Past, Present and Future of long baseline neutrino experiments
Noble Prize 2015

BreakThrough Prize 2015

Morphing neutrinos provide clue to antimatter mystery

Excitement rises over chance of new physics from particle-du-jour.

Elizabeth Gibney
Neutrino oscillations

\[
\begin{pmatrix}
\nu_e \\
\nu_\mu \\
\nu_\tau
\end{pmatrix} =
\begin{pmatrix}
U^*_{e1} & U^*_{e2} & U^*_{e3} \\
U^*_{\mu 1} & U^*_{\mu 2} & U^*_{\mu 3} \\
U^*_{\tau 1} & U^*_{\tau 2} & U^*_{\tau 3}
\end{pmatrix}
\begin{pmatrix}
\nu_1 \\
\nu_2 \\
\nu_3
\end{pmatrix}
\]

\[|\nu_\alpha\rangle = \sum_i U^*_{\alpha i}|\nu_i\rangle \]

\(U_{cd}\) are expressed in terms of 3 mixing angles \((\theta_{13}, \theta_{23}, \theta_{12})\) and a phase \(\delta_{CP}\).

\[P(\nu_\alpha \rightarrow \nu_\beta)\]

neutrino oscillation probability also depends on mass differences: \(\Delta m^2_{ij}\)

- **Long baseline neutrino accelerator** experiments observe \(\nu_\mu \rightarrow \nu_{\mu/e}\):
  - \(|\Delta m^2_{32}|\) known at \(\sim 4\%\), \(\theta_{23} \sim \pi/4\) \(\rightarrow\) maximal mixing? **Mass ordering** unknown. (\(\theta_{13}\) and \(\theta_{12}, \Delta m^2_{21}\) measured with solar and reactor experiments)
    - \(\rightarrow\) flavour pattern may indicate the symmetry beyond \(\nu\) oscillation (door to New Physics!)
    - \(\rightarrow\) precise measurement needed to test unitarity of PMNS matrix

- **\(\delta_{CP}\) phase** (unknown) parametrize the difference between \(\nu\) and \(\bar{\nu}\) oscillation
  - \(\rightarrow\) involved with **matter-antimatter asymmetry** in leptogenesis scenarios
T2K

Huge water cherenkov detector (50 kTon) with optimal $\mu/e$ identification to distinguish $\nu_e, \nu_\mu$

Full tracking and particle reconstruction in near detectors (magnetized TPC!): measure precisely neutrino flux before oscillation

NOVA

Same technology for near and far detector (14kTon): cells filled of scintillator oil
A bit of (recent) history...

SuperKamiokande
1996 – today!
1998 Discovery of $\nu$ oscillation from zenith angle dependence of atmospheric $\nu_\mu$ rate

Need confirmation from accelerator experiment: high purity and tunable neutrino flux

(1999-2006) K2K
(2003-2015) MINOS (→ MINOS+)

Beyond $\theta_{23}$ and $\Delta m_{32}$:
\[ \rightarrow \text{observation of } \nu_e \text{ apperance} \]
\[ \rightarrow \text{to measure MH, longer baseline: NOVA started last year} \]
\[ \rightarrow \text{first results on } \delta_{CP} ! \]

Sudbury Neutrino Observatory (SNO)
1999 – today!
2001 Solution of solar puzzle: $\nu_e / \Sigma \nu_\alpha \sim 1/3$

(2008-2012) OPERA: 5 $\nu_\mu \rightarrow \nu_\tau$ events obs.

NOVA started last year (2008-2012) OPERA: 5 $\nu_\mu \rightarrow \nu_\tau$ events obs.
T2K data

- \( \nu \)-mode: \( 7.48 \times 10^{20} \) POT
- \( \bar{\nu} \)-mode: \( 7.47 \times 10^{20} \) POT

Large disappearance signal and clear oscillation shape (beyond counting experiment)

Clear signal in antineutrino as well!

