PREDICTING THE NEUTRINO FLUX WITH HADRO-PRODUCTION MEASUREMENTS
T2K (Tokai to Kamioka)

Physics goals

- Discovery of $\nu_{\mu} \rightarrow \nu_e$ appearance $\Rightarrow \sin^2 2\theta_{13}$
- Precise meas. of disappearance $\nu_{\mu} \rightarrow \nu_x$ $\Rightarrow \sin^2 2\theta_{23}$ and $\Delta m^2_{23}$
- Neutral current events
- Discovery of CP violation (Phase2)

Super-K: 50 kton Water Cherenkov

$\sim 1$GeV $\nu_{\mu}$ beam ($\times 100$ of K2K)

J-PARC

0.75MW 50GeV PS

Phase2: Hyper-K

295km

Kamioka

Tokai

Phase2: 4 MW

12 countries

~60 institutions

~180 collaborators
Off-Axis-Beam for T2K

More flux and less background
Very narrow energy spectrum with small high energy tail (almost mono-energetic beam)
Energy “tuned” to oscillation maximum Reduces the backgrounds in the electron neutrino measurement

1. neutrino energy $E_\nu$ almost independent of parent pion energy
2. horn focusing cancels partially the $p_T$ dependence of the parent pion

In reality things are more complicated and the predicted n spectrum depends on the hadro-production data / models used
**νμ → νχ disappearance**

Basic analysis strategy

Measure νμ flux and energy spectrum with near detectors

Make a νμ flux prediction at the far detector by extrapolating the near detector measurements to the far detector using a (energy-dependent) far-to-near ratio prediction from the beam MC assuming no oscillations

Compare the measured νμ flux (rate and energy spectrum) at the far detector with the no-oscillation predictions

5 years running

<table>
<thead>
<tr>
<th>No oscillation</th>
<th>Δm² = 2.5 x 10⁻³ eV²</th>
<th>Δm² = 2.0 x 10⁻³ eV²</th>
</tr>
</thead>
<tbody>
<tr>
<td>events/SD MeV/2/5kt/5yr</td>
<td></td>
<td></td>
</tr>
<tr>
<td>non-QE</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Goal

δ(sin²2θ₂₃) ~ 0.01
δ(Δm²) ~ <3 x 10⁻⁵
**T2K ν beam**

1. predict $\nu_\mu$ flux at far detector
2. estimate $\nu_e$ background

\[ \Phi_{SK}^{exp} = R_{F/N} \cdot \Phi_{ND}^{obs} \]

Near and far detectors see different solid angles:

1. far detector: point-like source at 2.5°
2. near detector: extended source 1° to 3° (wide off axis angular range)

$\Rightarrow$ complicated far to near flux ratio

to predict the $\nu$ flux ratio correctly need to know the details of the $\nu$ parent hadro-production kinematics

instead of hadronization models (Fluka et al.)
use measured pion and kaon x-sections

**note:** no measurements at these beam energies (30 – 50 GeV) and phase space (very large angles)
Spectrum at far site is different from near site even w/o oscillation
- Effect of non-point-like source

T2K analysis

Expected flux at SK
\[ \Phi_{SK}^{exp} = R_{F/N} \cdot \Phi_{ND}^{obs} \]

Far/Near ratio
\[ R_{F/N} = \frac{\Phi_{SK}}{\Phi_{ND}} \]

Determined by Hadron prod. (&geometry)

no measurement of particle production off carbon with 30 (,40,50) GeV protons \(\rightarrow\) NA61
Far / Near Flux ratio

near/far ratio for disappearance $\nu_\mu$ is *not* flat

near/far ratio for backgrounds is quite flat (here $\nu_e$)
Beam studies issues

impact of NA61 measurement

far to near flux ratio

- Effects of
  - $K^+/\pi^+$, $K^0/\pi^+$ ratio
  - angular distribution ($p_T$)
  - longitudinal distribution
  - target and horns misalignment

- $\nu + N$ n.c. $\pi^0$ prod.
  near / far ratio for $\nu_\mu$, $\nu_e$, $\pi^0$

