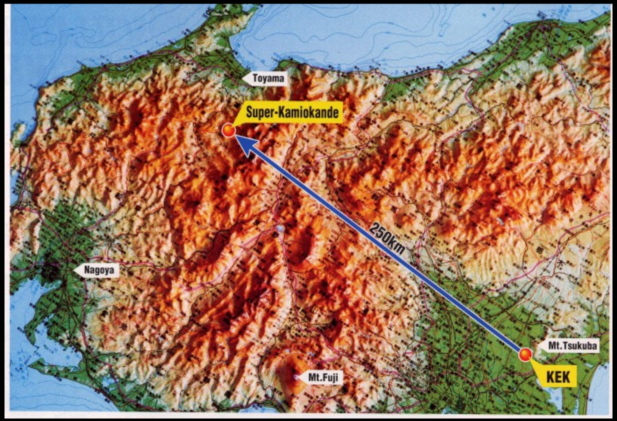
# Unit 3:
# Neutrino Oscillations with Terrestrial Sources






*Conventional neutrino beams from accelerators: from short to long baseline experiments*

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***HEP PostGraduate Lectures 2016-17 University of London***

# Outline

- Main characteristics of neutrino oscillation experiments with terrestrial sources (main parameters, sensitivity and design considerations)
- A few examples from real life:
  - Short baseline experiments
  - Long baseline experiments
- Today: first generation of long-baseline experiments that confirmed the 3-ν oscillation mechanism

# Sensitivity to Oscillations vs E/L

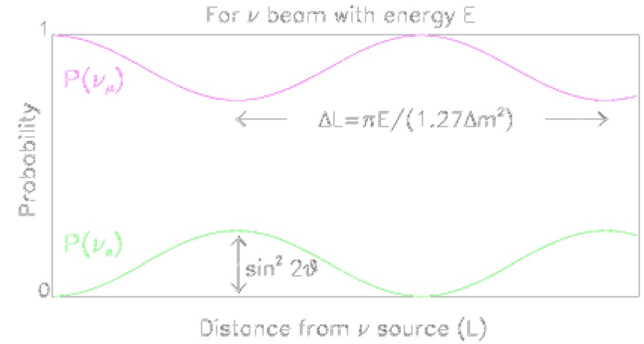
For vacuum oscillations between 2-flavours

**$P(\nu_\alpha \rightarrow \nu_\beta) = \sin^2 2\theta \sin^2 (1.27\, \Delta m^2\, L/E)$,**

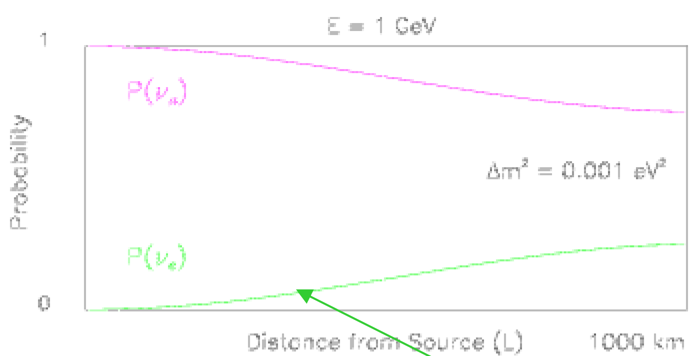
with $\Delta m^2$ ($eV^2$), L(Km)/E(GeV)

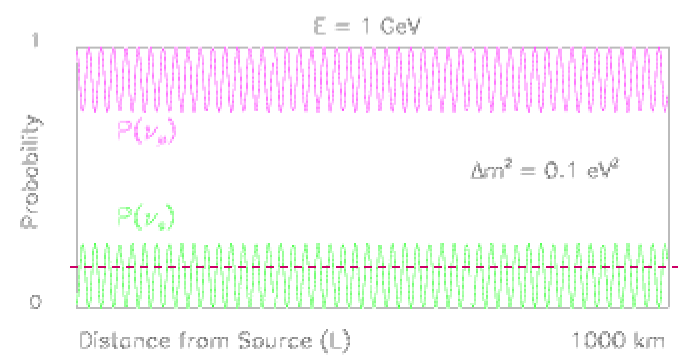
**2 Experimental L, E and**

**2 Fondamental Parameters ($\sin^2 2\theta$, $\Delta m^2$)**




Max sensitivity (Max P) for $\Delta m^2\, L/E \sim 1$, i.e., $E/L \sim \Delta m^2$




For $E/L \gg \Delta m^2 \Rightarrow P \ll \sin^2 2\theta$

For $E/L \ll \Delta m^2$ P oscillates very rapidly as a function of L/E and given the finite energy resolution of the experimental apparatus sensitivity to $\Delta m^2$ is lost:

**$P(\nu_\alpha \rightarrow \nu_\beta) = \sin^2 2\theta \sin^2 (1.27\, \Delta m^2\, L/E)$**

**$\rightarrow \langle P(\nu_\alpha \rightarrow \nu_\beta) \rangle = 1/2 \sin^2 2\theta$**

# Short and Long Baseline Experiments

**L/E can be tuned to be sensitive to different $\Delta m^2$ regions with experiment at accelerators/nuclear reactors** (Sun much harder to move…though you can look for anomalous effects in the flux seasonal variations, due to elliptic Earth orbit around Sun)

Max experimental sensitivity: $E/L \sim \Delta m^2$

**Short-baseline (SBL)** experiments are sensitive to large $\Delta m^2$

**Long-baseline (LBL)** experiments to small $\Delta m^2$

**Typical $\nu_\mu$ beam from accelerator** $\langle E \rangle \sim 1$– 50 GeV

for $\langle L \rangle \sim 1$ Km (short-baseline) $\Delta m^2 > 1$ eV$^2$

$\Rightarrow$ no sensitivity in the atmospheric region

for $\langle L \rangle > 100$ Km (long-baseline) $\Delta m^2 < 10^{-2}$ eV$^2$

$\Rightarrow$ sensitive to the atmospheric region (K2K)

**Reactors: anti-$\nu_e$ with E ~ few MeV** , L ~ 10 m(brave physicists!)-100 m are considered short baseline

L ~ 1 Km/200Km long/verylong baseline

(Kamland, $\langle L \rangle \sim 200$ Km, is sensitive to solar $\Delta m^2 \sim 10^{-5}$ eV$^2$!)

# Appearance and Disappearence Experiments

Disappearance experiment:

Search for a reduction of the flux at distance L from the source. It measures:

$$P(\nu_\alpha \rightarrow \nu_\alpha) = 1 - P(\nu_\alpha \rightarrow \nu_\beta) = 1 - \sin^2 2\theta \sin^2 (1.27\, \Delta m^2\, L/E)$$

Requires good knowledge of the beam intensity

Normally 2 (or more) detectors:

- NEAR detector - measure flux before oscillation
- FAR detector - measure flux at distance L

Appearance experiment:

Search for a $\nu$ of a different flavor than the one of the beam, measuring $P(\nu_\alpha \rightarrow \nu_\beta) = \sin^2 2\theta \sin^2 (1.27\, \Delta m^2\, L/E)$

Number of observed $\nu_\beta$ interactions:

$N^{osc} = P(\nu_\alpha \rightarrow \nu_\beta) \times \phi(\nu_\alpha) \times \sigma(\nu_\beta) \times n_{scat} \times$ detection efficiency x t (integration time)

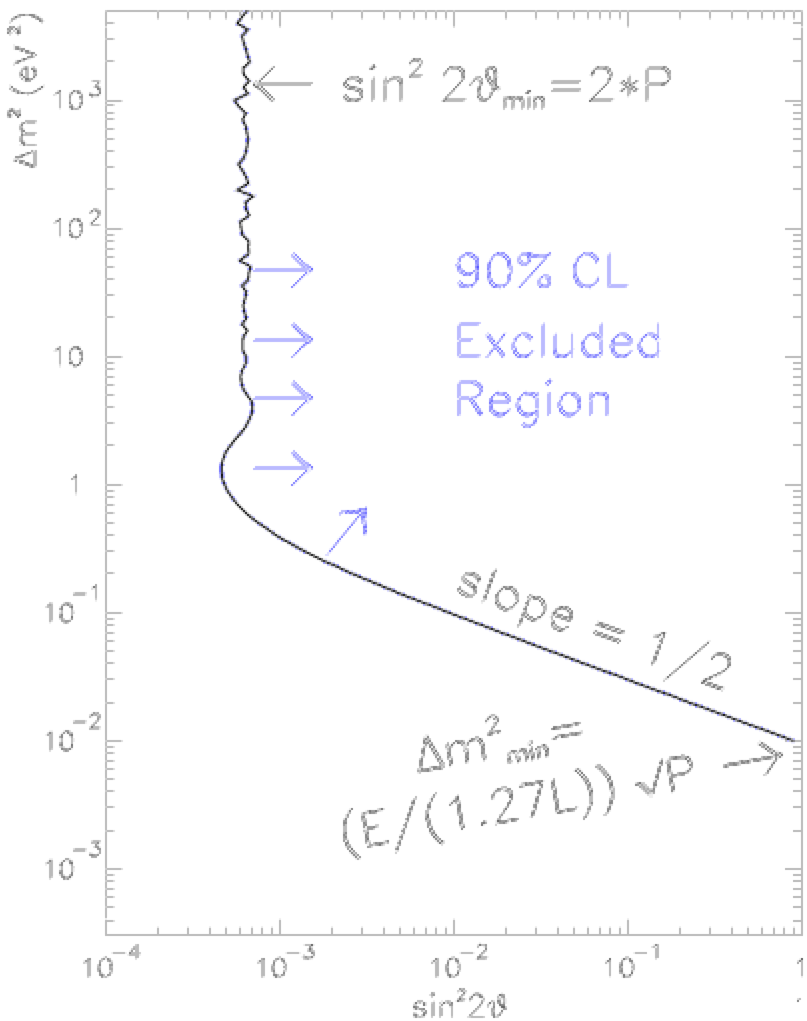
# Sensitivity vs Data Sample Size

Sensitivity:== 90% C.L. set by the experiment in case NO OSC. observed

**In an appearance experiment measuring P($\nu_\alpha \rightarrow \nu_\beta$)**
**with $N^{max}$ = observable $\nu_\beta$ events if P=1**
**and $N^{osc}$ $\nu_\beta$ events due to oscillation**
**P= $N^{osc}/N^{max}$**
**assuming no $\nu_\beta$ events are observed (and no background) then $N^{osc}$ = 0**
**P <2.3/$N^{max}$ is the 90% CL limit of sensitivity (solid line in plot)**

**At high $\Delta m^2$:**
**<$\sin^2$ (1.27 $\Delta m^2$ L/E)> =1/2**
**P=1/2 $\sin^2 2\theta$**
**For appearance experiments with zero background, sensitivity to small mixing angle is high at high $\Delta m^2$ and improves linearly with number of events (or $N^{max}$)**
**For sin2θ=1 and small $\Delta m^2$:**
**P= $\sin^2$ (1.27 $\Delta m^2$ L/E) ~ (1.27 $\Delta m^2$ L/E)$^2$**
**sensitivity to small $\Delta m^2$ improves only with $\sqrt{P}$ therefore with $\sqrt{N^{max}}$**

**In presence of background it is easily shown That the sensitivity to $\sin^2 2\theta$ improves with $\sqrt{N}$ (for $\Delta m^2$>>) and to $\Delta m^2$ with $N^{1/4}$ (for $\sin^2 2\theta$ =1)**



