Recent results from the MINOS experiment

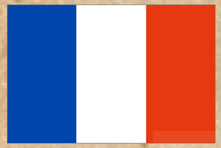
Mayly Sanchez
Harvard University

APS Meeting - April 2007

Outline of this talk

- The MINOS experiment
  - Physics goals
  - The hardware: the beam and the detectors
- The ν_μ disappearance analysis
  - Results from the first year of running now published in PRL
- Progress in other MINOS Physics
  - Time-of-flight analysis
  - Neutral Current analysis
  - ν_e appearance analysis

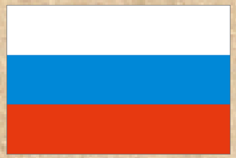
The MINOS Collaboration


32 institutions

175 physicists



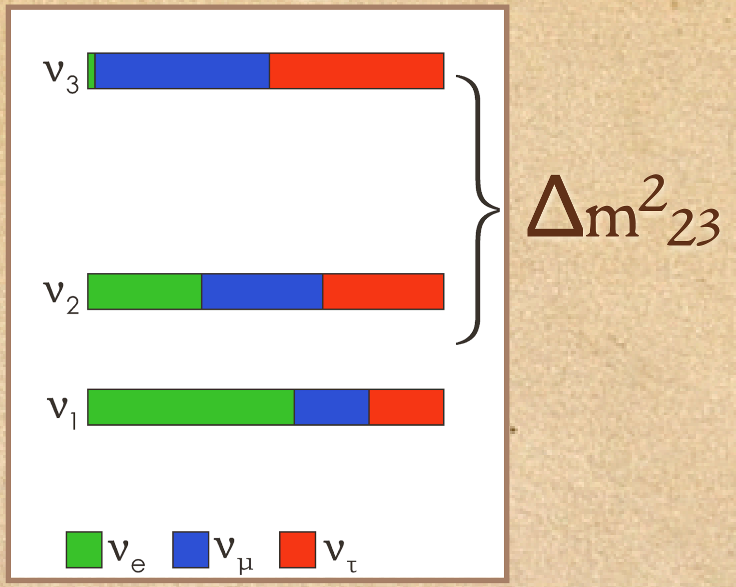


Brazil ❧ France ❧ Greece
Russia ❧ UK ❧ USA

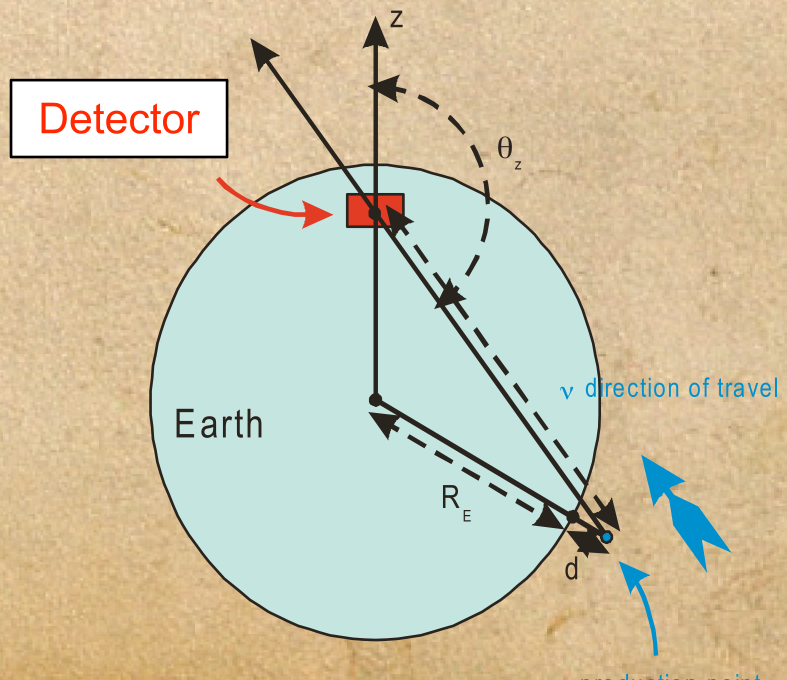
Argonne ❧ Athens ❧ Benedictine ❧ Brookhaven ❧ Caltech ❧ Cambridge ❧ Campinas ❧ Fermilab
College de France ❧ Harvard ❧ IIT ❧ Indiana ❧ ITEP-Moscow ❧ Lebedev ❧ Livermore
Minnesota-Twin Cities ❧ Minnesota-Duluth ❧ Oxford ❧ Pittsburgh ❧ Protvino ❧ Rutherford
Sao Paulo ❧ South Carolina ❧ Stanford ❧ Sussex ❧ Texas A&M
Texas-Austin ❧ Tufts ❧ UCL ❧ Western Washington ❧ William & Mary ❧ Wisconsin

MINOS physics goals

- Test for the $\nu_\mu \rightarrow \nu_\tau$ oscillation hypothesis
  - Measure precisely $|\Delta m^2_{23}|$ and $\sin^2 2\theta_{23}$
- Search for and constrain exotic phenomena
  - Sterile ν, ν decay, etc.
- Search for sub-dominant $\nu_\mu \rightarrow \nu_e$ oscillations (ie measure U_{e3})
- Atmospheric neutrino oscillations
  - Compare ν and $\bar{\nu}$ oscillations
    Phys. Rev. D73, 072002 (2006)



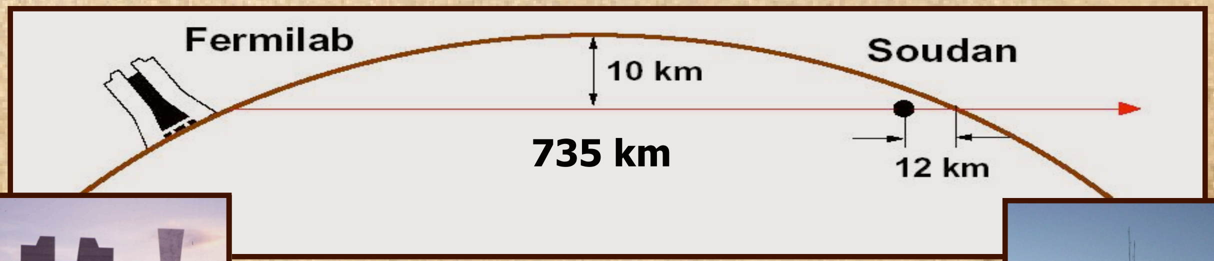
$$U = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix}$$

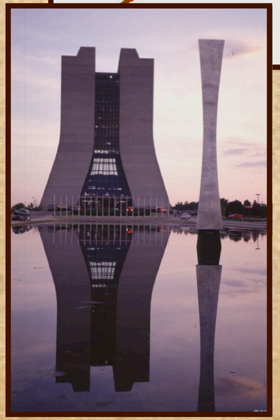


MINOS basic idea

Main Injector Neutrino Oscillation Search

- Produce a high intensity beam of neutrinos at Fermilab.
- Measure the energy spectrum at a Near location (Fermilab).
- Measure the energy spectrum at a Far location, 735 km away (Soudan).
- If neutrinos oscillate, you will see evidence of the oscillation at the Far location.

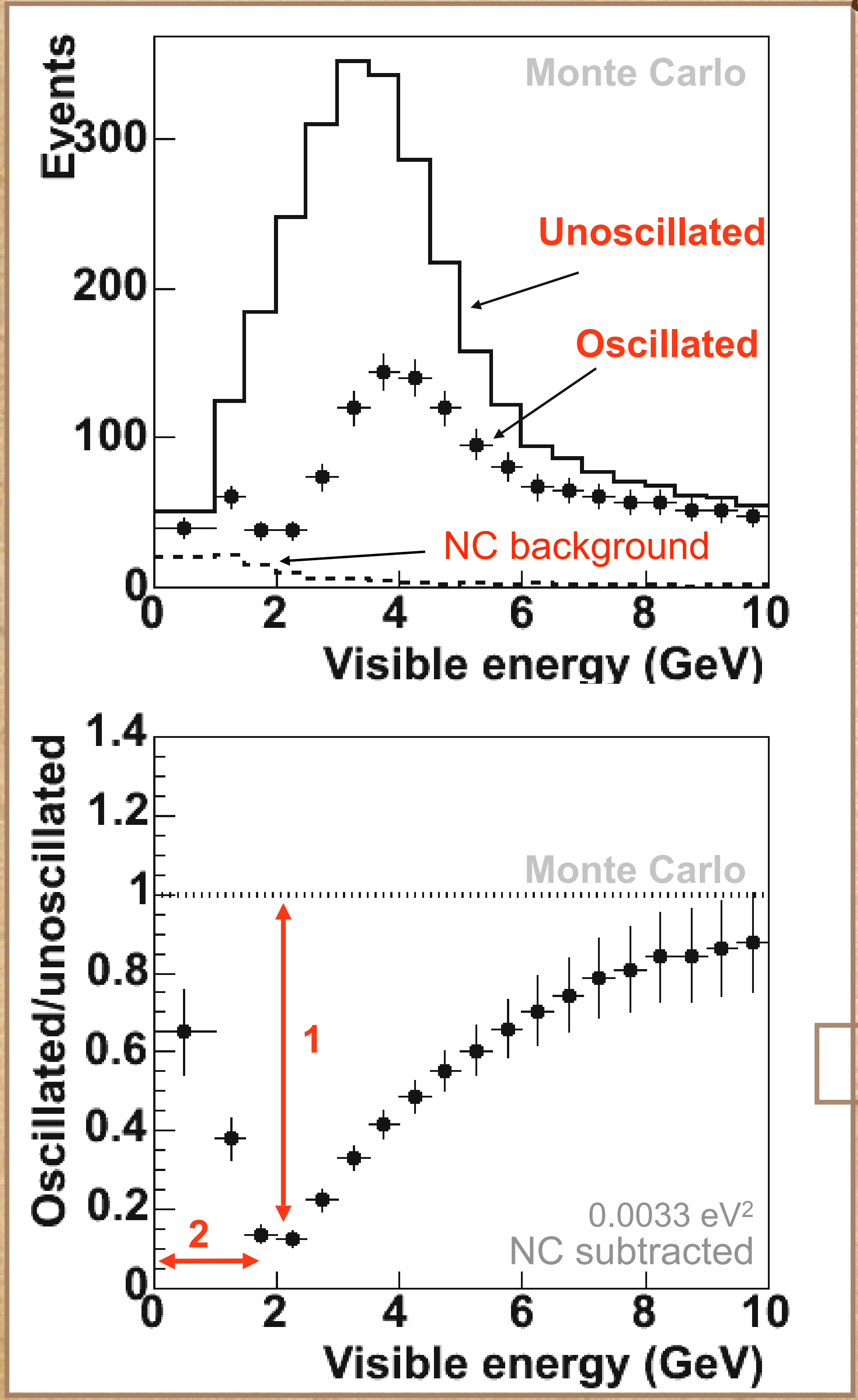




←long baseline→

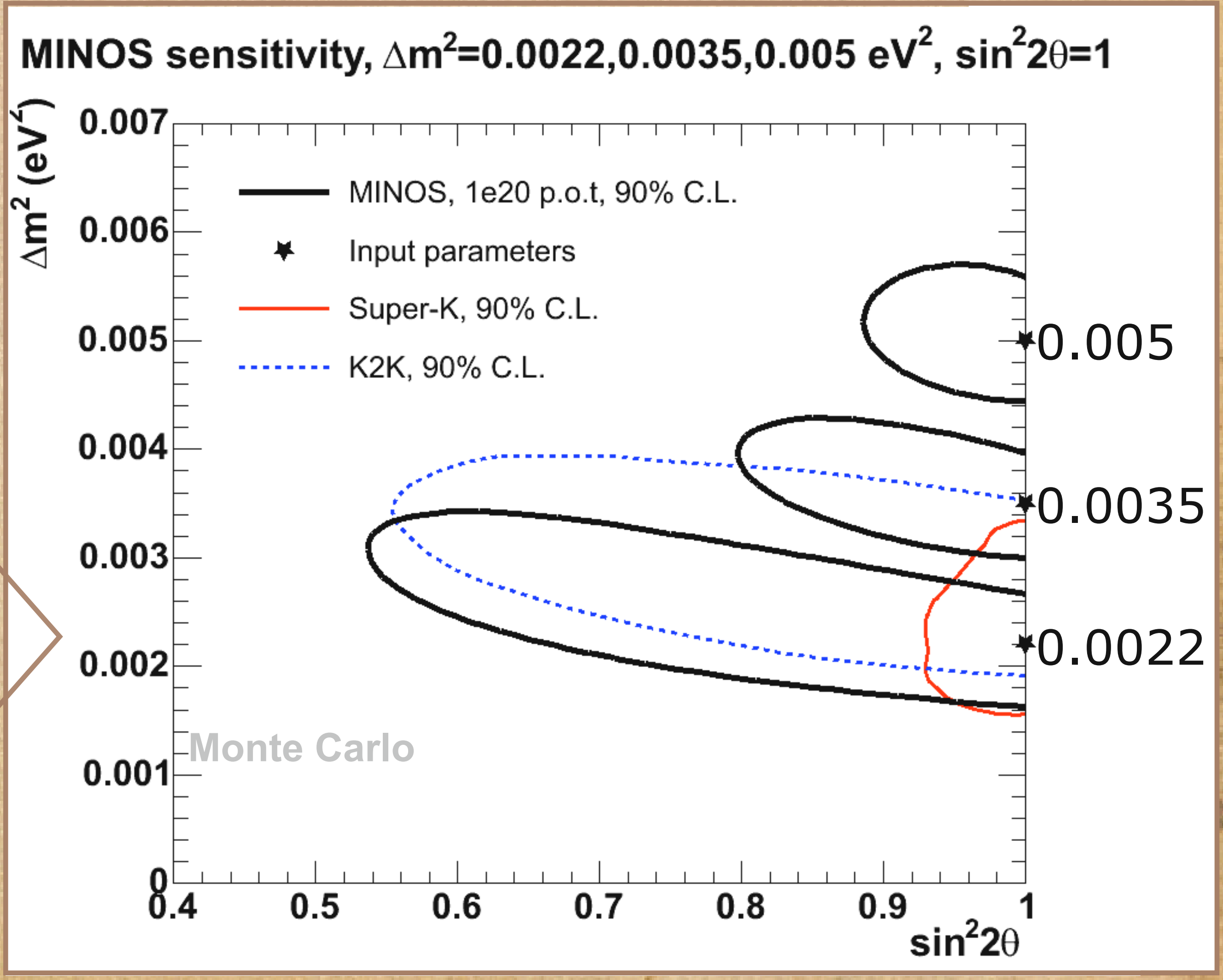
MINOS physics goals

Seeing ν_μ disappearance



$$P(\nu_\mu \rightarrow \nu_\tau) = \sin^2(2\theta)\sin^2\left(\frac{1.27\Delta m_{23}^2 L}{E_\nu}\right)$$