7.5 sigma observation of \( \nu_e \) appearance

Growing statistics of \( \nu_e \) appearance: (~20% of final design statistics)
$\delta_{CP}$ and MH mainly from $\nu_\mu \rightarrow \nu_e / \bar{\nu}_\mu \rightarrow \bar{\nu}_e$

Expected events as a function of $\delta_{CP}$ and MH:

- $\nu_e$ events
  - ▲ Normal Hierarchy (NH)
  - △ Inverted Hierarchy (IH)

- $\bar{\nu}_e$ events

$\delta_{CP} = -\pi/2$ (maximal CPV)

$\delta_{CP} = 0$ (CP conserved)

$\delta_{CP} = \pi/2$ (maximal CPV)

$\delta_{CP} = +/-\pi$ (CP conserved)
\( \delta_{CP} \) and MH mainly from \( \nu_\mu \rightarrow \nu_e / \bar{\nu}_\mu \rightarrow \bar{\nu}_e \)

Expected events as a function of \( \delta_{CP} \) and MH:

- \( \bar{\nu}_e \) events
  - Normal Hierarchy (NH)
  - Inverted Hierarchy (IH)

32 observed \( \nu_e \) events
4 observed \( \nu_e \) events

\( \delta_{CP} = -\pi/2 \) (maximal CPV)
\( \delta_{CP} = 0 \) (CP conserved)
\( \delta_{CP} = +/-\pi \) (CP conserved)

Results favour maximal CP violation (and slightly favour NH)
First 90% limits on $\delta_{CP}$!!

Full joint fit of all data ($\nu_\mu \rightarrow \nu_{\mu/e}$ and $\bar{\nu}_\mu \rightarrow \bar{\nu}_{\mu/e}$) with all proper statistical and systematic uncertainty included and exploiting also shape information:

Feldman-Cousins confidence interval:

$\delta_{CP} = [-3.13, -0.39]$ NH

$[-2.09, -0.74]$ IH

(NH slightly favoured)

Not Gaussian behaviour → need to through toys to evaluate correct confidence interval

Feldman-Cousins confidence interval:
NOVA in agreement with T2K: favours maximal CPV and slightly favour NH

NOVA has taken $6.05 \times 10^{20}$ POT in $\nu$ mode (no $\bar{\nu}$ data yet):

- $\nu_\mu \rightarrow \nu_e$ events

First combination of all data (T2K, NOVA, SK, ...)

CP conservation excluded at 2$\sigma$

Lisi et al.
NEUTRINO 2016
The other oscillation parameters ($\theta_{23}$, $|\Delta m^2_{32}|$):
mostly from $\nu_\mu$ and $\bar{\nu}_\mu$ disappearance

- $\sin^2\theta_{23}$ enhance/suppress both $\nu_\mu$ and $\bar{\nu}_\mu$ disappearance
- $|\Delta m^2_{32}|$ regulate the position of the oscillation maximum as a function of the energy

T2K data show maximal disappearance $\rightarrow$ prefer maximal mixing: $\theta_{23} = \pi/4$ ($\sin^2\theta_{23} = 0.5$)

NOVA data excludes maximal mixing at 2.5$\sigma$

| $\sin^2\theta_{23}$ | $|\Delta m^2_{32}|$ [$10^{-3}$ eV$^2$] |
|-----------------|------------------|
| T2K (NH)        | NOVA (NH)        |
| 0.532$^{+0.046}_{-0.068}$ | 0.40$^{+0.03}_{-0.02}$ $0.63^{+0.02}_{-0.03}$ |
| 2.545$^{+0.081}_{-0.084}$ | 2.67 $\pm$ 0.12 |
Prospects to 2026

NOVA – T2K combination with final dataset (~2021)

Request for new run of T2K beyond design statistics \( (7.8 \times 10^{21} \text{ POT by}) \rightarrow 20 \times 10^{21} \text{ POT by 2026} \)

- good chances to observe CP violation at > 3\( \sigma \) by 2026 for a sizeable fraction of values
- large impact of systematics

For definitive \( \delta_{CP} \) measurement need new generation of long baseline experiments: HyperKamiokande, DUNE

- change from 1% to 3% of neutrino cross-section systematics equivalent to a factor 2 in exposure!
Main systematics

Let's take the $\nu_e$ sample at T2K

- total systematics before the ND constraints 11.9%
- total systematics after the ND constraints 5.41%

- specific to SuperKamiokande: 3.46%
- flux and $\nu$ cross-section: 4.17%
  - flux 8.94% (before ND constr.) → 3.64% (after ND constr.)
  
  Flux simulated (target and beamline with FLUKA/GEANT) and tuned to hadron scattering data in dedicated experiments (NA61)

  - xsec 7.17% (before ND constr.) → 5.12% (after ND constr.)
  