# Designing a $\nu$ Oscillation Experiment

- Define oscillation search: $\nu$ flavor, $\Delta m^2$, $\sin^2 2\theta$

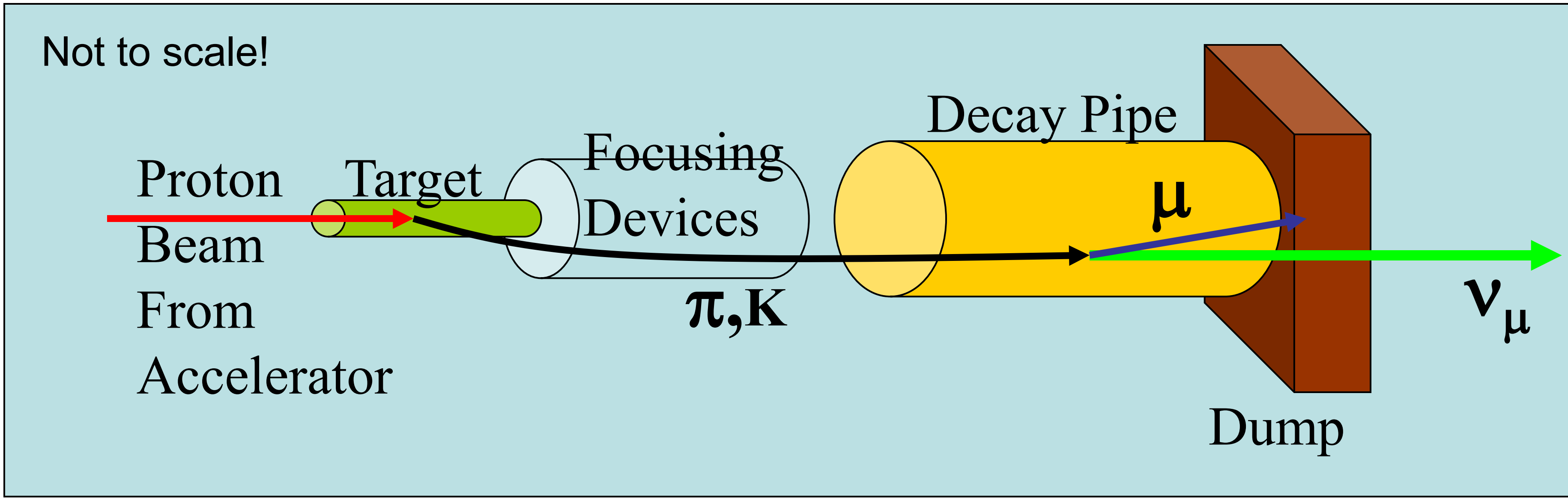
- Choose the "philosophy":
  -Appearance(accelerator) vs disappearance(reactor or accelerator);

- Choose baseline:
  -optimize $\Delta m^2$ sensitivity ($\Delta m^2\downarrow$ as $L\uparrow$)
  vs N, $N \propto \phi \times \sigma$ = flux x cross-section ($\phi \sim 1/L^2 \uparrow$ as $L\downarrow$)

- Choose energy:
  -optimize $\Delta m^2$ sensitivity ($\Delta m^2\downarrow$ as $E\downarrow$)
  vs N, $N \propto \phi \times \sigma$ = flux x cross-section ($\sigma\uparrow$ as $E\uparrow$)

- Choose target mass and detector technology:
  - Cherenkov ["cheap and easy" to scale to very large mass] vs sampling calorimeter [performance (energy resolution,PID) improves with E]. Other possibilities: Nuclear Emulsions, TPC…

# A "Conventional" $\nu_\mu$ Beam




Proton beam: POT = proton on target (the higher the better!)

Target: Low Z material to minimize re-interactions, typically 1m Beryllium rod

Focusing: Magnetic Horn (high currents, pulsed in coincidence with proton spill)
Focalises secondary $\pi$,K of wanted charge in a chosen momentum-window (broad or narrow)

Decay Pipe: "vacuum pipe", can be filled with He (25—250 m long,depending on energy)

Dump: hundreds m of earth, concrete, iron to absorb accompanying particles (sometimes a magnet)
Contains detectors to monitor muon flux (intensity and beam profile)

$\nu$ Beam: Mainly $\nu_\mu$ from $\pi^+$,$K^+$ decay, but also contamination of $\nu_e$ (few %) from $K_{e3}$ and $\mu$ decay, and anti$\nu$

Reverse the polarity of the Focusing Magnets to create an anti-$\nu\mu$ beam. Easy!
But flux normally less-intense (leading positive charge of mesons produced by protons : $\pi^+ \rightarrow \mu^+ \nu_\mu$ )

# CHORUS: $\nu_\mu \rightarrow \nu_\tau$ Short-baseline Appearance Experiment (1994-1997)

## Why $\nu_\mu \rightarrow \nu_\tau$?

Atmospheric neutrinos is the motivation now. No evidence 15 years ago, when first dedicated experiments were designed. Why then? Massive neutrinos 1-10 eV were good candidate for hot dark matter

## Which detection technique?

Unambiguous proof of oscillations would be “seeing” $\nu_\tau$, in a beam which does not contain “any” $\nu_\tau$, through detection of $\tau$ produced **in** CC events

$\nu_\tau$ contamination in the CERN $\nu_\mu$ beam is small ($<10^{-7}$)

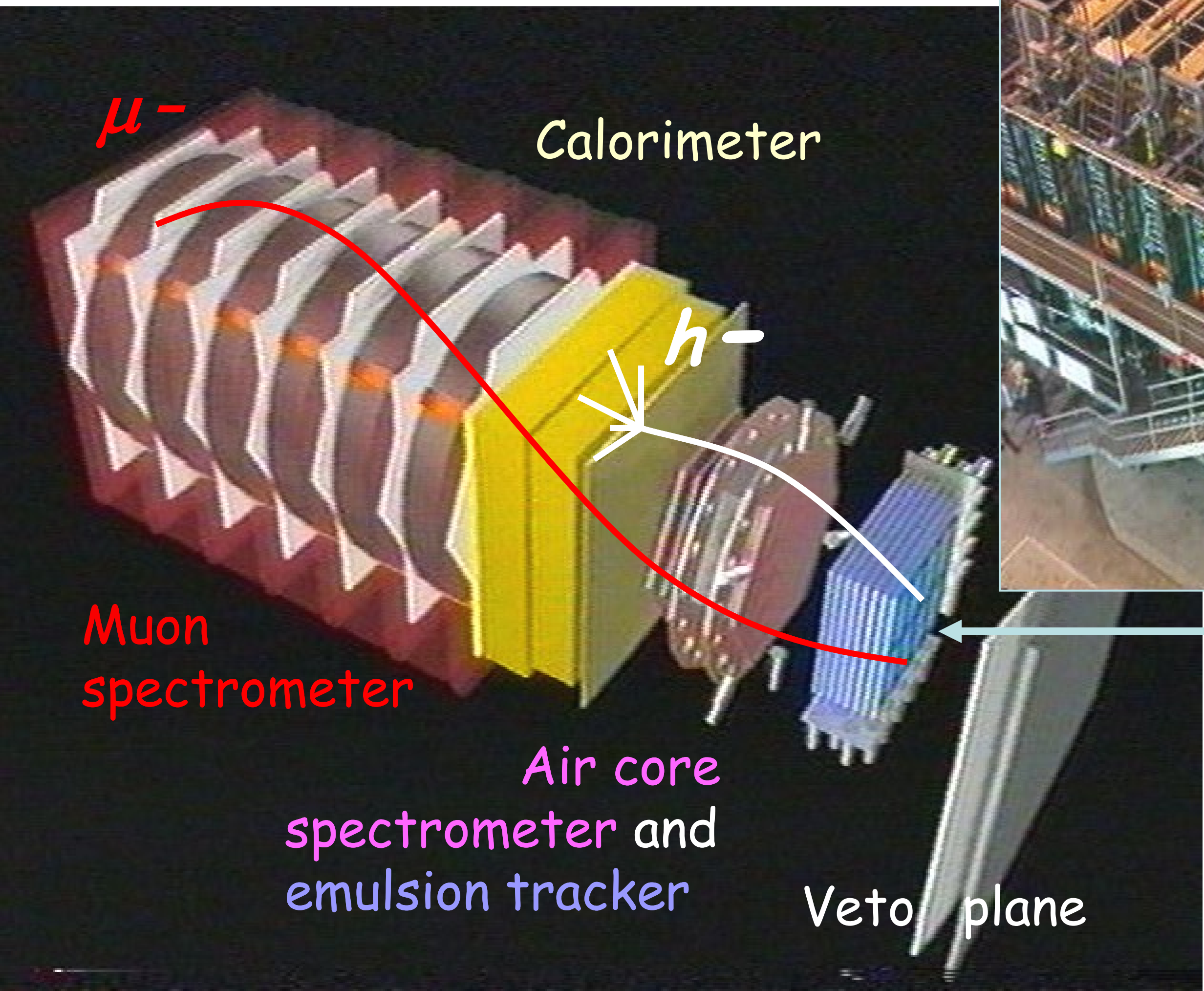
( $m_\tau$ = 1.8 GeV, can’t be produced in pions nor kaons decays) OK!

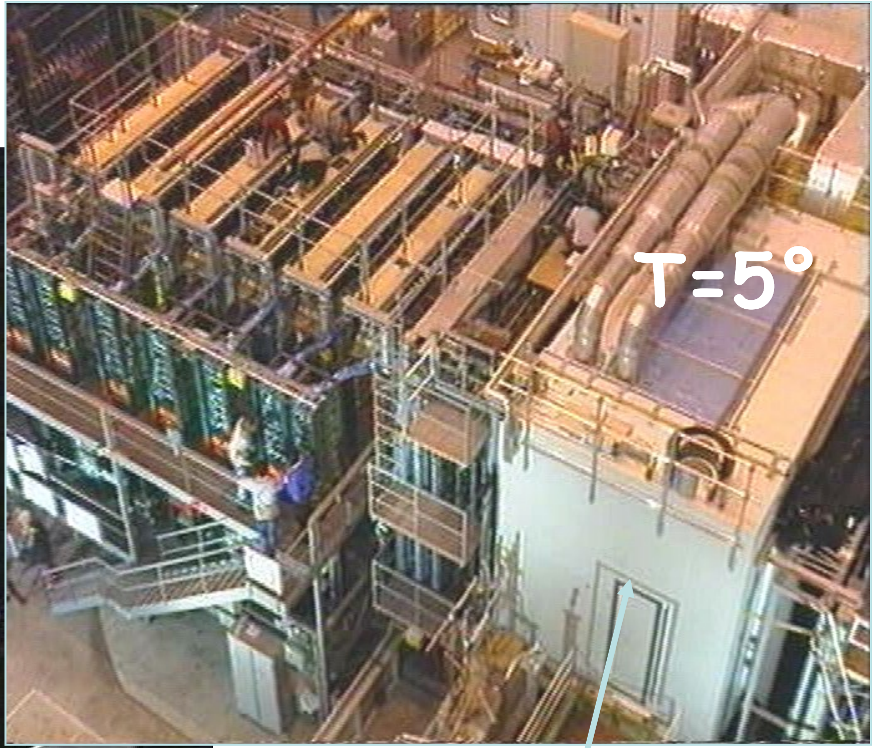
## What is the challenge?

Detecting $\tau$ means searching a short-lived particle, $L_{decay}$ <1mm ($E\tau \sim$ 10 GeV )

We need a massive detector with spatial resolution of ~micron!

