



# High Statistics Anti-Neutrino nucleus CCQE Like cross-section measurements on CH Target with $\langle E_\nu \rangle \sim 6$ GeV



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## Introduction

The MINERvA Experiment is a neutrino cross-section measurement experiment based in Fermilab that aims to study the neutrino cross-sections in different nuclei for neutrino energy ranging from 1 to 10 GeV to understand the nuclear effects on neutrino nucleus scattering and help the current and future oscillation experiments.

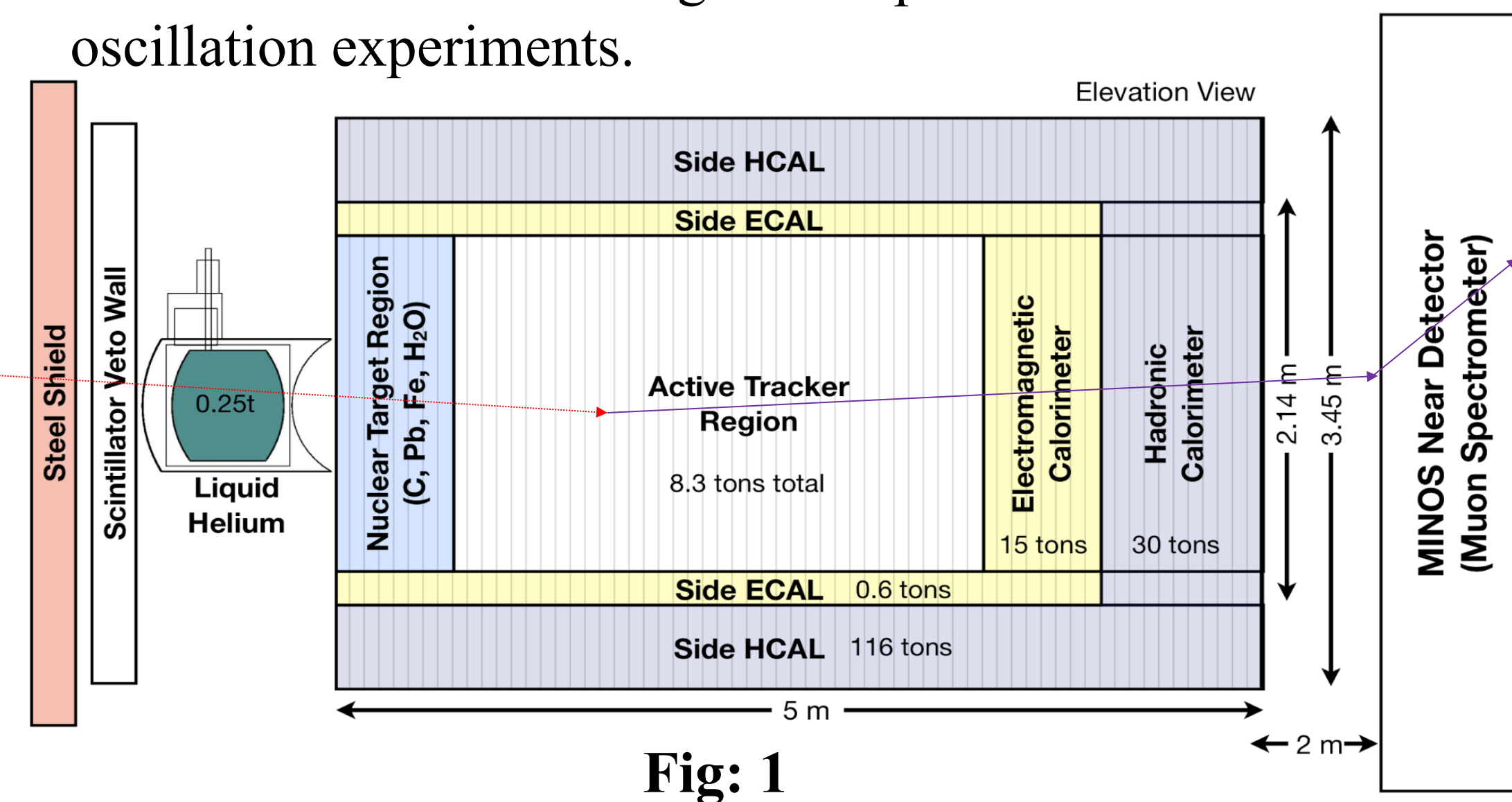


Fig: 1

Schematic diagram of MINERvA detector with MINOS near detector on the downstream end of the MINERvA detector

## Motivation

- CCQELike interactions are one of the dominating interactions seen by current (NOvA, T2K) and future (DUNE, Hyper K) oscillation experiments.
- Muon kinematics alone to reconstruct incoming neutrino energy.
- Initial and final State interactions need to be understood in the complex nuclear environment.

## Signal Definition

- True CCQE Event : Incoming antineutrino interacts with a proton inside target nucleus to produce a neutron by exchanging W boson, and a positive muon. ( $\bar{\nu}_\mu + p \rightarrow \mu^+ + n$ )
- Nuclear effect can change the final state particles faking a true CCQE event due to nuclear effects.
- **Define Signal based on Final State Particles (CCQELike)**