  Dominated by nuclear effects which may give difference between $\nu_e/\nu_\mu$ and $\bar{\nu}_e/\bar{\nu}_\mu$ cross-section

Xsec measured with limited precision on free nucleons in old bubble chamber experiments. In modern experiment $\nu$ interacts with target detectors of carbon, water or argon → large nuclear effects not well known (very peculiar theoretical expertise)
Neutrino-nucleus interaction

Crucial role of **T2K Near Detector (ND280)**: TPC (MicroMegas) developed at CEA for tracking, particle identification and momentum measurement

Cross section of main T2K signal:

- Charged Current Quasi-Elastic
- higher order corrections in nuclear target

Model developed by Martini et al. (SphN)

**CCQE**

**CCQE + multi-nucleon interactions**

\[ 0.70 < \text{true } \cos \theta_{\mu} < 0.80 \]

\[ 0.70 \leq \text{True-}\mu \cos \theta < 0.80 \]

\( \nu \) interactions on **carbon**

\( \nu \) interactions on **water**

\[ d^2\sigma \left( 10^{-38} \text{ cm}^2 \right) / d\cos \theta_{\mu} (\text{nucleon GeV}) \]

\[ d^2\sigma_{\mu} (\text{true } p_{\mu} \left[ \text{GeV} \right]) \]
ND280 Upgrade for T2K Phase II

- T2K-II will require a 2% precision on the expected number of events at SK (5% today) to match the 400 $\nu_e$ appearance events
  
  → We are currently studying an upgrade of the near detector ND280 comprising 4 additional TPCs and two new active targets (to be installed in 2020)

Aim: acceptance over the full polar angle, with better tracking inside the target and lower proton threshold

- Workshop at CERN November 8-9th (open to all interested people!)
Summary

- First 90% CL exclusion of CP conservation: hint for maximal $\nu - \bar{\nu}$ asymmetry

- T2K and NOVA: agreement on $\delta_{CP}$ while 2.5σ difference for $\theta_{23}$ measurement

Still mostly statistical limited

Heavy work ahead:

- keep collecting data: NOVA, T2K-2 → next generation of long baseline experiments (DUNE and HyperKamiokande)

- need to minimize the systematics for high statistics measurement:
  - precise measurements of $\nu$-nucleus xsec and better theoretical nuclear modeling
  - upgrade of the T2K near detector under study
BACKUP slides
Non standard scenarios

- **CPT violation** in T2K by comparing disappearance $\nu_\mu \rightarrow \nu_\mu$ and $\nu_\mu \rightarrow \nu_\mu$

- **Sterile neutrinos**: combination of MINOS, DayaBay and Bugey

- Limits on non-standard neutrino interactions from MINOS+

→ important to constrain to avoid degeneracies and biases with future precise $\delta_{CP}$ measurement!
NOVA – T2K comparison: nue appearance

- Observe 33 events passing $\nu_e$ selection
- On 8.2 background
NOVA – T2K comparison: $\nu_\mu$ disappearance

### NOA Preliminary

- **NOvA 6.05 \times 10^{20} \text{ POT-equiv.}**
  - Best fit prediction
  - Unoscillated prediction
  - Data

### Events / 0.25 GeV

<table>
<thead>
<tr>
<th></th>
<th>NOVA $\nu$</th>
<th>T2K $\nu$</th>
<th>T2K $\bar{\nu}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Expected w/o oscillations</td>
<td>473 ± 30</td>
<td>522 ± 26</td>
<td>185 ± 10</td>
</tr>
<tr>
<td>Best fit</td>
<td>82</td>
<td>136</td>
<td>64</td>
</tr>
<tr>
<td>Observed</td>
<td>78</td>
<td>135</td>
<td>66</td>
</tr>
</tbody>
</table>

**T2K: agreement between $\nu$ and $\bar{\nu}$ data**

No clear suspect → T2K-NOVA difference is maybe just a statistical fluctuation?
## T2K Systematics Uncertainties (Joint Oscillation Analysis)