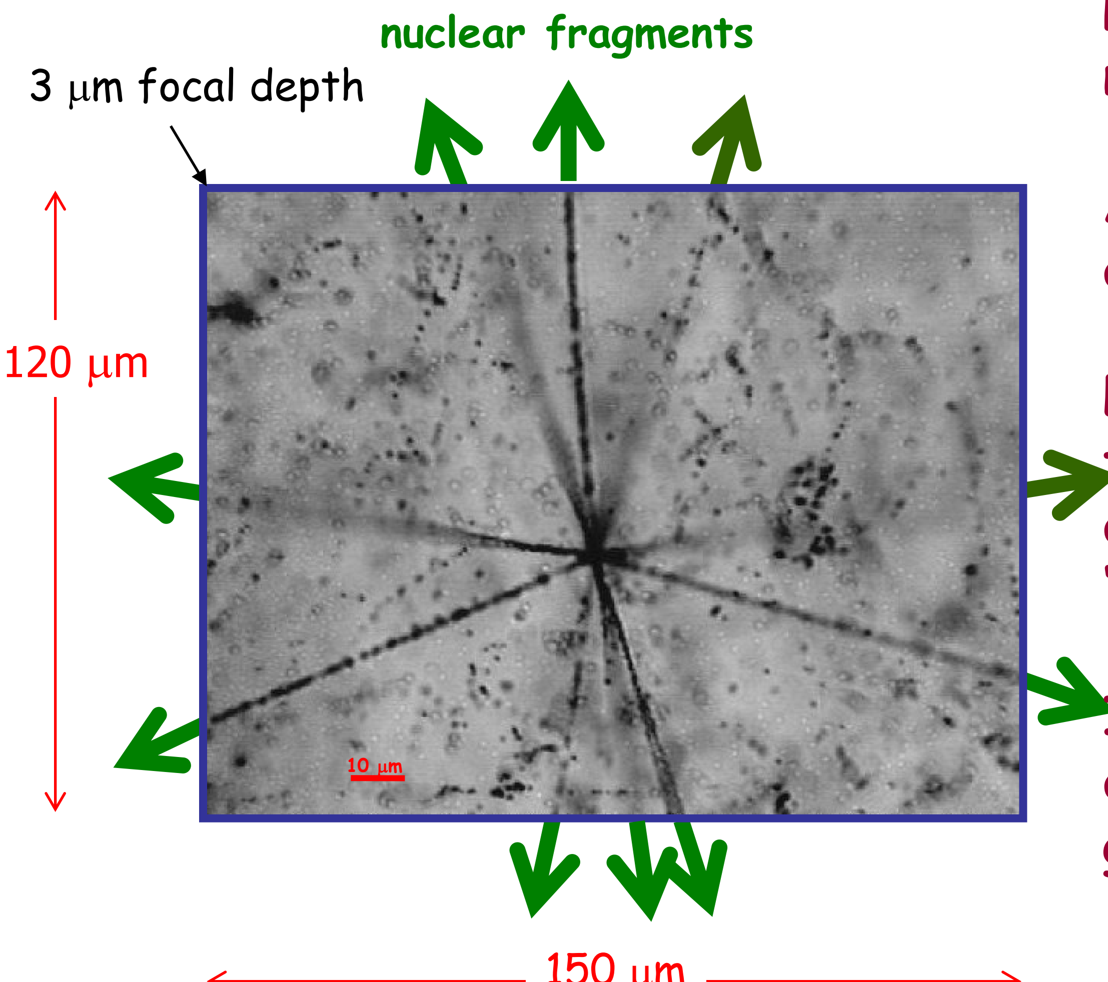
# The CHORUS Detector




800 kg nuclear emulsion target and scintillating fibre tracker

# A picture of a ν interaction!




A microscope view

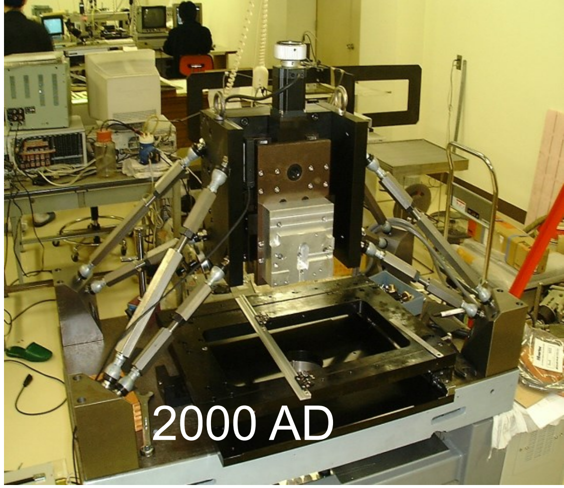
Plates are orthogonal to the neutrino beam

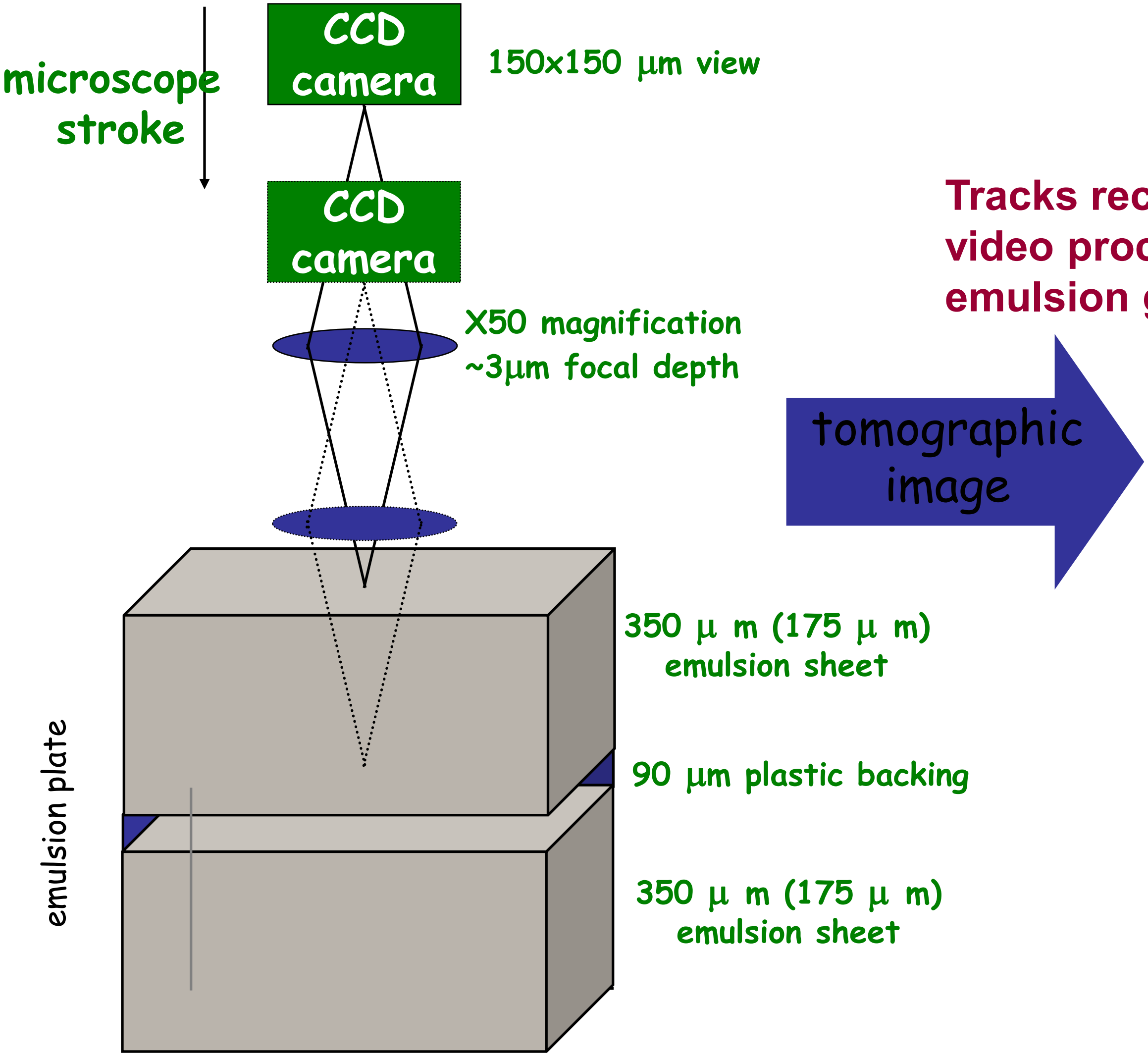
An AgBr emulsion grain has about 0.5 μm diameter

Large angle nuclear fragments (if any) are seen as a 'star' of heavy ionizing 'tracks' in the vertex view

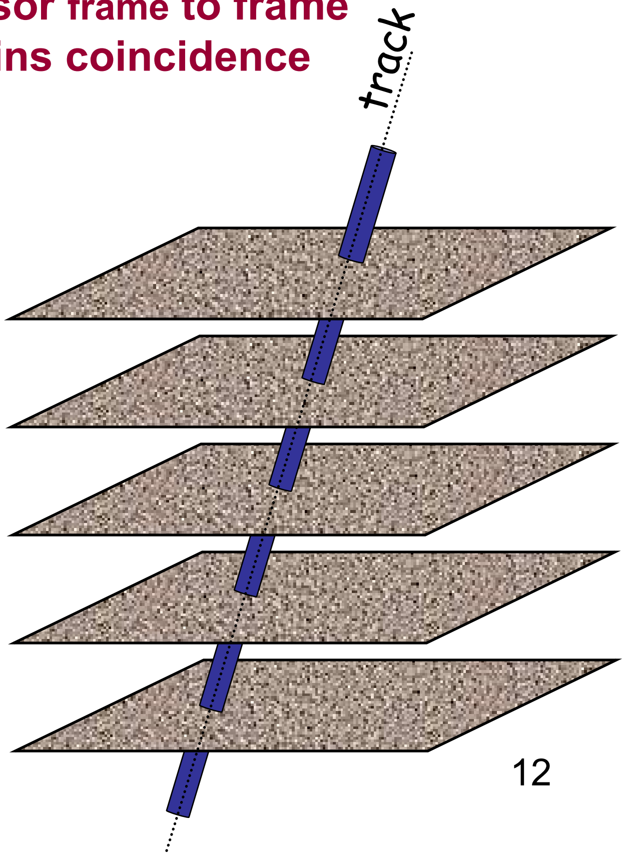
Interaction tracks are seen as the coincidence of a single grain from each view


# Nuclear Emulsions: automatic scanning

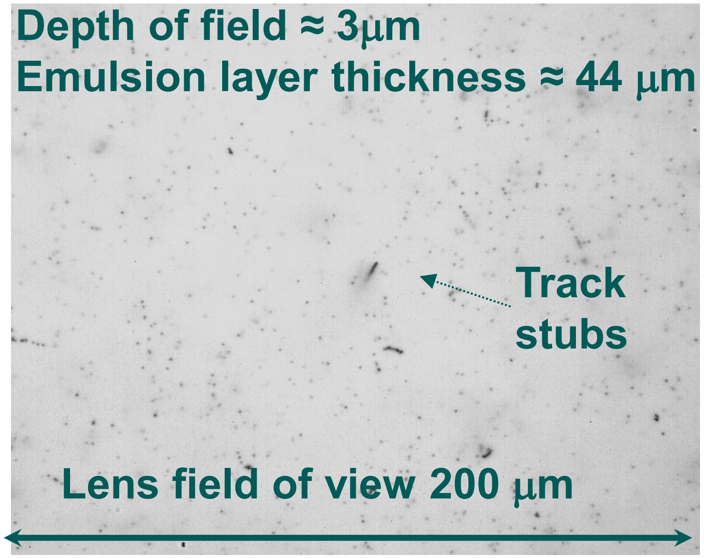


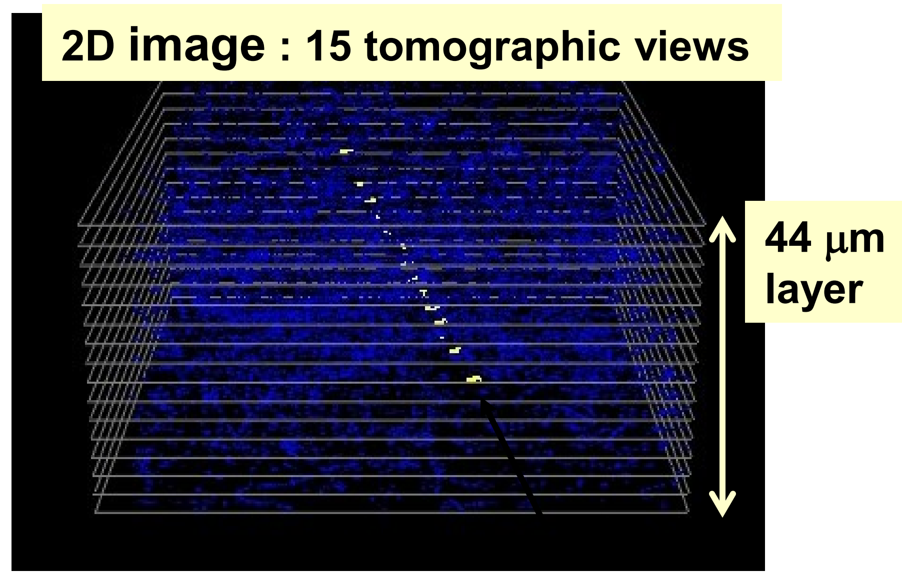



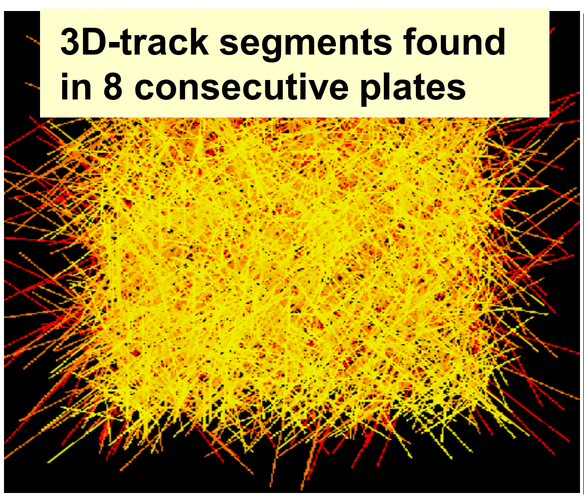

**Tracks reconstructed by a hardware video processor frame to frame emulsion grains coincidence**

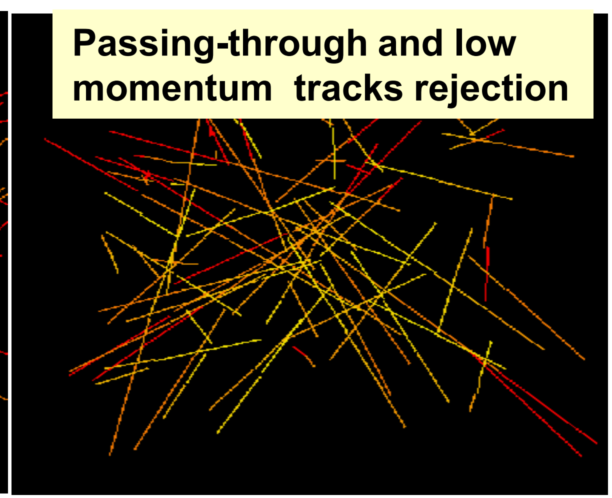


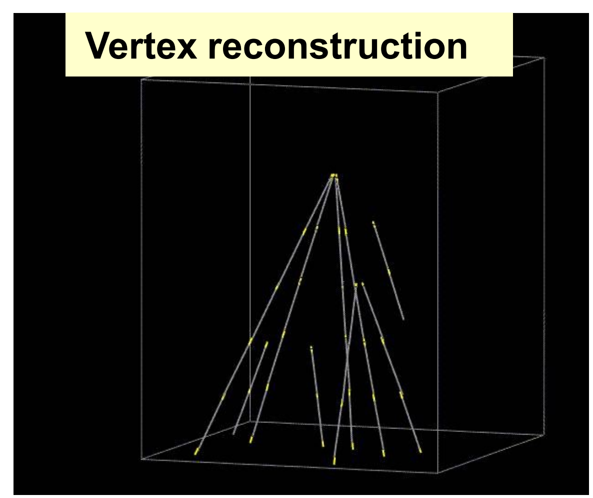
# How to scan for tracks in nuclear emulsion



