Pion Production At MINERvA:

Overview of Results from the Low Energy NuMI Beam Configuration

Aaron Bercellie

On Behalf of the MINERvA Collaboration

NuINT 2018

October 16, 2018

Pions in the Low Energy Beam

- With our latest measurement of $\overline{\nu_\mu} CC1\pi^-$, MINERvA has measured all single pion production channels on scintillator
  - Discrepancies between data and GENIE in all channels
- Quick overview for this talk:
  1. Single pion production channels and how MINERvA measures them
  2. Comparisons between kinematic distributions of each channel
  3. NUISANCE Pion Tune with MINERvA Data

$\nu_\mu CC1\pi^+$

$\overline{\nu_\mu} CC1\pi^-$

$\nu_\mu CC1\pi^0$

$\overline{\nu_\mu} CC1\pi^0$

The four incoherent single pion production channels

$\nu_\mu CC1\pi^+, \nu_\mu CCN\pi^+$

$\nu_\mu + \text{CH} \rightarrow \mu^- + 1\pi^+ + X(\text{nucleons})$

$\nu_\mu + \text{CH} \rightarrow \mu^- + N\pi^+ + X'(\text{baryons/mesons})$

Phys.Rev.D **92** (2015) 092008

Phys.Rev.D **94** (2016) 052005

$\overline{\nu_\mu} CC1\pi^-$

$\overline{\nu_\mu} + \text{CH} \rightarrow \mu^+ + 1\pi^- + X(\text{nucleons})$

In preparation

$\nu_\mu CC1\pi^0$

$\nu_\mu + \text{CH} \rightarrow \mu^- + 1\pi^0 + X(\text{nucleons})$

Phys.Rev.D **96** (2017) 072003

$\overline{\nu_\mu} CC1\pi^0$

$\overline{\nu_\mu} + \text{CH} \rightarrow \mu^+ + 1\pi^0 + X(\text{nucleons})$

Phys.Lett.**B749** (2015) 130-136

Phys.Rev.D **94** (2016) 052005

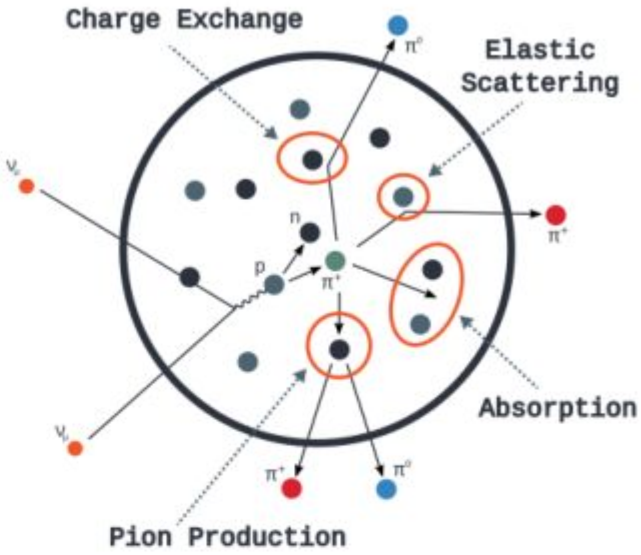
- These results were taken using the low energy beam configuration
    - All plots for the **Nπ^+** results are in the backup slides

Why measure all four incoherent single pion production channels

- Difficult to disentangle nucleon and nuclear effects
- For example, final state interactions (FSI) can migrate between charged pion and neutral pion events

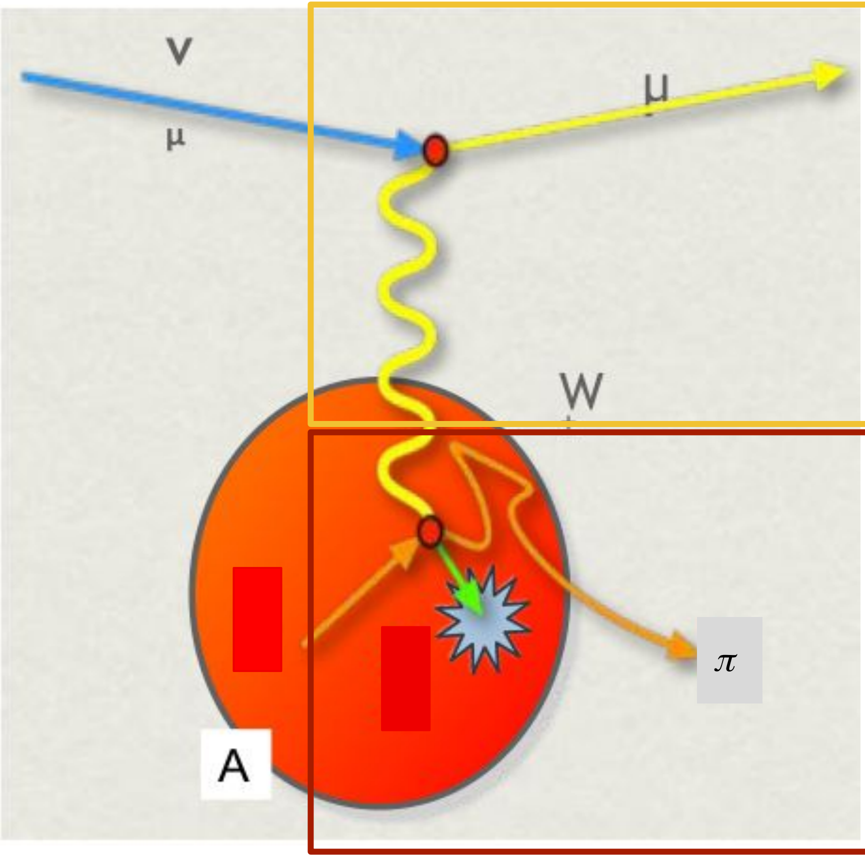
$$\nu_\mu CC1\pi^+ \longleftrightarrow \nu_\mu CC1\pi^0$$

  - Discrepancies in one channel may show up in the other
- Initial nuclear state cares about ν_μ vs $\overline{\nu_\mu}$ modes



from T. Golan

Looking at muons and pions



Muon

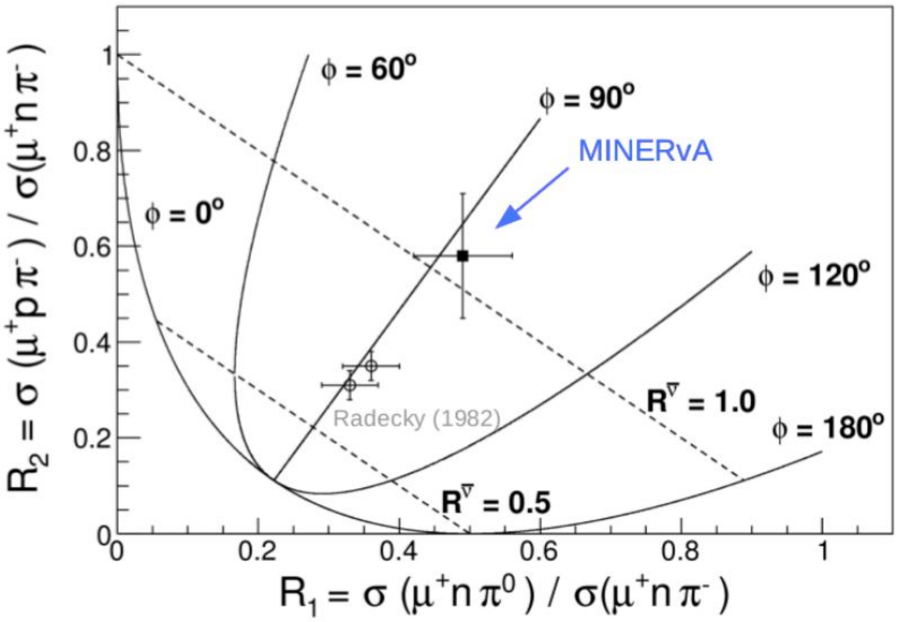
- Provides information on the initial state of the nucleons within the nucleus

Pion

- Undergoes final state interactions within the nucleus
- By comparing to muon kinematics, allows isolation of final state effects

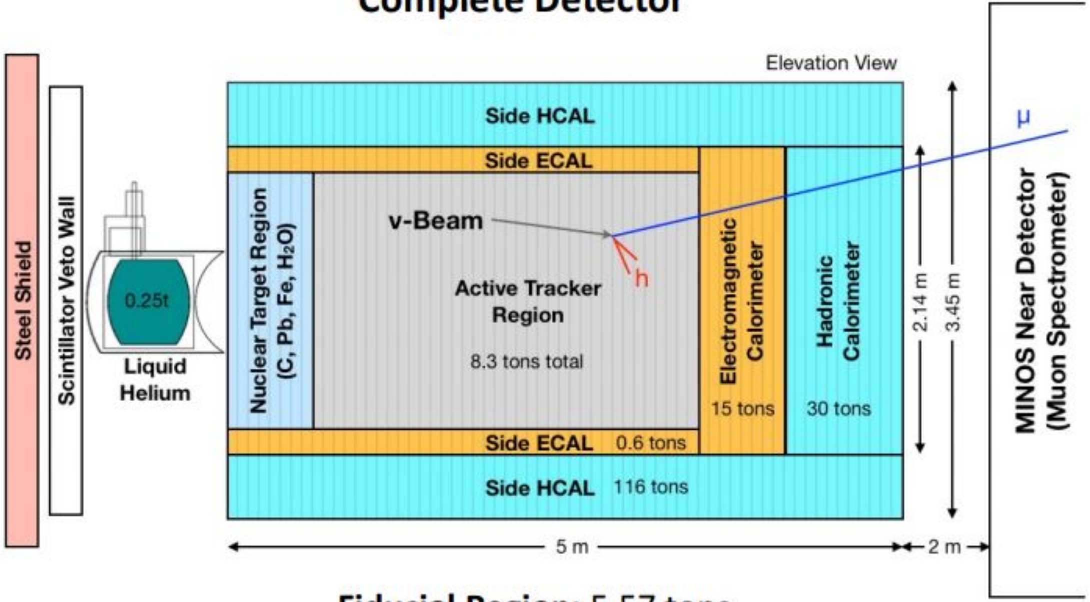
Measurement of isospin amplitudes

- Can decompose different channels into nucleon level cross sections
- Allows us to find the relative strength and phase between the amplitudes of isospin *I* = 1/2, 3/2



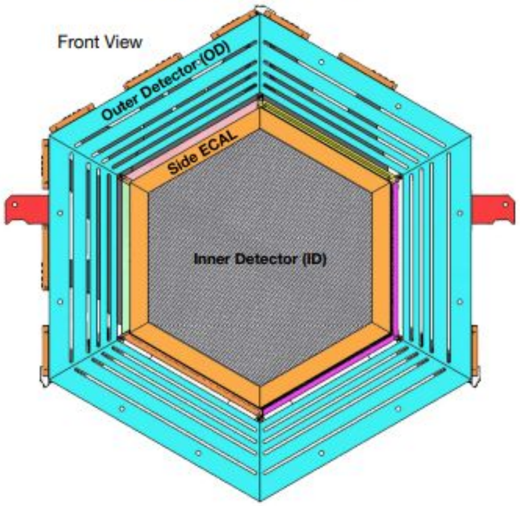
MINERvA Detector

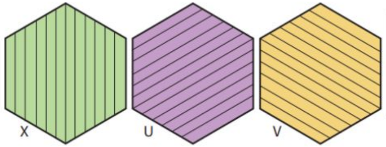
Side View
Complete Detector



Fiducial Region: 5.57 tons

Front View
Single Module



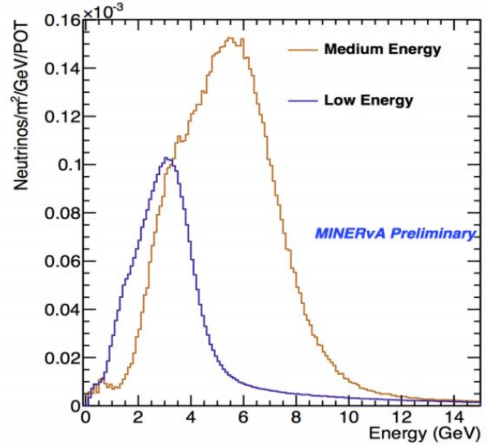


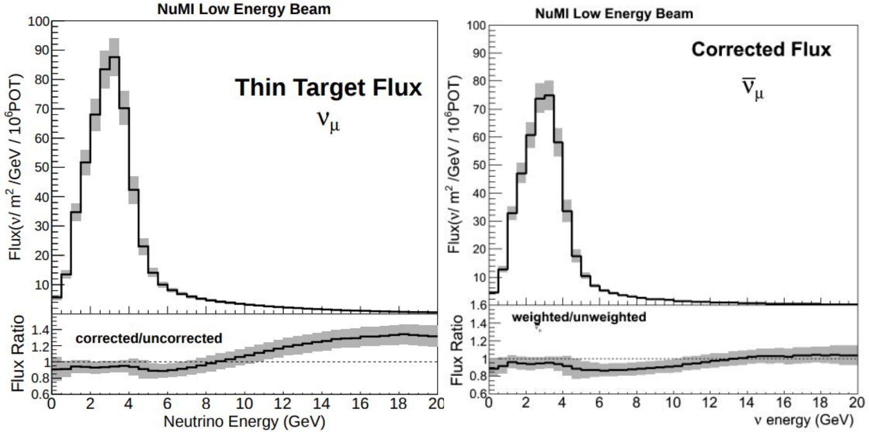
127 plastic (CH) scintillator strips/plane for 3-d reconstruction

Nucl. Instrum. Methods Phys. Res., Sect. A 743, 130 (2014).
Nucl. Instrum. Methods Phys. Res., Sect. A 789, 28 (2015).

