Recent Results From MINOS
and
Future Plans For MINOS+

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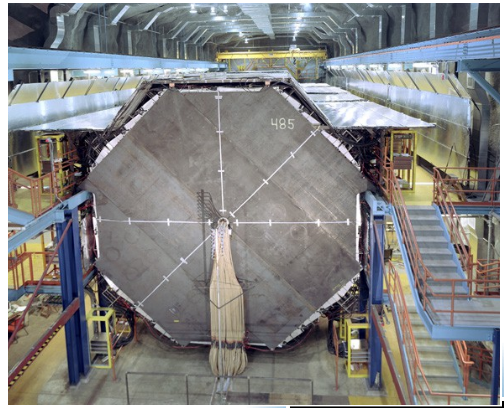
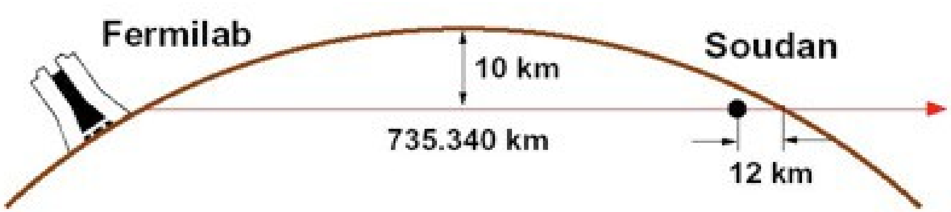
MINOS



- MINOS or Main Injector Neutrino Oscillation Search
- Uses Neutrinos from the NuMI beam line
- Has a peak L/E of ~250km/GeV
- Leading measure of $\left|\Delta m^2_{atm}\right|$

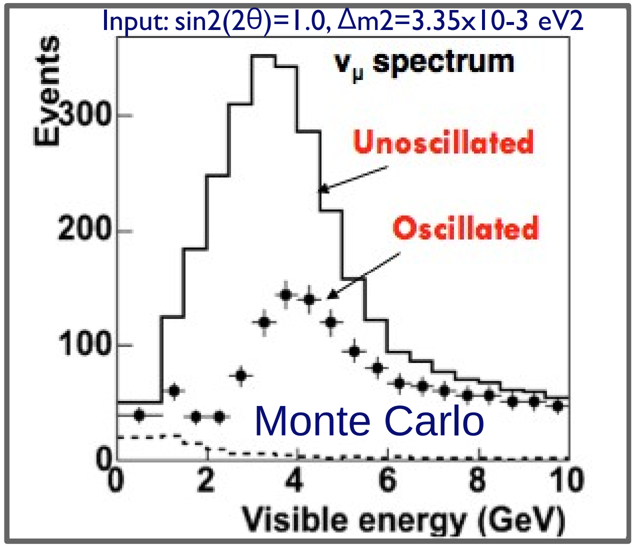


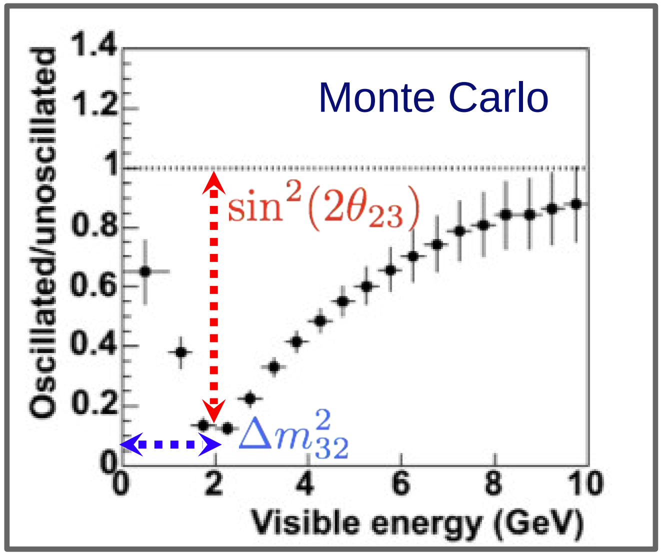
MINOS Physics Goals

- Precise measurement of muon neutrino disappearance
- Direct measurement of muon antineutrino disappearance
- Far detector prediction from near detector is compared to far detector measurement
- Neutrino oscillations deplete rate and distort the energy spectrum

$$P(\nu_\mu \rightarrow \nu_\mu) \approx$$

$$1 - \sin^2(2\theta_{23}) \sin^2\left(\frac{1.27\Delta m^2_{atm} L}{E}\right)$$





MINOS Physics Goals

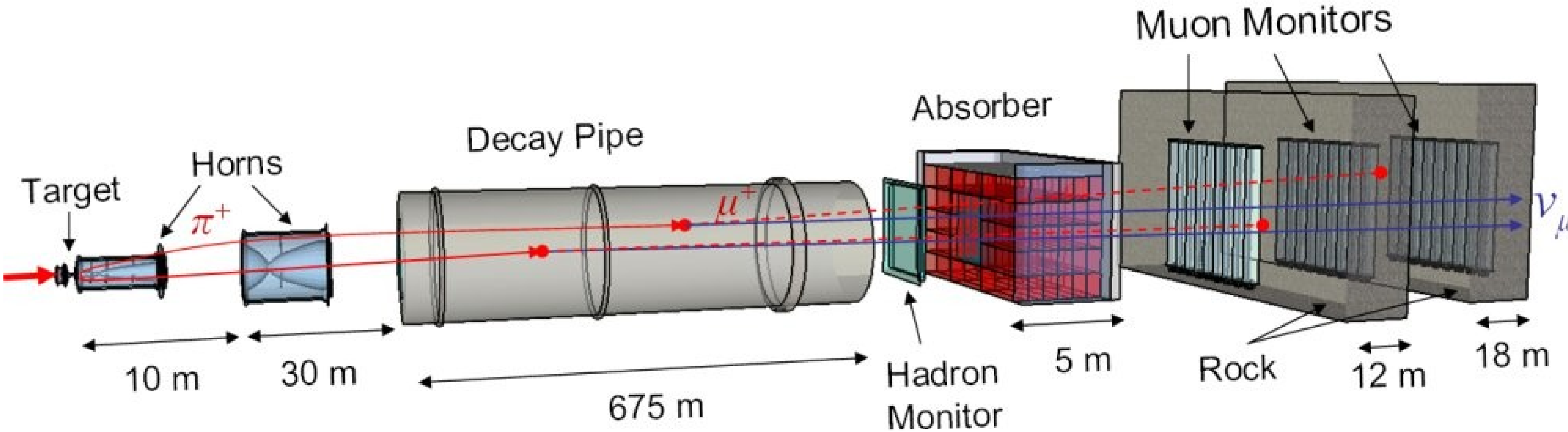
- Precise measurement of muon neutrino disappearance
- Direct measurement of muon antineutrino disappearance
- Muons can also oscillate into electron neutrinos
  - θ_{13}
  - δ_{cp}
  - Mass hierarchy

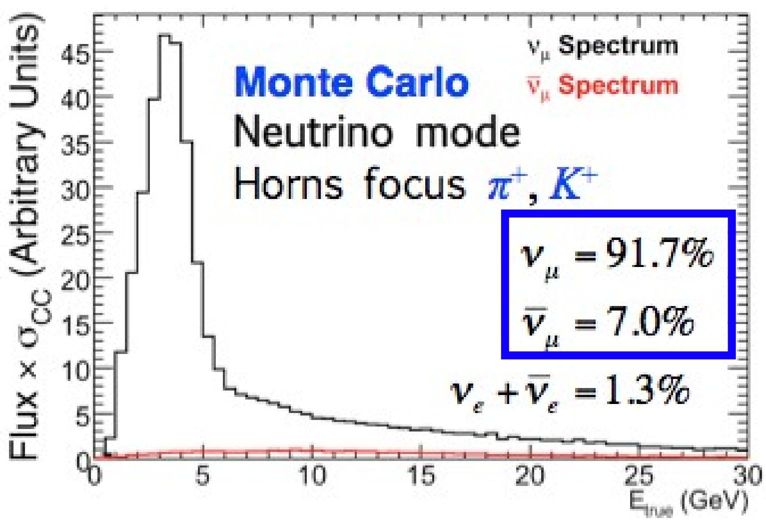
$$P(\nu_\mu \rightarrow \nu_e) = \left| \sqrt{P_{atm}} e^{-i \frac{\Delta m^2_{32} L}{4E} + \delta_{cp}} + \sqrt{P_{sol}} \right|$$

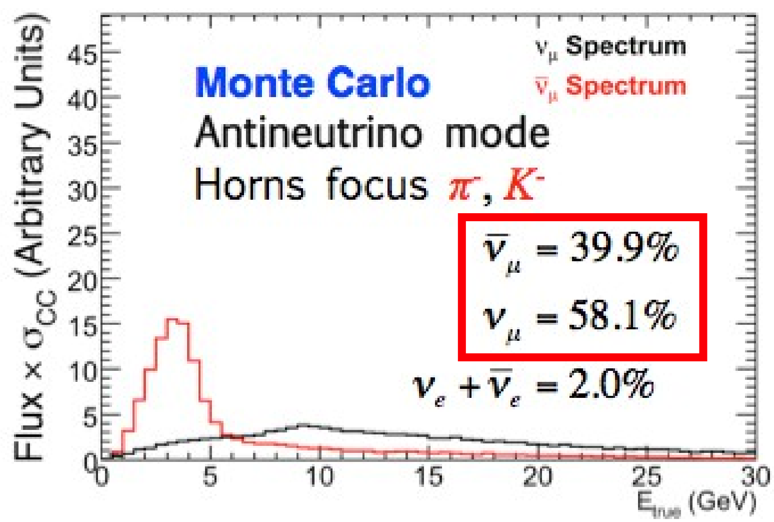
$$P_{atm} = \sin^2\theta_{23} \sin^2\theta_{13} \sin^2\left(\frac{\Delta m^2_{31} L}{4E}\right)$$