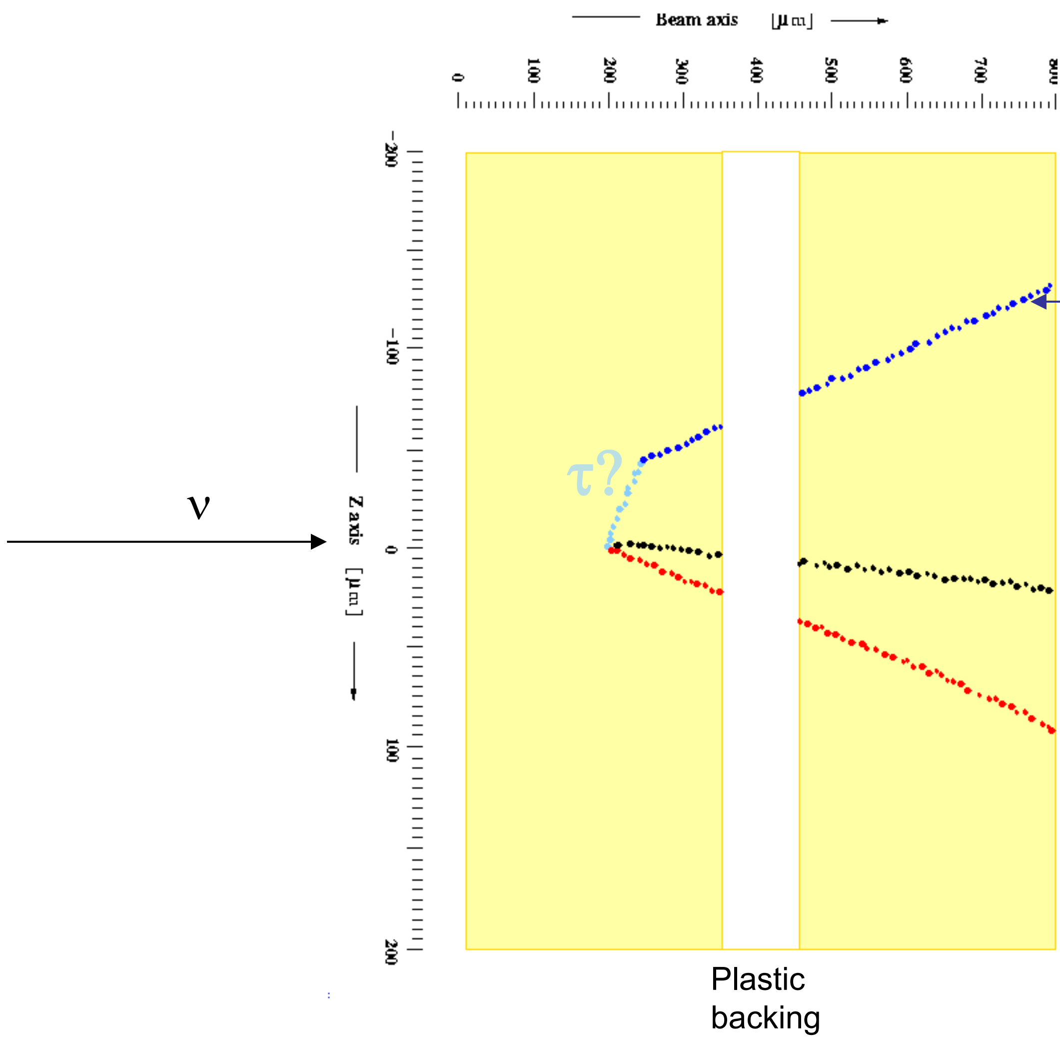




Example from the Opera experiment (G. Wilquet, EPS2007)

# $\tau$ kink detection in emulsion




Side view of an emulsion plate

Look for oscillation $\nu_\mu \to \nu_\tau$ with $\nu_\tau N \to \tau^- X$ (CC interaction) followed by $\tau^- \to \mu^- \nu \nu$

$\mu$ seen also in the downstream spectrometer

This is how a $\tau$ decay could look like in emulsion

However, spectrometer found $\mu$ charge sign positive! $\Rightarrow$ Kink is not a $\tau^-$ decay
but a $D^+ \to \mu^+$ + *neutrals*
*Background* $\nu_\mu$ *event*

# Calculating the sensitivity of CHORUS

N number of observed CC $\nu$ events

$\varepsilon$ Efficiency: $\varepsilon(\nu_\tau) \sim \varepsilon(\nu_\mu) \times \varepsilon_{KINK}$

B Branching Fraction $\tau^- \rightarrow \mu^- \nu\, \nu = 17.4\,\%$

$\sigma$ Cross-section $\nu$ CC: $\sigma(\nu_\tau) = 0.53\, \sigma(\nu_\mu)$ @ Chorus energies

$\phi$ Flux

$N(\nu_\mu) = \phi(\nu_\mu) \times \sigma(\nu_\mu) \times \varepsilon(\nu_\mu)$

$N(\nu_\tau) = \phi(\nu_\tau) \times \sigma(\nu_\tau) \times \varepsilon(\nu_\tau) \times B$
$= P(\nu_\mu \rightarrow \nu_\tau) \times \phi(\nu_\mu) \times \sigma(\nu_\tau) \times \varepsilon(\nu_\tau) \times B$
$= P(\nu_\mu \rightarrow \nu_\tau) \times N(\nu_\mu) \times \sigma(\nu_\tau) / \sigma(\nu_\mu) \times \varepsilon_{KINK} \times B$

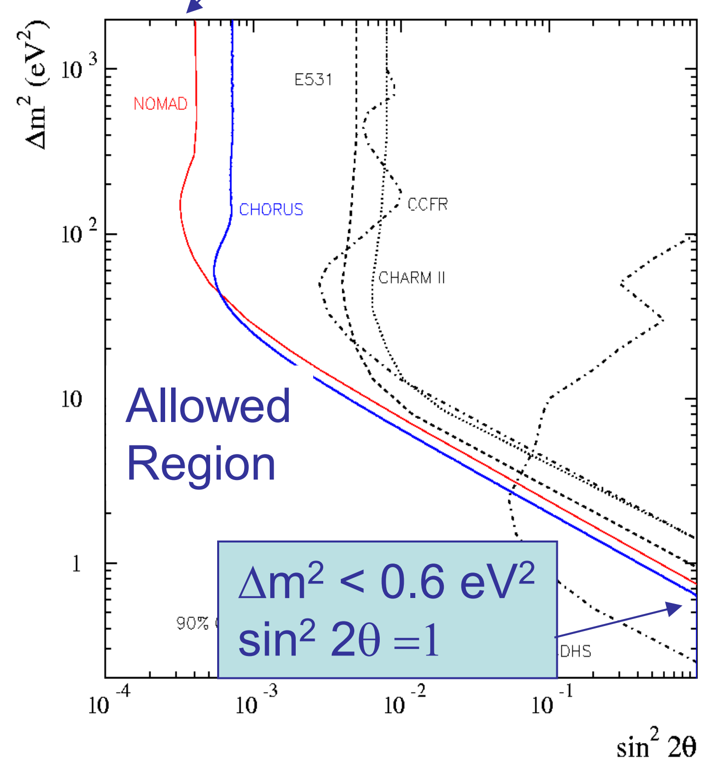
$\Rightarrow$ (P=1) $N^{max}_\tau = N(\nu_\mu) \times \sigma(\nu_\tau) / \sigma(\nu_\mu) \times \varepsilon_{KINK} \times B$

For 150K located $N(\nu_\mu)$ events in emulsion and measured $\varepsilon_{KINK} = 35\% \Rightarrow N^{max}_\tau \sim 5{,}000$

$N_\tau^{obs} = 0 \Rightarrow P(\nu_\mu \rightarrow \nu_\tau) < 2.3 / N^{max}_\tau = 5 \times 10^{-4}$

Published CHORUS: $P < 3.4 \times 10^{-4}$ (including also some sensitivity to other $\tau$ decays)

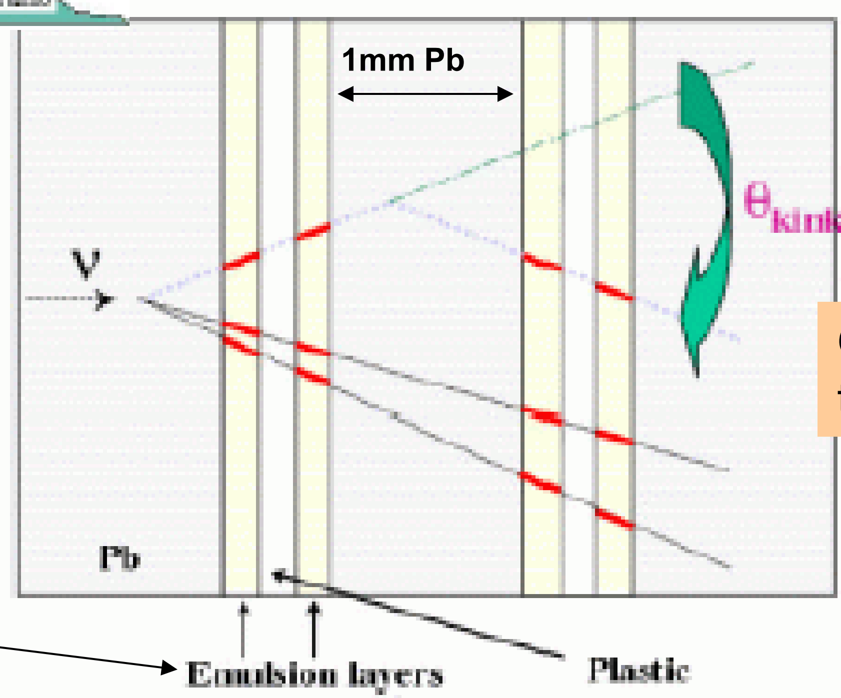
$\sin^2 2\theta < 6.8 \times 10^{-4}$ (90%CL) at high $\Delta m^2$



# OPERA (data-taking 2008-2012)


LBL $\nu_\mu \rightarrow \nu_\tau$ appearance experiment

Beam Source at CERN
$\langle E_\nu \rangle \sim 17$ GeV
Detector under Gran Sasso, L~700km
Flux $4.5\times10^{19}$ POT/year, 200 days/year
(about what CHORUS got in 4 years)

