Status of Neutrino-Nucleus Data

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Emphasis on resonances above the P33(1232)

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- Main existing data for
  - p, d targets (bubble chamber)
  - CH target (Minerva)
- How do we go forward?

Bubble Chamber data

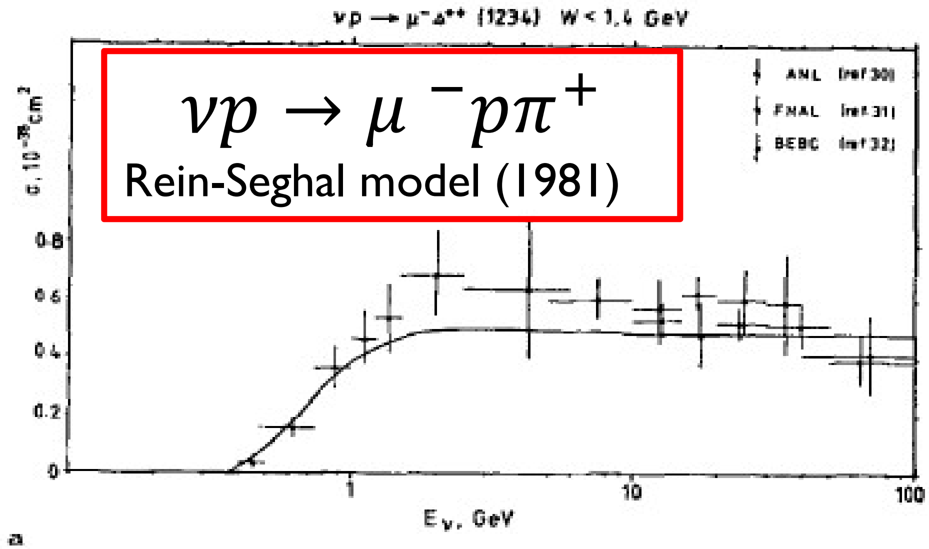
- Summarized nicely in Rein-Sehgal (RS) (1981)
  - π^+, π^-, and π^0 data (ANL, not BNL)
  - Basic information behind their model
  - Many complaints about this – "old and out-moded"
- Knowledge about resonances/non resonant bkgd has greatly improved since 1981!!
- Electron scattering experiments (my 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)

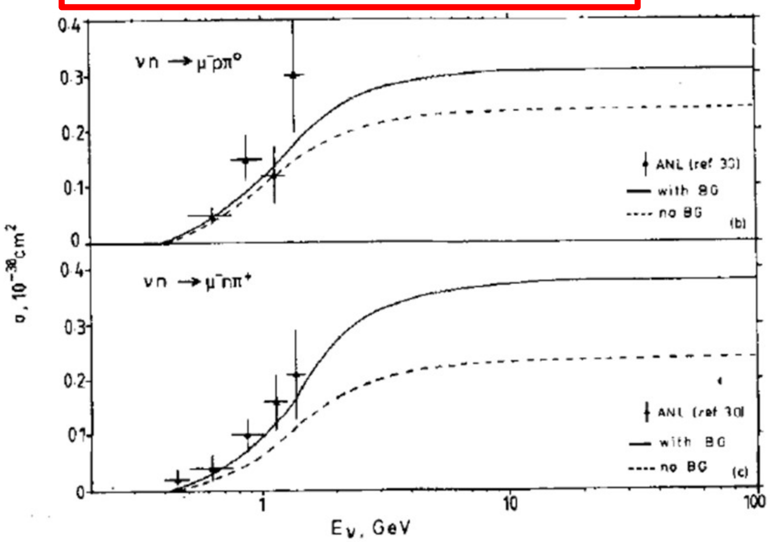
- Low statistics, excellent channel identification

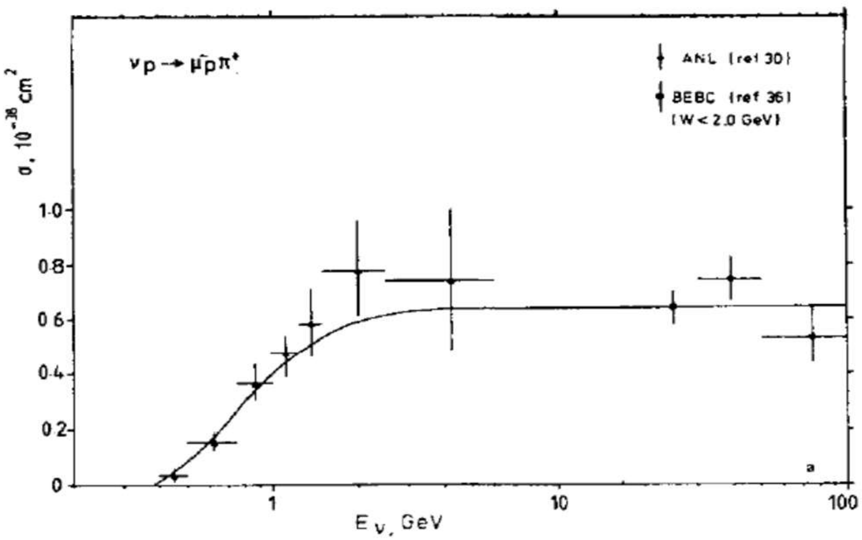
$$\nu p \to \mu^- p \pi^+$$

Rein-Seghal model (1981)