"Solar Term" contributes <1% at MINOS L/E

NuMI Neutrino Beam

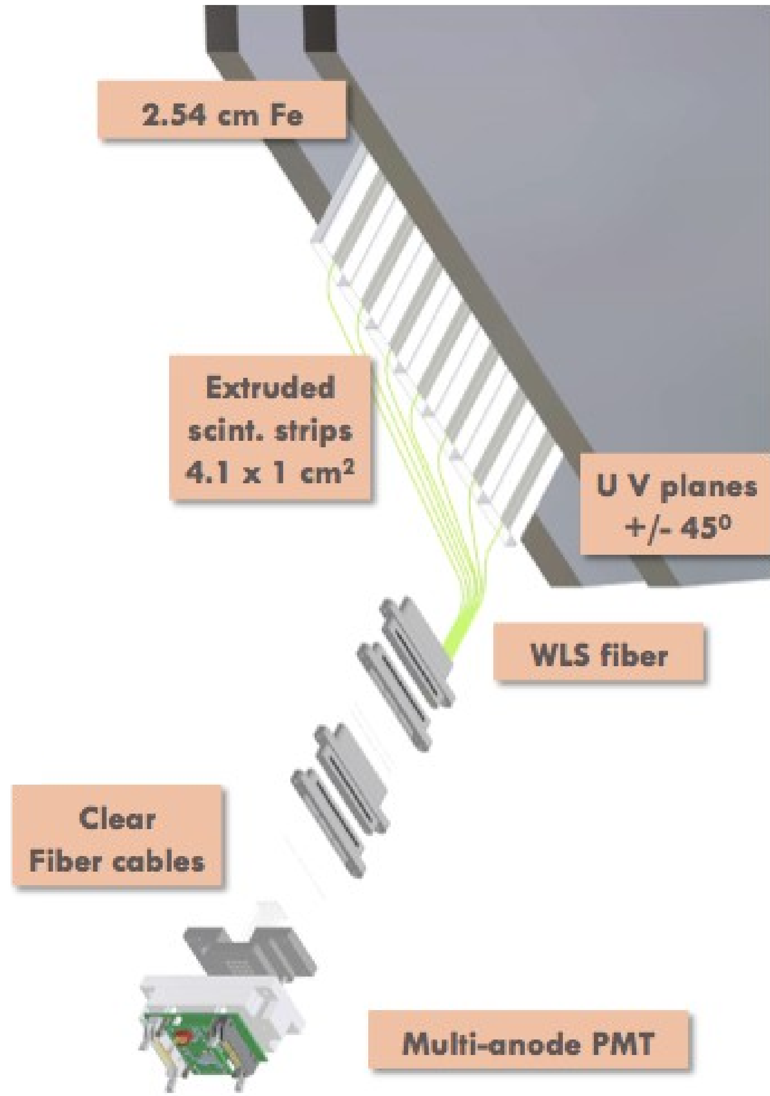


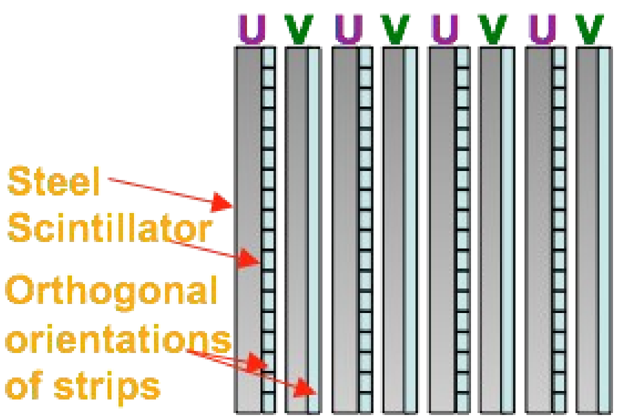


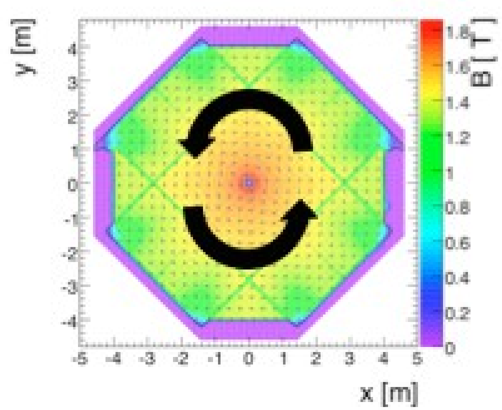


MINOS Detector

- Steel/Scintillator Tracking Calorimeter
  - 2.54 cm-thick steel plates
  - 1 cm-thick, 4.1 cm-wide extruded polystyrene scintillator strips
- Magnetized at <B> ~1.3T
  - Able to distinguish between μ^- and μ^+

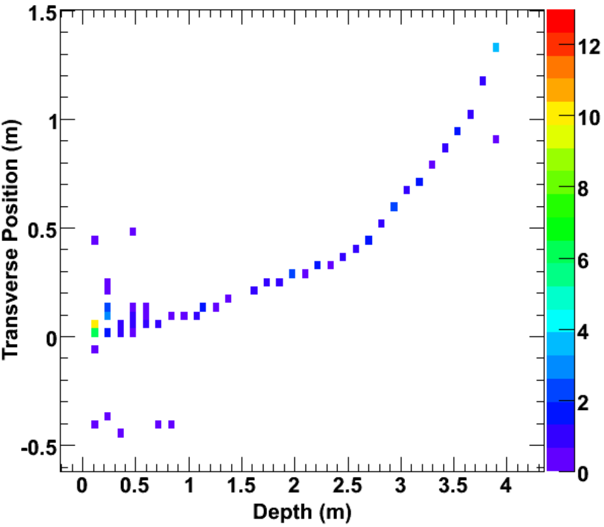




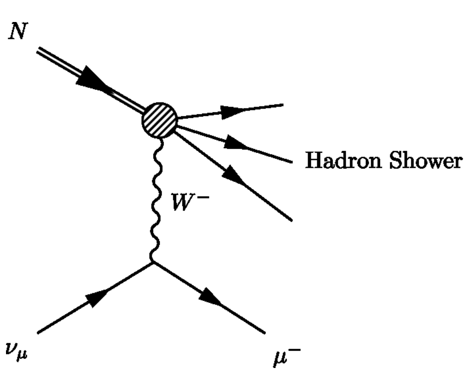


MC Event Topologies

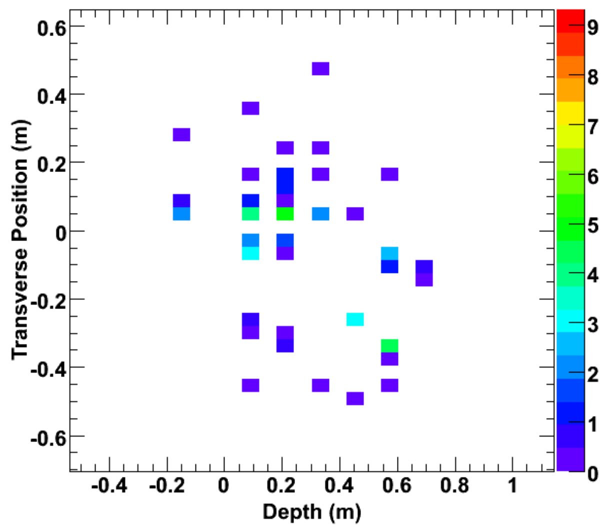
ν_μ Charged Current (CC)



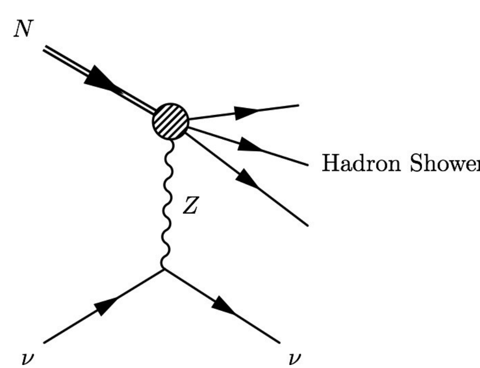
$$\nu_\mu + N \rightarrow \mu^- + X$$



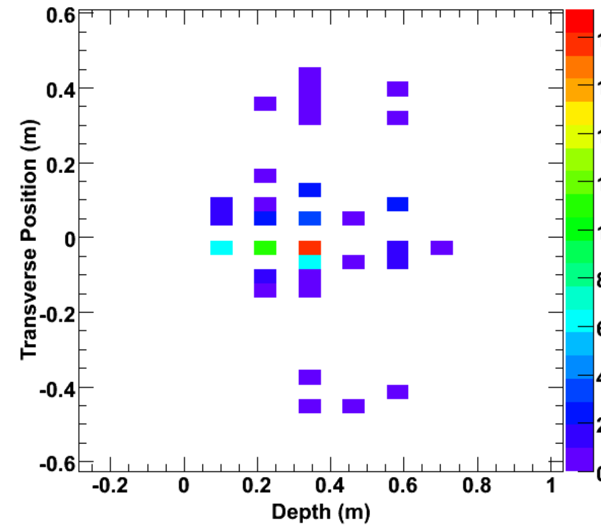
Neutral Current (NC)