MINERvA Low Energy Flux

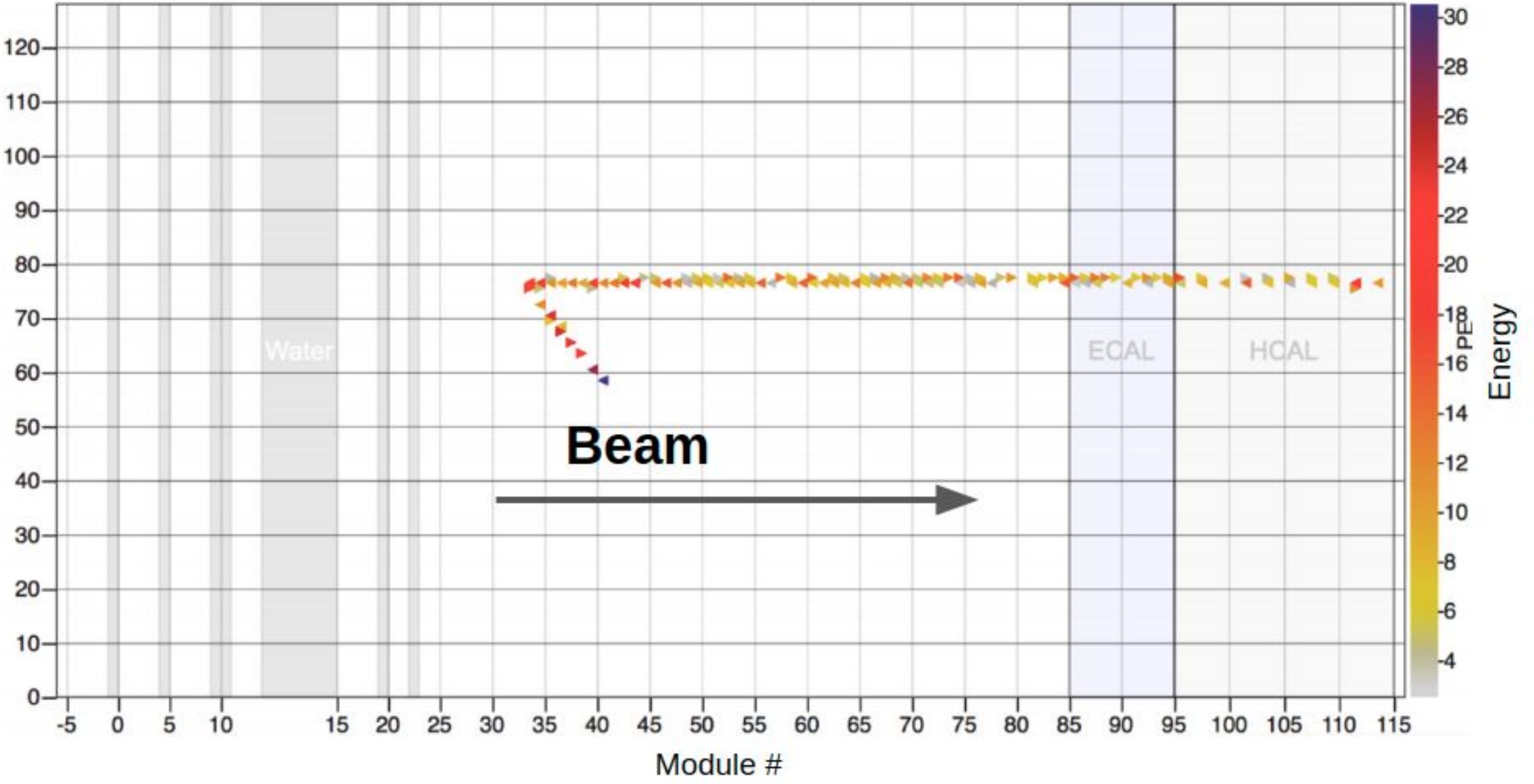
- From 2005-2012 (2010-2012 full detector), MINERvA received both neutrino and antineutrinos from the NuMI beamline in low energy mode
  - 4e20 protons on target
- Improved our prediction of flux using simulation tuned to world hadron production data as well as in situ measurements (low nu method, neutrino electron scattering)
  - Deepika Jena will be giving a talk about the MINERvA flux in the medium energy era





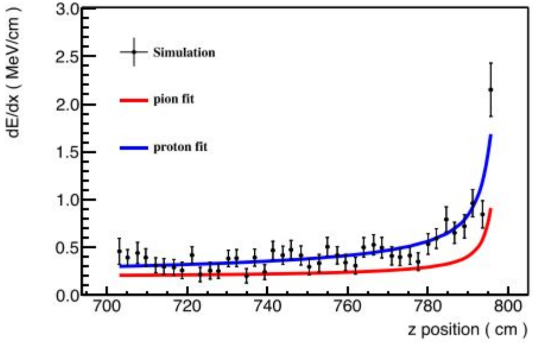
L.Aliaga et al., PRD **94** 092005 (2016)

Arachne Display of MINERvA Event

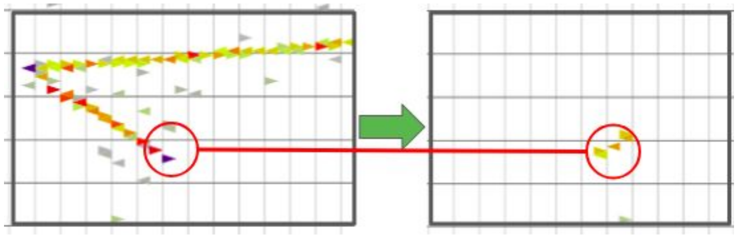


$\pi^\pm$ Pion Reconstruction

- dE/dX profile of track consistent with $\pi^\pm$
- Momentum found from dE/dX fit (by range)



$$\nu_\mu + \text{CH} \rightarrow \mu^- + 1\pi^+ + X(\text{nucleons})$$



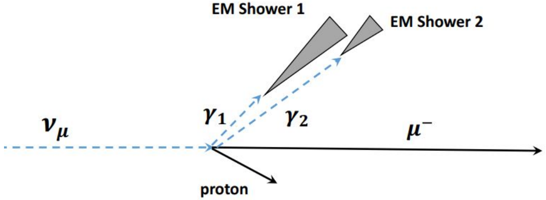
- Michel electron matched to the end of track
- No Michel electron

$$\overline{\nu_\mu} + \text{CH} \rightarrow \mu^+ + 1\pi^- + X(\text{nucleons})$$

- Ability to see charged pions in MINERvA has energy thresholds ~[50,300] MeV
  - Tracking requirements, pion interactions
- π^- typically absorbed into nucleus
  - Hard to tag with Michel electron, difficult to reconstruct momentum

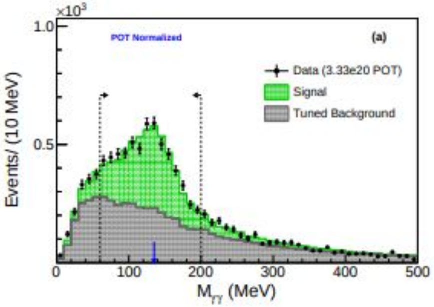
π^0 Pion Reconstruction

- Has two photon candidates
- Photon conversion distance from interaction vertex > 15 cm (> 14 cm for most energetic ɣ)
- Energy found calorimetrically, energy distribution fitted to invariant mass peak



Invariant π^0 Mass

$$M^2_{\gamma\gamma} = 2E_{\gamma 1}E_{\gamma 2}(1 - cos(\theta_{\gamma\gamma}))$$



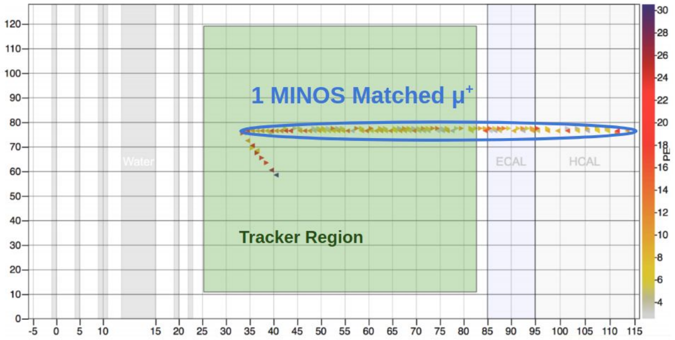
$\nu_\mu + \text{CH} \rightarrow \mu^- + 1\pi^0 + X(\text{nucleons})$

$\overline{\nu_\mu} + \text{CH} \rightarrow \mu^+ + 1\pi^0 + X(\text{nucleons})$

- Easier to see additional nucleons due to clearer vertex
- Large energy thresholds ~[0, 1000] MeV

Event Selection

$\nu_\mu + \text{CH} \rightarrow \mu^- + 1\pi^+ + X(\text{nucleons})$

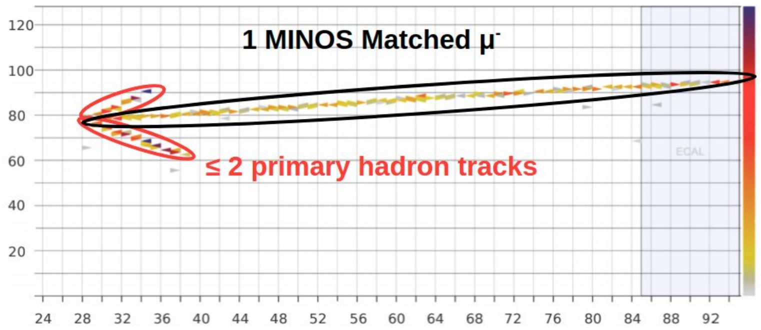


$\overline{\nu_\mu} + \text{CH} \rightarrow \mu^+ + 1\pi^- + X(\text{nucleons})$

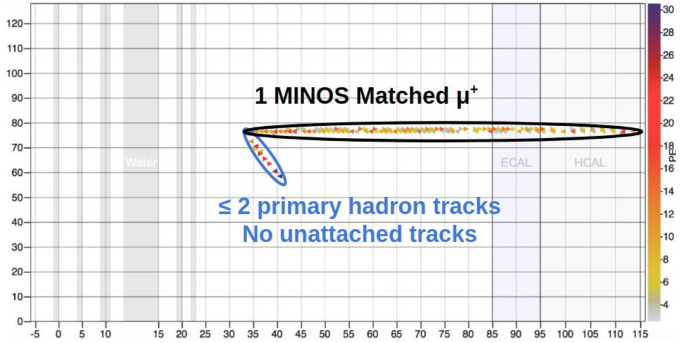
$\nu_\mu + \text{CH} \rightarrow \mu^- + 1\pi^0 + X(\text{nucleons})$

$\overline{\nu_\mu} + \text{CH} \rightarrow \mu^+ + 1\pi^0 + X(\text{nucleons})$

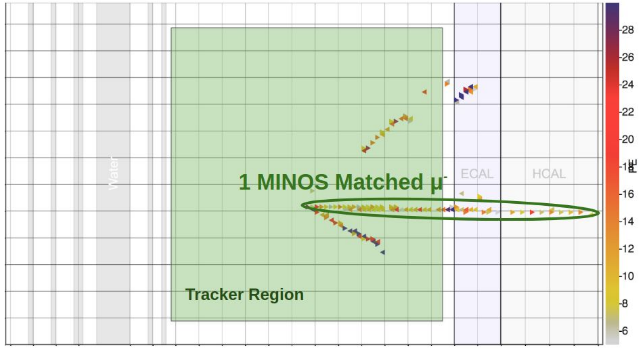
Event Selection



$\nu_\mu + \text{CH} \rightarrow \mu^- + 1\pi^+ + X(\text{nucleons})$



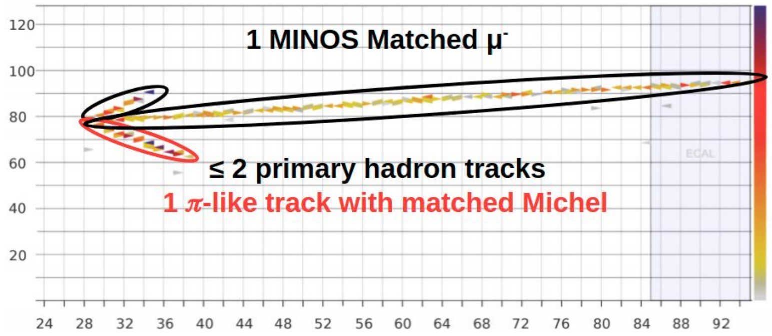
$\overline{\nu_\mu} + \text{CH} \rightarrow \mu^+ + 1\pi^- + X(\text{nucleons})$