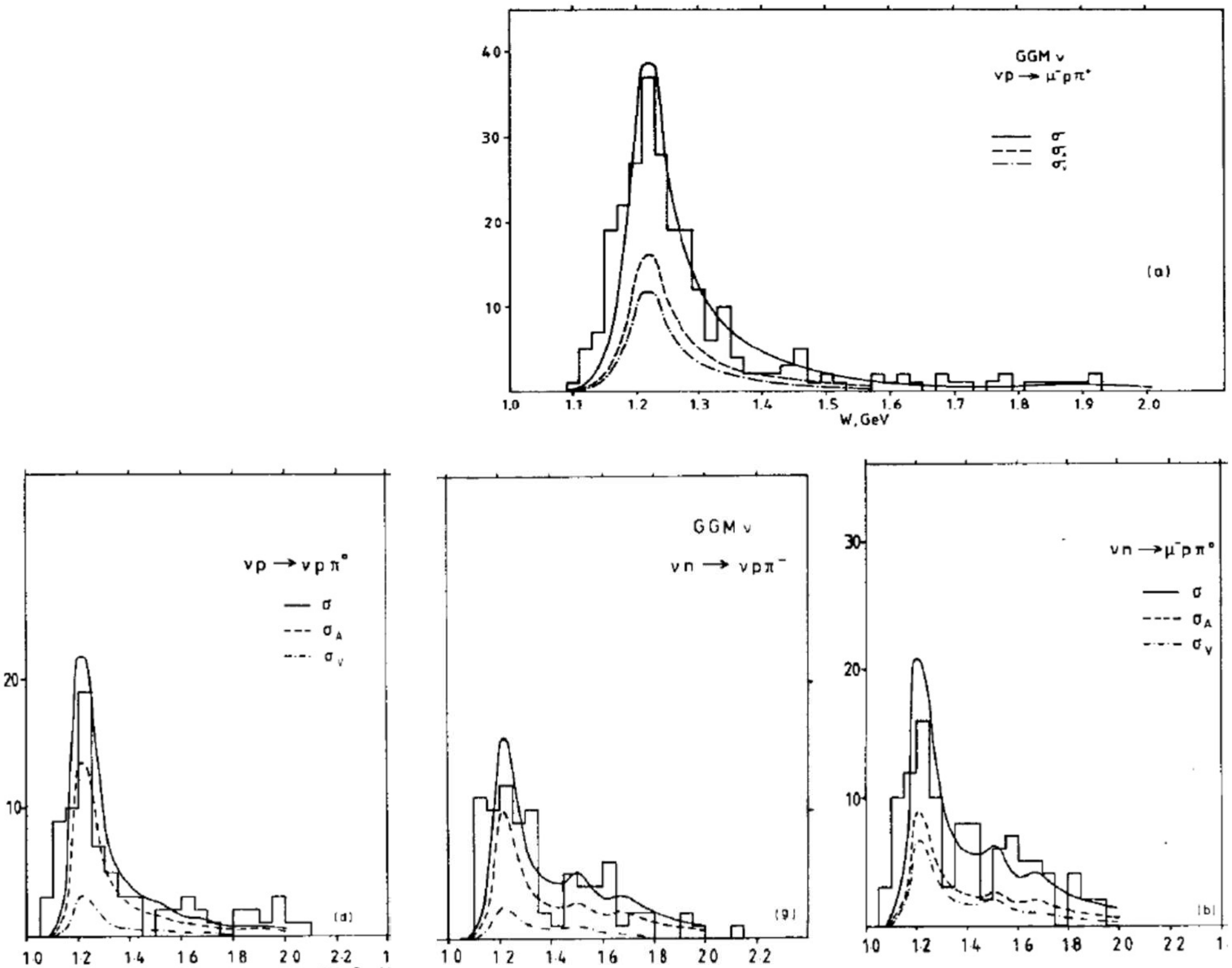
$$\nu n \to \mu^- p \pi^0$$
$$\nu n \to \mu^- n \pi^+$$





W spectra (GGM ν)

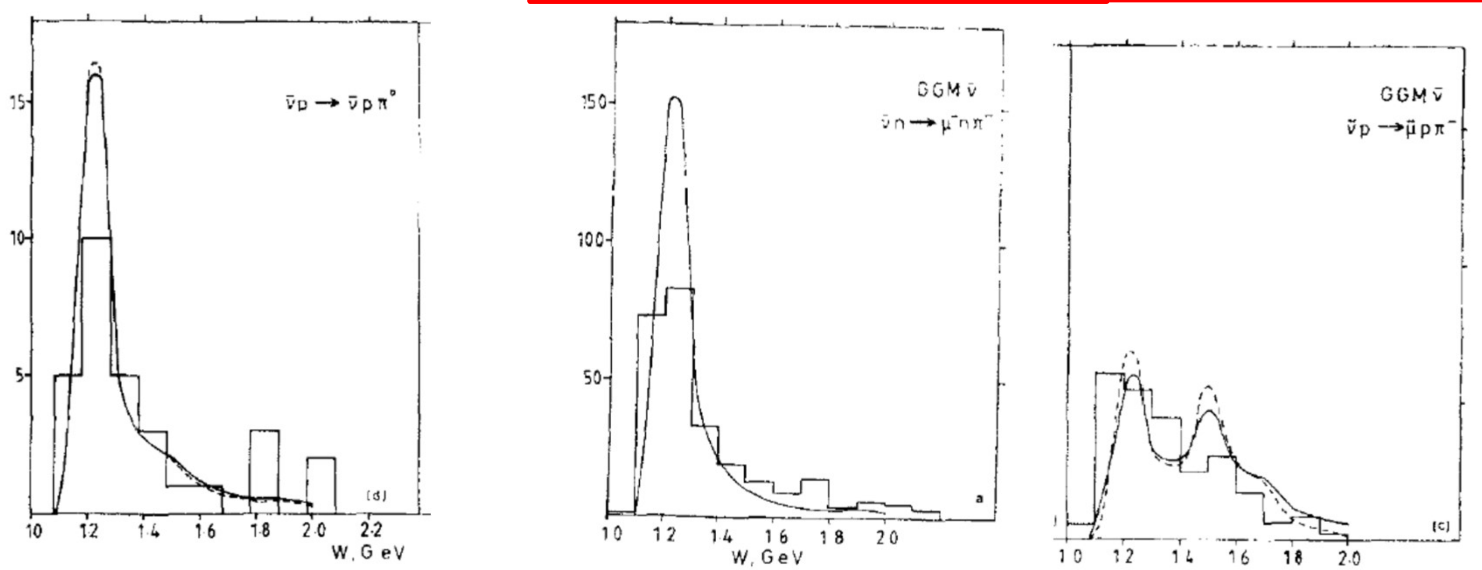
- c



W spectra (GGM nbar)

