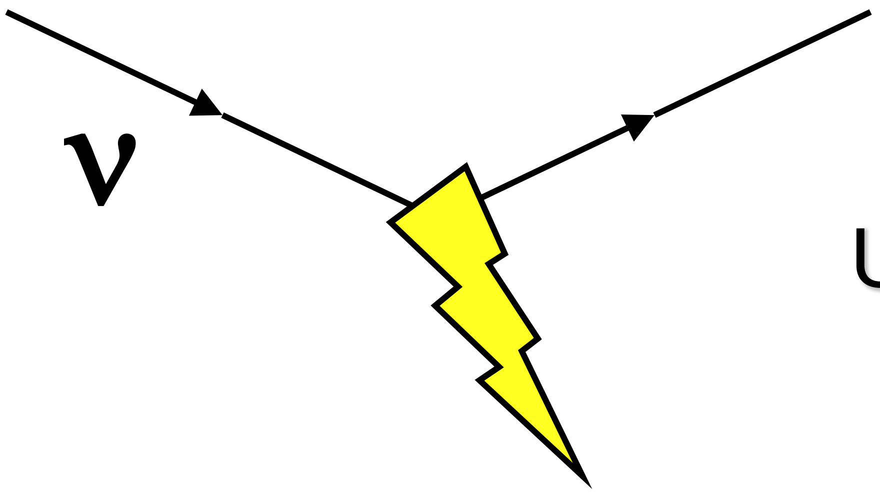
Pion Production: Data, Inferences, Prospects



Kevin McFarland
University of Rochester

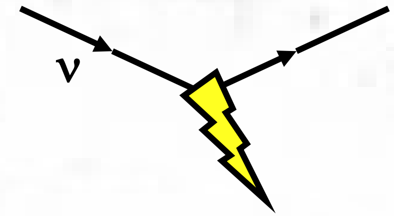
NuINT 2015
University of Osaka

Outline

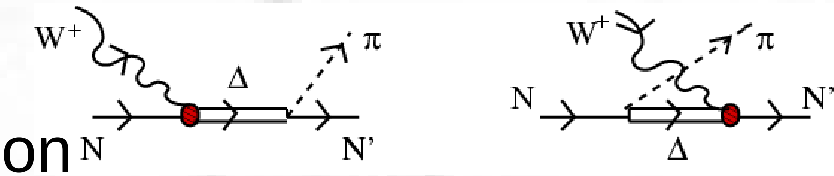
- Goals for studying pion (meson) production
- Important datasets and interpretations
- Summary and Prospects

Who Cares? And Why?

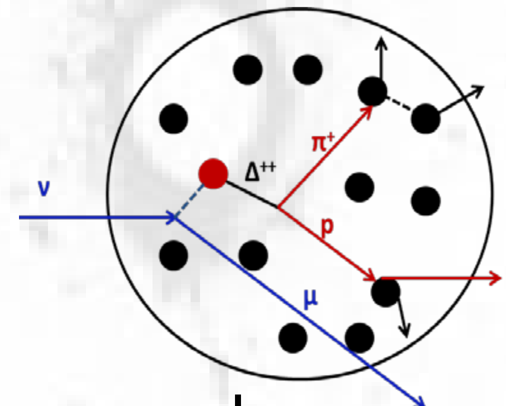
Physics of Pion Neutrinoproduction



- Pions are produced in a hard neutrino interaction with a nucleon
- Those pions may or may not survive to escape the nucleus
- Other processes may produce pions purely from interactions of hadrons within the nucleus

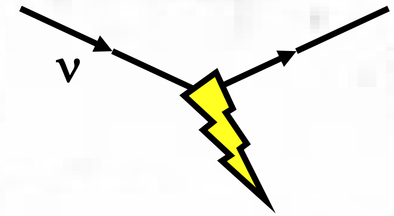


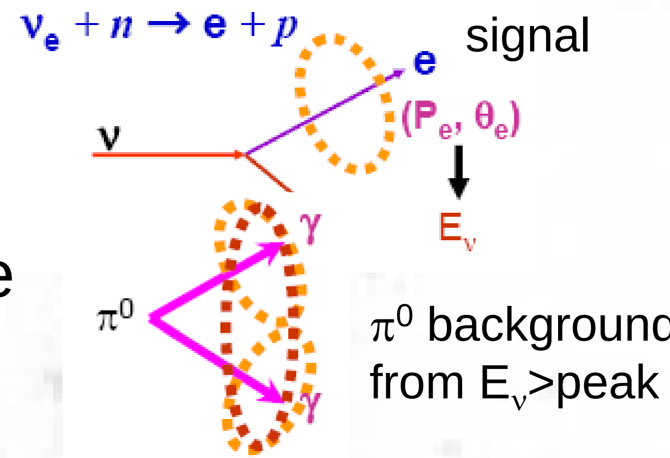
Subset of figures from E. Hernandez, PRD87 (2013) 113009



- By studying pion production by neutrinos, we learn
  - Is the hard process modified within the nucleus?
  - Do we model the final state interactions correctly?

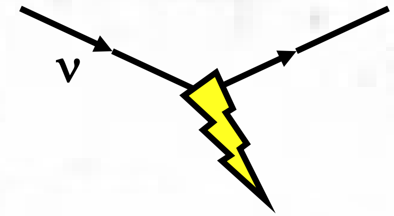
In Oscillation Experiments… Categorizing Events



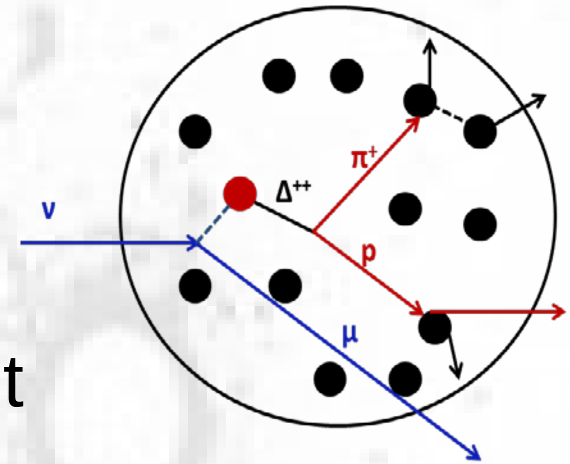


- ν_e appearance? very sensitive to processes from non-ν_e
  - even rare backgrounds contribute
- ν_μ disappearance? signal is big
  - but $\pi^\pm$ are excellent at faking $\mu^\pm$
- Oscillation experiments use measurements of the process elsewhere (their own near detector, or other data) and scale to the far detector
  - The model used for this scaling must know about neutrino energy dependence and details of the final state of the neutrino interactions

In Oscillation Experiments… Energy Reconstruction



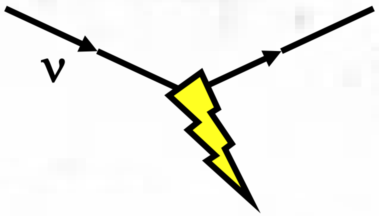
- Must include estimate of pion energy in inelastic events.
- But produced hadrons inside the nuclear targets interact as they exit
  - On balance, net energy transfer from pions to nucleons inside nucleus
  - Detector response is unlikely to be uniform for charged and neutral pions, protons and neutrons



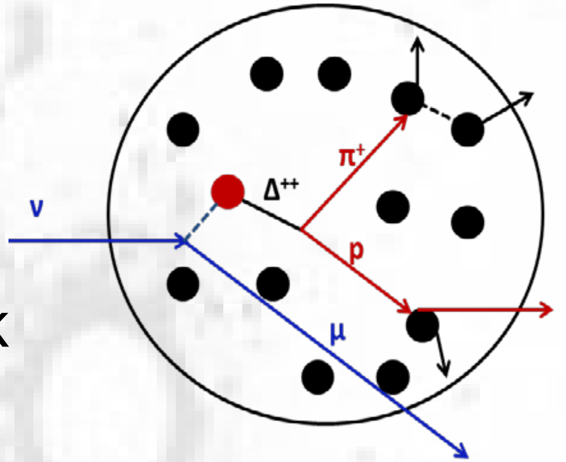
- Modeling this is non-trivial.
  Verifying the modeling is even more difficult.

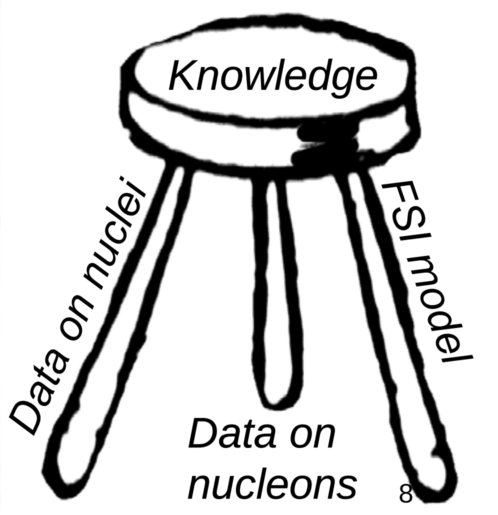
Light Target Pion Production

The Role of Hydrogen and Deuterium Experiments



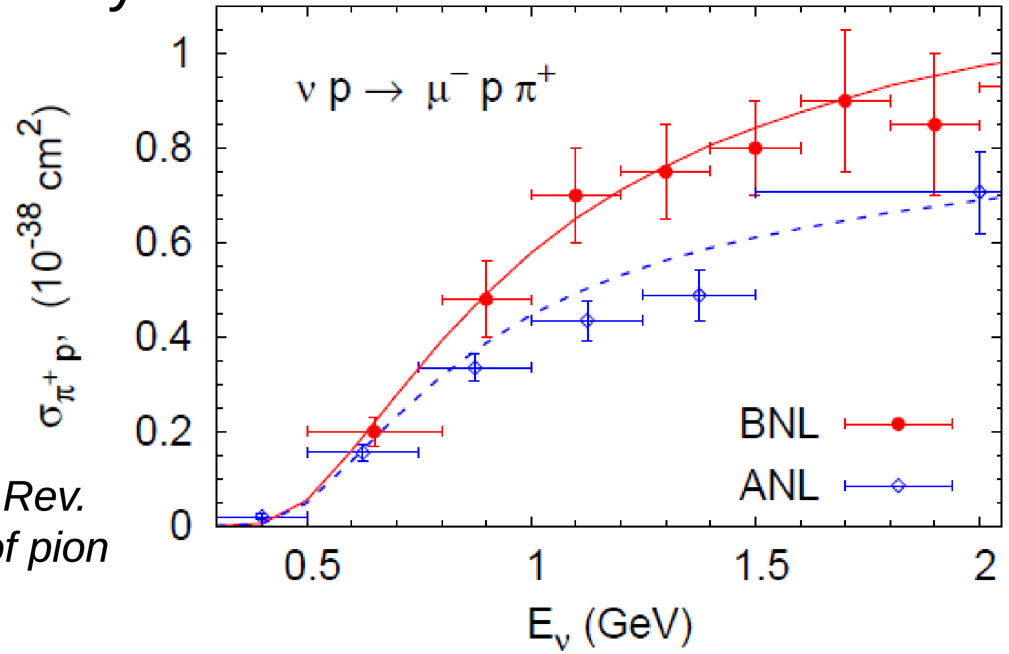
- *“Verifying the modeling is even more difficult.”*
  - Good data on “free” nucleons (H_2 and D_2 bubble chambers) as a benchmark is extremely important. But that data is unlikely to be improved.
  - Comparing different nuclei is a possible approach with modern data
- Important note: NN final state interactions in D_2 may be significant in some phase space (spectator-target swap), *e.g., J. Wu, T. Sato and T.-S. Lee, Phys. Rev. C91 (2015) 035203*





