Charged Current Coherent Pion Production at MINERvA

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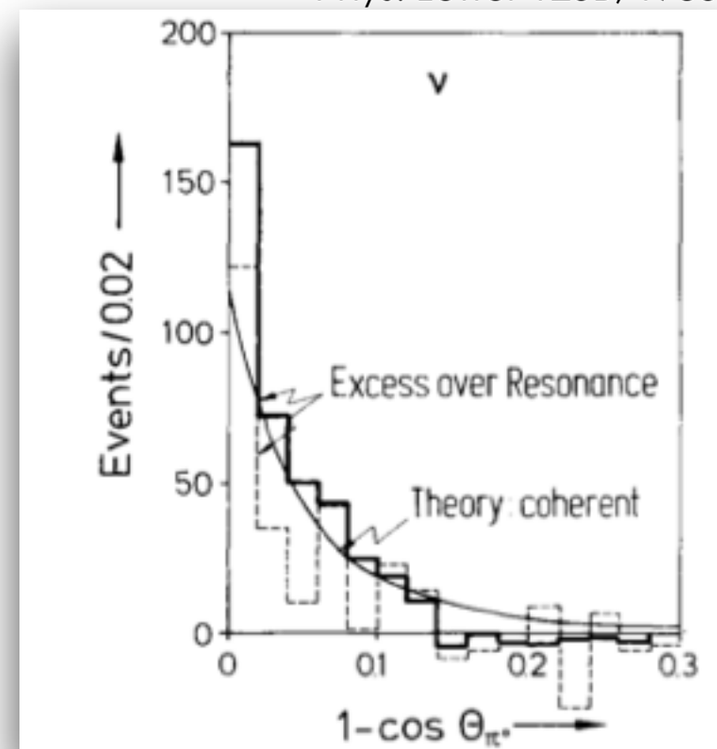
Outline

- Coherent pion production by neutrinos
- The MINERvA experiment
- Measurement of CC coherent pion production in MINERvA
- Results
- Conclusions

Coherent Pion Production by Neutrinos

Phys. Letter 125B, 1983



- In 1978 the Aachen-Padova collaboration measured the ν_μ e scattering and found an excess of showers in the forward direction
- The coherent emission of a photon $\nu+A\rightarrow\nu+A+\gamma$ was proposed to explain this excess; however this mechanism could not account the observed excess
- In 1983 the coherent production of a π^0 in a neutrino interaction was proposed by D. Rein and L. Sehgal (Nucl. Phys. B223, 1983)
- The observation of $\nu+A\rightarrow\nu+A+\pi^0$ was first reported in 1983 by Aachen-Padova collaboration (Phys. Letter 125B, 1983)

Coherent Pion Production by Neutrinos

$$\nu_l(k) + A(p) \to l^-(k') + A(p') + \pi^+(p_\pi)$$

- The matrix element for the process is

$$\mathcal{M} = \frac{G_F}{\sqrt{2}} \bar{l}\gamma^\mu(1-\gamma_5)\nu_l \langle A|J_\mu^V + J_\mu^A|A\rangle$$

- When the lepton mass is neglected and in the limit $Q^2 \to 0$ (the momentum carried by the current) the lepton emerges with its momentum parallel to the neutrino (Adler's theorem) and invoking PCAC (Partially Conserved Axial Current) we have

$$|\mathcal{M}|^2 = \frac{8\ G_F^2 E\ \ E'}{\nu^2} f_\pi^2 \sigma(\pi + A \to \pi + A)$$

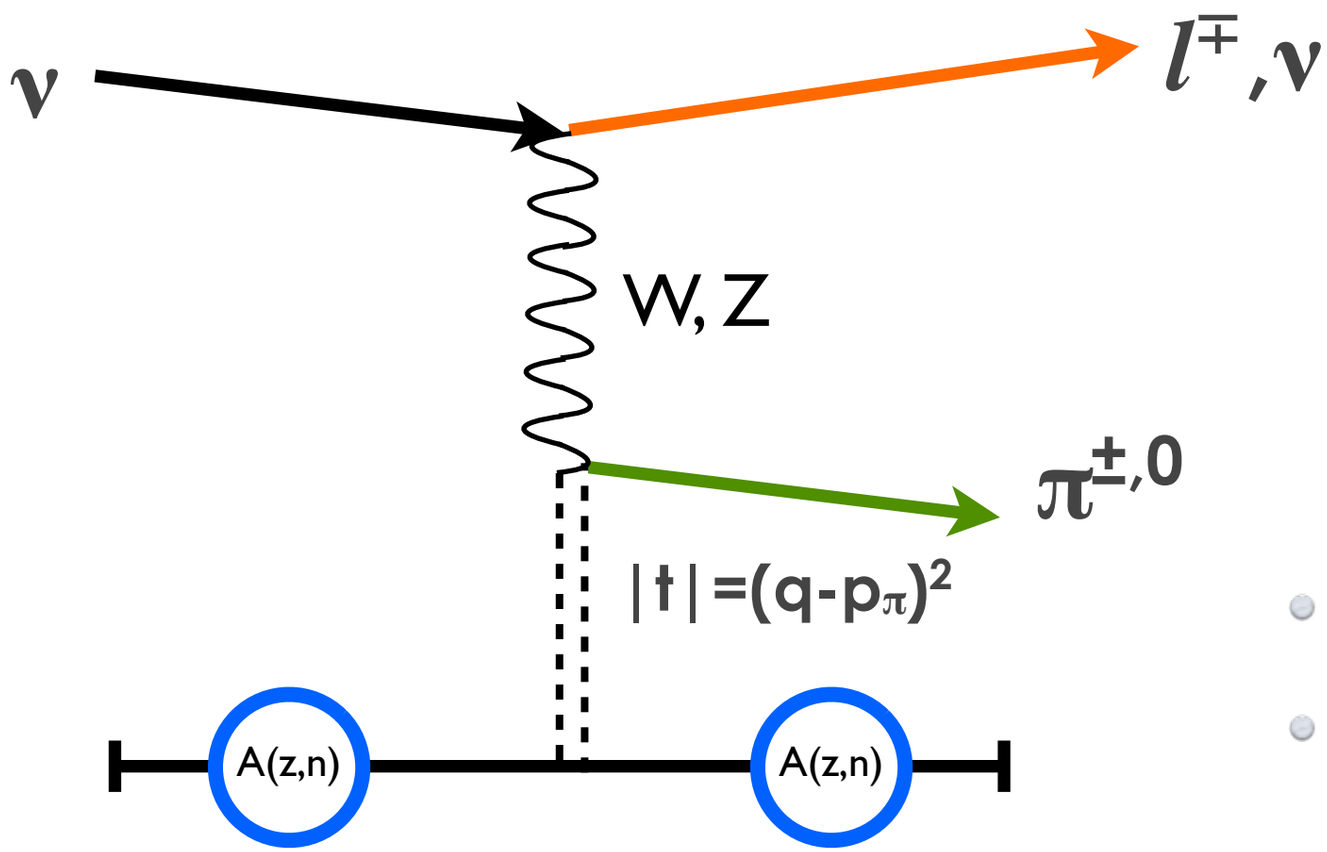
Coherent Pion Production by Neutrinos

- This has the remarkable consequence of relating the weak reaction $\nu + A \rightarrow l + \pi + A$ in the forward direction to the elastic process $\pi + A \rightarrow \pi + A$

$$|\mathcal{M}|^2 = \frac{8\ G_F^2 E\ \ E'}{\nu^2} f_\pi^2 \sigma(\pi + A \rightarrow \pi + A)$$

- These approximations are valid for NC(neutral current) and higher energy CC(charged current) with $Q^2 << m^2$; low energy CC reactions demand modifications because of the lepton mass
- We need to extrapolate this to $Q^2 \neq 0$
- When $Q^2 \neq 0$, there can be a vector component, then neutrino and antineutrinos cross sections could be different

Coherent Pion Production by Neutrinos



Experimental signature

- Two final state particles $l^{\mp} + \pi^{\pm,0}$
- Small transfer momentum to the nucleus, $|t| = (q-p_\pi)^2$
- No visible recoil

Coherent Pion Production by Neutrinos

Diffractive process

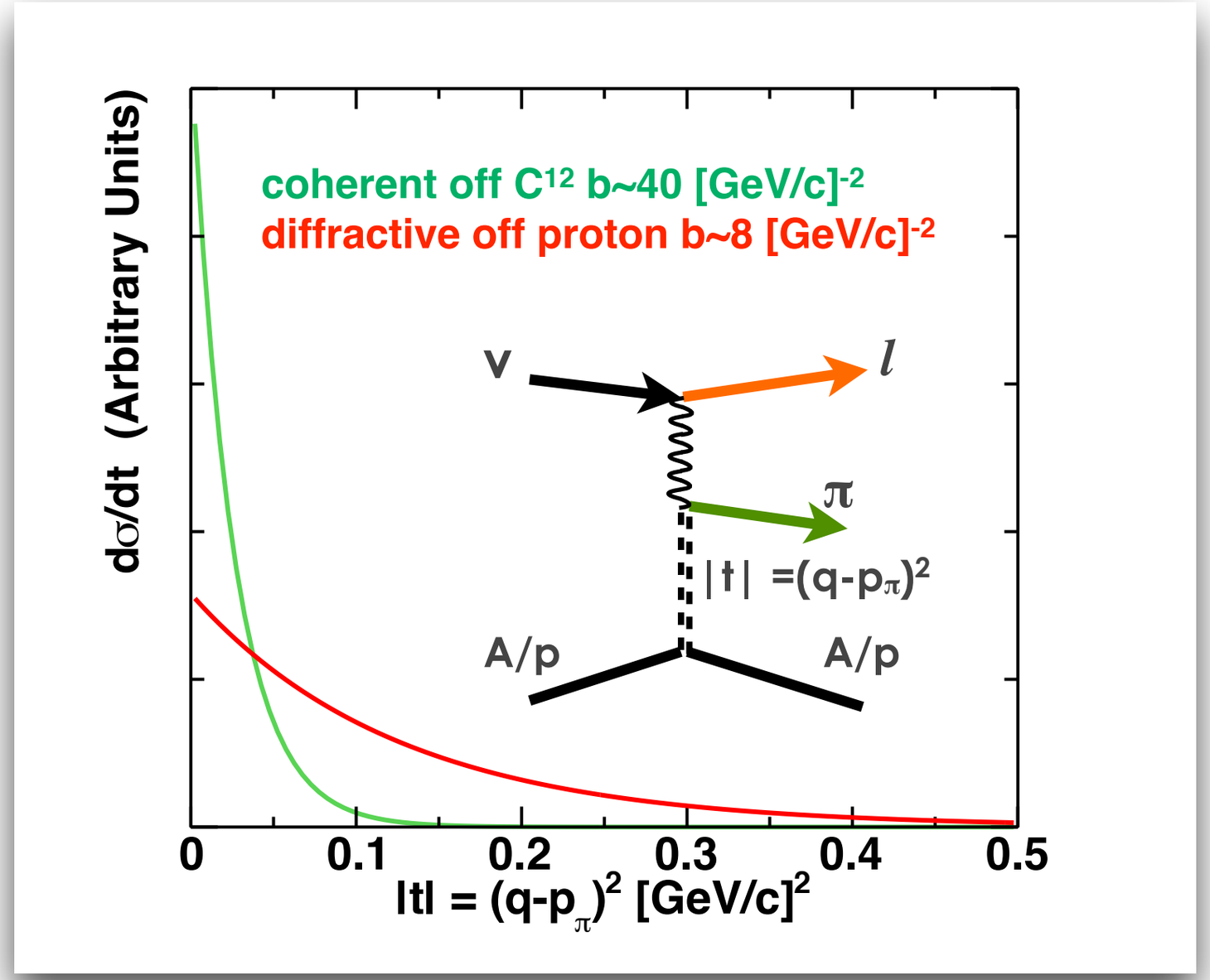
$$\frac{d\sigma}{dt} \sim A(E_\pi)e^{-b|t|}$$

where b [GeV/c]$^{-2}$ ~radius of the target

|t| threshold for coherent pion production

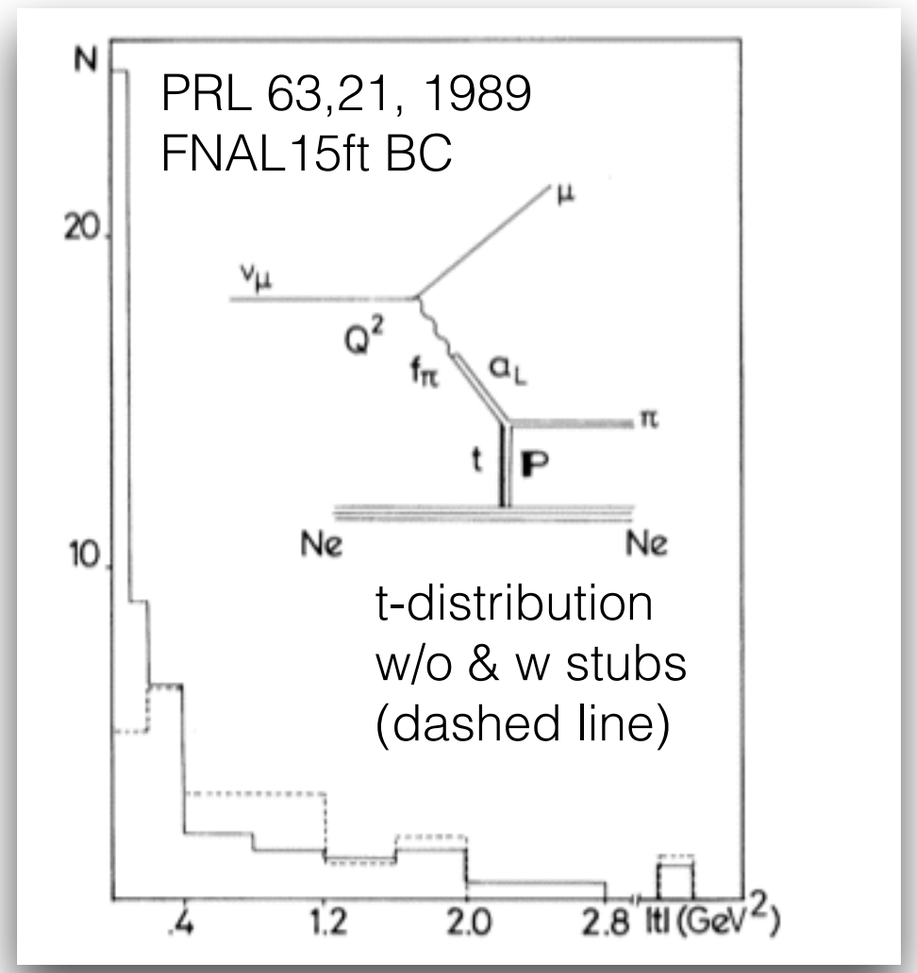
$$|t_{\min}| \geq \left(\frac{Q^2 + m_\pi^2}{2\nu}\right)^2$$

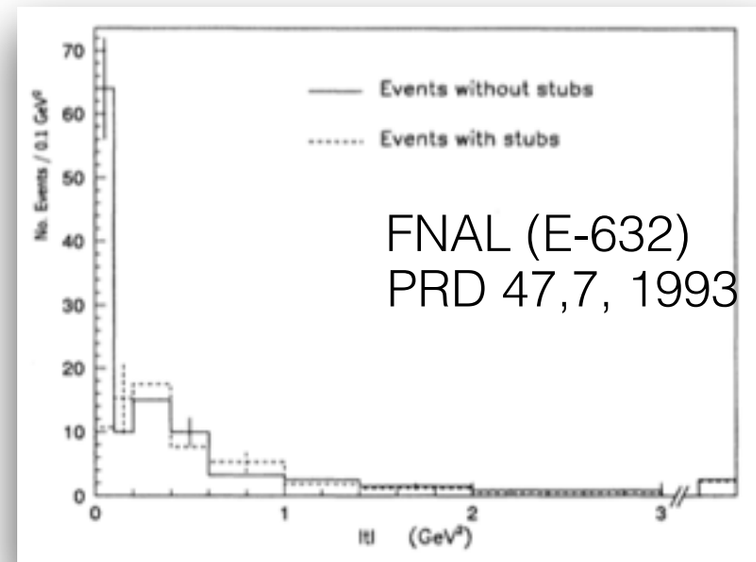
PRD 80, 03305, 2009



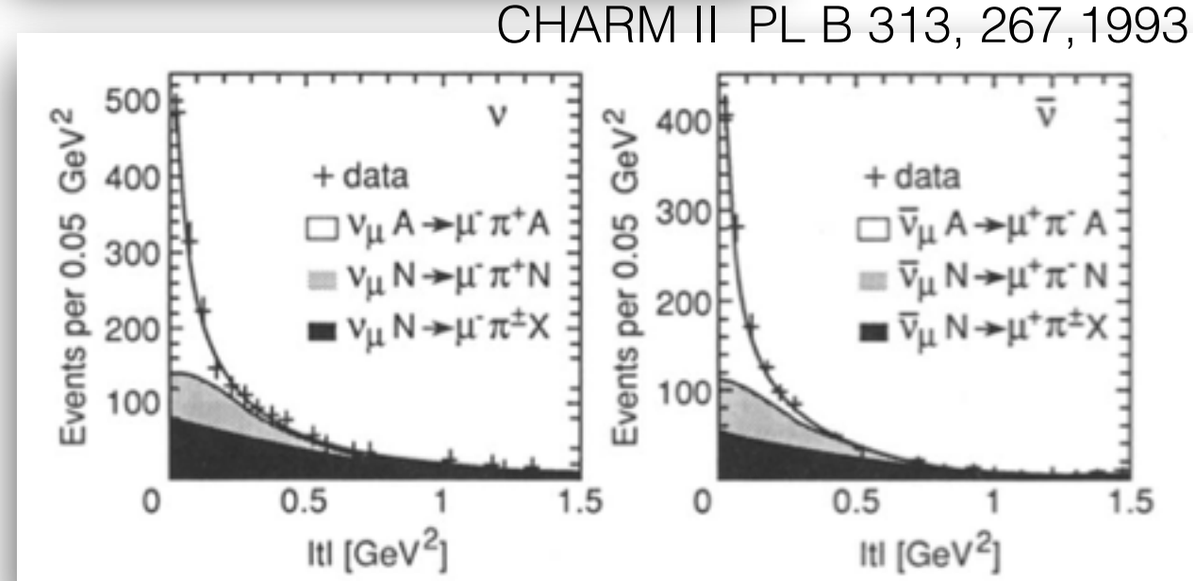
Coherent Pion Production Previous Measurements

- CC measurements: look for $\pi^{\pm}$, no stubs (no extra particles from the vertex) and low $|t| = (q-p_{\pi})^2$





CHARM II PL B 313, 267,1993



Coherent Pion Production Previous Measurements

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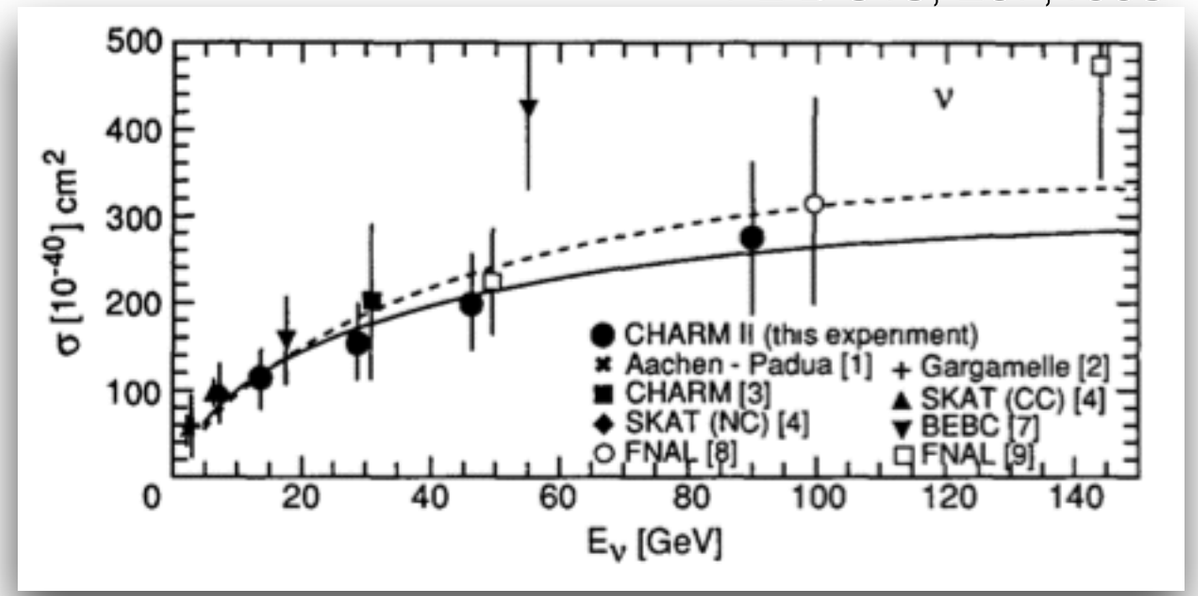
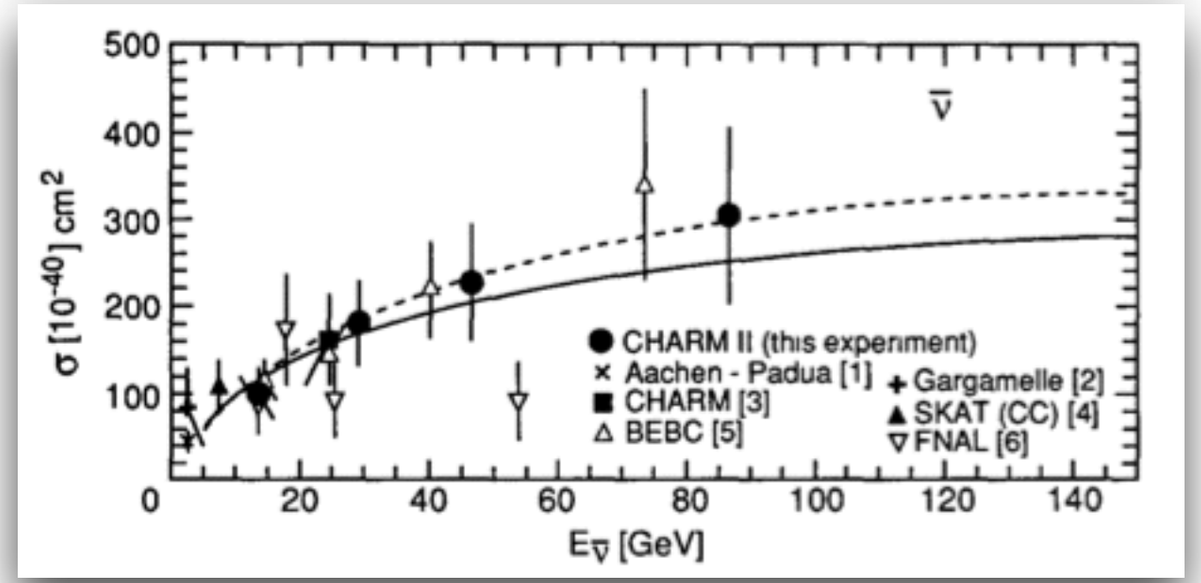
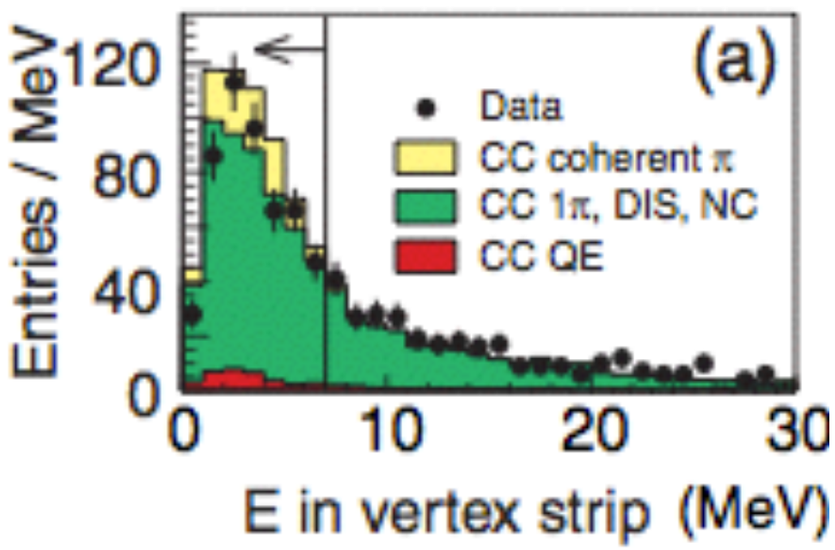




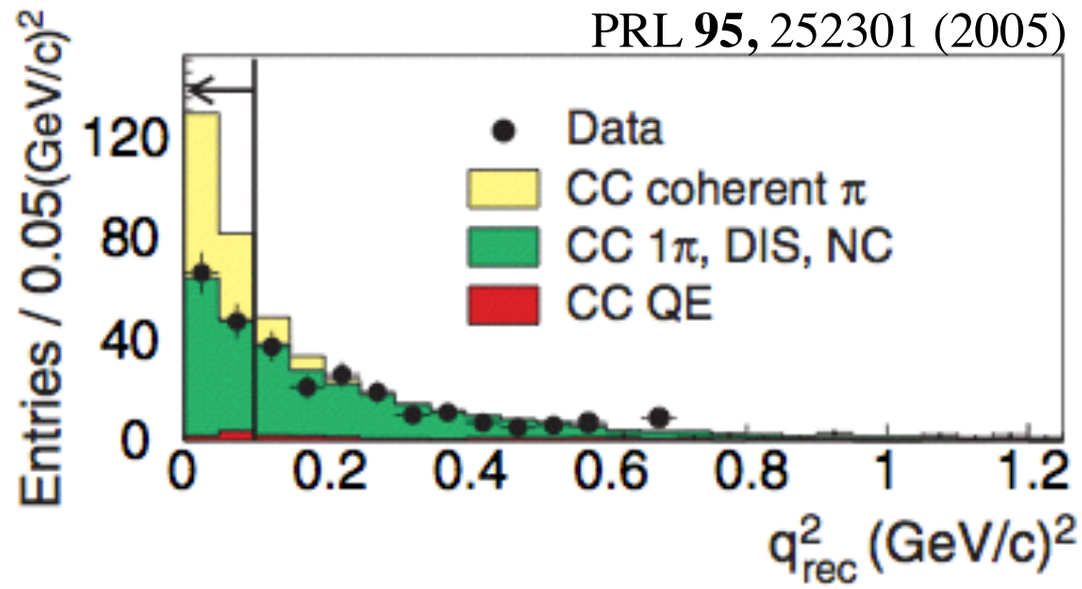
- High energy measurements
  - FNAL (Ne, A= 20)
  - BEBC (Ne, A=20)
  - CHARM II (Glass, A=21)
  - Aachen-Padova (Al, A= 27)
  - SKAT (Freon, A=30)
  - Gargamelle (Freon, A=30)
- Rein-Sehgal model reproduces high energy data

Coherent Pion Production
Previous Measurements

K2K experiment (CH) $\langle E_\nu \rangle$ = 1.3 GeV



PRL **95,** 252301 (2005)



$$q^2_{rec} = 2E^{rec}_\nu(E_\mu - p_\mu cos\theta_\mu),$$

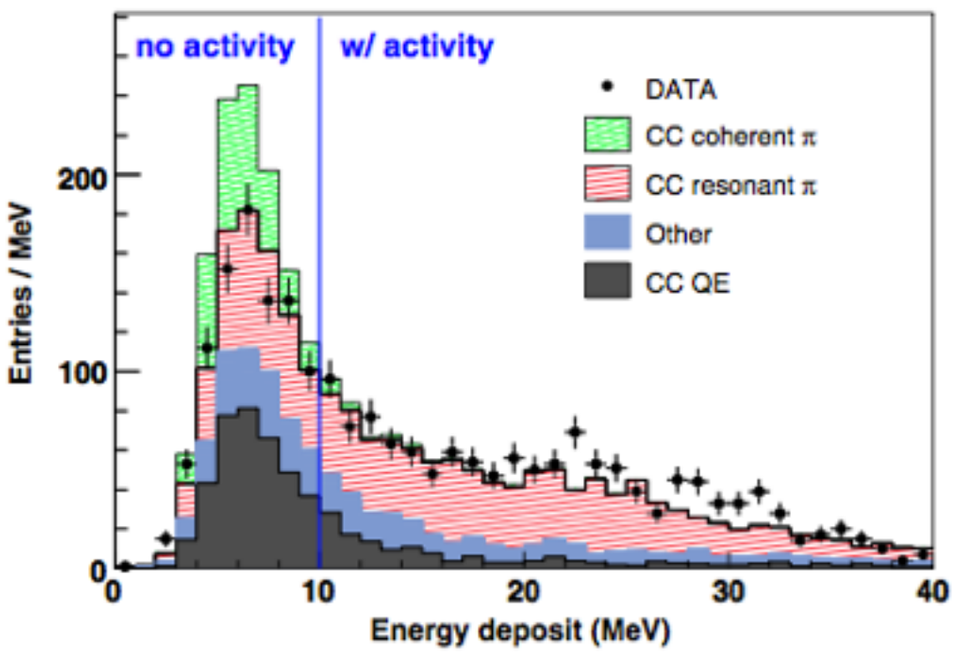
$$E^{rec}_\nu = \frac{M_p^2 - m_\mu^2 + 2E_\mu(M_n - V) - (M_n - V)^2}{-E_\mu + (M_n - V) + p_\mu cos\theta_\mu}$$

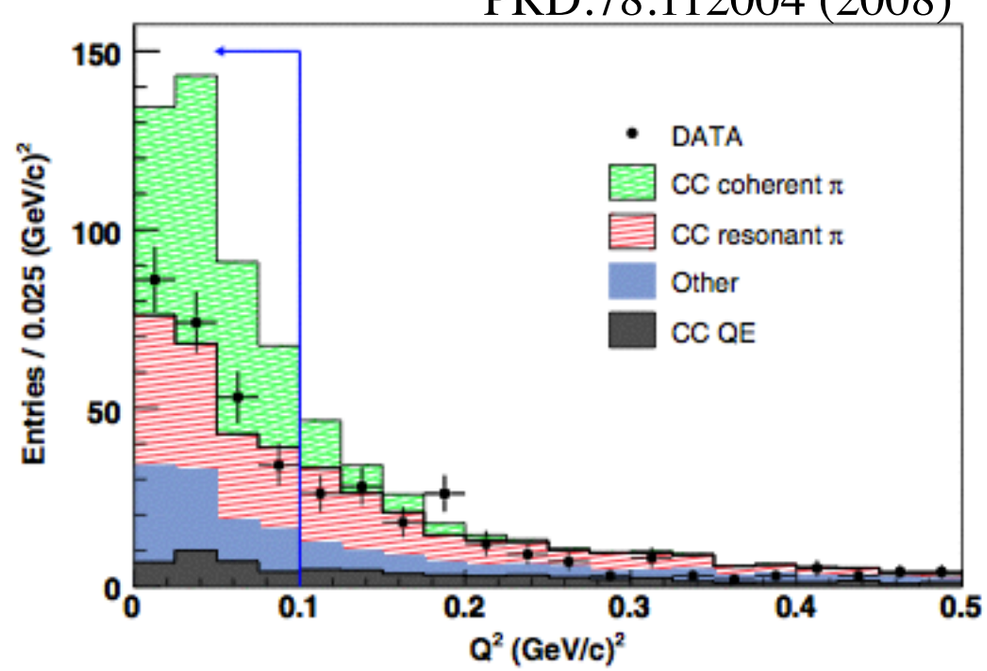
We report the result from a search for charged-current coherent pion production induced by muon neutrinos with a mean energy of 1.3 GeV. The data are collected with a fully active scintillator detector in the K2K long-baseline neutrino oscillation experiment. No evidence for coherent pion production is observed, and an upper limit of 0.60×10^{-2} is set on the cross section ratio of coherent pion production to the total charged-current interaction at 90% confidence level. This is the first experimental limit for coherent charged pion production in the energy region of a few GeV.

