ν_e appearance in MINOS

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for the MINOS collaboration

RPM Seminar

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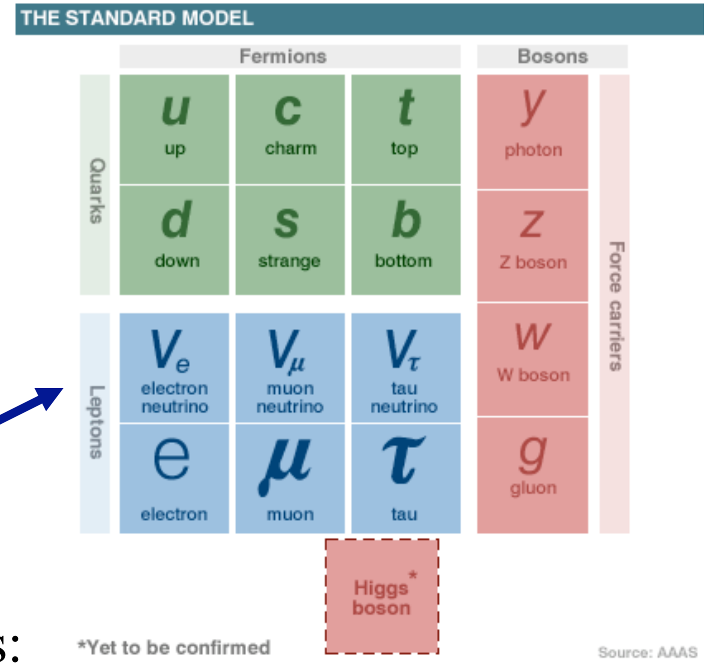
Outline

- **Introduction**
- **Overview of MINOS**
  - NuMI Beam
  - MINOS Detectors
- **Physics in MINOS**
  - ν_μ disappearance
  - Sterile neutrinos
  - Anti-neutrinos
- **ν_e appearance**
  - Selection
  - Backgrounds
  - Outlook
- **Summary**

Argonne – Arkansas Tech - Athens – Benedictine – Brookhaven – Caltech – Cambridge – Campinas – Fermilab – Harvard – IIT – Indiana – Minnesota, Twin Cities – Minnesota, Duluth – Oxford – Pittsburgh – Rutherford Lab – Sao Paulo – South Carolina – Stanford – Sussex – Texas A&M – Texas-Austin – Tufts – UCL – Warsaw – William & Mary

Introduction

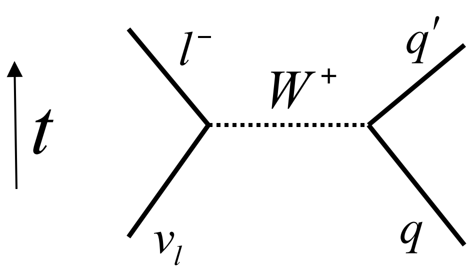
- The **Standard Model** includes neutrinos:
  - massless particles
  - interact only through the weak interaction
  - 3 generations of neutrinos



- Distinguish 2 types of ν interactions:

Charged Current (CC)

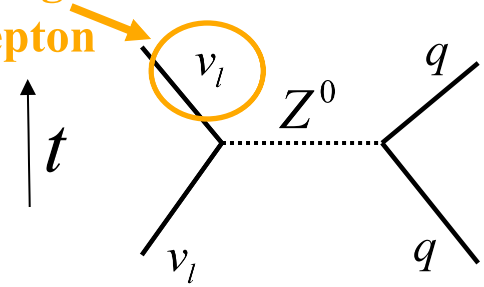
$$\nu_l + q \rightarrow l^- + q'$$



Neutral Current (NC)

$$\nu_l + q \rightarrow \nu_l + q$$

no outgoing charged lepton



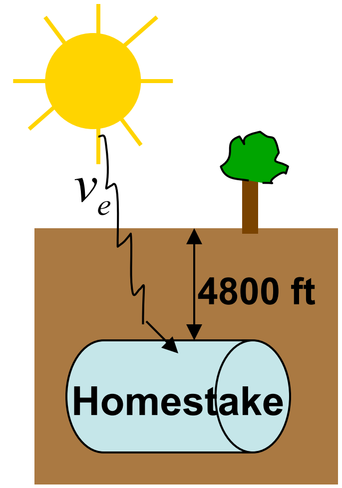
cannot determine incident ν energy

But the SM picture is incomplete …

❖ The recent discovery that neutrinos change flavors has revolutionized their place in physics and in our universe.

- First indication came with the **solar neutrino problem** (R. Davis, 1969):

  Found only ~1/3 of the expected solar ν_e flux

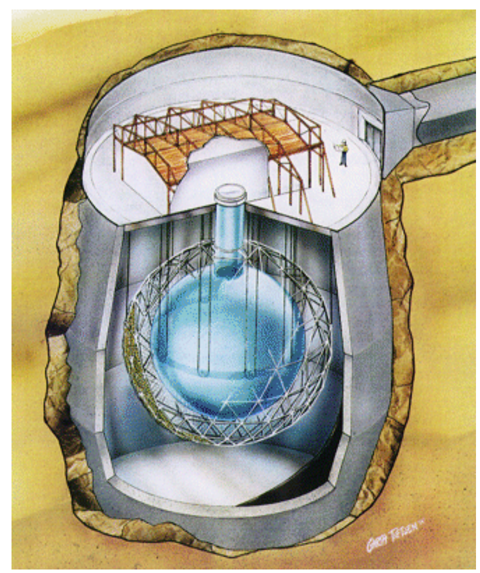


- ~30 years later the **Sudbury Neutrino Observatory (SNO)** vindicated the solar model:

  ✓ ~2/3 deficit in solar ν_e flux.

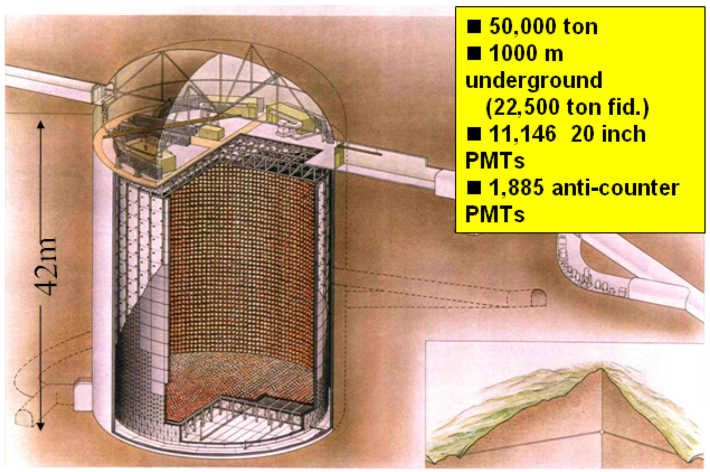
  ✓ Total number of neutrinos of all types in perfect agreement with solar standard model.

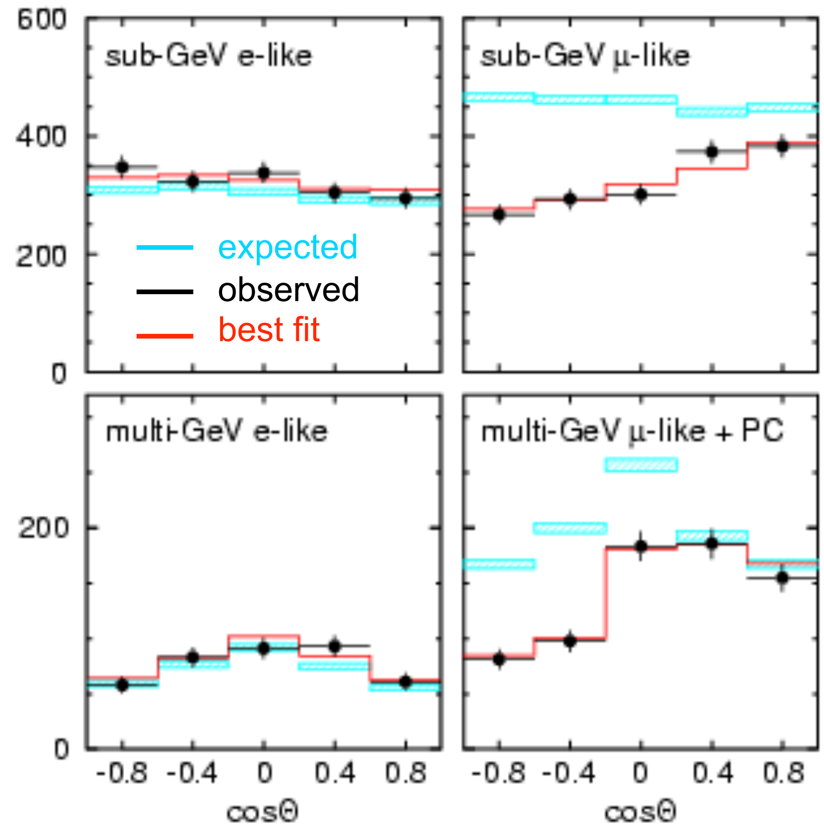
  - Conclusion: solar ν_e's oscillate to other flavors on their way to earth.



More evidence for neutrino oscillations

➢ In addition, in 1998 the **Super-Kamiokande** experiment provided conclusive evidence for **atmospheric ν_μ oscillations**:

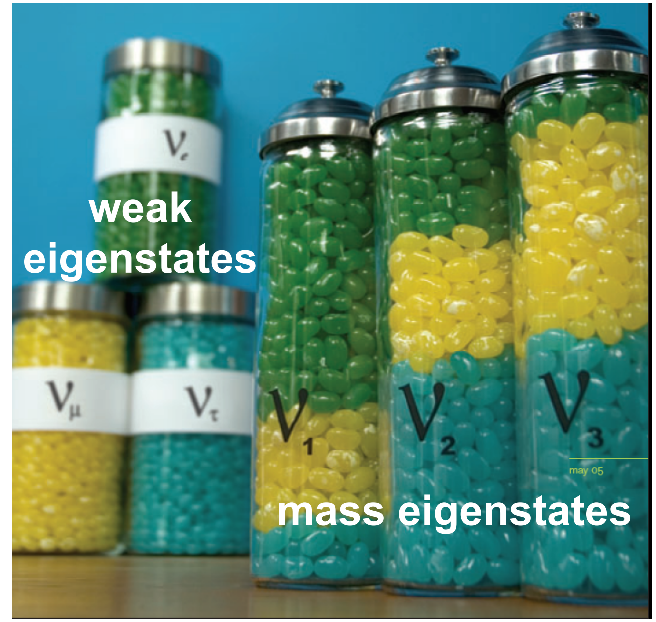




- ✓ Deficit observed in flux of atmospheric $\nu_\mu / \bar{\nu}_\mu$ that go through earth.
- ✓ Flux of atmospheric $\nu_e / \bar{\nu}_e$ unaffected.
- ✓ Conclusion: $\nu_\mu \rightarrow \nu_\tau$ oscillations

➢ **Neutrino oscillations is now a well established phenomenon**: seen by MACRO, Soudan 2, SNO, Kamland, SuperKamiokande, MINOS…

Basics of Neutrino Oscillations



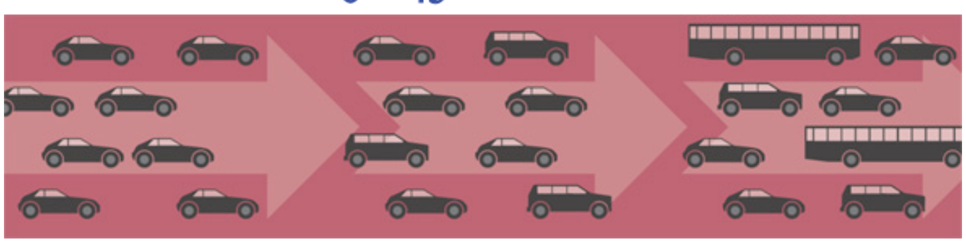
- The solar neutrino problem can be explained by neutrino oscillations → **they are massive!**
- Underlying principle:

weak eigenstates ≠ mass eigenstates

$$|\nu_\alpha\rangle = \sum_i U^*_{\alpha i}|\nu_i\rangle$$

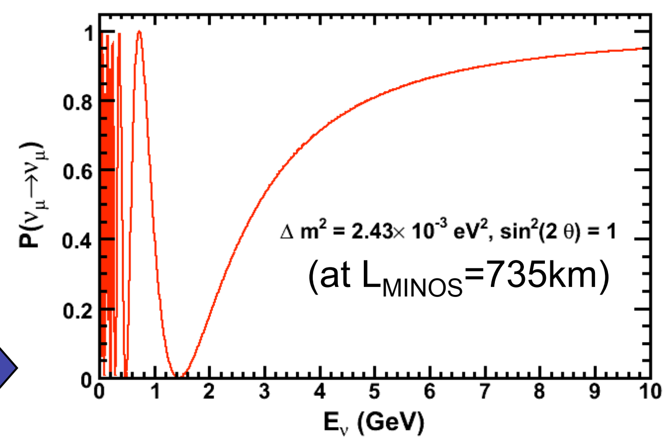
with
$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \times \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \times \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \times \begin{pmatrix} e^{i\alpha_1/2} & 0 & 0 \\ 0 & e^{i\alpha_2/2} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

Atmospheric $\theta \sim 45°$ | Cross-Mixing | Solar $\theta \sim 34°$ | Majorana CPV phases



2-flavor approximation: If $|\nu(0)\rangle = |\nu_\mu\rangle$ then

$$P(\nu_\mu \to \nu_\mu) = |\langle \nu_\mu|\nu(t)\rangle|^2 = 1 - \sin^2(2\theta)\sin^2\left(\frac{\Delta m^2 L}{4E}\right)$$

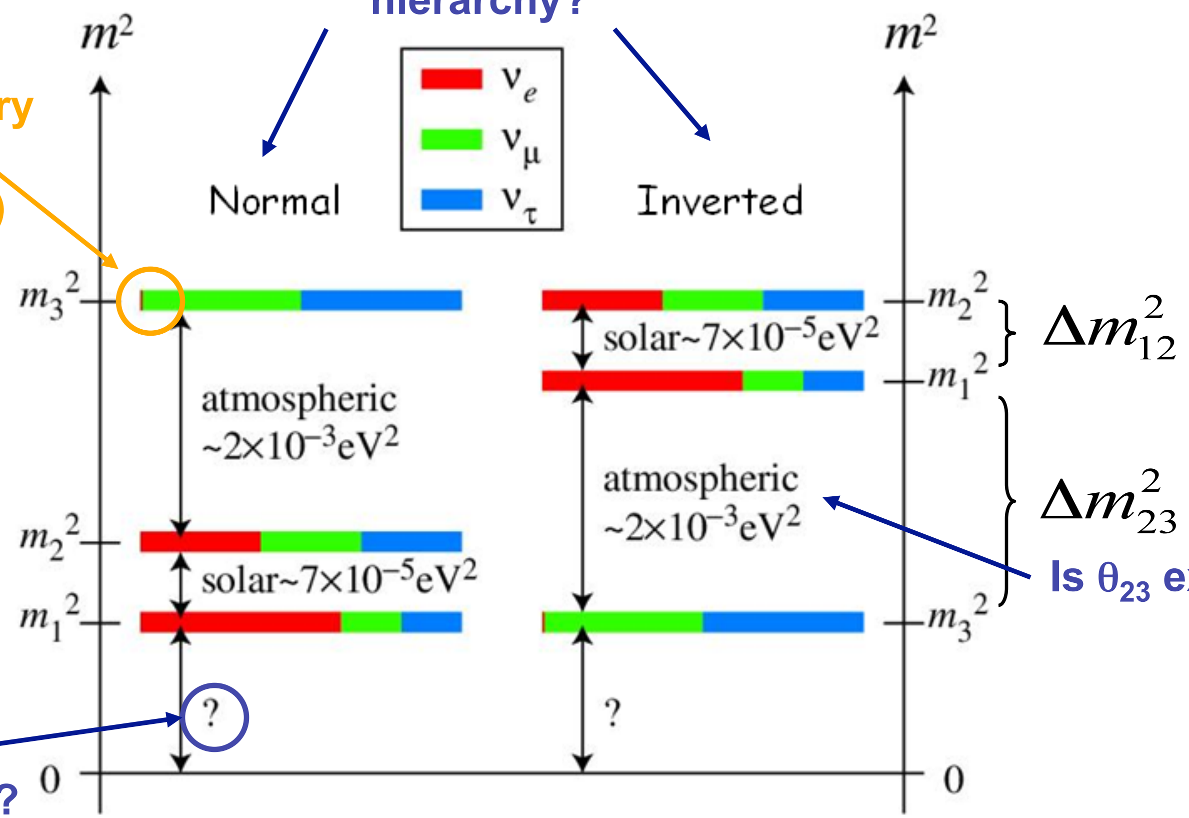


However, our knowledge of neutrinos remains <u>incomplete:</u>

MINOS

What is the right mass hierarchy?

Is θ_{13}=0 or just very small?
(Topic of this talk)



Is θ_{23} exactly $\pi/4$?

What is the rest mass of neutrinos?

And also:
- Are neutrinos their own antiparticles?
- Are there more than 3 neutrinos (sterile, heavier than Z)?
- Do neutrinos obey CP, CPT?

→ **Plenty of room for discovery!**

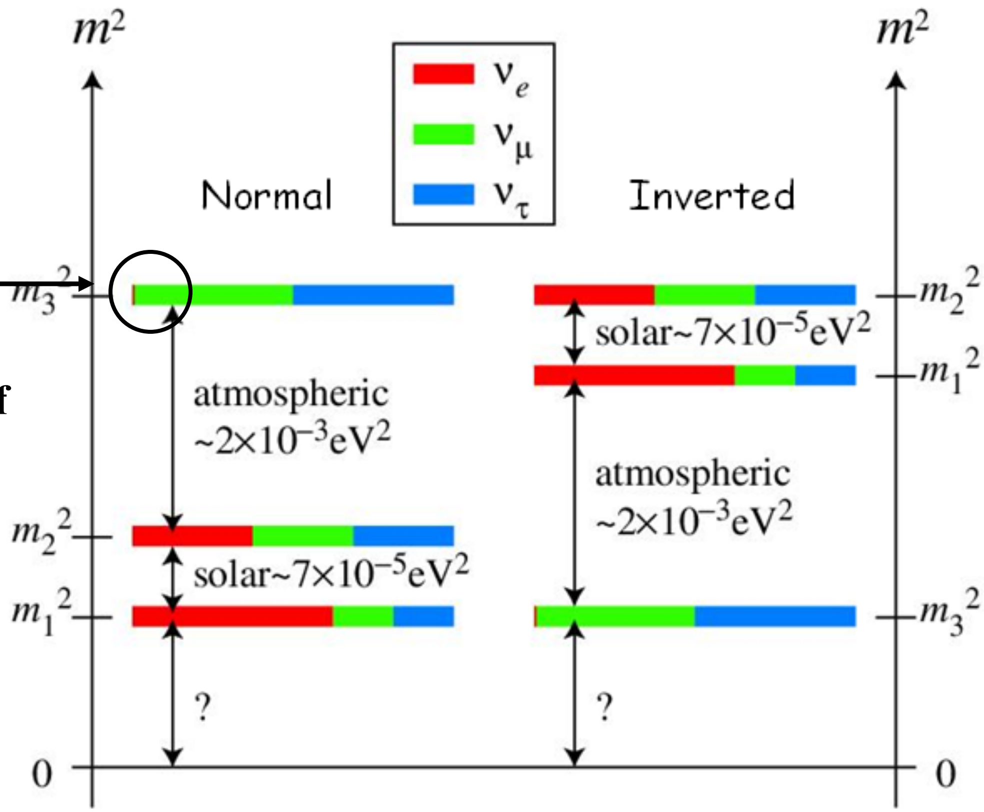
Where does MINOS fit in this picture?

MINOS

MINOS:

Search for ν_e appearance:

First measurement of θ_{13}?



