Neutrino / anti-neutrino single π production (Experiments)

Yoshinari Hayato (Kamioka, ICRR, Univ. of Tokyo)

Introduction

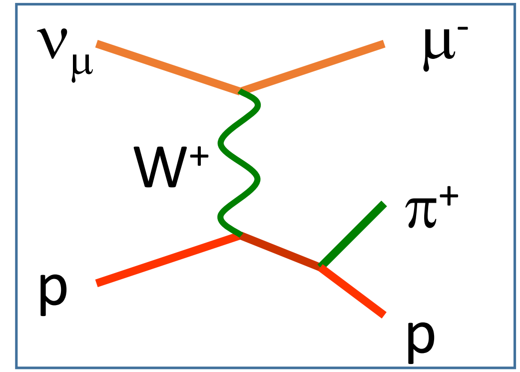
Neutrino and anti-neutrino induced π production

Pre-dominant interaction in a few GeV region

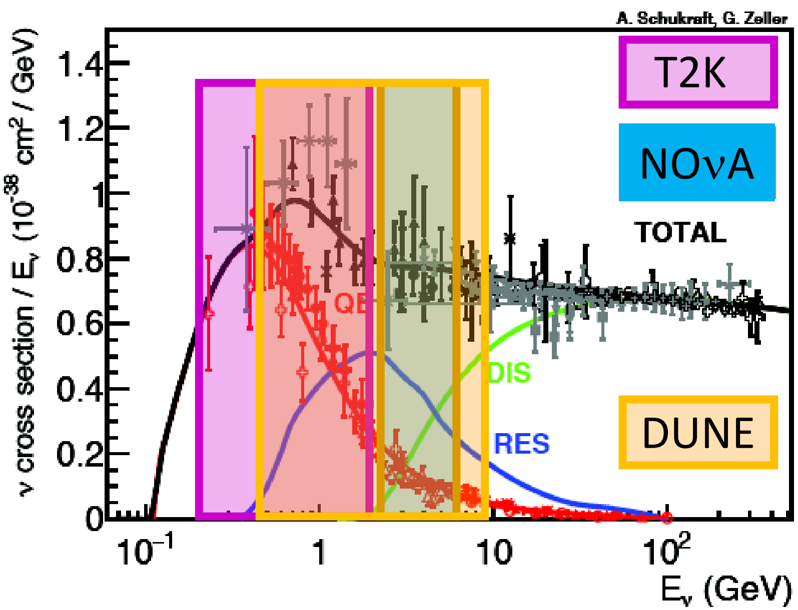
Signal or background of

long baseline neutrino oscillation experiments

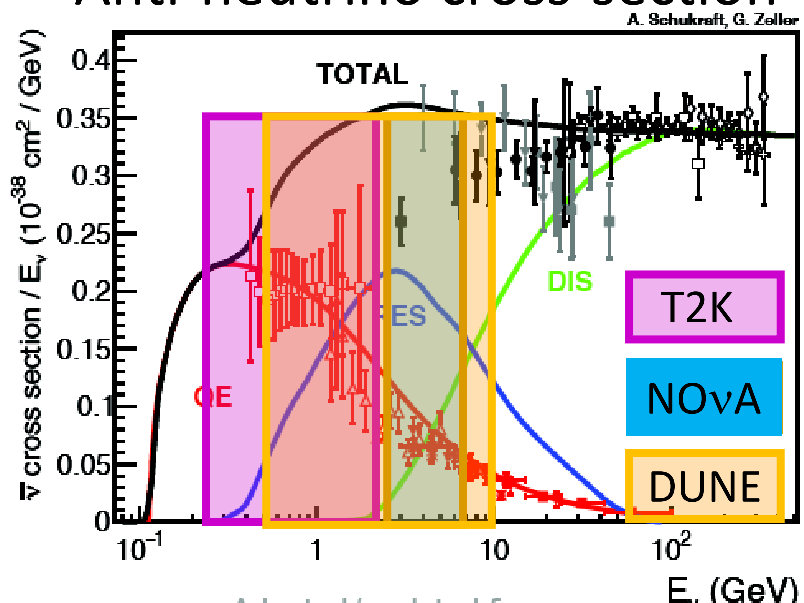
Major background in the nucleon decay search



Neutrino cross-section



Anti-neutrino cross-section

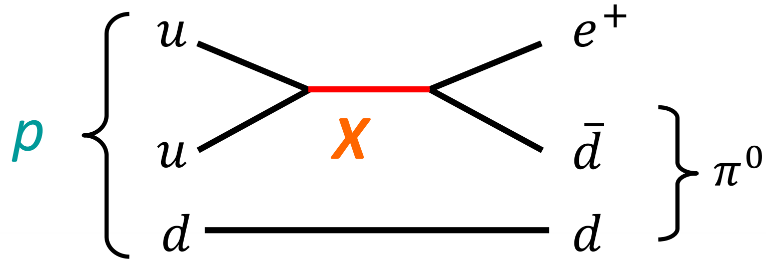


Adapted/updated from
J.A. Formaggio, G.P. Zeller, Rev. Mod. Phys. 84 (2012) 1307

Introduction

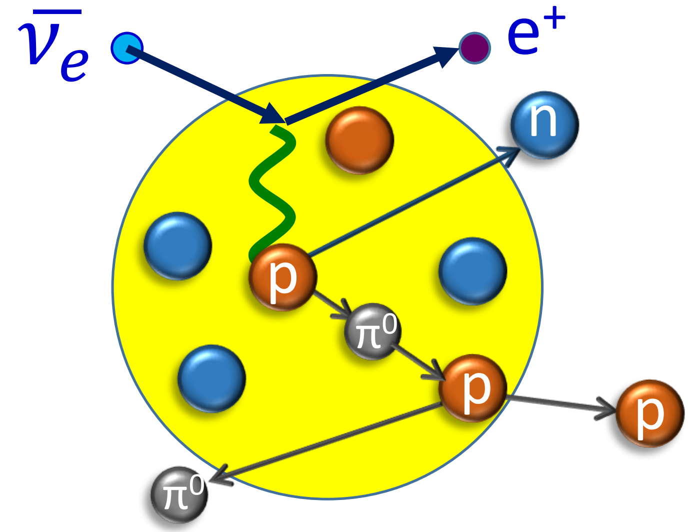
Proton decay signal

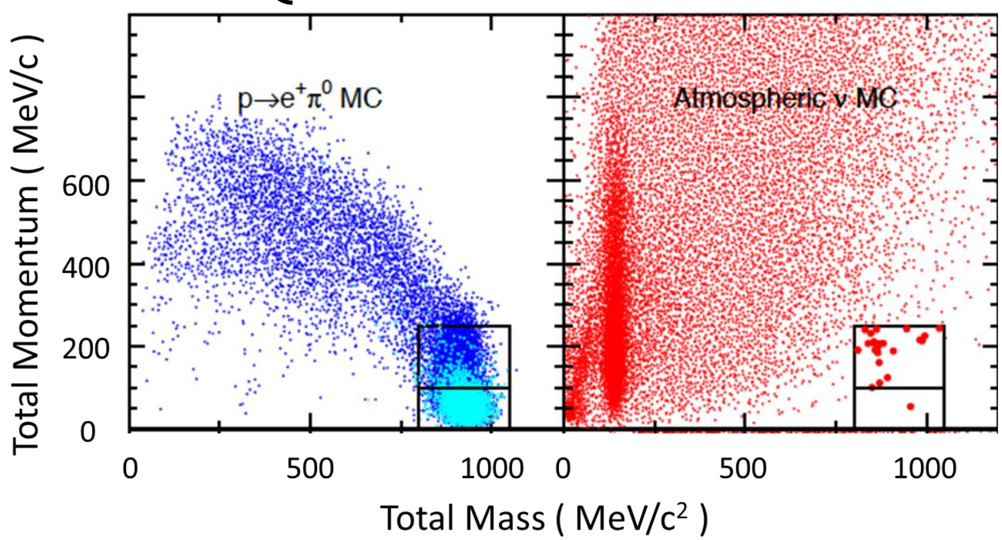
$$p \rightarrow e^{+} + \pi^{0}$$



Background (example)

$$\bar{\nu}_e + p \rightarrow e^{+} + \pi^{0} + n$$





SK-IV	Low P_{tot}	High P_{tot}
Signal efficiency	18.7 (±1.9) %	19.4 (± 3.4) %
Background (/Mt*yr)	$0.18^{+0.25}_{-0.13}$	1.1 ± 0.3

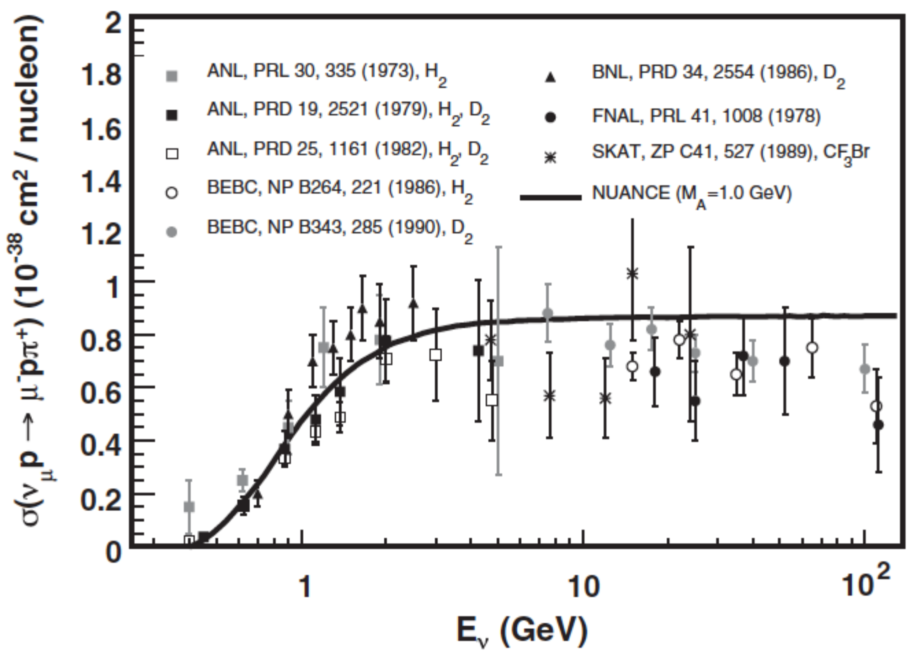
Bubble chamber experiments (1970's ~ 1980's)

Neutrino induced single π production

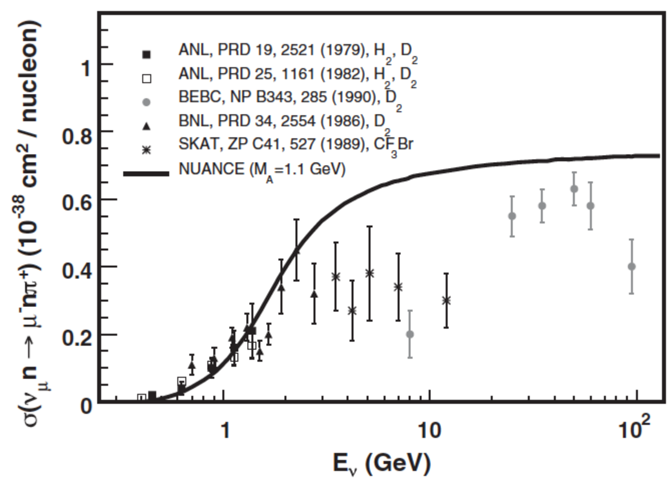
H_2 or D_2 target ~ Bubble chamber experiments

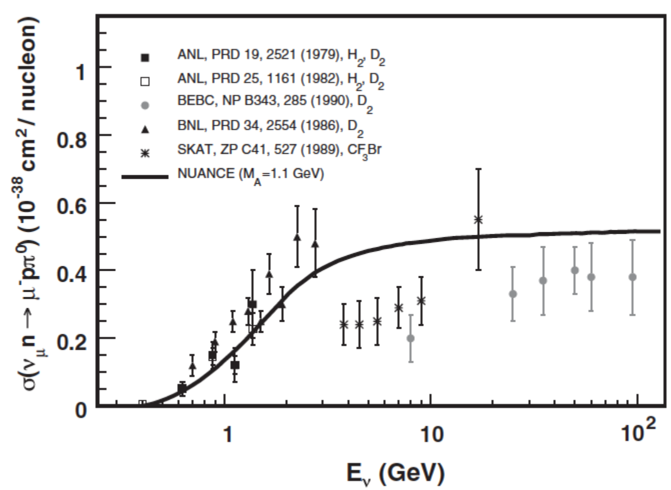
ANL and BNL measured cross-section at rather low energy

BEBC and FNAL measured at higher energy



(SKAT used CF_3Br)



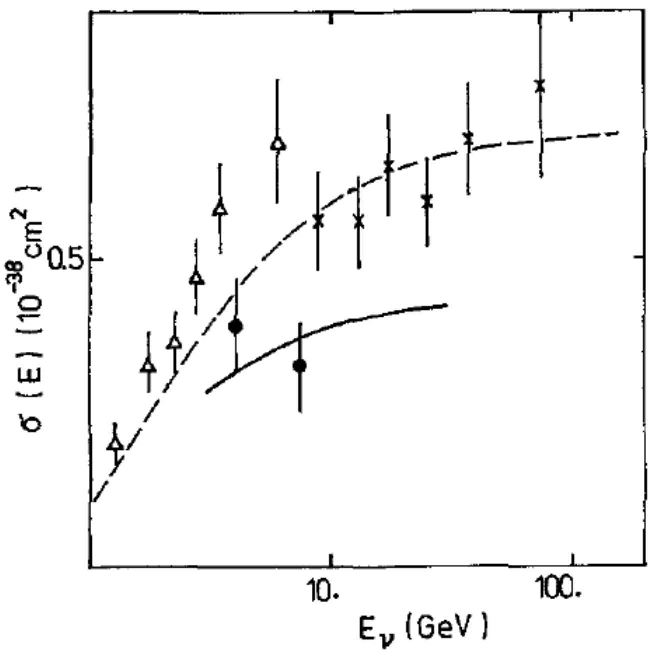


Bubble chamber experiments (1970's ~ 1980's)

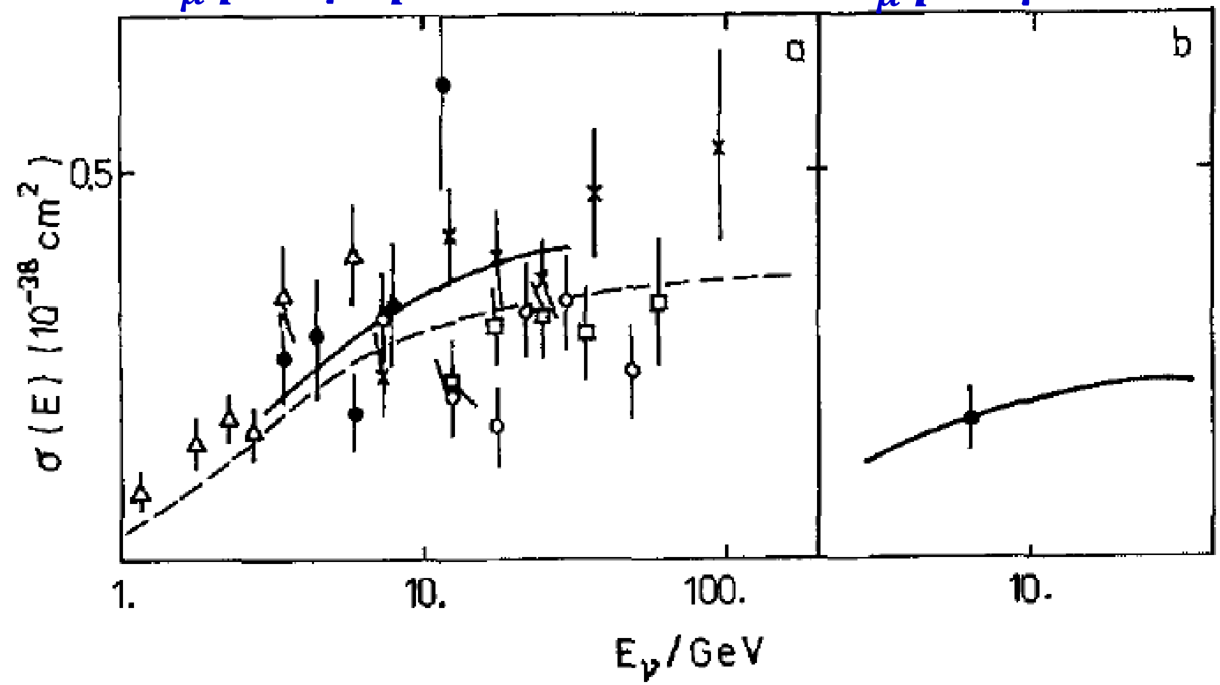
Anti-neutrino induced single π production

