Measurement of ν_μ–CC(π^0) on Hydrocarbon using MINERvA

$$\nu_\mu + \mathrm{CH} \rightarrow \mu^- + \pi^0 + \mathrm{nucleon(s)}$$

Ozgur Altinok

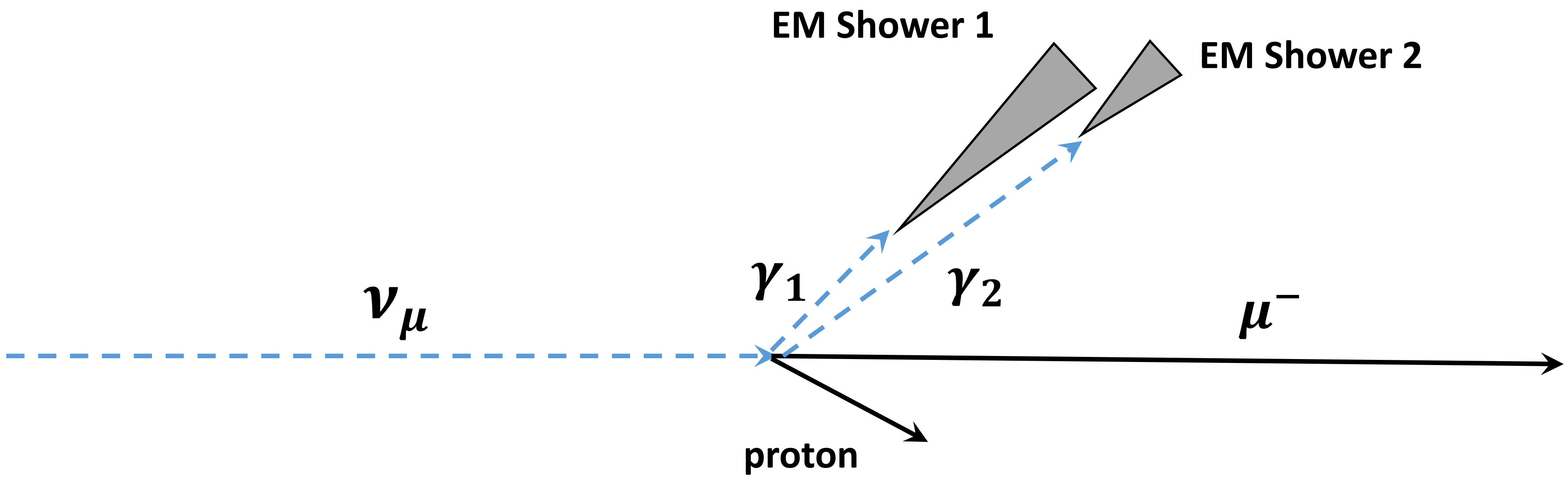
MINERvA Neutrino Experiment

July 7, 2017

$\nu_\mu + \mathrm{CH} \rightarrow \mu^- + \pi^0 + \mathrm{nucleon(s)}$

Example: $\nu_\mu + \{n\}_C \rightarrow \mu^- + \pi^0 + p$

$\pi^0 \rightarrow 2\gamma$



$\nu_\mu + CH \rightarrow \mu^- + \pi^0 + \text{nucleon(s)}$

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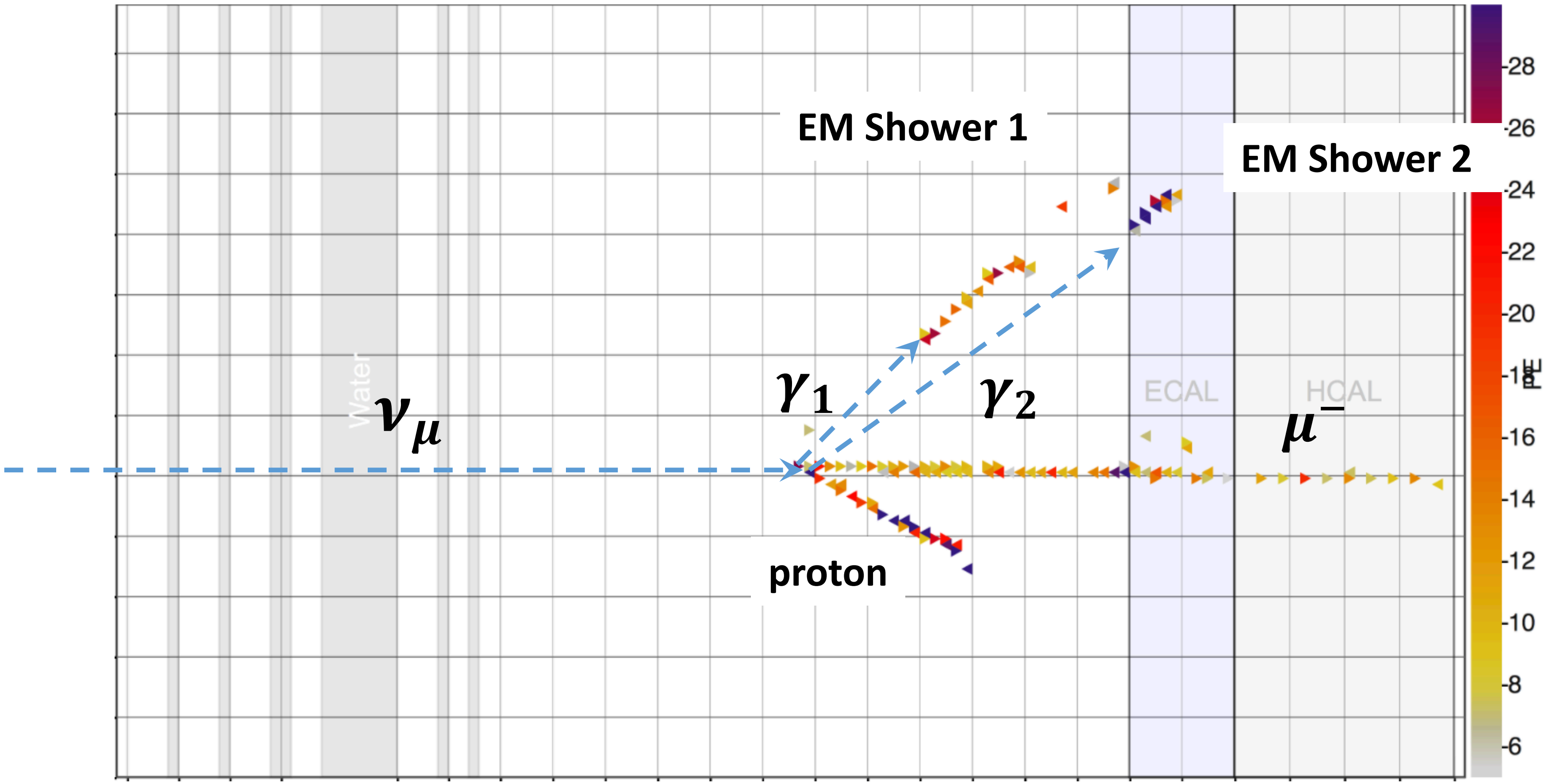
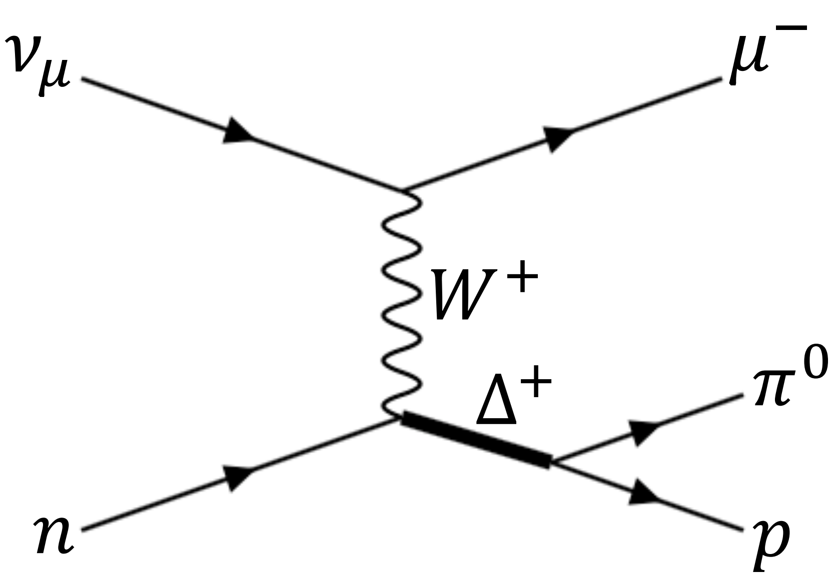


ν_μ–CC(π^0) Production: Component Processes

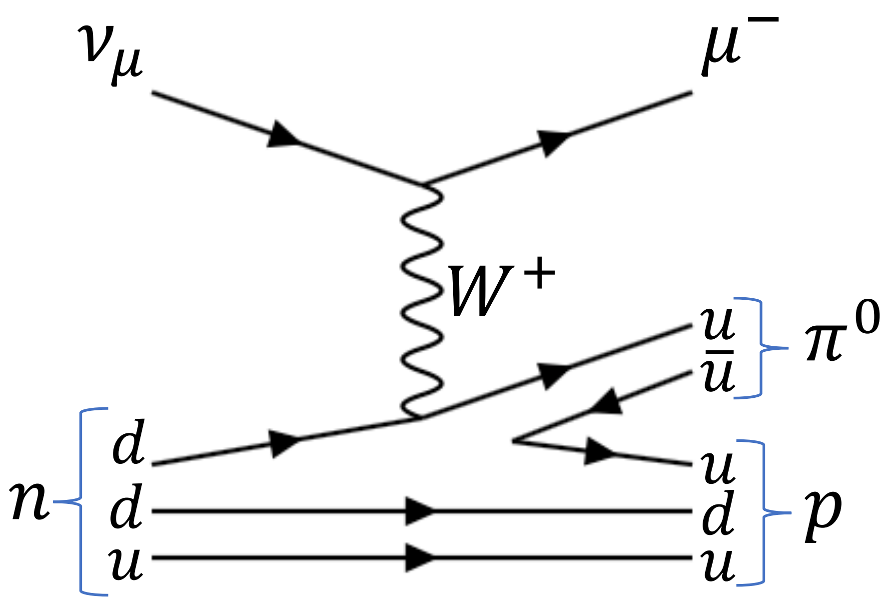
Baryon Resonance Production

Δ^+(1232), higher-mass N*



Non-Resonant Production

and Deep Inelastic Scattering

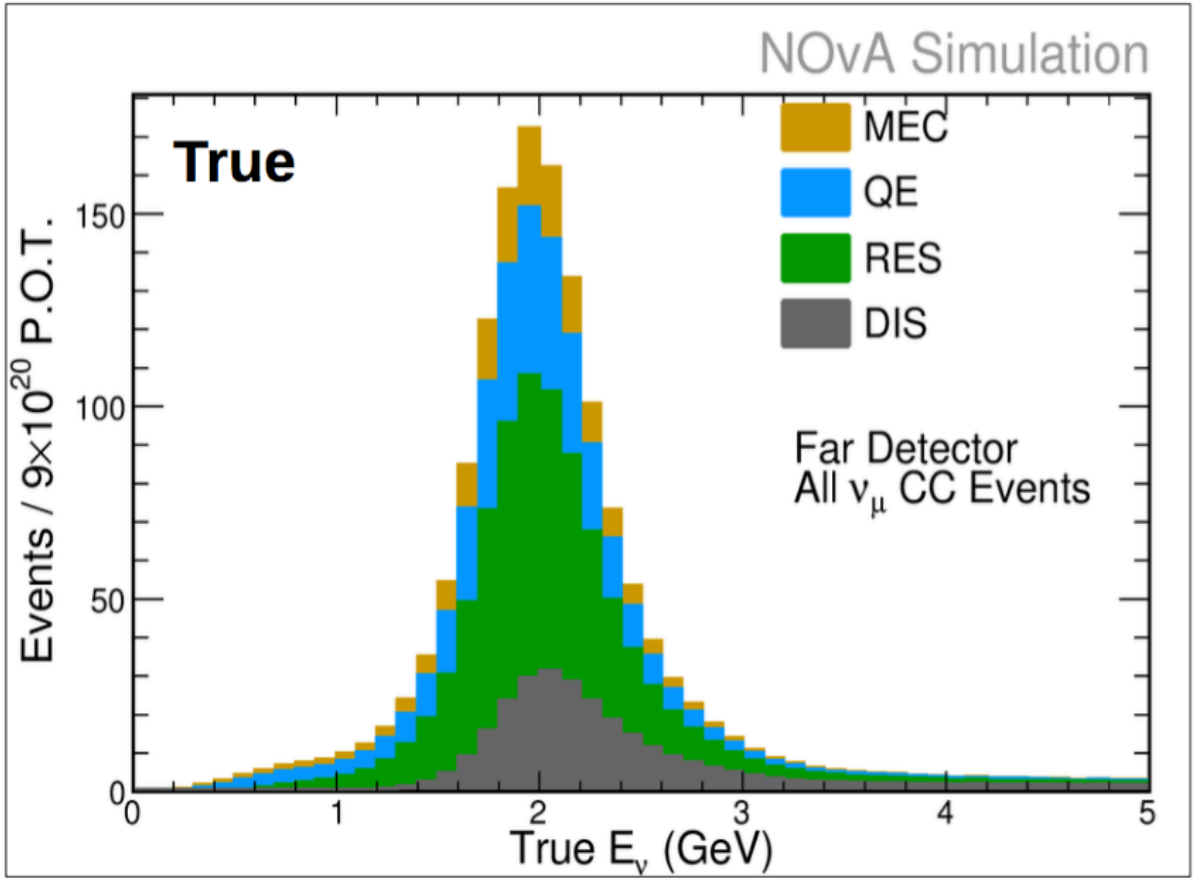


Why ν_μ–CC(π^0) Production?

Importance to Neutrino Oscillation Experiments

- CC(π) production gives significant rate in neutrino oscillation experiments
- ν_μ–CC(π^0) provides insight on ν_μ–NC(π^0) background to ν_e appearance
- Oscillations depend on L/E_ν and accurate E_ν estimation requires knowledge of final states
- Knowledge of CC(π) production constrains systematics for resonance and non-resonant models

Example: NOvA Neutrino Oscillation Experiment



Jeremy Wolcott - Tufts University, NuInt 2017

- **NOvA Leading Interaction is CC(1π)**
  - comes from RES and DIS
- **NOvA Detector Material**
  - Liquid Scintillator (CH)

My Measurement is ν_μ–CC$(1\pi^0)$
on Hydrocarbon (CH)
$1.5 < E_\nu < 20$ GeV

CC(1π) -- Important for DUNE too!

Why ν_μ–CC(π^0) Production?

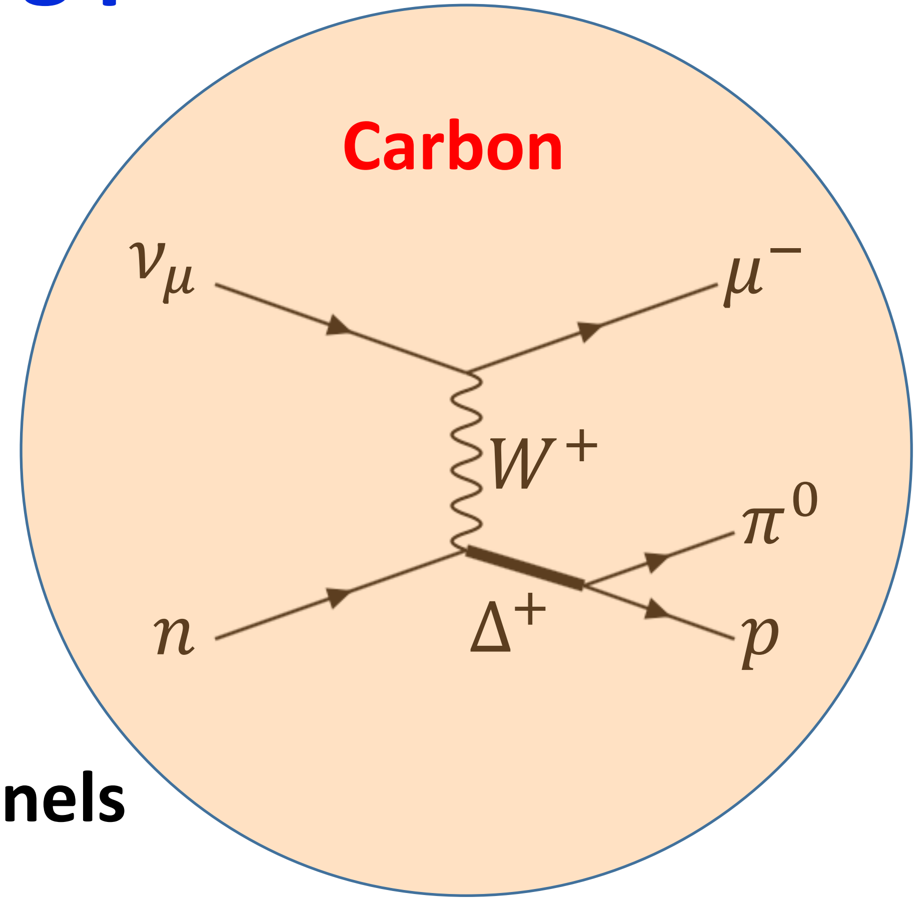
Interesting as a scattering process

- **CC(π^0) production rates for**
  - Δ^+(1232) and N* states
  - Non-resonant production

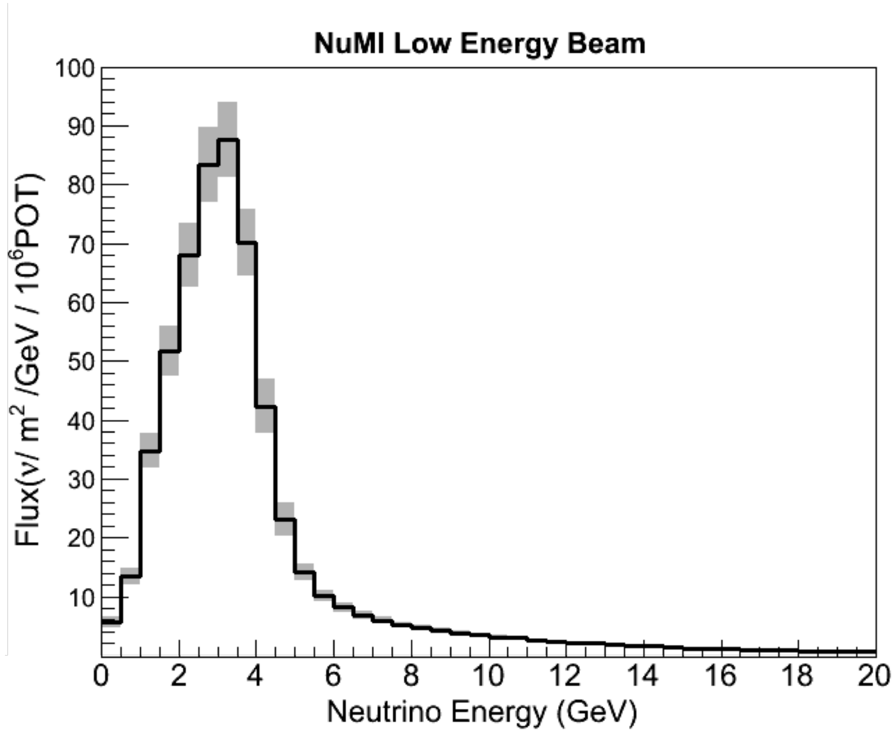
- **Physics of Δ^+(1232) rich sample**
  - Proton-Pion invariant mass
  - Δ^+(1232) polarization

- **Isospin relates CC(π^0) to other CC(π) channels**

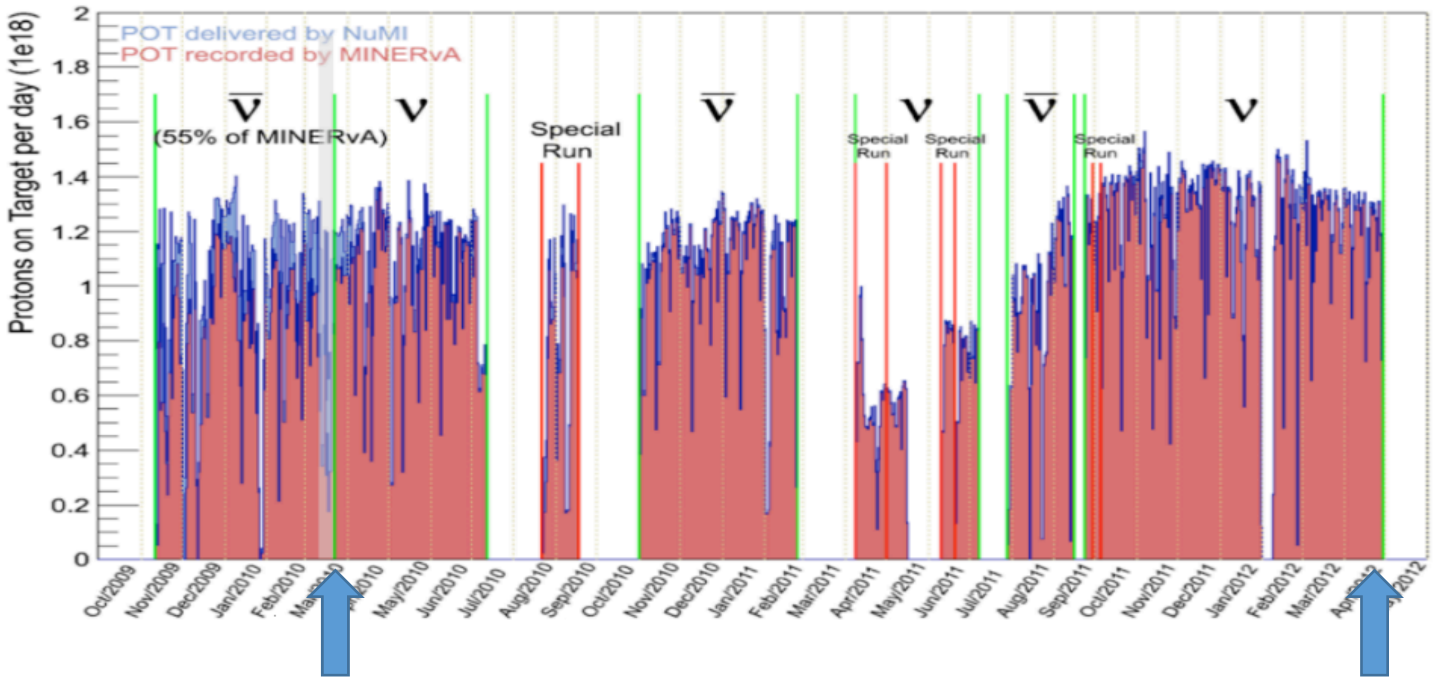
- **Pion Final State Interactions in Carbon**



Low Energy Neutrino Beam ($\langle E_\nu \rangle = 3.5$ GeV)

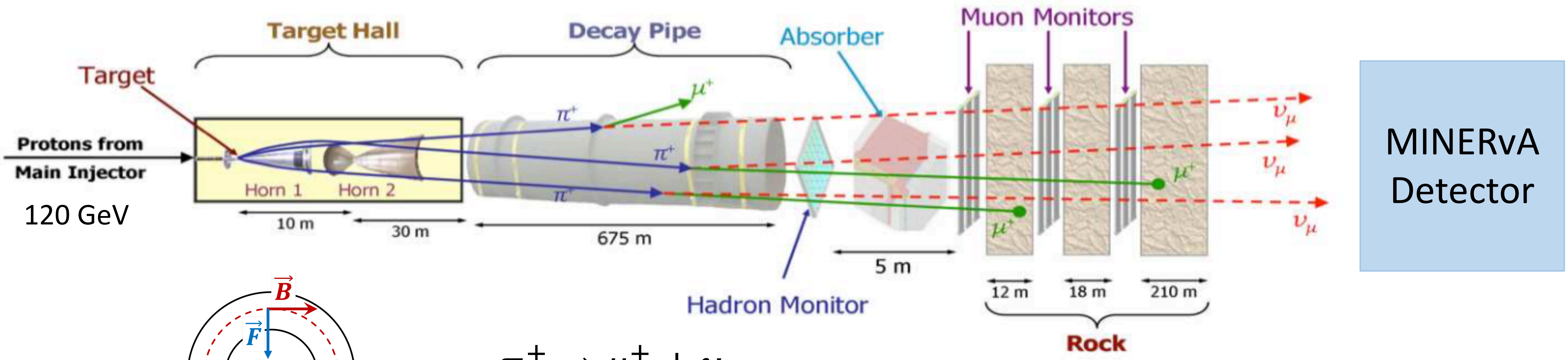


Phys. Rev. D 94, 092005 (2016)

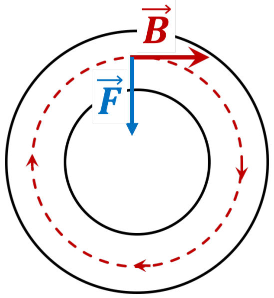


- **Data Collection:** March 2010 - April 2012
- **Protons on Target (P.O.T) Used:** 3.33e20

NuMI Neutrino Beam



120 GeV



Horns Focuses
Charged Particles (π^+, K^+)
to center of beam line

$$\pi^+ \rightarrow \mu^+ + \nu_\mu$$
$$K^+ \rightarrow \mu^+ + \nu_\mu$$

Thanks to Accelerator Division!

Nucl. Instrum. Meth. A806, 279 (2016).

MINERvA (Main INjector ExpeRiment: ν-A)

The MINERvA international collaboration consists of 65 particle and nuclear physicists from 21 institutions

- **Uses high-intensity beam to study neutrino and antineutrino reactions with different nuclei (Scintillator(CH), Carbon, Iron, Lead)**
- **Neutrino and Antineutrino induced CC Single Pion Production Cross Sections**
  - PRD **94**, 052005 (2016), PRD **92**, 092008 (2015), PLB **749,** 130-136 (2015)

Published $\nu_{\mu}\text{–CC}(\pi^{+})$

$\bar{\nu}_{\mu}\text{–CC}(\pi^{0})$ **Published**

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Published $\nu_{\mu}-\mathrm{CC}(\pi^{+})$

This Work $\nu_{\mu}-\mathrm{CC}(\pi^{0})$ $\bar{\nu}_{\mu}-\mathrm{CC}(\pi^{0})$ **Published**

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  - PRD **94**, 052005 (2016), PRD **92**, 092008 (2015), PLB **749**, 130-136 (2015)

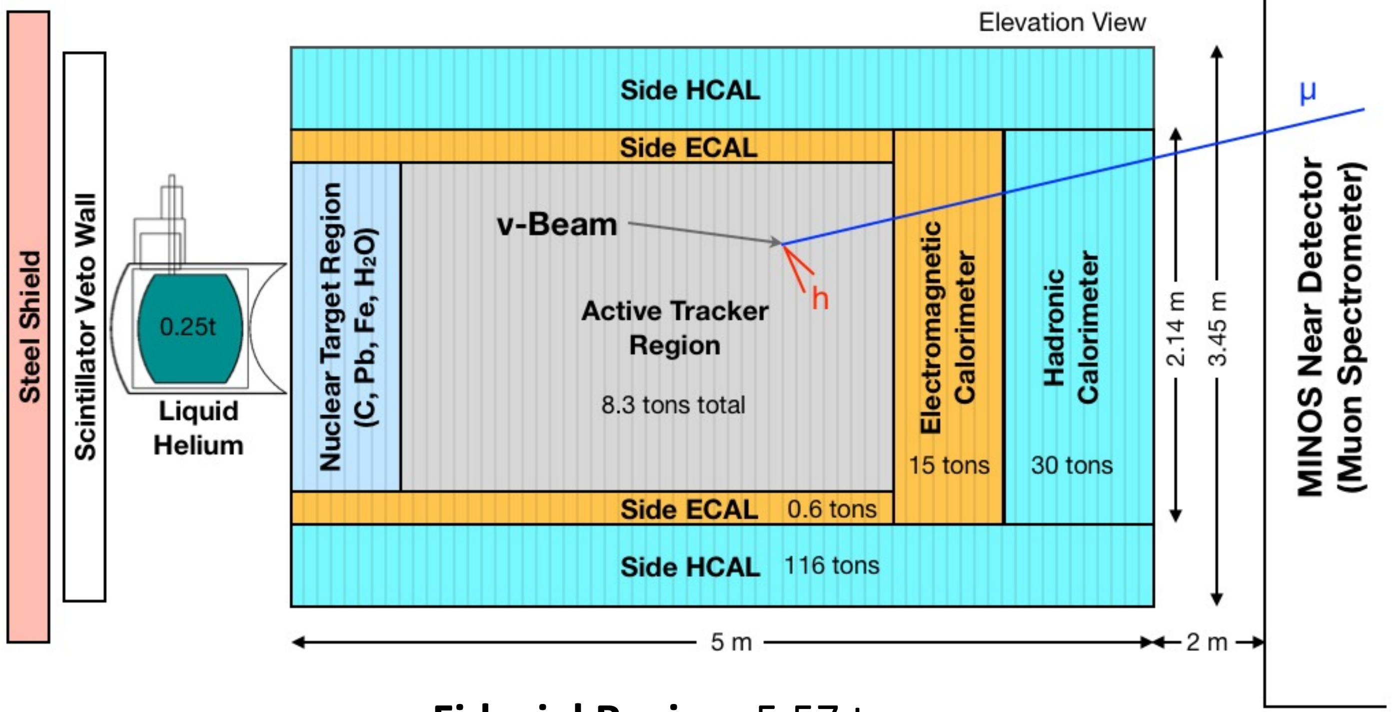
Published $\nu_{\mu}-CC(\pi^{+})$ $\bar{\nu}_{\mu}-CC(\pi^{-})$ **In Progress**

This Work $\nu_{\mu}-CC(\pi^{0})$ $\bar{\nu}_{\mu}-CC(\pi^{0})$ **Published**

Aim is to complete the set of dominant $CC(1\pi)$ channels.

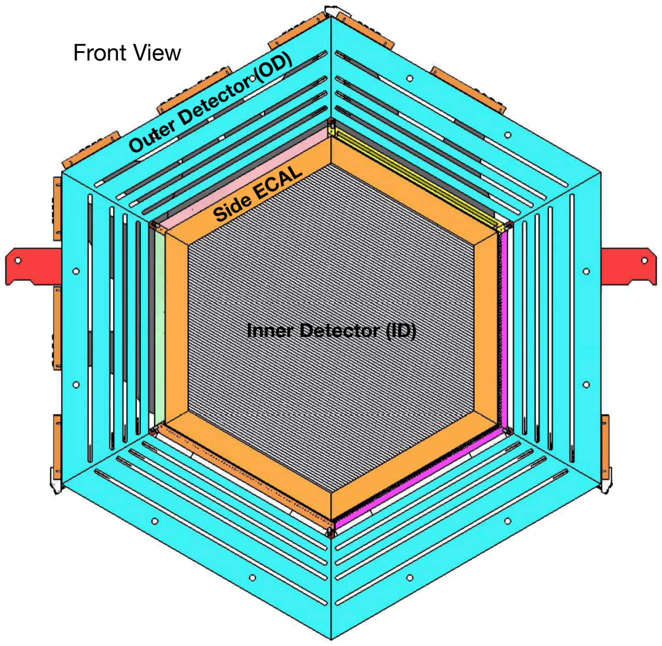
MINERvA Detector

Side View
Complete Detector



Fiducial Region: 5.57 tons

Front View
Single Module



Scintillator - Tracking
Lead - EM calorimetry
Steel - Hadronic calorimetry

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

Neutral Pion (π^0) detection inside MINERvA

- **Signal Reaction:** $\nu_\mu + \mathrm{CH} \rightarrow \mu^- + \pi^0 + \mathrm{nucleon(s)}$

  $\pi^0 \rightarrow 2\gamma$

- **Due to the 40 cm radiation length in scintillator, photons convert away from vertex**
  - Vertex activity is not included in showers

- **According to the simulation ≈80% of the showers convert inside the MINERvA detector**

Detector Region	Material	Radiation Length
Active Tracker	Scintillator (CH)	40 cm
ECAL	Lead	0.5 cm
HCAL	Steel	1.7 cm

Simulation Software

- **Neutrino Interactions are simulated via GENIE Event Generator v2.8.4 with Tuning**
- **Particle propagation through matter is simulated using GEANT4 v9.4.2**

	GENIE v2.8.4	NuWro v17.01
Resonance	Modified Rein-Sehgal	Adler, Δ(1232)
Non-Resonant	Scaled Bodek-Yang	Scaled Bodek-Yang
Nuclear Model	Relativistic Fermi Gas	Local Fermi Gas
FSI Model	Effective Cascade	Salcedo-Oset, Full Cascade

- **Resonance Models**
  - **GENIE:** Rein-Sehgal, but neglects muon mass and does not include resonance interference
  - **NuWro:** Explicit Δ(1232) with background added incoherently as a fraction of DIS.

Refinements to GENIE v2.8.4

- **Recent analyses show that GENIE v2.8.4 has some shortcomings**
  - **$\Delta^{++}(1232)$ anisotropy is included**
    - Phys. Rev. D 92, 092008 (2015).
  - **Down-weighted Non-Resonant pion production based on fits to $\nu_\mu D_2$ bubble chamber data**
  - **We updated/reduced model systematics in GENIE based on current information**
    - Eur. Phys. J. C 76, 8, 474 (2016).
  - **We added an additional sample of CCQE-like two-particle two-hole (2p-2h) events**
    - Valencia model, Phys. Rev. D 88, 113007 (2013).
    - MINERvA-Tuned, Phys. Rev. Lett. 116, 071802 (2016).

