First Measurement of Single Charged Pion Production in Charged Current Neutrino and Antineutrino Events on Argon

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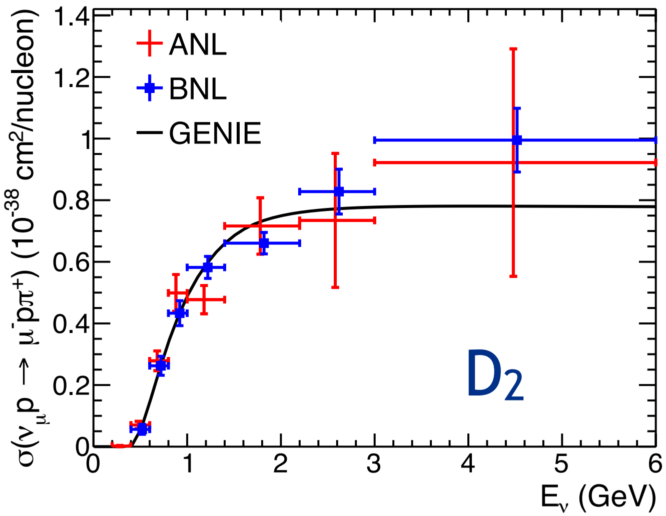
Introduction

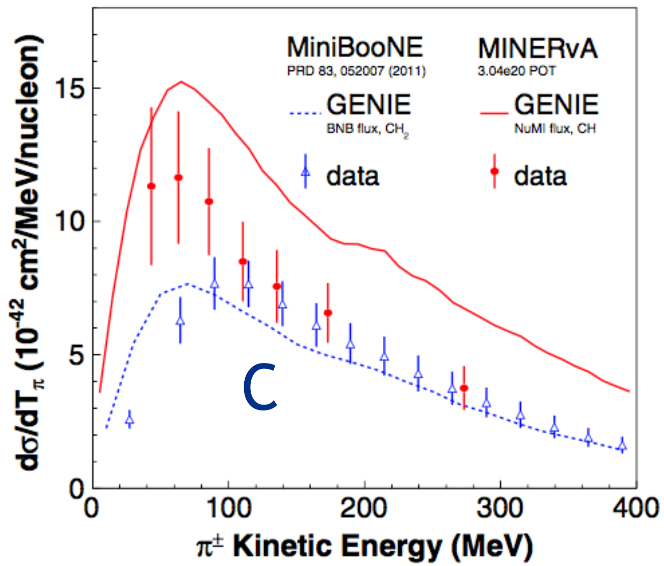
- Single charged pion production is an important process in the few-GeV neutrino-nucleus interactions.
- Early experiments used bubble chamber and free nucleon targets.
  - Tension between BNL and ANL measurements resolved in a recent reanalysis of BNL and ANL data, which favors ANL measurement.
- Recent experiments measured single pion production cross sections using heavy targets (C, O), mainly neutrino data, no argon measurements yet.

Previous measurements

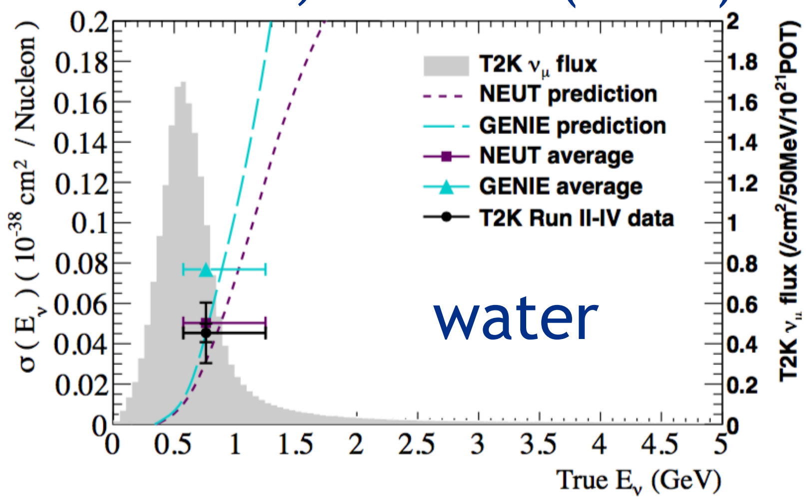
PRD 90,112017 (2014)



PRD 90, 112017 (2014)



PRD 95, 012010 (2017)



- Tension between MINERvA and MiniBooNE measurements.
  - “Pion puzzle”

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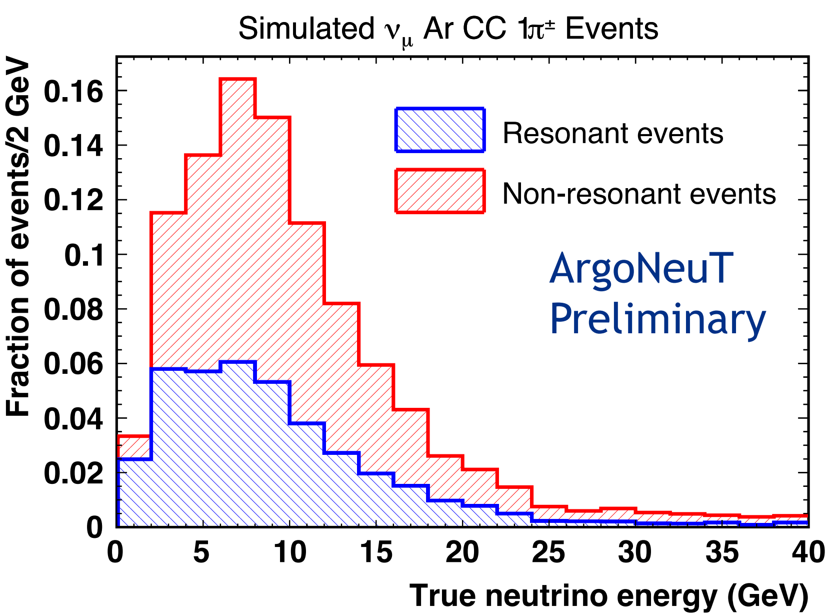
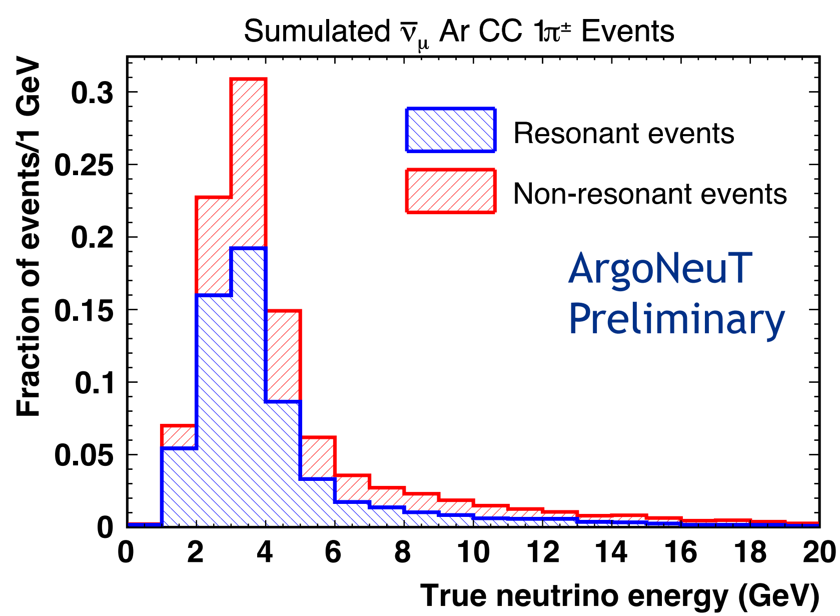
ArgoNeuT Charged Current (CC) 1π± measurements

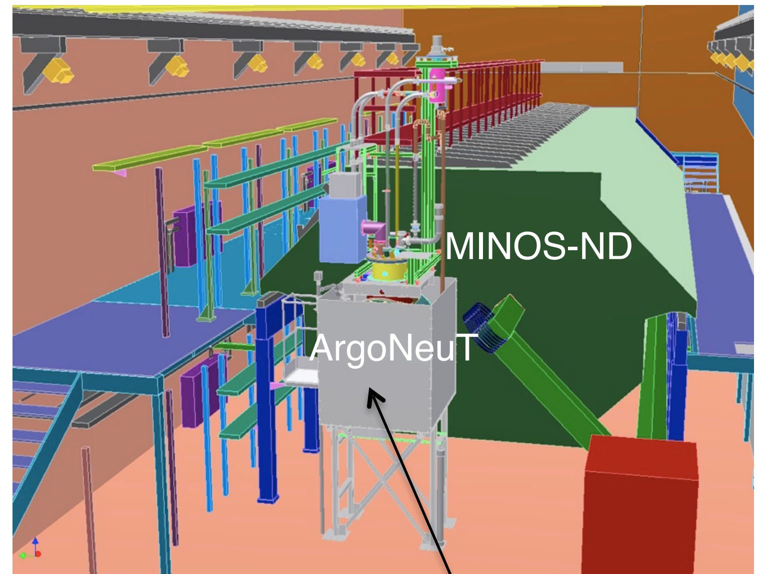
- We present the measurement of CC1$\pi^{\pm}$ cross sections using ArgoNeuT antineutrino data.
- **Giacomo Scanavini** (Università degli Studi di Pisa)'s master thesis analysis.
- The signal is defined to be a CC interaction with exactly one charged pion above 100 MeV/c in the final state.
  - No neutral pions or neutral or charged kaons should be present in the final state.
  - There is no restriction on other mesons or nucleons.
- Based on GENIE prediction, for neutrino CC1Pi sample, 39% events are resonance events. For antineutrino CC1Pi sample, 61% events are resonance events.