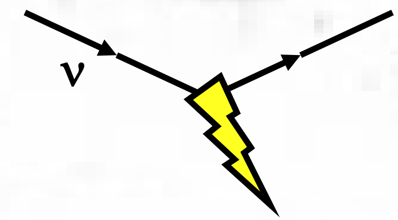
Existing Deuterium Data

- Two main datasets from H_2 and D_2 bubble chambers, "ANL" [G. Radecky et al., Phys. Rev. D25, 1161 (1982)] and "BNL" [T. Kitagaki et al., Phys. Rev. D34, 2554 (1986)] that comprehensively measure pion production
- Published results disagree by 30-40% and this is a major problem in attempts to extract axial form factors

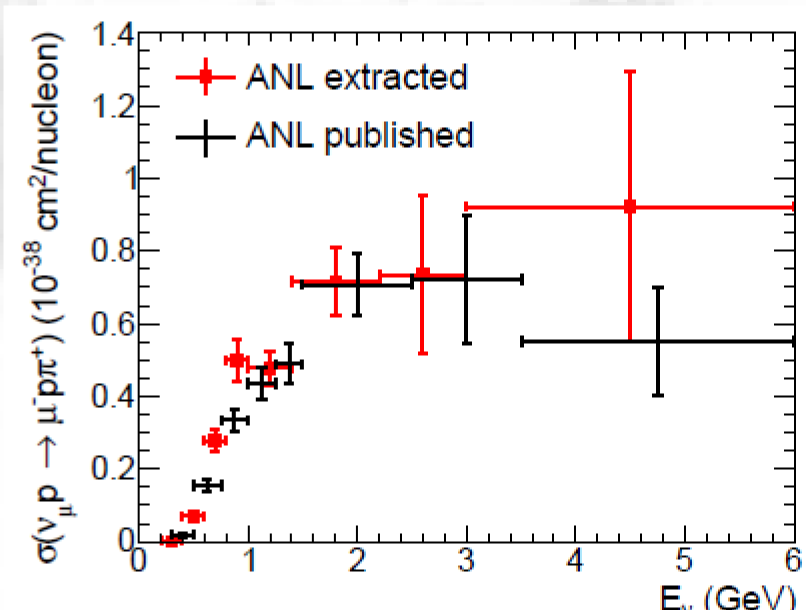


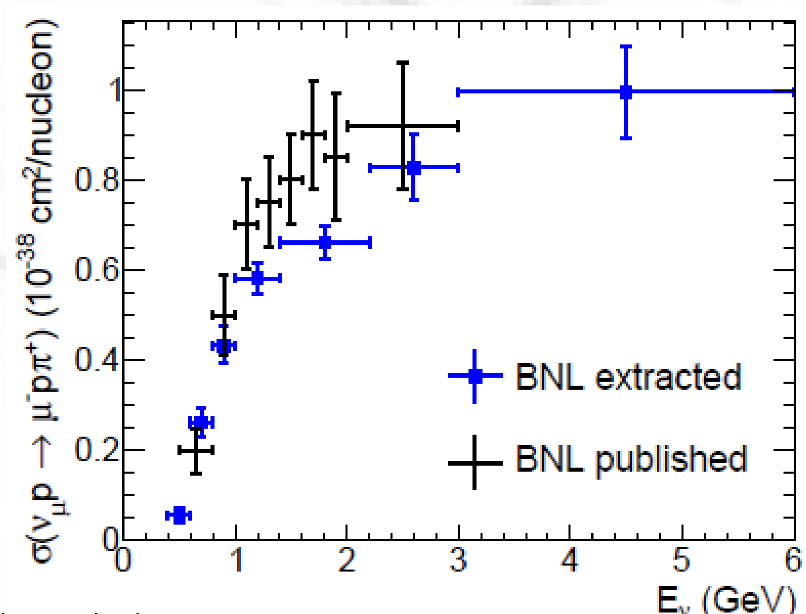
From O. Lalakulich and U. Mosel, , Phys. Rev. C87, 014612 (2013). Curves are ranges of pion production on D_2 from GiBUU model.

Resolving the Deuterium "Problem"

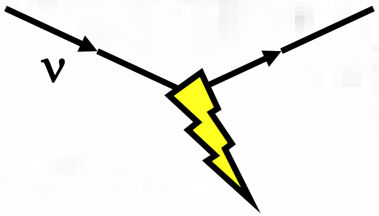


- Both experiments had large and difficult to quantify flux uncertainties. Recent observation: ratios of pion production to other processes are consistent.
  - Therefore "correct" results using reliable predictions of CCQE with axial form factor set by electroproduction of pions. *[C. Wilkinson, P. Rodrigues et al, Phys Rev D90 (2014) 112017]*





Next Step: Extracting Weak Form Factors from D_2 Data



- Needed for model building, but difficult with limited datasets, “background” (non-resonant) form factors interfering with Δ(1232), higher resonances, etc.
  - Next steps will use work on nuclear effects in deuterium, improved production models and resolution of “ANL/BNL”

Sato, T. et al. Phys.Rev. C67 (2003) 065201
Matsui, K. et al. Phys.Rev. C72 (2005) 025204
Paschos, Emmanuel A. et al. Phys.Rev. D69 (2004) 014013
Lalakulich, Olga et al. Phys.Rev. D71 (2005) 074003
Lalakulich, Olga et al. Phys.Rev. D74 (2006) 014009
Hernandez, E. et al. Phys.Rev. D76 (2007) 033005
Graczyk, K.M. et al. Phys.Rev. D80 (2009) 093001
Hernandez, E. et al. Phys.Rev. D81 (2010) 085046
Lalakulich, O. et al. Phys.Rev. D82 (2010) 093001
Hernandez, E. et al. Phys.Rev. D87 (2013) 113009
Graczyk, K., Zmuda, J. and Sobczyk, J. and, Phys.Rev. D90 (2014) 093001
Wu, J. et al., Phys. Rev. C91 (201) 035203
Nakamura, S.X. et al, Phys.Rev. D92 (2014) 7, 074024
Alam, M.R. et al, arXiV:1509.08622
Alvarez Ruso, L. et al, arXiV:1510.0626

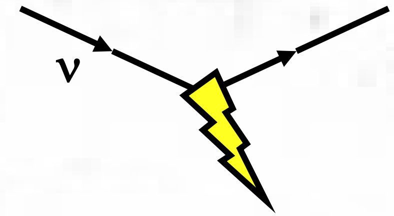
A selection of recent references in this field. I’m sure it’s not comprehensive!

See also discussion from Luis Alvarez Ruso in his talk on Monday.

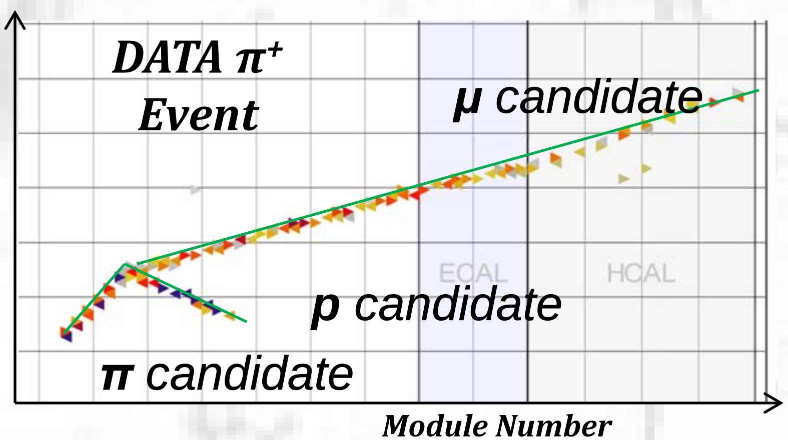
See also Wilkinson & Rodrigues and Kabirnezhad posters

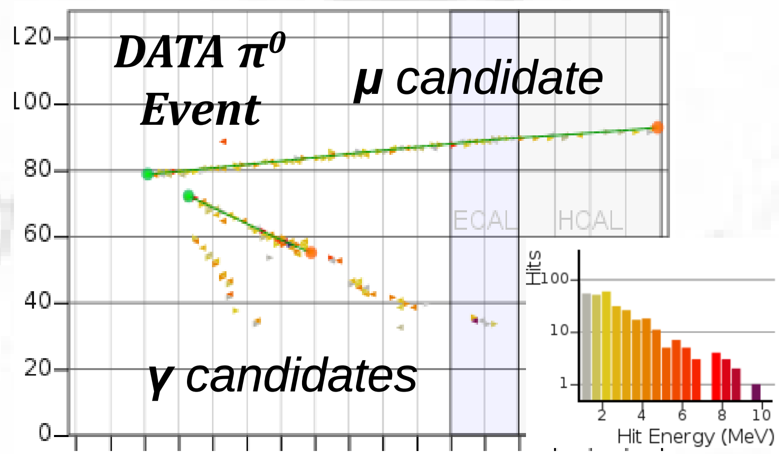
Data on Heavier Nuclei

MINERvA Pion Measurements

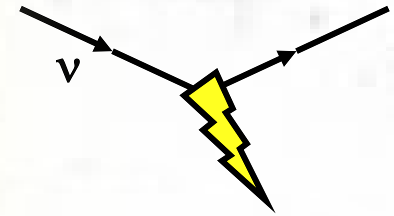


- MINERvA is segmented scintillator
  - Can track charged pions, protons
    - o ~2cm granularity sets an energy threshold
  - Photons and electrons also show up as “tracks” in low density material

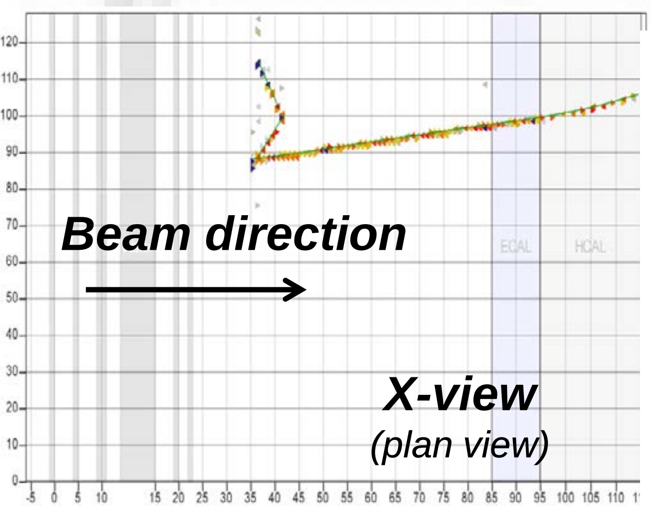


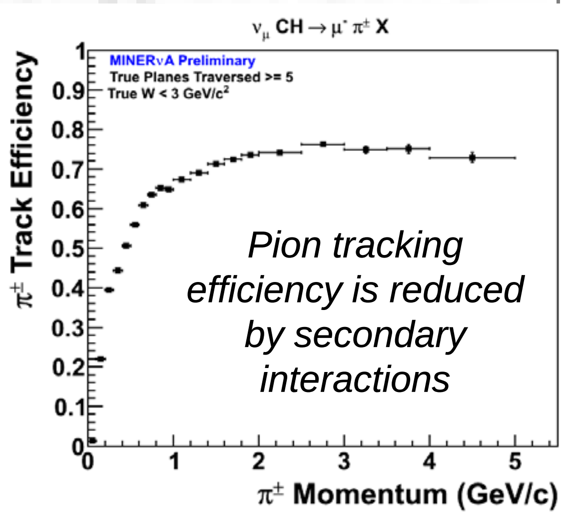


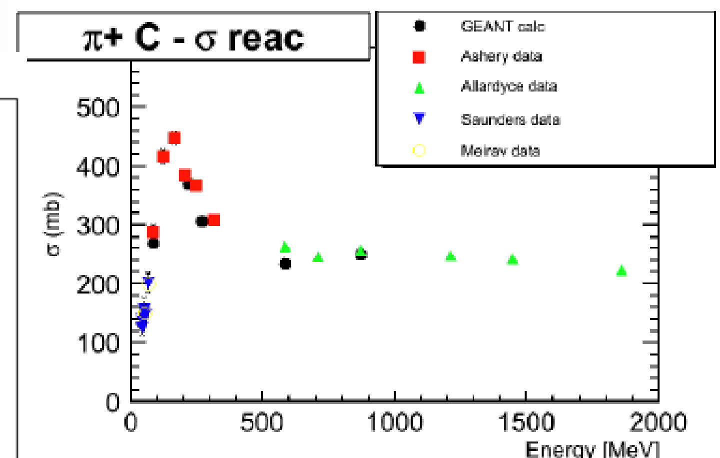
Charged Pion Reconstruction

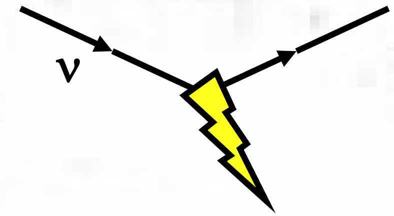


- Identification of a track as a pion by energy loss as a function of range from the vertex
- Confirmed by presence of Michel electron, $\pi \rightarrow \mu \rightarrow e$
- Elastic or inelastic scattering in scintillator is a significant complication of reconstruction
  - Study uncertainties by varying pion reactions, constrained by data