Signal Definition

$$\nu_{\mu} + \mathrm{CH} \rightarrow \mu^{-} + \pi^{0} + \mathrm{nucleon(s)}$$

$$(\nu_{\mu} + \{n\}_{C} \rightarrow \mu^{-} + \pi^{0} + p)$$

1. CC – Muon Neutrino Interaction
2. Vertex inside Fiducial Volume
3. Muon Angle is less than 25 degrees

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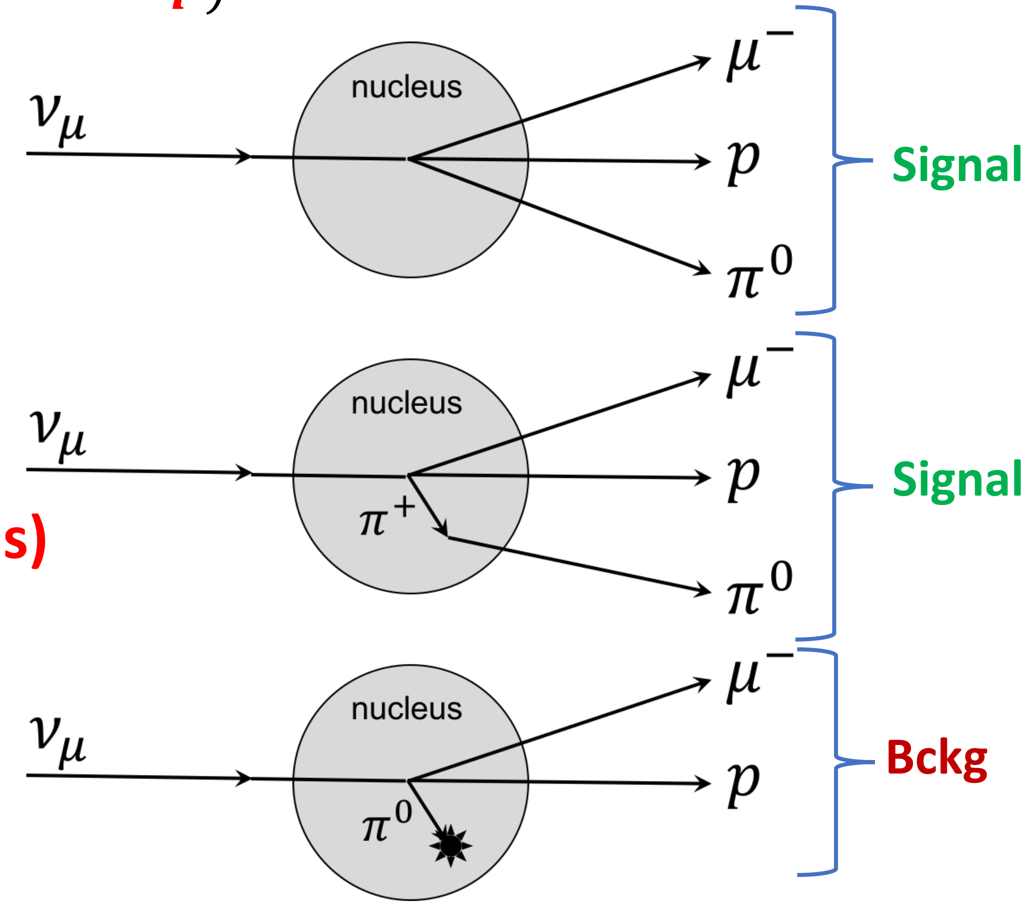
3. Muon Angle is less than 25 degrees

4. 1 π^0 out-of-nucleus
5. No other particles out-of-nucleus (except nucleons)



Signal Definition

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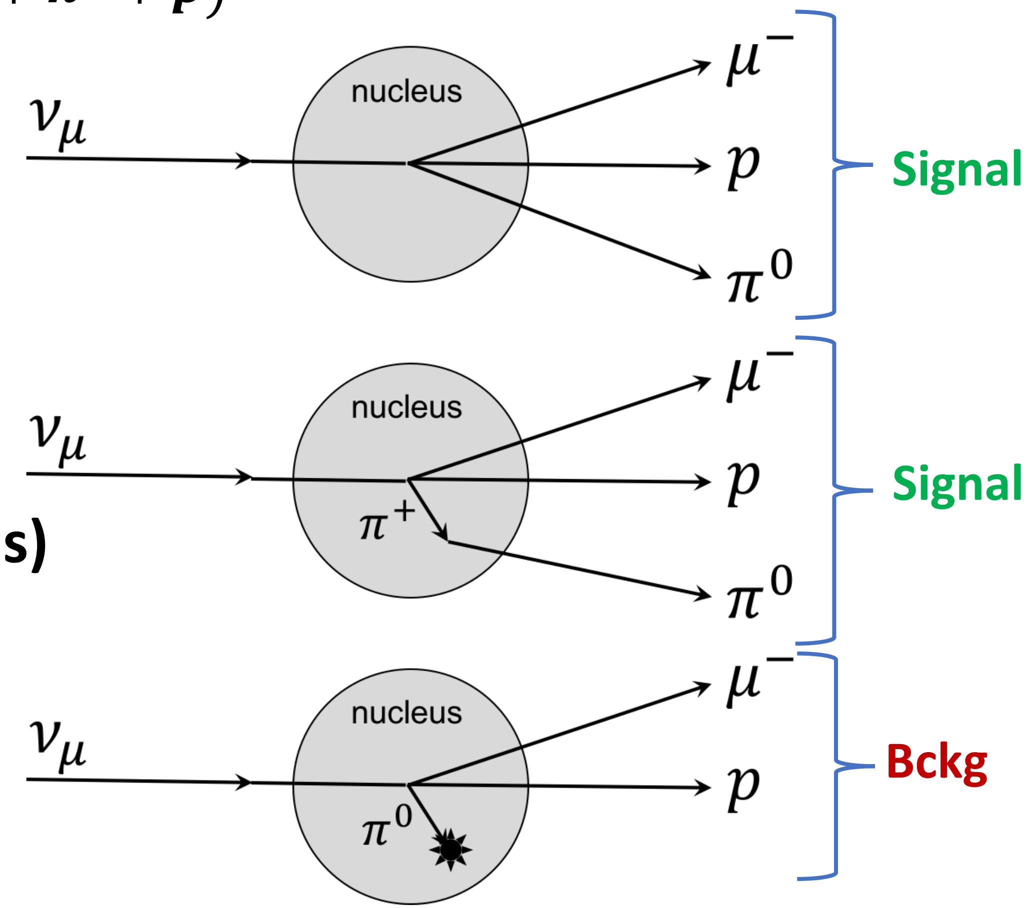
$$(\nu_\mu + \{n\}_C \rightarrow \mu^- + \pi^0 + p)$$

1. CC – Muon Neutrino Interaction
2. Vertex inside Fiducial Volume
3. Muon Angle is less than 25 degrees

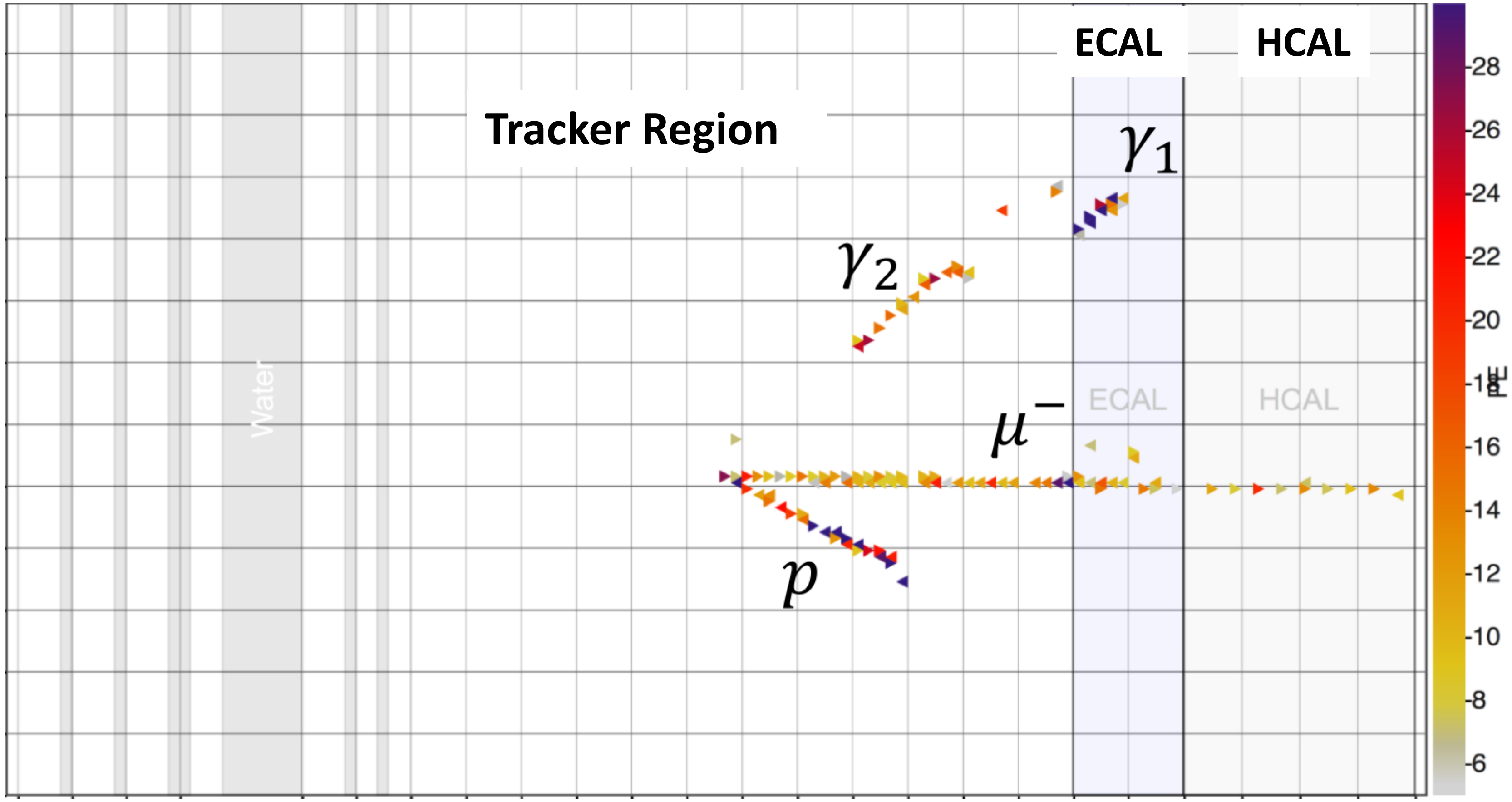
4. 1 π^0 out-of-nucleus
5. No other particles out-of-nucleus (except nucleons)

6. Incoming Neutrino Energy is limited [1.5, 20] GeV
7. Hadronic Invariant Mass W_{exp} less than 1.8 GeV



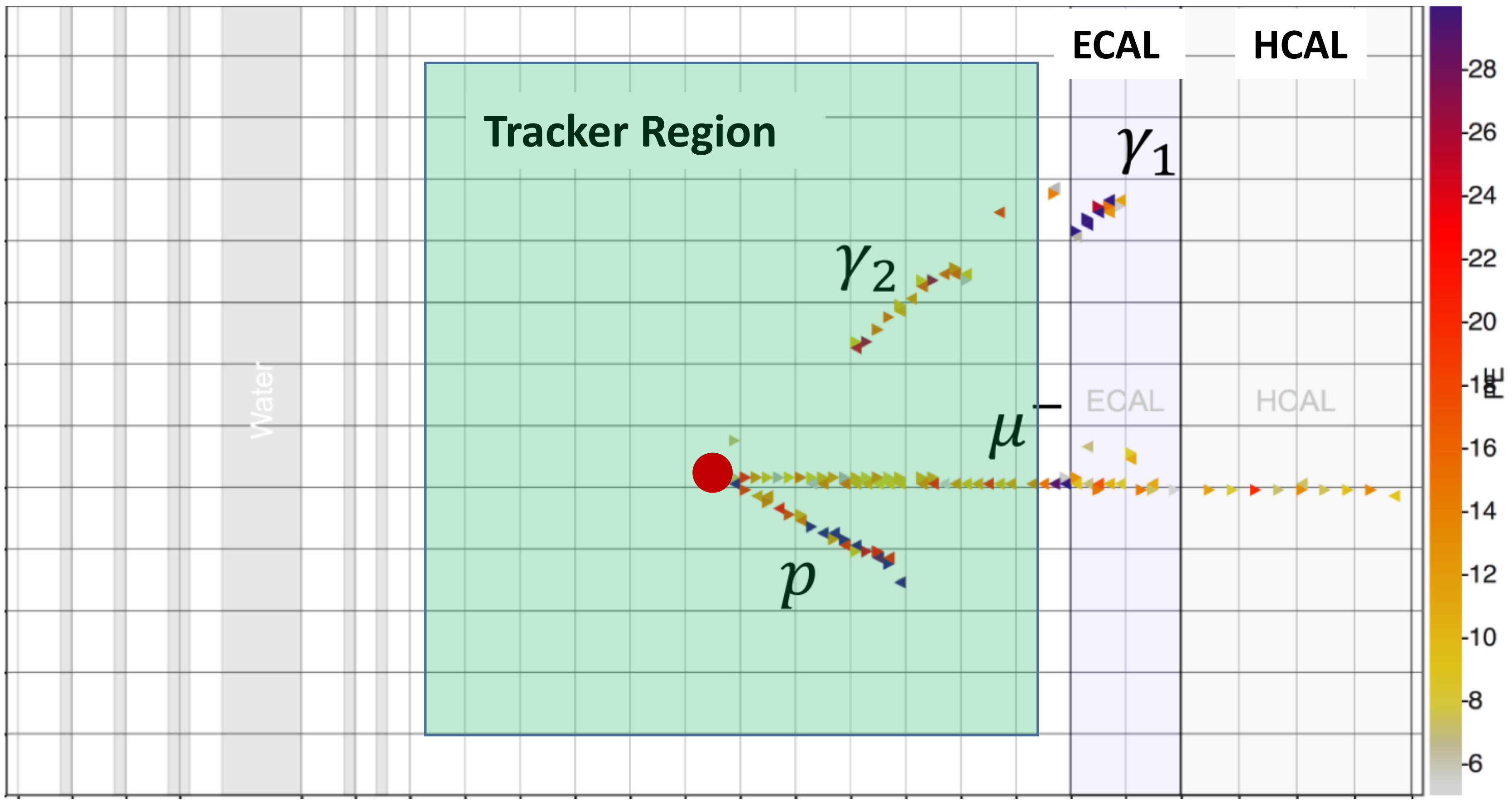
Signal Candidate in Data

- **Data Event:** 2021/23/449
  - $E_{\gamma 1} = 618$ MeV $E_{\gamma 2} = 140$ MeV



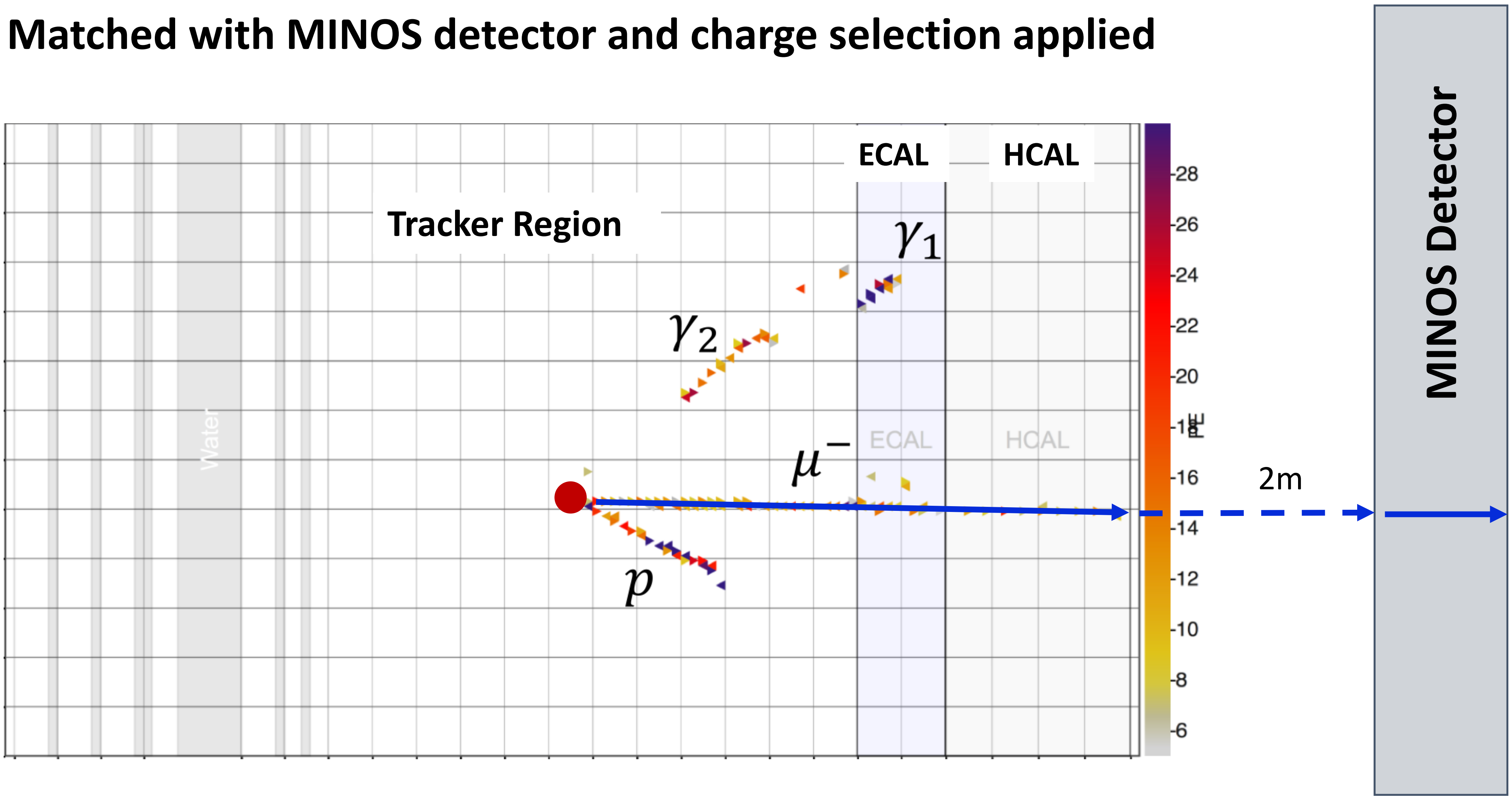
Event Selections: Vertex

1. Event Vertex inside fiducial volume of the MINERvA Detector



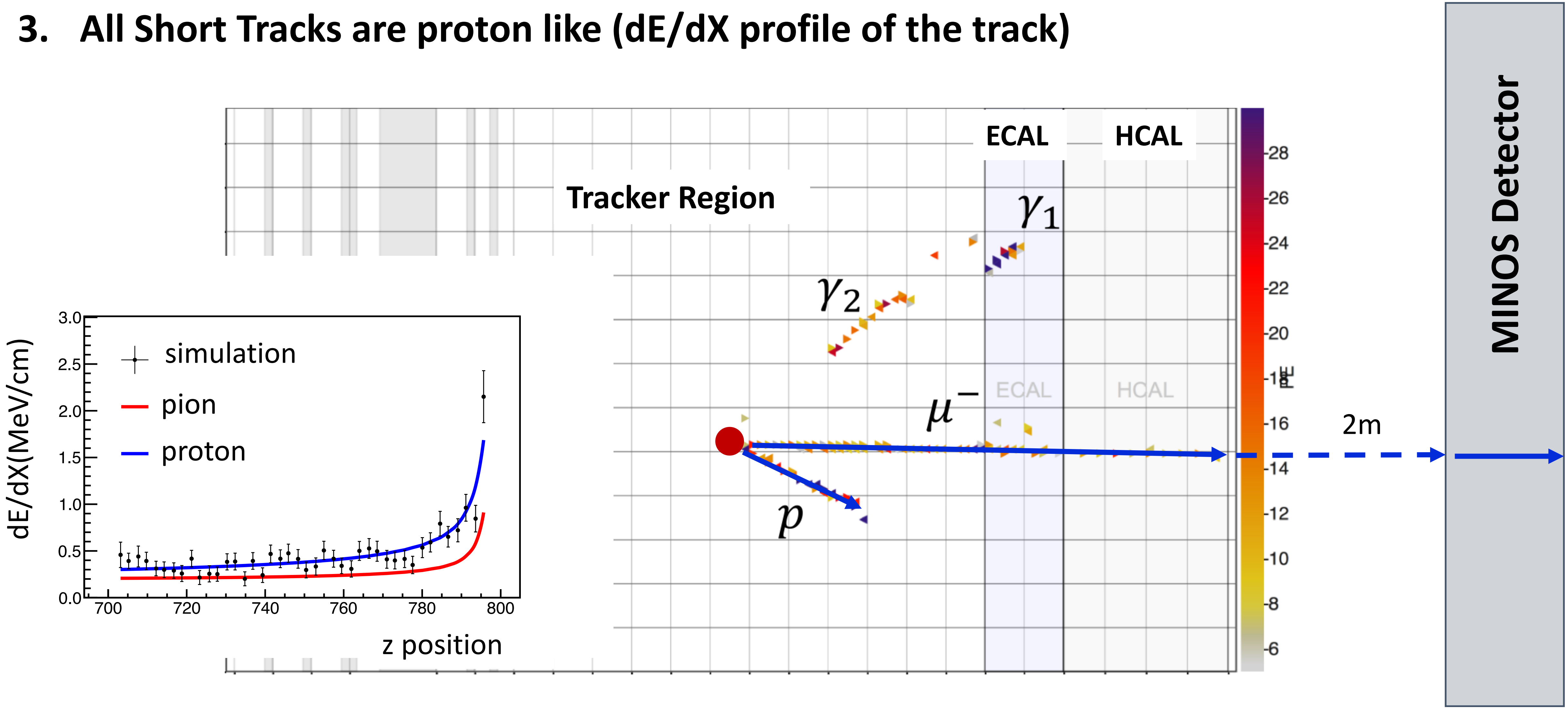
Event Selections: Muon Track

2. **Muon is Matched with MINOS detector and charge selection applied**



Event Selections: Short Tracks

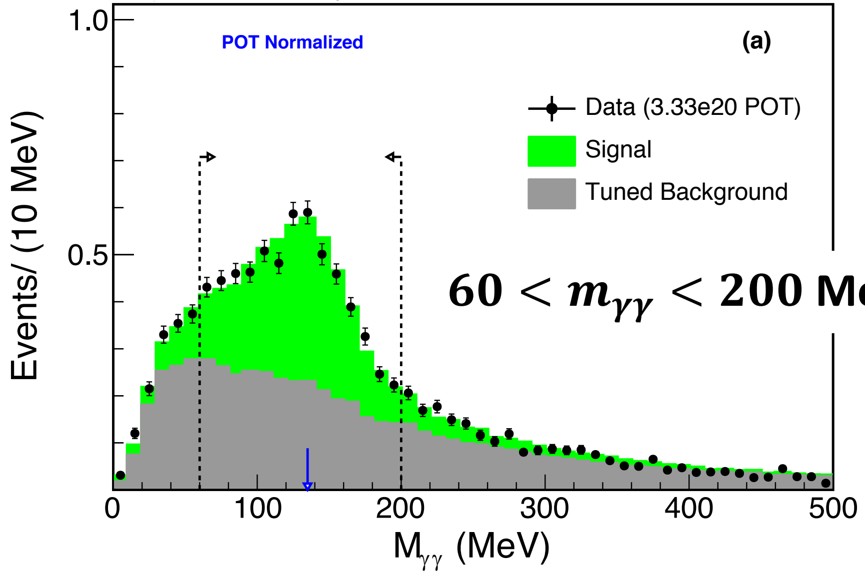
3. All Short Tracks are proton like (dE/dX profile of the track)



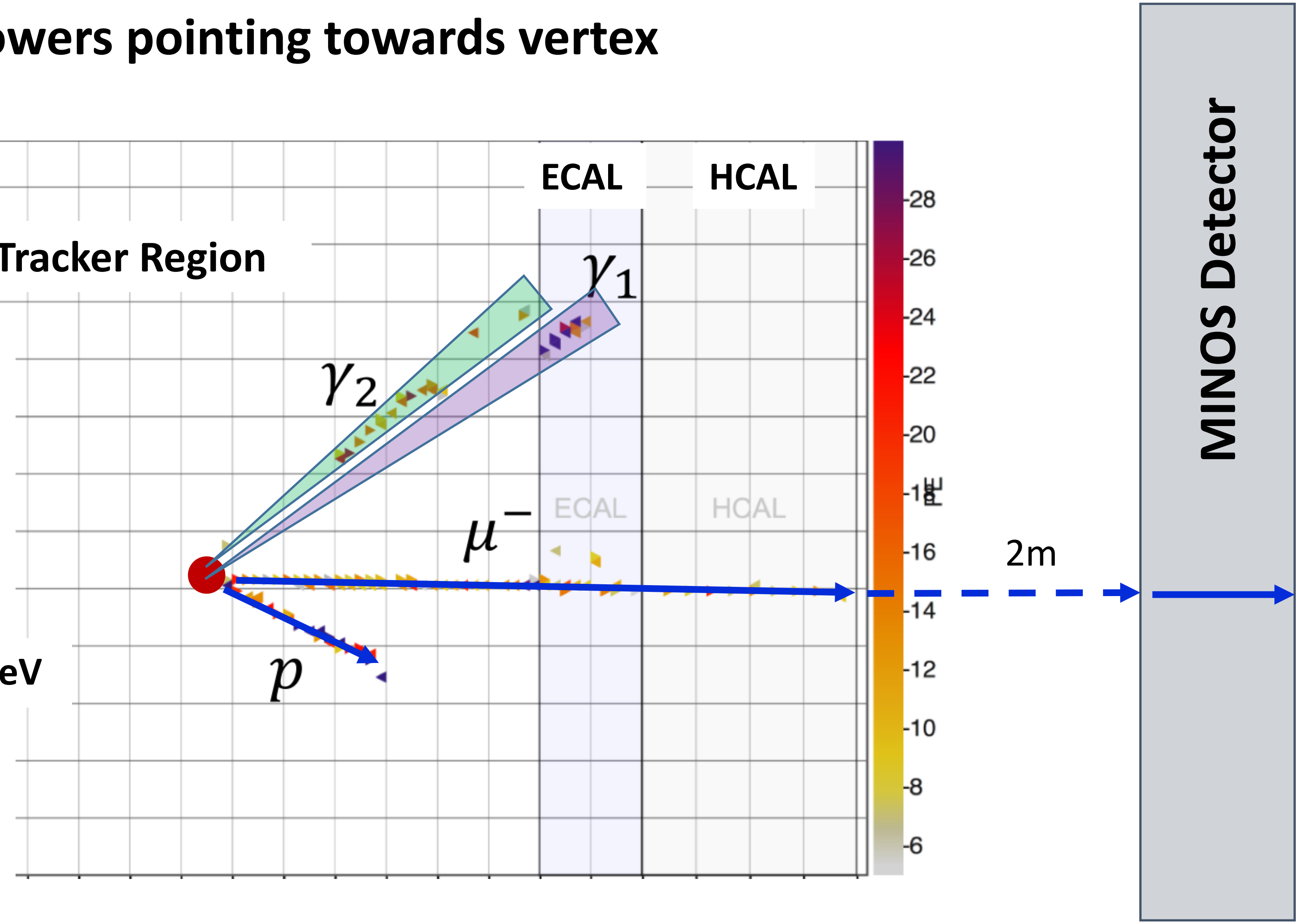
Event Selections: Distant Showers

4. **Find two distant (>14cm) showers pointing towards vertex**

$$m_{\gamma\gamma} = \sqrt{2E_{\gamma_1}E_{\gamma_2}(1-\cos\theta_{\gamma\gamma})}$$



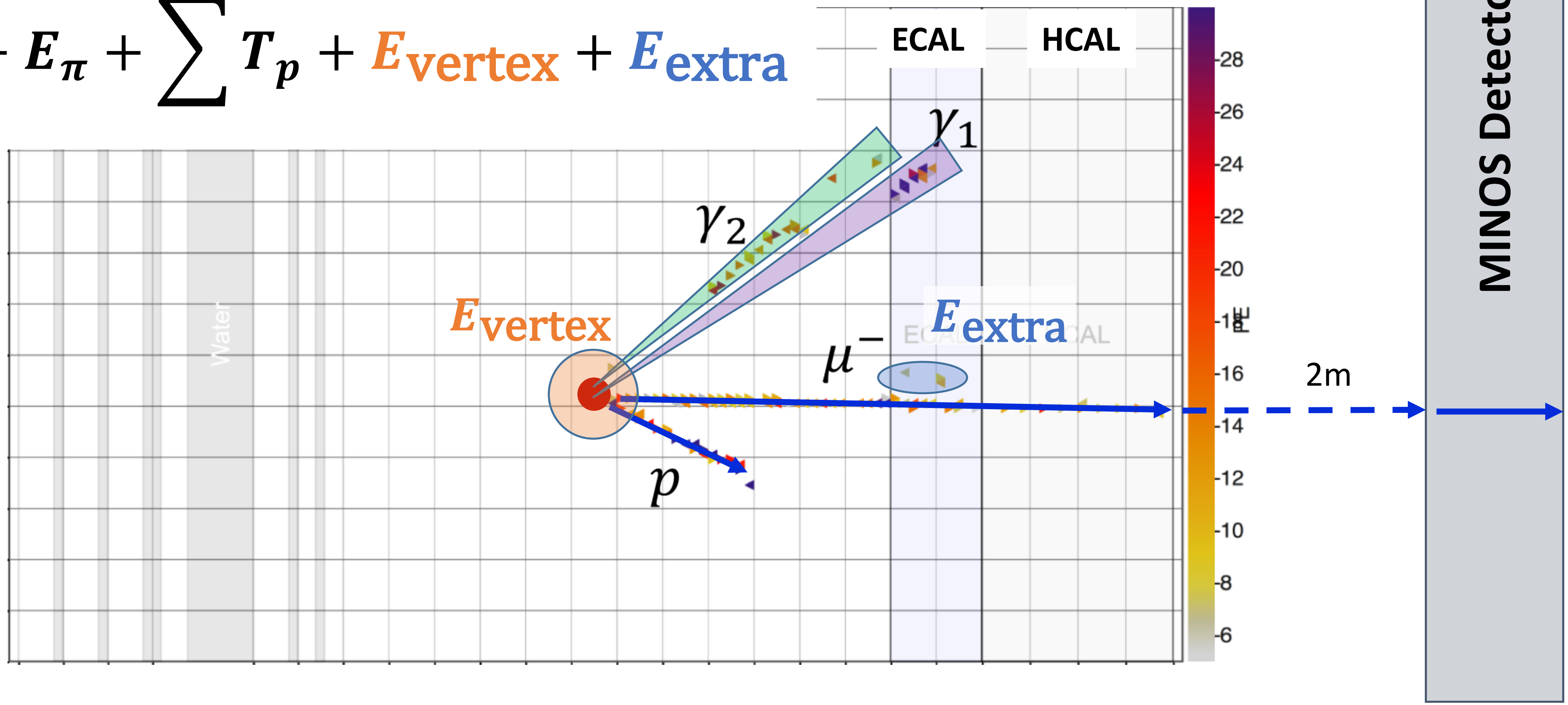
$60 < m_{\gamma\gamma} < 200$ MeV



Event Selections: Kinematics Selection

5. Estimate Neutrino Energy using all final state particles + vertex & extra energy

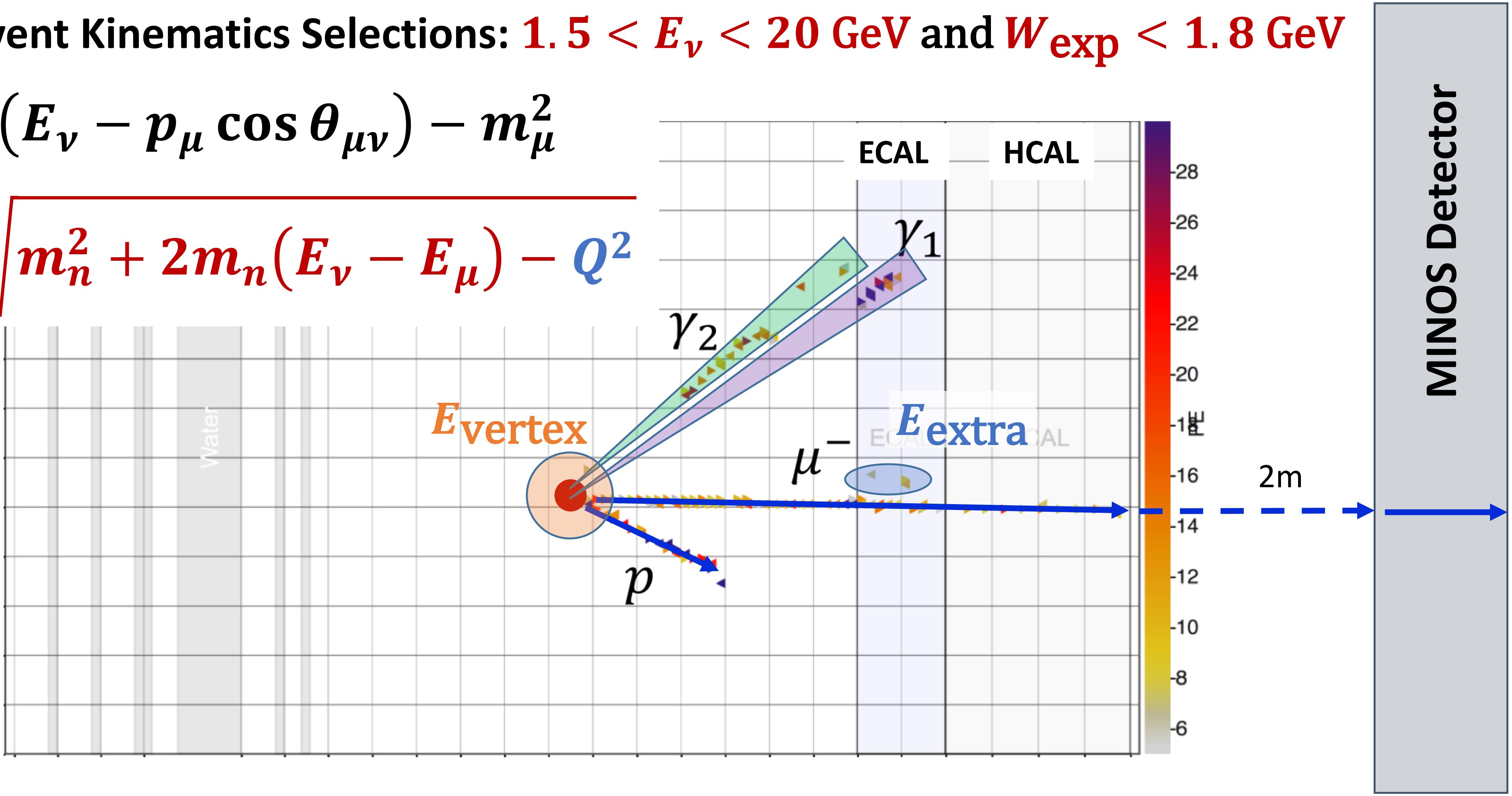
$$E_\nu = E_\mu + E_\pi + \sum T_p + E_{vertex} + E_{extra}$$



Event Selections: Kinematics Selection

6. Apply Event Kinematics Selections: $1.5 < E_\nu < 20\ \mathrm{GeV}$ and $W_{\mathrm{exp}} < 1.8\ \mathrm{GeV}$

- $Q^2 = 2E_\nu(E_\nu - p_\mu \cos\theta_{\mu\nu}) - m_\mu^2$
- $W_{\mathrm{exp}} = \sqrt{m_n^2 + 2m_n(E_\nu - E_\mu) - Q^2}$



Event Selections: Kinematics Selection

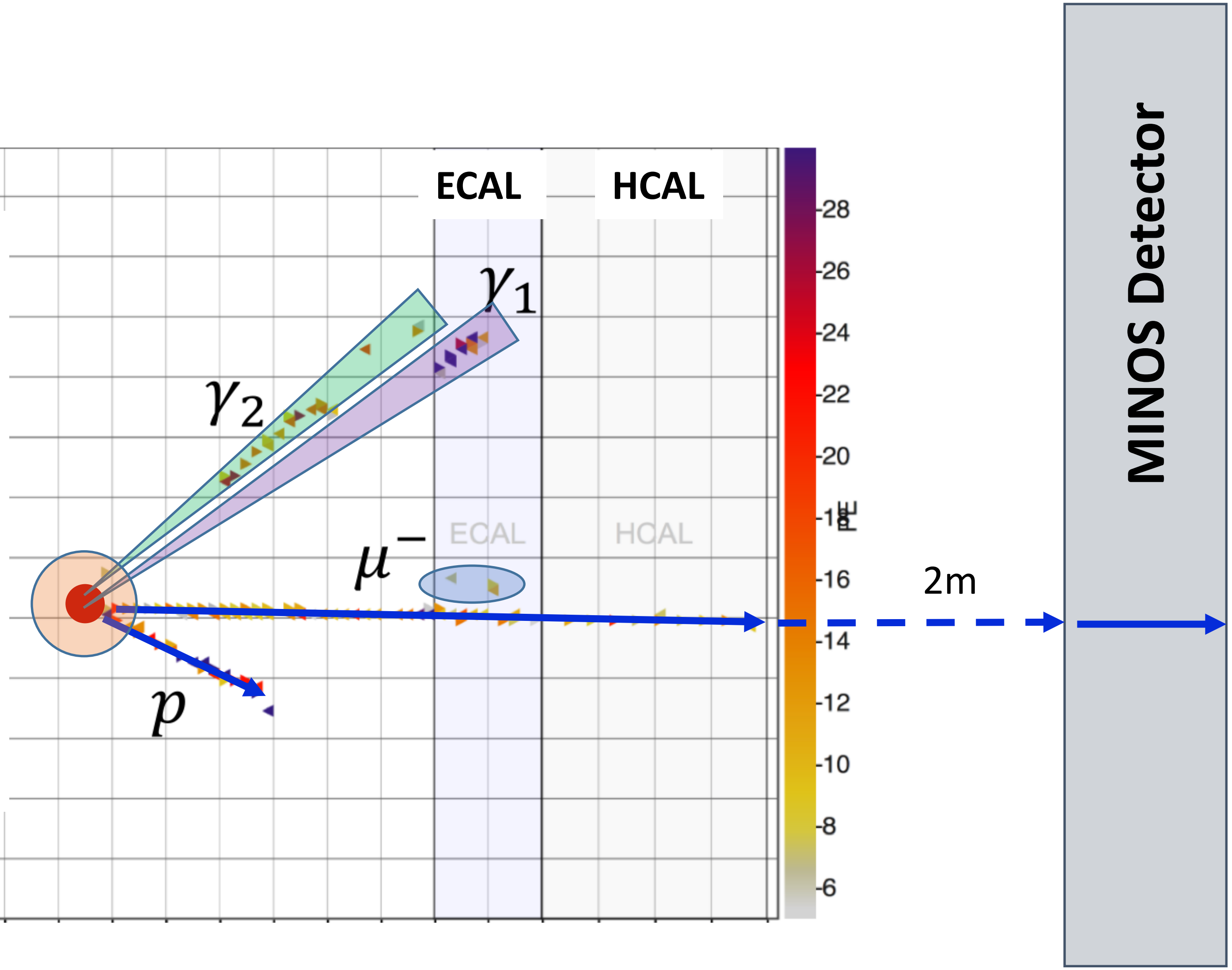
7. **Final Analysis Efficiency & Purity**

