Neutrino oscillations results from MINOS

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for the MINOS Collaboration

VI[th] Rencontres du Vietnam
Nanophysics and Particle astrophysics
Nanophysics : from fundamentals to applications
Challenges in Particle astrophysics
Hanoi, Vietnam, August 6 - 12, 2006

MINOS

Main Injector Neutrino Oscillation Search

OUTLINE

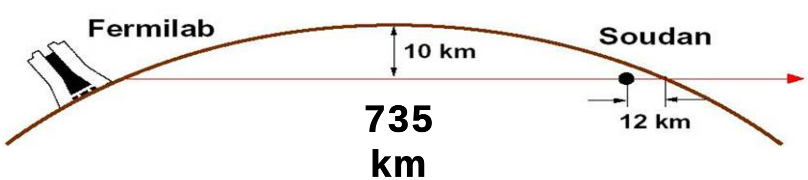
- Strategy & physics program
- Experimental setup
  - Main Injector & NuMI Beam
  - Detectors Near/Far/Calibration
  - Data sets
- Results from the first year (May 2005 – Feb 2006)
  - 1.27×10^{20} protons on target
  - Analysis
  - Oscillation parameters
- Summary and prospects

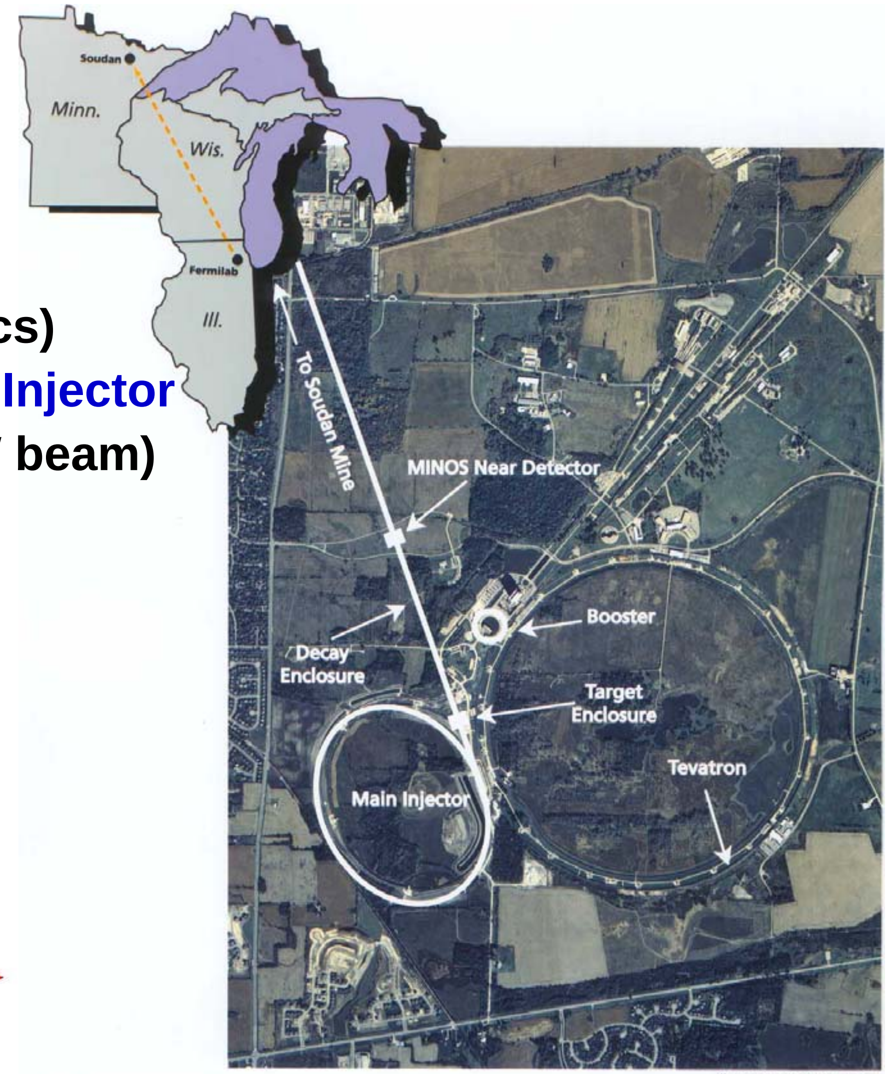
MINOS

Main Injector Neutrino Oscillation Studies

Strategy for precision measurements:

- **Two-detector measurement**
  - long baseline (735km)
  - underground (CR shielding + physics)
- **High intensity beam from 120 GeV Main Injector**
  - (up to) 4×10^{13} protons/pulse (0.4 MW beam)
    (potential for ~4×10^{20} protons/year)
  - single turn extraction (8.67 μs)
- **Flexible & well-controlled beam**
  - two parabolic magnetic horns
  - movable target (→energy spectrum)





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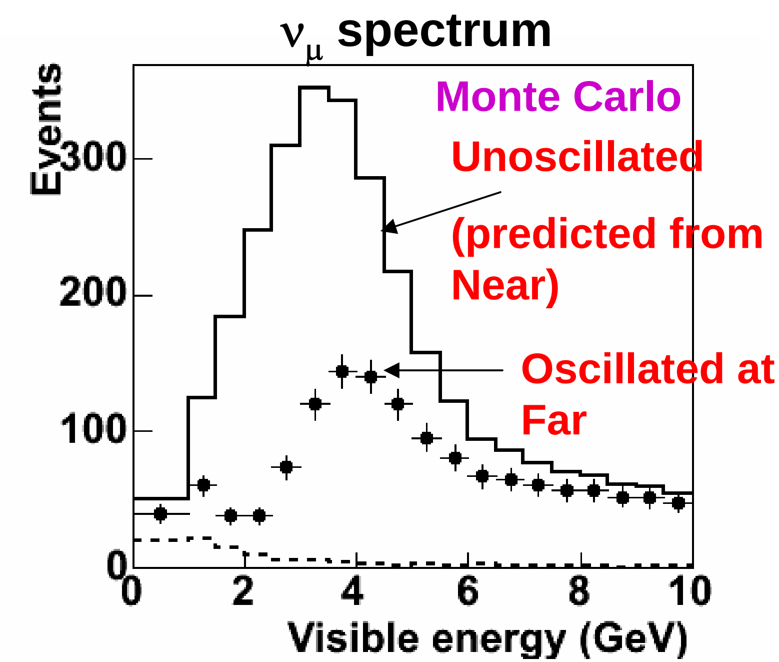
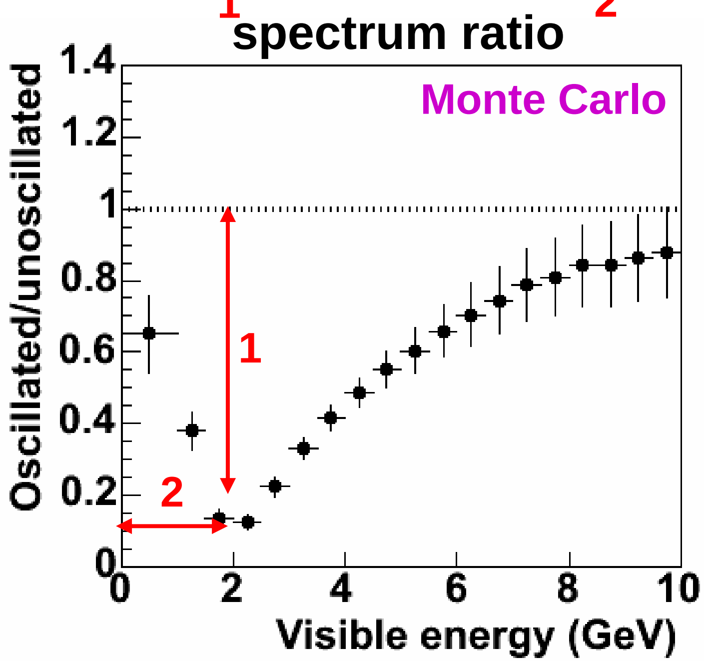
Main goals:

- Decisive low-systematics observation of disapearannce ($\nu_\mu \rightarrow \nu_x$)
- Determine $|\Delta m_{32}^2|$ and $\sin^2 2\theta_{23}$ with ~10% accuracy
- Measure (or improve limits) on $\nu_\mu \rightarrow \nu_e$ / $\nu_\mu \rightarrow \nu_{sterile}$ / "exotic" transitions
- Test CPT in atmospheric CC_μ charge-separated interactions

The method:

$$P(\nu_\mu \rightarrow \nu_\mu) = 1 - \boxed{\sin^2 2\theta}_{\,1} \sin^2(1.267 \boxed{\Delta m^2}_{\,2} L/E)$$





Monte Carlo plots for $\Delta m^2 = 0.003\ eV^2$ and 7.4×10^{20} pot

Experimental setup: the Main Injector

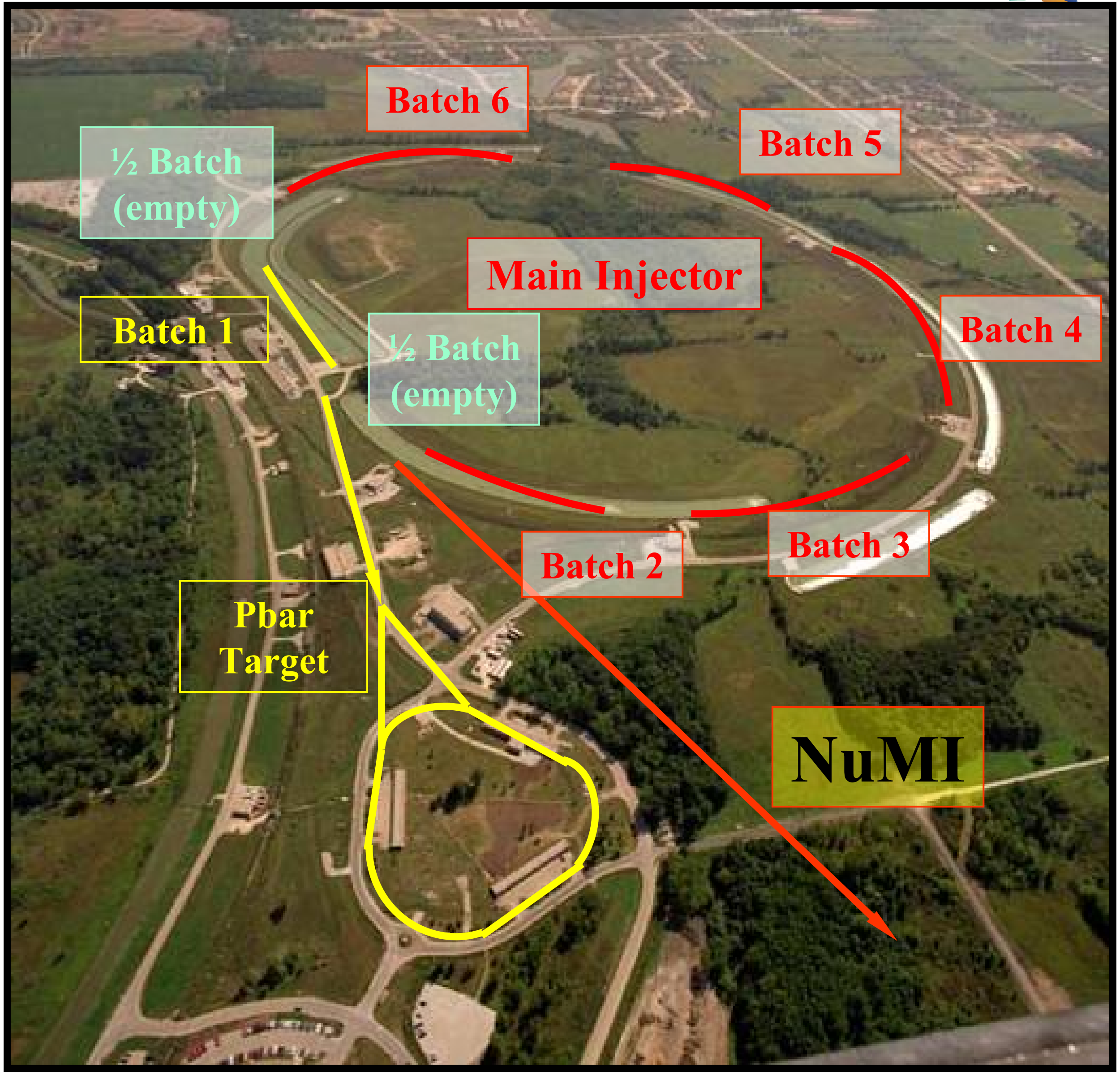
(Main Injector = MI)

- MI is fed 1.56 μs batches from 8 GeV Booster
  (MI ramp time ~1.5sec)

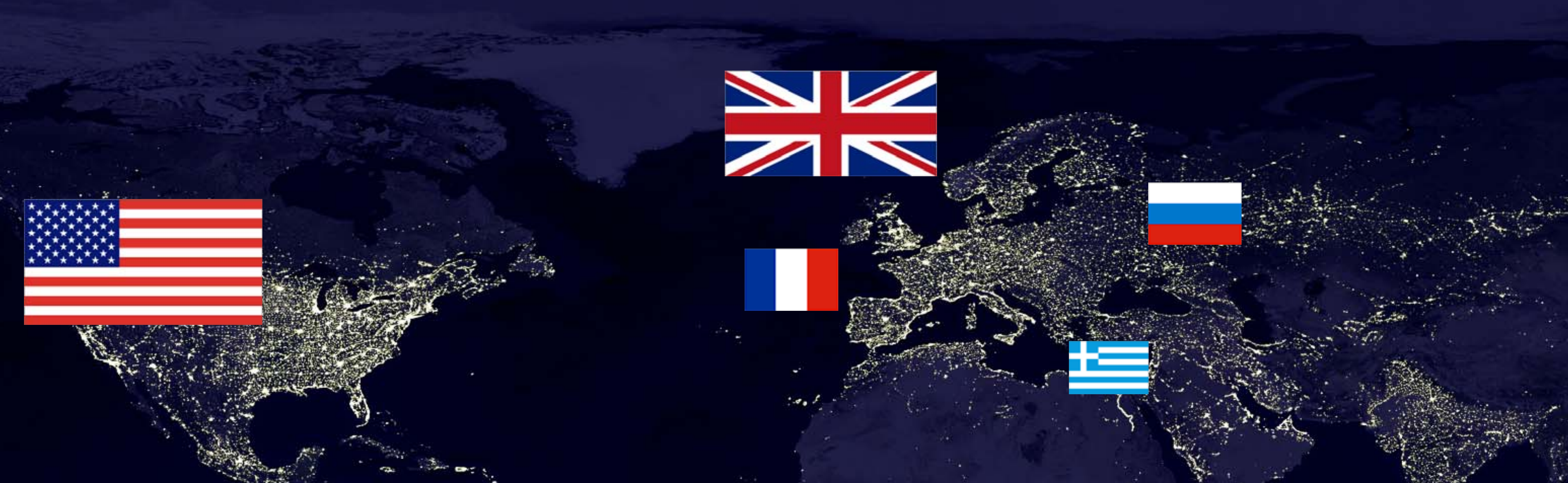
- NuMI designed for
  - 8.67 μsec single turn extraction
  - 4×10^{13}ppp @ 120 GeV
  - 1.9 second cycle time
  - beam power ~400kW

