CC Coherent Pion Production at MINERνA

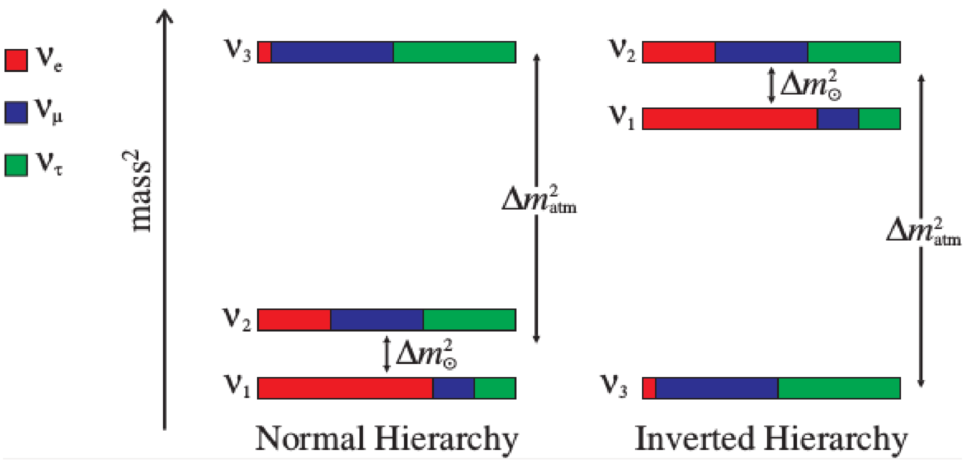
Aaron Mislivec
University of Rochester
Argonne Seminar
Nov 23, 2015

Outline

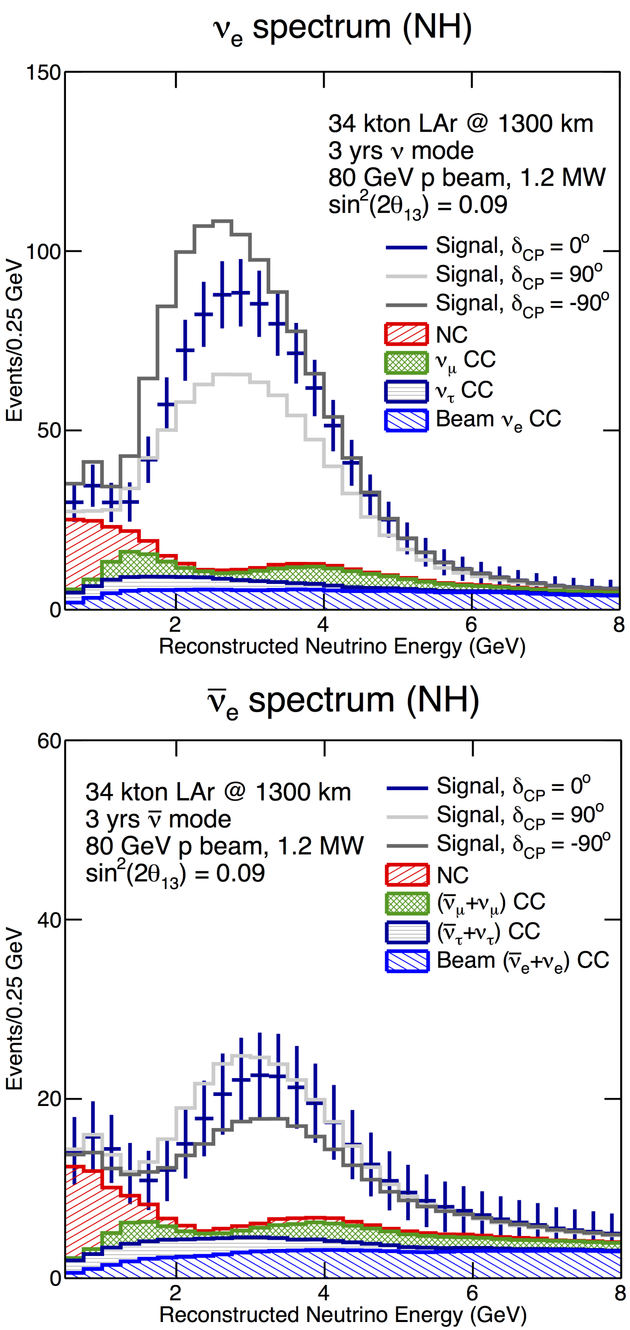
- Neutrino oscillation experiments and coherent pion production
- CC coherent pion production at MINERνA
- T2K and coherent pion production

Neutrino Oscillation Experiments and Coherent Pion Production

Neutrino Oscillation Measurements



- We are in the era of precision neutrino oscillation measurements
- Current and future oscillation experiments aim to
  - resolve mass hierarchy
  - measure CP violation

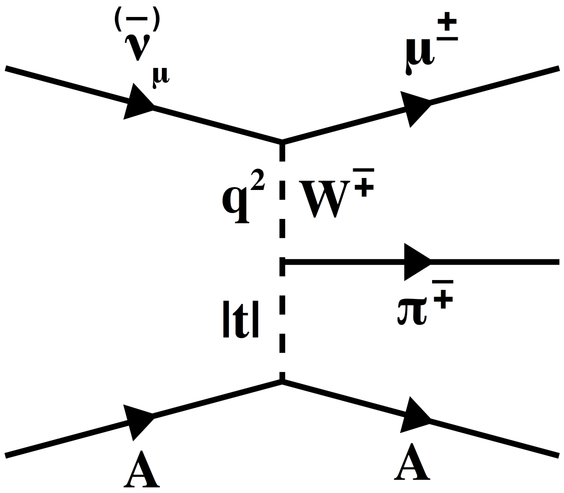


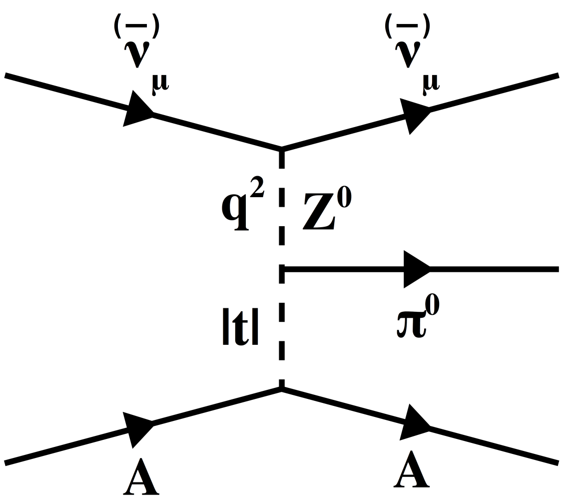
Predicted CP violation effect at DUNE
arXiv:1307.7335

Neutrino Oscillation Experiments and Neutrino-Nucleus Interactions

- All neutrino oscillation experiments
  - must measure neutrino energy E_ν
  - predict the E_ν spectrum, which requires neutrino-nucleus (νA) interaction models
- νA interaction models predict
  - interaction rate as a function of E_ν
  - final state used in reconstructing E_ν
- Oscillation experiments use neutrino event generators (e.g. GENIE, NEUT) – Monte Carlo simulation of νA interactions

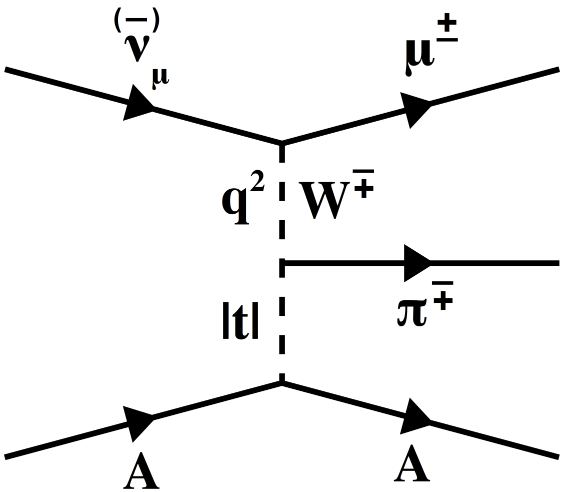
Coherent Pion Production

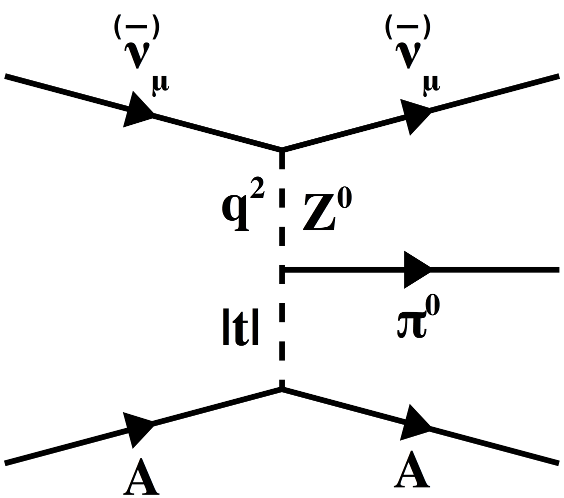




- Produces forward lepton and pion while leaving nucleus in its ground state
- Model independent features:
  - No nuclear break-up
  - Small 4-momentum transfer to the nucleus, $|t| = |(p_\nu - p_\mu - p_\pi)^2| \lesssim \hbar^2/R^2$
- CC coherent π^+production a background for ν_μ disappearance
  - Affects E_ν reconstruction
  - Important at low-θ_μ
- NC coherent π^0production a background for ν_e appearance ($\pi^0 \rightarrow \gamma\gamma$)

Coherent Pion Production Model





To date, neutrino event generators employed by oscillation experiments use the Rein-Sehgal model for coherent scattering:

- Per Adler's PCAC theorem,

$$\left.\frac{d\sigma^{\pi^+}}{dQ^2 dy d|t|}\right|_{Q^2=0} = \frac{G_F^2 M}{2\pi^2} f_{\pi^+}^2 \frac{1-y}{y} \left.\frac{d\sigma(\pi^+ A \to \pi^+ A)}{d|t|}\right|_{E_\pi = Ey}$$

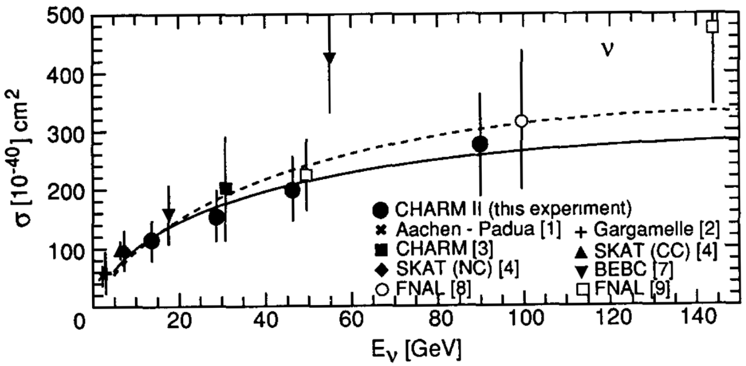
- Extrapolates to $Q^2 > 0$ via a multiplicative axial vector dipole form factor with $M_A \approx 1$ GeV

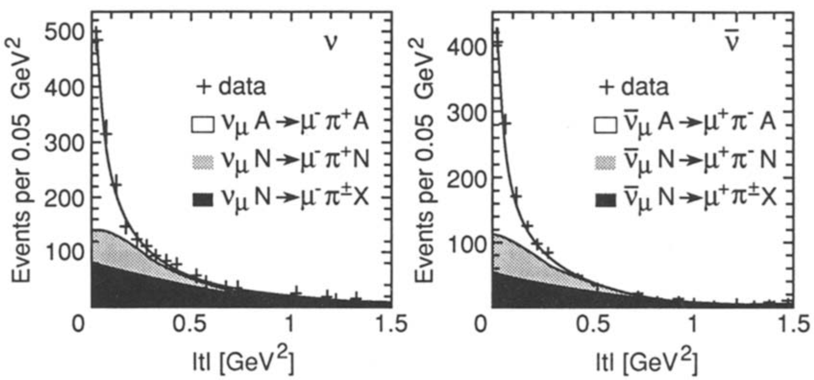
$$F(Q^2) = 1/(1 + Q^2/M_A^2)^2$$

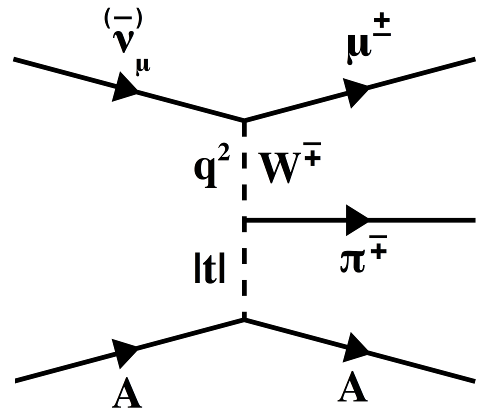
- πA cross section
  - parameterized using πN scattering data
  - Falls with increasing $|t|$: $\sim e^{-|t|R^2/\hbar^2}$
- For CC reaction, correction for final state lepton mass

CC Coherent Pion Production Data

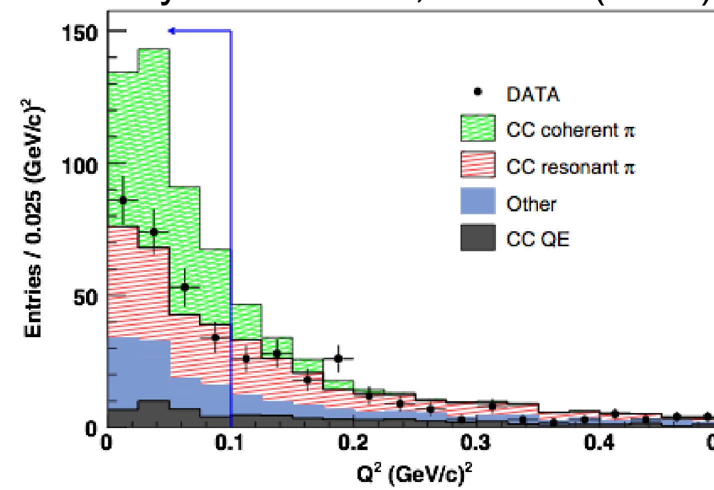
CHARM II
Phys. Lett. B 313, 267 (1993)







SciBooNE
Phys. Rev. D 78, 112004 (2008)



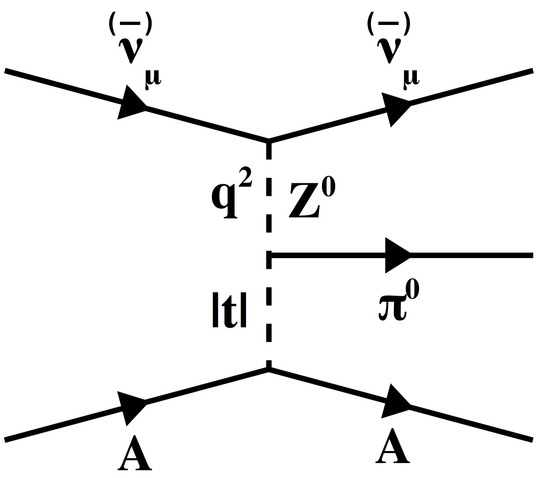
Recent measurements at $E_\nu \sim 1$ GeV (K2K, SciBooNE)

- Unable to measure E_π, |t|
- Found no evidence for coherence at low-Q^2

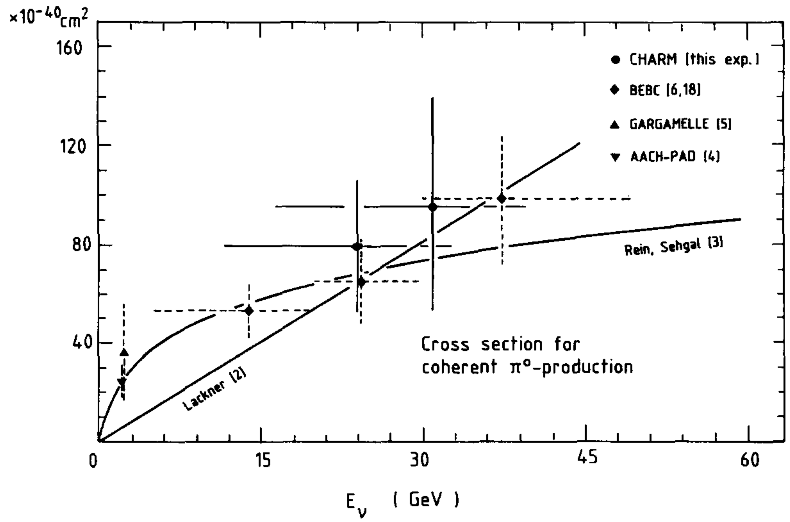
Past measurements for $E_\nu \geq 2$ GeV

