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Rutherford Appleton Laboratory

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Recent Results from the MINOS Experiment

Costas Andreopoulos (*)

** for the MINOS collaboration*

International Nuclear Physics Conference 2007 (INPC07), June 3-8, Tokyo

Outline

- **Introduction**
  - Neutrino Oscillations
  - Open Questions
  - MINOS Physics Goals
- **The MINOS Experiment**
  - How is it done?
  - The NuMI beamline at Fermilab
  - The Detectors
    - *Detector technology*
    - *The FAR & NEAR detectors*
    - *MINOS calibration*
  - Interaction types & Event topologies
- **The nu_mu CC disappearance analysis**
  - Event selection
  - NEAR Detector Energy Spectra
  - Hadron production tuning
  - Predicting the FAR Detector Energy Spectrum
  - Observed Rates & Best fit spectrum
  - Allowed Regions & Best fit parameters
  - Systematics
  - Projected Sensitivity
- Summary

Neutrino Oscillations

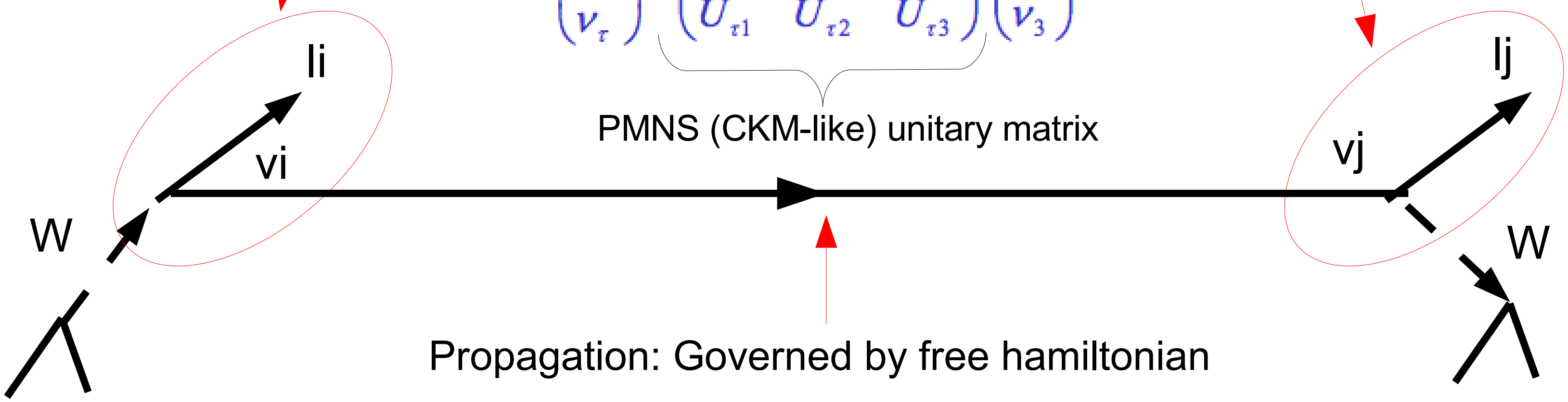
A quantum-mechanical interference effect

Production & Detection: Governed by electoweak hamiltonian

Producing / detecting interaction eigenstates

(superposition of **mass eigenstates**)

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \underbrace{\begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix}}_{\text{PMNS (CKM-like) unitary matrix}} \cdot \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$



Propagation: Governed by free hamiltonian

Each mass eigenstate propagates at different pace !

Relative mixture of mass eigenstates changes!

Flavour oscillations are possible

$$P(\nu_\alpha \rightarrow \nu_\beta) = \delta_{\alpha\beta} - 4 \Sigma\Sigma\, U_{\alpha i}U_{\beta i}U_{\alpha j}U_{\beta j} \sin^2[\Delta m_{ij}{}^2 L/4E_\nu]$$

Phenomenon has been observed with:
solar, **atmospheric**, **reactor** & **accelerator** neutrinos!

Open Questions

Goals:

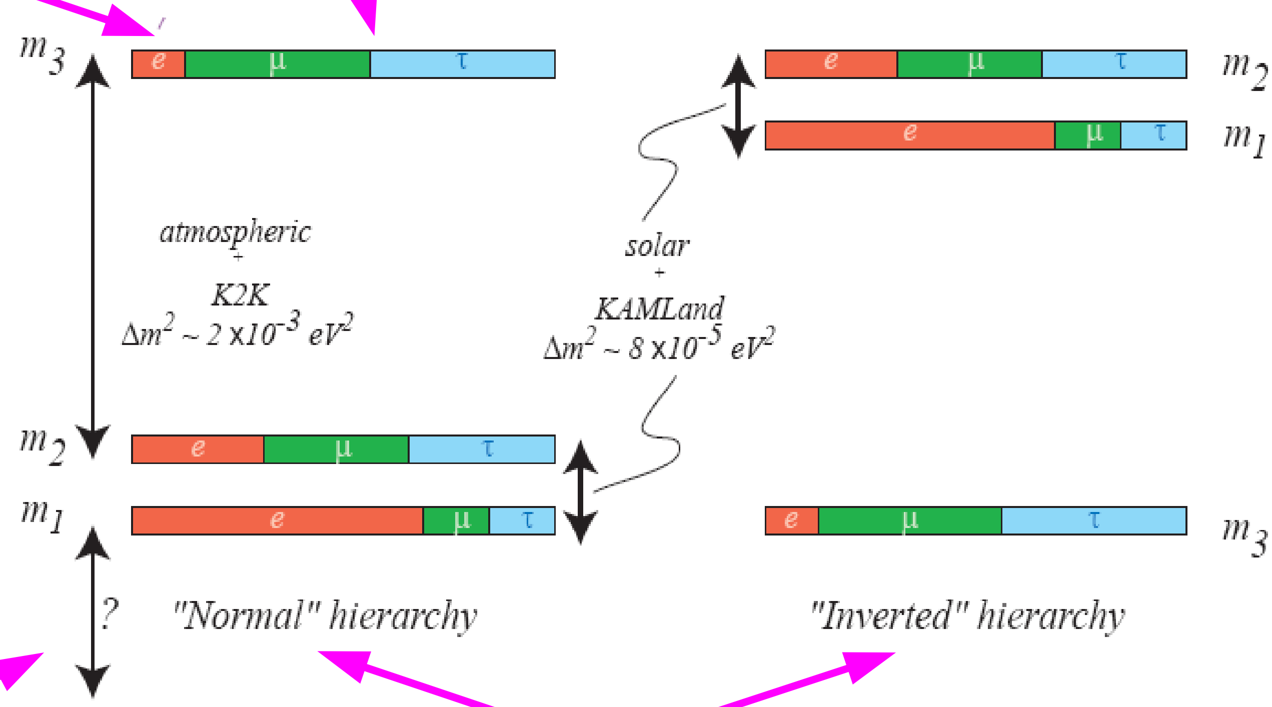
- *Determine the elements of the PMNS matrix*
- *Determine neutrino mass (splittings)*

- Impressive progress over the past decade - A 'precision measurement' era for neutrinos
- **Still many open questions :**

How close to 0 is theta13?
(hidden symmetry?)

Is theta23 maximal?
(hidden symmetry?)

Is CP violated at the leptonic sector?



Can we measure the absolute scale?
(not accessible with oscillations)

Which one? … or none (quasi-degenerate)?

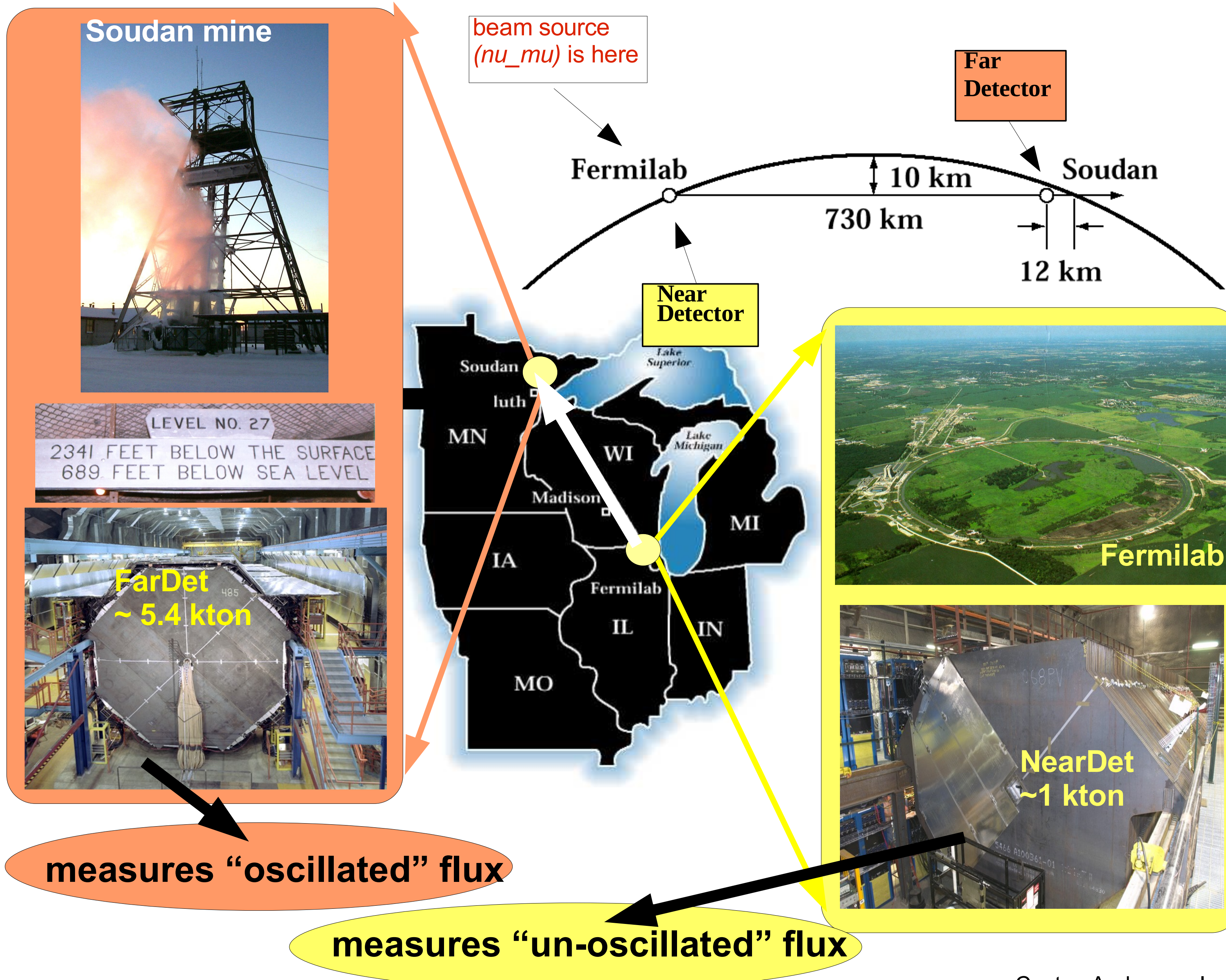
Physics Goals for MINOS

MINOS: A precision oscillation experiment

- Test the $\nu_\mu \rightarrow \nu_\tau$ oscillation hypothesis
  - Measure precisely $|\Delta m^2_{32}|$ and $\sin^2 2\theta_{23}$
- Search for sub-dominant $\nu_\mu \rightarrow \nu_e$ oscillations
- Search for/constrain exotic phenomena
- Compare ν_μ, $\overline{\nu_\mu}$ oscillations
- Atmospheric neutrino oscillations
  - Phys. Rev. D73, 072002 (2006)

How the experiment is done

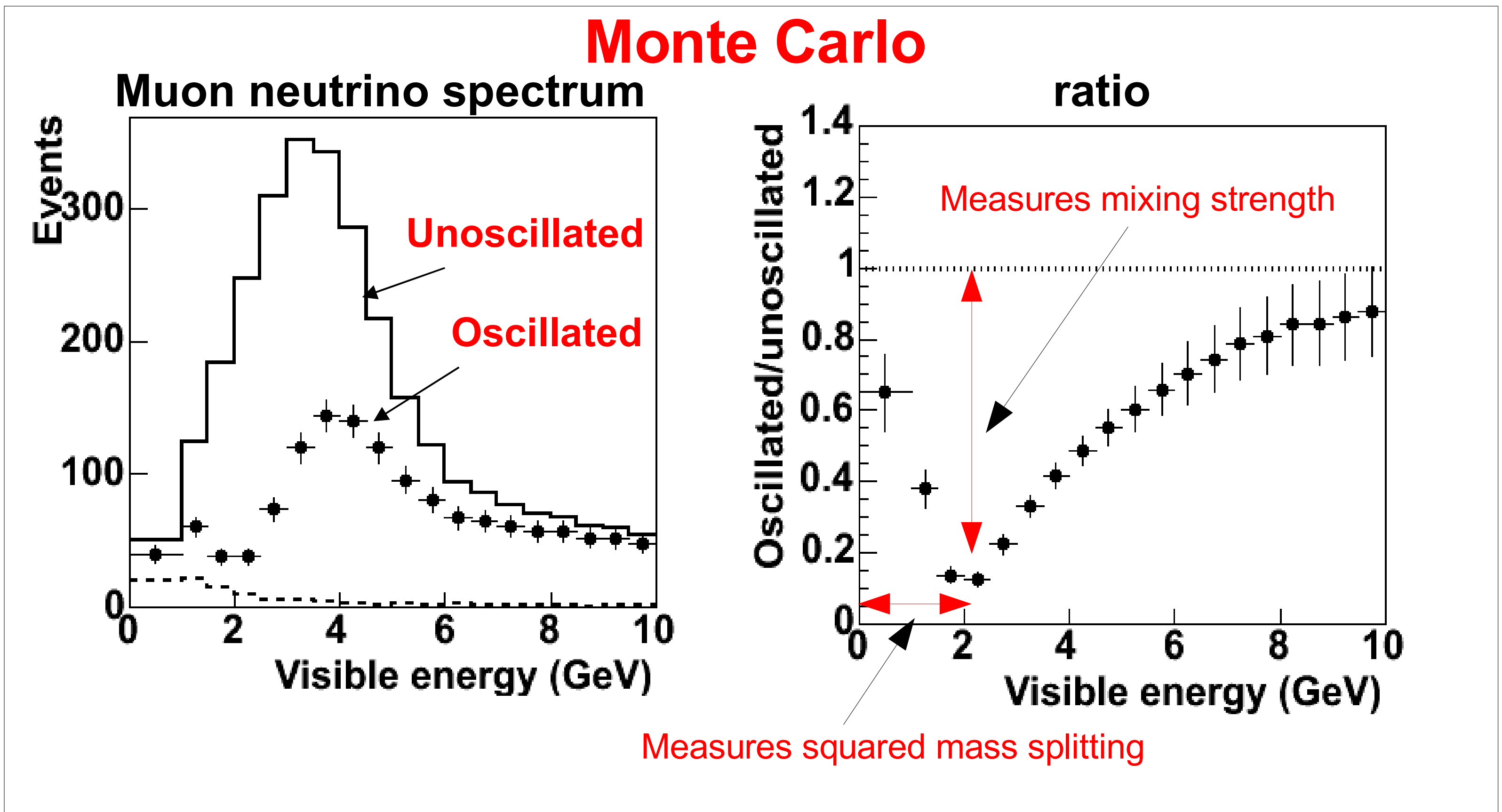
A 2 detector, long-baseline neutrino experiment using an intense, accelerator-made beam



Why a 2 detector experiment?