Fractional error on the number of expected events at SK with and without ND280

<table>
<thead>
<tr>
<th>Source of Uncertainty</th>
<th>$\nu_\mu$ Sample $1R_\mu$ FHC</th>
<th>$\nu_e$ Sample $1R_e$ FHC</th>
<th>$\bar{\nu}<em>\mu$ Sample $1R</em>\mu$ RHC</th>
<th>$\bar{\nu}_e$ Sample $1R_e$ RHC</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\nu$ flux w/o ND280</td>
<td>7.6%</td>
<td>8.9%</td>
<td>7.1%</td>
<td>8.0%</td>
</tr>
<tr>
<td>$\nu$ flux with ND280</td>
<td>3.6%</td>
<td>3.6%</td>
<td>3.8%</td>
<td>3.8%</td>
</tr>
<tr>
<td>$\nu$ cross-section w/o ND280</td>
<td>7.7%</td>
<td>7.2%</td>
<td>9.3%</td>
<td>10.1%</td>
</tr>
<tr>
<td>$\nu$ cross-section with ND280</td>
<td>4.1%</td>
<td>5.1%</td>
<td>4.2%</td>
<td>5.5%</td>
</tr>
<tr>
<td>$\nu$ flux+cross-section</td>
<td>2.9%</td>
<td>4.2%</td>
<td>3.4%</td>
<td>4.6%</td>
</tr>
<tr>
<td>Final or secondary hadron int.</td>
<td>1.5%</td>
<td>2.5%</td>
<td>2.1%</td>
<td>2.5%</td>
</tr>
<tr>
<td>Super-K detector</td>
<td>3.9%</td>
<td>2.4%</td>
<td>3.3%</td>
<td>3.1%</td>
</tr>
<tr>
<td>Total w/o ND280</td>
<td>12.0%</td>
<td>11.9%</td>
<td>12.5%</td>
<td>13.7%</td>
</tr>
<tr>
<td>Total with ND280</td>
<td>5.0%</td>
<td>5.4%</td>
<td>5.2%</td>
<td>6.2%</td>
</tr>
</tbody>
</table>
# T2K systematics uncertainties (joint oscillation analysis)

**Fractional error on the number of expected events at SK**

<table>
<thead>
<tr>
<th>Source of Uncertainty</th>
<th>(\bar{\nu}_\mu) sample 1R(\mu) FHC</th>
<th>(\bar{\nu}_e) sample 1R(e) FHC</th>
<th>(\bar{\nu}_e) sample 1R(\mu) RHC</th>
<th>(\bar{\nu}_\mu) sample 1R(\mu) RHC</th>
<th>(\bar{\nu}_e) sample 1R(e) RHC</th>
<th>1R(e) FHC/RHC</th>
</tr>
</thead>
<tbody>
<tr>
<td>(\nu) flux+cross-section constrained by ND280</td>
<td>2.8%</td>
<td>2.9%</td>
<td>3.3%</td>
<td>3.2%</td>
<td>2.2%</td>
<td></td>
</tr>
<tr>
<td>(\nu_e/\nu_\mu) and (\bar{\nu}<em>e/\bar{\nu}</em>\mu) cross-sections</td>
<td>0.0%</td>
<td>2.7%</td>
<td>0.0%</td>
<td>1.5%</td>
<td>3.1%</td>
<td></td>
</tr>
<tr>
<td>NC (\gamma)</td>
<td>0.0%</td>
<td>1.4%</td>
<td>0.0%</td>
<td>3.0%</td>
<td>1.5%</td>
<td></td>
</tr>
<tr>
<td>NC other</td>
<td>0.8%</td>
<td>0.2%</td>
<td>0.8%</td>
<td>0.3%</td>
<td>0.2%</td>
<td></td>
</tr>
<tr>
<td>Final or secondary hadron int.</td>
<td>1.5%</td>
<td>2.5%</td>
<td>2.1%</td>
<td>2.5%</td>
<td>3.6%</td>
<td></td>
</tr>
<tr>
<td>Super-K detector</td>
<td>3.9%</td>
<td>2.4%</td>
<td>3.3%</td>
<td>3.1%</td>
<td>1.6%</td>
<td></td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>5.0%</strong></td>
<td><strong>5.4%</strong></td>
<td><strong>5.2%</strong></td>
<td><strong>6.2%</strong></td>
<td><strong>5.8%</strong></td>
<td></td>
</tr>
</tbody>
</table>
How does it work?

