CBPF
Centro Brasileiro de Pesquisas Físicas

Charge-current ν_μ and $\bar{\nu}_\mu$ cross sections on hydrocarbon in the shallow inelastic scattering region

NuINT 2024, 14th International Workshop on Neutrino-Nucleus Interactions

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Expanding the definition of Shallow Inelastic Scattering (SIS)

- SIS is nonresonant meson production as well as the region where Q^2 increases and interactions take place within the nucleon ($Q^2 \gtrsim 1$ GeV^2). This means it also extends into the experimental "DIS" region.

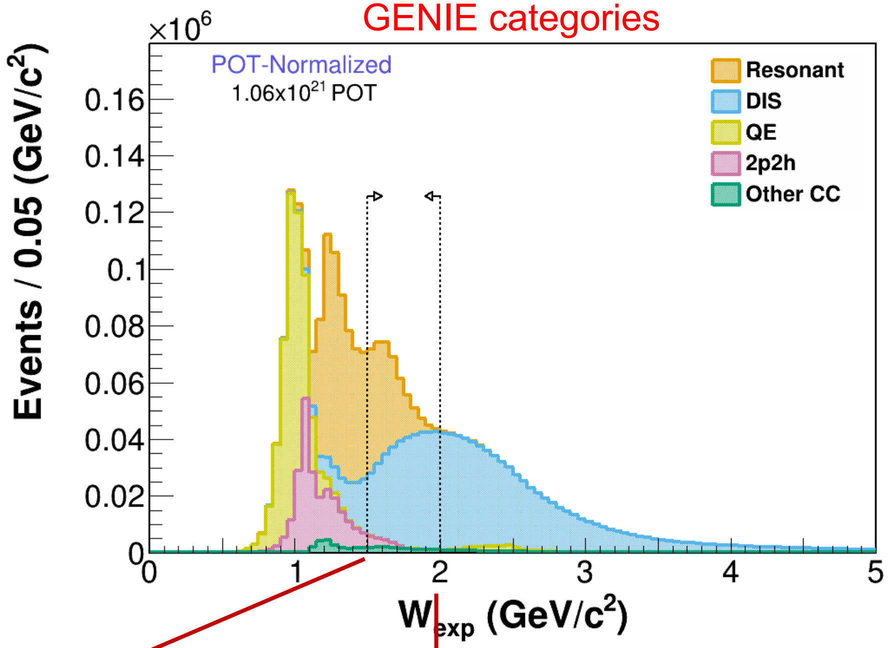
- The SIS domain then includes multi-quark interactions within the nucleon until the region $Q^2 \sim 4$ GeV^2 where single-quark interactions are used for the determination of parton distribution function. ***See Jorge's talk tomorrow***

- For MINERvA, the SIS region is defined experimentally as inclusive meson production in the region $1.5 < W_{exp} < 2$ GeV, with and without a $Q^2 > 1$ GeV^2 cut.

- The $Q^2 > 1$ GeV^2 cut is to emphasize the multi-quark component of SIS.

- This includes nonresonant meson production, resonant meson production, SIS quark-fragmented meson production, and the interference between them.

- W_{exp} is the invariant mass of the hadronic system, assuming the target nucleon is at rest:
  $(W_{exp} = \sqrt{M_N^2 + 2E_{had}M_N - Q^2})$.



$W_{exp} > 1.5$ GeV decreases the contribution of resonance pions (Delta)

$W_{exp} < 2$ GeV reduces the inclusion of single-quark DIS events

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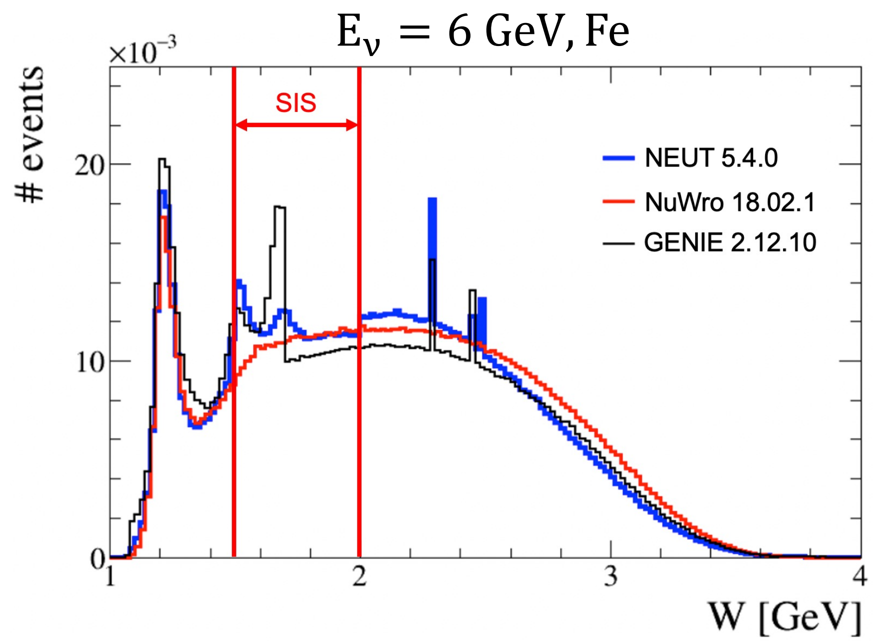
Importance of the SIS Measurements

- MC neutrino event generators predict different neutrino cross sections for this SIS experimental region.

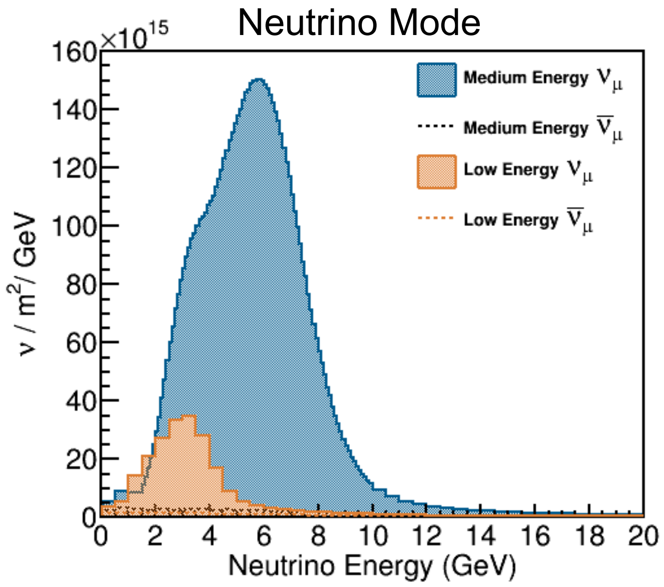
- A detailed study is very necessary to reduce systematic uncertainty for oscillation experiments. For example, DUNE expects more than 45% of events with W > 1.5 GeV.

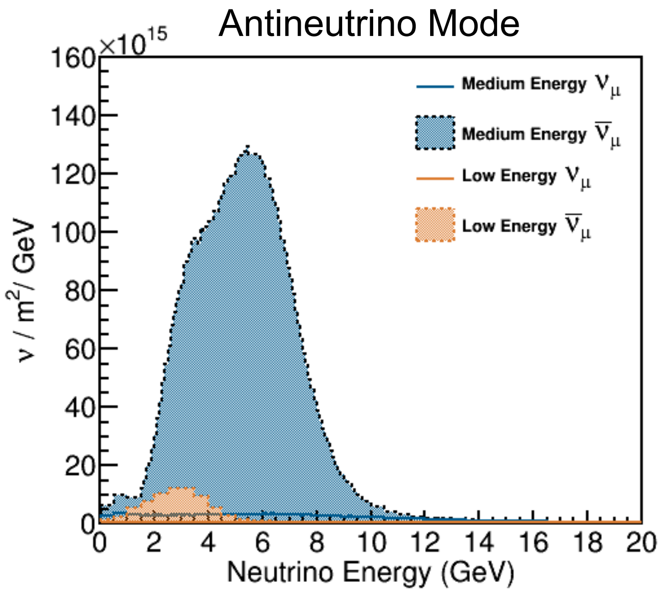
- This is the first measurement of the neutrino/antineutrino cross sections of this SIS experimental region since low statistics bubble chamber experiments 40 years ago.

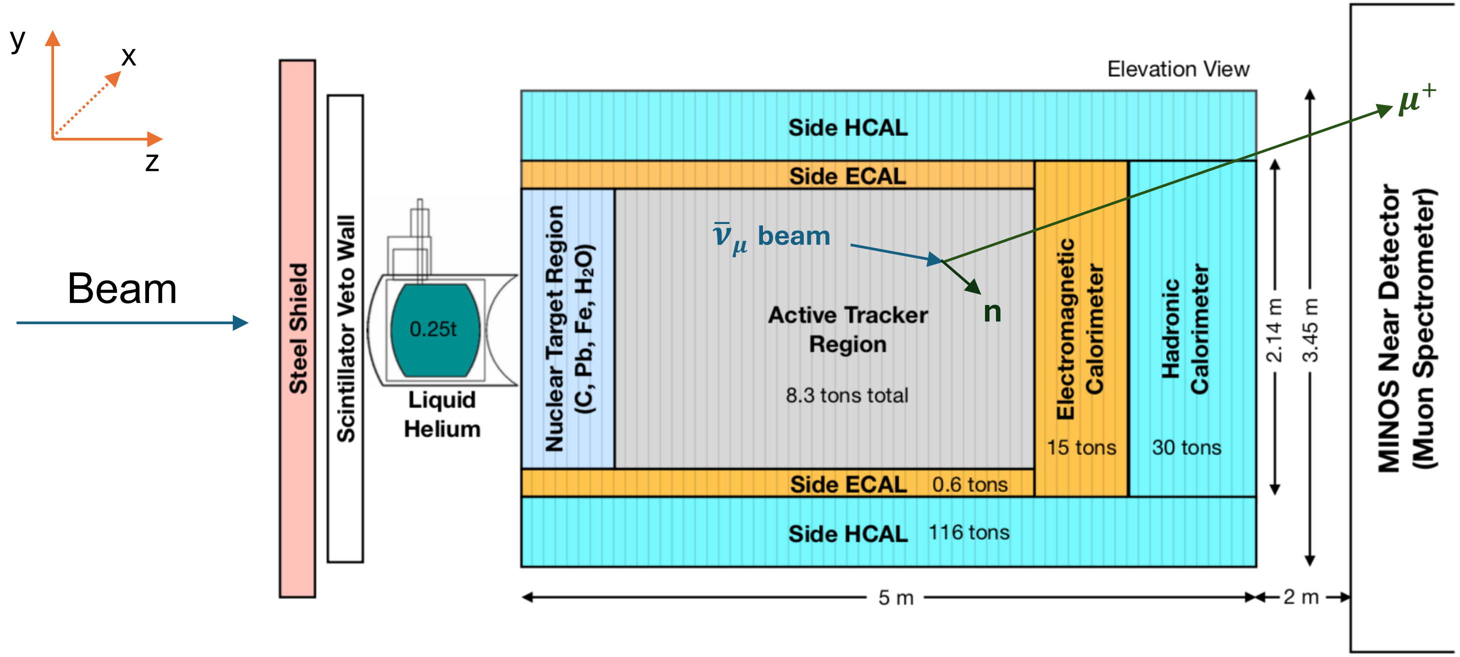


arXiv:1608.02716 (2016)

Experimental Setup







ME 2013-2019
- ν: 12.1 x 10^{20} POT
- $\bar{\nu}$: 12.4 x 10^{20} POT

Simulation

- **GEANT4 simulates the flux.**
  - Hadron production models are constrained using external data.
  - The flux uncertainty is reduced from 7.6% (7.8%) to 3.3% (4.7%) for ν_μ ($\bar{\nu}_\mu$) using $\nu_\mu + e$ and inverse muon decay constraints (***Phys. Rev. D 107, 012001 (2023)***). ***See Luis's talk on Tuesday***

- **GENIE 2.12.6 simulates the neutrino interactions.**
  - Neutrino event generator
    - Handles all nuclear targets and neutrino flavors.
    - Processes from MeV to PeV energy scales.
  - Neutrino interactions
    - Quasielastic → Llewellyn-Smith formalism
    - Resonance production → Rein-Sehgal single π model
    - SIS and DIS → Bodek-Yang model

- **GEANT4 4.9.3.p6 models the final state particle interactions in the detector.**

MINERvA Tuning of Rein-Sehgal and Bodek-Yang models

This tune is called MINERvA Tune v2 and used in this analysis. The relevant part for SIS is in red

- QE events simulation was improved by including the random phase approximation (RPA).
  Phys. Rev. C 70, 055503 (2004), ***arXiv:1705.02932 (2017)***

- Valencia model to simulate 2p2h.
  - 2p2h model enhanced by fitting the simulation with the data in the low recoil analyses.
    Phys. Rev. Lett. 116, 071802 (2016)

- Nonresonant pion production was reduced by 43% using datasets of neutrino-deuterium cross sections. This is a modification of the Bodek-Yang model for W < 2 GeV.

  Eur. Phys. J. C 76, 474 (2016)

- Low Q^2 resonant suppression. The tuning was performed using data from MINERvA pion production measurements on hydrocarbon.

  Phys. Rev. D 100, 072005 (2019)

How do we extract a cross section?

$$\left(\frac{d\sigma}{d\beta}\right)_i = \frac{1}{T_n \Phi \Delta\beta_i} \frac{\sum_j U_{ij}\left(N_j^{data} - N_j^{bkg}\right)}{\epsilon_i}$$

Kinetic Variables

- $E_\nu = E_{had} + E_\mu$
- $Q^2 = 2E_\nu(E_\mu - p_\mu \cos\theta_\mu) - m_\mu^2$
- $W = \sqrt{M_N^2 + 2E_{had}M_N - Q^2}$
- $p_{T\mu} = p_\mu \sin\theta_\mu$
- $p_{\parallel\mu} = p_\mu \cos\theta_\mu$
- $x = \frac{Q^2}{2M_N E_{had}}$
- $\xi = \frac{2x}{1+\sqrt{1+\frac{4M_N^2 x^2}{Q^2}}}$

We measure the cross section as a function of $\mathbf{Q^2}$, $\mathbf{p_{T\mu}}$, $\mathbf{p_{\parallel\mu}}$, $\mathbf{x}$, $\boldsymbol{\xi}$

- The p muon variables are less sensitive to the hadron system systematic.
- MINERvA has done this for several analyses.