$\nu_\mu + \text{CH} \rightarrow \mu^- + 1\pi^0 + X(\text{nucleons})$

$\overline{\nu_\mu} + \text{CH} \rightarrow \mu^+ + 1\pi^0 + X(\text{nucleons})$

Event Selection

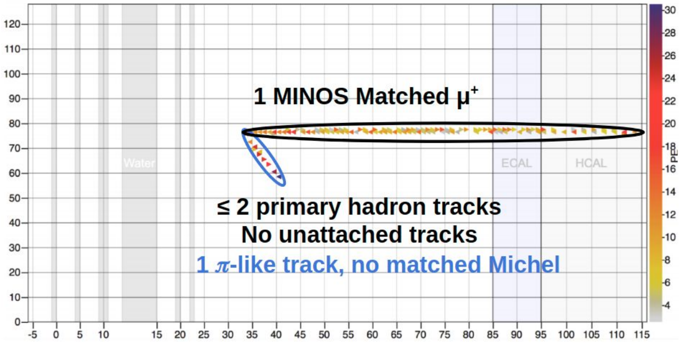


1 MINOS Matched μ⁻

≤ 2 primary hadron tracks

1 π-like track with matched Michel

$\nu_\mu + \text{CH} \rightarrow \mu^- + 1\pi^+ + X(\text{nucleons})$



1 MINOS Matched μ⁺

≤ 2 primary hadron tracks

No unattached tracks

1 π-like track, no matched Michel

$\overline{\nu_\mu} + \text{CH} \rightarrow \mu^+ + 1\pi^- + X(\text{nucleons})$

1 MINOS Matched μ⁻

Tracker Region

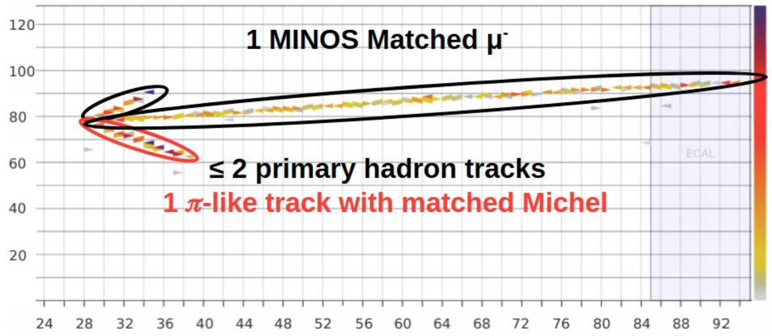
$\nu_\mu + \text{CH} \rightarrow \mu^- + 1\pi^0 + X(\text{nucleons})$

1 MINOS Matched μ⁺

Tracker Region

$\overline{\nu_\mu} + \text{CH} \rightarrow \mu^+ + 1\pi^0 + X(\text{nucleons})$

Event Selection

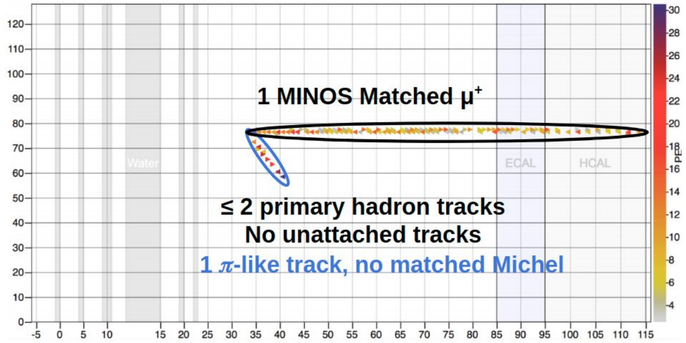


1 MINOS Matched μ⁻

≤ 2 primary hadron tracks

1 π-like track with matched Michel

$\nu_\mu + \text{CH} \rightarrow \mu^- + 1\pi^+ + X(\text{nucleons})$



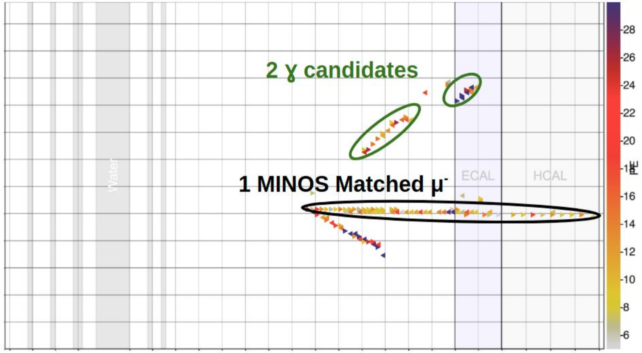
1 MINOS Matched μ⁺

≤ 2 primary hadron tracks

No unattached tracks

1 π-like track, no matched Michel

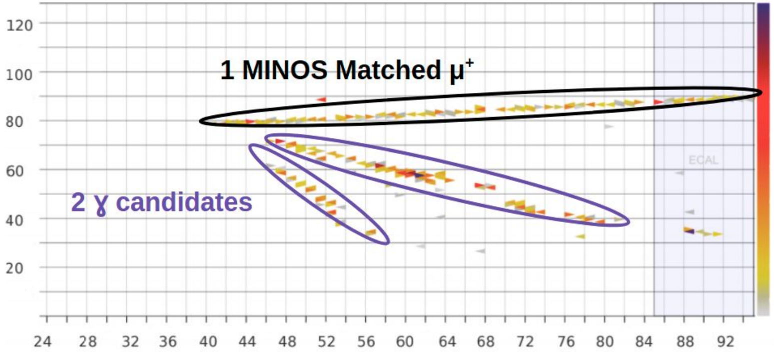
$\overline{\nu_\mu} + \text{CH} \rightarrow \mu^+ + 1\pi^- + X(\text{nucleons})$



2 ɣ candidates

1 MINOS Matched μ⁻

$\nu_\mu + \text{CH} \rightarrow \mu^- + 1\pi^0 + X(\text{nucleons})$

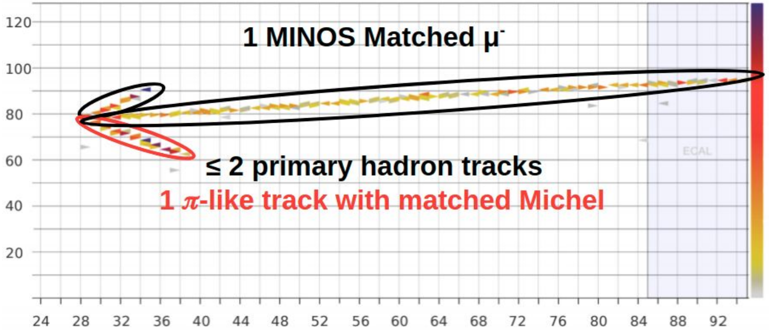


1 MINOS Matched μ⁺

2 ɣ candidates

$\overline{\nu_\mu} + \text{CH} \rightarrow \mu^+ + 1\pi^0 + X(\text{nucleons})$

Event Selection

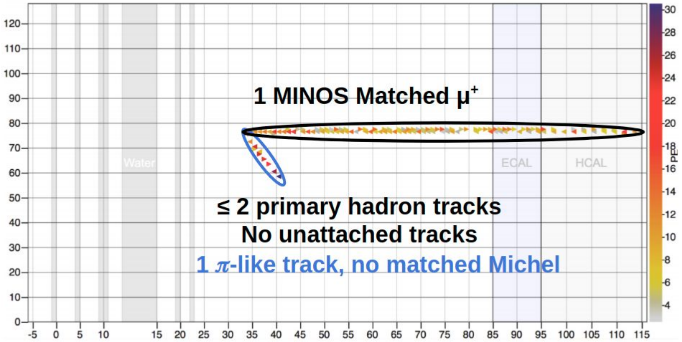


1 MINOS Matched μ⁻

≤ 2 primary hadron tracks

1 π-like track with matched Michel

$\nu_\mu + \text{CH} \rightarrow \mu^- + 1\pi^+ + X(\text{nucleons})$



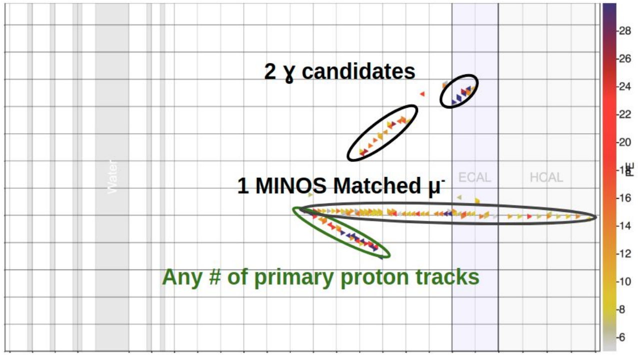
1 MINOS Matched μ⁺

≤ 2 primary hadron tracks

No unattached tracks

1 π-like track, no matched Michel

$\overline{\nu_\mu} + \text{CH} \rightarrow \mu^+ + 1\pi^- + X(\text{nucleons})$

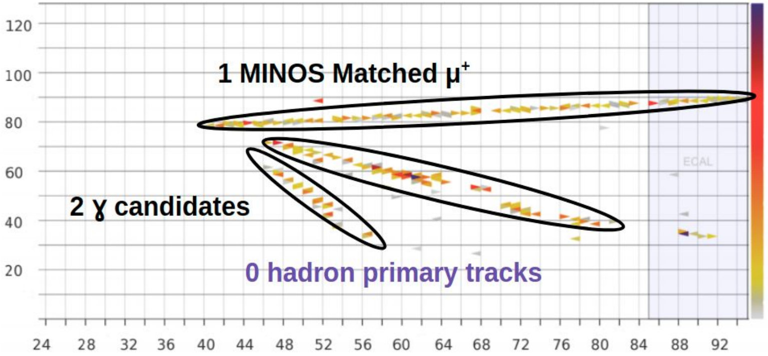


2 ɣ candidates

1 MINOS Matched μ⁻

Any # of primary proton tracks

$\nu_\mu + \text{CH} \rightarrow \mu^- + 1\pi^0 + X(\text{nucleons})$



1 MINOS Matched μ⁺

2 ɣ candidates

0 hadron primary tracks

$\overline{\nu_\mu} + \text{CH} \rightarrow \mu^+ + 1\pi^0 + X(\text{nucleons})$

Kinematic Definition

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

- Four momentum transfer
- Primarily relies on muon kinematics
- Neutrino energy is typically the muon energy + calorimetric hadronic energy

$$W_{exp}^2 = -Q^2 + m_N^2 + 2m_N E_H \ (m_N = \text{nucleon mass})$$

- Invariant hadronic mass

Event Selection and Phase Space

$$\nu_\mu + \mathrm{CH} \rightarrow \mu^- + 1\pi^+ + X(\text{nucleons})$$

$$E_\nu = E_\mu + E_H \text{ (E_H determined calorimetrically)}$$

- Reconstructed $E_\nu \in [1.5, 10]$ GeV
- $1\pi^+$: $W < 1.4$ GeV
- $N\pi^+$: $W < 1.8$ GeV

$$\overline{\nu_\mu} + \mathrm{CH} \rightarrow \mu^+ + 1\pi^- + X(\text{nucleons})$$

$$E_\nu = E_\mu + E_H \text{ (E_H determined calorimetrically)}$$

- Reconstructed $E_\nu \in [1.5, 10]$ GeV
- $W < 1.8$ GeV

$$\nu_\mu + \mathrm{CH} \rightarrow \mu^- + 1\pi^0 + X(\text{nucleons})$$

$$E_\nu = E_\mu + E_{\pi^0} + \Sigma T_p + E_{vtx} + E_{extra}$$

- Reconstructed $E_\nu \in [1.5, 20]$ GeV
- Invariant π^0 mass $\in [60, 200]$ MeV/c^2
- $W<1.8$ GeV

$$\overline{\nu_\mu} + \mathrm{CH} \rightarrow \mu^+ + 1\pi^0 + X(\text{nucleons})$$

$$E_\nu = E_\mu + E_H \text{ (E_H determined calorimetrically)}$$

- Reconstructed $E_\nu \in [1.5, 10]$ GeV
- Invariant π^0 mass $\in [75, 195]$ MeV/c^2
- $W< 1.8$ GeV

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

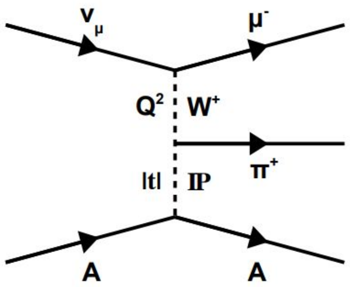
$$W_{exp}^2 = -Q^2 + m_N^2 + 2m_N E_H \text{ (m_N = nucleon mass)}$$

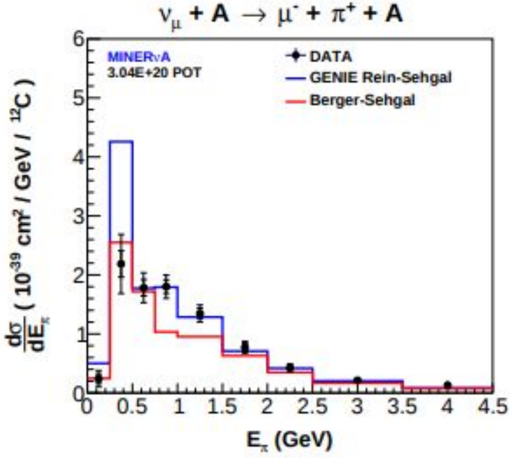
Coherent Pion Production

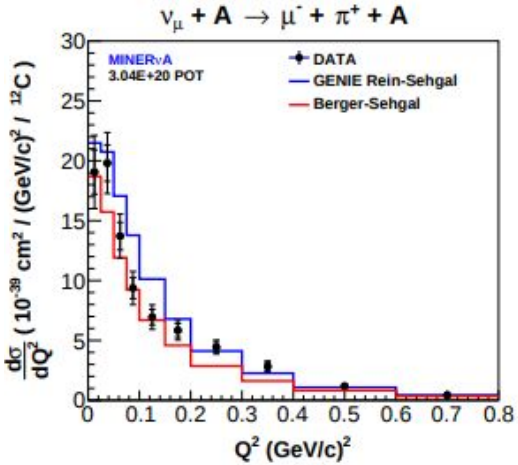
- MINERvA has also published results on neutrino and antineutrino induced coherent pion production
- Data shows preference for the Berger-Seghal over GENIE’s Rein-Seghal model
    - **Rein-Seghal:** $A^{1/3}$ scaling, uses elastic π-nucleon scattering data
    - **Berger-Seghal:** $A^{2/3}$ scaling, uses elastic π-C scattering data
    - NEUT RS prediction was poor at low E_π
- Berger-Seghal has been implemented in GENIE
- Coherent pion production provides an important contribution at low Q^2 for $\pi^\pm$ channels
    - MINERvA has that scaled simulation at low E_π to MINERvA data, which suppresses $Q^2 \sim 0.1\ \text{GeV}^2$