- statistics required
  T2K not statistics limited ($\nu_\mu$ disappearence)
  200k $\pi$ events -> $\sim$ 2-3 % error on the flux ratio

studies based on current beam MonteCarlo
no ND included (yet)
note: this is not a cross section
it shows the distributions of π and K giving the ν of the T2K beam

need to cover this kinematical region and identify the outgoing hadrons
K component important for ν<sub>e</sub> appearance signal (it represents a background)
need to measure K production with similar precision as π production

requires: large acceptance and particle ID
Statistics / precision required

a 2 – 3 % error on the far/near flux ratio is required for $\nu_\mu$ and $\nu_e$

$\sim 200k \, \pi^+ \text{ tracks are needed (crude estimate)}$

$\sim 200k \, K^+ \text{ tracks are needed (crude estimate)}$

in phase space of T2K beam

with a simple interaction trigger (no charge / flavor selection)

for $10^6$ interactions will also have (NB $\sim 10\%$ acceptance !)

$\sim 100k \, \pi^- \text{ tracks}$

$\sim 10k \, K^+ \text{ tracks}$
Why?

- measure $\pi^{+/\ -}$, $K^{+/\ -}$, $K^0$ production in phase-space of T2K $\nu$ beam
- no data at these energies 30 – 50 GeV, in particular for large production angles ($\theta > 100$ mrad)
  extrapolations possible but not too reliable
- reinteractions / absorption of few GeV pions poorly described
  (up to factors of $\sim 2$)
- Large uncertainties on K production
- prefer to base $\nu$ beam description on actual measurements rather than more or less reliable hadron interaction models
Systematic uncertainties due to “models”

It is difficult to evaluate the validity of the hadron production model!!

→ The uncertainty is probably not less than the difference among several models inspired by similar data sets.

**G-FLUKA vs. MARS vs. FLUKA**

**Ratios of F/N ratios**

up to ~20% difference!

F/N ratio difference among hadron production models:

~ 20% @ $E_{\nu} \leq 1$ GeV

Syst. error due to F/N

- $\nu_e$ appearance
  - $\delta(N_{tb}) \sim 15\%$
- $\nu_\mu$ disappearance
  - $\delta(\sin^2 2\theta_{23}) \sim \pm 0.015 - 0.03$
  - $\delta(\Delta m_{23}^2) \sim \pm 5 \cdot 10^{-5}$ eV$^2$

Impossible to achieve T2K GOAL!

Goal of T2K

- $\nu_e$ appearance
  - $\delta(N_{tb}) \leq 10\%$
- $\nu_\mu$ disappearance
  - $\delta(\sin^2 2\theta_{23}) \sim \pm 0.01$
  - $\delta(\Delta m_{23}^2) \sim \pm 3 \cdot 10^{-5}$ eV$^2$
Improvement that the NA49 data could bring to the T2K results on atmospheric oscillation parameters:

\[ 90\% \text{CL} \iff \Delta \chi^2 = 4.7 \]
HARP Result (p-Al at 12.9 GeV)

- doubly differential cross-section
- results based on ~200 k reconstructed tracks
- comparison to previous data: large normalization uncertainty
- HARP Sanford-Wang parametrization
- HARP data points
K2K F/N flux ratio prediction

K2K / HARP final result

three different predictions, within errors, are consistent with each other

HARP: almost factor of 2 error reduction for all energies compared to previous assumptions
Systematic error on n flux from ~7% down to ~4%

<1 GeV: Cho/CERN errors
>1 GeV: PIMON errors

All energies: HARP (plus others) errors
NA61 setup

Detector as used by NA49 collaboration: some upgrades required for NA61 physics (incl. T2K)
Typical Proton Event

Heavy Ion Event
**NA49 Cross Sections (158 GeV p beam)**

**total cross sections**
(with simple interaction trigger)

\[
\begin{array}{|c|c|}
\hline
\sigma_{\text{trig}} & 28.23 \text{ mb} \\
\text{loss from } p & 3.98 \text{ mb} \\
\text{loss from } \pi, K & 0.33 \text{ mb} \\
\text{contribution from } \sigma_{\text{el}} & -1.08 \text{ mb} \\
\text{predicted } \sigma_{\text{inel}} & 31.46 \text{ mb} \\
\text{literature value} & 31.78 \text{ mb} \\
\hline
\end{array}
\]

