LBL experiments in the US

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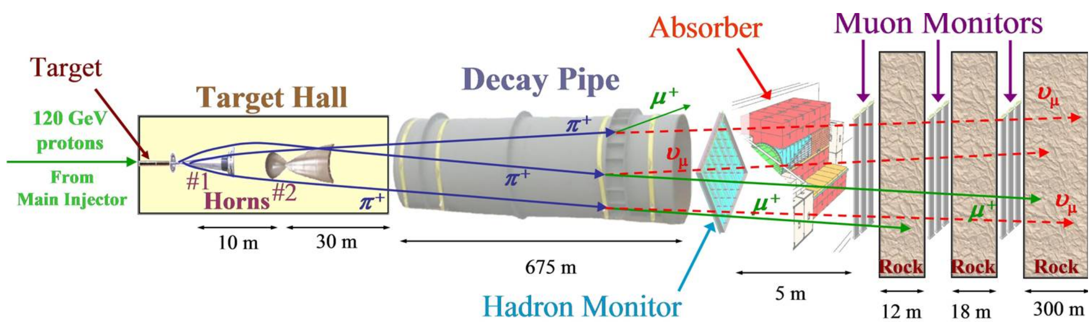
Overview

- Potential:- NuMI beamline at Fermilab
- Exciting physics is imminent:- MINOS (centre-of-gravity of this talk)
- NOvA ($\longrightarrow$ more in P.Litchfield talk)
- FLARE
- Superbeam projects are not covered by this talk

NuMI Beamline - Introduction 1

- First neutrinos are expected in december 2004
- 120 GeV protons from Fermilab Main Injector
- Initial intensity 2.5 $\times 10^{20}$ protons/year



A.Godley DPF 2004

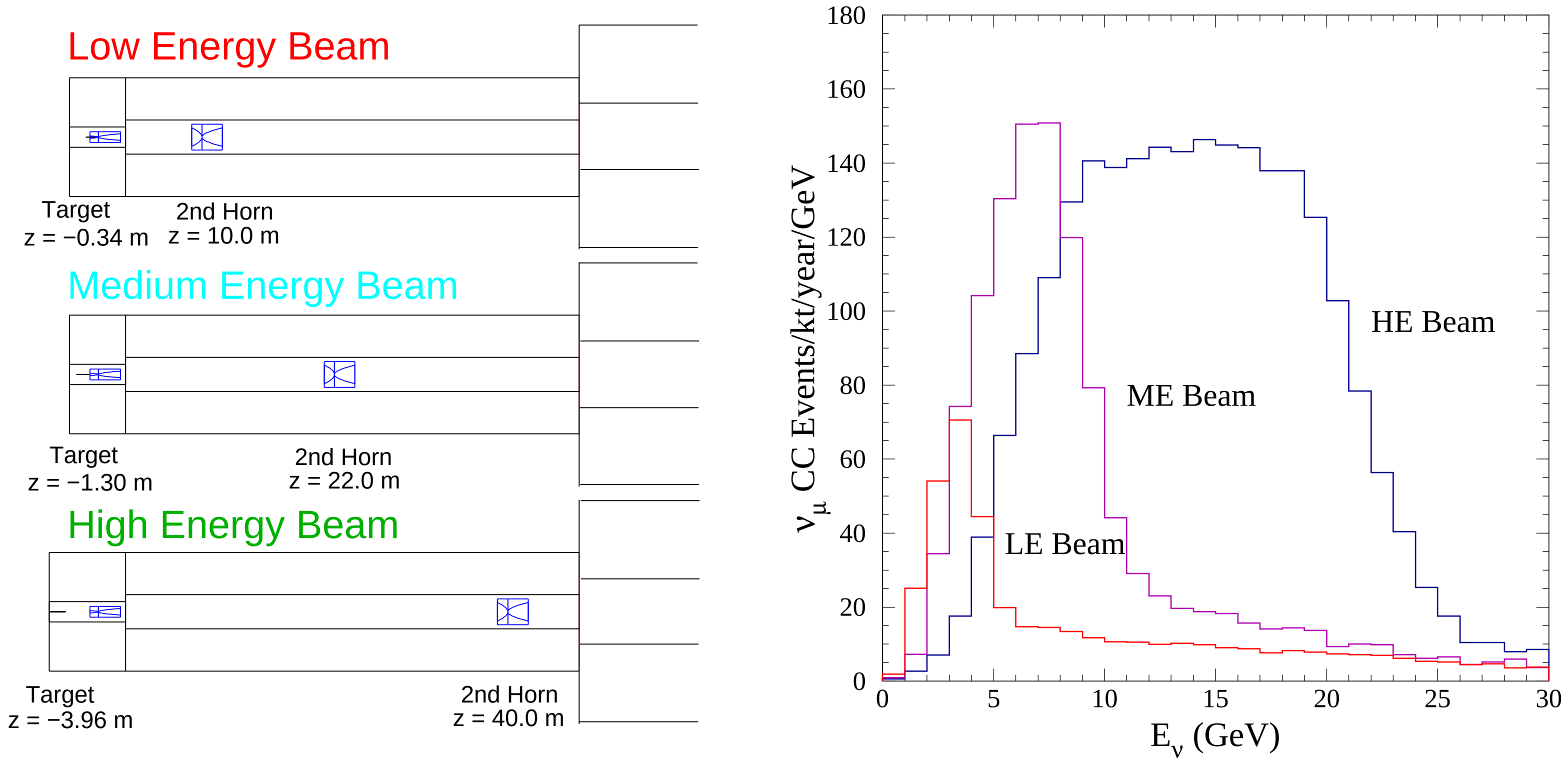
- Protons hit a meter long, water cooled graphite target
- π^+, K^+ are focused by two parabolic magnetic horns
- Pions and kaons decay in 675m long decay pipe (evacuated to 1.5 Torr)

NuMI Beamline - Introduction 2

- 8.7 μs ν beam spill every 1.9s
- Predominantly ν_μ beam
- Small fraction ($<\sim 1\%$) of ν_e, $\overline{\nu_e}$ from kaons and muons decays
- The neutrino flux predictions will be soon much more accurate. The MIPP experiment at Fermilab is going to measure secondary K and π production on the NuMI target. It has already taken the first test data !

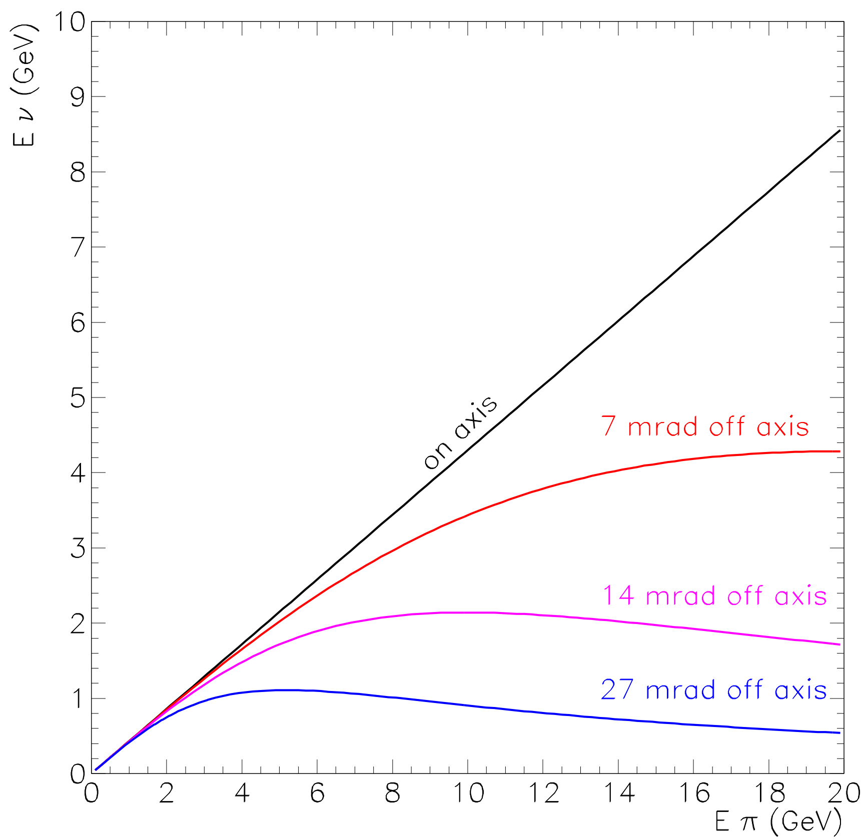
Tunable beam

- A unique feature of the NuMI beam is the ability to change relative positions of horns and target and therefore tune beam energy