Analysis Efficiency & Purity

$$\text{Efficiency} = \frac{\text{Selected Signal}}{\text{All Signal}} = 8.4\%$$

$$\text{Purity} = \frac{\text{Selected Signal}}{\text{All Selected}} = 51.0\%$$

N(Data) in Final Sample = 6110

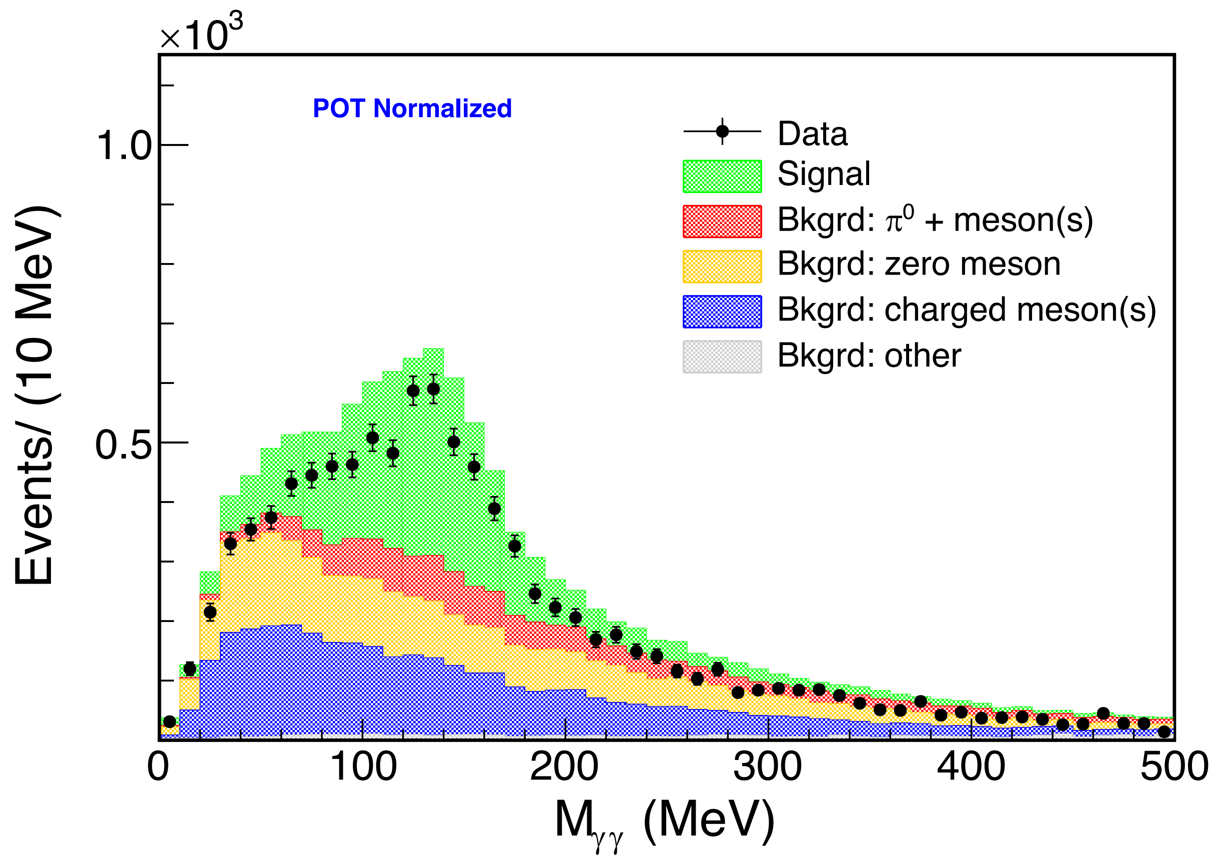


Data vs Simulation w/o Background Constraint

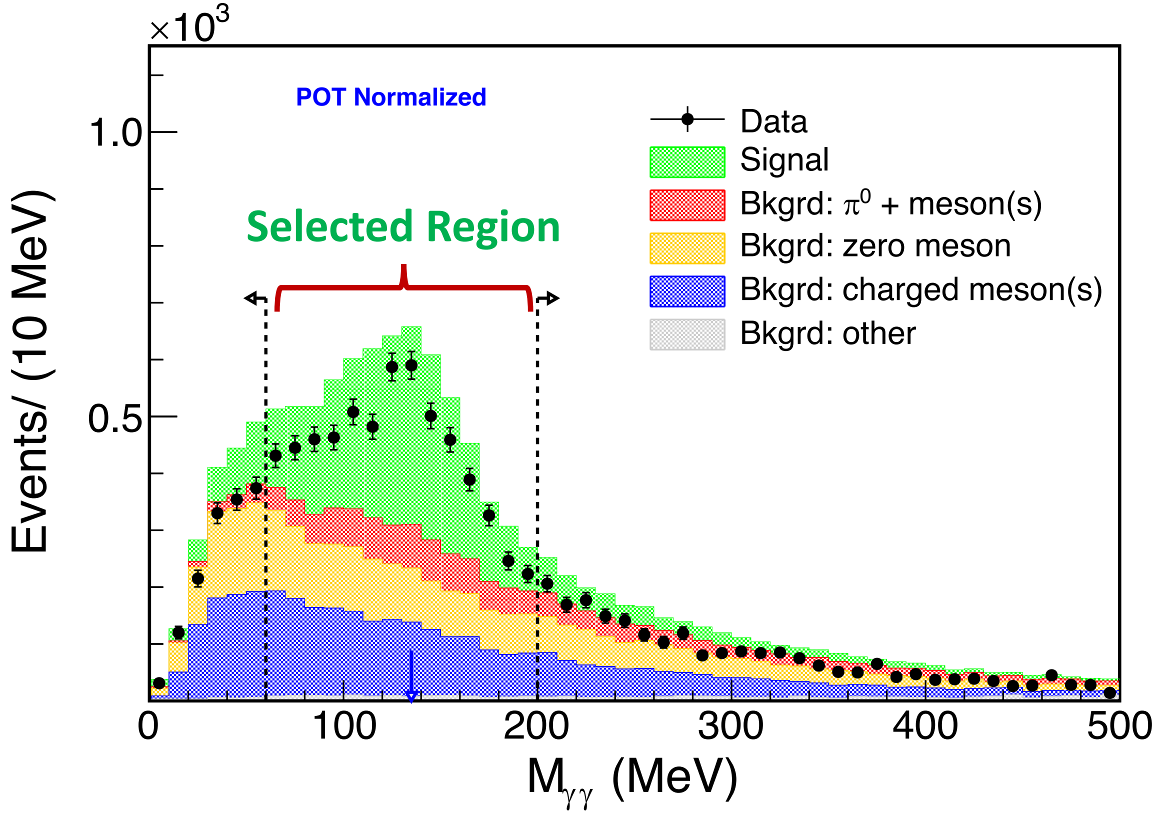
- **Data Events**

- **Simulation Prediction**
  - **Signal: ν_μ–CC(π^0)**

  - **Background with π^0**
  - **Background zero meson (QE Like)**
  - **Background with charged meson(s)**
  - **Background Other $(\bar{\nu}_\mu)$**



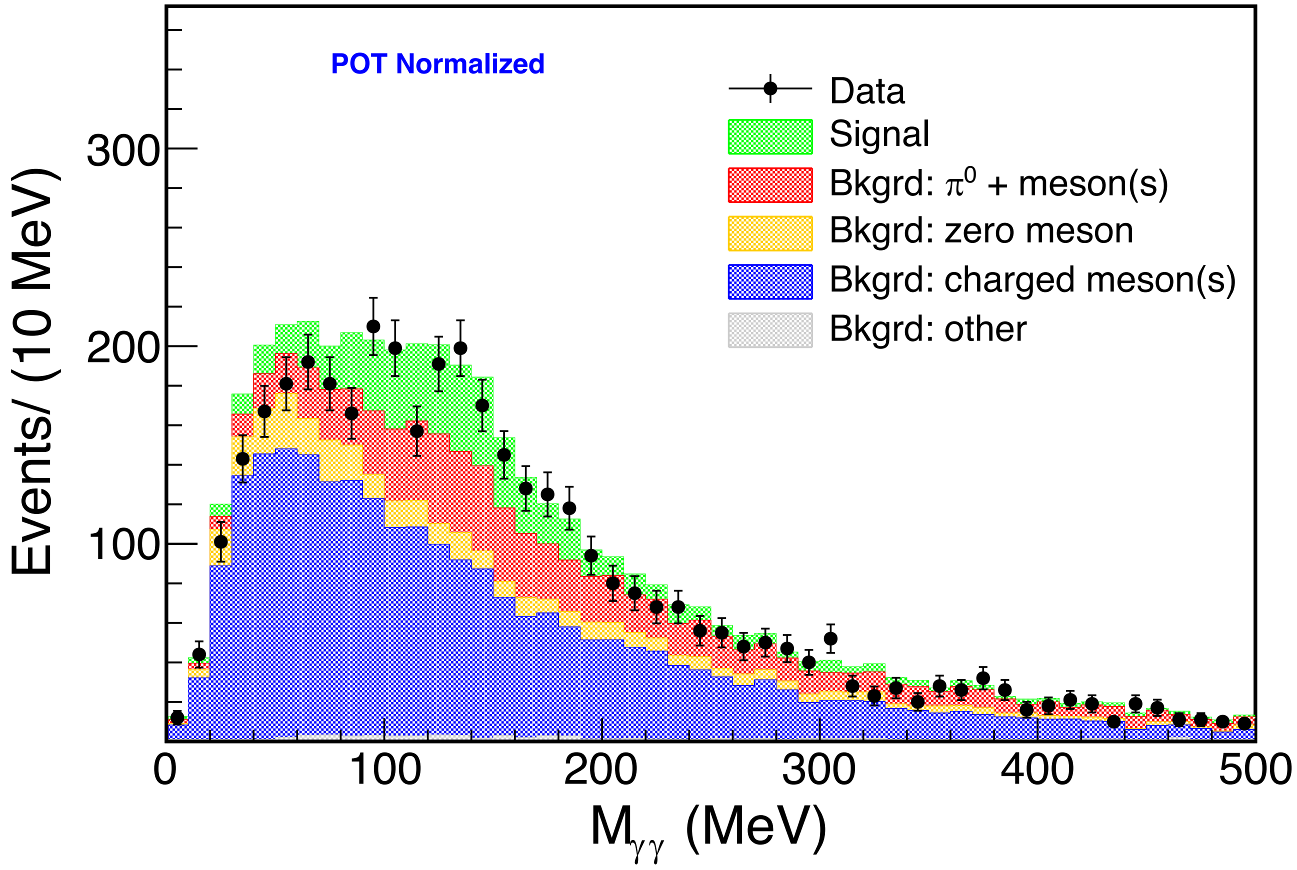
Background Constraint using Side Bands (4 in Total)



- **Side Bands are specific sub-samples**
  - Rejected during event selections
  - Contains mostly background Events
- **Two Side Bands on π^0 Invariant Mass**
  - Events with $m_{\gamma\gamma} < 60$ MeV
  - Events with $m_{\gamma\gamma} > 200$ MeV
- **Constrain Background Normalizations**
  - **Background with π^0**
  - **Background zero meson (QE Like)**
  - **Background with charged meson(s)**

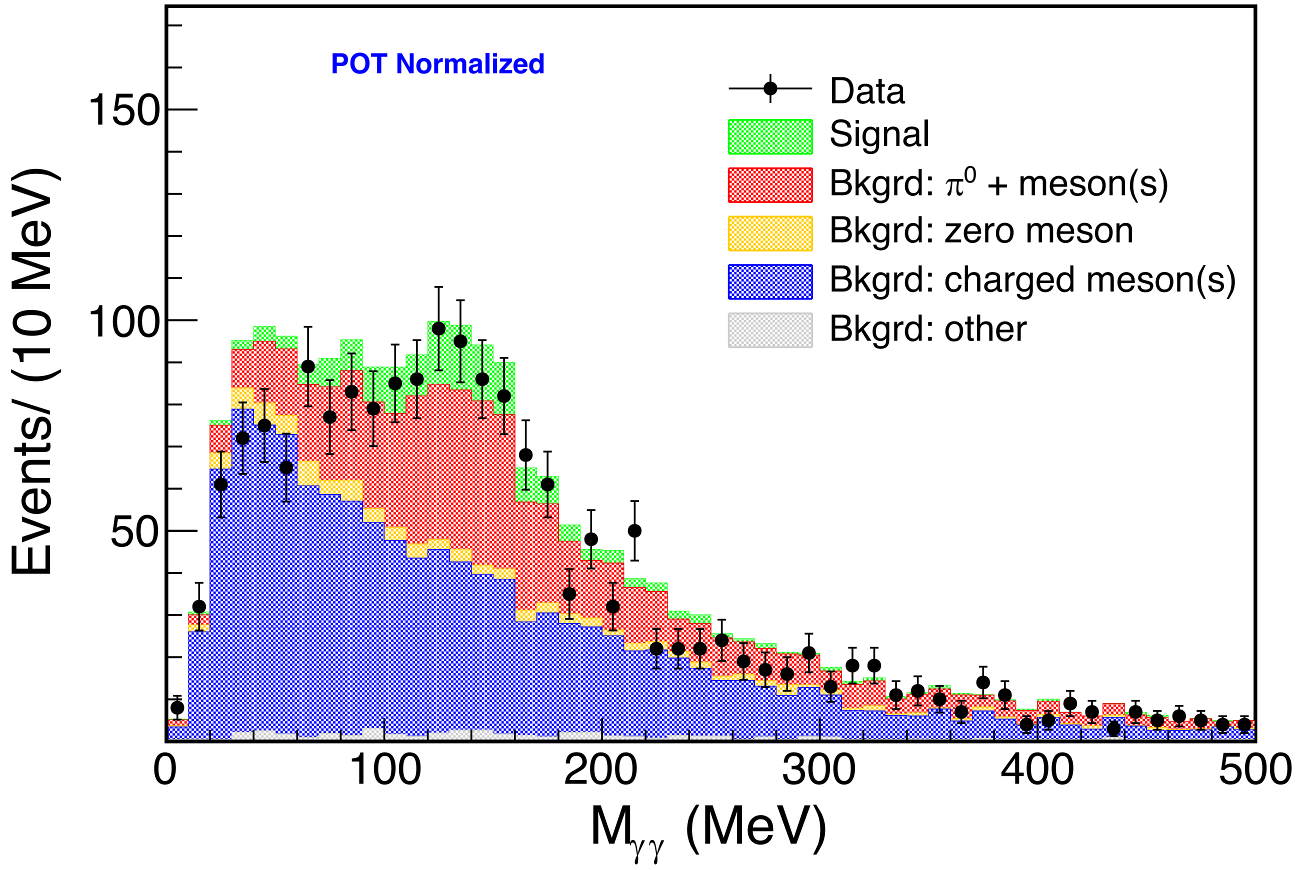
3rd Side Band: Low Proton Score

- Events with a short track whose dE/dX profile is similar to $\pi^{\pm}$



4^{th} Side Band: Michel Electron

- Stopping π^+ in the detector decays to a μ^+ and ν_μ
- This μ^+ decays to a positron and two neutrinos



Background Constraint using 4 Side Bands

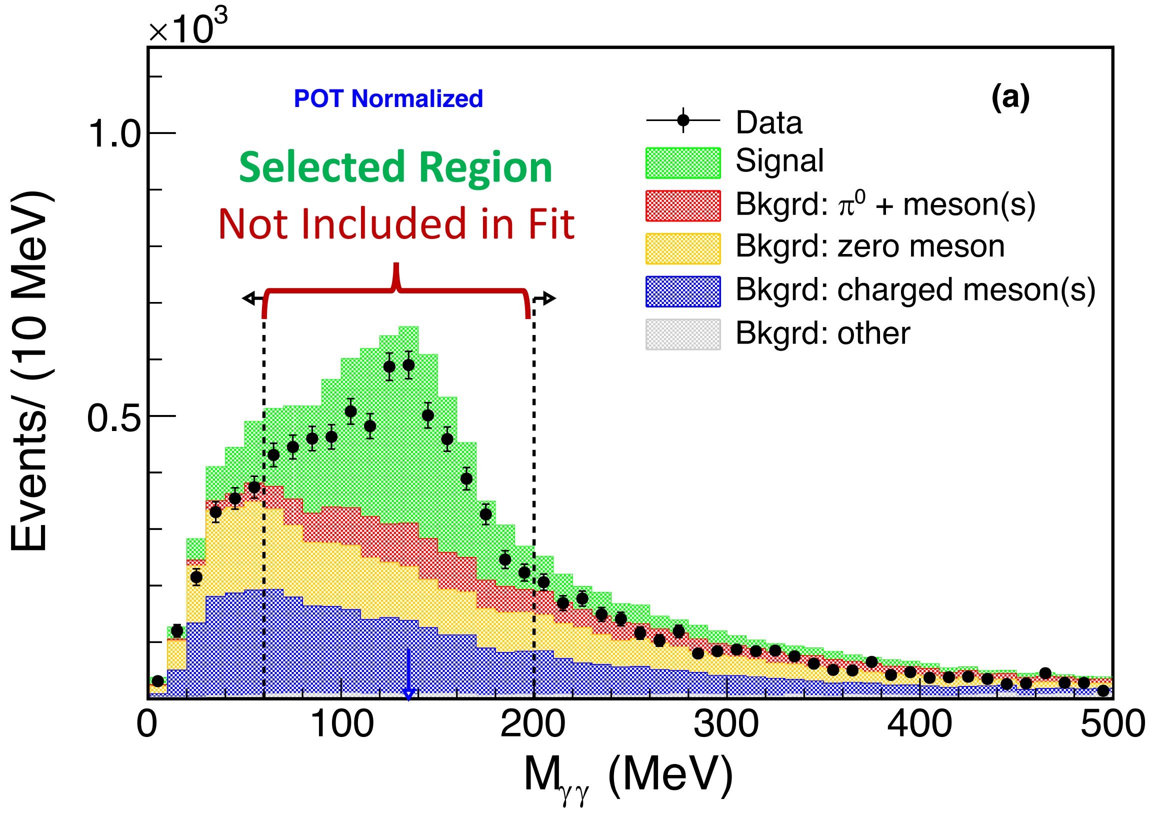
1. **Low Invariant Mass:** $m_{\gamma\gamma} < 60\ \mathrm{MeV}$
2. **High Invariant Mass:** $m_{\gamma\gamma} > 200\ \mathrm{MeV}$
3. **Low Proton Score**
4. **Michel Electron Detected**

Minimize the global χ^2
in all side bands at once

Side Band Fitting – Before and After

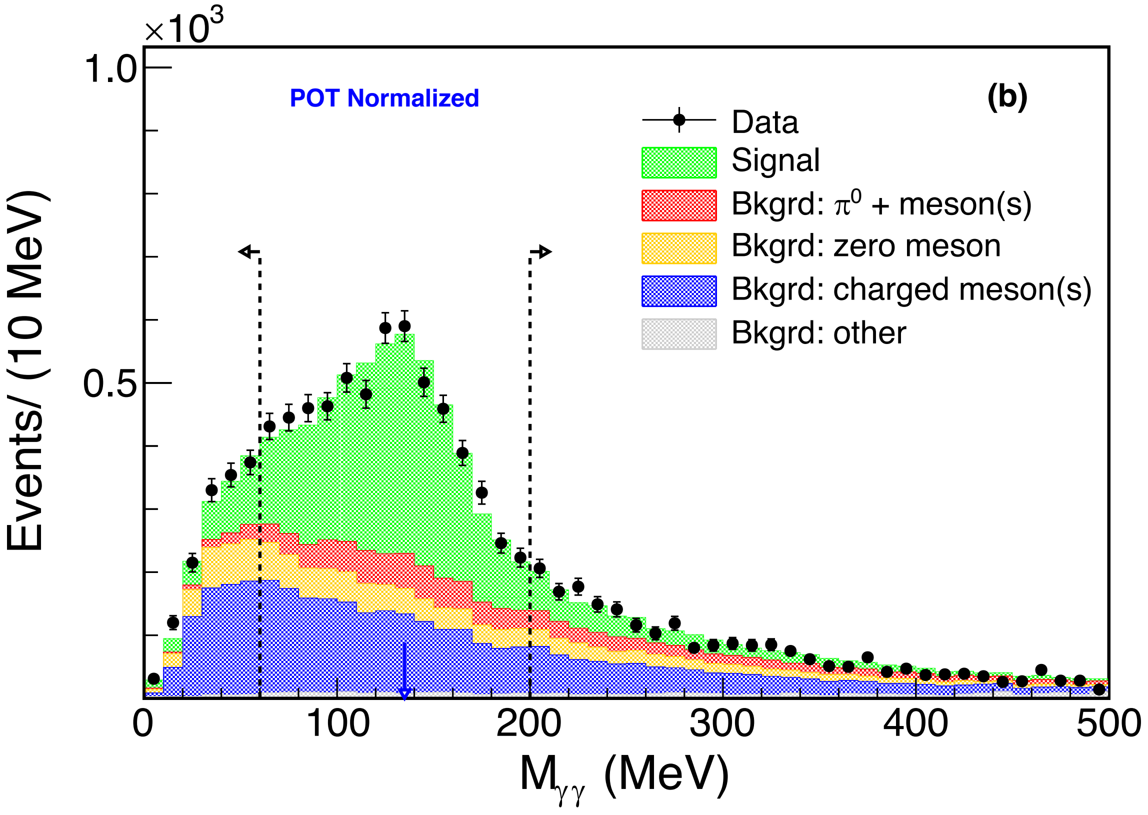
Before Fit

$\chi^2/dof = 13.40$



After Fit

$\chi^2/dof = 1.80$



Cross Section Calculation

$$\left(\frac{d\sigma}{dP_\mu}\right)_i = \frac{1}{\Phi_\nu T_N}\frac{1}{(\Delta P_\mu)_i}\frac{\sum_j U_{ij}\left(\boldsymbol{N_j^{data}} - N_j^{bckg}\right)}{\epsilon_i}$$

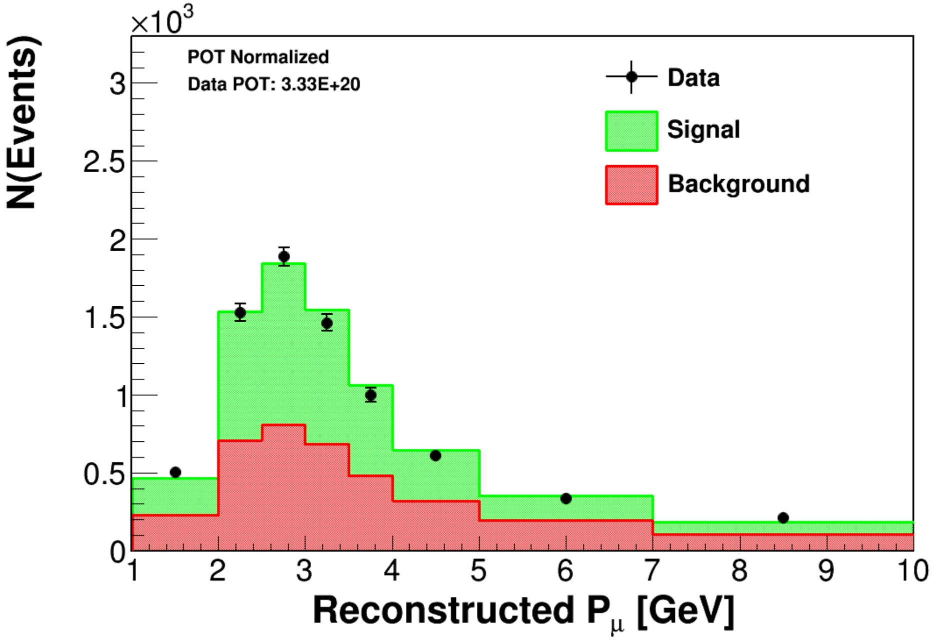
1. **Obtain Data Distribution** after the event selections

Cross Section Calculation

$$\left(\frac{d\sigma}{dP_\mu}\right)_i = \frac{1}{\Phi_\nu T_N}\frac{1}{(\Delta P_\mu)_i}\frac{\sum_j U_{ij}\left(N_j^{data} - \boldsymbol{N_j^{bckg}}\right)}{\epsilon_i}$$

1. **Obtain Data Distribution** after the event selections

2. **Subtract Background**



Cross Section Calculation

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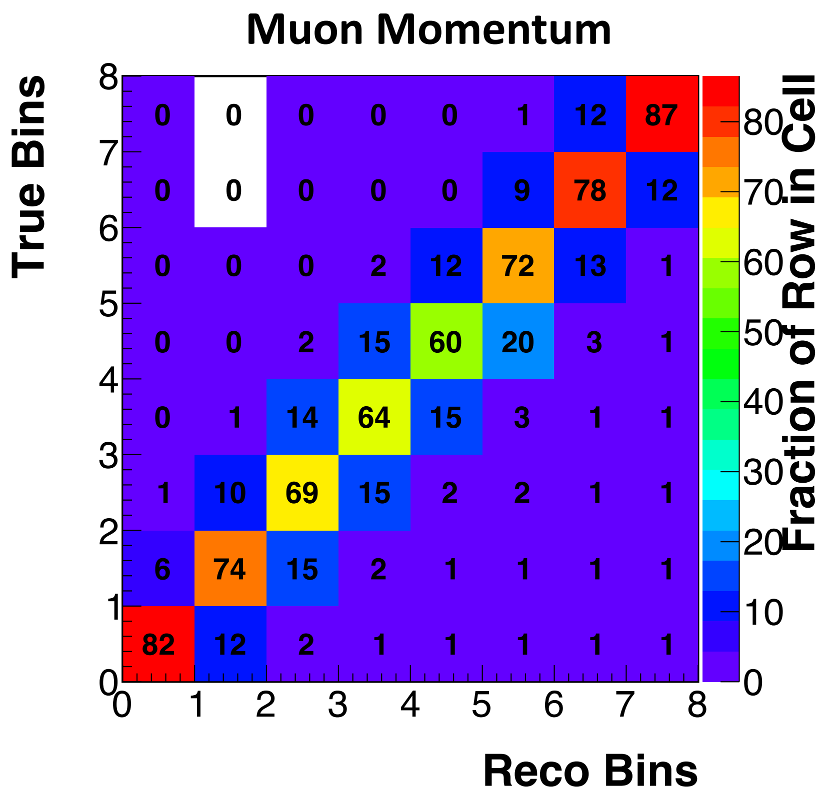
1. **Obtain Data Distribution** after the event selections

2. **Subtract Background**

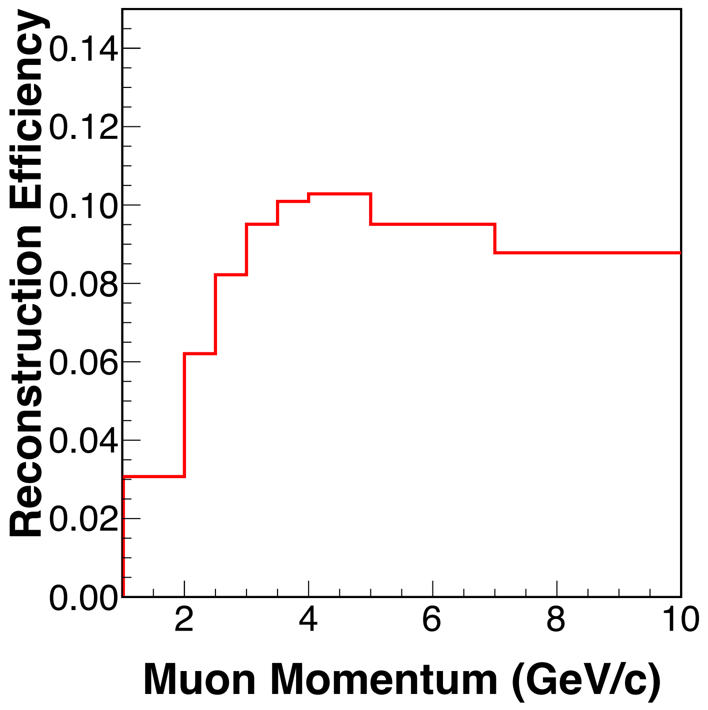
3. **Unfold Data** to remove reconstruction effects



Cross Section Calculation

$$\left(\frac{d\sigma}{dP_\mu}\right)_i = \frac{1}{\Phi_\nu T_N} \frac{1}{(\Delta P_\mu)_i} \frac{\sum_j U_{ij}\left(N_j^{data} - N_j^{bckg}\right)}{\epsilon_i}$$

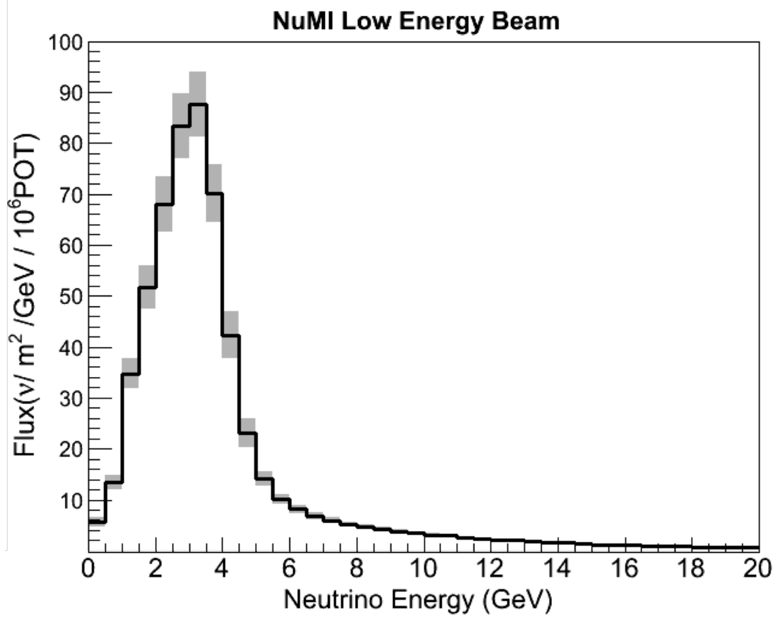
1. **Obtain Data Distribution** after the event selections
2. **Subtract Background**
3. **Unfold Data** to remove reconstruction effects
4. **Correct for Efficiency** to remove acceptance effects



Cross Section Calculation

$$\left(\frac{d\sigma}{dP_\mu}\right)_i = \frac{1}{\boldsymbol{\Phi_\nu T_N}} \frac{1}{(\boldsymbol{\Delta P_\mu})_i} \frac{\sum_j U_{ij}\left(N_j^{data} - N_j^{bckg}\right)}{\epsilon_i}$$

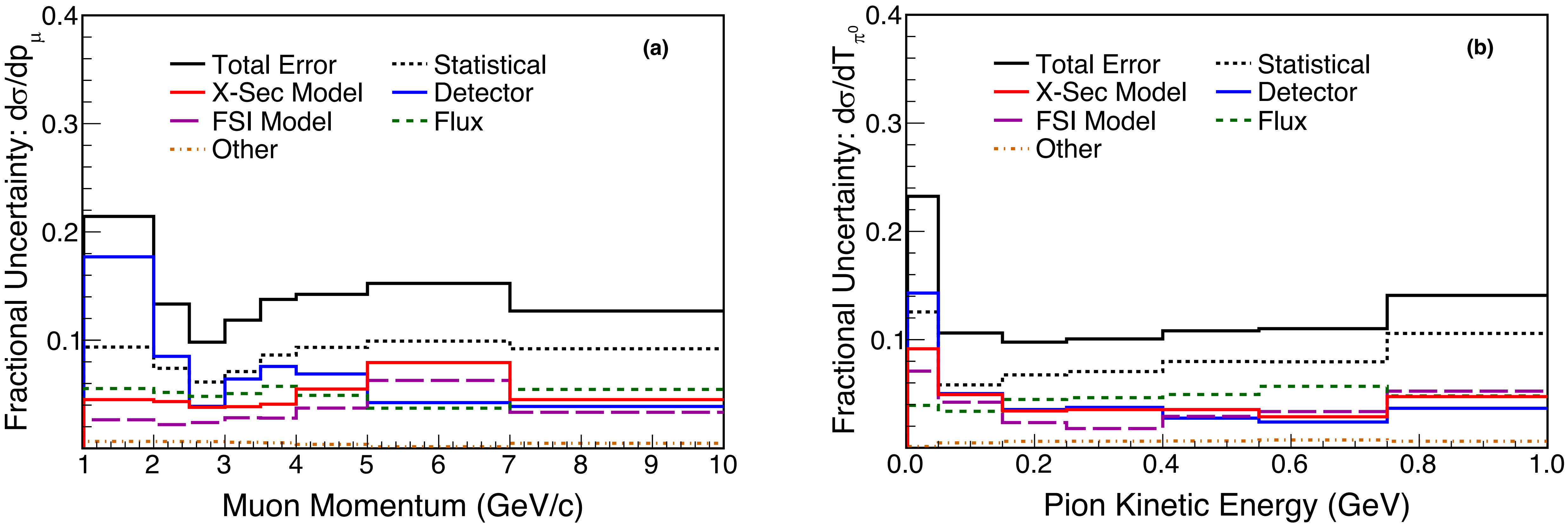
1. **Obtain Data Distribution** after the event selections
2. **Subtract Background**
3. **Unfold Data** to remove reconstruction effects
4. **Correct for Efficiency** to remove acceptance effects
5. Divide by **neutrino flux** and **number of targets**
6. Present cross section as **bin-width normalized**



Systematic Uncertainty Categories

- **Cross-Section Model Uncertainties**
  - Form factors used to calculate Resonance Cross Sections
  - Predicted event rate for Non-Resonant Pion Production
- **Detector Response Uncertainties**
  - Electro-magnetic (EM) energy scale or muon angle
- **Final State Interactions (FSI) Model Uncertainties**
  - Pion Absorption or charge exchange inside the nucleus
- **Flux Uncertainties**
  - Hadron interaction models and beamline geometry
- **Other**
  - Side Band Fit: Bckg constraint

Statistical and Systematic Uncertainties



MINERvA CC(π) Results for W < 1.8 GeV

Results are shown in this layout

$\boldsymbol{\nu_{\mu} + \mathrm{CH} \rightarrow \mu^{-} + \pi^{0} + \mathrm{nucleon(s)}}$

- Semi-exclusive Process
- $1.5 < E_\nu < 20$ GeV
- $\theta_\mu < 25$ degrees
- GENIE v2.8.4 with Tuning
- Isospin Composition: $\boldsymbol{A_{3/2}, A_{1/2}}$