- Typical performance to date:
  - 2.3×10^{13} ppp @ 120 GeV
  - 2.2 second cycle time

- Achieved records:
  - 3×10^{13} ppp @ 120 GeV
  - 2.0 second cycle time
  - 280 kW

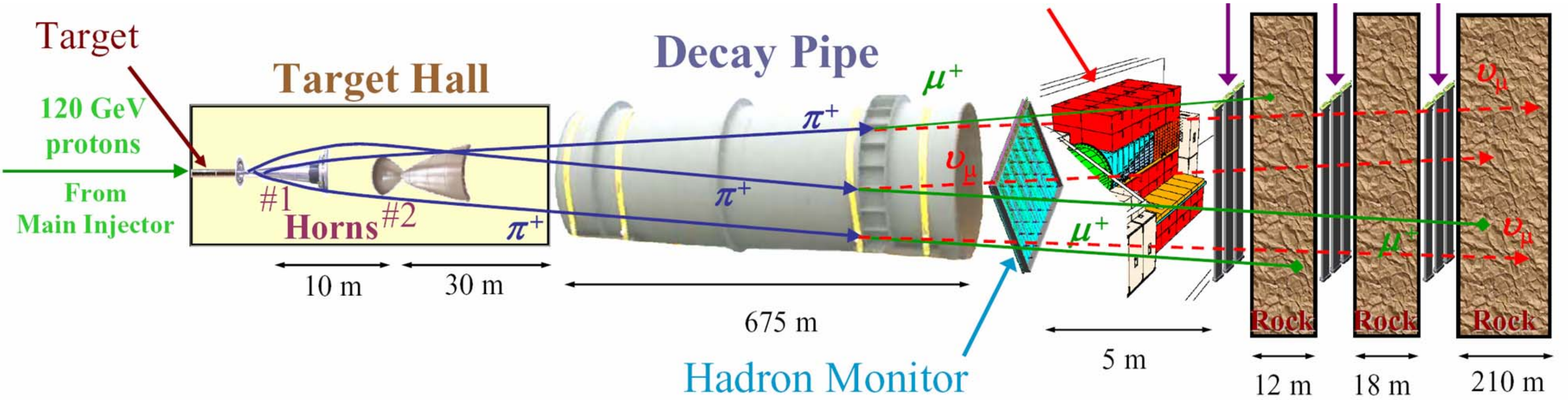


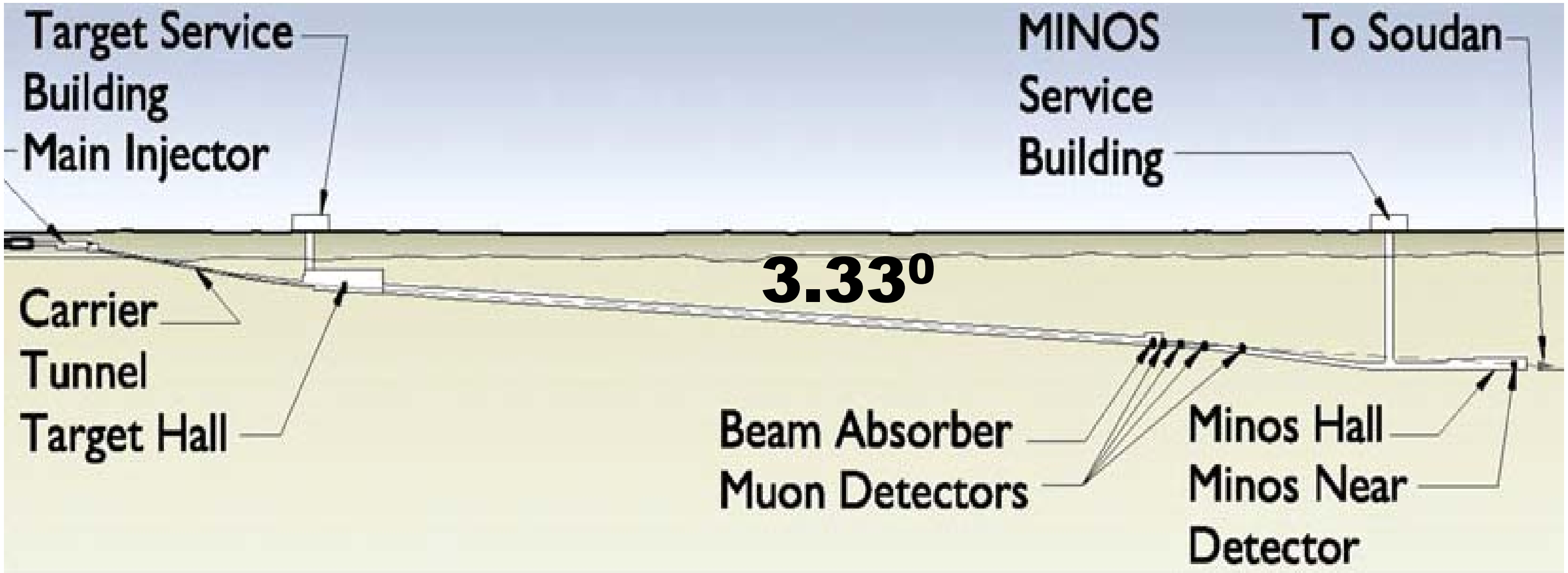
MINOS Collaboration



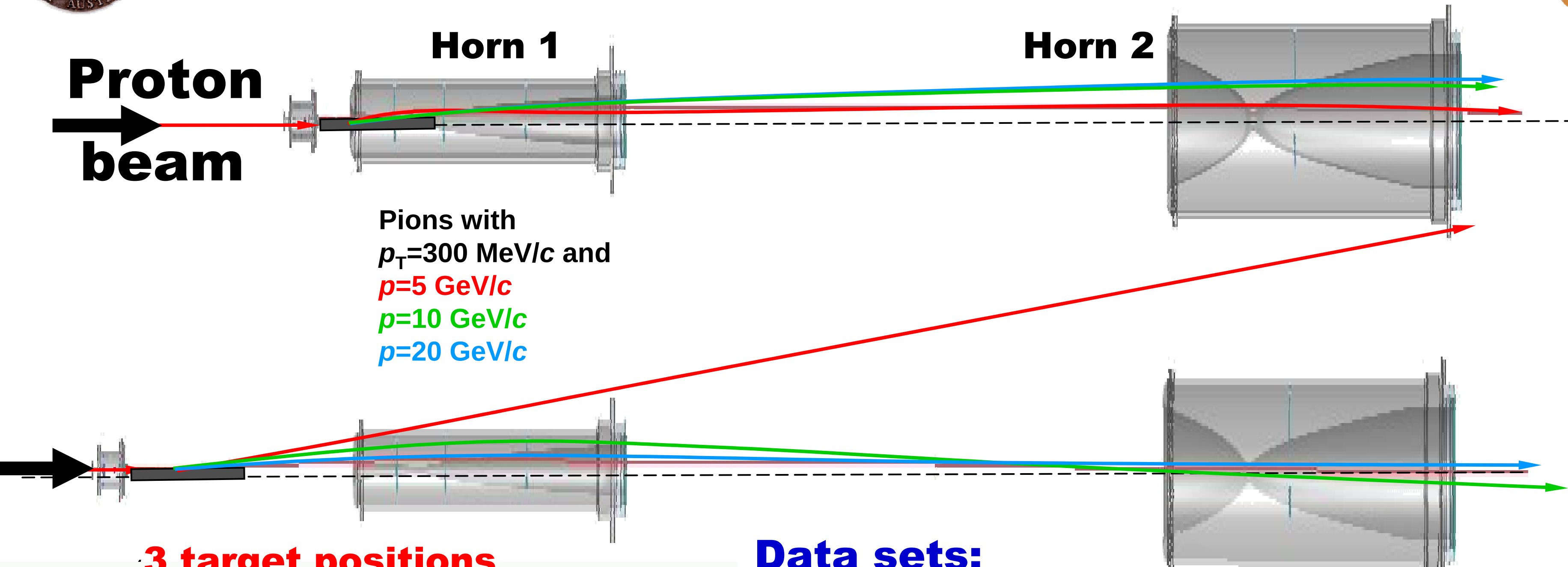
32 institutions
175 collaborators

Experimental setup: NuMI beam

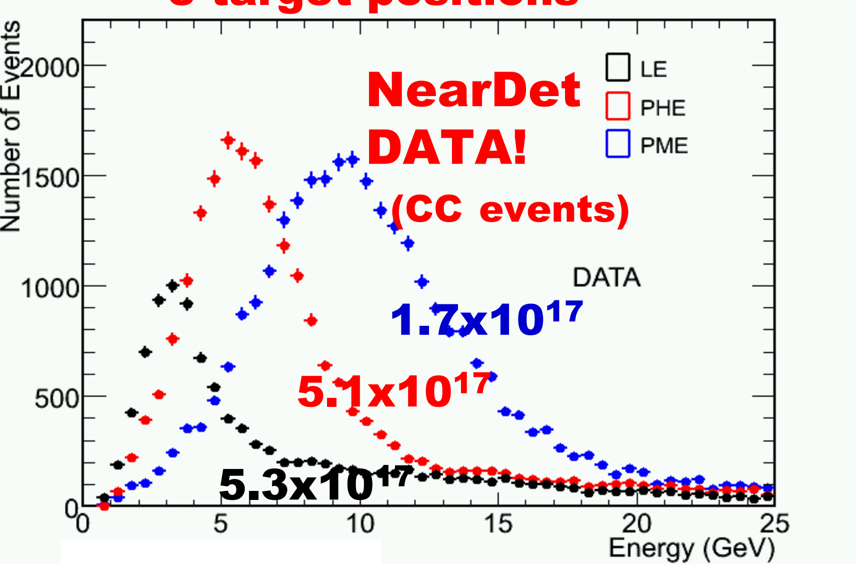




NuMI – multi-beam



3 target positions



Data sets:

Beam	Target z position (cm)	FD Events per 1×10^{20} pot	Horn Current (kA)
LE-10	-10	390	0,170,185,200
pME	-100	970	200
pHE	-250	1340	200

95% data

LE-10: Far Det: 1 event / ~4hrs

Flavor composition: 92.9% ν_μ
5.8% anti- ν_μ,
1.2% ν_e, 0.1%anti- ν_e

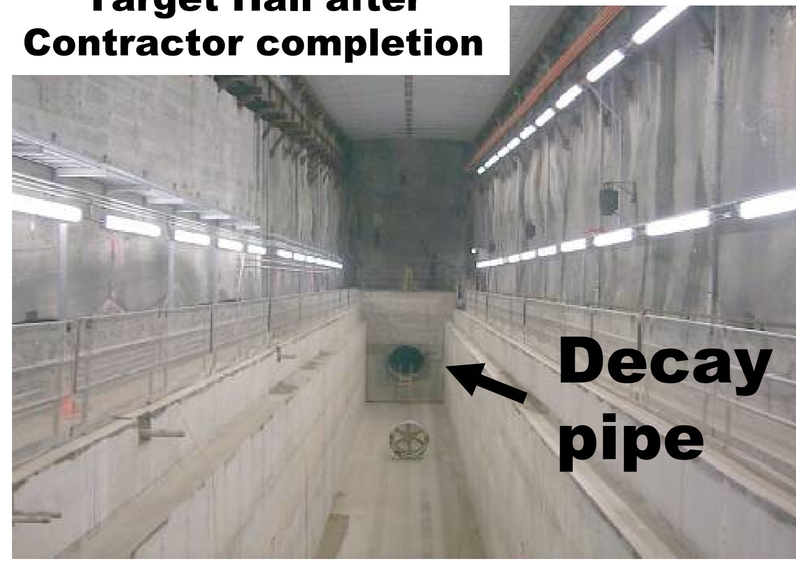
Modern tools of experimental particle physics: TBM – Tunneling Boring Machine