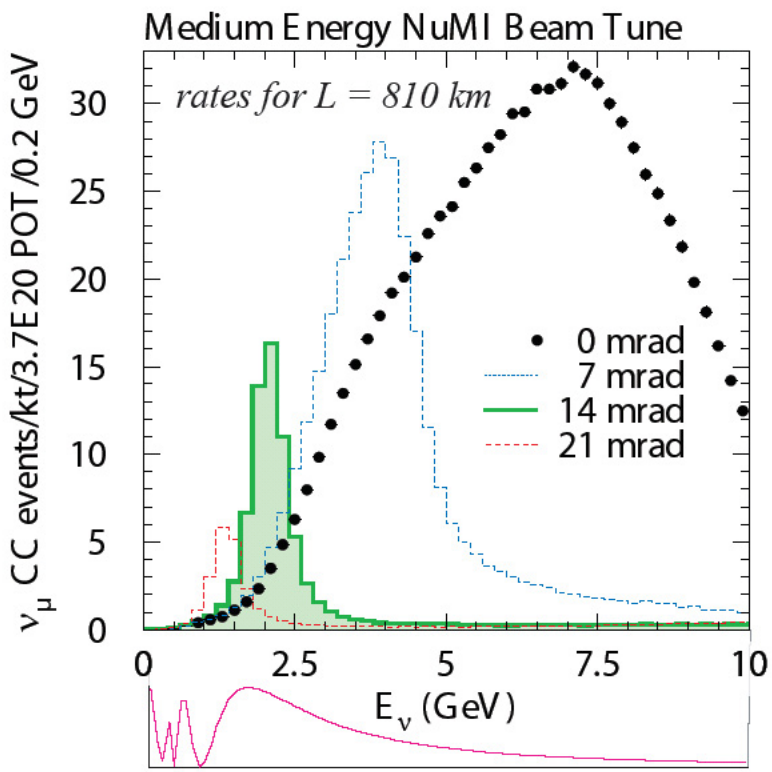
Start with low energy beam

Going off-axis 1



- For small off-axis angles, neutrino energy very weakly depends on energy of a pion $E_\nu = 0.43 E_\pi / (1 + \gamma^2\theta^2)$ θ is the angle between the pion direction and neutrino direction
- Off-axis energy spectrum is more narrow
- High energy tail is suppressed

Going off-axis 2



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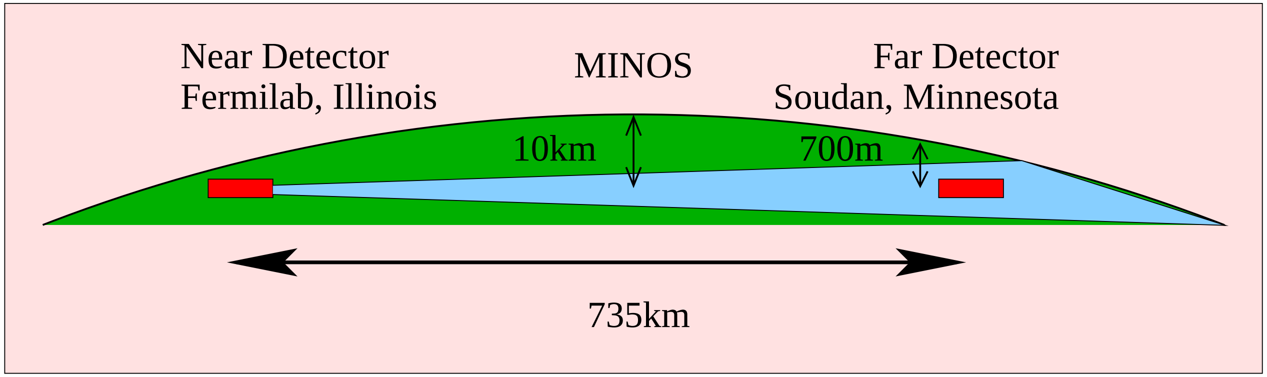
- The peak can be moved to the position which corresponds to the maximum of oscillations
- Energy of the beam is determined primarily by θ angle (transverse position of the detector)
- Optics configuration (LE,ME or HE) affects mainly the intensity of the beam

MINOS: First user of NuMI beam



- Second long-baseline accelerator experiment
- Detectors located on NuMI beam axis
- Near Detector (1kt) is located at Fermilab, ~ 1km downstream of target
- Far Detector (5.4 kt) is 735km away in Soudan mine, Minnesota
- First beam data early 2005

MINOS Physics Goals

- Measure ν_μ disappearance probability as a function of neutrino energy
  - confirm flavour oscillations describe data
  - provide high statistics discrimination against other models
- Improve knowledge of oscillation parameters Δm^2_{23} (to better than 10 %) and $\sin^2(2\theta_{23})$
- Search for $\nu_\mu \rightarrow \nu_e$ oscillations
  Possibility of first indication of non-zero θ_{13} !

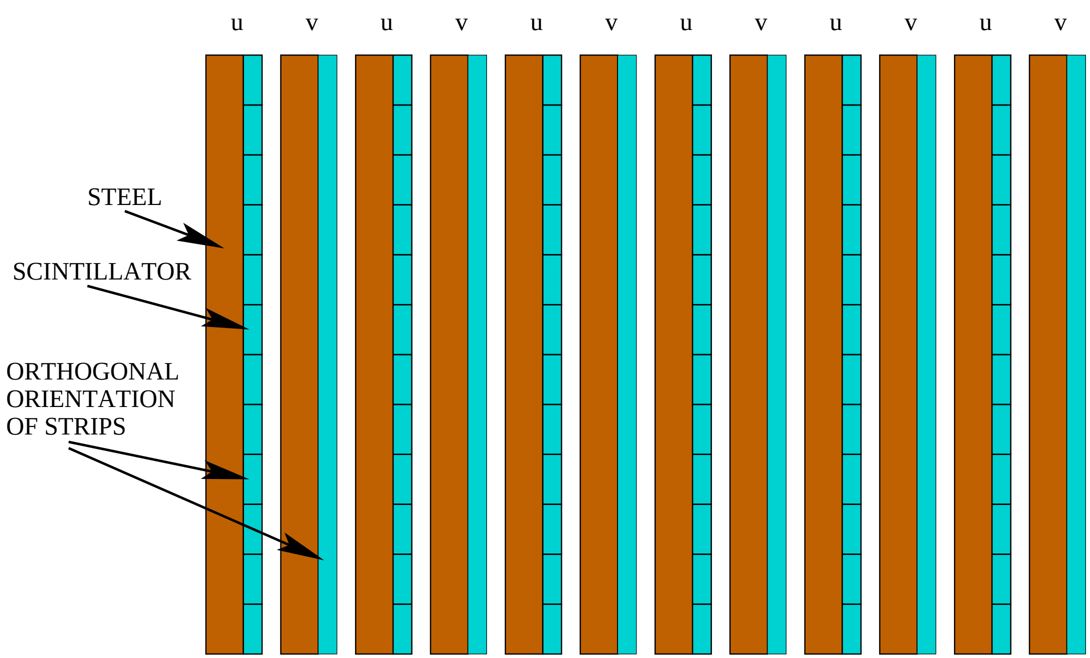
also

- First direct measurements of ν vs $\overline{\nu}$ oscillations from atmospheric neutrino events !
  (First magnetized underground detector)

MINOS Near and Far Detectors

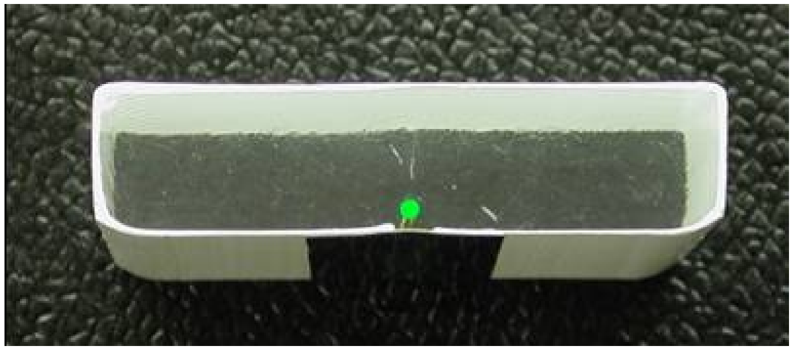
Near and Far detectors have the same basic design:

- steel-scintillator sandwich
- 2.54 cm of steel + 1cm of solid scintillator (U and V)
- alternate planes have orthogonal strip orientations