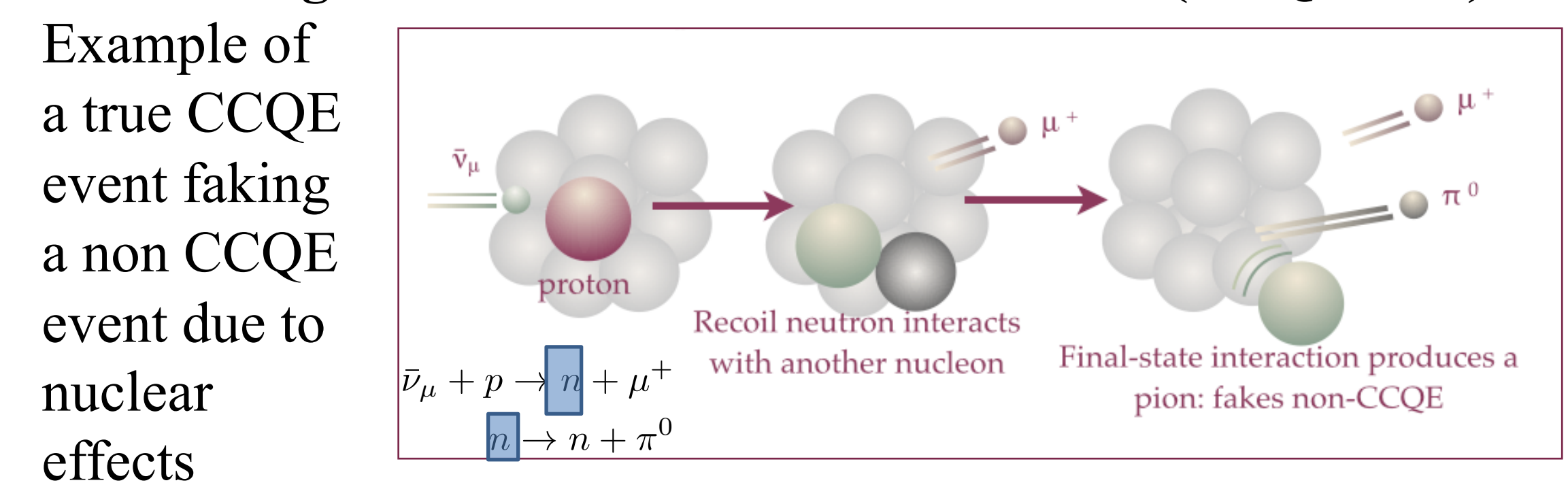


Fig: 2

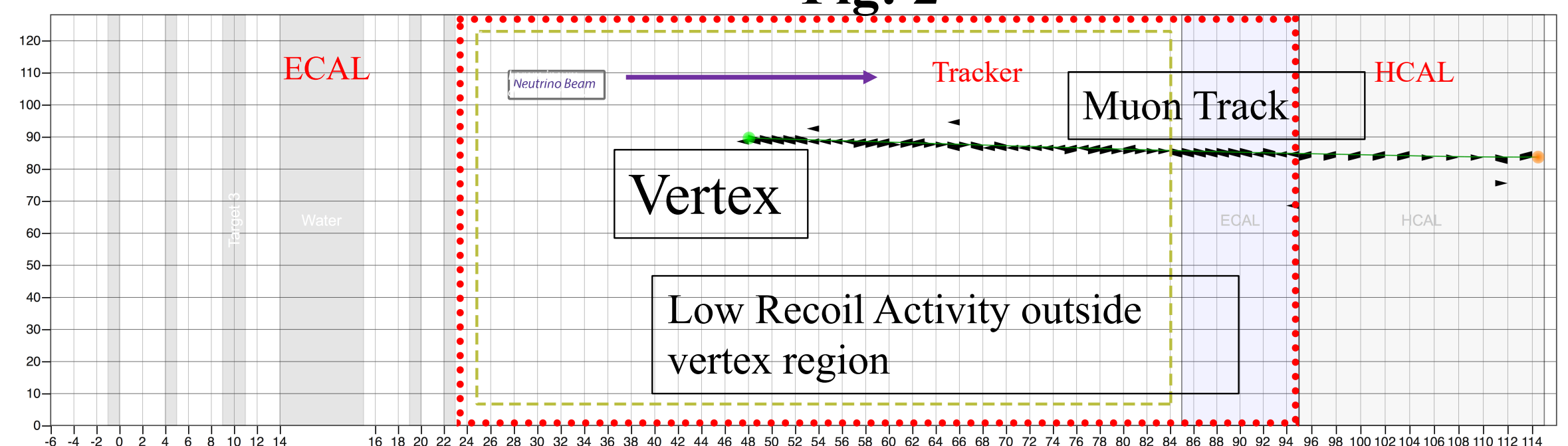


Fig: 3 Event display of a typical reconstructed CCQELike Event

### True CCQELike Event:

- One Muon track
- Any number of neutrons
- Any number of protons with KE < 120 MeV
- No mesons or Baryons

### Selection Cuts:

- Interaction vertex inside Tracker
- 1 MINOS matched muon with angle less than 20° w.r.t beam
- Low recoil activity outside the interaction vertex region

