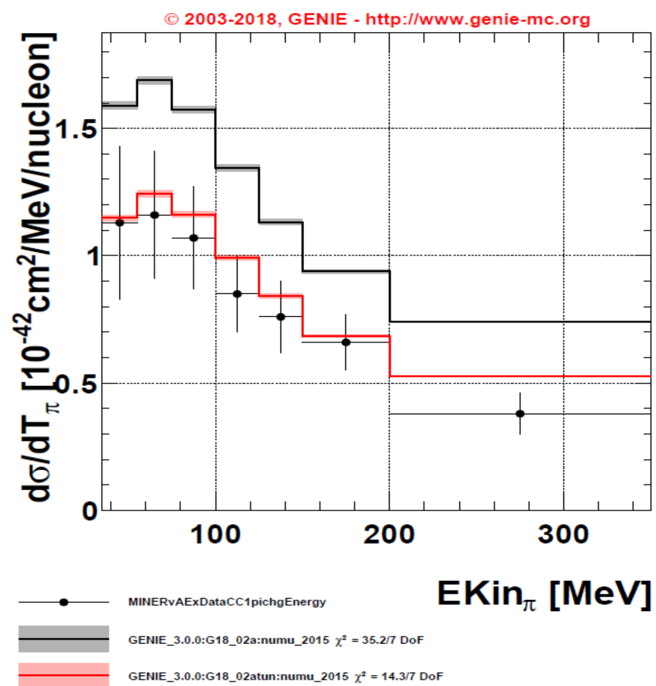
$\nu_\mu\, p \rightarrow \mu^- \pi^+ p$



More recent developments

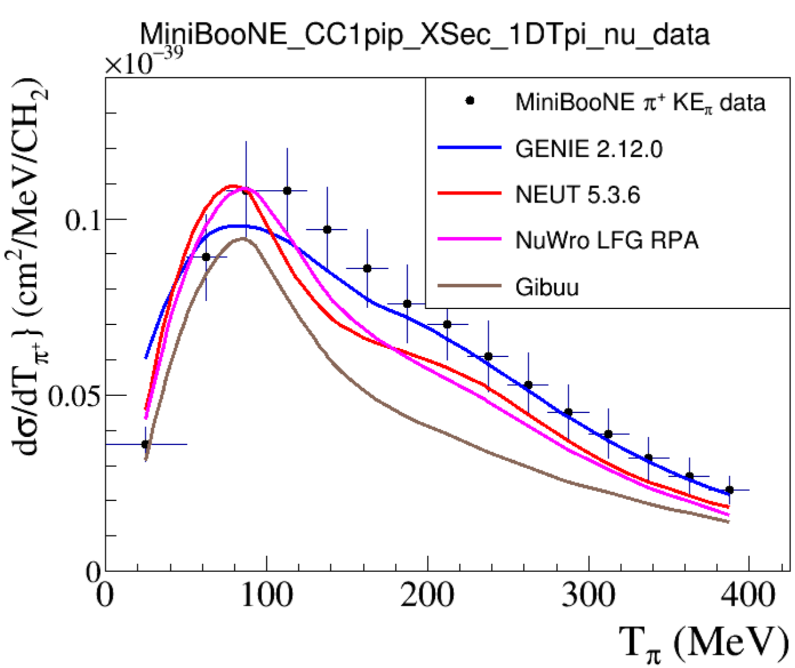
- We discovered differences in data treatment, no issues
- All generators evolve, but tension remains
- GENIE new fit to Δ data decreases all pion calculations
  - **Old tune** agrees with MiniBooNE, new tune agrees with MINERvA

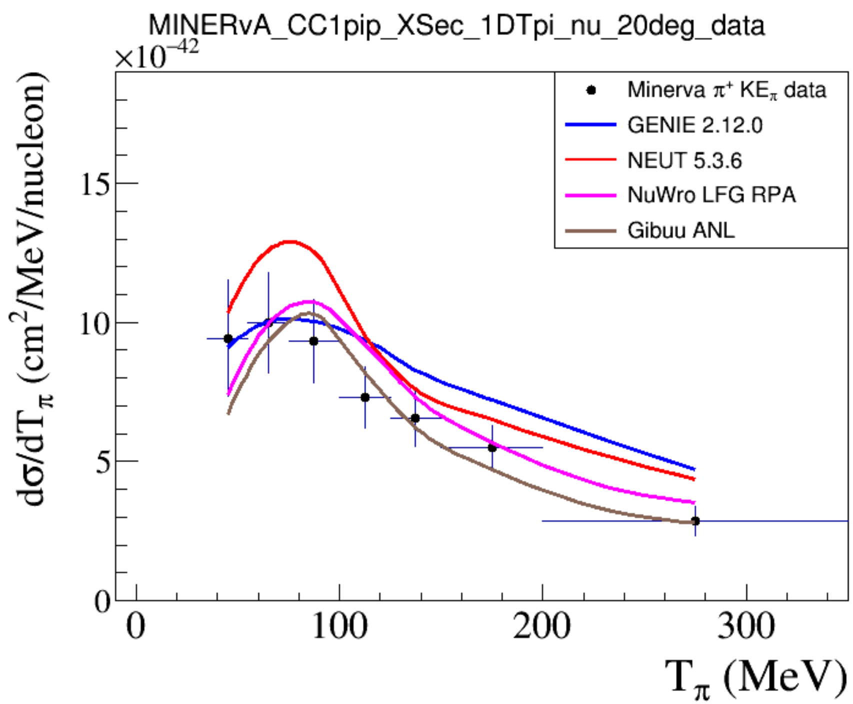




TENSIONS - More global set of comparisons

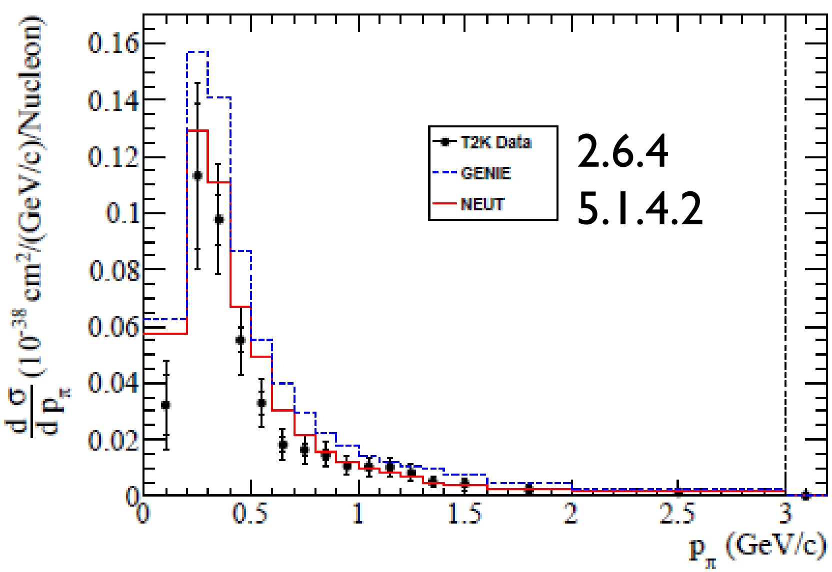
- Workshop in 2016, published Phys. Repts. **773**, 1 (2018)
- Both magnitude and shape discrepancies ~10-20%
- FSI bigger issue than nuclear structure