Reducing systematic errors

- Effect of large flux & cross-section uncertainties minimized
- Detector / reconstruction effects minimized
- 'Unoscillated' FAR spectrum extrapolated from NEAR



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The MINOS Collaboration

Outline
ν Oscillations

MINOS Goals
MINOS Overview
Beamline
Detectors
Events

Event Id
ND Spectra
Tuning
FD Prediction
Observed spectrum
Allowed Regions
Systematics
Projected Sensitivity

Summary

Brazil

Campinas – Sao Paulo

France

College de France

Greece

Athens

Russia

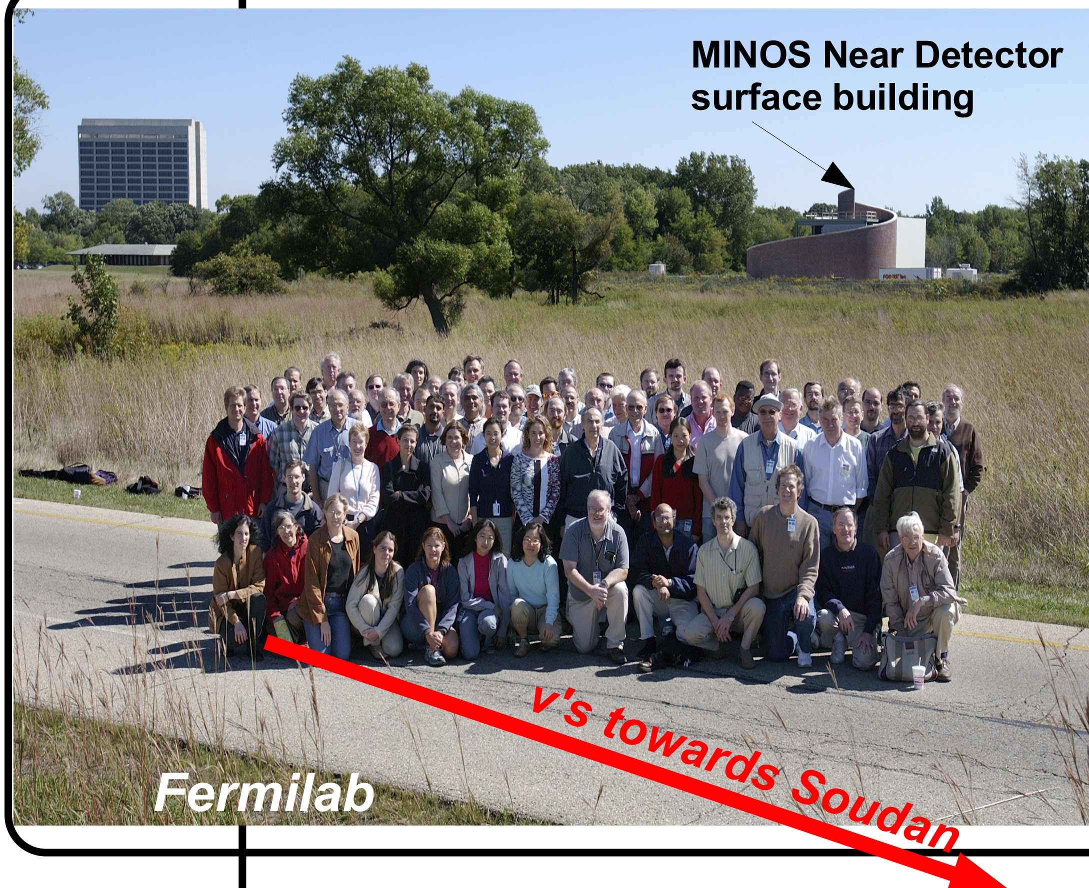
ITEP Moscow – Lebedev – Protvino

UK

Cambridge – Oxford – RAL – Sussex - UCL

USA

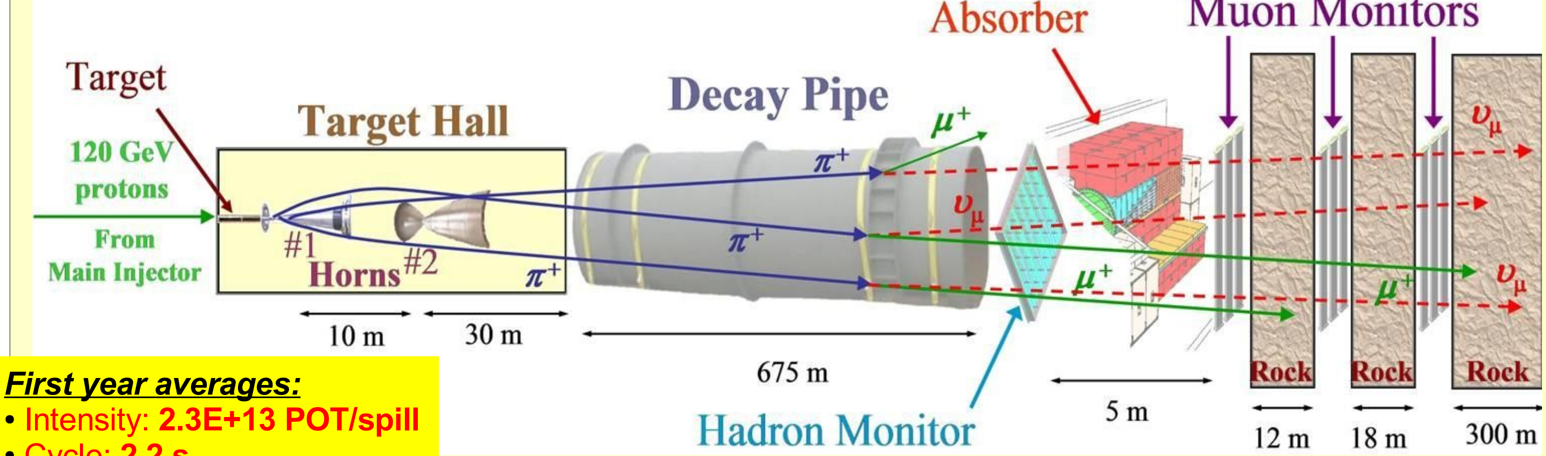
Argonne – Benedictine – Brookhaven – Caltech – Fermilab – Harvard – IIT – Indiana – Livermore – Minnesota, Twin Cities – Minnesota, Duluth – Pittsburgh – South Carolina – Stanford – Texas A&M – Texas-Austin – Tufts – Western Washington – William & Mary - Wisconsin



- **6 countries**
- **32 institutions**
- **~175 physicists**

The NuMI beamline @ Fermilab

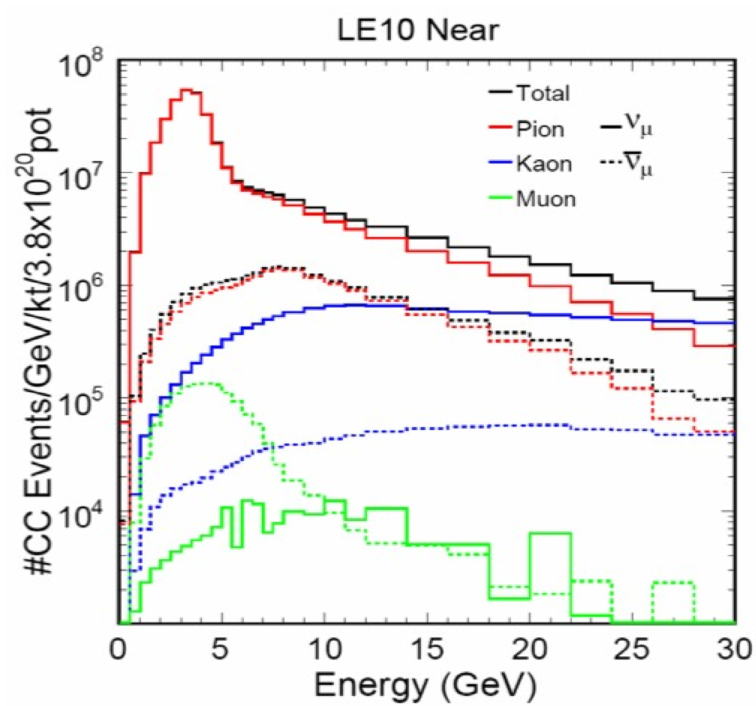
a 'conventional' neutrino beam

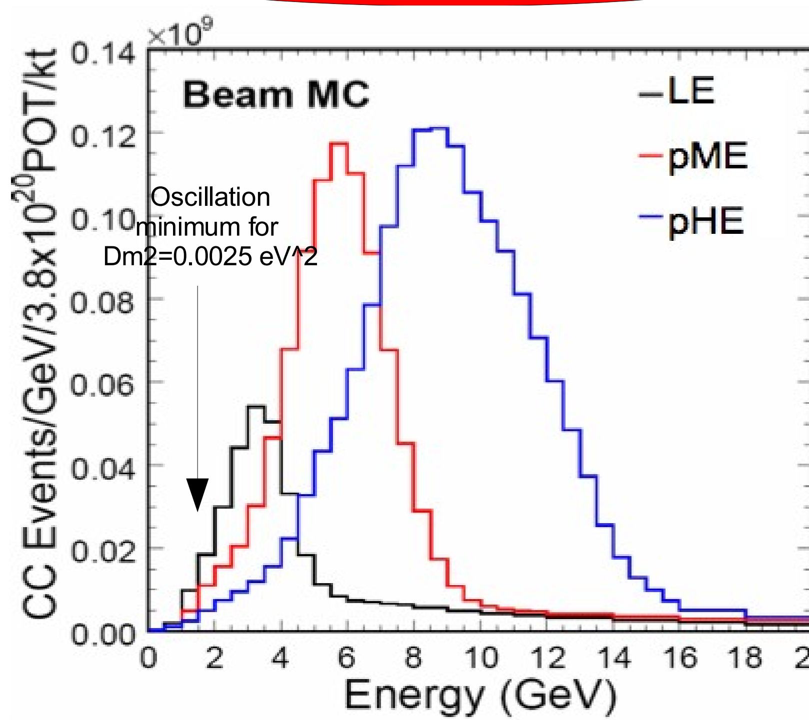


First year averages:
- Intensity: **2.3E+13 POT/spill**
- Cycle: **2.2 s**
- Power: **170 kW**

~pure / intense muon neutrino beam

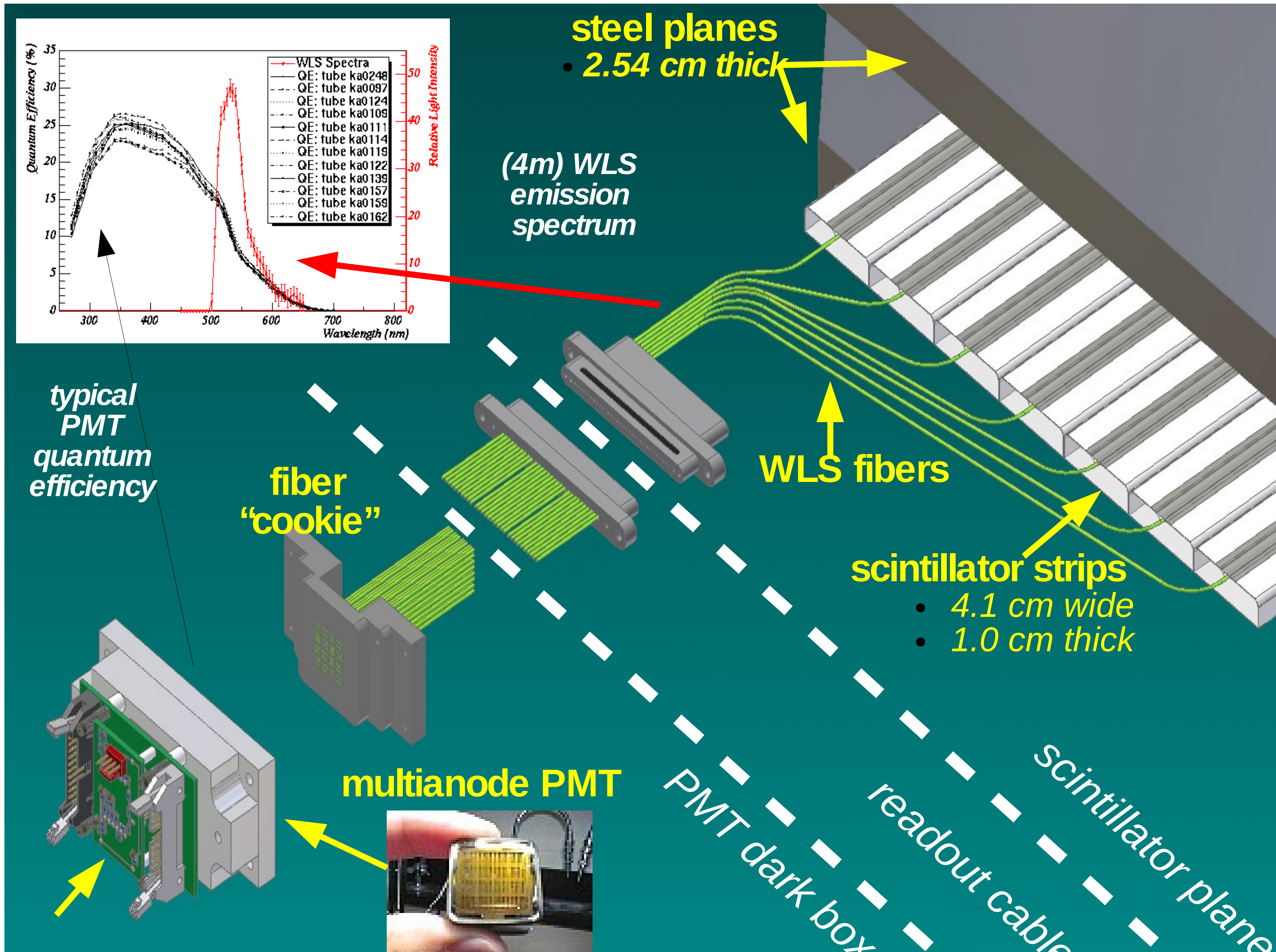
tunable energy





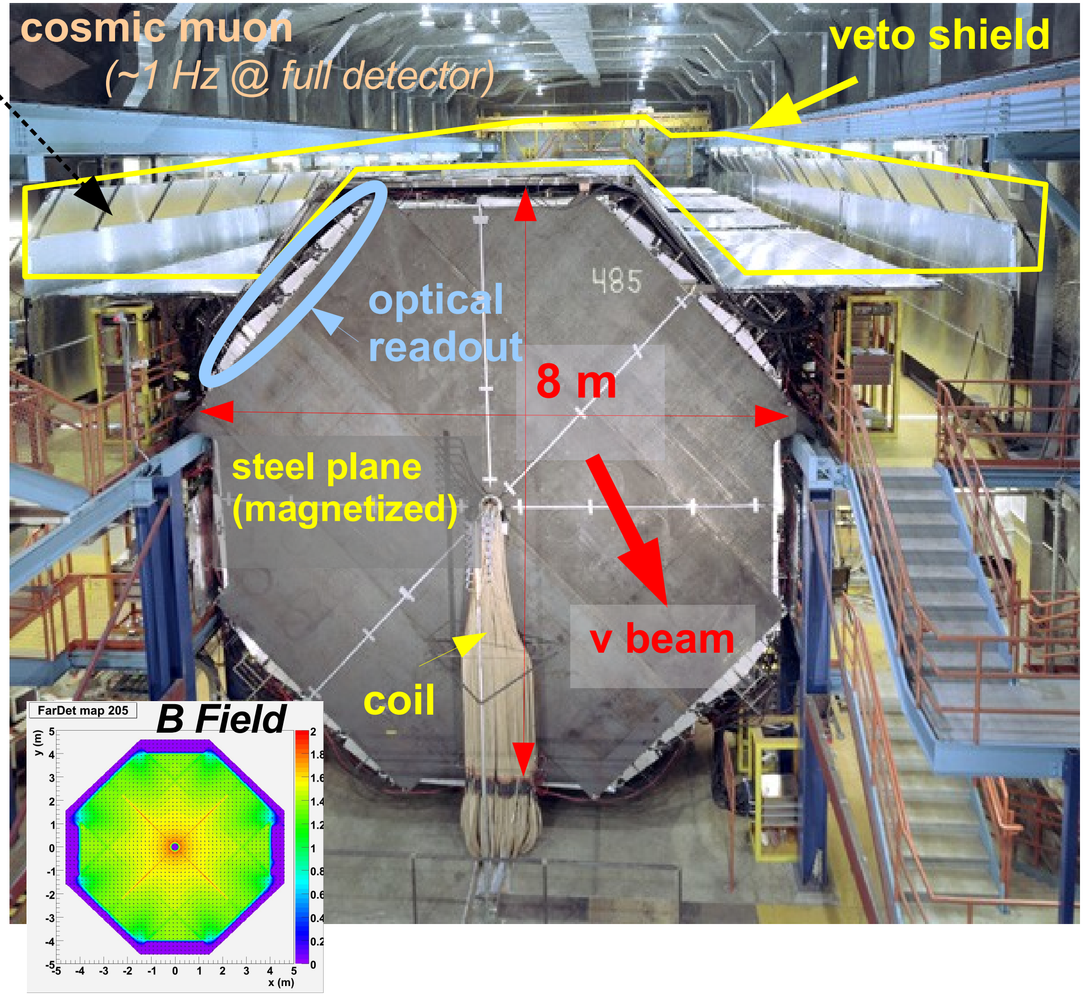
Detector Technology

Massive segmented iron calorimeters, with inexpensively produced plastic scintillator as active material. The scintillation light is collected by WLS fibers read out by multianode PMTs.



