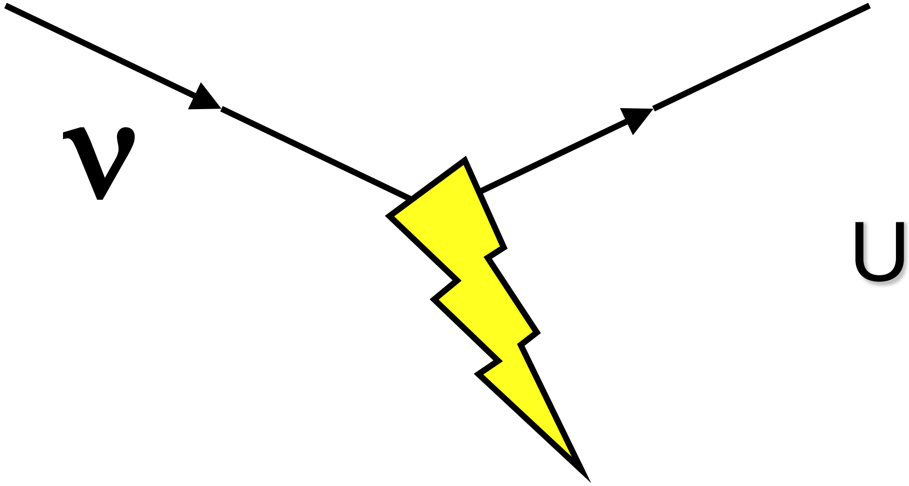
Neutrinoproduction of Pions



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NSTAR 2015
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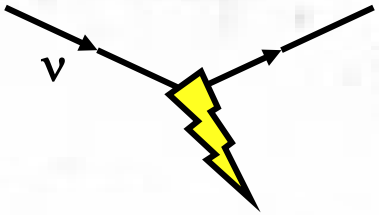
Outline

- Goals of the new neutrino experiments
- Important datasets and interpretations
- Summary and Prospects

Neutrino Mass, Mixings and Oscillations



- Neutrinos oscillate because the flavor eigenstates, associated with charged-current weak interactions are not the mass eigenstates

$$\nu_{\text{flavor},\,\alpha} = \sum_{\text{mass eigenstates},\,i} U_{\alpha i}\nu_i$$

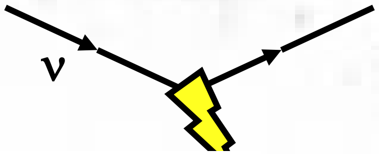
- For two generation oscillations in vacuum:

$$P(\nu_\alpha \to \nu_\beta) = \left|U_{\alpha 1}U_{\alpha 2}U_{\beta 1}U_{\beta 2}\right| \sin^2\left(\frac{(m_2^2 - m_1^2)L}{4E}\right)$$

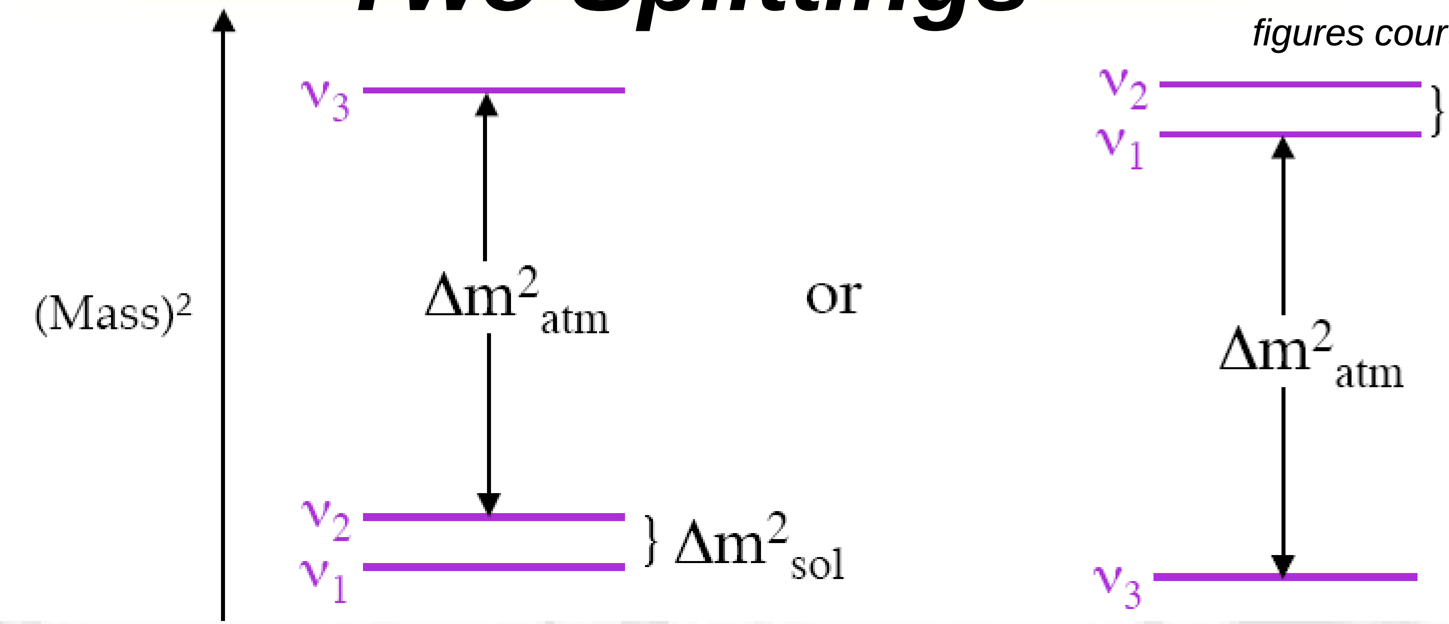
appropriate units give the usual numerical factor ***1.27 GeV/km-eV²***

  - Oscillations require mass differences
  - Oscillation parameters are mass-squared differences, **δm²**, and unitary mixing matrix, **U**.

Three Generations: Two Splittings

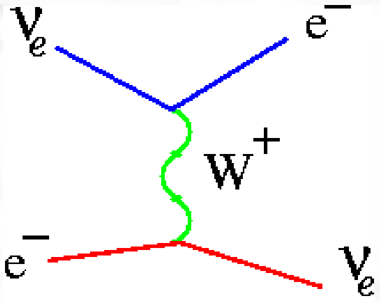


figures courtesy B. Kayser

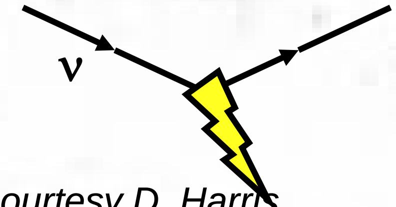


$\delta m_{sol}^2 \rightarrow \delta m_{12}^2 \approx 8\mathrm{x}10^{-5} eV^2$ $\delta m_{atm}^2 \rightarrow \delta m_{23}^2 \approx 2.5\mathrm{x}10^{-3} eV^2$

- Oscillations have told us the splittings in m^2, but nothing about the hierarchy
- *Electron neutrino potential in matter due to coherent forward scattering can resolve the sign of mass splittings*



Three Generation Mixing



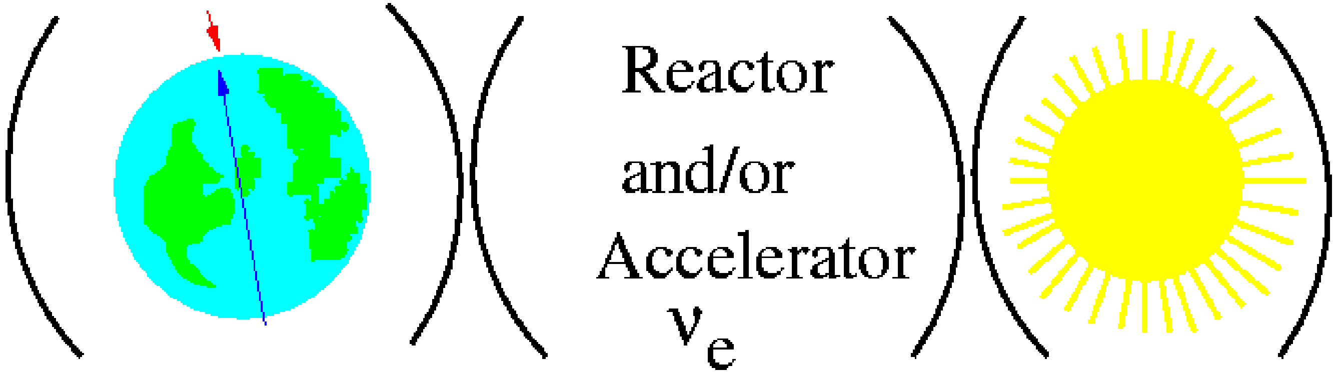
slide courtesy D. Harris

Lesson Learned from CKM: 3 mixing angles and a phase

Call them $\theta_{12}, \theta_{23}, \theta_{13}, \delta$ if $s_{ij} = \sin\theta_{ij}, c_{ij} = \cos\theta_{ij}$, then

$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{-i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

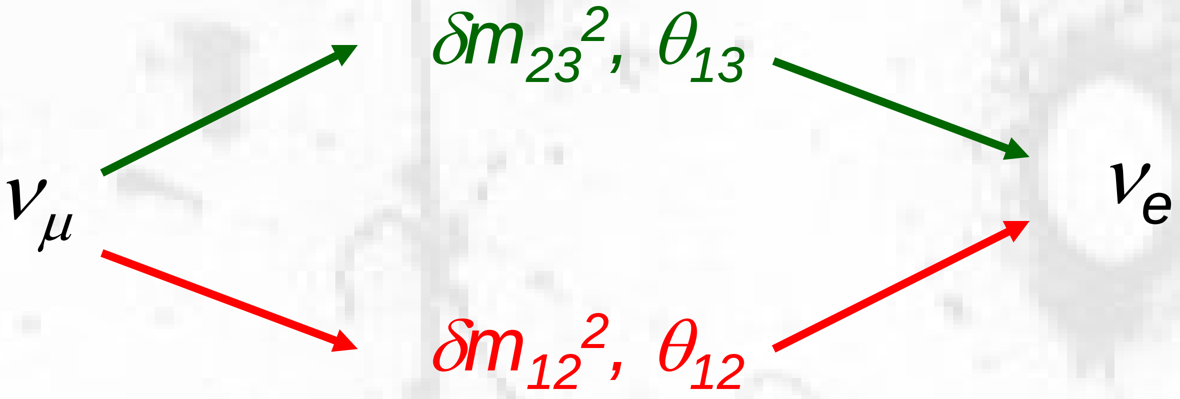
U=



- Note the new mixing in middle, and the phase, δ

Are Two Paths Open to Us?

- If “reactor” mixing, θ_{13}, is small, but not too small, there is an exciting possibility



ν_μ

$\delta m_{23}^2,\ \theta_{13}$

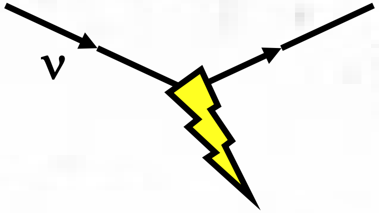
$\delta m_{12}^2,\ \theta_{12}$

ν_e

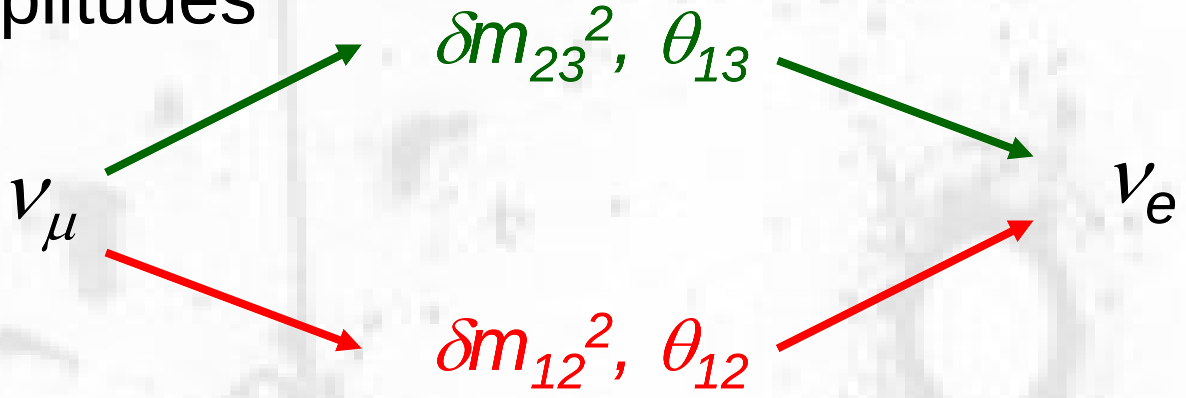
- At atmospheric L/E,

$$P(\nu_\mu \to \nu_e) = \underset{\text{LARGE}}{\overset{\text{SMALL}}{\sin^2 2\theta}}\, \underset{\text{SMALL}}{\overset{\text{LARGE}}{\sin^2\left(\frac{(m_2^2 - m_1^2)L}{4E}\right)}}$$

Implication of two paths



- Two amplitudes


ν_μ

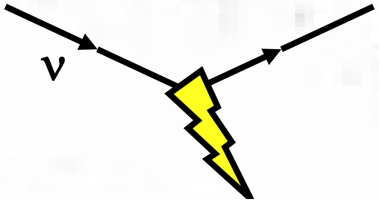
$\delta m_{23}^2,\ \theta_{13}$

$\delta m_{12}^2,\ \theta_{12}$

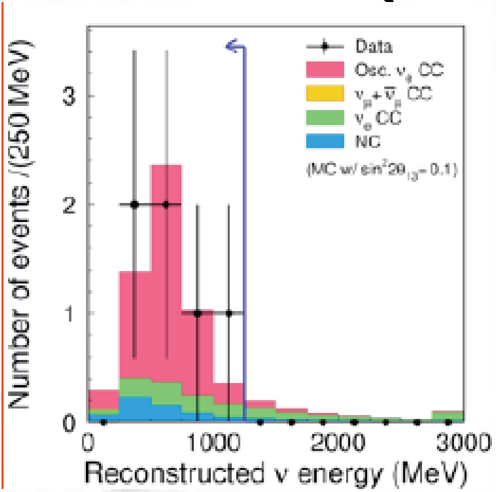
ν_e

- If both small,
  but not too small,
  both can contribute ~ equally
- Relative phase, δ, between them can lead to CP violation (neutrinos and anti-neutrinos differ) in oscillations!

