Experimental Summary

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Experimental Sessions

- Systematic Uncertainties and Impact on Oscillation Measurements
- Electron Scattering and other Non-neutrino measurements
- Shallow Inelastic, Deep Inelastic, and Inclusive Scattering
- Neutrino Flux Calculations and Measurements
- Neutrino Pion Production and other Inelastic Interactions
- Neutrino NC and CC Scattering without Pions
- Future Experiments
- Low Energy Neutrino Scattering

Compare to NuINT 2015 Experimental Summaries

09:00	**Summary 1 : Neutrino flux** *Icho-Kaikan, Osaka University Suita Campus*	*Dr. Megan FRIEND* 09:00 - 09:20
	Summary 2 : Systematics *Icho-Kaikan, Osaka University Suita Campus*	*Prof. Richard GRAN* 09:20 - 09:40
	Summary 3 : CC and NC quasi-elastic scatterings *Icho-Kaikan, Osaka University Suita Campus*	*Kevin MCFARLAND* 09:40 - 10:00
10:00	**Summary 4 : Pion production and the other inelastic interactions** *Icho-Kaikan, Osaka University Suita Campus*	*Prof. Sajjad ATHAR* 10:00 - 10:20
	Summary 5 : Shallow and deep inelastic scatterings *Icho-Kaikan, Osaka University Suita Campus*	*Dr. Jorge MORFIN* 10:20 - 10:40
11:00	**Summary 6 : Low energy neutrino scattering** *Icho-Kaikan, Osaka University Suita Campus*	*Dr. Yusuke KOSHIO* 11:00 - 11:20
	Summary 7 : Electron scatterings *Icho-Kaikan, Osaka University Suita Campus*	*Prof. Omar BENHAR et al.* 11:20 - 11:40
	Summary 8 : Generators *Icho-Kaikan, Osaka University Suita Campus*	*Dr. Hide-Kazu TANAKA* 11:40 - 12:00
12:00	**Summary 9 : Future experiments** *Icho-Kaikan, Osaka University Suita Campus*	*Dr. Mark HARTZ* 12:00 - 12:20

- 35 minutes instead of 3 hours…choices were made

Focus of this talk: Results shown at NuINT2017

- Pion Scattering measurements
- New Flux Predictions
- Electron Scattering measurements
- Inclusive CC Measurements
  - All Recoil
  - Electron Neutrinos
  - Low Recoil
- Neutrino-Pion Production Measurements
- Pion-less Neutrino CC Measurements

- Looking ahead: are we there yet?

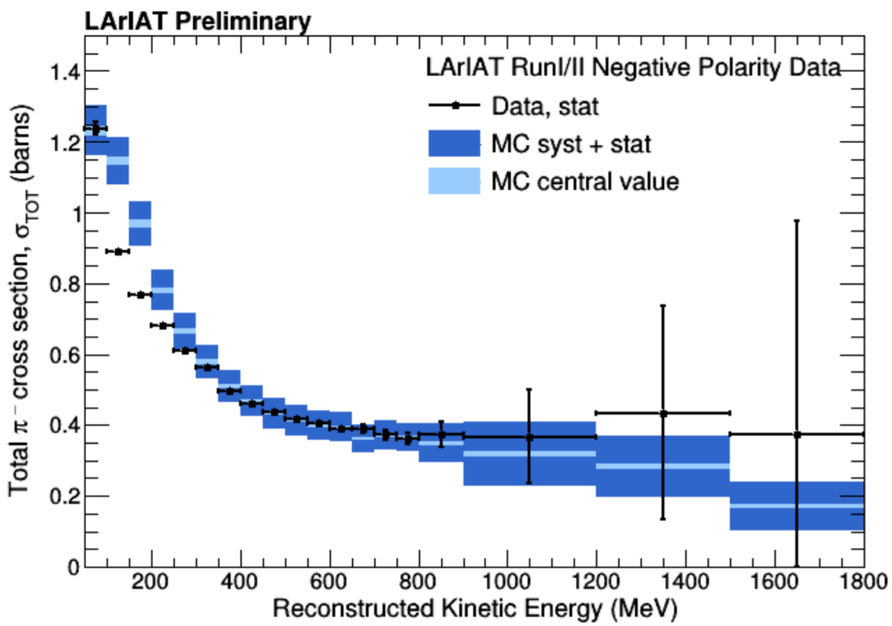
All momentum transfer

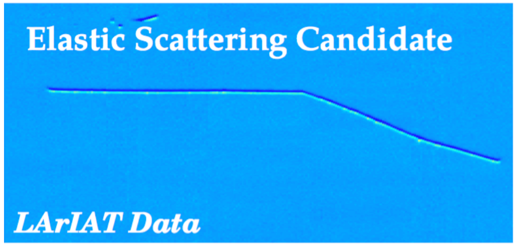
Low momentum transfer

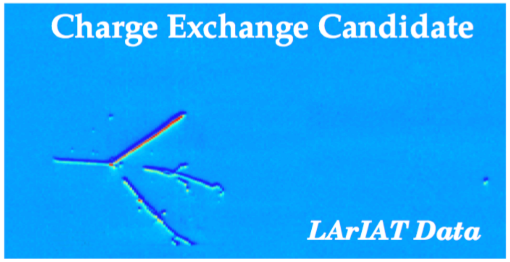
Pion Scattering Results

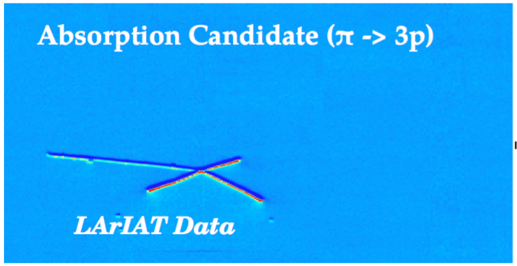
Pion Scattering Results: LArIAT

- Thin slice technique for cross section (J. Asaadi)



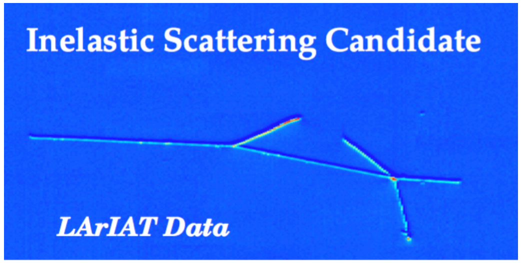


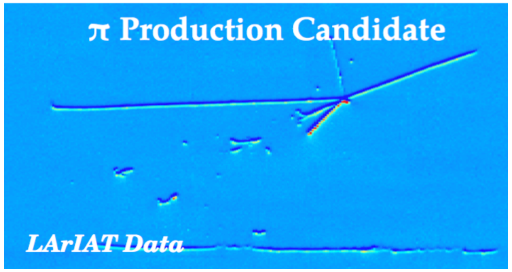




$$P_{\text{Interacting}} = 1 - (1 - \sigma n \delta z + \ldots)$$

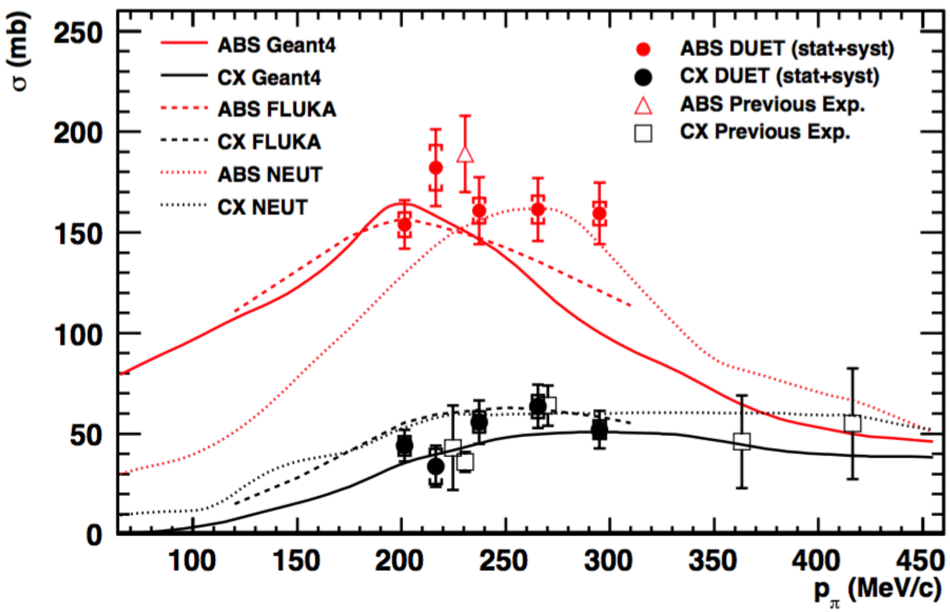
$$\sigma(E) \approx \frac{1}{nz} P_{\text{Interacting}} = \frac{1}{nz} \frac{N_{\text{interacting}}}{N_{\text{Incident}}}$$

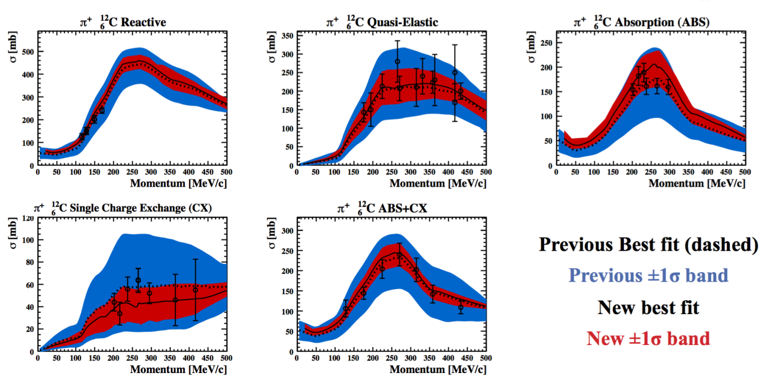




Pion Scattering Results: DUET

- Multi-faceted experiment at Triumf (Pinzon)





Data spanning five decades!

Reference	Polarity	Targets	p_π [MeV/c]	Channel(s)
B. W. Allardyce et al. [11]	$\pi^\pm$	C, Al, Pb	710-2000	REAC
A. Saunders et al. [12]	$\pi^\pm$	C, Al	116-149	REAC
C. J. Gelderloos et al. [13]	π^-	C, Al, Cu, Pb	531-615	REAC
F. Binon et al. [14]	π^-	C	219-395	REAC
O. Meirav et al. [15]	π^+	C, O	128-169	REAC
C. H. Q. Ingram [16]	π^+	O	211-353	QE
S. M. Levenson et al. [17]	π^+	C	194-416	QE
M. K. Jones et al. [18]	π^+	C, Pb	363-624	QE, CX
D. Ashery et al. [19]	$\pi^\pm$	C, Al, Fe	175-432	QE, ABS+CX
H. Hilscher et al. [20]	π^-	C	156	CX
T. J. Bowles [21]	$\pi^\pm$	O	128-194	CX
D. Ashery et al. [22]	$\pi^\pm$	C, O, Pb	265	CX
K. Nakai et al. [23]	$\pi^\pm$	Al, Cu	83-395	ABS
E. Bellotti et al. [24]	π^+	C	230	ABS
E. Bellotti et al. [25]	π^+	C	230	ABS
I. Navon et al. [26]	π^+	C, Fe	128	ABS+CX
R. H. Miller et al. [27]	π^-	C, Pb	254	ABS+CX
E. S. Pinzon Guerra et al. [28]	π^+	C	206-295	ABS, CX

Exhaustive literature search to constrain NEUT

Pion Scattering Conclusions

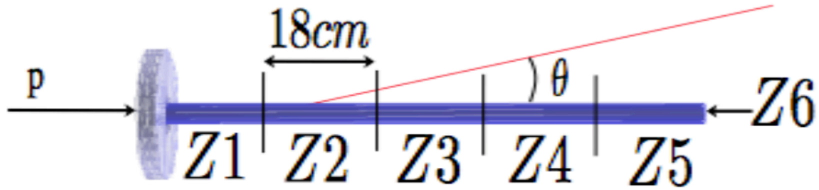
- These are hard measurements
- A lot of progress has been made on several materials
- Starting to get handles on pion scattering in Argon

- Need this component to be able to make best use of our neutrino data
  - Clues to role of final state interactions
  - Critical for simulating detector response
- Especially in the longer term: DUNE needs to keep pions as signal process, will need more work here to prepare for that

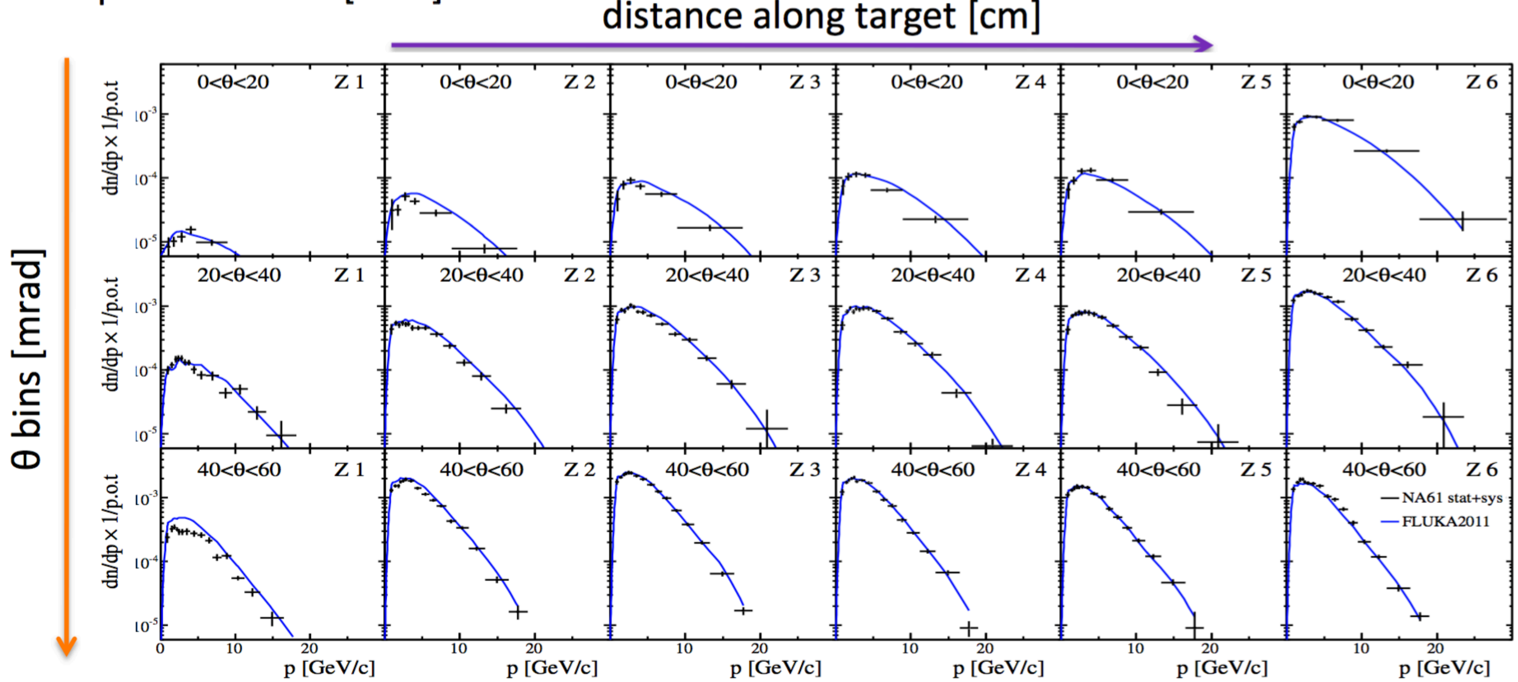
New Results on Flux Predictions

New Results shown at NuINT 2017: NA61/SHINE

- Old results use thin target prediction, now the thick target results are available (K. Kowalik)