TBM

ca. 2001

Tunneling

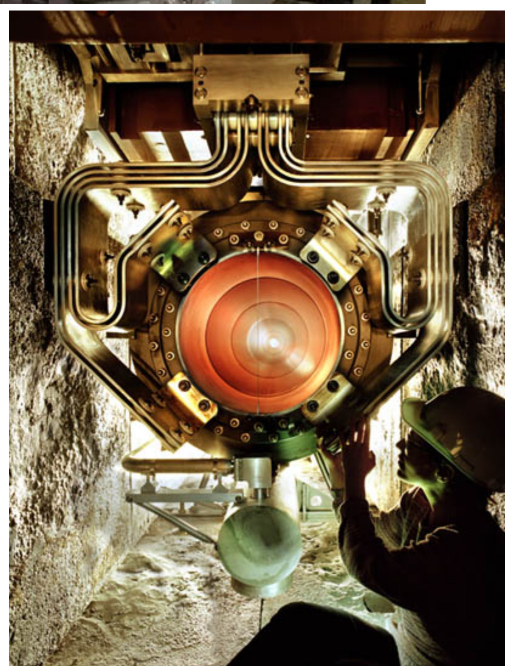
Target Hall after Contractor completion



Target Hall shielding installation

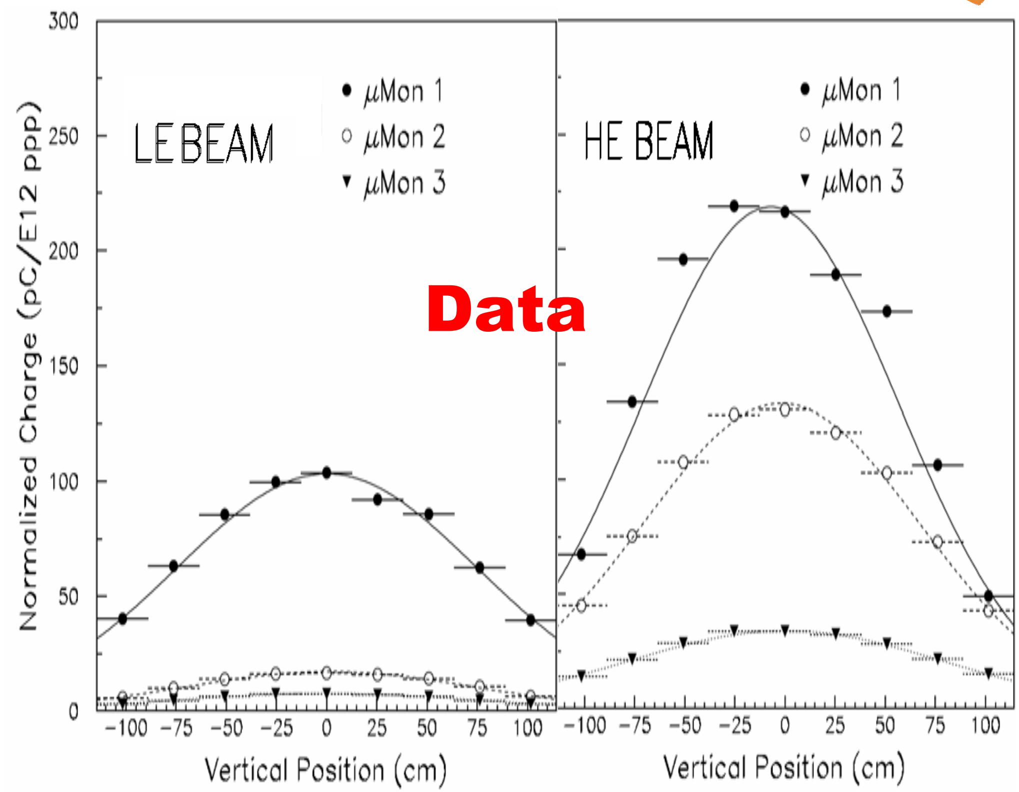
MINOS Target Hall

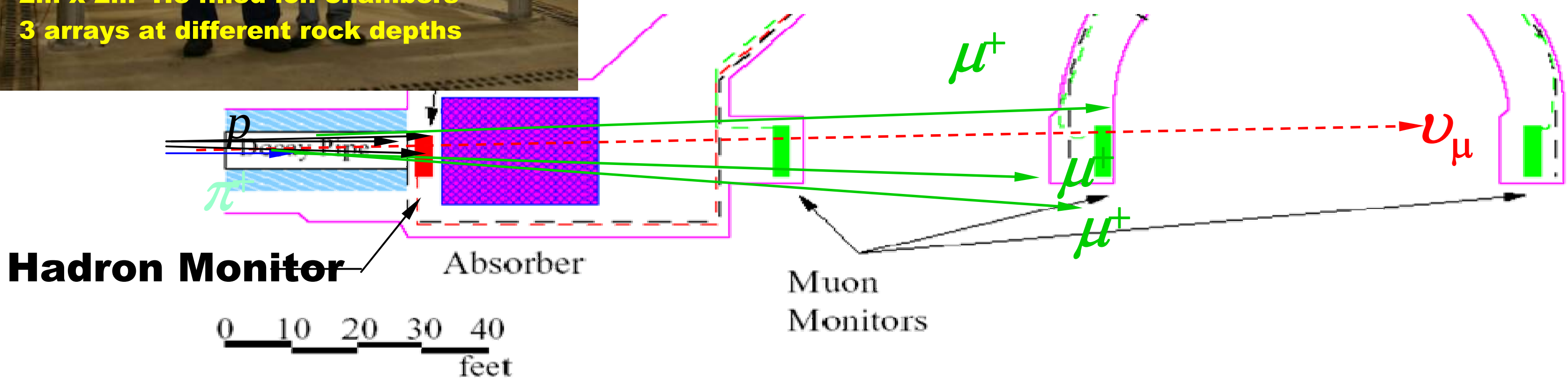

Hall probe



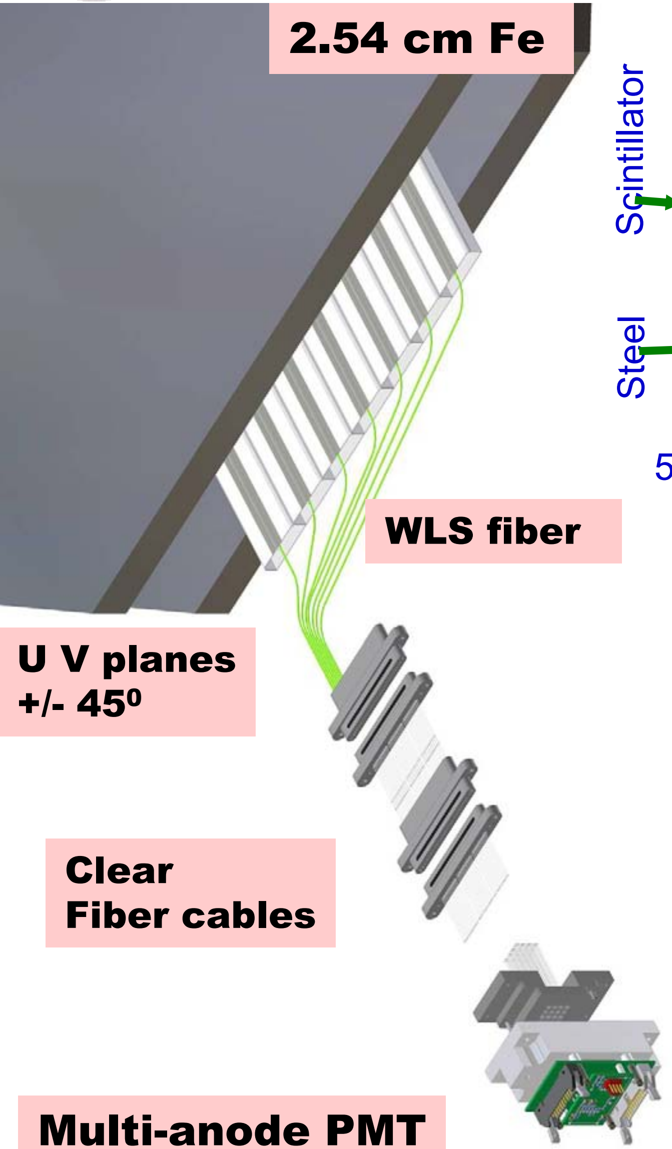

Horn 2 suspended from shielding module being lowered into shielding pit

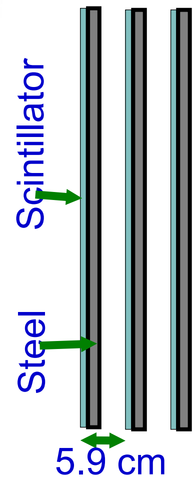
Muon Monitors to Study ν Beam

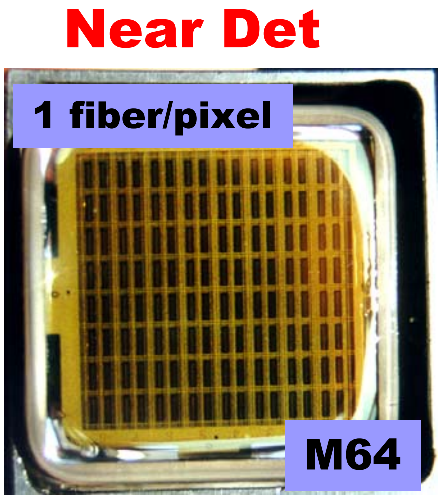




“MINOS technology”

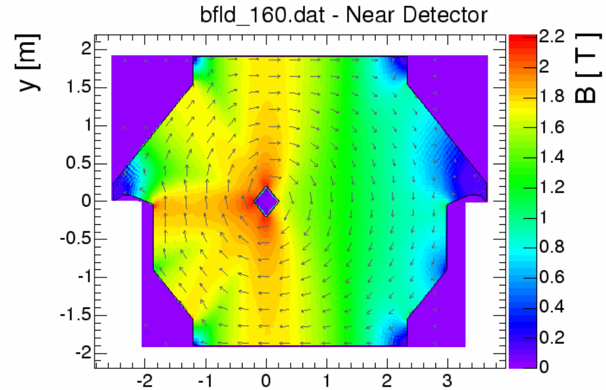






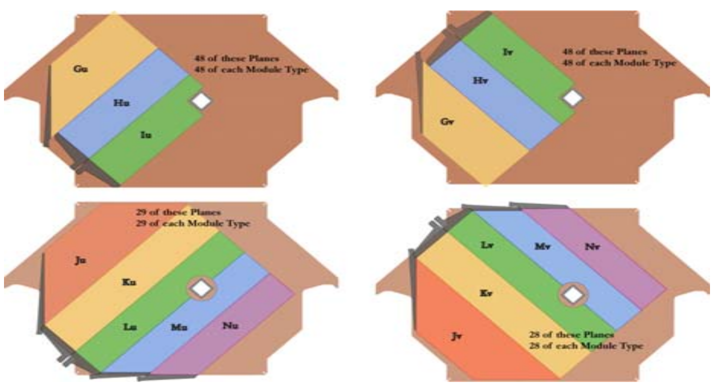
Near Detector – 1,040 m from the target at Fermilab

- veto - target - μ spectrometer
- mass = 1 kT
- 153 scintillator planes
- QIE-based front-end
- 3.8 x 4.8 “squeezed” octagon
- 12,300 scint.strips
- 1-end readout
- no-multiplexing
- 220 M64s
- 282 steel planes
- 65 km WLS fiber
- 51 km clear fiber



103 m underground

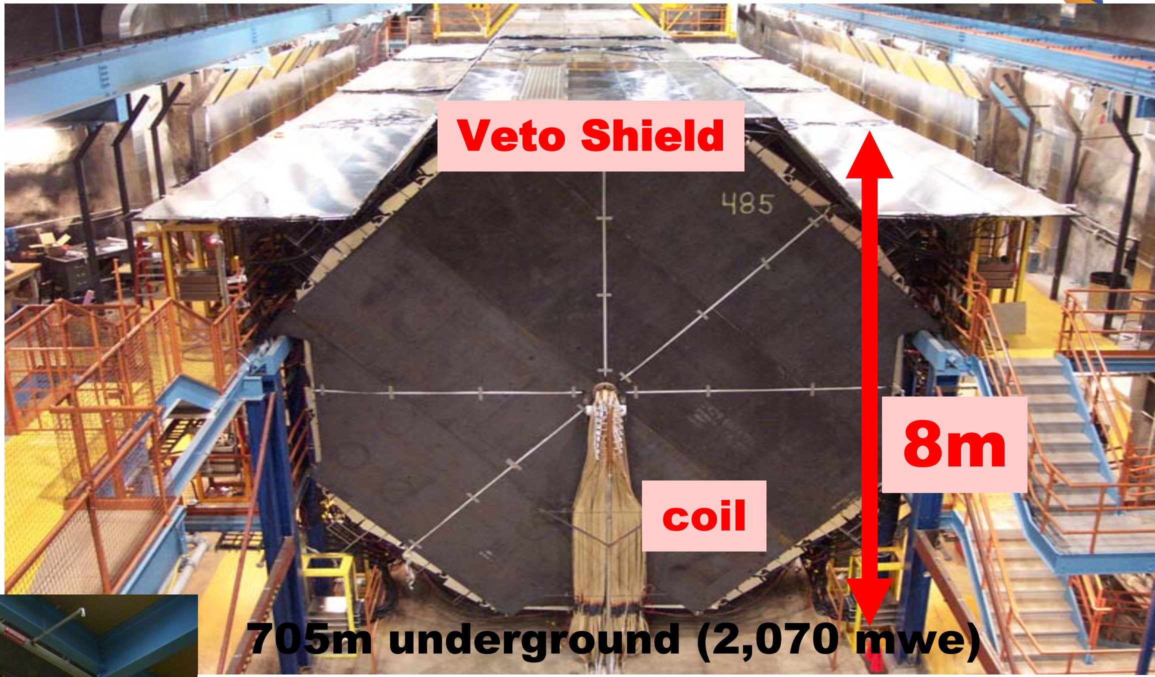
ν target region



μ spectrometer region

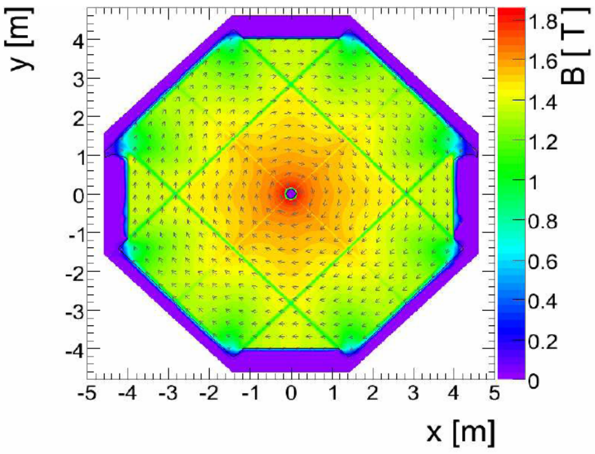
Far Detector – 735.3 km away (Soudan Mine, Mn)

