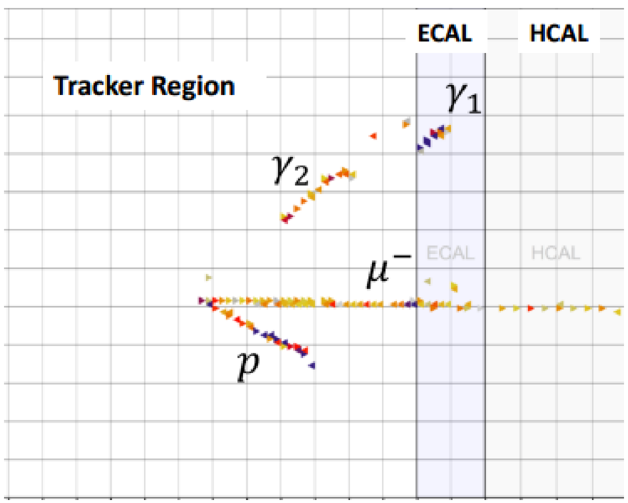
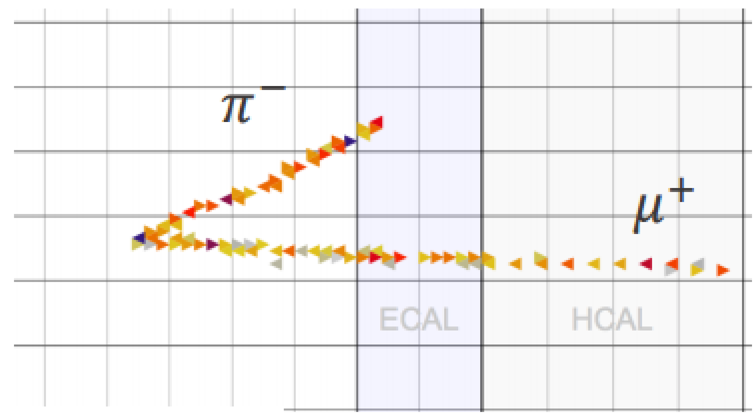
CC Single Pion Production on CH: the MINERvA perspective





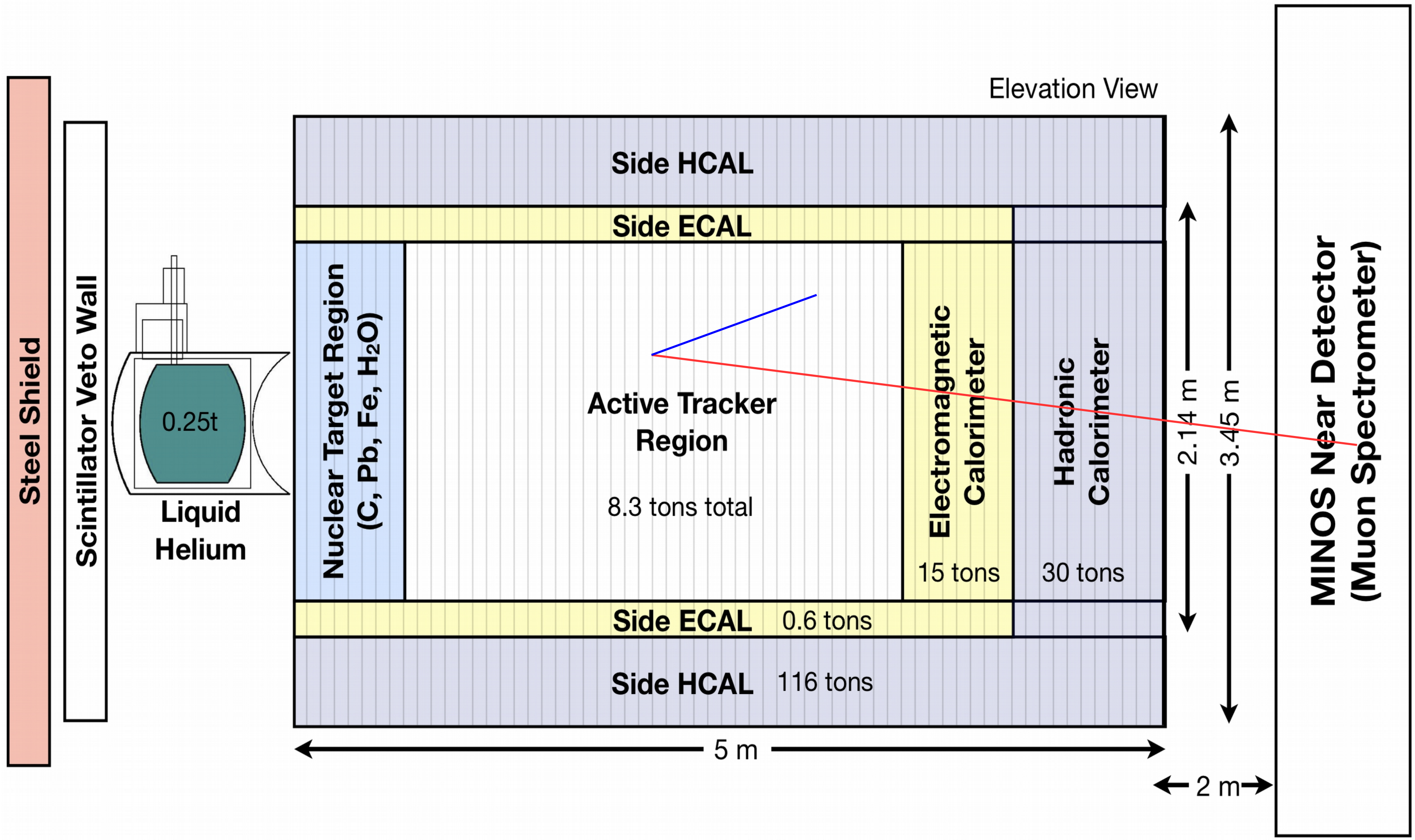
Trung Le
Tufts University

NuSTEC Workshop, Oct 2-5, Pittsburgh

Outline

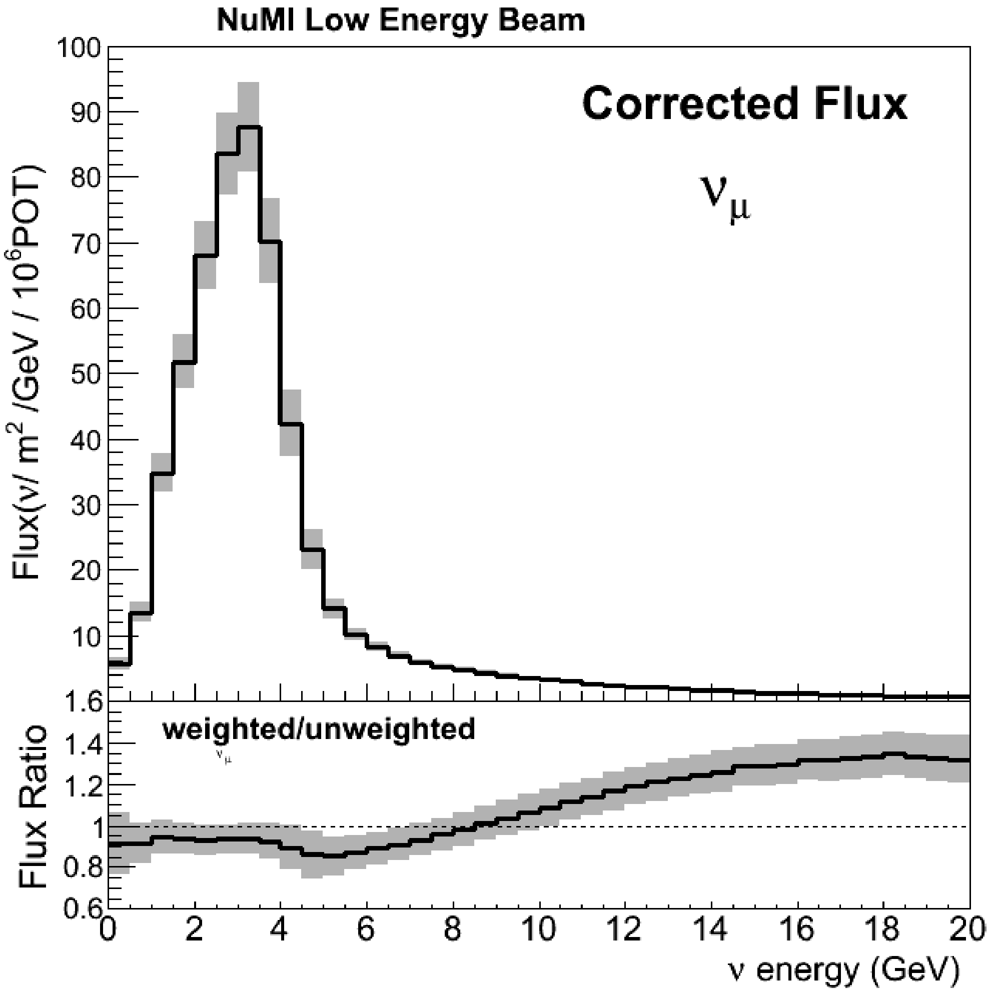
- Brief overview of Minerva detector
- Minerva CC pion measurements
  - Muon observables as probe of interaction models
  - Pion variables as probe of FSI models
  - ν_μ and $\bar{\nu}_\mu$ CCπ cross section versus E_ν
  - Low Q^2 suppression
  - Hadronic invariant mass
- Status and future plans
  - Ongoing low-energy (LE) analyses
  - Medium-energy (ME) analyses

MINERvA detector

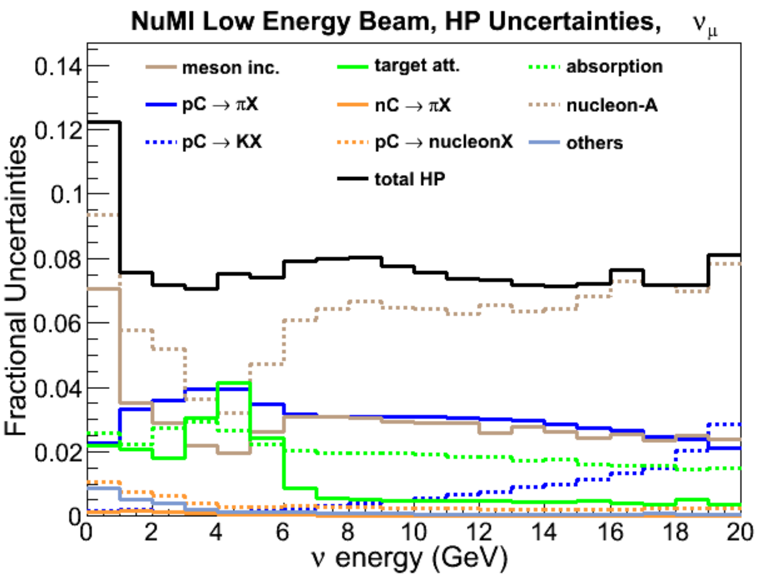


All CC pion results shown here are in the tracker region (CH)

NuMI low-energy ν_μ flux



L. Aliaga et al, PRD 94 092005



- NuMI “low energy” beam tune, ~3.5 GeV peak energy, with ~8% uncertainty dominated by hadron production (HP).
- Additional constraint using ν-e elastic scattering.

CC pion reactions

$$\nu_\mu + \mathrm{CH} \rightarrow \mu^- + \pi^\pm + X(\text{no mesons})$$

- $1.5 < E_\nu < 10$ GeV
- $W < 1.8$ GeV
- $1\pi^+$ result $W < 1.4$ GeV
- Coherent contribution

PRD 92, 092008 (2015)

$$\nu_\mu + \mathrm{CH} \rightarrow \mu^- + 1\pi^0 + X(\text{no mesons})$$

- $1.5 < E_\nu < 20$ GeV
- $W < 1.8$ GeV
- $\theta_\mu < 25$ degrees

PRD 96, 072003 (2017)

$$\bar{\nu}_\mu + \mathrm{CH} \rightarrow \mu^+ + 1\pi^0 + X(\text{no mesons})$$

- $1.5 < E_\nu < 10$ GeV
- $W < 1.8$ GeV

PRD 94, 052005 (2016)

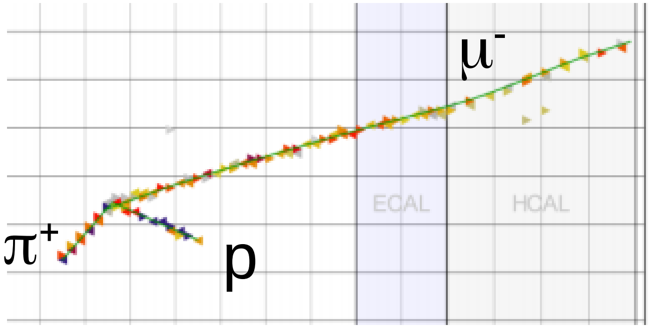
$$\bar{\nu}_\mu + \mathrm{CH} \rightarrow \mu^+ + 1\pi^- + X(\text{no mesons})$$

- $1.5 < E_\nu < 10$ GeV
- $W < 1.8$ GeV
- $\theta_\mu < 25$ degrees
- Coherent contribution

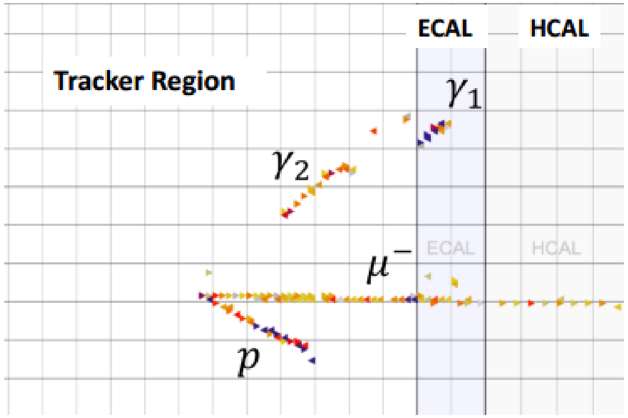
PRD 100, 052008 (2019)