The FAR Detector @ Soudan mine

Purpose:
- Measure nu_mu CC, NC –– energy spectra & rates
- Search for nu_e appearance
- *Atmospheric Neutrino physics studies (upgoing muons, contained neutrino events,...)*
- *Cosmic Ray physics studies (mu+/mu- charge ratio, point sources, ...)*



- at Soudan mine, MN
- **~ 735 km** from NuMI target
- depth: **~ 750 m**

- **~ 5.4 kton**
- **486** steel planes
- B ~ **1.3 T**

- **2-ended readout**
- **16-anode PMTs** *(HPK M16)*
- **x8** optical **multiplexing**

- **VA electronics**

operational since
June 2003

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The NEAR Detector @ Fermilab

Purpose:

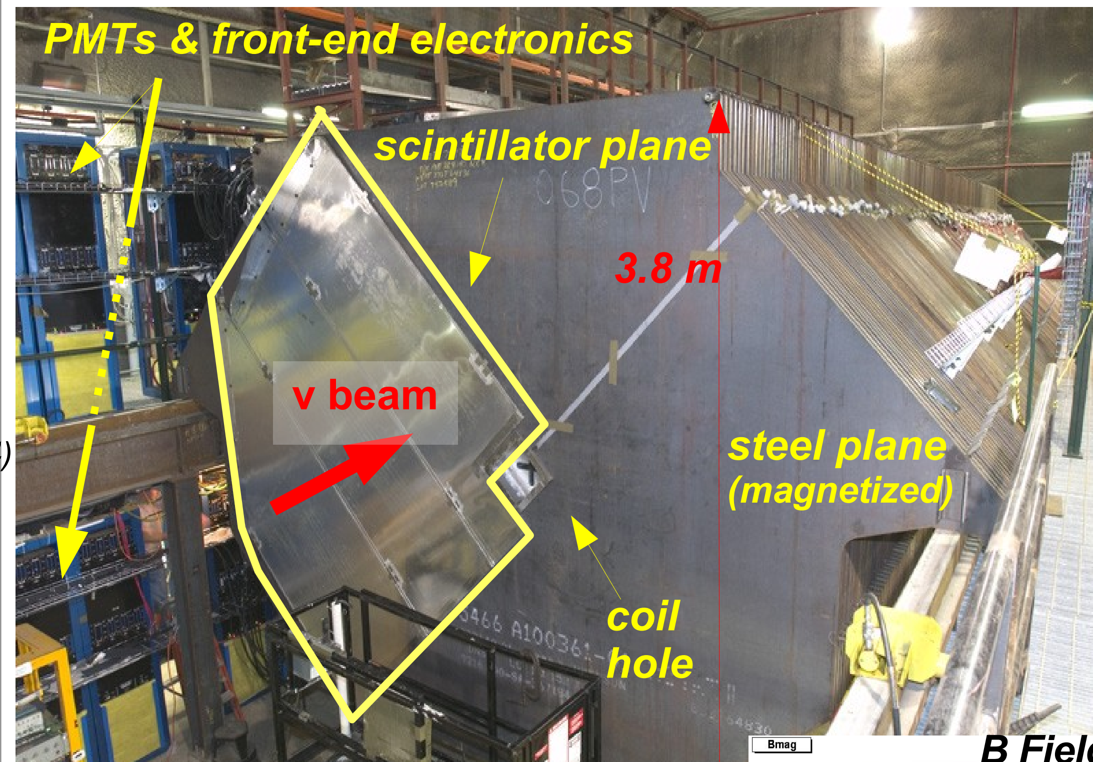
- Measure beam with high statistics before oscillations
- Tune neutrino & beam / hadron-production MC
- Predict Far detector spectrum

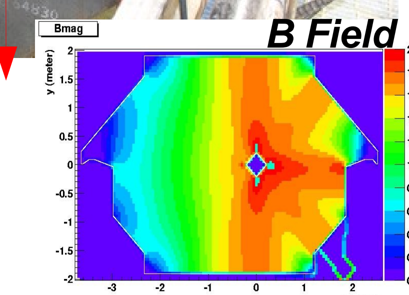
- at Fermilab
- **~ 1 km** from NuMI target
- swallow depth: **~ 100 m**

- **~ 1 kton**
- **282** steel planes
- B Field ~ **1.2 T**

- **1-ended readout**
- **64-anode PMTs** *(HPK M64)*
- no multiplexing upstream
- 4x MUX in spectrometer

- Very high rates
- **QIE electronics**
  (no deadtime during spill)



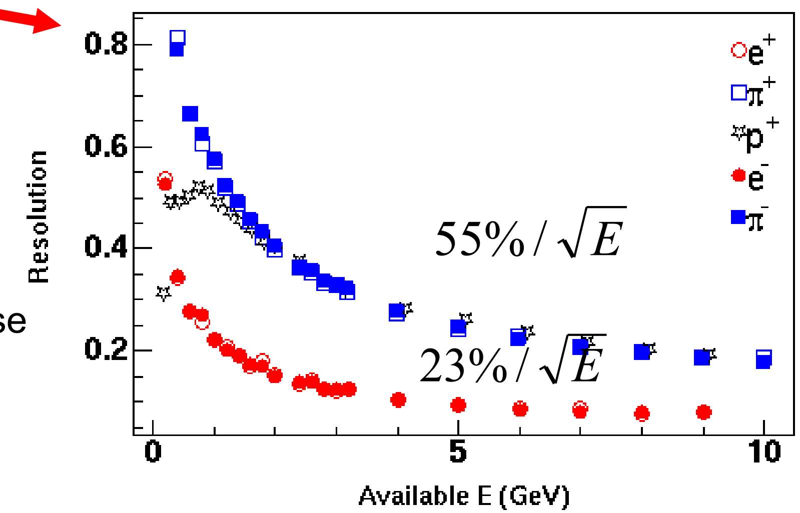


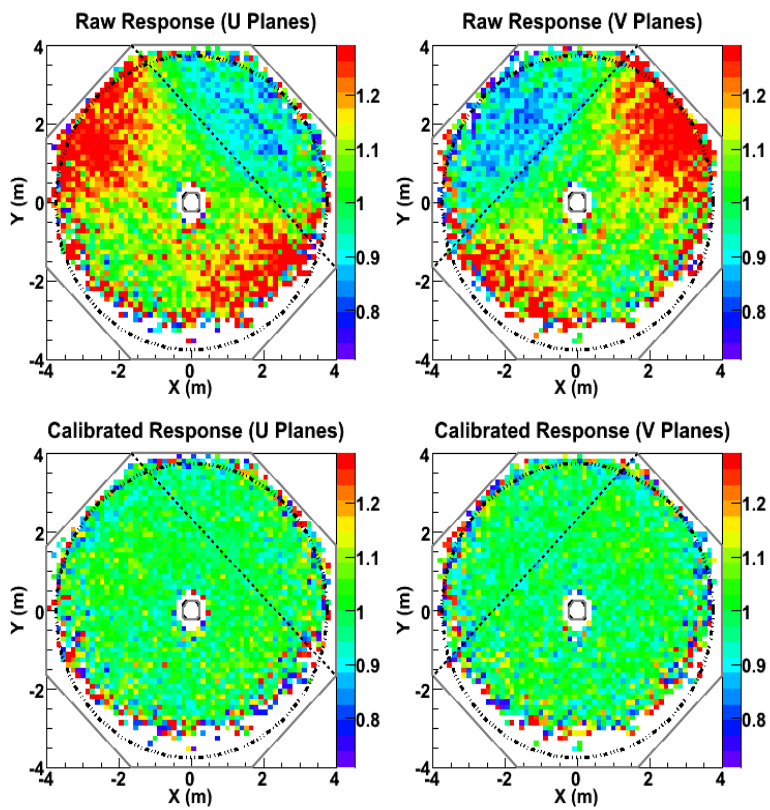
operational since
~ November 2004

MINOS Calibration

- Calibration detector
  - Determine overall energy scale
- Light Injection system
  - Determine/monitor PMT gains
- Cosmic ray muons
  - Equalize strip to strip response
  - Equalize detector to detector response

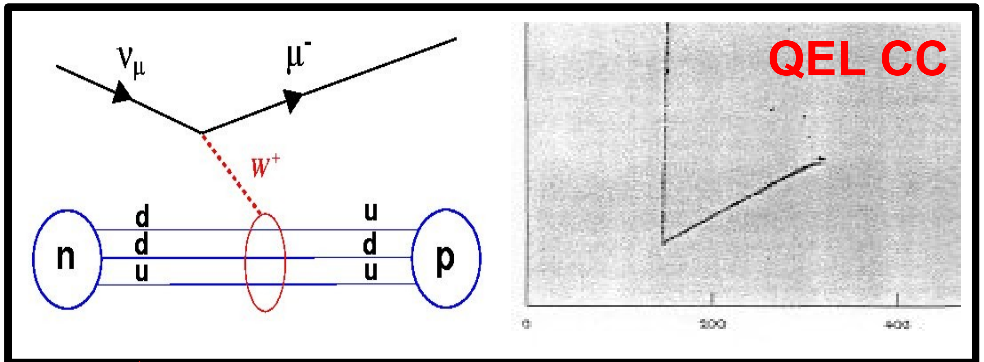
Single particle energy resolution

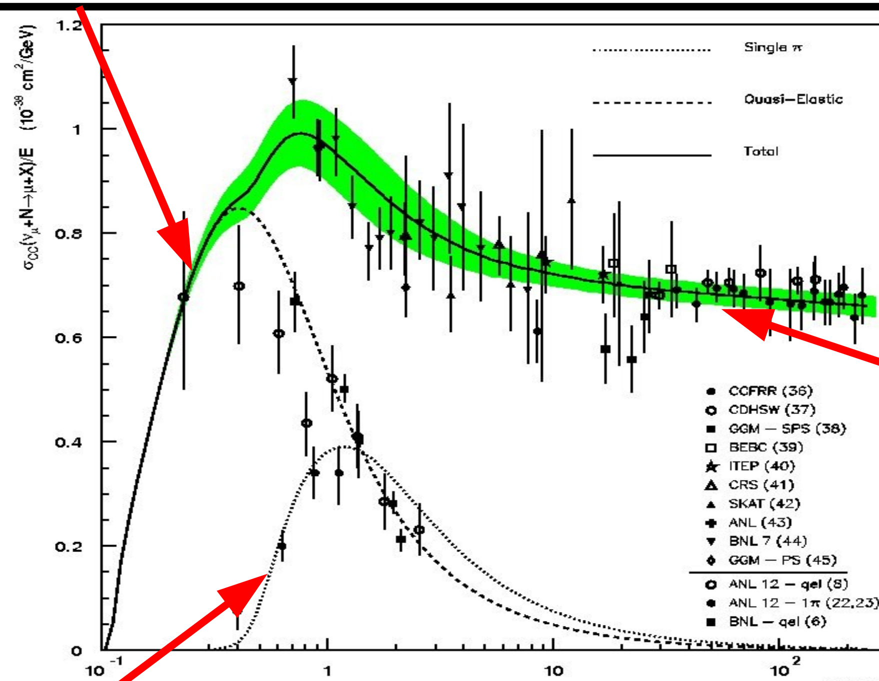


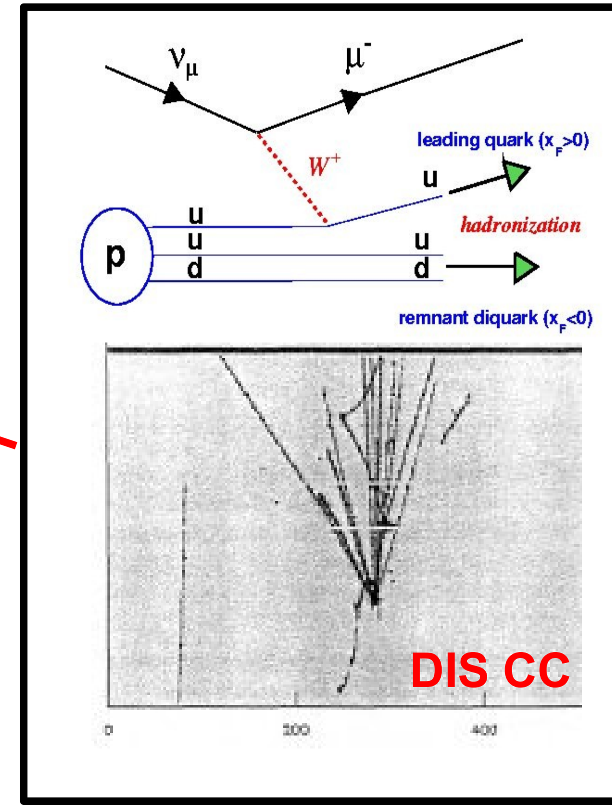


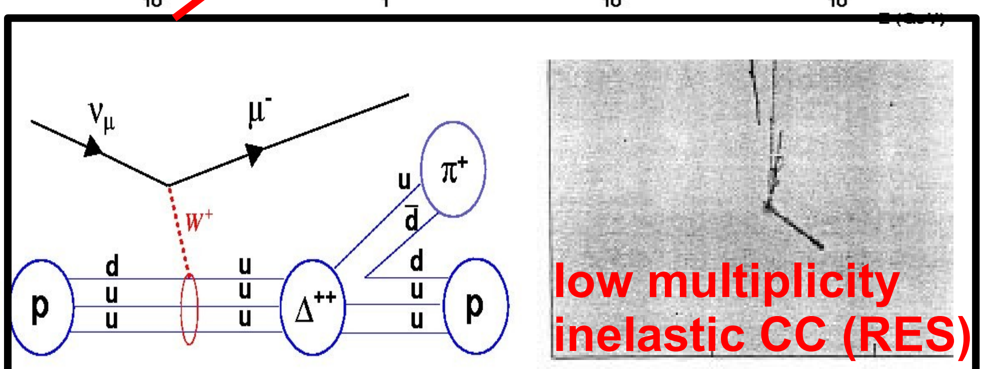
Energy scale calibration:
- 1.9% absolute error in ND
- 3.5% absolute error in FD
- 3% relative

How do neutrinos interact at few GeV?







