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Recent Results from the MINOS Experiment

Costas Andreopoulos (*)

** for the MINOS collaboration*

Double Beta Decay & Neutrinos 2007 (DBD07), June 11-13, Osaka, Japan

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

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A quantum-mechanical interference effect

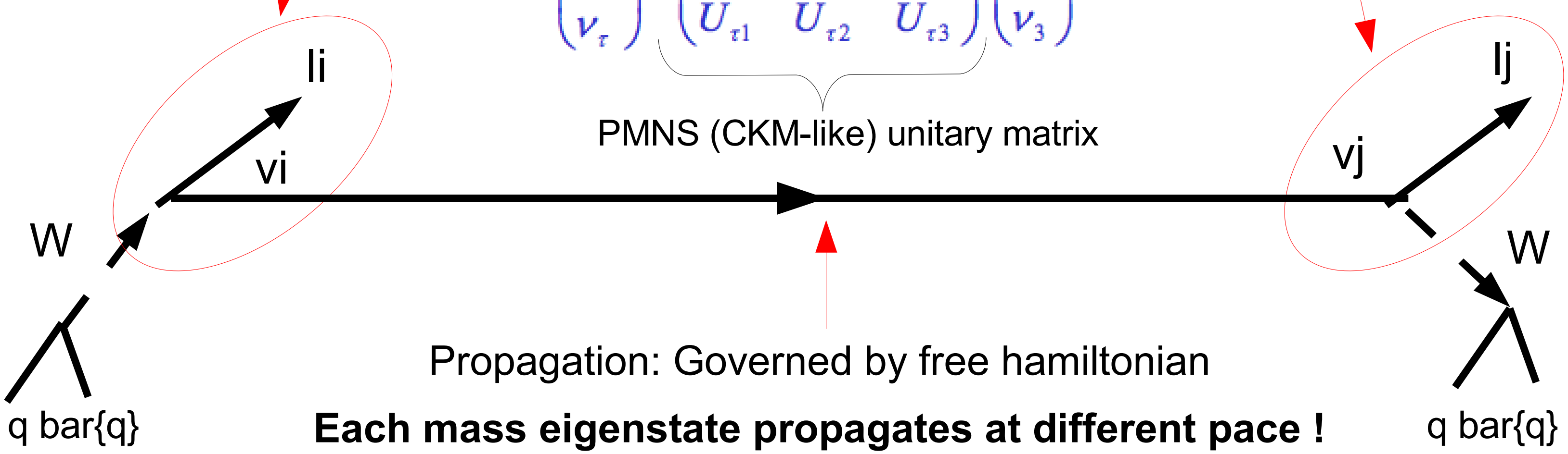
Production & Detection: Governed by electoweak hamiltonian

Producing / detecting interaction eigenstates

(superposition of **mass eigenstates**)

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

PMNS (CKM-like) unitary matrix



Propagation: Governed by free hamiltonian

Each mass eigenstate propagates at different pace !

Relative mixture of mass eigenstates changes!

Flavour oscillations are possible

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

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

Open Questions

Goals:

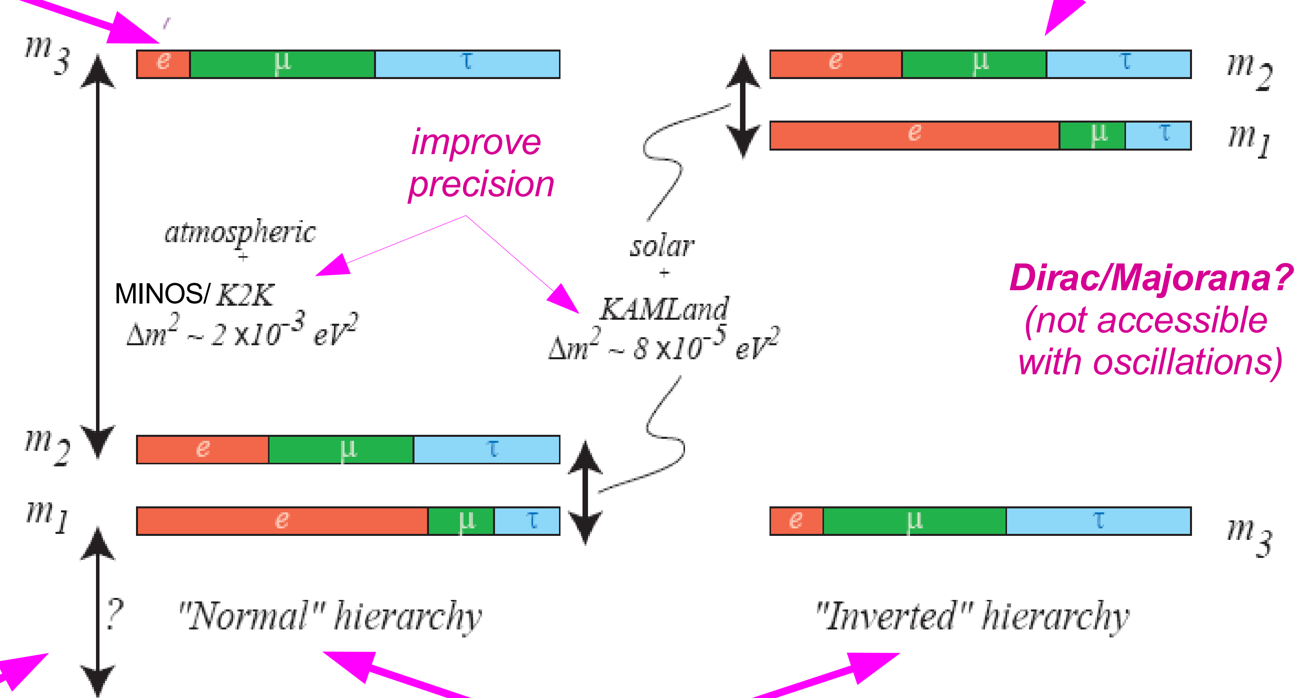
- *Determine the elements of the PMNS matrix*
- *Determine neutrino mass (splittings)*

- 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 CP violated at the leptonic sector?

Is theta23 maximal? *(hidden symmetry?)*



Dirac/Majorana? *(not accessible with oscillations)*

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

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

Physics Goals for MINOS

MINOS: A <u>precision</u> oscillation experiment

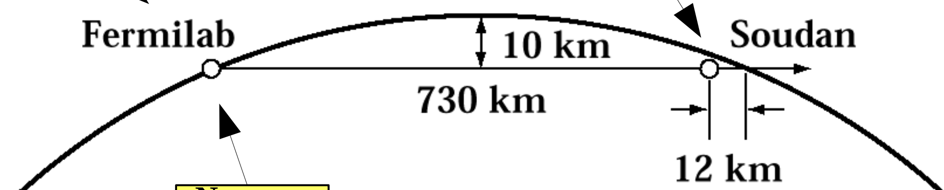
- Test the $\nu_\mu \rightarrow \nu_\tau$ oscillation hypothesis
  - Measure precisely $|\Delta m^2_{32}|$ and $\sin^2 2\theta_{23}$
- Search for sub-dominant $\nu_\mu \rightarrow \nu_e$ oscillations
- Search for/constrain exotic phenomena
- Compare ν_μ, $\overline{\nu_\mu}$ oscillations
- Atmospheric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

How the experiment is done

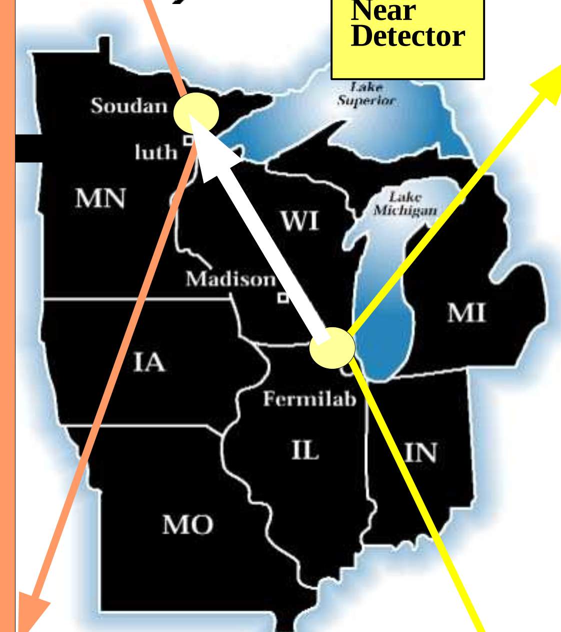
A 2 detector, long-baseline neutrino experiment using an intense, accelerator-made beam

beam source
(nu_mu) is here

Far Detector



Near Detector



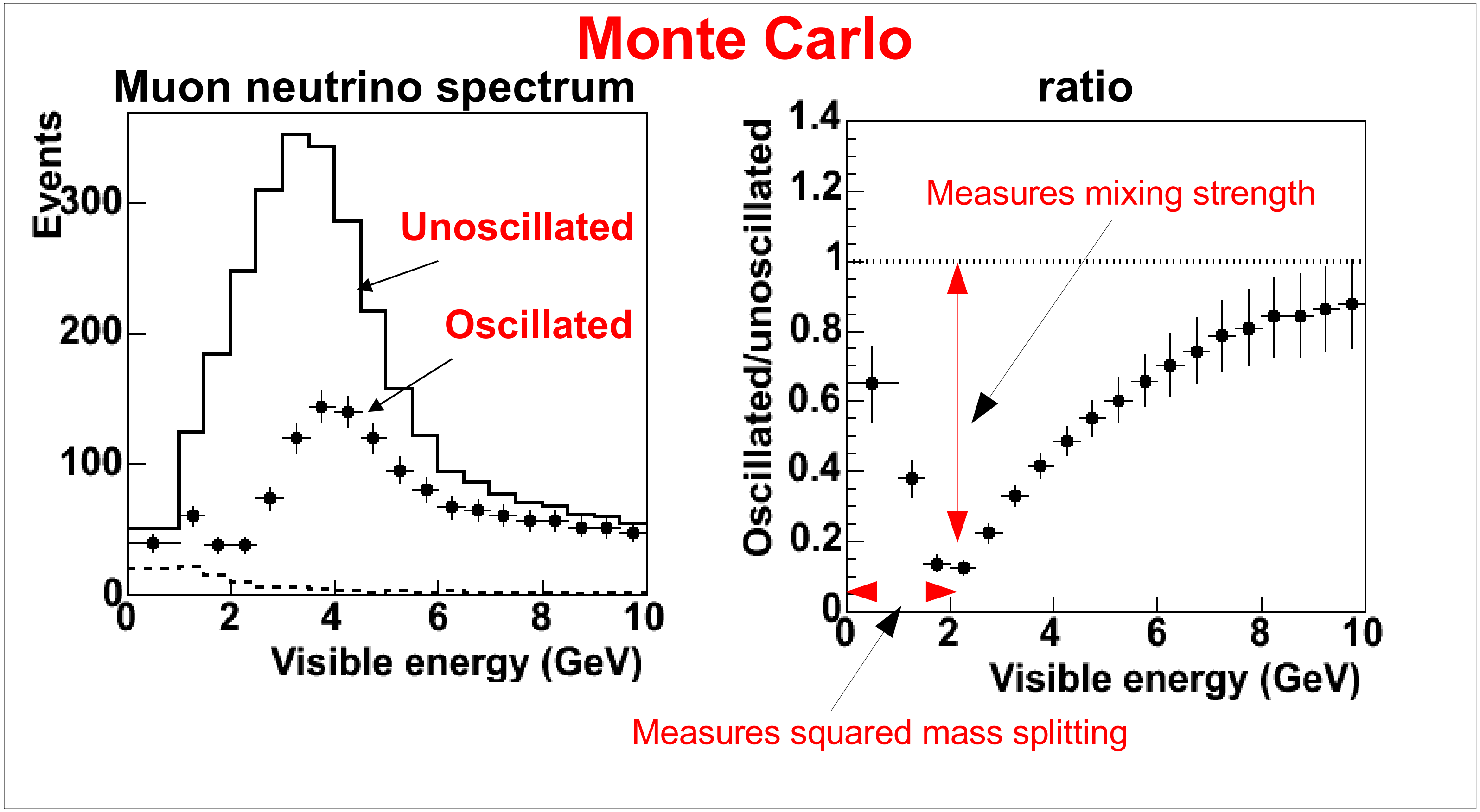
measures "oscillated" flux

measures "un-oscillated" flux

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



Cross Section Uncertainty

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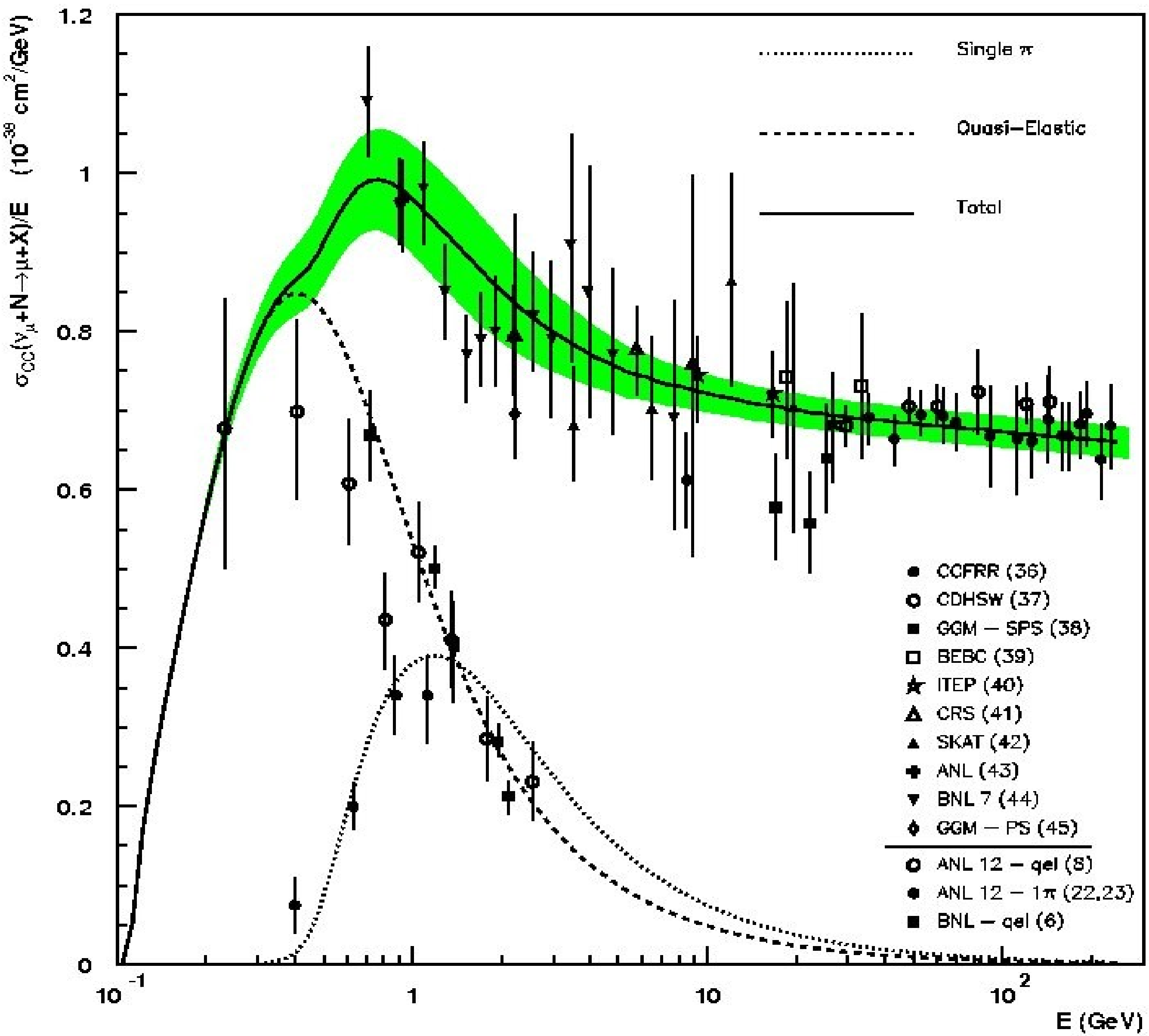
Why a 2 detector experiment? Reducing systematic errors