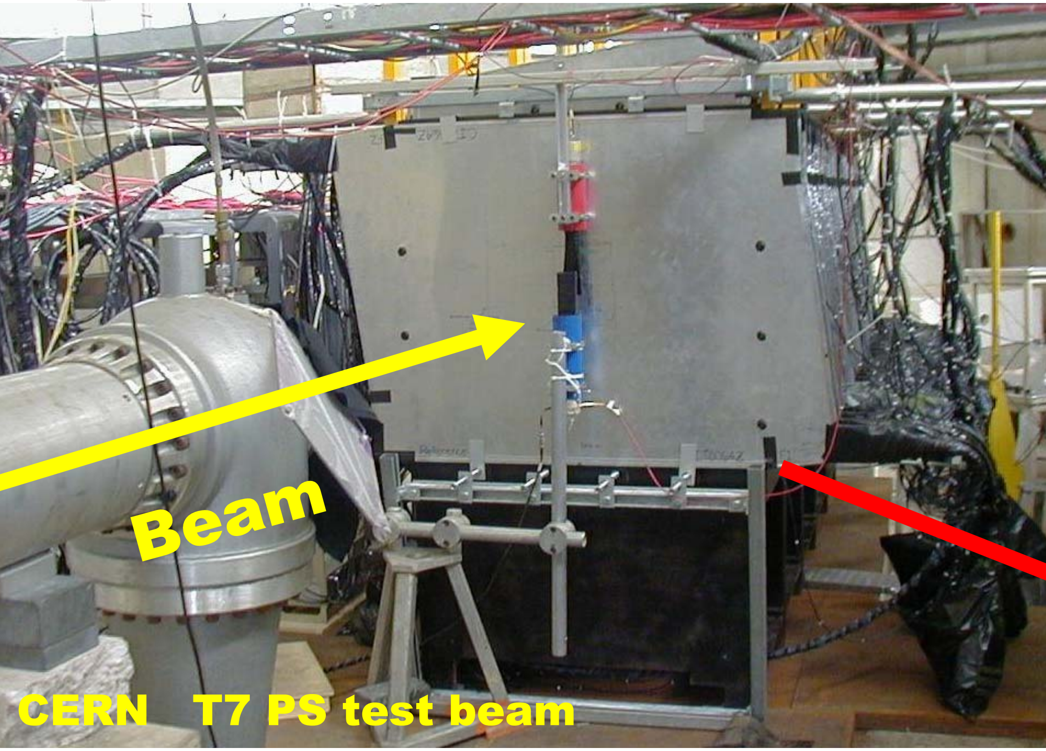
- 2 Supermodules
- 5.4 kT
- 484 scint. planes
- CR veto shield (2,070mwe)
- B ~ 1.5T (R=2m)
- 93,120 strips (4.1 x 1.0 cm)
- 8-fold MUXed 2-ended readout
- 1551 M16s
- 722 km of WLS fiber
- 794 km of clear fiber
- HAD = 56% / $E^{1/2}$
- EM = 23% / $E^{½}$



Running since July 2003

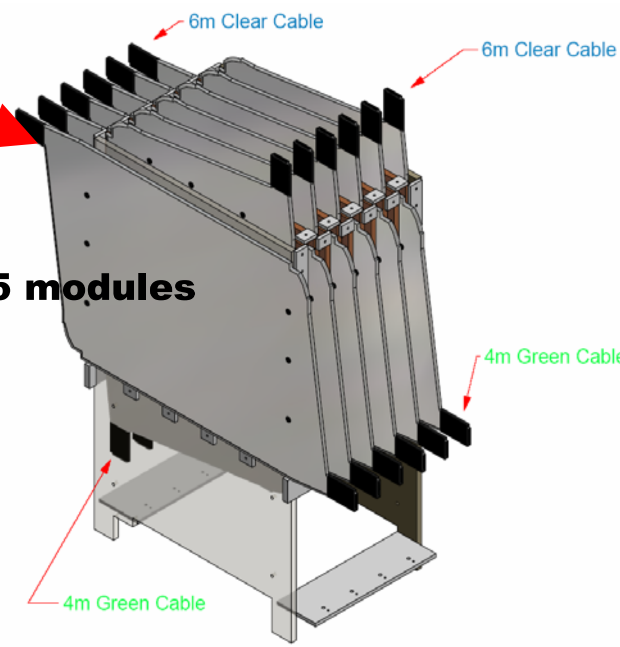
Scintillator Plane
(8 modules, 192 strips)





MINOS is a 3-detector Experiment!

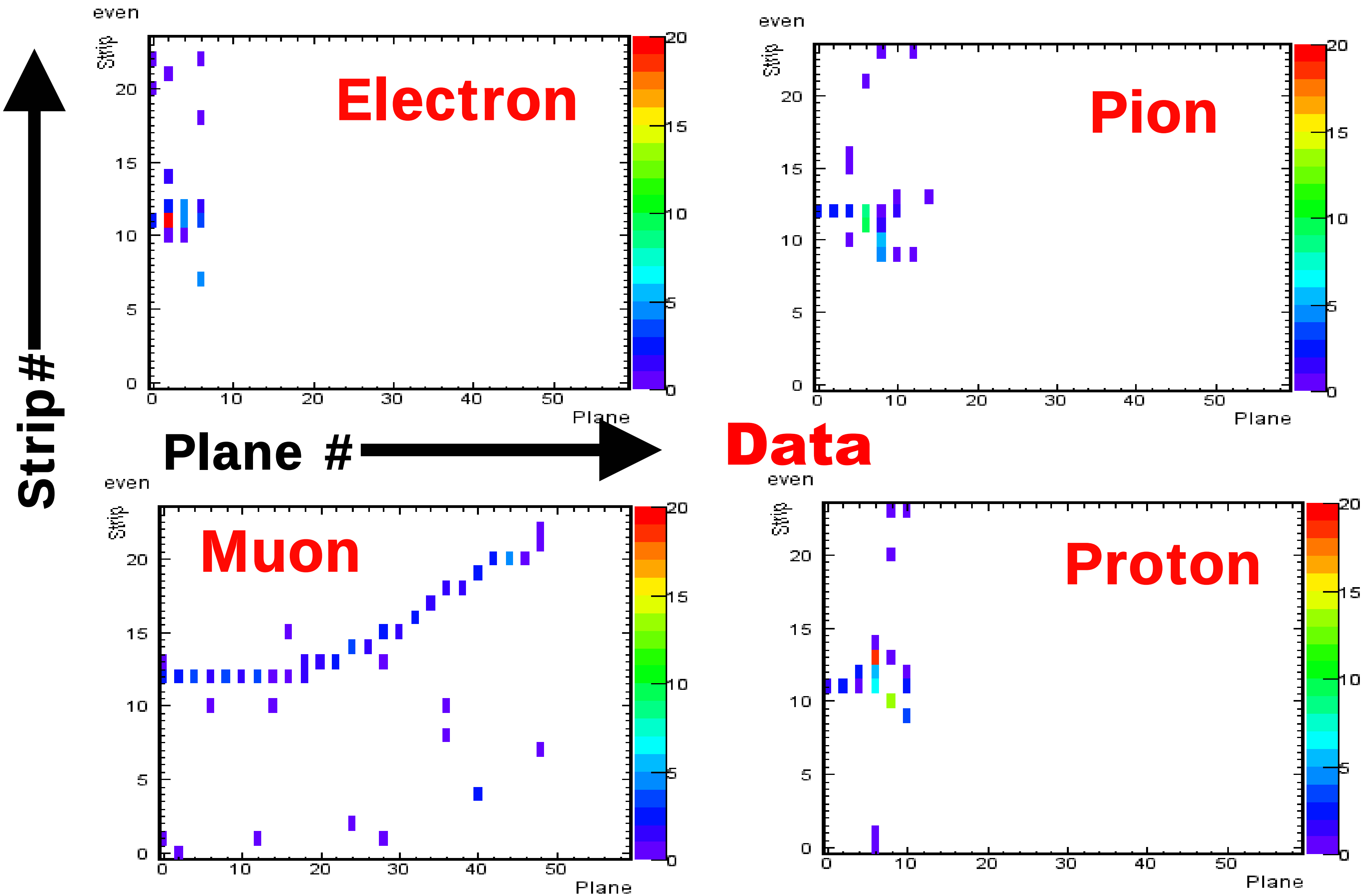
- 5 tons (5 modules for moving)
- 1 m x 1 m x 3.7 m
- 60 MINOS planes
- Long WLS andClear fiber cables
- No B field
- 24 strips/plane (a total of 1440 strips)
- X-Y views
- FarDet and/or NearDet readout



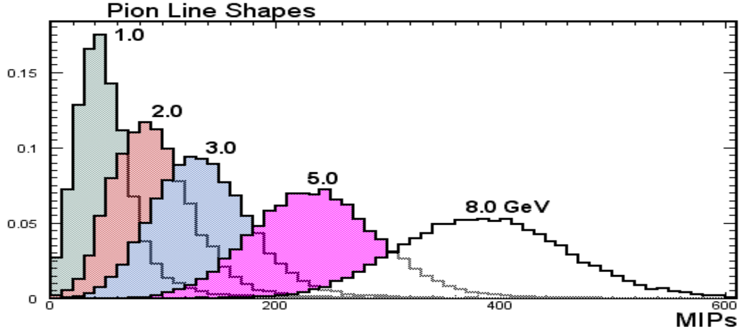
1 of 5 modules

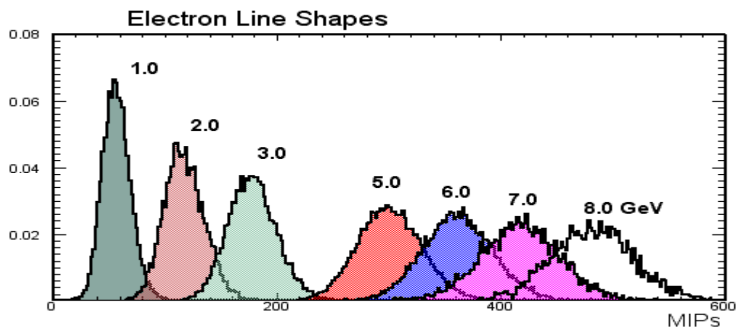
- ◆Exercise a full MINOS calibration scheme
- ◆Determine the absolute energy scale to <5%
- ◆Establish relative energy scale <2%
- ◆Energy and topology response
- ◆Monte Carlo tuning
- ◆Beam p,π,e,μ 05-10 GeV/c
- ◆Cosmic ray muons (stopping)

MINOS Calibration Detector – 2 GeV events

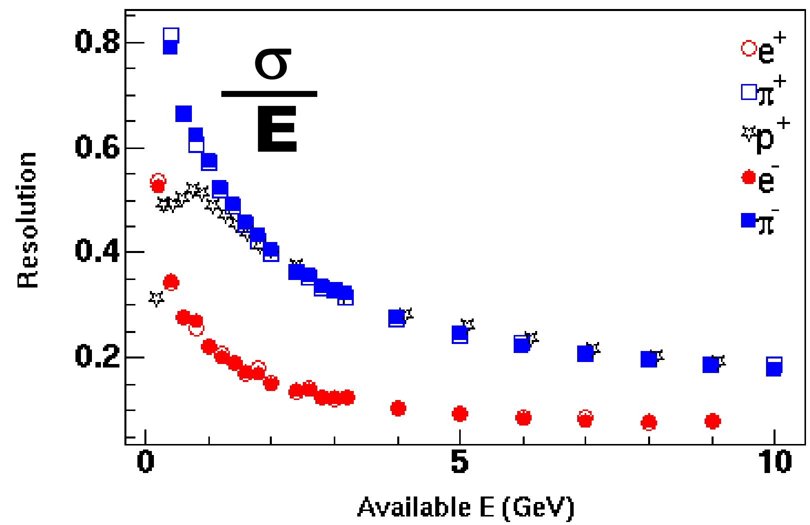


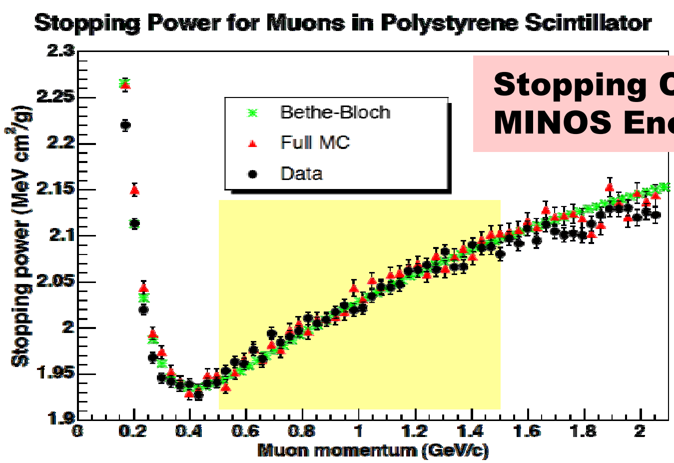
MINOS Calibration Detector Response





Energy resolution



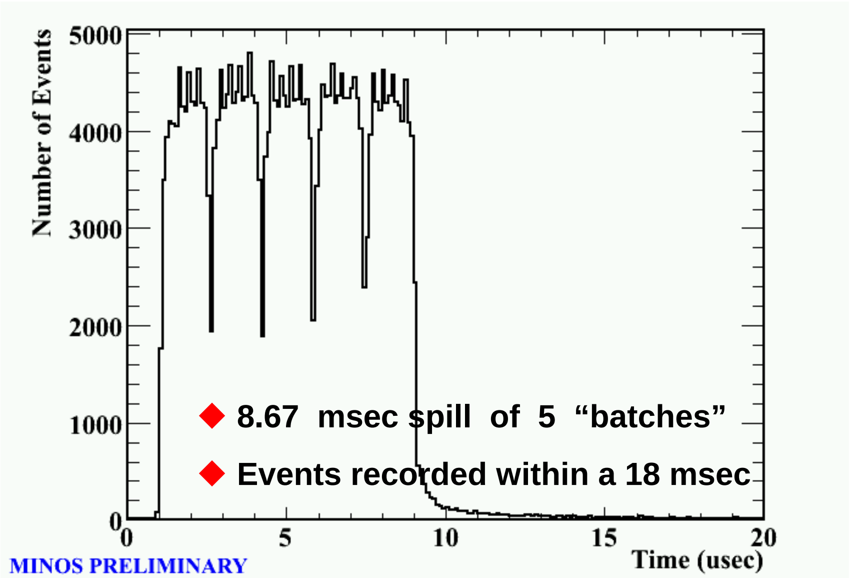


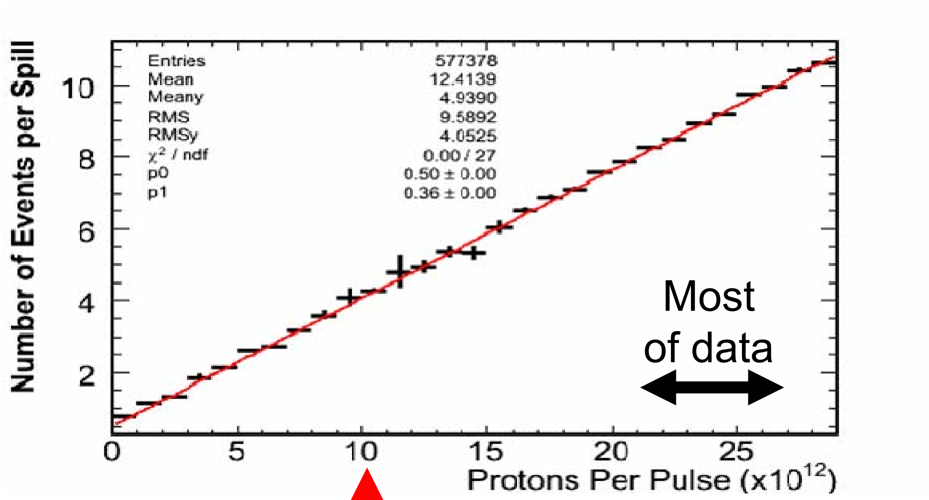
Stopping CR muons:
MINOS Energy Unit (MEU)

