Indication of $\nu_\mu \rightarrow \nu_e$ appearance in the T2K EXPERIMENT

Alain Blondel – University of Geneva
On behalf of the T2K collaboration
There are today **THREE** compelling and firmly established observational facts that the Standard Model fails to account for:

-- neutrino masses
-- the existence of dark matter
-- the baryon asymmetry of the universe

The fact that neutrino have masses and mix is established by neutrino oscillations

The neutrino masses offer a chance to explain the baryon asymmetry in the most natural way via

*** LEPTOGENESIS ***

by a combination of
-- fermion number violation  (authorized by neutrino masses and GUT)
-- three families of neutrinos  ==> leptonic CP violation
  (authorized by the mixing of three families with large mixing angles)
The neutrino mixing matrix: 3 angles and a phase $\delta$

$\theta_{13}$ (Chooz) $< 13^0$

$\theta_{23}$ (atmospheric) $= 45^0$, $\theta_{12}$ (solar) $= 32^0$

$\Delta m_{23}^2 = 2 \times 10^{-3} eV^2$

$\Delta m_{12}^2 = 8 \times 10^{-5} eV^2$

$\Delta m_{13}^2 = 8 \times 10^{-5} eV^2$

$_{\text{OR?}}$

$\Delta m_{23}^2 = 2 \times 10^{-3} eV^2$

$\theta_{13}$, phase $\delta$, sign of $\Delta m_{13}^2$

$U_{\text{MNS}}$: $
\begin{pmatrix}
\sim \frac{\sqrt{2}}{2} & \sim -\frac{\sqrt{2}}{2} & \sin \theta_{13} e^{i\delta} \\
\sim \frac{1}{2} & \sim \frac{1}{2} & \sim -\frac{\sqrt{2}}{2} \\
\sim \frac{1}{2} & \sim \frac{1}{2} & \sim \frac{\sqrt{2}}{2}
\end{pmatrix}$

eta_13
Conventional three-neutrino oscillations

**Neutrino oscillations: where we are**

**Updated global 6-parameter fit (including δ_{CP}):**
- **Solar:** Cl + Ga + SK-I + SNO-Ieta (I+II) + SNO-III + BX-low + BX-high;
- **Atmospheric:** SK-I + SK-II + SK-III;
- **Reactor:** Chooz + KamLAND;
- **Accelerator:** K2K + Minos-DIS + Minos-APP;

**BPS09(GS):** best-fit and 1σ (3σ):
\[ \theta_{12} = 34.4 \pm 1.0 \left( ^{+3.2}_{-2.9} \right), \quad \Delta m^2_{21} = 7.59 \pm 0.20 \left( ^{+0.61}_{-0.69} \right) \times 10^{-3} \text{ eV}^2, \]
\[ \theta_{23} = 42.8^{+4.7}_{-2.9} \left( ^{+10.7}_{-7.3} \right), \quad \Delta m^2_{31} = \begin{cases} -2.36 \pm 0.11 \left( ^{+0.37}_{-0.37} \right) \times 10^{-3} \text{ eV}^2, \\ +2.46 \pm 0.12 \left( ^{+0.37}_{-0.37} \right) \times 10^{-3} \text{ eV}^2, \end{cases} \]
\[ \theta_{13} = 5.6^{+3.0}_{-2.7} \left( \leq 12.5 \right), \quad \delta_{CP} \in [0, 360] ; \]

**BPS09(AGSS):** same as above except:
\[ \theta_{12} = 34.5 \pm 1.0 \left( ^{+3.2}_{-2.8} \right), \quad \theta_{13} = 5.1^{+3.0}_{-3.3} \left( \leq 12.0 \right) ; \]

**“θ_{13} ≠ 0”:**

<table>
<thead>
<tr>
<th></th>
<th>Solar model</th>
<th>Sol+Kam</th>
<th>Global</th>
</tr>
</thead>
<tbody>
<tr>
<td>BPS09(GS)</td>
<td>1.26σ</td>
<td>1.31σ</td>
<td></td>
</tr>
<tr>
<td>BPS09(AGSS)</td>
<td>1.05σ</td>
<td>1.17σ</td>
<td></td>
</tr>
</tbody>
</table>

Consequences of 3-family oscillations:

I. There will be $\nu_\mu \leftrightarrow \nu_e$ and $\nu_\tau \leftrightarrow \nu_e$ oscillation at $L_{atm}$

\[
\begin{align*}
\text{P (acc)} (\nu_\mu \leftrightarrow \nu_e)_{\text{max}} & \approx \frac{1}{2}\sin^2 2\theta_{13} + \ldots \text{(small)} \\
\text{P (reactor)} (\nu_e \leftrightarrow \nu_e)_{\text{max}} & \approx 1 - \sin^2 2\theta_{13} + \ldots \text{(small)}
\end{align*}
\]

II. There will be CP or T violation

CP: $P (\overline{\nu}_\mu \leftrightarrow \overline{\nu}_e) \neq P (\nu_\mu \leftrightarrow \nu_e)$

T: $P (\nu_\mu \leftrightarrow \nu_e) \neq P (\nu_e \leftrightarrow \nu_\mu)$

1st maximum $\neq$ second maximum

III. We do not know if the neutrino $\nu_1$ (which contains more $\nu_e$) is the lightest one (natural?) or not.
Alain Blondel – UNIGE seminar – The T2K experiment – \( \theta_{13} \)

\[
P(\nu_e \rightarrow \nu_\mu) = |A|^2 + |S|^2 + 2 A S \sin \delta
\]

\[
\bar{P}(\nu_e \rightarrow \nu_\mu) = |A|^2 + |S|^2 - 2 A S \sin \delta
\]

\[
\frac{P(\nu_e \rightarrow \nu_\mu) - P(\bar{\nu}_e \rightarrow \bar{\nu}_\mu)}{P(\nu_e \rightarrow \nu_\mu) + P(\bar{\nu}_e \rightarrow \bar{\nu}_\mu)} = A_{CP} \frac{\sin \delta \sin (\Delta m^2_{12} L/4E) \sin \theta_{12} \sin \theta_{13}}{\sin^2 2\theta_{13} + \text{solar term...}}
\]

