MUON NEUTRINO SCATTERING ON LIQUID HELIUM USING THE MINERVA DETECTOR

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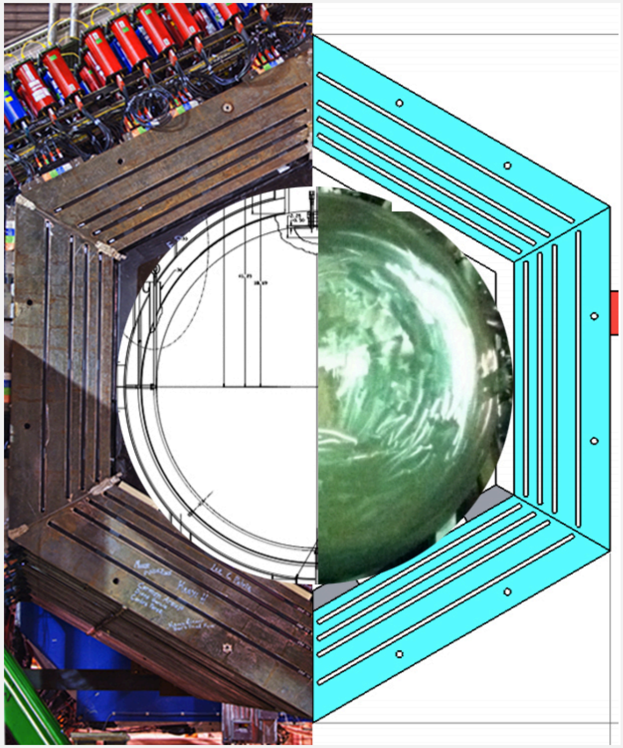

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MOTIVATION

- Entered age of precision oscillation experiments

Measuring neutrino mixing parameters:

- $\theta_{12}, \theta_{13}, \theta_{23}$
- $\Delta(m_{21})^2, \Delta(m_{32})^2, \Delta(m_{31})^2$
- δ_{CP}
- Mass hierarchy

NOvA

T2K

MINOS

μBooNE

LArTPC

DUNE

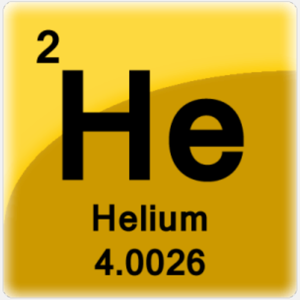
DEEP UNDERGROUND NEUTRINO EXPERIMENT

MOTIVATION

- Oscillation experiments need to predict number of events in their detectors
  - Look for appearance of neutrinos not expected in their flux
  - Look for disappearance of neutrinos expected in their flux
- Requires cross section inputs
  - Constrained by internal or external measurements
  - One of the largest sources of systematic errors
- Oscillation experiments use heavy nuclei to increase statistics (Iron, Carbon, etc..)
- Scattering off nucleus is much different than scattering off an individual nucleon
  - Much more difficult to predict
    - Final state interactions, modification of quark momentum distributions, mysterious effects like EMC effect

MOTIVATION

- Scattering off light nuclei is the ideal way to study nuclear effects
- Smallest number of protons and neutrons possible
  - Leads to least complicated nuclear structure and more easily predicted behavior by models
- Scattering off deuterium would be ideal but no one likes a detector that explodes at the first spark
  - so………