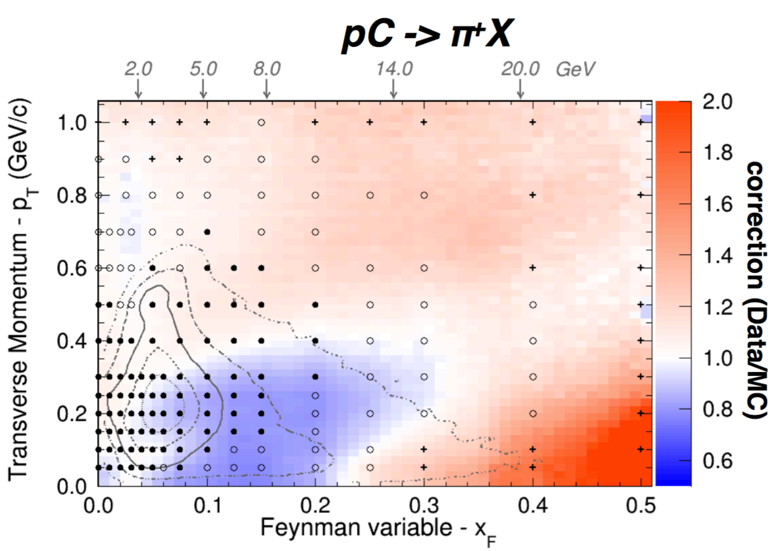


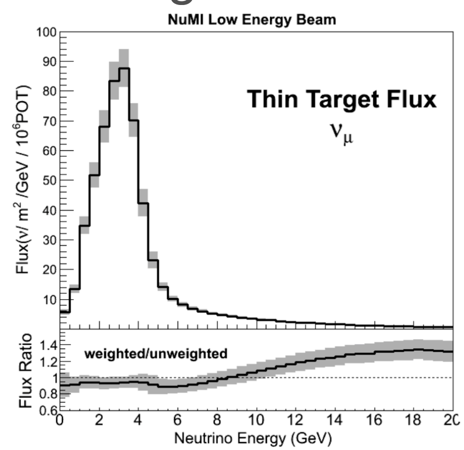
Example of π⁻ for θ [0-60]mrad

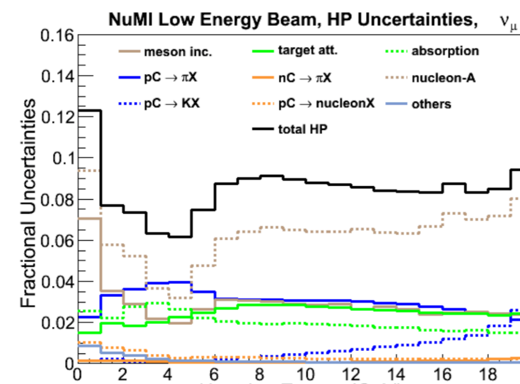


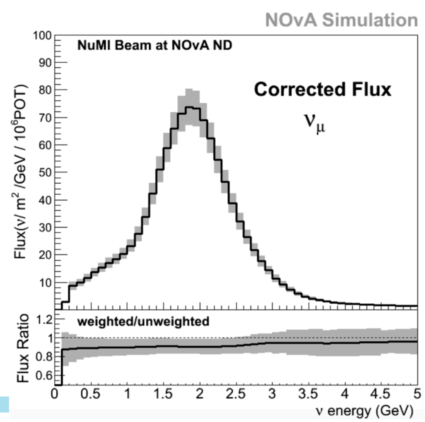
"New" Results shown at NuINT 2017: NuMI flux

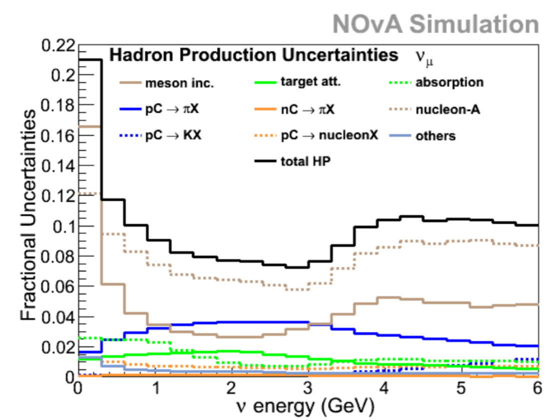
- New since last NuINT 2017: NuMI Flux Predictions(L. Aliaga)
  - Exhaustive campaign to correct GEANT simulation to the world's hadron production and interaction data
  - NA49 plays biggest role in reducing the uncertainties
  - Can be used for NOvA too!











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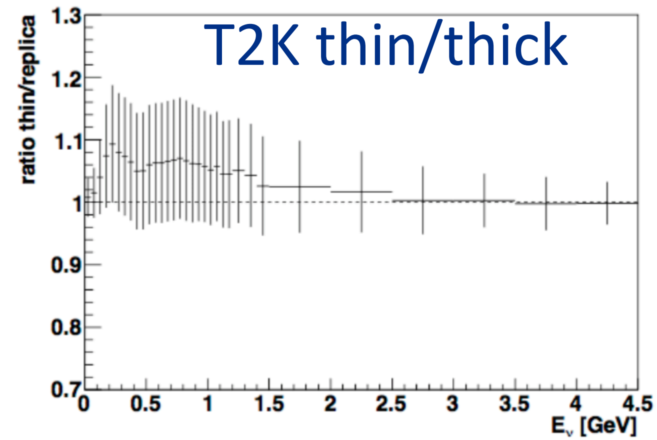
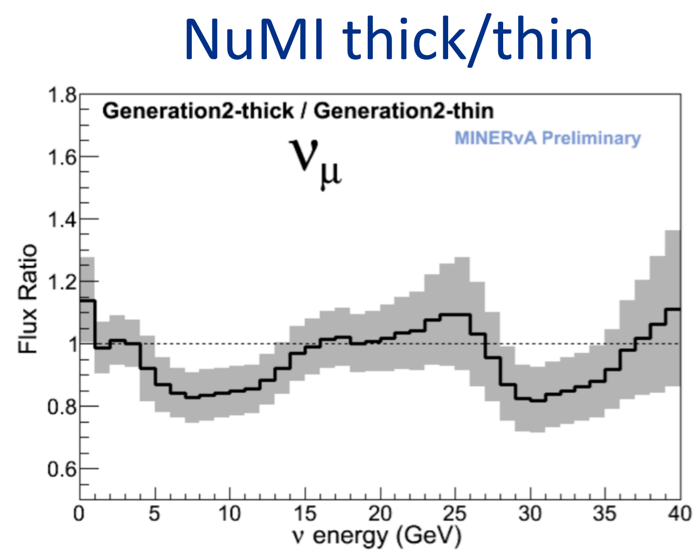
Flux Conclusions

- Absolute cross section measurements only as good as flux
- Efforts worldwide to harness available data
  - T2K: NA61/SHINE (K. Kowalik)
  - NuMI: NA49++ (L. Aliaga)
  - Booster Neutrino Beam: HARP
  - LBNF (for DUNE): SHINE? (A. Bashyal)
- These data answer some questions, raise others: why do thin and thick target-based flux predictions disagree?
- Efforts worldwide to get new data
  - Better instrumentation in very forward region of NA61/SHINE
  - New spectrometer for LBNF with replica beamline

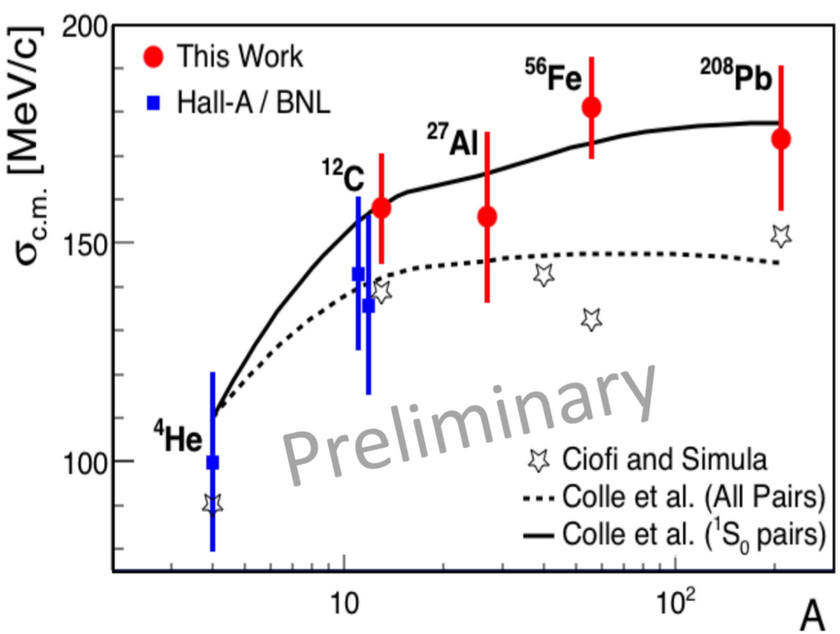




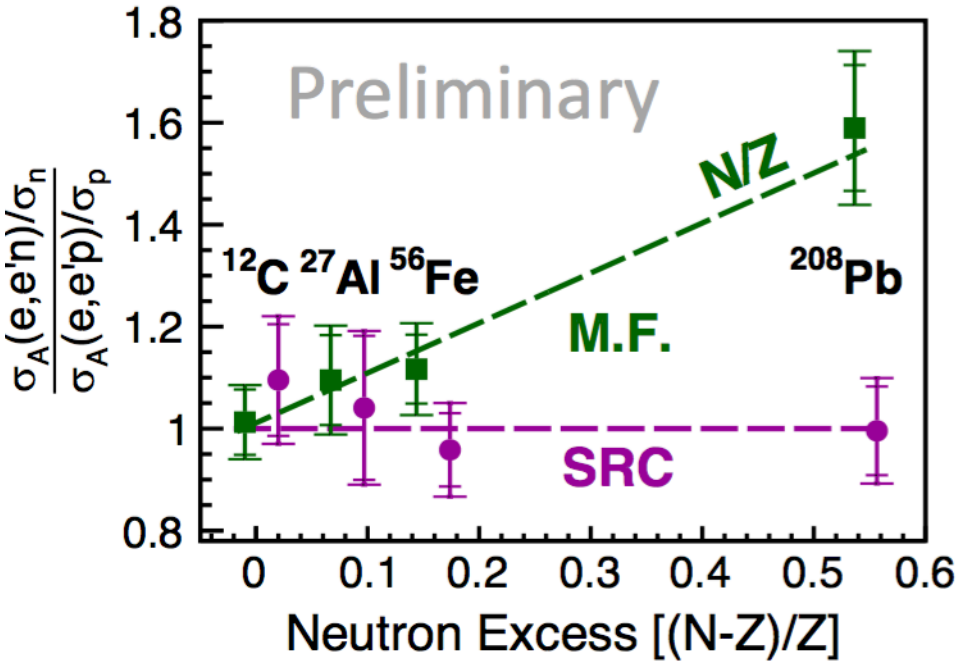
Electron Scattering Results

Electron Scattering Results: CLAS

- Looking at ratios of different final states in e-scattering: see a dependence of nuclear asymmetry (O. Hen)



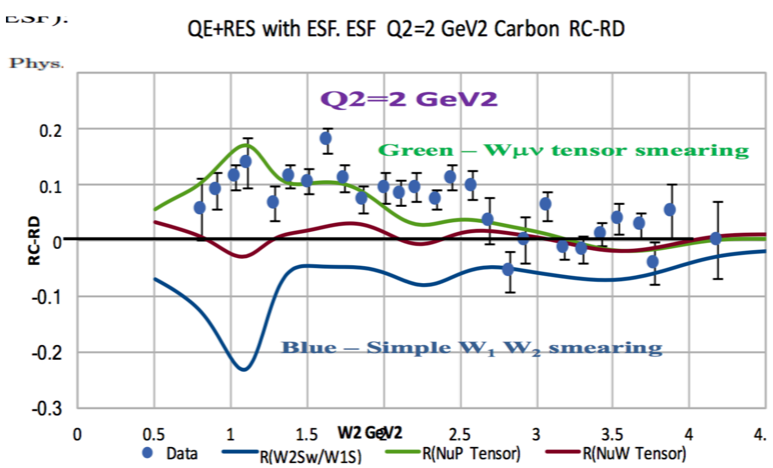
Correlated nucleons have Low center of mass momentum but high relative momentum

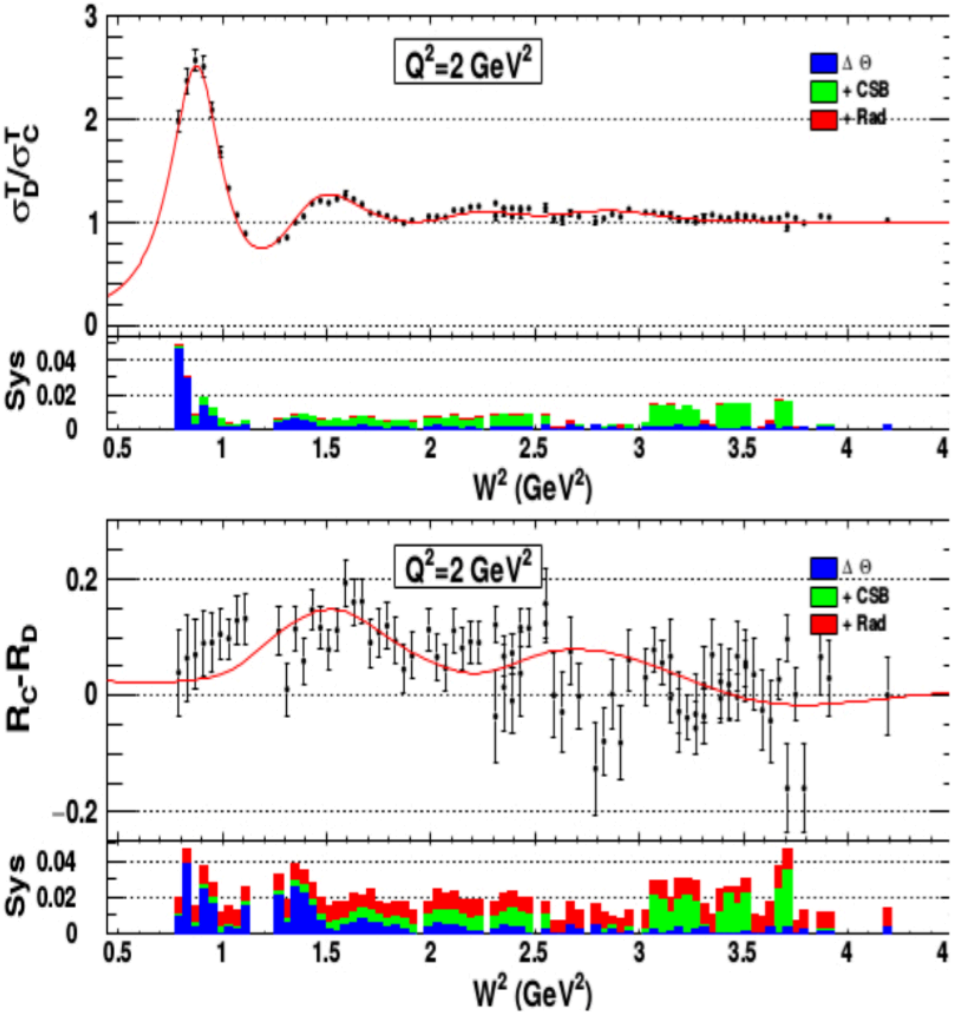


Same number of high momentum protons and neutrons!