**SUPERKAMIOKANDE**
- **Signal:** $(\text{anti})\nu_\mu \rightarrow (\text{anti})\nu_e$ oscillation
- **Backgrounds:**
  - Outer volume with outward facing PMT to veto external background
  - **PMT timing** to select beam bunches and reconstruct vertex position in fiducial volume

**ν interactions from beam:**
- intrinsic $\nu_e$ component in the beam
- pions: $\pi^+/-$ **undetected** and $\pi^0 \rightarrow \gamma\gamma \rightarrow$ e-like ring + $\gamma$ **undetected**
- $\bar{\nu}$ oscillations: intrinsic $\nu$ component in the beam

No magnetic field $\rightarrow$ no charge measurement ($\nu/\bar{\nu}$)

**R&D: Gd doping** to tag neutrons to distinguish: $\nu n \rightarrow l^- p$ from $\nu p \rightarrow l^+ n$

**HYPERKAMIOKANDE:**
- Working to improve PMTs and on Gd doping.
- Electronics and calibration system very similar to SuperK
From SuperK to HyperK

<table>
<thead>
<tr>
<th></th>
<th>Total volume</th>
<th>Fiducial volume</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 cylindrical</td>
<td>50 kTon</td>
<td>990 kTon</td>
</tr>
<tr>
<td>2 egg-shape</td>
<td>22.5 kTon</td>
<td>560 kTon</td>
</tr>
<tr>
<td>tanks</td>
<td></td>
<td></td>
</tr>
<tr>
<td>outer detector</td>
<td>11.129</td>
<td>50.000</td>
</tr>
<tr>
<td>inner detector</td>
<td>1885</td>
<td>25.000</td>
</tr>
</tbody>
</table>

Photocoverage
- 40% (Collection x Quantum eff.)
- 20%

Sensor efficiency
- 18% (22x80%)
- 29% (30x95%)

Tanks and PMT design under discussion:
- minimize risk due to pressure on PMTs (avoid cascade implosion as in SK 2001 incident)
- minimize cost (volume vs #PMTs)
- need PMT R&D (next slide)
R&D on PMTs

- Optimization should include pressure resistance
  possible to put protective cover → need precise control of glass quality

- Response to single photoelectron:
  charge resolution
  time resolution

<table>
<thead>
<tr>
<th></th>
<th>SK PMT</th>
<th>HighQE/CE PMT</th>
<th>HighQE hybrid det.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Quantum Eff. (QE)</td>
<td>22%</td>
<td>30%</td>
<td>30%</td>
</tr>
<tr>
<td>Collection Eff. (CE)</td>
<td>80%</td>
<td>93%</td>
<td>95%</td>
</tr>
<tr>
<td>Timing resol (FWHM)</td>
<td>5.5 nsec</td>
<td>2.7 nsec</td>
<td>1 nsec</td>
</tr>
</tbody>
</table>

Integrated system of inner and outer PMTs under study (solve problems of pressure and in-water electronics)
Gadolinium doping

- $\bar{\nu}_p \rightarrow l^+ n \rightarrow n$ get captured in Gd with emission of few $\gamma \sim 8$MeV
- for beam neutrino physics: $\nu$ vs $\bar{\nu}$ separation, but also useful to enhance sensitivity to SuperNova $\nu$ and proton decay
- R&D studies (eg, WATCHMAN) as reactor monitoring
- **EGADS: 200 ton scale model of SuperK fully operative in Kamioka mine**

Neutron capture time tested with Am/Be source: data-MC perfect agreement

All the trick is about keeping water pure and transparent without losing Gd (dedicated filtration system)

- SuperKamiokande will run with loaded Gd in next years!

S.Bolognesi (CEA,Saclay)

IFD – Torino – December 2015
Liquid Argon technology

Ionizing particle in LAr → 2 measurements:
- **charge from ionization** → tracking and calorimetry
- **scintillation light** → trigger and $t_0$
  (drift time → third coordinate for non-beam events)

**DUNE**: staged approach with 4 modules of ~10kTon fiducial mass each

- **$\mu$** track momentum from range
  (or from multiple scattering if not contained)
- PID from $dE/dx$
- Very good electron/$\gamma$ ID and $\pi^0$ reconstruction
- Calorimetric energy from total collected charge (+ light)
Result of years of R&D

Single-Phase

ICARUS

35-t prototype

protoDUNE

DUNE Reference Design

basis for first 10 kt module

46 times larger than ICARUS

Dual-Phase

2016

WA105: 1x1x3 m³

2018

DUNE Alternative Design
Single-phase VS Double-phase

- Very long charge drift path → diffusion and attenuation

Single Phase charge readout → limited to short drift distances: 4 drift regions of 3.6m each

Double Phase charge readout → high signal/noise thanks to avalanche multiplication in gas

IFD – Torino – December 2015
Charge signal

- $W_e = 23.6$ eV → mip produces $\sim 100k$ e- per cm → 60k e- after recombination
- drift velocity $\sim$mm/µs ($\rightarrow$ total drift time $\sim$10 ms)