H_2 or D_2	BEBC and FNAL
CF_3Br	GGM and SKAT

$\bar{\nu}_\mu n \to \mu^+ n \pi^-$



$\bar{\nu}_\mu p \to \mu^+ p \pi^-$ $\bar{\nu}_\mu p \to \mu^+ n \pi^0$



- ● SKAT (Z. Phys. 41, 527)
- △ GGM (Phys. Lett. B81, 303)
- × BEBC (Z. Phys. 20, 95)
- ○ BEBC (Nucl. Phys. B264, 221)

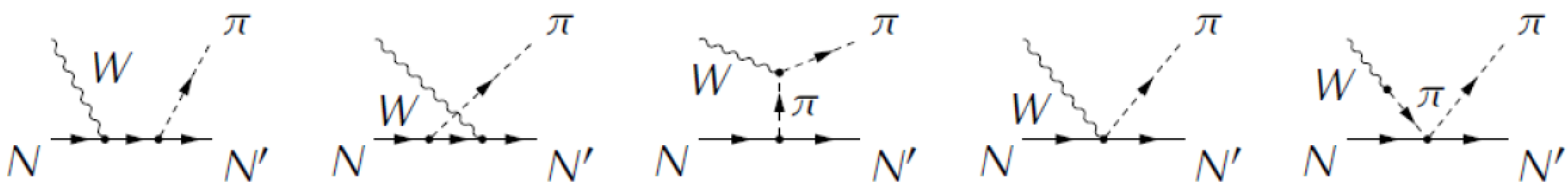
H.J. Grabosch et al., Z. Phys. 41, 527

Not so many data samples, especially below a few GeV

Alternative calculation of 1π production cross-sections

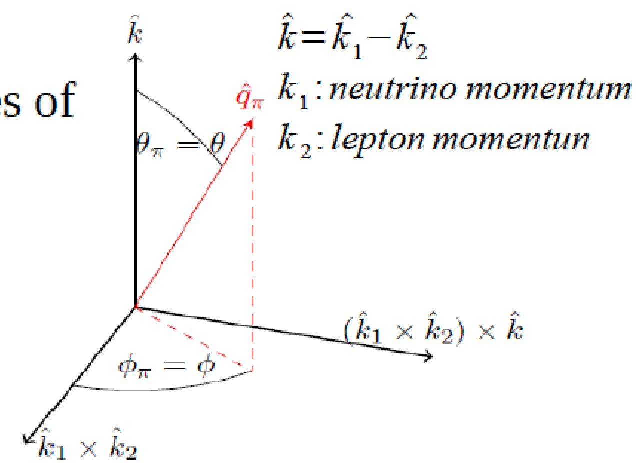
Model is implemented by M. Kabirnezhad
Adapt for Neut by C. Wret

- **The new model includes resonant (Rein-Sehgal model) and non-resonant interactions (5 diagrams from Hernandez et.al) coherently!**



E. Hernandez, J. Nieves and M. Valverde, Phys. Rev. D **76** (2007) 033005

- We need to define a common framework to calculate the helicity amplitudes, Isobaric system.
- The main challenge is to calculate helicity amplitudes of the above diagrams in this frame.
- It is suitable for neutrino generators.
- The new model output is $d\sigma / dW\, dQ^2\, d\,\Omega_\pi$
  pion angles are part of cross-section!



The main effects of nonresonant bkg is for pion angles due to the interference terms with resonances!

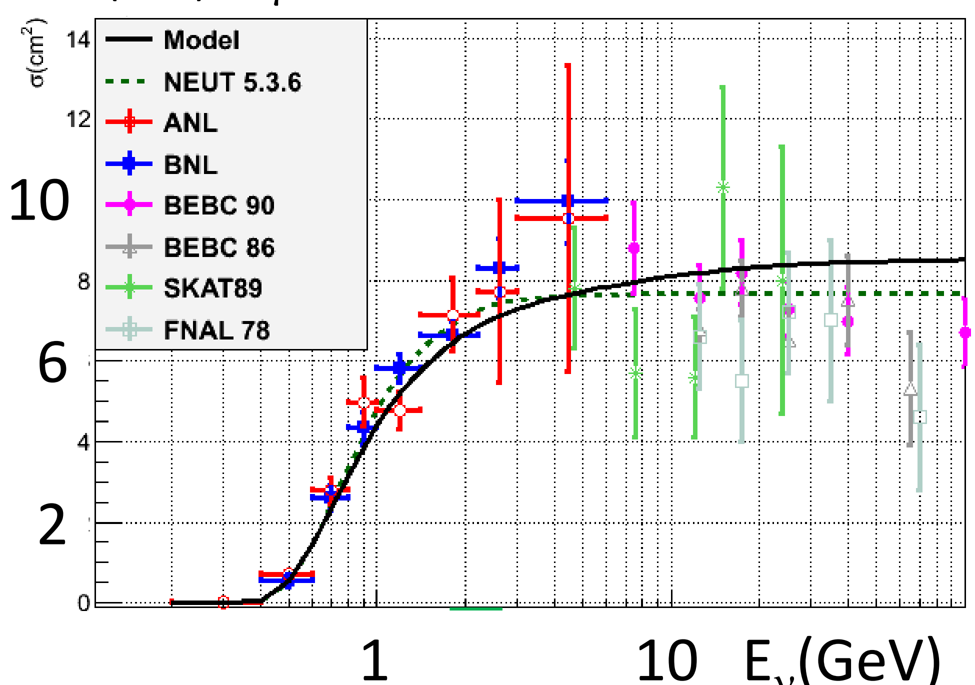
(Slide by M. Kabirnezhad)

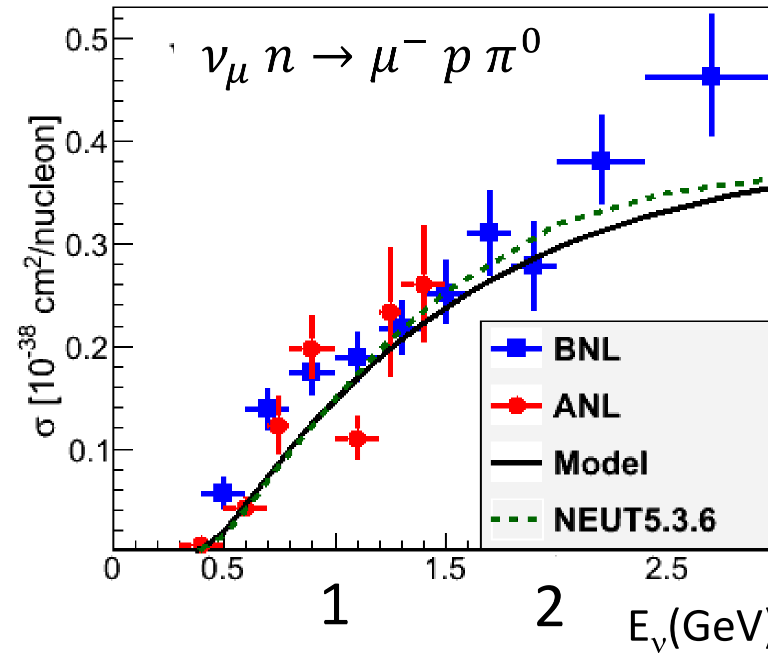
Comparisons of 1π production cross-sections

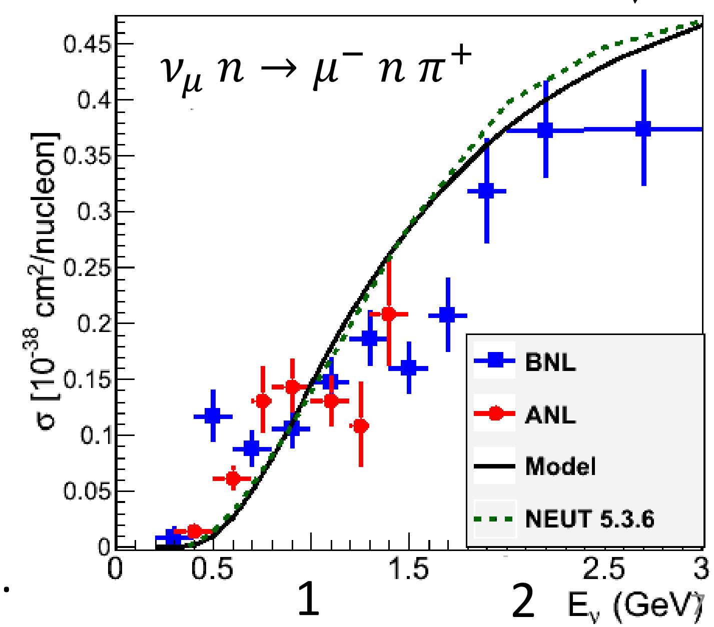
New π model is implemented
by M. Kabirnezhad
Adapt for Neut by C. Wret

Interaction cross-sections

10^{-39}(cm^2) $\nu_\mu\, p \rightarrow \mu^-\, p\, \pi^+$ (W < 2GeV/c^2)





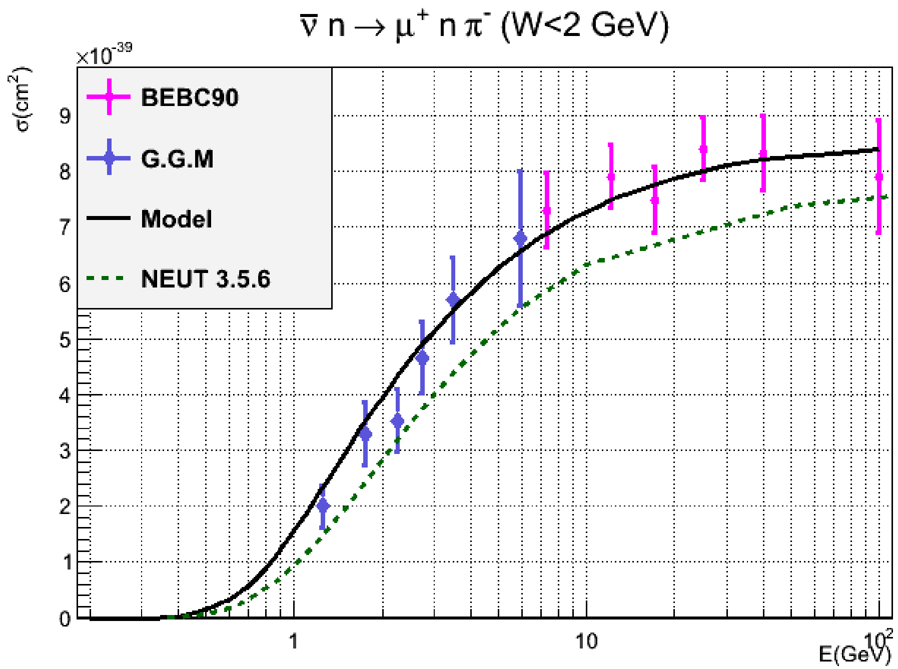


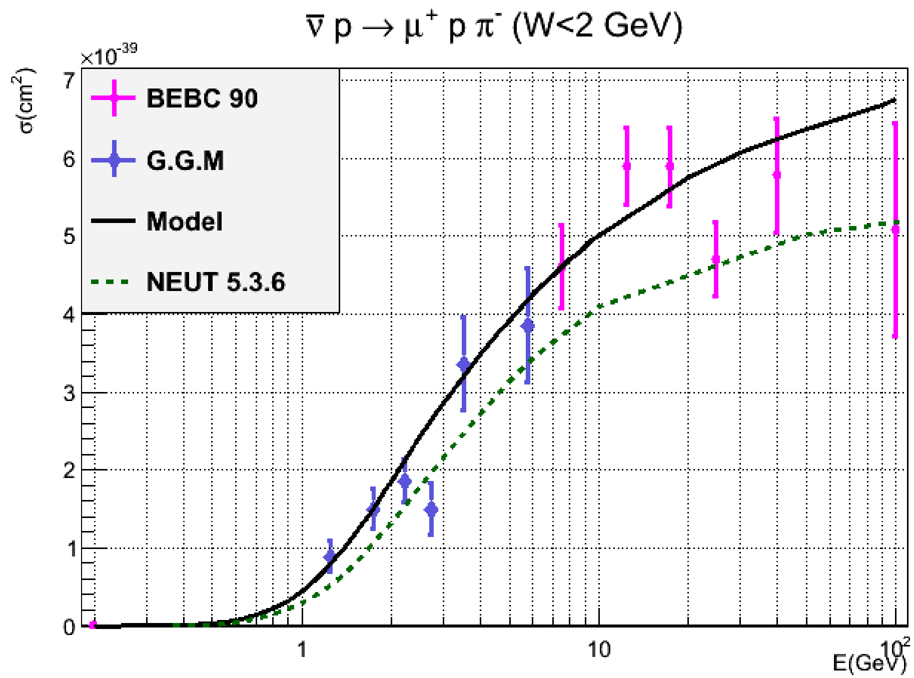
Figures by M. Kabirnezhad,
ANL & BNL data is reanalyzed by C. Wilkinson et al.

Comparisons of 1π production cross-sections

New π model is implemented
by M. Kabirnezhad
Adapt for Neut by C. Wret

Interaction cross-sections are similar for neutrinos
but quite different (~ 30%) for anti-neutrino.



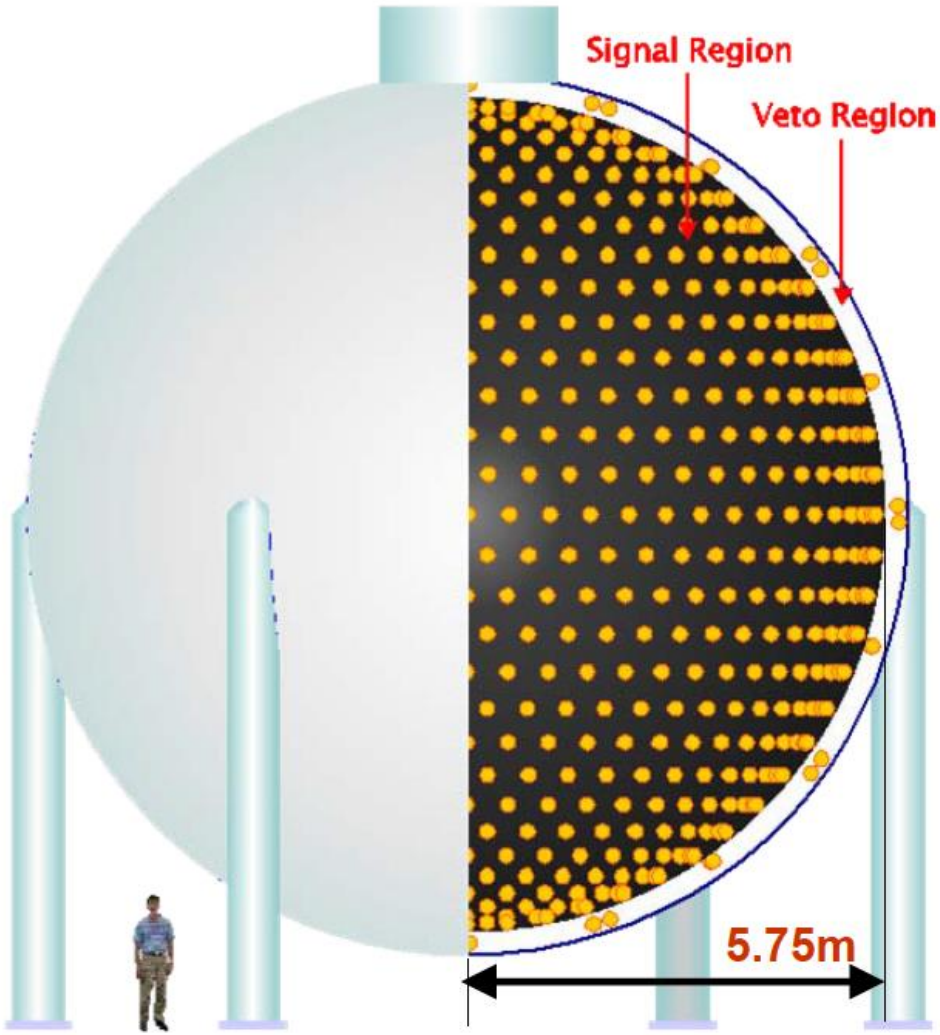


Need more data for the validation.