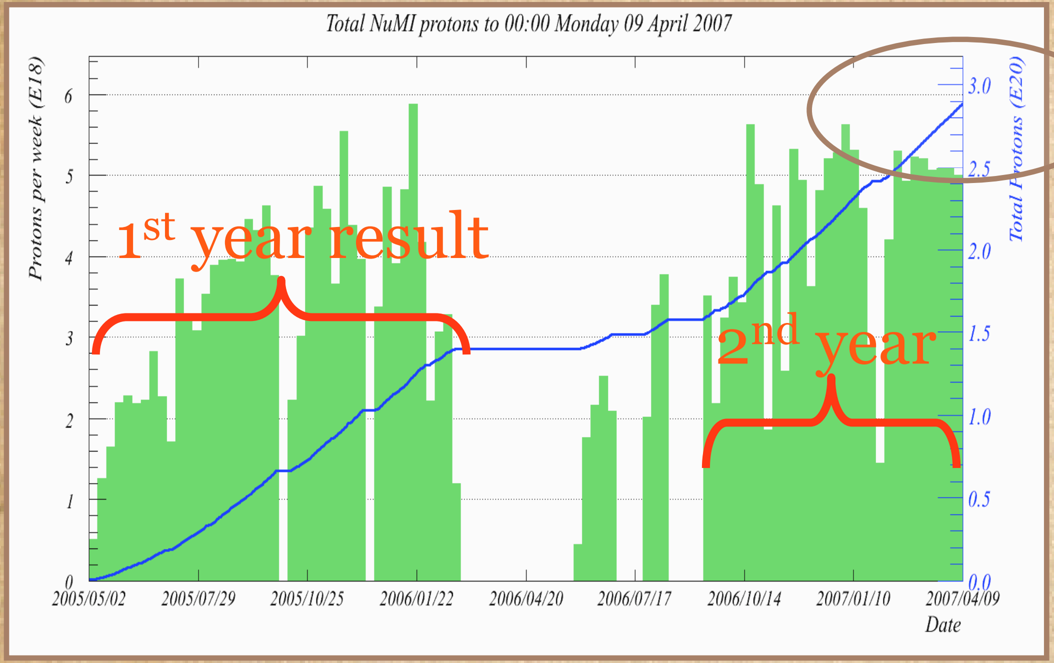
1 2

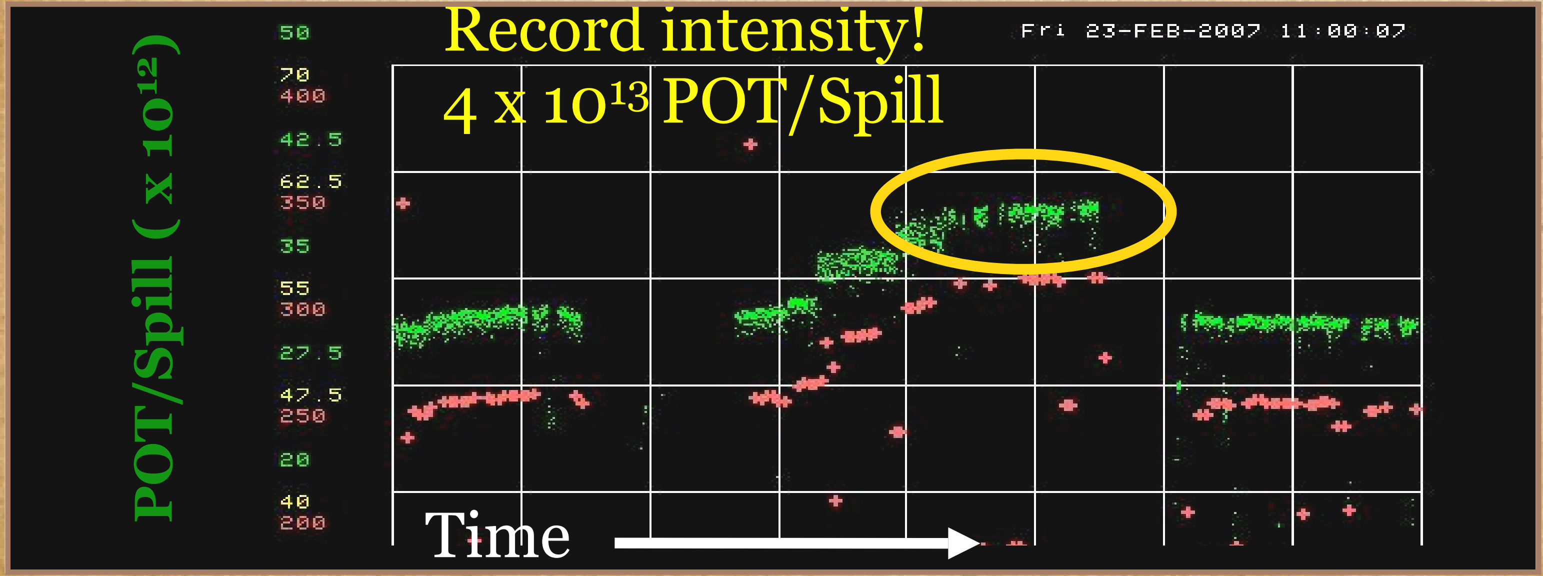


The NuMI facility

Where do we produce the neutrinos?

April 2, 2007: ~2.6×10^{20} POT
Doubled the data of 1st year result!



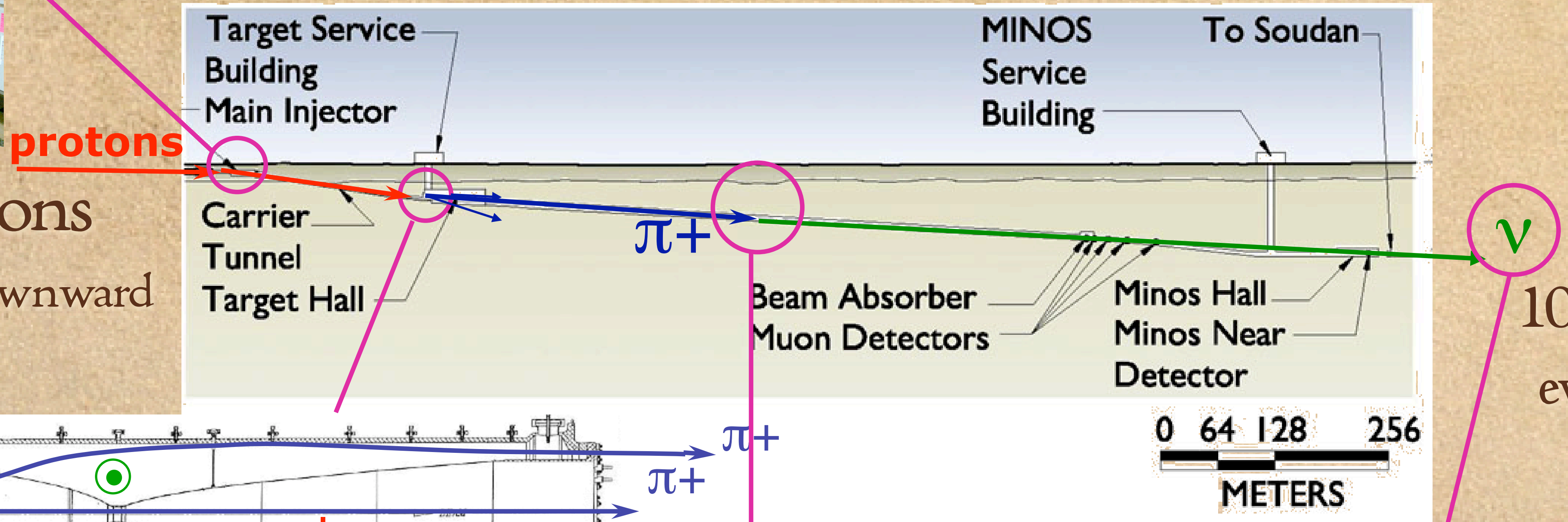


- 120 GeV protons from the Main Injector.
- Main Injector can accept up to 6 Booster batches/cycle.
  - Either 5 or 6 batches for NuMI.
- ~1.9 second cycle time.
- Intensity: 4×10^{13} POT/spill
- Single turn extraction: ~10μs spill.
- Beam power: 0.4 MW.

- Averages (first year):
  - Cycle spacing 2.2s.
  - Intensity 2.3×10^{13} POT/spill.
  - Power 170kW.

The NuMI beamline

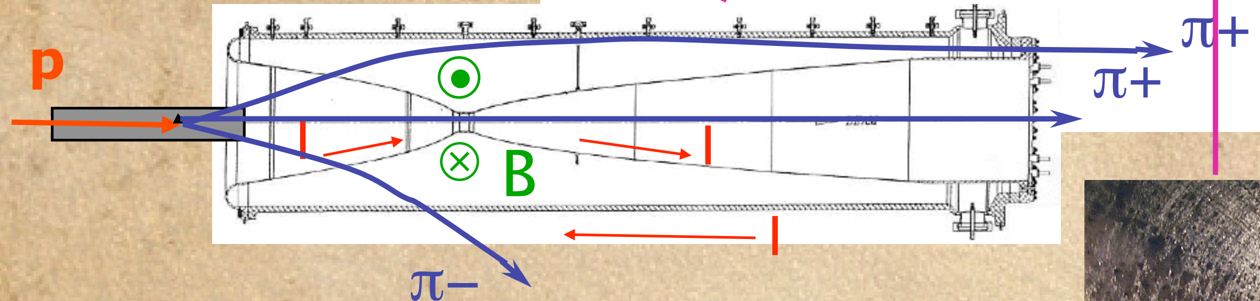
How do we produce the neutrinos?



Extract protons

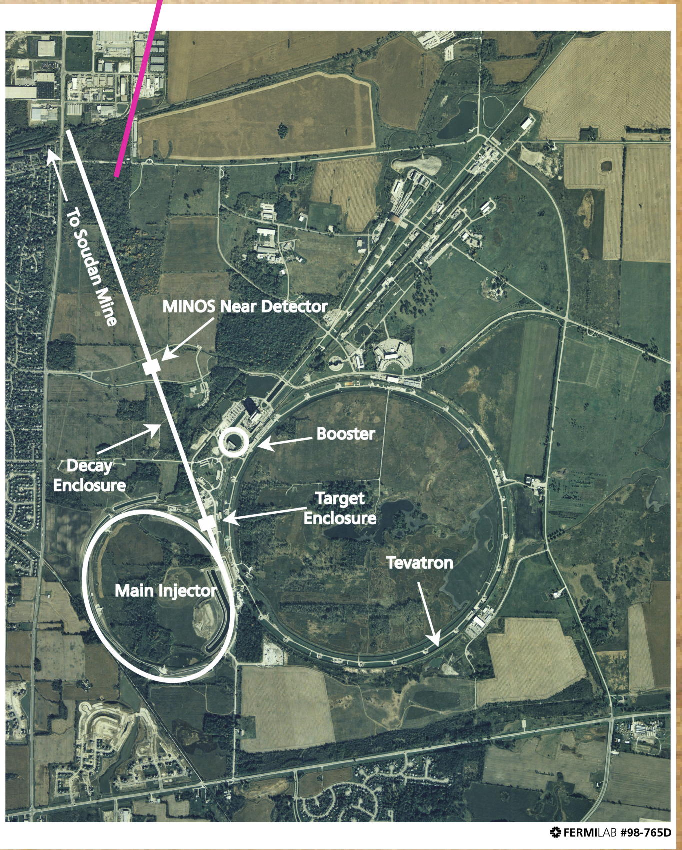
Point them 3.3° downward

10 μs spill every 1.9s



- 120GeV protons hit graphite target, producing pions.
- Horn pulsed at 200kA, toroidal field focuses pions.
- 675m long decay pipe, evacuated to 1.5 Torr.

Pion decay produces muons and neutrinos.



The NuMI beamline

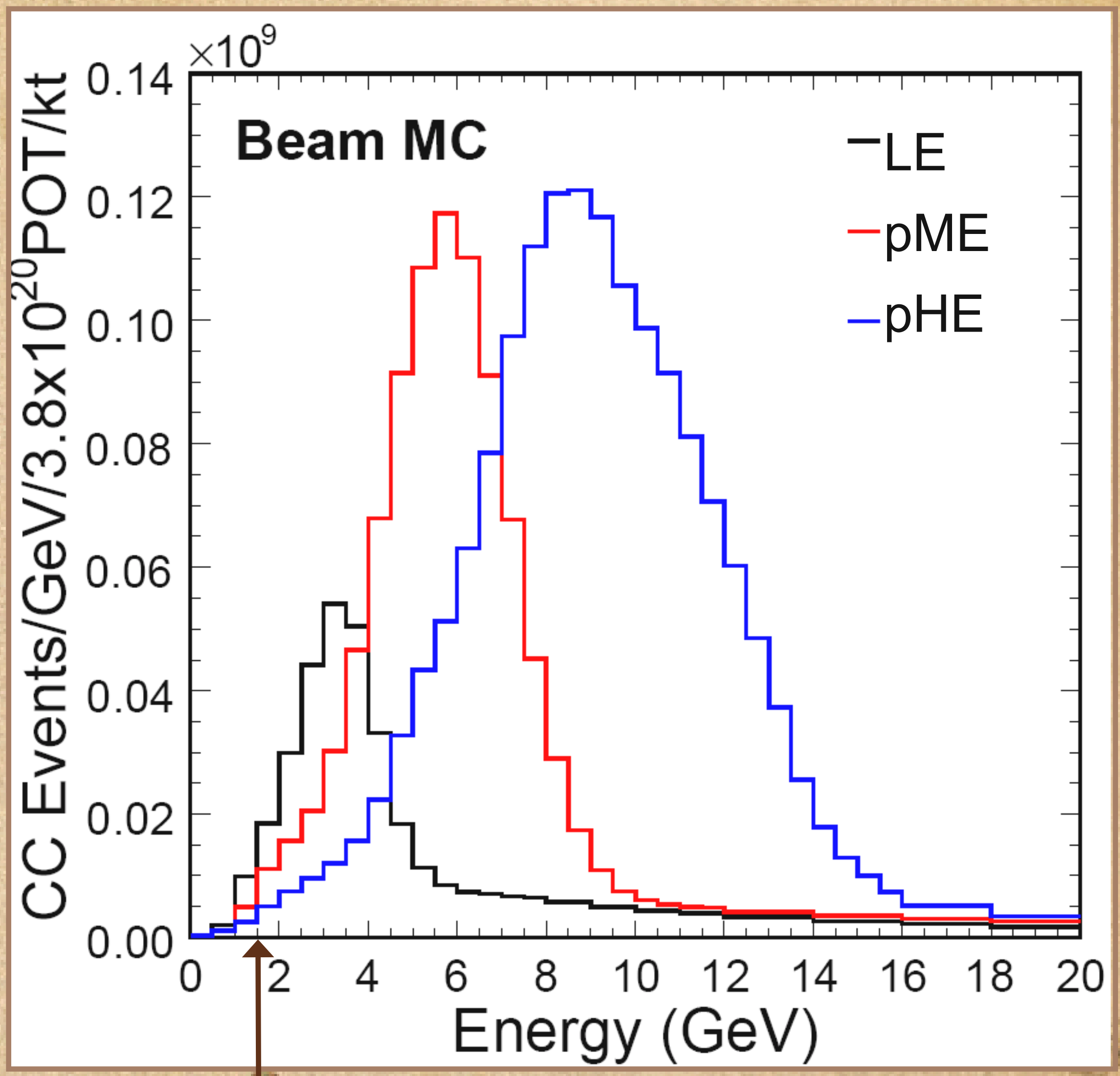
What neutrino energies can we produce?