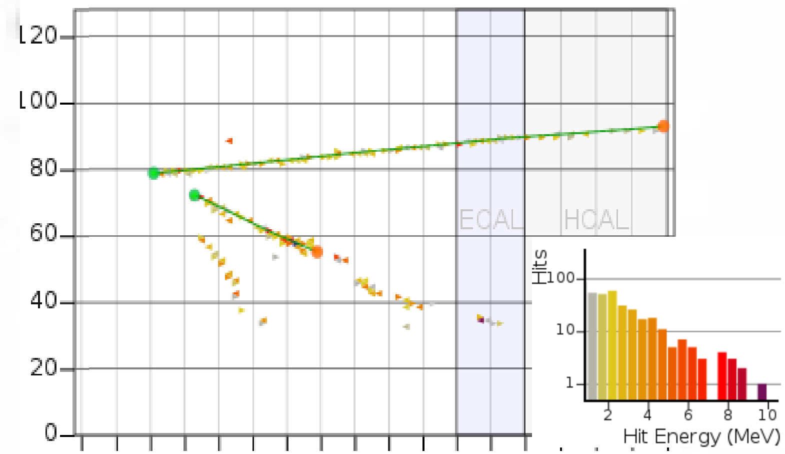




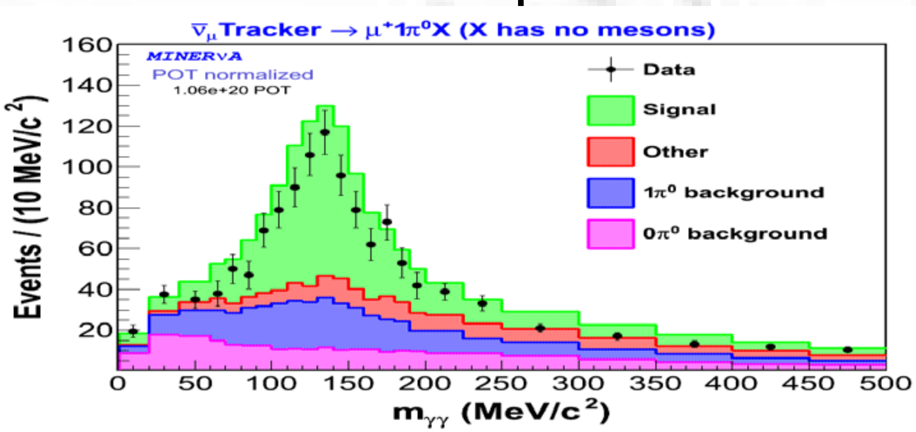


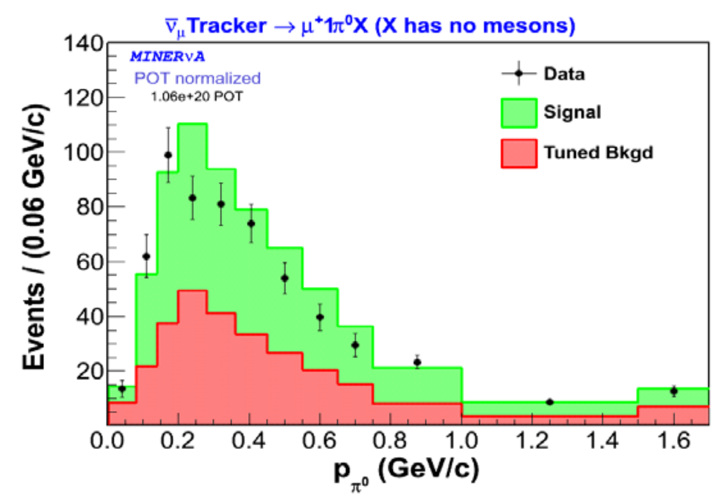
Neutral Pion Reconstruction

- Reaction is $\bar{\nu}_\mu + \mathrm{CH} \to \mu^+\pi^0 X$
  $\quad\quad\quad\quad\quad\quad\quad\quad\quad\quad\quad \hookrightarrow \gamma\gamma$

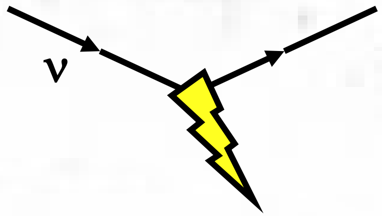


- Reconstruction strategy is to find muon and "detached" vertices
  - Photons shower slowly in plastic, so they look like "fat tracks"
- Backgrounds can be constrained with pion mass

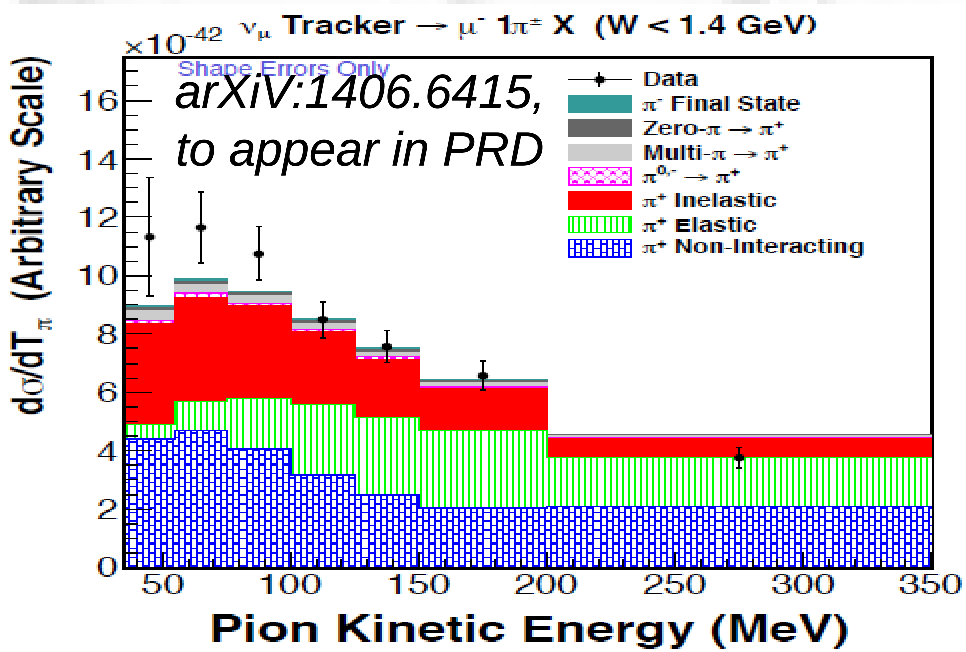


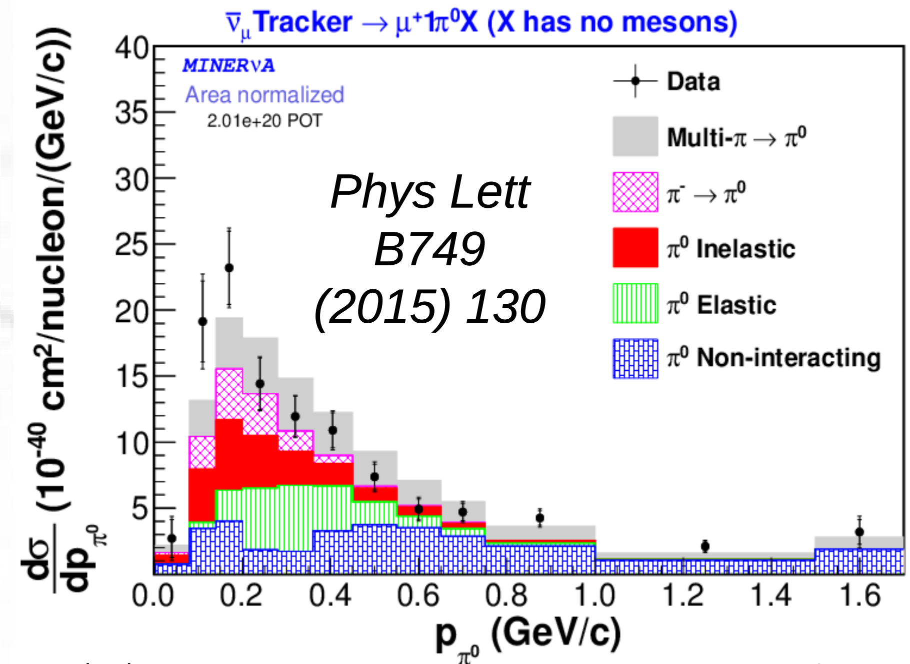


MINERvA: Pion Spectrum as Probe of Final State Effects

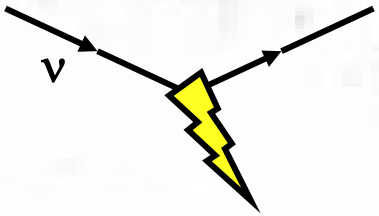


- MINERvA has measured both π^+ and π^0 production. Both prefer slightly softer pions than GENIE's final state cascade model predicts.
  - Next steps: compare with other FSI models, i.e., GiBUU
  - Fine print: this is MINERvA "gen 1" flux, and not yet corrected

