MINOS Oscillation Results from the First Year of Beam Exposure

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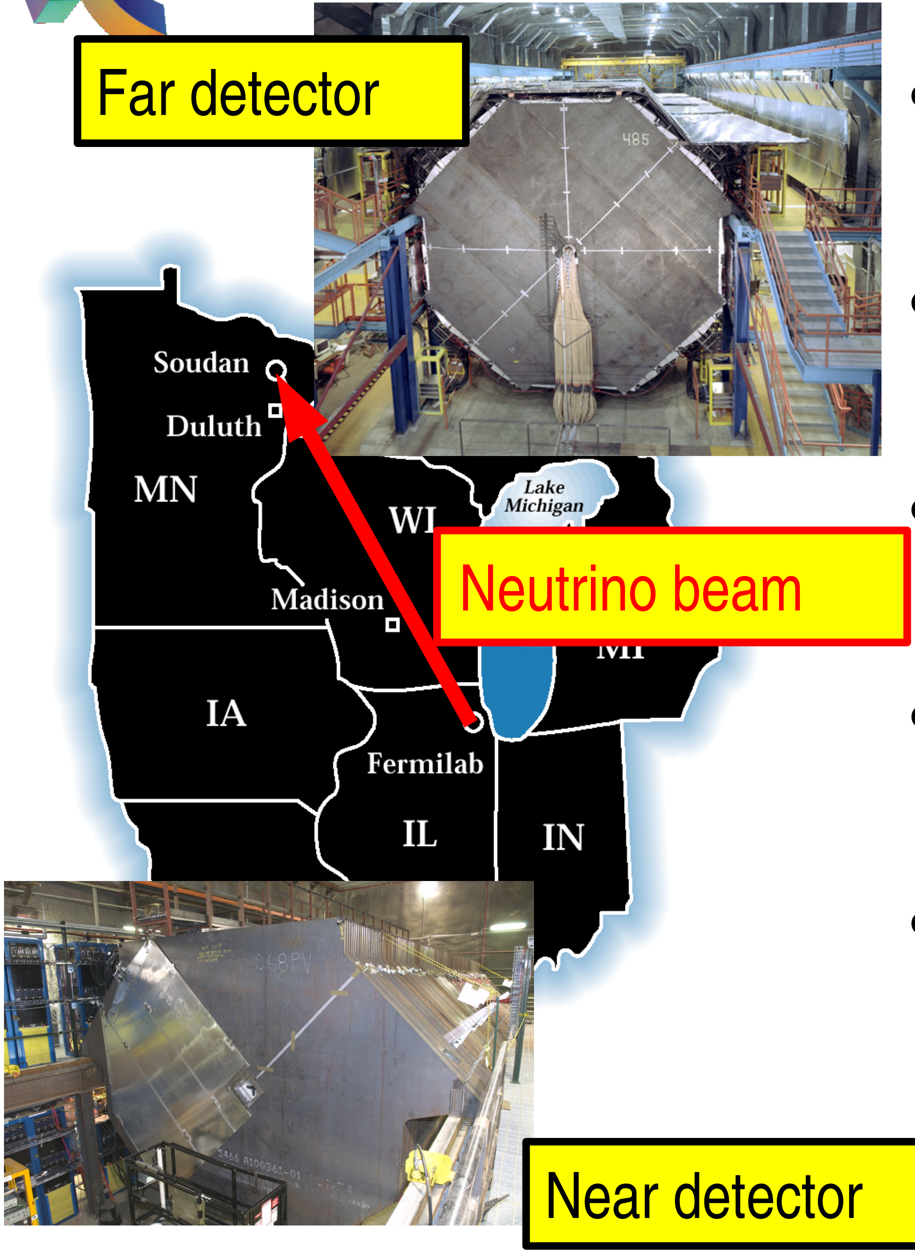
on behalf of the

MINOS Collaboration

Overview

- Introduction to NuMI and MINOS
  - Physics Goals
  - NuMI beam and MINOS detectors
- Experiment operation
  - Data collection and calibration
  - Event reconstruction and selection
  - Near and far detector distributions
- Oscillation Analysis for first year of data
  - Prediction of the Far Detector spectrum (no oscillations)
  - Oscillation fits, parameter extraction for 1.27×10^{20} protons on target

MINOS Experiment



- MINOS = Main Injector Neutrino Oscillation Search
- Muon neutrino beam produced by 120 GeV/c Main Injector at Fermilab
- Two functionally identical detectors, separated by 735km
- Near Detector at Fermilab measures beam composition, energy spectrum
- Far Detector at Soudan, MN searches for distortions w.r.t. the Near Detector

MINOS Collaboration

32 institutions, 175 scientists, Funding: DOE, NSF, PPARC

Neutrino Oscillations

Eigenstates

$$\nu_e, \nu_\mu, \nu_\tau \Leftrightarrow \nu_1, \nu_2, \nu_3$$

Flavor Mass

MNS Mixing Matrix

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

Mixing

$$\Psi_\alpha = \sum_j U^*_{\alpha j} \Psi_j$$

Flavor Mass

Propagation (vaccum)

$$\Psi_\alpha(L) = \sum_j U^*_{\alpha j} \Psi_j \exp(-i L m_j^2 / 2\mathrm{p})$$

(L=distance)

Transition Probability

$$P(\nu_\alpha \rightarrow \nu_\beta) = \delta_{\alpha\beta} - 4 \sum_{i>j} \Re[U^*_{\alpha i} U_{\beta i} U^*_{\beta j} U_{\alpha j}] \sin^2(\Delta m^2_{ij} L/4E)$$

$$+ 2 \sum_{i>j} \Im[U^*_{\alpha i} U_{\beta i} U^*_{\beta j} U_{\alpha j}] \sin(\Delta m^2_{ij} L/2E)$$

$$\Delta m^2_{ij} = m^2_i - m^2_j$$

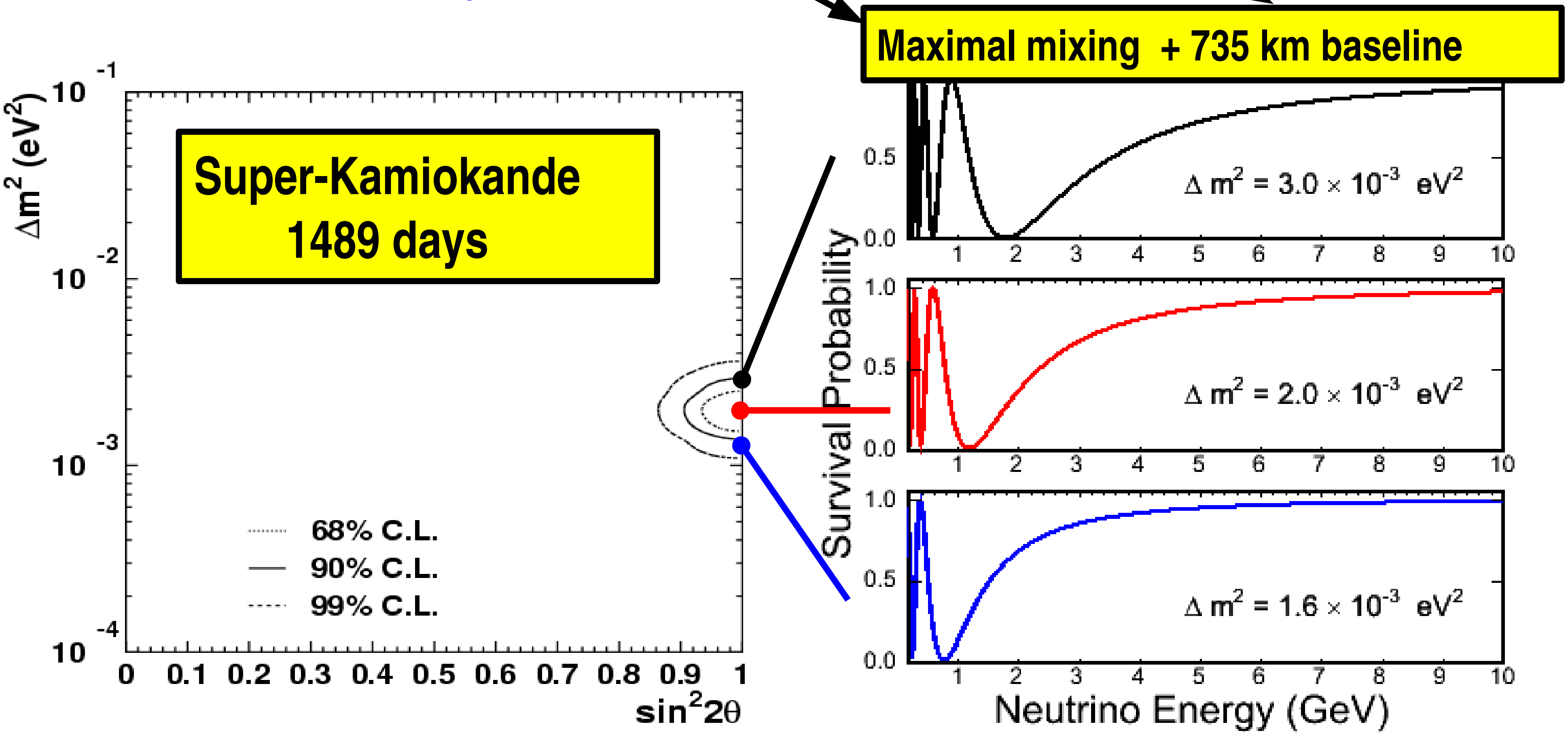
To be simplified!

ν_μ Disappearance

$$P(\nu_\mu \rightarrow \nu_e) = 1 - 4|U_{\mu 3}|^2 (1 - |U_{\mu 3}|^2) \sin^2(\Delta m^2_{23} L/4E)$$

$$= 1 - \sin^2(2\theta_{23}) \sin^2(\Delta m^2_{23} L/4E)$$

Survival Probability



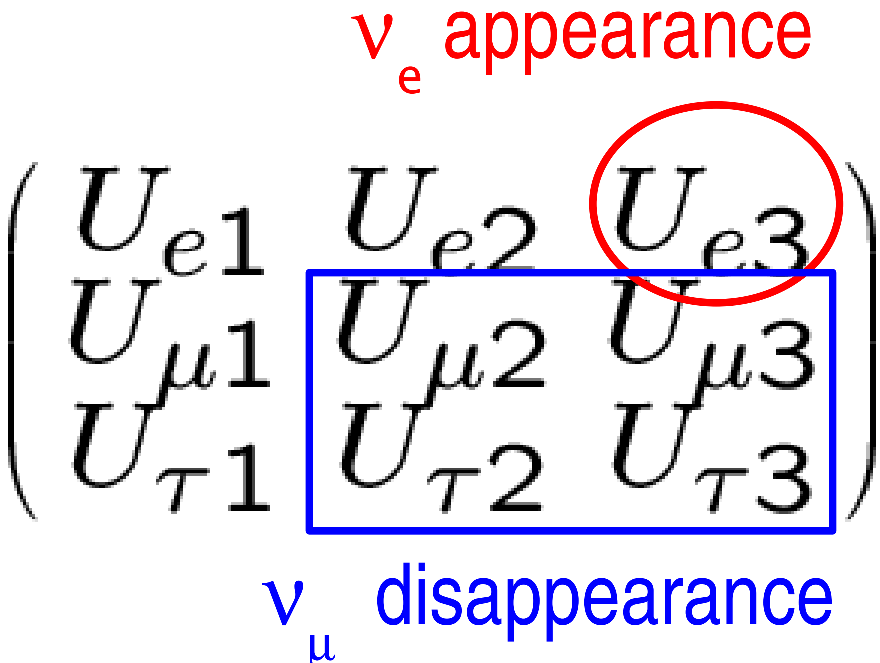
Maximal mixing + 735 km baseline

Super-Kamiokande 1489 days

MINOS Physics Goals

- Verify muon-neutrino diappearance
- Test oscillation hypothesis
  - rule out exotic phenomena (e.g. neutrino decay)
- Measure mixing parameters Δm^2_{23} and $\sin^2(2\theta_{23})$
- Search for sub-dominant $\nu_\mu \to \nu_e$ oscillations
- Place limit on $\nu_\mu \to \nu_s$
- Verify neutrinos and anti-neutrinos oscillate in the same way (CPT)

$$P(\nu_\mu \to \nu_e) \approx 4|U_{\mu 3}|^2 |U_{e 3}|^2 \sin^2(\Delta m^2_{23} L/4E)$$



ν_e appearance

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

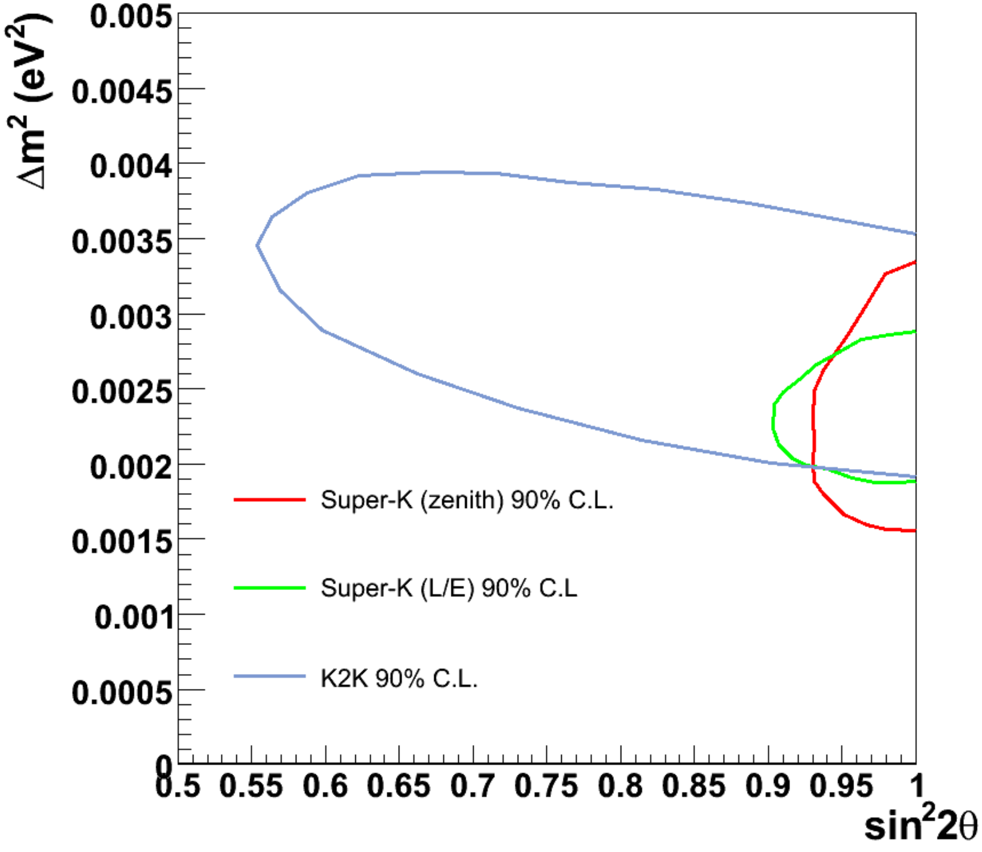
ν_μ disappearance

$$P(\nu_\mu \to \nu_e) = 1 - \underbrace{4|U_{\mu 3}|^2 (1 - |U_{\mu 3}|^2)}_{=\sin^2(2\theta_{23})} \sin^2(\Delta m^2_{23} L/4E)$$

Existing Parameter Measurements

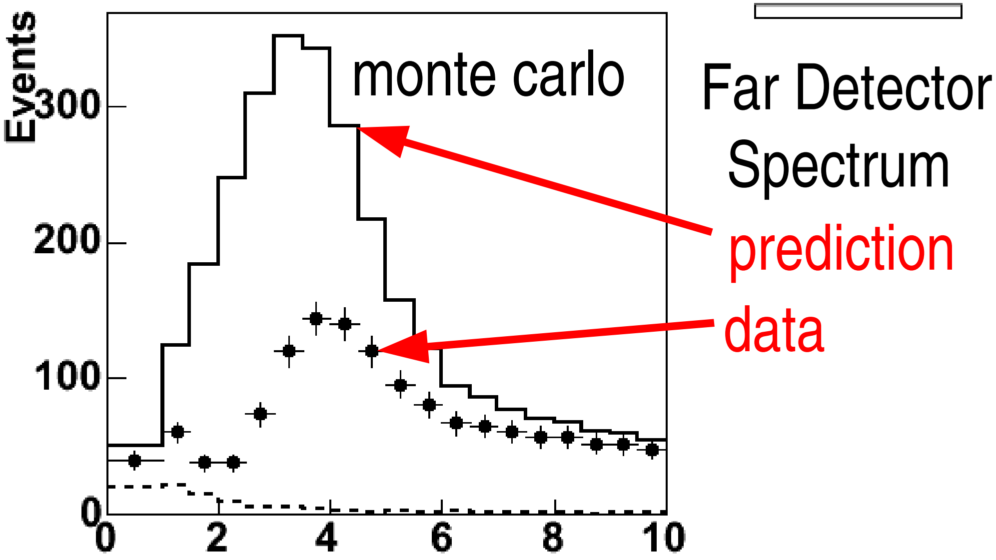
- Best previous measurements of Δm^2_{23} and $\sin^2 2\theta_{23}$ are provided by Super-Kamiokande (atmospheric neutrino analysis) and K2K (9×10^{19} pot)
- Their limits (at 90% C.L.) are:
  - $\sin^2 2\theta > 0.9$
  - $1.9 < \Delta m^2 < 3.0 \times 10^{-3}$ eV^2
- The analysis presented in this talk, which is for 1.27×10^{20} POT, provides a measurement of the mixing parameters that is competitive with these results

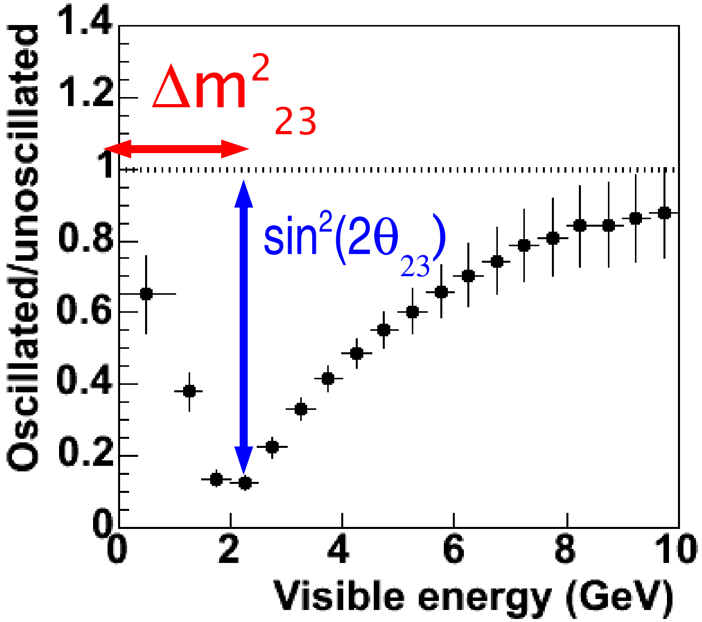
Allowed regions from Super-K and K2K



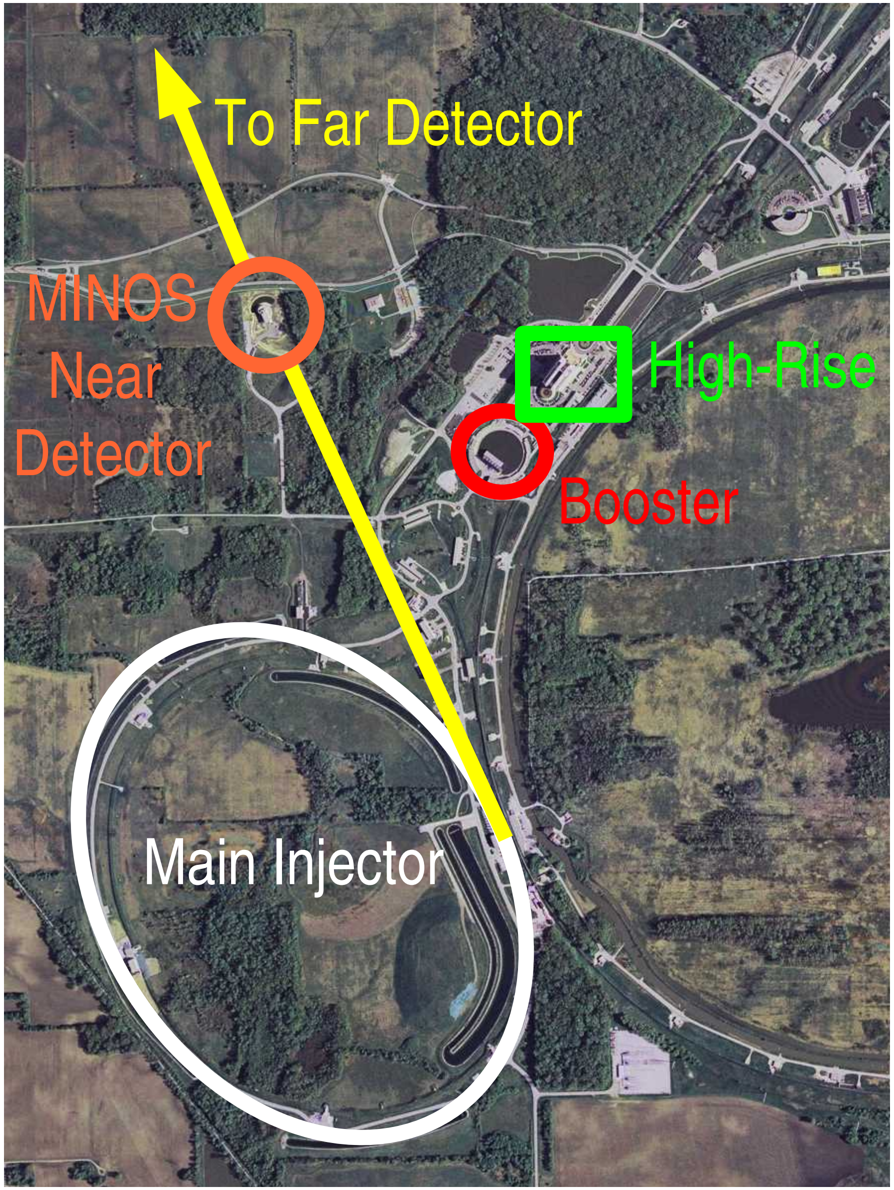
Oscillation Measurement

- Challenge: Look for distortion in ν_μ spectrum at some distance L from the source
- Uncertainties: original spectrum, cross-sections, detector acceptance
- Solution: Two detectors
  - Measure ν_μ spectrum close to source with Near Detector
  - Use Near Detector measurements to predict Far spectrum w/o oscillations
  - Measure Far Detector spectrum
- Interpret results





The NUMI facility

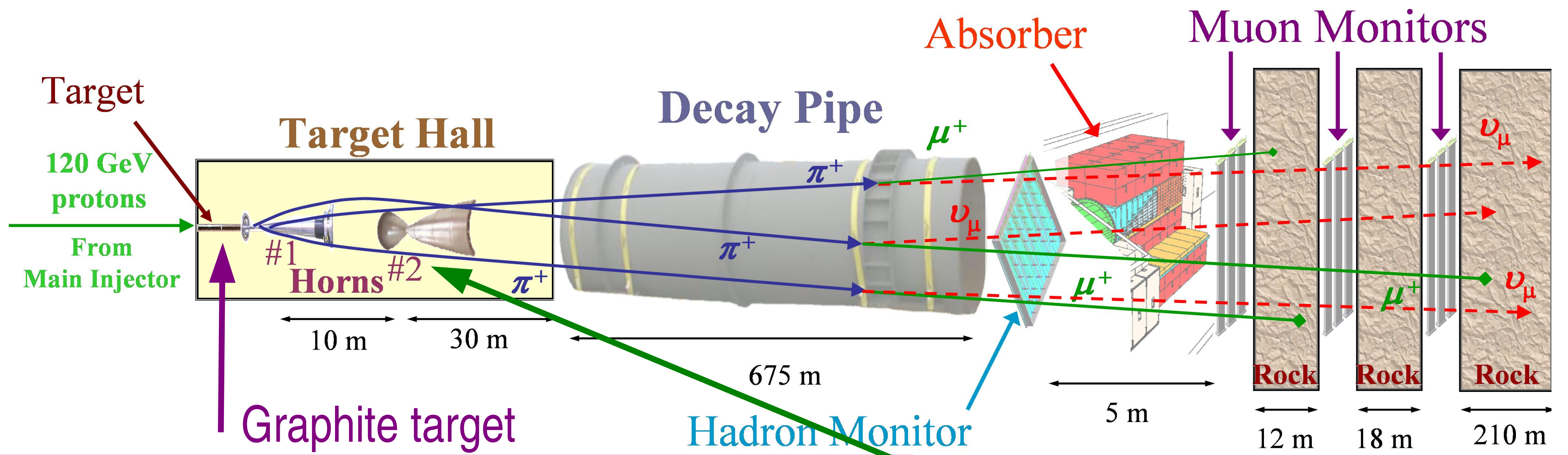


- NuMI= Neutrinos at the Main Injector
- 120 GeV/c protons from the Main Injector
- Main Injector can accept up to 6 Booster batches/cycle,
- Either 5 or 6 batches for NuMI
- Single turn extraction (~10 μs spill)

NuMI performance

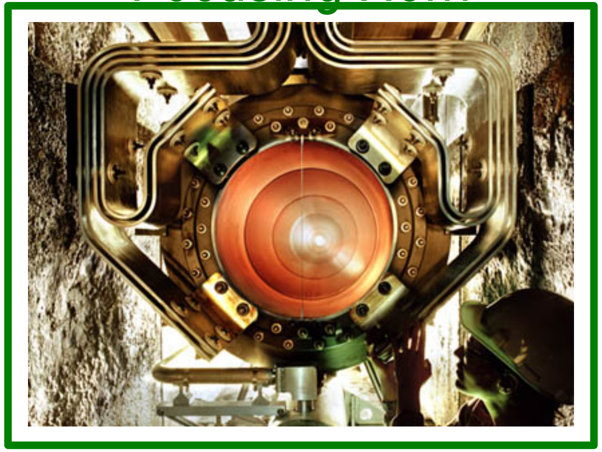
	Average	Record	Design Limit
Cycle Time (sec)	2.20	2.00	1.87
Beam Intensity (1e13 POT/spill)	2.30	3.00	4.00
Beam Power (MW)	0.17	0.29	0.40

Producing the neutrino beam



to Near Detector

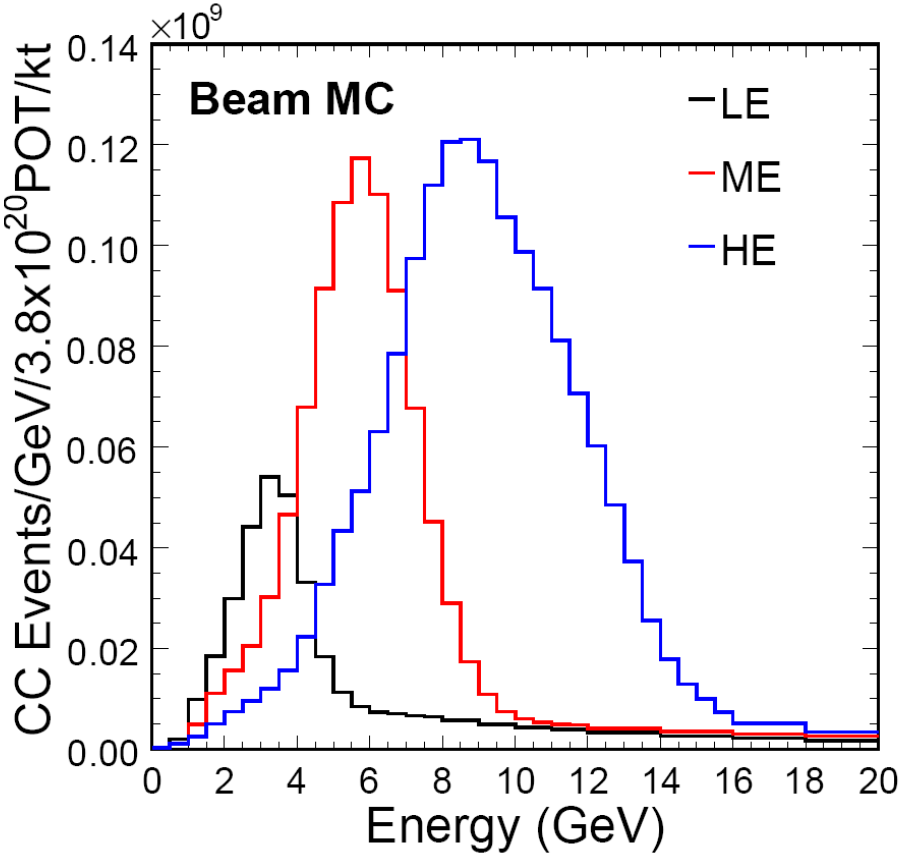
Focusing Horn



- Variable target position = variable beam energy!
- Two magnetic focusing horns
- Sign selected beam: neutrino or anti-neutrino enriched

The NuMI neutrino beam

- LE most suitable for oscillation analysis with SK parameters
  - 95% of data
- Data from 5 other configurations used to study systematics, improve beam model



LE Beam Composition

ν_μ = 92.9%

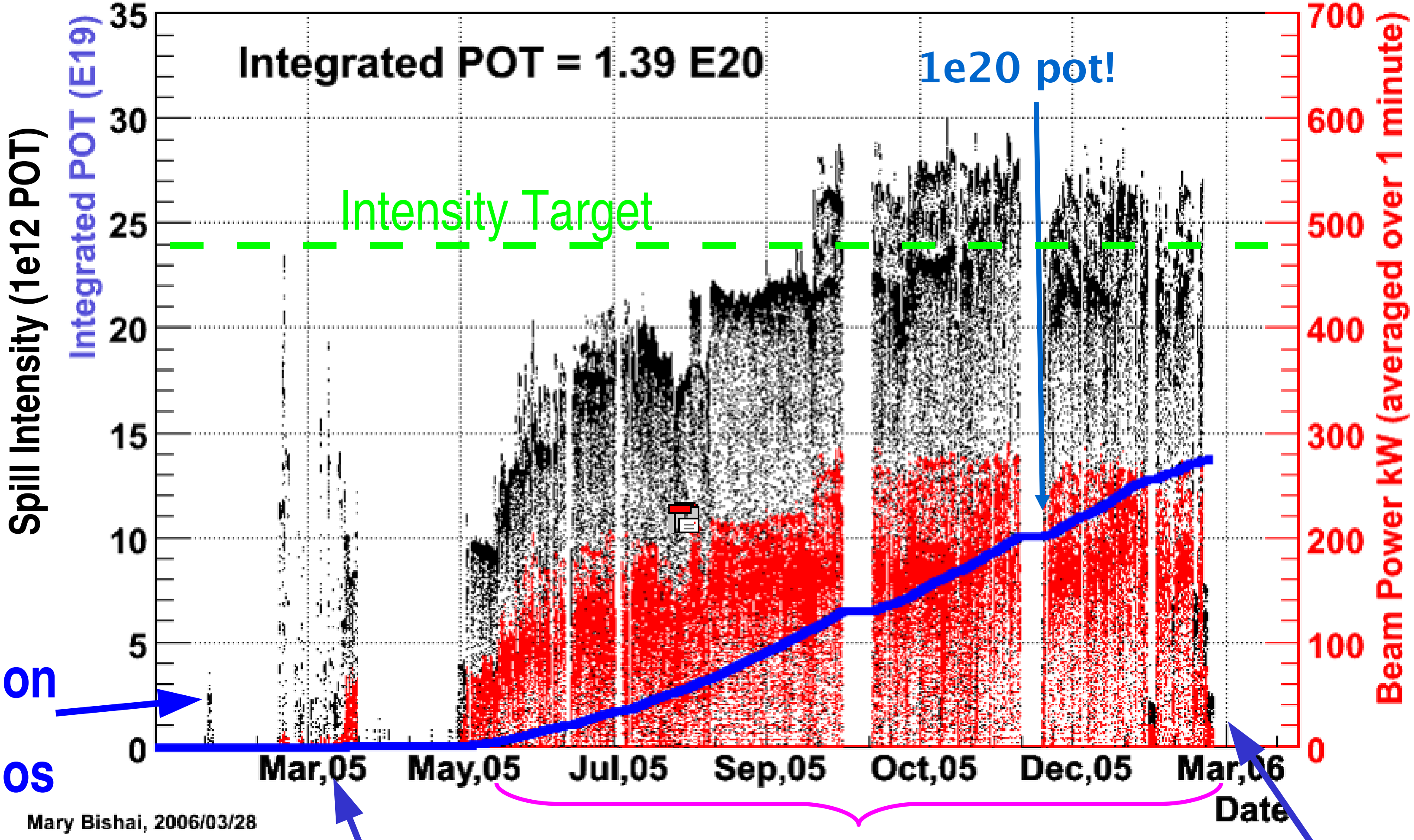
$\bar{\nu}_\mu$ = 5.8%

$\nu_e + \bar{\nu}_e$ = 1.5%

Expected no of events (no osc.) in Far Detector

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

First Year of MINOS running



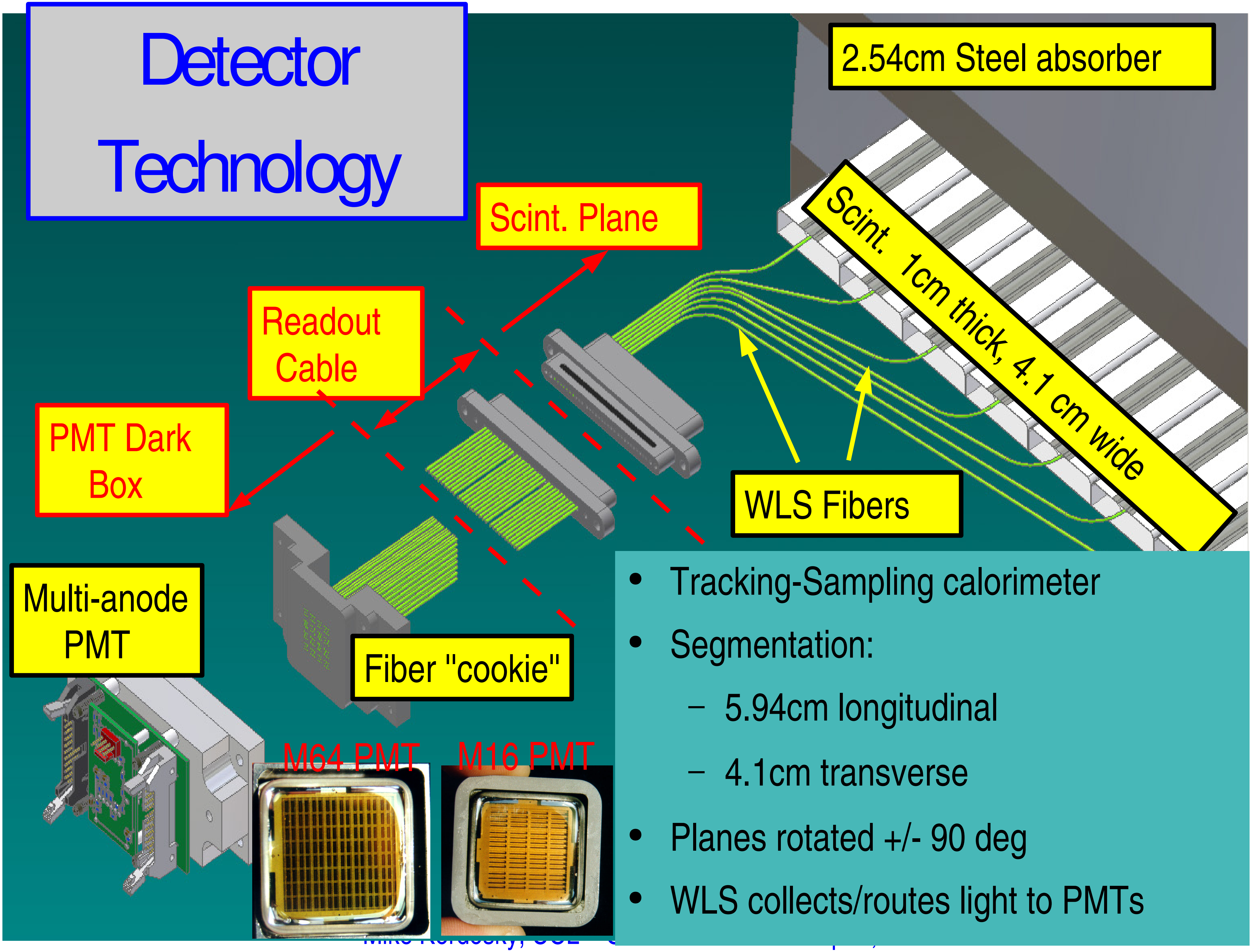
Observation of neutrinos in Near Detector!

