First Neutrino Disappearance Results from MINOS

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BNL Particle Physics Seminar
April 06, 2006

- ν oscillations
- NuMI & MINOS
- disappearance analysis
- conclusions

ν oscillations

- 2-neutrino mixing
- 3-neutrino mixing
- Current results

Two neutrino oscillations

ν: produced/detected as WEAK eigenstates
propagates as MASS eigenstates

Quantum Mechanics: weak $\neq$ mass states

$\Rightarrow$ mixing:

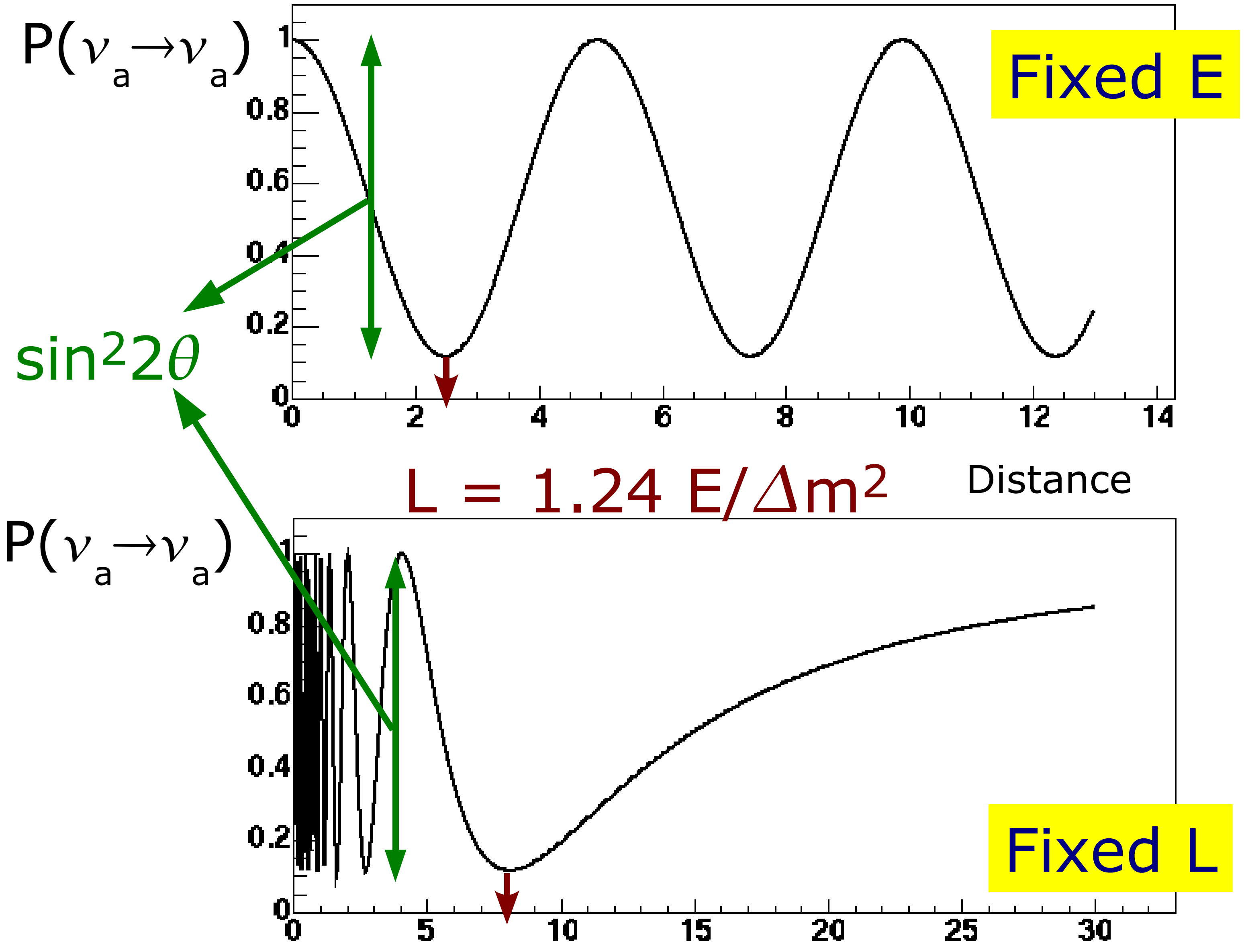
$$\begin{pmatrix} \nu_a \\ \nu_b \end{pmatrix} = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \end{pmatrix}$$

$$|\nu(0)\rangle = |\nu_a\rangle = \cos\theta|\nu_1\rangle + \sin\theta|\nu_2\rangle$$

survival prob: $P(\nu_a \rightarrow \nu_a) = 1 - \sin^2 2\theta \cdot \sin^2\left(\frac{1.27\, L\, \Delta m^2_{21}}{E}\right)$

with L in km, E in GeV, $\Delta m^2_{21} = m_2^2 - m_1^2$ in eV^2

Two neutrino oscillations



$P(\nu_a \rightarrow \nu_a)$

$\sin^2 2\theta$

Fixed E

$L = 1.24\, E/\Delta m^2$

Distance

$P(\nu_a \rightarrow \nu_a)$

Fixed L

$E = 0.81\, L\, \Delta m^2$

Energy

3 generation ν mixing

Pontecorvo-Maki-Nakagawa-Sakata (PMNS) Matrix:

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

⇨ 3 mixing angles
1 CP phase
(2 CP Majorana phases)

$$U = \begin{pmatrix} \cos\theta_{12} & \sin\theta_{12} & 0 \\ -\sin\theta_{12} & \cos\theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} \cos\theta_{13} & 0 & \sin\theta_{13} e^{i\delta} \\ 0 & 1 & 0 \\ -\sin\theta_{13} e^{i\delta} & 0 & \cos\theta_{13} \end{pmatrix} \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_{23} & \sin\theta_{23} \\ 0 & -\sin\theta_{23} & \cos\theta_{23} \end{pmatrix}$$

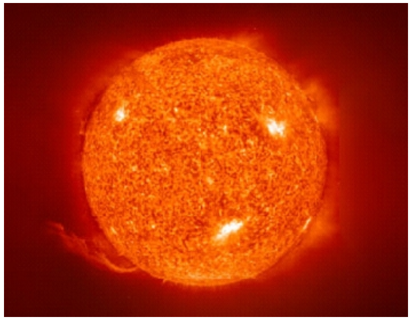
solar

atmospheric

Neutrino oscillations described by 6 new parameters:

$\theta_{12}, \theta_{13}, \theta_{23}, \delta$
$\Delta m^2_{21}, \Delta m^2_{32}$

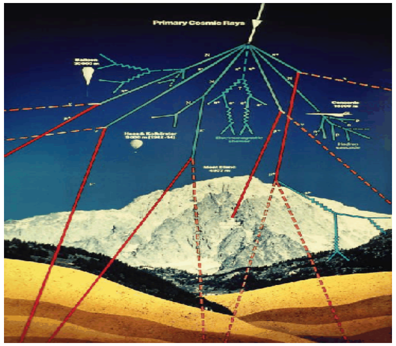
Current Results



SNO, KamLAND, Super-K,...

$$7.2 < \Delta m^2_{21} < 8.6 \cdot 10^{-5}\, eV^2$$

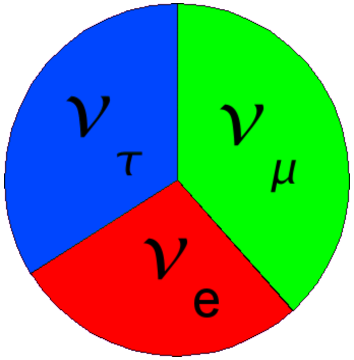
$$0.78 < \sin^2 2\theta_{12} < 0.93 \qquad (\theta_{12} \approx 34^o)$$



Super-K, K2K,...

$$1.78 < \left|\Delta m^2_{32}\right| < 2.90 \cdot 10^{-3}\, eV^2$$ sign?

$$\sin^2 2\theta_{23} > 0.90 \qquad (\theta_{23} \approx 45^o)$$



Chooz,...

$$\sin^2 2\theta_{13} < 0.13$$

$$\delta_{CP} = ???$$

all limits at 95% C.L.

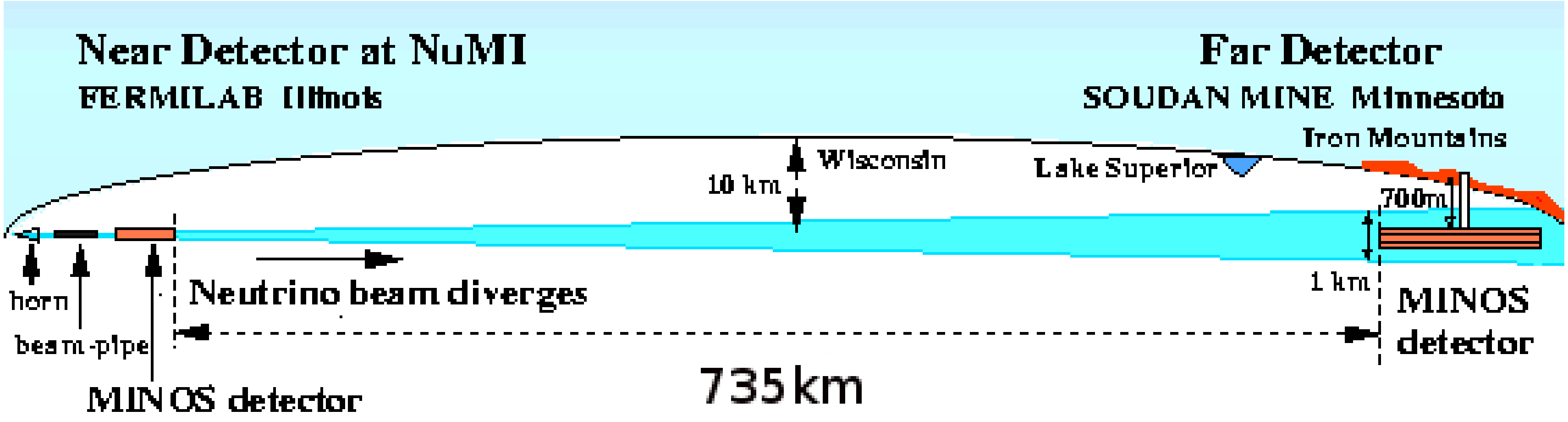
ref: Fogli et al, hep-hp/0506083

LSND $\Delta m^2 \sim 1\ eV^2$

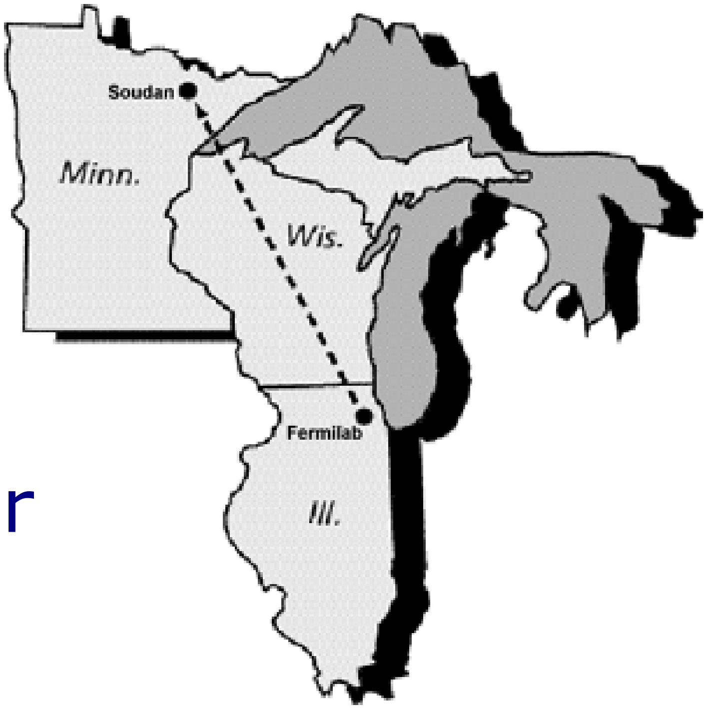
NuMI/MINOS

- The concept
- NuMI beamline
- Near detector
- Far detector
- Calibration
- Physics reach

The Concept



High intensity ν_μ beam from Fermilab to Soudan (MN)

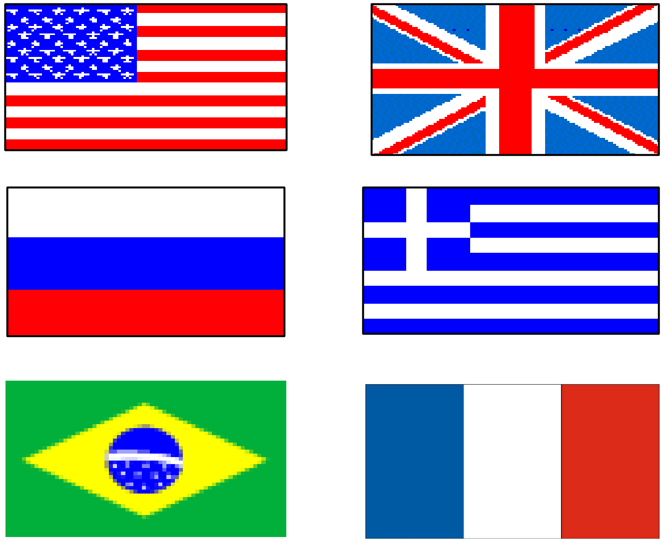


compare energy spectrum:
near detector ⇔ far detector
unoscillated ⇔ oscillated

MINOS Collaboration

Main Injector Neutrino Oscillation Search

collaboration of
- 175 physicists
- 32 institutes
- 6 countries



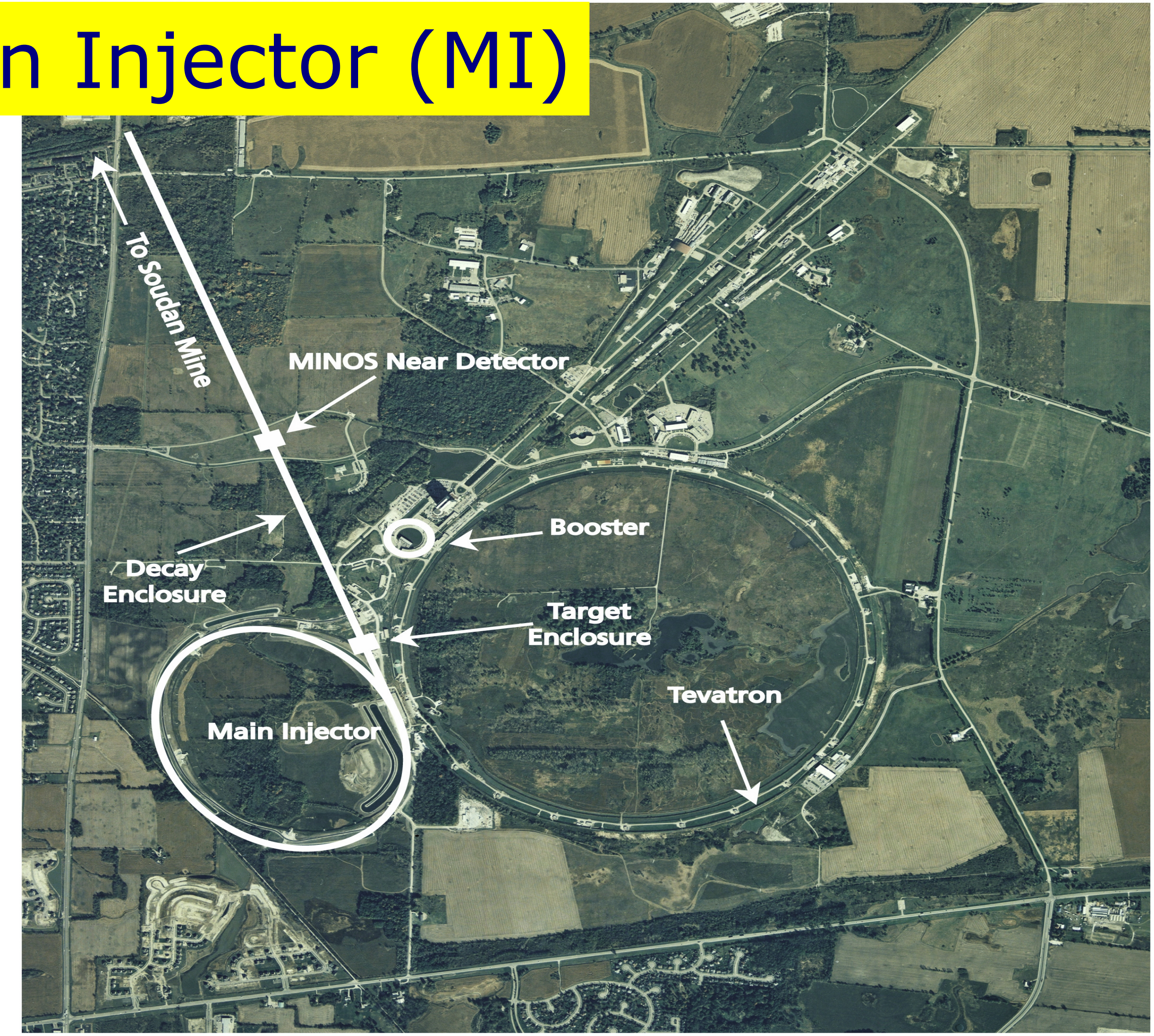
Argonne – Athens – Benedictine - Brookhaven – Caltech – Cambridge – Campinas – Fermilab – College de France – Harvard – IIT – Indiana – ITEP Moscow – Lebedev – Livermore – Minnesota, Twin Cities – Minnesota, Duluth – Oxford – Pittsburgh – Protvino – Rutherford Appleton – Sao Paulo – South Carolina –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

NuMI Beamline

Fermilab Main Injector (MI)

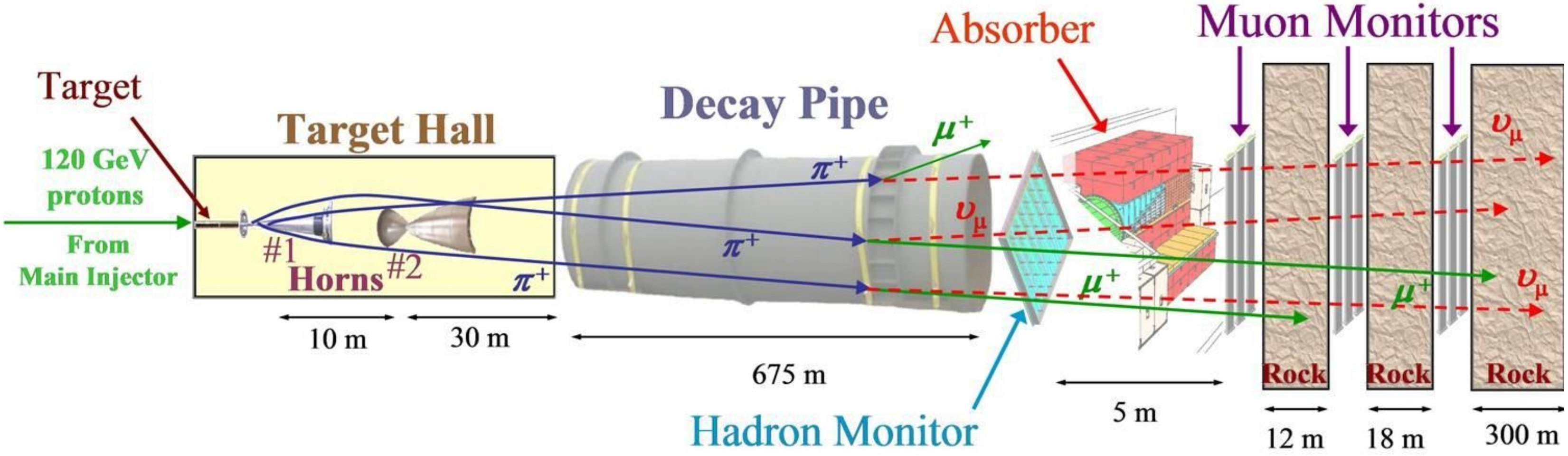
- 120 GeV protons
- 5 or 6 booster batches in MI
- 4.0 10^{13} protons on target (PoT) per spill
- 1.9s rep. rate
- ~10 μs spill

⇒ beam power: 400 kW

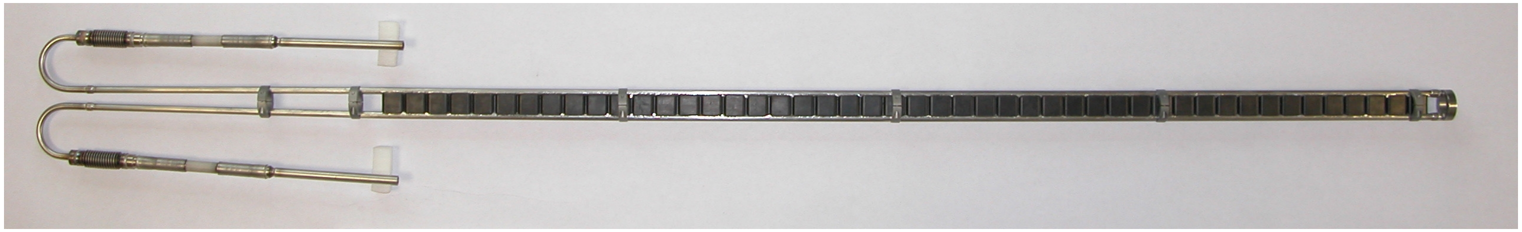


FERMILAB #98-765D

NuMI Beamline



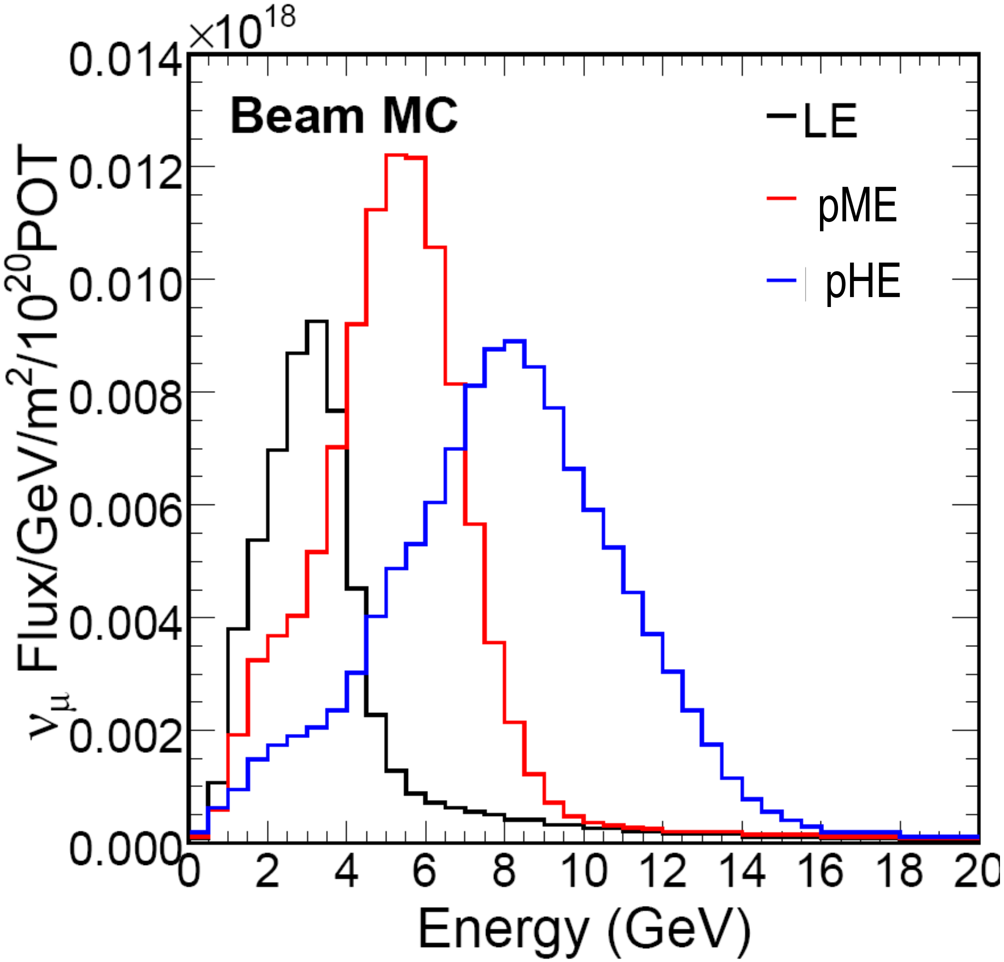
- graphite target:
  - 47 segments, 6.4x15x20mm^3



- 2 magnetic focusing horns:
  - pulsed, 200kA, 3T field

NuMI Beamline

- tunable beam energy by modifying target and/or horn positions



	target position (cm)	expected unoscillated FD events per 10^{20} pot
LE-10	-10	390
pME	-100	970
pHE	-250	1340

Beam composition LE-10:

92% ν_μ 6.5% $\bar{\nu}_\mu$

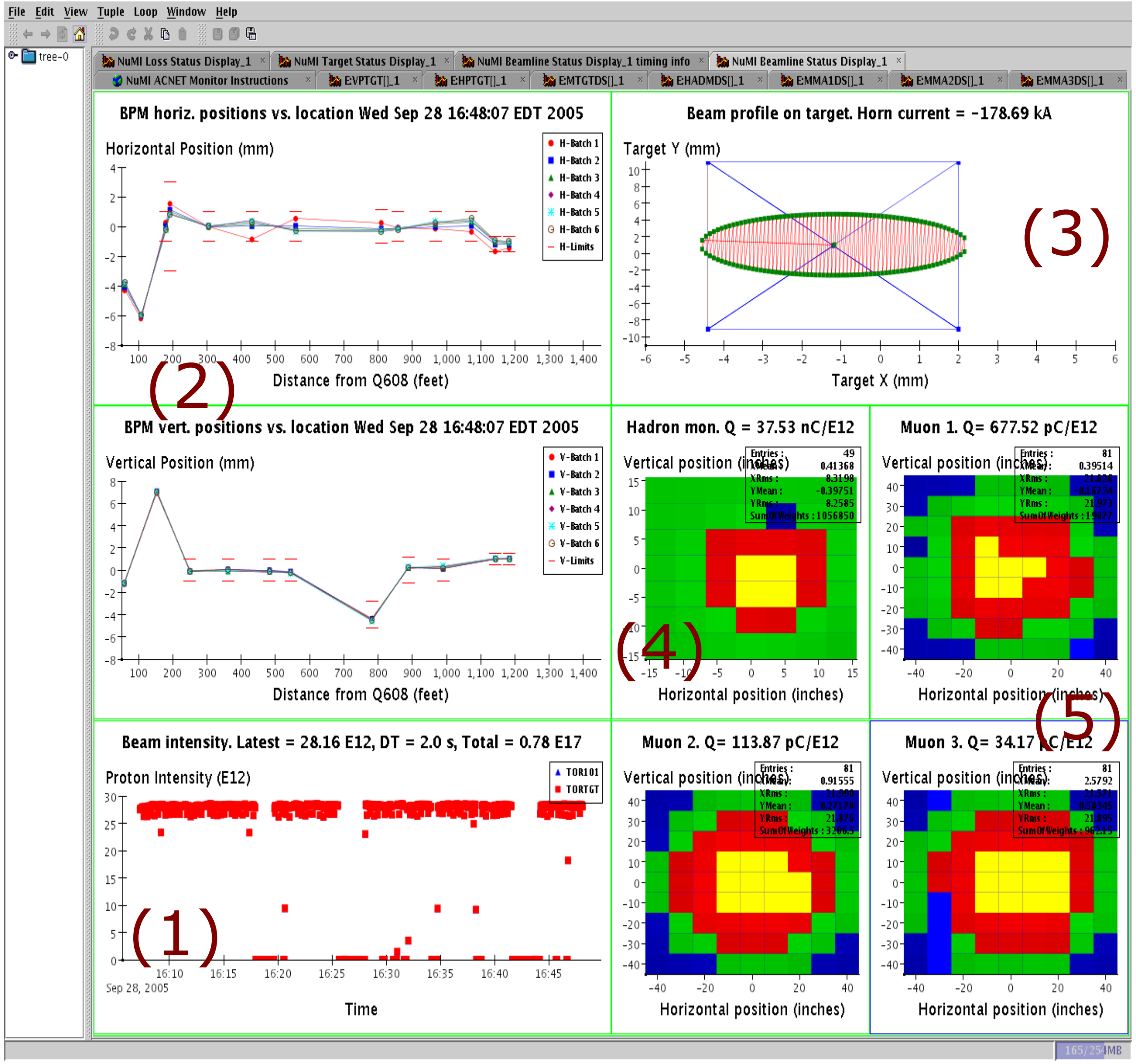
1.5% $\nu_e + \bar{\nu}_e$

NuMI Beamline

- beam line instrumentation:

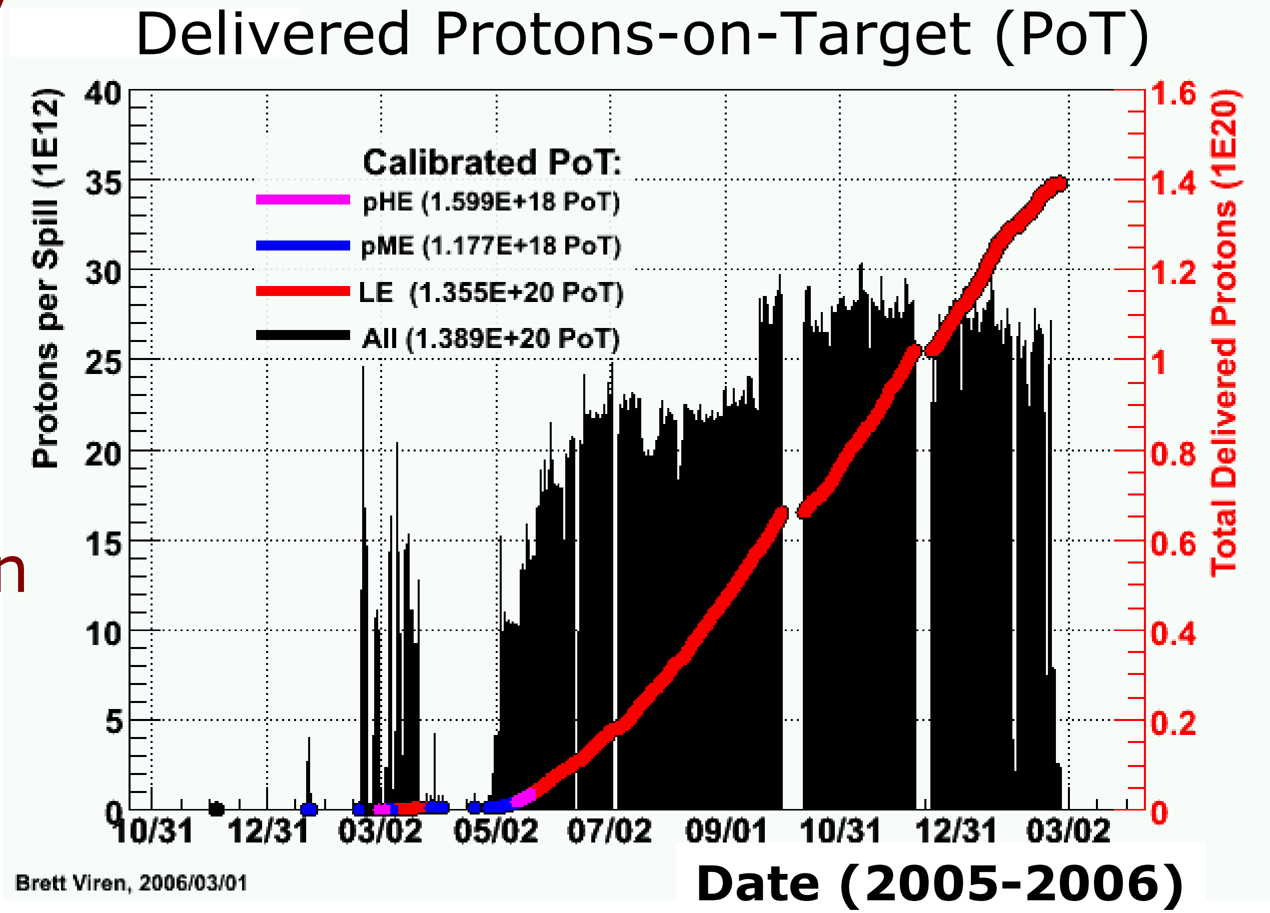
  (1) toroids (intensity)
  (2) position
  (3) profile
  (4) hadron monitors
  (5) muon monitors

- info recorded for every spill
- offline beam data quality cuts



NuMI Beamline

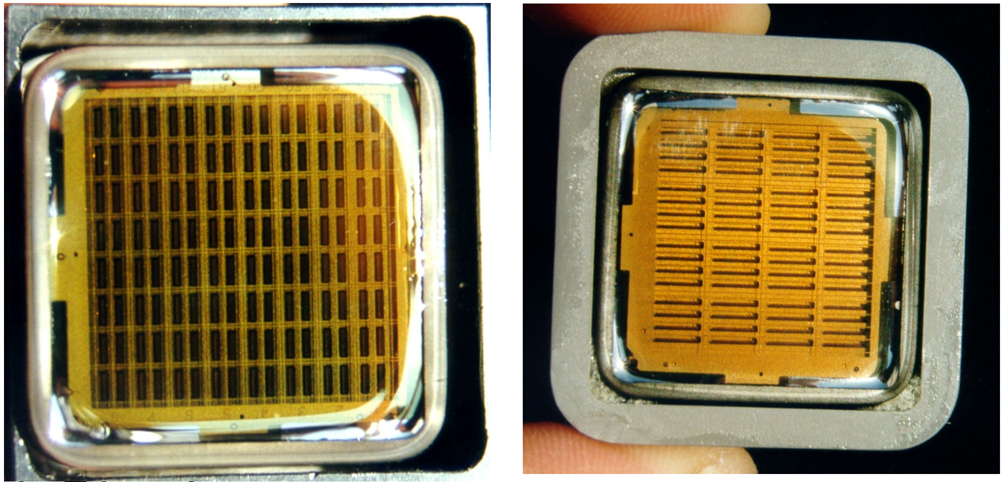
- First neutrino interaction in ND: Jan. 21, 2005
- Physics run: March 05 – Feb. 06: 1.4x10^{20} PoT
  - Most at Low Energy configuration for maximum sensitivity to atmospheric oscillation result
  - Shorter runs in pME and pHE position
- Achievements:
  - ✓ 3x10^{13} PoT/spill
  - ✓ 270 kW (~30 min)

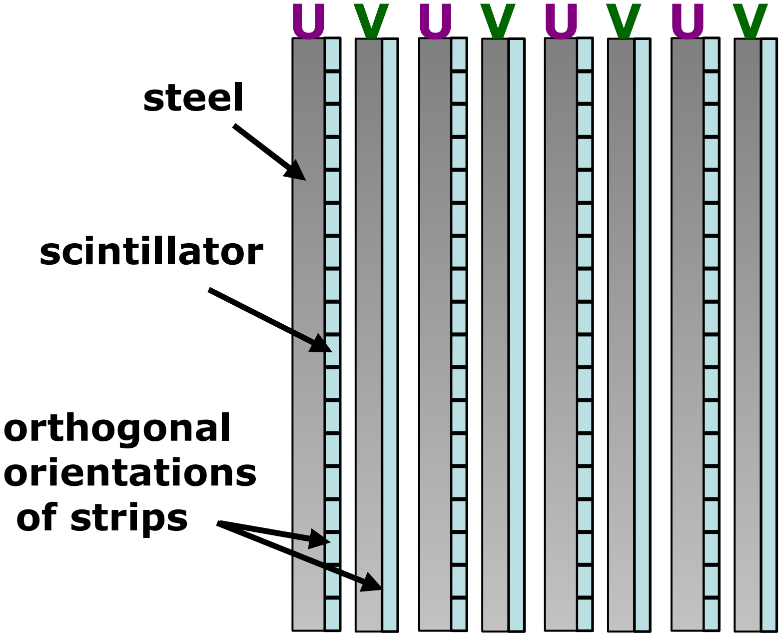


Detector Concept

Common detector technology:

- 1 inch steel planes
- 1.2T field
- 4.1x1cm^2 scintillator strips
- consecutive planes have orthogonal strips
- 1.2mm wavelength shifting fiber
- Hamamatsu multi-channel PMTs
- GPS timestamps to match data



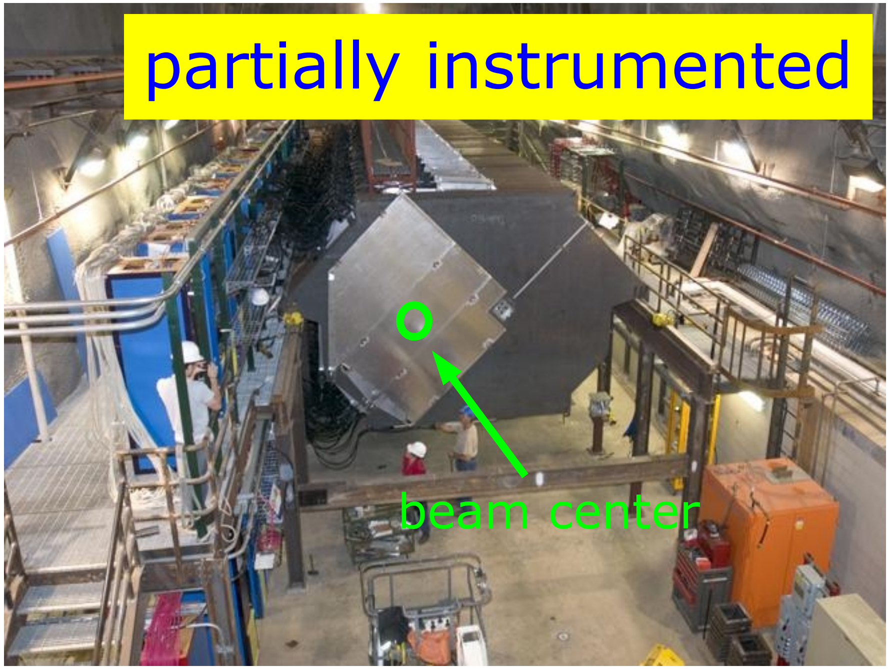


Near Detector (ND)

- located 100m underground at 1km from target
- 3.8m x 4.8m steel planes
- 282 planes: 0.98 kT

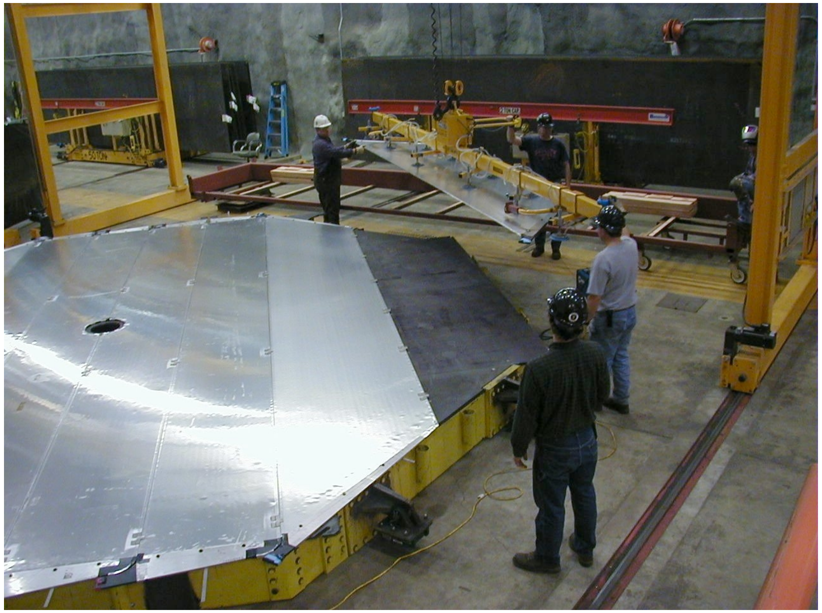
- calorimeter region: 120 pl. 4 part. + 1 fully instrum.
- spectrometer region: 162 pl. only every 5th instrumented
- strips read out one side
- spectrometer multiplexed

- fast 'QIE' electronics: continuous digitization during spills: 19ns time slices



Far Detector (FD)

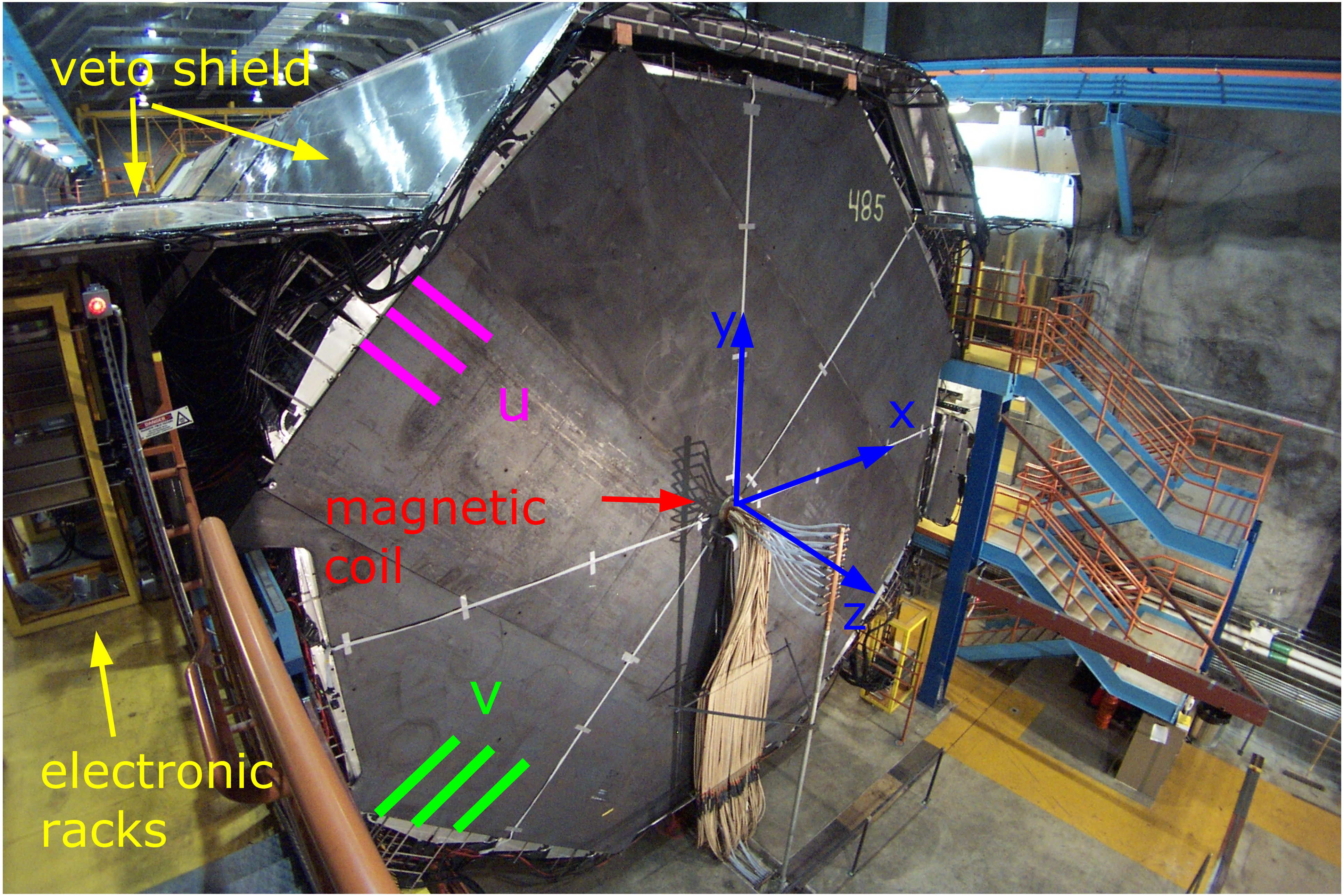
- SOUDAN underground lab
- ~700m underground
- 8m octagonal steel plates
- 486 planes in total
  ⇒ 5.4 kton



- all planes fully instrumented
- both strip ends read out
- 8 fibers to 1 channel multiplexed

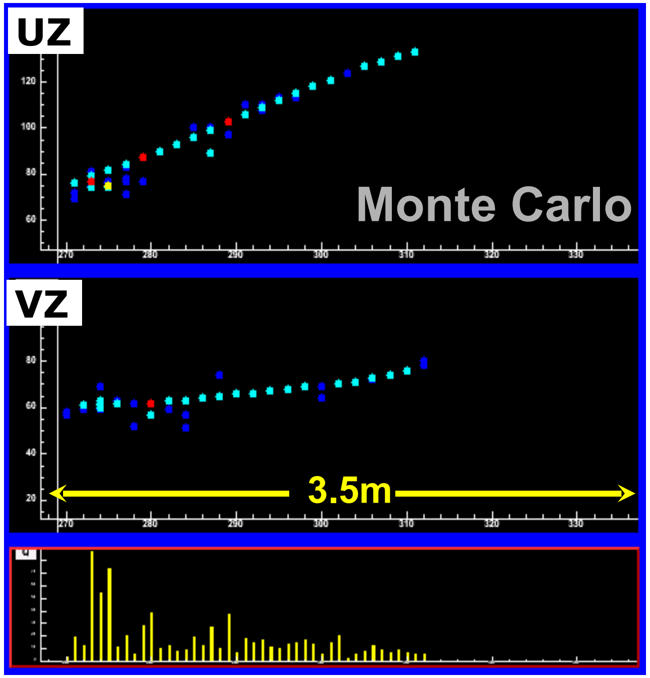
- veto shield for cosmic muons
- completed July 2003

Far Detector



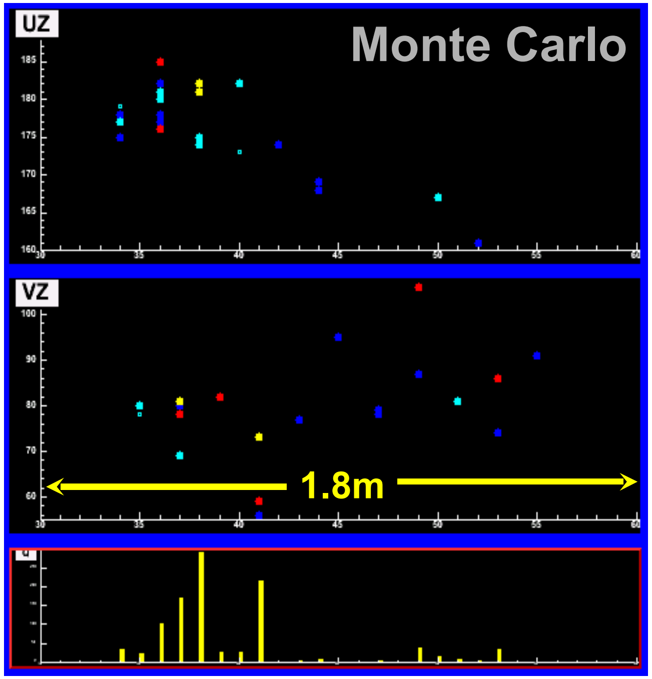
Event Topologies

ν_μ charged current (CC)



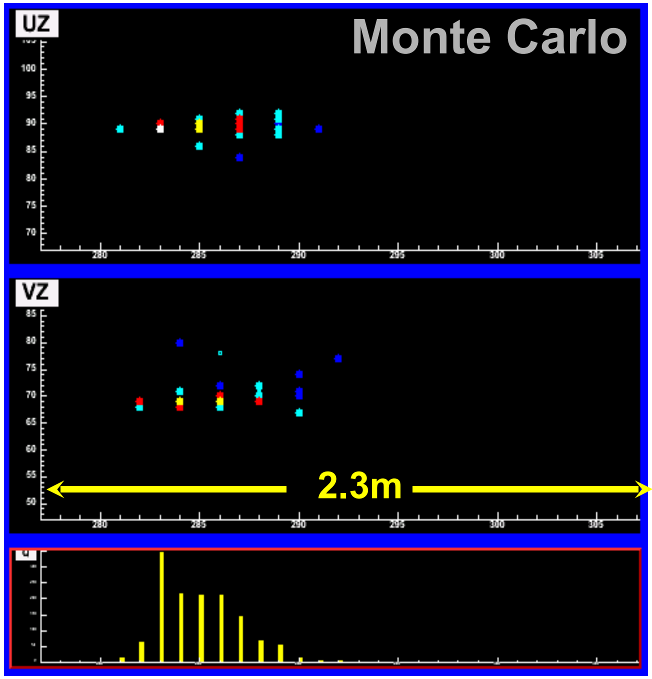
- long track (μ)
- hadronic activity near vertex

ν_x neutral current (NC)



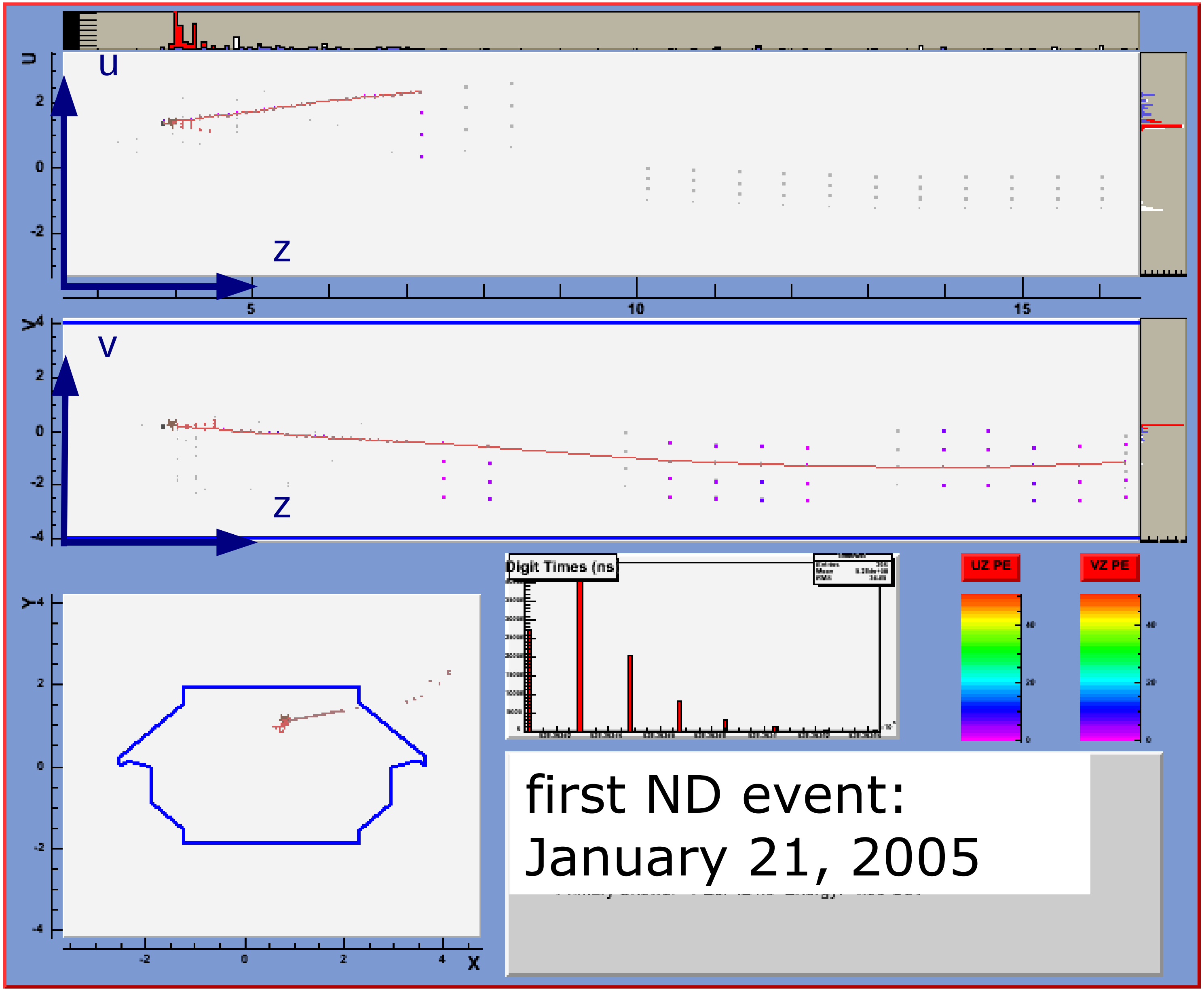
- short event
- diffuse

ν_e charged current (ν_e)