Coherent Pion Production
Previous Measurements

SciBooNE experiment (CH) $\langle E_\nu \rangle$ =1.1 GeV, 2.2 GeV

PRD.78.112004 (2008)



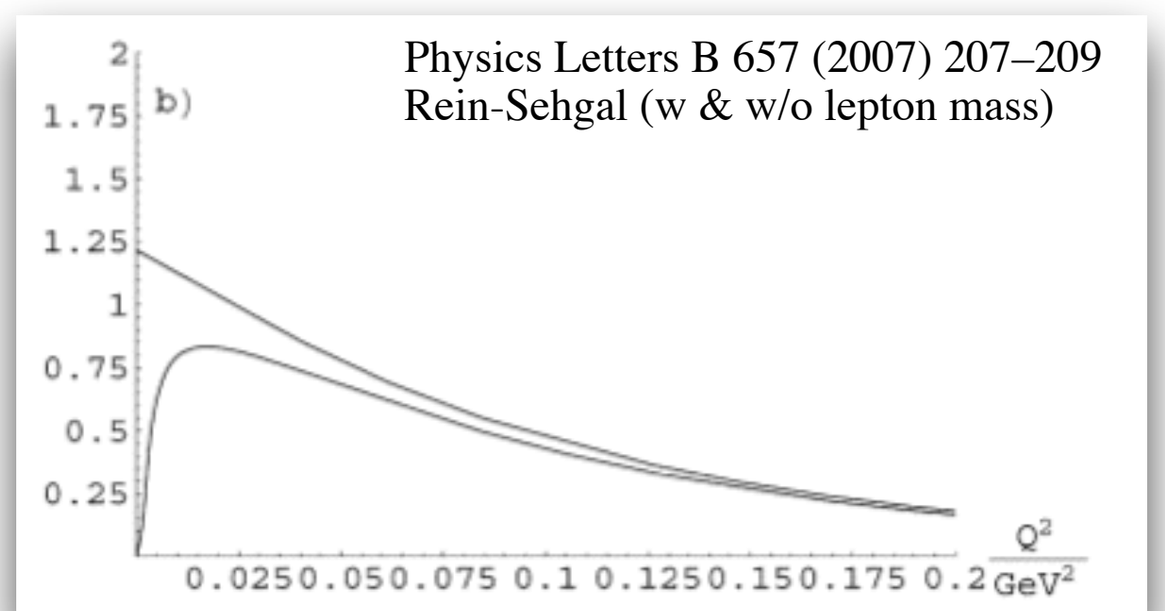


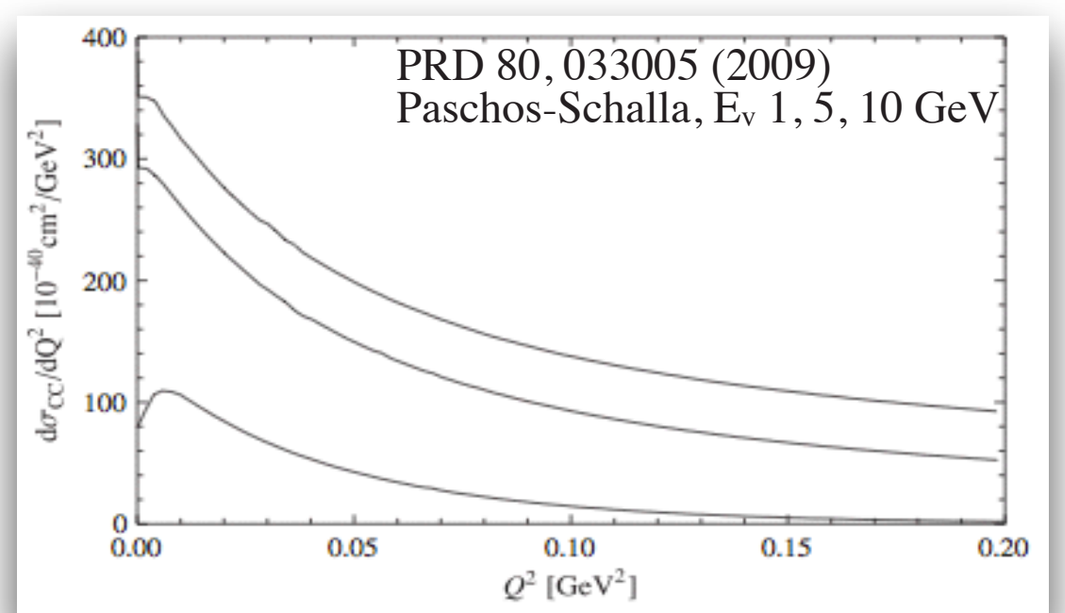
The SciBooNE Collaboration has performed a search for charged current coherent pion production from muon neutrinos scattering on carbon, $\nu_\mu {}^{12}\mathrm{C} \rightarrow \mu^- {}^{12}\mathrm{C}\pi^+$, with two distinct data samples. No evidence for coherent pion production is observed. We set 90% confidence level upper limits on the cross section ratio of charged current coherent pion production to the total charged current cross section at 0.67×10^{-2} at mean neutrino energy 1.1 GeV and 1.36×10^{-2} at mean neutrino energy 2.2 GeV.

Coherent Pion Production

Few-GeV coherent crisis?

- Does the CC process occur at few-GeV energies?
  - Is the CC process suppressed by the kinematics, particularly the lepton mass?
- Does the theory properly describe the process?
  - For $Q^2 \neq 0$ models have to add Q^2 dependence

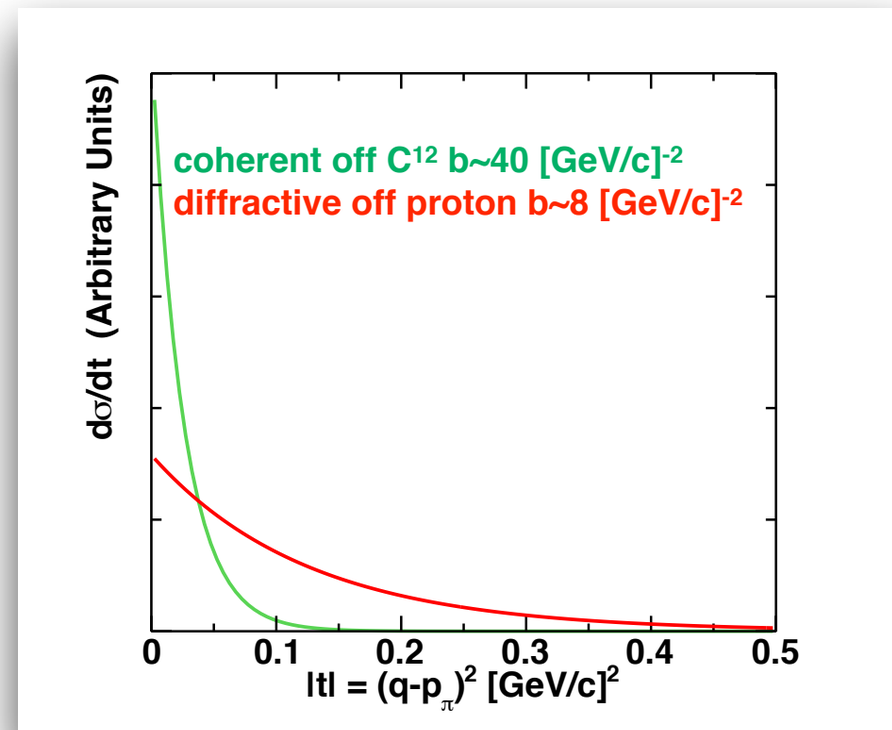




Coherent Pion Production

- Model dependent measurements? K2K and SciBooNE use Q^2 as a discriminating variable and relied on a correct model of the signal and the background at low Q^2

- **Neither of the recent experiments selected coherent candidates based on ltl**
- **By definition, ltl gives a model independent signature for coherent scattering**



Coherent Pion Production by Neutrinos

- The original Rein-Sehgal model [Nucl.Phys. B223, 29 (1983)] could not describe low energy measurements. An updated version of the original model that accounts for lepton mass terms was introduced by Rein-Sehgal [Phys. Letters B657, 207 (2007)]

- The updated Rein-Sehgal model has become the "universal" model used by all neutrino event generators (they differ on the implementation)

- GENIE (neutrino event generator) [Nucl. Instrum. Methods A 614, 87 (2010)] uses the updated version of the Rein-Sehgal model, with kinematic thresholds

Coherent Pion Production by Neutrinos

- Berger-Sehgal, an updated version of the Rein-Sehgal model where, instead of using models for pion nucleus scattering as used in Rein-Sehgal, they use the available data on pion-carbon scattering [Phys.Rev. D79, 053003 (2009)]

- Paschos-Schalla, suited for charged current coherent scattering, since it has the exact mass lepton term included [Phys.Rev. D80, 033005 (2009)]

- Microscopic models introduce the production of the pion through baryon resonances, dominantly $\Delta(1232)$, and include background terms. However these models are valid only at low energies, $E_\nu < 1.5$ GeV

Oscillation Needs

- Single pion production is a background to neutrino oscillation experiments (low energy pions)
- Understanding the pion production rate and pion energies is crucial for oscillation experiments
- T2K applies a 100% normalization uncertainty to the NEUT CC coherent pion production (since no clear signal has been observed at Ev *O*(1)GeV) for the electron appearance in a muon neutrino beam analysis

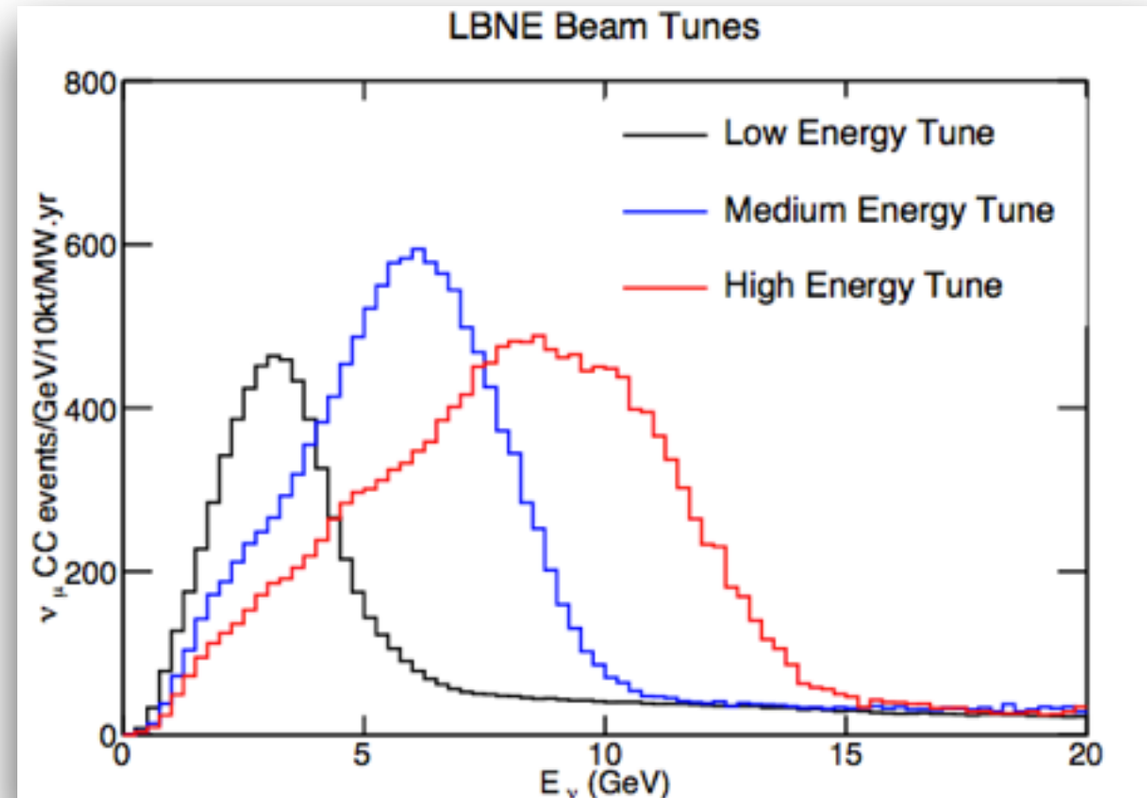
T2K, Phys. Rev. D88 (2013) 032002.

Parameter	Input Value	Uncertainty
M_A^{QE} (GeV)	1.21	0.43
x_1^{QE}	1.00	0.11
x_2^{QE}	1.00	0.30
x_3^{QE}	1.00	0.30
x_{SF}	0.0	1.0
$p_F(^{12}\mathrm{C})$ (MeV/c)	217	30
$p_F(^{16}\mathrm{O})$ (MeV/c)	225	30
M_A^{RES} (GeV)	1.16	0.11
$x_1^{CC1\pi}$	1.63	0.43
$x_2^{CC1\pi}$	1.00	0.40
$x^{NC1\pi^0}$	1.19	0.43
$x_{1\pi E_\nu}$	off	on
W_{eff}	1.0	0.51
$x_{\pi-less}$	0.2	0.2
$x^{CCcoh.}$	1.0	1.0
$x^{NCcoh.}$	1.0	0.3
$x^{NCother}$	1.0	0.3
$x_{CCother}$ (GeV)	0.0	0.4
x_{ν_e/ν_μ}	1.0	0.03

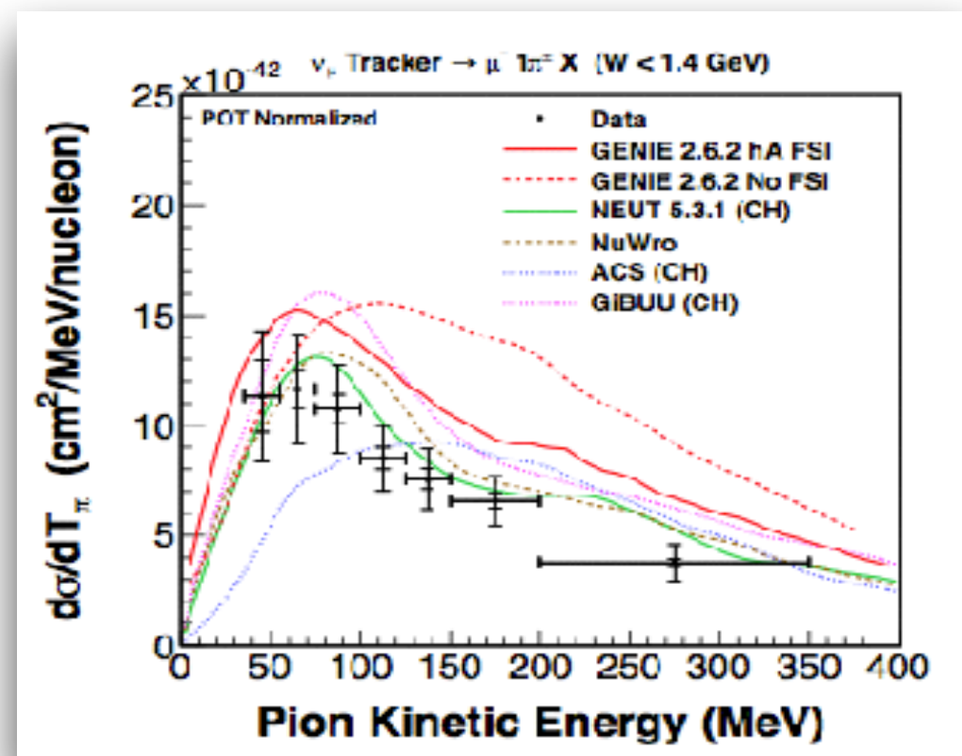
Oscillation Needs

- At neutrino energies higher than ~2 GeV pion production dominates over Quasi-Elastic scattering

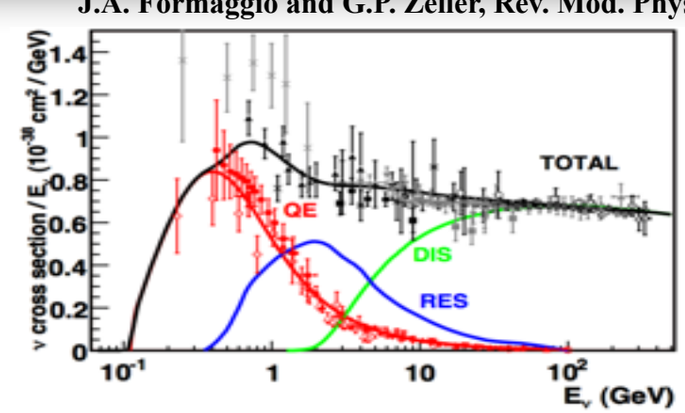
LBNE arXiv:1307.7335



MINERvA arXiv:1406.6415



J.A. Formaggio and G.P. Zeller, Rev. Mod. Phys., 2012



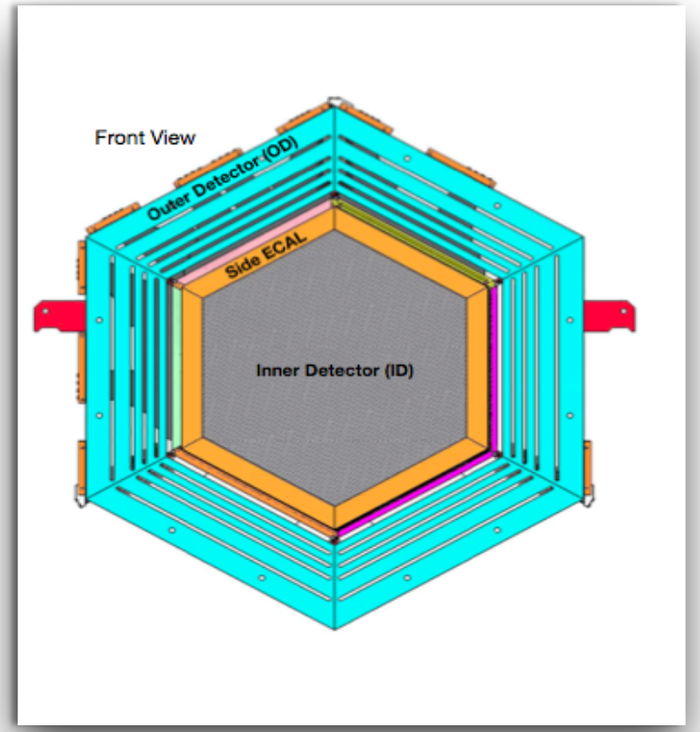
MINERvA Experiment

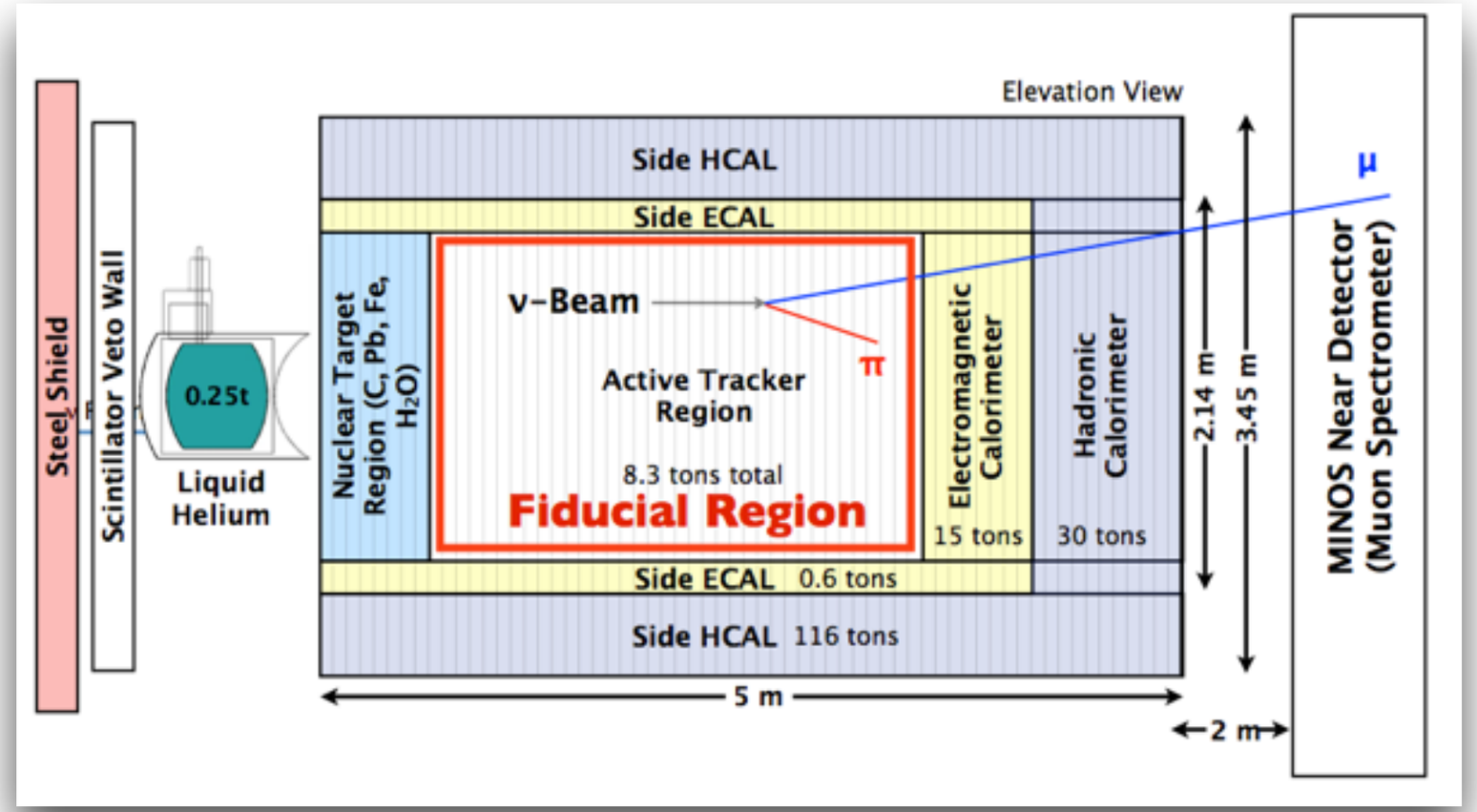
- Main INjector ExpeRiment v-A
  MINERvA is a neutrino scattering experiment in the NuMI beamline at Fermilab

- Designed to measure neutrino cross sections, final states and nuclear effects on a variety of targets in the few-GeV region

- 21 Institutions (~60 authors from particle and nuclear physics)

MINERvA Detector





- Active region made of plastic scintillator (CH)
- 120 modules ~32K channels
- X, U, V orientation (60^0)
- EM and hadronic calorimeter

Nucl. Inst. and Meth. A743 (2014) 130

NuMI Beamline

- 120 GeV/c protons from Main Injector
- Graphite target
- Tunable spectrum
- Neutrino and Anti-Neutrino

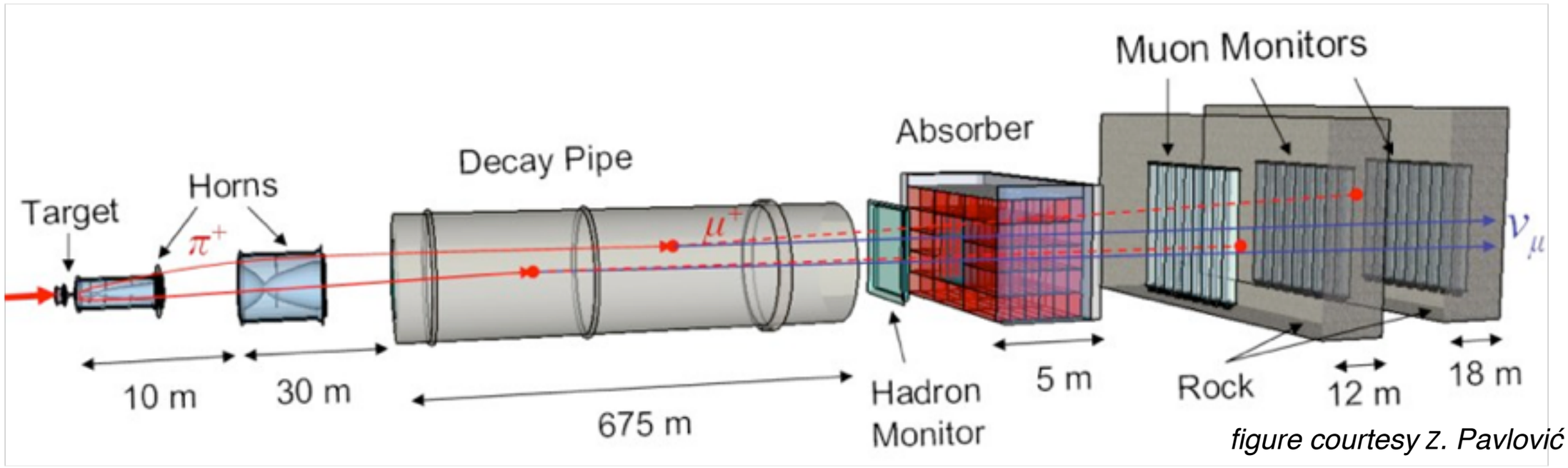
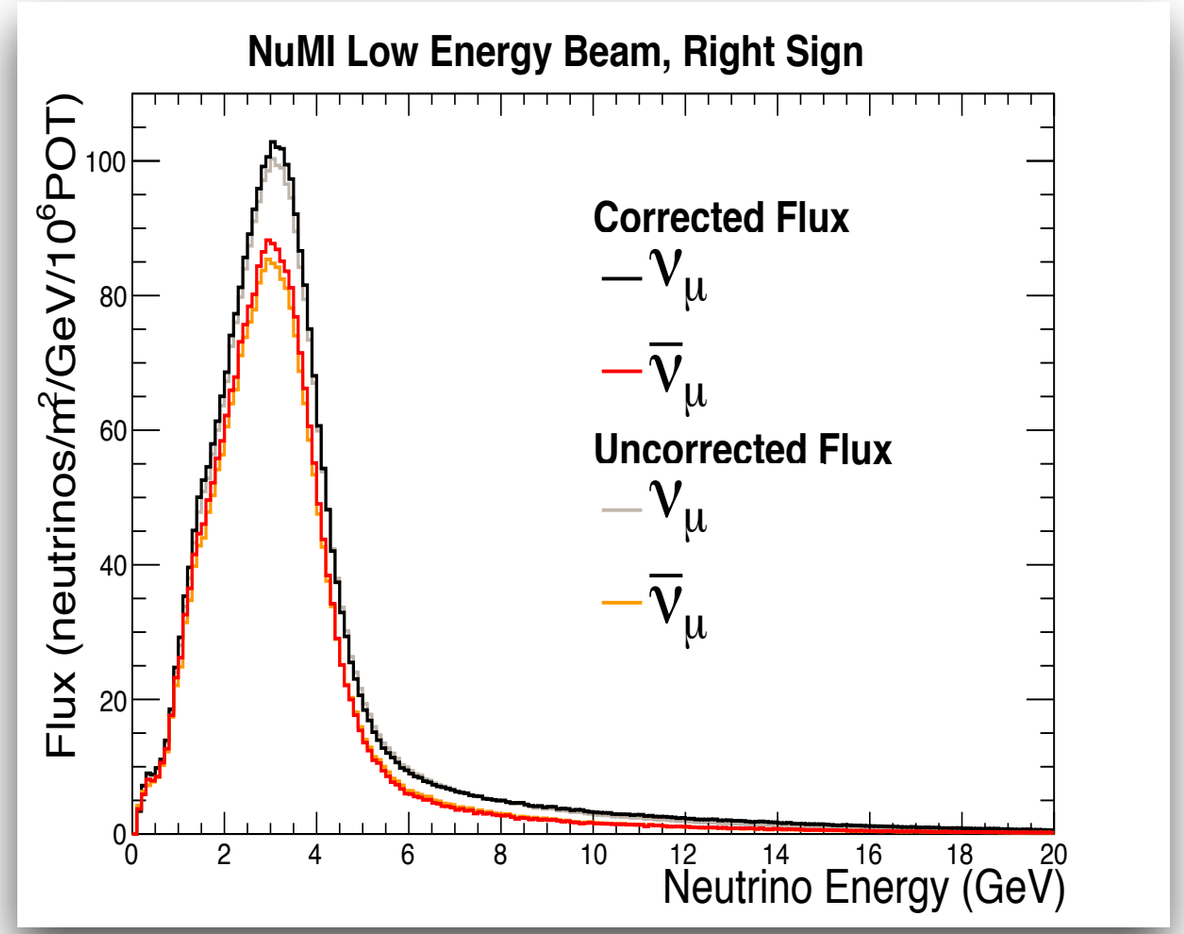


figure courtesy Z. Pavlović

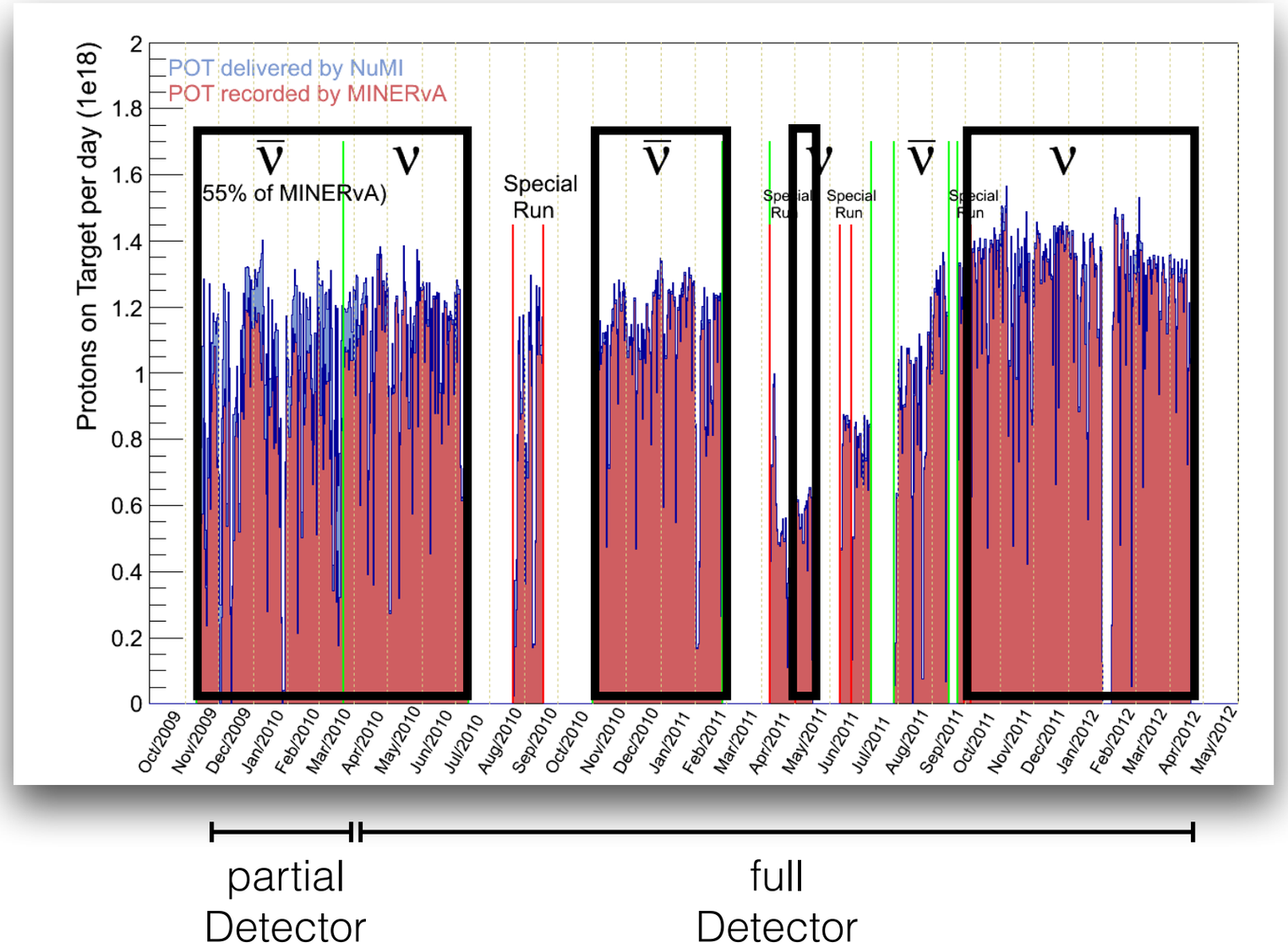
MINERvA Flux Constraint



- Hadron production tune uses NA49 and MIPP data
- Where no data exists, use differences between models to estimate uncertainties
- ~10% systematic on flux at the focusing peak

- Future plans
  - v+e → v+e scattering (expect ~6% uncertainty on flux)
  - Special runs (different target configurations)
  - MIPP recent results

MINERvA Data

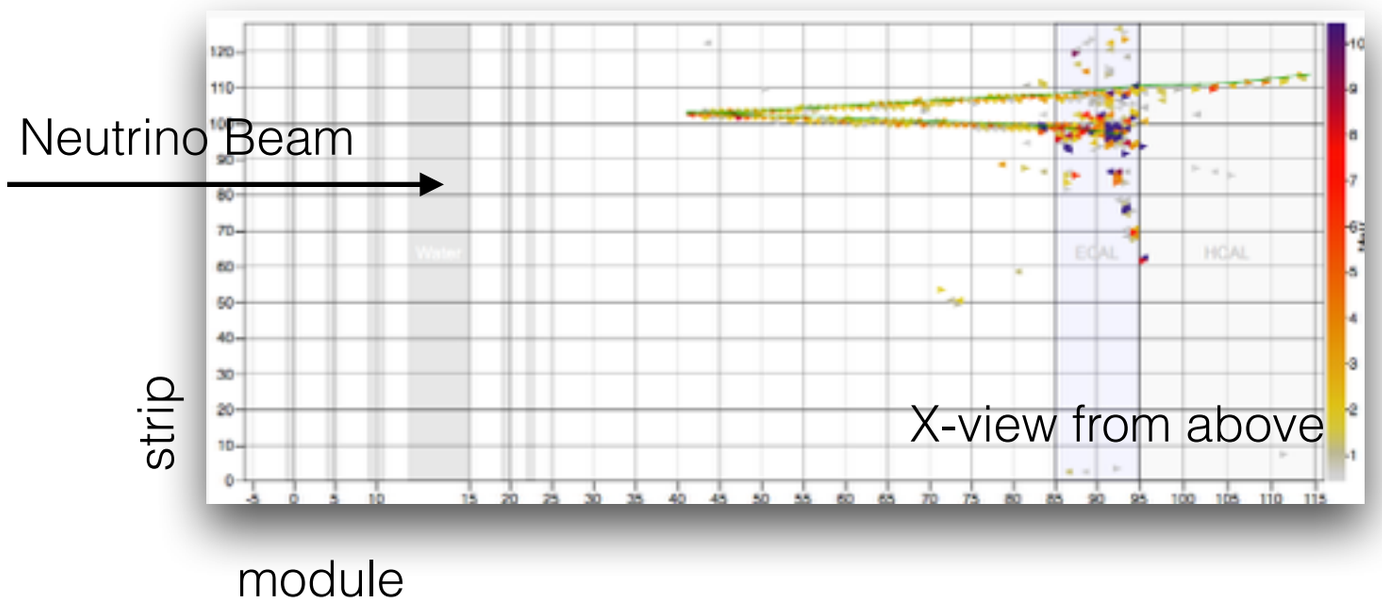


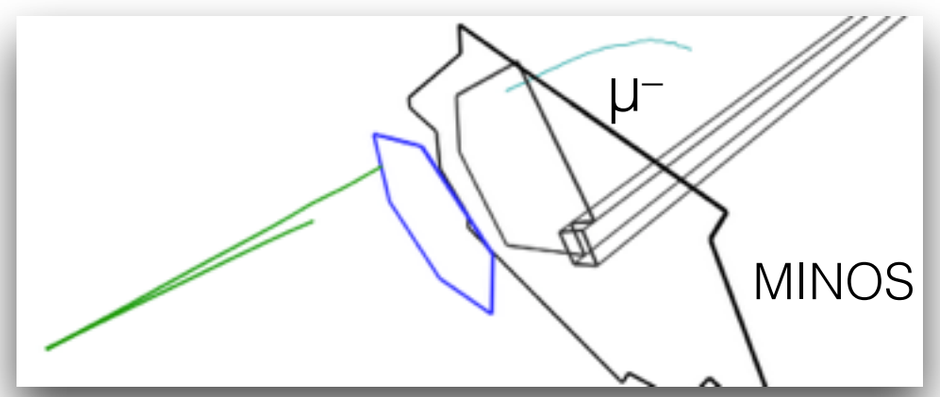
Thanks for the beam!!

