Within the SM there are 3 different families of particles. Each lepton has a neutrino associated with it.

Neutrinos are one of the fundamental particles and have only weak interaction.

Neutrino has a zero mass, a zero charge and a spin 1/2.

Direct measurement of the neutrino mass by kinematical analysis of weak decays:

\[ m < 2.3\text{eV} \]
\[ m < 170\text{keV} \]
\[ m < 18.2\text{MeV} \]
The sources of neutrinos

Natural sources

Solar

Atmospheric

Earth (Geo v)

Supernovae

BigBang

Artificial sources

Accelerators

Reactors

\[ \Phi_v = 6 \times 10^{10} \text{v/cm}^2 \]

\[ E_v \sim 0.1-20 \text{ MeV} \]

\[ \rho_v = 330/\text{cm}^3 \]

\[ E_v = 0.0004 \text{ eV} \]

S-Kamiokande

Sun Neutrinos

Relic Neutrinos

S-Neutrinos

\[ \bar{\nu} = 6 \times 10^{10} \text{v/cm}^2 \]

\[ \nu = 0.1-20 \text{ MeV} \]

\[ \bar{\nu} \equiv 0.1-20 \text{ MeV} \]
### A Brief History of the Neutrino

<table>
<thead>
<tr>
<th>Year</th>
<th>Event</th>
</tr>
</thead>
<tbody>
<tr>
<td>1914</td>
<td>The β-decay energy conservation crisis.</td>
</tr>
<tr>
<td>1930</td>
<td>Pauli proposes a new neutral particle is emitted in β-decay.</td>
</tr>
<tr>
<td>1932</td>
<td>Fermi names the new particle “neutrino” and introduces four-fermion interaction.</td>
</tr>
<tr>
<td>1956</td>
<td>The first observation of electron anti-neutrinos by Reines and Cowan.</td>
</tr>
<tr>
<td>1957</td>
<td>Bruno Pontecorvo proposes neutrino-antineutrino oscillations.</td>
</tr>
<tr>
<td>1962</td>
<td>Ziro Maki, Masami Nakagawa and Sakata introduce neutrino flavor mixing and flavor oscillations (MNSP matrix).</td>
</tr>
<tr>
<td>1962</td>
<td>The muon neutrino is observed at BNL.</td>
</tr>
<tr>
<td>1973</td>
<td>Discovery of neutral currents at CERN.</td>
</tr>
<tr>
<td>1998</td>
<td>Super-Kamiokande announced the evidence of atmospheric neutrino oscillations</td>
</tr>
<tr>
<td>2000</td>
<td>First direct evidence for the tau neutrino</td>
</tr>
</tbody>
</table>
Measured $\beta$ spectra were continuous instead of discrete for 2-body decay.

Niels Bohr even suggested that perhaps energy conservation did not hold inside the nucleus.

"At the present stage of atomic theory, however, we may say that we have no argument, either empirical or theoretical, for upholding the energy principle in the case of $\beta$-ray disintegrations."

Pauli proposed that a neutral particle shared the energy of beta decay with the emitted electron.

«I have done a terrible thing. I have postulated a particle that cannot be detected.» (1930)

Fermi builds a new theory of to explain $\beta$-decay based on the current-current interaction and named a new particle “neutrino.”
The first experimental detection came from the high flux of neutrinos created in Savannah River reactor.

The inverse β decay produces two signals in tanks:

\[
\bar{\nu}_e + p \rightarrow n + e^+ \]

\[
e^+ + e \rightarrow \gamma \]

Prompt signal producing two 0.511 MeV γ’s

A few μs later

Delayed signal from n capture on cadmium producing 9 MeV in γ’s

Science 124 (1956) 103; Phys. Rev. 113 (1959) 273

The Nobel Prize in Physics 1995 was awarded to Frederick Reines "for the detection of the neutrino"
In 1962, Schwartz, Steinberger and Lederman built the very first neutrino beam and presented evidence for the muon neutrino.
800 GeV protons from TeVatron (FNAL) on Tungsten target produce Ds mesons

Decay of Ds meson and next τ lepton decay give $\nu_\tau$

$D_s \to l + \nu_\tau + \bar{\nu}_\tau$, $l = e$,

$\tau_\tau = 2.9 \times 10^{-13}$

9 clean $\nu_\tau$ CC events were observed
Weinberg and Salam develop a theory of electroweak interactions, but it requires a “neutral” weak current. The model introduces two types of weak interaction: Charged current (CC) and Neutral current (NC).