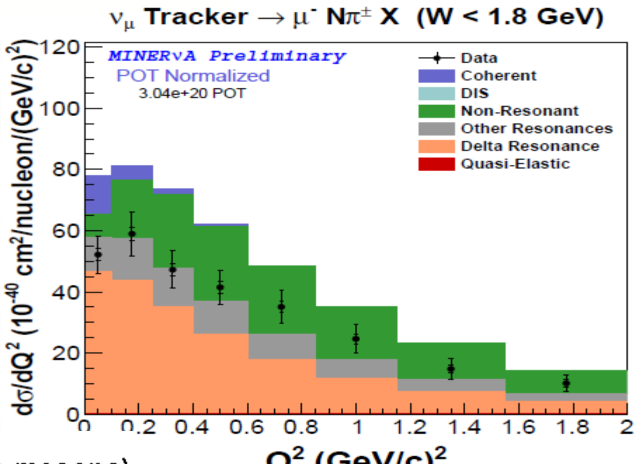


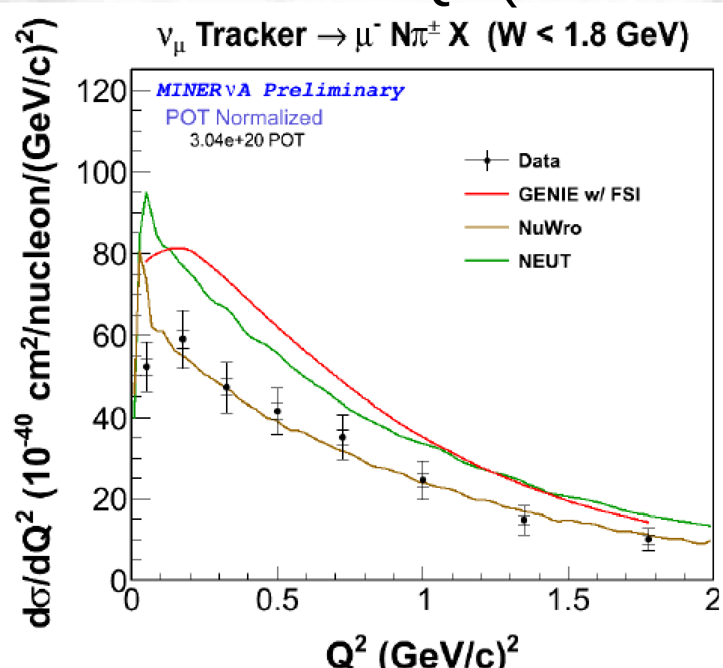


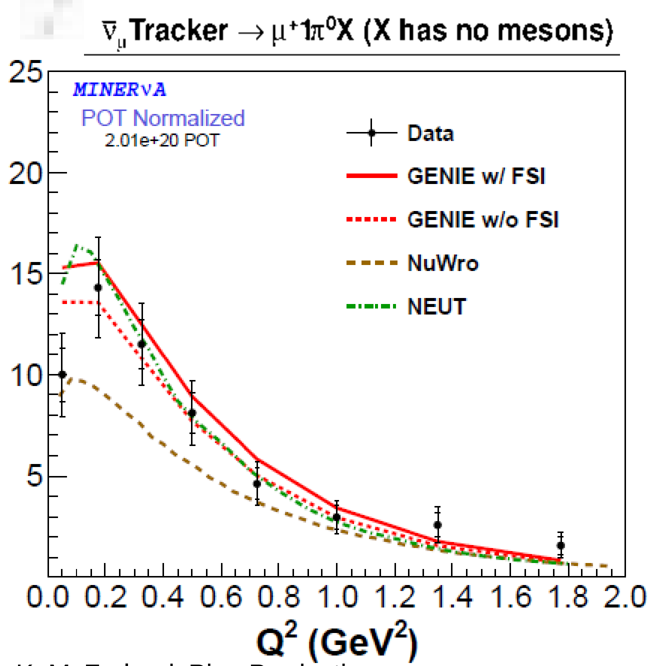
MINERvA: Muon Variables



- What can we learn?
  - Compare neutrino and antineutrino
  - $d\sigma/dQ^2$ is ~insensitive to pion FSI
  - But may see nuclear modifications at low Q^2 (or elsewhere)





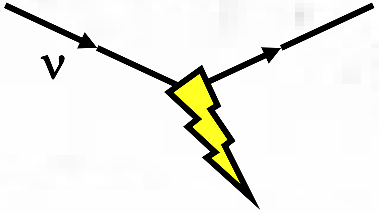


Two modes have similar content, except coherent contribution to π^+.

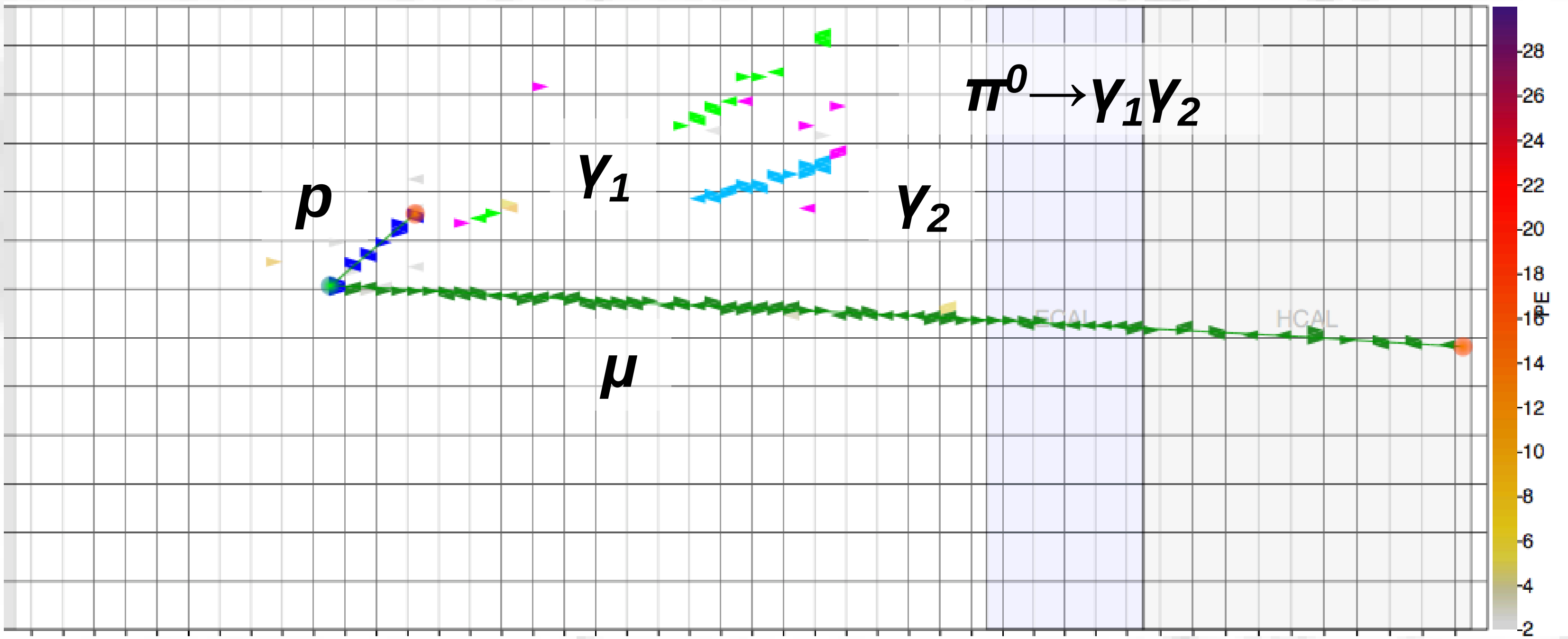
Modest indication of low Q^2 suppression.

Normalizations to model inconsistent?

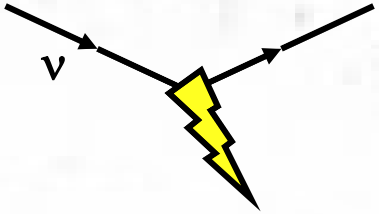
MINERvA: Neutrino vs Anti-neutrino and Semi-Inclusive



- Neutrino π^0 and semi-inclusive $p+\pi^0$ in the CH target in process with similar π^0 selection
  - Direct comparison of neutrino and anti-neutrino π^0
  - $p+\pi^0$ correlations give another handle on FSI effects



MINERvA: Different Nuclei

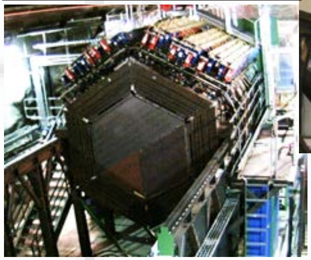


- MINERvA also has passive nuclear targets to allow comparison of π^+ (and maybe π^0) on Pb and Fe to CH. Requires statistics of full dataset.

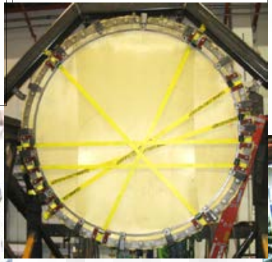
1” Fe / 1” Pb
323kg / 264kg

1” Pb / 1” Fe
266kg / 323kg

3” C / 1” Fe / 1” Pb
166kg / 169kg / 121kg

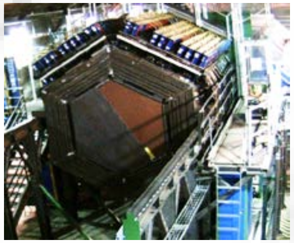


6” 500kg Water

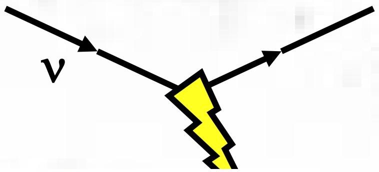


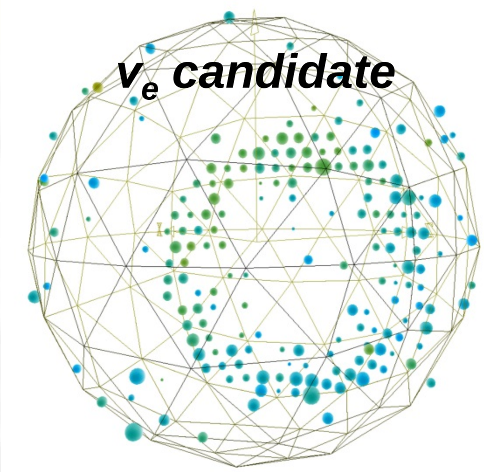
0.3” Pb
228kg

.5” Fe / .5” Pb
161kg/ 135kg



MiniBooNE Datasets

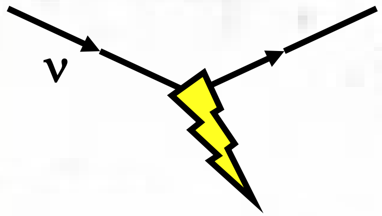




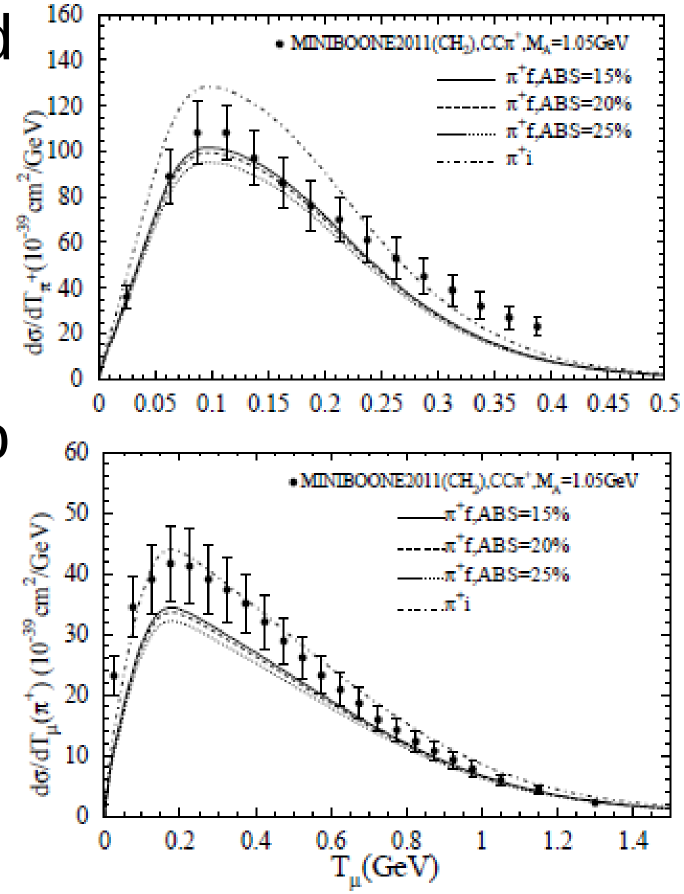
- Mineral oil Cerenkov (some scintillation also), 4π acceptance.
- Measured charged-current π^0 and π^+ on CH_2 from ~1 GeV neutrinos.
  - Photon acceptance and separation from μ is good
  - π/μ separation is much more difficult, but look for events with π+μ in final state
- Dataset has "complete" measurements of π and μ kinematic distributions and derived quantities.

A. Aguilar-Arevalo et al., Phys.Rev.D 83, 052007 (2011)
A. Aguilar-Arevalo et al., Phys.Rev.D 83, 052009 (2011)

Axial Form Factors + FSI can explain Nuclear Data?