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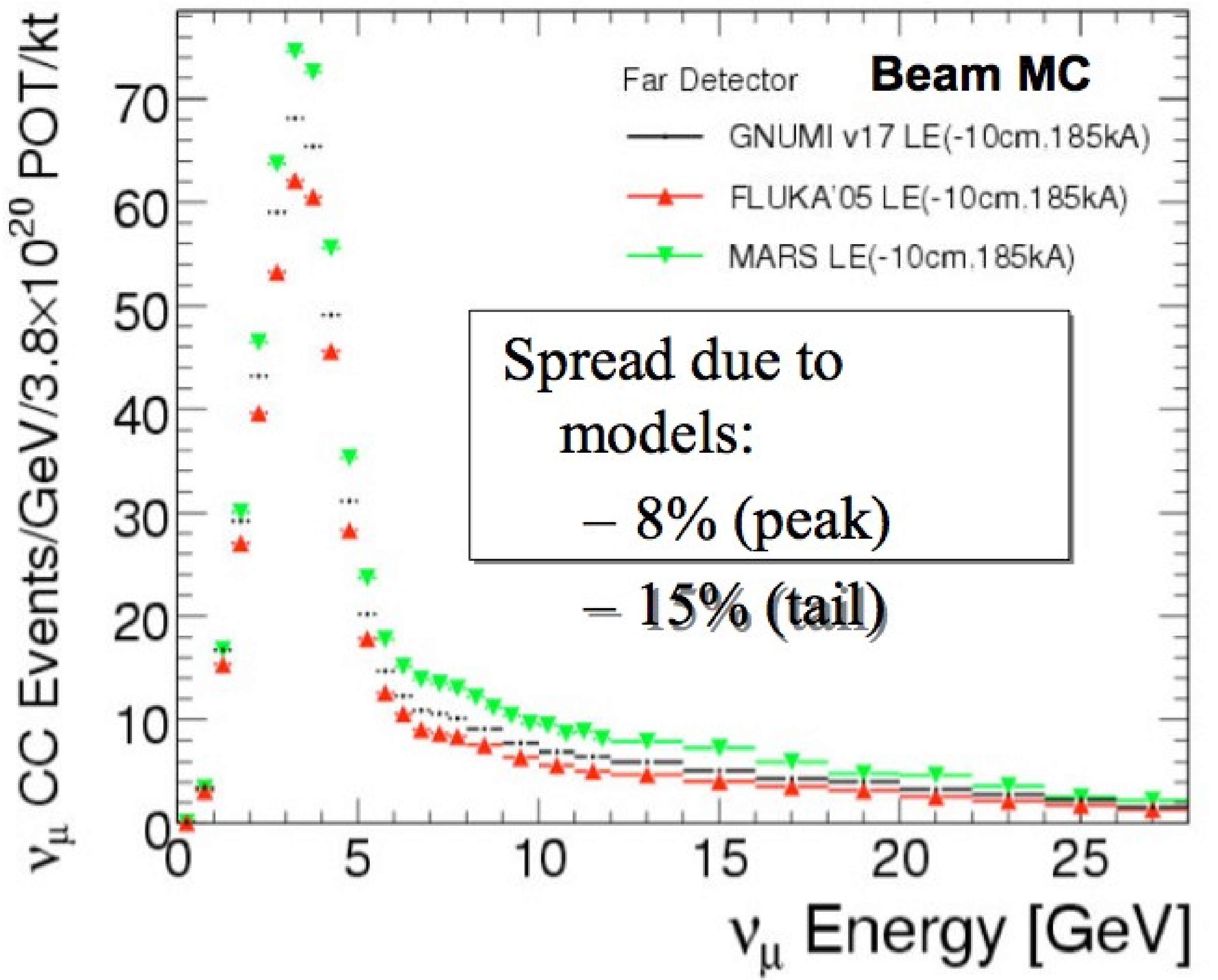
Hadron Production Uncertainty

Why a 2 detector experiment? Reducing systematic errors



The MINOS Collaboration

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Summary

Brazil

Campinas – Sao Paulo

France

College de France

Greece

Athens

Russia

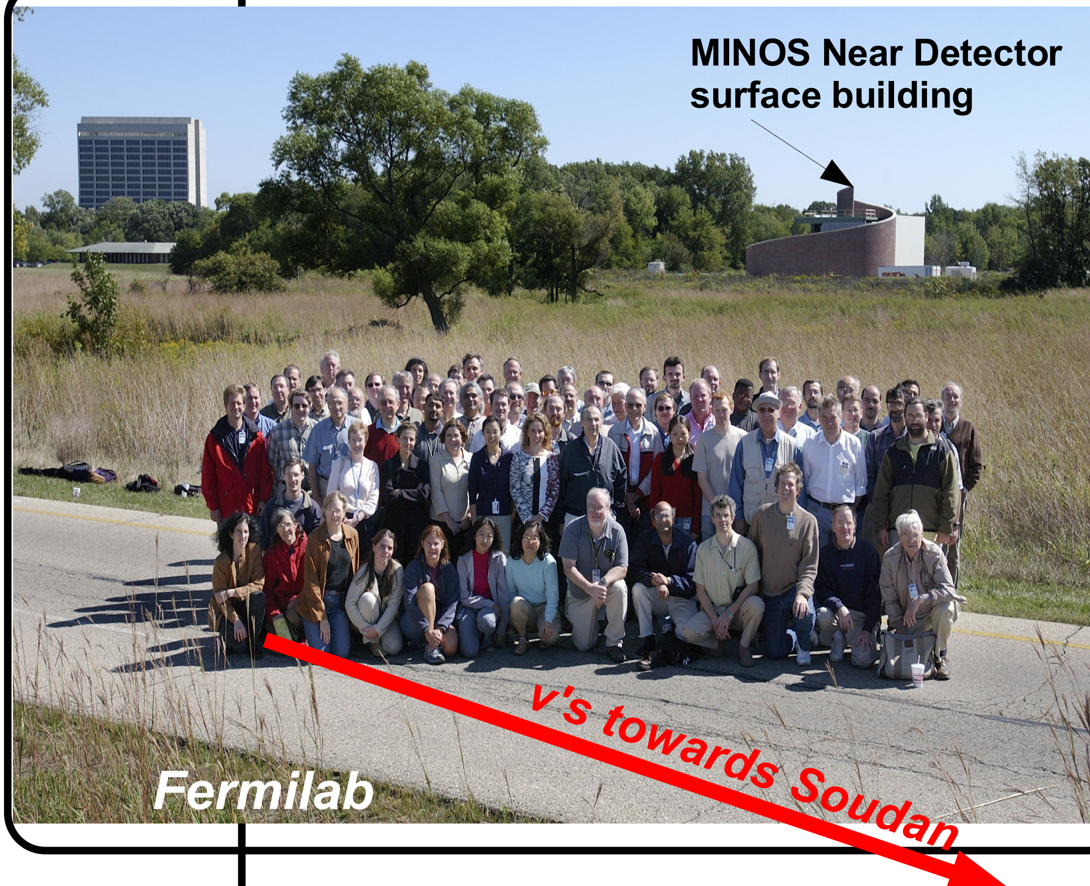
ITEP Moscow – Lebedev – Protvino

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**

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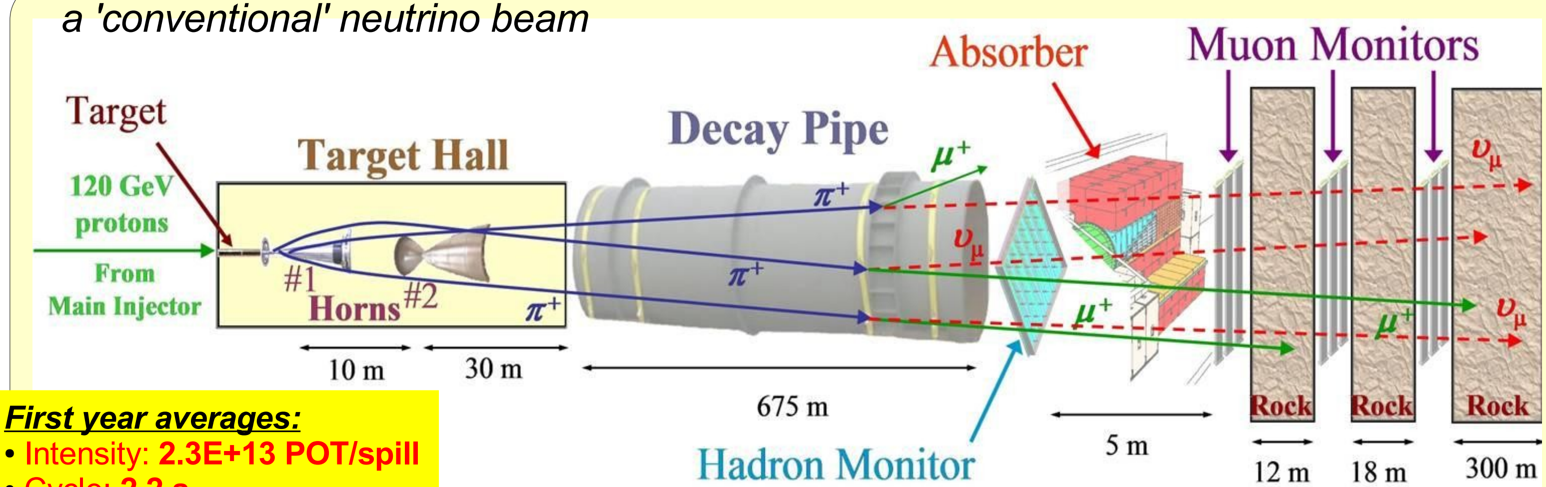
The NuMI beamline @ Fermilab

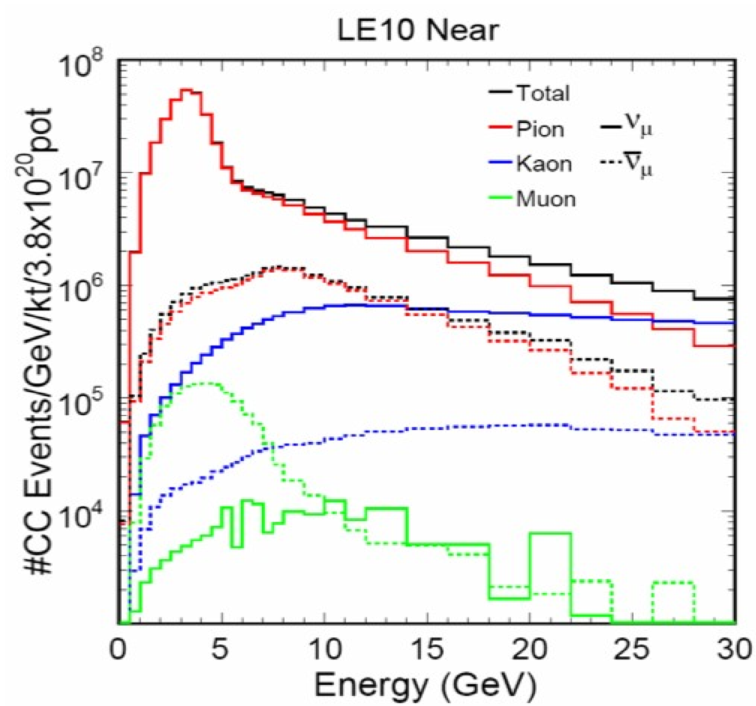
a 'conventional' neutrino beam

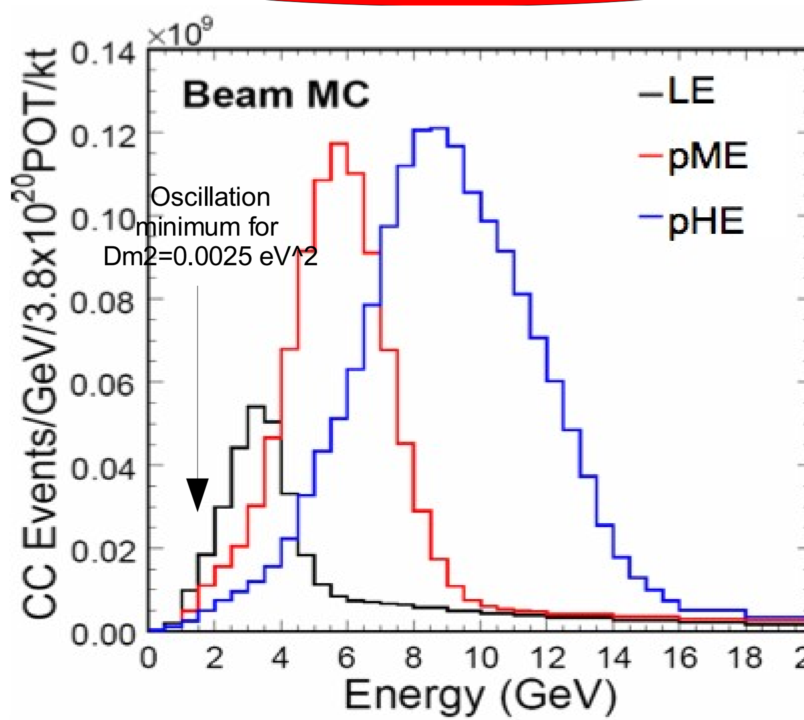


First year averages:
- Intensity: **2.3E+13 POT/spill**
- Cycle: **2.2 s**
- Power: **170 kW**