## Signal Selection

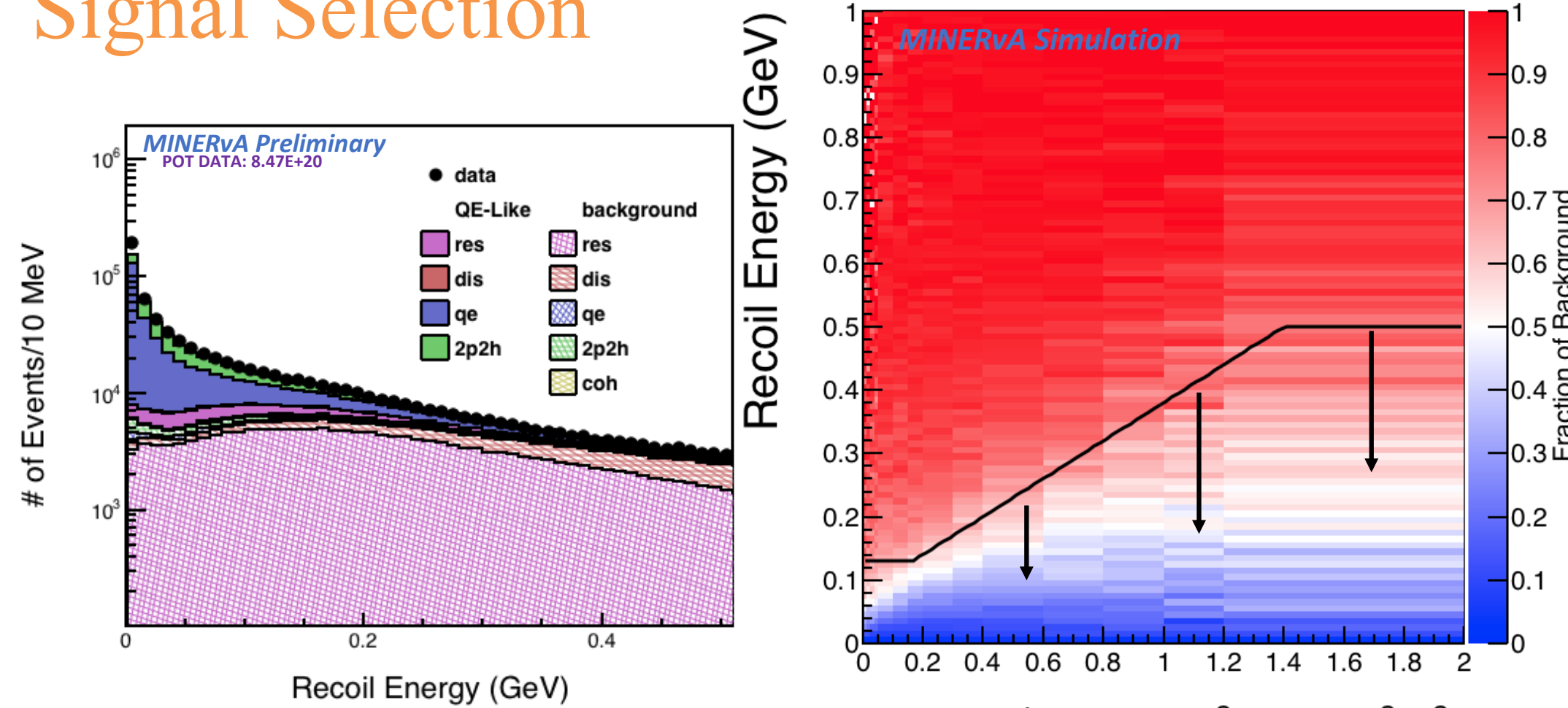


Fig: 4

Fig: 5  $Q_{QE}^2$  (GeV<sup>2</sup>/c<sup>2</sup>)

- Recoil energy (Fig: 4) to select signal events from the background
- Signal events are in the low recoil region
- Optimal Signal Selection cut varies with  $Q^2$  (black line in Fig: 5)
- Based on Optimization of signal efficiency and purity

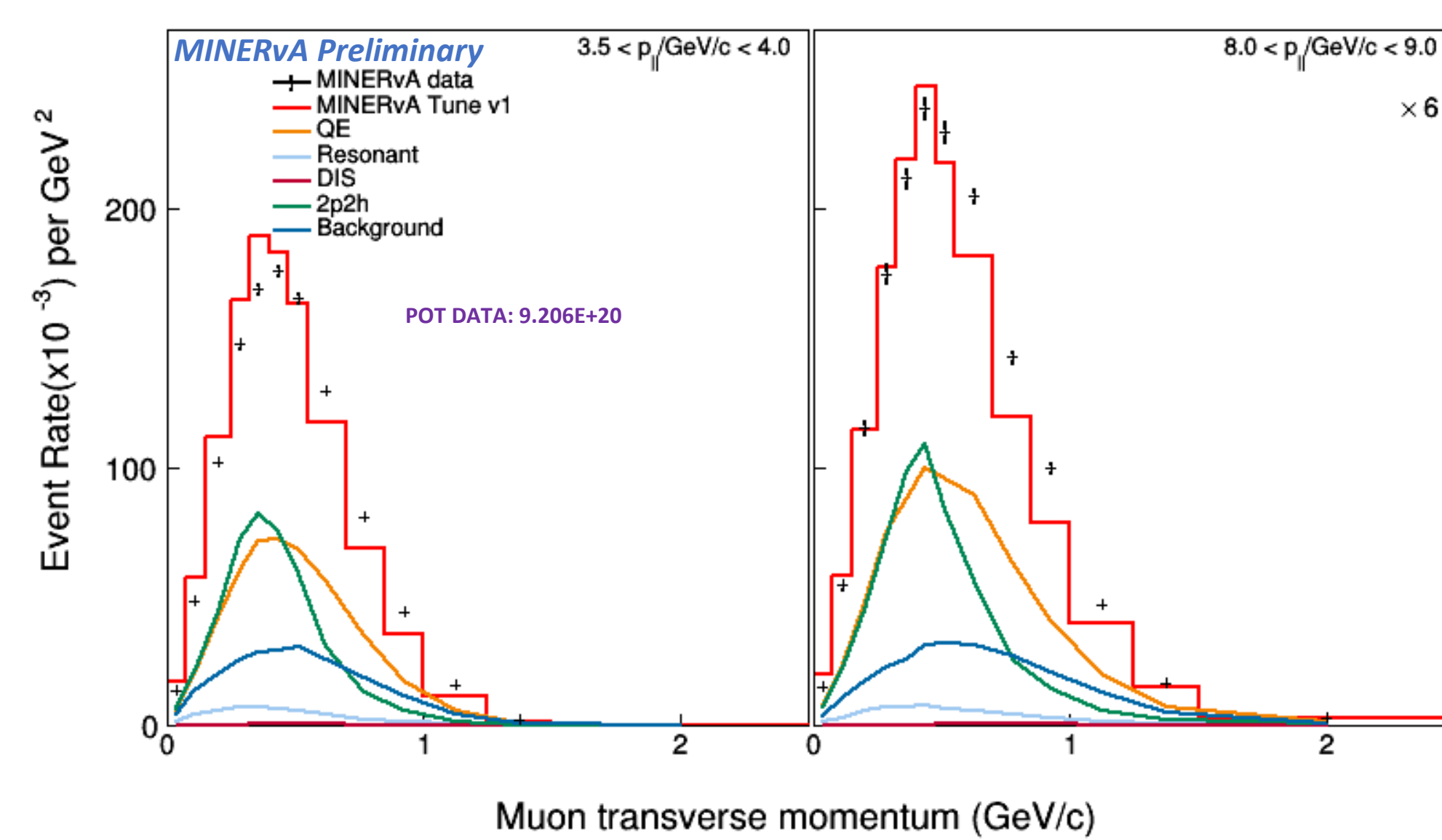


Fig: 6

- Reconstructed raw events as a function of  $p_T$  in the bins of  $p_{||}$ . Two  $p_{||}$  bins from rising and falling part of  $p_{||}$  distribution to show the events passing reconstruction cuts
- Simulation MINERvA tune v1 : GENIE 2.12.6<sup>1</sup> + Nieves 2p2h<sup>2</sup> + Non Resonant Pion Reduction + Neutrino Low Recoil Fits + Valencia RPA applied to QE
- QE and 2p2h dominate the signal events.
- Low resonance contribution