Neutrino induced single π production

Charged current @ MiniBooNE (CH_2 target)

MiniBooNE detector



800 ton CH_2 detector

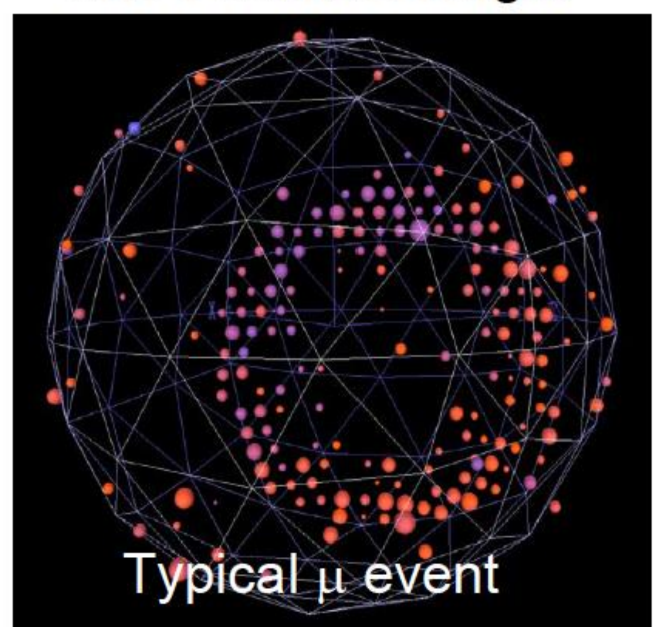
Signal region

1280 8inch PMTs

Veto region

240 8inch PMTs

Use Cherenkov light and scintillation light

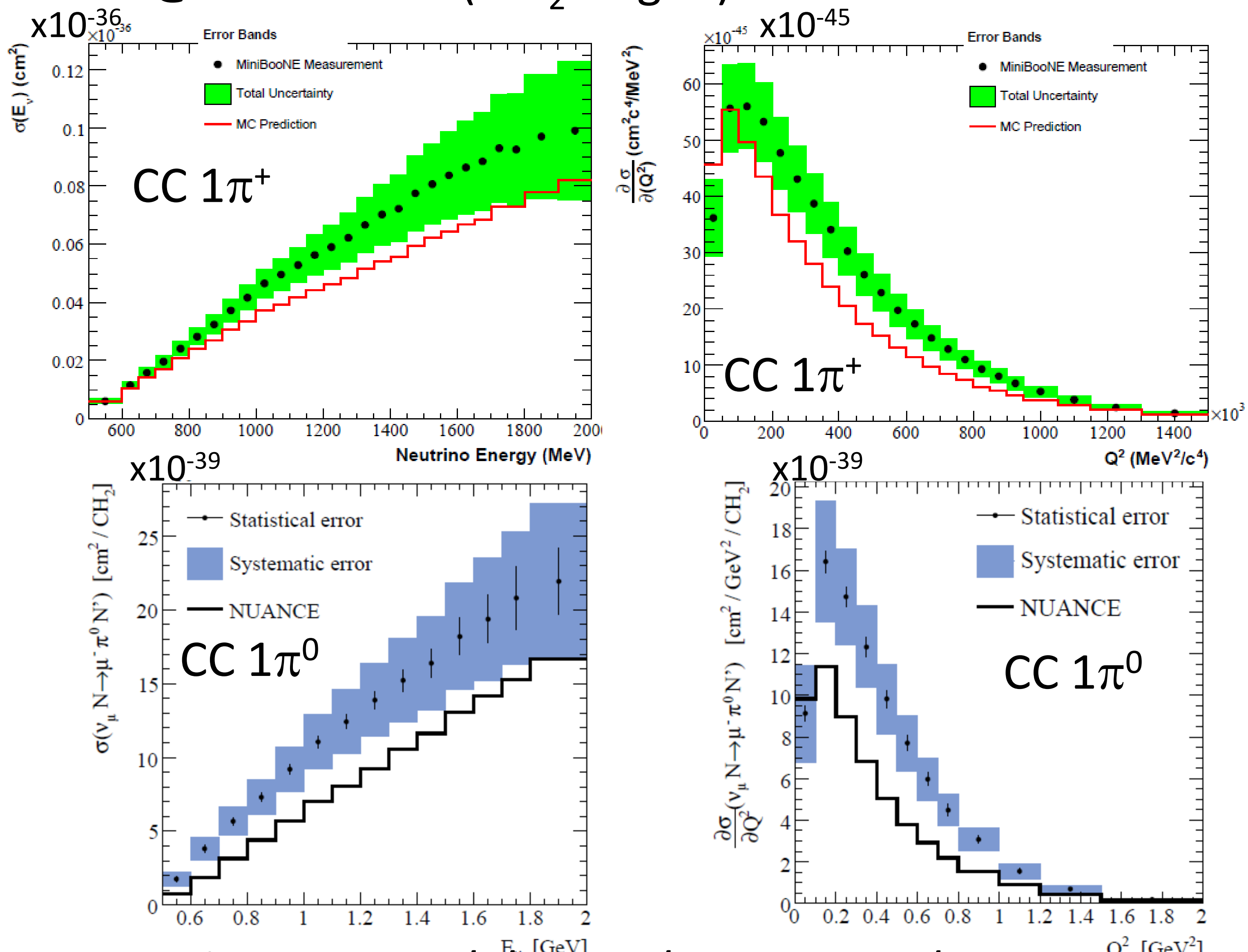


Neutrino induced single π production data

Charged current @ MiniBooNE (CH_2 target)

Phys. Rev. D83, 052007 (2011)

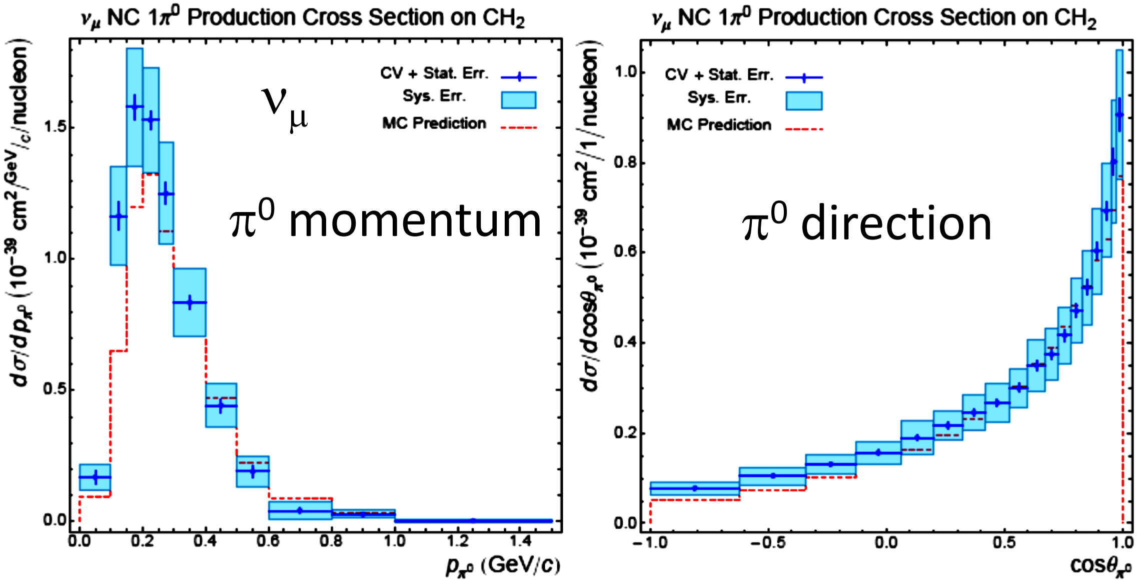
Phys. Rev. D83, 052009 (2011)



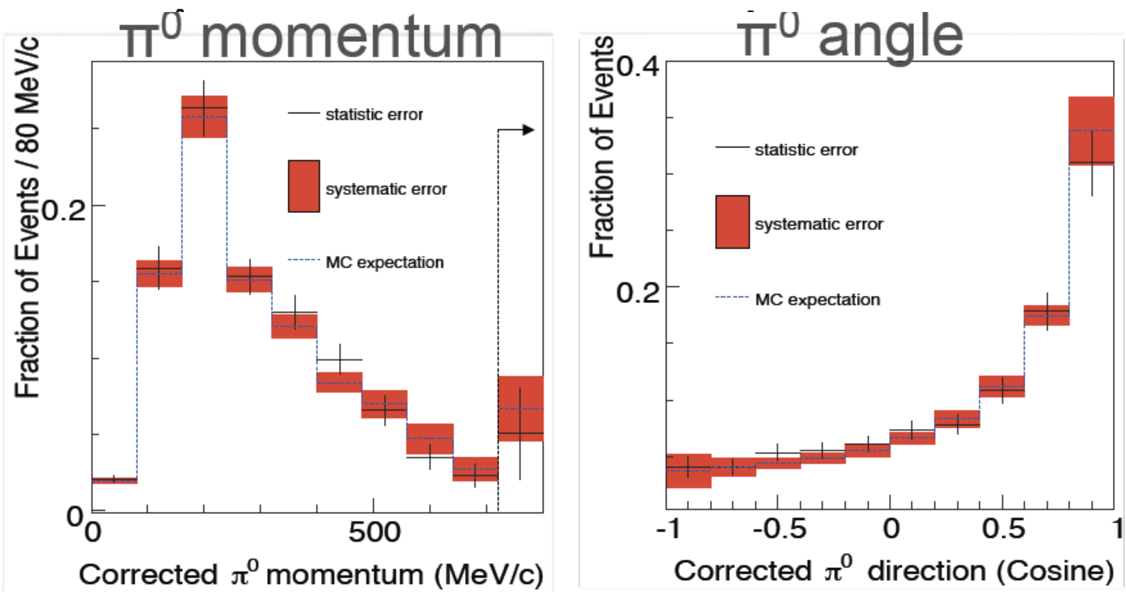
Cross-section was much larger than expected.

Neutrino induced single π production data

Neutral current π^0 @ MiniBooNE (CH_2) and SciBooNE (CH)



MiniBooNE
Phys. Rev. D81, 013005 (2010)



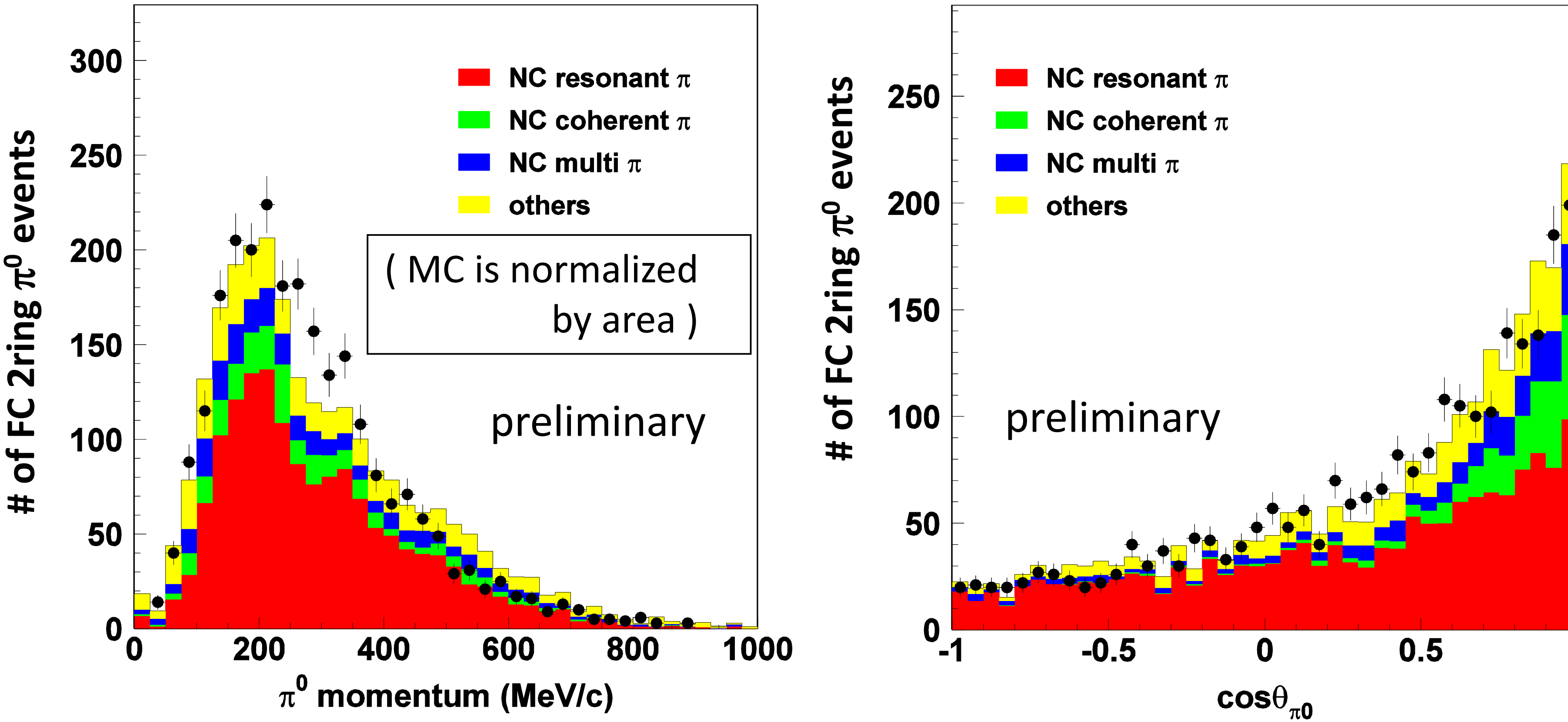
SciBooNE
Phys. Rev. D 81, 033004 (2009)

Agreements are quite well.

Neutrino induced single π production data

Neutral current π^0 @ K2K 1kt Water Cherenkov detector (H_2O)

momentum and direction of π^0

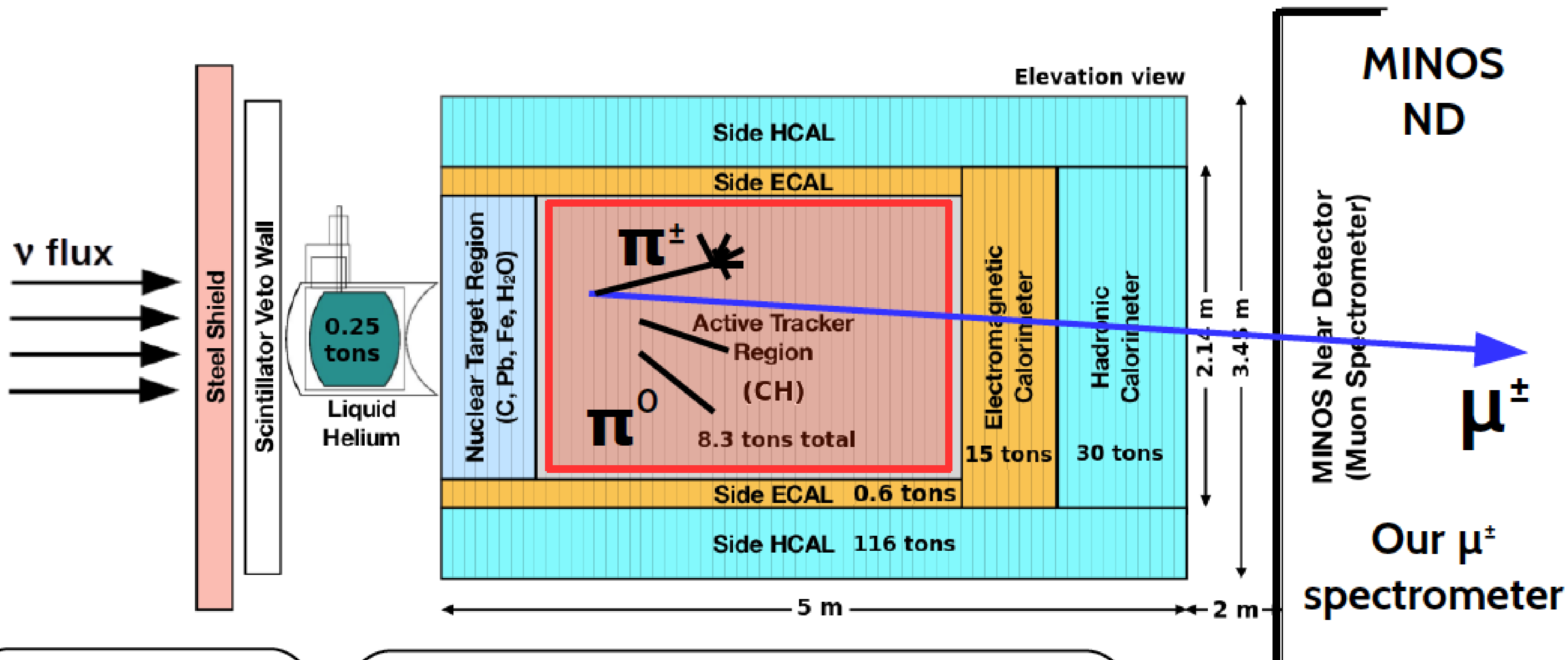


Shape only comparison but the agreements are quite reasonable.