- Nachtmann variable corrects the Bjorken x distribution for target mass effects.
- We want to use x and $\boldsymbol{\xi}$ to understand how this grows into the DIS region.
- Both can be used to test duality. ***See Jorge's talk tomorrow***

Event Selection

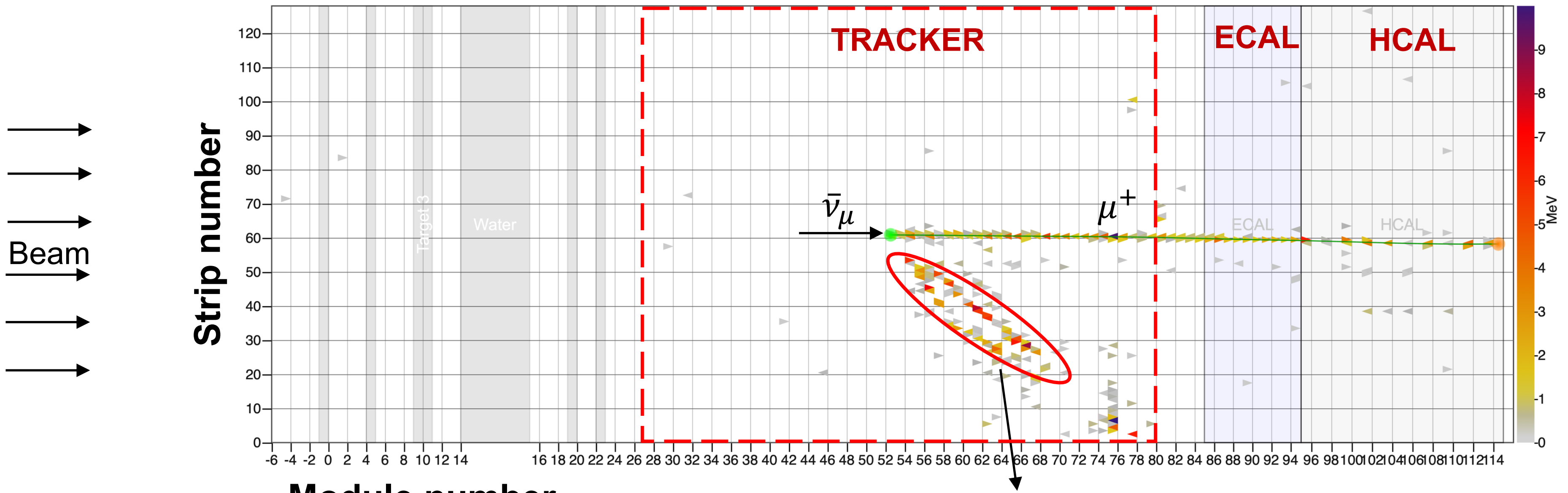
Signal Definition

- $\nu_\mu(\bar{\nu}_\mu)$ CC
- $1.5 < W_{exp} < 2$ GeV
- $\theta_\mu < 20°$ wrt beam
- $2 < E_\mu < 20$ GeV

Event Selection

- Muon track in MINERvA that matches with a track in MINOS
- $1.5 < W_{exp} < 2$ GeV
- Quality cuts

SIS data candidate event



$$E_\nu = E_{had} + E_\mu$$

- **E_{had} is reconstructed calorimetrically from the visible energy of all clusters that are not part of the muon track.**
- **A correction is applied to compensate for the loss of visible energy.**

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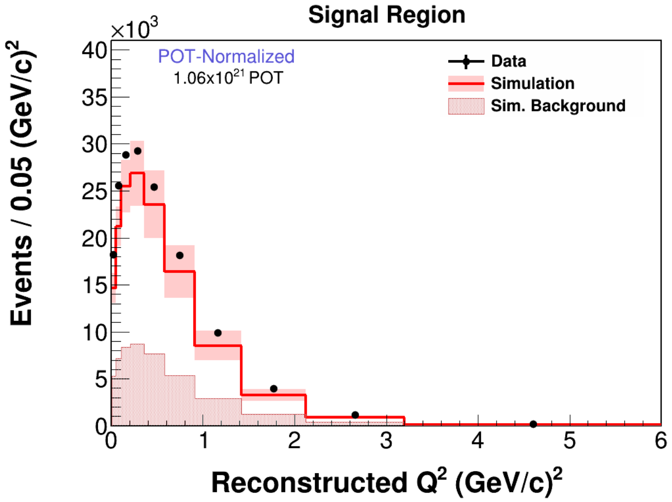
Selected Sample (Neutrino)

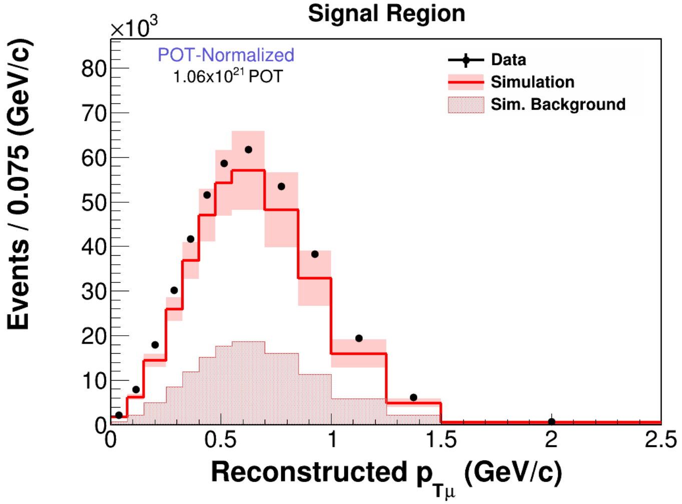
1.5 < Reco W_{exp} < 2 GeV

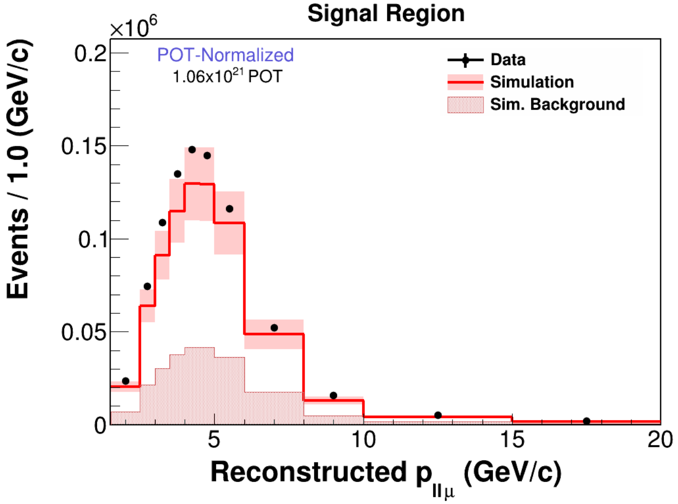
- The sample purity is 66% (53%) for Q^2 > 0 GeV^2 (Q^2 > 1 GeV^2).

617,953 events for Q^2 > 0 GeV^2
174,089 events for Q^2 > 1 GeV^2

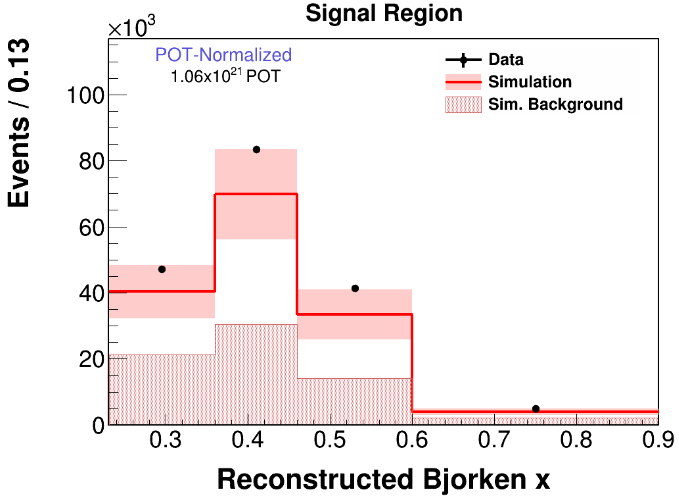


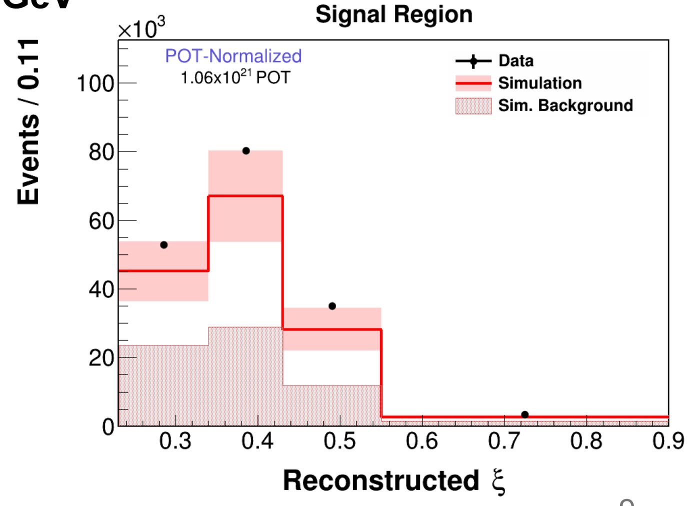
Q^2 > 0 GeV^2





Q^2 > 1 GeV^2



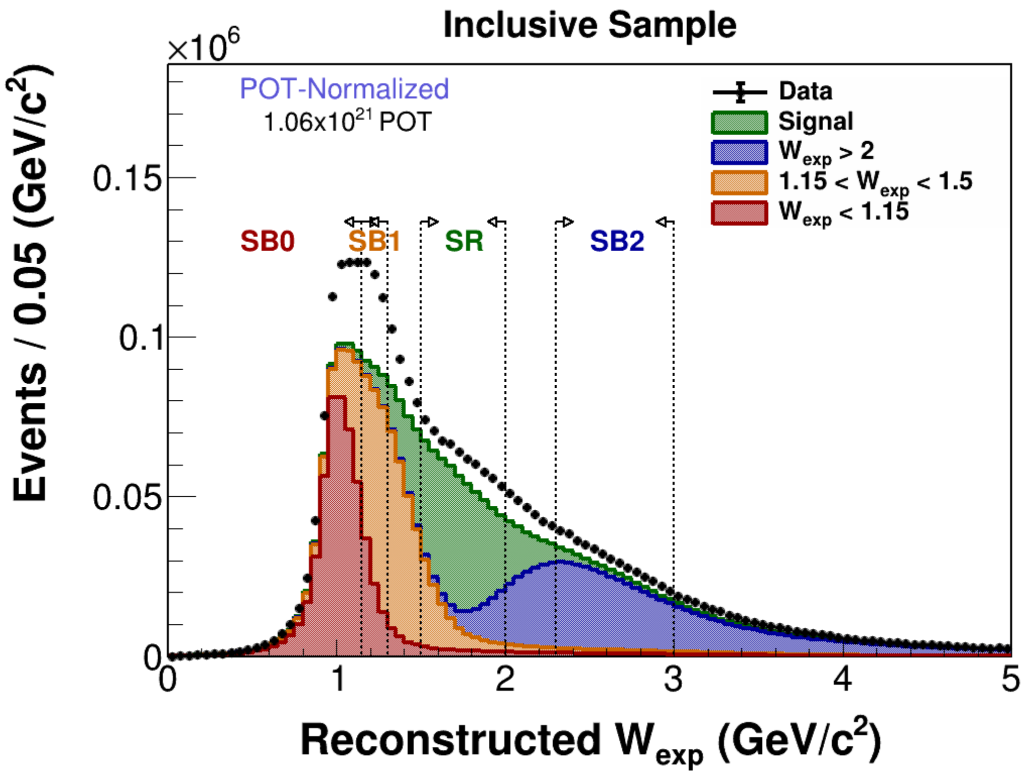


Non-SIS Background

$$\left(\frac{d\sigma}{dX}\right)_i = \frac{1}{T_n \Phi \Delta X_i} \frac{\sum_j U_{ij}\left(N_j^{data} - N_j^{bkg}\right)}{\epsilon_i}$$

- Remember, MINERvA SIS signal region is defined as 1.5 < Reconstructed W_{exp} < 2 GeV.
- We want to subtract events that aren't truly signal events but have been smeared into the signal region.
- The data outside the signal region is used to constrain the MC to the data.
- The regions used for the constraint are called sidebands.
- The sidebands are separated into kinematic regions:

True W_{exp} < 1.15 GeV → is mainly experimental QE
1.15 < True W_{exp} < 1.5 GeV → is mainly experimental resonance
True W_{exp} > 2 GeV → is mainly experimental DIS



Non-SIS Background

$$\left(\frac{d\sigma}{dX}\right)_i = \frac{1}{T_n \Phi \Delta X_i} \frac{\sum_j U_{ij}\left(N_j^{data} - N_j^{bkg}\right)}{\epsilon_i}$$

- A χ^2 minimization fit is used to extract weight functions that tune the MC sideband to data.
- Q^2 was the variable to perform the fit and fix the data MC discrepancy for other variables.

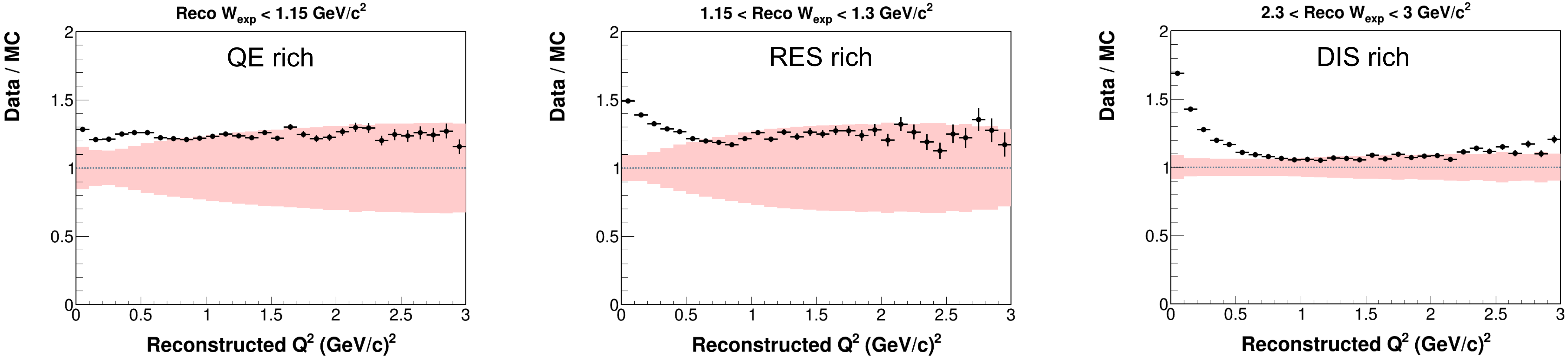
$$\chi^2 = \sum_s \sum_i \frac{\left(N_{s,i}^{MC} - N_{s,i}^{Data}\right)^2}{N_{s,i}^{Data}}$$

s = {QE rich, RES rich, DIS rich}

$i \rightarrow Q^2$ bins

$$N_{s,i}^{MC} = f_0 N_{s,i}^{W<1.15} + f_1 N_{s,i}^{1.15<W<1.5} + f_2 N_{s,i}^{W>2} + N_{s,i}^{Signal}$$

