RECENT RESULTS ON PION PRODUCTION AT MINERνA

NuInt 2017

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Outline

Pions at MINERvA

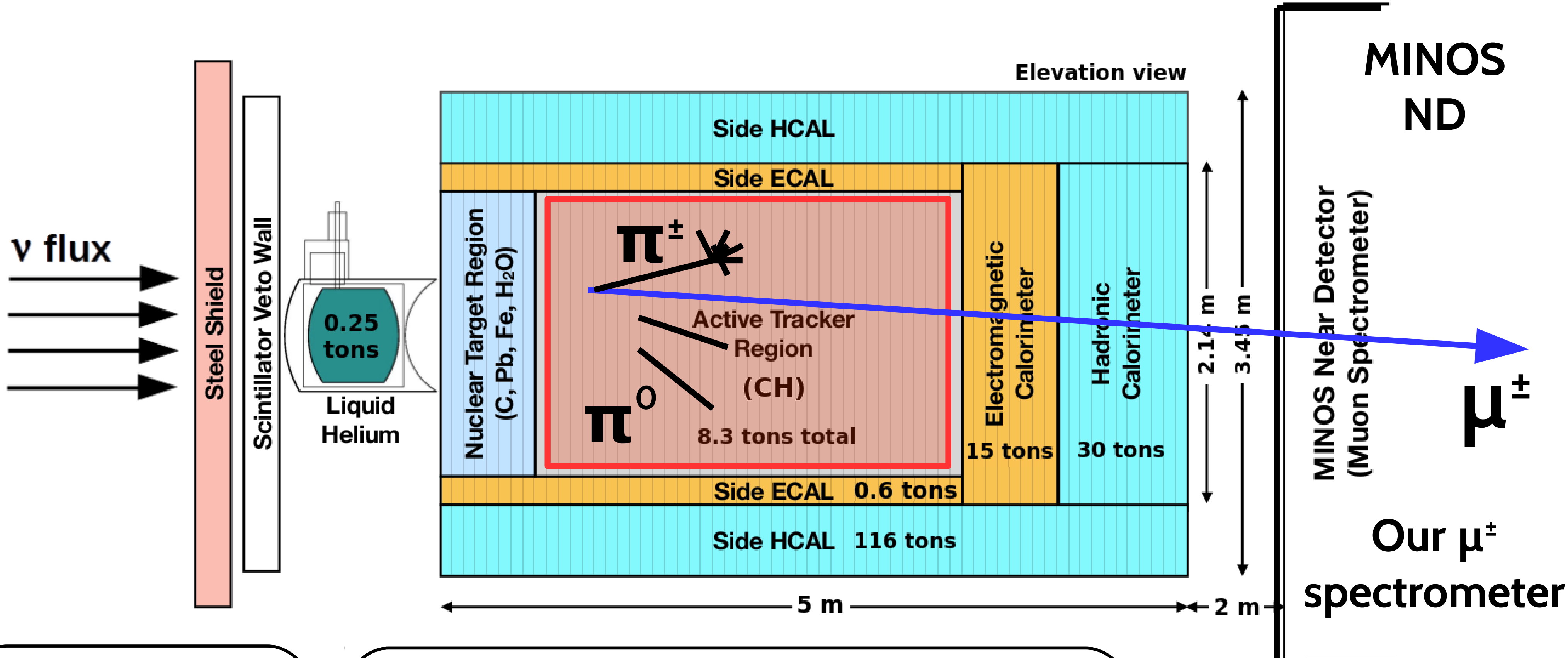
Updates on $\overset{(-)}{\nu}_\mu$ – CC $\pi^{\pm(0)}$

Advances on $\bar{\nu}_\mu$ – CC π^-

New Results on ν_μ – CC π^0

Pions at MINERνA

MINERνA Pion Reconstruction



$\pi^+ \pi^- \pi^0$

Reconstruction

- Event Vertex Inside Tracker Region
- MINOS Acceptance
- 1.5 GeV < E_ν < 20 GeV ($E_\nu = E_\mu + E_{recoil(had)}$)
- Energy Reconstruction by Calorimetry

LE Beam
Eν~3.5 GeV

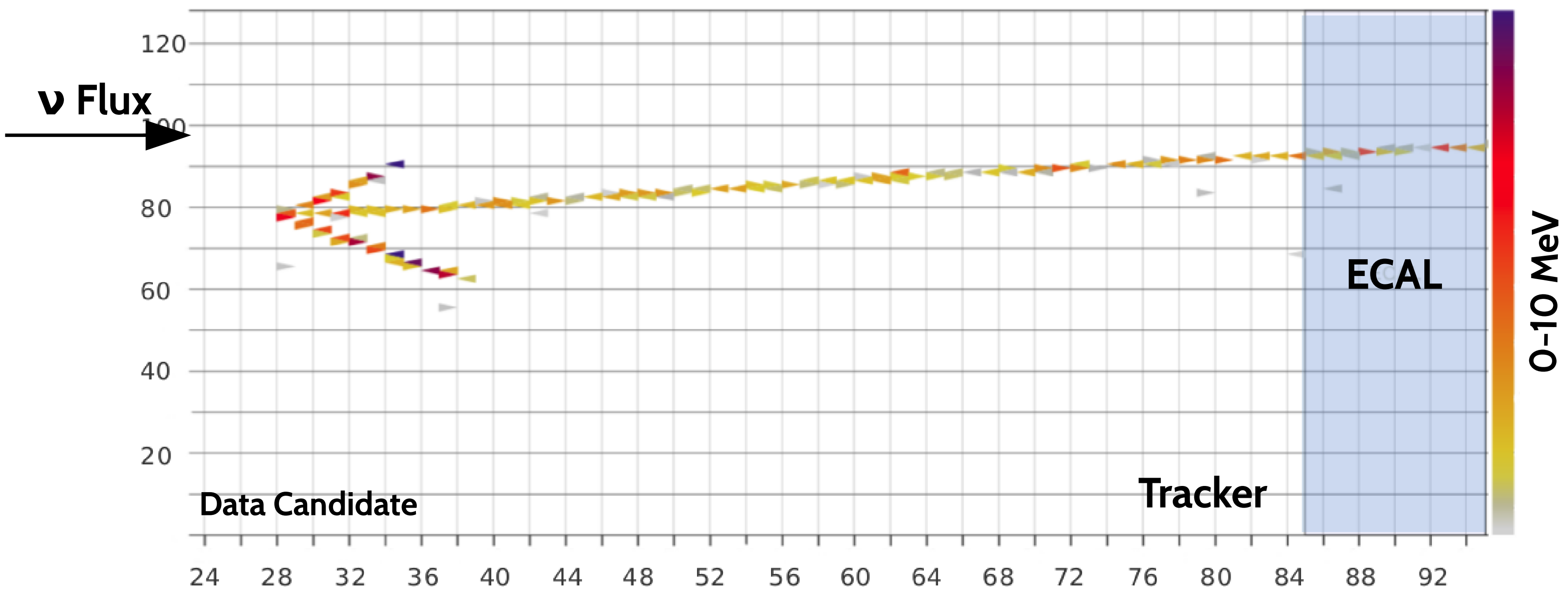
MINERνA Pion Reconstruction

$\pi^{\pm}$

Pion Kinetic Energy ~35-350 MeV

dE/dx on Pion Candidate

Michel $e^{\pm}$ requirement



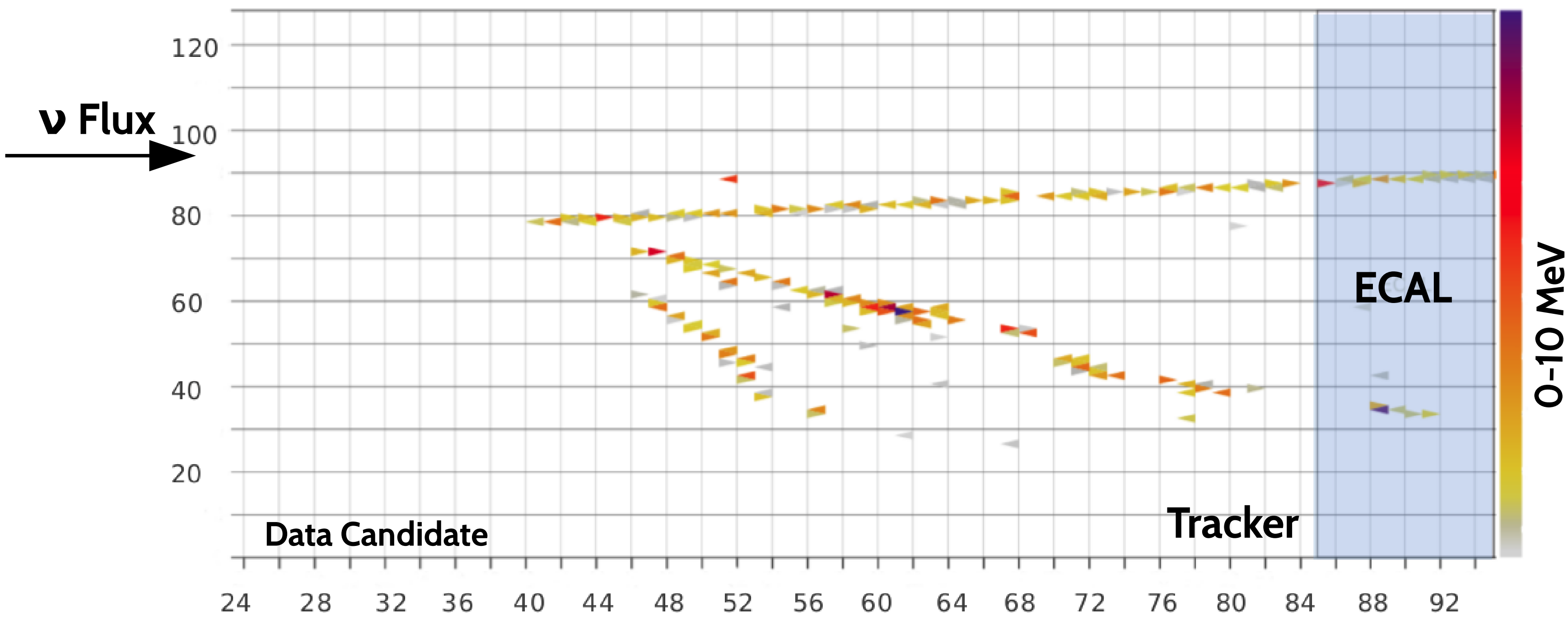
MINERνA Pion Reconstruction

π^0

Pion Kinetic Energy ~50-2500 MeV

2γ showers

γ Conversion Distance From the Vertex



CC Production At MINERνA

$\nu_\mu CH \rightarrow \mu^- \pi^+ X$

Updated

$\bar{\nu}_\mu CH \rightarrow \mu^+ \pi^0 X$

Updated

$\nu_\mu CH \rightarrow \mu^- \pi^0 X$

Brand New!

$\bar{\nu}_\mu CH \rightarrow \mu^+ \pi^- X$

Preliminary

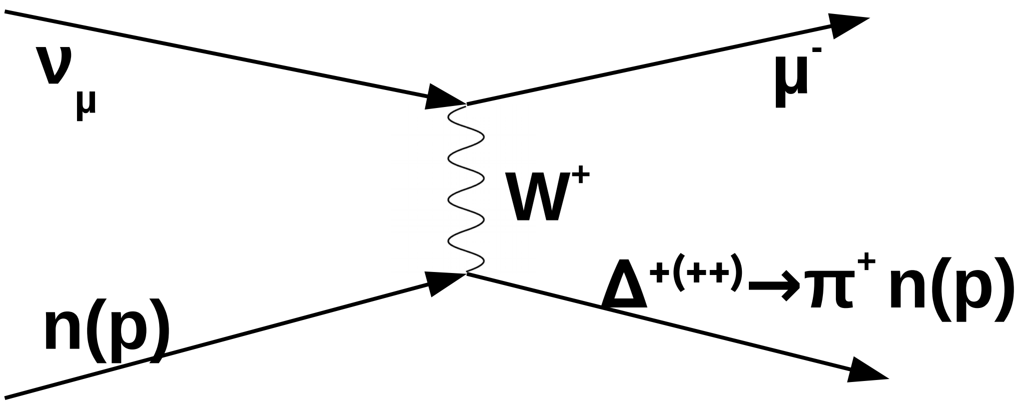
Updates on

$\overset{(-)}{\nu}_{\mu}$ – CC $\pi^{\pm(0)}$

$\overset{(-)}{\nu}_\mu$ - CC $\pi^{\pm(0)}$

Signal Definition

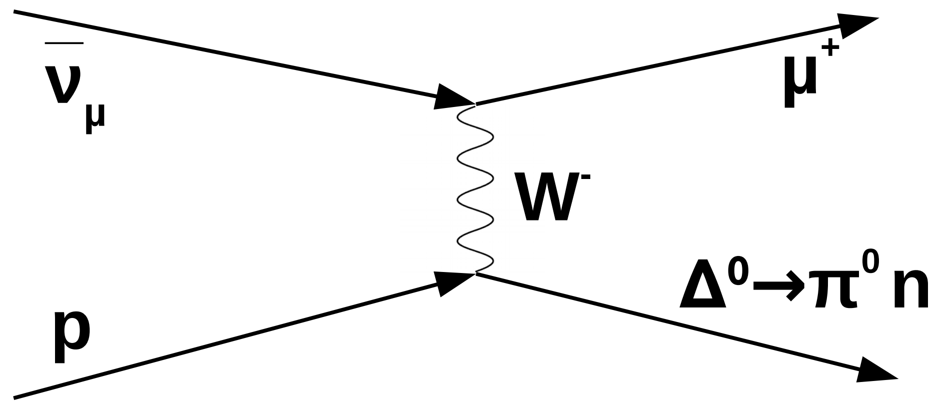
$\nu_\mu CH \rightarrow \mu^- 1(N)\pi^\pm X$