Scintillator planes

- Each scintillator plane is segmented into 4cm wide strips

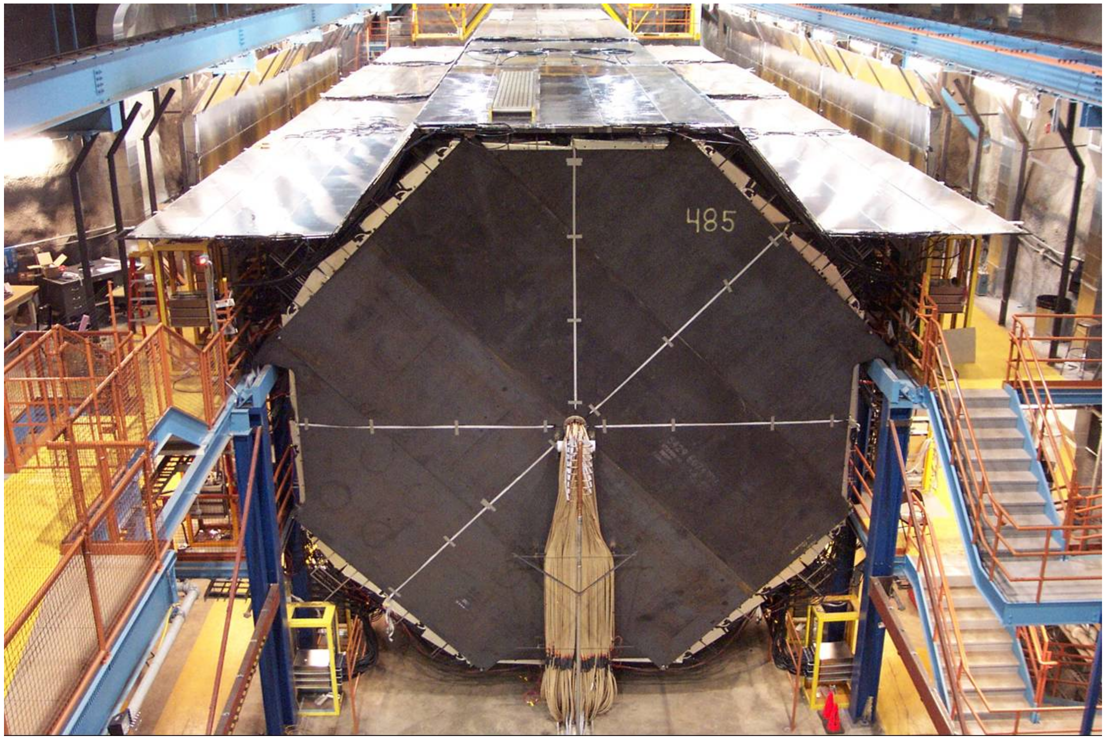


- scintillator light collected by WLS fibre glued into groove
- signals are readout by multi-pixel Hamamatsu PMT’s
- Scintillator planes are encased in aluminium

MINOS Near Detector

- 1 kt
- 282 planes
- 3.8m high
- calorimeter section: first 121 planes
- spectrometer section: rear 161 planes, reduced sampling
- Plane installation finished in August 2004
- Currently installing coil and commissioning planes with cosmic muons

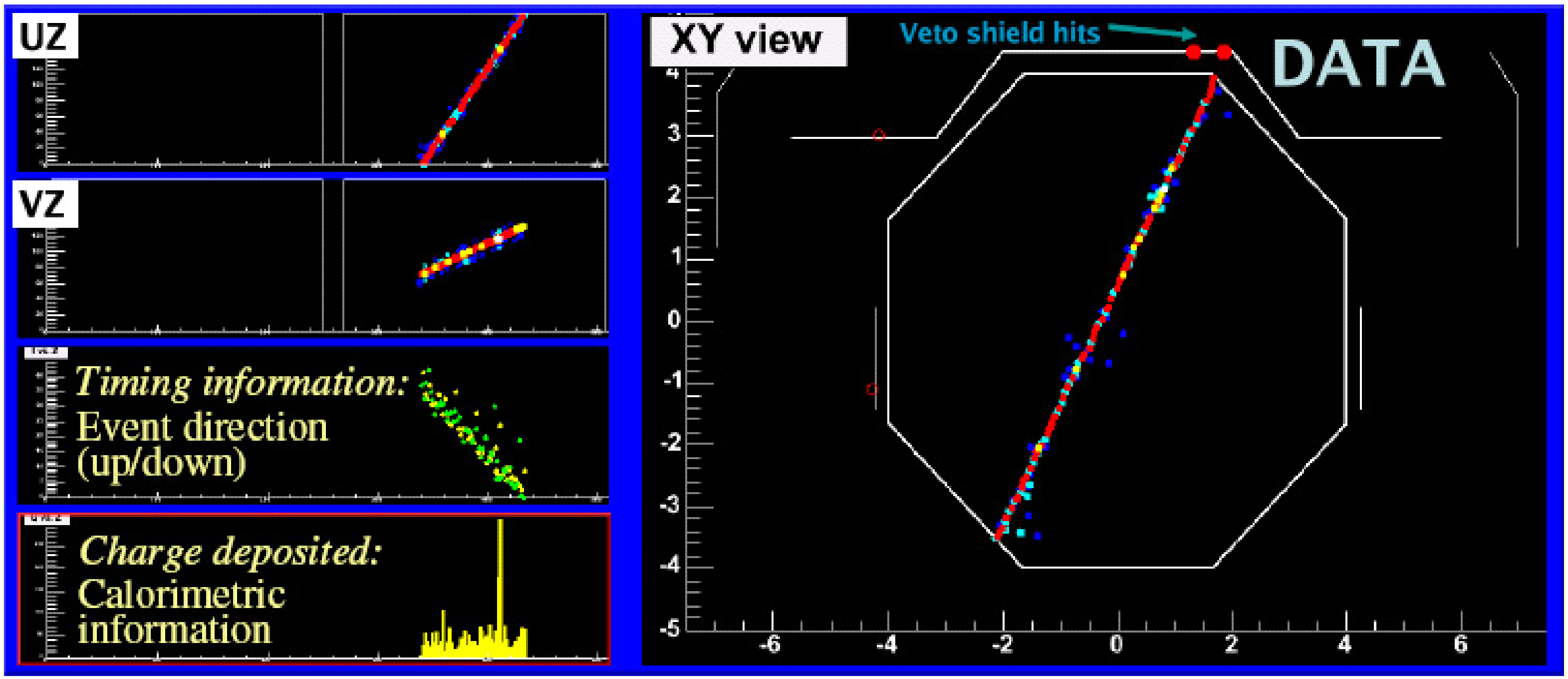
MINOS Far Detector



- 5.4 kt
- 485 planes
- detector composed of 2 modules, 15m long, 8m high
- active veto shield (scintillator modules)
- Construction was fully completed in July 2003
- Taking data (cosmic ray muons + atmospheric ν)

MINOS Event Reconstruction

- Spatial information
  two 2D views of event: UZ and VZ
  (Z axis along the beam direction)

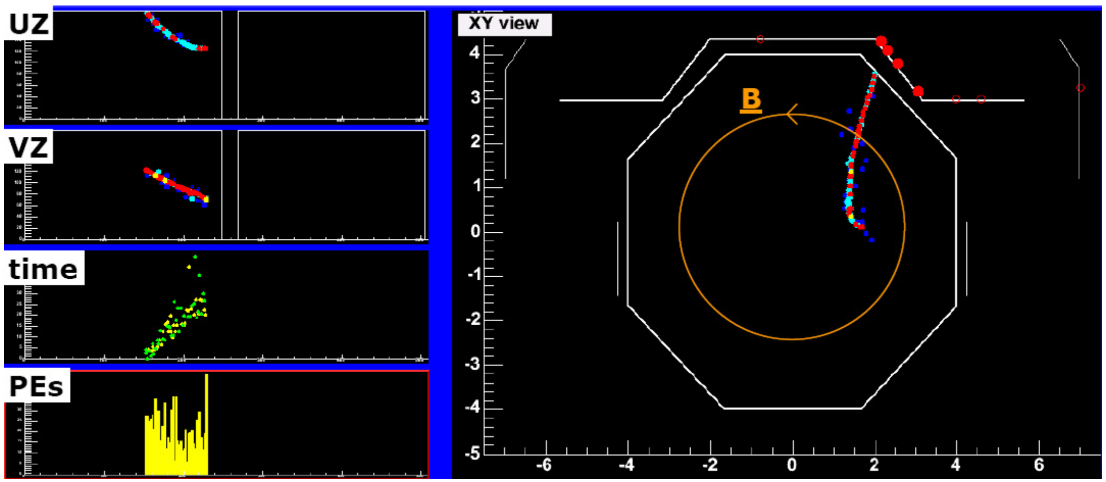


Left plots: Information directly available
Right plot: Output of reconstruction: 3D event

MINOS B-Field

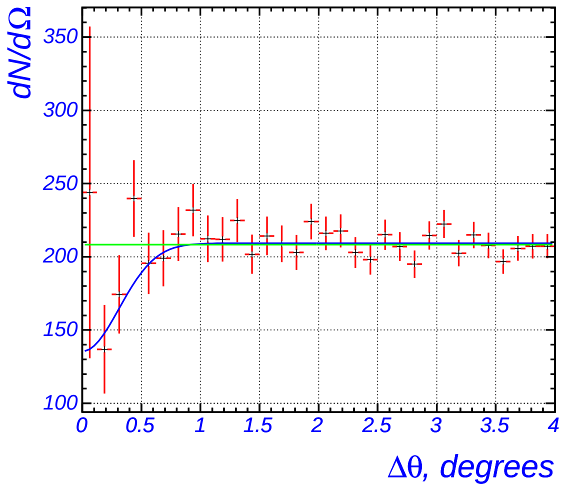
Near and Far detectors are magnetized (B $\sim$ 1.5 T) $=>$