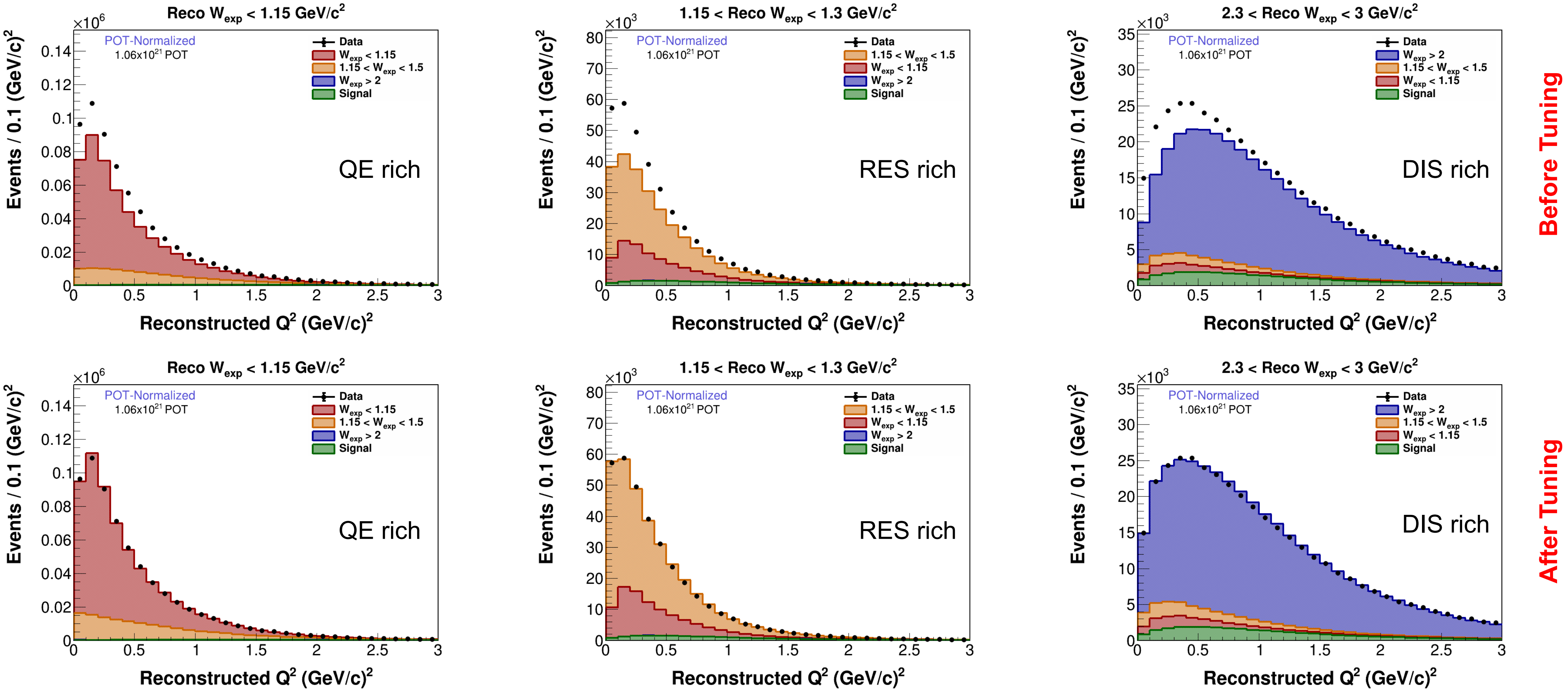
The pink band is the MC systematics



Non-SIS Background (Neutrino)

$$\left(\frac{d\sigma}{dX}\right)_i = \frac{1}{T_n \Phi \Delta X_i} \frac{\sum_j U_{ij}\left(N_j^{data} - N_j^{bkg}\right)}{\epsilon_i}$$

- We have brought the MC prediction to the data.



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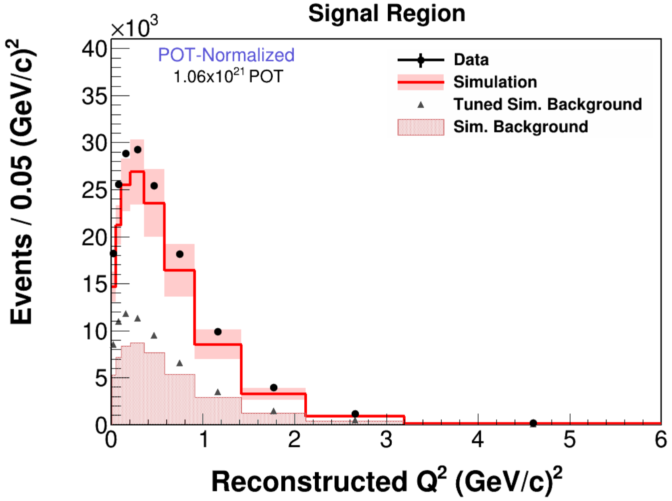
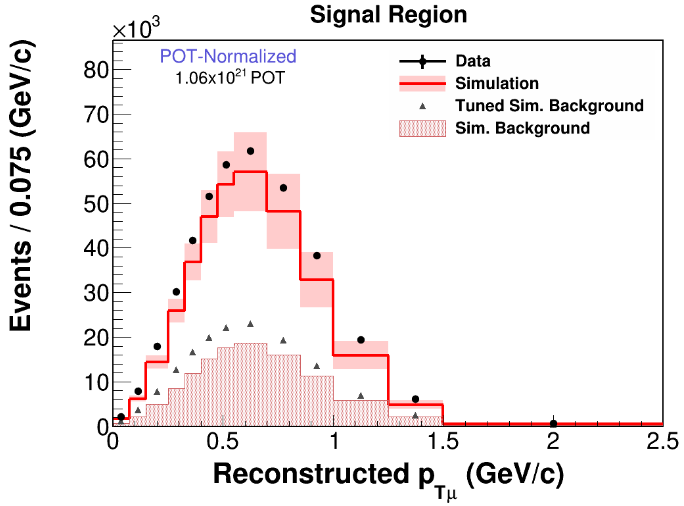
SIS Sample (Neutrino)

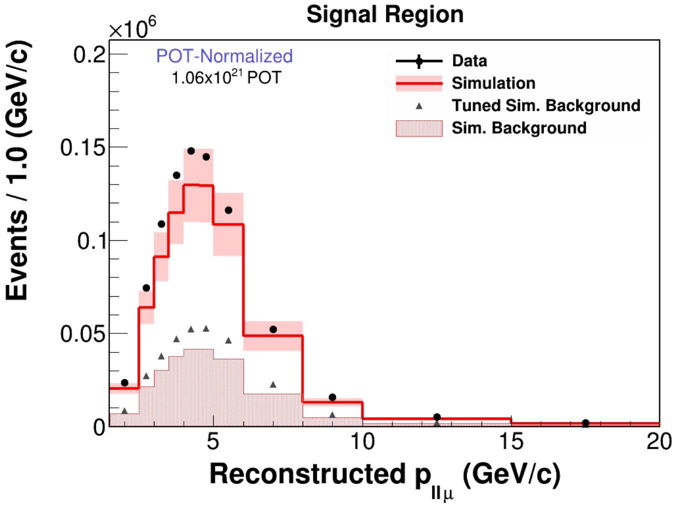
$$\left(\frac{d\sigma}{dX}\right)_i = \frac{1}{T_n \Phi \Delta X_i} \frac{\sum_j U_{ij}\left(N_j^{data} - N_j^{bkg}\right)}{\epsilon_i}$$

- The weight functions are applied to the background in the signal region.

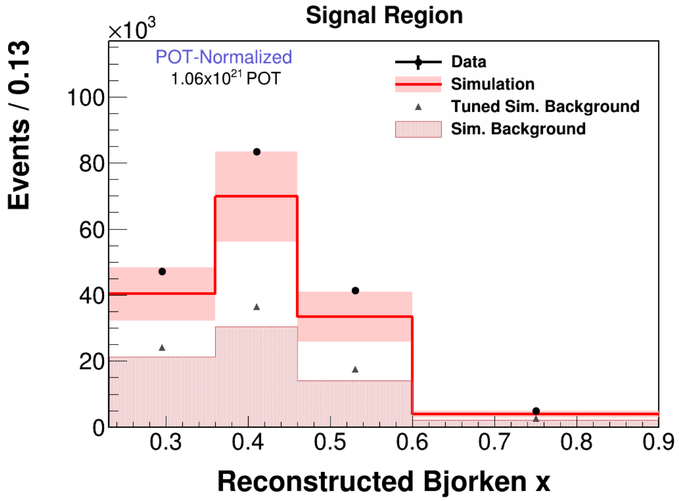


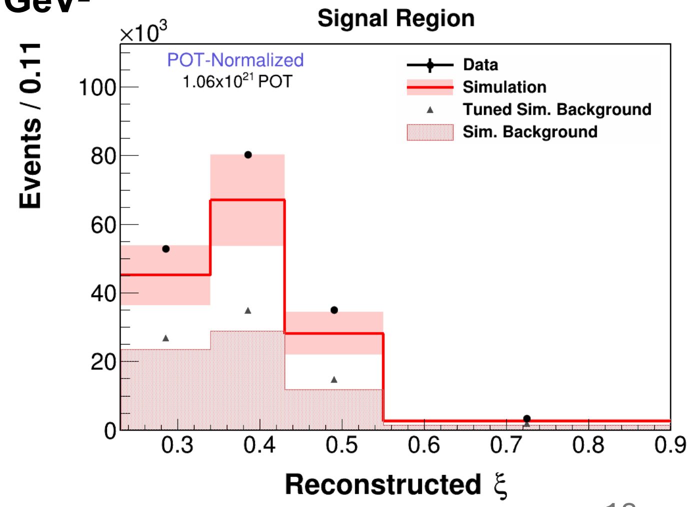
$Q^2 > 0$ GeV^2





$Q^2 > 1$ GeV^2



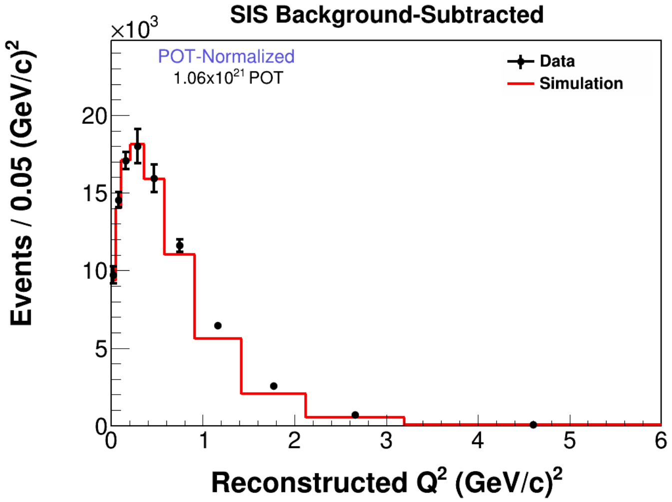


SIS Background-Subtracted Sample (Neutrino)

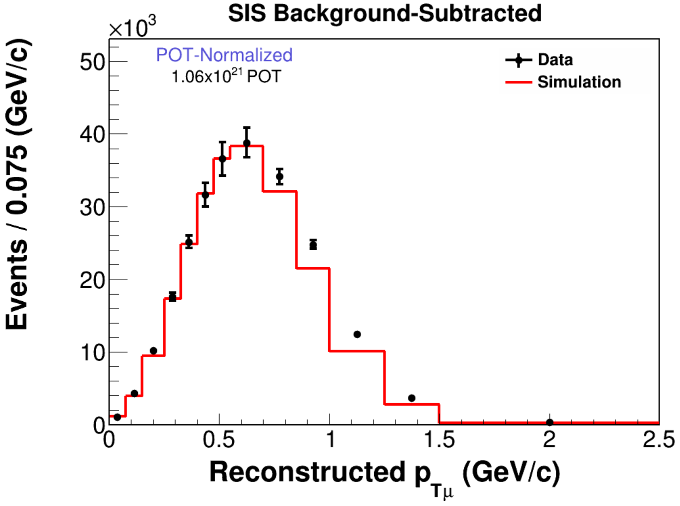
$$\left(\frac{d\sigma}{dX}\right)_i = \frac{1}{T_n \Phi \Delta X_i} \frac{\sum_j U_{ij}\left(N_j^{data} - N_j^{bkg}\right)}{\epsilon_i}$$

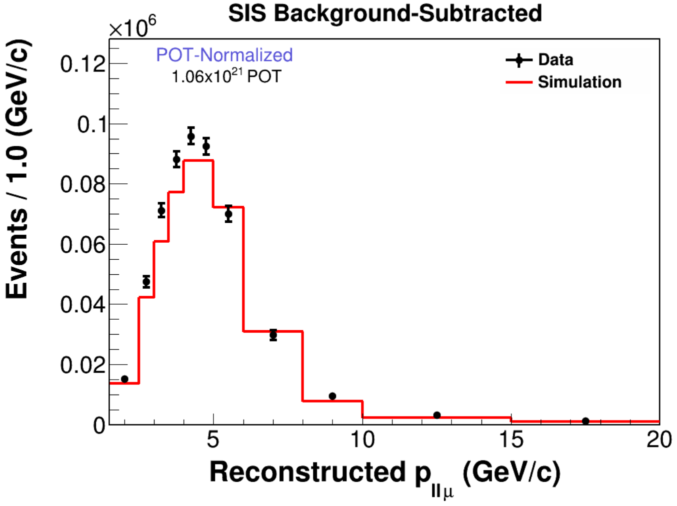
- The tuned simulated background is subtracted bin-by-bin from the sample.

383,494 events for $Q^2 > 0$ GeV^2
93,410 events for $Q^2 > 1$ GeV^2

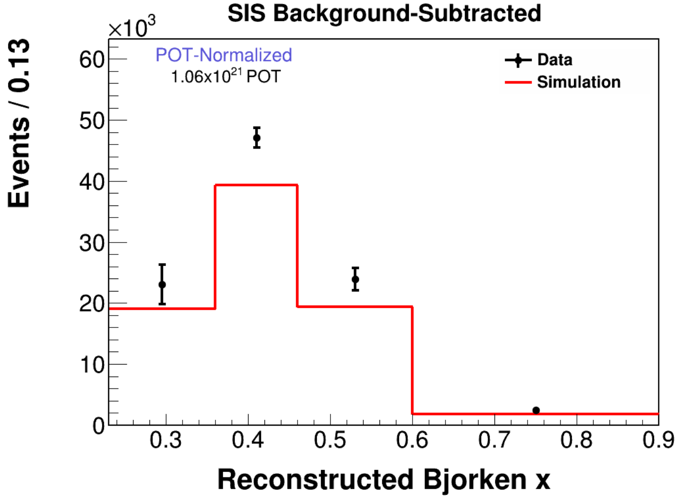


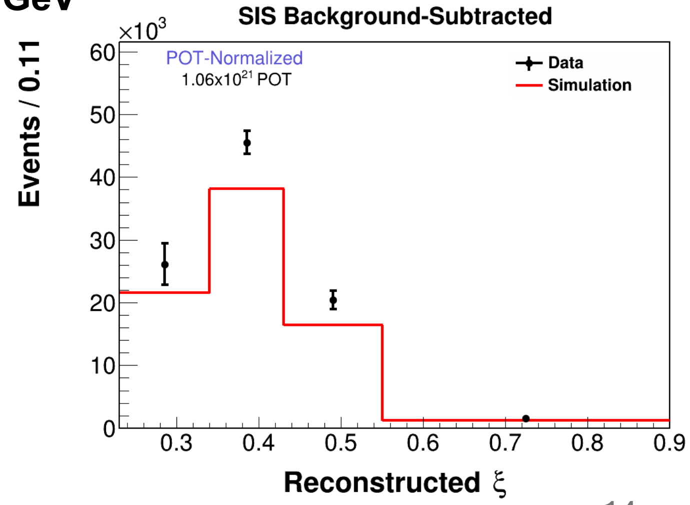
$Q^2 > 0$ GeV^2





$Q^2 > 1$ GeV^2





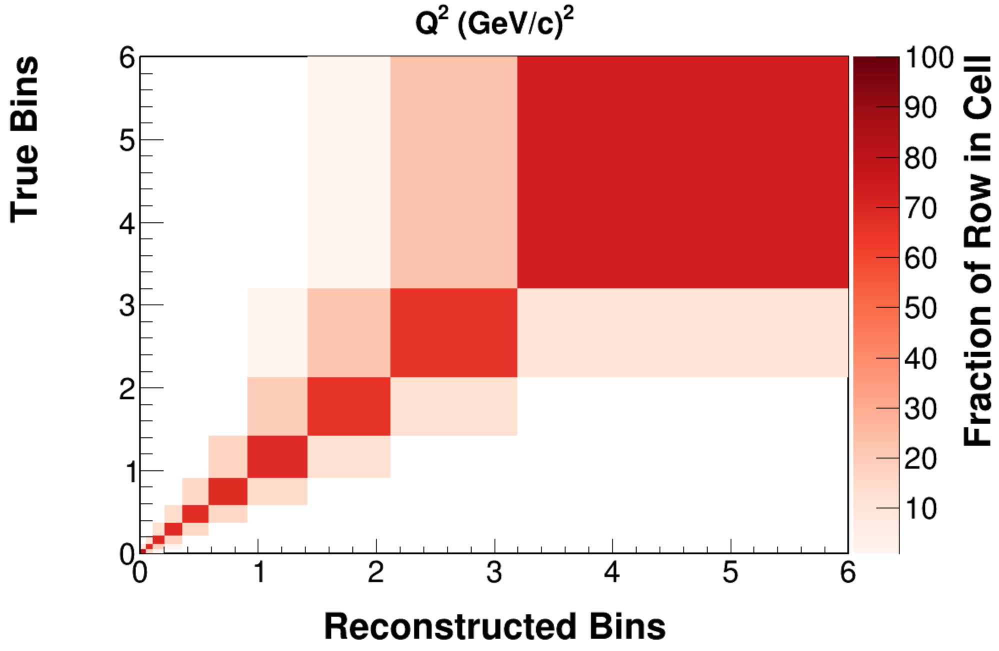
Unfolding

$$\left(\frac{d\sigma}{dX}\right)_i = \frac{1}{T_n \Phi \Delta X_i} \frac{\sum_j U_{ij}\left(N_j^{data} - N_j^{bkg}\right)}{\epsilon_i}$$