X = any mesons and nucleons

W<1.4(1.8) GeV

$\bar{\nu}_\mu CH \rightarrow \mu^+ 1\pi^0 X$



X = any nucleons

W<1.8 GeV

75MeV/c < $m_{\gamma\gamma}$ <195MeV/c

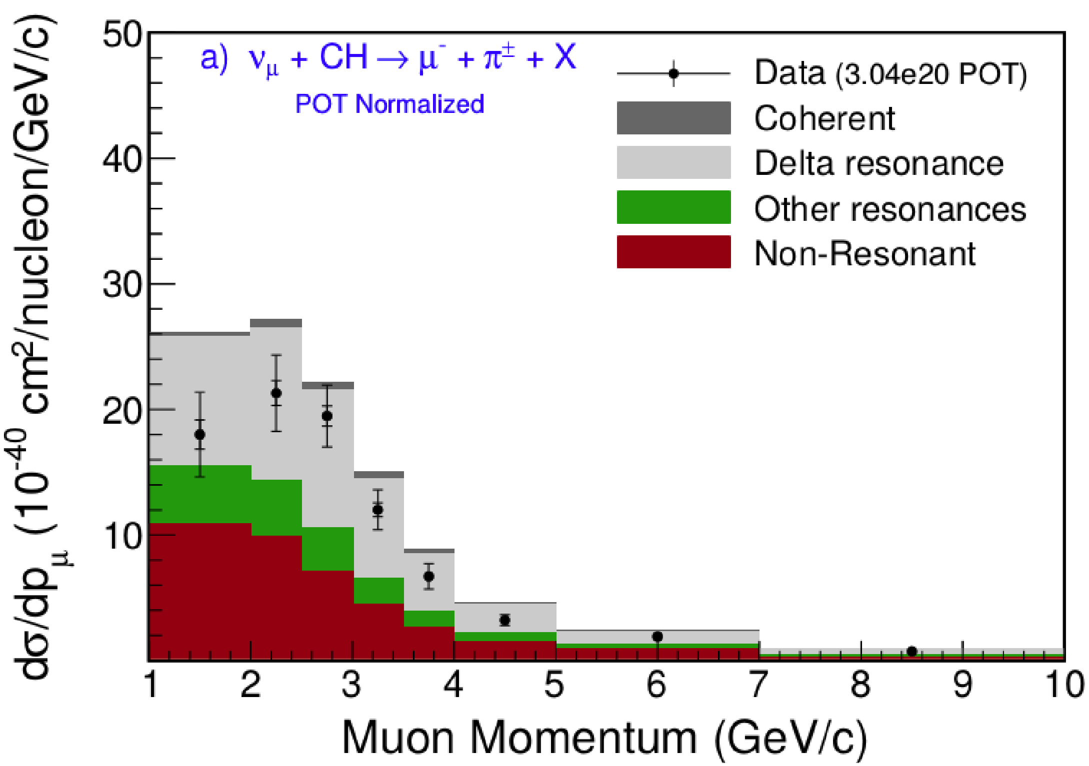
$$W^2 = m_N^2 + 2m_N\left(E_\nu - E_\mu\right) - Q^2$$

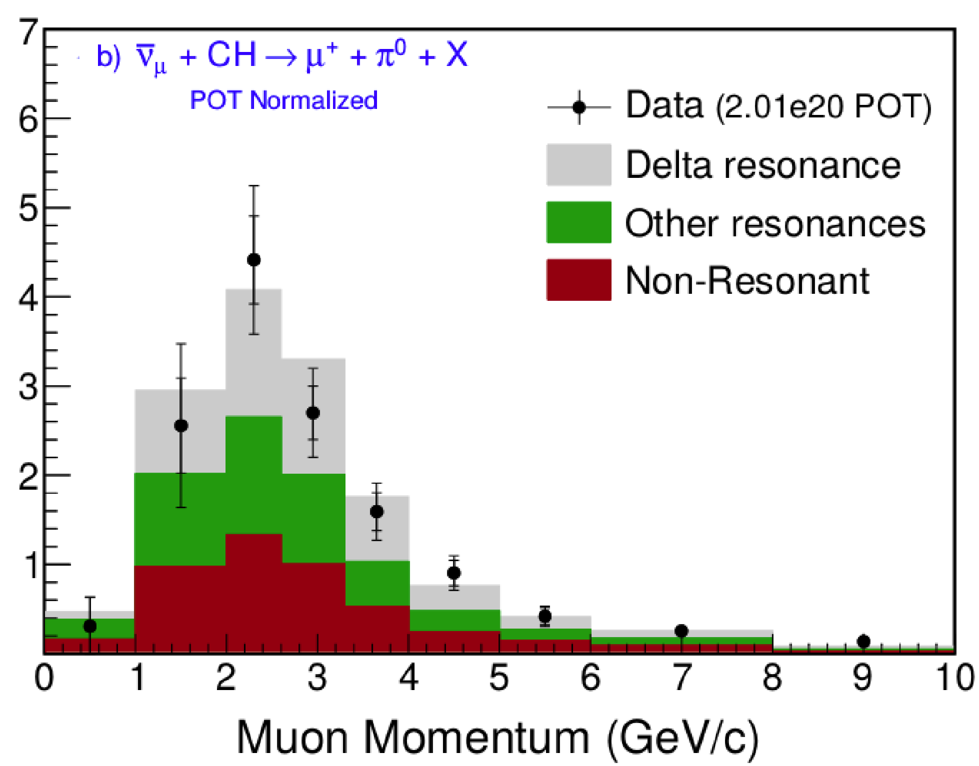
$$m_{\gamma\gamma}^2 = 2E_{\gamma 1}E_{\gamma 2}\left(1 - \cos\theta_{\gamma\gamma}\right)$$

$\overset{(-)}{\nu}_\mu$ - CC $\pi^{\pm(0)}$

Muon Variables

- PRD 092008 (2015) and Phys.Lett. B749 (2015) showed pion variables only.
- PRD 052005 (2016) added cross sections of muon variables.

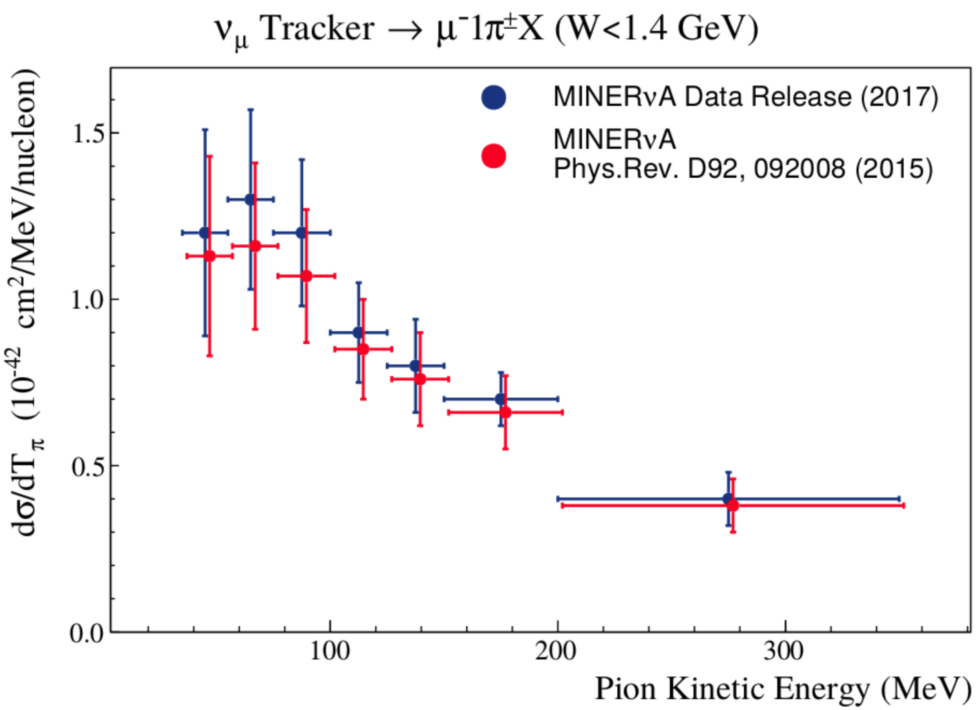


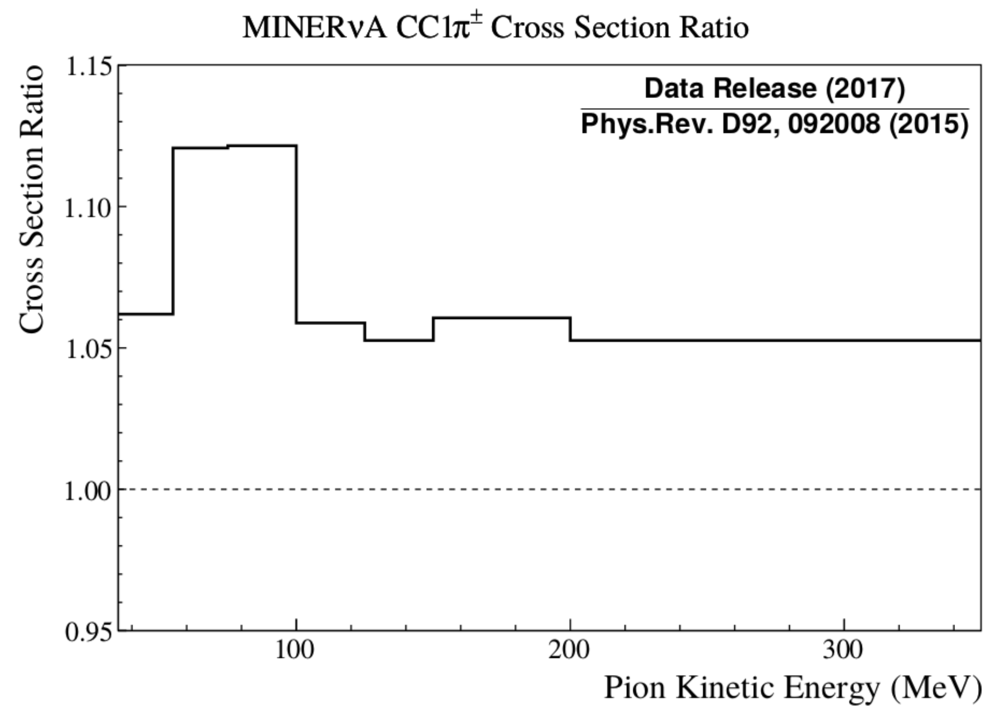


$\overset{(-)}{\nu}_\mu$ - CC $\pi^{\pm(0)}$

Further Improvements

- New ν-e flux constraint (cross sections +~10%)
- Improved signal definition, $W_{true} \rightarrow W_{exp}$ (cross sections -~1-3%)