- CX

$\nu n \rightarrow \mu^{+} n \pi^{-}$ | $\nu p \rightarrow \mu^{+} p \pi^{-}$

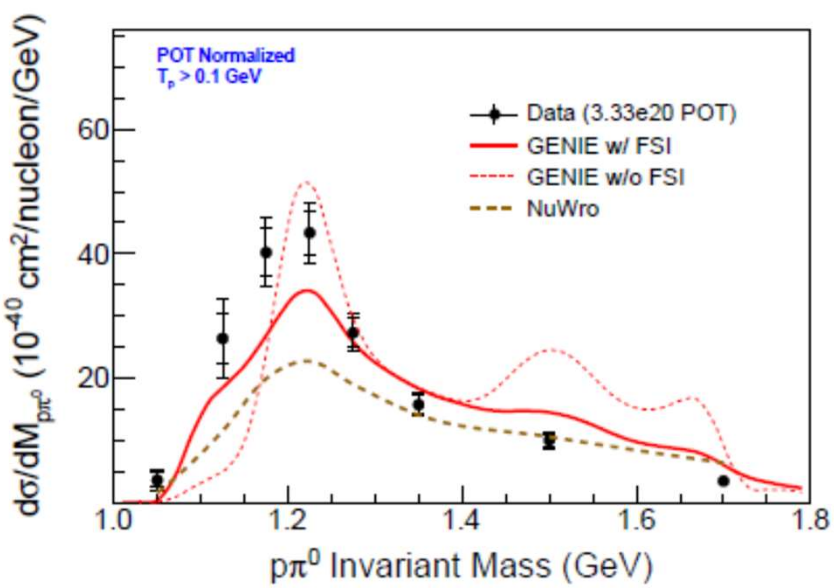


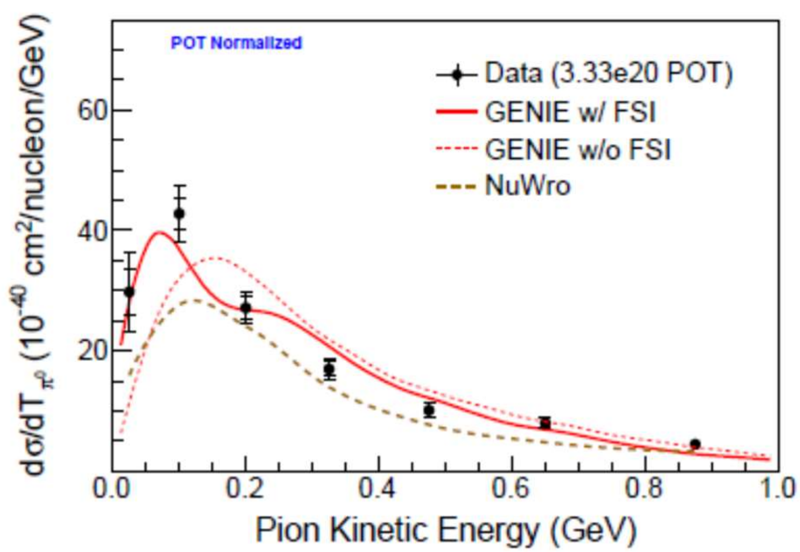
Relevant published work - nuclei

- B. Eberly et al. (MINERvA) Phys. Rev. D92, 092008 (2015)
  - ν_μ CH $\rightarrow$ $\pi^\pm$ X (no π^0, no baryons) W_{true}<1.4, <1.8 GeV; 1.5<E_ν<10 GeV
  - Signal definition using W_{true} causes model dependence, we now know it changes magnitude, not shape.
  - Very small contribution from π^- (Michel tag)
  - No published W spectra since used as in signal definition
- C.L. McGivern et al. (MINERvA) Phys. Rev. D94, 052005 (2016)
  - ν_μ CH$\rightarrow\pi^\pm$ X, $\overline{\nu_\mu}$ CH$\rightarrow$1π^0 X (no π^0, no baryons) W_{exp}<1.8 GeV; 1.5<E_ν<10 GeV
  - Improved signal, no effect on physics interpretation
  - Added muon KE & θ, Q^2, E_ν
- O. Altinok et al. (MINERvA) Phys. Rev. D96, 072003 (2017)
  - ν_μ CH $\rightarrow$ 1π^0 X (no $\pi^\pm$, no baryons) W_{exp}<1.8 GeV; 1.5<E_ν<10 GeV
  - Contribution from π^0p meas

MINERvA ν_μ $1\pi^0$ (2017)