- Identified coherence by measuring |t|
- Agreement with Rein-Sehgal model

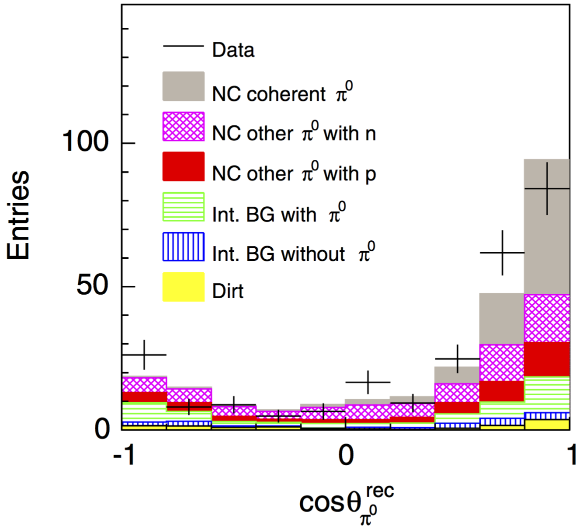
NC Coherent Pion Production Data



CHARM
Phys. Lett. B157, 469 (1985)

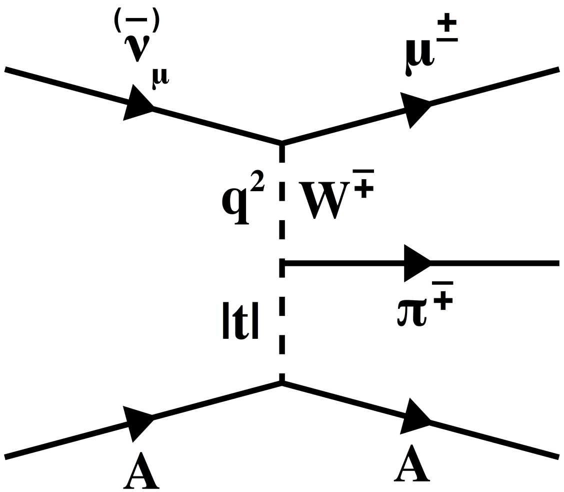


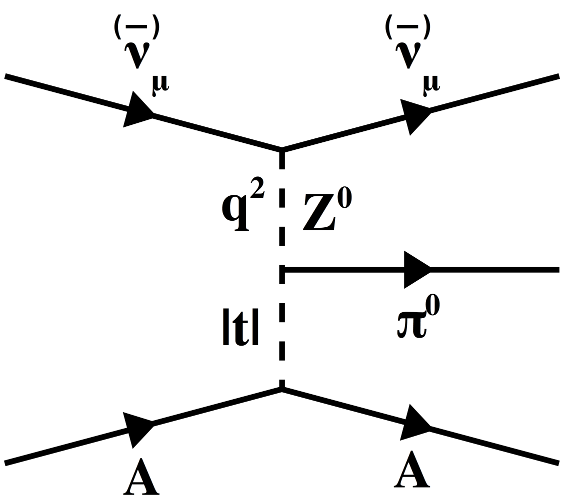
SciBooNE
Phys. Rev. D81, 111102 (2010)



- Model dependent measurement
  - Can't measure E_ν, |t|
  - For bare π^0 events, look for excess at low-θ_π
- Flux averaged measurement, $<E_\nu>$

NC Coherent Pion Production Constraint





In the PCAC picture, the CC channel provides a constraint on the NC channel:

- Again, per Adler's PCAC theorem,

$$\left.\frac{d\sigma^{\pi^+}}{dQ^2 dy d|t|}\right|_{Q^2=0} = \frac{G_F^2 M}{2\pi^2} f_{\pi^+}^2 \frac{1-y}{y} \left.\frac{d\sigma(\pi^+ A \to \pi^+ A)}{d|t|}\right|_{E_\pi = Ey}$$

- For isoscalar targets

$$\frac{d\sigma(\pi^+ A \to \pi^+ A)}{d|t|} = \frac{d\sigma(\pi^0 A \to \pi^0 A)}{d|t|}$$

- Then

$$\frac{d\sigma^{\pi^+}}{dQ^2 dy d|t|} = 2\left(\frac{d\sigma^{\pi^0}}{dQ^2 dy d|t|}\right) \times \ l.m.c$$

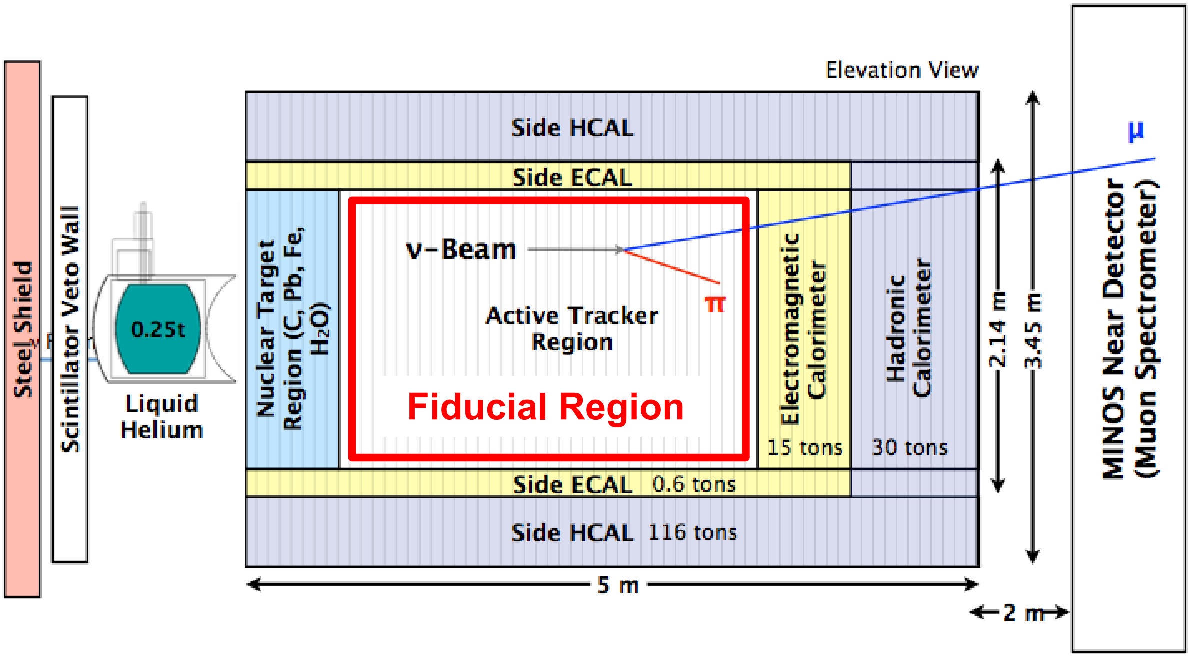
since $f_{\pi^+}^2 = 2 f_{\pi^0}^2$

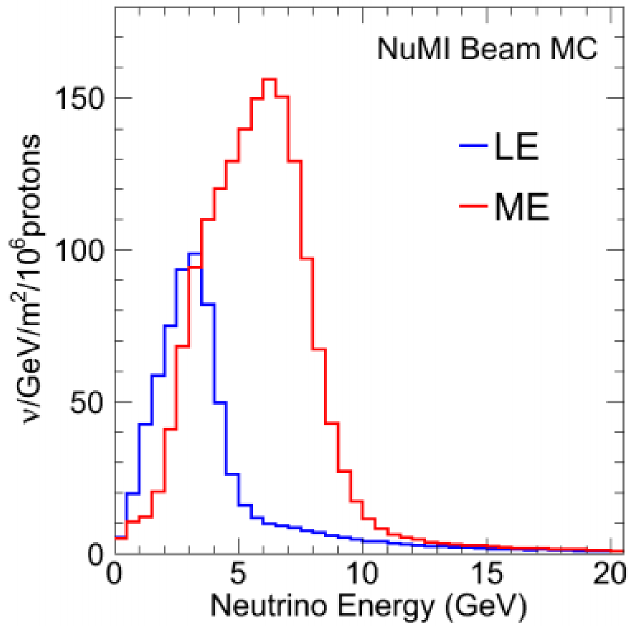
Other Coherent Models

- Newer coherent models include
  - Berger-Sehgal
    - Based on Adler's PCAC theorem
    - Main difference from Rein-Sehgal is πA cross section from empirical fit to πC scattering data
  - Alvarez-Ruso
    - Microscopic model
    - Sum of 1π production on all nucleons in the nucleus
    - Initial and final state nucleon constrained to the same state
    - π distortion in nuclear medium

CC Coherent Pion Production at MINERνA

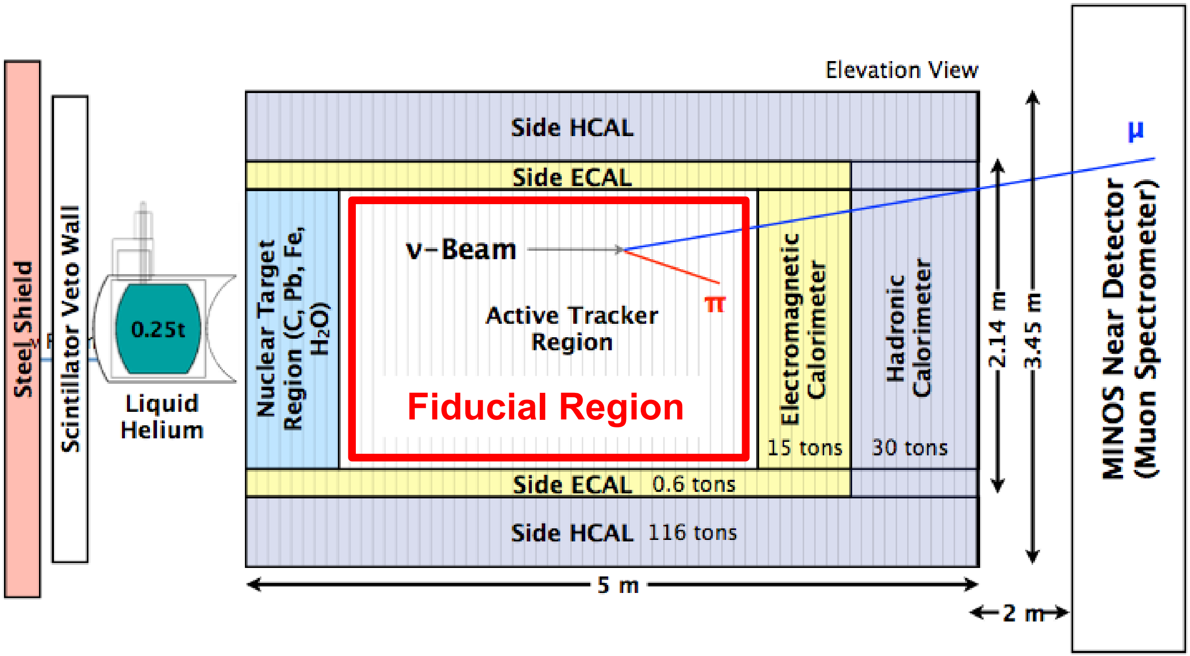
MINERνA

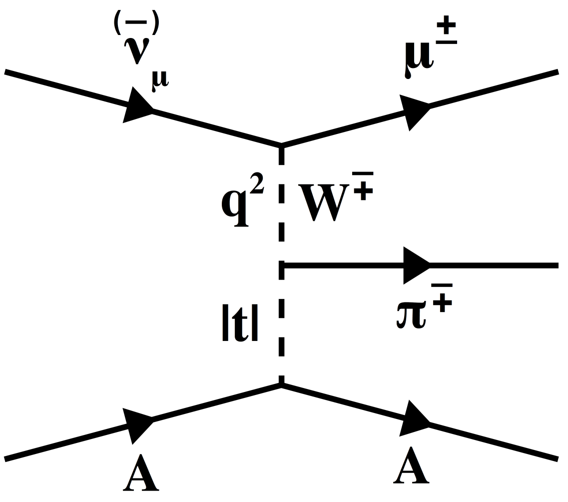




- Dedicated νA scattering experiment
- Precision measurements of νA cross sections and nuclear effects at few GeV E_ν
- Testing ground for the GENIE neutrino event generator
- Utilizes Fermilab's NuMI ν-beam
- Results shown herein from low energy (LE) beam configuration