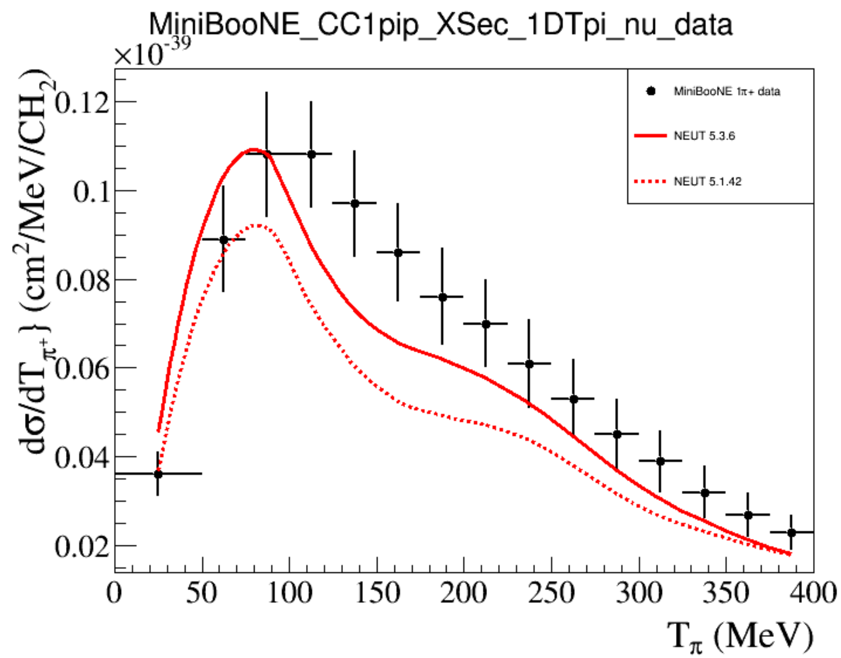




New T2K data - Just accepted in PRD

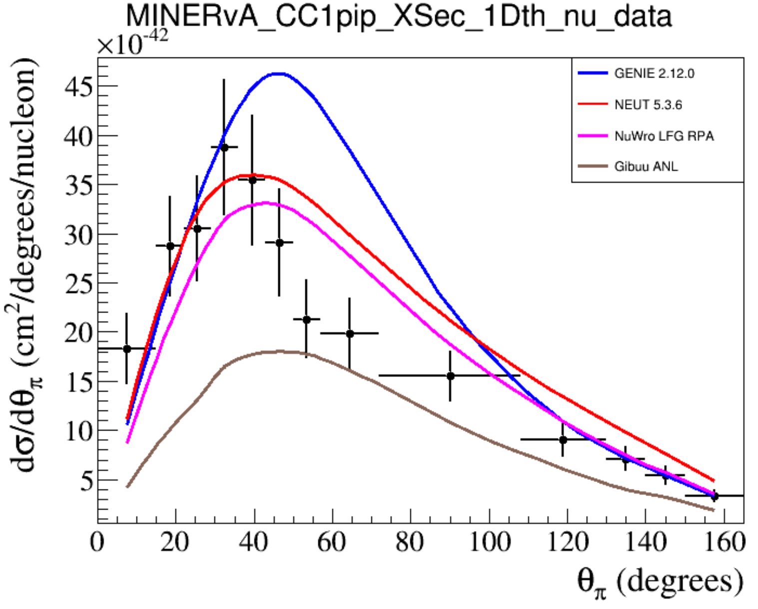
- Compared to (very) old GENIE, NEUT
- published despite no reference to MiniBooNE data!?
- Need generator/Nuisance/Tensions paper for comparison
- Looks like T2K is ~same as NEUT 5.1.4.2 which is below mB, therefore in better agreement with MINERvA from E dep (got that?)

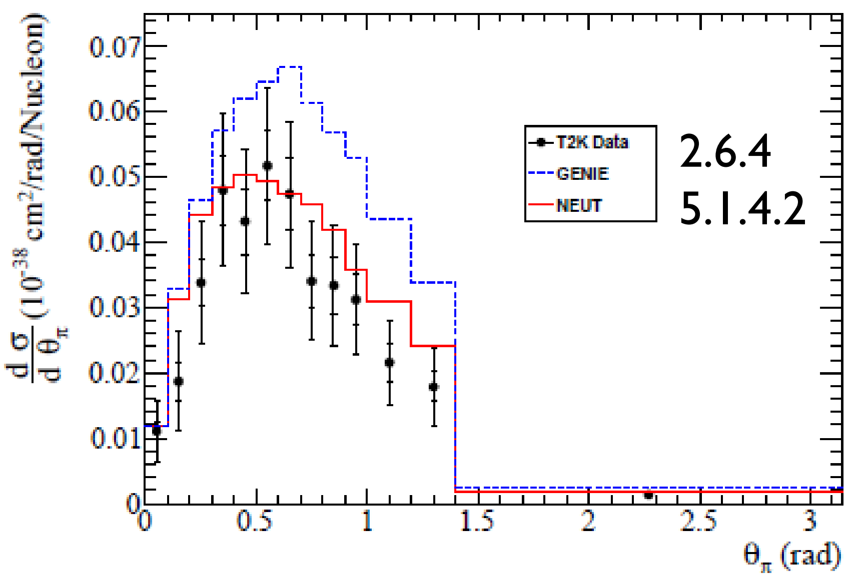




θ_{pion} might also have problems

- GiBUU BNL is better, shape similar to the generators
- modern generators all have isotropic Δ decay, no strong sensitivity seen so far.
- TENSIONS-2016 comparison (L), T2K 2019 (R)
- Could be a problem for only MINERvA, also seen in 2019 π^- paper



