SuperKamiokande + K2K results

- Neutrinos oscillate
- There is at least one oscillation in the frequency range $\Delta m^2 \sim 1 - 4 \times 10^{-3}$ 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 $\Delta m^2$
- 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

Expected CC Events Rates in Minos 5kt detector

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

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

Two functionally identical neutrino detectors

Fermilab

Det. 1

Det. 2

Soudan

Duluth

MN

WI

Lake Superior

Lake Michigan

IA

Madison

IL

IN

MO
'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

$\Delta m^2$

$\sin^2\theta = 0.9, \Delta m^2 = 0.0035$
In Dec. 1999 CERN council approved the CNGS project:

- build an intense $\nu_\mu$ beam at CERN-SPS
- search for $\nu_\tau$ appearance at Gran Sasso laboratory (730 km from CERN)

“long base-line” $\nu_\mu -- \nu_\tau$ oscillation experiment
Detecting $\nu_\tau$ at Gran Sasso

-> look for the $\tau$ lepton:
  extremely difficult -
  $\tau$ 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
2000 tons of “detector mass”
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 1 year of CNGS operation, expect:

- **Protons on target**: $4.5 \times 10^{19}$
- **$\nu_\mu$ in 100 m$^2$ at Gran Sasso**: $3.5 \times 10^{12}$
- **$\nu_\mu$ "charged current" events per 1000 t ($\nu + N \to N' +\mu$)**: $\approx 2500$
- **$\nu_\tau$ events (from oscillation)**: $\approx 20$ “detectable”
- **$\nu_\tau$ events detected “in OPERA”**: $\approx 2.5$ (b.g. 0.15)
Next-to-Next Step: going beyond SuperK

- $1 - \sin^2 2\theta_{23}$
  - $\sin^2 2\theta_{23} = 1 \iff$ 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:
  - $\Delta m_{12}$ not too small
  - $|U_{e3}|^2$ not too small

- Neutrino factories?
  - $\Delta(1 - \sin^2 2\theta_{23})$
- Superbeams?
  - Determine/limit $|U_{e3}|^2$
- NuMI beam!
  - If sizeable $\rightarrow$ get a shot at the mass hierarchy/CP
NuMI Neutrino Beams

- $L = 730 \text{ km}$
- $\Delta m^2 = 1-3 \times 10^{-3} \text{ eV}^2$
- $\Rightarrow$ maximum effect at $E_{\nu} = 1-3 \text{ GeV}$

- 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

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

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

1/3 of the flux with medium energy beam
Low/Medium Energy: Beam Composition

THE CONTRIBUTIONS FROM PIONS AND KAGONS (LE)

THE CONTRIBUTIONS FROM PIONS AND KAGONS (ME)

pions

kaons
Disappearance Experiment, 10 kty
\[ \Delta m^2 = 0.0015/0.002 \text{ eV}^2 \]
Disappearance Experiment, 10 kty
$\Delta m^2 = 0.003 \text{ eV}^2$

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

$\Delta m^2 \approx 0.003 \text{ eV}^2$

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

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

Oscillatory pattern: re-appearance after a minimum
Disappearance Experiment, 10 kty
$\Delta m^2 = 0.0025/0.0035$ 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\( (E_\nu) \) at the far detector.

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

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

Decay angle $Q_N \neq Q_F$, hence $E_N \neq E_F$.

Take as an example two neutrino energy bins:

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

- 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 different particle production models.

Four different histograms superimposed

Total flux predictable to ~1%.
νₑ appearance experiment

- Large number of νₘ oscillating away (~ 800 per 10 kton*years)
- Below τ threshold ➞ no background
- The only backgrounds due to
  - νₑ 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
$\nu_e$ Background: ME case

$\nu_e/\nu_\mu \sim 0.5\%$ in the peak/signal region
Sensitivity to $|U_{e3}|^2$
20 kton x years exposure

CHOOZ

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

• Detector located at 10 km the most sensitive one
• Sensitivity down to the level $|U_{e3}|^2 \sim 0.003$ (factor ~15 beyond the CHOOZ limit)
Mass hierarchy? CP?

Minakata and Nunokawa, hep-ph/0108085

\[ \Delta m^2_{13} = 3 \times 10^{-3} \text{ eV}^2 \]

\[ \Delta m^2_{12} = 5 \times 10^{-5} \text{ eV}^2 \]

\[ \sin^2 2\theta_{13} = 0.05 \]

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 $\mu$'s
  - Cosmic-induced neutrons

- **But:**
  - Duty cycle $0.5 \times 10^{-5}$
  - 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

Nue Detector

plastic pellets

Target mass = 70 ton/plane

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
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..
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).