Event displays

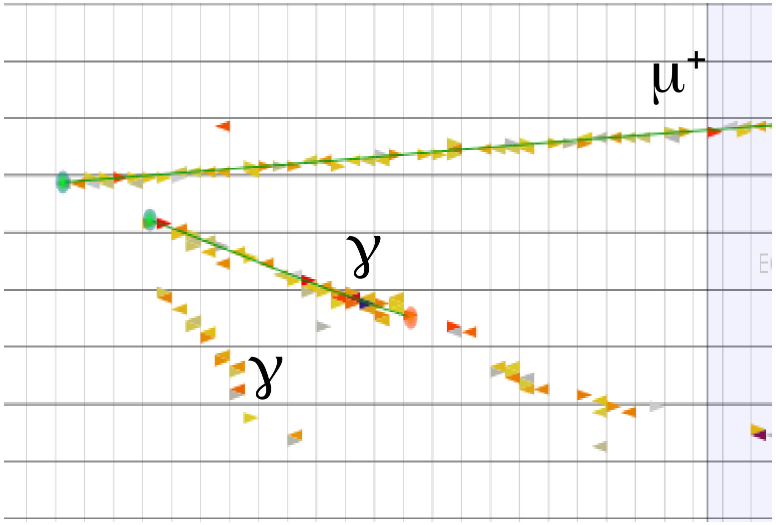
$\nu_\mu + \mathrm{CH} \rightarrow \mu^- + 1\pi^+ + X(\text{no mesons})$



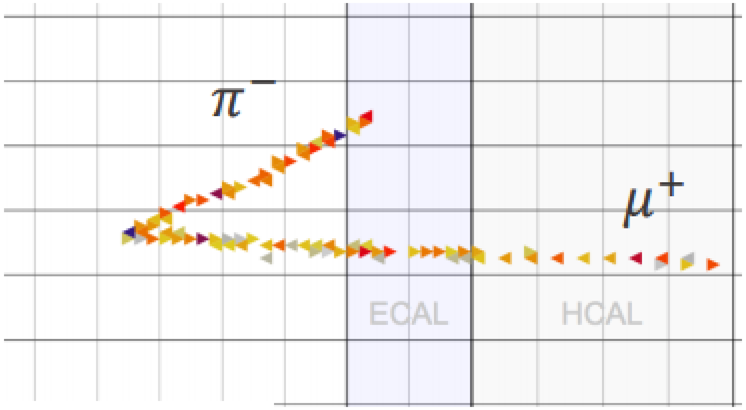
$\nu_\mu + \mathrm{CH} \rightarrow \mu^- + 1\pi^0 + X(\text{no mesons})$



$\bar{\nu}_\mu + \mathrm{CH} \rightarrow \mu^+ + 1\pi^0 + X(\text{no mesons})$



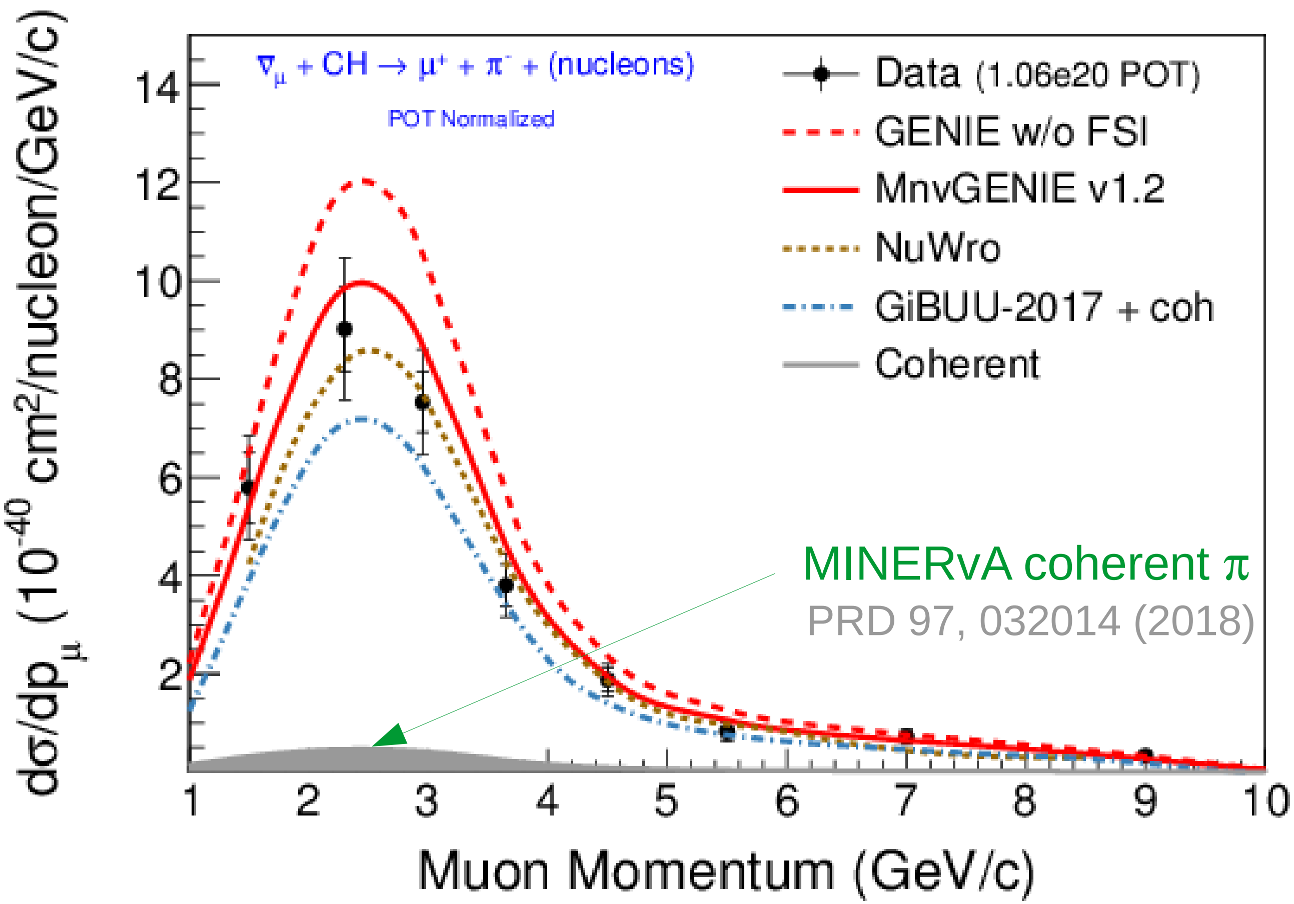
$\bar{\nu}_\mu + \mathrm{CH} \rightarrow \mu^+ + 1\pi^- + X(\text{no mesons})$



Pions reconstruction in tracker (CH)

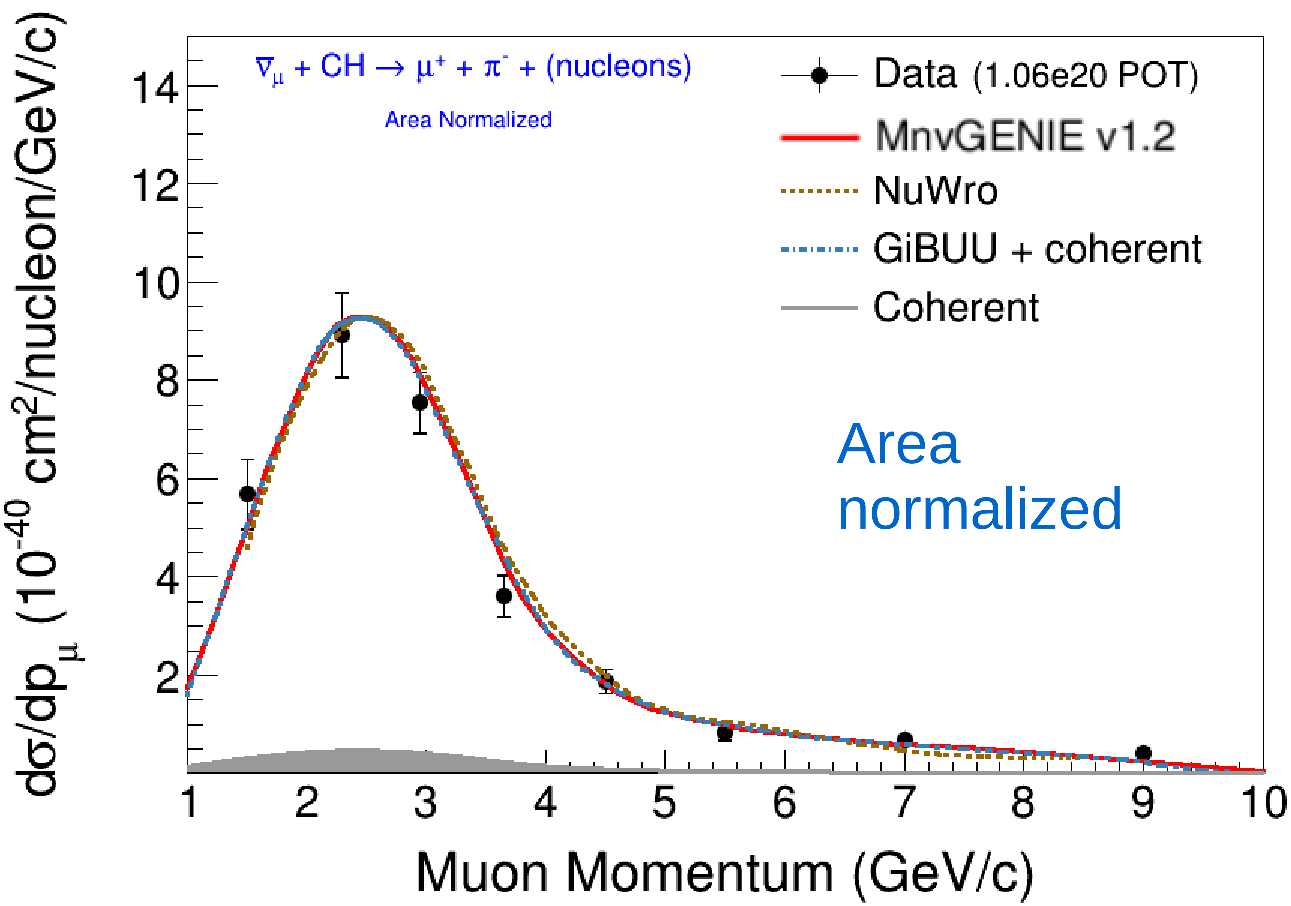
- π^0
  - Can reconstruct $\gamma\gamma$ invariant $\rightarrow$ reject non-π^0 background
  - No tracking threshold, down to $T_\pi = 0$
  - Full angular acceptance
- $\pi^\pm$
  - p/π separation using dE/dx
  - Kinetic energy T_π reconstructed from range
  - No angular acceptance between 70 - 110 degrees
- π^- is harder to reconstruct than π^+
  - π^+ can be positively identified using Michel tag while no tag for π^- due to capture
  - Michel tag also improves energy resolution for π^+

Muon momentum



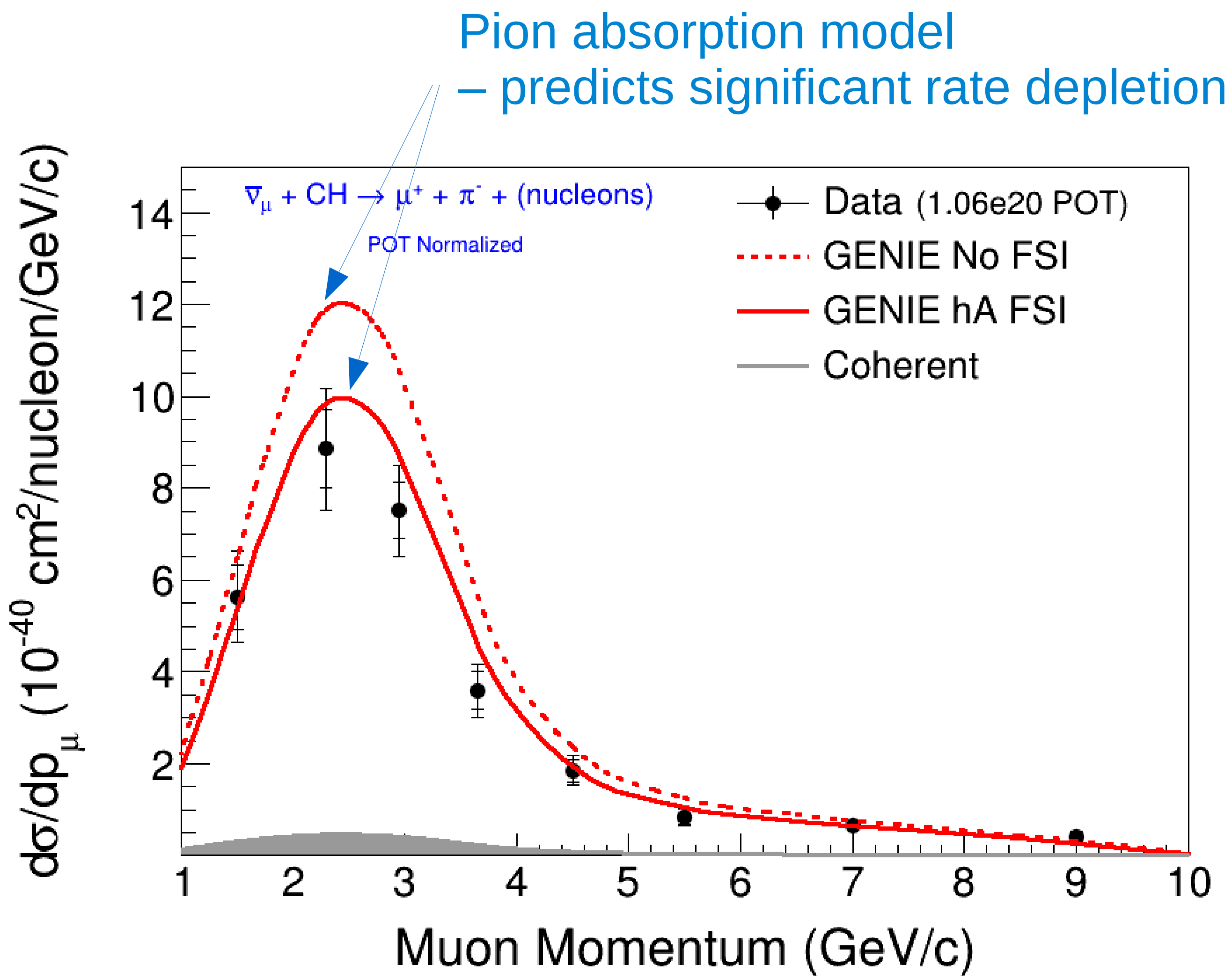
- Observe rate difference among generators.
- FSI has strong impact on rate prediction.