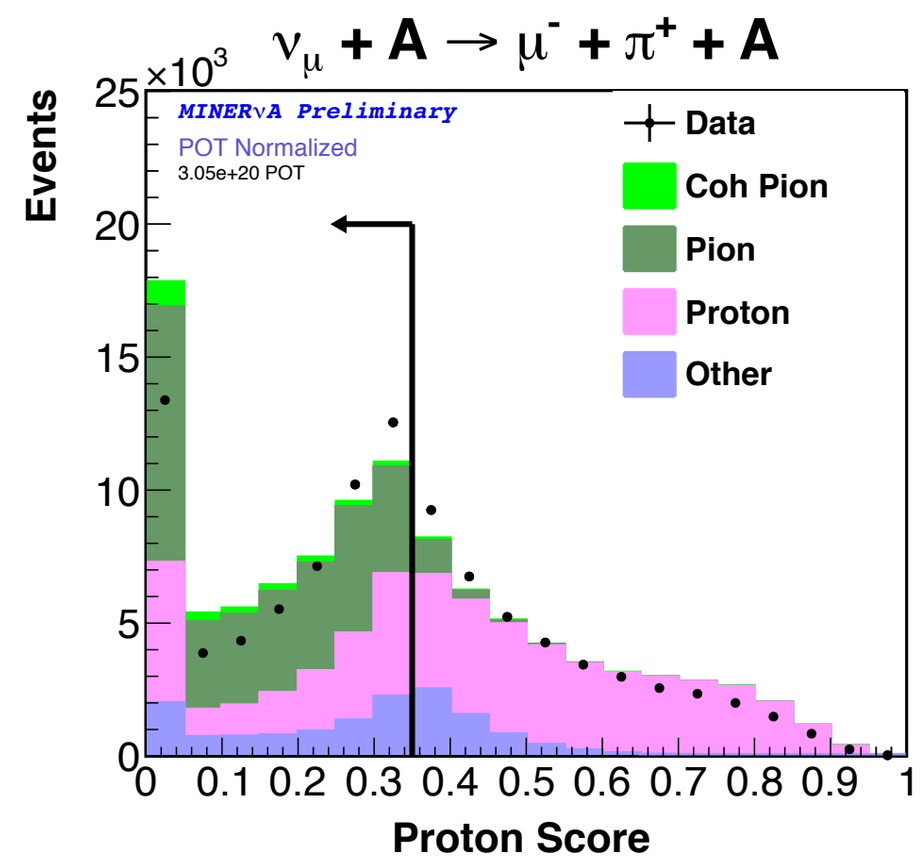
- Today's result uses all of the physics data
- Neutrino (3.05e20 POT) and antineutrinos (2.01e20 POT)

Event Selection for CC Coherent Pion Production at MINERvA

- CC candidate μ∓ (MINOS spectrometer)
- Two final state particles μ∓ + π±



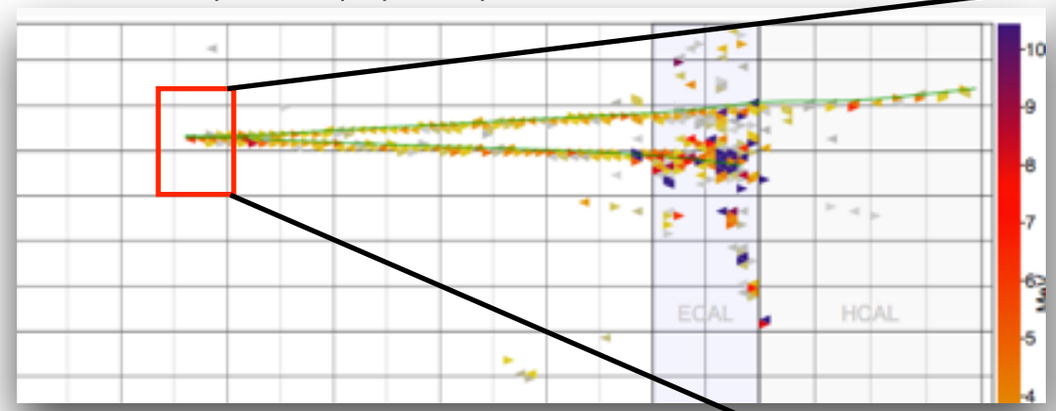


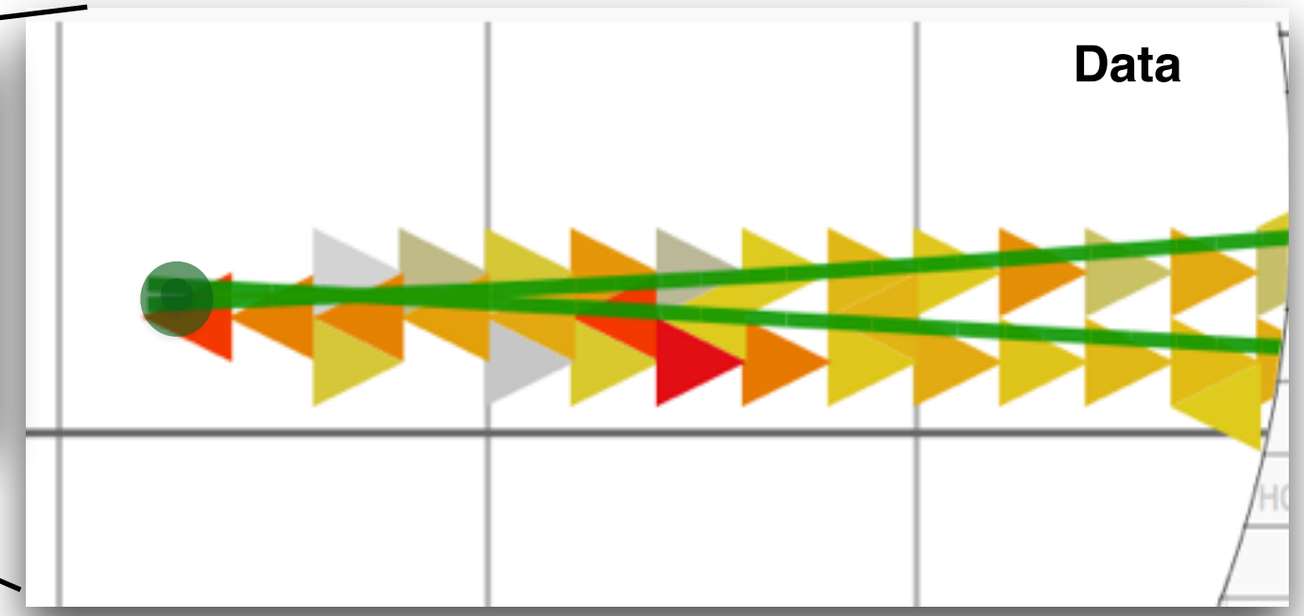


- Requires that the hadron candidate resembles a pion
- Requires that the dE/dx is consistent with stopping proton (Bragg peak at end)

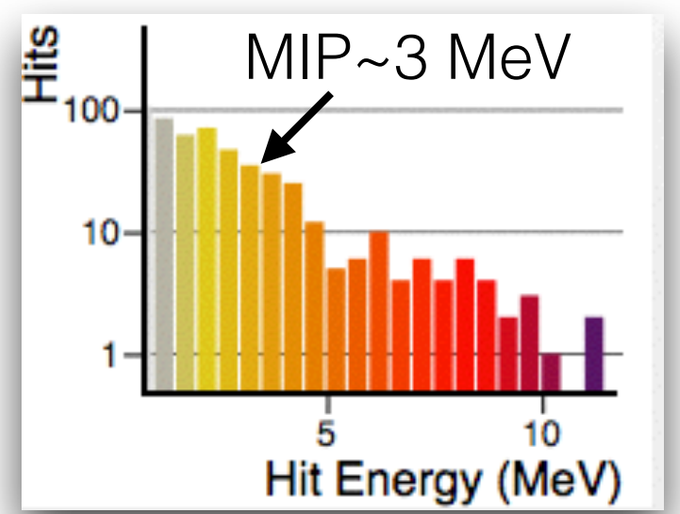
Event Selection for CC Coherent Pion Production at MINERvA

Data run/2019/5/339/1



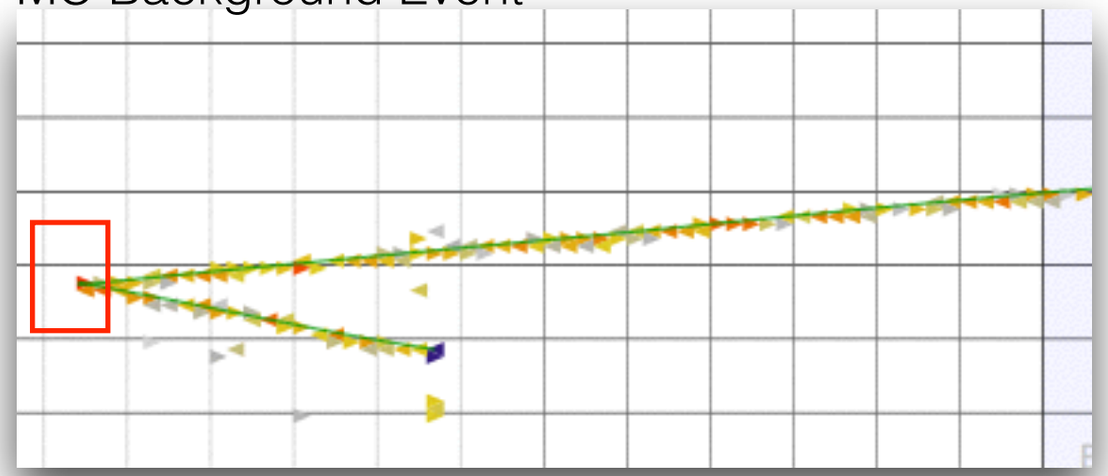


- Two final state particles $\mu^{\mp} + \pi^{\pm}$
- No extra visible recoil
- We require the total energy within a region around the vertex be consistent with a $\mu^{\mp} + \pi^{\pm}$



Event Selection for CC Coherent Pion Production at MINERvA

MC Background Event



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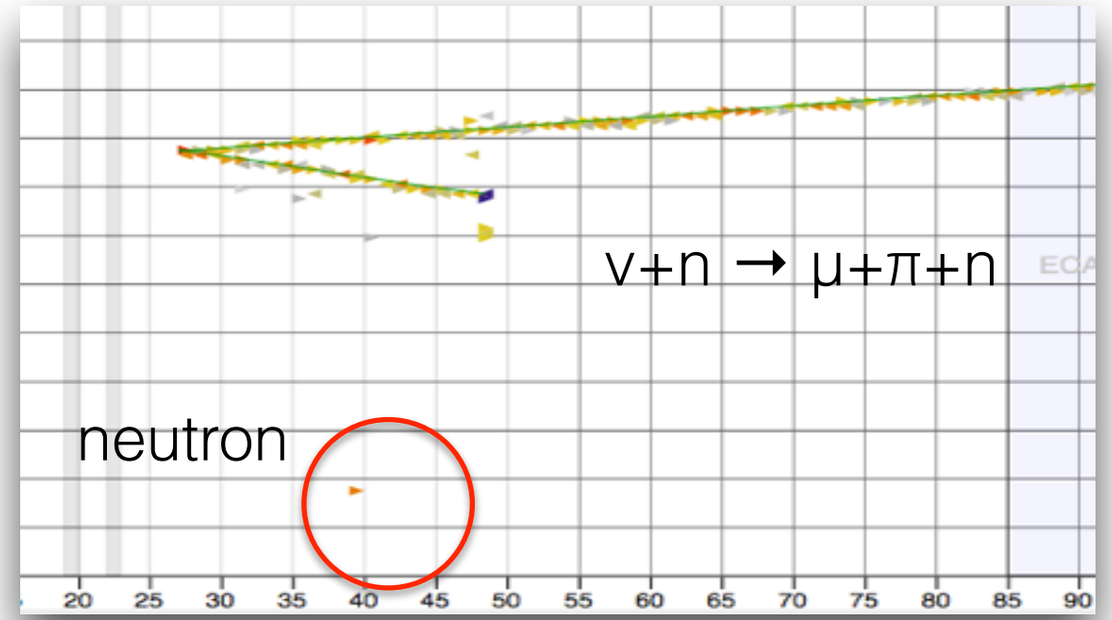

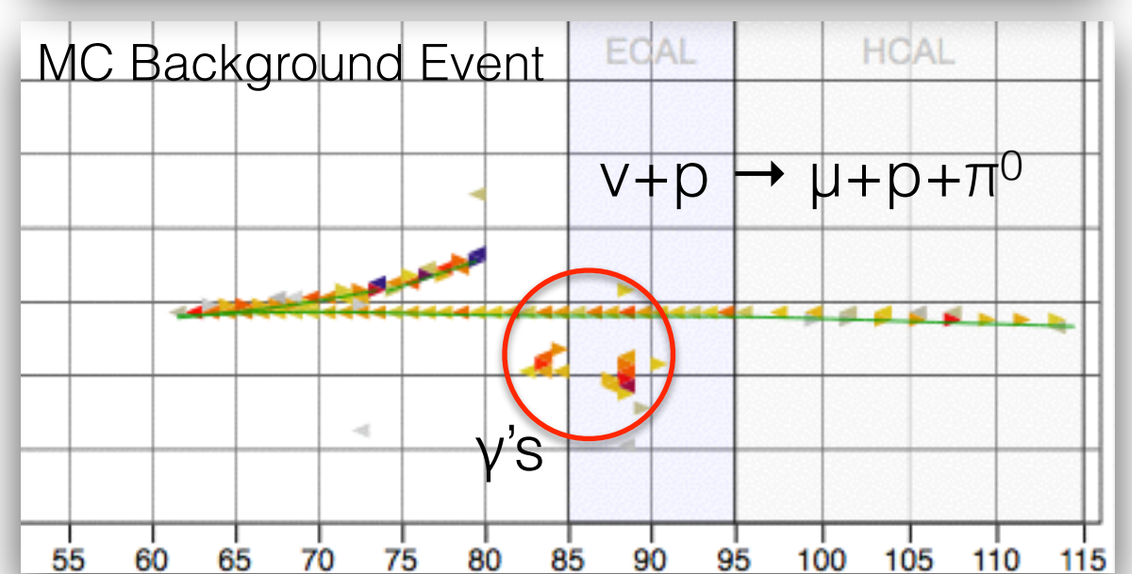

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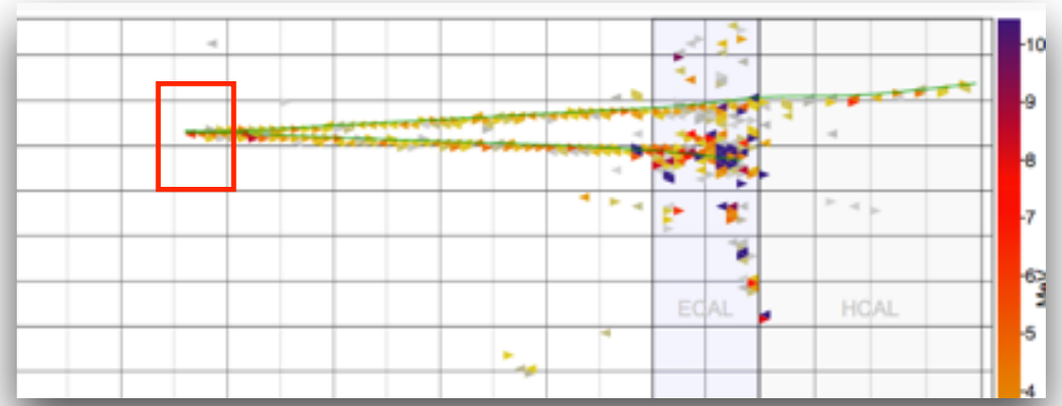
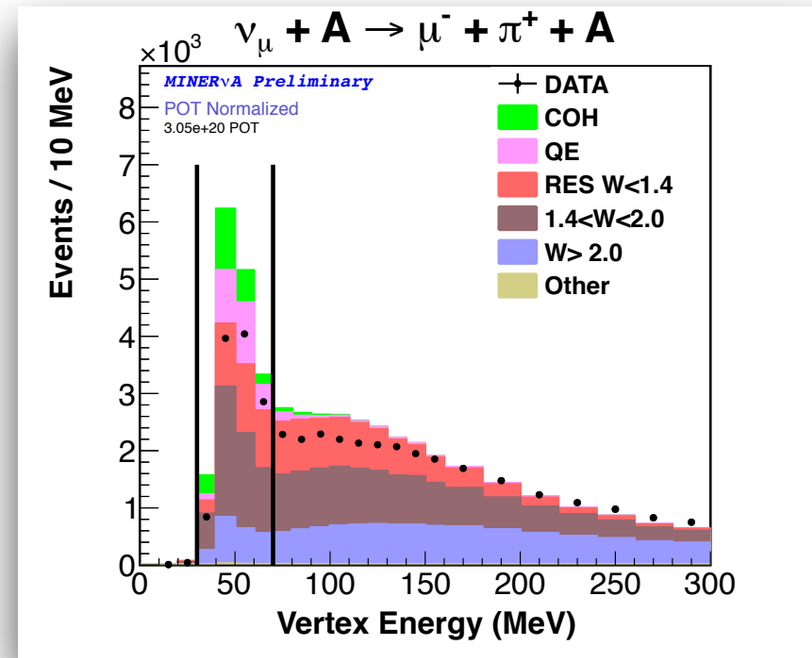
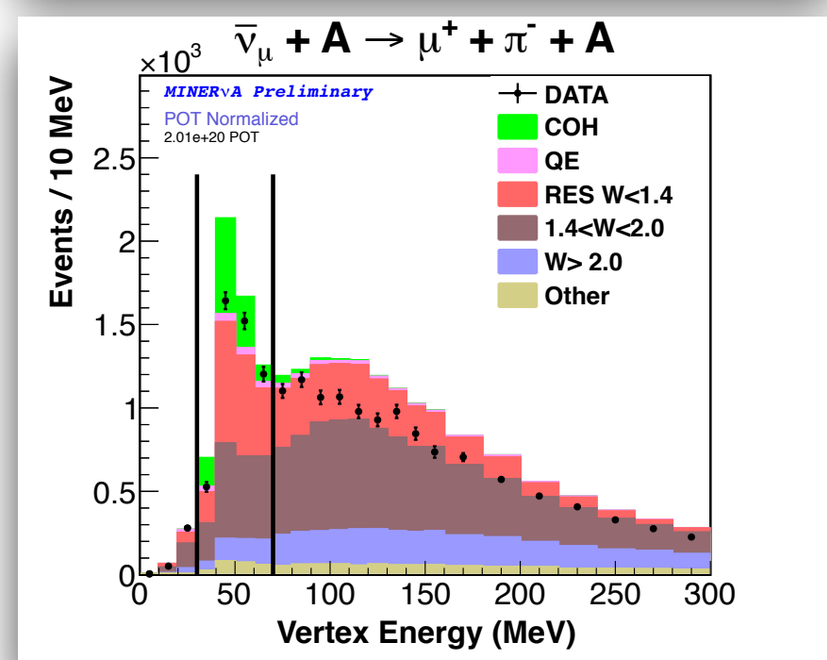






- Two final state particles $\mu^\mp + \pi^\pm$
- No extra visible recoil
- We require the total energy within a region around the vertex be consistent with a $\mu^\mp + \pi^\pm$

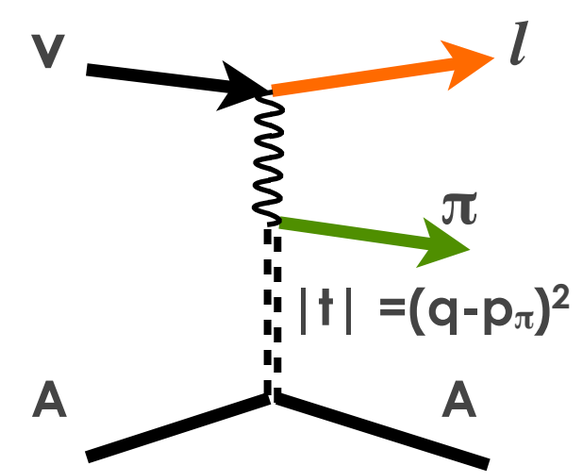
Kinematics

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

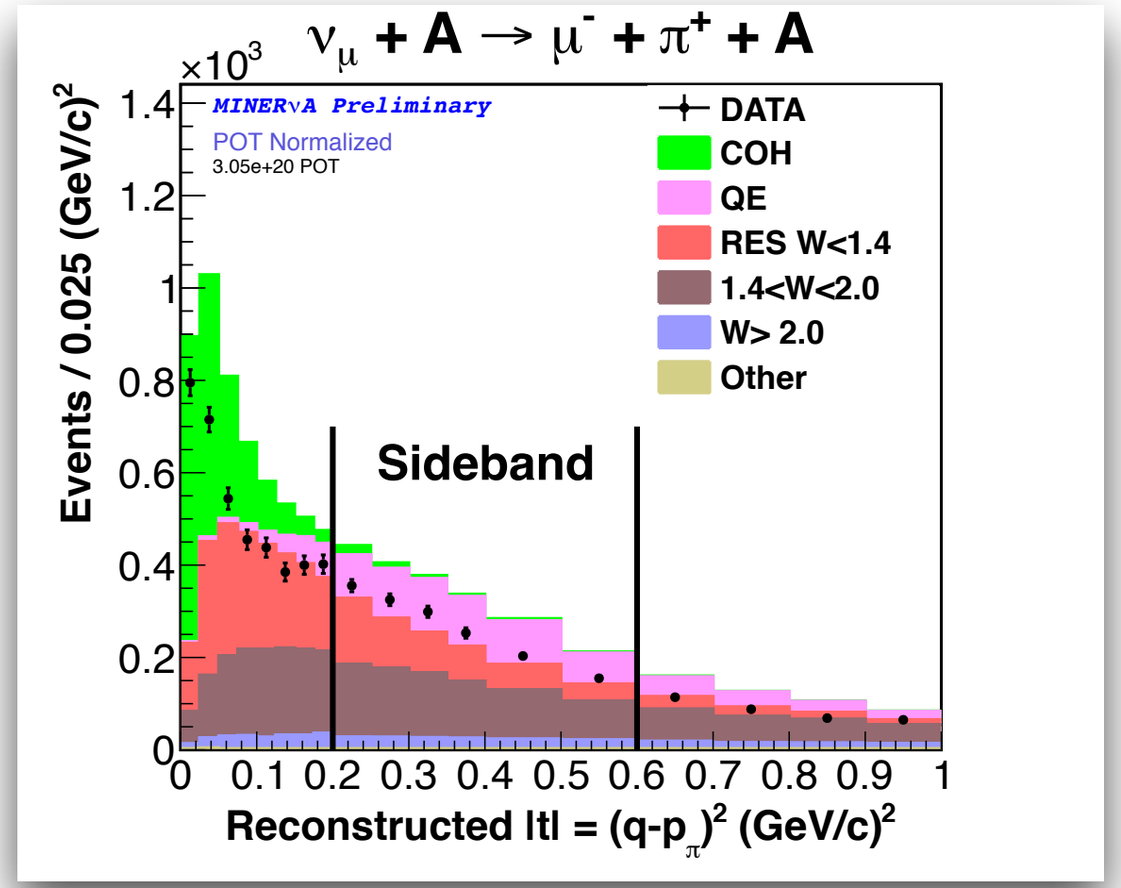
$$Q^2 = 2E_\nu(E_\mu - P_\mu cos\theta_\mu) - m_\mu^2$$

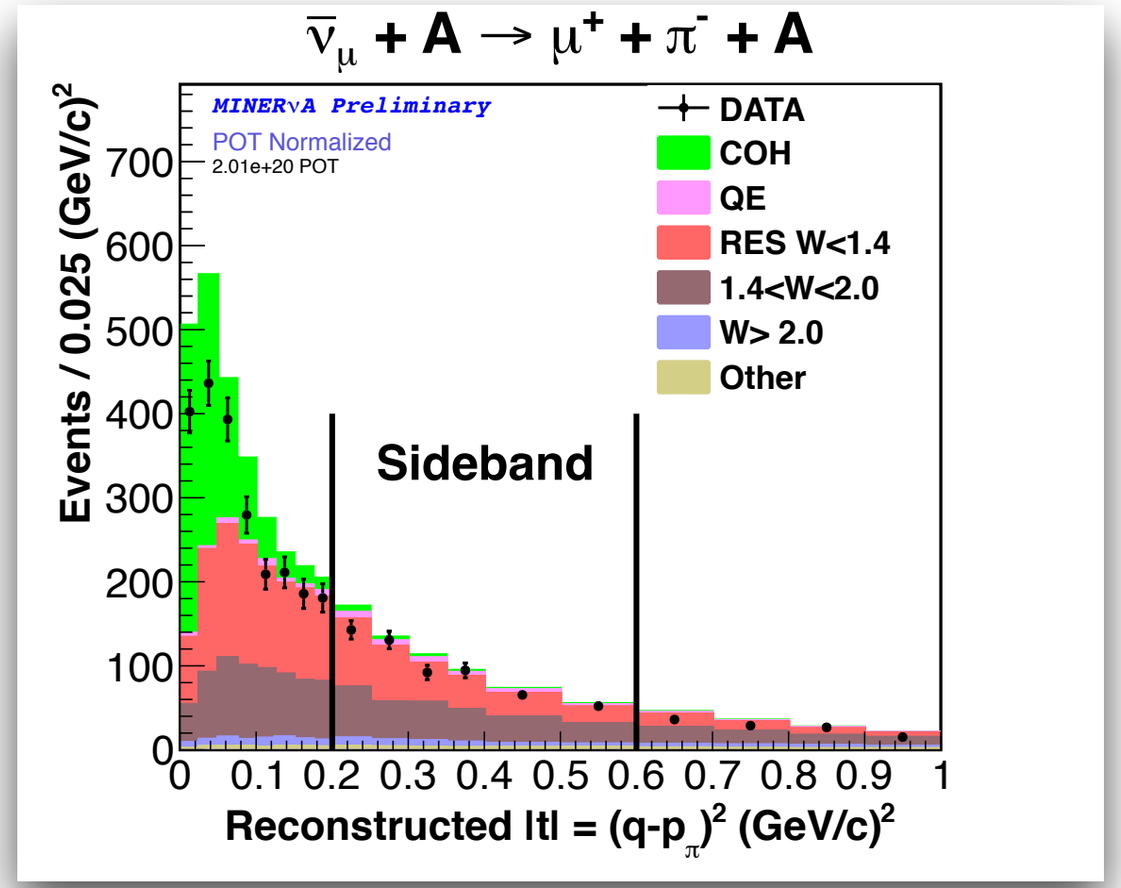
$$|t| = -Q^2 - 2(E_\pi^2 + E_\nu p_\pi cos\theta_\pi - p_\mu p_\pi cos\theta_{\mu\pi}) + m_\pi^2$$

- p_μ is measured from a reconstructed muon in the MINOS ND
- E_π is reconstructed calorimetrically
- Asume neutrino direction is parallel to the beam axis



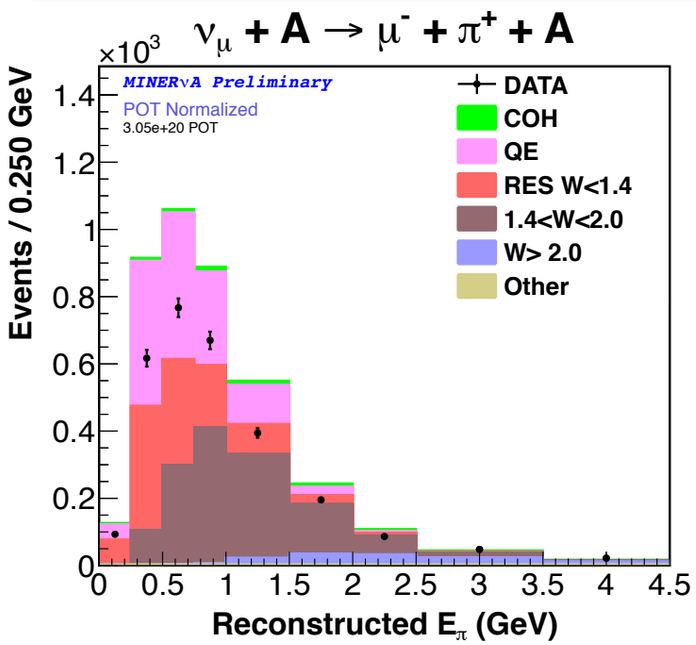
Event Selection for CC Coherent Pion Production at MINERvA

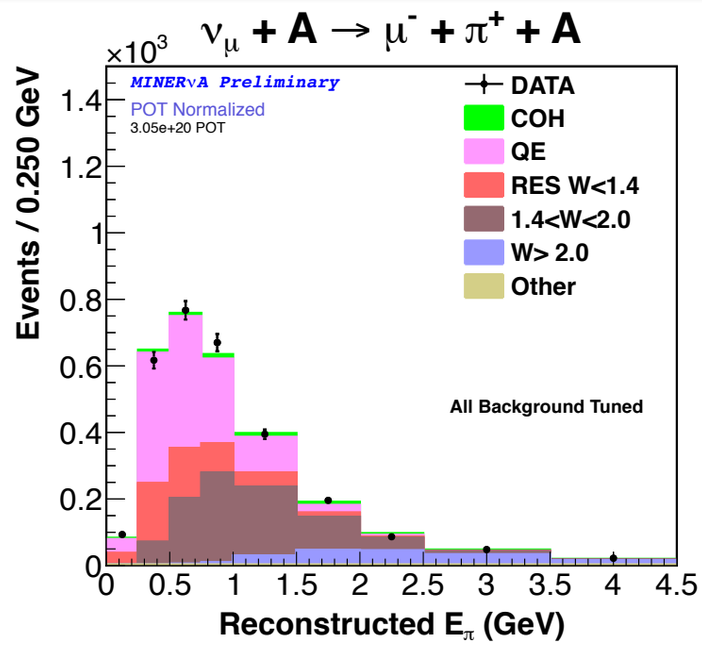


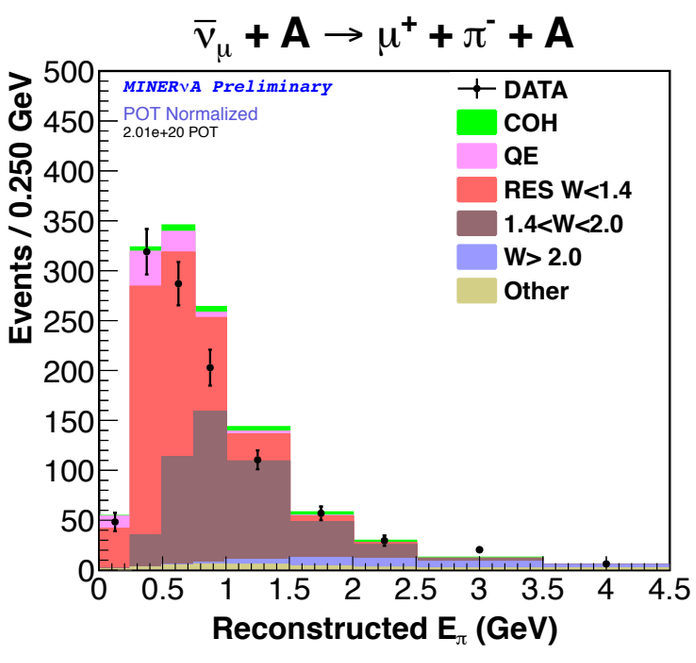


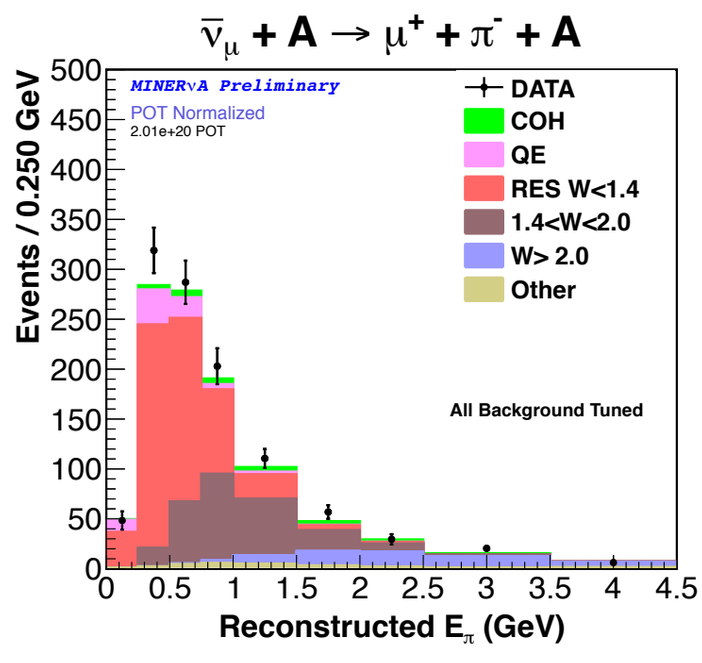
- Low $|t| = (q-p_\pi)^2$ is a strong signature of coherent events
- Out of the box GENIE overestimates the non-coherent pion production
- We use moderate |t| as a sideband for background tuning