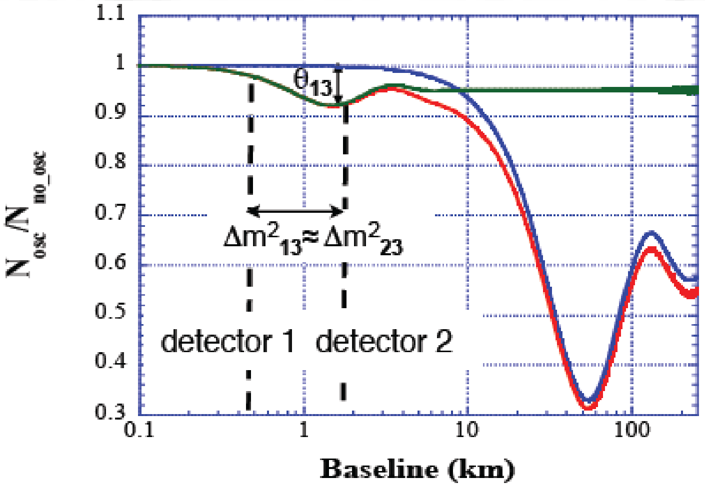
Lesson from Current Experiments: θ_{13} is HUGE

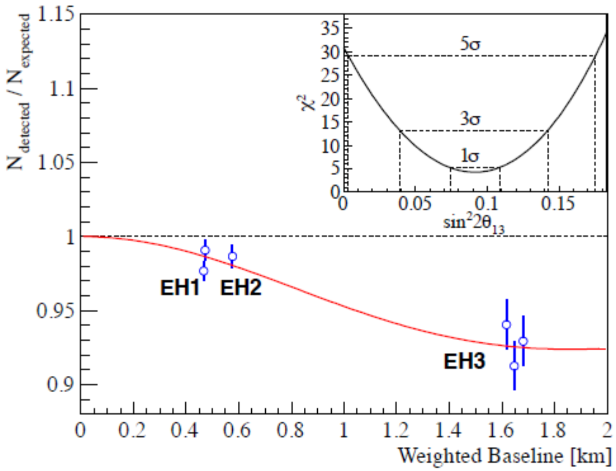


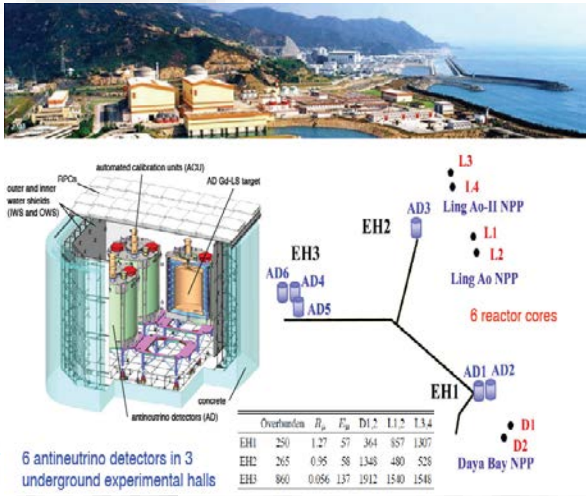
- T2K 2011 hint of $\nu_\mu \to \nu_e$…



- … dramatically confirmed by Daya Bay and RENO reactor experiments in 2012





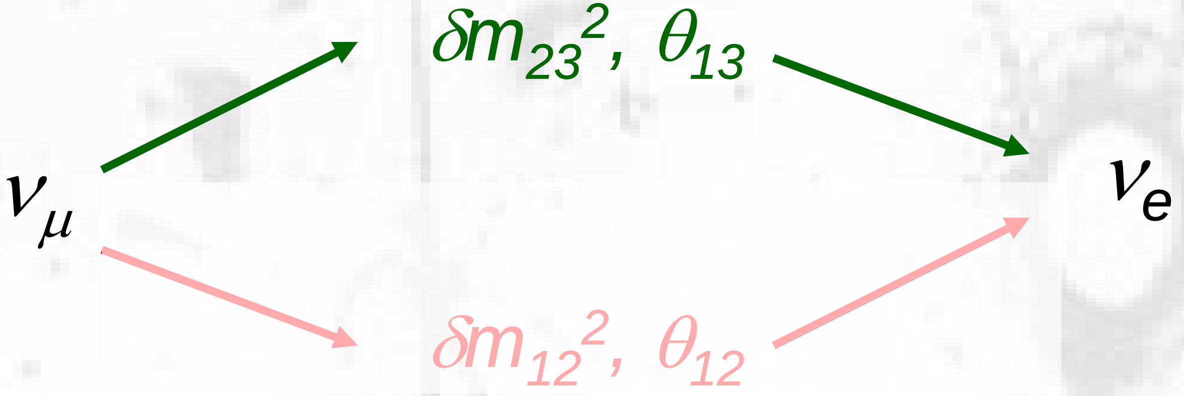


6 antineutrino detectors in 3 underground experimental halls

	Overburden	R_μ	E_μ	D1,2	L1,2	L3,4
EH1	250	1.27	57	364	857	1307
EH2	265	0.95	58	1348	480	528
EH3	860	0.056	137	1912	1540	1548

Implications of Large θ_{13}

- If θ_{13} is large, then one of the two paths



ν_μ

$\delta m_{23}^2, \theta_{13}$

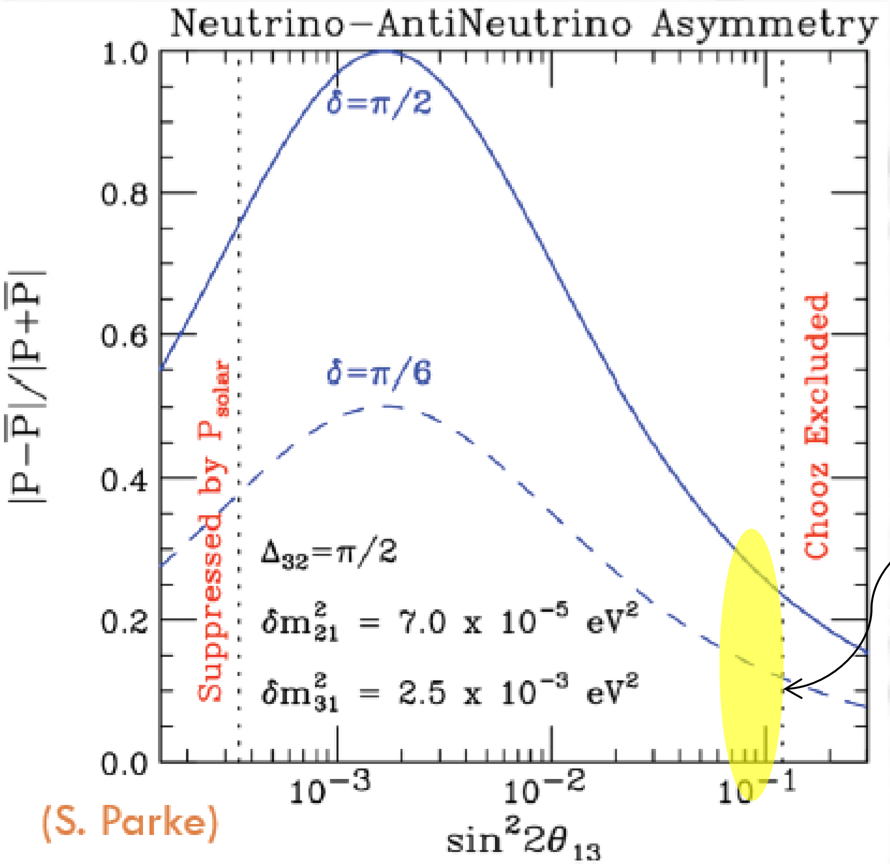
$\delta m_{12}^2, \theta_{12}$

ν_e

is larger than the other.

- This implies large signals, but small CP asymmetries

Implications of Large θ_{13}



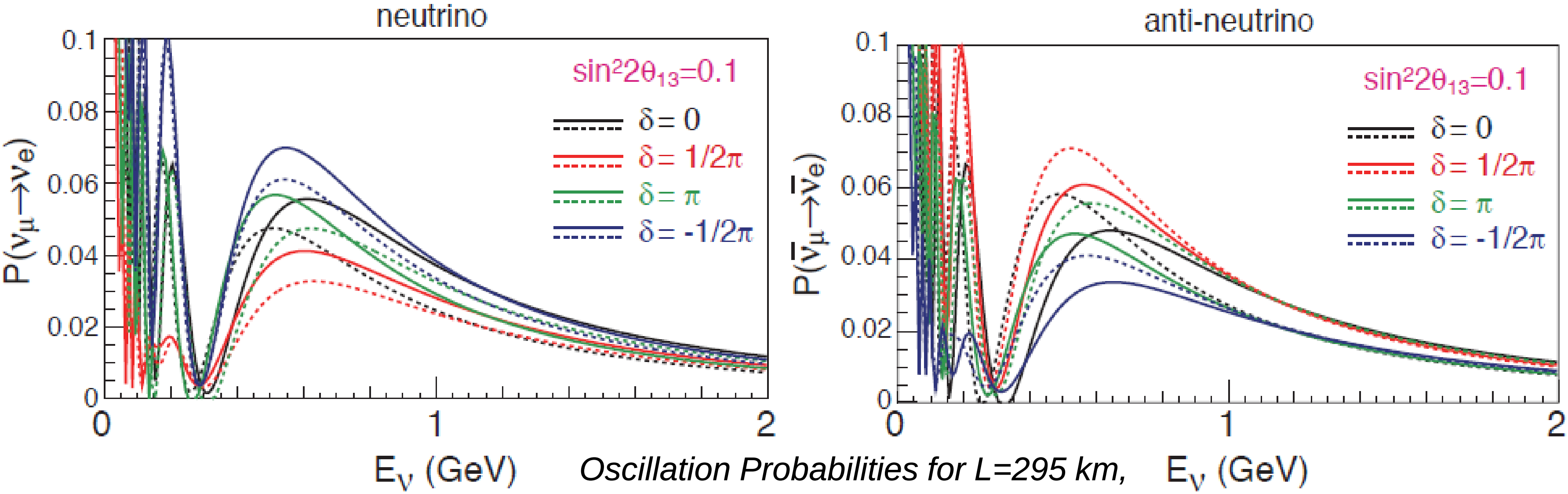
(S. Parke)

- Quantitative analysis to illustrate this expected behavior
  - Fractional asymmetry decreases as θ_{13} increases
- We live here
- Statistics are (relatively) high, so the challenge will be controlling systematic uncertainties.

The Oscillation Challenge

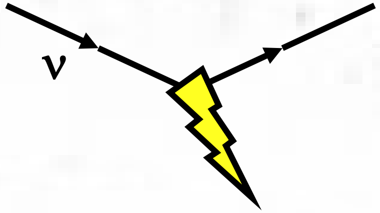
(example, Hyper K)

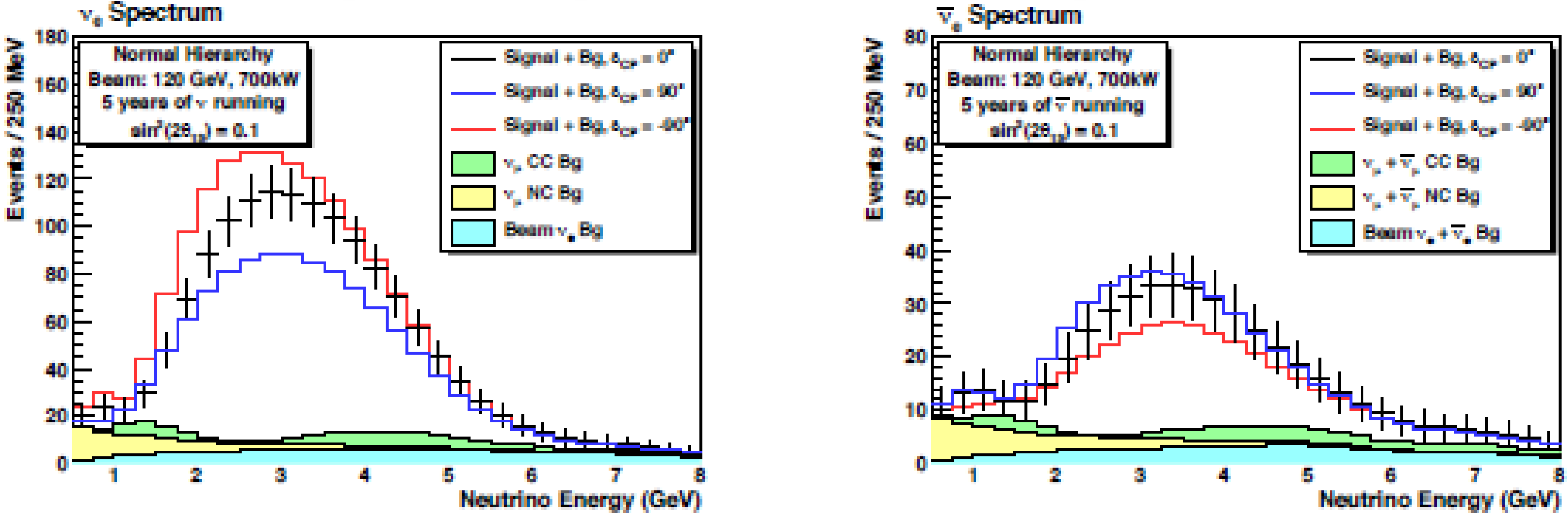
- Discovery of CP violation in neutrino oscillations requires seeing distortions of $P(\nu_\mu \rightarrow \nu_e)$ as a function of neutrino and anti-neutrino energy



Oscillation Probabilities for L=295 km, Hyper-K LOI

The Oscillation Challenge
(example, at DUNE)

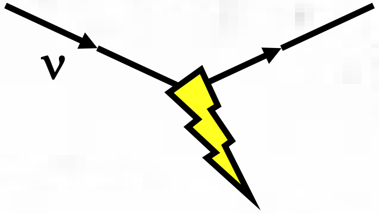




These are not for the latest DUNE designs

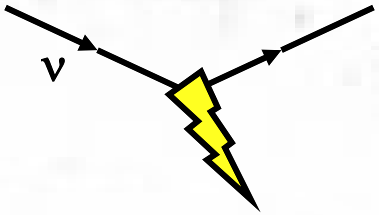
- Maximum CP violation effect is range of red-blue curve
- Backgrounds are significant, vary with energy and are different between neutrino and anti-neutrino beams
- Spectral information is particularly important in wideband beams, but anyway all experiments need to measure E_ν
  - CP effect may show up primarily as a rate decrease in one beam and a spectral shift in the other

Neutrino Facts of Life

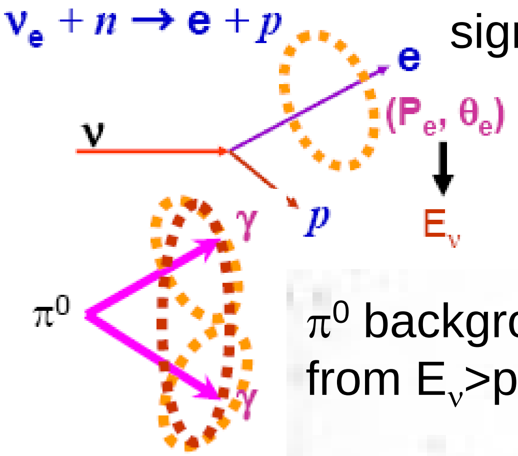


- Neutrino experiments require massive targets to carry out goals
  - Few 10^4 or 10^5 kg of target material of current and "near future" experiments
- We only know what we see in the final state
  - Beam has wide and poorly known range of energies
- Targets are large nuclei
  - Carbon, Oxygen, Argon, Iron are all being used in current or near future experiments
- Detectors have severe limitations
  - Need to measure interactions throughout target
  - Must balance expense vs. capability

Pions that look like Leptons?