Neutrino induced single π production data

Charged current $\pi^{\pm}$production @ MINERnA (CH target)

MINERνA Pion Reconstruction



π^+ π^- π^0

Reconstruction

- Event Vertex Inside Tracker Region
- MINOS Acceptance
- 1.5 GeV < E_ν < 20 GeV ($E_\nu = E_\mu + E_{recoil(had)}$)
- Energy Reconstruction by Calorimetry

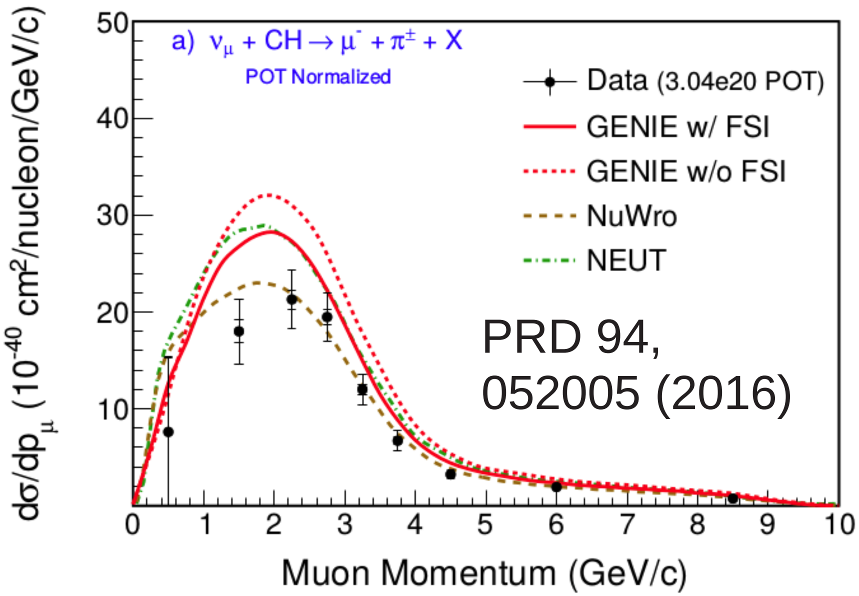
LE Beam

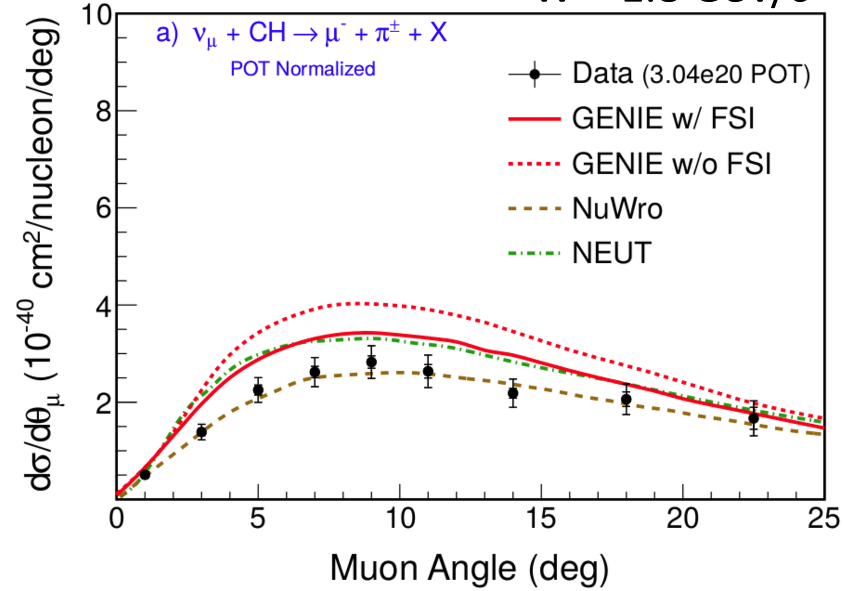
Eν~3.5 GeV

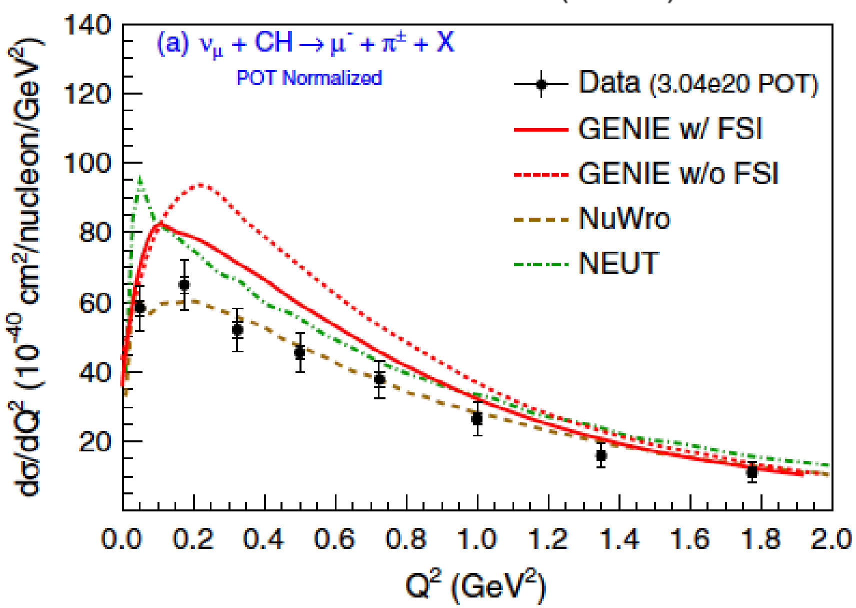
Neutrino induced single π production data

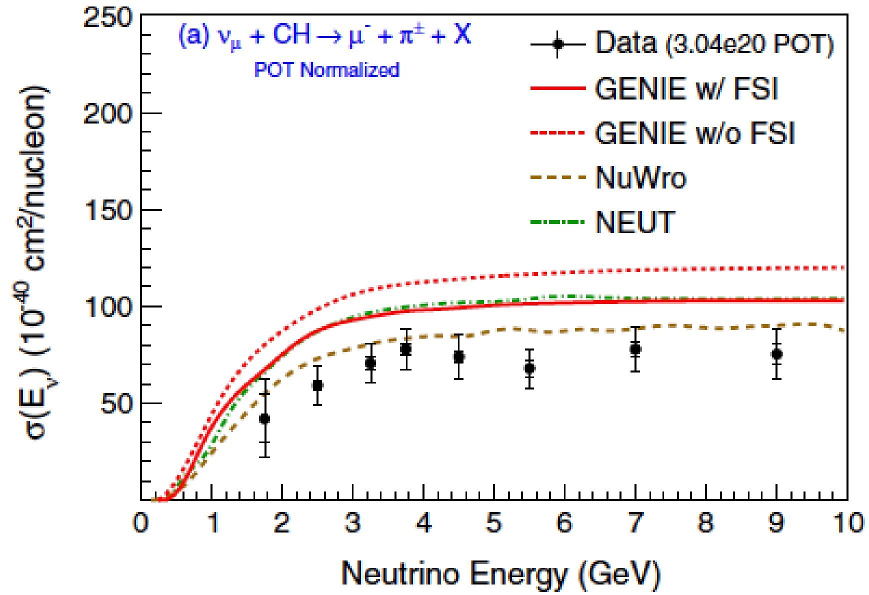
Charged current $\pi^{\pm}$ production @ MINERnA (CH target)

W < 1.8 GeV/c^2



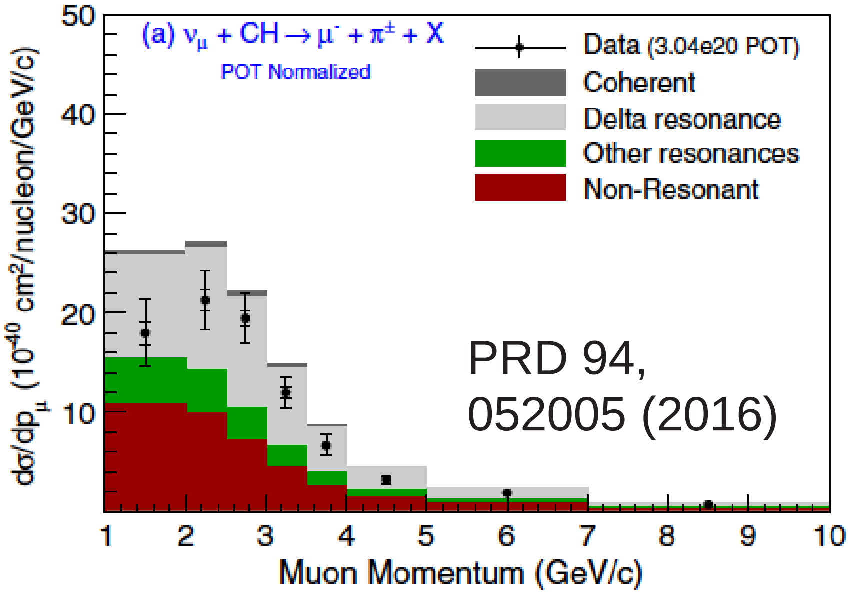


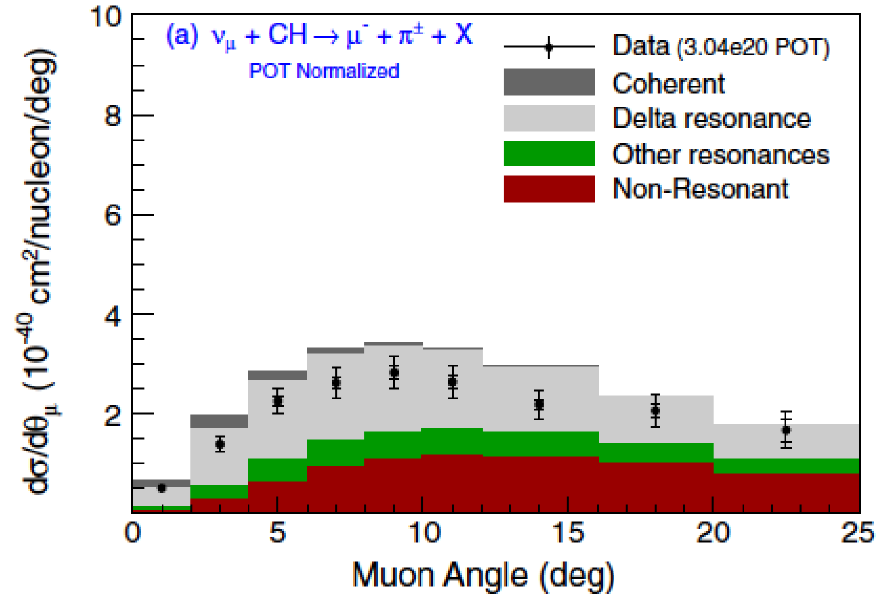


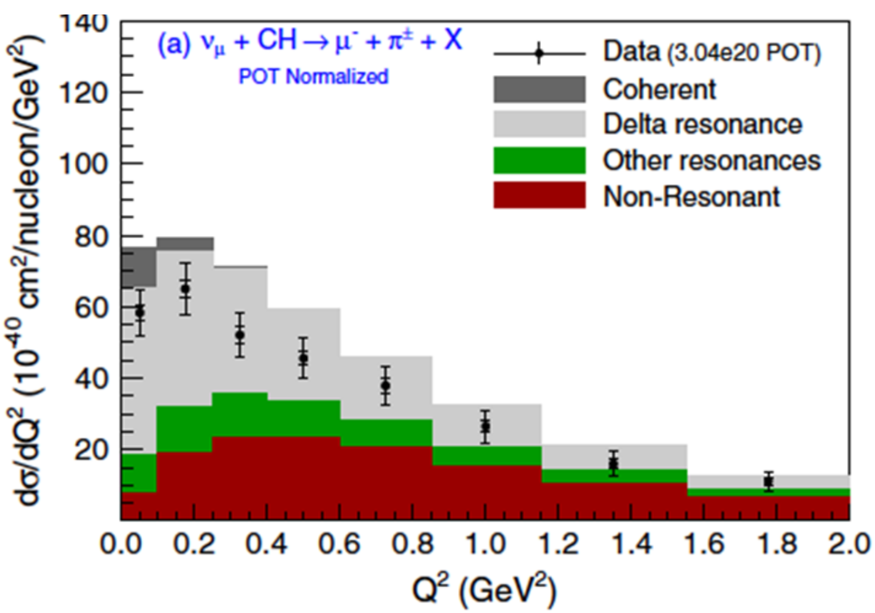


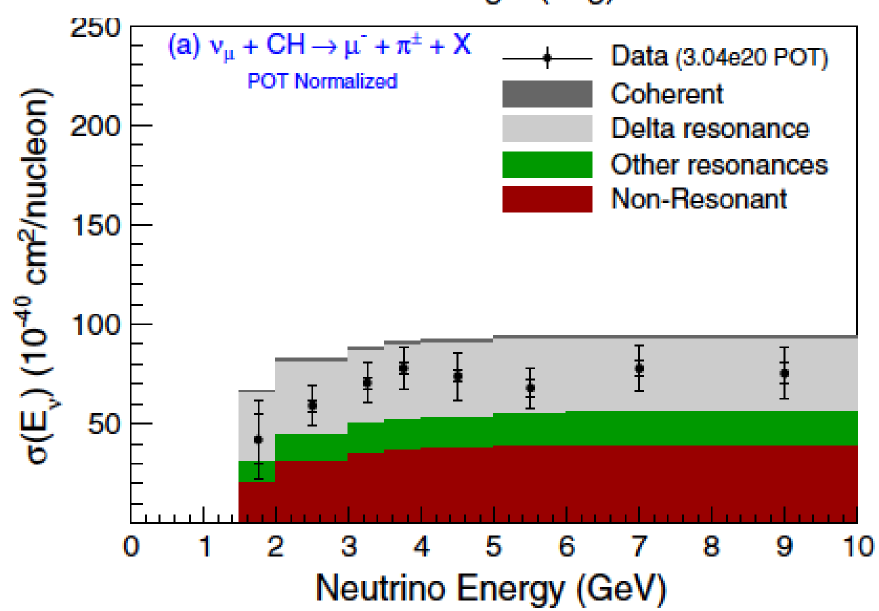
Neutrino induced single π production data

Charged current $\pi^{\pm}$ production @ MINERnA (CH target) W < 1.8 GeV/c^2



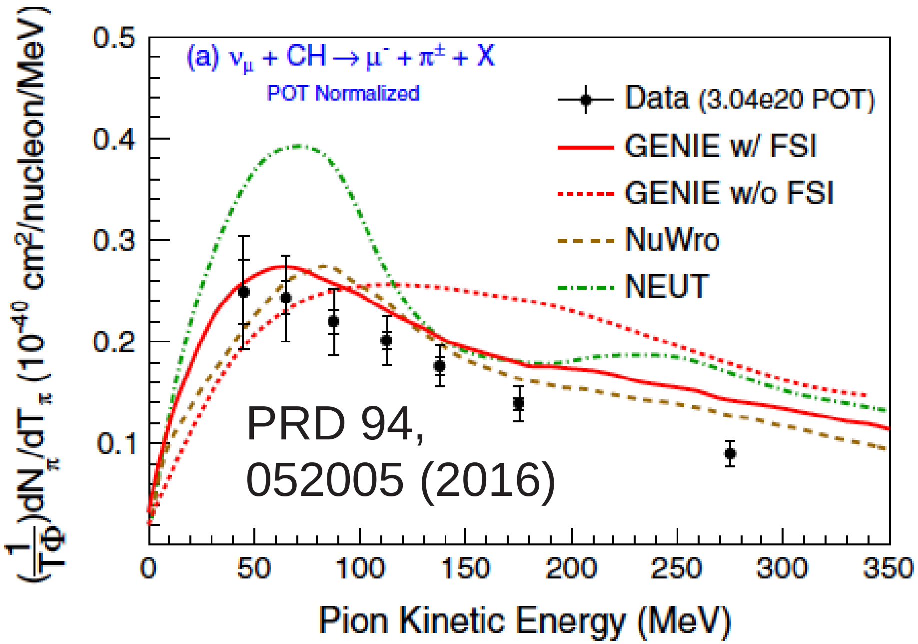


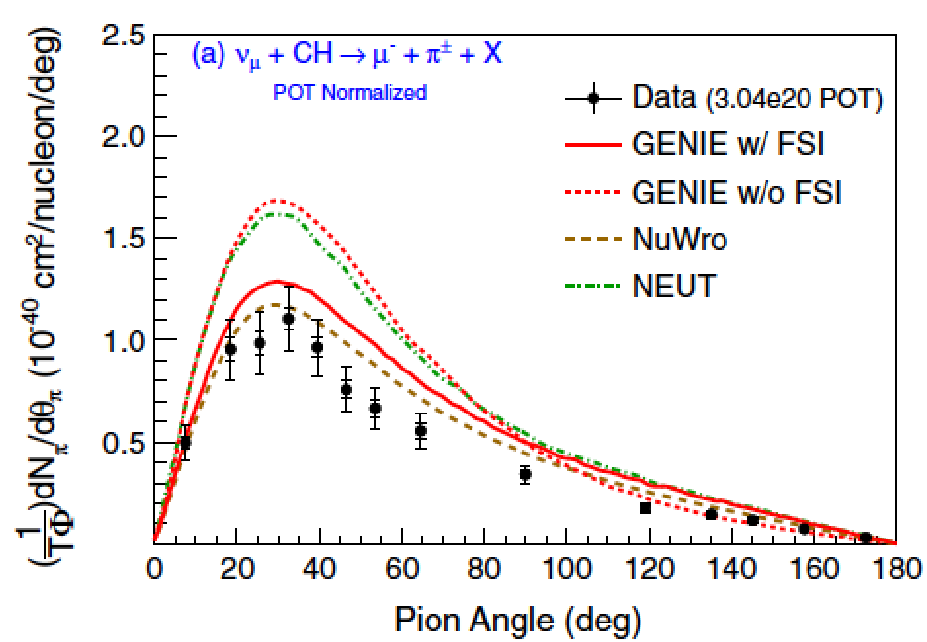




Neutrino induced single π production data

Charged current $\pi^{\pm}$ production @ MINERnA (CH target) $W < 1.8\ \mathrm{GeV}/c^2$





Results from NuWro agrees quite well

but the observed energy is slightly softer than the prediction.