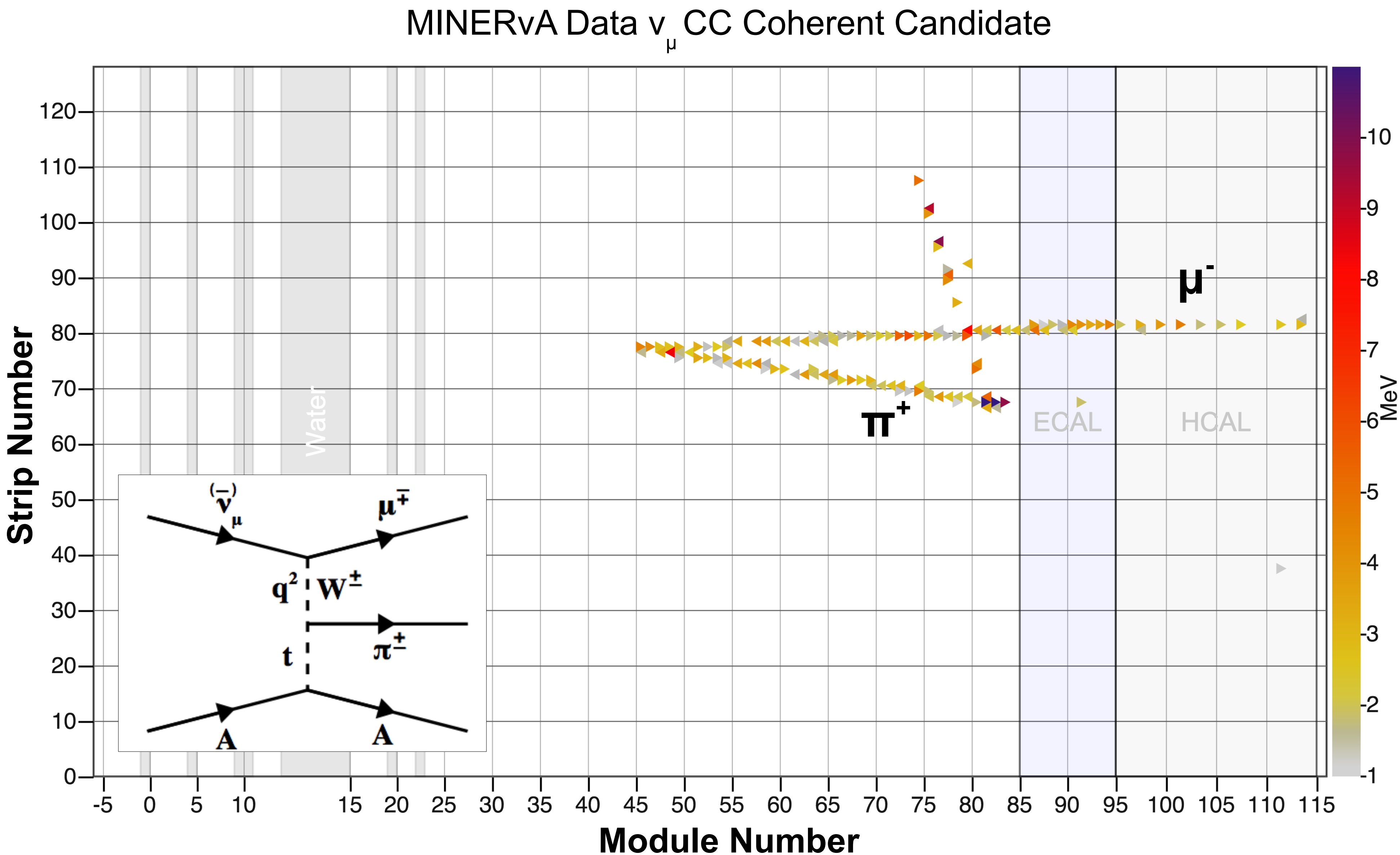
Coherent Pion Production at MINERνA



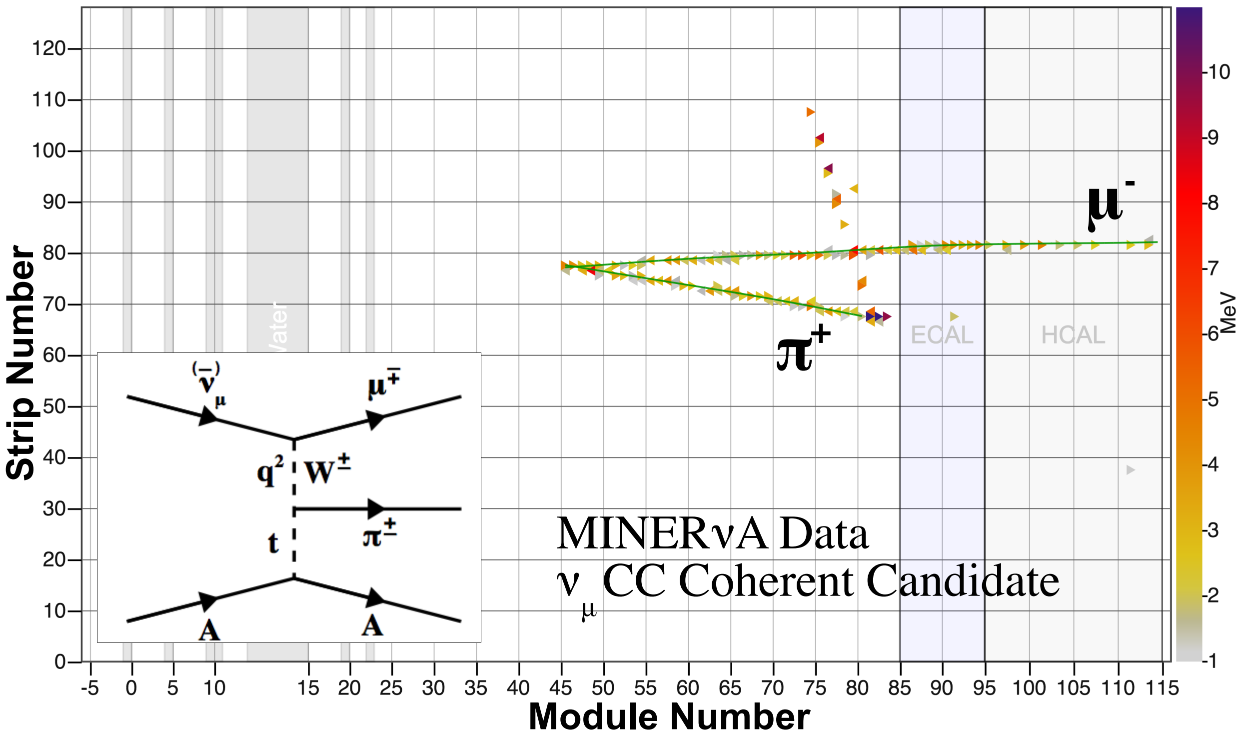


- MINERνA has measured CC coherent π production on carbon in its fully active tracker region (CH) for $1.5 < E_\nu < 20$ GeV
- Model-independent identification of coherent interactions by
  - resolving vertex activity
  - reconstructing $|t|=|(p_\nu - p_\mu - p_\pi)|^2$

CC Coherent Pion Production Candidate

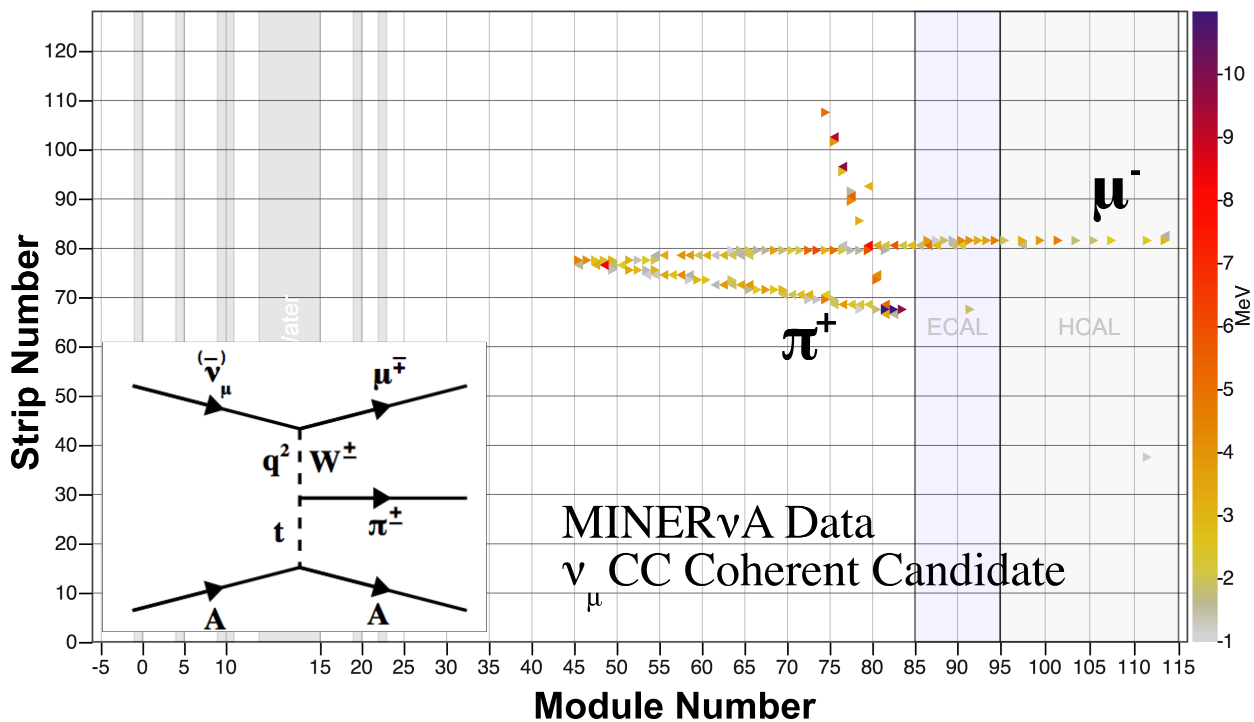


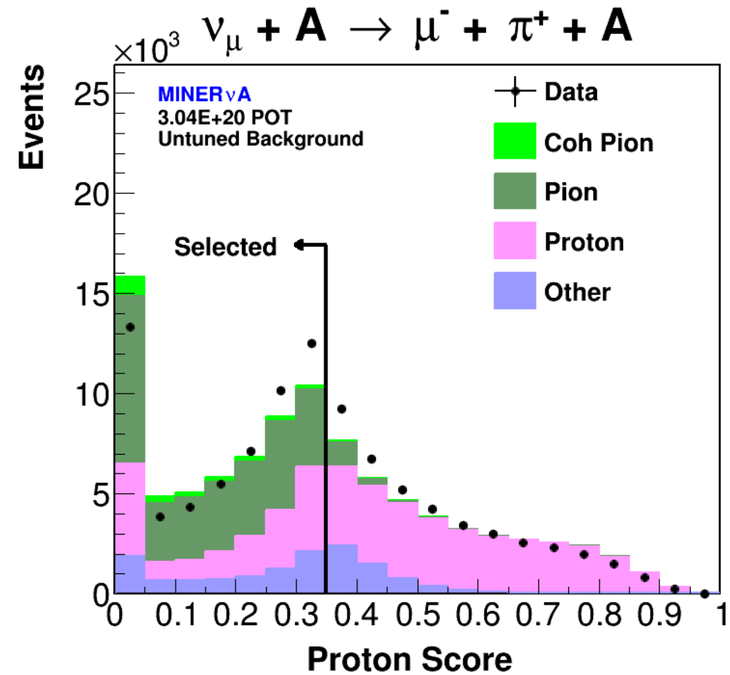
Event Selection: Reconstruction Cuts



- Reconstructed vertex in tracker region (CH)
- Muon reconstructed in both MINERνA and MINOS for p_μ and charge
- Second reconstructed track at vertex for θ_π
- $E_\nu > 1.5$ GeV: muon reconstruction threshold
- $E_\nu < 20$ GeV: flux uncertainties

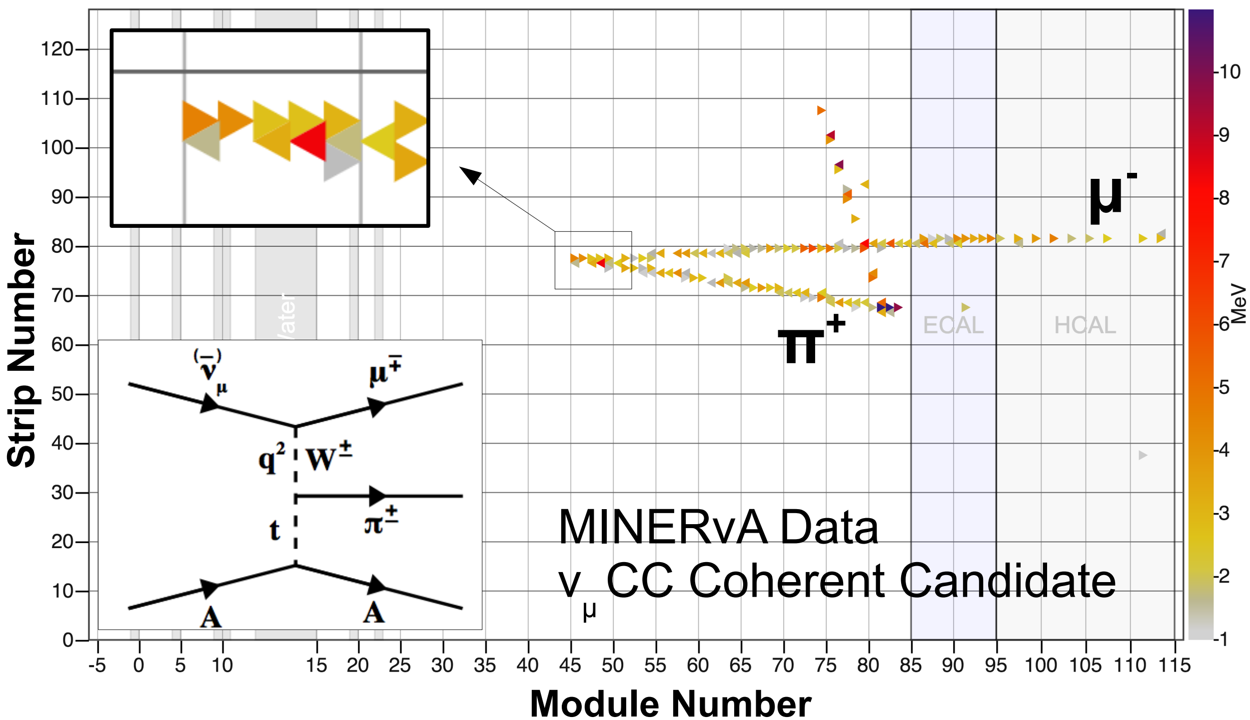
Event Selection: Proton Score

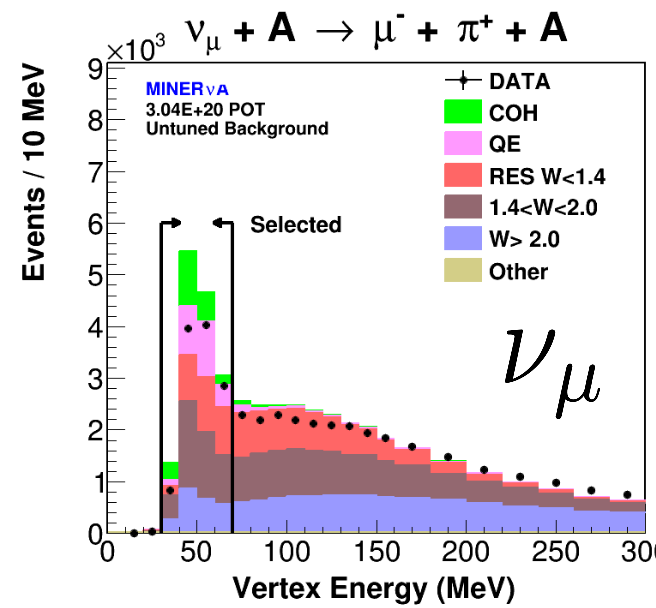


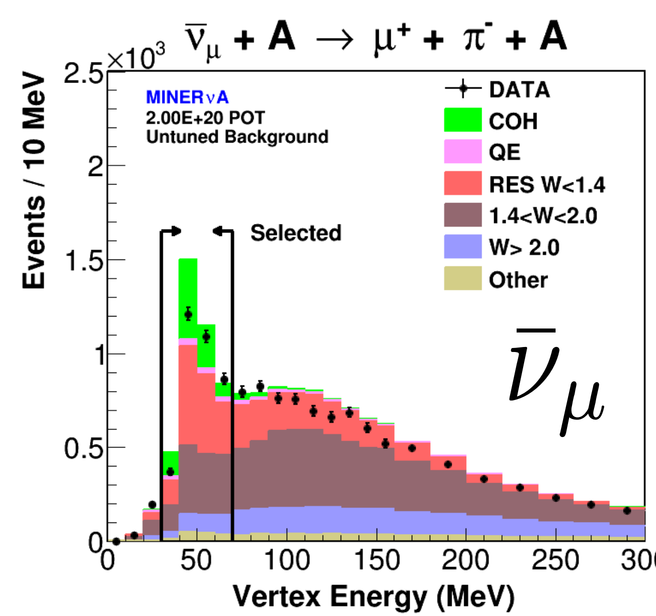


- Proton Score – likelihood that dE/dx profile along hadron track is due to a proton
- ν_μ measurement requires Proton Score < 0.35 to suppress CC quasi-elastic and resonance background

Event Selection: Vertex Energy



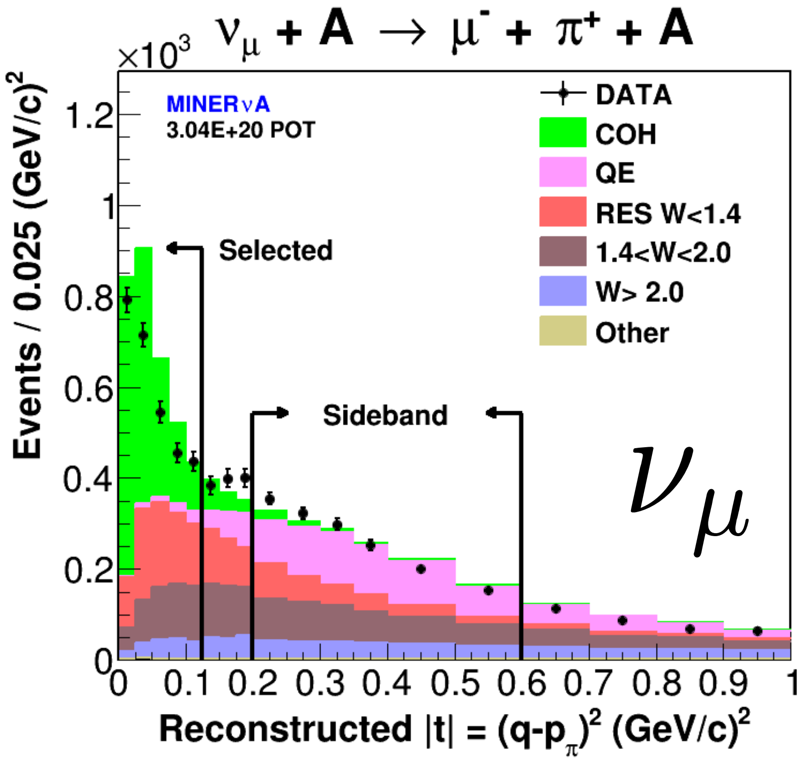


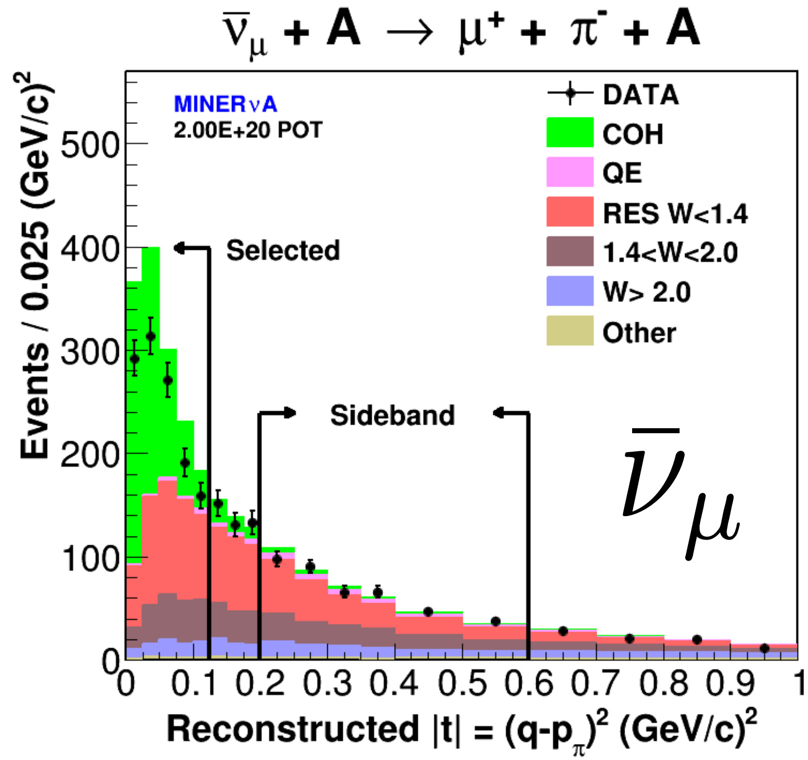


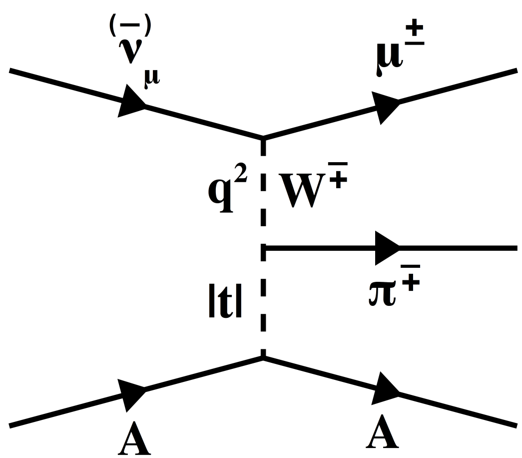
Visible energy within a region around the vertex is required to be consistent with a minimum ionizing muon and pion:

$30 < E_{vtx} < 70$ MeV

Event Selection: |t|

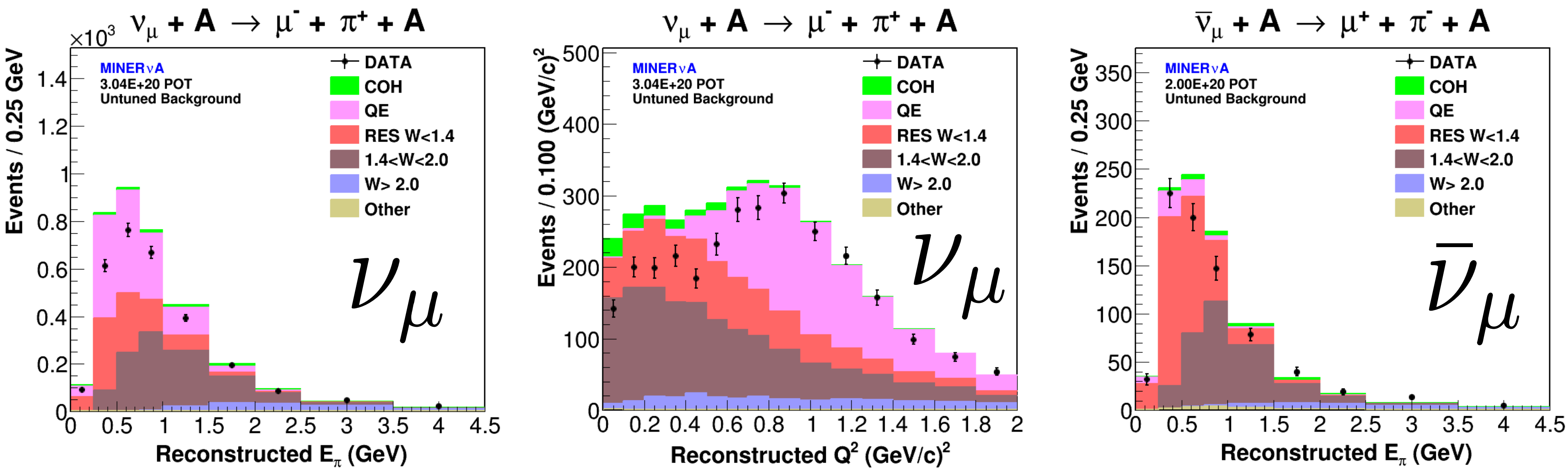






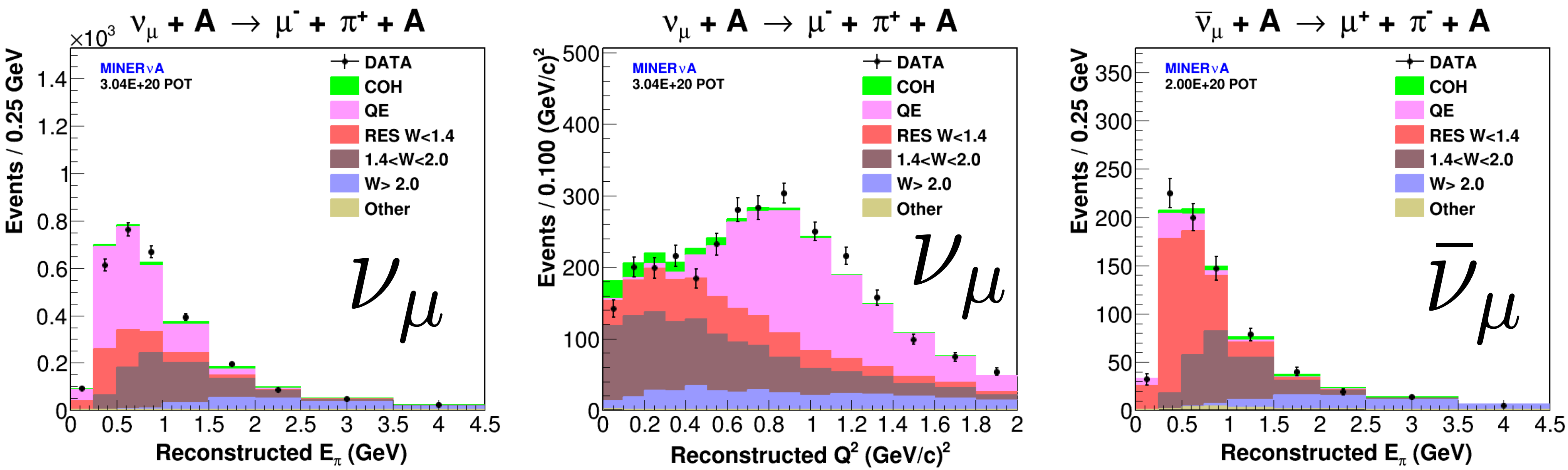
- MINERνA is able to reconstruct the 4-momentum transfer to the nucleus, $|t|=|(p_\nu-p_\mu-p_\pi)|^2$
- Coherent candidates: $|t| < 0.125$ GeV^2
- Sideband for tuning background: $0.2 < |t| < 0.6$ GeV^2

Background Tuning



- Above plots: sideband ($0.2 < |t| < 0.6$ GeV^2) distributions used for background tuning
- Background normalizations fit to data in
  - E_π and Q^2 for ν_μ
  - E_π only for anti-ν_μ
- Sideband sample passes E_{vtx} cut – minimize sensitivity of background tuning to data-MC disagreement in E_{vtx} cut efficiency due to mis-modeled vertex activity

Background Tuning



Above plots show sideband distributions after applying background normalizations from the fit

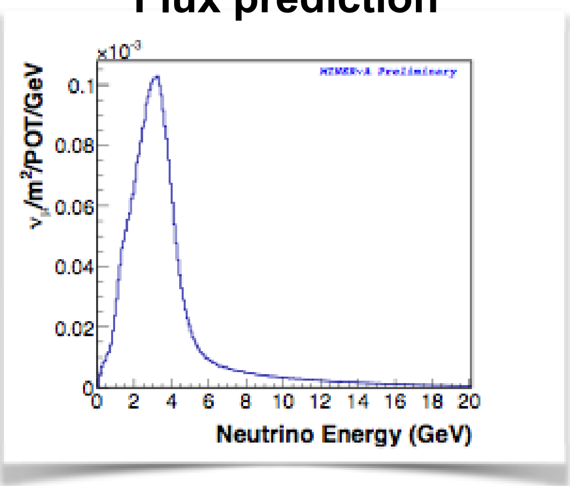
Background	ν_μ	Anti-ν_μ
CCQE	1.03 +/- 0.04	1.0 (fixed)
Non-CCQE W < 1.4 GeV	0.64 +/- 0.07	0.94 +/- 0.07
1.4 < W < 2.0 GeV	0.70 +/- 0.05	0.72 +/- 0.08
W > 2.0 GeV	1.4 +/- 0.2	2.2 +/- 0.3

Cross Section Calculation

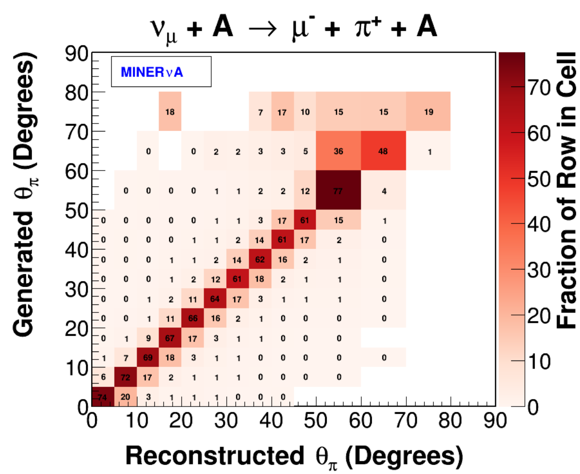
$$\left(\frac{d\sigma}{d\theta_\pi}\right)_i = \frac{1}{T_n \Phi_\nu} \cdot \frac{1}{(\Delta\theta_\pi)_i} \cdot \frac{\sum_j U_{ij}(N_j^{data} - N_j^{bkgd})}{\epsilon_i}$$

Number of scattering targets

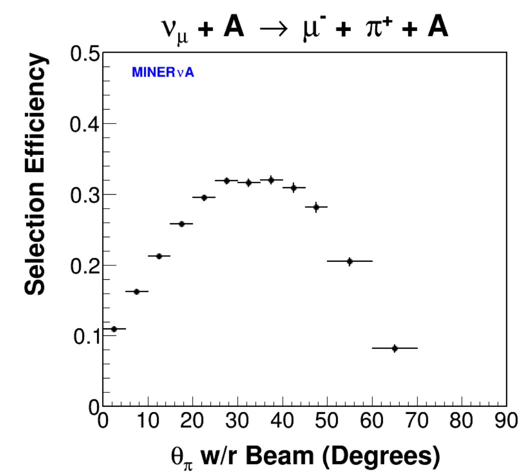
Flux prediction



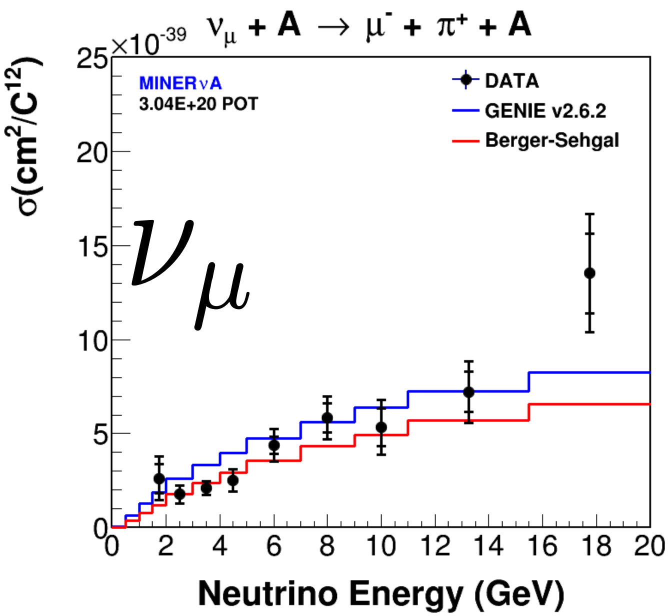
Unfolding to correct for resolution

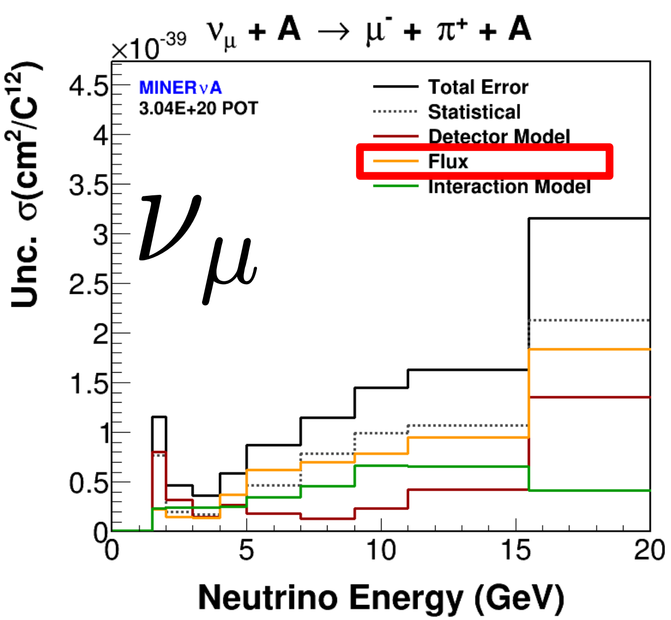


Efficiency & acceptance



Systematics: Flux

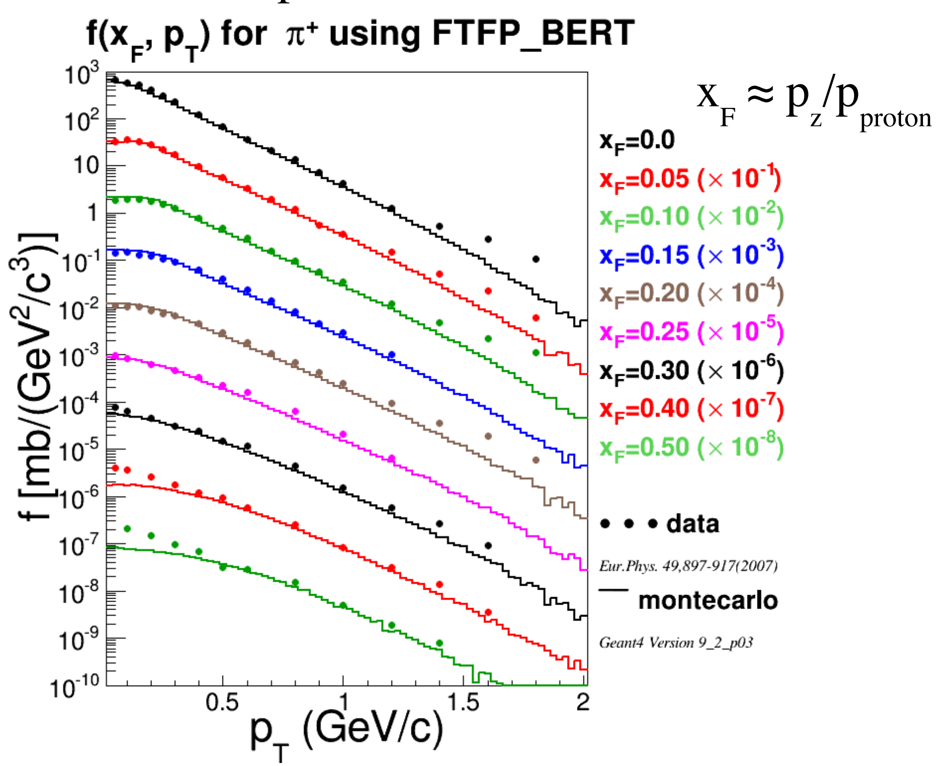




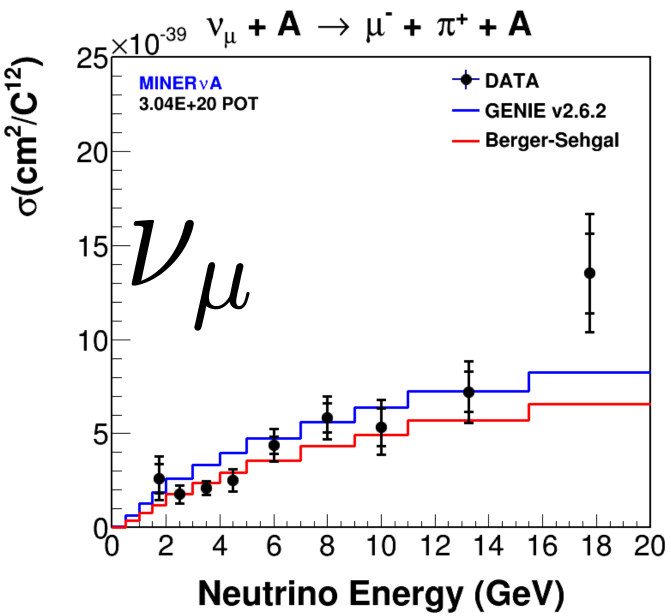
Flux Prediction Uncertainties:

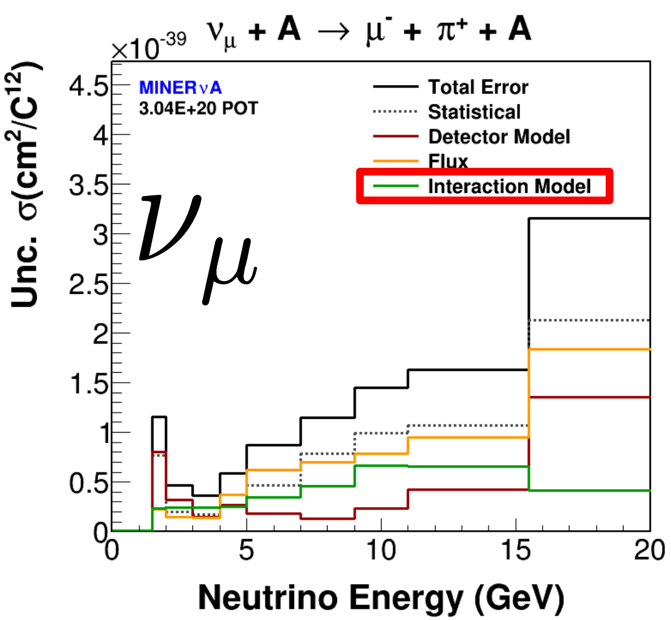
- Hadron production at NuMI target constrained by external data (NA49)
- Beam focusing & unconstrained interactions

pC→πX



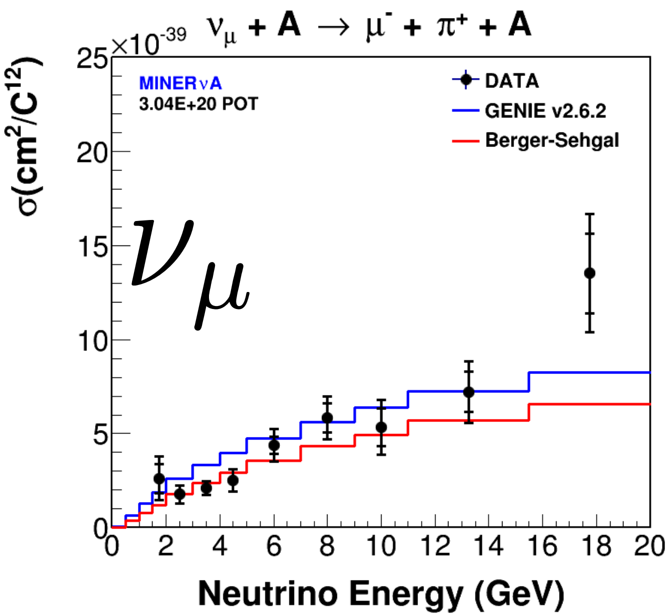
Systematics: Interaction Model

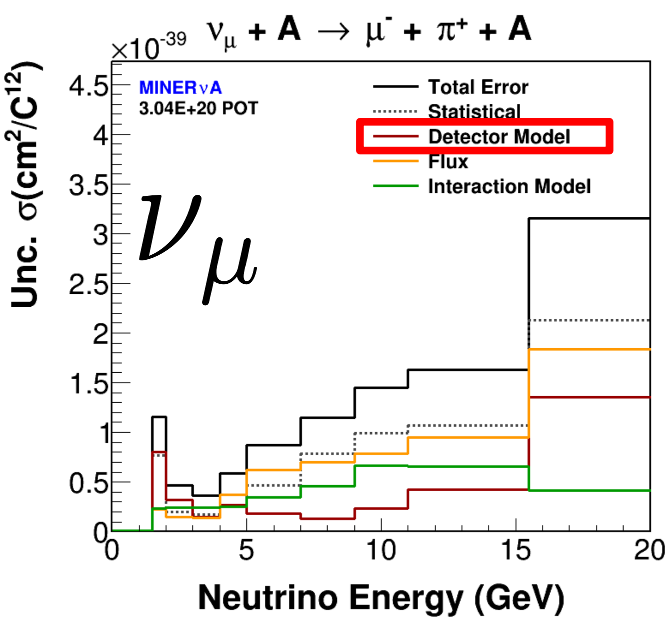




- GENIE interaction model parameters
  - M_ARES, intra-nuclear scattering, etc.
- Sideband Model
  - Accounts for remaining θ_π disagreement in the sideband after background tuning
- Vertex Energy
  - Accounts for unsimulated multi-nucleon effects
  - Guided by MINERvA's CCQE results, add a final state proton to 25% of events with a target neutron

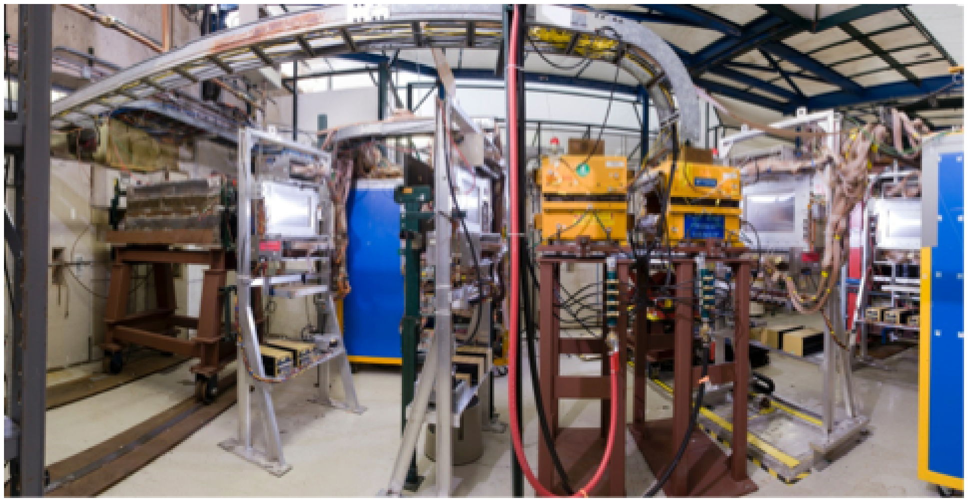
Systematics: Detector Model

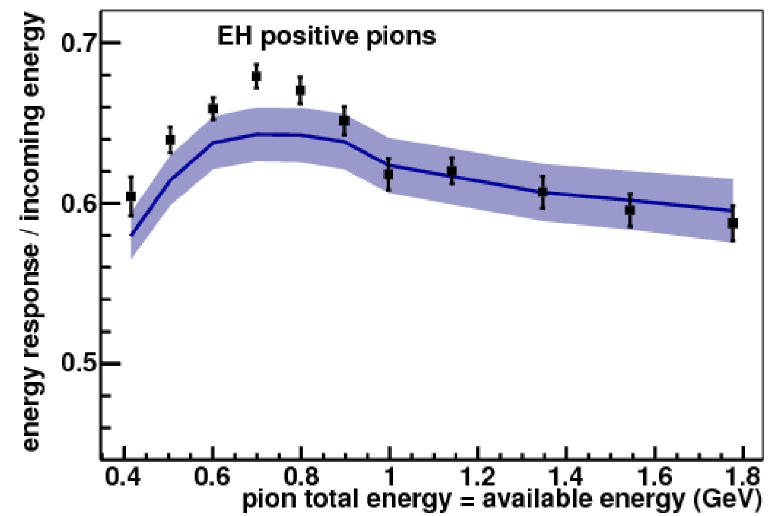


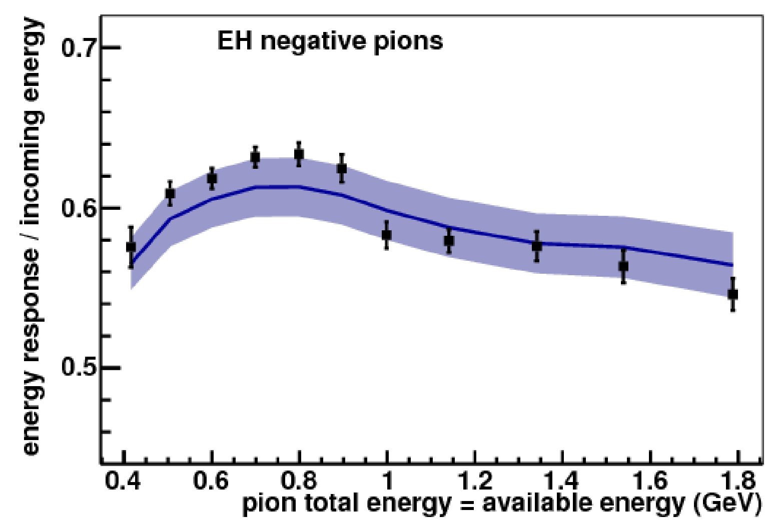


- GEANT hadron propagation constrained by external hA data
- Detector alignment wrt neutrino beam
- Energy Response
  - Muon energy uncertainty from range/curvature
  - Pion/proton response constrained by test beam program

MINERνA Test Beam

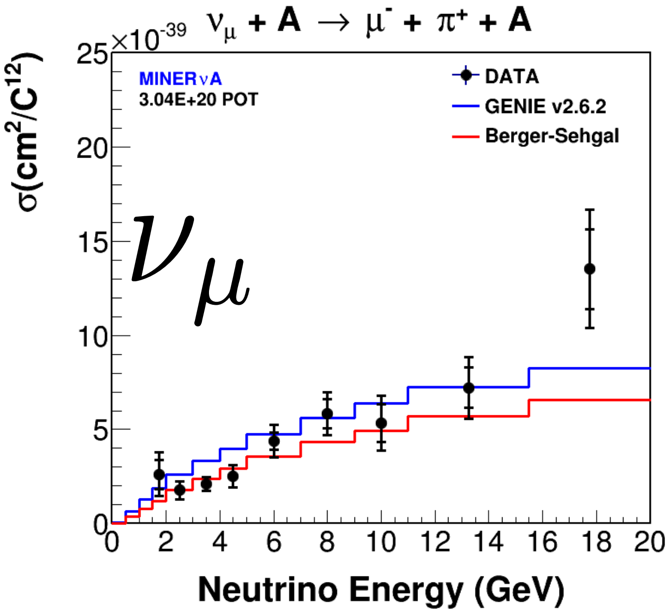


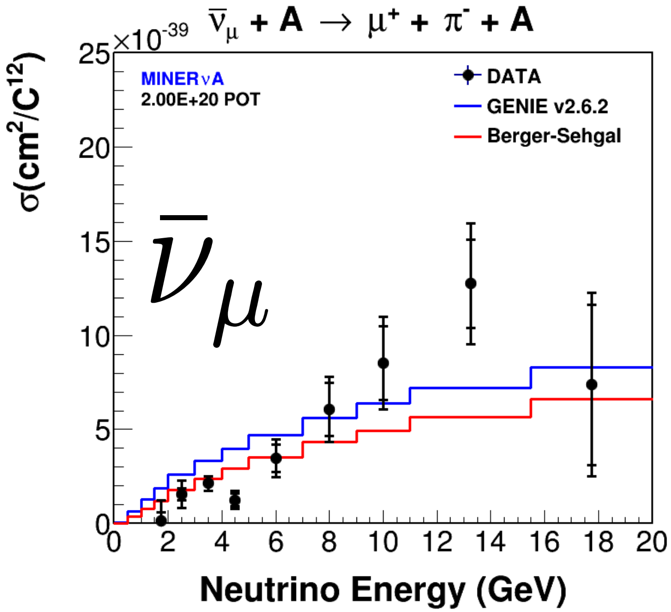


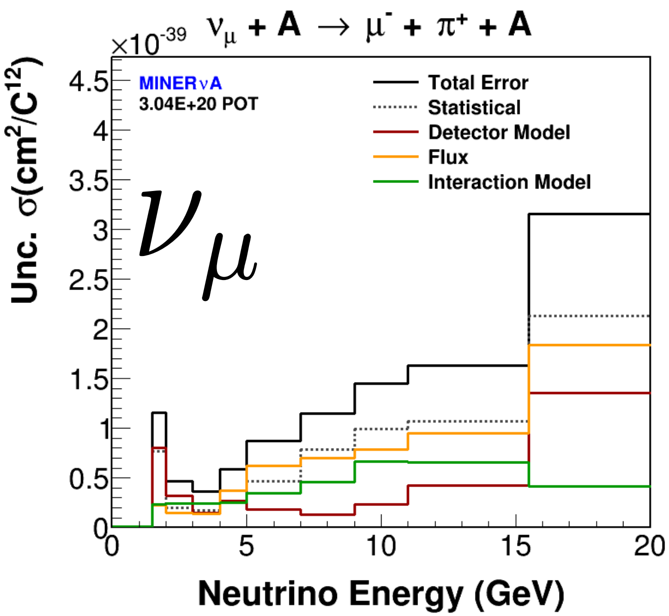


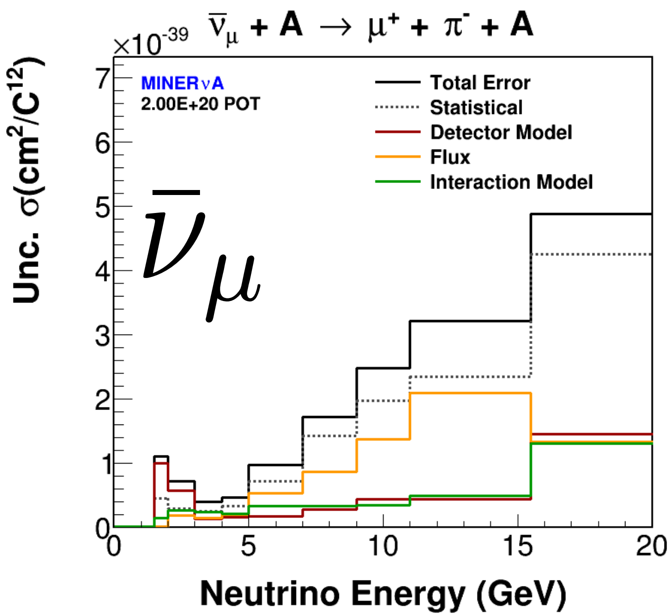
- A scaled-down version of the MINERνA detector in a tertiary pion beam at the Fermilab Test Beam Facility
- Constrains the uncertainty on MINERνA's response to pions (protons) to 5% (3%)
  - Detector mass model and absolute energy scale
  - Scintillator optical model
  - Photomultiplier tube (PMT) model