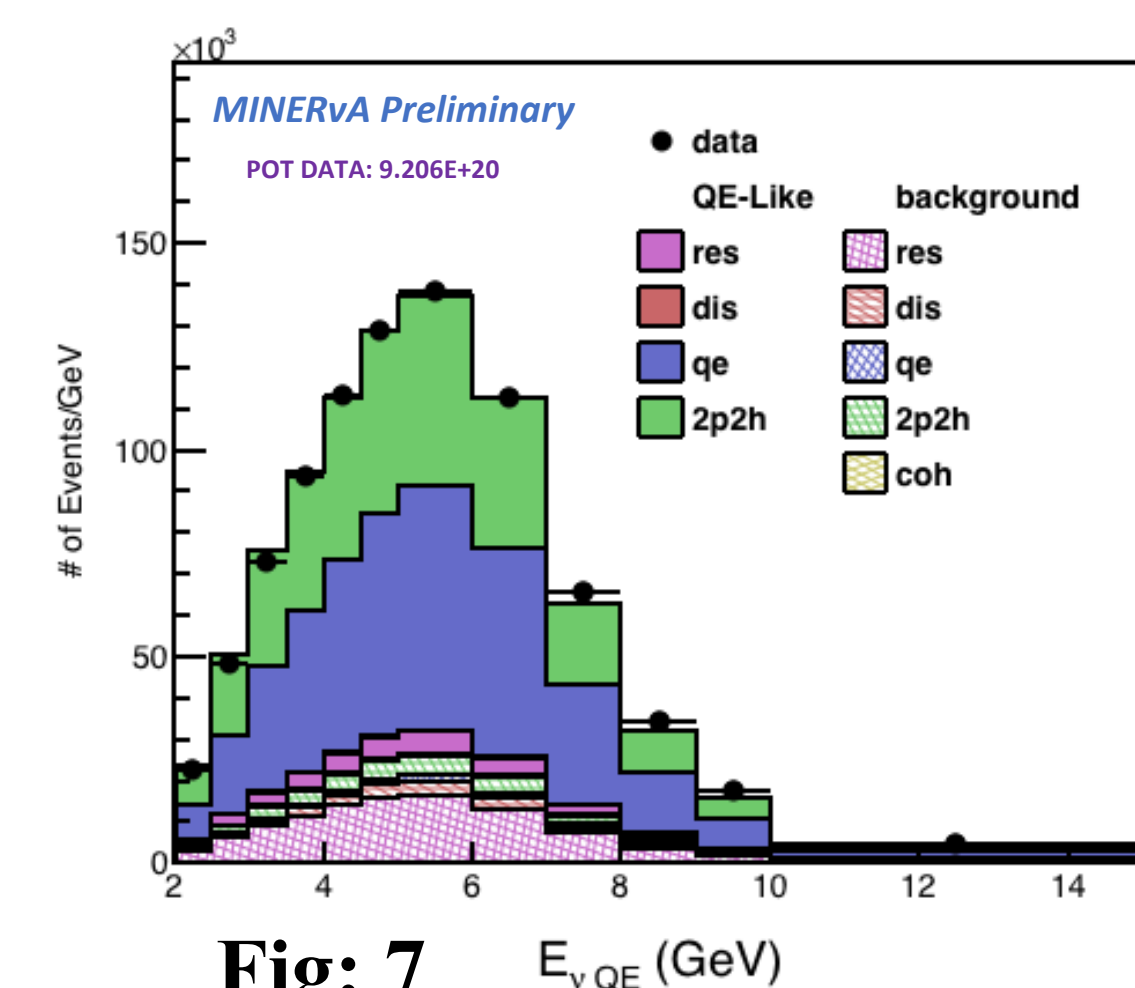


Fig: 7

Reconstructed incoming neutrino energy based on CCQE hypothesis (using muon kinematics only)

$$E_\nu^{QE} = \frac{m_p^2 - (m_n - E_b)^2 - m_\mu^2 + 2(m_n - E_b)E_\mu}{2(m_n - E_b - E_\mu + p_\mu \cos \theta_\mu)}$$