First example of NC

**Neutral currents: triumph of the electro-weak unification (1973)**

Gargamelle bubble chamber filled with freon (CF₃Br)
Large neutrino calorimeter type detectors

A large sampling calorimeters can measure large statistics CC and NC data

Neutrino cross section is very low

$$\sigma^{\nu p} \sim 10^{-38} \text{cm}^2 \frac{E_\nu}{\text{GeV}}$$

**FNAL** (700 GeV)
CITF, HPWF, CCFR/NuTeV

**BNL** (28 GeV)
E-776, E-816

**CERN** (400 GeV)
Aachen-Padova, CDHS, CHARM

**IHEP** (70 GeV)
IHEP-ITEP, IHEP-JINR

3/24/2011
### 1. Cross section measurements

| + N + X | - CC DIS | + N + X | - NC DIS | + e + e | - ve-scattering | + n + p | - CC QE | + p + p | - NC Elastic | + e + e | - Inverse μ-decay |

\[
\frac{1}{E_\nu} \frac{d^2 \sigma^{\nu(\bar{\nu})}}{dx dy} = \frac{G_F^2 M_N}{\pi} \left[ \frac{1}{2} y^2 \cdot 2xF_1 + \left( 1 - y - \frac{M_N x y}{2E_\nu} \right) F_2 \pm \left( y - \frac{1}{2} y^2 \right) x F_3 \right]
\]

Bjorken scaling variables in the laboratory system

\[ x = \frac{Q^2}{2\nu M_N}, \quad y = \frac{\nu}{\nu + E_\mu}\]

- Energy transferred to nucleon

\[ Q^2 = 2E_\nu (E_\mu - p_\mu \cos \theta_\mu) - m_\mu^2 \simeq 4E_\nu p_\mu \sin^2 \frac{1}{2} \theta_\mu \]

- 4-momentum transfer

**In terms of the quark distribution functions**

\[
\begin{align*}
2x F_1^\nu & = F_2^\nu = 2x(d + \bar{u} + s + \bar{c}) \\
2x F_1^{\bar{\nu}} & = F_2^{\bar{\nu}} = 2x(\bar{d} + u + \bar{s} + c)
\end{align*}
\]

### 2. Nucleon structure functions measurements

### 3. Measurement of \( \sin^2 \theta_W \) SM parameters

\[
R^\nu = \frac{\sigma(\nu_\mu N \rightarrow \nu_\mu X)}{\sigma(\nu_\mu N \rightarrow \mu^- X)} = \frac{1}{2} \sin^2 \theta_W + \frac{5}{9} (1 + r) \sin^4 \theta_W
\]

Paschos–Wolfenstein relation removes the effects of sea quark scattering and is much less sensitive to heavy quark production

\[
R^- = \frac{\sigma_{NC}^\nu - \sigma_{NC}^{\bar{\nu}}}{\sigma_{CC}^\nu - \sigma_{CC}^{\bar{\nu}}} = \frac{R^\nu - r R^\bar{\nu}}{1 - r} = \frac{1}{2} - \sin^2 \theta_W
\]

### 4. Beam-dump experiments

Search prompt neutrinos from charm particles production, Higgs, axion, heavy neutrino, ...

### 5. Neutrino oscillations
CHARM has a fine grained calorimeter with low Z target planes for good identification of electron from elastic \( \ell \bar{\ell} \)-scattering.

