Next Generation of Long Baseline Experiments. Status and Prospects.

SuperKamiokande + K2K results

- Neutrinos oscillate
- There is at least one oscillation in the frequency range $\Delta m^2 \sim 1\text{-}4 \times 10^{-3}\ eV^2$
- $\nu_\mu \rightarrow \nu_\tau$ with $\sin^2 2\theta \sim 1$

Next step: independent experimental verification

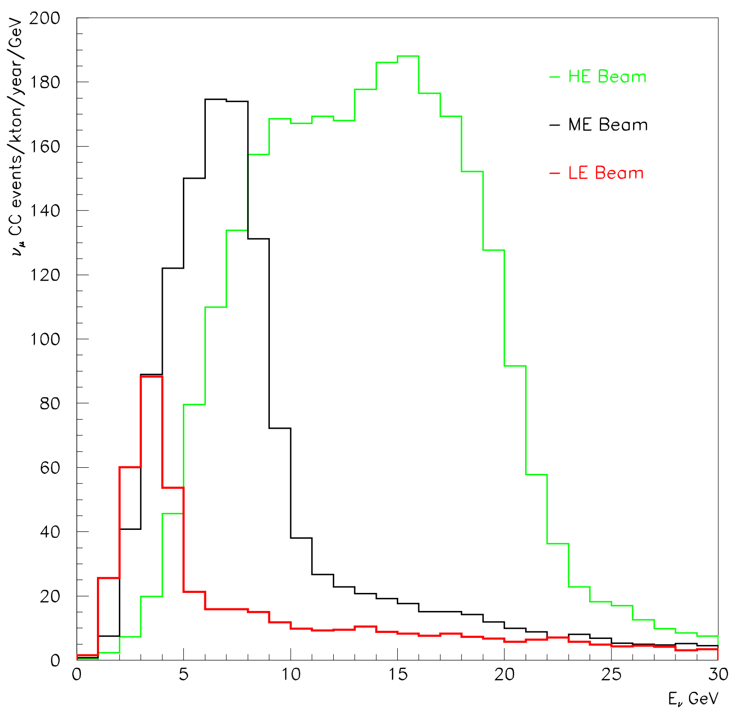
- MINOS: the oscillatory pattern, improve the knowledge of Δm^2
- CNGS (OPERA/ICARUS): $\nu_\mu \rightarrow \nu_\tau$

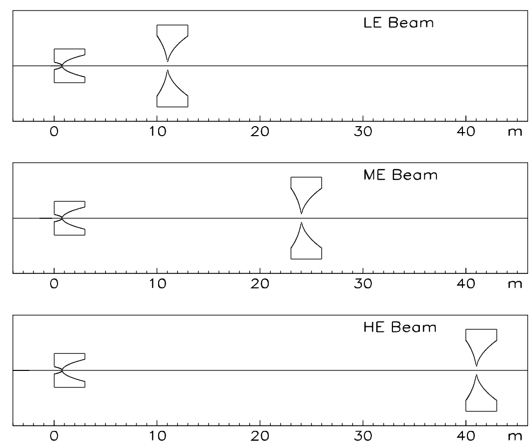
A. Para
Fermilab
WIN02

Next Generation of Long Baseline Experiments. Part I: Status

Under construction

NuMI: Flexible Neutrino Beam





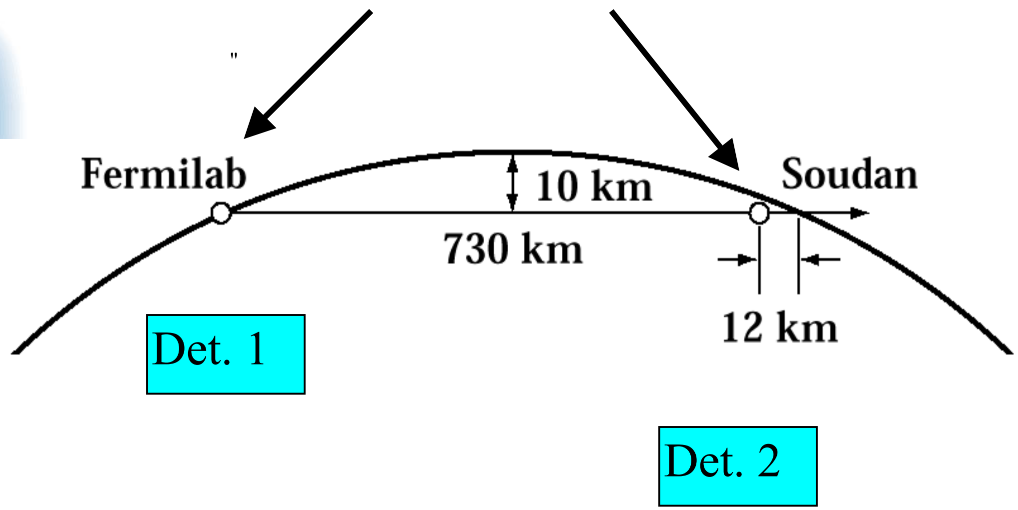
'zoom' lens:
Vary the relative distances of the source and focusing elements

Expected CC Events Rates in Minos 5kt detector

- High 16,000 ev/yr
- Medium 7,000 ev/yr
- Low 2,500 ev/yr

The NUMI Beamline

Two functionally identical neutrino detectors

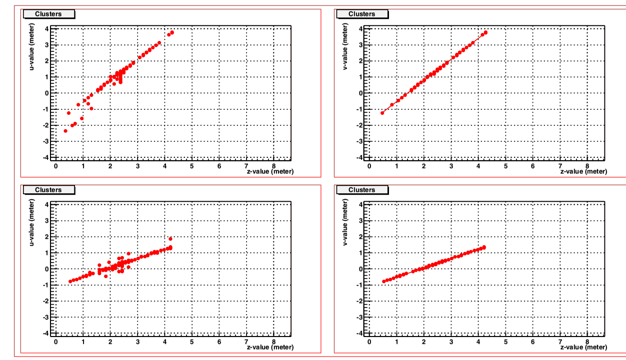


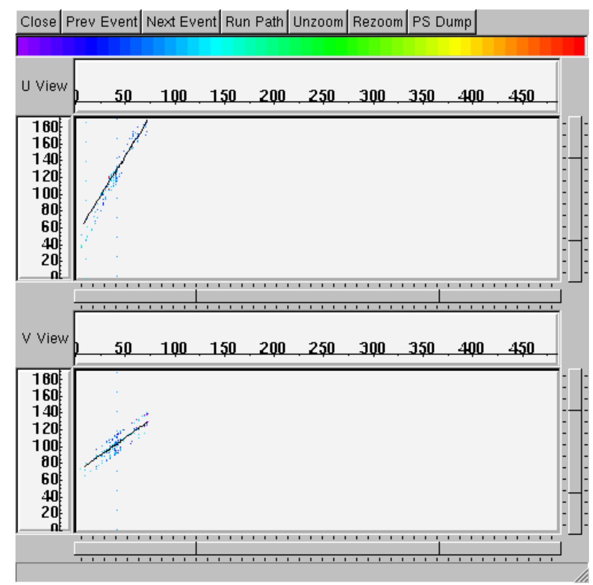
'Far End' Status

- Cavern constructed
- Detector being built

(> 1kton installed)

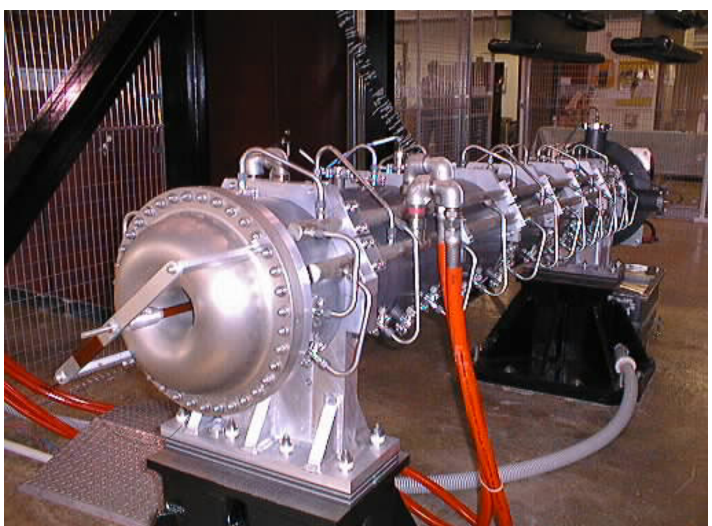
- Cosmic rays recorded and reconstructed





'Near End' Status

Target hall, decay pipe tunnel, near detector hall excavated

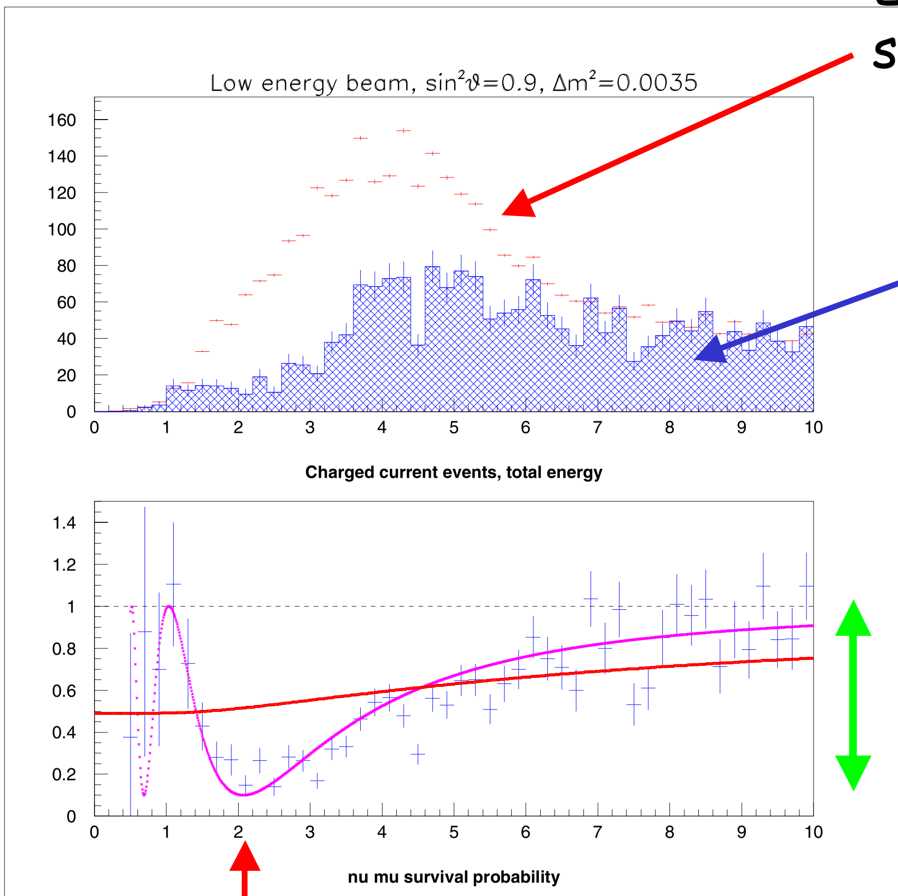


Target, horns, infrastructure designed

Prototypes built and tested

Horn construction started

Possible result in 2005(?)