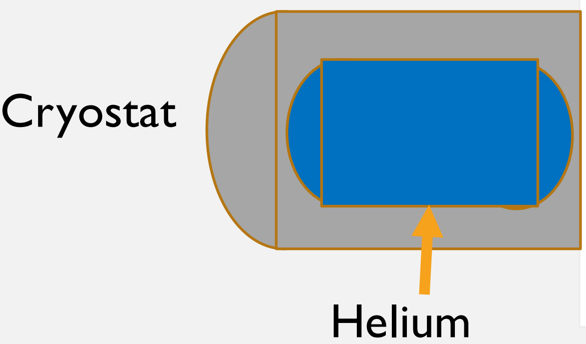


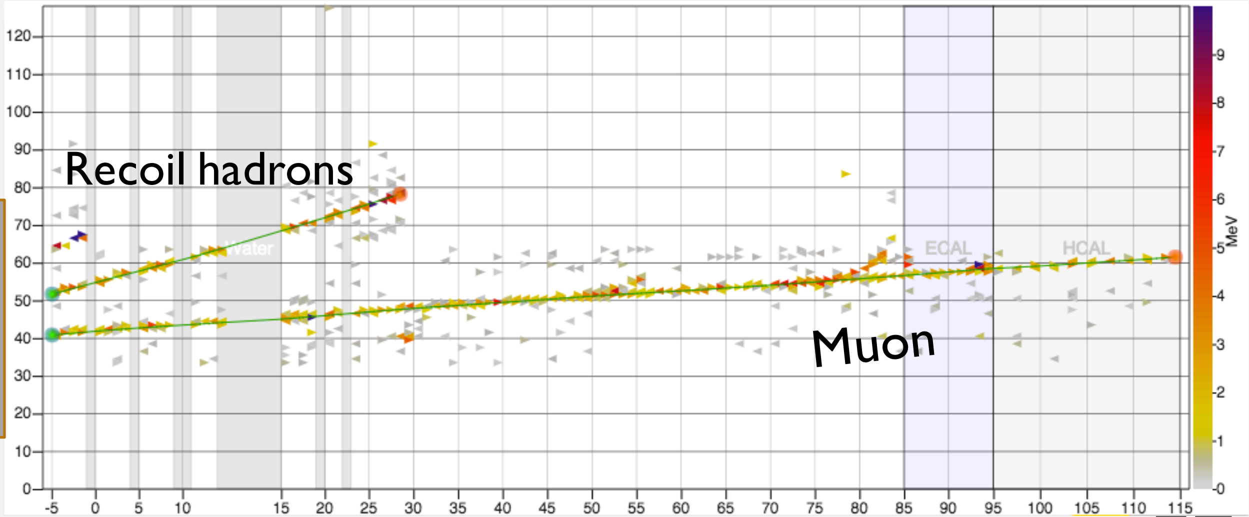
Helium to the rescue!!

  - And so begins our story

HELIUM CROSS SECTIONS

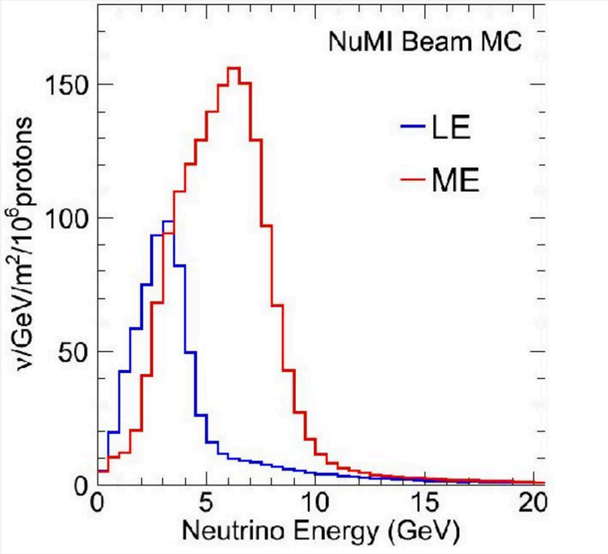
- 2300L of liquid helium inside aluminum cryostat
- Upstream of MINERvA
- Reconstruct events in the helium by projecting 2 (or more) tracks in MINERvA back into the helium target and looking for an intersection (neutrino interaction vertex!)
- Measure charged current inclusive $d\sigma/dE_{\mu}$ and $d\sigma/d\theta_{\mu}$, compare with heavier nuclei