- Relative positions of the target to the horns allow the energy of the beam to be tuned.

Beam	Target z position (cm)	FD Events per 10^{20} POT
LE-10	-10	390
pME	-100	970
pHE	-250	1340

Events in Fiducial Volume

- We took ~1.5 x 10^{18} POT in pME and pHE configurations.
- Beam composition: 92.9% ν_μ, 5.8% $\bar{\nu}_\mu$, 1.3% $\nu_e+\bar{\nu}_e$

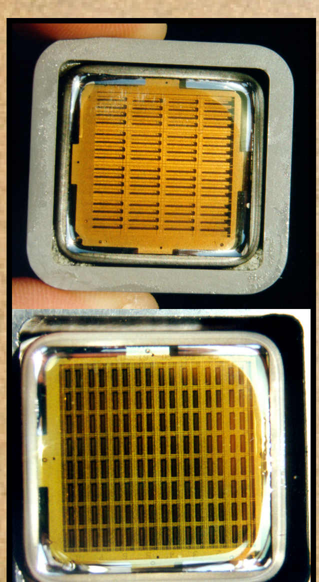


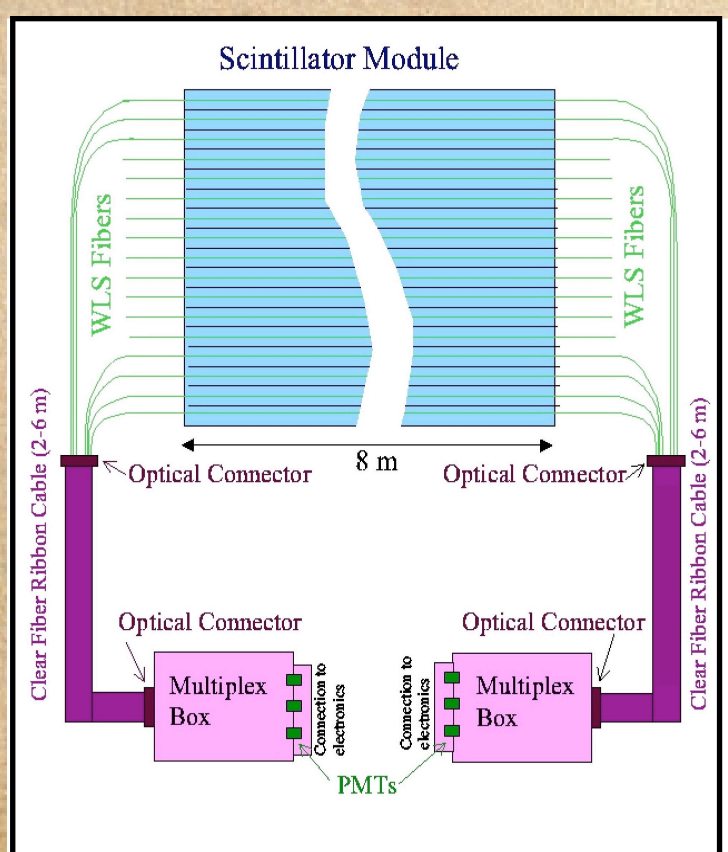
Position of osc. minimum for Δm^2=0.0025 eV^2

We have started running with the low energy beam, which is best for Δm^2~0.0025 eV^2.

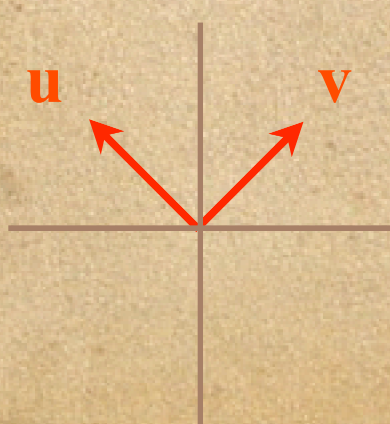
Detector technology

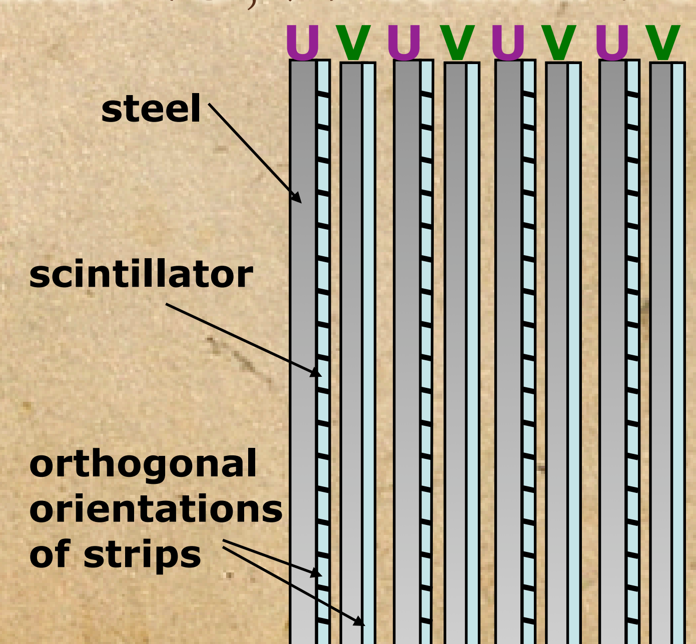
Iron/scintillator tracking calorimeter





- 2.54cm steel planes, 1.2T field.
- 4.1 x 1cm scintillator strips, up to 8m long. Extruded polystyrene (TiO_2 coating).
- Readout via wavelength shifting fibers (1.2mm).
- Hamamatsu multi-anode PMTs, (M16 Far and M64 Near).
- GPS timestamps to match data.
- Alternate planes (U,V) rotated 90°, for 3D hits.

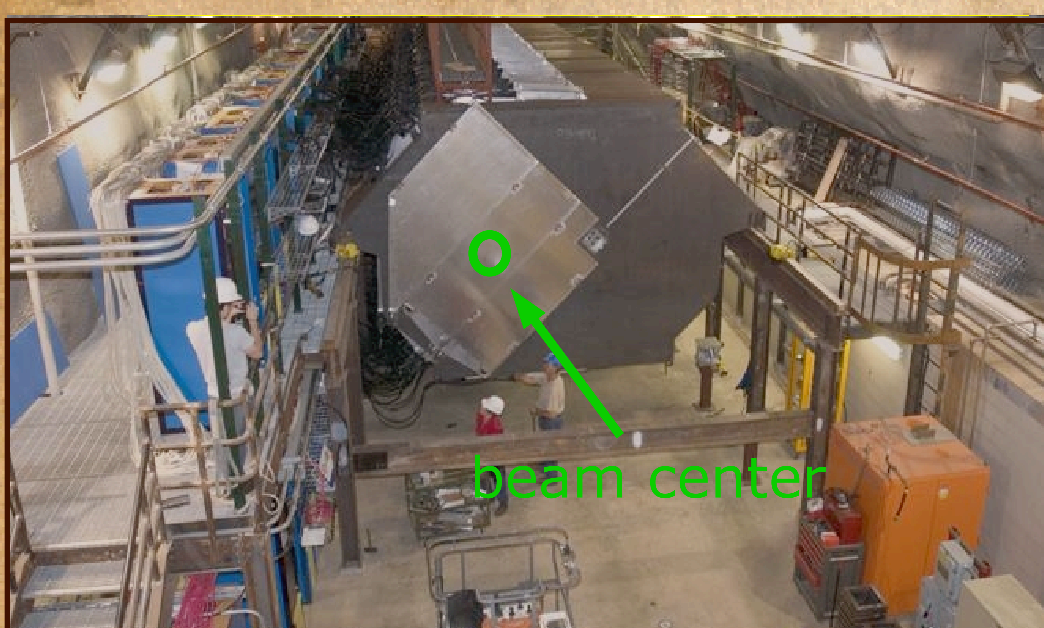




MINOS Near

What is the neutrinos' first stop?
Fermilab, IL

- ~1 kton (980 tons) total mass
- Squashed octagons (4.8 x 3.8m), since beam cross section small
- Partially instrumented (282 planes of steel, 153 planes of scintillator)
- Fast QIE electronics, continuous digitization during spill, 19ns time slices.
- Strips readout from one side only.
- Spectrometer multiplexed (x4).

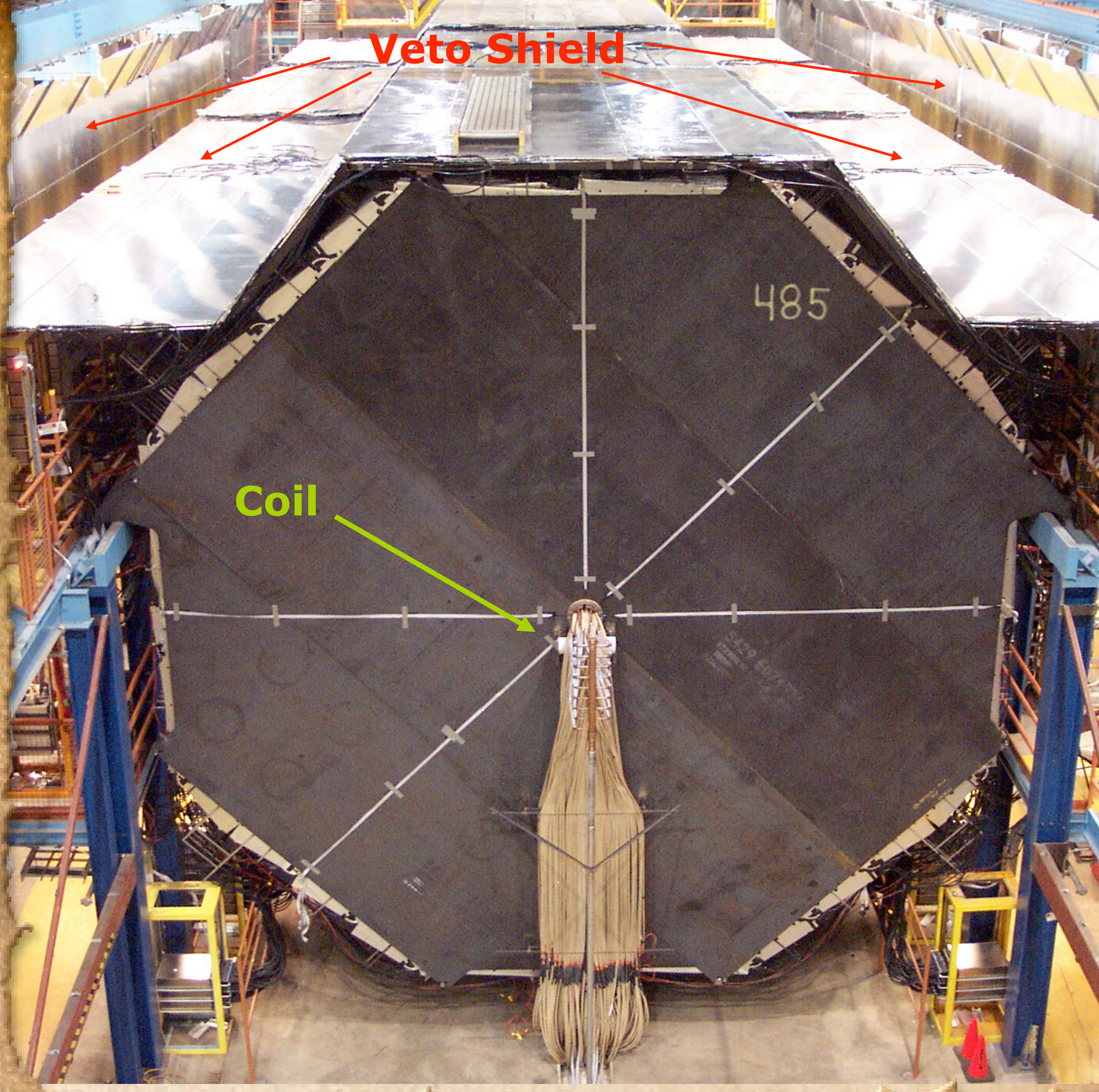


100m deep

MINOS Far

Where do the neutrinos travel to?
Soudan, MN

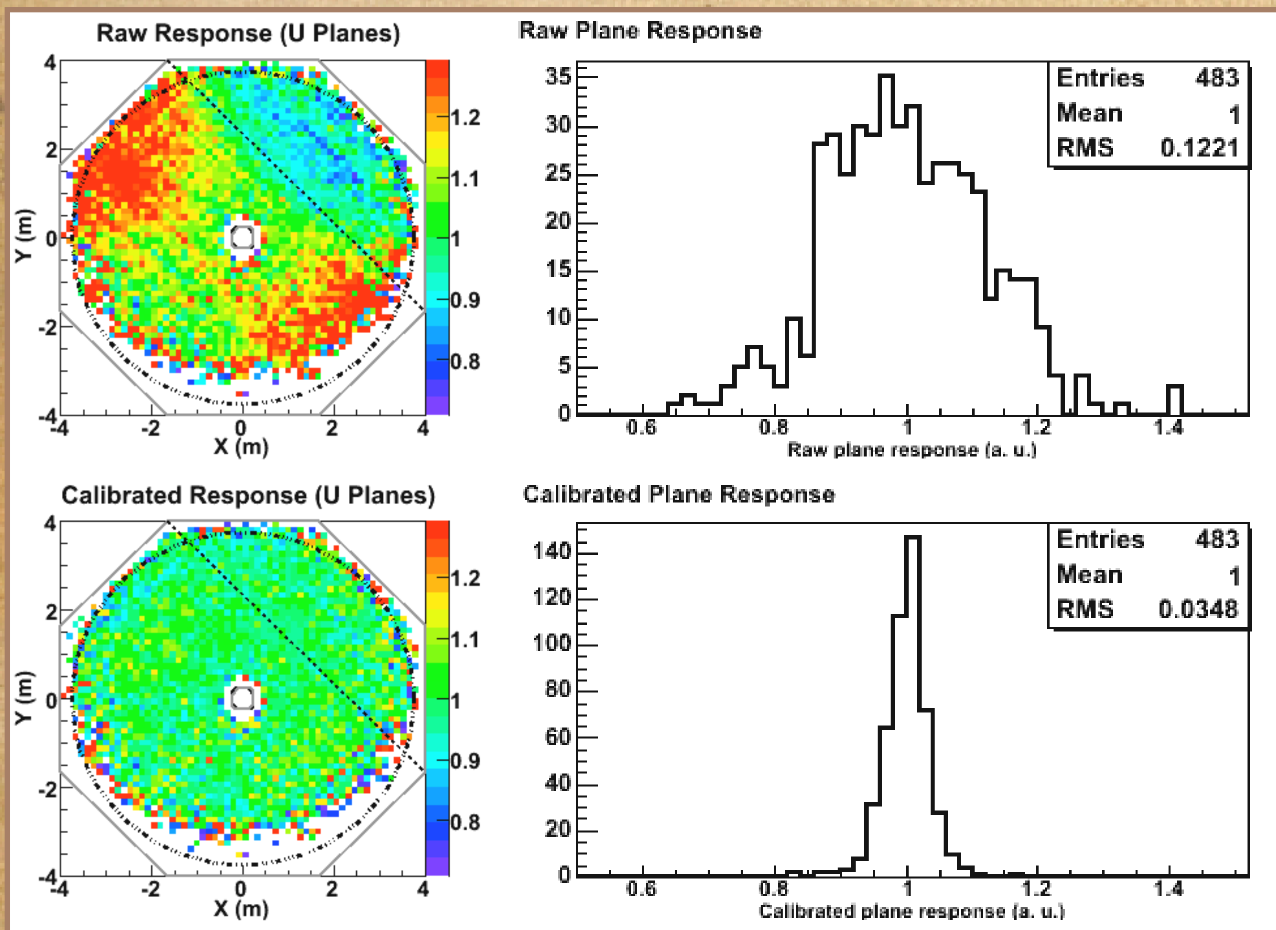
- 2 supermodules (~15m each).
- 486 steel planes (8m octagons, 2.54cm thick) alternated with 484 scintillator planes.
- 5.4 kton total mass.
- VA electronics.
- Both sides strip readout.
- Multiplexing 8 fibers to 1 channel.
- Continuous untriggered readout of the whole detector.
- Data taking since December 2001. Installation fully completed in July 2003.