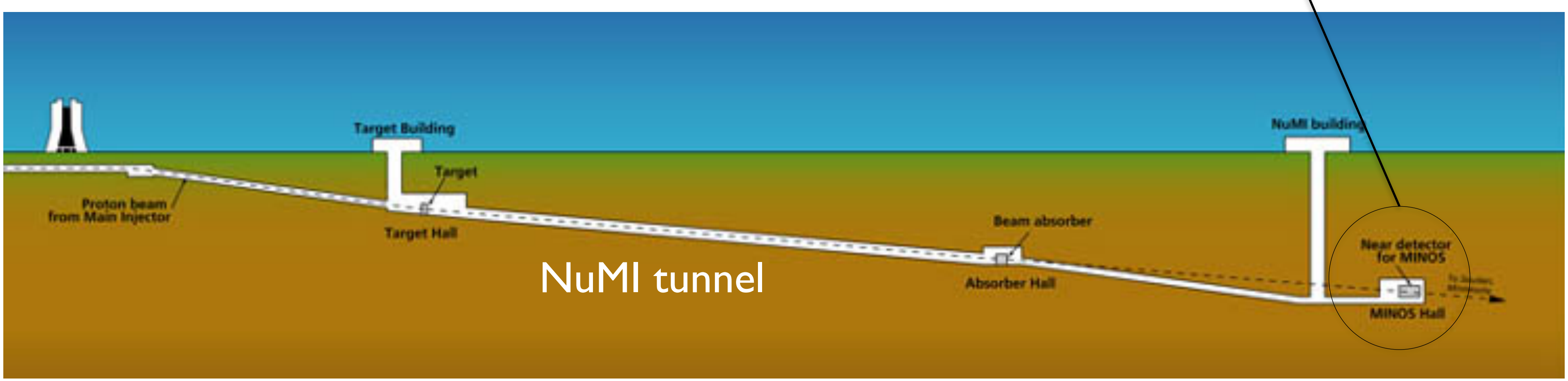




ArgoNeuT - Argon Neutrino TesT

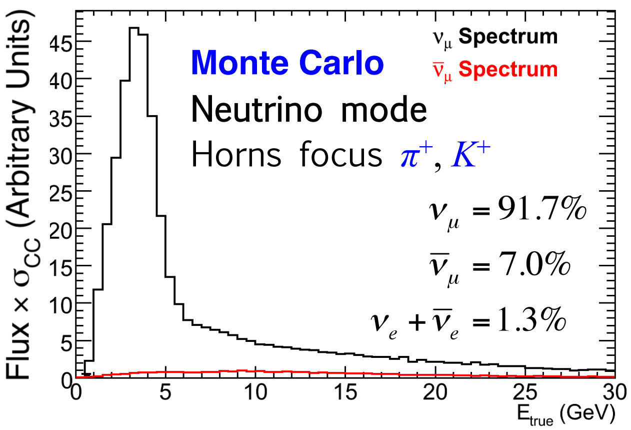
- First LArTPC in a neutrino beam in the US
- Sitting in NuMI beam
- Located in front of MINOS near detector
- 47×40×90 cm^3 (170 L), wire spacing 4 mm



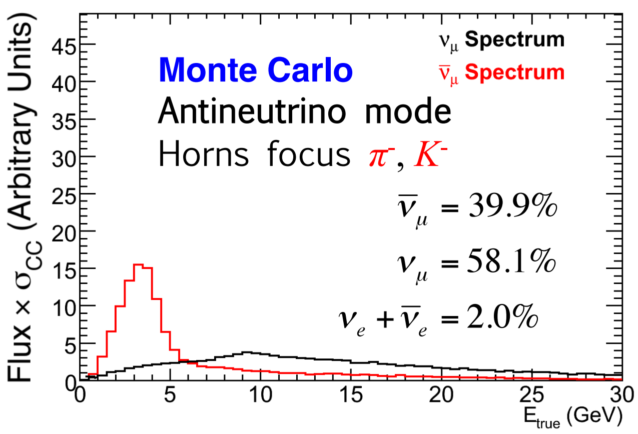


ArgoNeuT's physics run

ν-mode (2 weeks): 0.085e20 POT



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

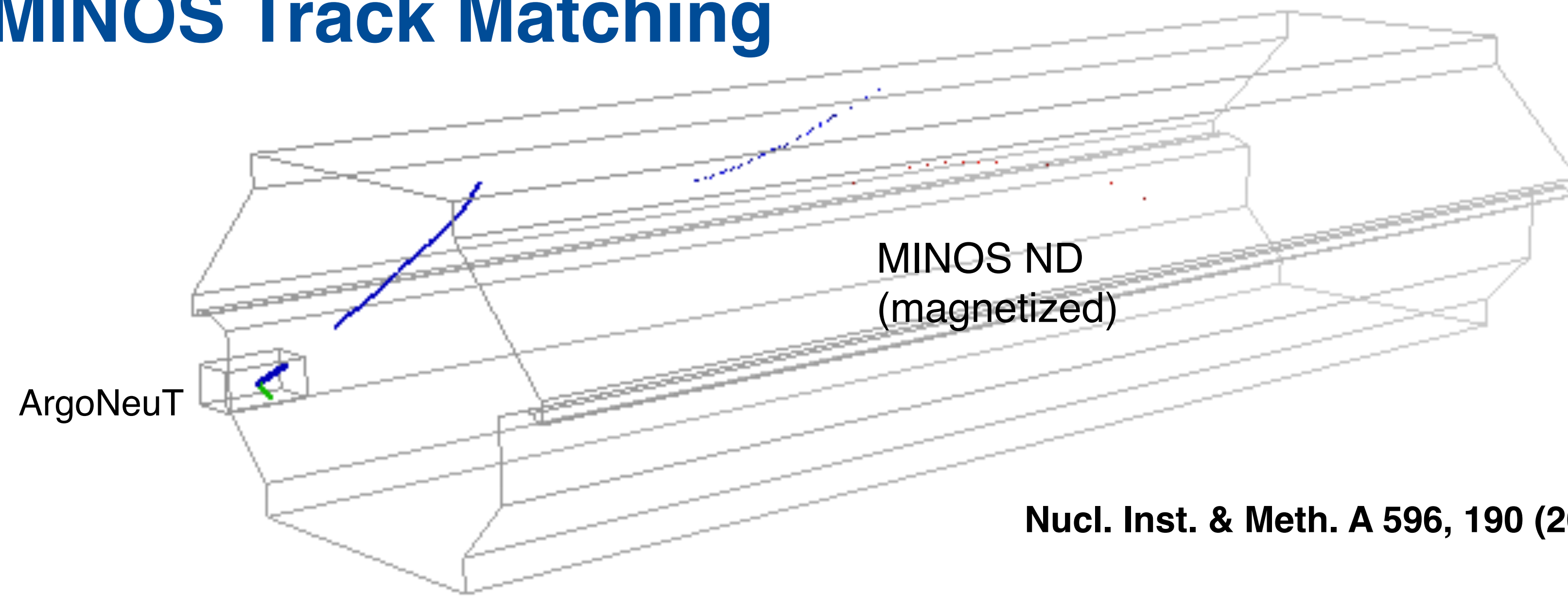


- ArgoNeuT completed taking data. (9/14/2009-2/22/2010)
- Physics goals:
  - Measure ν-Ar CC cross sections
  - Develop automated reconstruction techniques
  - ArgoNeuT has published 9 papers, 5 on cross section measurements.
- We performed CC1Pi cross section measurements using antineutrino data.