Candidate Neutrino - Helium Event

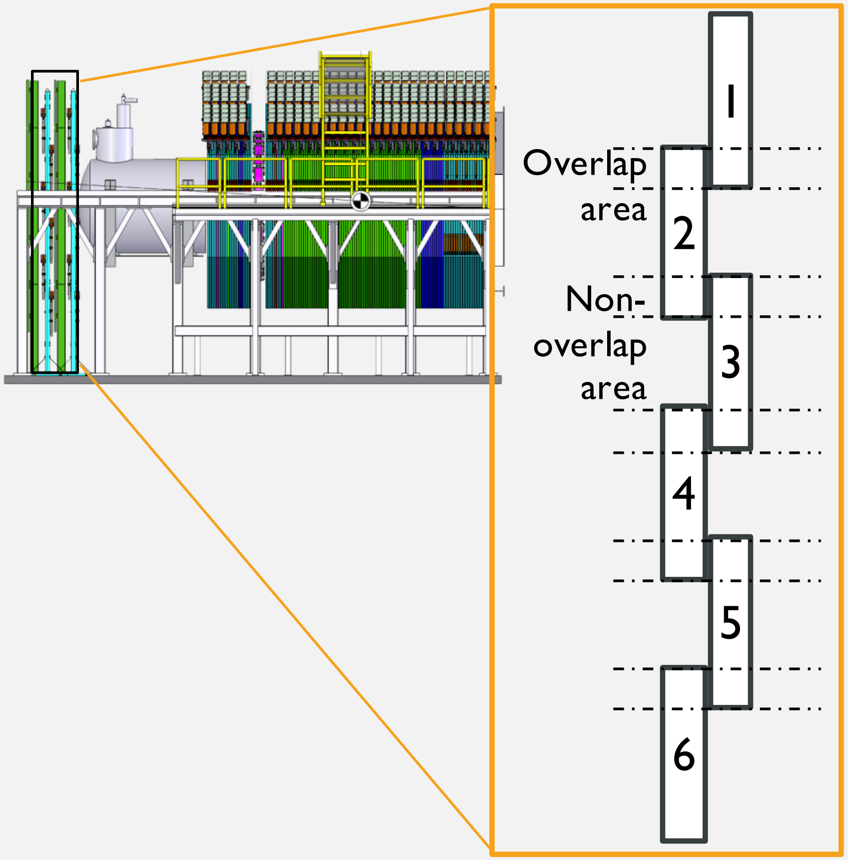
DATA SETS



- Using NuMI low energy beam
- Data:
  - Filled helium target
    - 1.25E20 Protons on target
  - Emptied helium target
    - 5.22E19 Protons on target
    - Use to characterize our background in data
- Monte Carlo:
  - Filled helium target
    - 1.1E21 Protons on target