Expected event spectrum

Observed event spectrum

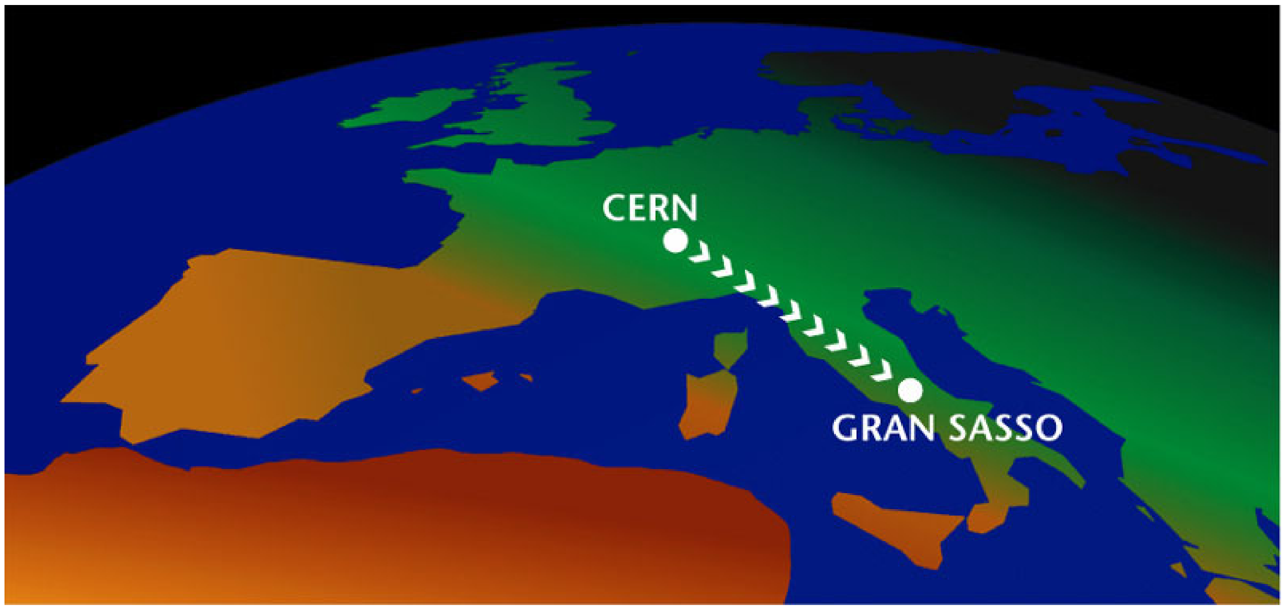
Ratio: survival probability

Shape: disappearance mechanism . Oscillations? Decays?

Mixing angle

Δm^2

CERN-Gran Sasso Neutrino Beam



In Dec. 1999 CERN council approved the CNGS project:

- build an intense ν_μ beam at CERN-SPS
- search for ν_τ appearance at Gran Sasso laboratory (730 km from CERN)

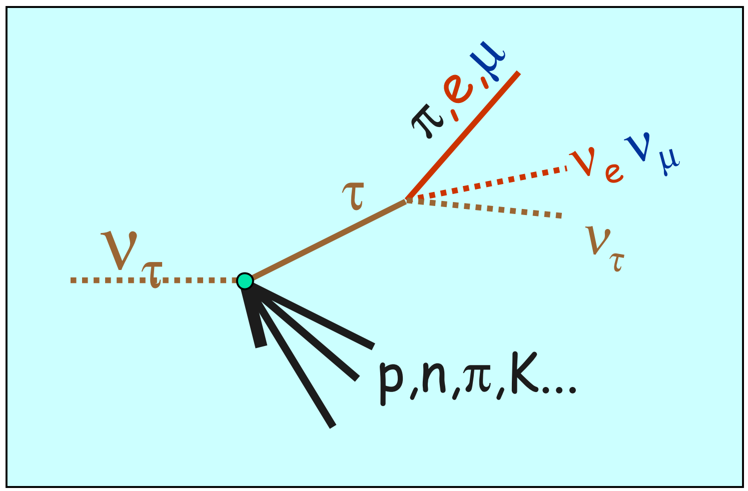
"long base-line" ν_μ -- ν_τ oscillation experiment

Detecting ν_τ at Gran Sasso

-> look for the τ lepton:

extremely difficult -

τ travels only about 1 mm before decaying



-> two approaches:

(a) very good position resolution (see the decay "kink") -> OPERA

(b) very good energy and angle resolution -> ICARUS

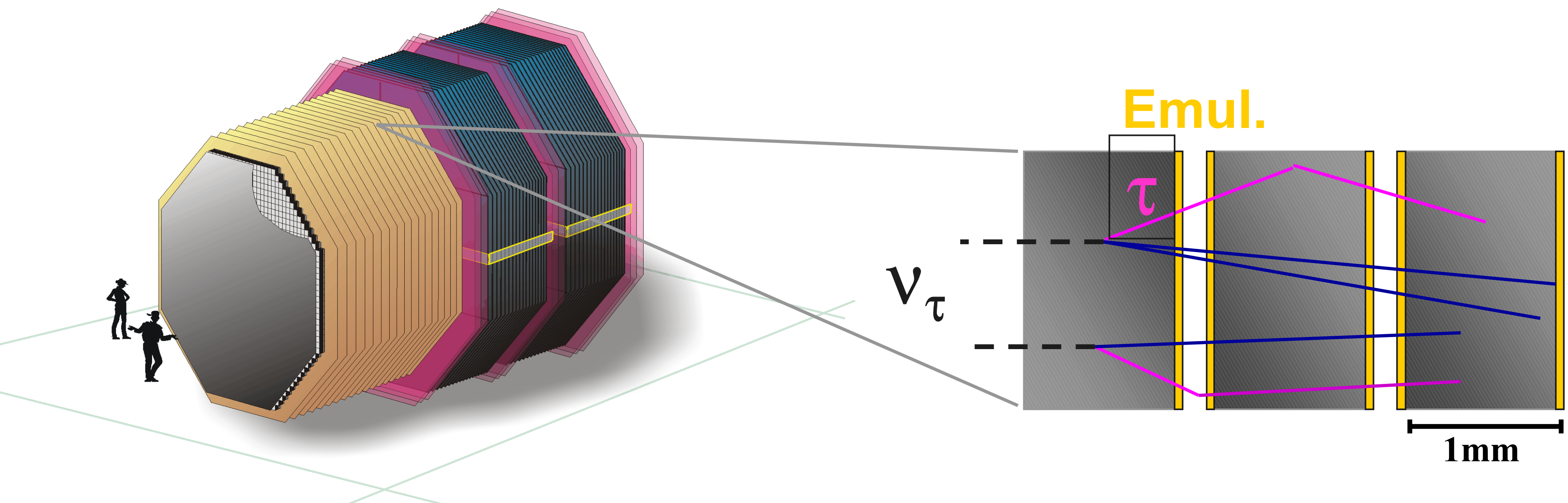
OPERA

<u>2000 tons of "detector mass"</u>

walls made of bricks (total more than 200'000)

-> bricks made of "sandwiches"

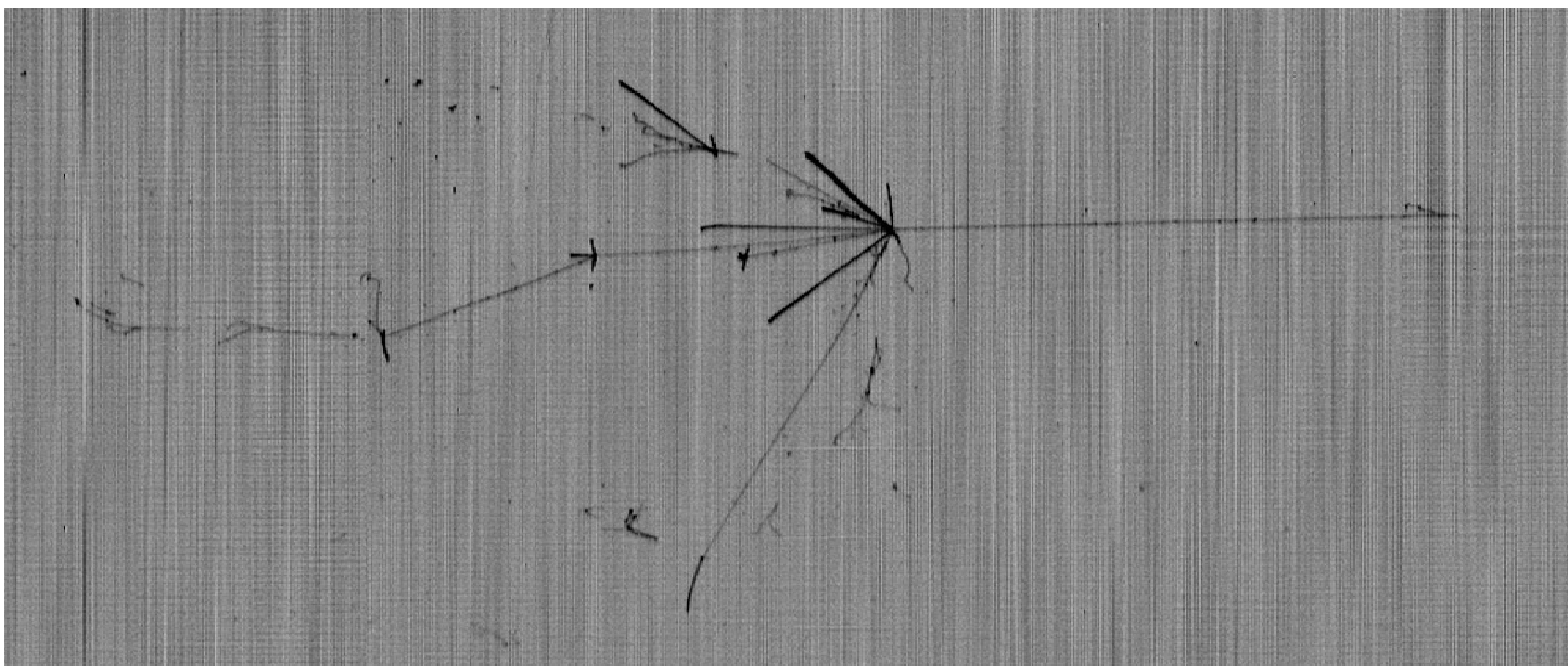
-> sandwiches made of lead and nuclear emulsion



ICARUS: electronic bubble chamber

- 5000 tons ultra-pure liquid argon
-provides "electronic" picture of interactions

-> example from 600 t module (2001 - cosmic ray):



CNGS: Expected rates

For <u>1 year of CNGS operation</u>, expect:

protons on target	4.5×10^{19}
ν_μ in 100 m^2 at Gran Sasso	3.5×10^{12}
ν_μ "charged current" events per 1000 t ($\nu + N \to N' + \mu$)	≈ 2500
ν_τ events (from oscillation)	≈ 20 "detectable"
ν_τ **events** detected "in OPERA"	$\approx$ **2.5** **(b.g. 0.15)**

Next-to-Next Step: going beyond SuperK

- $1-\sin^2 2\theta_{23}$
  - $\sin^2 2\theta_{23} = 1$ ↔ new symmetry ? Broken? How badly?
- Subdominant oscillation $\nu_\mu \rightarrow \nu_e$: $|U_{e3}|^2$ Key to CP violation