~pure / intense muon neutrino beam

tunable energy





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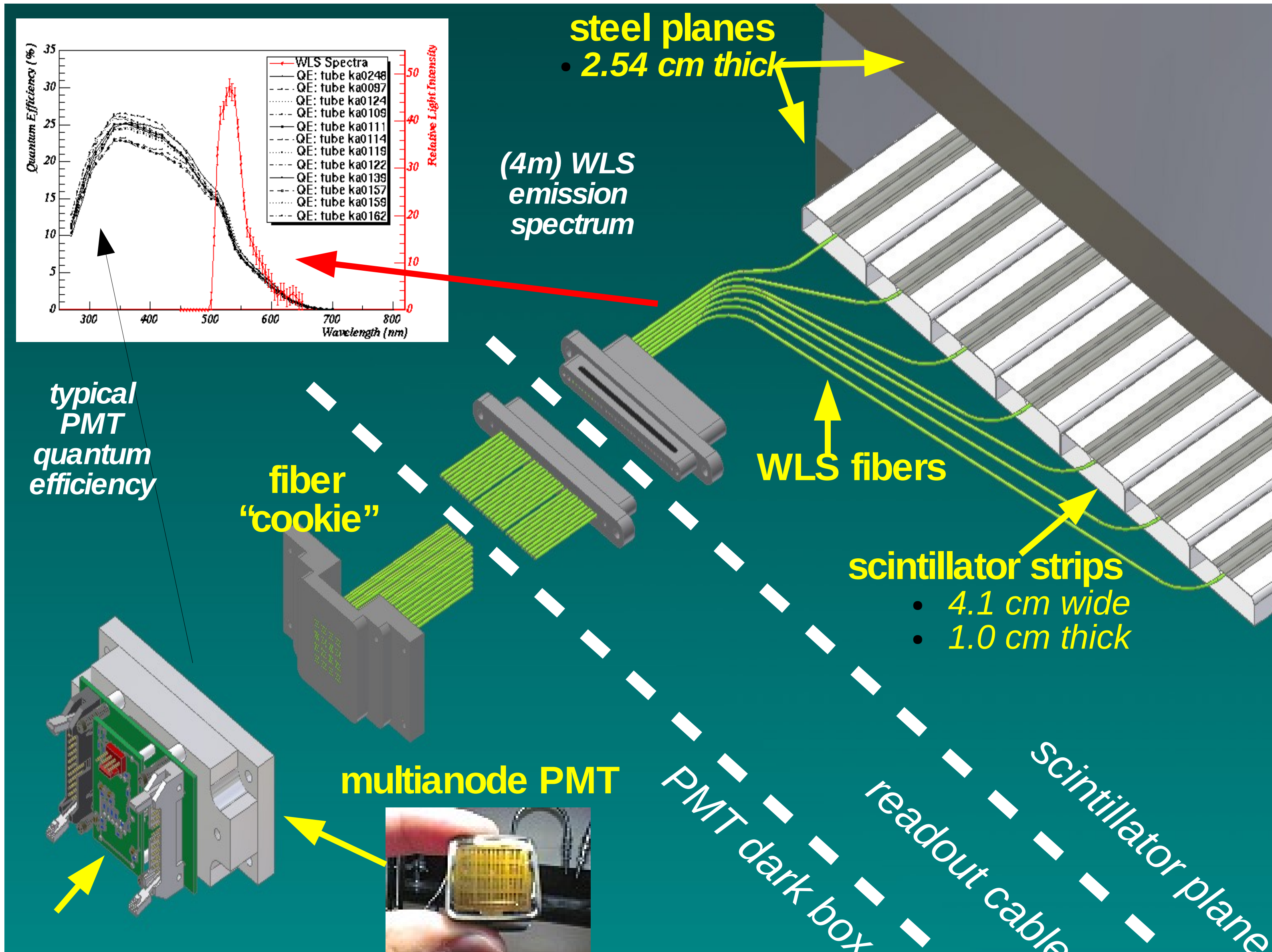
Detector Technology

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

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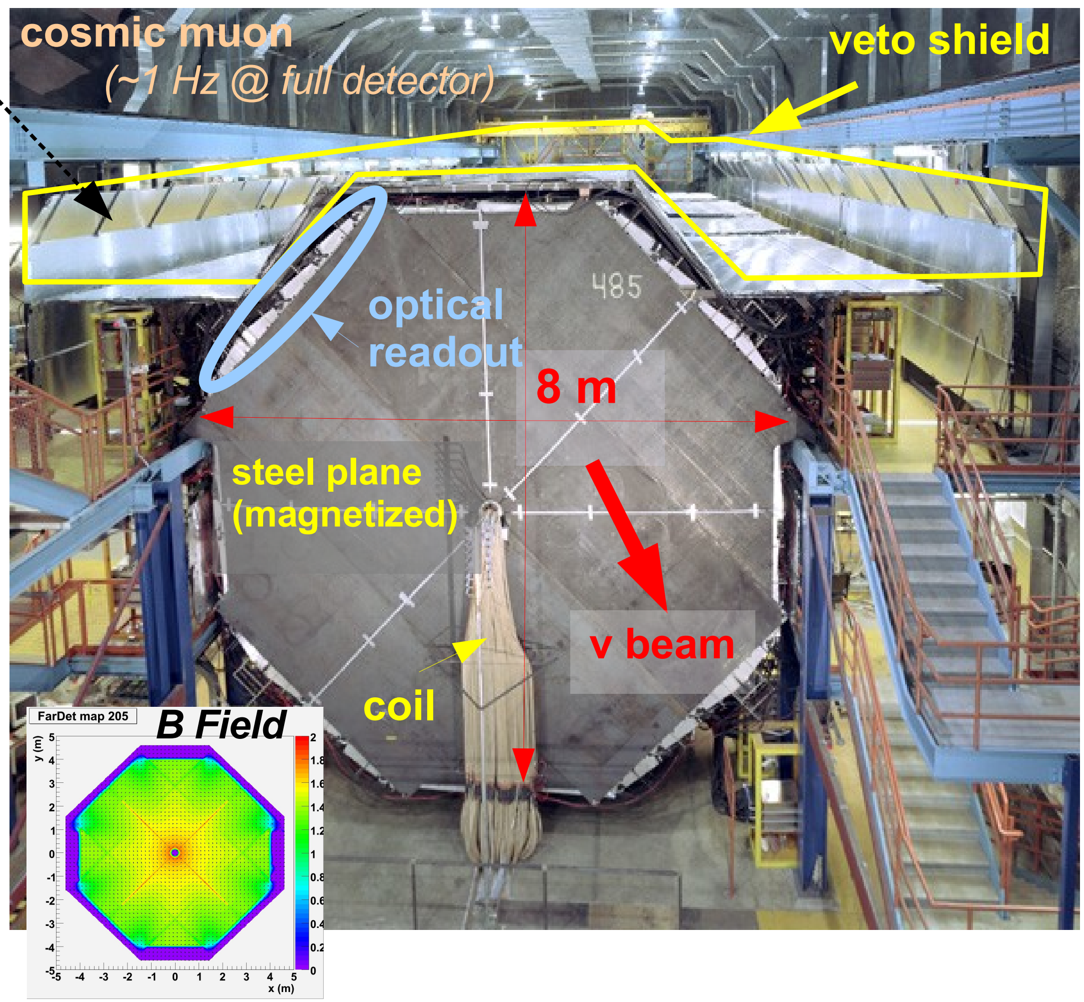
Purpose:
- Measure nu_mu CC, NC –– energy spectra & rates
- Search for nu_e appearance
- *Atmospheric Neutrino physics studies (upgoing muons, contained neutrino events,...)*
- *Cosmic Ray physics studies (mu+/mu- charge ratio, point sources, ...)*



- 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

The NEAR Detector @ Fermilab

Purpose:

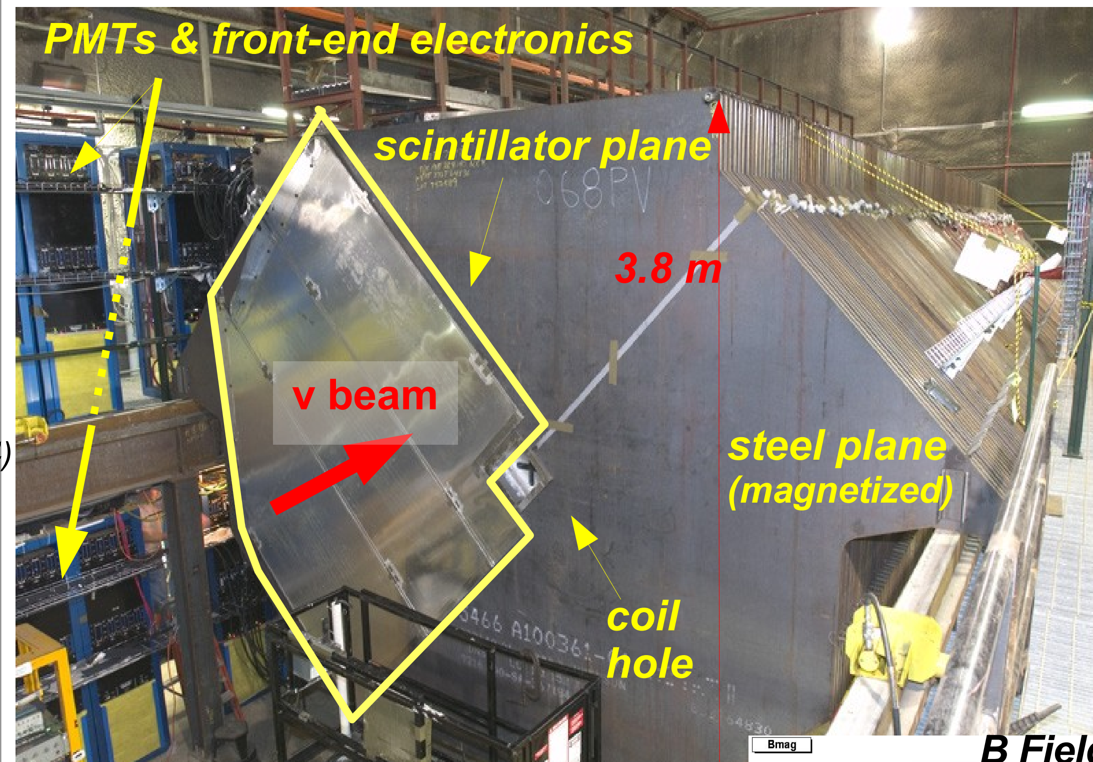
- Measure beam with high statistics before oscillations
- Tune neutrino & beam / hadron-production MC
- Predict Far detector spectrum

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

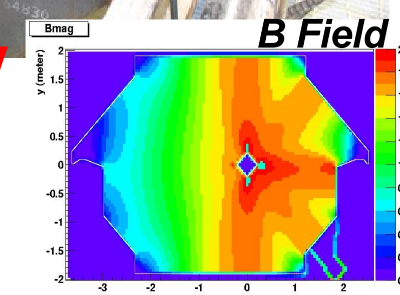
- **~ 1 kton**
- **282** steel planes
- B Field ~ **1.2 T**

- **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

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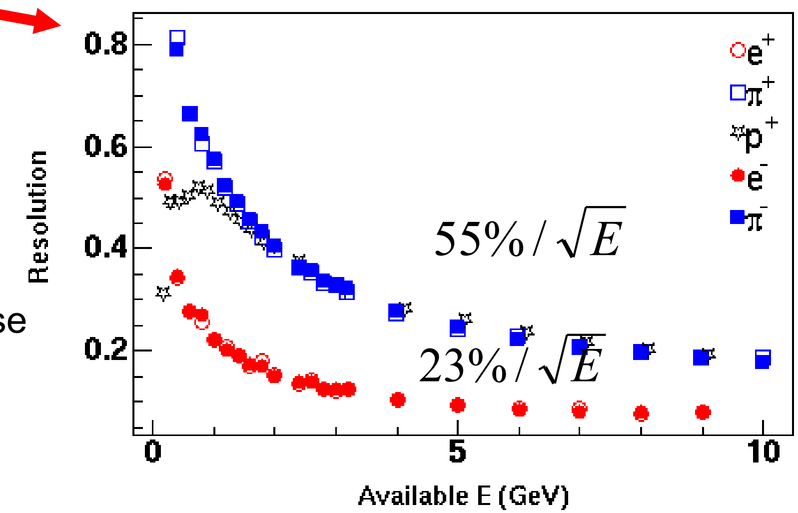
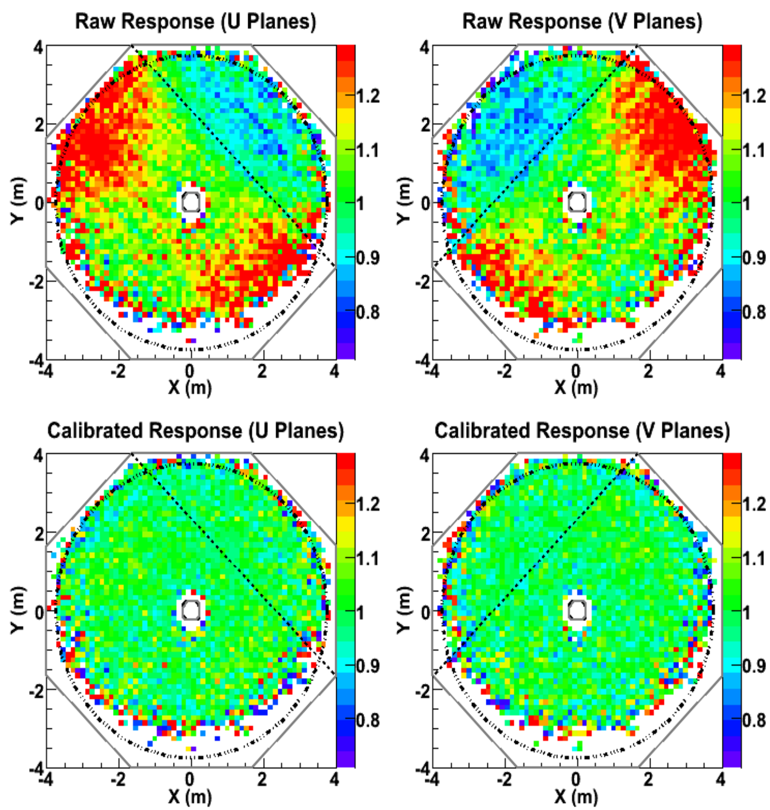
- Calibration detector
  - Determine overall energy scale
- Light Injection system
  - Determine/monitor PMT gains
- Cosmic ray muons
  - Equalize strip to strip response
  - Equalize detector to detector response

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?