Electron Scattering Results: JUPITER

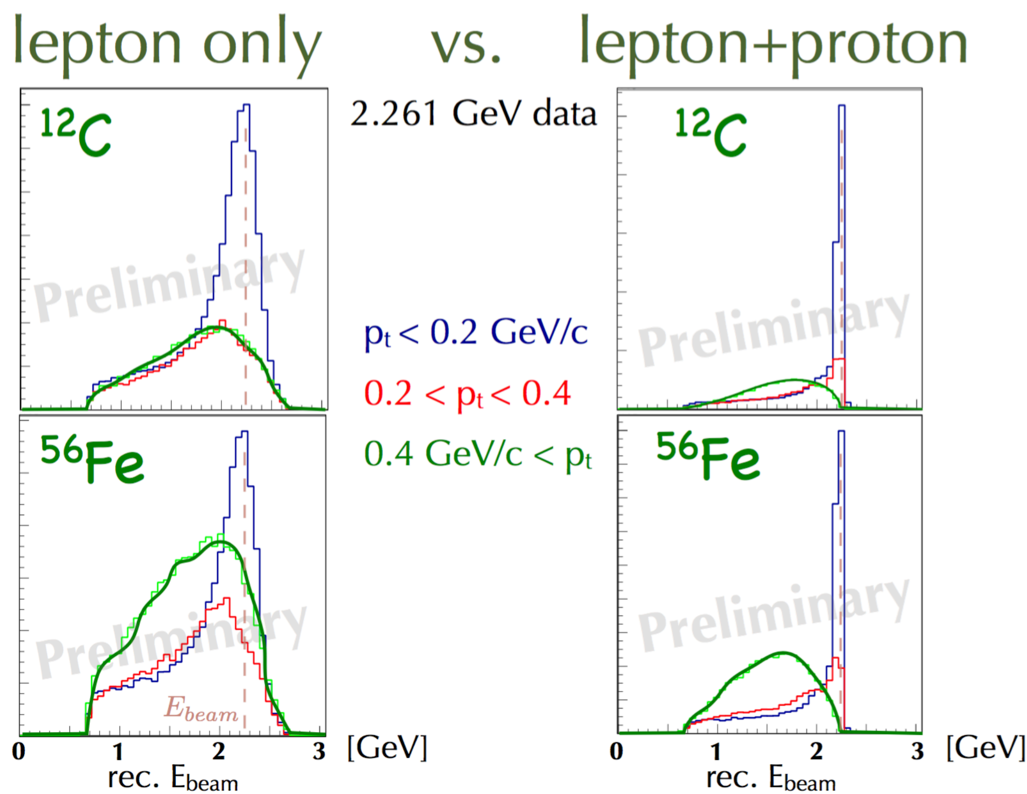
- New measurements of R (σ_l/σ_T) in electron scattering to measure nuclear effects (A. Bodek)
- Shows that simple Fermi smearing doesn't work
- More nuclei measurements soon to follow





Future Electron Scattering Results: CLAS

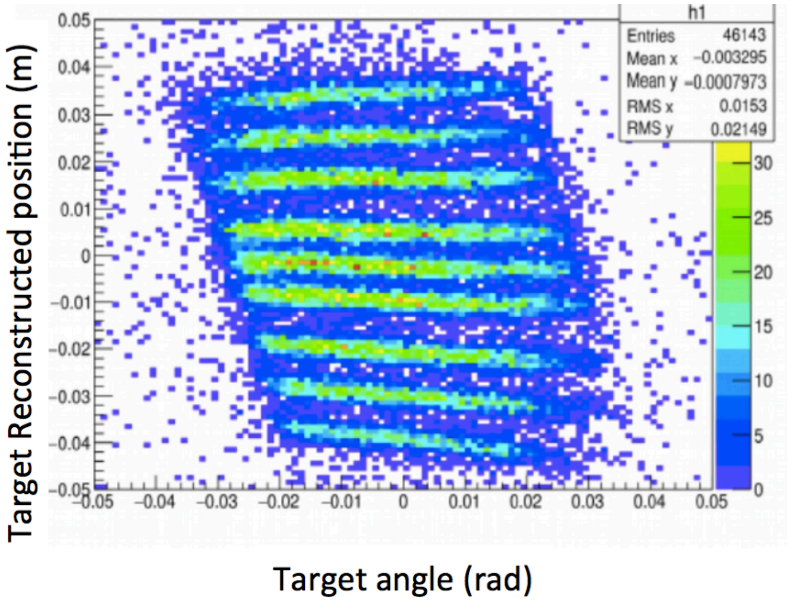
- New way to look at e- data: reconstruct initial e^- beam energy (E. Cohen)
  - Generator comparisons are underway
  - Powerful tool to test models of FSI even for ν interactions
  - Will also look at "transverse" variables
  - Plots at right are simulation, but data is available



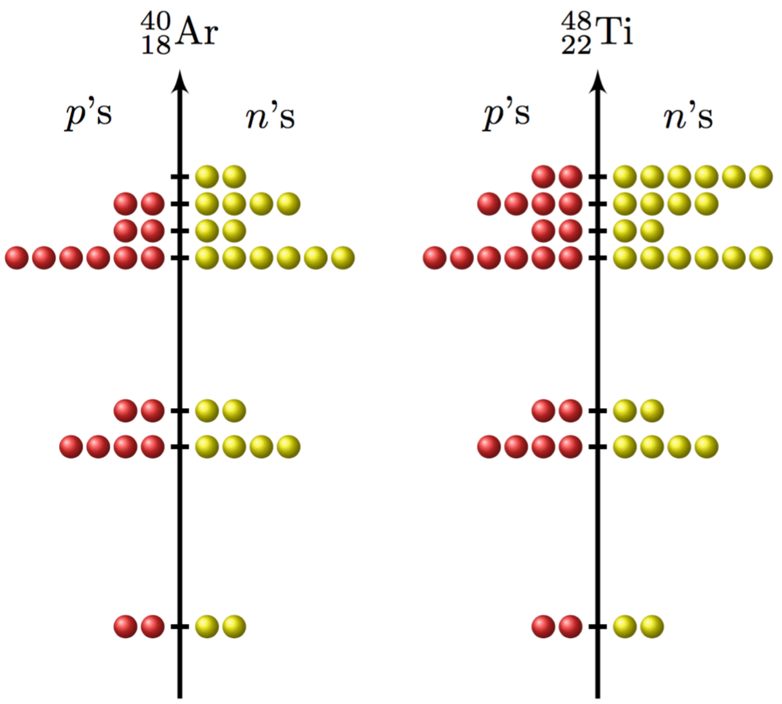
Two ways of estimating energy, same events: "QE-hypothesis", or "add proton and muon energy"

Future Electron Scattering Results: E12-14-012

- New data taken this Spring on Ti and Ar at JLAB (C. Mariani)
- Spectral functions for Argon to be measured for p and n both here!



$$e + A \rightarrow e' + p + (A - 1)$$



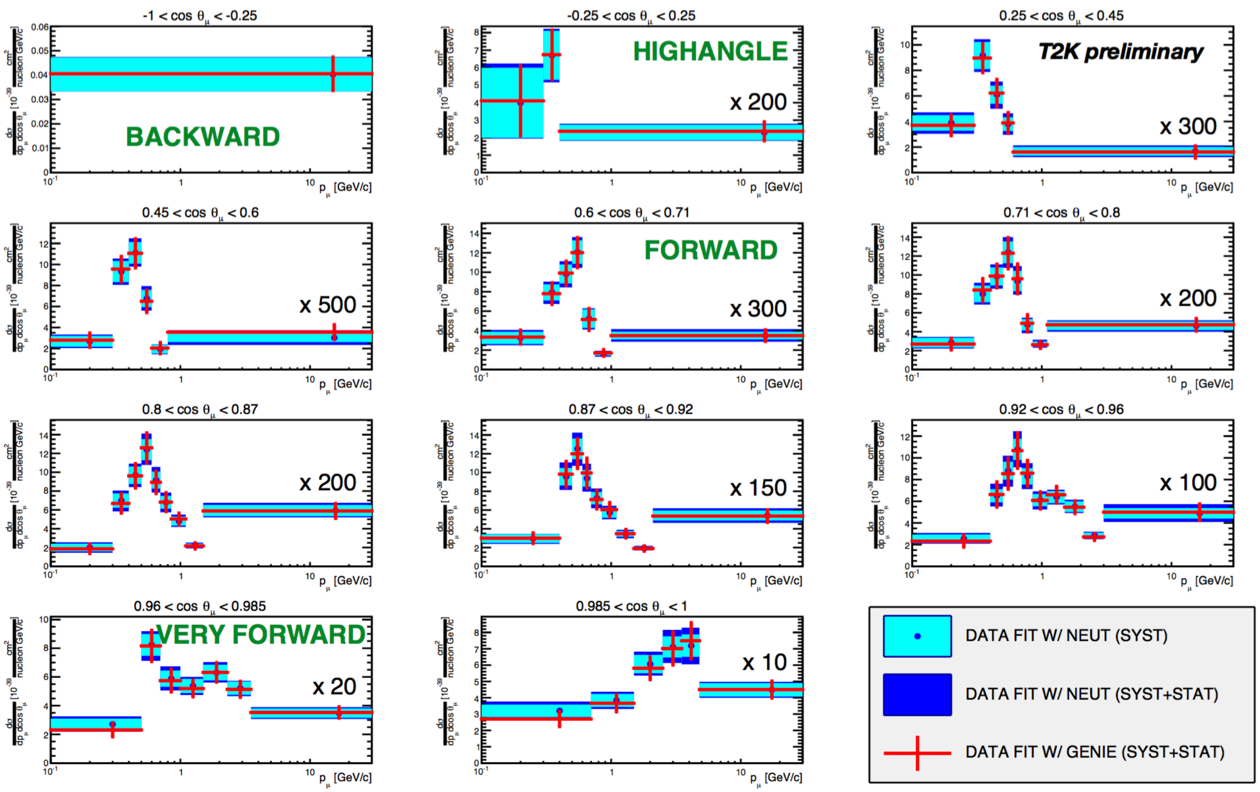
Electron Scattering Conclusions

- This is an important part of model building
- People are coming up with new ways to use the electron scattering data that already has been taken
- New proposals (and new data!) are out there to get even more help with models
- More work needs to be done to make sure that the theory side is also consistent with the electron scattering data

Inclusive Charged Current Measurements

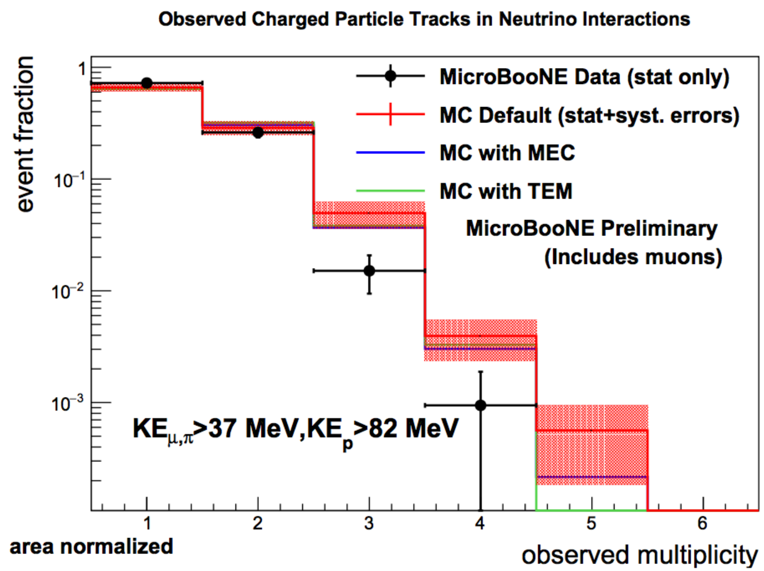
Inclusive ν_μ cc: T2K

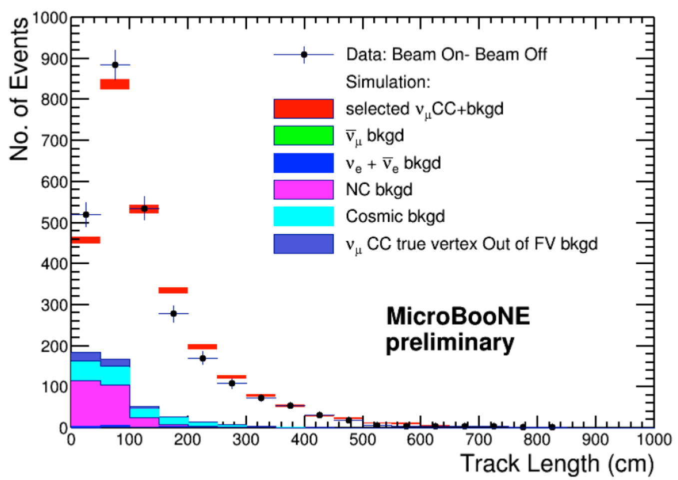
- Improved selection for higher coverage, better purity
- Cross Sections in 2 dimensions on carbon, ready for comparisons with Models! (A. Garcia)