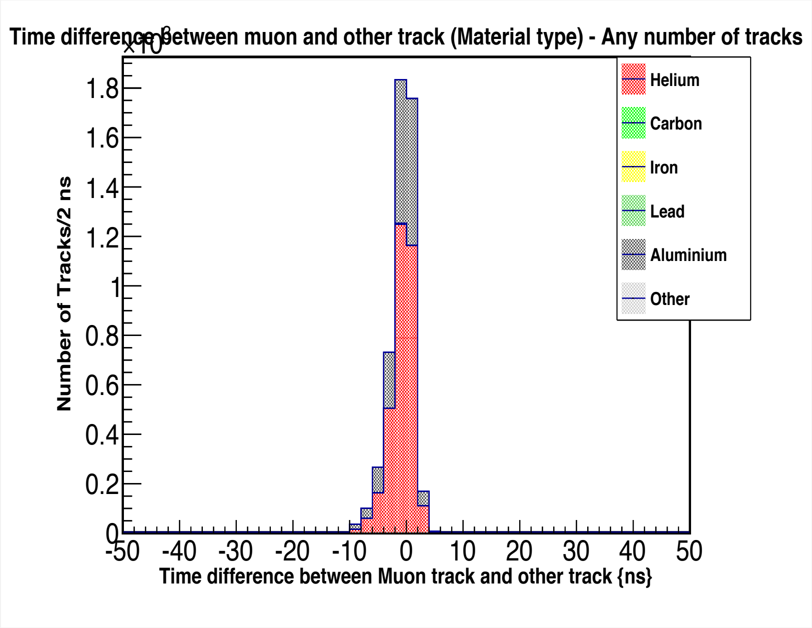
HELIUM EVENT SELECTION

- Reject rock muons
  - Muons coming from neutrino interactions with surrounding rock
  - Can mimic signal
  - Use two veto walls
    - Reject by matching tracks in time to scintillator paddles on veto wall(s)



HELIUM EVENT SELECTION

- Two or more tracks vertexed in the helium target
- MINOS matched muon with negative charged
- $\theta_\mu < 17$ degrees and $E_\mu > 2$ GeV
  - MINOS acceptance falls off dramatically outside this region
- Other MINOS track quality cuts
- Tracks must be within 10ns of each other in MINERvA
  - Only possible because of the amazing timing resolution of MINERvA



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HOW TO CALCULATE A CROSS SECTION

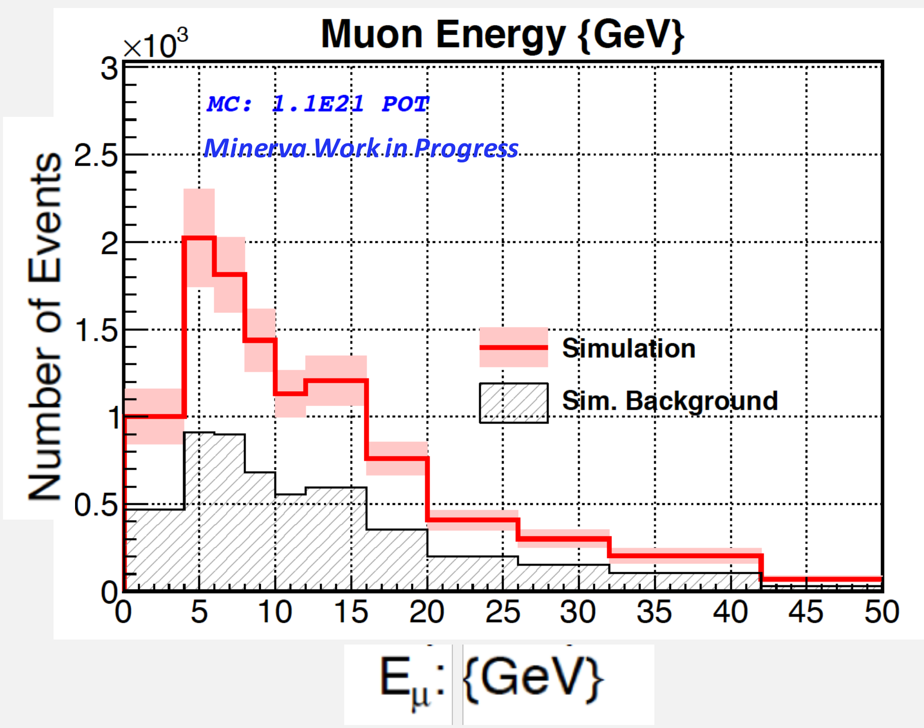
$$\frac{d\sigma}{d\zeta_i} = \frac{\sum_j U_{ij}(d_j - b_j)}{\epsilon_i \Phi T \Delta\zeta_i}$$