$\boldsymbol{\nu_{\mu} + \mathrm{CH} \rightarrow \mu^{-} + \pi^{\pm} + X}$

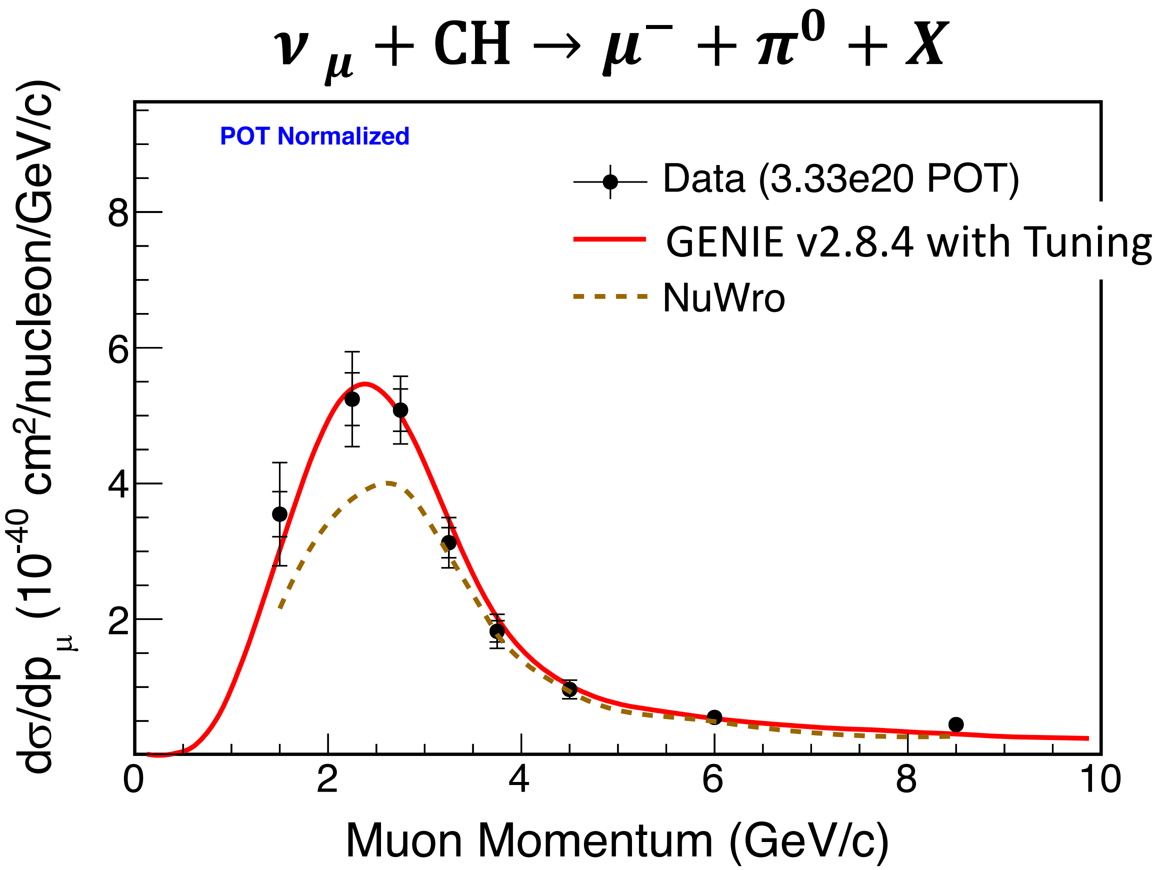
- Semi-inclusive Process
- $1.5 < E_\nu < 10$ GeV
- No constraint on θ_μ
- GENIE v2.6.2
- Isospin Compositions: $\boldsymbol{A_{3/2}}$ and $\boldsymbol{A_{3/2}, A_{1/2}}$

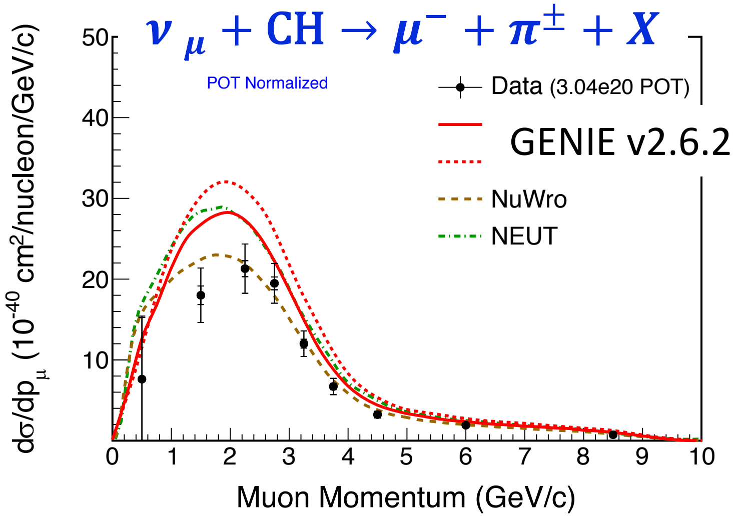
$\boldsymbol{\bar{\nu}_{\mu} + \mathrm{CH} \rightarrow \mu^{+} + \pi^{0} + \mathrm{nucleon(s)}}$

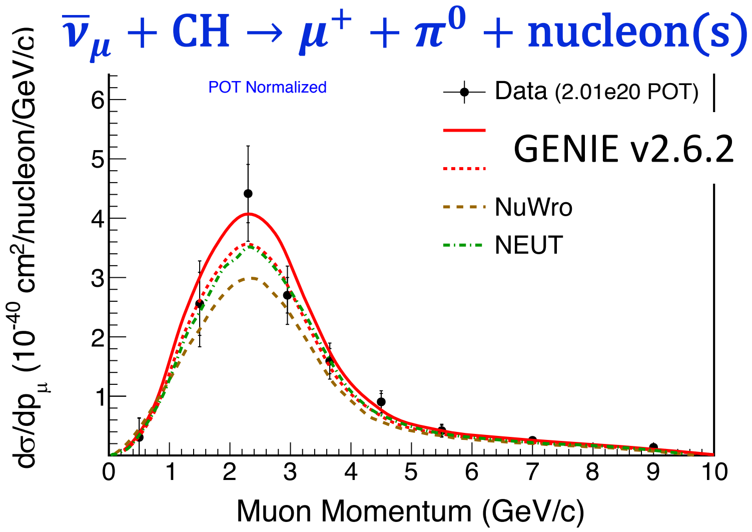
- Semi-exclusive Process
- $1.5 < E_\nu < 10$ GeV
- No constraint on θ_μ
- GENIE v2.6.2
- Isospin Composition: $\boldsymbol{A_{3/2}, A_{1/2}}$

Muon Momentum

PRD **94**, 052005 (2016)

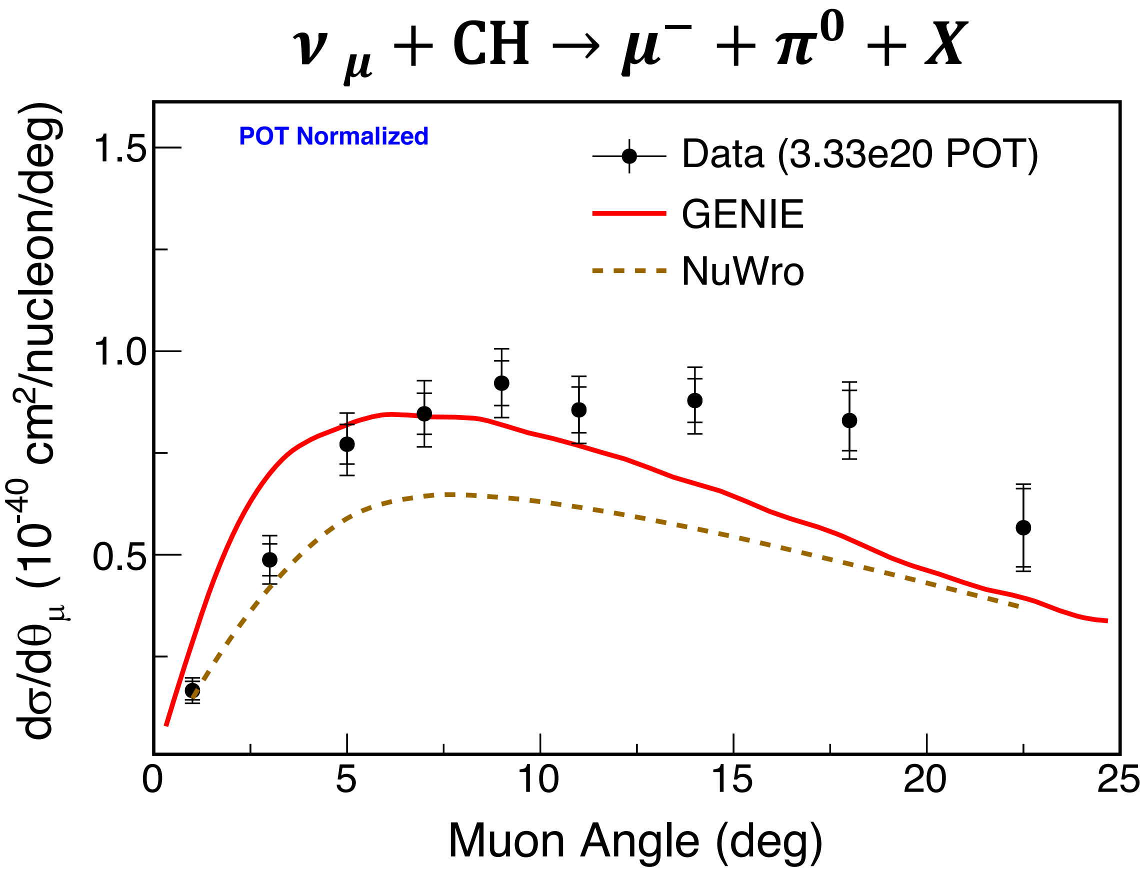


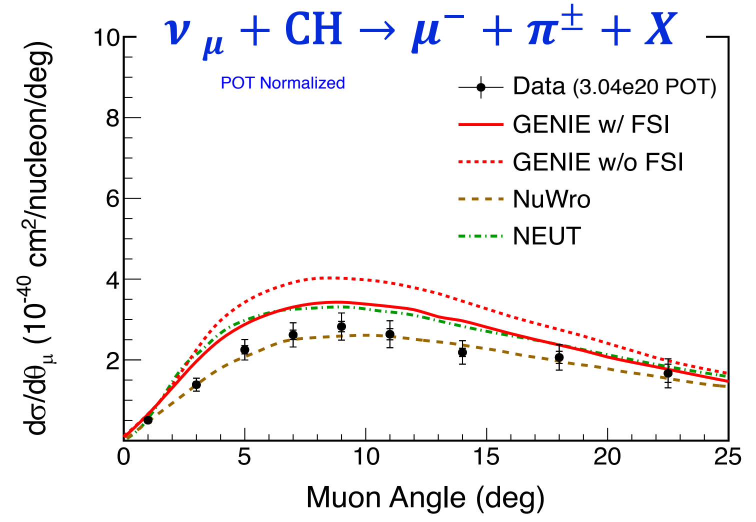


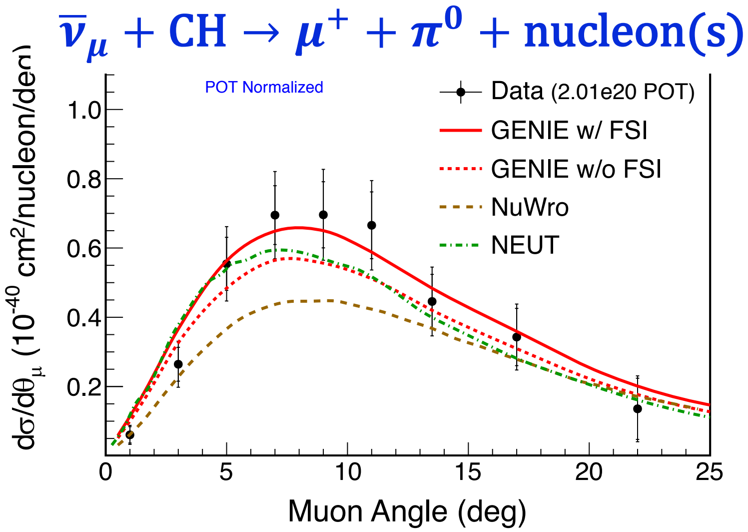


Muon Production Angle

PRD **94**, 052005 (2016)





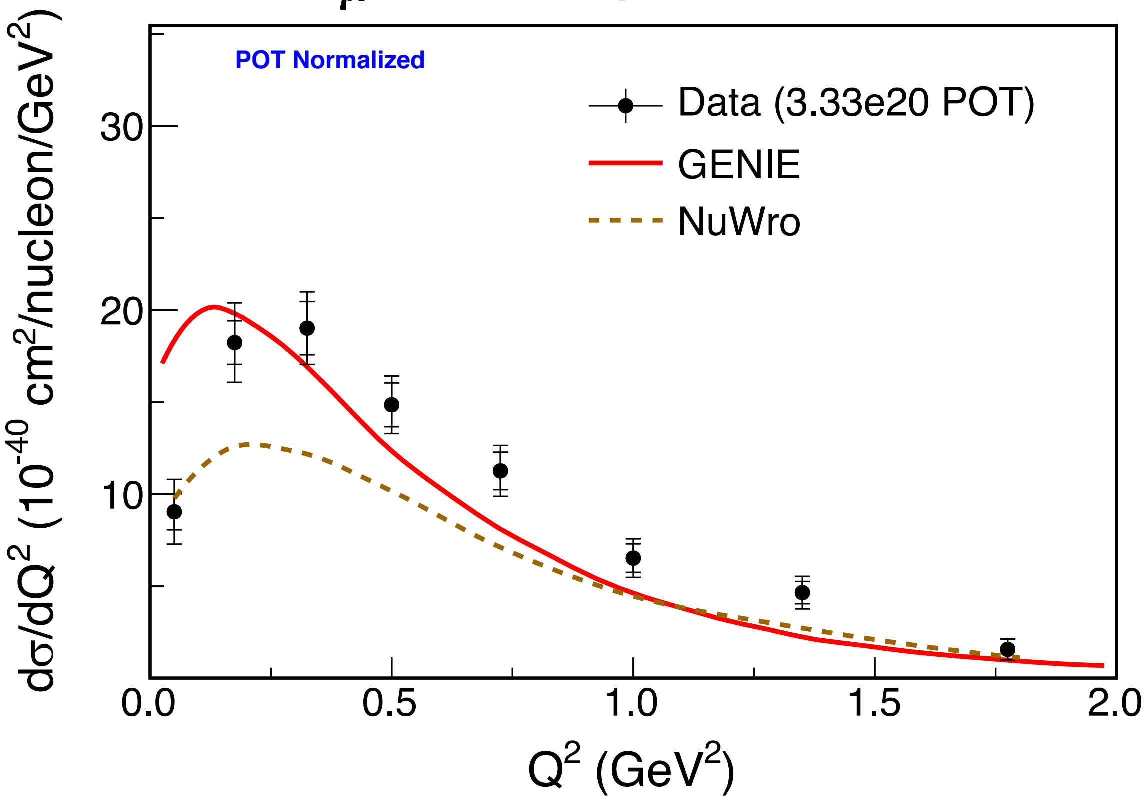


Four-Momentum Transfer Squared Q^2

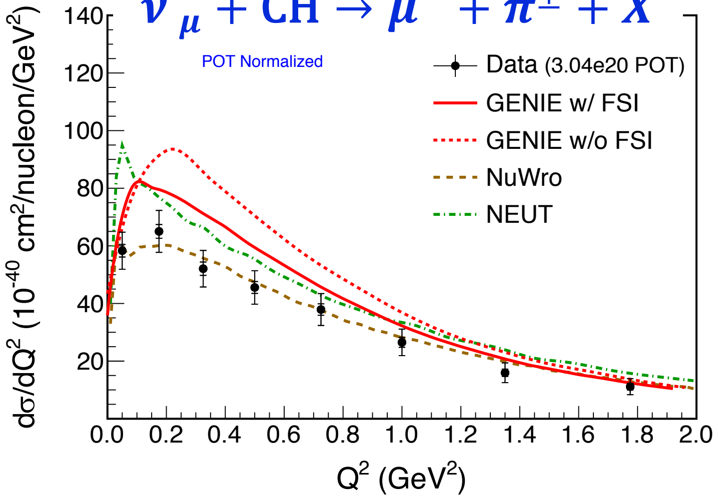
PRD **94**, 052005 (2016)

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

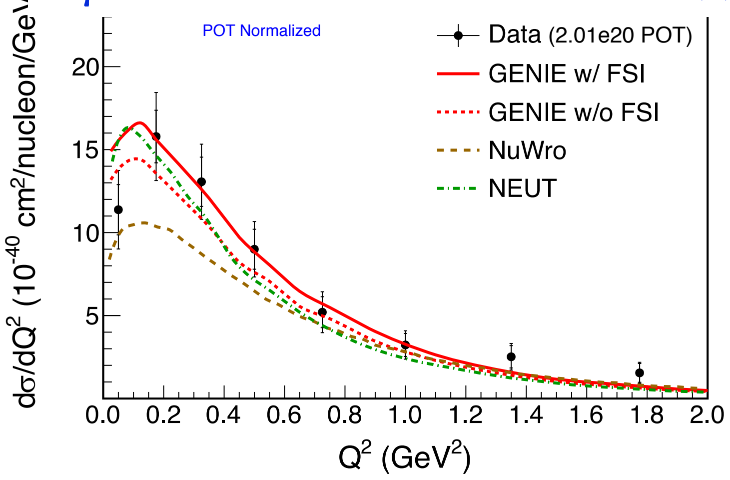
$\nu_\mu + CH \rightarrow \mu^- + \pi^0 + X$



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



$\bar{\nu}_\mu + CH \rightarrow \mu^+ + \pi^0 + \text{nucleon(s)}$

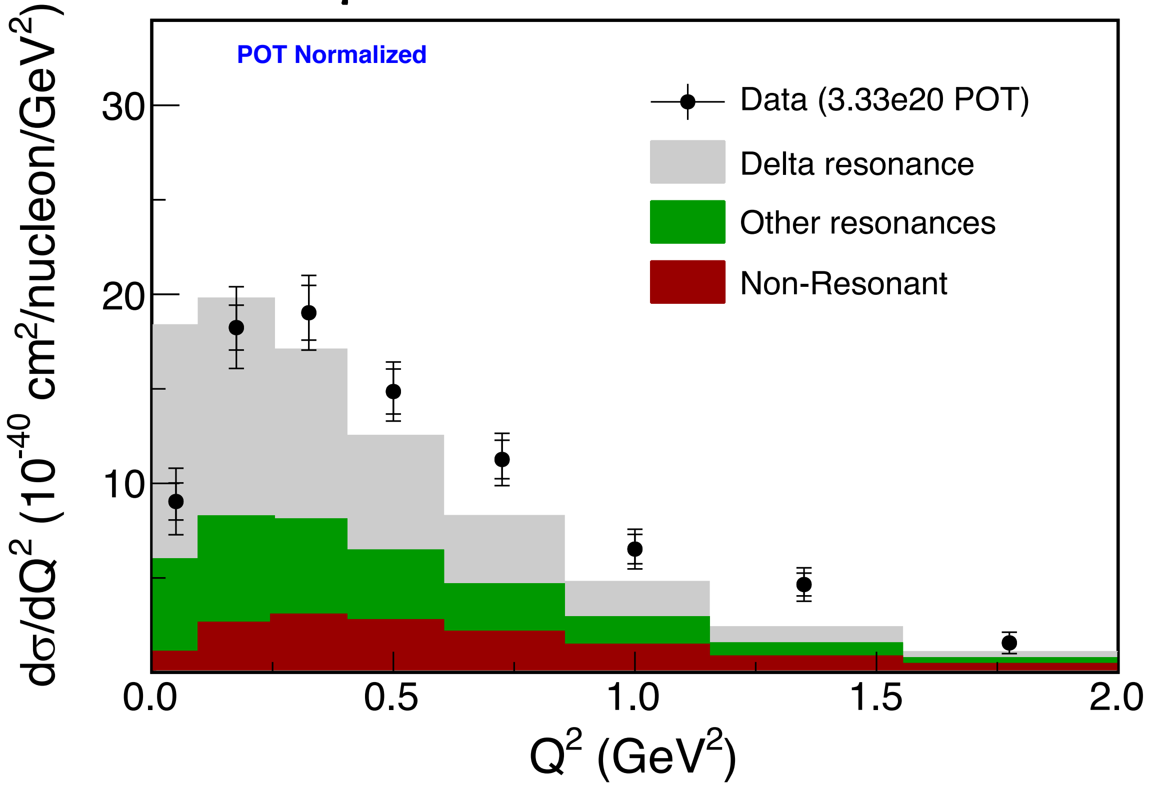


Four-Momentum Transfer Squared Q^2

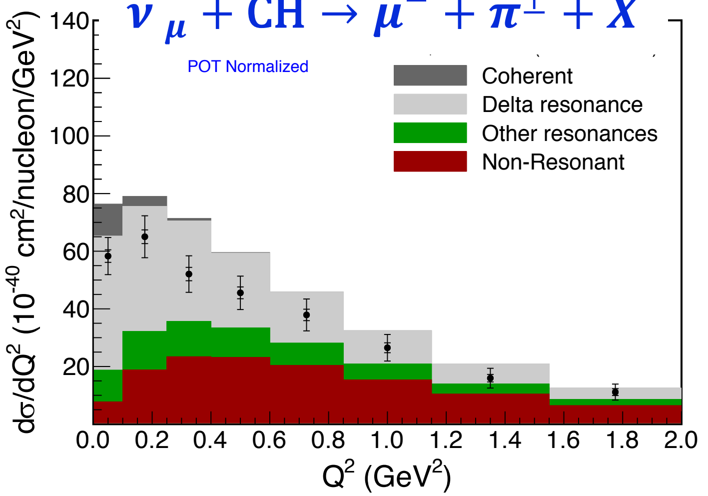
PRD **94**, 052005 (2016)

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

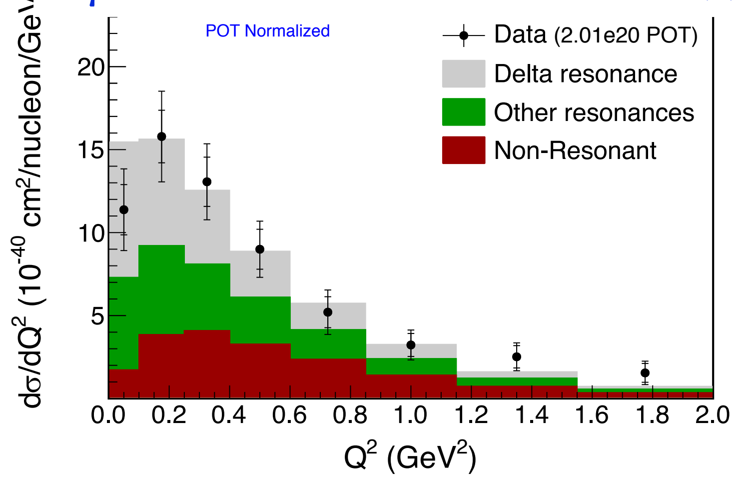
$\nu_\mu + CH \rightarrow \mu^- + \pi^0 + X$



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



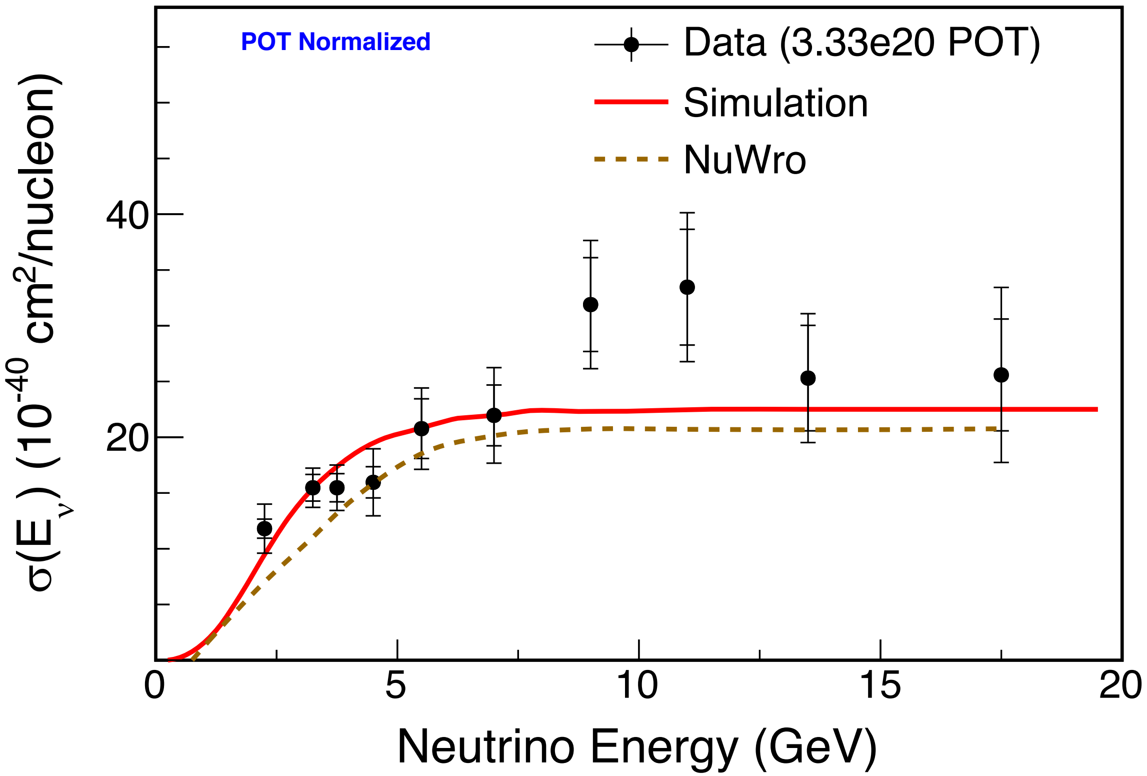
$\bar{\nu}_\mu + CH \rightarrow \mu^+ + \pi^0 + \text{nucleon(s)}$



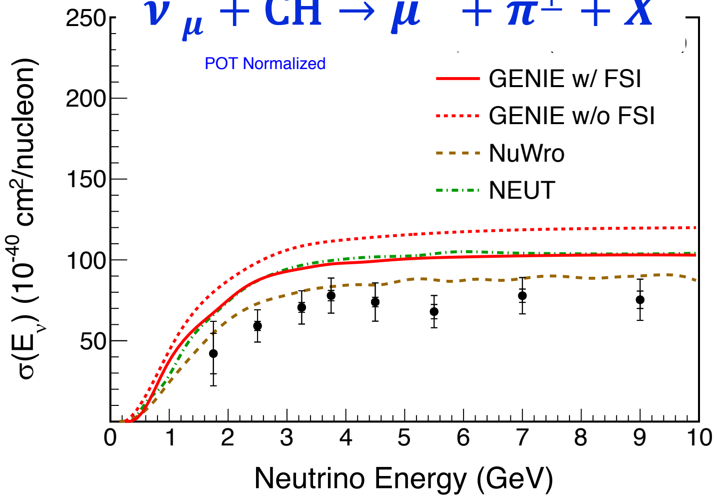
Neutrino Energy

PRD **94**, 052005 (2016)

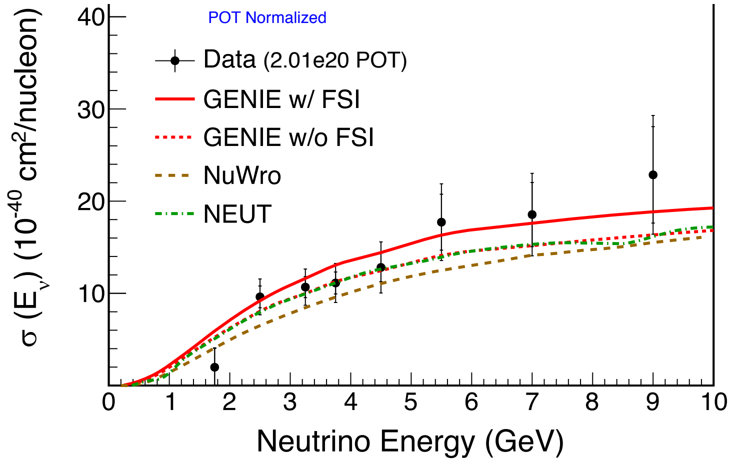
$\nu_\mu + CH \rightarrow \mu^- + \pi^0 + X$



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



$\bar{\nu}_\mu + CH \rightarrow \mu^+ + \pi^0 + \text{nucleon(s)}$



Final State Interaction (FSI) Model in GENIE v2.8.4

- **FSI can modify Pion momentum and direction**
  - Modifies measured cross section

- **FSI can obscure Original Interaction Type**
  - Changes event classification

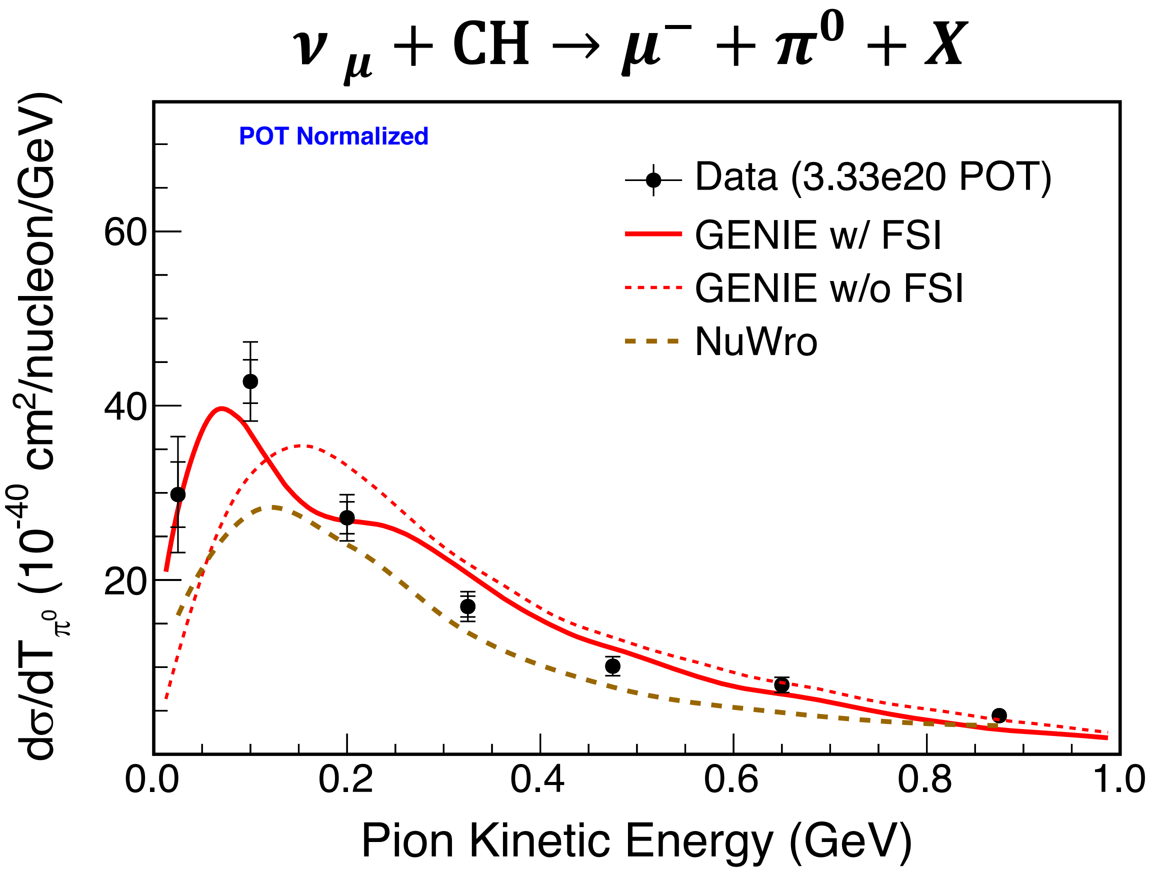
- **Feed Out (24.5%): Signal → Background**
  - π^0 Absorption
  - $\pi^0 \rightarrow \pi^{\pm}$
  - $\pi^0 \rightarrow$ Multi−π
  - Other Meson ($\pi^0 \rightarrow \pi^0 + X$)

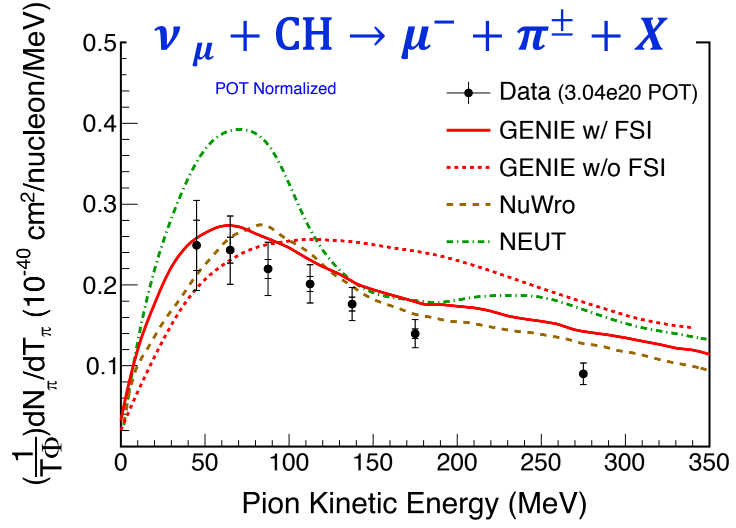
- **Feed In (20.9%): Background → Signal**
  - Multi−π $\rightarrow \pi^0$
  - $\pi^{\pm} \rightarrow \pi^0$
  - Zero−π $\rightarrow \pi^0$

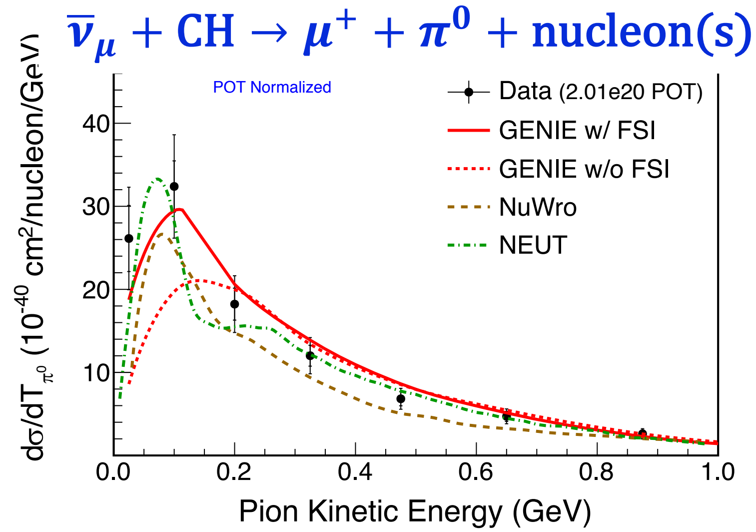
- **Net change for Signal Type =** -3.6%

Pion Kinetic Energy

PRD **94**, 052005 (2016)



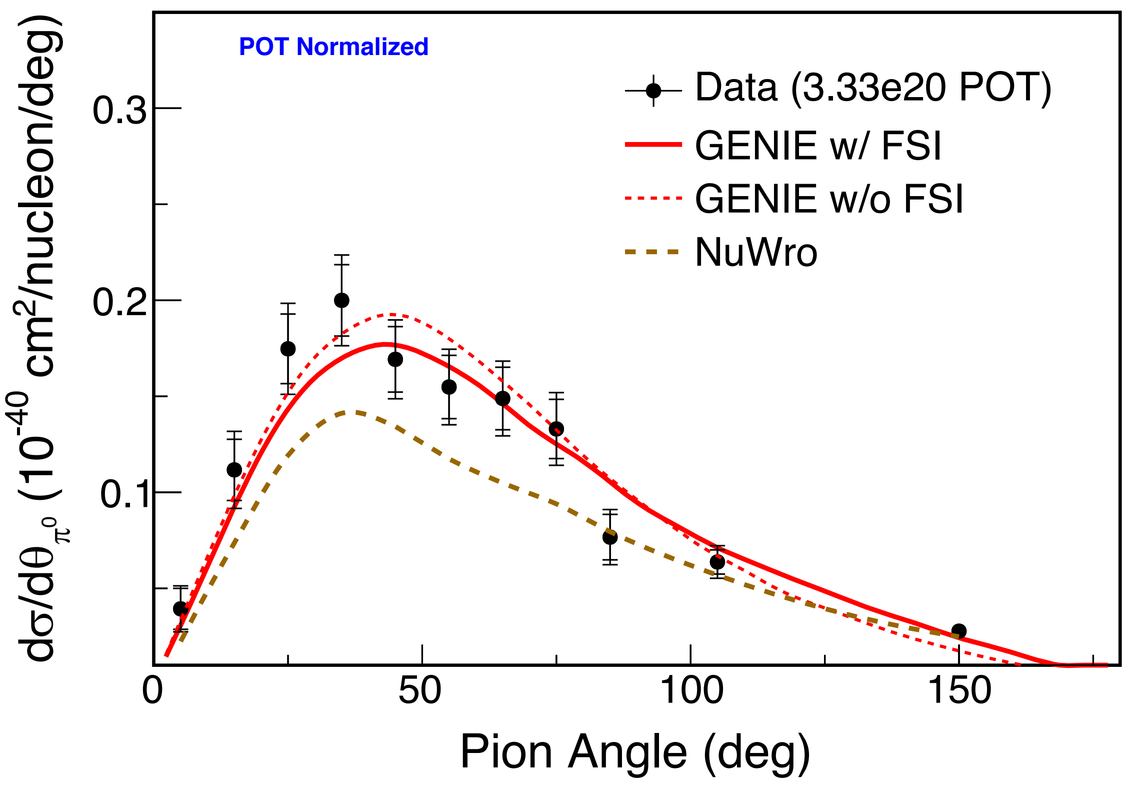




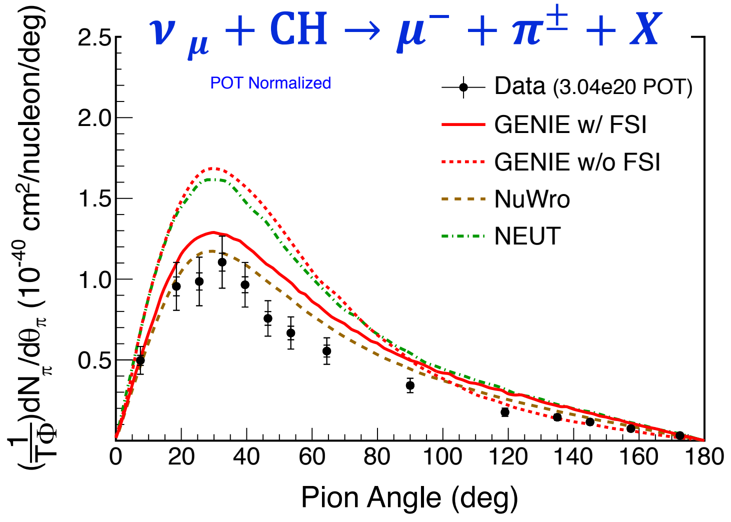
Pion Production Angle

PRD **94**, 052005 (2016)