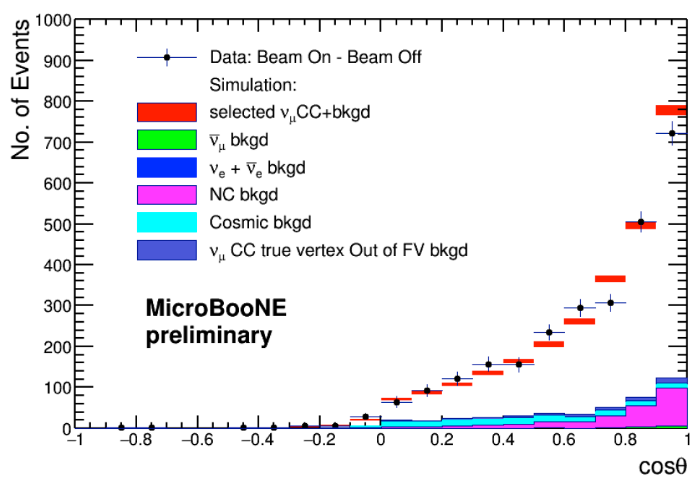


Inclusive ν_μ cc: MicroBooNE

- Shape normalized event distributions so far, looking forward to cross sections (A. Furmanski)
- First look at multiplicity
- Large cosmic ray subtraction, but better cosmic rejection methods in the works

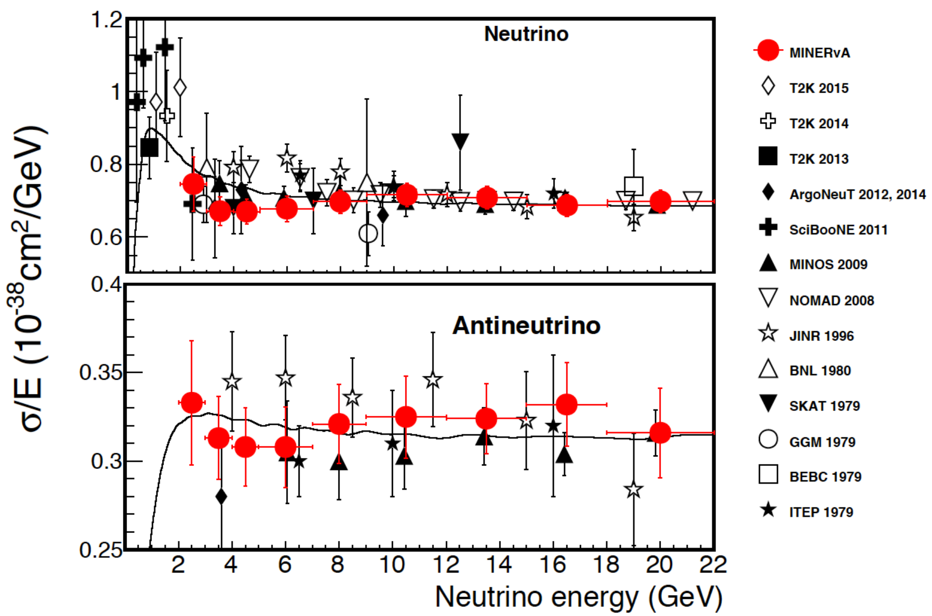


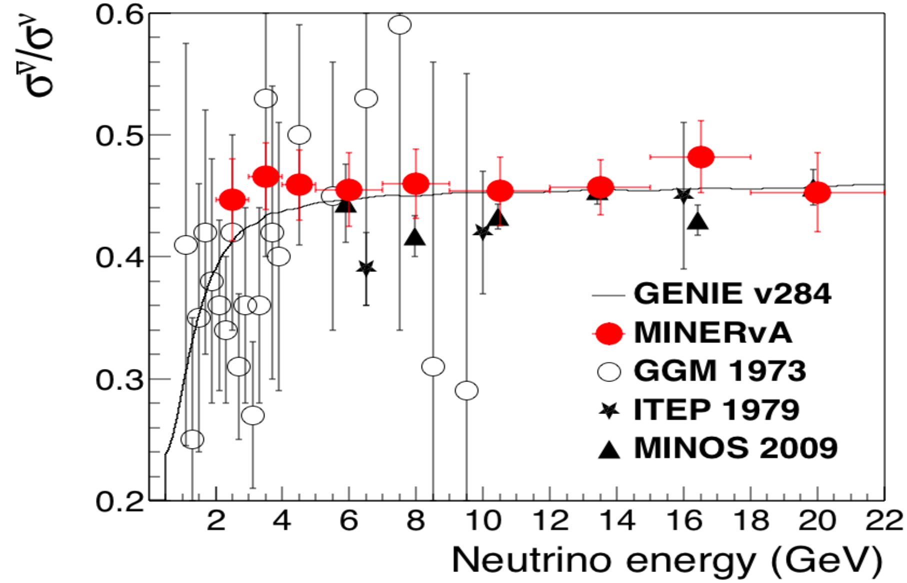




Inclusive ν_μ cc and anti-ν_μ cc: MINERvA

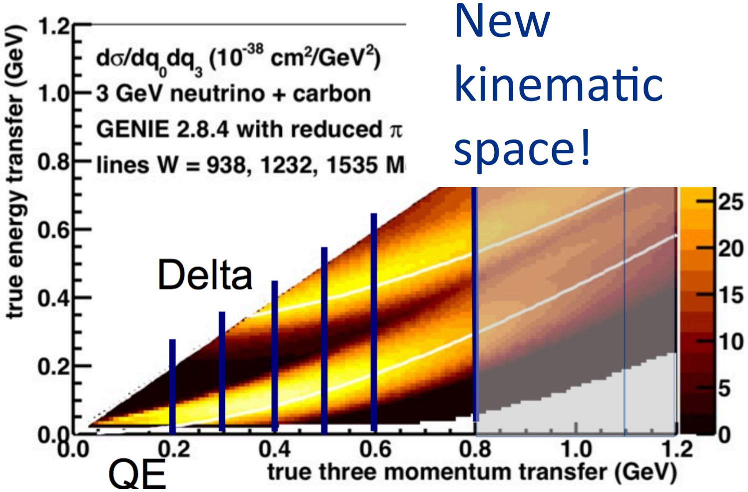
- Use the "low-ν" method to determine flux, reduces systematic uncertainties (D. Rimal, as interpreted by J. Nelson)
- Updated result from earlier measurement with new model and anti-ν_μ/ν_μ normalization



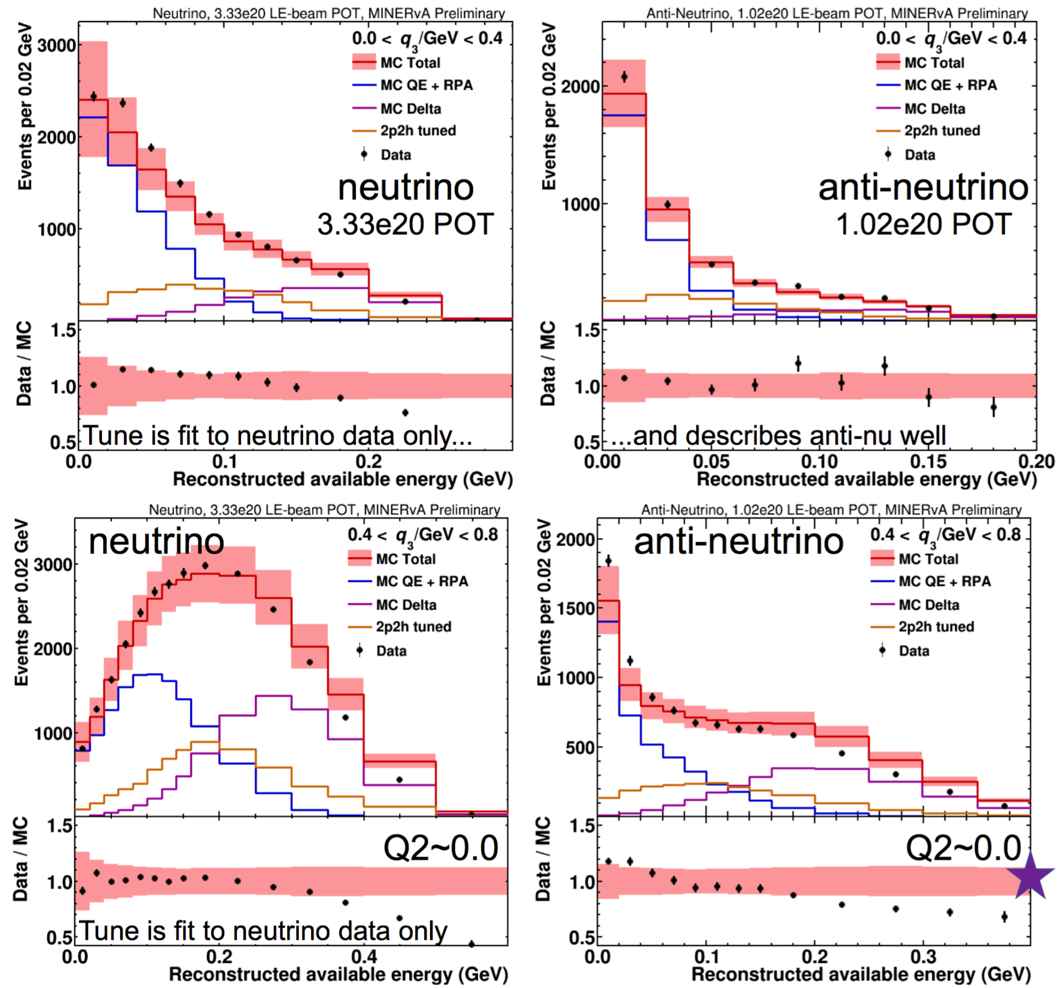


Inclusive ν_μ cc and anti-ν_μ cc "low q": MINERvA

- Low recoil "Inclusive" ν_μ cc interactions in antineutrinos: MINERvA (R. Gran)



New kinematic space!



- Model that works for "filling in the dip" in neutrino data also agrees with antineutrino data!
- Cross Sections extracted

Inclusive ν_e and anti-ν_e cc: T2K

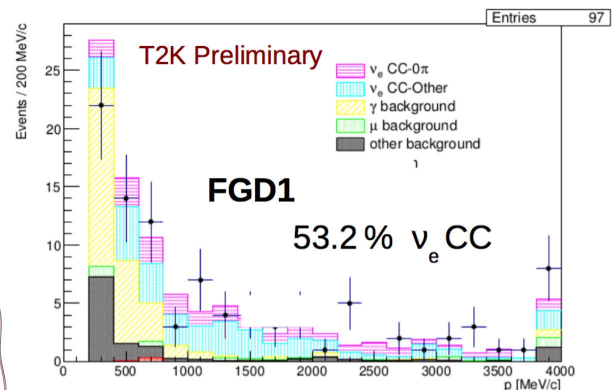
- First glimpse at "pure" antineutrino CC events!(S. King)
  - Quoting normalization to predicted ν_e event rate, biggest systematic is acceptance

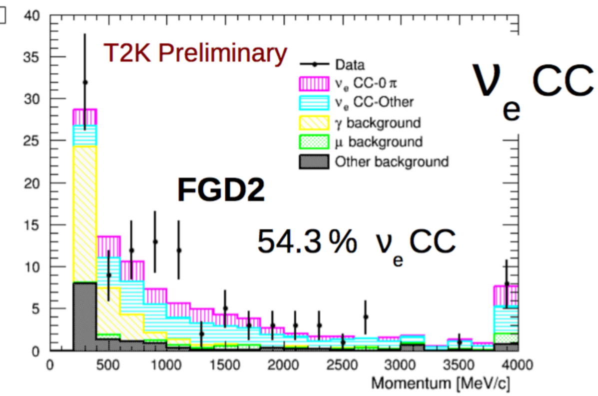
Scale factor results:

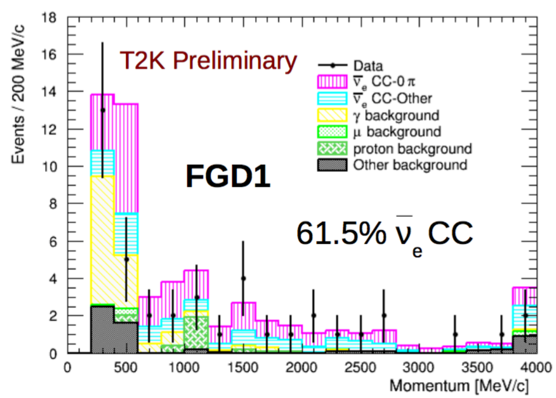
$f(\nu_e) = 1.250 \pm 0.135$ (stats.) ± 0.122 (syst.)

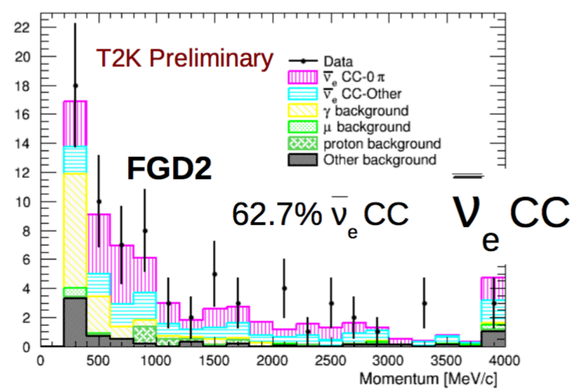
$f(\bar{\nu}_e) = 1.142 \pm 0.144$ (stats.) ± 0.132 (syst.)