Neut predicts much larger # of events and

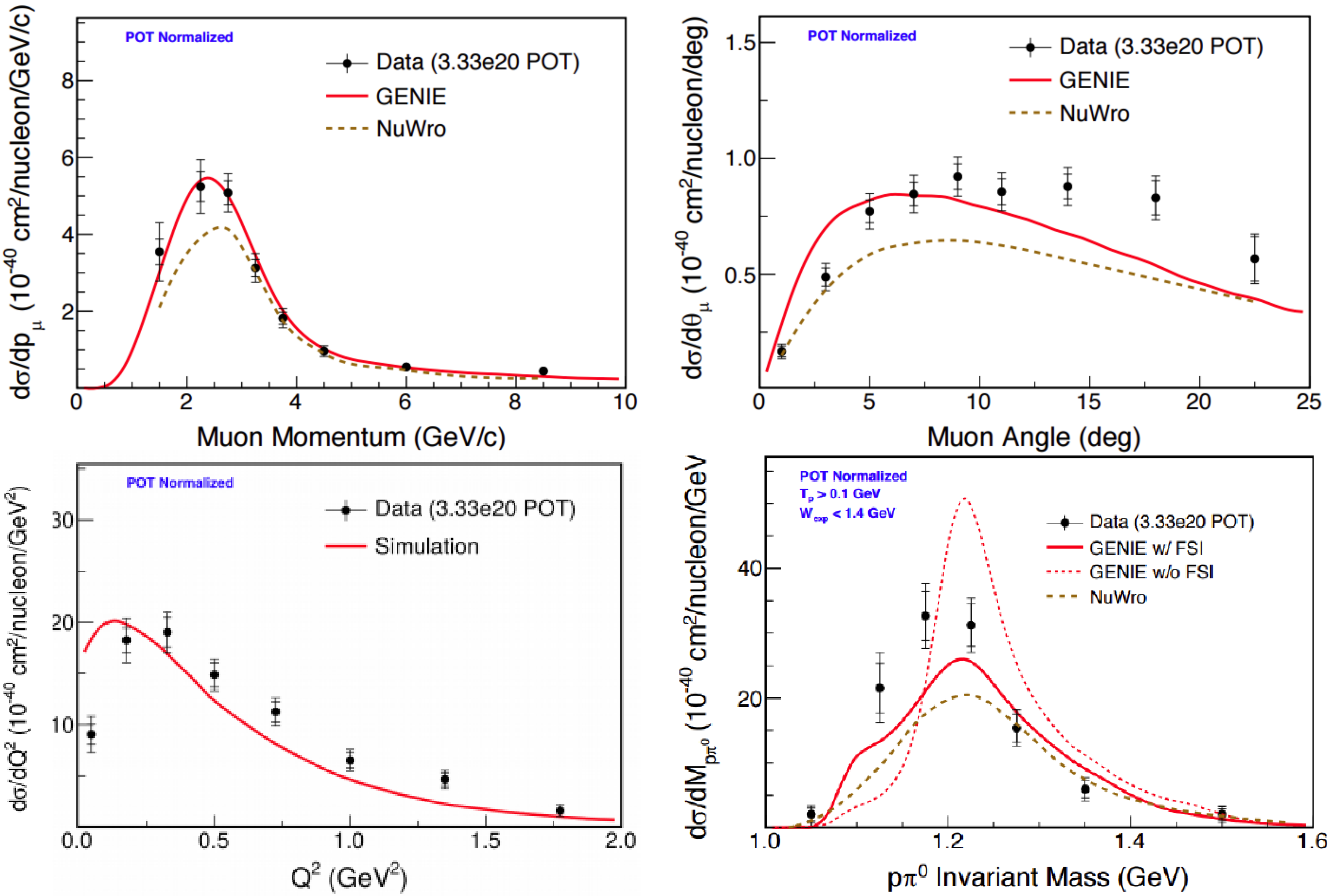
the structure may indicate larger contributions

from resonance production.

Neutrino induced single π production data

A. Ramirez @ NuINT17

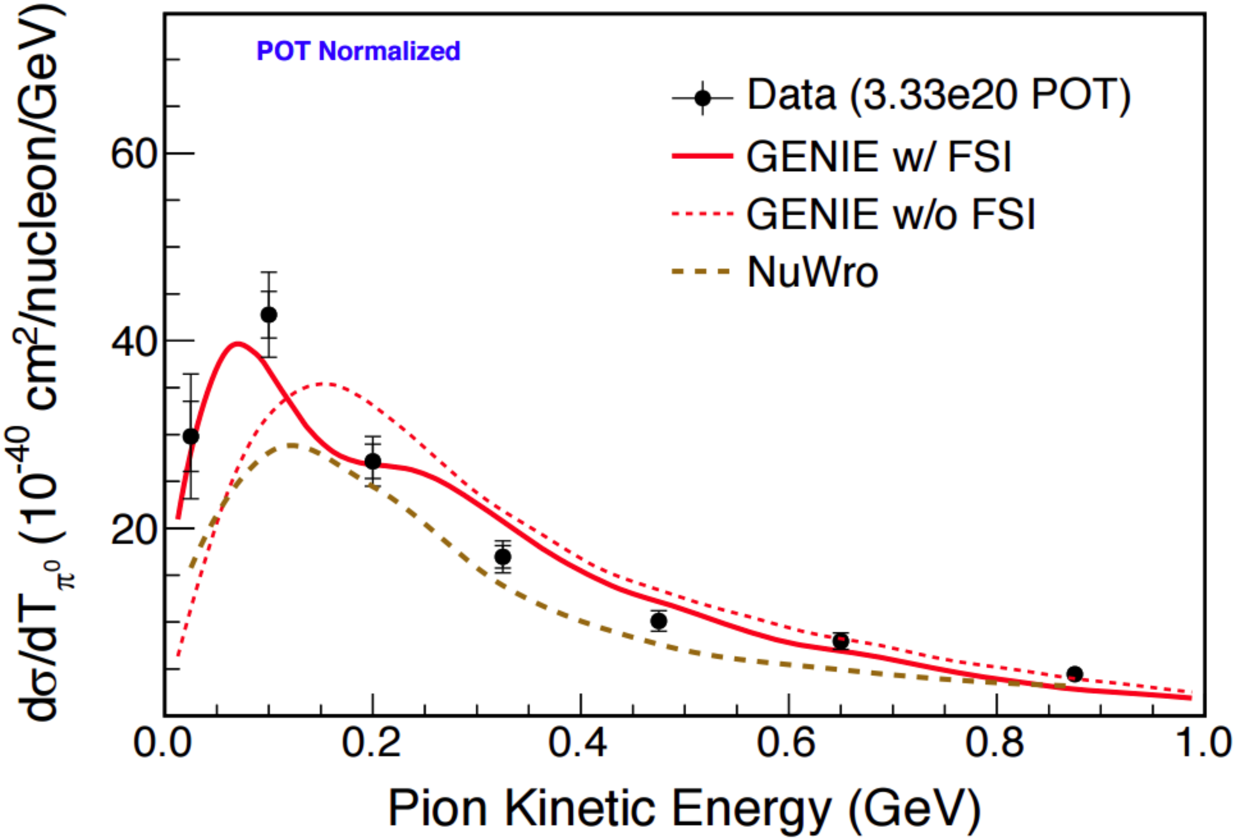
Charged current π^0 production @ MINERnA (CH target)



Neutrino induced single π production data

A. Ramirez @ NuINT17

Charged current π^0 production @ MINERnA (CH target)



20.9% signal increase from FSI

24.5% signal decrease from FSI

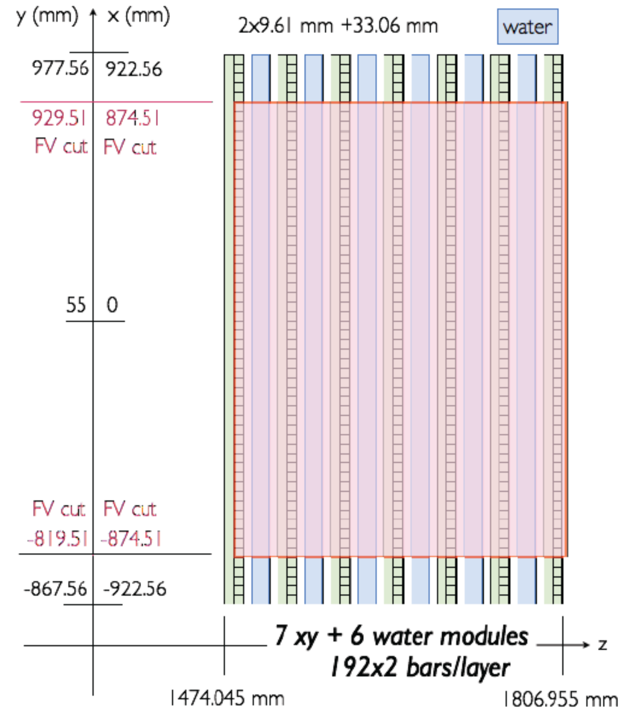
Enhancement at ~100MeV id due to $\pi^+ \rightarrow \pi^0$ feed-in.

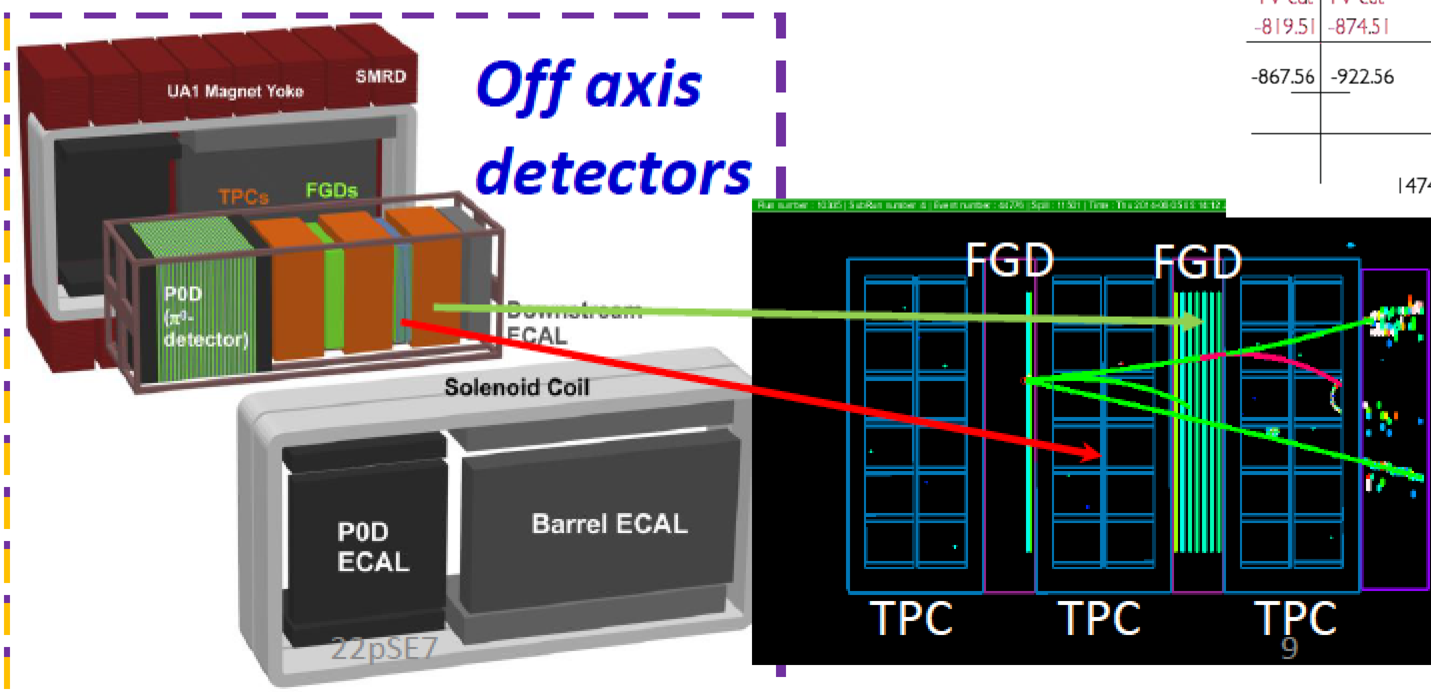
Depletion at ~240MeV is due to pion absorption

Neutrino induced single π production data

Charged current π^+ production @ T2K (H_2O target)

T2K uses 2 FGD, one is fully active
and the other has water layer.

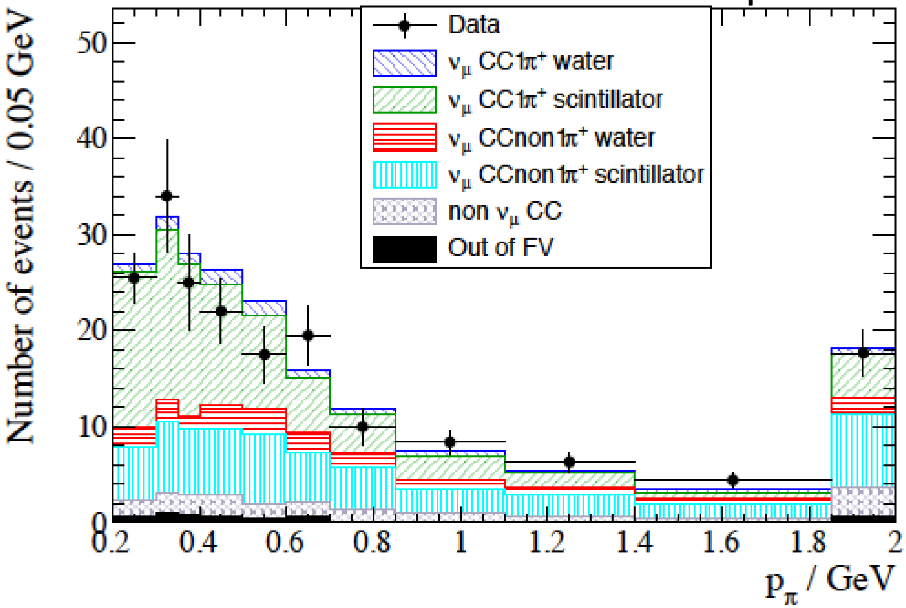




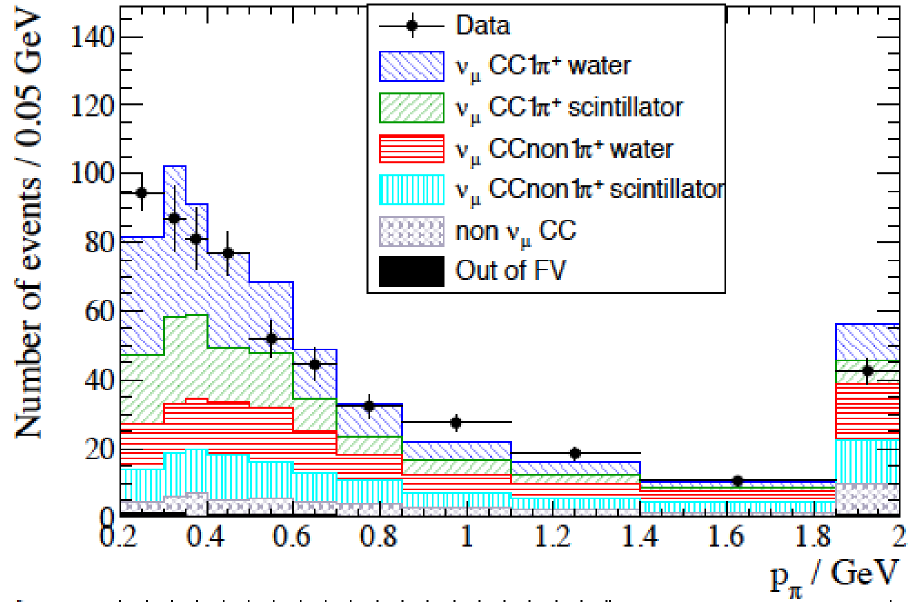
Neutrino induced single π production data