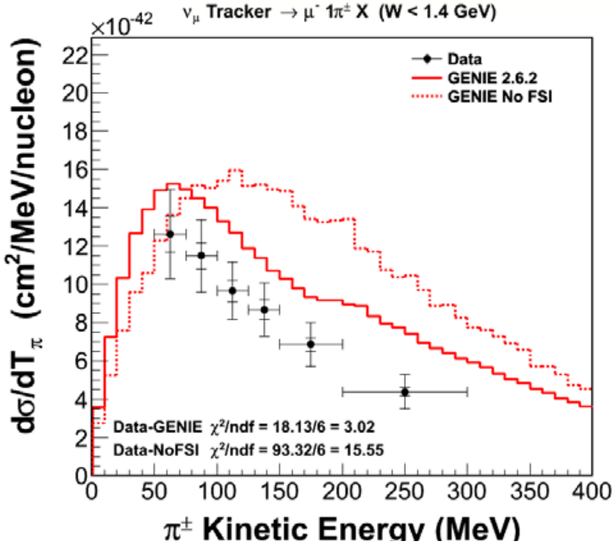
- Some authors have bravely compared nuclear models with CH_n data *[e.g., J.-Y. Yu et al, Phys. Rev. D91 (2015) 054038 shown here. See also Lalakulich, O. and Mosel, U., Phys. Rev. C87 (2013) 014612]*
- Difficult to get all distributions, even within a single experiment, to agree to the same model *(MiniBooNE at right)*
- FSI problem or hard scattering model problems? Which is it? Much to do.
  - Move beyond Rein-Sehgal for hard scattering
  - Test all FSI models.
  - Is one (or more) dataset wrong?

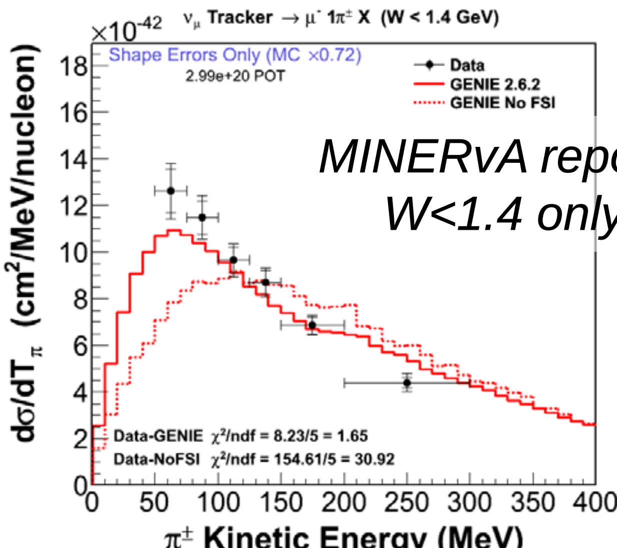


m_Δ [GeV]	Γ_0 [GeV]	$C_3^V(0)$	M_V [GeV]	$C_5^A(0)$	M_A [GeV]
1.232	0.120	1.95	0.84	1.2	1.05

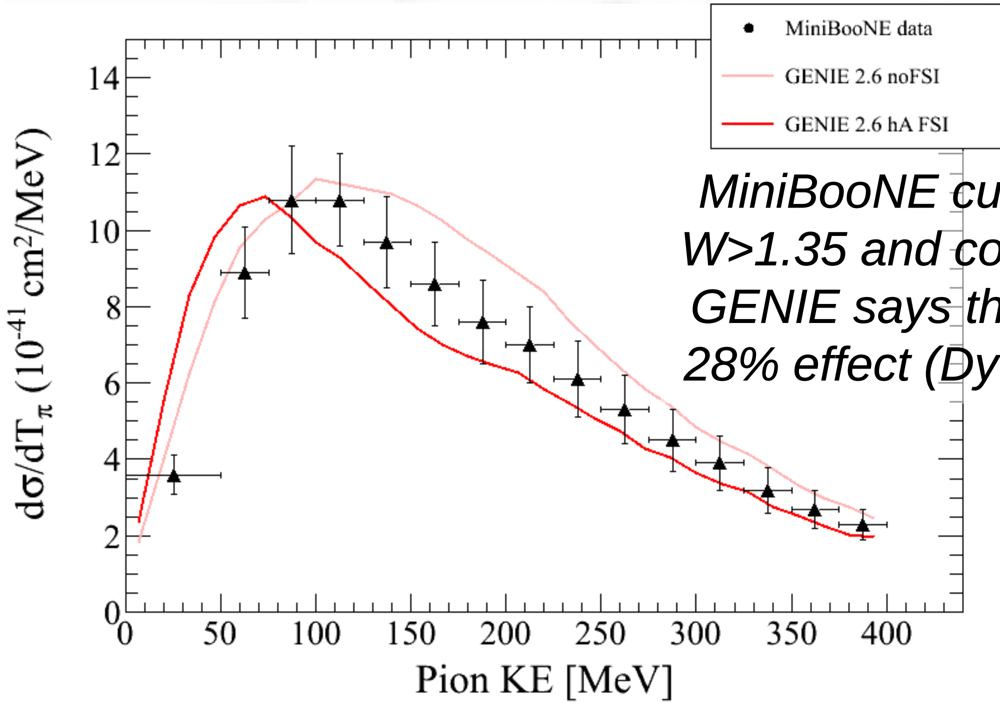
Table I: Input parameters for the Δ resonance production [10].

MINERvA π^+ comparison to MiniBooNE





MINERvA reports W<1.4 only

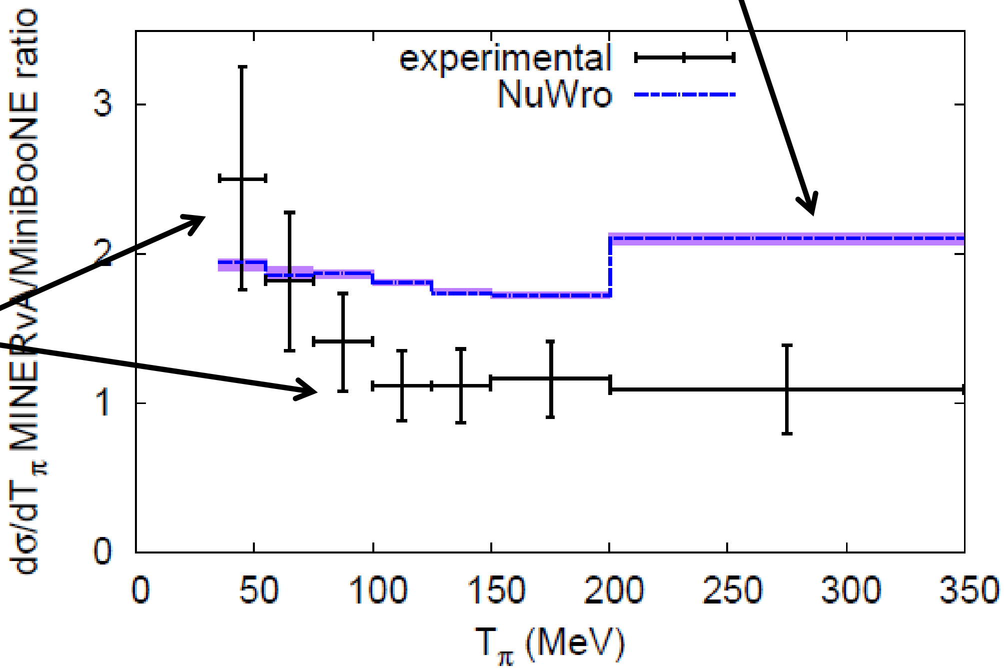


MiniBooNE cuts out W>1.35 and corrects. GENIE says this is a 28% effect (Dytman).

- Even with ~10% flux uncertainties from both experiments, there is ~2σ tension between MINERvA and MiniBooNE
- Shape tension also
- Note, MINERvA π^+ and π^0 are similar in rate and shape

Consistent with Production or Cascade FSI Uncertainties?

- Interesting study by Sobczyk and Zmuda (arXiV:1410.7788) asks if uncertainties in final state “cascade” models and pion production to explain MiniBooNE-MINERvA difference
- Their conclusion: it cannot. Theory uncertainties on the ratio are very small.

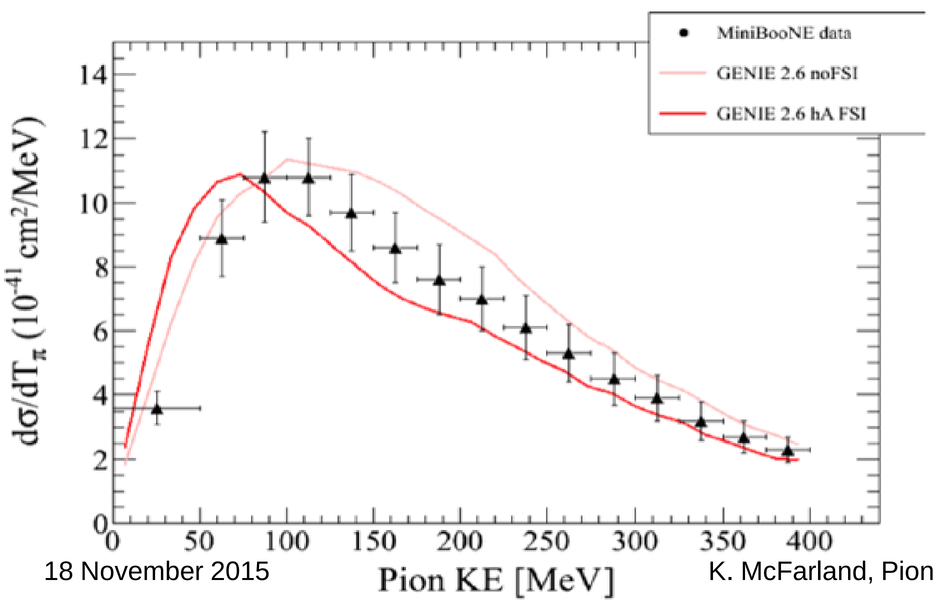


- *Uncertainties in bins are highly correlated, so maybe explains high energy part?*
- *And maybe low energy is a statistical fluctuation?*
- *Unlucky or real?*

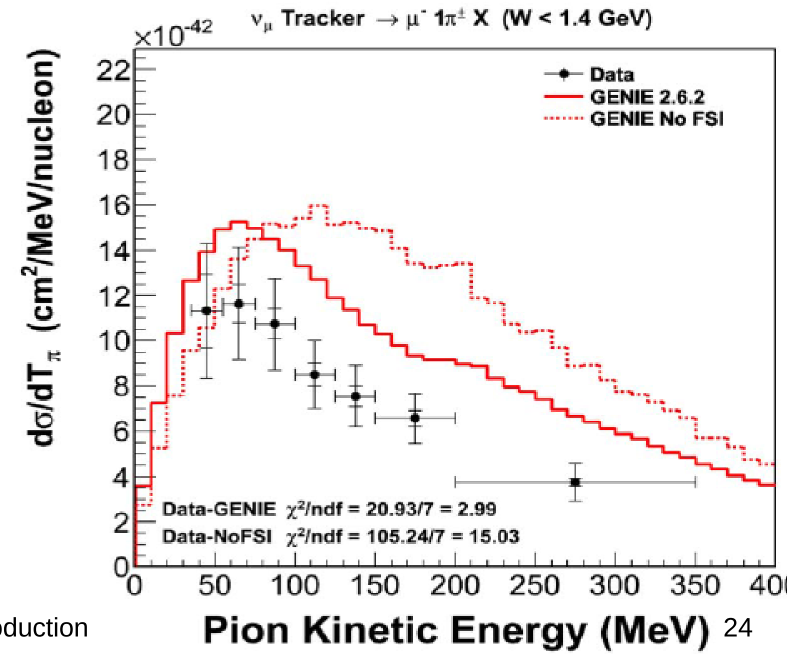
Consistent with Production or Cascade FSI Uncertainties?