- short event
- EM shower profile

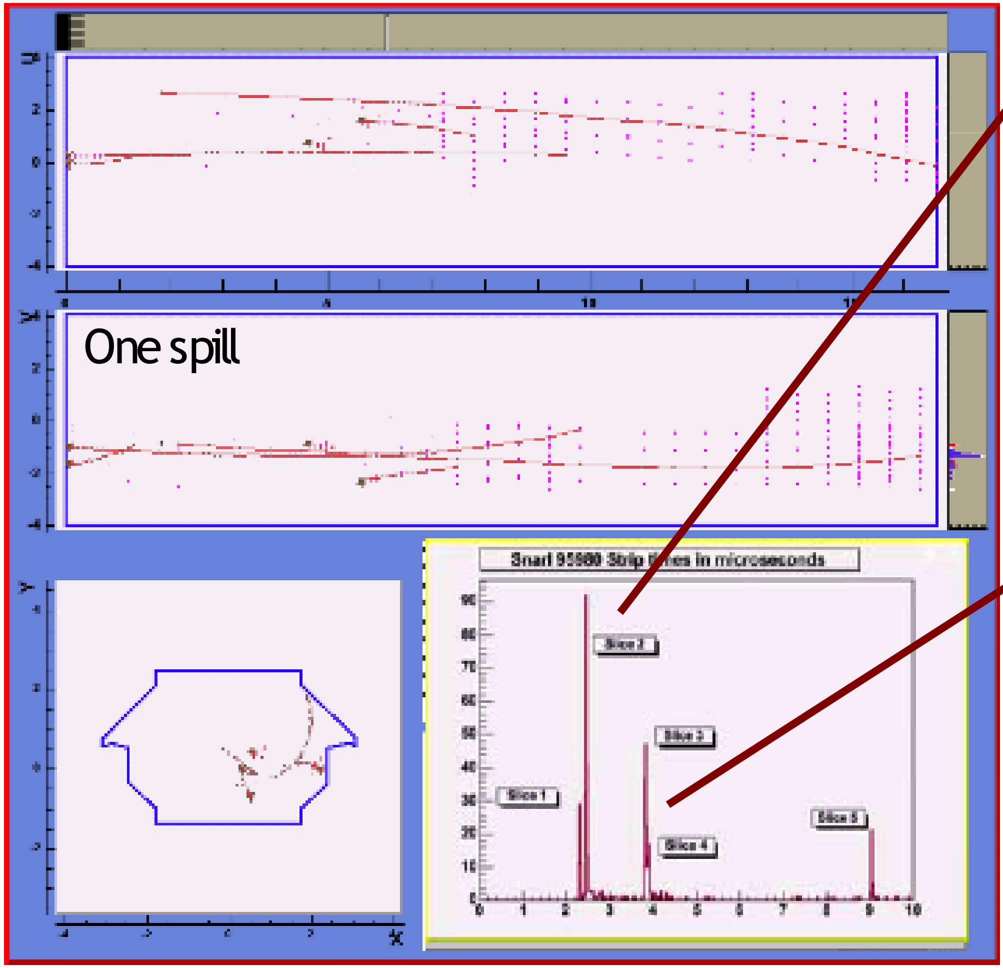
First Beam Events in ND

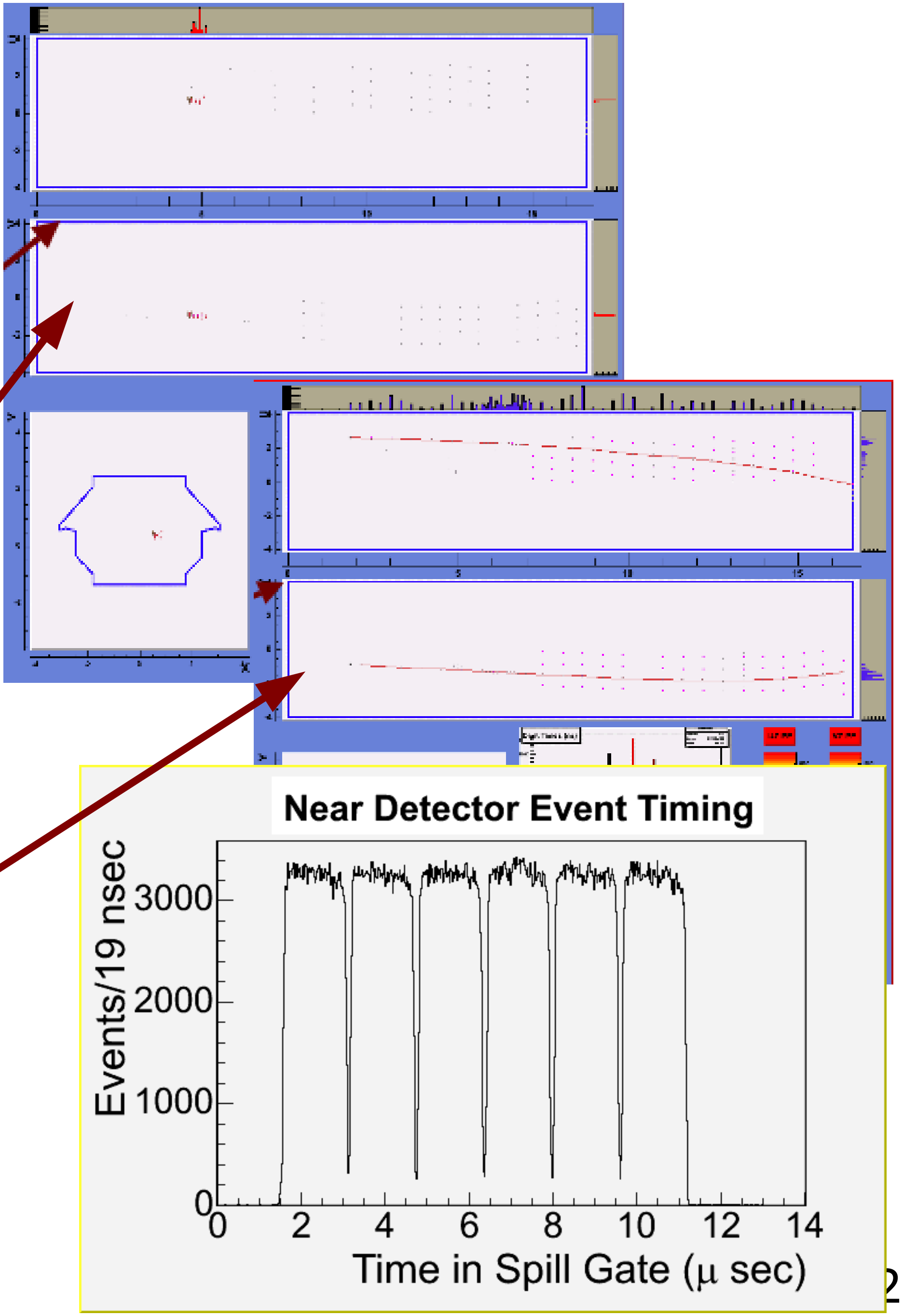


first ND event:
January 21, 2005

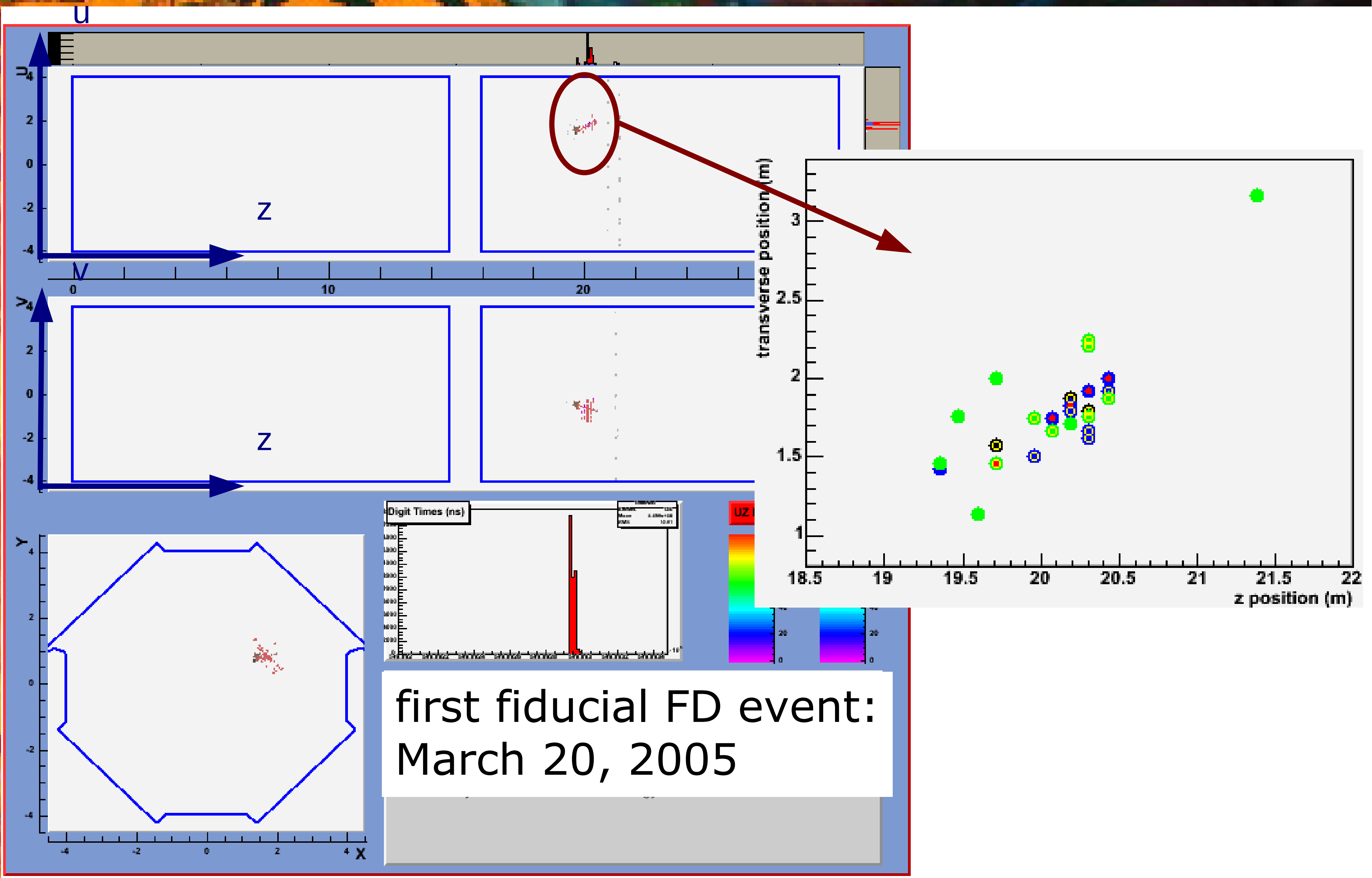
ND Events

- Multiple interactions per spill in Near Detector





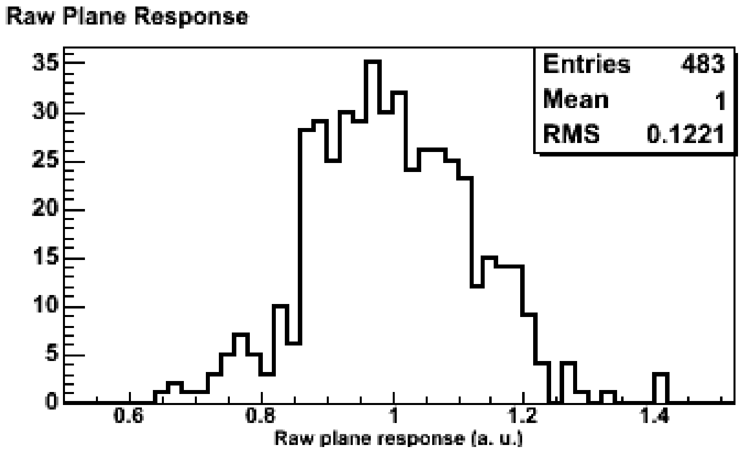
First FD Beam Event

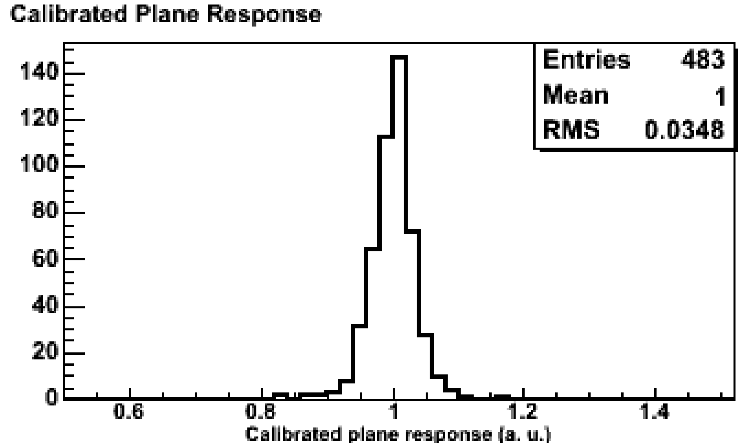


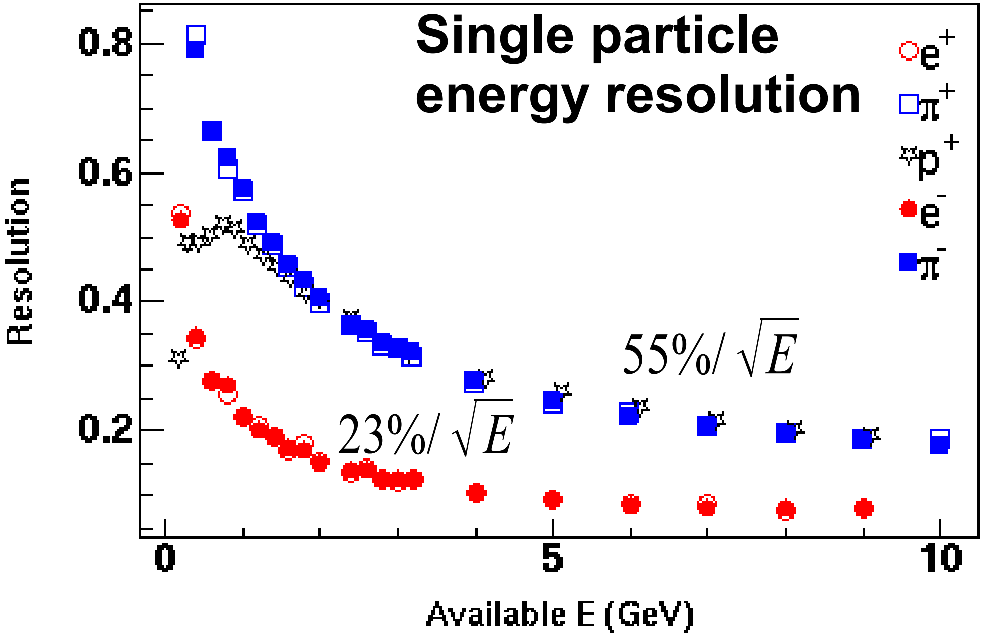
first fiducial FD event:
March 20, 2005

Calibration

- Light injection: PMT gain
- cosmic ray μ: strip-to-strip, inter-detector
- calibration detector: absolute calibration
  - 'mini-MINOS' at CERN test beam


Raw Plane Response


Calibrated Plane Response



Energy scale calibration:

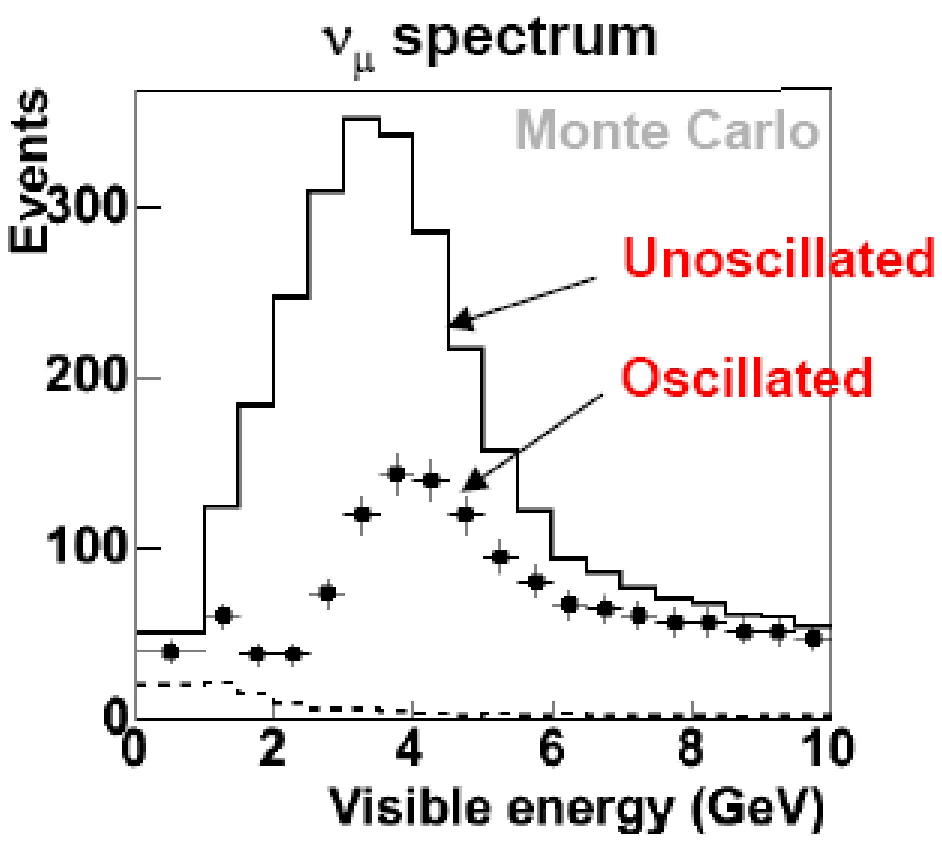
- ND abs: 1.9%
- FD abs: 3.5%
- ND-FD rel: 2.0%

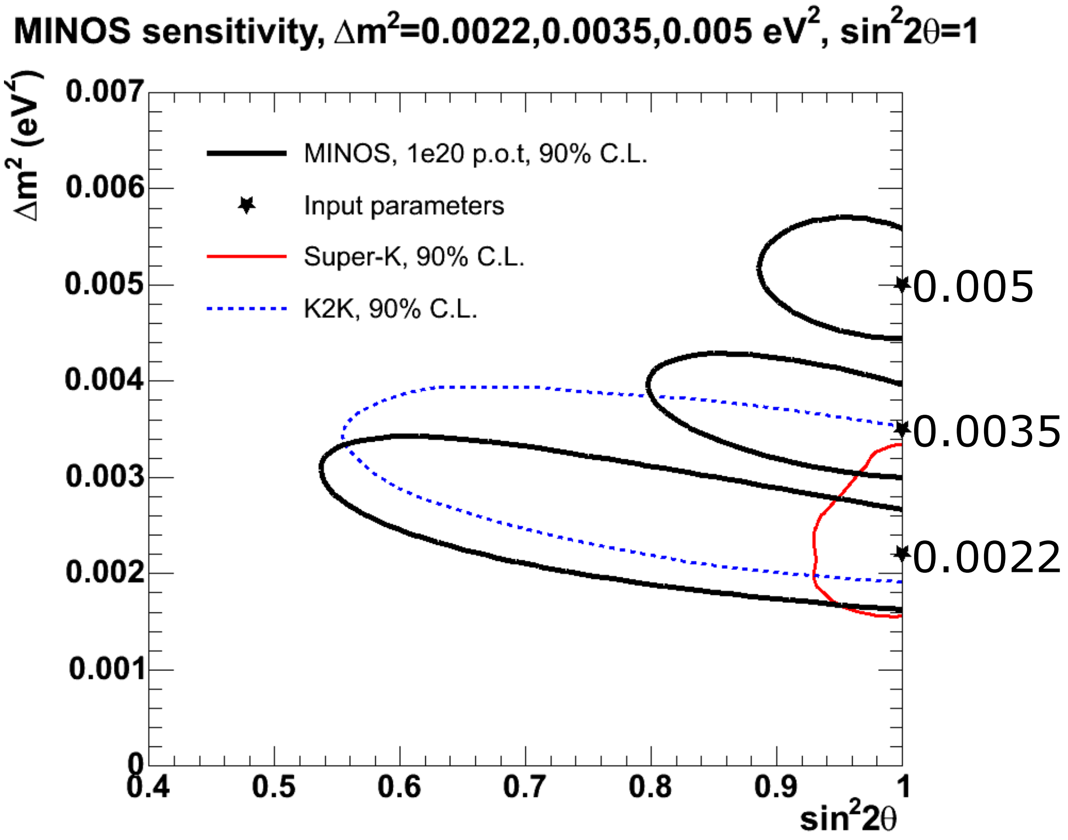
Physics Reach

ν_μ disappearance

$$P(\nu_\mu \rightarrow \nu_\mu) = 1 - \sin^2 2\theta_{23} \cdot \sin^2\left(1.27\,\Delta m^2_{32} \frac{L}{E}\right)$$

10^{20} protons on target (PoT)

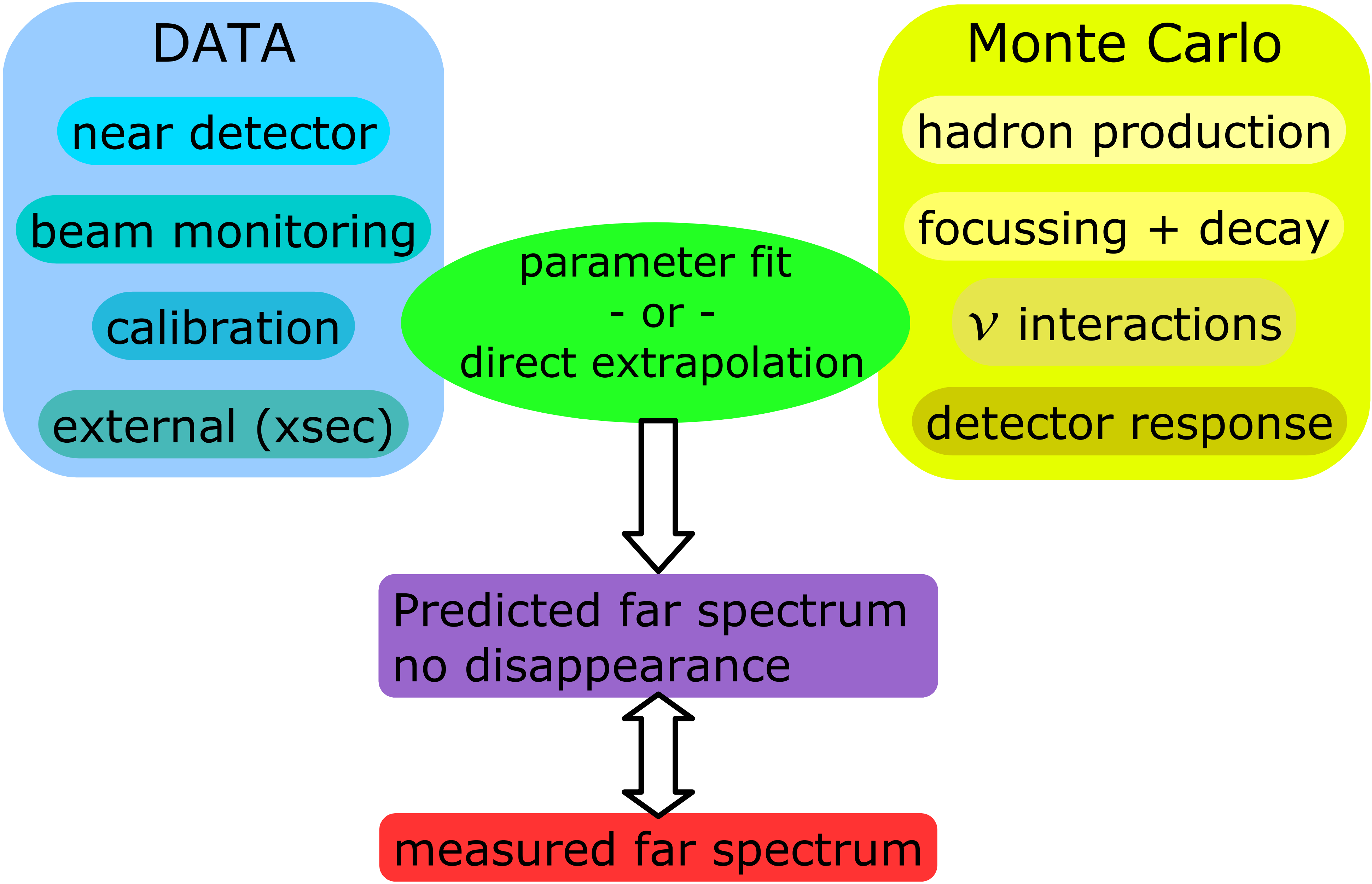




ν_μ disappearance analysis

- Analysis sketch
- Event selection
- Near detector distributions
- Near to far extrapolation
- Far detector distributions
- Oscillation fit

ν_μ Disappearance Analysis



DATA

- near detector
- beam monitoring
- calibration
- external (xsec)

Monte Carlo

- hadron production
- focussing + decay
- ν interactions
- detector response

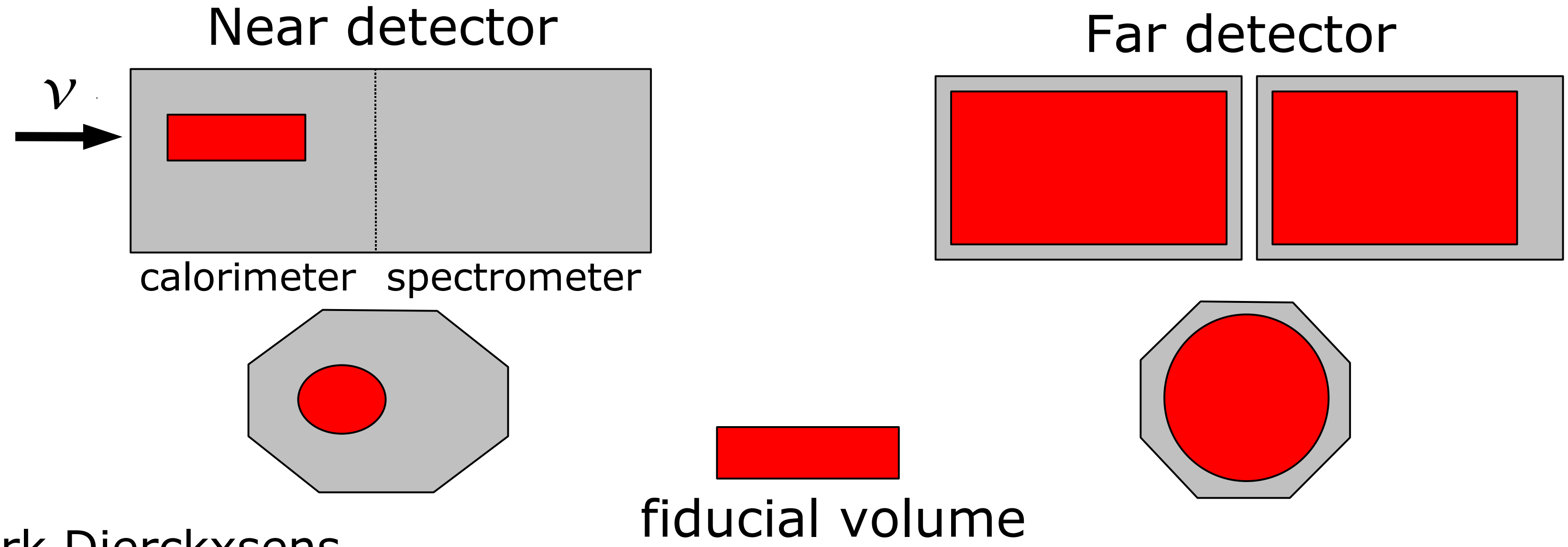
parameter fit
- or -
direct extrapolation

Predicted far spectrum
no disappearance

measured far spectrum

CC Event Selection

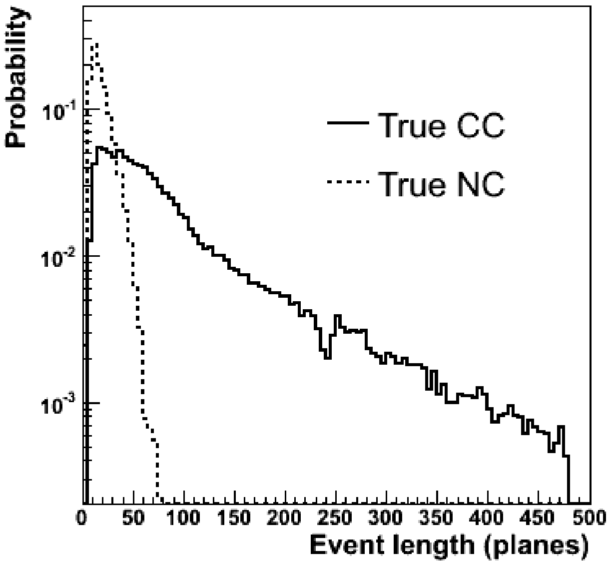
- beam monitoring and detector quality cuts
- CC pre-selection:
  - ✔ # good reconstructed track > 0
  - ✔ select only tracks with negative curvature
  - ✔ fiducial volume cuts on vertex:
    - ✗ ND: 1m < z < 5m; r < 1m w.r.t. beam center
    - ✗ FD: z > 50cm from edge, z>2m from end; r < 3.7m



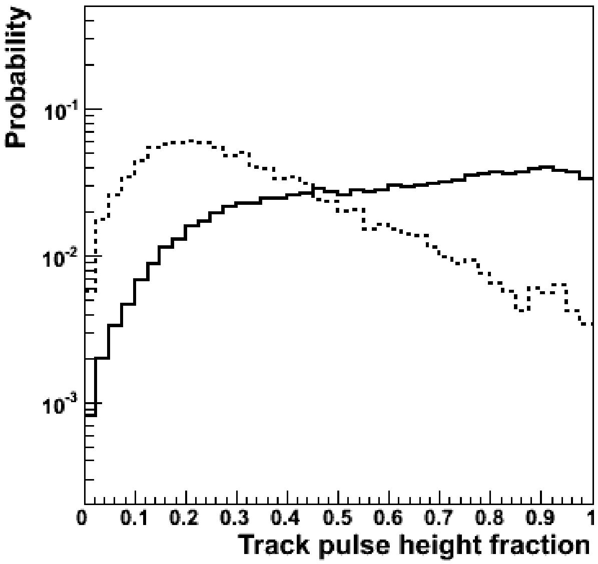
CC Event Selection

- CC/NC separation using likelihood-based method
- Three probability density functions (PDFs) used:

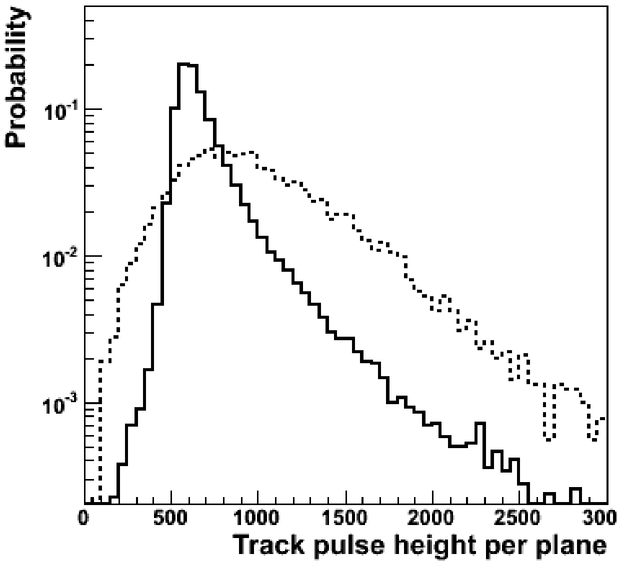
event length
~p_μ



track pulse
height fraction
~inelasticity



track pulse
height per plane
~ dE/dx



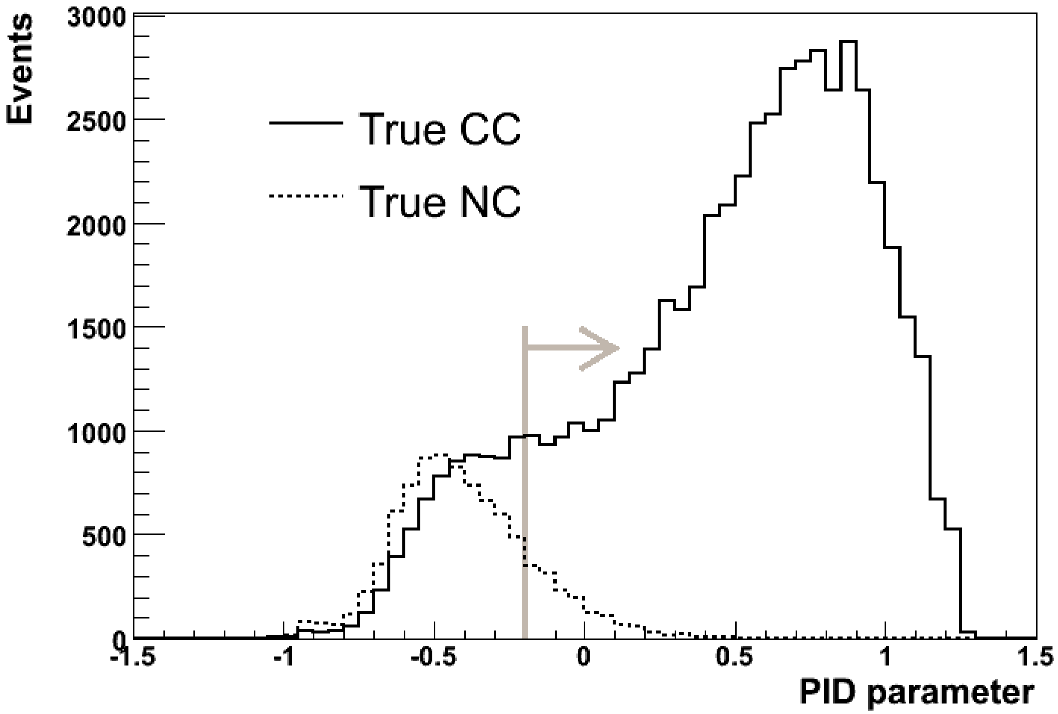
CC Event Selection

- Particle ID (PID) defined as:

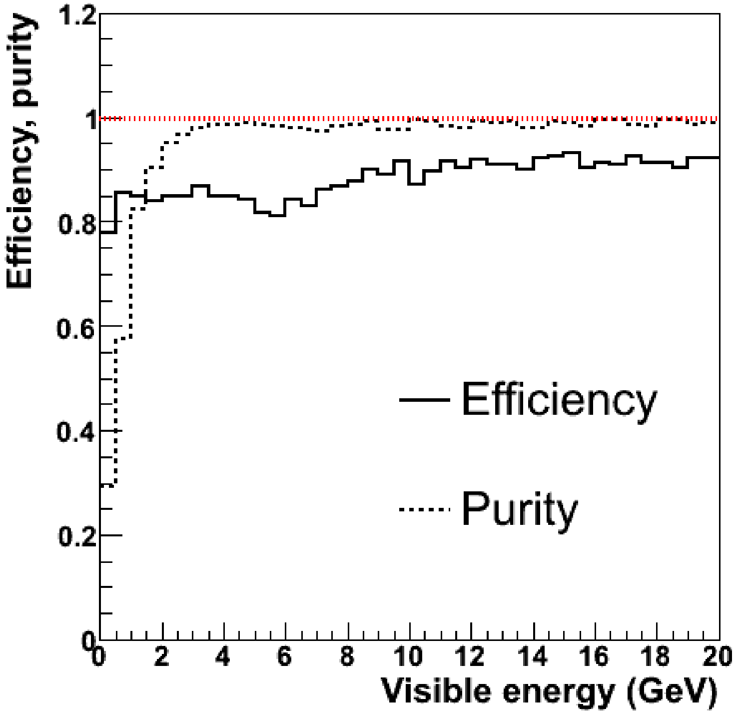
$$PID=-\sqrt{-\log P_{CC}}+\sqrt{-\log P_{NC}}$$