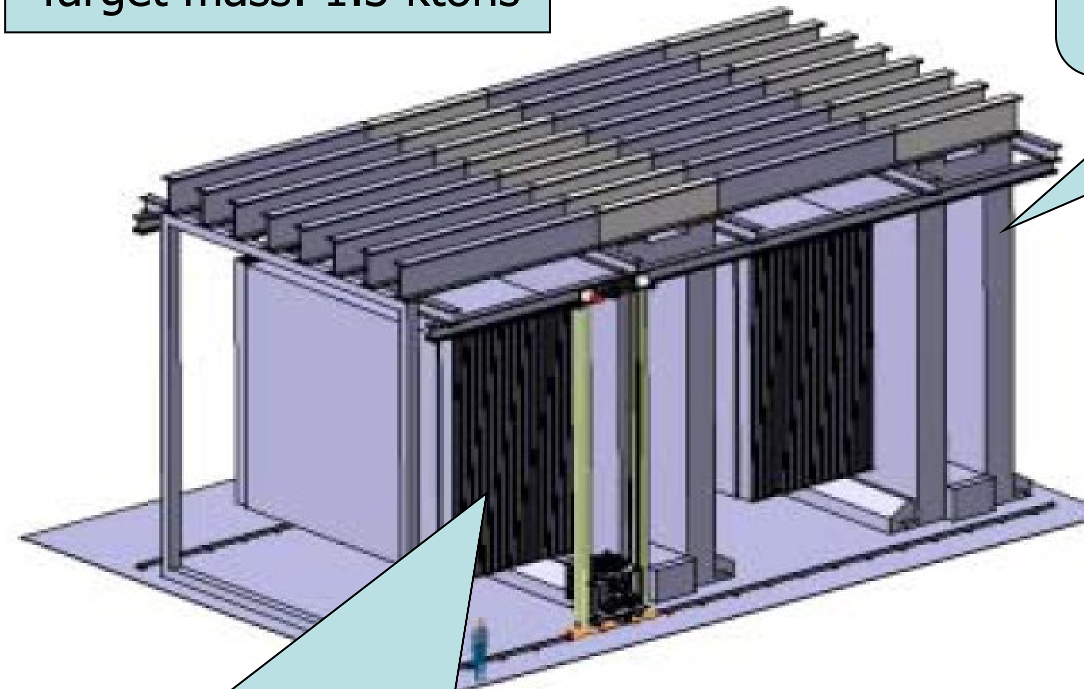



Observe $\tau$ decay topology in a brick

**Emulsion foil =**
**2 emulsion layers**
**(44 μm thick) glued onto a**
**200 μm plastic base**

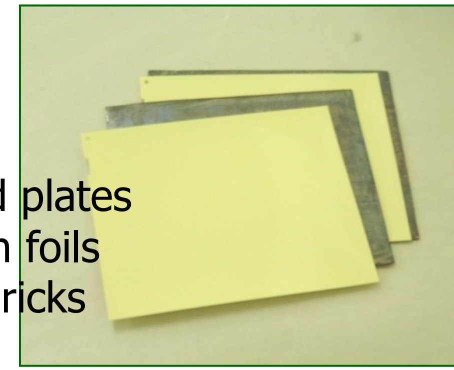
# Opera Detector

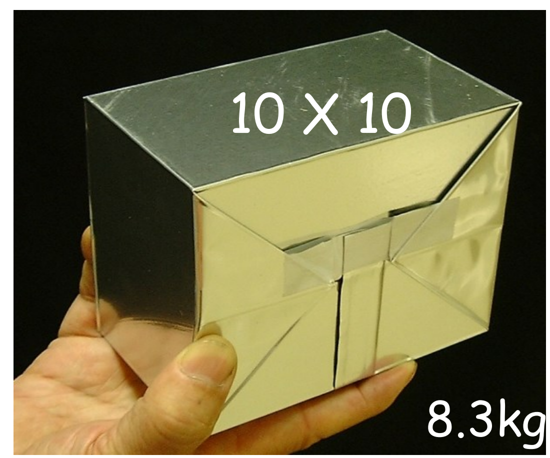
Target mass: 1.3 ktons



μ spectrometer:
Magnetized Iron Dipoles (1.6T)
Drift tubes and RPCs

Brick:
• 56 thin lead plates
• 57 emulsion foils
➔ 206,336 bricks






ν target and τ decay detector:
Sequence of modules consisting of
- "wall" of lead/emulsion "bricks"
- two planes of orthogonal scintillator strips (target tracker)

# You can predict Opera sensitivity now!

A very rough estimation for an OPERA-like experiment :

L 760 Km = CHORUSx1000

E similar to CHORUS (30 GeV) } $\Rightarrow \Delta m^2 \sim E/L \downarrow \sim 10^{-2} - 10^{-3} eV^2$

Flux $\propto 1/L^2$ down also $10^{-6}$ ☹

Try to recover: increasing target mass: 1.3 ktons = CHORUS x 1500

increasing flux x run-time: 4.5 $x10^{19}$ pot/y x 5y = CHORUS x 5

detection efficiency: similar to CHORUS!

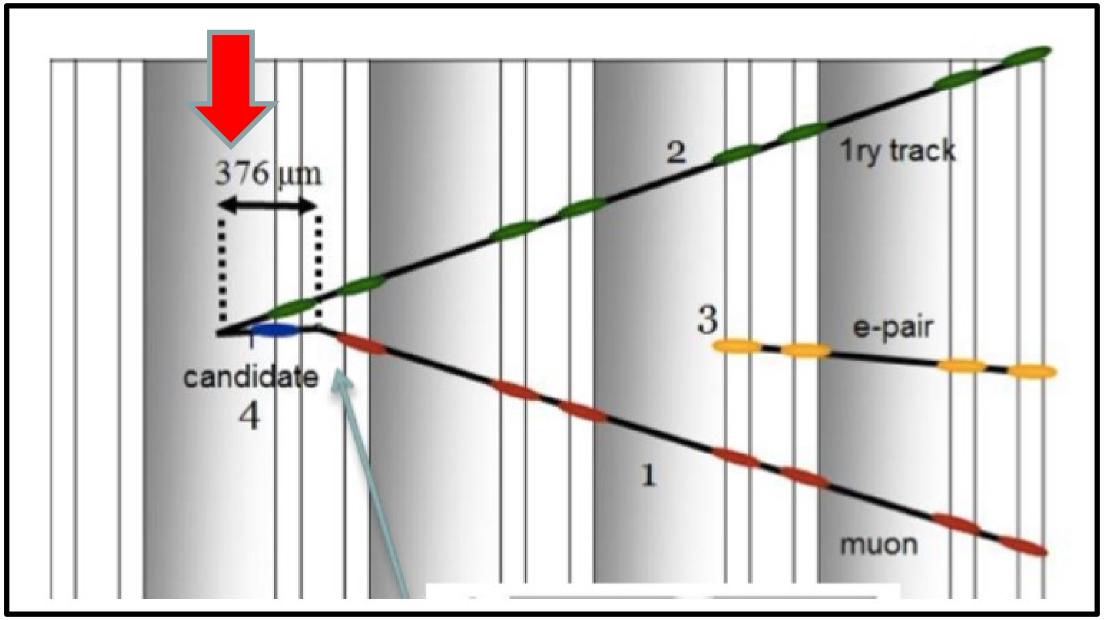
$\Rightarrow N_\tau^{max}$ = CHORUS (5,000) x $10^{-6}$ x 1500 x 5 ~ 38 events

Official OPERA numbers (from proposal):

12.8 events (0.8 BKG) expected for $\Delta m^2 = 2.4 \times 10^{-3} eV^2$ after 5 years of data-taking

***a $\nu_\tau$ appearance experiment is difficult!***

## $\tau \rightarrow \mu$ candidate




5 candidates observed so far

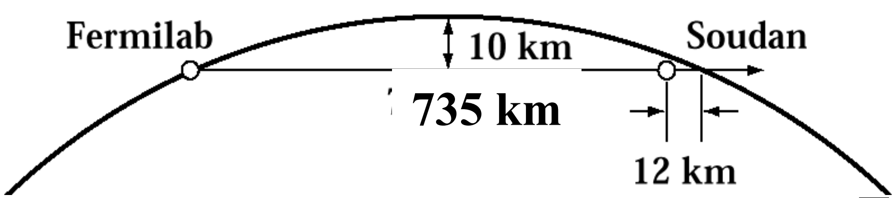
$5\sigma$ $\nu_\tau$ appearance announce in July 2015 (together with observation of 5th candidate)

arXiv:1507.01417

Expected signal and background normalised to the number of located events

| Decay | Expected signal $\Delta m_{23}^2$ =2.3meV$^2$ | Background | Observed |
|---|---|---|---|
| $\tau \rightarrow h$ | 0.52 ± 0.10 | 0.04 ± 0.01 | 3 |
| $\tau \rightarrow 3h$ | 0.73 ± 0.14 | 0.17 ± 0.03 | 1 |
| $\tau \rightarrow \mu$ | 0.61 ± 0.12 | 0.004 ± 0.001 | 1 |
| $\tau \rightarrow e$ | 0.78 ± 0.16 | 0.03± 0.01 | 0 |
| **Total** | **2.64 ± 0.53** | **0.25 ± 0.05** | **5** |

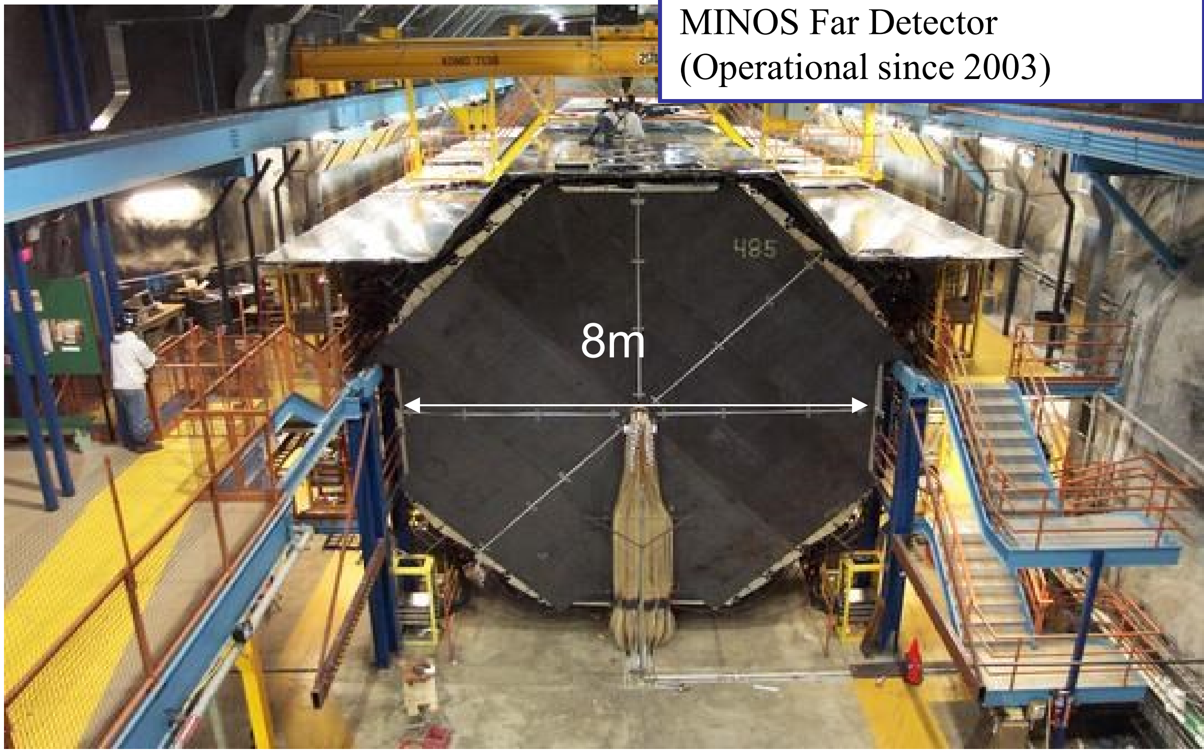
# MINOS (2005-2012)


## Main Injector Neutrino Oscillation Search

- $\Delta m^2$ and $\sin^2(2\theta)$ measurement in $\nu_\mu$ disappearance
- Beam from Fermilab Main Injector: Mostly $\nu_\mu$, tunable energy
- 2 detectors separated by 735km baseline
  - Near Detector: 1kt detector at Fermilab
  - Far Detector: 5.4kt detector at Soudan
- At 735 km (as CERN to GranSASSO!) $\Rightarrow E_\nu$ ~1-4 GeV for maximum sensitivity to disappearance in the atmospheric $\Delta m^2$ region
- $\nu_\mu \rightarrow \nu_e$ appearance search too!