Marble planes

Glass planes

\( M = 692 \, \text{t} \)
CDHS experiment was designed to study CC DIS and NC DIS neutrino interactions. Detector combined the functions of a muon spectrometer and hadron calorimeter.

\[ / E_e = 0.23 / \sqrt{E_e (GeV)} \] - electrons
\[ / E = 0.56 / \sqrt{E (GeV)} \] - hadrons

19 magnetized iron modules

M = 1250 ton
FV = 700 ton
Neutrino target: liquid scintillator
Active detector: spark chamber and scintillator planes

Neutrino target: iron planes
Active detector: drift chamber and scintillator planes

FNAL: HPWF and NuTeV experiments

M = 700 ton
At \( t=0 \) we have a flavor eigenstates \( \psi_e \) and which are both mixtures of mass eigenstates \( \psi_1 \) and \( \psi_2 \):

\[
\begin{align*}
| \psi_e(0) \rangle &= \cos | \psi_1 \rangle + \sin | \psi_2 \rangle \\
| \psi_1(0) \rangle &= \sin | \psi_1 \rangle + \cos | \psi_2 \rangle
\end{align*}
\]

According to Schrödinger equation the mass eigenstates \( \psi_1 \) and \( \psi_2 \) with energy \( E_1 \) and \( E_2 \) evolve in time as plane waves:

For relativistic neutrinos (\( E \gg m \))

\[
E = \sqrt{p^2 + m^2} = p + \frac{m^2}{2E}
\]

Assuming the same energy for both neutrino components we can write:

\[
| \psi_\mu(t) \rangle = e^{i(p+m^2/2E)\mu} | \psi_1 \rangle \sin \theta + | \psi_2 \rangle e^{-it m^2/E} \sin \theta
\]

The transition probability is, then, given by

\[
P(\psi_e) = | \langle \psi_e | \psi(t) \rangle |^2 = | \sin \cos (1 - e^{it m^2/2E}) |^2
\]

If we measure \( \Delta m^2 \) in eV\(^2\), \( L \) in km, and \( E \) in GeV we can write the above as:

\[
P(\psi_e) = \sin^2 2 \sin^2 \left( \frac{1.27}{E} \frac{m^2 L}{2} \right)
\]

\[
P(\psi_e^{24/2011}) = \sin^2 2 \sin^2 \left( \frac{1.27}{E} \frac{m^2 L}{2} \right)
\]
Neutrinos are produced by cosmic ray interactions in Earth’s atmosphere.

41.4m x 39.3m (Diameter) 50 ktons of pure water tank with ≈11,000 20” PMTs

Particle identification is based on the pattern recognition of Cherenkov rings arising in water.

Neutrino Oscillations Discovery (1998)

SK was measured the number of $\nu_\mu$ and $\nu_e$ interactions as a function of zenith angle.
Neutrino Oscillations Discovery (1998)

The registration efficiency for muons and electrons is very different

Takeuchi, Neutrino 2010

At the Neutrino 98 conference, SK experiment presented new data on the deficit in muon neutrinos produced in the Earth's atmosphere. This deficit depends on the distance the neutrinos travel - an indication that neutrinos oscillate and have mass.

\[ R = 0.63 \pm 0.03 \pm 0.05 \text{ (sub-GeV)} \]
\[ R = 0.65 \pm 0.05 \pm 0.08 \text{ (multi-GeV)} \]

\[ \Delta m^2 = 2.1 \times 10^{-3} \]
\[ \sin^2 \theta_{13} = 0.0, \sin^2 \theta_{13} = 0.5 \]

The Nobel Prize in Physics 2002 was awarded to Masato Koshiba "... for pioneering contribution to astrophysics, in particular for the detection of cosmic neutrinos"
IHEP-JINR Neutrino Detector

Member of the IHEP-JINR Neutrino Detector Collaboration from 1979 to 2000

- Neutrino Detector
- Beam dump Experiment
  - Search of the light Higgs bosons and Axion
  - Limit on the charm production cross section
- Oscillation Experiment
- Total cross section measurement
The 70 mkm Mylar container with liquid scintillator is inserted into 3mm Al box.