- We need to correct the distortion and smearing caused by physical effects, detector resolution and detector imperfections.

- The MINERvA collaboration uses the iterative D'Agostini method and is implemented in the RooUnfold framework.

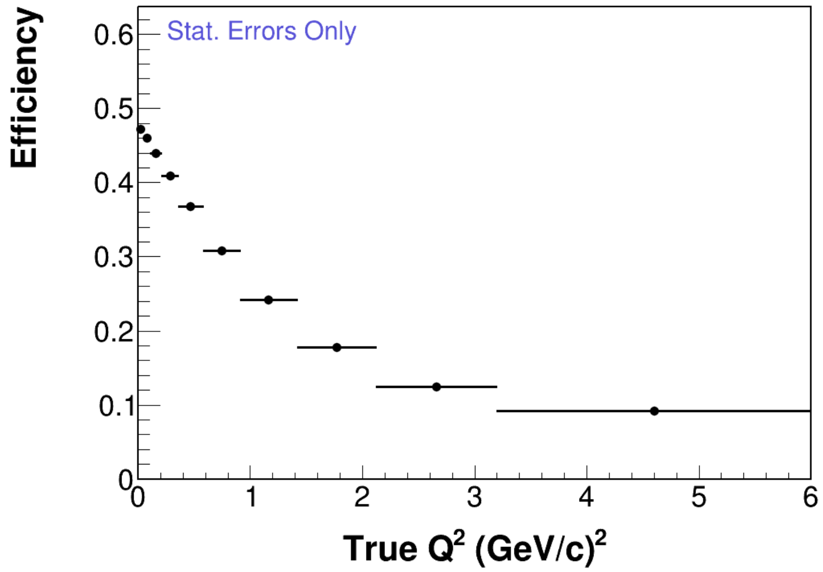
- A study was performed to determine how many iterations are required to recover the original distribution:
  - Fake data based on data MC disagreement.
  - Fake data based on physics model disagreement.



Efficiency and Normalizations

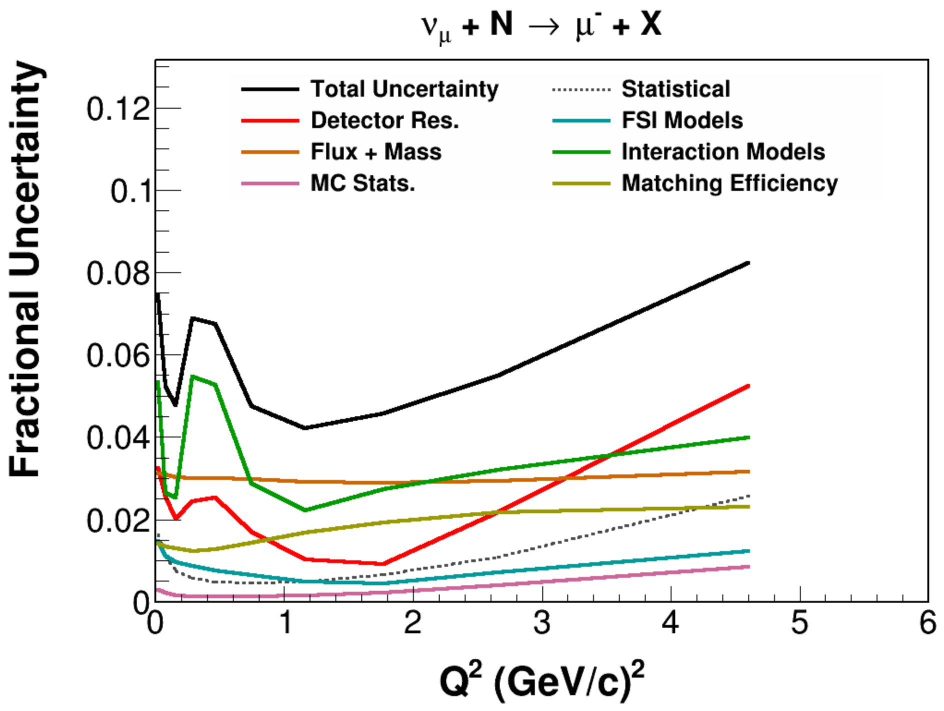
$$\left(\frac{d\sigma}{dX}\right)_i = \frac{1}{T_n \Phi \Delta X_i} \frac{\sum_j U_{ij}\left(N_j^{data} - N_j^{bkg}\right)}{\epsilon_i}$$

- The selection efficiency is the fraction of simulated signal events that were detected and selected by the analysis selection cuts.
- Efficiency decreases with the increasing of the angle due to MINOS acceptance.
- Average selection efficiency:
  - 30% (35% $\bar{\nu}_\mu$) for $Q^2 > 0$ GeV^2
  - 17% (19% $\bar{\nu}_\mu$) for $Q^2 > 1$ GeV^2
- Integrated flux ($0 \leq E_\nu \leq 120$ GeV).
- 3.23 x 10^{30} nucleons in the fiducial volume.
- Bin width.



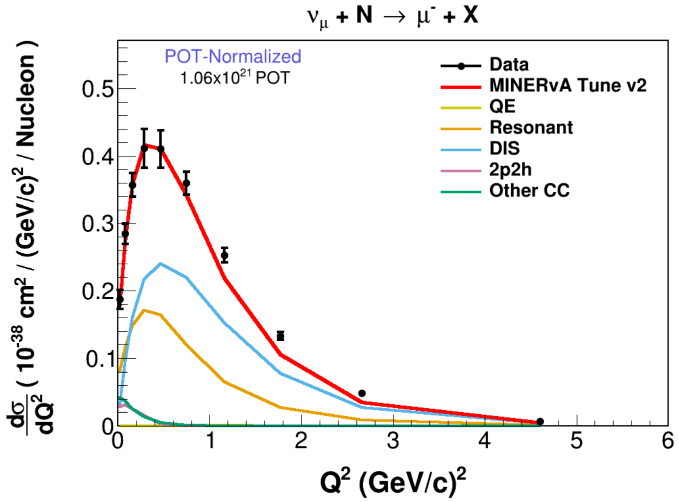
Uncertainties

- **Flux + Mass (~3-9%)**
  - Flux (~3.3% (~4.7% $\bar{\nu}_\mu$) at focusing peak)
  - Mass (1%)
- **Interaction Models (~2-6%)**
  - Cross section models that GENIE uses
  - Dominates by M_A^{RES}, M_V^{RES}, M_A^{CCQE}
- **Detector Response (~1-8%)**
  - E_μ, θ_μ, E_{had}
- **Matching Efficiency (~1-2%)**
- **FSI Models (~1%)**
  - Final state interactions simulated in GENIE
- **MC Statistics (~0.5-1%)**

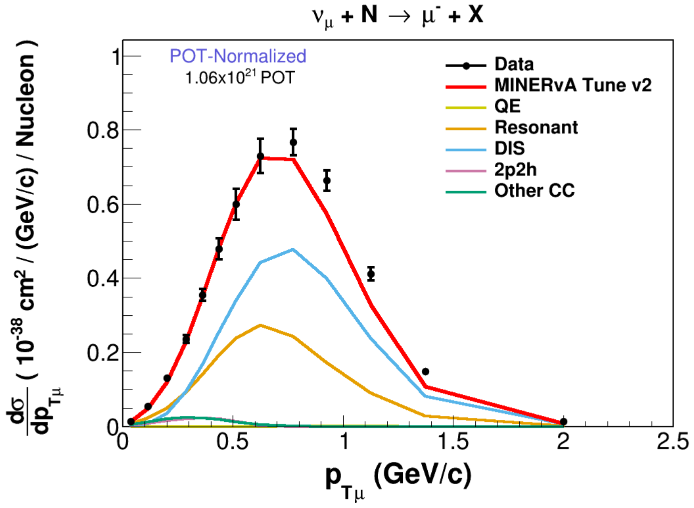


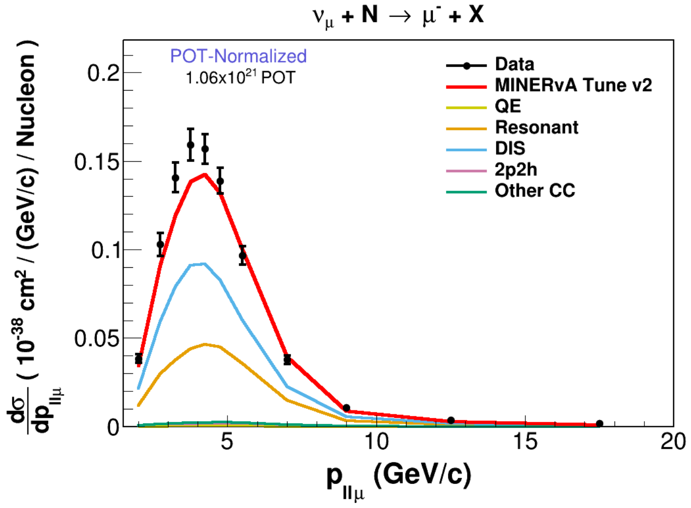
Cross Section (Neutrino)

- Resonant and DIS components dominate in this SIS range of W.

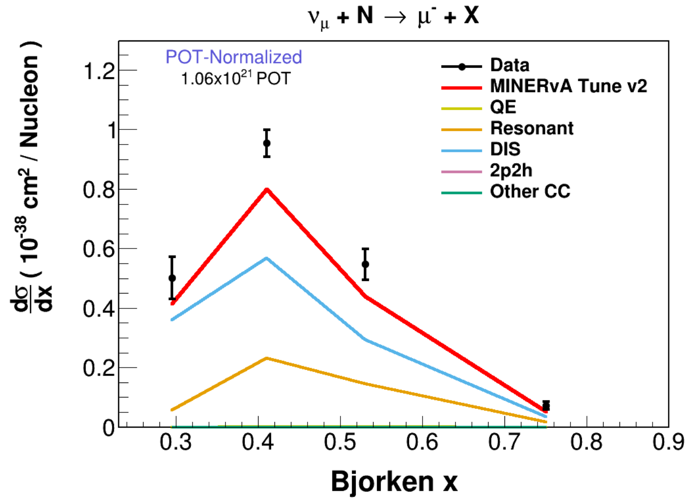


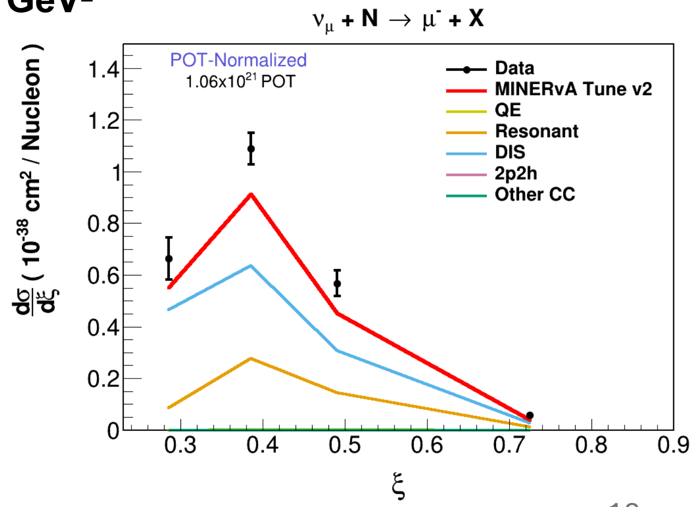
$Q^2 > 0$ GeV²





$Q^2 > 1$ GeV²





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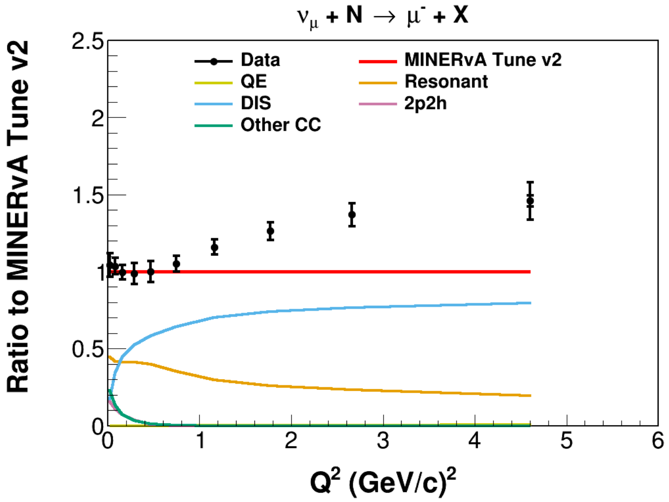
Cross Section Ratios (Neutrino)

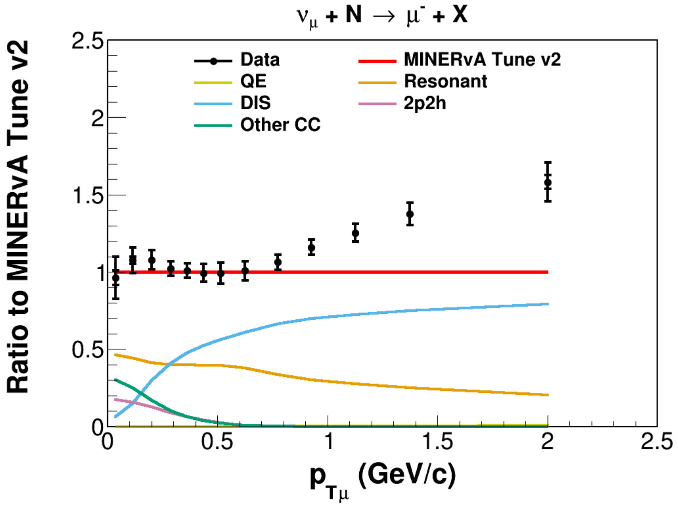
- Resonant and DIS components dominate in this SIS range of W.