	Detector syst	Flux + xsec syst
ν_e CC	6.5%	7.5%
$\bar{\nu}_e$ CC	6.5%	9.5%









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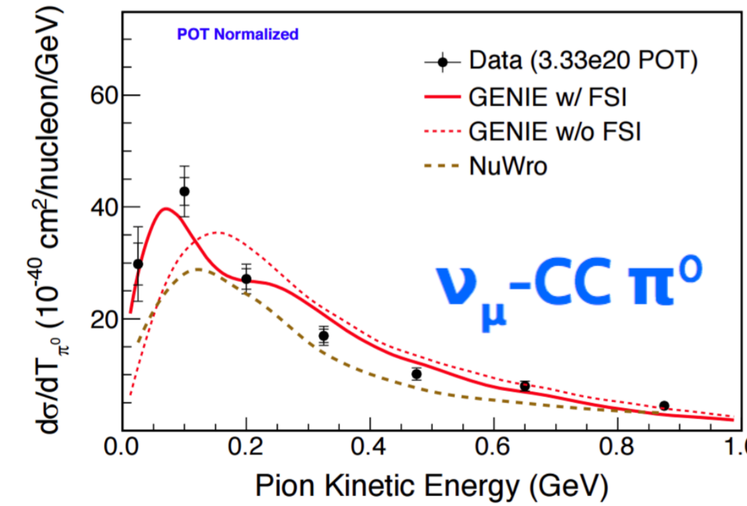
Inclusive CC measurement Conclusions

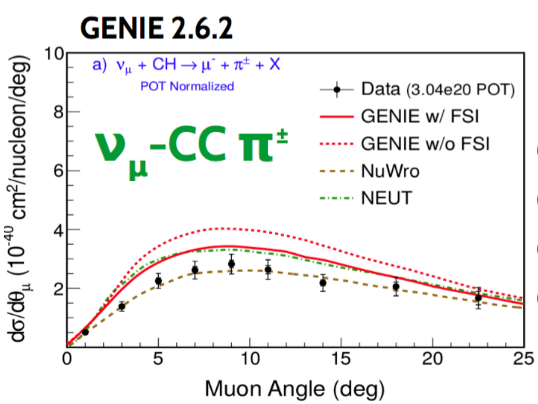
- Starting to accumulate large inclusive CC data sets
  - Muon and electron neutrinos
  - Neutrinos and antineutrinos
  - Single and double differentials
- Inclusive measurements are "final cross-check" of model but are hard for model building since there could be processes missing
- See that ν_e's are very hard experimentally, will need theory to get most precise ν_e/ν_μ ratios (K. McFarland)
- New ways of looking at inclusive data: use two dimensions that correlate the hadronic side and the lepton side (q0,q3)
- See that a model that was fit to neutrino data works with antineutrinos!

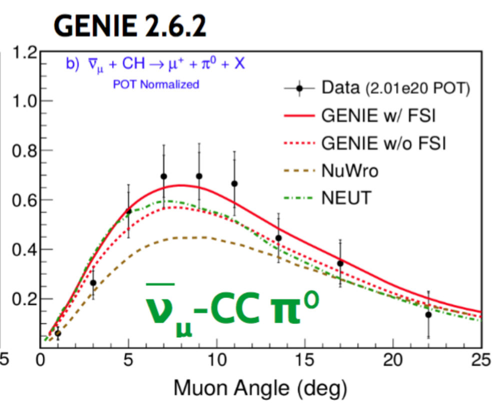
Pion Production Measurements

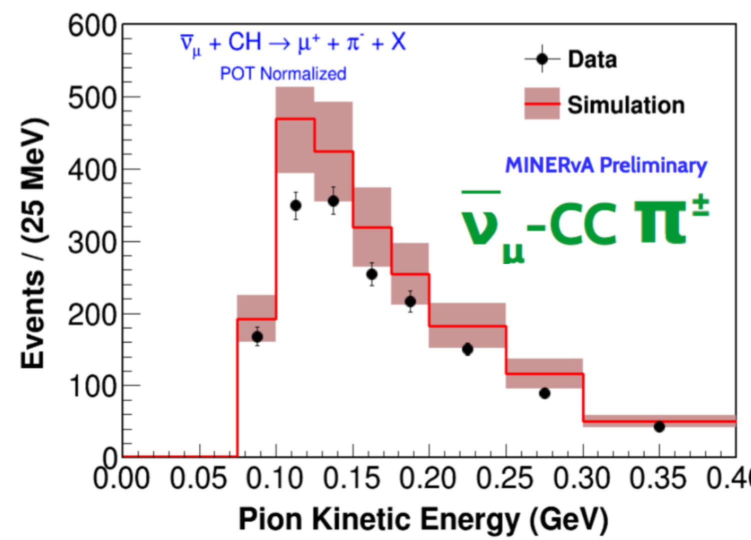
CC Pion Production (times 4): MINERvA

- All 4 combinations shown: ν,anti-ν, $\pi^{\pm}$, π^0(A. Ramirez)
- Brand new: ν π^0 production
  - See O. Altinok @FNAL, July 7
- First glimpse: ,anti-ν $\pi^{\pm}$ production
- Updates for previous pion measurements with better flux also ready



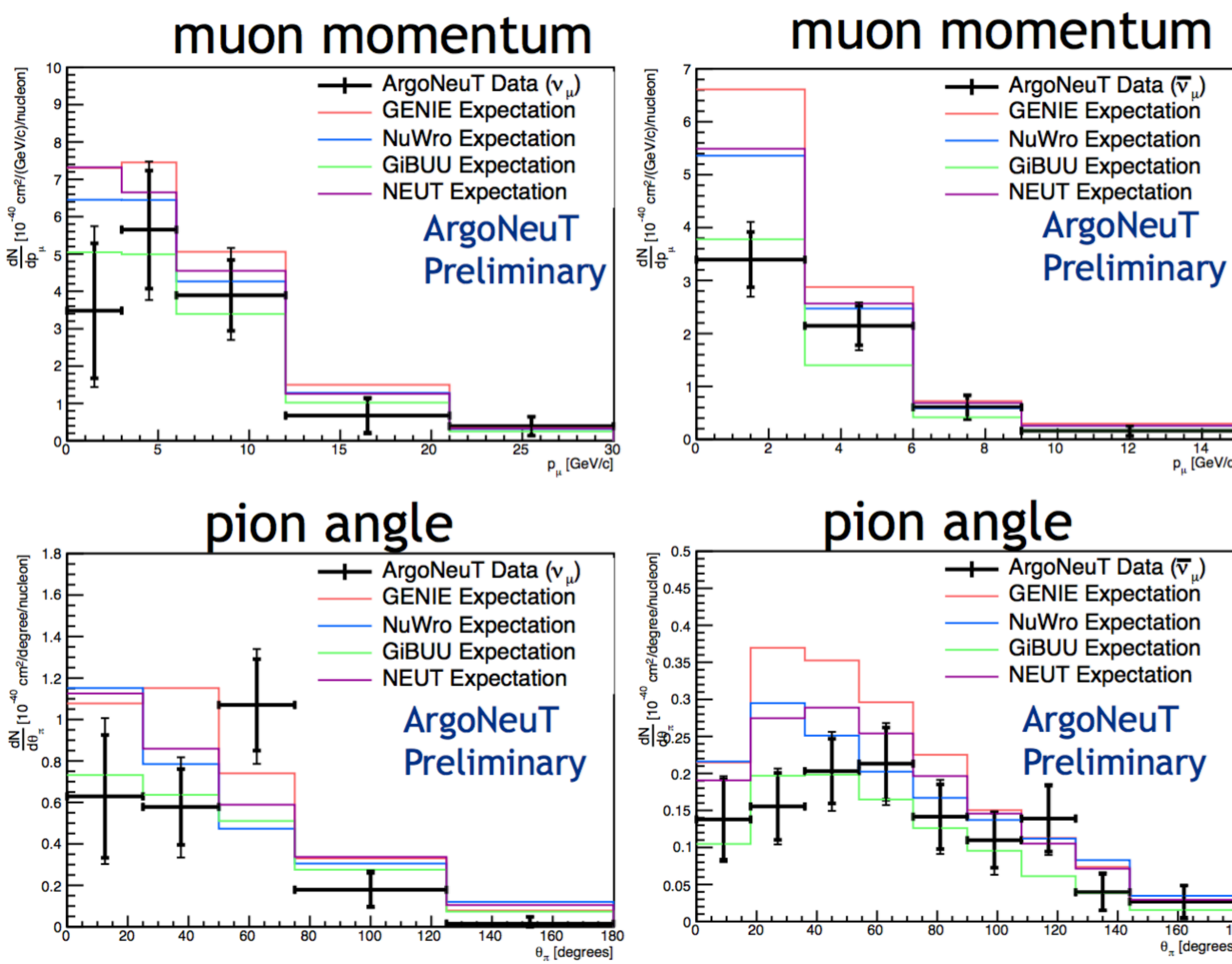






CC $\pi^{\pm}$ production on Argon: Argoneut

- Identify one muon and one other track with PID like a pion (T. Yang)
- Neutrino and Antineutrino events shown
- Other variables also reported (pion angle, mu-pi angle)



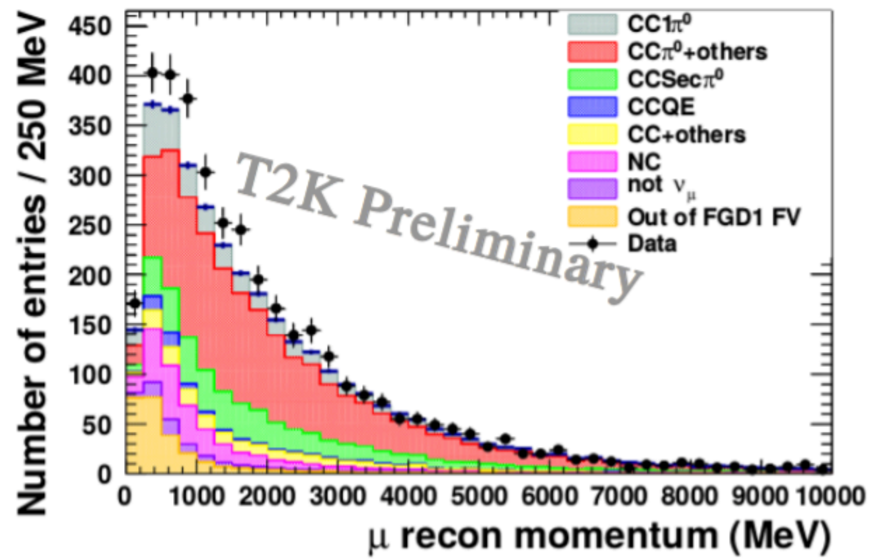
CC π^0 production on CH: T2K

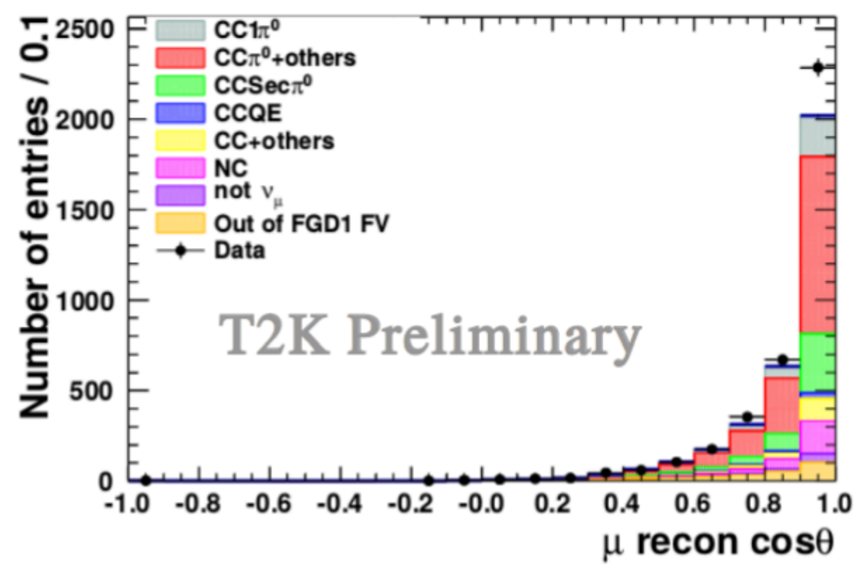
- Contributions from resonant and DIS interactions (M. Batkiewicz)
- Cuts end up selecting high energy events, mostly multi-π production
- Total cross section:

$$\sigma^{data} = (1.239 \pm 0.034(stat)$$

$$^{+0.157}_{-0.158}(syst)^{+0.175}_{-0.149}(flux))$$

$$\cdot 10^{-39}\, cm^2/nucleon$$

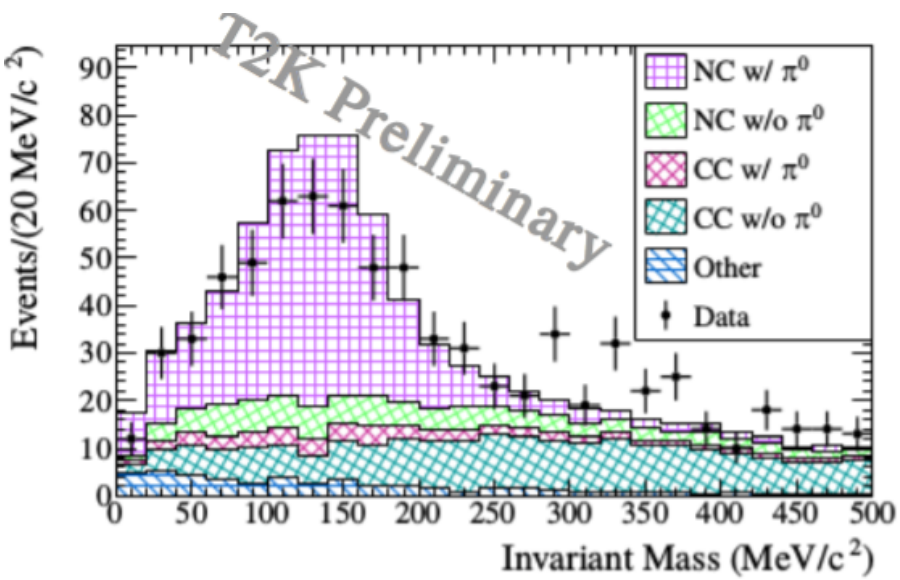




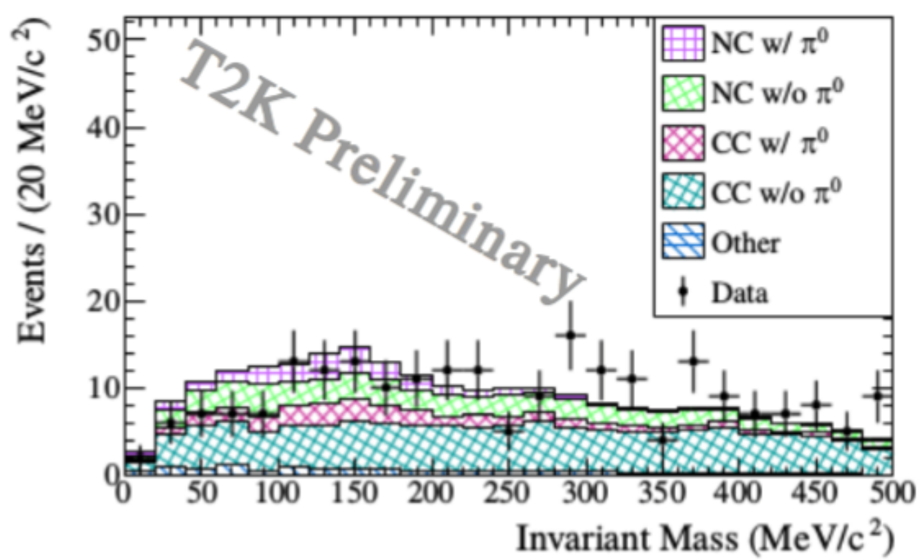
NC π^0 production on water: T2K

- Water-in – water out subtraction (M. Batkiewicz)
- Two backgrounds: non-π^0 events on water, plus non-water events
- Result quoted as ratio to NEUT prediction