- Select CC-like events:
  - ✓ PID>-0.2 in FD
  - ✓ PID>-0.1 in ND

PDF PID parameter distribution for true CC and NC events

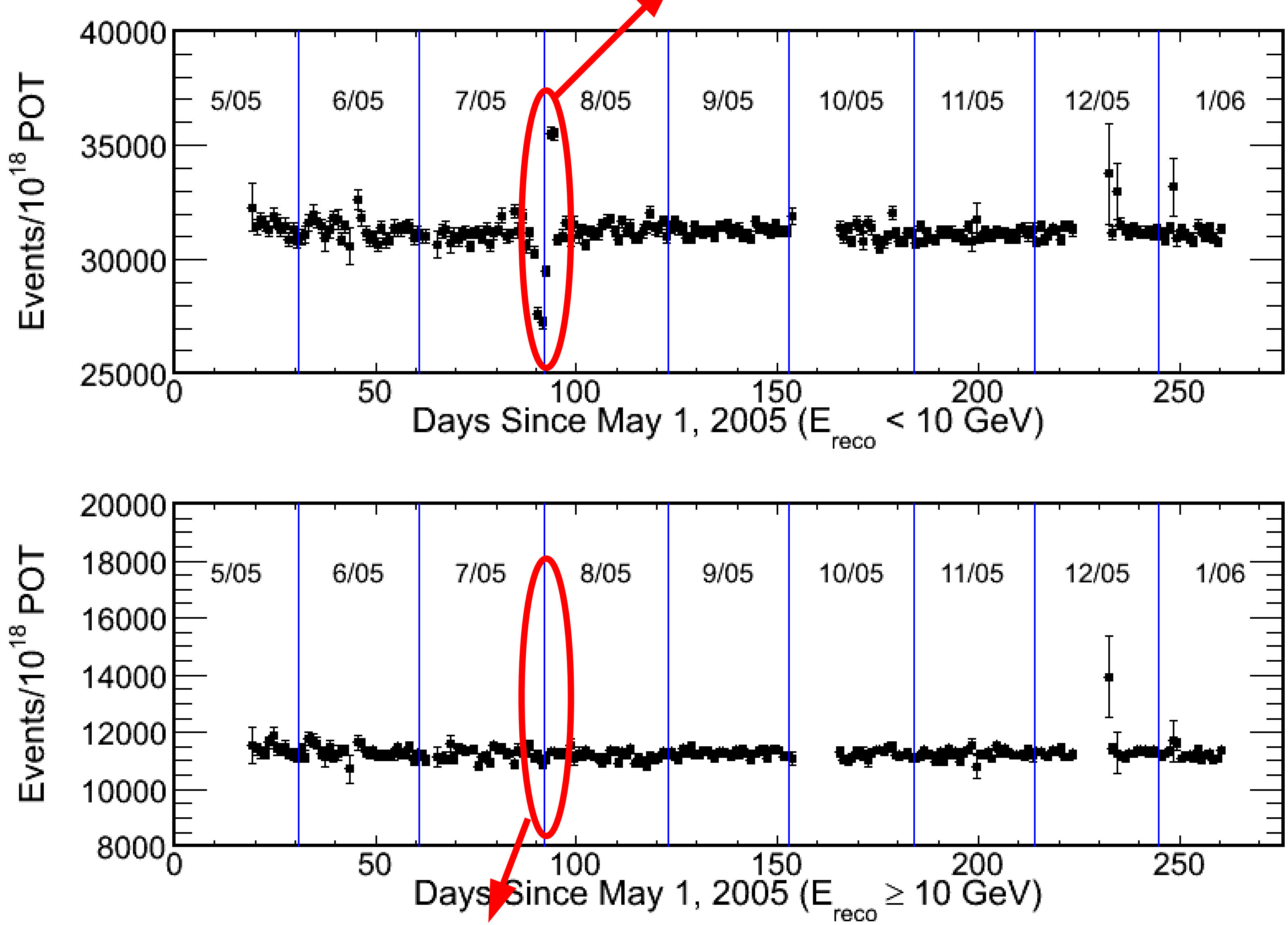


CC selection efficiencies and purities



ND data

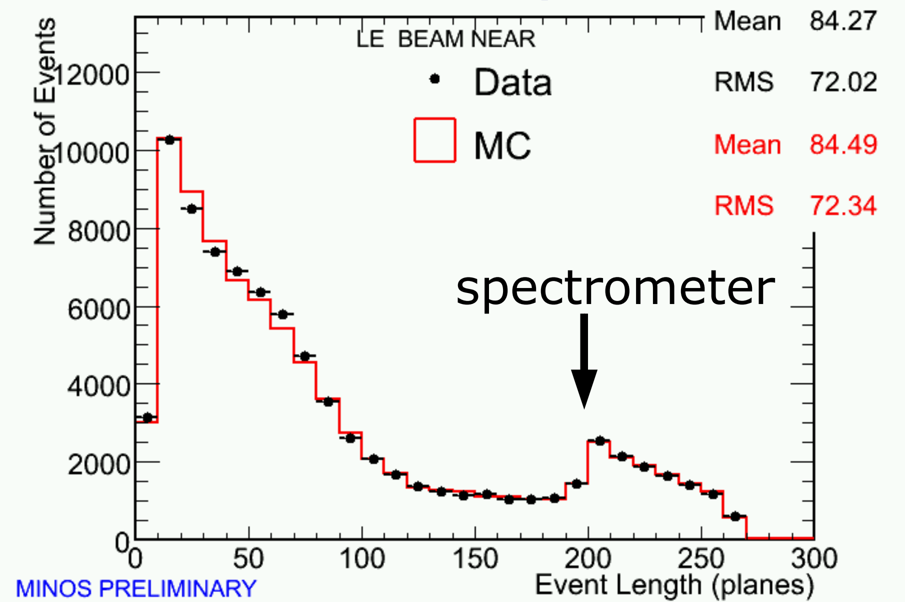
Horn Current Test Runs

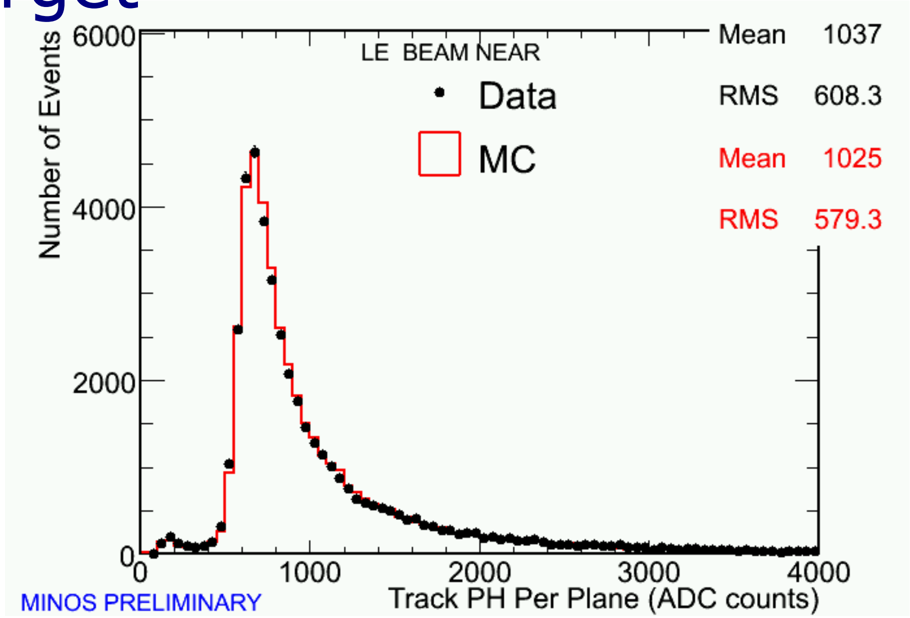


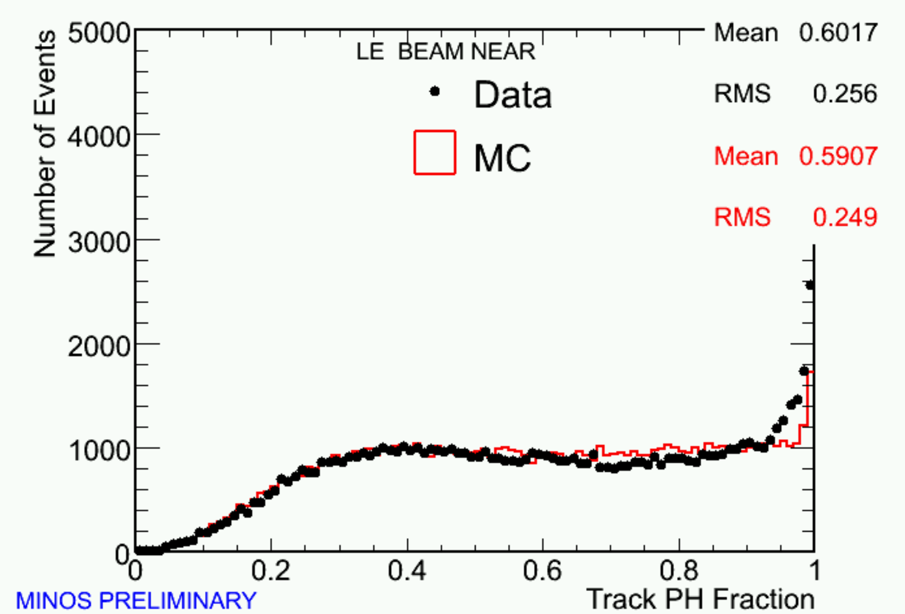
High energy spectrum not affected

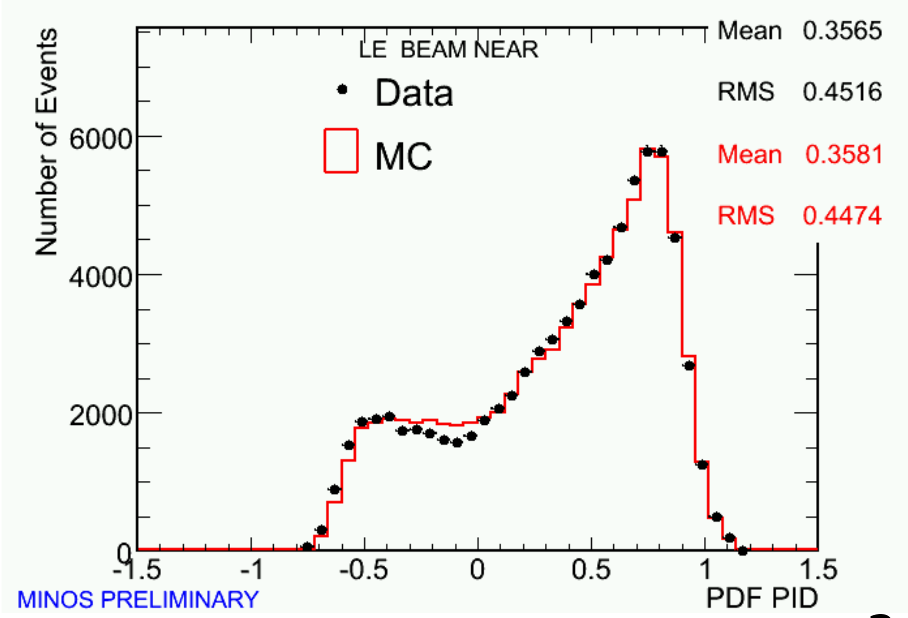
ND LE-10 data

- normalized to protons on target

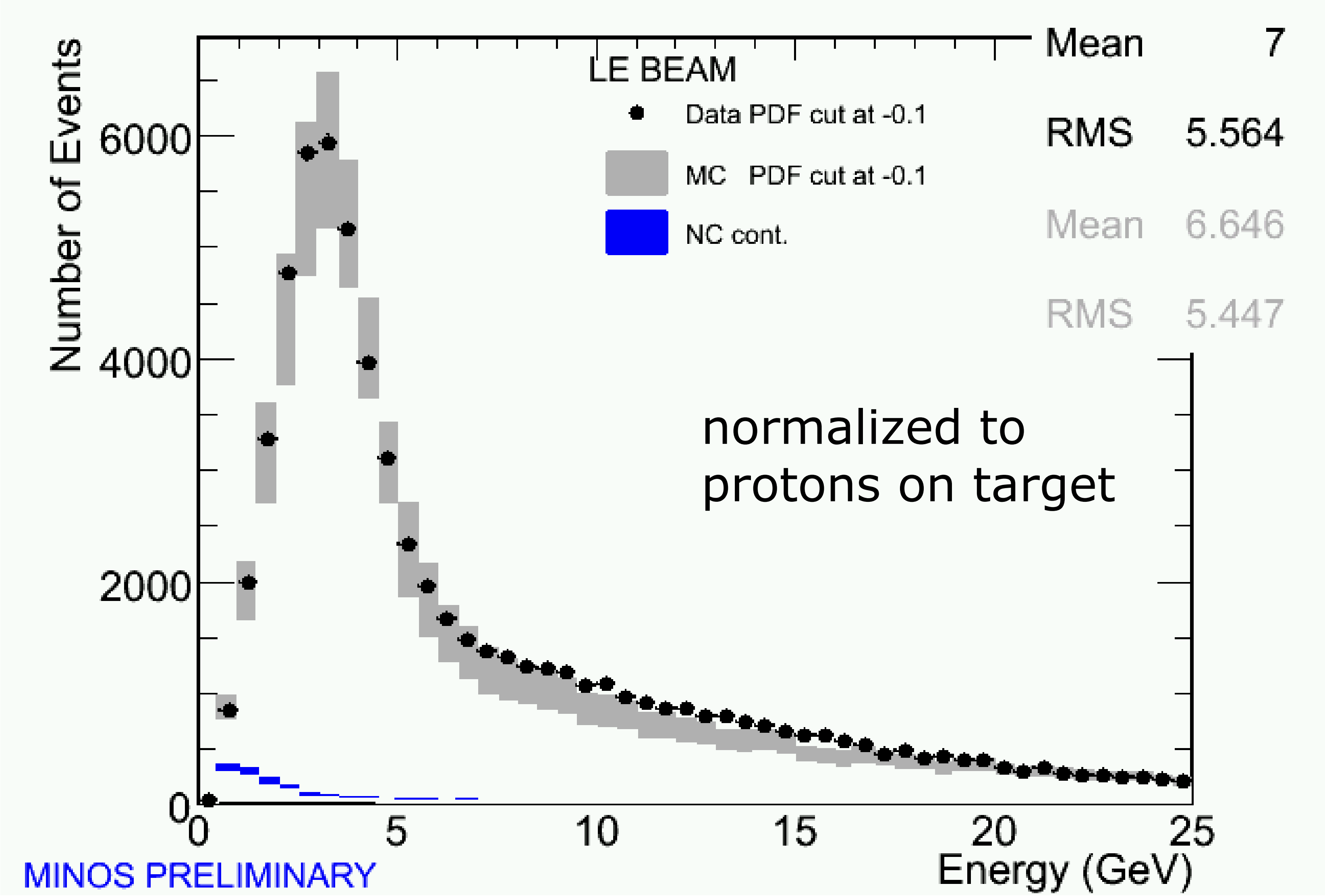








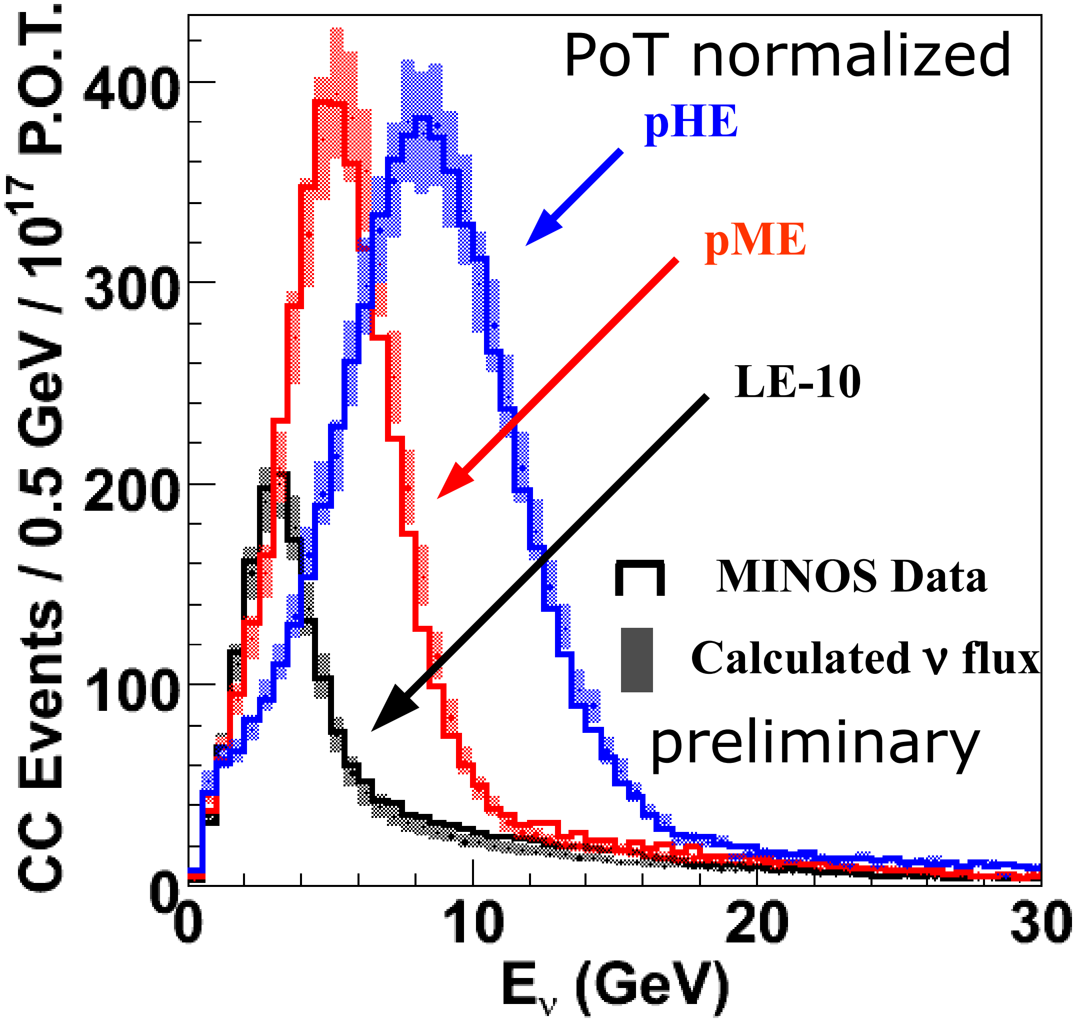
ND LE-10 data



- MC error envelope: uncertainties due to cross section modeling, beam modeling and calibration

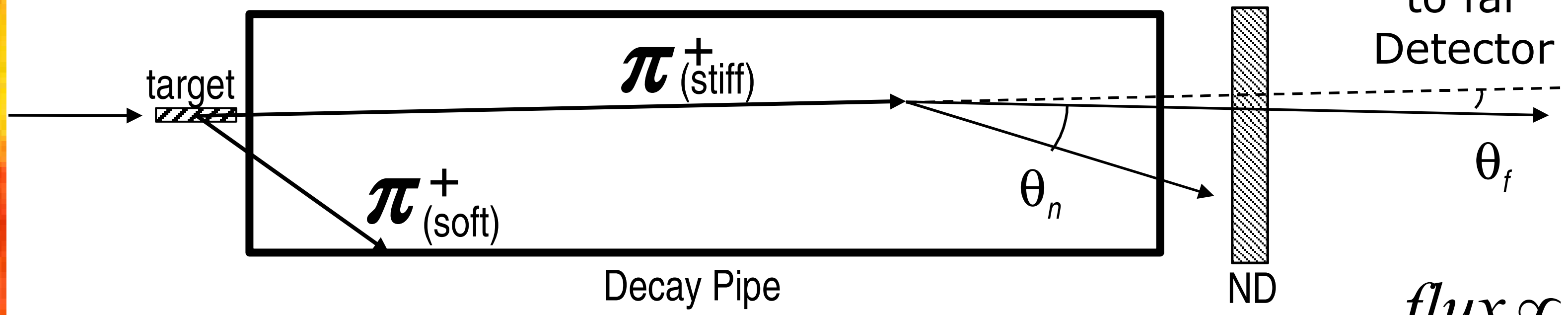
Other ND data

- Various test runs:
  - target in medium & high energy position
  - target scans
  - diff. horn currents
  - horn current scans
  - horn off
  - low intensity



Near/Far extrapolation

- FD spectrum is predicted from ND data:
  - ND sees extended neutrino source
  - extrapolation calculated from pion decay kinematics and knowledge of beamline geometry



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

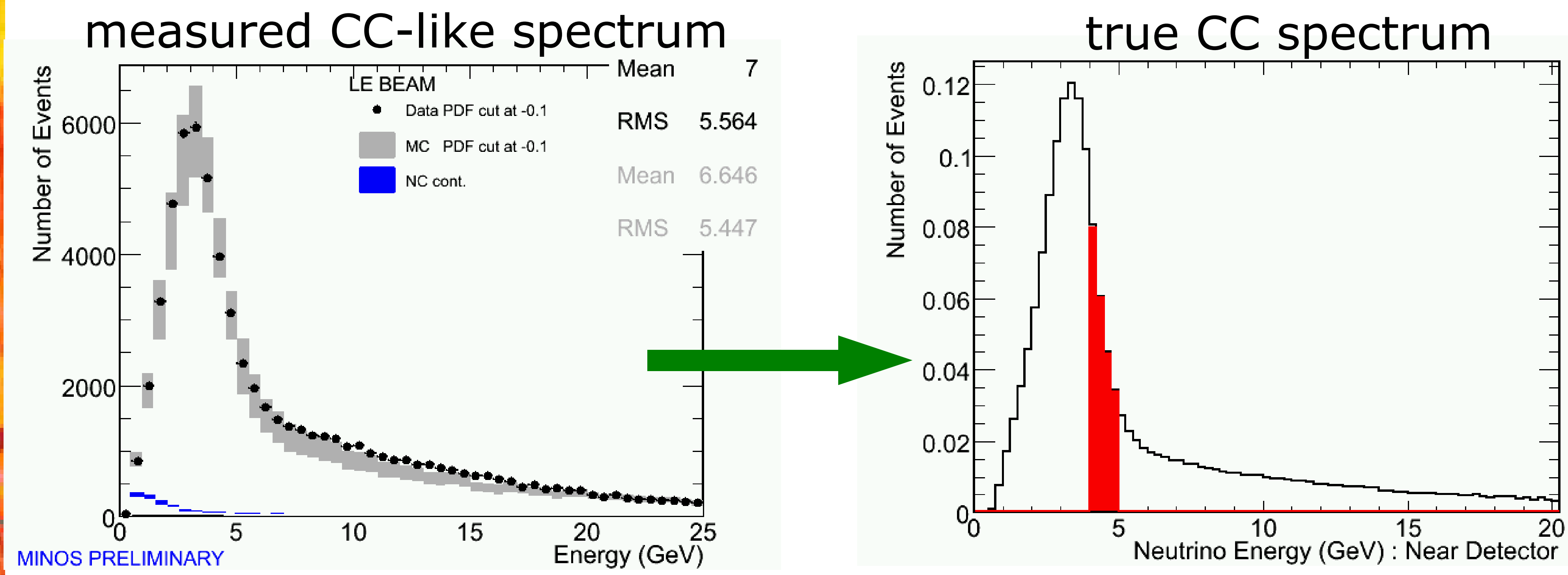
$$flux \propto \frac{1}{L^2}\left(\frac{\gamma}{1+\gamma^2\theta^2}\right)^2$$

- Beam matrix method:

(A) obtain ND true CC spectrum
(B) transport matrix ND to FD
(C) predict FD spectrum without disappearance

Beam Matrix Method

- step (A):
  - ✓ NC background subtraction
  - ✓ deconvolve detector response
  - ✓ efficiency correction

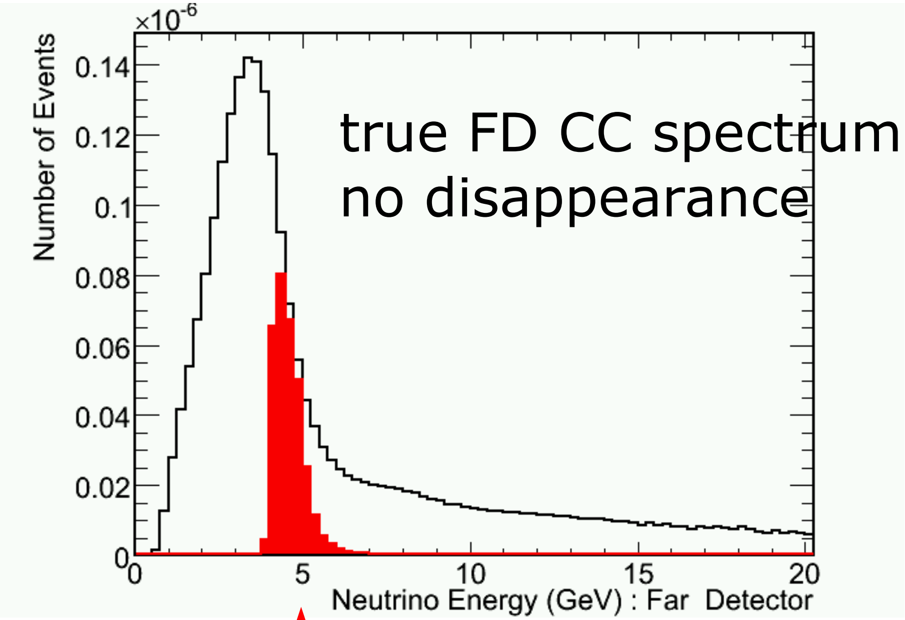


measured CC-like spectrum

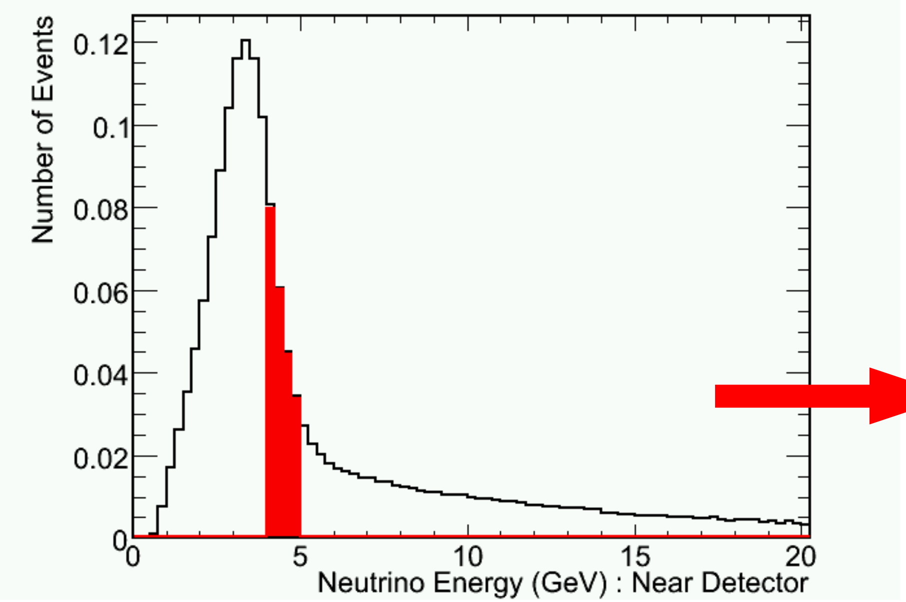
true CC spectrum

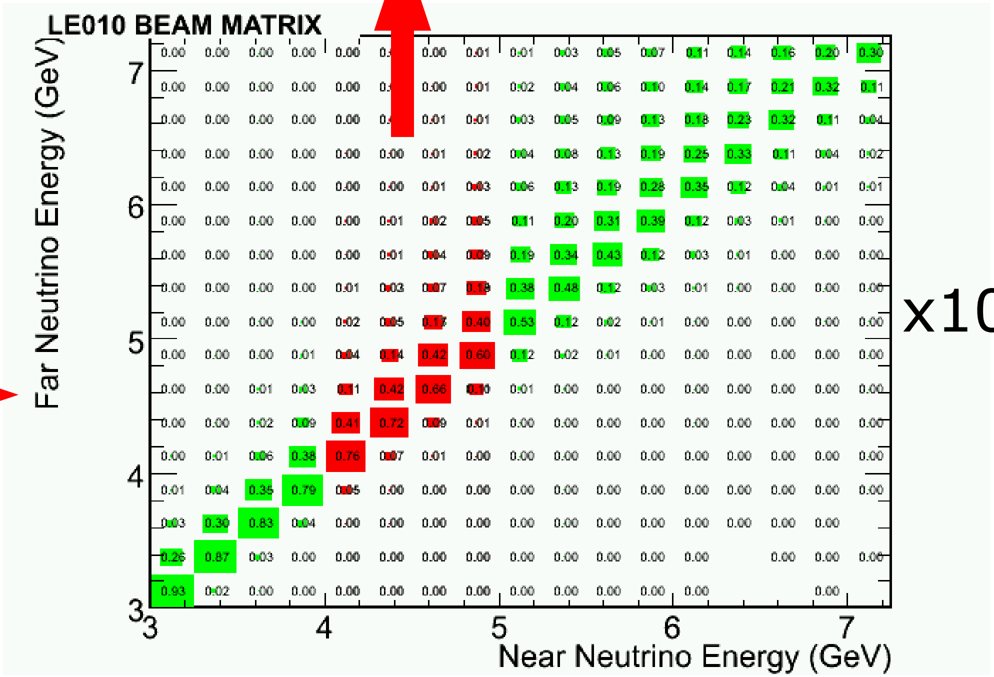
Beam Matrix Method

- step (B):
  - ✓ construct beam transport matrix to map true near to far energy


true FD CC spectrum
no disappearance

true ND CC spectrum




LE010 BEAM MATRIX

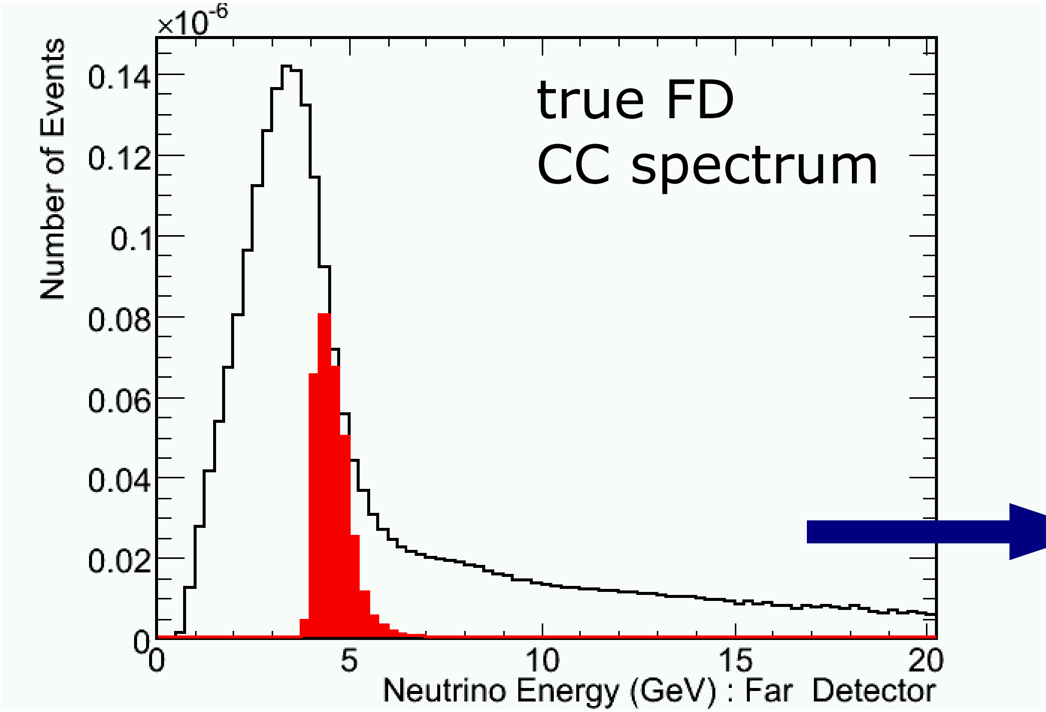
0.00	0.00	0.00	0.00	0.00	[illegible]	0.00	0.01	0.01	0.03	0.05	0.07	0.11	0.14	0.16	0.20	0.30
0.00	0.00	0.00	0.00	0.00	[illegible]	0.00	0.01	0.02	0.04	0.06	0.10	0.14	0.17	0.21	0.32	0.11
0.00	0.00	0.00	0.00	0.00	[illegible]	0.01	0.01	0.03	0.05	0.09	0.13	0.18	0.23	0.32	0.11	0.04
0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.02	0.04	0.08	0.13	0.19	0.25	0.33	0.11	0.04	0.02
0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.03	0.06	0.13	0.19	0.28	0.35	0.12	0.04	0.01	0.01
0.00	0.00	0.00	0.00	0.00	0.01	0.02	0.05	0.11	0.20	0.31	0.39	0.12	0.03	0.01	0.00	0.00
0.00	0.00	0.00	0.00	0.00	0.01	0.04	0.09	0.19	0.34	0.43	0.12	0.03	0.01	0.00	0.00	0.00
0.00	0.00	0.00	0.00	0.01	0.03	0.07	0.18	0.38	0.48	0.12	0.03	0.01	0.00	0.00	0.00	0.00
0.00	0.00	0.00	0.00	0.02	0.05	0.17	0.40	0.53	0.12	0.02	0.01	0.00	0.00	0.00	0.00	0.00
0.00	0.00	0.00	0.01	0.04	0.14	0.42	0.60	0.12	0.02	0.01	0.00	0.00	0.00	0.00	0.00	0.00
0.00	0.00	0.01	0.03	0.11	0.42	0.66	0.10	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
0.00	0.00	0.02	0.09	0.41	0.72	0.09	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
0.00	0.01	0.06	0.38	0.76	0.07	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
0.01	0.04	0.35	0.79	0.05	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
0.03	0.30	0.83	0.04	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	
0.26	0.87	0.03	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00		0.00	0.00	0.00
0.93	0.02	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00			0.00	