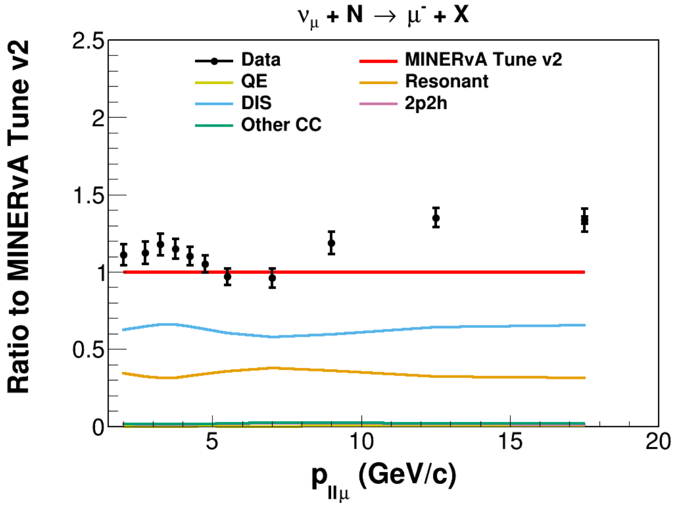
In general, MINERvA Tune v2 tends to underpredict the cross section.



Good agreement at low Q^2 and $p_{T\mu}$ because of the low Q^2 suppression of pion production.

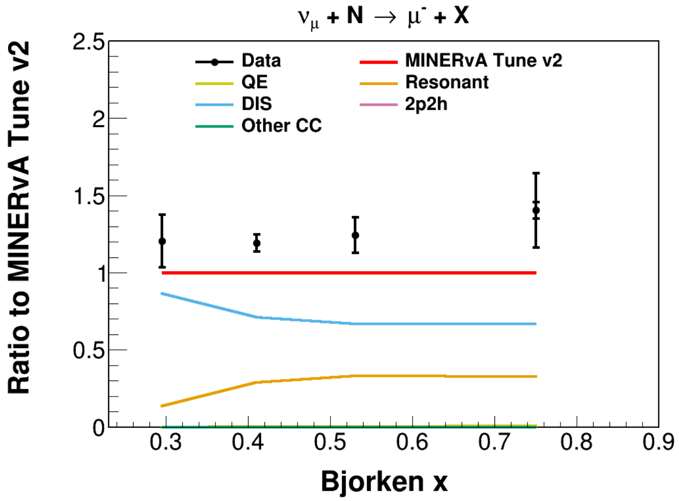
Q^2 > 0 GeV^2

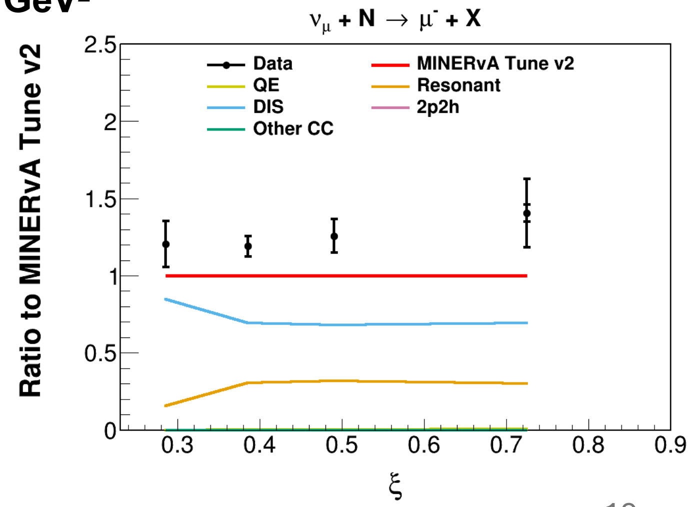




63% DIS
34% RES

Q^2 > 1 GeV^2





73% DIS
26% RES

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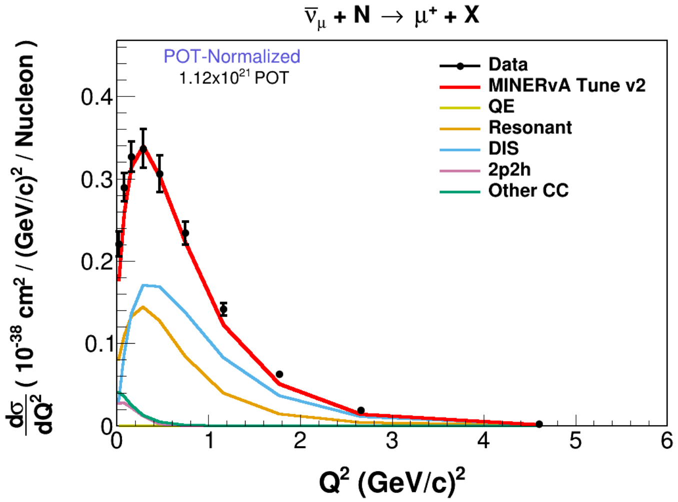
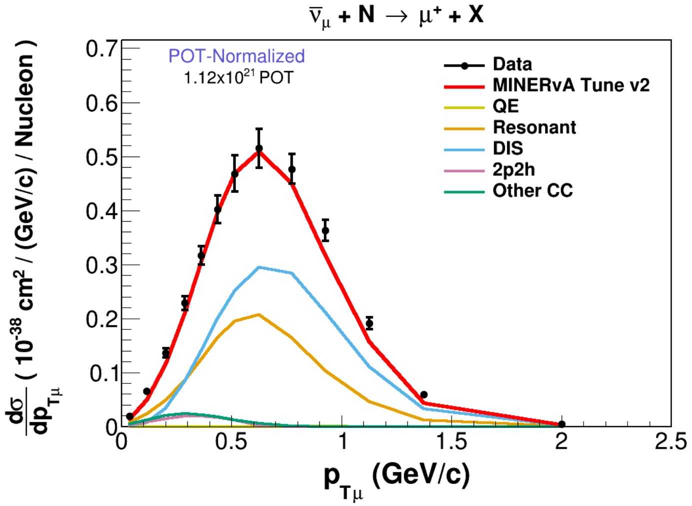
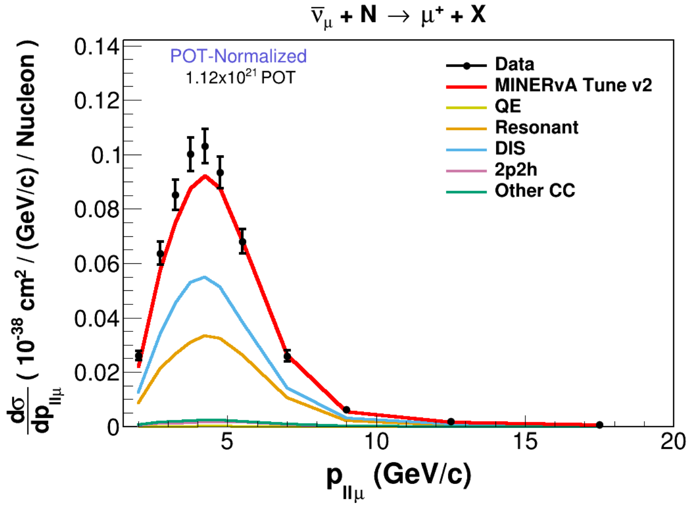
Cross Section (Antineutrino)

- Resonant and DIS components dominate in this SIS range of W.

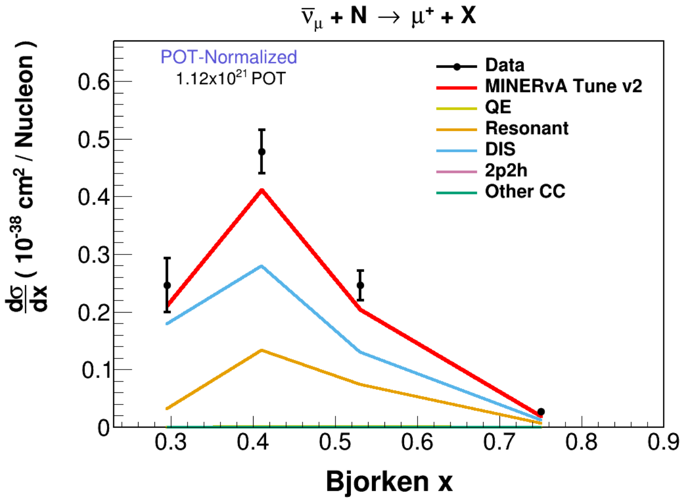


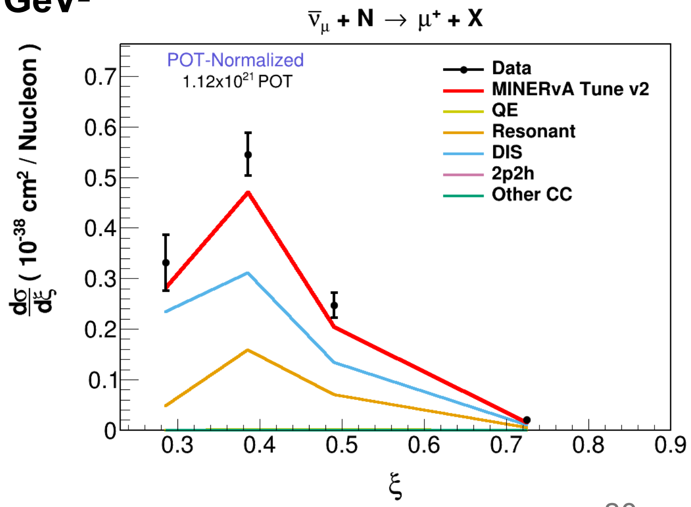
Q^2 > 0 GeV^2





Q^2 > 1 GeV^2

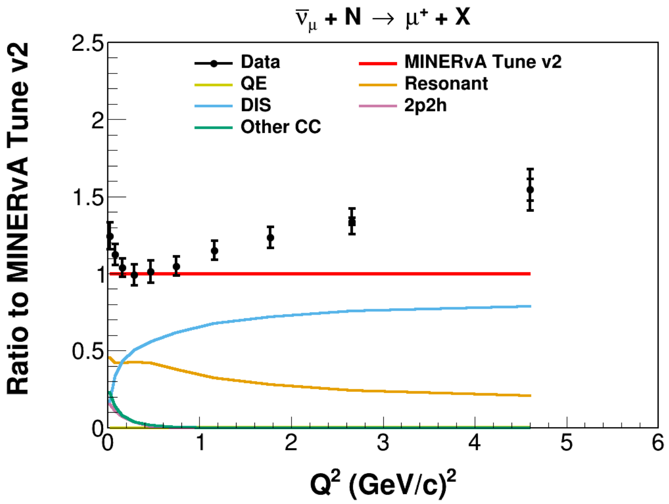




Cross Section Ratios (Antineutrino)

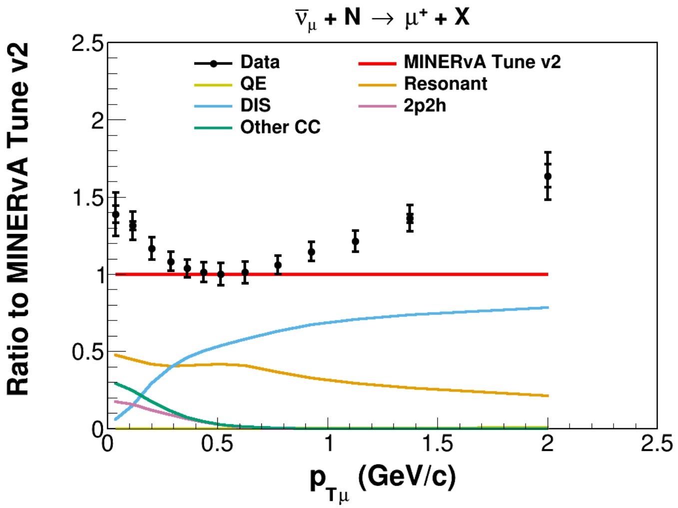
- Resonant and DIS components dominate in this SIS range of W.

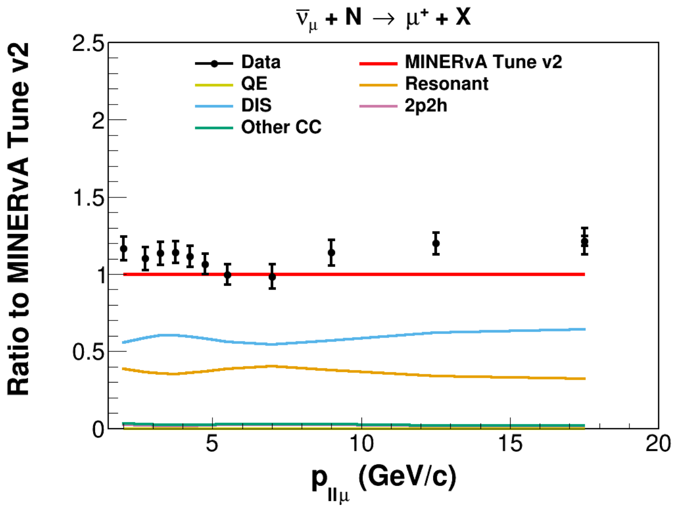
In general, MINERvA Tune v2 tends to underpredict the cross section.



The low Q^2 suppression of pion production, determined for neutrino, is too strong when applied to low Q^2 and low $p_{T\mu}$ antineutrino.