$$data/MC\,ratio = 0.68 \pm 0.26(stat) \pm 0.44(syst) \pm 0.12(flux)$$



Water in, all cuts

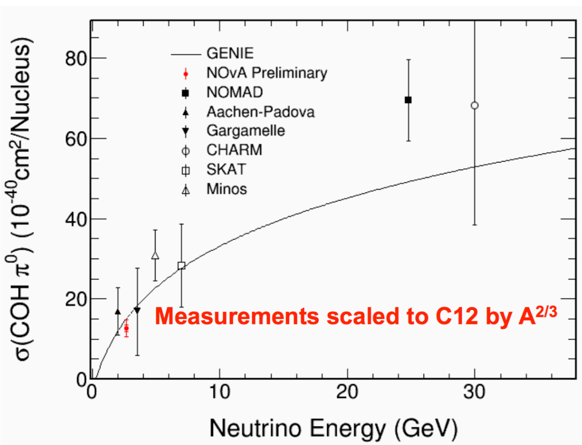


Water in, muon cut reversed

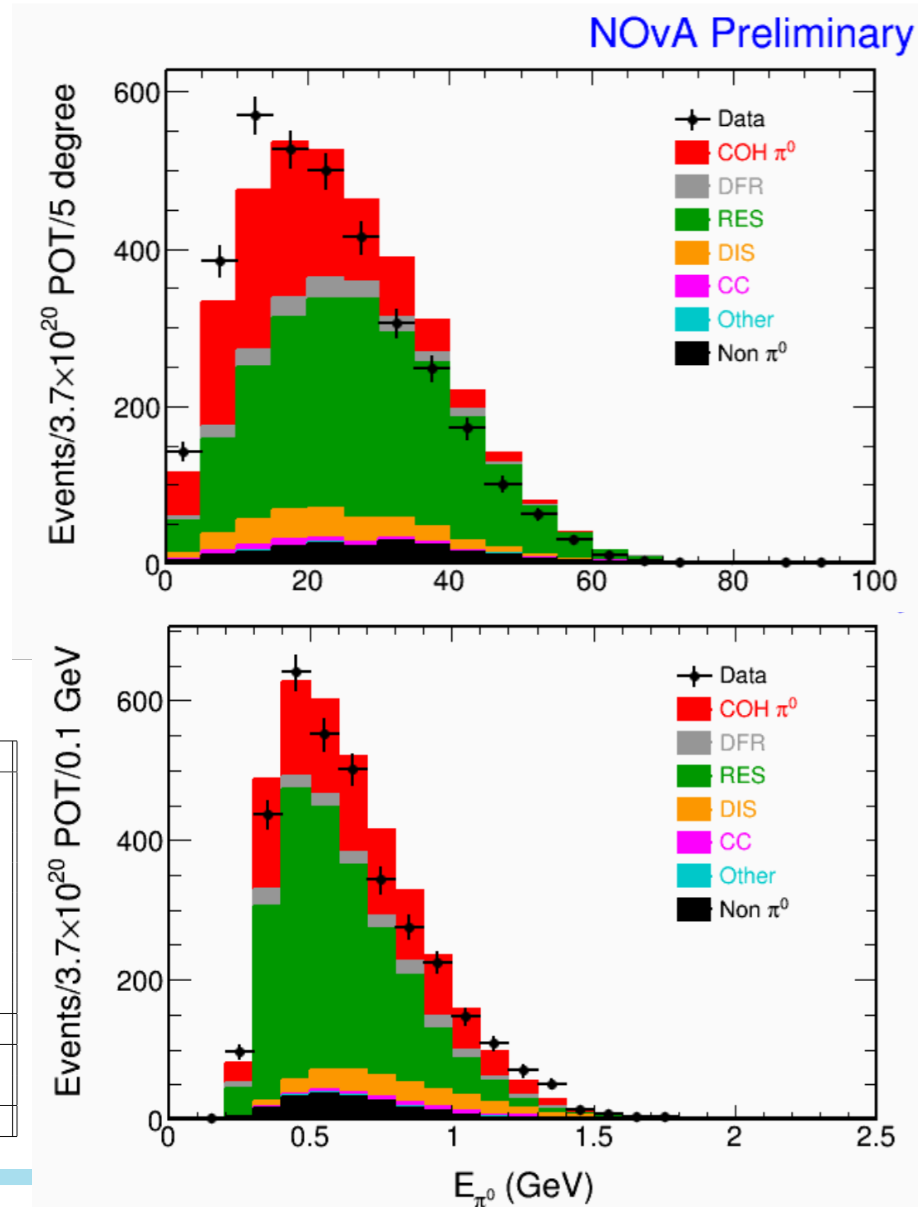
NC Coherent π^0 production: NOvA

- Challenging analysis, large backgrounds (H. Duyang)
- Proof that there's much work to be done on all NC interactions!

Flux-averaged cross section: 14.0±0.9(stat) ±2.1(syst) $\times 10^{-40} cm^2$/nucleus



Source	$\delta(\%)$
Calorimetric Energy Scale	3.4
Background Modeling	10.0
Control Sample Selection	2.9
EM Shower Modeling	1.1
Coherent Modeling	3.7
Rock Event	2.4
Alignment	2.0
Flux	9.4
Total Systematics	15.3
Signal Sample Statistics	5.3
Control Sample Statistics	4.1
Total Uncertainty	16.7



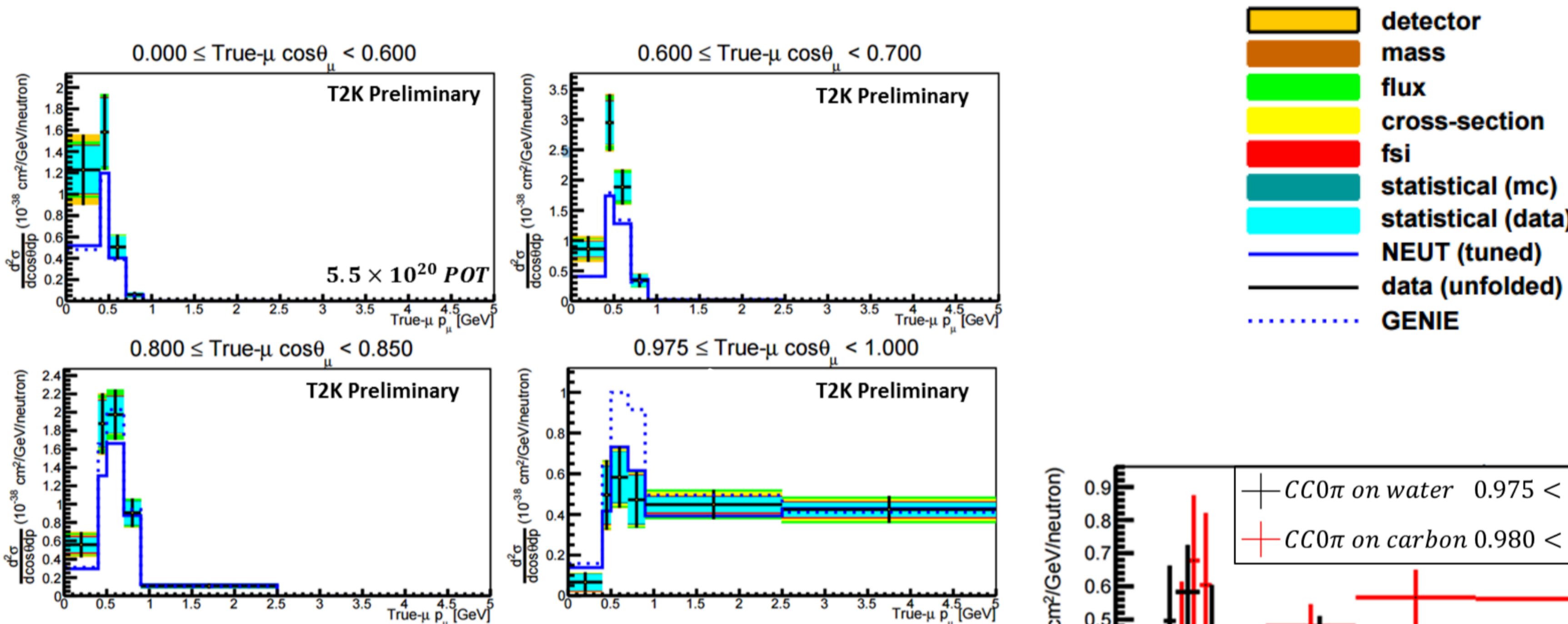
Pion Production Conclusions

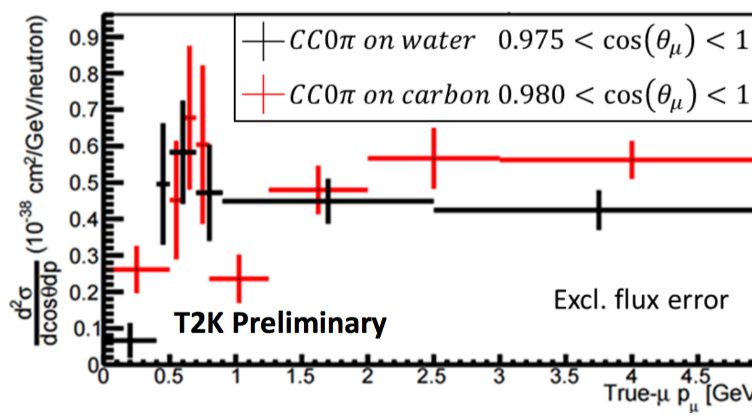
- Gathering many more channels on pion production
  - Neutrino, antineutrino, charged neutral
- Gathering new nuclei on pion production!
  - Water and Argon joining the mix, plus new CH and CH_2 results
- Clearly a long way to go on neutral current channels
- Many Puzzles exist in all these measurements
- Pion production can pick out higher neutrino energies than 0-pion channels in T2K, big overlap in all these measurements
- Will be able to beat T2K and MINERvA measurements against eachother to solve the puzzle:
  - Is it theory, signal definition, measurement technique, all of the above?

Pion-less Charged Current Measurements

Pion-less CC on CH and Water: T2K

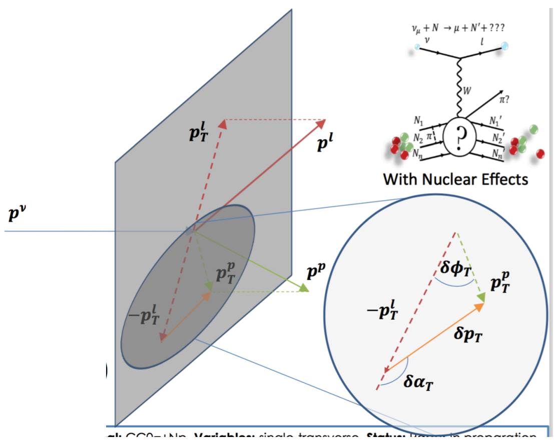
- Shows new distributions for double differential variables on Water: welcome to A-dependence! (S. Dolan)

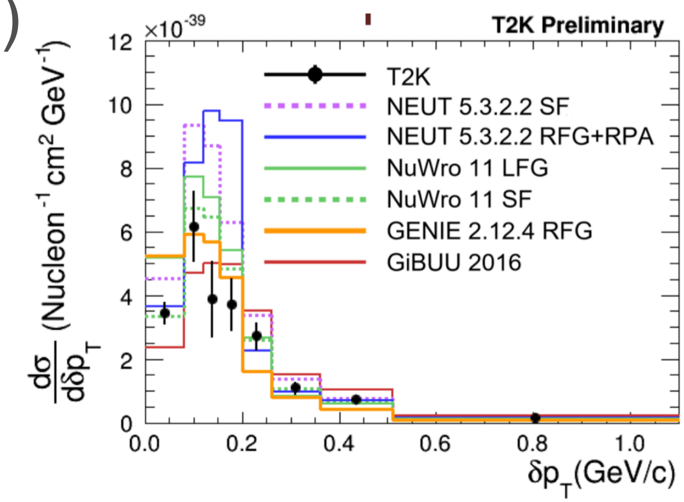




Pion-less CC, from the proton side: T2K

- When you reconstruct proton angle and momentum, many new variables are available (S. Dolan)