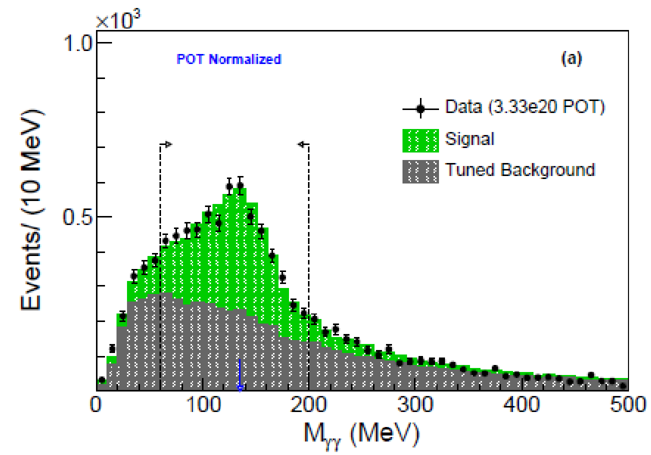


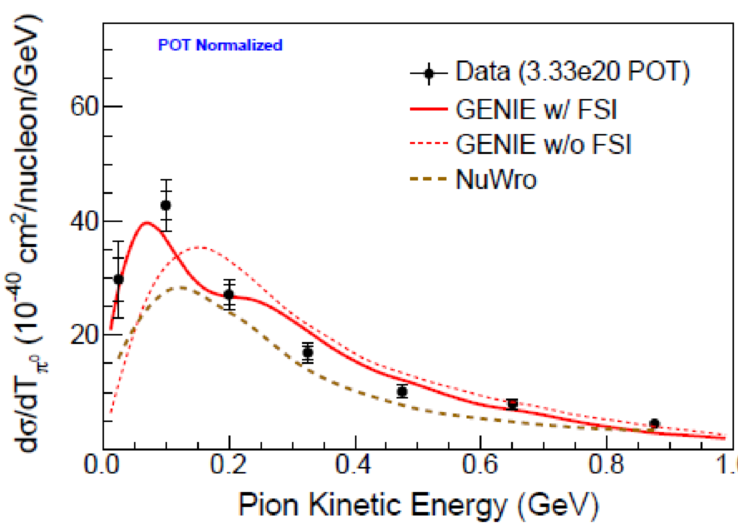
Relevant published work from MINERvA

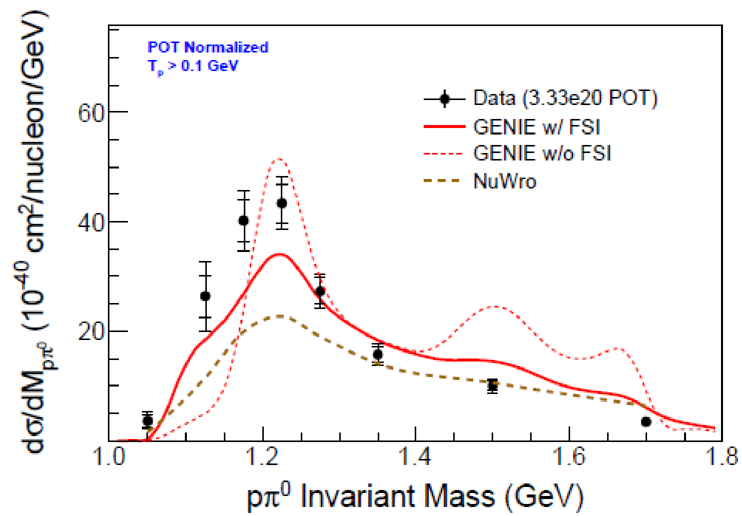
- B. Eberly et al. (MINERvA) Phys. Rev. D92, 092008 (2015)
  - ν_μ CH $\to \pi^\pm$ X (no π^0, no baryons) W_{true}<1.4 GeV, <1.8 GeV
  - Signal definition using W_{true} causes model dependence
- C.L. McGivern et al. (MINERvA) Phys. Rev. D94, 052005 (2016)
  - ν_μ CH $\to \pi^\pm$ X (no π^0, no baryons) W_{exp}<1.8 GeV, (<1.4 GeV)
  - $\bar{\nu}_\mu$ CH $\to 1\pi^0$ X (no $\pi^\pm$, no baryons) W_{exp}<1.8 GeV
  - Added muon KE & θ, Q^2, E_ν
- O. Altinok, et al. Phys. Rev D96, 072003 (2017)
  - ν_μ CH $\to \pi^0$ (p)X W_{exp}<1.8 GeV
- Trung Le et al. (MINERvA) Phys. Rev. D100, 052008 (2019)
  - $\bar{\nu}_\mu$ CH $\to 1\pi^-$ X W_{exp}<1.8 GeV
  - Completes a complete set of 4 results

CC π^0 - MINERvA

- π^0 identification isn't easy
  - π^- even harder
  - Purity ~50%
- Reconstruction of W difficult
  - π^0 p invariant mass
- MnvGENIE used here