Phys. Rev. D97 (2018) 032014

Phys. Rev. Lett. 13 (2014) 261802

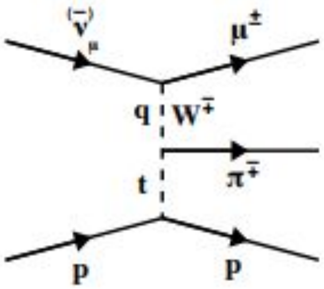


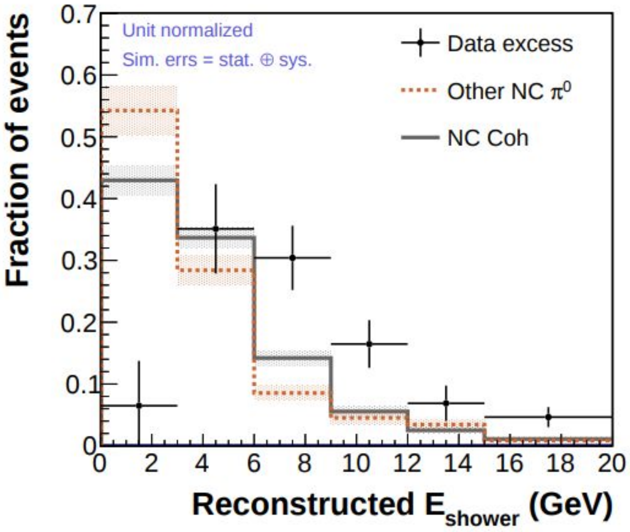




High Energy Diffractive π^0

Phys. Rev. Lett. 117 (2016) 111801





- In electron neutrino analyses, found an excess of events with photon like showers
- These events are most consistent with high energy charged current diffractive π^0 production
- Production channel is missing in GENIE
  - Therefore, our GENIE predictions are missing a sample of neutral pions with E_π> 2 GeV at low Q^2

Simulation Software

- **GENIE Event Generator v2.8.4 with Tuning** simulates neutrino interactions
- **GEANT v9.4.2p02** simulates particle propagation through matter

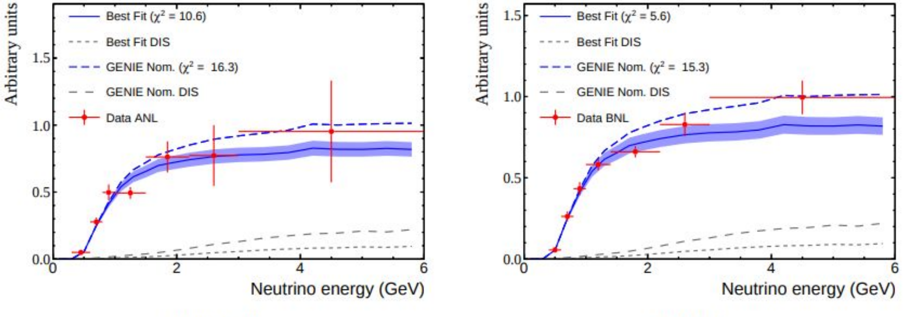
	GENIE 2.8.4	NuWro v17.01
Resonance	**Rein Seghal (W<1.7 GeV)**	**Δ(1232) w/ Rarita Schwinger**
Non-Resonant	**Scaled Bodek-Yang**	**Scaled Bodek-Yang**
Nuclear Model	**Relativistic Fermi Gas** **No Pauli blocking for res production**	**Local Fermi Gas**
FSI Model	**Effective Cascade**	**Salcedo-Oset, Full Cascade**

- **Resonance Models**
  - **GENIE:** Rein-Seghal with modern baryon-resonance parameters
    - No resonance interference, no lepton mass
  - **NuWro:** Explicit Δ(1232) with background added incoherently as a fraction of DIS

Refinements to GENIE v2.8.4

- **Recent analyses have led to tuning that improves GENIE v2.8.4 ability to fit to MINERvA and external data**
  - **MnvGENIE-v1: Tune to Deuterium Data** (C. Wilkinson, P. Rodrigues & K. McFarland Eur.Phys.J. C76 (2016) no.8, 474.)
    - Reanalysis of ANL/BNL data on single pion production on deuterium
    - Primary effect is a reduction of non-resonant pion production
      - Leads to better agreement for CCInclusive analyses
    - For MINERvA tunes, we scaled the default GENIE $\nu_\mu(\bar{\nu}_\mu)$ non-resonant pion production rate by 0.43± 0.04 (0.50 ± 0.50)

Model	GENIE default	ANL/BNL Tune
M_A^{RES} [GeV]	1.12 ± 0.22	0.94 ± 0.05
NormRES [%]	100 ± 20	115 ± 30
NonRES1π [%]	100 ± 50	43 ± 4

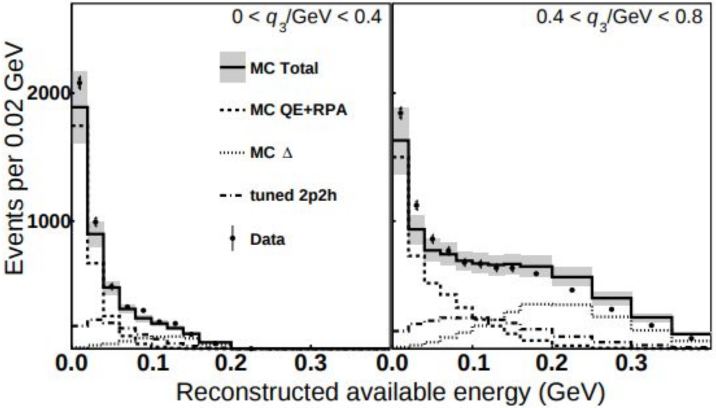


(a) ANL E_ν

(b) BNL E_ν

Further Refinements to GENIE v2.8.4

- **MnvGENIE-v1: Added a sample of CCQE-like 2p2h events tuned to MINERvA data**
  - Using the Valencia model prediction for 2p2h, reweighted events in (q_0,q_3) space to MINERvA data
  - Negligible effect on the pion production analyses
  - Valencia model, Phys. Rev. D **88**, 113007 (2013).
  - MINERvA-Tuned, Phys. Rev. Lett. **120**, 221805 (2018).

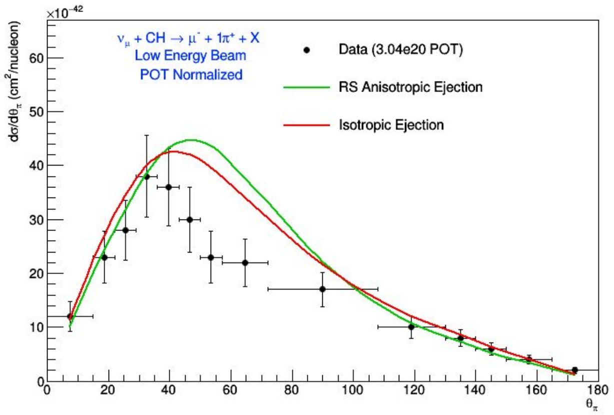


- **MnvGENIE-v1.1: Reweighted CC coherent scattering model to match with MINERvA measurements**
  - The outline of this tune was previously described in slide 19
  - Phys. Rev. D 97, 032014 (2018).

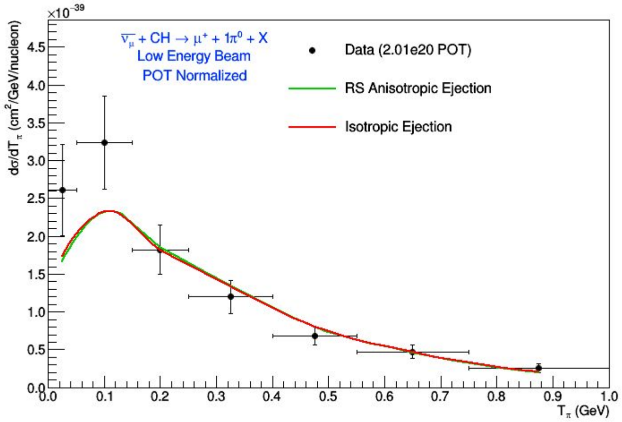
Important Caveat

- **Two channels: $\nu_\mu CC1\pi^+$ and $\overline{\nu_\mu} CC1\pi^0$ use GENIE v2.10.10 w/ MnvGENIE-v1.1**
  - Only difference between v2.8.4 and v2.10.10 is the anisotropy of the Δ(1232) decay
    - **v2.8.4:** Δ^{++} decays anisotropically using 50% of the RS prediction, all other Δ decay isotropically
    - **v2.10.10:** all Δ decay isotropically
  - The difference between angular decay is small
  - Deuterium data prefers anisotropic decay, but all models shown today try to use isotropic decay

$\nu_\mu CC1\pi^+$



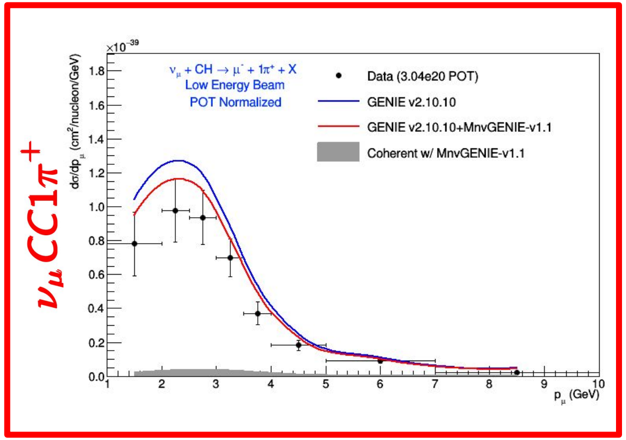
$\overline{\nu_\mu} CC1\pi^0$

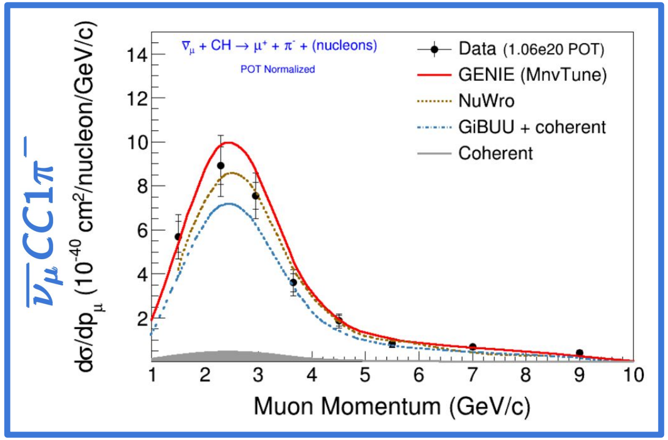


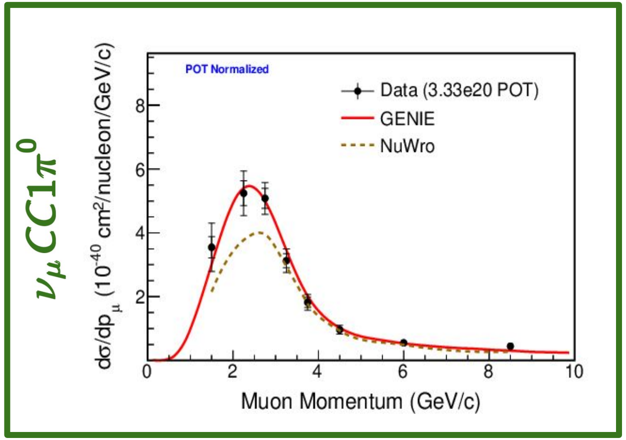
Muon Momentum

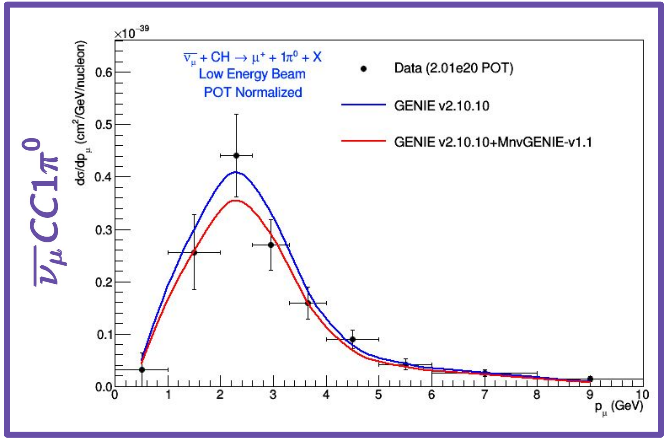
- **For the following slides, the key curve is the solid red line, which is GENIE+MnvGENIE-v1.1**
- MINERvA data has good shape agreement to the GENIE prediction in muon momentum
- GENIE overpredicts **$CC1\pi^{\pm}$** production, but it seems to do well for **$CC1\pi^{0}$** production
- NuWro has better agreement for charged pion production, but it underestimates neutral pion production
- FSI causes normalization losses in $\pi^{\pm}$, gains in π^{0}