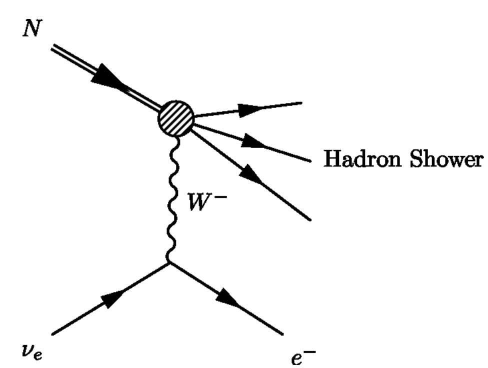
$$\nu + N \rightarrow \nu + X$$



ν_e CC



$$\nu_e + N \rightarrow e^- + X$$



Muon Neutrino Disappearance

Neutrino Disappearance

- Five distinct data sets are used to study muon neutrino disappearance:
  - 15.6x10^{20} POT from NuMI over seven years
    - 10.7x10^{20} POT in “neutrino-enhanced” NuMI beam
      - Muon neutrino charge current interactions
      - Anti muon neutrino charge current interactions
    - 3.4x10^{20} POT in “antineutrino-enhanced” NuMI beam
      - Anti-muon neutrino charge current interactions
  - 37.9 kton-years of atmospheric neutrinos
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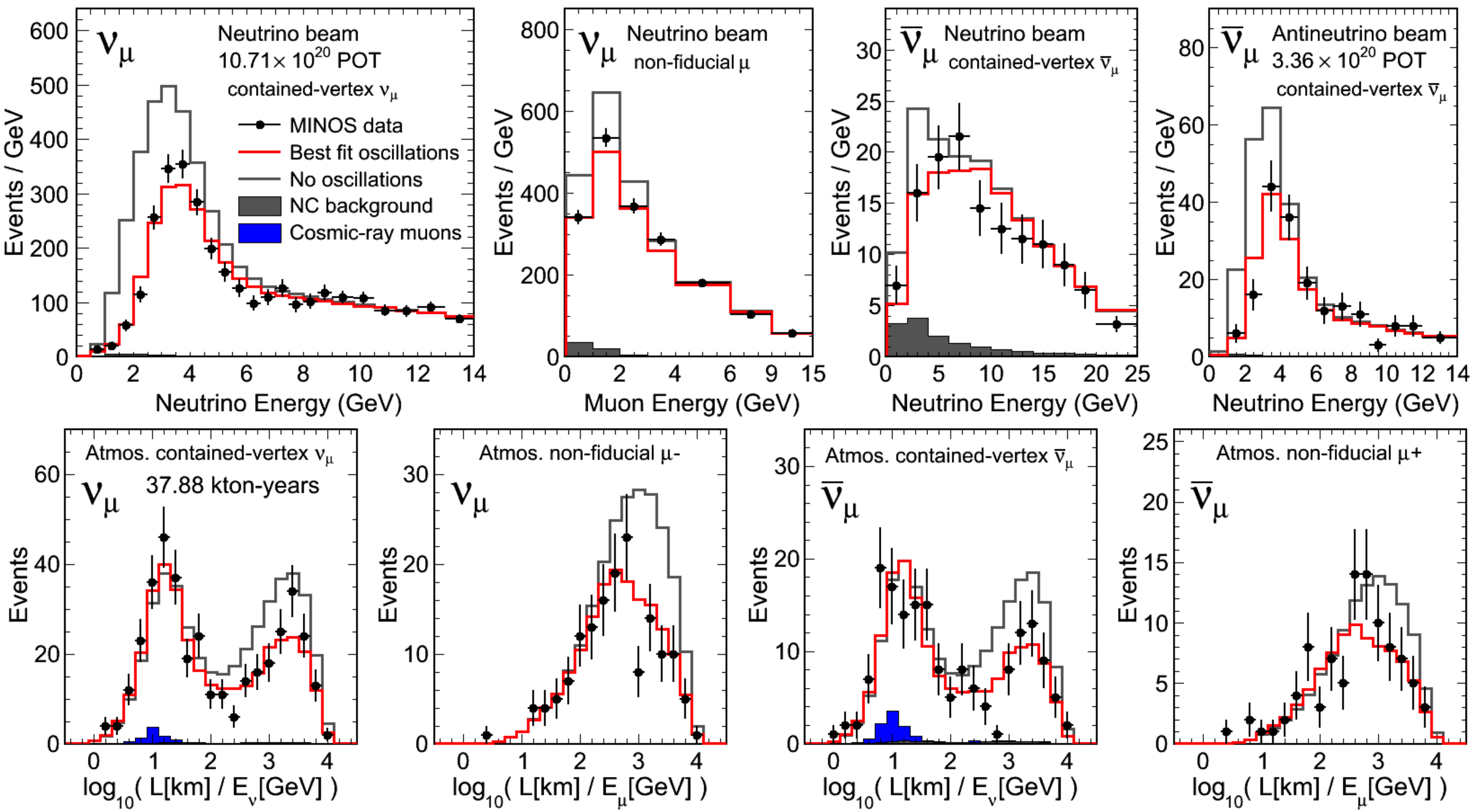
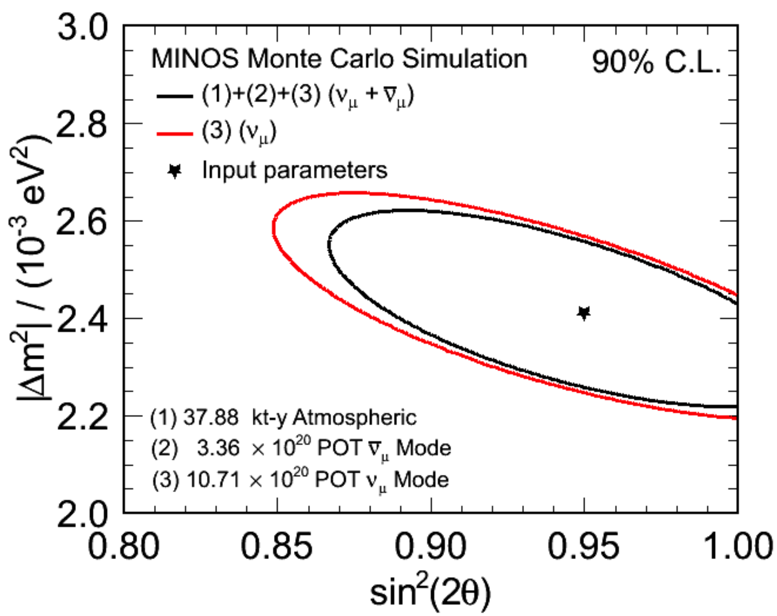
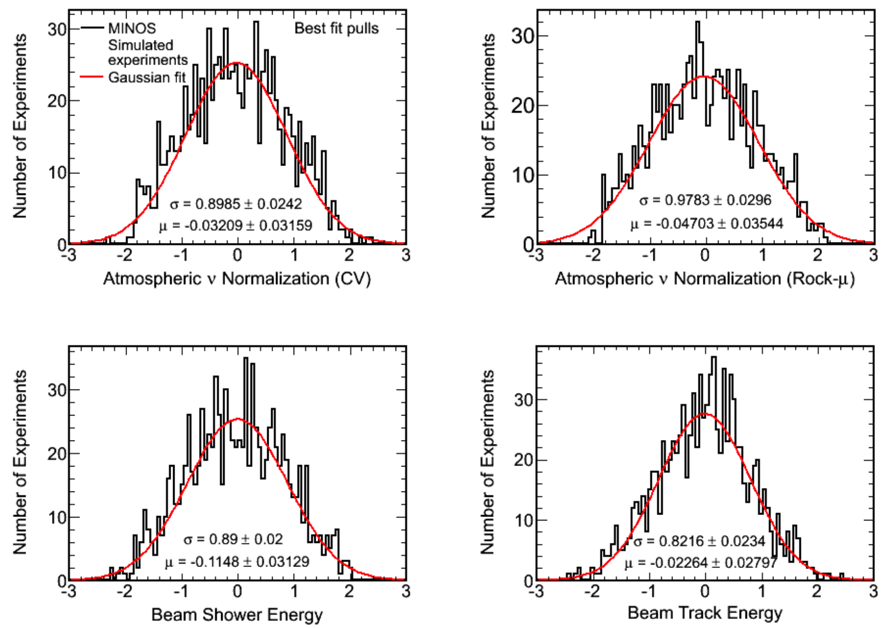


Combined Beam and Atmospheric Neutrino Disappearance Best Fit

- 2 parameter fit assumes identical neutrino and antineutrino oscillations
- 15 systematics included as nuisance parameters
- Monte Carlo studies showed a well behave fit and significant increase in sensitivity:





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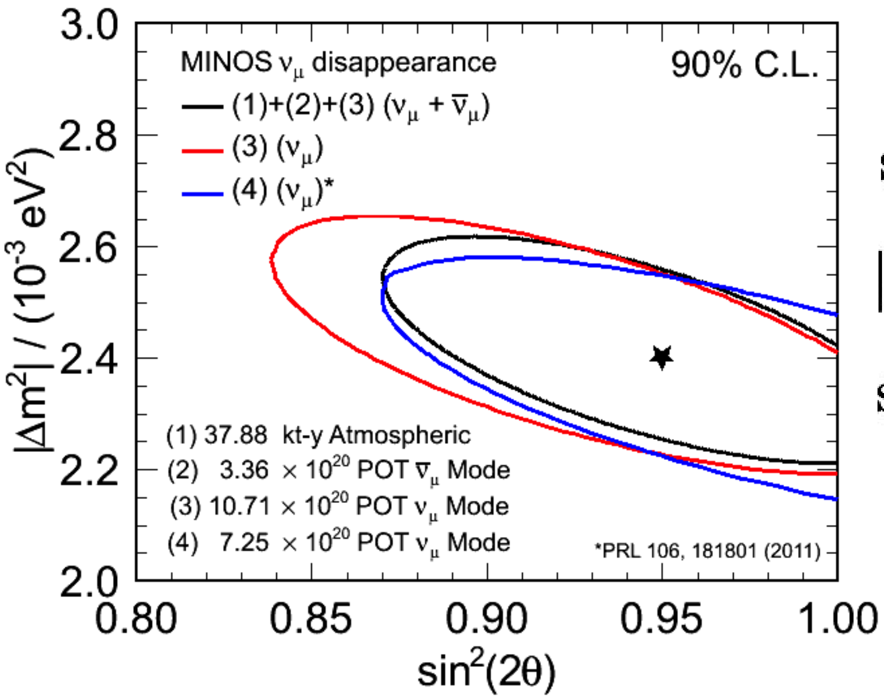


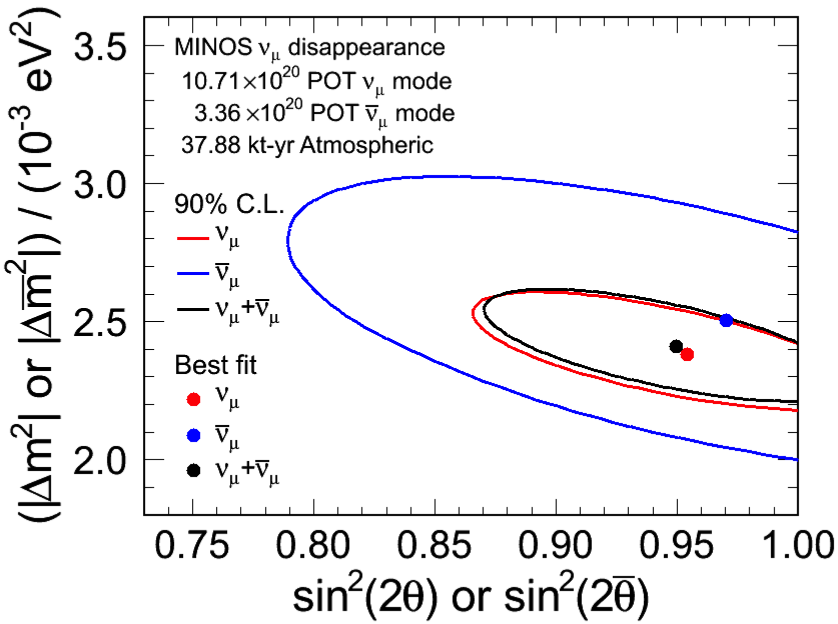
$$\sin^2(2\theta) = 0.95^{+0.035}_{-0.036}$$

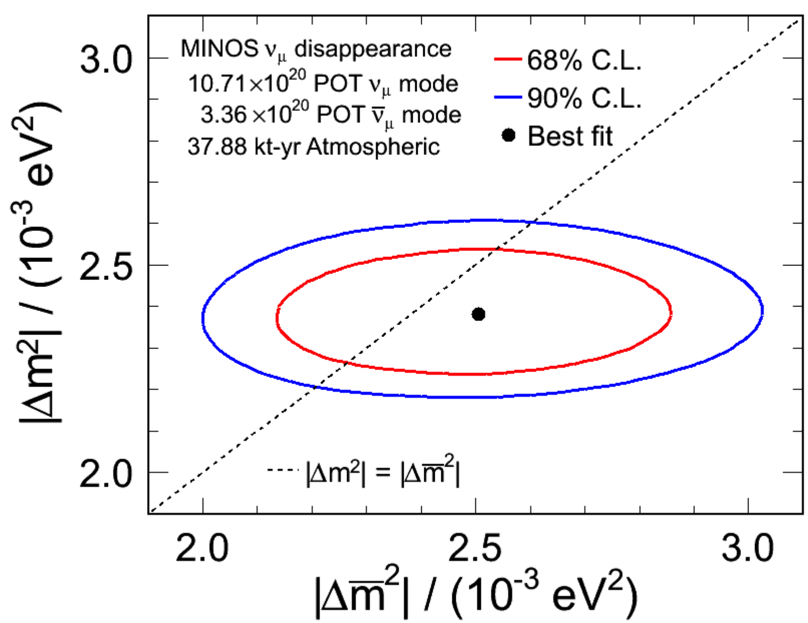
$$|\Delta m^2| = 2.41^{+0.09}_{-0.10} \times 10^{-3} eV^2$$

$$\sin^2(2\theta) > 0.89 \ \ (90\% C.L.)$$

Neutrino and Antineutrino Disappearance Best Fits

- 4 parameter fit allows different neutrino and antineutrino oscillations
- Historically some tension with our neutrino best fit
- Difference has decreased dramatically with more data





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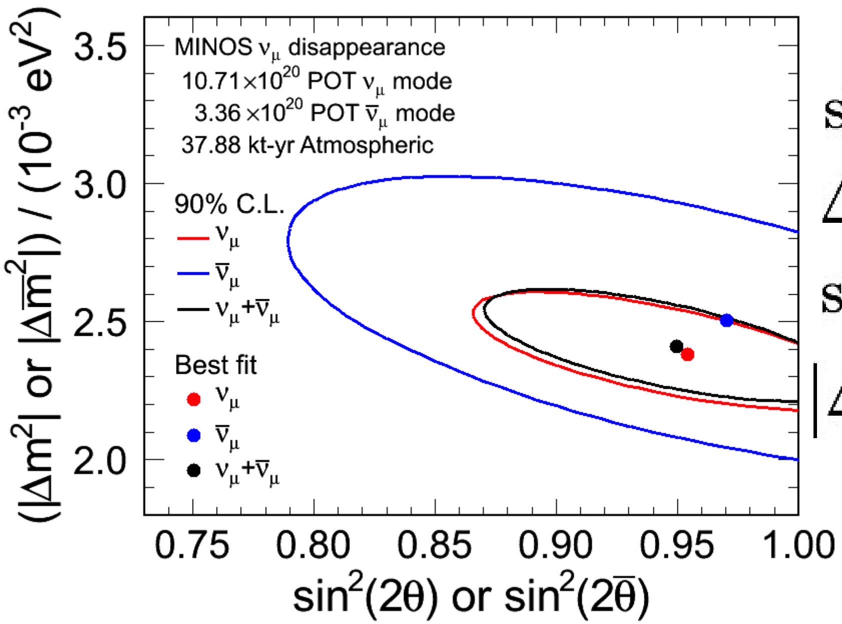