Had: $\frac{56\%}{\sqrt{E}} \oplus 2\%$

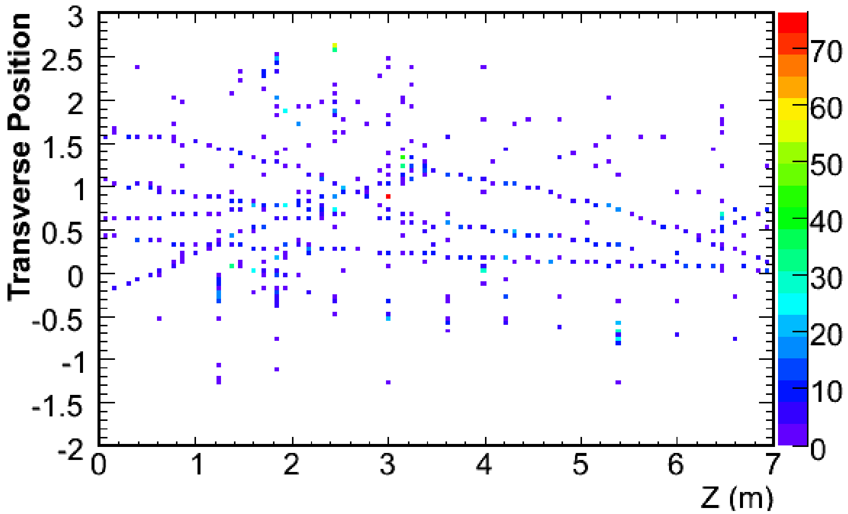
EM: $\frac{21.4\%}{\sqrt{E}} \oplus \frac{4.1\%}{E}$