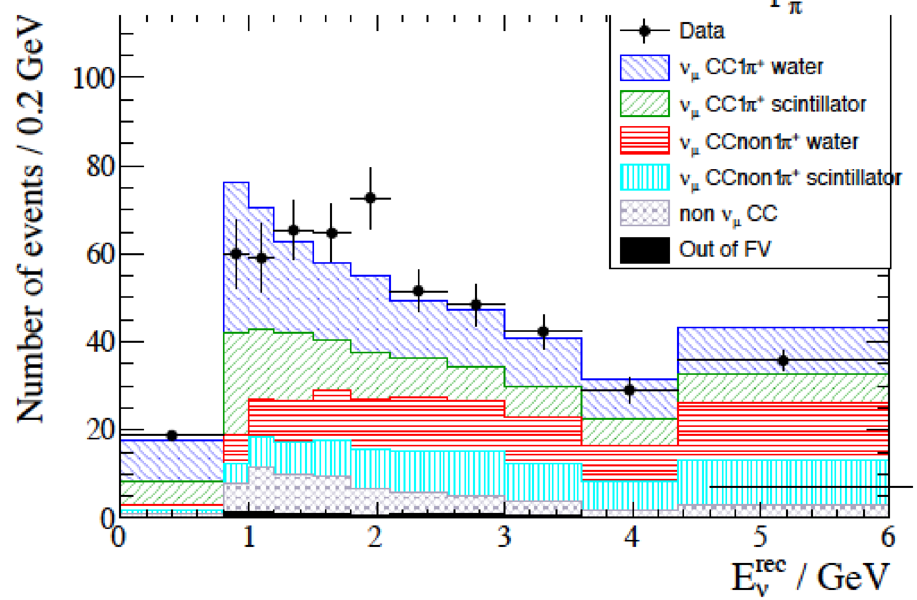
Charged current π^+ production @ T2K (H_2O target)

Scintillator enhanced sample



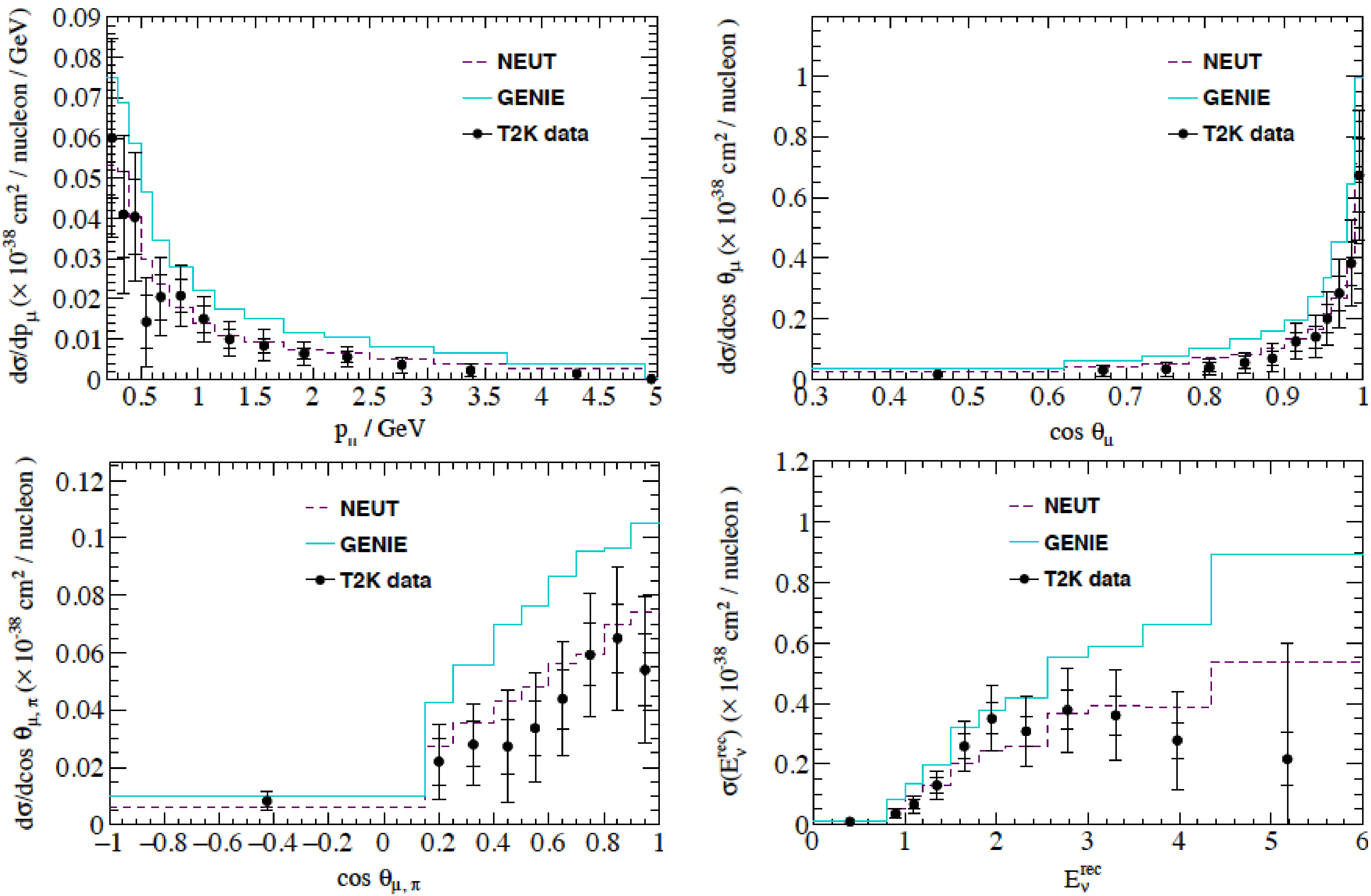
Water enhanced sample





Neutrino induced single π production data

Charged current π^+ production @ T2K (H_2O target)



Neutrino induced single π production data

Charged current π^+ production @ T2K (H_2O target)

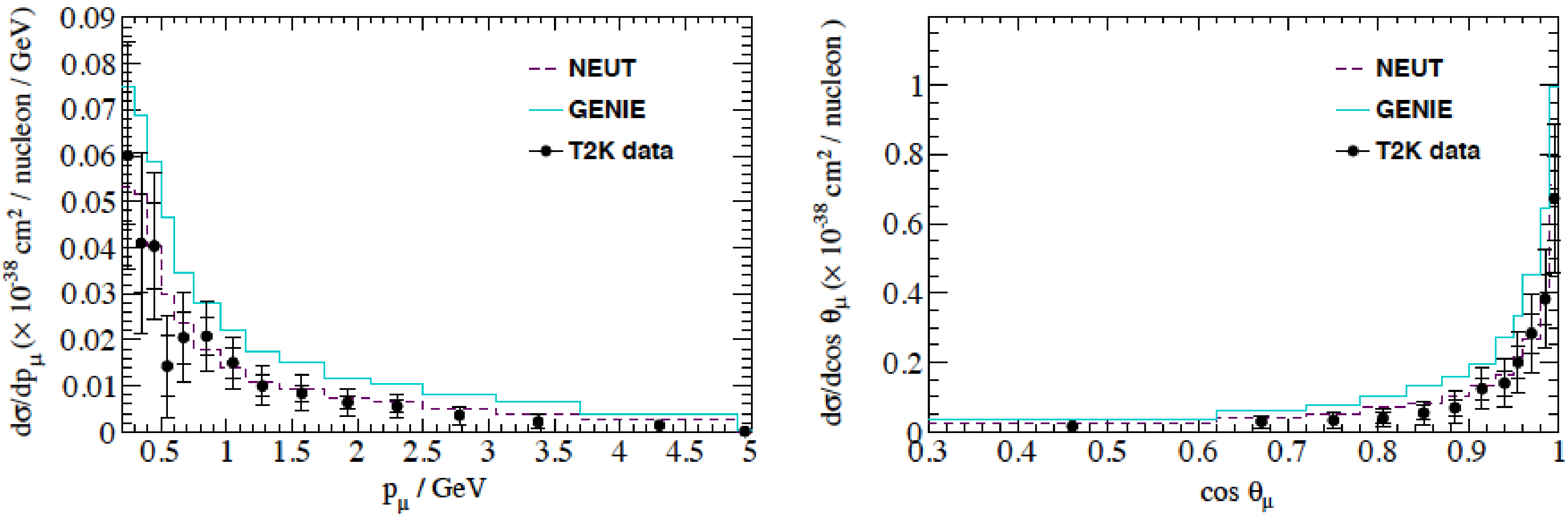


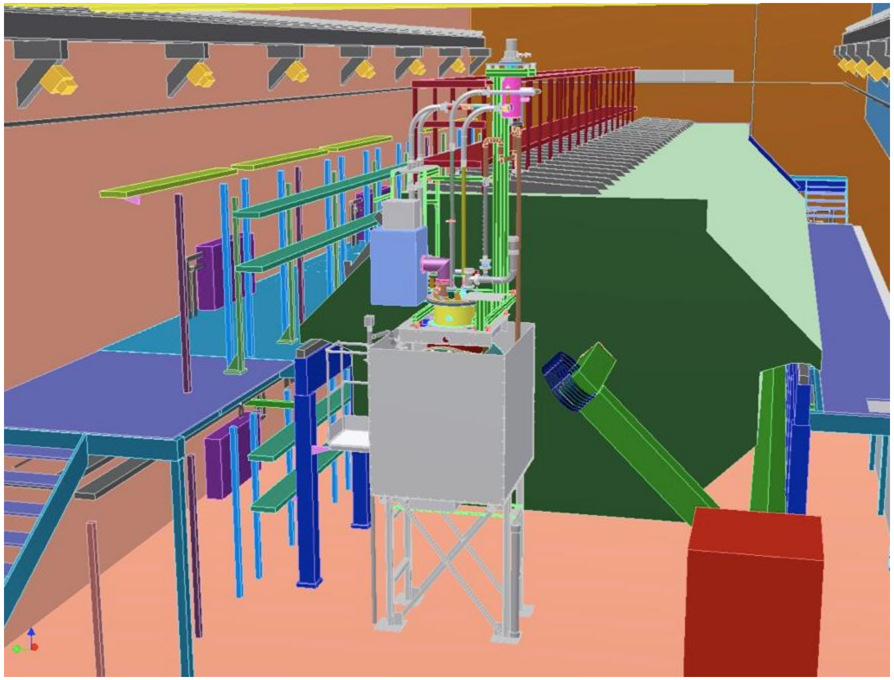
FIG. 4. Unfolded ν_μ CC1π^+ differential cross sections as a function of pion kinematics (top), muon kinematics (center), $\cos(\theta_{(\mu,\pi^+)})$ (bottom left) and E_ν^{rec} (bottom right) in the reduced phase-space of $p_{\pi^+} > 200$ MeV/c, $p_\mu > 200$ MeV/c, $\cos(\theta_{\pi^+}) > 0.3$ and $\cos(\theta_\mu) > 0.3$. For the E_ν^{rec}, the $\sigma(E)$ is presented as a model dependent result. The inner (outer) error bars show the statistical (total) uncertainty on the data. The dashed (solid) line shows the NEUT, version 5.1.4.2, (GENIE, version 2.6.4) prediction.

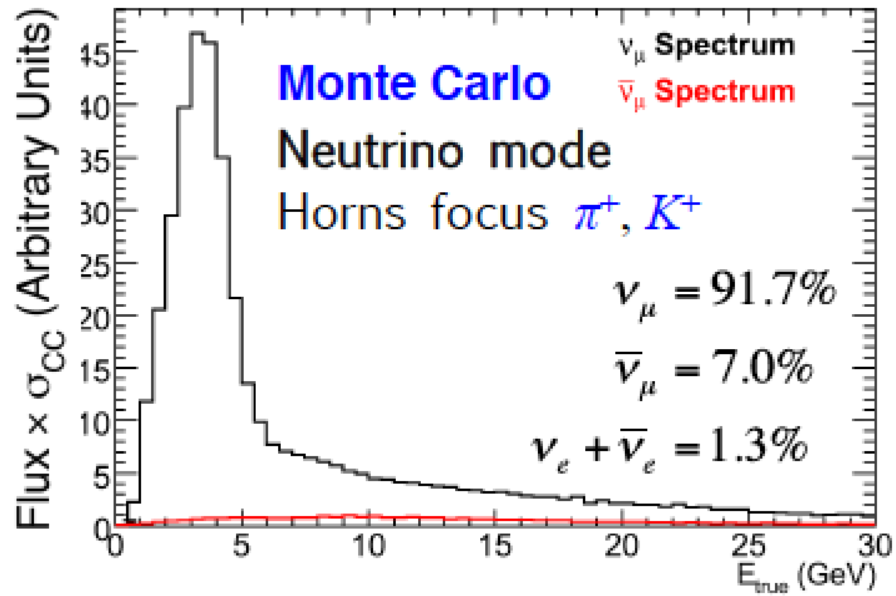
Interestingly, NEUT gives smaller cross-section compared to GENIE in T2K.

May be due to the event selection (selection of the final state).

Neutrino induced single π production data

Charged current π^+ production @ ArgoNeut (Ar target)