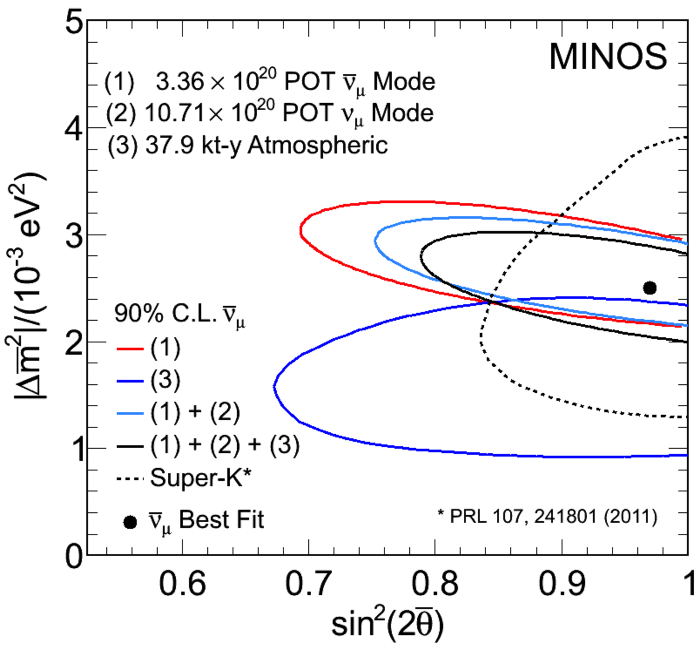
$$\sin^2(2\overline{\theta}) = 0.97^{+0.03}_{-0.08}$$

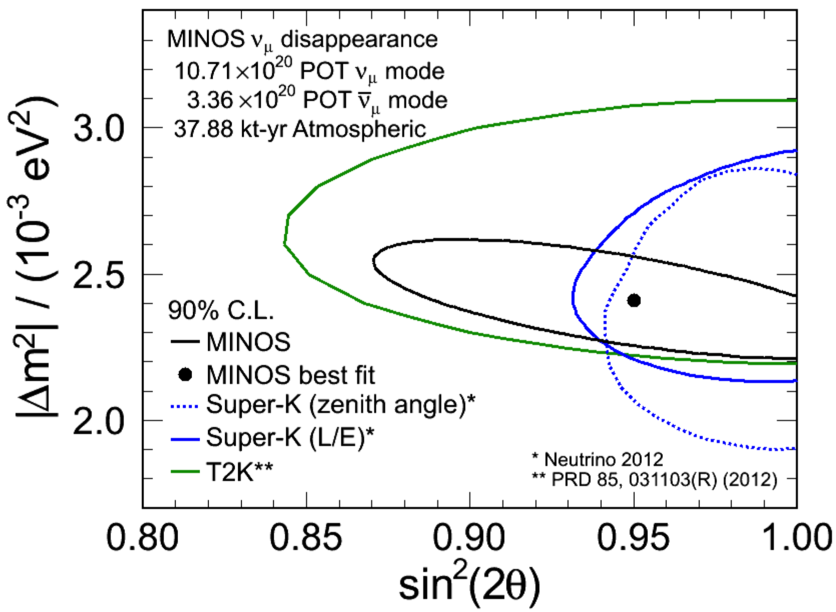
$$\Delta\overline{m}^2 = 2.50^{+0.23}_{-0.25} \times 10^{-3} eV^2$$

$$\sin^2(2\overline{\theta}) > 0.83 \ (90\% C.L.)$$

$$\left|\Delta\overline{m}^2\right| - \left|\Delta m^2\right| = 0.12^{+0.24}_{-0.26} \times 10^{-3} eV^2$$

Neutrino and Antineutrino Disappearance Best Fits





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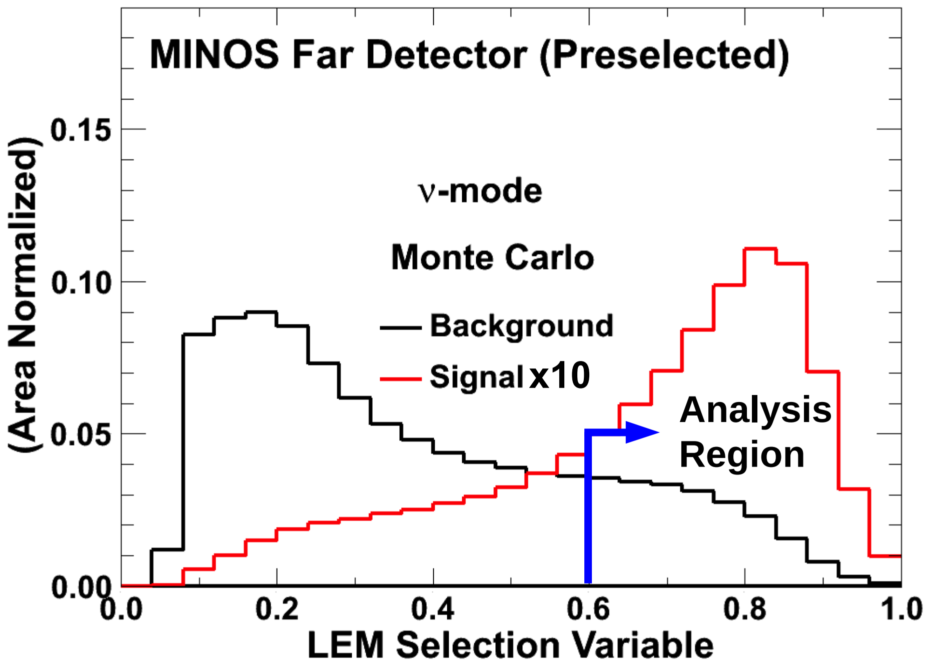
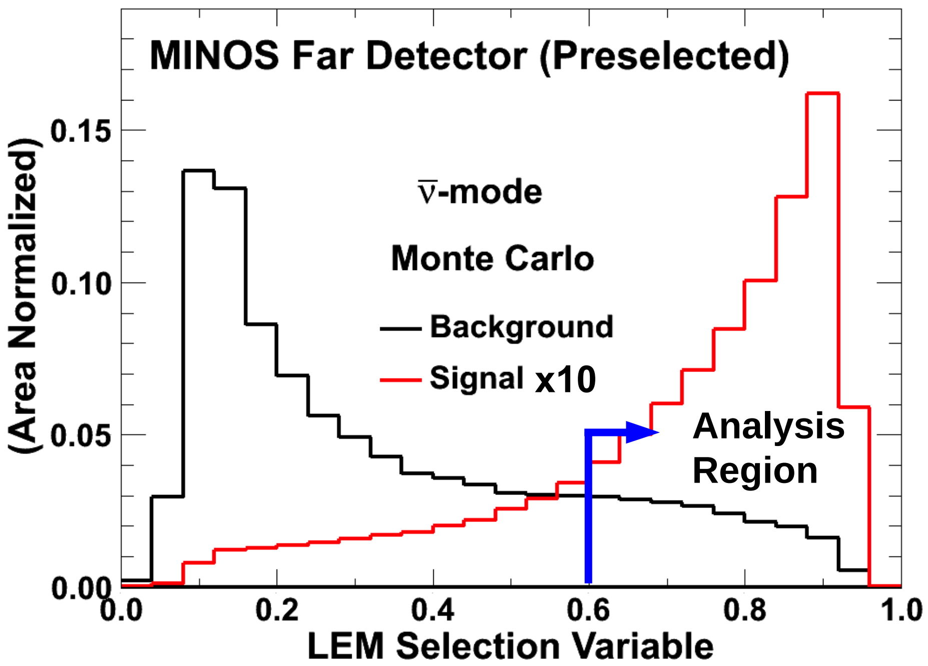
Electron Neutrino Appearance

Electron Neutrino Appearance

- MINOS detector granularity makes ν_e CC identification challenging
- Compare candidate events to a library of MC using "Library Event Matching" (LEM)
- Compute discriminating variables based on truth information from library events that best match the candidate

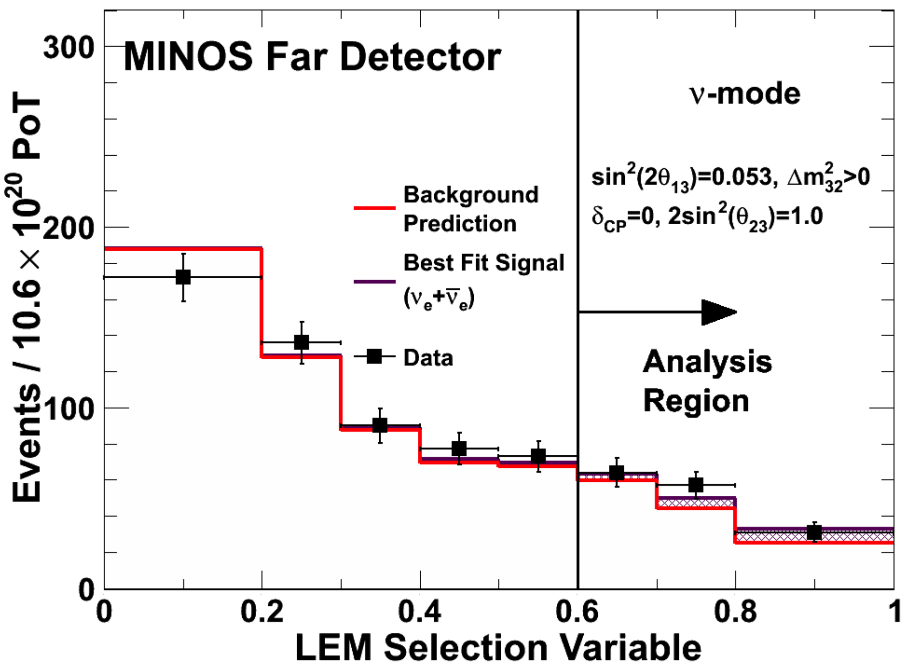




Electron Neutrino Appearance

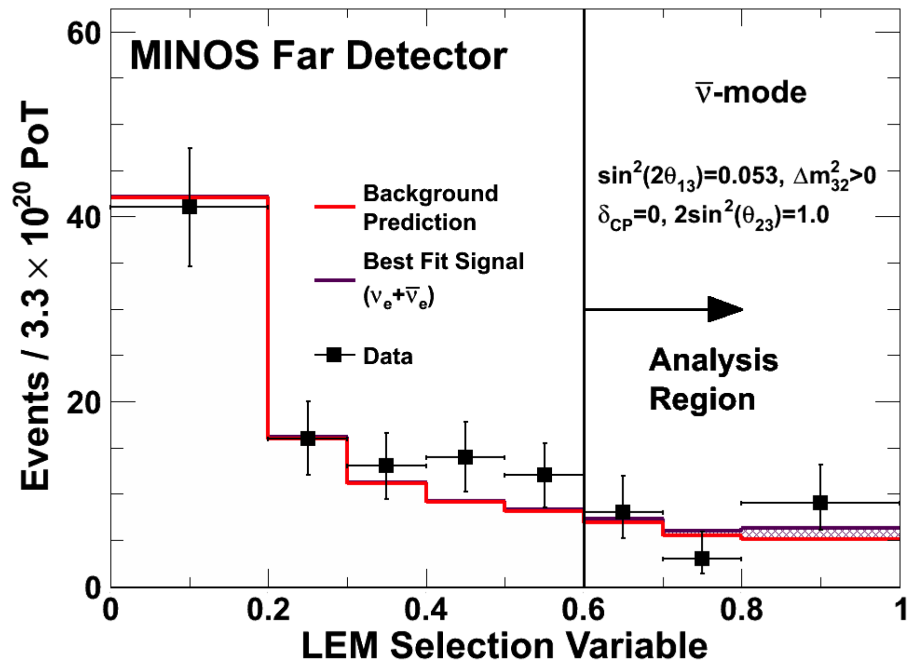
With the *neutrino-enhanced* beam in Signal Enhanced Region:

- If θ_{13} = 0: 128.6 BG Events
- If $\sin^2(2\theta_{13})$ = 0.1: +32.5 Events
- Total Prediction: 161 Events
- Observed: 152 Events



With the *antineutrino-enhanced* beam in Signal Enhanced Region:

- If θ_{13} = 0: 17.5 BG Events
- If $\sin^2(2\theta_{13})$ = 0.1: +3.7 Events
- Total Prediction: 21.2 Events
- Observed: 20 Events



Combined Electron Neutrino Appearance

Cannot distinguish between ν_e and anti-ν_e events, so we perform a combined analysis:

$$\text{At } \delta_{CP} = 0 \text{ and } \theta_{23} < \pi/4,$$

- Assuming normal hierarchy:

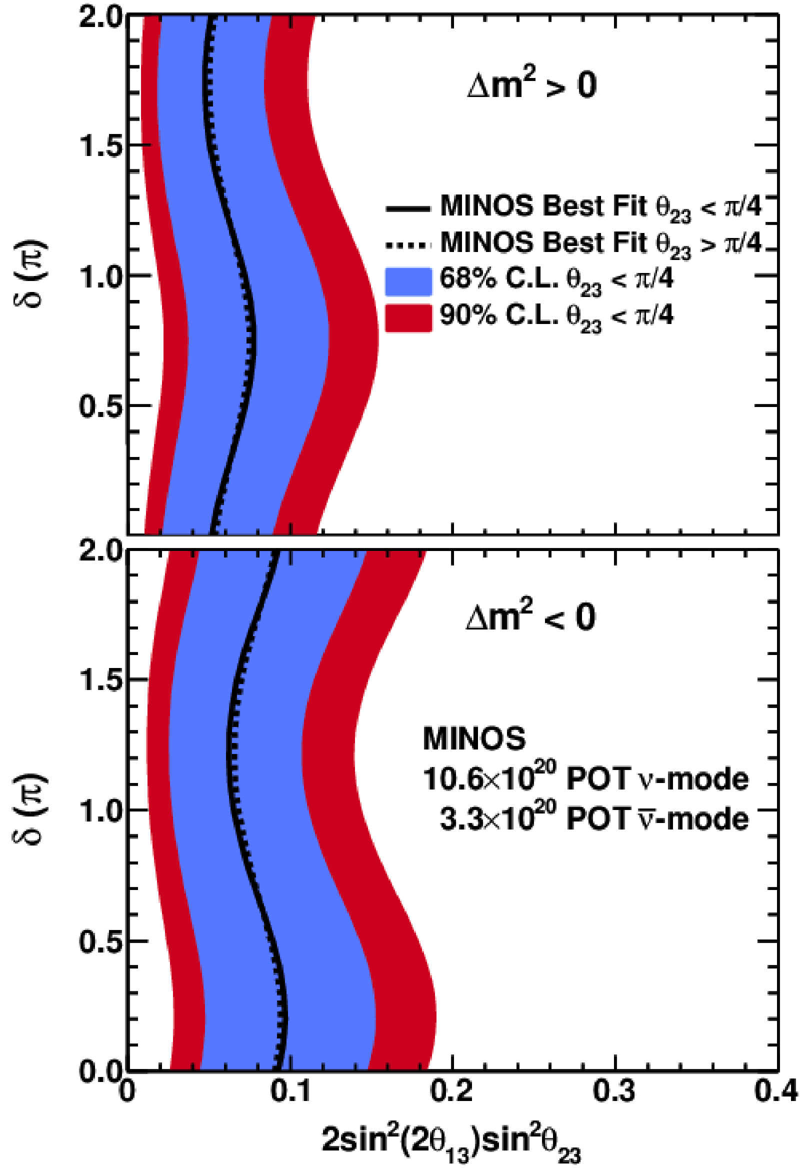
$$2\sin^2(2\theta_{13})\sin^2(\theta_{23}) = 0.051^{+0.038}_{-0.030}$$

$$0.01 < 2\sin^2(2\theta_{13})\sin^2(\theta_{23}) < 0.12 \text{ (90\% C.L.)}$$

- Assuming inverted hierarchy:

$$2\sin^2(2\theta_{13})\sin^2(\theta_{23}) = 0.093^{+0.054}_{-0.049}$$

$$0.03 < 2\sin^2(2\theta_{13})\sin^2(\theta_{23}) < 0.18 \text{ (90\% C.L.)}$$



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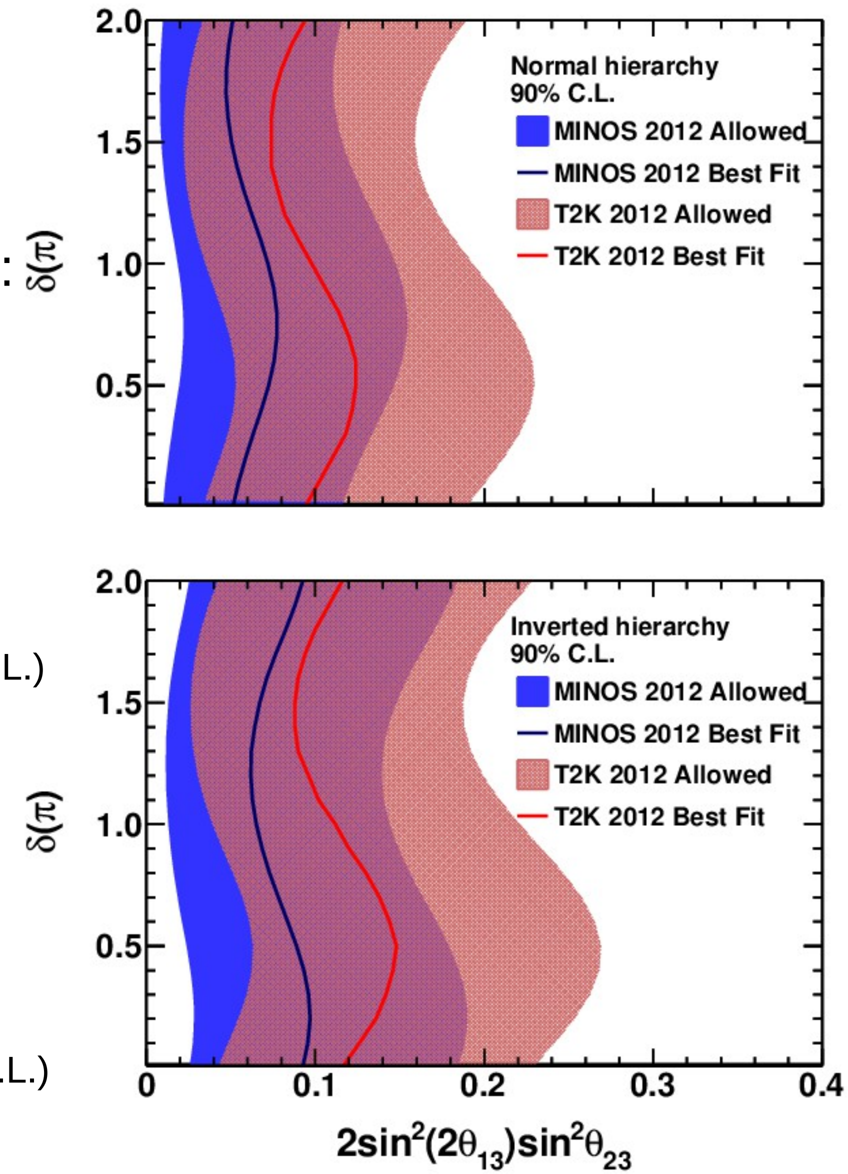
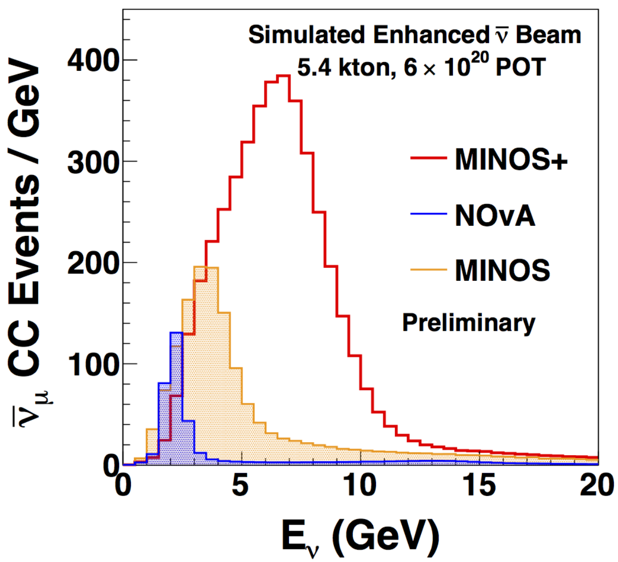
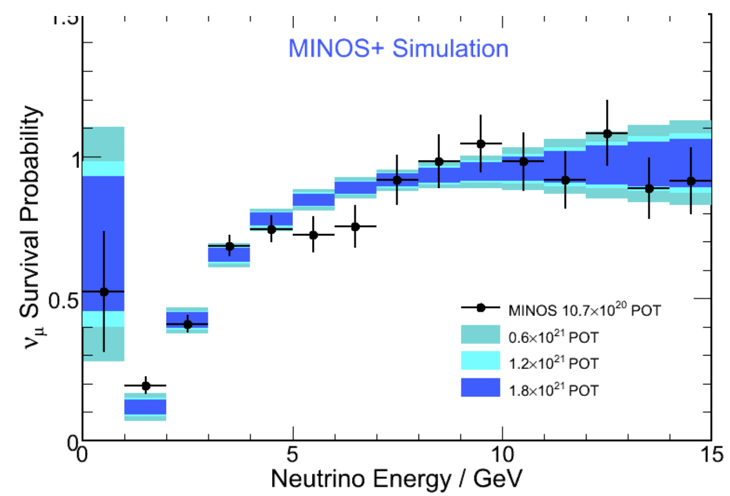