Background Tuning







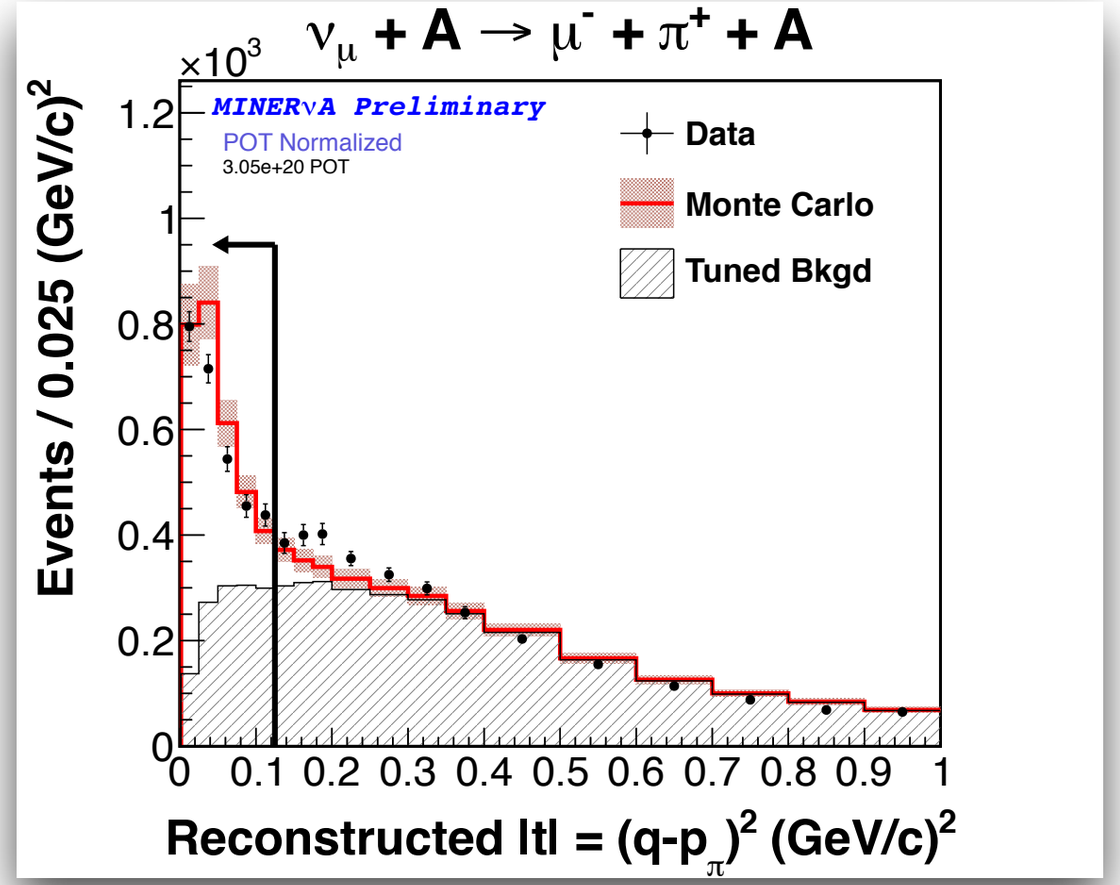


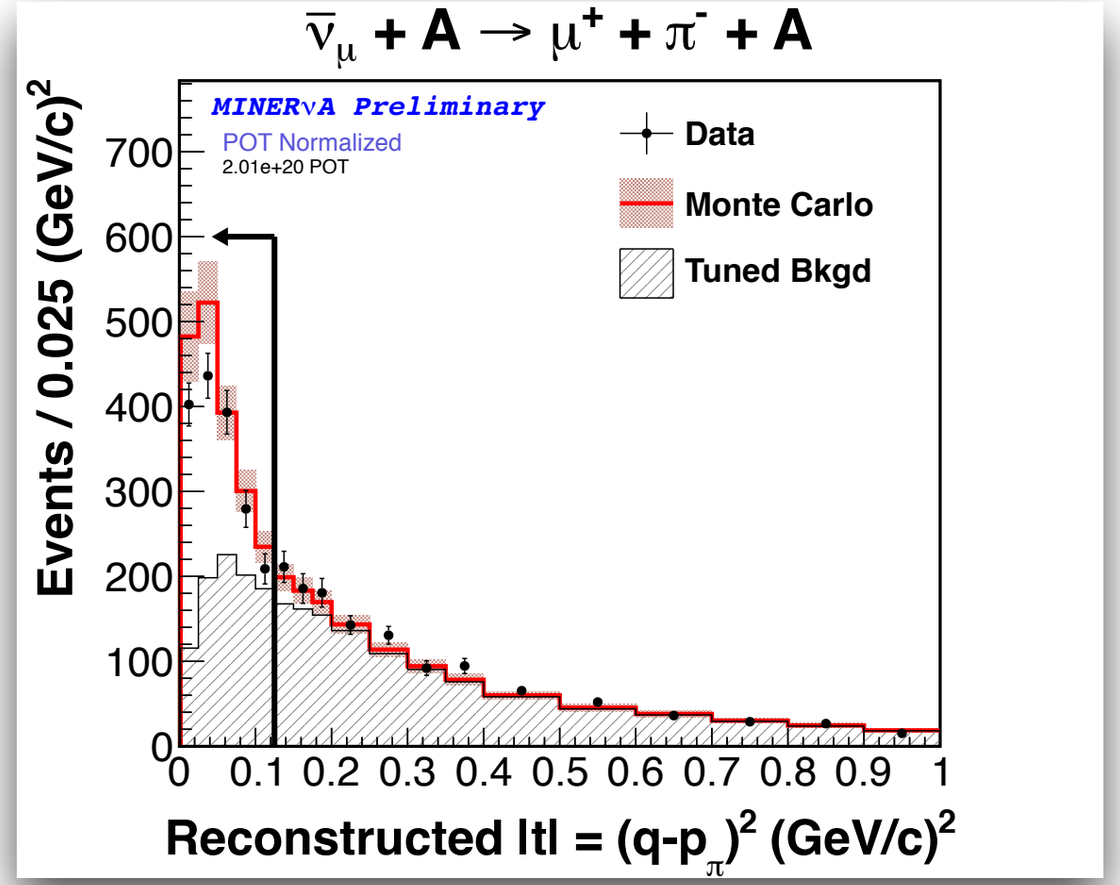
- Sideband

  $0.2 < |t| < 0.6\ (\mathrm{GeV}/c)^2$
- Background tuning performed after vertex energy cut to minimize the sensitivity to mis-modeling vertex activity
- Tune background as on regions of W

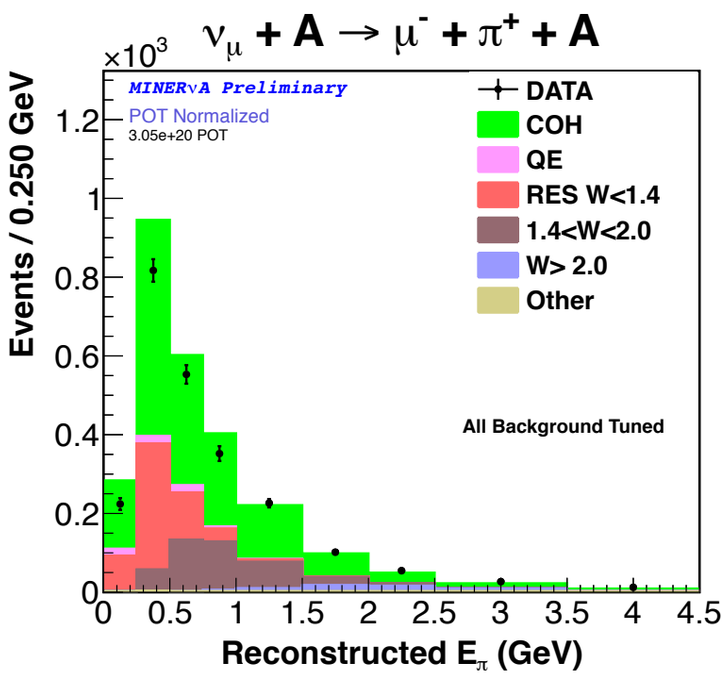
Search for CC Coherent Pion Production at MINERvA

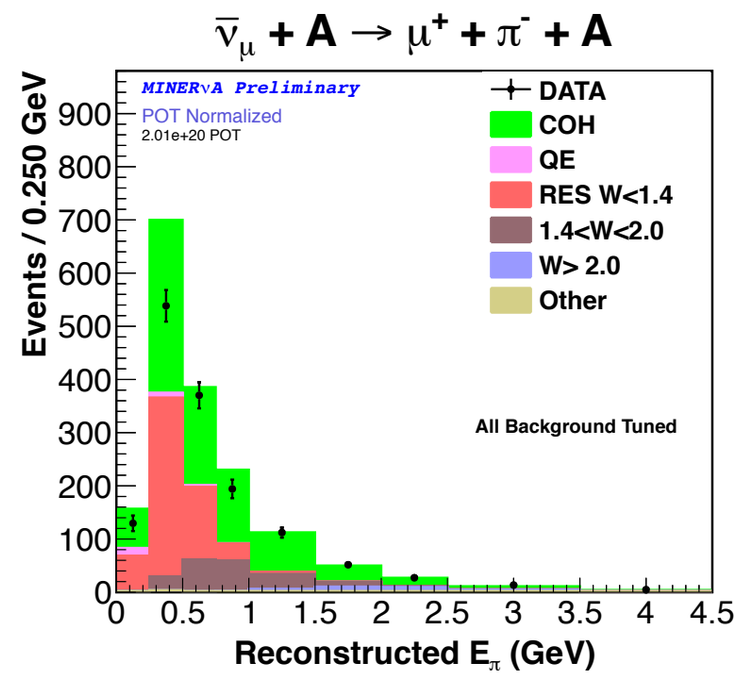
- Low $|t| = (q-p_\pi)^2$ is model independent signature of coherent pion production
- Select event with $|t| < 0.125\ (\mathrm{GeV}/c)^2$

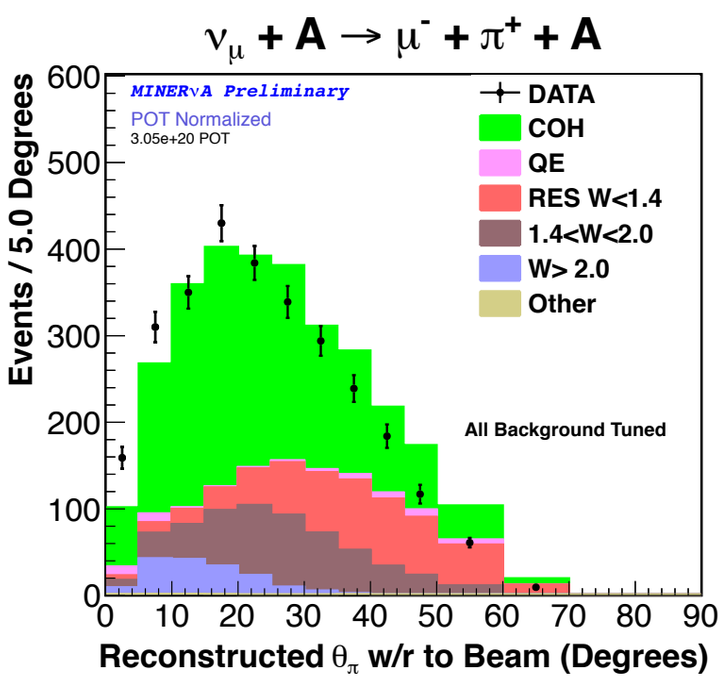


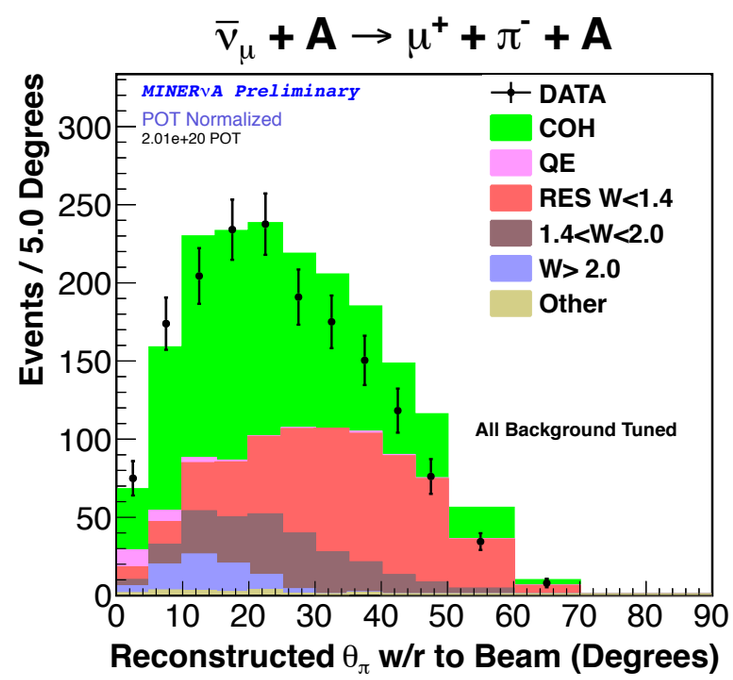


Pion Kinematics of Selected Sample

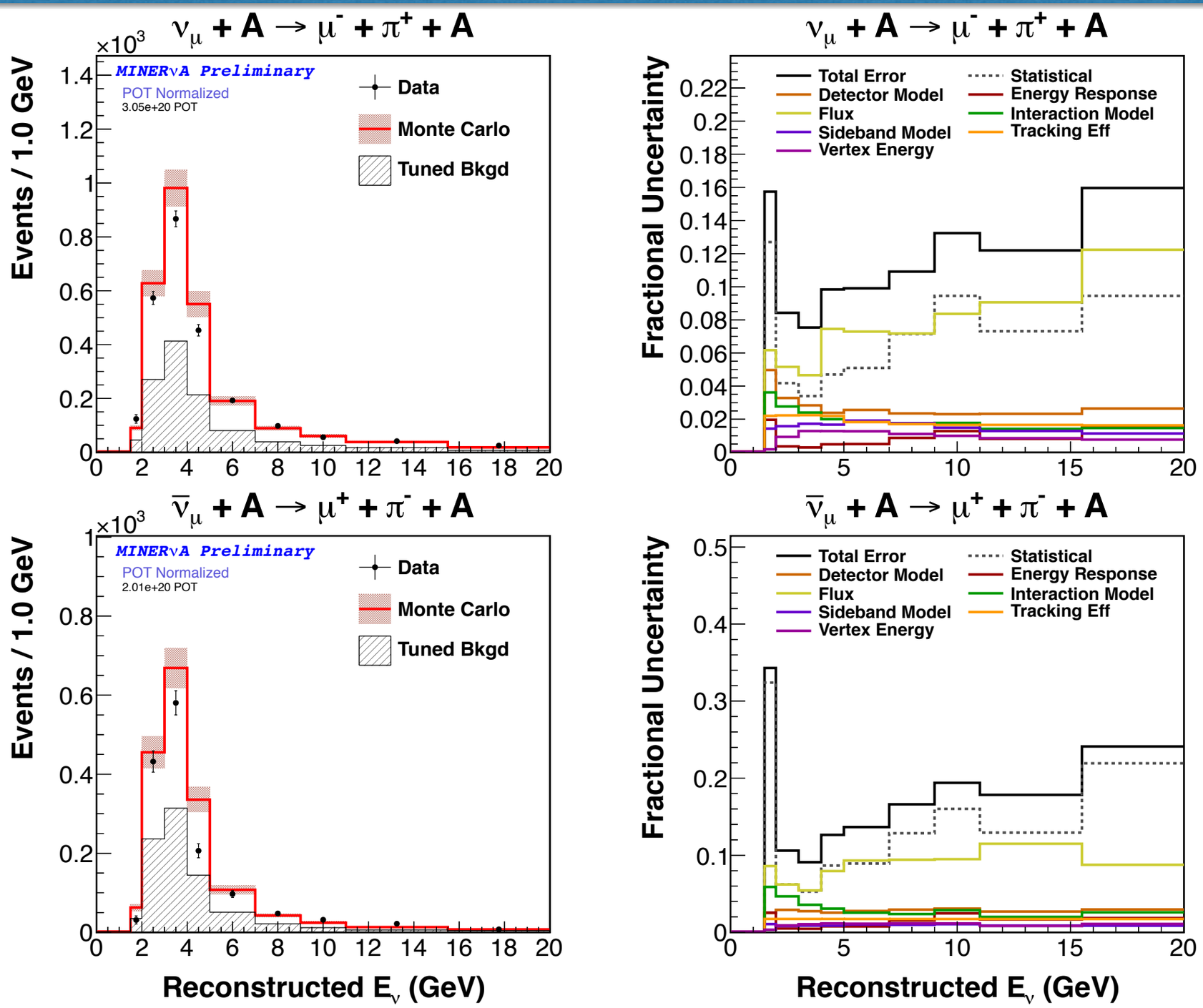




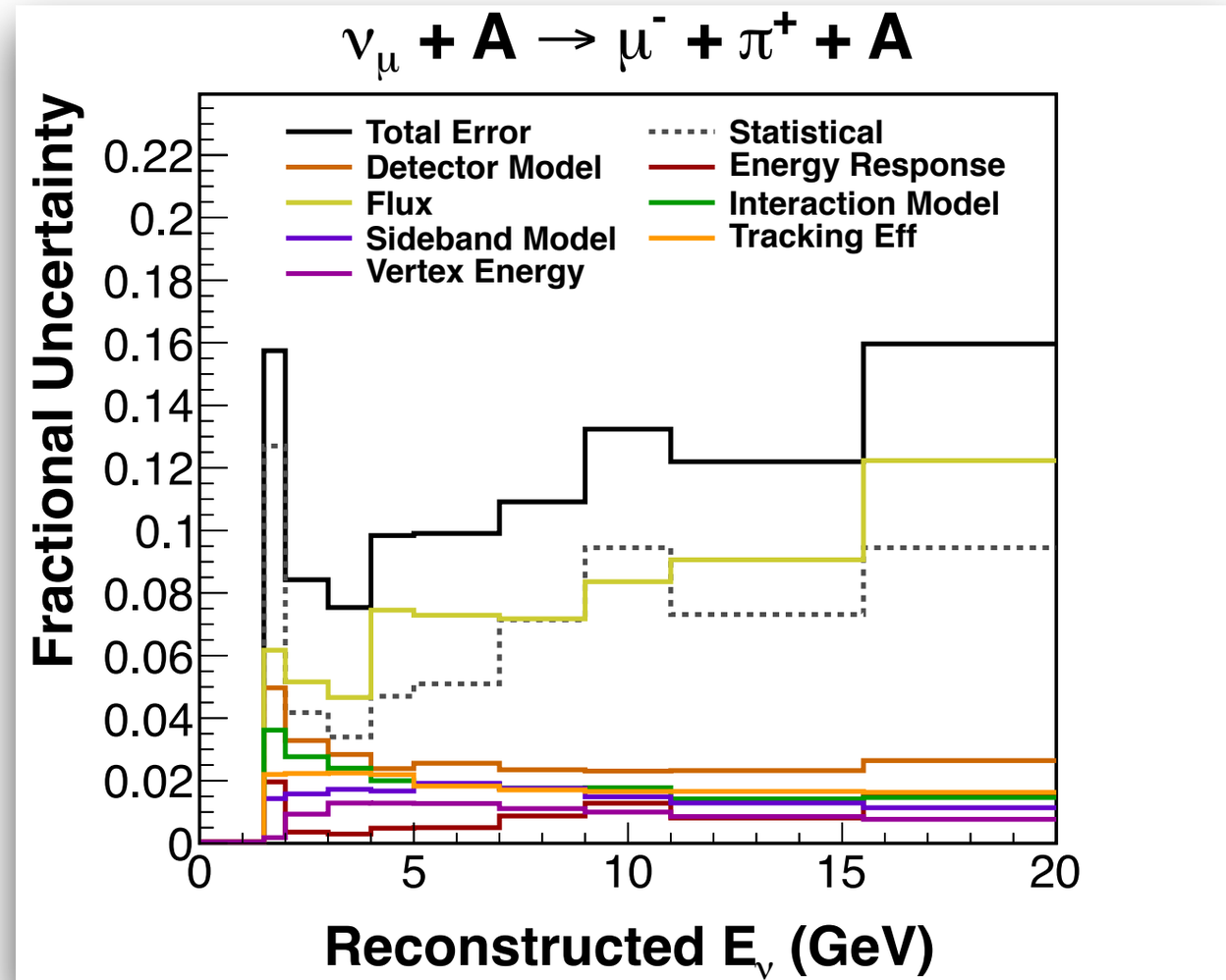




Neutrino Energy of Selected Events

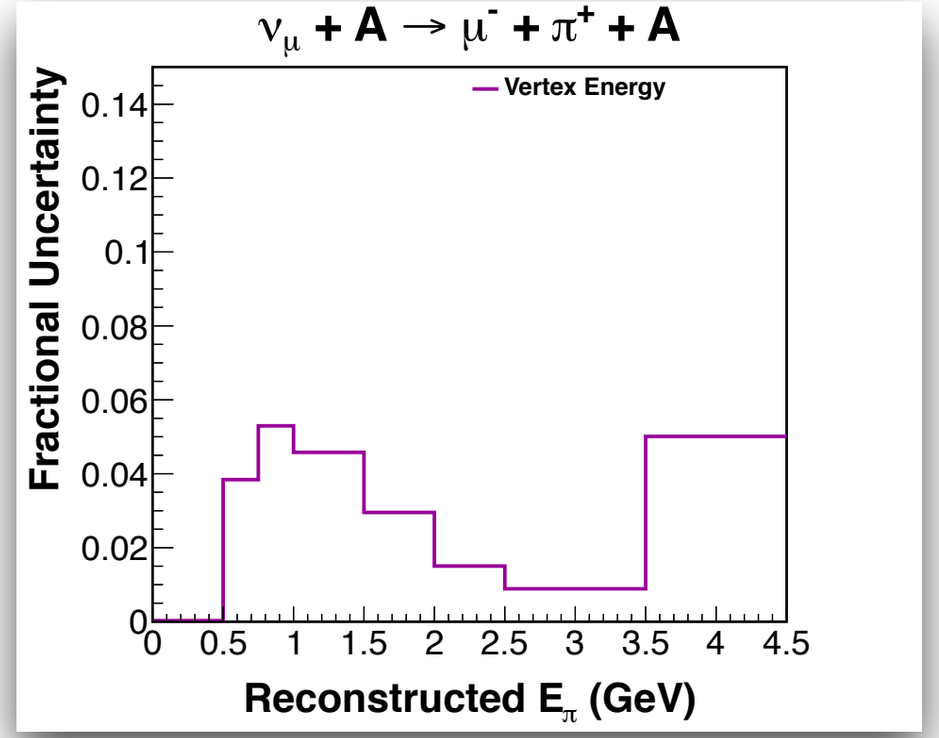


Systematic Summary
Selected Events



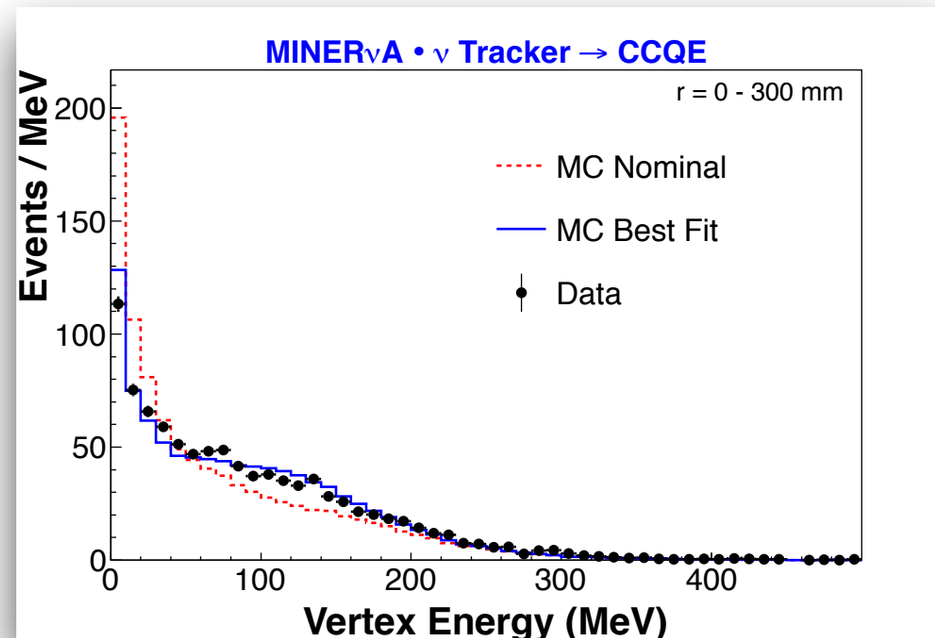
Interaction Model: GENIE v2.6.2 (largest contribution from pion FSI and CC Resonances)
Flux: Beam focusing system and hadron production
Tracking Eff: Tracking efficiencies data/MC

Systematic Summary

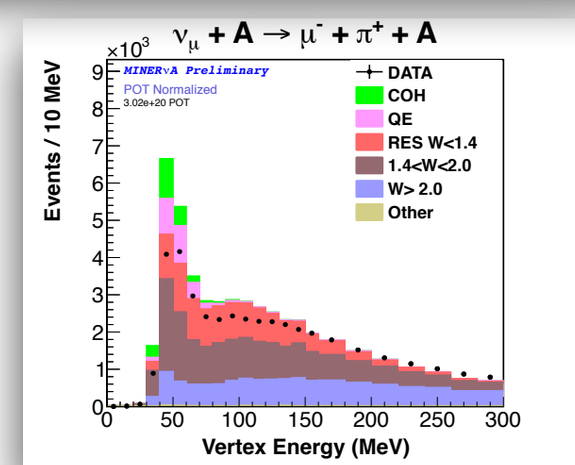


Vertex Energy: Mis-modeling of the vertex energy

PRL 111.022502 2013

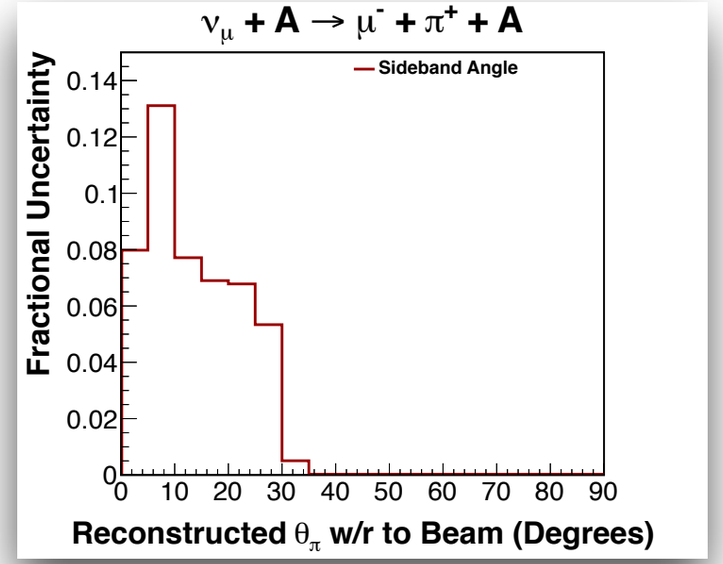


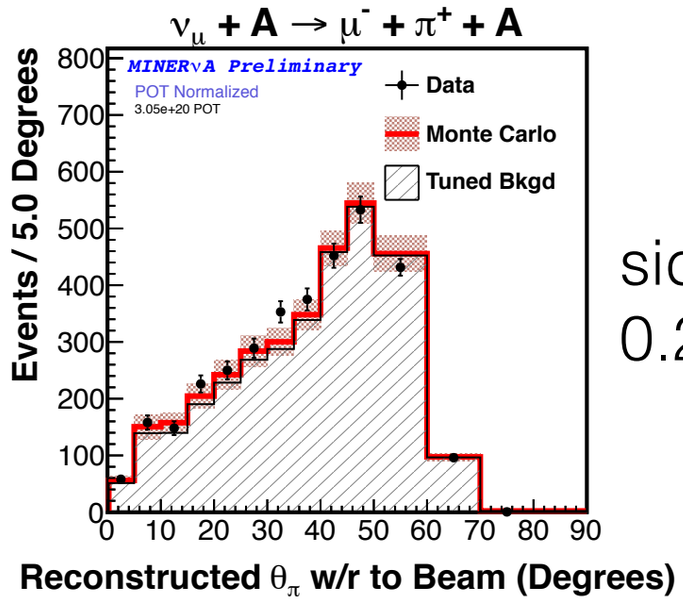
- To estimate the effect of mis-modeling vertex activity
  - Overlay a proton with KE < 225 MeV onto 25% of the background events with a neutron as a target (motivated by MINERvA's QE results)



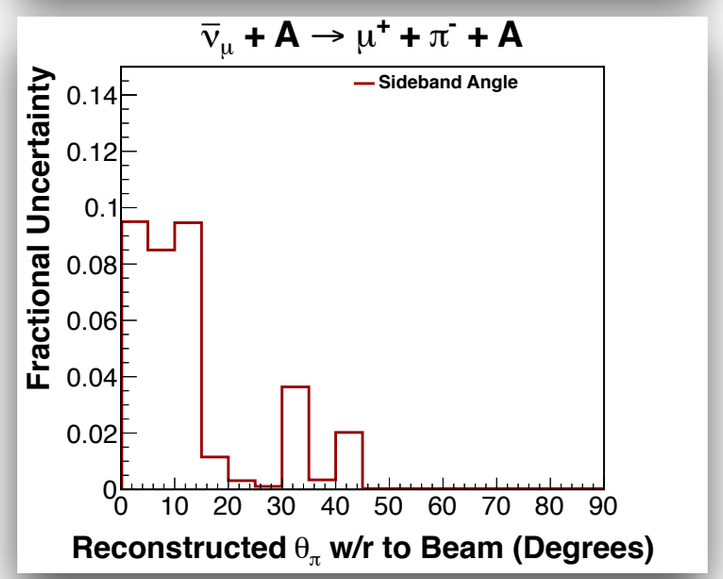
Systematic Summary

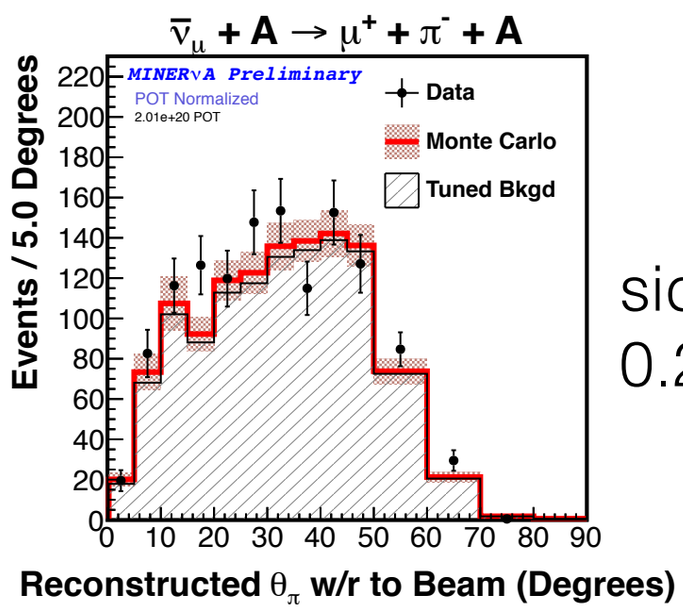
Sideband Model: We apply an additional systematic to the background to cover disagreement in the sideband





sideband
$0.2 < |t| < 0.6\ (\mathrm{GeV}/c)^2$



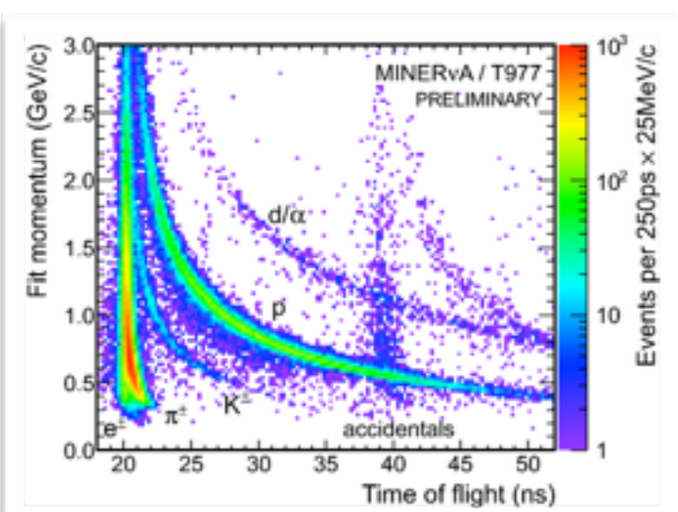


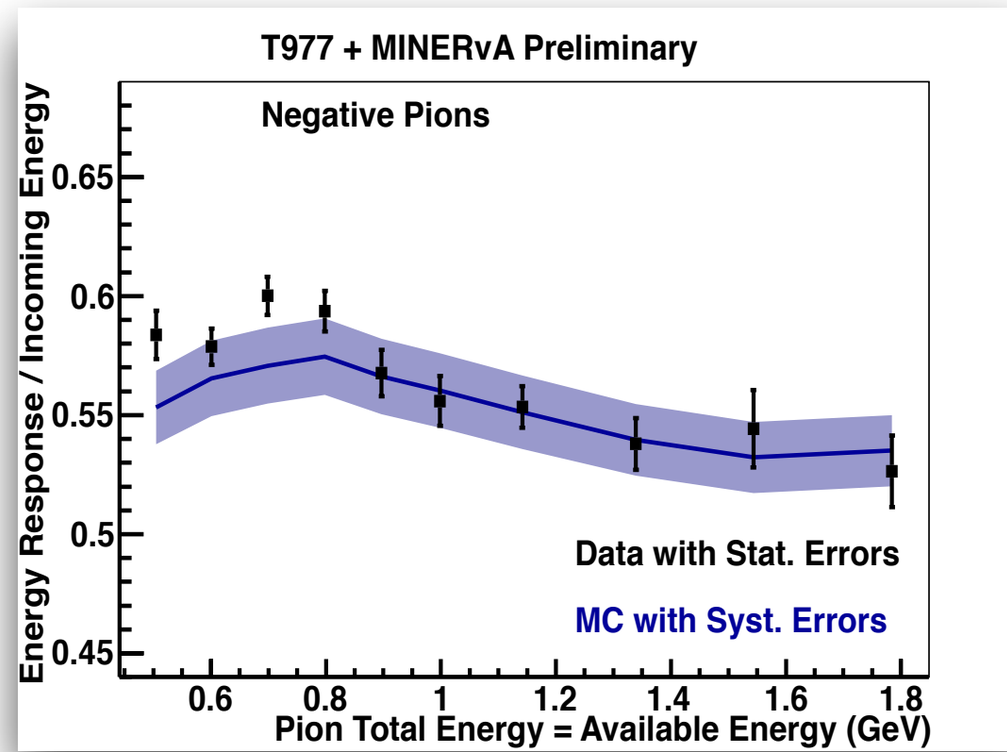
sideband
$0.2 < |t| < 0.6\ (\mathrm{GeV}/c)^2$