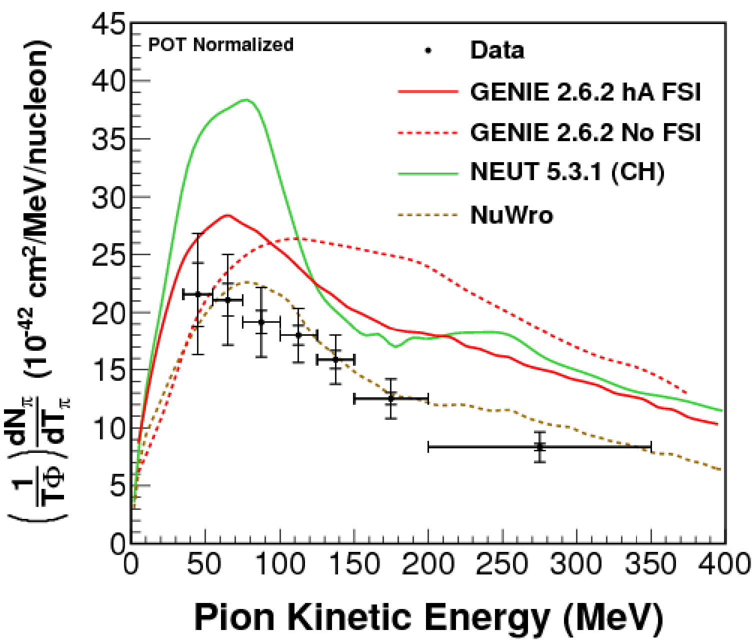


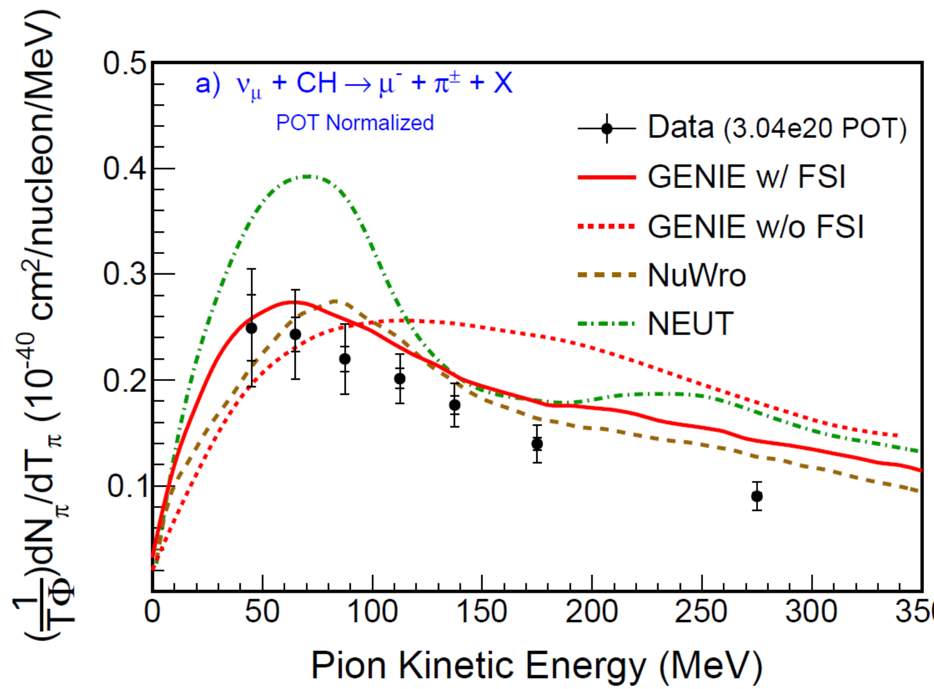




$N\pi^{\pm}$ 2015 vs. 2016

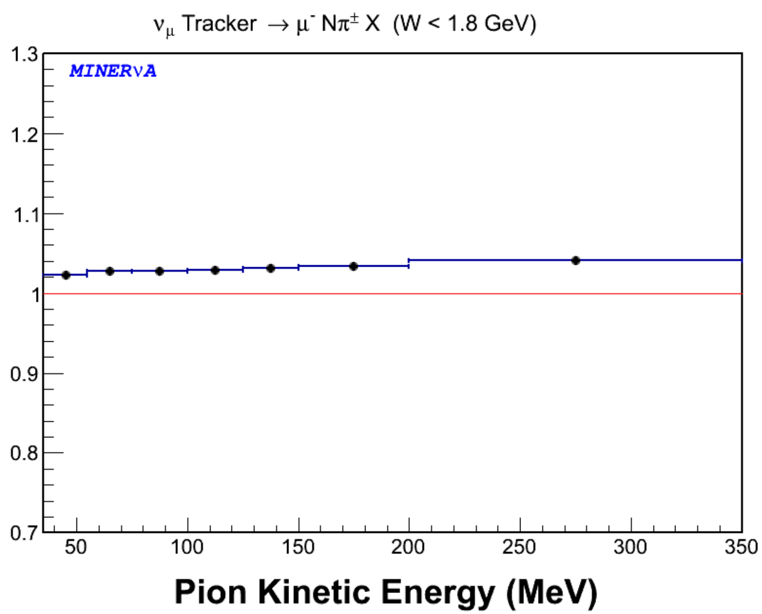
- Same event sample, different signal definition, updated flux
  - W_{exp} instead of W_{true} (~18% larger cross section)
- Updated MC calculations
- Not a true cross section because multiplicity not measured
  - Can be calculated within any model

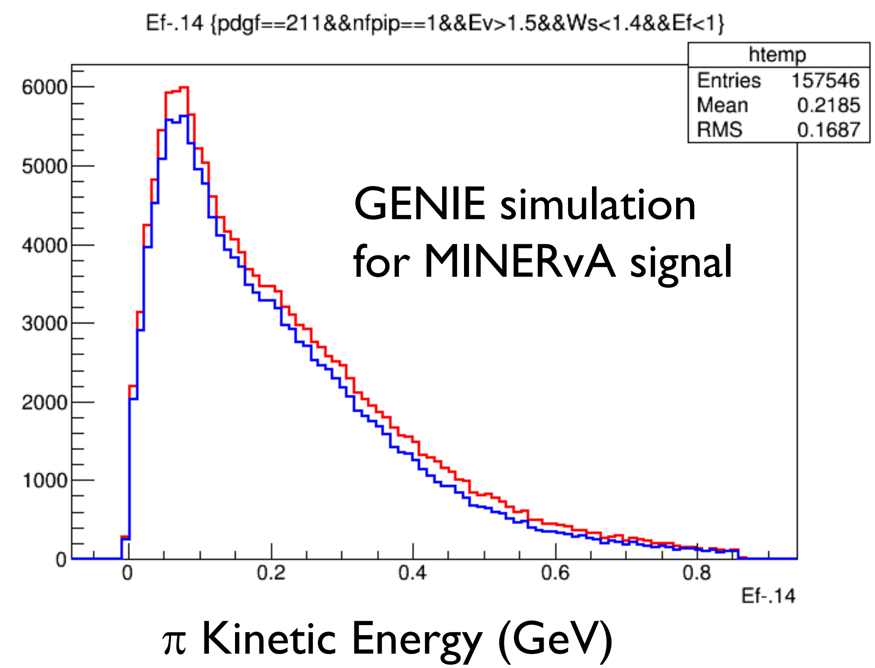




New analysis of Minerva 1$\pi^{\pm}$ data
(really almost all π^{+})