Overview of CC1Pi cross section measurements

- Event selection
  - Use MINOS information to select CC events.
  - Use LArTPC topology and calorimetric information to select CC1Pi events.
- Background estimation
  - Boosted decision trees to reduce and estimate background.
- Unfolding
  - Correct for efficiency and smearing
- Systematics
  - Detector, flux and cross section models

MINOS Track Matching

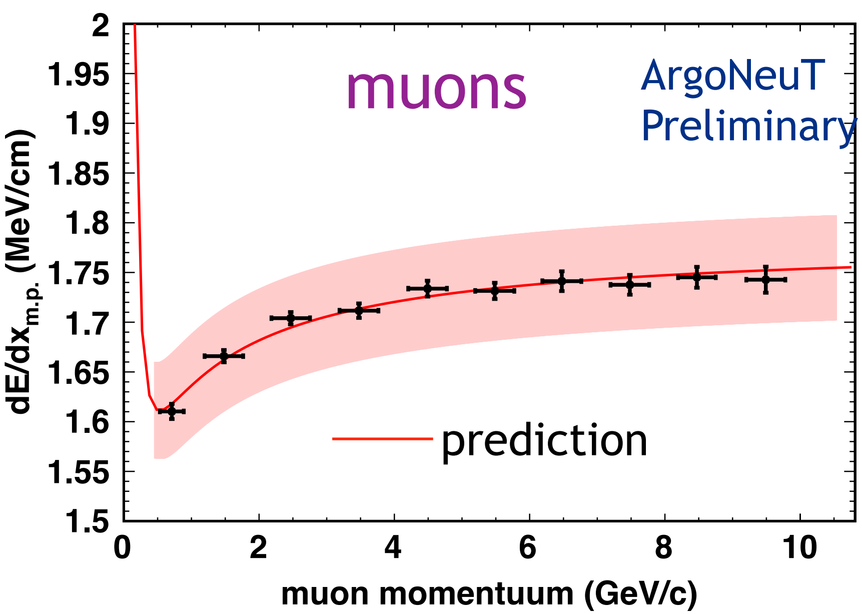


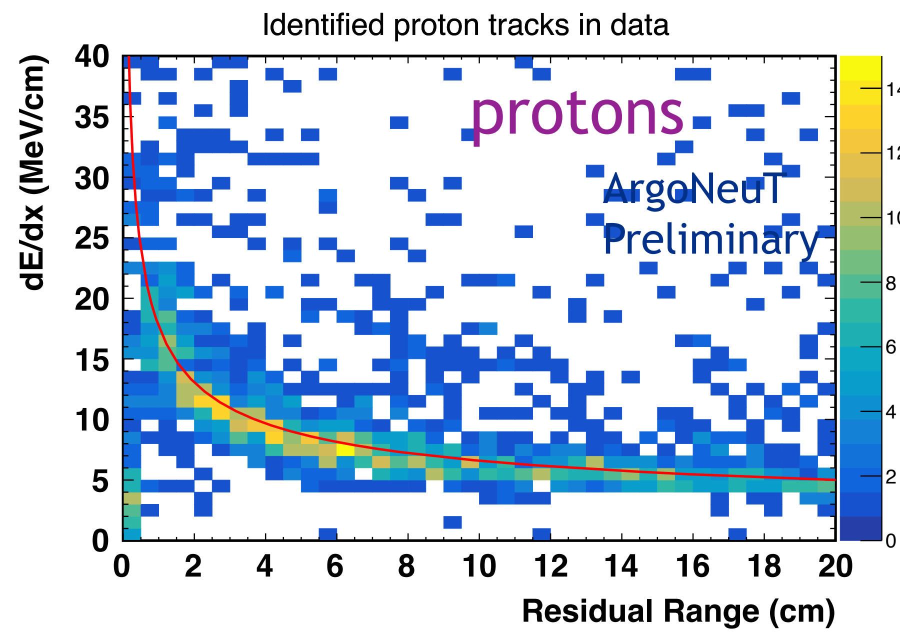
Nucl. Inst. & Meth. A 596, 190 (2008)

- The presence of the MINOS ND allows for energy reconstruction and charge identification of escaping muons.
- Majority of matched tracks are muons - selection of CC events.
- Because of the small size of ArgoNeuT detector and its proximity to the MINOS detector, we have good acceptance for muons up to 40 degrees.

Calorimetry reconstruction

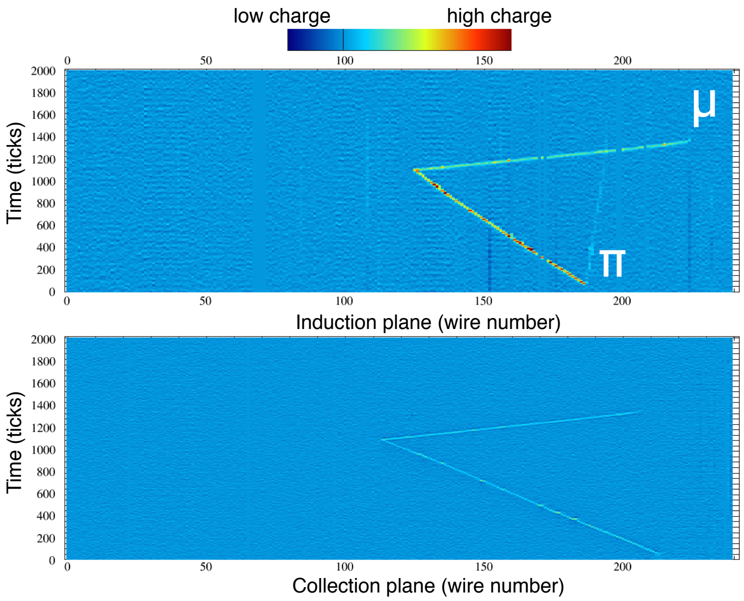
- Convert dQ/dx to dE/dx after correcting for electron lifetime and recombination effects - crucial for particle identification in LArTPC.
- Tune calorimetry constants using muons.
- Good efficiency to identify stopping protons.
- Exiting protons look similar to MIPs.





Event selection

- Reconstructed neutrino vertex is in the fiducial volume.
- One TPC track is matched to a MINOS track.
- At least one more track around the vertex in addition to the muon track. Either one or two tracks from vertex are identified as MIP-like tracks.

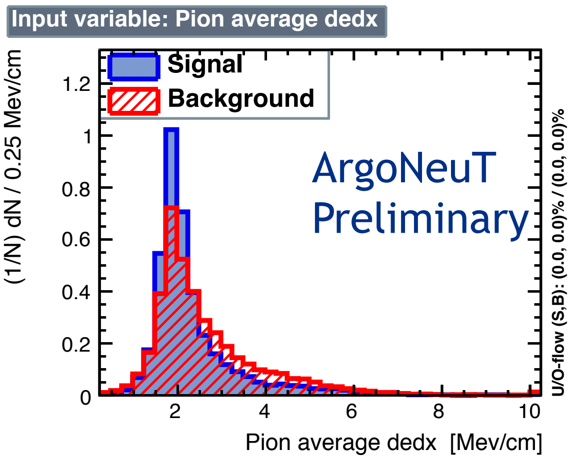


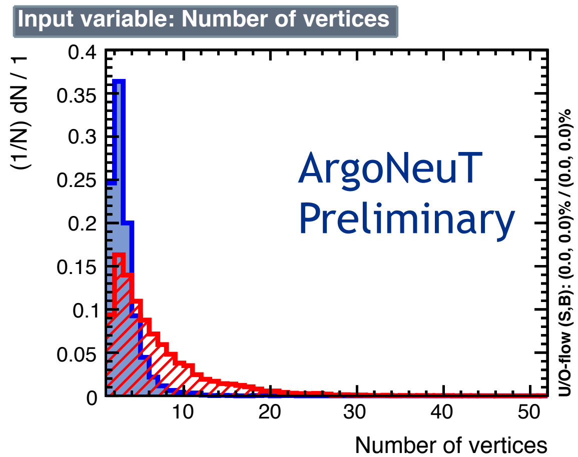
	numu	numubar
CC-inclusive	1862	1756
One or two MIP-like tracks	907	624

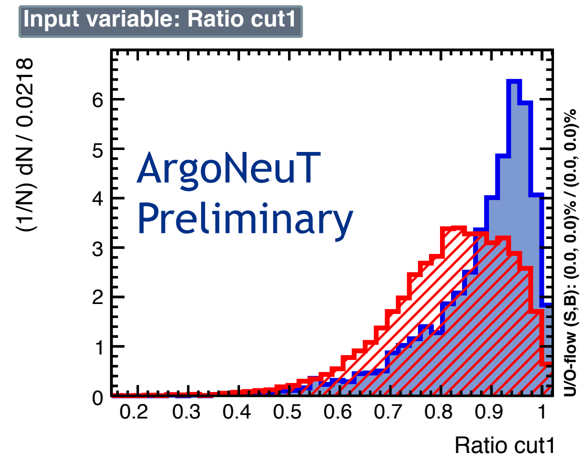
Boosted Decision Trees

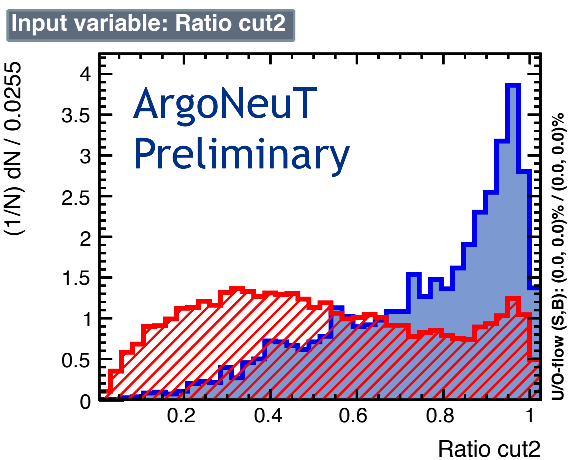
- To further reduce background and estimate background, we built boosted decision trees with 5 variables:
  - Average dE/dx calculated using the last 5 cm of the pion track
  - Number of MIP-like tracks (one or two)
  - Number of reconstructed vertices
  - Fraction of charge that is associated with all reconstructed tracks - ratio cut 1
  - Fraction of charge that is associated with reconstructed tracks originated from the reconstructed neutrino interaction vertex - ratio cut 2
- Only use calorimetric and topological information.