Systematic Summary

Energy Response: Our test beam provides an error band on the response to single pions (5%) and protons (3%)

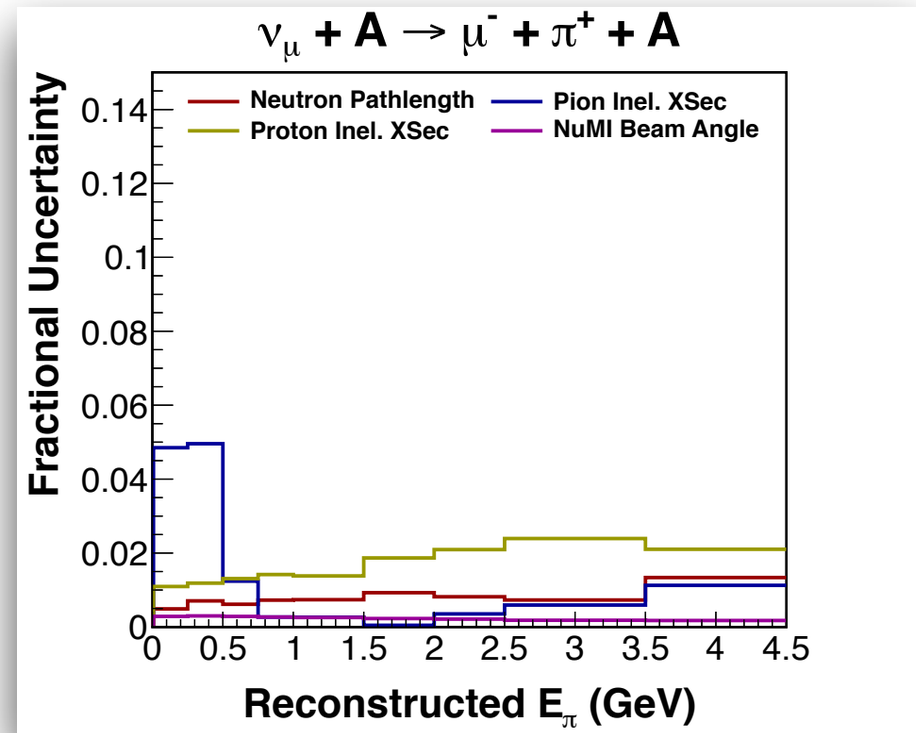
MINERvA Test Beam

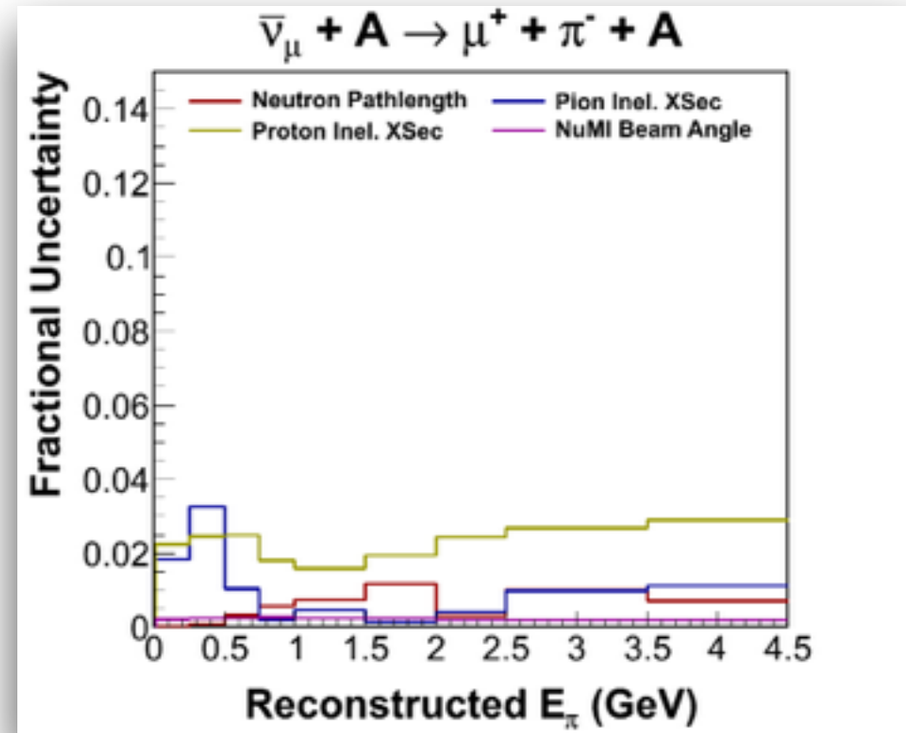




Systematic Summary

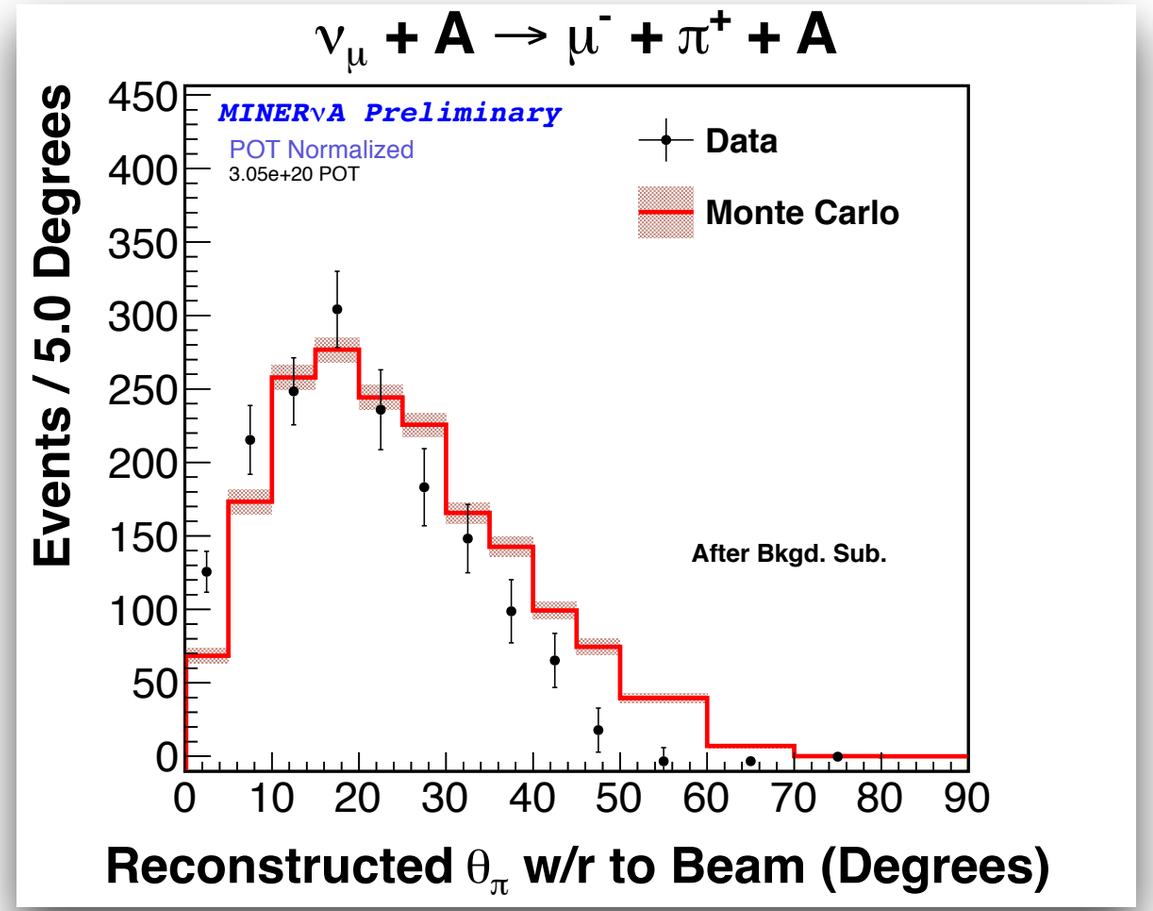
Detector Model: GEANT 4 detector simulation

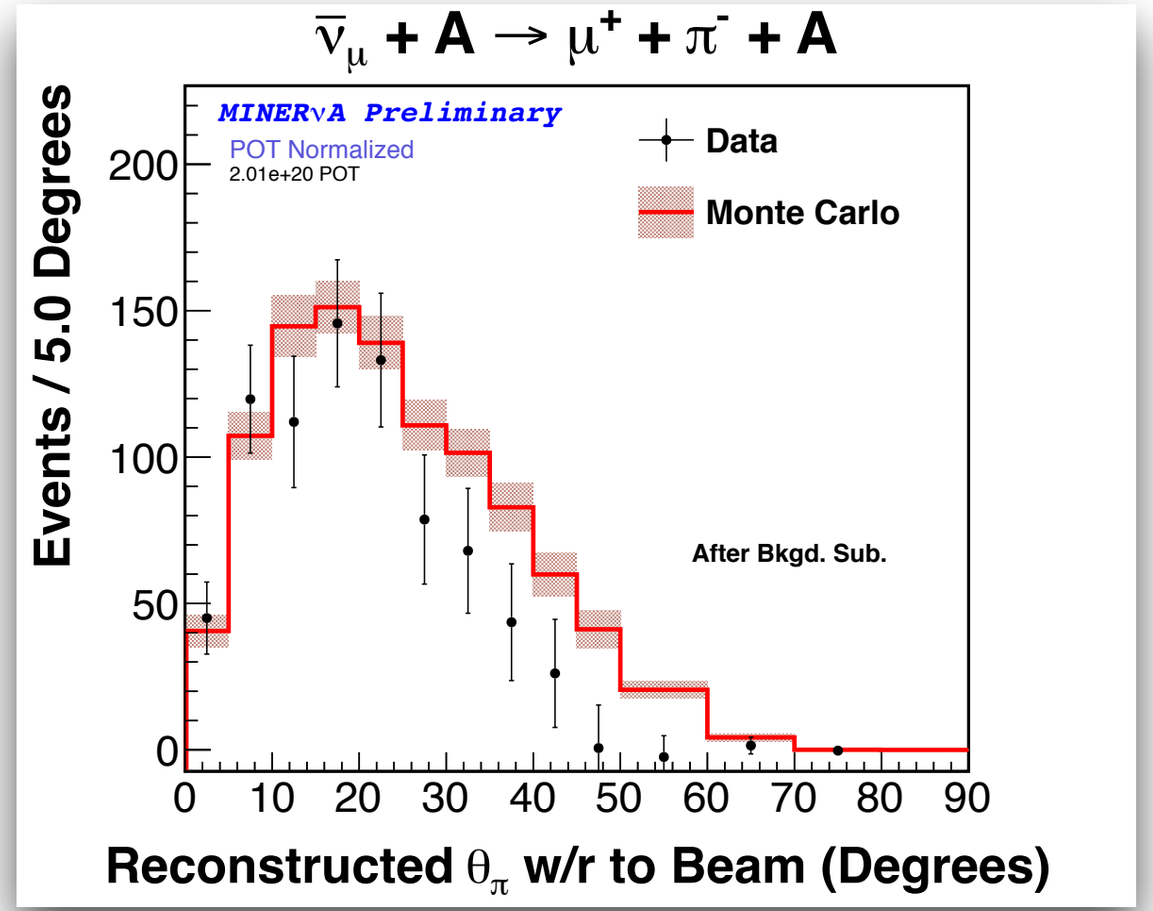




- Variation of the pion and proton total inelastic cross section and the neutron path length ±10% (data-driven by comparing GEANT to low energy scattering data)
- NuMI Beam Angle: uncertainty on the neutrino beam angle

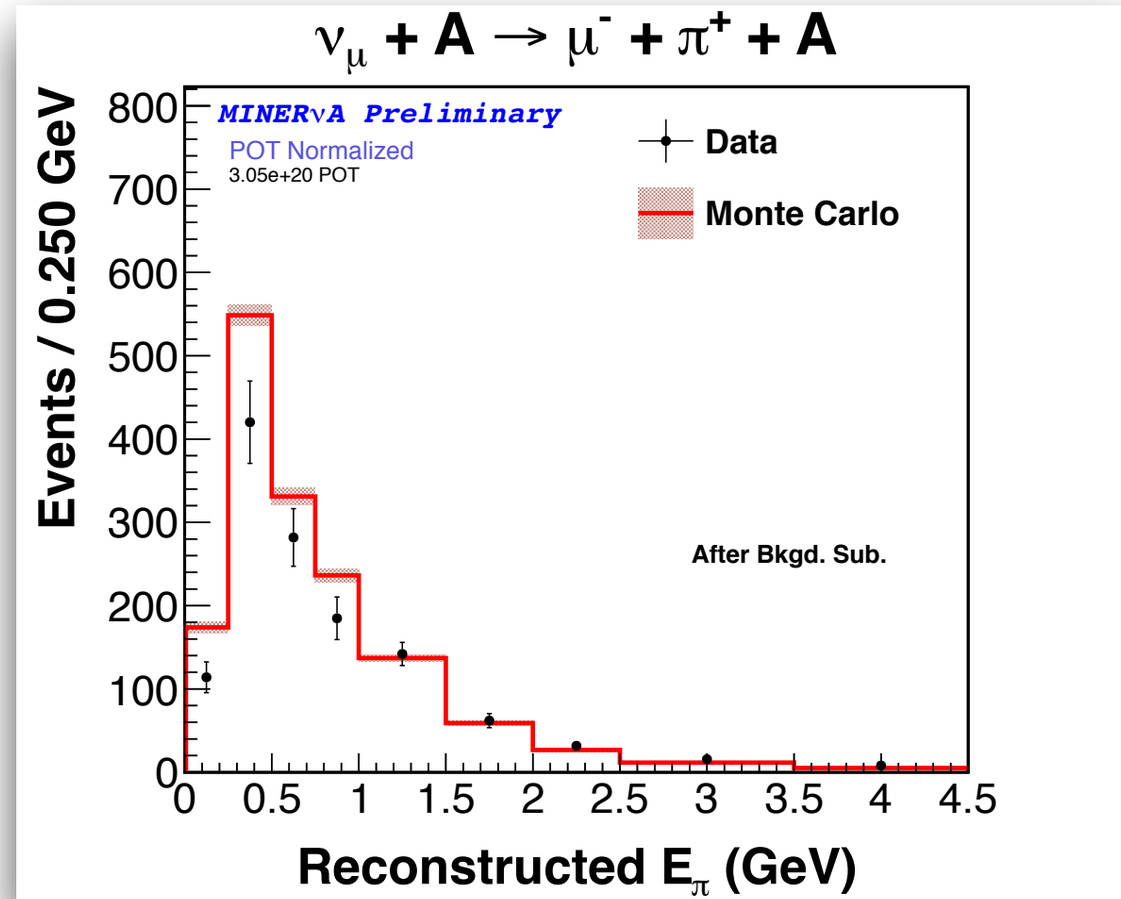
CC Coherent Candidates

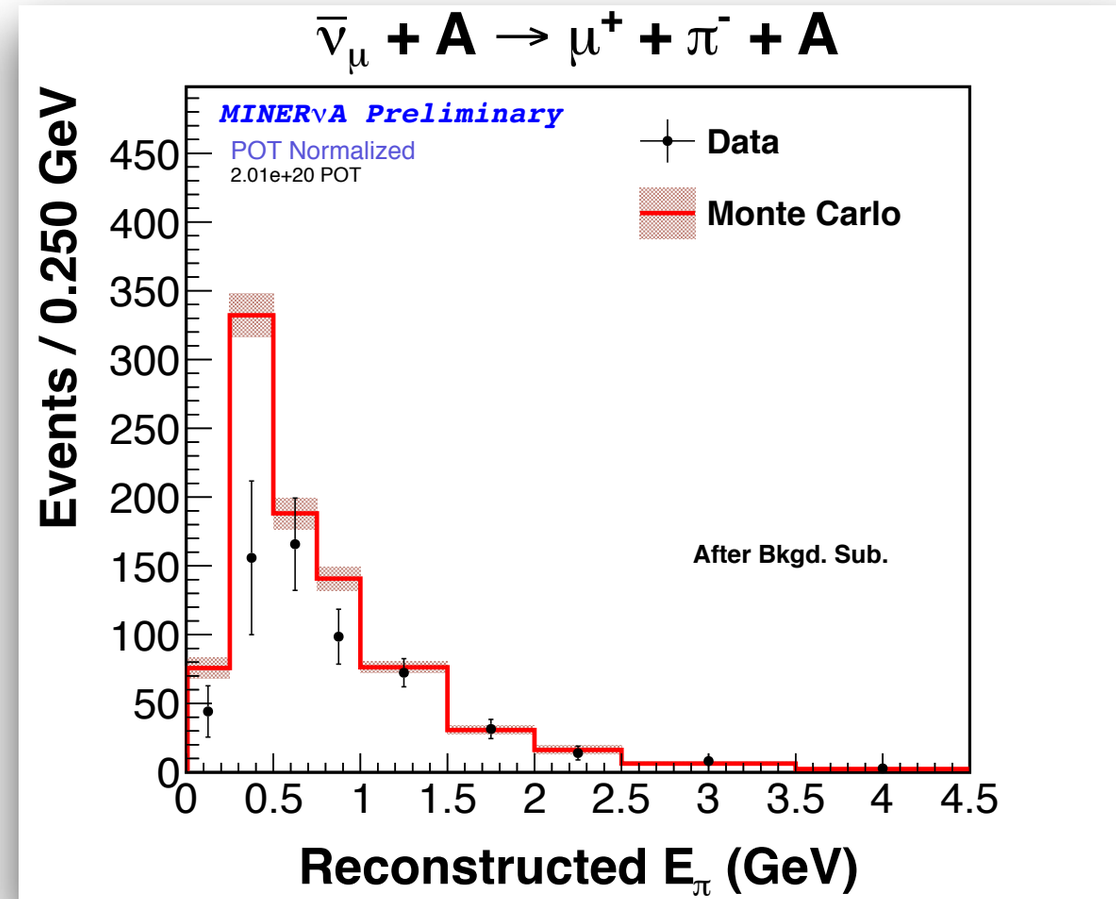




- After background subtraction: ~1.6K (~900) events neutrino (antineutrino)
- This is the highest statistics sample!

CC Coherent Candidates

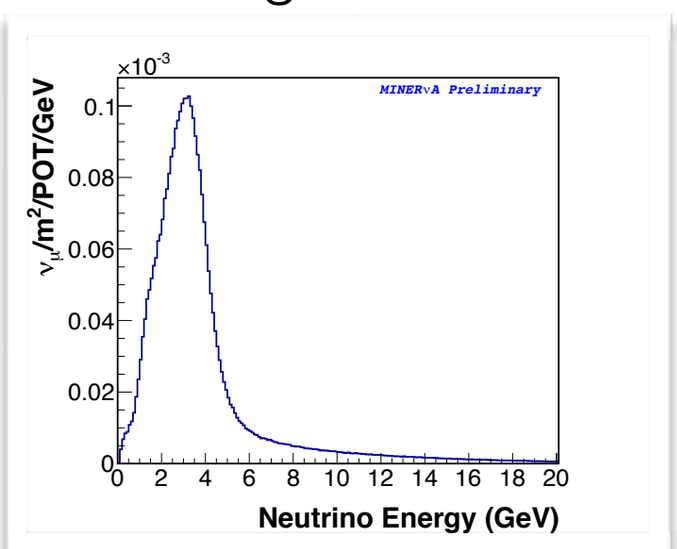




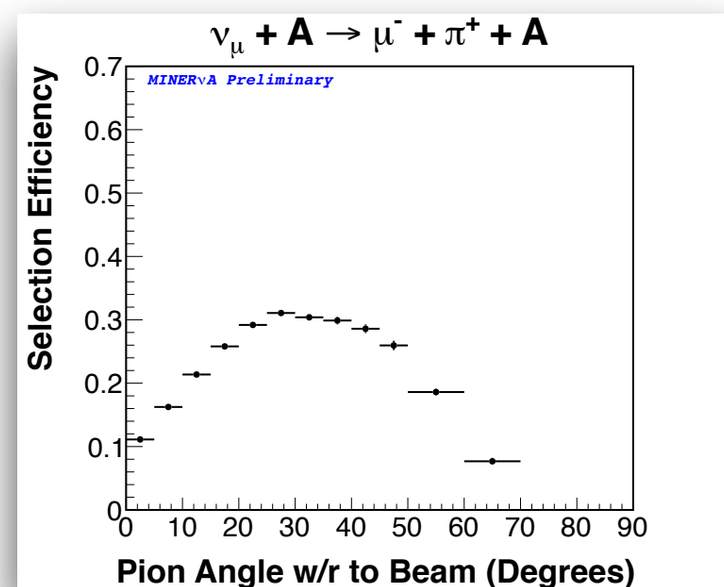
MINERvA Cross Section

$$\left(\frac{d\sigma}{d\theta_\pi}\right)_i = \frac{1}{\Phi_\nu \times T_n} \cdot \frac{1}{(\Delta\theta_\pi)_i} \cdot \frac{\sum_j U_{ij}(N_j^{data} - N_j^{bkgd})}{\epsilon_i}$$

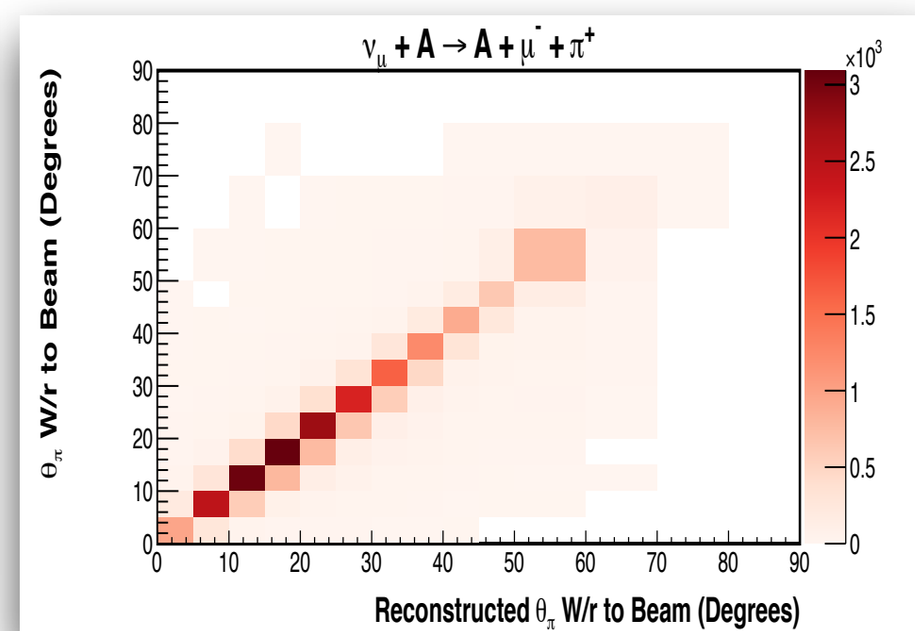
Integrated Flux



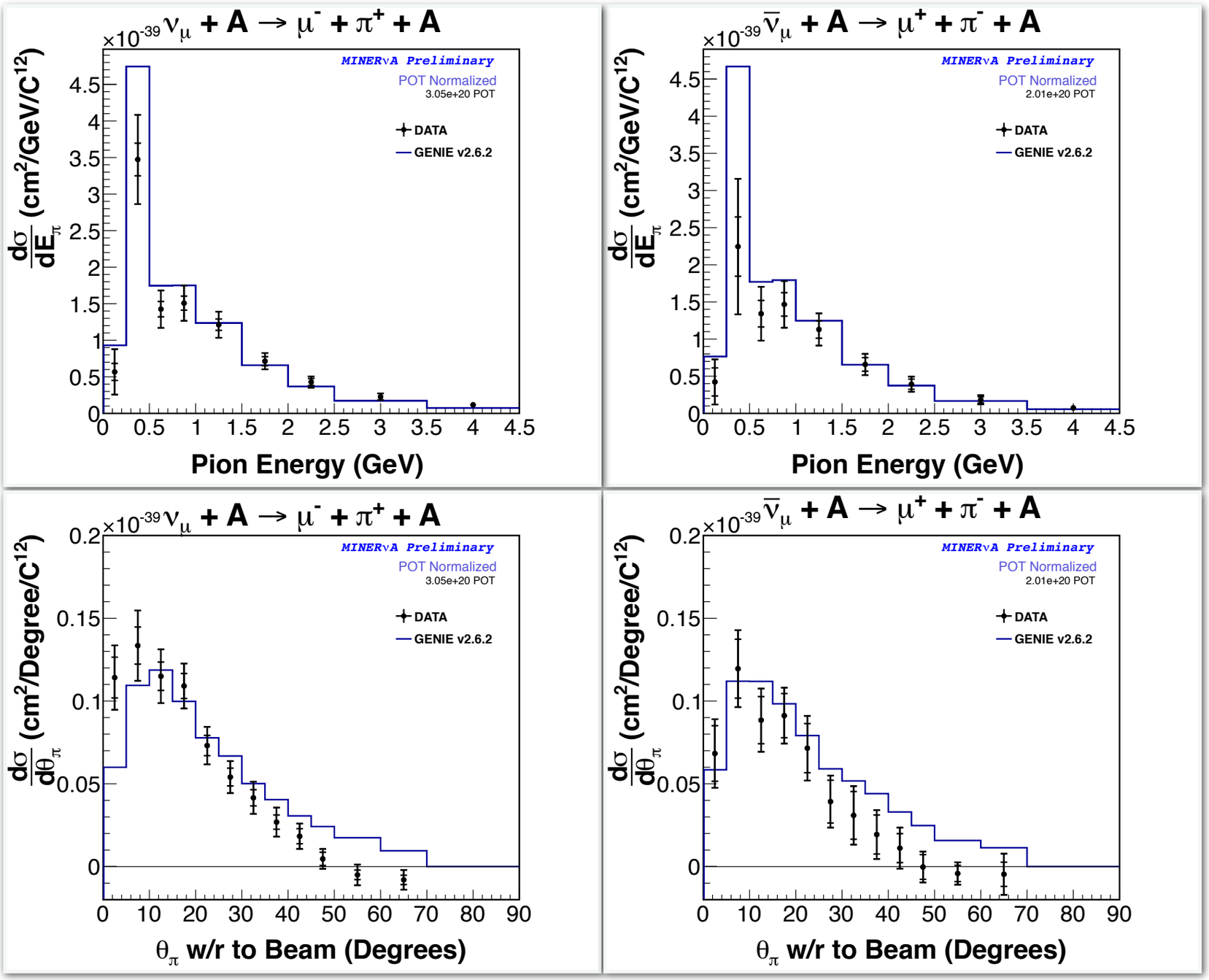
Acceptance and Efficiency



Unfolding
Migrations due to reconstruction effects

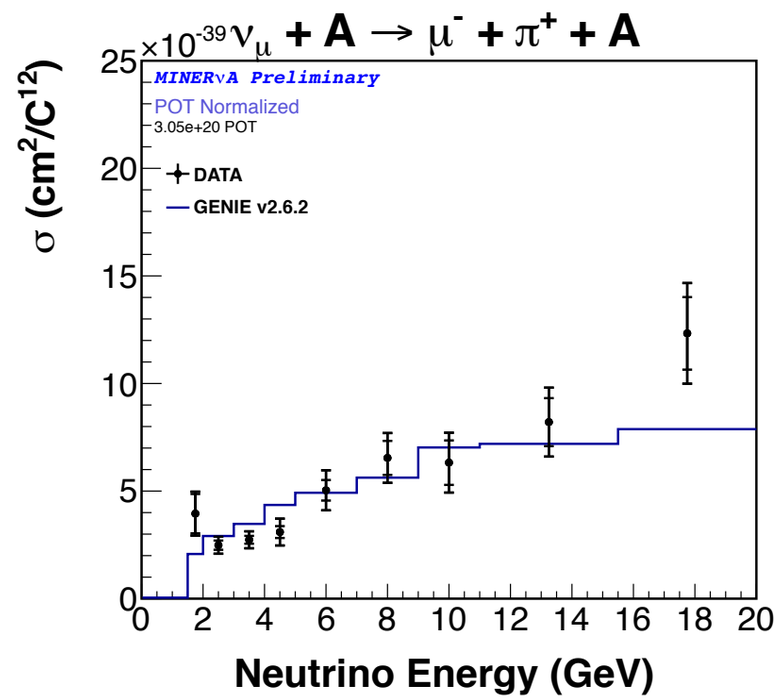


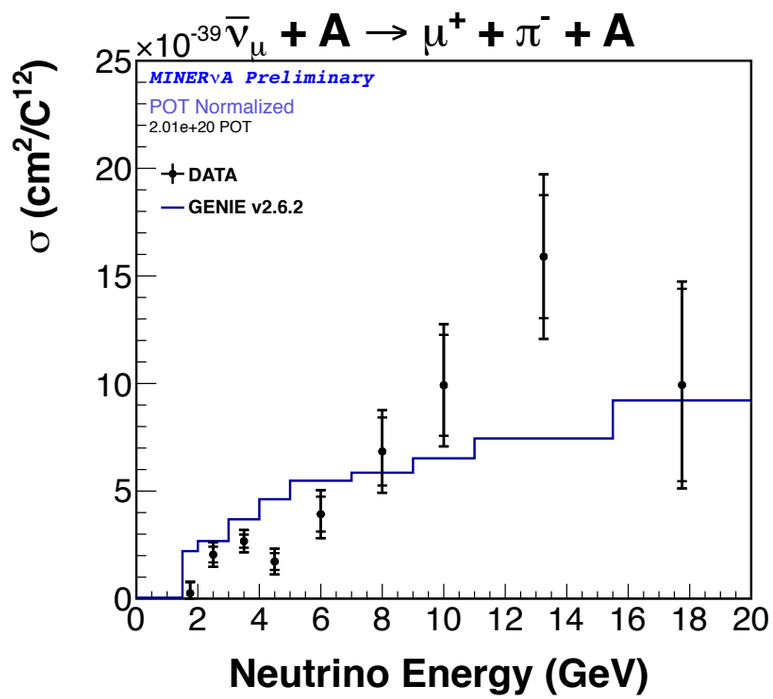
MINERvA Results

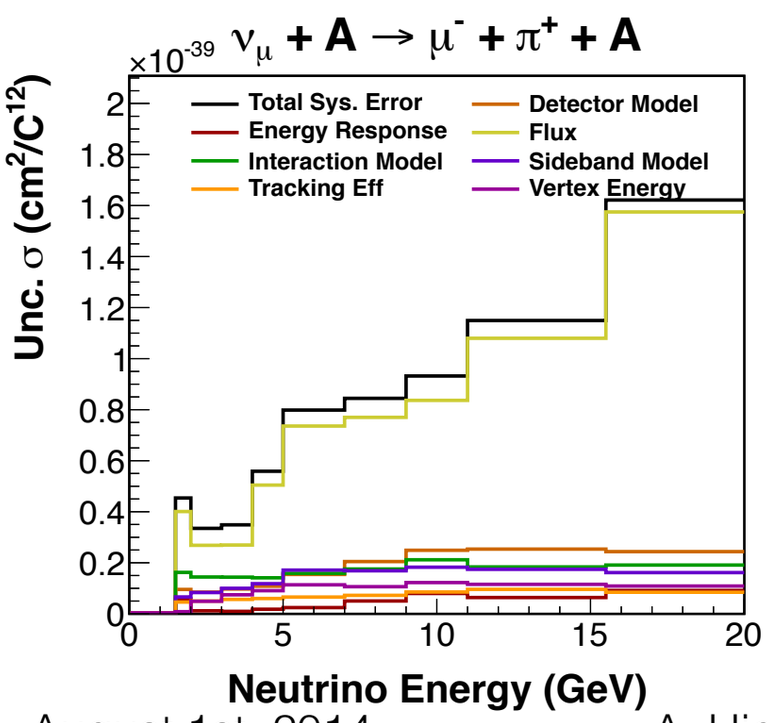


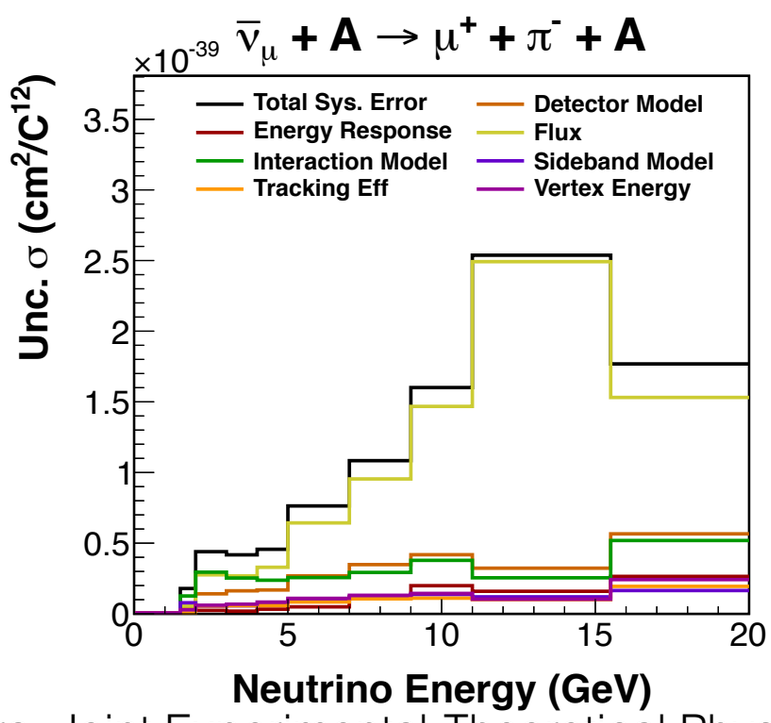
- By selecting low |t| events, MINERvA provides a model-independent measurement of the differential cross-section for coherent scattering of both neutrinos and anti-neutrinos on carbon
- Data prefer a more forward pion angle distribution and harder pion energy distribution