# Minos Detectors



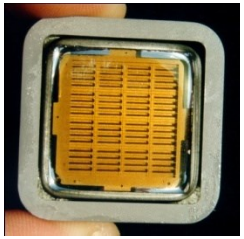

MINOS Far Detector
(Operational since 2003)

Near Detector:
- 1kt iron-calorimeter

Same sampling as Far Detector

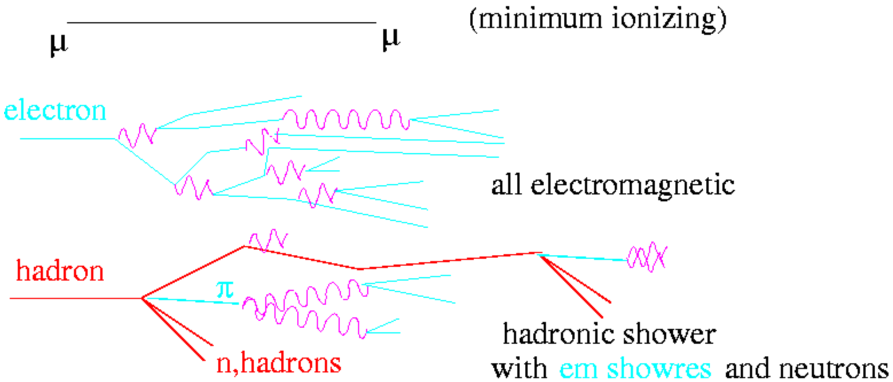
Far Detector:

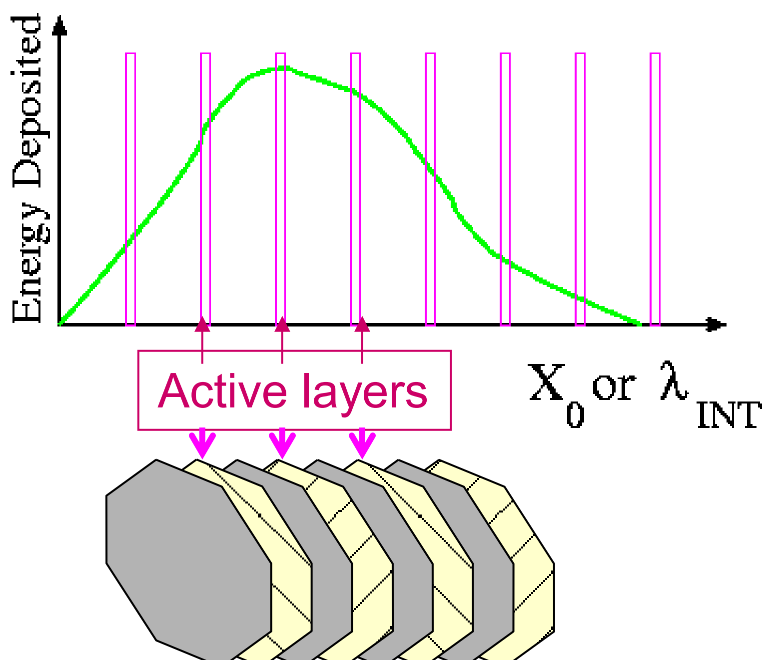
- 5.4kt total
  - 484 planes
  - Each plane 8m octagon
  - 2.54cm **magnetized** Fe, 1cm Scintillator
  - ~1.5T Magnetic field
- Readout
  - 2 ended readout (~90k strips)
  - 8x optical multiplexing into M16 multi-anode PMTs (~20K channels)
- Overburden
  - 710 m (2090 mwe)



1st Large Underground detector with Magnetic Field

# Sampling Calorimeters




Absorber. Choices:

-Low Z material - larger radiation length allows frequent sampling with coarser transverse segmentation, but big showers so harsh fiducial containment

-High Z material - small showers, compact detectors, but finer segmentation needed (Less Mass/sampling pitch $X^0$)

MINOS sampling 1.4 $X^0$ (Steel $X^0$ = 1.8 cm)

Active layers. Main choices:

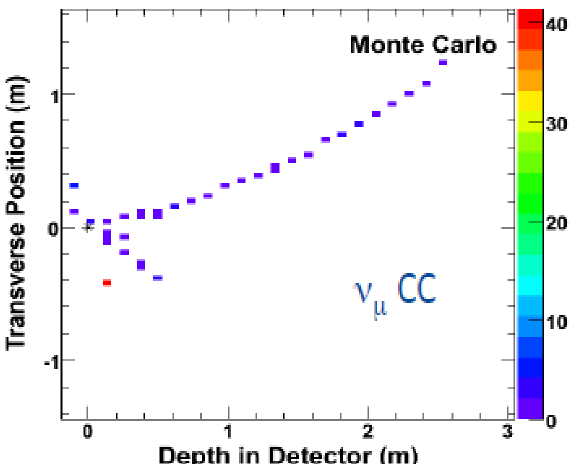
-Scintillators

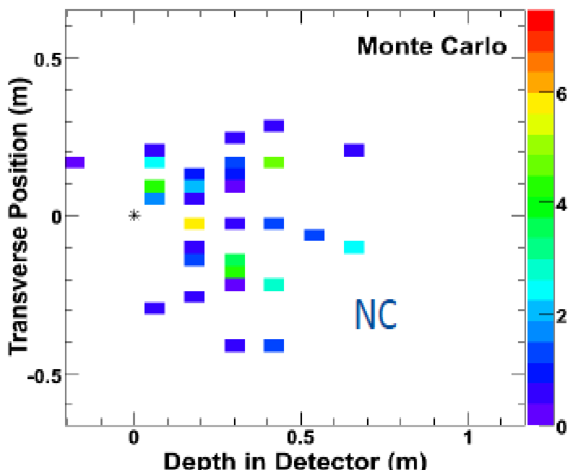
-Good for energy resolution (MINOS)

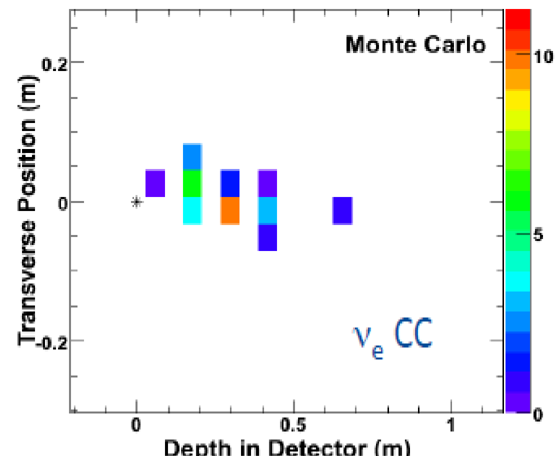
-Gaseous chambers

-Cheaper, good for tracking

# Neutrino Events in MINOS (MC)



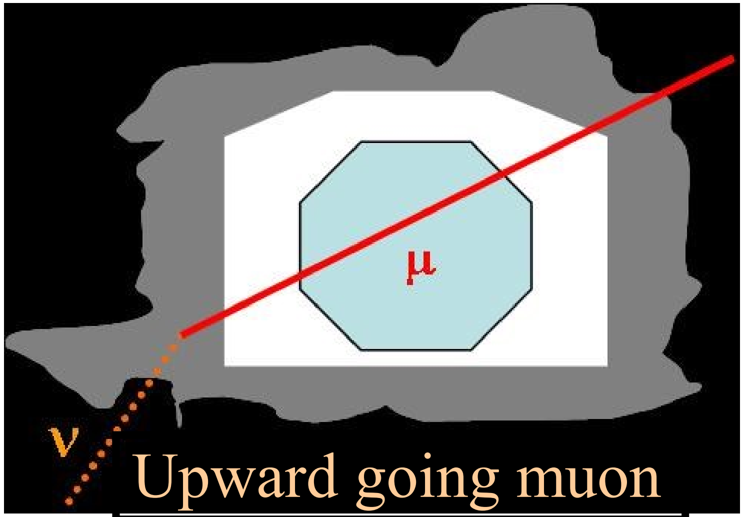



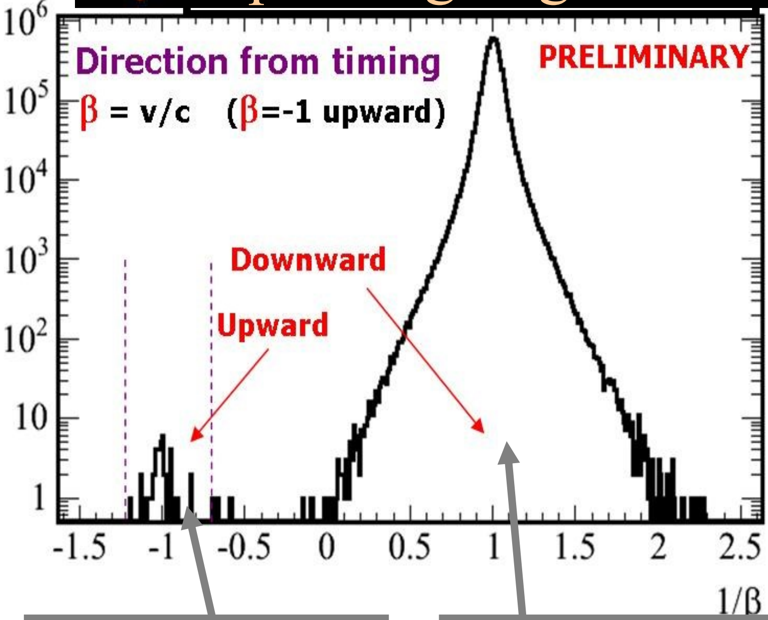
# MINOS: Atmospheric neutrinos

- Up Going Muons: $\nu$ interactions below detector
  - Use timing to select upward going muons
- Magnetic Field
  - Distinguish $\mu^-$, $\mu^+$

$\nu_\mu$ vs $\overline{\nu}_\mu$

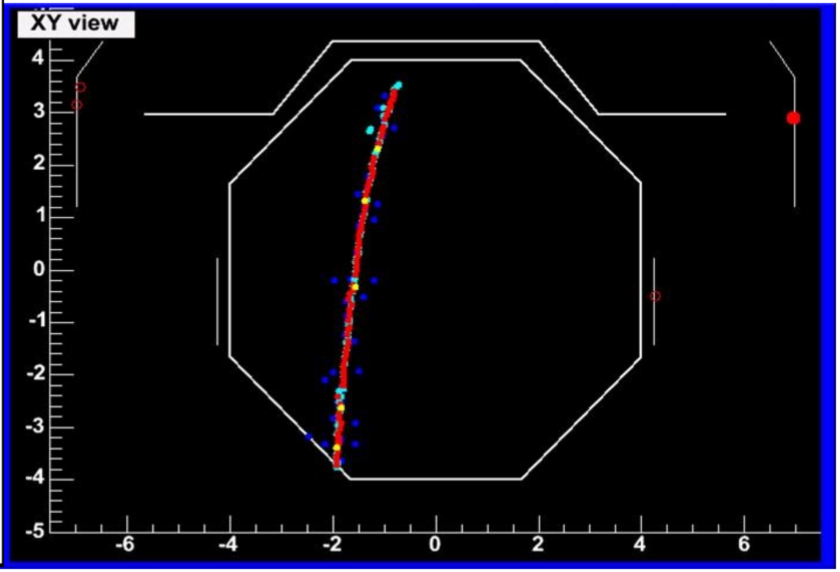
–CPT test: $P(\nu_\mu \to \nu_\mu) = P(\overline{\nu}_\mu \to \overline{\nu}_\mu)$?