\( p - p \) collisions
hep-ex/0510009

\[
\begin{array}{|c|c|}
\hline
\sigma_{\text{trig}} & 210.1 \text{ mb} \\
\text{loss from } p & 17.1 \text{ mb} \\
\text{loss from } \pi \text{ and } K & 2.4 \text{ mb} \\
\text{contribution from } \sigma_{\text{el}} & -3.3 \text{ mb} \\
\text{predicted } \sigma_{\text{inel}} & 226.3 \text{ mb} \\
\text{literature value} & 225.8 \text{ mb} \\
\hline
\end{array}
\]

\( p - C \) collisions
hep-ex/0606028

**\( \pi^+ \) statistical errors**

**\( 400 \text{ mrad} \)**

**\( 200 \text{ mrad} \)**

\( @ 30 \text{ GeV} \)

**\( \pi^+ \) production**

**total statistics (p – C)**

<table>
<thead>
<tr>
<th>Events taken</th>
<th>Events after selection</th>
</tr>
</thead>
<tbody>
<tr>
<td>Full target</td>
<td>Empty target</td>
</tr>
<tr>
<td>Full target</td>
<td>Empty target</td>
</tr>
<tr>
<td>535.7 k</td>
<td>31.2 k</td>
</tr>
<tr>
<td>377.6 k</td>
<td>11.8 k</td>
</tr>
</tbody>
</table>
π production
Cross Sections
\( (P_{\text{beam}} = 158 \text{ GeV}) \)

total systematical error
(\( \pi^+ \) and \( \pi^- \) production)

<table>
<thead>
<tr>
<th>Source</th>
<th>Error (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Normalization</td>
<td>2.5%</td>
</tr>
<tr>
<td>Tracking efficiency</td>
<td>0.5%</td>
</tr>
<tr>
<td>Trigger bias</td>
<td>1%</td>
</tr>
<tr>
<td>Feed-down (from decays)</td>
<td>1-2.5%</td>
</tr>
<tr>
<td>Detector absorption</td>
<td></td>
</tr>
<tr>
<td>Pion decay ( \pi \rightarrow \mu + \nu_\mu )</td>
<td>0.5%</td>
</tr>
<tr>
<td>Re-interaction in the target</td>
<td></td>
</tr>
<tr>
<td>Binning</td>
<td>0.5%</td>
</tr>
<tr>
<td>Total (upper limit)</td>
<td>7.5%</td>
</tr>
<tr>
<td>Total (quadratic sum)</td>
<td>3.8%</td>
</tr>
</tbody>
</table>

statistical error ~ few %

~ 400 k reconstructed tracks
Kaon production

~ 5 to 10 x smaller $\sigma$ compared to $\pi$

systematical error:

~ 5% 
(~10 % acc. edges)
Some data on K production

from NA49 publication
nucl-ex/0205002
Heavy Ion data and
pp data (for comparison)

pp data compiled by
M. Gazdzicki
hep-ex/9607004

from this plot
$\langle K^+ \rangle / \langle \pi^+ \rangle \sim 0.06 - 0.08$
at 30 GeV

clearly the situation is not satisfactory at all
The 2007 NA61 run

first NA61 run in October 2007 (~30 days)

~ 2 weeks for set up
~ 2 weeks of data taking
  12 days using a thin C target (4% $\lambda_I$)
  3 days with the T2K replica target

data collected:

- 660 k triggers with thin target
- 220 k triggers with replica target
- 100 k calibration events
Typical proton event

incoming beam definition

large angle track bended back into NA61 acceptance

vertex resolution $\sigma_z \sim 5 \text{ mm}$
momentum resolution $\Delta p/p^2 \sim 10^{-4}$

majority of “T2K” particles in this region!
ToF Acceptance

extended acceptance with new ToF wall
Why the acceptance is so small in the phase space of the T2K beam? (i.e. around 10 - 15%)

horizontal acceptance: ~ 250 mrad
not an issue

vertical acceptance: ~ 45 mrad!
limited by vertical size of TPCs and ToF

large angle tracks produced close to the horizontal plane and bend back by $\mathbf{B}$
will be detected:
e.g. for $\theta > 150$ mrad, $\Delta \phi \sim 30^0 \rightarrow 1/12$ acc.
ToF Performance (online)

\[ \sigma \approx 6 \]