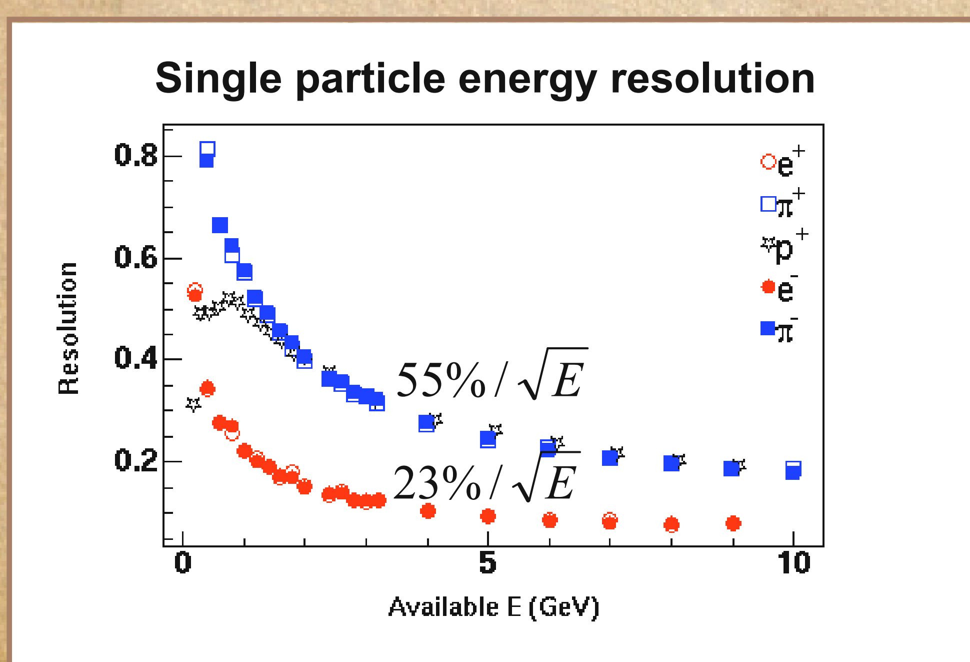


Iron tracking calorimeter

710m deep

MINOS calibration system





- Calibration of ND and FD response using:
  - Light Injection system (PMT gain)
  - Cosmic ray muons (strip to strip and inter-detector)
  - Calibration detector (overall energy scale)
    - mini-Minos on a CERN test beam
- Energy scale calibration:
  - 5.6% absolute error
  - ND-FD rel: 2.0%

The ν_μ disappearance analysis

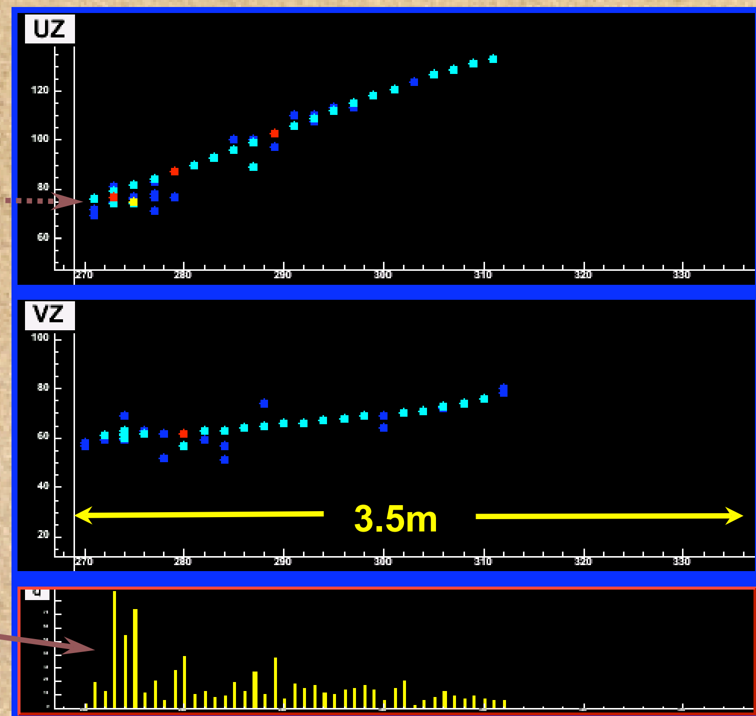
Neutrino Event topologies

What do neutrinos look like?

ν_μ CC event

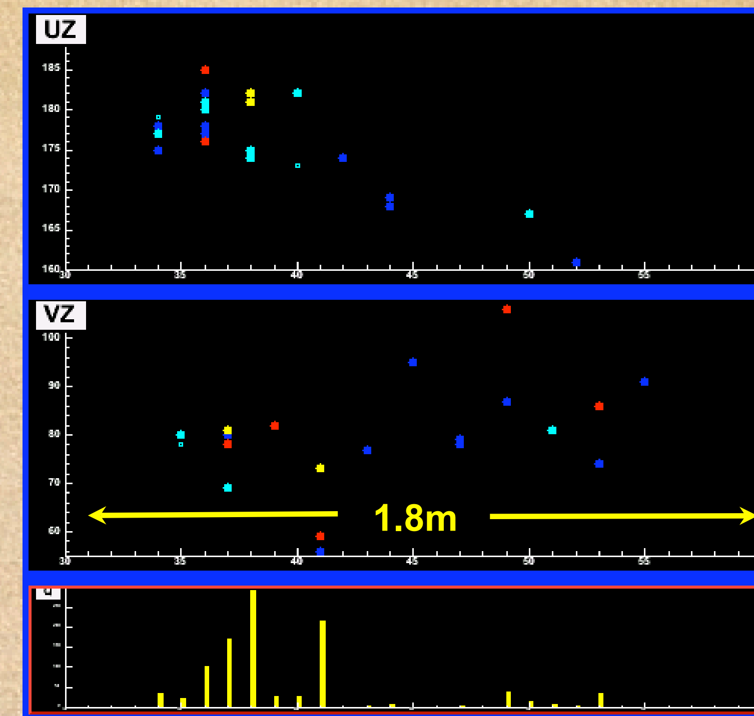
ν

- μ track
- +hadronic activity



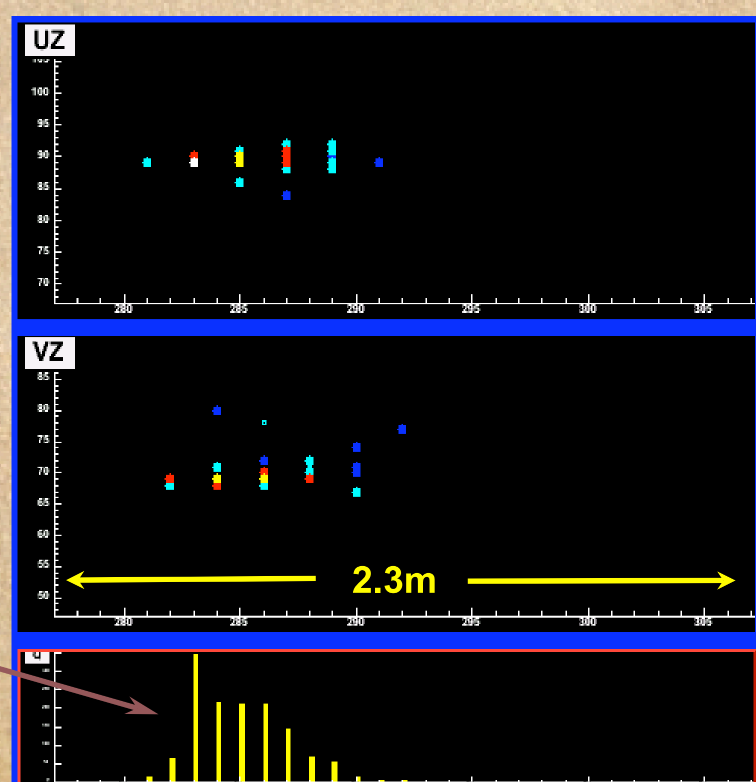
NC event

- often diffuse



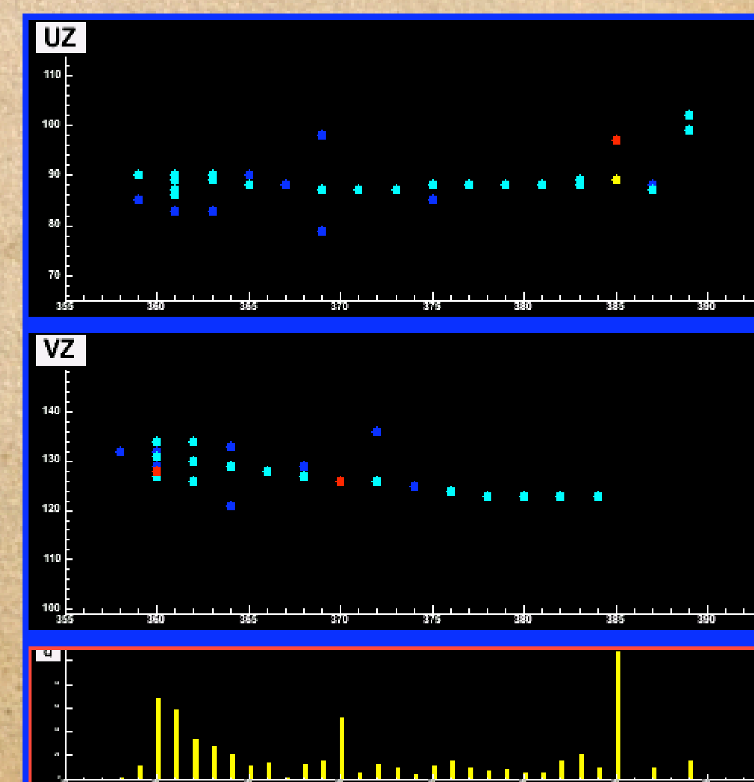
ν_e CC event

- compact shower
- typical EM shower profile



NC event

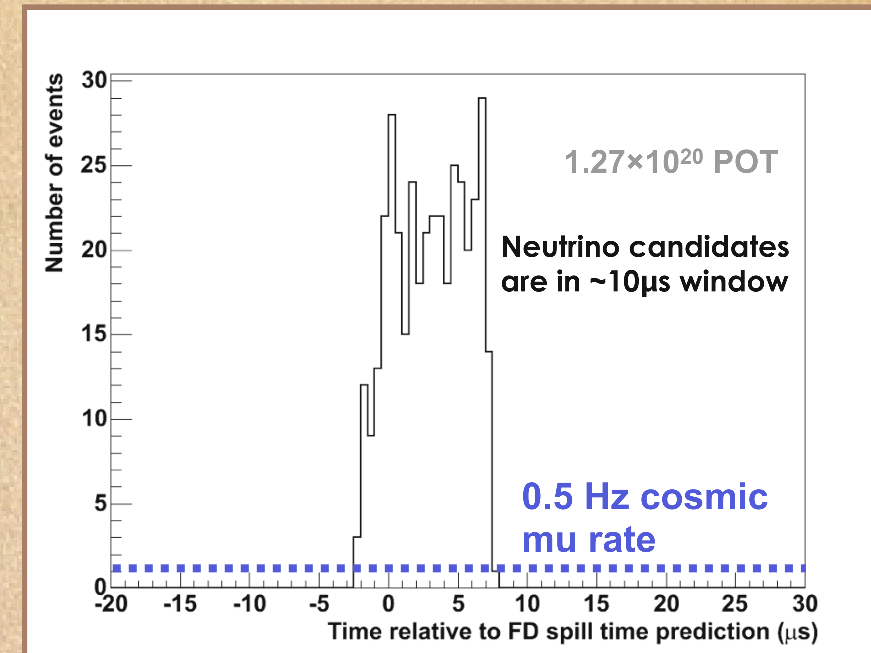
- can mimic ν_μ , ν_e

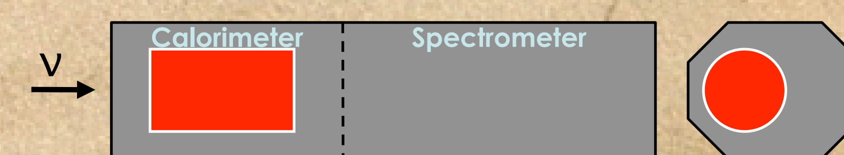


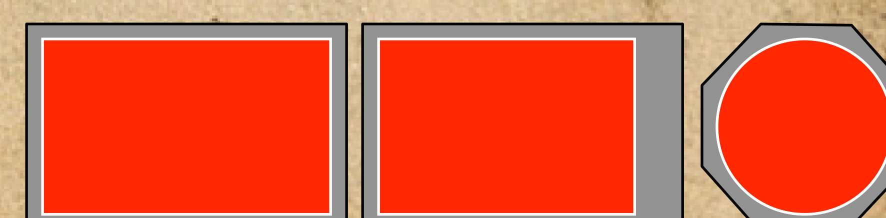
The event selection cuts

- Events in time with the beam.
- At least one good reconstructed track.
- The fitted track should have negative charge.
- The reconstructed track vertex should be within the fiducial volume of the detector:
  - Near:
    1m < z < 5m from detector front
    r < 1m from beam center
  - Far:
    z > 50 cm from edge, z > 2m from end, r < 3.7 from detector center