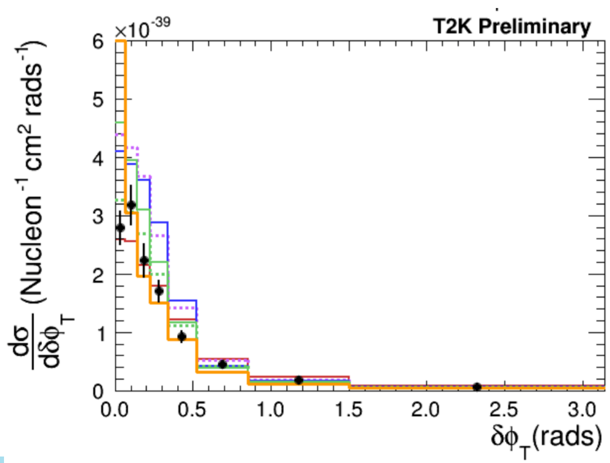


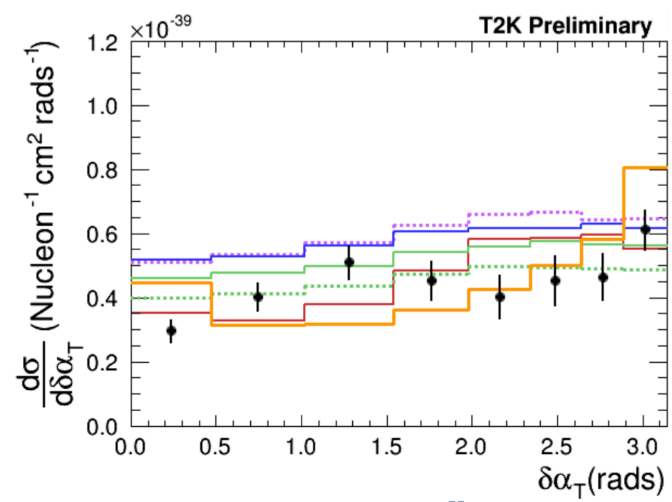
$p_\mu > 250\ MeV/c$

$\cos(\theta_\mu) > -0.6$

$450\ MeV/c < p_\mu < 1\ GeV/c$

$\cos(\theta_p) > 0.4$

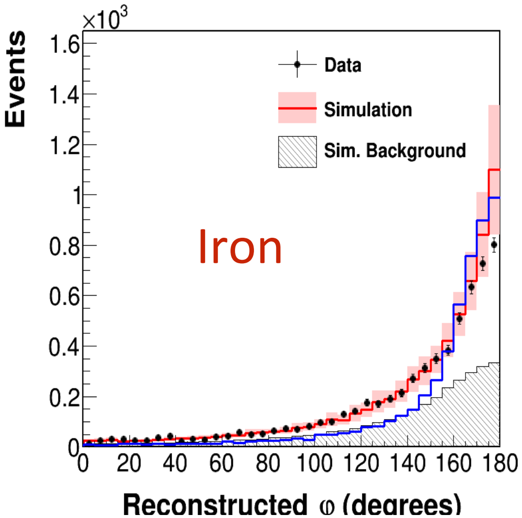


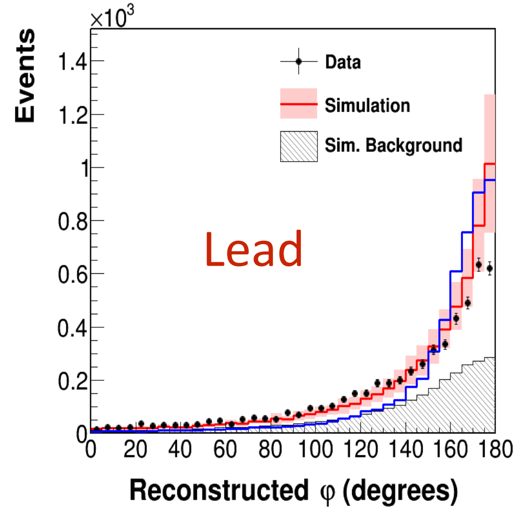


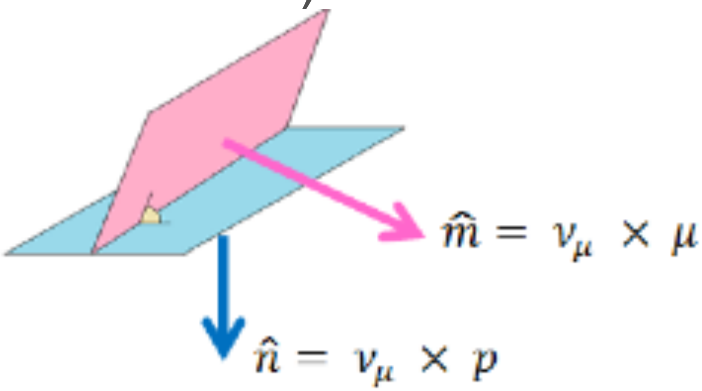
Fermilab

Pion-less CC, from the proton side: MINERvA

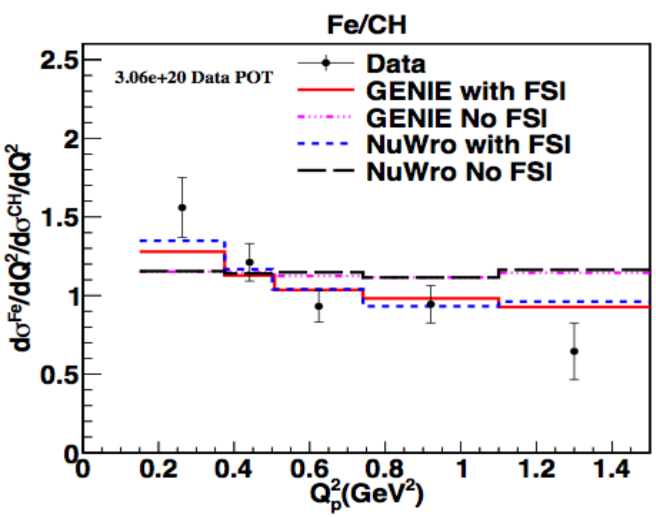
- Compare C, Fe, Pb to Scintillator (M. Betancourt)

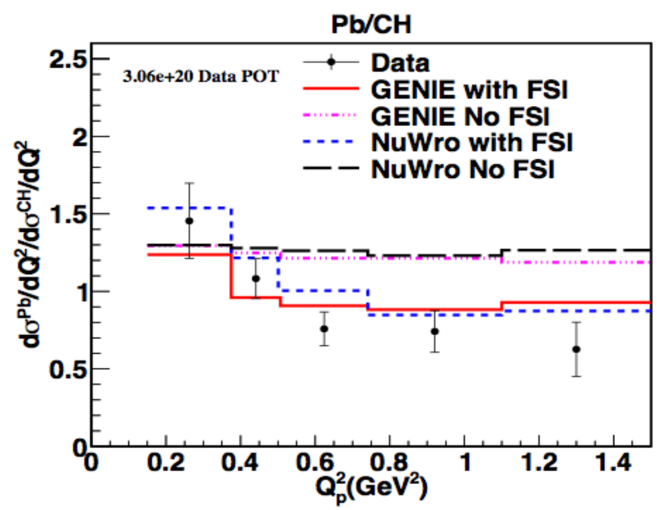






$$\varphi = \cos^{-1}\left(\frac{(\hat{\mathbf{p}}_\nu \times \hat{\mathbf{p}}_\mu)\cdot(\hat{\mathbf{p}}_\nu \times \hat{\mathbf{p}}_p)}{|\hat{\mathbf{p}}_\nu \times \hat{\mathbf{p}}_\mu||\hat{\mathbf{p}}_\nu \times \hat{\mathbf{p}}_p|}\right)$$

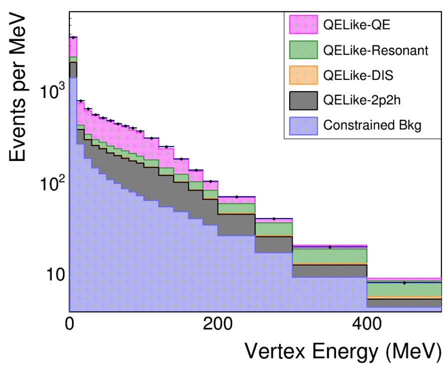


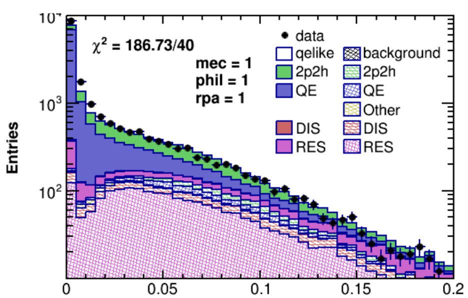


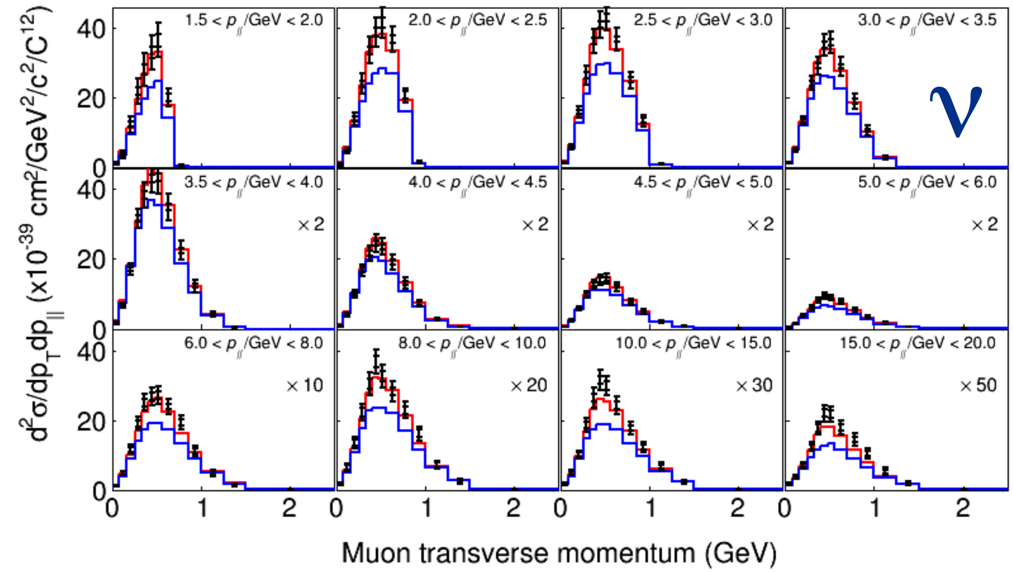
Fermilab

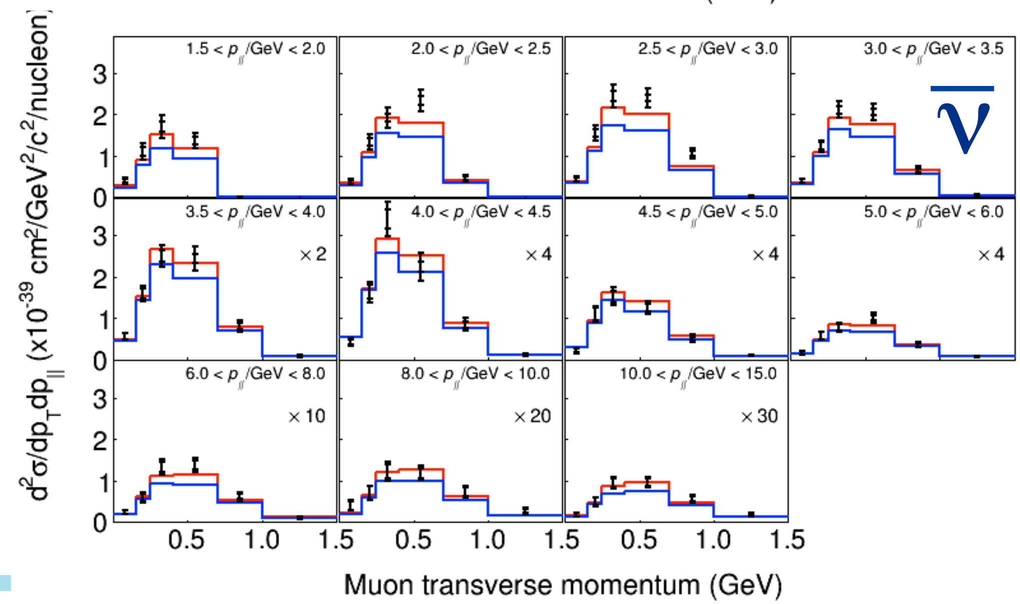
Pion-less CC, from the proton side: MINERvA

- Neutrino and antineutrino double differential cross sections both favor neutrino-mode “q0-q3” fit (D. Ruterbories)



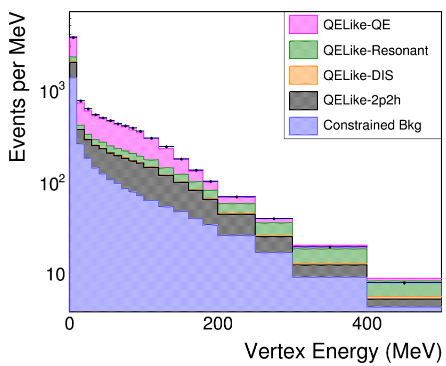


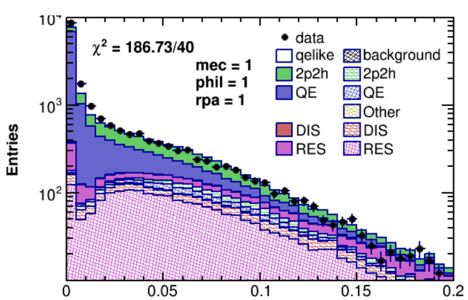


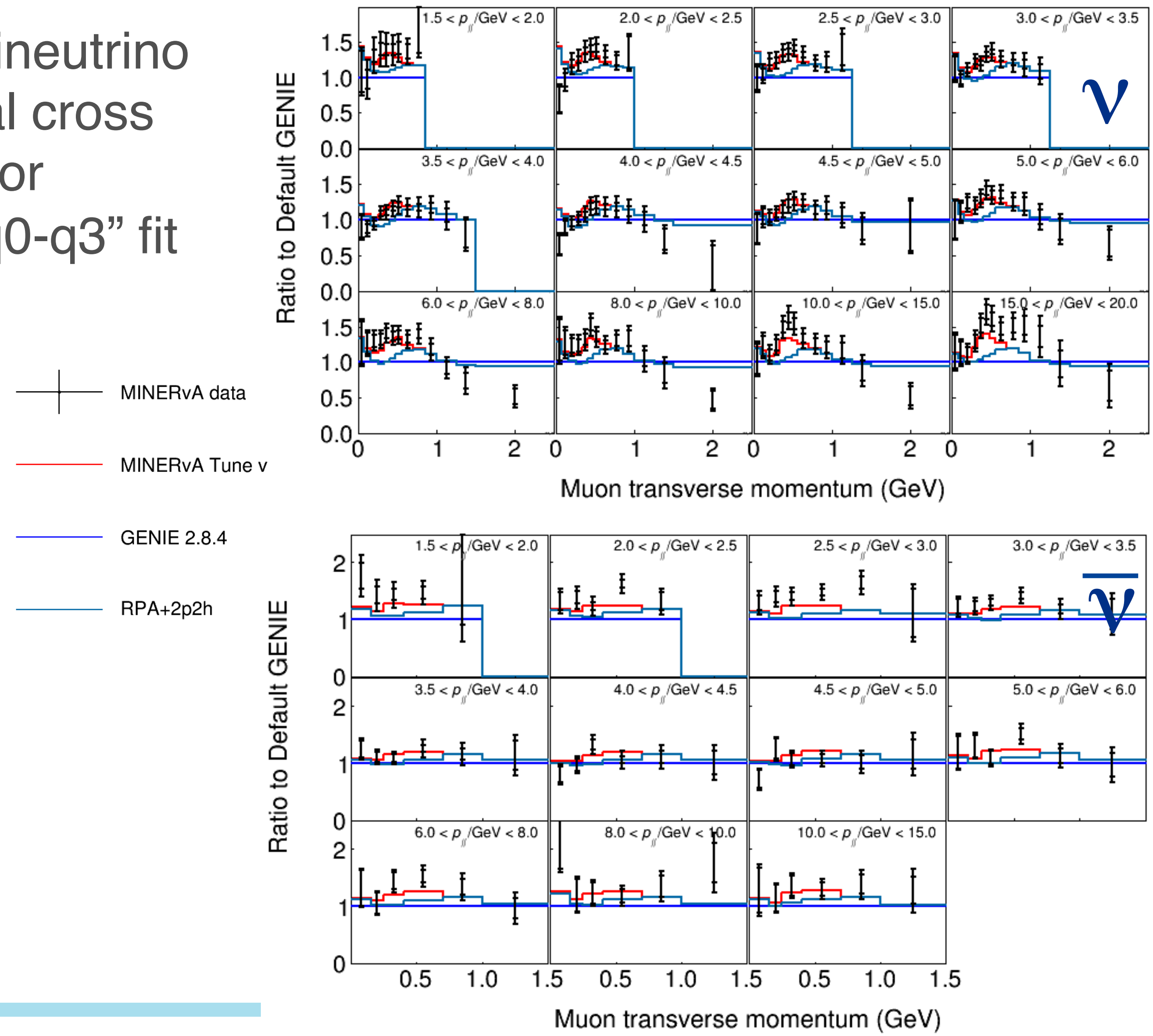


Pion-less CC, from the proton side: MINERvA

- Neutrino and antineutrino double differential cross sections both favor neutrino-mode “q0-q3” fit (D. Ruterbories)