- ν_e appearance is very sensitive
  - signal rate is low so even rare backgrounds contribute!
  - similar ν_μ problem: signal is big, but $\pi^\pm$ are excellent at faking μ

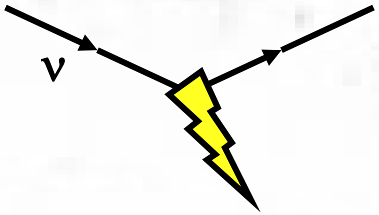


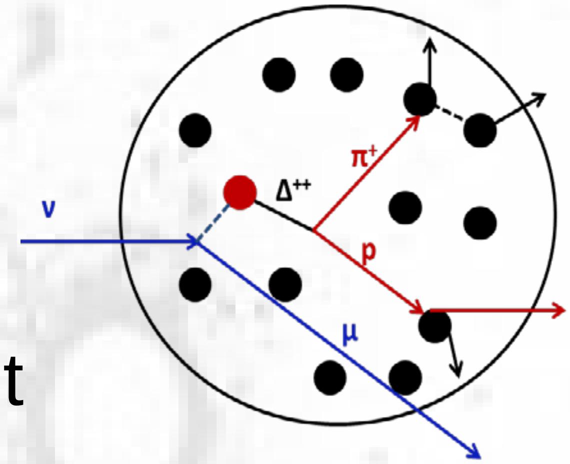
signal

π^0 background from E_ν>peak

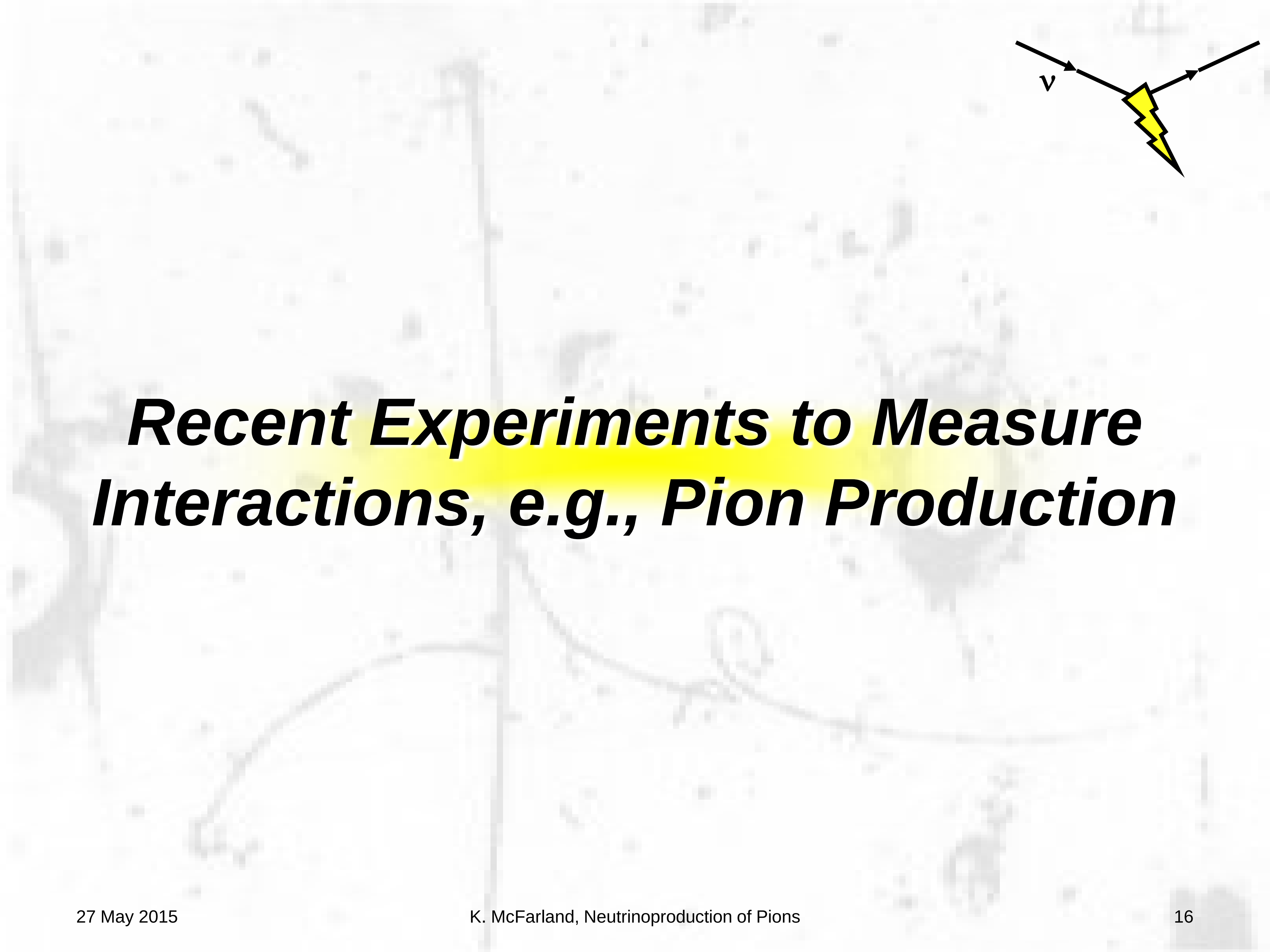
- Current approach is to measure the process elsewhere and scale to the oscillation detector
  - But in practice, there are always corrections that have to come from models that describe the neutrino data

Pion Energy Reconstruction Problem



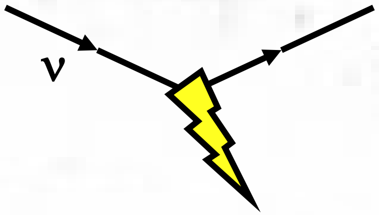


- Must include estimate of pion energy in inelastic events.
- But produced hadrons inside the nuclear targets interact as they exit
  - Detector response is unlikely to be uniform for charged and neutral pions, protons and neutrons
- Modeling this is non-trivial and verifying the knowledge is even more difficult
  - Data on free nucleons is limited. More later on this.
  - Comparing different nuclei may be helpful



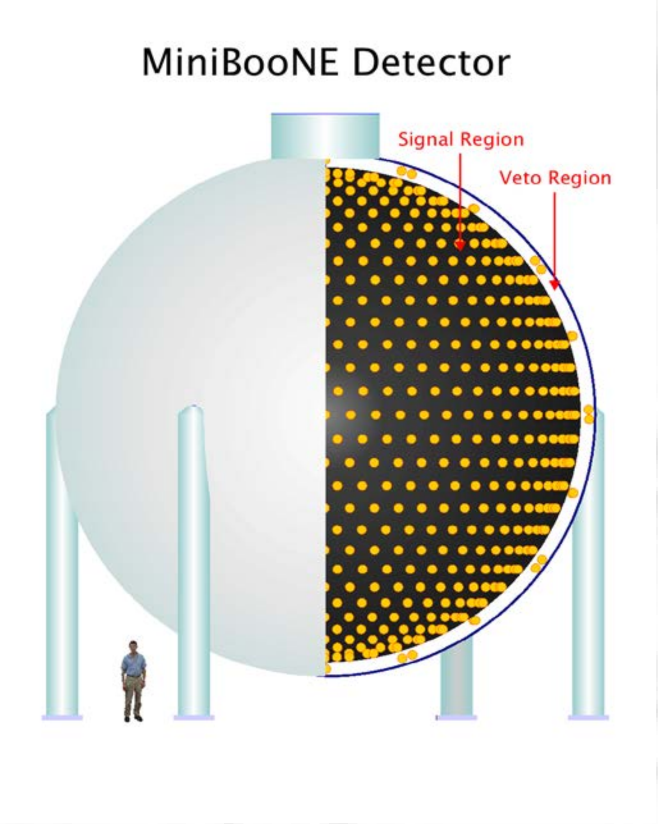
Recent Experiments to Measure Interactions, e.g., Pion Production

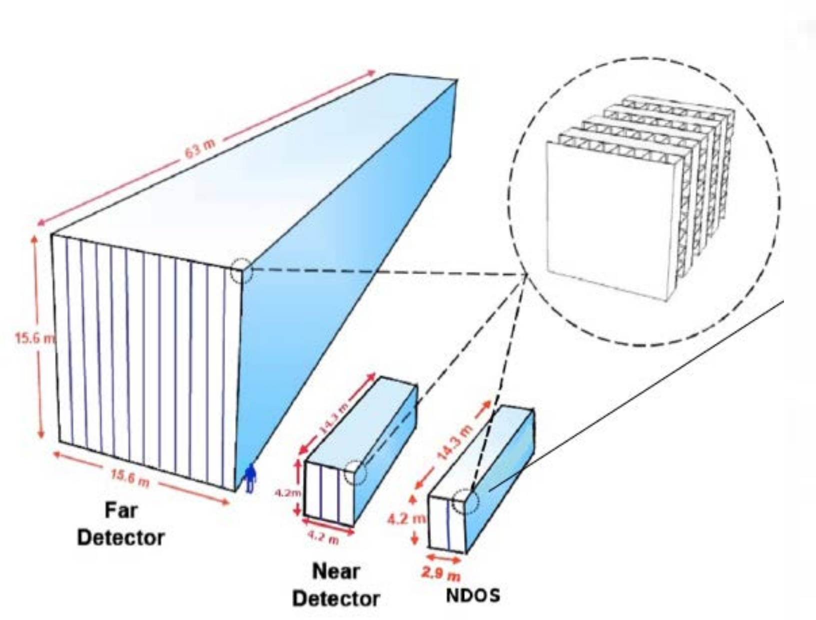
Neutrino Interaction Experiments are Everywhere

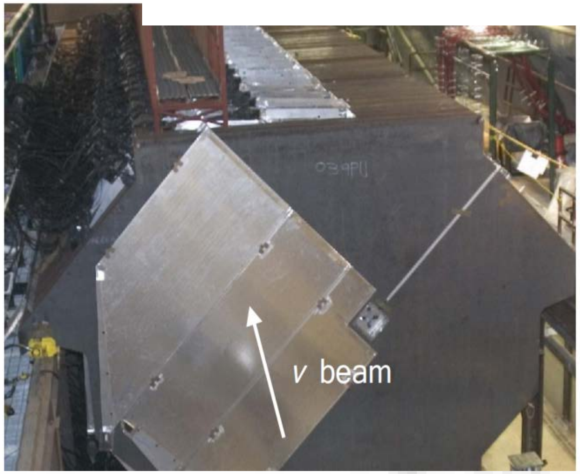


- Well, at nearly at all accelerator beams for neutrino oscillations
- Wide band conventional beams (ν_μ), both on and off axis
- Near detectors ("identical" or not to far detector) for oscillation experiments
    - K2K, MiniBooNE, MINOS, T2K, NOvA
- Dedicated experiments with enhanced detectors
    - NOMAD, SciBooNE, T2K, MINERvA, MicroBooNE