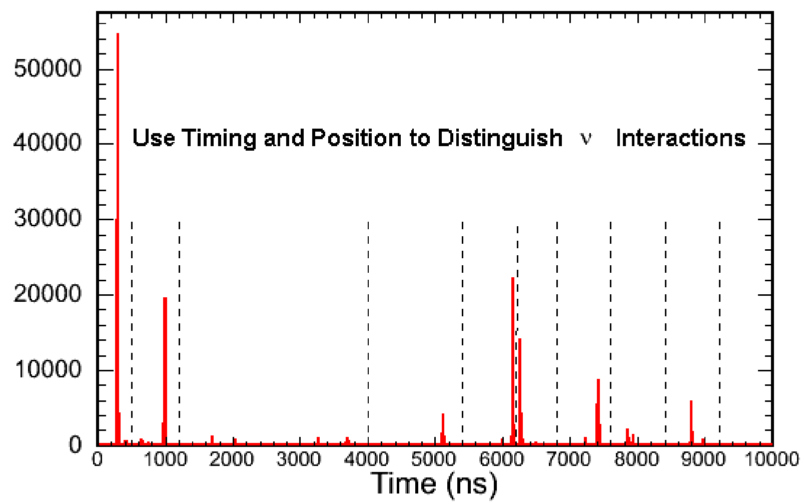
Near Detector spill





10^{13} **protons per pulse**

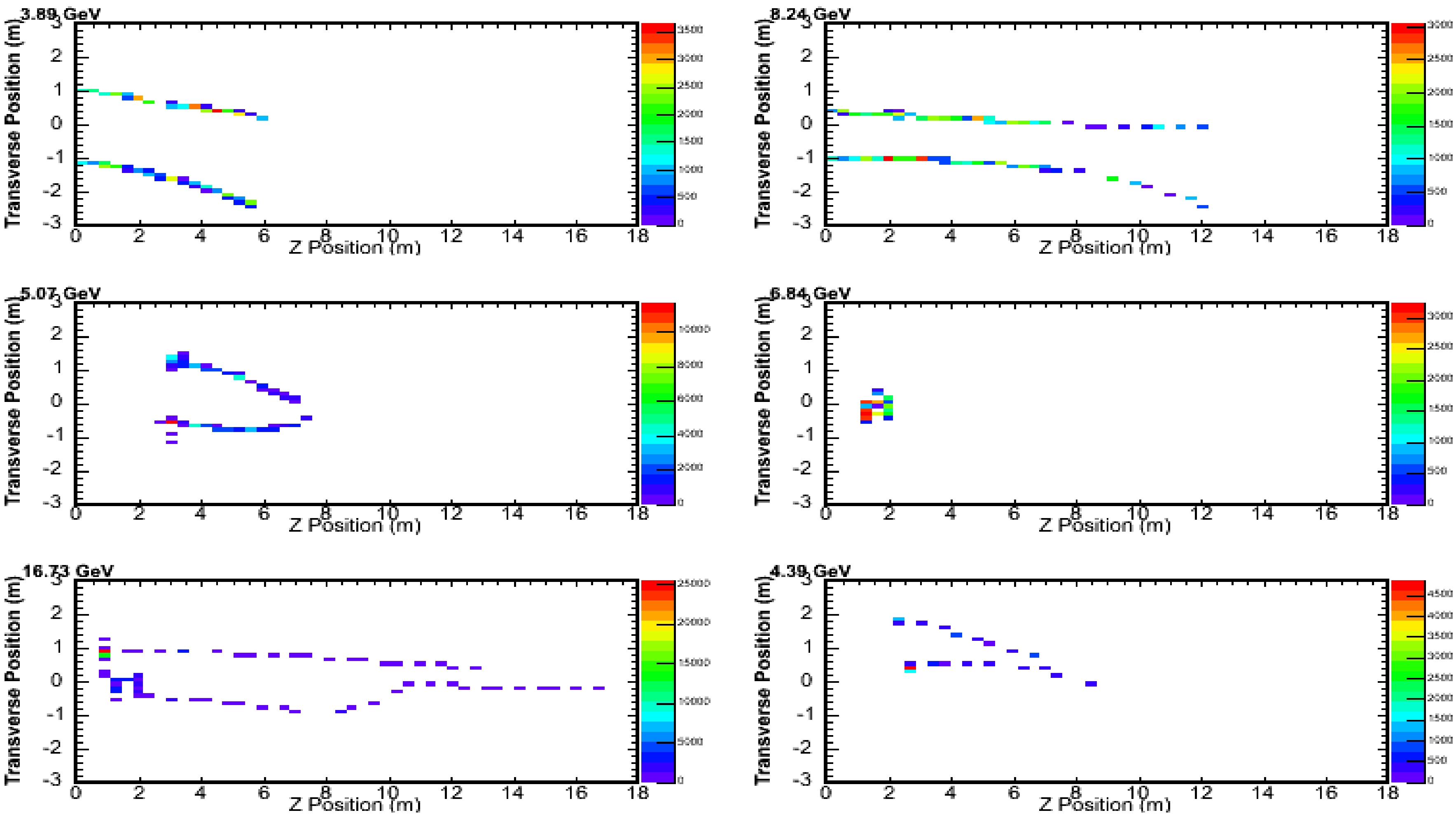




New experimental challenges in neutrino physics - intensity

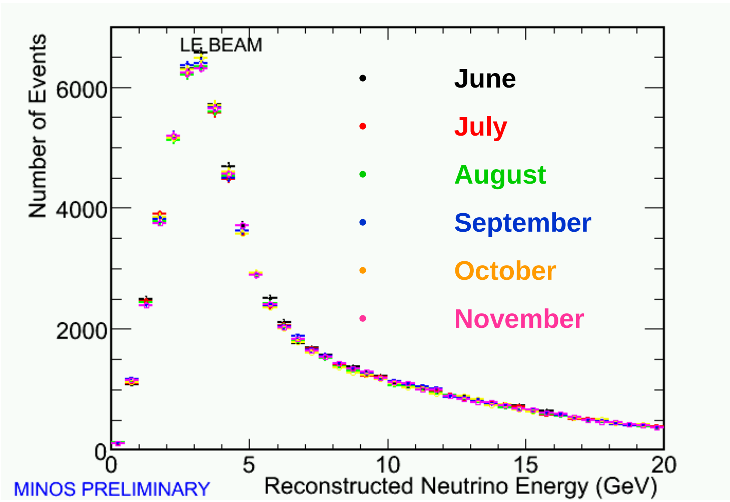
Near Detector spill

1 spill lasts ~10 μs

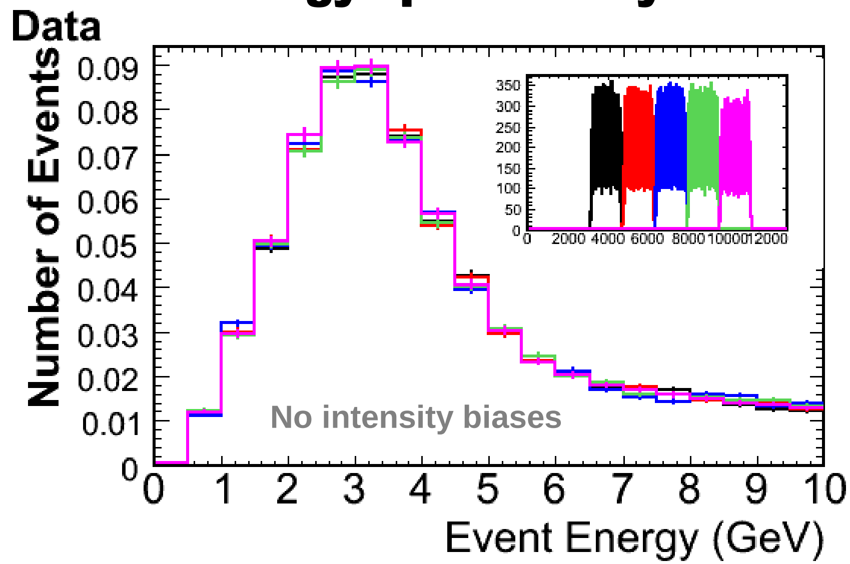


Near Detector data stability

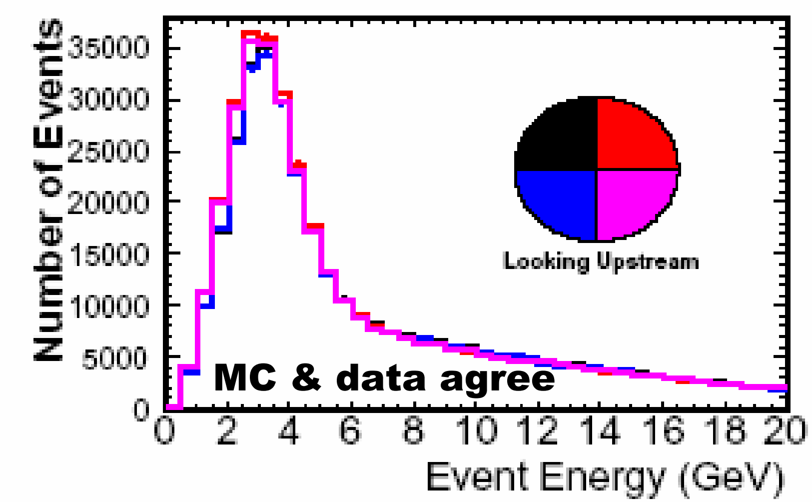
Energy spectrum by Month



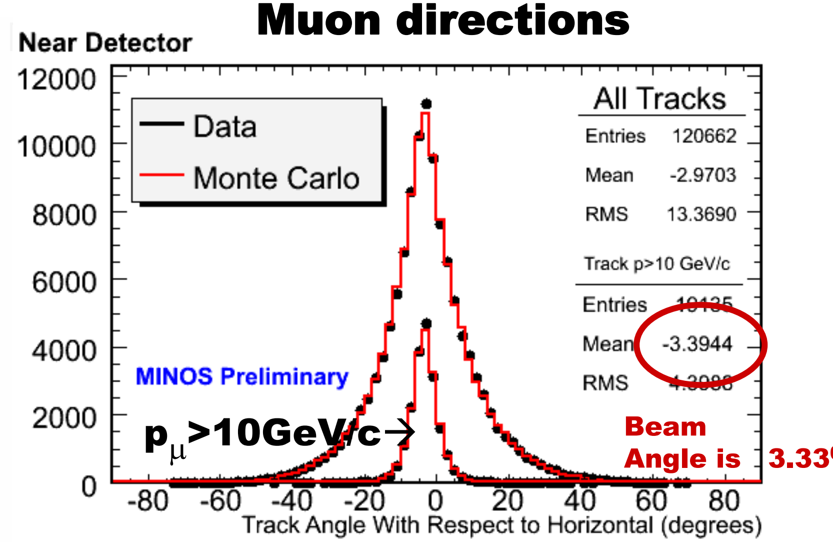
Energy spectrum by batch



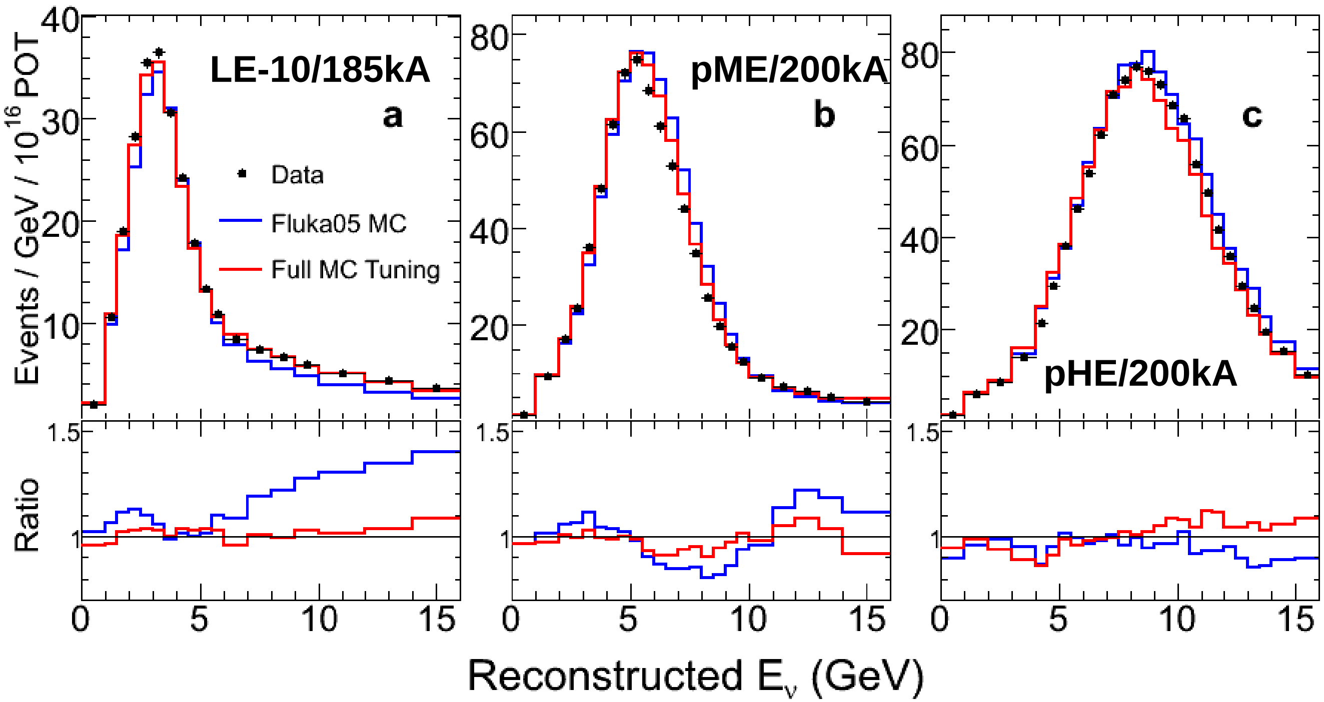
No reconstruction biases



Muon directions

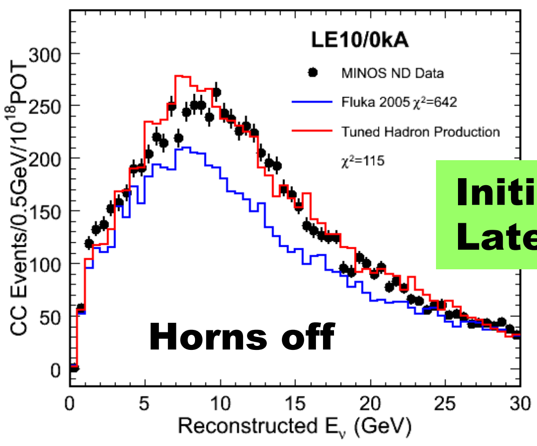


Hadron production tuning

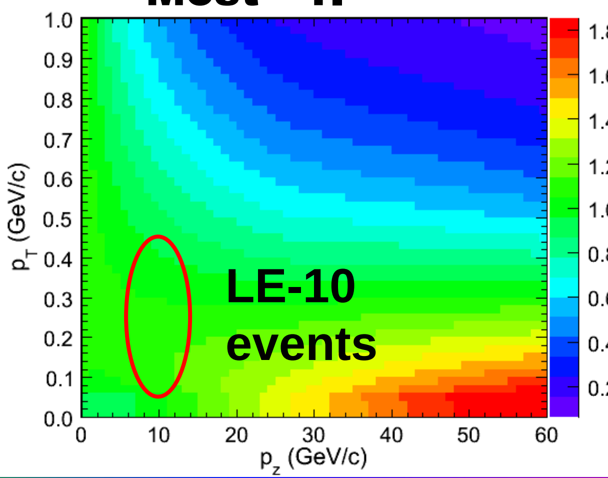


Tuning factors (weights) applied as a function of hadronic x_F and p_T.

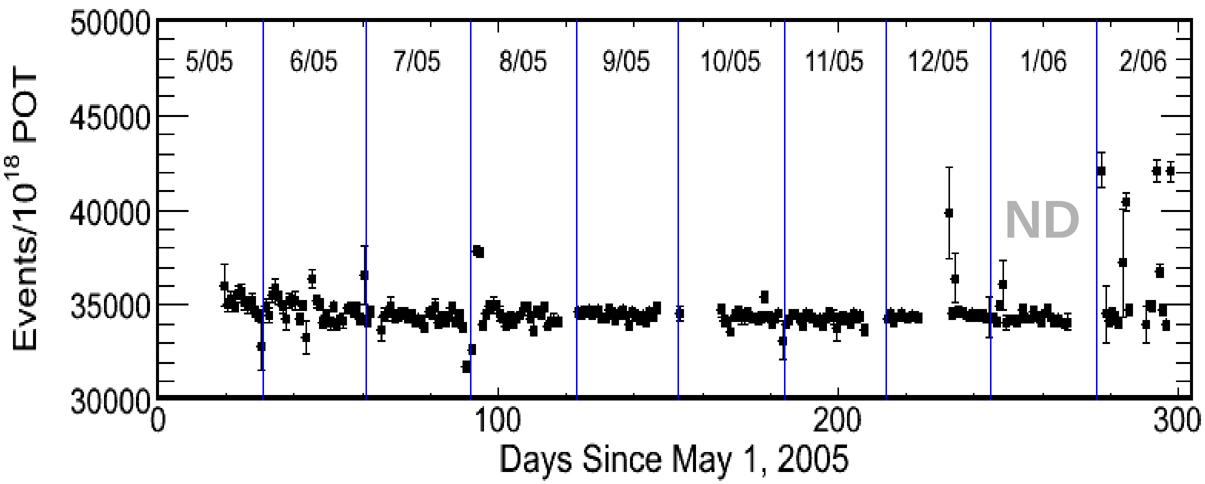
Most ~1.



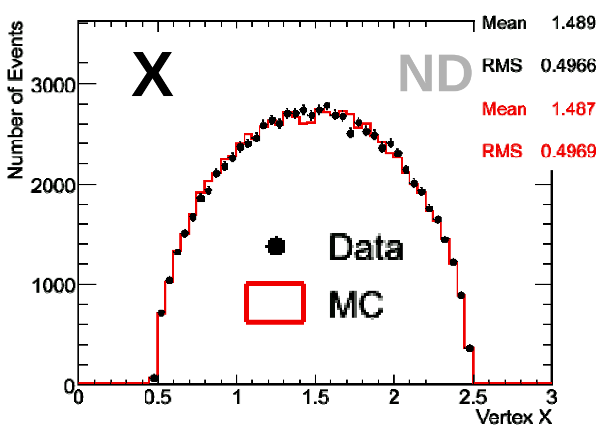
Initially predicted,
Later used in the fit

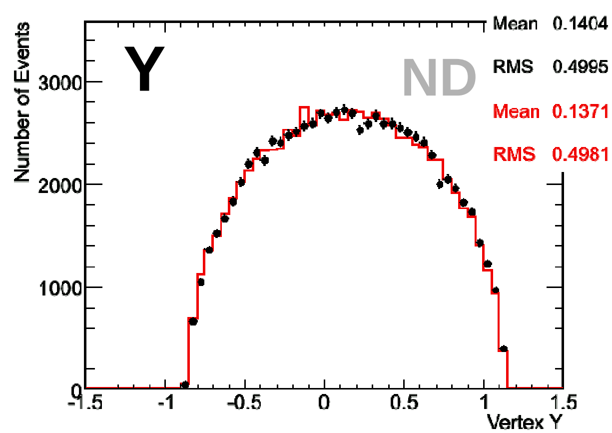


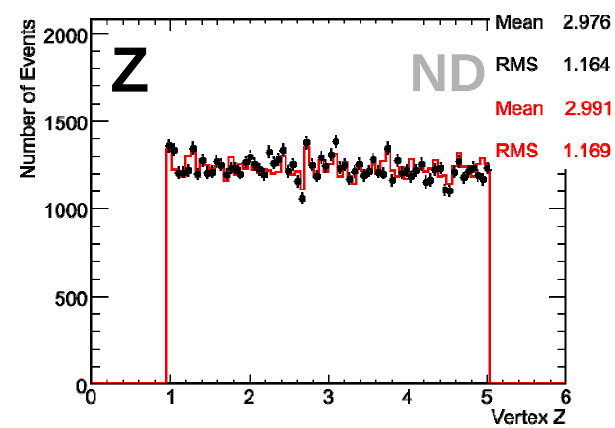
Near detector rate & event vertices



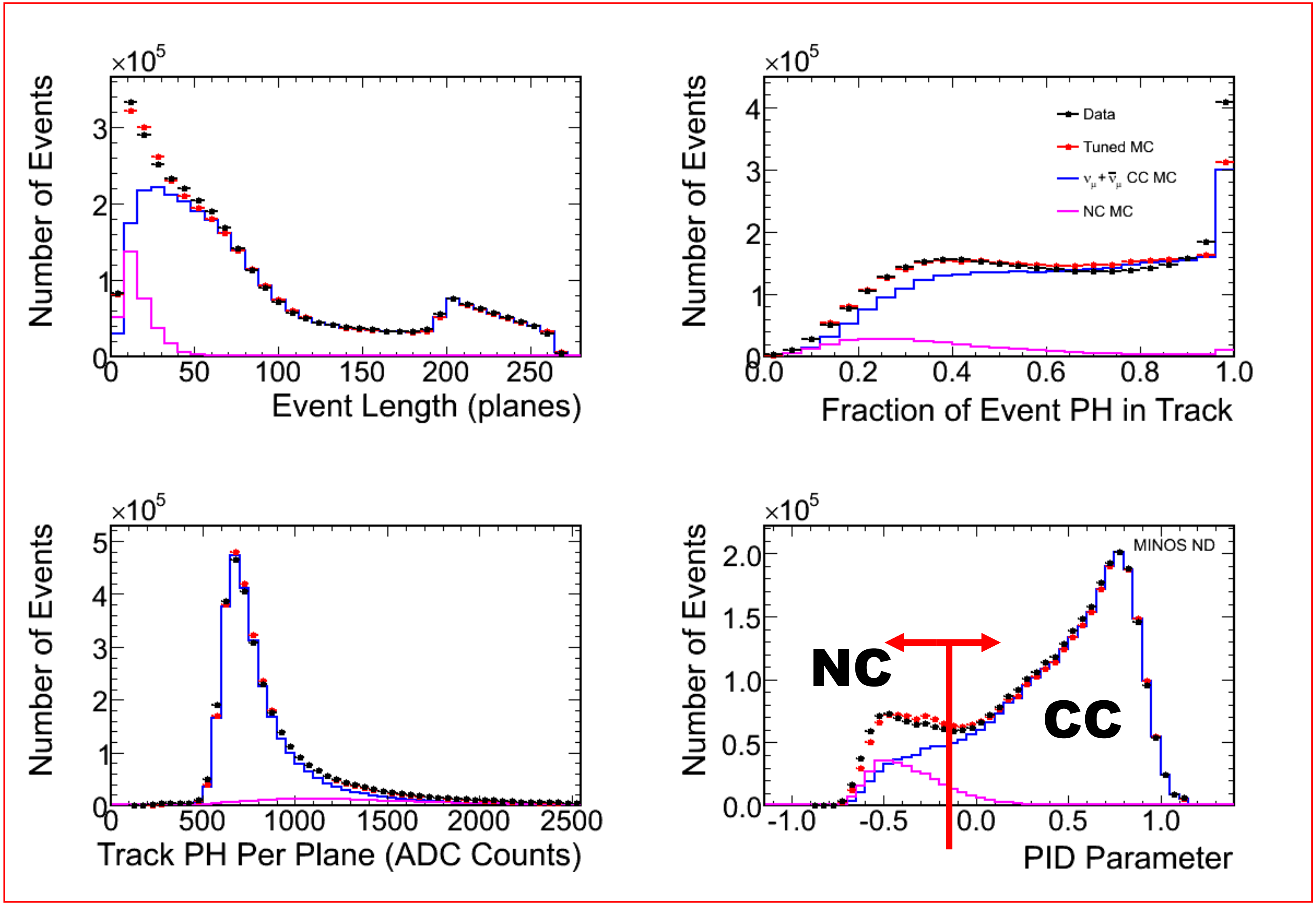
- **Stable data**
- **Took several special runs**
- **MC reasonably well agrees with data**