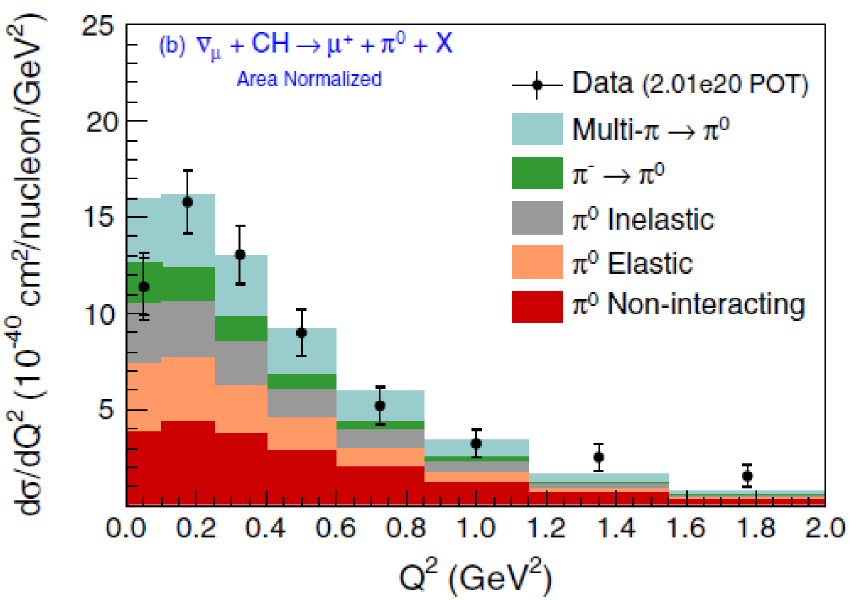
- Improved definition of W in signal – W_{reco}
  - Takes away fear of strong model dependence
  - ~10% decrease in cross section independent of kinematics
- Improved flux (now in all Minerva LE results)
  - ~10% decrease in cross section independent of kinematics
- New data should be used in future,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

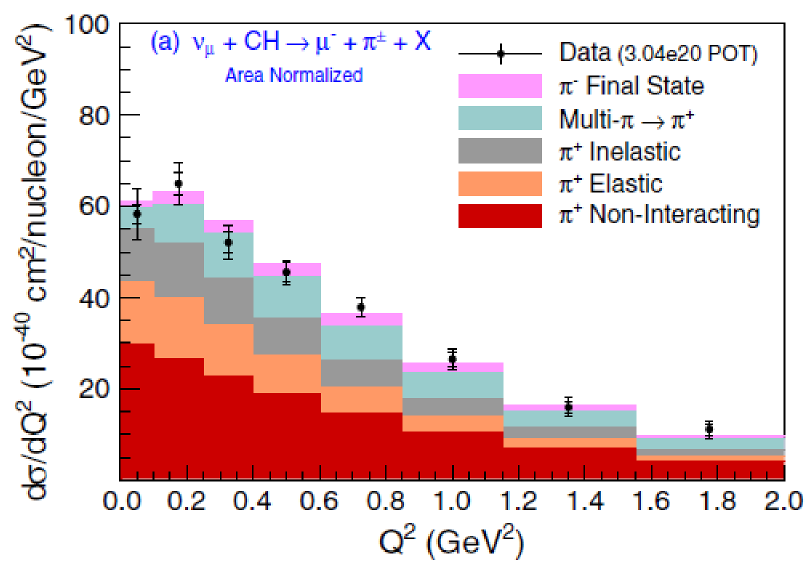




Q^2 detail - FSI decomposition

- CC





Theory of resonances
start with electron and hadron beams

- Long history with hadron and electromagnetic probes
  - Best knowledge of vector interaction by far
- This is subject of Jerry Miller's following talk
  - Sidelight: I first learned about $\Delta(1232)$ from Jerry at CMU ~1973
- Many experiments with single energy beams and very high statistics
- Many theory efforts start with electron scattering (validation of nuclear structure, vector interactions)
- Axial interactions then get added on based on validation with existing data (see earlier slides)
- Generators do their best to keep up with theory (~~easy~~)

Short review

- Valencia (Hernandez, Nieves, Vicente-Vacas)
  - Analytic model for nucleon→nucleus
  - Focus on $\Delta(1232)$, but have also investigated $D_{13}(1520)$
  - Talk this workshop by Juan Nieves
- GiBUU (Mosel, Leitner, Buss….)
  - Monte Carlo well beyond Generators used in experiments
  - Semi-classical calculation that allows medium corrections
  - Talk this workshop by Ulrich Mosel
- MK (Minoo Kabirnizhad)
  - Updates Rein-Sehgal model in significant ways
  - Adds nonresonant amplitudes/interference with resonances
  - Limited to 1π production
  - Talk this workshop by Minoo

Nonresonance/resonance interference

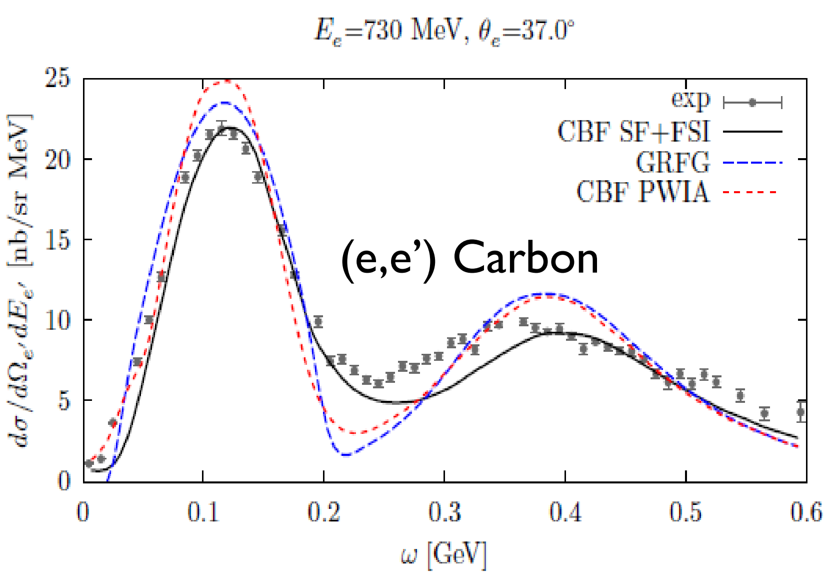
- Since final states are same, interference is natural
- However, this is difficult to include in a Generator (use cross sections rather than amplitudes for random nos.)
- Existing generators add cross sections for NonRes and Res from different sources (ugh!)
- Some resonances interfere, e.g. $S_{11}(1535)$ and $S_{11}(1650)$. Does it matter?