MINERνA CC Coherent Cross Sections: E_ν



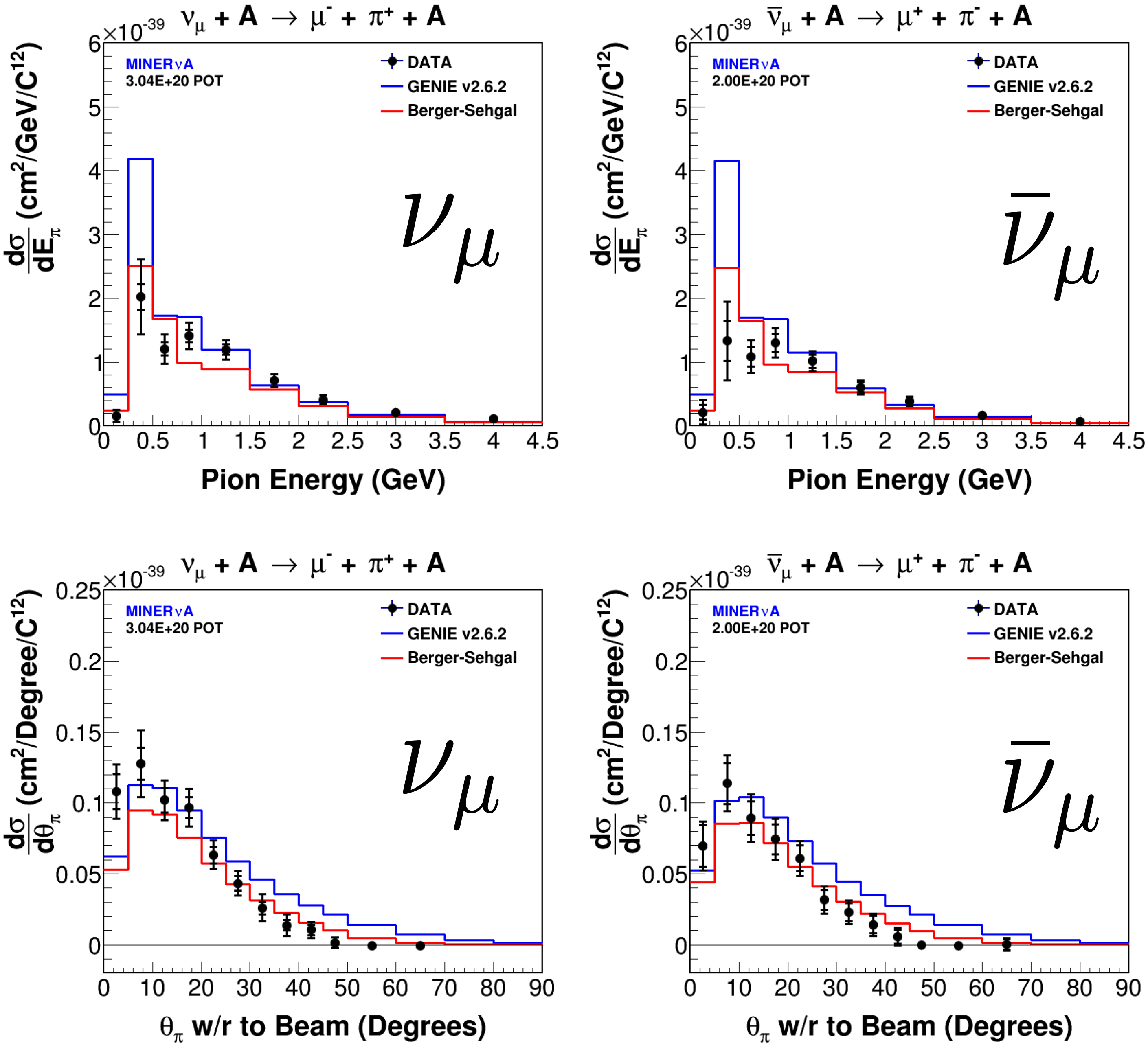






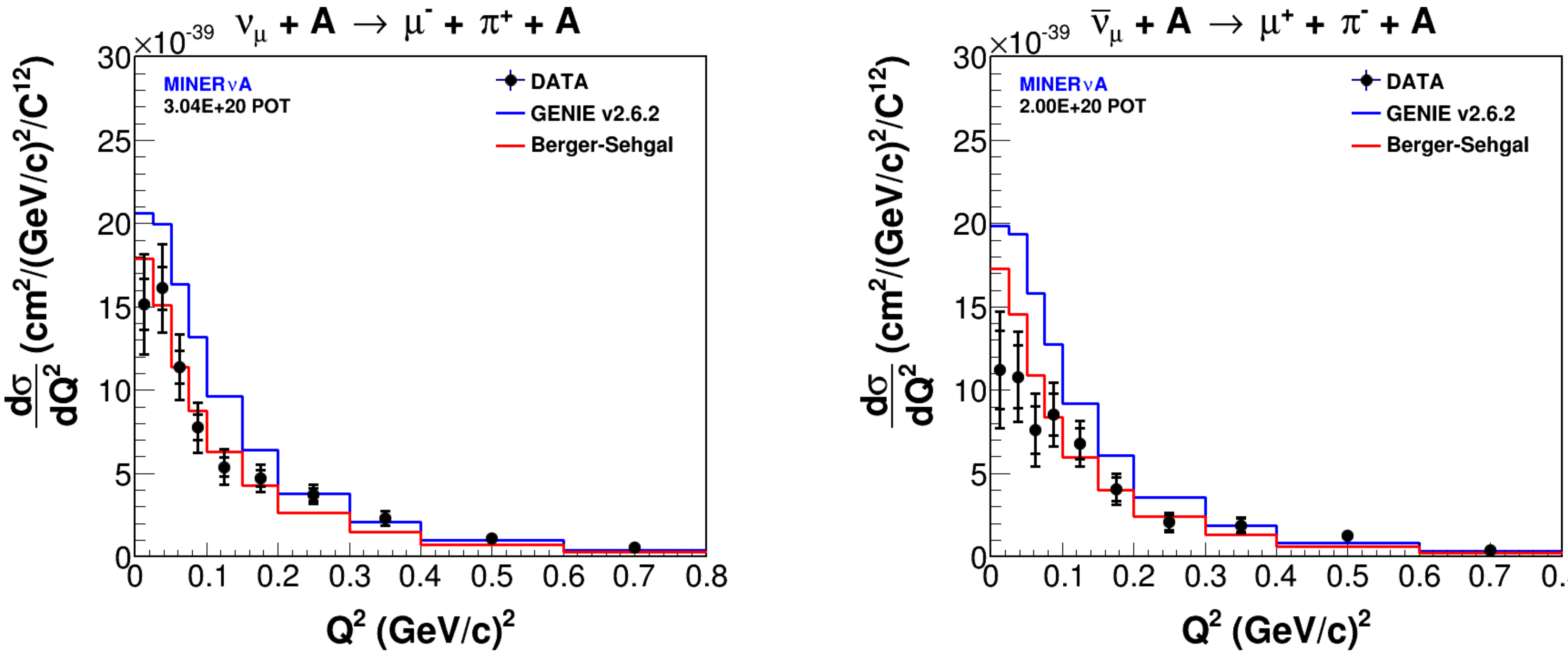
At few GeV, the cross section from MINERνA data is smaller than the prediction of the Rein-Sehgal coherent model as implemented in GENIE

MINERνA CC Coherent Cross Sections: E_π & θ_π



MINERνA data for coherent scattering exhibits harder and more forward pions than the prediction of the Rein-Sehgal coherent model as implemented in GENIE

MINERνA CC Coherent Cross Sections: Q^2

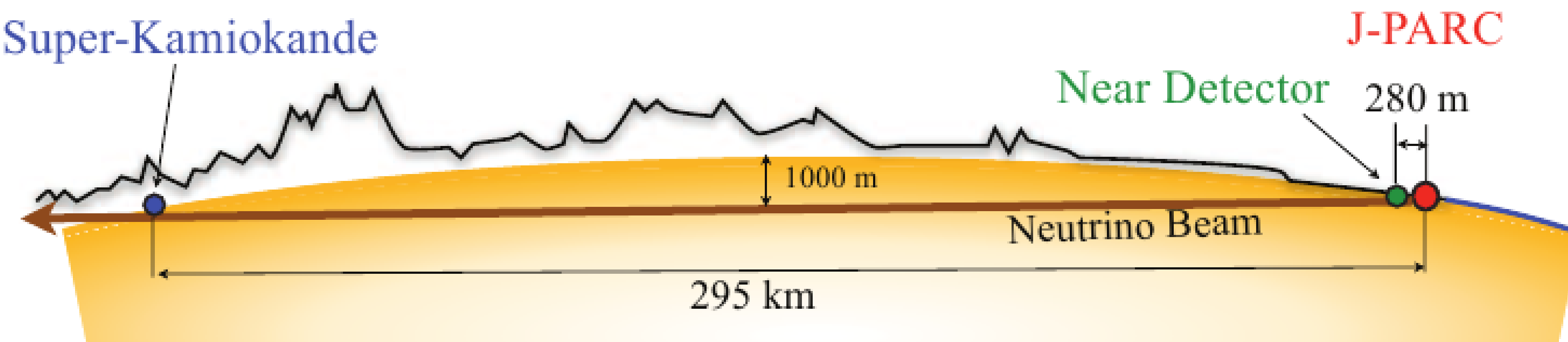


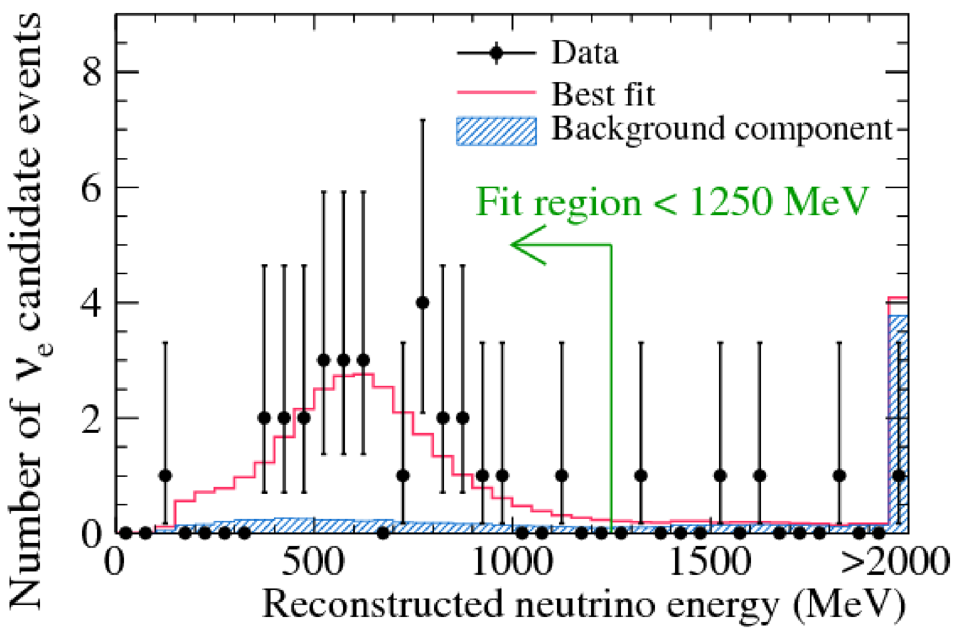
MINERνA data can also test PCAC models' (e.g. Rein-Sehgal) extrapolation from $Q^2 = 0$:

$$F(Q^2) = 1/(1 + Q^2/M_A^2)^2,\ M_A \approx 1\,\mathrm{GeV}$$

T2K and Coherent Pion Production

T2K





Phys.Rev.Lett. 112 (2014) 061802

J-PARC/Super-K off-axis neutrino oscillation experiment measuring $\nu_\mu \rightarrow \nu_\mu$ and $\nu_\mu \rightarrow \nu_e$

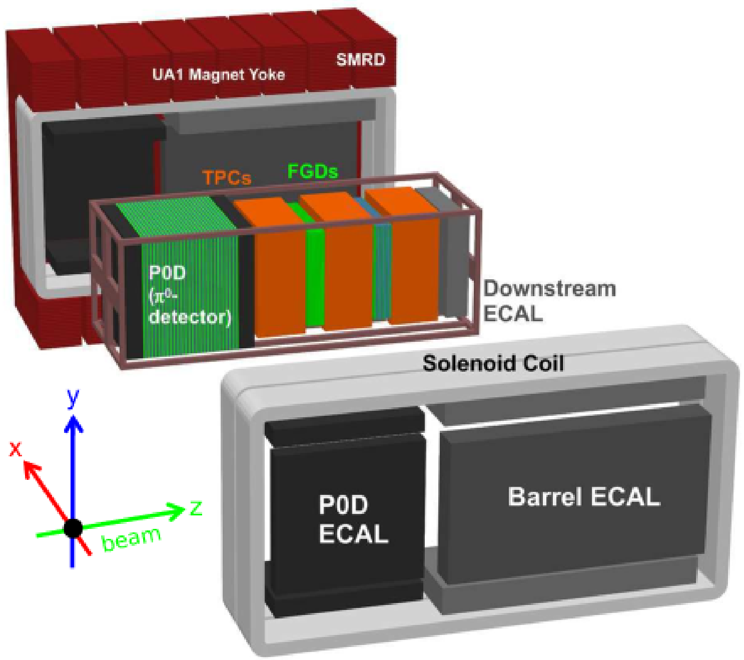
T2K & Neutrino-Nucleus Interactions

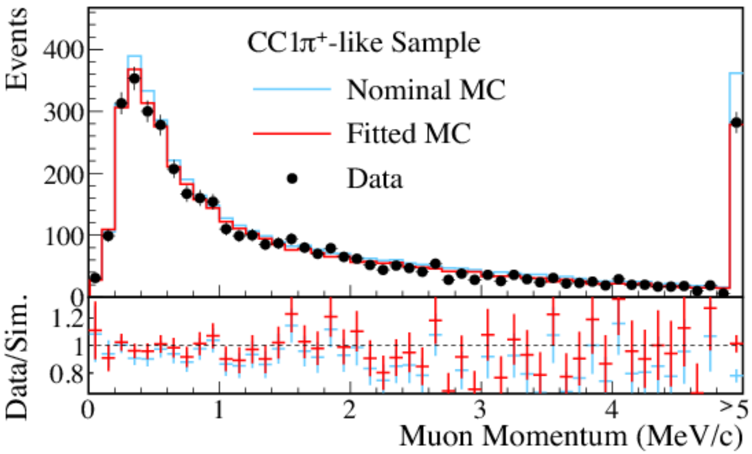
Phys.Rev. D91 (2015) 7, 072010

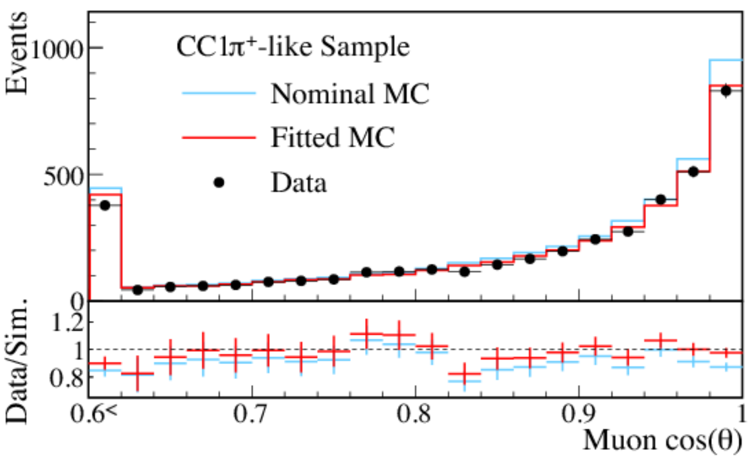
Source of uncertainty	ν_μ CC	ν_e CC
Flux and common cross sections		
(w/o ND280 constraint)	21.7%	26.0%
(w ND280 constraint)	2.7%	3.2%
Independent cross sections	5.0%	4.7%
SK	4.0%	2.7%
FSI+SI(+PN)	3.0%	2.5%
Total		
(w/o ND280 constraint)	23.5%	26.8%
(w ND280 constraint)	7.7%	6.8%

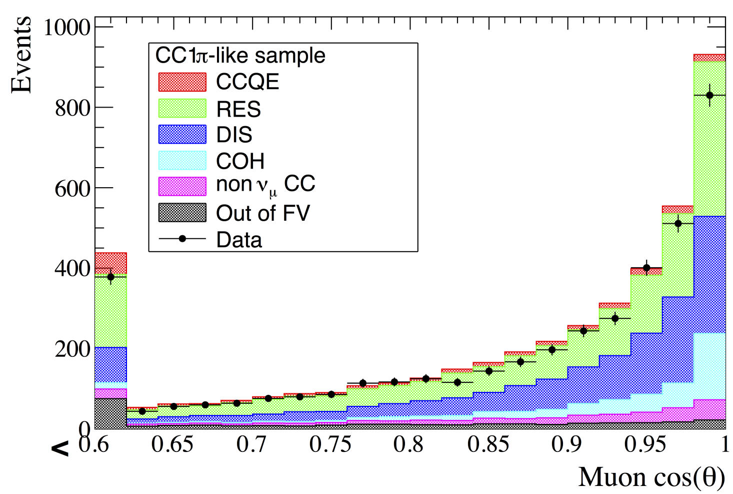
T2K relative uncertainty (1σ) on the predicted ν_μ CC and ν_e CC oscillated event rate