Start of LE running

Dataset used for today's results

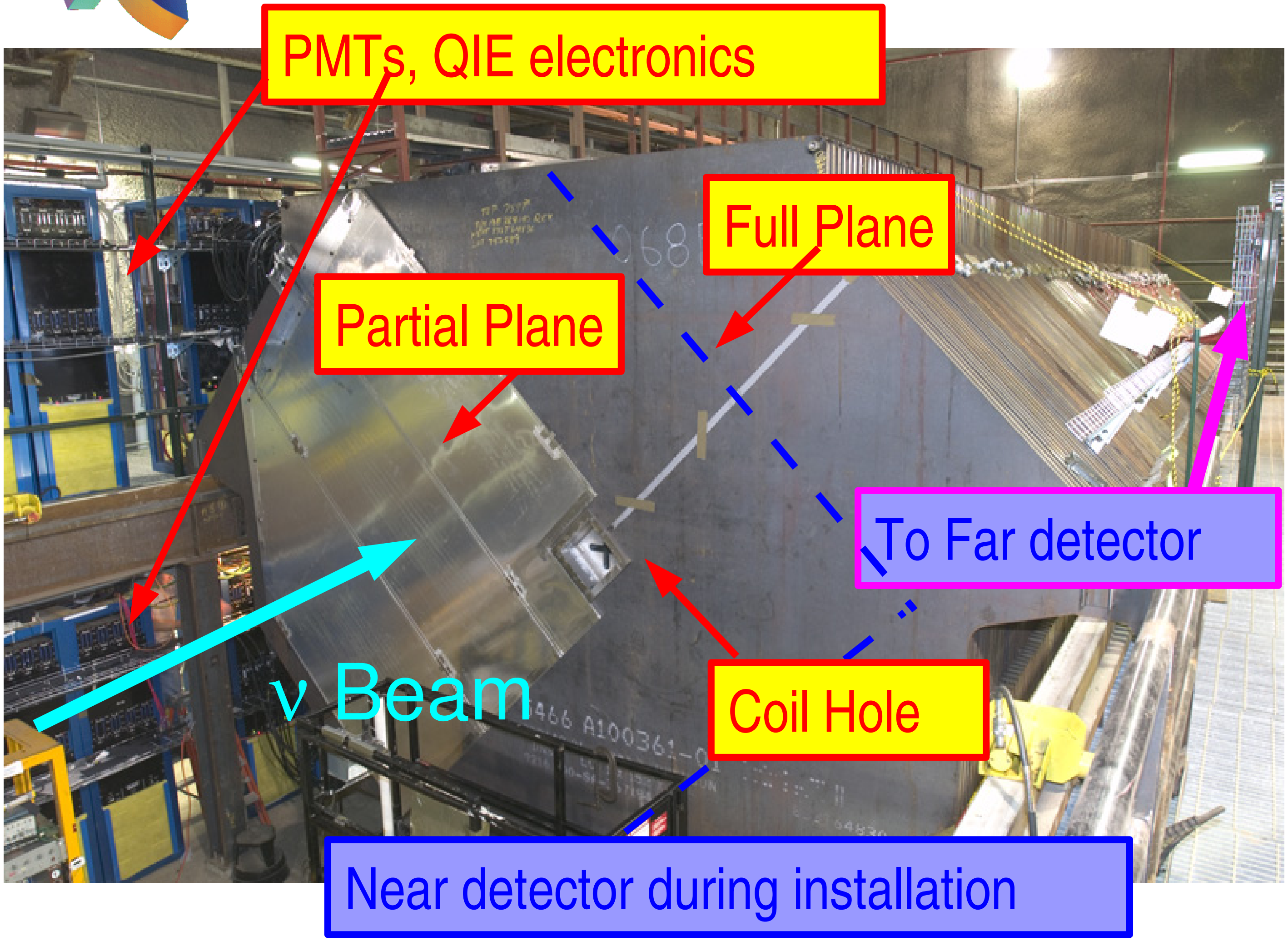
Main Injector Shut-down

Detector Technology



- Tracking-Sampling calorimeter
- Segmentation:
  - 5.94cm longitudinal
  - 4.1cm transverse
- Planes rotated +/- 90 deg
- WLS collects/routes light to PMTs

Near Detector



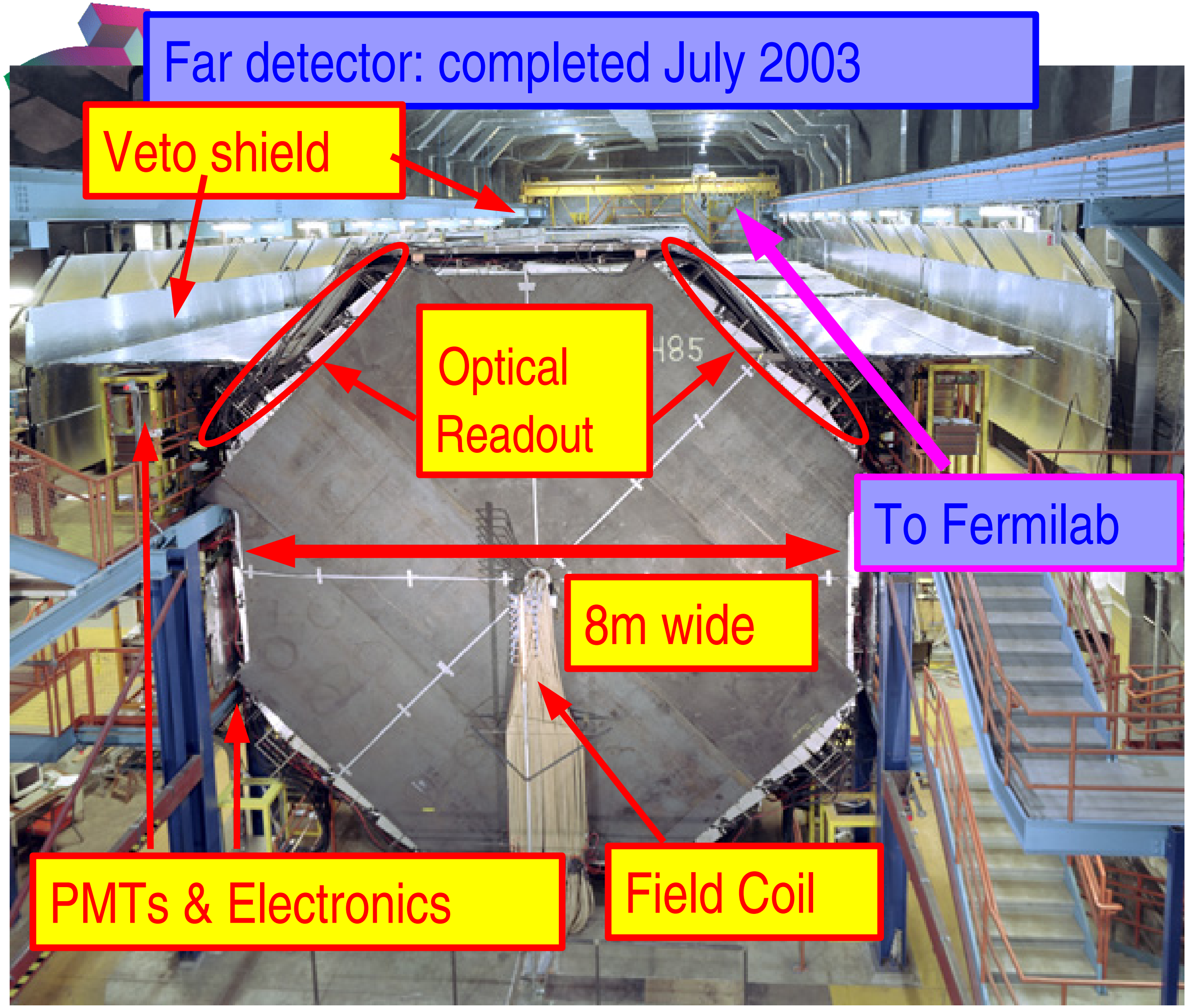
Near detector during installation

- 1km from Target
- 0.98 kton
- 282 steel planes
  - 0-120 = calorimeter
  - 120+ = spectrometer
- B=1.2 T
- 64-anode PMTs
- High Rates
- QIE electronics
  - no deadtime!

Purpose

Measure beam before oscillations, Predict Far Detector spectrum

Far Detector



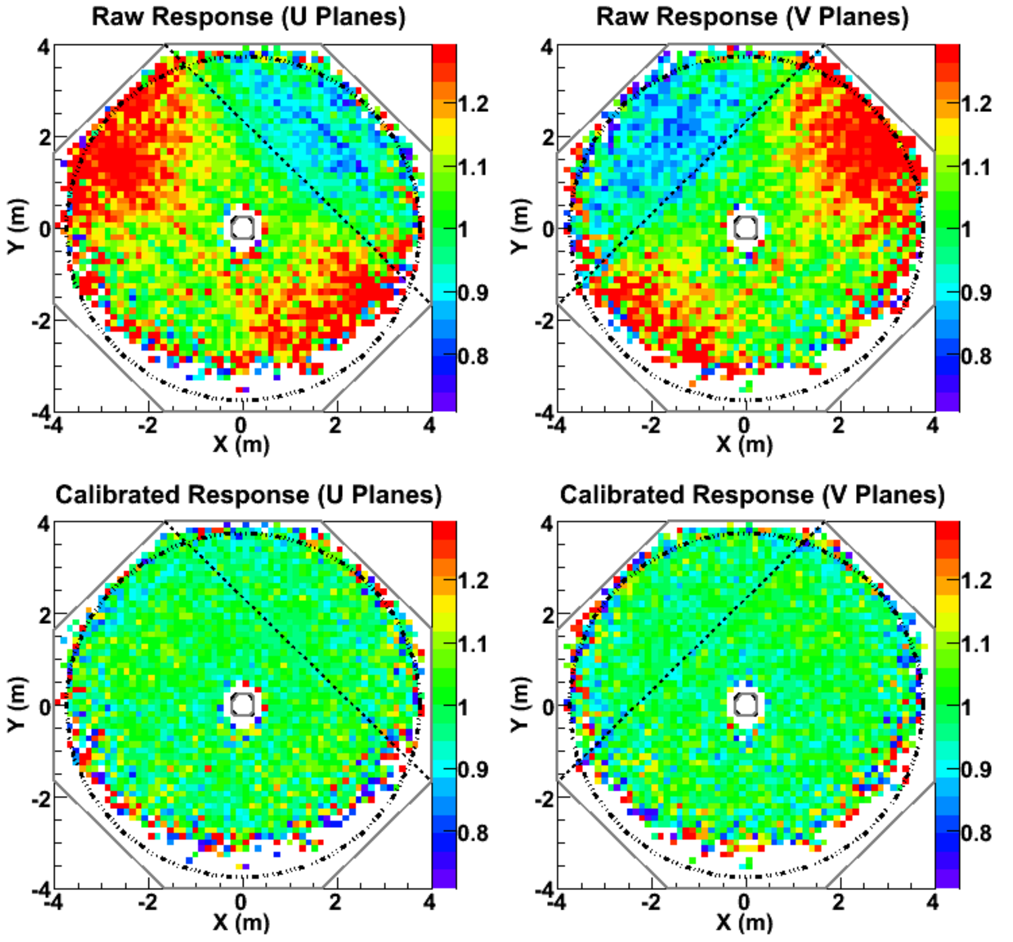
- Soudan, MN
- 735 km from source
- 5.4 kton
- 486 steel planes
- B=1.3 T
- 16-anode PMTs
- 8x multiplexed
- VA electronics
- GPS synched to ND
- Spill signal over IP

Purpose

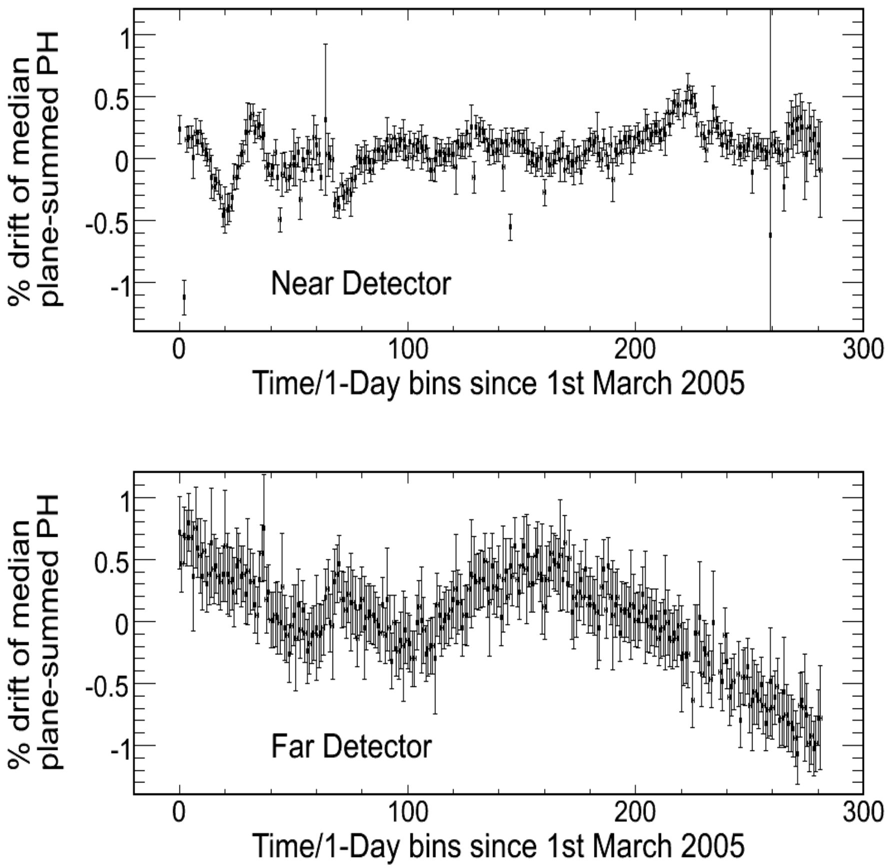
Measure ν_μ-CC, NC energy spectra, rates

Search for ν_e appearance, observe atmospheric neutrinos

Calibration

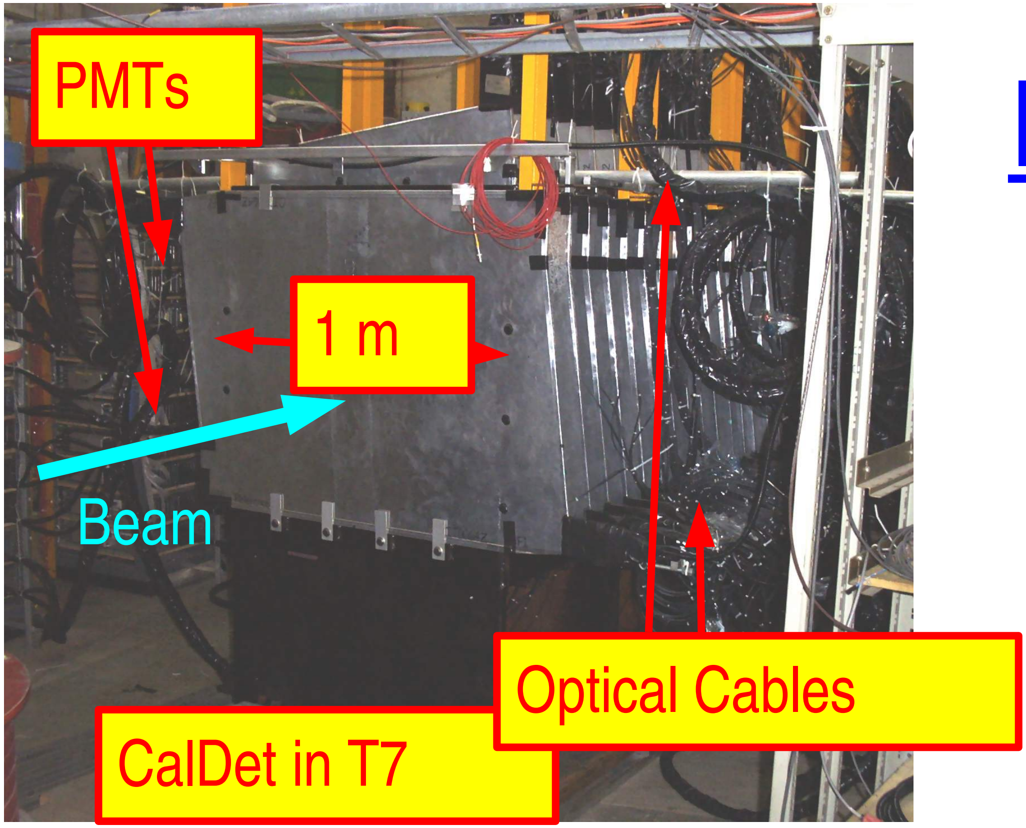


Cosmic-ray muons remove variations between and along strips

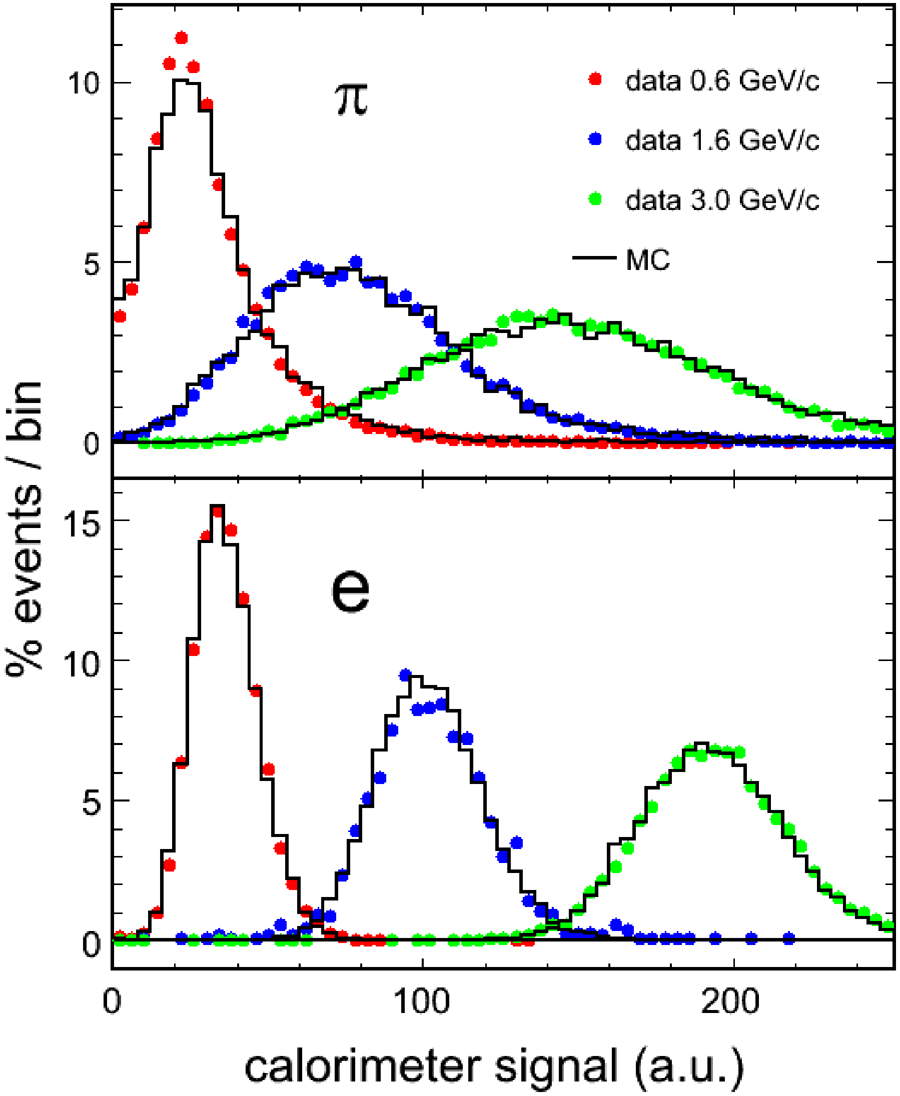


LED based light-injection tracks channel gain over time

Energy Scale



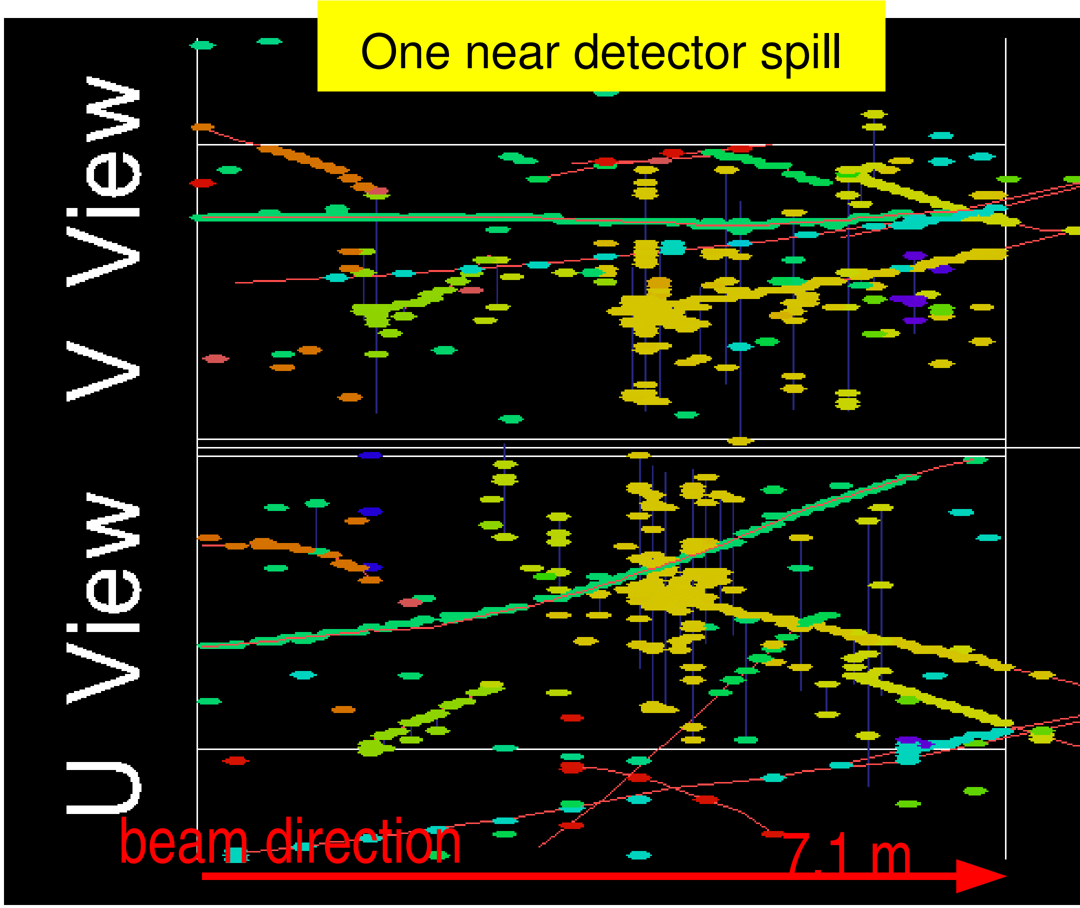
- Calibration Detector = mini-MINOS
- Ran @ CERN PS
- Sixty 1-m^2 planes
- Near and Far Electronics
- π, e, p and μ response at few GeV/c

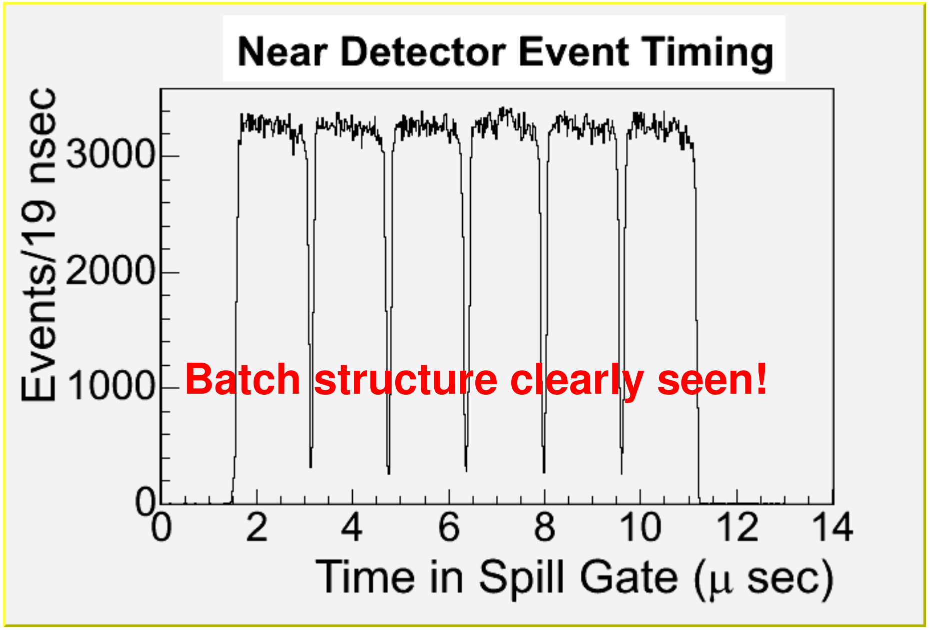


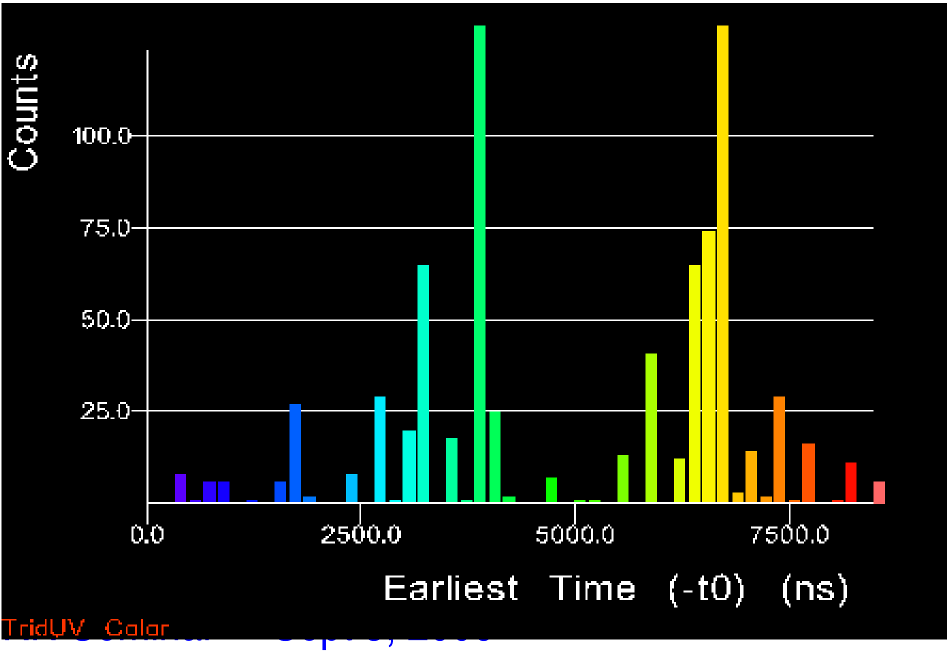
Mike Kordosky – NuFact 06 - Aug 27, 2006

Near detector events

- High rate in Near detector results in multiple neutrino interactions per spill
- Events are separated by topology and timing (19ns resolution)

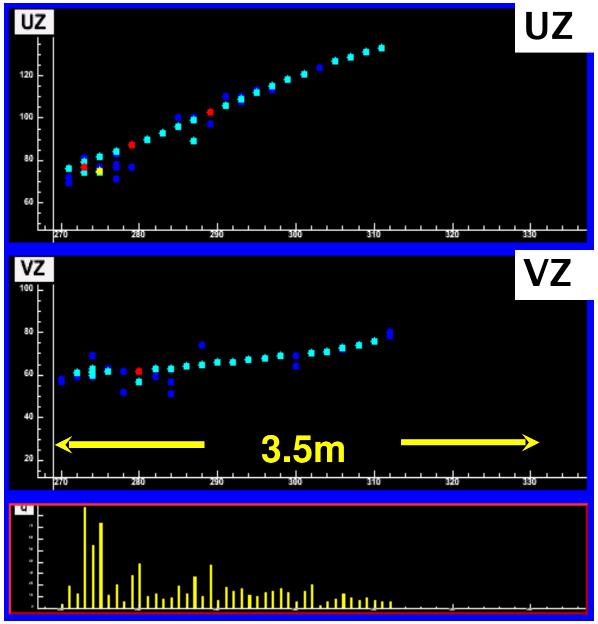

One near detector spill


Batch structure clearly seen!

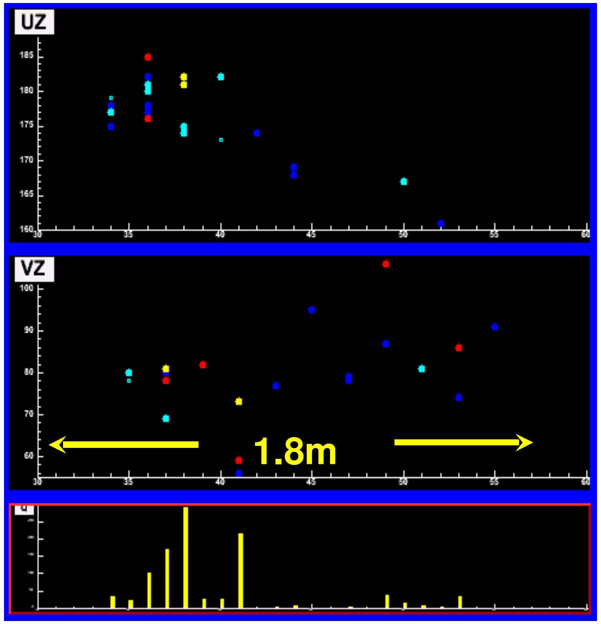


Event topologies

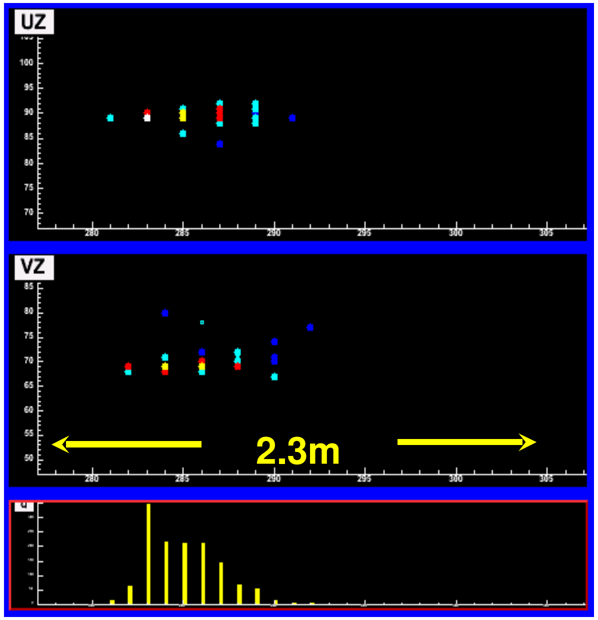
Monte Carlo



ν_μ CC Event



NC Event



ν_e CC Event

- long μ track+ hadronic activity at vertex

- short event, often diffuse

- short, with typical EM shower profile

$$E_\nu = E_{shower}+P_\mu$$

Muon Energy Resolution
6% range, 13% curvature

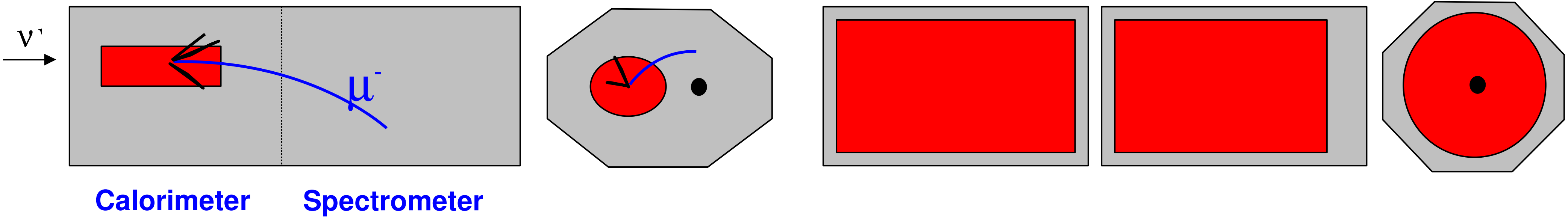
Shower Energy Resolution: ~ 56%/√E

ν_μ-CC event selection

- ν_μ CC-like events are selected in the following way:

1. Event must contain at least one good reconstructed track
2. The reconstructed vertex should be within the fiducial volume of the detector:
   - NEAR: 1m < z < 5m (z measured from the front face of the detector), R< 1m from beam centre.
   - FAR: z>50cm from front face, z>2m from rear face, R< 3.7m from centre of detector.

Near Detector **Far Detector**

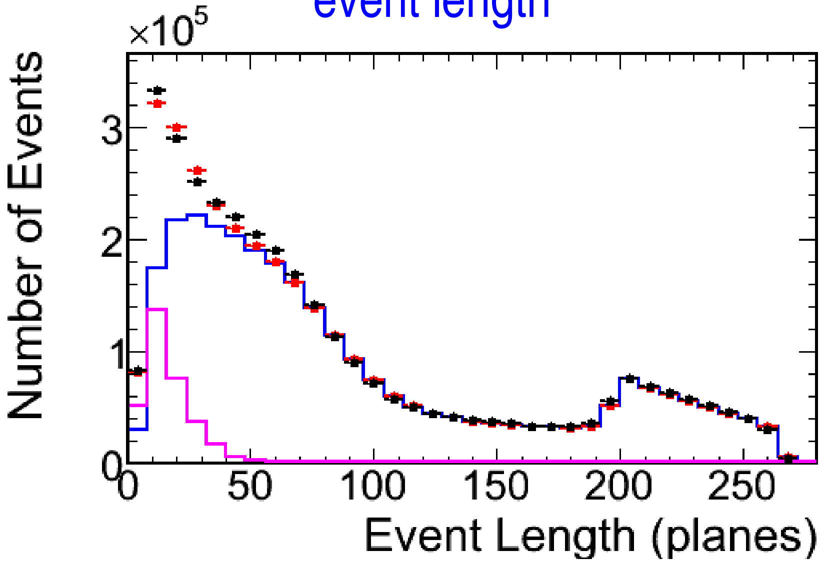


3. The fitted track should have negative charge (selects ν_μ)
4. Additional cuts in FD to remove events polluted by light injection, steep cosmic tracks
5. Cut on likelihood-based Particle ID parameter used to separate CC and NC events.

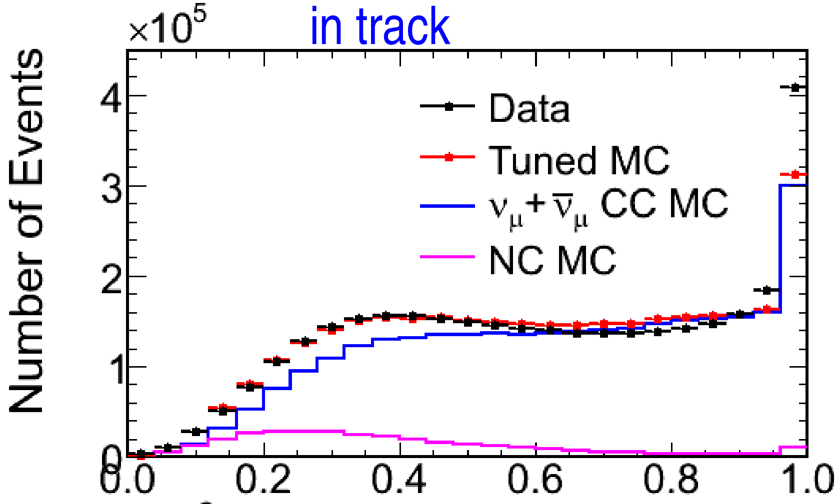
PID : Data vs. MC

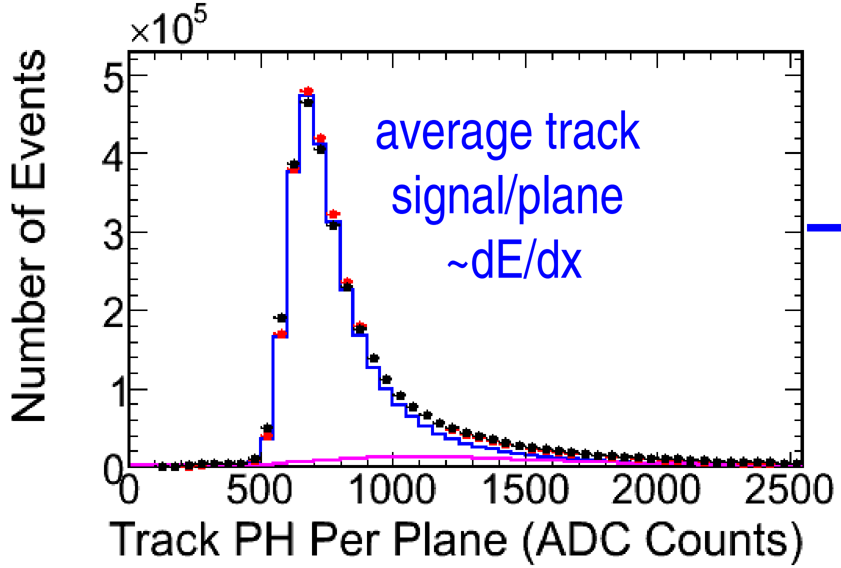
Near Detector

event length

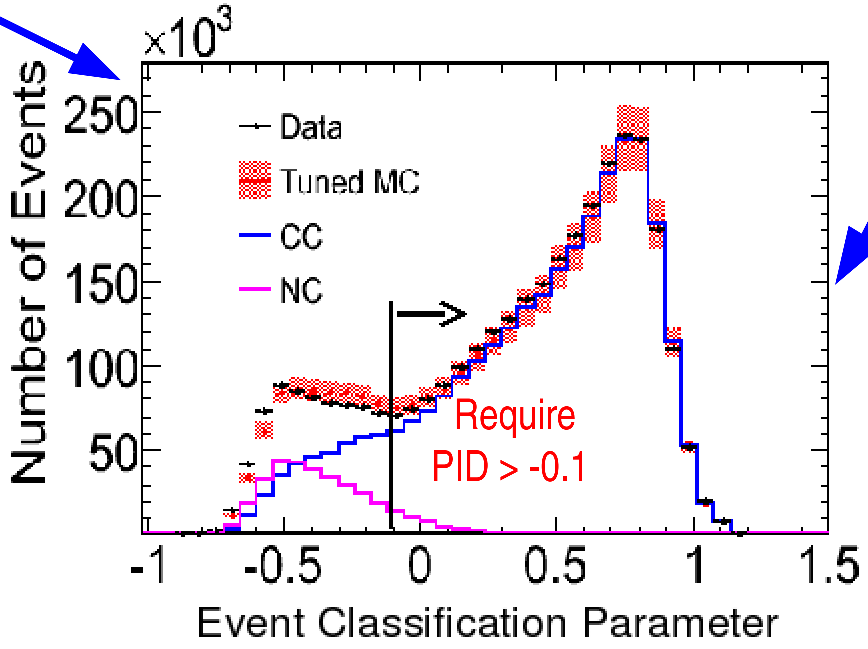


fraction of signal in track



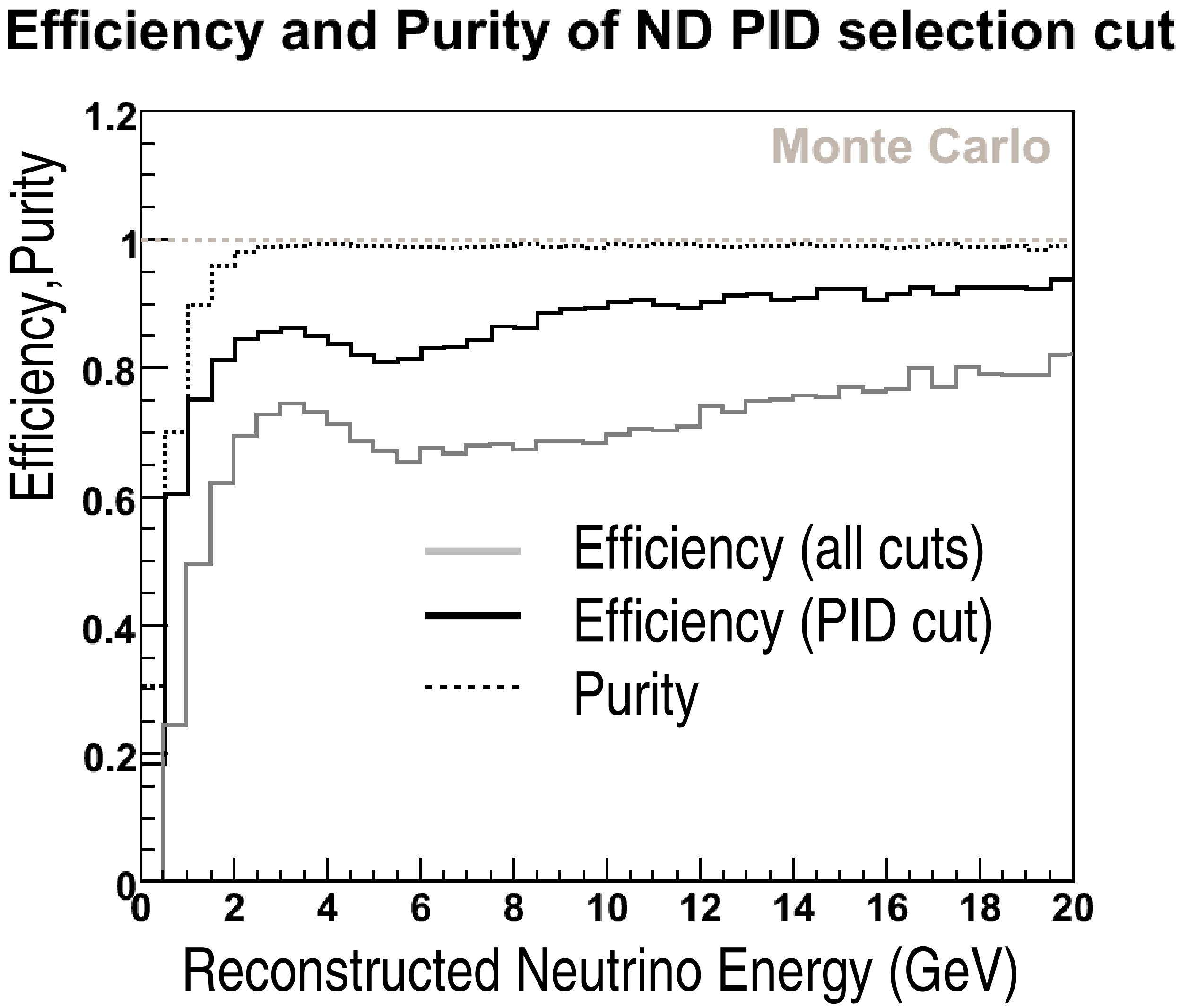


average track signal/plane ~dE/dx



Require PID > -0.1

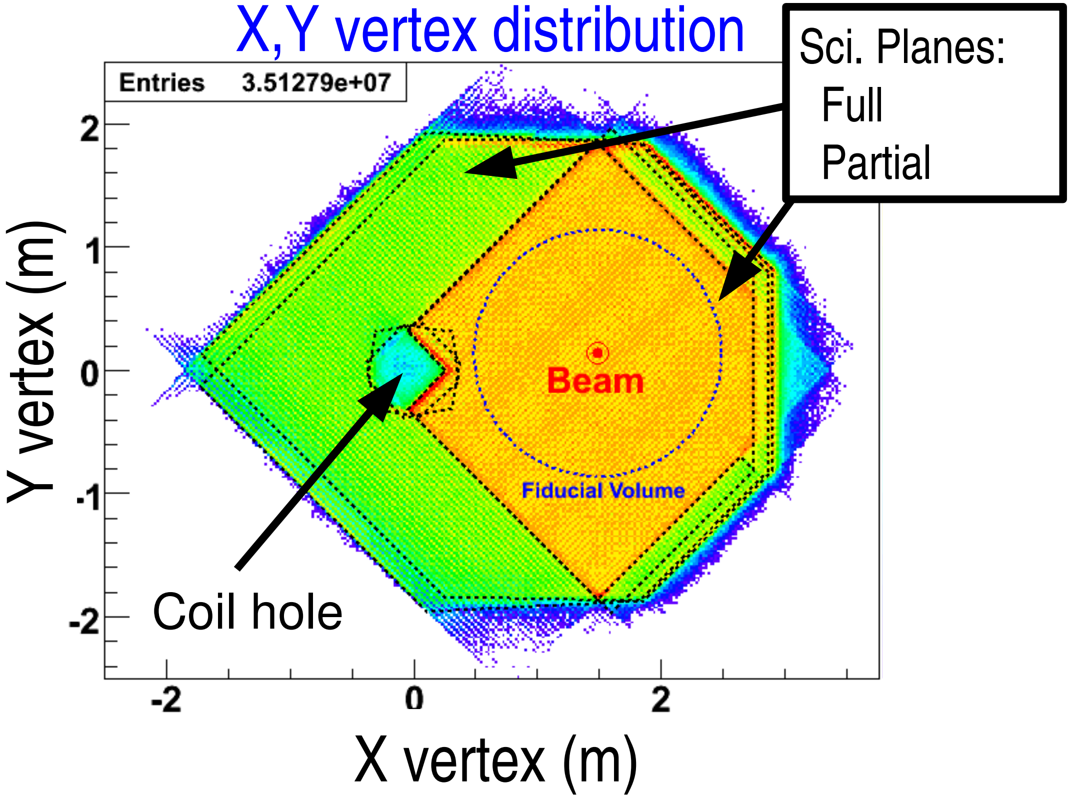
CC: Selection Efficiency



Near Detector distributions

- High event rates in the Near detector
  - ~8 events / spill
  - >2e6 events in the fiducial volume for 1.27e20 pot
  - Luxurious in neutrino physics!
- Large dataset used to
  - Demonstrate understanding of beam, cross-sections, acceptance
  - Confront and tune MC