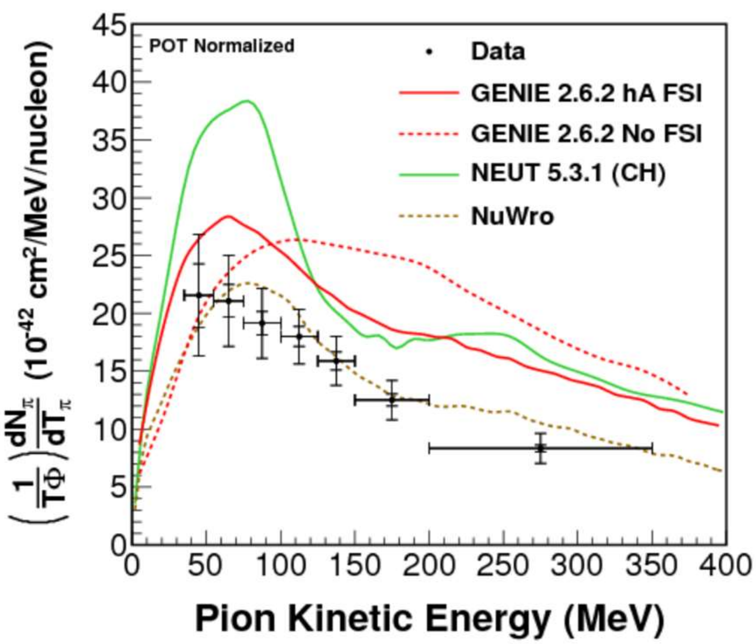
- W spectrum from $p\pi^0$ coincidence
  - For $p\pi^0\pi^+$ events, measure Δ-like component
- Smooth spectrum above Δ

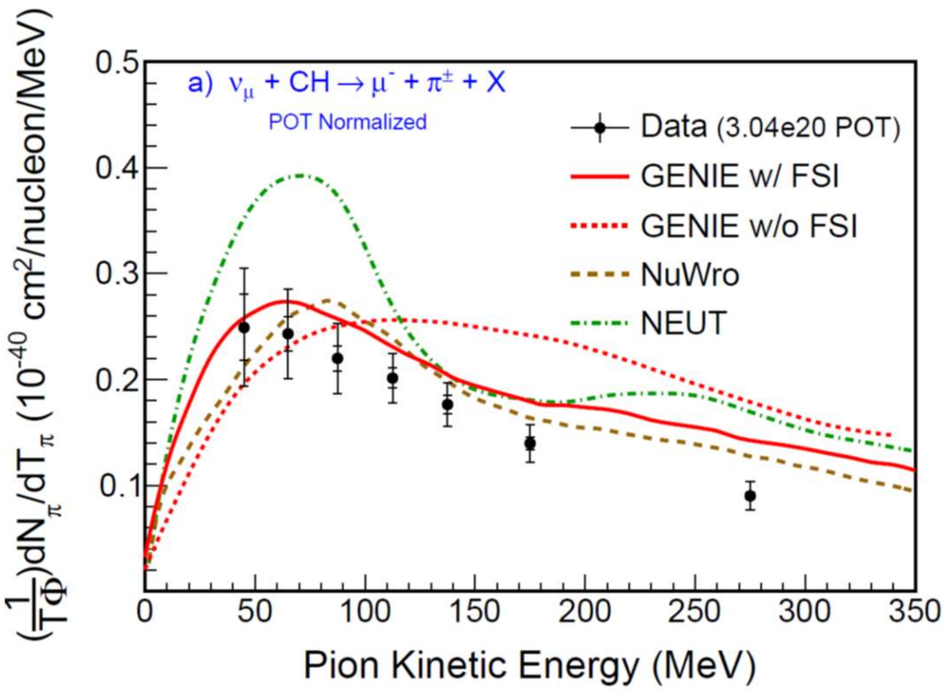




$N\pi^{\pm}$ 2015 vs. 2016

- Same event sample, different signal definition, updated flux
  - W_{exp} instead of W_{true} (~10-15% larger cross section)
- Updated MC calculations
- Not a true cross section because multiplicity not measured
  - Can be calculated within any full model with complete final state