MINOS:

Study oscillation behavior of υ_μ:

- **Measure Δm^2_{32} and $\sin^2(2\theta_{23})$ precisely** (PRL 101: 131802, 2008)
- **Discriminate against other disappearance models.**

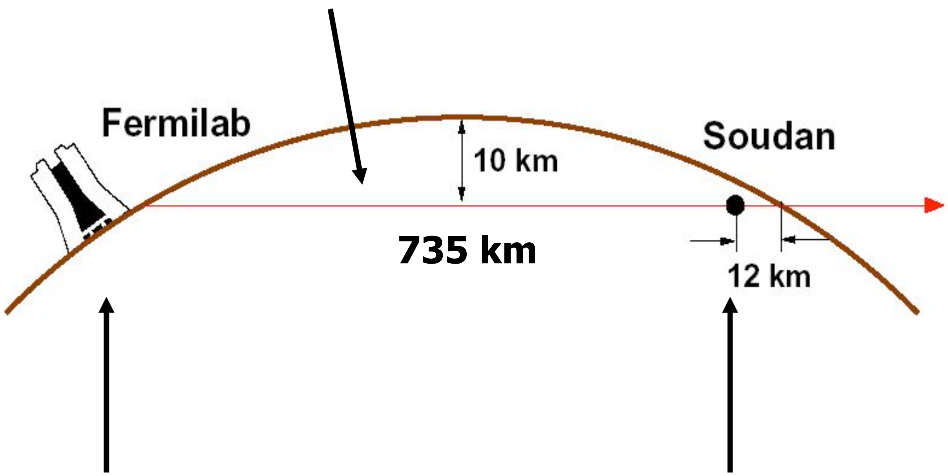
MINOS:

Also:
- **Probe neutrinos and antineutrinos separately (CPT)**
- **Sterile neutrino search** (arXiv:hep-ex/0807.2424)
- **Neutrino-nucleon interaction physics**
- **Atmospheric oscillations** (Phys.Rev.D73:072002,2006)
- **Cosmic ray physics** (Phys. Rev. D. 76:052003, 2007)

The MINOS Experiment

- **MINOS (<u>M</u>ain <u>I</u>njector <u>N</u>eutrino <u>O</u>scillation <u>S</u>earch)** is a long-baseline neutrino oscillation experiment:

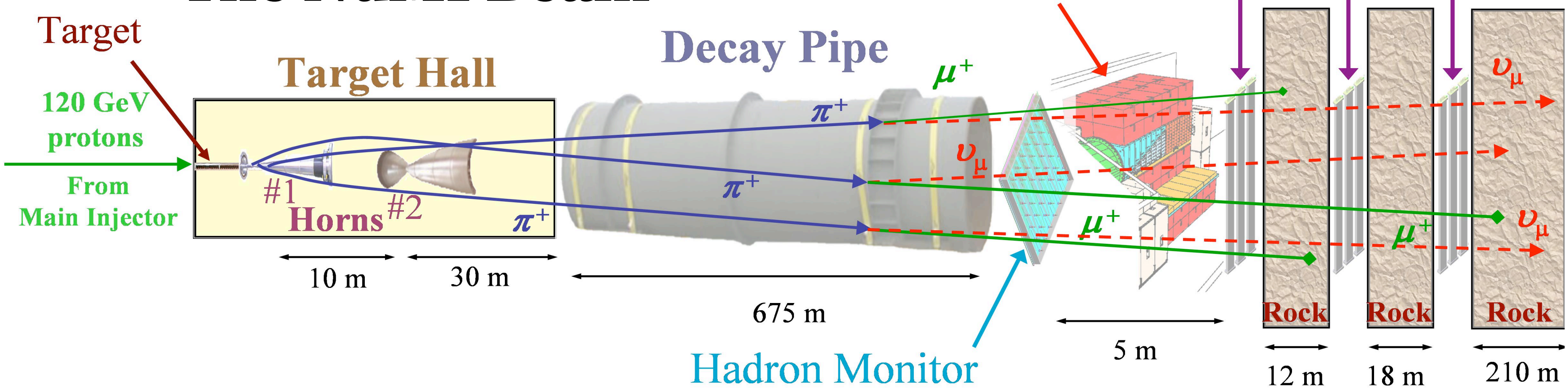
The NuMI neutrino beam provided by 120 GeV protons from the Fermilab Main Injector



A Near detector at Fermilab to measure the beam composition and energy spectrum.

A Far detector at the Soudan Mine in Minnesota to search for neutrino oscillations.

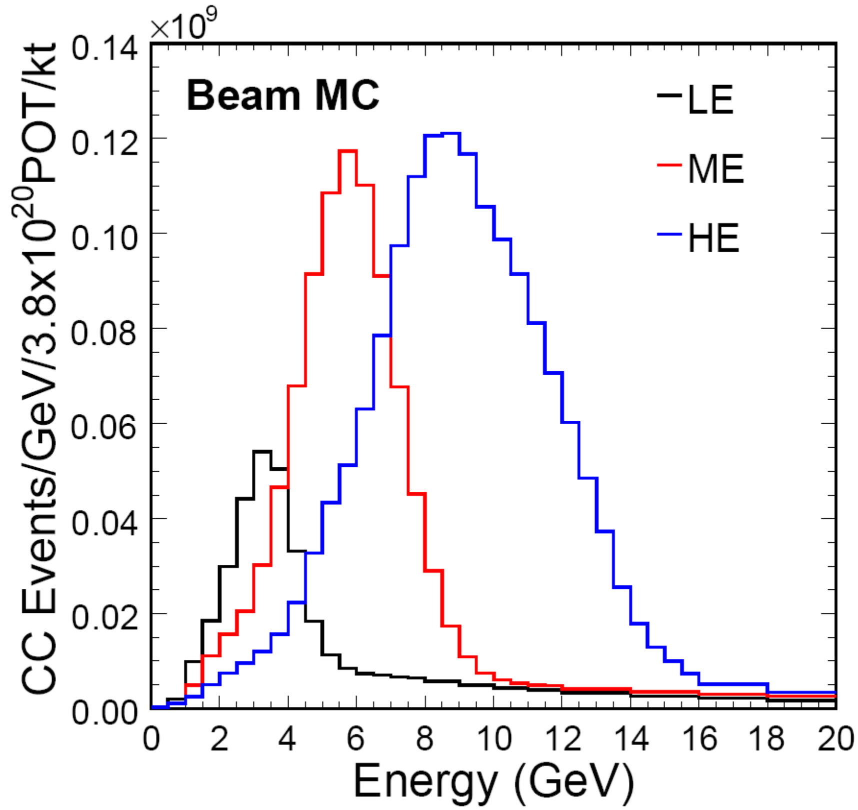
The NuMI Beam

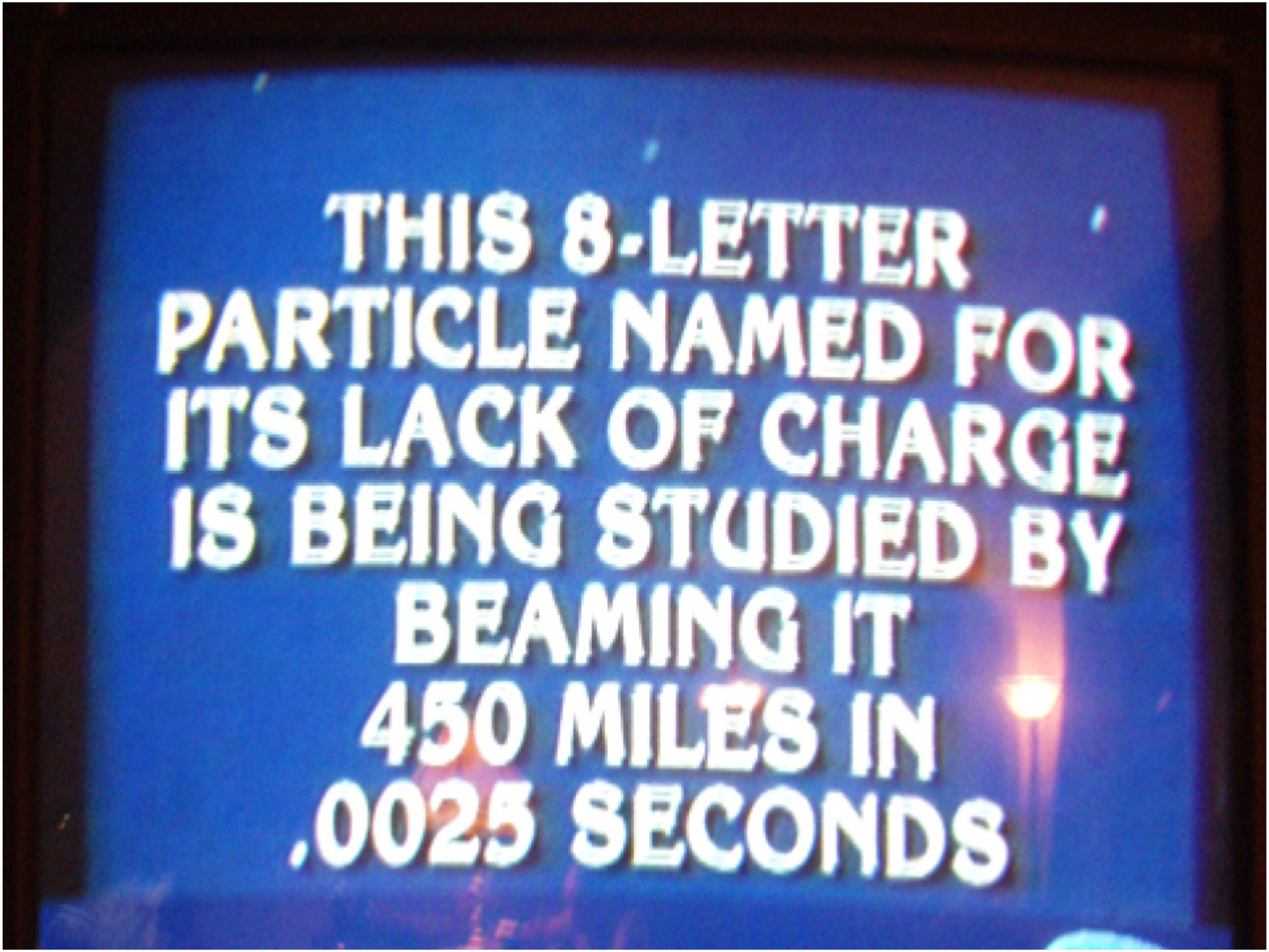


- Moveable target relative to horn 1 allows for different beam configurations.
- Designed for 1.867s cycle time, 4×10^{13} protons/pulse and 0.4MW.

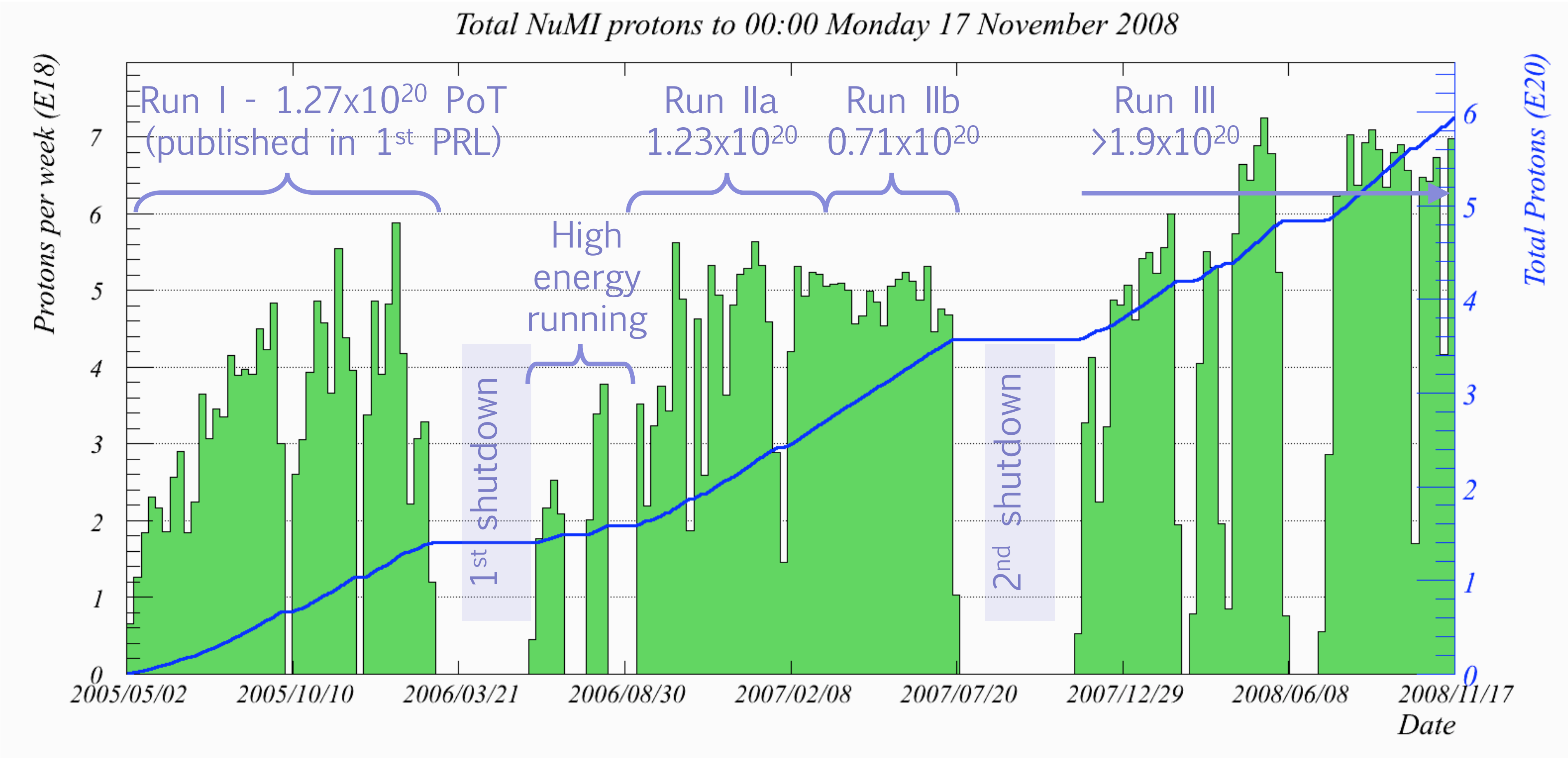
Number of expected CC interactions at the FD (no oscillations)

Beam	Target z position (cm)	FD Events per 1e20 pot
LE-10	-10	390
pME	-100	970
pHE	-250	1340




THIS 8-LETTER
PARTICLE NAMED FOR
ITS LACK OF CHARGE
IS BEING STUDIED BY
BEAMING IT
450 MILES IN
.0025 SECONDS

Three and a half years of MINOS running

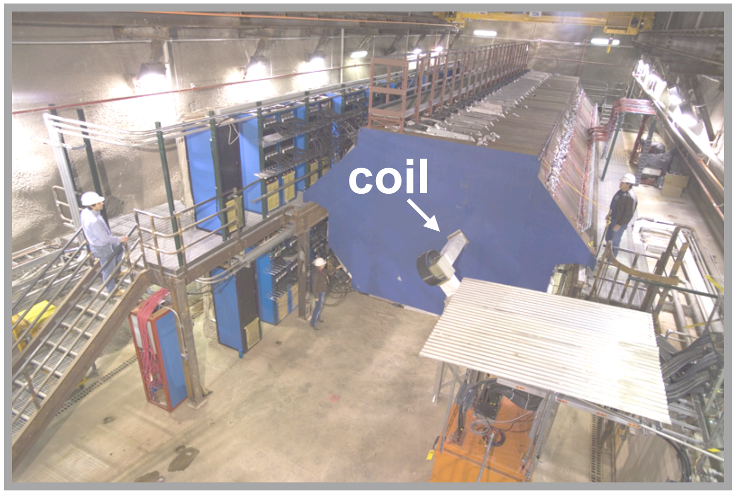


- **Have now accumulated 5.93x10^{20} protons-on-target (POT)**
- Anticipate 10x10^{20} POT by August 2010.

The MINOS detectors

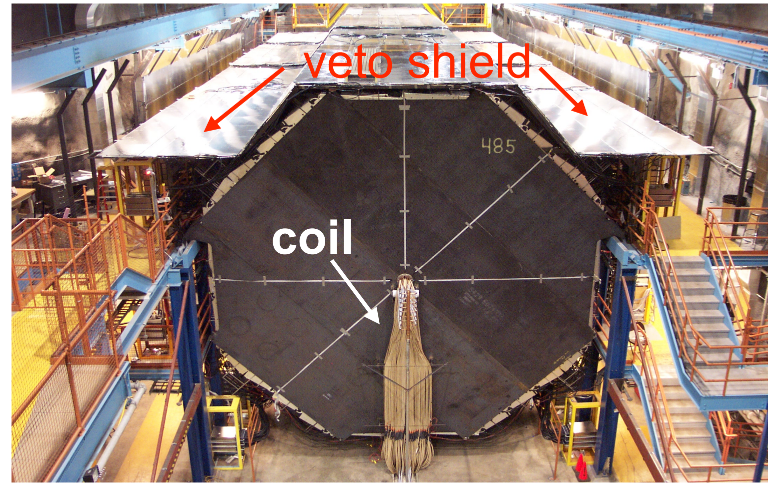
MINOS

NEAR DETECTOR



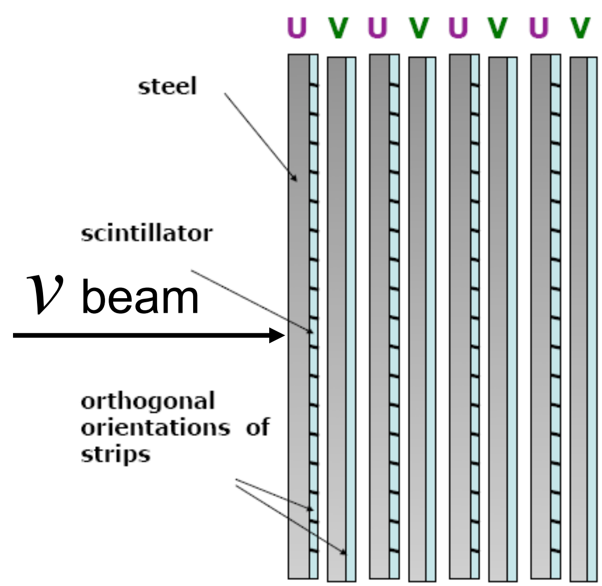
1 kton mass
282 steel and 182 scintillator planes

FAR DETECTOR



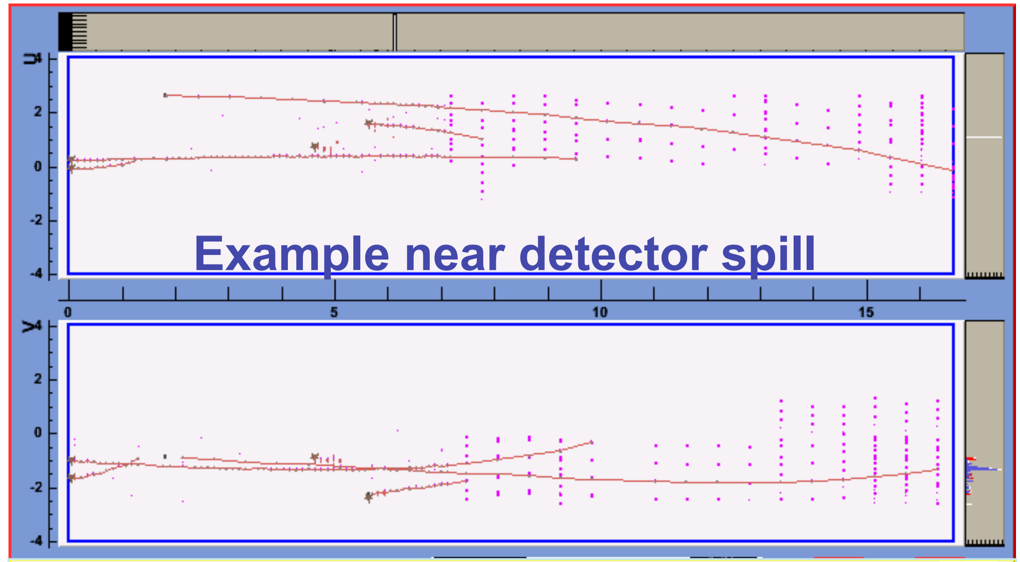
5.4 kton mass
484 scintillator/steel planes

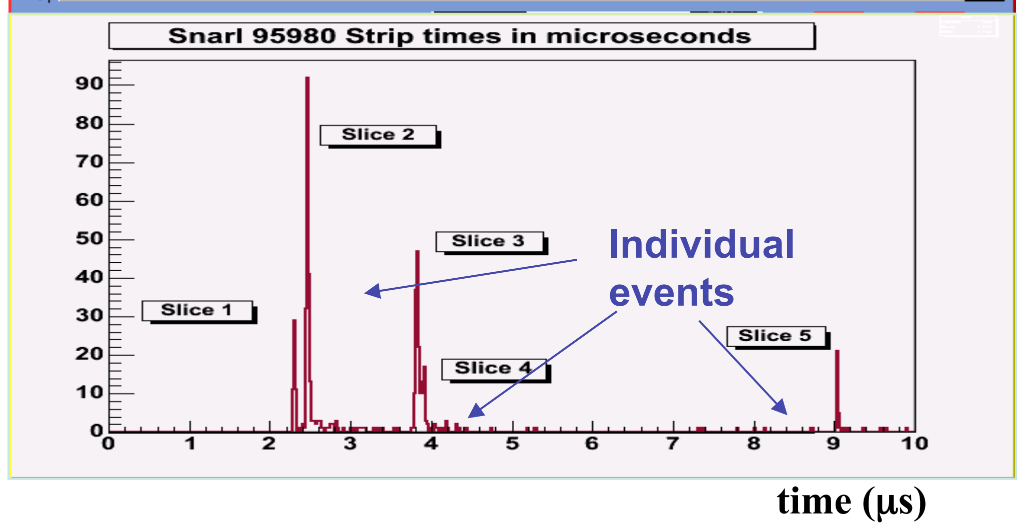
- **Functionally identical detectors:**
  - Iron-scintillator sampling calorimeters.
  - Magnetized steel planes B ≈ 1.2T
  - GPS time stamping to synchronize FD with ND/beam.