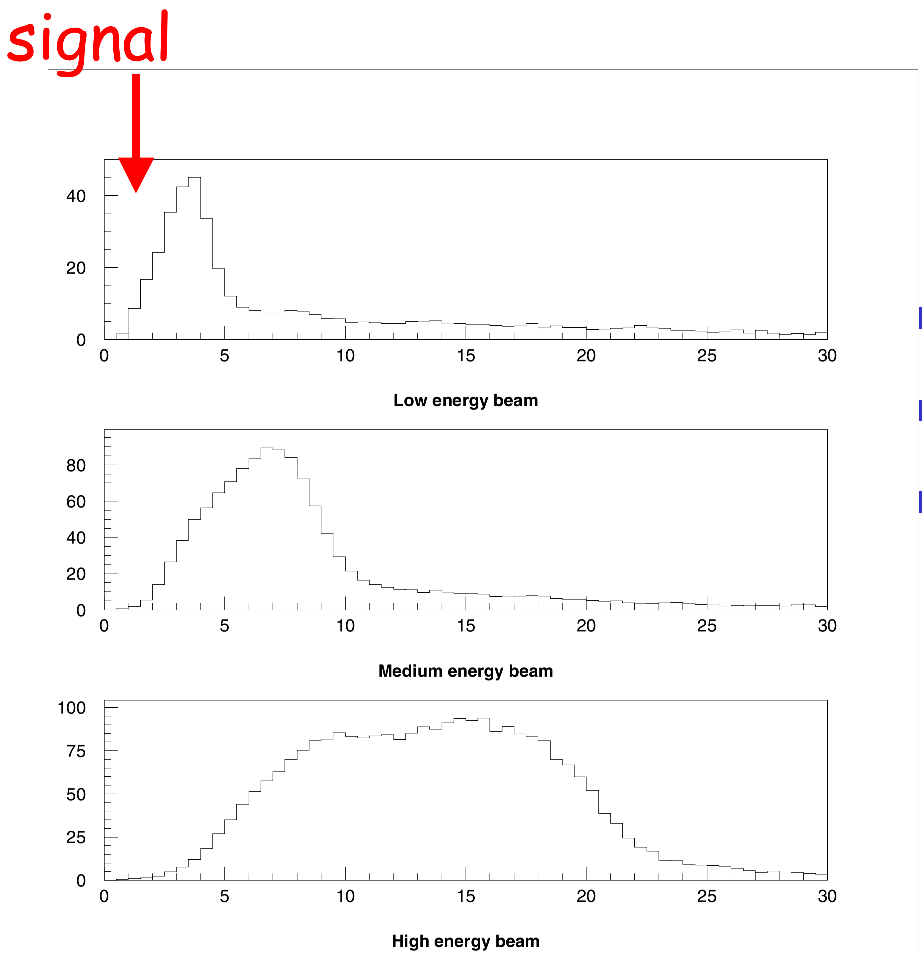
  Magnitude of symmetry breaking (Mohapatra)?
- Determine the mass hierarchy
- CP violation, if permitted by:
  - Δm_{12} not too small
  - $|U_{e3}|^2$ not too small

The next step ?

- $\Delta(1-\sin^2 2\theta_{23})$
- Determine/limit $|U_{e3}|^2$
- If sizeable → get a shot at the mass hierarchy/CP

- Neutrino factories?
- Superbeams?
- NuMI beam!

NuMI Neutrino Beams

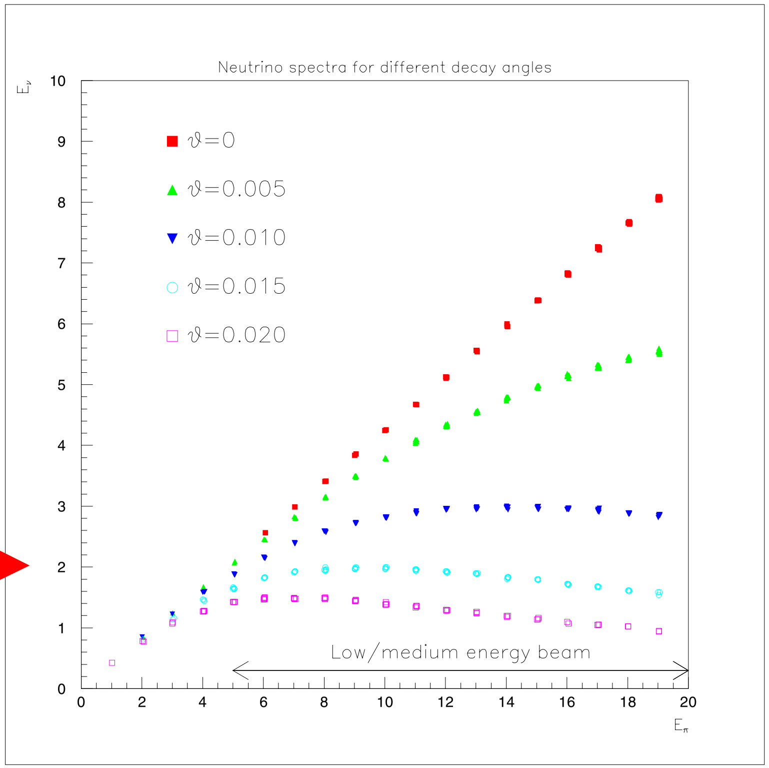


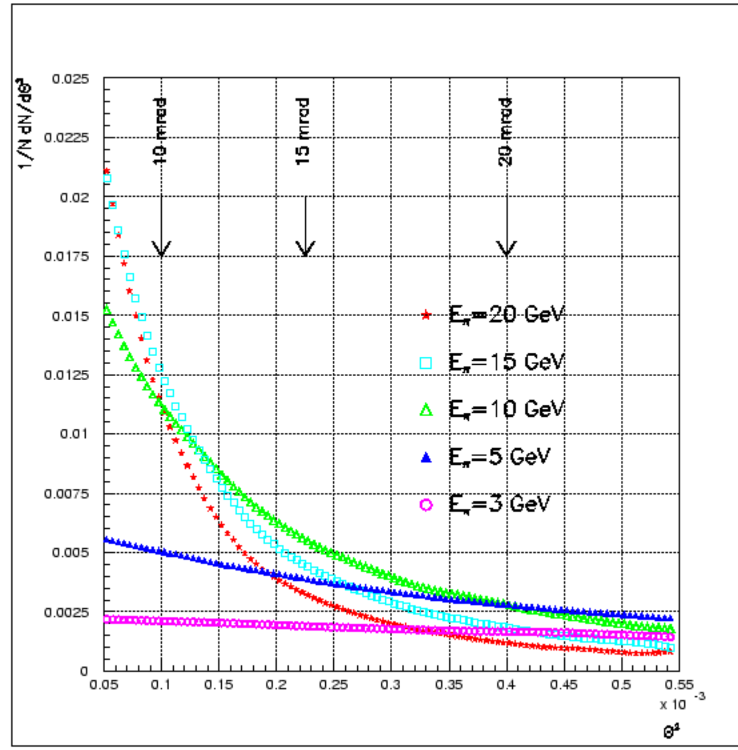
- L=730 km
- Δm^2= 1-3 x10^{-3} eV^2
- ➔ maximum effect at E_ν=1-3 GeV

➢Increase the flux in 1-2 GeV region ?

➢Reduce/eliminate the high(er) energy tail ?

Off-axis 'magic' (⟵⟶ two body decay kinematics)

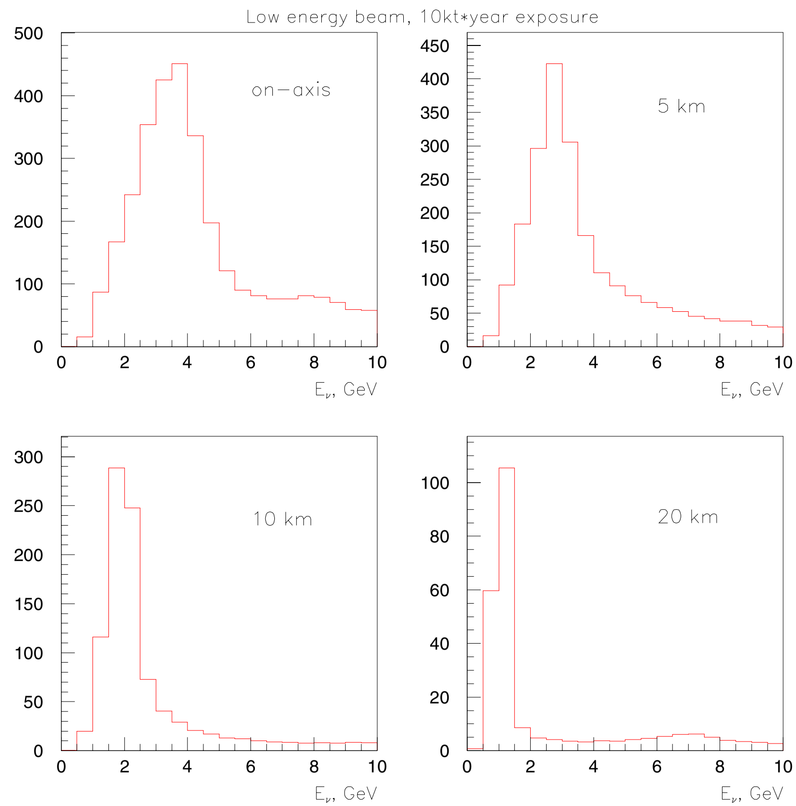




1-3 GeV intense beams with well defined energy in a cone around the nominal beam direction

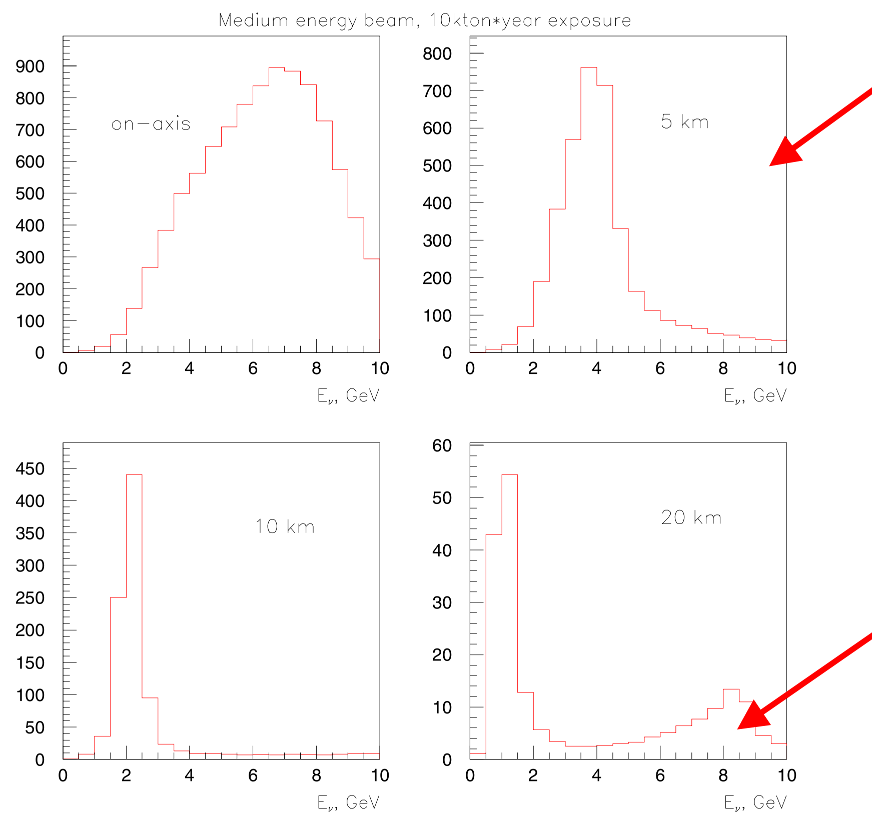
$$Flux = \left(\frac{2\gamma}{1+\gamma^2\theta^2} \right)^2 \frac{A}{4\pi z^2}$$