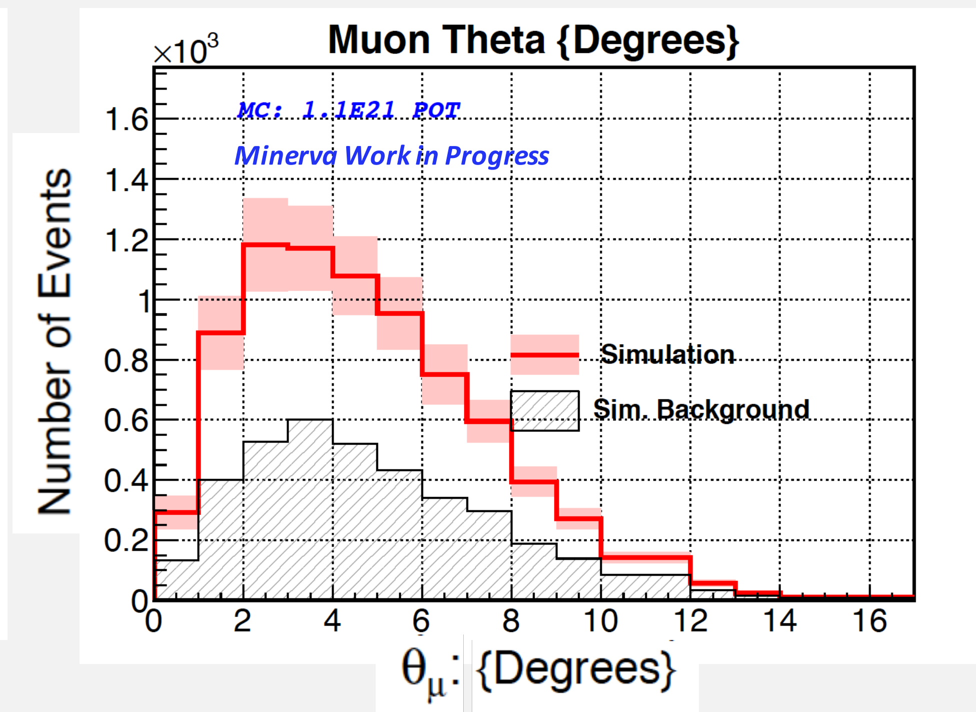
1. $\frac{d\sigma}{d\zeta_i}$: Differential cross section in variable ζ in bin i
2. $(d_j - b_j)$: Data events minus background events in bin j
3. U_{ij} : Unsmearing matrix which takes reconstructed quantities in bin j to true quantities in bin i
4. ϵ_i : Efficiency for bin i
5. ΦT : Integrated flux times the number of target helium atoms
6. $\Delta\zeta_i$: Bin width

HOW TO CALCULATE A CROSS SECTION

$$\frac{d\sigma}{d\zeta_i} = \frac{\sum_j U_{ij}(d_j - b_j)}{\epsilon_i \Phi T \Delta\zeta_i}$$

- MC events which passed event selection cuts
- Events from 1.1E21 POT
- Background is mostly aluminum from the cryostat