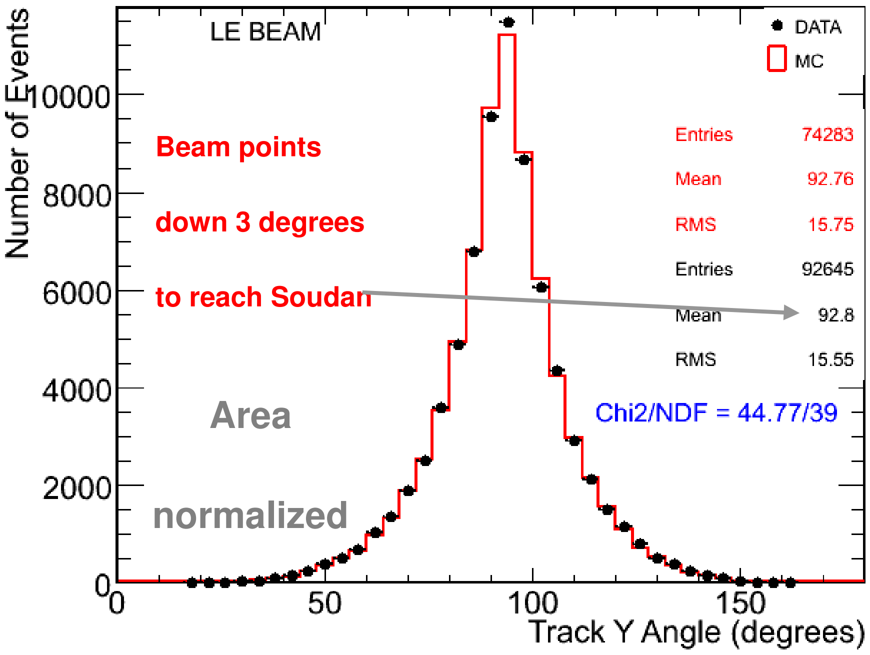
X,Y vertex distribution



Sci. Planes:
Full
Partial

Coil hole

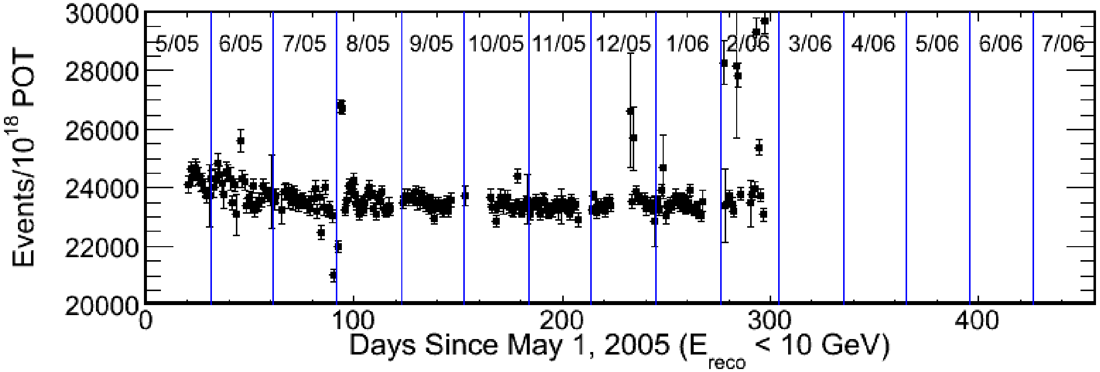
Track angle w.r.t. vertical

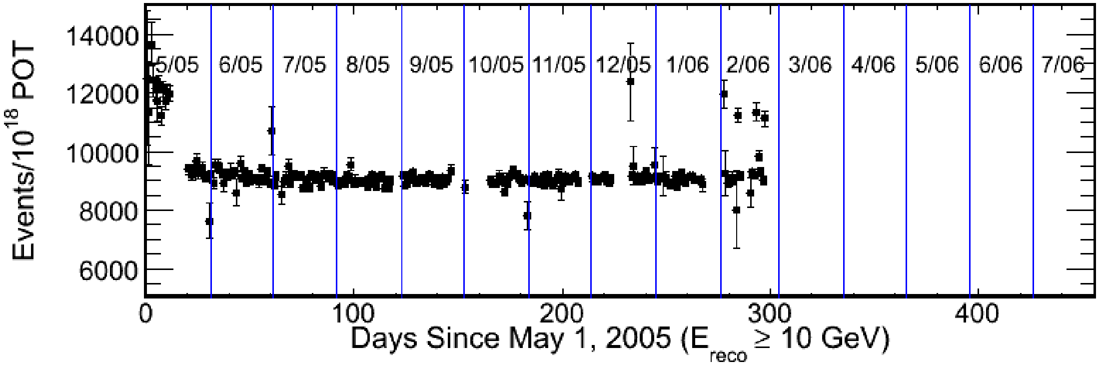


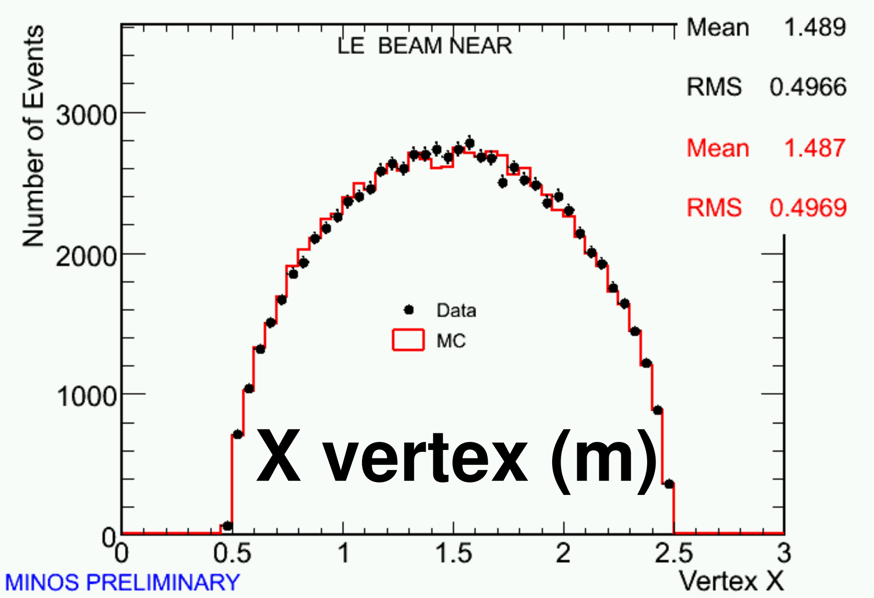
Beam points down 3 degrees to reach Soudan

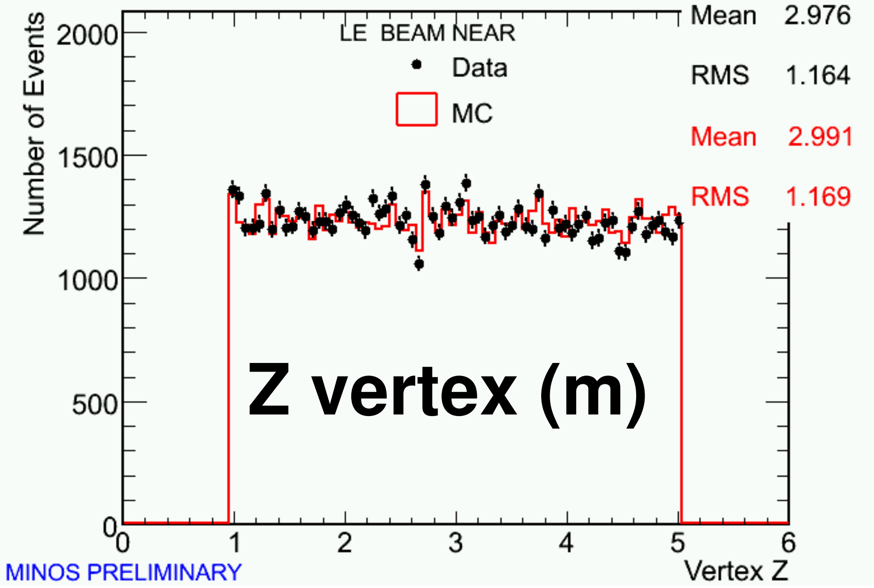
Area normalized

Event rate and vertex distributions







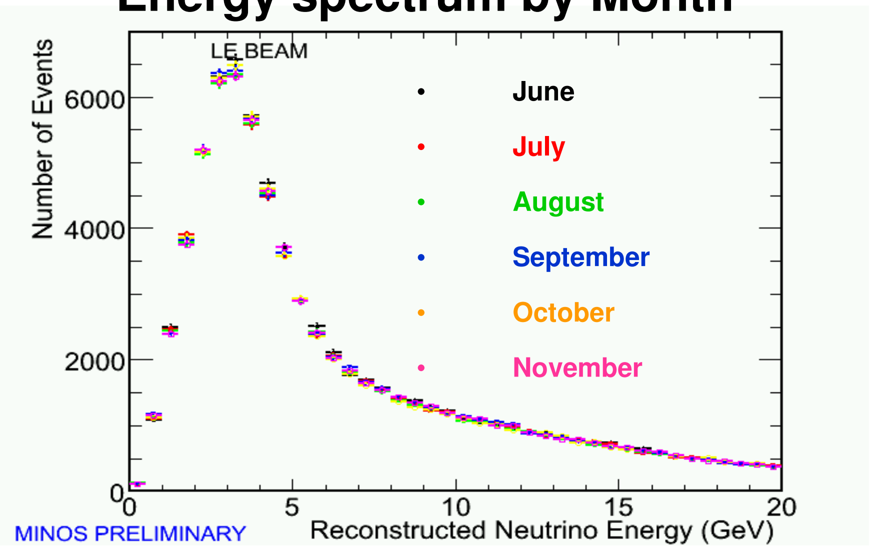


- Event rate is flat as a function of time
- High Energy Beam – late May 2005
- Horn current scans – July 29 – Aug 3
- Low intensity, horn off running: Feb 2006

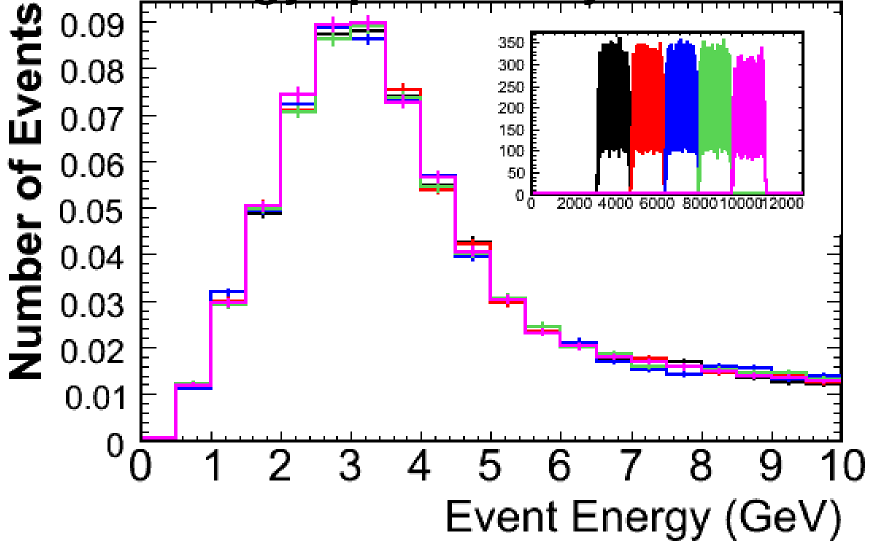
Energy spectrum & reconstruction stability

proton intensity ranges from 1e13 ppp - 2.8e13 ppp

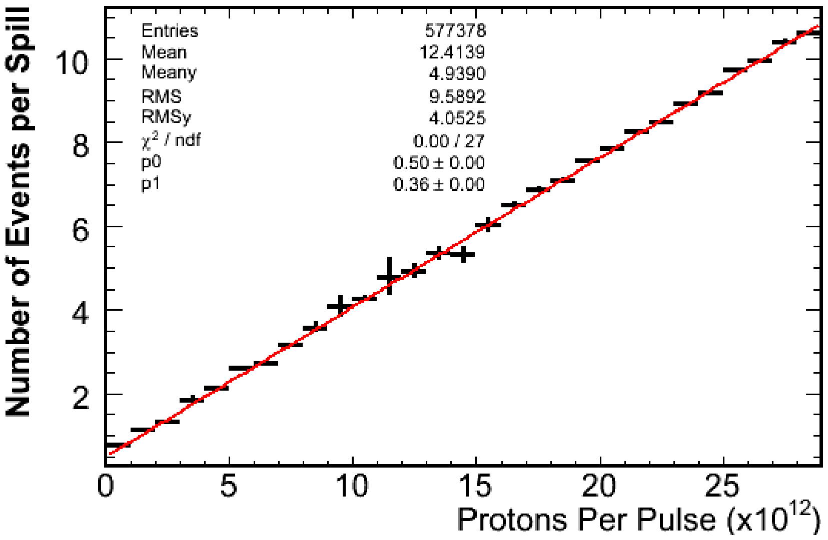
Energy spectrum by Month



Data **Energy spectrum by batch**

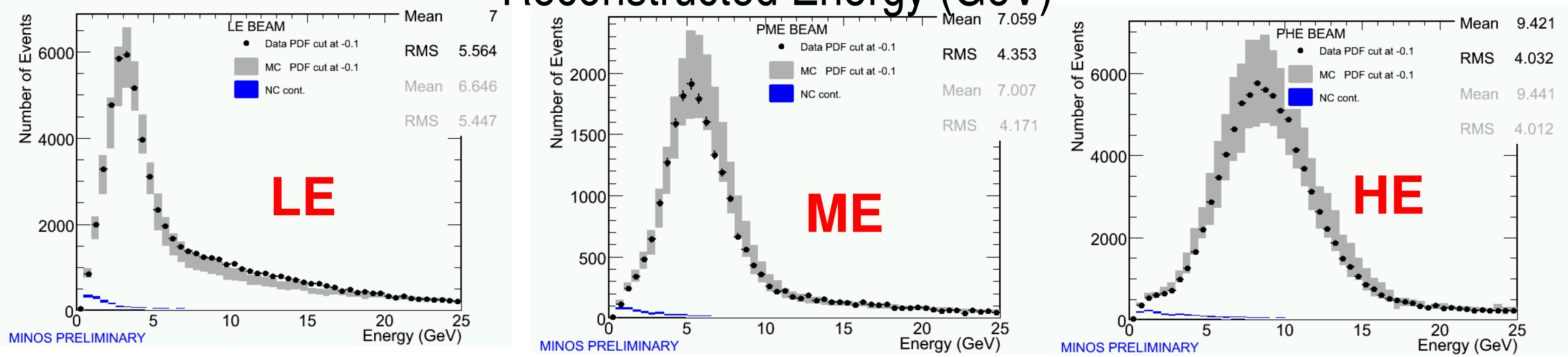


- Reconstructed energy distributions agree to within statistical uncertainties (~1-3%)
- Beam is very stable and there are no significant intensity-dependent biases in event reconstruction.

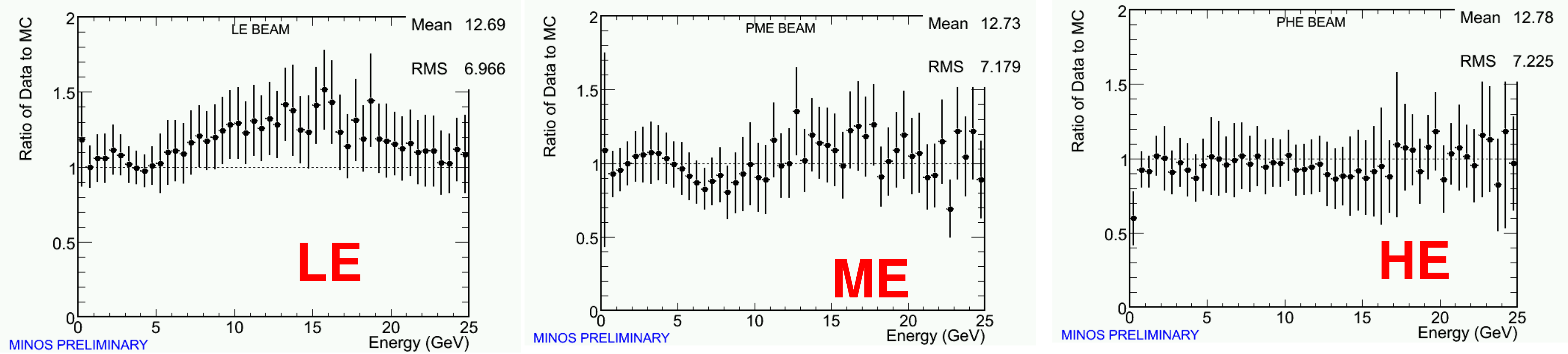


Energy spectra & ratios (CC-like events)

Reconstructed Energy (GeV)



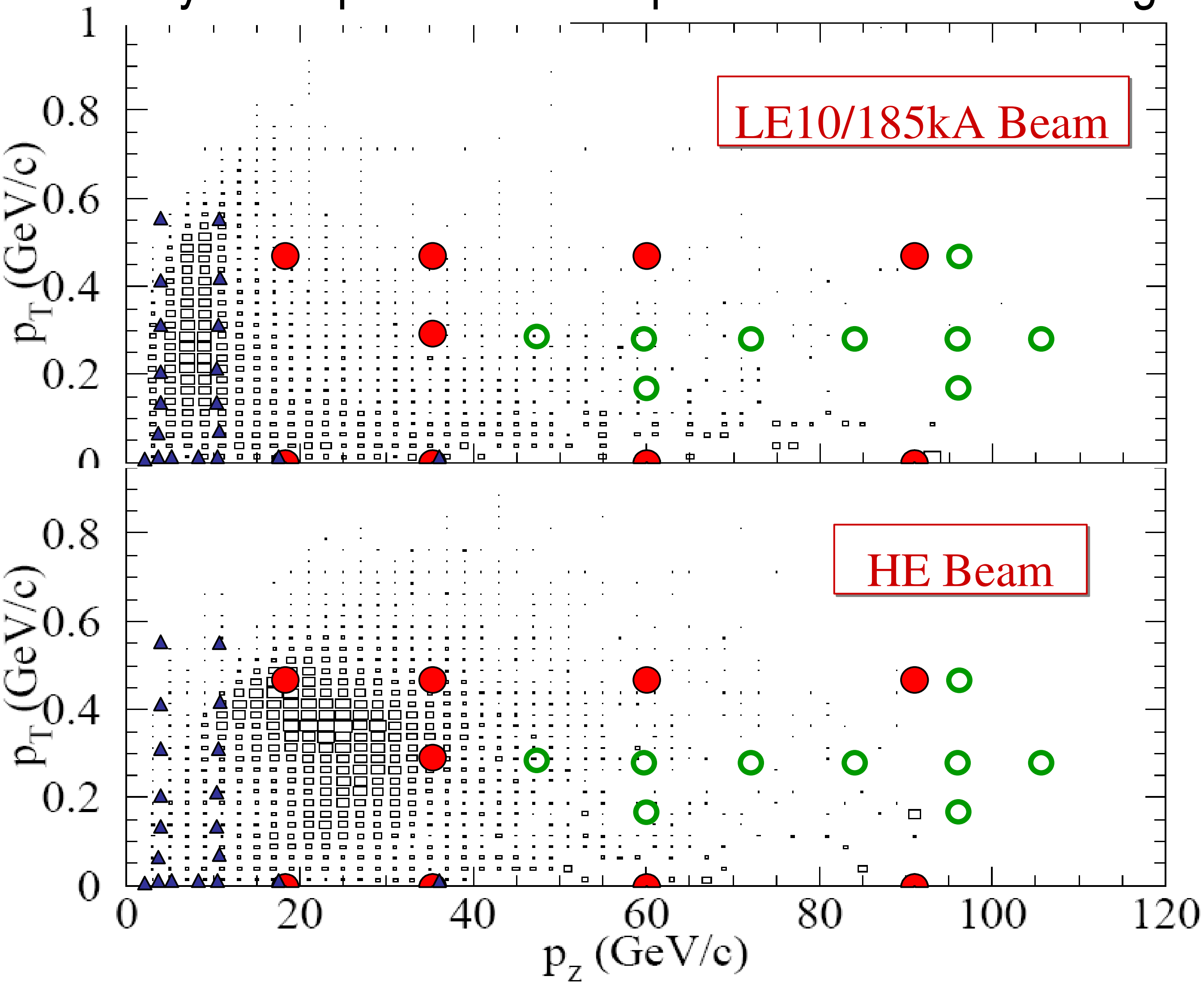
Ratios of Data/MC



Error envelopes shown on the plots reflect uncertainties due to cross-section modelling, beam modelling and calibration uncertainties

Interlude - Hadron Production

Why we expected hadron production to be the largest uncertainty



● Atherton

400 GeV/*c* p-Be

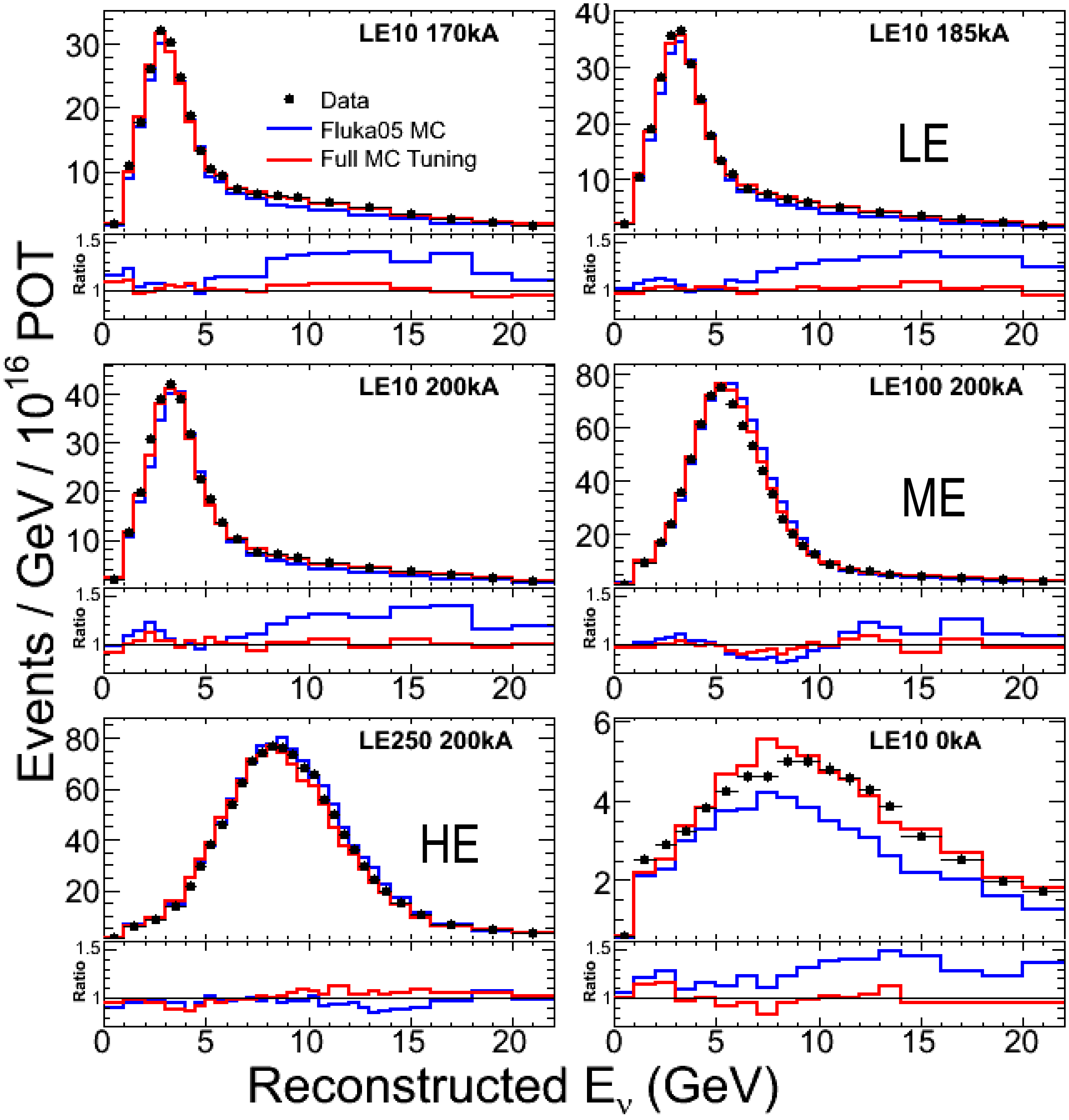
○ Barton

100 GeV/*c* p-C

▲ SPY

450 GeV/*c* p-Be

Energy Spectrum Tuning

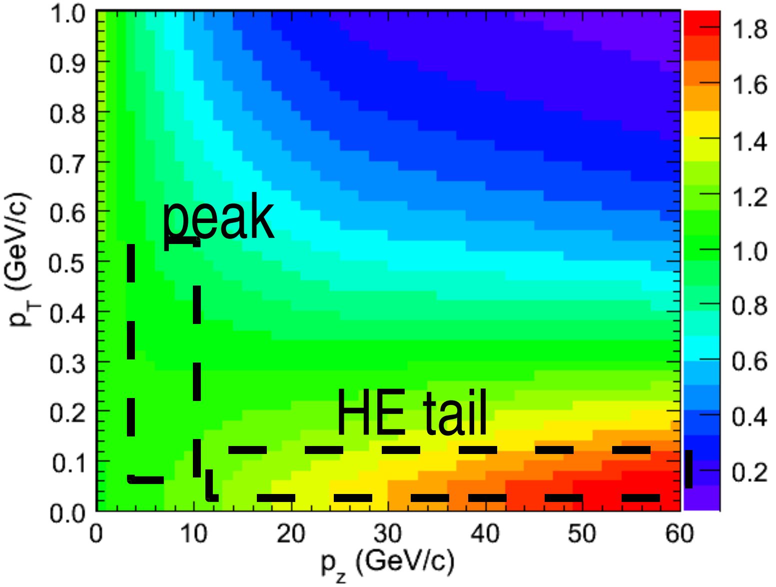


Reweight pion x_F and p_T to improve data/MC agreement

Include horn focusing, NC norm and energy scale as nuisance parameters

Osc. analyses use these weights

P_T v P_z weights



Summary of ND Data/MC agreement

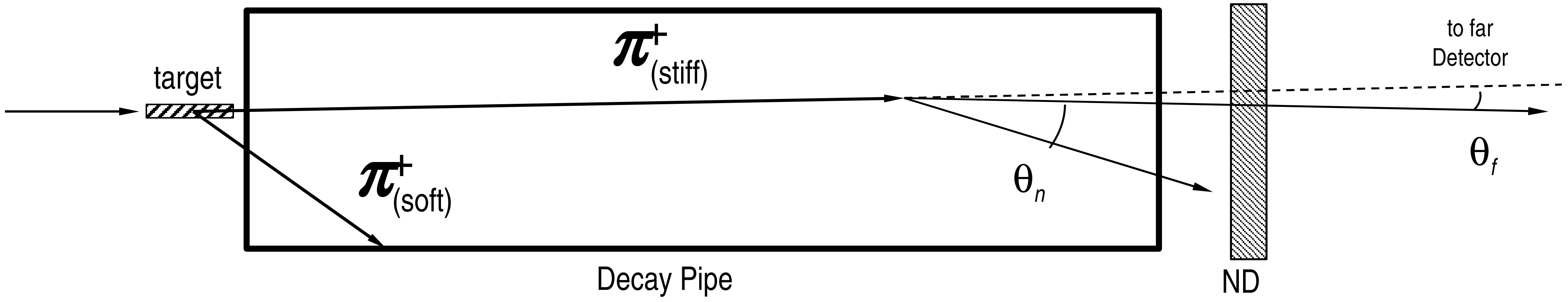
- Data/MC comparison of low-level quantities indicates that we can adequately model neutrino interactions in our detectors
- Broadly good agreement independent of specifics of the event selection
- Detector operation and reconstruction is stable
  - No drift in energy spectrum over the run
  - No dependence on time within spill
  - No pathological behavior with intensity
- High level quantities agree to within the expected systematic uncertainties from cross-sections, beam modelling and calibration uncertainties
  - agreement can be improved by reweighting on the xF and pT of parent hadrons in the Monte Carlo

Prediction of FD spectrum

- MINOS has developed several procedures for predicting the FD spectrum
  - "Far/Near": F/N spectral ratio from MC. Multiply by measured ND spectrum
  - "Beam Matrix": 2D matrix links each FD energy bin with ND spectrum
  - "ND-Fit": Describe ND distributions by fitting physics quantities, predict FD spectrum from best fit (e.g., by re-weighting MC)
  - "2D-grid": As in ND-Fit but includes bin-by-bin re-weighting in y v. E plane
- These methods yield compatible results, at 1.27e20 POT exposure, for all sources of systematic error we have studied
- I will describe F/N and the Beam Matrix today and show final results from the Beam Matrix.

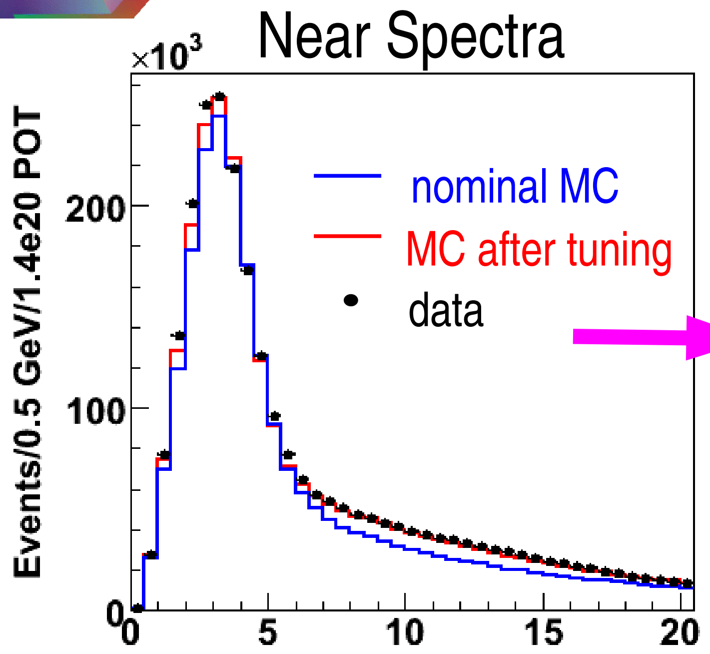
Near to Far Extrapolation

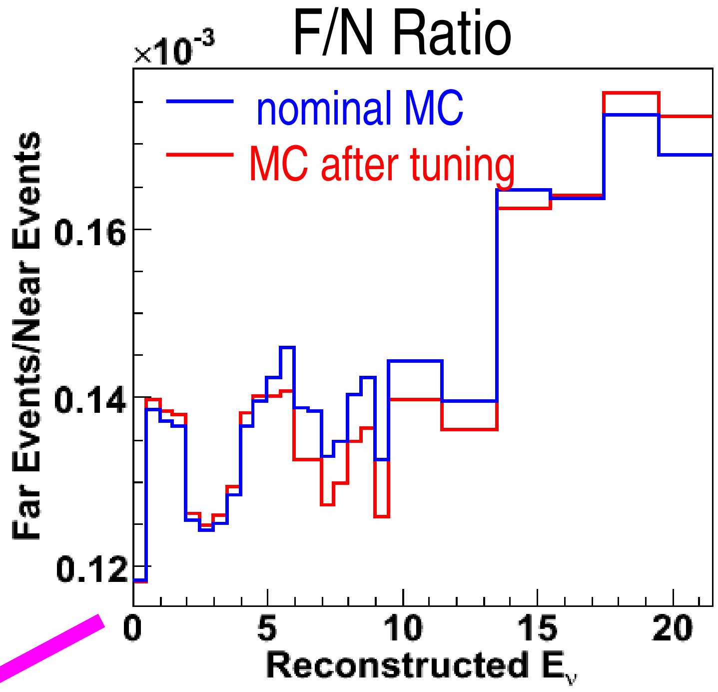
- For a given p,K trajectory and decay the observed neutrino energy spectrum differs in the two detectors:
  - Near sees a line source with a relatively wide angular acceptance
  - Far sees a point source with narrow angular acceptance

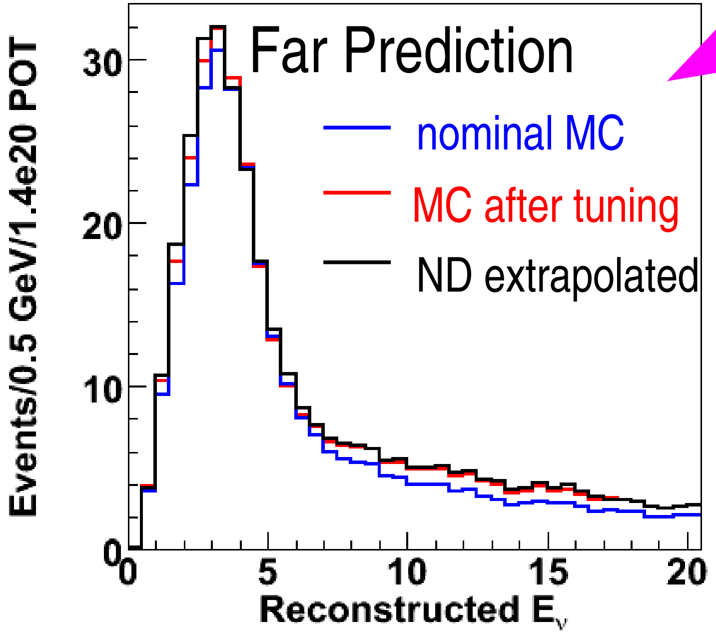


- Geometry and p,K decay kinematics relate the contents of a given Near Detector energy bin to the contents of a given Far Detector bin.
  - The F/N method implements this knowledge as a ratio
  - The “Beam Matrix” method implements this knowledge as a transport matrix.