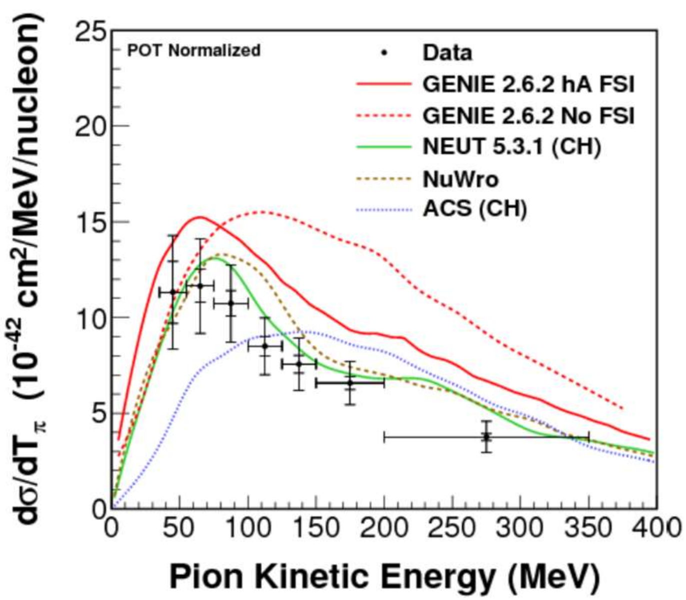


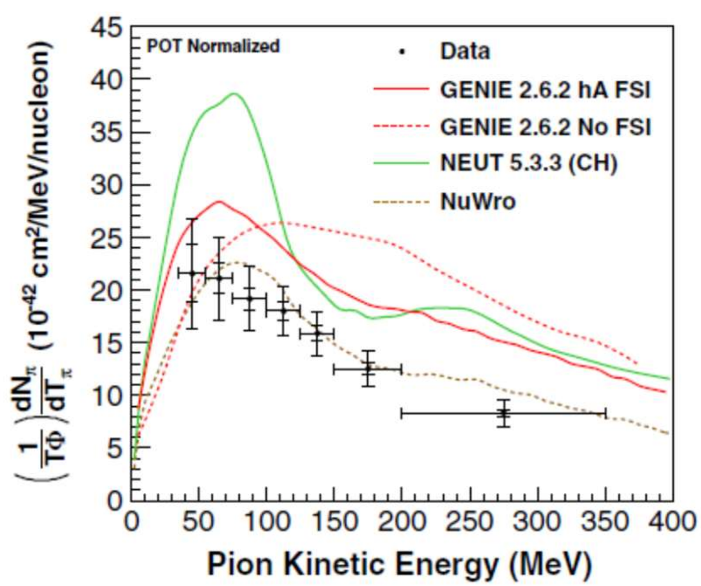
Note on Nπ cross section

- π energy spectra can have multiple entries per event
  - ~10% of events in data have 2 pions, none with 3 pions
- Multiplicity not measured as a cross section
  - no correction for bin migration
- To get a cross section, divide by the average multiplicity (I think)

KE $1\pi^\pm$ vs. $N\pi^\pm$ (both 2015)

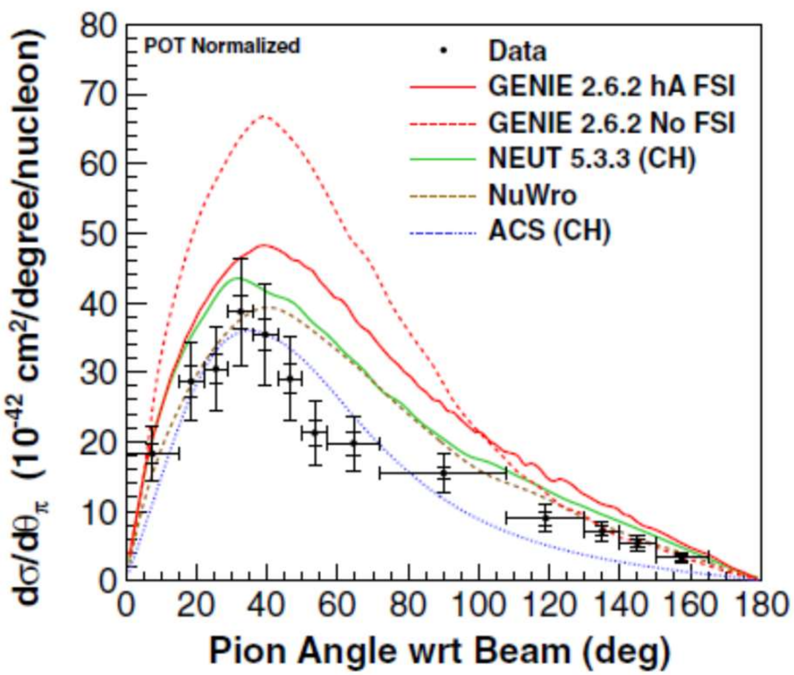
- Change in shape not significant – more high energy π's
- Cross section for 1.4<W<1.8 GeV from difference
- Shift in NEUT is biggest surprise, must have large contribution from 1.4<W<1.8 GeV
- With average multiplicity of 1.1, peak xs~ 20 x 10^{-42} cm^2

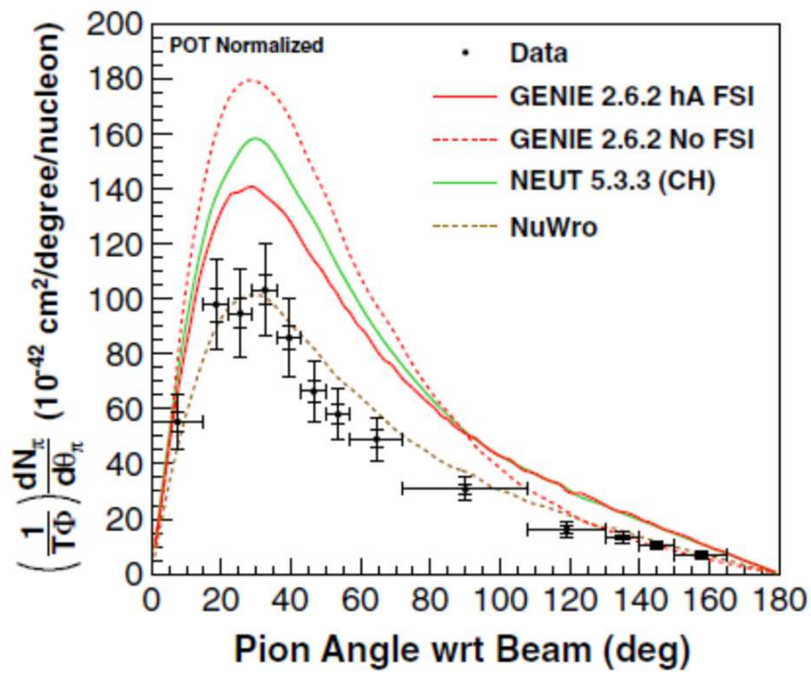




θ $1\pi^{\pm}$ vs. $N\pi^{\pm}$ (both 2015)