... need large values of \( \sin \theta_{12} \), \( \Delta m^2_{12} \) (LMA-- we have it!) but *not* large \( \sin^2 \theta_{13} \)

... need APPEARANCE ... \( P(\nu_e \rightarrow \nu_e) \) is time reversal symmetric (reactors or sun are out)

... can be large (100\%) for suppressed channel (one small angle vs two large)

... asymmetry is opposite for \( \nu_e \rightarrow \nu_\mu \) and \( \nu_e \rightarrow \nu_\tau \)

Alain Blondel – UNIGE seminar – The T2K experiment – \( \theta_{13} \)
Three family oscillations and $\nu_\mu \rightarrow \nu_e$ oscillation

Figure 3: Sketch of $P(\nu_\mu \rightarrow \nu_e)$ as function of the baseline computed for monochromatic neutrinos of 1 GeV in the solar baseline regime for $\delta_{CP} = 0$ (left) and in the atmospheric baseline regime for $\delta_{CP} = -\pi/2$ (right), where the different terms of eq. 4 are displayed. The following oscillation parameters were used in both cases: $\sin^2 2\theta_{13} = 0.01$, $\sin^2 2\theta_{12} = 0.8$, $\Delta m_{23}^2 = 2.5 \times 10^{-3}$ eV$^2$, $\Delta m_{12}^2 = 7 \times 10^{-5}$ eV$^2$. 
\[
P(\nu_e \rightarrow \nu_\mu) = |A|^2 + |S|^2 + 2 A S \sin \delta
\]

\[
\bar{P}(\nu_e \rightarrow \nu_\mu) = |A|^2 + |S|^2 - 2 A S \sin \delta
\]

\[
\frac{P(\nu_e \rightarrow \nu_\mu) - P(\bar{\nu}_e \rightarrow \bar{\nu}_\mu)}{P(\nu_e \rightarrow \nu_\mu) + P(\bar{\nu}_e \rightarrow \bar{\nu}_\mu)} = \alpha \frac{\sin \delta \sin (\Delta m_{12}^2 L/E)}{\sin^2 2\theta_{13} + \text{solar term}} \sin \theta_{12} \sin \theta_{13}
\]

\[
\text{... need large values of } \sin \theta_{12}, \Delta m_{12}^2 \text{ (LMA-- we have it!) but *not* large } \sin^2 \theta_{13}
\]

\[
\text{... need APPEARANCE ... } P(\nu_e \rightarrow \nu_\mu) \text{ is time reversal symmetric (reactors or sun are out)}
\]

\[
\text{... can be large (100%) for suppressed channel (one small angle vs two large)}
\]

\[
\text{... at wavelength at which ‘solar’ = ‘atmospheric’ and for } \nu_e \rightarrow \nu_\mu, \nu_\tau
\]

\[
\text{... asymmetry is opposite for } \nu_e \rightarrow \nu_\mu \text{ and } \nu_e \rightarrow \nu_\tau
\]

Alain Blondel – UNIGE seminar – The T2K experiment – theta_13
NOTES:

Asymmetry can be very large.

Stat. sensitivity in absence of bkg is $\sim$independent of $\theta_{13}$ down to max. asym. point

Asymmetry changes sign from one max. to the next.

Sensitivity at low values of $\theta_{13}$ is better for short baselines, sensitivity at large values of $\theta_{13}$ is better for longer baselines (2d max or 3d max.)

Sign of asymmetry changes with max. number.
Idea of T2K was born 1999-2001 hep-ex/0106019 combining:

-- existing SuperKamiokande detector (50kton W.Č., 22.5 kton fiducial)

-- JAERI-KEK Japanese Proton Accelerator Research Complex (JPARC) at TOKAI including a high power, 0.75MW/50GeV Proton Synchrotron

-- baseline 295 km $\Rightarrow$ neutrino energy for first maximum is $\sim$600 MeV achievable by pion-decay beam at 2.5 degrees off-axis
T2K

神岡
Kami oka

東海
Tō kai
~500 members, 61 Institutions, 12 countries

<table>
<thead>
<tr>
<th>Country</th>
<th>Institutions</th>
</tr>
</thead>
<tbody>
<tr>
<td>France</td>
<td>CEA Saclay, IPN Lyon, LLR E. Poly, LPNHE Paris</td>
</tr>
<tr>
<td>Germany</td>
<td>Univ. Aachen</td>
</tr>
<tr>
<td>Italy</td>
<td>INFN, Univ. Rome, INFN, Univ. Naples, INFN, Univ. Padua, INFN, Univ. Bari</td>
</tr>
<tr>
<td>Japan</td>
<td>ICRR Kamioka, ICRR RCCN, KEK, Kobe Univ., Kyoto Univ., Miyagi Univ. of Educ., Osaka City Univ., Univ. Tokyo</td>
</tr>
<tr>
<td>Poland</td>
<td>Soltan Inst., Warsaw, Niewodniczanski Inst., Cracow, Technical Univ. Warsaw, Univ. Silesia, Katowice, Univ. Warsaw, Univ. Wroclaw</td>
</tr>
<tr>
<td>Russia</td>
<td>INR</td>
</tr>
<tr>
<td>S. Korea</td>
<td>N. Univ. Chonnam, Univ. Dongshin, Univ. Sejong, N. Univ. Seoul, Univ. Sungkyunkwan</td>
</tr>
<tr>
<td>Spain</td>
<td>IFIC, Valencia, Univ. A. Barcelona</td>
</tr>
<tr>
<td>Switzerland</td>
<td>Univ. Bern, Univ. Geneva, ETH Zurich</td>
</tr>
<tr>
<td>United Kingdom</td>
<td>Imperial C. London, Queen Mary Univ. L., Lancaster Univ., Liverpool Univ., Oxford Univ., Sheffield Univ., Warwick Univ.</td>
</tr>
</tbody>
</table>
University of Geneva:
OVERVIEW