“Far/Near” Method

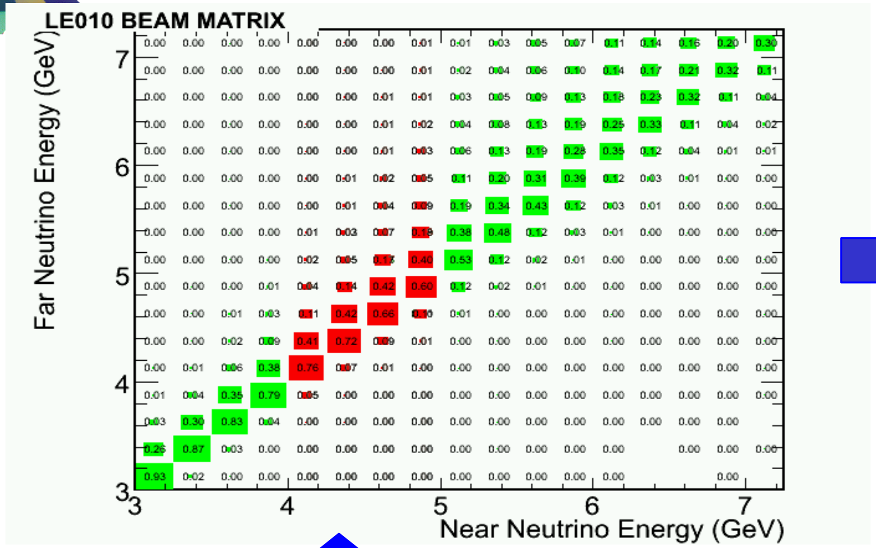


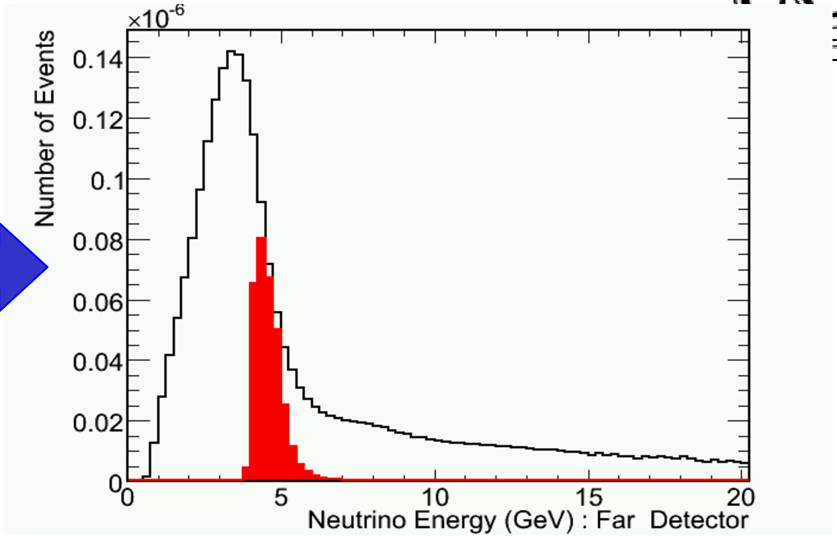


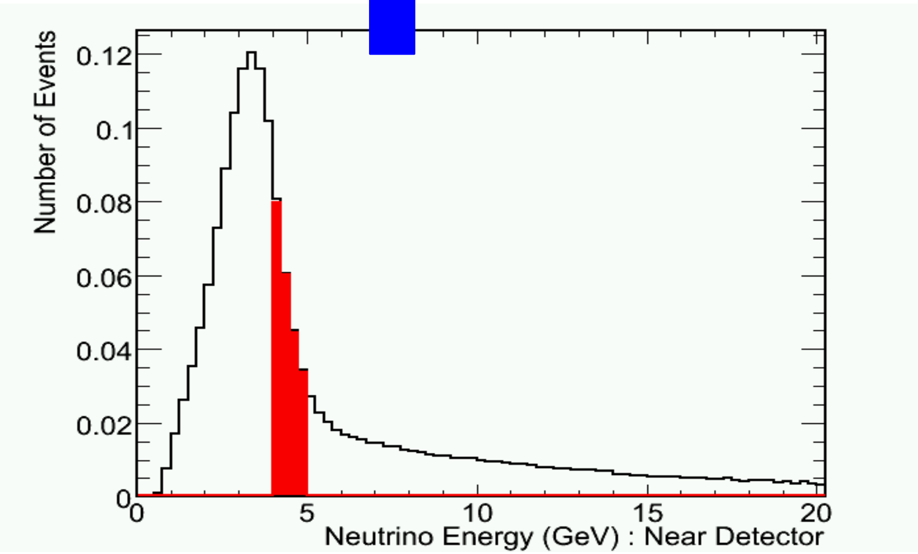


- Simplest possible method
- Makes direct use of 2 detector design
- (Near Data) x (F/N) = Far Prediction
- Done in reconstructed energy
- Use F/N ratio after MC tuning

Beam Matrix: Near → Far





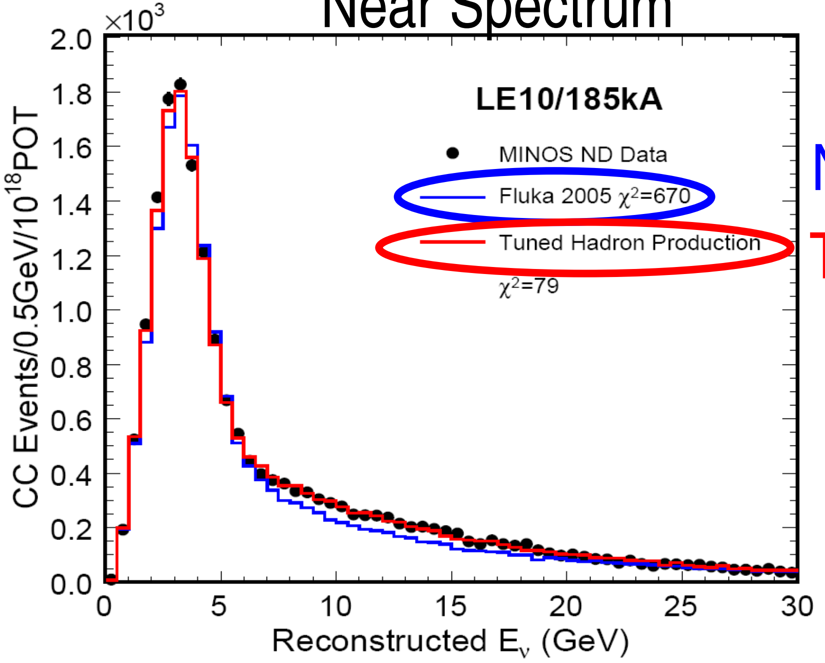


Beam Matrix Method

- Encapsulates the knowledge of pion 2-body decay kinematics & geometry.
- Predicts a Far Detector spectrum for each bin in the Near Detector

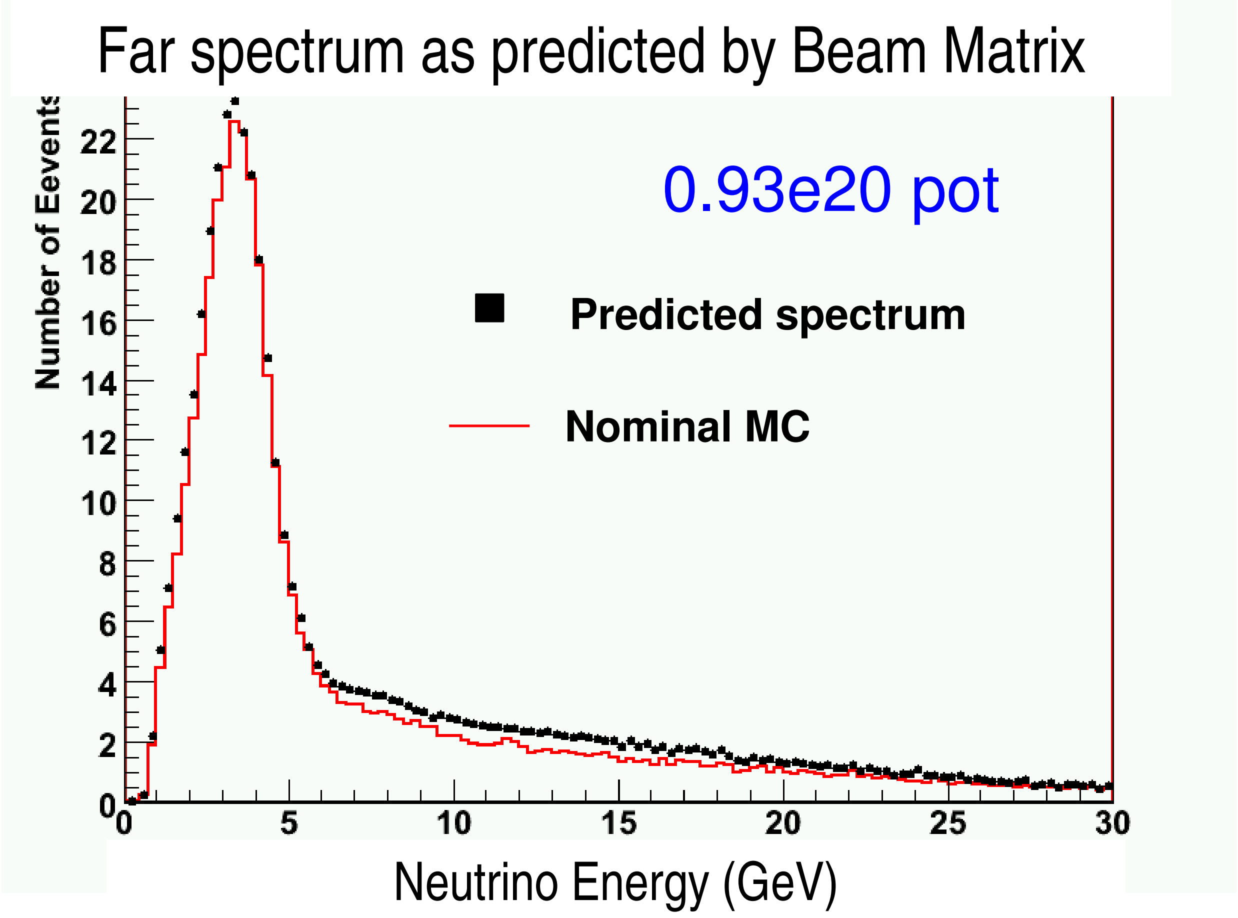
Predicted Far Spectrum

Near Spectrum



Nominal MC

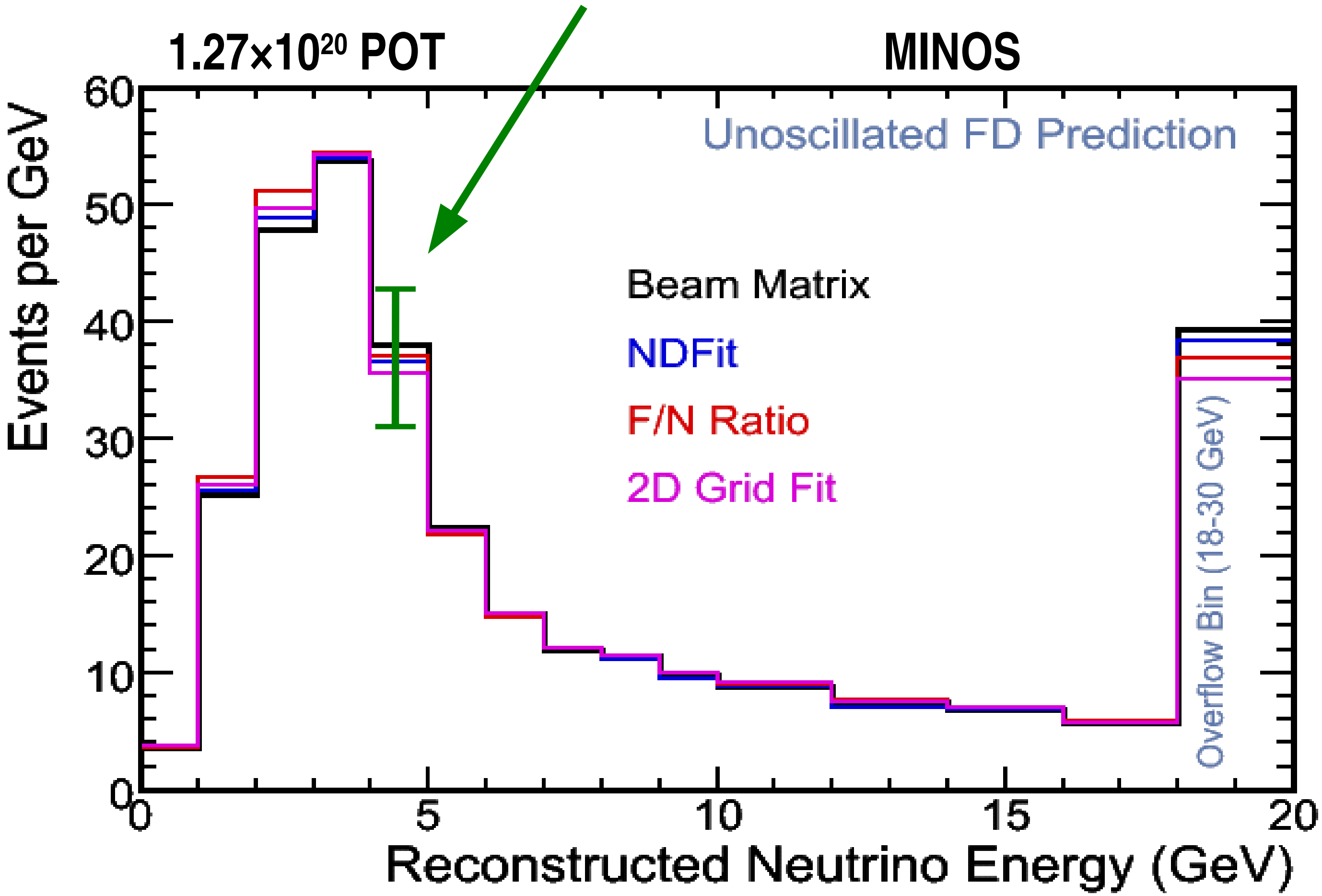
Tuned MC


Far spectrum as predicted by Beam Matrix

- Predicted spectrum higher in tail and on falling edge of peak
- This is the behavior seen in the ND

FD Prediction From All Methods

Size of statistical error



All methods agree to within ~ 5% bin-by-bin

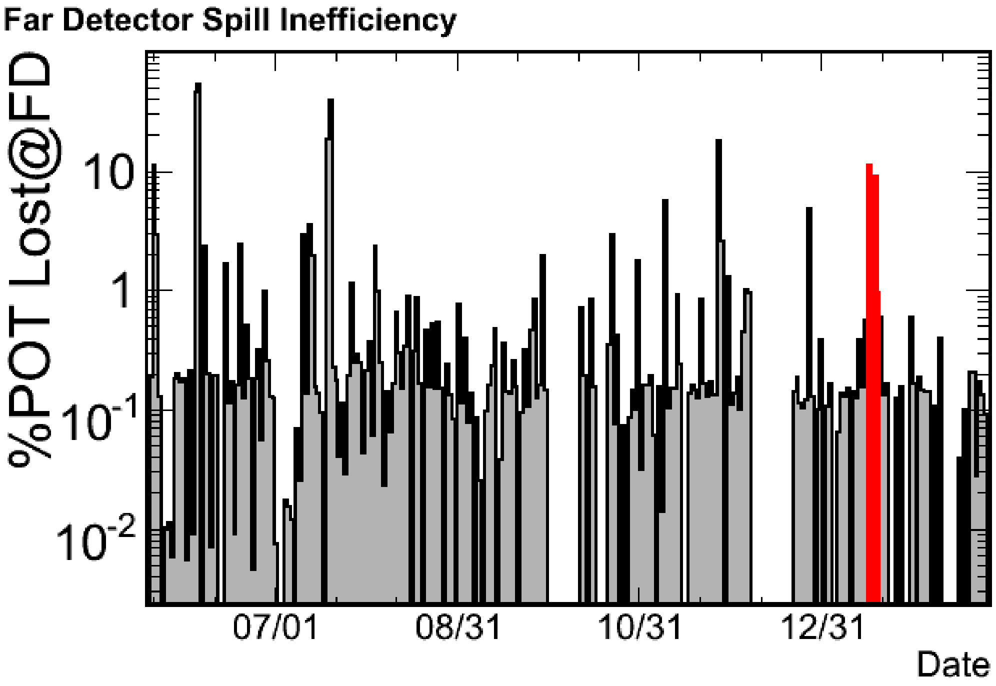
Acceptable considering current exposure

Performing a blind analysis

- The MINOS collaboration decided to pursue a “blind” analysis policy for the first accelerator neutrino results
  - The blinding procedure hides an unknown fraction of our events based on their length and total energy deposition.
- Unknown fraction Far Detector Data was “open” - used them to perform extensive data quality checks.
- Remaining fraction was “hidden”. Final analysis was performed on total sample once box was opened. Box opening criteria were:
  - Checks on open sample should indicate no problems with the FD beam dataset (missing events, reconstruction problems etc.)
  - Oscillation analysis (cuts and fitting procedures) should be pre-defined and validated on MC. No re-tuning of cuts allowed after box opening

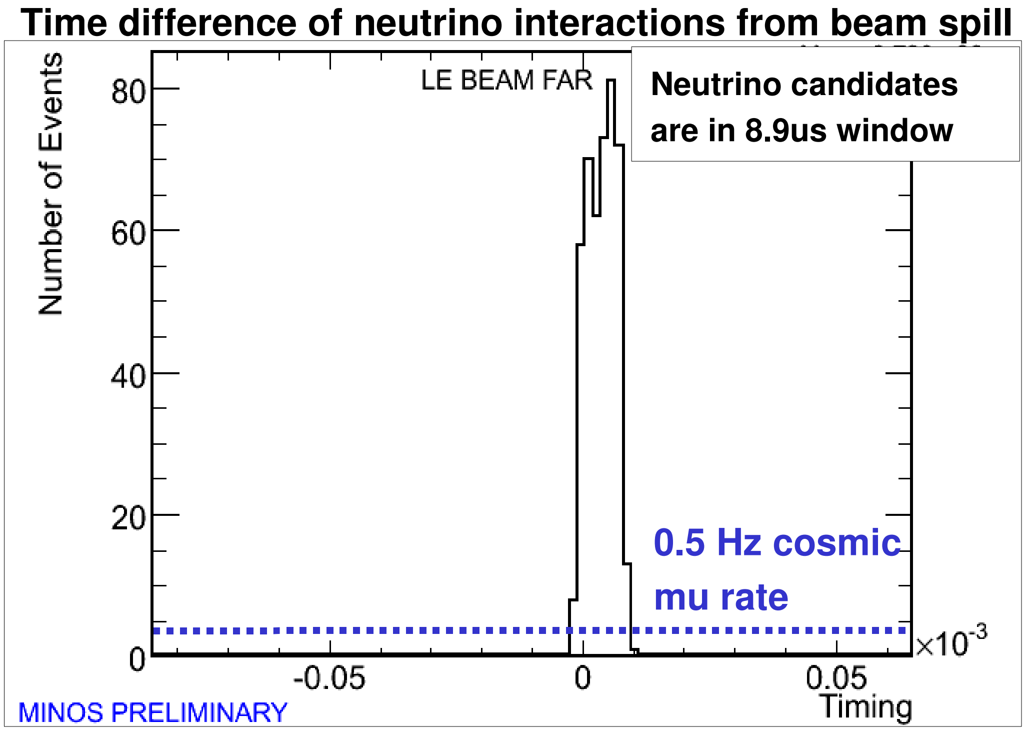
Far Detector Beam Analysis

- Oscillation analysis performed using data taken in the LE-10 configuration from May 20th 2005 – March 3rd 2005: Total integrated POT=1.27e20
  - We exclude periods of “bad data” – coil and HV trips, periods without accurate GPS timestamps. The effect of these cuts are small
  - The POT-weighted livetime of the Far detector for this time period is **99.0%**
  - Neglects exceptional period with 1/16 of detector dead (shown in red ~ 2% of data) , not used, should be recoverable



Selecting beam induced events

- Time stamping of the neutrino events is provided by two GPS units (located at Near and Far detector sites).
  - FD Spill Trigger reads out 100us of activity around beam spills
- Far detector neutrino events have very distinctive topology and are easily separated from cosmic muons (0.5 Hz)



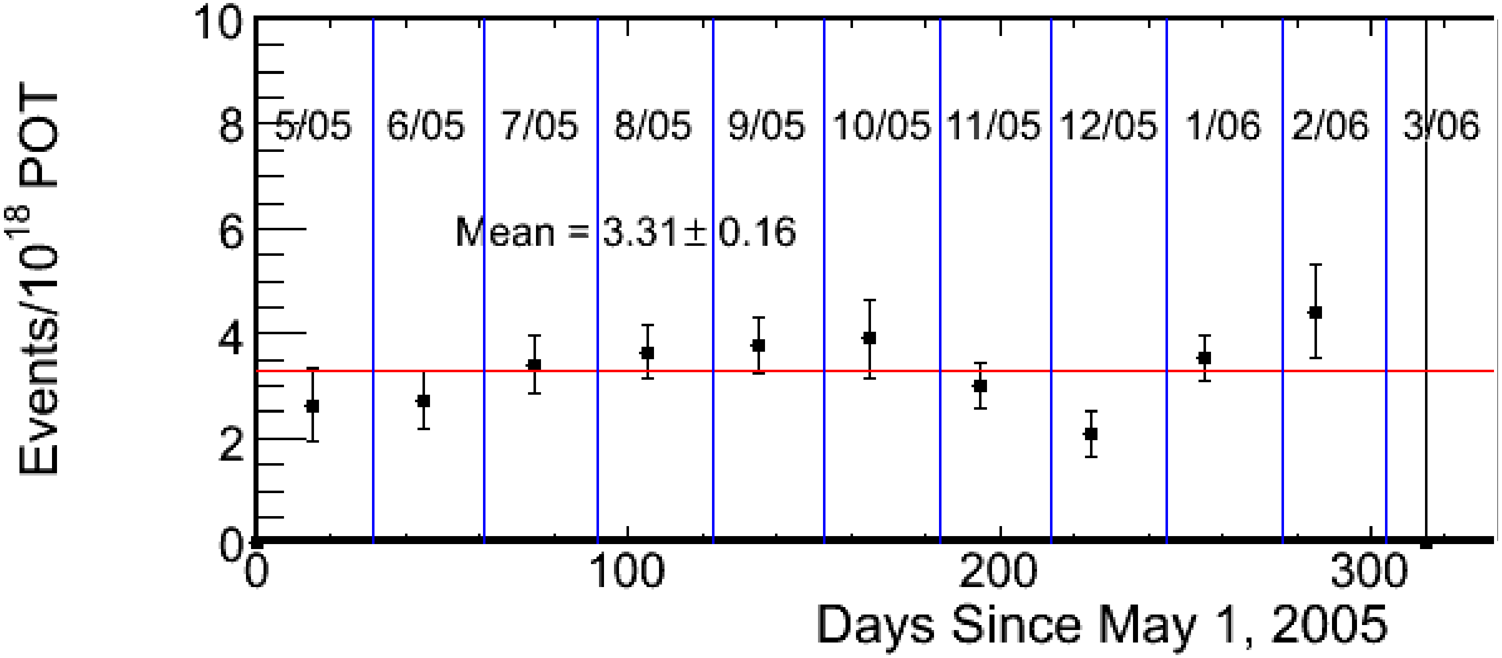
Neutrino candidates are in 8.9us window

0.5 Hz cosmic mu rate

Cosmic ray background estimated (via sidebands) at 0.5 events (90% CL).

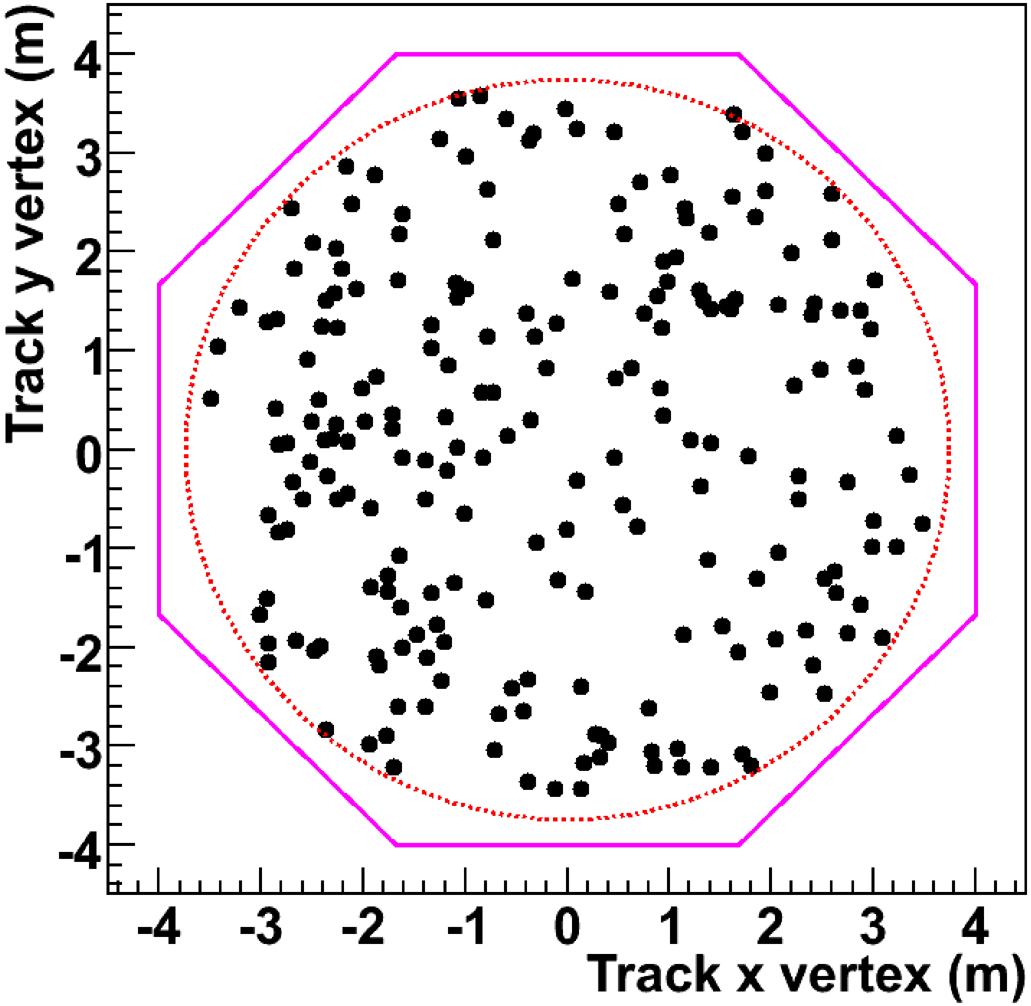
Visual scan identifies zero cosmic ray events in the sample.

Selected events as a function of time

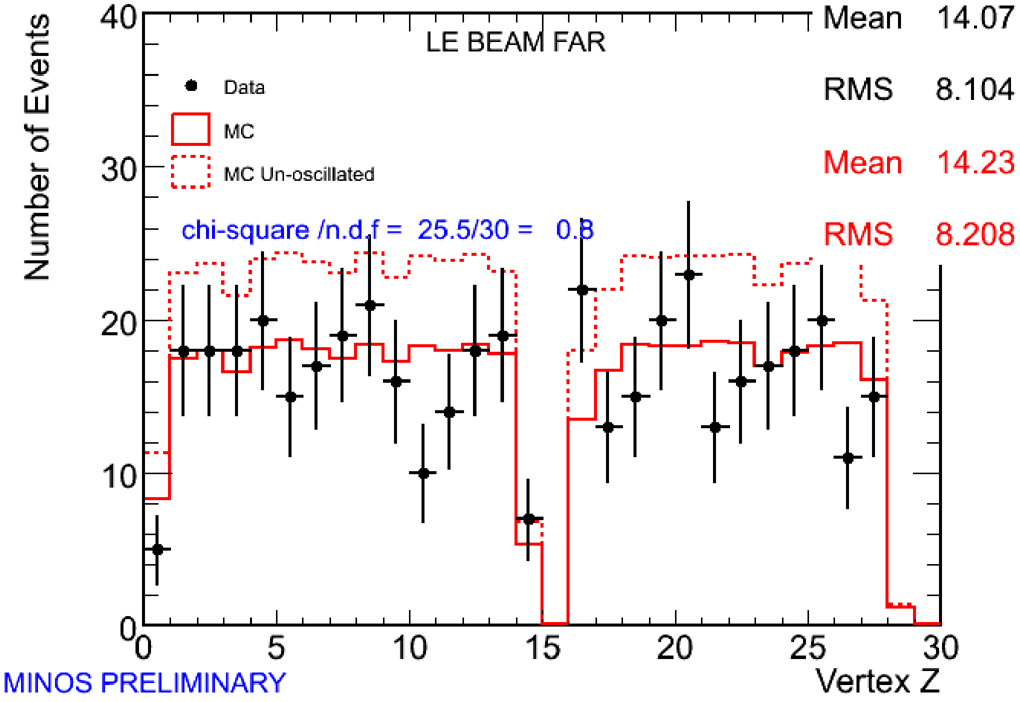


- Neutrino events per P.O.T are flat as a function of time.

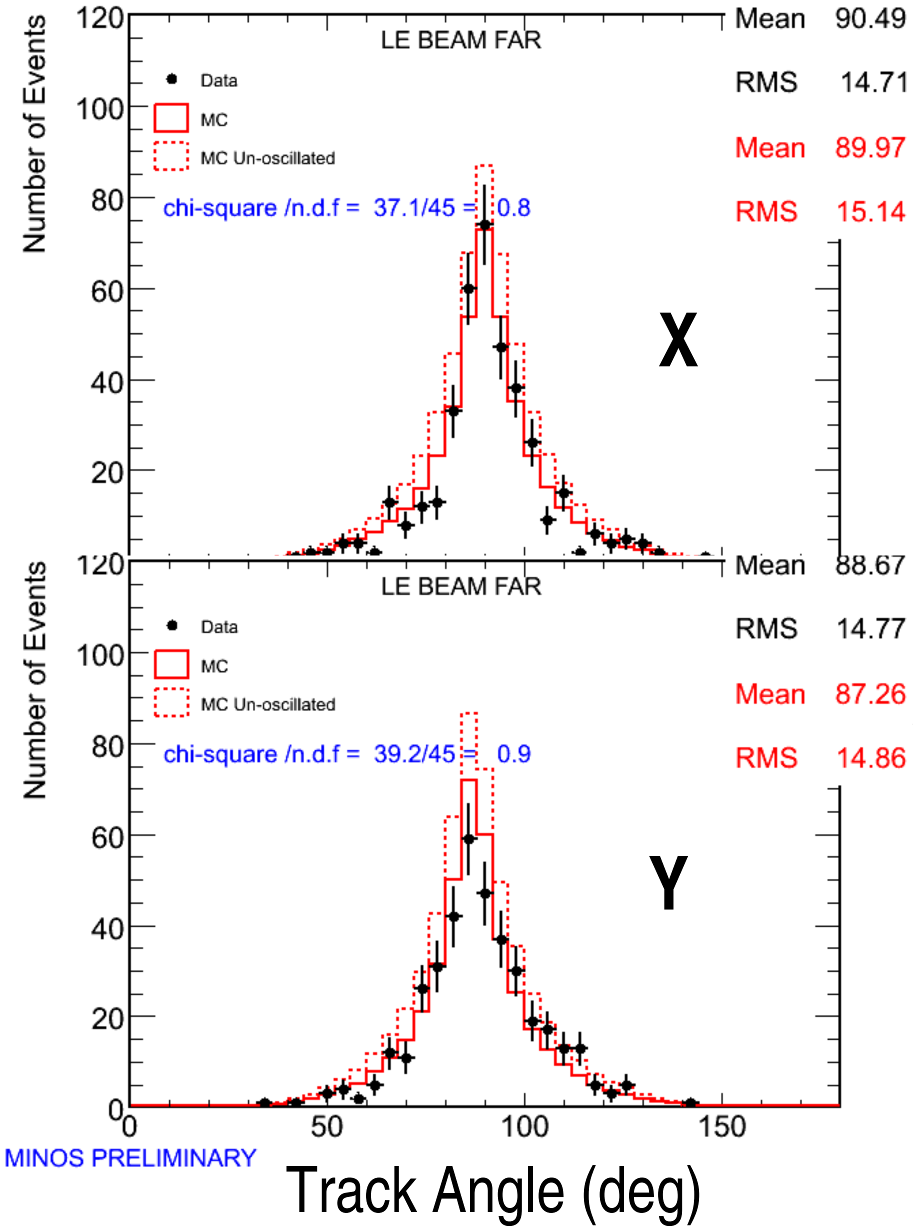
Vertex distributions

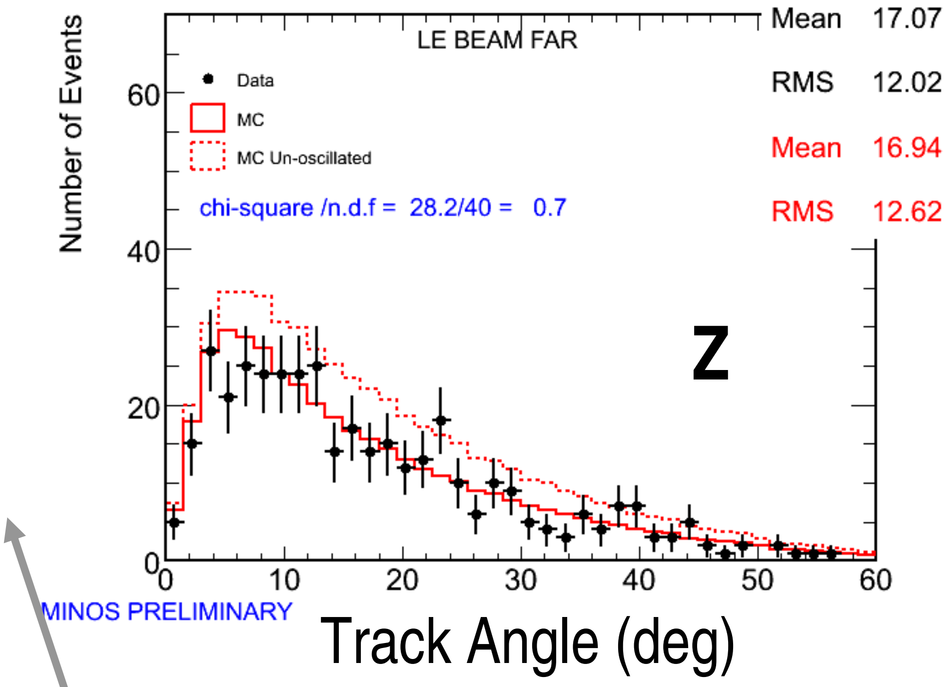


- 215 events selected as CC – no evidence of background contamination.
- Distribution of selected events consistent with neutrino interactions



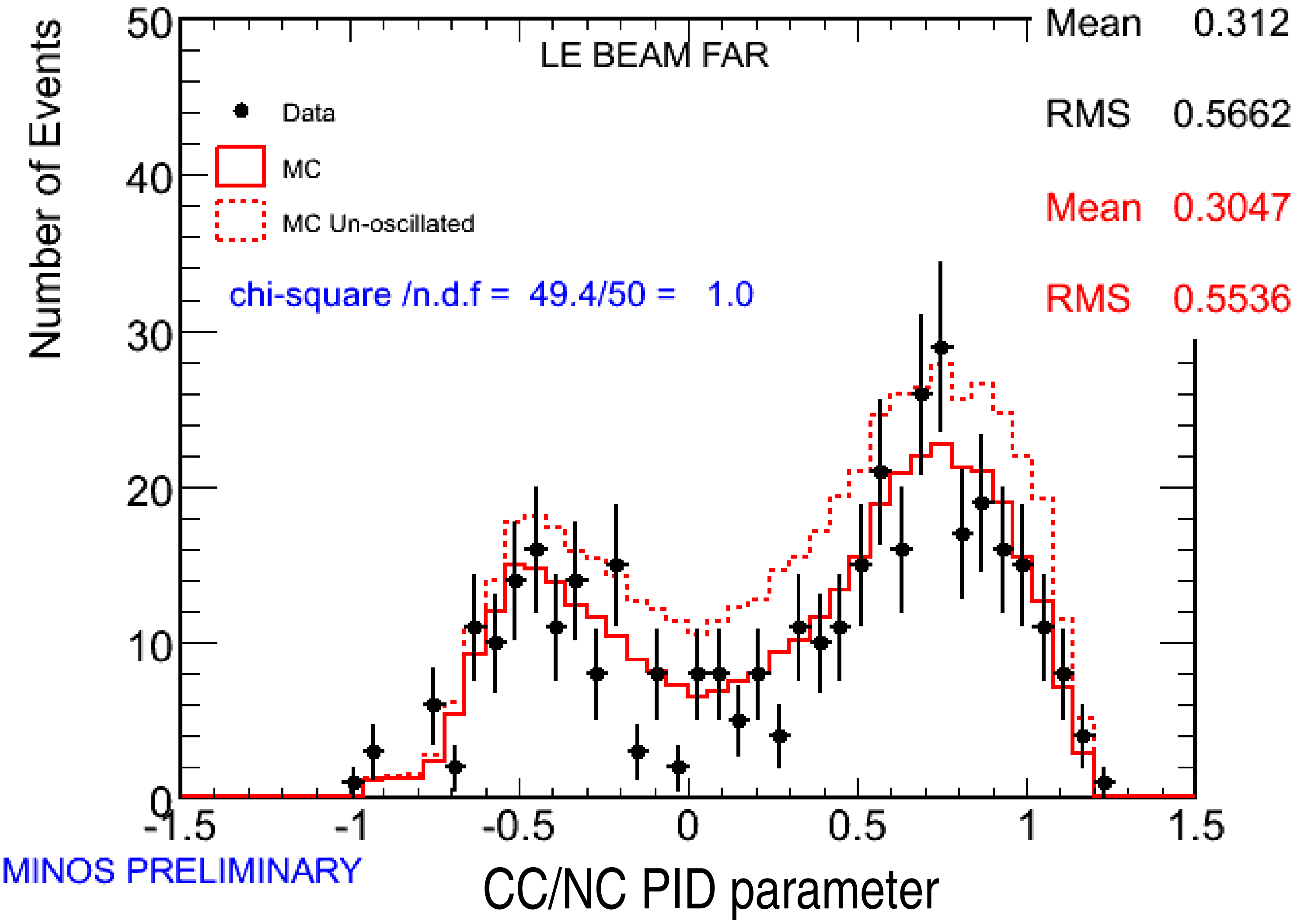
Track angles





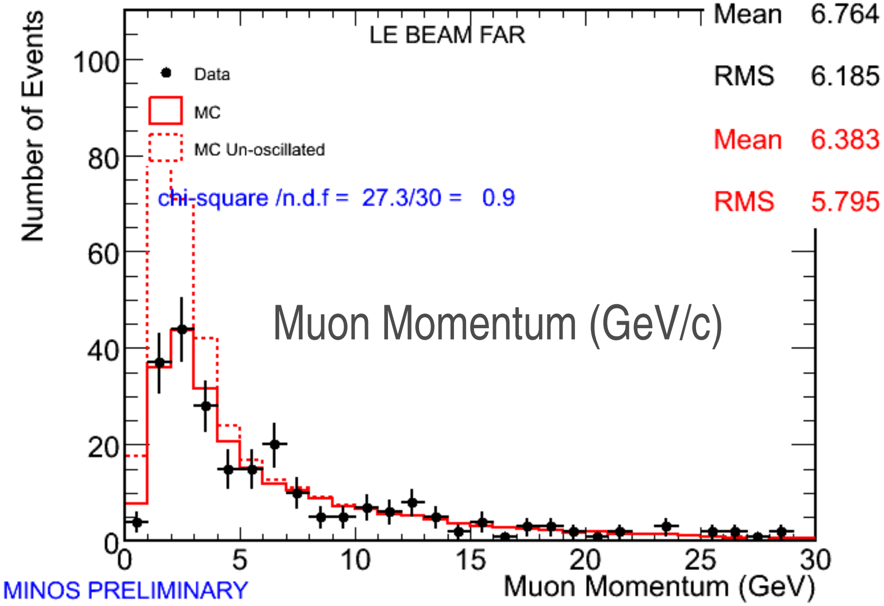
- Notice that beam is pointing 3 degrees up at Soudan!