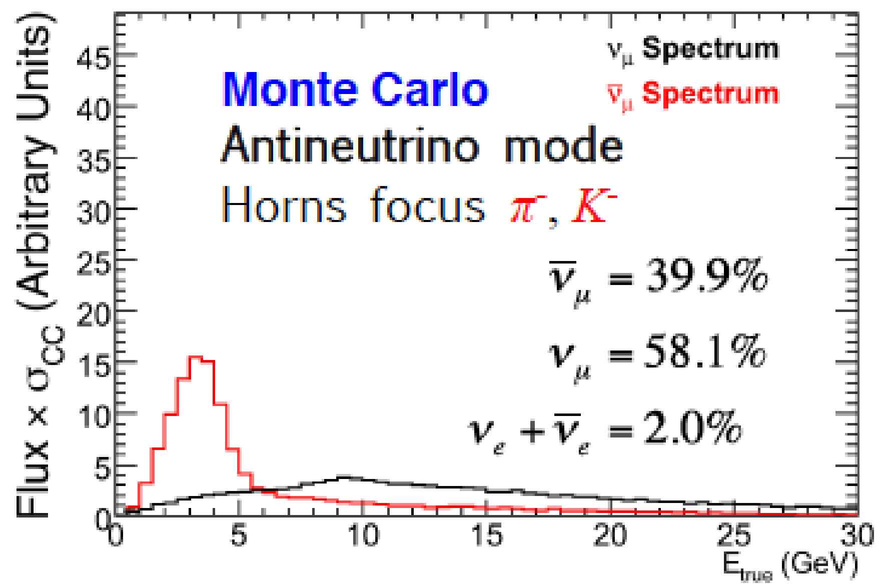




Lq. Ar TPC detecor
located just in front of MINOS ND

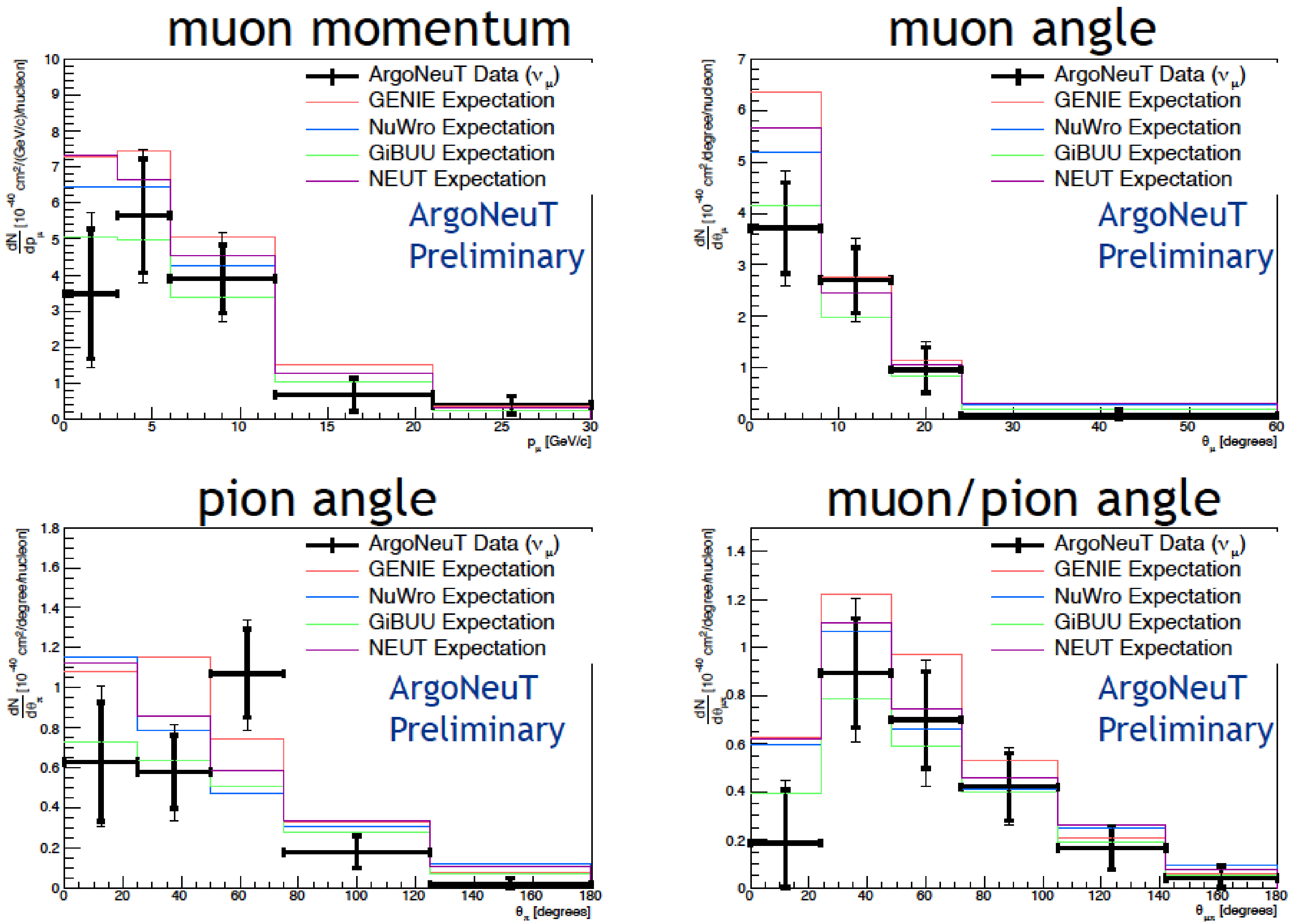
ν-mode (2 weeks): 0.085e20 POT

$\bar{\nu}$-mode (5 months): 1.25e20 POT



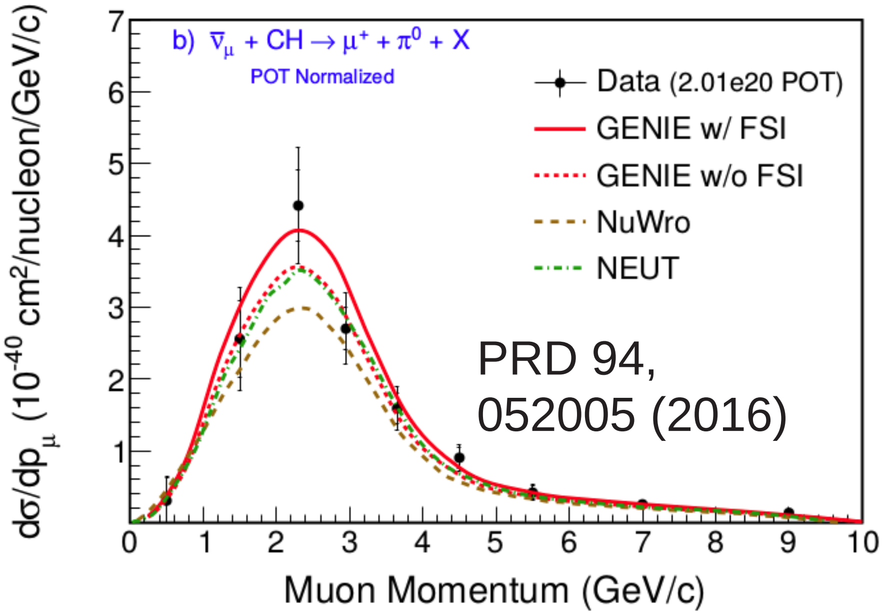
Neutrino induced single π production data

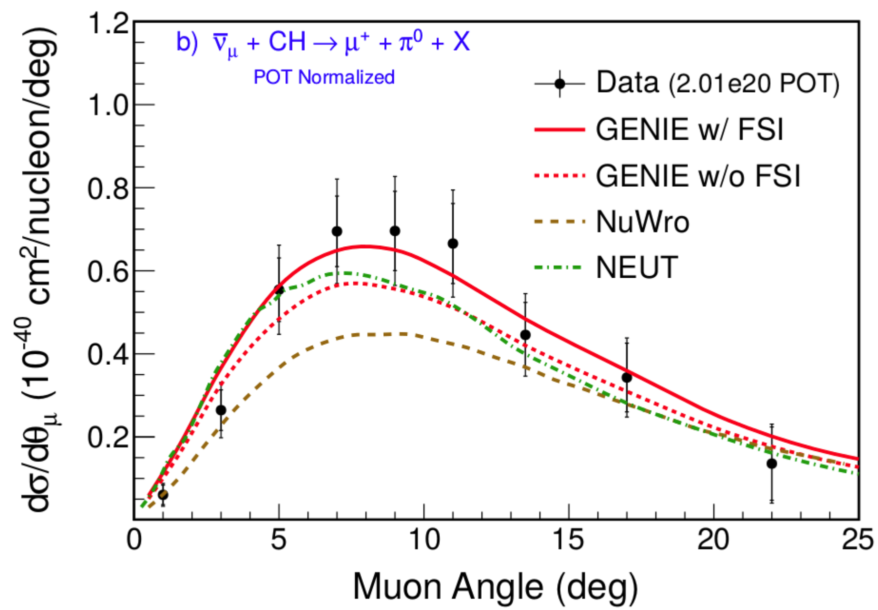
Charged current π^+ production @ ArgoNeut (Ar target)

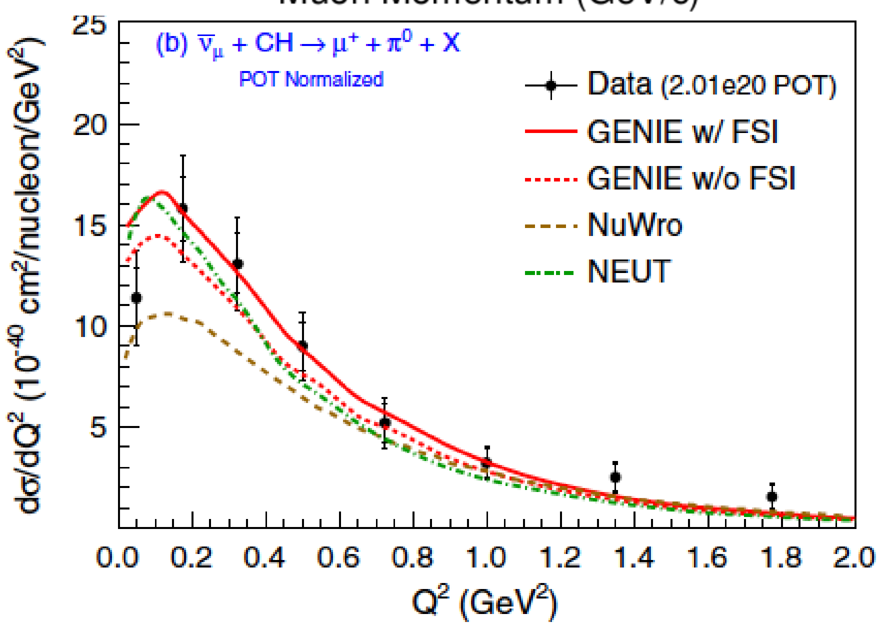


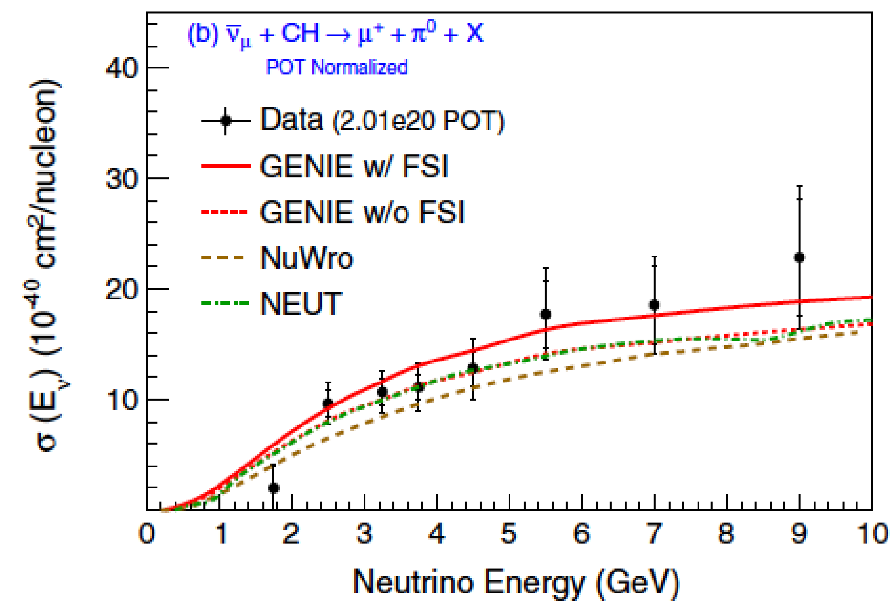
Anti-neutrino induced single π production data

Charged current π^0 production @ MINERνA (CH target)



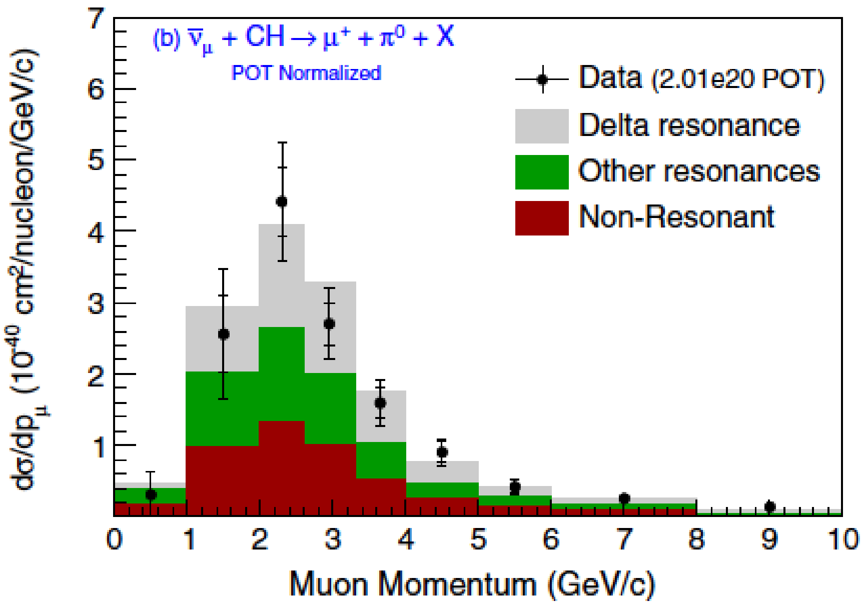


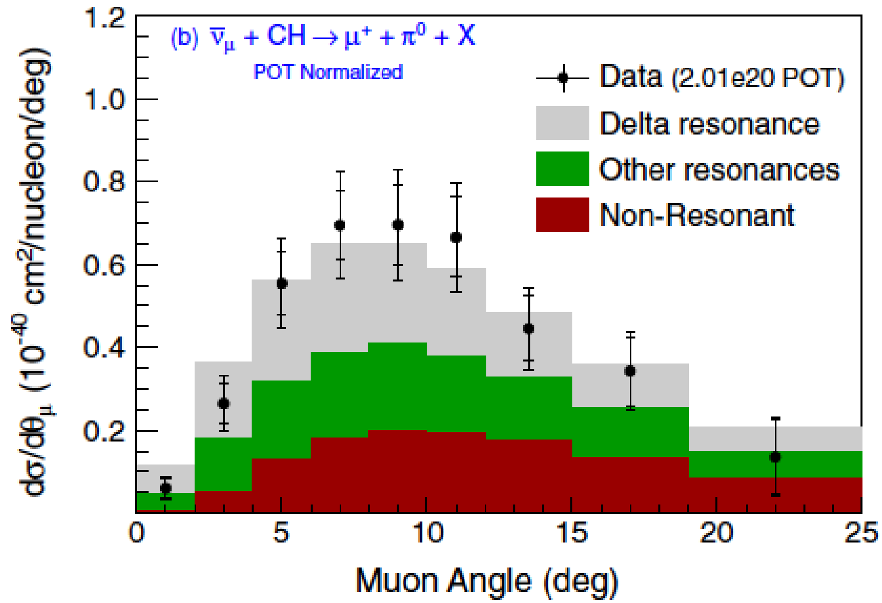


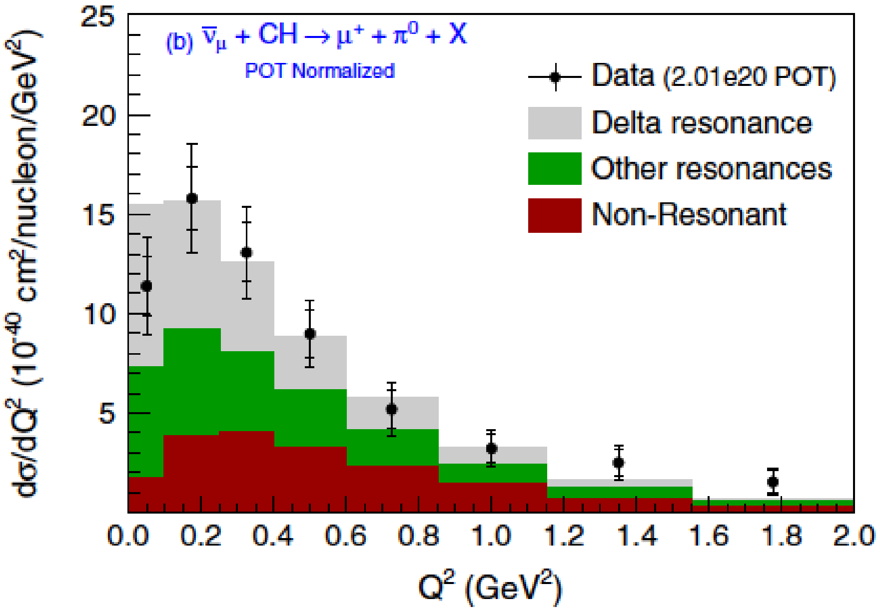


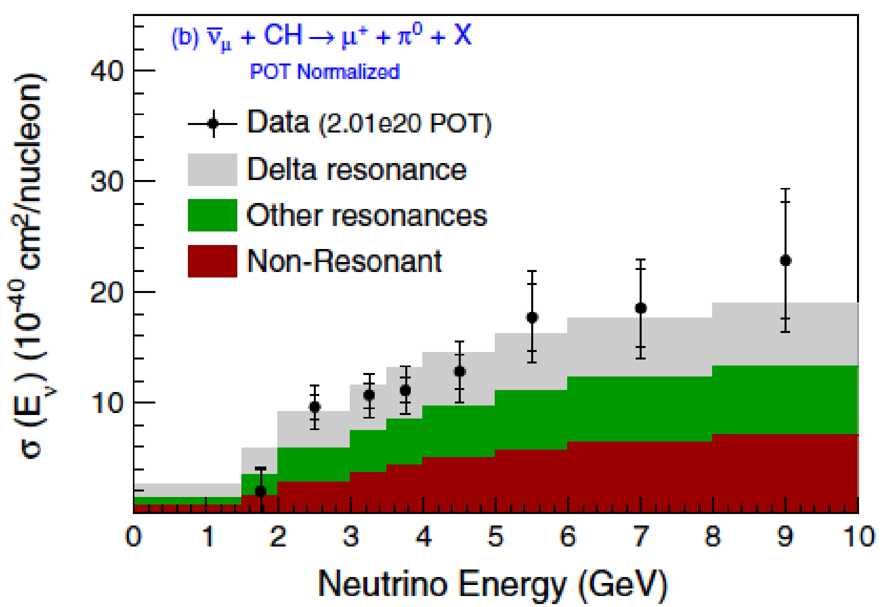
Anti-neutrino induced single π production data

Charged current π^0 production @ MINERνA (CH target)