✦ 2.5 degrees off-axis beam
  - Low energy, narrow band beam tuned at osc. max.
  - Neutrino peak ~600 MeV/c

✦ Near detector @ 280 m from target
  ⇒ extrapolate ν energy spectrum and flux to SK
  - INGRID: on axis to monitor beam direction
  - ND280: off axis to measure ν_µ and ν_ν interaction rates and backgrounds

✦ NA61 at CERN
  ⇒ hadro-production measurement

✦ Far detector SuperKamiokande @ 295 km
  - Very large water Cerenkov detector
  - Very good µ/e separation capability for sub-GeV neutrinos
Experiment is optimized for the search of $\nu_\mu \rightarrow \nu_e$ oscillation $\Rightarrow \theta_{13}$

$$P(\nu_\mu \rightarrow \nu_e) \equiv \sin^2 2\theta_{13} \sin^2 \theta_{23} \sin(1.27 \Delta m^2_{23} L/E_\nu)$$

--- is also able of precision measurement of $\nu_\mu \rightarrow \nu_\mu$ oscillation $\Rightarrow \theta_{23}, \Delta m^2_{23}$

$$P(\nu_\mu \rightarrow \nu_\mu) \equiv 1 - \sin^2 2\theta_{23} \sin (1.27 \Delta m^2_{23} L/E_\nu)$$

--- and measurements of cross-sections around 600 MeV in the near detector

Alain Blondel – UNIGE seminar -- The T2K experiment – theta_13
90% C.L. 750kW X 5 years X 22.5 kton fid.

short baseline ➞ little sensitivity to matter effects, but sensitive to $\delta_{CP}$

$\sin^2 \theta_{12} = 0.8704$

$\sin^2 \theta_{23} = 1.0$

$\Delta m^2_{12} = 7.6 \times 10^{-5} \text{ eV}^2$

$\Delta m^2_{23} = 2.4 \times 10^{-3} \text{ eV}^2$
17

Alain Blondel – UNIGE seminar -- The T2K experiment – $\theta_{13}$

90% CL $\theta_{13}$ Sensitivity 750kW

Systematic Error Fraction
- 5% sys error
- 10% sys error
- 20% sys error
- Normal Hierarchy

$\sin^2 2\theta_{13} < 0.008$ (90% C.L.)
for 5 years@750kW
$= 8.3 \times 10^{21}$ p.o.t@30 GeV

MINOS & Super-K preliminary @ Nu’10

T2K nominal: 3.75MW$\times 10^7$s

$\Delta m^2_{23} < 1\times10^{-4}$ eV$^2$

spectrum centered on oscillation maximum

very rapidly sensitive to Atm. Params.

$\Delta\sin^2 2\theta_{23} \approx 0.01$
T2K 1st $\nu$ event in Super-K

Super-Kamiokande IV
T2K Beam Run 0 Spill 1143942
Run 66498 Sub 160 Event 37004533
15-02-26 06:06:06
T2K beam $dt = 2362.3$ ns
Inner: 1205 hits, 2344 ps
Outer: 2 hits, 1 ps
Triggers: Da00000007
D_wall: 558.6 cm

[ 1st ring + 2nd ring ]
Invariant mass: 133.8 MeV/c²
(close to $\pi^0$ mass)
Momentum: 148.3 MeV/c
Beam Monitors

Proton beam precisely tuned (<1mm) to minimize beam loss, and control direction of secondary beam

Muon monitors (SiPIN and ionization chambers):

- measure beam direction and intensity spill-by-spill
- requirement: <1mrad ($\Delta E_v^{peak} \sim 2\%/$mrad)
Near Detector Complex ND280

**Off-Axis** suite of fine grain detectors/tracker inside a 0.2 T magnetic field (UA1/NOMAD magnet)

**ND280:**
- measurements of
  - $CC\nu_\mu$ events (normalization, disappearance)
  - $CC\nu_e$ events
  - $\pi^0$ events
- Backgrounds to $\nu_\mu \rightarrow \nu_e$ search

**On-axis** INGRID
- scintillator-iron detectors
- measurement of beam angular profile

incoming neutrino beam
IN GRID

INGRID first neutrino event candidate

Side view

Top view

v beam

v beam

Nov. 22, 2009

MR Shot #19655
T2K Spill# 241792
\( \nu \) beam stability

Stability of \( \nu \) beam direction (INGRID)

Stability of \( \nu \) interaction rate normalized by \# of protons (INGRID)

\[ \text{INGRID } \nu \text{ int. rate stability} \]
\[ \text{Run 1+2 / Run 1 < 1\%} \]

\( \nu \) beam dir. stability < 1 mrad

Beam dir. stability < 1 mrad
Search for $\nu_\mu \rightarrow \nu_e$ appearance

1. Event selection at SK
2. Prediction of number of expected events (oscillation/no oscillation)
3. Systematic errors
4. Open the last three cuts
5. Inspect what you see
6. results

most slides that follow from T2K seminar at KEK, K. Sakashita (KEK)
T2K Signal & Background for $\nu_e$ appearance

• Signal = single electron event
  - oscillated $\nu_e$ interaction:
    \[ v_\mu \rightarrow v_e \rightarrow e \rightarrow p \]

CCQE: $\nu_e + n \rightarrow e + p$
(dominant process at T2K beam energy)

• Background
  - intrinsic $\nu_e$ in the beam (from $\mu$, $K$ decays)
  - $\pi^0$ from NC interaction
Unbiased event selection

SK event selection was fixed before run.
⇒ Possible because SK is a mature & well understood detector.