References for plots on slide 3





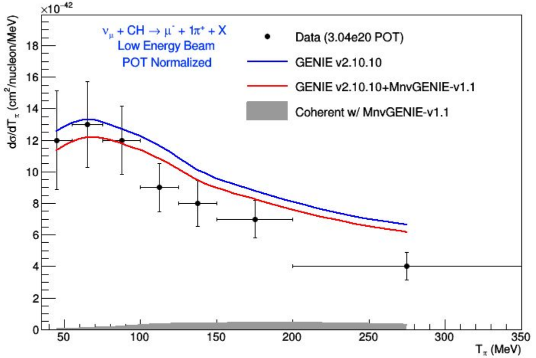




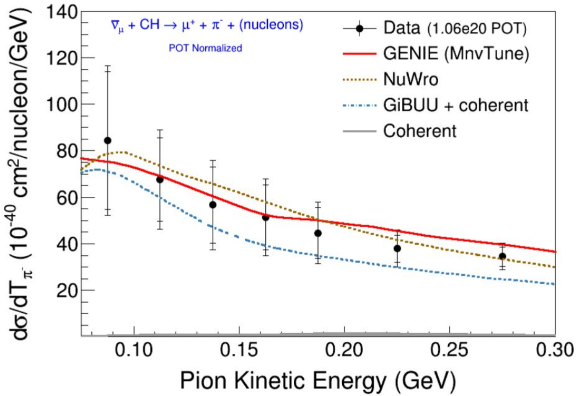
Pion Kinetic Energy

- GENIE w/ FSI has better agreement here than GENIE w/o FSI
    - Inelastic scattering is the primary cause of the hump at low kinetic energy
- Overall, GENIE underestimates at low T_π, and overestimates at higher T_π

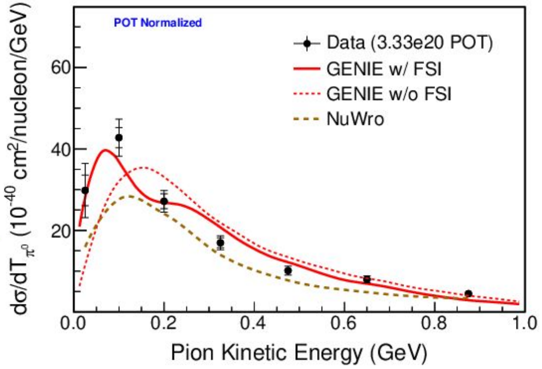
$\nu_\mu CC1\pi^+$



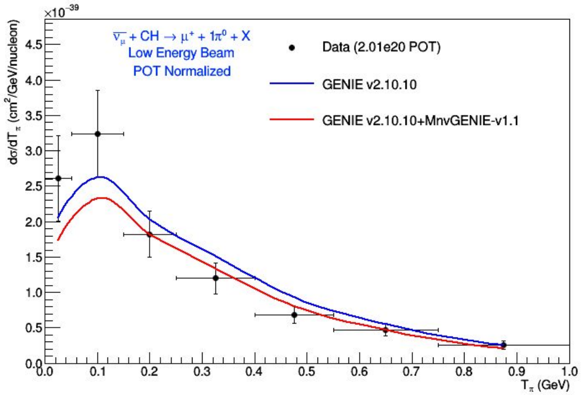
$\overline{\nu_\mu} CC1\pi^-$



$\nu_\mu CC1\pi^0$



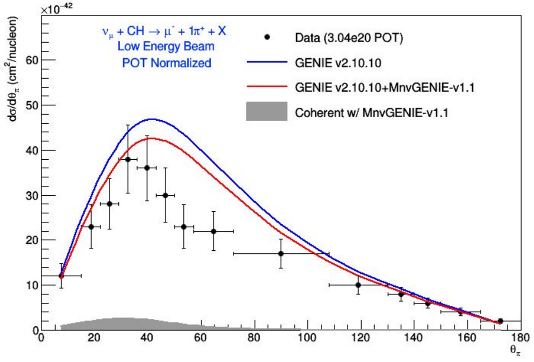
$\overline{\nu_\mu} CC1\pi^0$



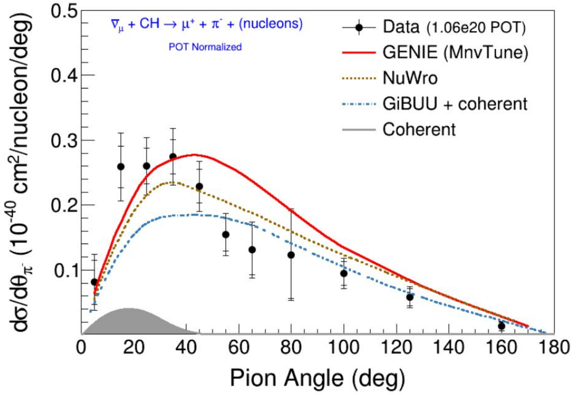
Pion Production Angle

- All channels show a preference for more forward going pions
    - Acceptance for charged and neutral pions is very different

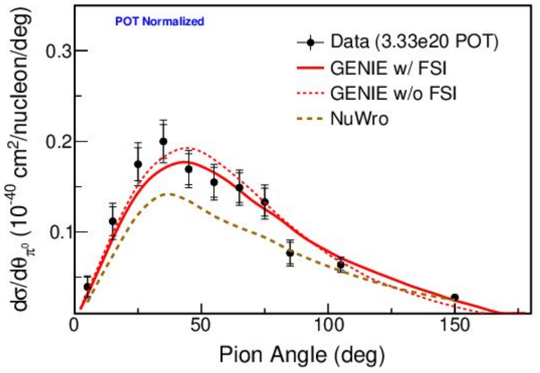
$\nu_\mu CC1\pi^+$



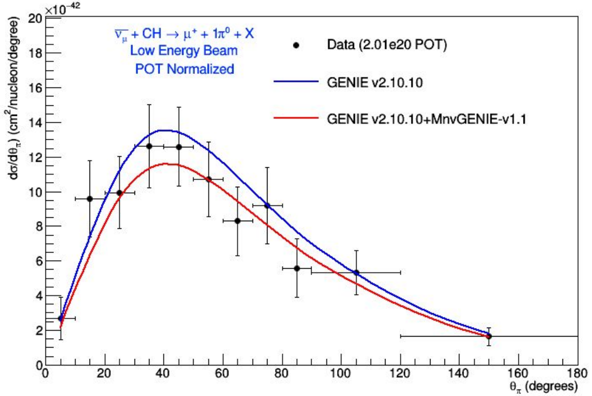
$\overline{\nu_\mu} CC1\pi^-$



$\nu_\mu CC1\pi^0$



$\overline{\nu_\mu} CC1\pi^0$

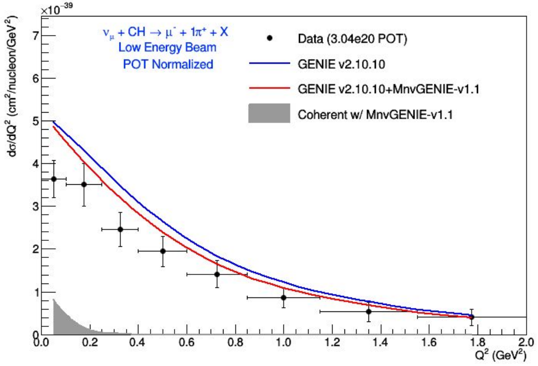


Q^2

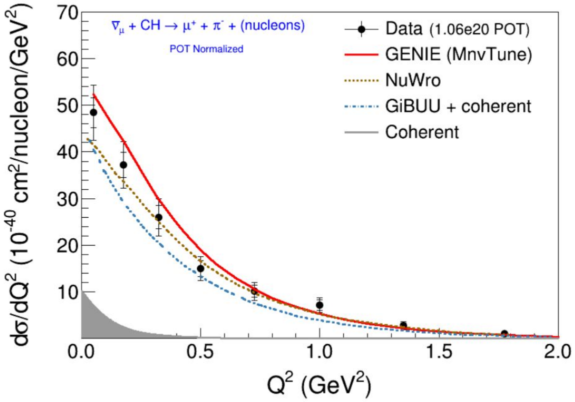
$$Q^2 = 2E_\nu(E_\mu - p_\mu \cos(\theta_{\mu\nu})) - m_\mu^2$$

- Deficit of pion production at low Q^2 in **$CC1\pi^0$** channels
- Due to the low Q^2 contribution from coherent pion production, there doesn't seem to be a significant deficit for the **$CC1\pi^\pm$** channels
- The lack of a turnover in data for the **$CC1\pi^\pm$** channels points to a process that provides events at low Q^2
  - This process is missing in neutral pion channels, i.e. a reaction where the target nucleon keeps its identity
  - Could diffractive scattering contribute to this?

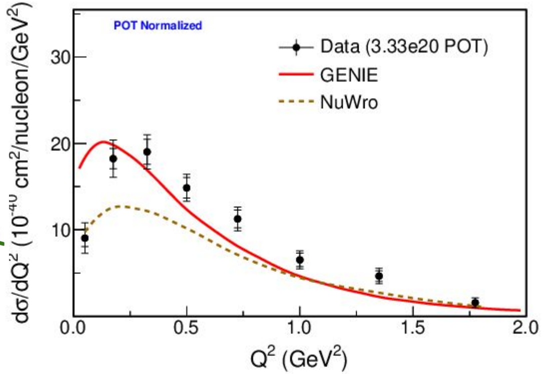
$\nu_\mu CC1\pi^+$



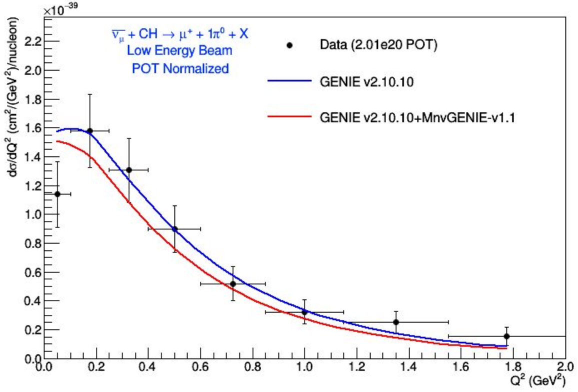
$\overline{\nu_\mu} CC1\pi^-$



$\nu_\mu CC1\pi^0$



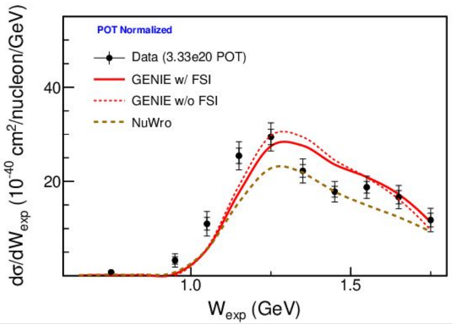
$\overline{\nu_\mu} CC1\pi^0$



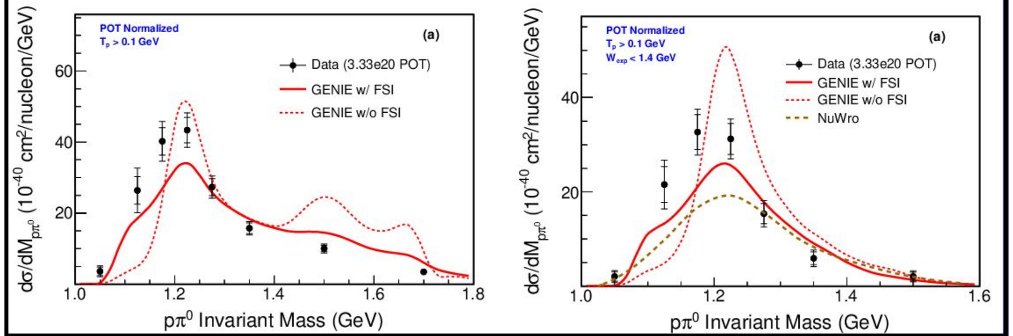
Δ(1232) Peak

$$W_{exp}^2 = -Q^2 + m_N^2 + 2m_N E_H \ (m_N = \text{nucleon mass})$$

- Currently, we only have differential cross sections for W in the $\overline{\nu_\mu}CC1\pi^0$ mode
  - We are working on equivalent cross sections for other channels
- MINERvA sees a shift in the pion spectra to lower values, which looks to be consistent with a shift to higher W in the delta peak
  - Shifts in Q^2 may induce a shift of 10 MeV
  - Possibly resonant/non-resonant interference that is absent from model
- In the $\overline{\nu_\mu}CC1\pi^0$ analysis, we had two enriched subsamples, where it is more accurate to call W the invariant mass of $p\pi^0$
  - $p\pi^0$ (W<1.8 GeV)
    - Data shows a Δ(1232) peak more pronounced than either generator
  - $\Delta^+(1232)$ enhanced region (W<1.4 GeV)
    - Low prediction at Δ peak with both generators



Subsamples



$\overline{\nu_\mu}CC1\pi^0$

So what have we done to account for these discrepancies?