MIP position resolution $\Delta X = 16$ cm
Neutrino Detector Calibration

Test beam with low momentum spread

Energy resolution vs momentum

Hadrons

Electrons

The examples of events from pion, electron, muon and neutrino interactions.

3/24/2011
The 70 GeV proton beam with $1.21 \times 10^{13}$ average proton intensity per accelerator pulse. Iron beam dump target was located in front of the 54 m long iron muon shield. The neutrino detector followed at a distance of 64 m downstream of the beam dump.

In two runs $1.1 \times 10^{18}$ and $0.6 \times 10^{18}$ protons on target were collected with relative target densities of $\rho = 1$ and $\rho = \frac{1}{2}$.
Beam dump: Search of Light Higgs and Axion

Two Higgs doublets with 3 neutral Higgs. Two from these particles (one scalar \( H \) and one pseudoscalar \( A \)) can be light.

The couplings of (pseudo)scalar to fermions

\[
g_{Hf} = i(\sqrt{2}G_F)^{1/2}m_fs_f
\]

\[
g_{Af} = i(\sqrt{2}G_F)^{1/2}m_fp_f
\]

\( s_f, p_f \) – model dependent coupling constants

MSSM

\( s_f = \cos \alpha / \sin \beta, \quad p_f = \cot \beta = 1/x \) for \( f = u, c, t \)

\( s_f = -\sin \alpha / \cos \beta, \quad p_f = \tan \beta = x \) for \( f = d, s, b, e, \mu, \tau \)

\( x = \nu_2/\nu_1 \) – ratio of vacuum expectations of Higgs doublets

SM

\( s_f = 1, \quad p_f = 0 \)

PQ axion \( p_f \) is the same as in MSSM

The search was performed for decays into \( \gamma \gamma \), \( e^+e^- \) and \( \mu^+\mu^- \) pairs

Cuts for \( \gamma \gamma \) and \( e^+e^- \)

1. \( E_{\text{elm}} > 3 \) GeV
2. No track at primary vertex
3. \( E_{\text{had}} < 1.5 \) GeV – resolution limit of reconstruction program
4. \( \theta_{\text{elm}} < 0.05 \) rad

Cuts for \( \mu^+\mu^- \)-pairs

1. Two long tracks (muons)
2. \( P_\mu > 3 \) GeV
3. \( \Delta P_\mu / P_\mu < 30\% \)
4. \( |E_{\text{dep}} - E_{\text{mip}}| < 0.5 \) GeV
5. \( \cos \theta_{\text{max}} > 0.99 \)
Higgs boson of SM was excluded for $m_H < 80$ MeV

Standard axion was excluded in the range $0.008 < x < 32$ and for mass range $0.2 - 3.2$ MeV for most $x > 1$
$0.2 - 11$ MeV for most $x < 1$

- a) Excluded by $e^+e^-$ and $\gamma\gamma$ decays
- b) Excluded by the $e^+e^-$ Bethe-Heitler process
- c) Excluded by the $\mu^+\mu^-$ Bethe-Heitler process
- d) Excluded by a combined fit using a) and b)
Beam dump: Charm Production Cross Section

Three types of interaction were studied for estimation of charm production cross section:
1. Prompt $\nu_e$ charged current interaction
2. Prompt $\nu_\mu$ charged current interaction
3. “Equilibrium” or “rock” muons produced in neutrino interaction at the end of muon iron shield.

Calculation of “prompt” events number

a) Extrapolation method
The charm production does not depend from target density. The production of conventional neutrinos is proportionally to the inverse target density.

$$N_{\text{prompt}} = 2N_{p=1} - N_{p=1/2} - \varepsilon(N_{p=1/2} - N_{p=1})$$

$\varepsilon$ - correction for the leakage of hadrons shower

b) Subtraction method
Subtraction of calculated contribution of conventional neutrino interactions from the total number of measured events.

$$\sigma_{\text{charm}} < 2.4 \, \mu\text{b/nucleon} \, (90\% \, \text{CL})$$

at $\sqrt{s} = 11.5 \, \text{GeV}$

Cuts for $\nu_e$ events
1. $E_{\text{elm}} > 3 \, \text{GeV}$
2. $Y = E_{\text{had}}/(E_{\text{elm}}+E_{\text{had}}) < 0.4$