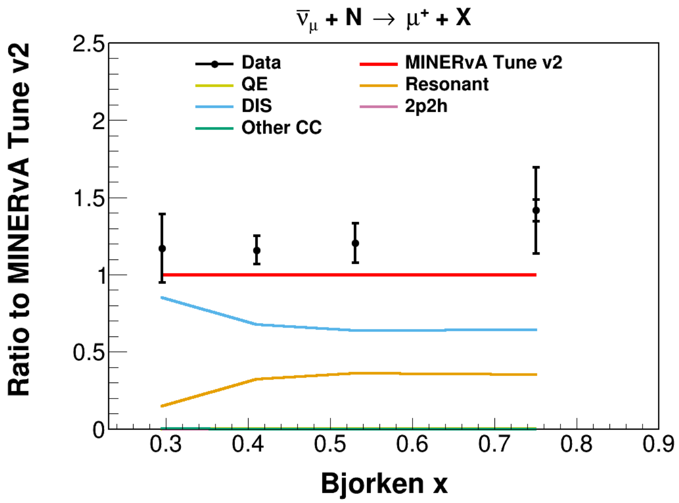
Q^2 > 0 GeV^2

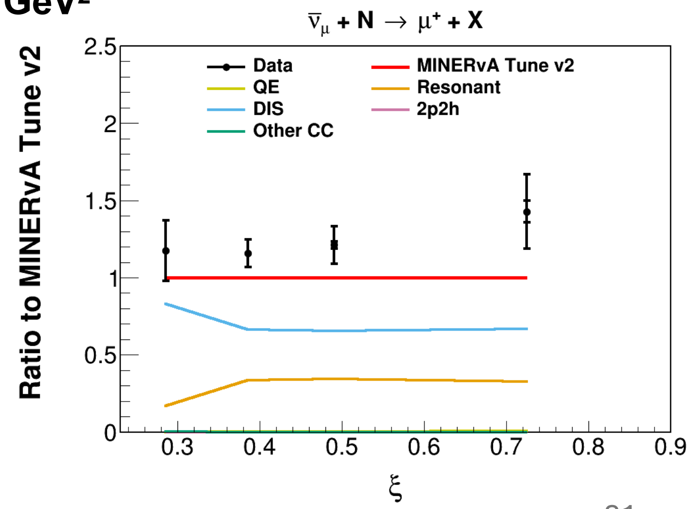




58% DIS
37% RES

Q^2 > 1 GeV^2





71% DIS
29% RES

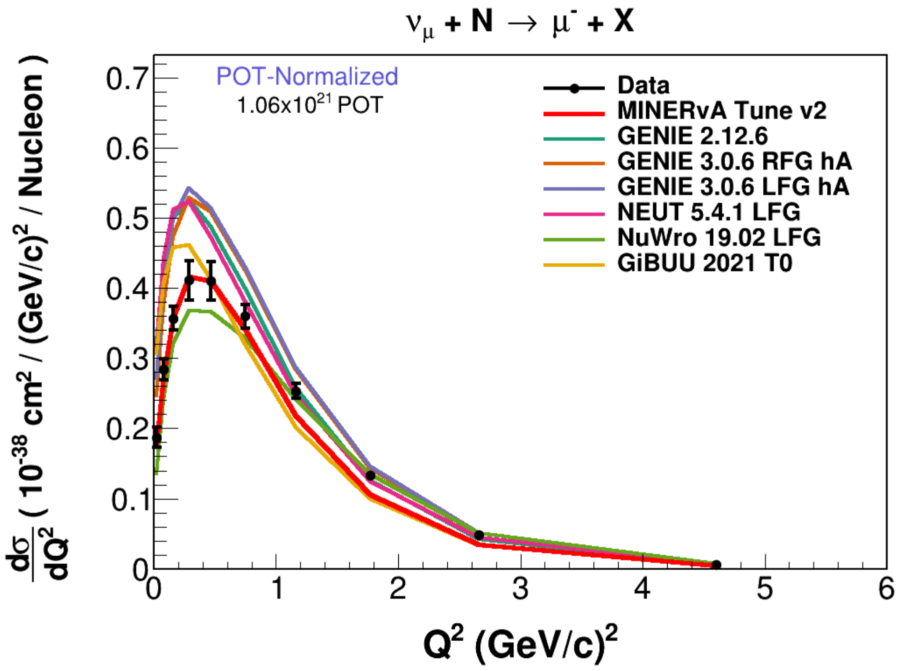
Model Comparison

- **Genie 3.0.6**
  - LFG is the Local Fermi Gas model as the nuclear ground state
  - RFG is the Relativistic Fermi Gas model as the nuclear ground state
  - hA is an effective intranuclear transport model

- **NEUT 5.4.1**
  - LFG is the Local Fermi Gas model as the nuclear ground state

- **NuWro 19.02**
  - LFG is the Local Fermi Gas model as the nuclear ground state

- **GiBUU 2021**
  - T0 scales the amount of 2p2h process

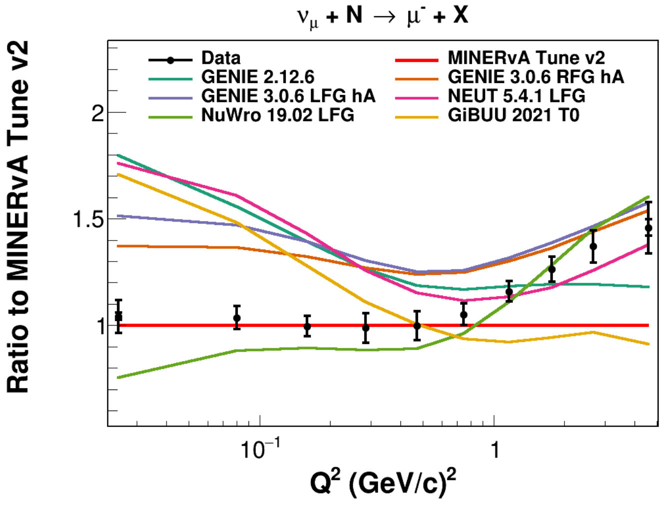


Model Comparison (Neutrino)

- None of the simulation programs describe the data across the full kinematic region for all considered variables.

GENIE 3.0.6 is a good match to the shape of the data at high Q^2 and $p_{T\mu}$.

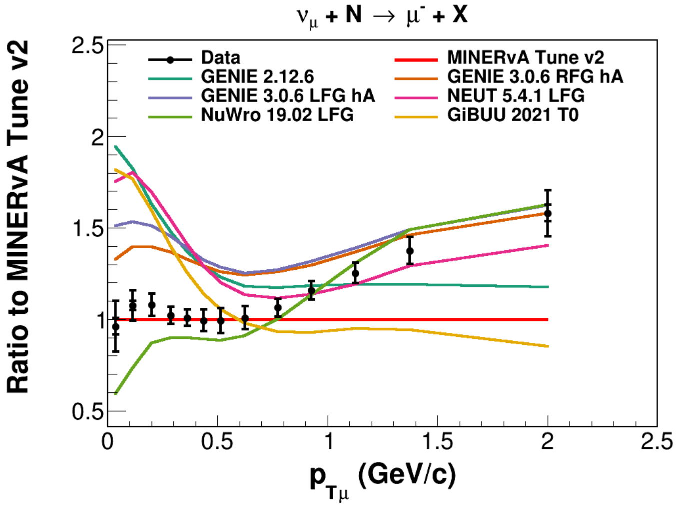
NuWro also fits our data.

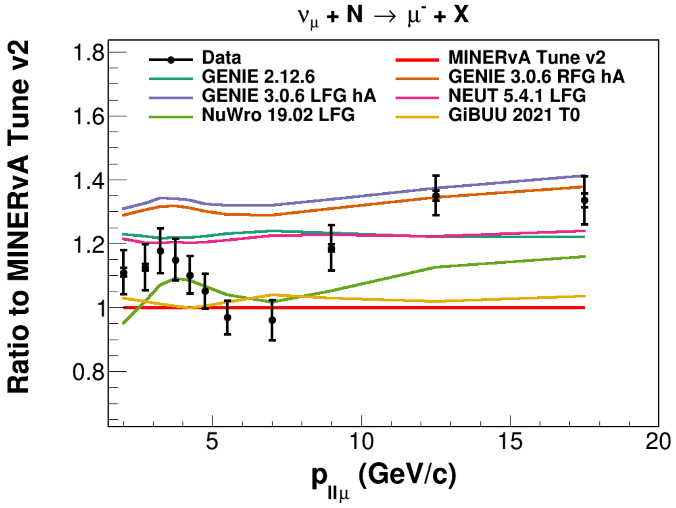


x, ξ, high $p_{\parallel\mu}$ are considerably better simulated by MINERvA Tune v2 without the nonresonant pion reduction (Genie 2.12.6).

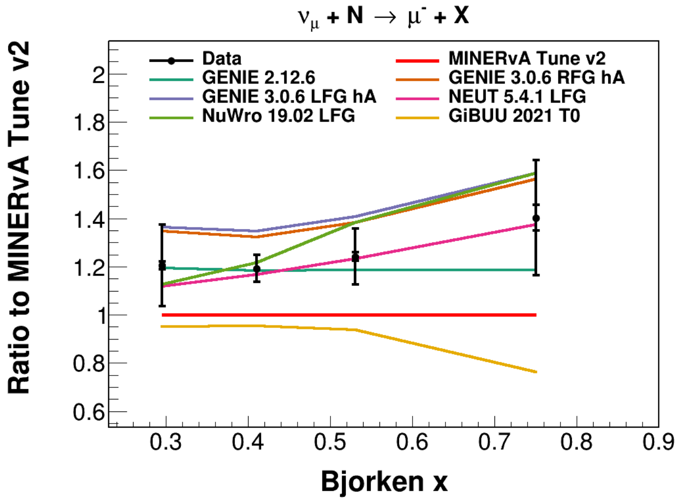
NEUT also fits x, ξ and high $p_{\parallel\mu}$ quite well.

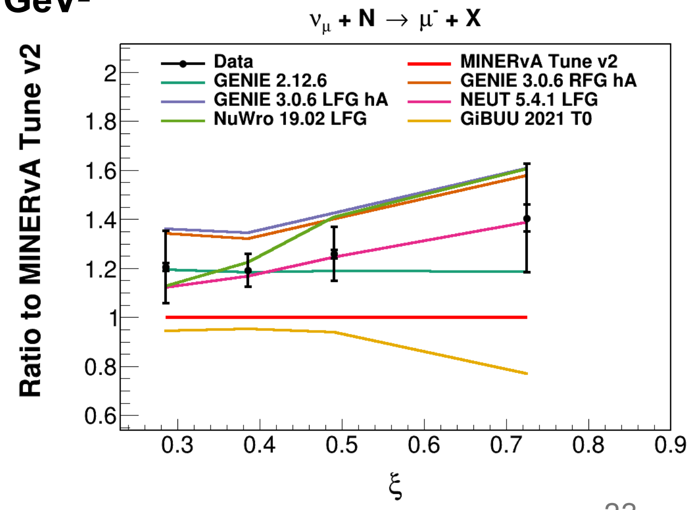
$Q^2 > 0$ GeV^2





$Q^2 > 1$ GeV^2

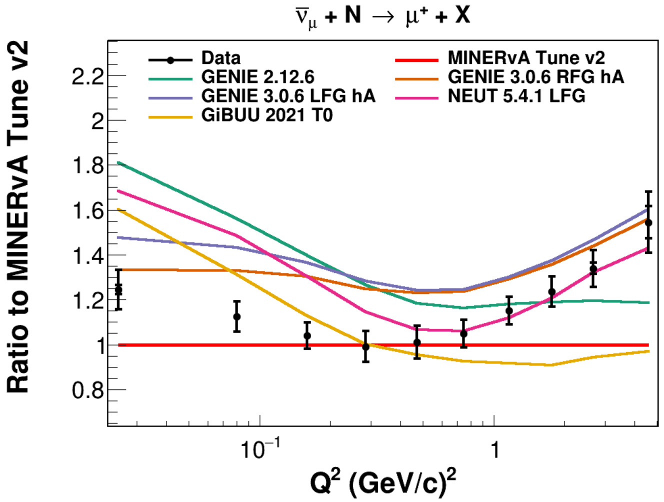




Model Comparison (Antineutrino)

- None of the simulation programs describe the data across the full kinematic region for all considered variables.

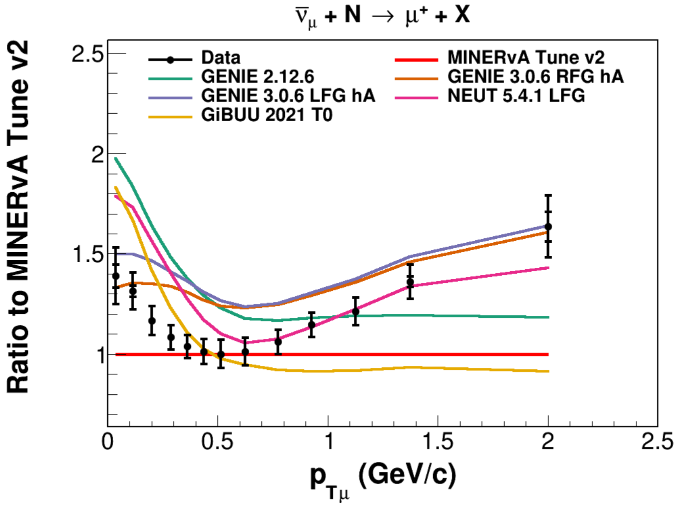
GENIE 3.0.6 is a good match to the shape of the data at high Q^2 and $p_{T\mu}$.

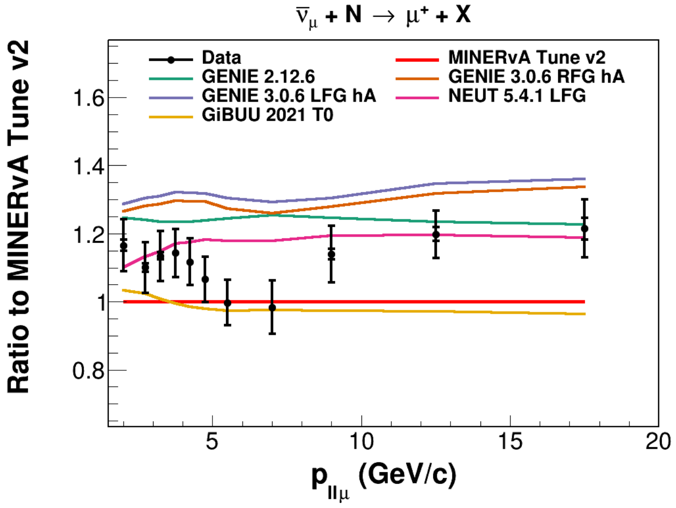


x, ξ, high $p_{\parallel\mu}$ are considerably better simulated by MINERvA Tune v2 without the nonresonant pion reduction (Genie 2.12.6).

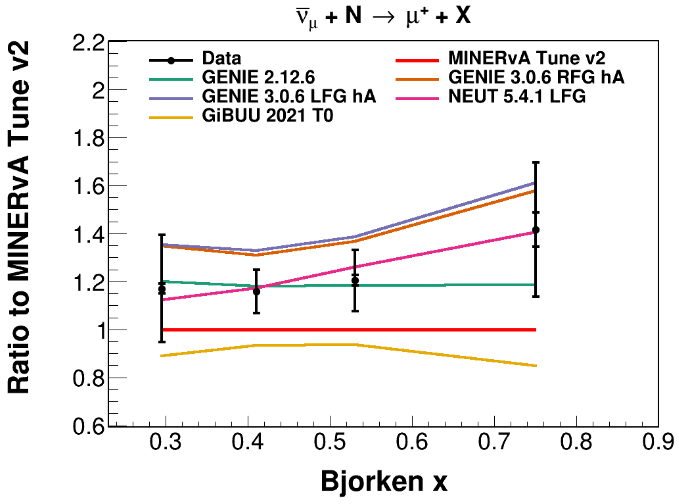
NEUT also fits x, ξ, high $p_{\parallel\mu}$, high $p_{T\mu}$ and high Q^2 quite well.