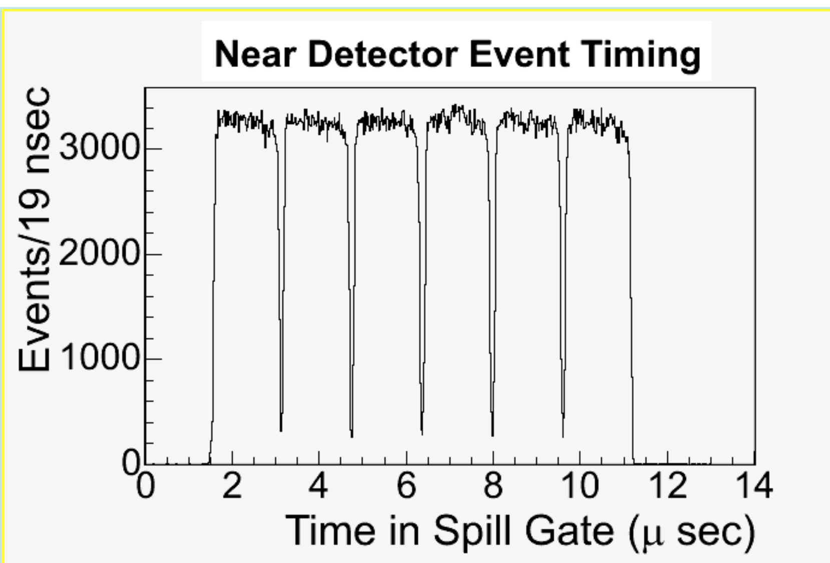


Near Detector Events

- **Multiple neutrino interactions per MI spill**
  - **Largest neutrino event library collected to date**
- Events are separated based on topology and time information.
- No significant bias due to high event rate



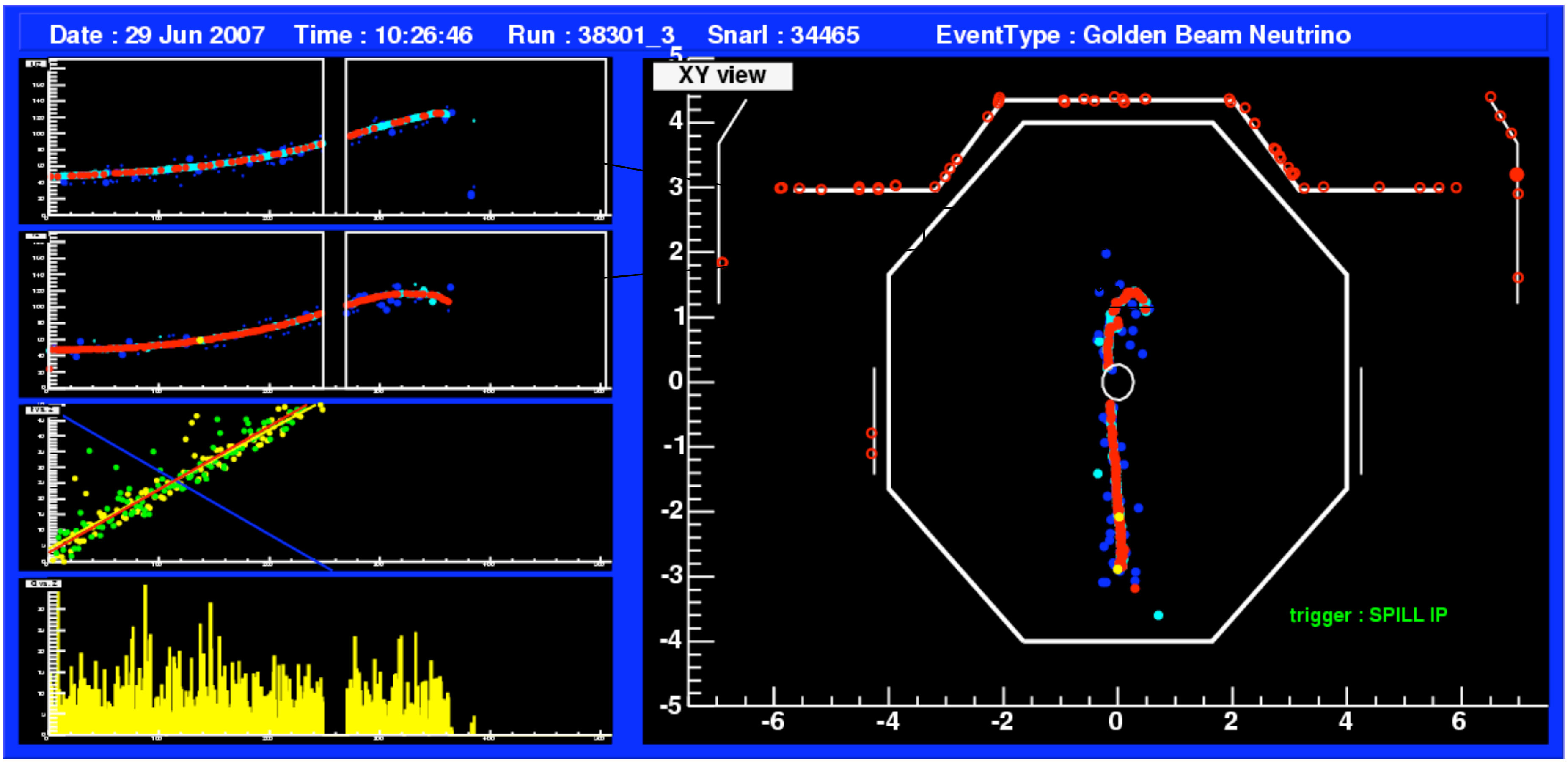




← **Batch structure clearly seen!**

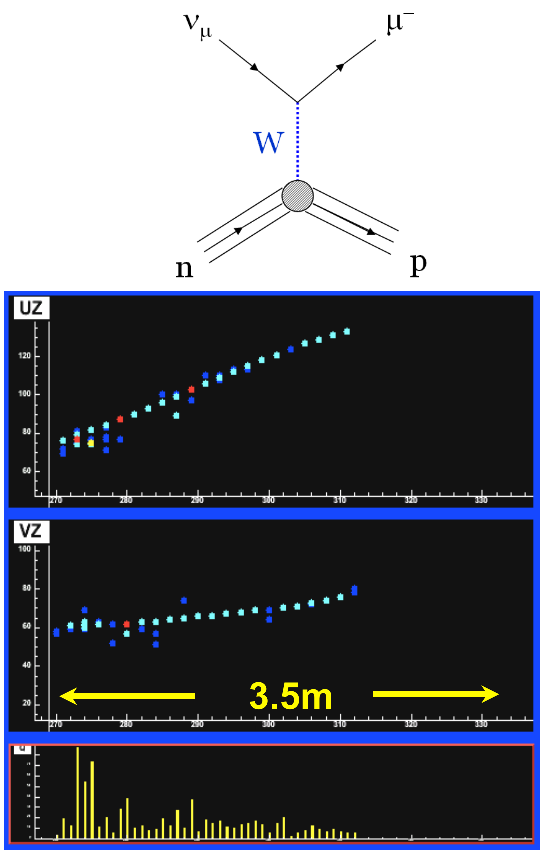
Far Detector Events

- Beam neutrino interaction rate is ~10^{-6} that of the near detector
- Beam events are identifiable in time with the spill trigger supplied from NuMI



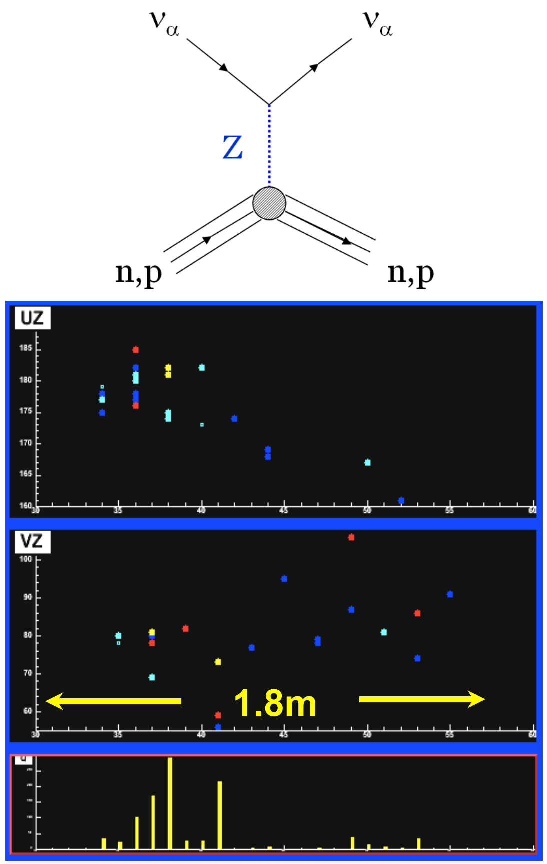
Event topology in MINOS

ν_μ CC Event



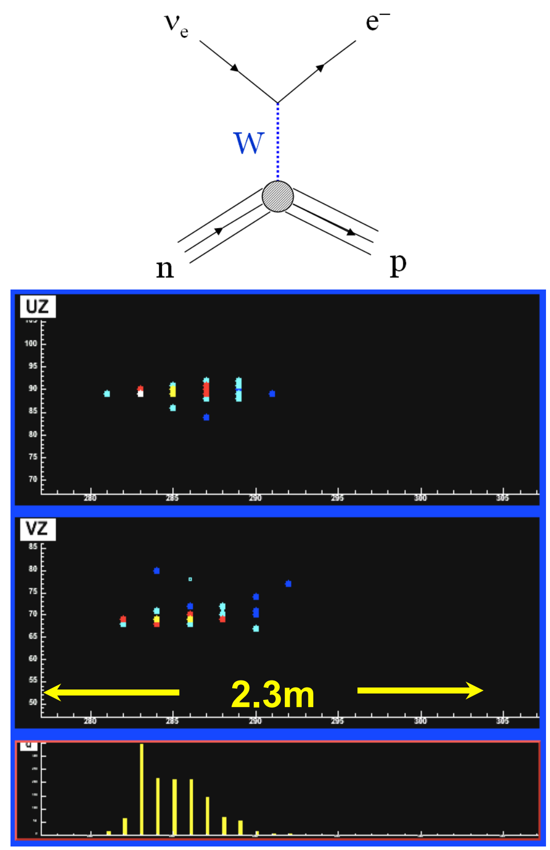
long μ track & hadronic activity at vertex

NC Event



short event, often diffuse

ν_e CC Event



short, with typical EM shower profile

- Challenging to distinguish NC from ν_e CC.
- Very clear signature for ν_μ CC events: $E_\nu = E_{shower} + P_\mu$

55%/√E (GeV)

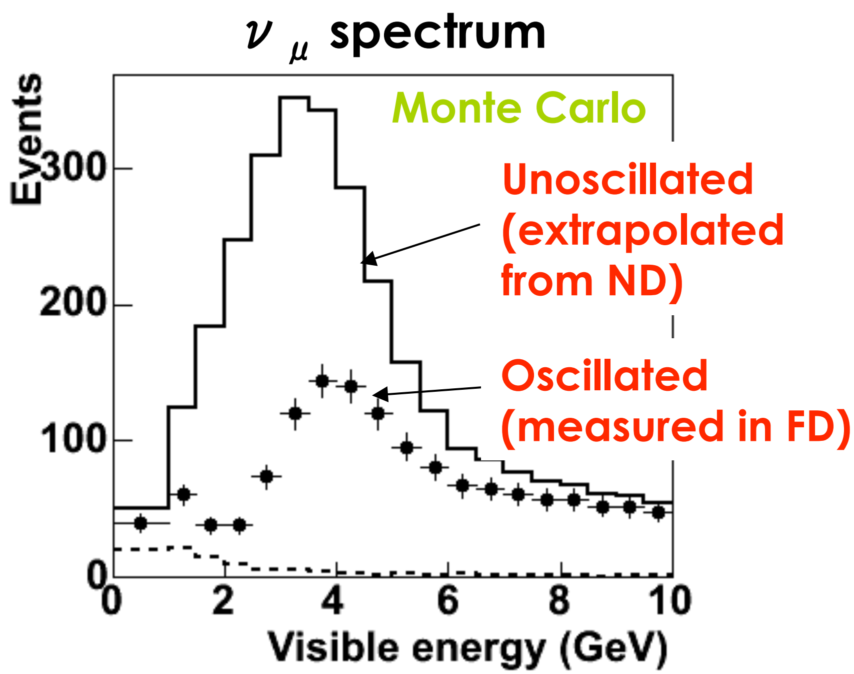
6% range,
13% curvature

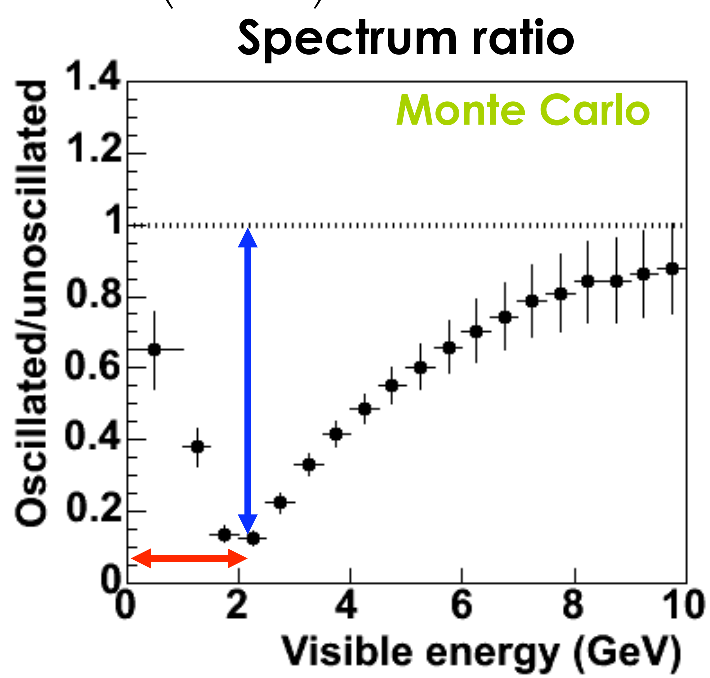
ν_μ disappearance

- **Most recent results with 3.36×10^{20} POT of exposure have been published in** PRL 101: 131802, 2008.

- Principle of the measurement:

$$P(\nu_\mu \rightarrow \nu_\mu) = 1 - \sin^2 2\theta \sin^2\left(\frac{\Delta m^2 L}{E}\right)$$

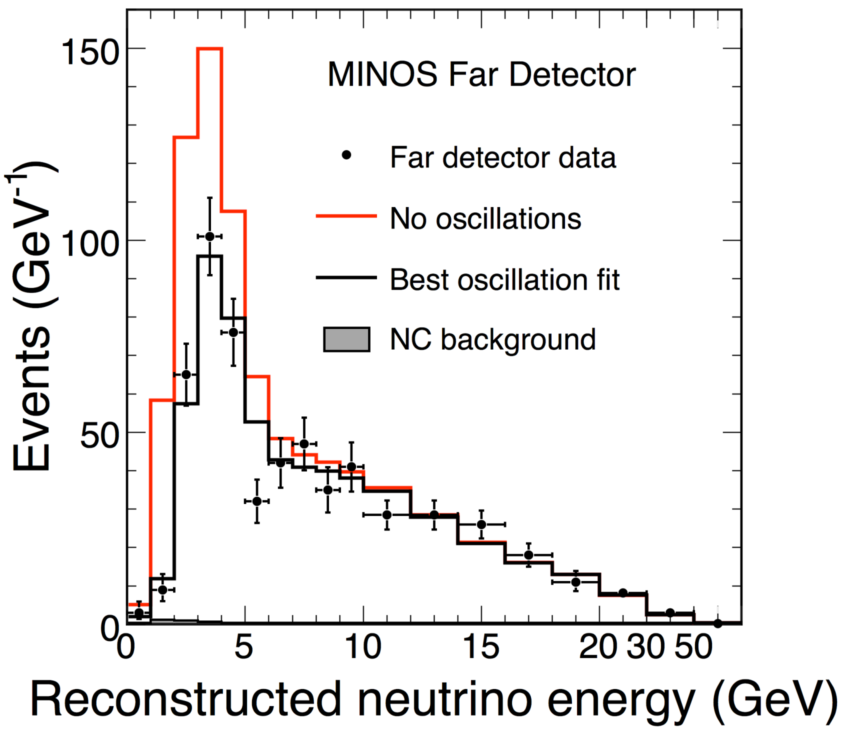


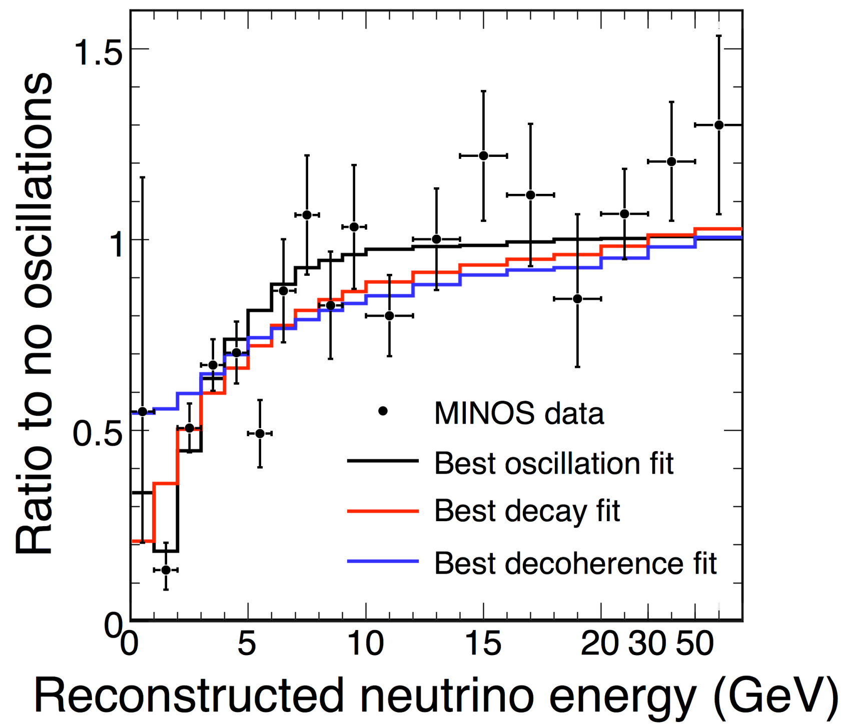


The Data

MINOS

- Expected 1065±60 events in the case of no oscillations, observed 848:





- Alternative hypotheses are disfavored by the data:

Neutrino decay:

$$P_{\mu\mu} = \left[\sin^2\theta + \cos^2\theta \ \exp(-\alpha L/E)\right]^2$$

V. Barger *et al.*, PRL82:2640(1999)

disfavored at 3.7σ

Neutrino decoherence:

$$P_{\mu\mu} = 1 - \frac{\sin^2 2\theta}{2}\left(1 - \exp\left(\frac{-\mu^2 L}{2E_\nu}\right)\right)$$

G.L. Fogli *et al.*, PRD67:093006(2003)

disfavored at 5.7σ

Allowed parameter space

- The oscillation hypothesis is a good fit to the data:

Best fit values:

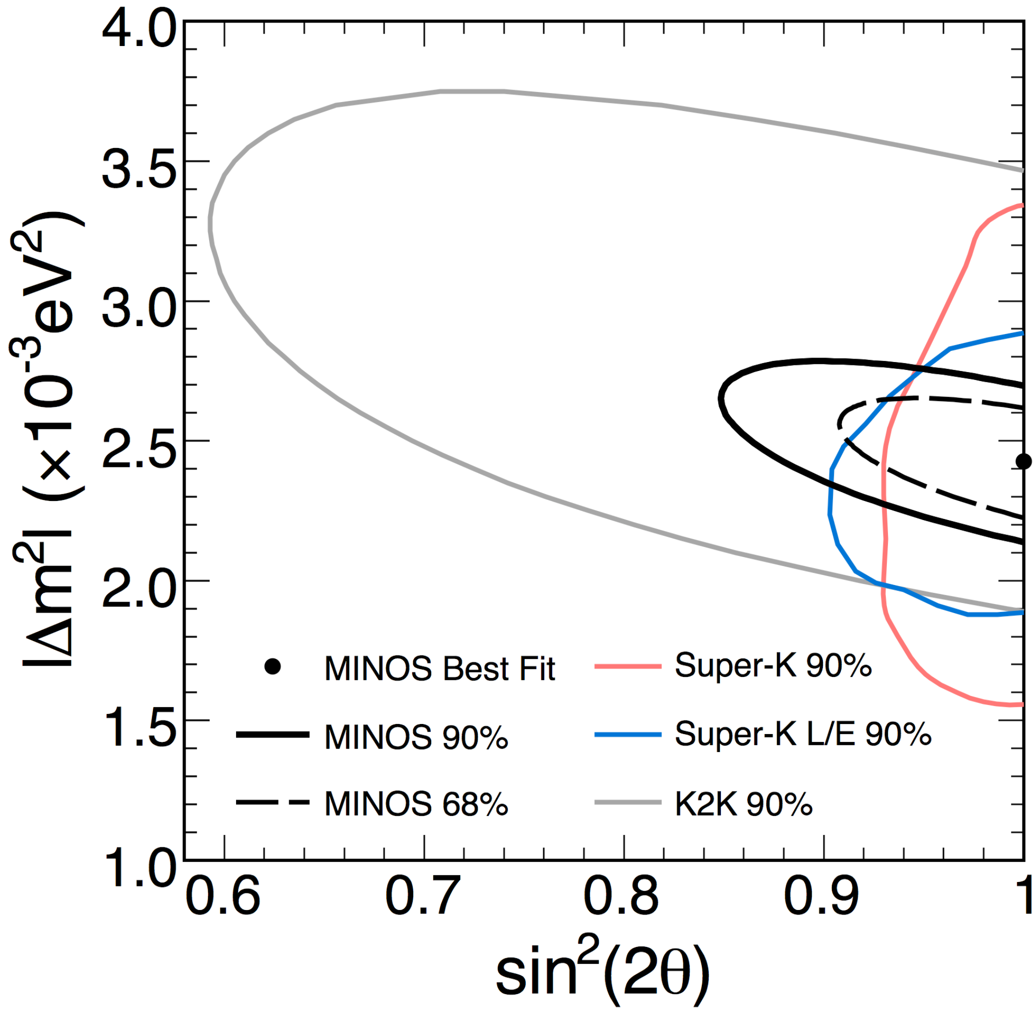
$$|\Delta m^2_{32}| = (2.43 \pm 0.13) \times 10^{-3}\ \text{eV}^2$$

$$\sin^2 2\theta_{23} > 0.90 \quad \text{(90\% C.L.)}$$

$$\frac{\chi^2}{N_{DoF}} = \frac{90}{97}$$

(the fit is constrained to the physical region)

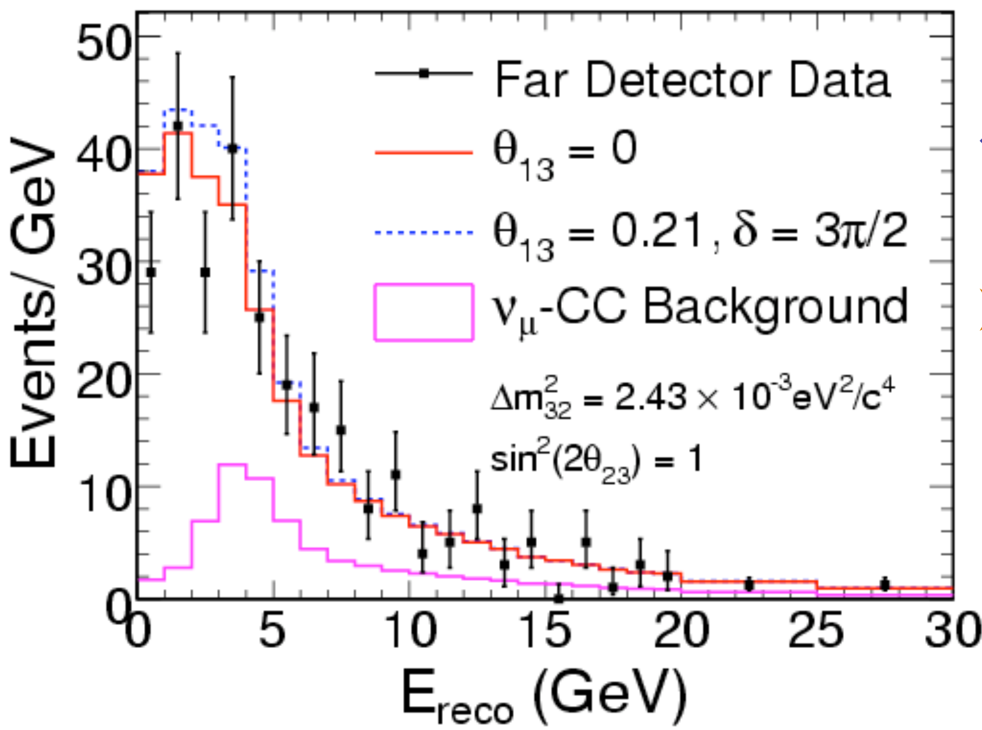
- **This constitutes the most precise measurement of $|\Delta m^2_{32}|$ to date.**



Oscillations to sterile neutrinos

MINOS

- Neutral current events are unaffected by standard oscillations:
  → Can test for oscillations to sterile neutrino(s)
- The data is consistent with no NC deficit and thus no oscillations to sterile neutrinos:



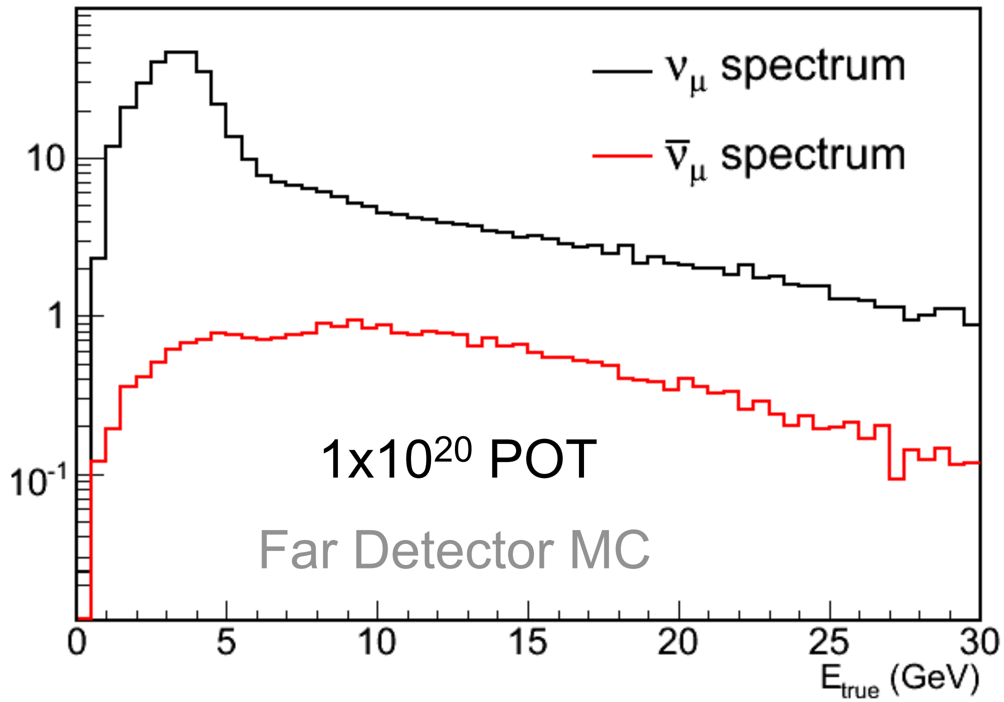
- Depletion of NC rate < 17% (90% C.L.)
- 3-flavor analysis results accepted by PRL **(arXiv:hep-ex/0807.2424)**
- Simultaneous fit to NC and CC energy spectra yields fraction f_s of ν_μ's oscillating into a sterile ν_s:

$$f_s = \frac{P(\nu_\mu \to \nu_s)}{1 - P(\nu_\mu \to \nu_\mu)} = 0.28^{+0.25}_{-0.28}(\text{stat.+syst.})$$

$$f_s < 0.68 \quad (90\% \text{ C.L.})$$

Anti-neutrino physics

- About ~6% of our beam is made of muon anti-neutrinos:



- Unique advantage: Both MINOS detectors are magnetized

→ allows us to separate neutrinos and anti-neutrinos on an event by event basis !

Anti-neutrino physics

❖ Very interesting physics can be done with anti-neutrinos:

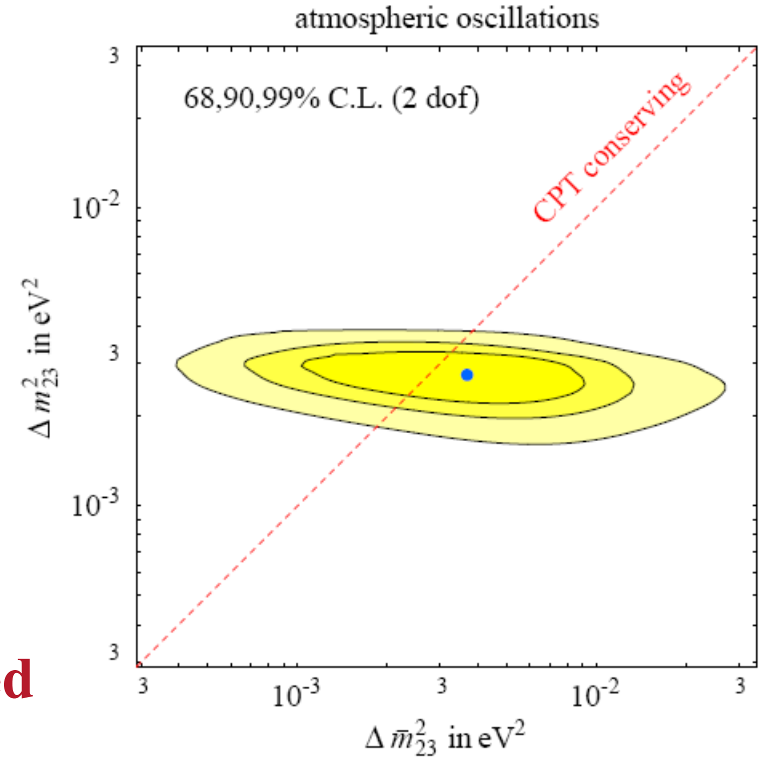
1) $\nu \rightarrow \bar{\nu}$ transitions: have never been looked for before in atmos sector.

- Some models beyond the SM predict them *(i.e. Langacker and Wang, Phys. Rev. D 58 093004).*
- Could fully explain the atmospheric neutrino results *(Alexeyev and Volkova, hep ex/0504282)*

2) Anti-neutrino oscillation analysis: large CPT violating region for $\Delta\bar{m}^2_{32}$ remains unexplored:

68%, 90%, 99% C.L. CPT violating regions still allowed by global fit (except LSND) ⟶

A. Strumia and F. Vissani, "Implications of neutrino data circa 2005", Nucl. Phys. B726 (2005)

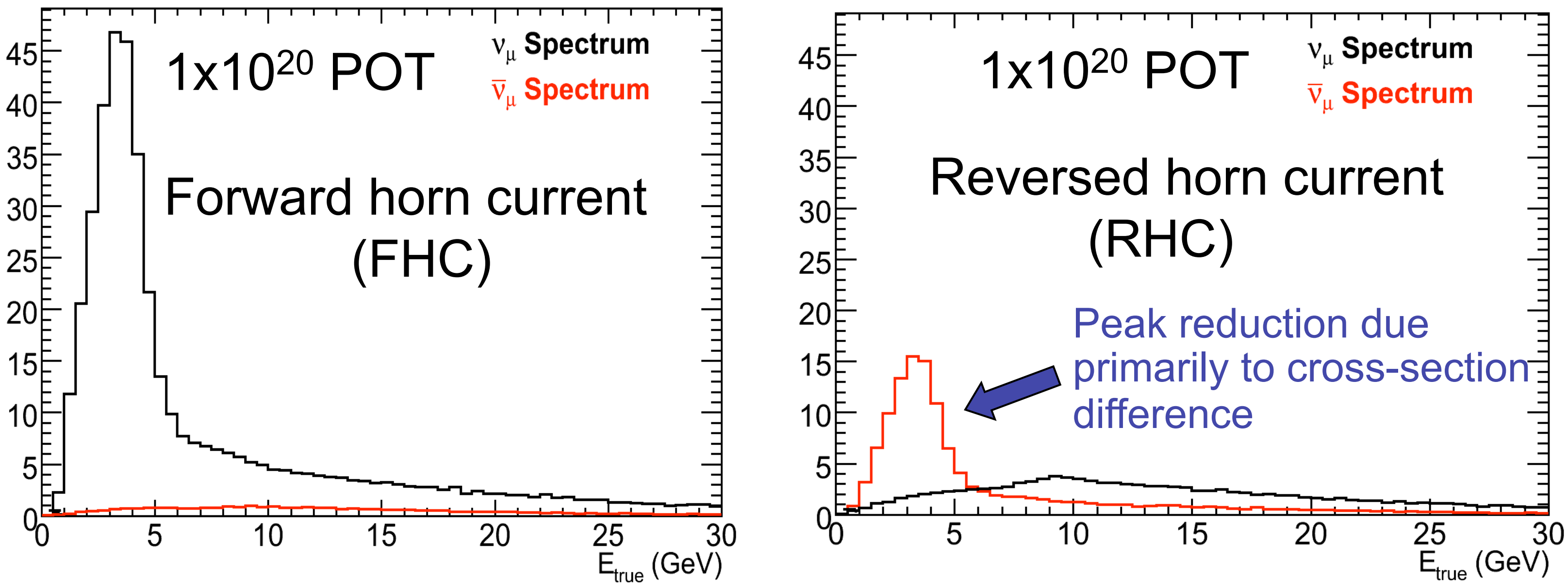


→ A result in these two areas is expected within the next couple of months

Reversed horn current running?

- **Can we further improve our reach?**
- Challenge comes from fact that the $\bar{\nu}_\mu$ spectrum peaks at higher energies

  →Have studied the possibility of running with reverse horn current



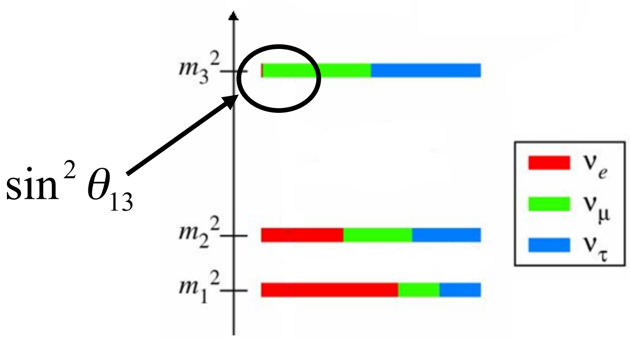
- In such case negative particles are focused by the horns thus yielding an anti-neutrino beam.

- Not a lot of RHC running needed to make a nice measurement of $|\Delta\bar{m}^2_{23}|$

  →Possibility currently being optimistically studied by collaboration.

ν_e appearance

- **Is θ_{13}=0 or just very small?**



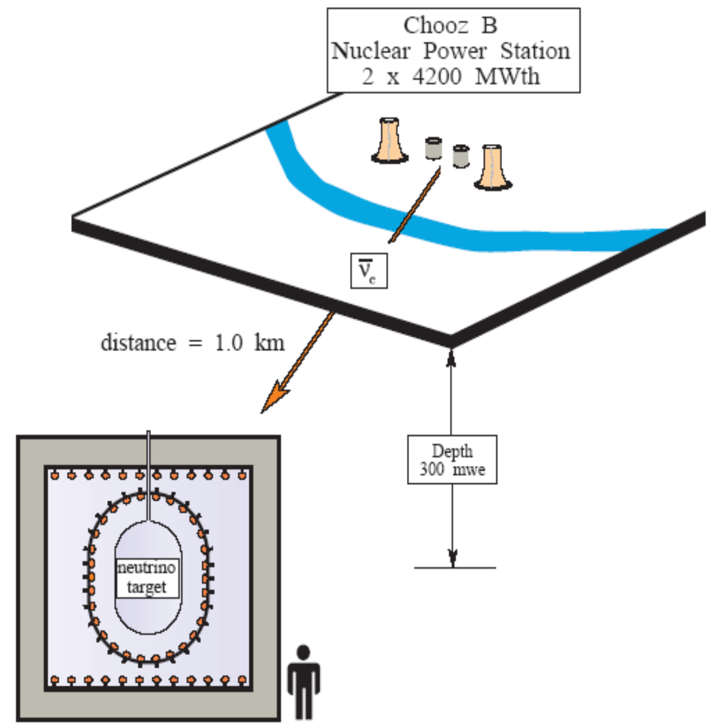
  - **A non-zero θ_{13} could give us a handle on <u>CP violation</u> and on the <u>mass hierarchy</u> of the neutrino sector.**
  - **Important implications in cosmology**

- Currently the world's best limit is set by CHOOZ:

$\sin^2(2\theta_{13}) < 0.15$ for $\lvert\Delta m_{32}\rvert^2 = \sim 2.5\times10^{-3}\,\text{eV}^2$

At CHOOZ' baseline (~1km):

$$P(\bar{\nu}_e \rightarrow \bar{\nu}_e) \cong 1 - \sin^2 2\theta_{13} \sin^2 \frac{\Delta m_{23}^2 L}{4E}$$



Chooz Underground Neutrino Laboratory
Ardennes, France

- At MINOS' baseline of 735 km, $P(\nu_\mu \rightarrow \nu_e) \cong \sin^2 2\theta_{13} \sin^2\theta_{23} \sin^2 \frac{\Delta m_{23}^2 L}{4E}$

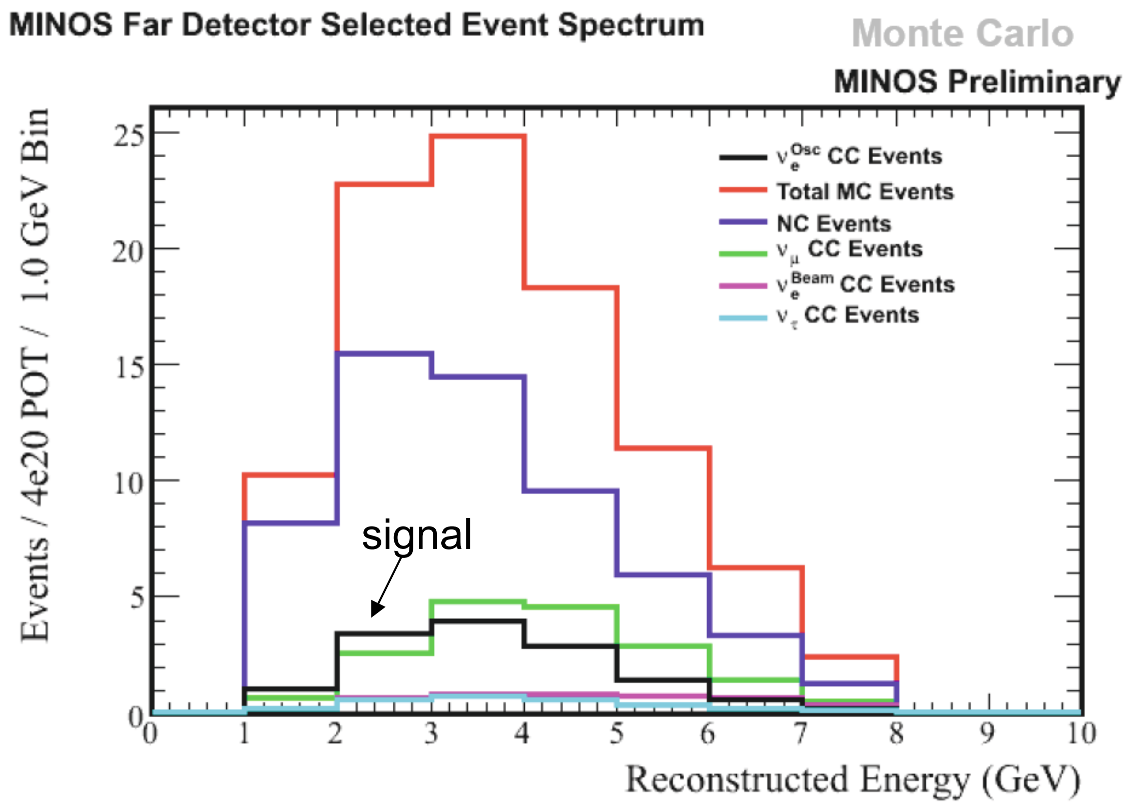
→If ν_μ's oscillate into ν_e's will see a signal over the predicted background.