Cuts for $\nu_\mu$ events
1. Track length in ND $\geq 3 \, \lambda_{\text{abs}}$
2. Track length in magnetized steel $\geq 50 \, \text{cm}$
3. $P_\mu \geq 3 \, \text{GeV}$
4. Start of track in the first plane of ND (for muons from muon shield only)

Third order QCD at $m_c = 1.2 \, \text{GeV}$ and $m_c = 1.5 \, \text{GeV}$
Oscillation Experiment

Oscillation experiment was initiated by paper of Prof. Conforto from Italy. He studied the results of 3 CERN experiments and was seeing some indication for oscillations. These detectors where exposed at the same time but located at the different distance from target.

$$P(e_x) = \sin^2 2 \theta \sin^2 1.27 m^2 L E$$

Special neutrino beam with 12 m short decay length was developed. The fraction of $\nu_e$ for such beam was 3.25% which is much higher than for standard neutrino beams.

The length of the decay cavity ($L = 12\text{ m}$) is short when compared to the distance from decay point to the detector (72 m average) and to the length of the neutrino detector ($L = 25\text{ m}$).

Give possibility to study L/E dependency

Minimization of $\chi^2 = (1 - R)^2$

with different $L/E$ parameters

$$R = \frac{N_{\exp}(L/E)}{N_{bkg}(L/E)}$$

$$\frac{N_{MC}(L/E)}{}$$
- T2K experiment
- ND280 detector
- P0D calibration with ‘rock’ muons
- CC QE events in P0D
- First preliminary results of T2K experiment
T2K (Tokai to Kamioka) experiment

First off-axis long baseline oscillation neutrino experiment with high power 30 GeV proton beam of J-PARC Main Ring

50-kT water Cherenkov detector

Kamioka
Tokai
Tokyo

295 km

Japan Proton Accelerator Research Complex

J-PARC

Super-Kamiokande

3/24/2011

CSU
Main Physics Goals

The Maki–Nakagawa–Sakata–Pontecorvo (MNSP) lepton mixing matrix relates the mass eigenstates \((\nu_1, \nu_2, \nu_3)\) to the flavor eigenstates \((\nu_e, \nu_\mu, \nu_\tau)\):

\[
U = \begin{pmatrix}
\cos \theta_{23} & \sin \theta_{23} & 0 \\
0 & \cos \theta_{12} & \sin \theta_{12} \\
-\sin \theta_{23} & \cos \theta_{23} & 0
\end{pmatrix}
\]

atmospheric, beam

sk atm, K2K, MINOS, (T2K)

\[
m_{23}^2 \sim 2.5 \times 10^3 \text{eV}^2
\]

solar, reactor

CHOOZ, (T2K)

\[
\sin^2 2 \theta_{13} < 0.14 (90\% \text{ CL})
\]

SNO, KamLAND

\[
m_{12}^2 \sim 8 \times 10^5 \text{eV}^2
\]

Measurements

- Measure the mixing parameter \(\theta_{13}\) by search \(\nu_e\) appearance

\[
P(\nu_e) \propto \sin^2 2 \theta_{13} \sin^2 2 \theta_{23} \sin^2 (1.27 \frac{m_{13}^2 L}{E})
\]

- Precise measurement \(\theta_{23}, |\Delta m_{23}^2|\) by observing \(\nu_\mu\) disappearance

\[
P(\nu_\mu) \propto \sin^2 2 \theta_{23} \sin^2 (1.27 \frac{m_{23}^2 L}{E})
\]

3/24/2011

CSU
Off-axis beam

- Neutrino energy depends on the angle relative to the beam axis
- Increasing of the angle gives narrower neutrino spectrum like monochromatic narrow beam
- Off-axis angle was set to $2.5^\circ$ where peak of $\text{Flux } \times \sigma_\nu$ has an oscillation maximum