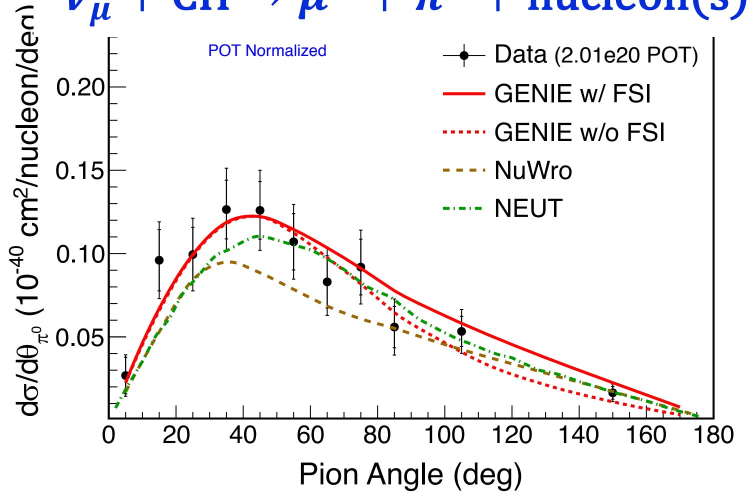
$\nu_\mu + CH \rightarrow \mu^- + \pi^0 + X$



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

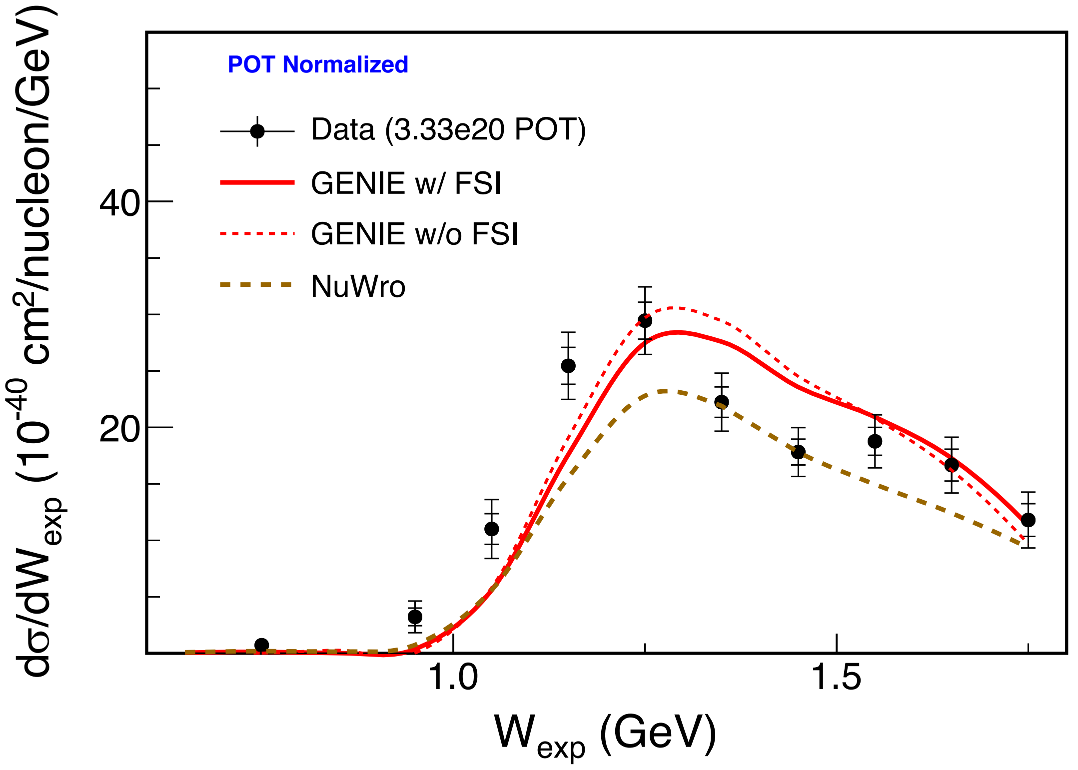


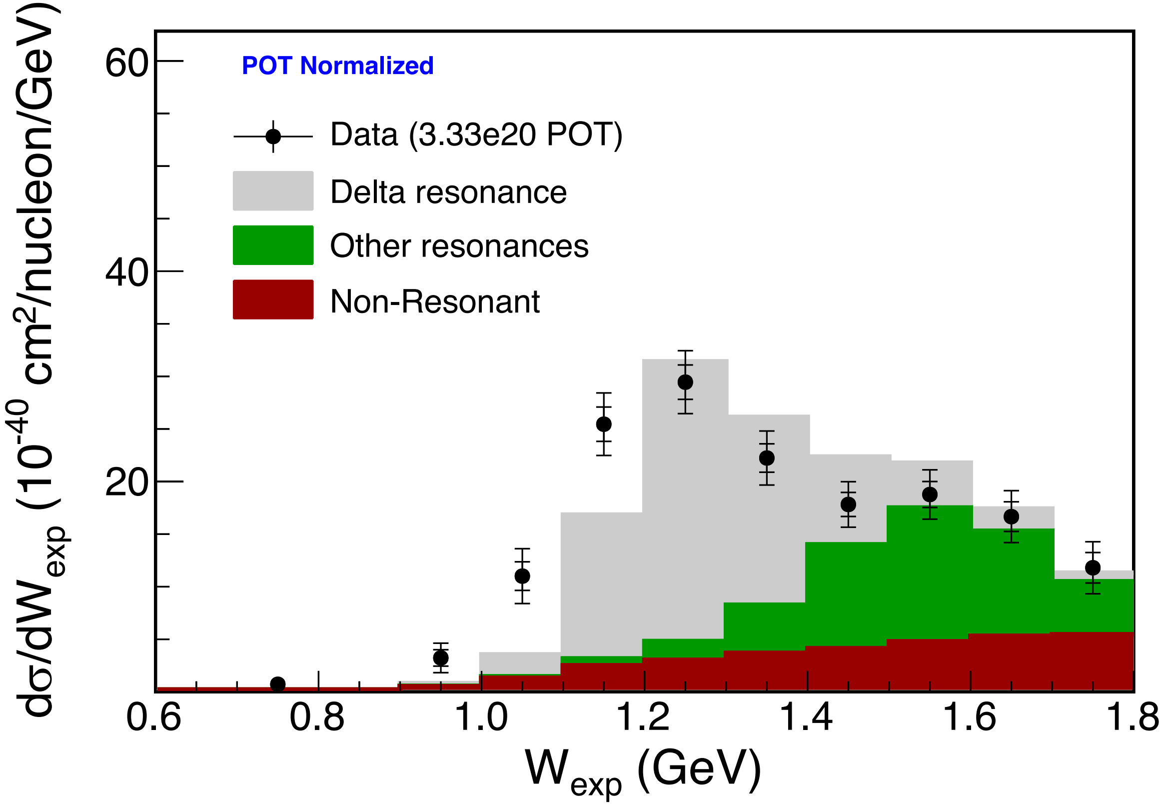
$\bar{\nu}_\mu + CH \rightarrow \mu^+ + \pi^0 + \text{nucleon(s)}$



Hadronic Invariant Mass, W_{exp}

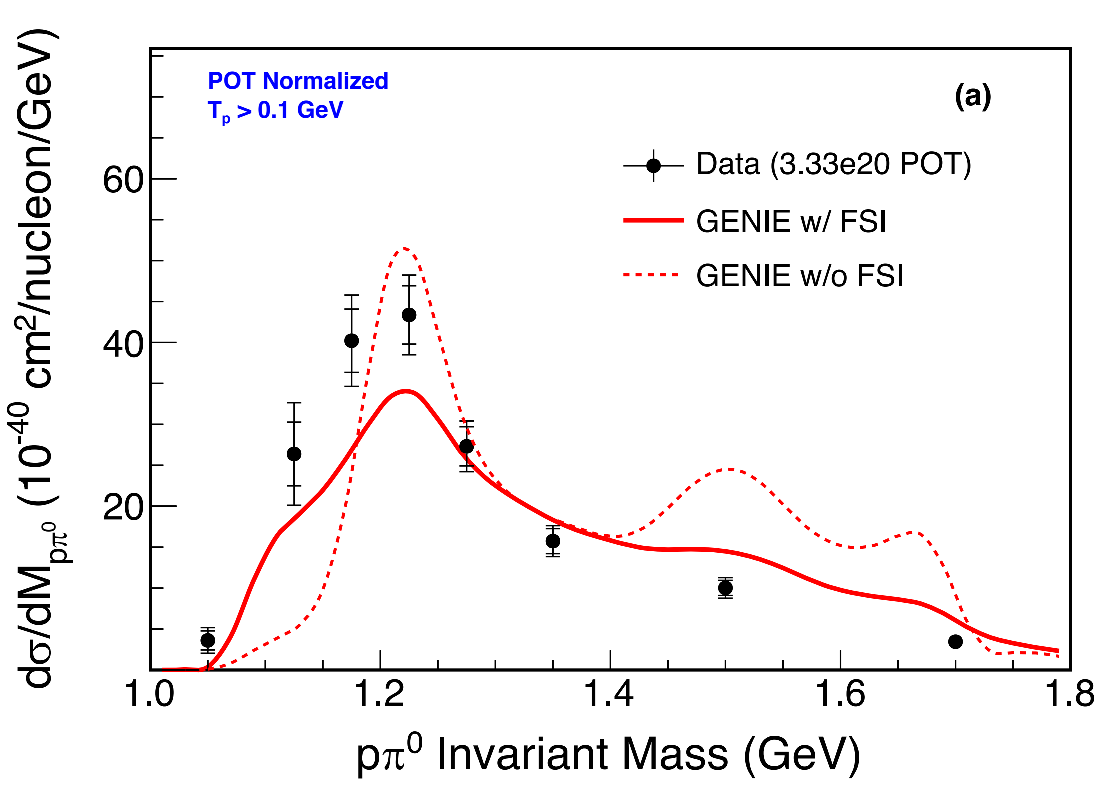
- W_{exp} is calculated using reco variables: $W_{exp} = \sqrt{m_n^2 + 2m_n(E_\nu - E_\mu) - Q^2}$

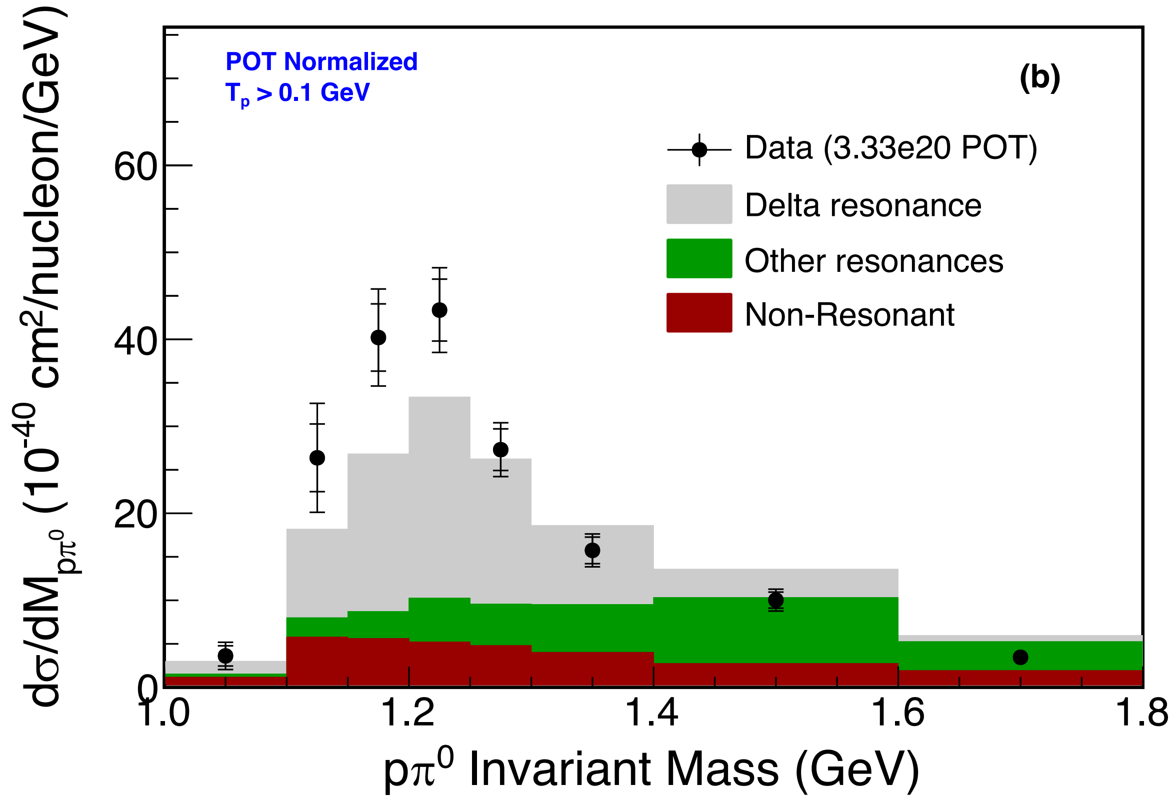




Proton-Pion Invariant Mass (Proton Reco sub-sample)

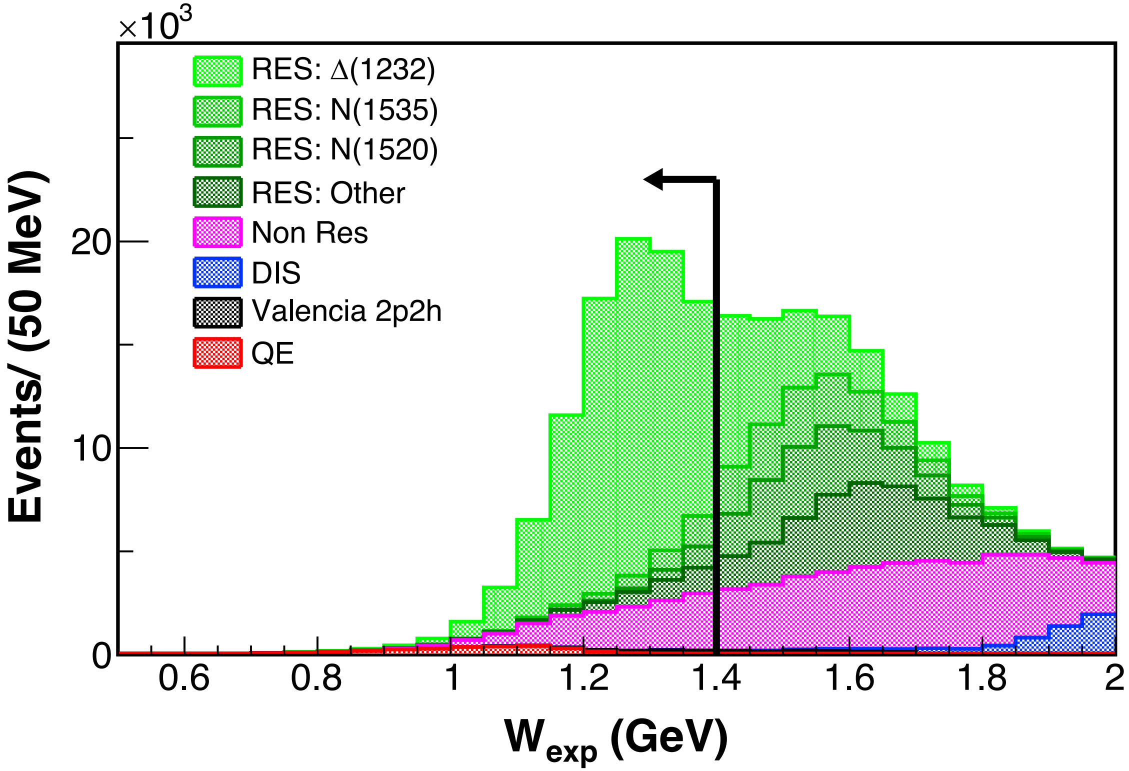
- $p\pi^0$ Invariant Mass is calculated using proton and pion 4-momentums
- Proton kinetic energy, T_p, is required to be greater than 0.1 GeV
- Size of background subtracted sample = 1522 data events (48.8% of original sample)





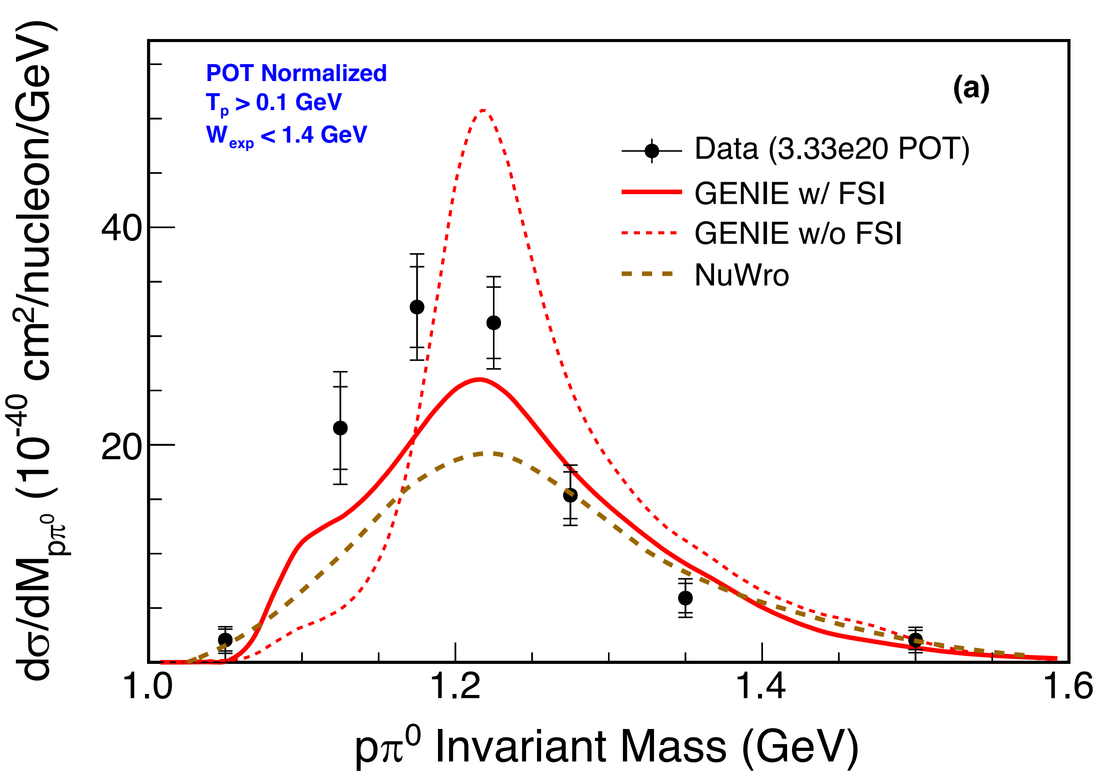
$\Delta^+(1232)$ enriched sub-sample: Selections

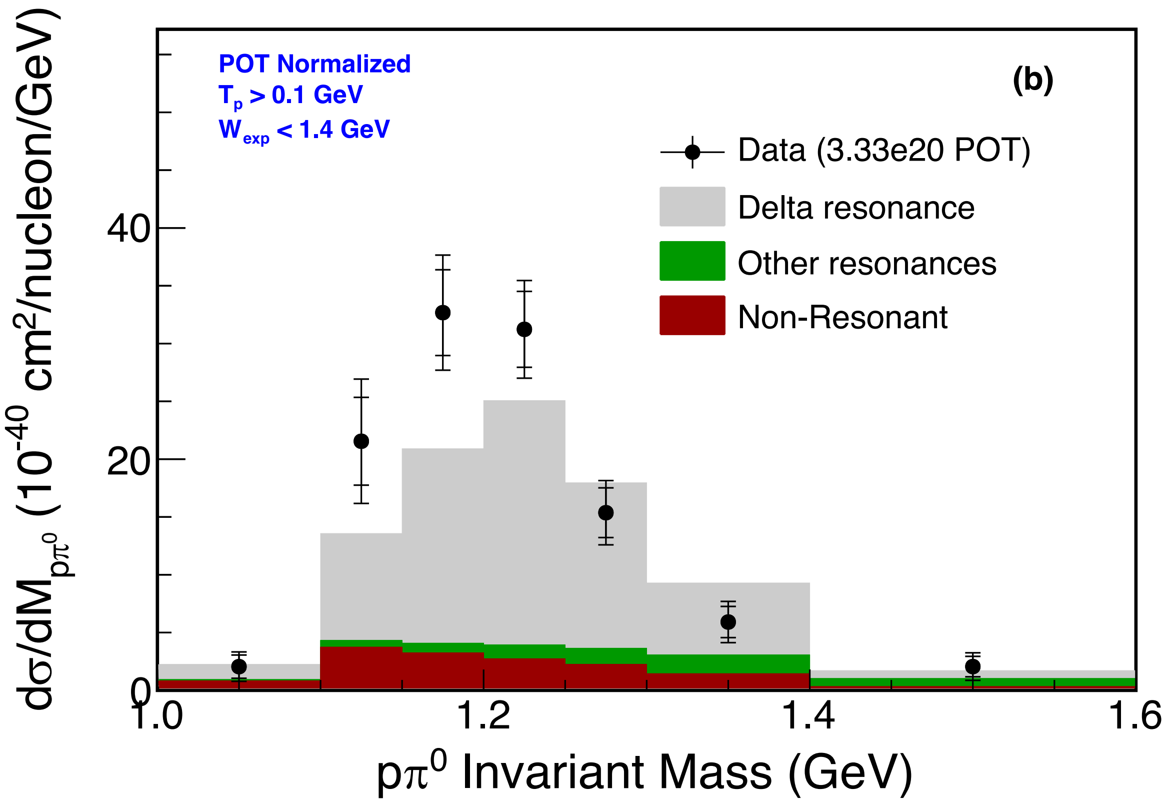
- **$\Delta^+(1232)$ enriched sub-sample is obtained by**
  - **Proton KE** > 0.1 GeV
  - **W** < 1.4 GeV
  - **Whole analysis is repeated!**
- **Estimated sub-sample Content**
  - 74% $\Delta^+(1232)$ resonance
  - 10% other resonances
  - 16% non-resonant
- **Size of background subtracted sample**
  - 757 data events (24.3% of original sample)



Proton-Pion Invariant Mass

- **Δ^+ enriched sub-sample**
- **$p\pi^0$ Invariant Mass is calculated using proton and pion 4-momentums**



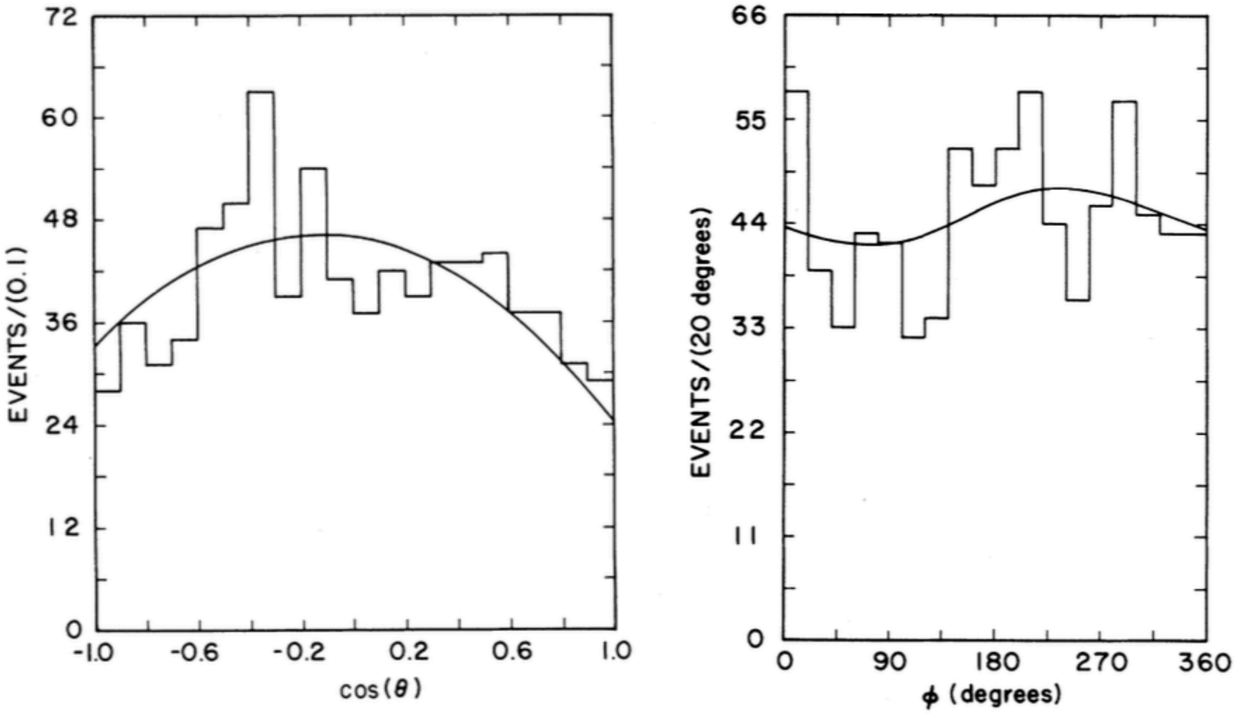


Search for Δ⁺(1232) Polarization

- **Δ^{++}(1232) Polarization Angles were studied in deuterium-filled bubble chambers**
  - **ANL:** Phys. Rev. D 25, 1161 (1982). and **BNL:** Phys. Rev. D 34, 2554 (1986).

The zenith (θ) and azimuthal (ϕ) angular distributions are observed to be non-isotropic.

- **Angular Distributions:**
  - cos(θ) distribution $\approx Y_2^0$
  - ϕ distribution $\approx -\sin\phi$



Solid curves are Adler Model Predictions

$\Delta^+(1232)$ Polarization – Coordinate Axes

1. Boost all particles to Δ rest frame

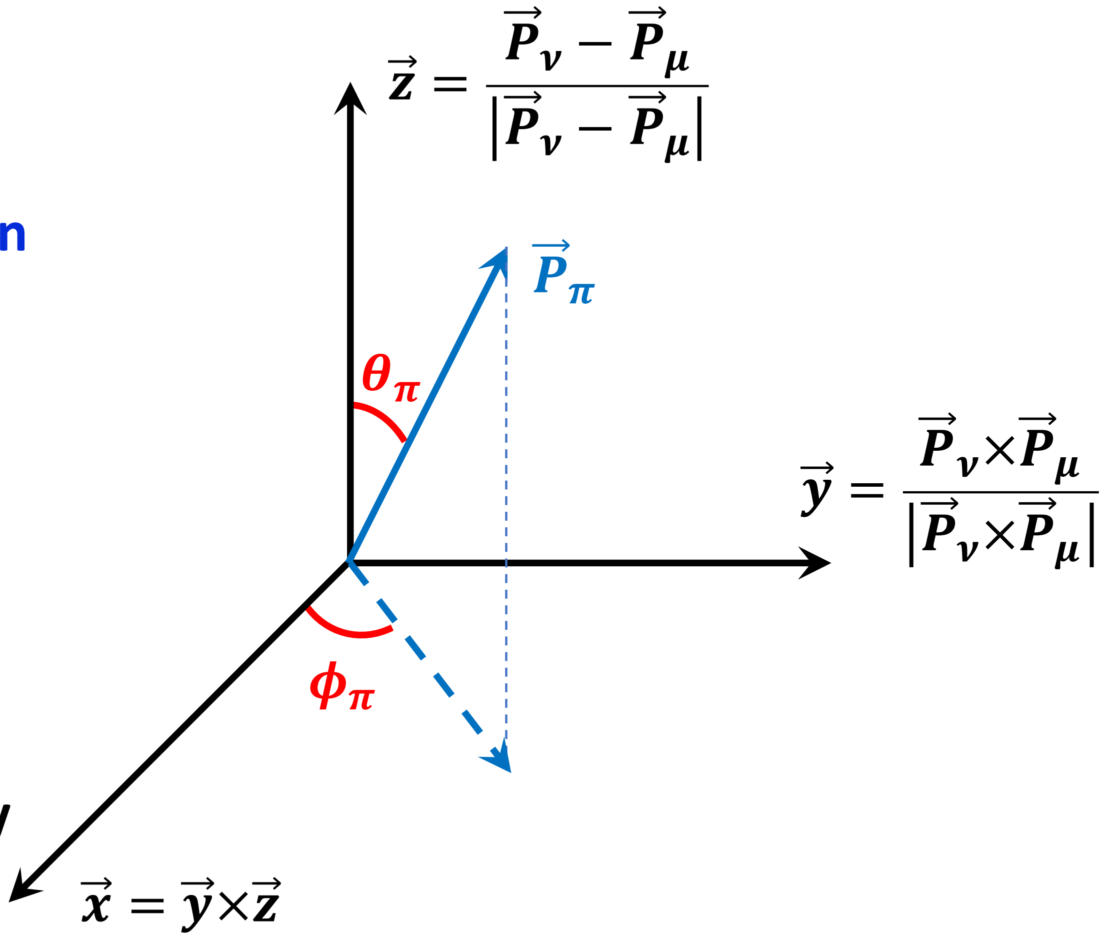
2. Form z-axis along the momentum transfer direction

3. Form y-axis along the production plane normal

4. Form x-axis assuming the system is Right-Handed

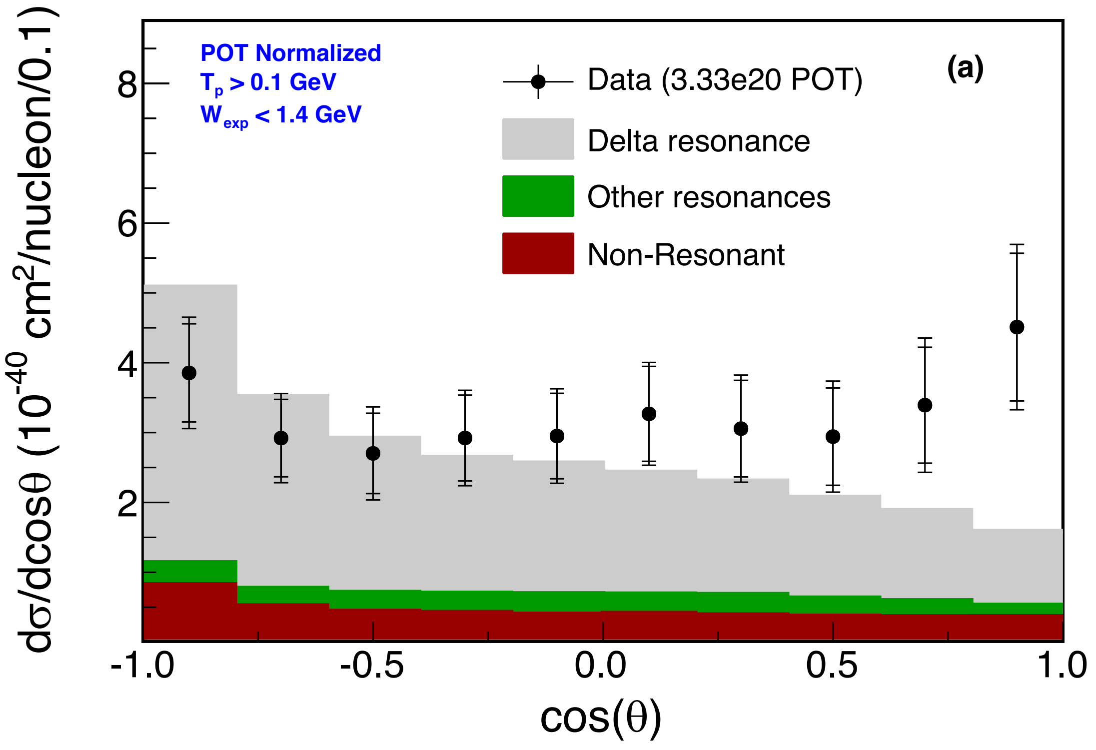
5. Angle θ is between z-axis and $\vec{P}_\pi$

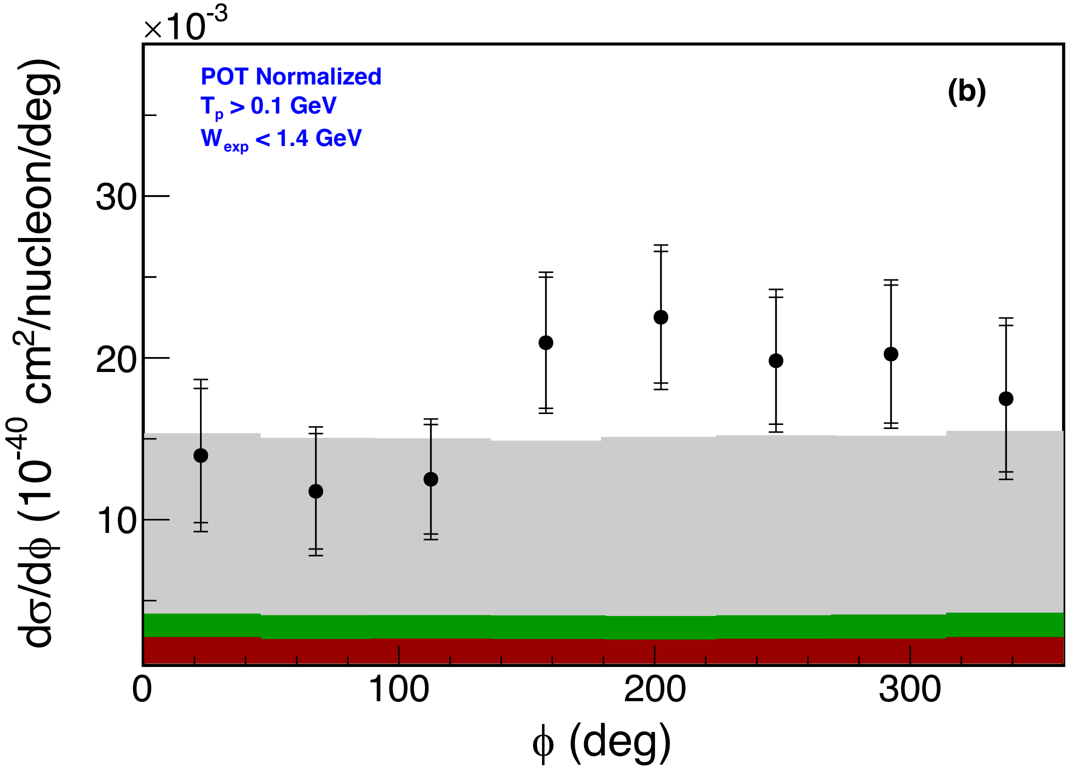
6. Angle ϕ is between x-axis and $\vec{P}_\pi$ projection on x-y plane