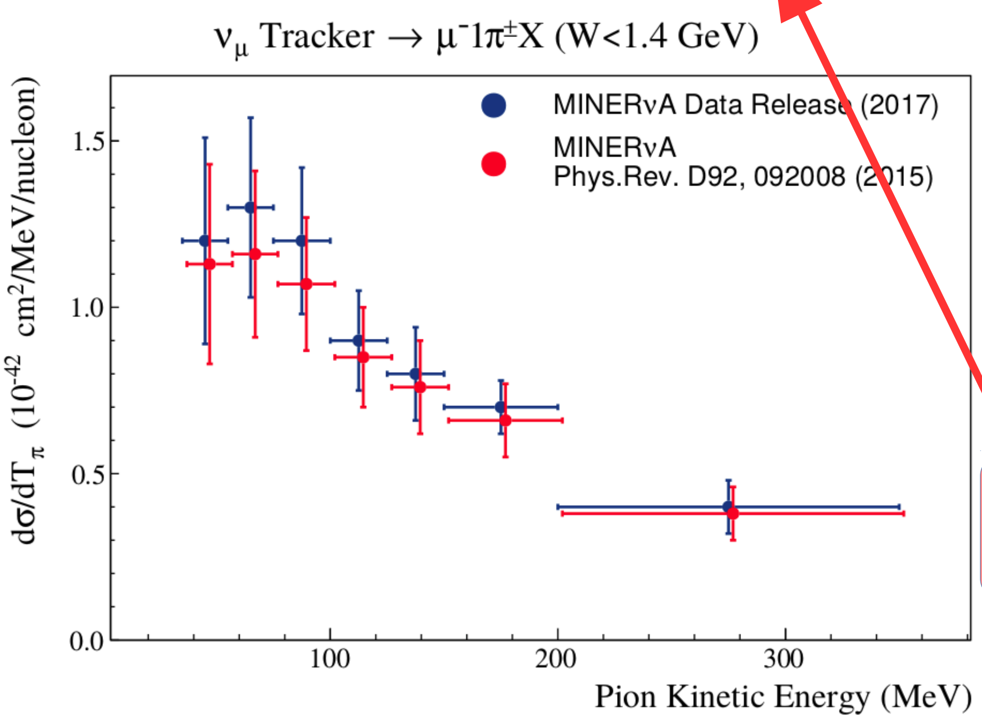


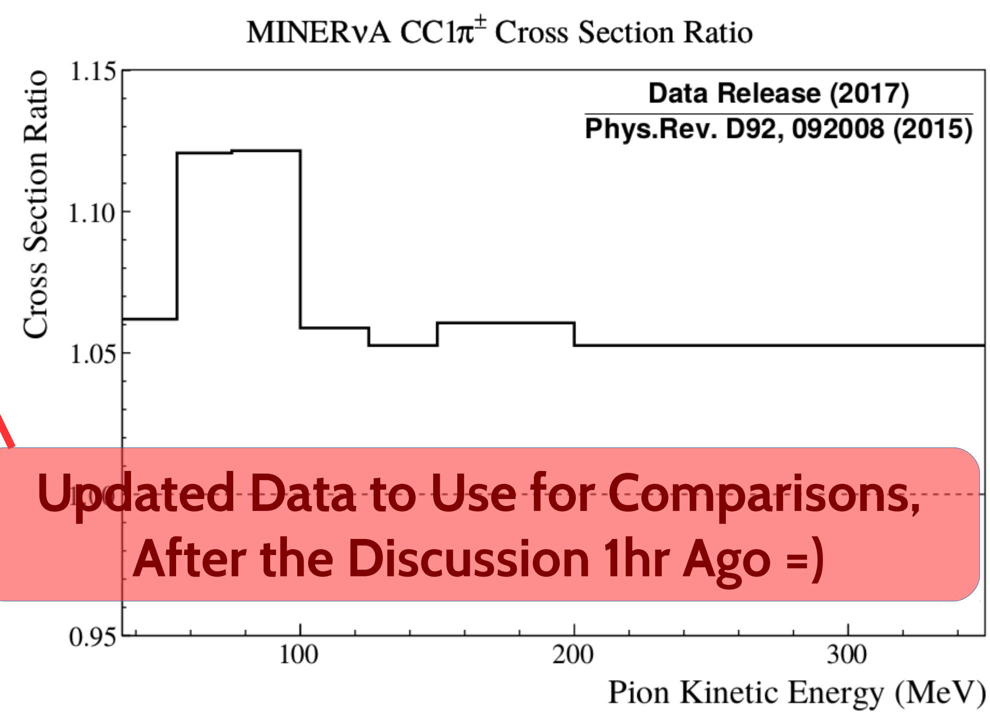


Further Improvements

- New ν-e flux constraint (cross sections +~10%)
- Improved signal definition, $W_{true} \rightarrow W_{exp}$ (cross sections -~1-3%)

http://minerva.fnal.gov/wp-content/uploads/2017/03/Updated_1pi_data.pdf





Updated Data to Use for Comparisons, After the Discussion 1hr Ago =)

W Redefinition

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

$$W^2 = m_N^2 + 2m_N \left(E_\nu - E_\mu\right) - Q^2$$

Experimental W

$$W^2 = m_N^2 + \left(p_\nu - p_\mu\right)^2 + 2p_n \cdot \left(p_\nu - p_\mu\right)$$

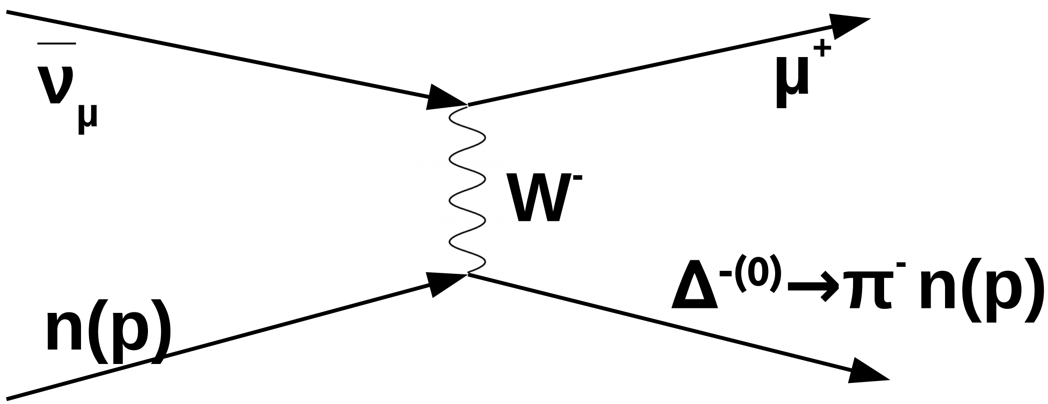
True W

Advances on

$\bar{\nu}_\mu$ – CC π^- Production

Signal Definition

$\bar{\nu}_\mu CH \rightarrow \mu^+ 1\pi^- X$



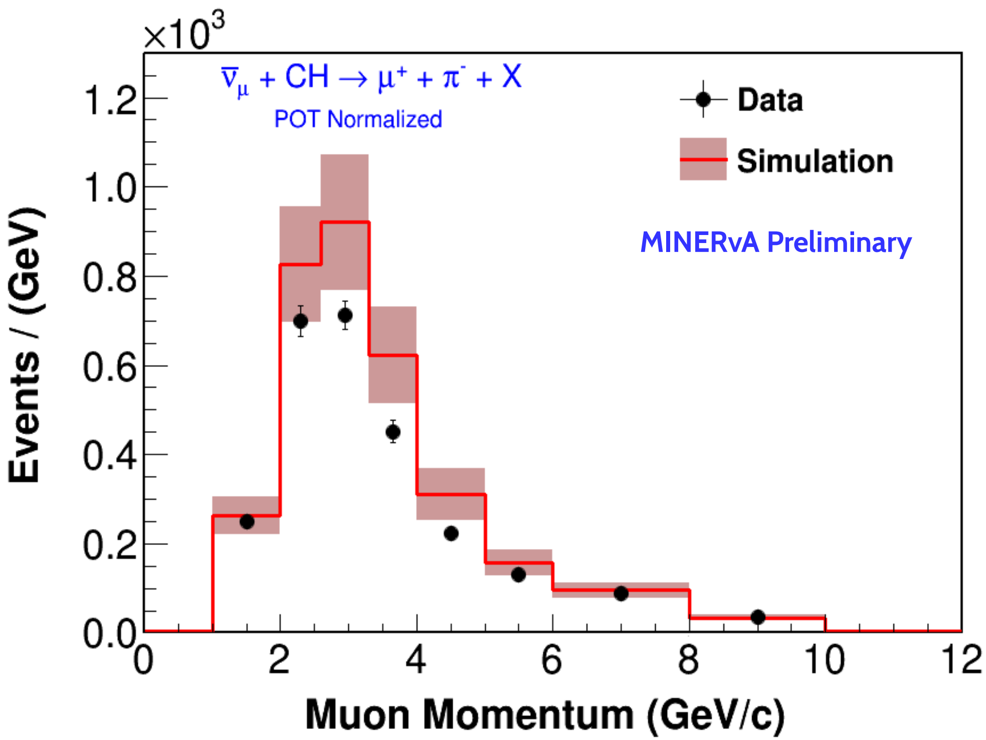
X = any nucleons

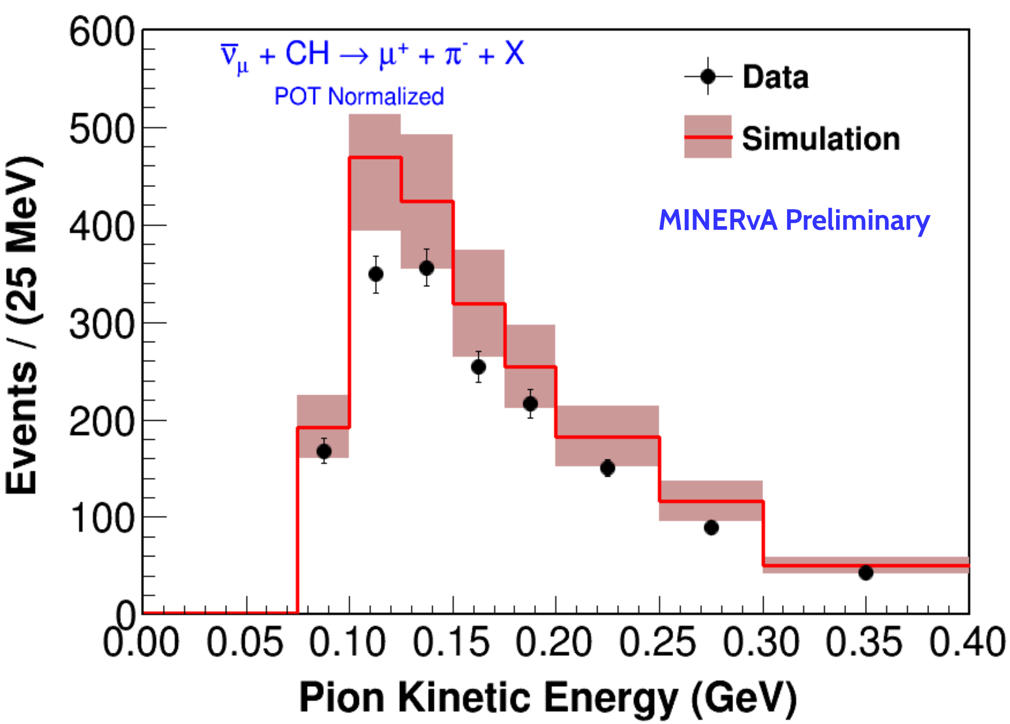
W<1.8 GeV

$$W^2 = m_N^2 + 2m_N\left(E_\nu - E_\mu\right) - Q^2$$

$\bar{\nu}_\mu$ - CC π^- Reconstructed Kinematics

- Signal/background for ν oscillation experiments.
- The remaining of the CC pion production channels.