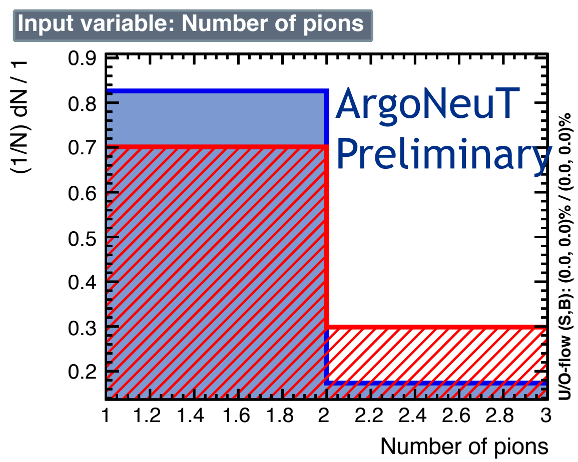
BDT variables - neutrino sample (GENIE MC)







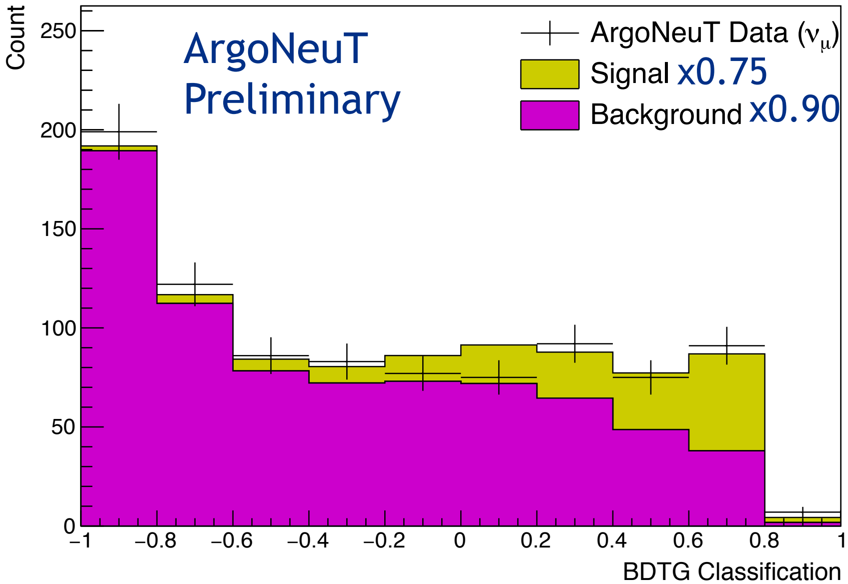


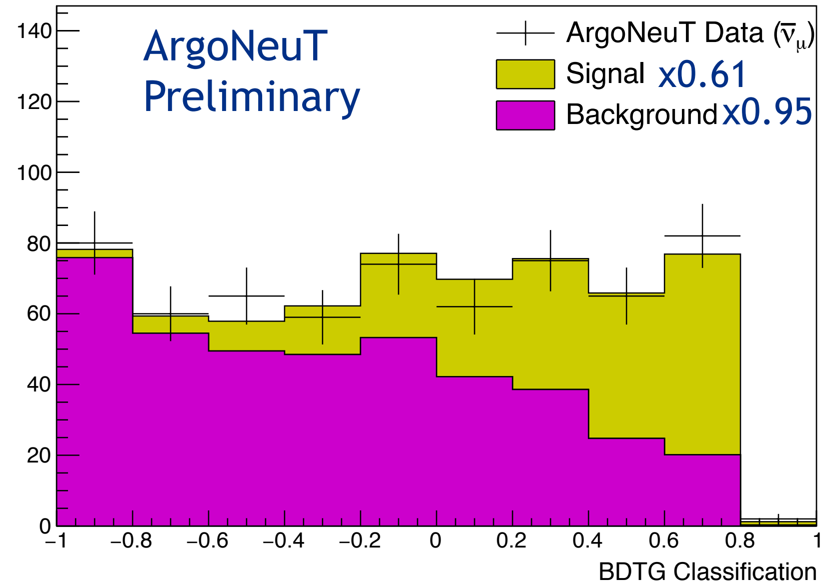


Cross section calculation

- $\sigma=(N-N_{bg})/(\varepsilon N_{Ar}\Phi)$
- N: measured number of data events
- N_{bg}: number of background event
  - Estimated by fitting to the BDT distributions
- ε: unfolding factor, correcting for efficiency and smearing, estimated using MC
- N_{Ar}: Number of argon nucleus, calculated using LAr density and fiducial volume.
- Φ: Neutrino flux - use MINERvA flux for this analysis (arXiv: 1607.00704).

Fit data using BDT signal/background templates





	ν_μ				$\overline{\nu}_\mu$			
	Data	MC Total	MC (Sig)	MC (Back)	Data	MC Total	MC (Sig)	MC (Back)
Total (after cuts)	907	907	157	750	624	624	216	408
Selected Region	340	348	123	225	286	290	126	163
Rejected	567	559	34	525	338	335	90	245

- We have to scale the default signal and background predictions to fit data.
- Signal region is defined as BDT>0. Background above 0 is subtracted from data.

Unfolding

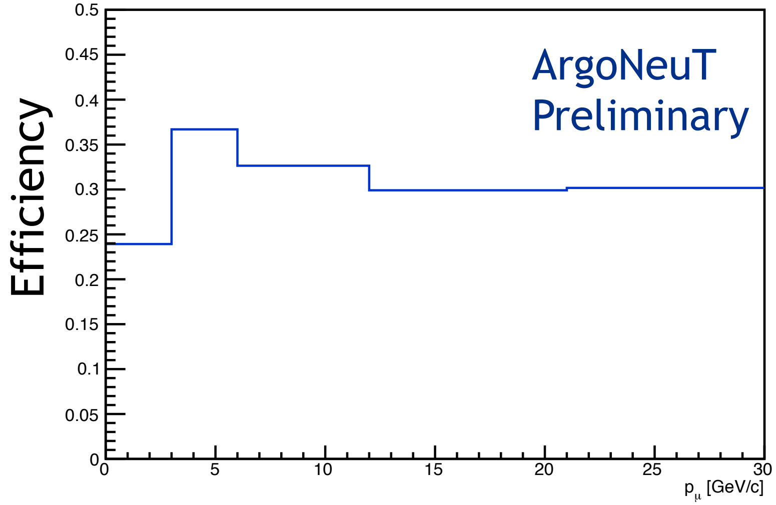
- Use unfolding factor to correct for efficiency and detector smearing effects.
- Unfolding factor is defined as:

$$\frac{\text{Reconstructed quantity of selected signal events}}{\text{True quantity of all generated signal events}}$$

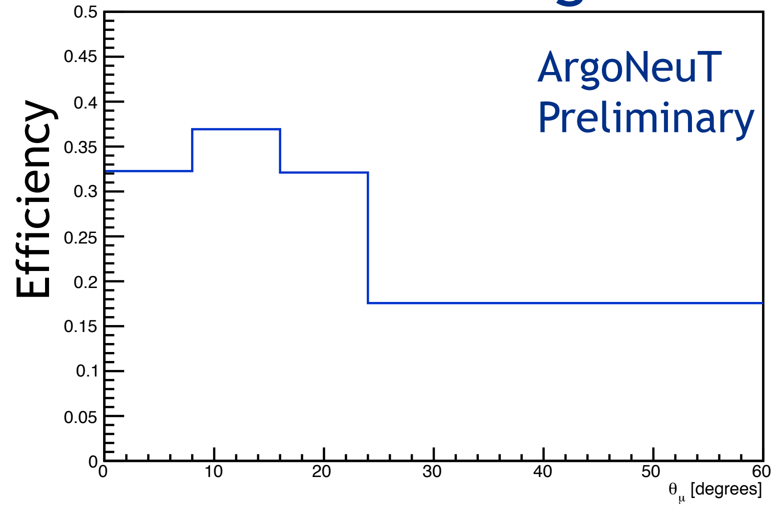
- We measure differential cross sections in 4 kinematic variables:
  - Muon momentum
  - Muon angle
  - Pion angle
  - Angle between muon and pion