- Narrow neutrino spectrum reduces the backgrounds in the electron neutrino measurement from DIS high energy interaction and the high energy $\nu_e$ beam contamination
- CC QE is dominant process in region of neutrino spectrum at $2.5^\circ$
**Sensitivity to $\theta_{13}$**

Detection of $\nu_e$ appearance: $\nu_\mu \rightarrow \nu_e$

Reconstructed $E_\nu$ in CC QE $\nu_e$ interaction

- $\sin^22\theta_{13} = 0.1$
- $\sin^22\theta_{13} : 0.1 \ 0.01$
- # of events in $0.35\sim0.85$ [GeV]
  - Signal ... 143 14
  - Beam $\nu_e$ BG ... 16 16
  - BG from $\nu_\mu$ ... 10 10

- 8.3x$10^{21}$ POT
- 5 years at 750 kW
- $0.006$ at $\delta_{CP} = 0$

Main backgrounds

- beam $\nu_e$ contamination
  - $\nu_e + n \rightarrow e^- + p$

- NC $\pi^0$ events
  - $\nu_\mu + N \rightarrow \nu_\mu + p + \pi^0$ → $\gamma + \gamma$

3/24/2011 CSU
Sensitivity to $\theta_{23}$ and $\Delta m_{23}^2$

Detection of $\nu_\mu$ disappearance

Oscillation changes a form of neutrino spectrum

$P(\nu_\mu \to \nu_\mu)$

Present limits

SK w/o oscillation

8 x 10^{21} POT

T2K sensitivity

$\delta(\sin^22\theta_{23}) < 0.01$

$\delta(\Delta m_{23}^2) < 1 \times 10^{-4}$ eV^{2}

stat. error only

$\sin^2 2 \theta = 1.0$

$\Delta m^2 = 2.25 \times 10^{-3}$ eV^{2}

$\Delta m^2 = 2.50 \times 10^{-3}$ eV^{2}

$\Delta m^2 = 2.75 \times 10^{-3}$ eV^{2}

(dashed lines: non-CCQE B.G.)
J-PARC accelerator facility

Near detectors

400 MeV Linac

3 GeV Synchrotron

Neutrino Beam

Main Ring Synchrotron

30 GeV proton accelerator

3/24/2011
ND280 detector consists of 5 subdetectors:

- **π⁰ detector (PØD)**
  - Optimized for **CC π⁰** and **NC π⁰** measurements
  - Measures $\nu_e$ contamination

- **Tracker**: fine-grained detector (FGD) and time projection chambers (TPC) measures **CC QE**, **CC 1π** and **NC 1π** interactions

- **Electromagnetic calorimeter (ECAL)** detects EM activities coming from PØD/Tracker

- **Side muon range detector (SMRD)** identification of side-going muons

All detectors housed in UA1/NOMAD magnet with field 0.2 T

Detector was commissioned in March 2010 and now taking the data during 1 year
Top view of ND280 detector
π⁰ detector (P0D)

- Upstream and Central Ecal γ-catchers
- Lead/Scint sandwich
- 17x35.5mm triangular bars
- Water Target Ecals
- Water/Scint sandwich

4 supermodules (p0dules)

Scintillator detectors read out via WLS fiber coupled to Si MPPC:
- 667 pixel avalanche photodiode,
- area of 1.3x1.3mm²

First large-scale use in HEP experiments: ~50,000 MPPCs for ND280
First neutrino event at ND280

Magnet off

First neutrino event (INGRID)

CCQE event at Tracker
First neutrino event at SK

Super-Kamiokande IV

First neutrino event at SK

1st ring + 2nd ring

Invariant mass: 133 MeV/c²
(close to π⁰ mass)

momentum: 148 MeV/c

2010/2/24 6:00:06
P0D calibration with ‘rock’ muons

‘Rock’ muons are going outside to P0D muons produced at neutrino interaction on the outer matter that is mainly magnet steel, pit construction concrete and rock ground.