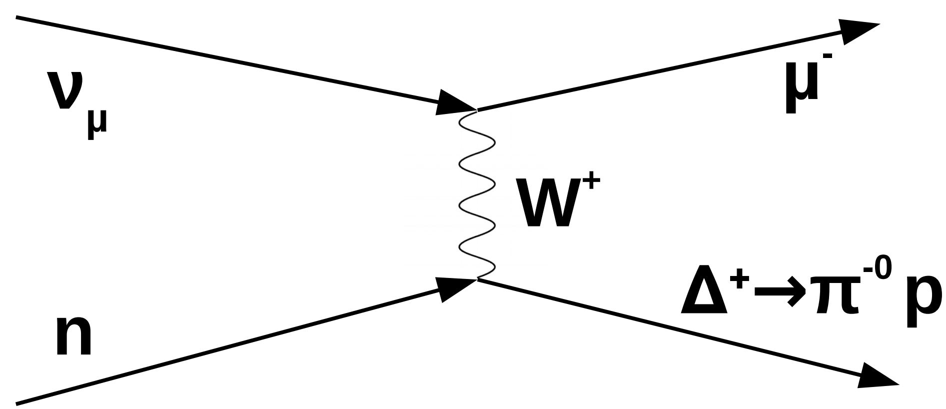
Work in Progress

New Results on

ν_μ – CC π^0 Production

Signal Definition

$$\nu_\mu CH \rightarrow \mu^- 1\pi^0 X$$



X = any nucleons

W < 1.8 GeV

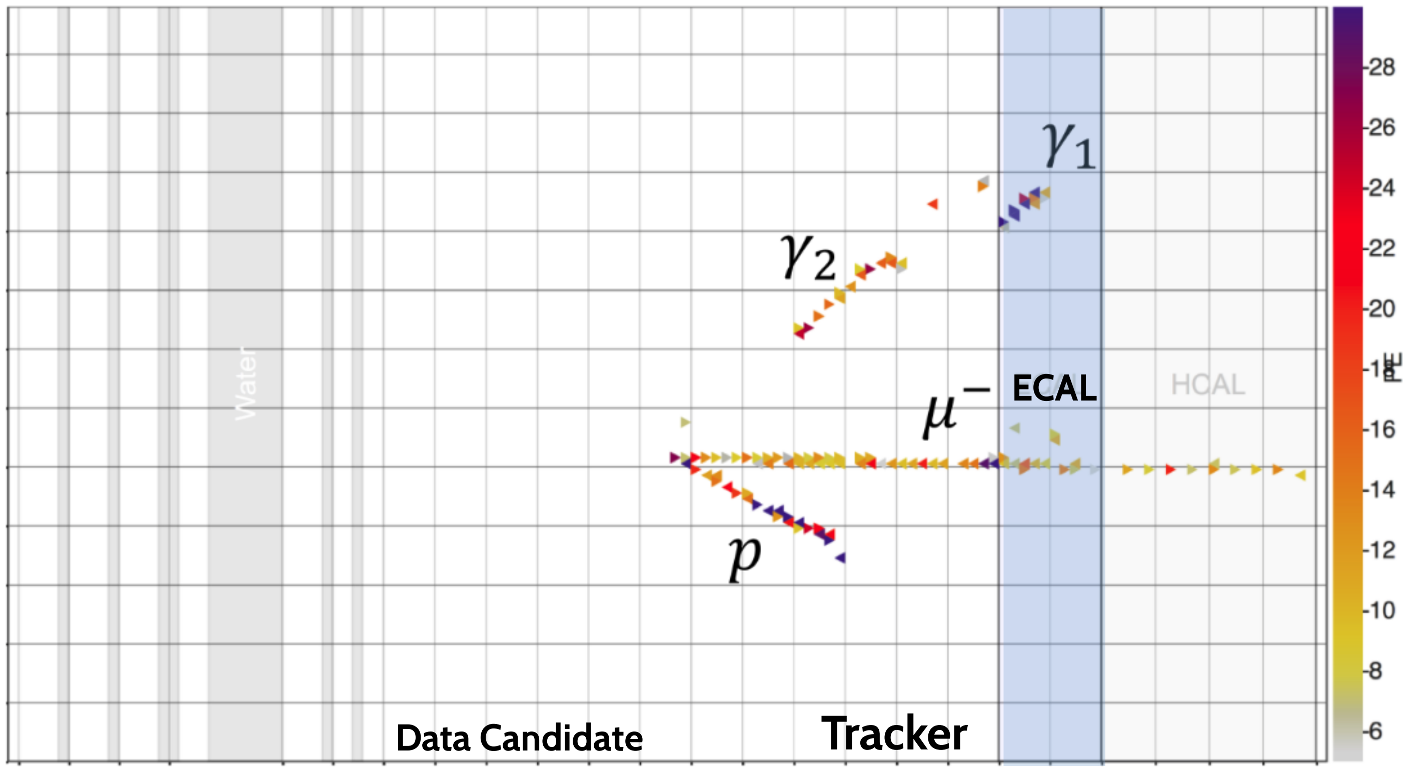
60MeV/c < $m_{\gamma\gamma}$ < 200MeV/c

$$W^2 = m_N^2 + 2m_N\left(E_\nu - E_\mu\right) - Q^2$$

$$m_{\gamma\gamma}^2 = 2E_{\gamma 1}E_{\gamma 2}\left(1 - \cos\theta_{\gamma\gamma}\right)$$

Signal Definition

$\nu_\mu CH \rightarrow \mu^- 1\pi^0 p$ Subsample



~50% of the times we see a proton in the final sample

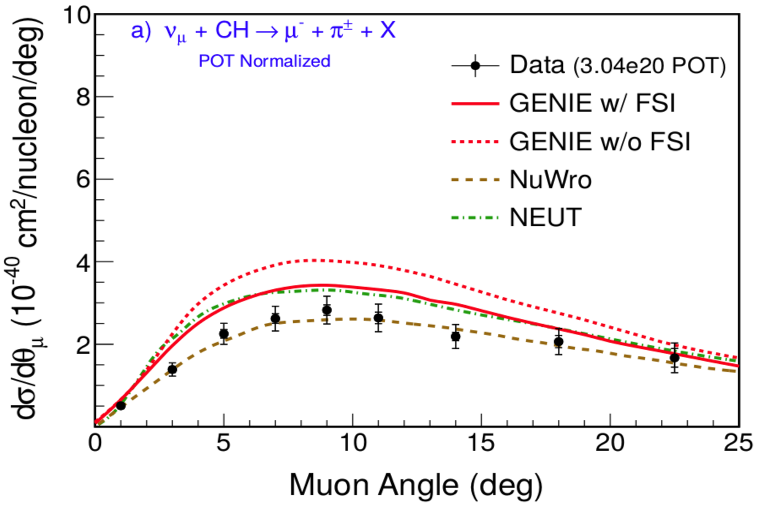
The Muon Side

Cross Section Measurements

Muon Angle

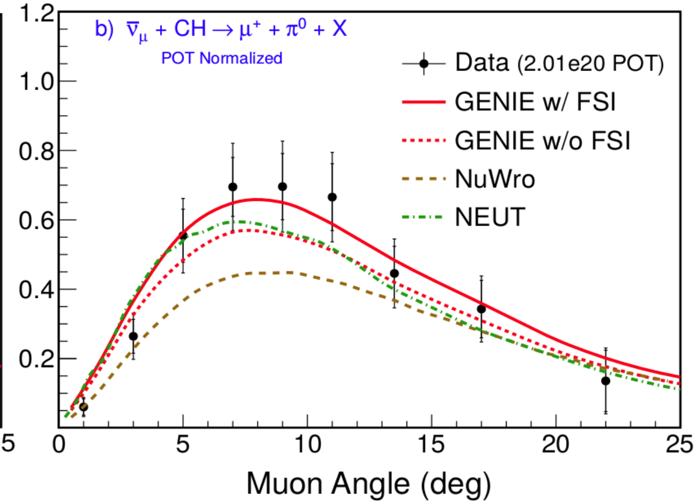
Comparison with previous pion results at MINERvA.

GENIE 2.6.2



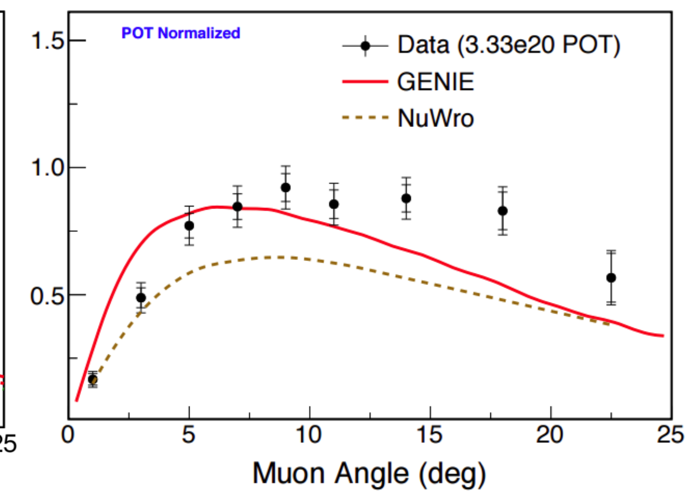
ν_μ-CC $\pi^\pm$

GENIE 2.6.2



$\bar{\nu}_\mu$-CC π^0

GENIE 2.8.4



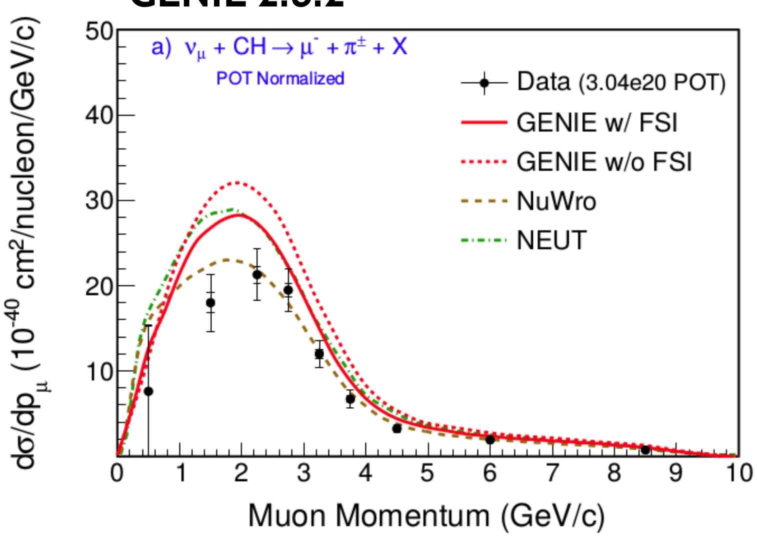
ν_μ-CC π^0

ν_μ - CC π^0 Cross Section Measurements

Muon Momentum

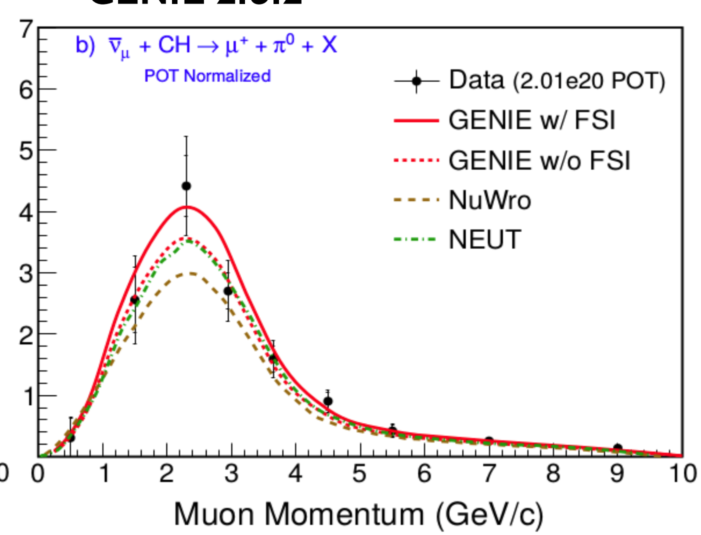
Comparison with previous pion results at MINERvA