MINOS+

MINOS+

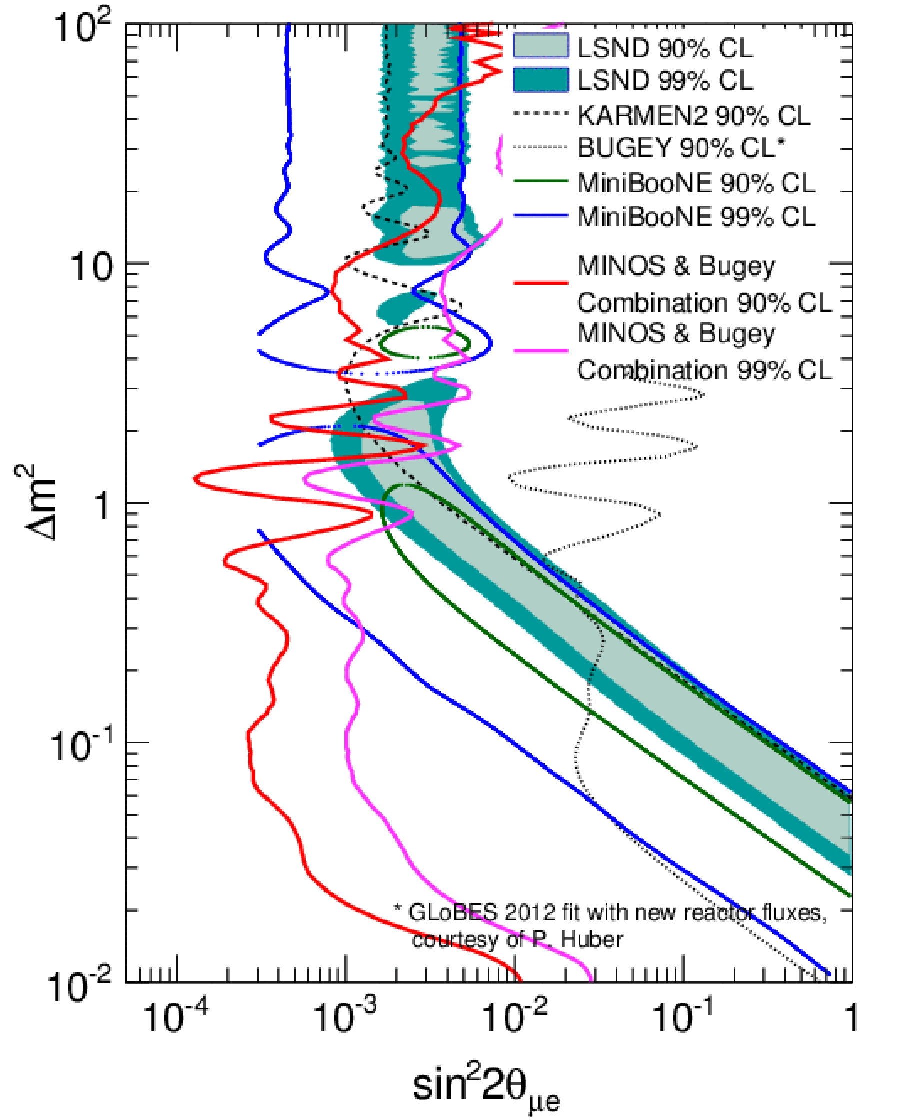
- Next generation using the MINOS detectors
- Employs on-axis NuMI beam
- 3 years of running in 4-10 GeV region
- Significant reduction in statistical uncertainty
- Collect ~3000 ν_μ CC events/year
- Physics goals:
  - Precision measurements of atmospheric oscillations
  - Probes higher energy region
  - Search for sterile neutrinos
  - Search for NSI





Sterile Neutrino Search

- Use both neutral-current (NC) and charged-current (CC) neutrino interactions.
- NC cross-sections are insensitive to standard neutrino mixing
- Energy dependant deficit would point to a sterile neutrino
- CC disappearance can also be used to probe sterile neutrino mixing.
- Sensitive if oscillations into sterile neutrinos are driven by a large mass-square difference $\Delta m^2_{41} \sim 10^{-2}$-$10\ eV^2$



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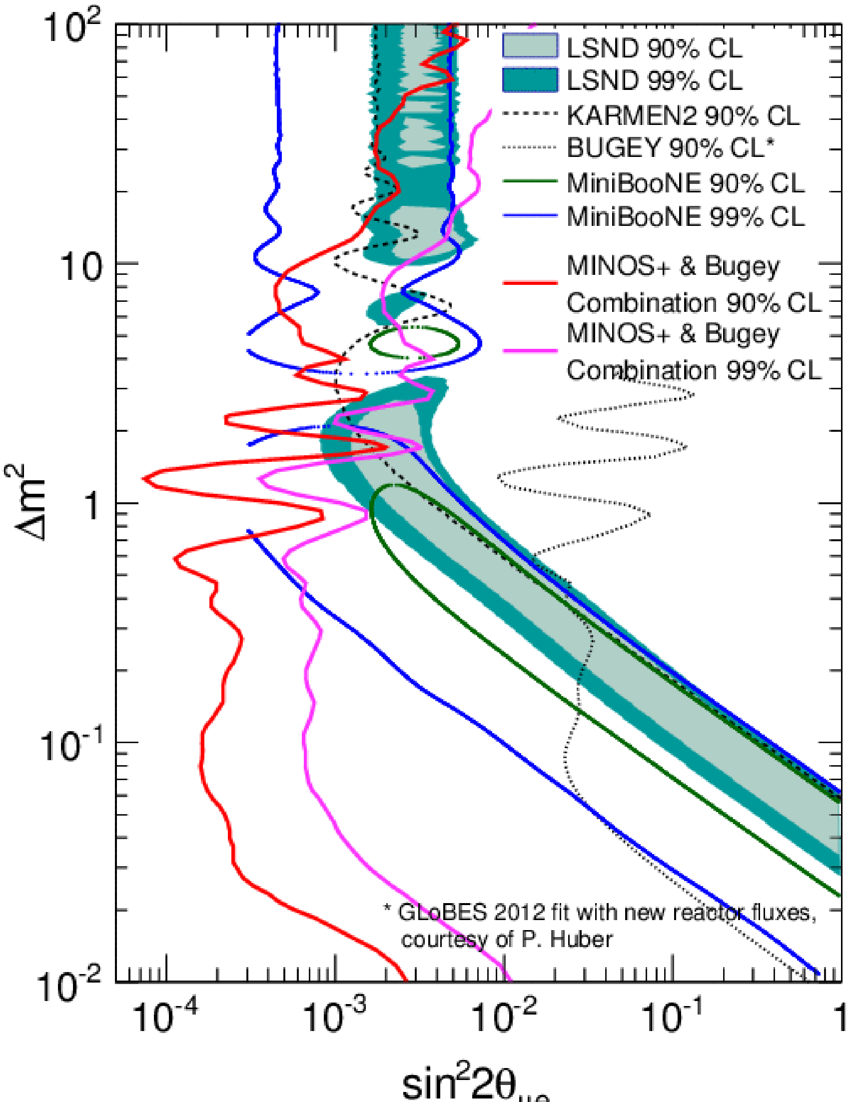

Summary

MINOS has completed a combined analysis of:

- 10.7×10^{20} POT to measure muon neutrino disappearance
- 3.4×10^{20} POT to measure muon antineutrino disappearance
- 37.9 kton-years of atmospheric data

MINOS has completed a combined analysis of:

- 10.6×10^{20} POT to measure electron neutrino appearance
- 3.3×10^{20} POT to measure electron antineutrino appearance

With many exciting new results on the horizon, including:

- Muon disappearance results in a three-flavor scenario
- Results of combined muon/electron neutrino fits
- MINOS and MINOS+ work to verify 3-(only) flavour scenario

Q&A

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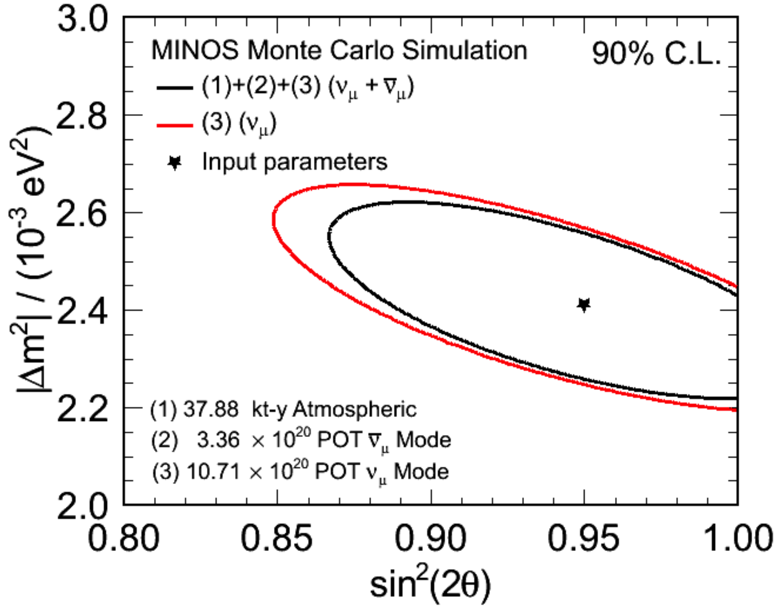
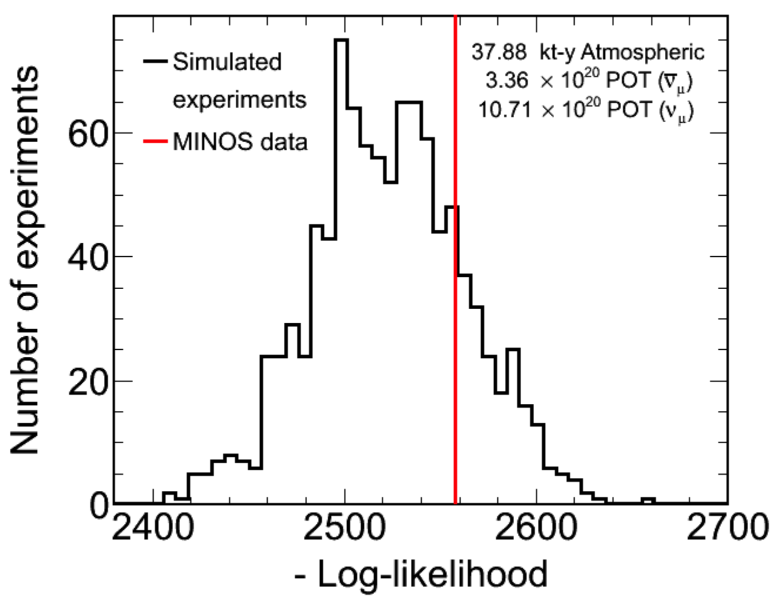
Combined Beam and Atmospheric Neutrino Disappearance Best Fit

- 2 parameter fit assumes identical neutrino and antineutrino oscillations
- 15 systematics included as nuisance parameters
- Oscillations fit the data well: 19% of pseudo experiments have worse $\chi 2$

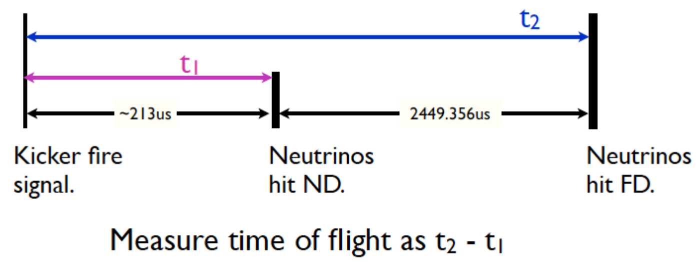




Time of Flight

- The time of the neutrino interaction in the ND (FD) tND (tFD) is recorded on a local atomic clock, corrected using gps measurements
- We compare these times to the time of the resistive current wall monitor t0 and correct for known timing delays