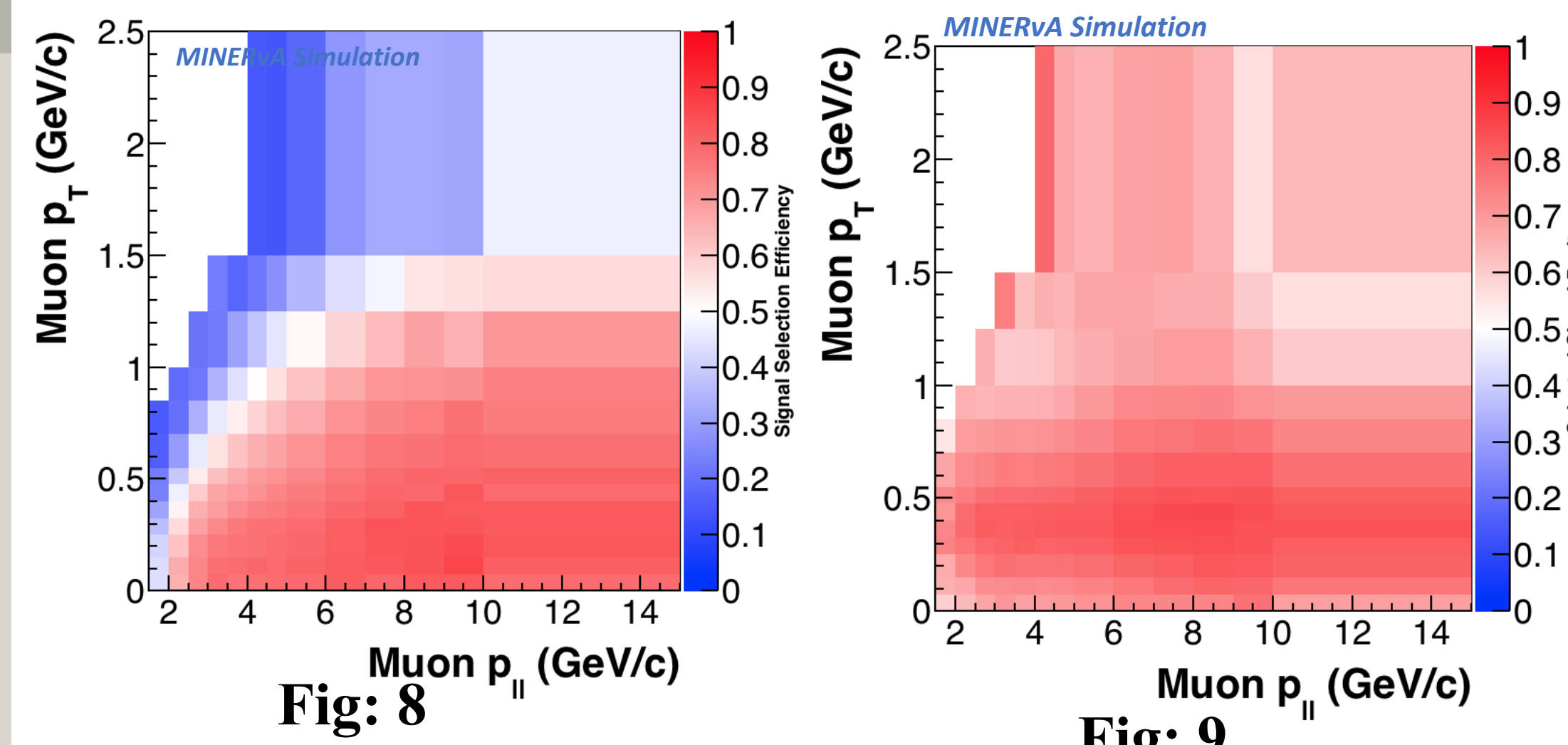
$$Q_{QE}^2 = 2E_\nu^{QE}(E_\mu - p_\mu \cos \theta_\mu) - m_\mu^2$$

$m_p$  and  $m_n$  are rest mass of proton and neutron and  $E_b$  is binding energy

$$\theta_\mu \text{ Angle between incoming neutrino and outgoing muon}$$

$$Q_{QE}^2 = -q^2 \text{ Four Momentum Transfer Squared from lepton to hadron system}$$

## Selection Efficiency and Purity



Signal Selection Efficiency :  $\frac{\# \text{ of True Signal Events passing cuts}}{\# \text{ of True Signal Events}}$

Purity :  $\frac{\# \text{ of True Signal Events passing cuts}}{\# \text{ of Events passing Cuts}}$

- 0 Efficiency/Purity at low  $p_{||}$  and high  $p_T$  due to 20 degree angle cut requirement on selection cut.
- 70 to 80% pure sample with high selection efficiency

## Background Subtraction

- Data driven fit in 14 different bins of  $p_T p_{||}$
- Fit to a recoil energy side band (100 to 500 MeV) that overlaps in some signal sideband regions
- Normalize the overall background using the fit