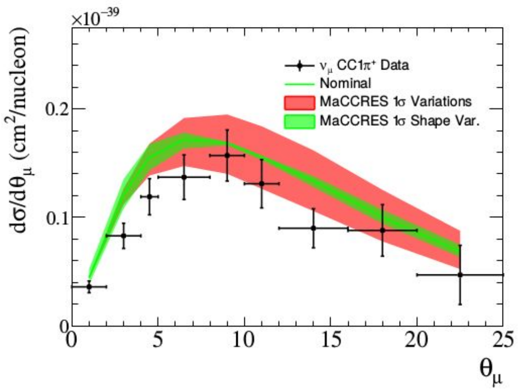
- Simulating pion production correctly requires that we improve our nucleon and nuclear models
    - Data on “free nucleons” (meaning deuterium) is limited
    - GENIE’s resonance model has a deficiency: there is no interference between non-resonant and resonant production
        - Electron scattering community believes Rein-Seghal does not describe resonance production well
        - Electron scattering uses MAID model which gets satisfactory results for non-resonant production.
        - Difficult to test versions with an axial piece with neutrinos
    - When discrepancies are found, it will be hard to disentangle whether these effects are **nucleon** or **nuclear** (FSI, initial state nuclear model)
- Still, in order to understand the discrepancy between model and MINERvA data, NUISANCE was used to tune pion production parameters in GENIE
    - This tune only looked at muon and pion kinematics
        - No Q^2 fit
    - Unfortunately, the recent $\overline{\nu}_\mu CC1\pi^-$ result could not be included in the fit in time for this talk

NUISANCE is a flexible framework in which neutrino interaction generators can be validated and/or empirically tuned to data

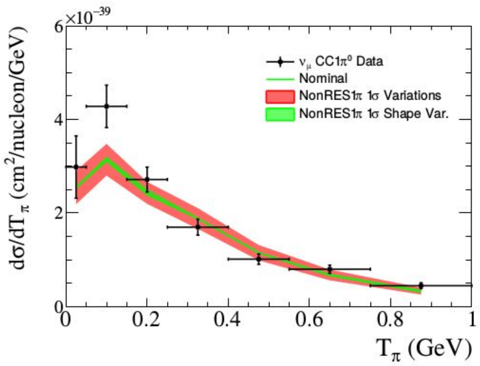
The following tunes come from Patrick Stowell’s work with the MINERvA collaboration.
(Publication in progress)

Rein-Seghal Tune

- GENIE has several parameters related to the pion production models
  - Form factors related to the Rein Seghal model (M_A^{RES}, Normalization)
  - Scaling for non-resonant 1π or 2π production
- Studied the effects of different nuclear and resonance models in GENIE (ie. LFG, Berger-Seghal, among others)
  - Changes normalization, but little change in shape
  - Used default Rein-Seghal implementation in GENIE for this study
- Fitted the model to both MINERvA and deuterium data
- The joint fit of all data sets does not produce a strong pull in either form factors or non-resonant terms



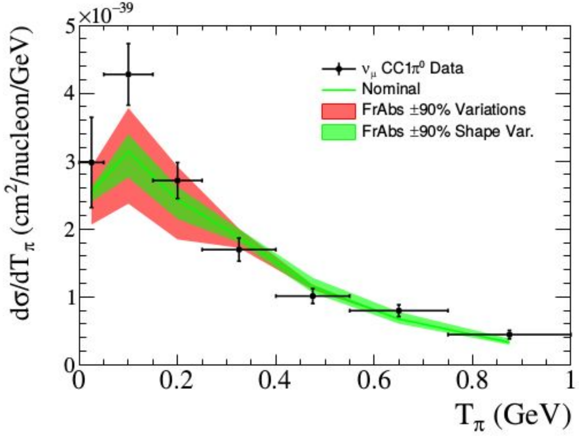
Effect of varying M_A^{RES} on the $\nu_\mu CC1\pi^+$ θ_μ



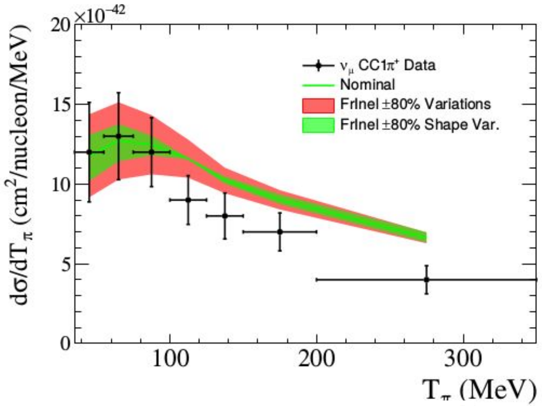
Effect of varying non-resonant 1π on the $\nu_\mu CC1\pi^0$ T_π

FSI Tuning

- While GENIE has several FSI related parameters, the study focused on two in particular due to the other having either strong prior constraints or little effect on the MINERvA MC
    - **FrAbs**: Pion absorption
    - **FrInel:** Inelastic scattering
- These parameters could not be varied at the same time
    - Varied individually and studied their behaviors
- In the joint fit of all data sets, both FSI parameters prefer the nominal
- To get any significant shape difference, the parameters need to be varied by +/- 3σ
- Points to either the need for strong FSI pulls or the need for other parameters that have more freedom to cover discrepancies in T_π and θ_μ



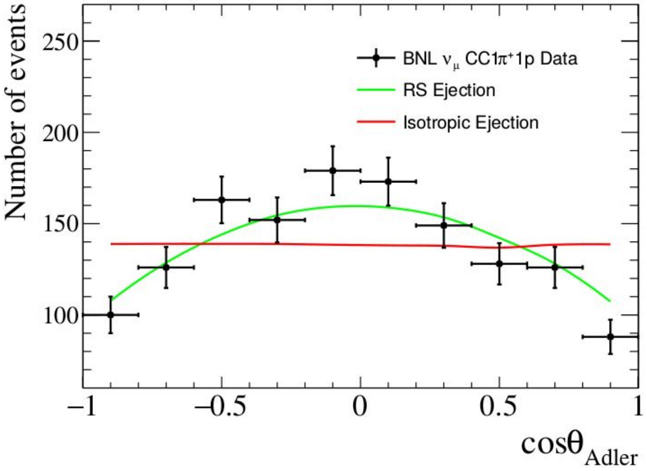
Effect of varying FrAbs on the T_π $\nu_\mu CC1\pi^0$ distribution

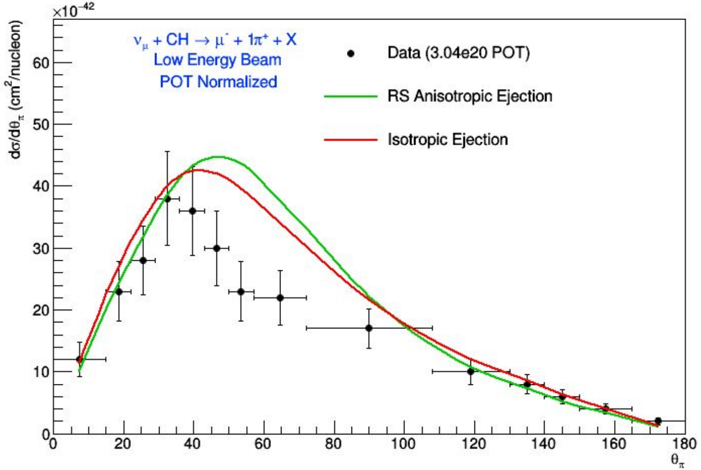


Effect of varying FrAbs on the T_π $\nu_\mu CC1\pi^+$ distribution

Tuning the Angular Ejection

- Can adjust pion angular ejection with **Theta-π** parameter
  - Allows for continuous reweighting between default anisotropic RS prediction and isotropic decay in rest frame
- Deuterium data prefers anisotropic emission
- Joint fit prefers isotropic emission, which improves agreement with MINERvA data
  - This perhaps says more about FSI than emission





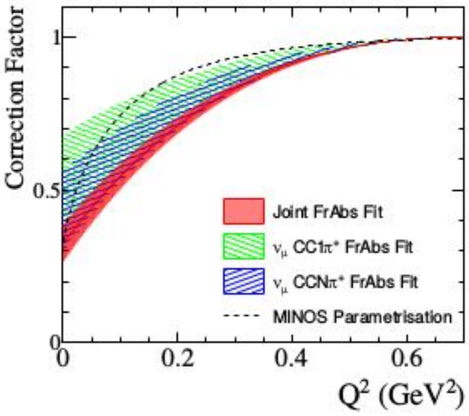
Ad-hoc Q^2 Suppression

- Several other experiments see discrepancies in low Q^2 and θ_μ distributions (MiniBooNE, MINOS)
  - MINOS introduced a suppression function tuned to Δ enriched sidebands that improved agreement to RES and RES-to-DIS enhanced samples
- MINERvA tried something similar with a different suppression function
  - π^0 production prefers strong low Q^2 suppression
  - π^+ production prefers smaller suppression
    - Charged coherent pion production partly fills the suppression at low Q^2

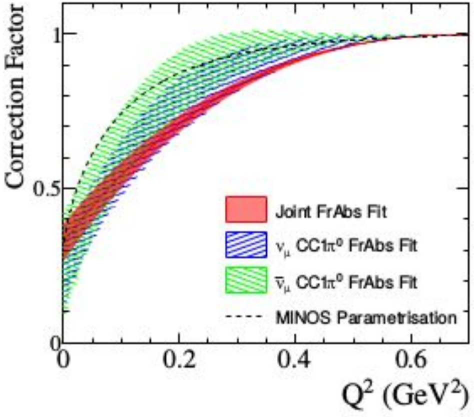
$$R(Q^2 < x_m) = \frac{R_1(x - x_2)(x - x_m)}{(x_1 - x_2)(x_1 - x_m)} + \frac{R_2(x - x_1)(x - x_m)}{(x_2 - x_1)(x_2 - x_m)} + \frac{(x - x_1)(x - x_2)}{(x_m - x_1)(x_m - x_2)}$$

$$W(Q^2) = 1 - (1 + R_1 + R(Q^2)(1 - R_1))^2$$

$$x_1 = 0.0\ GeV^2; x_2 = 0.35\ GeV^2; x_m = 0.7\ GeV^2$$



$CC1\pi^\pm$ Suppression Curve

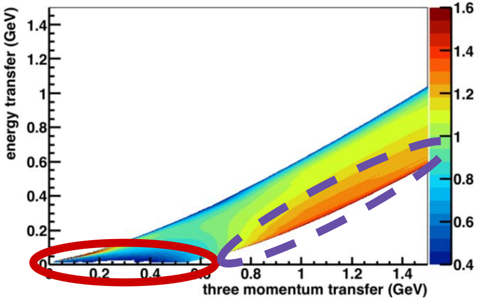


$CC1\pi^0$ Suppression Curve

Should we use RPA predictions for pion interactions?

- There is a similar deficiency at low Q^2 in $CC0\pi$
  - Apply the Valencia RPA multinucleon effect to CCQE events
  - Primarily a suppression in energy transfer, not Q^2
- Seems flawed to shift Valencia model to Δ region
  - Includes several nuclear corrections
  - Also, fundamentally flawed to move a low q_0 process into the pion region, which requires a significant q_0 transfer
  - <u>But</u>, the real effect could have interesting shape in (q_0,q_3) space
    - Prediction helpful

RPA Correction

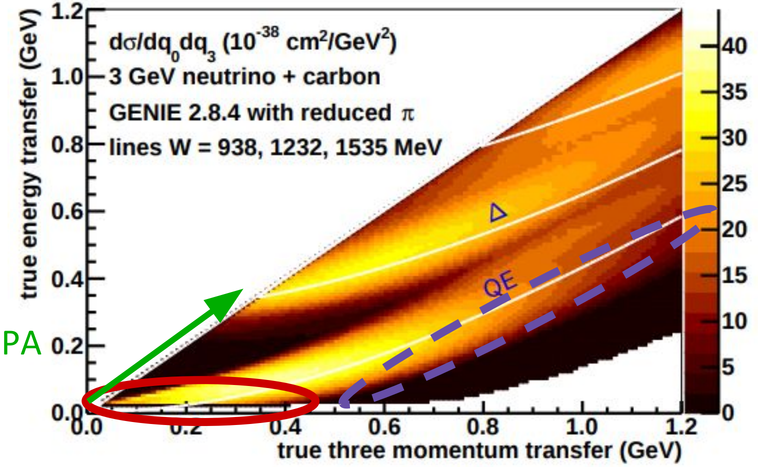


Energy Transfer q_0

$$q_0 = E_\nu - E_\mu$$

Momentum Transfer q_3

$$q_3 = \sqrt{Q^2 + q_0^2}$$



Shifting the RPA predictions

Conclusions

- MINERvA has measured all four charged current pion production channels in Δ(1232) dominated samples off of carbon in our low energy beam
  - We have uncovered important discrepancies between simulation and data in charged pion and neutral pion production, particularly in low Q^2
  - Current framework does not give enough tools to cover these discrepancies
- It seems that MINERvA has a decent understanding of coherent pion production. Working on effective A scaling
  - Diffraction pion production is tougher, will require more effort
- Theory can improve the situation with the nucleon model
  - We are happy to work with generator developers
    - Many thanks to NUISANCE developers
- Medium energy beam results coming soon!
  - More POT, more flux, higher statistics
  - Will allow us to look at heavier nuclei

This material is based upon work supported by U.S. Department of Energy award DE-SC-0008475

Thank you

Backup Slides

Additional Event Selection

$$\nu_\mu + \text{CH} \rightarrow \mu^- + 1\pi^+ + X(\text{nucleons})$$

- No matched michels
  - Interaction vertex, showers, track endpoints
- Photon conversion distance > 15 cm
- $E_{vis} \in$ [80 MeV, 2 GeV]

$$\overline{\nu_\mu} + \text{CH} \rightarrow \mu^+ + 1\pi^- + X(\text{nucleons})$$