$\times 10^{-6}$

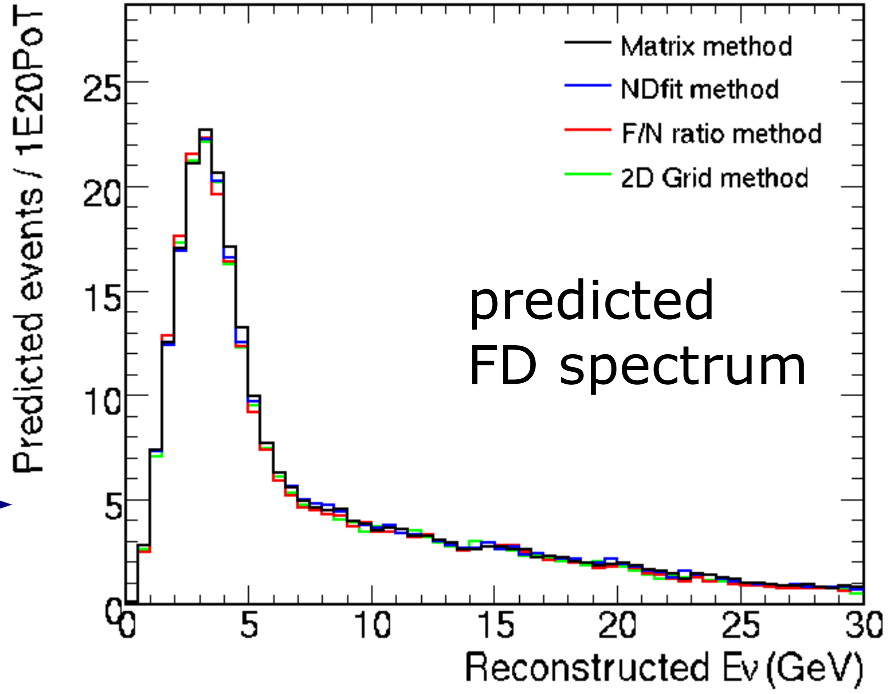
Beam Matrix Method

- step (C):
  - ✓ add detector response
  - ✓ efficiencies
  - ✓ background
  - ✓ oscillations

different extrapolation methods give consistent predictions



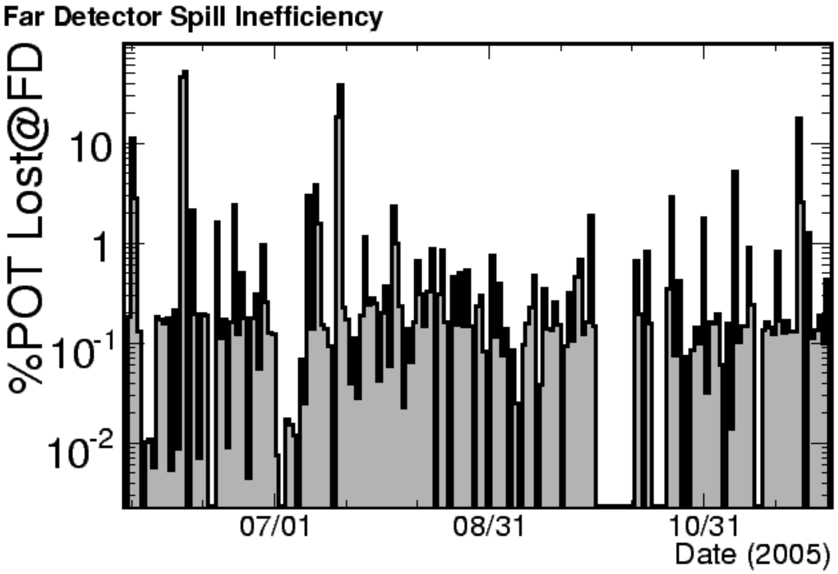
true FD CC spectrum



predicted FD spectrum

FD Data Sample

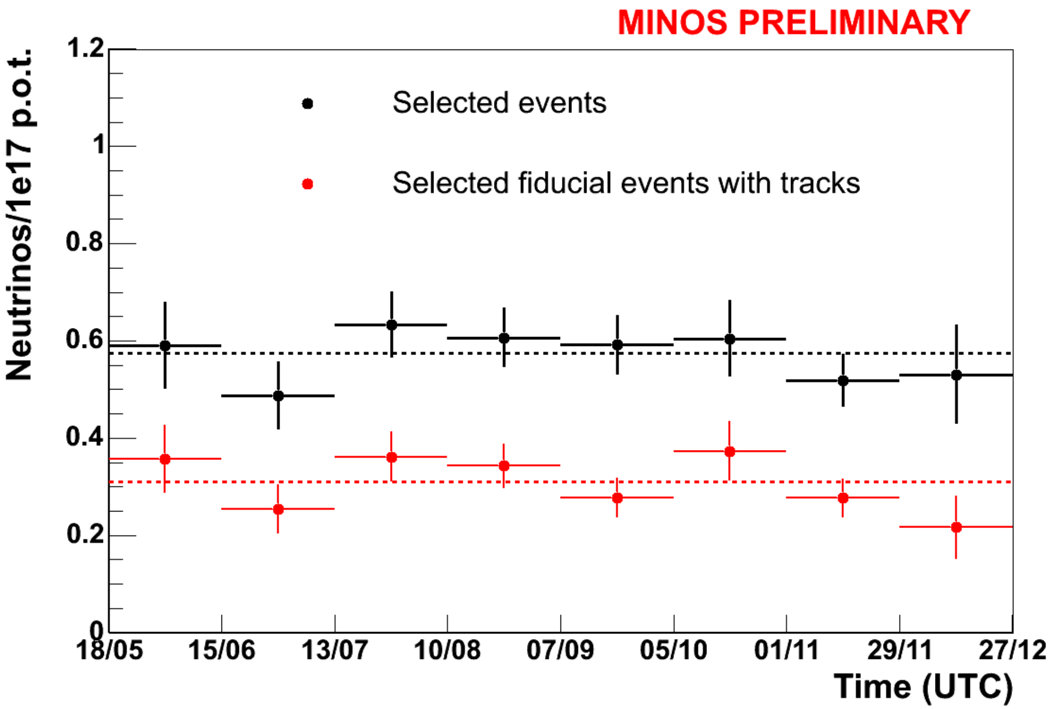
- Data sample: May 20th 2005 – Dec. 6th 2005
  - Integrated PoT: 0.93×10^{20}
  - Far detector livetime: 98.9% (PoT weighted)

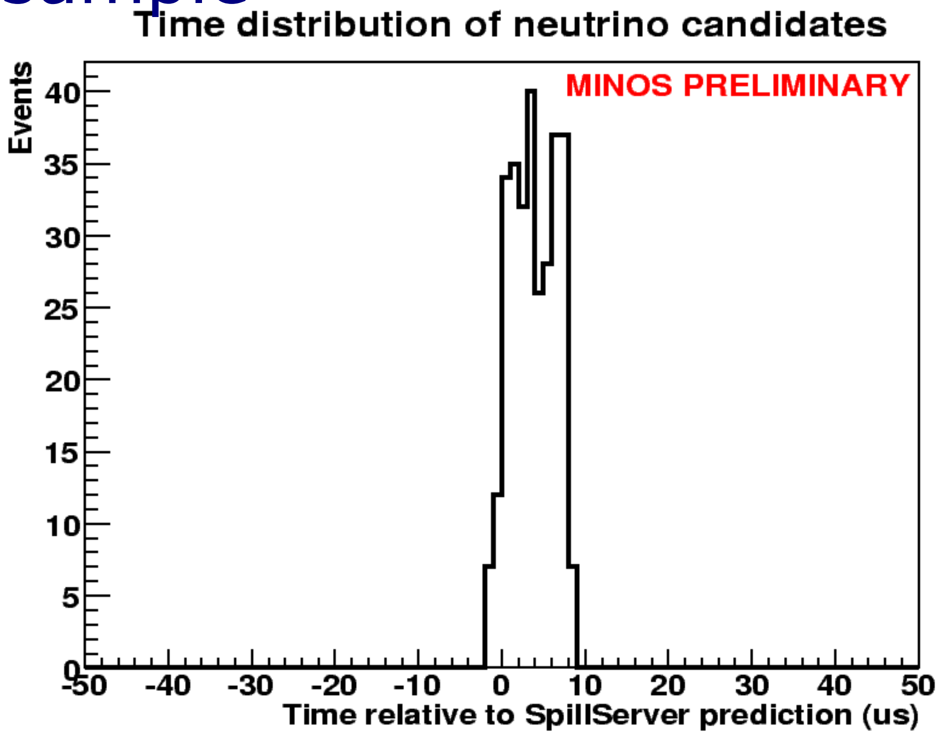


- Blind analysis policy:
  - unknown fraction hidden, based on event length and total energy deposit
  - open set used to perform data quality checks
  - oscillation analysis defined and validated on MC
  - no changing of cuts after box opening

FD data distributions

full data sample



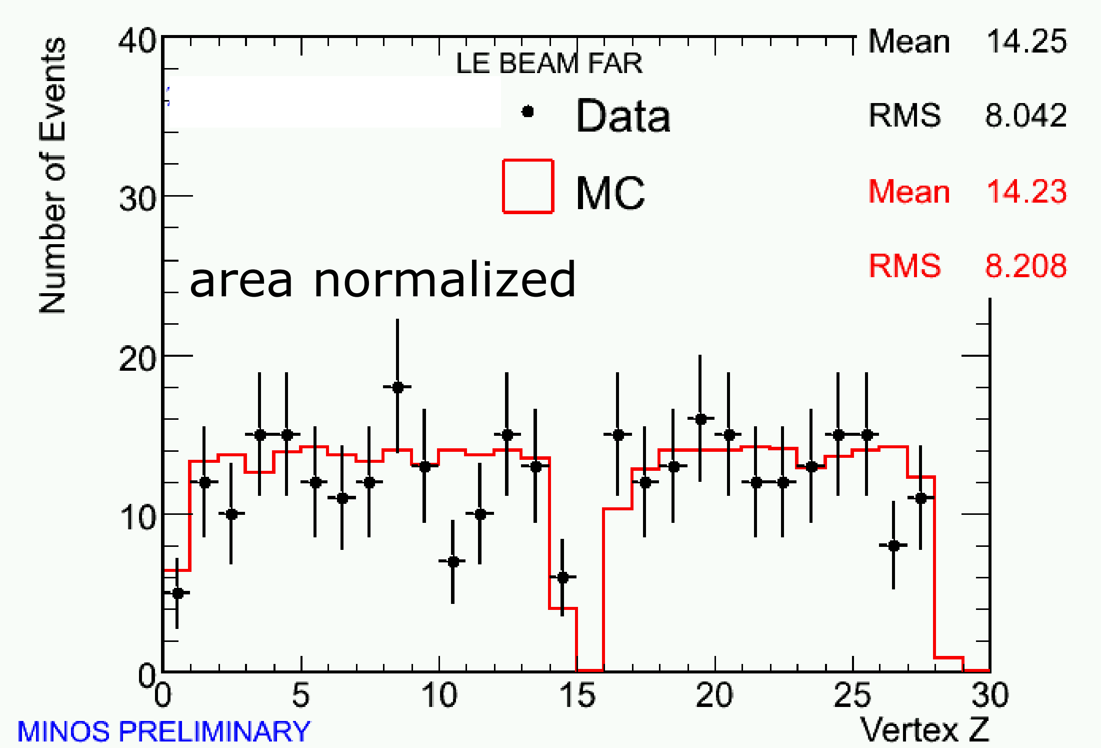


- event rate consistent over time

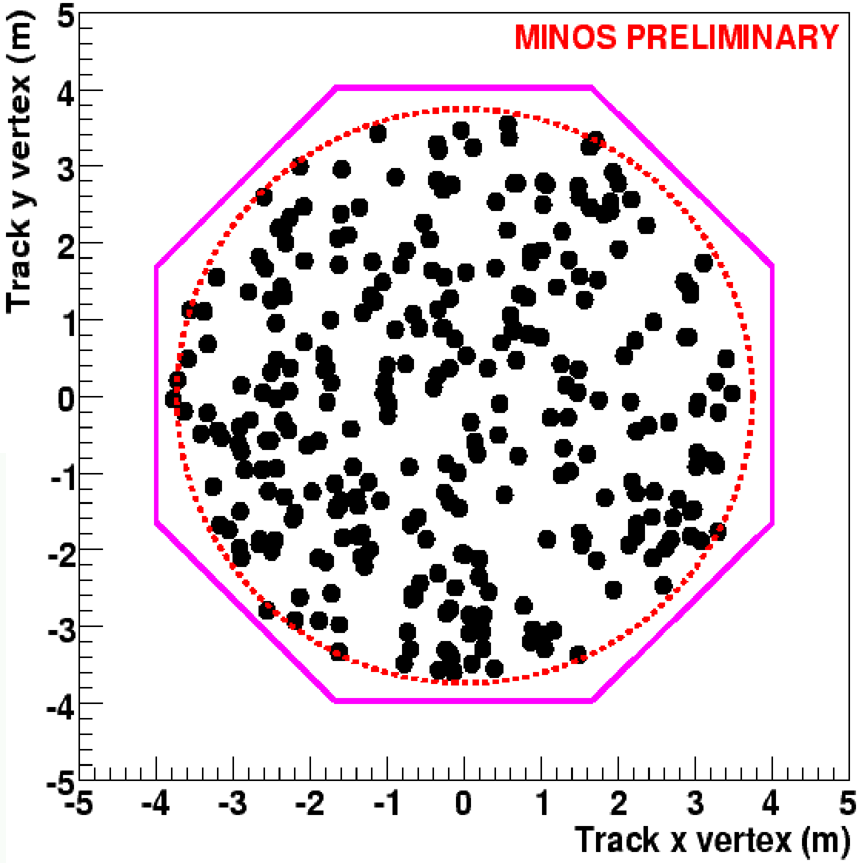
- event time consistent with spill time
- no evidence for cosmic muon background, estimate from "fake" spills < 1.7 at 90% C.L.

FD data distributions

- 296 events with track selected in fiducial volume
- uniformly distributed over detector



Reconstructed track vertices of neutrino candidates



FD data selection

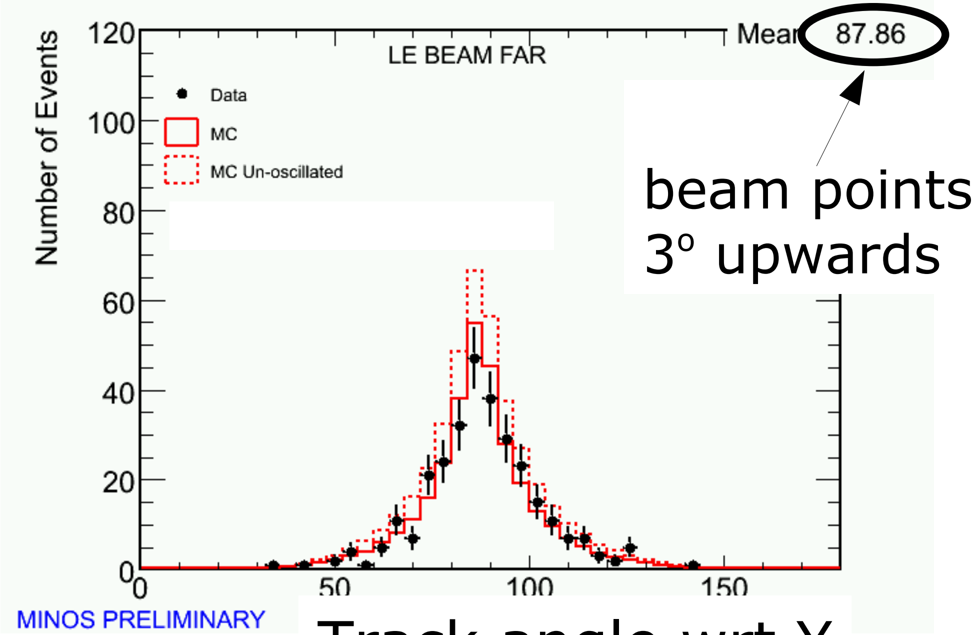
Cut	Events	Efficiency
all events in fid. vol.	331	-
at least one track	296	89.1%
track quality cuts	281	95.3%
PID cut (CC-like)	204	72.9%
negative track charge sign	186	91.2%
reconstr. energy < 30 GeV	166	89.2%

FD Observed vs. Expected

Data sample	observed	expected	ratio	significance
all CC events ($\nu_\mu + \overline{\nu}_\mu$)	204	298±15	0.69	4.1σ
ν_μ only (<30 GeV)	166	249±14	0.67	4.0σ
ν_μ only (<10GeV)	92	177±11	0.52	5.0σ

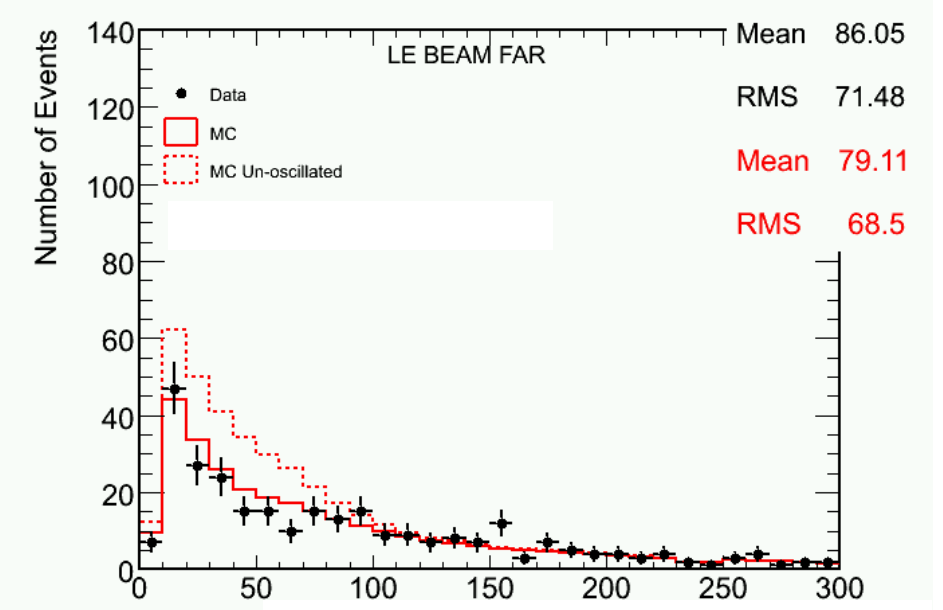
- Observe a 33% deficit between 0 and 30 GeV with respect to no disappearance hypothesis
- Statistical significance is 5 standard deviations

FD Data Distributions

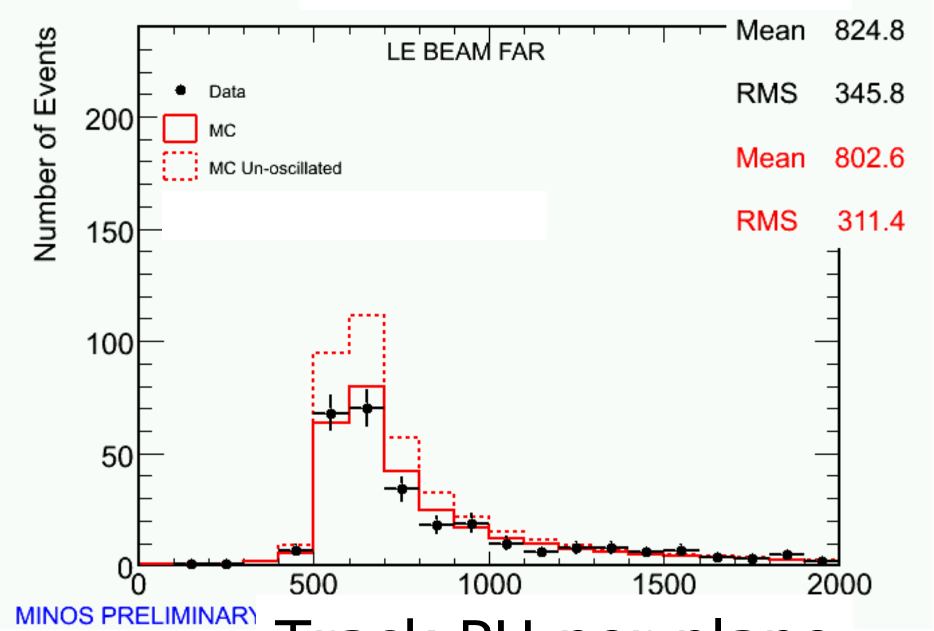


beam points 3° upwards

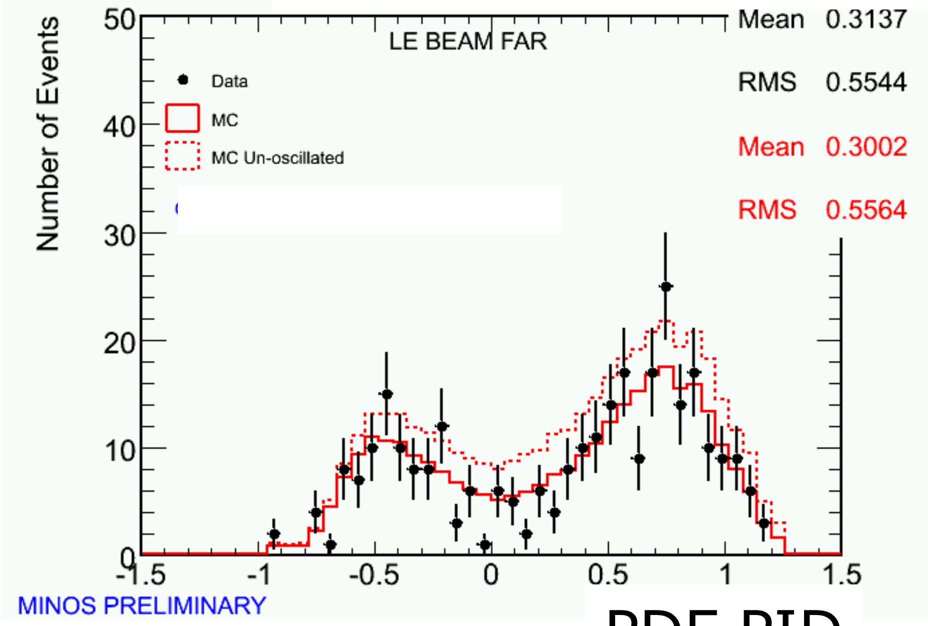
Track angle wrt Y



Track length (planes)

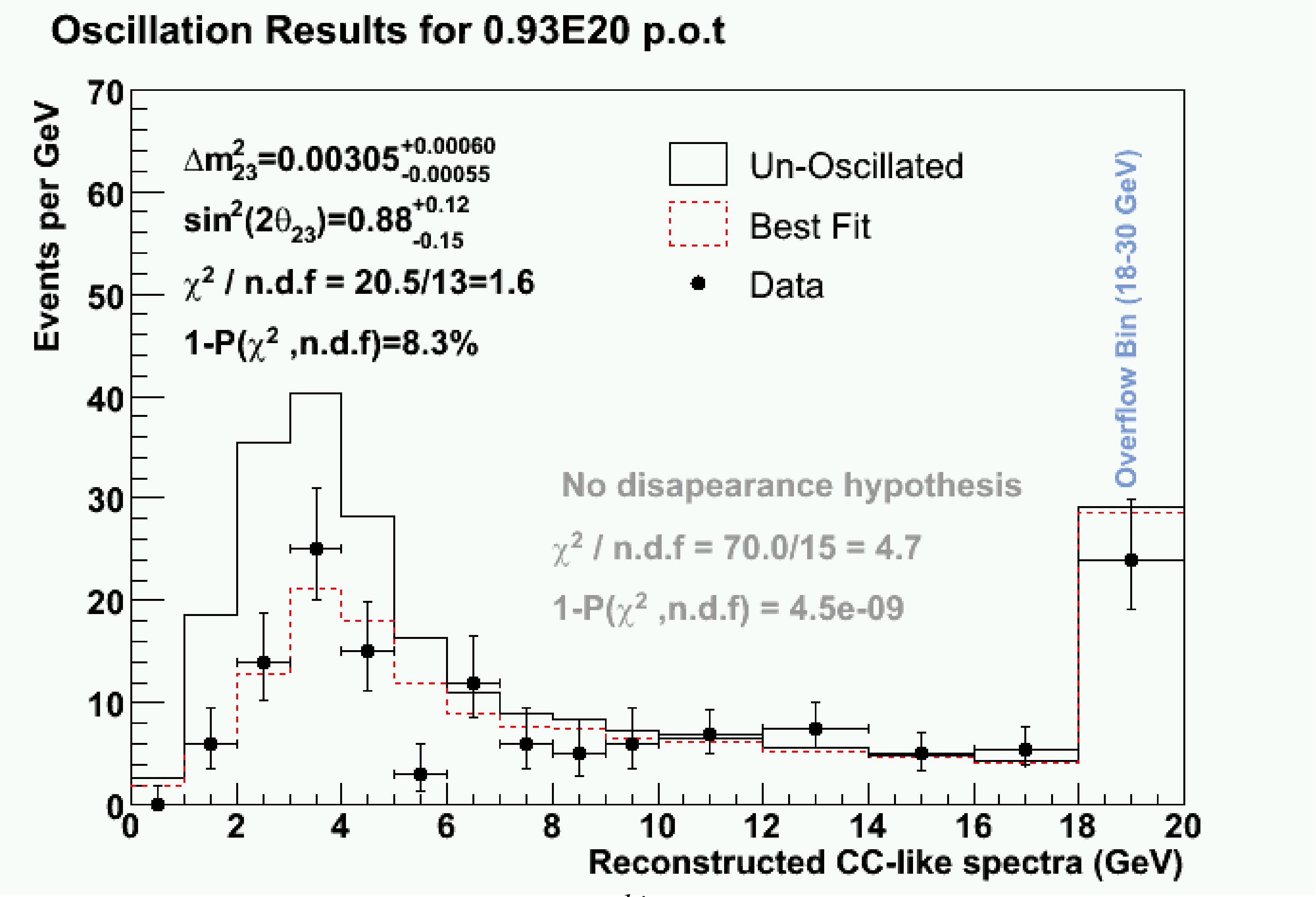


Track PH per plane



PDF PID

FD spectrum & fit



$$\chi^2(\Delta m^2, \sin^2 2\theta_{23}) = \sum_{i=1}^{nbins} 2(e_i - o_i) + 2 o_i \ln(o_i / e_i)$$