<table>
<thead>
<tr>
<th>For $\nu_\mu$ disappearance analysis</th>
<th>For $\nu_e$ appearance search</th>
</tr>
</thead>
<tbody>
<tr>
<td>Timing coincident w/ beam time (+TOF)</td>
<td></td>
</tr>
<tr>
<td>Fully contained (No OD activity)</td>
<td></td>
</tr>
<tr>
<td>Vertex in fiducial volume (Vertex &gt;2m from wall)</td>
<td></td>
</tr>
<tr>
<td>$E_{\text{vis}} &gt; 30\text{MeV}$</td>
<td>$E_{\text{vis}} &gt; 100\text{MeV}$</td>
</tr>
<tr>
<td>$n^0$ of rings =1</td>
<td></td>
</tr>
<tr>
<td>$\mu$-like ring</td>
<td>$e$-like ring</td>
</tr>
<tr>
<td></td>
<td>No decay electron</td>
</tr>
<tr>
<td></td>
<td>Inv. mass w/ forced-found 2$^\text{nd}$ ring &lt; 105MeV</td>
</tr>
<tr>
<td></td>
<td>$E_{\nu_{\text{rec}}} &lt; 1250\text{MeV}$</td>
</tr>
</tbody>
</table>

NB: slide shown at NUFACT10 October 2010
**Ve selection at far detector (SK)**

*The selection criteria were optimized for initial running condition*

The selection criteria were fixed before data taking started to avoid bias.

**7 selection cuts**

1. T2K beam timing & Fully contained (FC)  
   (synchronized with the beam timing,  
   no activities in the OD)

2. In fiducial volume (FV)  
   (distance btw recon. vertex and wall > 200 cm)

* Events too close to the wall are difficult to accurately reconstruct vertex  
* Reject events which are originated outside the ID  
* Define FV 22.5kton

3. Single electron  
   (# of ring is one & e-like)
4. Visible energy > 100 MeV
(Visible energy = electron energy deposited in ID)
* Reject low energy events, such as NC background and decay electrons produced by invisible muons

5. No decay electron observed
(no delayed electron signal)
* Reject events with muons or pions which are invisible or mis-identified as electron (νμ events or CC non-QE events)

T2K MC
\[ \sin^22\theta_{13} = 0.1 \]

- This cut rejects 14% of NC, 30% of νμ CC bkg.
- 98% signal efficiency for this cut

T2K MC
\[ \sin^22\theta_{13} = 0.1 \]

- This cut rejects 85% of νμ CC bkg.
- 90% signal efficiency for this cut
6. Reconstructed invariant mass \((M_{\text{inv}}) < 105 \text{ MeV/c}^2\)

* Suppress NC \(\pi^0\) background

Find 2nd e-like ring by forcing to fit light pattern under the 2 e-like rings assumption, and then reconstruct invariant mass of these 2 e-like rings

Demonstrate to reconstruct invariant mass using atmospheric \(\nu\) data

**T2K MC**
- Osc. \(\nu_e\) CC
- \(\nu_\mu + \nu_\tau\) CC
- \(\nu_e\) CC
- NC

\(\sin^2 2\theta_{13} = 0.1\)

This cut rejects 71% of NC background

91% signal efficiency for this cut
CERN NA61/SHINE measurement

Measure hadron(π, K) yield distribution in 30 GeV p + C inelastic interaction
- thin target 4%λ (2cm)

π+ production: Two analysis for different momentum region

NA61/SHINE setup

Large acceptance spectrometer + TOF

Detector performance

σ(p)/p² \approx 2 \times 10^{-3}, 7 \times 10^{-3}, 3 \times 10^{-2}(\text{GeV}/c)^{-1} \quad \sigma(\text{dE}/\text{dx})/(\text{dE}/\text{dx}) \approx 0.04

for p > 5, p = 2, p = 1 \text{ GeV}/c

σ(\text{TOF-F}) \approx 115 \text{ ps}
Neutrino flux prediction

T2K Neutrino beam simulation based on Hadron production measurements

\[ \frac{\int \tilde{\Phi}^{SK}(E_\mu) \cdot P_{\mu \rightarrow e}(E_\nu) \cdot \sigma(E_\nu) \cdot \epsilon_{SK}(E_\nu) \, dE_\nu}{\int \Phi^{ND}(E_\mu) \cdot \sigma(E_\nu) \cdot \epsilon_{ND}(E_\nu) \, dE_\nu} \]

- **Hadron production in 30GeV proton + C**
  - **Use CERN NA61/SHINE pion measurement**
    -(large acceptance: >95% coverage of \( \nu \) parent pions)
  - Kaon, pion outside NA61 acceptance, other interaction in the target were based on FLUKA simulation
  - Secondary interaction x-sections outside the target were based on experimental data
The T2K experiment – $\theta_{13}$
Results of pion production from thin target (2007 data)

\[ \text{Differential cross section for } \pi^+ \text{ production in 30GeV } p+C \]

Error bars = stat. + syst. in quadrature
no normalization error is shown

Systematic uncertainty was evaluated in each \((p, \theta)\) bin
typically 5-10%

The normalization uncertainty is 2.3% on the overall \((p, \theta)\)

→ Propagate the systematic uncertainty in each \((p, \theta)\) bin into the expected number of events in T2K

→ Input to T2K neutrino beam simulation
Total # of protons used for analysis

Run 1 (Jan. ’10 - June ’10)
- $3.23 \times 10^{19}$ p.o.t. for analysis
- 50kW stable beam operation

Run 2 (Nov. ’10 - Mar. ’11)
- $11.08 \times 10^{19}$ p.o.t. for analysis
- ~145kW beam operation

Total # of protons used for this analysis is $1.43 \times 10^{20}$ pot
2% of T2K’s final goal and ~5 times exposure of the previous report
End of exposure was dramatically decided by external event.
**Predicted neutrino flux (center value)**

- $\Phi_{\nu_\mu}^{\text{SK}}(E_\nu)$
- $\Phi_{\nu_e}^{\text{SK}}(E_\nu)$

$\mu$ decay is dominated at low energy:

- $\pi^+ \rightarrow \mu^+\nu_\mu$
- $\mu^+ \rightarrow e^+\bar{\nu}_\mu\nu_e$

NA61 pion measurement predicts the beam $\nu_e$ from pion origin.
$\nu_\mu$ interaction rates at near detector

- Measure # of inclusive $\nu_\mu$ charged current interaction ($N_{ND}^{\text{Data}}$)

Select events which have FGD hits and $\mu$-like tracks reconstructed in single TPC