Low Energy Beam: Off-axis



Neutrino event spectra at putative detectors located at different locations

Medium Energy Beam: Off-axis

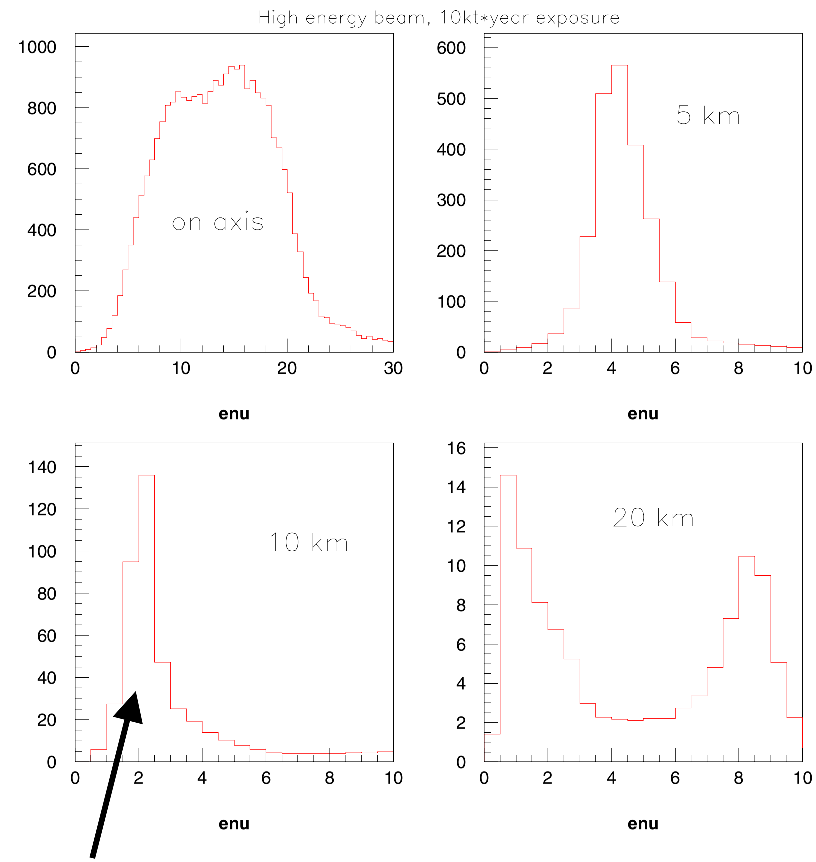


More flux than low energy on-axis (broader spectrum of pions contributing)

Neutrinos from K decays

Neutrino event spectra at putative detectors located at different locations

High Energy Beam: Off-axis

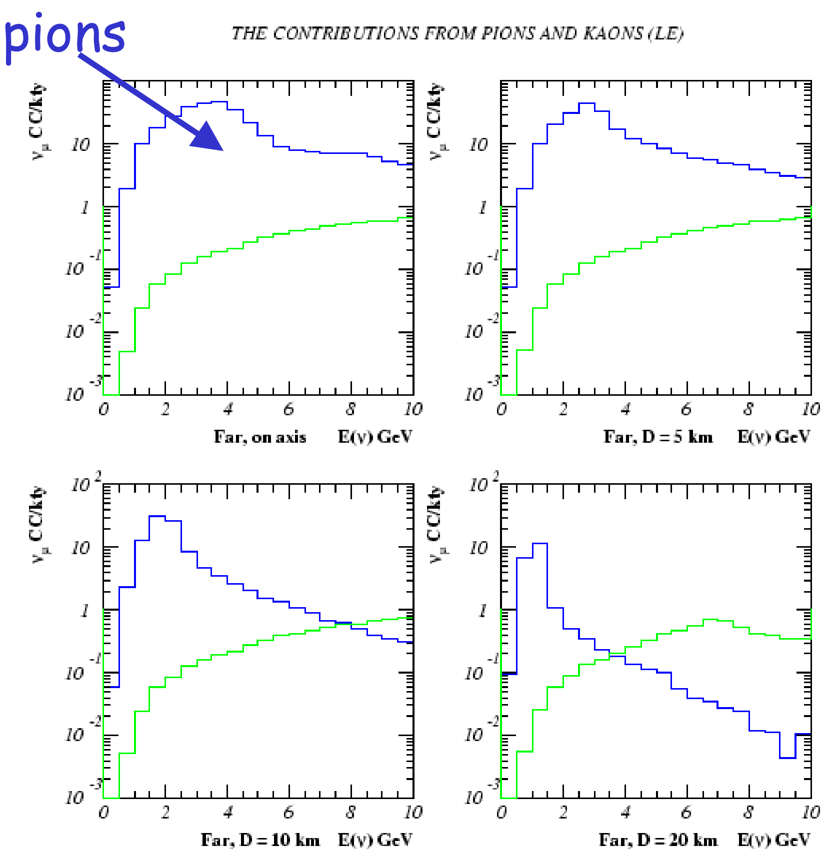


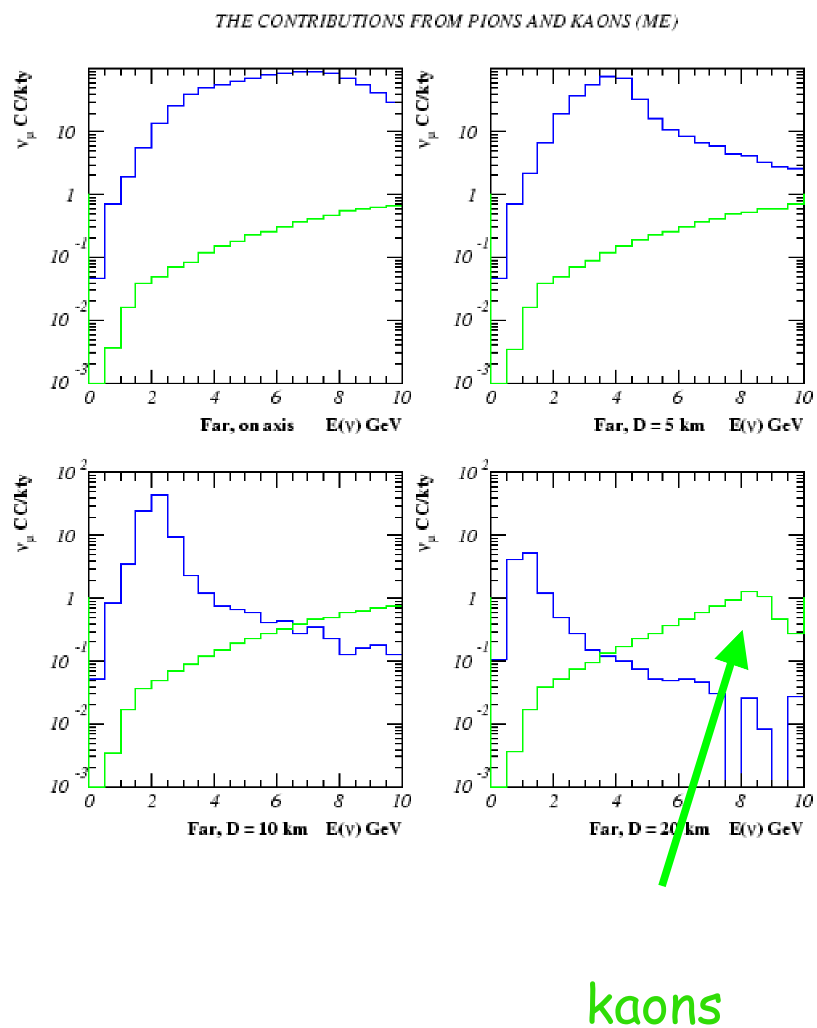
1/3 of a the flux with medium energy beam

- Similar spectra and beam characteristics as in the medium/low energy case
- Reduced flux by

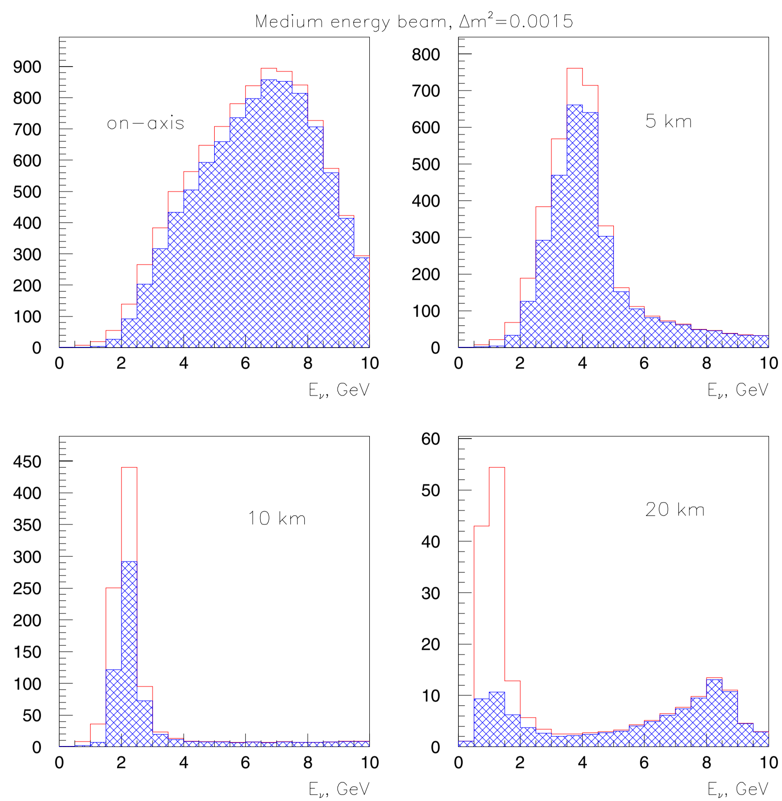
$$\left(\frac{2\gamma}{1+\gamma^2\theta^2}\right)^2 \frac{A}{4\pi z^2}$$