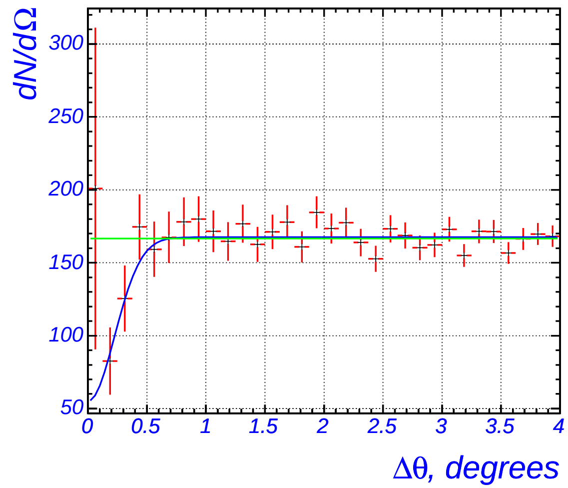
- charge separation
- momentum measurement



- Momentum measurement from curvature resolution $\sim 15\%$
- Momentum measurement also from range (for stopping muons) resolution $\sim 6\%$

Moon Shadow





moon direction $\theta = 0^\circ$

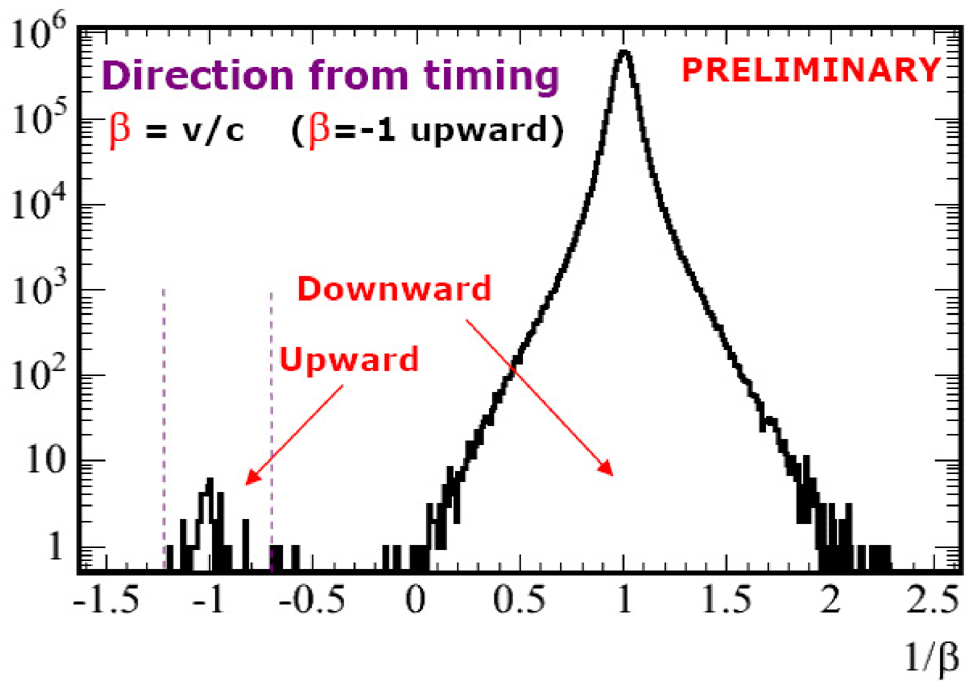
No p_μ cut $\qquad$ $p_\mu > 20GeV$ cut

- MINOS has recorded $> 10^7$ cosmic muons
- Shadow of the moon is clearly seen
- Angular resolution is improved by selecting high momenta muons

Event reconstruction in Far Det is performing well

MINOS Upward-Going Muons

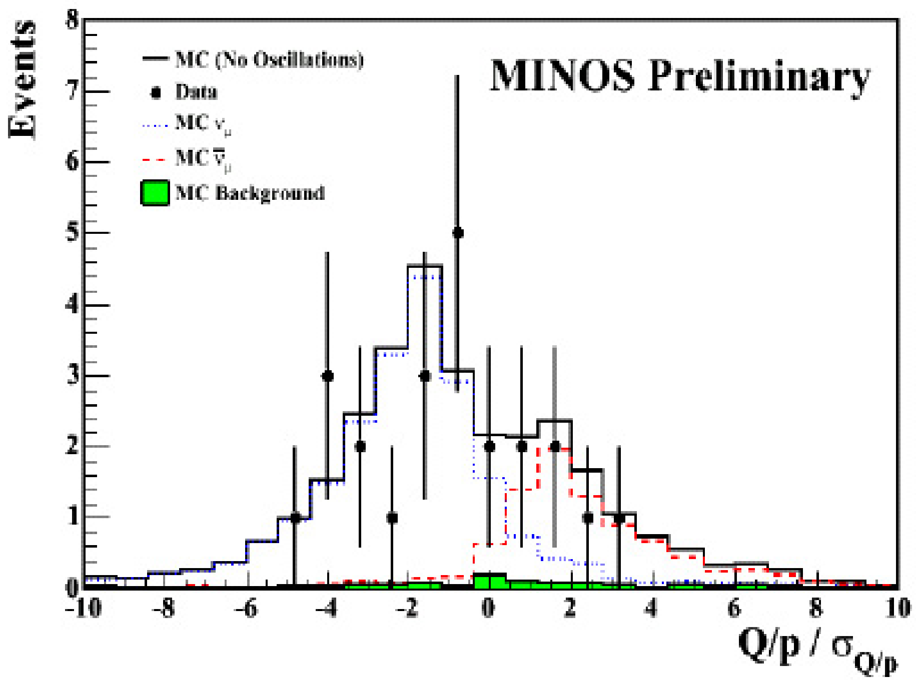
- Timing information gives event direction
  Single hit resolution = 2.5 ns



Clear separation of upward and downward going muons. MINOS already collected 48 upward (from neutrinos interacting in rock) events.

MINOS Contained Events

- First contained events
  37 candidates: 6$\overline{\nu}$, 17 ν, 14 too short to identify $\overline{\nu}/\nu$



- $N(\overline{\nu})/N(\nu) = 0.35 \pm 0.17$
- Thanks to the veto shield (efficiency $\sim 97\%$) efficiency of finding contained events $\sim 75\%$ with 98% purity

MINOS Calorimetry

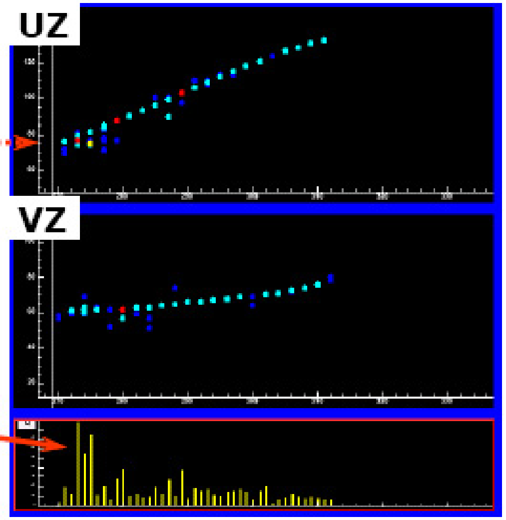
- MINOS used the third detector CalDet, to measure response to hadronic and electromagnetic interactions
- 12 ton detector, steel, scintillator and readout system as in the Near and Far detectors
- In the years 2001-2003 CalDet measured the interactions of p, π, e, μ between 0.2-10 GeV at T7 and T11 test beams at CERN PS accelarator
- Energy resolution (E in GeV):
  $\sigma_E/E \sim 55\%/\sqrt(E)$ for hadrons
  $\sigma_E/E \sim 23\%/\sqrt(E)$ for electrons