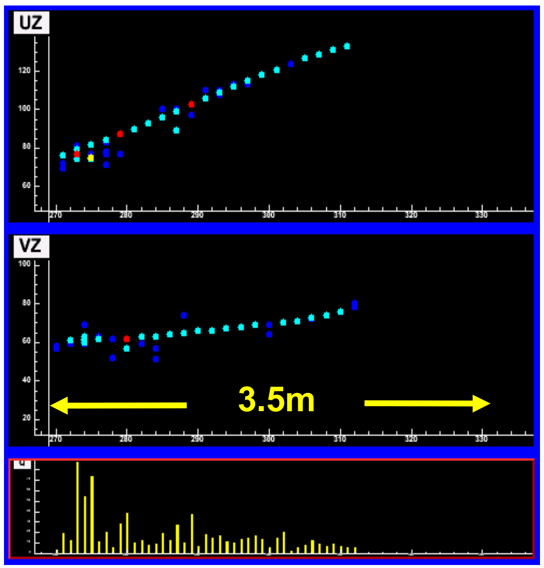


LAr images, courtesy A.Curioni

Event topologies

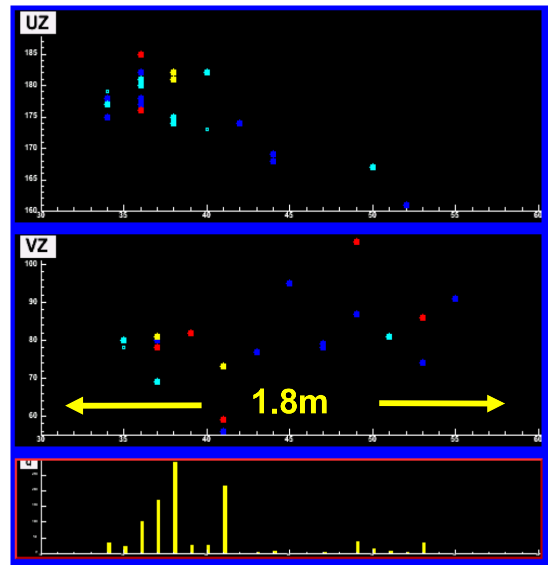
Monte Carlo Events

nu_mu CC



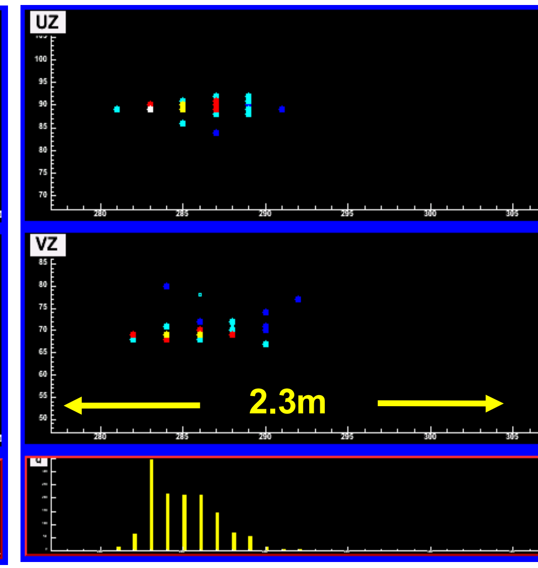
- long μ track
- hadronic activity at vertex

NC



- short event
- often diffuse

nu_e CC



- short event
- typical EM shower profile

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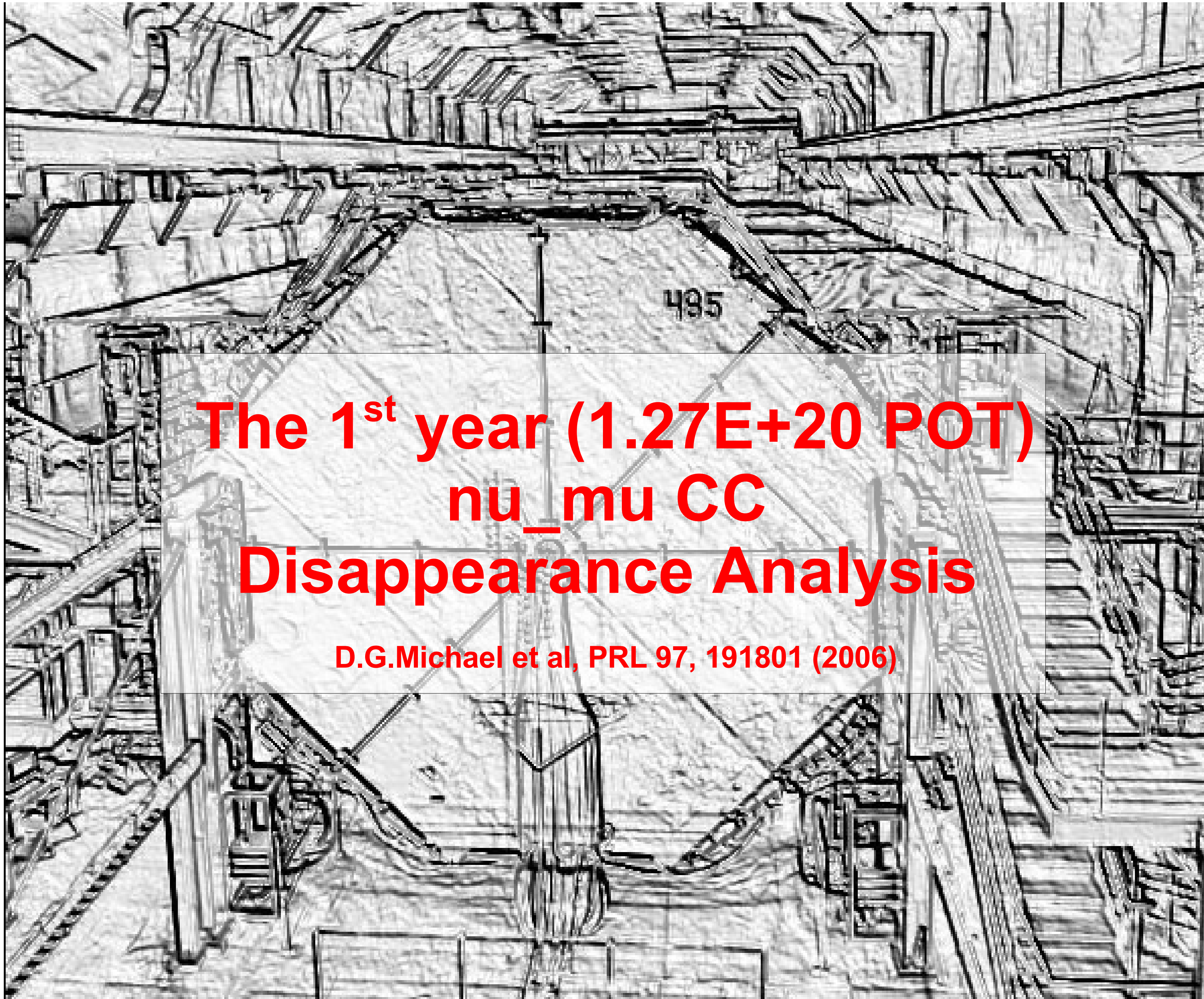
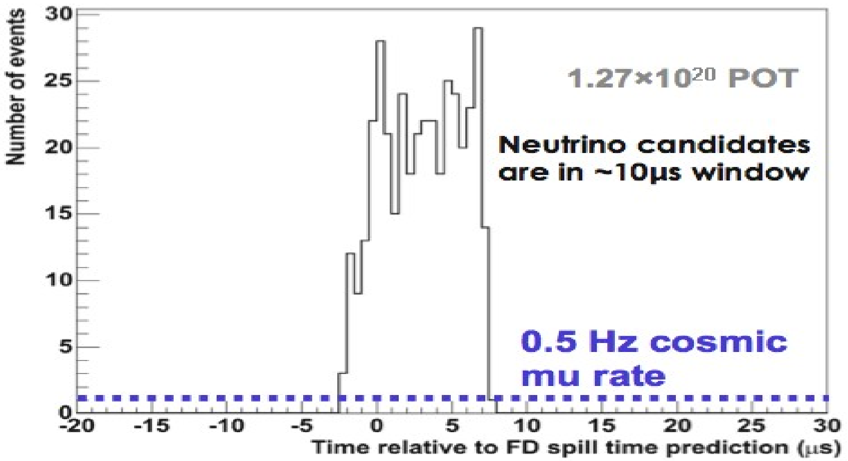


The 1st year (1.27E+20 POT) nu_mu CC Disappearance Analysis

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

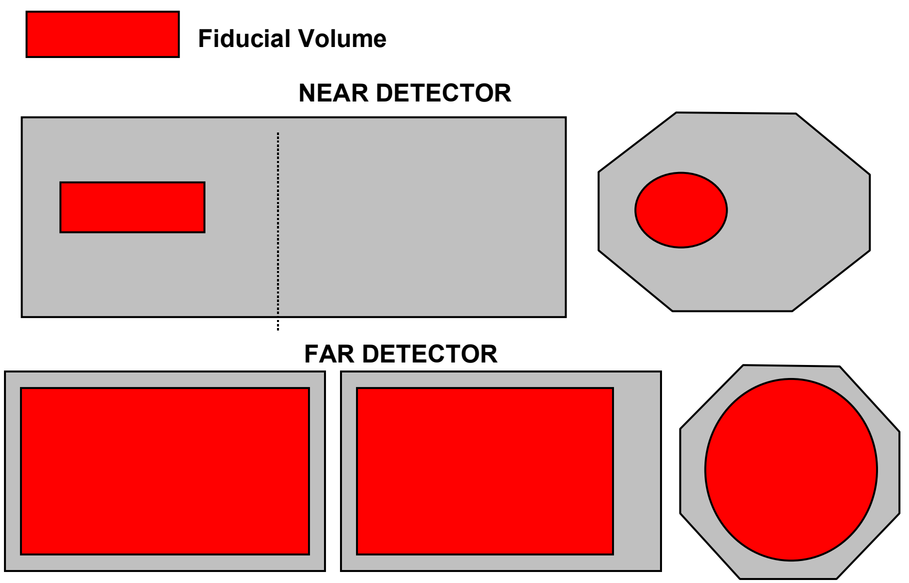
Selection cuts

Events in time with the beam



Vertex in fiducial volume

FAR:
z > 0.50 m from edge, z > 2 m from end, within 3.7 m of detector centre
NEAR:
1m < z < 5m from upstream end, within 1 m of the beam centre

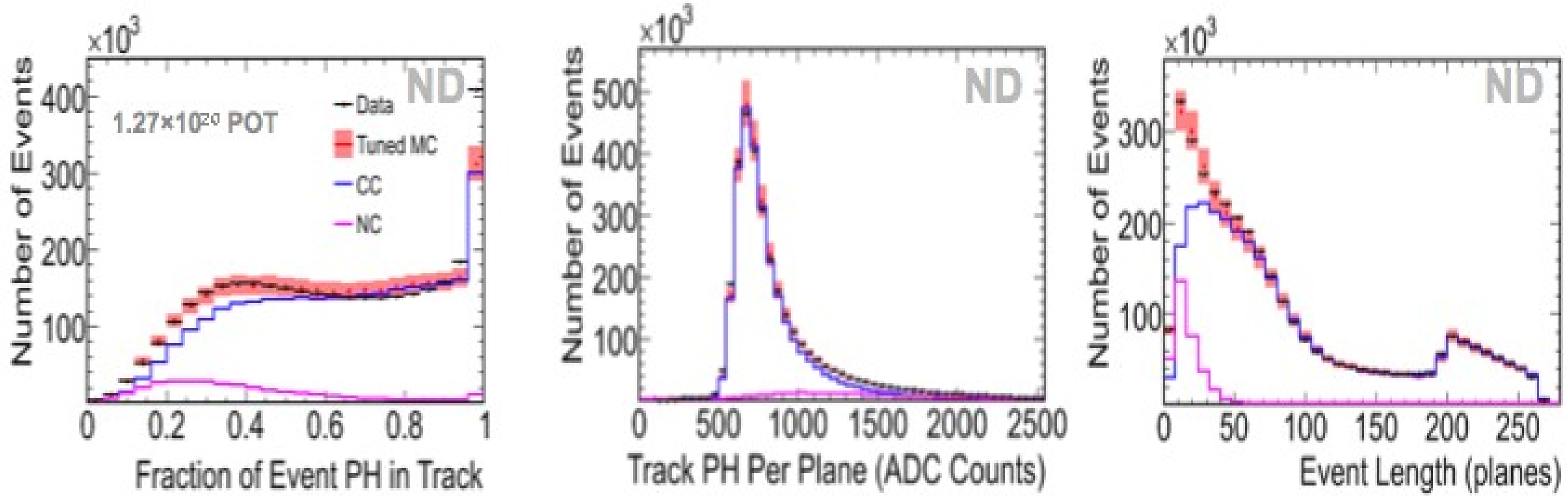


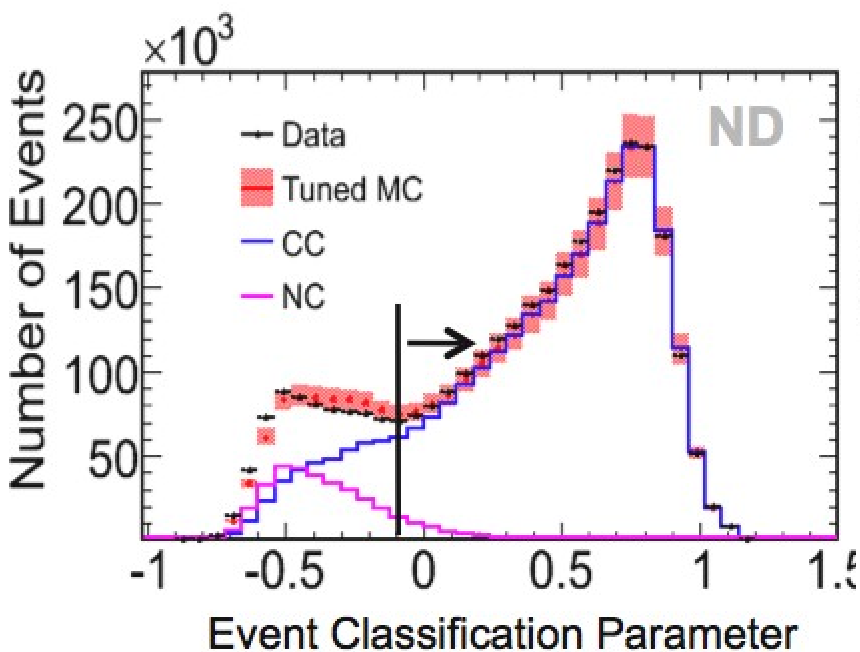
At least one good reconstructed track

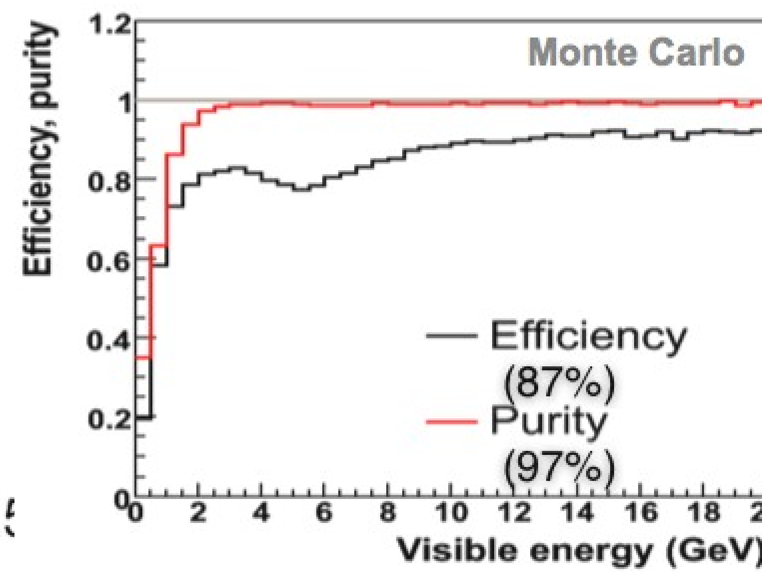
- With negative charge

Event Selection

Using a maximum likelihood technique with 3 input PDFs:







NEAR detector energy spectrum

Outline
ν Oscillations

MINOS Goals
MINOS Overview
Beamline
Detectors
Events

Event Id
<u>ND Spectra</u>
Tuning
FD Prediction
Observed spectrum
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Systematics
Projected Sensitivity

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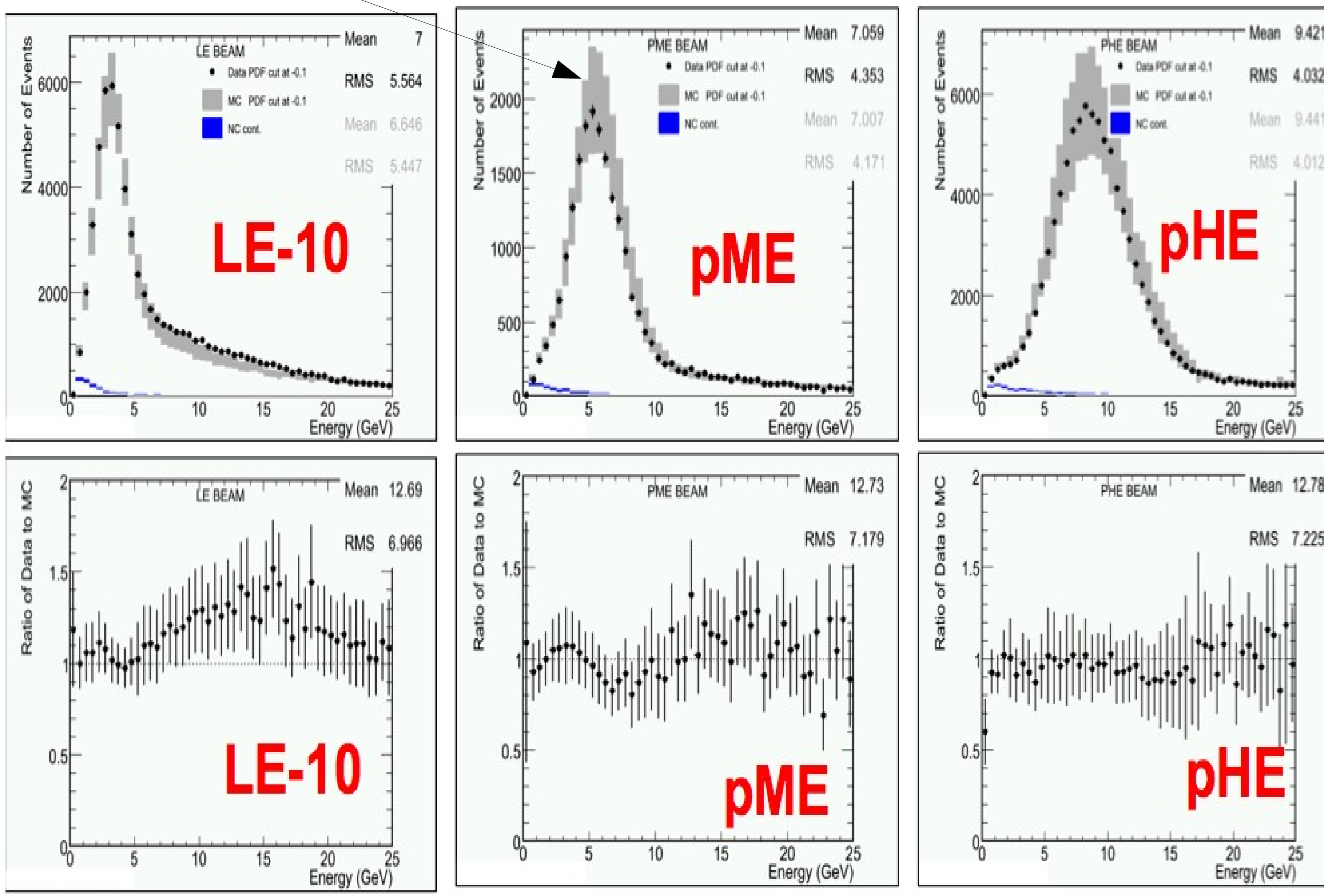
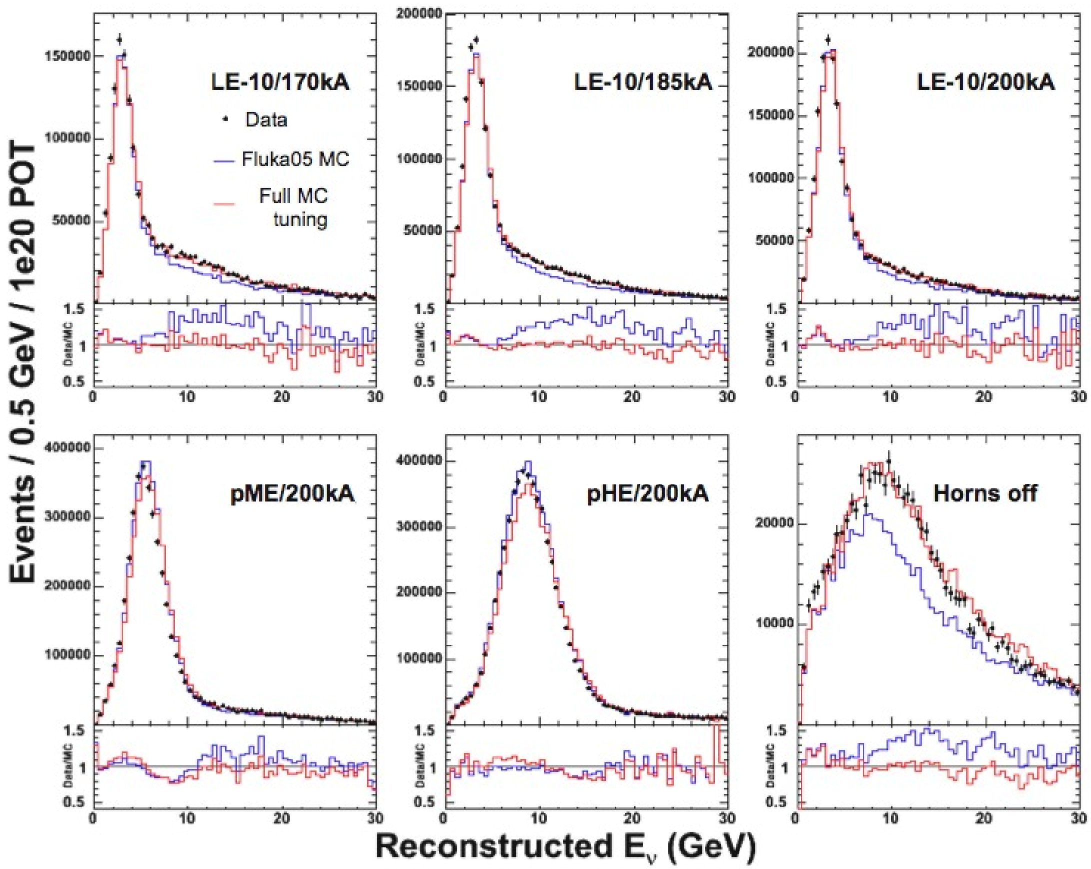
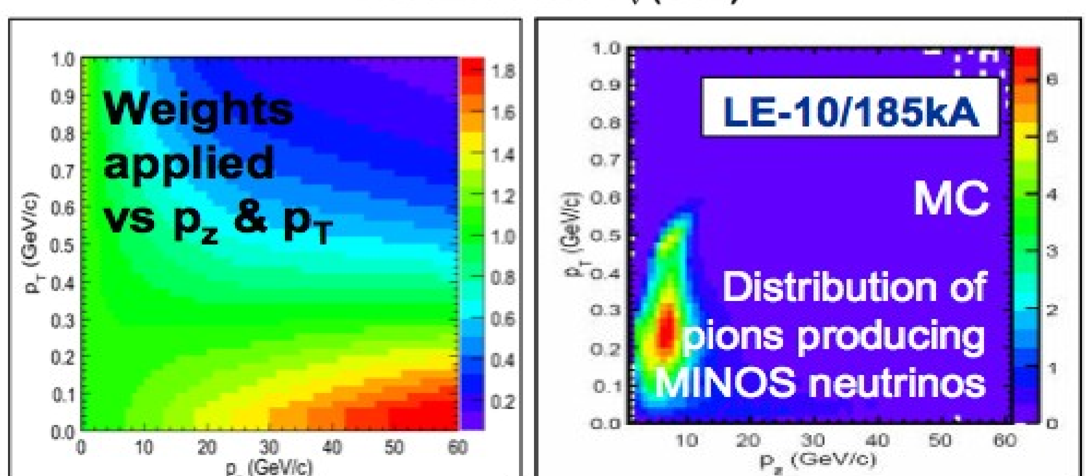
Error envelopes indicates size of beam modelling,
neutrino interaction modelling and calibration uncertainties (combined).



Good Data / MC agreement

Hadron production tuning





- Hadro-production *(Fluka05 based beam simulation)* tuning
- Even better data / MC agreement is obtained
- Applied weights as function of xF and pT

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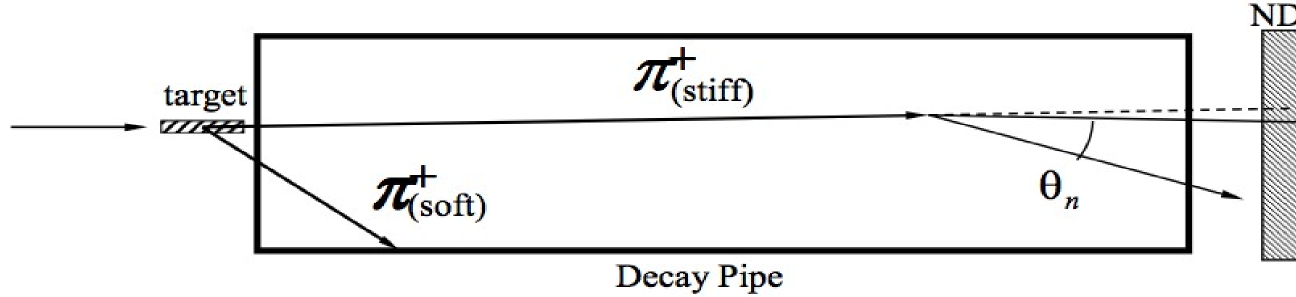
Prediction of FAR spectrum

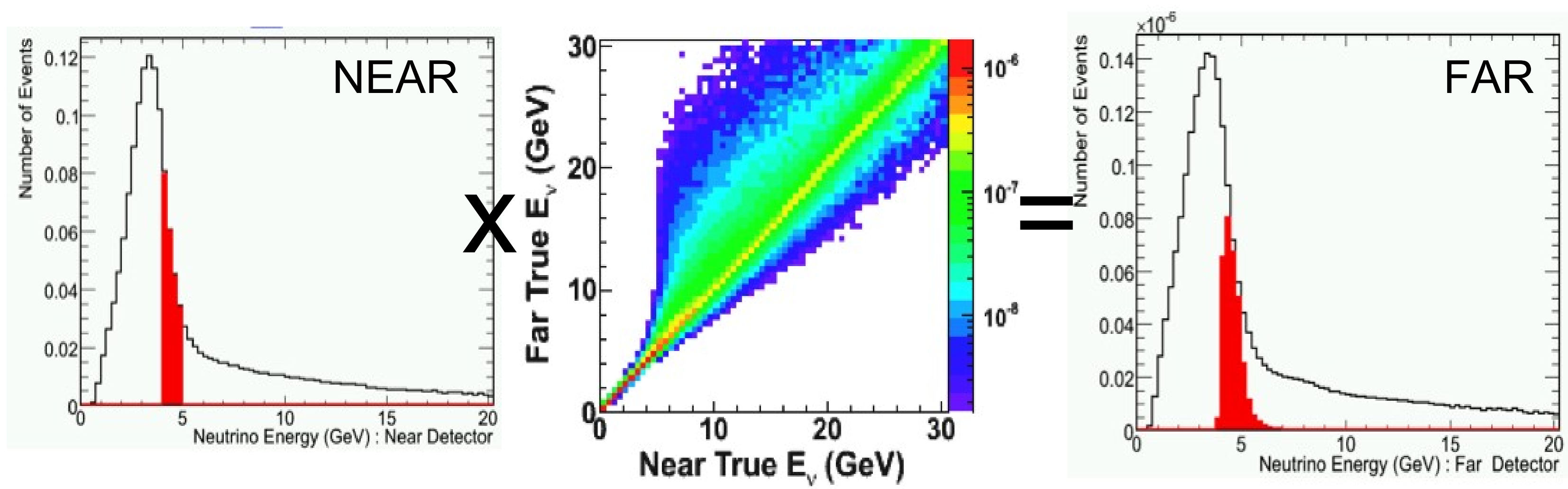
The 'Matrix' method:

- **The un-oscillated FAR spectrum is determined by the NEAR spectrum**
- No dead-reckoning based on MC. The MC is used only for providing corrections
- Measured NEAR spectrum is extrapolated based only on knowledge of pion decay kinematics & the beamline geometry