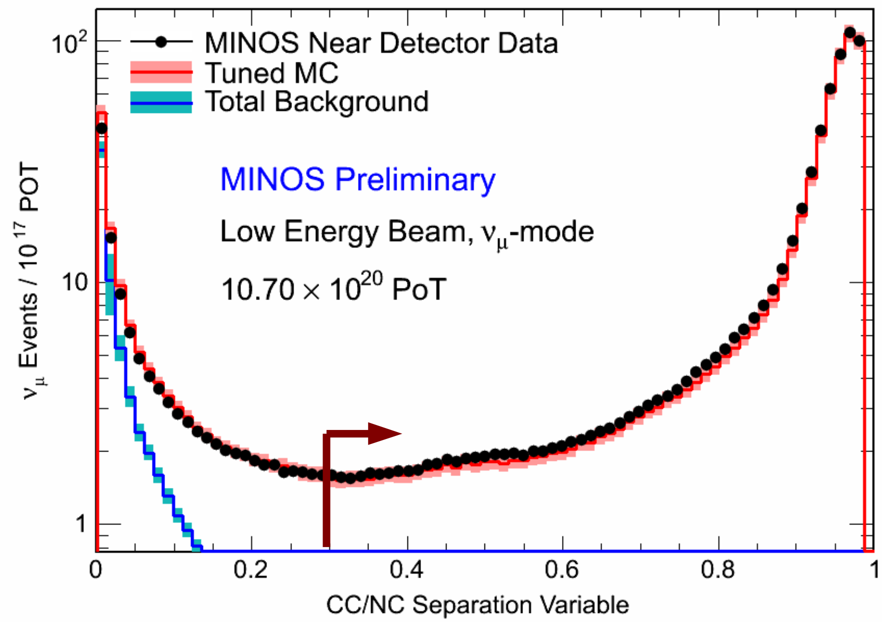
Systematic uncertainty	Value
Inertial survey at FD	2.3 ns
Relative ND-FD latency	1.0 ns
FD TWTT between surface and underground	0.6 ns
GPS time transfer accuracy	0.5 ns
TOTAL	2.6 ns



- Correct for known delays
- Neutrino arrival time fitted to proton bunch structure as measured by current wall monitor
- Time from monitor to ND and monitor to FD subtracted to form ND-FD TOF
- Baseline ND – FD = 2,449,316.3 ns
- Time of flight ND – FD
  = 2,453,935.0 ± 0.1 - 4621.1
  = 2,449,313.9 ± 0.1 ns
- **$(v/c-1)=(1.0\pm1.1)\times10^{-6}$**

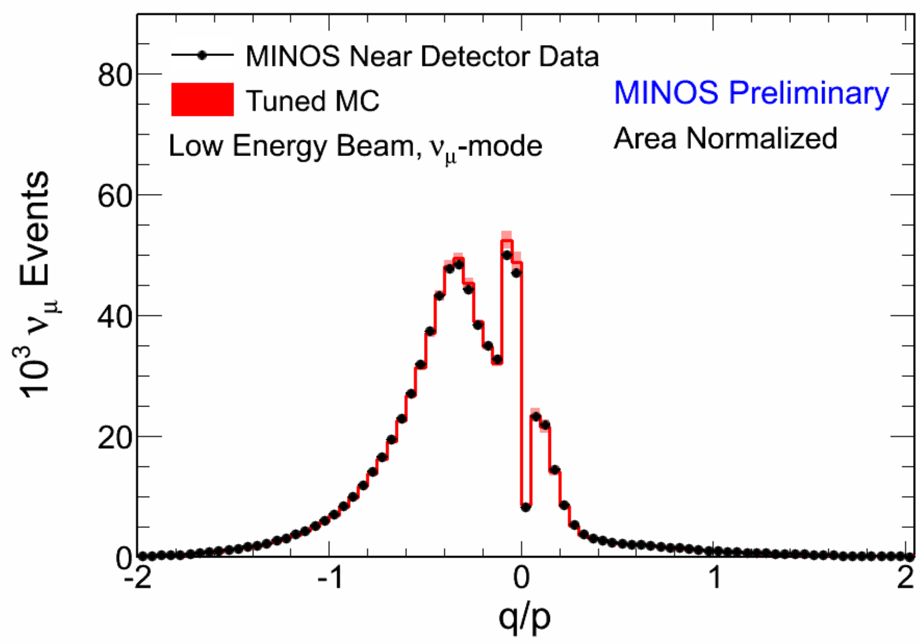
MINOS: Selection I

- The actual analysis selection can be broken down into two main parts.
- The first is the selection of muon like events by using a kNN (k nearest neighbour) algorithm. This takes advantage of the way muon tracks deposit energy, specifically:
  - Track Length.
  - Mean signal in track planes.
  - Transverse track profile.
  - Signal fluctuation in the track.

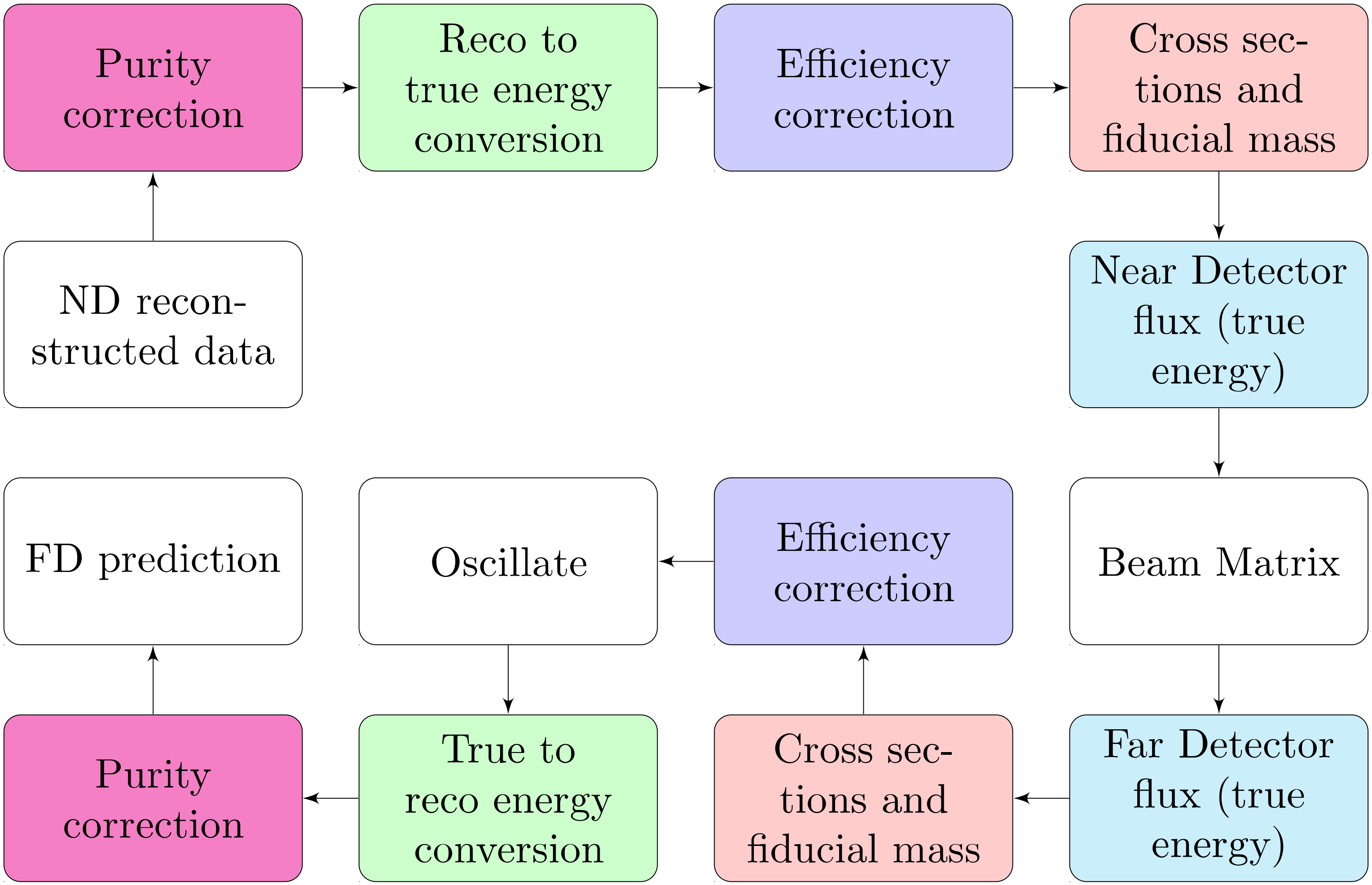


MINOS: Selection II

- The next is charge sign selection, judged by looking at the q/p of the track.
- Particularly important in the anti-neutrino analysis which aims to perform its fit with only anti-neutrinos.
- Less important for the 2 parameter analysis which includes positive sign CC events in its sample.

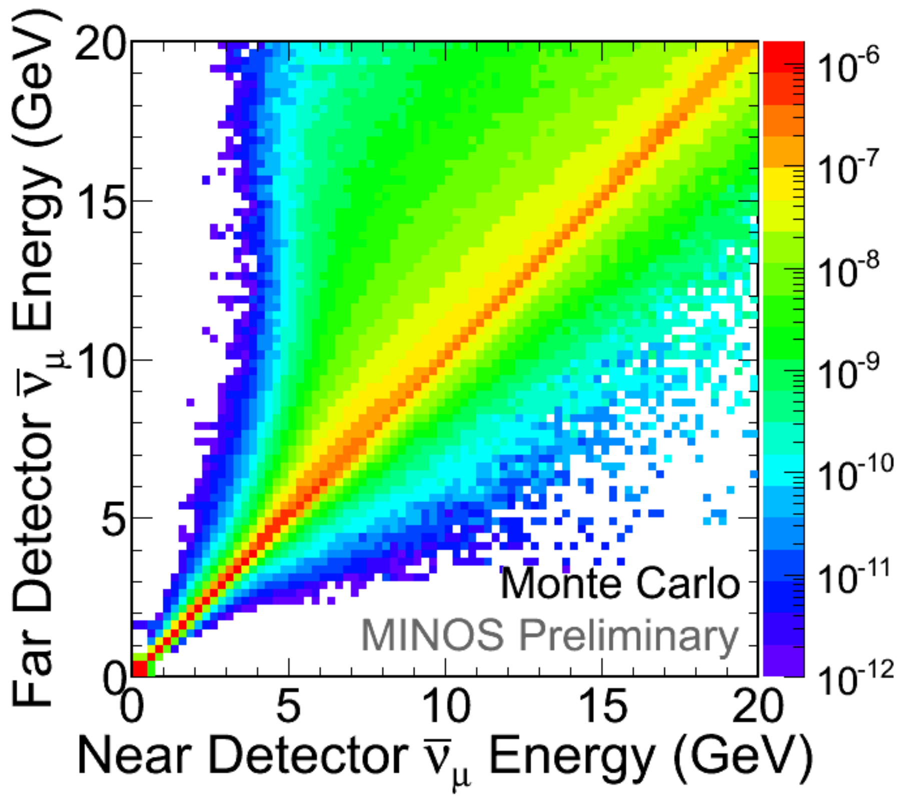


Near to Far Extrapolation



Beam Matrix

- To achieve this we use the a beam matrix
- This matrix describes the energy dependant differences in the neutrino flux seen at the near and far detector.
- π/K/μ producing events of a given energy in the near detector produce a range of energies in the far detector, yielding the energy smearing seen.