MINOS Beam Physics

ν_μ CC Event

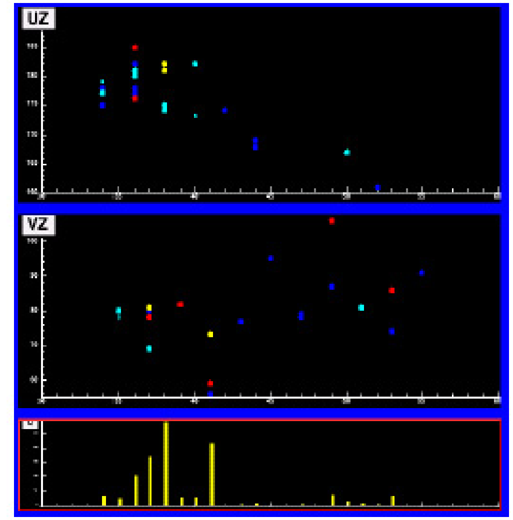
ν

- μ track
- +hadronic activity



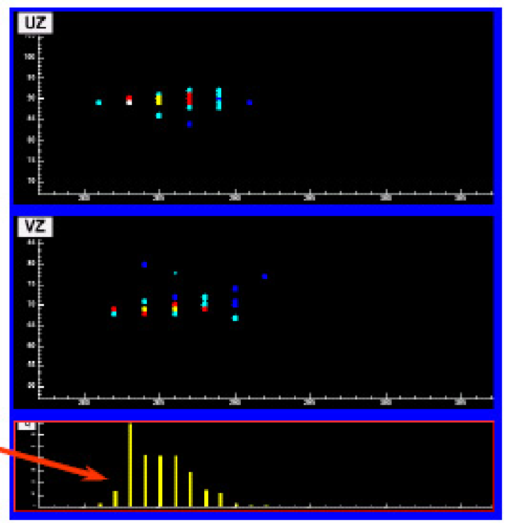
NC Event

- often diffuse



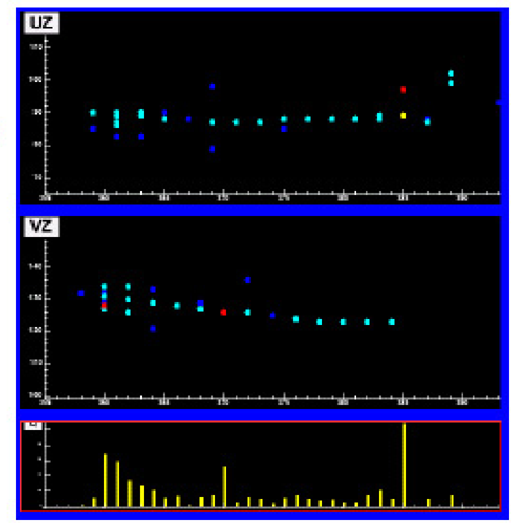
ν_e CC Event

- compact shower
- typical EM shower profile



NC Event

- can mimic ν_μ , ν_e



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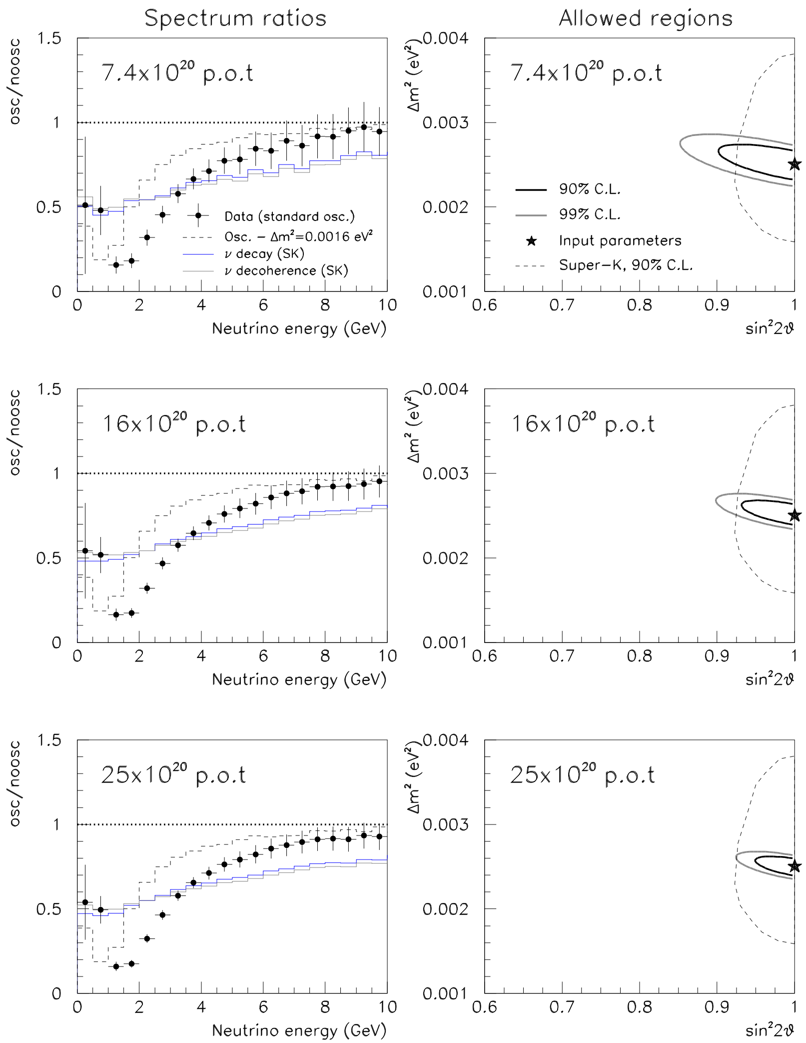
MINOS Physics Reach

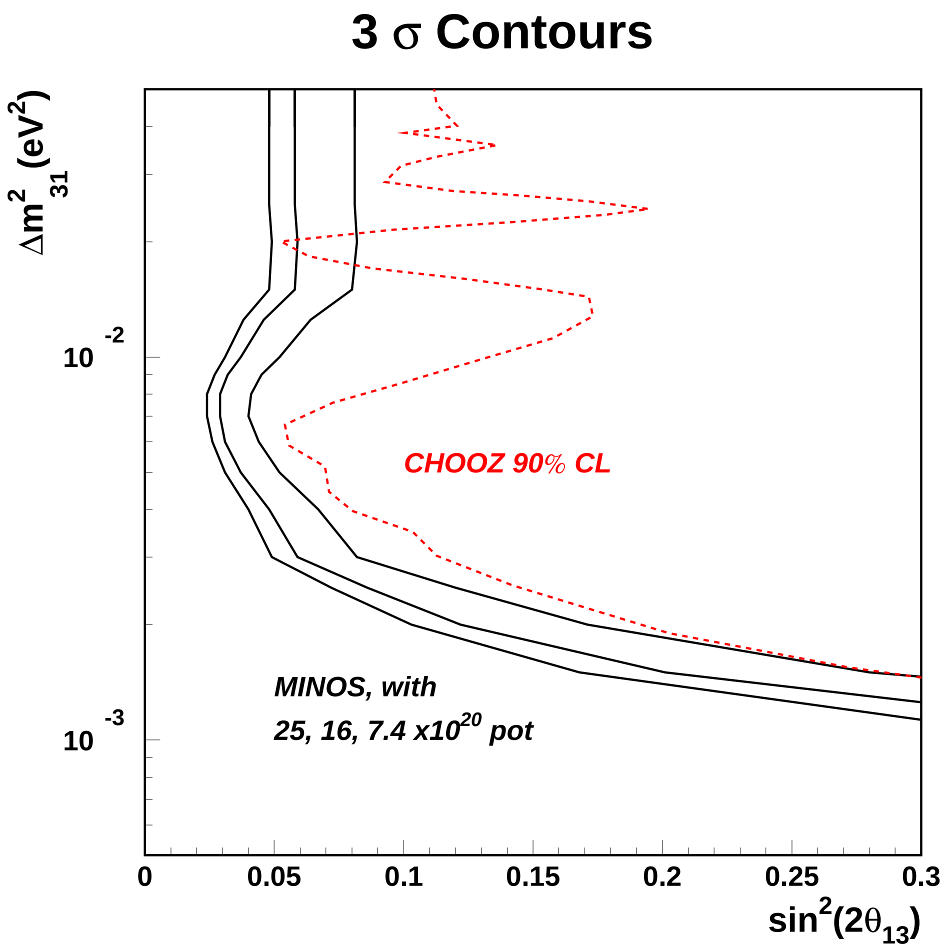


ν_μ disappearance

Measurement of Δm^2_{23} and $\sin^2(2\theta_{23})$ Plots for $\Delta m^2_{23} = 2.5 \times 10^{-3} eV^2$ and $\sin^2(2\theta_{23}) = 1.0$

Sensitivity depends on number of protons on target.

MINOS Physics Reach



ν_e appearance:

Possibility of first indication of non-zero θ_{13} !

Reach depends on number of protons on target.

MINOS - Summary

- Far Detector is taking cosmic muon and atmospheric data since July 2003
- First atmospheric neutrinos have been observed.
- Detector is performing very well
- Installation of Near Detector planes has been completed in August. Currently is being commissioned with cosmic muons.
- Exciting times for MINOS:
  first beam physics data early 2005 !