Δ⁺(1232) Polarization – cos(θ) and φ

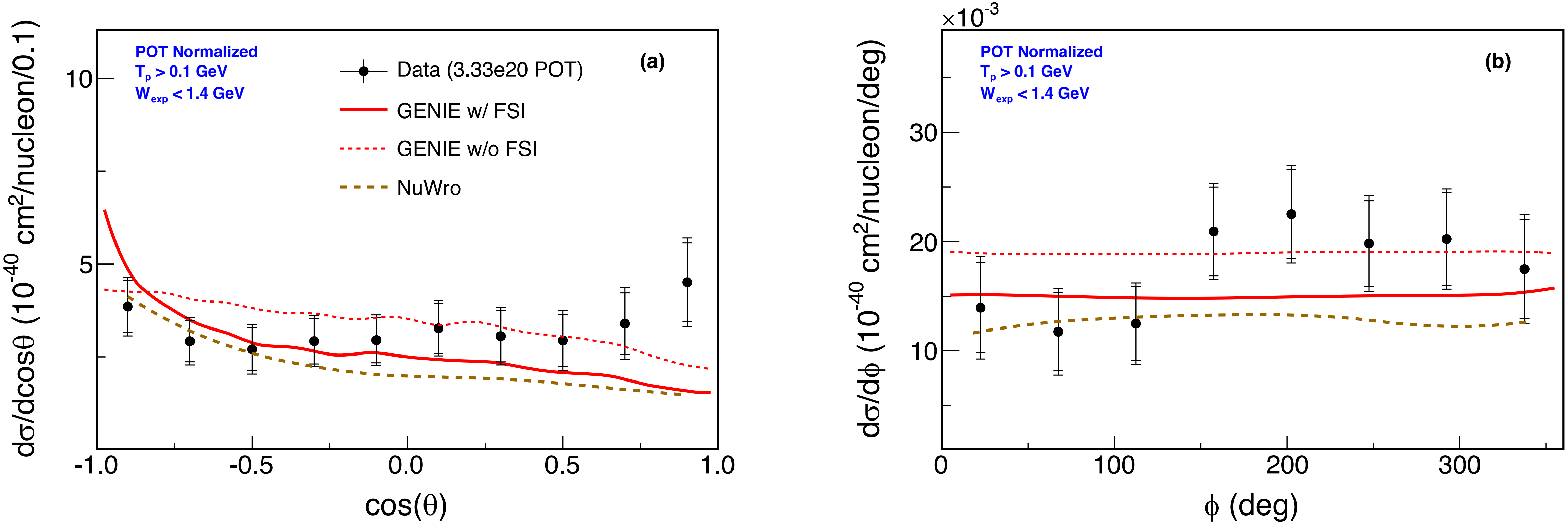
- **Δ⁺ enriched sub-sample**
- **GENIE assumes isotropic Δ⁺(1232) decay**



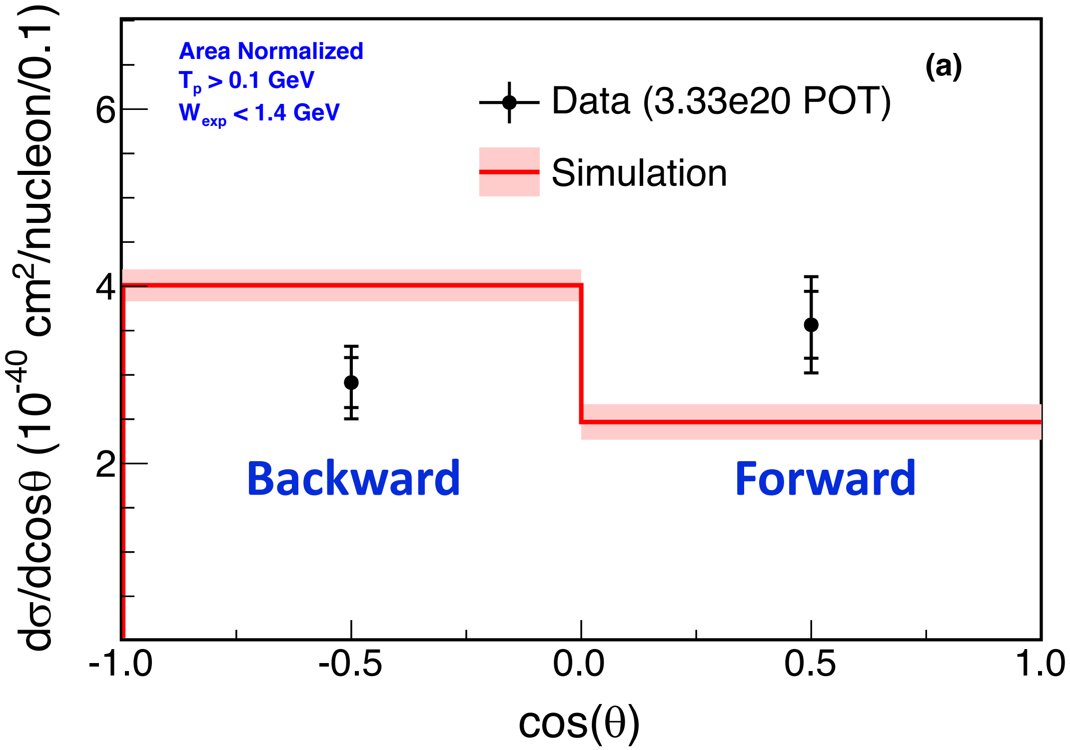


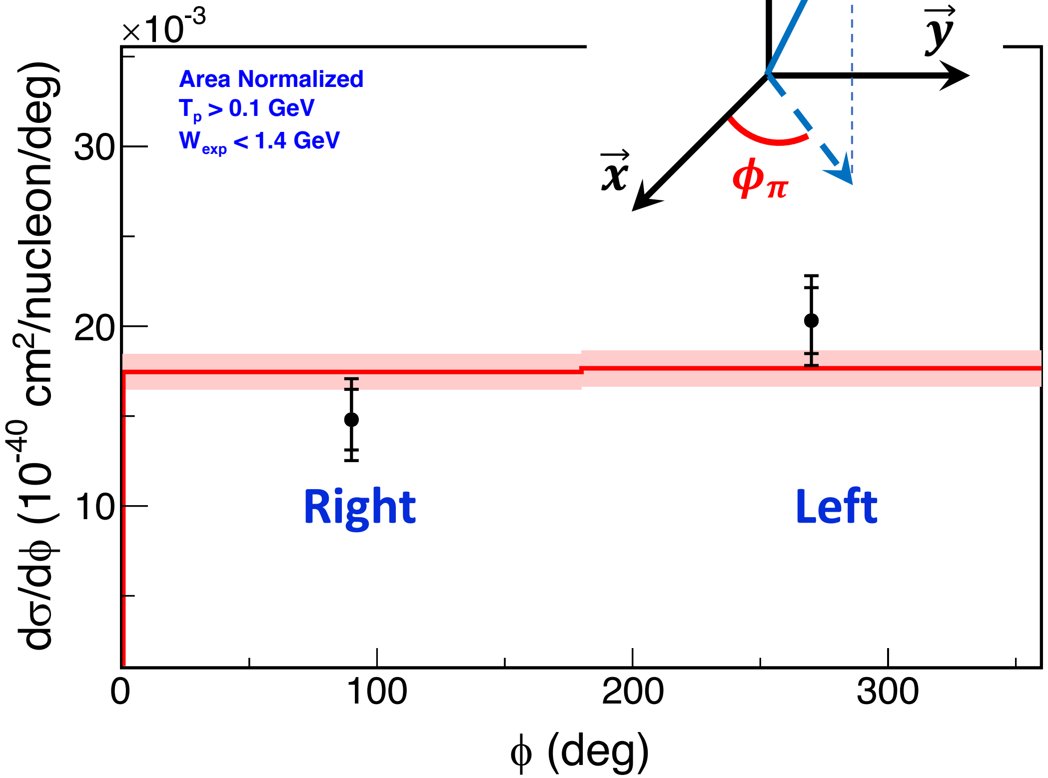
$\Delta^+(1232)$ Polarization – cos(θ) and ϕ

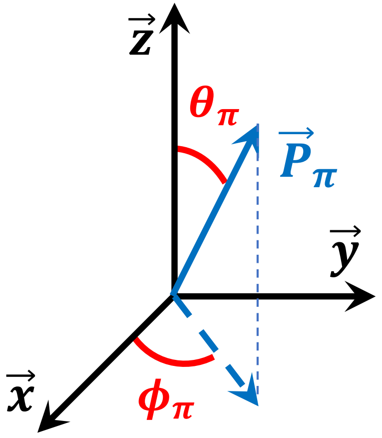
- Δ^+ enriched sub-sample
- GENIE and NuWro assume isotropic $\Delta^+(1232)$ decay



$\Delta^+(1232)$ Polarization – cos(θ) and ϕ







$$\frac{(N_F/N_B)_{\text{data}}}{(N_F/N_B)_{\text{MC}}} = \frac{1.23 \pm 0.41}{0.62} = 1.99 \pm 0.41$$

$$\frac{(N_L/N_R)_{\text{data}}}{(N_L/N_R)_{\text{MC}}} = \frac{1.37 \pm 0.27}{1.01} = 1.36 \pm 0.27$$

Conclusion: New Measurements

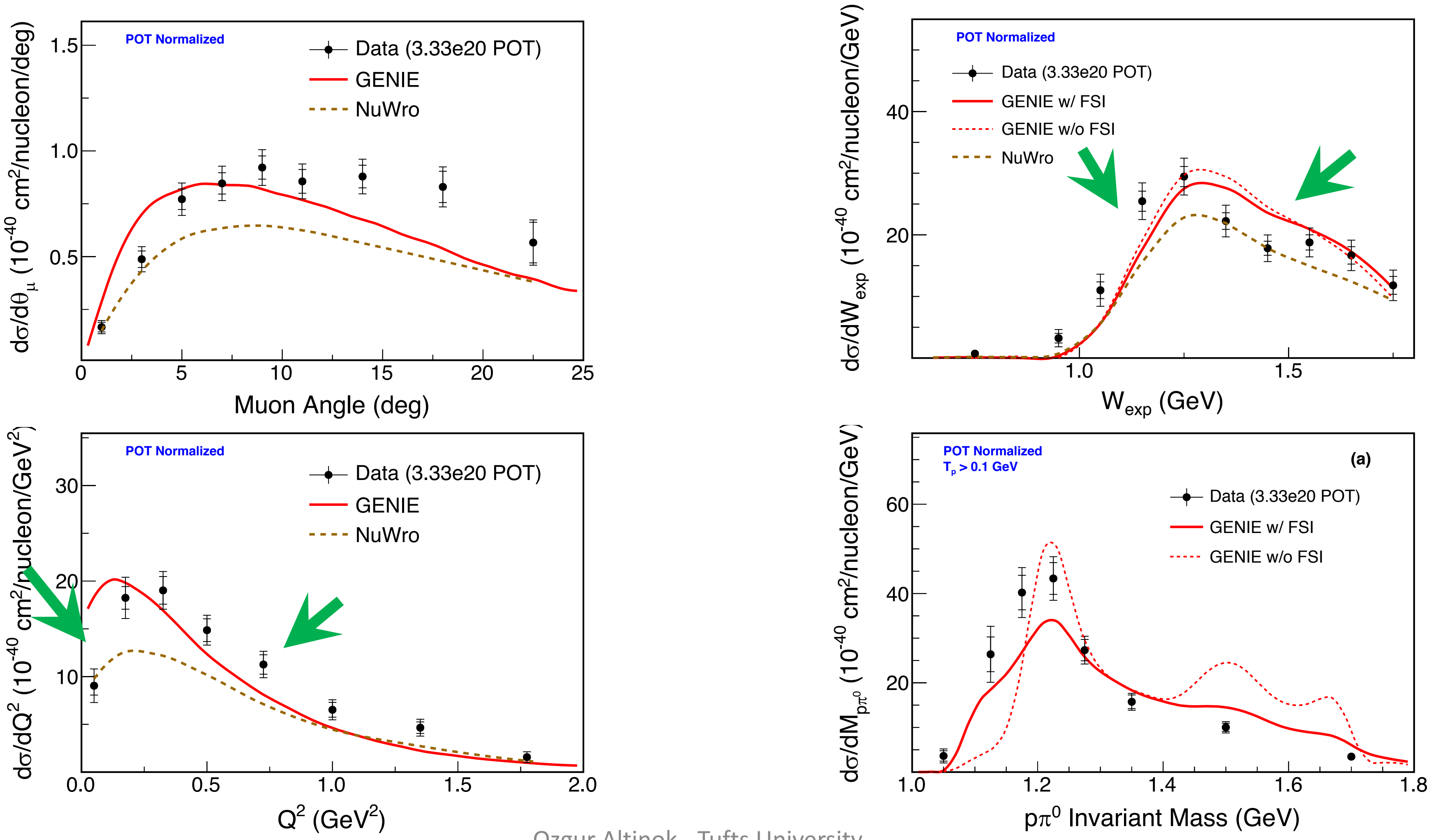
$$\nu_\mu + \mathrm{CH} \rightarrow \mu^- + \pi^0 + \mathrm{nucleon(s)}$$

- Muon Momentum
- Muon Production Angle
- Pion Momentum
- Pion Kinetic Energy
- Pion Production Angle
- Four-momentum transfer squared, Q^2
- Hadronic Invariant Mass, W
- Neutrino Energy
- Proton-pion Invariant Mass
- $\Delta^+(1232)$ Decay Polarization Angles

These measurements provide a detailed view of the signal channel

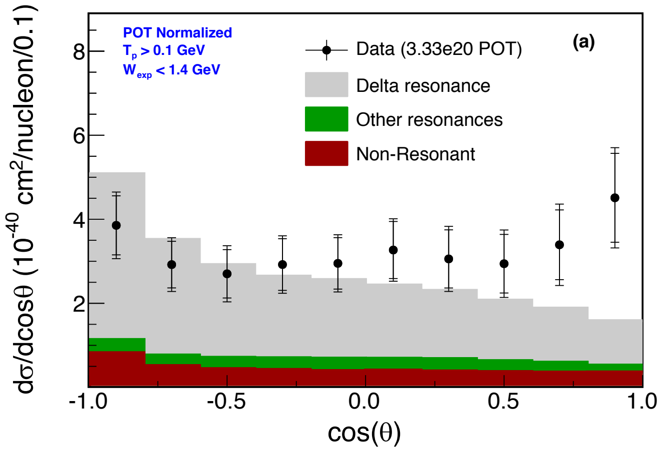
Conclusion: Observed Data vs MC disagreements

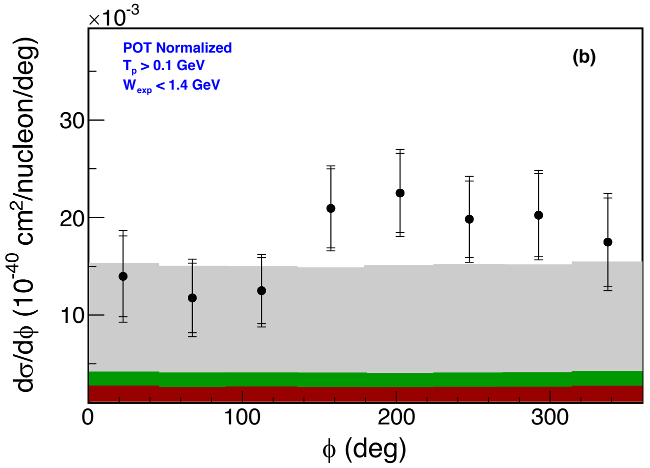
These disagreements identify areas in need of improvement.



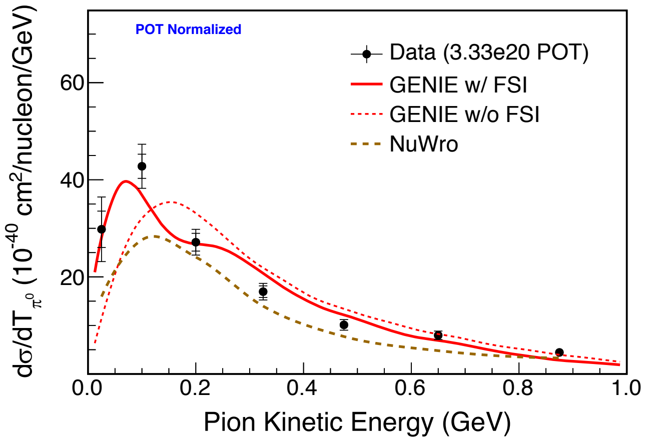
Conclusion: Behavior of hadronic system

- **$\Delta^+(1232)$ decay angles are measured for the first time!**





- **Provided information for pion FSI model constraints**



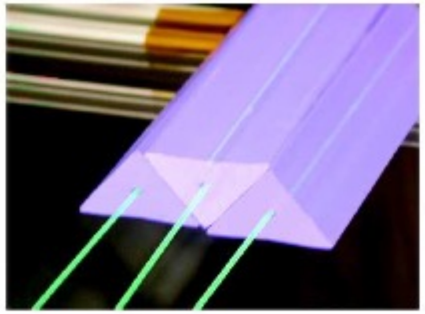
Thank you!

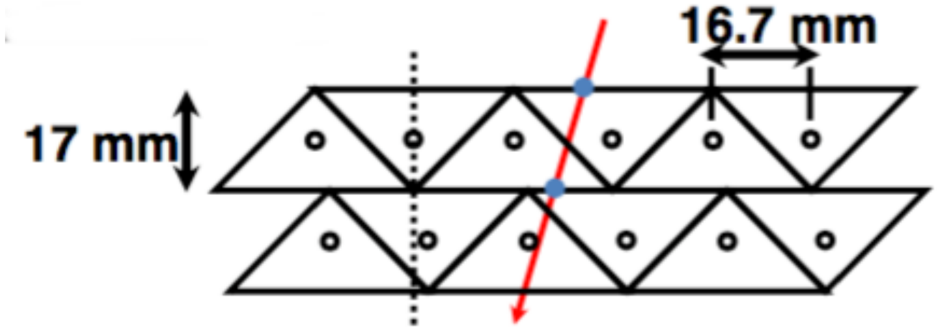
MINERνA Collaboration

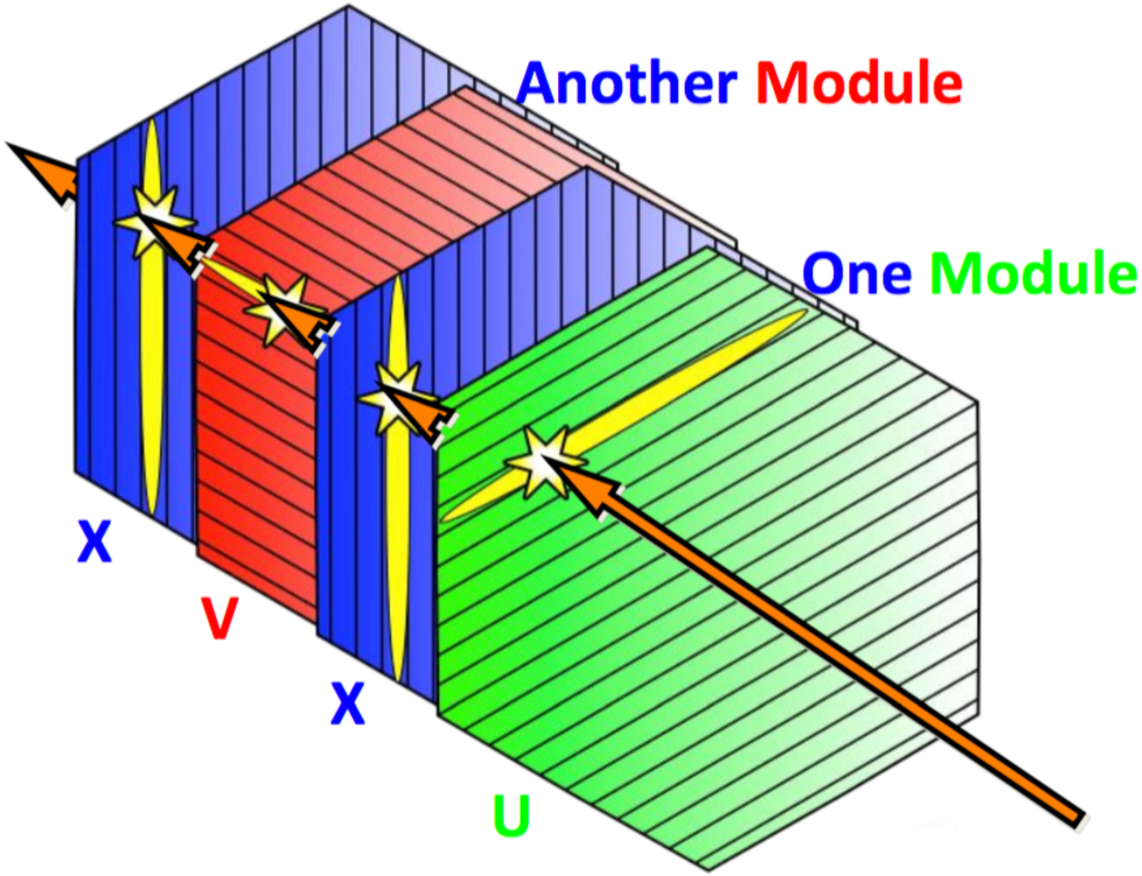
BACKUP

Tracking in MINERvA Detector

- **Charged particle must traverse at least 4 planes (≈70mm)**
  - Kinetic energy threshold for protons is 100 MeV
  - Tracking resolution is 3mm

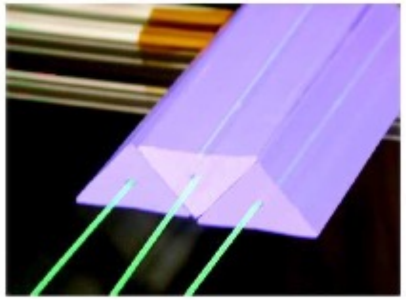




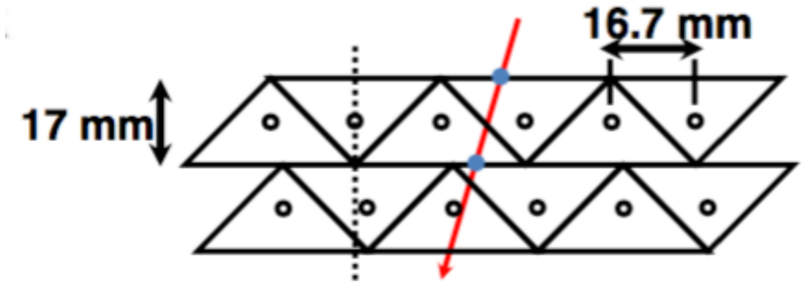


Tracking in MINERvA Detector

- **Each MINERvA plane is constructed with 127 triangular scintillators**
  - An optical fiber is inserted to the center of the strips for signal read out.



- **Single module in MINERvA Detector has two planes in different views (XU or XV)**
  - This configuration guarantees scintillation signal in a minimum of two strips.



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

GENIE v2.8.4 with Tuning

- **Refinements to GENIE Models**
  1. $\Delta^{++}(1232)$ Anisotropic Decay → Phys. Rev. D 92, 092008 (2015).
  2. Down-weight CC-NonRES 1π Channels
  3. Reduce $M_A^{RES} = \mathbf{1.12} \rightarrow \mathbf{0.94\ GeV}$
  4. Increase CC-RES normalization

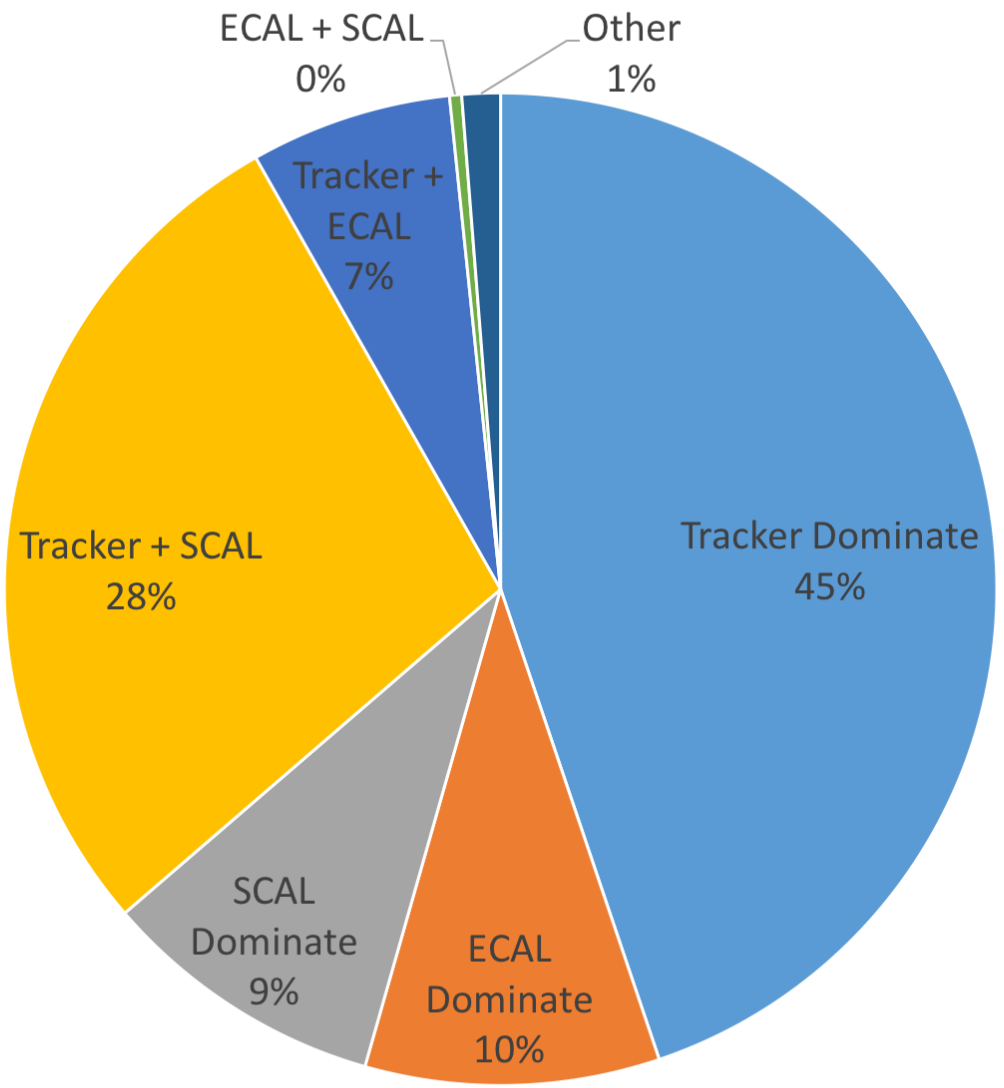
  (Items 2–4: Eur. Phys. J. C 76, 8, 474 (2016).)

  5. Include sample of QE-Like 2p2h Events → Phys. Rev. D 88, 113007 (2013).

- **Changes to Systematic Uncertainties**
  1. Reduce systematic error assignments
  2. Include new systematic for CC-RES Norm

  (Items 1–2: Eur. Phys. J. C 76, 8, 474 (2016).)

π^0 Shower Topology

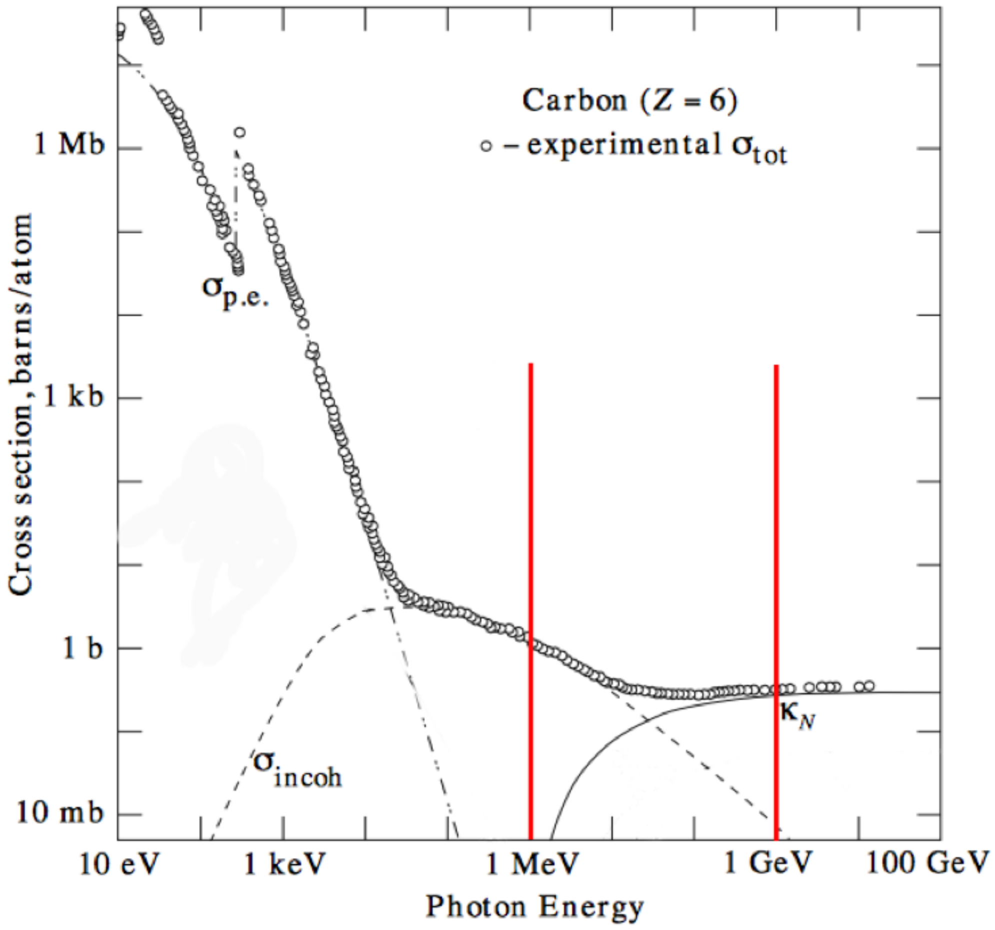


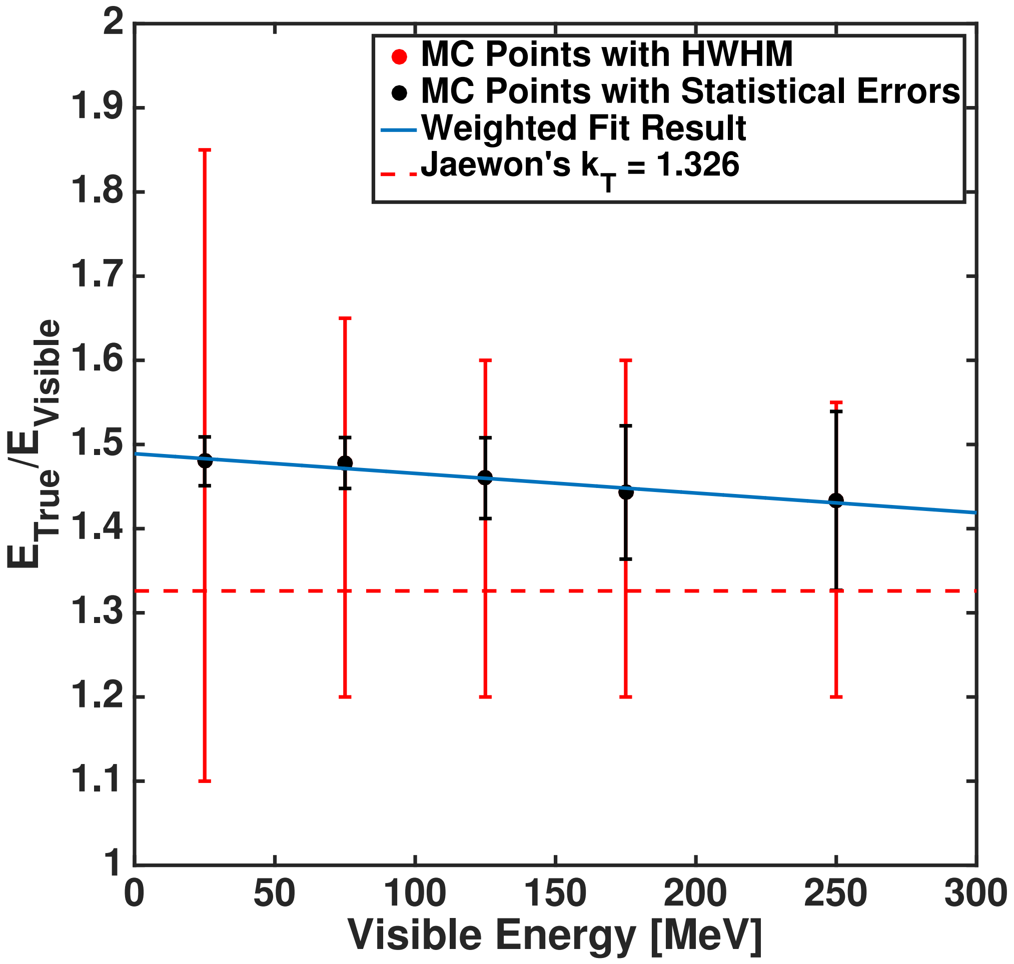
- **Single Region Showers* (64%)**
  - **Tracker:** 45%
  - **ECAL:** 10%
  - **Side ECAL:** 9%
- **Double Region Showers† (36%)**
  - **Tracker + SCAL:** 28%
  - **Tracker + ECAL:** 7%
  - **ECAL + SCAL:** <%1

37% showers have Side ECAL Energy

* **Single Region Requirement:** 80% Energy deposited in one region
†**Double Region Requirement:** At least 20% Energy in BOTH regions