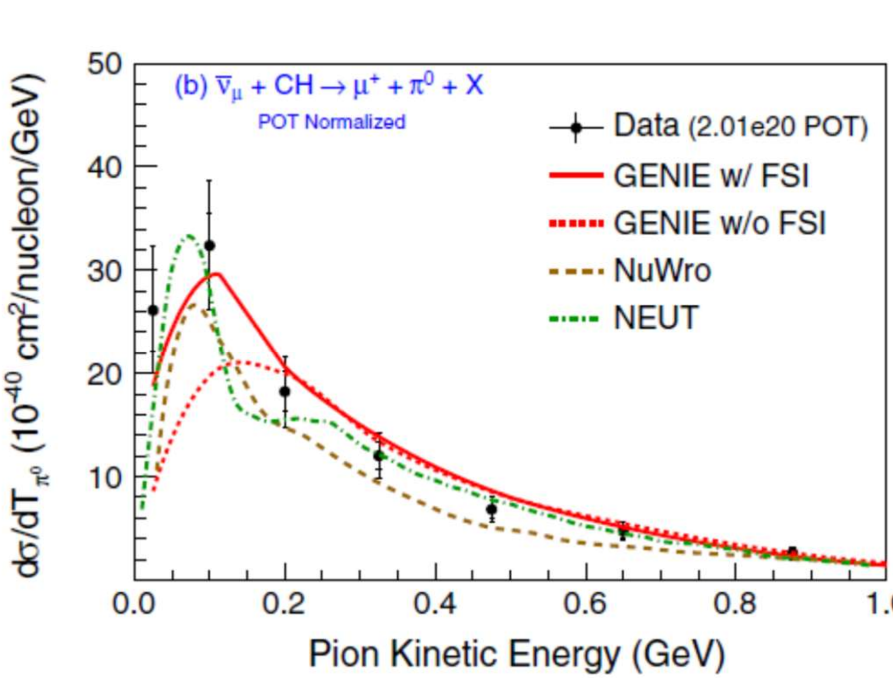
- Shapes are very similar
- 2π contribution will have different angular distribution, typically 1 pion at forward, other at backward angle

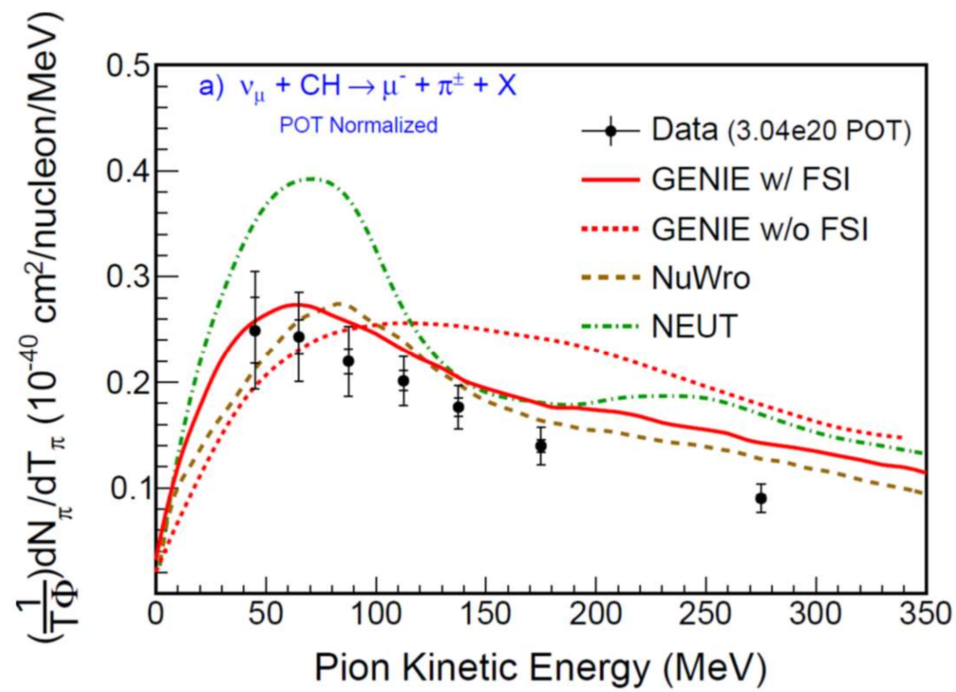




Pion KE - ν_μ $\pi^\pm$ vs. $\bar{\nu}_\mu$ $1\pi^0$

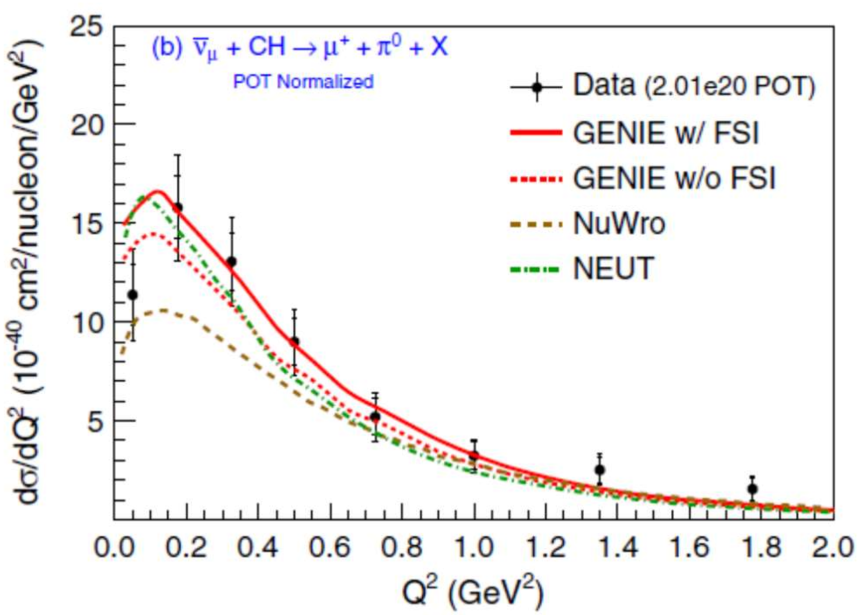
- Both have signal W_{exp}<1.8 GeV
- Models have better agreement for π^0 (surprising)
  - Principal cross section poorly known
  - π^0 FSI only from calculation (isospin)