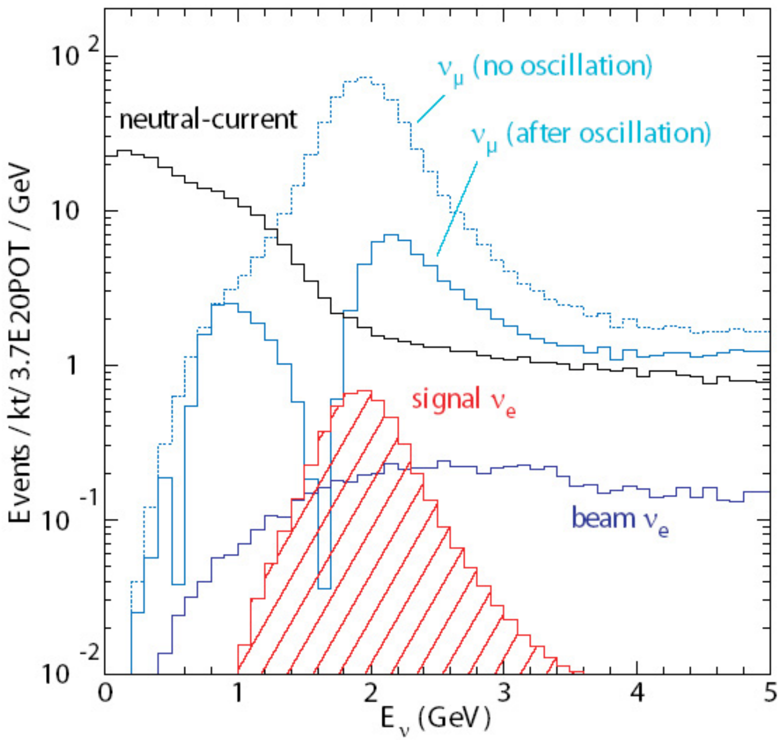
US LBL Physics Goals after MINOS

- Measure or put a stringent limit on $\sin^2(2\theta_{13})$ (NOvA sensitivity down to $\sim$ 0.01)
- Precision measurement of $\sin^2(2\theta_{23})$ (NOvA measurement to 1-2% accuracy)
- Resolution of mass hierarchy via matter effects or important contribution to it
- Contribution to study CP violation in neutrino sector (Proton Driver)

How to achieve these goals ?

- 1) Locate detector off NuMI beam axis to tune neutrino energy spectrum and reduce backgrounds which tend to have much broader spectrum

Event rates off NuMI beam axis:



Event rates for:

- L = 810 km, T = 12 km
- $\Delta m^2_{23} = 2.5 \times 10^{-3} eV^2$
- $\sin^2 2\theta_{23} = 1$, $\sin^2 2\theta_{13} = 0.01$

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How to achieve these goals ?

- 2) Increase mass of the detector
  - discussed sizes: 50 kt or 25 kt
- 3) Detector requirements:
  1. good energy resolution (to reduce background from intrinsic electron-neutrino component of the beam)
  2. very good e/π^0 separation (to reduce NC (CC) background)
  3. (... at reasonable cost)

  - Liquid scintillator + particle board + PVC (NOvA baseline design)
  - Liquid scintillator + PVC (NOvA alternative solution TASD - Totally Active Scintillator Detector)
  - or Liquid Argon ?

How to achieve these goals ?

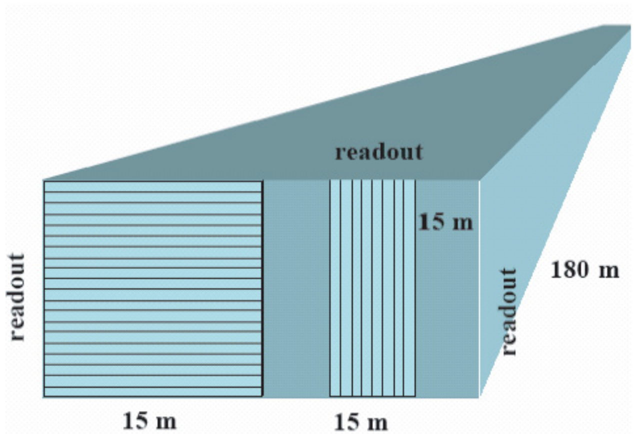
- 4) Choose long baseline to enhance matter effects
  - $>$ 800 km
- 5) Detector has to be on surface (no existing mine)
  - active shield
  - or fully active detector

NOvA

- NuMI Off-Axis ν_e Appearance Experiment (P929)
- Advanced project
- Letter of Intent October 2002
- Proposal 15 March 2004
- Time schedule: detector can be completed in 2011 (2009)

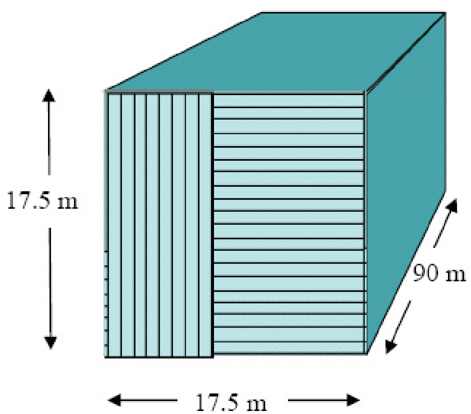
NOvA - Two detector options

- 50 kt liquid scintillator + PVC + particle board absorber



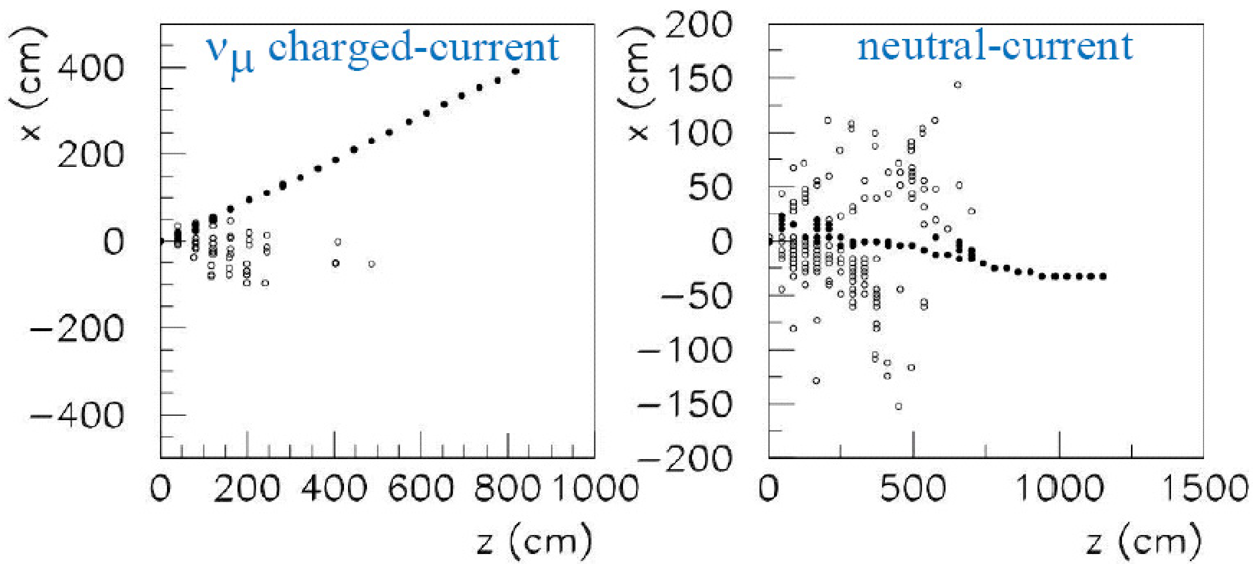
- 14 % active
- absorber $1/3X_0$ per plane
- active shield

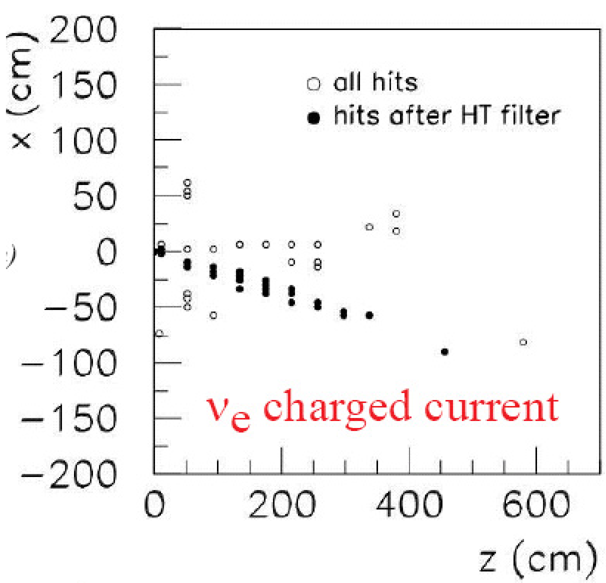
- TASD 25 kt liquid scintillator + PVC extrusions