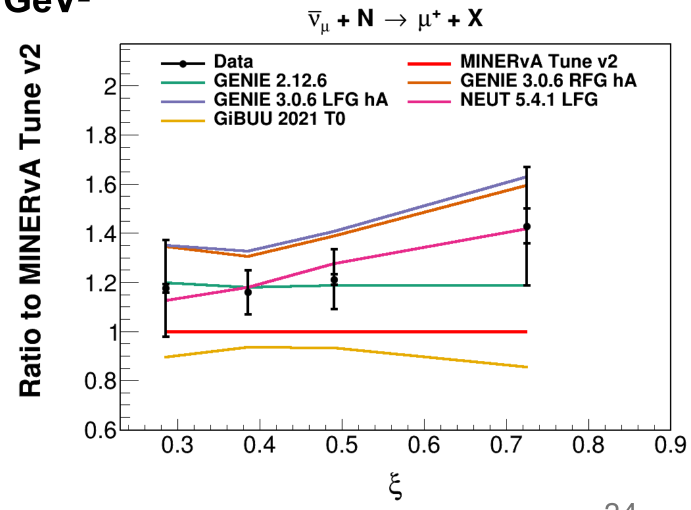
Q^2 > 0 GeV^2





Q^2 > 1 GeV^2





Conclusions

- First high-statistics measurement of SIS neutrino cross sections.
- Performed measurement of SIS cross section in neutrino and antineutrino as a function of Q^2, $p_{T\mu}$, $p_{\parallel\mu}$, x and ξ.
- MINERvA Tune v2 does not describe the SIS measurements across the full kinematic region:
  - Good agreement at low Q^2 and $p_{T\mu}$ for neutrinos.
  - The $Q^2 > 1$ GeV^2 data prefers no nonresonant meson reduction.
  - A less strong suppression of pion production at low Q^2 is suggested for antineutrinos.
- The measurements were compared to other neutrino generator programs.
- These cross sections can be used as a reference for better understanding and modeling of neutrino-nucleus scattering physics.
- The results will also help to reduce the systematic uncertainties for neutrino oscillation experiments.

Thank You!

CBPF
Centro Brasileiro de Pesquisas Físicas

CNPq

Drexel UNIVERSITY

Fermilab

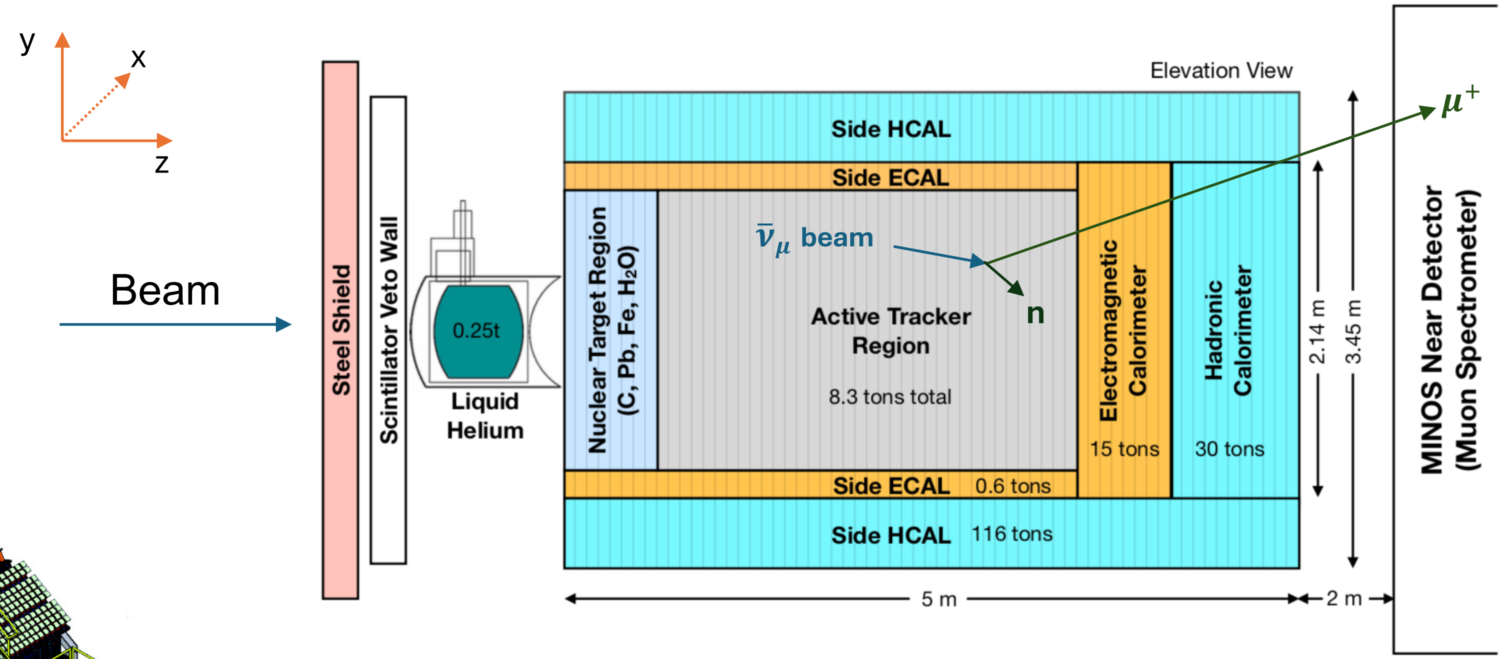
MINERvA Week 2023 Collaboration (12-15 June)

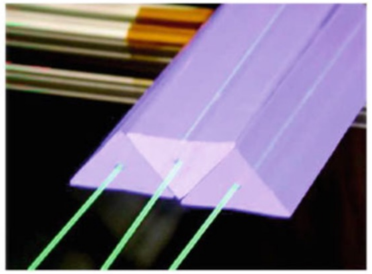
Adrian Lozano Sánchez (Drexel University/CBPF)

Backup

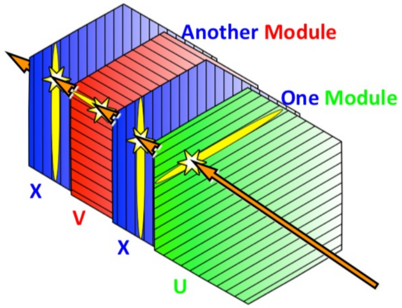
MINERvA Detector

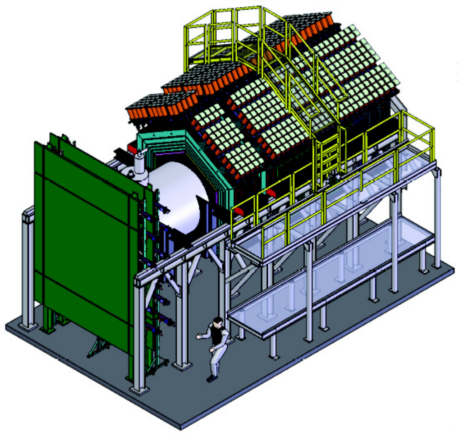
- High statistics neutrino scattering experiment.
- Measurements of neutrino interactions on various nuclei at 1-50 GeV in the NuMI beam.
- Study of nuclear effects in neutrino interactions.





Triangular strips arranged to give a better position resolution





- Different targets (He, C, Fe, Pb, H_2O, CH).
- Calorimeters: ECAL (Pb and CH sheets) and HCAL (steel and CH sheets).
- MINOS spectrometer: muon momentum and charge.

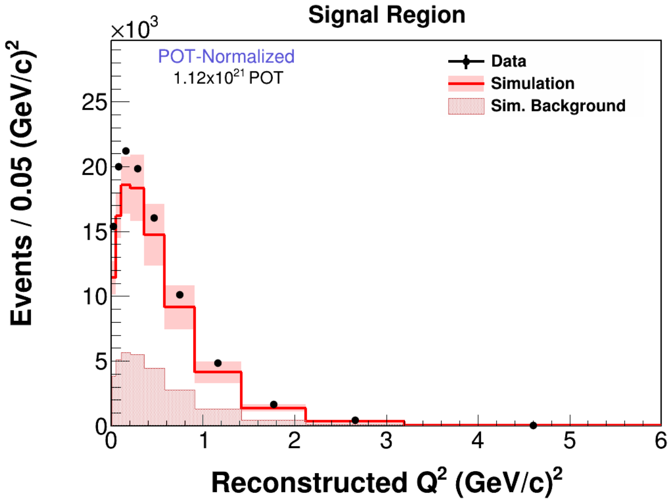
Adrian Lozano Sánchez (Drexel University/CBPF)

Selected Sample (Antineutrino)

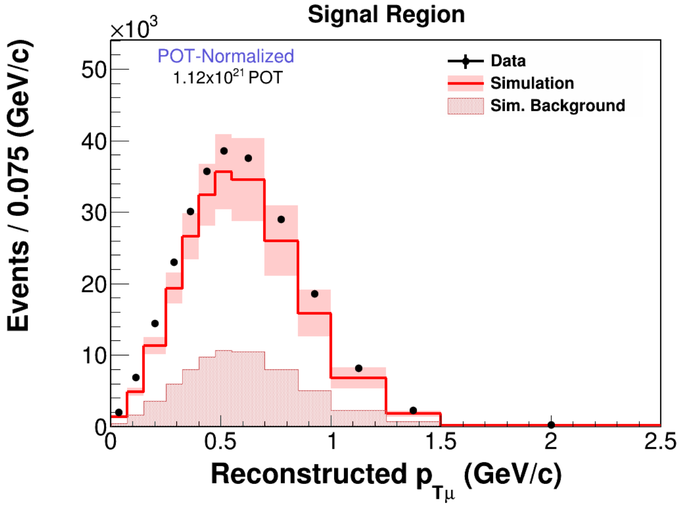
1.5 < Reco W_{exp} < 2 GeV

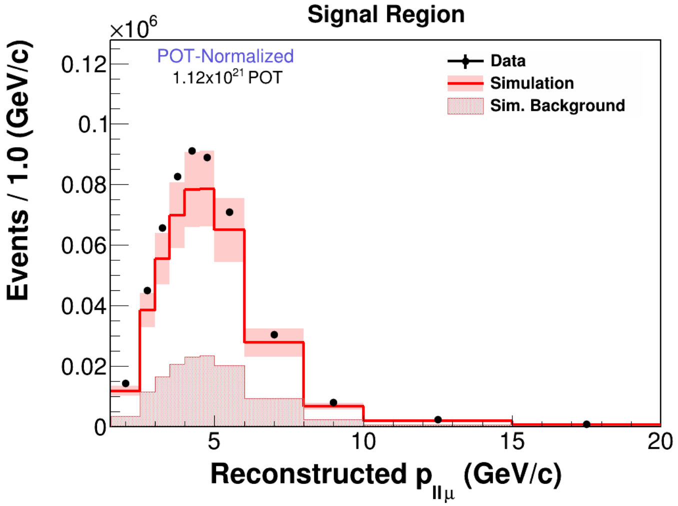
- The sample purity is 69% (55%) for $Q^2 > 0$ GeV^2 ($Q^2 > 1$ GeV^2).

364,082 events for $Q^2 > 0$ GeV^2
74,380 events for $Q^2 > 1$ GeV^2

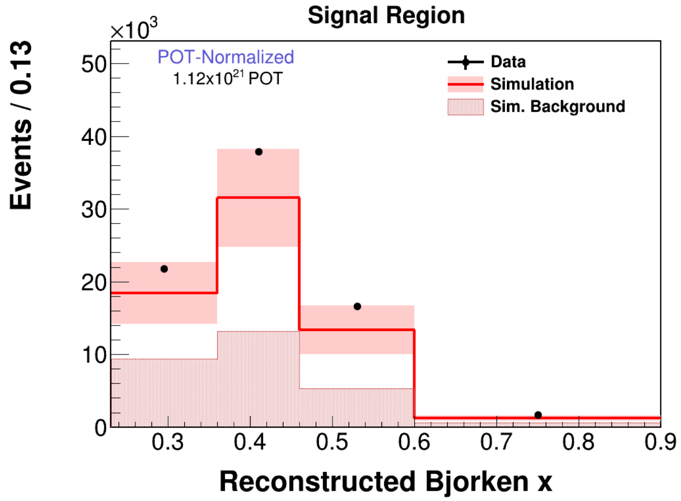


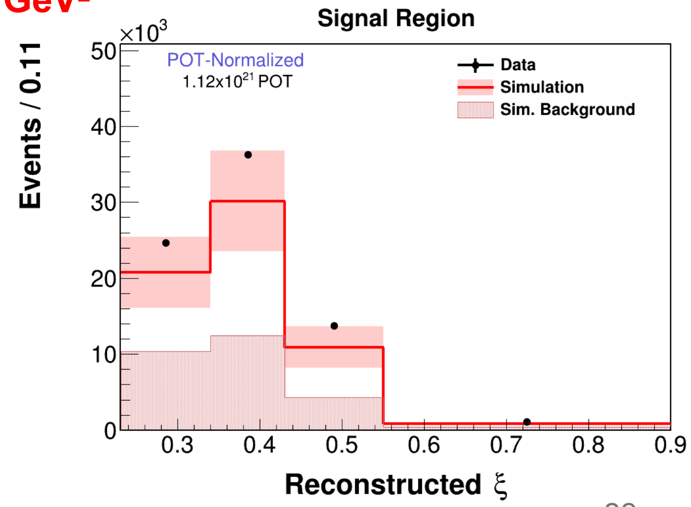
$Q^2 > 0$ GeV^2





$Q^2 > 1$ GeV^2





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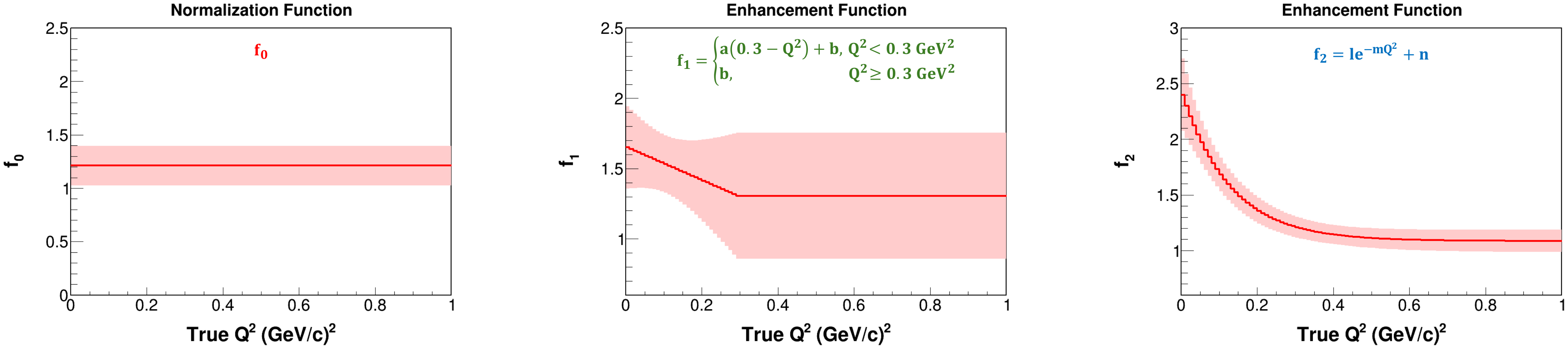
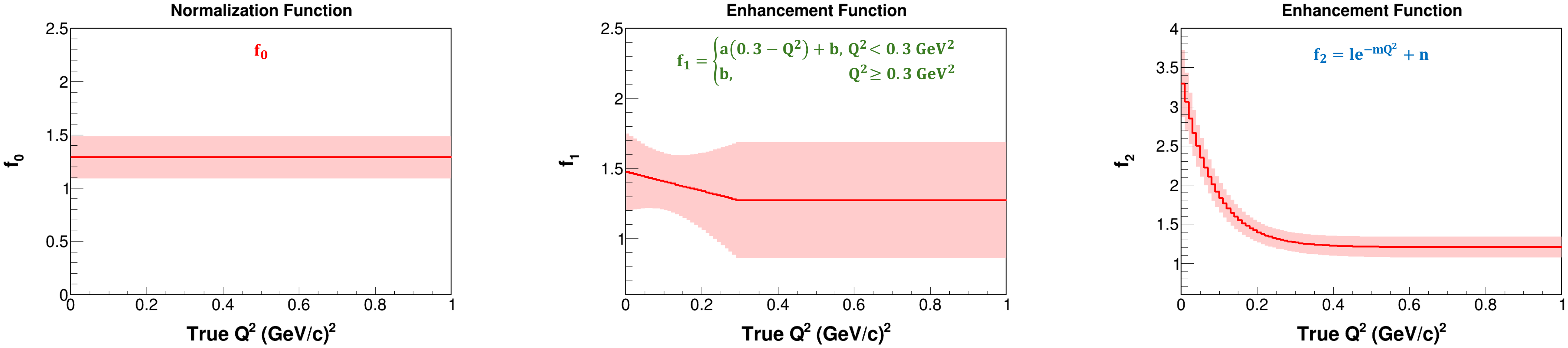
Non-SIS Background, Weight Functions