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

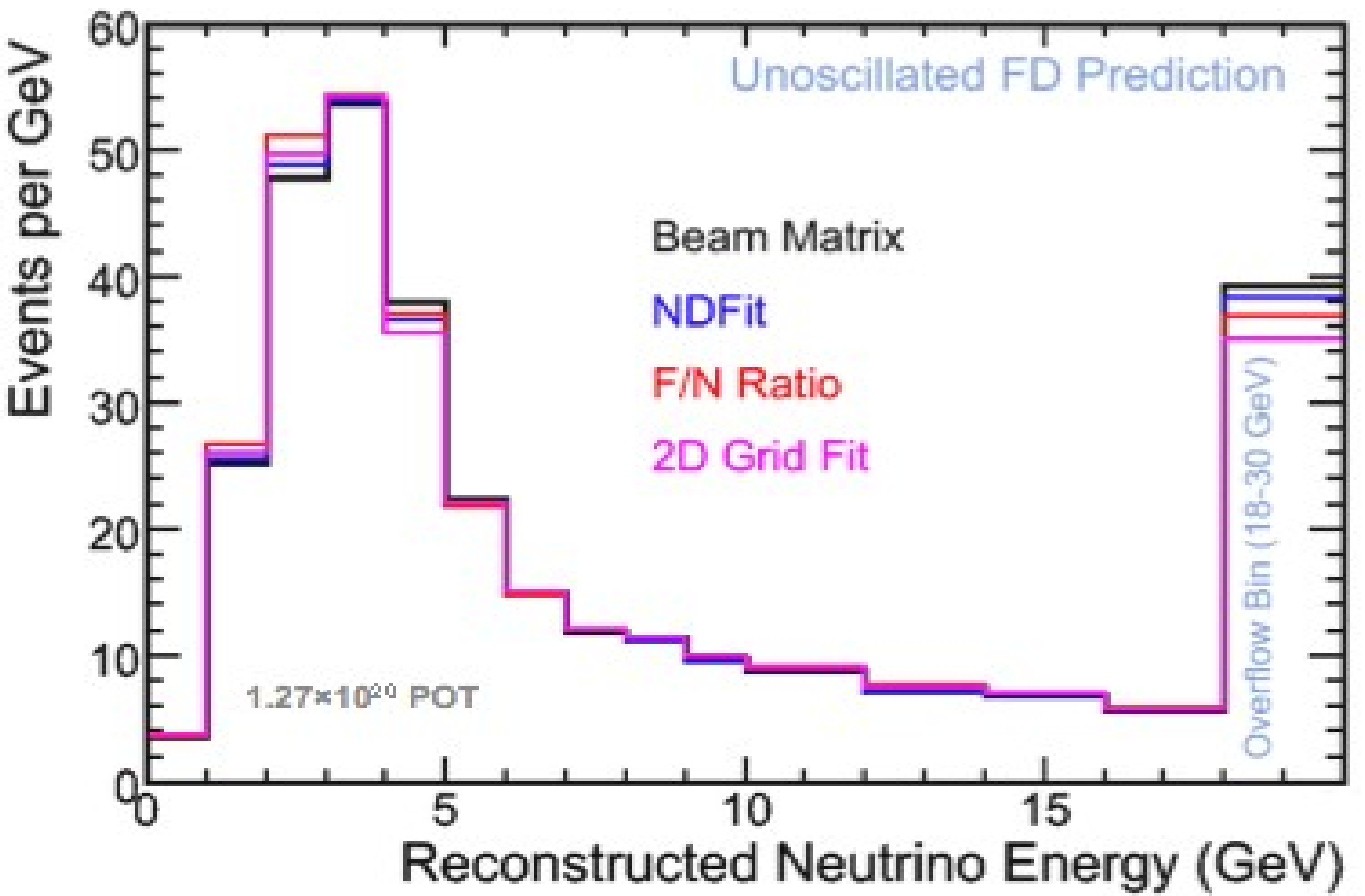


$$Flux \propto \frac{1}{L^2}\left(\frac{1}{1+\gamma^2\theta^2}\right)^2$$



Prediction of FAR spectrum

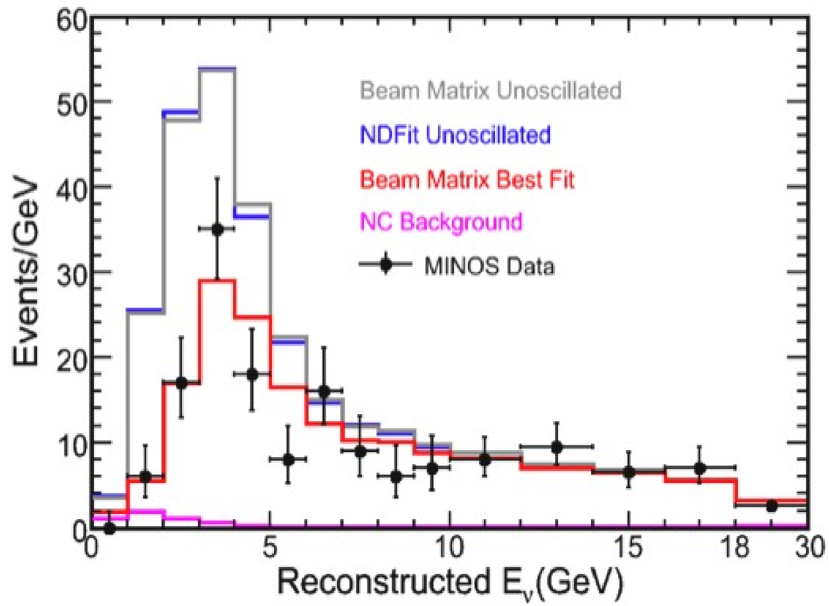
- Alternative extrapolation methods give nearly identical results
- Confidence in out ability to predict the un-oscillated FAR spectrum
- Having a 2-detector experiment pays off!



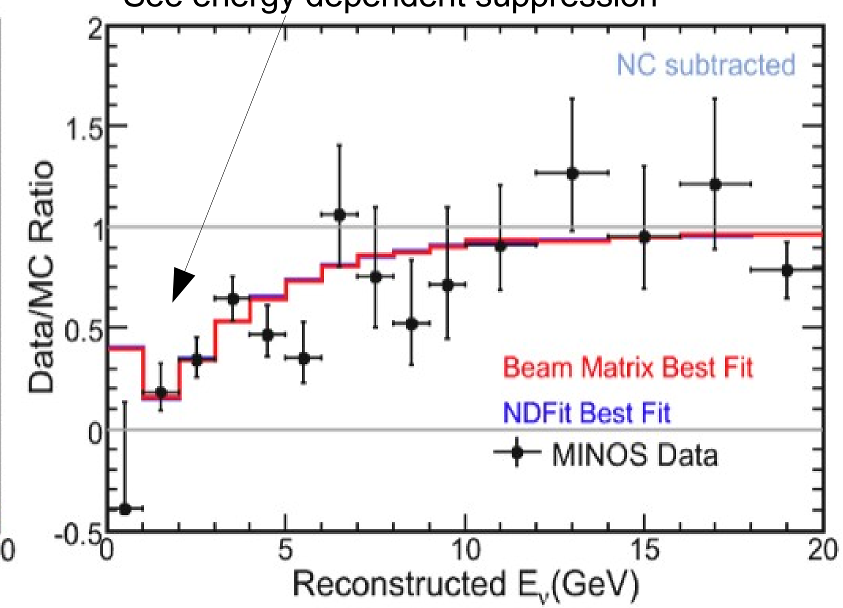
Observed rates & best-fit spectrum

Data sample	observed	expected	ratio	significance
ν_μ only (<30 GeV)	215	336.0±14.4	0.64±0.05	5.2σ
ν_μ only (>10 GeV)	93	97.3±4.2	0.96±0.04	0.4σ
ν_μ only (<10 GeV)	122	238.7±10.7	0.51±0.06	6.2σ

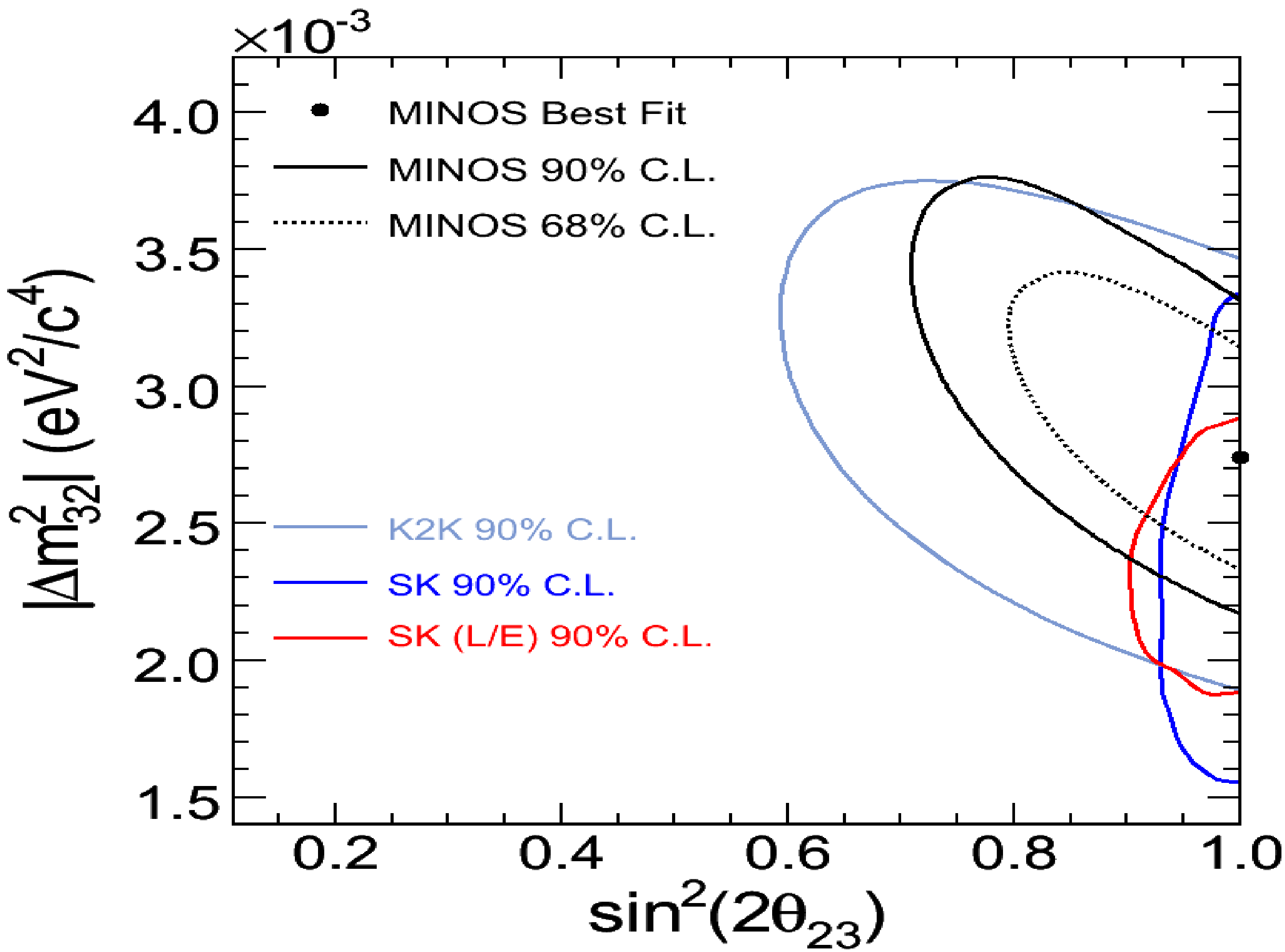
$$\chi^2 = \sum_{i=1}^{\mathrm{nbins}} \left[2(e_i - o_i) + 2 o_i \ln(o_i / e_i) \right] + \sum_{j=1}^{\mathrm{nsys}} \Delta s_j^2 / \sigma_{s_j}^2$$



See energy dependent suppression



Allowed regions & Best fit parameters



Best fit parameters:

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

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

Systematic errors

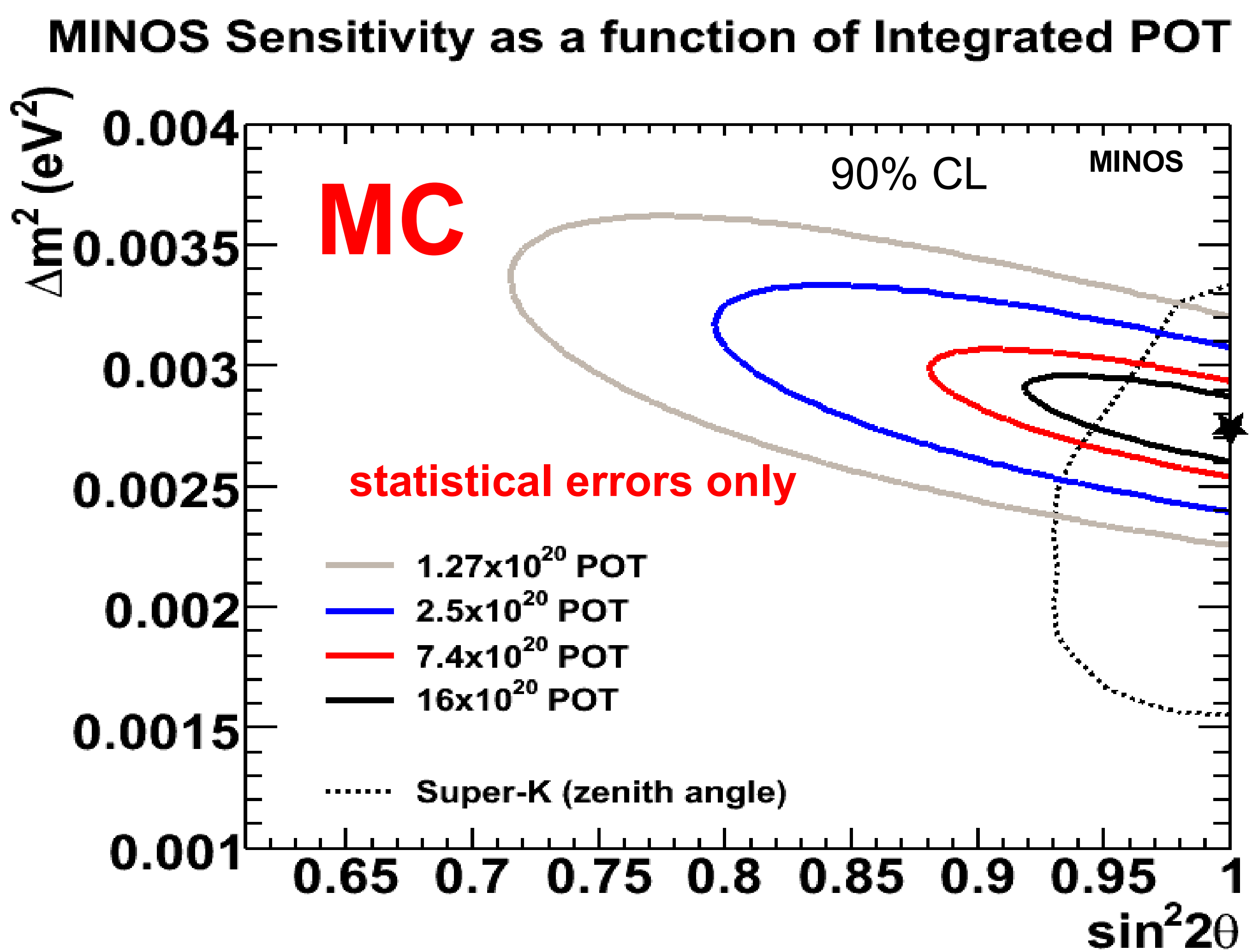
Computed with fake (mc) data at Δm^2=0.0027eV^2, $\sin^2 2\theta$=1.0

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

- 3 largest uncertainties included in oscillation fit as nuisance parameters
- Size of uncertainties are obtained by doing MC studies
- Table shows shift in the oscillation parameters by fitting fake data

Current Status / Projected Sensitivity

An updated analysis is coming soon (~2.6E+20 POT)



Ιvπυτσ: Δm^2=0.00274eV^2, $\sin^2 2\theta$=1.0

Summary

MINOS has completed / published a numu CC disappearance analysis of the first year's beam exposure (1.27E+20 POT)

Exclude no-oscillations at 6.2σ (rate only)

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

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

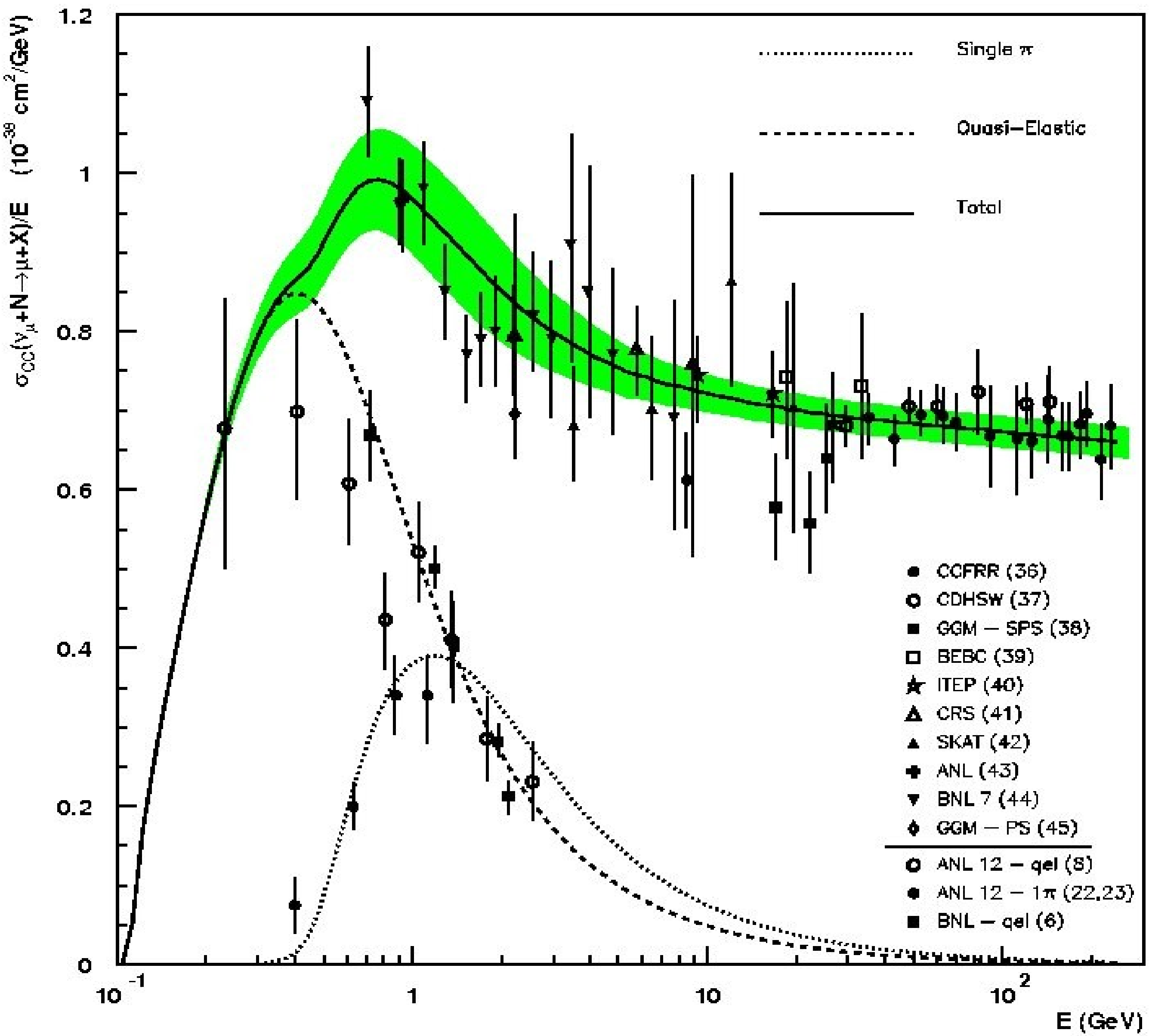
Analysis of the second year's data in progress

More analyses under way (numu->nue, search for sterile nus,...)