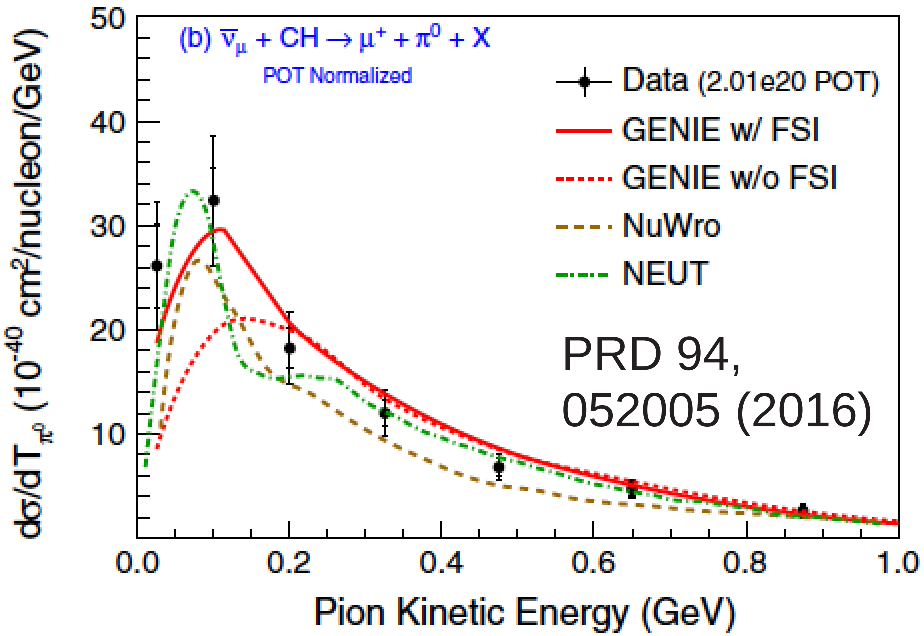


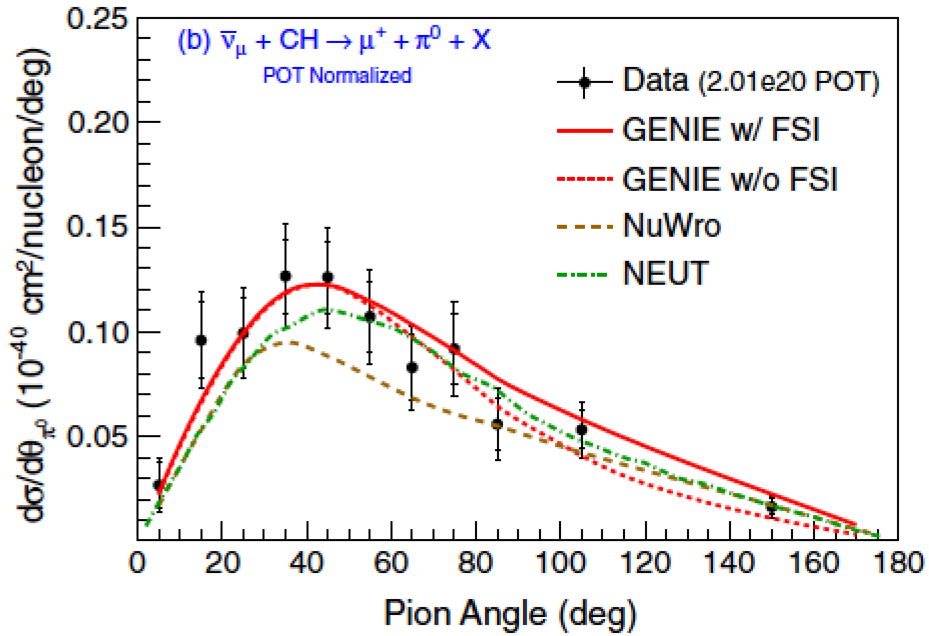




Anti-neutrino induced single π production data

Charged current π^0 production @ MINERνA (CH target)





Results from GENIE agrees quite well.

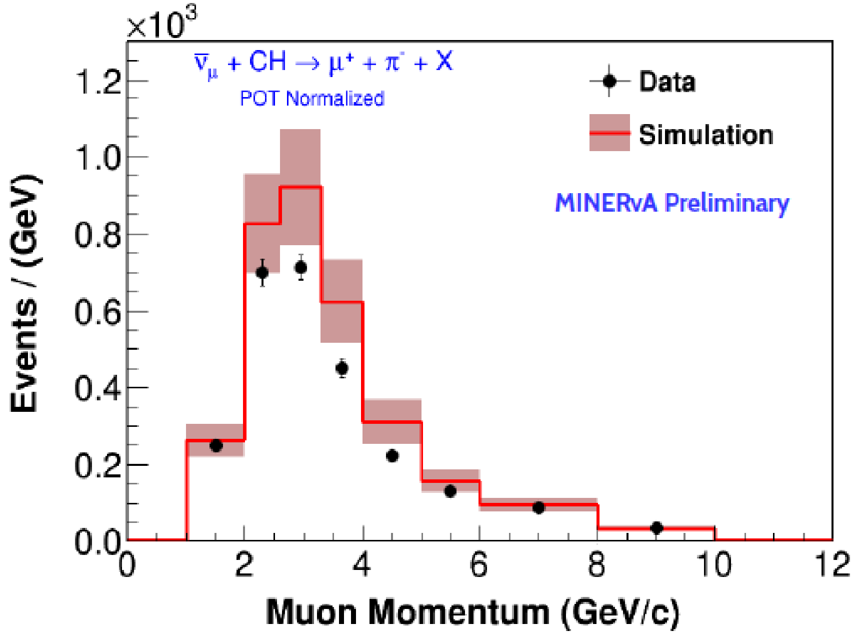
The other two generators seem to be not so bad.

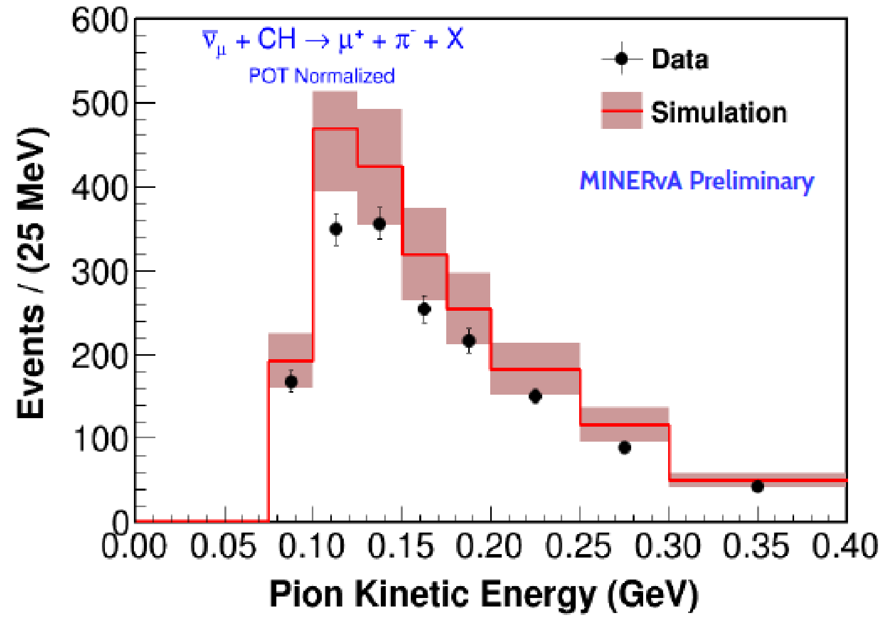
GENIE with FSI is larger than without FSI.

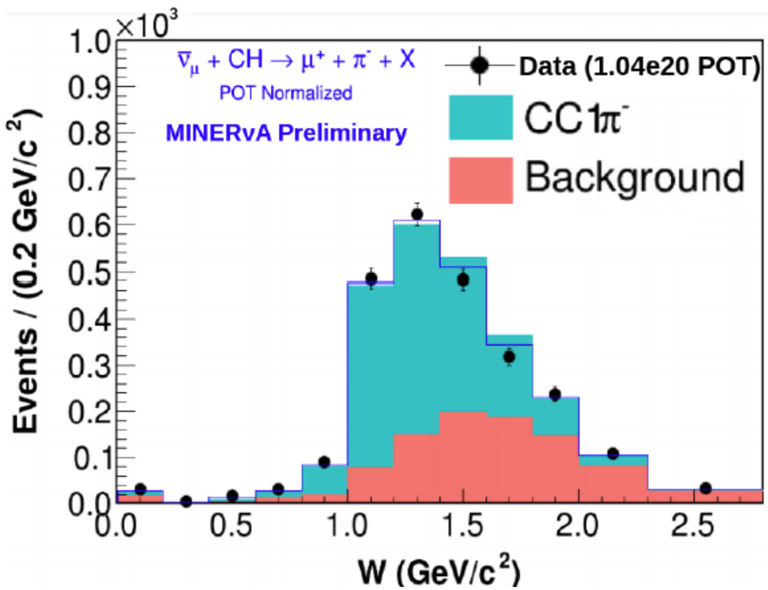
The conversions from charged pions have large effect.

Anti-neutrino induced single π production data

Charged current π^- production @ MINERνA (CH target)



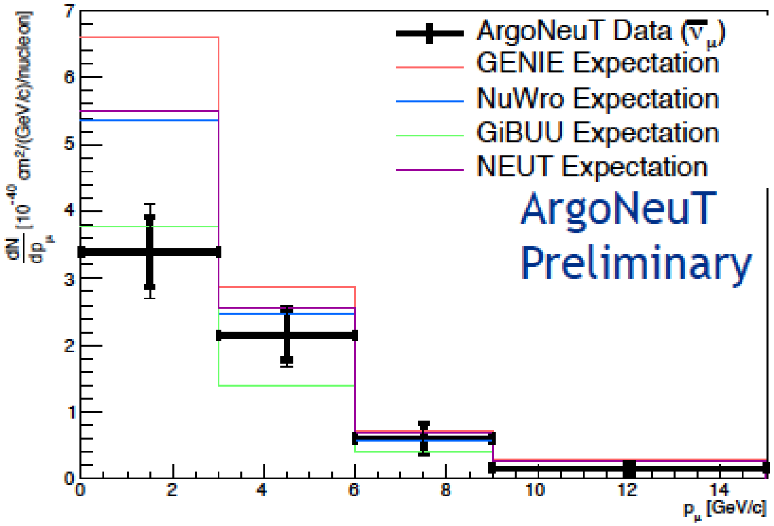




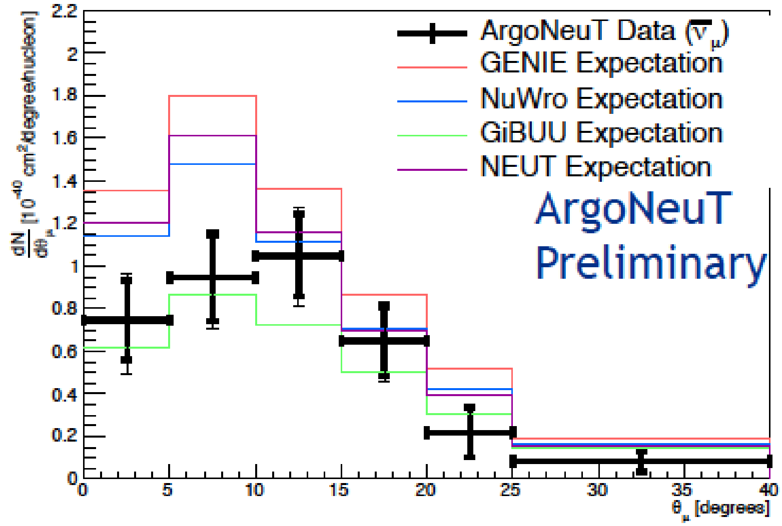
Anti-neutrino induced single π production data

Charged current $\pi^{\pm}$ production @ ArgoNeut (Ar target)

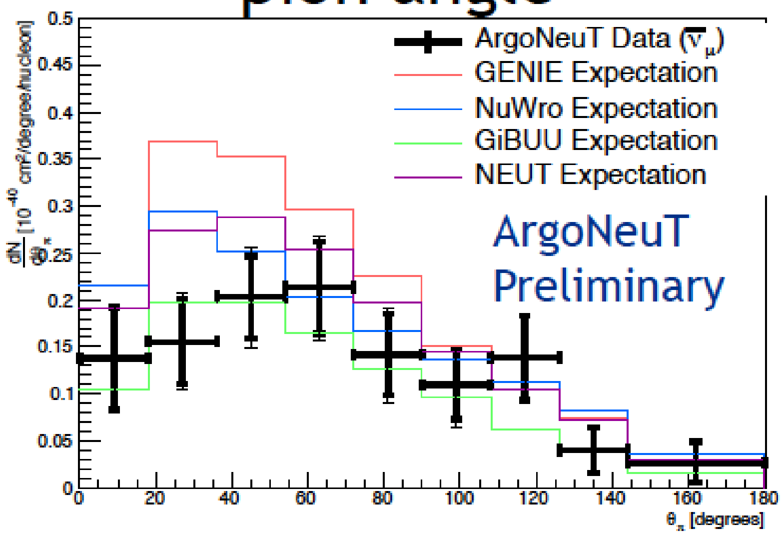
muon momentum



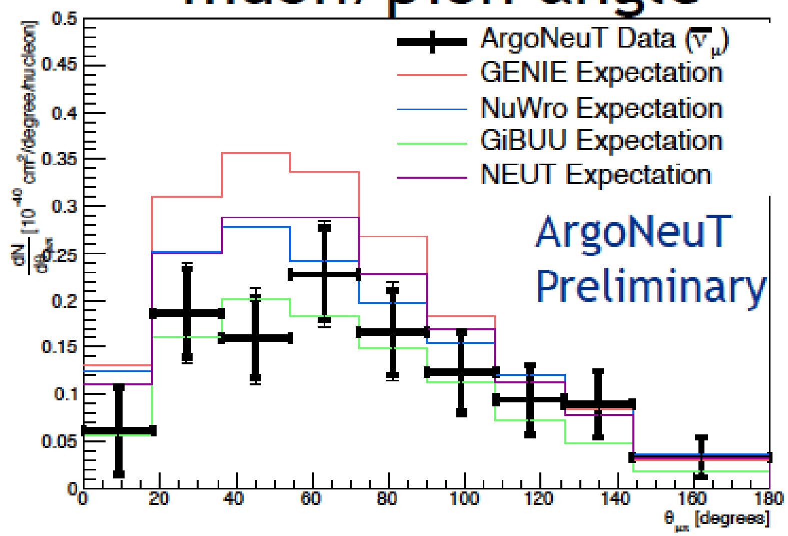
muon angle



pion angle



muon/pion angle



Summary

There were few (low energy) anti-neutrino pion production data.
Future neutrino oscillation experiments needs to reduce uncertainties of anti-neutrino pion productions.

There are several new neutrino / anti-neutrino induced $1\ \pi$ production data.

However, we need careful treatments of the data because the target material are nucleus and also, energy ranges are rather wide.

Also, event selection criteria (or definition of the signal) are quite different from experiment to experiment.

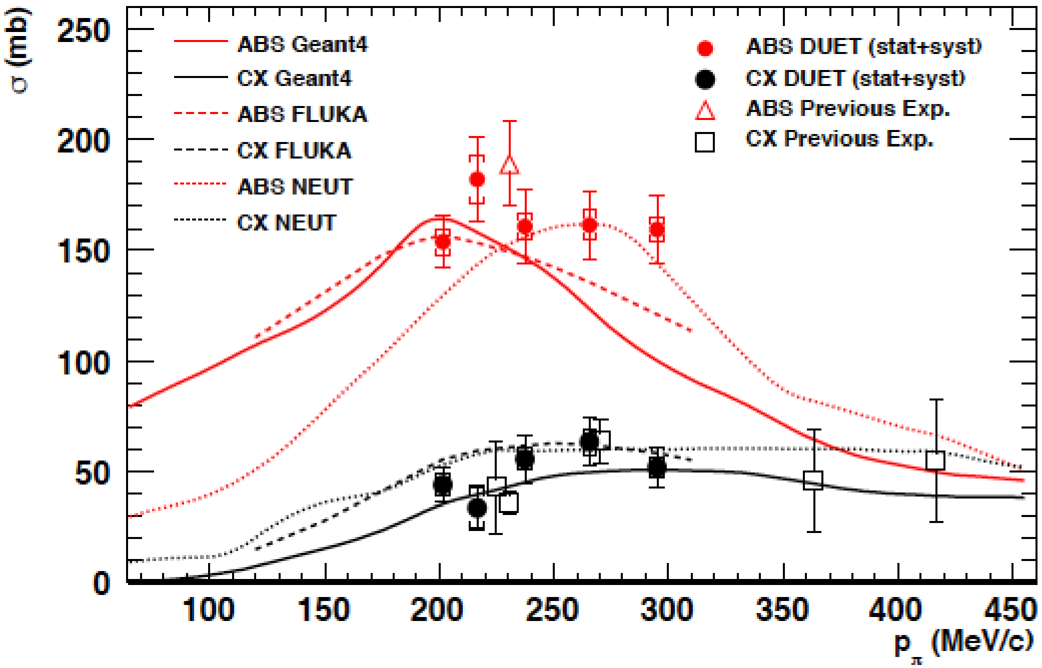
Comparisons the cross-sections of Carbon, Oxygen and Argon may be useful to understand the nuclear effects of pions.

	ν_μ (10^{-37}cm^2/Ar)	$\bar{\nu}_\mu$ (10^{-38}cm^2/Ar)
ArgoNeuT data	2.7±0.5(stat)±0.5(syst)	8.6±0.9(stat)+0.9-1.1(syst)
GENIE	3.8	13.3
NuWro	3.3	11.0
GiBUU	2.6	7.3
NEUT	3.5	11.4

Tingjun Yang (Fermilab) for the ArgoNeuT Collaboration

June 27, 2017

NuINT 2017, University of Toronto



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