High purity: 90% $\nu_\mu$ Charged Current int. (50% CCQE)
The Off-Axis Near Detector

Cannot be Water Cherenkov:
-- pile-up
-- (worse) granularity of small vs large detector

UA1/NOMAD magnet donated by CERN

Fine grain detector of light material (even water!)
-- Scintillators with MPPC readout (60'000 channels!)
-- TPC tracker
FGD: 2 x 1.3 Ton active target
- 1st FGD: plastic only
- 2nd FGD: plastic + water

- Scintillators similar to K2K SciBar
- Light detection by Geiger mode
  Avalanche Photodiodes (MPPC)
- About 9500 channels
TPC’s

3 TPC’s, 1.8 x 2 x 0.70 m³ sensitive area
World’s Largest TPC
with micro-pattern read out (MicroMeGas)

TPC modules built at CERN/UNIGE→
A few ND280 neutrino interaction candidates

- quasi-elastic candidate
- single pion candidate
- DIS candidate
Intrinsic Beam $\nu_e$ background at Far detector

- The number of beam $\nu_e$ background events at far detector is predicted using the $\nu$ beam simulation based on NA61 measurements (pion) and FLUKA (kaon).

- ND measurements ($\mu$ momentum and event rate) are consistent with MC based on the $\nu$ beam simulation.

\[
N_{SK \ beam \ \nu_e \ bkg.}^{exp} = R_{ND}^{\mu, Data} \times \frac{N_{SK \ beam \ \nu_e \ bkg.}^{MC}}{R_{ND}^{\mu, MC}}
\]

\[
\frac{N_{SK \ beam \ \nu_e \ bkg.}^{MC}}{R_{ND}^{\mu, MC}} = \left( \frac{\Phi_{\nu_e}^{SK}(E_{\nu}) \cdot P_{\nu_e \rightarrow \nu_e}(E_{\nu}) \cdot \sigma(E_{\nu}) \cdot \varepsilon_{SK}(E_{\nu})}{\Phi_{\nu_\mu}^{ND}(E_{\nu}) \cdot \sigma(E_{\nu}) \cdot \varepsilon_{ND}(E_{\nu})} \right) dE_{\nu} \cdot \frac{M_{SK}}{M_{ND}^{\mu}} \cdot \text{POT}^{SK}
\]
The expected number of events for $\sin^2 2\theta_{13}=0$

The expected number of events with $1.43 \times 10^{20}$ p.o.t.

$$N_{\text{exp} \text{SK tot.}} = 1.5 \text{ events}$$

<table>
<thead>
<tr>
<th>The expected # of events at SK</th>
<th>Beam $v_e$ background</th>
<th>NC background</th>
<th>Oscillated $v_\mu \rightarrow v_e$ (solar term)</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0.8</td>
<td>0.6</td>
<td>0.1</td>
<td>1.5</td>
</tr>
</tbody>
</table>

# of NC background is calculated by

$$N_{\text{exp} \text{SK NC bkg.}} = R_{\text{ND}}^{\mu, \text{Data}} \times \frac{N_{\text{MC} \text{SK NC bkg.}}^{\mu, \text{MC}}}{R_{\text{ND}}^{\mu, \text{MC}}}$$
Systematic uncertainty on $N_{SK}^{exp}$

<table>
<thead>
<tr>
<th>error source</th>
<th>syst. error</th>
<th>for $\sin^2 2\theta_{13} = 0$</th>
</tr>
</thead>
<tbody>
<tr>
<td>(1) $\nu$ flux</td>
<td>$\pm 8.5%$</td>
<td>$N_{SK}^{exp}=1.5\pm0.3$ events</td>
</tr>
<tr>
<td>(2) $\nu$ int. cross section</td>
<td>$\pm 14.0%$</td>
<td></td>
</tr>
<tr>
<td>(3) Near detector</td>
<td>$+5.6% \quad -5.2%$</td>
<td></td>
</tr>
<tr>
<td>(4) Far detector</td>
<td>$\pm 14.7%$</td>
<td></td>
</tr>
<tr>
<td>(5) Near det. statistics</td>
<td>$\pm 2.7%$</td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>$\pm 22.8% \quad -22.7%$</td>
<td></td>
</tr>
</tbody>
</table>

$$N_{SK}^{exp} = R_{\mu, ND}^{\mu} \times \frac{N_{MC}}{R_{\mu, ND}^{\mu}}$$
Neutrino flux uncertainty

Uncertainties in hadron production and interaction are dominant sources

Error source

- Pion production
  - NA61 systematic uncertainty in each pion’s \((p, \Theta)\) bin

- Kaon production
  - Used model (FLUKA) is compared with the data (Eichten et. al.) in each kaon’s \((p, \Theta)\) bin

- Secondary nucleon production
  - Used model (FLUKA) is compared with the experimental data

- Secondary interaction cross section
  - Used model (FLUKA and GCALOR) is compared with the experimental data of interaction x-section (\(\pi, K\) and nucleon)
Summary of $\nu$ flux uncertainties on $N_{SK}^{exp}$ for $\sin^2 2\theta_{13}=0$

\[
N_{SK}^{exp} = R_{ND}^{\mu, Data} \times \frac{N_{SK}^{MC}}{R_{ND}^{\mu, MC}}
\]