Muon momentum



- Generator models predict a nearly identical shape.
- The predicted shape is in good agreement with data.

Muon momentum

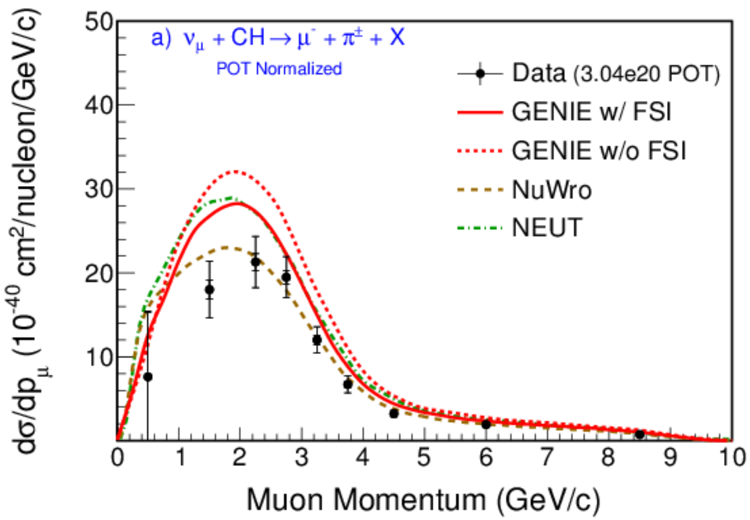


FSI has negligible effect on muon kinematics. However, FSI can have strong effects on signal event population for CCπ.

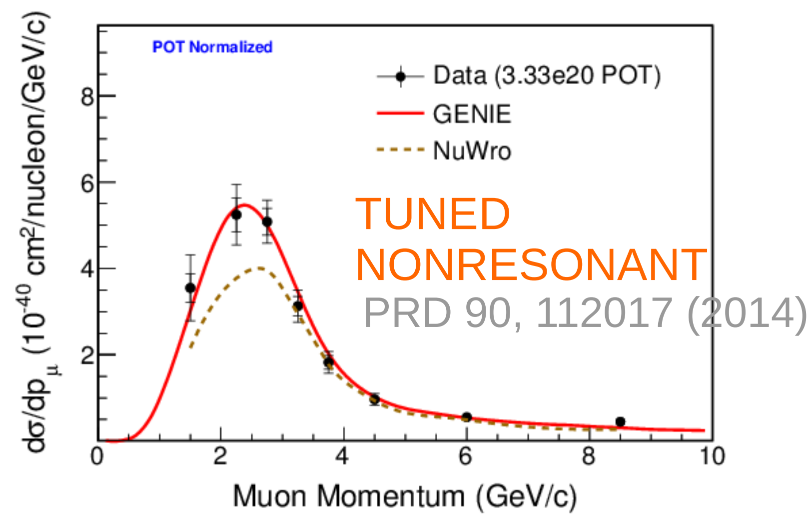
Muon momentum

Generators differ in their absolute rate prediction and there are some discrepancies with the data

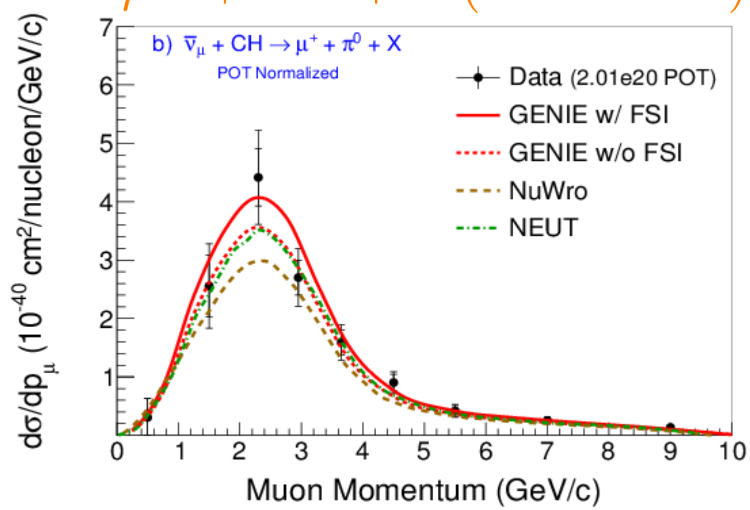
$\nu_\mu + \mathrm{CH} \to \mu^- + \pi^\pm + X\,(\text{no mesons})$



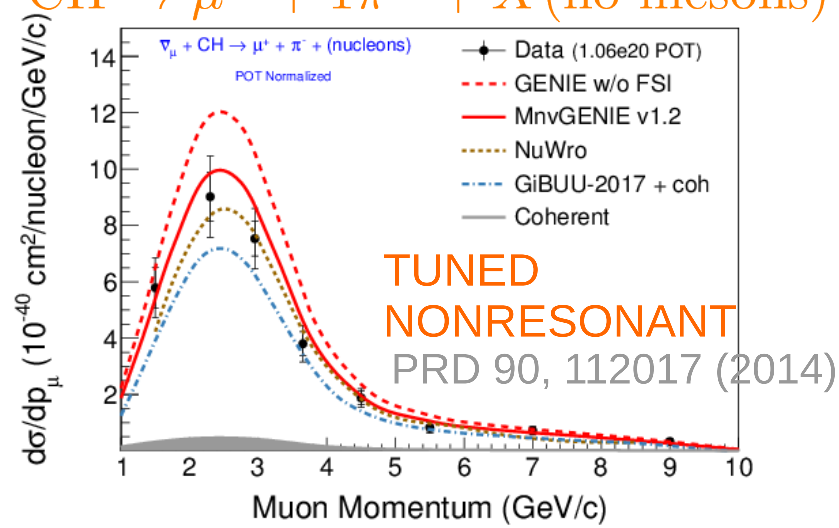
$\nu_\mu + \mathrm{CH} \to \mu^- + 1\pi^0 + X\,(\text{no mesons})$



$\bar{\nu}_\mu + \mathrm{CH} \to \mu^+ + 1\pi^0 + X\,(\text{no mesons})$



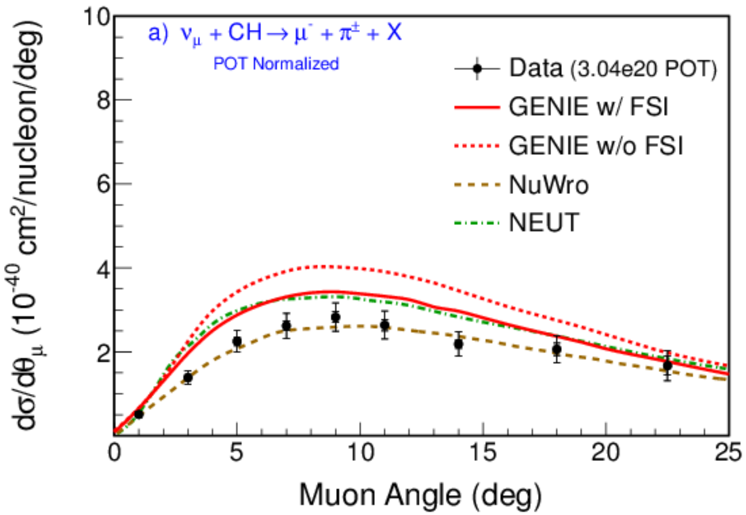
$\bar{\nu}_\mu + \mathrm{CH} \to \mu^+ + 1\pi^- + X\,(\text{no mesons})$



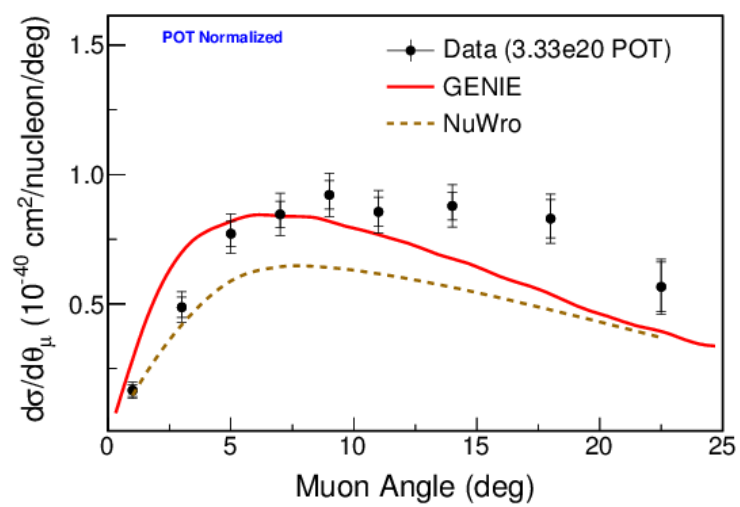
Muon angle

Again, some rate discrepancies; shape discrepancy in $\mu^{-} + \pi^{0}$ channel

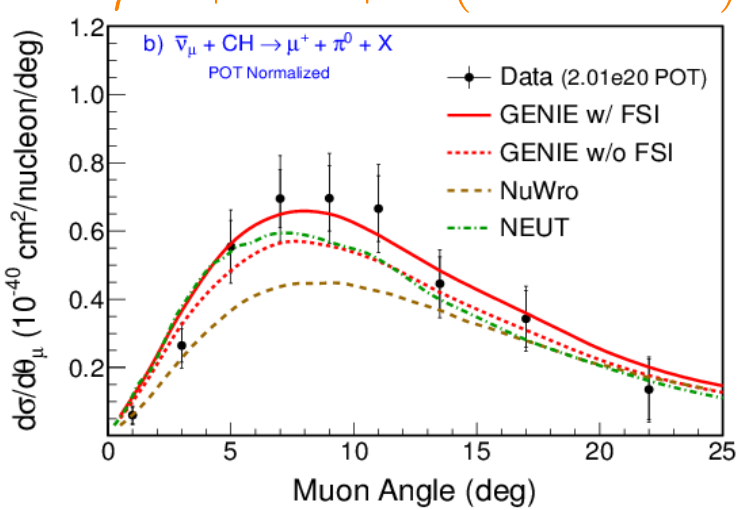
$\nu_\mu + \mathrm{CH} \rightarrow \mu^- + \pi^\pm + X\,(\text{no mesons})$



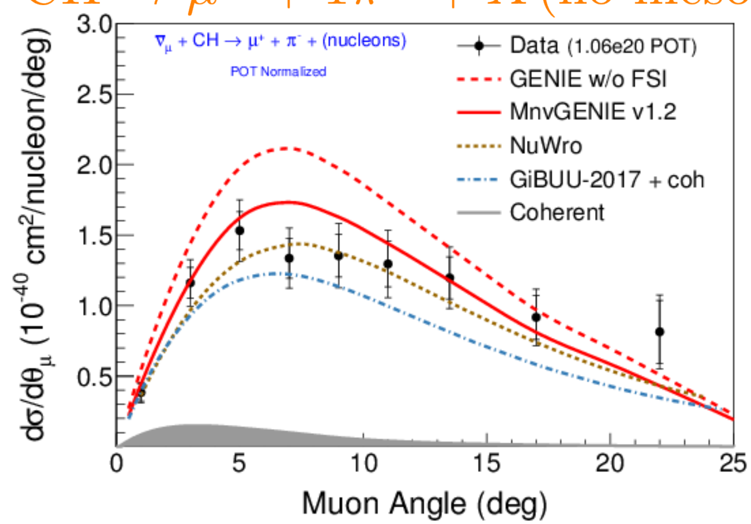
$\nu_\mu + \mathrm{CH} \rightarrow \mu^- + 1\pi^0 + X\,(\text{no mesons})$



$\bar{\nu}_\mu + \mathrm{CH} \rightarrow \mu^+ + 1\pi^0 + X\,(\text{no mesons})$



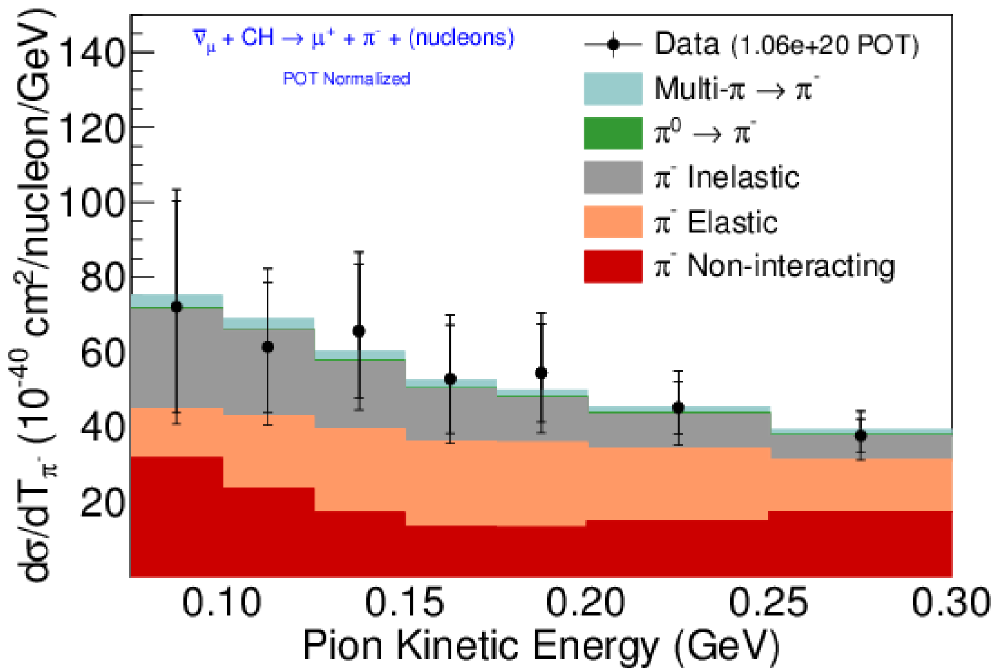
$\bar{\nu}_\mu + \mathrm{CH} \rightarrow \mu^+ + 1\pi^- + X\,(\text{no mesons})$