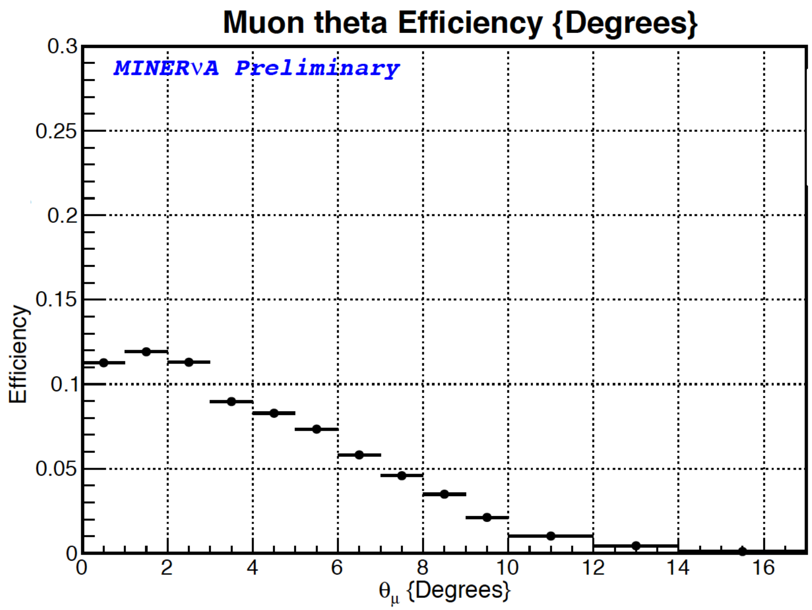


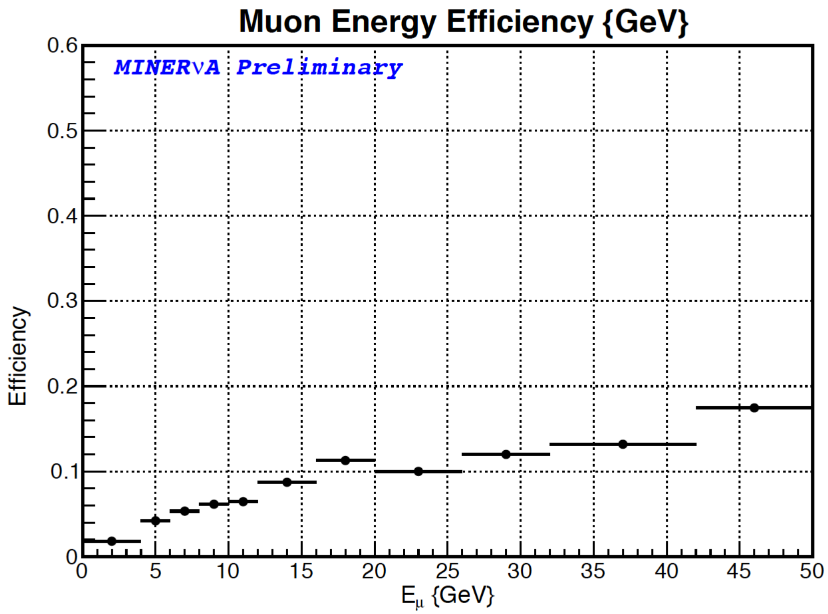


HOW TO CALCULATE A CROSS SECTION

$$\frac{d\sigma}{d\zeta_i} = \frac{\sum_j U_{ij}(d_j - b_j)}{\epsilon_i \Phi T \Delta\zeta_i}$$