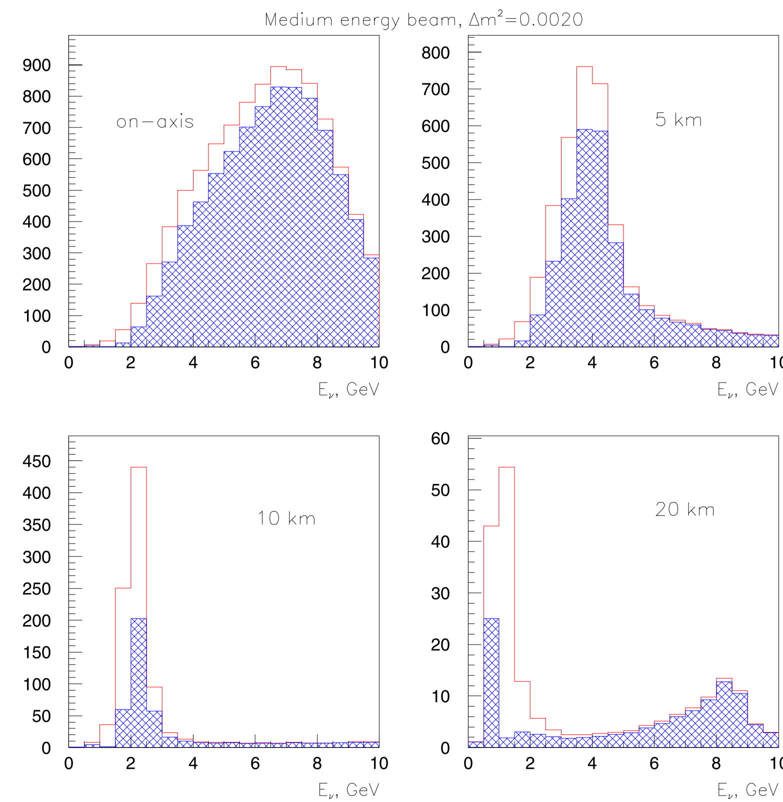
Low/Medium Energy: Beam Composition





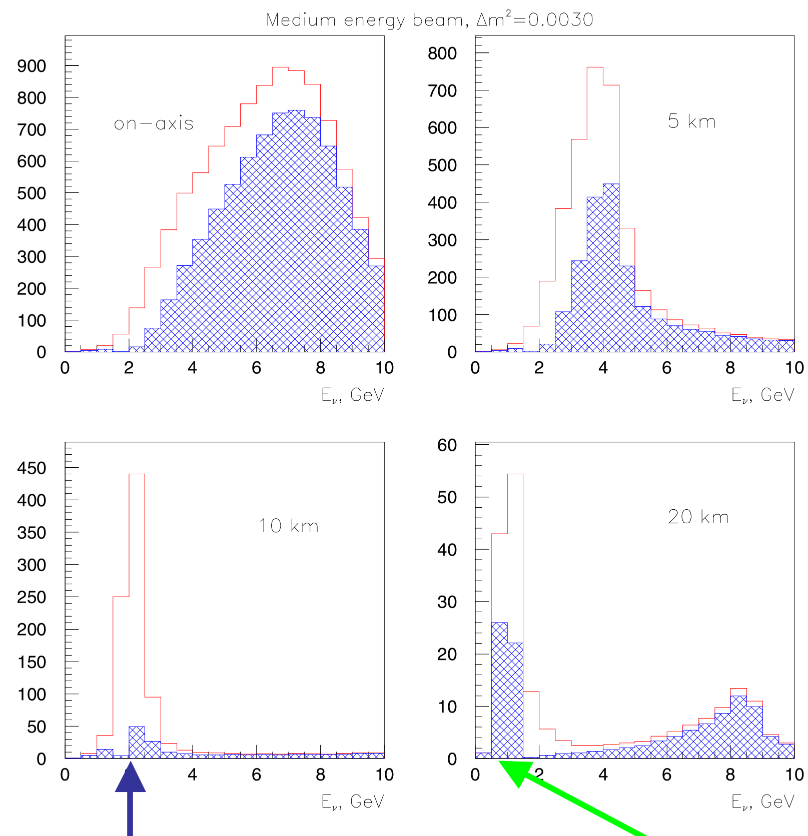
Disappearance Experiment, 10 kty
Δm^2=0.0015/0.002 eV^2





Disappearance Experiment, 10 kty
$\Delta m^2 = 0.003\ eV^2$

Three additional detectors at a distance of 5,10 and 20 km (transverse to the beam axis)

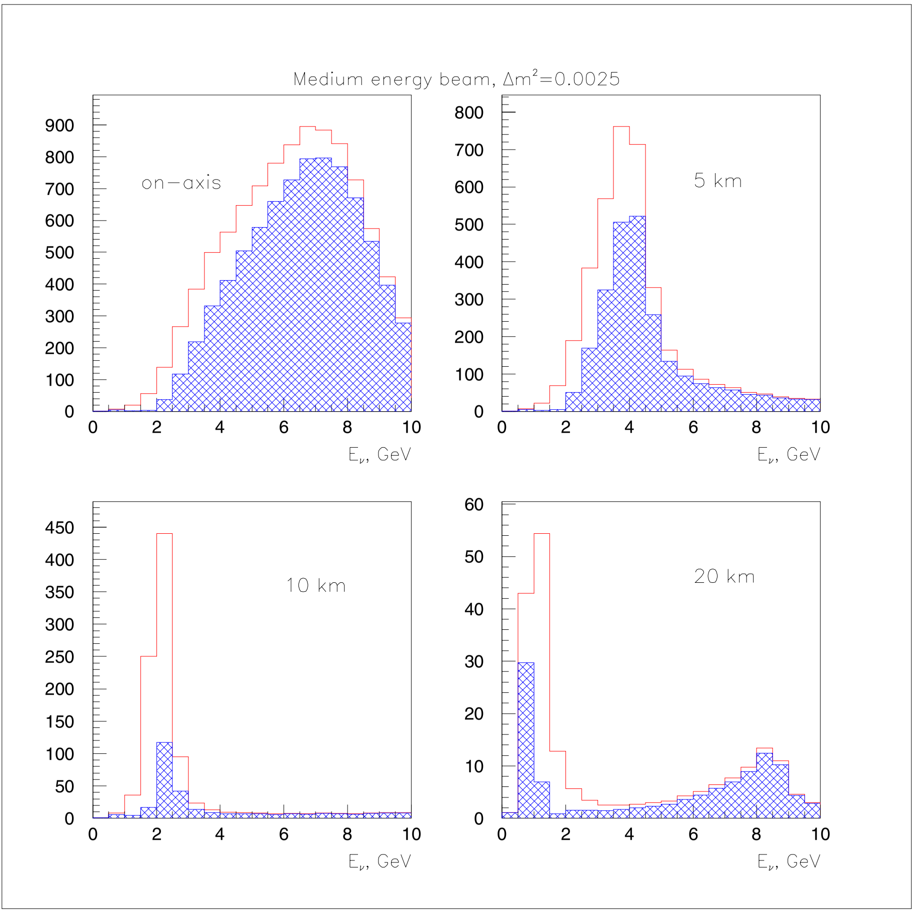


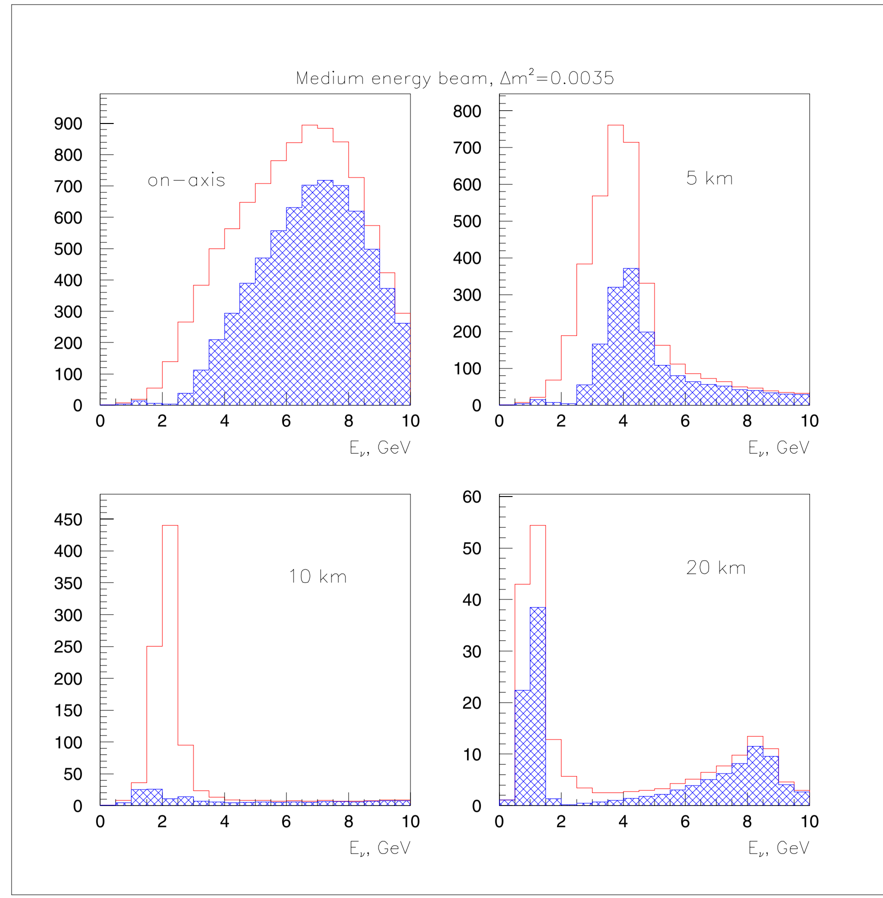
~1-$\sin^2 2\theta_{23}$

Oscillatory pattern: re-appearance after a minimum

$$\Delta \sin^2 2\theta_{23} \approx \frac{\sqrt{80}}{800} \approx 0.01 \qquad (10 \quad kton \times year)$$

Disappearance Experiment, 10 kty Δm^2=0.0025/0.0035 eV^2





Do we need a dedicated near detector? A.k.a predicting the off-axis spectrum.

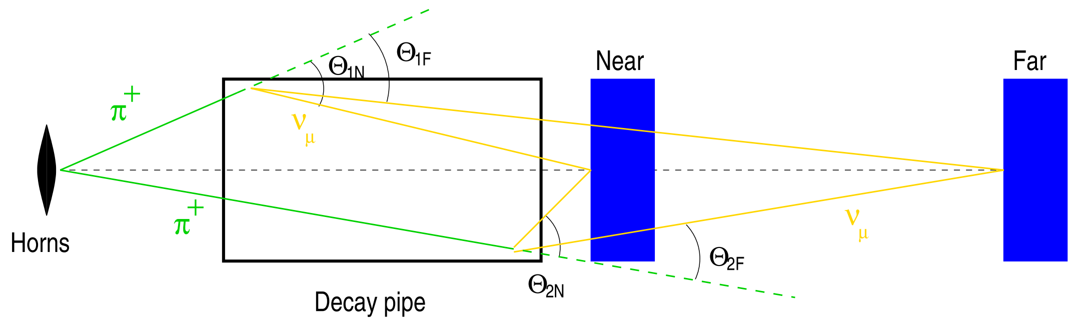
Neutrino fluxes detected at the near and far detectors produced by the same parent hadron beam, hence:

> every neutrino event observed at the near detector implies a certain flux(E_ν) at the far detector.

$$\frac{dN^{far}}{dE^{far}} = \int M(E^{near}, E^{far}) \frac{dN^{near}}{dE^{near}}$$

Correlation function M depends mostly on the focusing system and the geometry of the beam line (hep-exp/011001). It depends on the location of the far detector.

How to predict the off-axis spectrum II



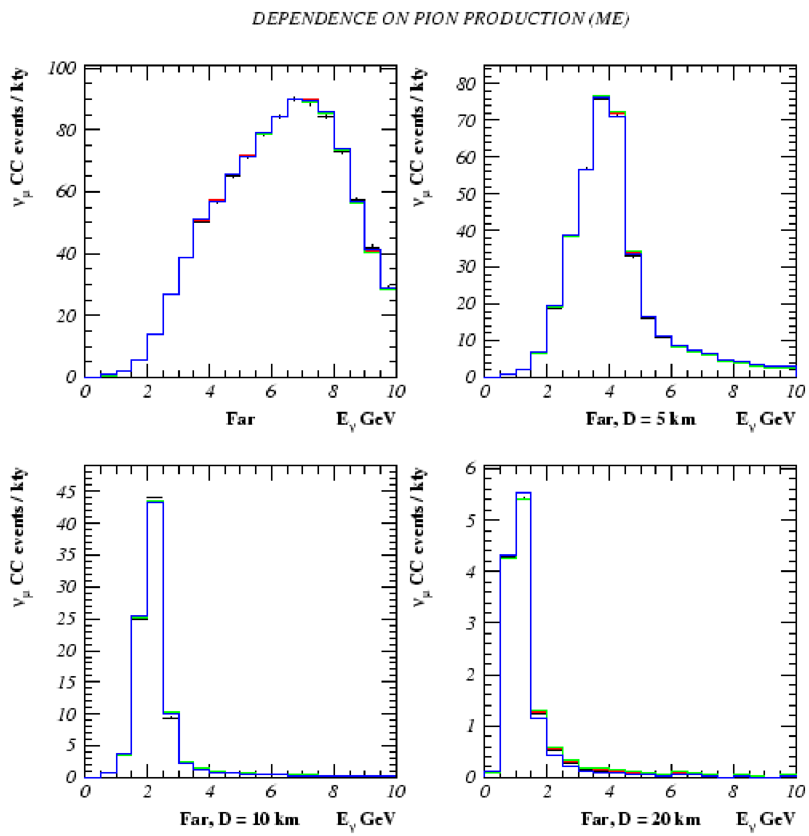
Decay angle $Q^N \neq Q^F$, hence $E^N \neq E^F$.