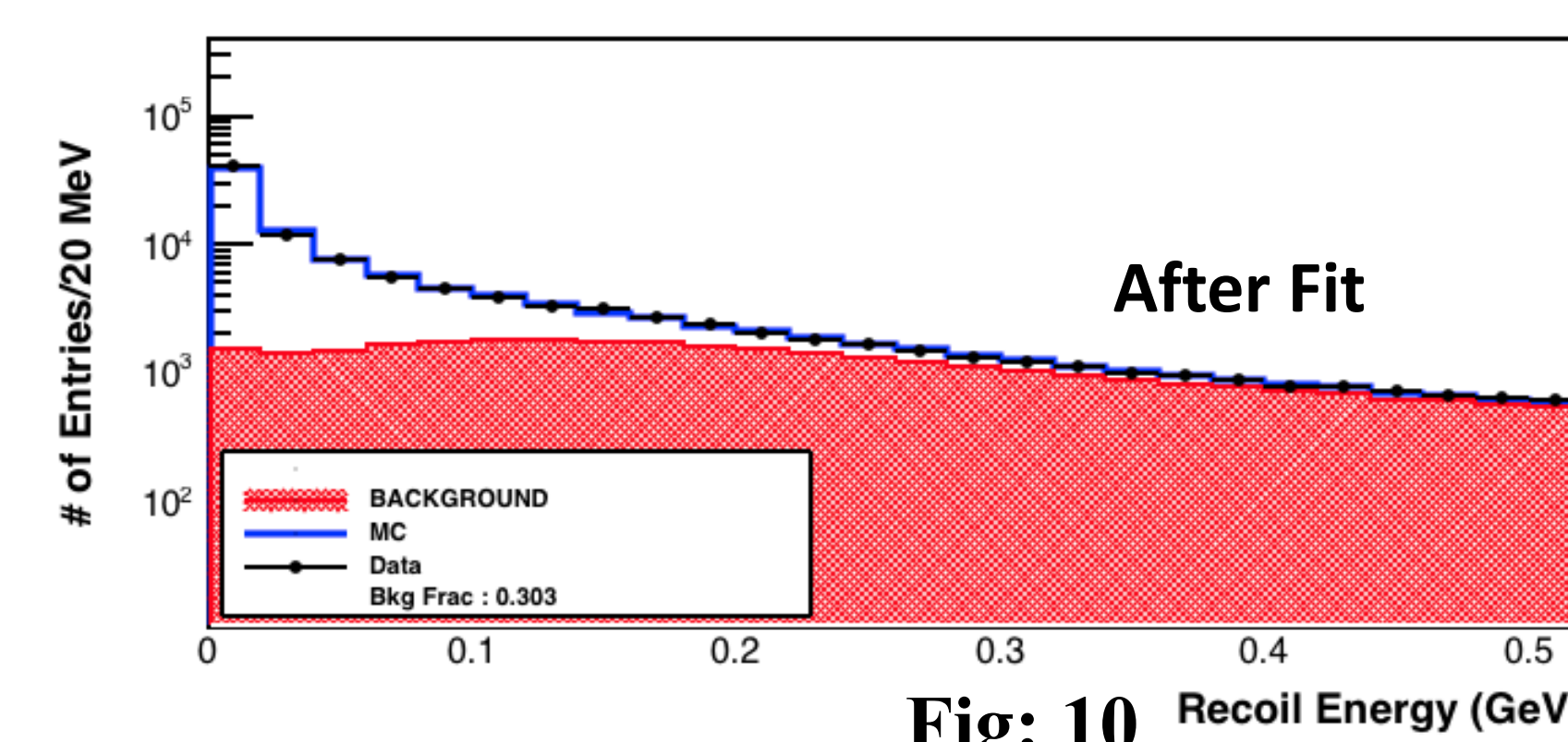
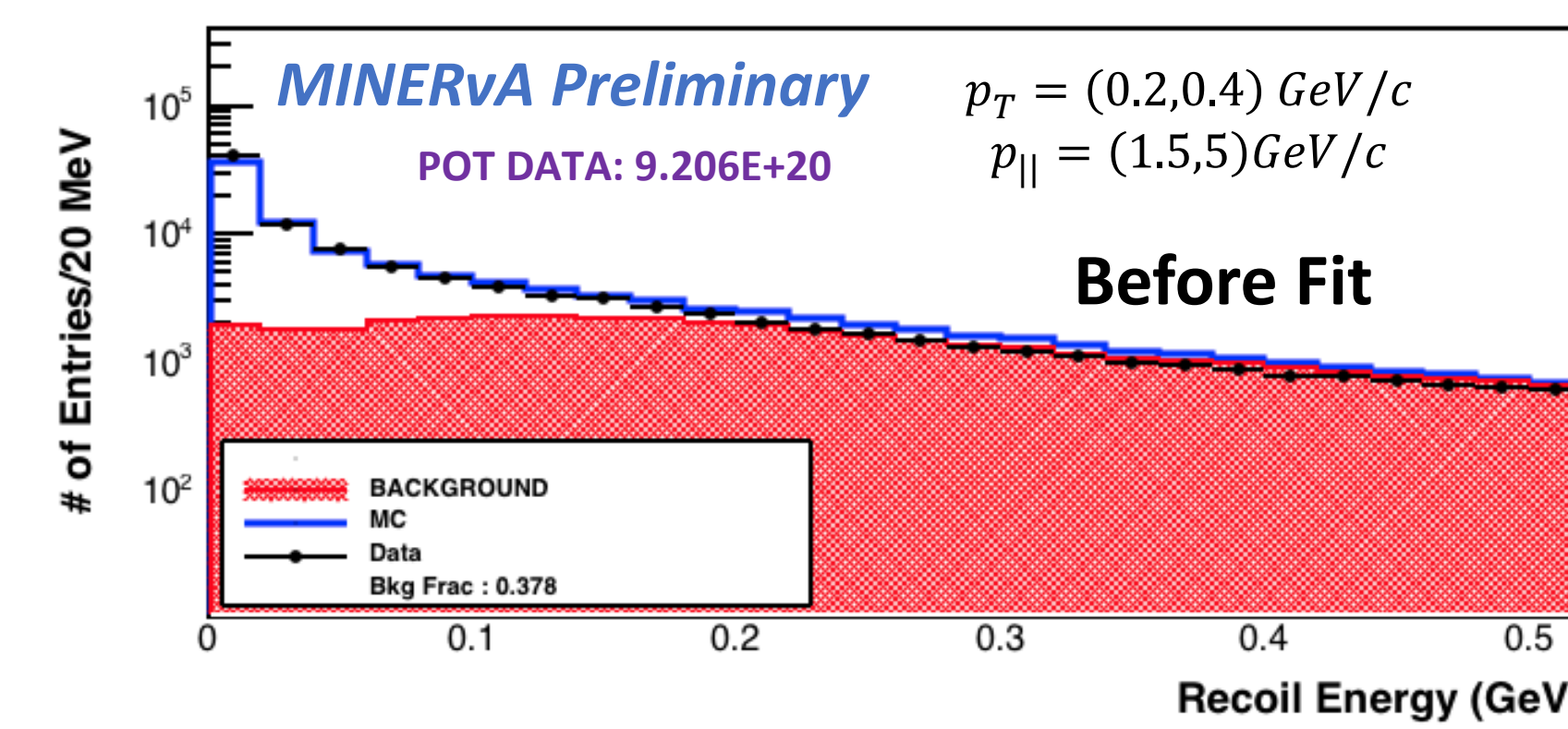