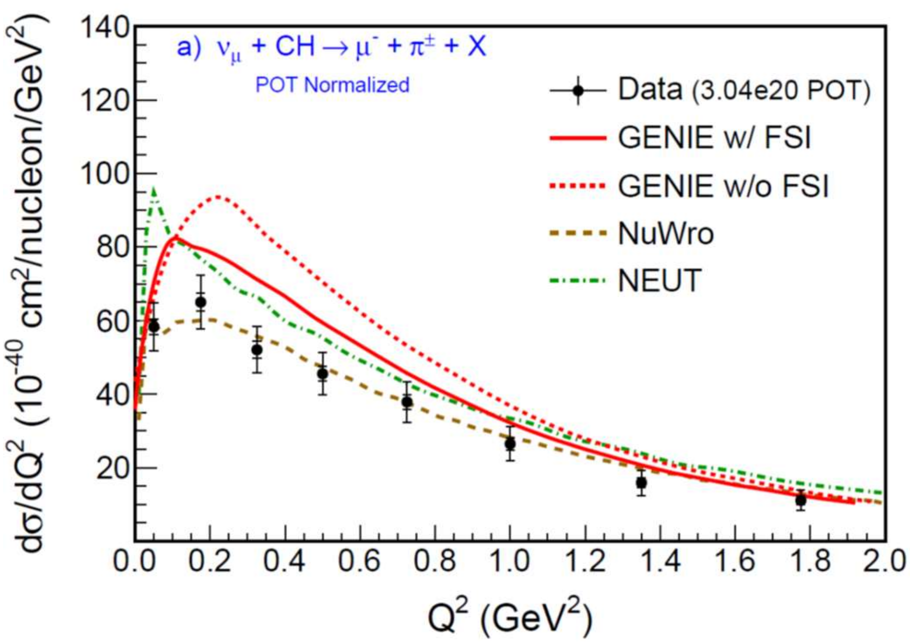




Q^2 $\pi^{\pm}$ vs. π^0

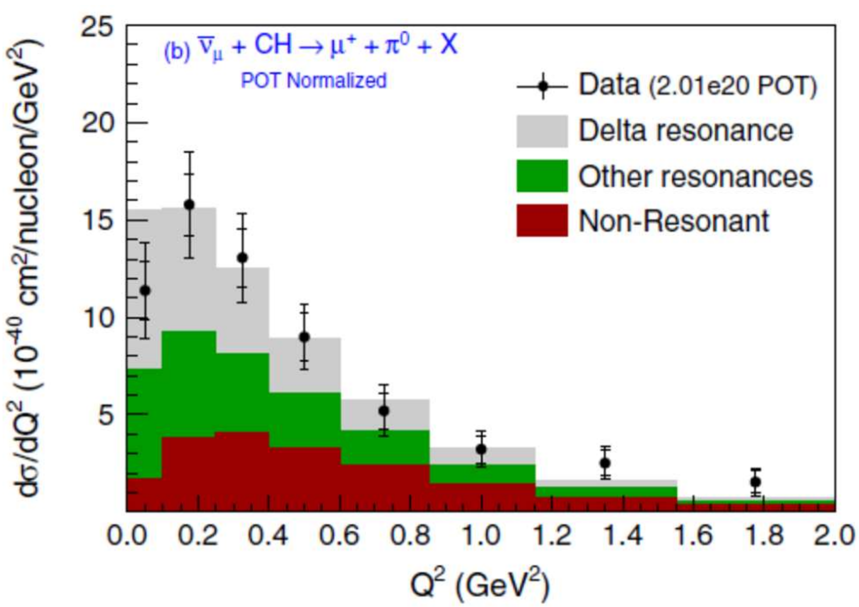
- Both W_{exp}<1.8 GeV
- Features at low Q^2 have been challenging (coherent, diffractive)