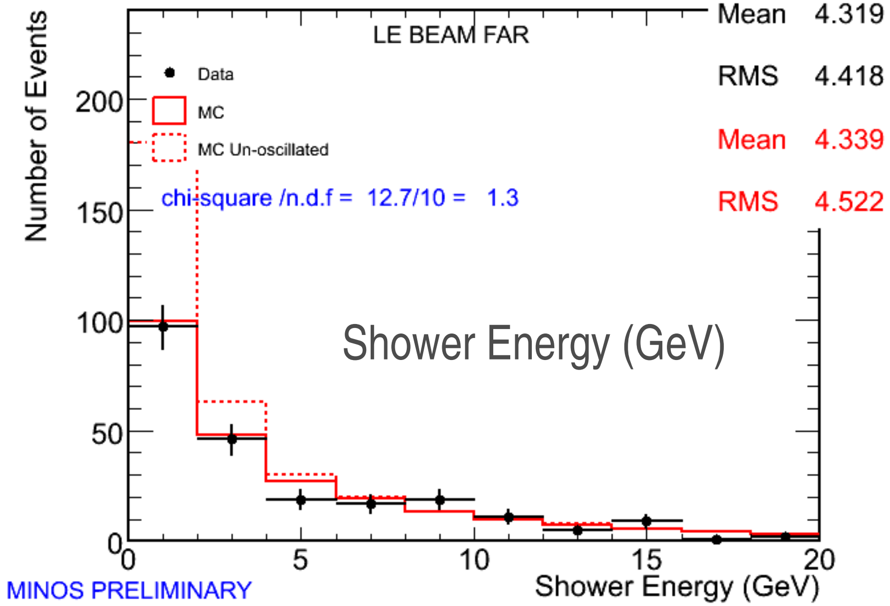
PID distribution

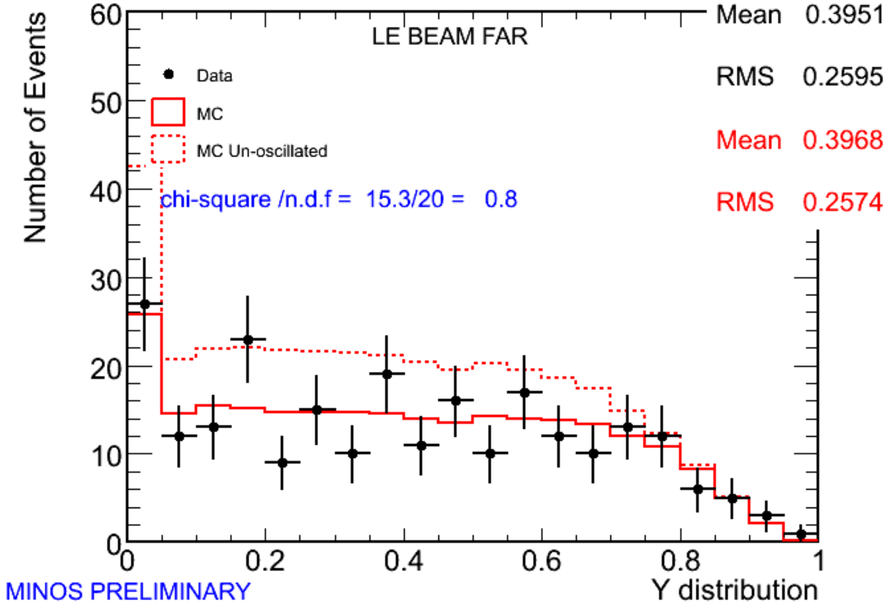


MINOS PRELIMINARY

Physics Distributions







$y = E_{shw}/(E_{shw}+P_{\mu})$

Breakdown of selected events

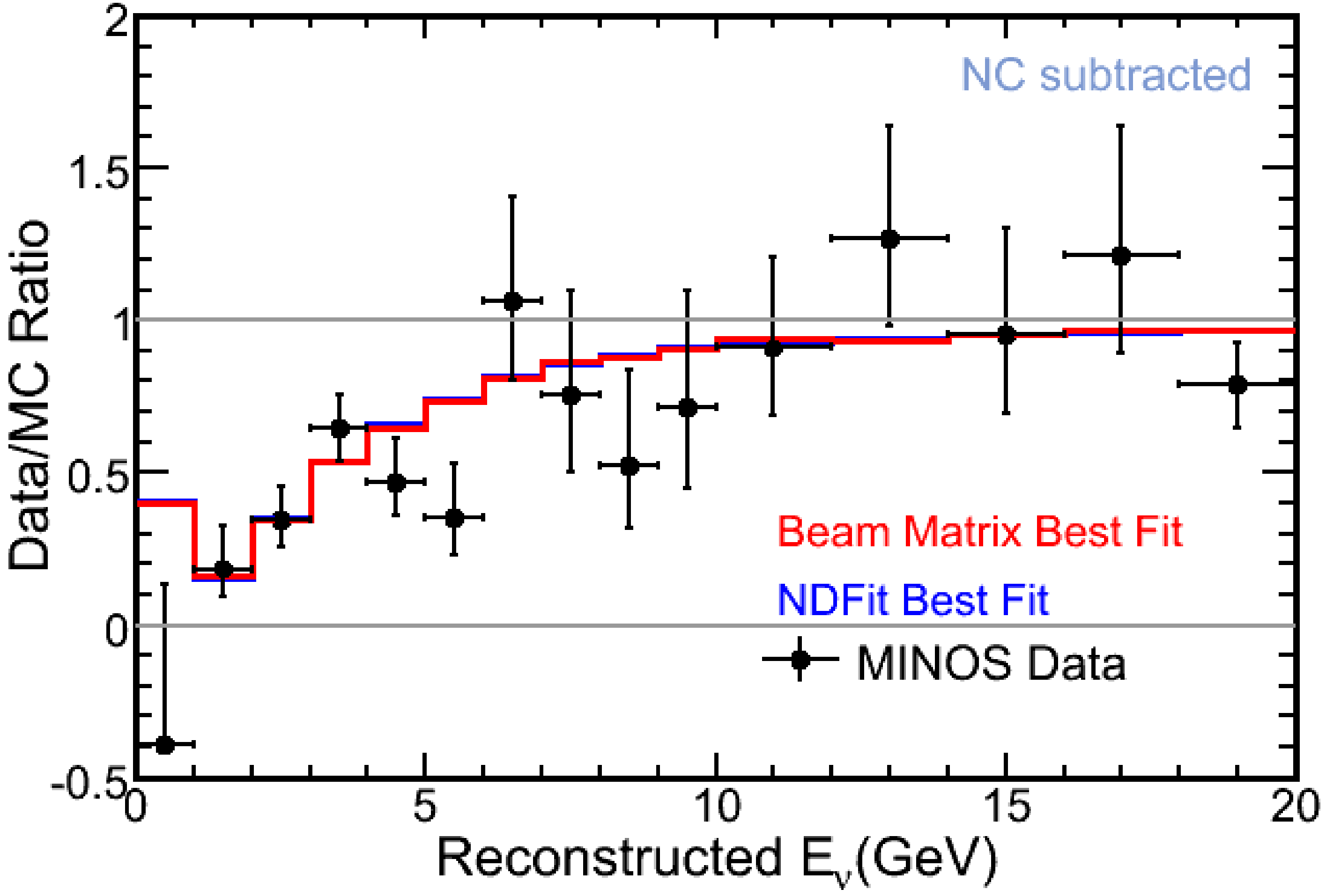
Cut	Events	efficiency
All events in fiducial vol	438	-
Events with a track	384	87.7%
Track quality cuts	365	95.1%
PID cut (CC-like)	267	73.2%
Track charge sign < 0	244	91.4%
Reconstructed energy < 30 GeV	215	88.1%

Number of observed and expected events

Data sample	observed	expected	ratio	significance
$\nu_\mu < 30$ GeV	215	336.0±14.4	.64±.05	5.2σ
$\nu_\mu > 10$ GeV	93	97.3±4.2	.96±.04	0.4σ
$\nu_\mu < 10$ GeV	122	238.7±10.7	.51±.06	6.2σ

- We observe a 36% deficit of events between 0 and 30 GeV with respect to the no oscillation expectation.
- **The statistical significance of this effect is 5.2 standard deviations**
- The observed/expected ratio is energy dependent, no deficit above 10 GeV

Ratio of Data/MC



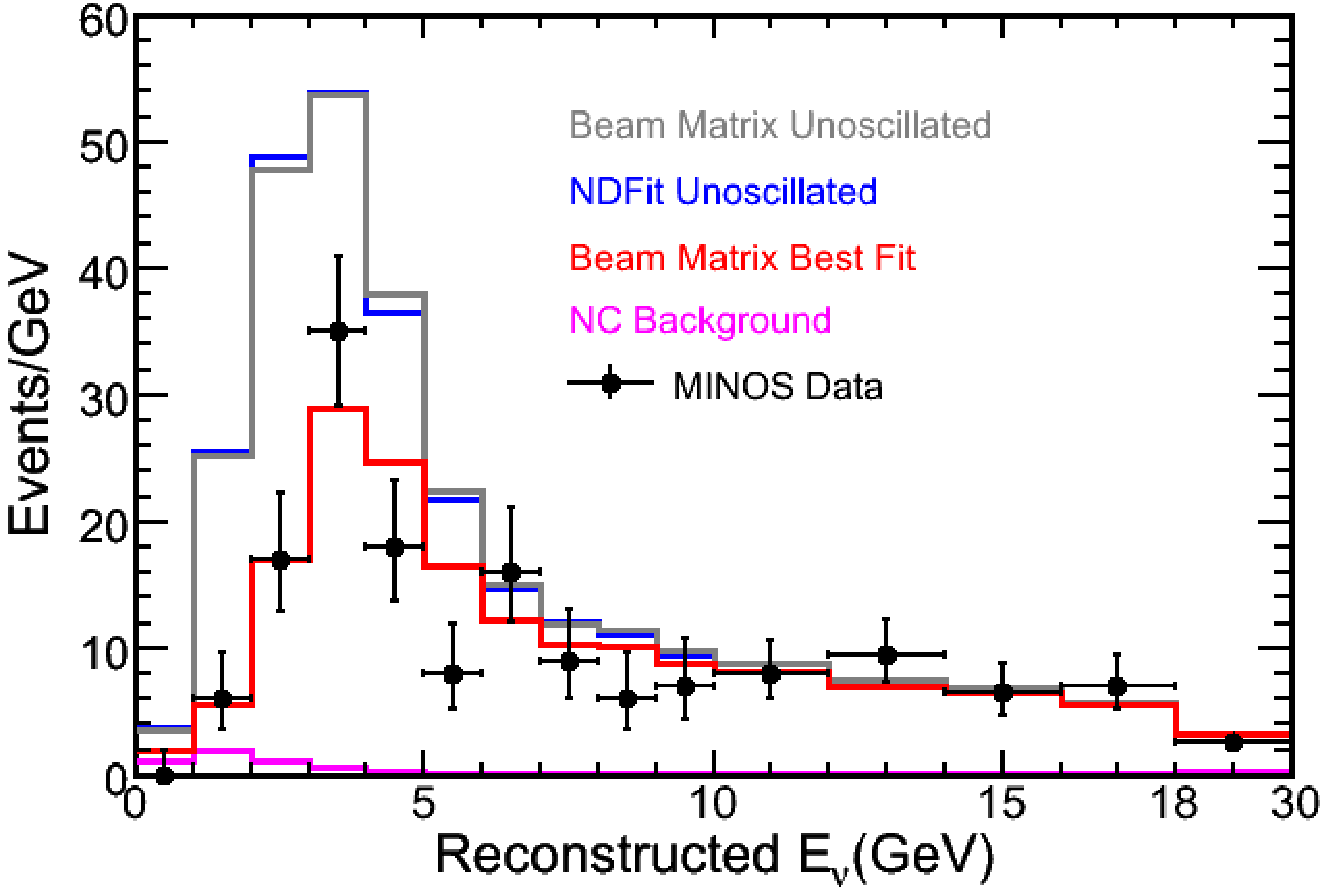
- Obvious "dip": clear sign of oscillations, not normalization
- Data is quite well-described by the 2ν oscillation hypothesis

Systematic Errors

Preliminary Uncertainty	Shift in Δm^2 (10^{-3} eV^2)	Shift in $\sin^2 2\theta$
Near/Far normalization ±4%	**0.050**	**0.005**
Absolute hadronic energy scale ±11%	**0.060**	**0.048**
NC contamination ±50%	**0.090**	**0.050**
All other systematic uncertainties	**0.044**	**0.011**
Total systematic (summed in quadrature)	**0.13**	**0.07**
Statistical error (data)	**0.36**	**0.12**

- Systematic shifts in the fitted parameters are computed using MC “fake data” samples at the best fit point
- The uncertainties and considered and shifts obtained.
- Three largest systematics, normalization, shower energy scale and NC contamination, are included as nuisance parameters in oscillation fit.
- Expect that these uncertainties will decrease with more study.

Best-fit spectrum



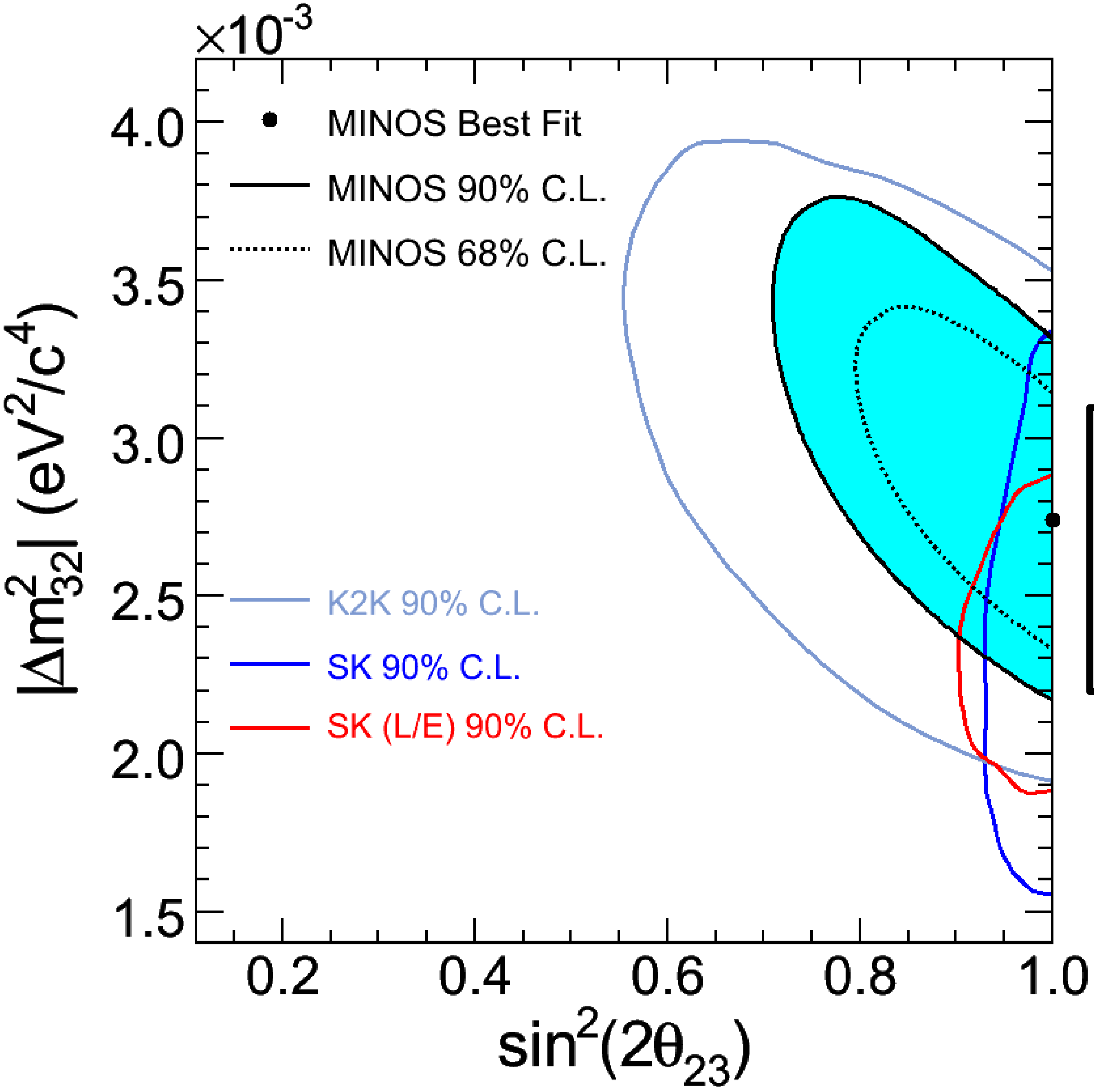
FD prediction by Beam Matrix

$\chi^2/\mathrm{NDF}=20.3/13$

$\mathrm{Prob}=8.9\%$

$$\chi^2=\sum_{i=1}^{\mathrm{nbins}} 2(e_i-o_i)+2\mathrm{o}_i\log(o_i/e_i)+\sum_{j=1}^{\mathrm{nsys}}\frac{\epsilon_j^2}{\sigma_j^2}$$

Allowed regions

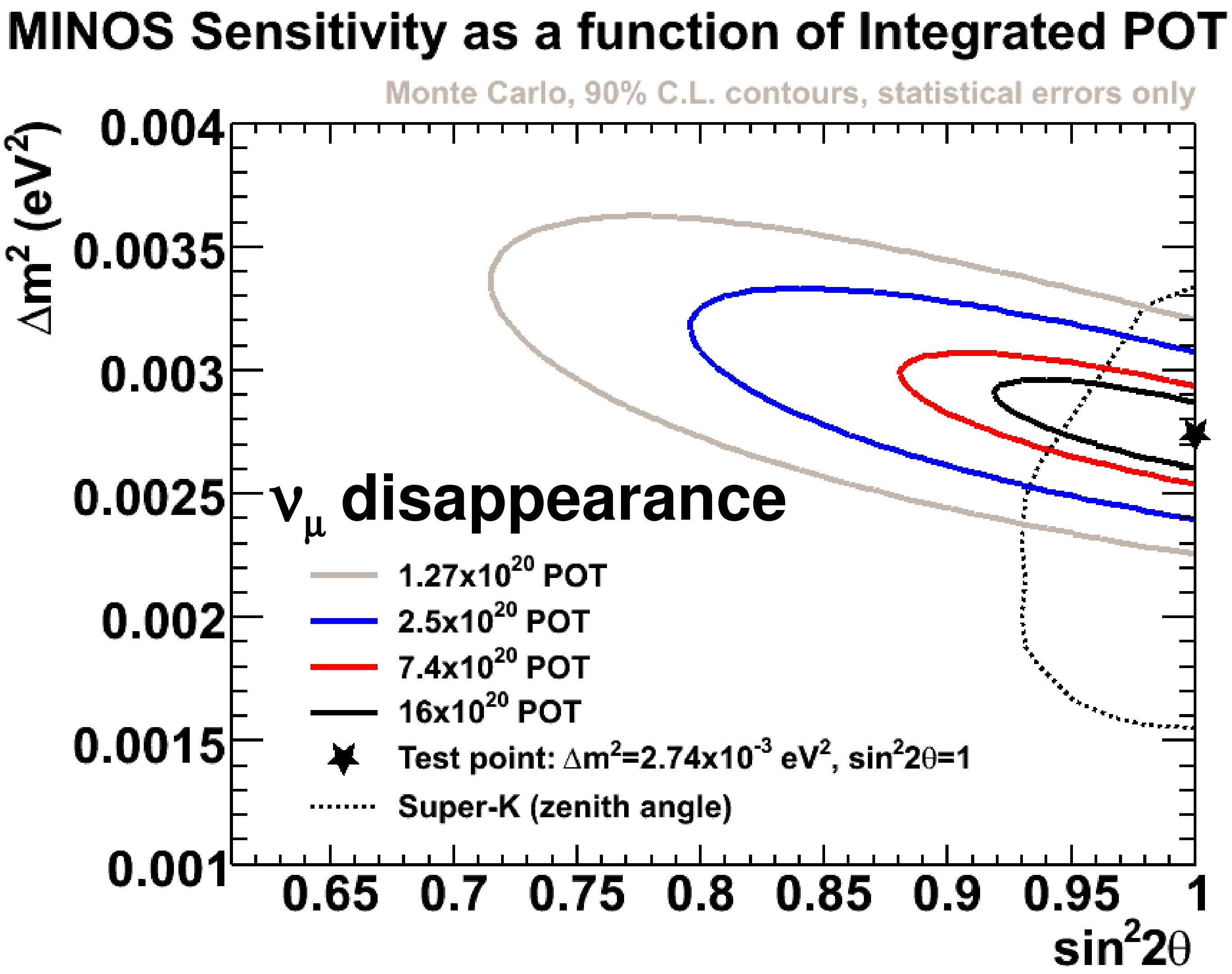


Best Fit Point
and
1 Dimensional Errors

$$\left|\Delta m^2_{23}\right| = 2.74^{+0.44}_{-0.26} \times 10^{-3}\, eV^2/c^4$$

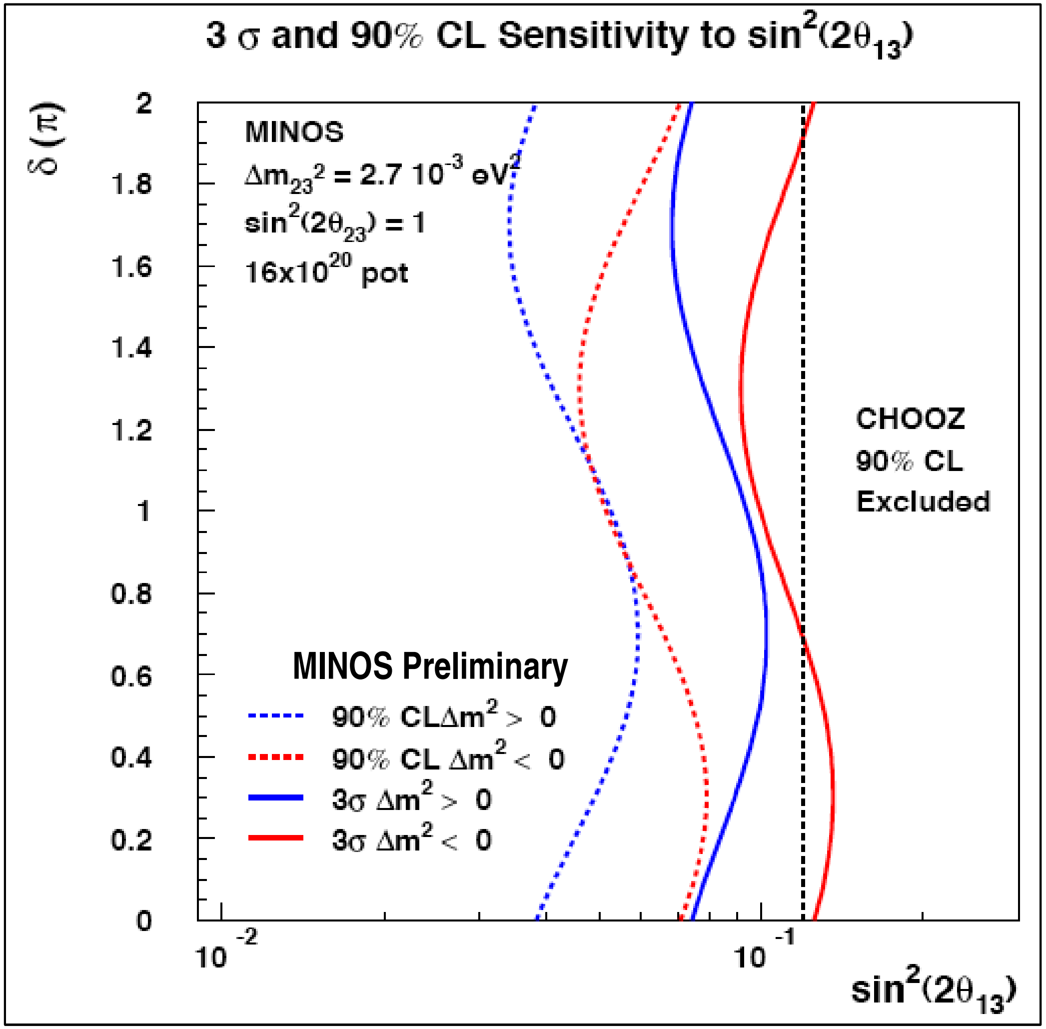
$$\sin^2 2\theta_{23} > 0.87\,(1\sigma)$$

Projected sensitivity of MINOS



Projected MINOS Sensitivity

ν_e Appearance



- MINOS in a position to make first ever measurement of θ_{13}
- Matter effects can change ν_e yield by ±30%
- Can improve on current best limit from CHOOZ
- Plot shows $\sin^2(\theta_{23})$ vs. δ_{CP} for 16e20 POT
- Reach depends strongly on POT

Future Projections

- Initial analysis now submitted to PRL, hep-ex/0607088
- More expansive PRD publication now being written
  - Multiple FD predictions
  - Expanded analysis details
- Rock Muon Analysis: similar statistics to contained vtx, lower resolution
- Oscillations v. decay v. ??:
  - sensitive to shape of dip, events in 5-10 GeV range help
  - collected ~1.5e19 POT in HE configuration this summer
- $\nu_\mu \rightarrow \nu_e$: Hopeful for 2007
- Sterile neutrinos: Summer 2007 ?

Summary and Conclusions

- In this talk I have presented the first accelerator neutrino oscillation results from a 1.27×10^{20} POT exposure of the MINOS detectors.
- Our result disfavors no oscillations at 5.2 σ and is consistent with ν_μ disappearance according to:

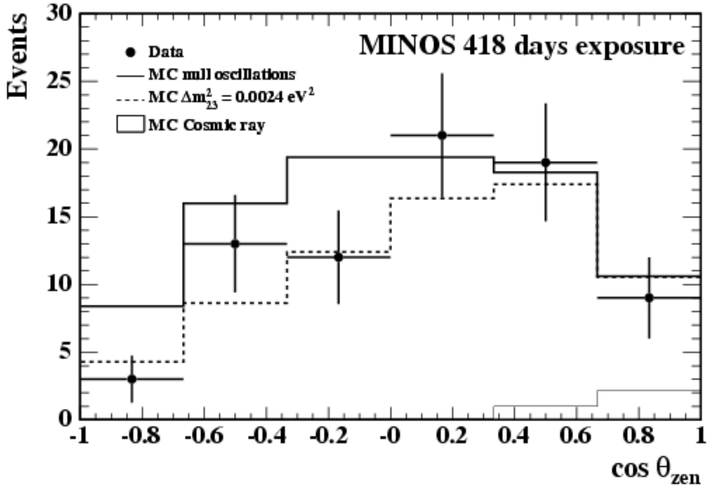
$$\boxed{\begin{gathered}|\Delta m^2_{23}| = 2.74^{+0.44}_{-0.26}\, eV^2/c^4 \\ \sin^2 2\theta_{23} > 0.87\,(1\sigma)\end{gathered}}$$

- Publication submitted to PRL. Meanwhile see: **`hep-ex/0607088`**
- The systematic uncertainties on this measurement are under control and we should be able to make significant improvements in precision with a larger dataset.
- We hope to achieve an eventual exposure of 16e20 POT, collecting ~3e20/yr

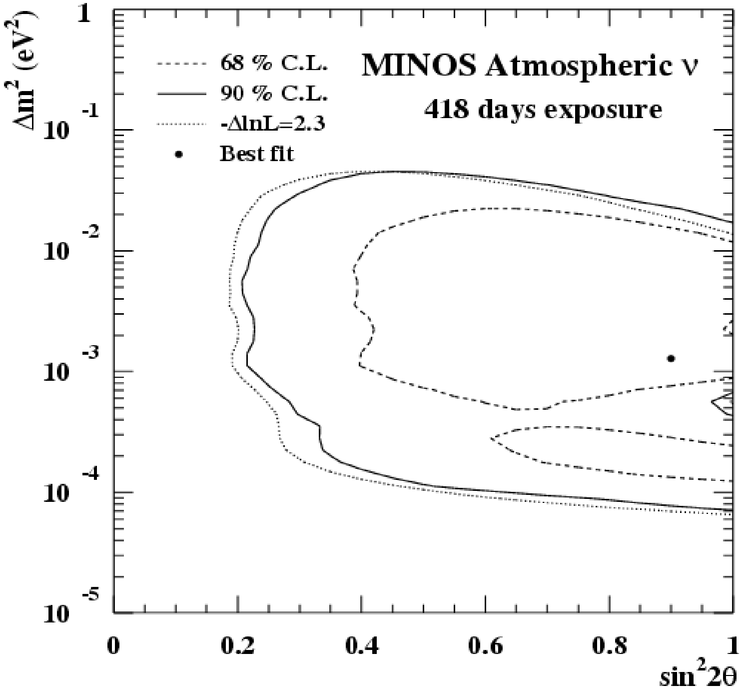
Backup Slides

Atmospheric neutrino analysis

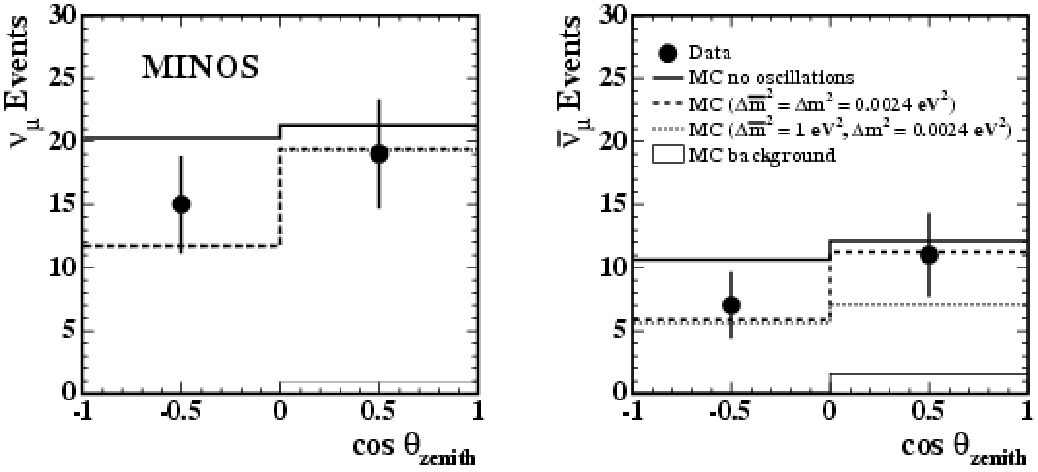
- First direct results on neutrino/anti-neutrino oscillations using atmospheric neutrinos
- **PRD 73, 072002 (2006)**



107 contained events



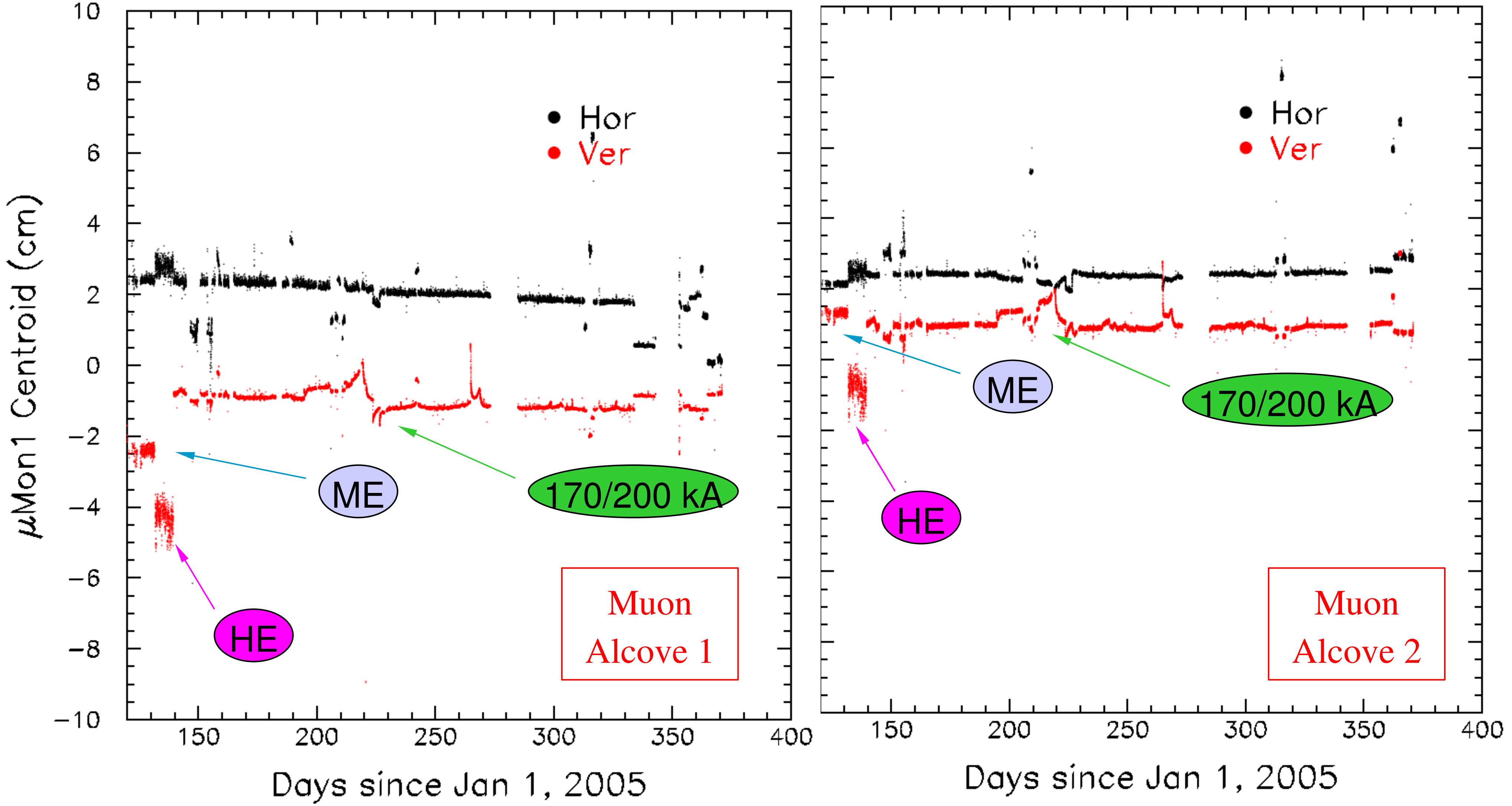
Selection	Data	Expected no oscillations	Expected $\Delta m^2_{23} = 0.0024\,\mathrm{eV}^2$
Low Res.	30	37 ± 4	28 ± 3
Ambig. $\nu_\mu/\overline{\nu}_\mu$	25	26 ± 3	20 ± 2
ν_μ	34	42 ± 4	31 ± 3
$\overline{\nu}_\mu$	18	23 ± 2	17 ± 2



Systematics

- Normalisation: ±4%
  - POT counting, Near/Far selection efficiency
- Relative shower energy scale: ±3%
  - Inter-Detector calibration uncertainty
- Muon energy scale: ±2%
  - Uncertainty in dE/dX in MC, range vs. curvature
- NC contamination of CC-like sample: ±30%
  - From shape and normalisation of ND PID distribution
- CC cross-section uncertainties:
  - M_A (qel) and M_A (res) - ±5%
  - KNO RES-DIS scaling factors - ±20%
- Intranuclear rescattering: ±10% shower energy scale uncertainty
- Beam uncertainty: difference between fits with weighted/unweighted MC

Beam pointing with μ monitors



- To keep distortions in the FD spectrum <1%, we require <100μrad mis-steering of the ν beam from FNAL
- At the muon monitors, a 10 cm shift in the muon beam centroid corresponds to a 130μrad angular deviation.

NuMI Alignment

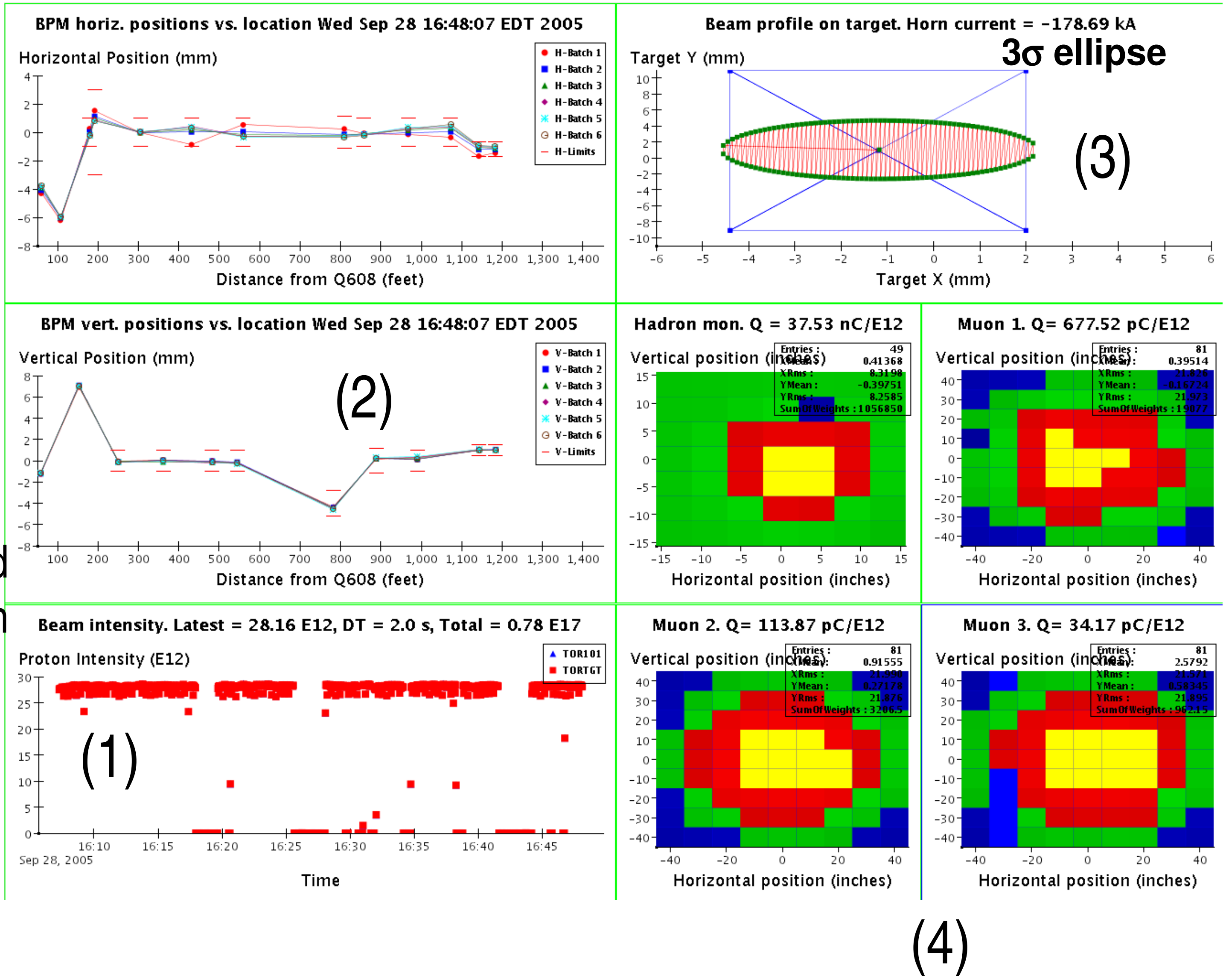
Align the center of ν beam to the Far Detector in the Soudan mine. Goal is within 12 m.