GENIE 2.6.2



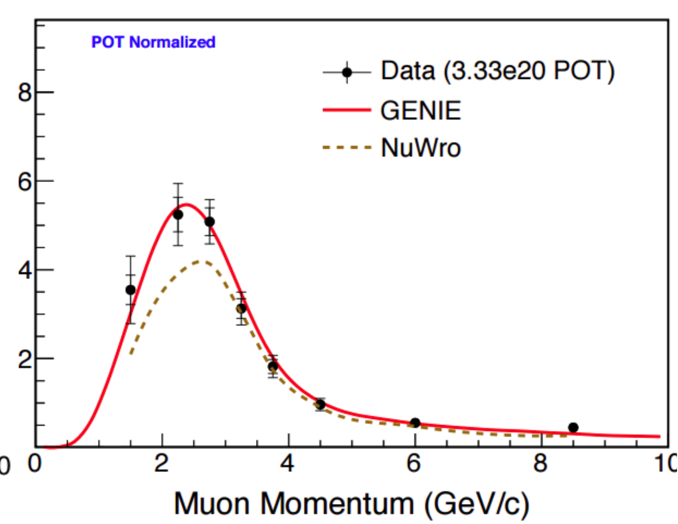
ν_μ-CC $\pi^\pm$

GENIE 2.6.2



$\bar{\nu}_\mu$-CC π^0

GENIE 2.8.4

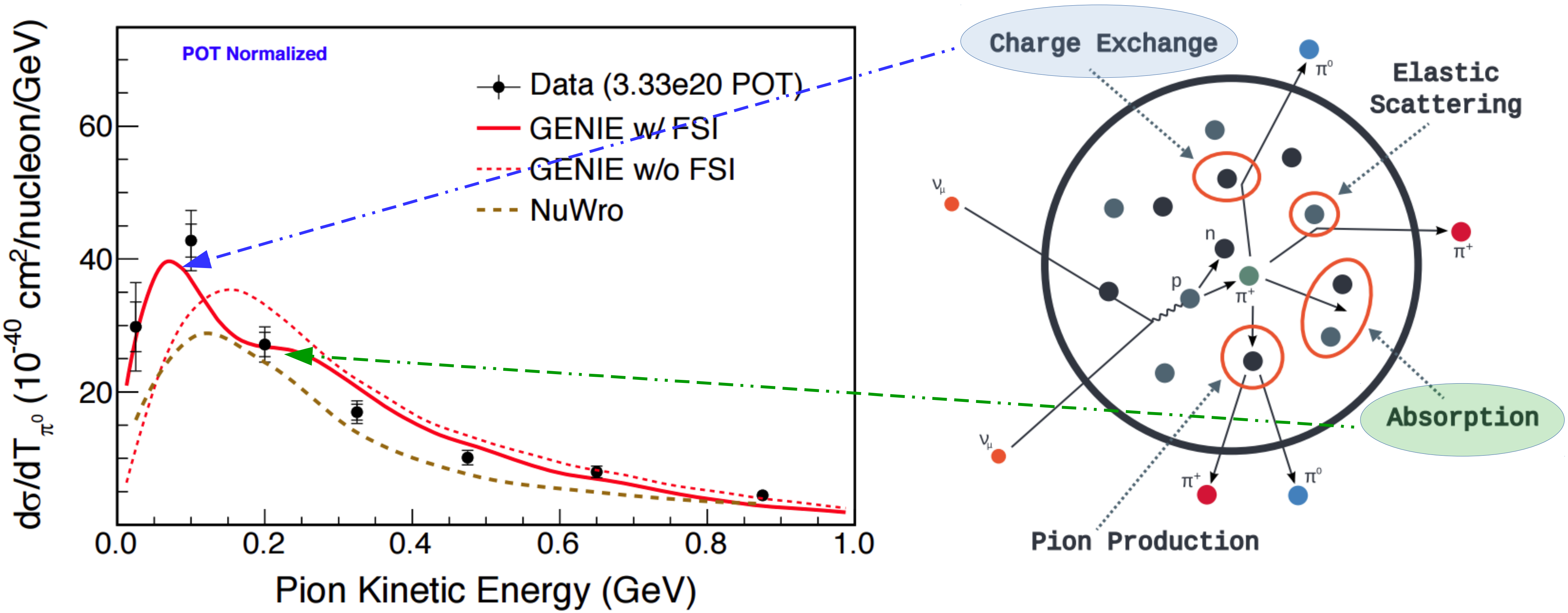


ν_μ-CC π^0

The Pion Side

Cross Section Measurements

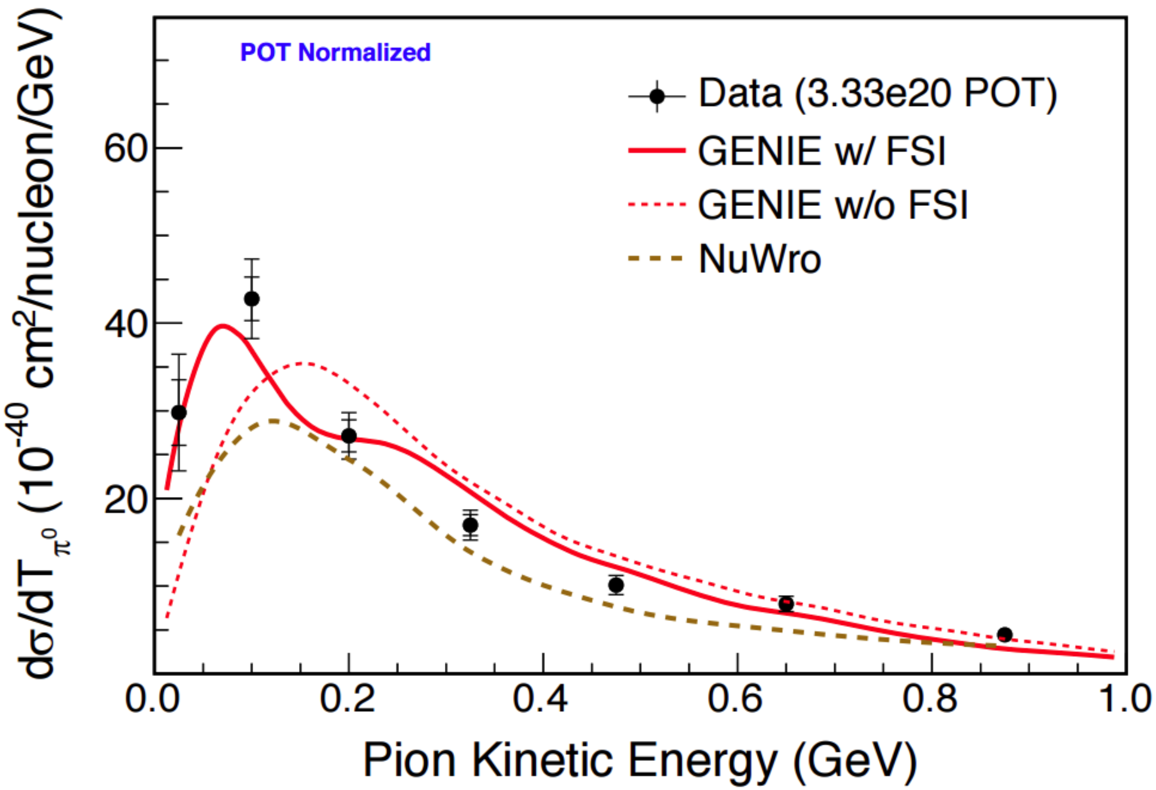
Pion Kinetic Energy

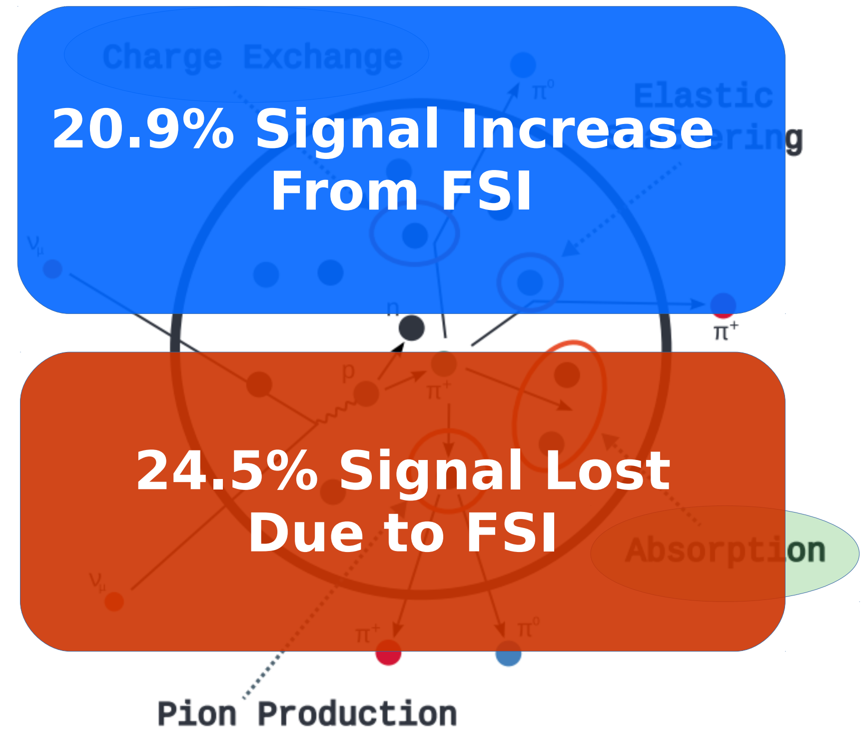


- Enhancement at ~ 100 MeV due to $\pi^+ \rightarrow \pi^0$ feed-in events.
- Depletion at ~240 MeV from π^0 absorption feed-out events.

ν_μ - CC π^0 Cross Section Measurements

Pion Kinetic Energy



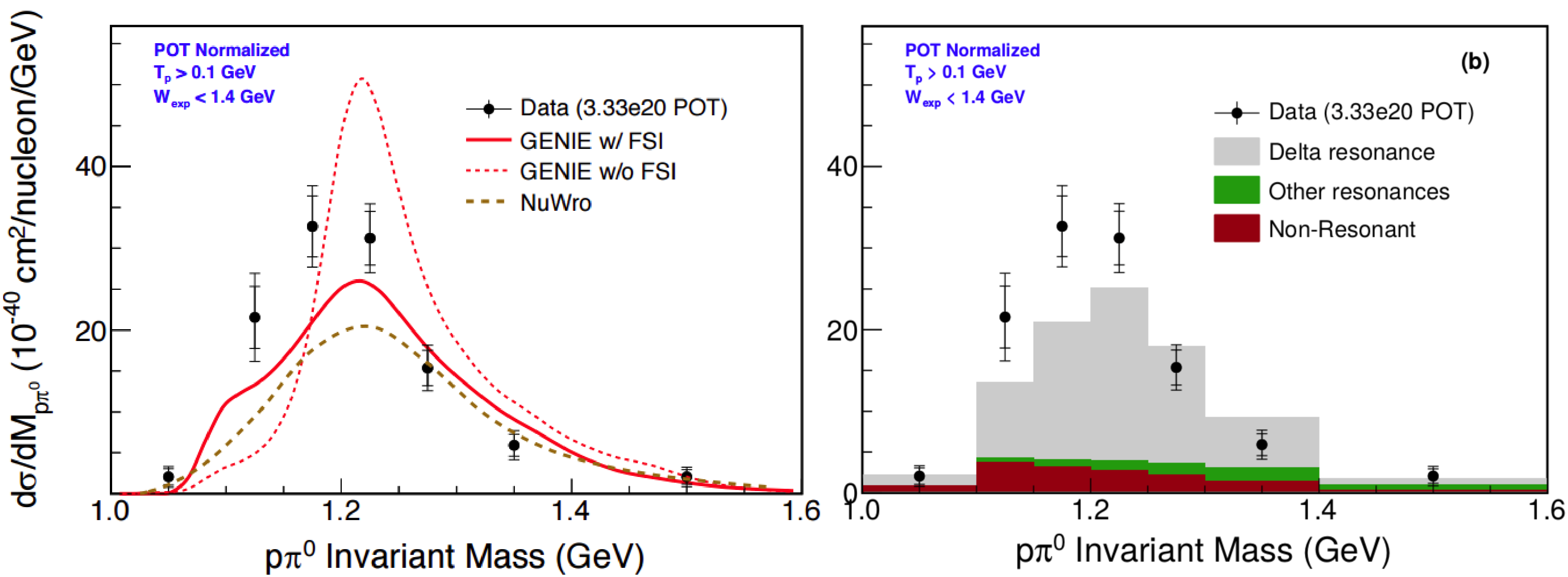


- Enhancement at ~ 100 MeV due to $\pi^+ \rightarrow \pi^0$ feed-in events.
- Depletion at ~240 MeV from π^0 absorption feed-out events.

Further Studies

$p\pi^0$ Invariant Mass

Subsample Selected to Study Δ^+ States



Possible Δ^+ Excess

Further Results:

- $p\pi^0$ Anisotropy Study
- Pion 2p2h Search
- And More!

To Be Presented On July 7 During the Joint Experimental-Theoretical Physics Seminar at Fermilab

Conclusions

MINERvA is on its way to finish the whole set of CC ν_μ-induced pion reactions in CH in the LE era.

Our latest result show the importance of more and better physics models in event generators.

We are now taking data in a more intense and energetic NuMI beam $\langle E_\nu \rangle$ = 6GeV. We have started some of the pion analyses in this new energy region.

Thanks a Lot!

Questions?

Backup

Leading Uncertainties

ν_μ - CC → π^+ Detector Response – Flux – Interaction Model

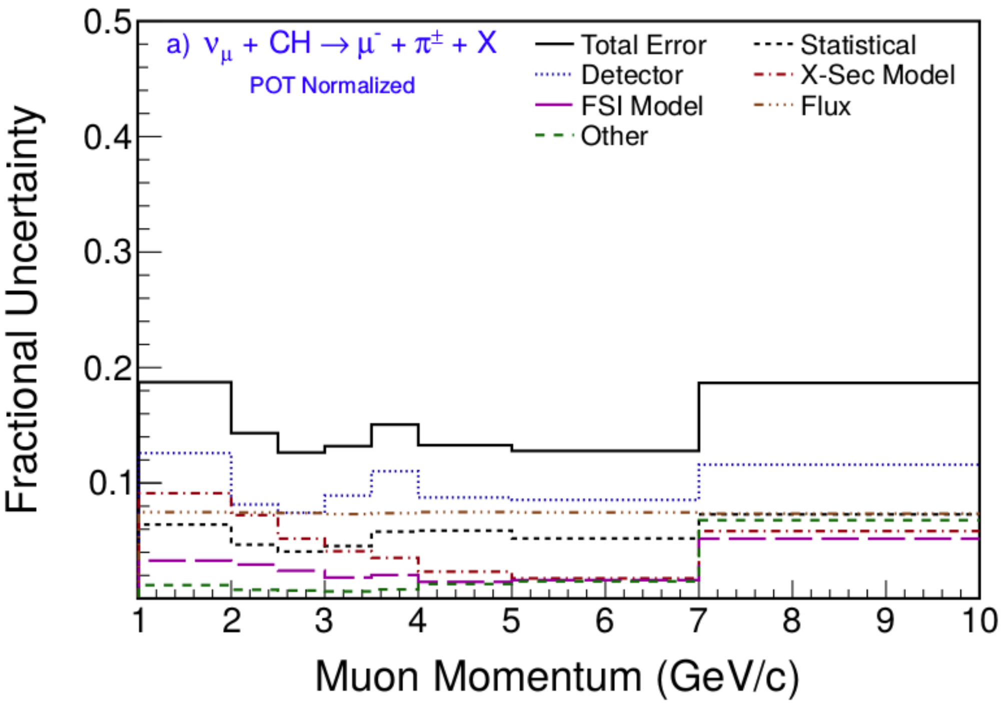
$\bar{\nu}_\mu$ - CC → π^0 Statistical - Interaction Model – Background Norm. and Unfolding