Neutrino



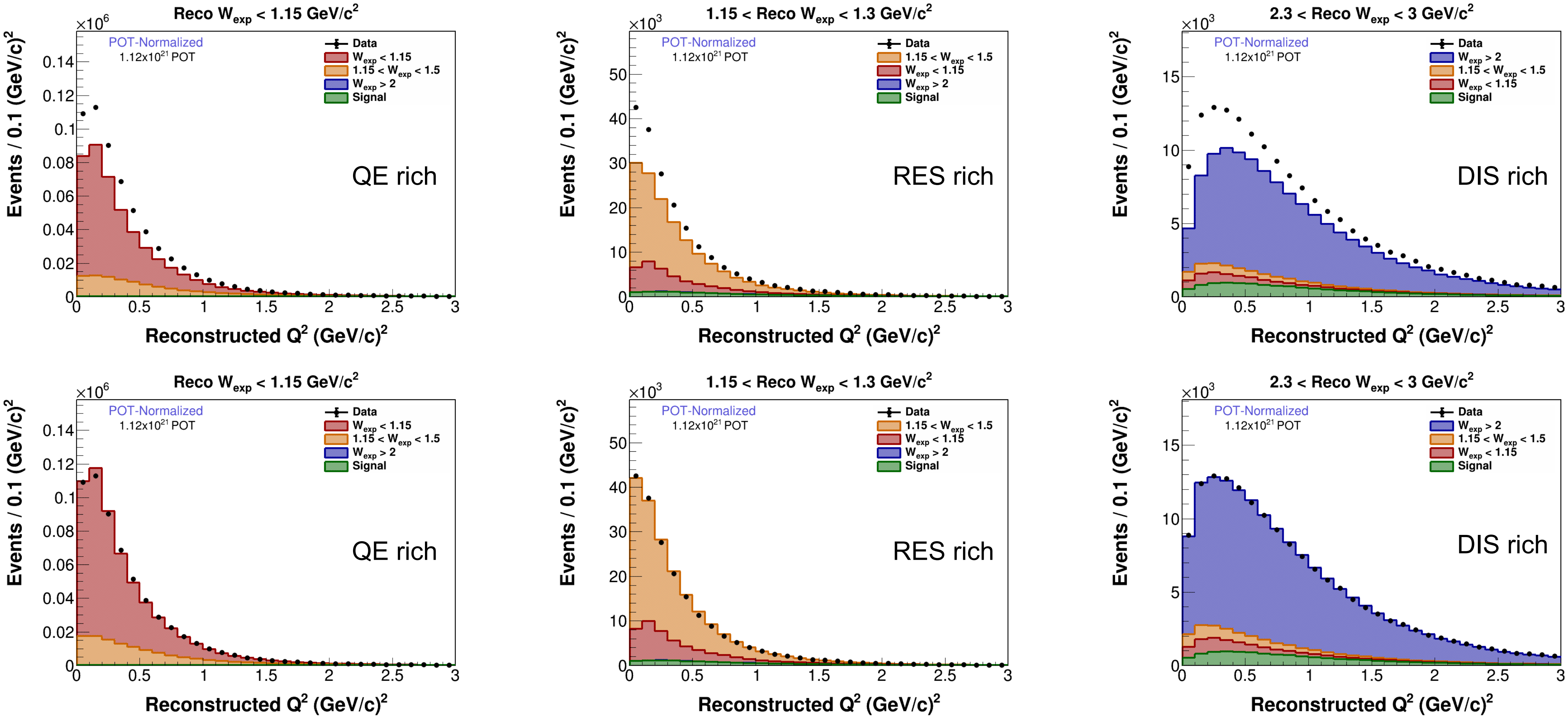
Antineutrino



Non-SIS Background (Antineutrino)

$$\left(\frac{d\sigma}{dX}\right)_i = \frac{1}{T_n \Phi \Delta X_i} \frac{\sum_j U_{ij}\left(N_j^{data} - N_j^{bkg}\right)}{\epsilon_i}$$

- We have brought the MC prediction to the data.



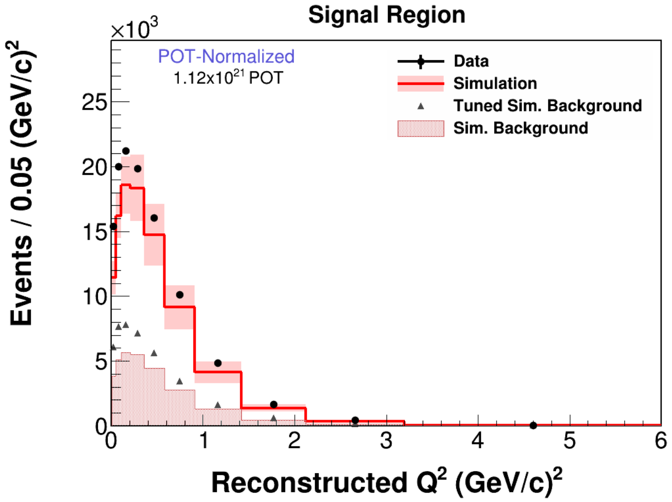
Before Tuning

After Tuning

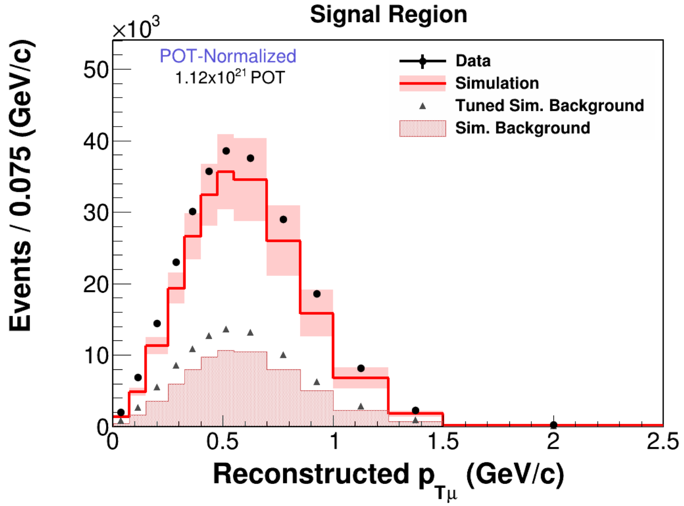
SIS Sample (Antineutrino)

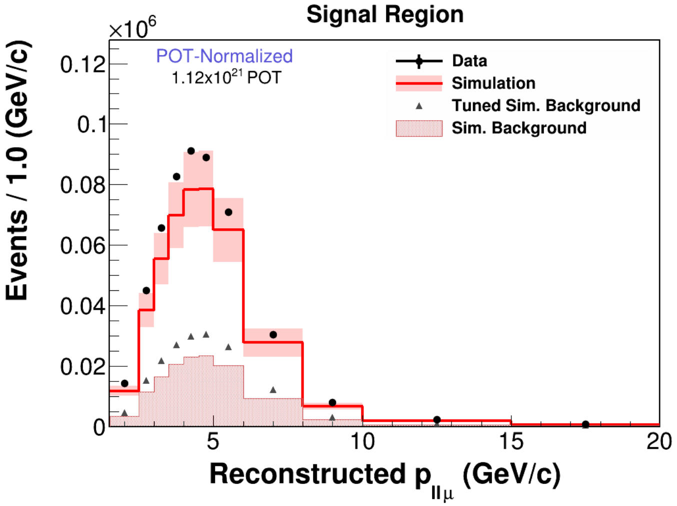
$$\left(\frac{d\sigma}{dX}\right)_i = \frac{1}{T_n \Phi \Delta X_i} \frac{\sum_j U_{ij}\left(N_j^{data} - N_j^{bkg}\right)}{\epsilon_i}$$

- The weight functions are applied to the background in the signal region.

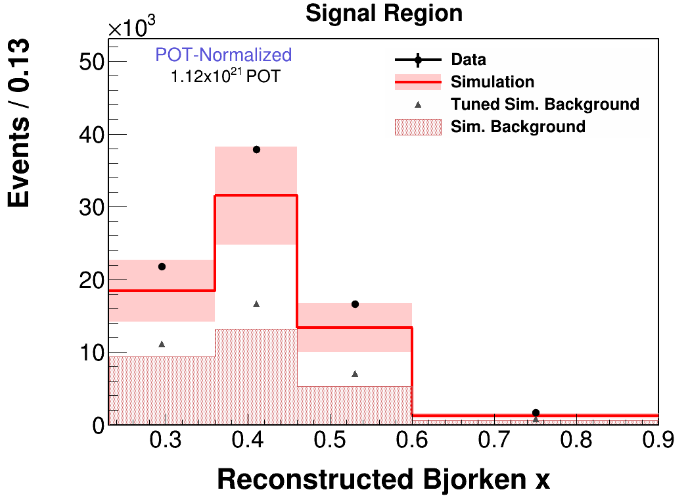


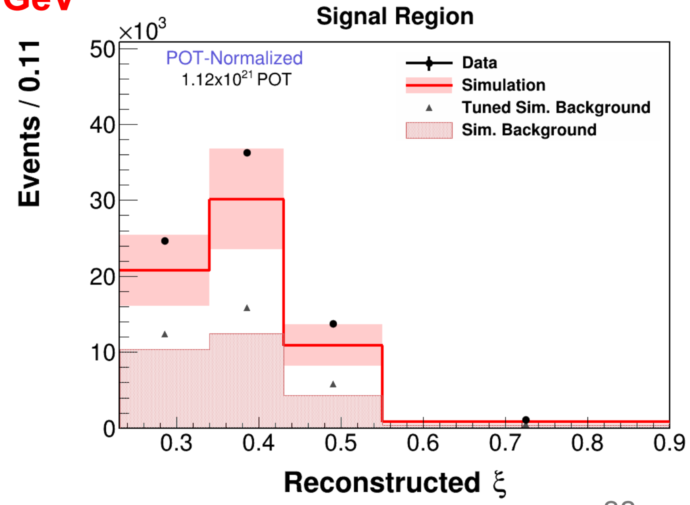
Q² > 0 GeV²





Q² > 1 GeV²



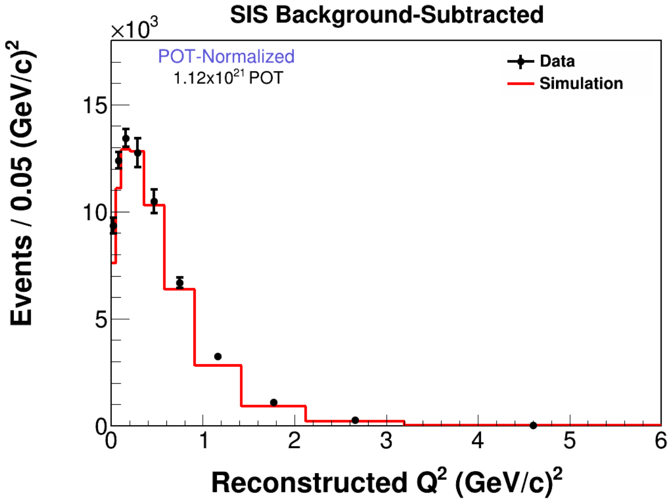


SIS Background-Subtracted Sample (Antineutrino)

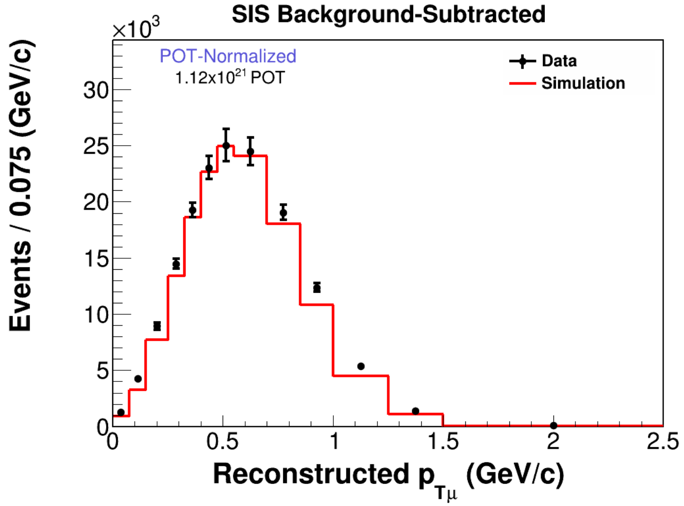
$$\left(\frac{d\sigma}{dX}\right)_i = \frac{1}{T_n \Phi \Delta X_i} \frac{\sum_j U_{ij}\left(N_j^{data} - N_j^{bkg}\right)}{\epsilon_i}$$

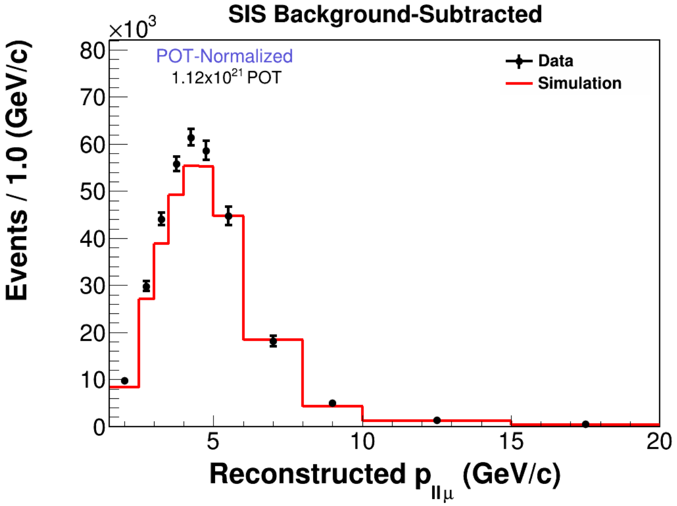
- The tuned simulated background is subtracted bin-by-bin from the sample.

235,017 events for $Q^2 > 0$ GeV^2
40,048 events for $Q^2 > 1$ GeV^2



$Q^2 > 0$ GeV^2





$Q^2 > 1$ GeV^2