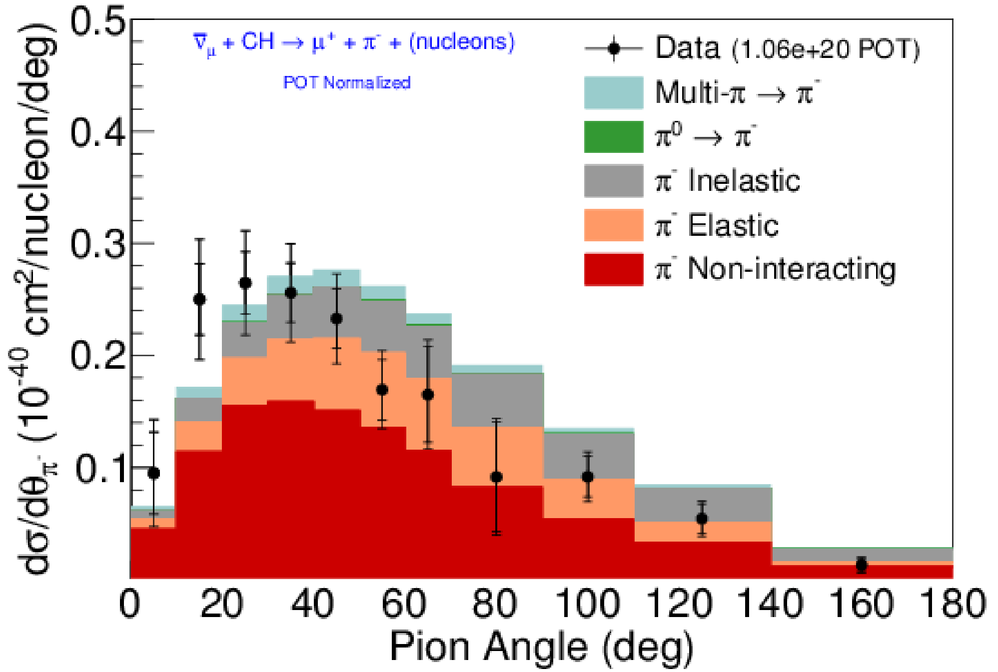


Pion observables

- Pion kinematics sensitive to pion FSI modeling
- FSI processes in GENIE hA
  - Pion absorption
  - Charge exchange
  - Inelastic scattering
  - Elastic scattering
  - No interaction

ANTINEUTRINO CC π^-

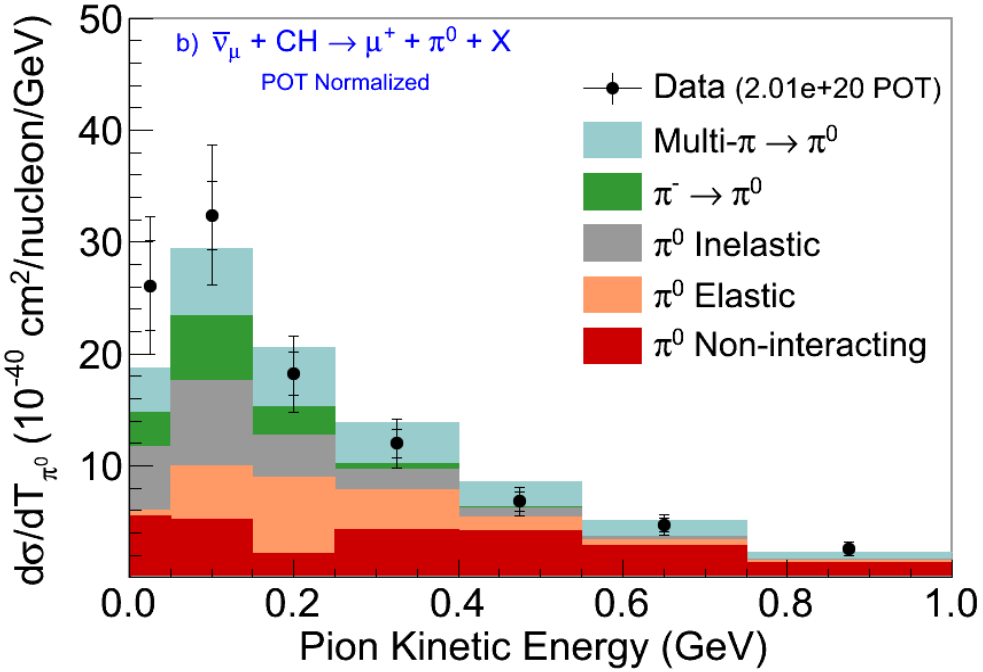


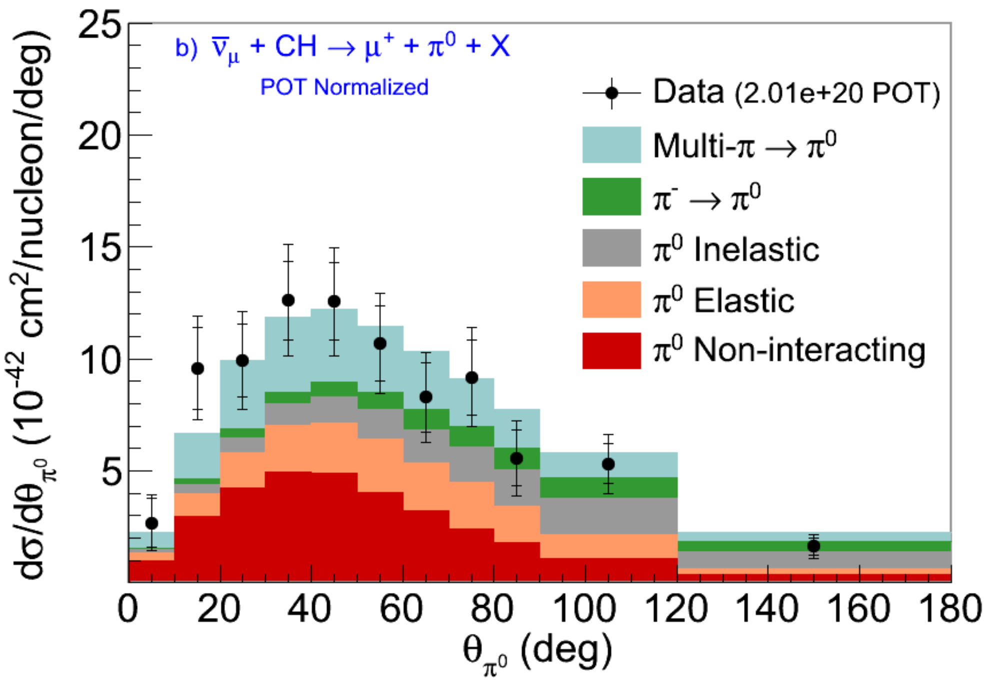


Pion observables

- Pion kinematics sensitive to FSI modeling
- Different π production channels sensitive to different FSI processes
  - Significant contribution from pion absorption and charge exchange in π^0 channel

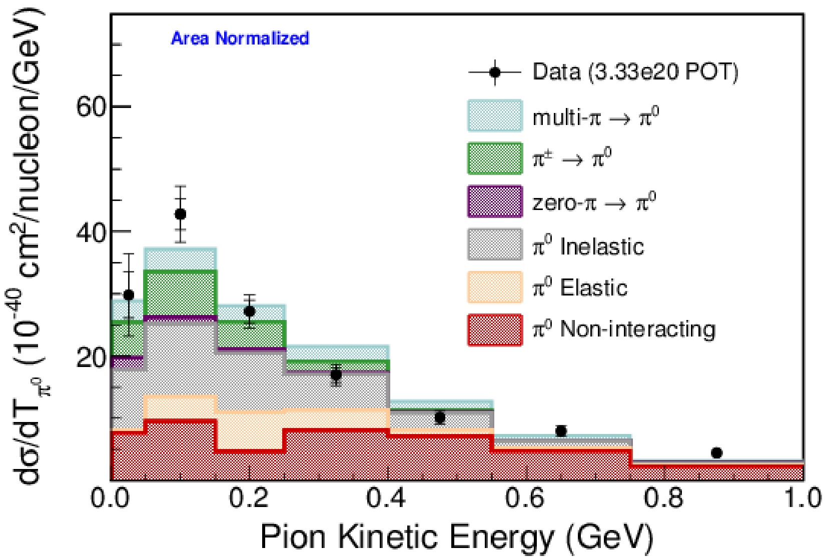
ANTINEUTRINO CC π^0



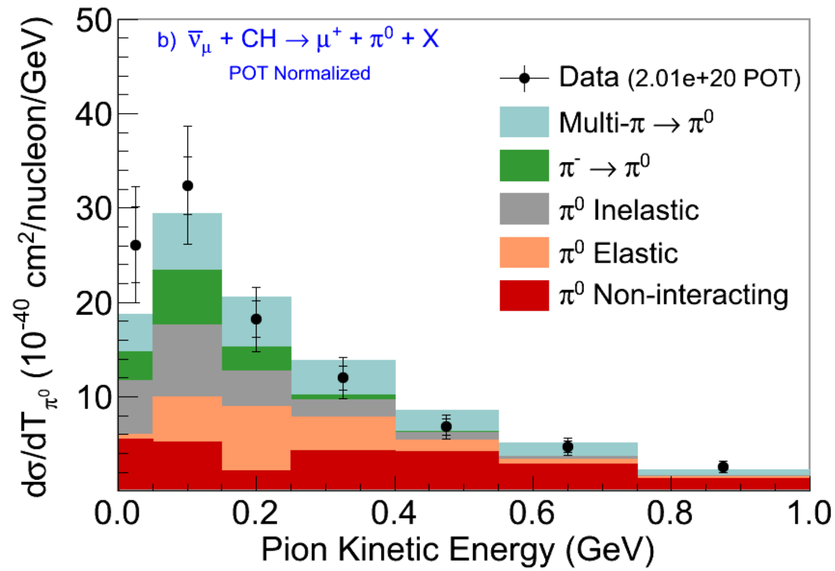


Pion Kinetic Energy and FSI

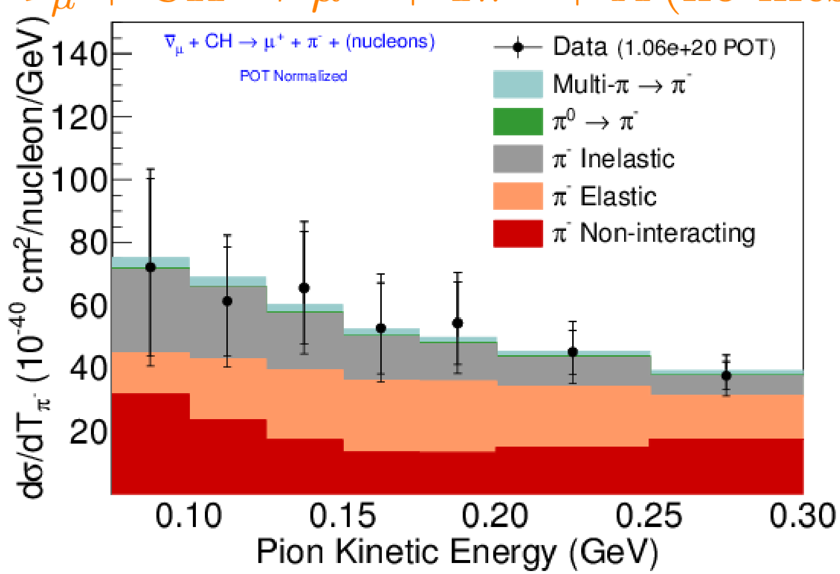
$\nu_\mu + \mathrm{CH} \rightarrow \mu^- + 1\pi^0 + X\,(\text{no mesons})$



$\bar{\nu}_\mu + \mathrm{CH} \rightarrow \mu^+ + 1\pi^0 + X\,(\text{no mesons})$



$\bar{\nu}_\mu + \mathrm{CH} \rightarrow \mu^+ + 1\pi^- + X\,(\text{no mesons})$

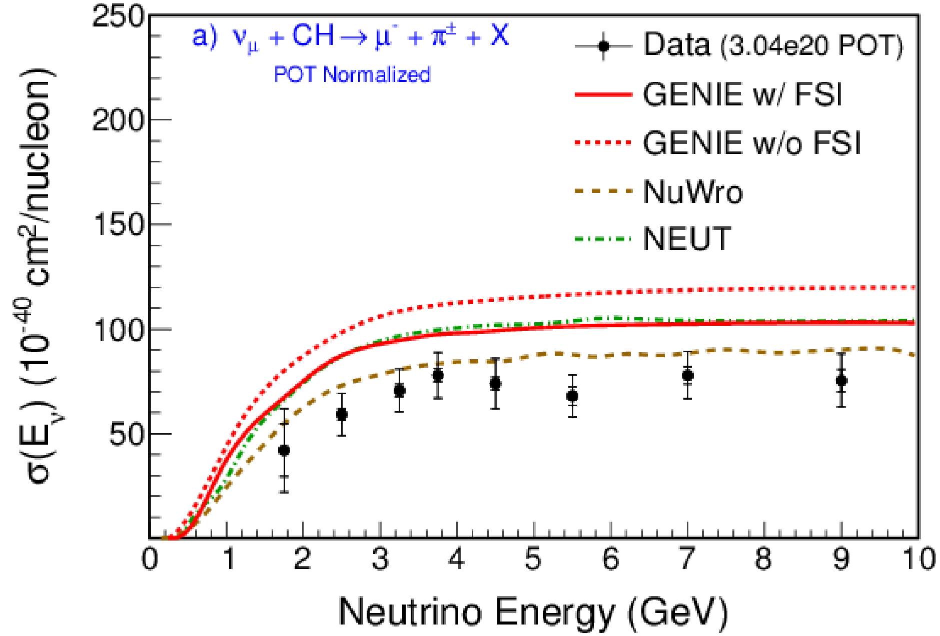


- GENIE hA FSI model with five processes gives respectable agreement with data.