MINERvA Results



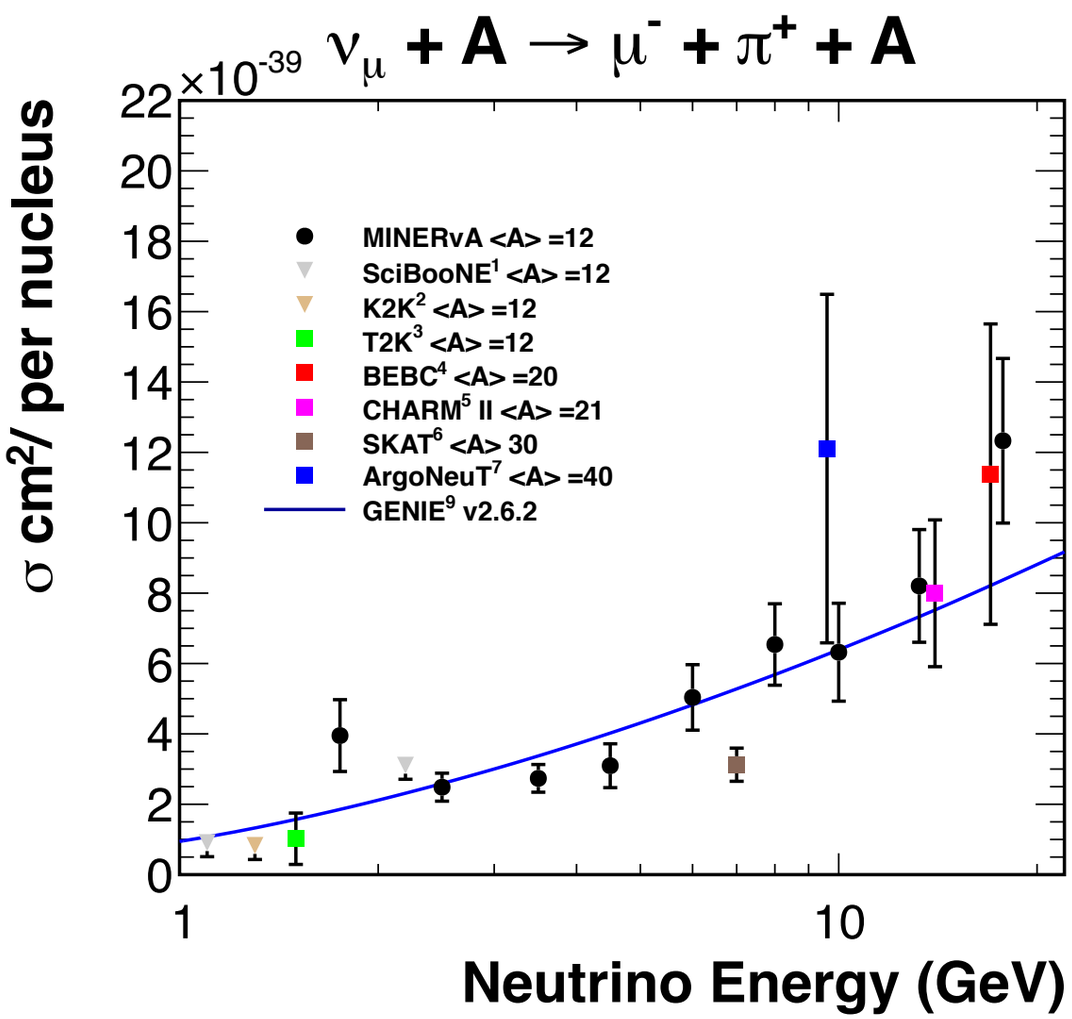


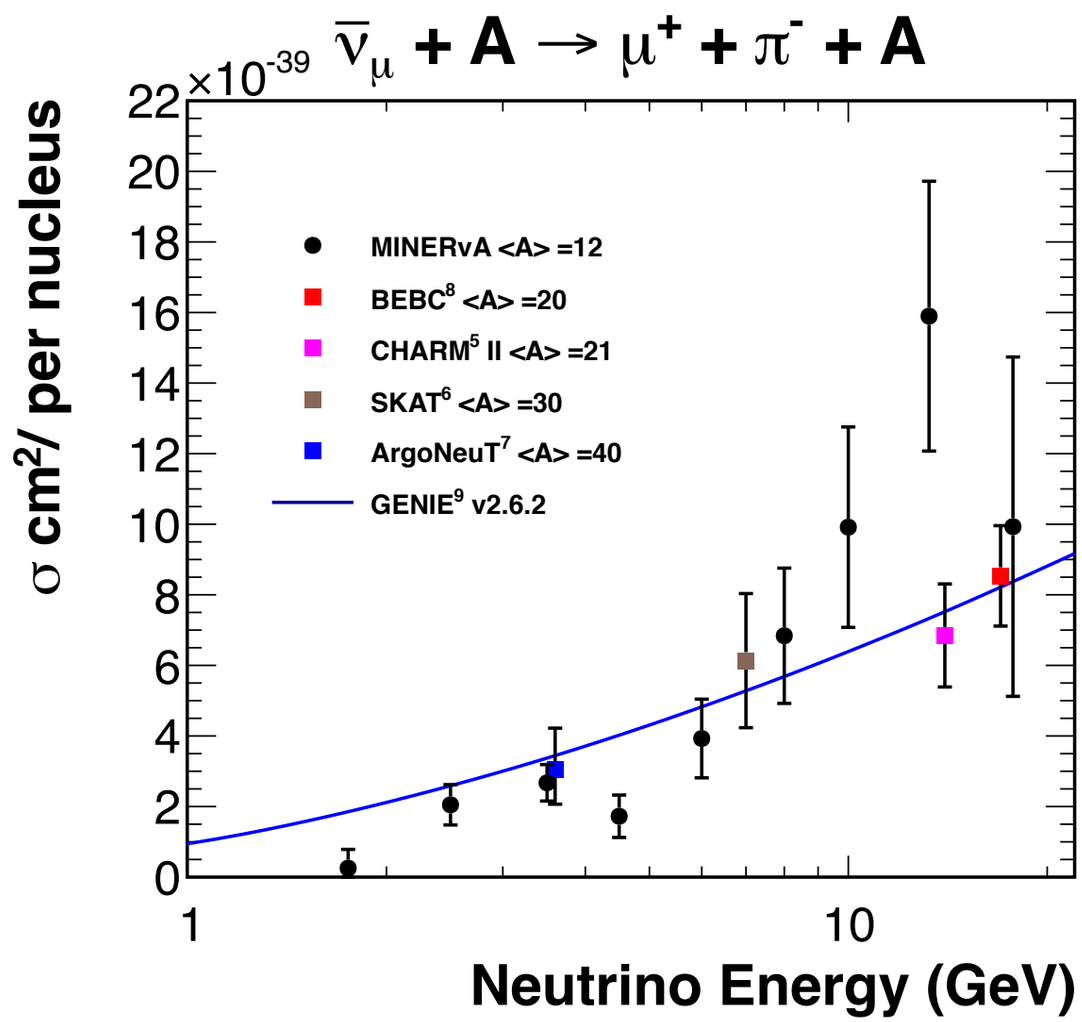




- MINERvA has isolated a coherent-rich sample using an event-by-event measurement of $|t| = (q-p_\pi)^2$
- High statistics

Coherent Cross Section





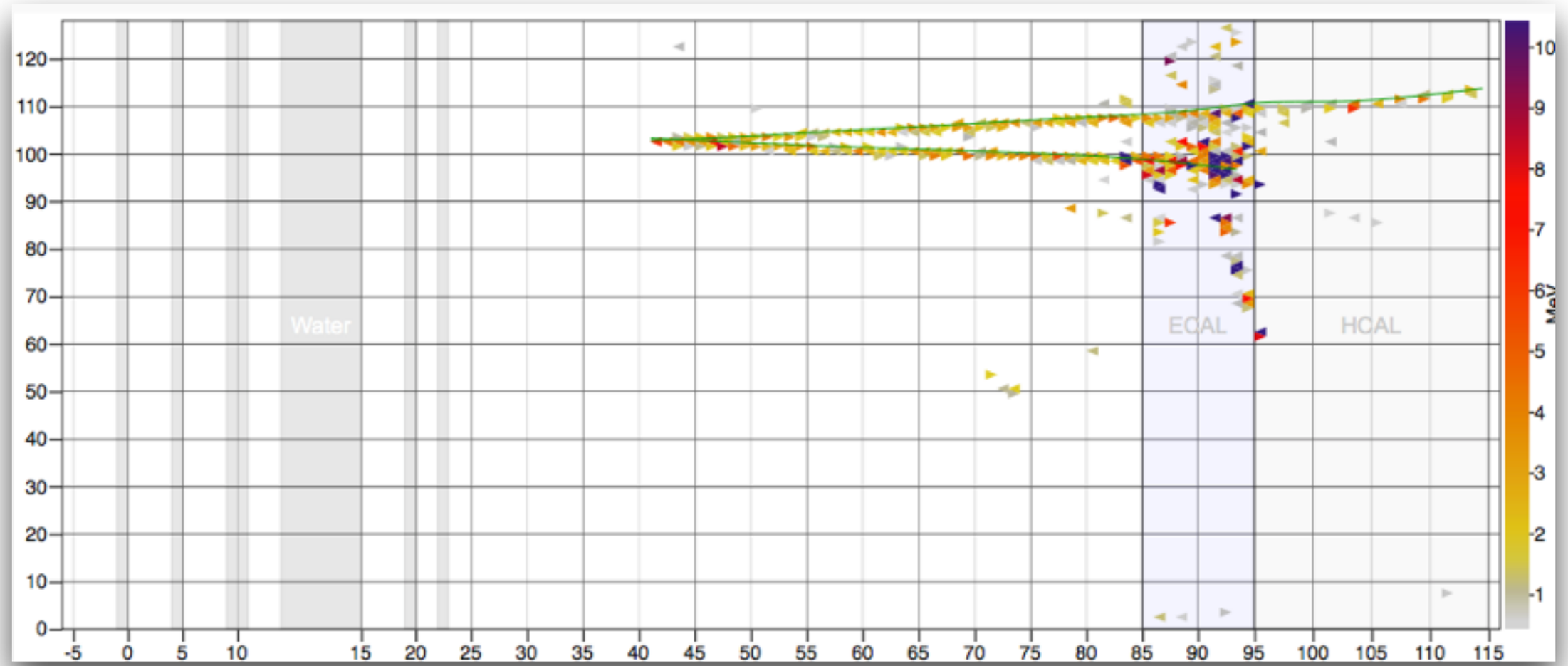
[1] SciBooNE Collaboration (K. Hiraide et al.), Phys. Rev. D 78, 112004 (2008)
[2] K2K Collaboration (M. Hasegawa et al.), Phys. Rev. Lett. 95, 252301 (2005)
[3] T2K Collaboration NuInt 2014 preliminary result
[4] BEBC WA59 Collaboration (P. Marage et al.), Z. Phys. C 31, 191 (1986)
[5] CHARM II Collaboration (P. Vilain et al.), Phys. Lett. B 313, 267 (1993)
[6] SKAT Collaboration (H.J. Grabosh et al.), Z. Phys. C 31, 203 (1986)
[7] ArgoNeuT Collaboration NuInt 2014 preliminary result
[8] BEBC WA59 Collaboration (P. Marage et al.), Z. Phys. C 43, 523 (1989)
[9] GENIE Collaboration (C. Andreopoulos et al.), Nucl. Instrum. Methods A 614, 87 (2010)

Conclusions

- MINERvA event selection based on low $|t| = (q-p_\pi)^2$ provides a model independent measurement for CC coherent pion production on Carbon by neutrino and antineutrinos
- Poor agreement is observed with the Rein-Sehgal model as implemented in GENIE v2.6.2
- MINERvA data will be a benchmark for testing new PCAC models (Berger-Sehgal, Paschos-Schalla)
- MINERvA data will also be a benchmark for testing Microscopic models from low energies to moderate energies
- These comparisons will set the level of systematic for oscillation experiments
- MINERvA is now running at ME NuMI beam configuration $\langle E_\nu \rangle$ ~6 GeV
- MINERvA's multiple passive targets (Pb, C, Fe) and increase in the statistics in ME beam will allow measurement of the A-dependence

Thanks for your attention!

Back-Up Slides



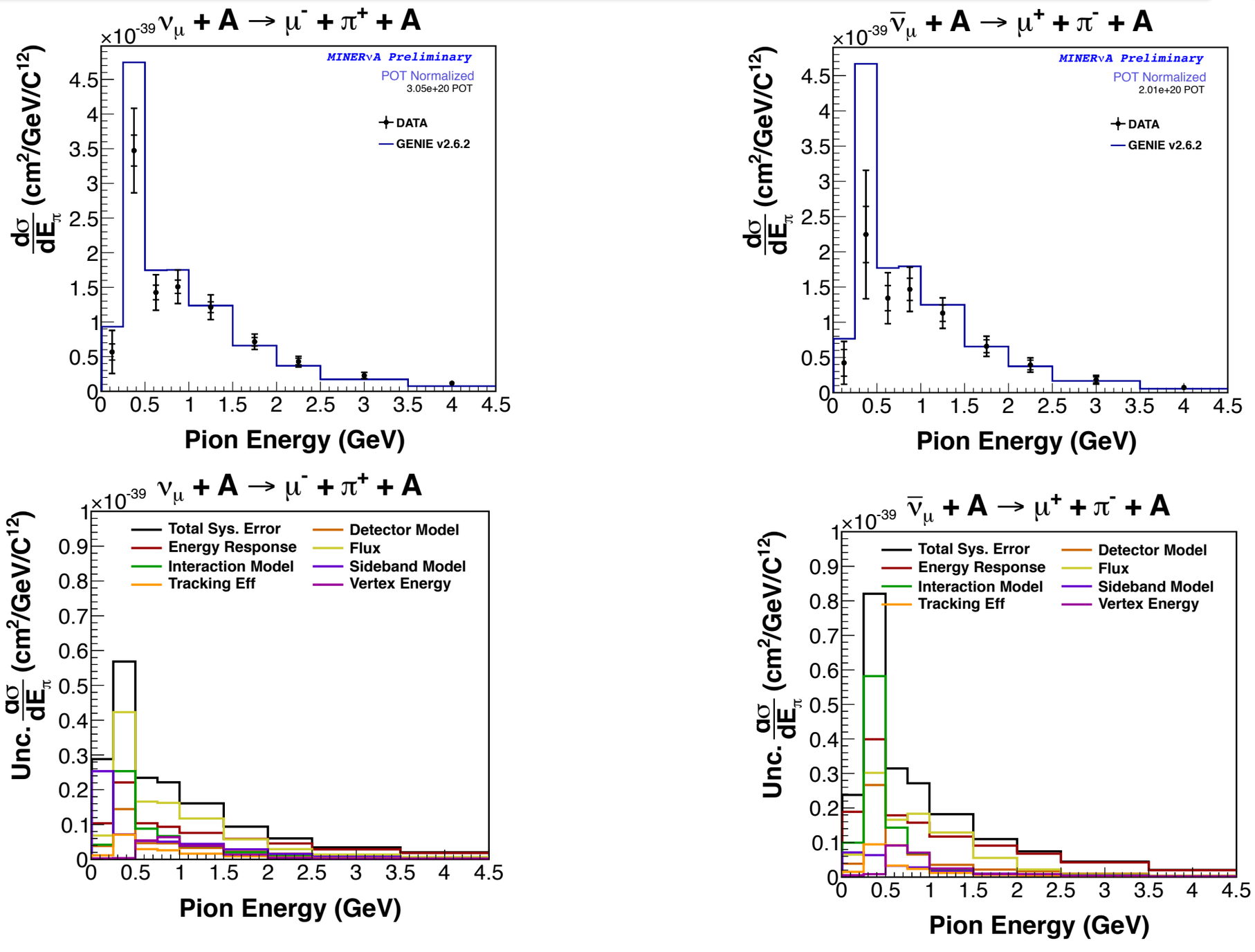
MINERvA Results

E_ν (GeV)	$\nu_\mu + C^{12} \rightarrow \mu^- + \pi^+ + C^{12}$ $(10^{-39}\mathrm{cm}^2/\mathrm{GeV}/C^{12})$
$1.5 - 2.0$	$3.95 \pm 0.91 \pm 0.45$
$2.0 - 3.0$	$2.49 \pm 0.21 \pm 0.33$
$3.0 - 4.0$	$2.74 \pm 0.18 \pm 0.35$
$4.0 - 5.0$	$3.10 \pm 0.28 \pm 0.56$
$5.0 - 7.0$	$5.04 \pm 0.48 \pm 0.80$
$7.0 - 9.0$	$6.54 \pm 0.79 \pm 0.84$
$9.0 - 11.0$	$6.32 \pm 1.03 \pm 0.93$
$11.0 - 15.0$	$8.20 \pm 1.12 \pm 1.15$
$15.0 - 20.0$	$12.33 \pm 1.69 \pm 1.62$

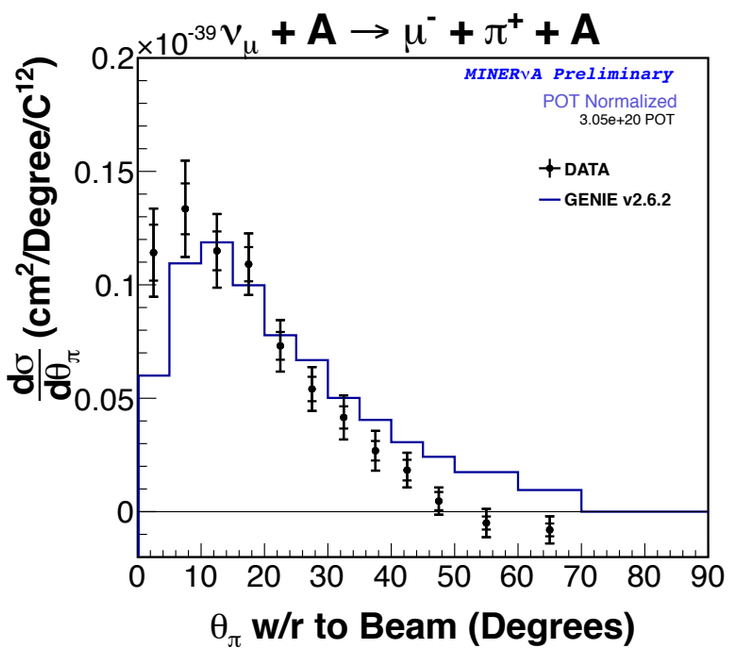
$E_{\bar{\nu}}$ (GeV)	$\bar{\nu}_\mu + C^{12} \rightarrow \mu^+ + \pi^- + C^{12}$ $(10^{-39}\mathrm{cm}^2/\mathrm{GeV}/C^{12})$
$1.5 - 2.0$	$0.25 \pm 0.50 \pm 0.18$
$2.0 - 3.0$	$2.05 \pm 0.37 \pm 0.44$
$3.0 - 4.0$	$2.67 \pm 0.30 \pm 0.42$
$4.0 - 5.0$	$1.72 \pm 0.39 \pm 0.46$
$5.0 - 7.0$	$3.93 \pm 0.81 \pm 0.76$
$7.0 - 9.0$	$6.84 \pm 1.58 \pm 1.08$
$9.0 - 11.0$	$9.92 \pm 2.35 \pm 1.60$
$11.0 - 15.0$	$15.90 \pm 2.86 \pm 2.54$
$15.0 - 20.0$	$9.93 \pm 4.47 \pm 1.77$

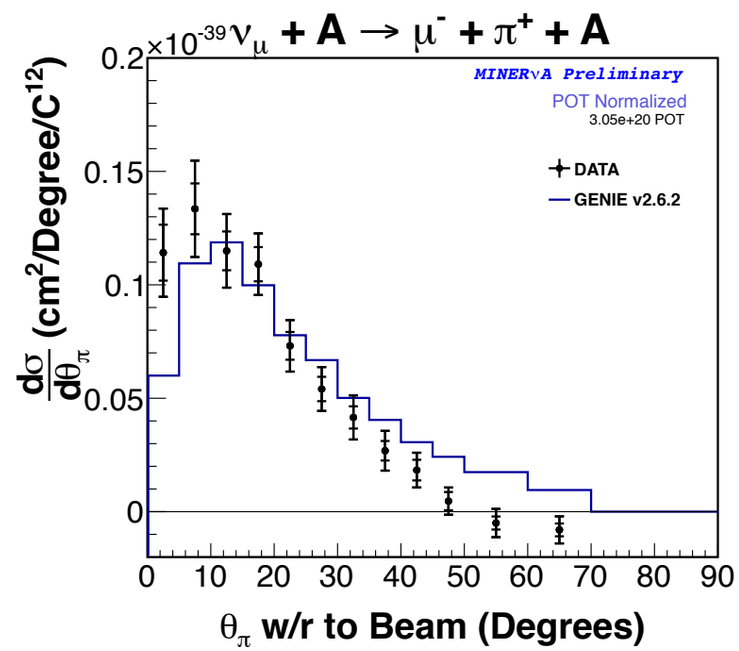
Cross section as a function of neutrino energy with statistics and systematic errors