$\bar{\nu}_\mu$ - CC → π^- Interaction Model – Flux – Detector Response

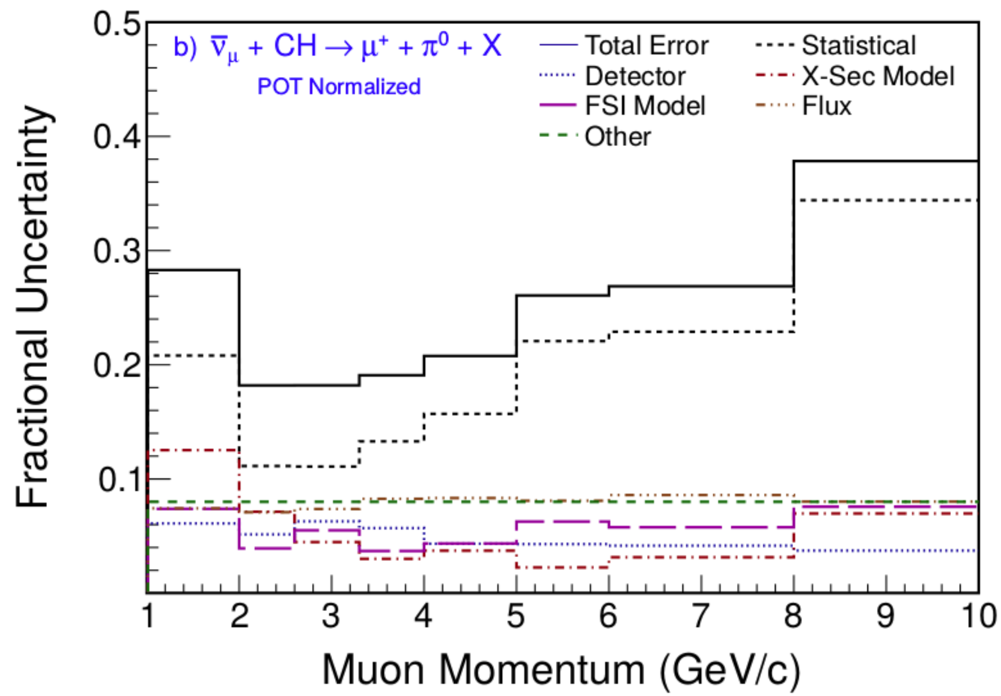
ν_μ - CC → π^0 Interaction Model – Detector Response - Statistical

Leading Uncertainties

ν_μ - CC → π^+



$\bar{\nu}_\mu$ - CC → π^0

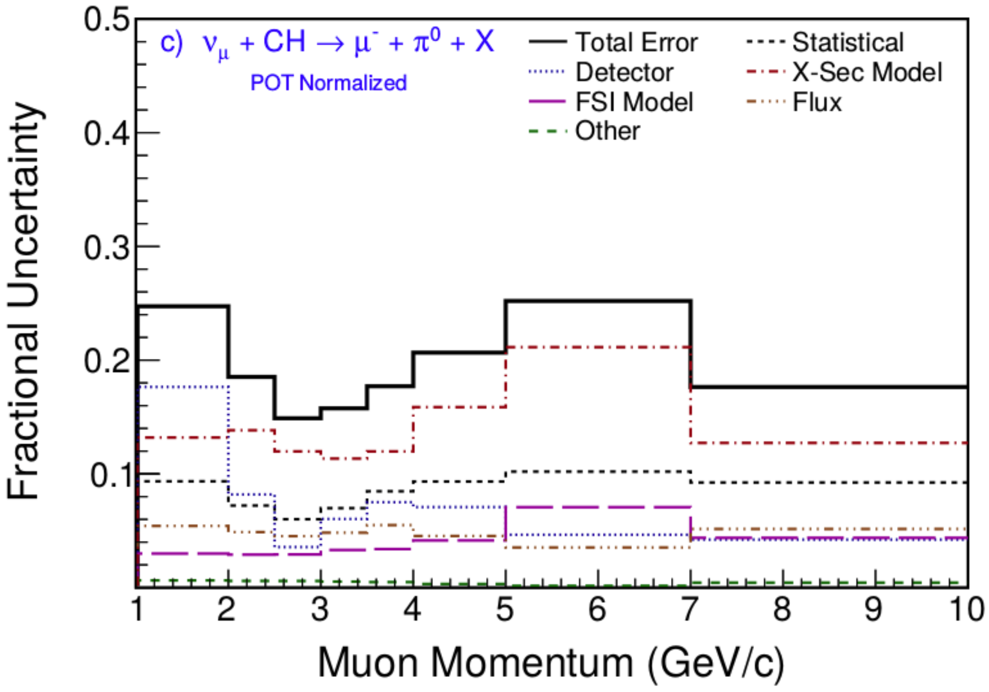


Leading Uncertainties

$\overline{\nu}_\mu$ - CC → π^-

In Progress

ν_μ - CC → π^0

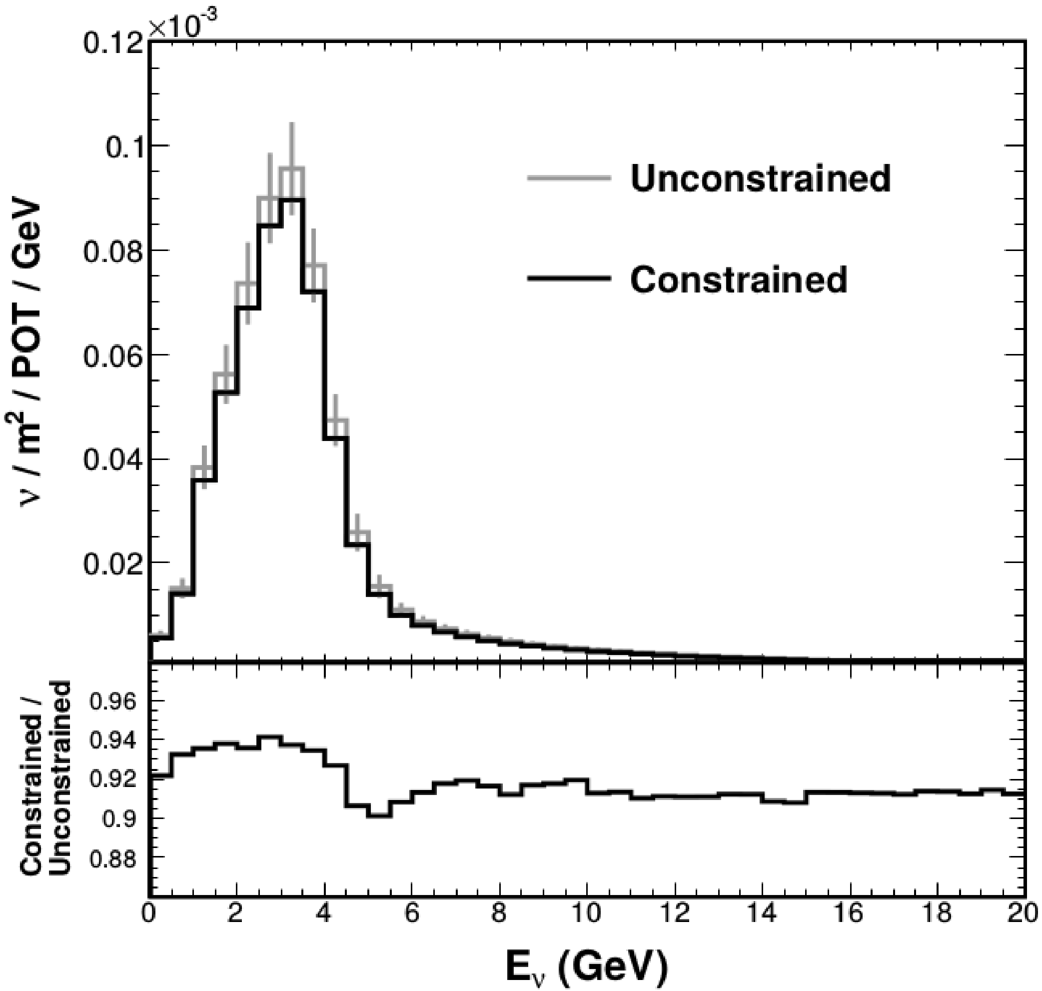


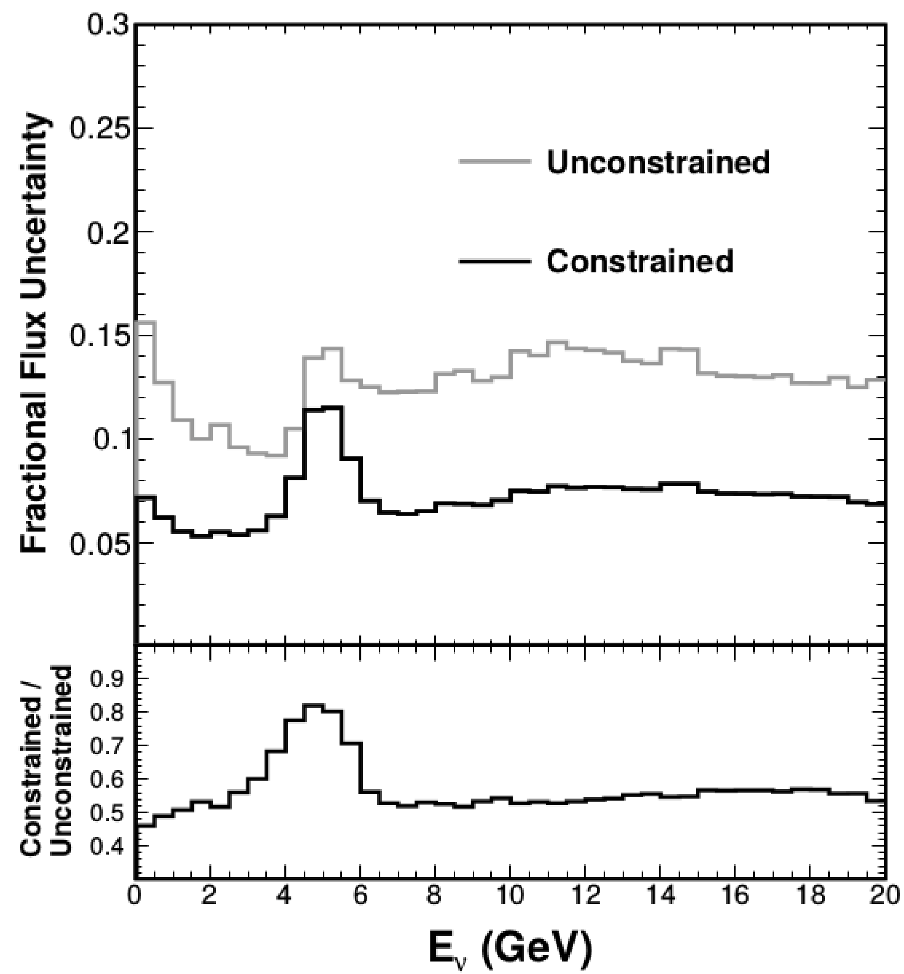
Overall Efficiencies and Purities

	Eff	Purity
ν_μ - CC → π^+	3%	86%
$\bar{\nu}_\mu$ - CC → π^0	6%	55%
$\bar{\nu}_\mu$ - CC → π^-	7.17%	69%
ν_μ - CC → π^0	8.4%	51%

ν – e Flux Constraint

Phys.Rev. D93 (2016) no.11, 112007





Background Summary

ν_μ - CC → π^+	• 69% pions with W>1.8GeV • 19% from protons misidentified as pions. • 9% from events with Enu > 10GeV • 3% other.
$\bar{\nu}_\mu$ - CC → π^0	• 70% from events with at least 1π^0 • 30% events with π^- and neutron-induced ionizations.
$\bar{\nu}_\mu$ - CC → π^-	• Non-cc1pi$^-$ background. • cc1pi- background where the proton is misidentified as π^-
ν_μ - CC → π^0	• 57% No π^0 + with charged mesons. • 20% at least 1π^0 + mesons. • 20% from proton and neutron-induced ionizations. • 3% others.