Fig: 10

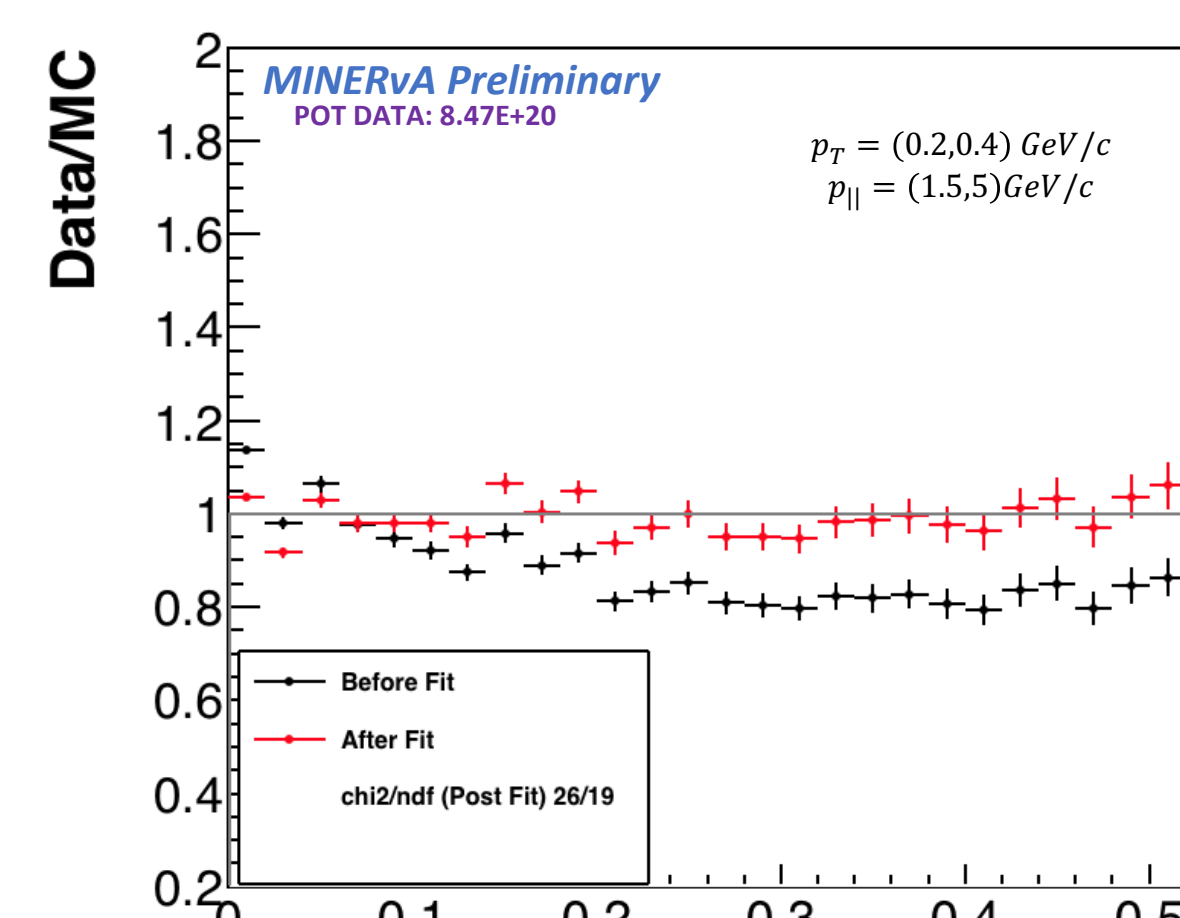


Fig: 11

Recoil energy distribution before and after fit (Fig 10) Ratio of Data and MC before and after fit (Fig 11)

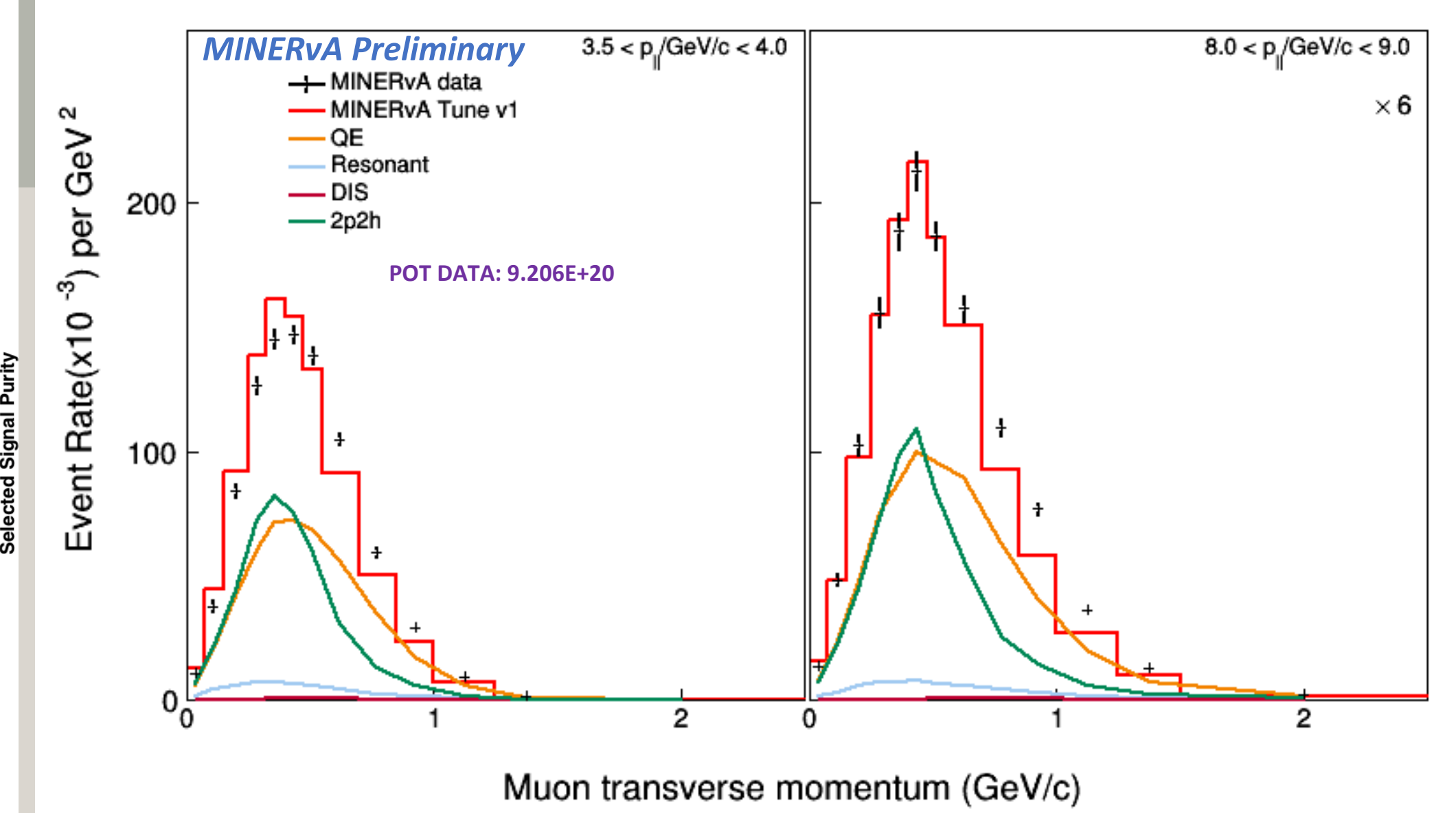


Fig: 12

- Figure 12 shows the background subtracted distribution along with the signal components of the MC.
- Dominated by true QE and 2p2h events.