Diverse Technologies

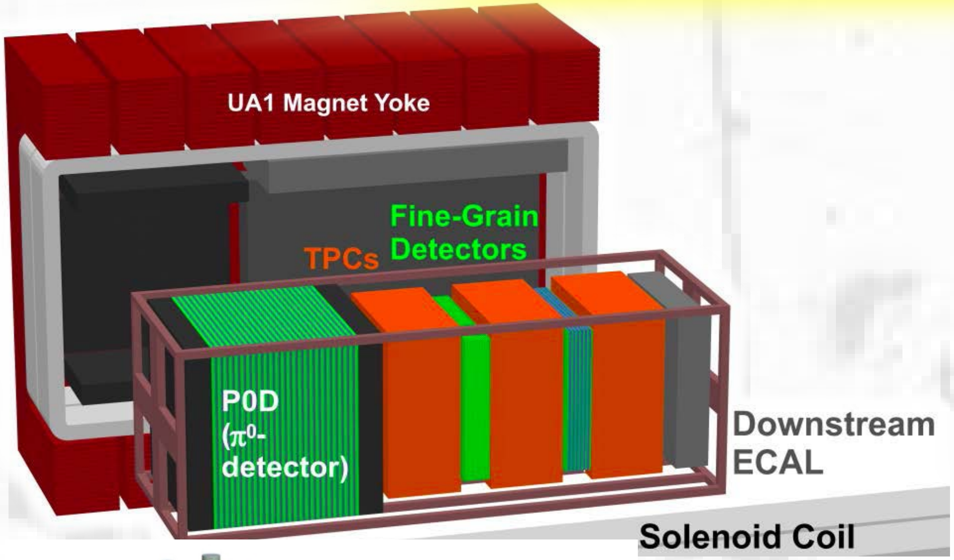


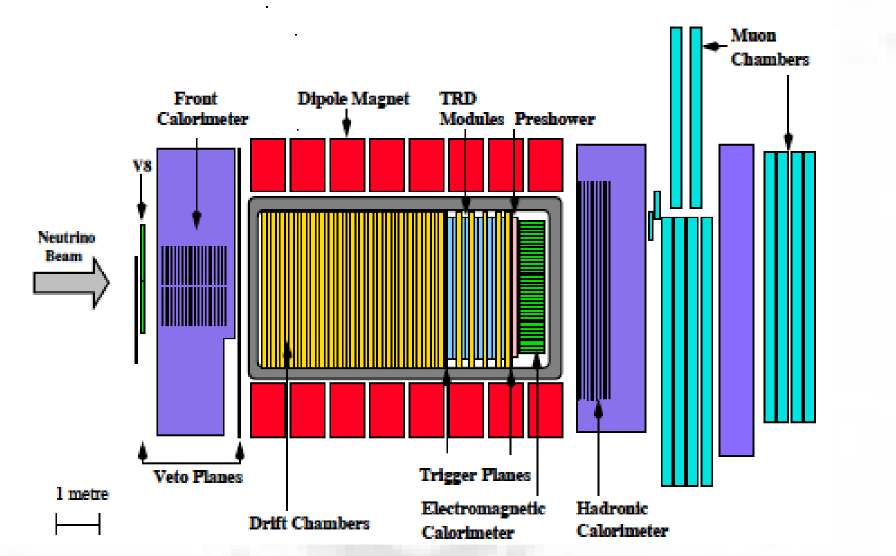


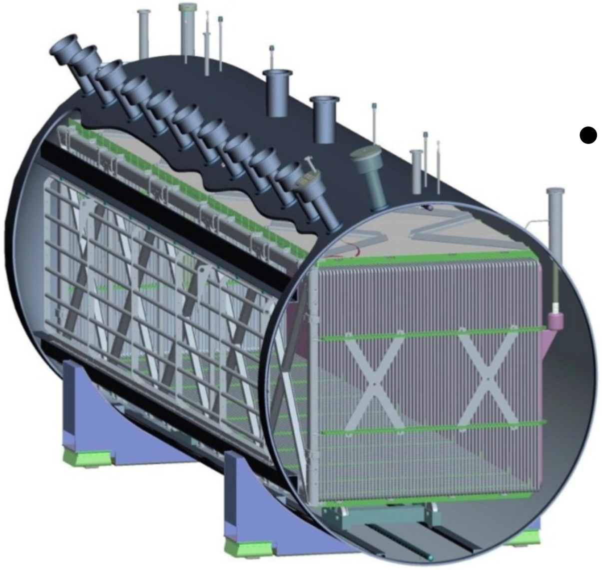


- Massive detectors for oscillation experiments

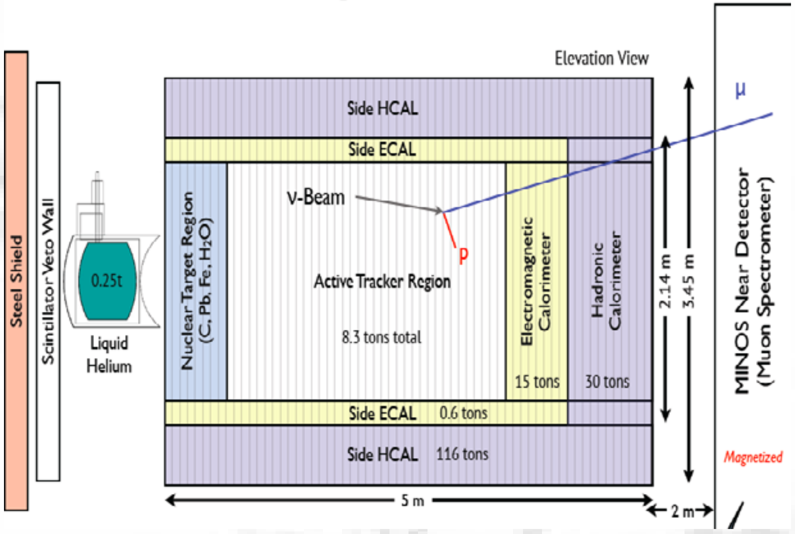
Diverse Technologies







- Fine-grained detectors

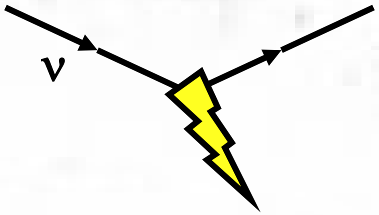


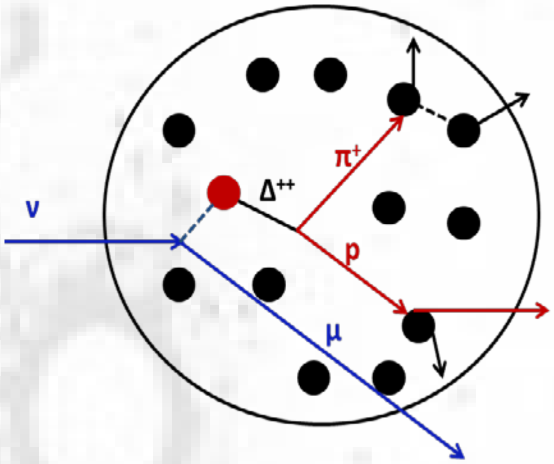
A Selection of Features

- Fine granularity for low thresholds and PID
    - Scintillator trackers (SciBooNE, T2K, MINERvA)
    - Thin target + open tracker in B field (NOMAD, T2K)
    - Liquid argon TPC (ArgoNeuT → MicroBooNE)
- Cerenkov spheres for 4π acceptance
- Multiple nuclei targets for forming flux-independent ratios of cross-sections on nuclei
- Off-axis beams (NOvA, T2K) are narrow band, *although "monochromatic" is an overstatement*
- For a variety of reasons, new hydrogen or deuterium target experiments are difficult

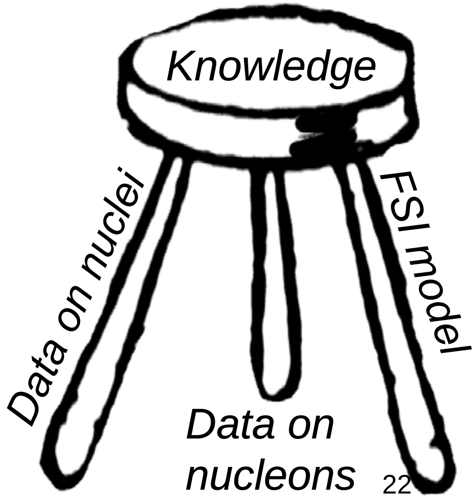
Light Target Pion Production

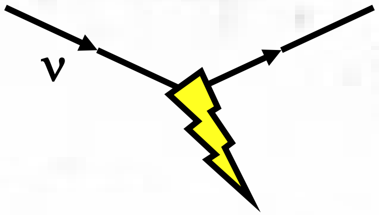
The Role of Hydrogen and Deuterium Experiments





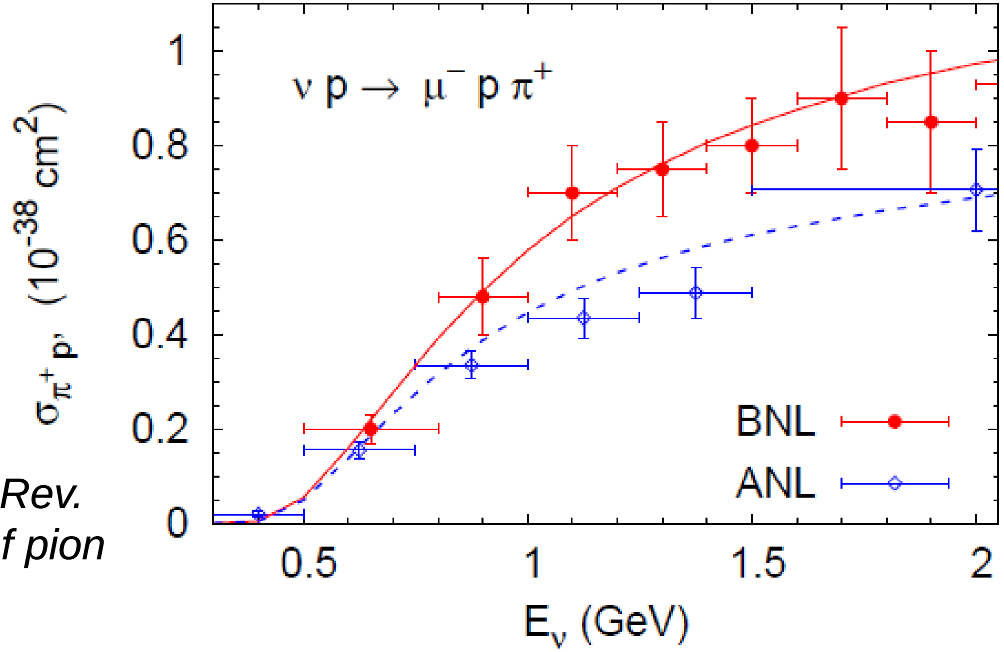
- Modeling of final state interactions is non-trivial and verifying the knowledge is even more difficult
  - Without good data on free nucleons (H_2 and D_2 bubble chambers) as a benchmark, this is difficult
  - Comparing different nuclei is the best substitute we have with modern data?
- Important note: NN final state interactions in D_2 appear significant, *e.g., J. Wu, T. Sato and T.-S. Lee, Phys. Rev. C91 (2015) 035203*





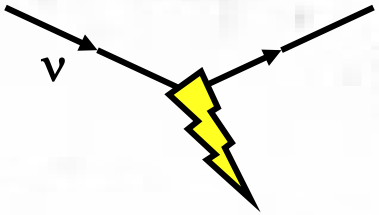
Existing Deuterium Data

- 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
- Results disagree by 30-40% and this is a major problem in attempts to extract axial form factors

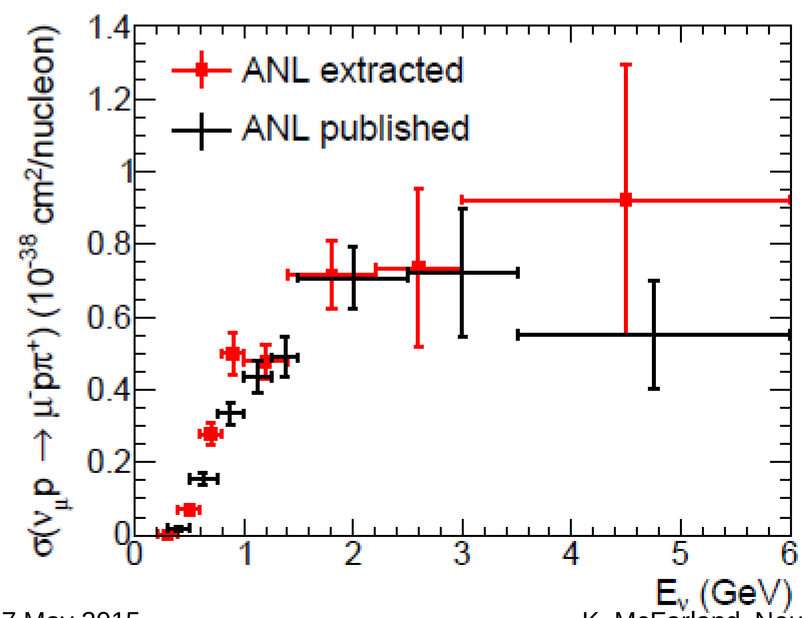


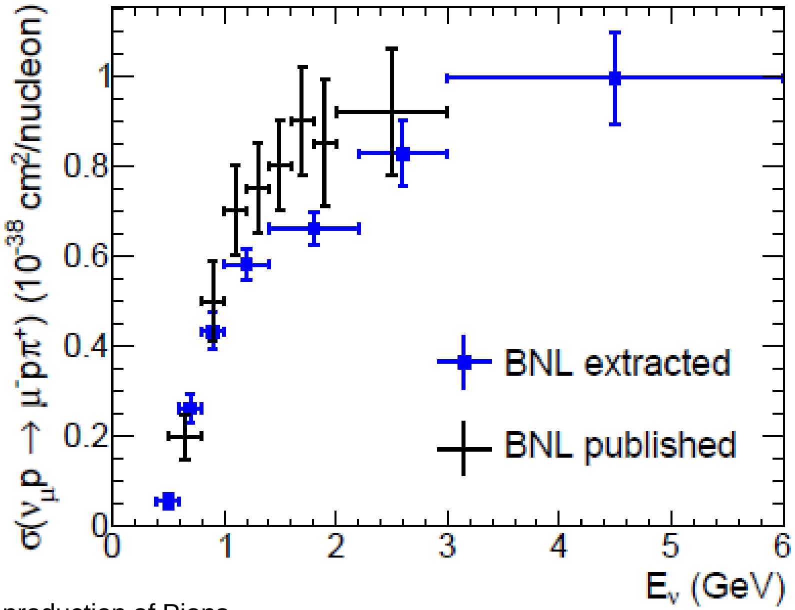
From O. Lalakulich and U. Mosel, , Phys. Rev. C87, 014612 (2013). Curves are ranges of pion production on D_2 from GiBUU model.