- Neutrino-nucleus interaction model uncertainties are the largest source of systematic error for T2K's oscillation analyses
- ND280 data used to constrain event rate as predicted by the NEUT event generator





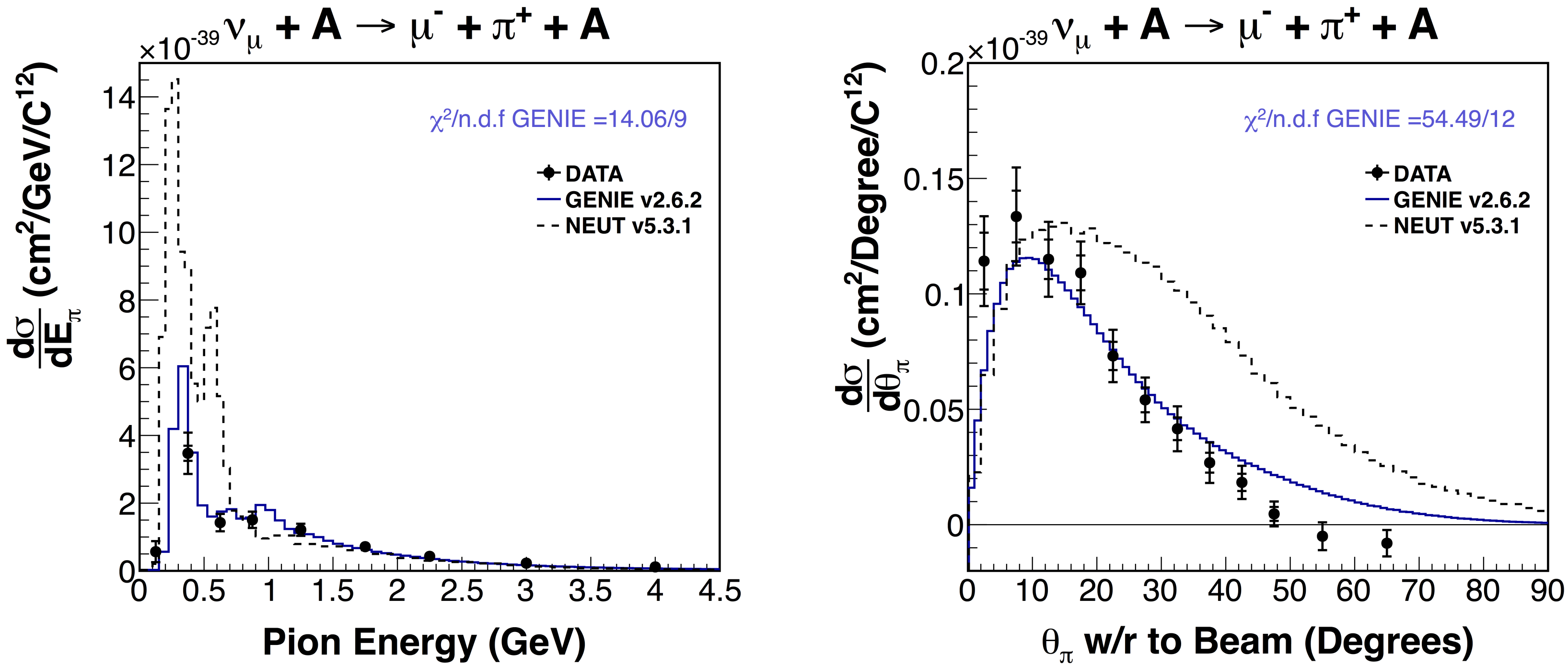




T2K & Coherent Pion Production

- NEUT cross section parameters constrained to ND280 CC0π, CC1π^{+}, CCOther data sets
- ND280 data does not have sensitivity to constrain CC or NC coherent π production
- CC coherent ~0.5% background for $\nu_\mu \rightarrow \nu_\mu$
- NC Coherent ~1% background for $\nu_\mu \rightarrow \nu_e$
- T2K applies 100% uncertainty on CC & NC coherent π production due to non-observation at E_ν ~ 1 GeV by K2K & SciBooNE
- Phys.Rev. D91 (2015) 7, 072010

NEUT vs. MINERνA



Phys.Rev.Lett. 113 (2014) 261802

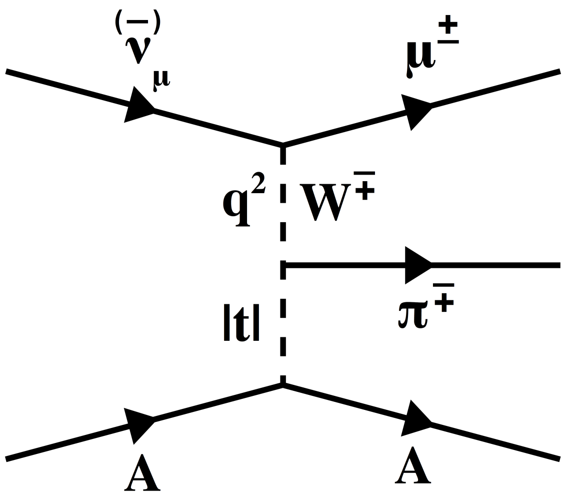
- MINERνA data shows NEUT mis-models the CC coherent pion kinematics
- Presumably due to mis-modeled πA elastic cross section
- T2K using MINERνA data to correct NEUT coherent prediction and constrain the uncertainty

Summary

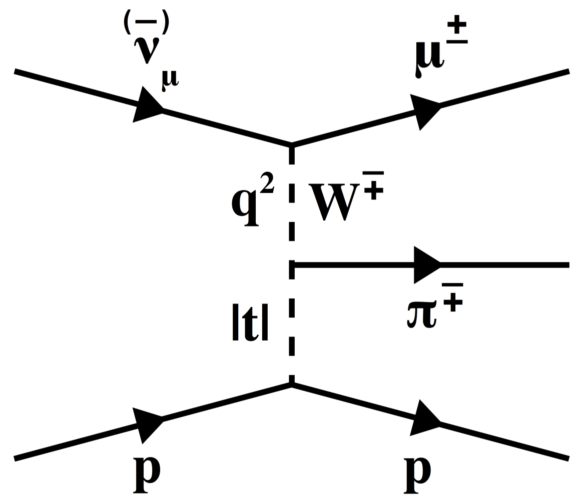
- Understanding coherent pion production is important for neutrino oscillation measurements
- MINERνA has made a model-independent measurement of CC coherent pion production that constrains the
  - interaction rate
  - pion kinematics
  - Q^2-dependence
- MINERνA measurement is already being used to
  - reduce systematic uncertainty in oscillation measurements
  - improve coherent pion production models

Extra:
Diffractive Pion Production

Diffractive Pion Production



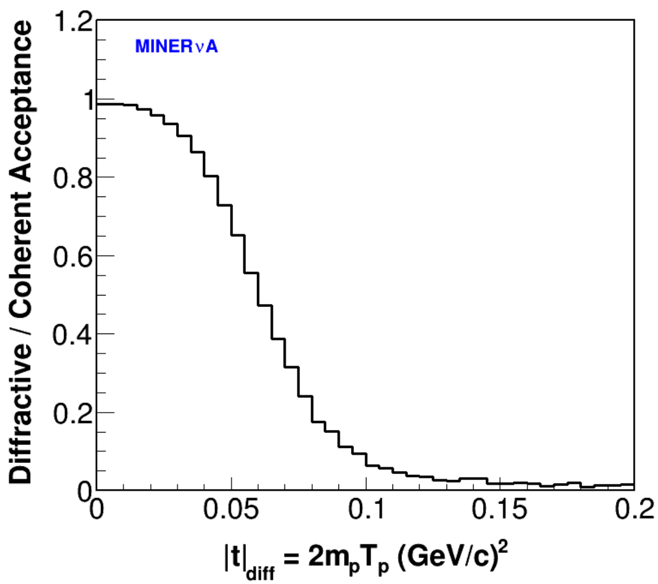
Coherent π Production

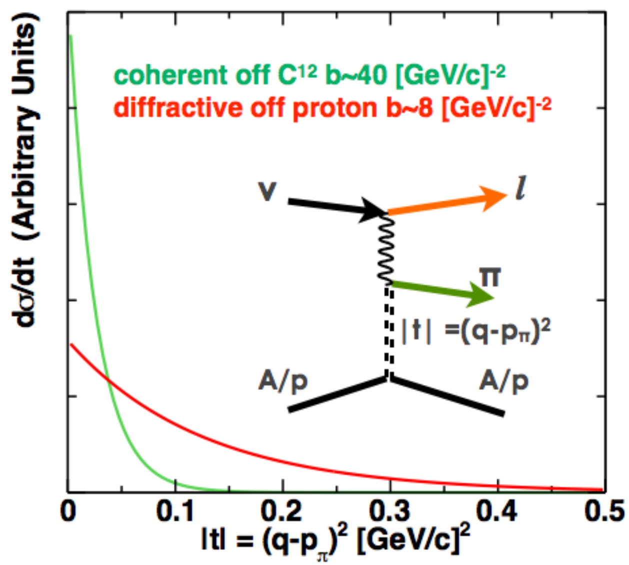


Diffractive π Production on H

- MINERνA's CH scintillator has free protons in equal number to the carbon nuclei
- Diffractive π production on hydrogen
  - indistinguishable from coherent π production when the recoil proton is undetected
  - not simulated in GENIE
  - No calculation of exclusive diffractive π production valid for W < 2 GeV

Diffractive Pion Production Acceptance

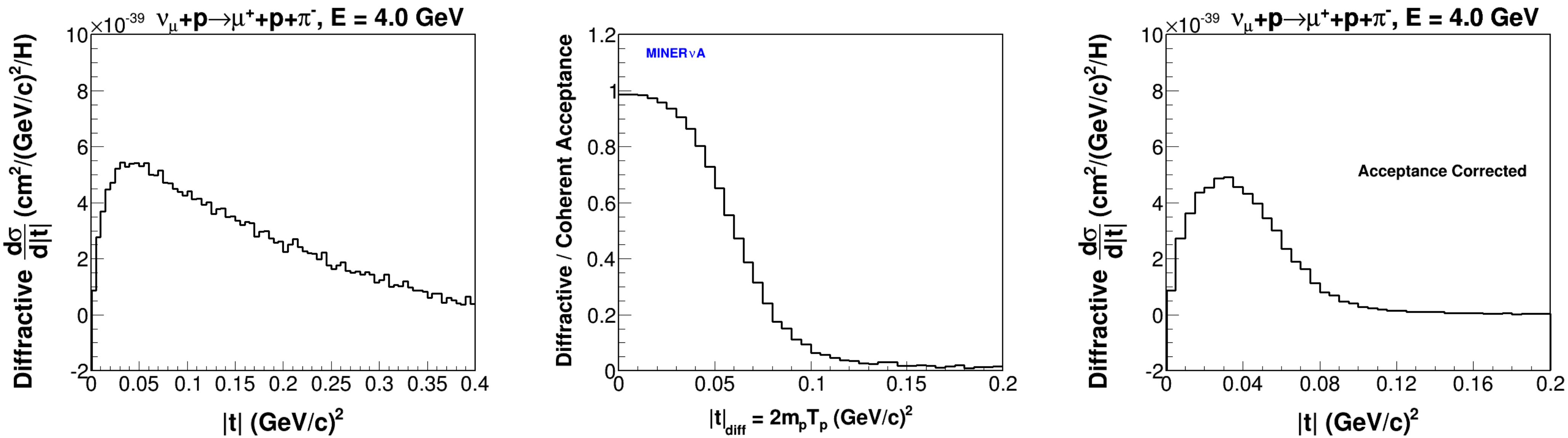




Estimated diffractive / coherent acceptance $\varepsilon_{c/d}$

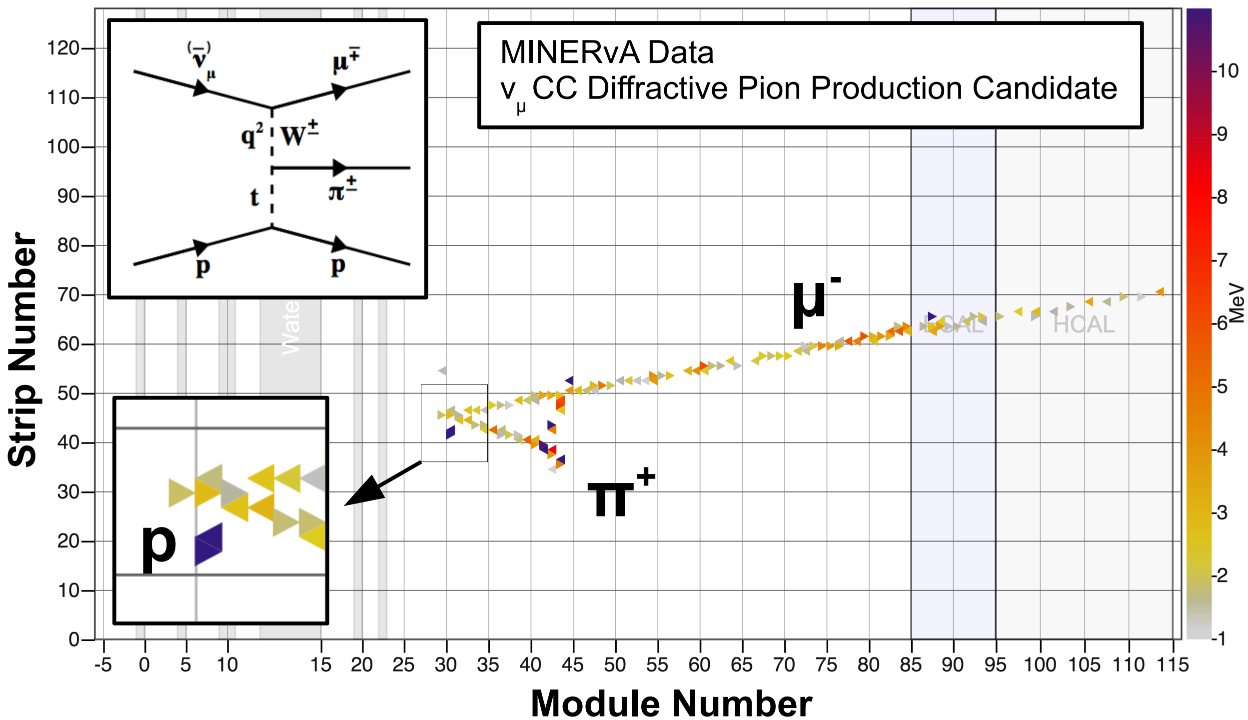
- Assume difference is due only to the recoil proton's ionization and the vertex energy cut
- Evaluate by adding the visible energy from a recoil proton to the vertex energy of simulated coherent interactions
- Calculate as a function of $|t|_{diff} = |(p_\nu - p_\mu - p_\pi)|^2 = 2m_p T_p$
- Integrated $\varepsilon_{c/d} \approx 20\%$

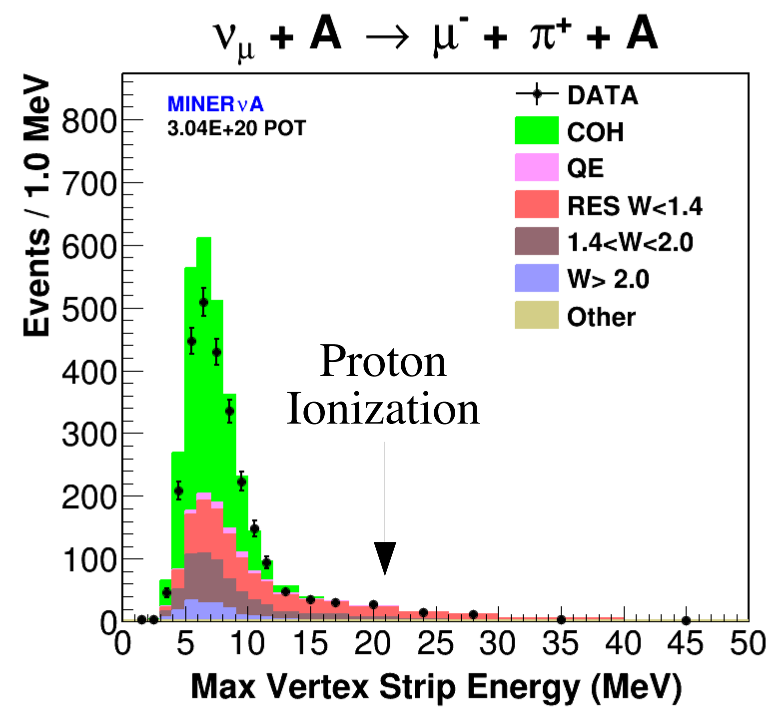
Diffractive Pion Production Estimate



- No calculation of exclusive diffractive π production valid for W < 2 GeV
- Calculate diffractive dσ/d|t| using
  - Inclusive ν_μ p → $\mu^- \pi^+$ p calculation by Kopeliovich et al. based on Adler's relation
  - GENIE to predict non-diffractive component
- From the diffractive dσ/d|t| and $\varepsilon_{c/d}$, the diffractive event rate is 7% (4%) of the ν_μ (anti-ν_μ) coherent event rate as predicted by GENIE