<table>
<thead>
<tr>
<th>Error source</th>
<th>$R_{ND}^{\mu, MC}$</th>
<th>$N_{SK}^{MC}$</th>
<th>$\frac{N_{SK}^{MC}}{R_{ND}^{\mu, MC}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pion production</td>
<td>5.7%</td>
<td>6.2%</td>
<td>2.5%</td>
</tr>
<tr>
<td>Kaon production</td>
<td>10.0%</td>
<td>11.1%</td>
<td>7.6%</td>
</tr>
<tr>
<td>Nucleon production</td>
<td>5.9%</td>
<td>6.6%</td>
<td>1.4%</td>
</tr>
<tr>
<td>Production x-section</td>
<td>7.7%</td>
<td>6.9%</td>
<td>0.7%</td>
</tr>
<tr>
<td>Proton beam position/profile</td>
<td>2.2%</td>
<td>0.0%</td>
<td>2.2%</td>
</tr>
<tr>
<td>Beam direction measurement</td>
<td>2.7%</td>
<td>2.0%</td>
<td>0.7%</td>
</tr>
<tr>
<td>Target alignment</td>
<td>0.3%</td>
<td>0.0%</td>
<td>0.2%</td>
</tr>
<tr>
<td>Horn alignment</td>
<td>0.6%</td>
<td>0.5%</td>
<td>0.1%</td>
</tr>
<tr>
<td>Horn abs. current</td>
<td>0.5%</td>
<td>0.7%</td>
<td>0.3%</td>
</tr>
<tr>
<td>Total</td>
<td>15.4%</td>
<td>16.1%</td>
<td>8.5%</td>
</tr>
</tbody>
</table>

The uncertainty on $N_{SK}^{exp}$ due to the beam flux uncertainty is 8.5%

Error cancellation works for some beam uncertainties (factor 2)
\( \nu \) int. cross section uncertainty

Evaluate uncertainty on F/N ratio by varying the cross section within its uncertainty.

**Main \( \nu \) interaction in each event category**
- NC background: NC1\( \pi^0 \)
- Beam \( \nu_e \) background: \( \nu_e \) CCQE
- Signal: \( \nu_e \) CCQE
- ND CC event: CCQE(50%)
  - CC1\( \pi \)(23%)

**Cross section uncertainty relative to the CCQE total x-section**

<table>
<thead>
<tr>
<th>Process</th>
<th>Cross section uncertainty</th>
</tr>
</thead>
<tbody>
<tr>
<td>CCQE</td>
<td>energy dependent (( \sim \pm 7% ) at 500 MeV)</td>
</tr>
<tr>
<td>CC 1( \pi )</td>
<td>30% (( E_\nu &lt; 2 \text{ GeV} )) – 20% (( E_\nu &gt; 2 \text{ GeV} ))</td>
</tr>
<tr>
<td>CC coherent ( \pi^0 )</td>
<td>100% (upper limit from [30])</td>
</tr>
<tr>
<td>CC other</td>
<td>30% (( E_\nu &lt; 2 \text{ GeV} )) – 25% (( E_\nu &gt; 2 \text{ GeV} ))</td>
</tr>
<tr>
<td>NC 1( \pi^0 )</td>
<td>30% (( E_\nu &lt; 1 \text{ GeV} )) – 20% (( E_\nu &gt; 1 \text{ GeV} ))</td>
</tr>
<tr>
<td>NC coherent ( \pi )</td>
<td>30%</td>
</tr>
<tr>
<td>NC other ( \pi )</td>
<td>30%</td>
</tr>
<tr>
<td>Final State Int.</td>
<td>energy dependent (( \sim \pm 10% ) at 500 MeV)</td>
</tr>
</tbody>
</table>

Uncertainty of \( \sigma(\nu_e)/\sigma(\nu_\mu) = \pm 6\% \)

**Cross section uncertainties are estimated by Data/MC comparison, model comparison and parameter variation**
**V int. cross section uncertainty on $N^{exp}_{SK}$ for $\sin^2 2\theta_{13}=0$**

<table>
<thead>
<tr>
<th>Error source</th>
<th>syst. error on $N^{exp}_{SK}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>CC QE shape</td>
<td>3.1%</td>
</tr>
<tr>
<td>CC 1\pi</td>
<td>2.2%</td>
</tr>
<tr>
<td>CC Coherent\pi</td>
<td>3.1%</td>
</tr>
<tr>
<td>CC Other</td>
<td>4.4%</td>
</tr>
<tr>
<td>NC 1\pi^0</td>
<td>5.3%</td>
</tr>
<tr>
<td>NC Coherent\pi</td>
<td>2.3%</td>
</tr>
<tr>
<td>NC Other</td>
<td>2.3%</td>
</tr>
<tr>
<td>$\sigma(\nu_e)$</td>
<td>3.4%</td>
</tr>
<tr>
<td>FSI</td>
<td>10.1%</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>14.0%</strong></td>
</tr>
</tbody>
</table>

The uncertainty on $N^{exp}_{SK}$ due to the $\nu$ x-section uncertainty is **14%** ($\sin^2 2\theta_{13}=0$)

Uncertainty in pion’s final state interaction is dominant
Far detector uncertainty

- Uncertainty due to the SK detector uncertainty
- Evaluation using control sample

$$\int \Phi_{\nu \mu}^\text{SK}(E_{\nu}) \cdot P_{\text{osc}}(E_{\nu}) \cdot \sigma(E_{\nu}) \cdot \epsilon_{\text{SK}}(E_{\nu}) \, dE_{\nu}$$

$$\int \Phi_{\nu \mu}^\text{ND}(E_{\nu}) \cdot \sigma(E_{\nu}) \cdot \epsilon_{\text{ND}}(E_{\nu}) \, dE_{\nu}$$

One of big error sources:

**Detection efficiency of NC 1π⁰ background**

*control sample with one data electron + one simulated γ*

Apply T2K $\nu_e$ selection and compare the cut efficiency between control sample data and its MC.