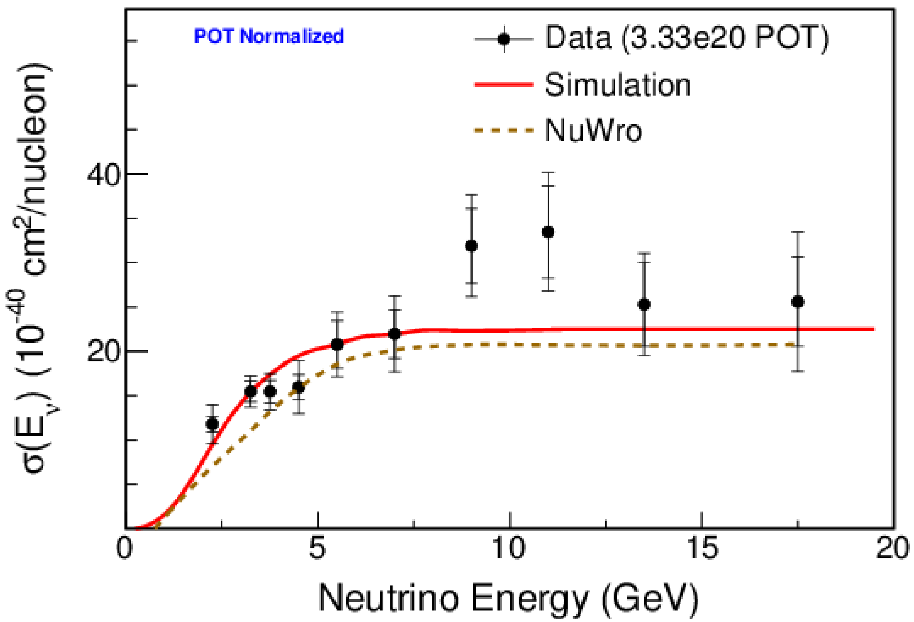
Neutrino Energy

- In neutrino CCπ, the hadronic vector (V) and axial vector (A) contribute constructively. This gives characteristic rise to flat- top for cross section vs E_ν.

$$\nu_\mu + \mathrm{CH} \rightarrow \mu^- + \pi^\pm + X \,(\text{no mesons})$$



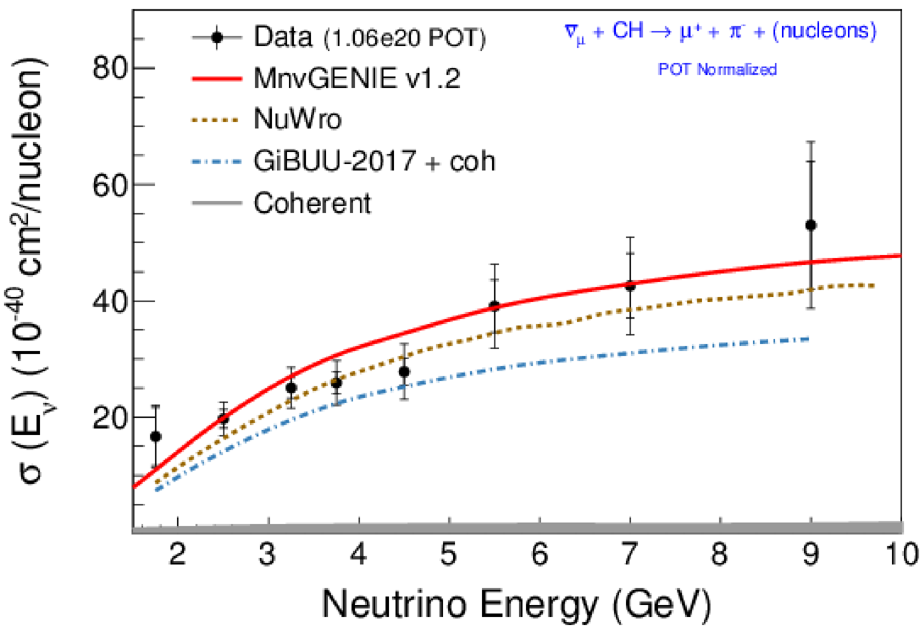
$$\nu_\mu + \mathrm{CH} \rightarrow \mu^- + 1\pi^0 + X \,(\text{no mesons})$$



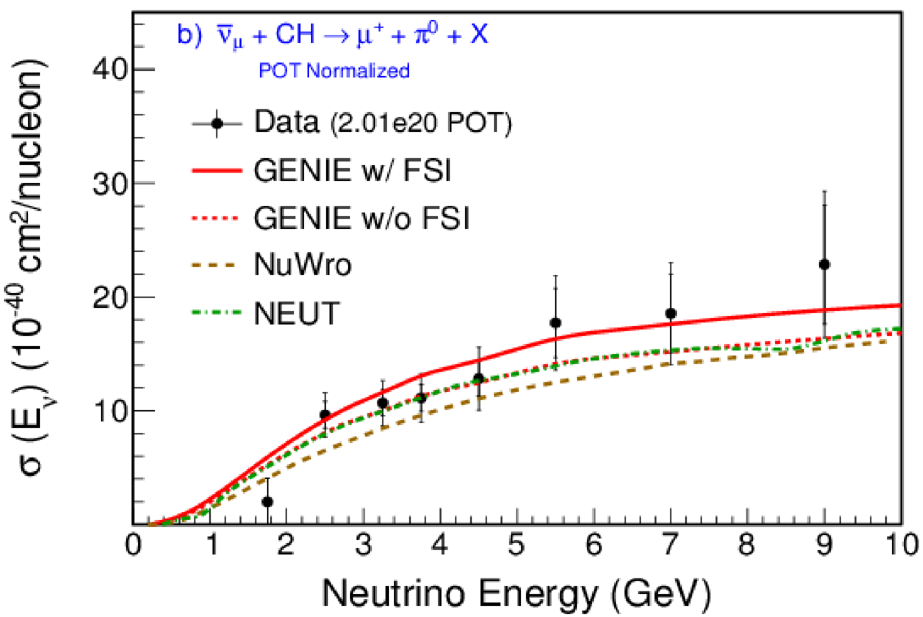
Neutrino Energy

- For antineutrino CCπ, the interference terms (VA) contribute destructively. Additionally, the VA interference terms diminish rapidly with increasing E_ν. As a result, the cross section rises more gradually with increasing E_ν for antineutrino CCπ.

$\bar{\nu}_\mu + \mathrm{CH} \rightarrow \mu^+ + 1\pi^- + X\,(\text{no mesons})$

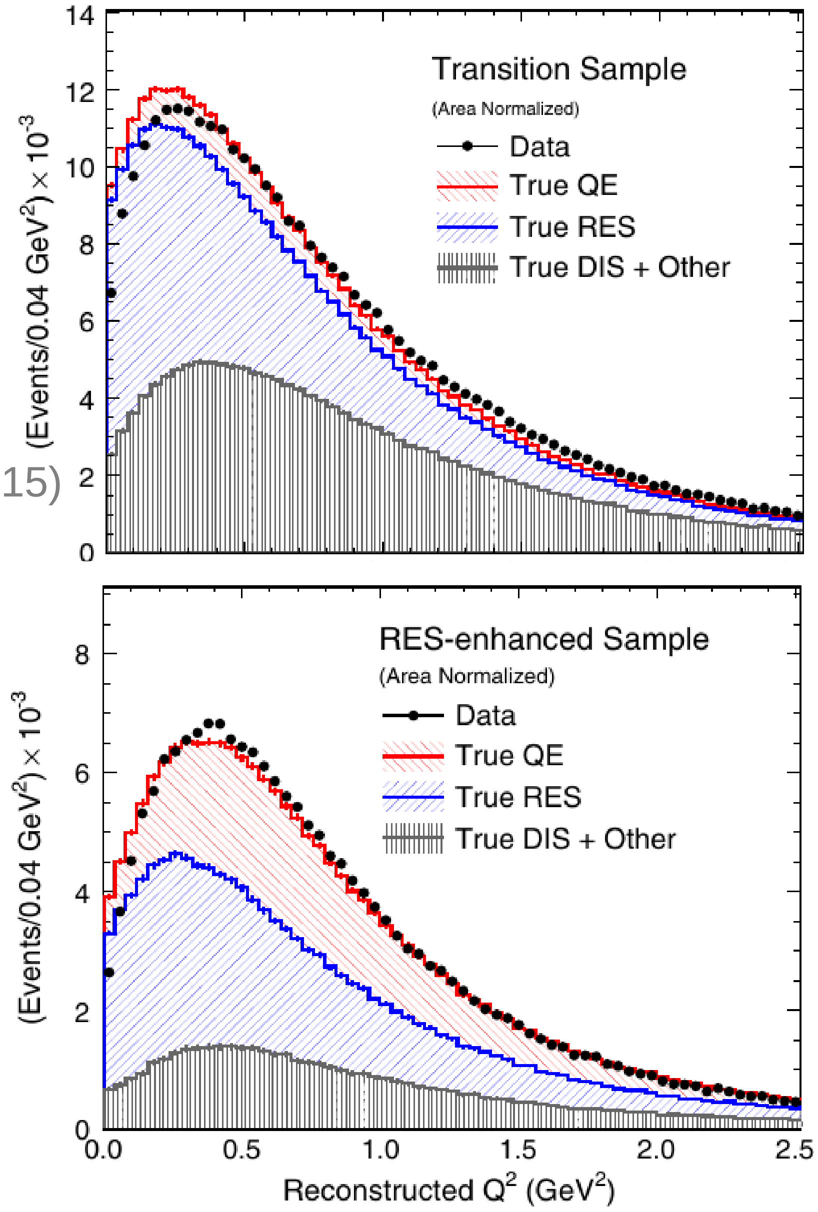


$\bar{\nu}_\mu + \mathrm{CH} \rightarrow \mu^+ + 1\pi^0 + X\,(\text{no mesons})$



Low Q^2 suppression

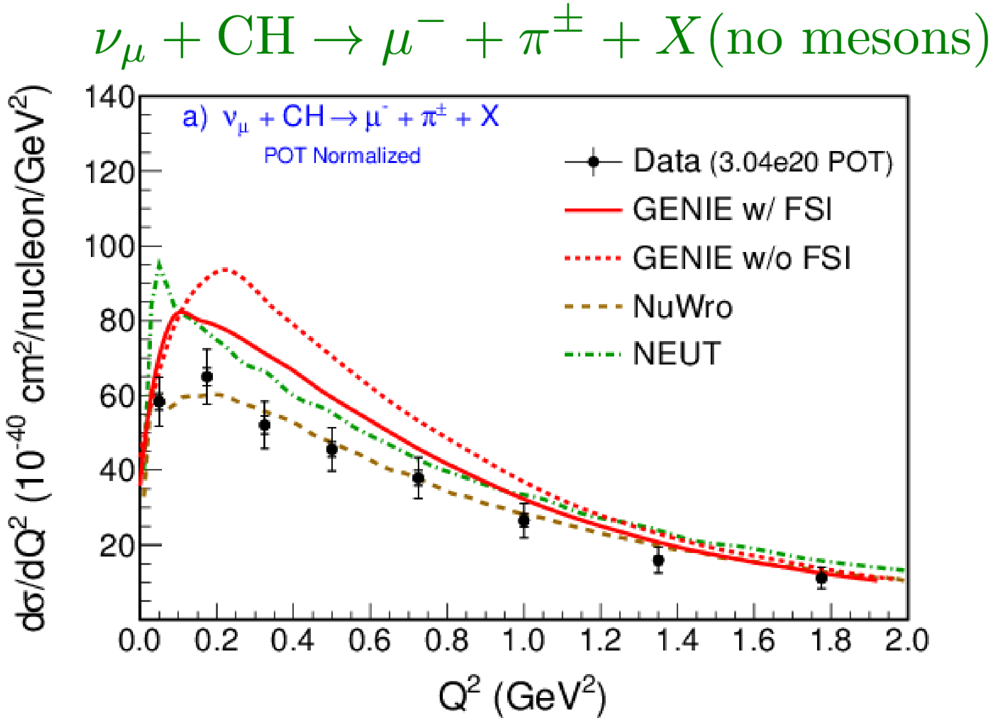
- MINOS observed low Q^2 suppression in their ν_μ CC interactions on Fe in the region $1.3 < W < 2$ GeV/c^2. PRD 91, 012005 (2015)
- MiniBooNE had seen similar suppression earlier on CH2 at lower neutrino energy (1 GeV). PRD 83, 052007 (2011)

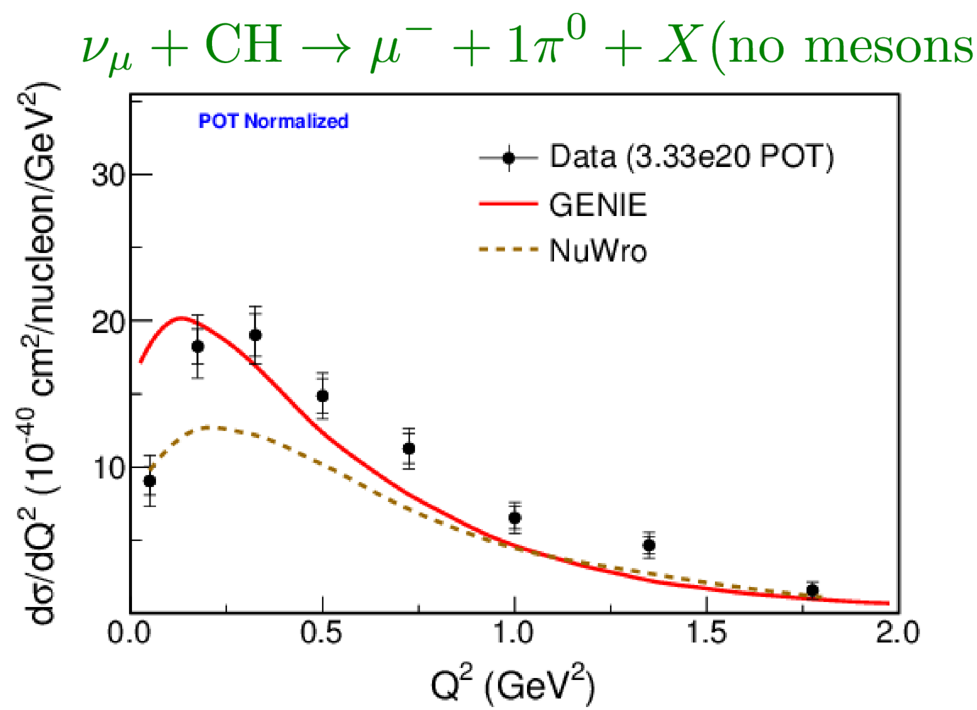


Low Q^2 suppression

Does MINERvA data show a suppression effect in CC π?