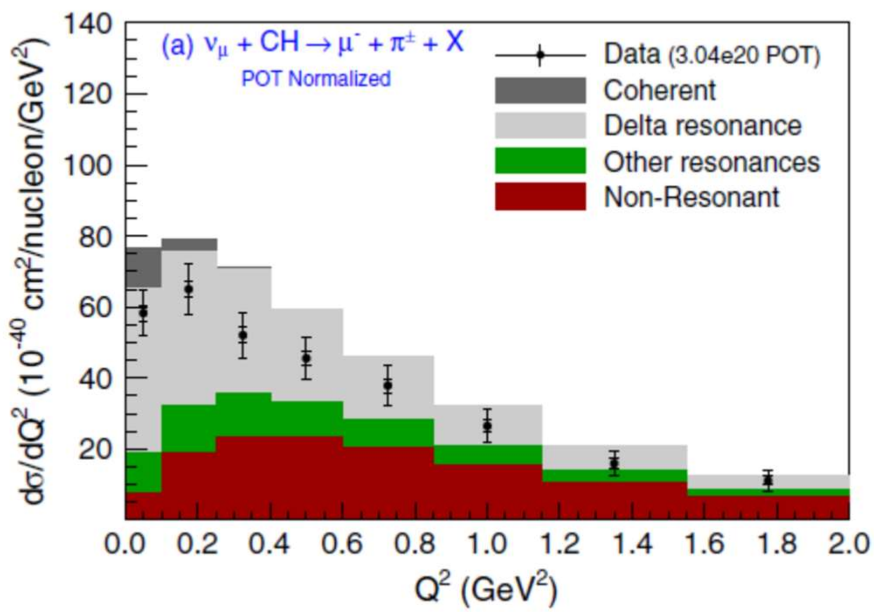




Q^2 detail - channels

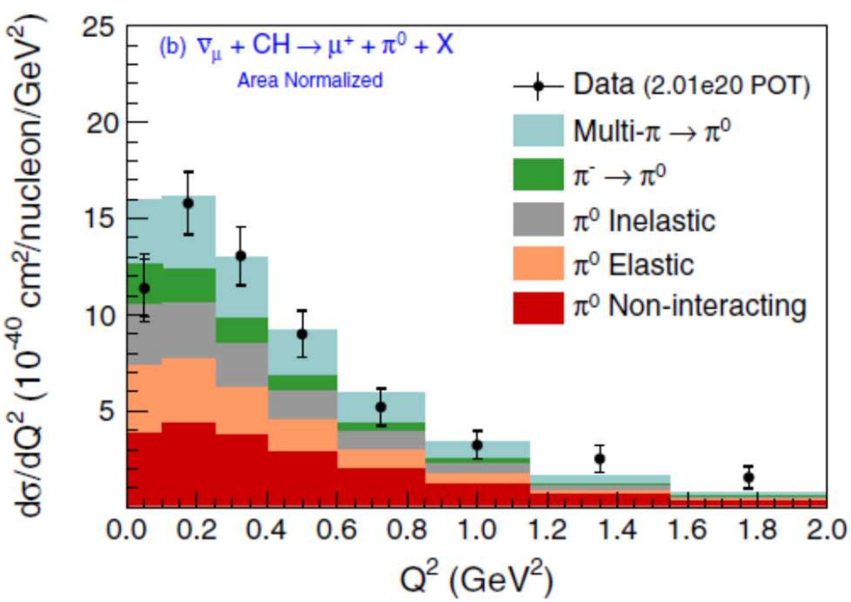
- Coherent channel is important at low Q^2 for charged pions
  - We now know diffraction xs also very important
- Contribution from non-Δ ~20% (π^+) ~80% (π^0)

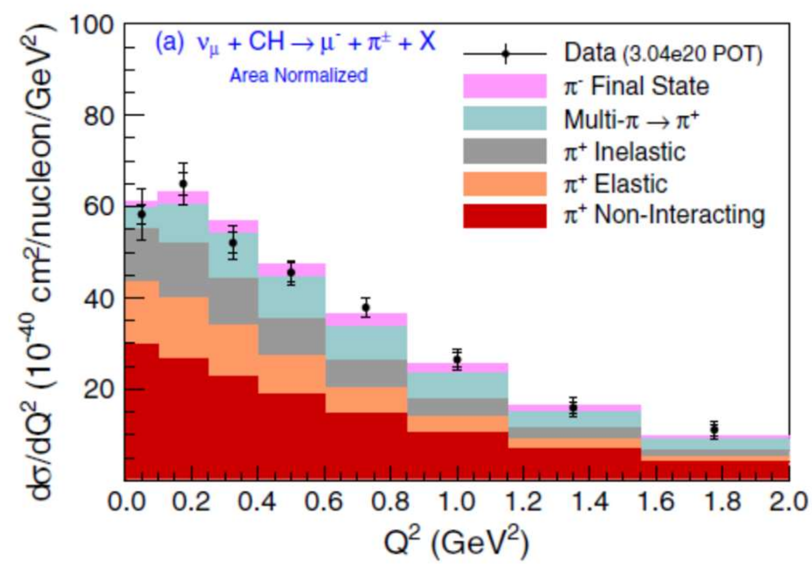




Q^2 detail - FSI decomposition

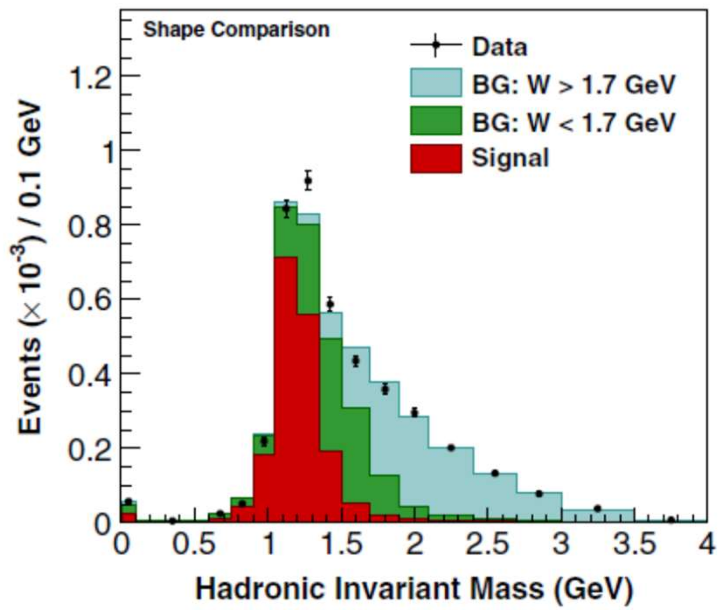
- π^0 subdominant channel, charge exchange net increase
- True π^- contribution to $\pi^\pm$ seen in right plot





significant work remaining, varied needs

- More νA data soon – MINERvA ME beam with C, Fe, Pb
- ν_μ CH $\rightarrow$ 1π, $N\pi$ X
  - Working to have W spectrum with minimal cuts
  - Larger flux*cross section *10
- ν_μ Fe, Pb $\rightarrow$ 1π, $N\pi$ X
  - Aim for same signal as ν_μ CH
  - Lower statistics but A dependence will be extremely valuable



Summary

- This is all I know about for resonances above Δ with ν, is there more?
- Statistics are not impressive, significant improvement is essential
- No W spectrum so far, also essential
- MINERvA, NOvA will provide best data at higher ν energy
- SBN will provide best data for Δ at lower ν energy

KE $\overline{\nu}_\mu$ $1\pi^0$ (2015 vs 2016)

- See affect of improved signal