Unfolding - neutrinos

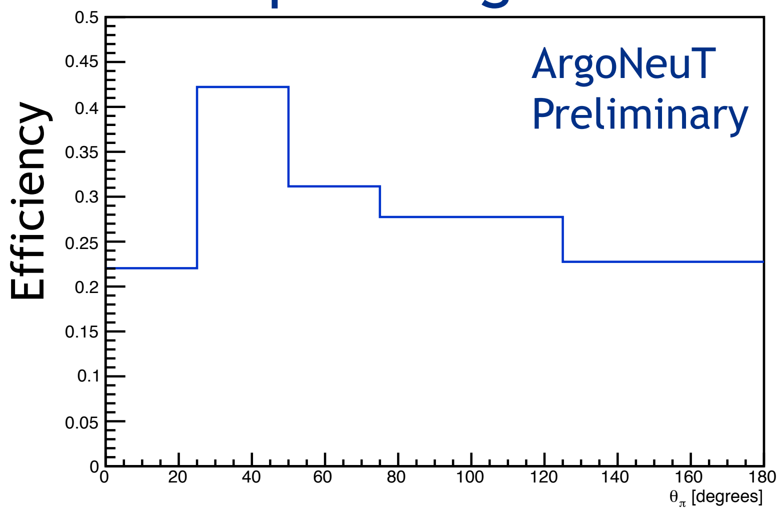
muon momentum



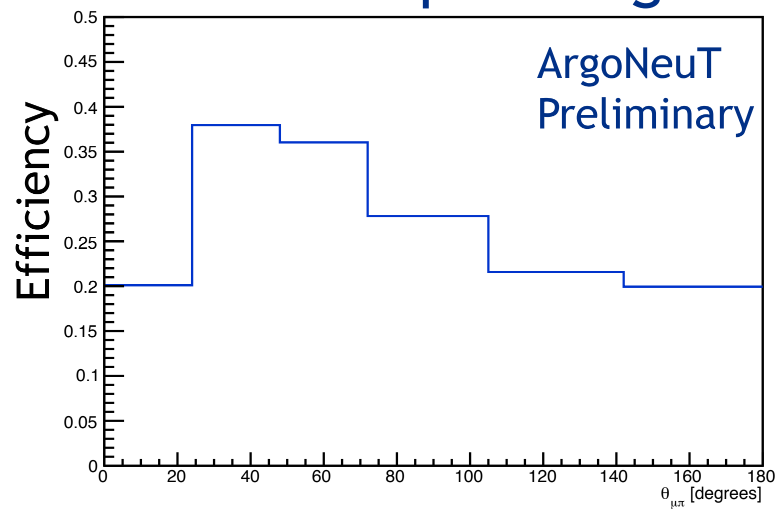
muon angle



pion angle



muon/pion angle



Systematic uncertainties

- Redo analysis after varying systematic effects.
- Flux
  - Assign 11% normalization error.
- Cross section
  - Reweight MC using GENIE weights after varying cross section parameters by $\pm 1\sigma$.
- Detector response
  - Vary calorimetry constants by 3%.
- POT: 1%.
- Number of Ar targets: 2%

Systematic uncertainties

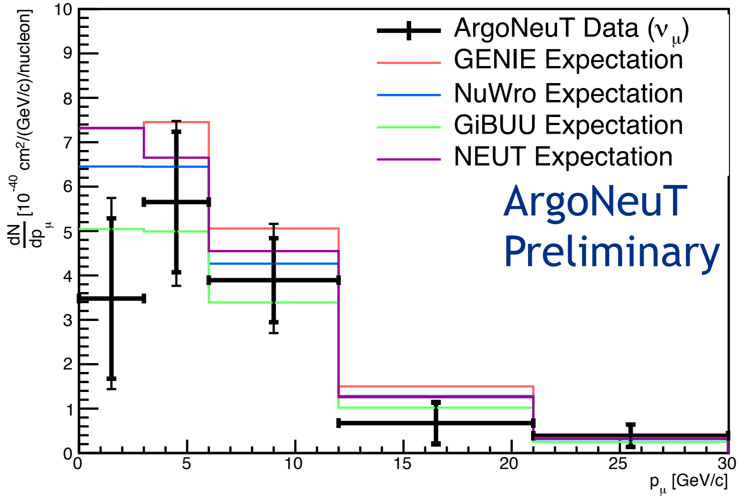
	Fractional cross section uncertainty [%]	
Systematic Uncertainty	ν_μ	$\overline{\nu}_\mu$
Qema	$^{+2.4}_{-6.8}$	$^{+0.5}_{-1.2}$
CcresAxial	$^{+6.8}_{-8.0}$	$^{+2.4}_{-1.7}$
CcresVector	$^{+2.8}_{-4.0}$	$^{+1.0}_{-1.1}$
CohMA	$^{+0.8}_{-0}$	$^{+0.9}_{-0}$
CohR0	$^{+0.8}_{-0}$	$^{+0.9}_{-0}$
NonResRvbarp1pi	$^{+8.4}_{-7.6}$	$^{+1.0}_{-1.2}$
NonResRvbarp2pi	± 2.0	$^{+0.7}_{-0.9}$
NonResRvp1pi	$^{+0.4}_{-0.8}$	$^{+0.9}_{-1.0}$
NonResRvp2pi	± 2.0	$^{+0.7}_{-0.9}$
FormZone	$^{+8.8}_{-0}$	$^{+0.9}_{-0.5}$
IntraNukePlabs	± 2.4	$^{+0.2}_{-0.4}$
CalorimetryConstant	$^{+4.8}_{-0}$	$^{+4.2}_{-4.7}$
POT	± 1.0	± 1.0
Flux Normalization	$^{+10.0}_{-12.0}$	$^{+10.0}_{-12.0}$
Number of Argon Targets	± 2.0	± 2.0
Total systematics	$^{+18.7}_{-18.6}$	$^{+11.6}_{-13.4}$

Comparison with neutrino generators

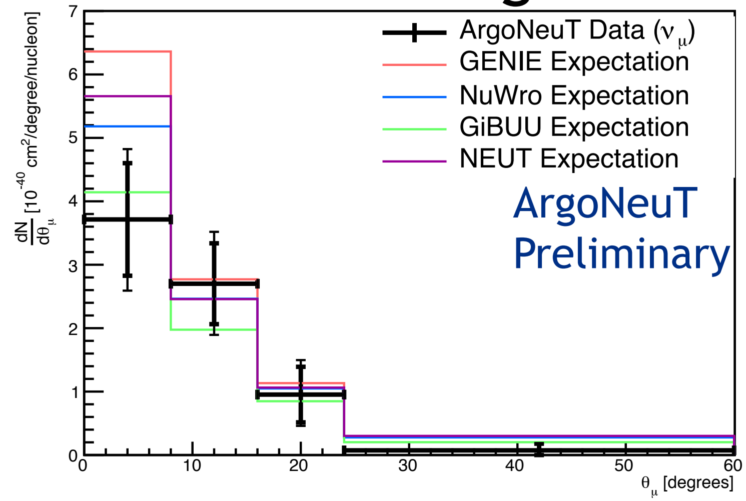
- GENIE v2_12_2, including MEC
  - Thanks to Costas Andreopoulos and Marco Roda for useful discussions.
- NuWro 17.01.1
  - Thanks to Jan Sobczyk and Tomasz Golan for useful discussions.
- GiBUU 2016
  - Thanks to Luke Pickering for useful discussions and instructions on GiBUUTools. Thanks to Ulrich Mosel for useful discussions.
- NEUT 5.3.7
  - Thanks to Yoshinari Hayato for providing the MC samples and useful discussions.