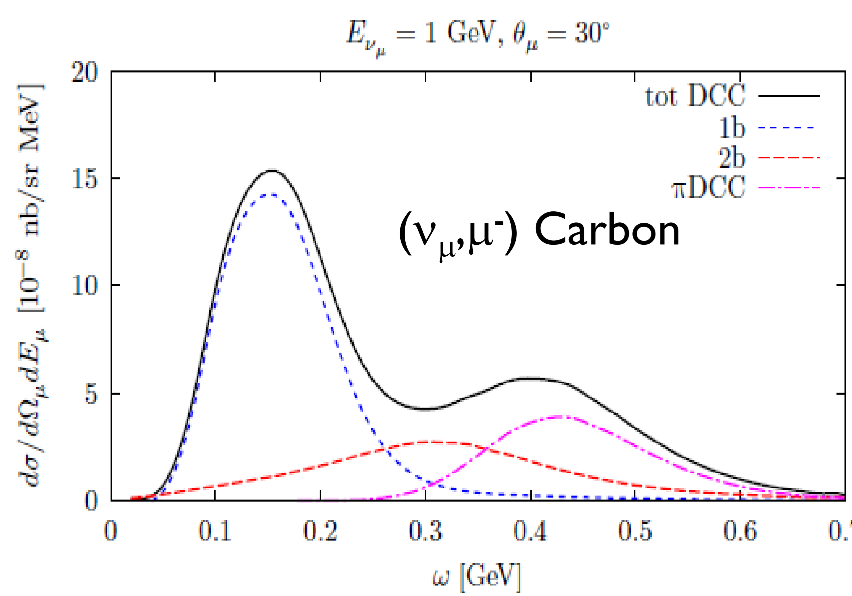
Resonance/DIS mixing

- Calculations done by different communities
- Where is the dividing line?
- How fuzzy is the dividing line?
- If final state is same, do they interfere?
- The resonance picture is more accurate than the DIS picture when you need to look at details of the final state. Which is more important, details or simple picture?

Recent article of interest

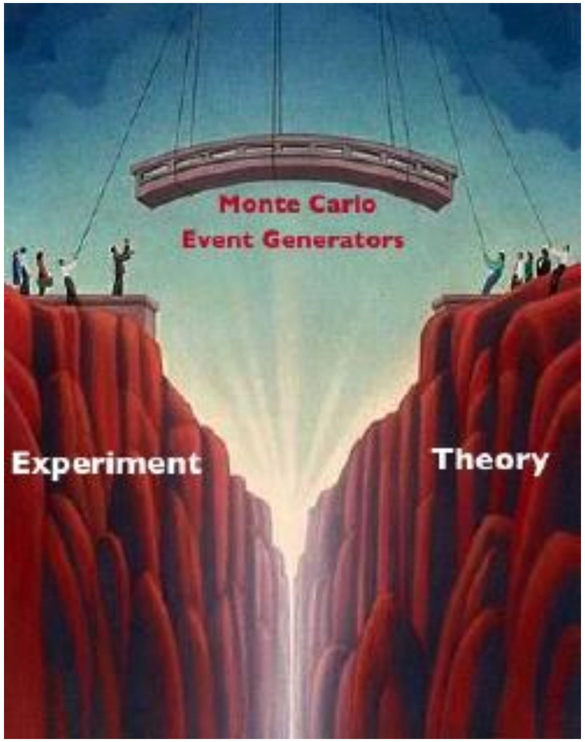
- N. Rocco, S. Nakamura, T.S.H. Lee, and A. Lovato
  - arXiv: 1907.01093[nucl-th]
- Merges nuclear structure of Benhar-Rocco with DCC model of Sato-Lee-Nakamura
- Left: model progression - GRFG= RFG, CBF PWIA adds Spectral Func, CBF+FSI adds FSI
- Right: components for CC – 1 body, 2 body, π production





Generators

- Link between theory and experiment
  - GENIE, NEUT largely experimenters
  - NuWro, GiBUU largely theorists
- Most theory comes from nuclear theorists
  - Gives best picture of nuclear structure, vector interaction
  - Subject to unfortunate barriers in DOE (must be rectified)
- Δ in nucleus well-studied in last few decades
  - Important subject of Jerry Miller



Generators as of 2016 (1st Tensions wkshp)