Time difference of neutrino interactions from beam spill

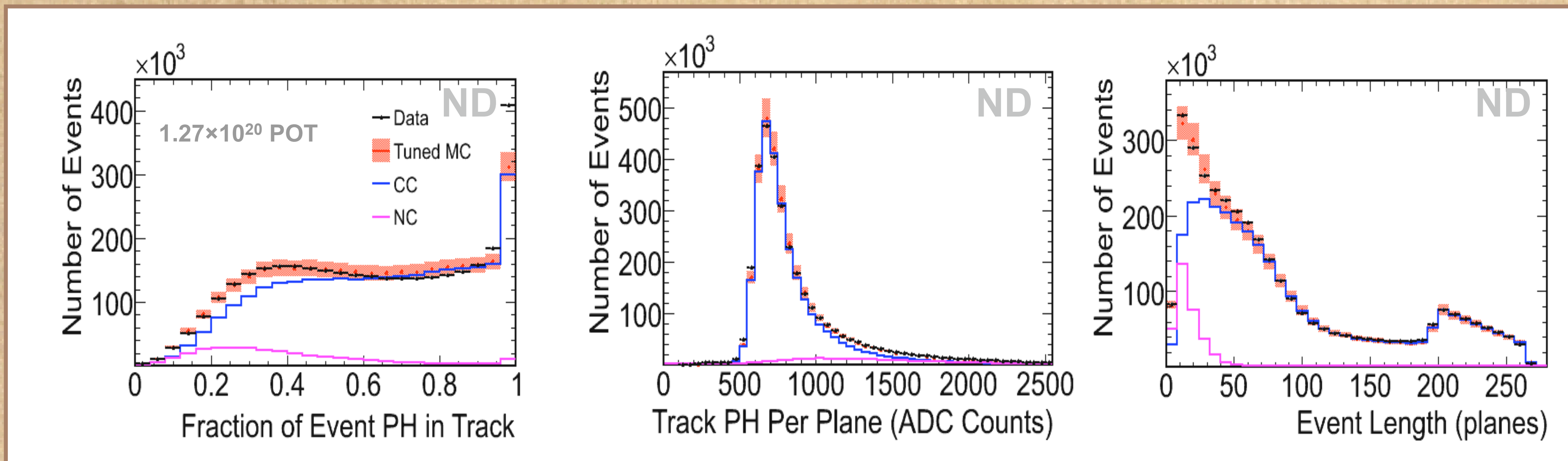




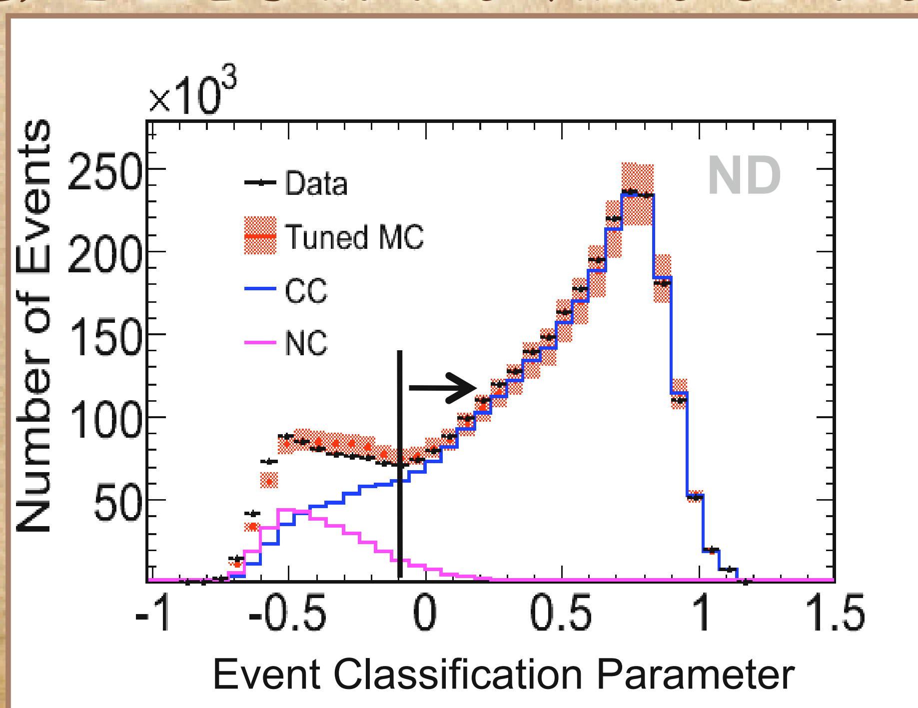


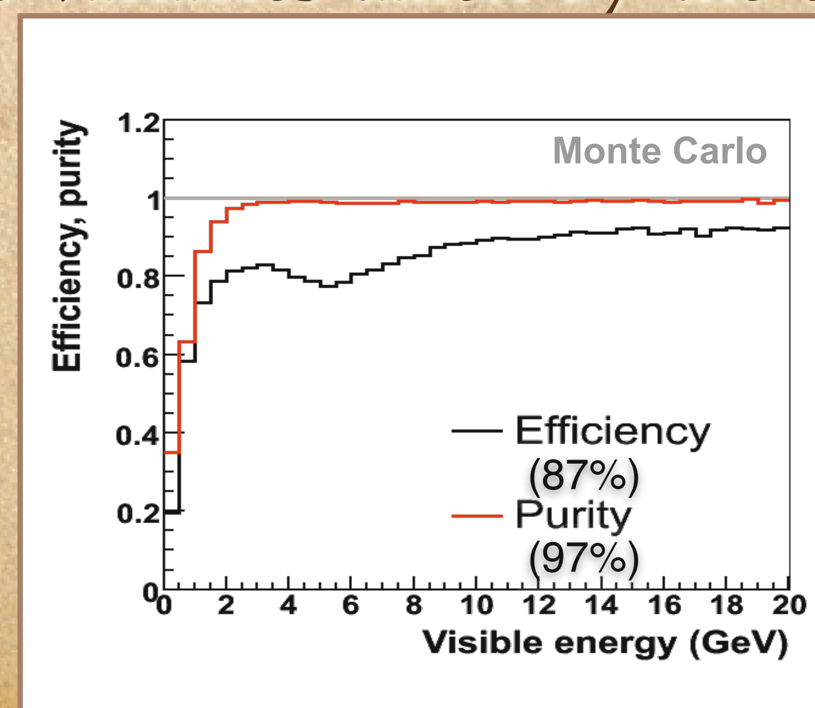
The event selection cuts

- Events selected by likelihood-based procedure, with 3 input probability functions (PDFs):



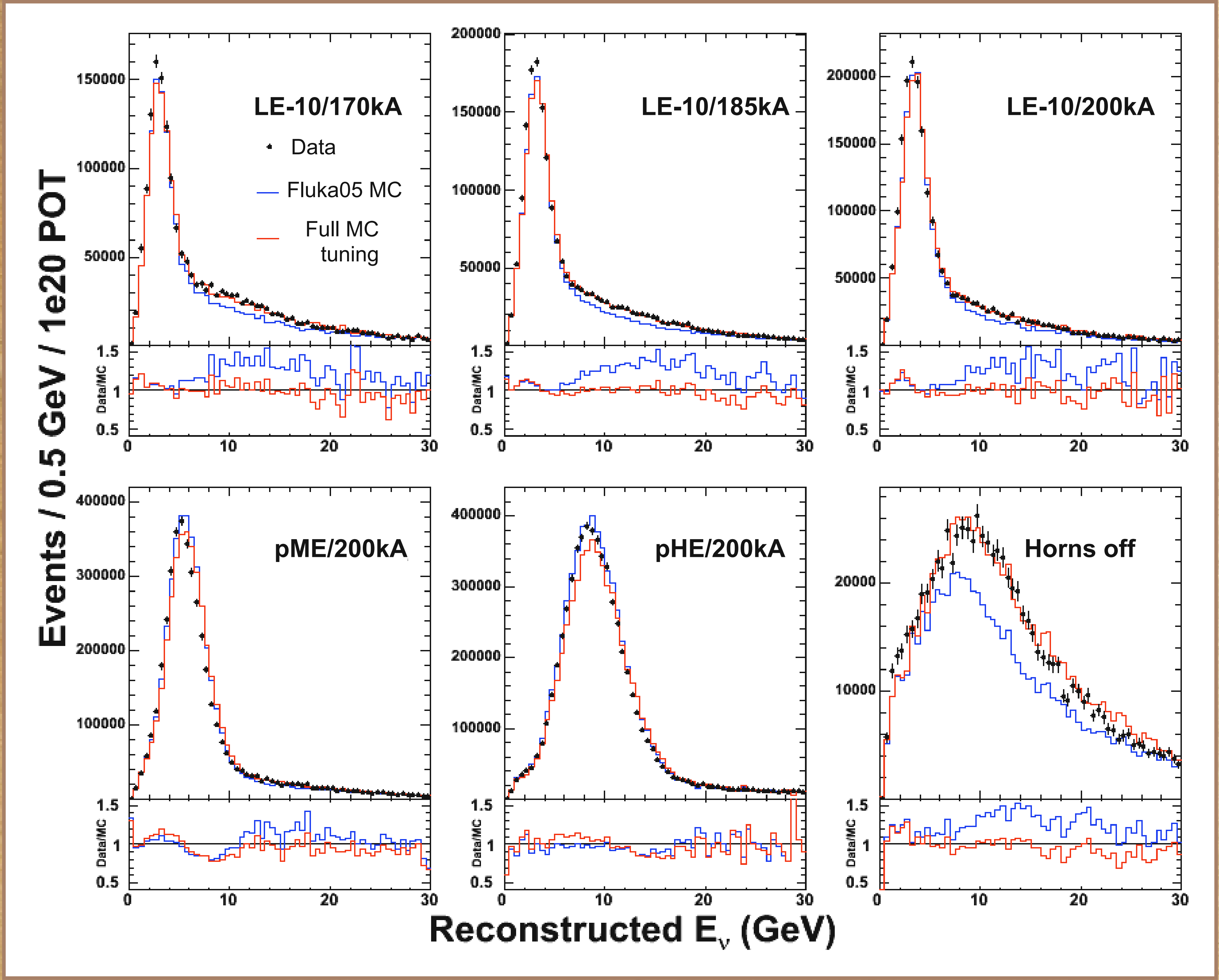
- We define the probability P_μ (P_{NC}) as the product of the 3 CC (NC) PDFs at the value of these variables taken by the event.

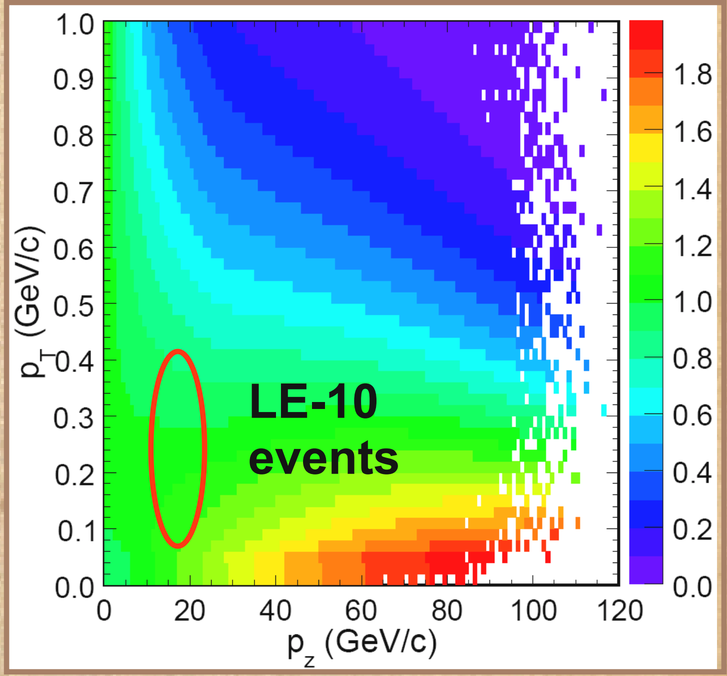




Hadron production tuning

- Agreement between data and Fluka05 Beam MC is pretty good, but by tuning to hadronic x_f and p_t, improved agreement can be obtained.

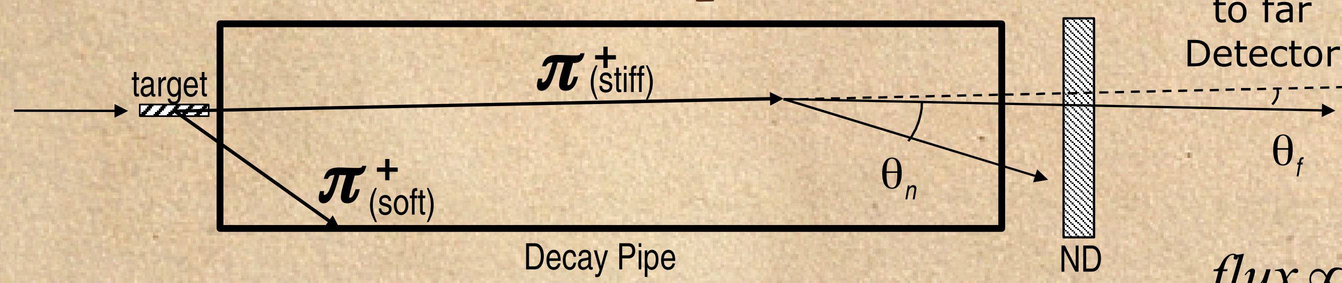




Weights applied as a function of hadronic x_f and p_t

Predicting the FD spectrum

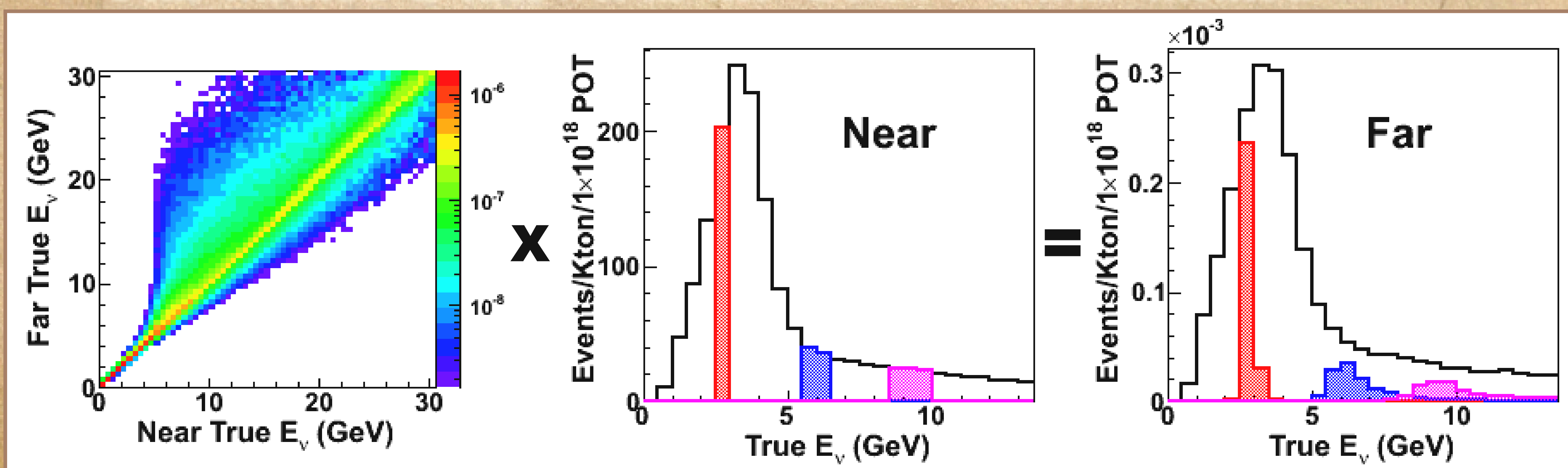
- Directly use Near Detector data to perform extrapolation between Near and Far. Have the Monte Carlo provide necessary corrections due to energy smearing and acceptance.
- Then use our knowledge of pion decay kinematics and geometry of our beamline to predict the FD energy spectrum from the measured ND spectrum.