- MINERvA target is CH, not Fe
- CC coherent π can obscure the effect
- CC π^+ shows very mild turnover
- Effect is more pronounced in CC π^0. Note that CC π^0 has no coherent contribution





Low Q^2 suppression

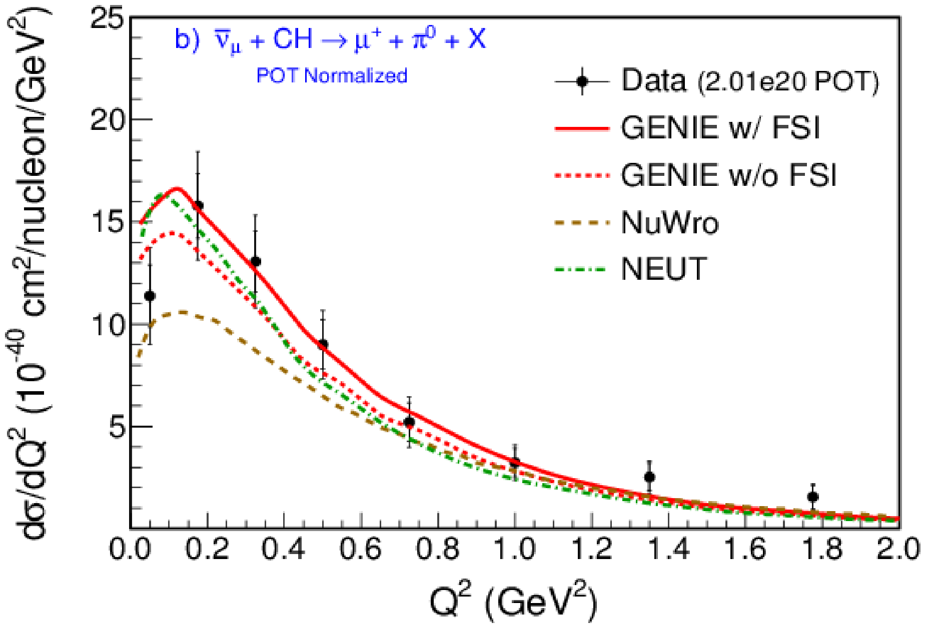
Does MINERvA data show a suppression effect in CC π?

In antineutrino CCπ

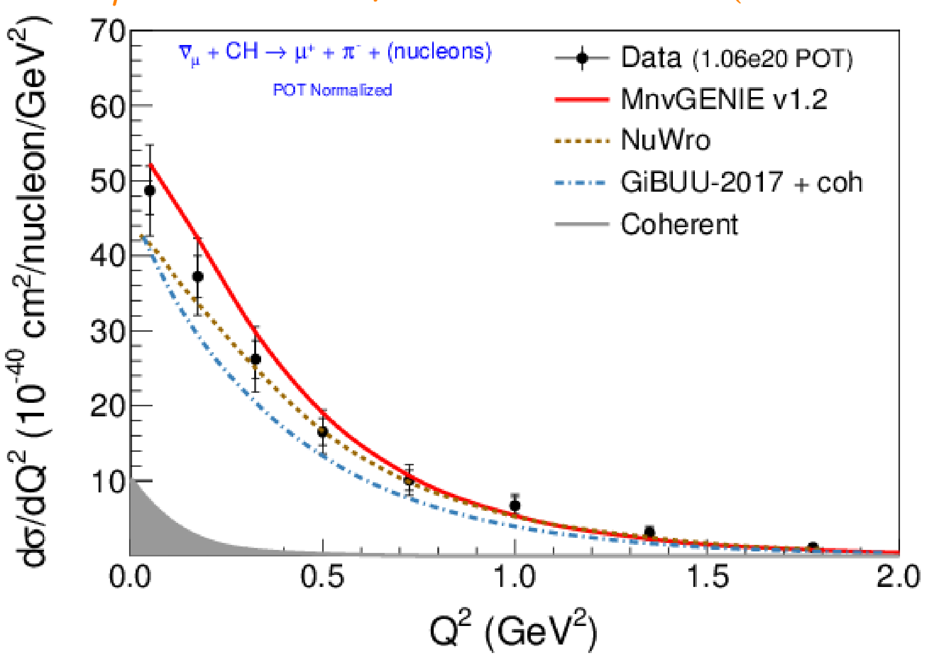
- Observe mild turnover in CC π^0
- Observe no turnover in CC π^- (even after coherent subtraction)

For slow Δ (1232) decaying inside the nucleus, expect some suppression due to Pauli exclusion.

$\bar{\nu}_\mu + \mathrm{CH} \rightarrow \mu^+ + 1\pi^0 + X\,(\text{no mesons})$

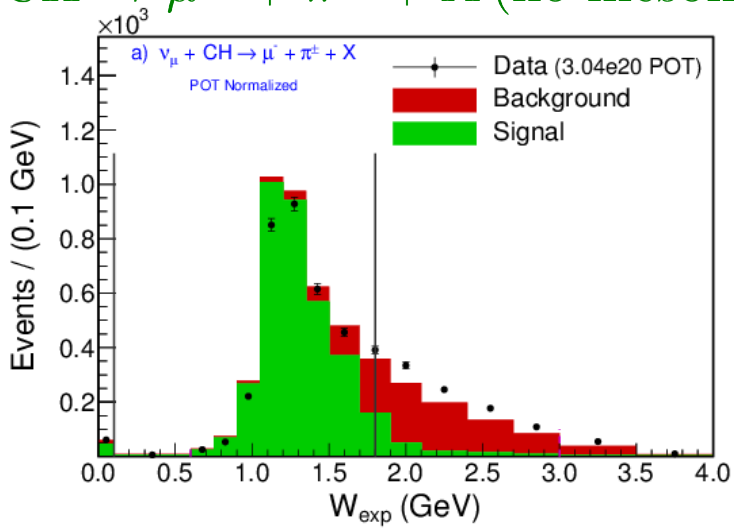


$\bar{\nu}_\mu + \mathrm{CH} \rightarrow \mu^+ + 1\pi^- + X\,(\text{no mesons})$

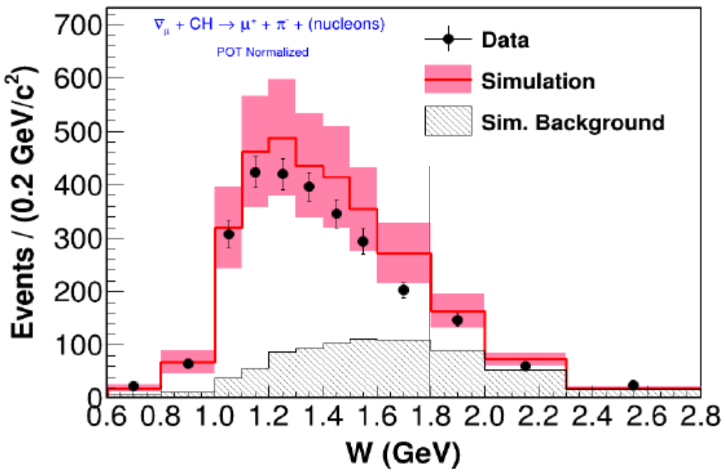


Second resonance region
(N*(1440), N*(1520), N*(1535))

$\nu_\mu + \mathrm{CH} \rightarrow \mu^- + \pi^\pm + X\,(\text{no mesons})$



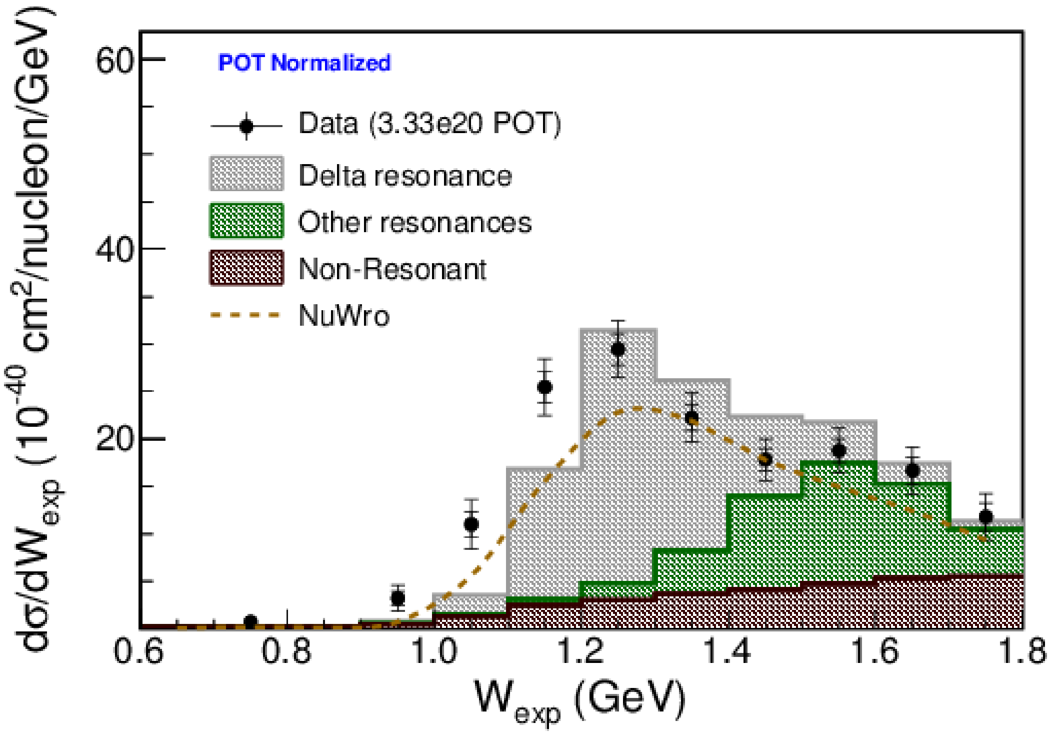
$\bar{\nu}_\mu + \mathrm{CH} \rightarrow \mu^+ + 1\pi^- + X\,(\text{no mesons})$



These two $\pi^\pm$ channels are dominated by $\Delta(1232)$ I = 3/2. The distributions show little structure above the $\Delta(1232)$.

Second resonance region
(N*(1440), N*(1520), N*(1535))

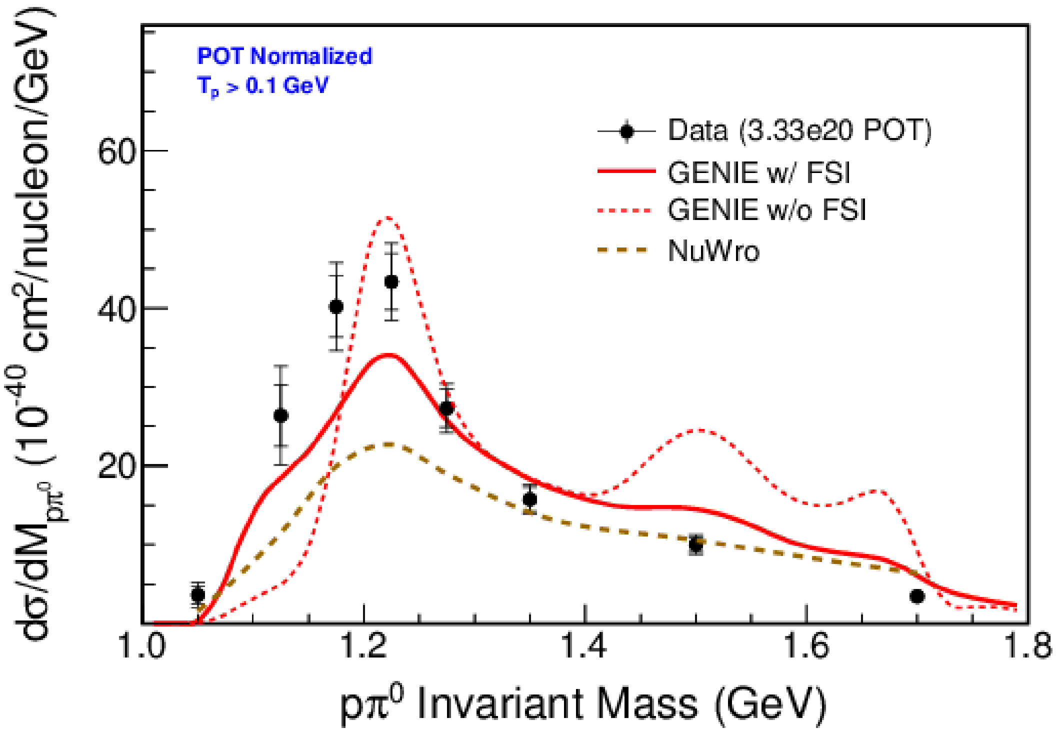
$\nu_\mu + \mathrm{CH} \to \mu^- + 1\pi^0 + X\,(\text{no mesons})$



In this π^0 channel, I=1/2 may contribute more significantly as seen from GENIE prediction.

Second resonance region
(N*(1440), N*(1520), N*(1535))

$$\nu_\mu + \mathrm{CH} \rightarrow \mu^- + 1\pi^0 + X\,(\text{no mesons})$$



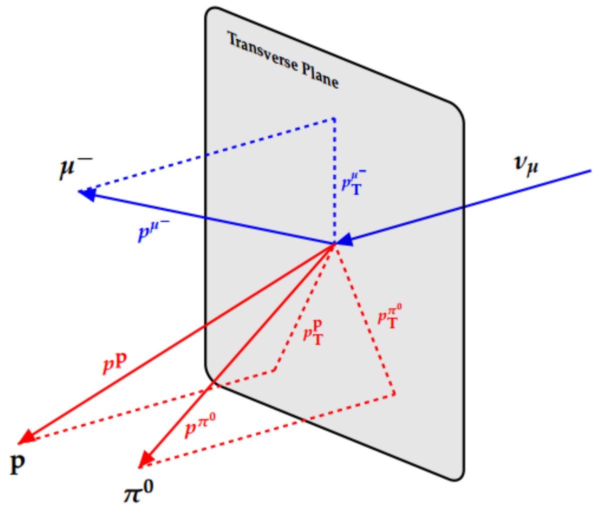
Unfortunately, the higher mass states are washed out by FSI and detector resolution effects, as predicted by GENIE simulation. It will be interesting to see whether MINERvA medium-energy $p+\pi^0$ data can give us a clearer picture in this region.