- Similar analysis by Steve Dytman (private communication)
  - FSI effect is nearly identical
  - Fine print again: updated MINERvA flux increases σ by 11%
    - o Sadly, not big enough to "fix" disagreement

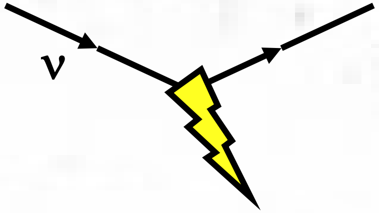
MiniBooNE data



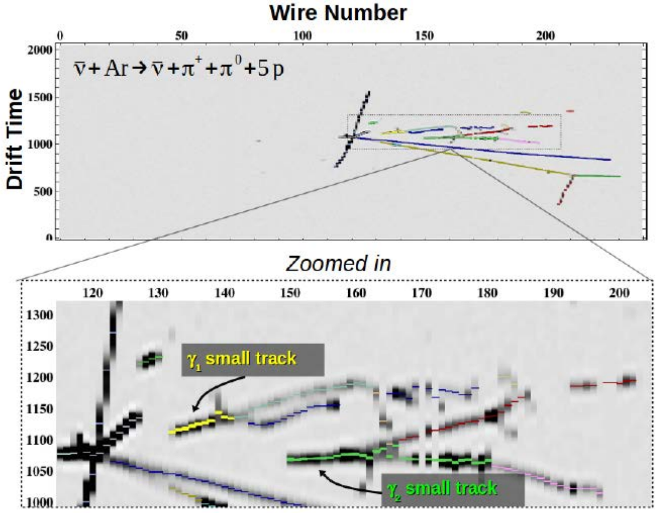
Minerva data



Last Week Tonight: ArgoNeuT NC π^0

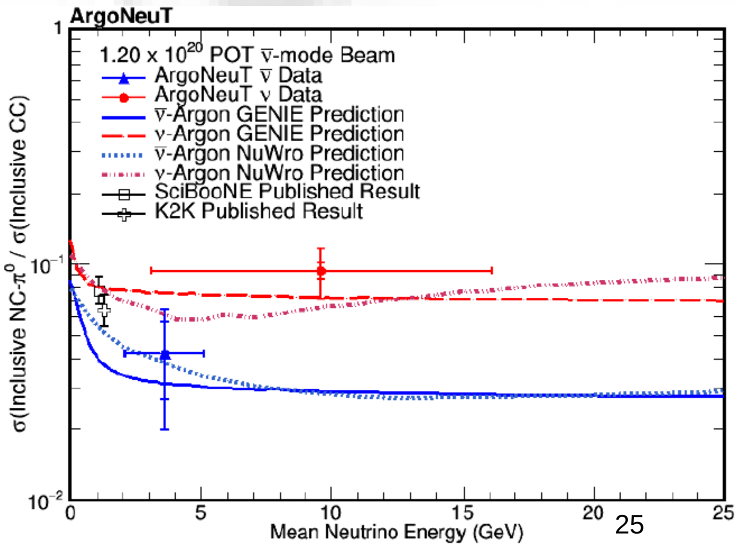


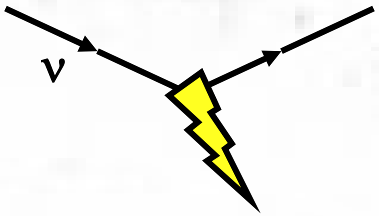
- ArgoNeuT identifies NC π^0, from events with two photons (maybe not contained) and no muon
  - Really interesting technical detail in the paper on liquid argon reconstruction, arXiV:1511.00941
  - ArgoNeuT is small, so statistics are probably not good enough to test models. Proof of principle for future.



Simulated ArgoNeuT event.

Photon leakage corrected with angles (m_π), shower profile and position.



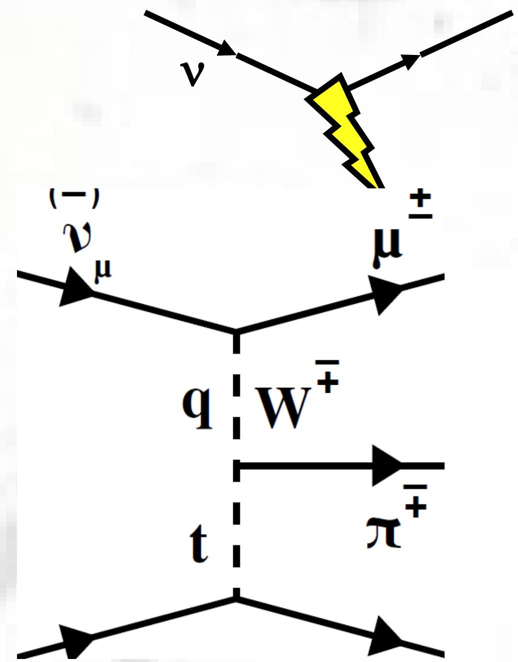


Coherent Pion Production

(not Kate's CEvNS reaction)

Coherent and Inelastic

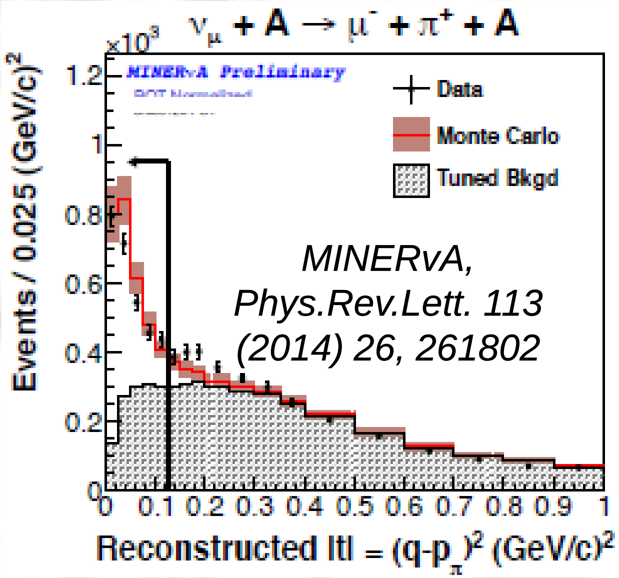
- Weak boson converts to pion in field of nucleus
- Gives energetic leading pion which is a potential lepton background in less capable detectors
- Model independent features: low momentum transfer, |t|, to target and no recoil activity at vertex



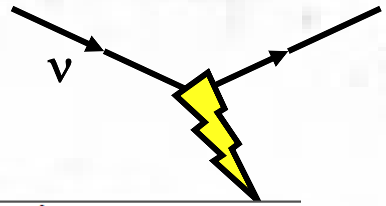
$$E_\nu = E_\mu + E_\pi$$

$$Q^2 = 2E_\nu(E_\mu - P_\mu cos\theta_\mu) - m_\mu^2$$

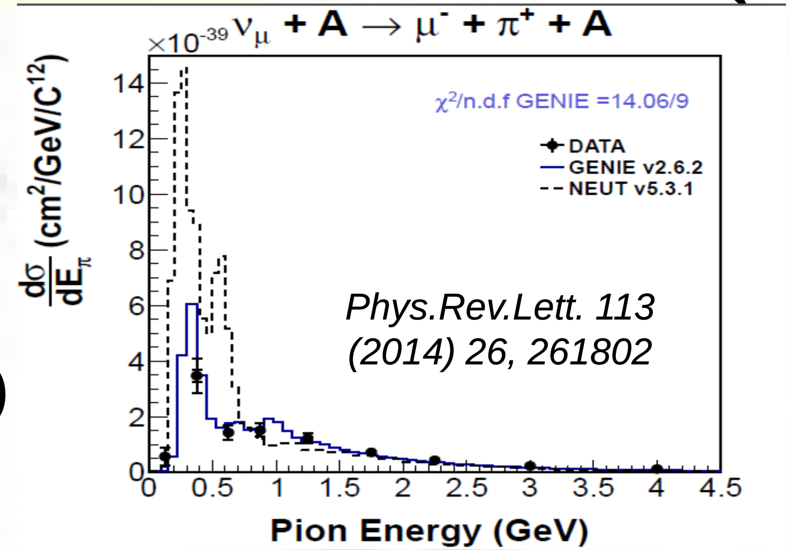
$$|t| = -Q^2 - 2(E_\pi^2 + E_\nu p_\pi cos\theta_\pi - p_\mu p_\pi cos\theta_{\mu\pi}) + m_\pi^2$$

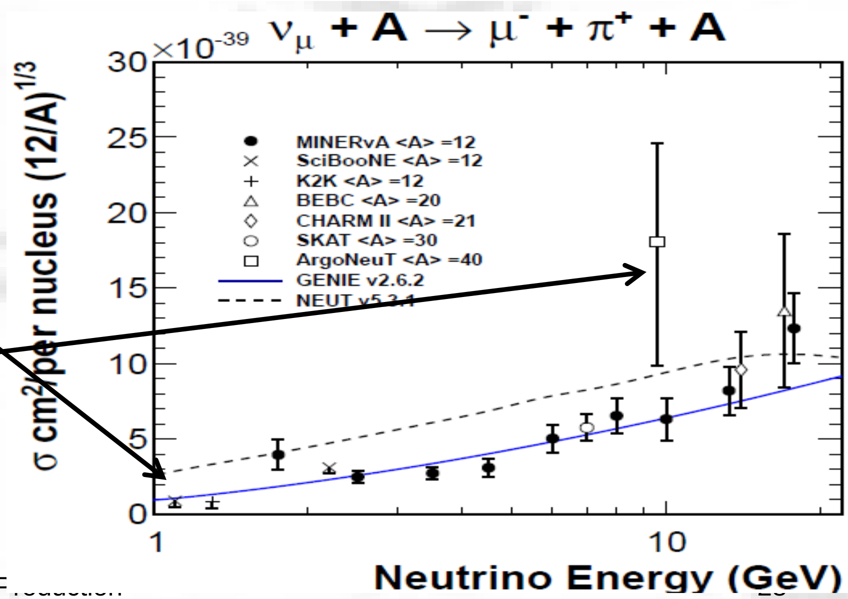


News on Coherent Pions

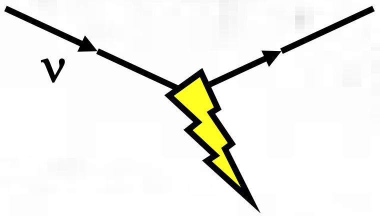


- Recent MINERvA data *(Phys.Rev.Lett. 113 (2014) 26, 261802)* shows overestimate of low energy pions in generators
- Updating (PRD in preparation)
- Biggest effect of low energy pions is at low E_ν
- Explains non-observations at K2K and SciBooNE?
- Note also recent ArgoNeuT measurement on Ar (low statistics), *Phys Rev. Lett 113 (2014) 261801*