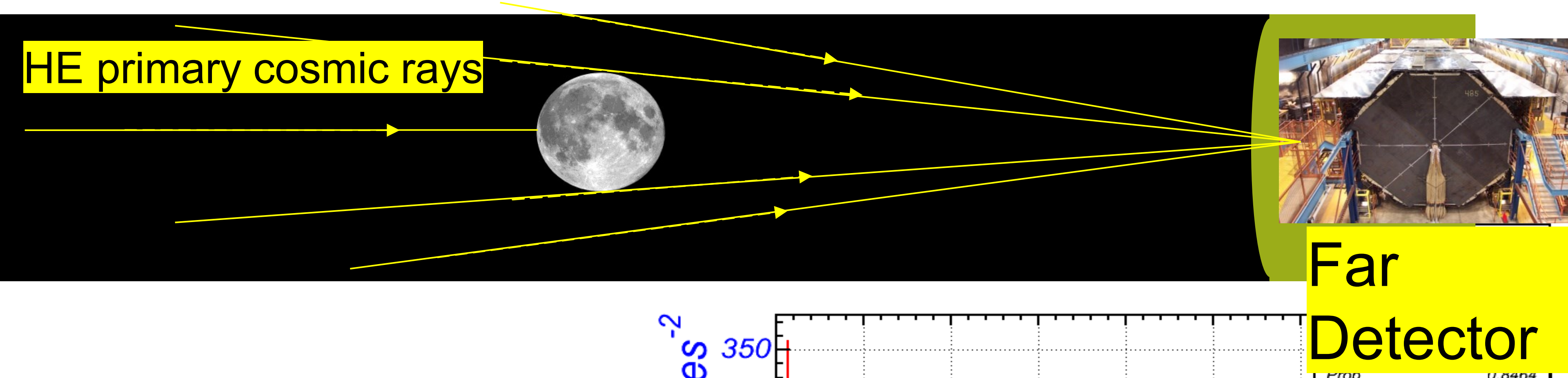




48 ν events

Cosmic Rays



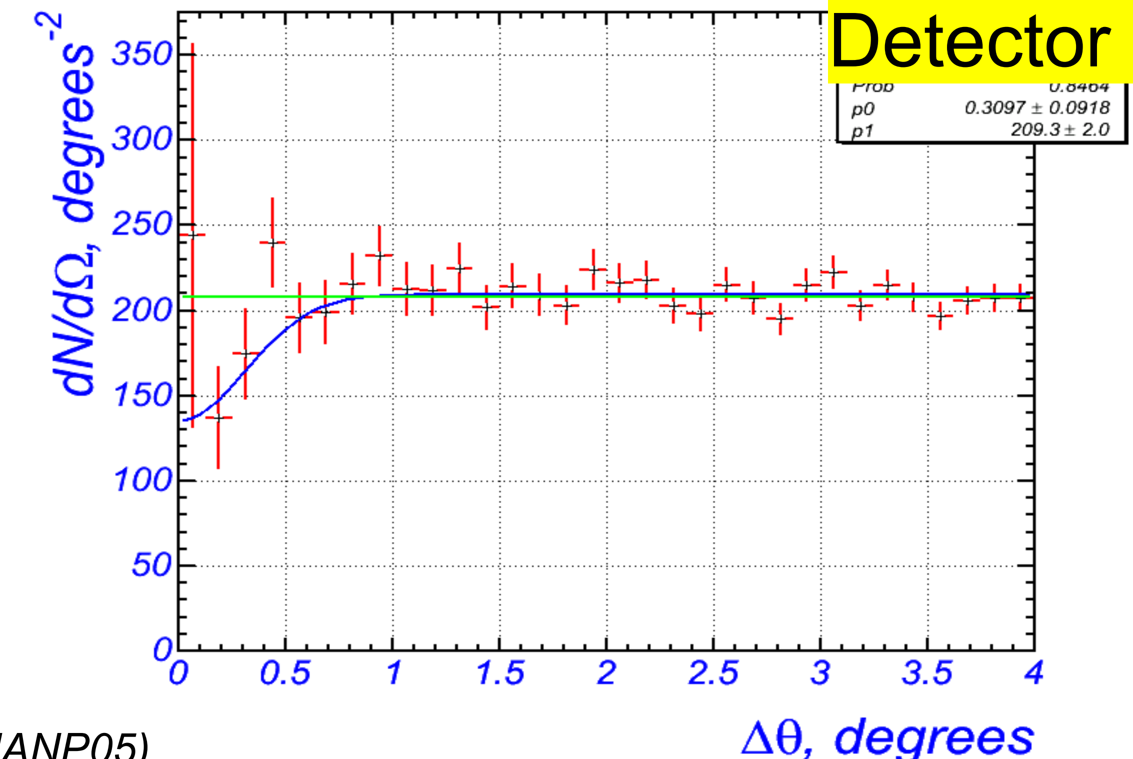
# MINOS: MOON Shadow




Muons recorded in the far detector

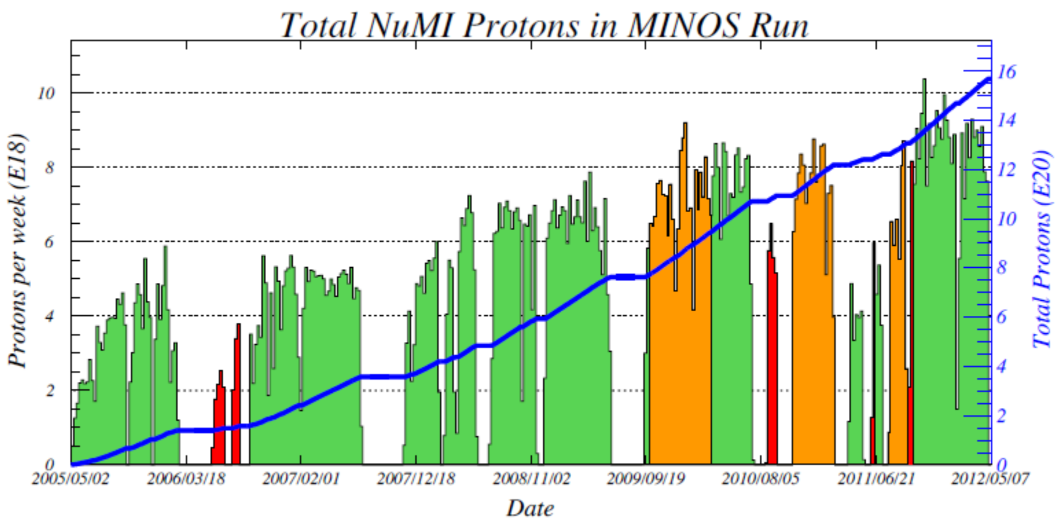
Can observe moon's shadow

Used to determine angular resolution: < 1 degree




*(presented by M. Kordosky, UCL at NANP05)*

# NuMI beam for MINOS




Low Energy Neutrino Beam

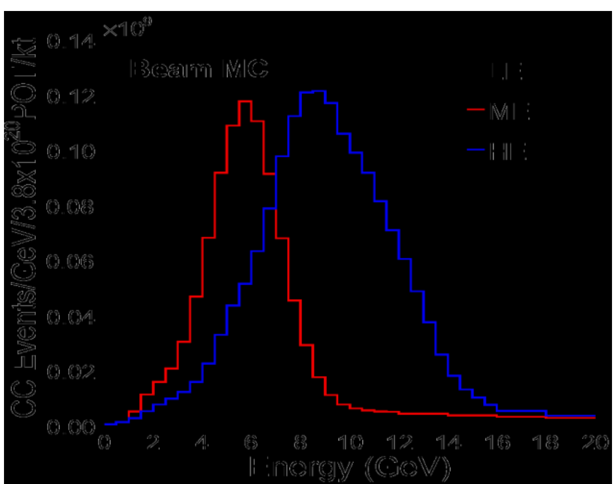
Low Energy Antineutrino Beam

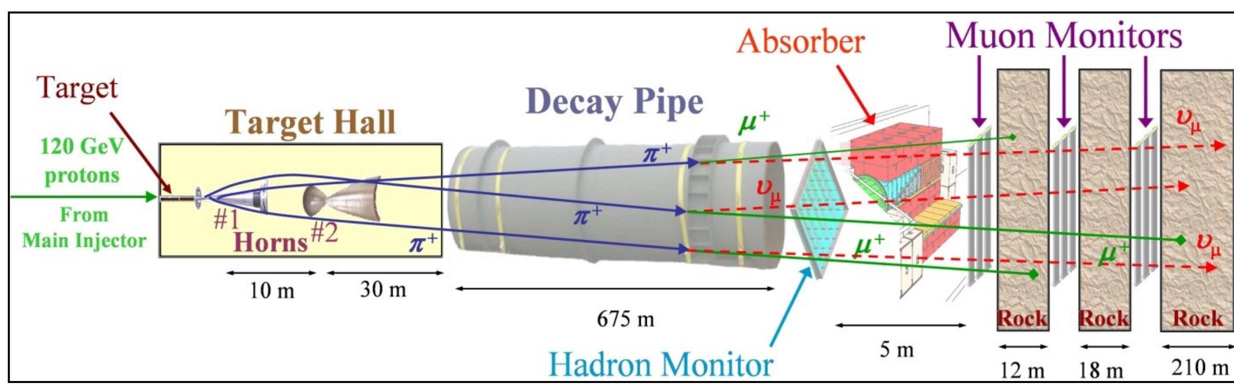
Special Running

7 years of data-taking with MINOS

Since September-2013 MINOS+ has started running concurrently with NOVA operation

Updated NuMI beam at higher energy for precision tests and searches for exotic phenomena

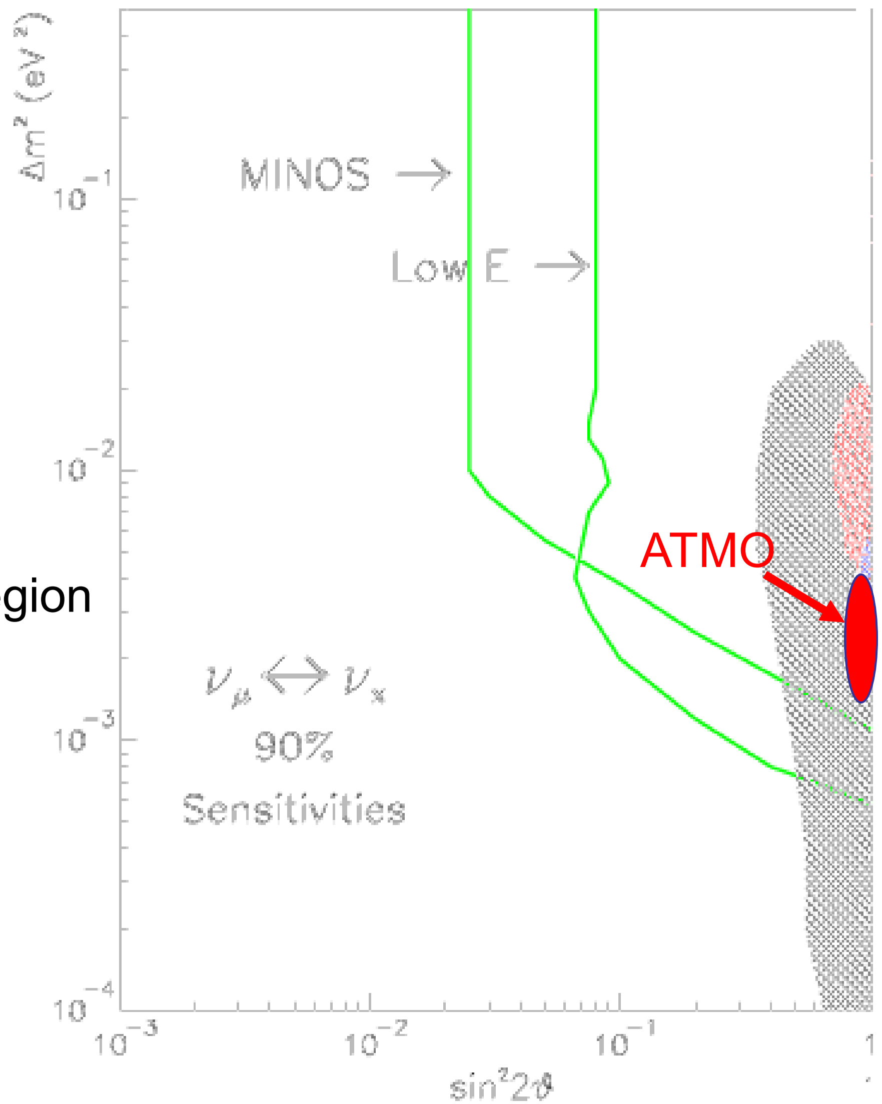


# MINOS Oscillation Sensitivity

(for didactic purposes only)

Minos Low E Sensitivity well covers the Atmospheric region




Beam energy can be tuned in the NUMI beamline

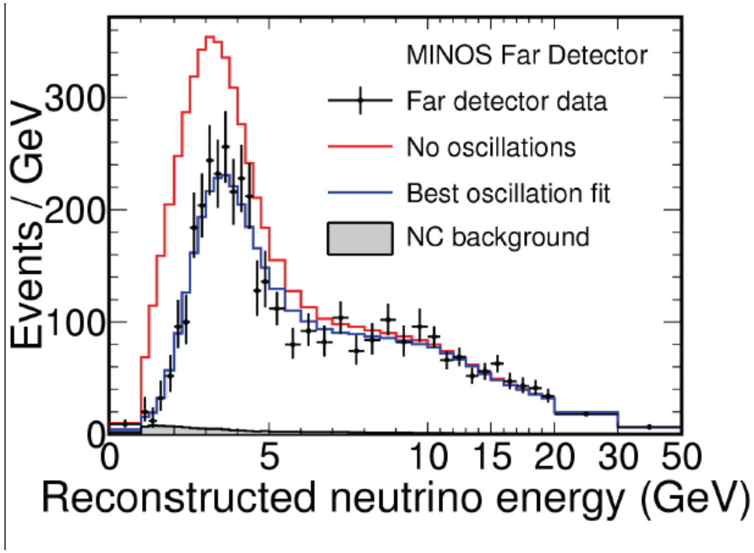
Now you are able to answer these 2 questions:

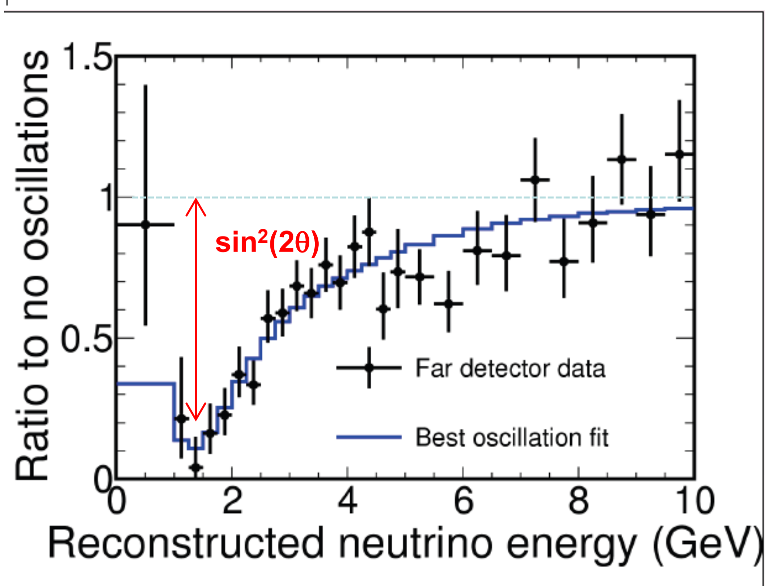
1) Why does the curve move down by lowering E?
2) Why does it move right ?