Energy deposition of muon was corrected by path length in scintillator.
Charged current quasielastic neutrino interaction (CCQE) in P0D

\( \nu_\mu + n \rightarrow \mu^- + p \)

CC QE is dominant process in the region of T2K off-axis neutrino spectra at 2.5° and has simple 2-body kinematics.

In the simplest case of invisible proton, \( E_\nu \) can be calculated from measured momentum and angle of \( \mu^- \).

\[
E_\nu^{\text{rec}} = \frac{m_N E_\mu - m_\mu^2/2}{m_N - E_\mu + p_\mu \cos \theta_\mu}
\]
NEUT MC for study of backgrounds, reconstruction efficiency and purity of 1-track and 2-track CCQE events
- The total data PoT’s number is 2.84x10\(^{19}\)
- The total PoT’s number of NEUT MC is 1.3x10\(^{20}\)
- MC distributions were normalized to the total number of data PoT’s

**Fiducial Volumes**
1. **Full P0D** \(-3224 < Z < -1016 \text{ mm}\)
   First 3 and last 1 P0Dules were excluded
2. **Water Target** \(-1236 < Z < -1348 \text{ mm}\)
   24 internal P0Dules
3. **Central Ecal** \(-3224 < Z < -1016 \text{ mm}\)
   5 internal P0Dules

**Requirements and cuts**
1. 1 or 2 track segments in TPC
2. Vertex should be at P0D Fiducial Volume
3. Long track should be negative
4. TPC PID corresponds to muon
CCQE: Full P0D True Vertex position
**CCQE: 1-track CCQE and backgrounds for selected events**

<table>
<thead>
<tr>
<th>Muon Momentum</th>
<th>Data</th>
</tr>
</thead>
<tbody>
<tr>
<td>Entries</td>
<td>2163</td>
</tr>
<tr>
<td>Mean</td>
<td>2338</td>
</tr>
<tr>
<td>RMS</td>
<td>2131</td>
</tr>
</tbody>
</table>

Full P0D

- Data
- CCQE
- $\pi^+$
- $\pi^-$
- $\eta$
- $\eta'$, $K^*$, DIS
- NC

<table>
<thead>
<tr>
<th>Muon Momentum</th>
<th>Data</th>
</tr>
</thead>
<tbody>
<tr>
<td>Entries</td>
<td>1402</td>
</tr>
<tr>
<td>Mean</td>
<td>2524</td>
</tr>
<tr>
<td>RMS</td>
<td>2206</td>
</tr>
</tbody>
</table>

Water

- Data
- CCQE
- $\pi^+$
- $\pi^-$
- $\eta$
- $\eta'$, $K^*$, DIS
- NC

<table>
<thead>
<tr>
<th>Muon Momentum</th>
<th>Data</th>
</tr>
</thead>
<tbody>
<tr>
<td>Entries</td>
<td>347</td>
</tr>
<tr>
<td>Mean</td>
<td>1630</td>
</tr>
<tr>
<td>RMS</td>
<td>1683</td>
</tr>
</tbody>
</table>

CEcal

- Data
- CCQE
- $\pi^+$
- $\pi^-$
- $\eta$
- $\eta'$, $K^*$, DIS
- NC

~200-300 MeV shift b/w Data and MC due to the Global reconstructed momentum is not corrected for track energy loss in P0D

Small ~50-100 MeV shift b/w Data and MC for Cecal due to the short track length in P0D

The shift will be corrected in upcoming version of nd280 software
CCQE: 1-track CCQE and backgrounds angles for selected events

Full P0D

Water

CEcal

Nice agreement between Data and MC
First T2K preliminary results

2010a data were collected during Jan - June 2010.

- Total SK data: $3.23 \times 10^{19}$ PoT (15.5 kW x $10^7$s)
- Stable running at $3.8 \times 10^{13}$ PoT/spill ($\approx 54$ kW) shots up to 100 kW

SK event pre-selection was based on FV cuts, ring counting and PID.