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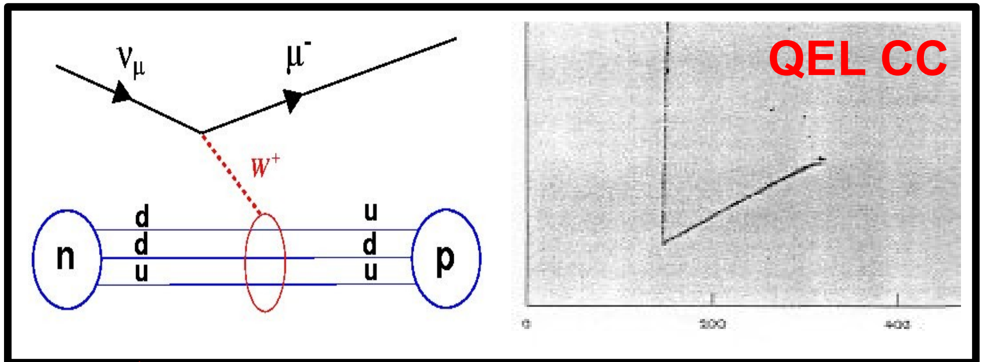
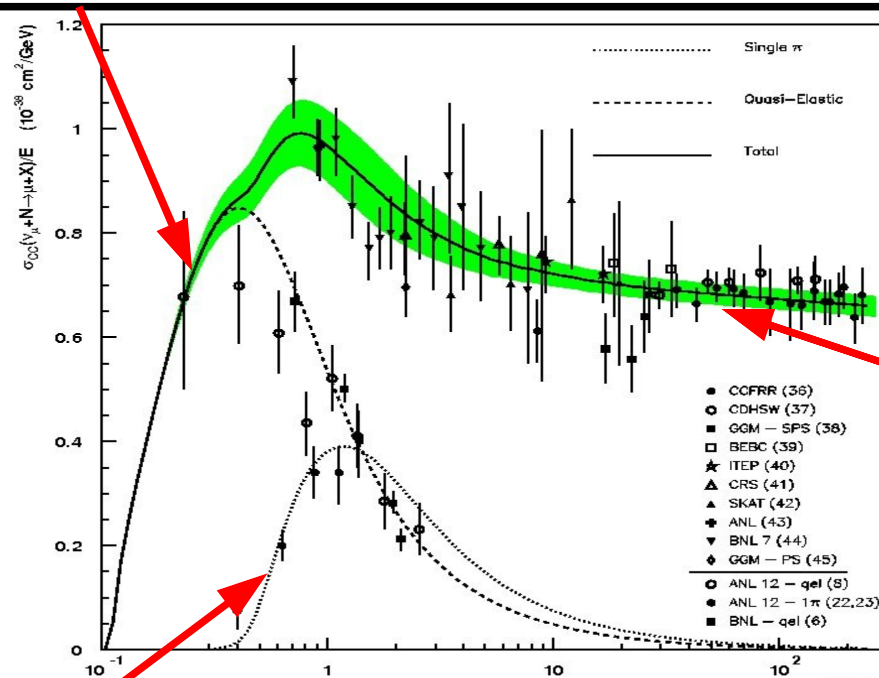
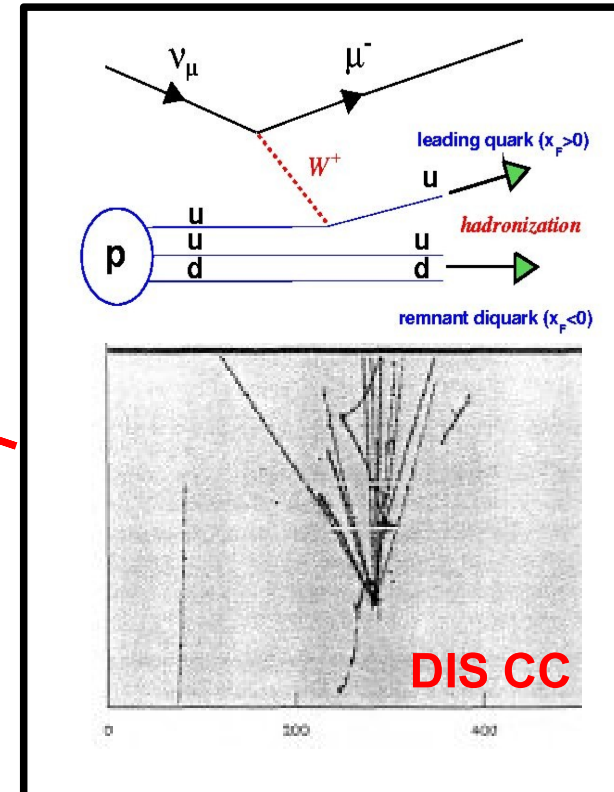
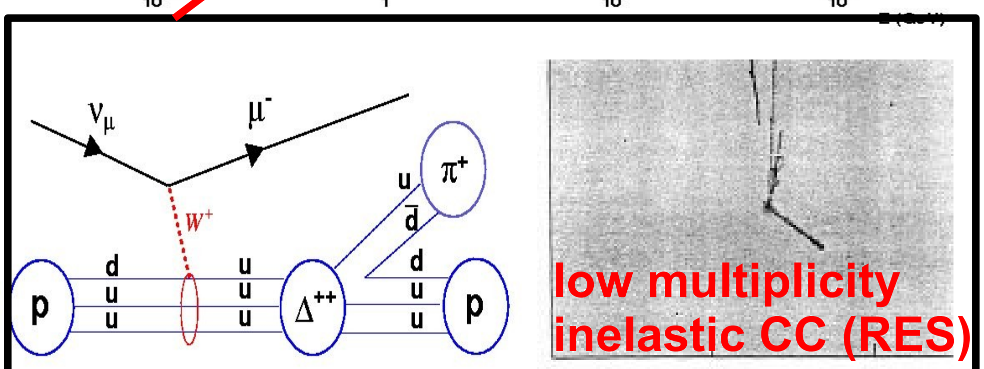






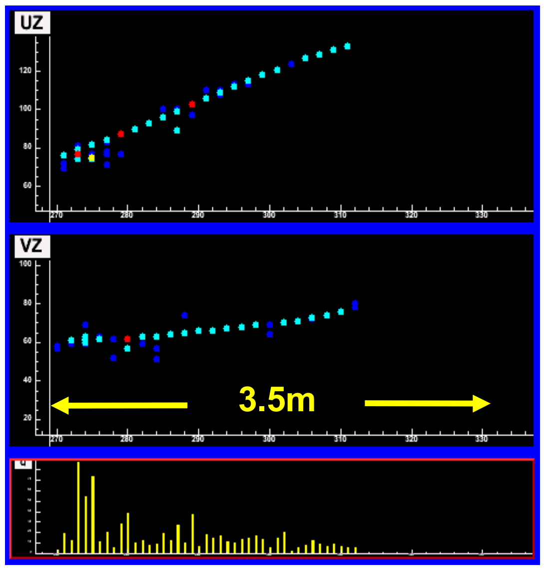


LAr images, courtesy A.Curríoni

Event topologies

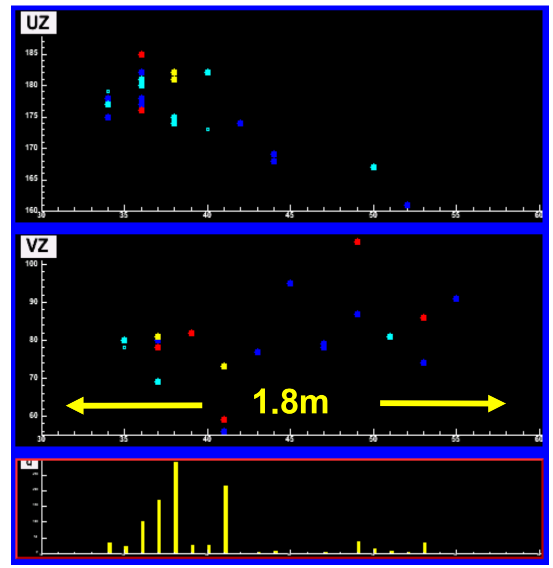
Monte Carlo Events

nu_mu CC



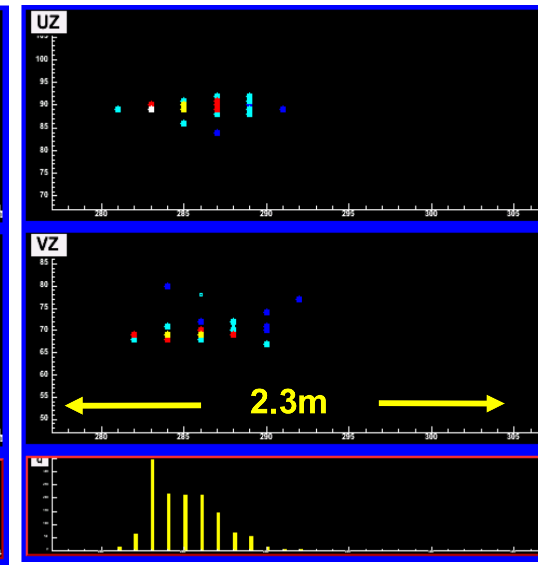
- long μ track
- hadronic activity at vertex