- **Very long drift path → diffusion and attachment**
  - diffusion $\sim$few mm with 1-0.5 kV/cm ($\rightarrow$ pitch readout few mm)
  - $O_2$ pollution captures ionization electrons → charge attenuation
    ($\rightarrow$ impurity $\sim$20 ppt $O_2$ needed)

S.Bolognesi (CEA, Saclay)
Charge readout plane (CRP)

- **Single Phase**
  - no gain
  - 3 views
  - uniform CRP design

- **Double Phase**
  - stable gain of 20 on 10x10cm LEM
  - 2 views (x,y) of equal quality
  - to scale up: CRP segmented in 50x50cm modules

Cosmic event in double phase TPC at effective gain-20
Many other challenges

- **scintillation light:** single phase: first test of wavelength shifting bars to SiPM integrated with a TPC
  
  double phase: standard PMTs (with coating),

- **high voltage on large surfaces:** cathode-anode $\Delta V \sim$few hundreds V (double phase)
  
  $\sim$180 V (single phase)

- **large number of channels**
  
  → electronics in gas accessible only in double phase design
  
  → calibration and uniformity
    (eg: flattening of cathode and of charge readout plane, E field between different modules of charge readout ...)

- **software for automatic reconstruction**
  
  huge amount of info (efficient zero suppression)

- **LAr TPC as calorimeter**
  
  fully omogeneous with very low threshold

  very good resolution and detailed tracking inside shower → potential to improve shower models!

  ICARUS:
  
  - Low energy electrons: $\sigma(E)/E = 11%/\sqrt{E(\text{MeV})} + 2\%$
  
  - Electromagnetic showers: $\sigma(E)/E = 3%/\sqrt{E(\text{GeV})}$
  
  - Hadron shower (pure LAr): $\sigma(E)/E \approx 30%/\sqrt{E(\text{GeV})}$
Hyperkamiokande much more sensitive to CP violation while DUNE much more sensitive to Mass Herarchy (see backup). But sensitivities depend on assumed beam power, detector mass and on baseline.

Comparison of technologies:

**WATER CHERENKOV**

- well known and solid technology
- very large mass (~MTon)
- info only about particles above Cherenkov threshold
  - model dependent assumptions to reconstruct $E_\nu$
  - no need of precise $E_\nu$ shape:
    - mainly a counting experiment

**LIQUID ARGON**

- successfull R&D → first very large scale realization
- size limited by drift length (~40KTON)
- full reconstruction of tracks and showers down to very low threshold, very good particle ID
  - precise $E_\nu$ shape accessible and needed for good sensitivity
  - need to reach very good control on detector calibration/uniformity and on neutrino interaction modelling
Sensitivities

HK 3 years (1MTon): CPV measured at 3s (5s) for 75% (60%) of dCP values

DUNE 10 years (40 kTon): CPV measured at 3s (5s) for >50% (~25%) of dCP values

DUNE 10 years: definitive determination of MH

HK 10 years: wrong MH excluded at 3s
Future experiments: $\nu_e$ and $\nu$ xsec

- We are interested to $\nu_e$ appearance and $\delta_{CP}$ from $\nu - \bar{\nu}$ comparison but in ND we mostly measure $\nu_\mu$ cross-sections.

- In future (HK, DUNE) large samples of 4 $\nu$ species → the uncorrelated uncertainties are relevant
  - **HK** needed uncertainty to have negligible impact on dCP:
    - $\nu_e - \bar{\nu}_e$ uncorrelated 1-2%
  - For **DUNE** assumed: uncorrelated $\nu_\mu - \bar{\nu}_\mu$ 5% and $\nu_e - \bar{\nu}_e$ 2%

<table>
<thead>
<tr>
<th></th>
<th>$\nu_\mu$ sample</th>
<th>$\nu_e$ sample</th>
<th>$\bar{\nu}_\mu$ sample</th>
<th>$\bar{\nu}_e$ sample</th>
</tr>
</thead>
<tbody>
<tr>
<td>T2K</td>
<td>7.7%</td>
<td>6.8%</td>
<td>11.6%</td>
<td>11.0%</td>
</tr>
</tbody>
</table>

(Shape of $\nu_\mu$ itself may be more important for DUNE: shape analysis and spanning over different xsec)
Moving to larger energies …
Moving to larger energies ...
Moving to larger energies ... 

Need to control well all different xsec, each process has very different detector acceptance.

T2K flux

DUNE

NOvA Preliminary