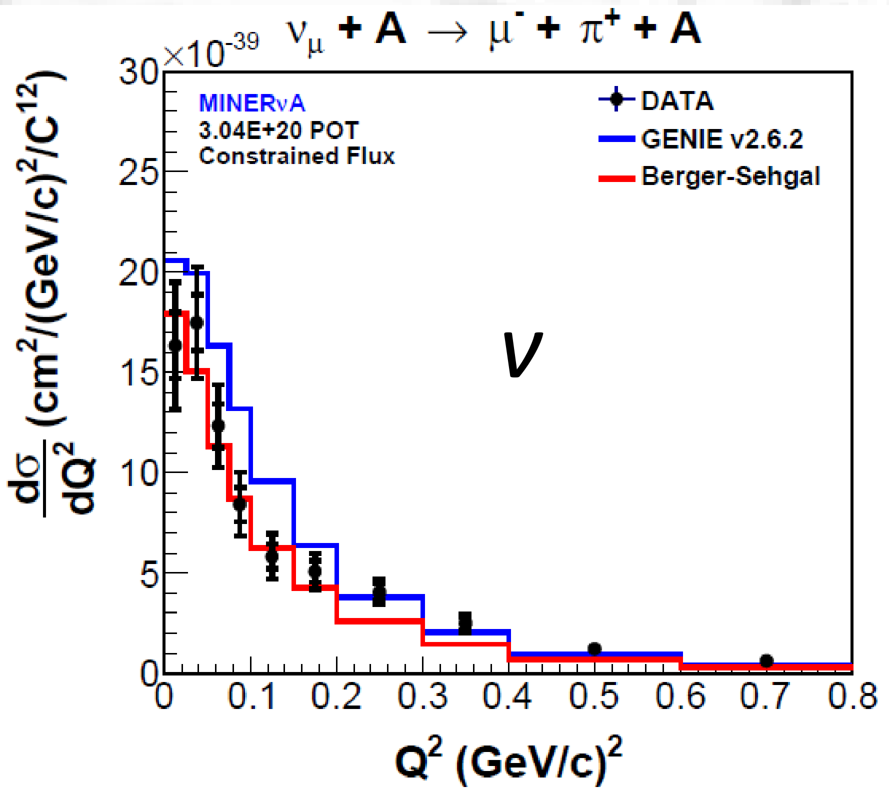


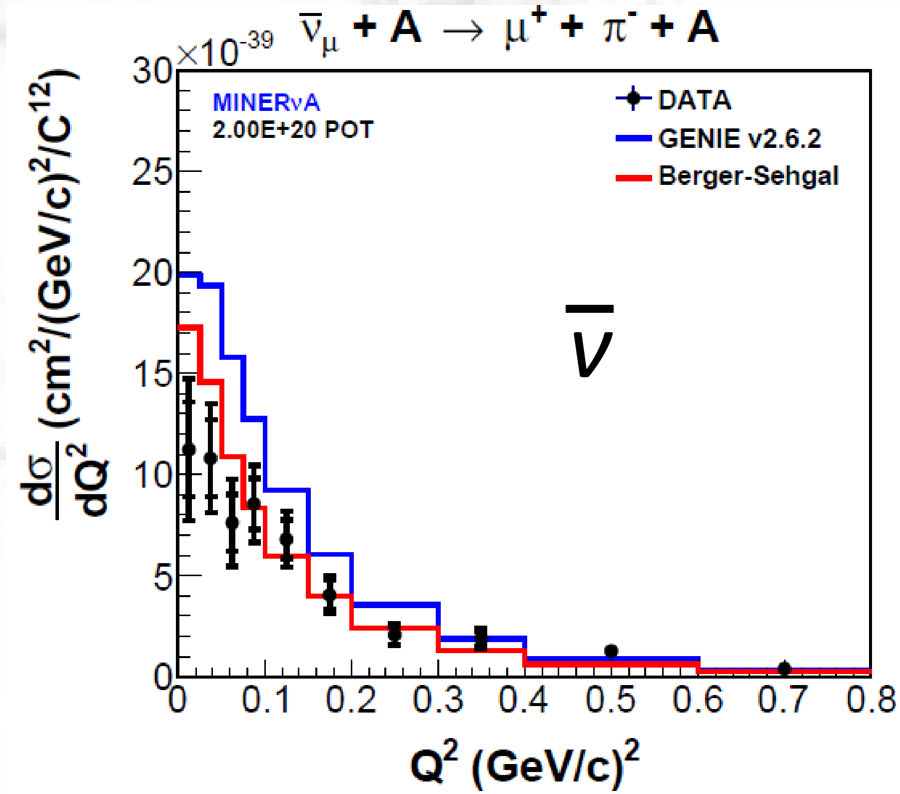


$d\sigma/dQ^2$ Coherent

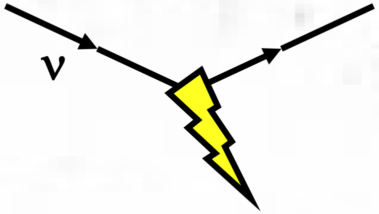


- Main new result is Q^2 dependence of reaction.
  - PCAC predicts identical cross section at $Q^2 \rightarrow 0$ limit
  - Q^2 distribution is a model-dependent assumption

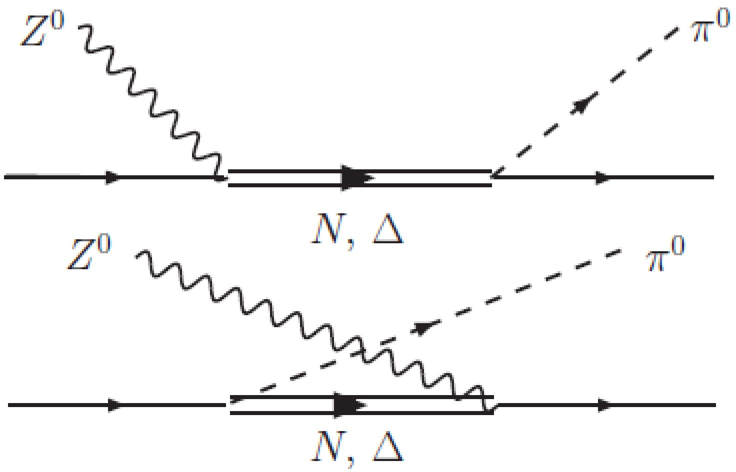




Can we learn from this Data?

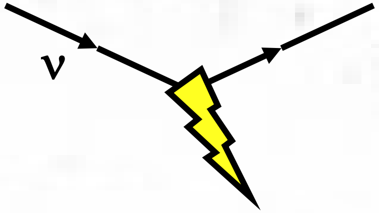


- Coherent pion production is usually interpreted in terms of PCAC models, but there are microphysical models as well, *e.g., Phys.Rev. C76 (2007) 068501, Phys.Rev. C80 (2009) 029904*

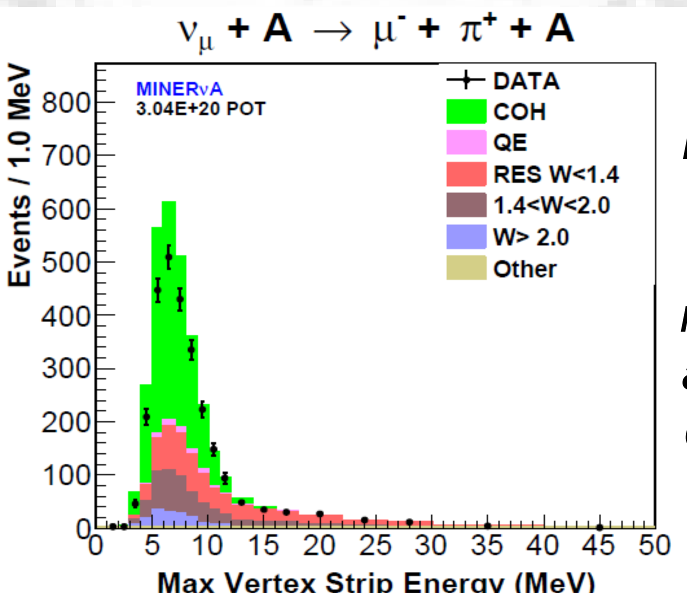


  - Can extract information on Δ(1232) form factors from low E_π spectrum with corrections for nuclear effects?
  - In this model, primary nuclear effect is modification of Δ(1232) properties inside the nucleus. No FSI *per se*.
  - Full statistics MINERvA data and data from liquid Argon experiments will both be critical for realizing this idea.

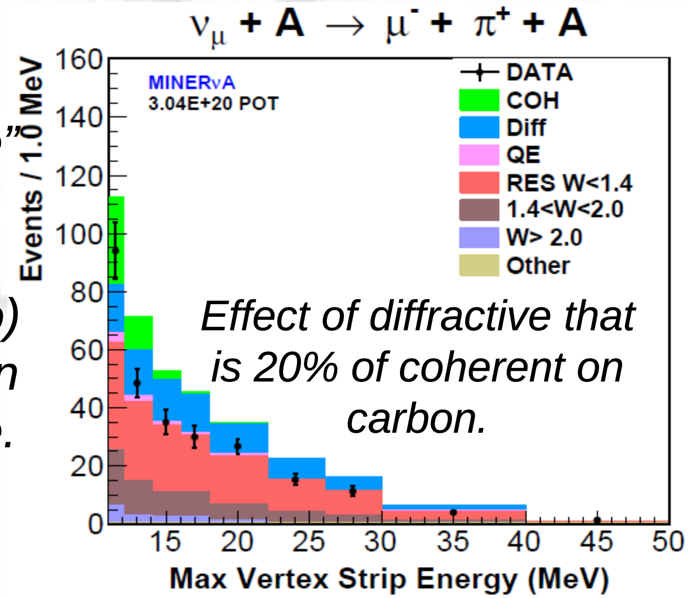
Diffractive Pion production from protons



- Innovation: explicit search for unmodeled “diffractive” events. Energy of recoil proton in a single scintillator strip from Bragg peak *(see Rodrigues talk from yesterday)*.
  - Prediction from model (Belkov and Kopeliovich, Sov. J. Nucl. Phys. 46, 499 (1987)) is rate increase of 7% (4%) of neutrino (antineutrino) sample, as described in published MINERvA result



Fit prefers “diffractive” contribution of -1±8% (-3±7%) to neutrino (antineutrino) as a % of coherent on carbon in our sample.

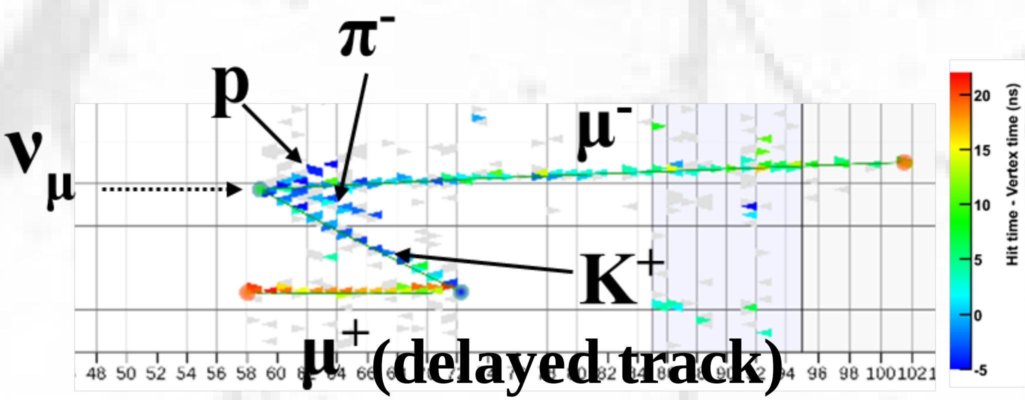


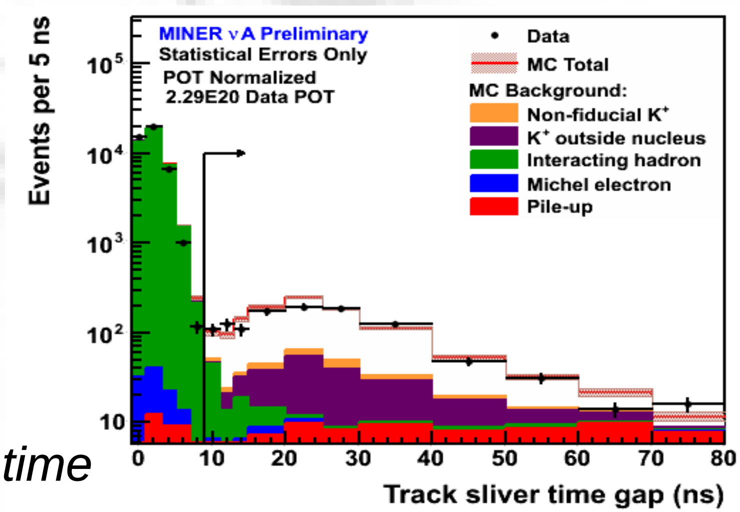
Effect of diffractive that is 20% of coherent on carbon.

Kaon Production

Isn't that a strange pion?

- Why measure kaon production?
  - Rate of kaon+"nothing" is important for atmospheric neutrino backgrounds to $p \rightarrow K^{+}\nu$ in water Cerenkov
  - Final state interactions of kaons are important for searches in bound protons, e.g., searches in LAr TPCs.
- Isn't this too hard to do? They're so… unusual.