150 ps

time resolution before calibration

\[ \chi^2/ndf \ 9.418 / 13 \]
Constant 79.57
Mean 1126
Sigma 5.890

Correlation
ToF – TPC tracks

hit distribution / scintillator

~2.5% hit/sc
1.6 hit/event
before oscillation
νμ disappearance after oscillation

ντ
νe

νμ disappearance
The Beam

400 GeV protons

SPS

400 GeV protons

primary production target

30 GeV π and p primary production target

PID beam particles CEDAR + Cerenkov

NA61 target

(S1·S2·V0bar·C)/(S1·S2·V0bar)

Pressure (bar)

16.2% of protons

1.65 bar

99.977

83.753

1.0

110

120

0.0

0.5

1.0

1.5

2.0

2.5

3.0

3.5

Pressure (bar)
The T2K Target

- Material: Isotropic graphite (C): $\rho = 1.82 \text{g/cm}^3$
- Length: 900mm = $1.9 \times \lambda_{\text{int}}$ (85%)
- Diameter: $\phi 26\text{mm}$
  $\leftrightarrow$ Beam size: $\sigma_x = \sigma_y = 4.2\text{mm}$
- Target is installed inside the Electromagnetic horn
  - EM horn generate the toroidal magnetic field to correct pions.
  - Materials between target and the magnetic field:
    - Cooling tube: $t = 2\text{mm}$ graphite (C) + 0.3mm Ti-Alloy + 0.5mm ceramic

Pulse current (320kA, $\sim 0.5\text{ms}$)

Proton beam
T2K Target replica

90 cm graphite 26 mm dia.

not easy installation and alignment
2008 run: important to improve on the alignment of the target!
Trigger setup

Trigger definition: S1 & S2 & V0 & V1 & S4

Beam definition: S1 & S2 & V0 & V1

Distances are not exact and do not include survey measurements taken at the end of the run. For more detailed information on beam and trigger see A.Marchionni’s talk.
Trigger counters installations

... and S4 between Vertex1 and Vertex2 magnets
Beam Profiles – Thin Target

Mean histograms

Thin target trigger target ‘in’ profiles

Beam spot at the Z position of the target

failed fits
Beam Profiles – Thick target

Trigger: \( B = S_1 \cdot S_2 \cdot C_1 \cdot \overline{C}_2 \), \( S_2 \) 28 mm diameter

new BPDs for 2008 with larger active area 48 x 48 mm\(^2\)
NA61 - p+C @ 30 GeV Data

- Target density: 1.8395 g/cm³.
- Target thickness 2.0 cm ⇒ effective thickness 1.948 cm.
- "20GeV" magnetic field (B_m=1.14 Tm).
- Note that only limited statistics has been used so far and results are preliminary.

<table>
<thead>
<tr>
<th>Target</th>
<th>Interaction rate (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>out</td>
<td>1.737 ± 0.021</td>
</tr>
<tr>
<td>in</td>
<td>7.077 ± 0.053</td>
</tr>
</tbody>
</table>

Fake trigger = 25%
Interaction probability = 5.34% ± 0.06%
NA61 - p+C @ 30 GeV Data (2)

- Using the described procedure from the interaction probability we calculate the trigger cross section:

\[ P_{\text{int}} : 5.34\% \pm 0.06\% \Rightarrow \sigma_{\text{trigger}} : 289.5 \pm 3.3 \text{ mb} \]

- We can therefore calculate the effective thickness of the target and correct the value of the trigger cross section:

\[ L = 2 \text{ cm}, \ L_{\text{eff}} = 1.948 \text{ cm} \Rightarrow \sigma_{\text{trigger}} : 297.2 \pm 3.4 \text{ mb} \]

- Using the values of \( \sigma_{\text{loss-p/π/K}} \) and \( \sigma_{\text{elastic contribution}} \), obtained from GEANT4 simulation, we can estimate the value of the interaction cross section:

<table>
<thead>
<tr>
<th>( \sigma ) contribution</th>
<th>value</th>
<th>comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \sigma_{\text{trigger}} )</td>
<td>297.2 \pm 3.4 mb</td>
<td></td>
</tr>
<tr>
<td>( \sigma_{\text{loss-p}} )</td>
<td>16.0 \pm 0.3 mb</td>
<td>GEANT4 correction</td>
</tr>
<tr>
<td>( \sigma_{\text{loss-π/K}} )</td>
<td>0.45 \pm 0.05 mb</td>
<td>GEANT4 correction</td>
</tr>
<tr>
<td>( \sigma_{\text{elastic contribution}} )</td>
<td>- 48.1 \pm 0.6 mb</td>
<td>GEANT4 correction</td>
</tr>
<tr>
<td>( \sigma_{\text{interaction}} )</td>
<td>265.25 \pm 3.5 mb</td>
<td>Expected: 247 mb</td>
</tr>
</tbody>
</table>
Online Display

1 track in GAP-TPC

1 track in MTPC-L
**Analysis Plan / Progress**

**STEP 1:** detector geometry and alignment, TPC drift velocity, space points, residual distortion corrections, database, …

(event reconstruction) (by end of Feb.)