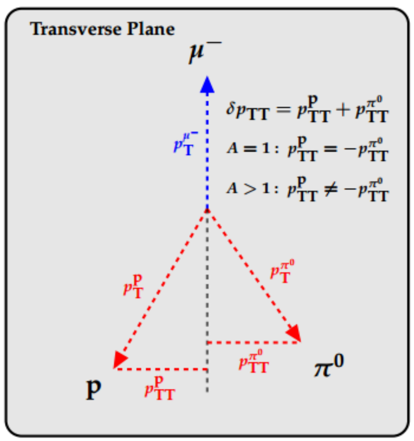
Status and future plans

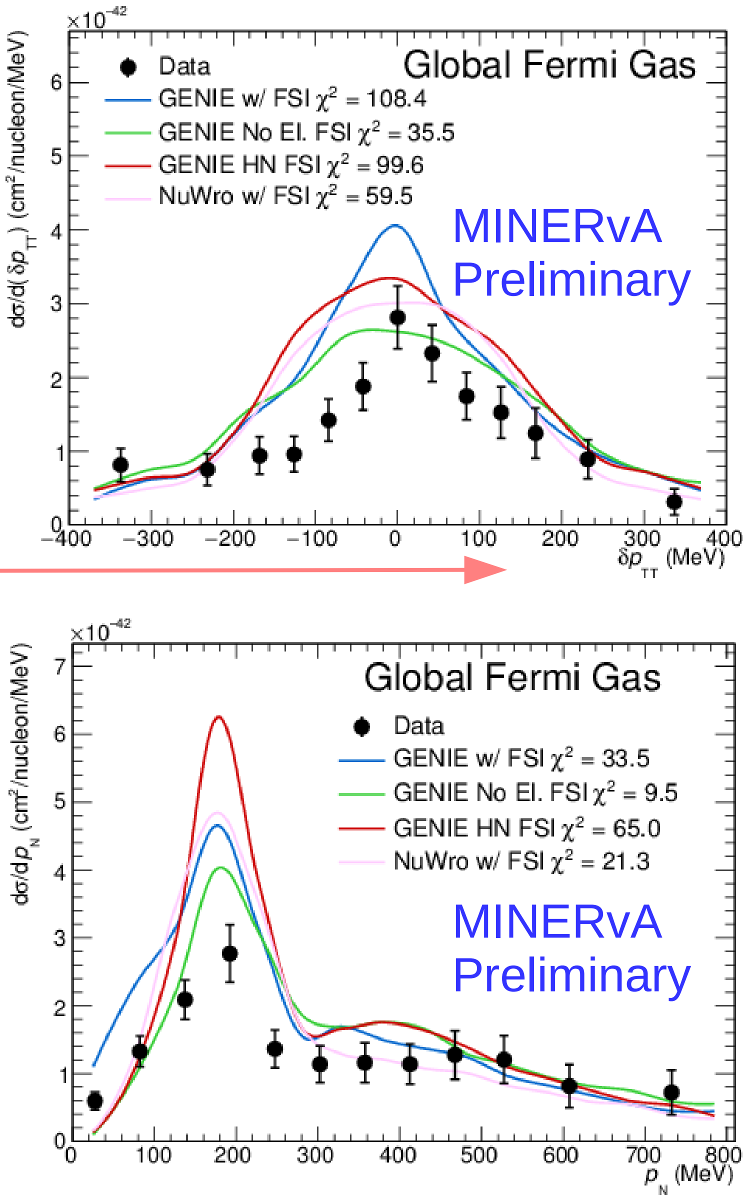
Ongoing low-energy analyses

- Transverse variables in $CC1\pi^0$ production (paper in preparation)

Transverse variables: X. Lu et al, PRD 92, 051302 (2015)







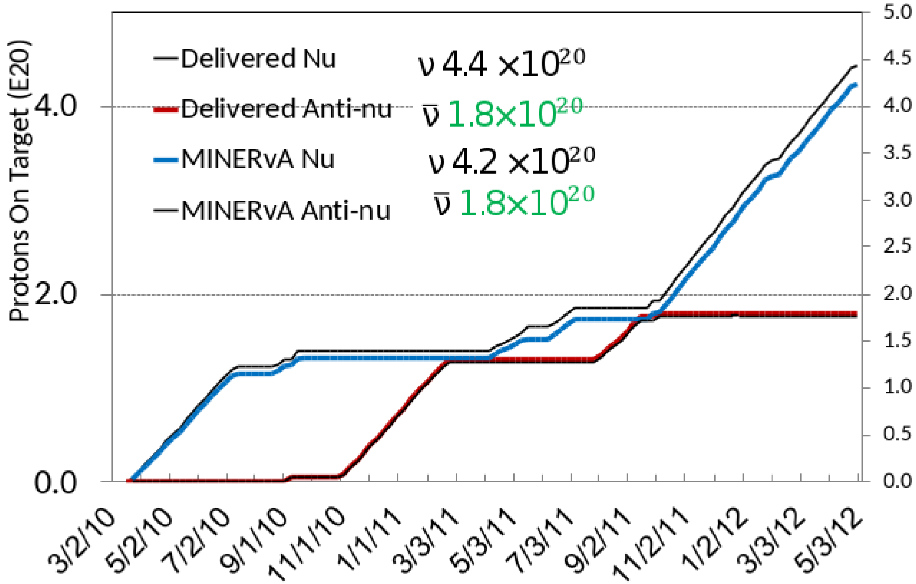
Clear discrepancy between data and generators (for local Fermi gas, see backup)

Ongoing low-energy analyses

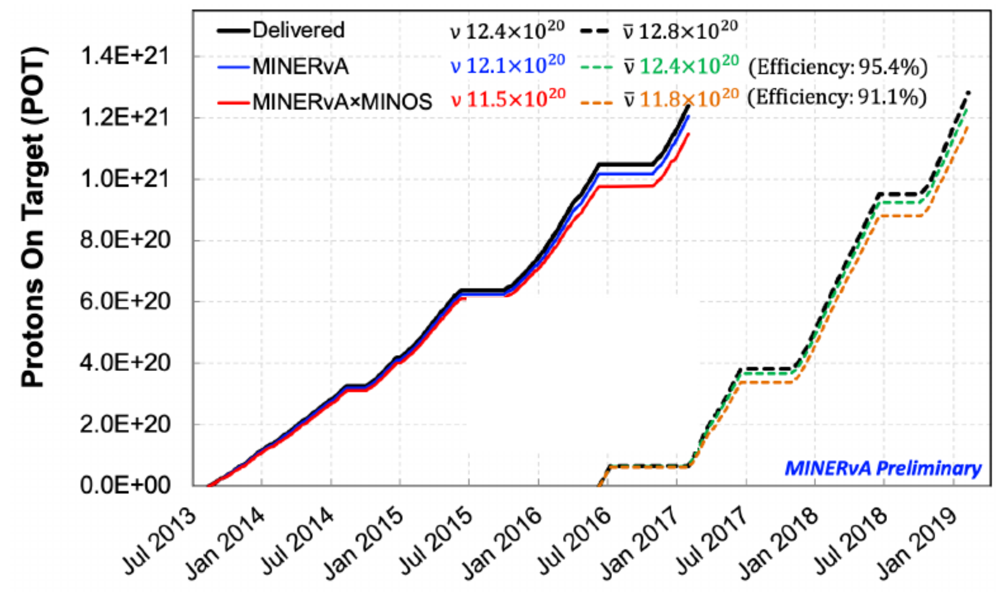
- Transverse variables in $CC1\pi^0$ production (paper in preparation)
- $NC1\pi^0$ (background to ν_e appearance)

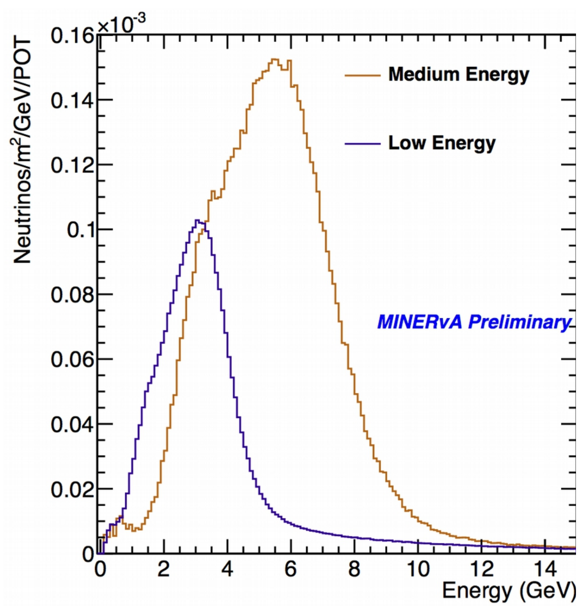
Medium-energy data

Low Energy



Medium Energy





Exposure:

ν_μ: 3x LE

$\bar{\nu}_\mu$: 12x LE

Event rates:

ν_μ: 10x LE

$\bar{\nu}_\mu$: 40x LE

Neutrino yield:

~ 2.5x

Medium-energy pion analyses

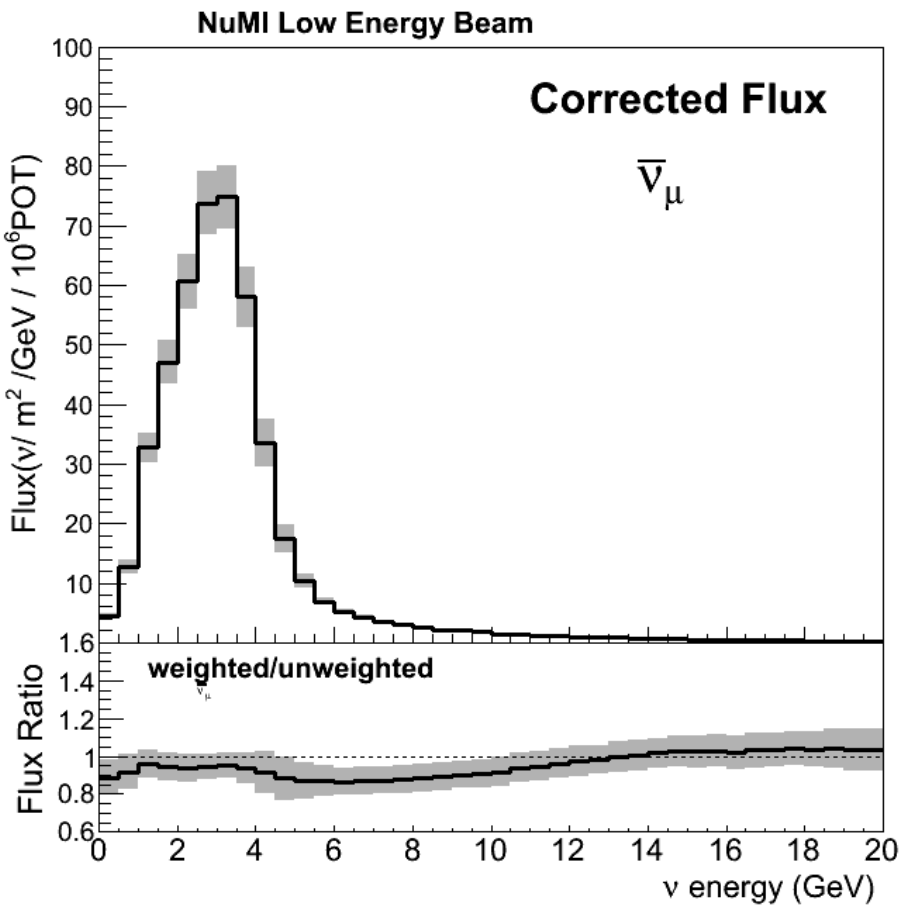
- With much higher statistics, we can make measurements on nuclear targets (C, Fe,Pb)
  - π^+ production
  - π^0 production
- π^0 production in CH (statistics was limited in LE)
- Pion production in transition region

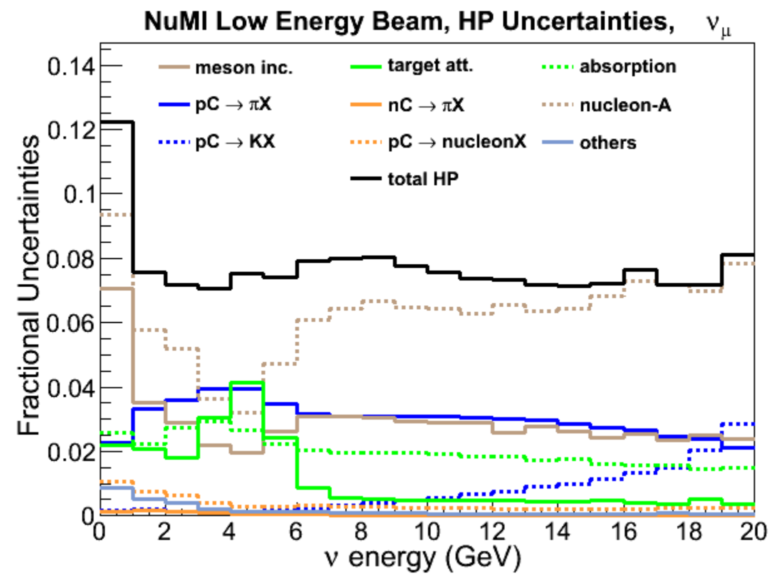
Conclusion and outlook

- We have measured all four pion production channels on CH by neutrinos and antineutrinos at E_ν ~ 3.5 GeV.
  - Muon kinematics probe generator shape and rate predictions
  - Pion kinematics probe details of pion FSI models
  - Cross sections as function of E_ν between (1.5, 10) GeV
  - Low Q^2 suppression in three out of four channels
  - Hadronic invariant mass: Δ dominated, second resonance region has yet to be resolved
- Ongoing analyses on pion production in nuclear targets (C, Fe, Pb) using much higher statistics at medium energy.