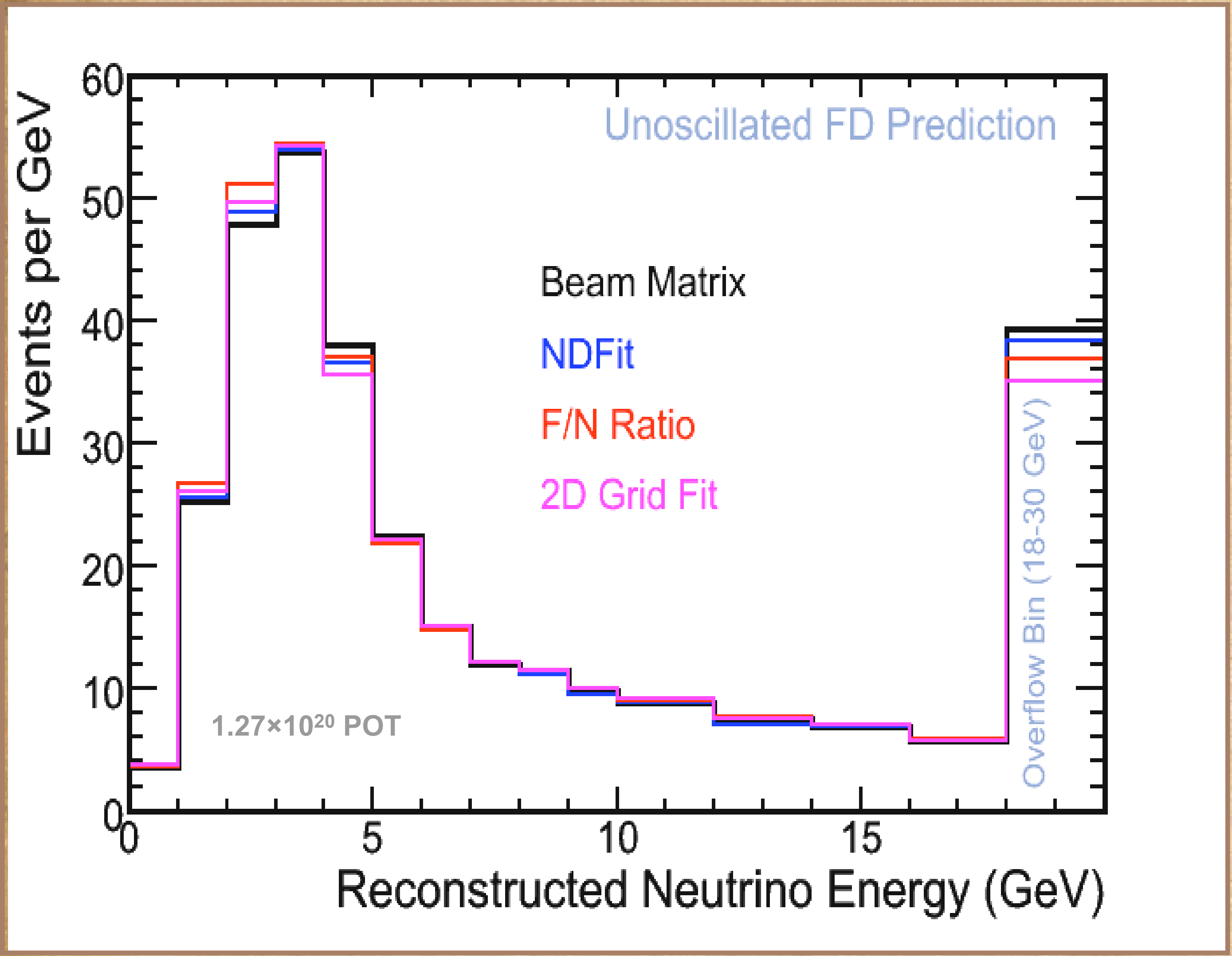
$$E_\nu = \frac{0.43\,E_\pi}{1+\gamma^2\theta^2}$$

$$flux \propto \frac{1}{L^2}\left(\frac{\gamma}{1+\gamma^2\theta^2}\right)^2$$

- This method is known as the "Beam Matrix" method.



Alternative ND/FD extrapolations



Results with all four methods are compared to check the robustness of our oscillation measurement.

- The matrix method is very powerful to extrapolate the Near detector spectrum to the Far. However we have investigated 3 other methods:
  - F/N ratio: Extrapolation using the Far/Near spectrum ratio from MC.
  - NDfit: Reweight the FD MC using systematic parameters obtained by the ND fit.
  - 2d Grid Fit: Reweight the FD MC using E vs y correction matrix and systematic parameters obtained by the ND fit.
- Results will be shown with the **Beam Matrix** and the **NDfit**.

Final Results from 1.27 x 10^{20} POT

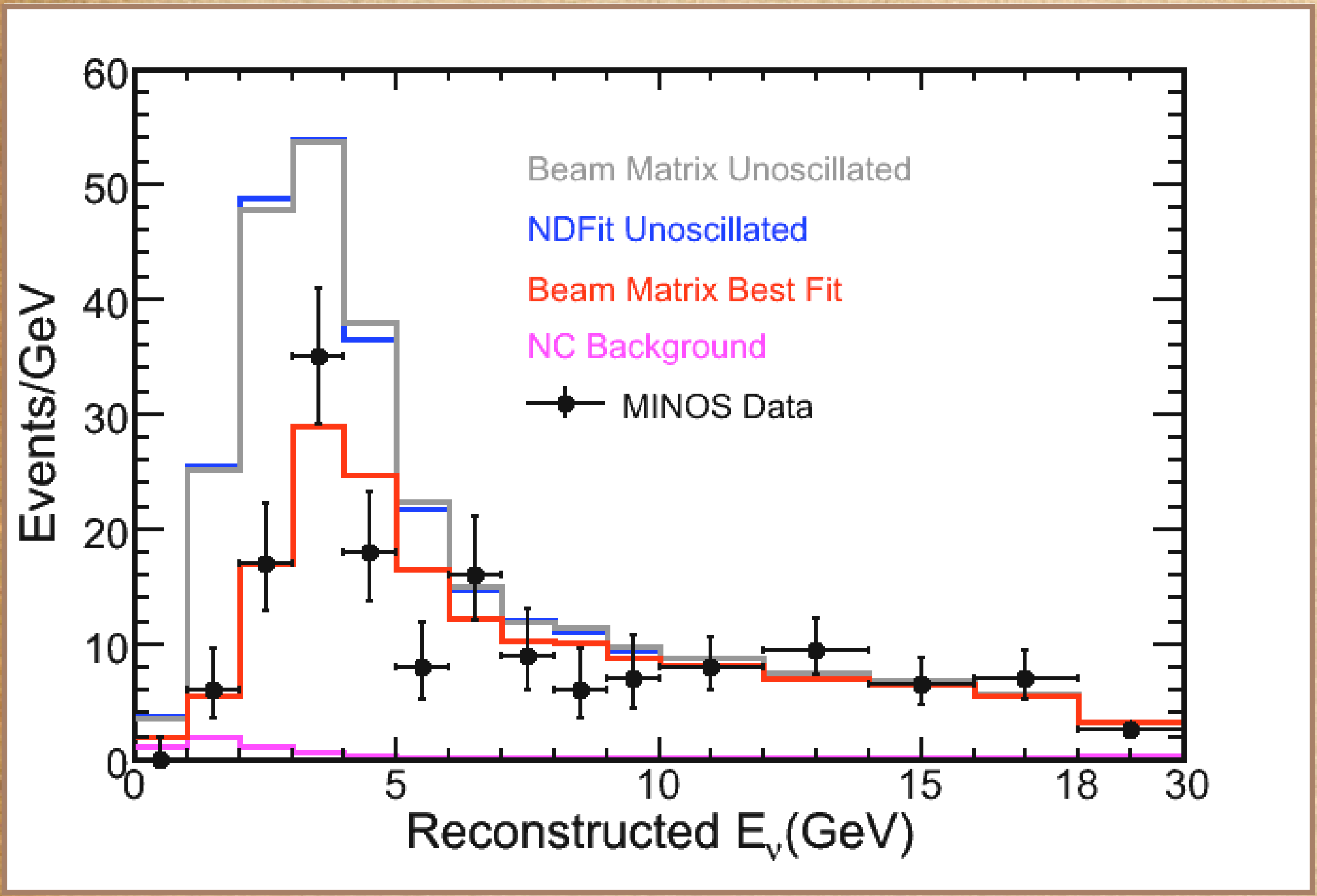
D.G Michael, et al., PRL 97, 191801 (2006)

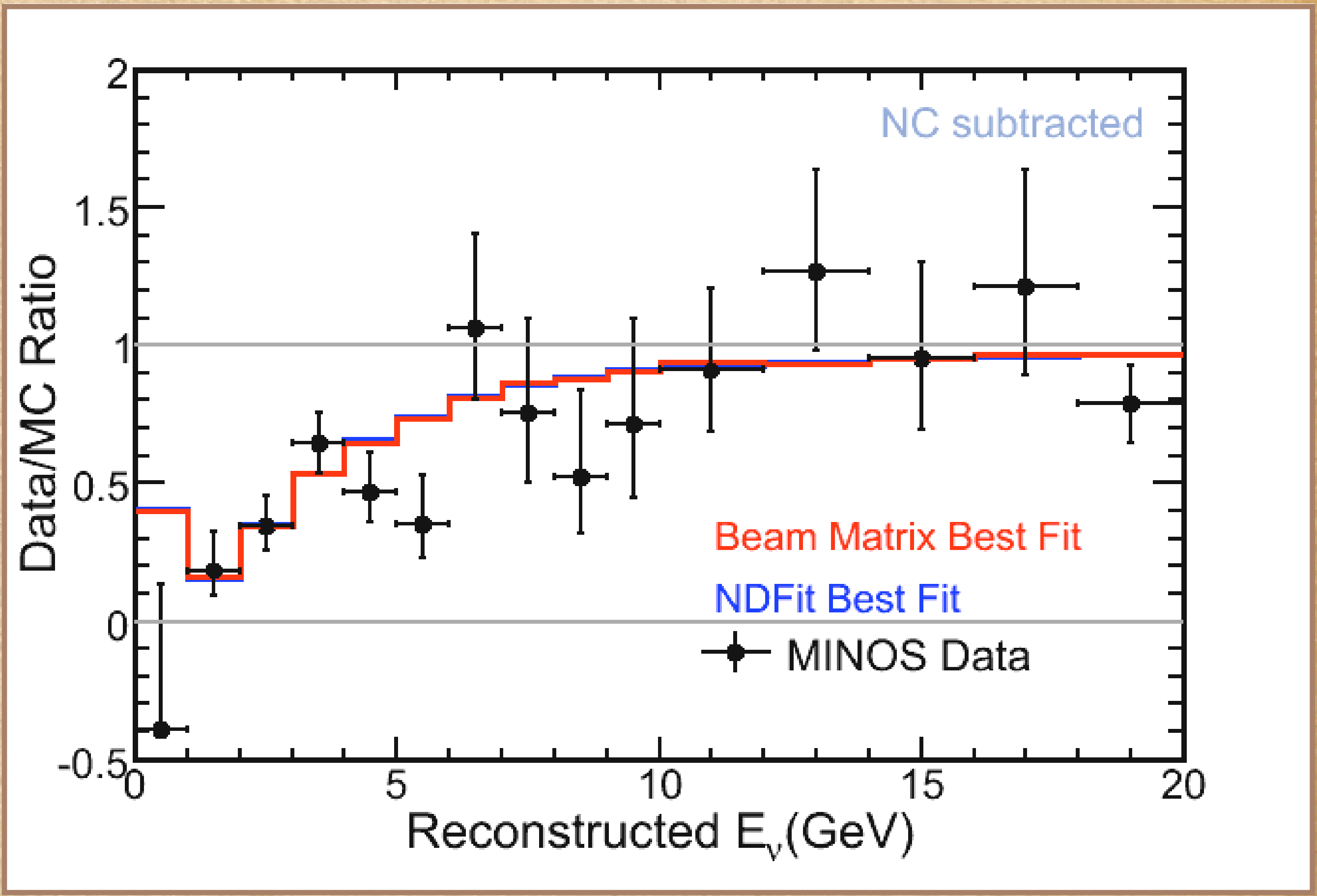
FD observed vs. expected

Data sample	observed	expected	ratio
ν_μ (<30 GeV)	215	336.0±14.4	0.64±0.05
ν_μ (<10 GeV)	122	238.7±10.7	0.51±0.05
ν_μ (<5 GeV)	76	168.4±8.8	0.45±0.06

- We observe a 49% deficit between 0 and 10 GeV with respect to the no disappearance hypothesis.
- The statistical significance is 6.2σ (stat+syst).

FD spectrum & ratio





$$|\Delta m^2_{32}| = 2.74^{+0.44}_{-0.26}(stat + syst) \times 10^{-3} eV^2$$

$$sin^2(2\theta_{23}) = 1.00_{-0.13}(stat + syst)$$

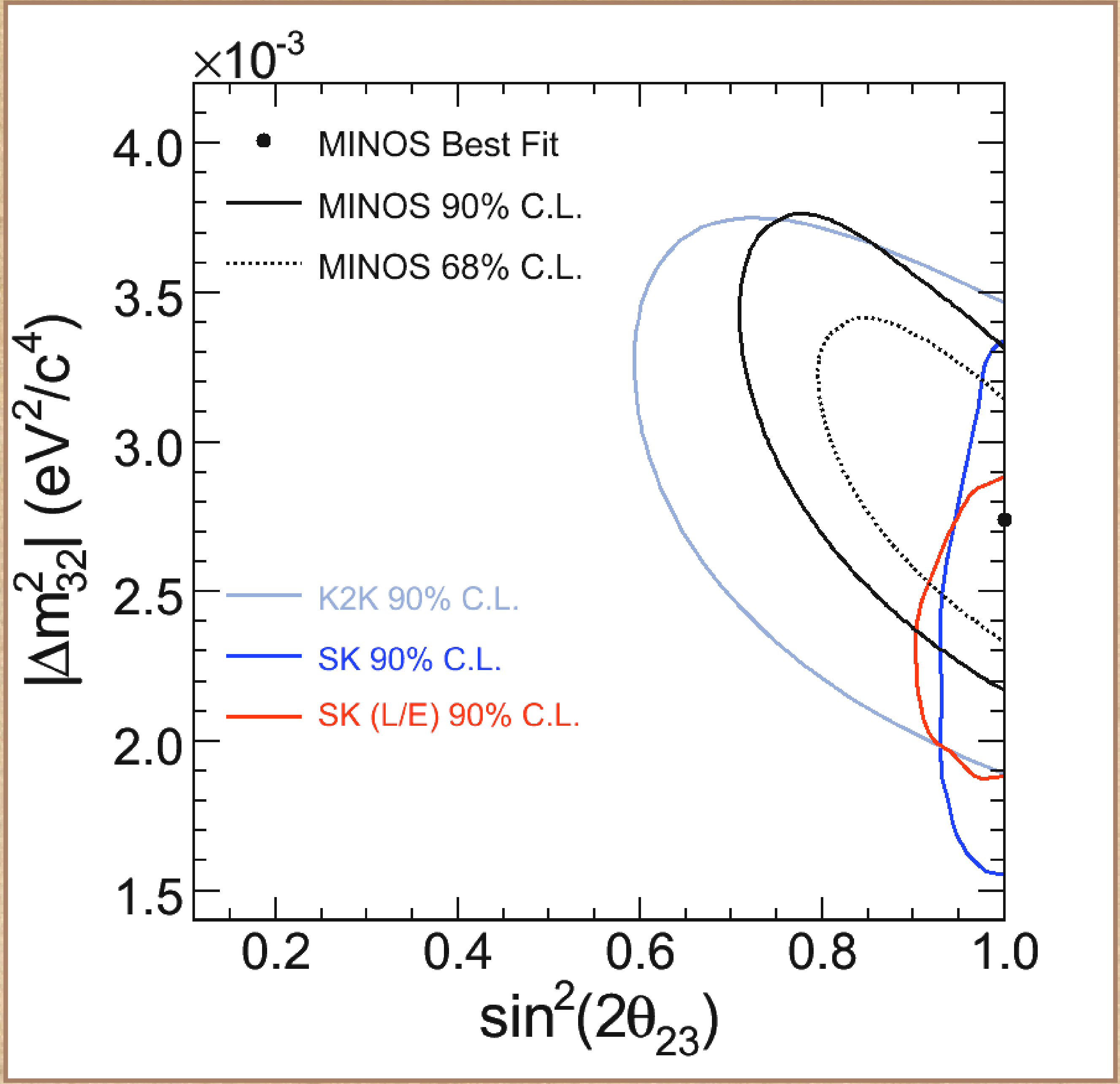
Systematic errors

- Systematic shifts in the fitted parameters have been computed with MC "fake data" samples for Δm^2=0.0027 eV^2, $\sin^2 2\theta$=1.0 for the following uncertainties:

Preliminary Uncertainties	Δm^2 shift (10^{-3} eV^2)	$\sin^2 2\theta$ shift
(1) N/F Normalization ± 4%	0.050	0.005
(2) Abs. hadronic energy scale ± 11%	0.060	0.048
(3) NC contamination ± 50%	0.090	0.050
(4) All other systematics	0.044	0.011
Total (sum in quadrature)	0.12	0.07
Statistical error (data)	0.36	0.12

- The main systematic uncertainties (1), (2) and (3) are used as nuisance parameters in fitting the data.