- 85 % active, no absorber
- more challenging engineering
- no active shield

NOvA - baseline detector





18 % signal efficiency

signal/background = 4.6

$\sin^2 2\theta_{23} = 1$, $\sin^2 2\theta_{13} = 0.1$,

$\Delta m^2 = 2.5 \times 10^{-3}$, 50kt $\times$ 5 years

$\times$ 4 $\times 10^{20}$ pot/year

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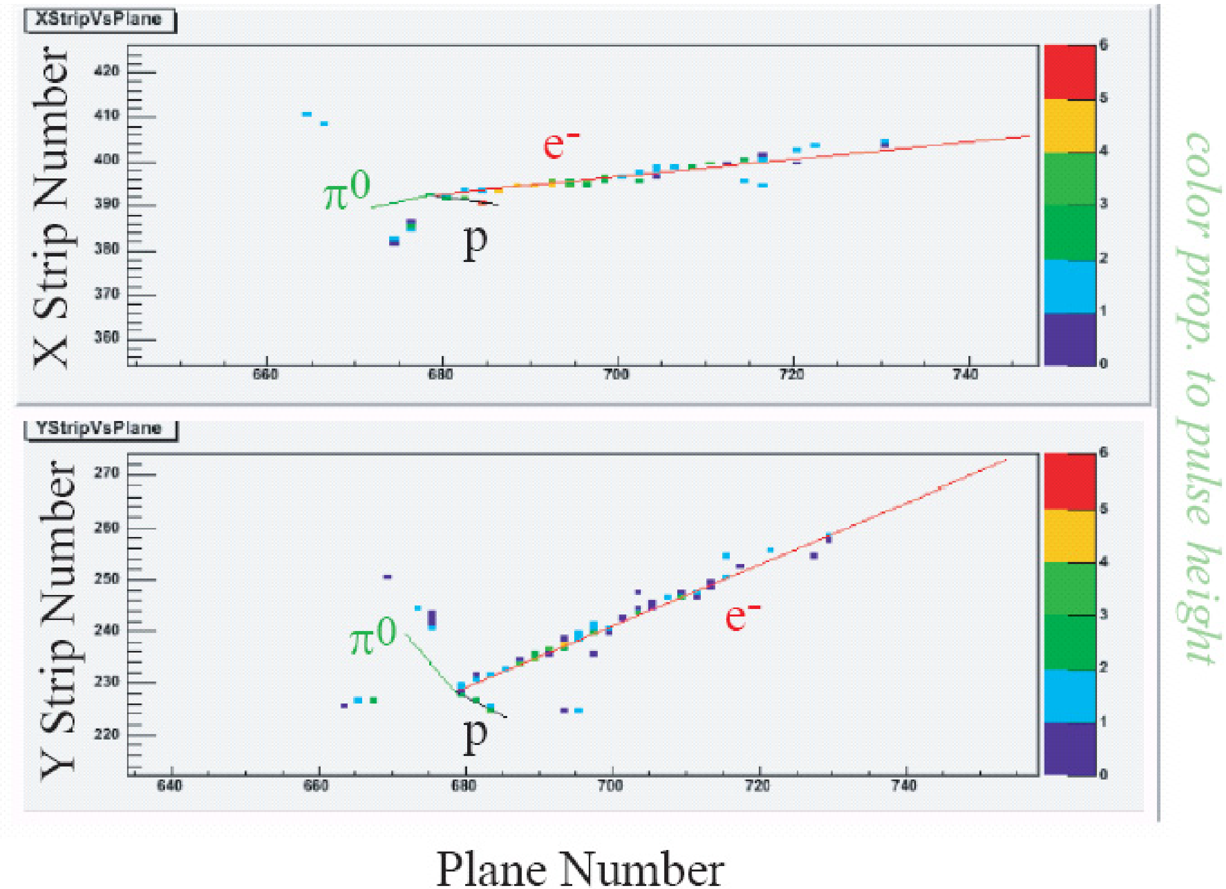
NOvA - TASD

$$\nu_e + n \rightarrow p + e^- + \pi^0 , \quad E_\nu = 1.65 \text{ GeV}$$



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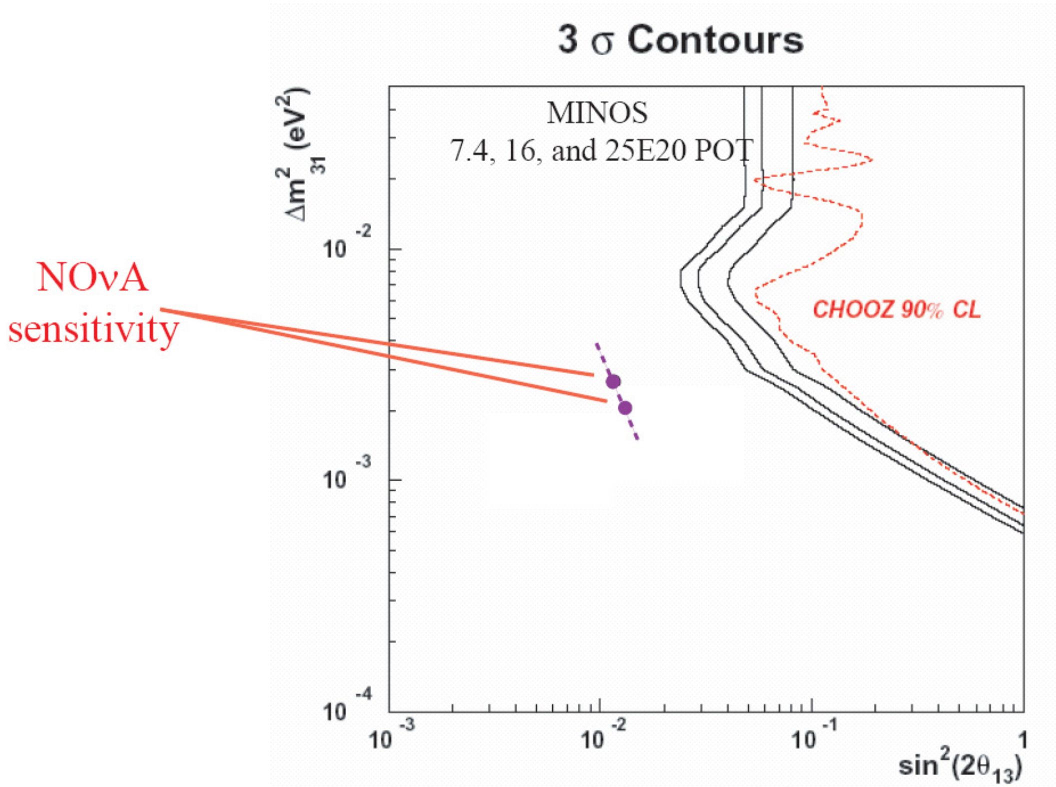
32 % signal efficiency, signal/background = 7.7

NOvA - Physics Reach

- ν_e appearance



Indication of NOvA sensitivity only ! Ambiguities: sensitivity depends on sign of Δm^2 and CP phase δ
Detailed discussion in P.Litchfield talk.

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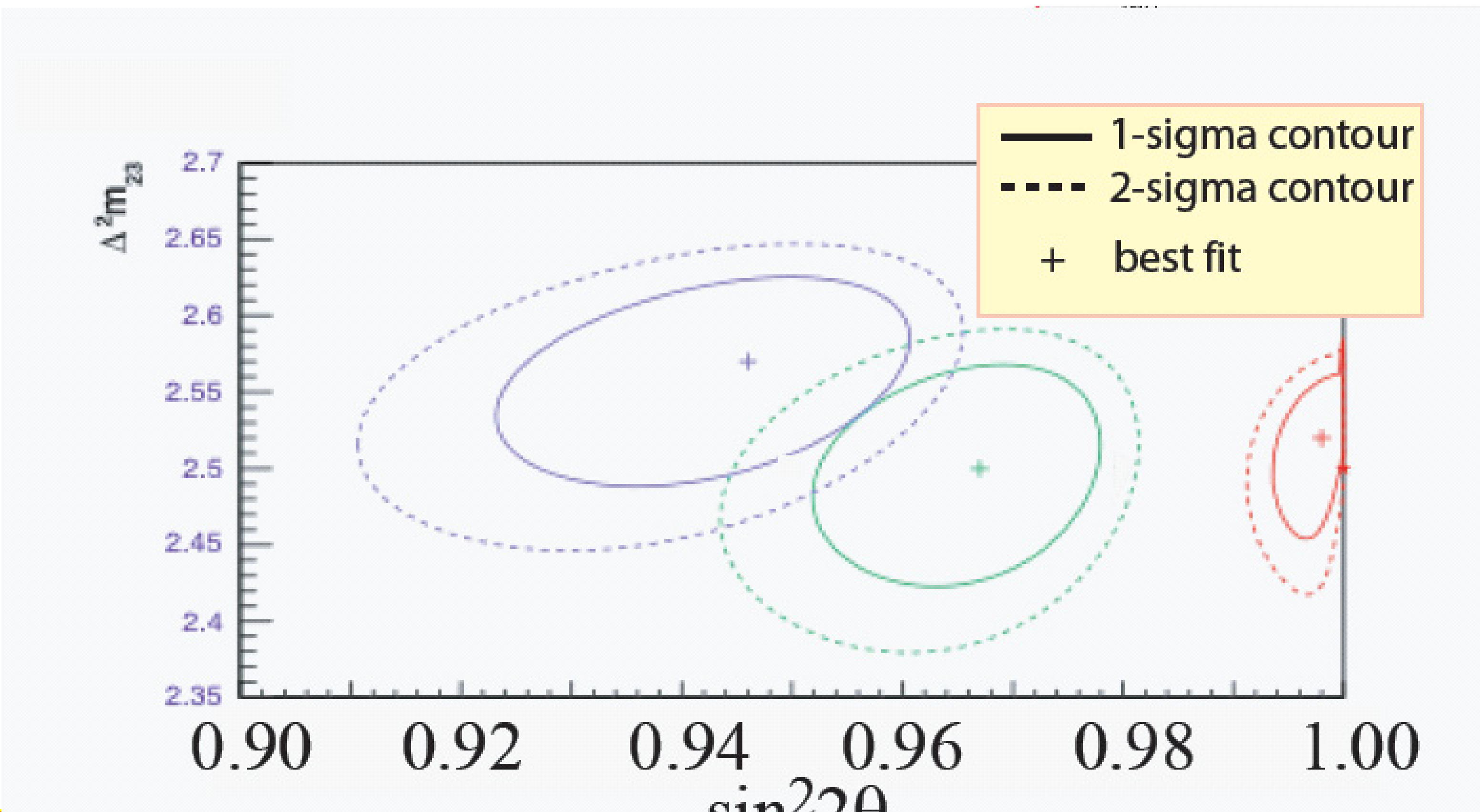
NOvA - Physics Reach