GENIE 2.8.4 With Tuning

Event Reweighting

- $\Delta^{++}(1232)$ Anisotropic Decay Reweight*
- Reweight all CC-NonRES 1π channels with 0.43†
- Reweight all CC-RES with 1.15†

Other Changes

- $M_A^{RES} = 1.12 \rightarrow 0.94$ GeV†
- Additional QE-Like 2p2h events‡

GENIE 2.8.4 With Tuning

Reduced Systematics

- Anisotropic decay reweight
- M_A^{RES} = 20% → 5%†
- Norm (Non-RES 1π) = 50% → 4%†
- New Systematic: CC-RES Norm: 7%†

References:

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

† Eur. Phys. J. C 76, 8, 474 (2016)

‡ Phys. Rev. D 88, 113007 (2013)

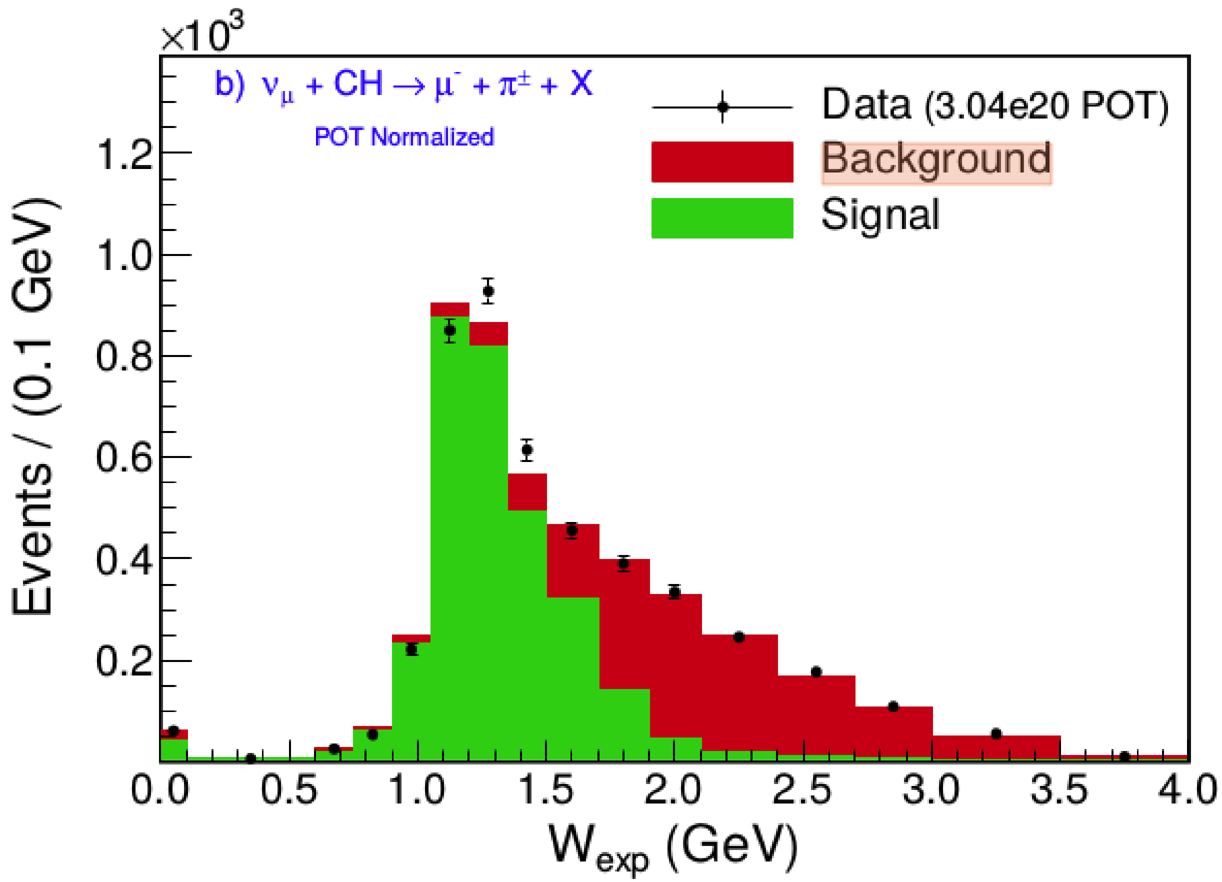
GENIE / NuWro Comparison

GENIE 2.8.4 (tuned)	NuWro 17.01	
-Relativistic Fermi gas	-Relativistic Fermi gas	Nuclear Model
-Rein-Sehgal	-Δ(1232)	Resonance
-Bodek-Yang	-Bodek-Yang	DIS
-Effective cascade	-Full cascade	FSI Model

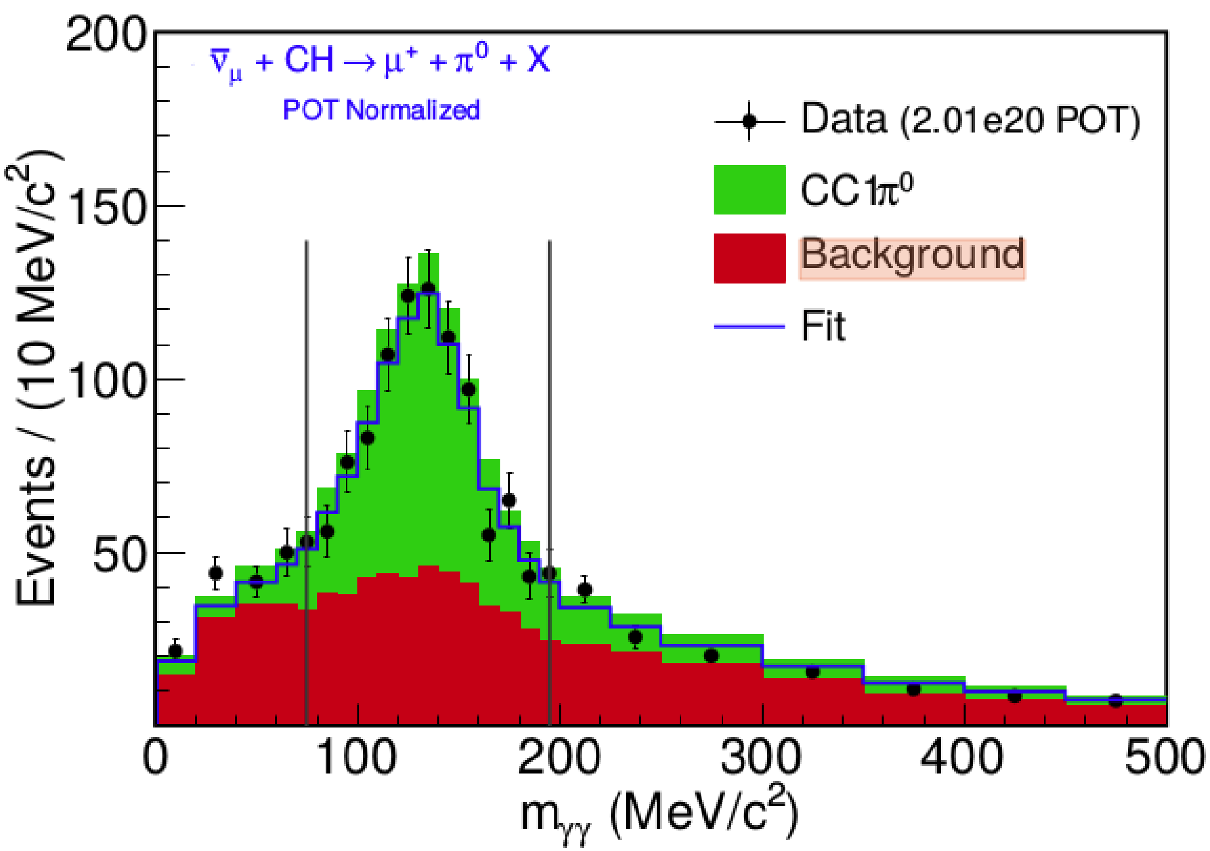
Some Additions to GENIE 2.8.4 Since GENIE 2.6.2

- Implementation of a Meson Exchange Current (MEC).
- **π^-,π^+** and n,p cross-section differences are taken into account.
- More complete modeling of pion absorption and nucleon knockout processes.
- Kaon re-scattering.
- Inelastic reactions now treated as quasielastic. Angle chosen from 2-body kinematics, includes binding energy and Fermi motion.