Diffractive Pion Production Search

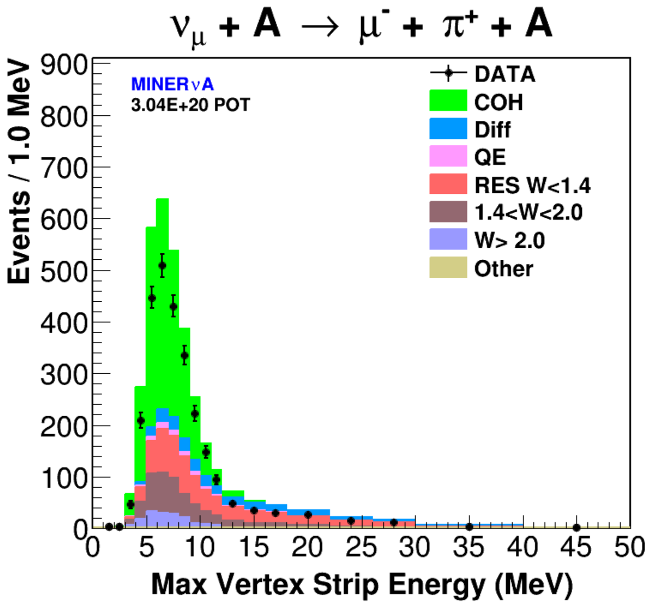


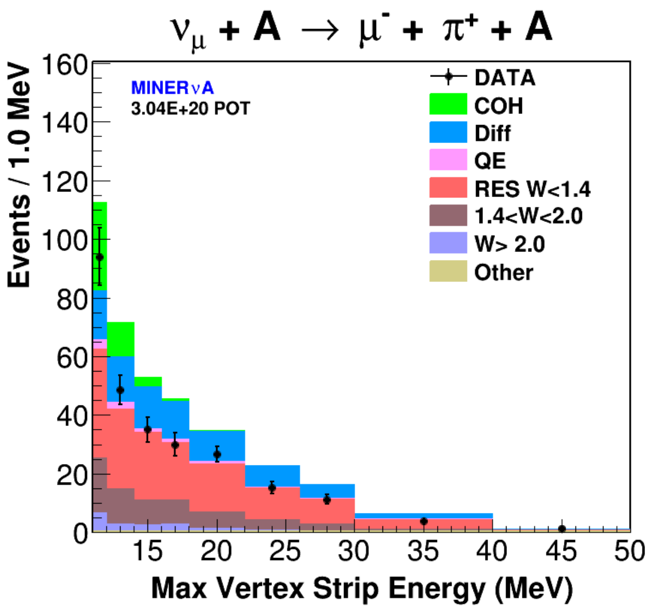


Amongst the events passing all selection cuts, look for a large energy deposition in a single strip resulting from the recoil proton ionization near the event vertex

- ±2 planes and ±70 mm from the event vertex
- corresponds to the range of a T_p = 50 MeV proton ($|t|_{diff} = 2m_p T_p \approx 0.1$ GeV^2)

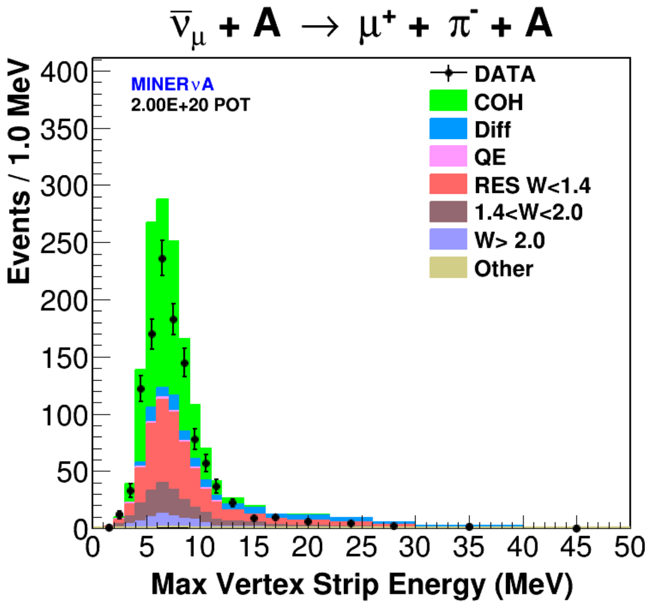
Neutrino Diffractive Pion Production Search

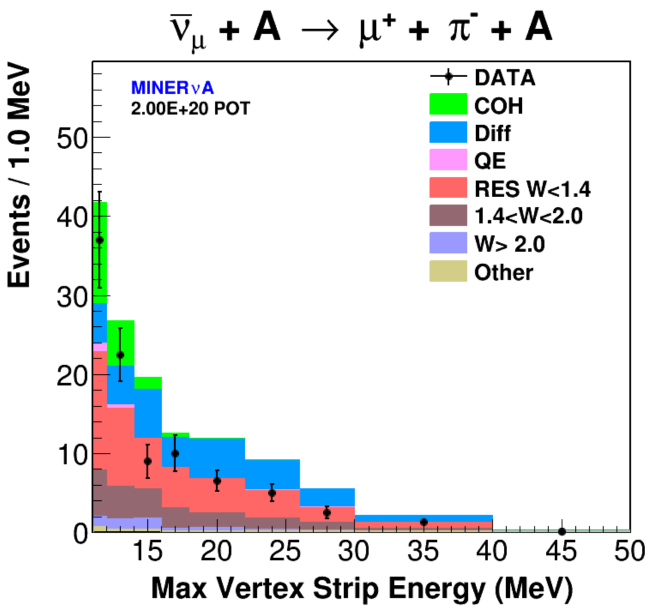




- Diffractive MC sample:
  - GENIE $\nu_\mu\, p \rightarrow \mu^- \pi^+ p$ passing selection cuts
  - weighted to the diffractive dσ/d|t| x $\varepsilon_{c/d}$ shape
- Diffractive normalization $\alpha_{diff} = N_{diff} / N_{coh}$, where N_{diff} and N_{coh} are integrated diffractive and coherent simulated event rates
- Plots show diffractive prediction for $\alpha_{diff} = 0.2$
- Fit for α_{diff} in the max vertex strip energy (MVSE) region 16 < MVSE < 40 MeV
- $\alpha_{diff} = 0.00 \pm 0.07$ from fit
- $\alpha_{diff} = 0.07$ from calculation

Antineutrino Diffractive Pion Production Search

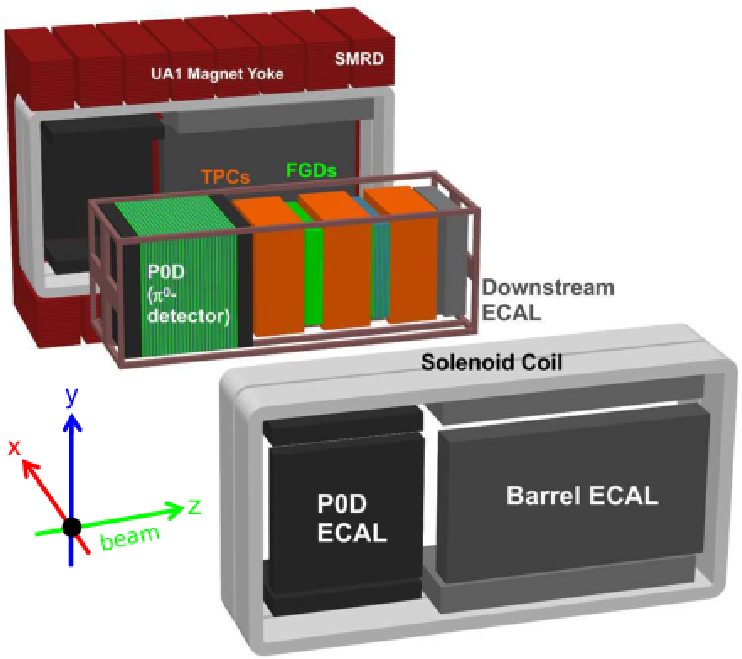




- Diffractive MC sample:
  - GENIE ν_μ p → $\mu^- \pi^+$ p passing selection cuts
  - weighted to the diffractive dσ/d|t| x $\varepsilon_{c/d}$ shape
- Diffractive norm α_{diff} defined as $N_{diff} = \alpha_{diff} N_{coh}$, where N_{diff} and N_{coh} are integrated diffractive and coherent simulated event rates
- Plots show diffractive prediction for $\alpha_{diff} = 0.2$
- Fit for α_{diff} in the max vertex strip energy (MVSE) region 16 < MVSE < 40 MeV
- $\alpha_{diff} = -0.03 \pm 0.07$ from fit
- $\alpha_{diff} = 0.04$ from calculation

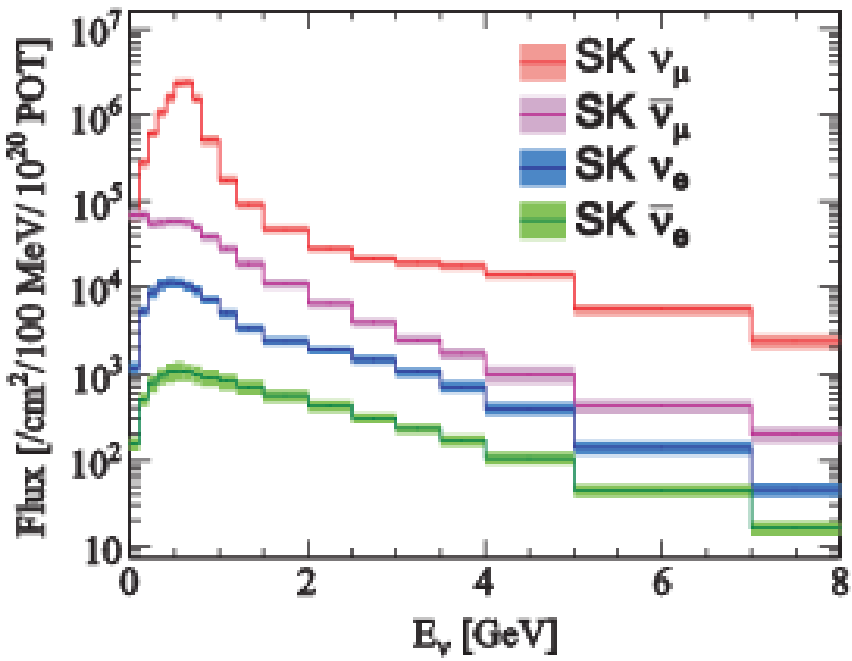
Backup

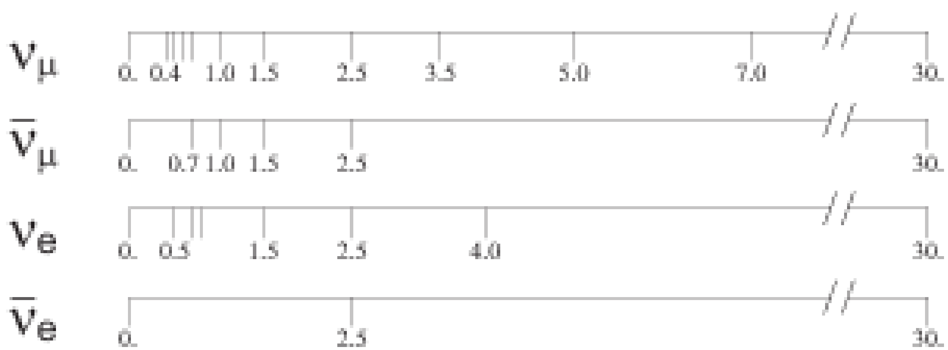
ND280



- T2K's off-axis near detector
- Scintillator tracker with interleaved TPCs
- Upstream π^0 detector (P0D)
- Side and downstream ECALs
- Constrain neutrino event rate/cross sections

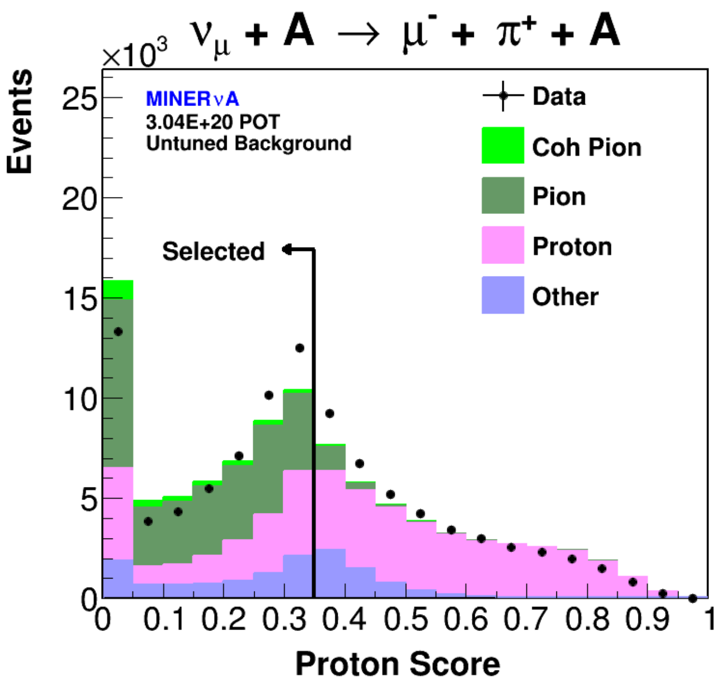
Flux at SK

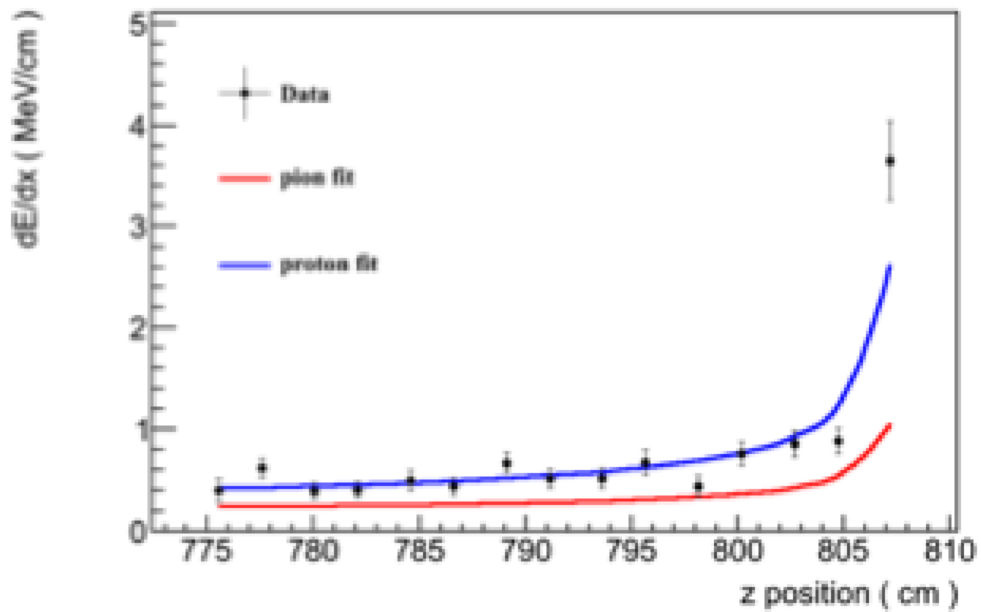




T2K unoscillated neutrino flux prediction at SK
Phys.Rev. D91 (2015) 7, 072010

Proton Score Calculation





$$score_{p(\pi)} = 1.0 - \frac{\left(\frac{\chi^2}{ndf}\right)^2_{p(\pi)}}{\sqrt{\left(\frac{\chi^2}{ndf}\right)^2_p + \left(\frac{\chi^2}{ndf}\right)^2_\pi}}.$$

MINERνA Test Beam Proton Response