*Plot from J.Conrad, NATO School Virgin Island 2000*

# MINOS: $\nu_\mu$–disappearance results

Phys. Rev. Lett. 106, 181801 (2011)

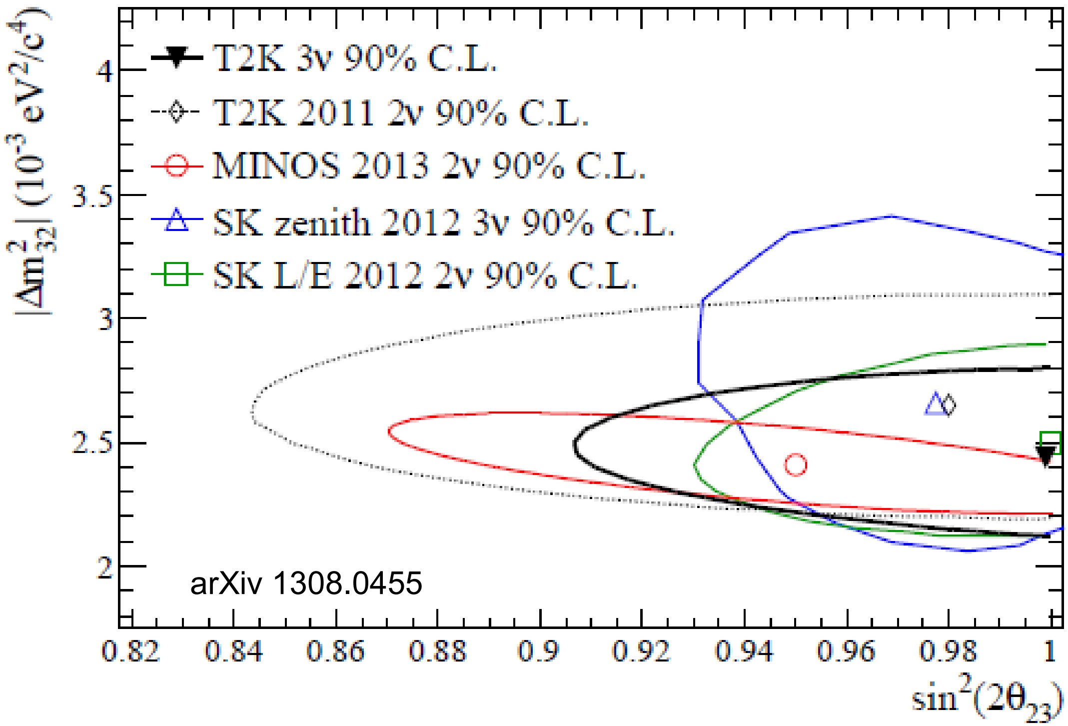



- Expected 2452 CC events in absence of oscillations at FAR detector (predicted energy spectrum)
- Observed 1946 CC events (measured energy spectrum)
- Compare predicted and measured energy spectrum at FAR detector to extract oscillation parameters
- Fit with the oscillation hypothesis

$$P(\nu_\mu \to \nu_\mu) = 1 - \sin^2(2\theta)\sin^2\left(\frac{1.27\Delta m^2 L}{E}\right)$$

# MINOS final results on oscillation parameters from $\nu_\mu$ disappearance analysis




All results from SK, MINOS, T2K are consistent

Best $\Delta m^2$ determination from MINOS.

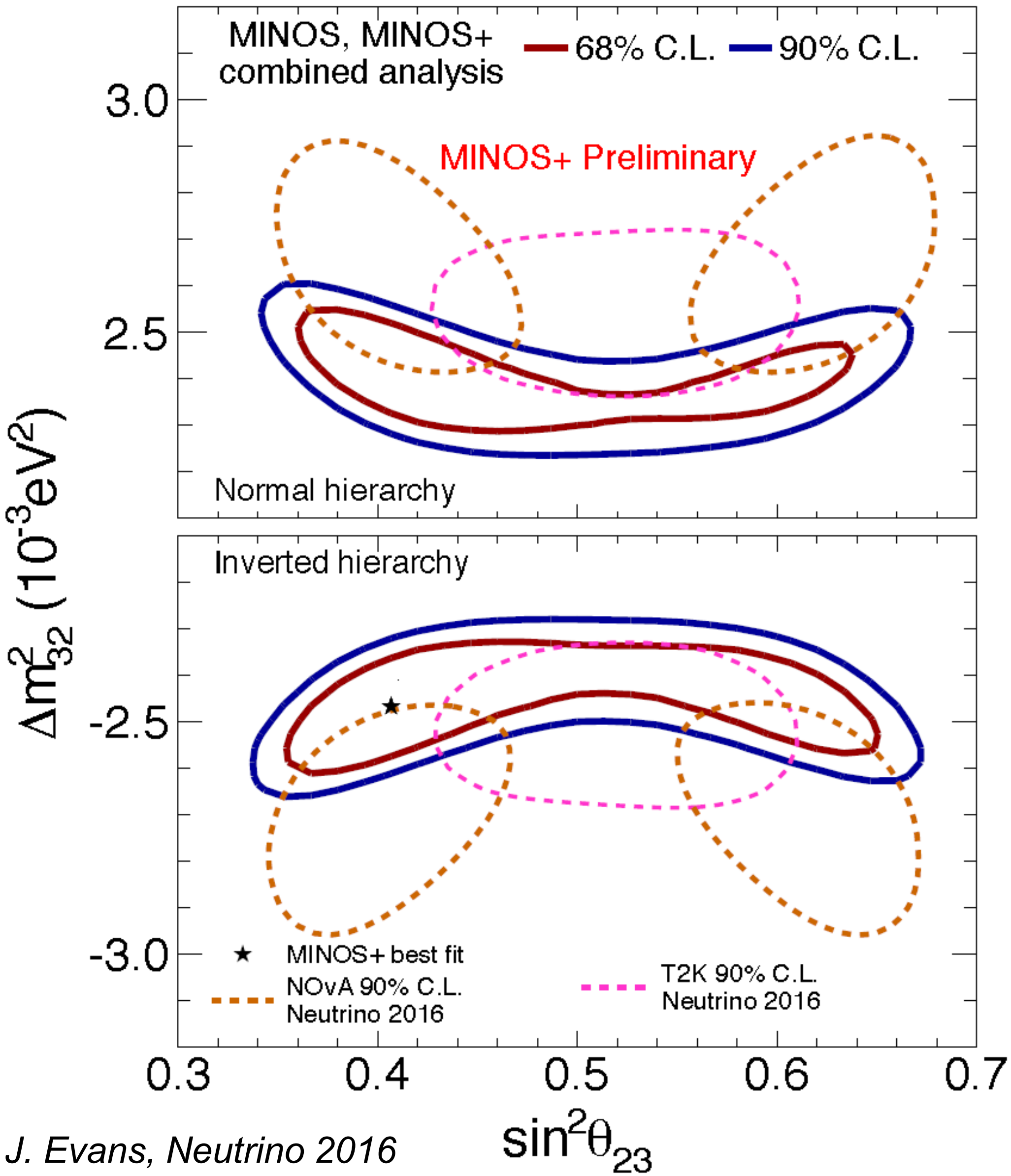
MINOS results with full data-sample:

$\Delta m^2 = (2.4 \pm 0.1)\ 10^{-3}$ eV$^2$

$\sin^2(2\theta_{23}) > 0.85$ @ 90%CL

Best fit position slightly off maximal mixing

# Combined MINOS & MINOS+




*J. Evans, Neutrino 2016*

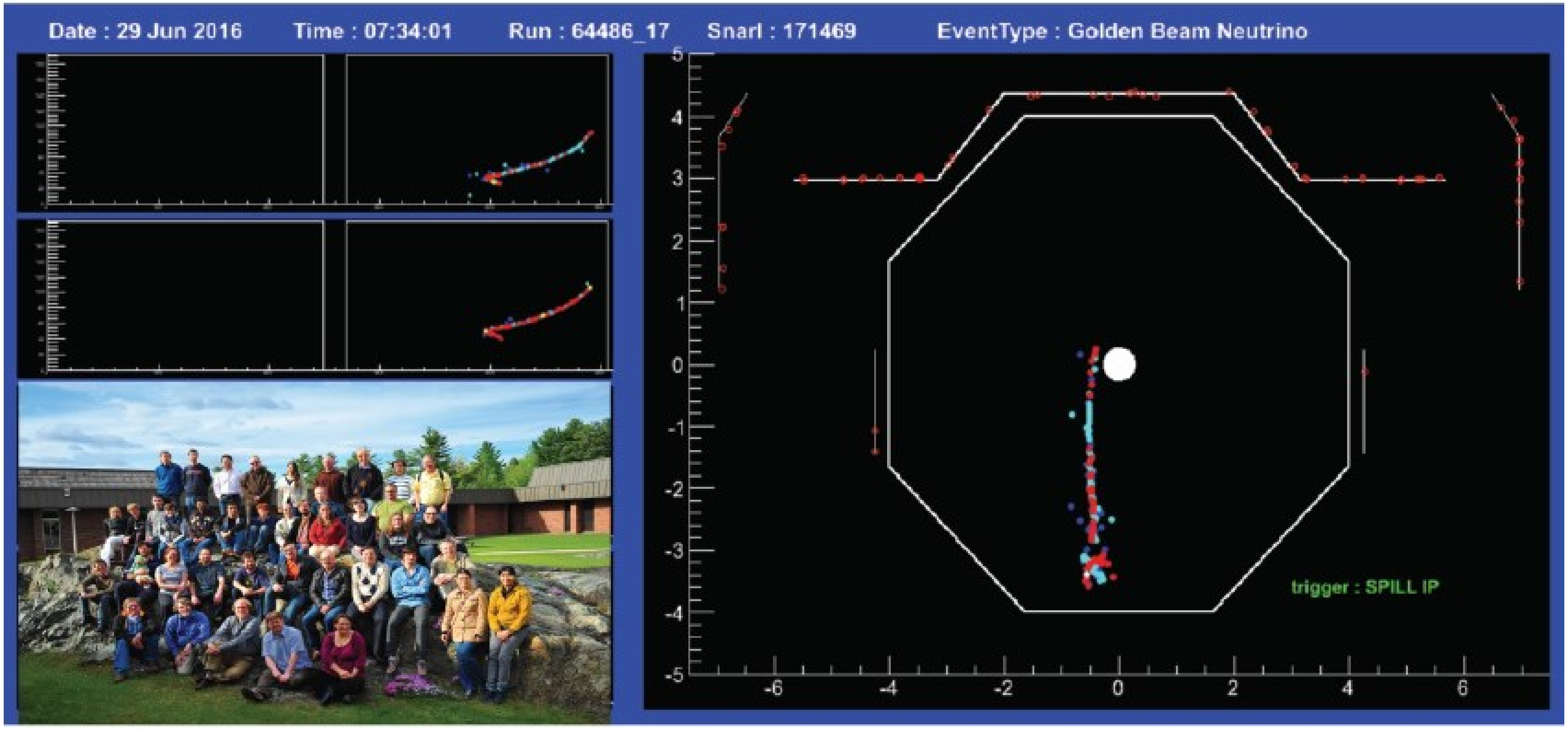
**MINOS+**

- Operating since 2013
- Improved electronics
- New NUMI beam line (optimised for Nova)
- Medium-energy: neutrino energy peak at 7 GeV (on-axis)
- ⇒ further away from oscillation max
- Higher energy and increased beam flux wrt MINOS enables high-precision searches for deviations from 3-ν flavour oscillation

MINOS/MINOS+ combined preliminary result:
confirm slight octant preference

# First generation LBL experiments end

The last ever MINOS beam neutrino




**After $2.62 \times 10^{21}$ protons on target**
**29th June 2016**