Differential cross sections - numu CC 1pi

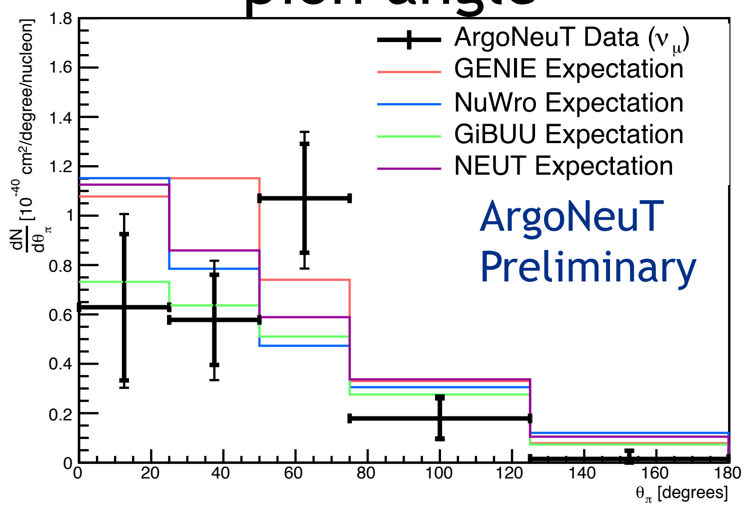
muon momentum



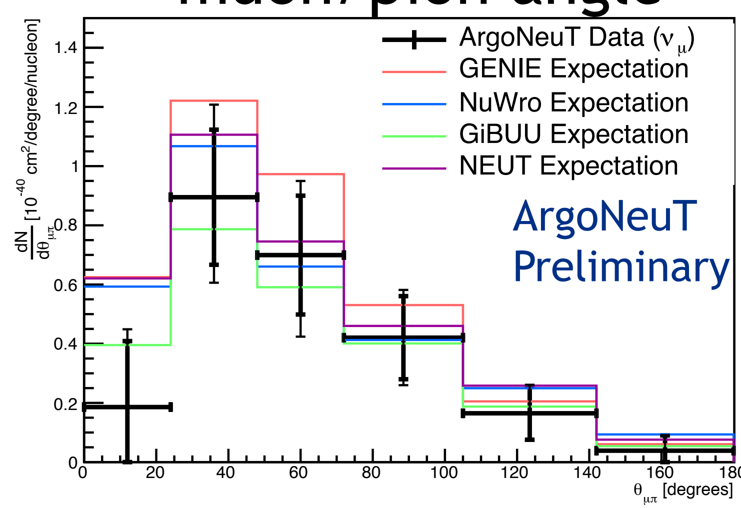
muon angle



pion angle



muon/pion angle



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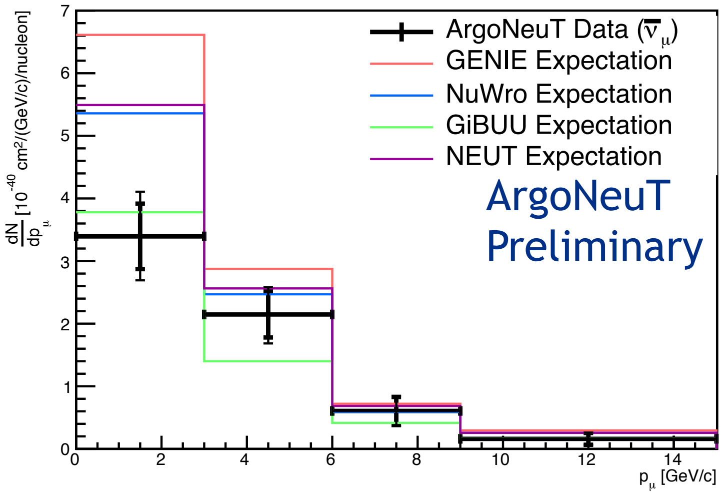
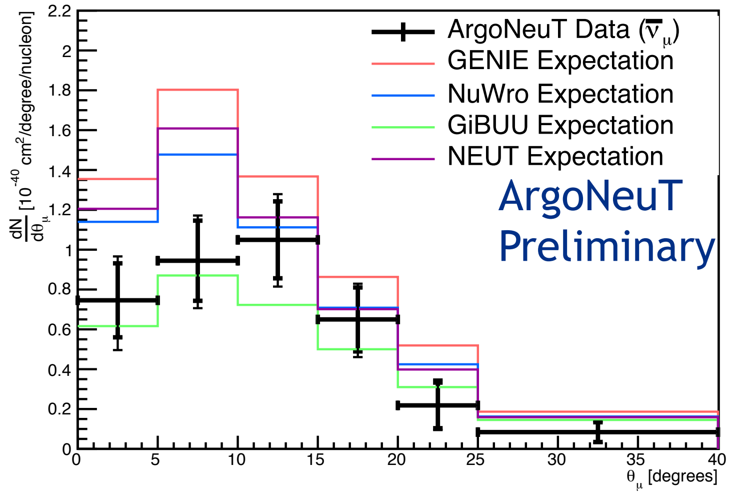
Differential cross sections - numubar CC 1pi

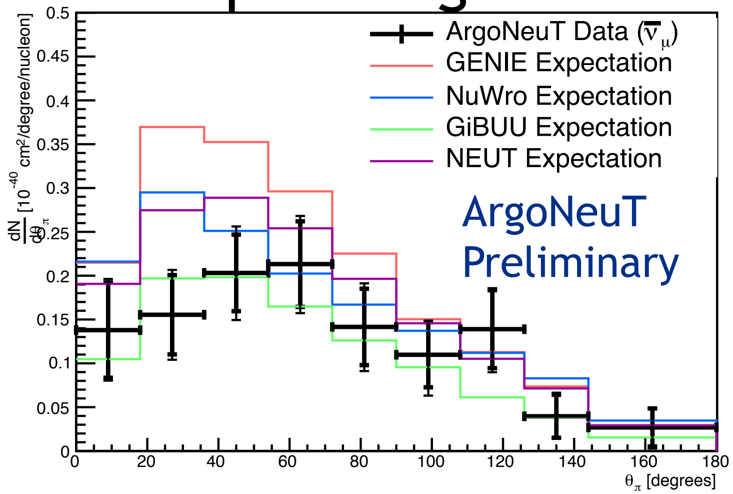
muon momentum



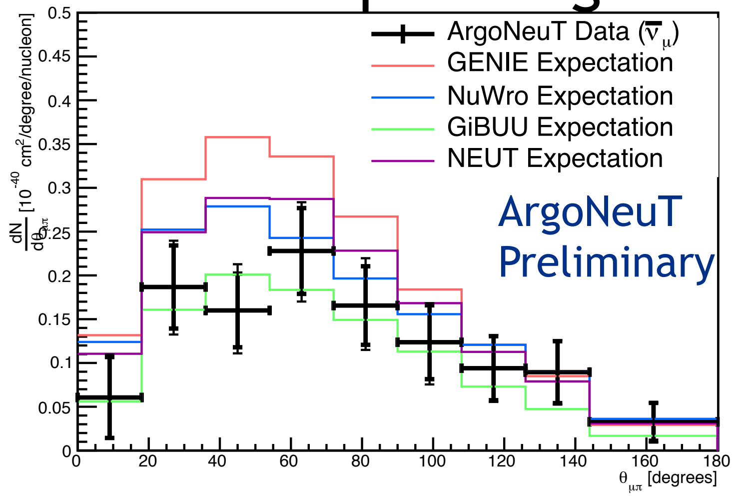
muon angle



pion angle



muon/pion angle



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Integrated cross sections and conclusions

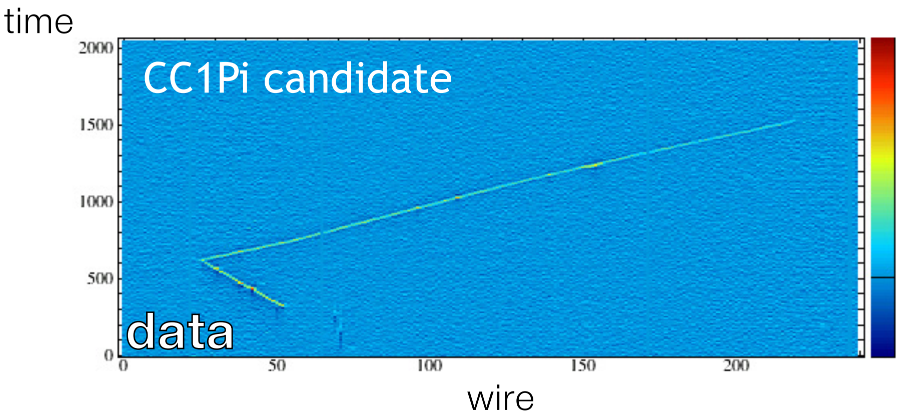
	ν_μ (10^{-37}cm^2/Ar)	$\bar{\nu}_\mu$ (10^{-38}cm^2/Ar)
ArgoNeuT data	2.7±0.5(stat)±0.5(syst)	8.6±0.9(stat)+0.9-1.1(syst)
GENIE	3.8	13.3
NuWro	3.3	11.0
GiBUU	2.6	7.3
NEUT	3.5	11.4

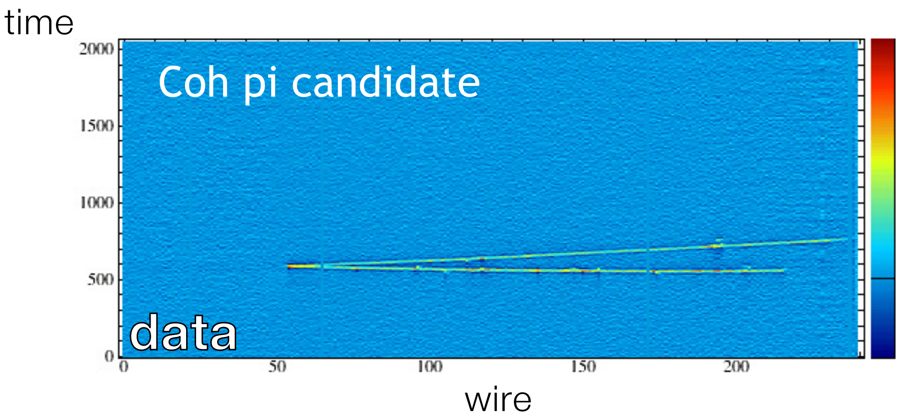
- We have performed the first CC1Pi cross sections measurements using the argon targets.
- We have compared the measured cross sections with 4 generators.

Backup slides

Coherent pion production

- This analysis is an extension to the ArgoNeuT CC coherent pion production cross section measurement:
    - "First Measurement of Neutrino and Antineutrino Coherent Charged Pion Production on Argon" PRL 113, 261801 (2014).
- The ~15 coherent pion production candidates in the previous analysis are considered signal in the CC1Pi analysis.





Why accept 2 pions?

- ArgoNeuT is small. A lot of protons exit the TPC. The part inside the TPC looks MIP-like.
- 1mu+1pi+1proton events are signal events. If the proton is not contained, both pion and proton can be identified as pion (MIP-like).
- Requiring 1 identified pion will reduce efficiency by 20%.
- The strategy is to keep events with 1 or 2 identified pions and estimate background later.

Table 1: This table shows the number of times the MC generated protons are reconstructed, with a track length of at least 4 cm, and are contained or not in the detector fiducial volume. From the last two rows it is clear that the separation between protons and pions is not efficient when the protons exit the detector.