**STEP 2:** B calibration, ToF calibration, dE/dx calibration, …

dst and mini-dst for physics analysis (by end of May)

**STEP 3:** physics analysis
cross section normalization, acceptance and eff. corrections, particle identification, …

(first results) (summer 2008)
Beam Momentum

- beam steered into the TPC (max B)
- $\Delta p / p \sim 1\%$ (p spread and TPC resolution)
momentum vs angle distribution

\[ p + C \rightarrow h + X \] - NA61 data

NO CORRECTIONS applied!
and not weighted for acceptance!
(raw distributions)

we have tracks over the whole T2K phase space
Secondary Interactions

- Effect of secondary Interaction vs. $L_{\text{target}}$
  - Is primary interaction dominant?
    - Fraction of pions from the proton to all the secondary pions.
  - Absorption
    - Fraction of pions which stops inside the target.
  - Multiple-scattering inside the target.
    - Compare $(p, \theta)$ for pions between the generation point and the target surface.

- Beam simulation (jnubeam) for several target configurations.
  - 2cm, 5cm, 10cm, 20cm, 45cm, 90cm.

Target material:
- $\rho = 1.82 \, \text{g/cm}^3$
- $\lambda_{\text{int}} = 47.4\, \text{cm}$
- $X_0 = 23.5\, \text{cm}$
- $(dE/dx)_{\text{min}} = 3.2\, \text{MeV/cm}$
Secondary Interactions in the 90 cm Target

- Origin of pions:
  - All $\pi$: 68% proton $\Leftrightarrow$ 32% non-proton
  - $\pi$ in T2K acceptance: 75% proton $\Leftrightarrow$ 25% non-proton

- Pion absorption for ($P_\pi > 0.5$ GeV)
  - 80% going out $\Leftrightarrow$ 20% stopped inside target

- Effect of secondary interaction: 20~30% level

Production point of $\pi$

- All $\pi$: $L_{tgt} = 90$ cm
  - 68% proton origin $\pi$
  - 32% non-proton origin $\pi$

- $\pi$ in T2K acceptance: $L_{tgt} = 90$ cm
  - 75% proton origin $\pi$
  - 25% non-proton origin $\pi$

- Stopped: 20%
  - Going out: 80%

Target length 90.0 cm
Secondary Interaction vs. Target Length

**1cm target:**
- Effect is less than a few%.

**10cm target:**
- Size of effect is ~1/2 compared to 90cm target
  - Suitable for Intermediate target.
strategy A:
- measure $d^2\sigma/dp\Omega$ for $p + C \rightarrow \pi/K + X$ with a thin C target
- use the measured x-section as input to the beam MC
  (secondary interactions, absorption, etc. described by e.g. FLUKA)
- compare the MC predictions to the $\pi/K$ yields measured off C targets
  of different lengths (including the T2K replica target) and adjust the
  MC accordingly

strategy B:
- measure $\pi/K$ yields off the T2K replica target
- use the measured $\pi/K$ yields as input to the beam MC
  (no simulation of secondary interactions required)

the difference in the predicted flux at SK with different models
would be an indication of the reliability of the procedure
Summary

$\pi^+ / K^+ / K^0$ measurements essential to achieve T2K physics goals
beam related sys. errors should be smaller than statistical ones
⇒ $R_{\mu,e} < 2 - 3\%$
⇒ $\pi$, K data samples of $\approx 200$ k tracks required

The NA61 2007 run quite successful:
+ we learned many things on the NA61 apparatus, beam, …
+ new ToF wall completed on time and successfully opearted
− very very slow DAQ, effective rate $\sim 1$ HZ

Collected enough data ($\sim 1$ M triggers) for a first look at the pC
cross section and secondary interactions in the target

Just started to develop a T2K focused analysis strategy

Look forward to the 2008 fall run