ν_e appearance in MINOS

MINOS

- **Challenge:** do not have the optimal granularity for EM and hadronic shower separation.
- **Consequence:** the typical ν_e selection is dominated by background
- Reach of ν_e analysis depends on the performance of the selection and on our knowledge of the backgrounds.

EM Showers in MINOS	Detector Parameters
Radiation length: 1.76 cm	Steel thickness: 2.54 cm
Molière radius: 3.7 cm	Strip width: 4.12 cm



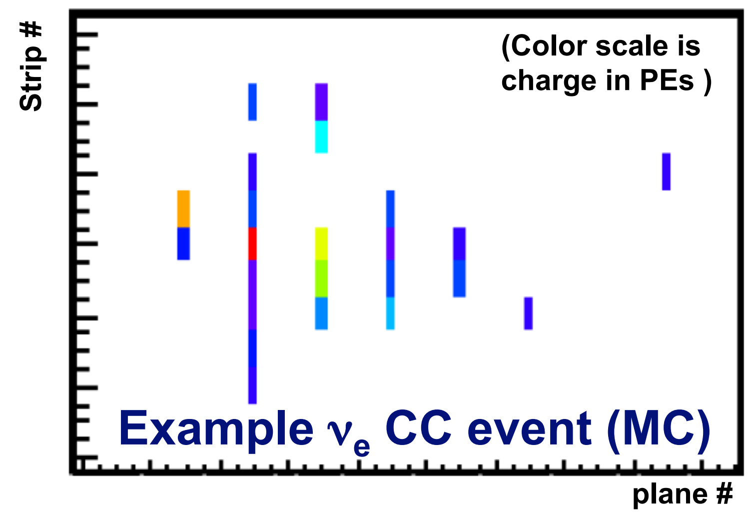
$(\sin^2(2\theta_{23})=1.0,\ \Delta m^2_{32}=0.0027\ eV^2,\ \sin^2(2\theta_{13})=0.1,\ 4\times10^{20}\ POT)$

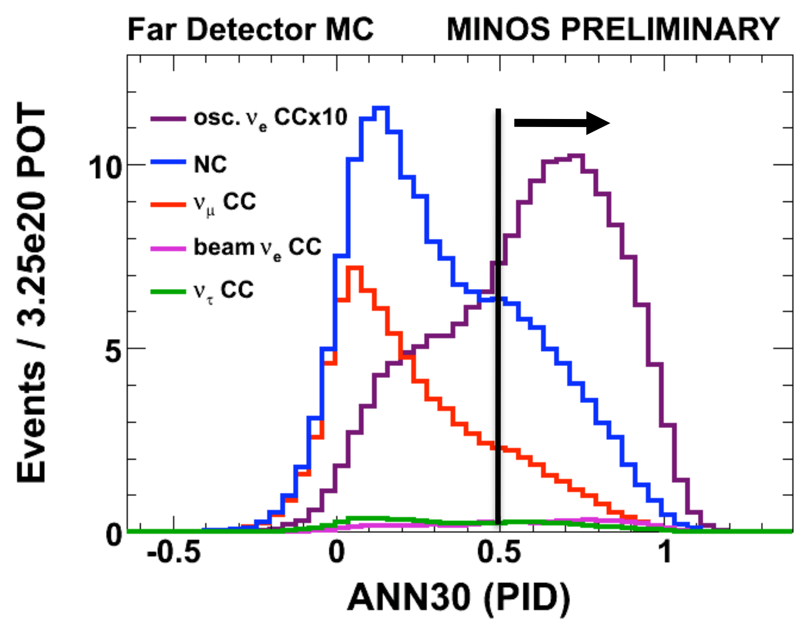
ν_e selections

- **Much work has gone into devising variables and PIDs to enhance signal and background separation.**
- All the information about a given event is contained in the **time**, **readout charge** and **position** of all strips hit during the event.
  - One approach is to construct variables from this information
    Example: Moliere radius = radius around shower axis which contains 90% of the visible energy
- Example of neural net with 30 variables (ANN30):

Signal	Tot.bg	NC	ν_μ CC	ν_τ CC	ν_e beam
12	42	29	8	3	2

($\sin^2(2\theta_{23})$=1.0, Δm^2_{32}=0.0024 eV^2, $\sin^2(2\theta_{13})$=0.15, 3.25x10^{20} POT)





A different approach

MINOS

- The amount of information present in each ν_e CC event is simply not that large:
  - Only 22 strips are hit in average during each ν_e CC event in the energy region of interest.
  - **Why not perform event identification using the strip information alone?**
- At Caltech I have developed the "Monte Carlo Nearest Neighbors" (MCNN) selection:
  - **Basic idea:**

1) Compare each input event to large libraries of MC ν_e CC and NC events.
2) Select N best matches
3) Construct discriminant from N best matches information (e.g. fraction of N best matches which are ν_e CC)

→ ν_e identification is turned into a pattern recognition problem!

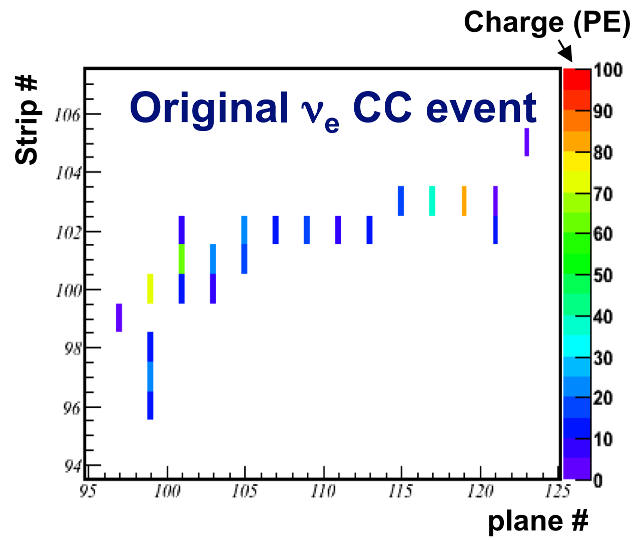
The MCNN selection

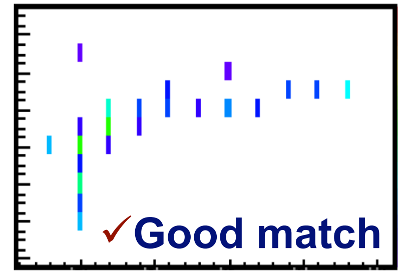
- We determine how well two events match each other by asking:

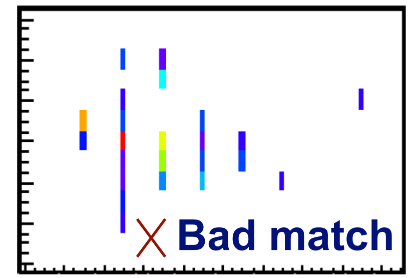
"what is probability the two events come from same hit pattern at PMTs?"

$$\ell = \sum_{pl} \sum_{st} \int_0^\infty P(n_1, \lambda) P(n_2, \lambda) d\lambda$$

Poisson







- Advantages:
  - ✓ **Approach is in principle optimal. No loss of information from raw → reconstructed quantities**
  - ✓ **Largely reconstruction-free.**

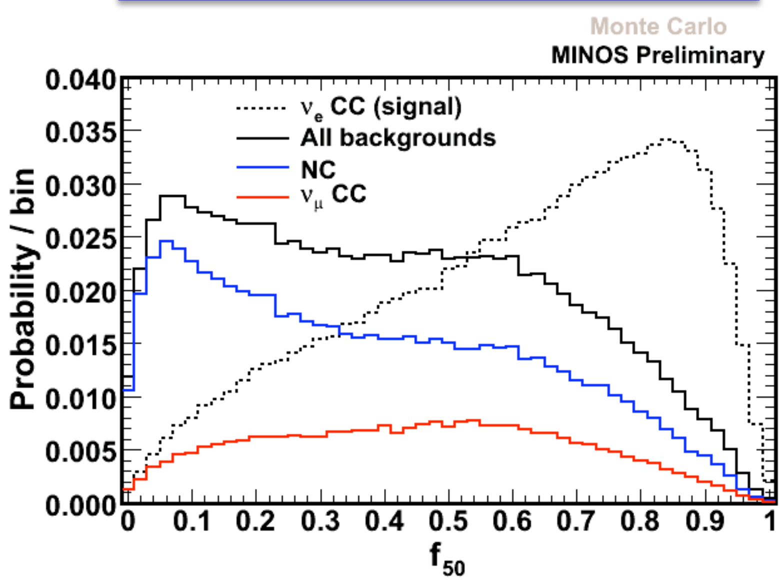
- Method is computationally expensive: must fully sample phase space for optimal results.
  - Using a 30M library of simulated NC and ν_e CC events
  - Can process an input event in ~12 seconds.

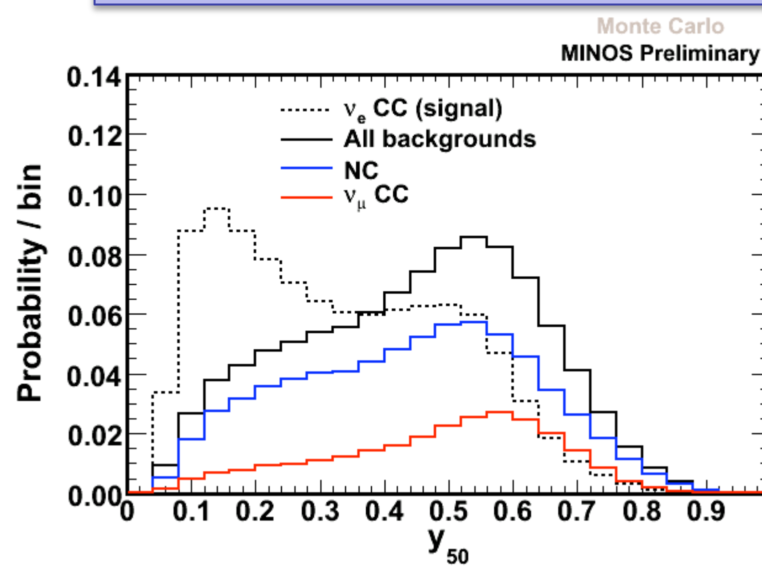
The MCNN selection

- **The information of the N best matches is very rich**; can construct variables such as:

f_{50}=fraction of best 50 matches that are ν_e CC with y<0.9

y_{50}=average y of best 50 matches that are ν_e CC with y<0.9





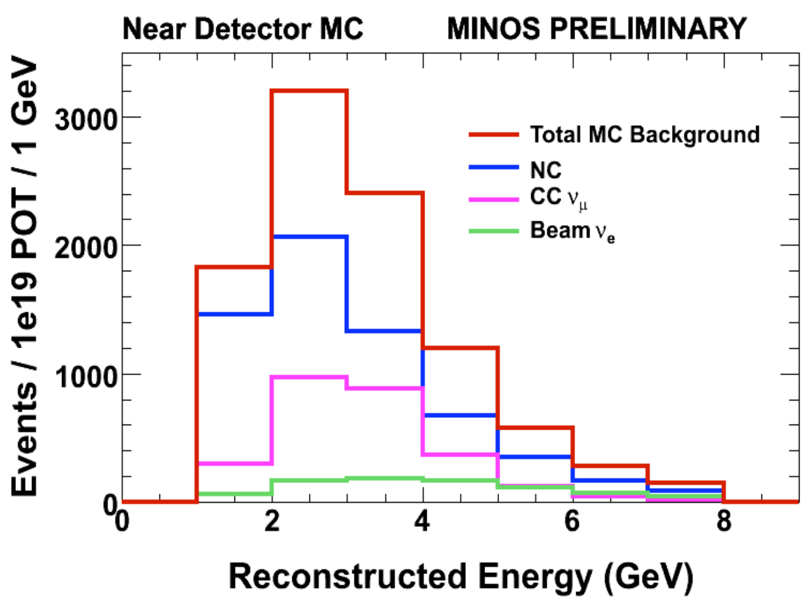
- These variables are then combined in a likelihood.
- The MCNN selection is a part of the next MINOS ν_e appearance analysis:
  - **The MCNN is 10-20% more sensitive to θ_{13} than the other selections.**
  - **Stay tuned for results coming in the next couple of months**

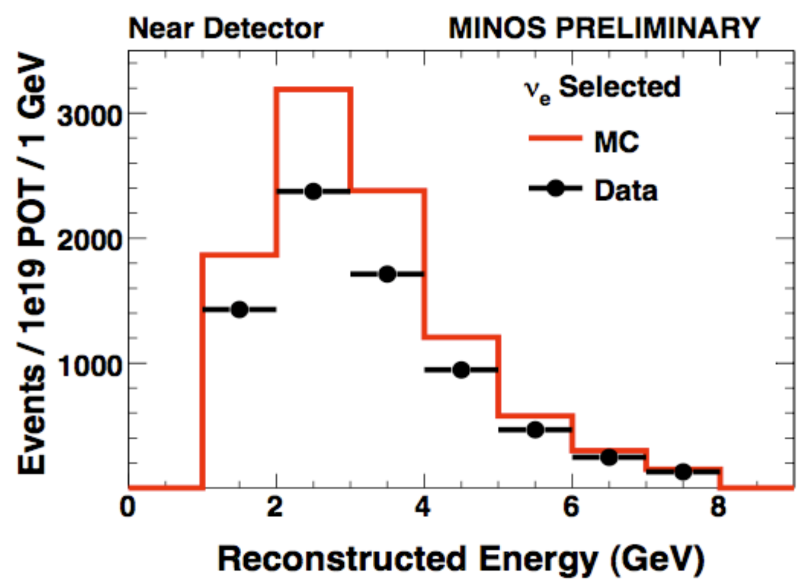
Background determination

Note: all plots shown from here onwards were done with the neural network selection. Nevertheless the strategy to measure the backgrounds is the same for both methods.

Challenge:

- For both of our selections the background still dominates over the signal
  → Need to predict these backgrounds in the FD as accurately as possible.





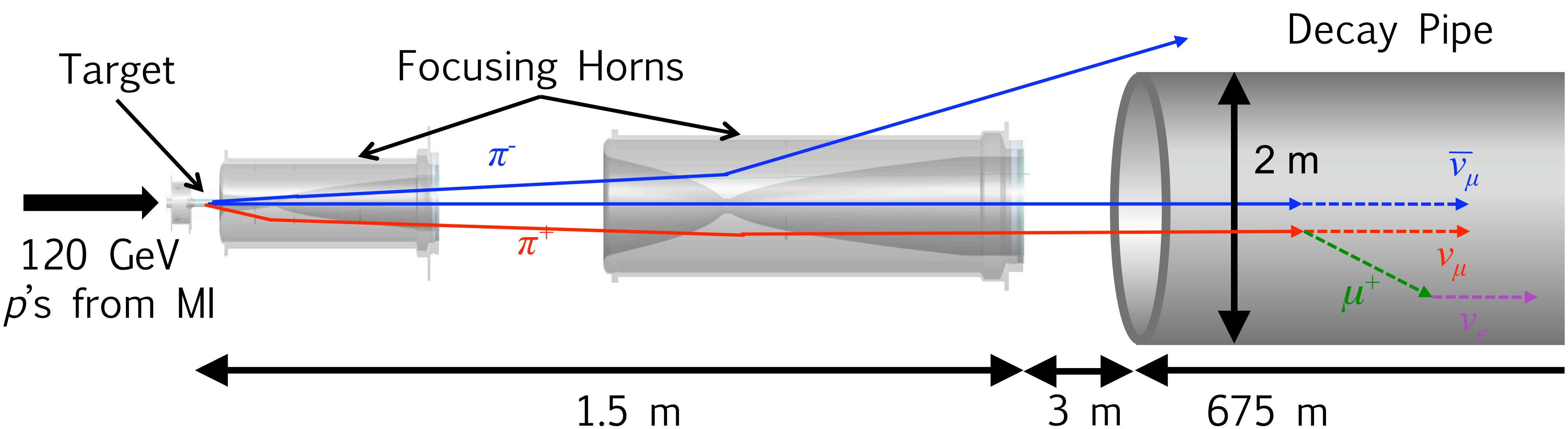
- Cannot rely solely on simulation

Solution:

➔ **Use the ND data to predict the FD background.**

Background determination

- However, our backgrounds extrapolate differently to the FD:
  - ν_μ CC's undergo oscillations
  - Parents of NC events are created in the target, whereas most parents of intrinsic beam ν_e's are created in the decay pipe



- **We need to decompose the measured ND data energy spectrum into NC, ν_μ CC and beam ν_e events.**

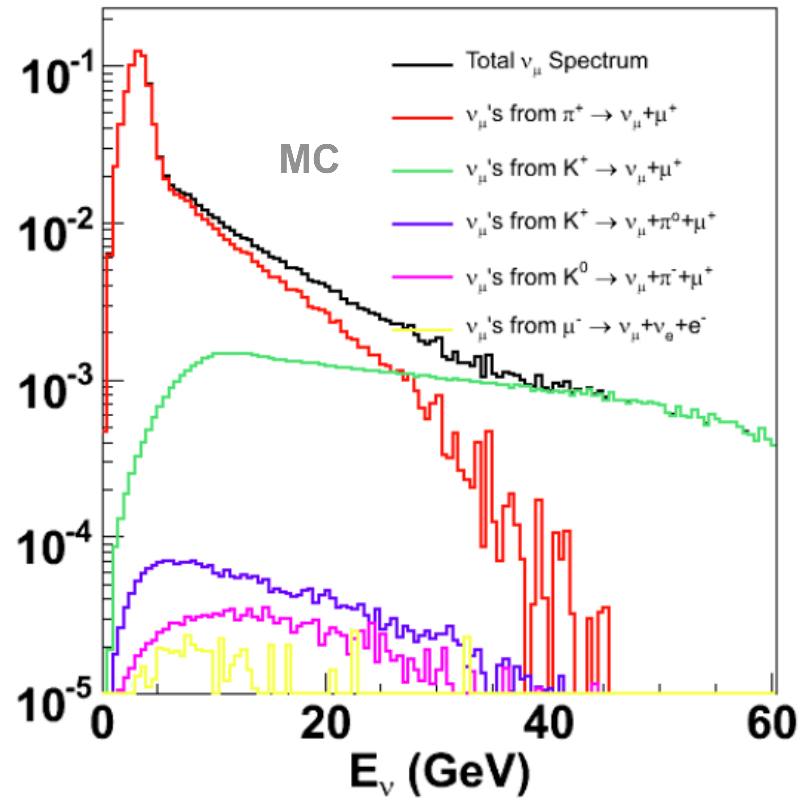
➔ Have developed some data-based techniques to achieve this.