- ν_μ disappearance
- Quasi-elastic events are very clean in TASD
- Allow for clean measurement of $\sin^2\theta_{23}$ to $\sim 1-2\%$



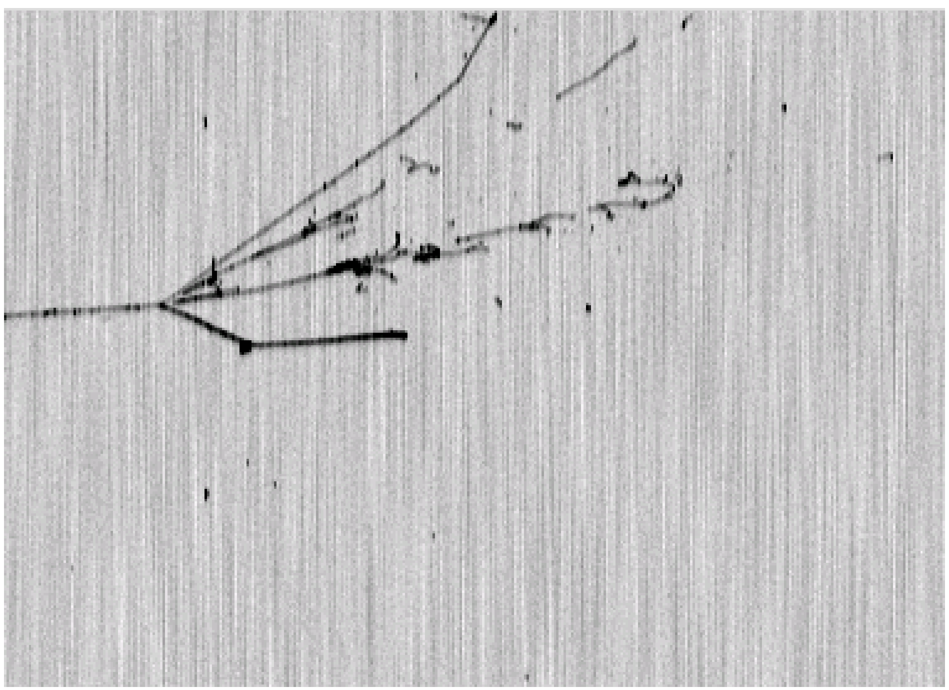
M.Messier

50kt Liquid Argon Experiment

- FLARE - Fermilab Liquid ARgon Experiments
  Letter of Intent hep-ex/0408121 (August 2004)
- Idea: use Liquid Argon technology (ICARUS) to build small 40t LAr detector and 50kt LAr detector at NuMI beam
- Detection technique undeniably excellent, but could it be cost-effective ?
- How big is the extrapolation from ICARUS ?

Liquid Argon Detection Technique

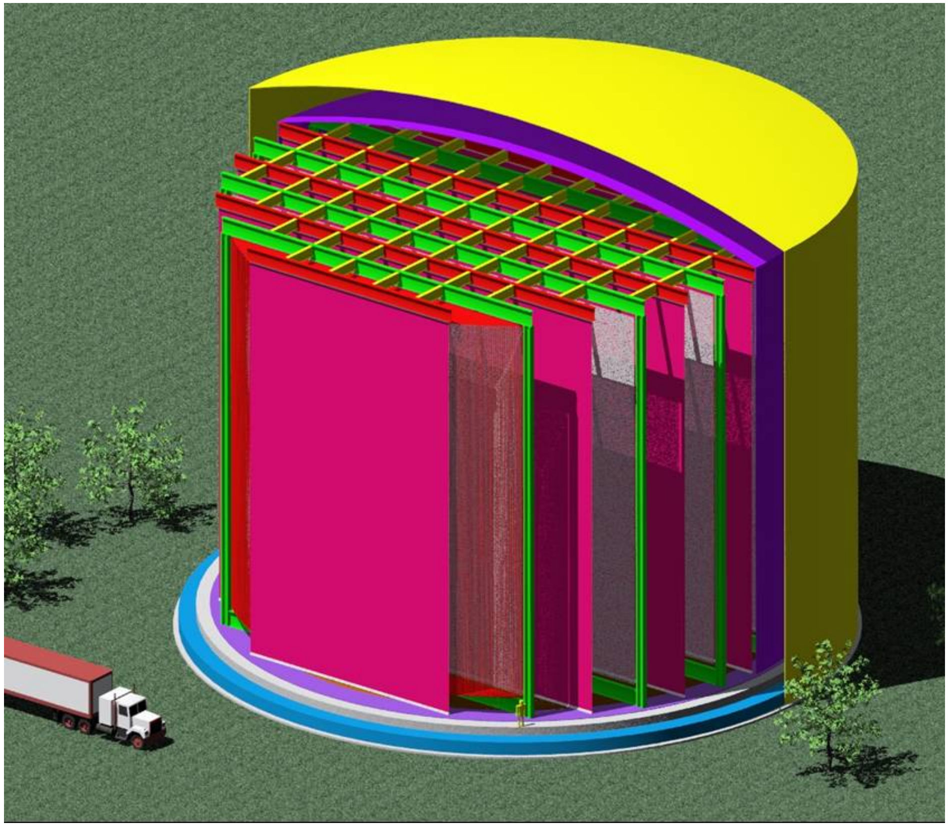
- LAr detector has parameters similar to bubble chamber: density 1.4 g/cm^3, radiation length 14 cm, similar granularity (3mm $\times$ 3mm $\times$ ($<$ 1mm))
- Interaction of 2.5 GeV π^- in LAr, FLUKA-ICA simulation (courtesy of Warsaw ICARUS group)



Liquid Argon Detection Technique

- Low detection threshold: all charged particles are detected
- Time Projection Chamber: 2 coordinates from wire position, third from timing
- Excellent e/π^0 separation (mean free path for photon conversion = 18 cm)
- Good particle identification: dE/dx is measured with accuracy $\sim 10\%$
- Good energy resolution
- 90 $\%$ efficiency of selecting ν_e interactions
- π^0 - induced background of the level of intrinsic ν_e component

50 kt Liquid Argon Detector



- Cryogenic tank, standard size H=30m, D=40m
- 35000 m^3 of liquid argon
- 7 cathode planes @ 150 kV (in pink)
- 6 wire chambers (in green)

50kt LAr Detector vs ICARUS

ICARUS (T600 module)

- 600t
- max drift distance 1.5m
- wire spacing 3mm
- third coordinate from timing resolution < 1mm
- HV 75kV (150kV tested)
- v_{drift} = 1.55 mm/μs
- t_{drift} = 1ms
- tested on surface

50 kt LAr

- 50 kt
- max drift distance 3m
- wire spacing 5mm
- third coordinate from timing resolution
- HV 150kV
- v_{drift} = 1.55 mm/μs
- t_{drift} = 2ms
- on surface

50kt LAr Detector

Potential problems:

- Detector on surface (cosmic rays induced background)
- Challenging engineering: long wires, up to 36m
- Argon purity which allows for drift distances up to 3m
- Large volume of data

Cost estimate of the order of NOvA.
Is it realistic ??

Conclusions

- NuMI beam installation is well advanced and on schedule
- The first user of NuMI will be MINOS
- MINOS is in good shape and is eagerly waiting for first beam data early 2005 !
- NOvA is the advanced project to build 50kt/25kt detector off NuMI beam axis ($\rightarrow$ more in P.Litchfield talk)
- There is also a brand new idea to build 50kt Liquid Argon detector on NuMI beam

- Thanks to P.Litchfield and A.Para