Back-up Slides

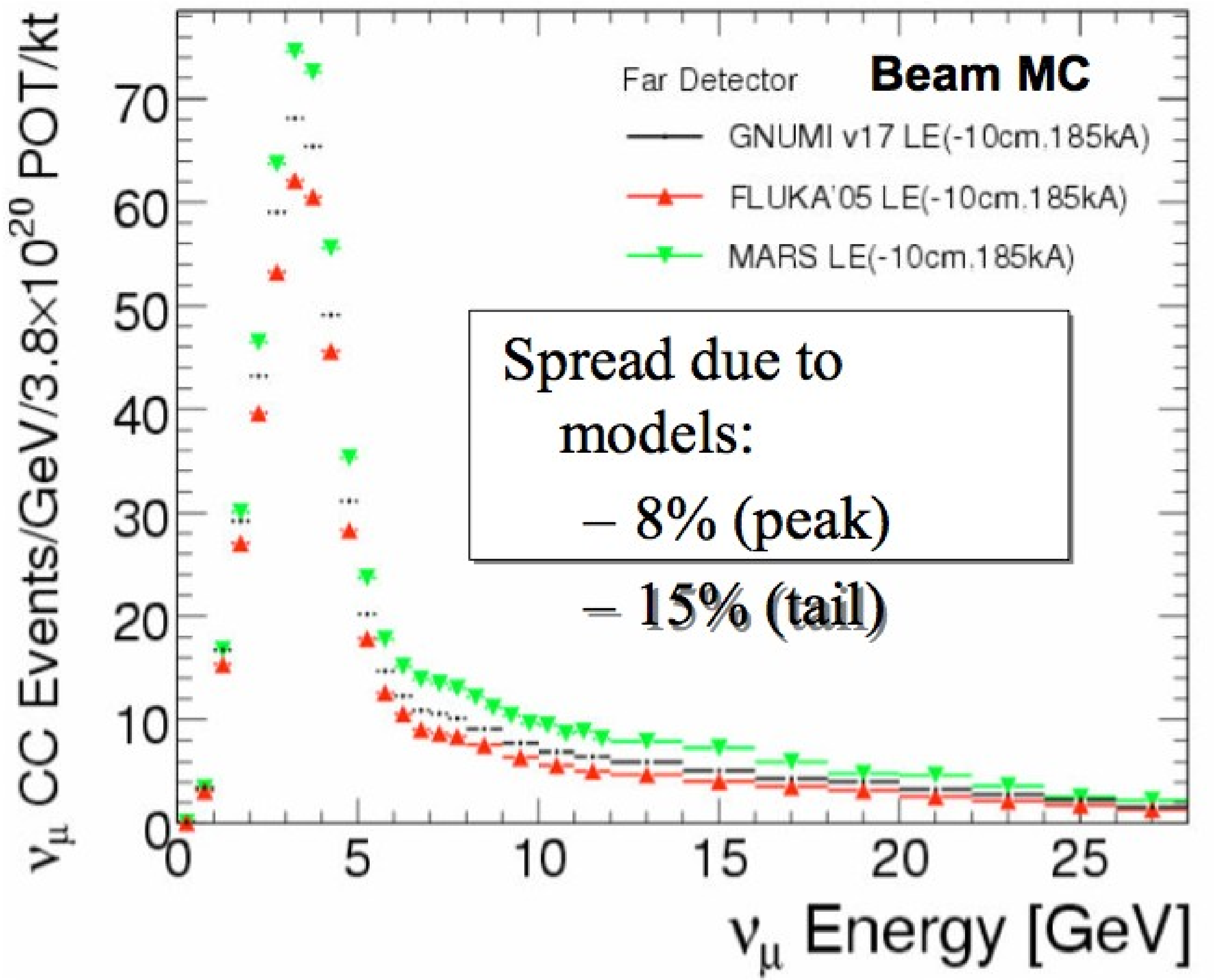
Cross Section Uncertainty

Back-up Slide

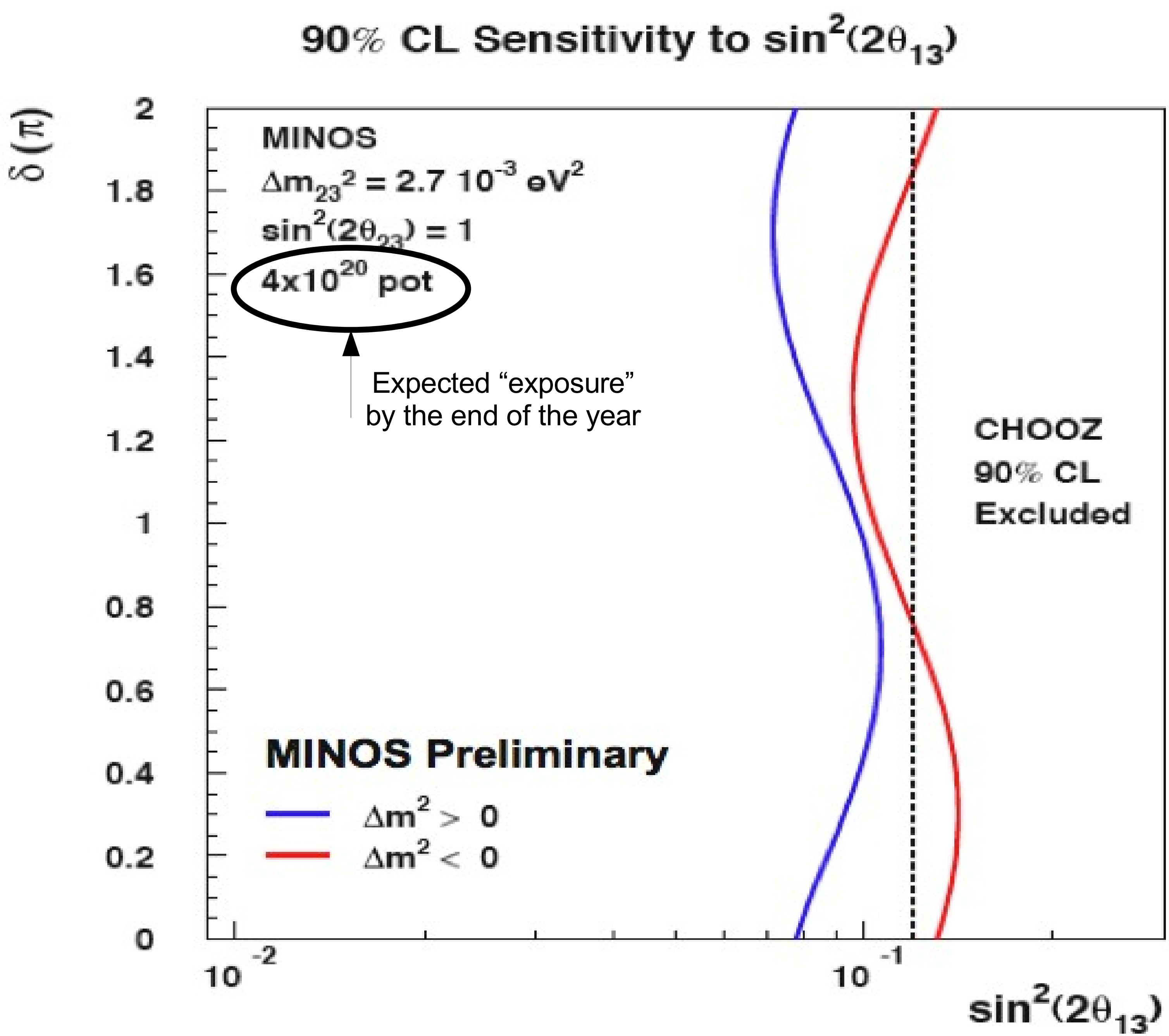


Hadron Production Uncertainty

Back-up Slide



Physics reach: nu_e appearance



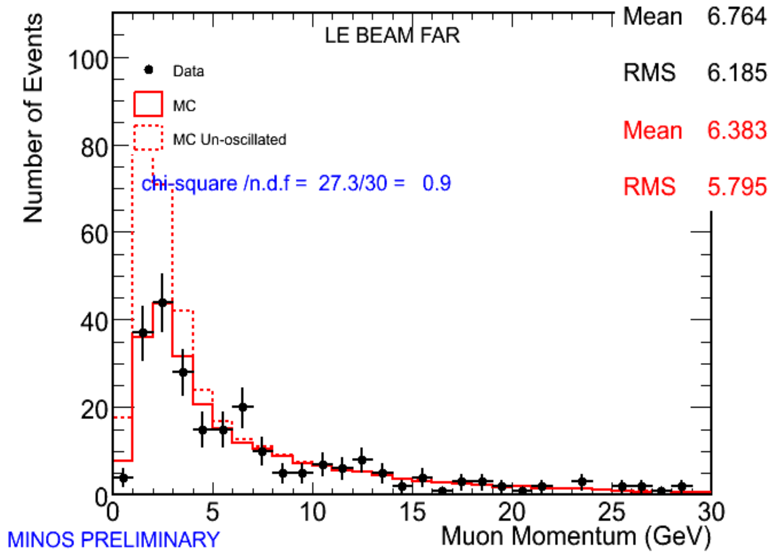
Physics Distributions

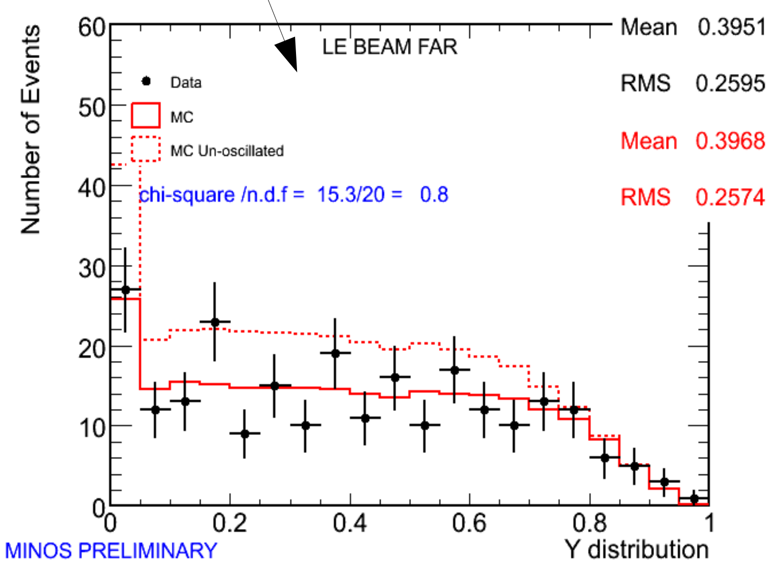
Back-up Slide

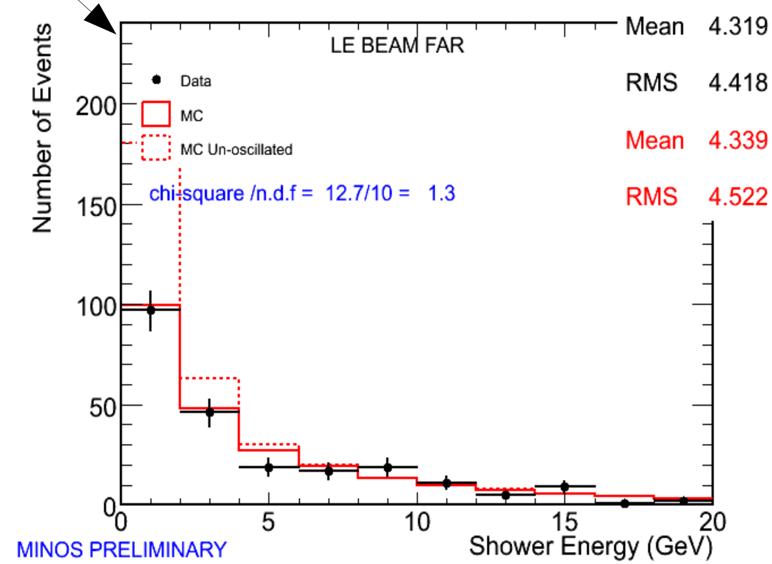
Muon momentum

Shower energy

Inelasticity y

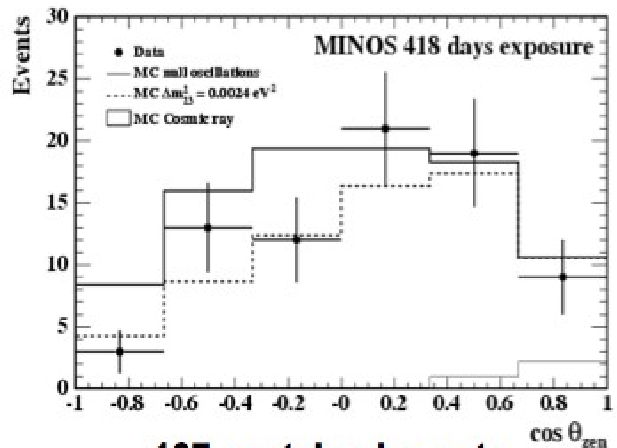






Atmospheric Neutrinos

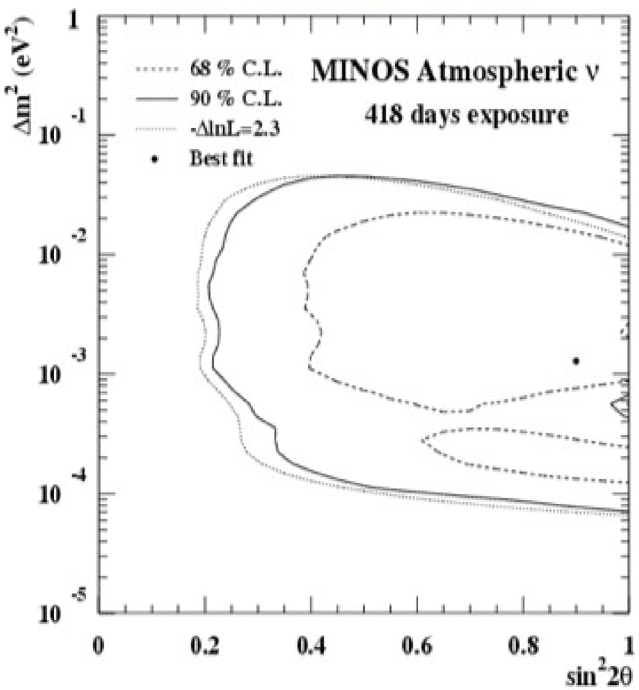
Back-up Slide

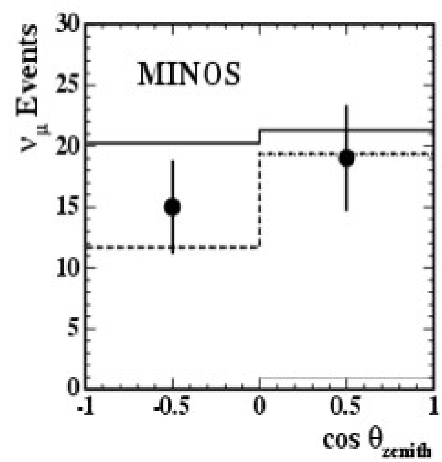


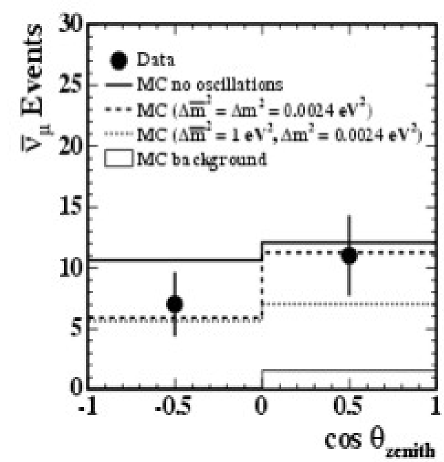
107 contained events

PRD 73, 072002 (2006)