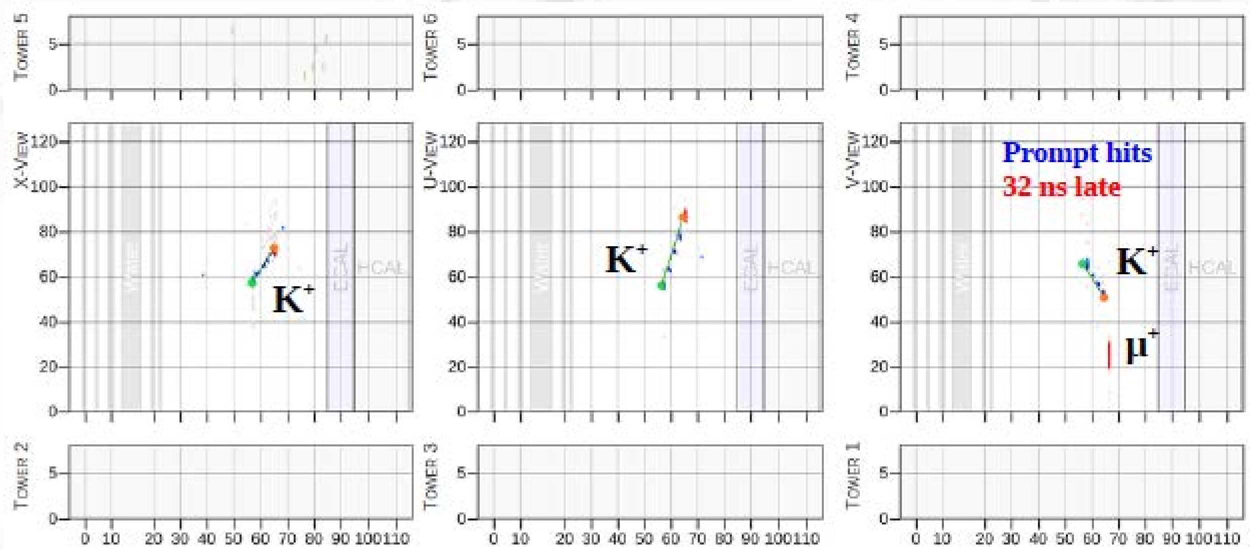




MINERvA Kaon candidate and delayed track time

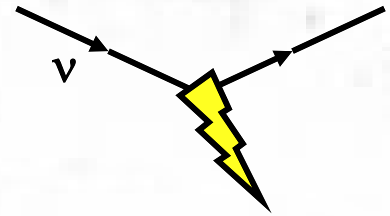
MINERvA progress towards neutral current kaons

- For proton decay at SK, want “kaon plus invisible in a water Cerenkov” events
  - We can find kaon plus nothing events

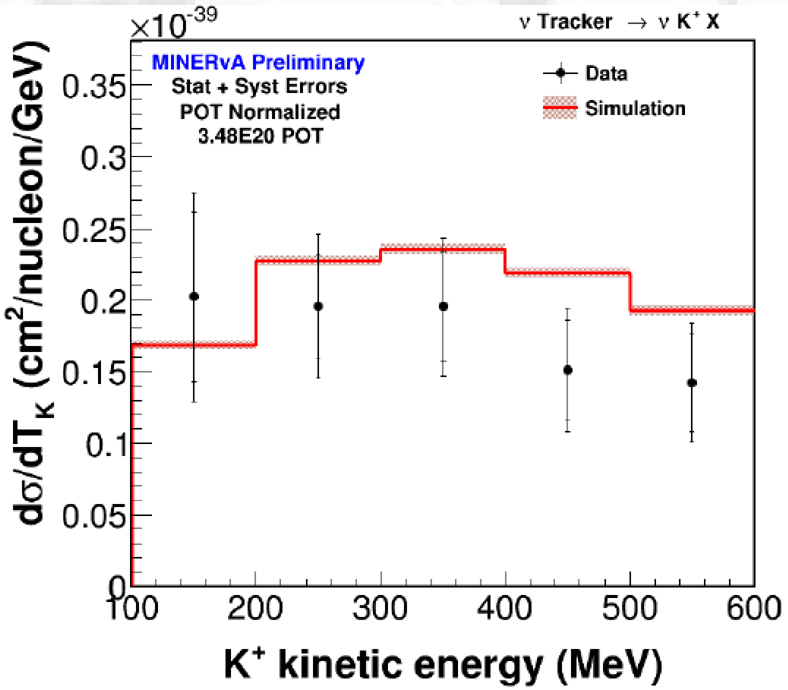


  - Kaon+ “invisible in water Cerenkov” is harder because sometimes it’s difficult to separate protons from $\pi^{\pm}$ and neutrons from π^0

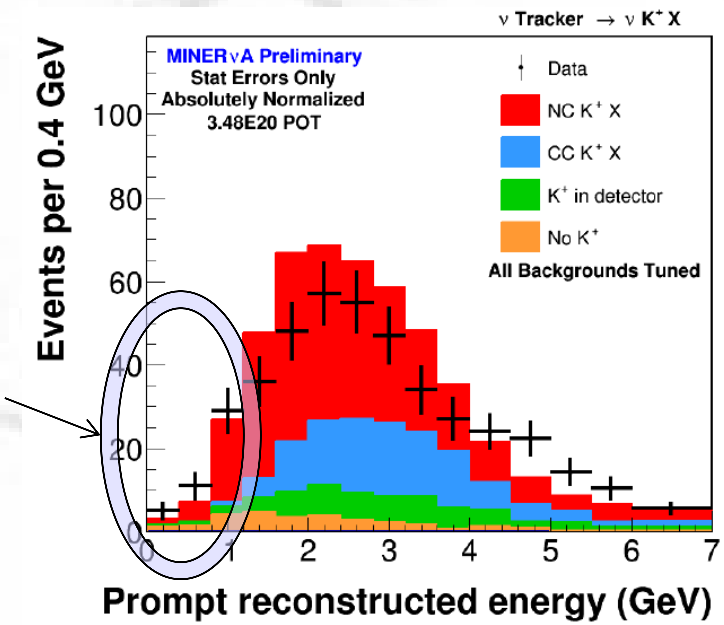
MINERvA progress towards neutral current kaons



- We have a preliminary cross-section as a function of kaon kinetic energy, and a visible energy spectrum. Working to learn more.

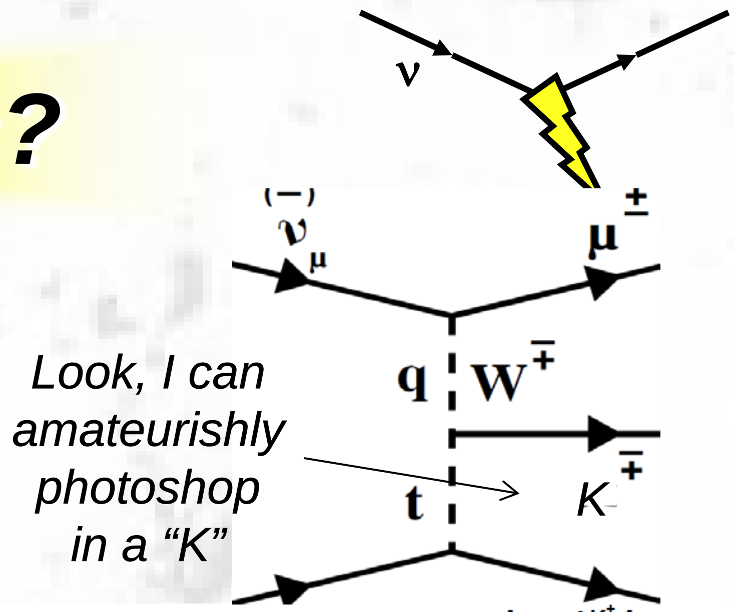


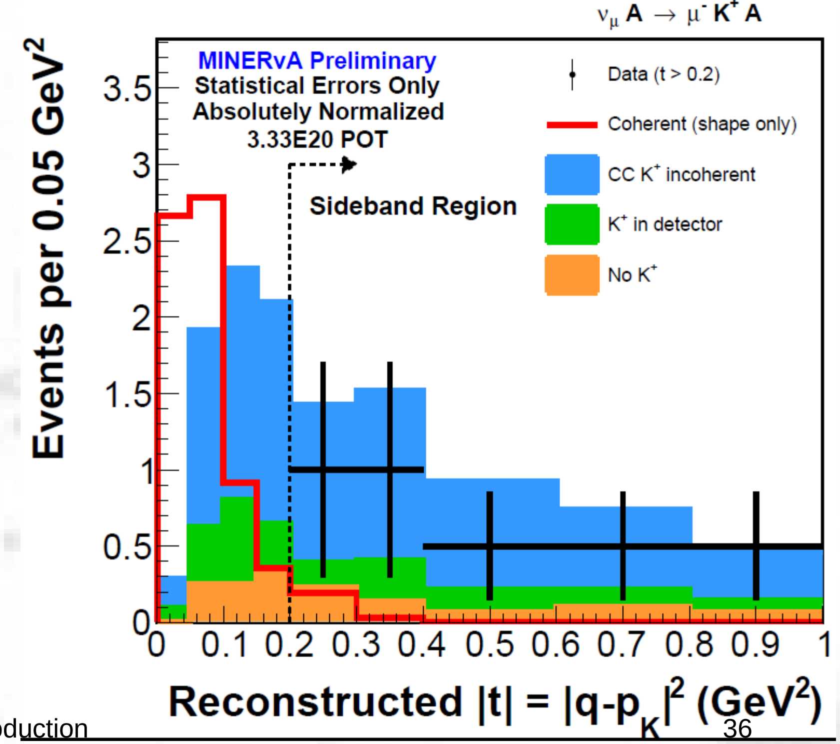
Events of greatest interest are these, at low prompt (non-K decay product) energies



Coherent Kaons?

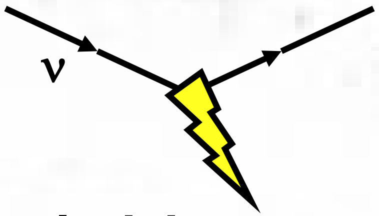
- If we produce pions coherently, we should also produce kaons
  - Cabibbo suppressed
  - Heavier kaon also eliminates the lowest |t| cross-section
- Same model independent technique as for pions
  - We can tune the predicted kaon background to match the high |t| sideband sample
  - Background at |t|<0.1 ~1 event
  - We haven't looked at data sample that passes the |t| cut to see if we have evidence for the process



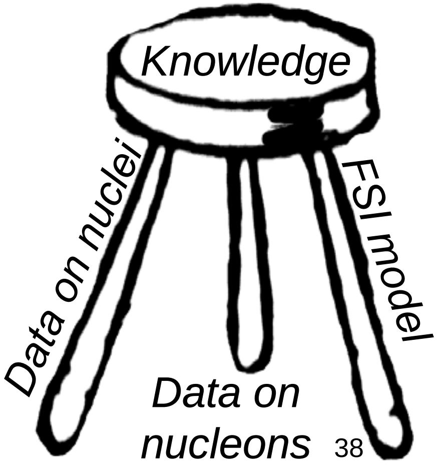


Summary and Prospects

Summary



- Pion (meson) production data on nuclei is out there, and more is on the way
  - Oscillation experimental ultimate precision relies on accurate models of this process, along with the effect of medium heavy nuclei
- The physics probed is the effect of the nucleus on production and survival
  - Hydrogen and deuterium reanalysis (finally) gives us a leg to stand on
  - Theory of initial state in nucleus is poor, e.g., compared w/ CCQE



Prospects

- Whether or not we have theory to describe it, experiments will continue to measure pion production on nuclei
  - More accurate results. More distributions. More measurements of exclusive processes, particularly on Argon targets (LArTPCs)
  - New comparisons on different medium-heavy and heavy nuclei. (But no new deuterium data)
- Need work on both "first principles" and "effective" models to describe new data.

Backup

MINERvA's Flux Changes

- All the MINERvA results on pion and kaon production shown (except one) are from the previous flux
  - Integral of flux over the relevant energies will decrease 11%, and therefore cross-sections will increase by roughly this amount
- The exception is the new coherent $d\sigma/dQ^2$ for neutrino mode, which uses νe scattering constraint, where flux will only decrease 5%