- Fermilab to Soudan surface done using GPS
  - determined vector to 0.01 m horiz., 0.06 m vertical
- Soudan surface to 27th level
  - 0.7 m per coordinate
- Fermilab surface to underground
  - gyrotheodolite with 0.015 mrad precision
  - 11 m at Soudan
- Transverse alignment of baffle, target and horn at 0.5 mm

Monitoring the NuMI beam

- Each spill we monitor:
  - •Intensity (1),
  - •Beam position (2)
  - •Beam profile at the target (3)
  - •hadron and muon profiles at the end of the decay volume (4)

•This information is then used offline to select good beam quality spills



Event generator

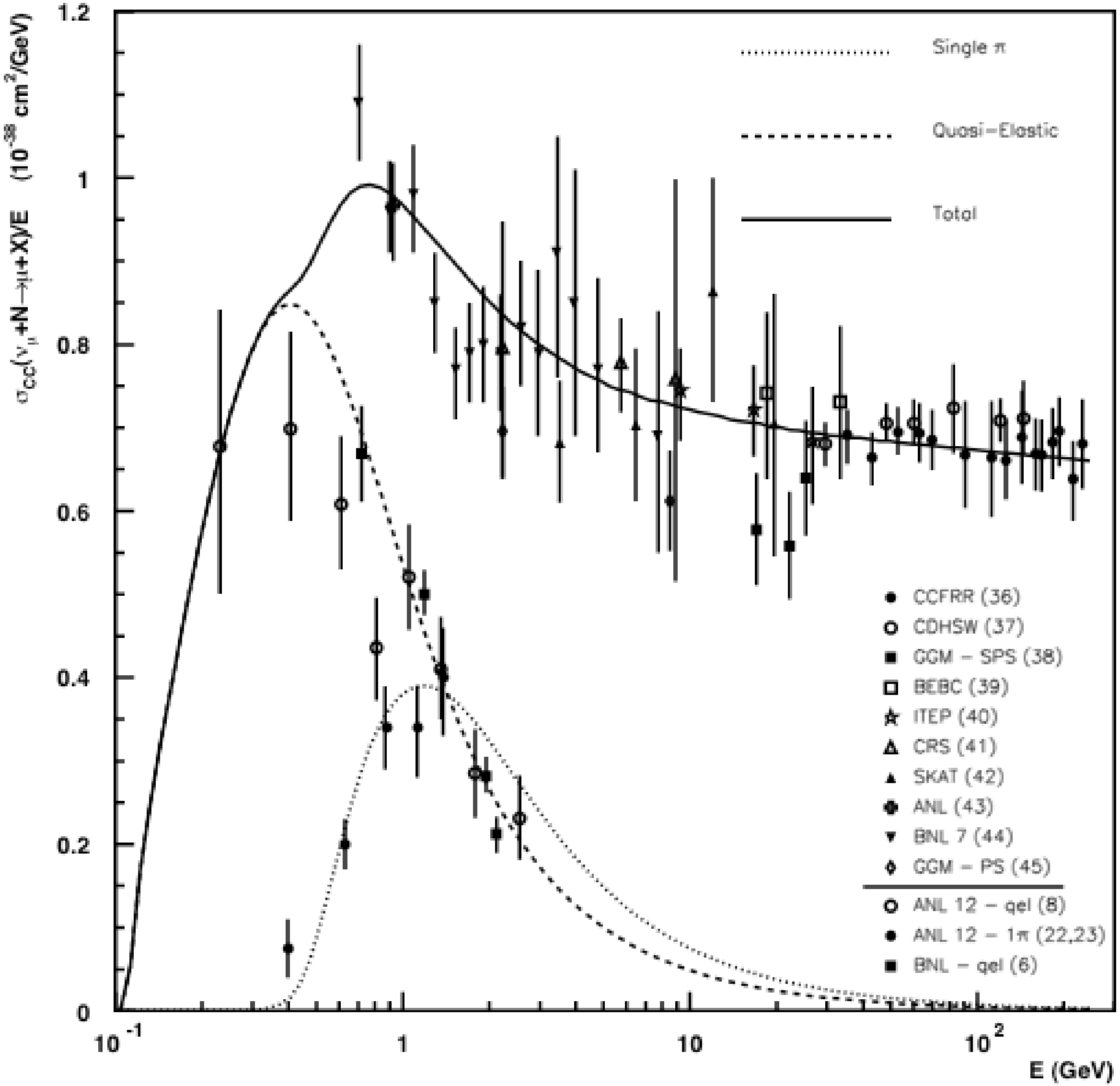
Neutrino-nucleus interactions were generated using the NEUGEN3 neutrino event generator
(H. Gallagher, Nucl.Phys.Proc.Suppl. **112**: 188-194, 2002

Quasi-Elastic: dipole parametrization of form factors with m_a=1.032 GeV/c^2.

Resonance Production:
Rein-Seghal model for W<1.7 GeV/c^2.
(Annals Phys. **133**: 79, 1981)

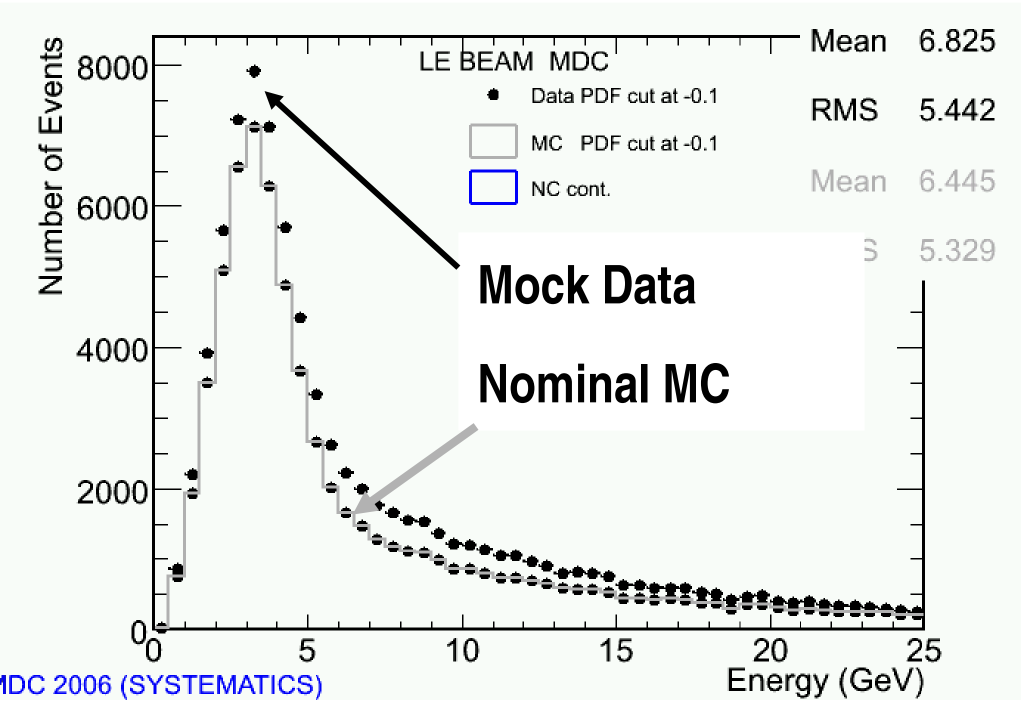
DIS: Bodek-Yang modified LO model.
For W<1.7 GeV tuned to electron and neutrino data in the resonance / DIS overlap region.
(Bodek-Yang, Nucl. Phys. Proc. Suppl. **139**: 113-118, 2005 and H. Gallagher, NuINT05 Proceedings)

Coherent Production:
Rein-Seghal (Nucl. Phys. B **223**: 29, 1983*)*



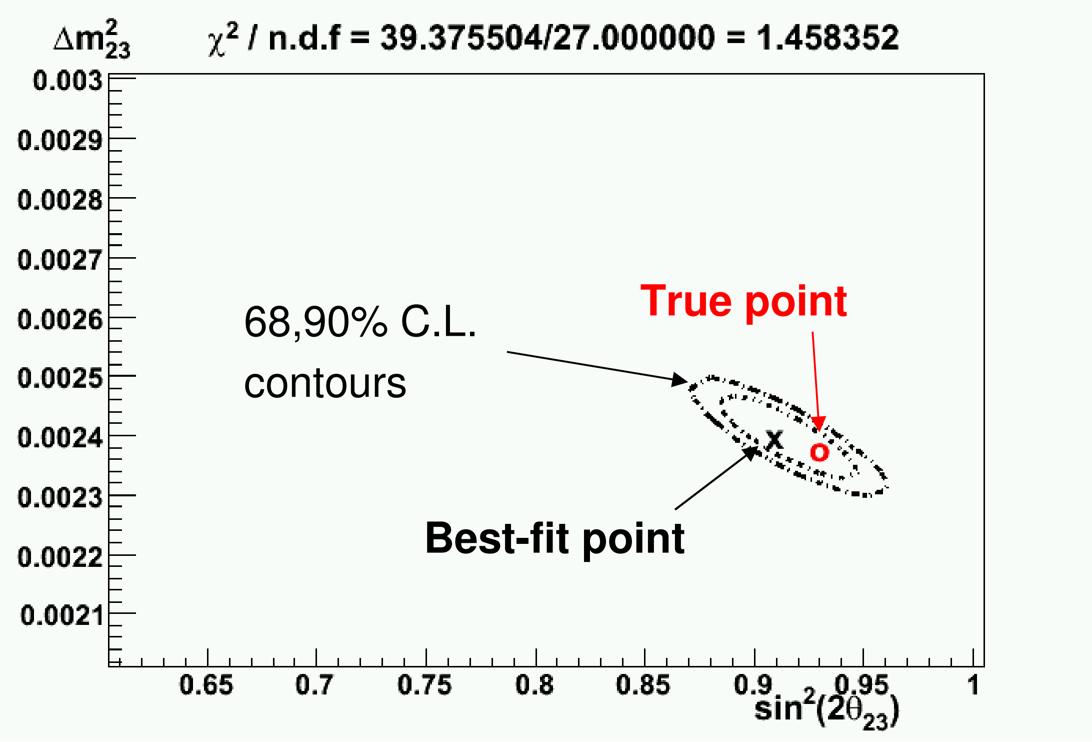
Systematics : Test on 1E22 p.o.t “Mock Data Challenge Set”

In order to test the robustness of the method, a “fake dataset” was generated with tweaked beam/generator parameters and unknown oscillation parameters.



Mock Data

Nominal MC



68,90% C.L. contours

True point

Best-fit point

Beam Matrix Method yields to an accurate estimation of the oscillation parameters despite the large differences between “Mock Data” and Monte Carlo (even for 1E22 protons on target!)

Outline of “Beam Matrix” Method

A)

$$E^{Reconstructed}_{Near\ \ CC\text{-}like} \Rightarrow E^{True}_{Near\ \ CC}$$

Correction for purity, Reconstructed =>True, Correction for efficiency

B)

$$E^{True}_{Near\ \ CC} \Rightarrow E^{True}_{Far\ \ CC}$$

BEAM MATRIX

C)

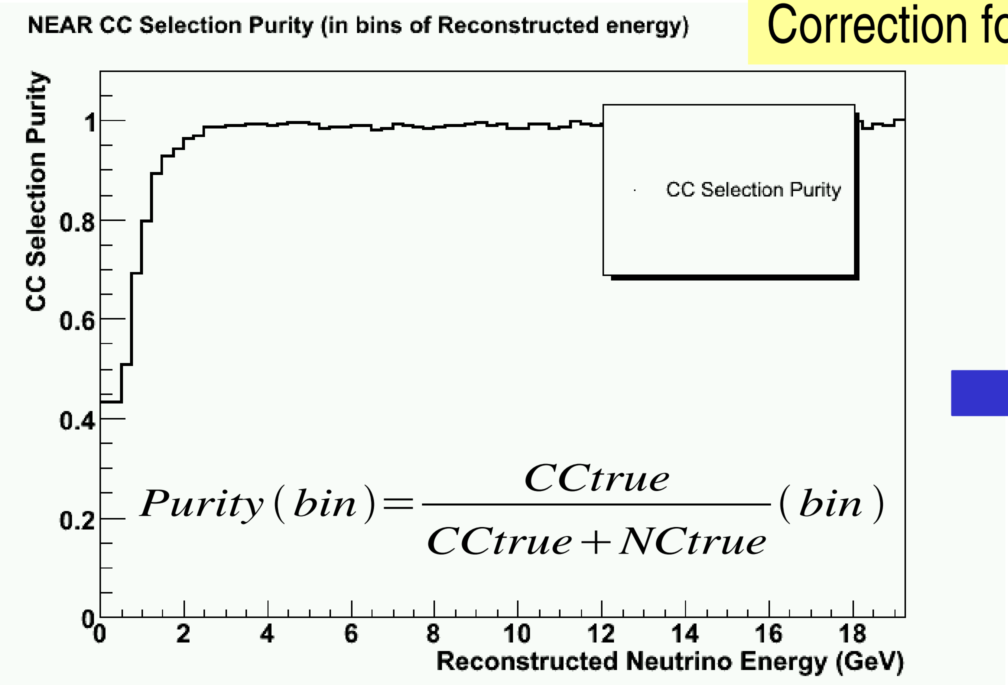
$$E^{True}_{Far\ \ CC} \Rightarrow E^{Reconstructed}_{Far\ \ CC\text{-}like}$$

i) Oscillation, True => Reconstructed, Correction for efficiency to obtain CC oscillated spectrum

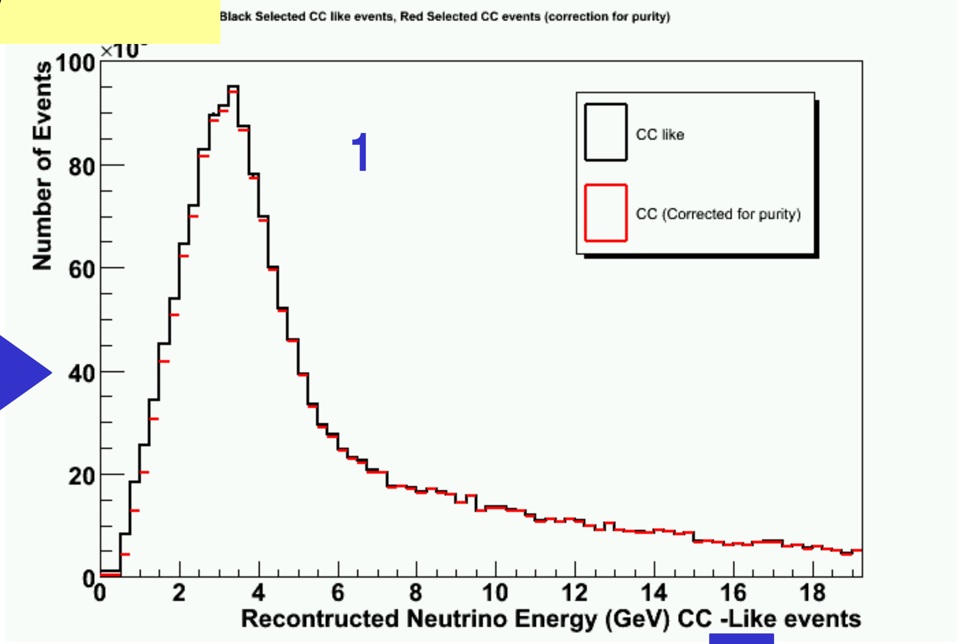
ii) Unoscillated True => Reconstructed, Use purity to obtain NC background

Step A of the “Beam Matrix”Method

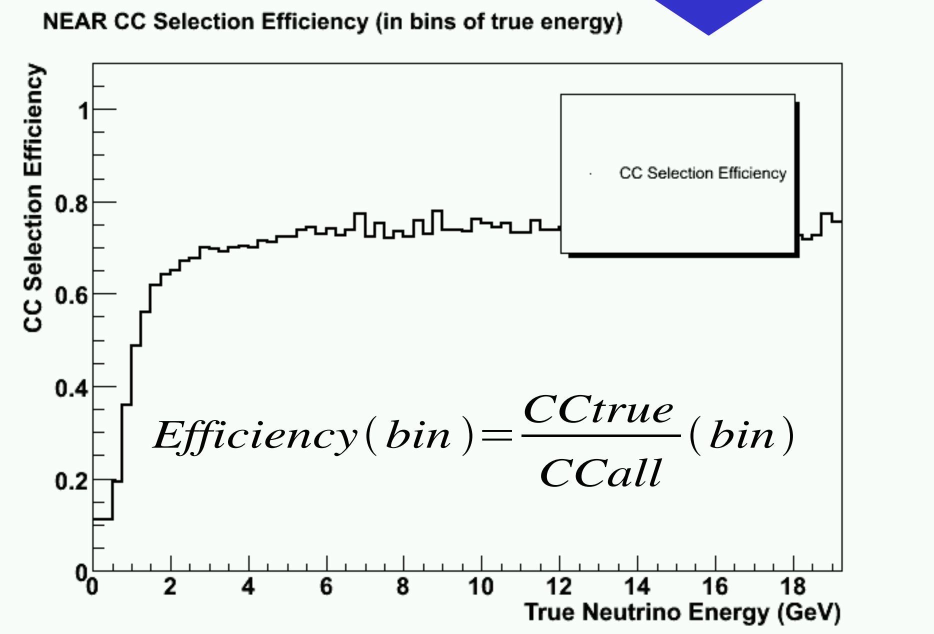
Correction for purity


NEAR CC Selection Purity (in bins of Reconstructed energy)

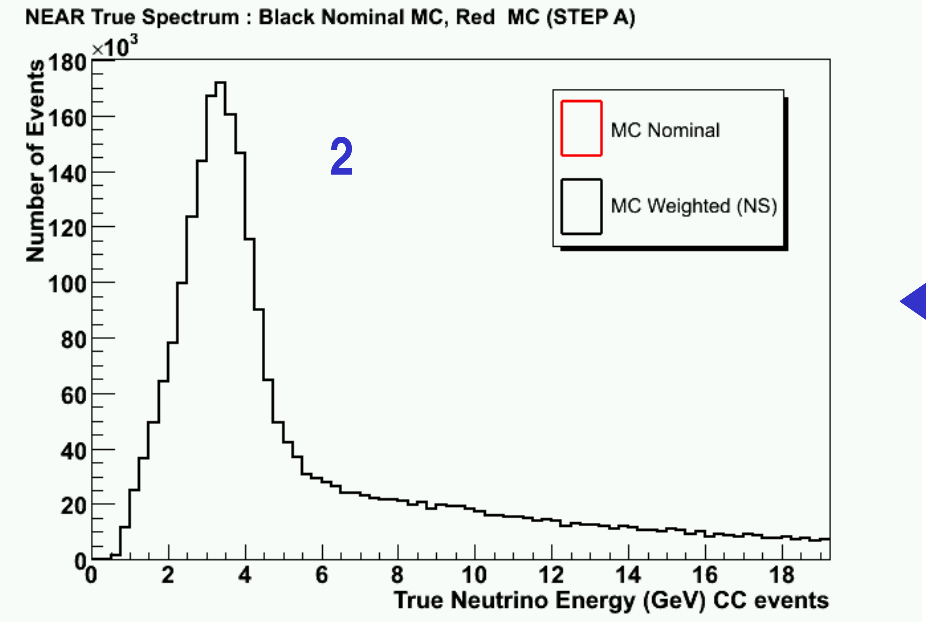
$$Purity(bin) = \frac{CCtrue}{CCtrue + NCtrue}(bin)$$


Black Selected CC like events, Red Selected CC events (correction for purity)

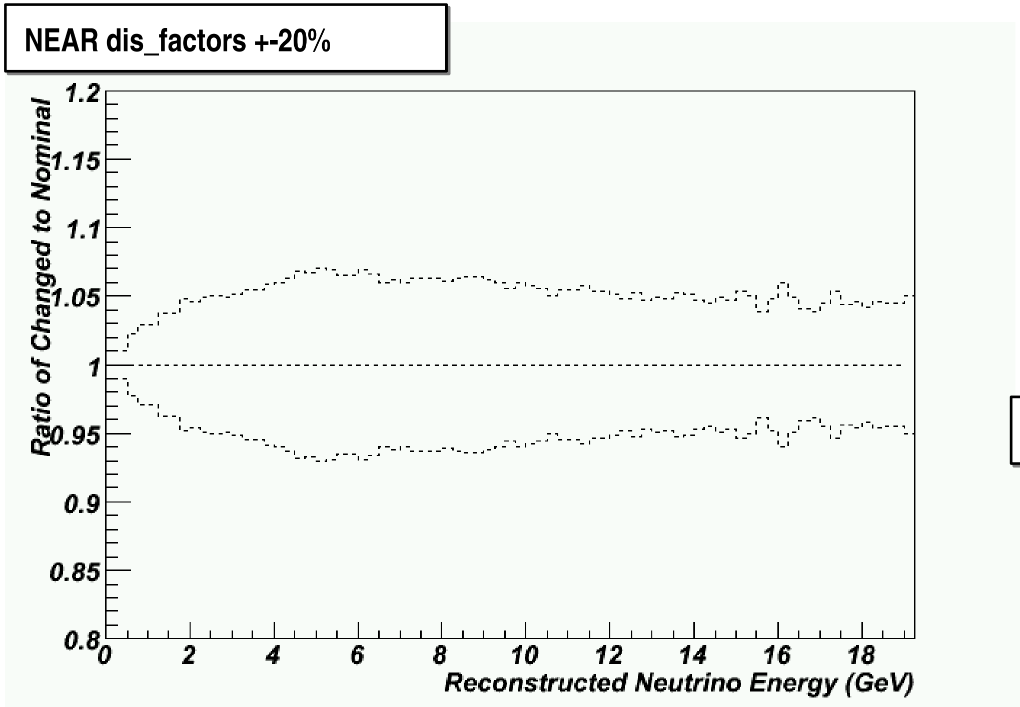
Reconstructed =>True and Correction for efficiency


NEAR CC Selection Efficiency (in bins of true energy)

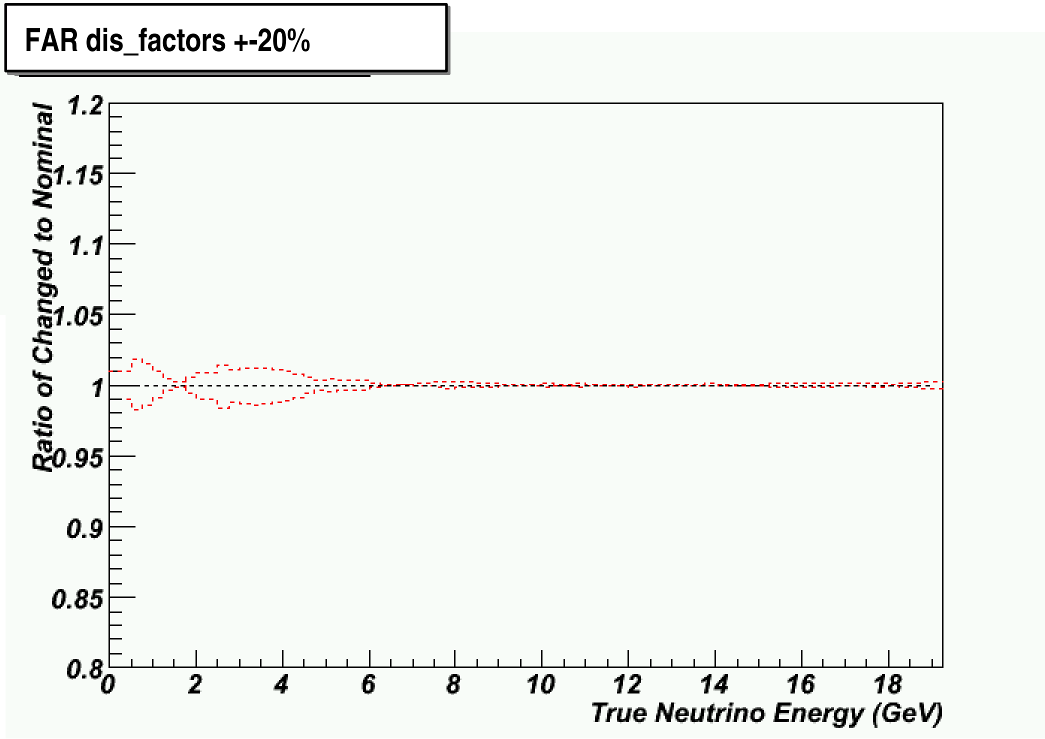
$$Efficiency(bin) = \frac{CCtrue}{CCall}(bin)$$


NEAR True Spectrum : Black Nominal MC, Red MC (STEP A)

Systematics : DIS-Resonance region cross section factors changed by ± 20%



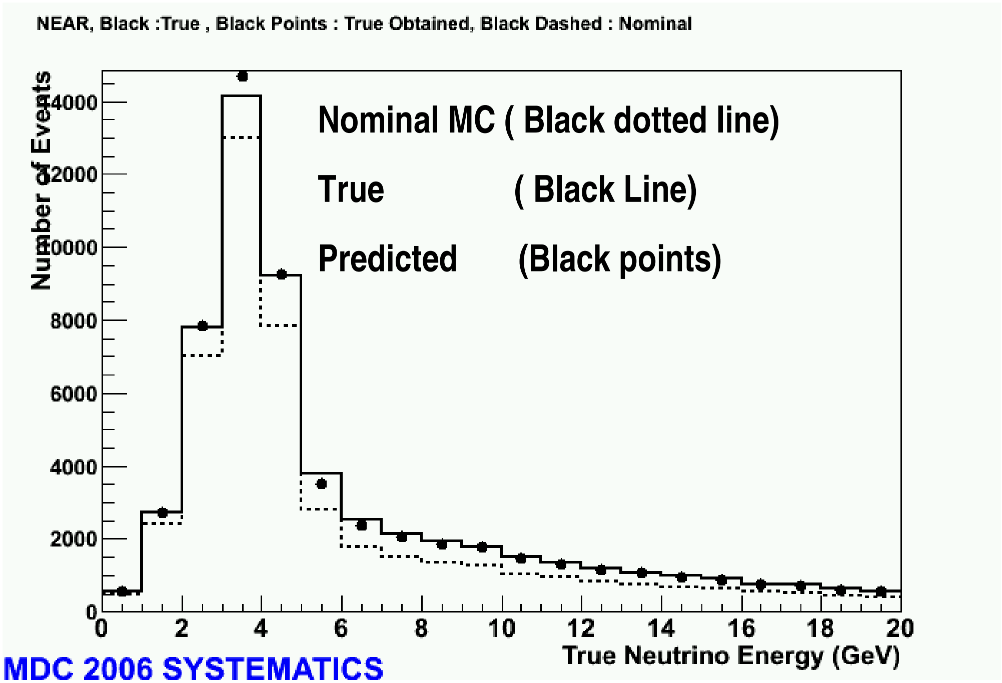
Far Detector Ratio of Predicted to "Data" : changes are of the order of < 1%

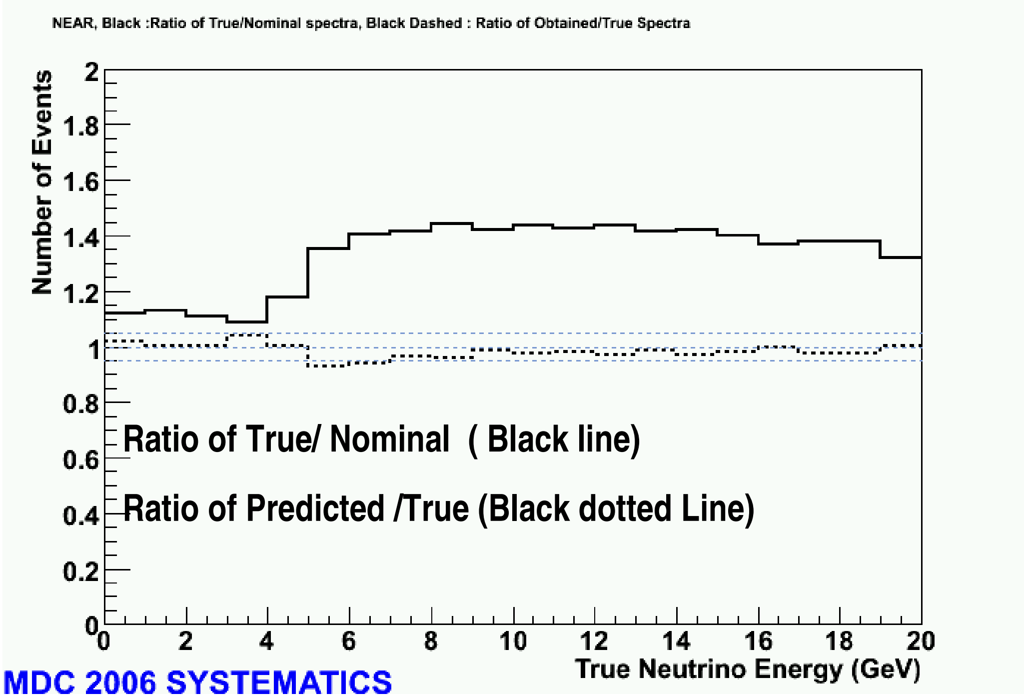


Near Detector Ratio of MC to "Data" : changes are of the order of 5-6%

- **Far Detector Predicted spectrum accurate to within 1%.**
- **Using the Beam matrix method cross sections cancel out to a large extent.**

Systematics : Test on 1E22 p.o.t Mock Data Challenge Set - STEP A

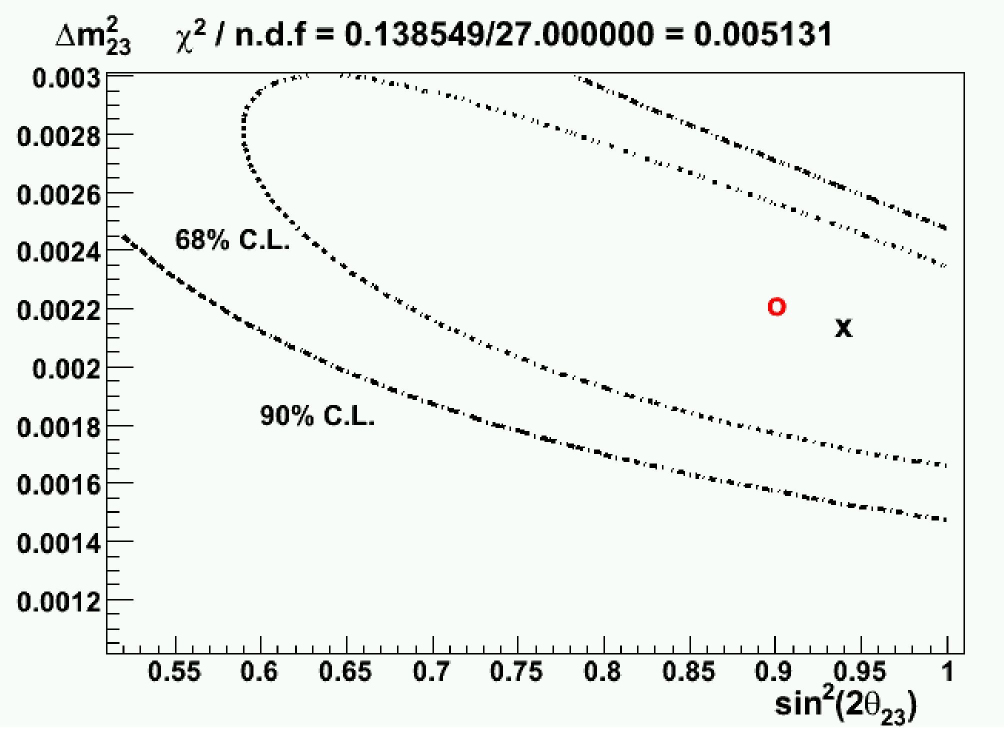


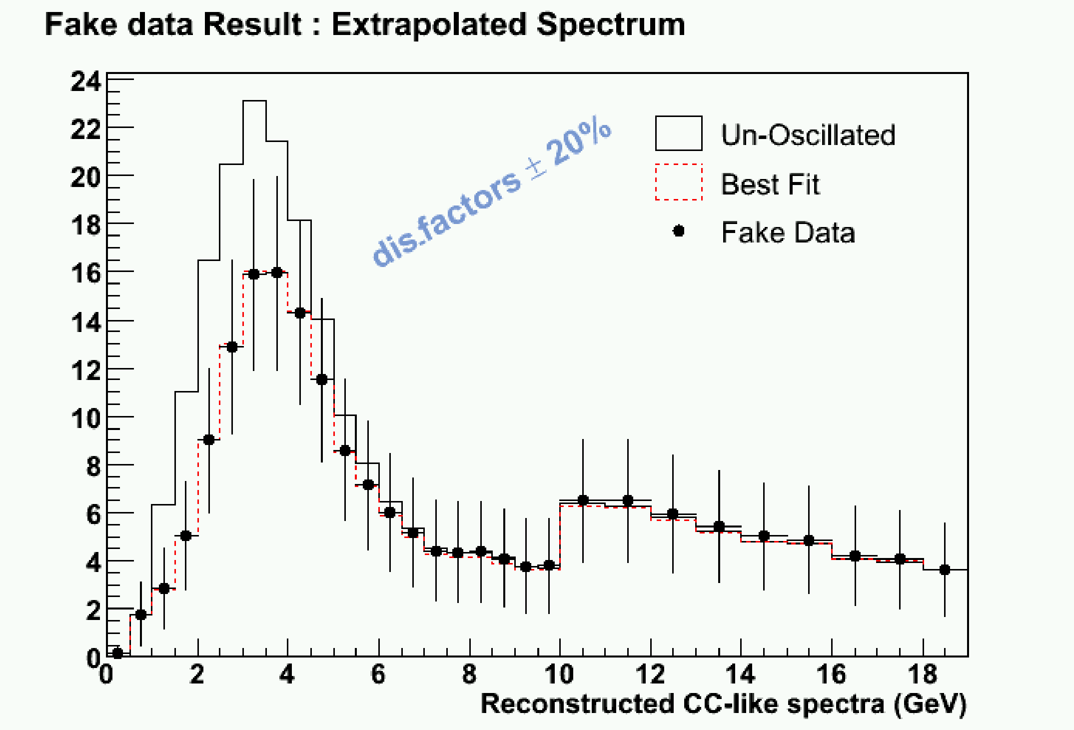


MC used to correct for efficiency, purity and unsmearing quite different than the “data”.

Since corrections are relatively small, STEP A accurately predicts the true Near Detector Spectrum.