Resolving the Deuterium "Problem"

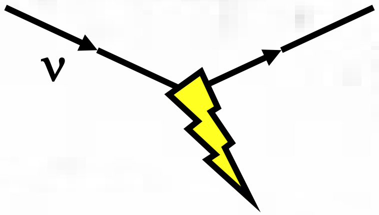


- Both experiments had large and difficult to quantify flux uncertainties. Recent observation: ratios of pion production to other processes are consistent.
  - Therefore can "correct" results using modern predictions of cross-sections, e.g., CCQE with axial form factor set by electroproduction of pions. [C. Wilkinson et al, arXiV:1411.4482]





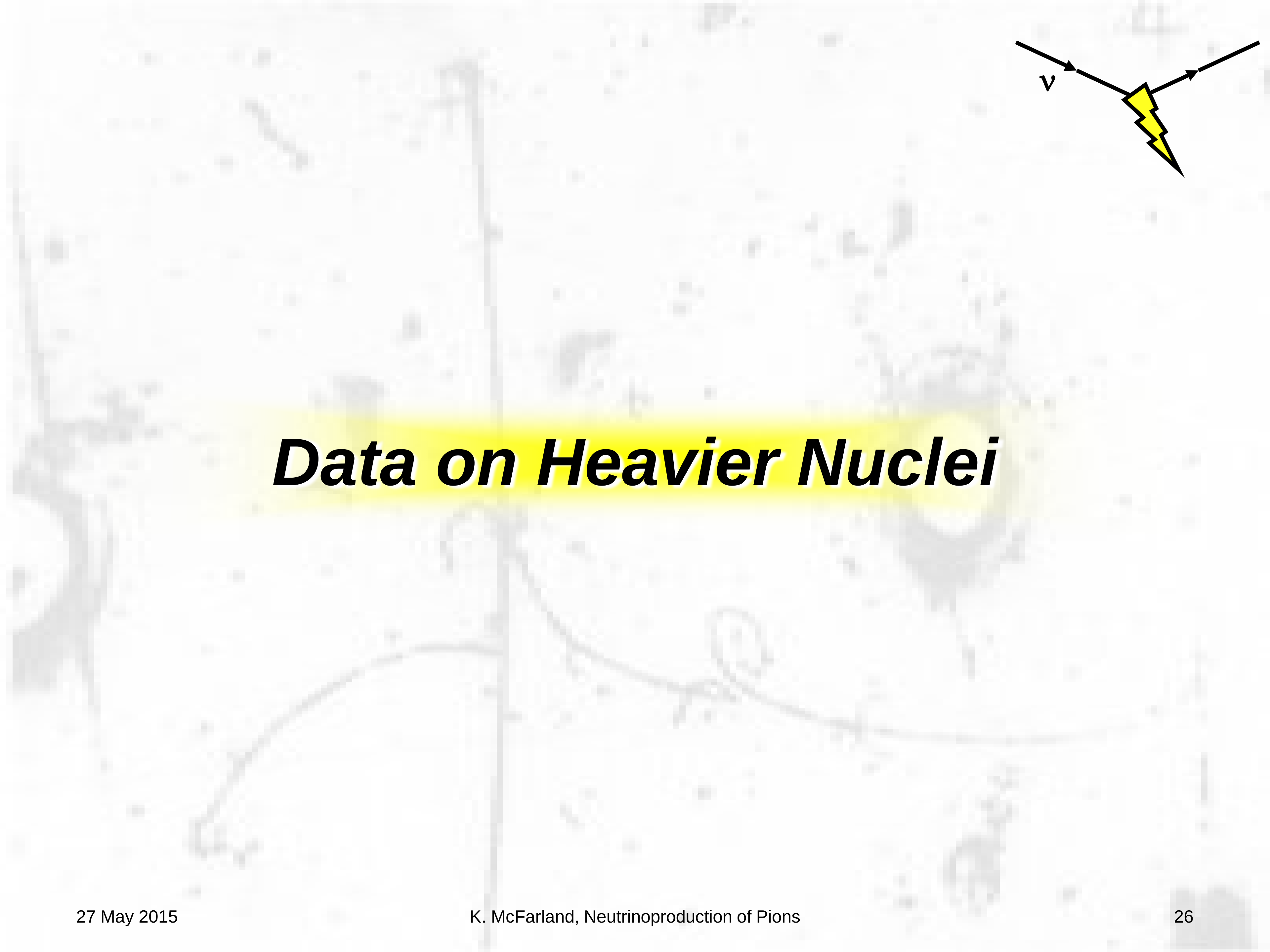
Extracting Weak Form Factors from Deuterium Data



- This is a very active but also very difficult endeavor with limited datasets, “background” 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 “problem”

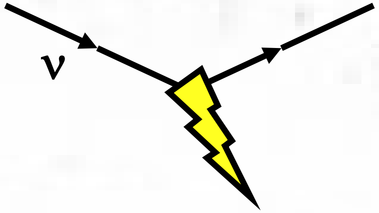
Sato, T. et al. Phys.Rev. C67 (2003) 065201
Matsui, K. et al. Phys.Rev. C72 (2005) 025204
Paschos, Emmanuel A. et al. Phys.Rev. D69 (2004) 014013
Lalakulich, Olga et al. Phys.Rev. D71 (2005) 074003
Lalakulich, Olga et al. Phys.Rev. D74 (2006) 014009
Hernandez, E. et al. Phys.Rev. D76 (2007) 033005
Graczyk, 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
J. Wu et al., Phys. Rev. C91 (2015) 035203
Zmuda, J. and, Graczyk, K., arXiV:1501.0308 (2015)

A selection of recent key references in this field. Probably not comprehensive!

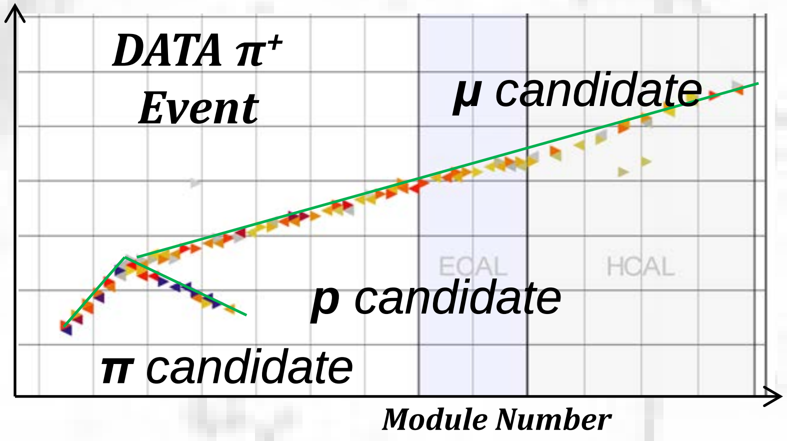


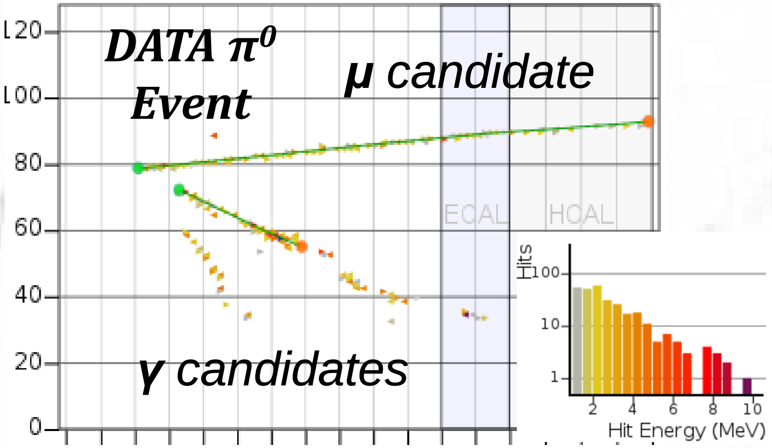
Data on Heavier Nuclei

MINERvA Pion Measurements

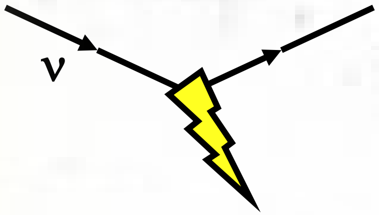


- MINERvA is segmented scintillator
  - Can track charged pions, protons
    - ~2cm granularity sets an energy threshold
  - Photons and electrons also show up as “tracks” in low density material

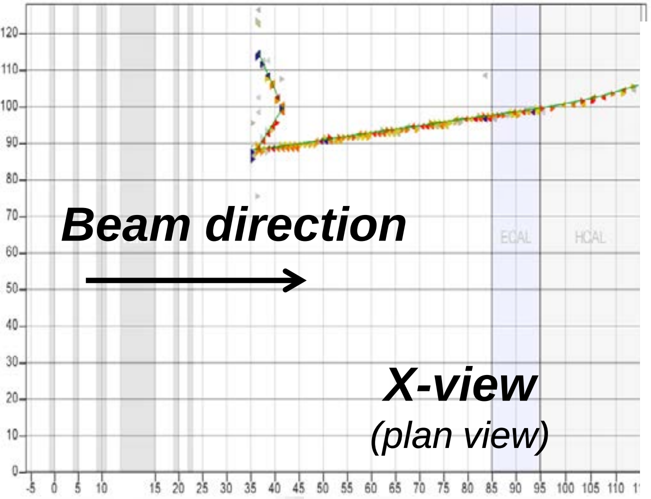




Charged Pion Reconstruction

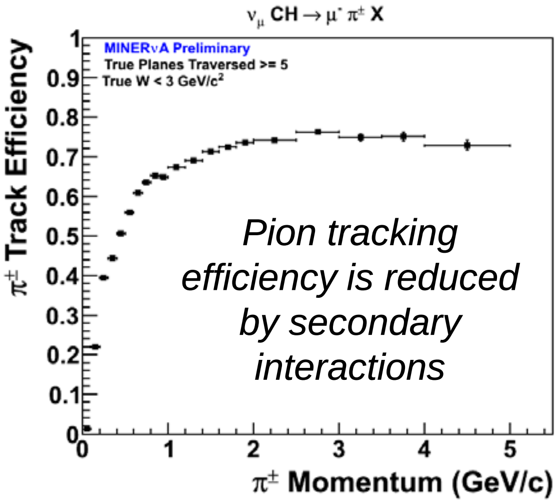


- Key is identification of a track as a pion by energy loss as a function of range from the vertex
- Confirmed by presence of Michel electron, π→μ→e
- Elastic or inelastic scattering in scintillator is a significant complication of reconstruction
  - Study uncertainties by varying pion reactions, constrained by data

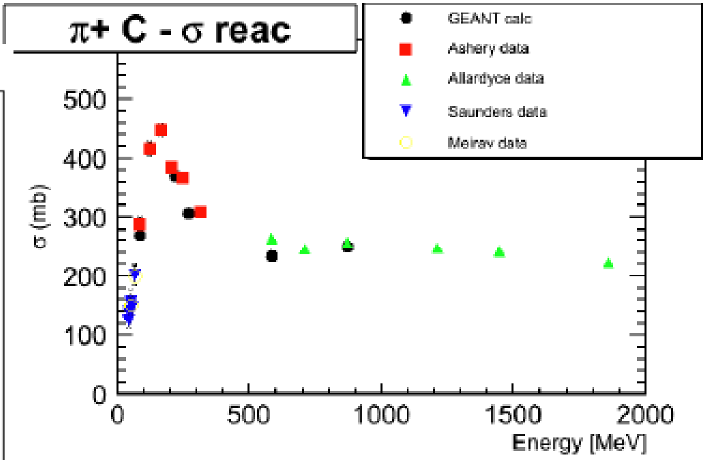


Beam direction

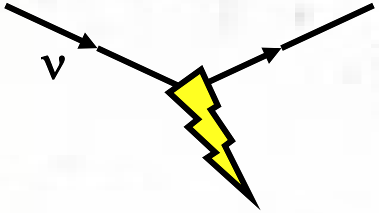
X-view
(plan view)



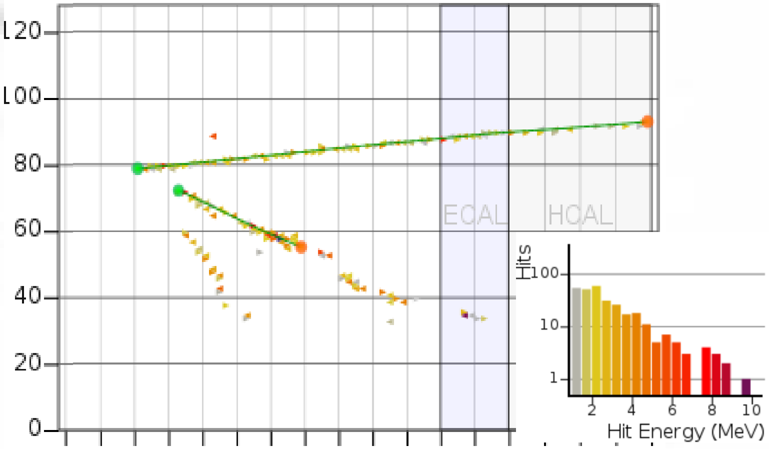
Pion tracking efficiency is reduced by secondary interactions



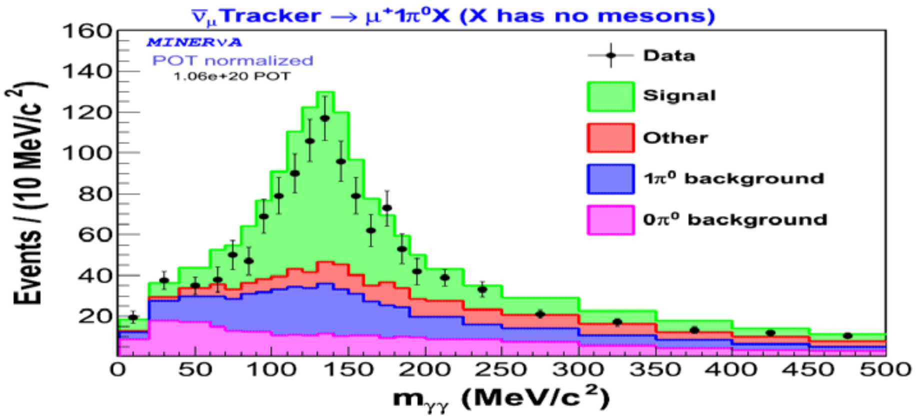
Neutral Pion Reconstruction

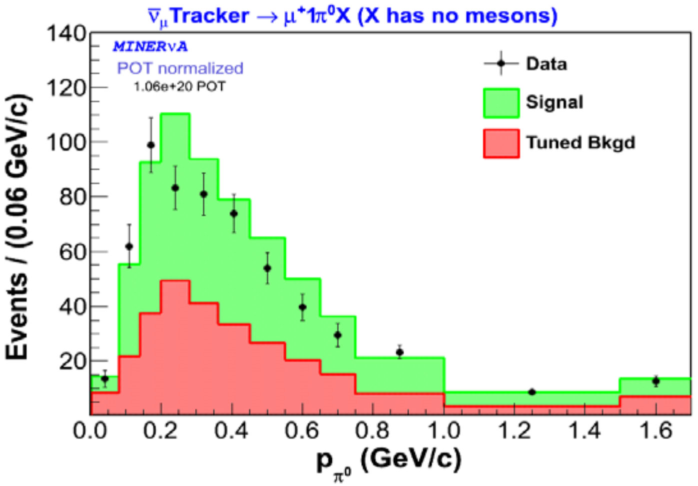


- Reaction is $\bar{\nu}_\mu + \mathrm{CH} \to \mu^+\pi^0 X$, $\pi^0 \to \gamma\gamma$

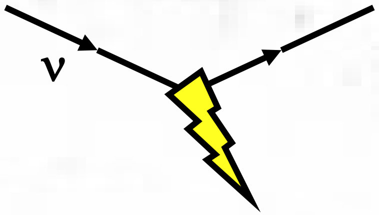


- Reconstruction strategy is to find muon and "detached" vertices
    - Photons shower slowly in plastic, so they look like "fat tracks"
- Backgrounds can be constrained with pion mass