→ difference is assigned as sys. error
## Summary of Far detector systematic uncertainty

<table>
<thead>
<tr>
<th>Error source</th>
<th>$\frac{\delta N_{MC}^{SK , \nu_e , sig.}}{N_{MC}^{SK , \nu_e , sig.}}$</th>
<th>$\frac{\delta N_{MC}^{SK , bkg. , tot.}}{N_{MC}^{SK , bkg. , tot.}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\pi^0$ rejection</td>
<td>3.9%</td>
<td>8.3%</td>
</tr>
<tr>
<td>Ring counting</td>
<td>3.8%</td>
<td>8.0%</td>
</tr>
<tr>
<td>Electron PID</td>
<td>5.1%</td>
<td>8.7%</td>
</tr>
<tr>
<td>Invariant mass cut</td>
<td>1.4%</td>
<td>1.4%</td>
</tr>
<tr>
<td>Fiducial volume cut etc.</td>
<td>0.4%</td>
<td>1.1%</td>
</tr>
<tr>
<td>Energy scale</td>
<td>0.1%</td>
<td>0.3%</td>
</tr>
<tr>
<td>Muon PID</td>
<td>-</td>
<td>1.0%</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>7.6%</strong></td>
<td><strong>15%</strong></td>
</tr>
</tbody>
</table>

\[ \rightarrow \text{The total uncertainty on } N_{MC}^{SK \, \text{tot.} } \text{ is 14.7 } \% \ (\sin^2 2\theta_{13}=0) \]

(uncertainty on the background + solar term oscillated $\nu_e$)
Total Systematic uncertainties

Summary of systematic uncertainties on $N_{expSK\,tot.}$ for $\sin^22\theta_{13}=0$ and 0.1

<table>
<thead>
<tr>
<th>Error source</th>
<th>$\sin^22\theta_{13}=0$</th>
<th>$\sin^22\theta_{13}=0.1$</th>
<th>cf.</th>
</tr>
</thead>
<tbody>
<tr>
<td>(1) Beam flux</td>
<td>±8.5%</td>
<td>±8.5%</td>
<td></td>
</tr>
<tr>
<td>(2) $\nu$ int. cross section</td>
<td>±14.0%</td>
<td>±10.5%</td>
<td></td>
</tr>
<tr>
<td>(3) Near detector</td>
<td>+5.6%, -5.2%</td>
<td>+5.6%, -5.2%</td>
<td></td>
</tr>
<tr>
<td>(4) Far detector</td>
<td>±14.7%</td>
<td>±9.4%</td>
<td></td>
</tr>
<tr>
<td>(5) Near det. statistics</td>
<td>±2.7%</td>
<td>±2.7%</td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>+22.8%, -22.7%</td>
<td>+17.6%, -17.5%</td>
<td></td>
</tr>
</tbody>
</table>

(cf. $\sin^2\theta_{13}=0$: 
#sig = 0.1 #bkg = 1.4
$\sin^2\theta_{13}=0.1$: 
#sig = 4.1 #bkg = 1.3

(due to small Far det. uncertainty for signal)

$N_{expSK\,tot.} = 1.5 \pm 0.3$ at $\sin^22\theta_{13}=0$
SK events in beam timing

- Events in the T2K beam timing synchronized by GPS

\[ \Delta T_0 = T_{GPS@SK} - T_{GPS@J-PARC} - TOF(\sim 985 \mu \text{sec}) \]
Number of T2K events at far detector

Number of events in on-timing windows (-2 ~ +10 μsec)

<table>
<thead>
<tr>
<th>Class / Beam run</th>
<th>RUN-1</th>
<th>RUN-2</th>
<th>Total</th>
<th>non-beam background</th>
</tr>
</thead>
<tbody>
<tr>
<td>POT (x $10^{19}$)</td>
<td>3.23</td>
<td>11.08</td>
<td>14.31</td>
<td></td>
</tr>
<tr>
<td>Fully-Contained (FC)</td>
<td>33</td>
<td>88</td>
<td>121</td>
<td>0.023</td>
</tr>
</tbody>
</table>

The accidental contamination from atmospheric $\nu$ background is estimated using the sideband events to be 0.023
Apply $\nu_e$ event selection

defined before the data collection
6 selection cuts in addition FC cut

Fiducial volume cut
(distance between recon. vertex and wall > 200cm)
Single electron cut (# of ring is one & e-like)

(MC w/ \( \sin^2 2\theta_{13} = 0.1 \))
Visible energy > 100 MeV

No decay electron
Invariant mass cut ($M_{\text{inv}} < 105$ MeV/c$^2$)

(MC w/ $\sin^2 2\theta_{13} = 0.1$)
Reconstructed $\nu$ energy cut ($E_{\text{rec}} < 1250 \text{ MeV}$): *Final cut*

- $N_{\text{exp}} = 1.5 \pm 0.3$ for $\sin^2 2\theta_{13} = 0$

- 6 candidates after all cuts!
\( v_e \) candidate event

**Super-Kamiokande IV**
- T2K Beam Run 0 Spill 103/022
- Run 67968 Sub 221 Event 218331034
- 10-12/22: 14:15:38
- T2K beam ct # 2782.6 ns
- Inner: 4964 hits, 2570 pe
- Outer: 4 hits, 3 pe
- Trigger: 0x00000007
- E=MeV: 144.2 em
- e-like, p = 1049.0 MeV/c

**Charge (pe)**
- >26.7
- 23.3-25.7
- 20.2-23.3
- 17.3-19.2
- 14.7-17.3
- 12.3-14.7
- 9.5-12.3
- 6.0-9.0
- 4.7-6.2
- 3.3-4.7
- 2.2-3.3
- 1.3-2.2
- 0.7-1.3
- 0.2-0.7
- < 0.2

**Visible energy**: 1049 MeV
**# of decay e**: 0
**2\gamma Inv. mass**: 0.04 MeV/c^2
**Recon. energy**: 1120.9 MeV

**Times (ns)**
- 0 mu e decay
Look at the events properties
Vertex distribution of $\nu_e$ candidate events

Events tend to cluster at large $R$
→ Perform several checks: for example
* Check distribution of events outside FV → no indication of BG contamination
* Check distribution of OD events → no indication of BG contamination
* K.S. test on the $R^2$ distribution yields a p-value of 0.03

hmmmmm....?
Result of the $\nu_e$ appearance search with $1.43 \times 10^{20}$ p.o.t.