Back-up

NuMI low-energy $\overline{\nu}_\mu$ flux

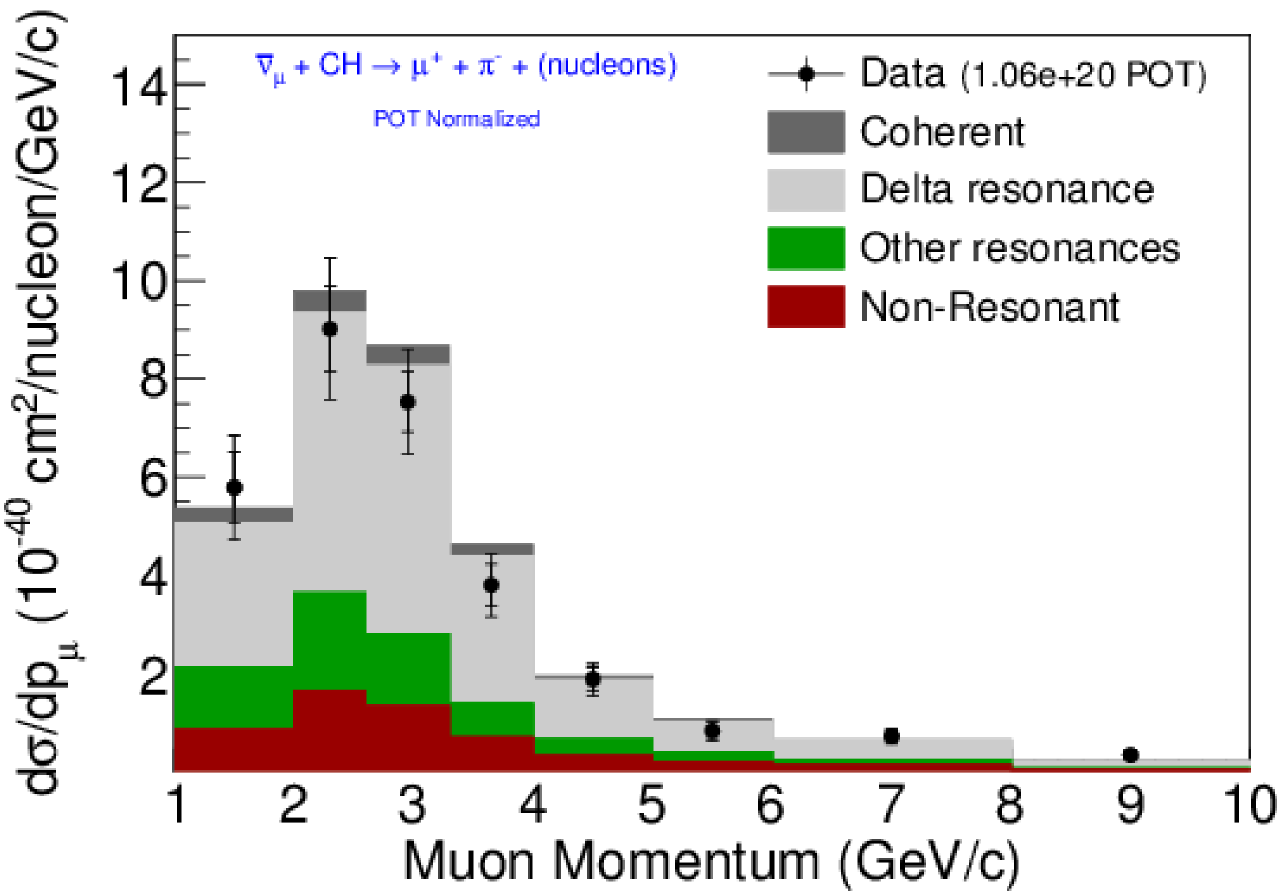




- NuMI "low energy" beam tune, ~3.5 GeV peak energy, with ~8% uncertainty dominated by hadron production (HP).
- Additional constraint using ν-e elastic scattering.

L. Aliaga et al, PRD 94 092005

Muon momentum



- Breakdown by primary processes

R-S

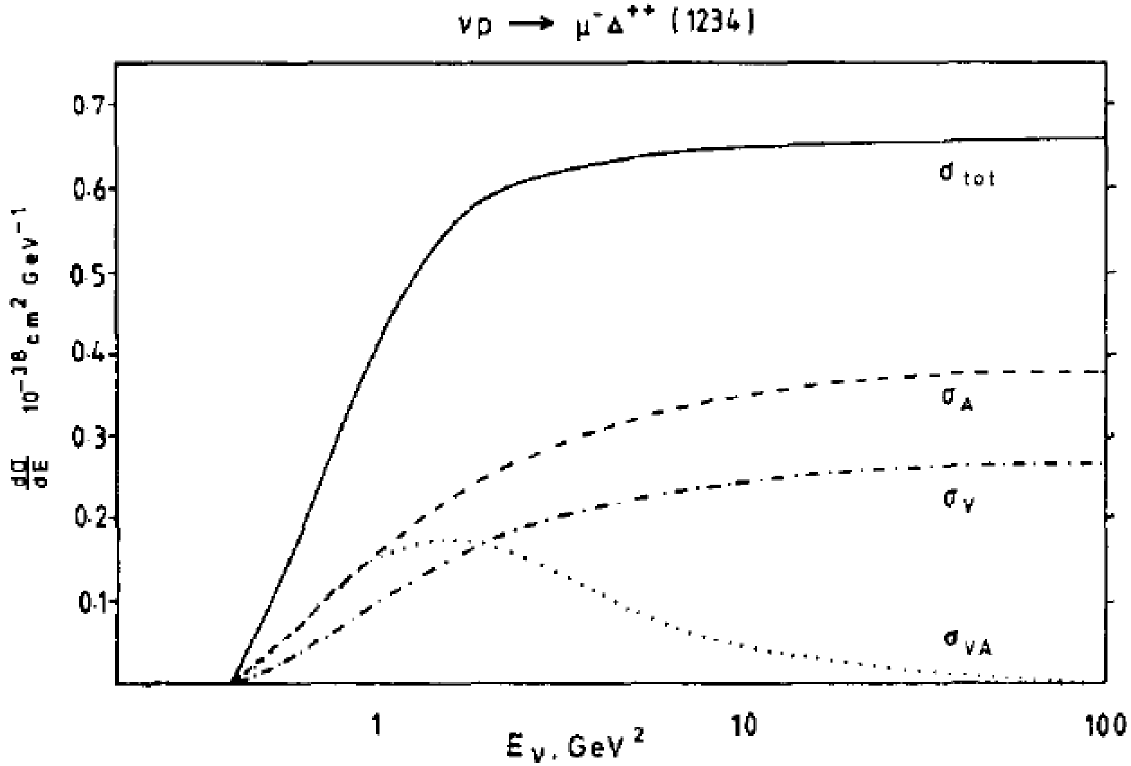
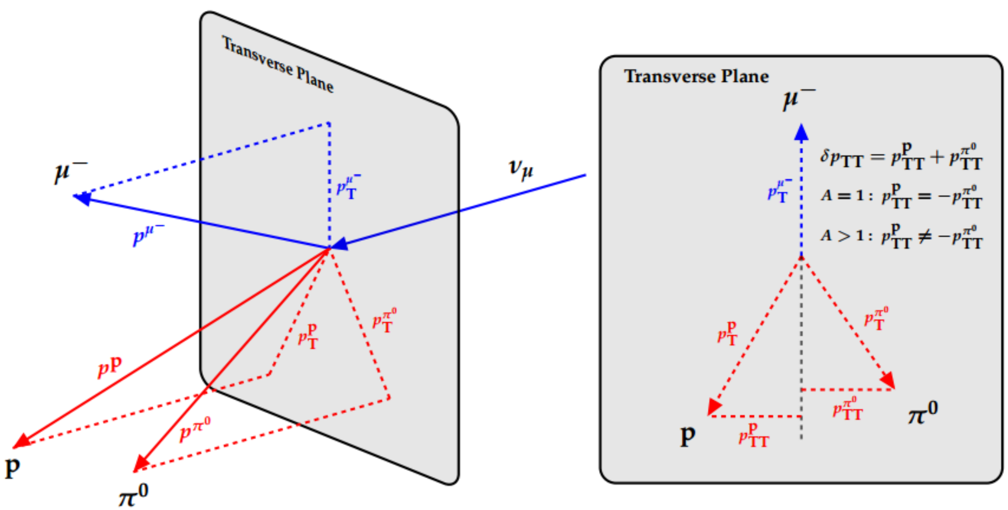
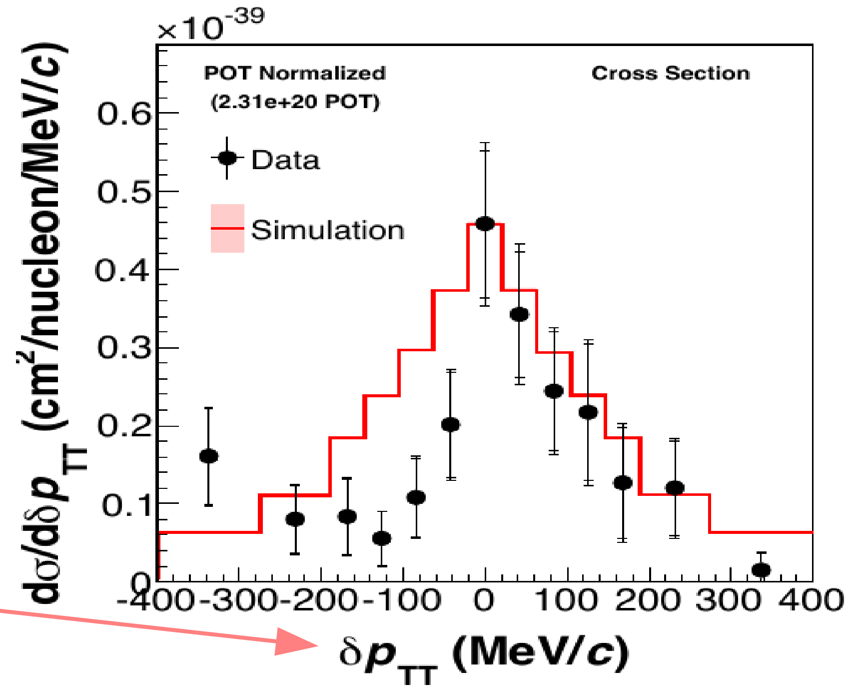


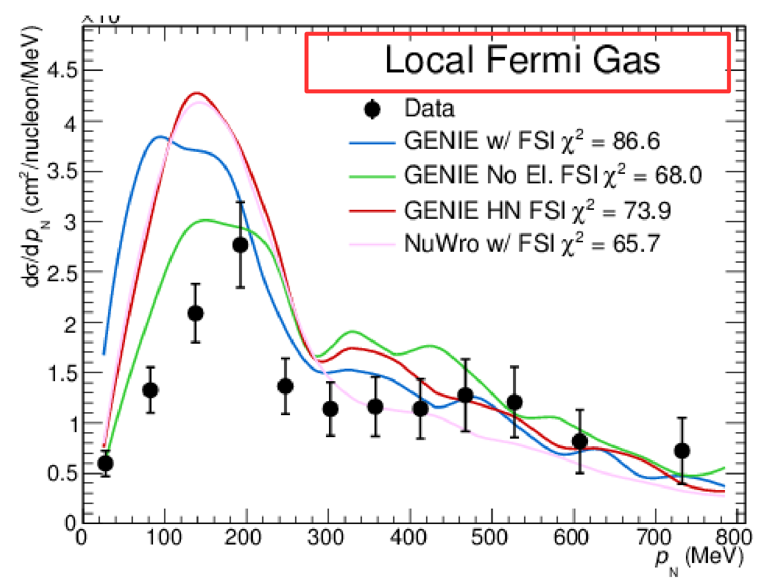
FIG. 4. Vector, axialvector, and VA-interference parts of the Δ^{++} cross section as functions of E_ν ($m_A = 0.95$ GeV/c²).

Ongoing low-energy analyses

- Transverse variables in CC1π^0 production (paper in preparation)

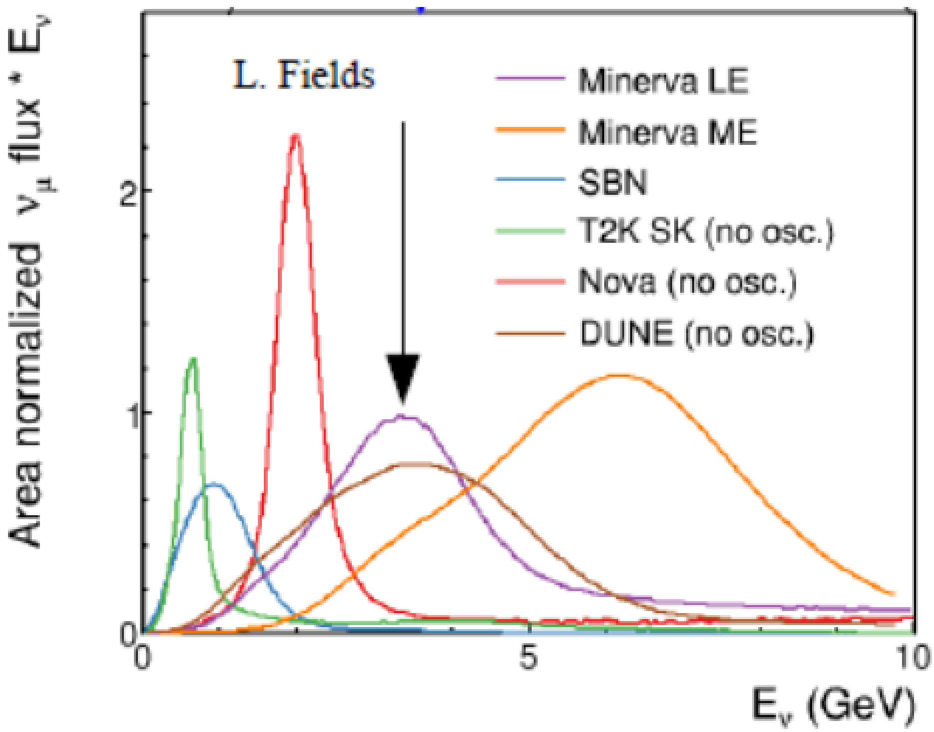






Clear discrepancy between data and GENIE (Global Fermi Gas)

Different fluxes



MnvGENIE v1

- GENIE 2.8.4
  - RPA screening
  - 2p2h
  - Neutrino low recoil fit
  - Nonresonant pion reduction
    - Reduce GENIE nonresonant 1π by 57% for neutrinos
    - Reduce GENIE nonresonant 1π by 0.5 ± 0.5 for antineutrinos since there is no deuterium data

MnvGENIE v1.2

- GENIE 2.8.4
  - RPA screening
  - 2p2h
  - Neutrino low recoil fit
  - Nonresonant pion reduction
  - Coherent pion reweight
    - Reweight to MINERvA coherent pion results, A. Mislivec, PRD **97**, 032014 (2018)