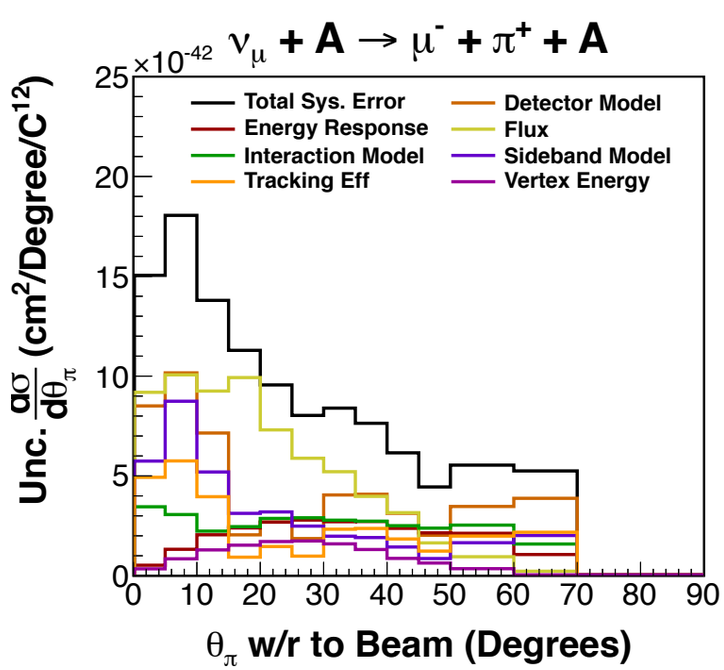
MINERvA Results

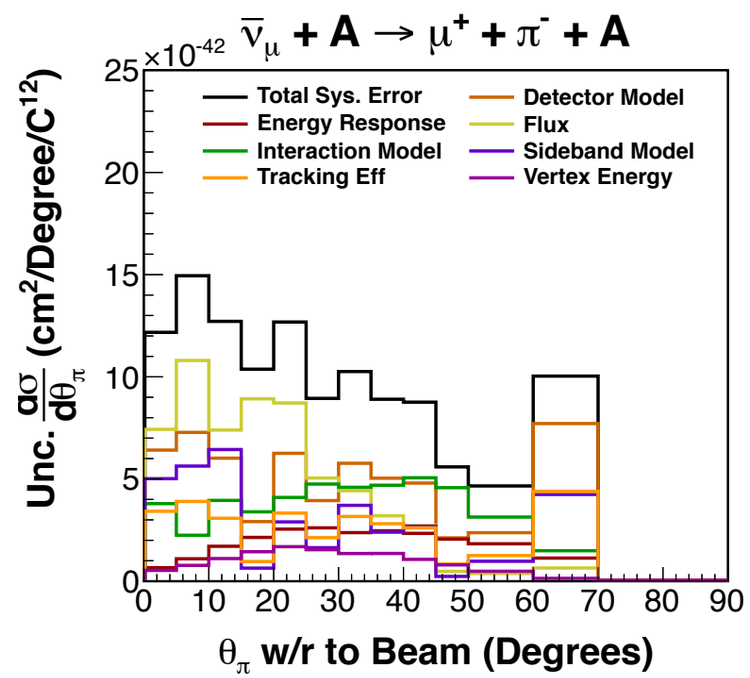


MINERvA Results

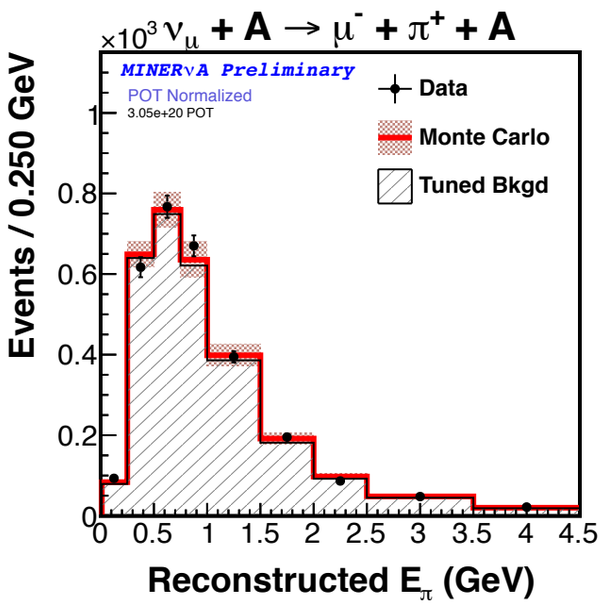


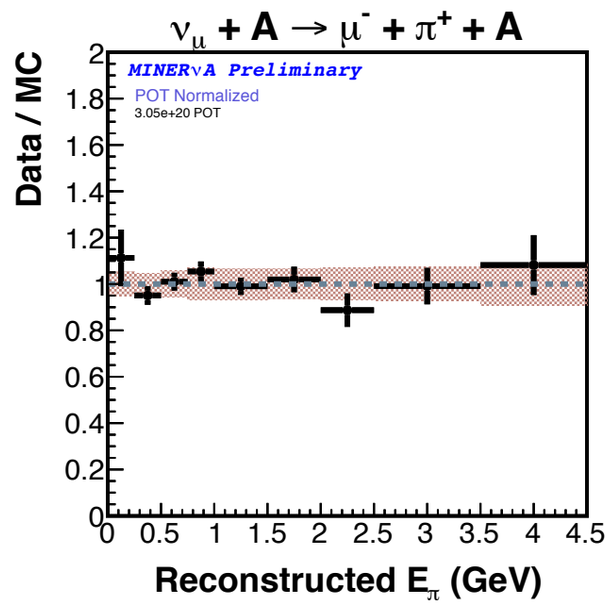






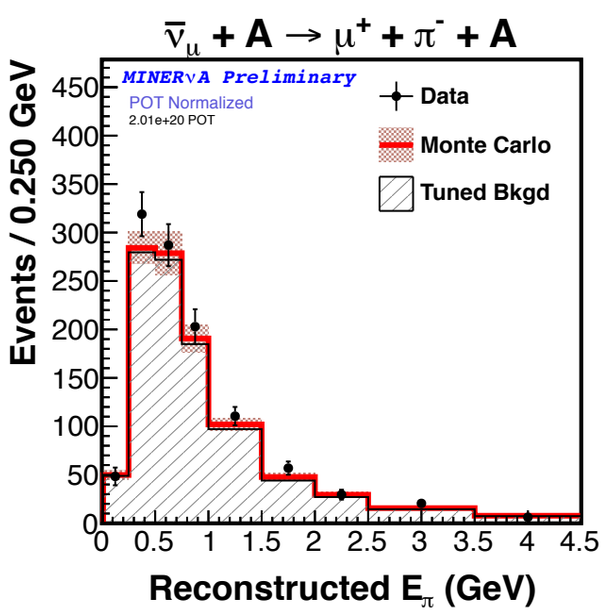
MINERvA Sideband Tuning

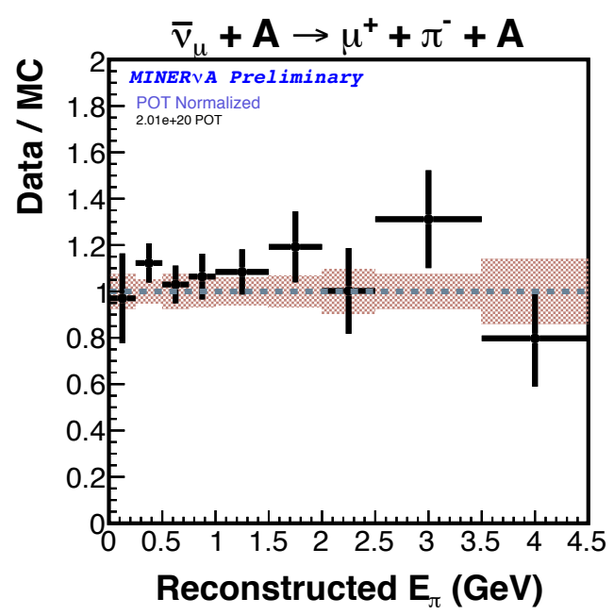




Neutrino Scale Factors

Res	= 0.5
QE	= 0.9
1.4<W<2.0	= 0.7
W>2.0	= 1.4

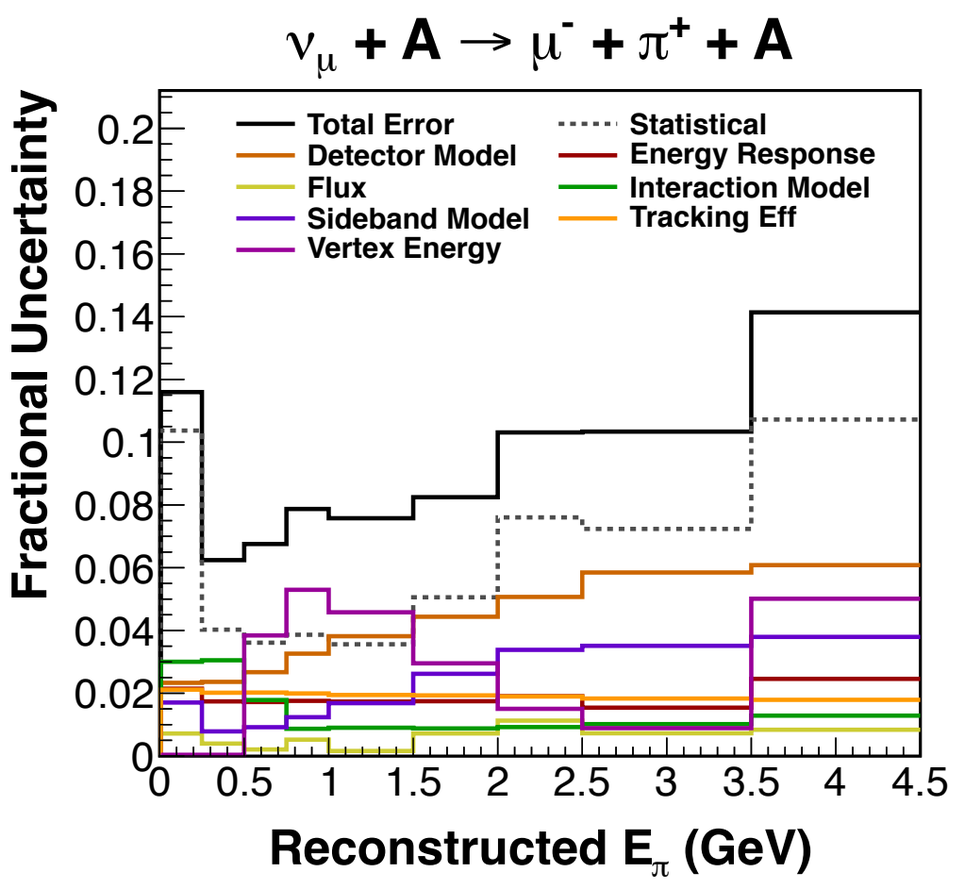


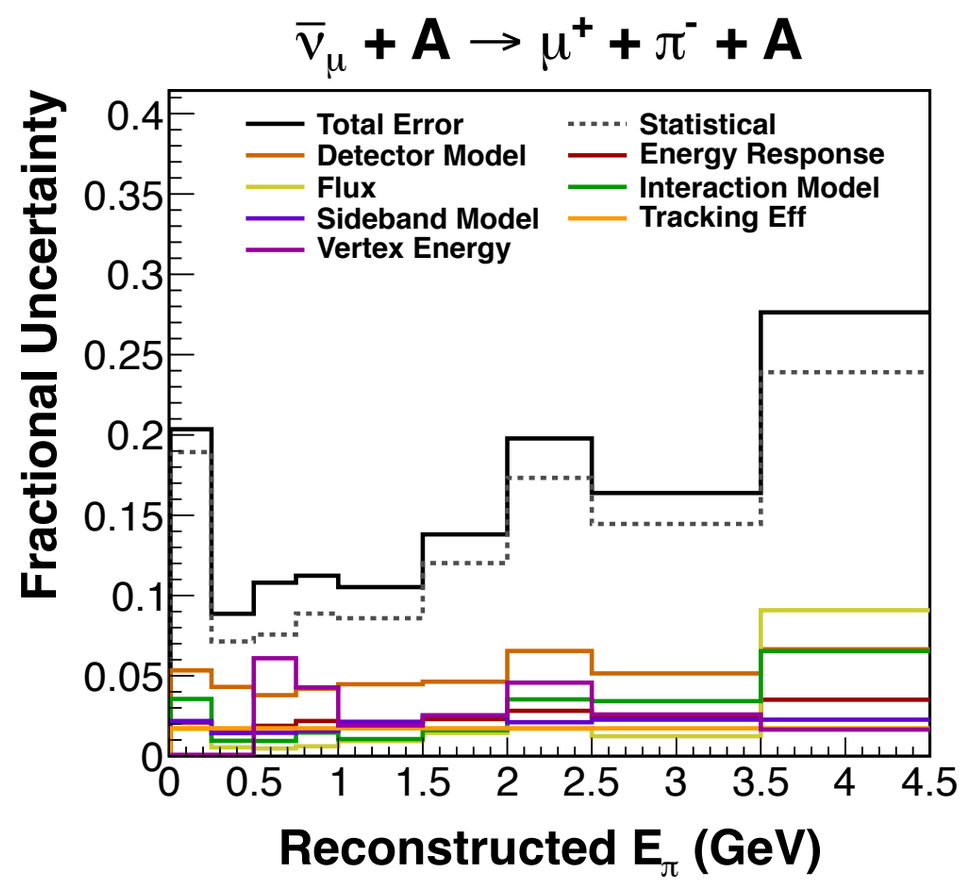


Antineutrino Scale Factors

Res	= 0.9
1.4<W<2.0	= 0.6
W>2.0	= 1.7

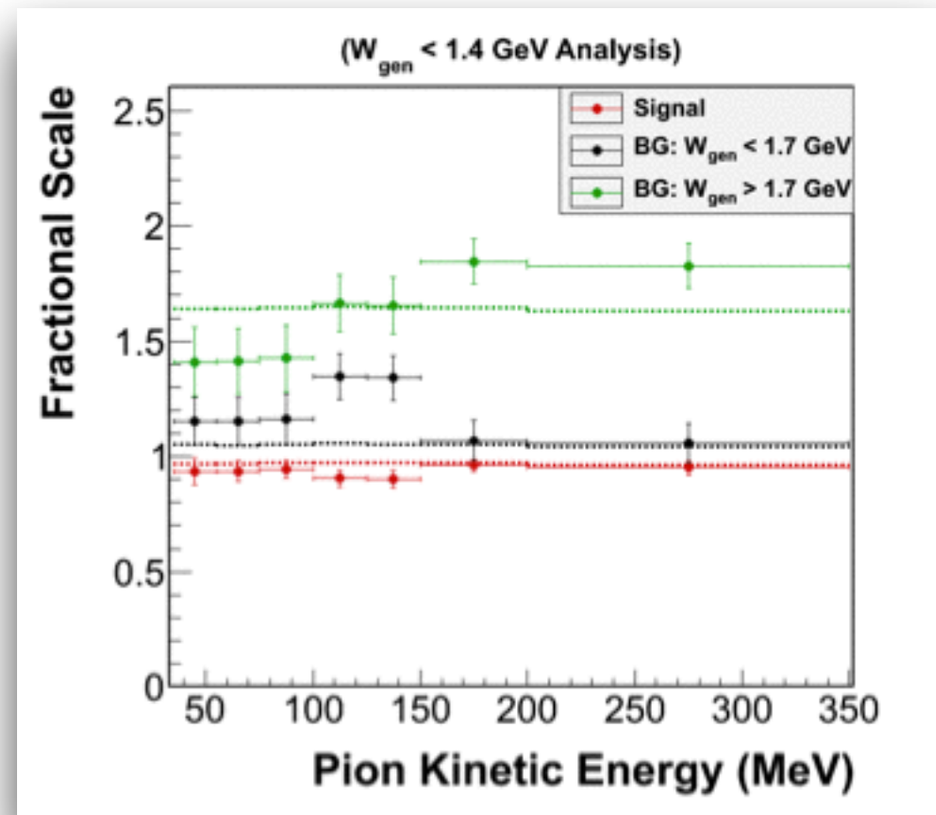
MINERvA Sideband Systematics

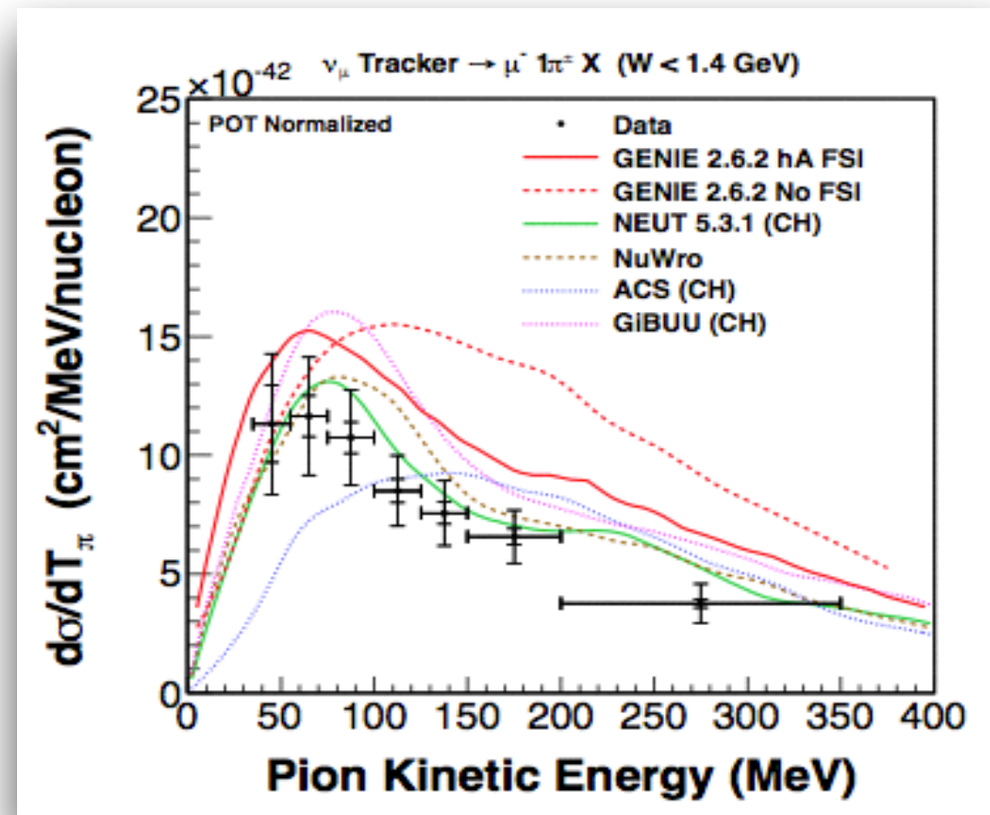




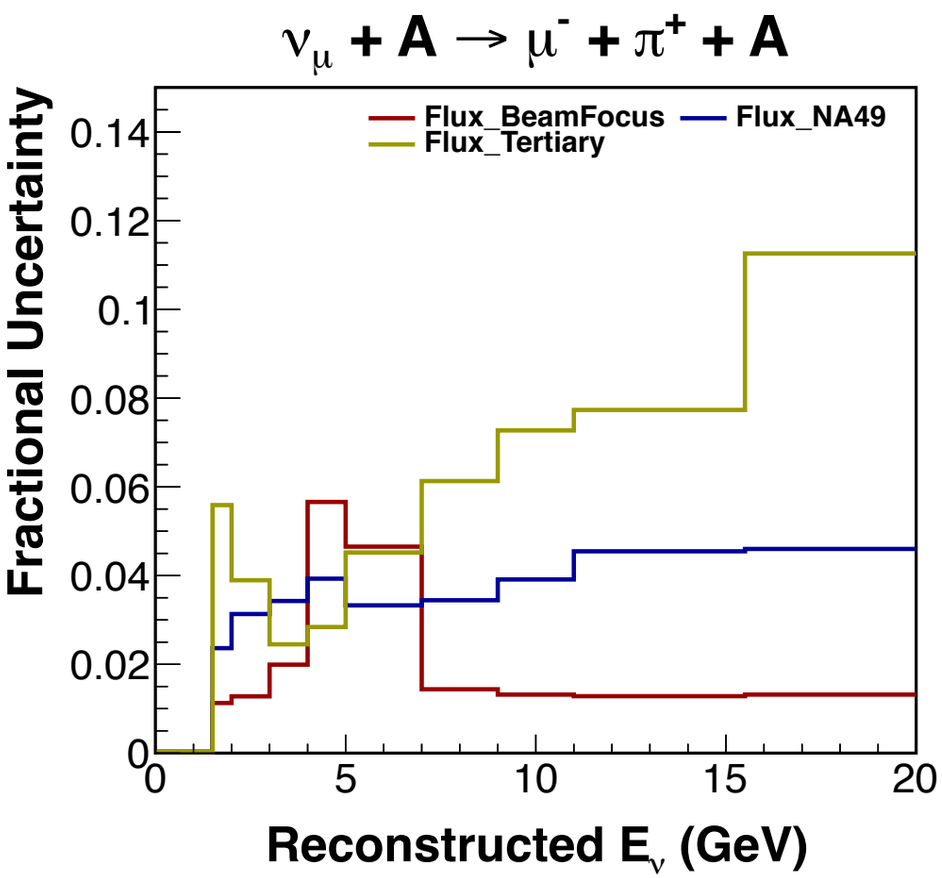
MINERvA 1π CC

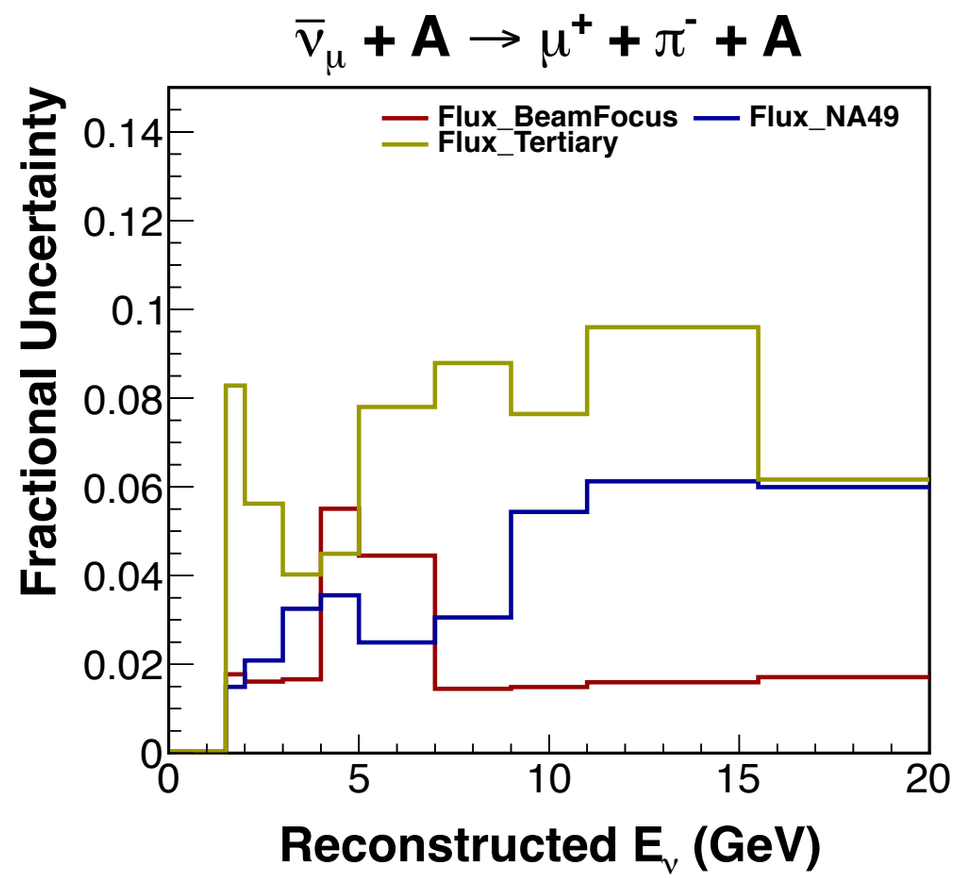
MINERvA 1π CC analysis



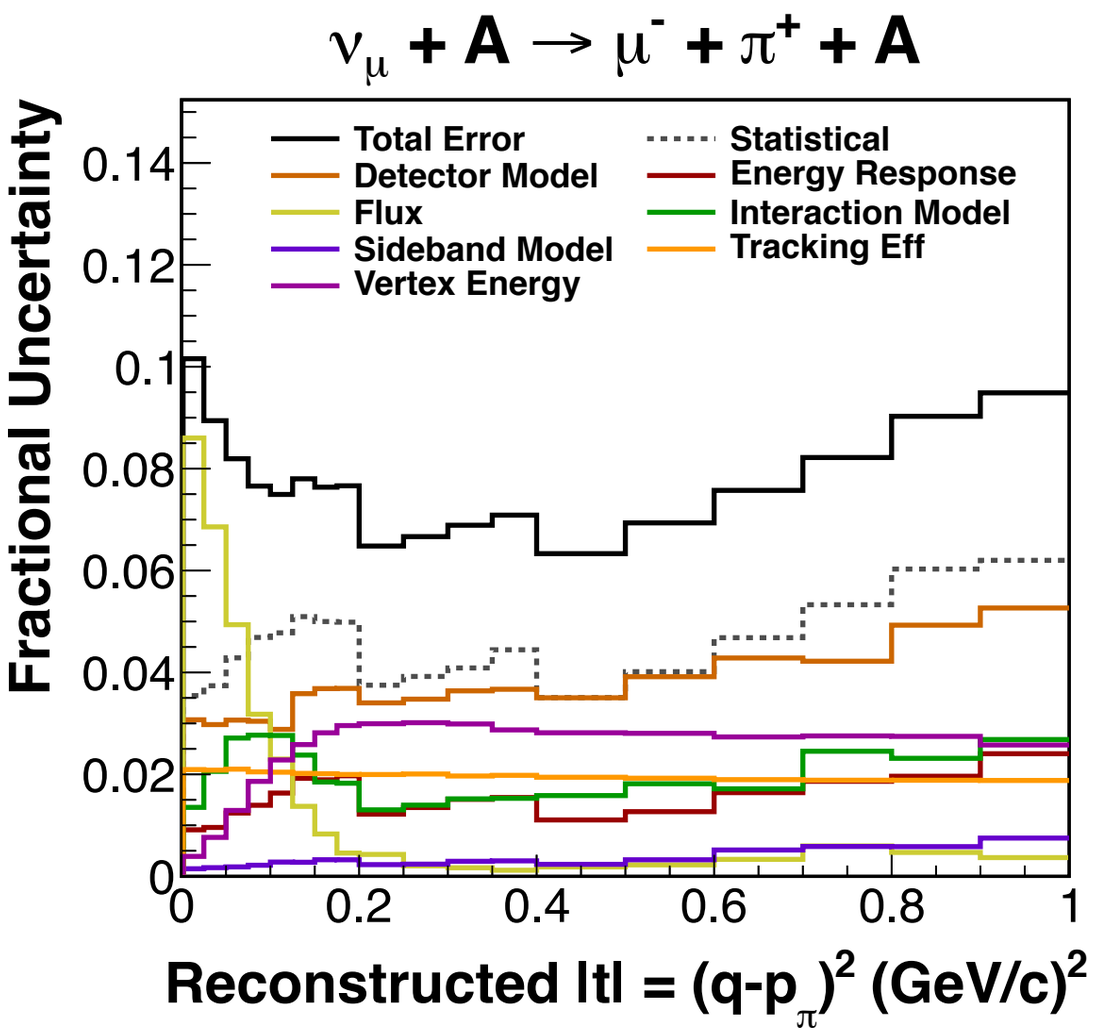


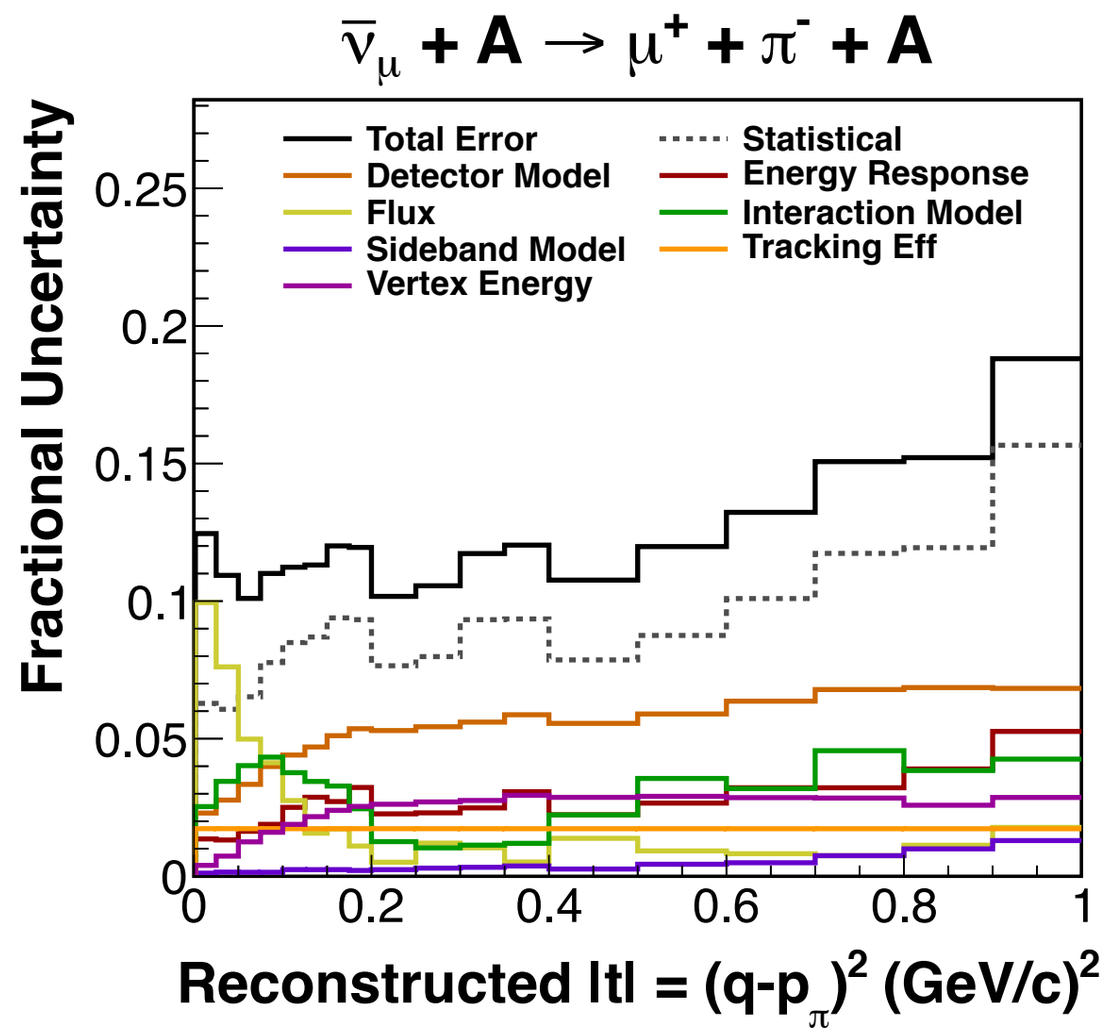
MINERvA Flux Systematics



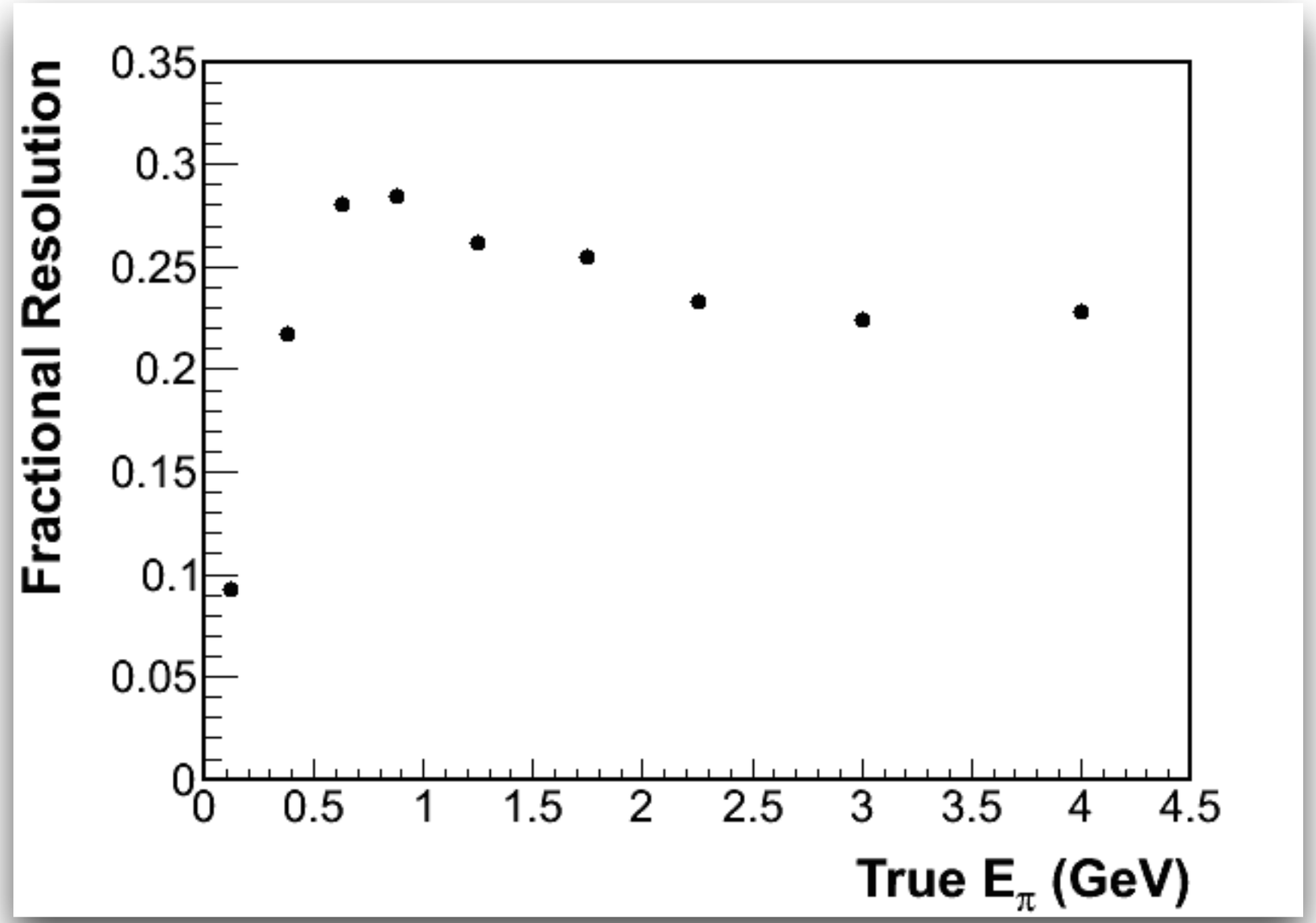


MINERvA Systematics on ltl

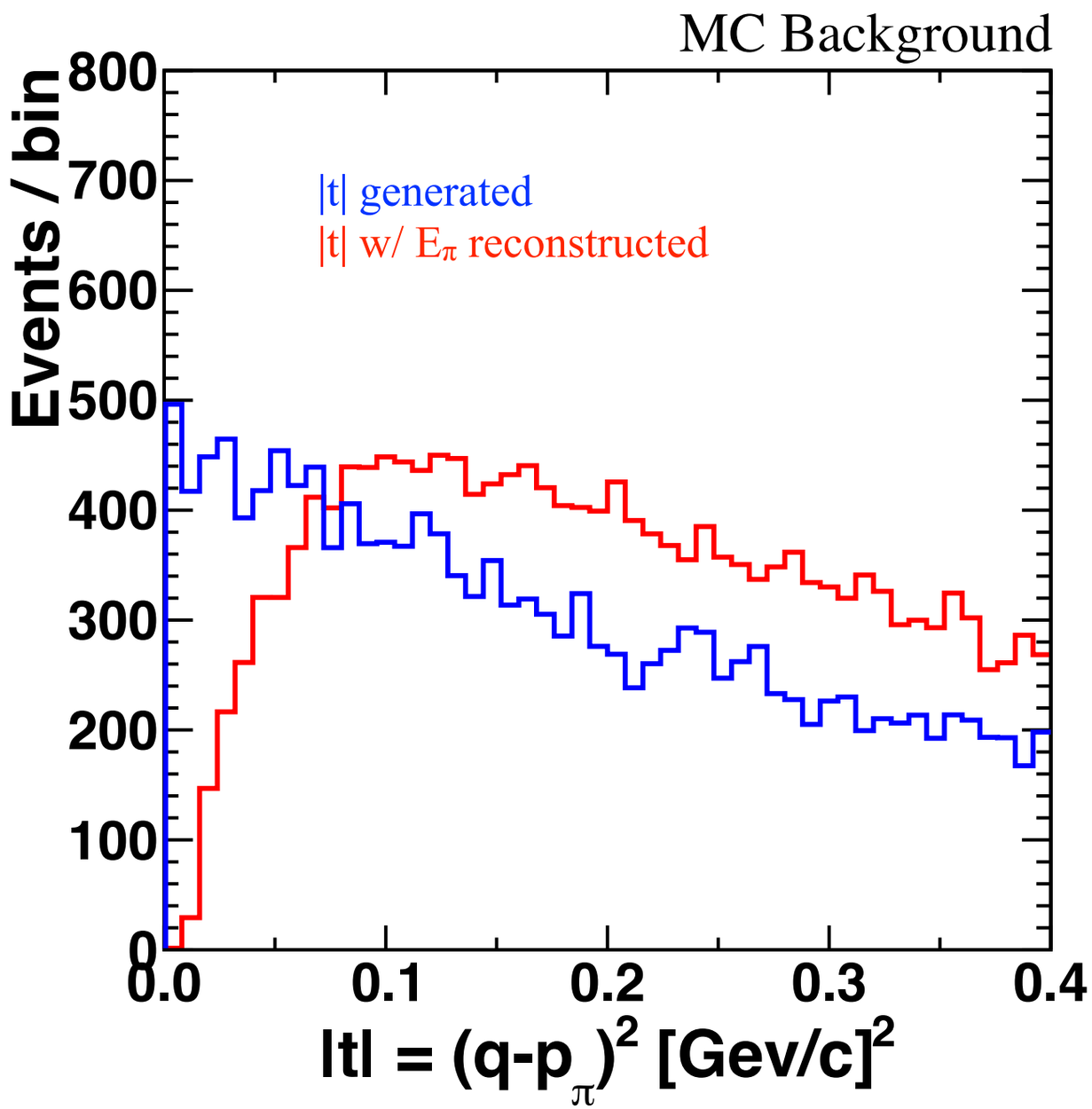


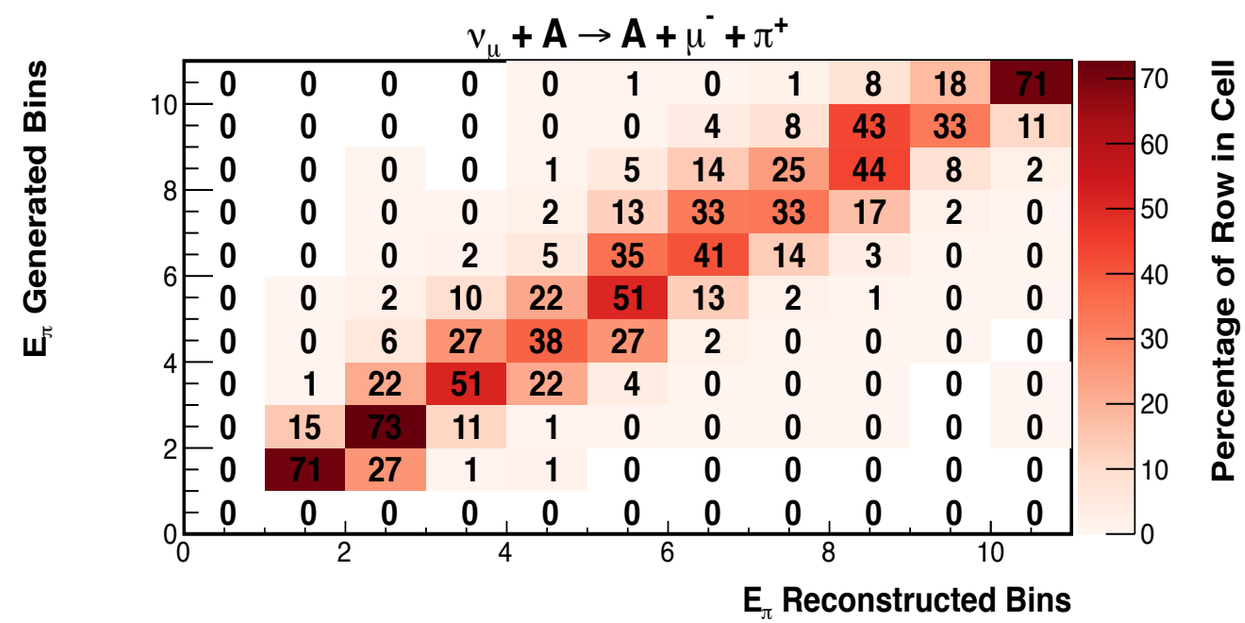


Pion Energy Resolution



Low ltl resolution

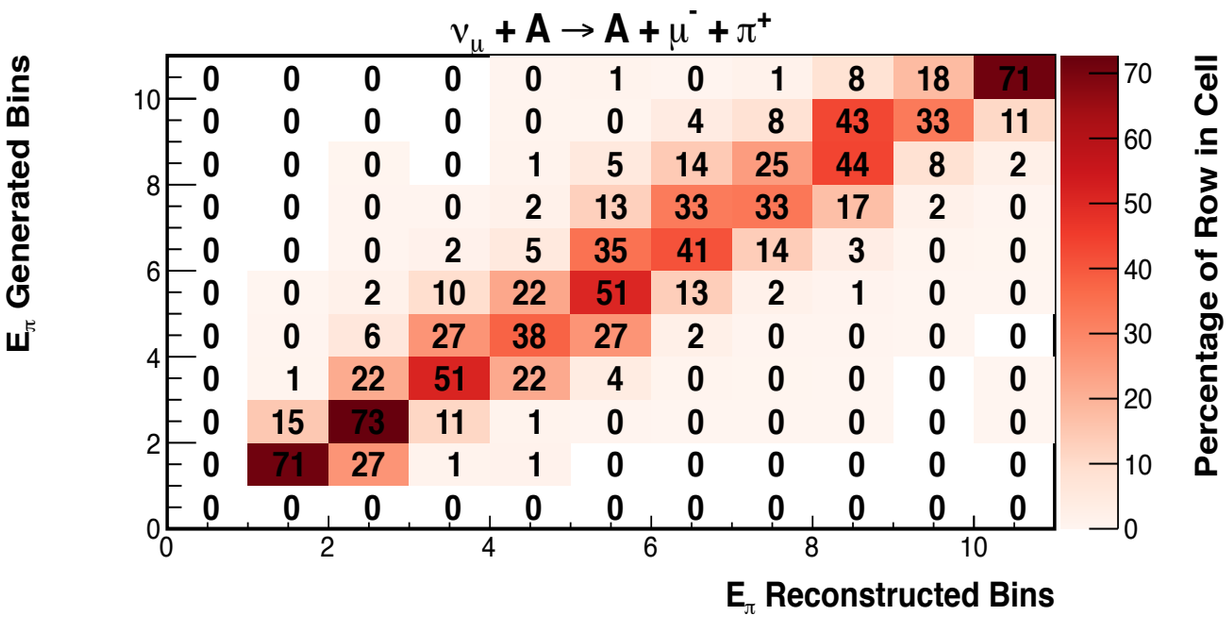


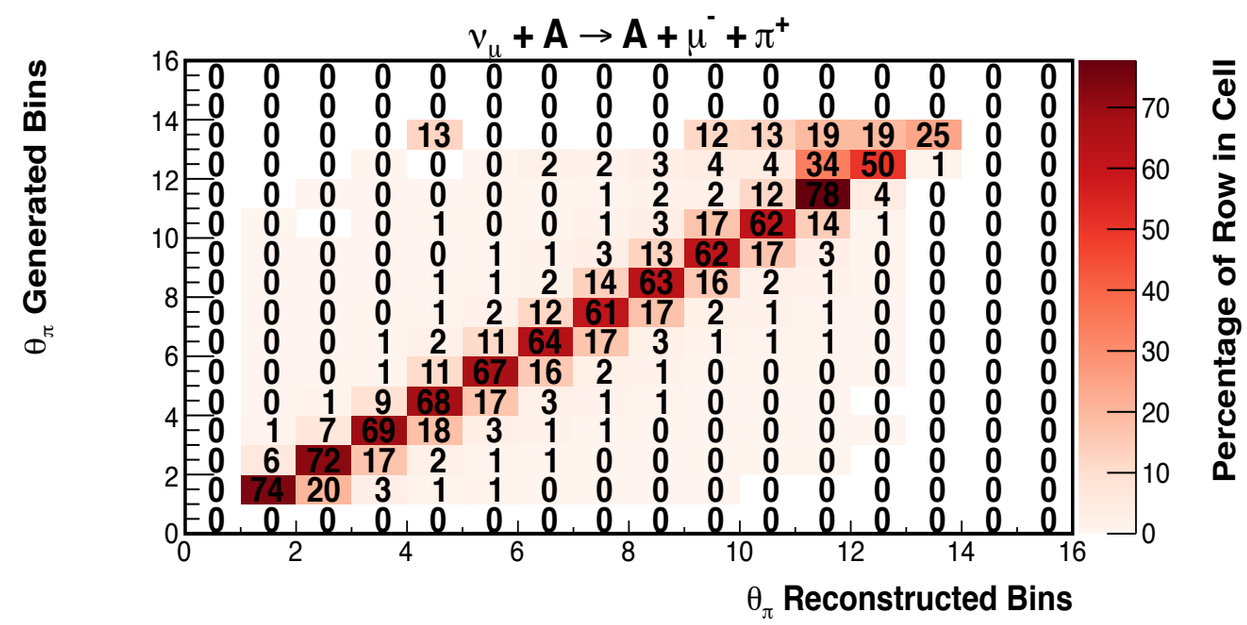


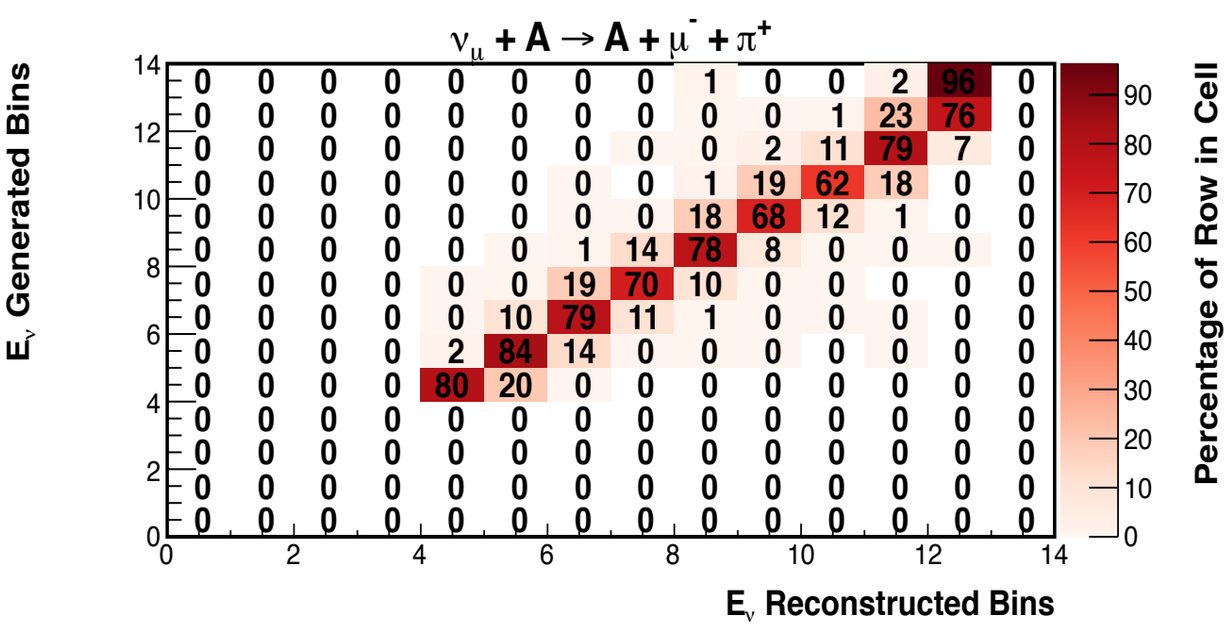
$$18\% + 8\%/\sqrt{E_\pi/1\mathrm{GeV}}$$