Pion-less CC Interaction Conclusions

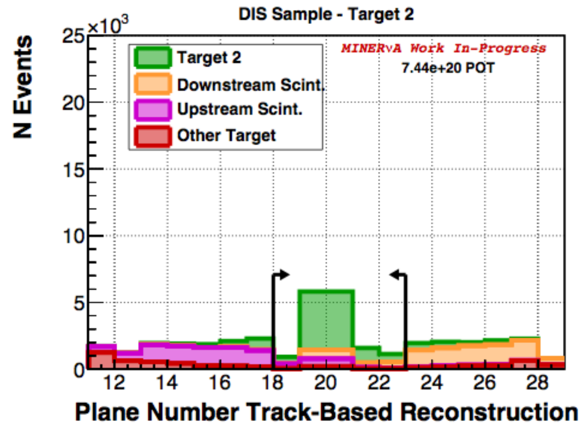
- MINERvA and T2K's measurements very mature
- Iterations with this community mean that we have evolved to a less model-dependent signal definition, and analysis cuts

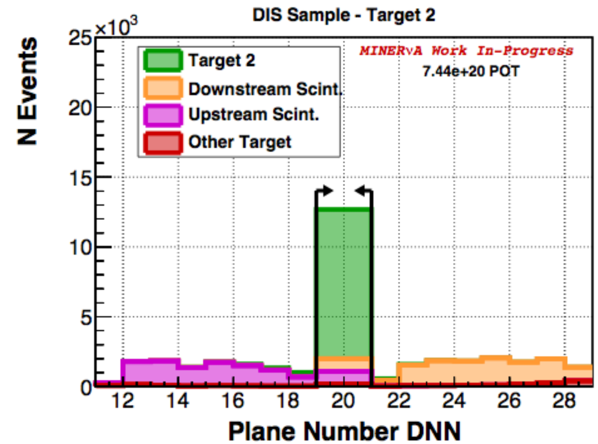
- By looking at the hadron side, you get a new handle on the nuclear effects, and even more so if you compare across different nuclei
- MINERvA's inclusive low recoil fits to NEUTRINO EVENTS provide a consistent model that works on antineutrino low recoil events AND the muon side alone!

- Huge progress since the last NuINT…

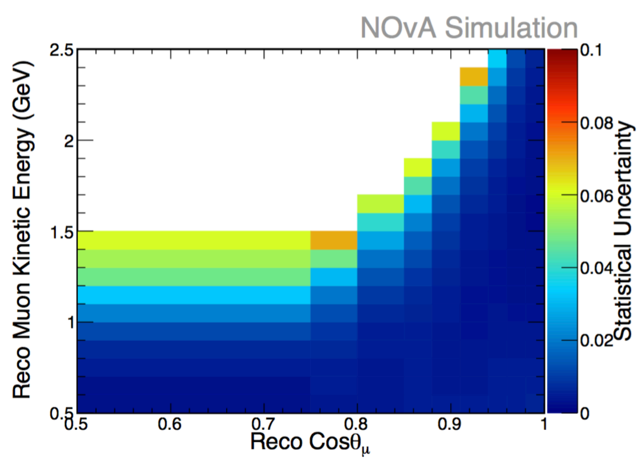
Future Neutrino Interaction Results

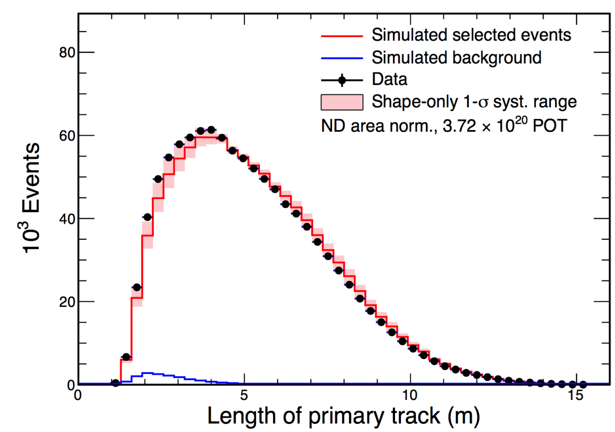
- MINERvA ME DIS Ratios: look forward to better statistics and systematics thanks to machine learning (A. Norrick)



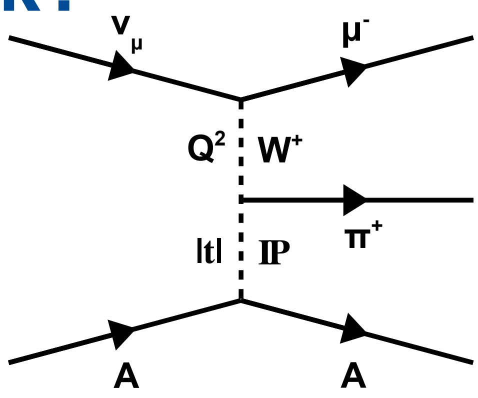


- T2K ν_e CC: look at 3 channels separately, CC0π, CC1π, CC multi-π
- MicroBooNE: coming soon: NC elastic, CC π^0, CC0π
- NOVA: Inclusive ν_μ cc and ν_e CC (J. Paley), CCπ^0, NCπ^0, CC$\pi^\pm$ (Duyang)



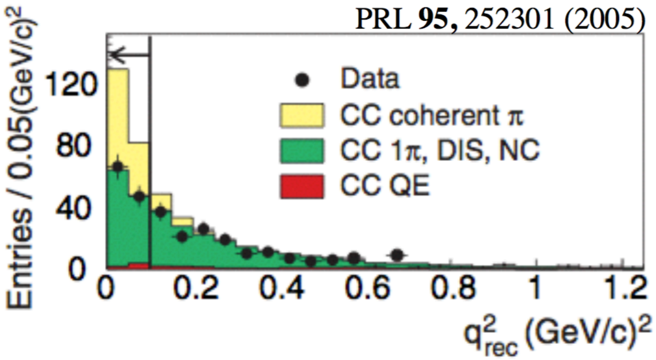


What DIDN'T we talk about this week?



- Remember the Coherent Pion puzzle?
  - Effect was seen at high energies but not at low energies
  - Low energy measurements plagued by not being able to reconstruct t
  - This meant that experiments had model-dependent efficiencies and background subtraction techniques
  - Eventually MINERvA and T2K measured this process in a model-independent way by reconstructing t and cutting there.
  - Measured Q^2 distributions did NOT match the generator…

PRL **95**, 252301 (2005)



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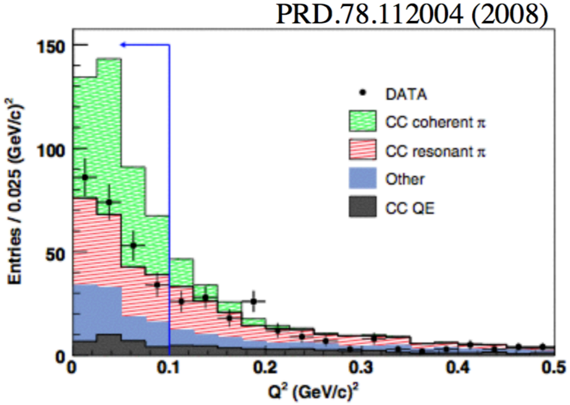


So, you want your result to be useful?

- Learning lessons about how to make a measurement that has an impact on generators and future models
- Be very clear about what your signal is
  - QE or Pion-less?
  - Do you only accept events within some angular region?
  - Does your detector naturally have a momentum threshold?
- Be careful about cuts to isolate your signal that you might not model well
  - Q^2, vertex energy for QE events, “acoplanarity”, etc.
- Try to constrain backgrounds with data whenever possible
  - Think hard about what strategy is least model dependent
- Make sure your systematics really cover the uncertainty
  - Example from MINERvA: if a process is missing, then you won’t have included uncertainty in that process, right?


ARE WE THERE YET !?!
MATT GROENING

The tools we need to get there

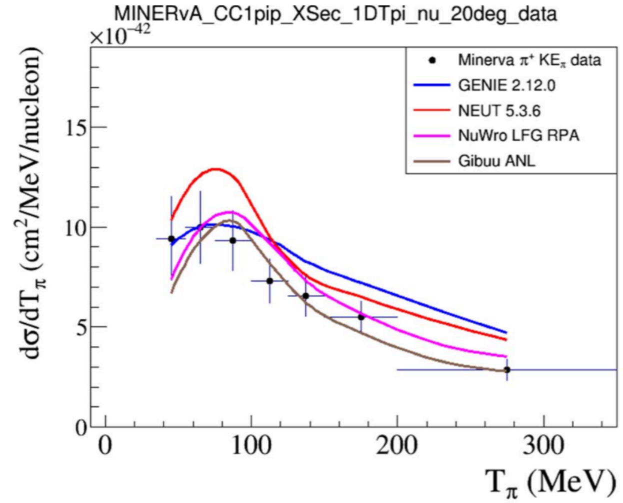
- Cross Section measurements
  - With full correlation matrices
  - With complete* model systematics
- Flux Predictions
  - Aided by hadron production measurements
  - In situ techniques for hadrons and neutrinos welcome!
- Pion scattering measurements
  - Again with full correlation matrices
- Electron Scattering comparisons
  - Across many nuclei
  - Finding new neutrino-like observables
- NUISANCE!

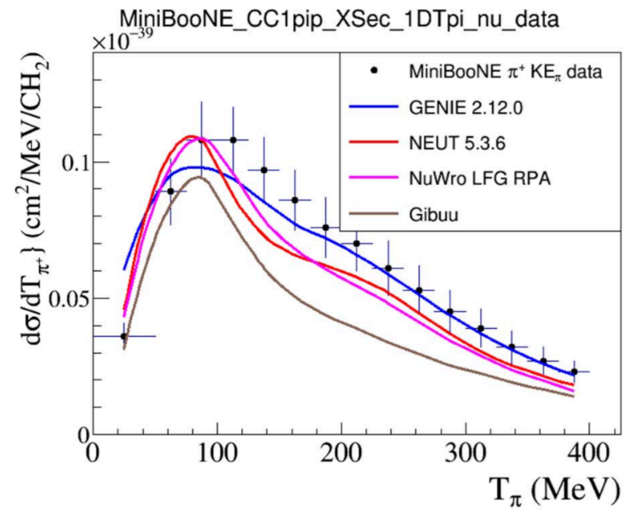
Are we there yet?

- For shallow and deep inelastic scattering: we have a long way to go
- Luckily we have time to get there
- DUNE will need to understand this region too, just like T2K has to understand pion production

Are we there yet?

- For pion production
  - Not yet…
  - Still see discrepancies
    - Between different channels
    - Between different experiments
  - Models in generators match in some pion channels but not others
    - Want to use full suite of pion production channels
  - We need to take the lessons we learned from 0-π measurements and apply them here: key for NOvA

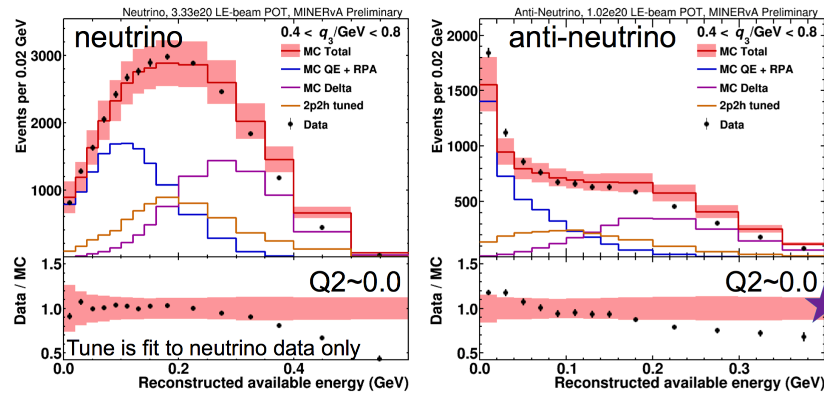




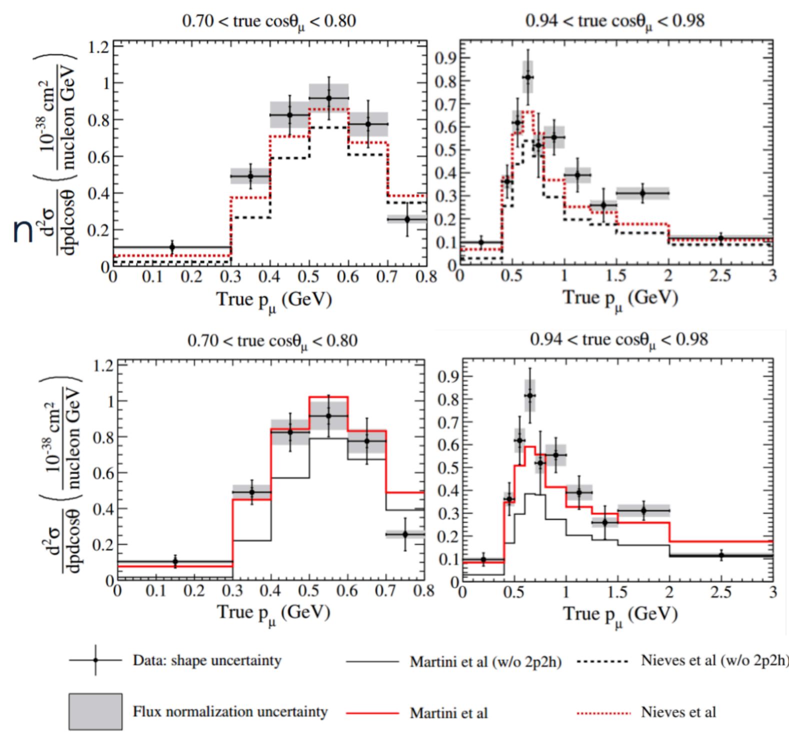
Are we there yet?

- For 0-π interactions:
  - We are, as long as we add
    - Multinucleon correlations (thank you e⁻ scattering)
    - Random phase approximation
  - See features across many measurements
    - From one experiment to another
    - From one neutrino helicity to another
  - Close to a data-constrained model based on theory to get us through the current generation of oscillation experiments

MINERvA



T2K



Thanks to our hosts!

- For providing such a welcoming home to inhabit
  - With such a well-stocked kitchen
- For accepting so many more of us than you planned to accept
- For providing such a beautiful city to explore