Efficiency: fraction of true signal events which were reconstructed



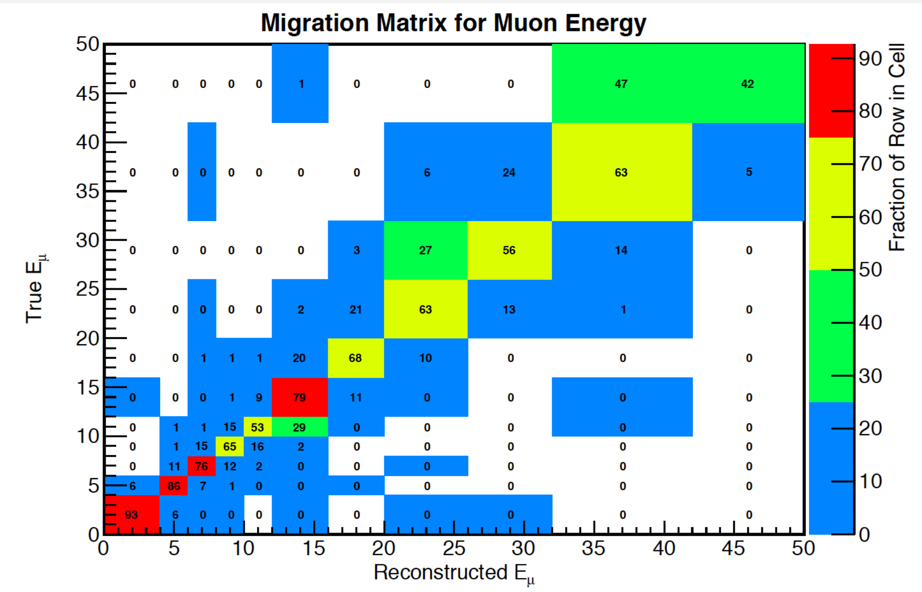


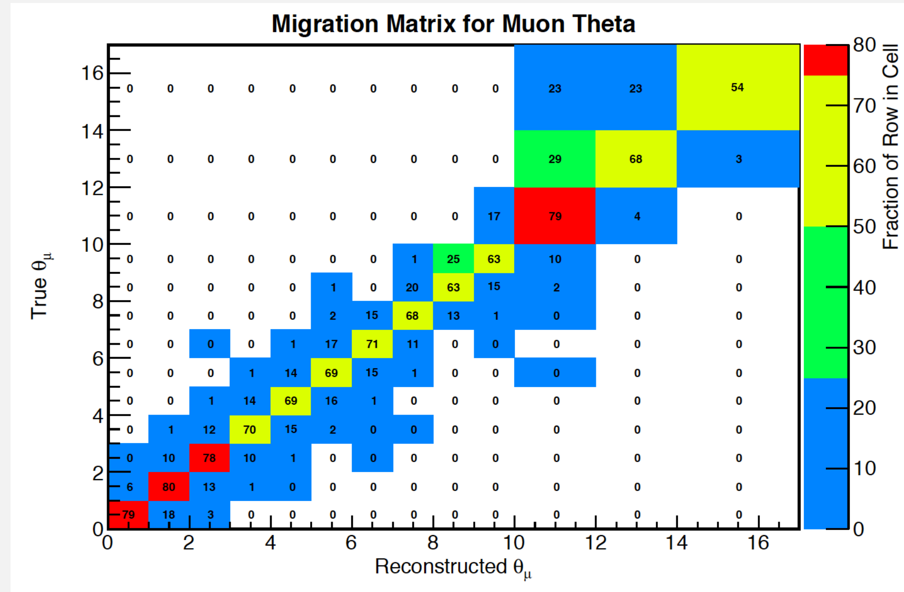
Biggest hit to efficiency is requirement that two tracks be reconstructed in MINERvA and MINOS matching

HOW TO CALCULATE A CROSS SECTION

$$\frac{d\sigma}{d\zeta_i} = \frac{\sum_j U_{ij}(d_j - b_j)}{\epsilon_i \Phi T \Delta\zeta_i}$$

Migration matrices: Correct for detector effects which smear true quantities





SYSTEMATIC UNCERTAINTIES

- Systematic uncertainties are evaluated using the many universes approach

- Regenerate MC with altered parameters (new universes)
  - +/- 2% more material in MINERvA
  - +/- 5mm shift in vtx position

- Cross section is recalculated in these "new universes"

- Uncertainty in the cross section assigned to that parameter is the difference between the new universe cross section and the central value cross section

SYSTEMATIC UNCERTAINTIES

Flux uncertainties

- Hadron product cross sections
- Focusing
- Tertiary interactions

Muon uncertainties

- Muon energy scale
- Angle smearing and bias
- Vertex smearing
- Muon tracking efficiency
- Helium mass

Genie cross section uncertainties

- Cross section models contain parameters that can only be measured by experiment

Final State Interactions

- Particles created from initial interaction with nuclei interact before exiting nucleus
- Affects number, species, and energy/angle of exiting particles

WRAPPING IT UP

- Currently only experiment measuring neutrino cross sections on liquid helium
- Cross section calculation is underway
- Medium Energy data has been taken
  - Higher statistics and Energy
  - 5 times more POT on the full helium target
- One of the many exciting results from MINERvA coming out in the future
- Thank you!