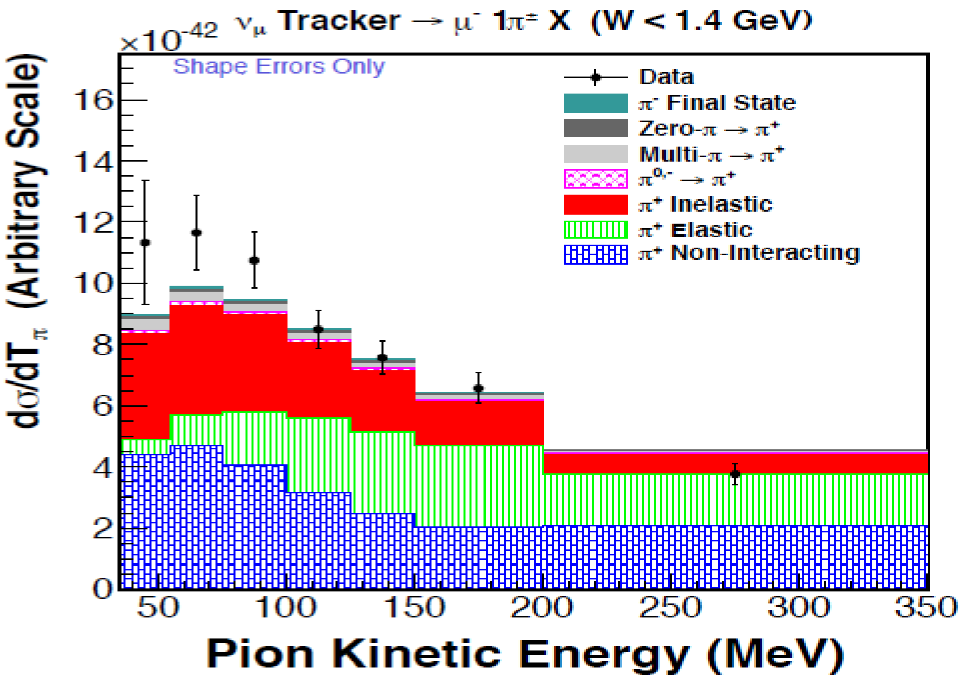


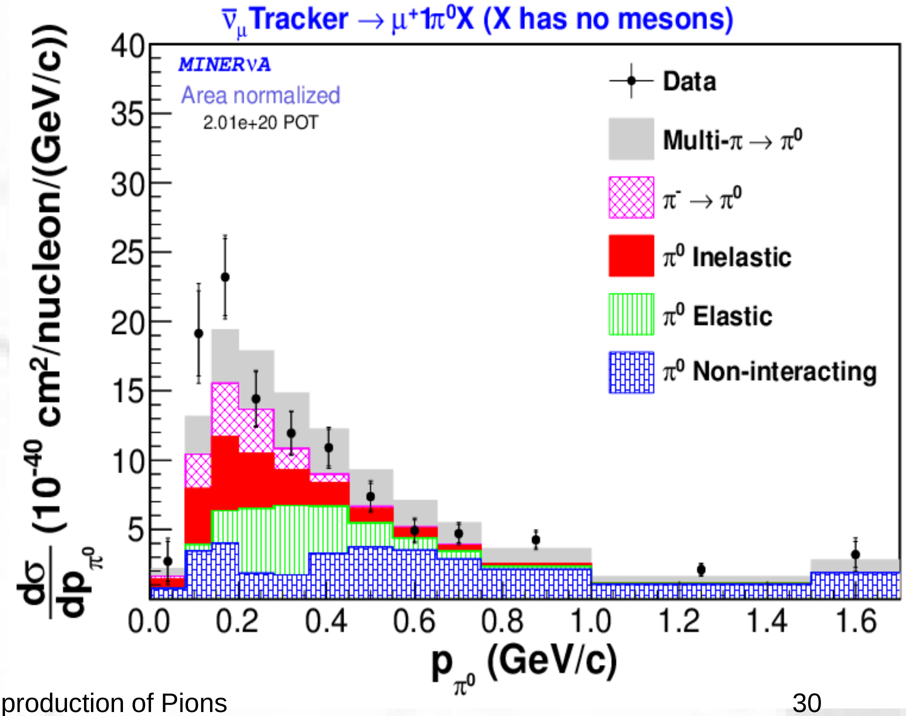


MINERvA: Pion Spectrum as Probe of Final State Effects



- 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





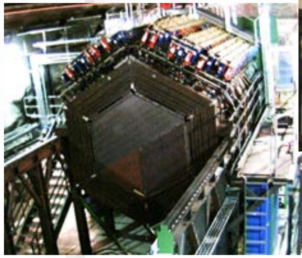
MINERvA Prospects

- MINERvA will publish (this fall) measurements of additional distributions, e.g., muon kinematics. Neutrino π^0 and semi-inclusive $p+\pi^0$ to follow.
- 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.

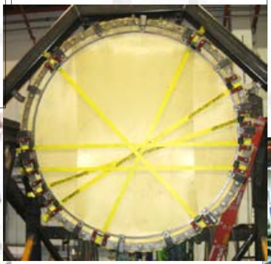
1” Fe / 1” Pb
323kg / 264kg

1” Pb / 1” Fe
266kg / 323kg

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

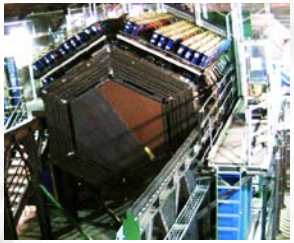


6” 500kg
Water

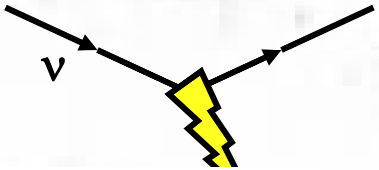


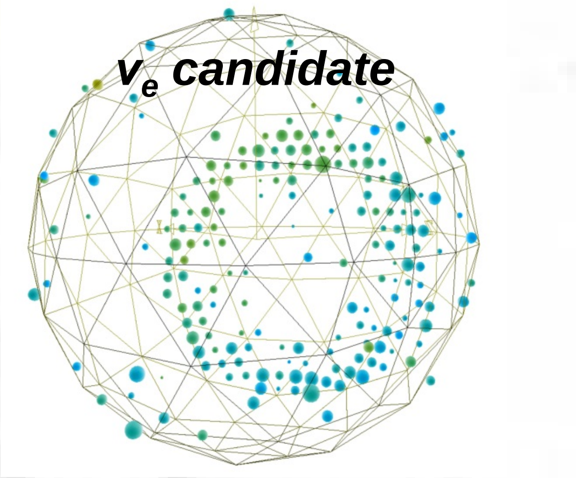
0.3” Pb
228kg

.5” Fe / .5” Pb
161kg/ 135kg



MiniBooNE Datasets



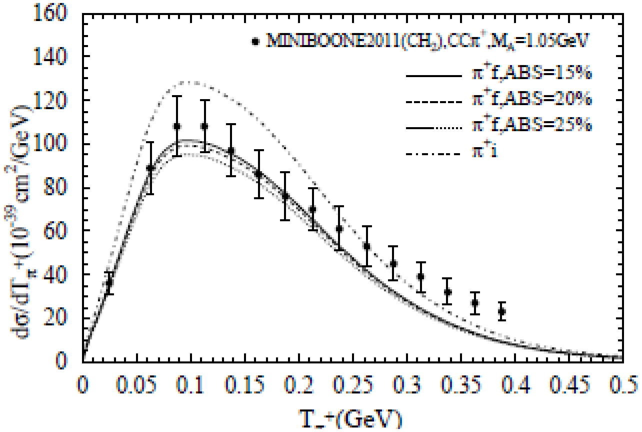


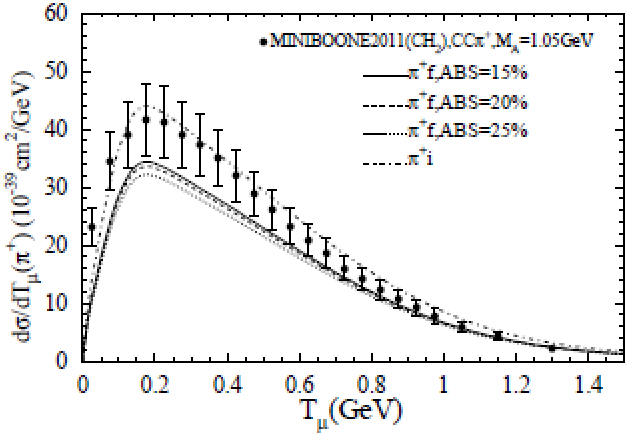
- Mineral oil Cerenkov (some scintillation also), 4π acceptance.
- Measured charged-current π^0 and π^+ on CH_2 from ~1 GeV neutrinos.
  - Photon acceptance and separation from μ is good
  - π/μ separation is much more difficult, but look for events with π+μ in final state
- Dataset has "complete" measurements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

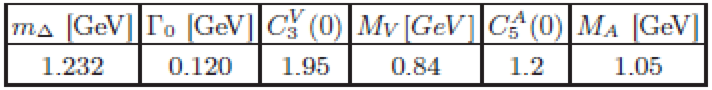
A. Aguilar-Arevalo et al., Phys.Rev.D 83, 052007 (2011)
A. Aguilar-Arevalo et al., Phys.Rev.D 83, 052009 (2011)

What are the Prospects for using this Data for Weak Form Factors?

- Nuclear corrections need to be well understood
  - In principle, could test a variety of FSI models
- Some authors have begun first steps, comparing 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 to agree to the same model. FSI problem?



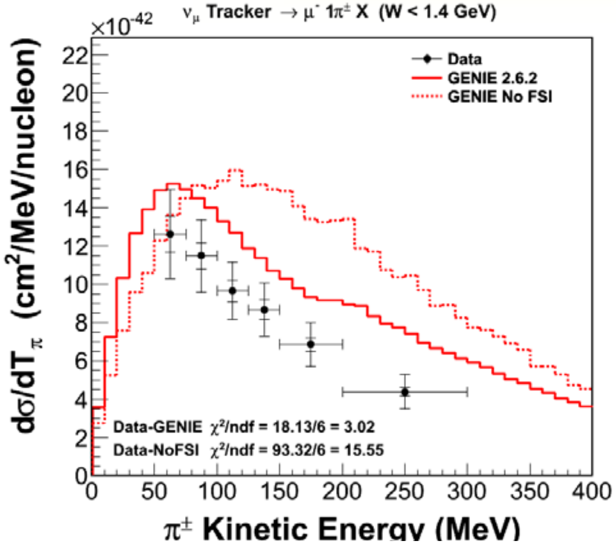


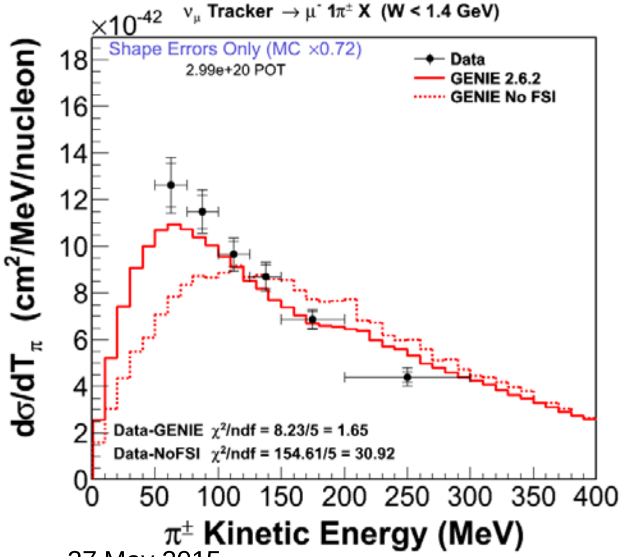


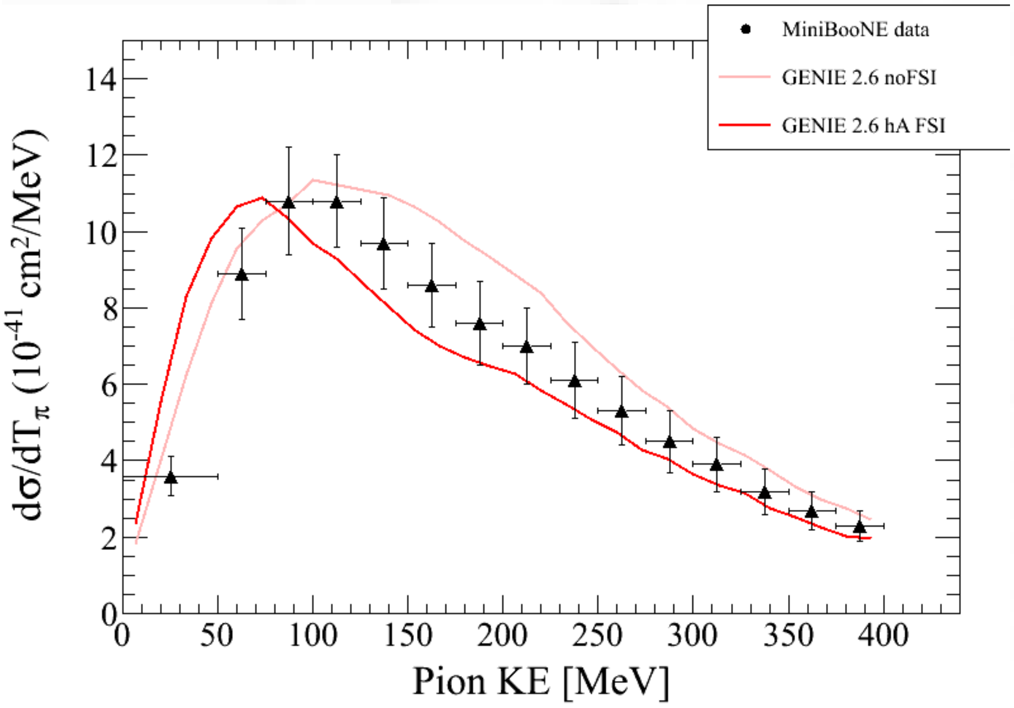
m_Δ [GeV]	Γ_0 [GeV]	$C_3^V(0)$	M_V [GeV]	$C_5^A(0)$	M_A [GeV]
1.232	0.120	1.95	0.84	1.2	1.05