Take as an example two neutrino energy bins:

$$(N_1^{Far}, N_2^{Far}) = \begin{bmatrix} M_{11} & M_{12} \\ M_{21} & M_{22} \end{bmatrix} \begin{bmatrix} N_1^{Near} \\ N_2^{Near} \end{bmatrix}$$

- Well focused, parallel beam of pions $M_{11}, M_{22} \neq 0$, $M_{12}=M_{21}=0$
- Realistic beam, far detector on axis $M_{11}, M_{12} \neq 0$, $M_{21} < M_{11}$, $M_{12} \sim 0$
- Off-axis beam $M_{11}, M_{22}, M_{21} \sim 0$, $M_{12} \neq 0$

Beam Systematics: Predict the Spectrum. Medium Energy Beam

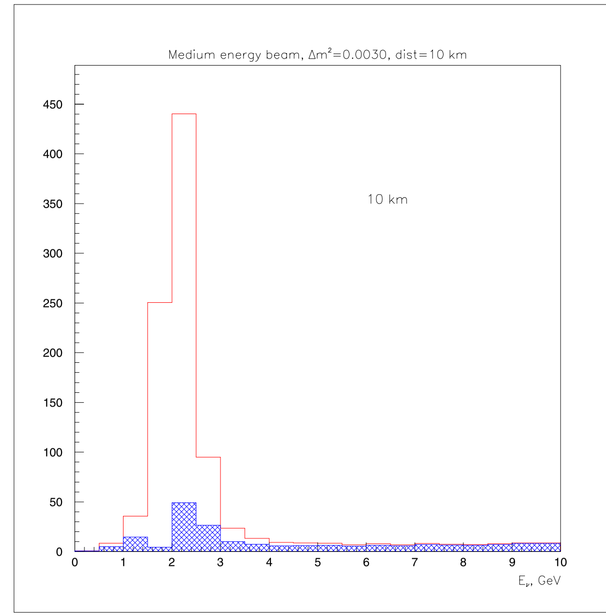


Event spectra at far detectors located at different positions derived from the single near detector spectrum using <u>different particle production models.</u>

Four different histograms superimposed

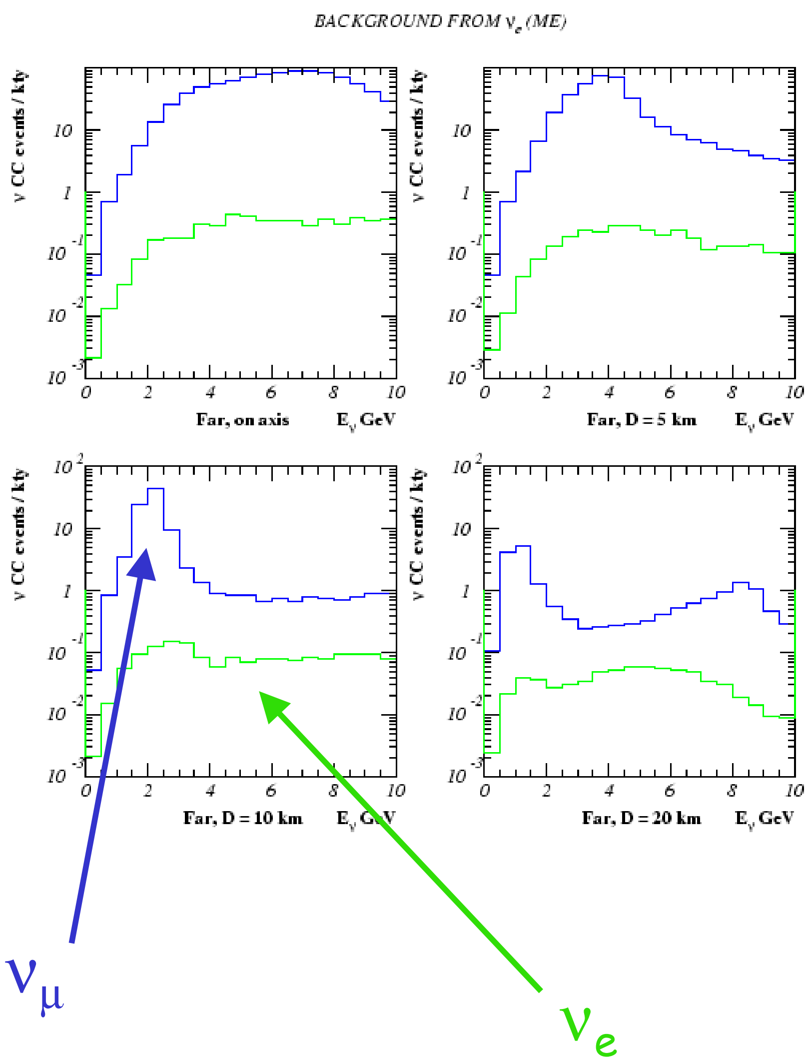
Total flux predictable to ~1%.

ν_e appearance experiment



- Large number of ν_μ oscillating away (~ 800 per 10 kton*years)
- Below τ threshold→ no background
- The only backgrounds due to
  - ν_e component of the beam
  - NC background
    - NC background as small as it can be (very small higher energy tail not contributing to the signal)
    - Total energy constraint

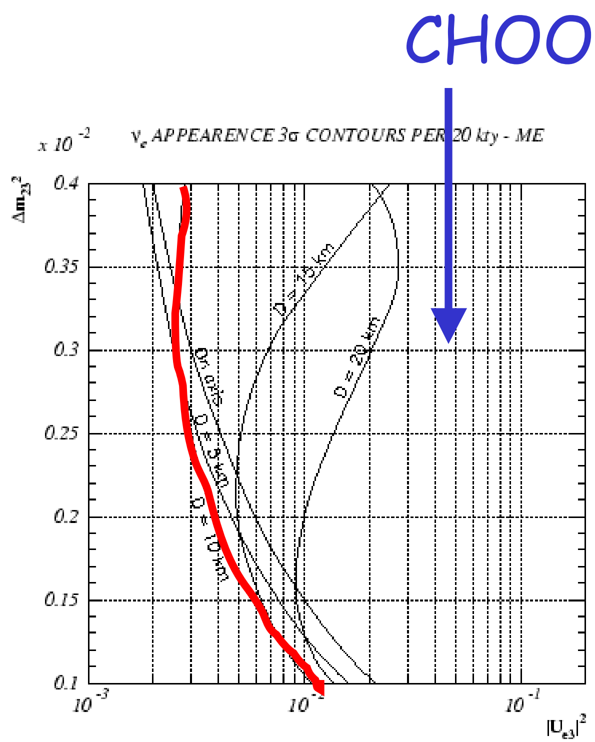
ν_e Background: ME case



ν_e/ν_μ ~0.5%

in the peak/signal region

Sensitivity to $|U_{e3}|^2$ 20 kton x years exposure

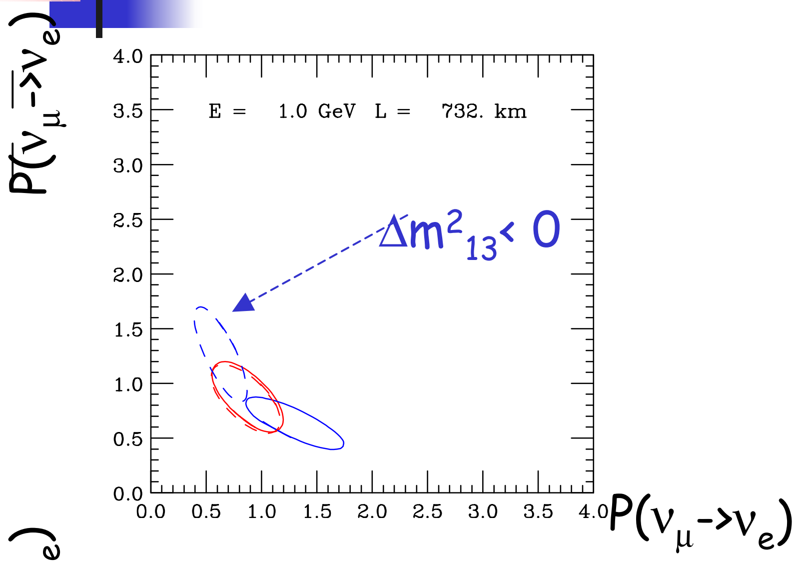


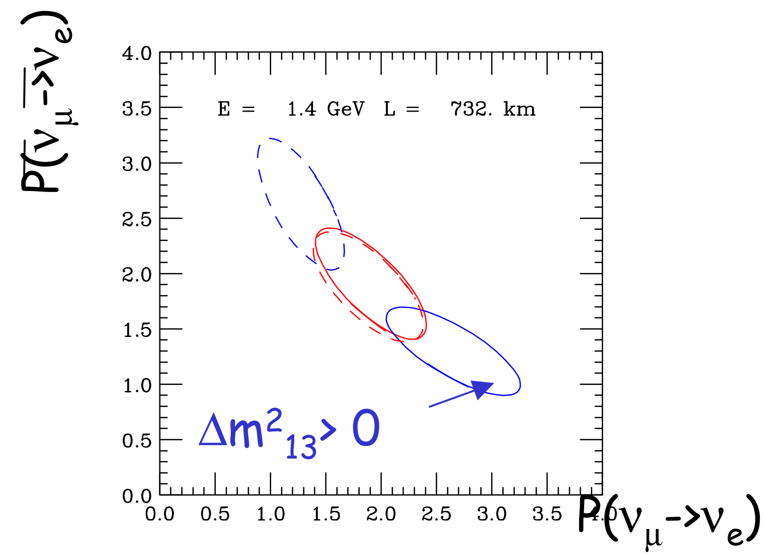
- Assuming that the NC background is reduced below the intrinsic ν_e level (~0.5%)
- Which detector location is most sensitive to $|U_{e3}|^2$?
- At which Δm^2

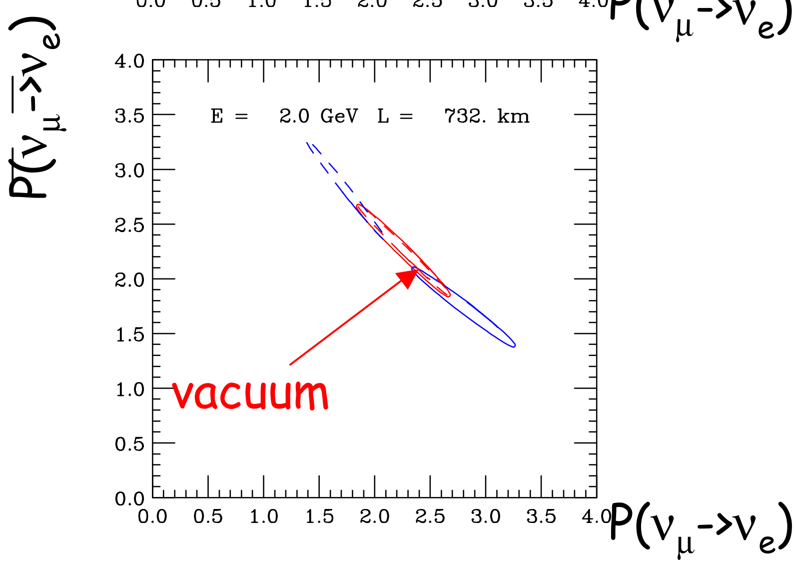
·Detector located at 10 km the most sensitive one

·Sensitivity down to the level $|U_{e3}|^2$ ~ 0.003 (factor ~15 beyond the CHOOZ limit)

Mass hierarchy? CP?