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

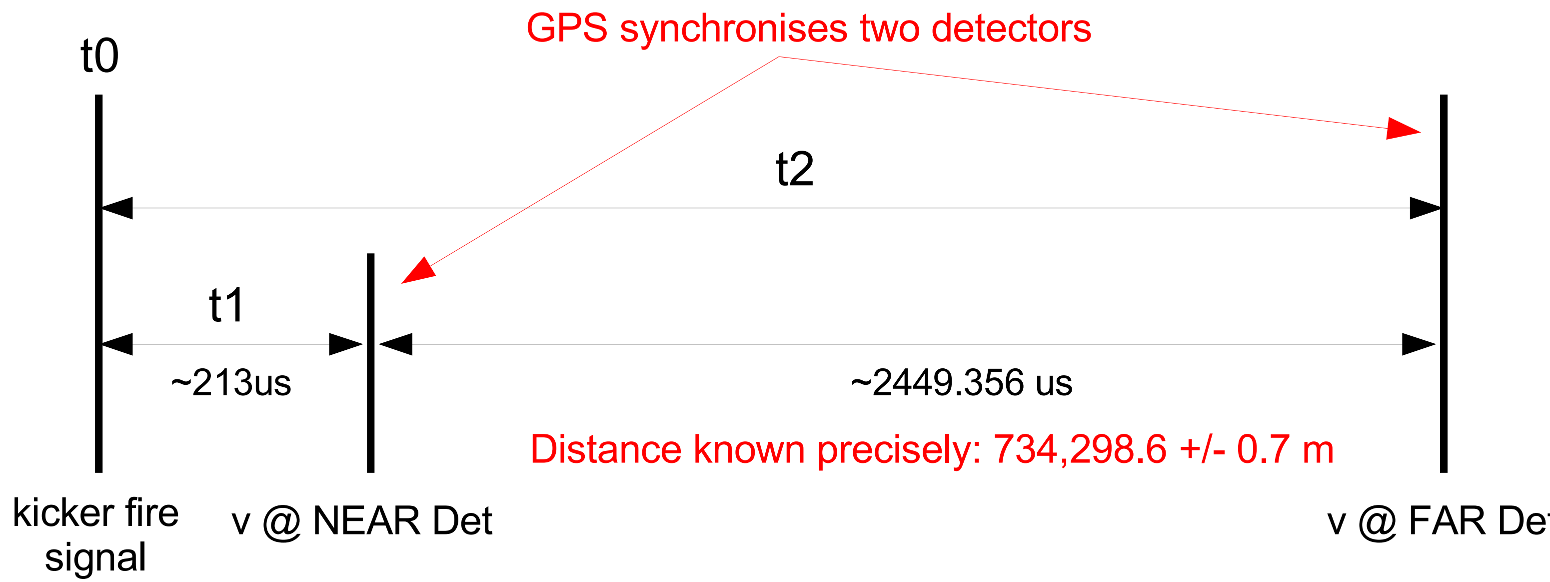


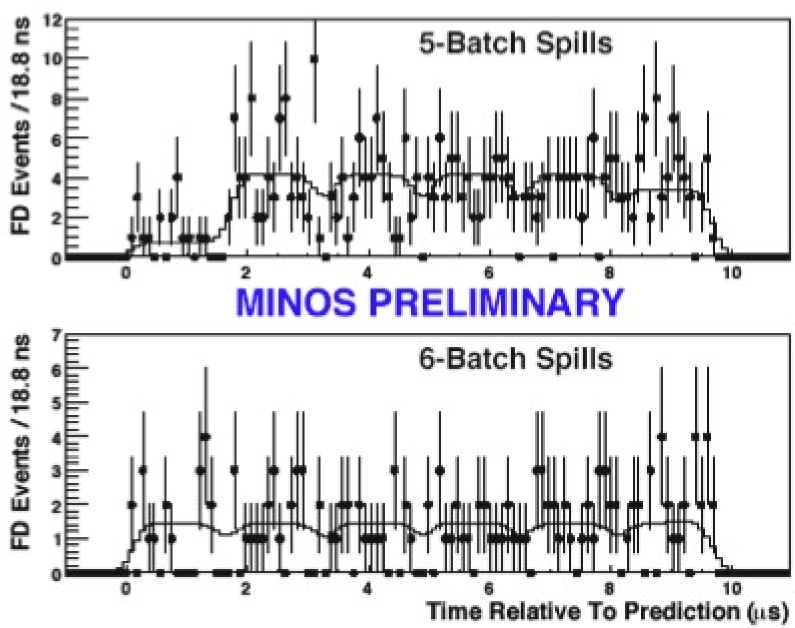




Neutrino Time Of Flight

Back-up Slide





Time of Flight Measurement:

Nominal: (734298.6 ± 0.7 m distance)
2449356 ns

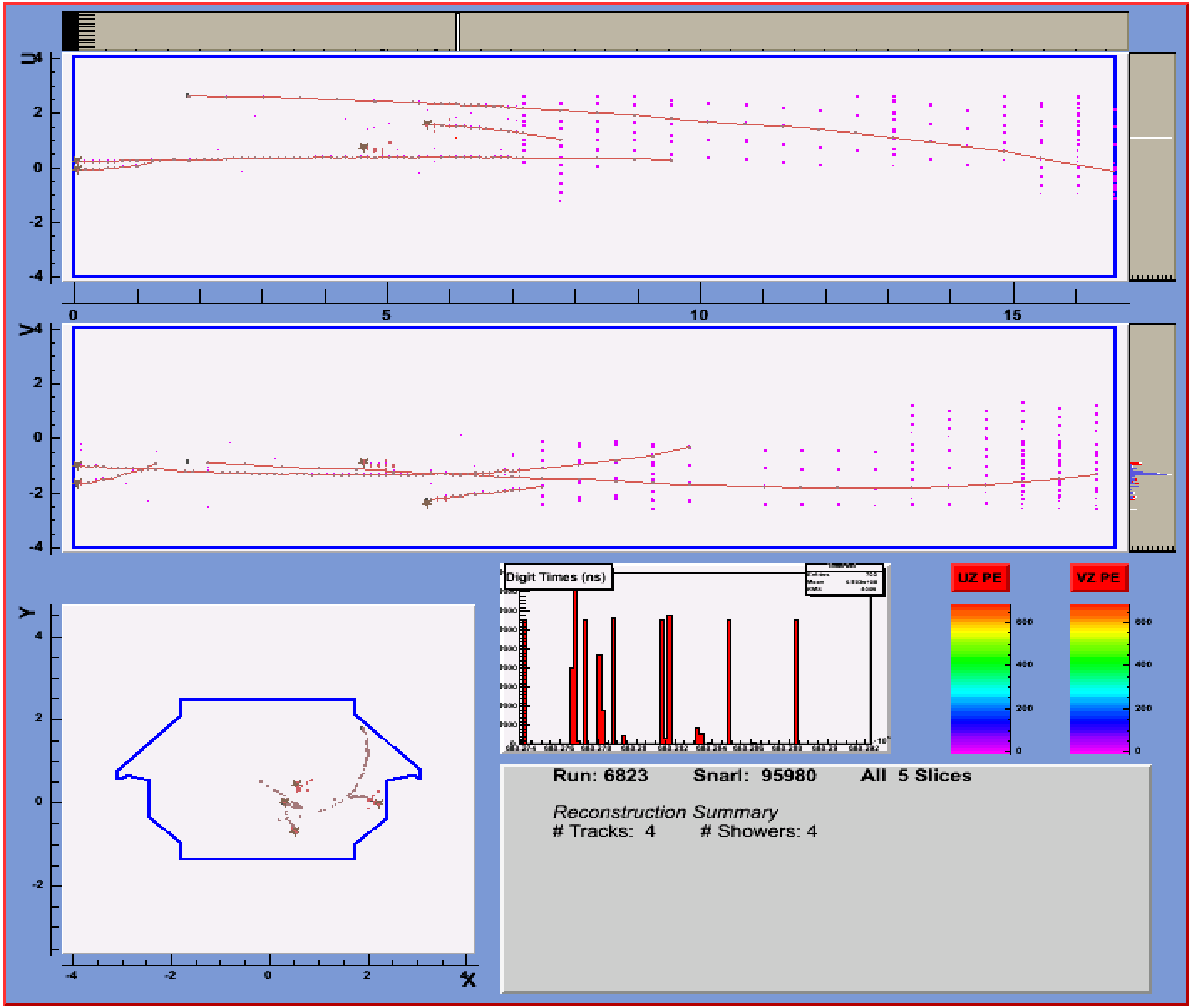
Measured:
2449223 ± 84 (stat) ± 164 (sys) ns
99% C.L.

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

NEAR Detector data events

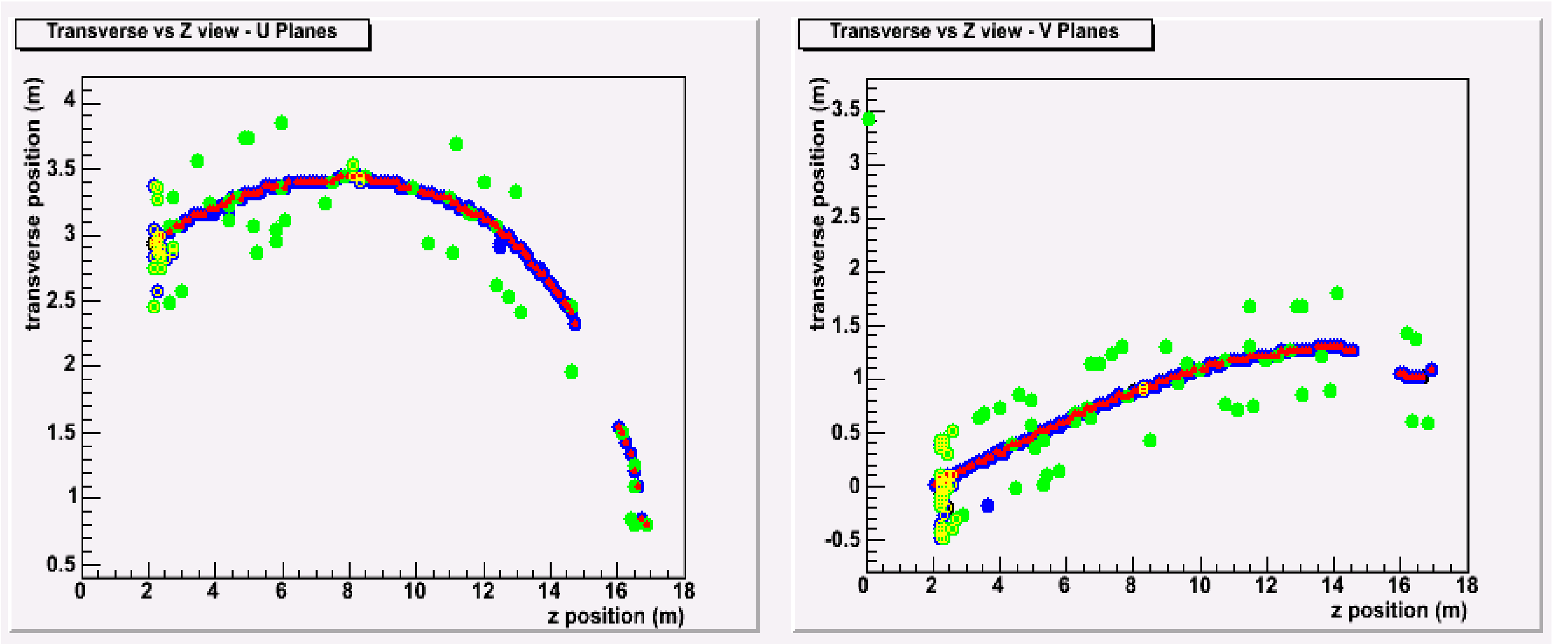
Back-up Slide

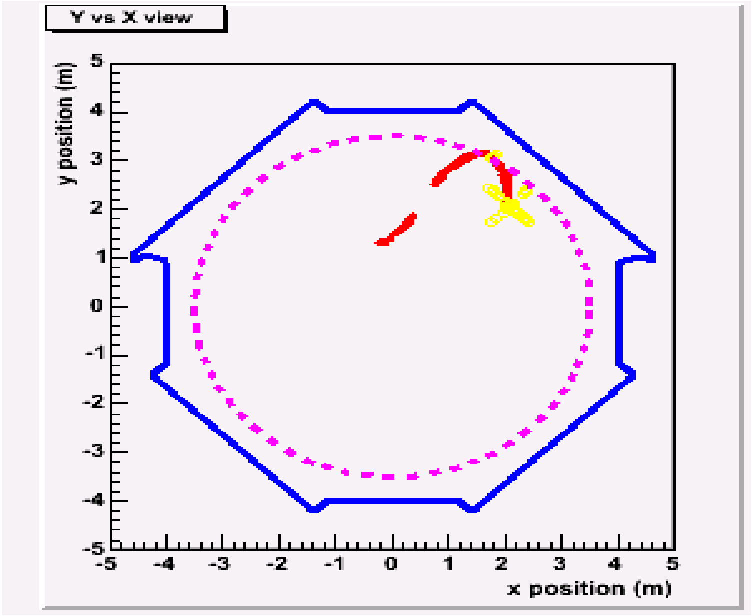
High rates, Multiple neutrino interactions per beam spill.



FAR Detector data events

Back-up Slide





Track energy from range: 9.596 GeV

Reconstructed Shower energy: 5.108 GeV