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

MINERvA π^+ comparison to MiniBooNE

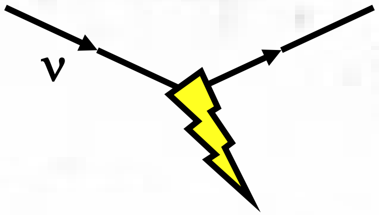




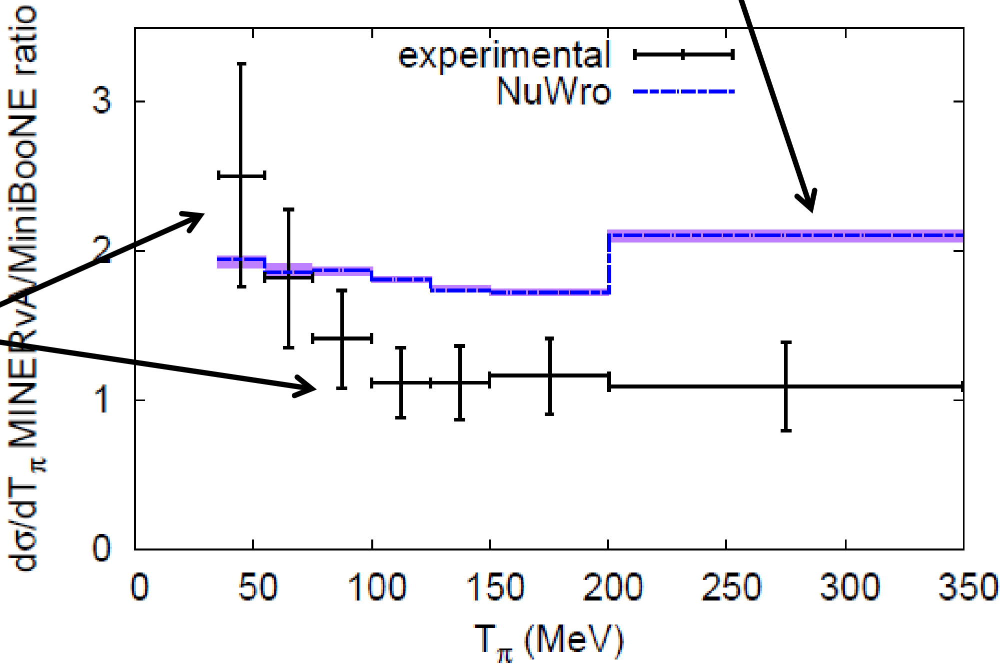


- Even with ~10% flux uncertainties from both experiments, there is ~2σ tension between MINERvA and MiniBooNE
- Shape tension also
- Note, MINERvA π^+ and π^0 are similar in rate and shape

Consistent with Production or Cascade FSI Uncertainties?



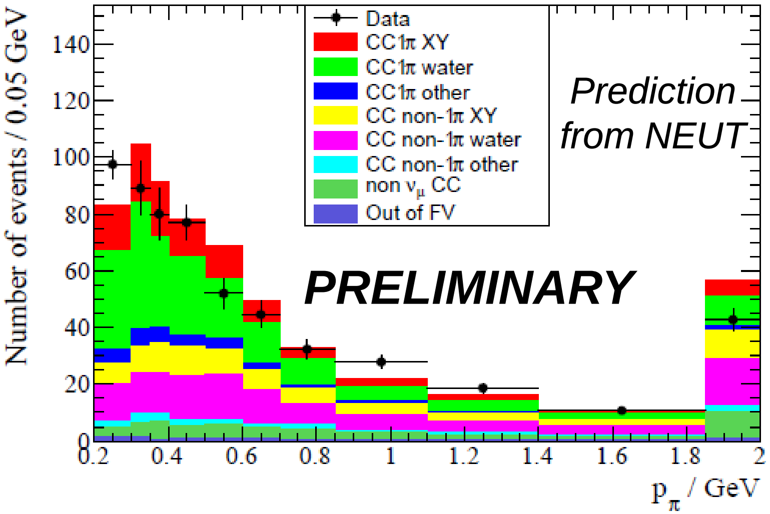
- Interesting study by Sobczyk and Zmuda (arXiV:1410.7788) asks if uncertainties in final state “cascade” models and pion production to explain MiniBooNE-MINERvA difference
- Their conclusion: it cannot. Theory uncertainties on the ratio are very small.



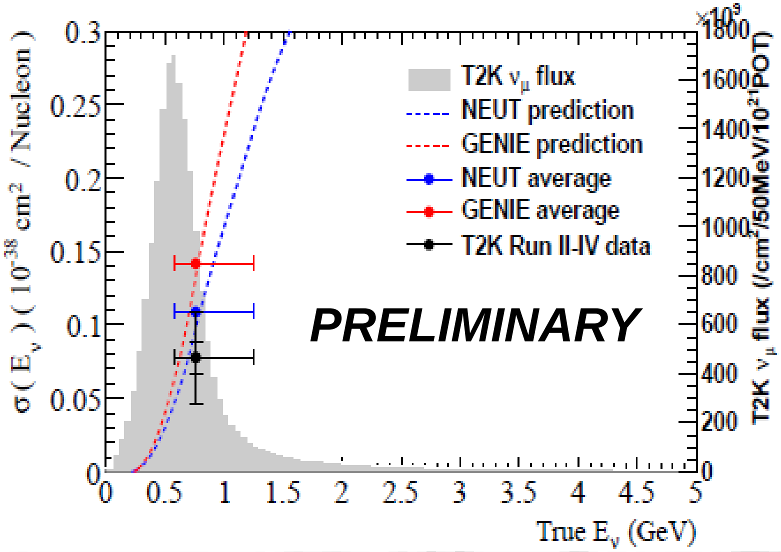
- *Uncertainties in bins are highly correlated, so maybe explains high energy part?*
- *And maybe low energy is a statistical fluctuation?*
- *Unlucky or real?*

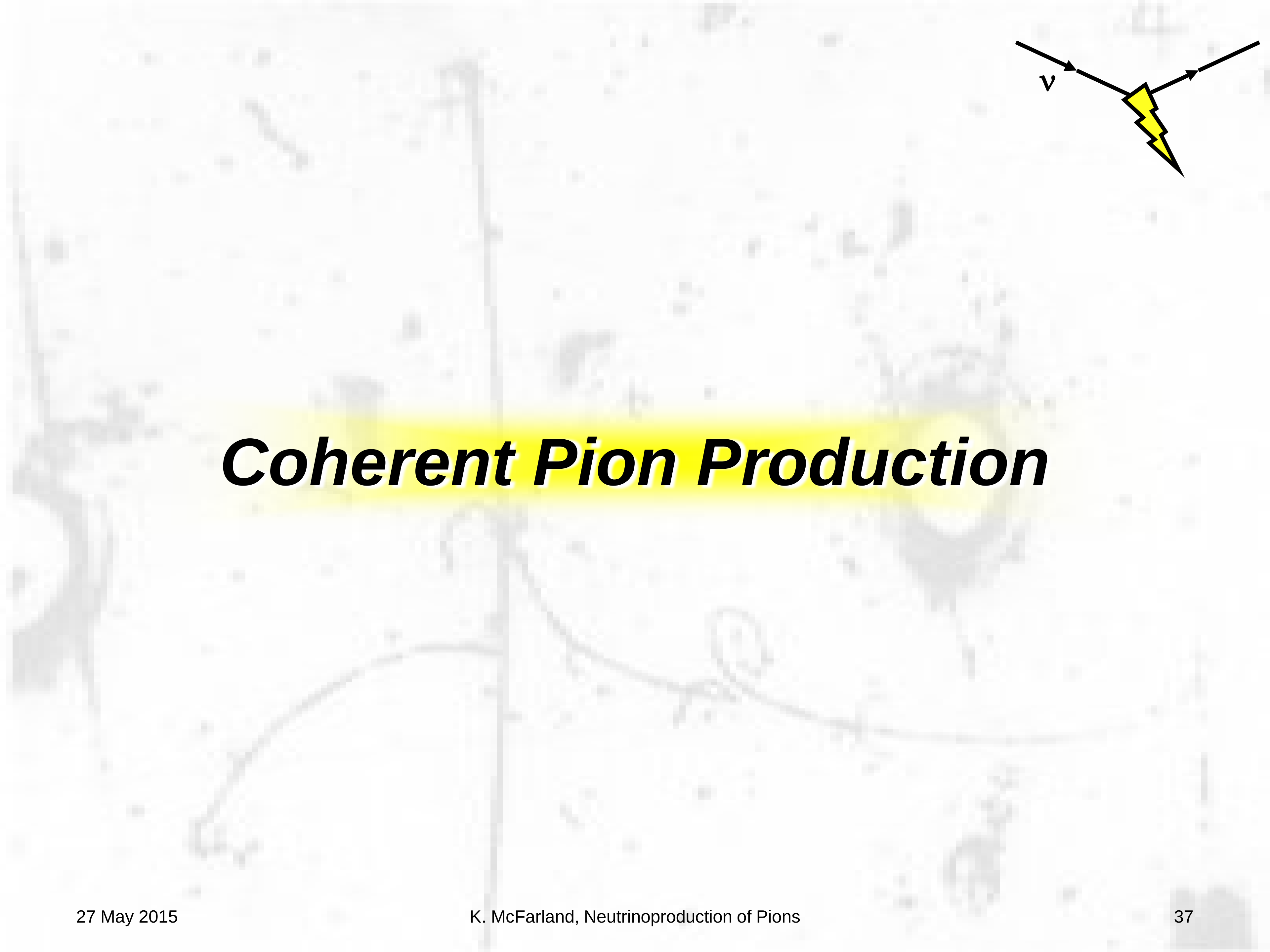
First Word from T2K…

- First results from pion production on T2K are arriving, though not yet published
- *Preliminary* CC1π$^+$ on H_2O target
    - Total cross-section and shape maybe closer to MINERvA than MiniBooNE? But need CH measurement to conclude this.



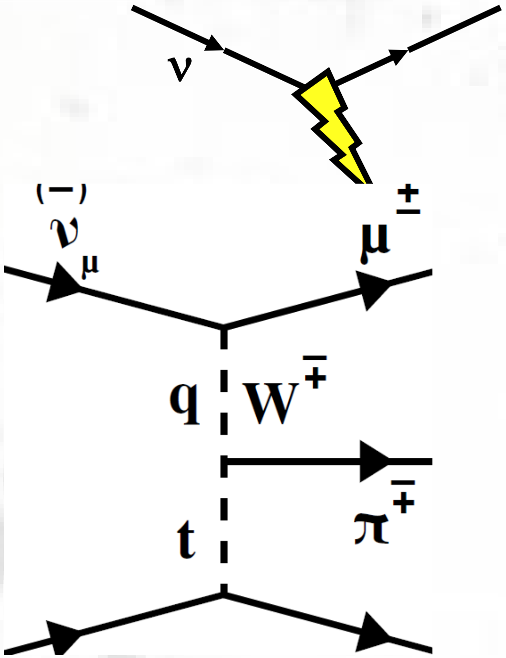
Prediction from NEUT





Coherent Pion Production

Coherent and Inelastic?

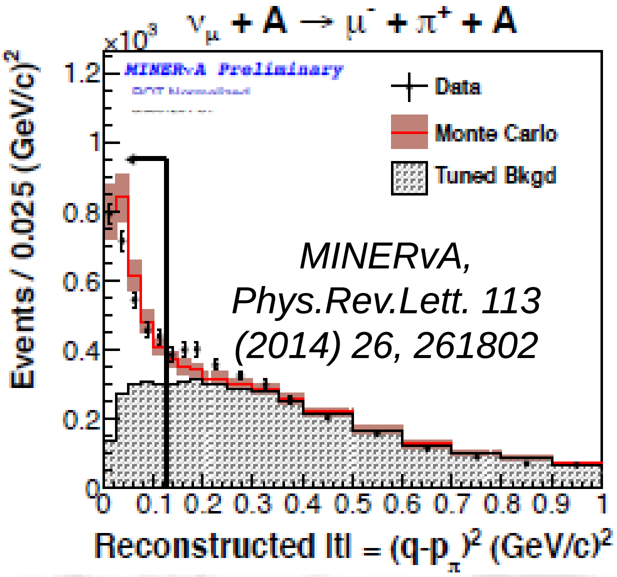


- Weak boson converts to pion in field of nucleus
- Gives energetic leading pion which is a potential lepton background in less capable detectors
- Model independent features: low momentum transfer, |t|, to target and no recoil activity at vertex

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

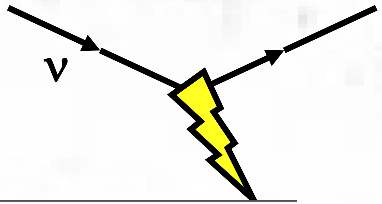
$$Q^2 = 2E_\nu(E_\mu - P_\mu cos\theta_\mu) - m_\mu^2$$