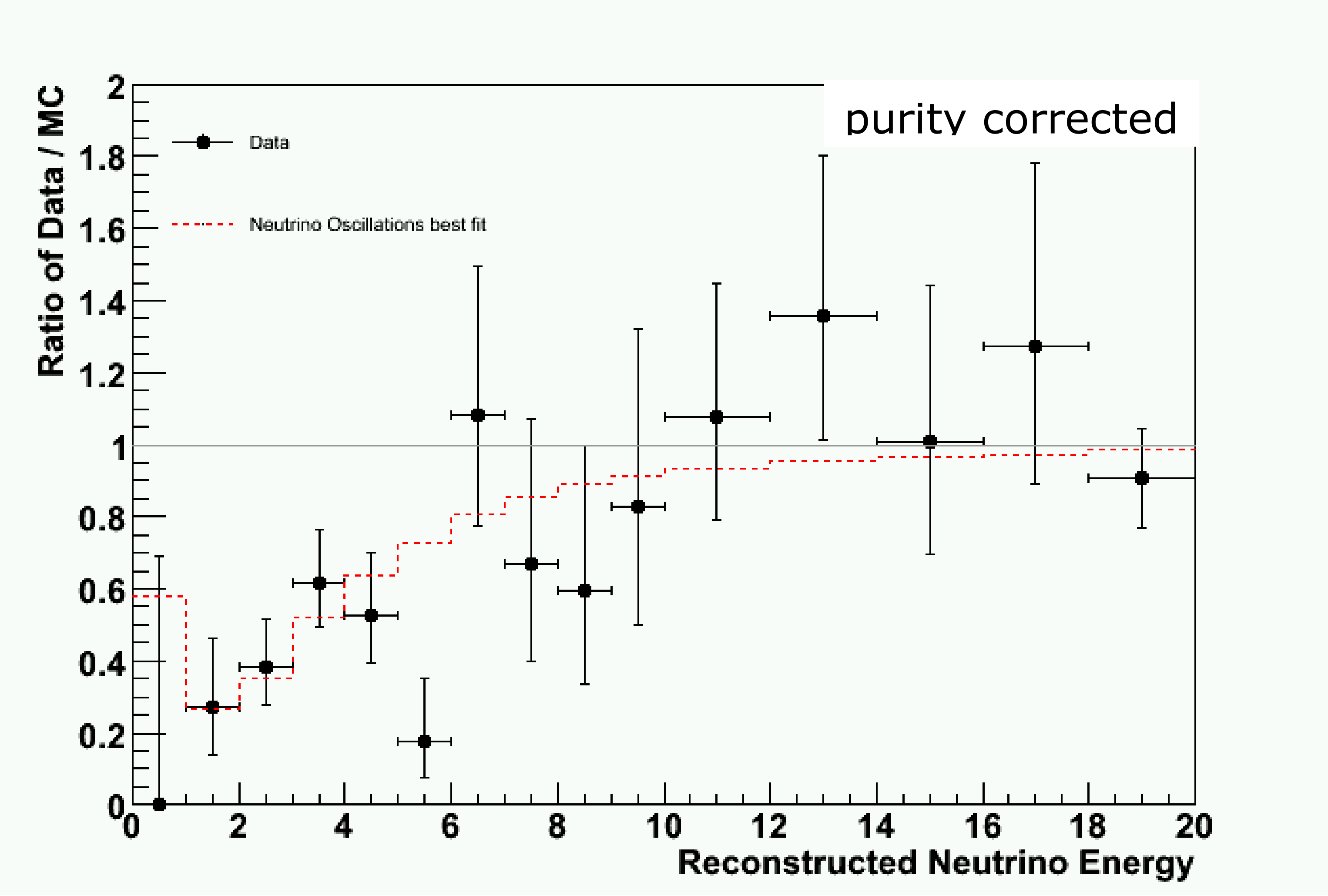
Mark Dierckxsens

Ratio Data/MC

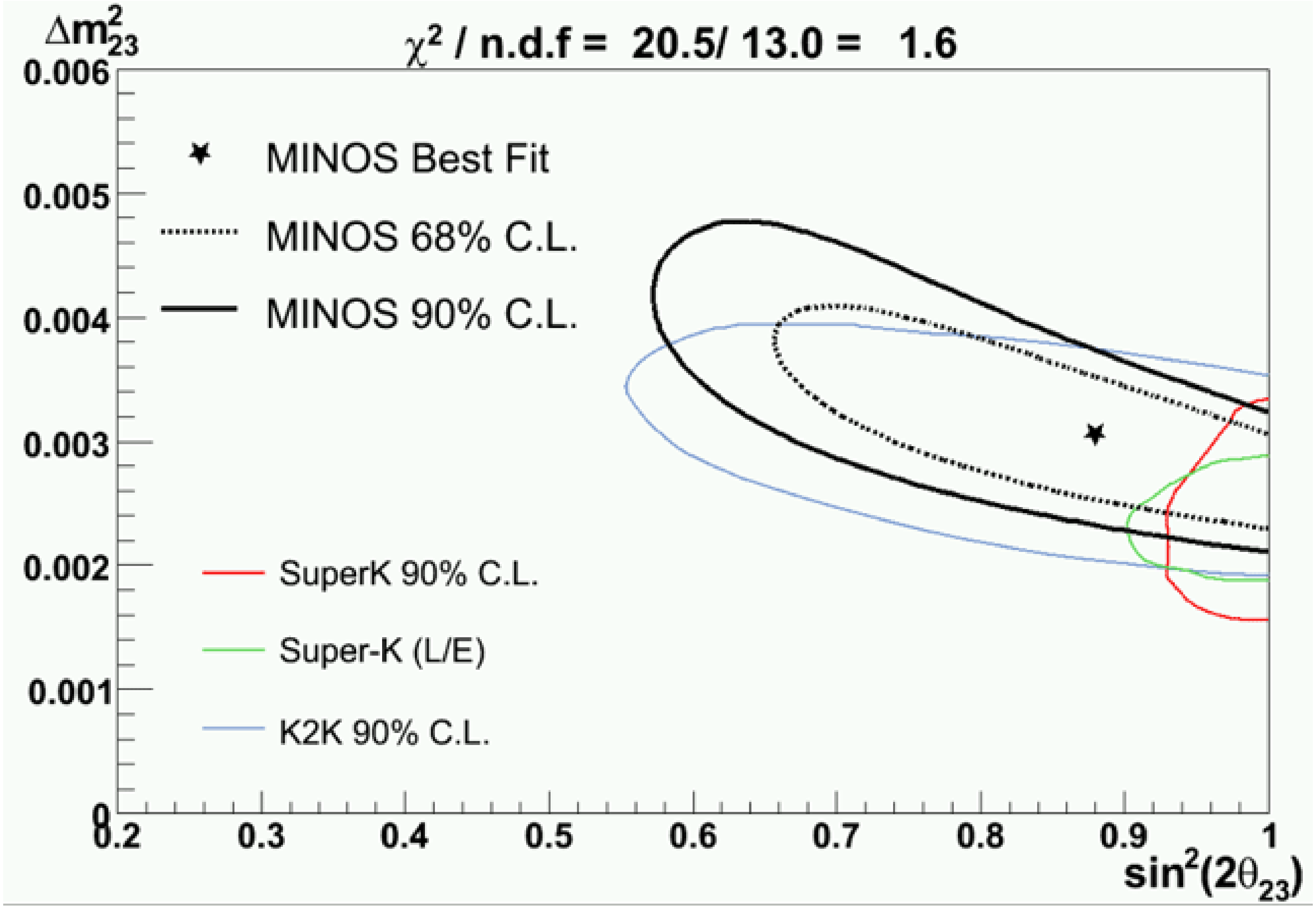
Fit result (68% C.L.):

$$\Delta m_{32}^2 = 3.05^{+0.60}_{-0.55} \cdot 10^{-3}\, eV^2$$

$$\sin^2 2\theta_{23} = 0.88^{+0.12}_{-0.15}$$



Comparison of fit results



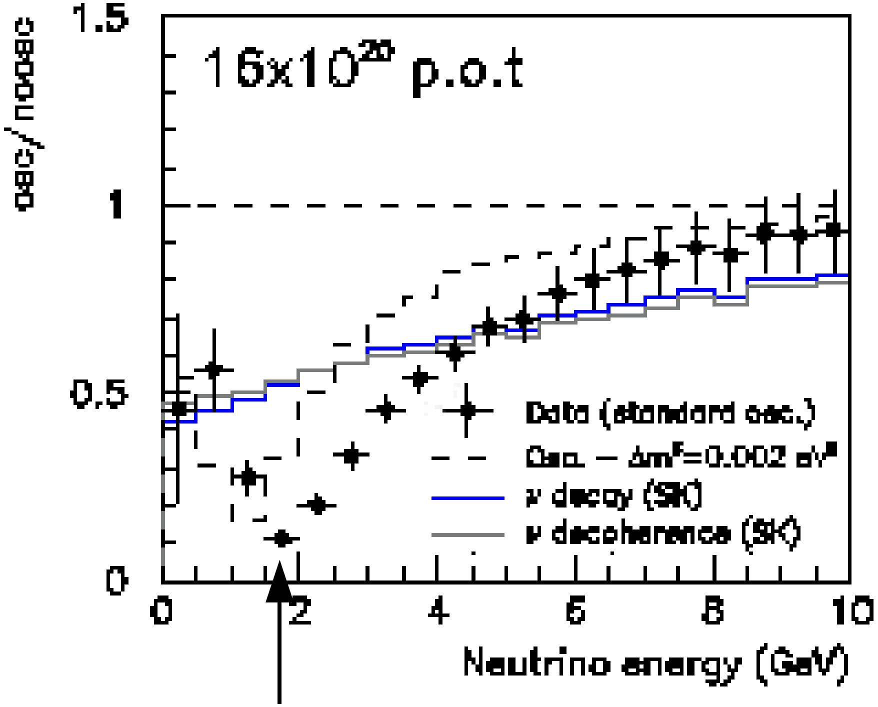
Systematic Uncertainties

uncertainty	Δm_{32}^2 (10^{-4} eV^2)	$\sin^2 2\theta_{23}$
normalization ±4%	0.63	0.025
muon energy scale ±2%	0.14	0.020
rel. shower energy scale ±3%	0.27	0.020
NC contamination ±30%	0.77	0.035
CC cross section uncertainty	0.50	0.016
beam uncertainties	0.13	0.012
intra-nuclear rescattering	0.27	0.030
total systematic uncertainty	1.19	0.063
statistical uncertainty	5.80	0.150

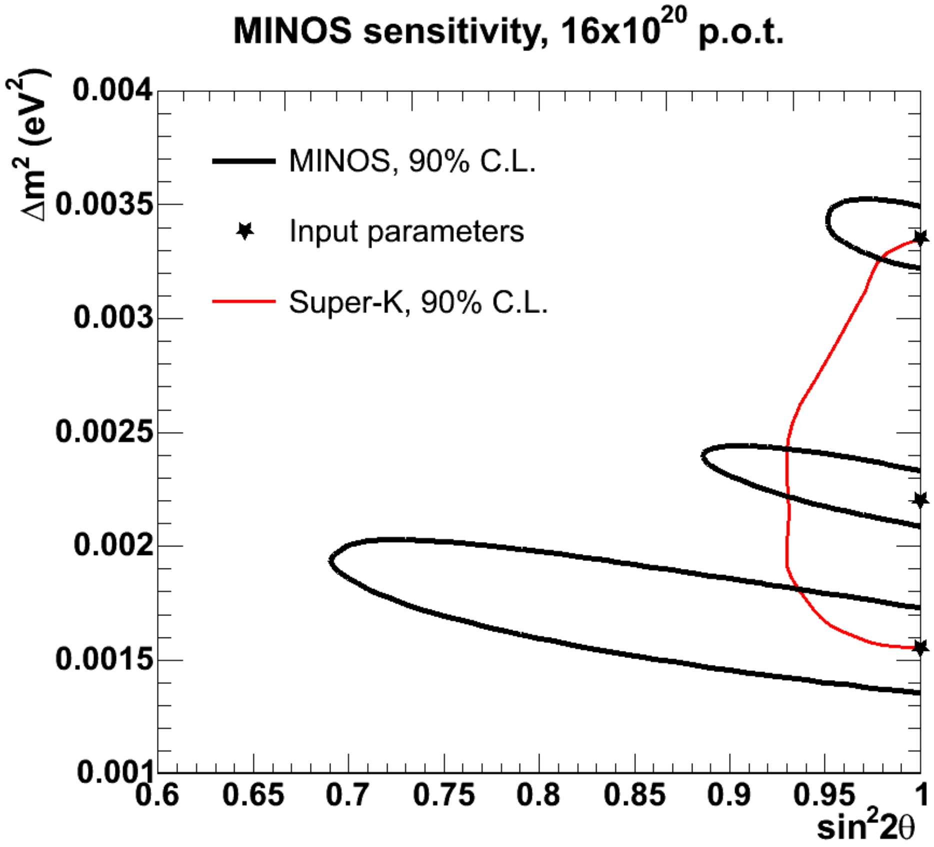
Physics Reach

ν_μ disappearance

- Projected spectrum and sensitivity for 16×10^{10} PoT (~5 years)



$\Delta m^2=0.0030$ eV^2



Physics Reach

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Search for $\nu_\mu \rightarrow \nu_e$

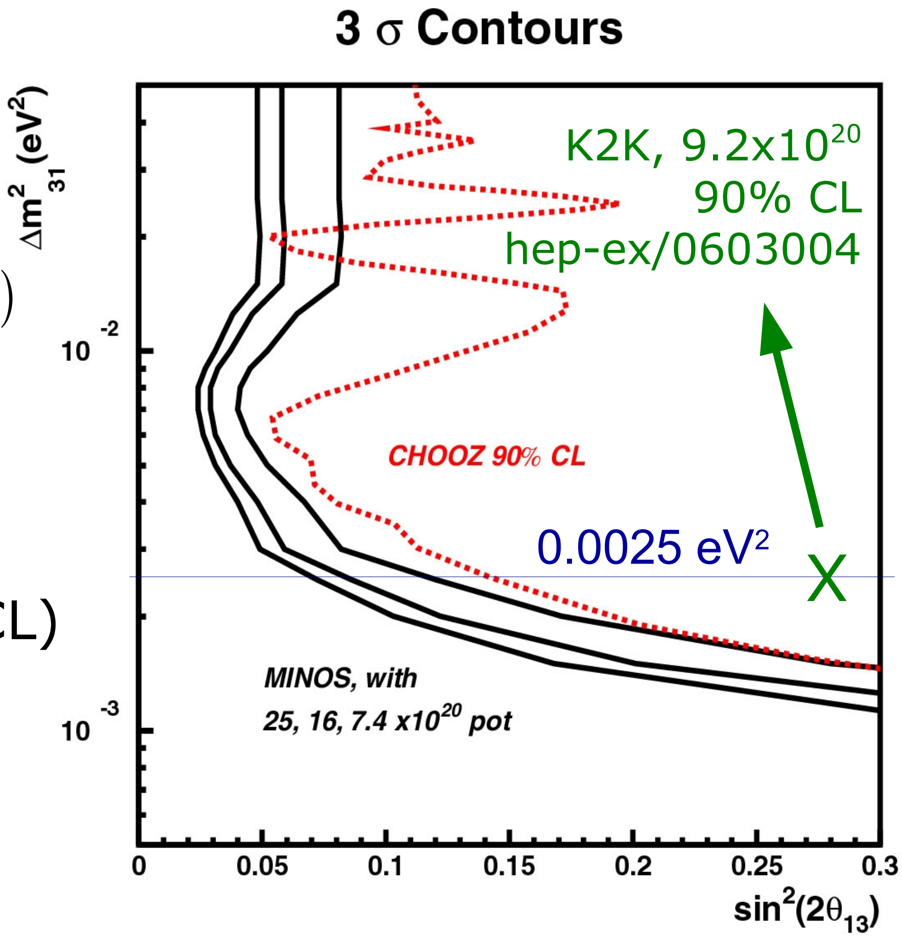
$$P(\nu_\mu \rightarrow \nu_e) = \sin^2\theta_{23}\sin^2 2\theta_{13}\sin^2(1.27\,\Delta m^2_{31}\frac{L}{E})$$

$$(\Delta m^2_{21} \ll \Delta m^2_{32} \simeq \Delta m^2_{31})$$

3 years: $\sin^2 2\theta_{13} < 0.12$

5 years: $\sin^2 2\theta_{13} < 0.09$

(90% CL)



Other physics

- atmospheric neutrinos: $\nu \leftrightarrow \text{anti-}\nu$
  hep-ex/0512036, accepted Phys. Rev. D
- neutrino cross sections, neutral current (sterile), anti-neutrinos, cosmic muons,...

Conclusions

- MINOS has performed a preliminary oscillation analysis using 0.93×10^{20} protons-on-target
- No-disappearance hypothesis excluded at 5σ level
- Oscillation fit results consistent with SuperK and K2K:

$$\Delta m_{32}^2 = 3.05^{+0.60}_{-0.55}(stat) \pm 0.12(syst) \cdot 10^{-3} eV^2$$

$$\sin^2 2\theta_{23} = 0.88^{+0.12}_{-0.15}(stat) \pm 0.06(syst)$$

- We have 40% more data waiting to be analyzed and we will start taking data again in June

Backup slides

Event Generator

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

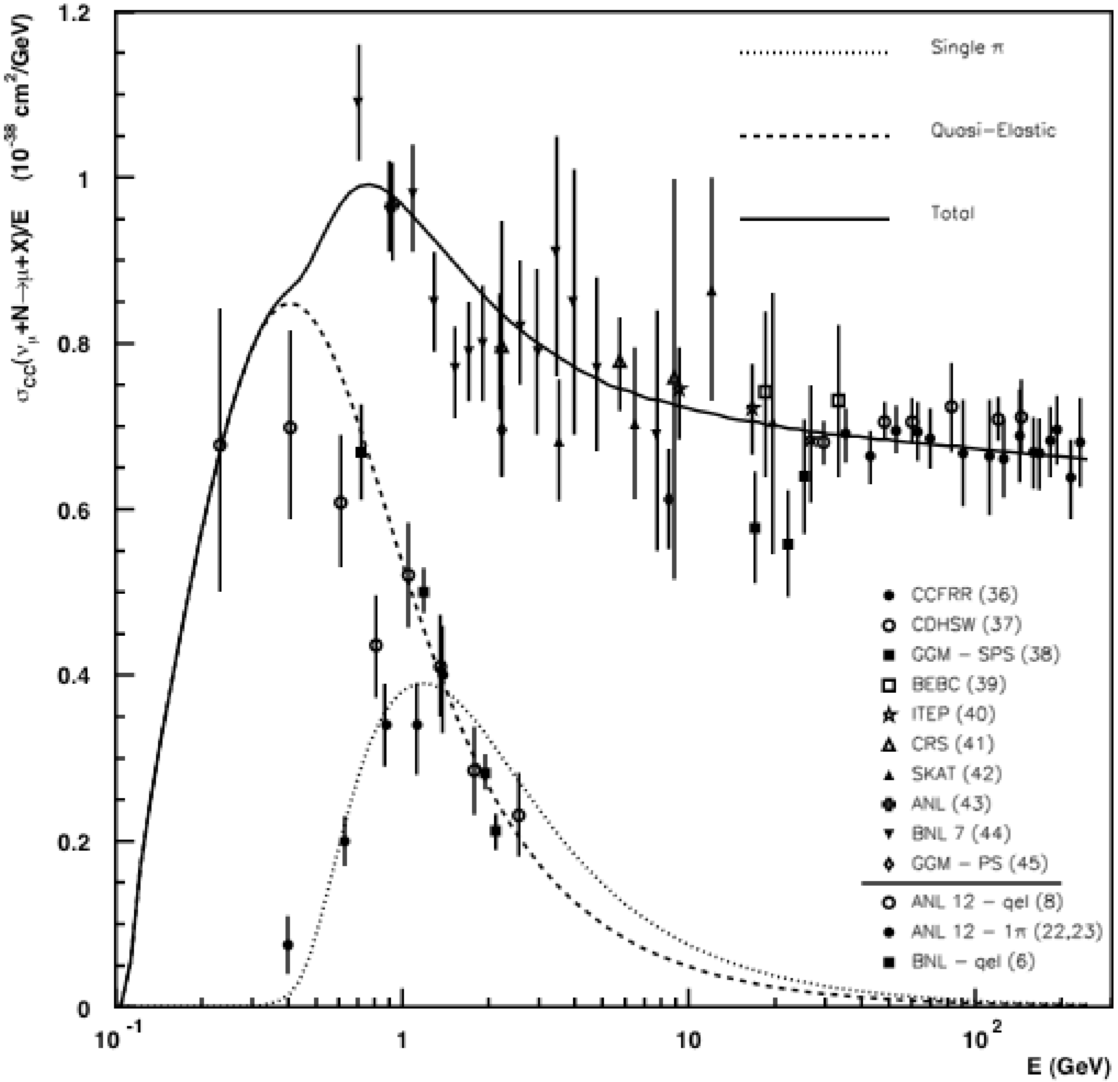
Quasi-Elastic: dipole param. of form factors with m_a=1.032 GeV/c^2.

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

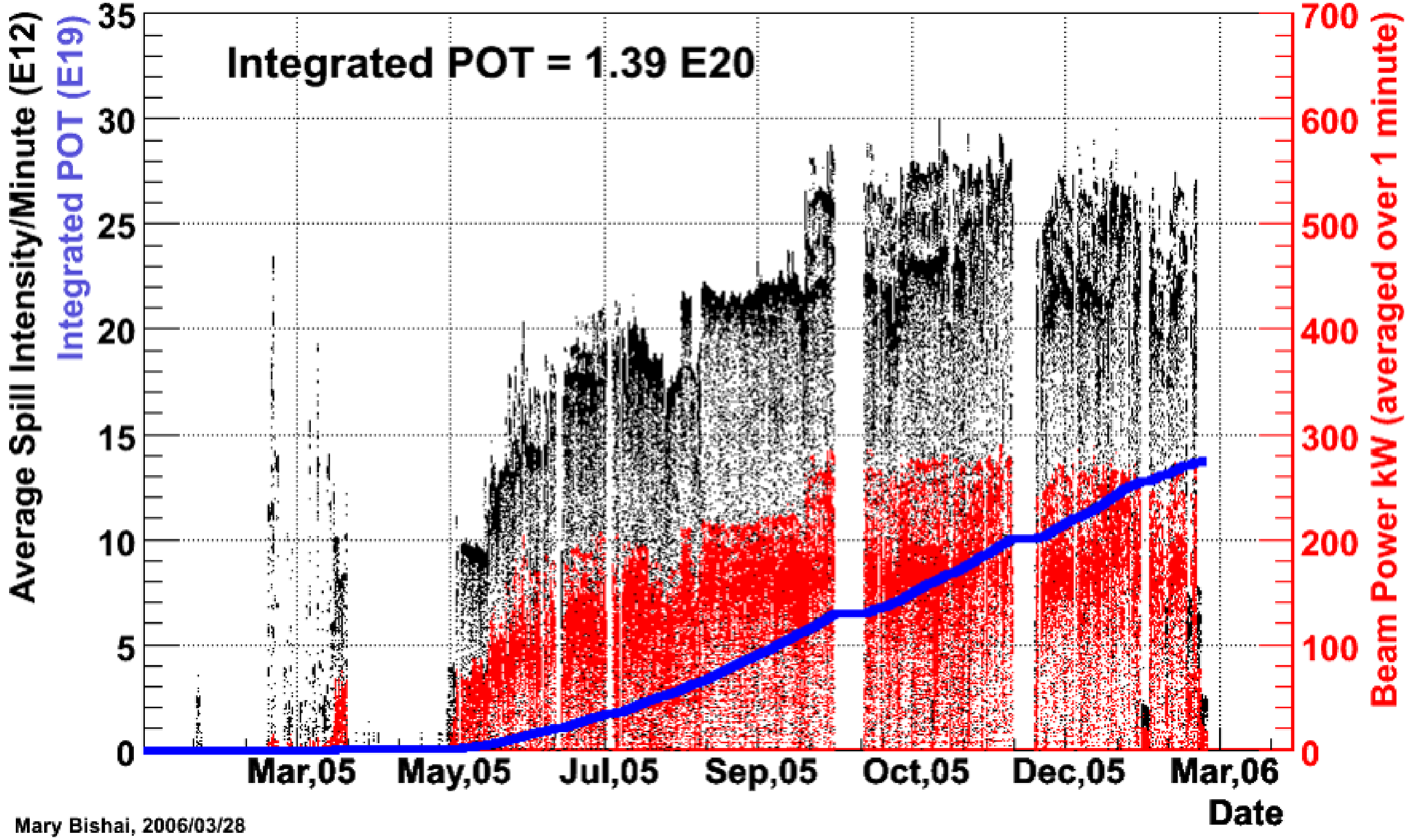
DIS: Bodek-Yang modified LO model.

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)



First year NuMi running



Mary Bishai, 2006/03/28

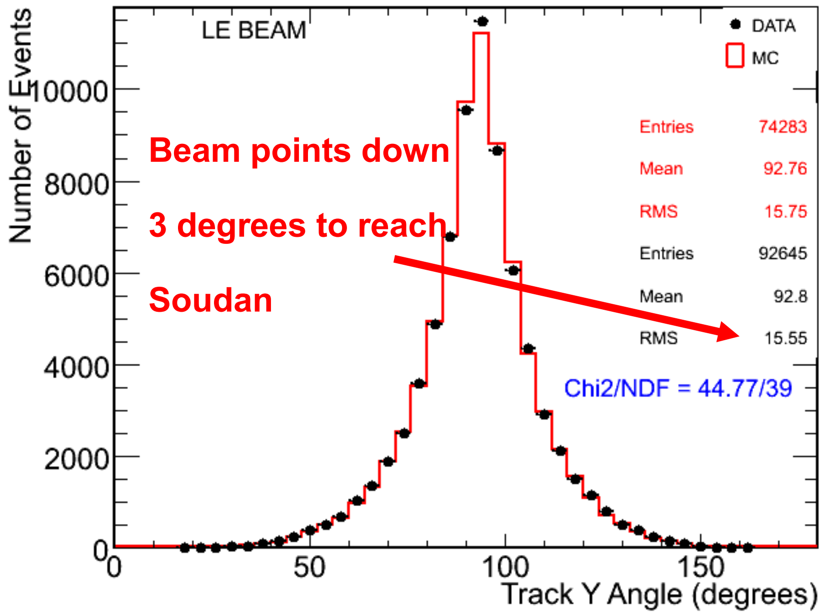
Averages from Oct 15- Jan 31:

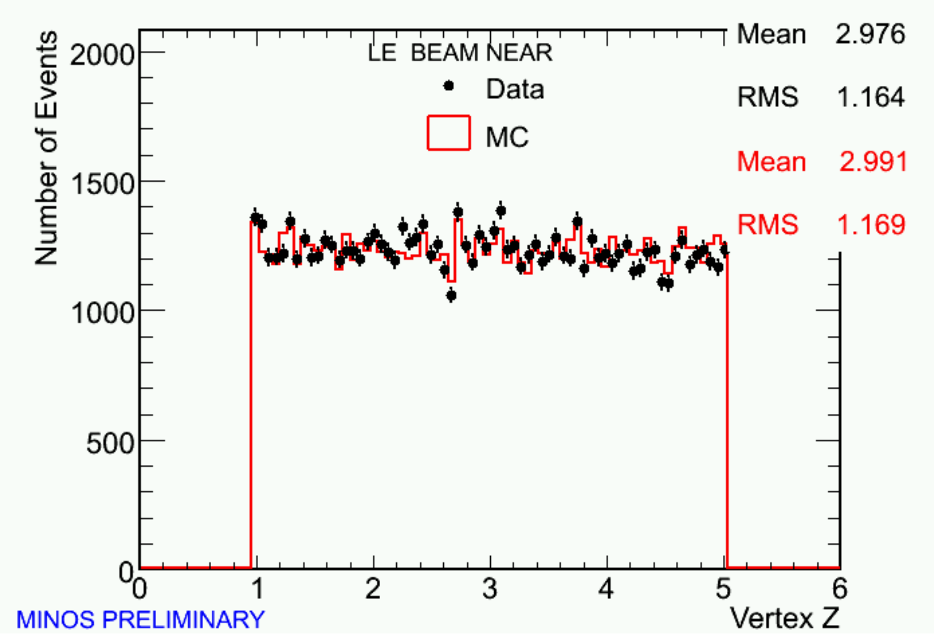
- ✓ power: 170 kW
- ✓ intensity: 2.3 1013 PoT/spill
- ✓ rep rate: 2.2s

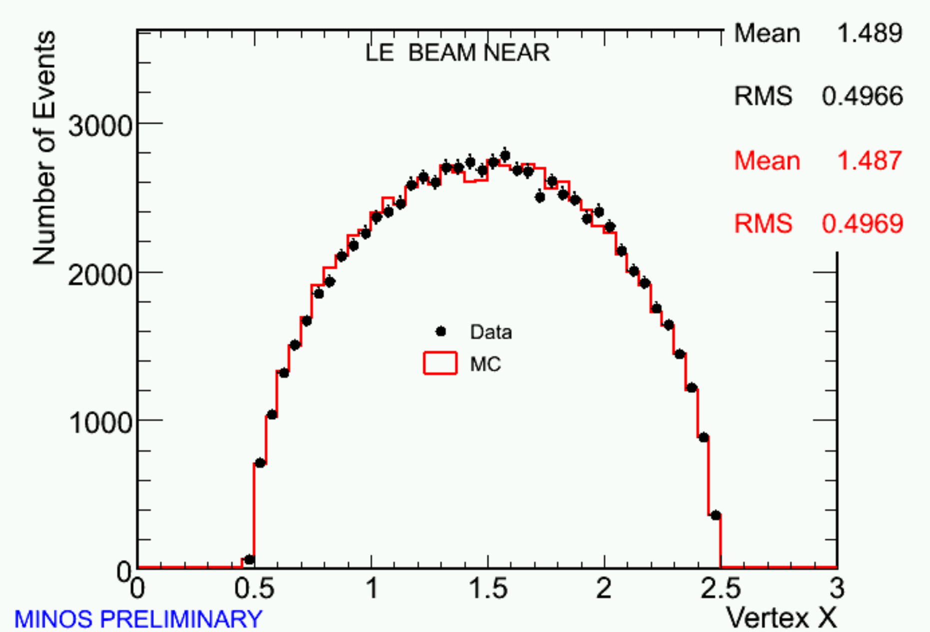
Records:

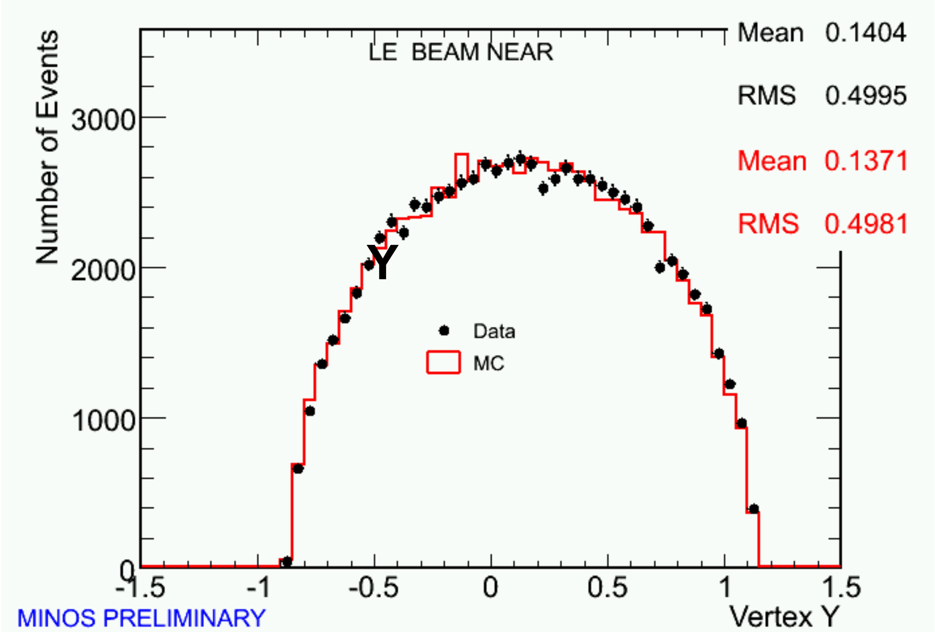
- ✓ power: 270 kW (30 min)
- ✓ intensity: 3.0 1013 PoT