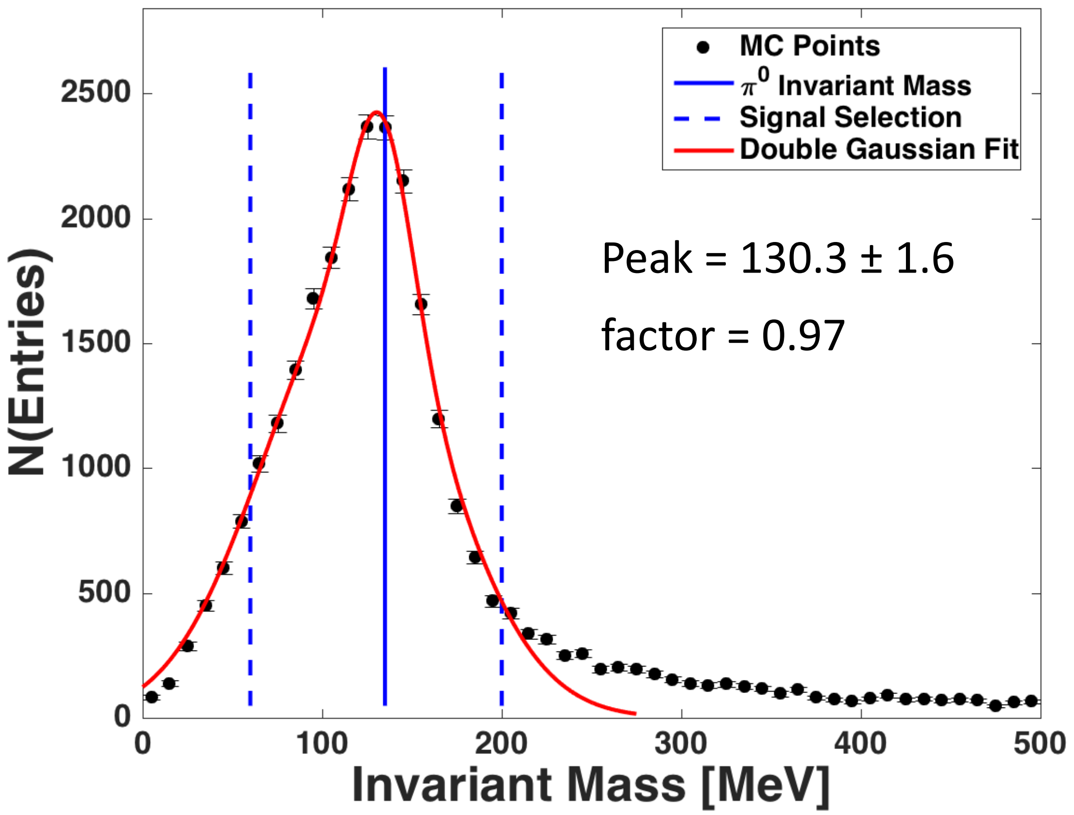
EM Energy Calibration



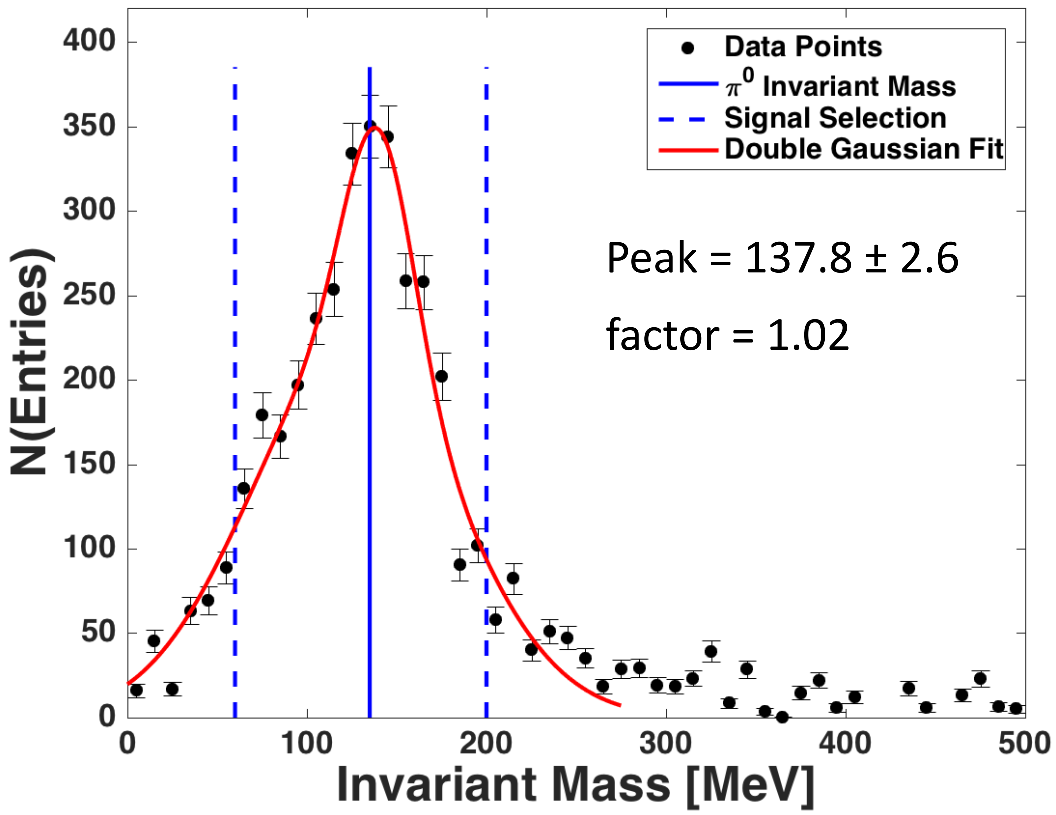


EM Energy Calibration

Simulation



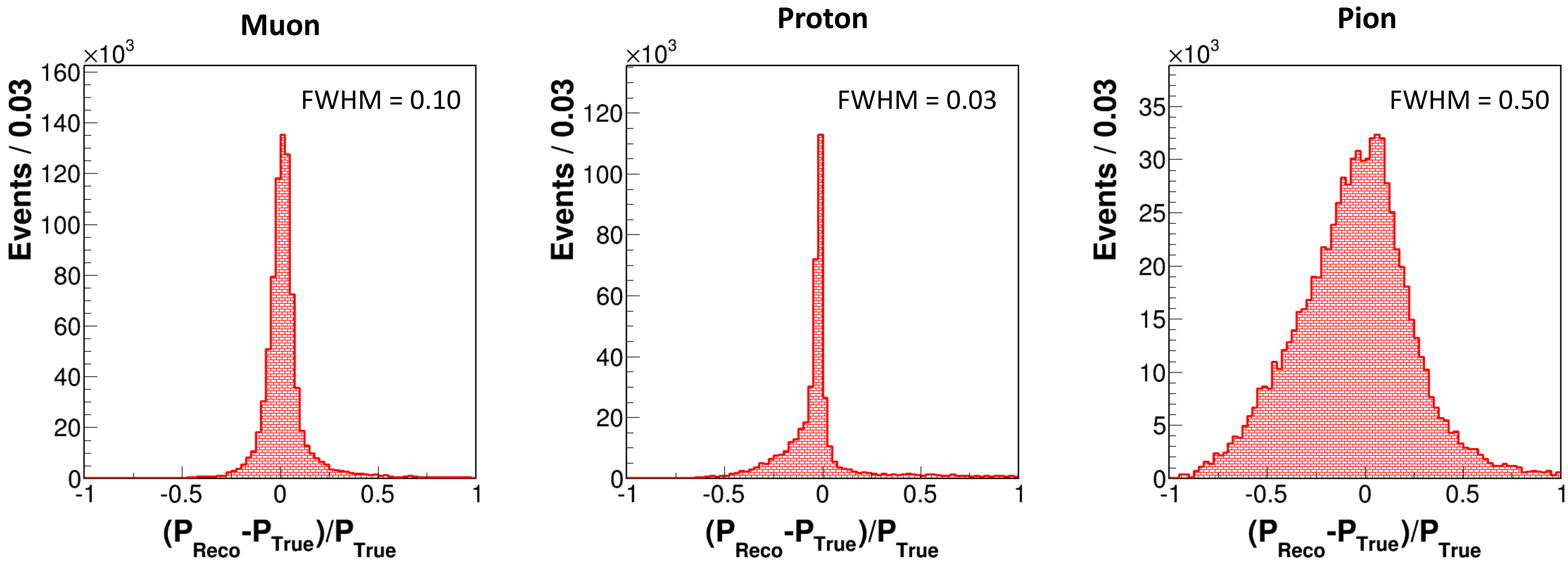
Data



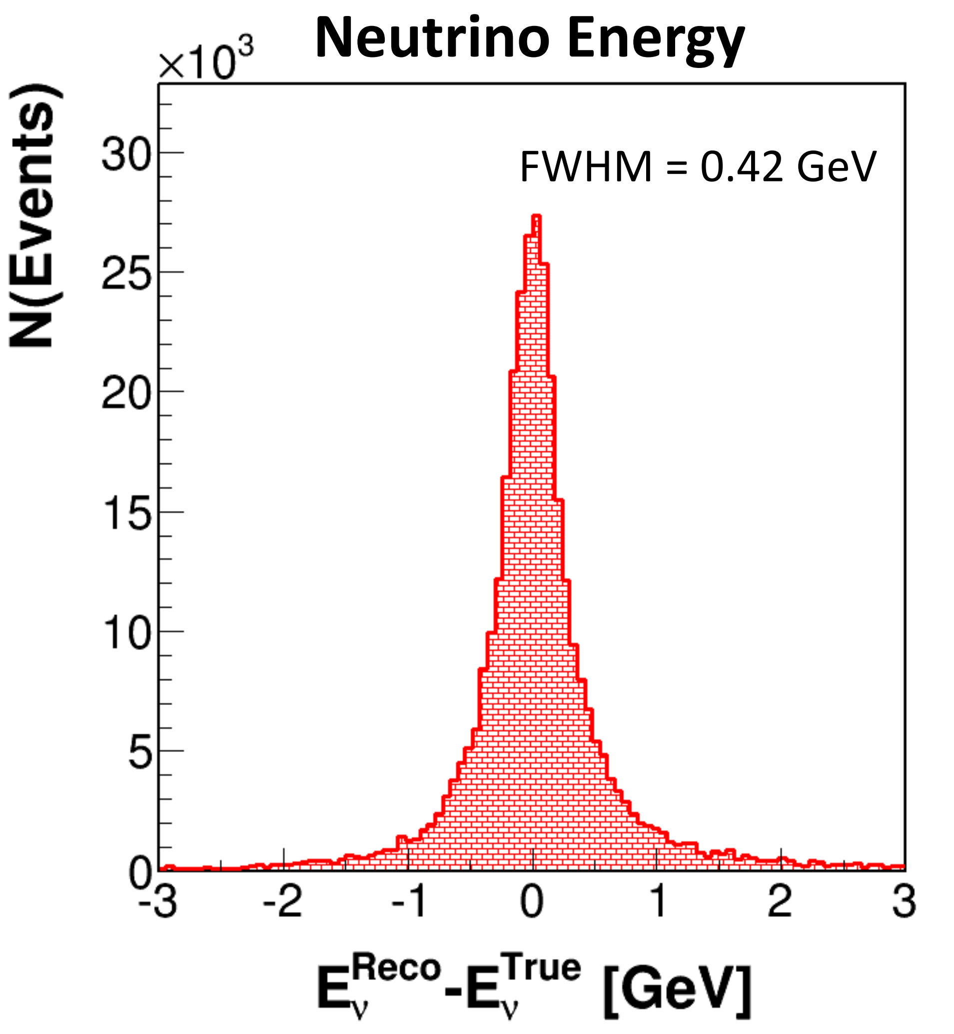
Event Selections

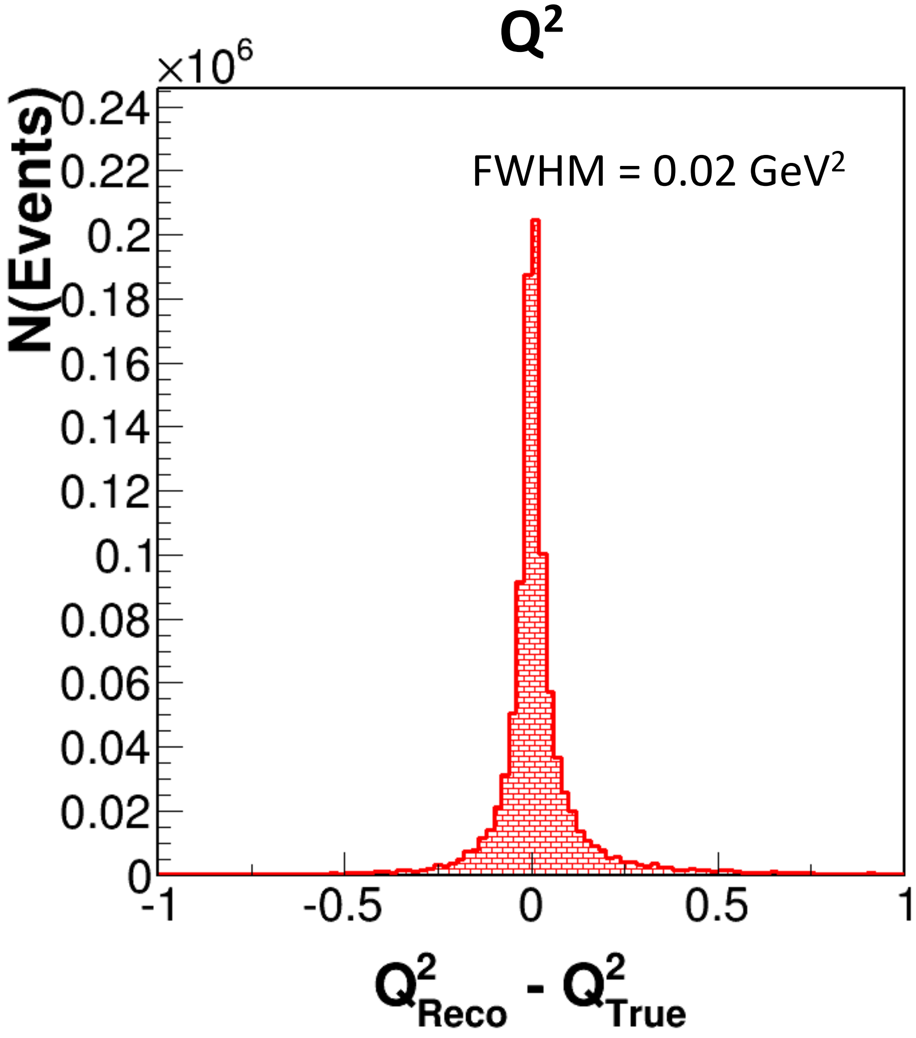
- **Vertex inside Fiducial Volume**
- **MINOS Matched Muon**
- **No Michel Electron**
  - Around Vertex
  - Around Track End Points
  - Around Shower End Points (applied after π^0 reconstruction)
- **Proton Score**
  - LLR > -10 for all Proton Candidates (plot on Backup)
- **PreFilter before Pi0 Reconstruction**
  - Unused Energy in Target < 20 MeV
  - Unused Energy in Detector > 50 MeV – Cannot be a Pi0
  - Unused Energy in Detector < 2500 MeV – DIS Events
- **Pi0 Reconstruction**
  - Require 2 EM Showers
  - Found EM Showers can be fitted to a line passing through vertex
- **Pi0 Quality**
  - Leading Gamma conversion distance > 14cm (plot on Backup)
  - 60 MeV < InvMass < 200 MeV

Particle Momentum Resolutions



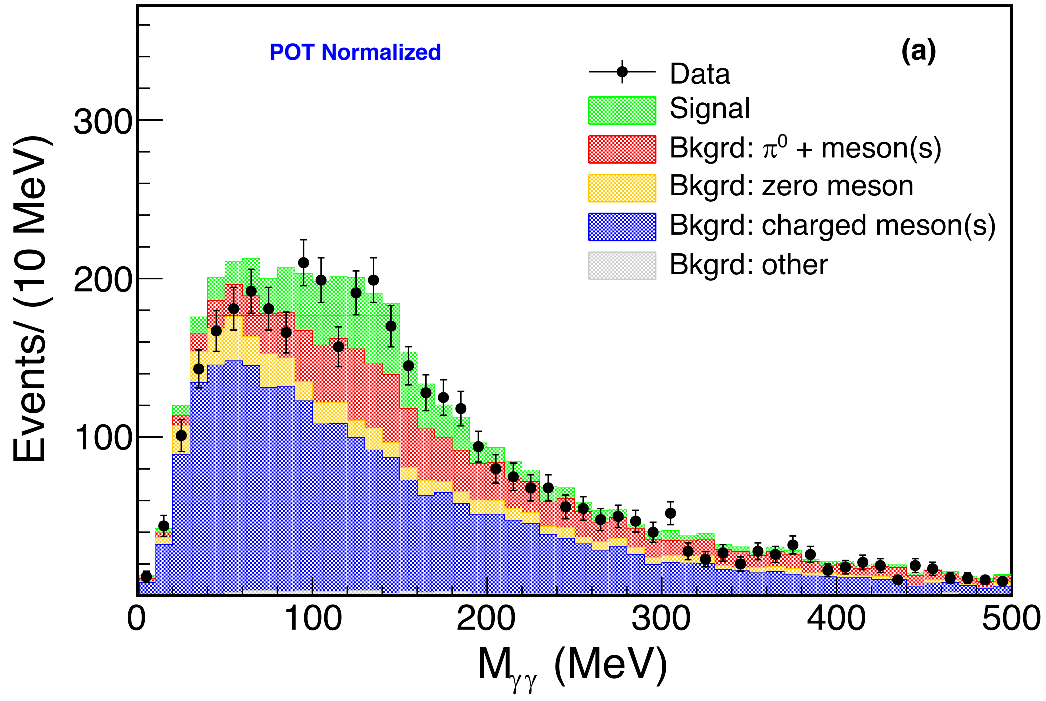
Interaction Kinematics Resolutions



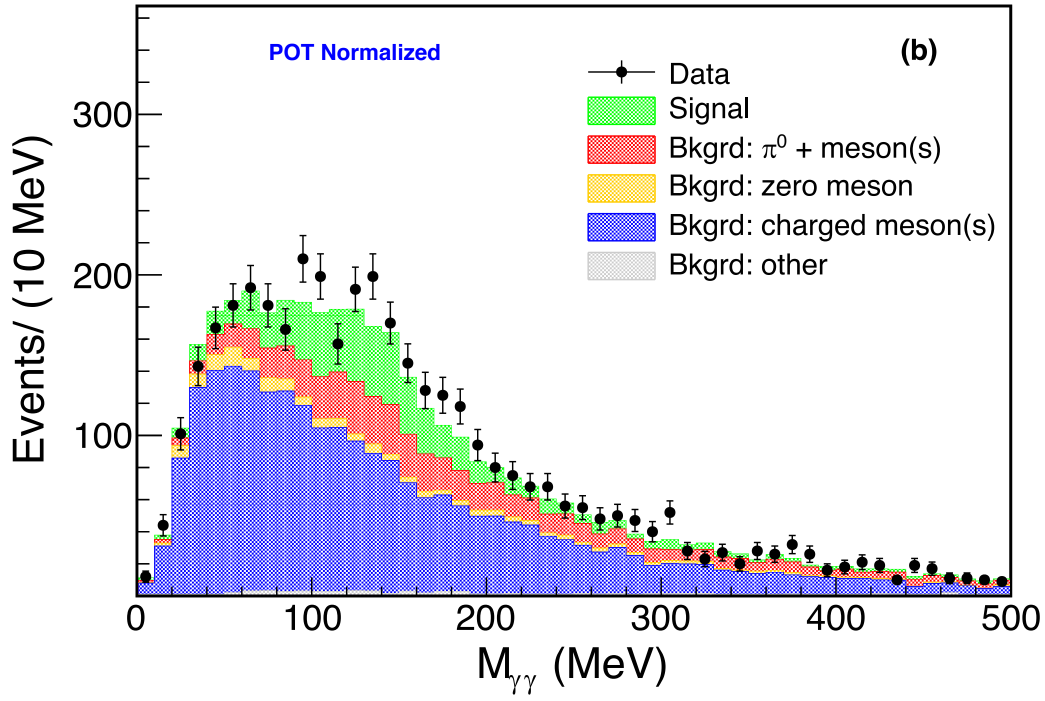


Side Band Fit – Low Proton Score

Before Fit

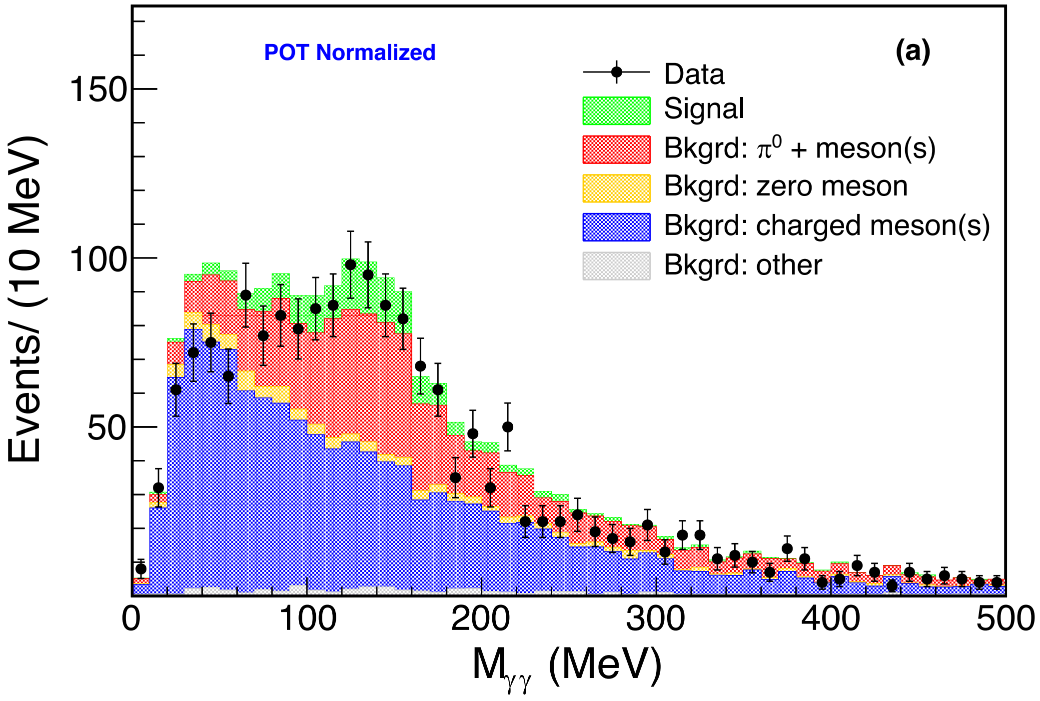


After Fit

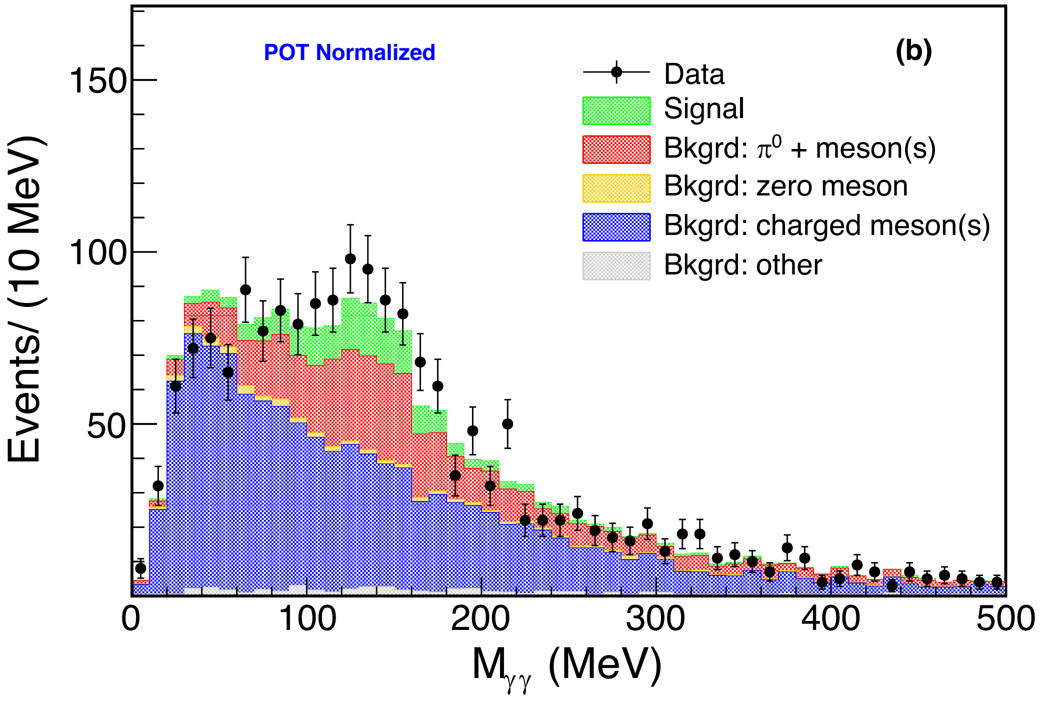


Side Band Fit Michel

Before Fit



After Fit

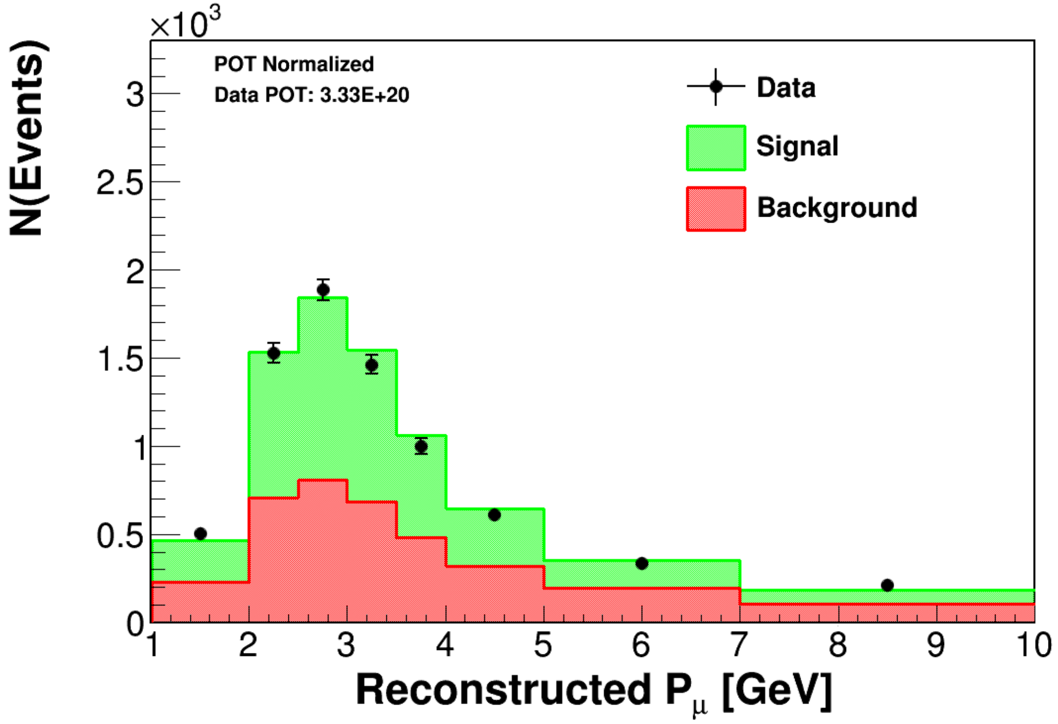


Background Subtraction

$$\left(\frac{d\sigma}{dP_\mu}\right)_i = \frac{1}{\Phi_\nu T_N} \frac{1}{(\Delta P_\mu)_i} \frac{\sum_j U_{ij} \left(N_j^{data} - \boldsymbol{N_j^{bckg}}\right)}{\epsilon_i}$$

- **After event selections, the final sample purity is 50.7%**
  - 1 out of 2 events is “not” signal (background)

- **We subtract the GENIE estimation for the shape of the background distribution from data**
  - Background Subtracted data is treated as 100% signal



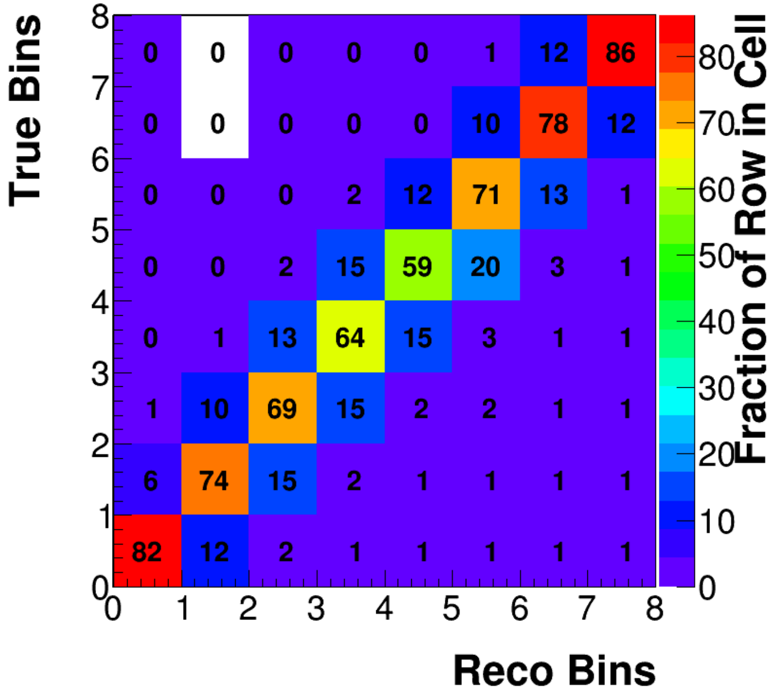
Unfolding

$$\left(\frac{d\sigma}{dP_\mu}\right)_i = \frac{1}{\Phi_\nu T_N}\frac{1}{(\Delta P_\mu)_i}\frac{\sum_j U_{ij}\left(N_j^{data} - N_j^{bckg}\right)}{\epsilon_i}$$

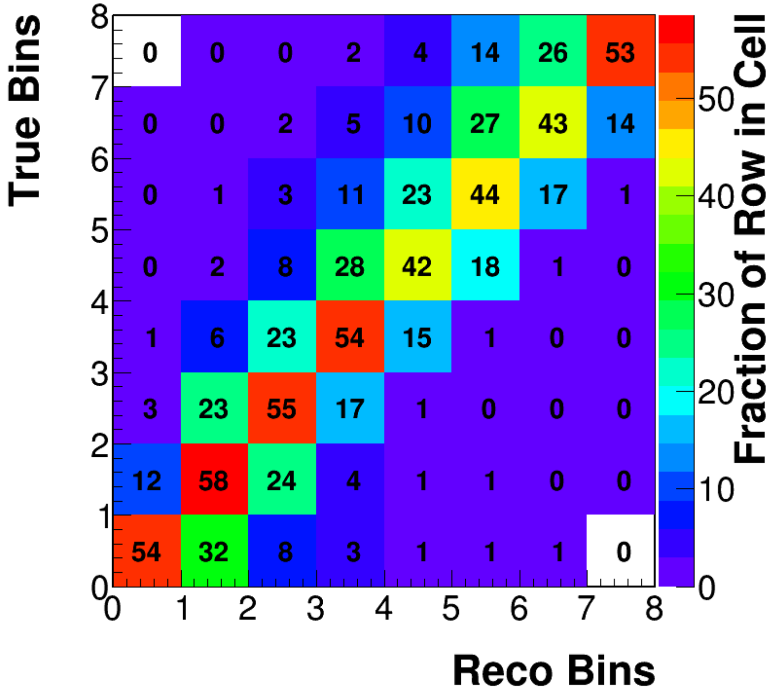
- **For the detected particles the momentum and direction estimations are not perfect**
  - Partial Tracking or Wrong Calibration

- **We use the GENIE estimation for the particle kinematic to correct our measurement**

Muon Momentum



π^0 Momentum

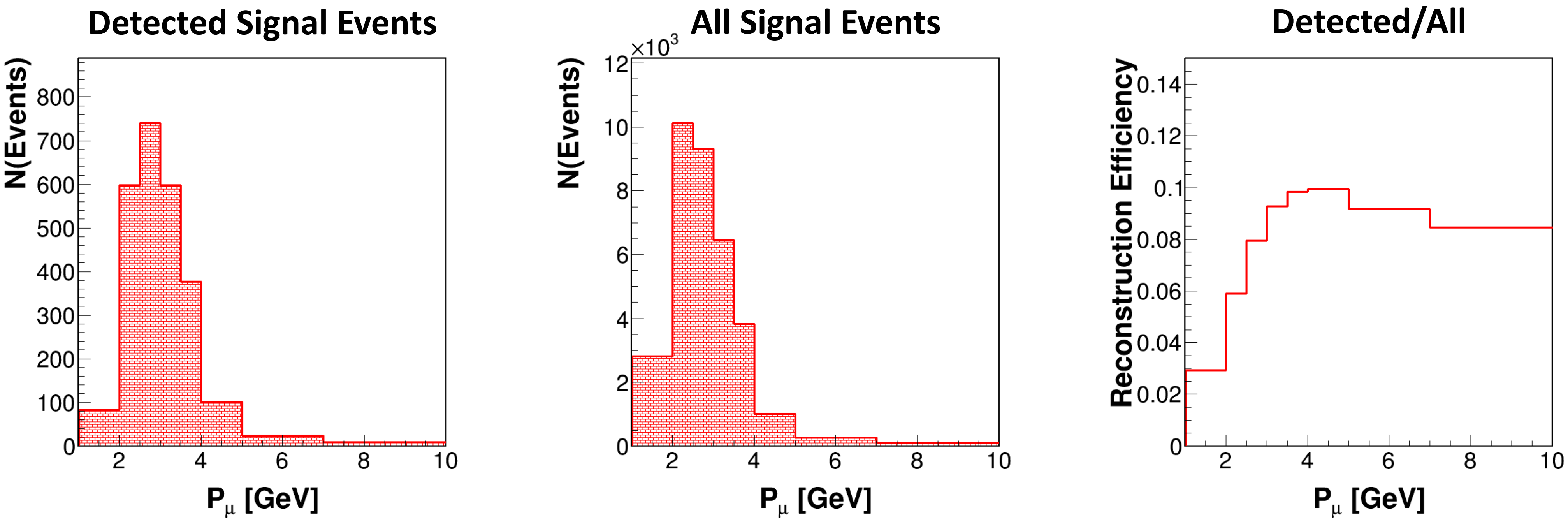


Efficiency Correction

$$\left(\frac{d\sigma}{dP_\mu}\right)_i = \frac{1}{\Phi_\nu T_N}\frac{1}{(\Delta P_\mu)_i}\frac{\sum_j U_{ij}\left(N_j^{data} - N_j^{bckg}\right)}{\epsilon_i}$$

- **We can not detect "all" signal events, our detection efficiency is 8.4%**
  - Particle out of acceptance (MINOS Match)
  - Particle Kinematics out of detector thresholds (low energy)

- **We use GENIE estimation for "detected" signal events and "all" signal events**

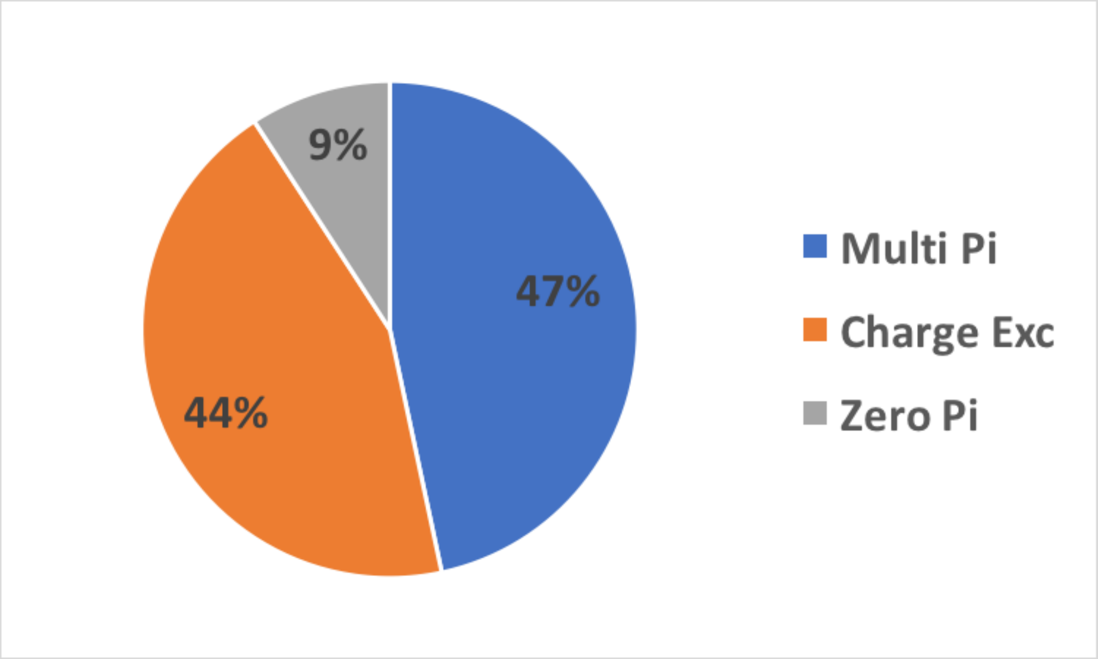


Systematics Grouping

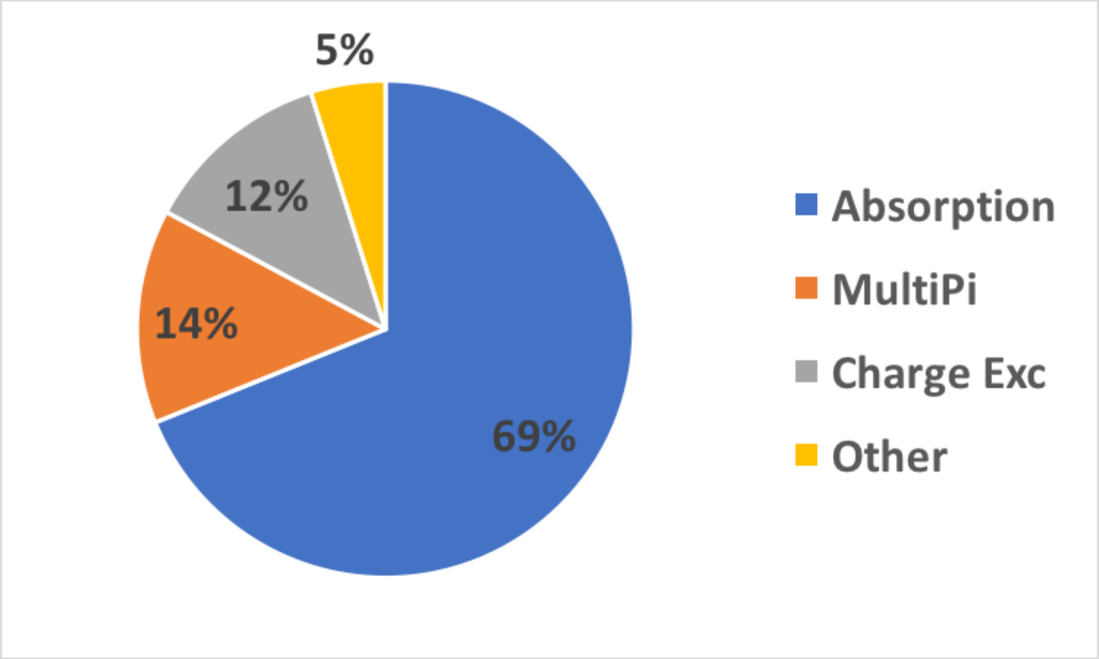
(I) Detector Response	(II) GENIE Cross Section	(III) GENIE FSI	(IV) Flux	(V) Other
EM_EnergyScale	GENIE_AhtBY	GENIE_AGKYxF1pi	Flux	WithPi0 Bckg Const.
Michel Fake	GENIE_BhtBY	GENIE_FrAbs_N		ChargedPion Bckg Const.
Michel True	GENIE_CCQEPauliSupViaKF	GENIE_FrAbs_pi		QELike Bckg Const.
Muon Momentum	GENIE_CV1uBY	GENIE_FrCEx_N		Unfolding
Muon Theta	GENIE_CV2uBY	GENIE_FrCEx_pi		
Muon Tracking	GENIE_EtaNCEL	GENIE_FrElas_N		
Neutron Response	GENIE_MaCCQE	GENIE_FrElas_pi		
Pion Response	GENIE_MaNCEL	GENIE_FrInel_N		
Proton Tracking	GENIE_MaRES	GENIE_FrInel_pi		
ProtonEnergy BetheBloch	GENIE_MvRES	GENIE_FrPiProd_N		
ProtonEnergy Birks	GENIE_NormDISCC	GENIE_FrPiProd_pi		
ProtonEnergy MassModel	GENIE_NormNCRES	GENIE_MFP_N		
ProtonEnergy MEU	GENIE_NormCCRES	GENIE_MFP_pi		
Target Mass	GENIE_Rvn1pi	GENIE_RDecBR1gamma		
	GENIE_Rvn2pi	GENIE_Theta_Delta2Npi		
	GENIE_Rvp1pi			
	GENIE_Rvp2pi			
	GENIE_VecFFCCQEshape			