Comparison of fit results



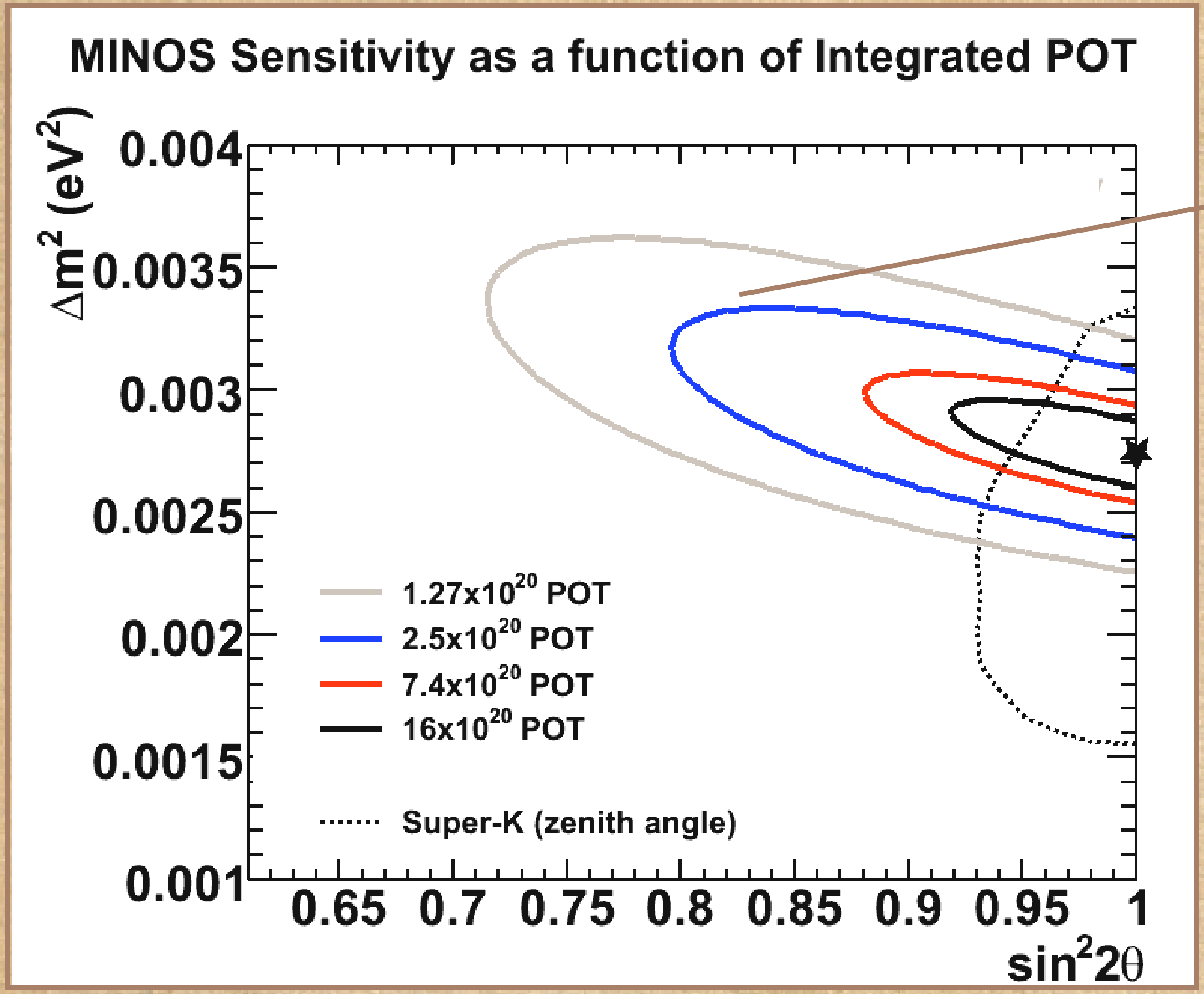
$$|\Delta m^2_{32}| = 2.74^{+0.44}_{-0.26}(stat + syst) \times 10^{-3} eV^2$$

$$sin^2(2\theta_{23}) = 1.00_{-0.13}(stat + syst)$$

More MINOS physics in progress

Physics reach of MINOS

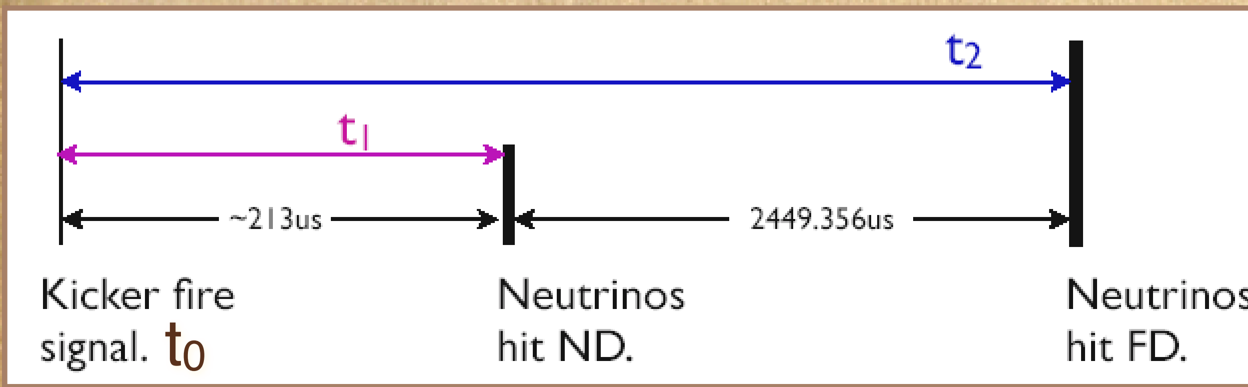
ν_μ disappearance



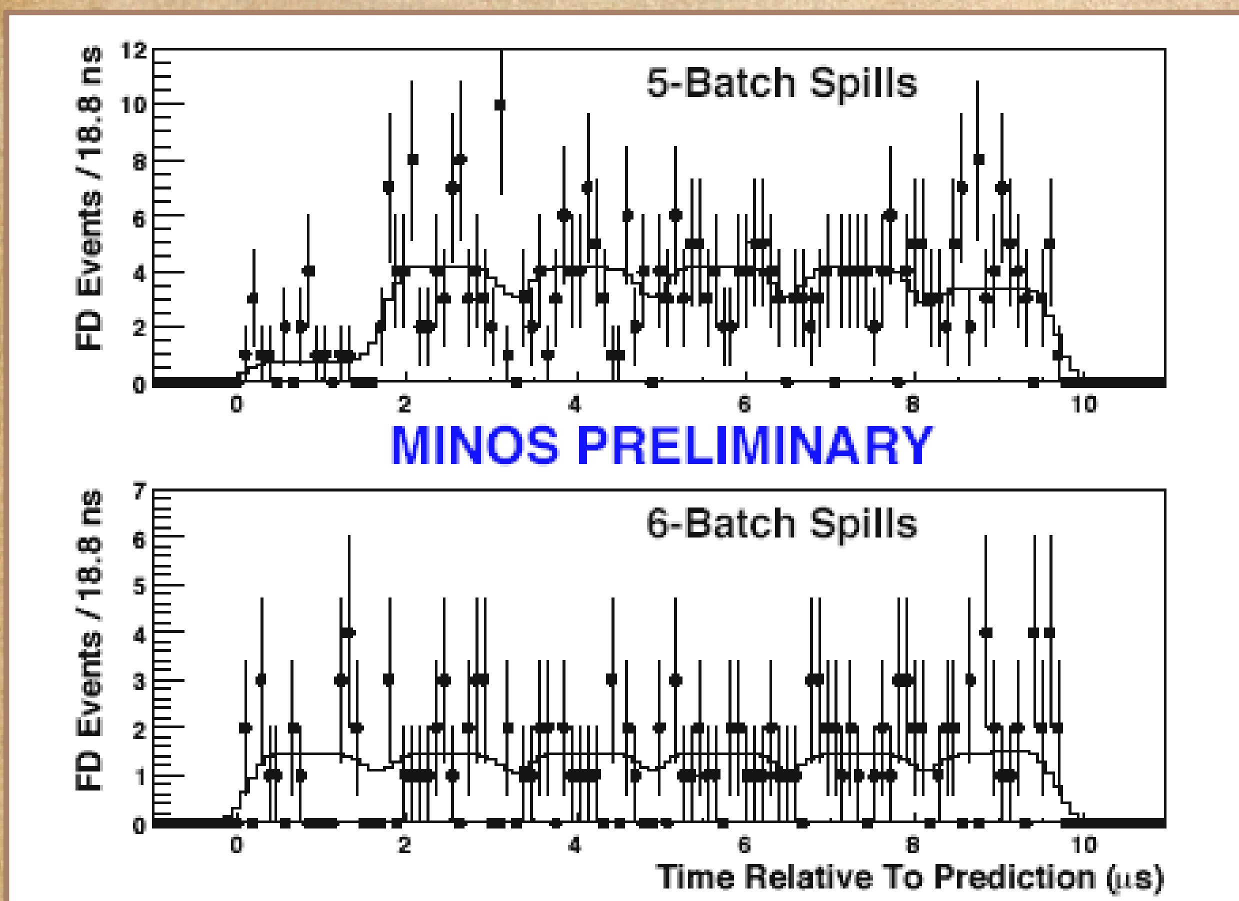
Coming soon: ~2.6x10^{20} POT
On track for this summer!

- Input parameters $|\Delta m^2_{32}| = 2.74 \times 10^{-3} eV^2, sin^2(2\theta_{23}) = 1.00$
- Statistical errors only (90% CL)

Neutrino time of flight



- GPS sync of the two detectors.
- We can measure the distribution times in the two detectors.
- Log likelihood fit then allows the time of flight for the neutrinos to vary.



Time of Flight Measurement:

Nominal: (734298.6 ± 0.7 m distance)
2449356 ns

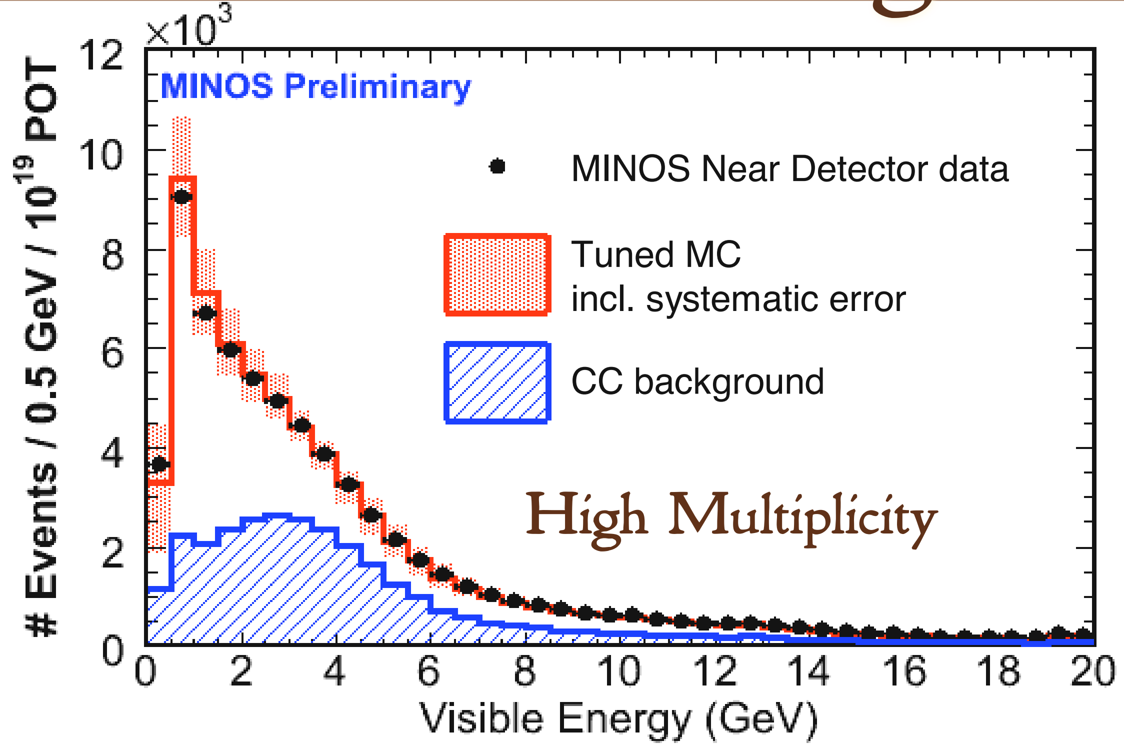
Measured:
2449223 ± 84 (stat) ± 164 (sys) ns
99% C.L.