- No matched michels
  - Interaction vertex, showers, track endpoints
- E_{vtx} = unassociated hits <9cm of interaction vertex
- Photon conversion distance > 14 cm
- Energy in nuclear targets < 20 MeV
- Non-track + vertex energy $\in$ [50 MeV, 2.5 GeV]

$$\nu_\mu + \text{CH} \rightarrow \mu^- + 1\pi^0 + X(\text{nucleons})$$

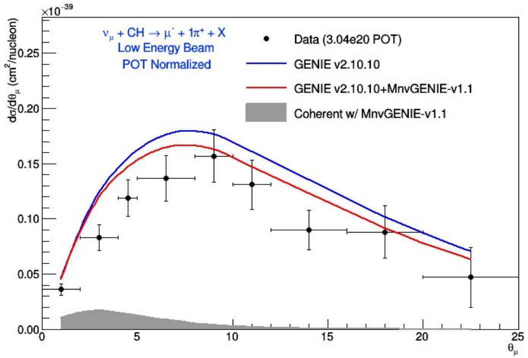
- No matched michels
  - Interaction vertex, showers, track endpoints

$$\overline{\nu_\mu} + \text{CH} \rightarrow \mu^+ + 1\pi^0 + X(\text{nucleons})$$

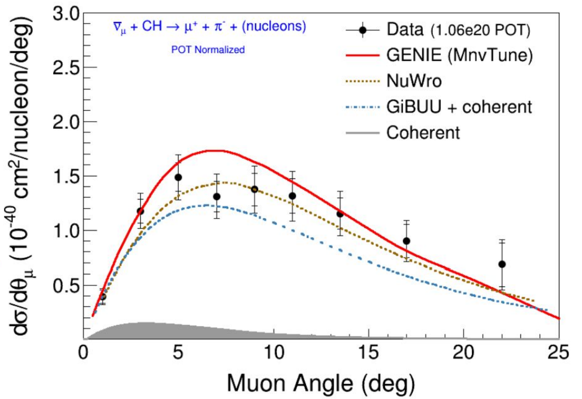
Muon Production Angle

- Due to the MINOS match requirement, MINERvA acceptance for $\theta_\mu<25^\circ$
- For ***CC*1π⁰** production, GENIE overestimates $\theta_\mu<5^\circ$

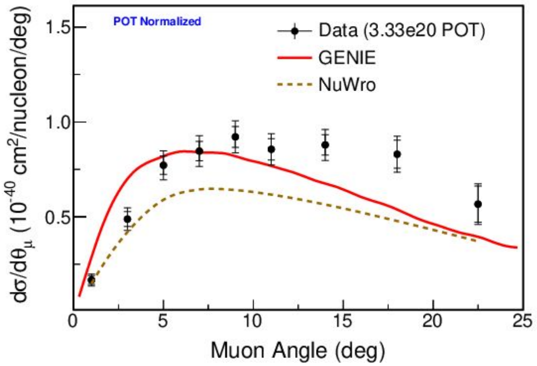
$\nu_\mu CC1\pi^+$



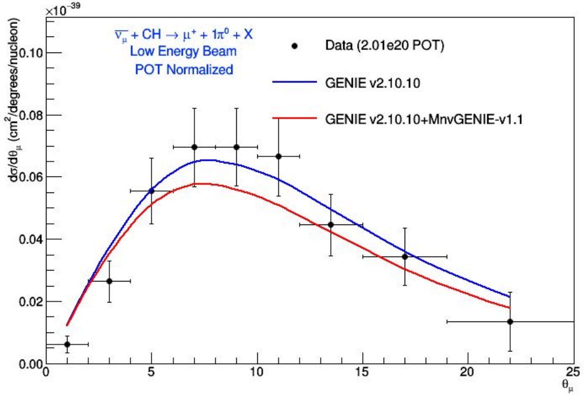
$\overline{\nu_\mu} CC1\pi^-$



$\nu_\mu CC1\pi^0$



$\overline{\nu_\mu} CC1\pi^0$

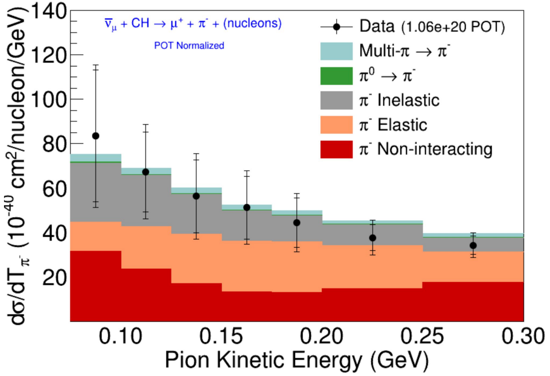


Pion Kinetic Energy with FSI

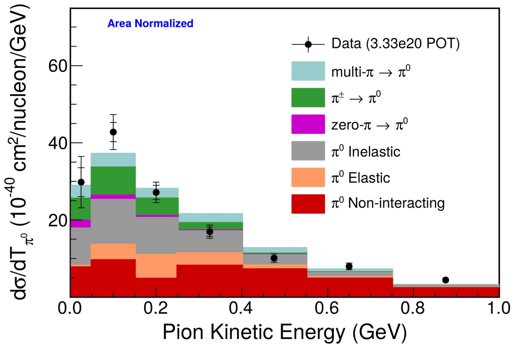
- There are no FSI plots using GENIE 2.8.4 + MnvGENIE-v1.1 for the $\nu_\mu CC1\pi^+$ and $\overline{\nu_\mu} CC1\pi^0$ channels
- Neutral pion result is area normalized, charged pion result is POT normalized

$\nu_\mu CC1\pi^+$

$\overline{\nu_\mu} CC1\pi^-$



$\nu_\mu CC1\pi^0$



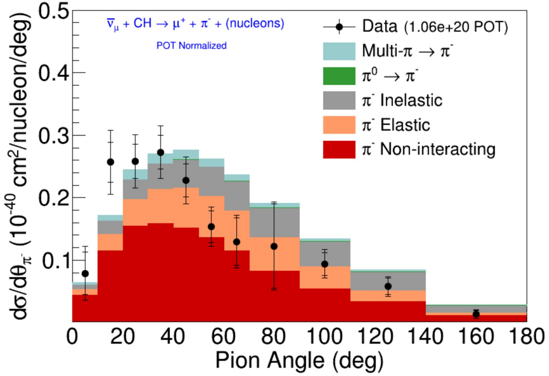
$\overline{\nu_\mu} CC1\pi^0$

Pion Angle with FSI

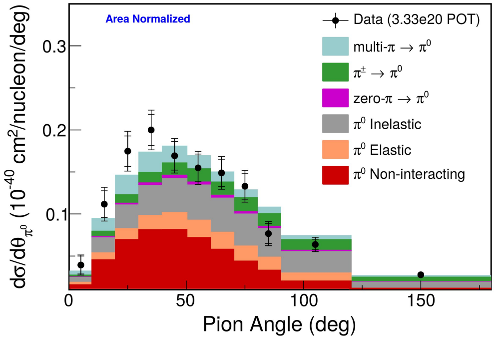
- There are no FSI plots using GENIE 2.8.4 + MnvGENIE-v1.1 for the $\nu_\mu CC1\pi^+$ and $\overline{\nu_\mu} CC1\pi^0$ channels
- Neutral pion result is area normalized, charged pion result is POT normalized