FSI Feed In vs Feed Out

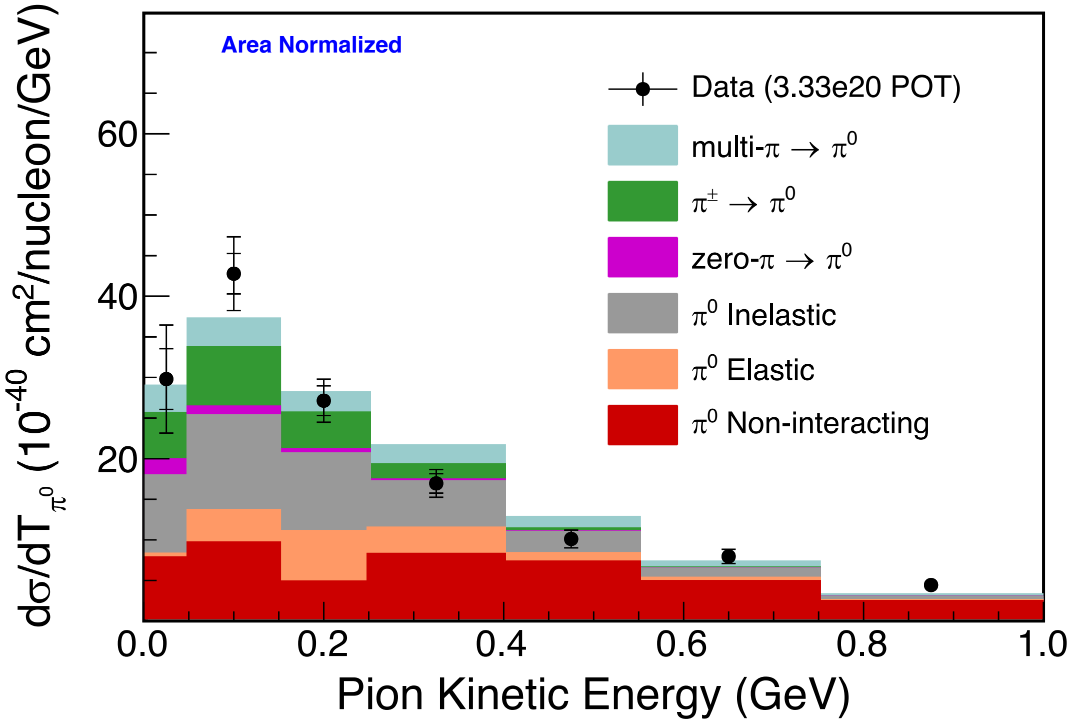
Feed In
Background → Signal

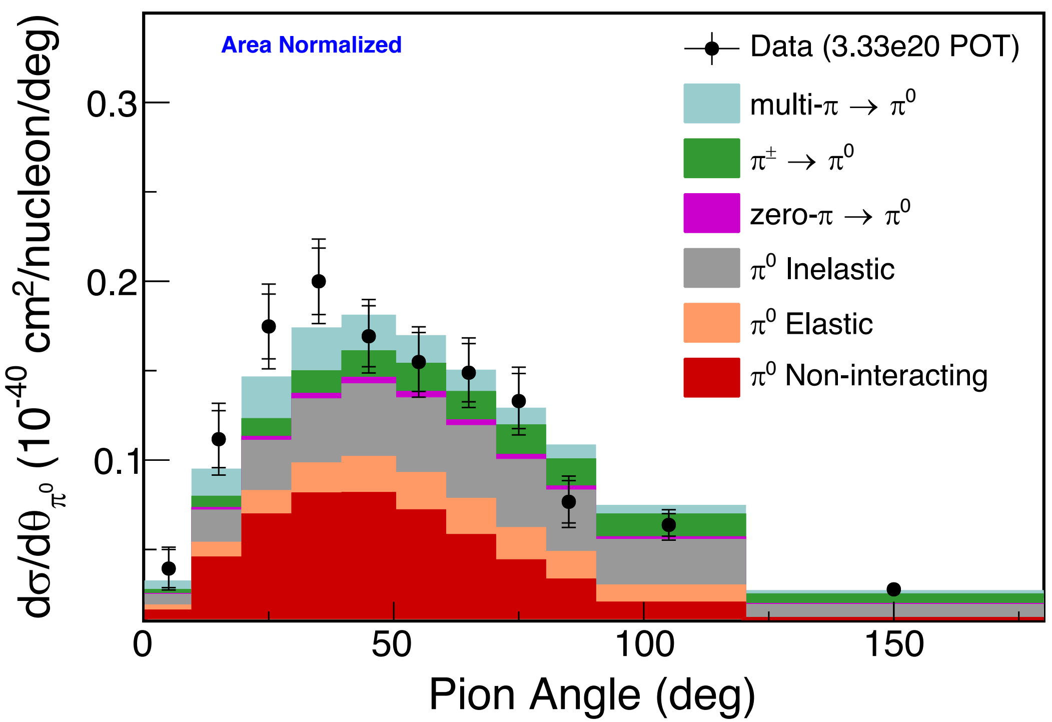


Feed Out
Signal → Background

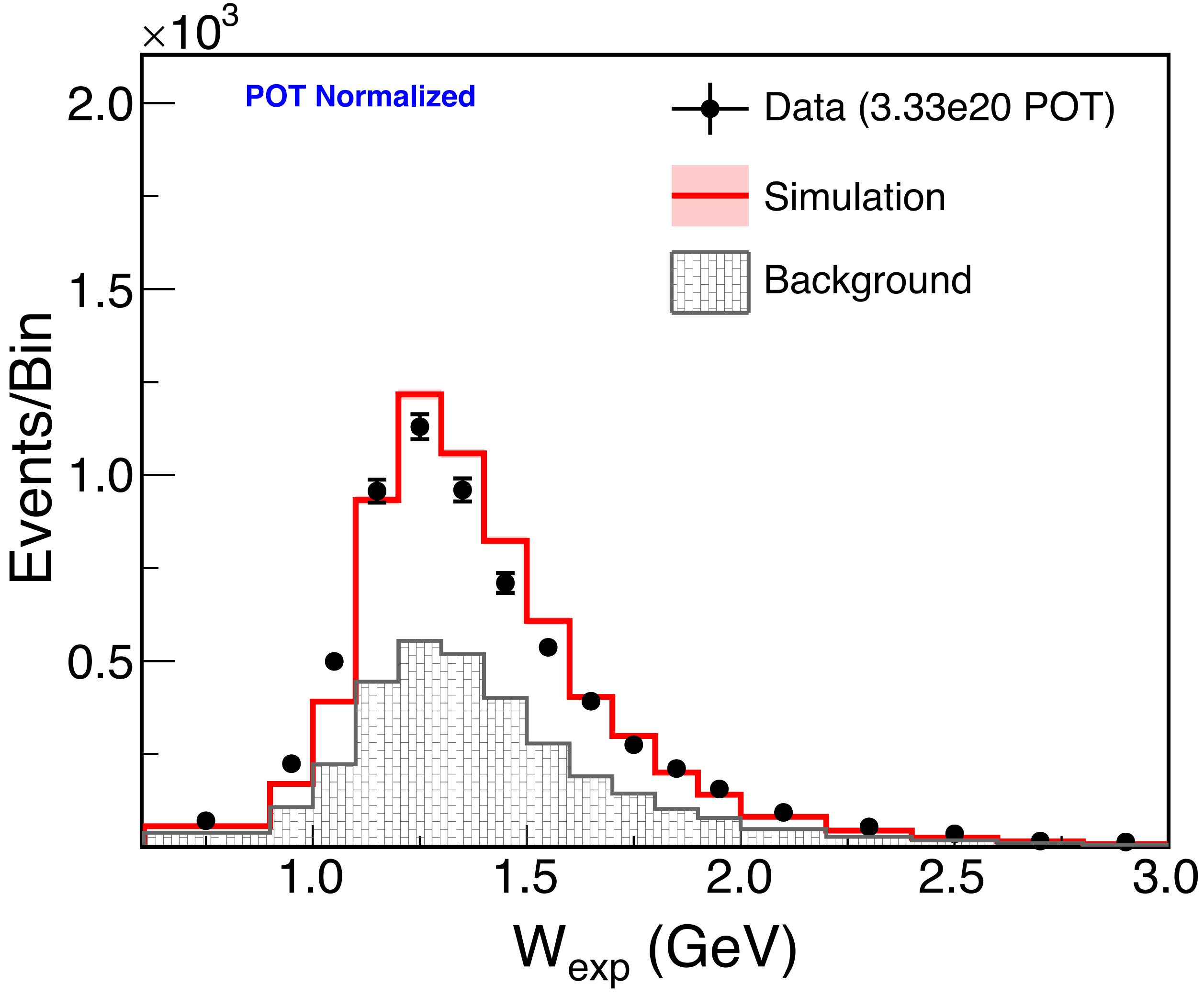


FSI Type decomposition for $d\sigma/dT_\pi$ and $d\sigma/d\theta_\pi$





W beyond 1.8 GeV

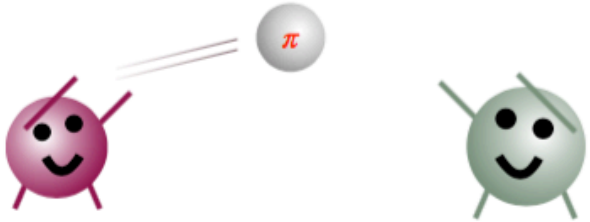


Correlation effects

Correlations can be **short range**…

- Bodek-Ritchie tail to RFG
- Spectral functions

… **medium range**…



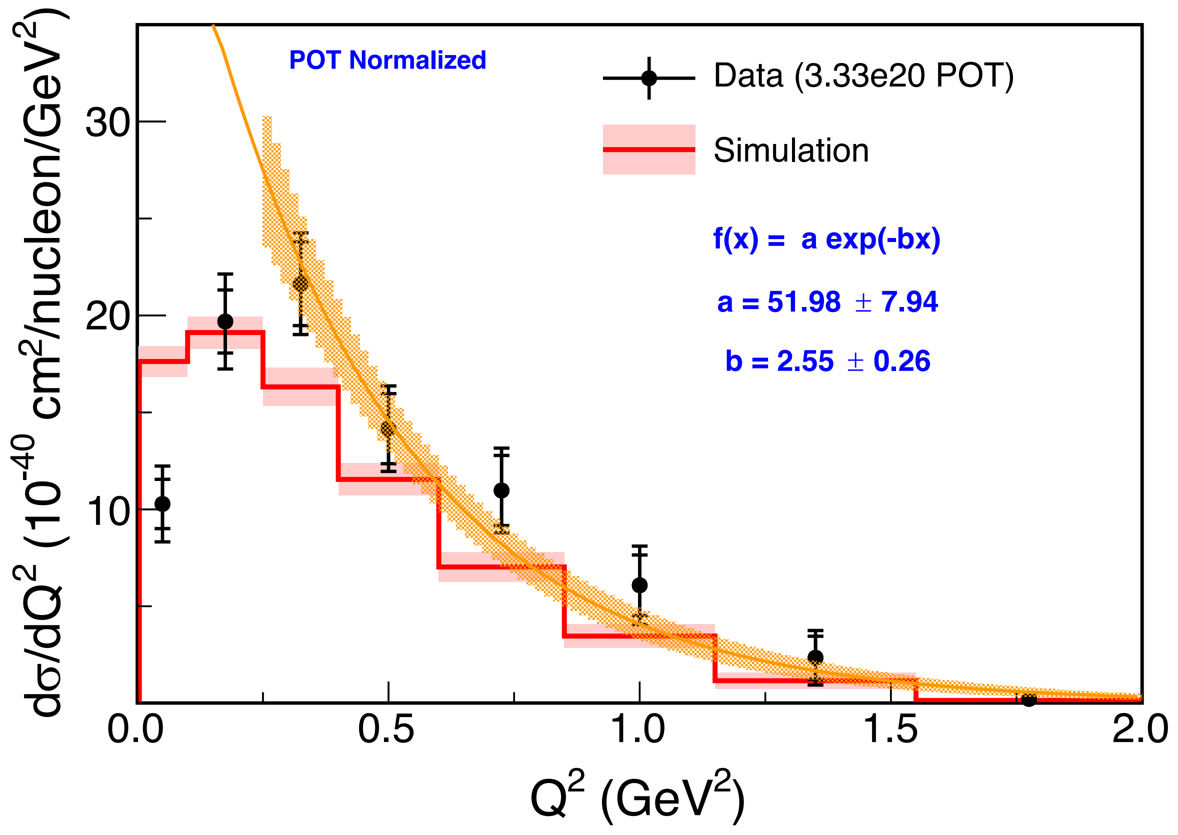
- Meson exchange currents
- Transverse enhancement model

… **or long range**…

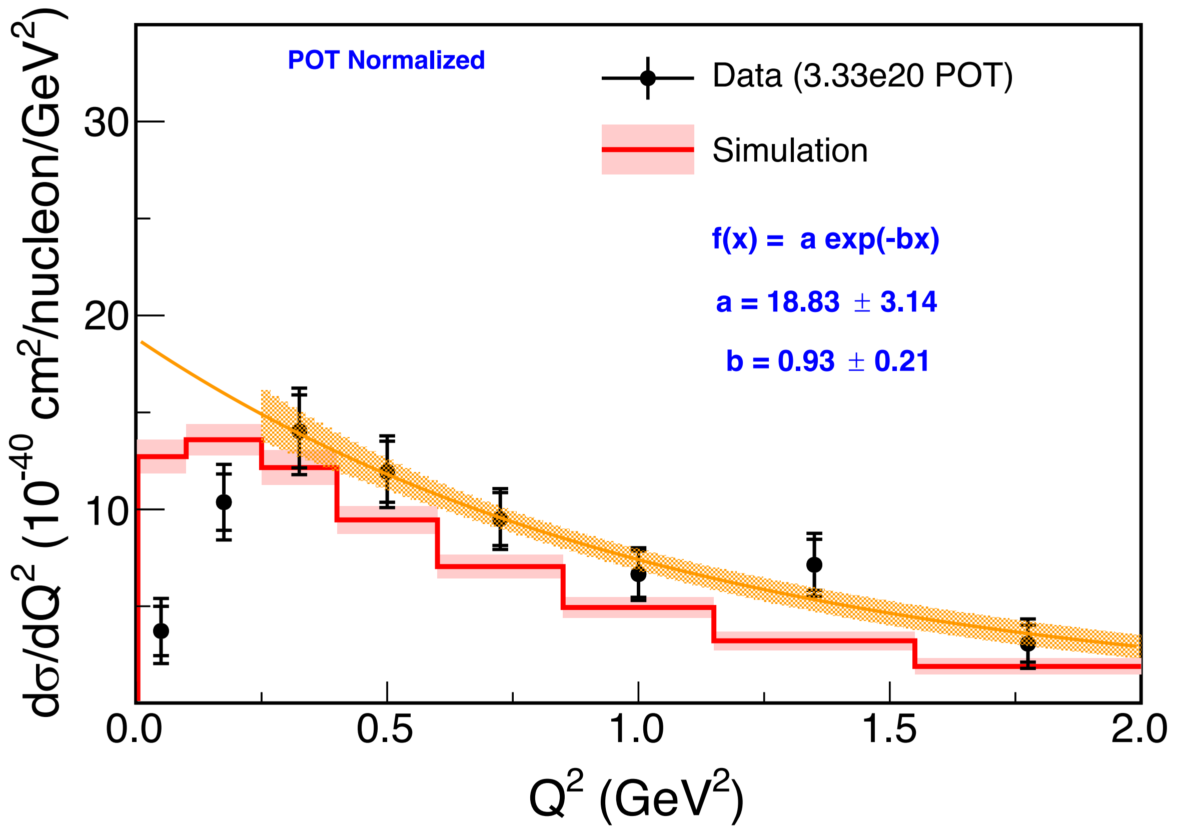
Random phase approximation

Q^2 Fit for Low E_ν and High E_ν

$1.5 \leq E_\nu < 4\text{GeV}$



$4.0 \leq E_\nu < 10\text{GeV}$



Isospin Amplitudes for CC Interactions

Neutrino **Antineutrino**

$$\mathcal{A}(\nu_\mu p \to \mu^- p \pi^+) \equiv \mathcal{A}(\bar{\nu}_\mu n \to \mu^+ n \pi^-)$$

$$\mathcal{A}(\nu_\mu n \to \mu^- p \pi^0) \equiv \mathcal{A}(\bar{\nu}_\mu p \to \mu^+ n \pi^0)$$

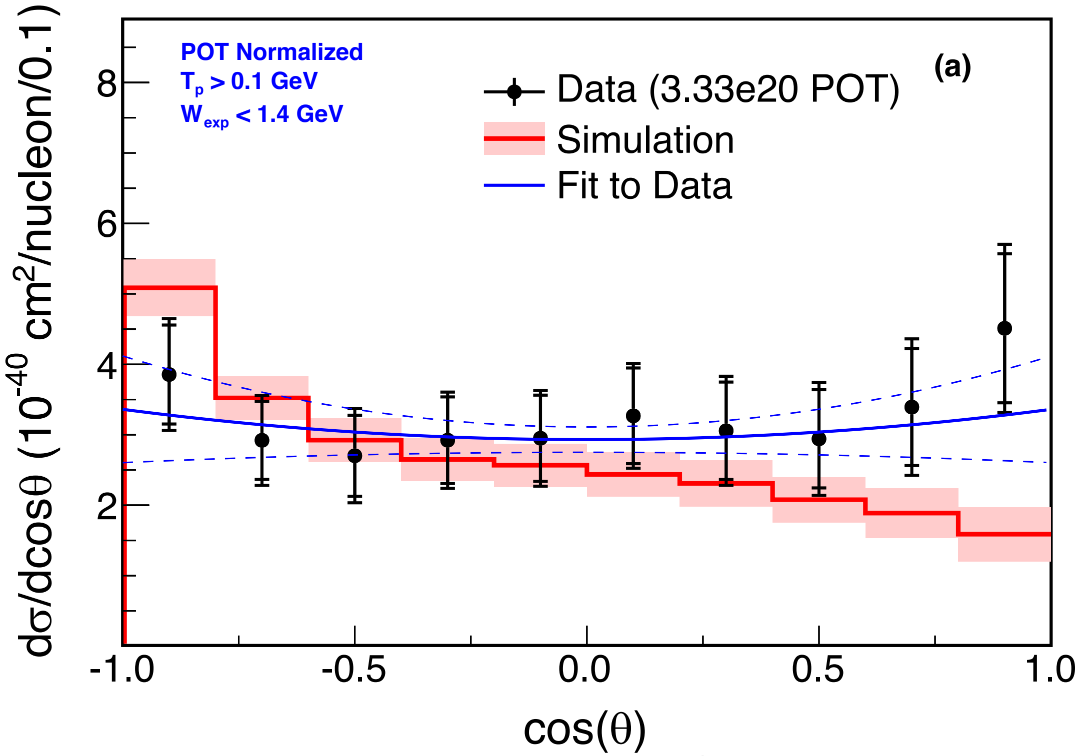
$$\mathcal{A}(\nu_\mu n \to \mu^- n \pi^+) \equiv \mathcal{A}(\bar{\nu}_\mu p \to \mu^+ p \pi^-)$$

$$\mathcal{A}(\nu_\mu p \to \mu^- p \pi^+) = \sqrt{2} A_3$$

$$\mathcal{A}(\nu_\mu n \to \mu^- p \pi^0) = \frac{2}{3}(A_3 - A_1)$$

$$\mathcal{A}(\nu_\mu n \to \mu^- n \pi^+) = \frac{\sqrt{2}}{3}(A_3 + 2A_1)$$

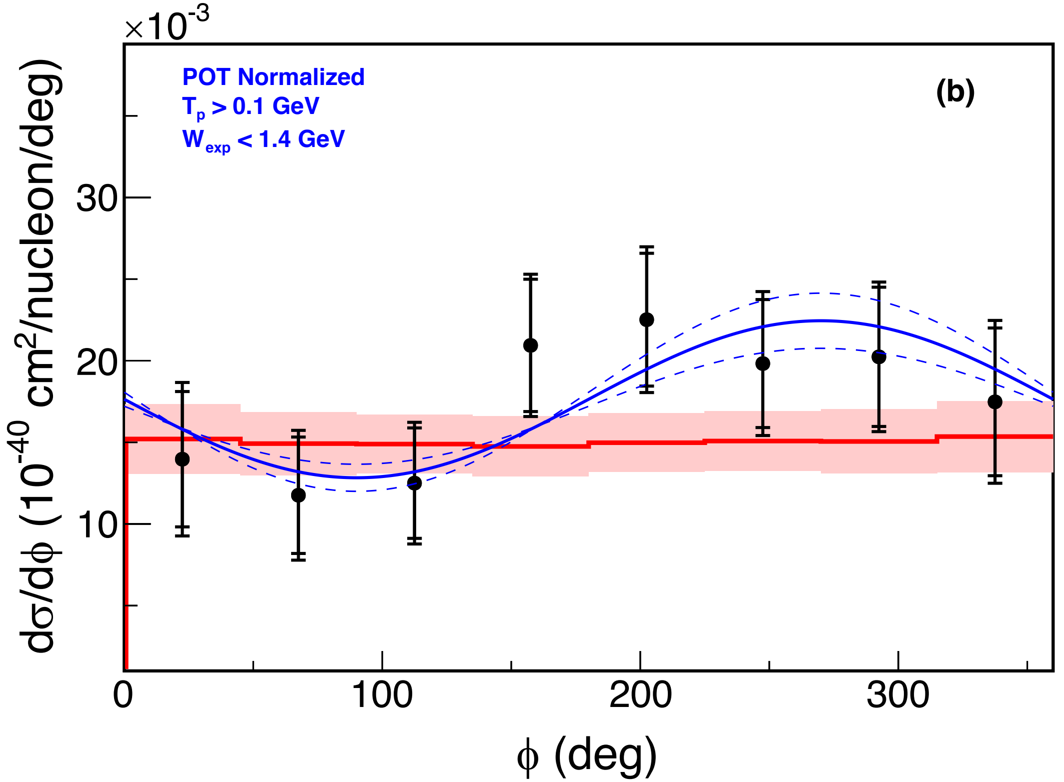
$\Delta^+(1232)$ Polarization – cos(θ) and ϕ



$$y = A + B(\cos\theta)^2$$

$A = 2.93 \pm 0.18$, $B = 0.43 \pm 0.58$

$$\frac{\chi^2_{MC}}{dof} = \frac{20.1}{9} = 2.3 \qquad \frac{\chi^2_{fit}}{dof} = \frac{2.9}{8} = 0.4$$

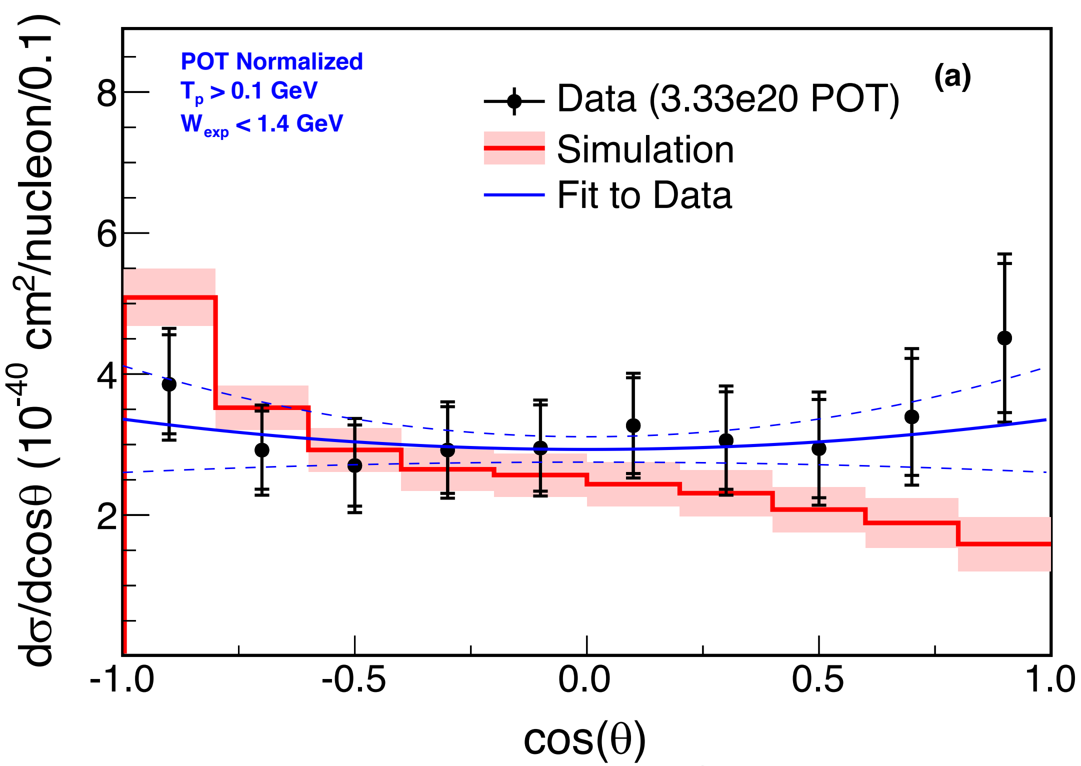


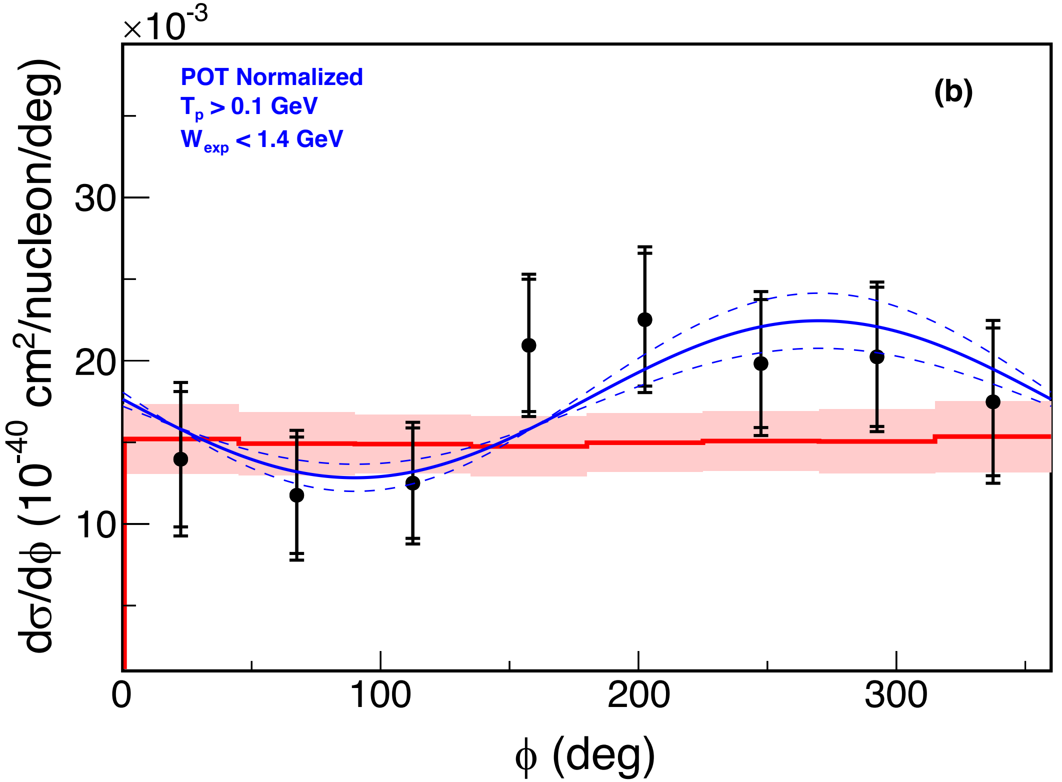
$$y = A + B\sin\phi$$

$A = 17.54 \pm 0.43$, $B = -4.81 \pm 1.26$

$$\frac{\chi^2_{MC}}{dof} = \frac{10.3}{7} = 1.5 \qquad \frac{\chi^2_{fit}}{dof} = \frac{3.3}{6} = 0.6$$

$\Delta^+(1232)$ Polarization – $\cos(\theta)$ and ϕ





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$$y = A + B\sin\phi$$

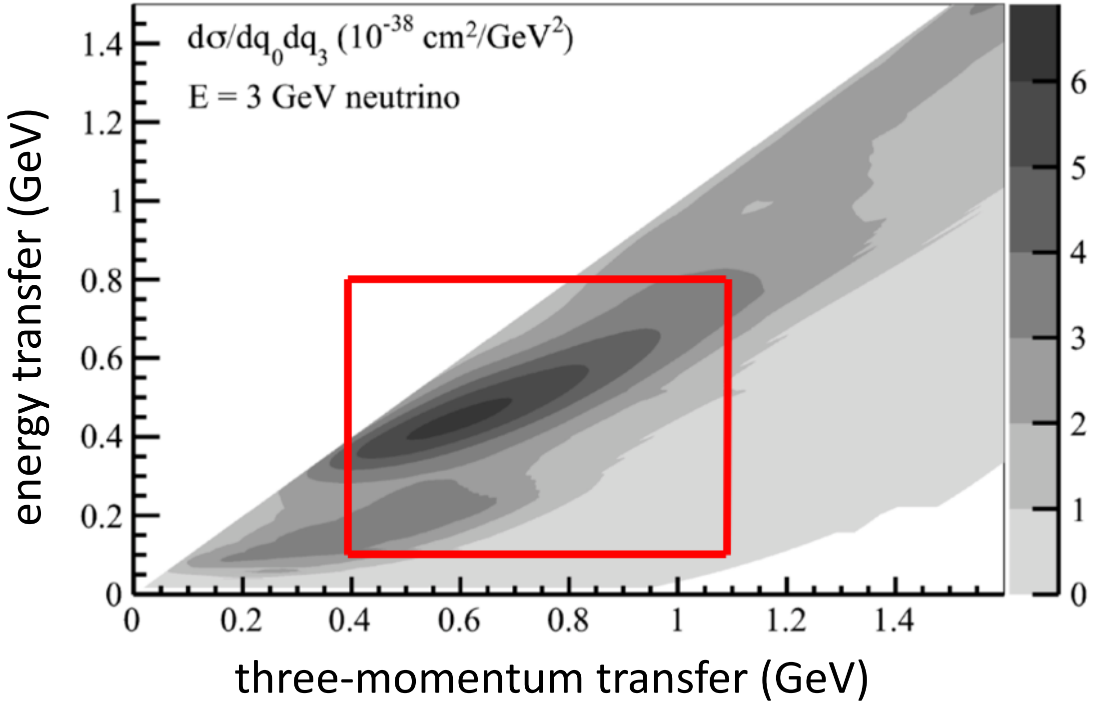
$A = 17.54 \pm 0.43, B = -4.81 \pm 1.26$

$\frac{\chi^2_{MC}}{dof} = 1.5$

$\frac{\chi^2_{fit}}{dof} = 0.6$

Search for 2p2h Contribution in ν_μ–CC(π^0)

- We searched for 2p2h contribution in our background subtracted distributions.
- We defined a search area based on QE-like 2p2h prediction
  - 0.1 < q_0 < 0.8 GeV and 0.4 < q_3 < 1.1 GeV



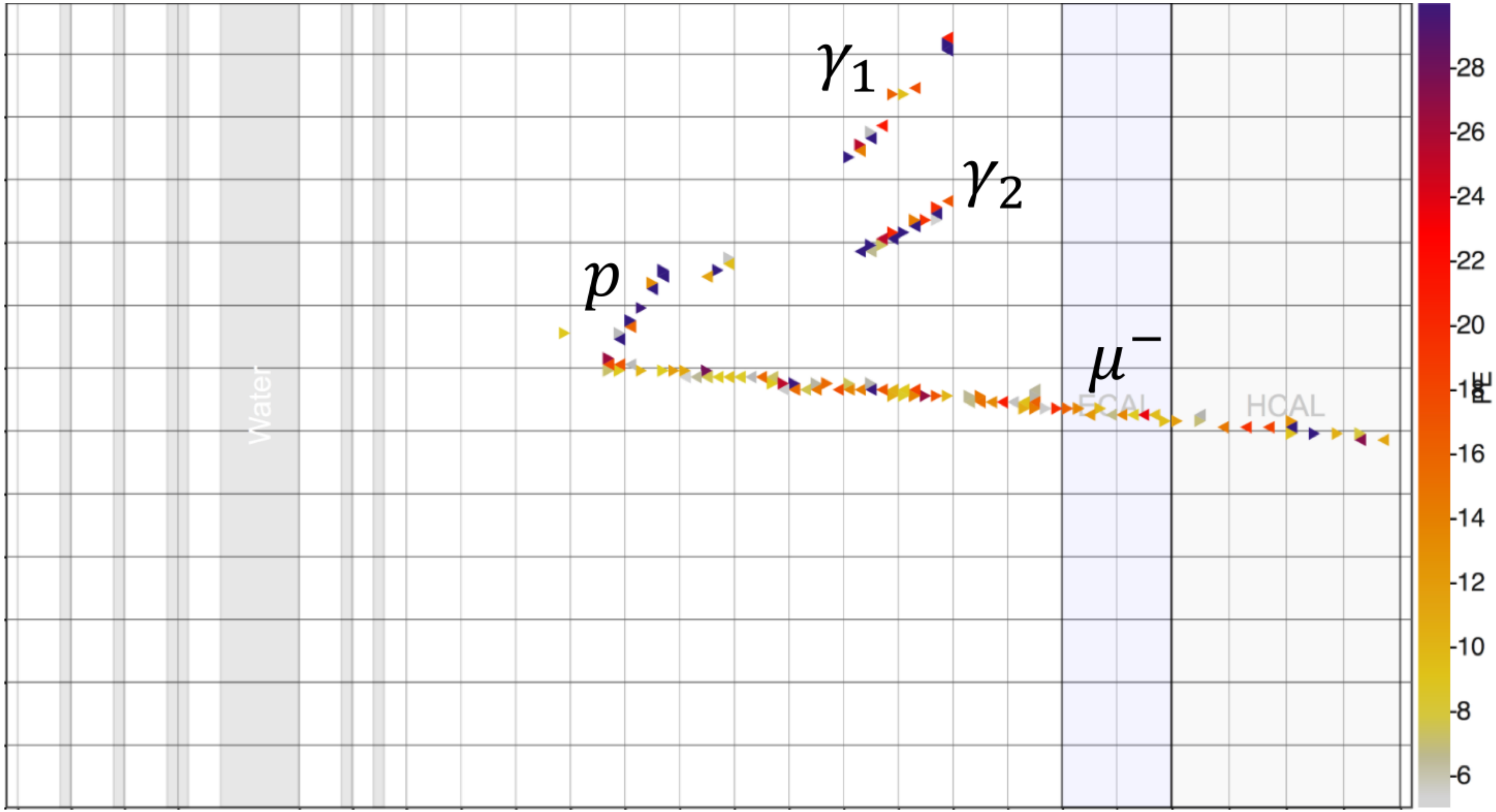
Phys. Rev. D 88, 113007 (2013).

We looked for a "Data Excess" in the search region

Observed an excess of 1.6% of total signal

Based upon this excess we calculated an upper-limit: 3.4% of total signal with 90% C.L.

Event Display: 2204/11/453



Event Display: 2037/17/807