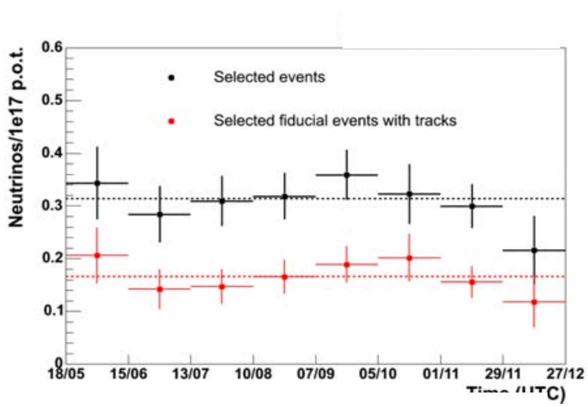
Event classification – Near Detector

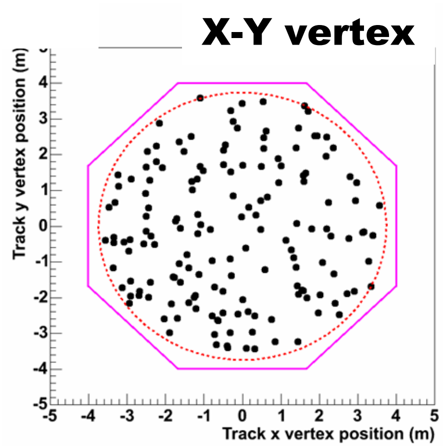


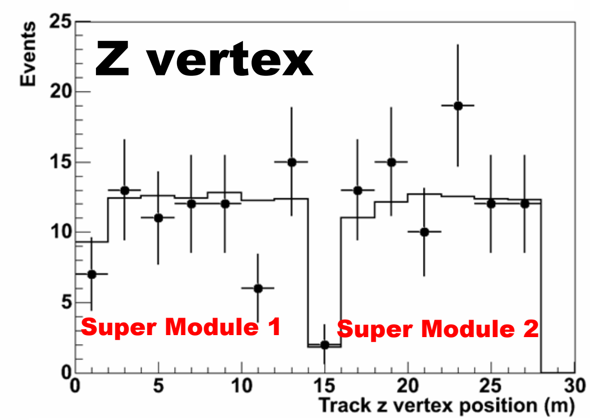
Far Detector events - blind analysis

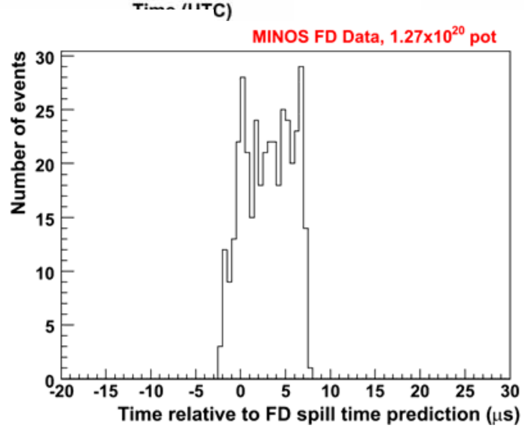
- The blinding procedure hides an unknown fraction of Far Detector events based on their length and total energy deposition
- Unknown fraction Far Detector data was "open"

  (used to perform extensive data quality checks)
- Remaining fraction was "hidden"
- Once all analysis details were specified, "the box was open" (i.e., two data sets were combined and analyzed as one final set)



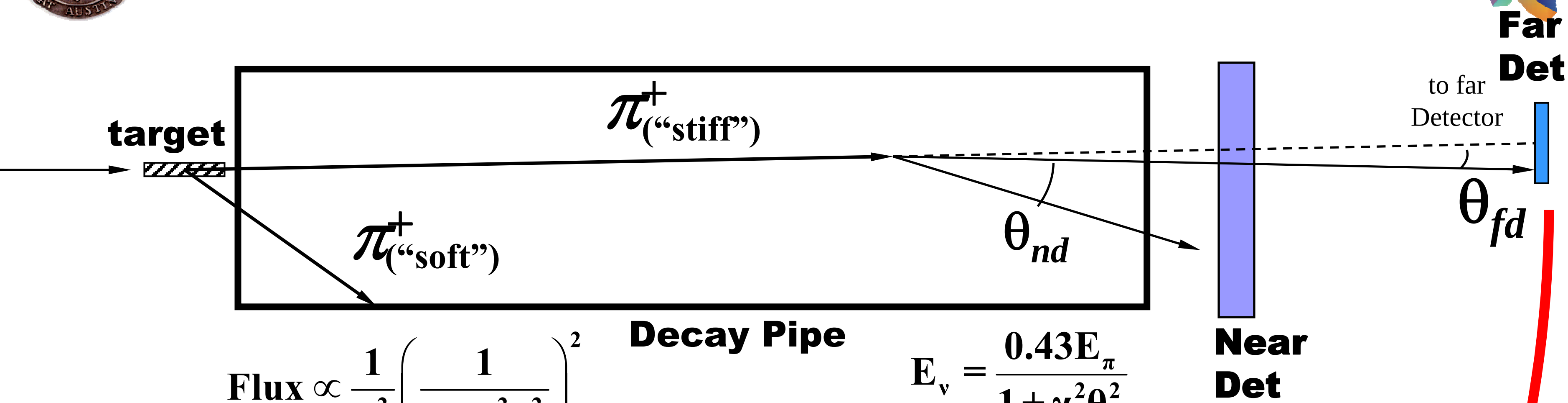






Require the muon angle < 53^0 wrt beam direction → CR bkg ~ < 0.5 event

4 methods for predicting the Far Det spectrum



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

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

4 methods of predicting the unoscillated CC energy spectrum from the Near to Far:

1) Near detector fitting:

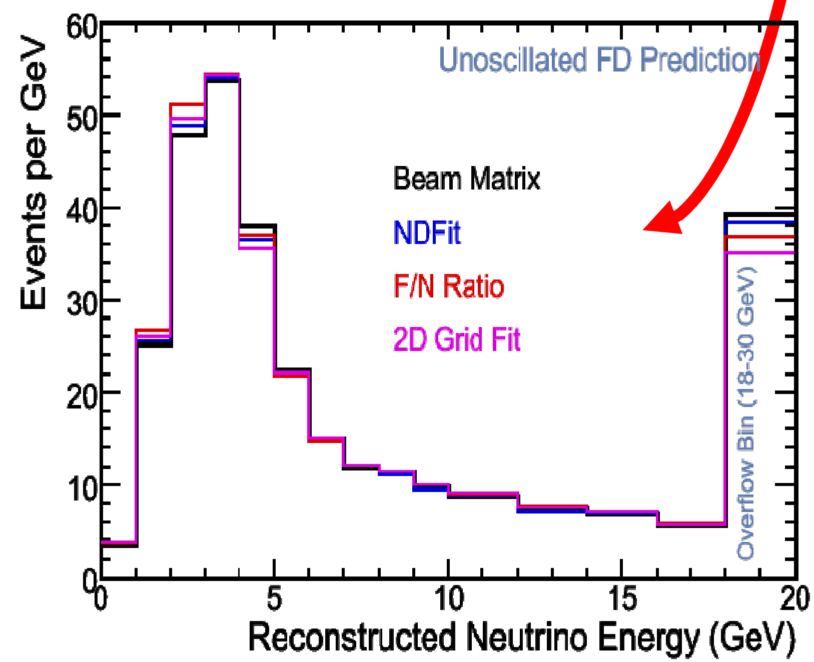
- fit Near E_ν spectra or E_ν – y grid with MC → employ for the FD prediction.

2) Extrapolation: scale bin-by-bin (F/N) or use a transfer matrix

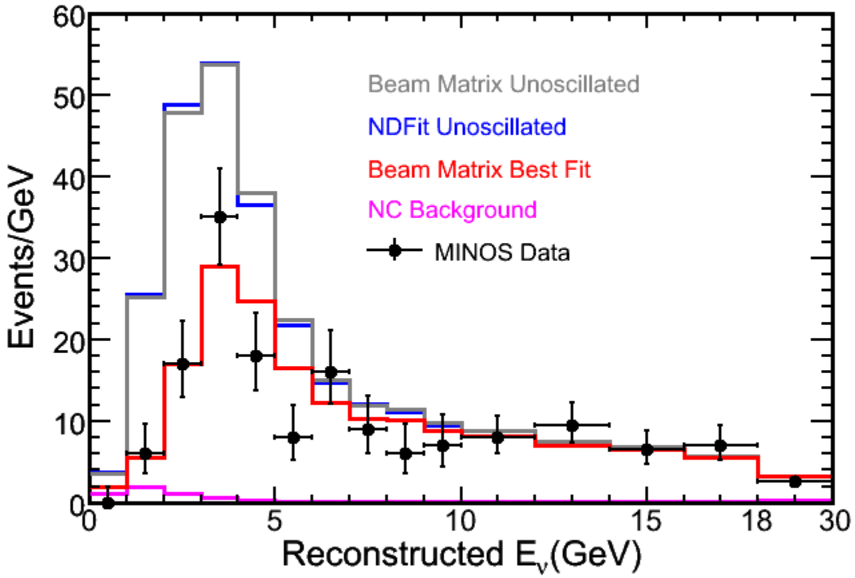
Official results with:

"Beam matrix"

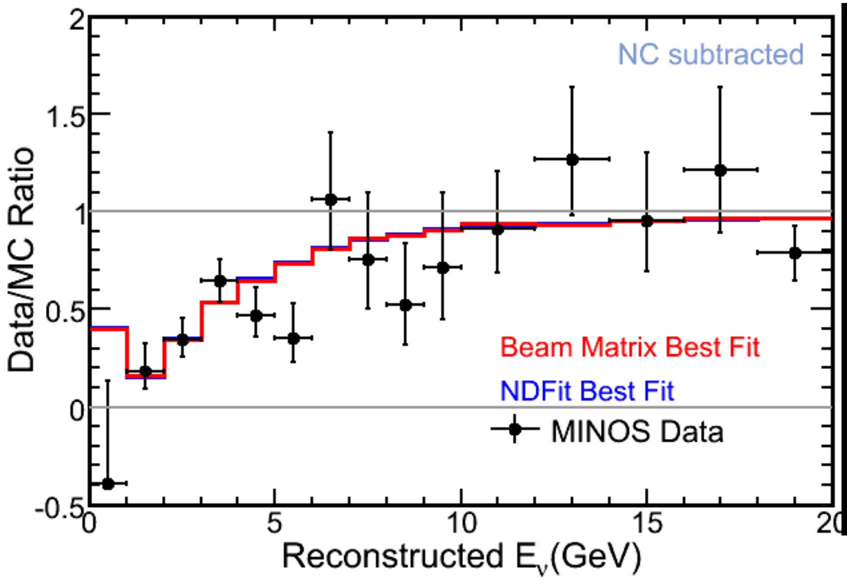
(with and "ND fit" check).



CC disappearance and energy spectra: observed versus expected (no oscillations)

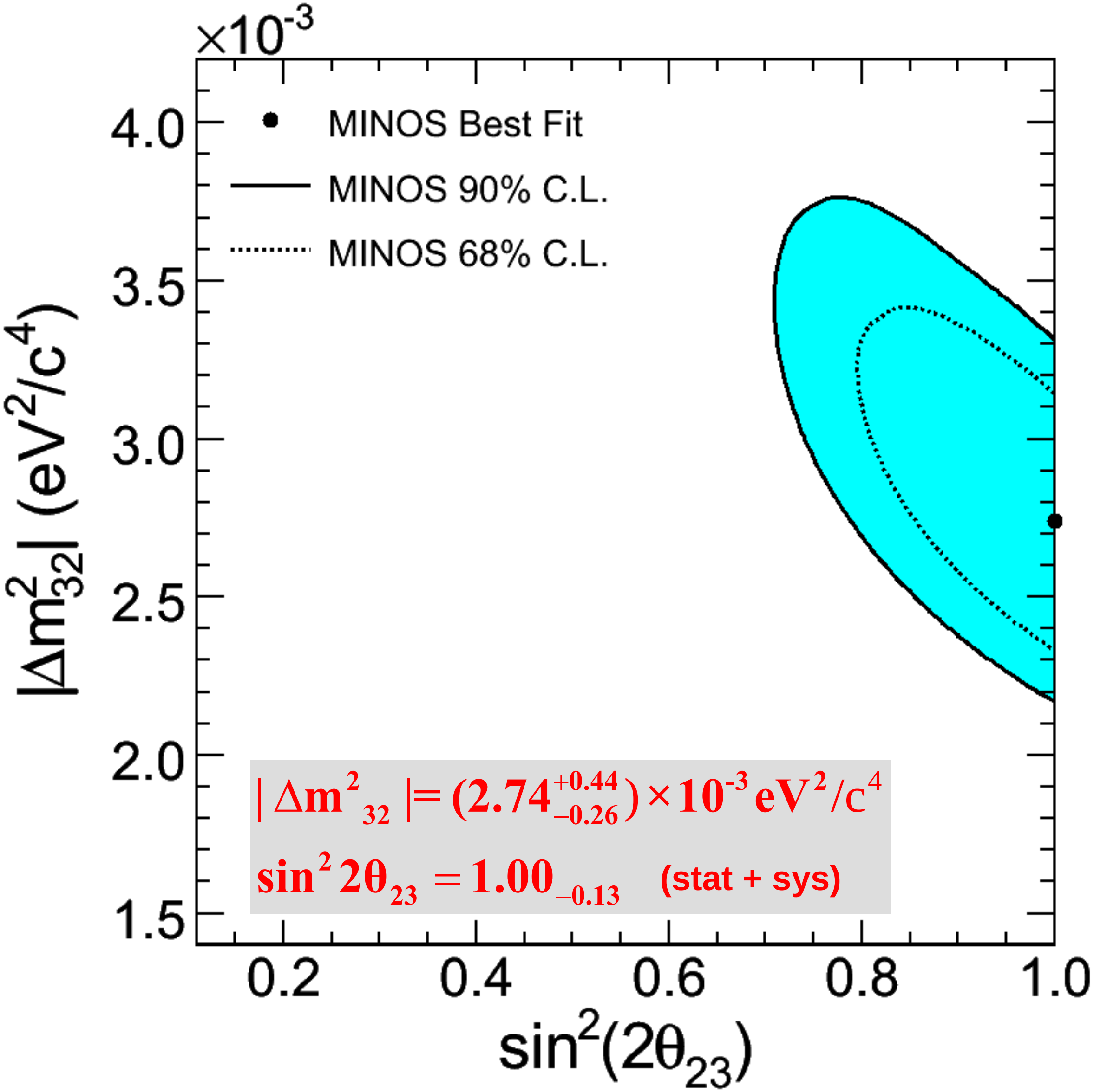


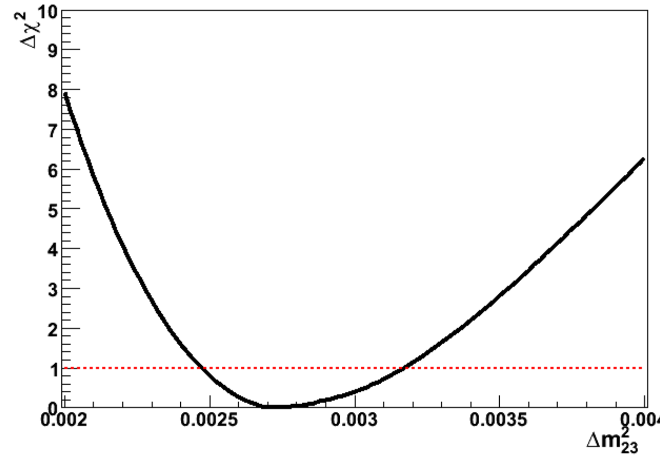
Energy range	Observed	Expected (no oscillations)
<30 GeV	215	336.0+/-14.4
<10 GeV	122	238.7+/-10.7
<5 GeV	76	168.4+/-8.8