Systematics : DIS cross sections changed by ± 20% fit on fake data

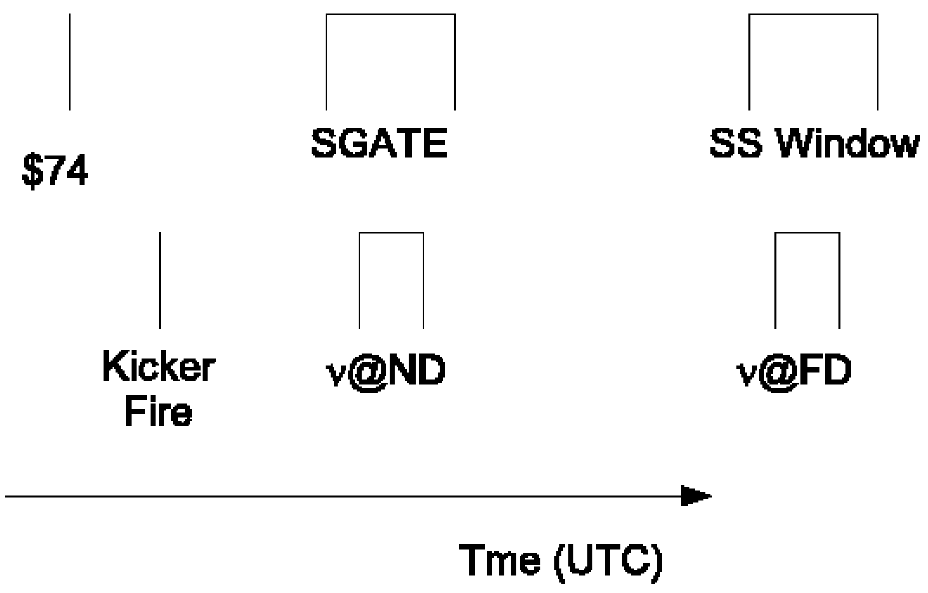



Fake data Result : Extrapolated Spectrum

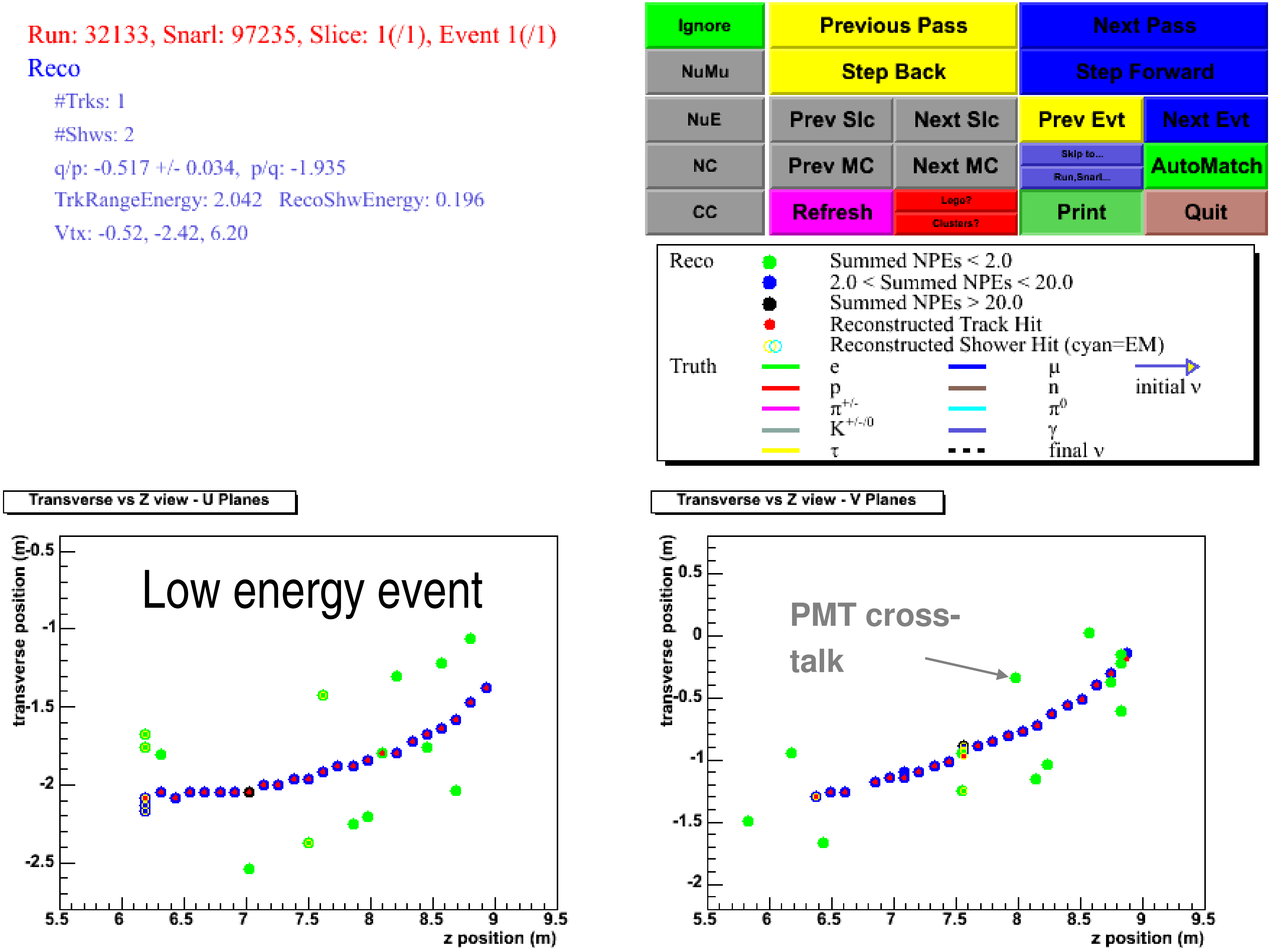
Event catching: Timing and Triggering

- The elements of the timing system are as follows:
  - $74 signal from Main Injector – tells kicker magnet (which extracts protons to NuMI) that it is in the queue to fire (which it does ~220 us later).
  - $74 signal sent to clock controller at ND & a spill gate (SGATE) window is opened (in hardware) for 13us around the time neutrinos hit the ND (with an offset of –1.5us)
  - SpillServer process at FD informed when most recent spill occurred.
  - FD trigger farm queries SpillServer process every second. If a spill signal has been received and the Spill Trigger is enabled, the DAQ reads out 100us of previously bufferred data around the predicted time that the neutrinos should have hit the FD

Global MINOS event timeline



Example event – 2 GeV ν_μ CC



Run: 32133, Snarl: 97235, Slice: 1(/1), Event 1(/1)

Reco

#Trks: 1

#Shws: 2

q/p: -0.517 +/- 0.034, p/q: -1.935

TrkRangeEnergy: 2.042   RecoShwEnergy: 0.196

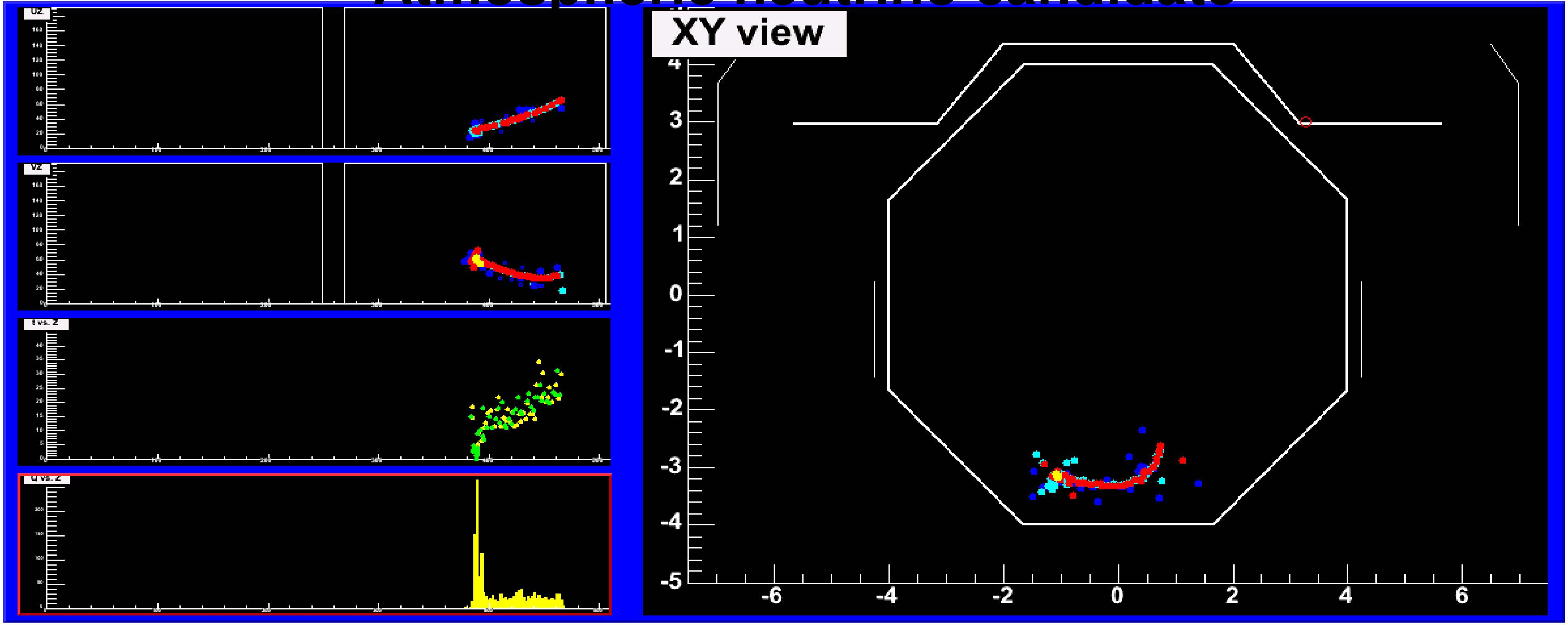
Vtx: -0.52, -2.42, 6.20

Low energy event

PMT cross-talk

Far detector events

Atmospheric neutrino candidate



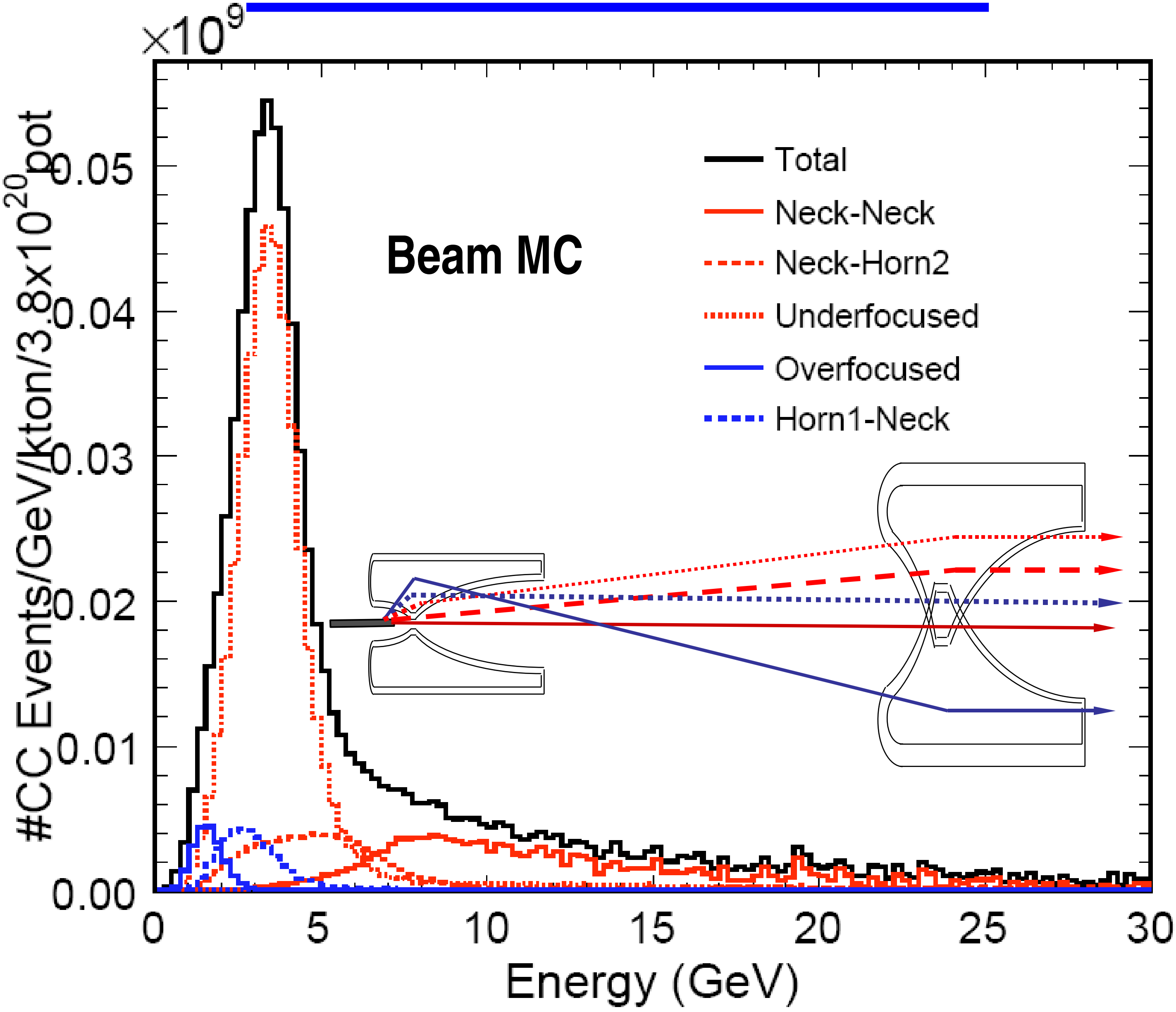
First MINOS results from atmospheric ν – hep-ex/0512036, to be published In Phys. Rev. D

- Typical ν_μ charged current event. Long muon track + hadronic shower at vertex.
- Visible energy $E_{vis} = E_\mu + E_{had}$

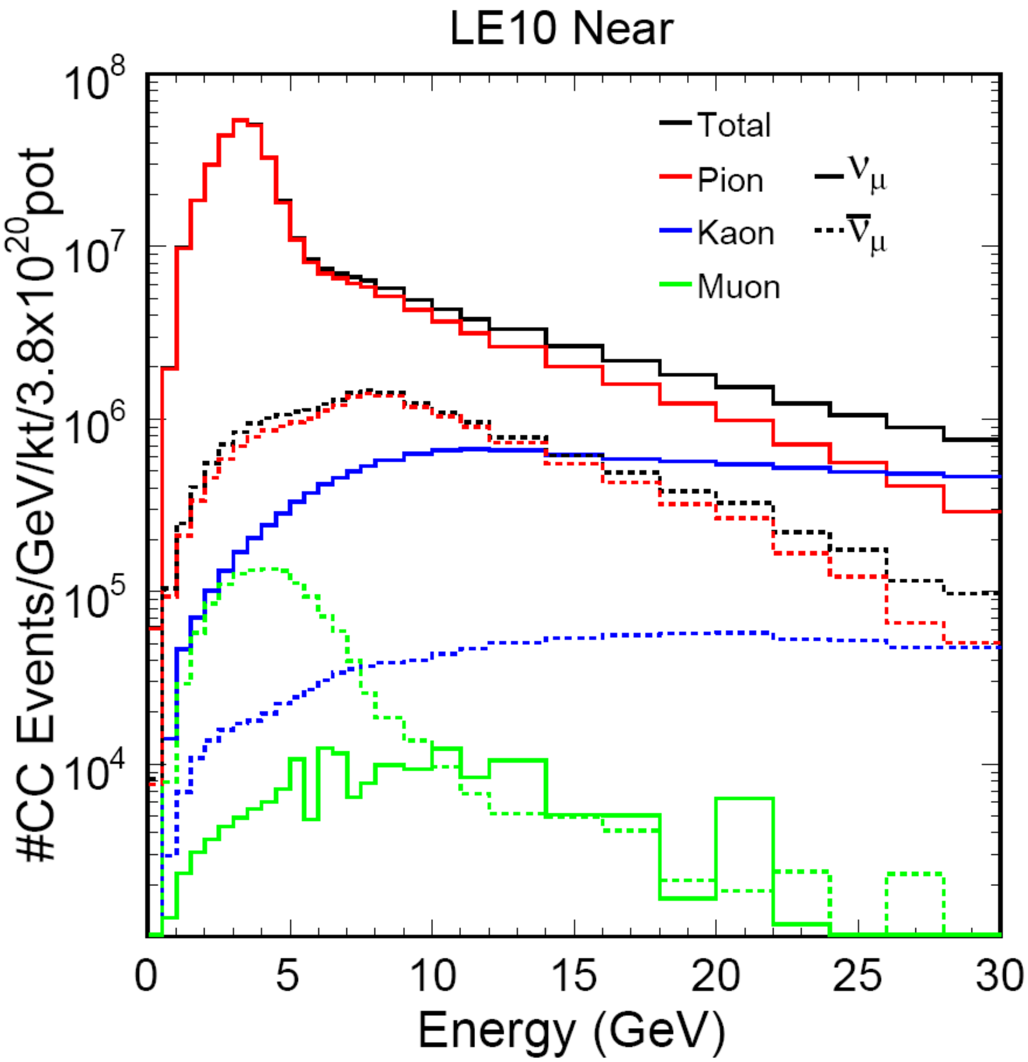
Range or curvature

Calorimetry (summed pulse height)

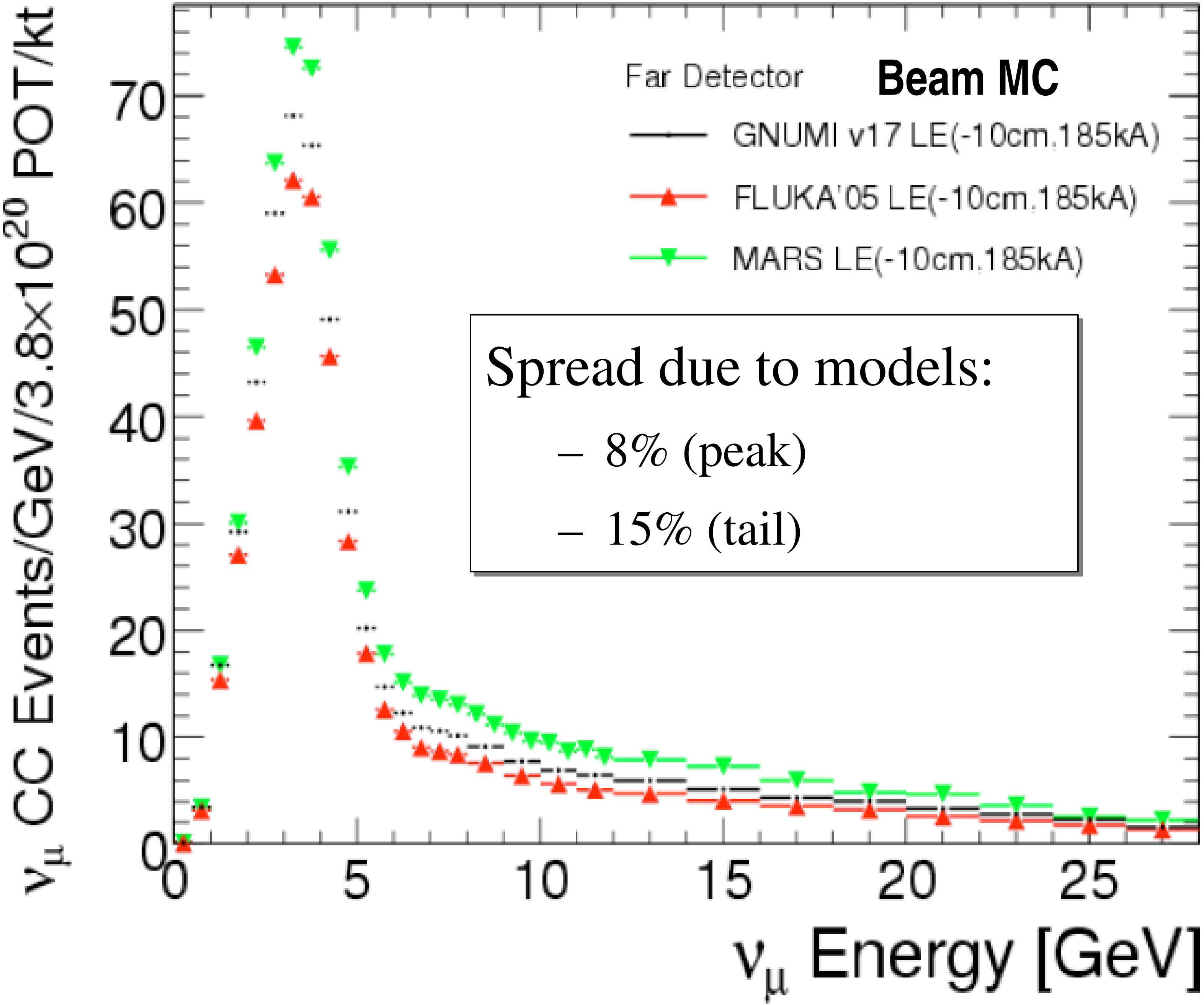
Neutrino Beams 101:



Beam MC

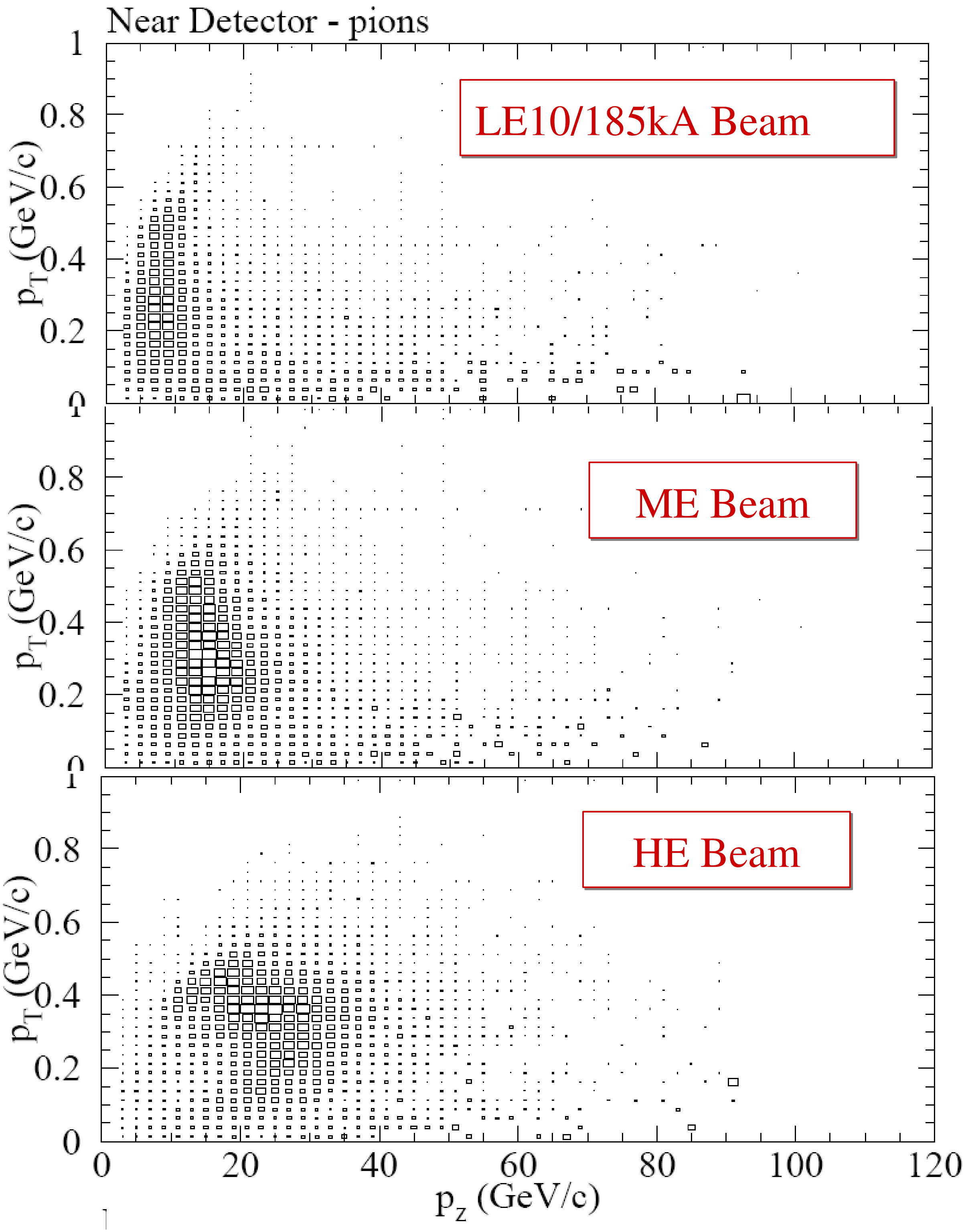

LE10 Near
Total
Pion
Kaon
Muon
ν_μ
$\bar{\nu}_\mu$
#CC Events/GeV/kt/3.8x10^{20}pot
10^4
10^5
10^6
10^7
10^8
0
5
10
15
20
25
30
Energy (GeV)

Hadron Production Uncertainty



Spread due to models:

- 8% (peak)
- 15% (tail)

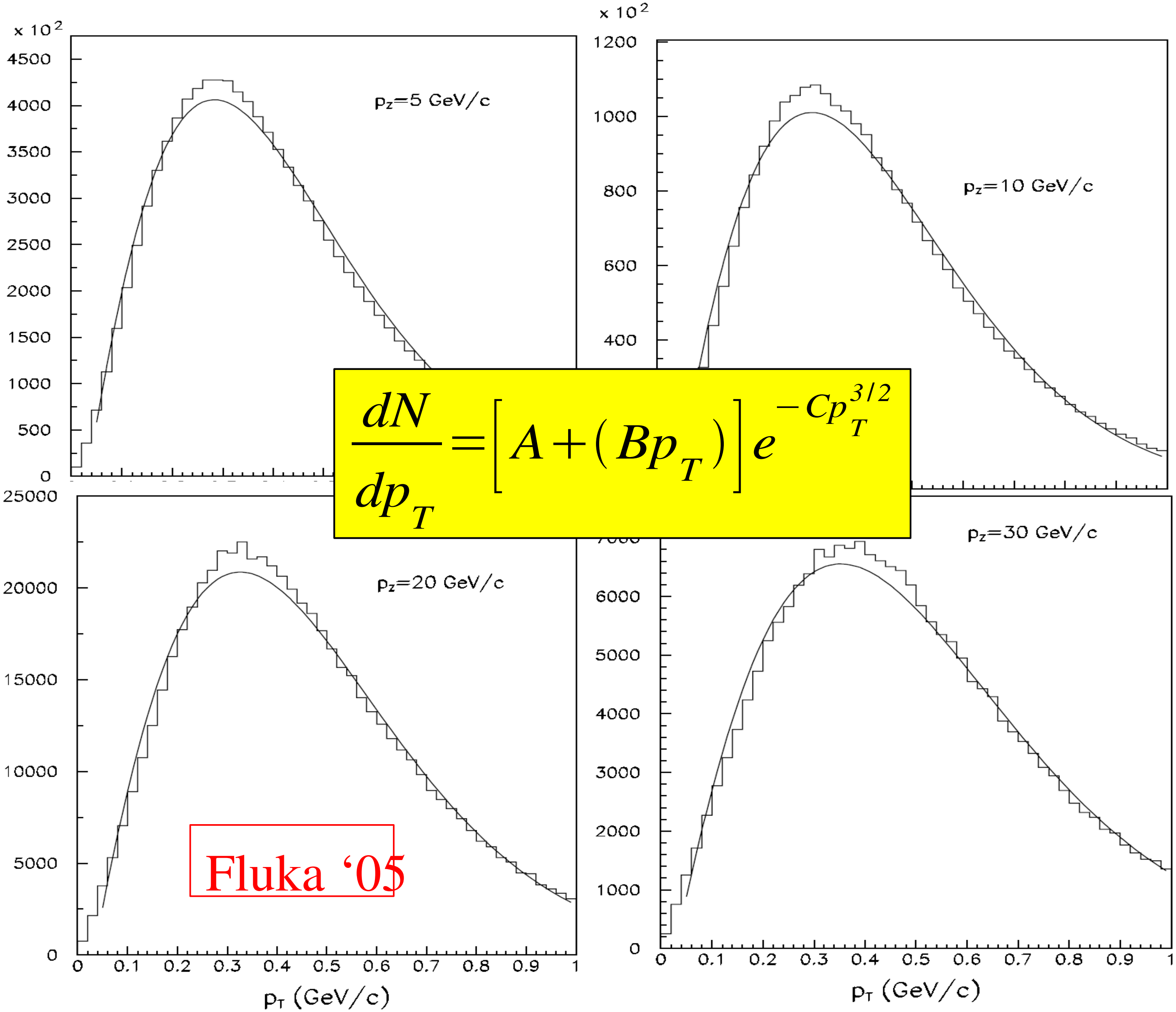


Horn Focusing

- This plot shows the p_z and p_T of pions that lead to neutrinos in the LE, ME, HE beams. Size of box is proportional to the neutrino flux in the ND.
- The NuMI horns focus particular ranges of x_F and p_T for particles emanating from the target.
- Variation of the target configuration (and also horn current) allows us to test our understanding of hadron production from the target across a wide range of x_F and p_T.

Parameterizing Hadron Production

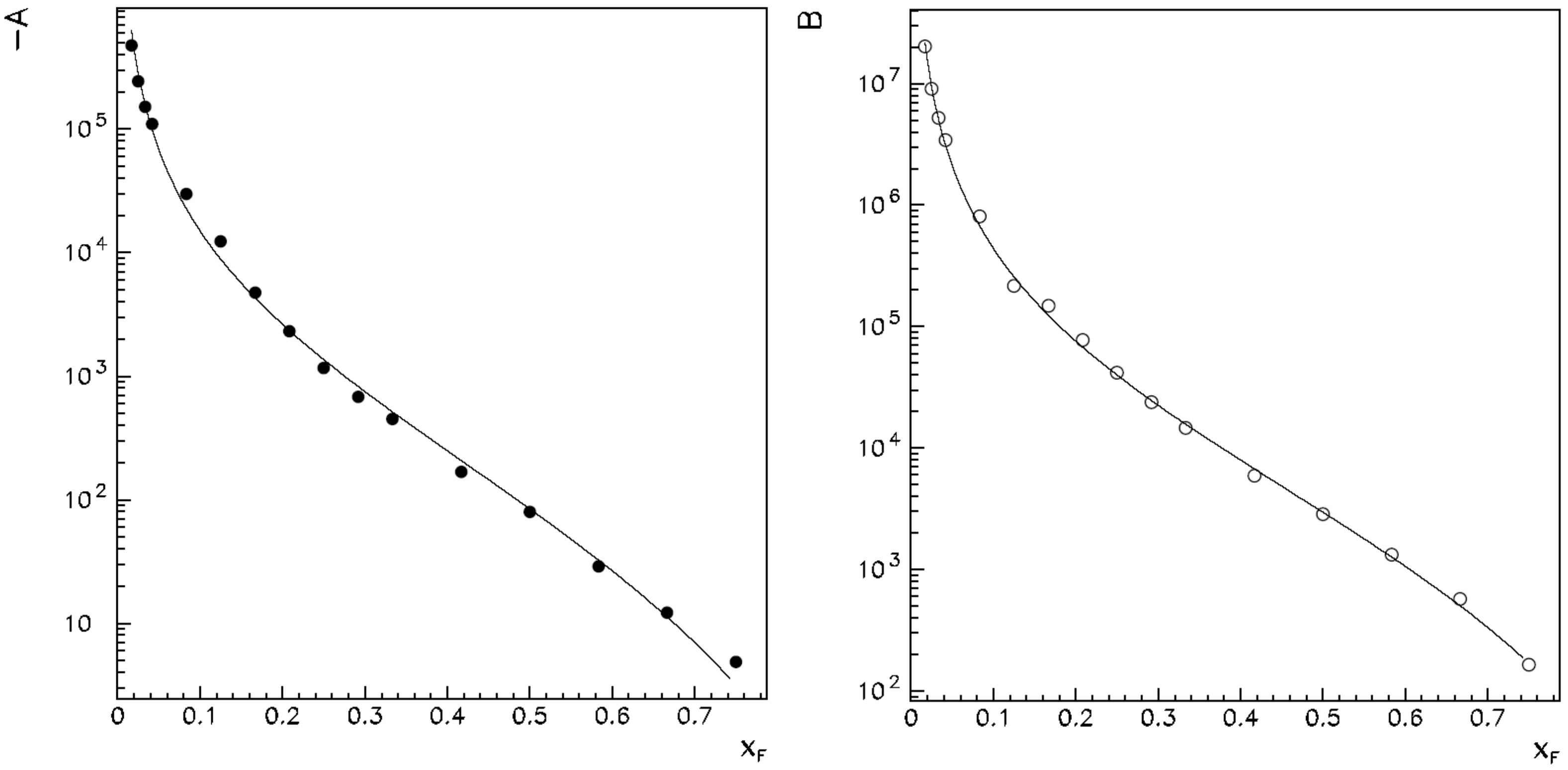
- We tried to parameterize the Fluka’05 (x_F, p_T) distributions with an empirical formula.
- In this fit,
  - $A = A(x_F)$
  - $B = B(x_F)$
  - $C = C(x_F)$
- This form is quite similar to BMPT
- The $(p_T)^{3/2}$ fits the data rather well.



$$\frac{dN}{dp_T} = \left[A + (Bp_T)\right] e^{-Cp_T^{3/2}}$$

Fluka ‘05

Fitting for Hadron Production (*cont'd*)

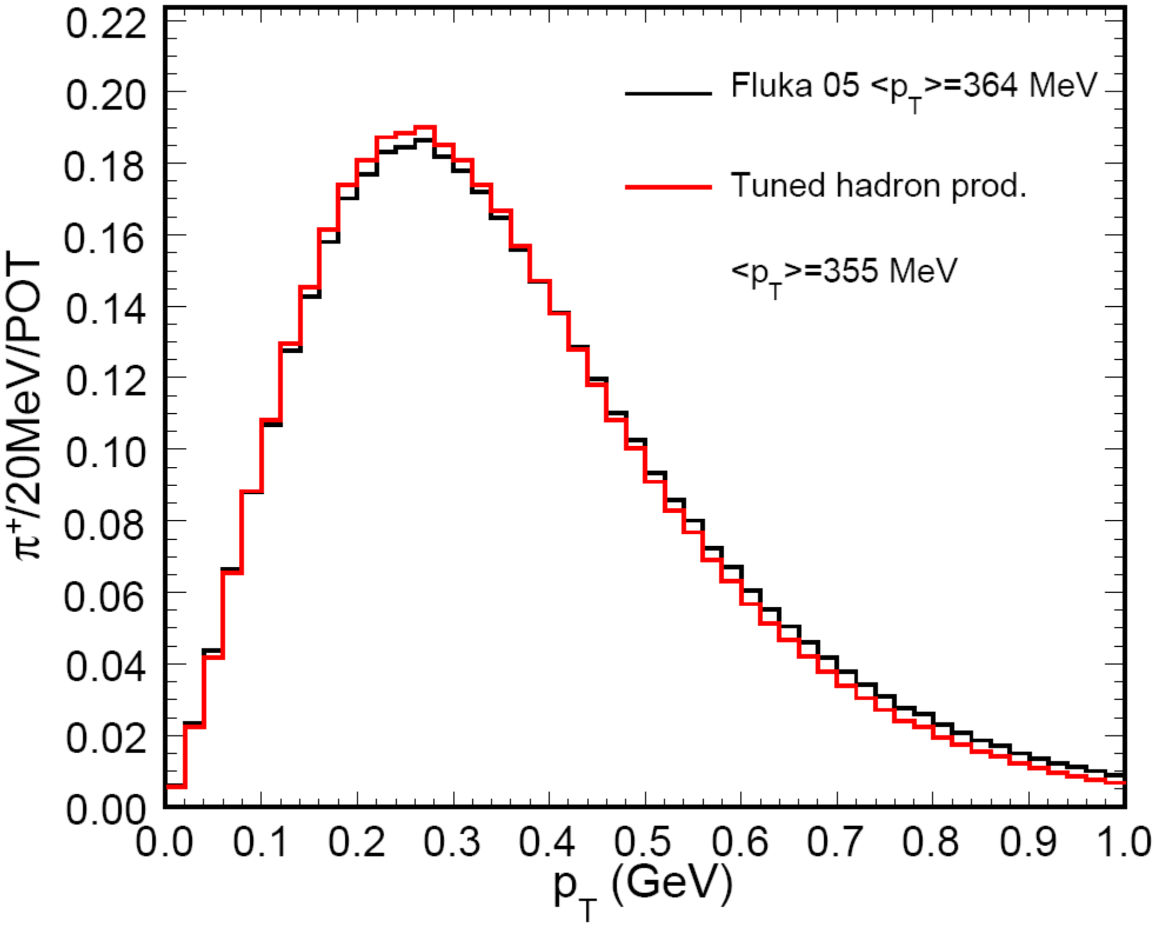


- Both $A(x_F)$ and $B(x_F)$ fit reasonably well to following shape

$$\left(1 - x_F\right) \quad \left(1 + b x_F\right) x_F^{-}$$

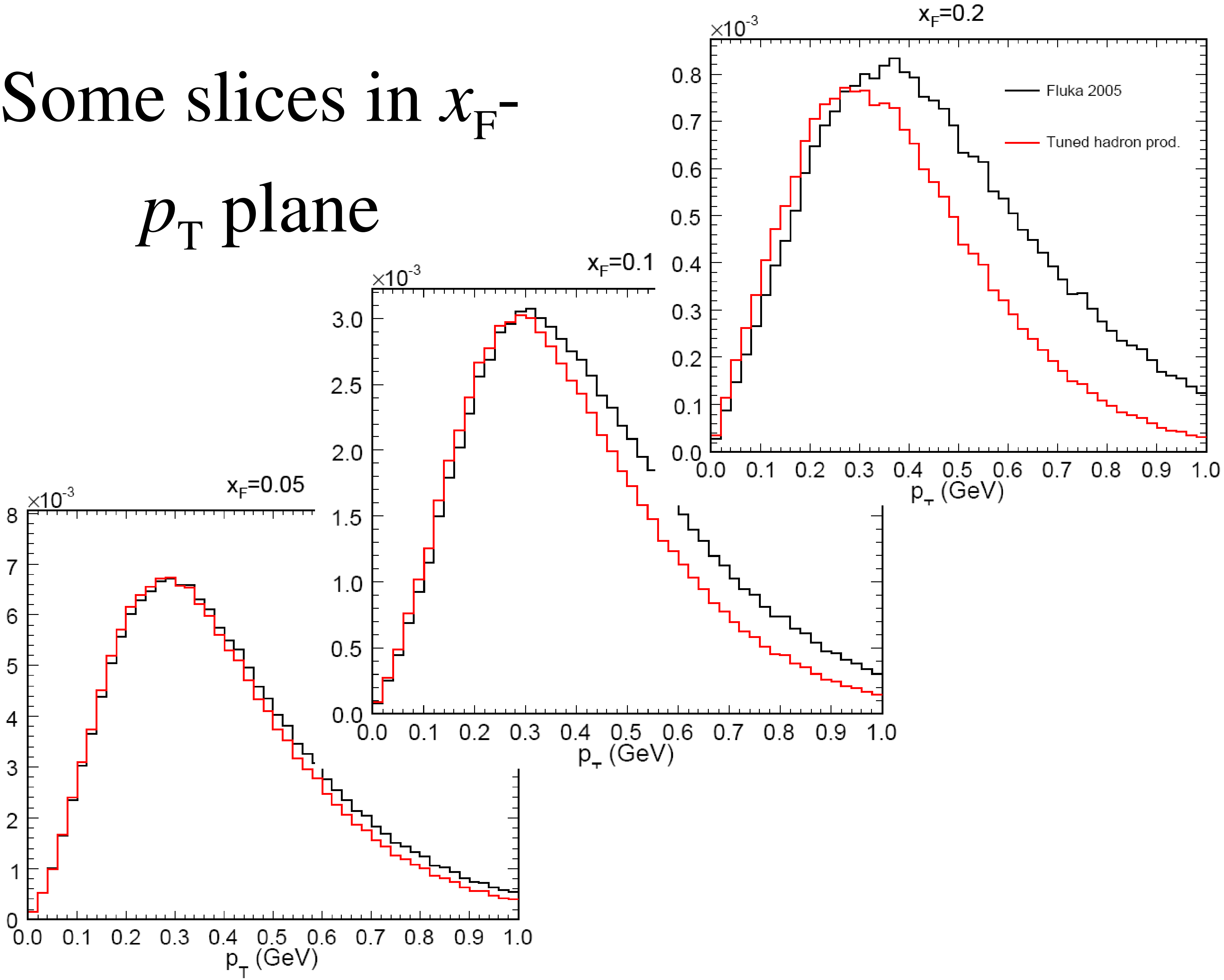
- The values of the exponents are different from BMPT's paper, but this is a thick target parameterization, and they quoted invariant cross section.
- Variations of these parameters were attempted to characterize allowed variations in hadron production.

Is this fitted x_F and p_T reasonable?