NC

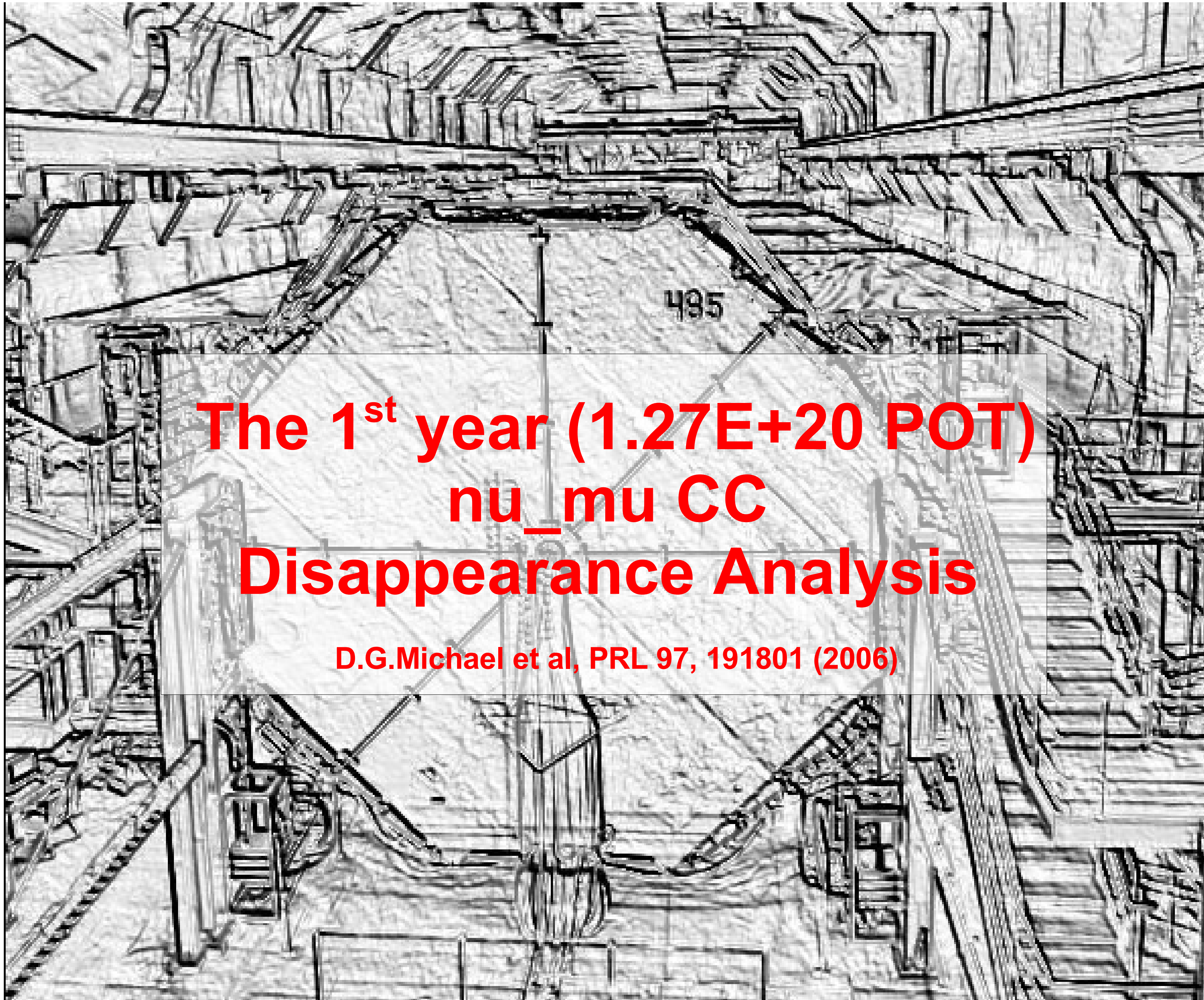


- short event
- often diffuse

nu_e CC



- short event
- typical EM shower profile

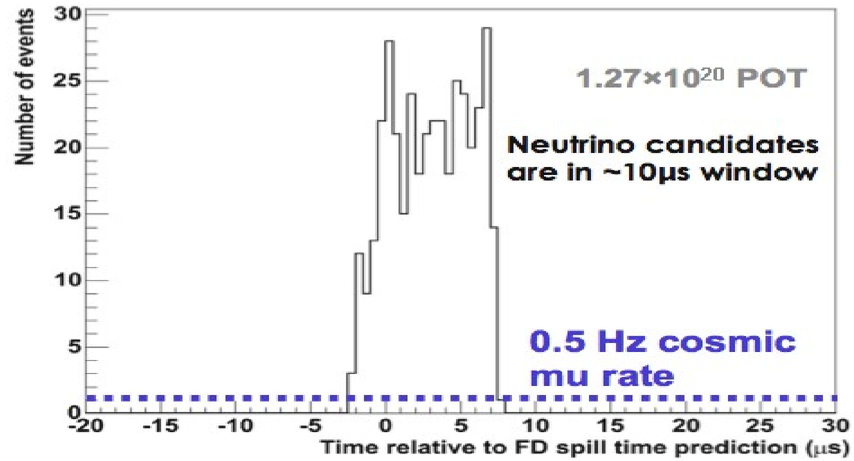


The 1st year (1.27E+20 POT) nu_mu CC Disappearance Analysis

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

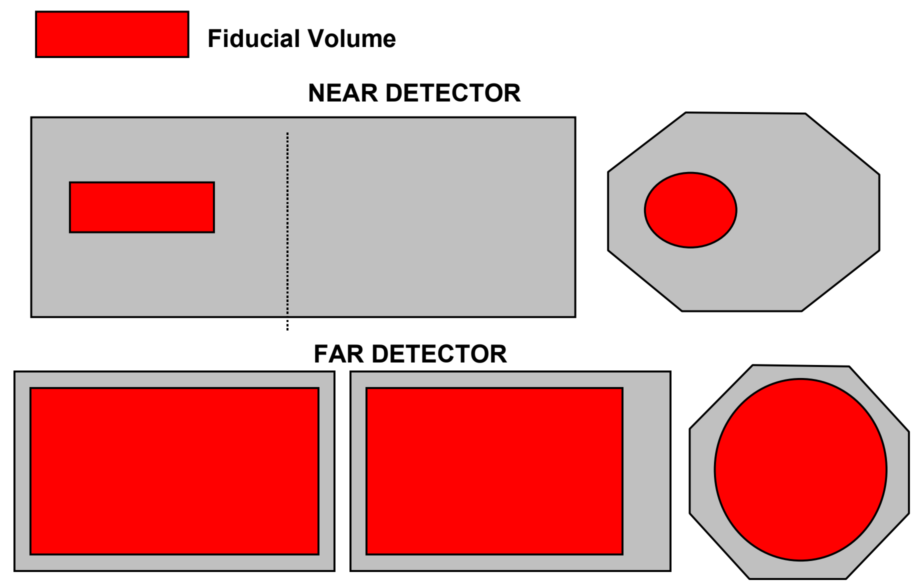
Selection cuts

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

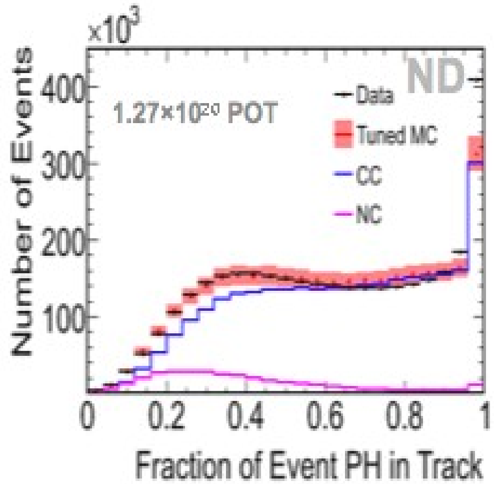


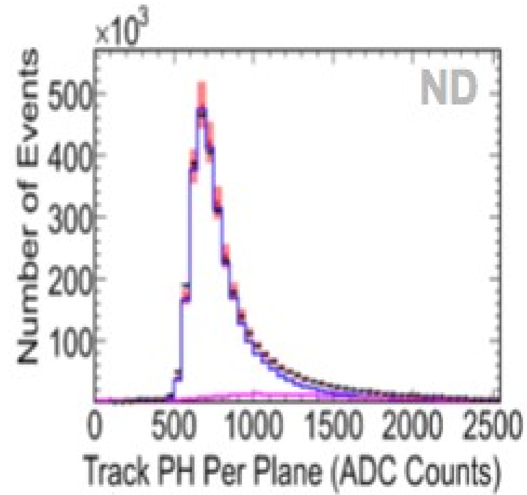
At least one good reconstructed track

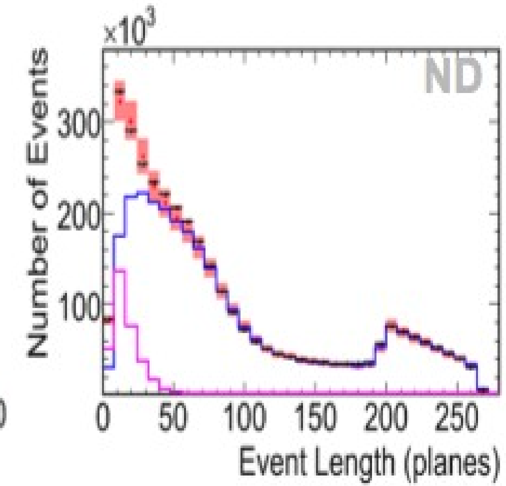
- With negative charge

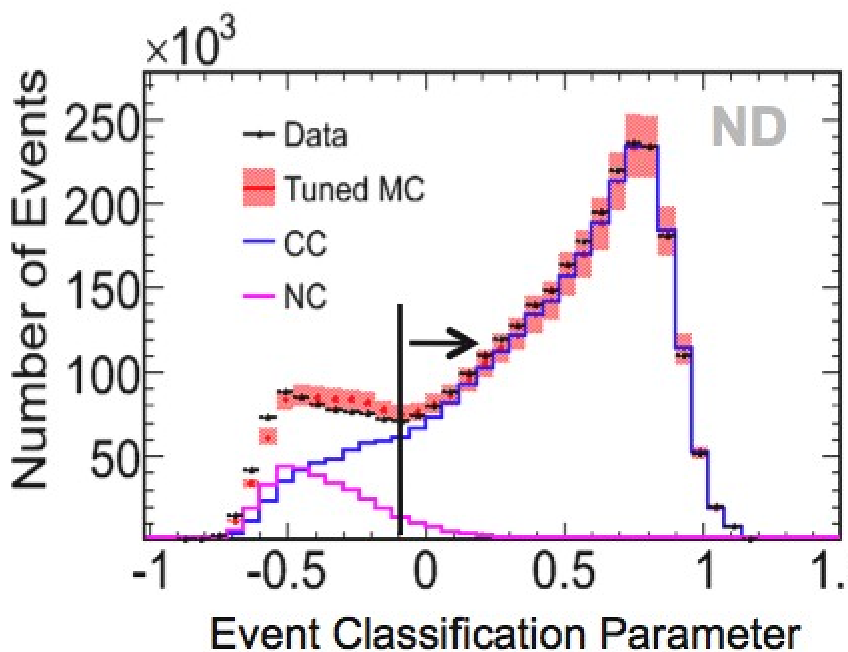
Event Selection

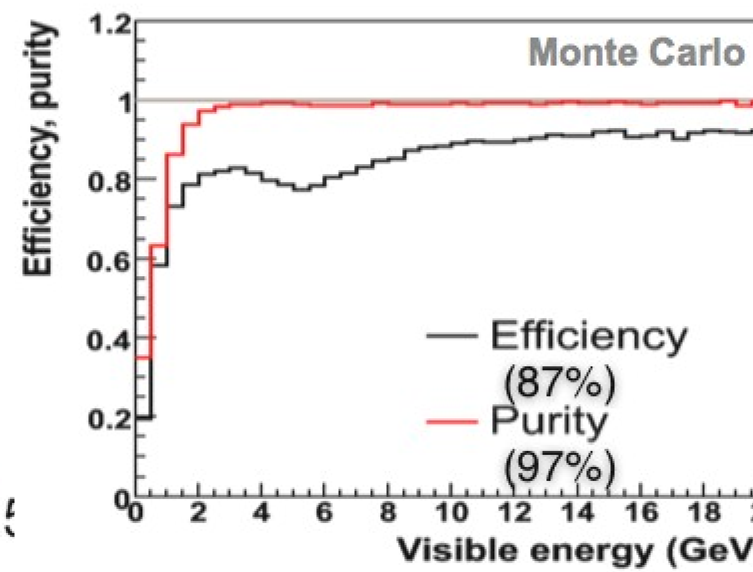
Using a maximum likelihood technique with 3 input PDFs:











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NEAR detector energy spectrum

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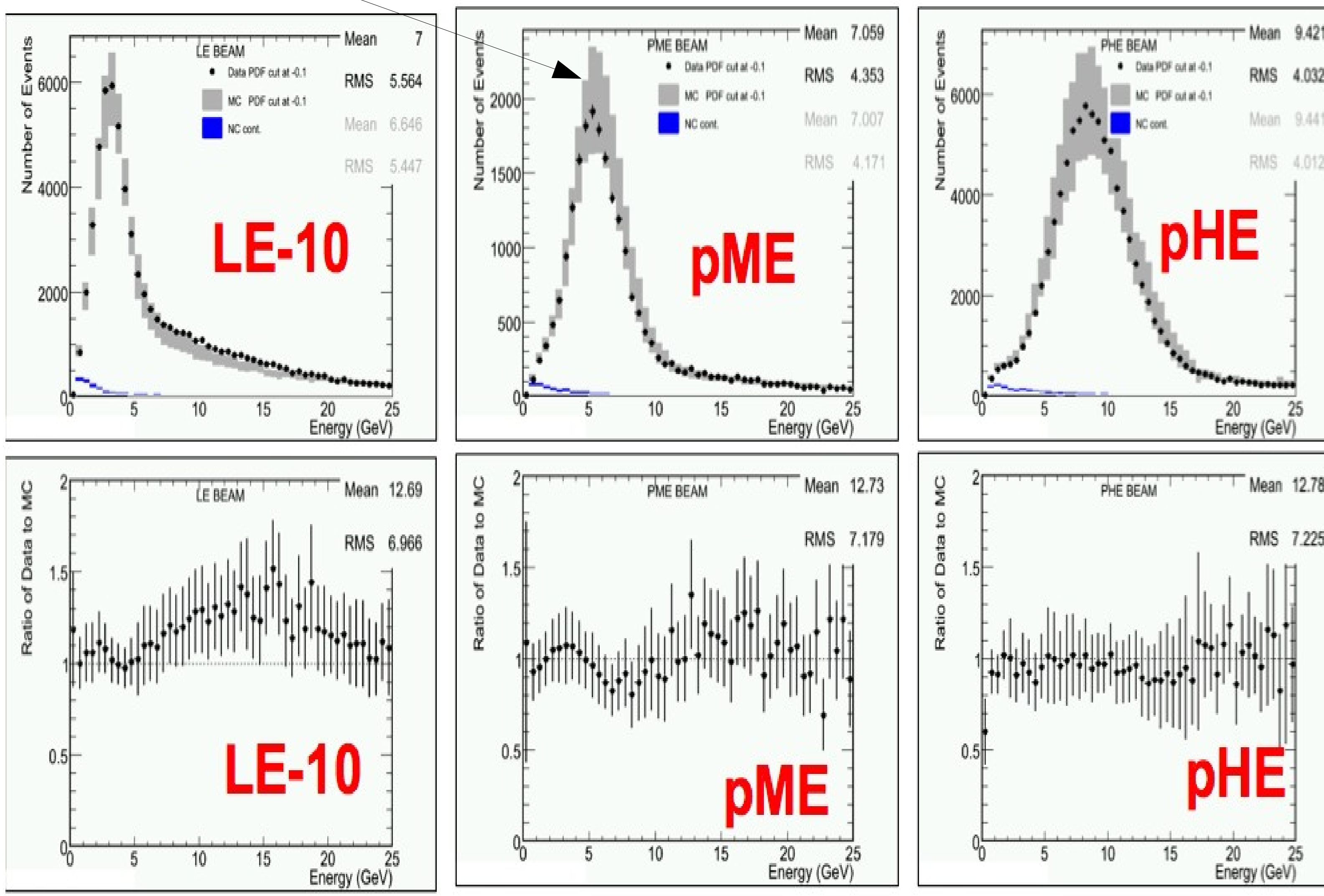
Error envelopes indicates size of beam modelling, neutrino interaction modelling and calibration uncertainties (combined).



Good Data / MC agreement

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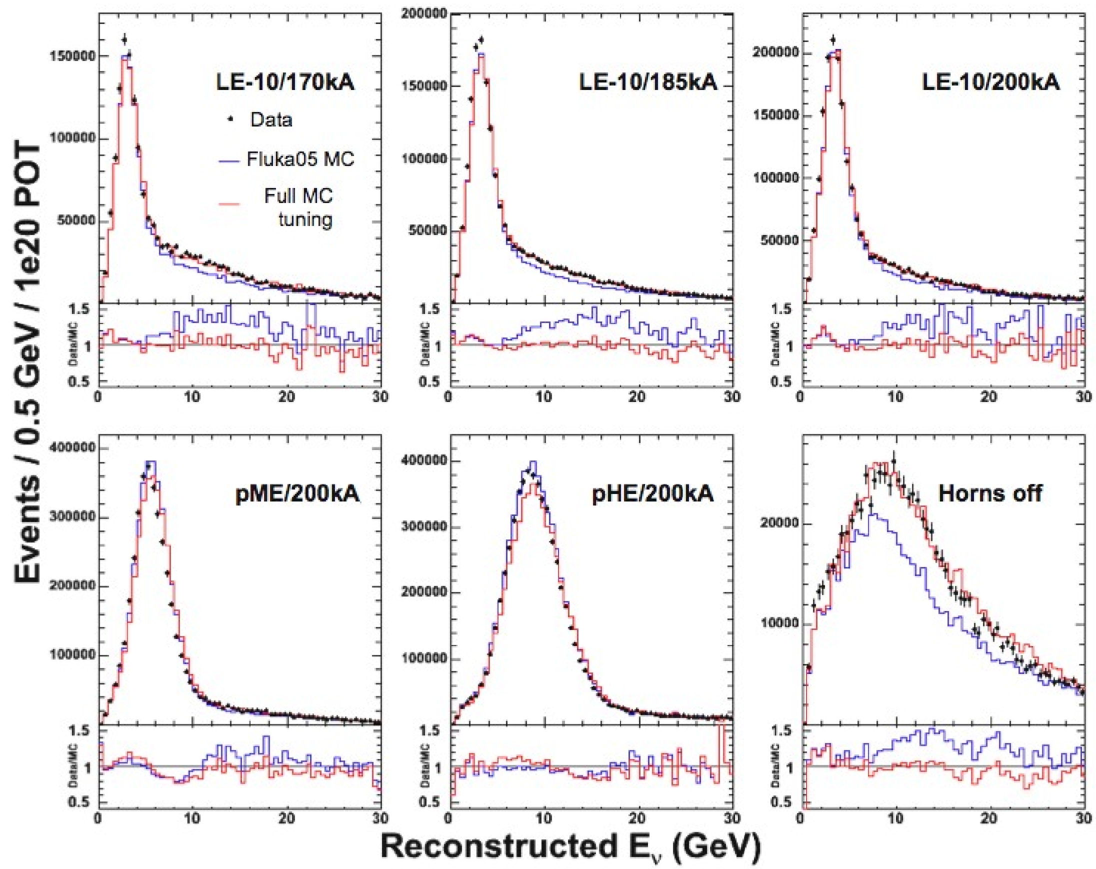
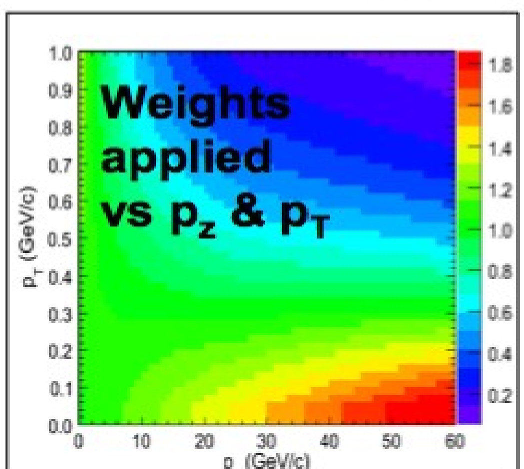
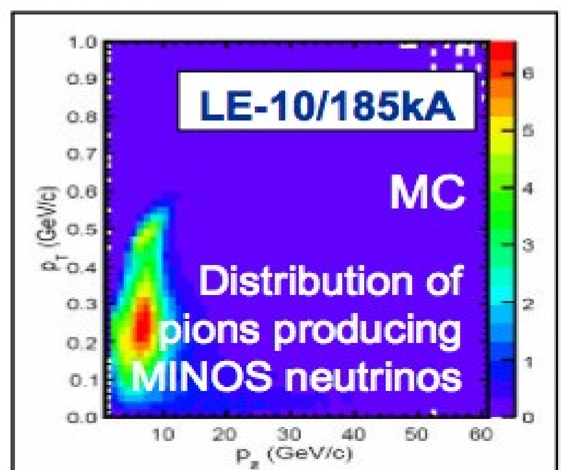
Hadron production tuning