Minakata and Nunokawa, hep-ph/0108085

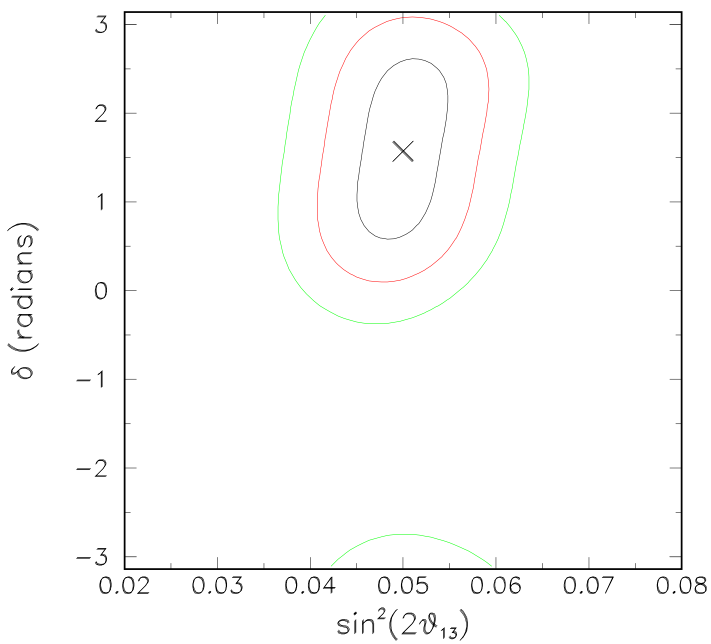
$\Delta m^2_{13} = 3 \times 10^{-3}$ eV^2

$\Delta m^2_{12} = 5 \times 10^{-5}$ eV^2

$\sin^2 2\theta_{13} = 0.05$

Use matter effects to establish the mass hierarchy

Measuring/constraining CP parameters?



Assume:

- 30 kton x year exposure (at a 'design' intensity) for neutrinos and 30 kton x year for antineutrinos
- $\Delta m^2_{13}=3\times10^{-3}$ eV^2
- $\Delta m^2_{12}=5\times10^{-5}$ eV^2
- $\sin^2 2\theta_{13}=0.05$

(F. de Jongh)

Have beam. Just add detector(s).

Given

- a sensible size detector (20 kton?)
- potential intensity upgrades (welcome, but not essential)

There is a great physics potential of the NuMI neutrino beam.

Detector(s) Challenge

- Surface (or light overburden)
  - High rate of cosmic μ's
  - Cosmic-induced neutrons
- But:
  - Duty cycle 0.5×10^{-5}
  - Known direction
  - Observed energy > 1 GeV

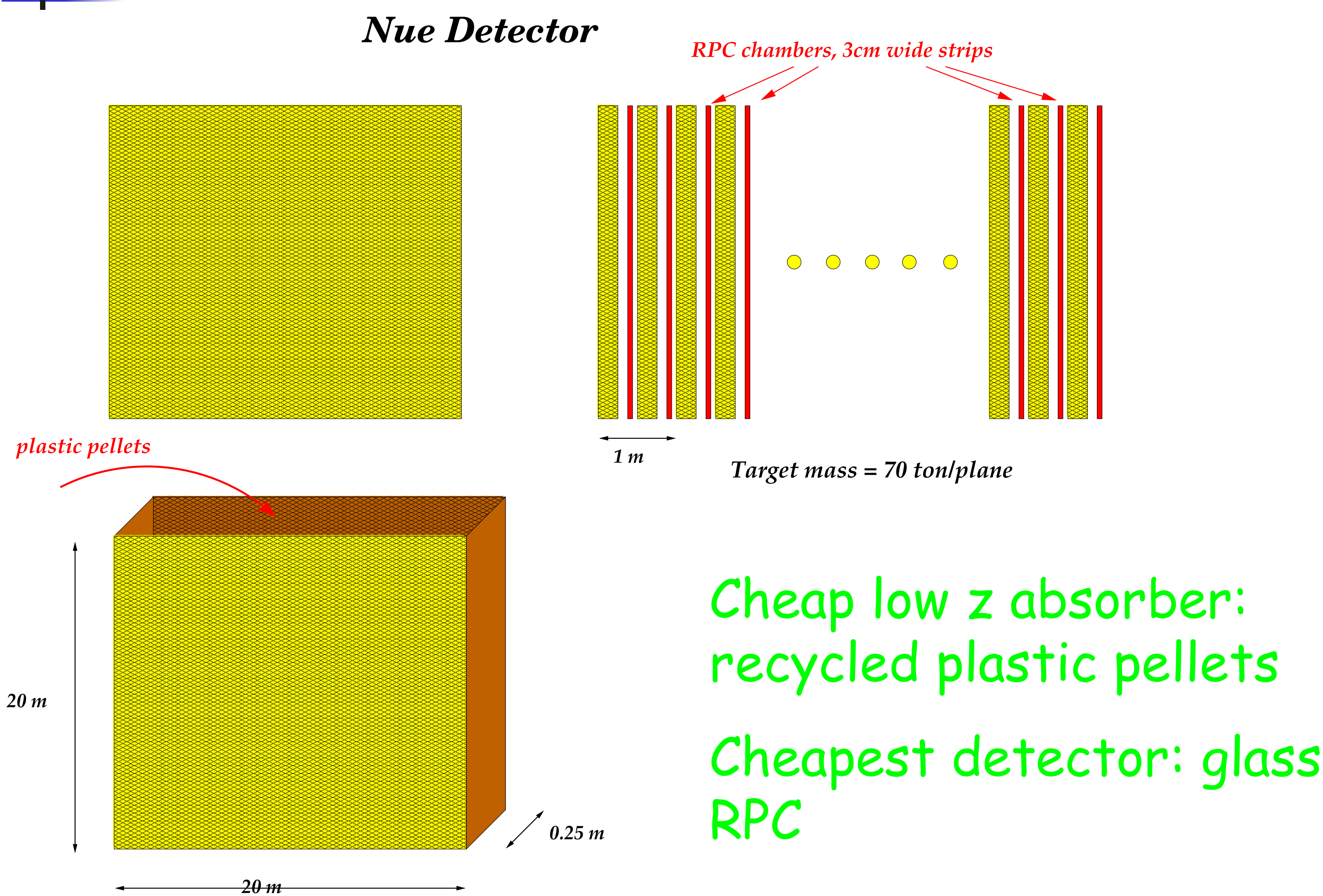
Principal focus: electron neutrinos identification

- Good sampling (in terms of radiation/Moliere length)

Large mass:

- maximize mass/radiation length
- cheap

A possible detector: an example



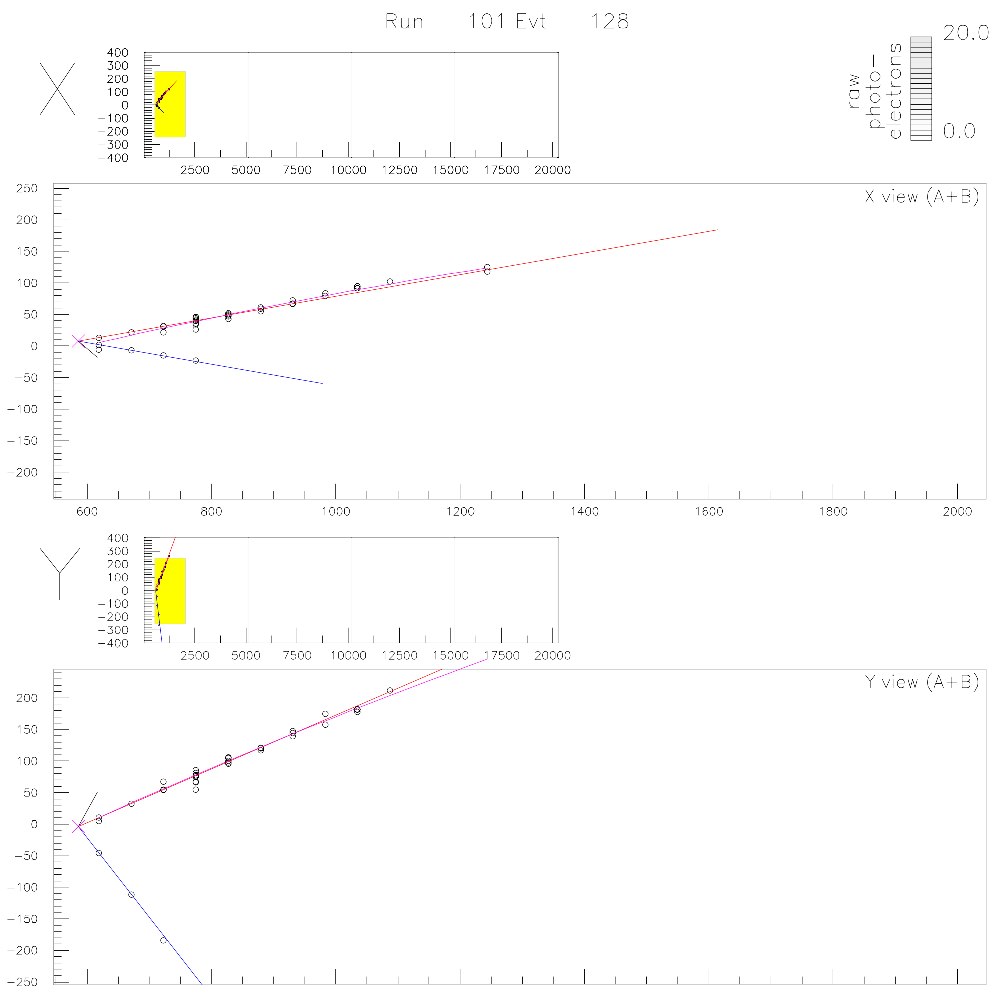
Cheap low z absorber: recycled plastic pellets