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

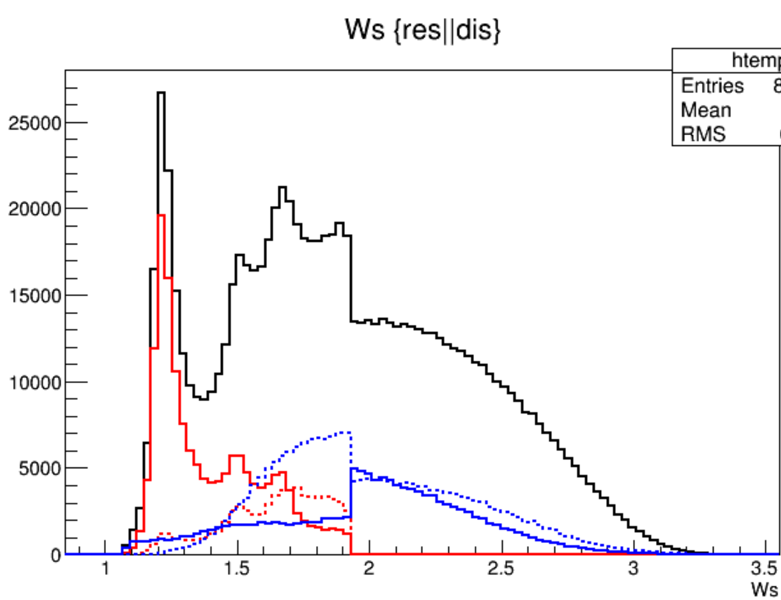
Comparison of models - 2017

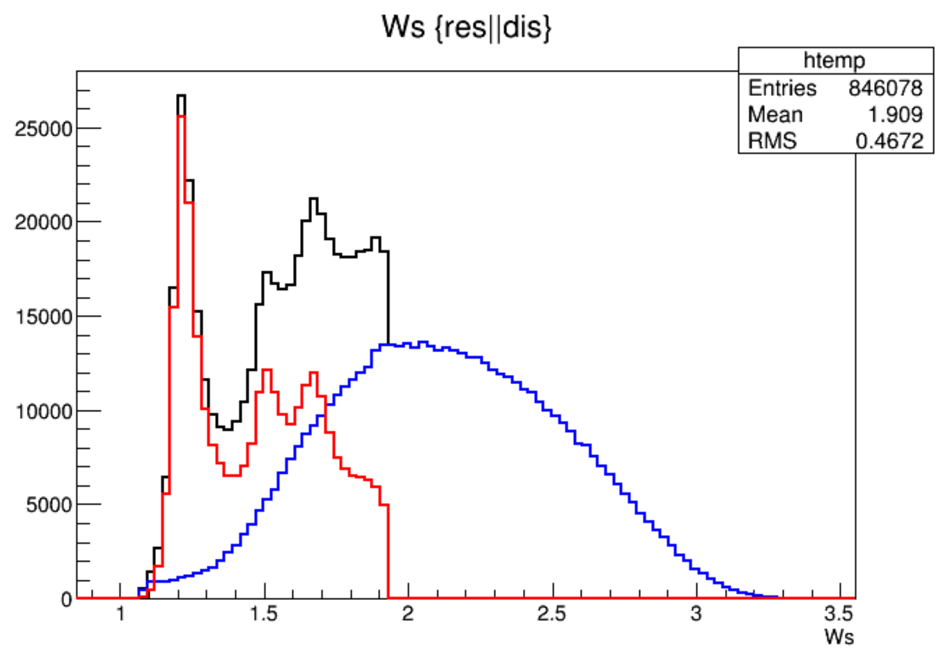
Model	N res	Non resonant	Nucleon Momentum	Δ mods	FSI
Athar	Schreiner-Von Hippel	none	Local Fermi gas	Fit to (γ,π)	Attenuation only
GiBUU	Leitner et al.	Lalakulich et al. - empirical	Local Fermi gas	Fit to (γ,π) Oset	Transport
Valencia	Hernandez et al.	Chiral model	Local Fermi gas	Fit to (γ,π)	Salcedo-Oset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

- GENIE has larger goals, therefore slower

Generator features - GENIE RES vs. DIS ν_μ C at E_ν=5 GeV

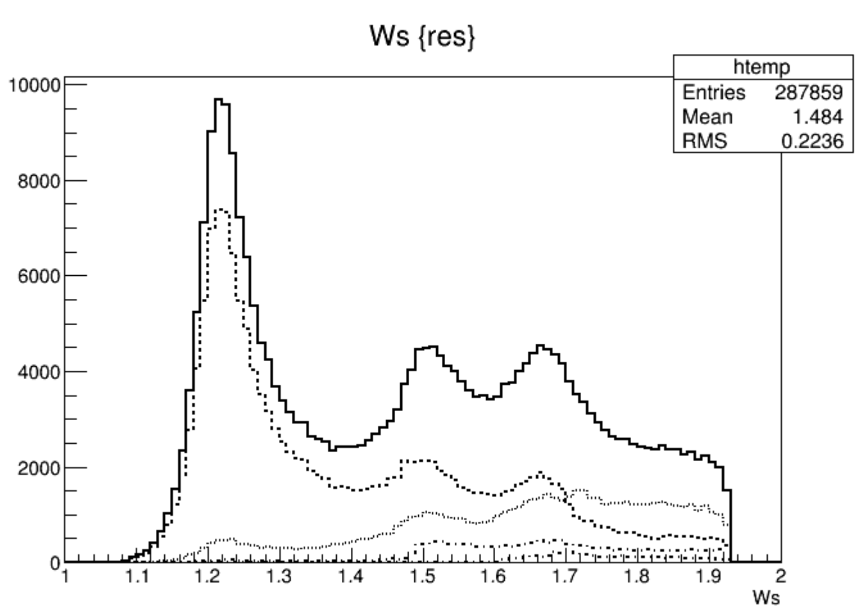
- DIS calculation from Bodek-Yang includes all processes
- RS or BS includes only resonances
- Use RS or BS up to W_{tr}, full BY above, scale down contribution below to match deuterium data