Pion energy resolution dominates the experimental resolution of |t|

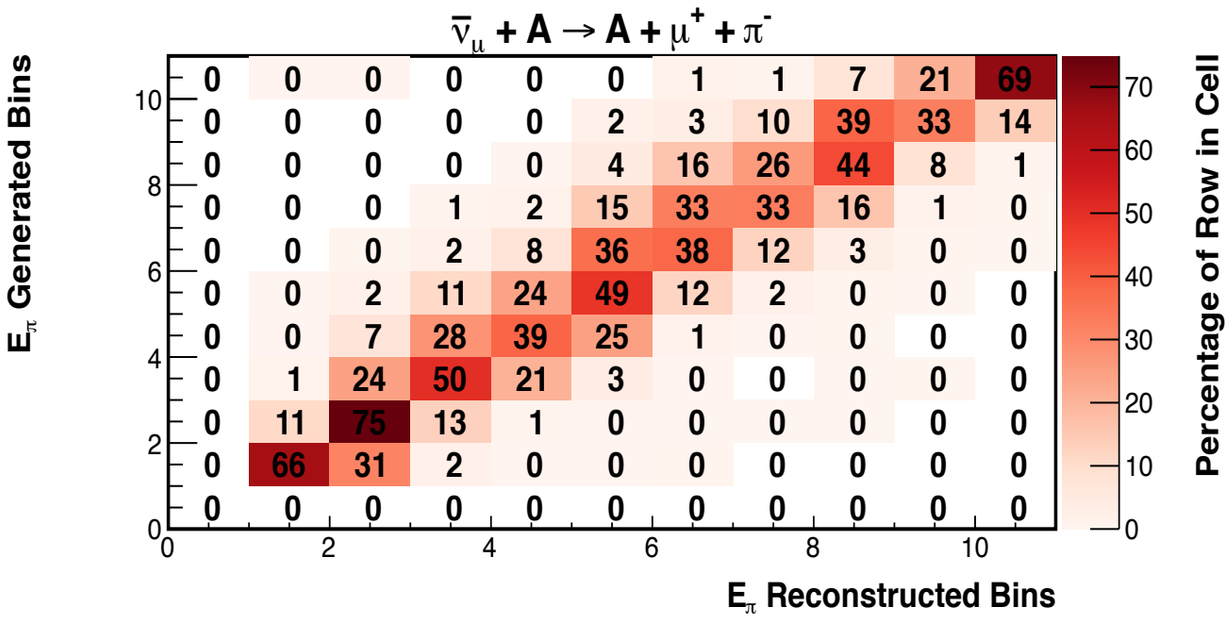
MINERvA Smearing Matrix

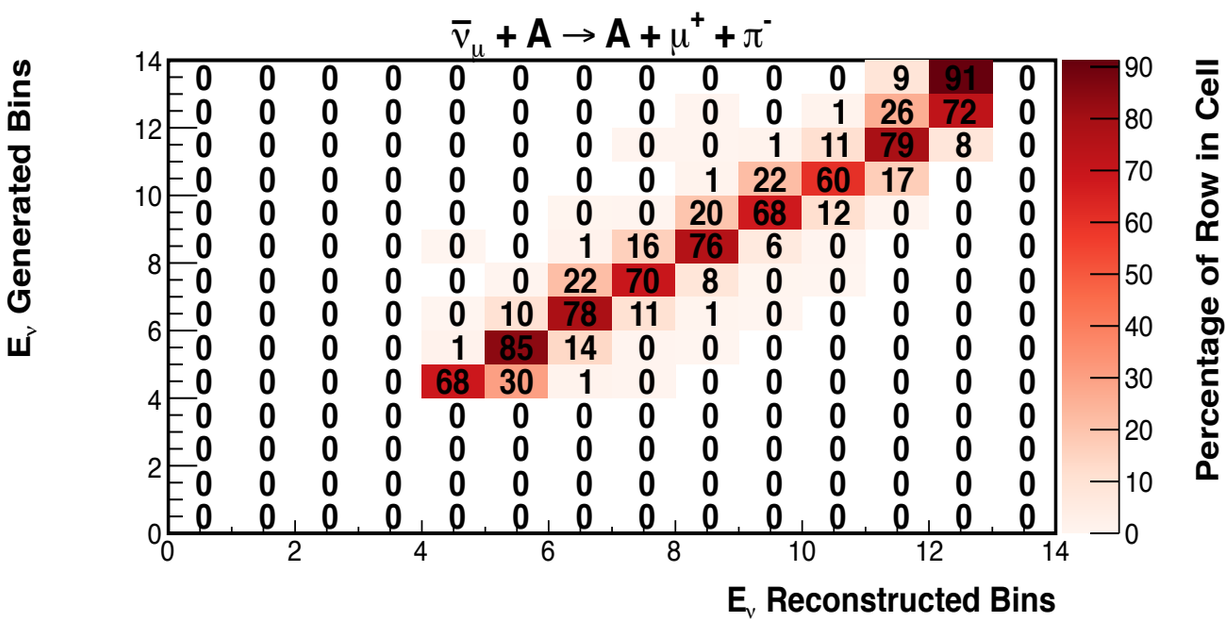


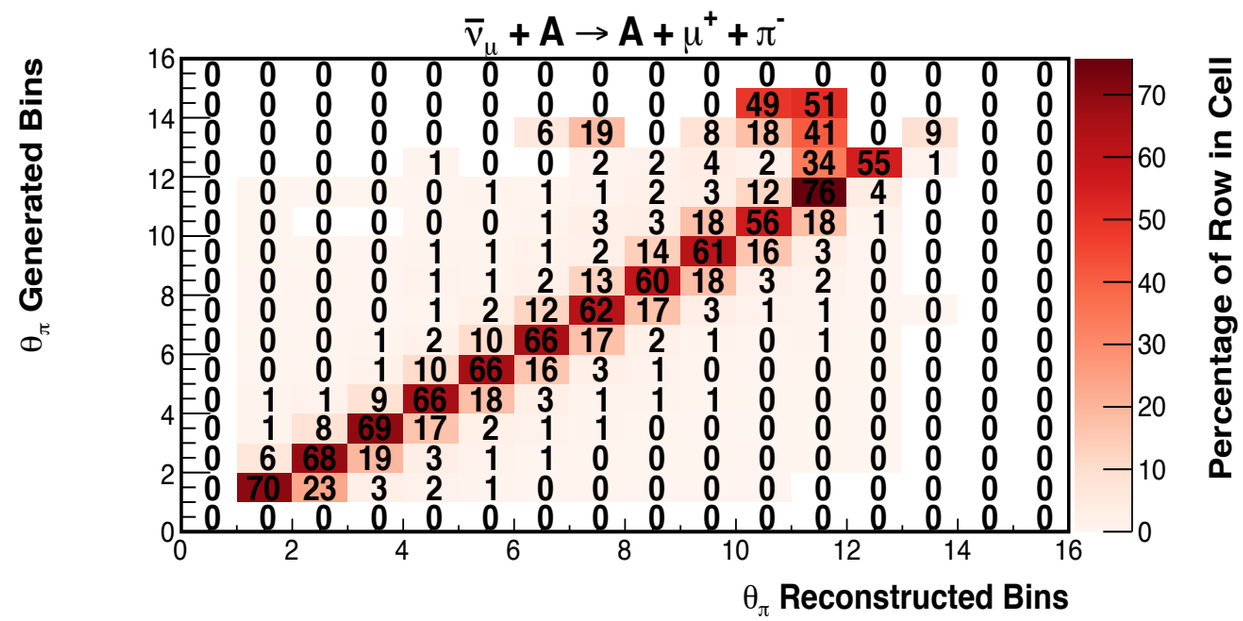




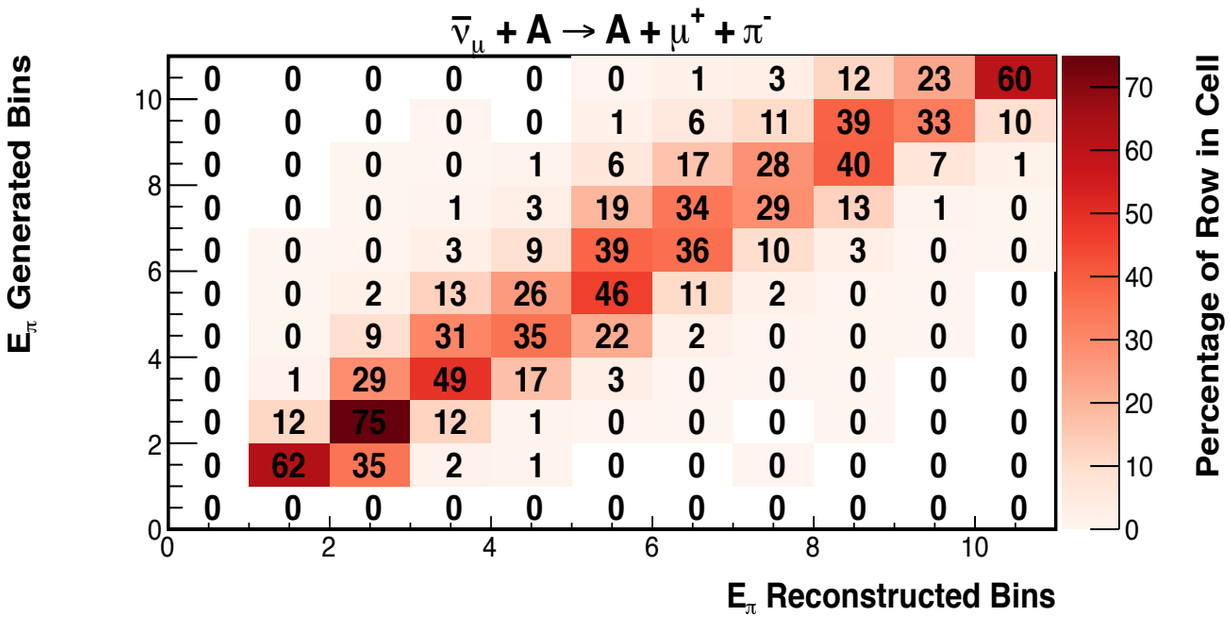
MINERvA Smearing Matrix



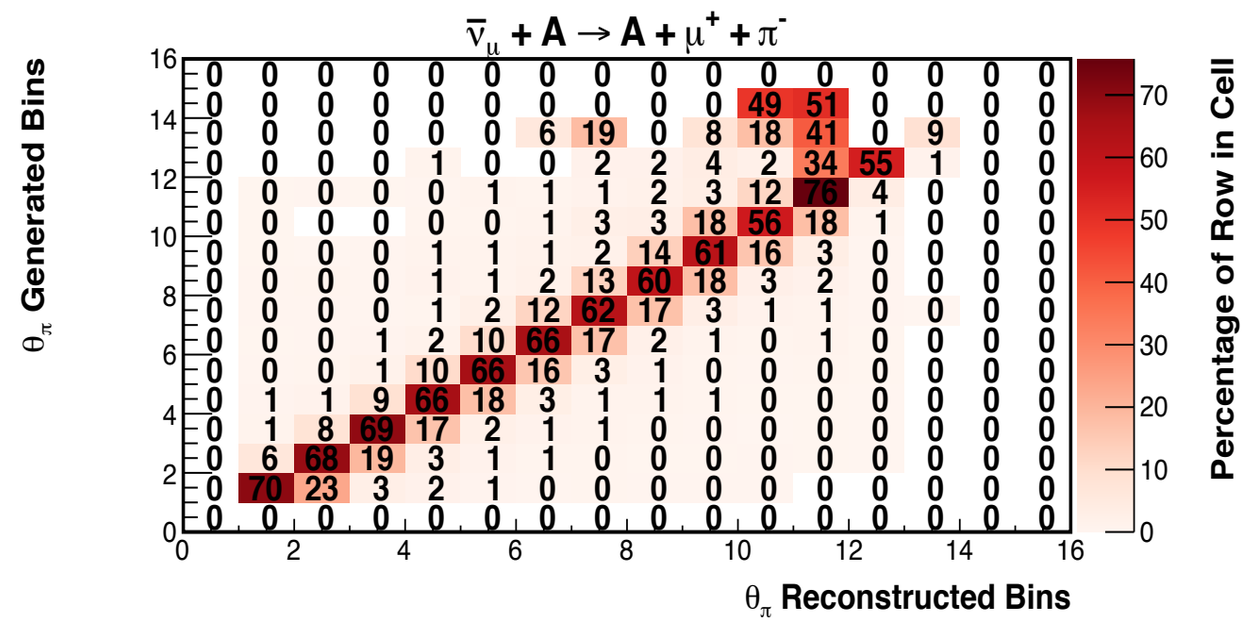


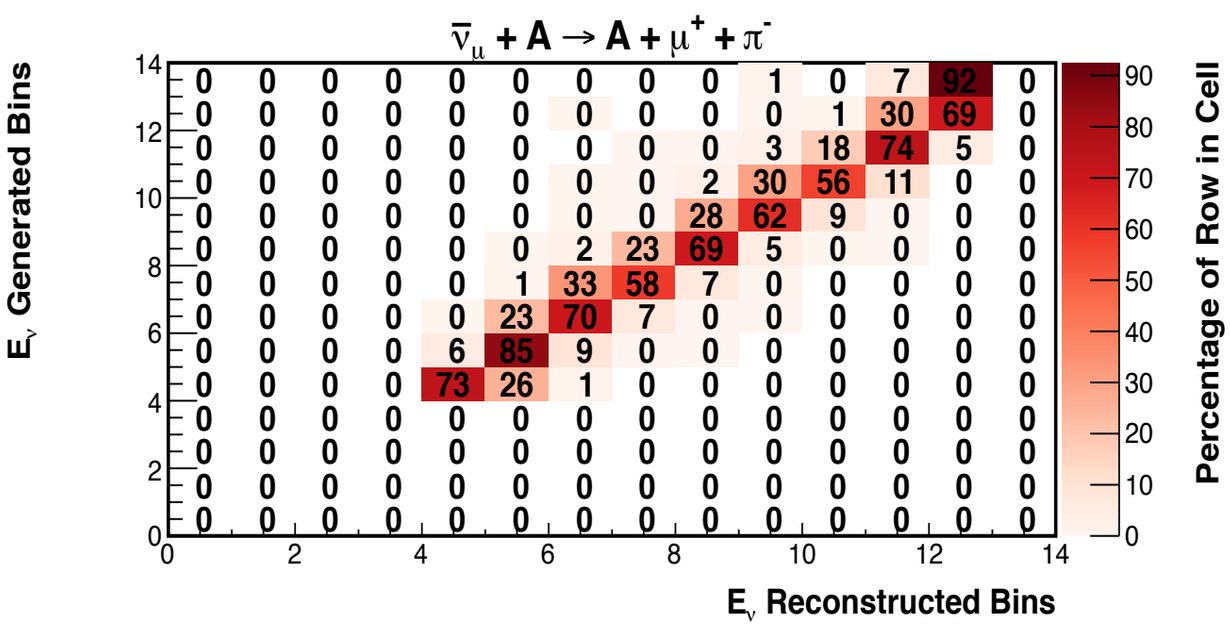


MINERvA Smearing Matrix

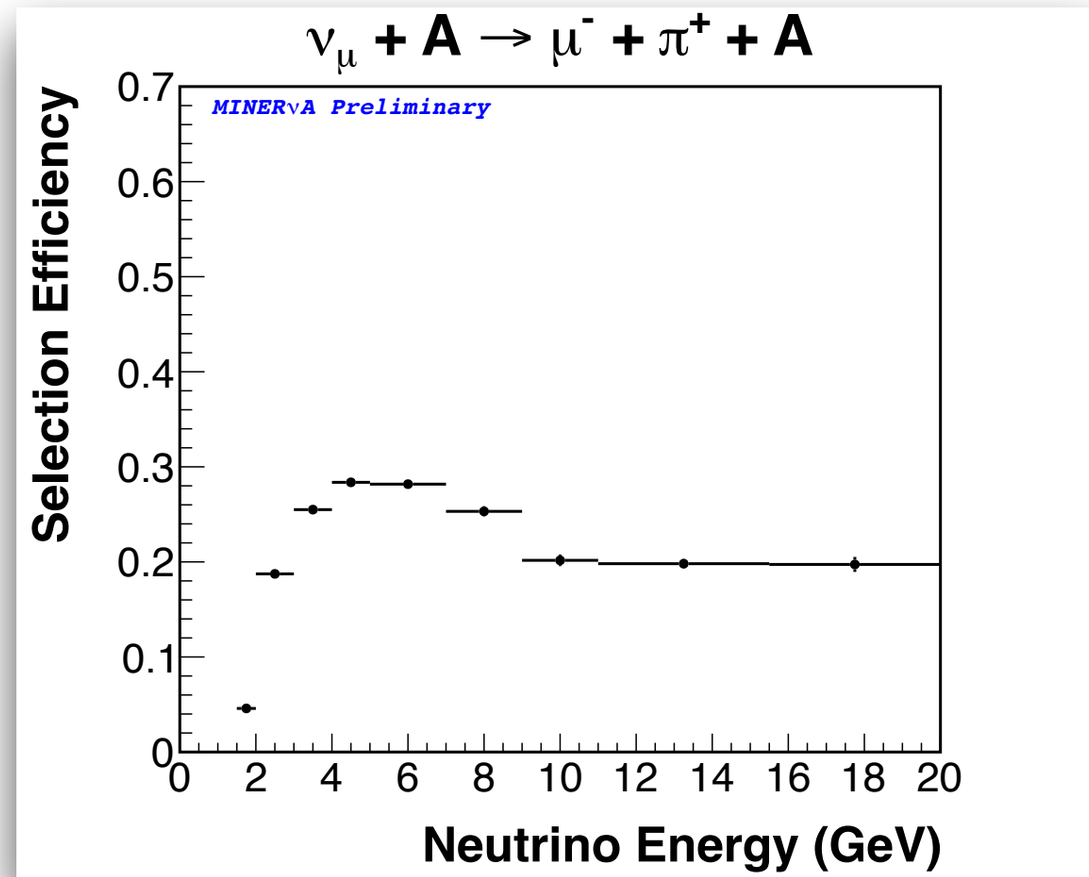


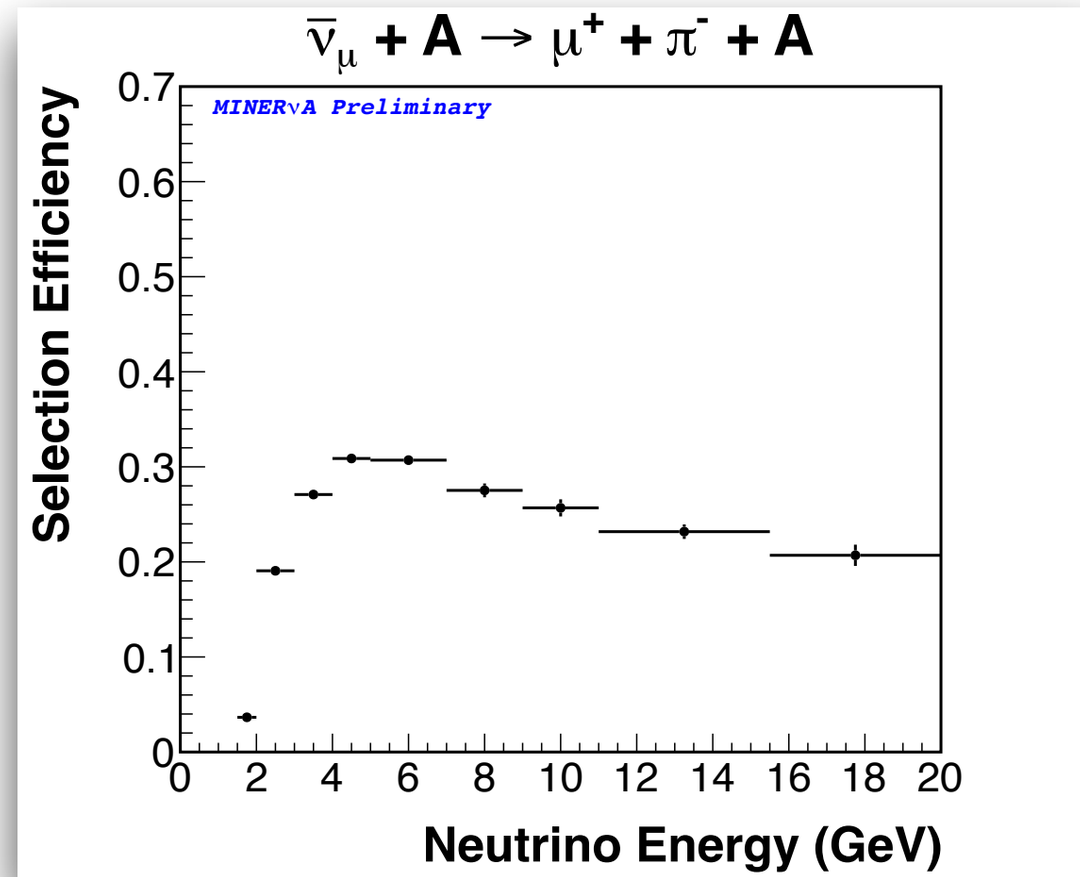
~50% of detector
ArgonNeuT downstream of MINERvA



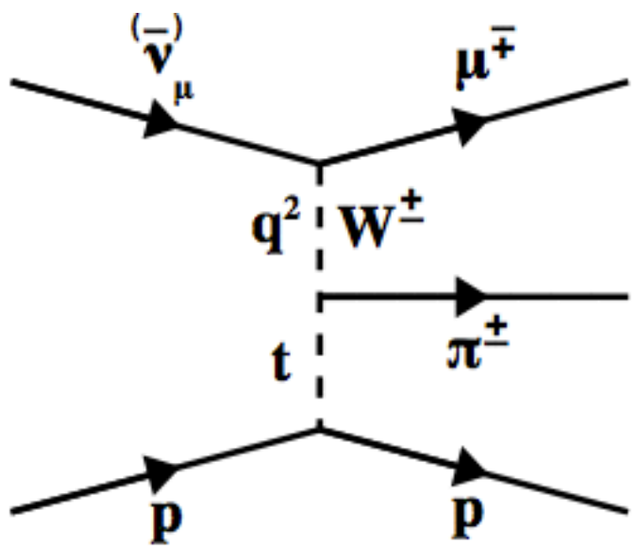


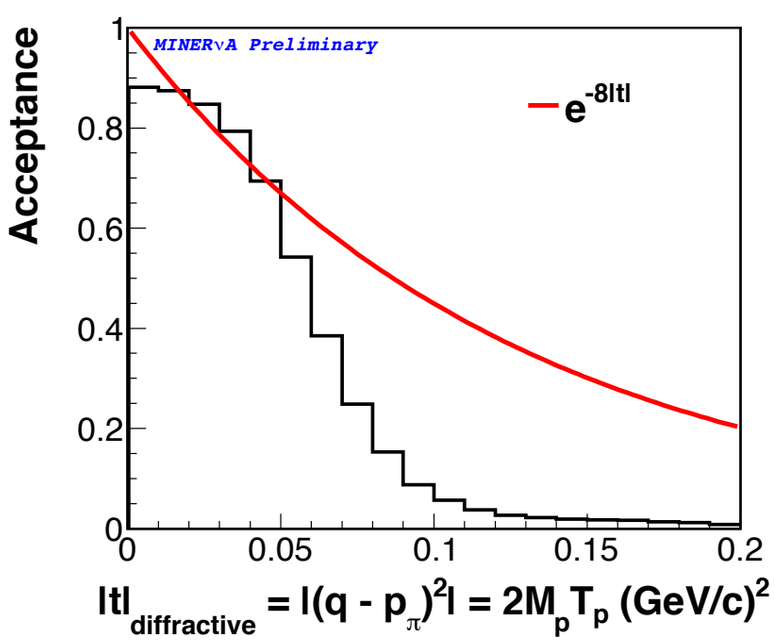
MINERvA Selection Efficiency





Diffractive Pion Production





By number, our fiducial volume targets are ~49% Carbon and ~49% Hydrogen

Vertex energy cut reduce ~60% of the diffractive when the proton carries KE > 50 MeV since we can detect the recoil proton in diffractive events when

$|t|_{diffractive} = |(q-p_\pi)^2| = 2M_pT_p > 0.1$ (GeV/c)^2

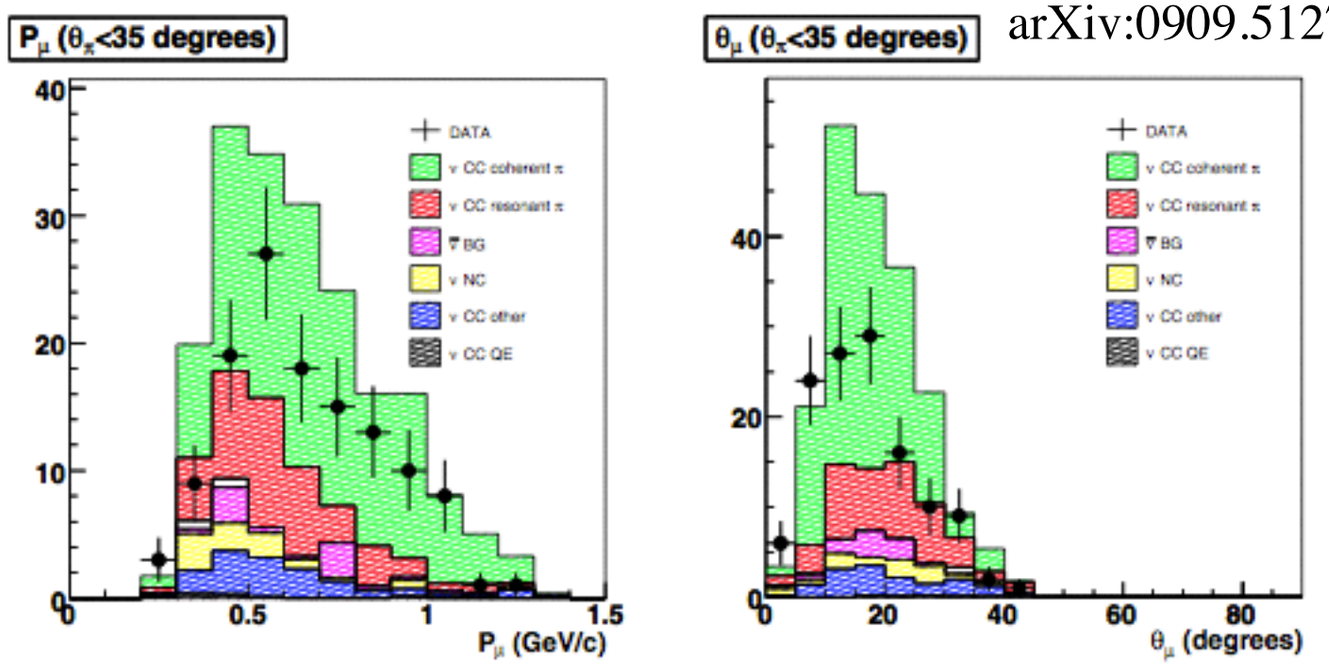
The calculations for the coherent pion production off carbon and diffractive pion production off protons based on the Adler theorem and PCAC relating coherent or diffractive pion production by neutrinos to pi+P/C —> pi+P/C cross sections are:

For Ev ~4.0 GeV and v ~0.9 GeV the ration of diffractive to coherent is ~0.012 (0.033) for neutrinos (antineutrinos)

Coherent Pion Production Measurements

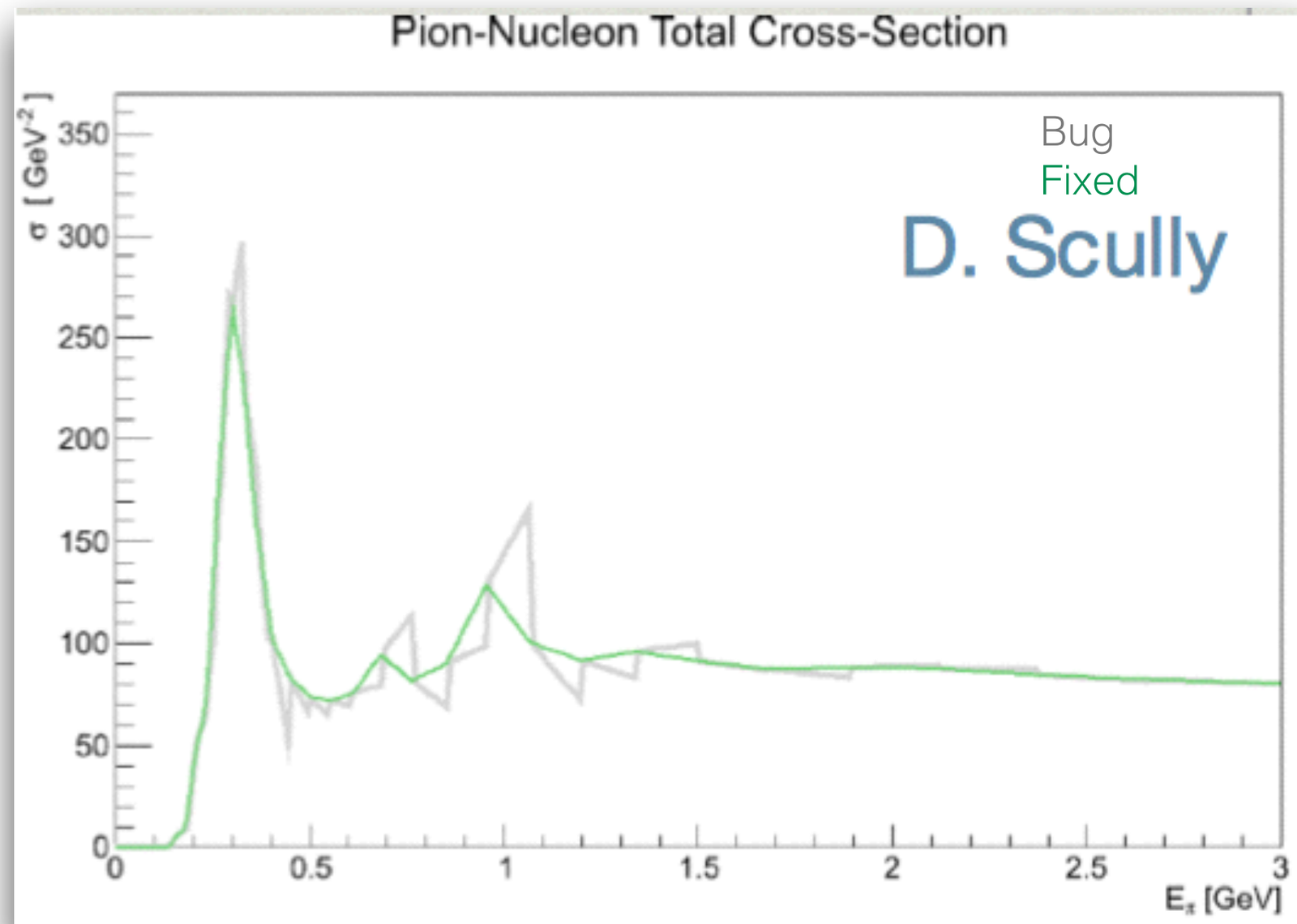
SciBooNE experiment <E_ν> 1.1 GeV & <E_ν> 2.2 GeV

arXiv:0909.5127



After looking in other kinematic distribution and cutting pion angle they observe signal above the predicted background (consistent with upper limit)

GENIE Pion-Nucleon Cross-Section



A bug in the way an array is indexed in Utils/ HadXSUtils.cxx (was also wrong in neugen3 code on which this is based). Identified and fixed by Daniel Cherdack and Dan Scully.

PCAC

- The non-conservation of the axial current leads to the decay of the pion

$$\pi^+ \to \mu^+ + \nu_\mu$$

- With matrix elements given by

$$\mathcal{M} = \frac{G_F}{\sqrt{2}} \langle 0 | J_\mu | \pi(q) \rangle \bar{\nu}_l \gamma_\mu (1 - \gamma_5) l$$

- Lorentz invariance of $\langle 0 | J_\mu | \pi(q) \rangle$ requires that the amplitude to be either vector or axial. Since the pion has not spin the only vector available is the four-momentum q

$$\langle 0 | J_\mu^A(x) | \pi(q) \rangle = i f_\pi q_\mu e^{-iqx}$$

PCAC

- Taking the divergence of the previous equation we have

$$\langle 0|\partial^\mu J^A_\mu(x)|\pi(q)\rangle = f_\pi q^2 e^{-iqx} = f_\pi m_\pi^2 e^{-iqx}$$

- We conclude from this relation that the axial current is not conserved, because neither f_π nor m_π is zero. However, the above expression also shows that the divergence of the axial current is small because the pion mass is small in comparison with the mass of all other hadrons

- This lead to the idea that the axial current is "partially" conserved