ND distributions

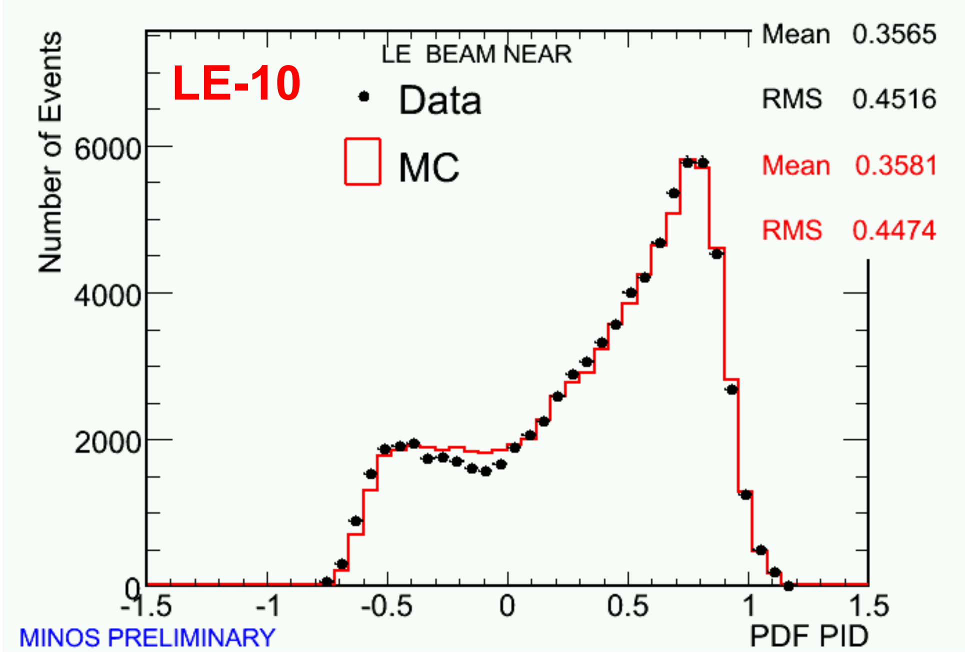

Beam points down 3 degrees to reach Soudan

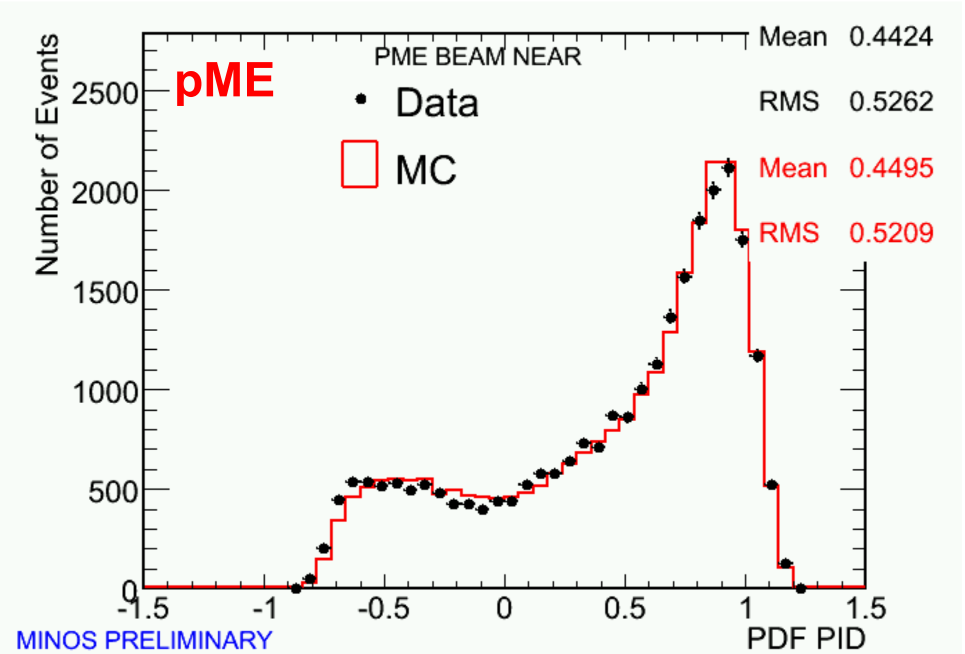


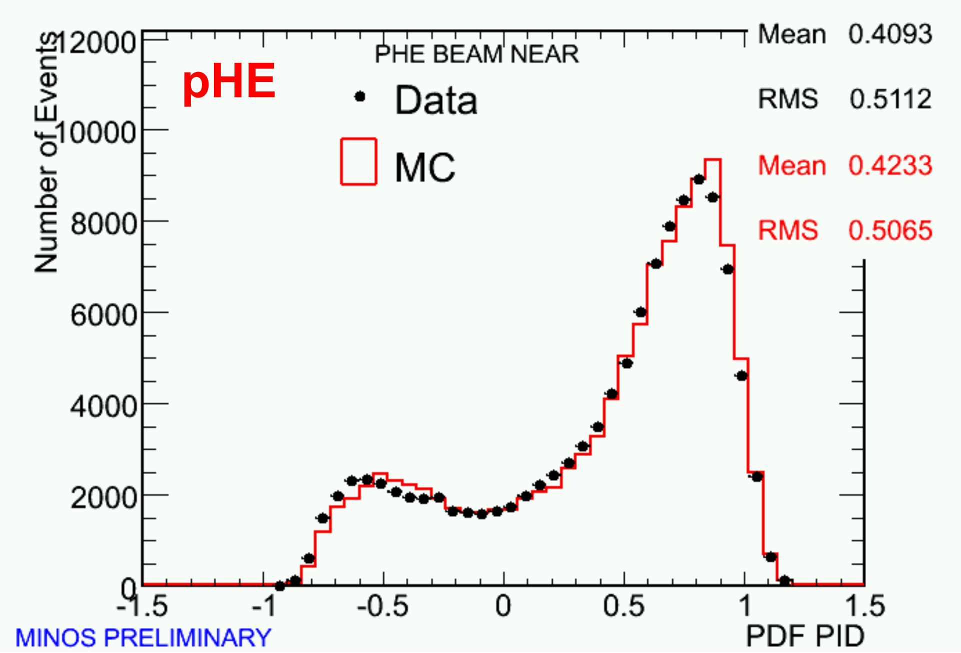




ND PID Distributions







PID cut to select CC-like events is at –0.1

ND spectra

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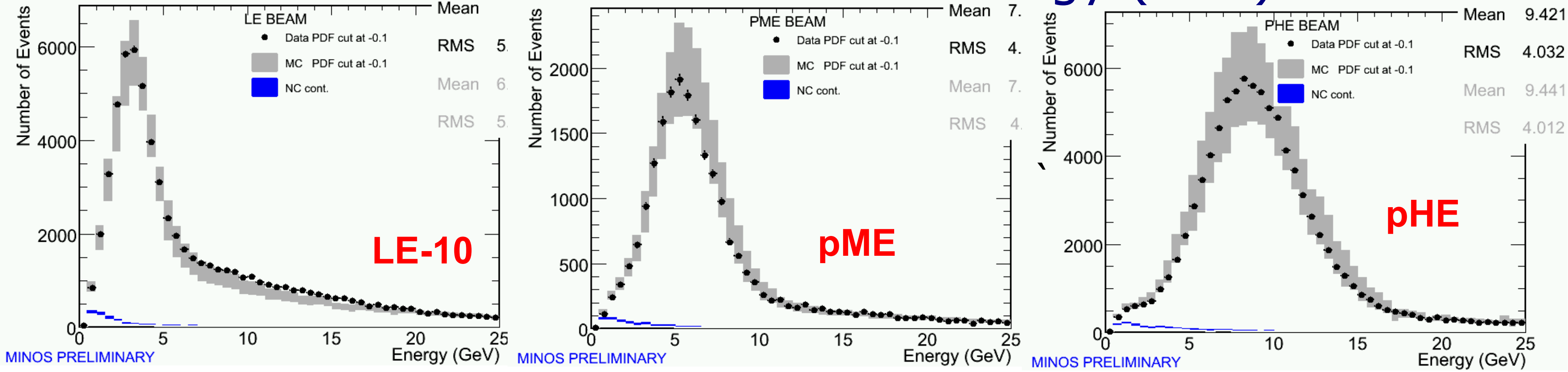
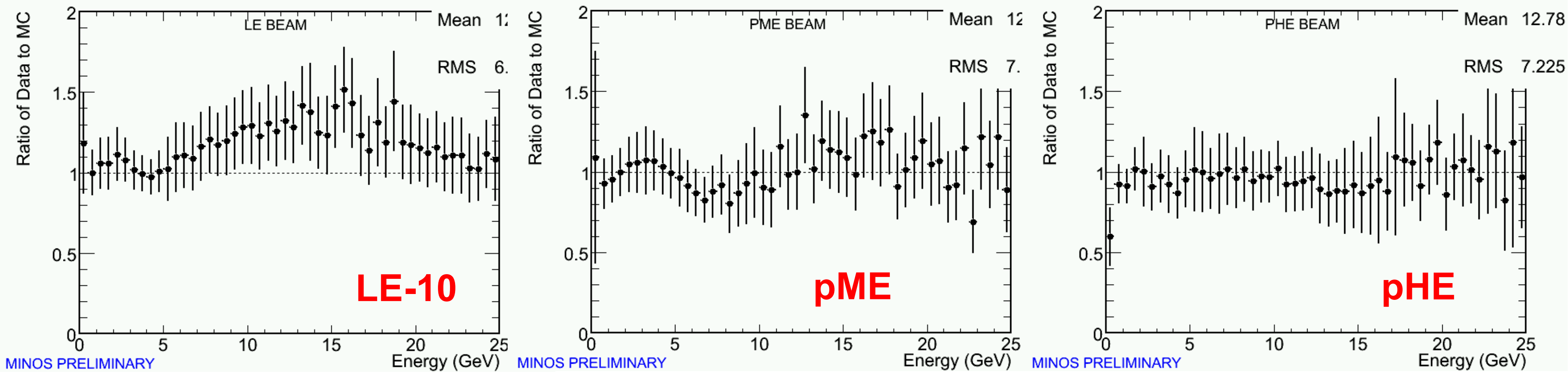
Reconstructed Event Energy (GeV)



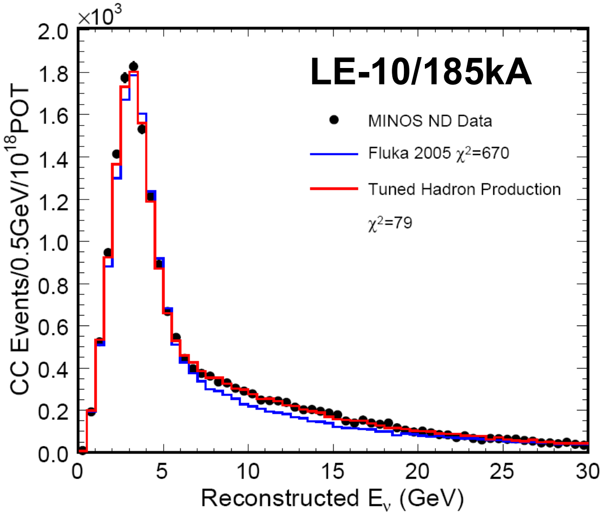
Ratios of Data/MC

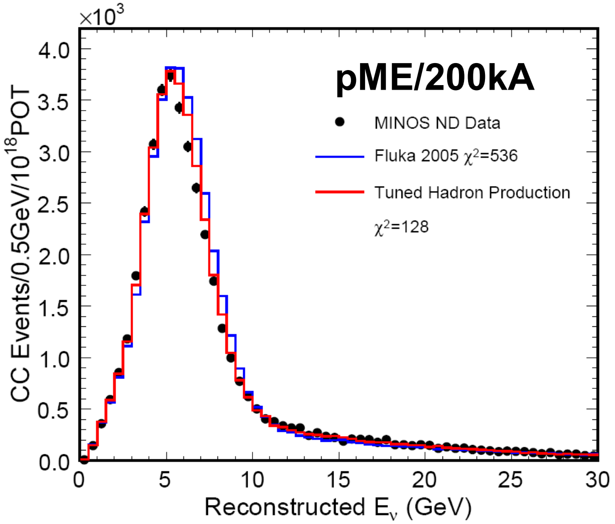


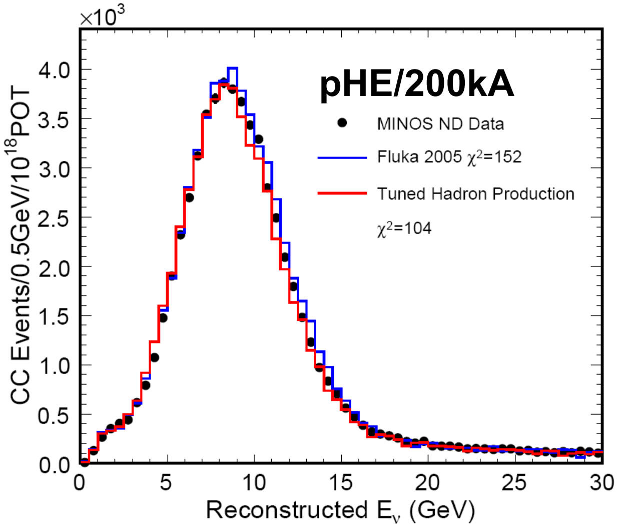
Error envelopes shown reflect uncertainties due to cross-section modelling, beam modelling and calibration uncertainties

Hadron production tuning

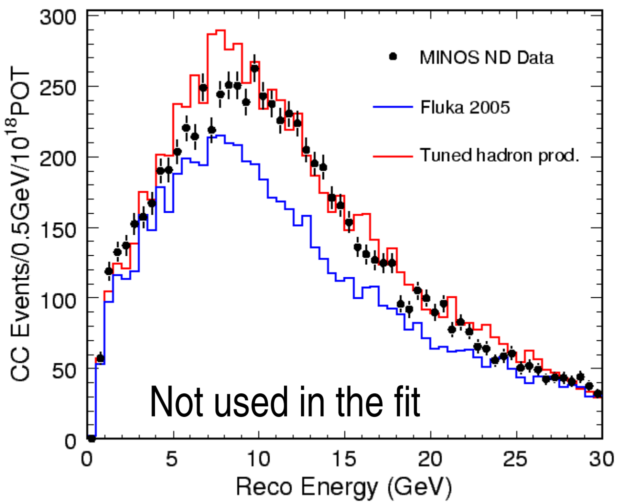
Good agreement data - Fluka05 Beam MC is, tuning MC by fitting to hadronic x_F and p_T, improves agreement.

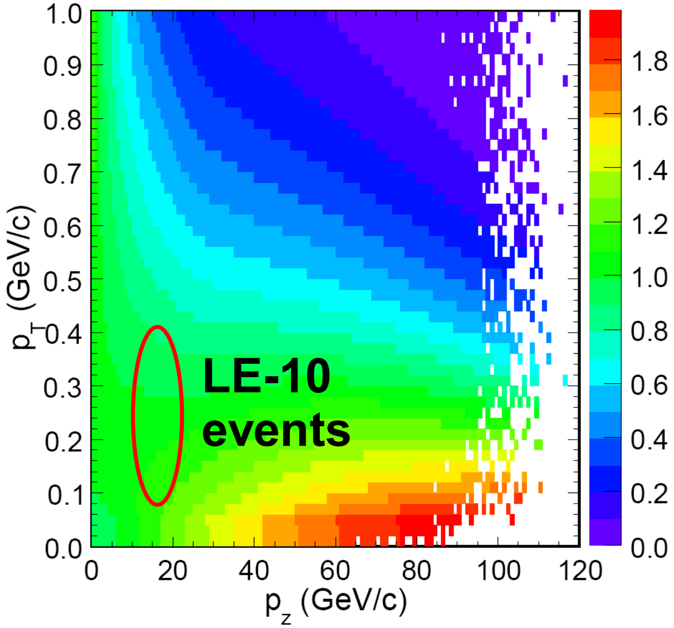






LE-10/Horns off

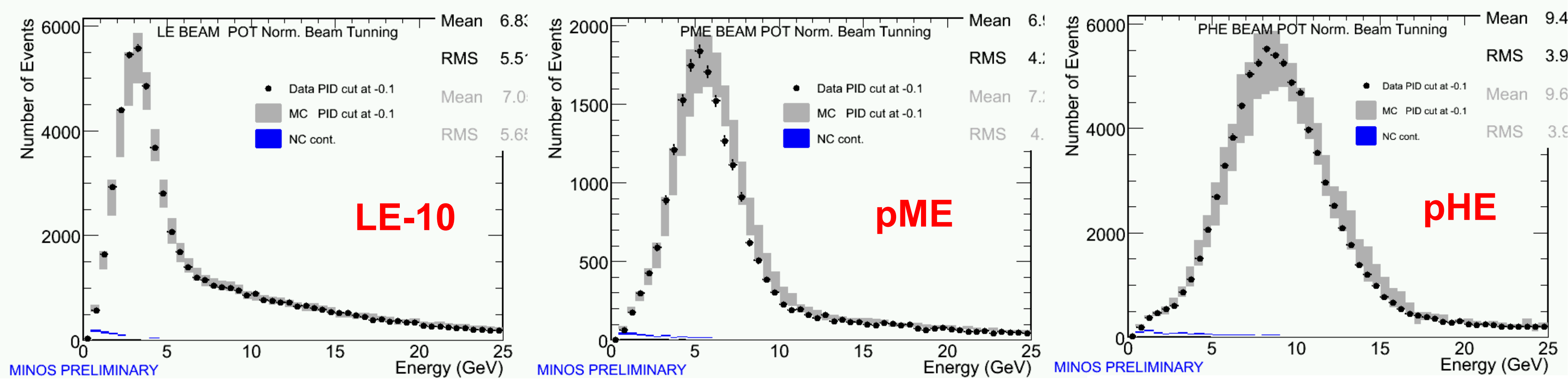




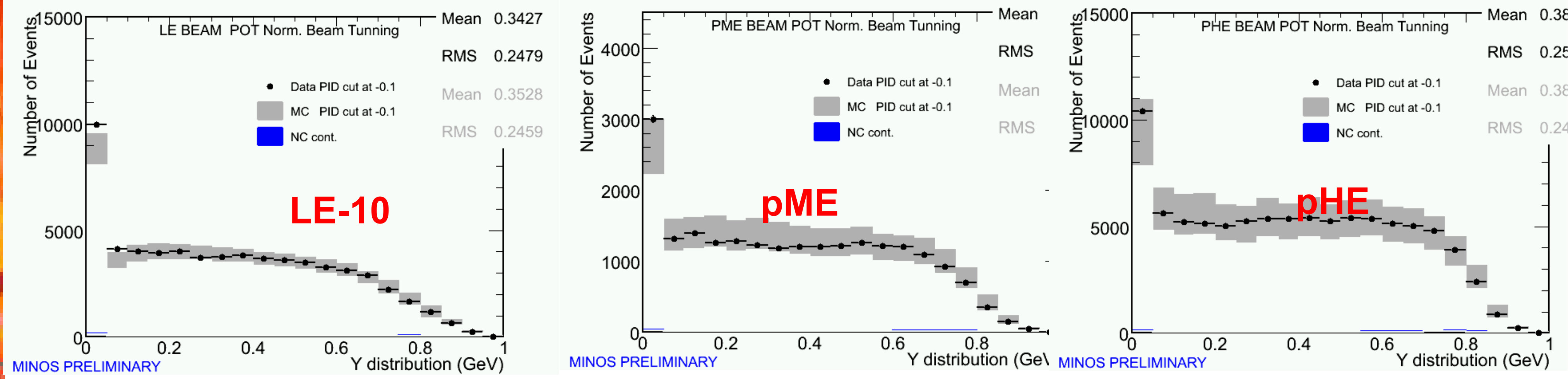
Weights applied as a function of hadronic x_F and p_T.

ND spectra & Y

Reconstructed Neutrino Energy (GeV)



Reconstructed Y $=E_{shw}/(E_{shw}+E_{\mu})$

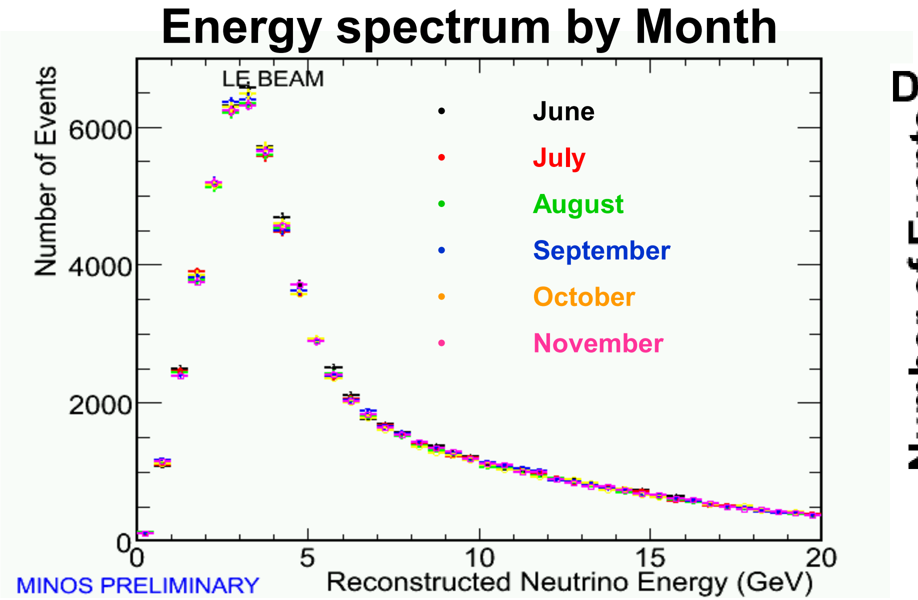


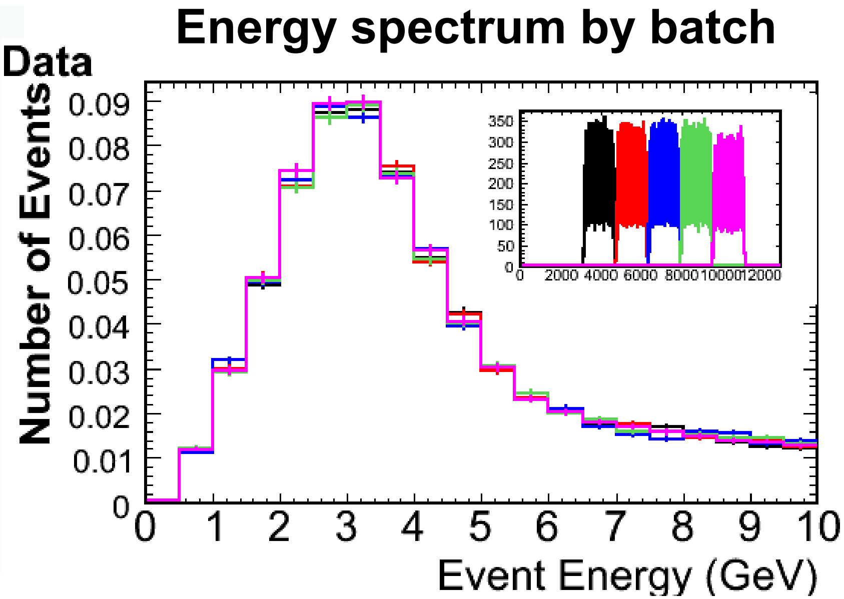
These distributions shown after x_F, p_T reweighting

Mark Dierckxsens

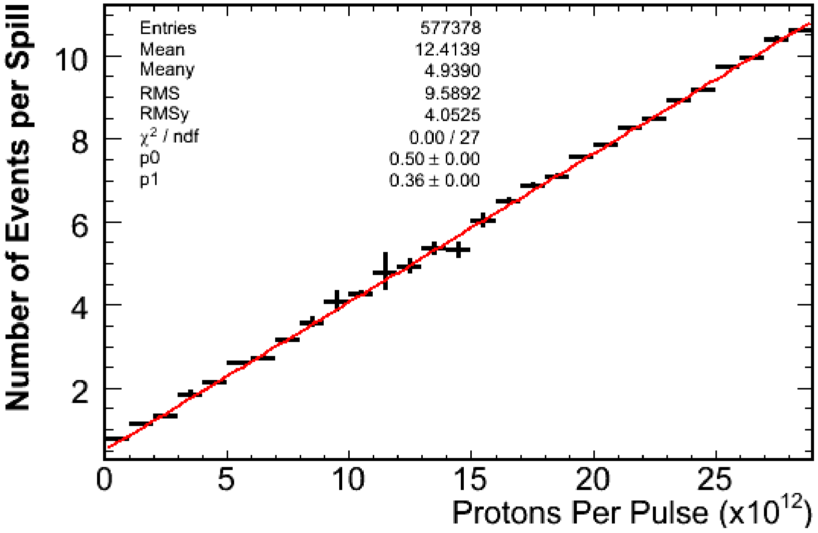
ND Spectrum Stability

- proton intensity ranges from 10^{13} ppp – $2.8\text{x}10^{13}$ ppp


Energy spectrum by Month


Energy spectrum by batch

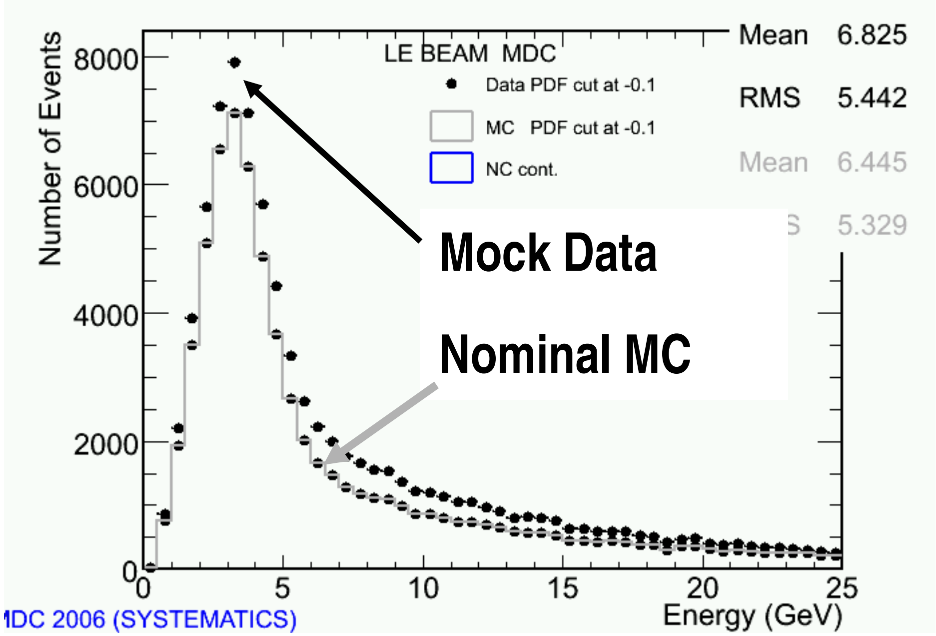
- Reconstructed energy distributions agree to within statistical uncertainties (~1-3%)
- Beam is very stable and there are no significant intensity-dependent biases in event reconstruction.

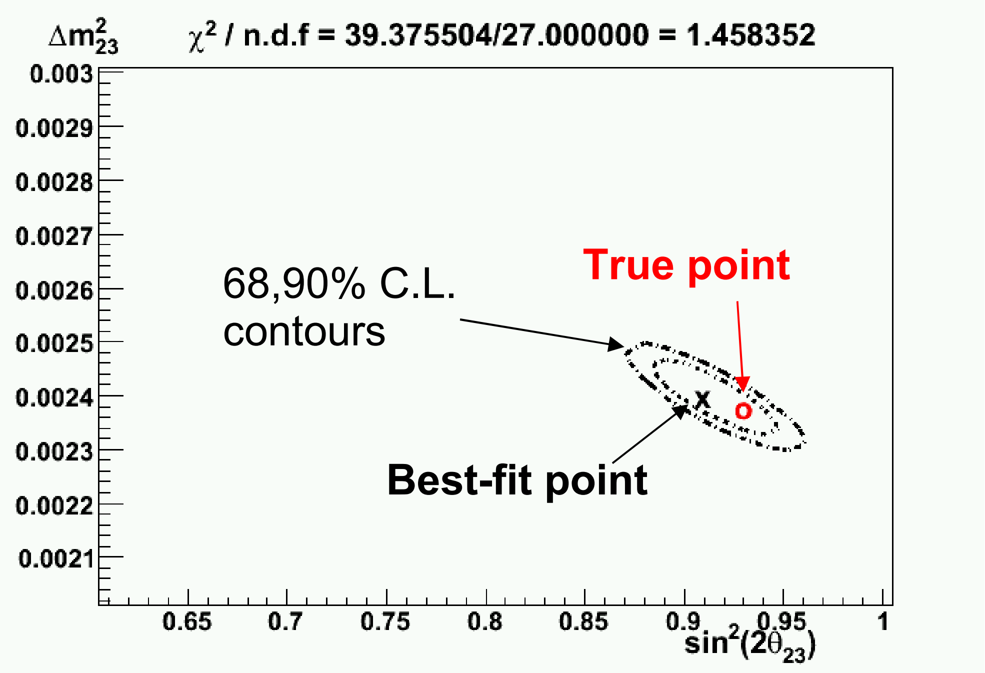


Mark Dierckxsens

Systematics

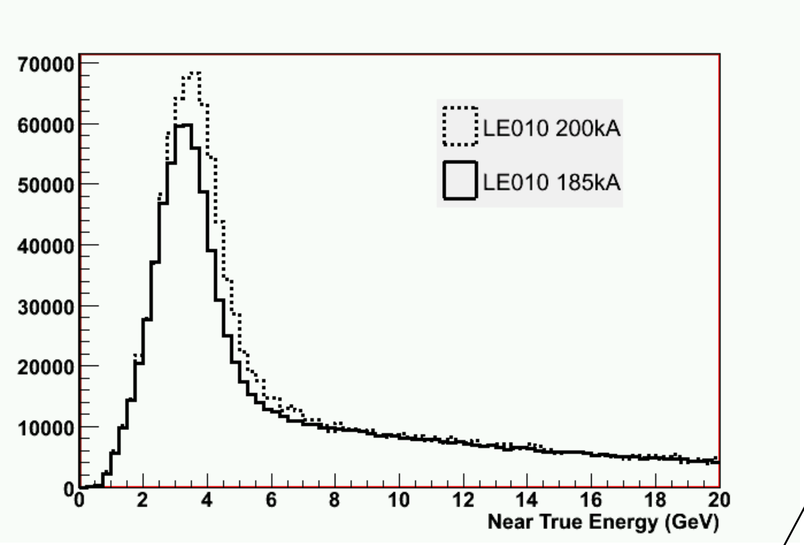
- test on 10^{22} PoT “Mock Data Chalange Set”
- fake dataset generated with tweaked beam/generator and unknown oscillation parameters





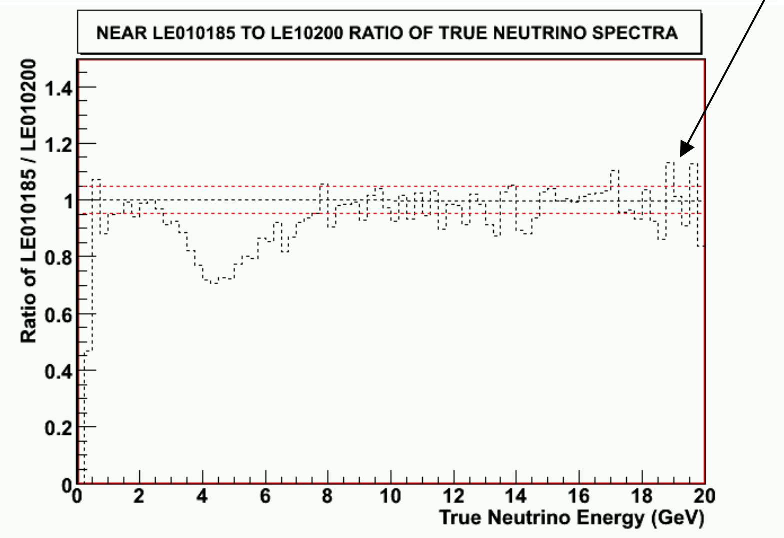
Beam Matrix Method yields to an accurate estimation of the oscillation parameters despite the large differences between “Mock Data” and Monte Carlo (even for 1E22 protons on target!)