Intrinsic beam ν_e's

- Most intrinsic beam ν_e's originate from

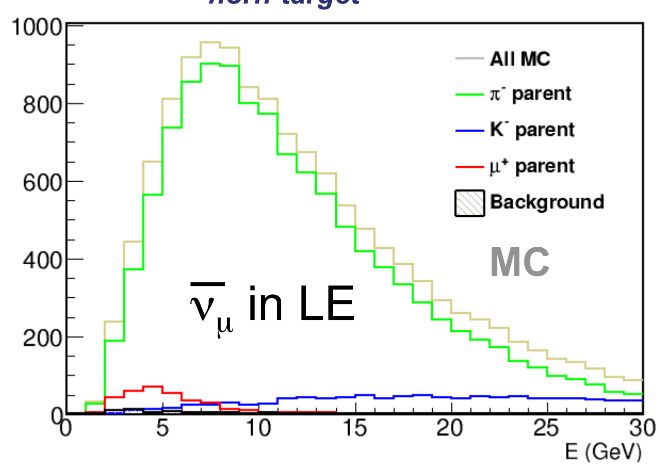
$$\mu^+ \rightarrow e^+ + \nu_e + \bar{\nu}_\mu$$

  - ν_μ CC event rate gives us handle on π^+ and K+ production at target (grandparents of beam ν_e's)
  - Use knowledge of decay kinematics and geometry to predict flux

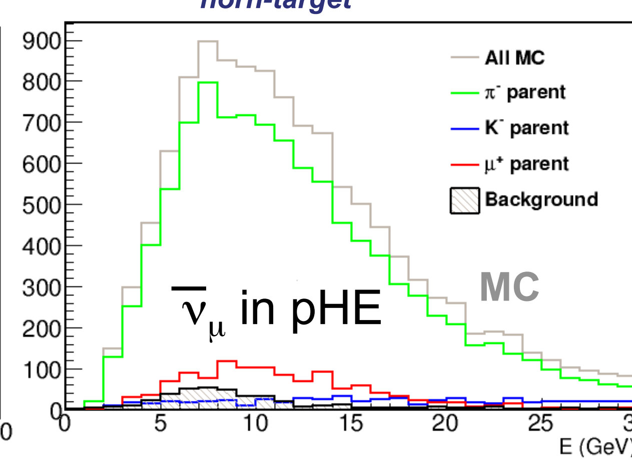


- **Cross-check done measuring anti-neutrinos from μ^+ decay:**
  - Most anti-neutrino parents are K^- and π^- that go undeflected through the two horns
  - Changing the horn-target separation only affects the $\bar{\nu}_\mu$'s from μ^+

Low Energy (LE)
$d_{horn\text{-}target}$ = -10cm



pseudo-High Energy (pHE)
$d_{horn\text{-}target}$ = 250cm

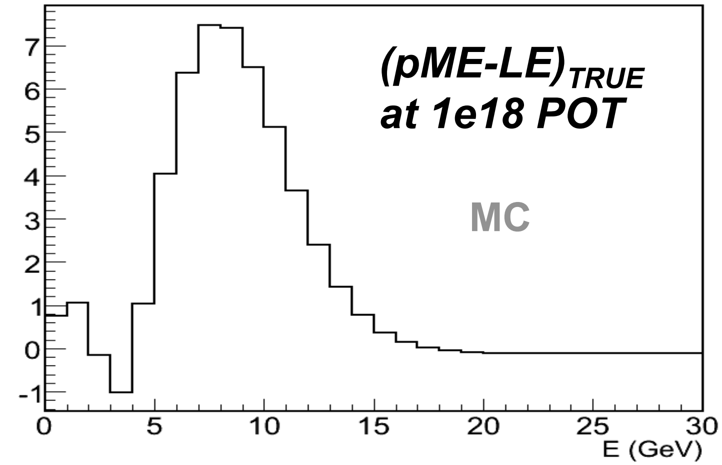


Intrinsic beam ν_e's

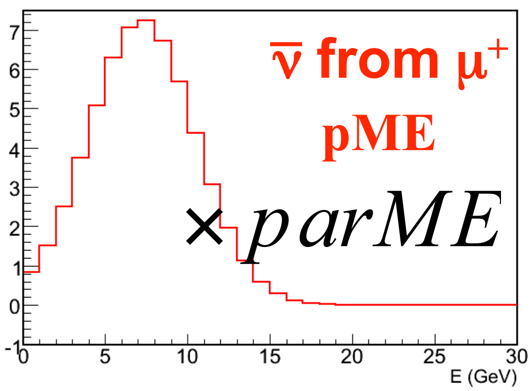
MINOS

The Technique:

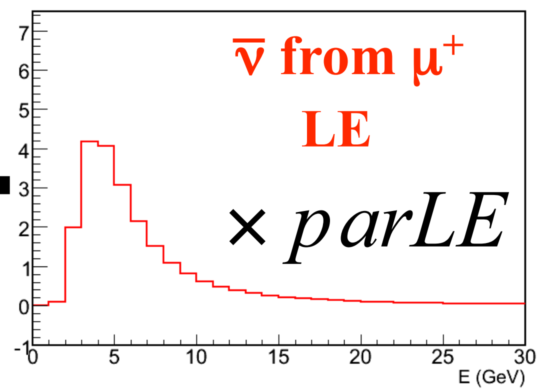
- **Scale pHE (or pME) and LE $\bar{\nu}_\mu$ data to same POT and take the difference**



- **Fit with using shapes from the MC:**



−



+

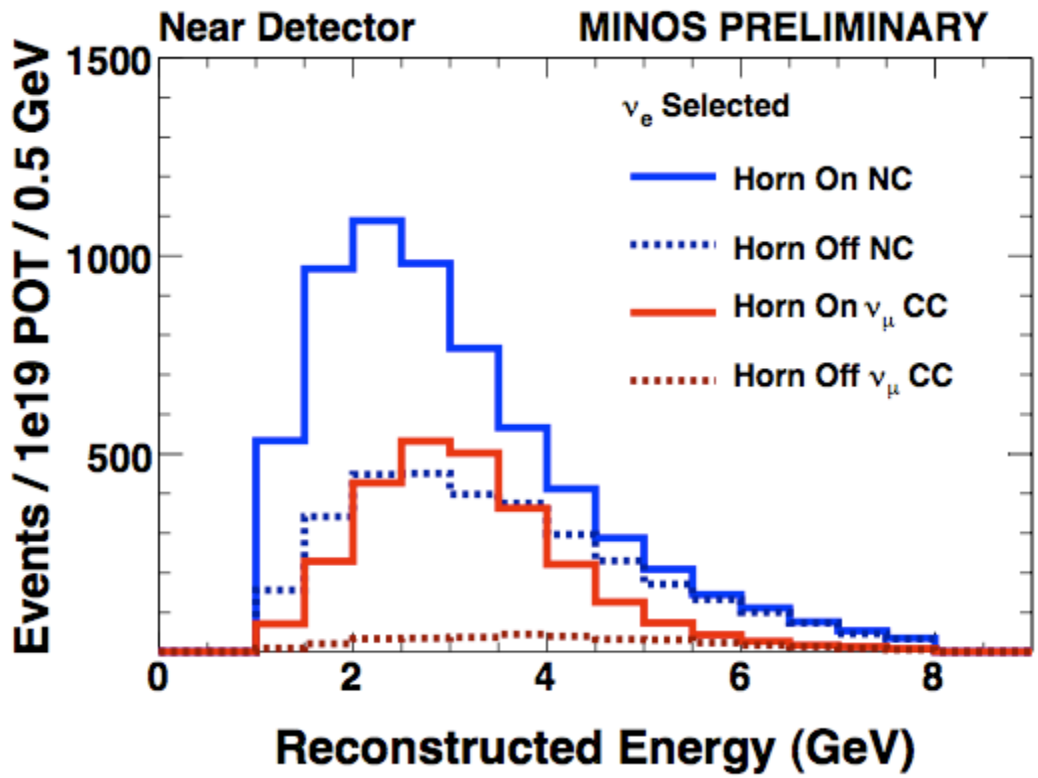
Corrections due to differences in the antineutrinos from π^- and K^-

- The method works with either pME or pHE data.
  - A preliminary result has been obtained with 1.6×10^{19} POT of pHE data.
  - **Official result and publication in the works !**

Horn-on/off (HOO) method

- The HOO method uses the horn-off data to estimate the NC and CC ν_μ components:

  - When the horns in the NuMI beam are turned off the pions coming off the target are no longer focused
  - The energy spectrum of the data taken in the horn-off configuration has a very different composition from the one obtained in the LE configuration:



→ The horn-off data constitutes an NC enriched sample

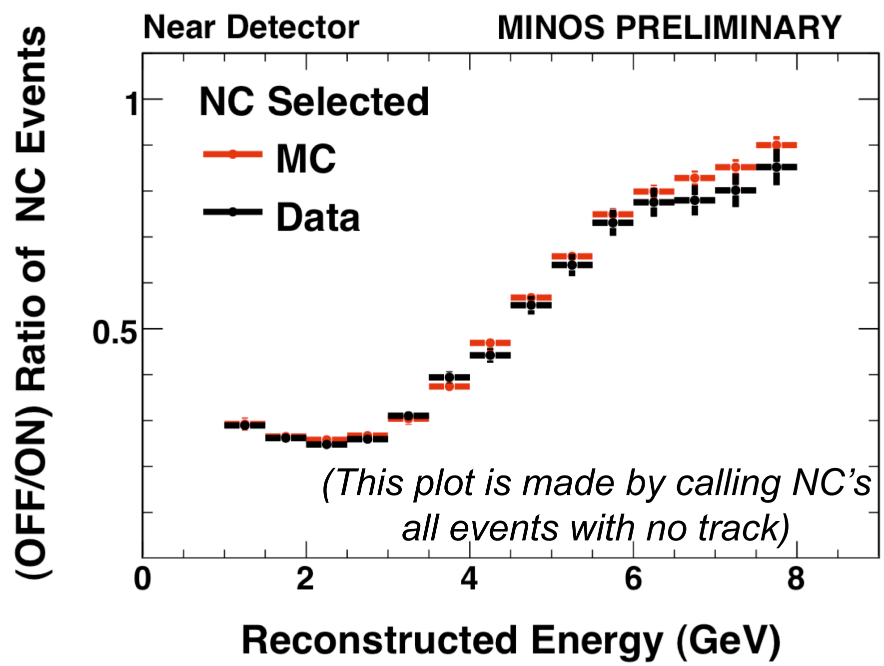
Horn-on/off (HOO) method

- The number of events selected in the horn-on/off configurations can be described by a system of two equations:

$$N^{on} = N_{NC} + N_{CC} + N_e$$
$$N^{off} = r_{NC}*N_{NC} + r_{CC}*N_{CC} + r_e*N_e$$

Can be solved for the two unknowns N_{NC} and N_{CC}

- ✓ The ratios $r_x = N_x^{off} / N_x^{on}$ are taken from the simulation and are <u>very robust against modeling uncertainties</u>.
- ✓ The number of selected beam ν_e's N_e is obtained from the tuned simulation, as described previously.



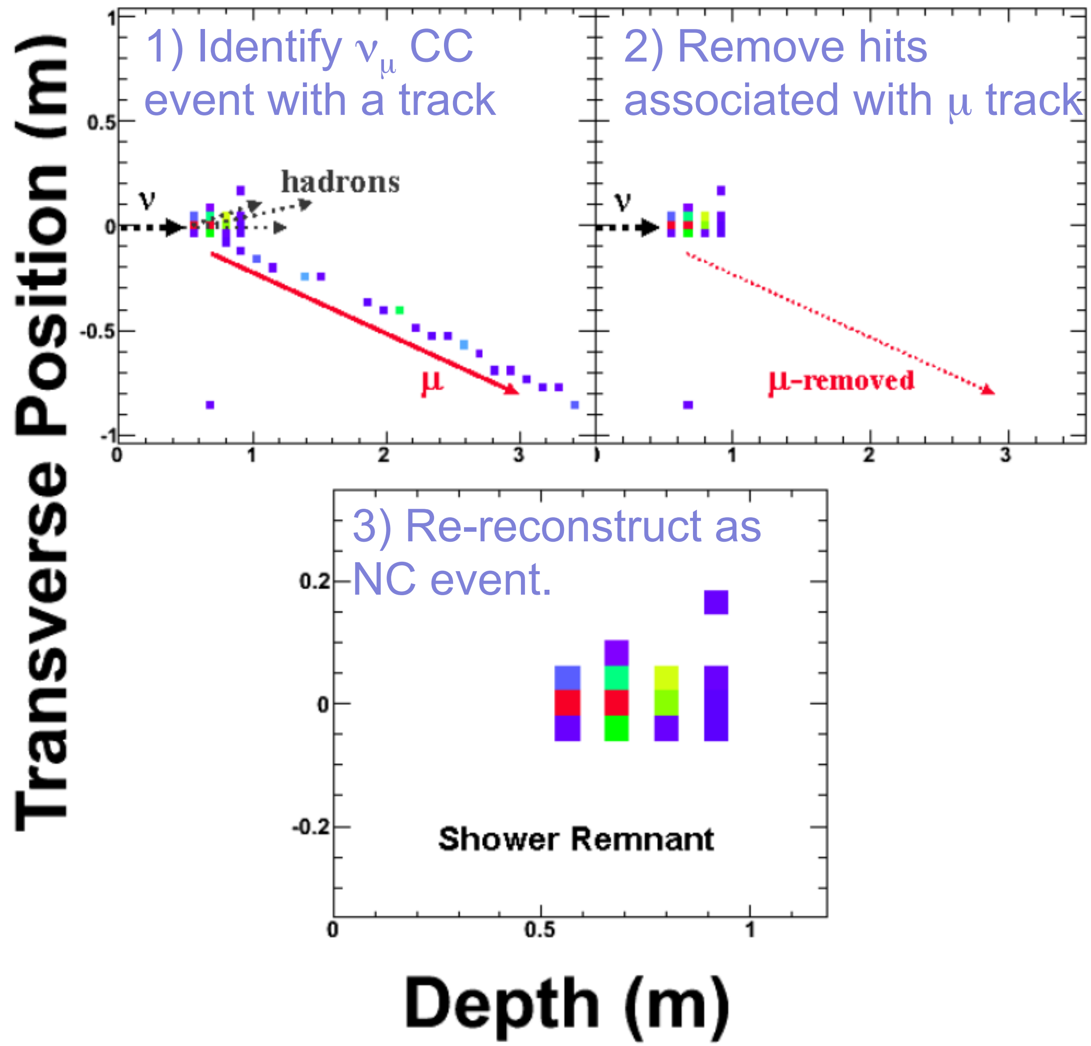
The Muon Removal (MRCC) Method

MINOS

- The MRCC method is another alternative to determining the NC and CC ν_μ components from the data:
  - The dominant uncertainty comes from the simulation of hadronic showers.
  - NC and CC ν_μ hadronic showers are very similar in the MINOS detectors.

→ By removing the muon from golden CC ν_μ events we get a pure sample of quasi-NC events.

The MRCC procedure:



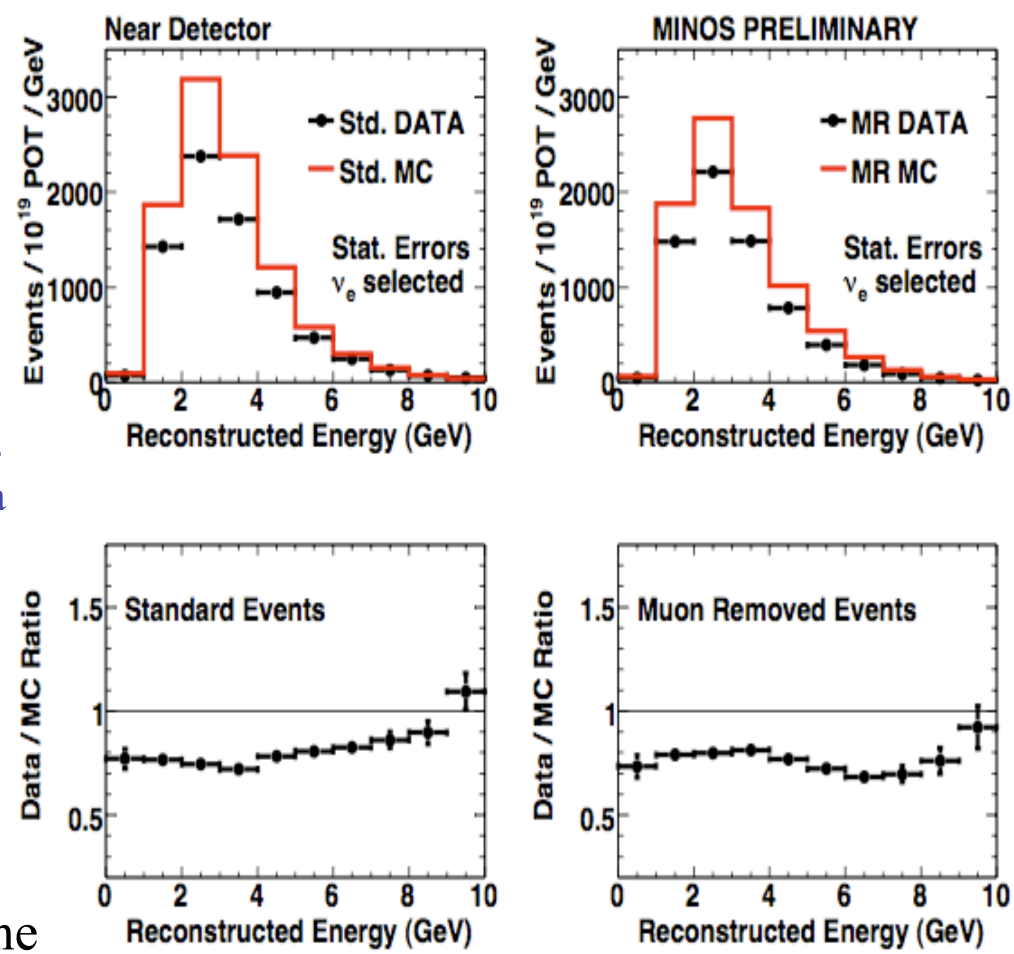
The Muon Removal (MRCC) Method

MINOS

- The data/MC discrepancy is very similar between the MRCC and standard samples
- The ratio of MRCC^{Data} to MRCC^{MC} is used to correct the MC expectation for NC events:

$$N^{pred} = \frac{N^{DATA}_{MRCC}}{N^{MC}_{MRCC}} N^{MC}$$

- N^{pred}: # of predicted NC events in ν_e analysis
- N^{DATA}_{MRCC}: # of ν_e candidates in MRCC data
- N^{MC}_{MRCC}: # of νe candidates in MRCC MC
- N^{MC}: # of ν_e candidates that are NC in MC

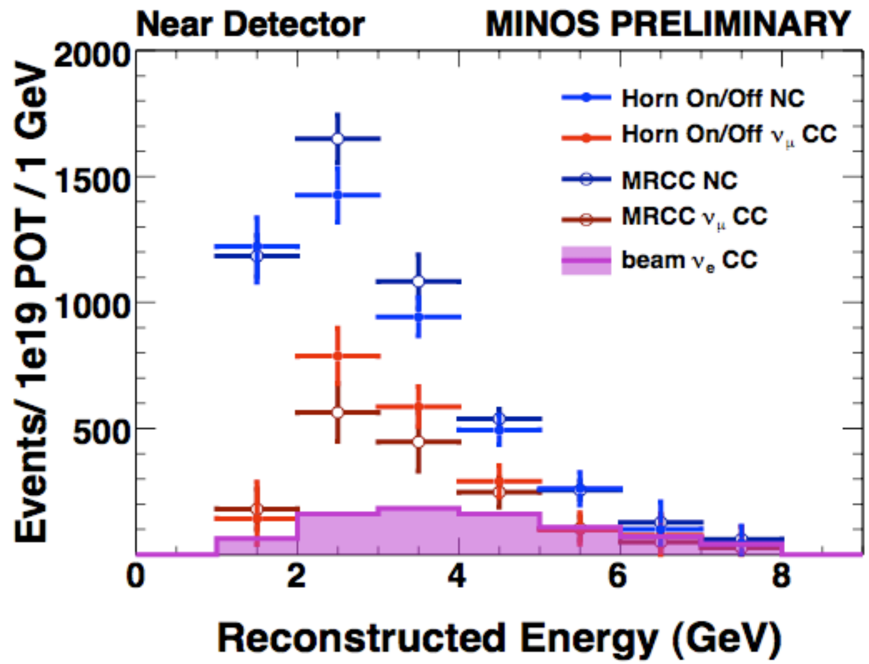


- In this fashion the systematics in the MRCC procedure cancel to 1st order.
- The remaining data/MC discrepancy is absorbed by the correction to the CC ν_μ component.

ND decomposition results

MINOS

- **The HOO and MRCC data driven methods produce consistent results**
- After being extrapolated to the FD, these numbers constitute the total background for the ν_e appearance analysis.