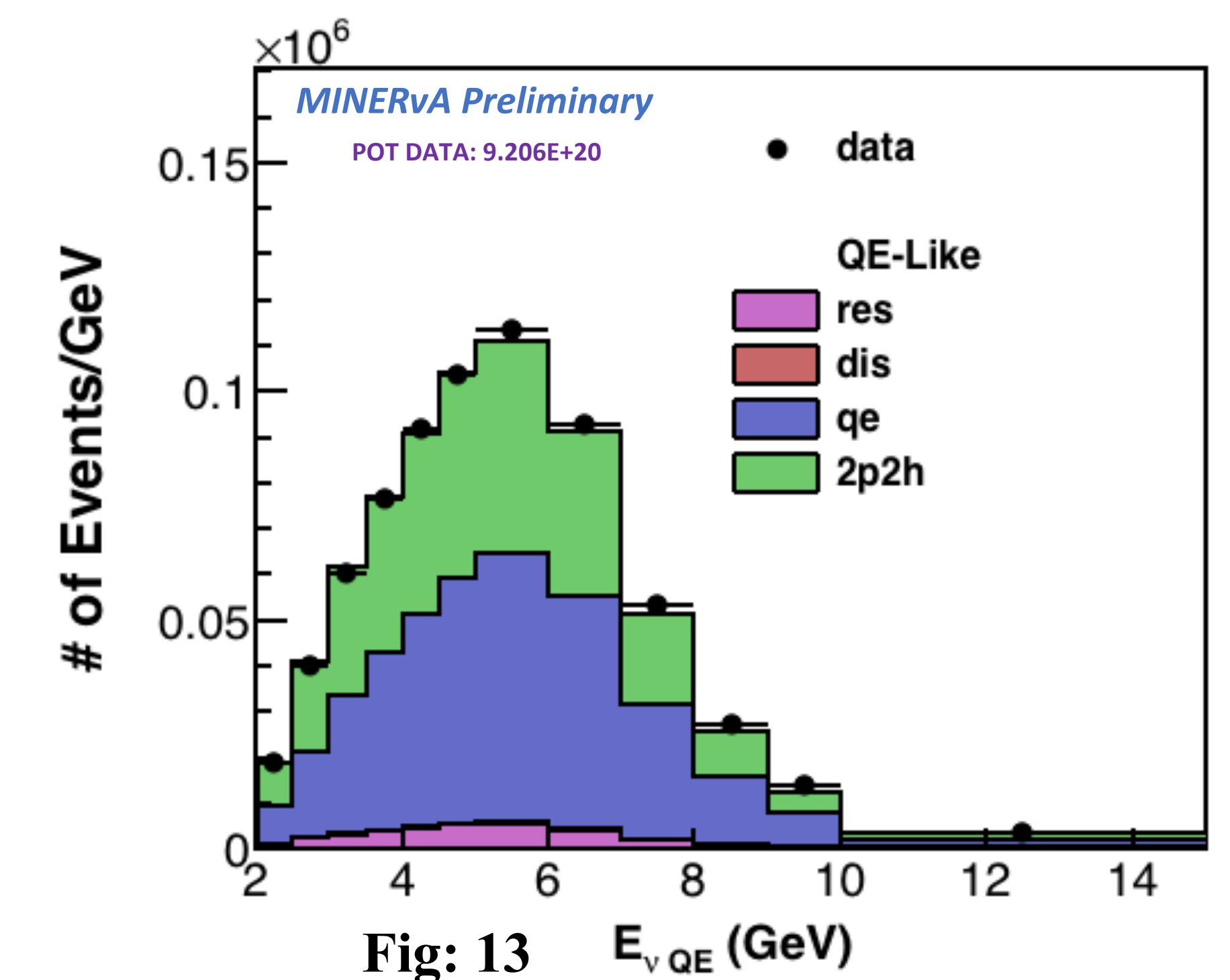


Fig: 13

- Neutrino energy (based on CCQE hypothesis) after background subtraction

## Conclusion

- Demonstrates that event selection to background subtraction procedure is robust.
- Ongoing work on cross-section extraction.
- The cross-section measurements in 2 different phase spaces ( $p_T$  vs  $p_{||}$  and  $E_{\nu_{QE}}$  vs  $Q_{QE}^2$ ) will have the advantage of much higher statistics compared to the measurement with neutrino flux of average energy 3.5 GeV
- Complements the neutrino mode side of CCQELike cross-section measurements with same beam that was recently published<sup>3</sup>.
- **Stay Tuned for Cross-section results!!**

## References

1. C. Andreopoulos et al., Nuclear Instrumental Methods, A 614,87 (2010) arXiv: 0905.2517
2. J Nieves, I.R. Simo, and M.J.V Vacas, Phys. Rev. C83, 045501 (2011)
3. Mateus Carnerio et al, Phys. Rev. Lett. 124,121801 (2020)

## Acknowledgement

"This document was prepared by members of the MINERvA Collaboration using the resources of the Fermi National Accelerator Laboratory (Fermilab), a U.S. Department of Energy, Office of Science, HEP User Facility. Fermilab is managed by Fermi Research Alliance, LLC (FRA), acting under Contract No. DE-AC02-07CH11359. Support for this research was also provided by NSF (1607241)"