The observed number of events is 6

The expected number of events is $1.5 \pm 0.3$ if $\theta_{13} = 0$

the probability to observe six or more candidate events is 0.007 (equivalent to 2.5σ significance)

We will be eagerly waiting for more data to obtain a larger significance!
Indication of Electron Neutrino Appearance from an Accelerator-produced Off-axis Muon Neutrino Beam

T2K Collaboration: K.Abe (49), N.Abgrall (16), Y.Ajima (18), H.Aihara (48), J.B.Albert (13), C.Andreopoulos (47), B.Andrieu (37), M.D.Anerella (6), S.Aoki (27), O.Araoka (18), J.Argyriades (16), A.Ariga (3), T.Ariga (3), S.Assylbekov (11), D.Autiero (32), A.Badertscher (15), M.Barbi (40), G.J.Barker (56), G.Barr (36), M.Bass (11), F.Bay (3), S.Bentham (29), V.Berardi (22), B.E.Berger (11), I.Bertram (29), M.Besnier (14), J.Beucher (8), D.Beznosko (34), S.Bhadra (59), F.d.M.Blaszczyk (8), A.Blondel (16), C.Bojechko (53), J.Bouchez (8, deceased), S.B.Boyd (56), A.Bravar (16), C.Bronner (14), D.G.Brook-Roberge (5), N.Buchanan (11), H.Budd (41), D.Calvet (8), S.L.Cartwright (44), A.Carver (56), R.Castillo (19), M.G.Calaresi (22), A.Cazes (32), A.Cervera (20), C.Chavez (30), S.Choi (43), G.Christodoulou (30), et al. (364 additional authors not shown)

(Submitted on 14 Jun 2011)

The T2K experiment observes indications of $\nu_e \rightarrow \mu$ appearance in data accumulated with $1.43 \times 10^{20}$ protons on target. Six events pass all selection criteria at the far detector. In a three-flavor neutrino oscillation scenario with $|\Delta m_{23}|^2 = 2.4 \times 10^{-3}$ eV$^2$, $\sin^2 2\theta_{13} = 0$ and $\sin^2 2\theta_{13} = 0$, the expected number of such events is $1.5 \pm 0.3$ (syst.). Under this hypothesis, the probability to observe six or more candidate events is $7 \times 10^{-3}$, equivalent to $2.5\sigma$ significance. At 90% C.L., the data are consistent with $0.03(0.04) < \sin^2 2\theta_{13} < 0.28(0.34)$ for $\Delta m_{\nu m}$ CP = 0 and normal (inverted) hierarchy.
Allowed region of $\sin^2 2\theta_{13}$ as a function of $\delta_{CP}$

(assuming $\Delta m_{23}^2=2.4 \times 10^{-3}$ eV$^2$, $\sin^2 2\theta_{23}=1$)

$90\%$ C.L. interval & Best fit point (assuming $\Delta m_{23}^2=2.4 \times 10^{-3}$ eV$^2$, $\sin^2 2\theta_{23}=1$, $\delta_{CP}=0$)

$0.03 < \sin^2 2\theta_{13} < 0.28$

$\sin^2 2\theta_{13} = 0.11$

$0.04 < \sin^2 2\theta_{13} < 0.34$

$\sin^2 2\theta_{13} = 0.14$
$\theta_{13}$

$\Delta m_{23}^2 > 0$

90% C.L.

Final remarks

1. the T2K experiment is working very well!

2. Although the significance is only 2.5 sigma the analysis procedure is such (cuts fixed in advance, sample defined by external events) that a statistical "fabrication" can be completely excluded.

3. T2K is now under reconstruction:
   beam expected to resume (if no bad surprise) in November 2011

4. if it is confirmed that $\theta_{13}$ is "large" this will have consequences on the design of the next generation of experiments (good for NOvA in first instance)

5. this summer will be very exciting on the neutrino front:
   new results from (at least) MINOS, OPERA, DCHOOZ are expected

COME TO NUFACT11 at CERN/GENEVA 1-6 August 2011!
http://nufact11.unige.ch
A few reserve slides
Event display
single-ring $\mu$-like events

$P_\mu = 1061$ MeV/c
1 decay-e

$P_\mu = 1025$ MeV/c
1 decay-e
Event display
multi-ring \( \mu \)-like event

**Super-Kamiokande IV**

T2K Beam Run 0 Spill 1679196
Run 66932 Sub 205 Event 46733749
10:06:10.17.46.11
T2K beam dc = 2495.3 ns
Inner: 6036 hits, 21915 pe
Outer: 1 hits, 1 pe
Trigger: 0006000007
E_wall: 990.8 cm

**Charge (pe)**
- \( >20.7 \)
- 23.3-20.7
- 20.2-23.3
- 21.7-23.2
- 24.7-17.3
- 25.2-14.7
- 28.0-12.8
- 5.6-10.8
- 6.2- 9.0
- 6.7- 6.2
- 3.3- 4.7
- 2.2- 3.3
- 1.3- 2.2
- 0.7- 1.3
- 0.2- 0.7
- \( < 0.2 \)

**\( P_\mu = 1438 \text{ MeV/c} \)**

2 decay-es

**Times (ns)**
Vertex and direction
(FC, Evis>30MeV)

**Points**: Reconstructed event vertex
**Arrow**: 1st-ring direction

---

**Vertex X vs Y**

- X-axis: Vertex X (cm)
- Y-axis: Vertex Y (cm)
- Points: Reconstructed event vertex
- Arrow: 1st-ring direction
- Beam direction
- FV
- ID wall

**Vertex R vs Z**

- R-axis: Vertex R (cm)
- Z-axis: Vertex Z (cm)
- Points: Reconstructed event vertex
- Arrow: 1st-ring direction
- Beam direction
- FV
- ID wall
Super KamiokaNDE
Energy scale stability

Energy scale has been quite stable.
Power upgrade plan of RCS and MR(FX)

For 8 bunches, 30 GeV at MR: \( P_{MR} = 1.6 \times \left( \frac{P_{RCS}}{T_{MR}} \right) \)

- 6 sec (27%)
- 3.52 sec (45%)
- 2.47 sec (66%)
- 2.23 sec (72%)

RCS POWER FOR MR

- MR POWER

RCS POWER FOR MLF (@25 Hz)


3-50BT collimator shields, RF (1st HH), FX kickers

Ring collimator shields, RF (6th F, 2nd HH), Inj. Sep 1

ACS Installation in JFY2012
400 MeV injection in the RCS

RF (3rd HH), Inj. Sep 2, FX Septa

750 kW in 2014