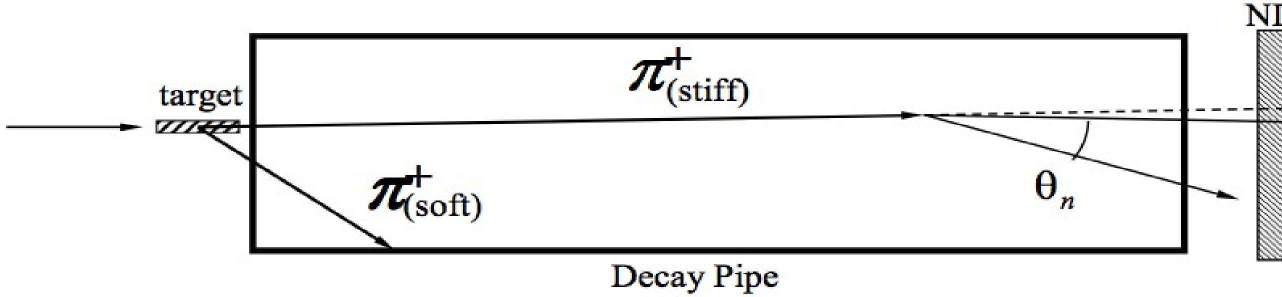


- Hadro-production *(Fluka05 based beam simulation)* tuning
- Even better data / MC agreement is obtained
- Applied weights as function of xF and pT

Prediction of FAR spectrum

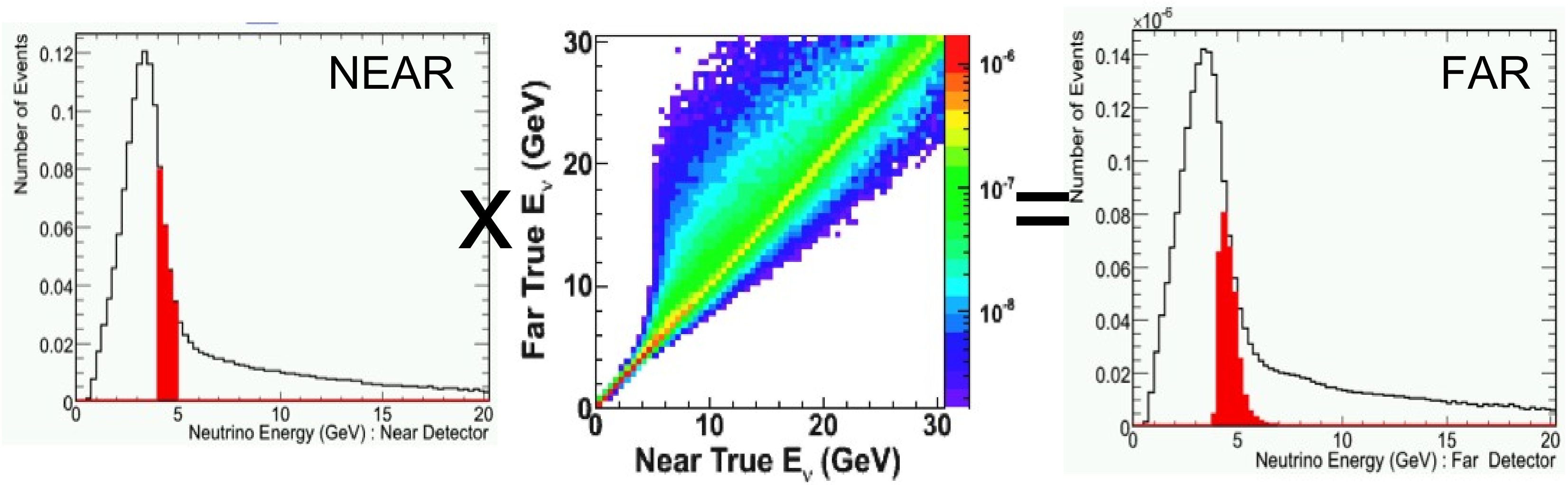
The 'Matrix' method:

- **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



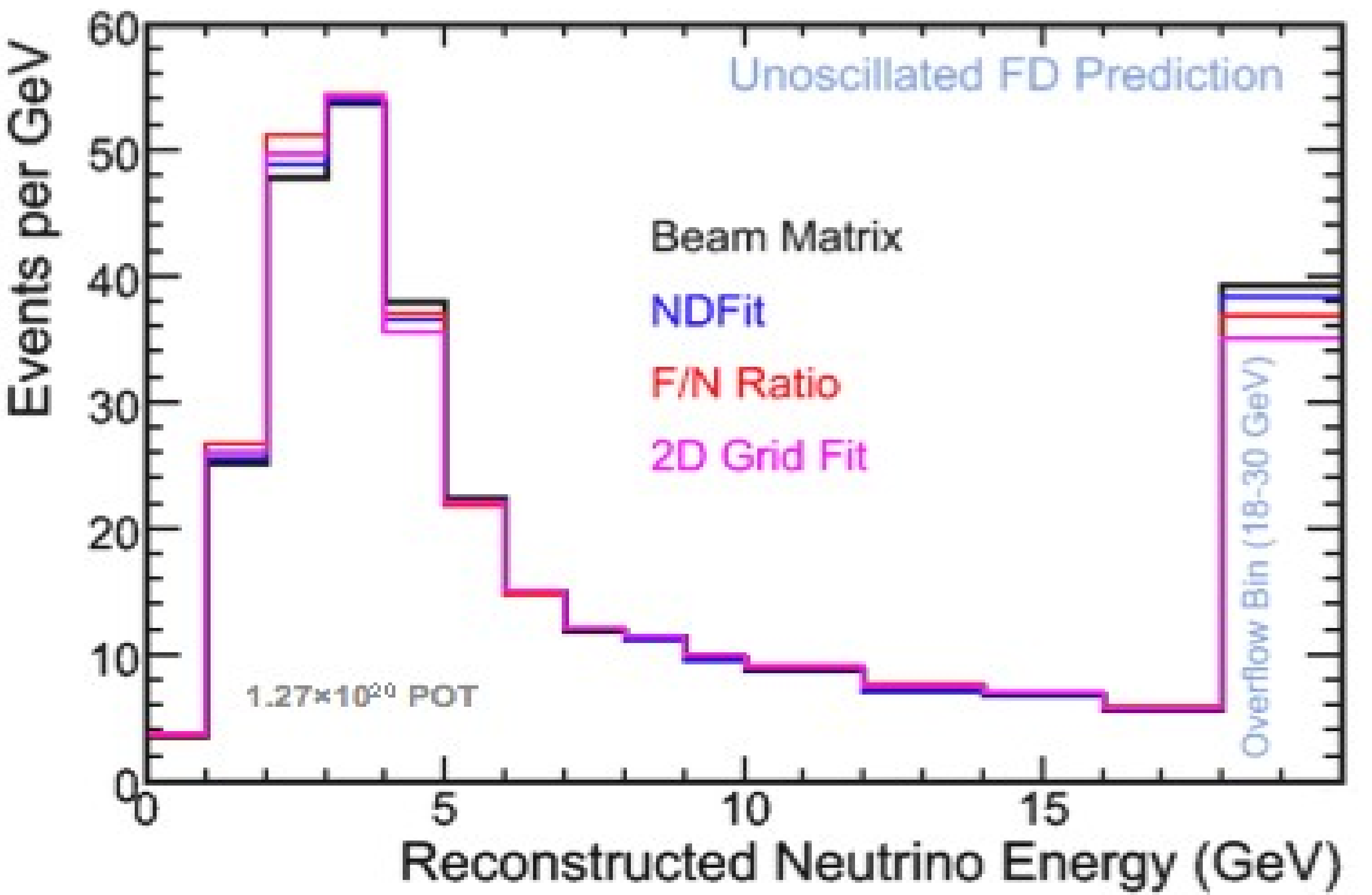
$$E_\nu = \frac{0.43 E_\pi}{1+\gamma^2\theta^2}$$

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



Prediction of FAR spectrum

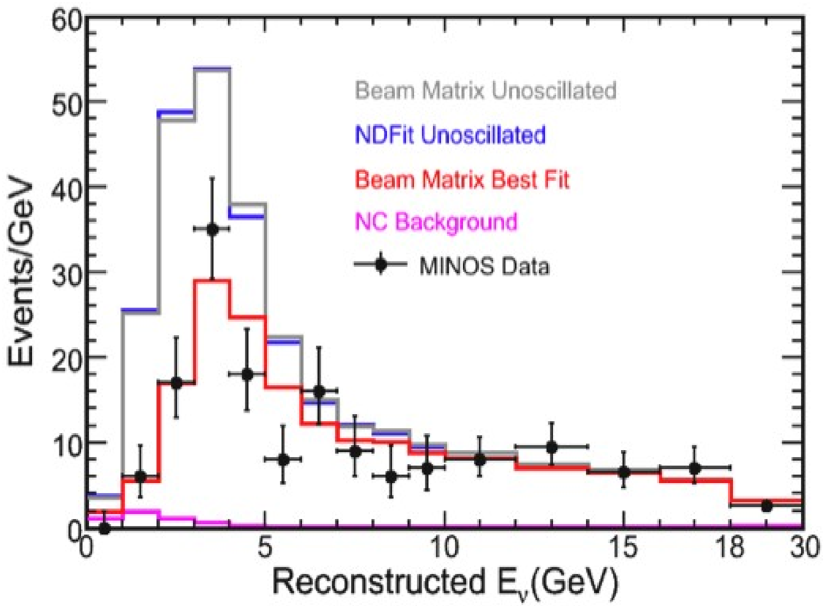
- Alternative extrapolation methods give nearly identical results
- Confidence in out ability to predict the un-oscillated FAR spectrum
- Having a 2-detector experiment pays off!