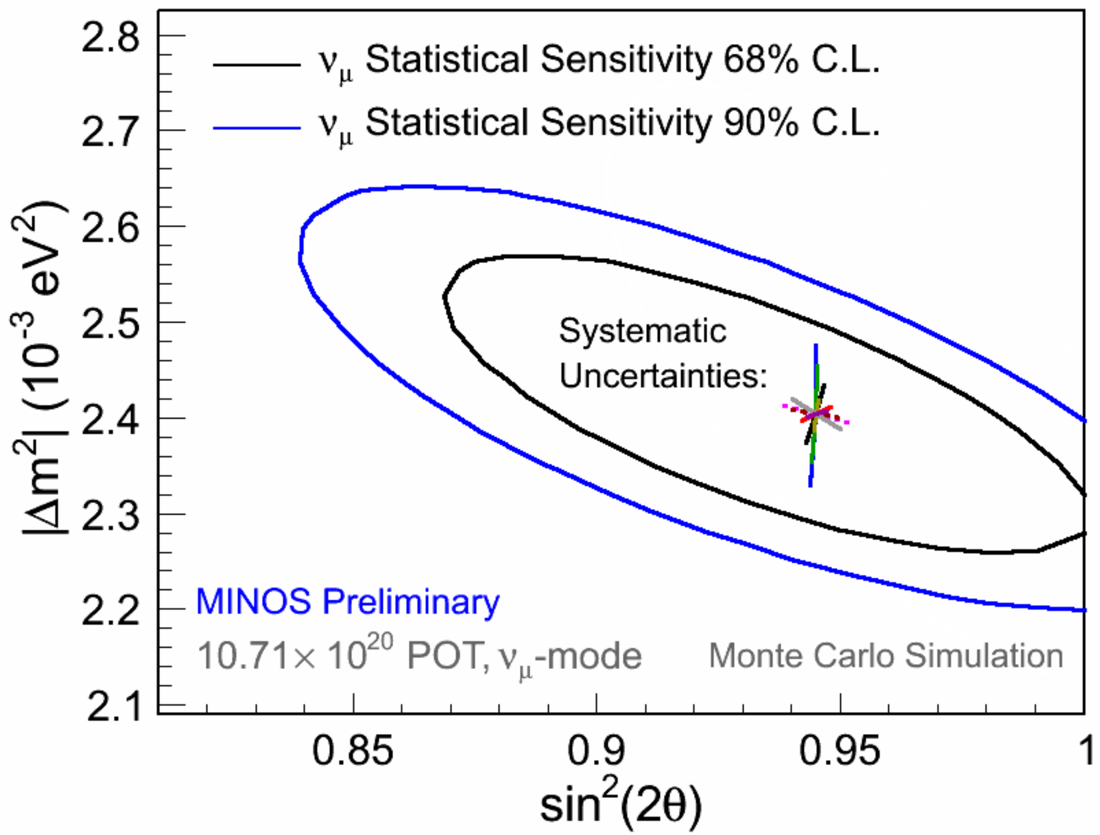


Selected Disappearance Events

Data Set	Simulation No osc.	Simulation With osc.	Events Observed
ν_μ from ν_μ beam	3201	2543	2579
$\overline{\nu}_\mu$ from ν_μ beam	363	324	312
Non-fiducial μ from ν_μ beam	3197	2862	2911
$\overline{\nu}_\mu$ from $\overline{\nu}_\mu$ beam	313	227	226
Atm. contained-vertex $\nu_\mu + \overline{\nu}_\mu$	1100	881	905
Atm. non-fiducial $\mu^- + \mu^+$	570	467	466
Atm. showers	727	724	701

Systematics & Statistics

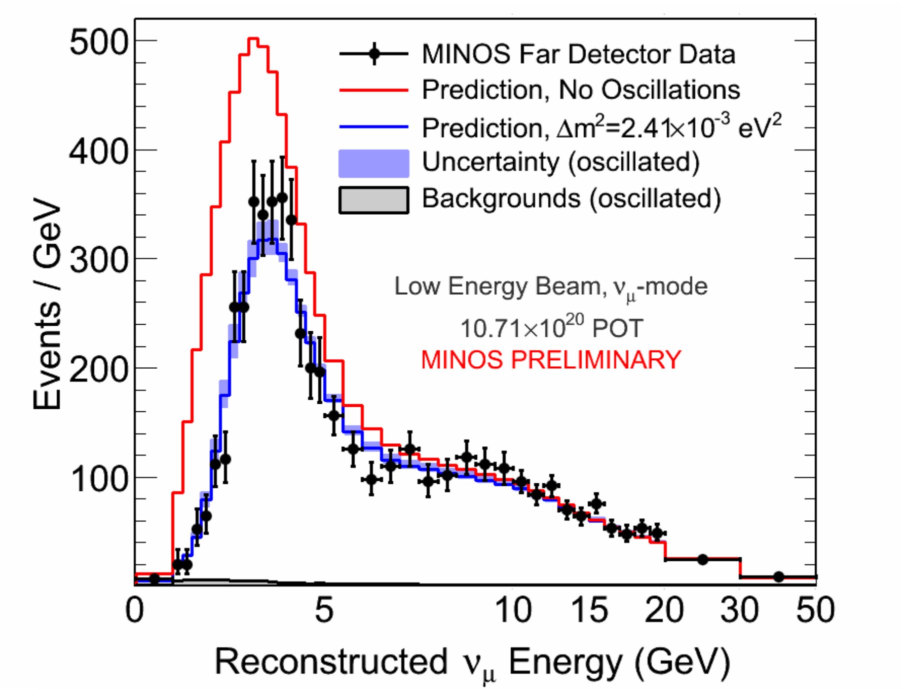
- Clearly we are still very much a statistically limited analysis:

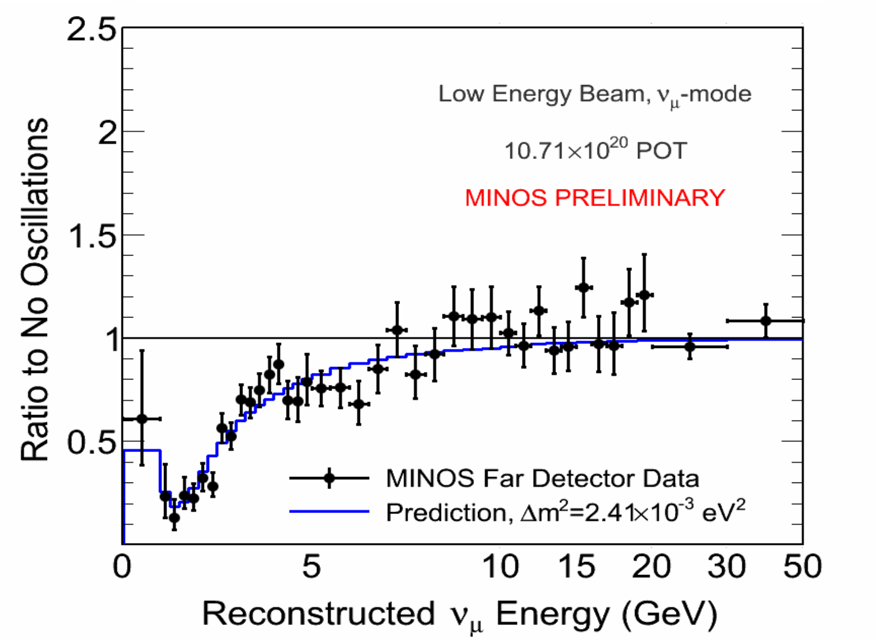


Neutrino FHC Beam Data Spectrum and Fit

- Expected Events: 3564 (Null Oscillations)
- Observed: 2895
- Best Fit:

$$\left|\Delta m^2\right| = 2.41^{+0.11}_{-0.10} \times 10^{-3} eV^2 \quad \sin^2(2\theta) = 0.94^{+0.04}_{-0.05}$$

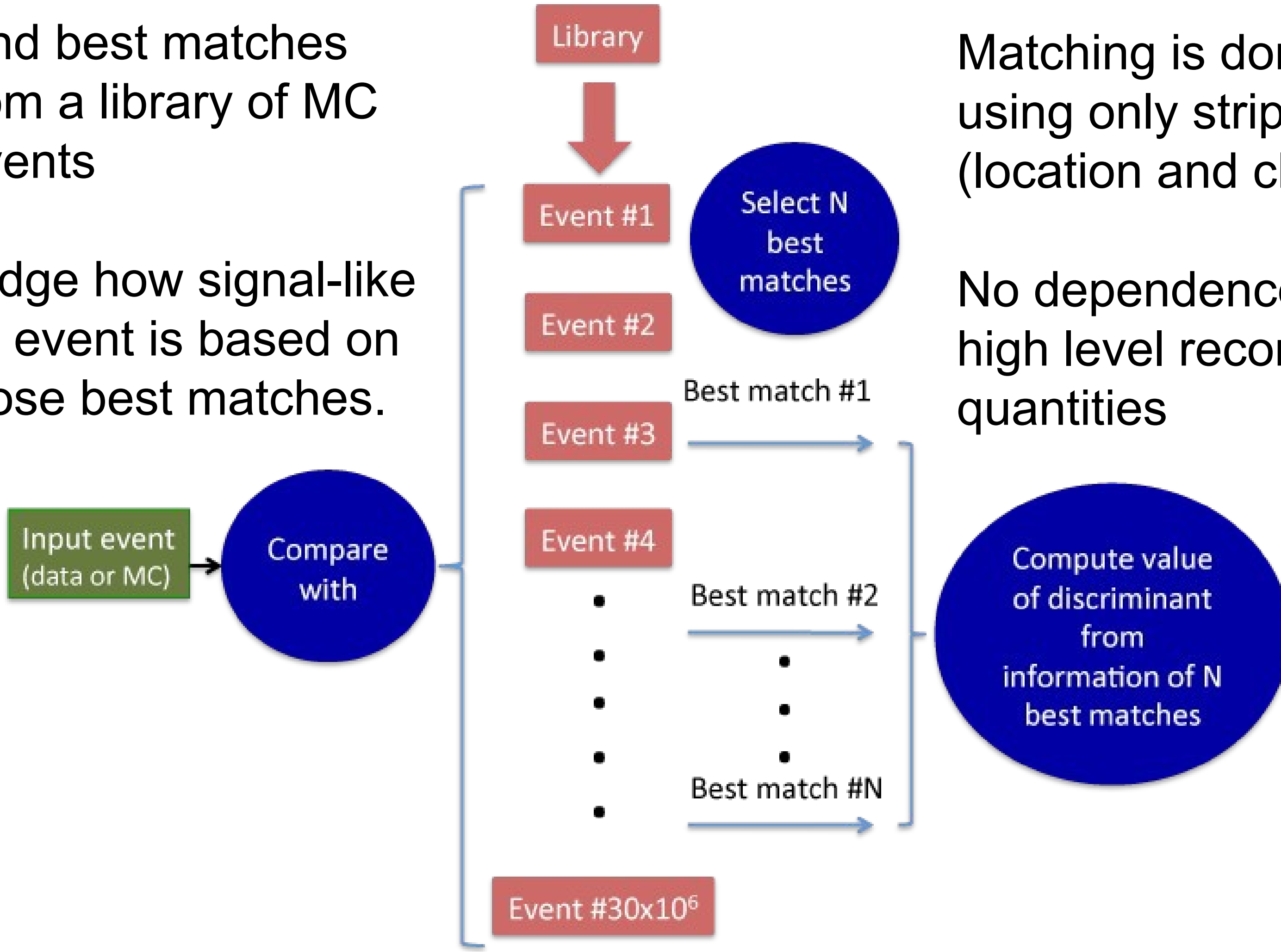




Library Event Matching (LEM)

Find best matches from a library of MC Events

Judge how signal-like an event is based on those best matches.



Matching is done using only strip info (location and charge)

No dependence on high level reconstructed quantities