Preliminary Uncertainty	Level of uncert.	Δm^2 (10^{-3} eV^2)	$\sin^2 2\theta$
Near/Far normalization	± 4%	0.050	0.005
Absolute had. energy	± 11%	0.060	0.048
NC contamination	± 50%	0.090	0.050
All other syst. uncert.		0.044	0.011
Total Systematic (summ in quadrature)		0.12	0.07
Statistical Error (data)		0.36	0.12

Δm_{32}^2 – $\sin^2(2\theta_{23})$

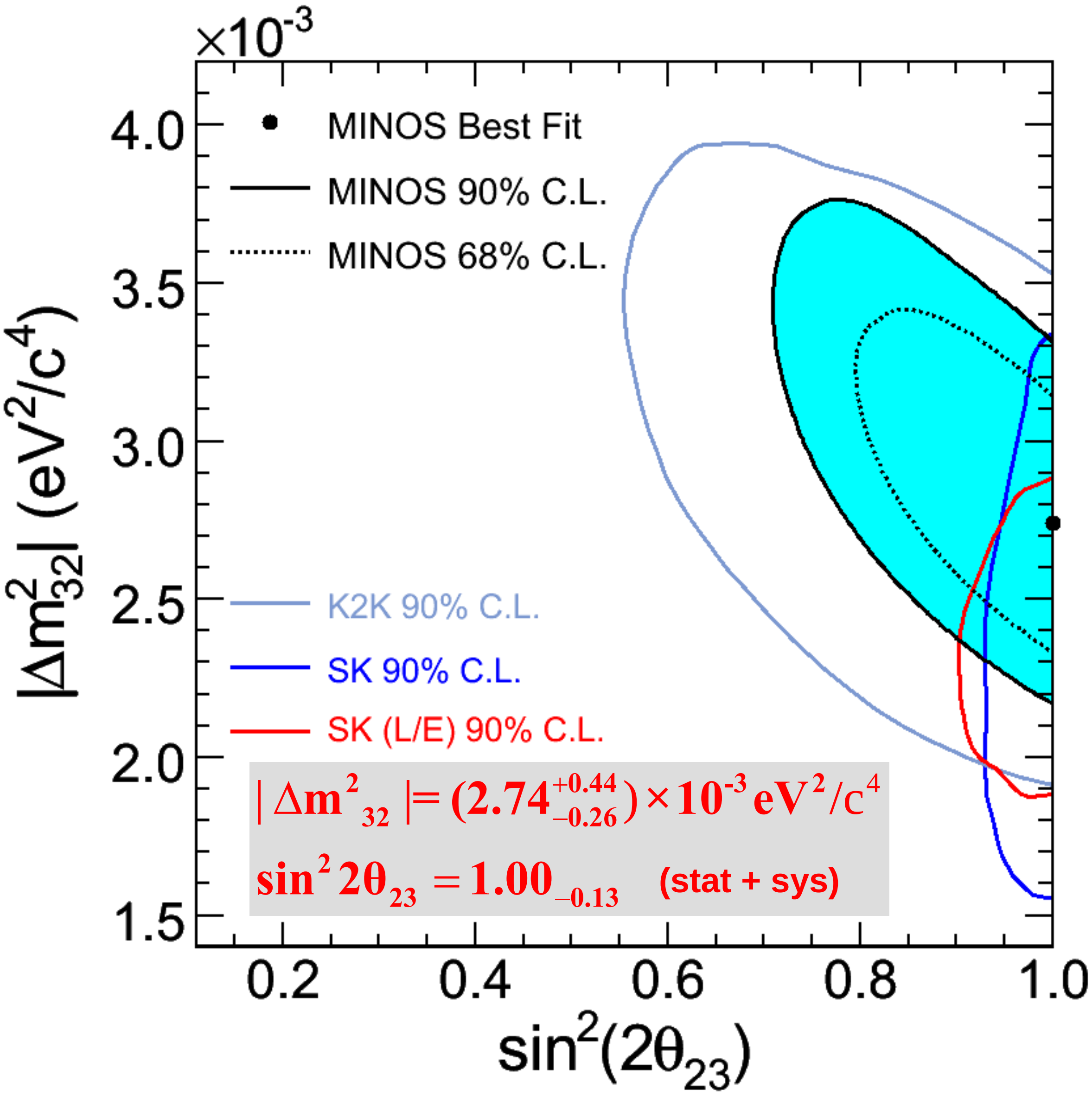




Systematic uncertainties incorporated in the fit.

Constrained to $\sin^2(2\theta_{23}) \leq 1$.

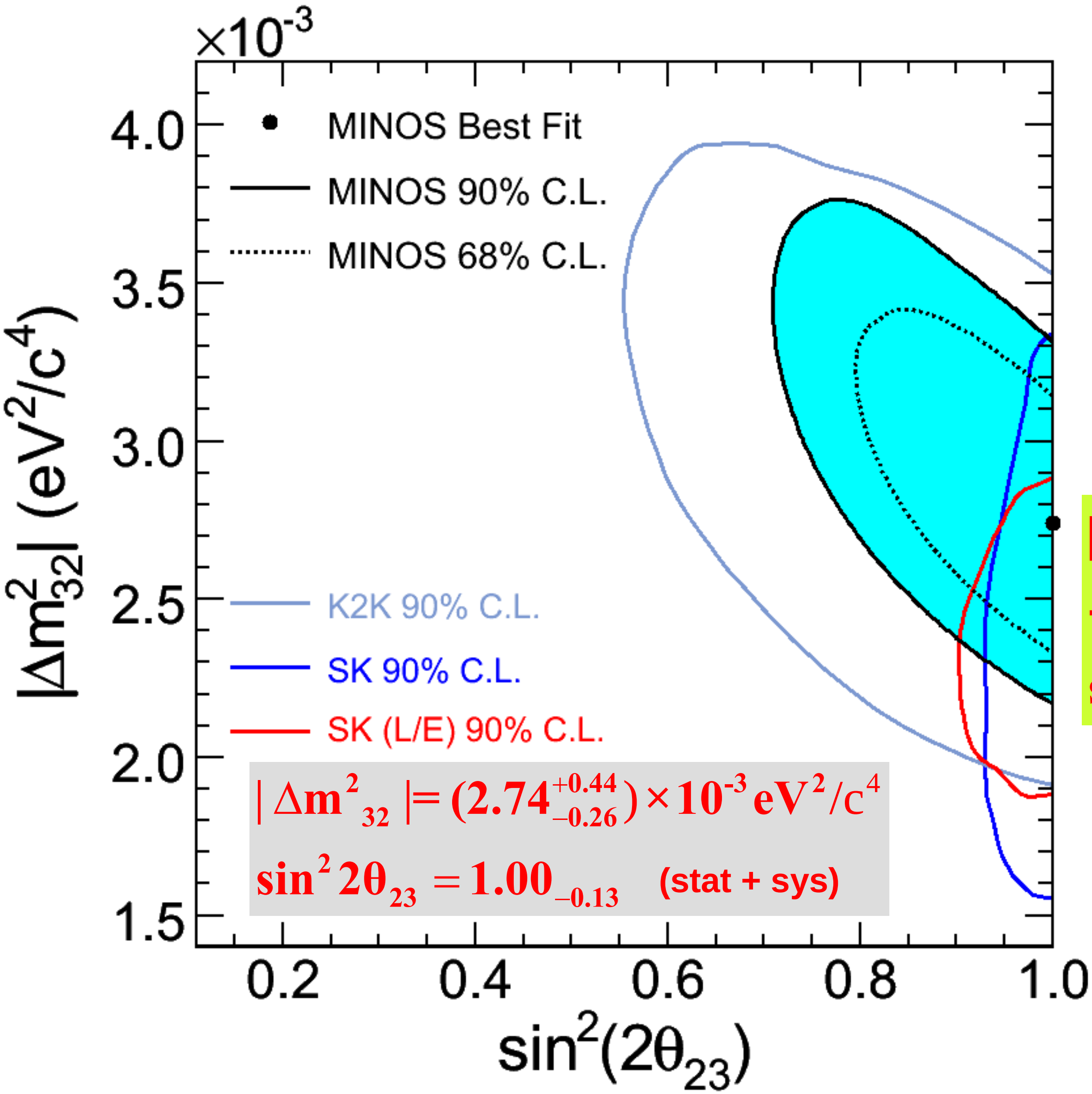
$\Delta m_{32}^2 - \sin^2(2\theta_{23})$



Systematic uncertainties incorporated in the fit.

Constrained to $\sin^2(2\theta_{23}) \leq 1$.

$\Delta m_{32}^2 - \sin^2(2\theta_{23})$



$|\Delta m^2_{32}| = (2.74 \pm 0.28) \times 10^{-3}\,\mathrm{eV}^2/c^4$

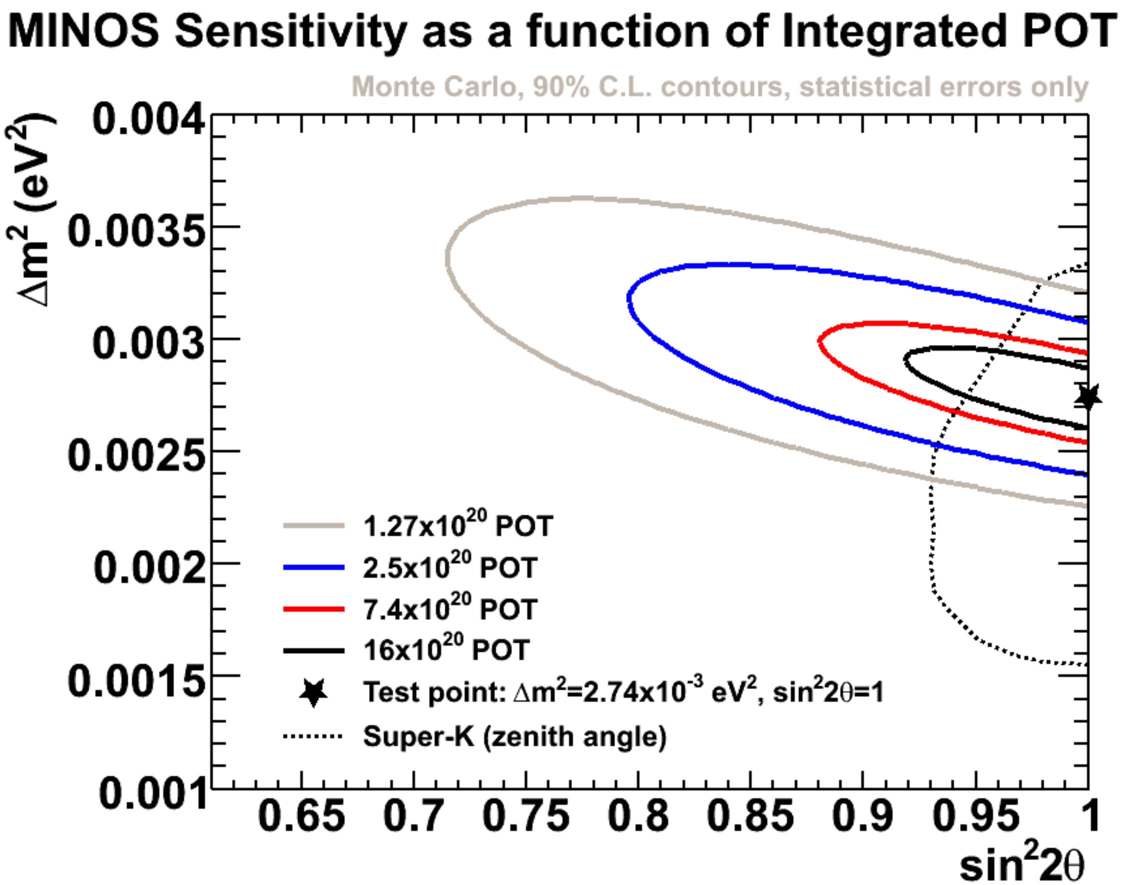
- if -

$\sin^2 2\theta_{23} \equiv 1.00$

Systematic uncertainties incorporated in the fit.

Constrained to $\sin^2(2\theta_{23}) \leq 1$.

Future of MINOS
(need protons!)



Statistical errors only 90% C.L.

Summary

- MINOS is under way: based on 1.27 x 10^{20} pot we observe disapearance of ν_μ with > 6.2σ significance (E_ν < 10 GeV)
- Analysis indicates that the data are consistent with neutrino oscillations:

$$|\Delta m^2_{32}| = (2.74^{+0.44}_{-0.26}) \times 10^{-3} \mathrm{eV}^2/c^4$$

$$\sin^2 2\theta_{23} = 1.00_{-0.13}$$

(stat + sys)

- Statistical uncertainties dominate current measurements
- MINOS is already competitive with best experiments to date
- Paper submitted to PRL; archived at hep-ex/0607088
- Near future:
  - analysis to search for sterile neutrinos
  - search for ν_e appearance (θ_{13})
- Will collect a lot more data