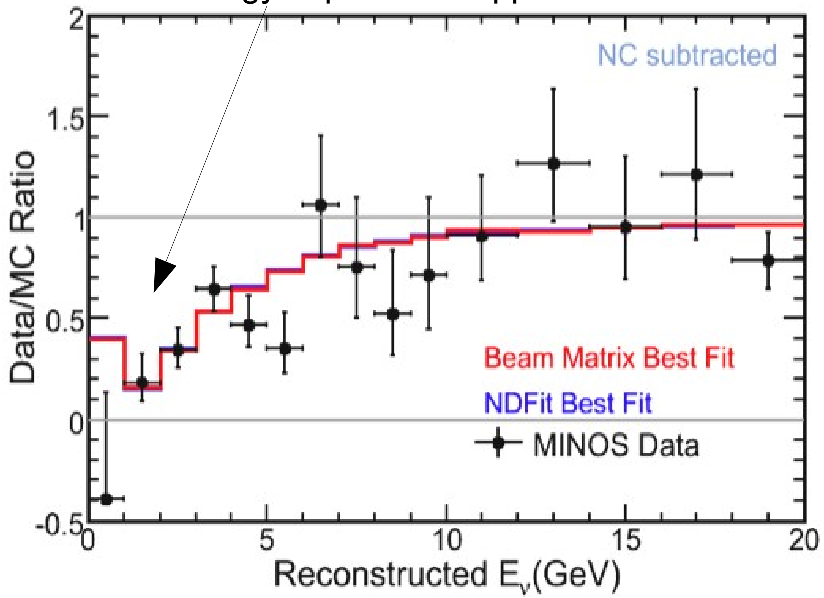
Observed rates & best-fit spectrum

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

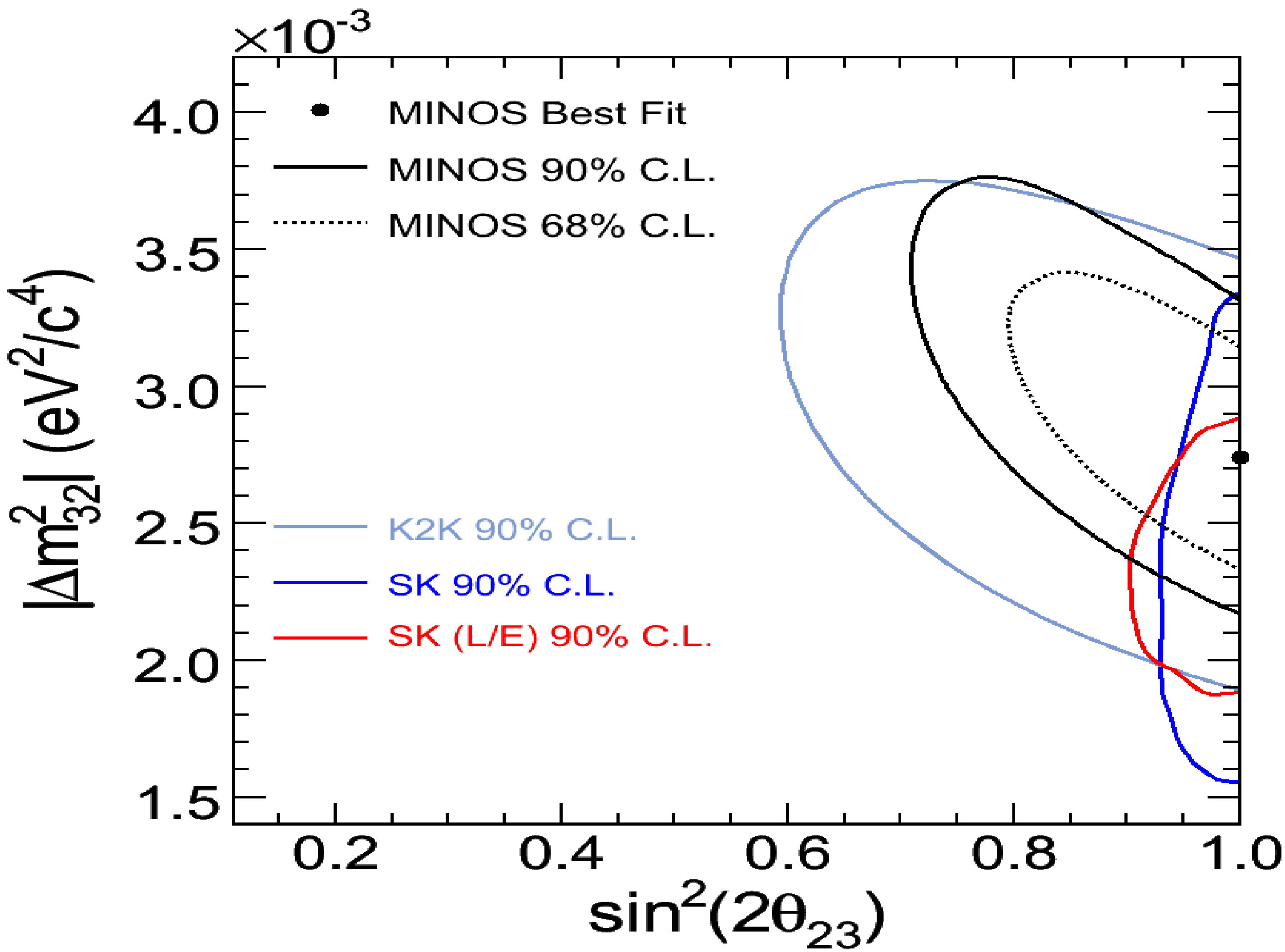
$$\chi^2 = \sum_{i=1}^{\mathrm{nbins}} \left[2(e_i - o_i) + 2 o_i \ln(o_i/e_i)\right] + \sum_{j=1}^{\mathrm{nsys}} \Delta s_j^2 / \sigma_{s_j}^2$$



See energy dependent suppression



Allowed regions & Best fit parameters



Best fit parameters:

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

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

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

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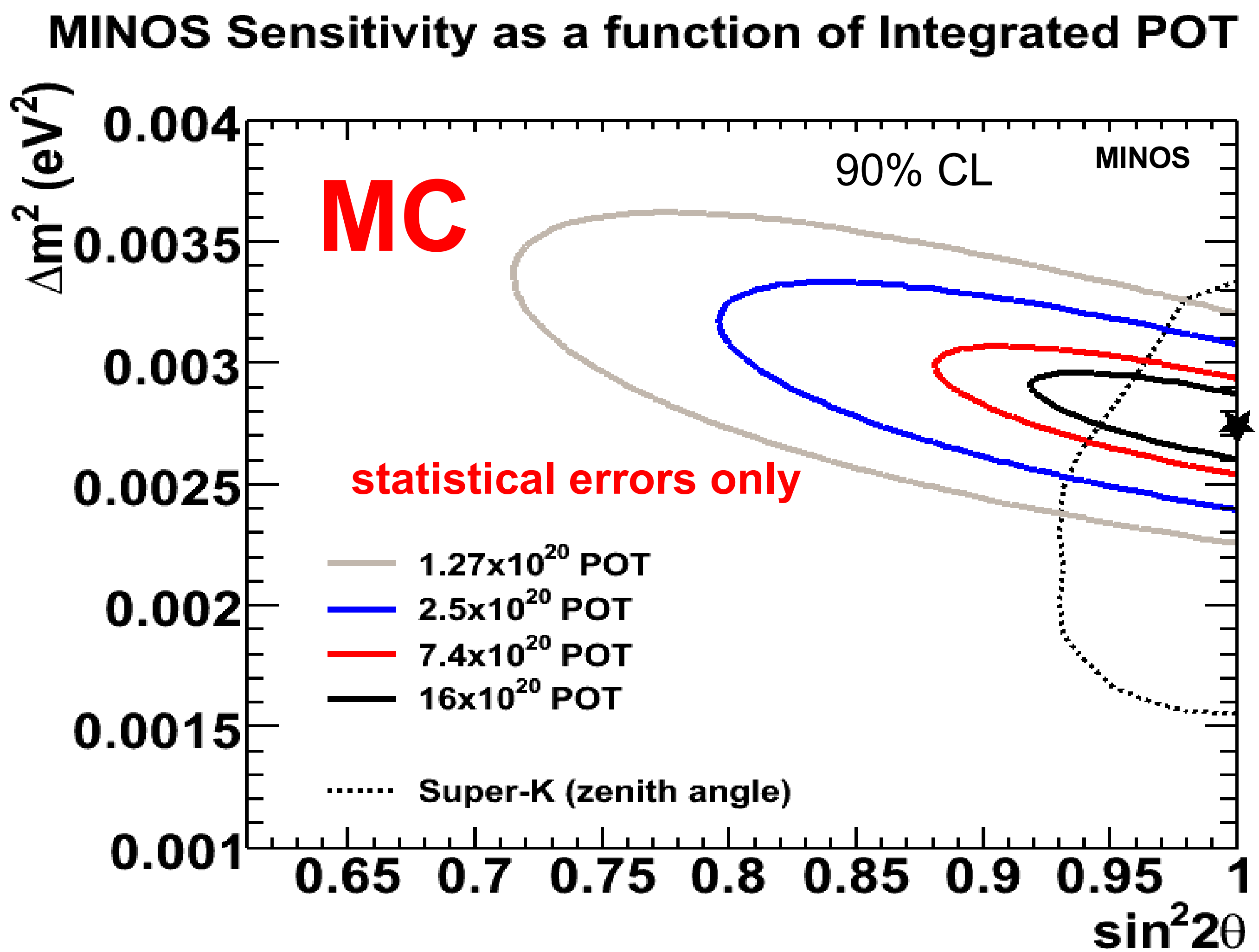
An updated analysis is coming soon (~2.6E+20 POT)



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)

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

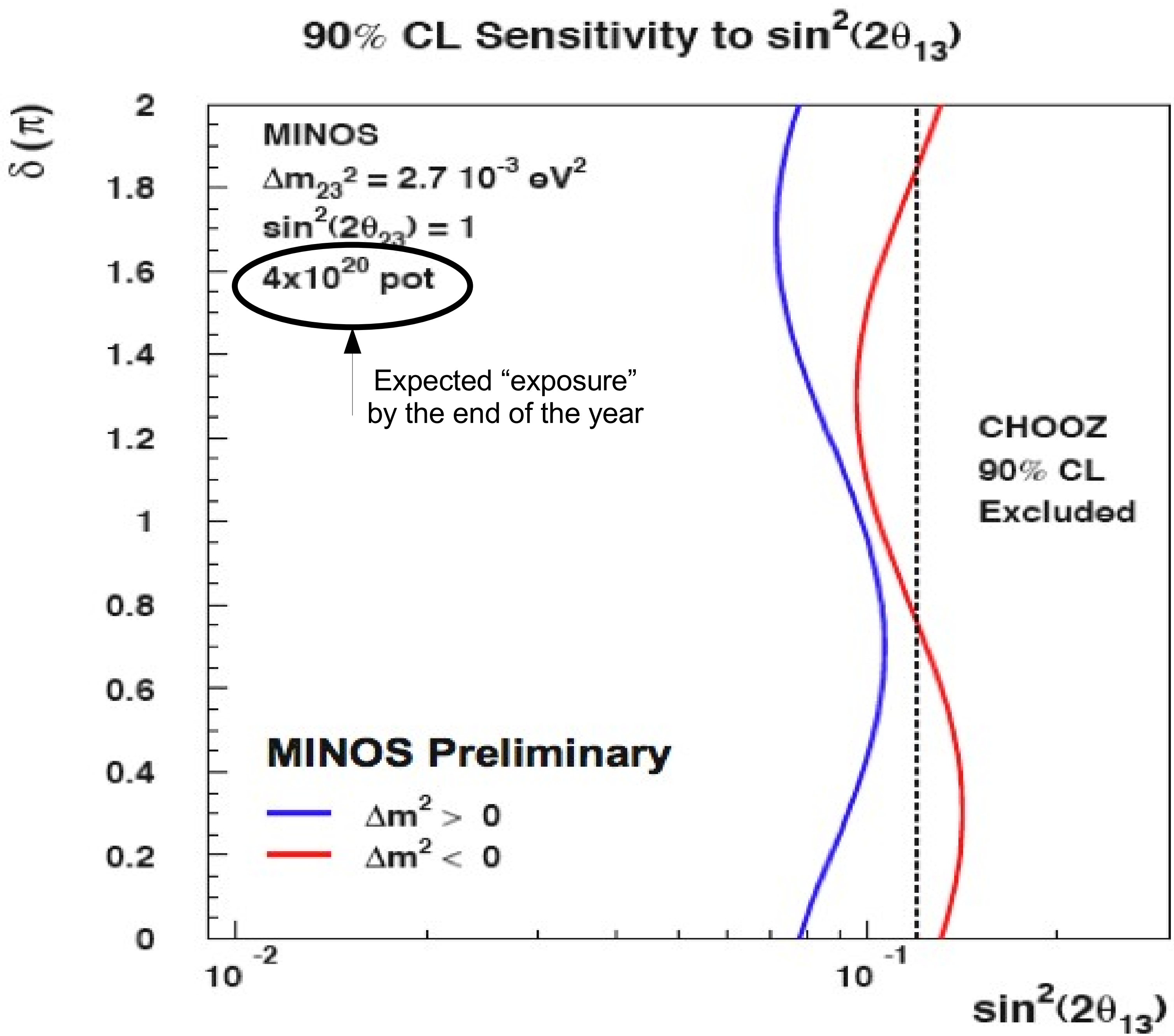
$$\sin^2 2\theta_{23} = 1.00_{\,-0.13}\,(\text{stat}+\text{syst})$$