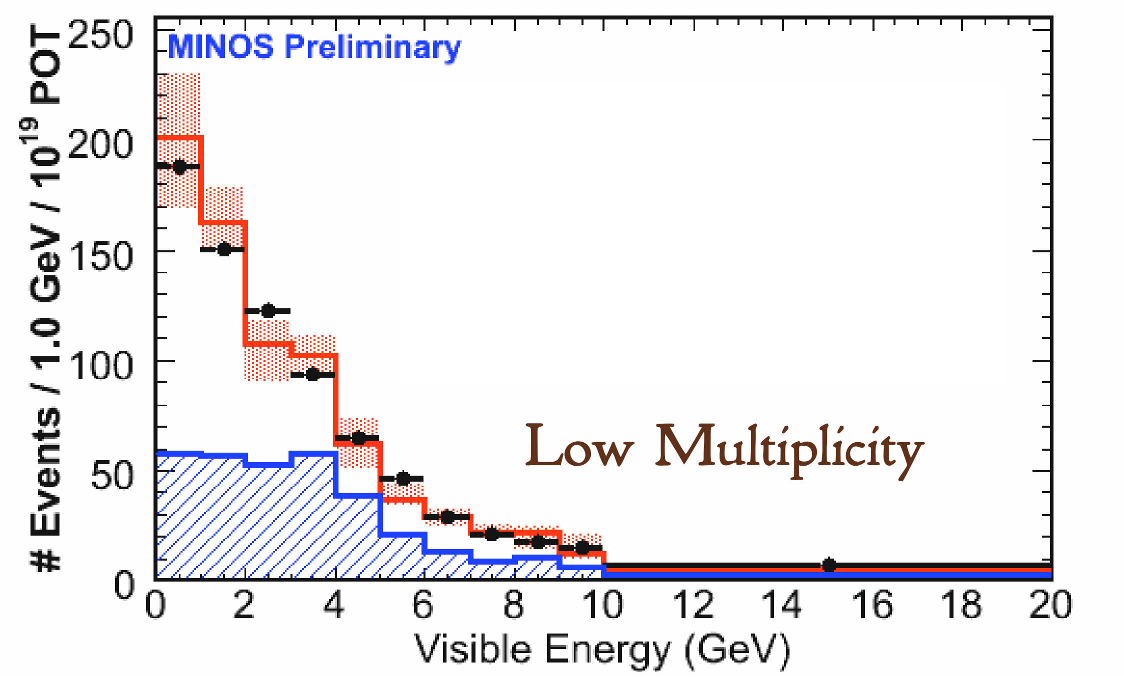
Neutrino Velocity:
$(v-c)/c = 5.4 \pm 7.5 \times 10^{-5}$
99% C.L.

- Current PDG value: $< 4\times10^{-5}$ (95%CL)

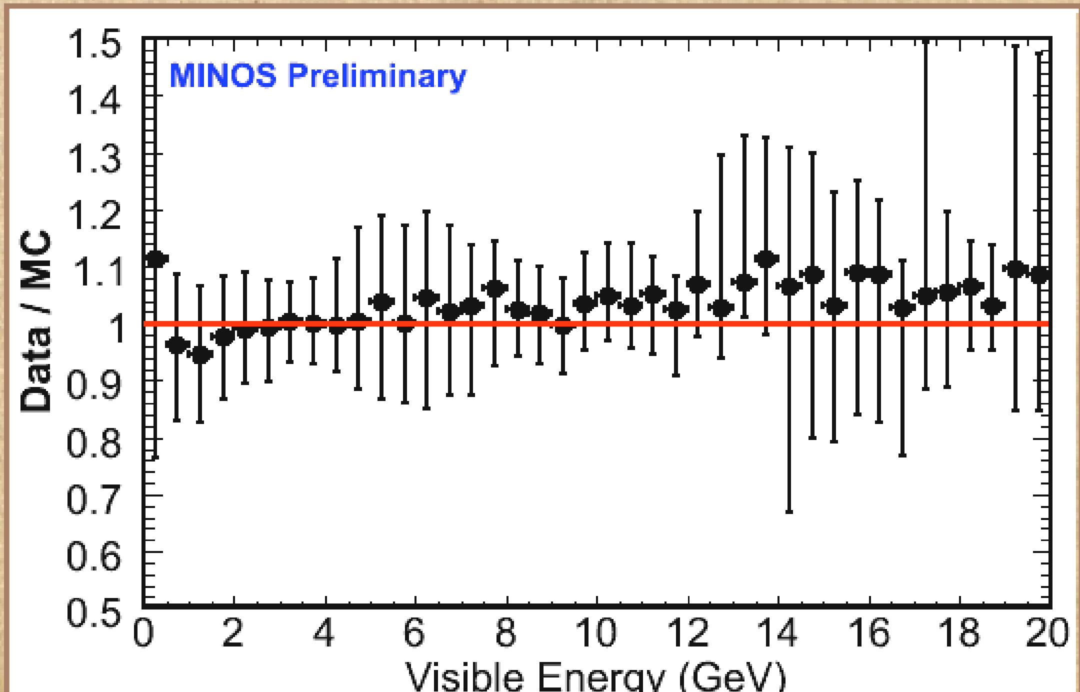
The NC measurement

looking for $\nu_\mu \rightarrow \nu_s$ or ν decay





- Comparing Near/Far Neutral Current spectrum, sensitive to sterile neutrinos.
- NC events are more prone to intensity related issues, so we first study the spectra in the Near with high and low multiplicity.

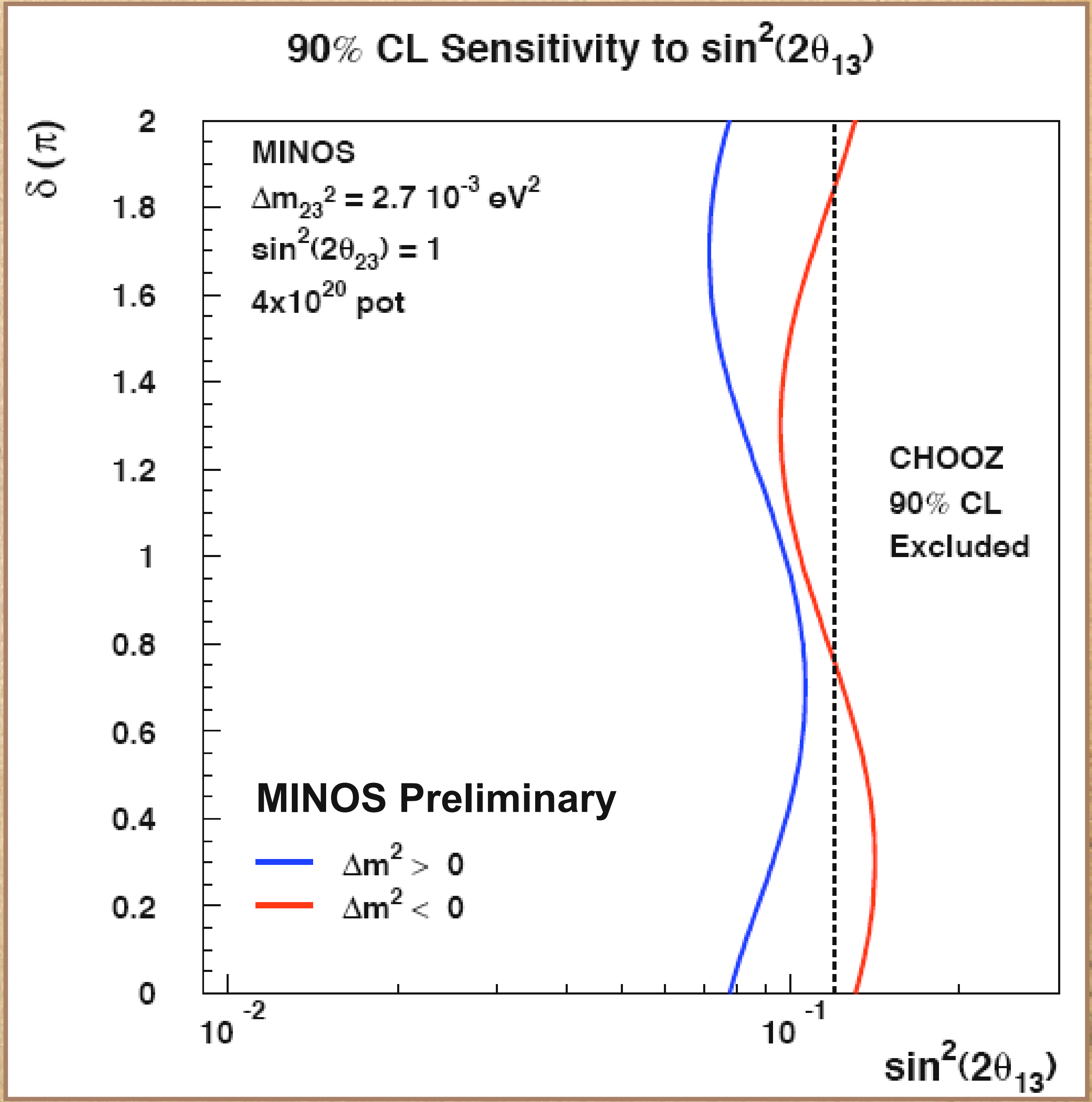


Look for first results in the fall!

Physics reach of MINOS

searching ν_e appearance

- We have a chance at making the first measurement of θ_{13}.
  - Matter effects can change ν_e yield by as much as ±20%
- Plot shows δ_{CP} vs. $\sin^2 2\theta_{13}$ for both hierarchies for MINOS best fit value at 4×10^{20} POT
  - 10% systematic effect included
- We can improve on current best limit (Chooz).



Expect 4×10^{20} POT by the end of the year

MINOS summary

- We have published an oscillation analysis of the first year of beam exposure for 1.27 x 10^{20} POT (PRL 97:191801, 2006).
- Our result disfavours no oscillations at 6.2 σ (rate only) and using the shape the data is consistent with ν_μ disappearance with the following parameters:

$$\begin{aligned} |\Delta m^2_{32}| &= 2.74^{+0.44}_{-0.26}(stat+syst)\times 10^{-3}eV^2 \\ sin^2(2\theta_{23}) &= 1.00_{-0.13}(stat+syst) \end{aligned}$$

- A fit constrained to the $\sin^2 2\theta_{23} = 1$ boundary yields:

$$|\Delta m^2_{32}| = 2.74 \pm 0.28 \times 10^{-3} eV^2$$

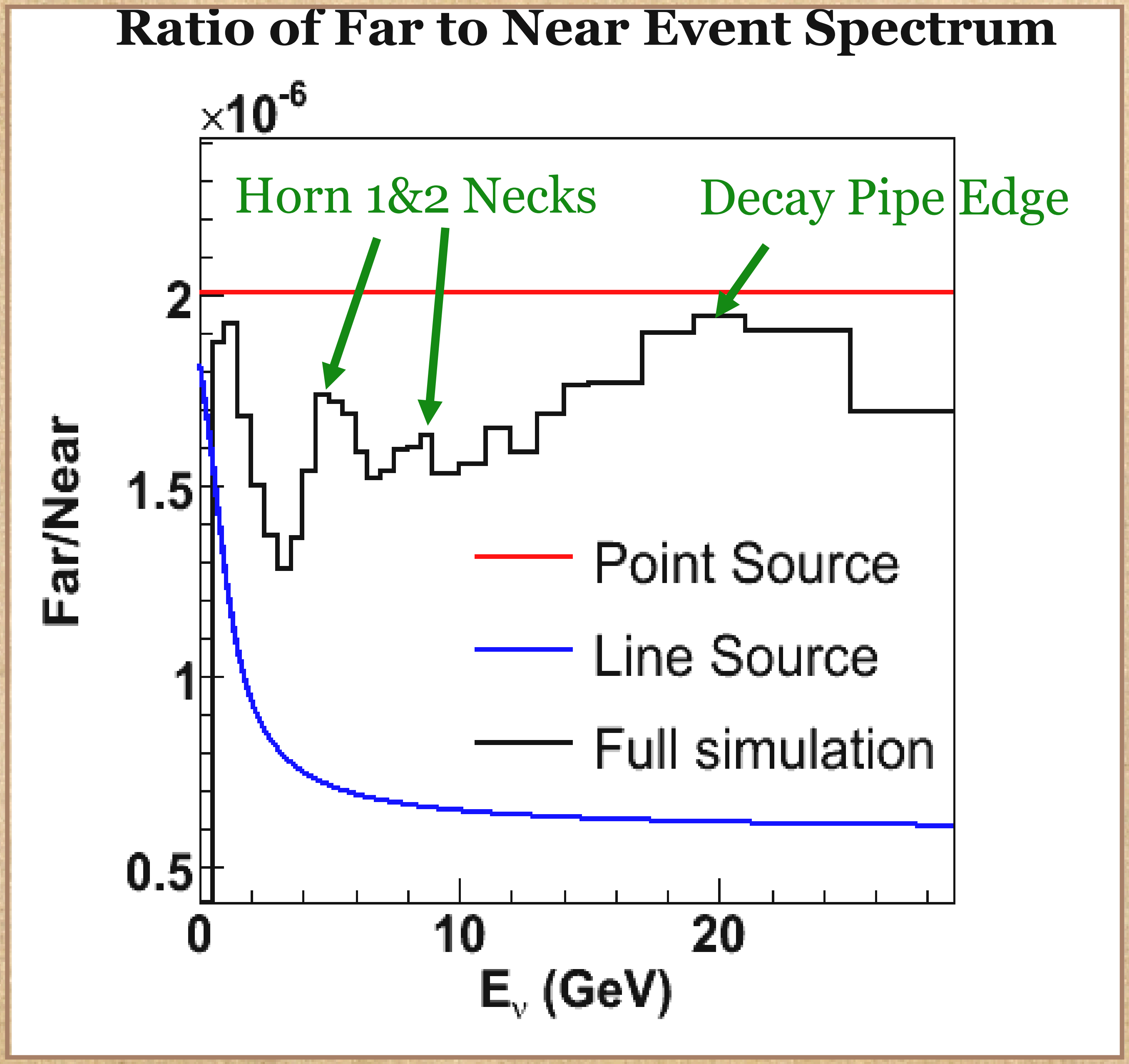
- The systematics uncertainties are under control and we should make significant improvements with a larger data set.
  - The second year of running is now done, expect results this summer.
- Stay tuned for our other measurements!

The End

Backup Slides

Systematics

- Normalization: ± 4 %
  - POT counting, Near/Far selection efficiency, Fiducial mass
- Absolute shower energy scale (± 6%) / Intranuclear rescattering (± 10%): ± 11 %
- NC contamination of CC-like sample: ± 50%
  - From shape and normalization of ND PID distributions
- Relative shower energy scale: ± 2%
  - Inter-Detector calibration uncertainty
- Muon energy scale: ±2%
  - Uncertainty in dE/dX in MC
- CC cross-section uncertainties
  - M_A(QEL) and M_A (RES): ± 5%
  - KNO RES-DIS scaling factor: ± 20%
- Beam uncertainty: difference between fits and weighted/unweighted MC


Ratio of Far to Near Event Spectrum
×10^-6
Horn 1&2 Necks
Decay Pipe Edge
Far/Near
2
1.5
1
0.5
0
10
20
Eν (GeV)
Point Source
Line Source
Full simulation

Physics reach of MINOS

ν_e appearance

- Expected events from MC for 1.4×10^{20} POT

NC	2.80 (66%)		$\sin^2\theta_{23}=1.0$
CC	0.62 (15%)		$\Delta m^2_{23}=0.0025$ eV^2
Beam ν_e	0.58 (14%)		$\sin^2(2\theta_{13})=0.12$
ν_τ	0.23 (5%)		↓
total bg	4.23	⟺	2.8 signal events

- Backgrounds will be estimated from data:
  - Horn off data in ND: disentangle NC-CC
  - Beam ν_e: measure $\bar{\nu}_\mu$ from $\mu^+ \rightarrow e^+\nu_e\bar{\nu}_\mu$ in ND
  - Muon removal in CC events: estimating NC bg.