	ν_μ [%]	$\overline{\nu}_\mu$ [%]
Contained	37	43
Not contained	63	57
Contained and reconstructed as MIP-like track	37	31
Not contained and reconstructed as MIP-like track	76	70

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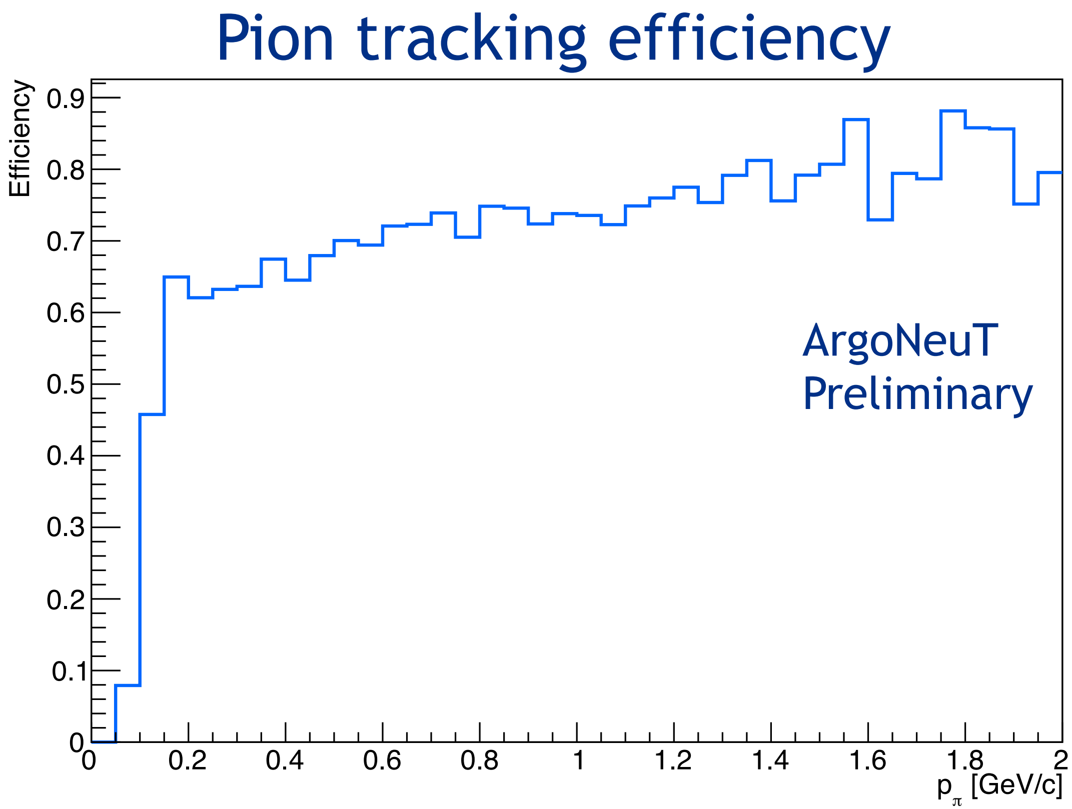
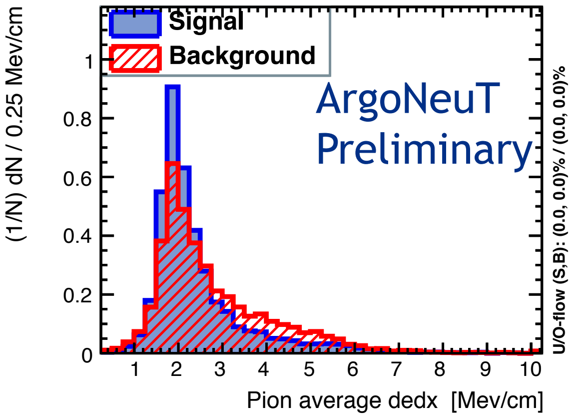
Pion threshold



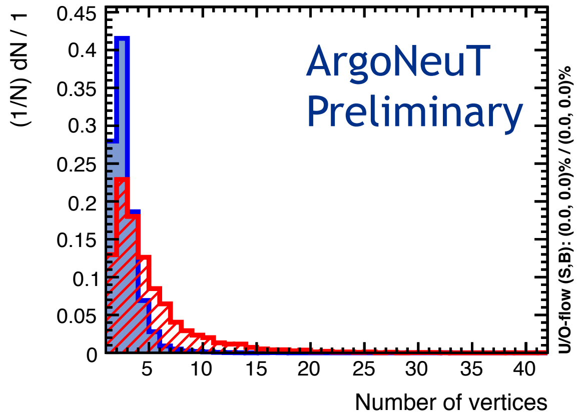
- Pion reconstruction efficiency is relatively high for pion momentum greater than 100 MeV/c.
- Require pion track length greater than 4 cm, corresponding to pion threshold of 100 MeV/c.