ν_μ - CC $\pi^\pm$ Hadronic Invariant Mass

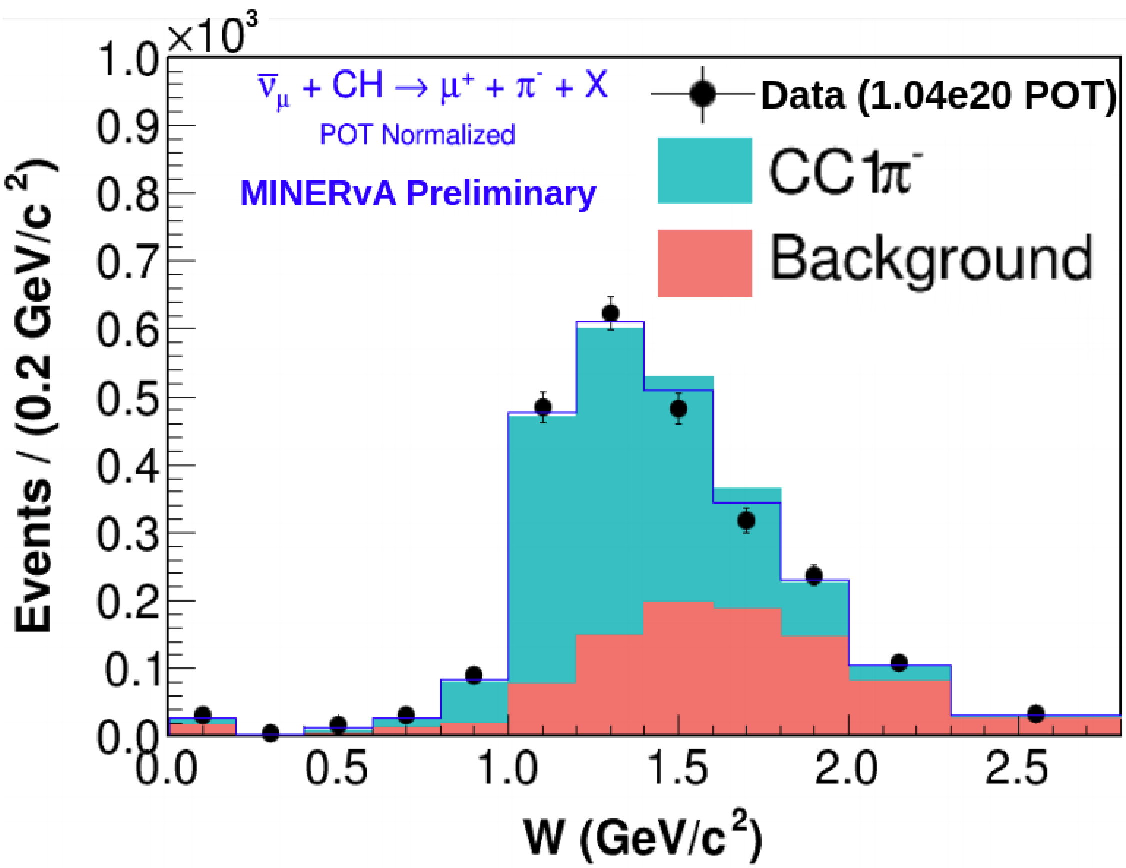


π^0 Invariant Mass



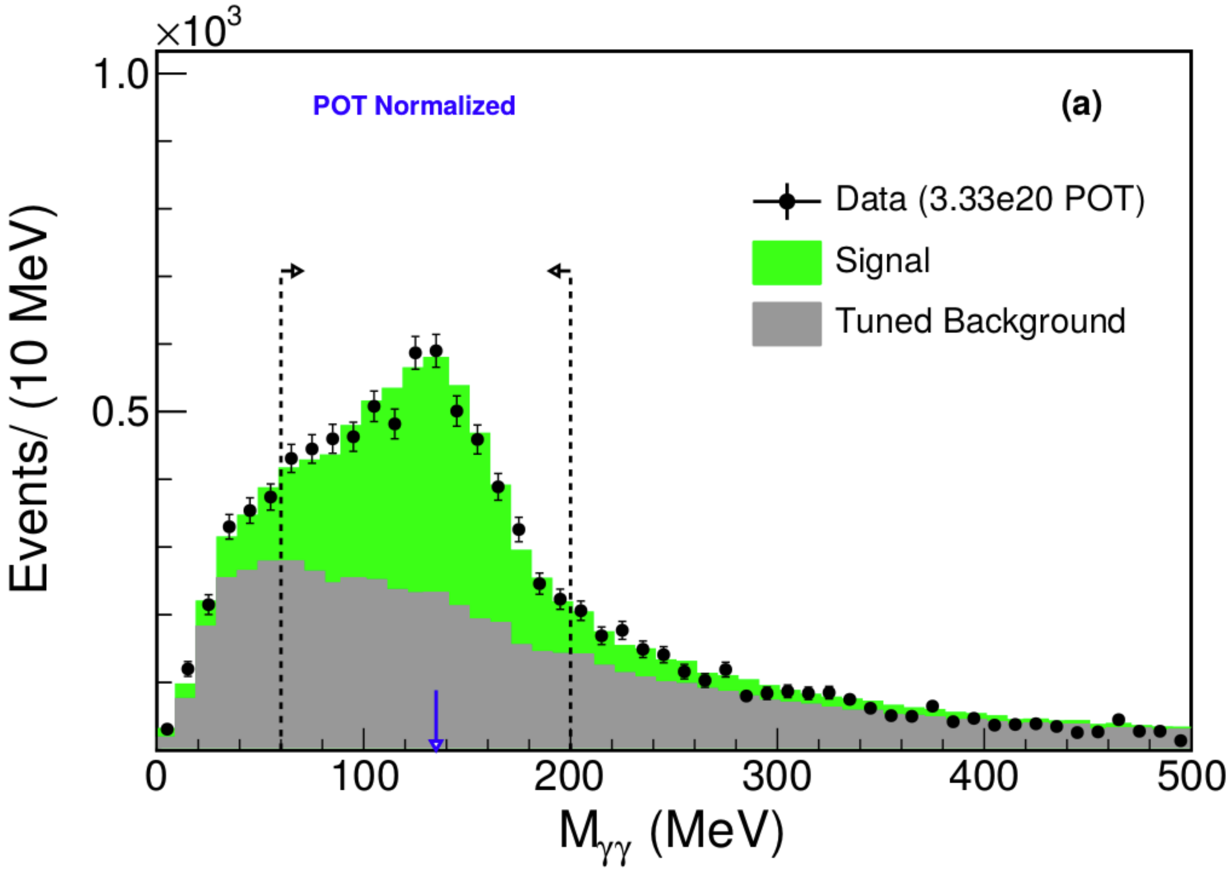
$\bar{\nu}_\mu$ - CC π^-

Hadronic Invariant Mass



ν_μ - CC π^0

π^0 Invariant Mass

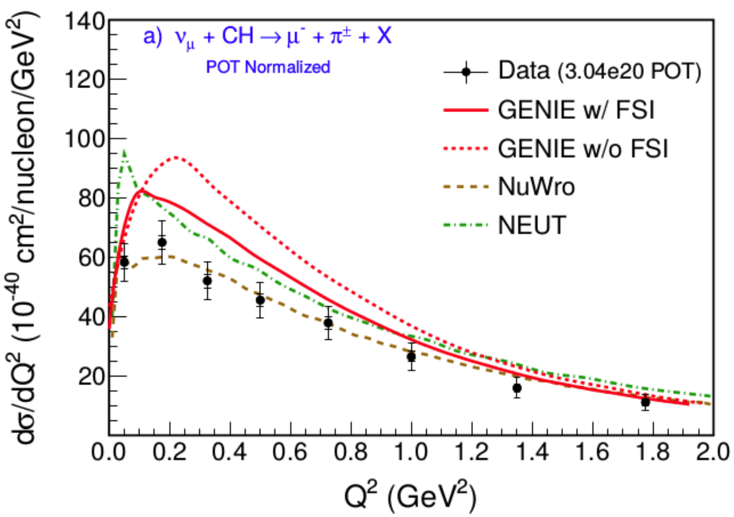


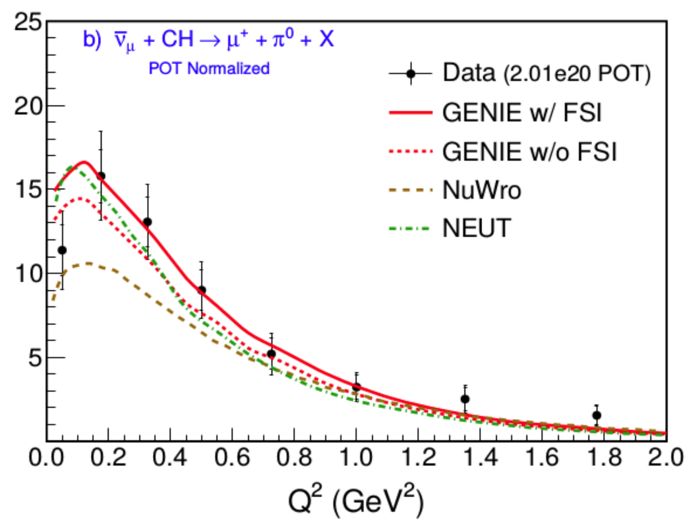
Hadronic Invariant Mass?
Wait for Ozgur's Altinok Seminar at Fermilab
On July 7th

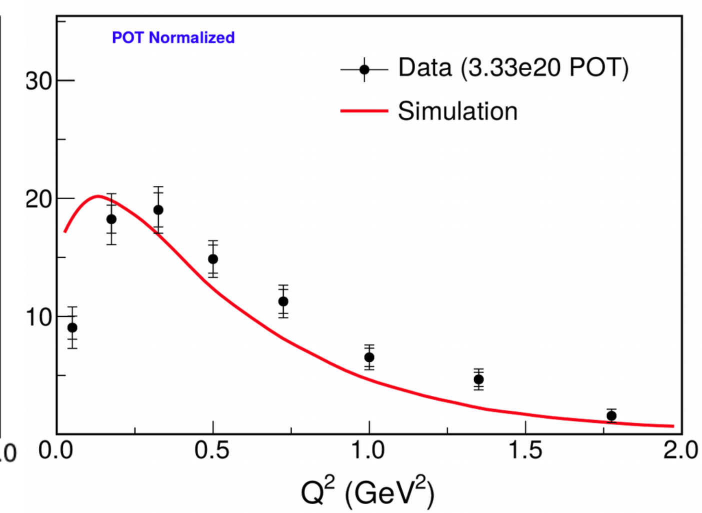
Cross Section Measurements

Q^2

Comparison with previous pion results at MINERvA

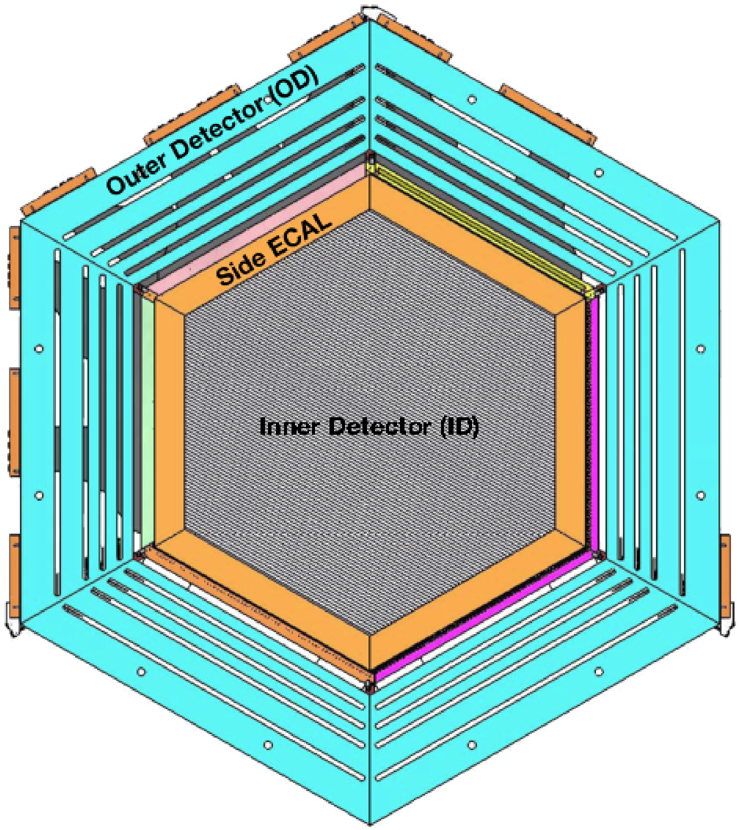


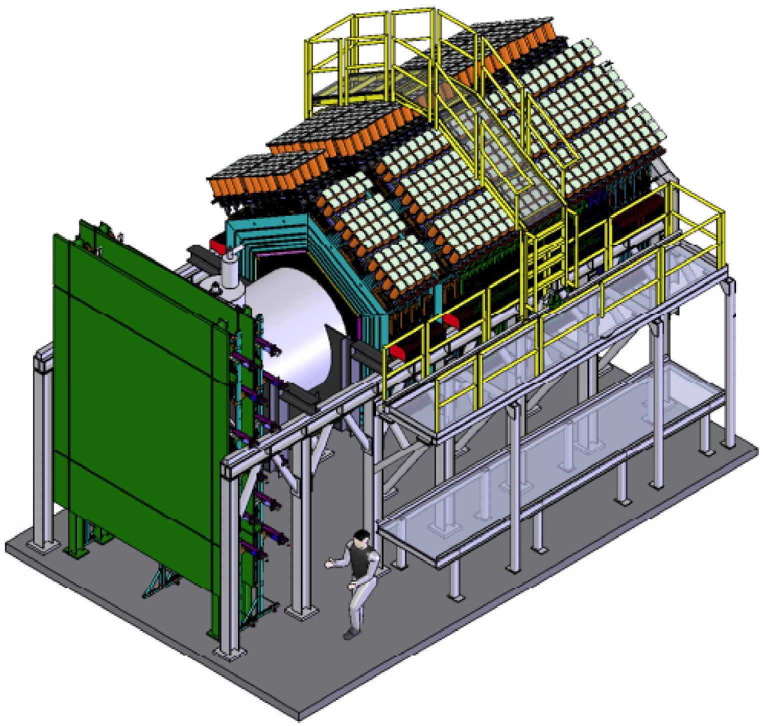


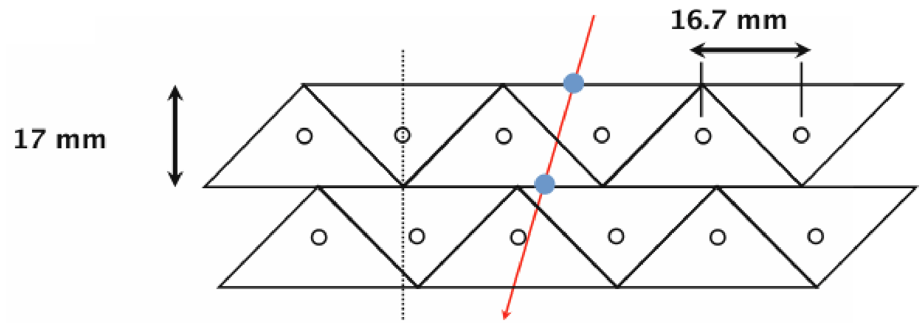


ν_μ-CC $\pi^\pm$ **$\bar{\nu}_\mu$-CC π^0** **ν_μ-CC π^0**

Detector Details







Other Formulae

$Q^2 = -(k-k')^2 = 2E_\nu(E_\mu - \lvert\mathbf{p}\rvert\cos\theta_\mu) - m^2_\mu$	**Momentum Transfer**
$W = (p+q)^2 = M^2_N + 2M_N(E_\nu - E_\mu) - Q^2$	**H. Invariant Mass**
$\mathbf{p}_{\pi^0} = \mathbf{p}_{\gamma 1} + \mathbf{p}_{\gamma 2}$	**pi0 Momentum**
$T_{\pi^0} = E_{\pi^0} - m_{\pi^0}, \rightarrow E_{\pi^0} = \sqrt{(\lvert\mathbf{p}_{\pi^0}\rvert^2 - m_{\pi^0}{}^2)}$	**pi0 Kinetic Energy**
$M^2_{\gamma\gamma} = 2E_{\gamma 1}E_{\gamma 2}(1 - \cos\theta_{\gamma\gamma})$	**pi0 Invariant Mass**
$M^2_{p\pi} = (E_p + E_\pi)^2 - \lvert\mathbf{p}_p + \mathbf{p}_\pi\rvert^2$	**p+-pi0 Invariant Mass**
$E_\nu = E_\mu + E_{\gamma 1} + E_{\gamma 2} + \Sigma T_p + E_{vtx} + E_{extra}$	**Neutrino Energy**
$(d\sigma/dX)_i = (1/T_n\Phi)(1/\Delta X_i)\,\Sigma_j\,[U_{ij}\,(N_j^{data} - N_j^{bkg})/\varepsilon_i]$	**Diff Cross Section**

Formulae for Enu

$$E_\nu = E_\mu + E_{recoil}, \rightarrow E_{recoil} = \beta\left(\alpha \sum_i C_i Ei\right) \qquad \nu_\mu CH \rightarrow \mu^- \pi^\pm X$$

$$E_\nu = E_\mu + E_{\pi^0} + T_n, \rightarrow T_n = \frac{1}{2}\frac{\left[\left(E_\mu - p_\mu^{\parallel}\right) + \left(E_\pi^0 - p_{\pi^0}^{\parallel}\right)\right]^2 + \left(\vec{p}_\mu^{\perp} + \vec{p}_{\pi^0}^{\perp}\right)^2}{m_N - \left(E_\mu - p_\mu^{\parallel}\right) - \left(E_{\pi^0} - p_{\pi^0}^{\parallel}\right)} \qquad \overline{\nu}_\mu CH \rightarrow \mu^+ \pi^0 X$$

$$E_\nu = E_\mu + E_{\pi^-} + E_{calo} \qquad \overline{\nu}_\mu CH \rightarrow \mu^+ \pi^- X$$

$$E_\nu = E_\mu + E_{\pi^0} + \sum T_p + E_{vertex} + E_{extra} \qquad \nu_\mu CH \rightarrow \mu^- \pi^0 X$$