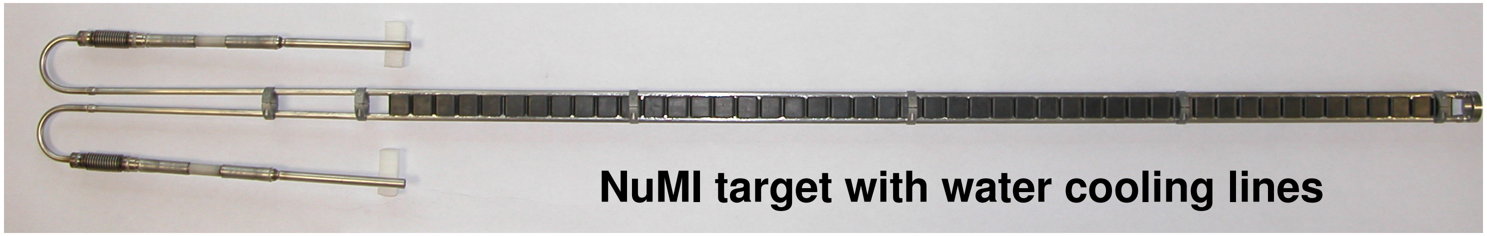


Model	$\langle p_T \rangle$ (GeV/c)
GFLUKA	0.37
Sanf.-Wang	0.42
CKP	0.44
Malensek	0.50
MARS – v.14	0.38
MARS – v.15	0.39
Fluka 2001	0.43
Fluka 2005	0.36
Our Fluka2005 (reweighted to ND)	0.36

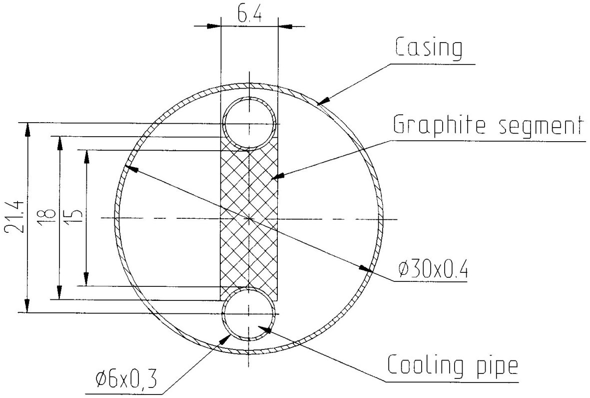
Some slices in x_F-p_T plane



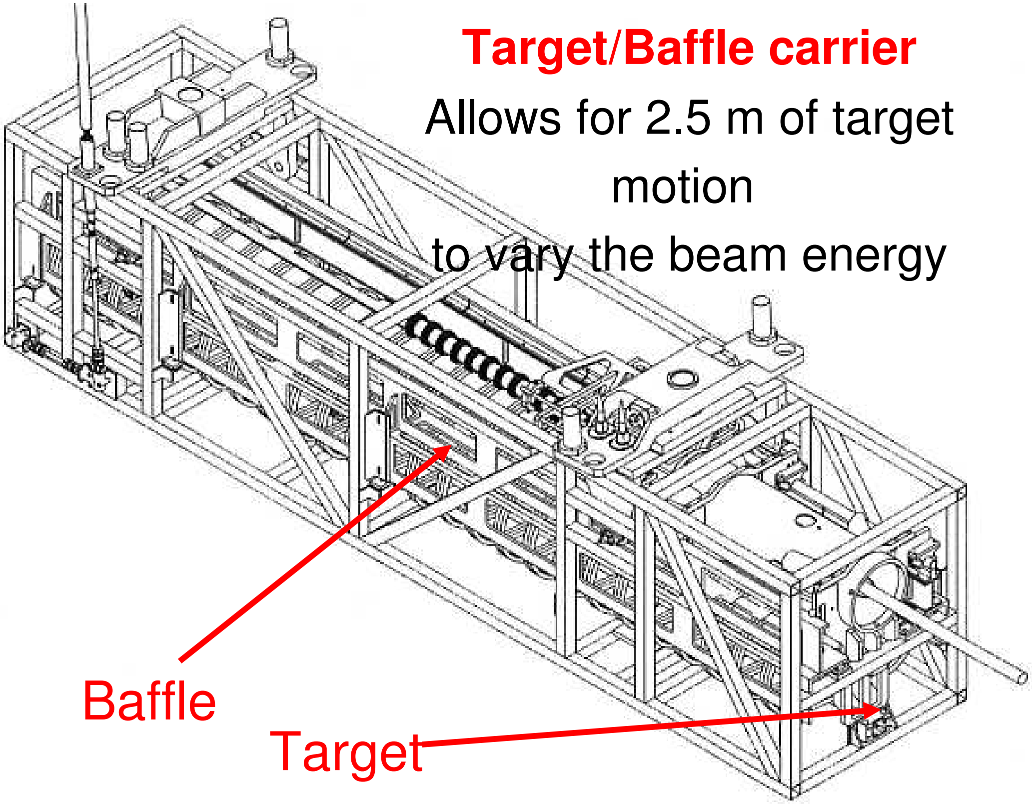
NuMI target



NuMI target with water cooling lines



- Target:
  - 47 segments of graphite of 20 mm length and 6.4×15 mm^2 cross section
  - 0.3 mm spacing between segments, for a total target length of 95.4 cm
- Baffle:
  - protects beamline components from beam mis-steering
  - 150 cm long graphite rod with 11mm diameter hole

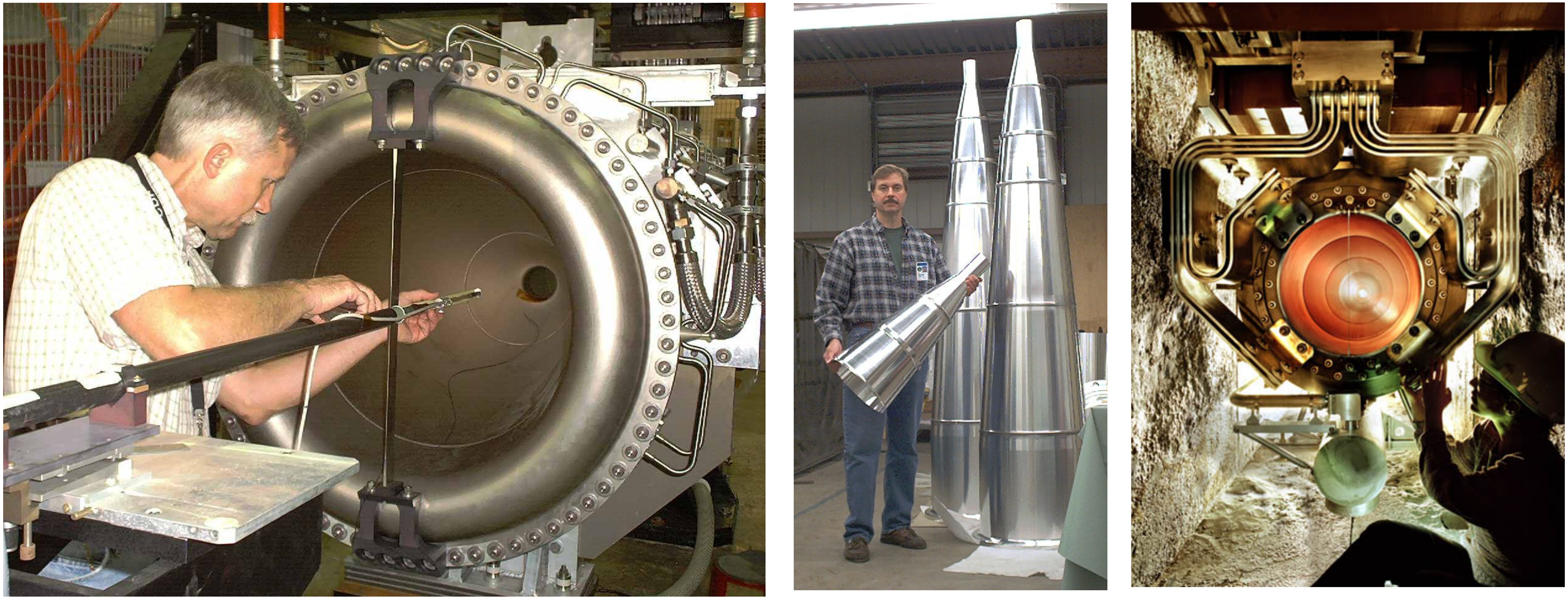


Target/Baffle carrier

Allows for 2.5 m of target motion
to vary the beam energy

Focussing horns

- Two parabolic focussing horns connected in series.
- Nominal horn current at 200 kA
- Produces 3.0 Tesla peak field



Formulae

$$\Psi_\alpha = \sum_j U^*_{\alpha j} \Psi_j$$

$$\nu_e, \nu_\mu, \nu_\tau \Leftrightarrow \nu_1, \nu_2, \nu_3$$

$$\Psi_\alpha(L) = \sum_j U^*_{\alpha j} \Psi_j \exp(-i L m_j^2/2\mathrm{p})$$

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

$$P(\nu_\alpha \to \nu_\beta) = \delta_{\alpha\beta} - 4 \sum_{i>j} \Re[U^*_{\alpha i} U_{\beta i} U^*_{\beta j} U_{\alpha j}] \sin^2(\Delta m^2_{ij} L/4E)$$
$$+ 2 \sum_{i>j} \Im[U^*_{\alpha i} U_{\beta i} U^*_{\beta j} U_{\alpha j}] \sin(\Delta m^2_{ij} L/2E)$$

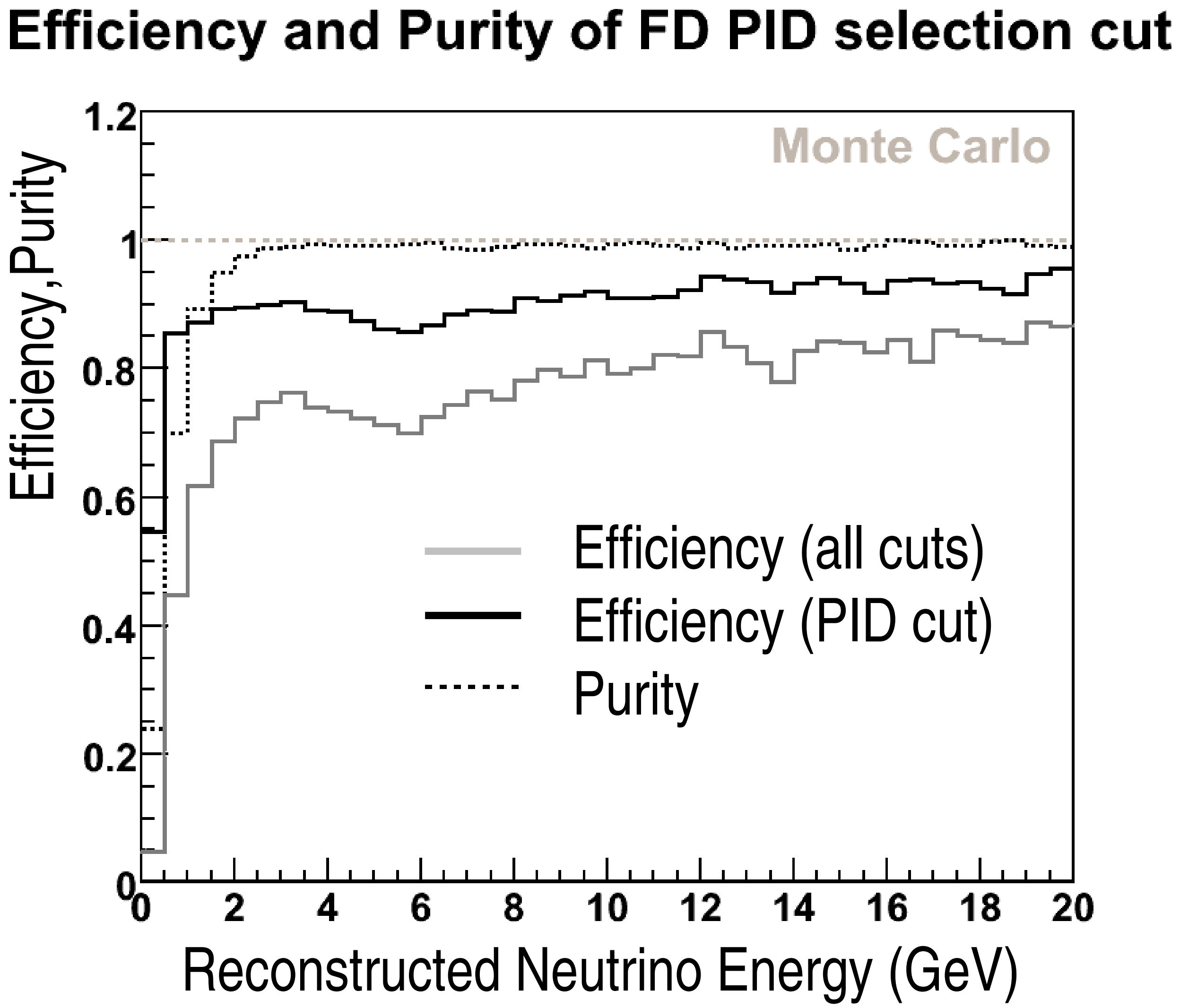
$$\nu_e, \nu_\mu, \nu_\tau \Leftrightarrow \nu_1, \nu_2, \nu_3$$

$$P(\nu_\mu \to \nu_e) = 1 - \underbrace{4|U_{\mu 3}|^2(1-|U_{\mu 3}|^2)}_{=\sin^2(2\theta_{23})} \sin^2(\Delta m^2_{32} L/4E)$$

$$P(\nu_\mu \to \nu_e) \approx 4|U_{\mu 3}|^2 |U_{e3}|^2 \sin^2(\Delta m^2_{32} L/4E)$$

$$P(\nu_\mu \to \nu_e) = 1 - 4|U_{\mu 3}|^2(1-|U_{\mu 3}|^2) \sin^2(\Delta m^2_{32} L/4E)$$
$$= 1 - \sin^2(2\theta_{23}) \sin^2(\Delta m^2_{32} L/4E)$$

CC: Selection Efficiency- FD



Number of observed and expected events

Data sample	observed	expected	ratio	significance
$\nu_\mu < 30$ GeV	215	336.0±14.4	.64±.05	5.2σ
$\nu_\mu < 10$ GeV	122	238.7±10.7	.51±.05	6.2σ
$\nu_\mu < 5$ GeV	76	168.4±8.8	0.45±.06	5.9σ

- We observe a 36% deficit of events between 0 and 30 GeV with respect to the no oscillation expectation.
- **The statistical significance of this effect is 5.2 standard deviations**
- The observed/expected ratio is energy dependent

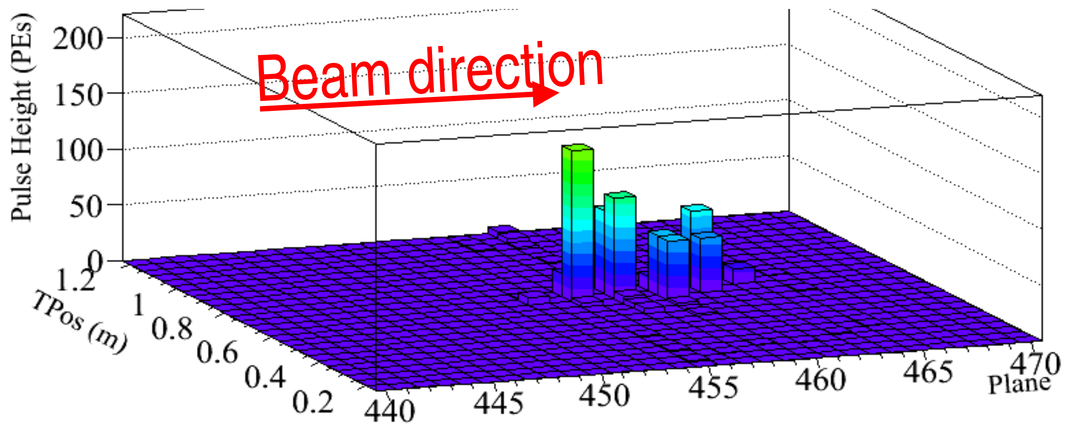
Candidate FD ν_e Event

Run: 32617 Snarl: 105322

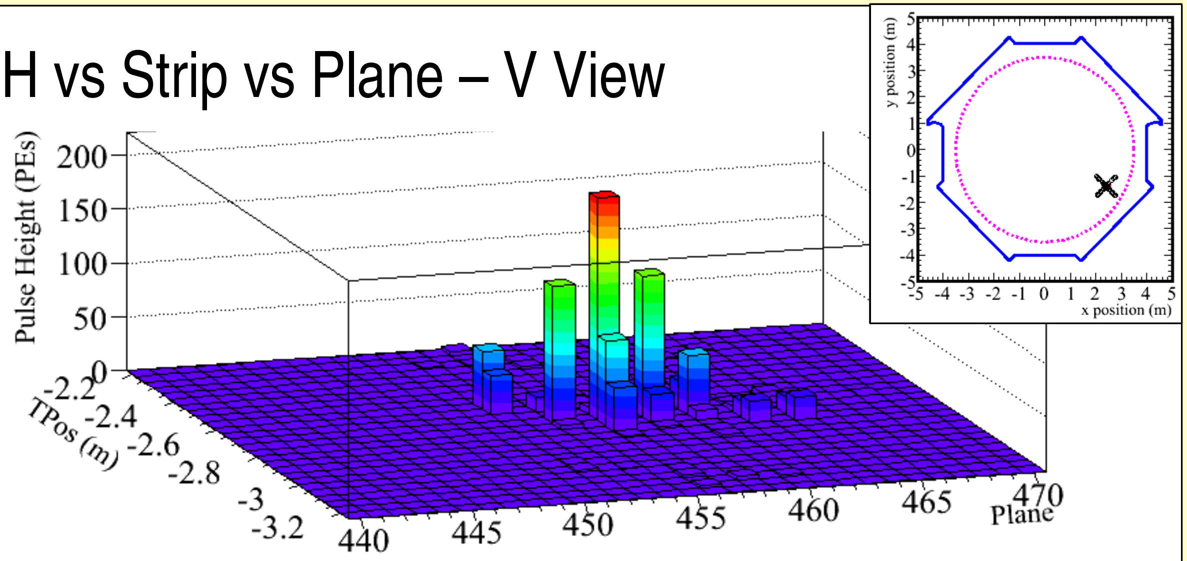
Reco Shower Energy: 8.7 GeV

ANN PID: 0.99

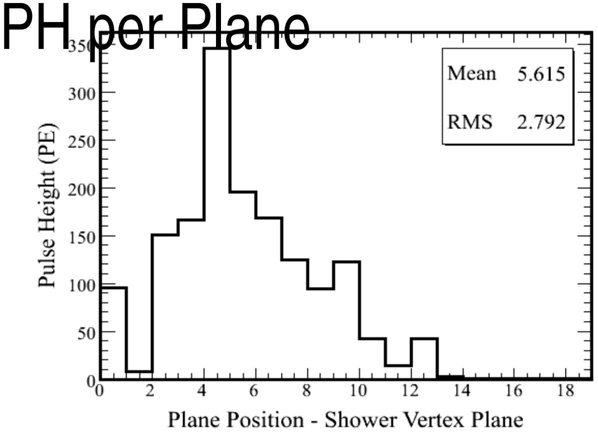
PH vs Strip vs Plane – U View



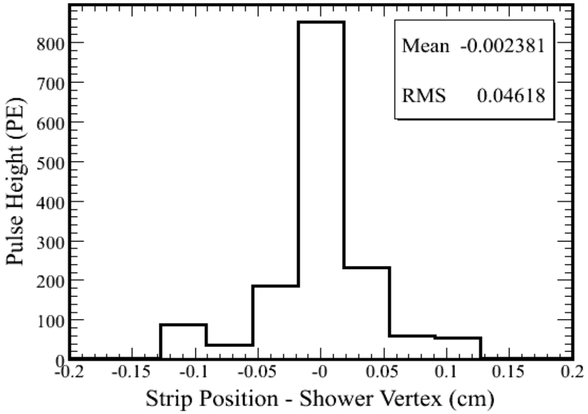
PH vs Strip vs Plane – V View



PH per Plane

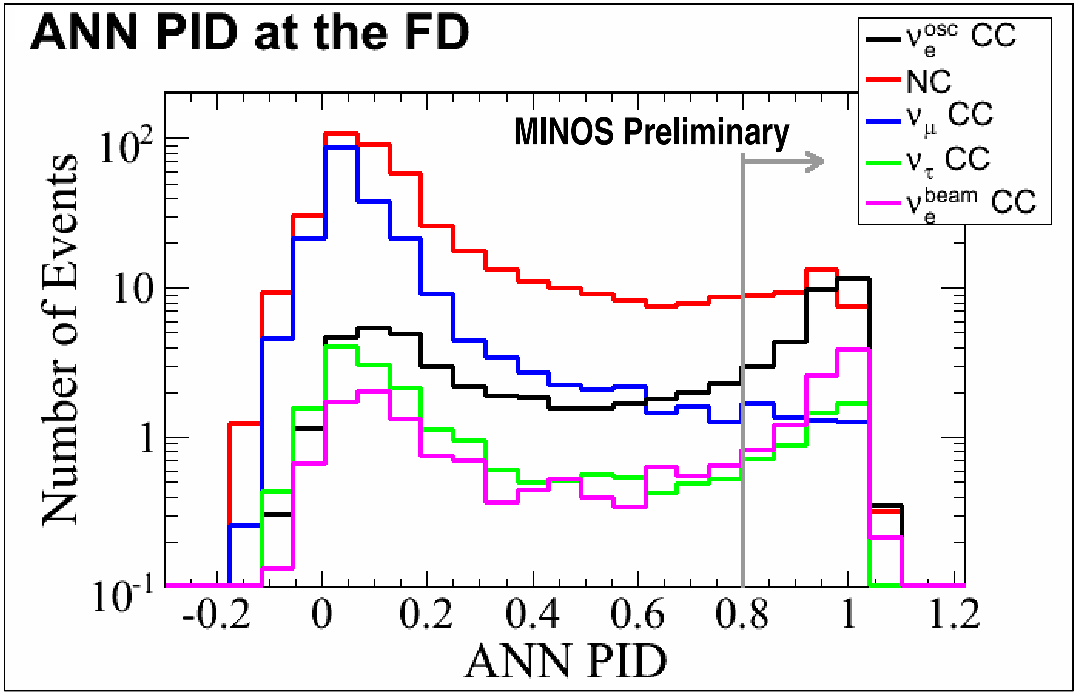


PH with Transverse Position



ν_e Signal / Background Separation

- Much effort has gone into to constructing variables that distinguish between EM and hadronic shower energy
- Several discriminating techniques have been tried to enhance signal/background separation
  - Cuts, Multivariate Discriminant Analysis, ANN, Image recognition



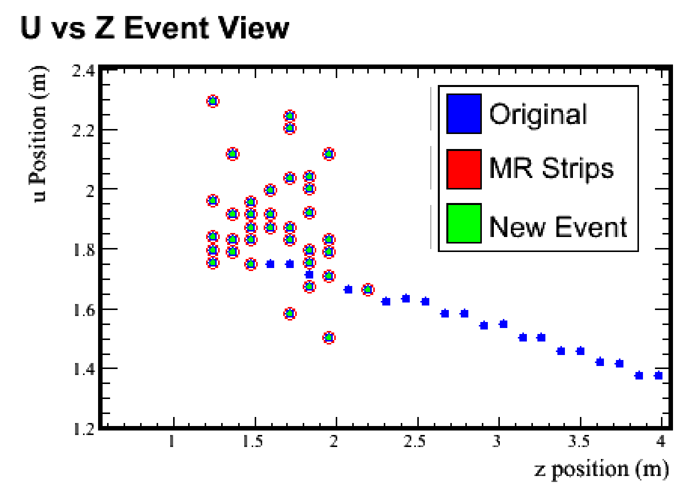
ν_μ CC	NC	ν_e^{beam}	ν_τ CC	Total	ν_e^{osc}
5.6	39.0	8.7	4.7	58.0	29.1

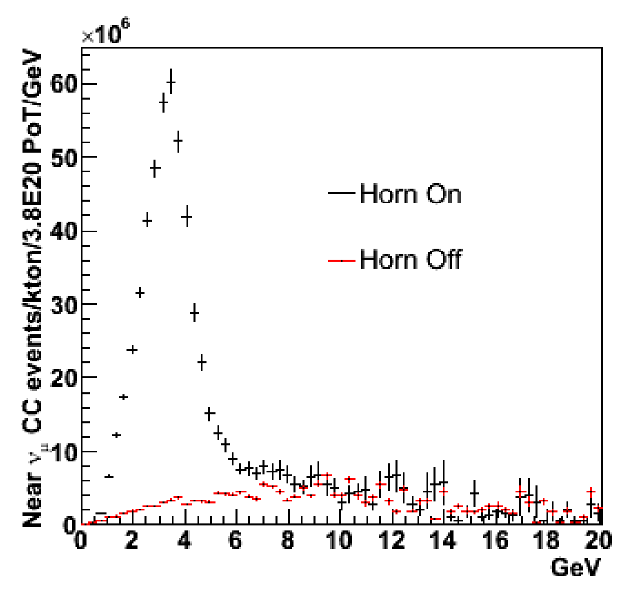
Neural Net example

- Oscillation parameters:
  $\sin^2(2\theta_{13}) = 0.1$
  $|\Delta m_{32}|^2 = 2.7\times10^{-3}\text{eV}^2$
  $\sin^2(2\theta_{23}) = 1$
- POT = $16\text{x}10^{20}$
- Oscillated ν_e are shown in black
- Cutting at 0.8:
  - ν_e purity ~ 30%
  - Signal/√Background = 3.8

Estimating ν_e Backgrounds from Data

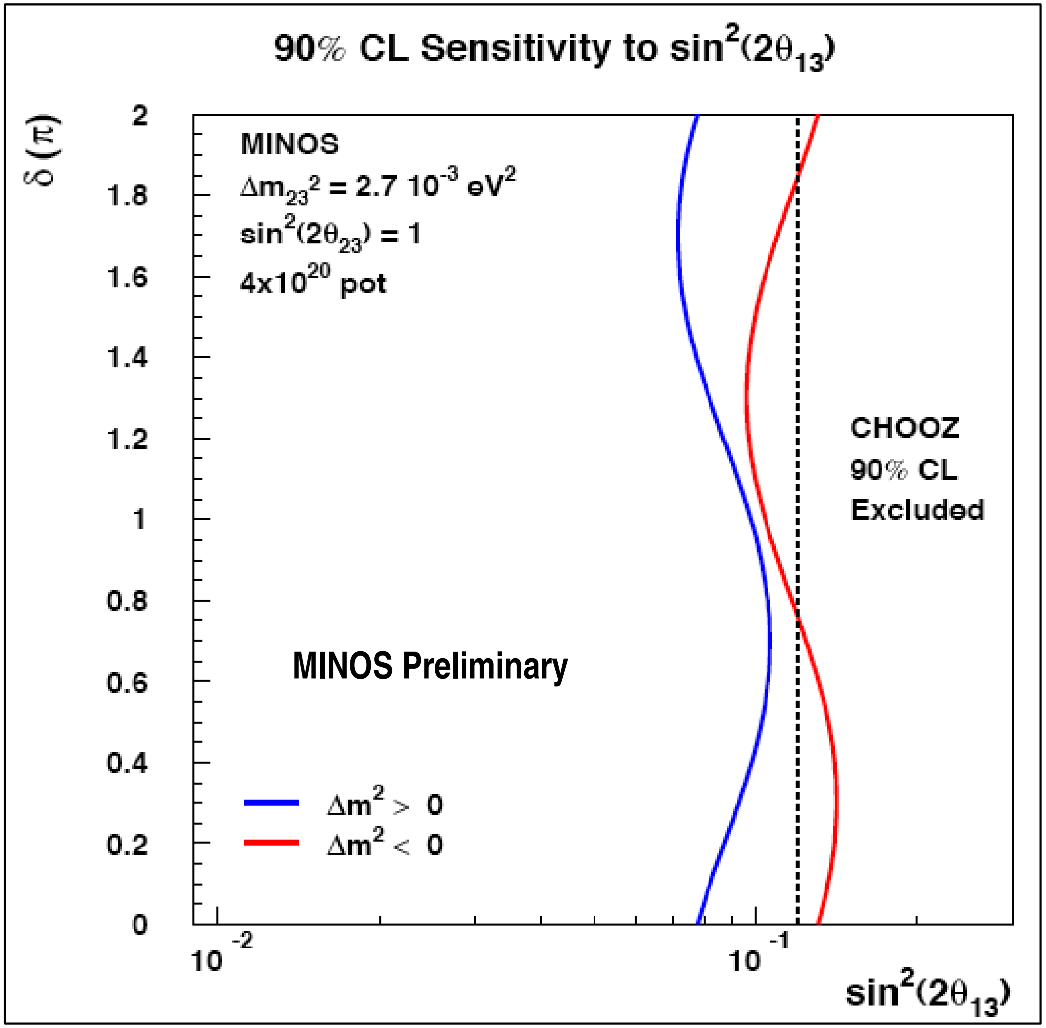
- Several techniques developed to measure backgrounds in ND:
- Muon removal from CC events to estimate NC contribution
  - Assumes similar hadron multiplicities/shower topologies
  - Requires some corrections from MC
- Using horn off data to resolve NC, ν_μ CC background components
  - During horn off running, pions are no longer focused and energy spectrum peak disappears
  - Running event selection on horn-off data enhances NC component of background





Projected MINOS Sensitivity

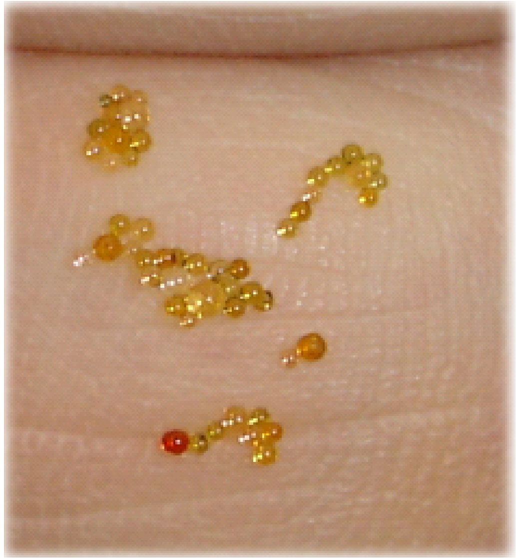
ν_e Appearance



- MINOS in a position to make first ever measurement of θ_{13}
  - Matter effects can change ν_e yield by ± 30%
- Can improve on current best limit from CHOOZ
- Plot shows δ_{CP} vs $\sin^2 2\theta_{13}$ for both mass hierarchies using MINOS ν_μ CC best fit values and 4×10^{20} POT
  - 10% systematic error on background included

Recent Horn-1 Problems (1)

- Horn-1 water cooling spray nozzles became clogged with resin beads from the de-ionizing system on 30th June
  - Happened as a result of a small over-pressure in RAW system and an incorrectly fitted check-valve



Resin beads ~20 mils

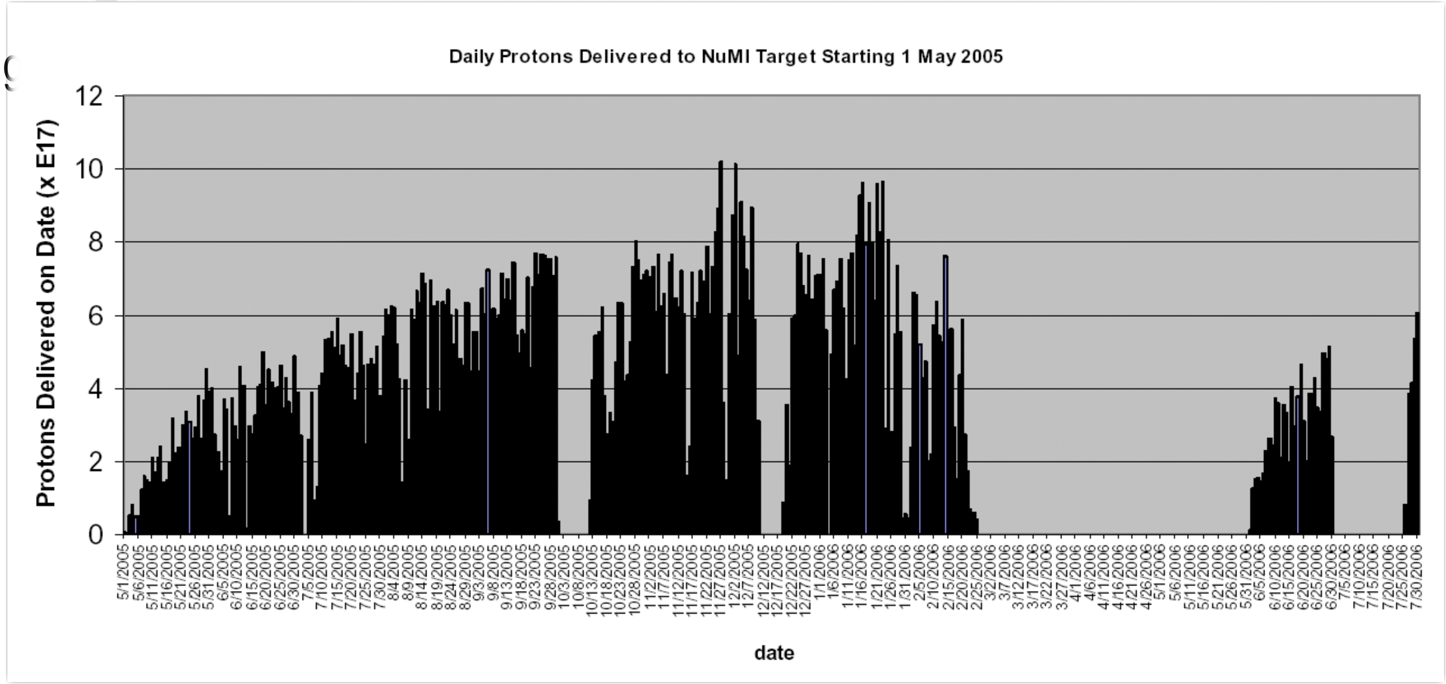
Horn nozzles:

- 48 x Inner conductor elliptical nozzles
  - ~40 mils across short direction
- 19 x Outer conductor circular nozzles
  - ~25 mils diameter

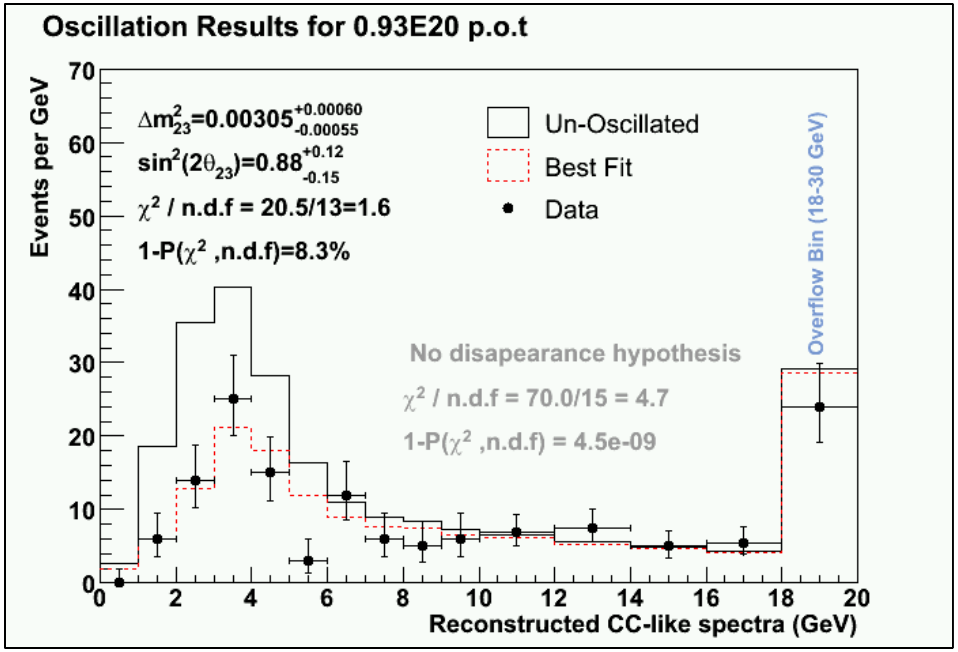
Recent Horn-1 Problems (2)

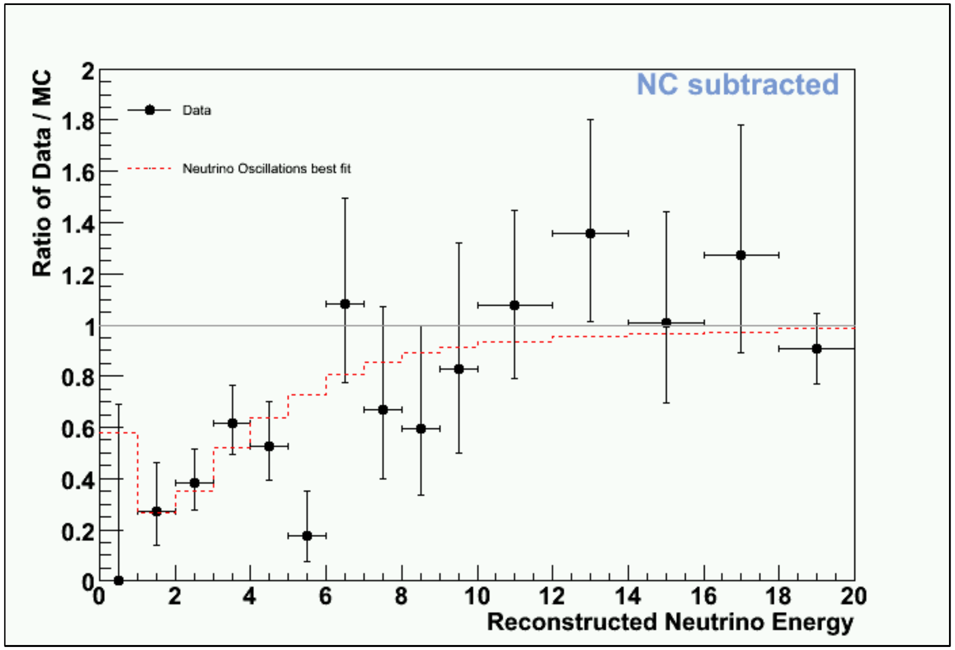
- Apparatus was set up to back-flow beads out with air (pressurizing horn, vacuuming headers)
  - Also several other things helped dislodge beads: pulsing the horn, re-filling with water to check air-flow, burping with Helium gas to dry beads
- After a week of hard work by Accelerator Division beam was returned to NuMI on July 26th
  - MINOS Collaboration g
- Protons delivered per day
- Total since May 2005:

  1.51x10^{20} POT
- Currently in pHE config



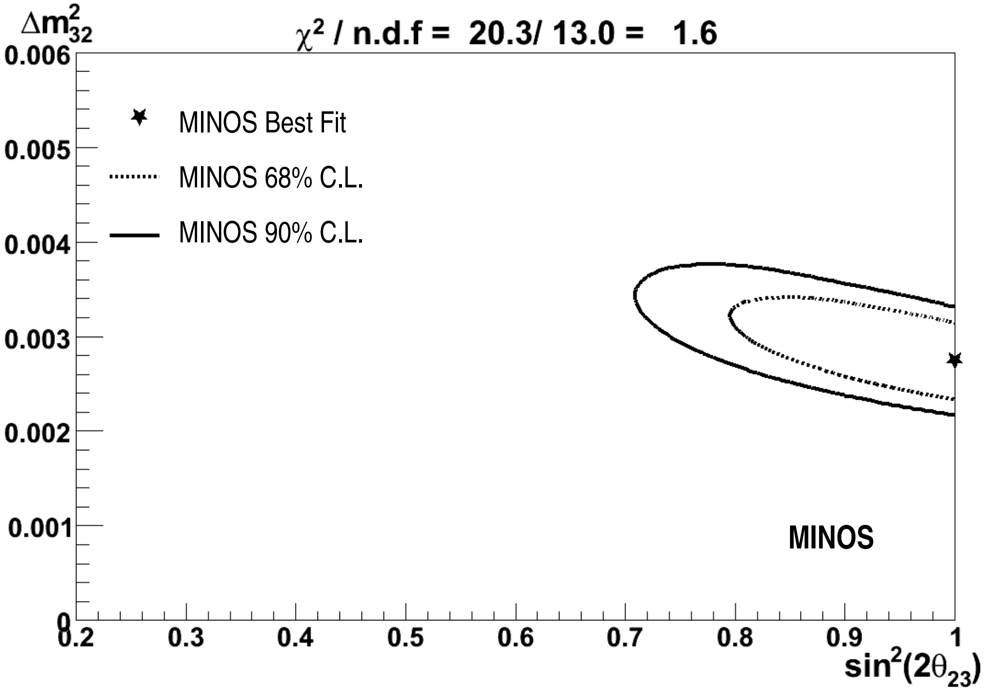
$0.93\text{x}10^{20}$ POT Analysis

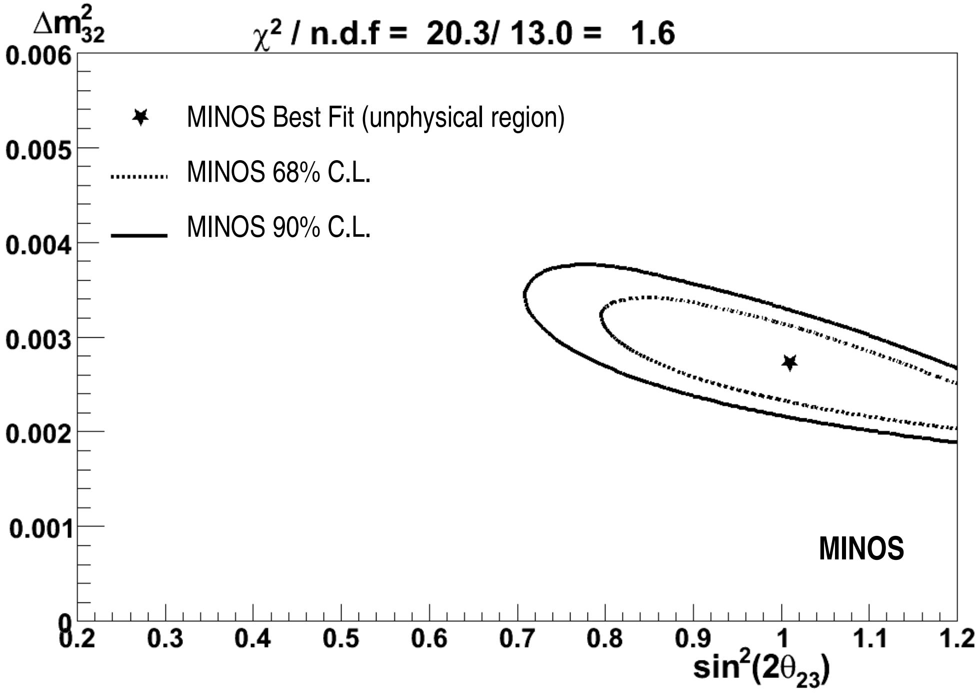




Fitting into the Unphysical Region

- Allowing fit to move into unphysical region
  - Small shift in best fit values





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

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

$|\Delta m^2_{32}| = 2.72 \times 10^{-3}$ eV^2

$\sin^2 2\theta_{23} = 1.01$

Contour evolution