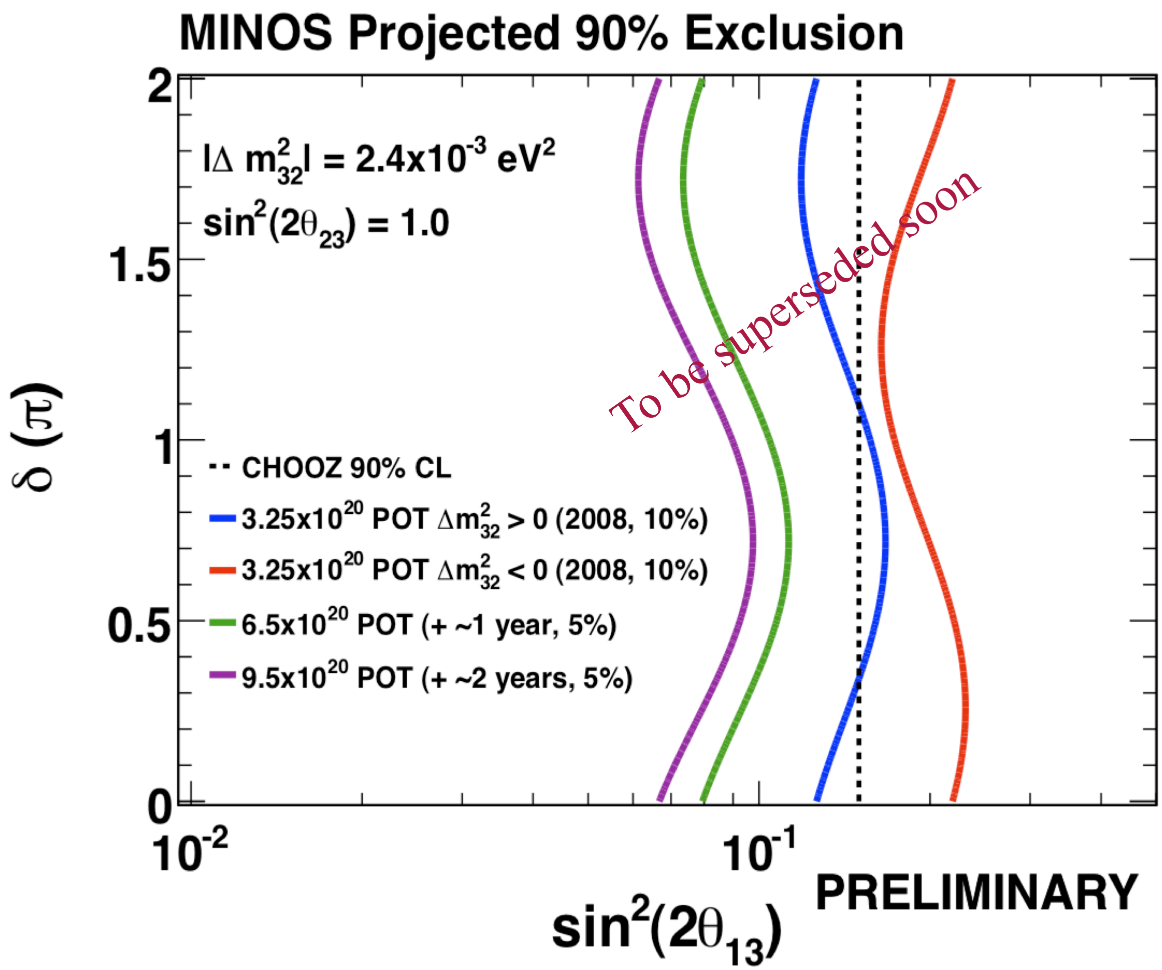
Method	Total	NC	CC	Beam ν_e
Raw MC	9668 ± 22	6230 ± 18	2651 ± 11	788 ± 118
HOO	7303 ± 41	4491^{+233}_{-224}	2025^{+244}_{-220}	788 ± 118
MRCC	7303 ± 41	4899 ± 176	1617 ± 202	788 ± 118

(all errors are statistical except for MRCC and beam ν_e)

Outlook

❖ Currently finalizing the systematic error estimations:

→ Systematic error on the background can most likely be kept below 10%



❖ Current reach comparable to CHOOZ

→ Expect first result in the next couple of months

❖ With full dataset will either make a discovery or extend the CHOOZ limit by about a factor of two

Summary

- MINOS has now been successfully running for more than three years and has at least two more to come.
- MINOS continues to make many important contributions in many areas such as anti-neutrino physics, oscillations to sterile neutrinos, and ν_μ CC disappearance:

$$|\Delta m^2_{32}| = (2.43 \pm 0.13) \times 10^{-3}\ \text{eV}^2$$

$$\sin^2 2\theta_{23} > 0.90 \quad \text{(90\% C.L.)}$$

The world's best measurement of $|\Delta m^2_{32}|$!

- **We have a chance of making the first measurement of a non-zero θ_{13}**
  - Have developed selection methods that enhance signal and background separation.
  - Have a working strategy for predicting the FD background based on the ND data with a total systematic error of only ~10%.
  - Expect the first result within the next months.

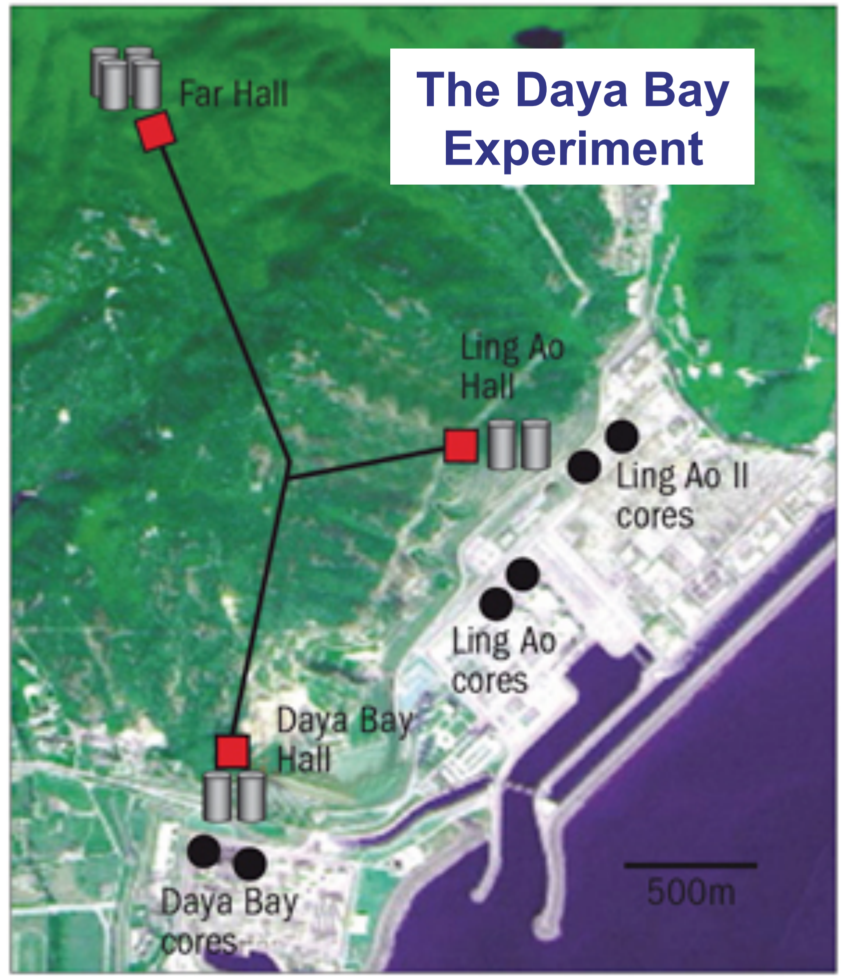
The future

❖ Future generation experiments are well underway to pursue the search for a non-zero θ_{13} beyond MINOS:

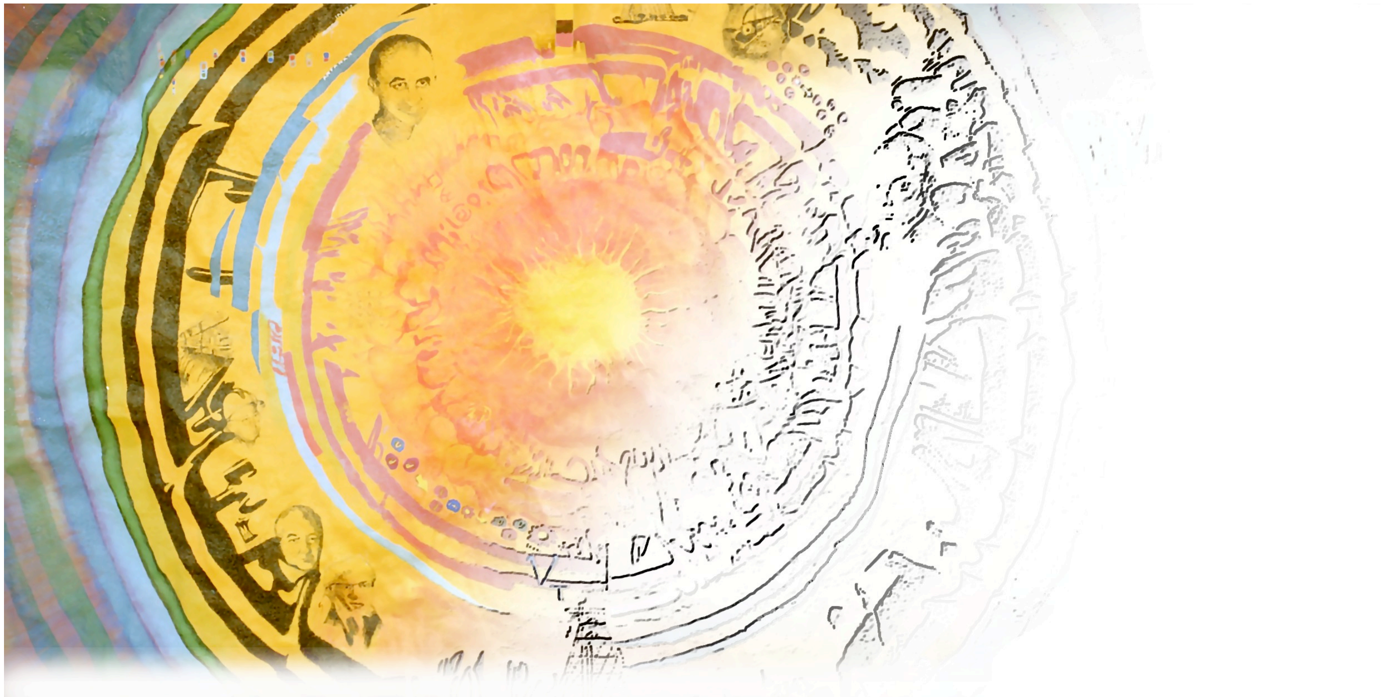
- Reactor experiments like Double CHOOZ (France) and Daya Bay (China) will either make a discovery or expand the CHOOZ limit by an order of magnitude.

- Accelerator based experiments like NOvA (US) and T2K (Japan) may be able to address CP violation and the mass hierarchy of the neutrino sector.

→ **Looking forward to continuing the search !**



Thank you for your attention !



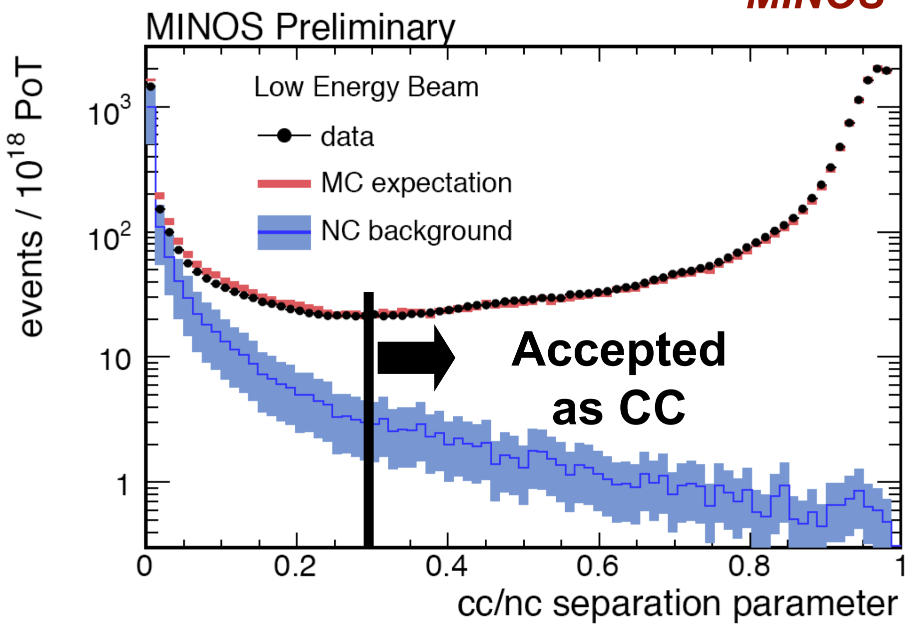
Backup

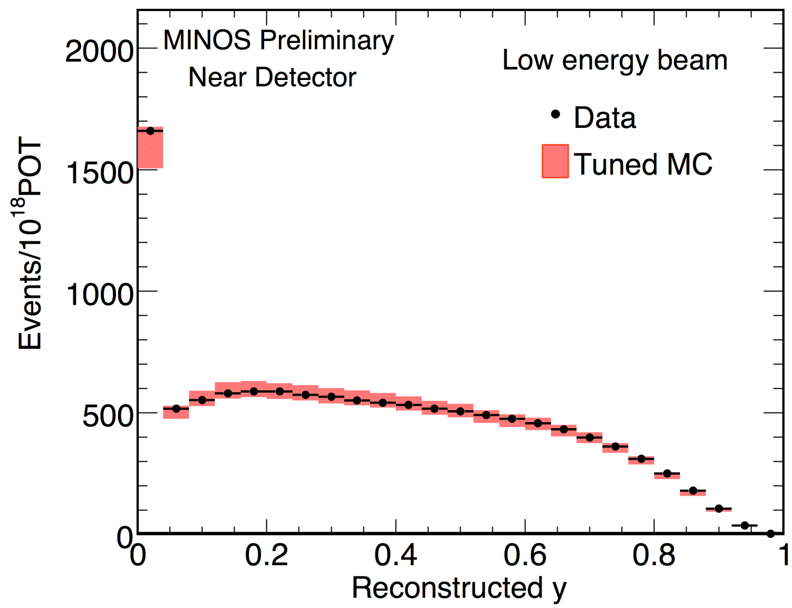
Improved ν_μ CC event selection

- Events are classified into charged current (CC) and neutral current (NC).

- k-nearest neighbor (kNN) algorithm based on:
  - Track length
  - Mean pulse-height per plane
  - Fluctuation in pulse-height
  - Tranverse track profile

- Data-MC agree very well.

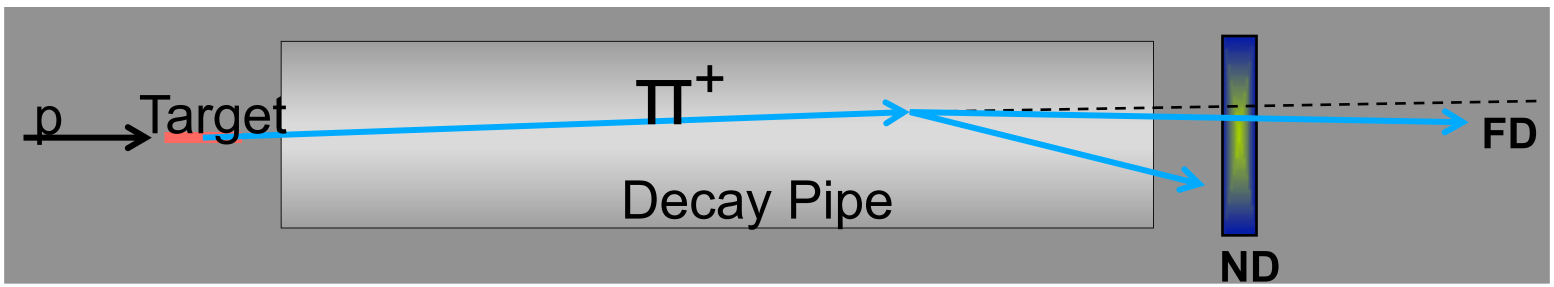




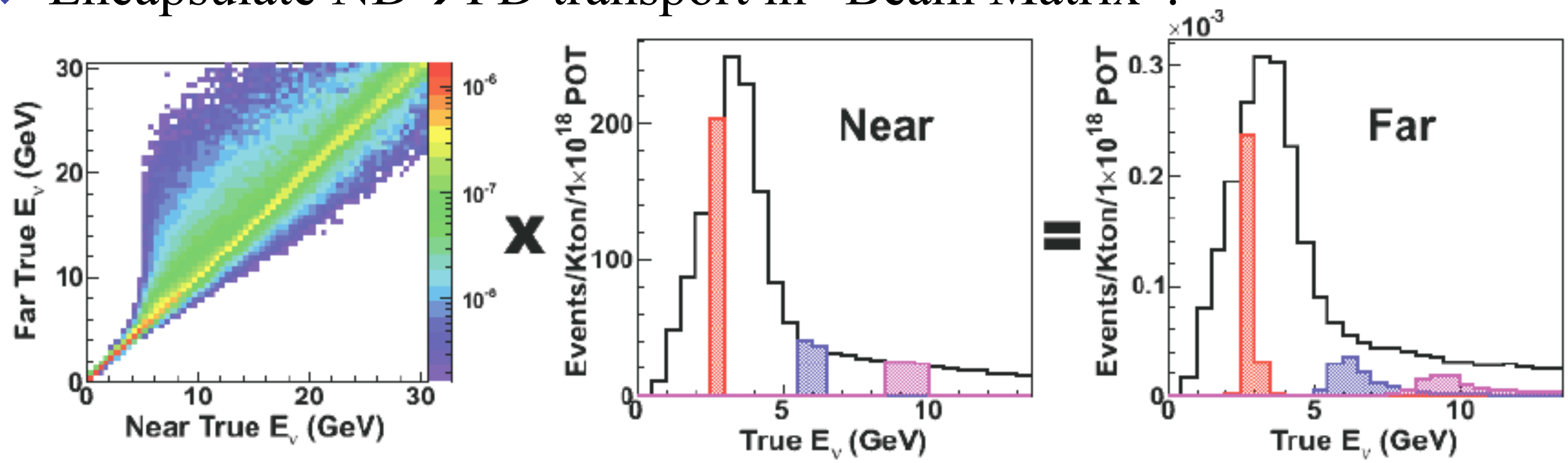
Predicting the FD spectrum

MINOS

- **Directly use ND data to perform extrapolation.**
- Use MC to provide necessary corrections for acceptance and energy smearing.
- Use knowledge of pion decay kinematics and geometry to predict FD spectrum from measured ND spectrum:

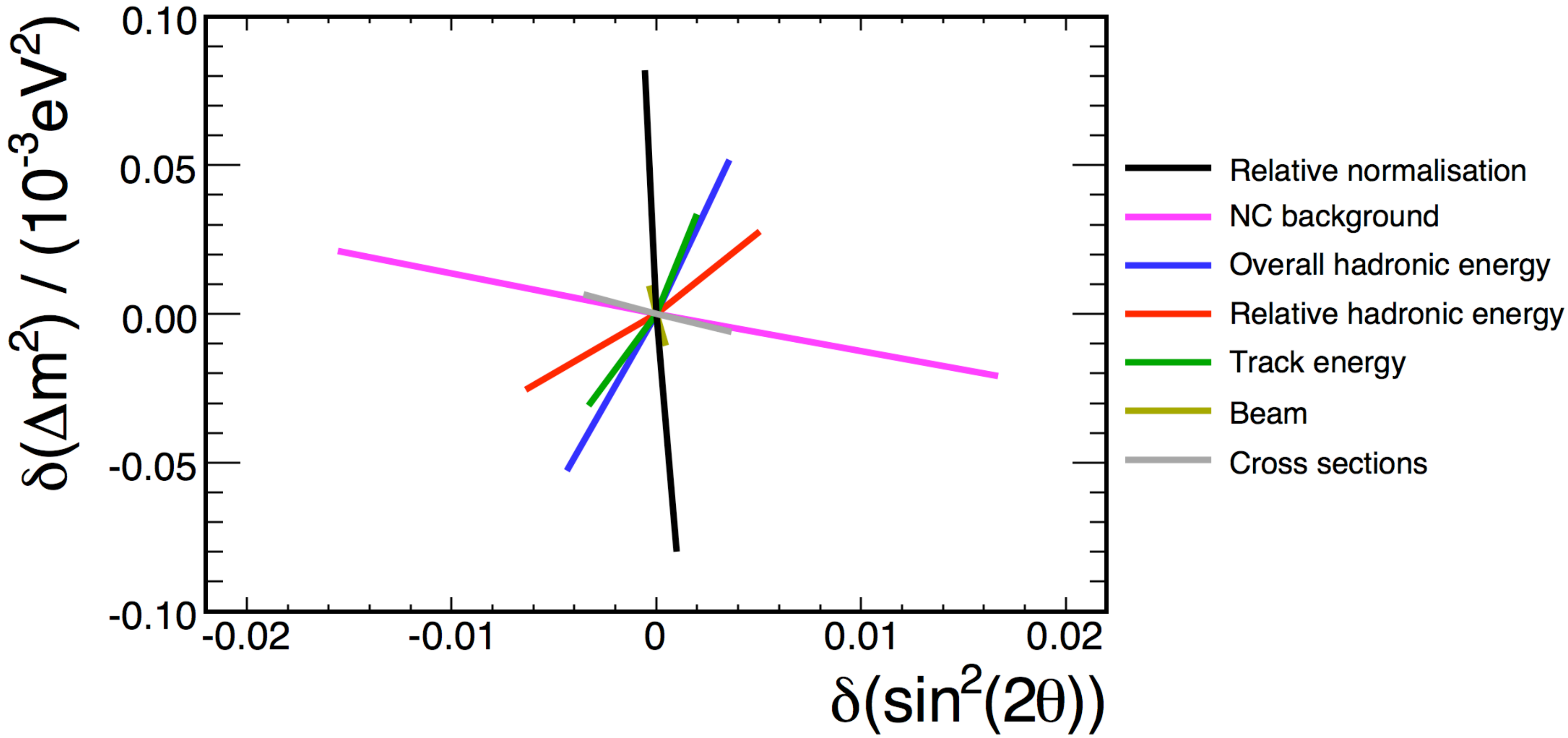


- Encapsulate ND→FD transport in “Beam Matrix”:



Systematics in CC ν_μ disappearance analysis

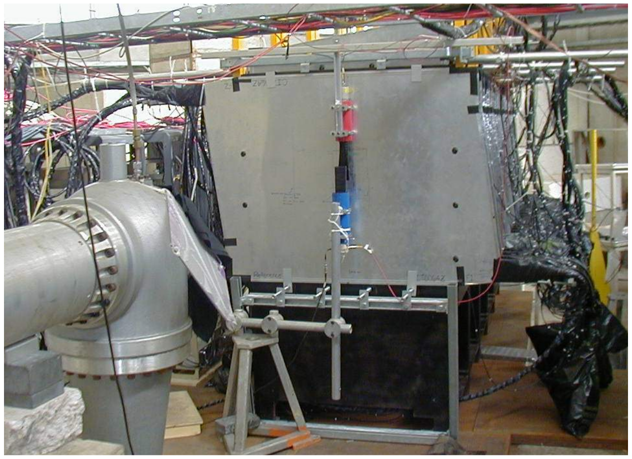
- The impact of different sources of systematic errors is evaluated by fitting modified MC samples in place of the data:



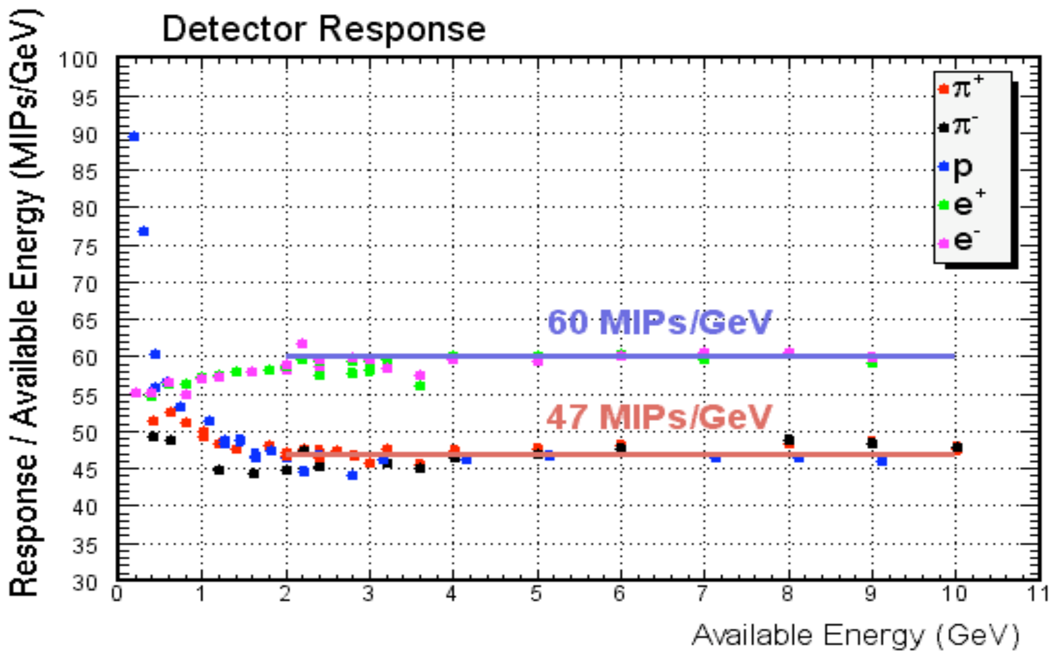
- The three largest parameters are included as nuisance parameters in the oscillation fit.

Calibration

- Overall energy scale set by Calibration Detector CALDET:
  - Mini-MINOS detector at CERN
  - Measured e/μ/π/p response



- In addition,
  - Light injection system (PMT gain)
  - Cosmic rays (strip to strip and inter-detector)



Energy resolution:
(E in GeV)

Hadrons:

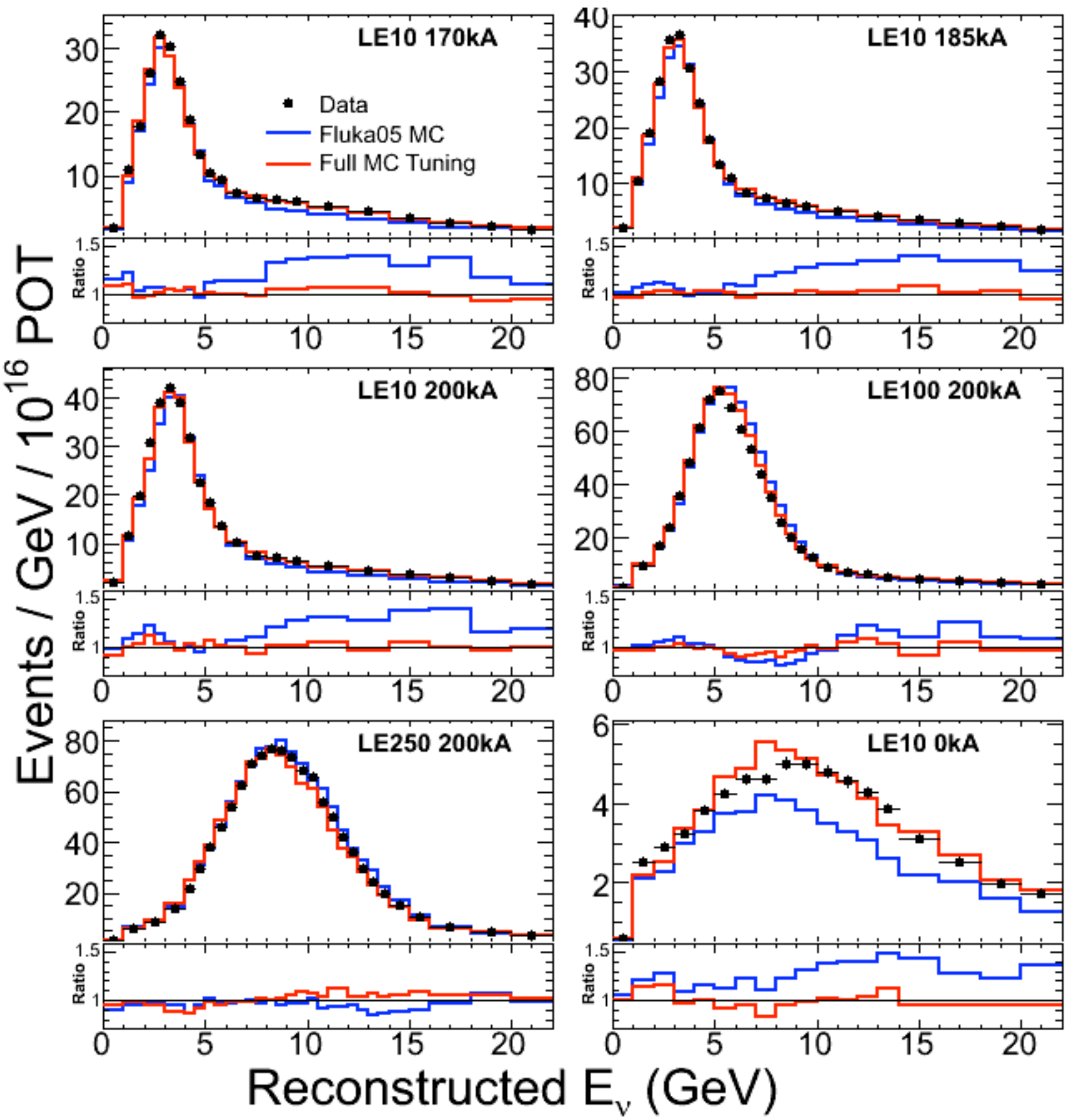
$56\% / \sqrt{E} \oplus 2\%$

Electrons:

$21\% / \sqrt{E} \oplus 4\% / E$

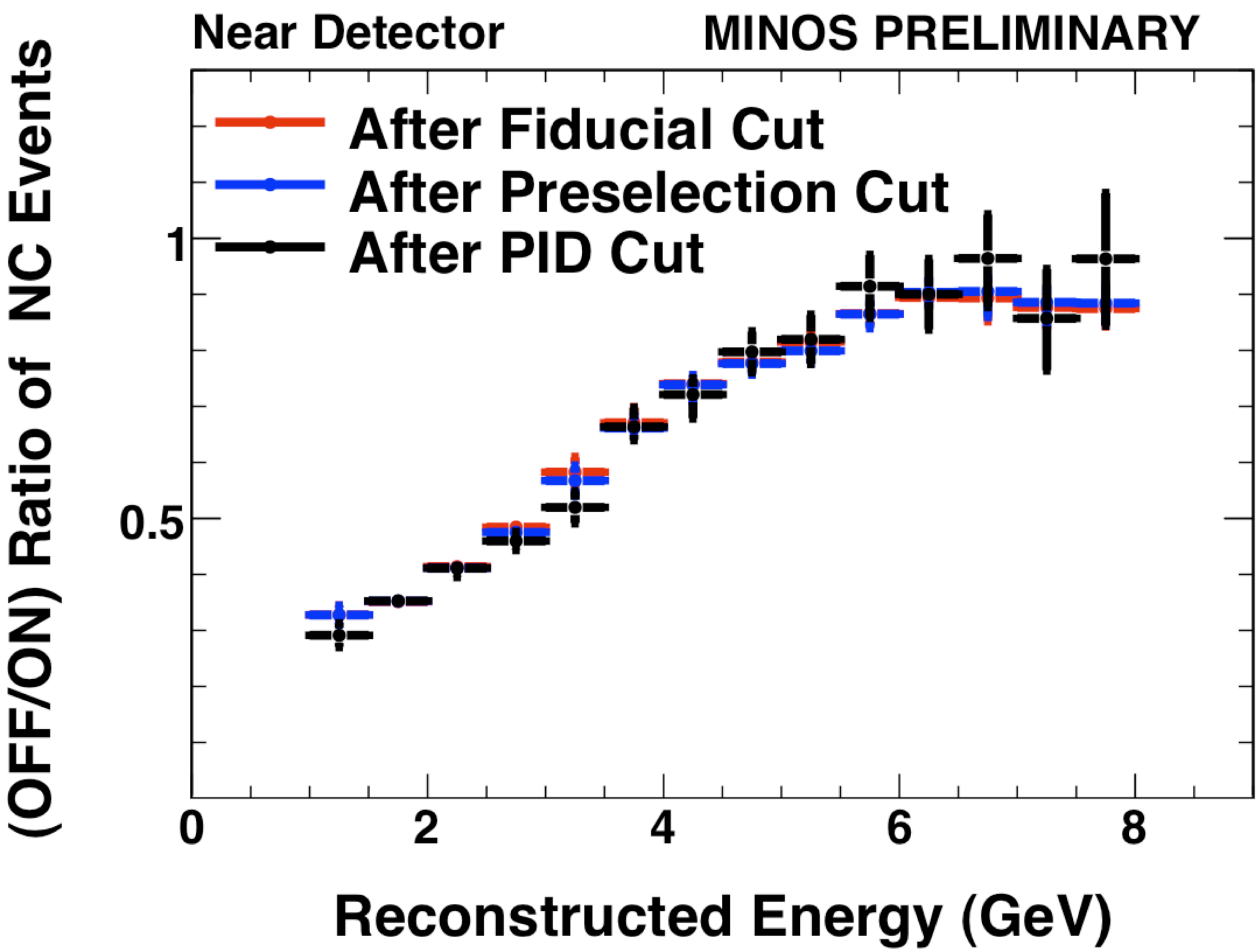
Hadron production tuning

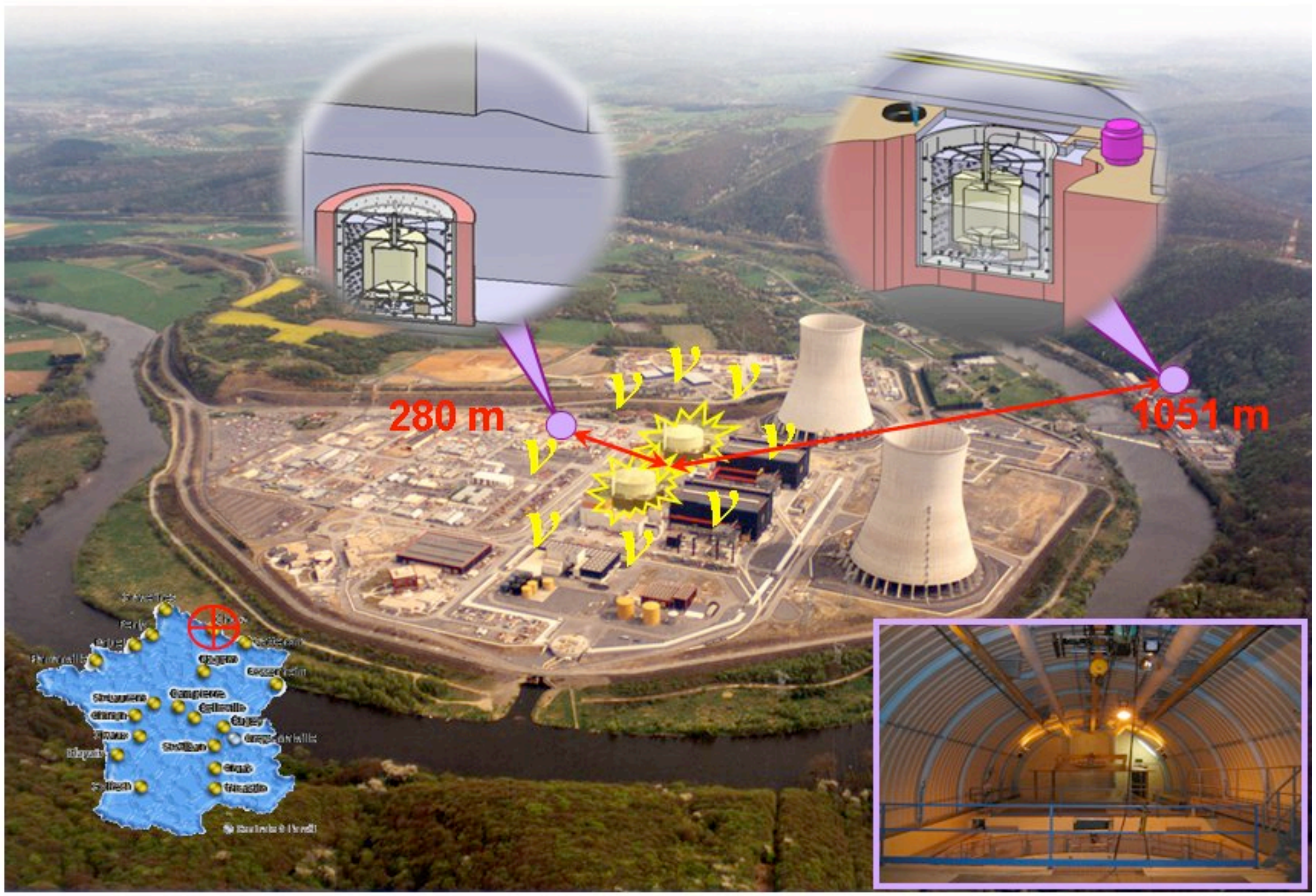
- Parameterize Fluka2005 prediction as a function of x_F and p_T
- Reweight pion x_F and p_T to improve data/MC agreement
- Nuisance parameters included in fits:
  - Horn focusing
  - Beam misalignments
- Also allow small changes in:
  - POT normalization
  - Neutrino energy scale
  - NC background



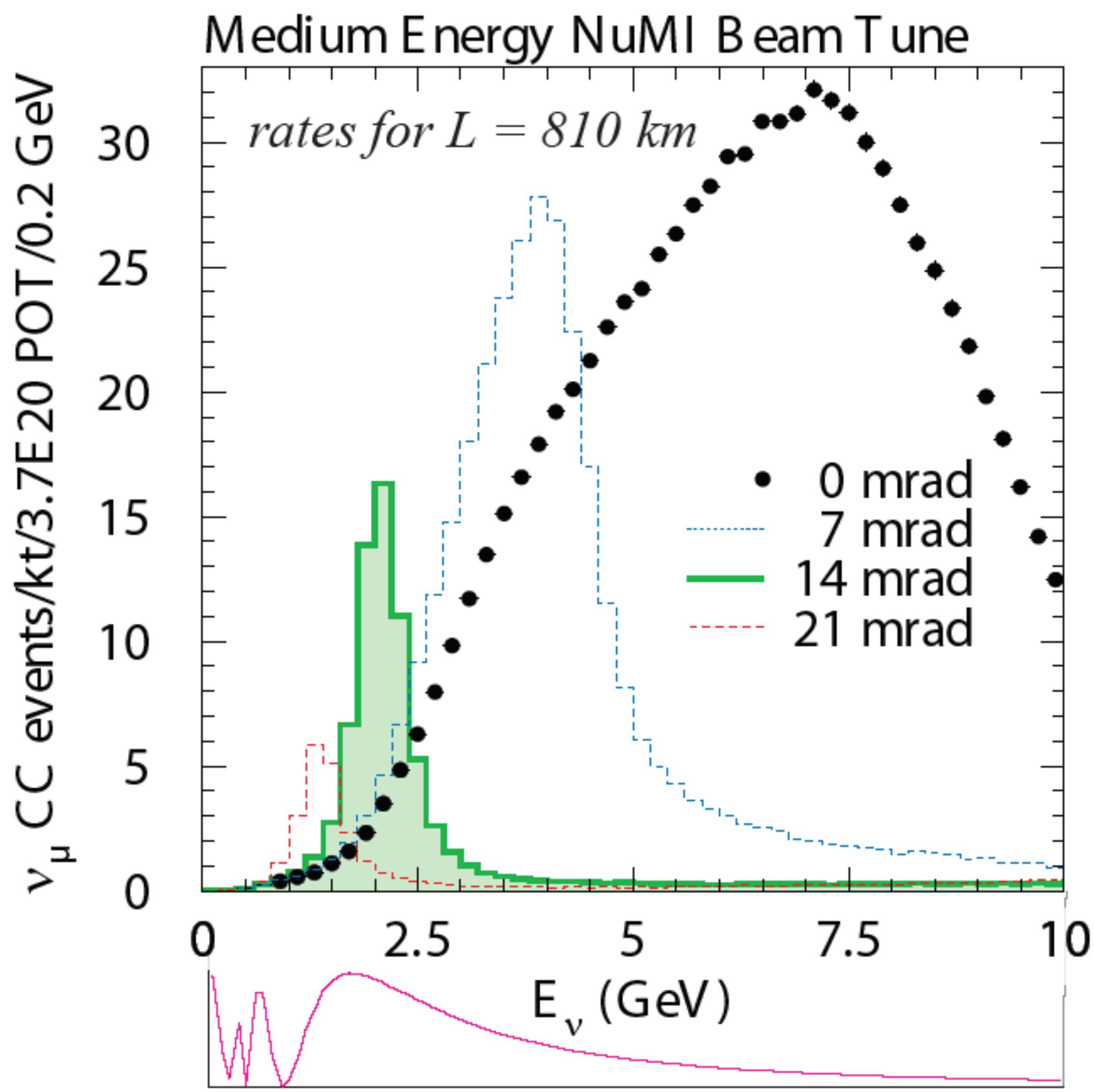
HOO ratios for NC events

MINOS




280 m
1051 m

MINOS


Medium Energy NuMI Beam Tune
rates for L = 810 km
0 mrad
7 mrad
14 mrad
21 mrad
ν_μ CC events/kt/3.7E20 POT/0.2 GeV
E_ν (GeV)
0
2.5
5
7.5
10
0
5
10
15
20
25
30