8 $\nu_\mu$ and 2 $\nu_e$ candidates were selected for next analysis.
**$\nu_\mu$ disappearance analysis**

<table>
<thead>
<tr>
<th></th>
<th>Data</th>
<th>MC</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td><strong>No oscillation</strong></td>
</tr>
<tr>
<td></td>
<td></td>
<td><strong>Oscillation</strong></td>
</tr>
<tr>
<td></td>
<td></td>
<td>$\Delta m^2 = 2.4 \times 10^{-3}$ (eV$^2$)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$\sin^2 2\theta_{23} = 1.0$</td>
</tr>
<tr>
<td>Fully-Contained</td>
<td>33</td>
<td>54.5</td>
</tr>
<tr>
<td></td>
<td></td>
<td>24.6</td>
</tr>
<tr>
<td>Fiducial Volume, $E_{\text{vis}} &gt; 30$MeV</td>
<td>23</td>
<td>36.8</td>
</tr>
<tr>
<td></td>
<td></td>
<td>16.7</td>
</tr>
<tr>
<td>Single-ring $\mu$-like ($P_\mu &gt; 200$MeV/c)</td>
<td>8</td>
<td>24.5 ±3.9</td>
</tr>
<tr>
<td></td>
<td></td>
<td>7.1 ±1.3</td>
</tr>
<tr>
<td>$N(\text{decay e}) &lt; 2$ ($E_{\text{rec}} &lt; 10$ GeV)</td>
<td>8</td>
<td>22.8 ±3.2</td>
</tr>
<tr>
<td></td>
<td></td>
<td>6.3 ±1.0</td>
</tr>
</tbody>
</table>

Number of events consistent with oscillation parameters measured by MINOS/SK/K2K
**Final $\nu_e$ event selection**

<table>
<thead>
<tr>
<th>Preliminary</th>
<th>Data</th>
<th>MC</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Preliminary</strong></td>
<td>*</td>
<td>***</td>
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<td>Fully-Contained</td>
<td>33</td>
<td>54.5</td>
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<tr>
<td>Fiducial Volume, $E_{\text{vis}} &gt; 30\text{MeV}$</td>
<td>23</td>
<td>36.8</td>
</tr>
<tr>
<td>Single-ring e-like ($P_e &gt; 100\text{MeV/c}$)</td>
<td>2</td>
<td>1.5 ±0.7</td>
</tr>
</tbody>
</table>

**Additional background rejection**
- no decay electron
- $m_{\gamma\gamma} < 105\text{ MeV assuming second ring exist}$
- reconstructed $E_{\nu} < 1250\text{ MeV}$

**When # of decay electron cut was applied only 1 candidate of $\nu_e$ event remains**

![Graph showing event selection](image)
\( \nu_e \) appearance analysis

Upper bound of \( \theta_{13} \) are evaluated by 2 independent methods:

A: Feldman-Cousins

B: Classical one-sided limit

Systematic uncertainties are took into account for both analysis.

<table>
<thead>
<tr>
<th>Hierarchy</th>
<th>Upper Limit</th>
<th>Sensitivity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Normal (( \Delta m^2_{23} &gt; 0 ))</td>
<td>0.50</td>
<td>0.35</td>
</tr>
<tr>
<td>Inverted (( \Delta m^2_{23} &lt; 0 ))</td>
<td>0.59</td>
<td>0.42</td>
</tr>
</tbody>
</table>

90% CL upper limit at \( m^2_{23} = 2.4 \times 10^{-3} \text{eV}^2, \; CP = 0 \)

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<tbody>
<tr>
<td>Normal (( \Delta m^2_{23} &gt; 0 ))</td>
<td>0.44</td>
<td>0.32</td>
</tr>
<tr>
<td>Inverted (( \Delta m^2_{23} &lt; 0 ))</td>
<td>0.53</td>
<td>0.39</td>
</tr>
</tbody>
</table>
Backup slides
Future prospects

Run 2010b (from Nov 2010 – March 2011)
- 9.3x10^{13} p/spill (8 bunches/spill/3.04s)
- Max beam power: ~145 kW
- Total data collected up to Mar 11: 1.45x10^{20} PoT
  (including run 2010a)