BDT variables - antineutrino sample

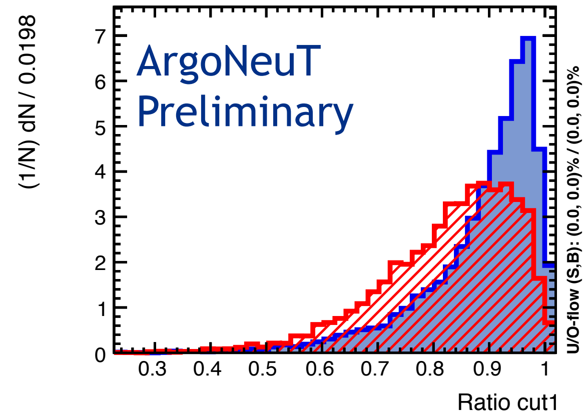
Input variable: Pion average dedx



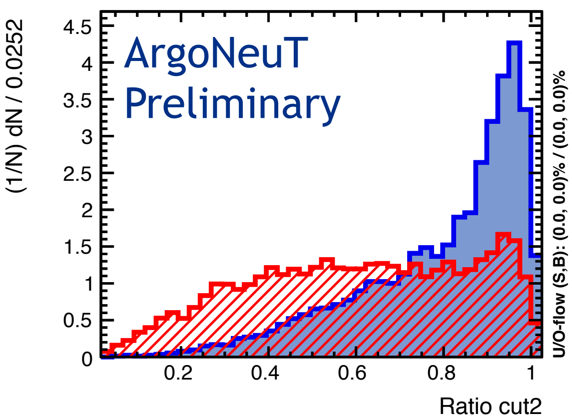
Input variable: Number of vertices



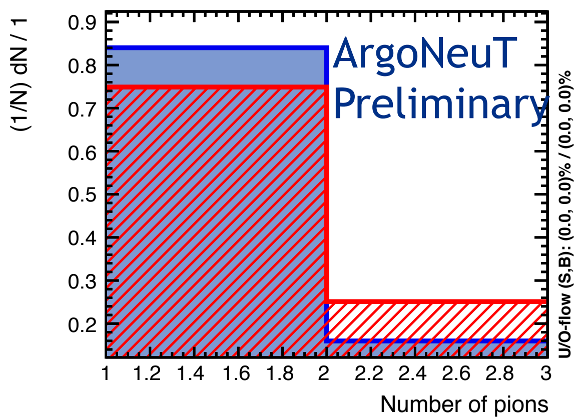
Input variable: Ratio cut1



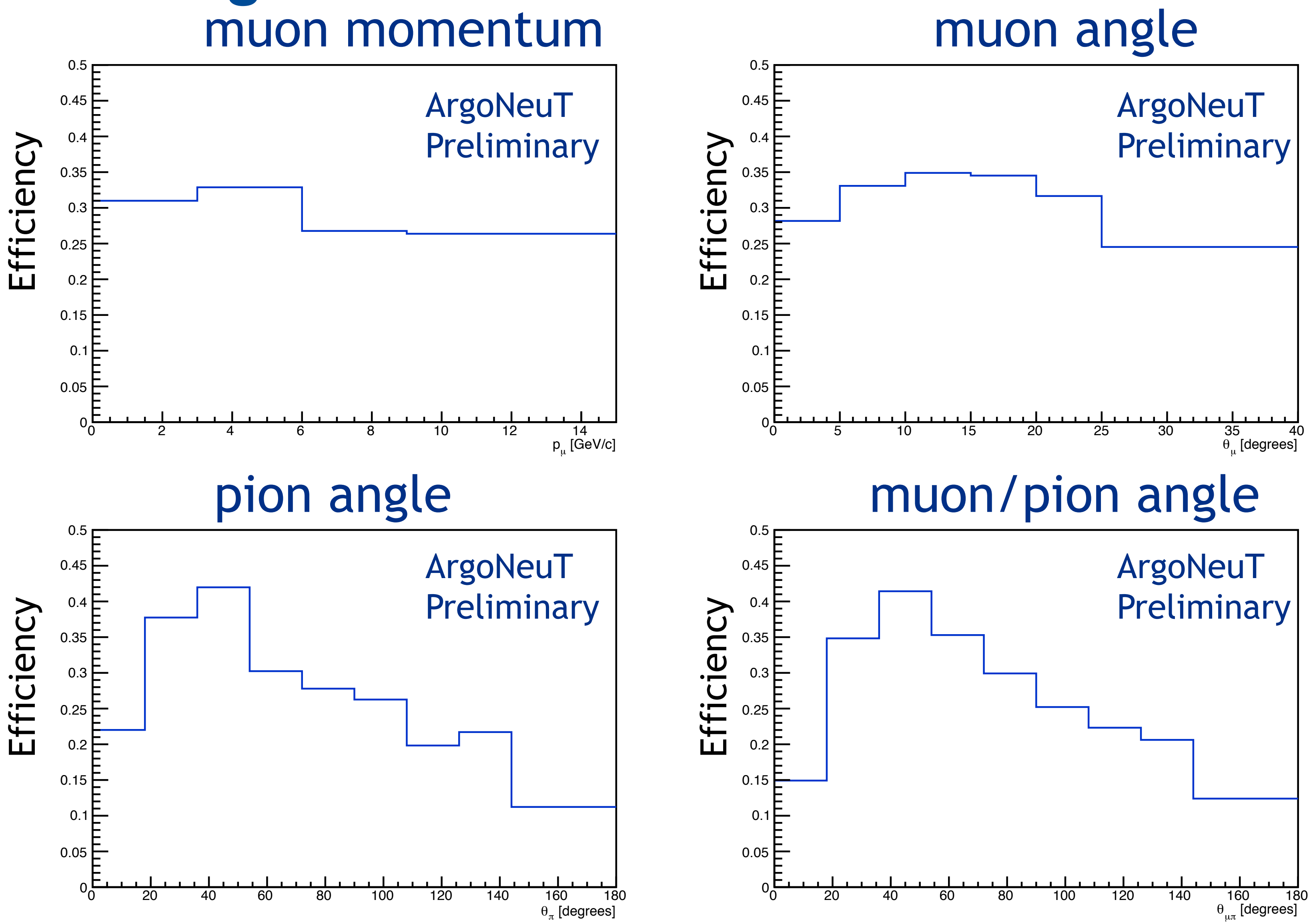
Input variable: Ratio cut2



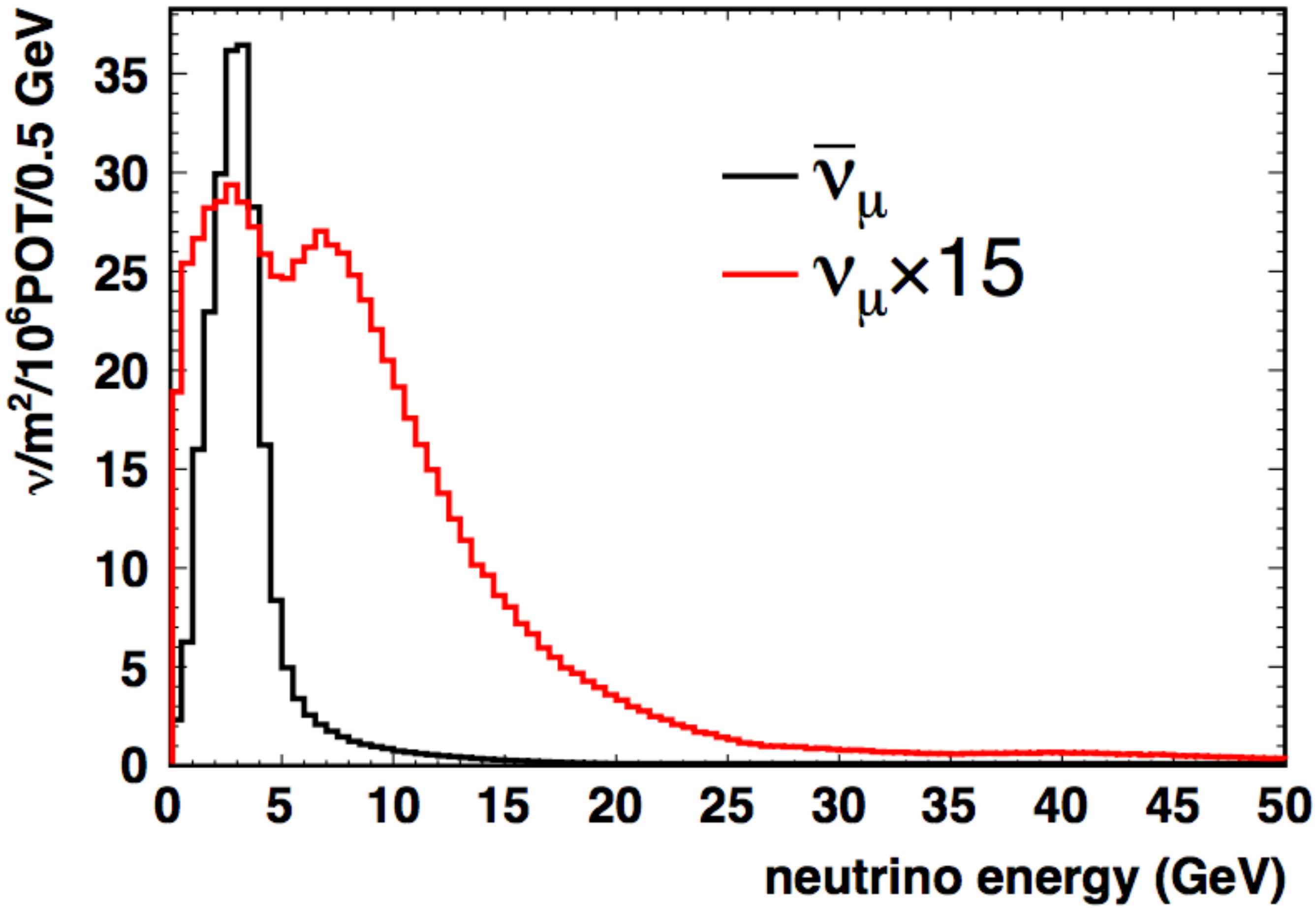
Input variable: Number of pions



Unfolding - antineutrinos

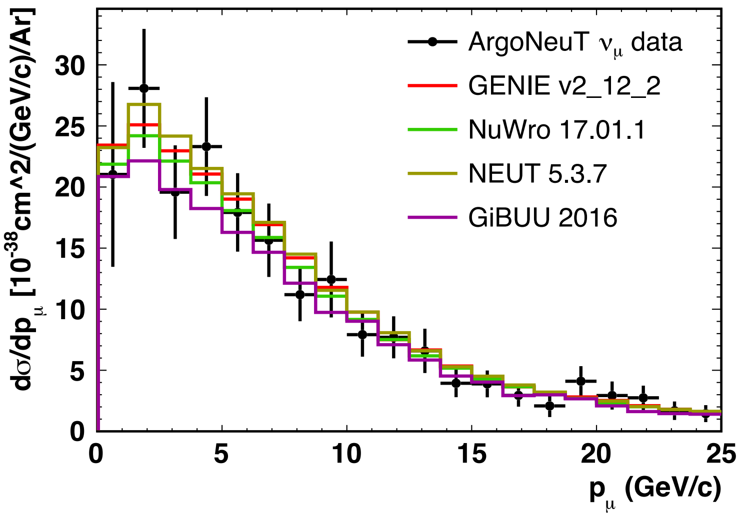


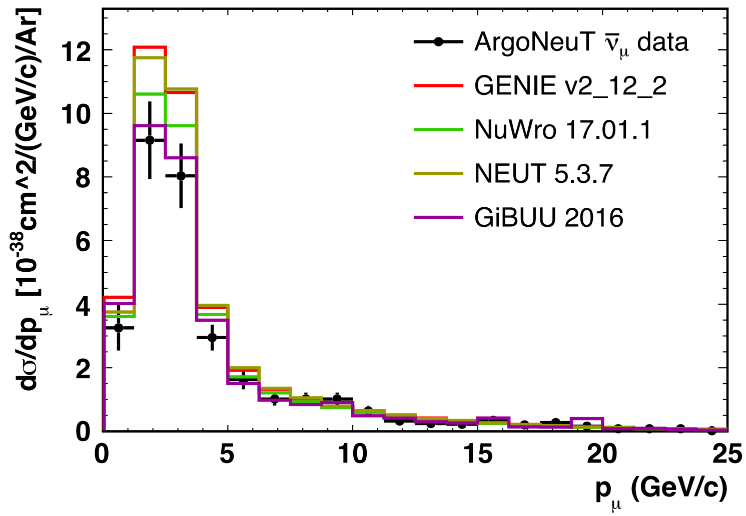
Flux



- User MINERvA fluxes reported in https://arxiv.org/abs/1607.00704.

Comparison to ArgoNeuT CC-inclusive measurements





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NuWro	2.7	4.4
GiBUU	2.4	4.1
NEUT	2.8	4.9

- ArgoNeuT cross sections are scaled by 1.036(1.017) for neutrinos(antineutrinos) to account for the difference between MINERvA flux and previous flux used in the ArgoNeuT CC-inclusive analysis.

Improvements to reconstruction

- Reconstruction in LArTPCs is always a challenge!
- Huge amount of effort and progress, new ideas being developed, advanced software tools available to multiple experiments, such as Pandora, PMA, TrajCluster, Wellcell.
- LArSoft is well maintained framework that hosts the shared reconstruction software and is essential to the LArTPC community.
- **TrajCluster** and **PMA** were used to reconstruct ArgoNeuT events.