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

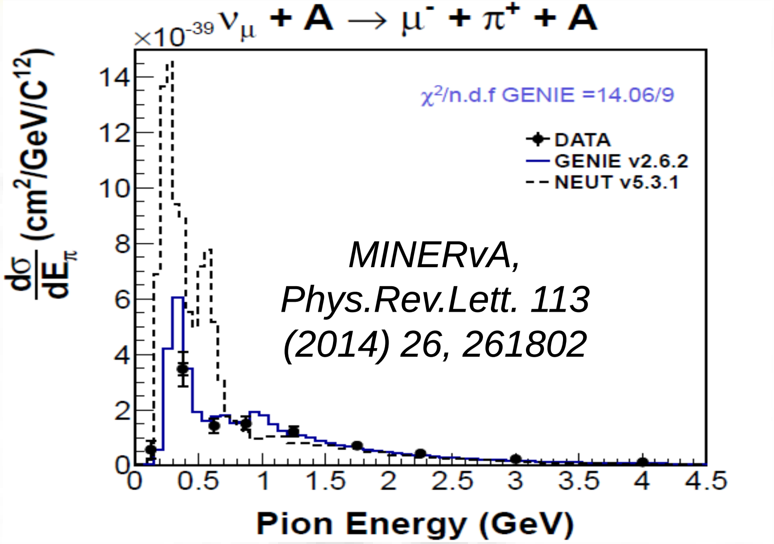


MINERvA, Phys.Rev.Lett. 113 (2014) 26, 261802

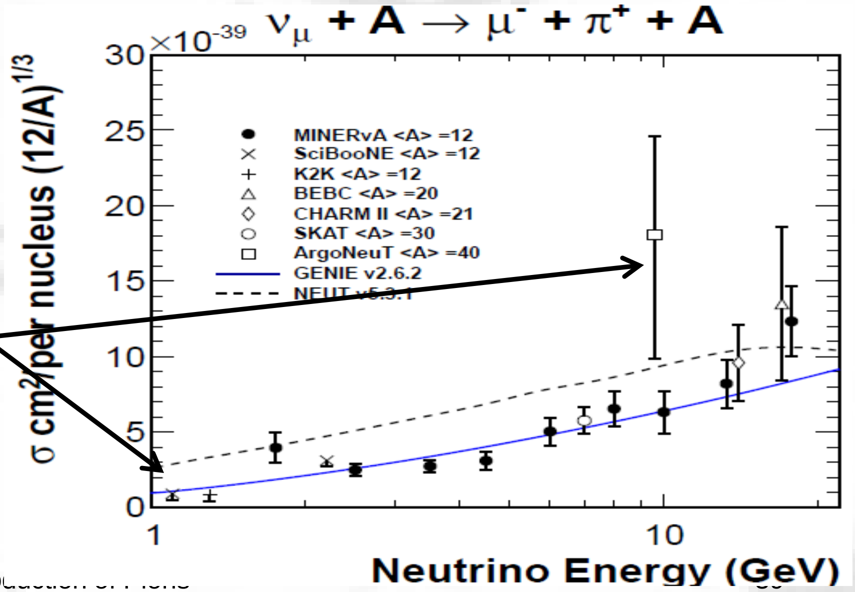
News on Coherent Pions



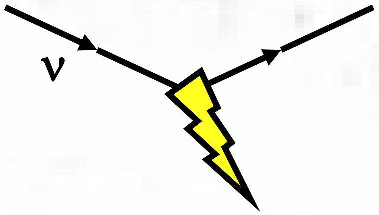
- Recent MINERvA measurement shows predictions overestimate low energy pions
- Biggest effect at low E_ν
- Explains non-observations at K2K and SciBooNE?
- Note also recent ArgoNeuT measurement on Ar (low statistics), *Phys Rev. Lett 113 (2014) 261801*



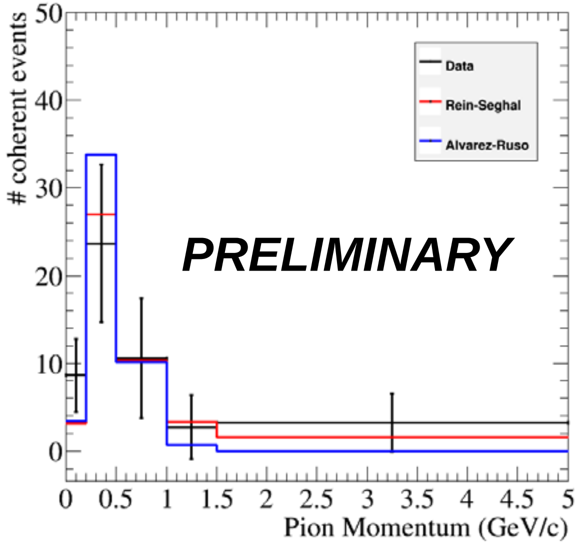
MINERvA, Phys.Rev.Lett. 113 (2014) 26, 261802

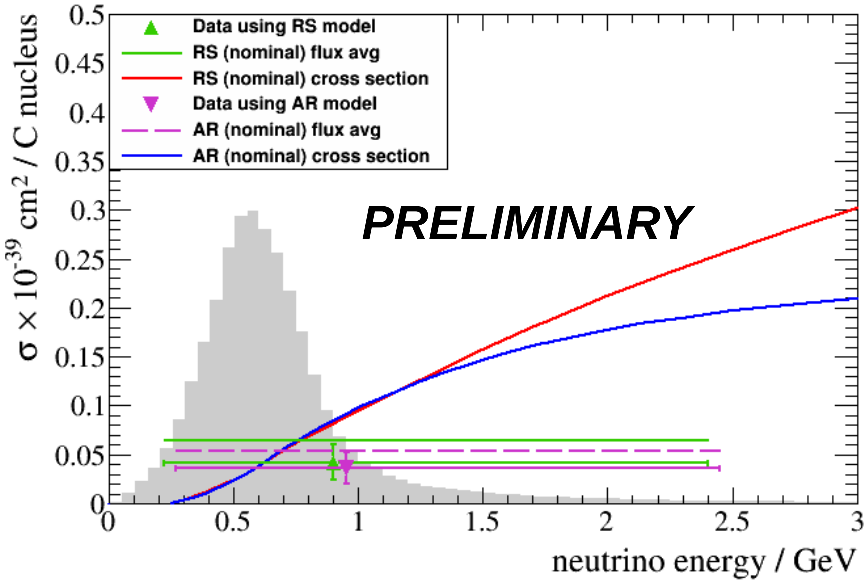


And Again from T2K…



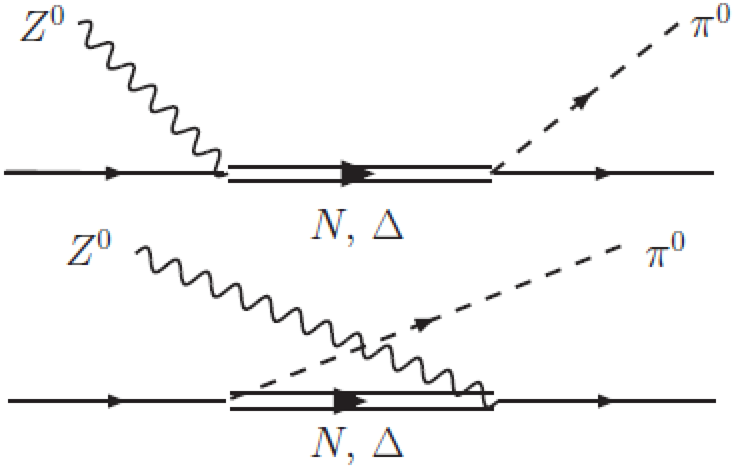
- *Preliminary* results with same model-independent technique as MINERvA on CH
  - Like MINERvA, cross-section is low, and maybe some hint of reduced low energy pions as well. But need more data to make firm conclusions.





Can we learn from this Data?

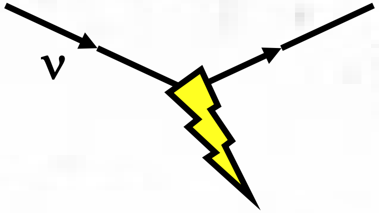
- Coherent pion production is usually interpreted in terms of PCAC models, but there are microphysical models as well, *e.g., Phys.Rev. C76 (2007) 068501, Phys.Rev. C80 (2009) 029904*



  - 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 nuclear. No FSI *per se*.
  - Full statistics MINERvA data and data from liquid Argon experiments will both be critical for realizing this idea.

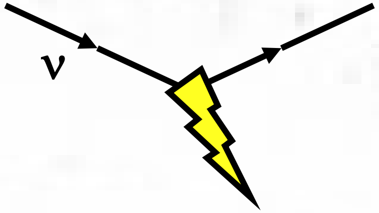
Summary and Prospects

Summary

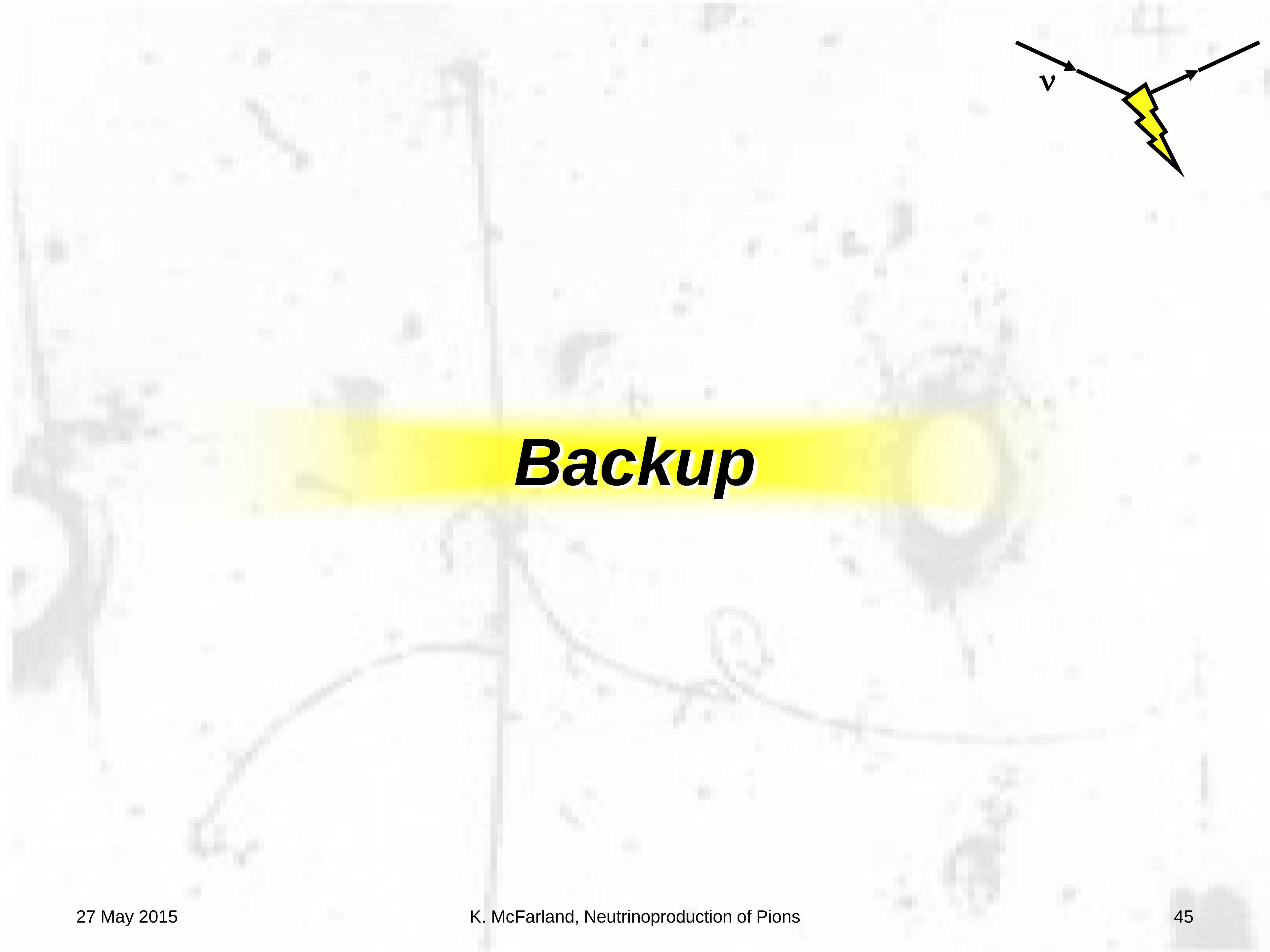


- Neutrino experiments need more information about pion production
  - Oscillation experimental ultimate precision relies on accurate models of this process, along with the effect of medium heavy nuclei
- It may be difficult to use this data to untangle resonance axial current coupling
  - Hydrogen and deuterium data is limited
  - Models of nuclear effect vary
  - New ideas here are very welcome!

Prospects



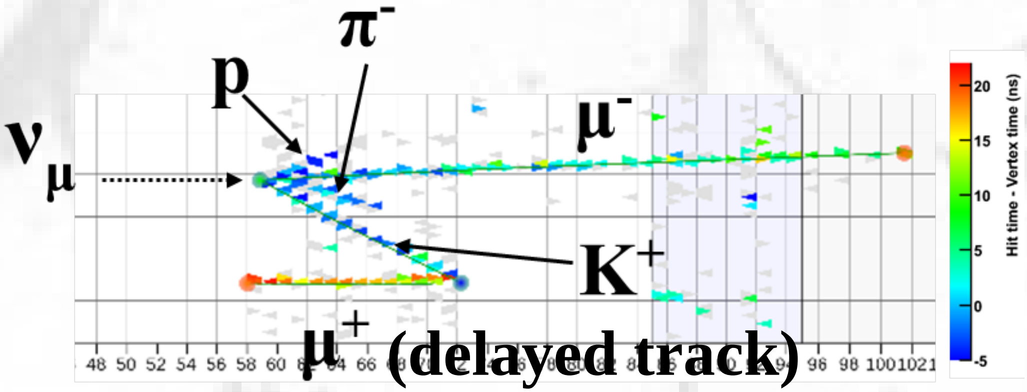
- Whether or not we have theory to accurately describe it, experiments will continue to measure pion production
  - More accurate results. More distributions. More measurements of exclusive processes, particularly on Argon targets (LArTPCs)
  - Direct comparisons on different medium-heavy and heavy nuclei. But not on light nuclei.
- Need work on both “first principles” and “effective” models to describe new data.

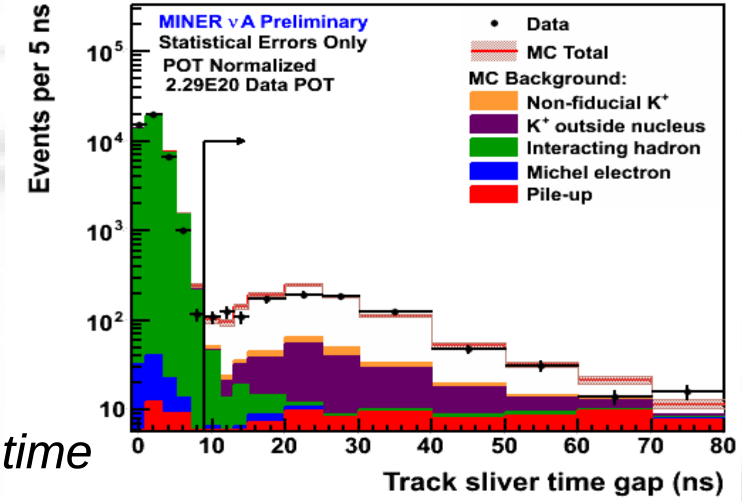


Backup

Strange Mesons?

- MINERvA and T2K are both interested in measuring kaon production
    - Rate of kaon+"nothing" is important for atmospheric neutrino backgrounds to $p \rightarrow K^+ v$ in water Cerenkov
    - Final state interactions of kaons are important for searches in bound protons, e.g., searches in LAr





MINERvA Kaon candidate and delayed track time