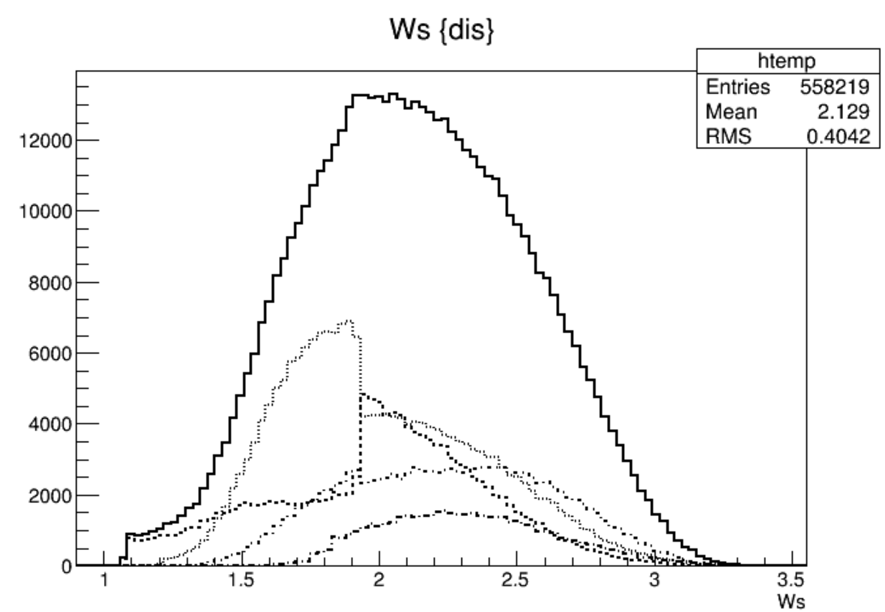




More detail

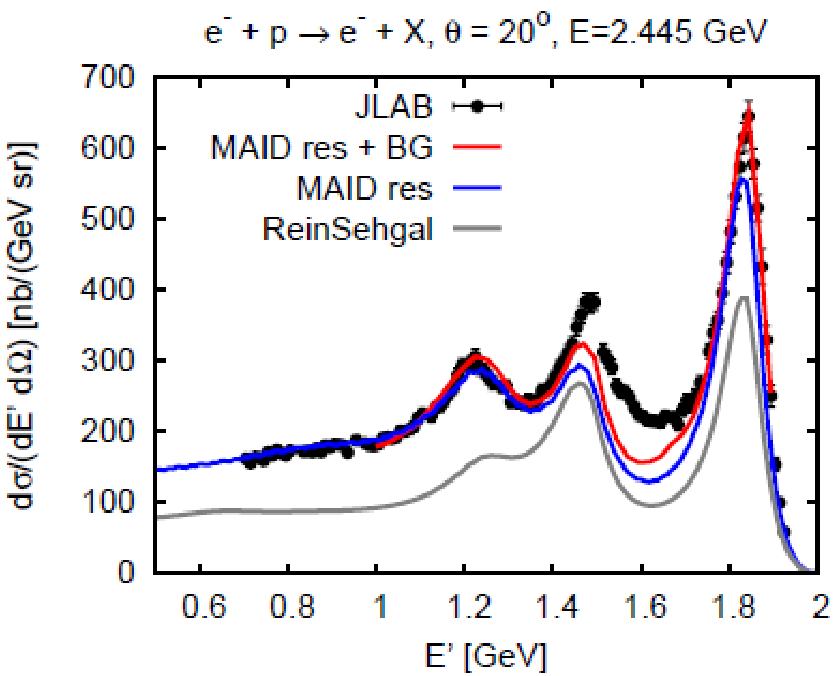
- RES on left, DIS on right
- Subdivided according to final state - all, 1, 2 pions, strange
- Goal for experiments? Even smeared out, would be great



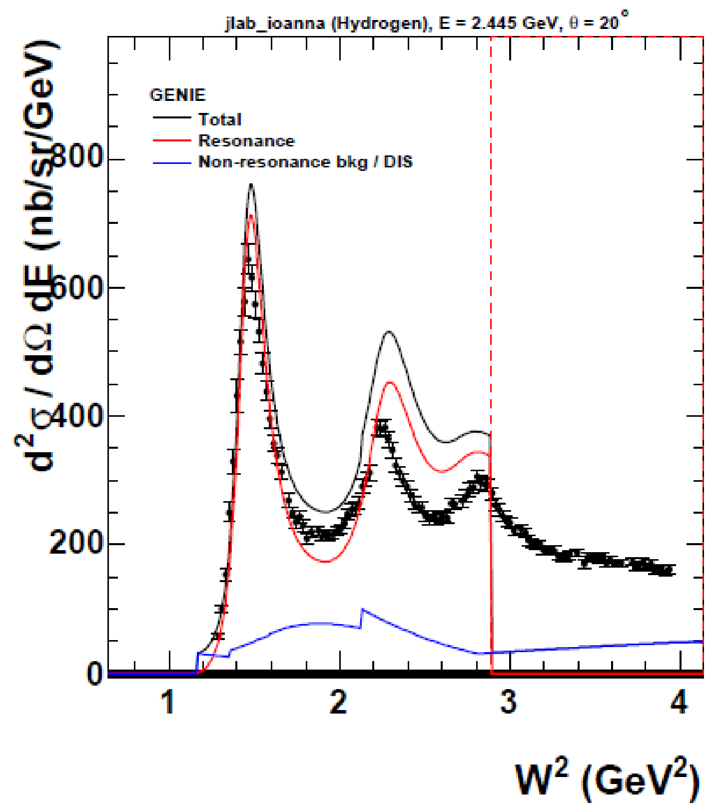


Repeat comparison from NUINT14

- Complaints about Rein-Sehgal often assume same masses, width, and form factors as 1981 paper.
- GENIE regularly updates resonance parameters



GiBUU from Tina Leitner, NUINT08



GENIE interaction systematics

- A list of some of the systematics available via reweighting
- Too many values only loosely based on data.
- Needs updates

Uncertainty	GENIE Knob name	1 σ	Weight In existing MC files?	Currently Included in GENIE Error band?	Notes
Pion mean free path	MFP_pi	± 20%	•	•	
Nucleon mean free path	MFP_N	± 20%	•	•	100% correlated with nucleon elastic fates cross section
Pion fates – absorption	FrAbs_pi	± 30%	•	•	
Pion fates – charge exchange	FrCEx_pi	± 50%	•	•	
Pion fates – Elastic	FrElas_pi	± 10%	•	•	
Pion fates – Inelastic	FrInel_pi	± 40%	•	•	
Pion fates – pion production	FrPiProd_pi	± 20%	•	•	
Nucleon fates – charge exchange	FrCEx_N	± 50%	•	•	
Nucleon fates – Elastic	FrElas_N	± 30%	•	•	100% correlated with nucleon mean free path
Nucleon fates – Inelastic	FrInel_N	± 40%	•	•	
Nucleon fates – absorption	FrAbs_N	± 20%	•	•	
Nucleon fates – pion production	FrPiProd_N	± 20%	•	•	
AGKY hadronization model – x_F distribution	AGKYxF1pi	± 20%	•	•	
Delta decay angular distribution	Theta_Delta2Npi	On/off	•	•	Reweight to more correct angular distribution (i.e. not isotropic).
Resonance decay branching ratio to photon	RDecBR1gamma	± 50%	•	•	

Generators - looking ahead

- Need better data – nucleon, nucleus
- With large data base, MAID has amplitudes for $(e,e'\pi)$ with resonant/nonresonant amplitudes
  - GiBUU has this model
  - Luis Alvarez-Ruso have tried to include in GENIE for many years
- $\Delta(1232)$ is well-studied in $(e,e'\pi)$
  - Medium corrections needed (Jerry Miller)
  - At this time, not included in GENIE (which one is best?)

challenges

- Semi-exclusive and exclusive eA data
  - Pion transparency (e4nu)
- Higher statistics, better defined νA data
  - Dedicated beams closer to monoenergetic
- Better νN data
  - Lots of discussion, high cost
- Better nuclear physics in generators
  - Underway, good progress
  - Need similar basis for res/nonres for $\Delta(1232)$
  - More realistic systematic errors (from fits to data)
- Better integration of what we've learned from eN and eA into ν theory/generators
  - Definitely underway

Summary

- Resonance structure is a rich subject
  - Can be seen with π, e, and ν (part of plan for this workshop)
  - Interesting similarities and differences, but the same resonances
- e data very detailed, rich
  - Far better for nucleon, strong need for e nucleus data
- ν data looks pale in comparison
  - Poor statistics for both nucleon and nucleus
  - Need clean definition despite broad flux distribution
  - Future for $\Delta(1232)$ good, tougher for higher resonances
- Recent theory efforts merge e and ν models – super!
- Generators are getting better at keeping up
  - Good efforts to include updated theory models underway

Note on Nπ cross section

- π energy spectra can have multiple entries per event
  - ~10% of events in data have 2 pions, none with 3
- Multiplicity not measured as a cross section
- To get a cross section, divide by the average multiplicity