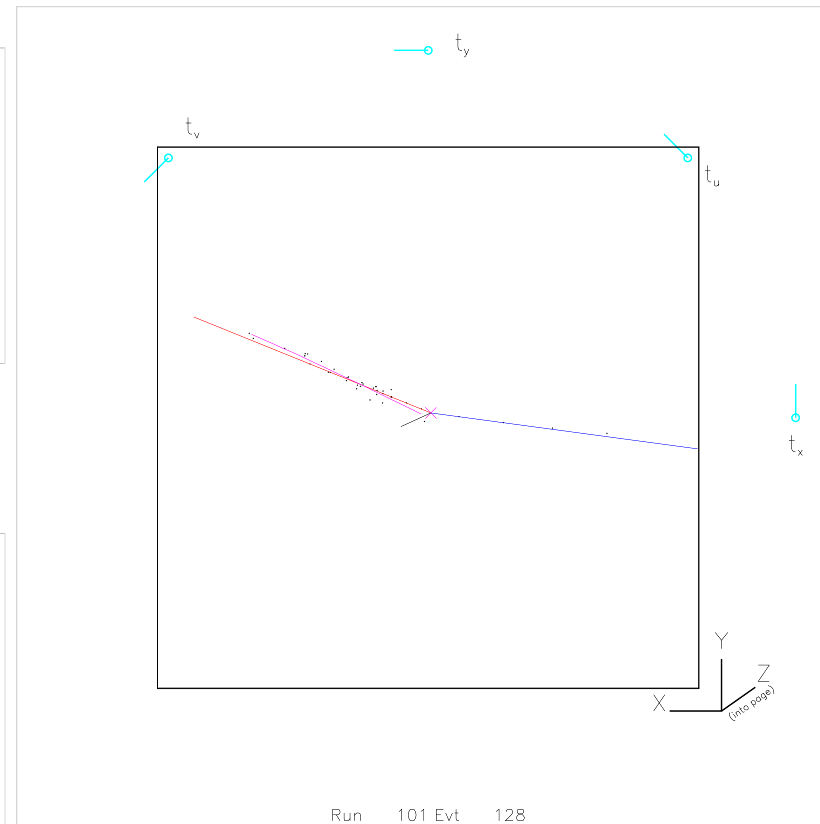
Cheapest detector: glass RPC

A step beyond a cartoon detector

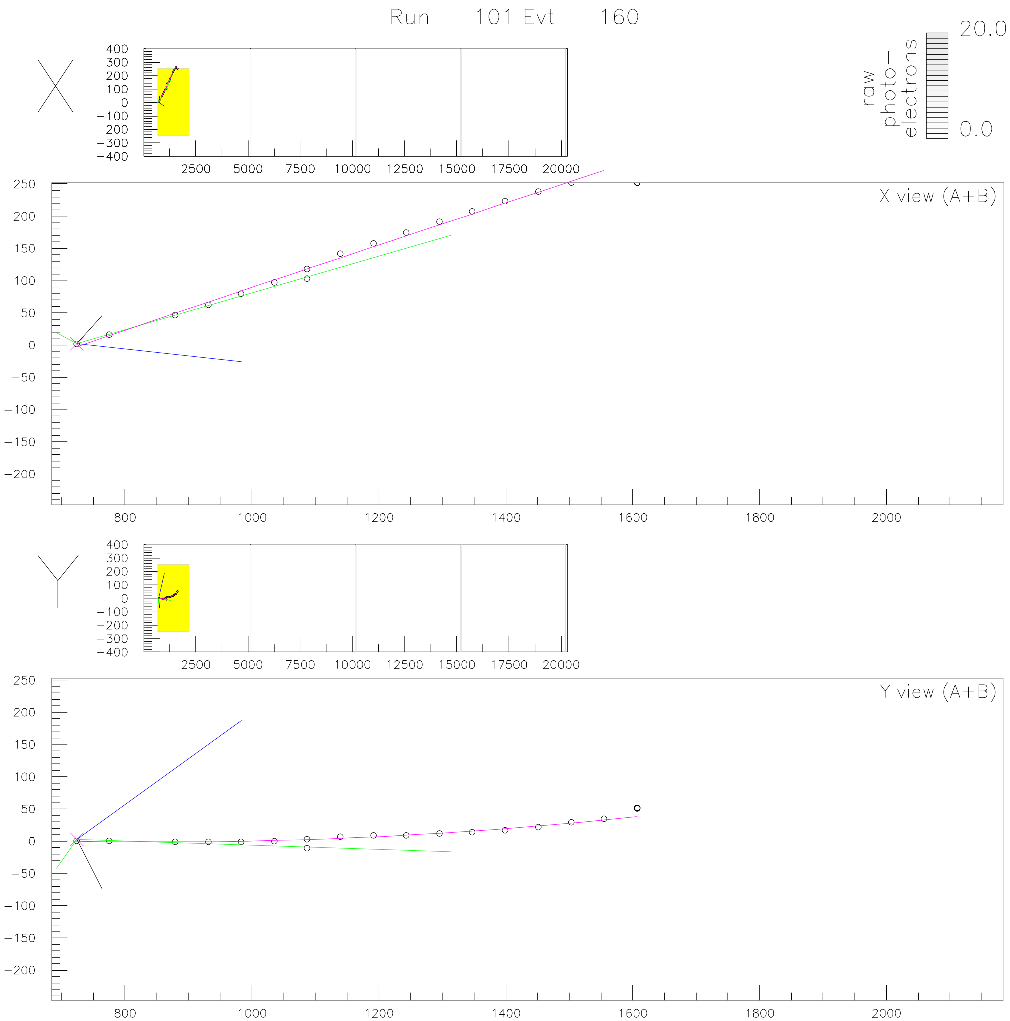
- Full GEANT simulation
- Event displays
- Simple event reconstruction:
  - Track finding (Hough transform, parabolic fit)
  - Energy reconstruction (hit counting)
- Simple analysis
  - Long track
  - Hit multiplicity along the track (em 'shower')
  - Large fraction of energy in a track (low y)
  - Small angle with respect to the beam direction

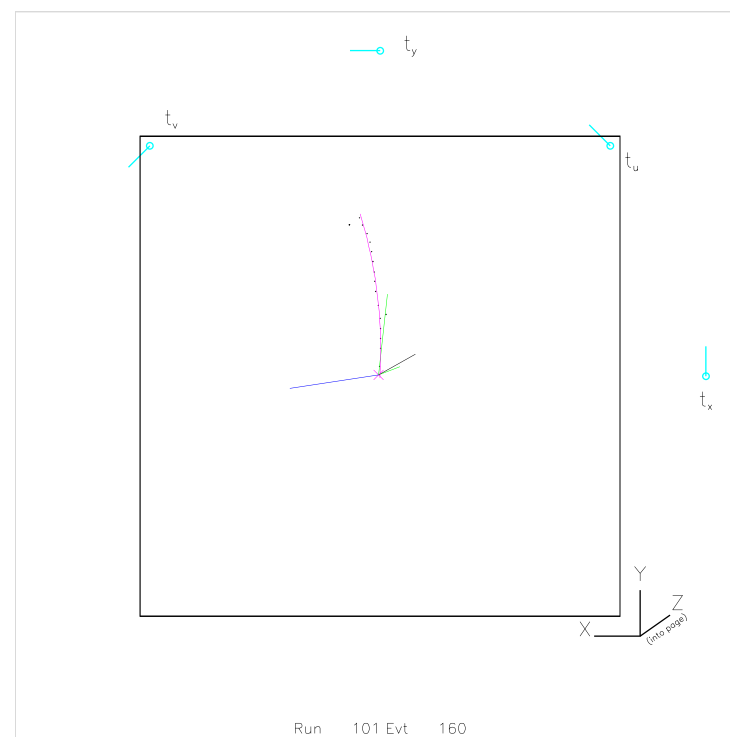
A 'typical' signal event





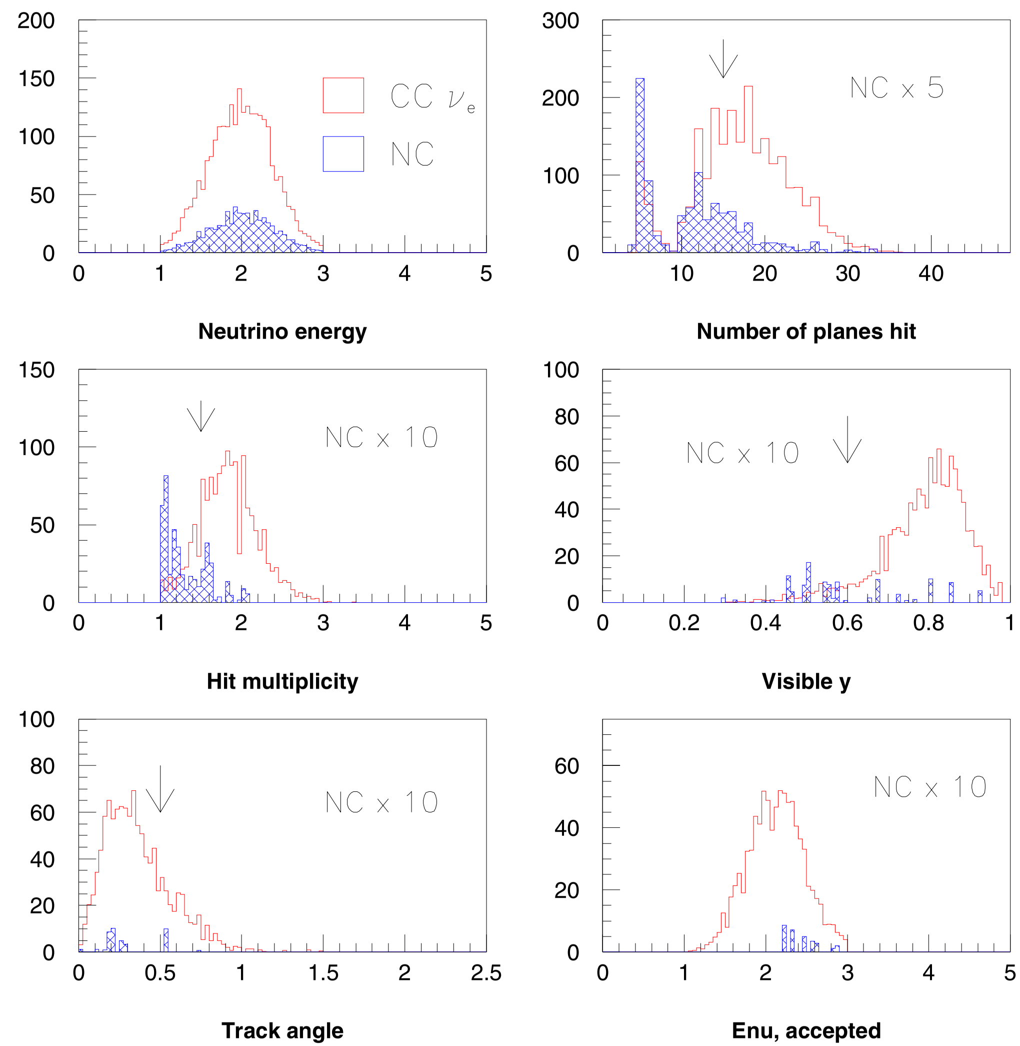
A 'typical' background event





And the result is:

- NC background sample reduced to 0.3% of the final electron neutrino sample (for 100% oscillation probability)
- 35% efficiency for detection/identification of electron neutrinos



This was just an 'existence proof'

- Better reconstruction
- Optimized analysis
- Better detector
- Cheaper detector
- Optimized location (energy and/or baseline)
- Beyond a GEANT detector: reality check (engineering, cost estimates, etc)
- Etc.. Etc..

Conclusion/Commercial

- There is an important physics opportunity, in addition to MINOS, offered by the 'existing' NuMI neutrino beam
- Large detectors capable of identifying electron neutrinos are possible and affordable
- A focused workshop:

'New Initiatives for the NuMI neutrino beam'
May 1-3, Fermilab

including: non-oscillation physics [some of it relevant for the oscillations]

Come and join. Bring your ideas and detector(s).