$\nu_\mu CC1\pi^+$

$\overline{\nu_\mu} CC1\pi^-$

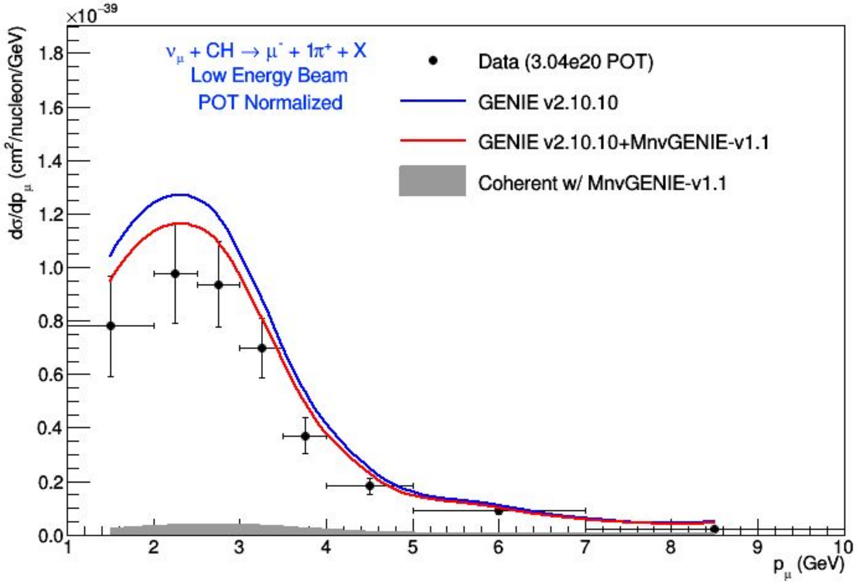


$\nu_\mu CC1\pi^0$

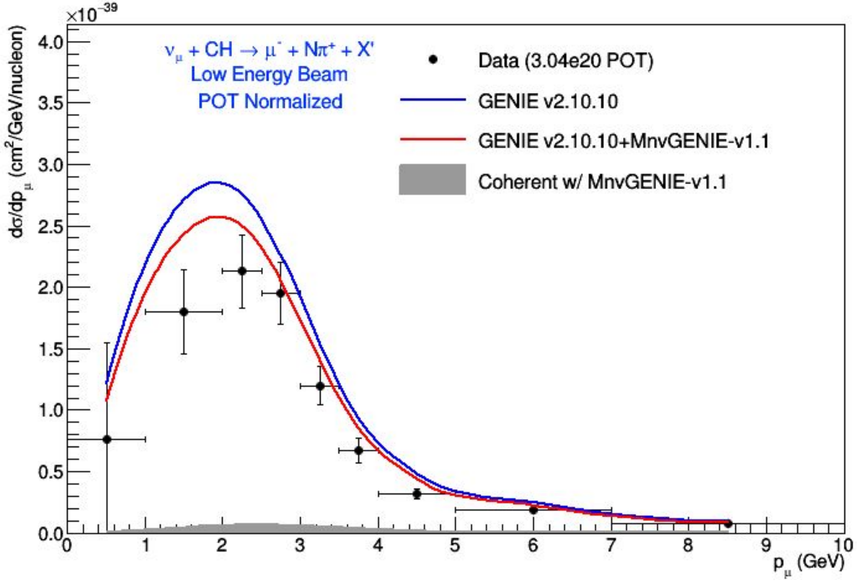


$\overline{\nu_\mu} CC1\pi^0$

ν_μCC1/Nπ^+ Muon Momentum



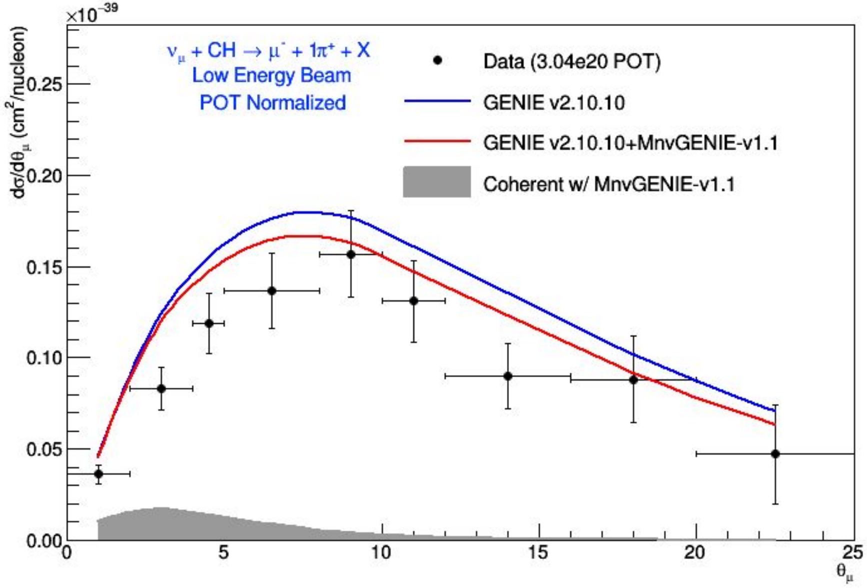
$\nu_\mu CC1\pi^+$



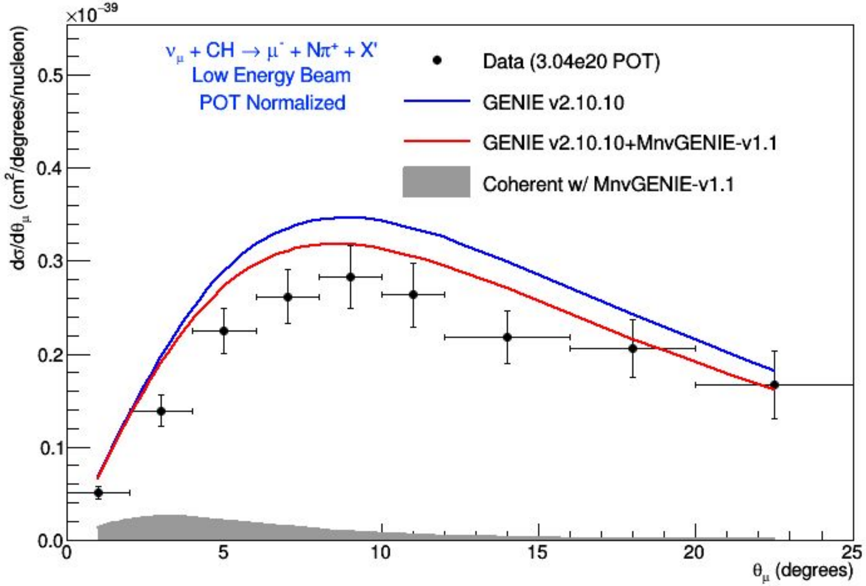
$\nu_\mu CCN\pi^+$

References for plots on slide 3

$\nu_\mu CC1/N\pi^+$ Muon Production Angle

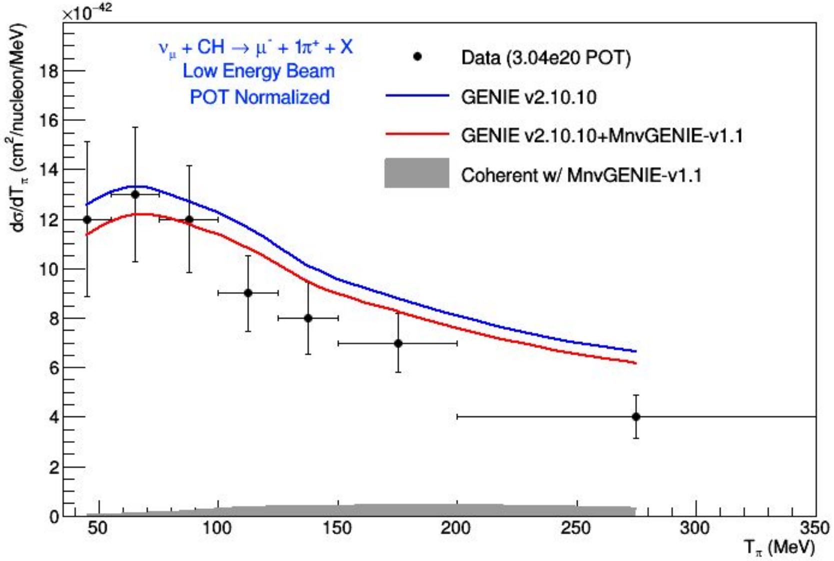


$\nu_\mu CC1\pi^+$

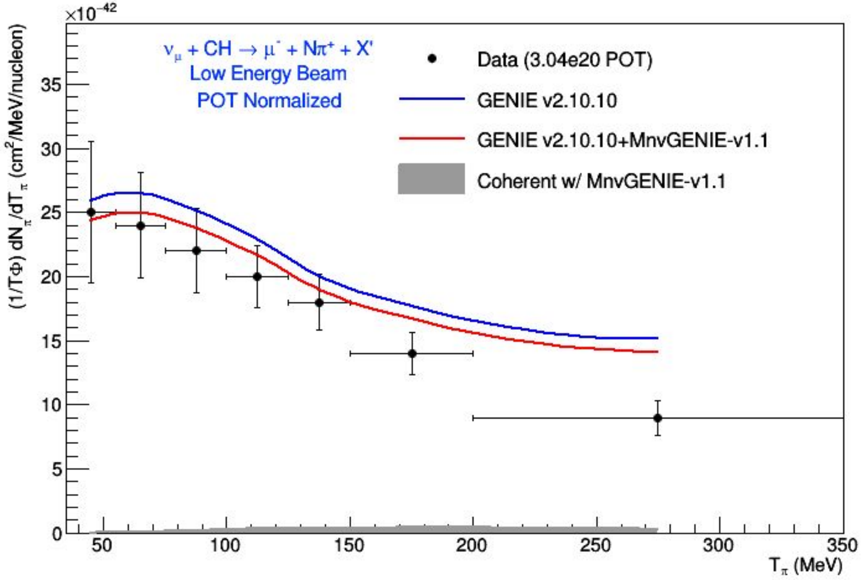


$\nu_\mu CCN\pi^+$

ν_μCC1/Nπ^+ Pion Kinetic Energy

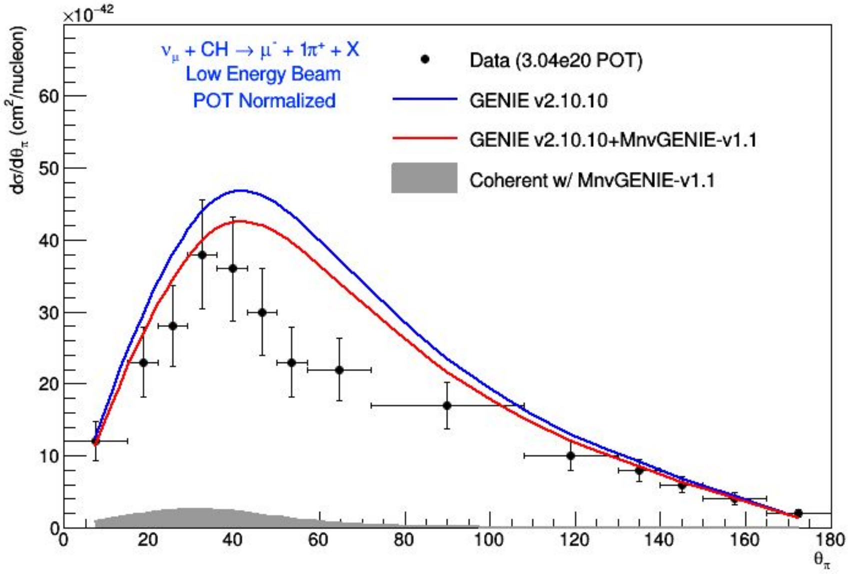


$\nu_\mu CC1\pi^+$

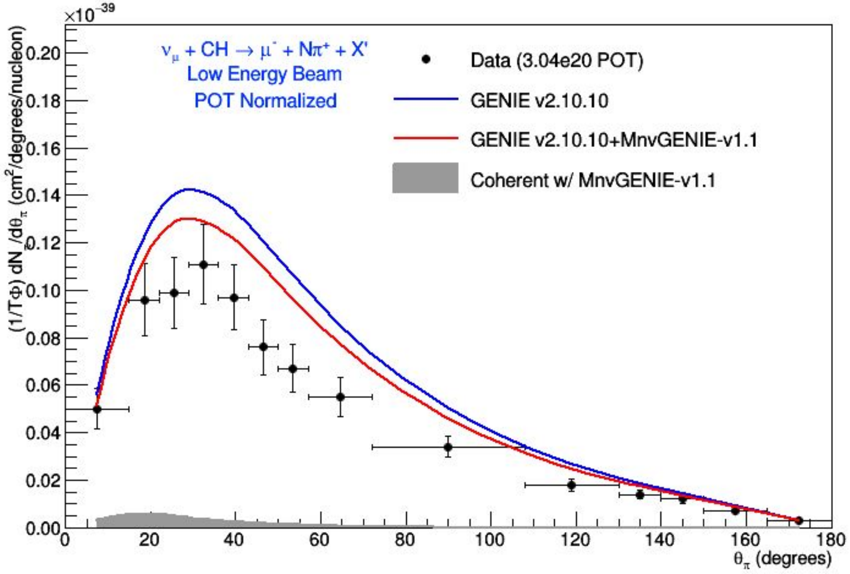


$\nu_\mu CCN\pi^+$

$\nu_\mu CC1/N\pi^+$ Pion Production Angle



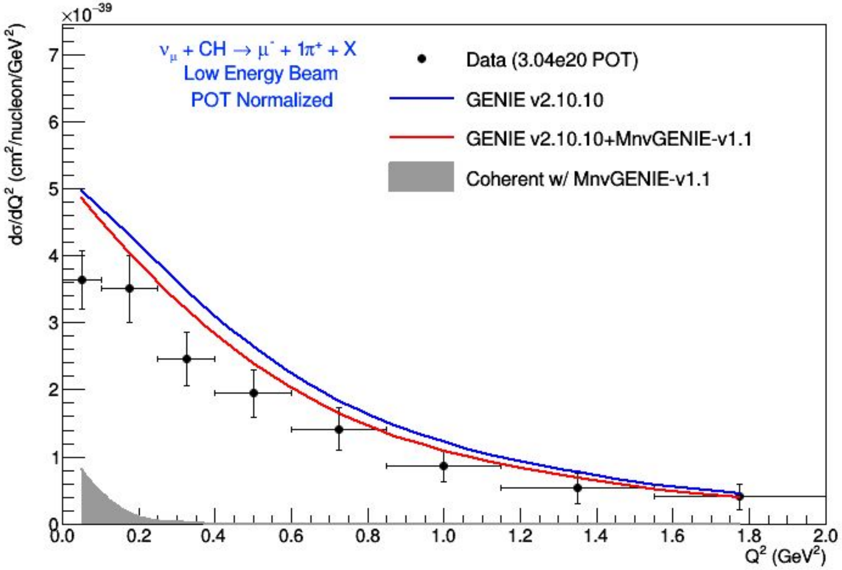
$\nu_\mu CC1\pi^+$



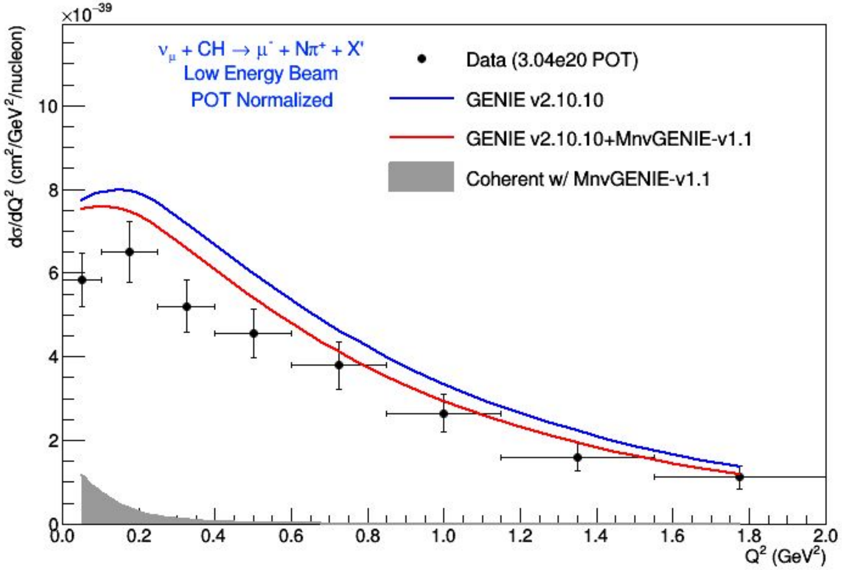
$\nu_\mu CCN\pi^+$

Q^2

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



$\nu_\mu CC1\pi^+$



$\nu_\mu CCN\pi^+$

χ^2/# of bins of Data vs GENIE 2.10.10 + MnvGENIEv1.1

Kinematic	$\nu_\mu CC1\pi^+$	$\nu_\mu CCN\pi^+$	$\nu_\mu CC1\pi^0$	$\overline{\nu_\mu} CC1\pi^0$	$\overline{\nu_\mu} CC1\pi^-$
p_μ	17.08/8	24.54/9	35.86/8	6.59/9	8.9/8
θ_μ	30.95/9	18.74/9	160.06/9	13.31/9	9.9/9
T_π	18.07/7	31.55/7	173.28/7	12.56/7	1.8/7
θ_π	80.11/14	29.76/14	130.25/11	5.45/11	32.0/11
Q^2	15.36/8	14.57/8	111.52/8	12.15/8	8.3/8
W_{exp}	N/A	N/A	141.88/10	N/A	N/A

- Caution when using these χ^2 to determine goodness of fit. The covariance matrices may not be fully complete

Measurement of isospin amplitudes

- The recent $\overline{\nu_\mu}CC1\pi^-$ result can decompose its signal sample into nucleon level cross sections using a vertex energy fit to find overall rate

$$\overline{\nu_\mu} n \to \mu^+ n \pi^-$$
$$\overline{\nu_\mu} p \to \mu^+ p \pi^-$$

- Also, the $\overline{\nu_\mu}CC1\pi^0$ result has an exclusive nucleon reaction channel

$$\overline{\nu_\mu} p \to \mu^+ n \pi^0$$

- It is then possible to find the relative strength and phase between the amplitudes of isospin *I* = 1/2, 3/2

$$\langle |A_3|^2 \rangle = \frac{1}{2} \sigma(\mu^+ n \pi^-)$$
$$\langle |A_1|^2 \rangle = \frac{3}{4} \left(\sigma(\mu^+ n \pi^0) + \sigma(\mu^+ p \pi^-) - \frac{1}{3} \sigma(\mu^+ n \pi^-) \right)$$
$$\langle \mathfrak{Re}(A_3^* A_1) \rangle = \frac{3}{8} \left(\sigma(\mu^+ p \pi^-) - 2\sigma(\mu^+ n \pi^0) + \frac{1}{3} \sigma(\mu^+ n \pi^-) \right)$$

$$R^{\overline{\nu}} = \left(\langle |A_1|^2 \rangle / \langle |A_3|^2 \rangle \right)^{1/2}$$
$$\cos \phi^{\overline{\nu}} = \langle \mathfrak{Re}(A_3^* A_1) \rangle / \langle |A_1|^2 \rangle^{1/2} \langle |A_3|^2 \rangle^{1/2}$$