Analysis of the second year's data in progress

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

Back-up Slides

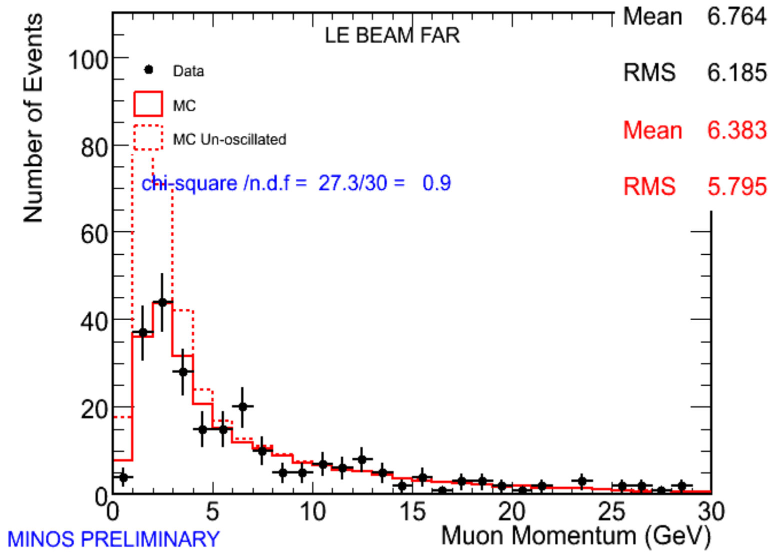
Physics reach: nu_e appearance



Physics Distributions

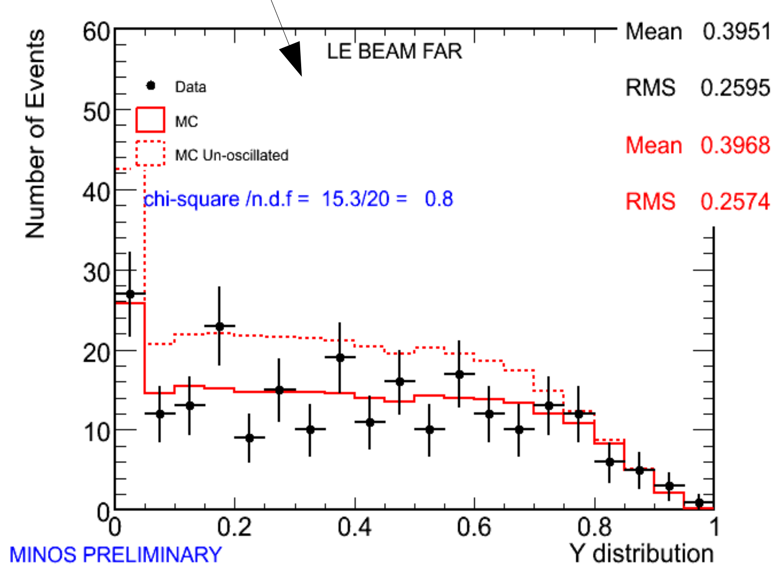
Back-up Slide

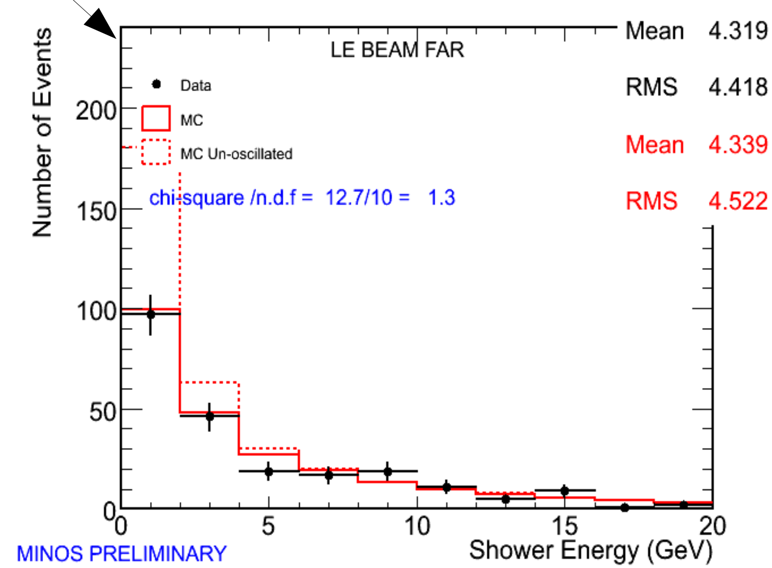
Muon momentum



Shower energy

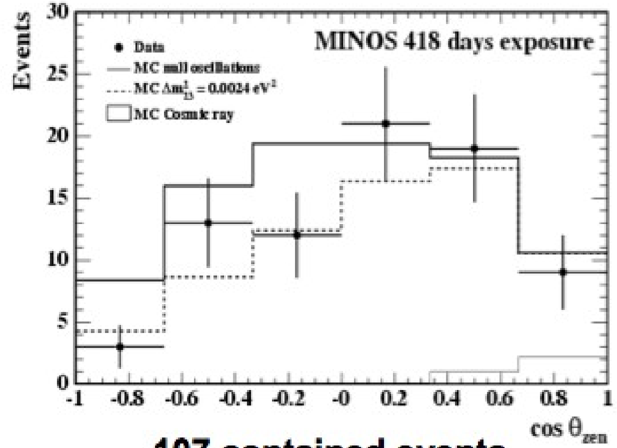
Inelasticity y



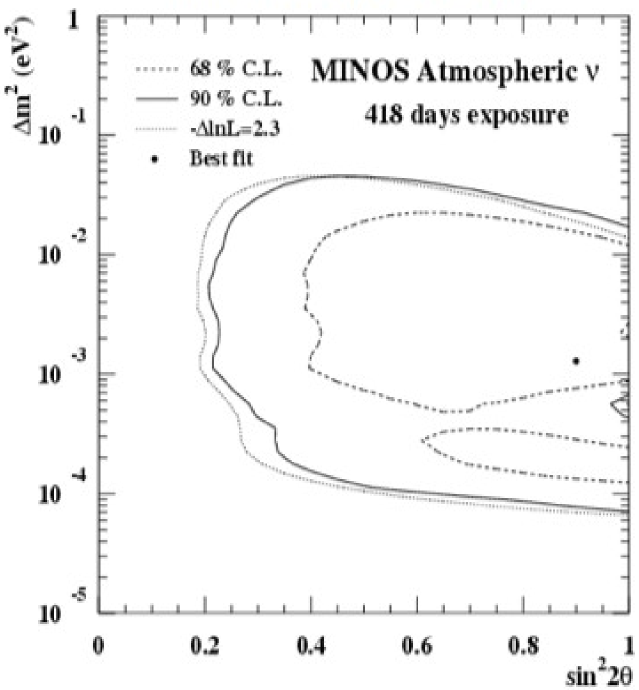


Atmospheric Neutrinos

Back-up Slide



107 contained events



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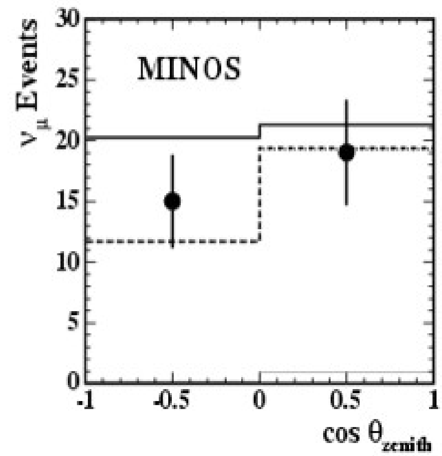
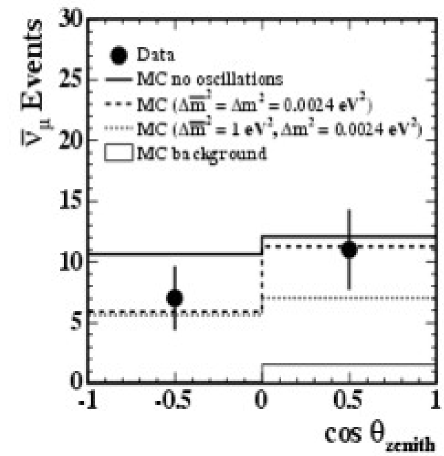
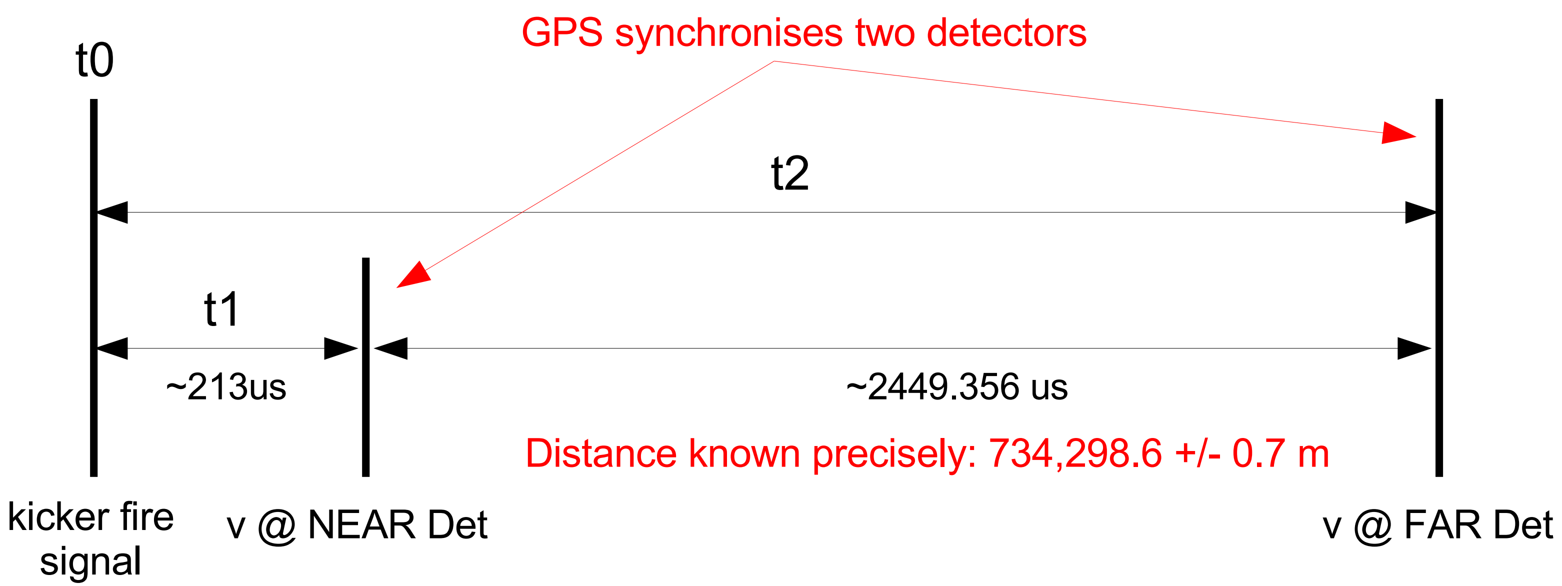
Selection	Data	Expected no oscillations	Expected $\Delta m^2_{23} = 0.0024\,\mathrm{eV}^2$
Low Res.	30	37 ± 4	28 ± 3
Ambig. $\nu_\mu/\overline{\nu}_\mu$	25	26 ± 3	20 ± 2
ν_μ	34	42 ± 4	31 ± 3
$\overline{\nu}_\mu$	18	23 ± 2	17 ± 2

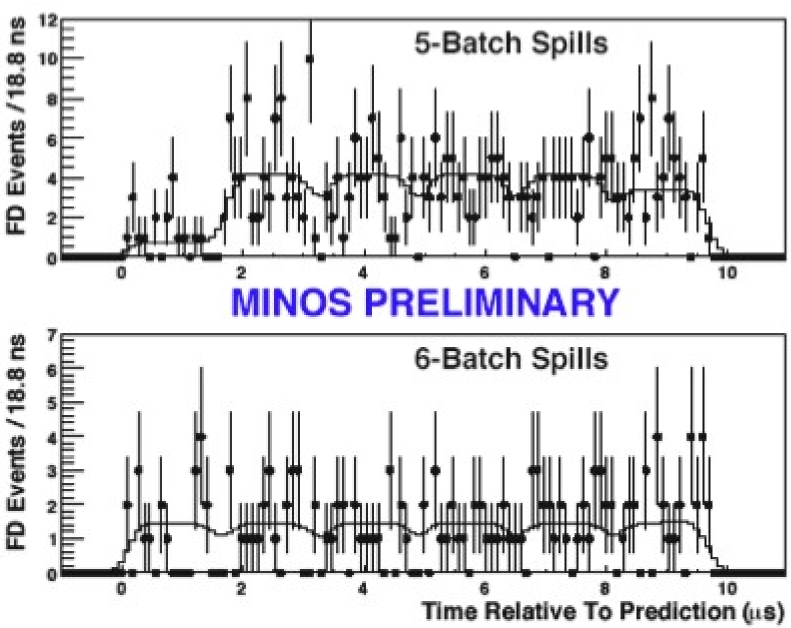




Neutrino Time Of Flight

Back-up Slide





Time of Flight Measurement:

Nominal: (734298.6 ± 0.7 m distance)
2449356 ns

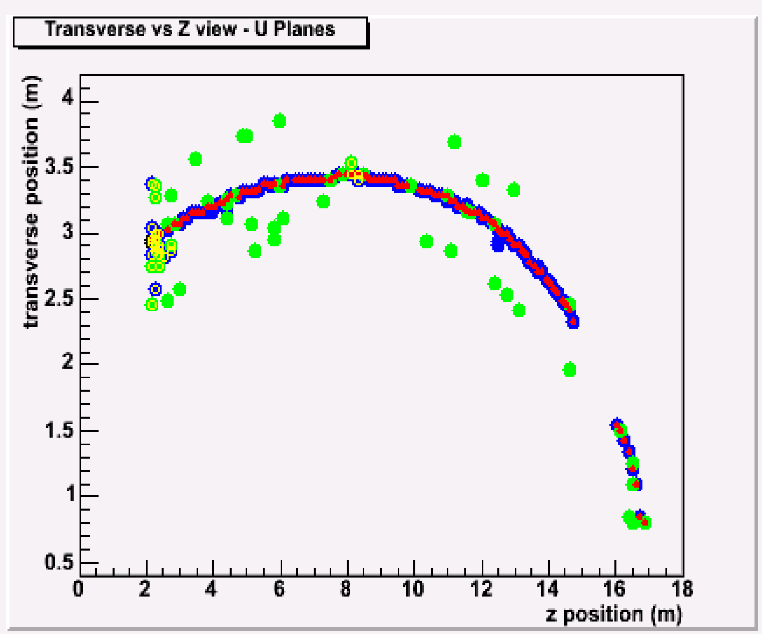
Measured:
2449223 ± 84 (stat) ± 164 (sys) ns
99% C.L.

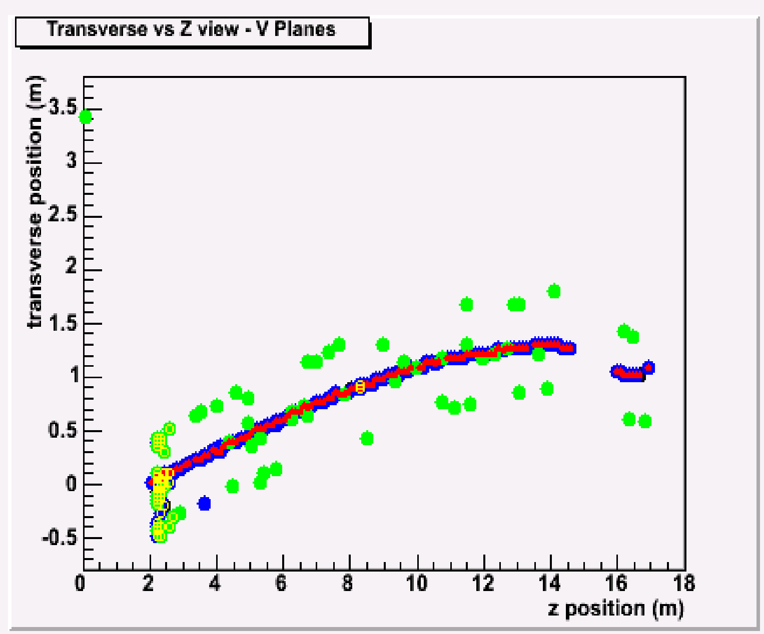
Neutrino Velocity:
$(v-c)/c = 5.4 \pm 7.5 \times 10^{-5}$
99% C.L.

Science & Technology Facilities Council
Rutherford Appleton Laboratory

FAR Detector data events

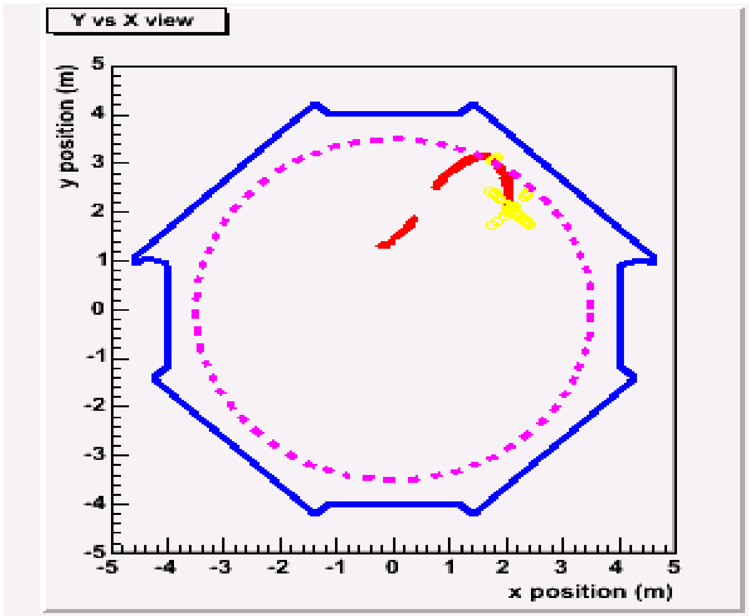
Back-up Slide





Track energy from range: 9.596 GeV

Reconstructed Shower energy: 5.108 GeV



NEAR Detector data events

Back-up Slide

High rates, Multiple neutrino interactions per beam spill.