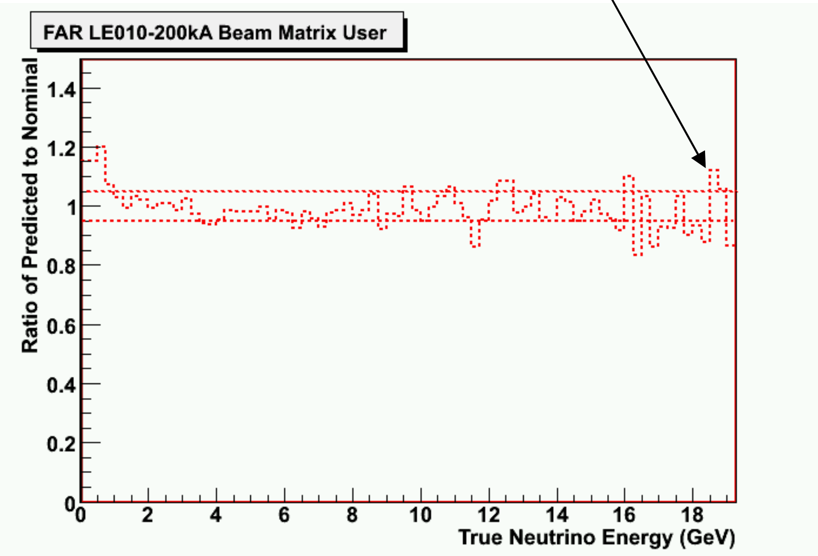
Systematics



- Use LE010 200kA matrix instead of LE10 185kA

NOTE :Red dotted bands are ± 5%.

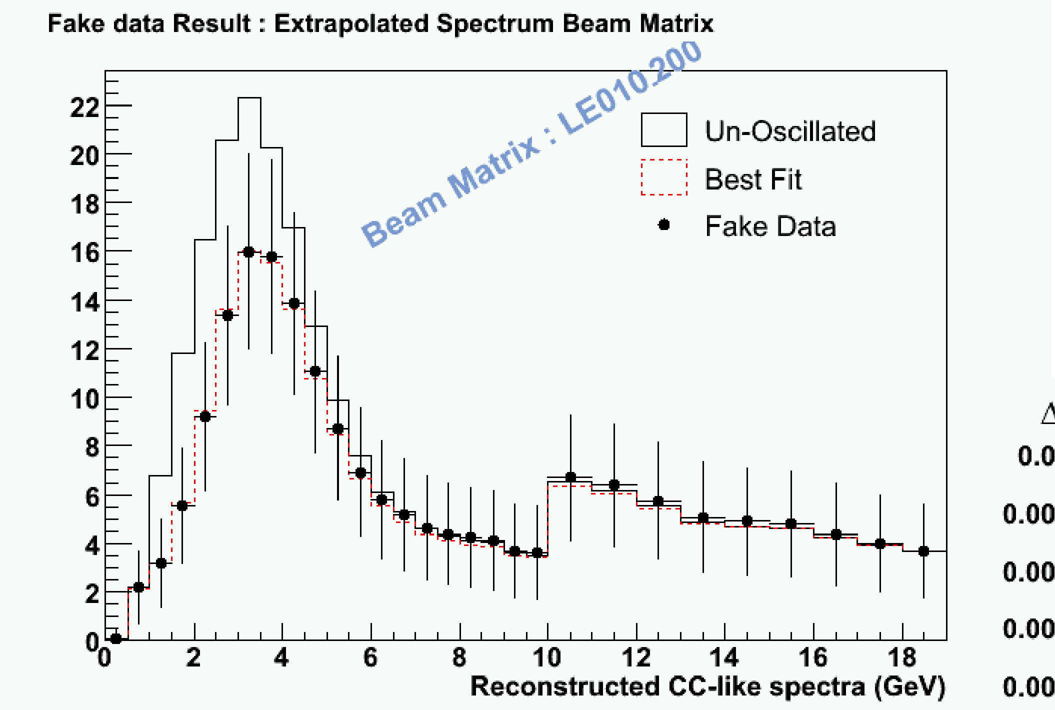


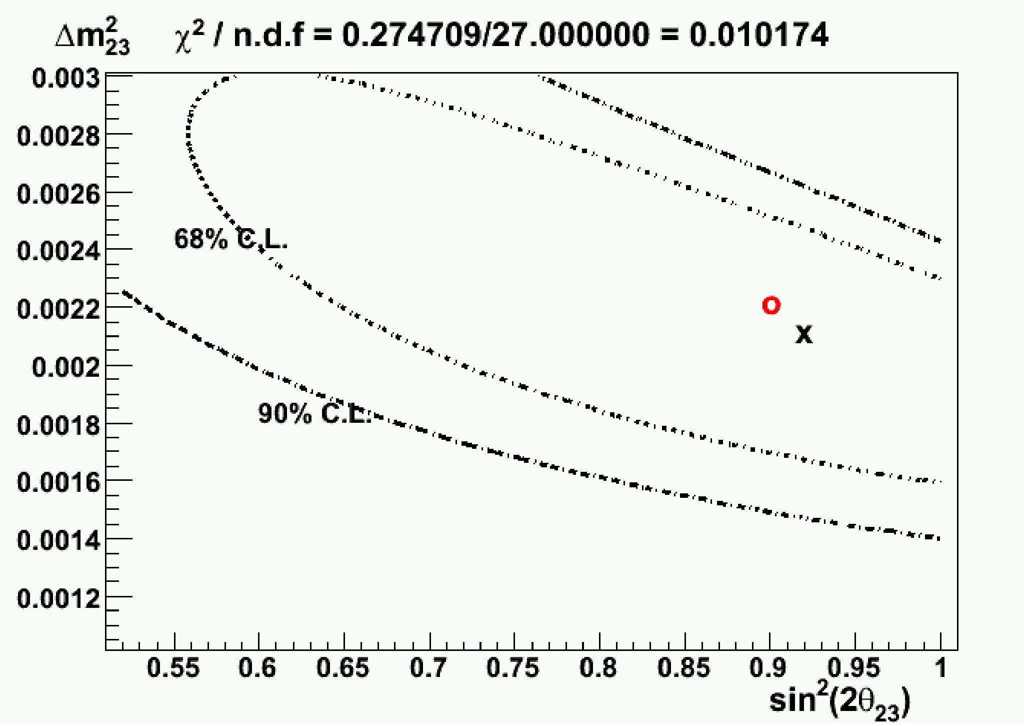


- The predicted FD spectrum is within 5% to the “actual” one.
- Beam Matrix Method quite robust to beam related uncertainties

Systematics

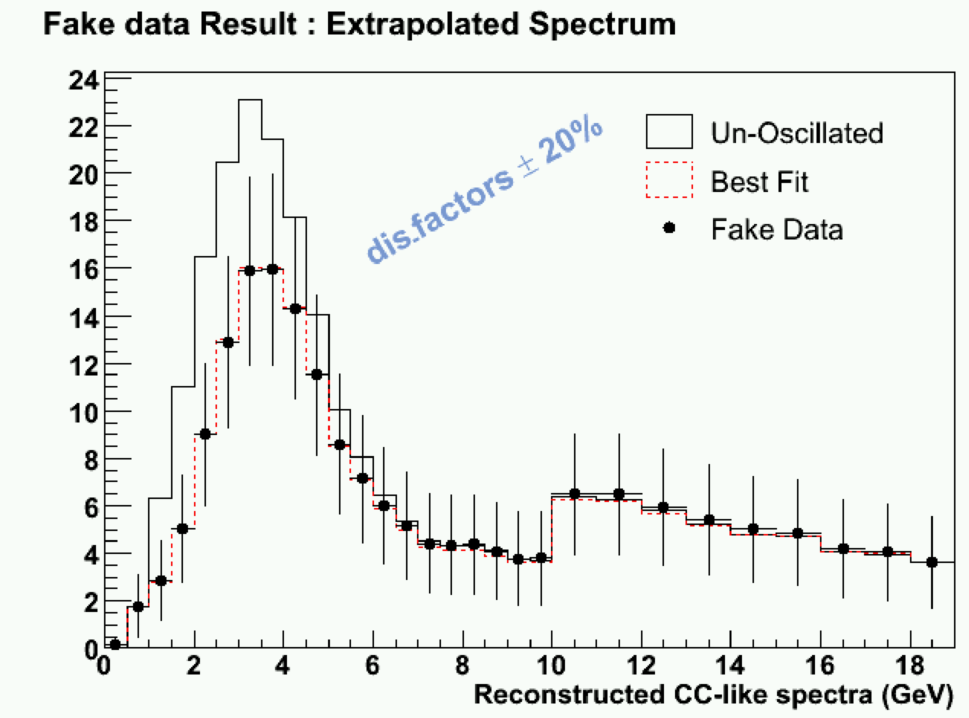
- Different beam matrix used for fit to fake data

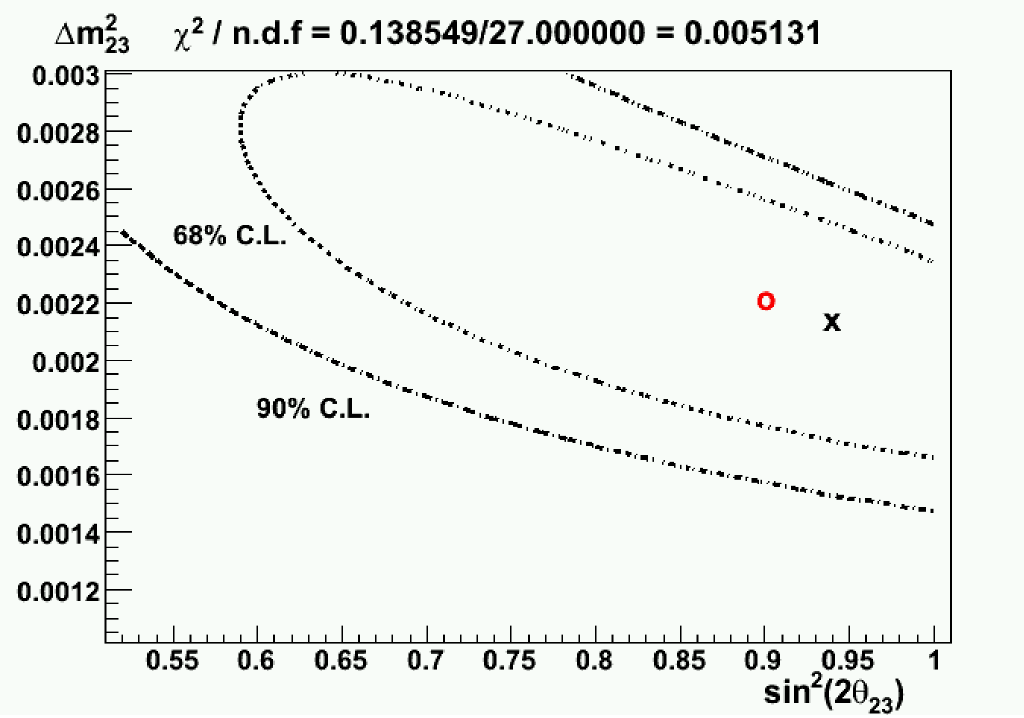




Systematics

- DIS cross section changed by 20% in fake data sample

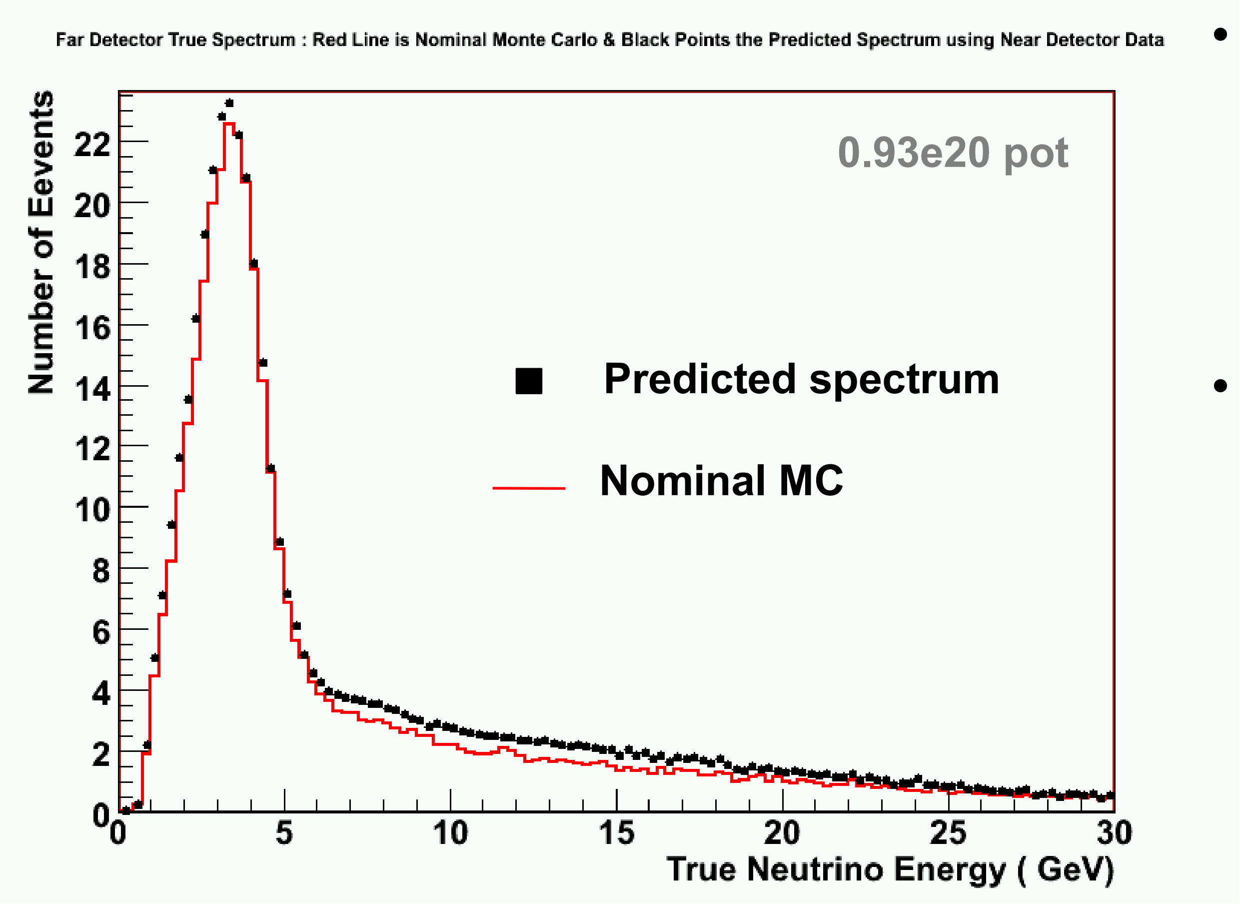




Systematics

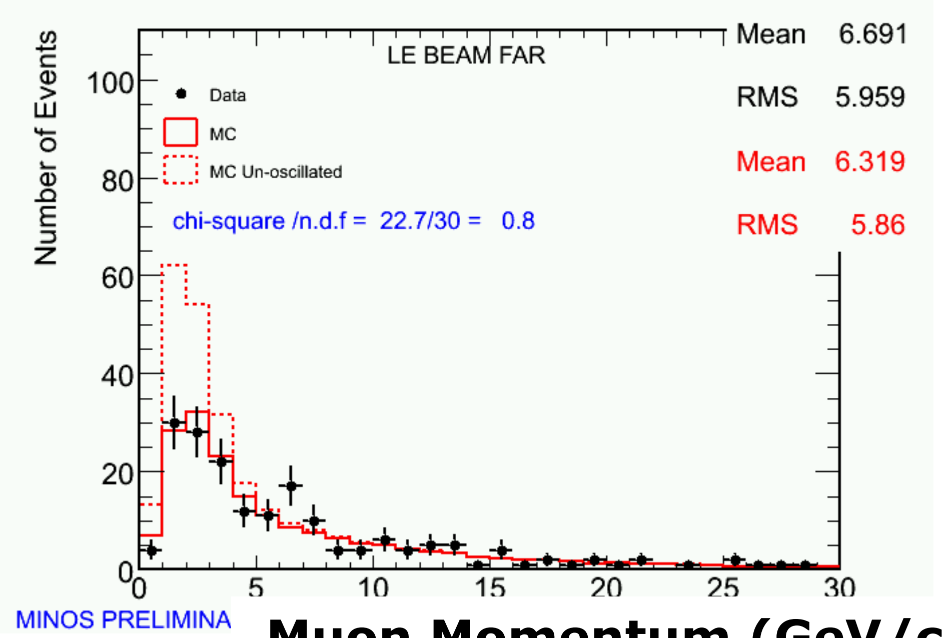
- Normalisation: ±4%
  - POT counting, Near/Far selection efficiency
- Relative shower energy scale: ±3%
  - Inter-Detector calibration uncertainty
- Muon energy scale: ±2%
  - Uncertainty in dE/dX in MC
- NC contamination of CC-like sample: ±30%
  - From shape and normalisation of ND PID distribution
- 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

Predicted FD spectrum

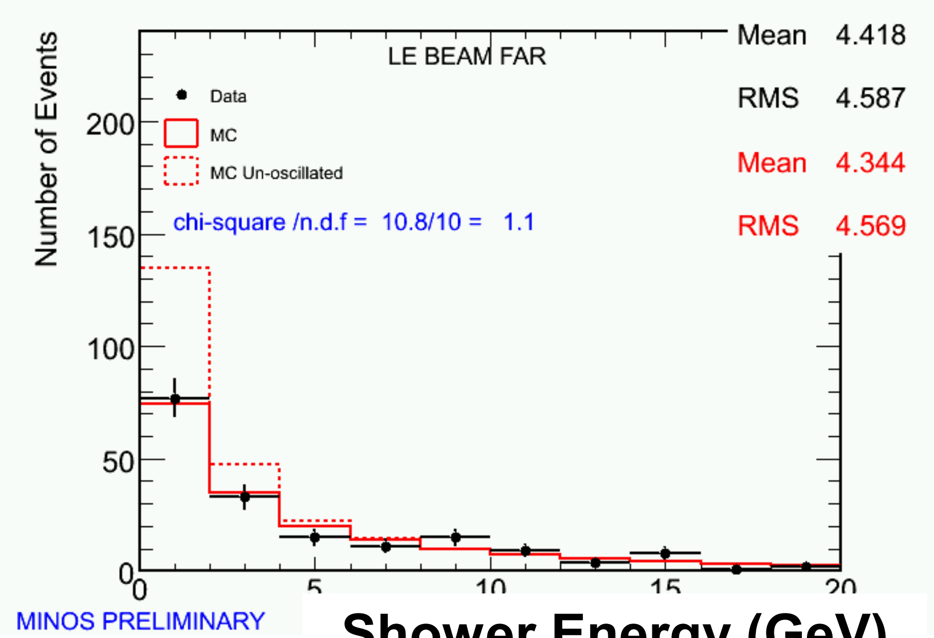


- The predicted FD true spectrum from the Matrix Method is shown on the left.
- **The spectrum is higher than the nominal FD MC in the high energy tail. This is as expected, given that the ND Data visible energy distribution is also higher than the nominal MC in this region.**

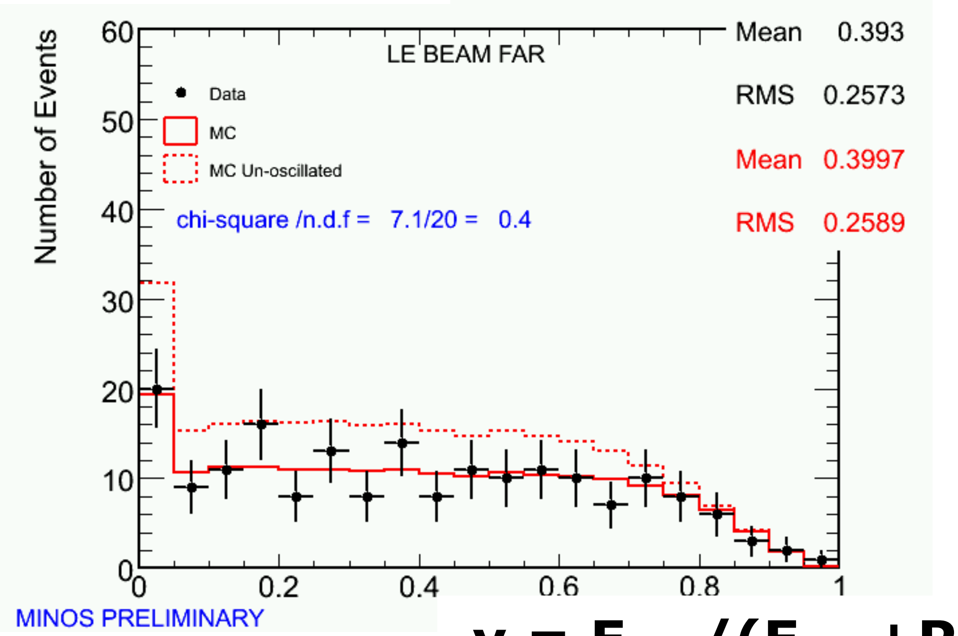
FD data distributions



Muon Momentum (GeV/c)



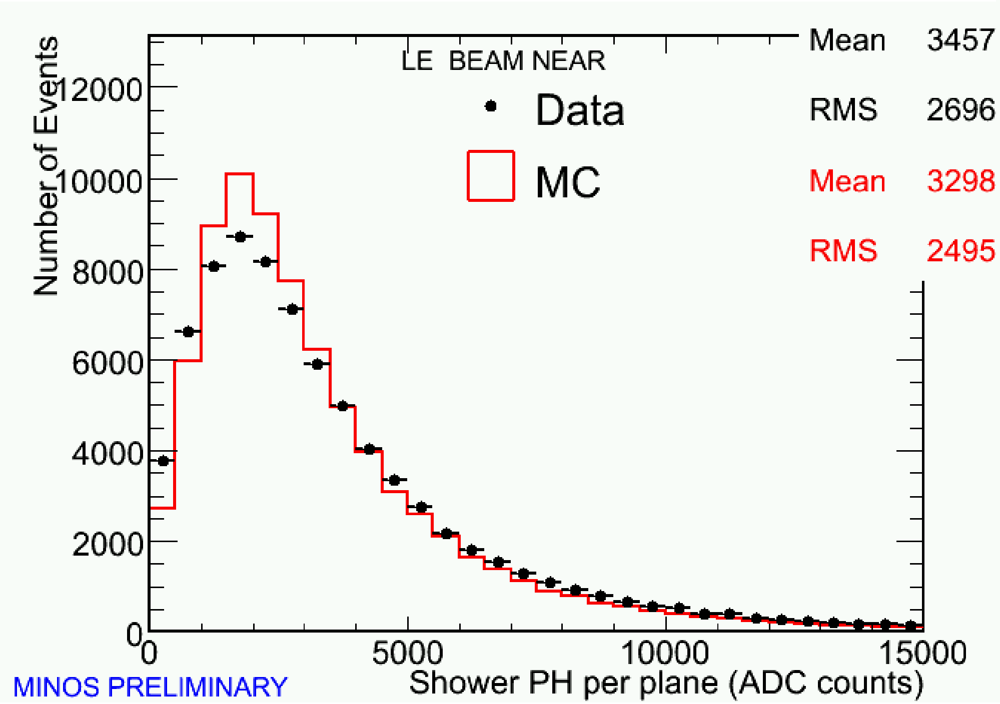
Shower Energy (GeV)

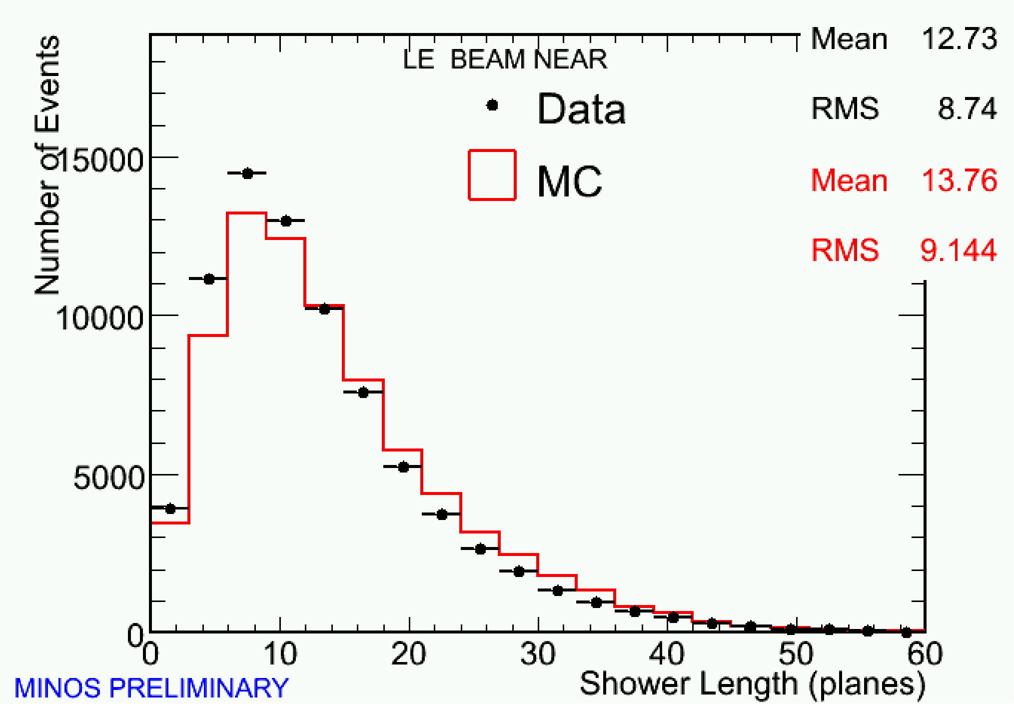


$\mathbf{y = E_{shw}/(E_{shw}+P_{\mu})}$

Mark Dierckxsens

Shower profiles





- Data showers tend to be slightly shorter and more “dense” than MC showers

ν_e appearance

- Expected events for $1.4\text{x}10^{20}$ PoT:

NC	2.80	(66%)
CC	0.62	(15%)
Beam ν_e	0.58	(14%)
ν_τ ($\Delta m^2 = 2.5\text{x}10^{-3}$ eV^2)	0.23	(5%)
total background	4.23	

$\sin^2 2\theta_{23} = 1.0$

$\Delta m^2_{32} = 0.0025$ eV^2

$\sin^2 2\theta_{13} = 0.12$

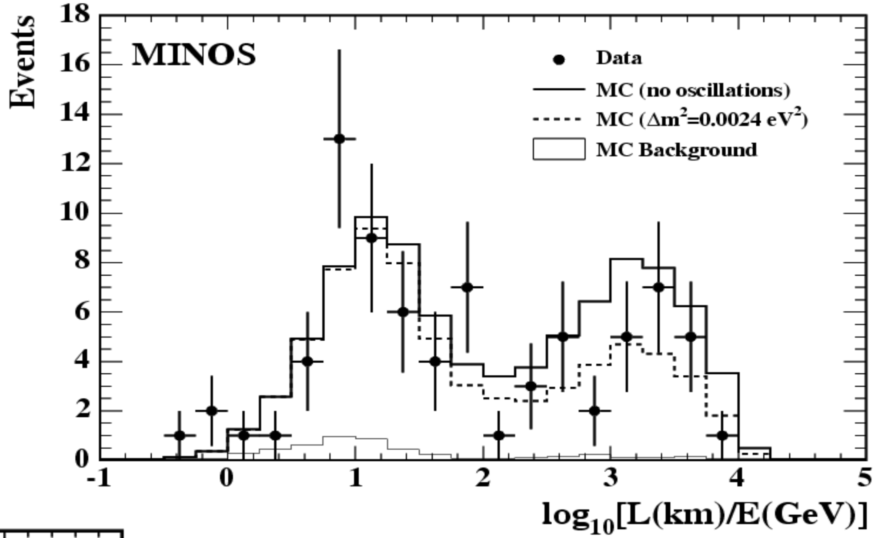
↓

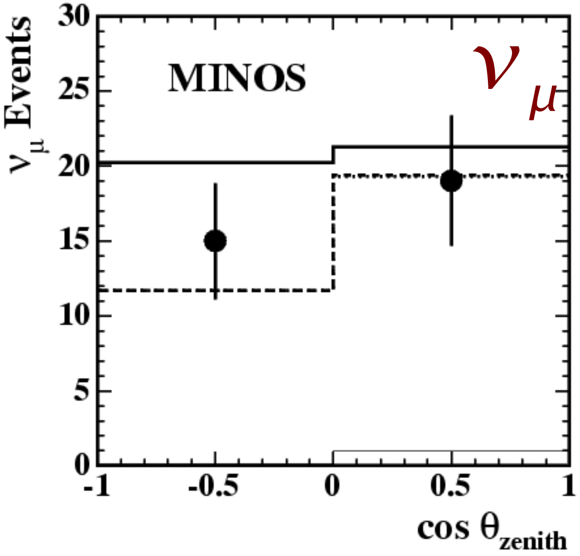
2.8 signal events

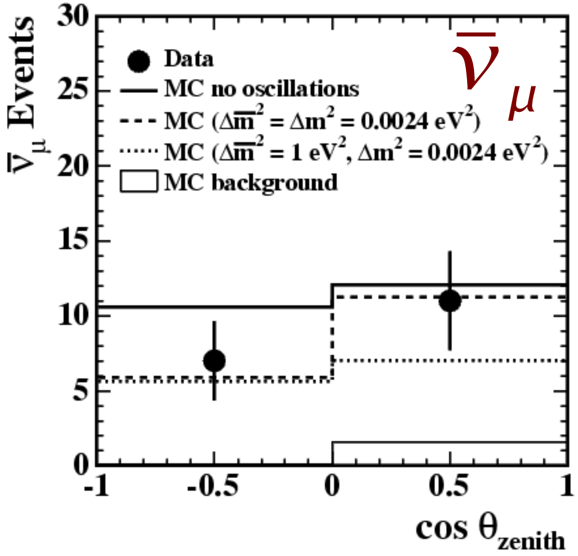
- Backgrounds will be estimated from data:
  - Horn off data in ND: disentangle NC – CC
  - Beam ν_e: measure $\bar{\nu}_\mu$ from $\mu^+ \rightarrow e^+ \nu_e \bar{\nu}_\mu$ in ND
  - muon removal in CC events

Atmospheric Neutrinos

- FD taken cosmic data since July 2003
- Fully and partially contained neutrino interactions
- oscillation analysis
- ν ⇔ anti-ν separation
- hep-ex/0512036
  accepted Phys. Rev. D







$$\frac{R^{data}_{\bar{\nu}/\nu}}{R^{MC}_{\bar{\nu}/\nu}} = 0.96^{+0.41}_{-\ 0.31}$$

assume equal oscillations for ν, $\bar{\nu}$