Large $\theta_{13}$

Challenge and Opportunity

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Experimental Seminar

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$\theta_{13}$ is large!

The Daya Bay result is

$$\sin^2 2\theta_{13} = 0.089 \pm 0.010\text{(stat)} \pm 0.005\text{(syst)},$$

which translates into a more than $5\sigma$ exclusion of $\theta_{13} = 0$, confirmed by RENO.

NB – a 1.5 years ago we had only $2\sigma$ indications.
Implications

In general, this raises the following questions

• Is neutrino physics essentially done?

• Will the mass hierarchy have been determined before the next generation of long-baseline experiments?

• Are new experiments beyond NO$\nu$A and T2K necessary to discover CP violation?

• Are superbeams sufficient for precision neutrino physics?

Any of this questions is both a challenge and opportunity!
The future of $\theta_{13}$

FAPP $\theta_{13}$ will be known to very high accuracy

At $\sin^2 2\theta_{13} = 0.1$ the measurement error at T2K will be 10%.

At $\sin^2 2\theta_{13} = 0.1$ the measurement error at Daya Bay will be <5%.

Agreement of values of $\theta_{13}$ from reactors (disappearance) and beams (appearance) constitutes a critical test of the 3 flavor framework.

Neutrinos are massive – so what?

Neutrinos in the Standard Model (SM) are strictly massless, therefore the discovery of neutrino oscillation, which implies non-zero neutrino masses requires the addition of new degrees of freedom.

The discovery of a light sterile neutrino could well be the most significant piece of BSM physics in the last 30 years.
We always knew they are . . .

The SM is an effective field theory, \( i.e. \) at some high scale \( \Lambda \) new degrees of freedom will appear

\[
\mathcal{L}_{SM} + \frac{1}{\Lambda} \mathcal{L}_5 + \frac{1}{\Lambda^2} \mathcal{L}_6 + \ldots
\]

The first operators sensitive to new physics have dimension 5. It turns out there is only one dimension 5 operator

\[
\mathcal{L}_5 = \frac{1}{\Lambda} (LH)(LH) \rightarrow \frac{1}{\Lambda} (L\langle H \rangle)(L\langle H \rangle) = m_{\nu\nu}
\]

Thus studying neutrino masses is, in principle, the most sensitive probe for new physics at high scales

Weinberg
Effective theories

The problem in effective theories is, that there are a priori unknown pre-factors for each operator

\[ \mathcal{L}_{SM} + \frac{\#}{\Lambda} \mathcal{L}_5 + \frac{\#}{\Lambda^2} \mathcal{L}_6 + \ldots \]

Typically, one has \( \# = \mathcal{O}(1) \), but there may be reasons for this being wrong

- lepton number may be conserved \( \rightarrow \) no Majorana mass term
- lepton number may be approximately conserved \( \rightarrow \) small pre-factor for \( \mathcal{L}_5 \)

Therefore, we do not know the scale of new physics responsible for neutrino masses.
Flavor models

Simplest un-model – anarchy Murayama, Naba, DeGouvea

\[ dU = ds_{12}^2 dc_{13}^4 ds_{23}^2 d\delta_{CP} d\chi_1 d\chi_2 \]

predicts flat distribution in \( \delta_{CP} \)

Simplest model – Tri-bimaximal mixing Harrison, Perkins, Scott

\[
\begin{pmatrix}
\frac{1}{\sqrt{3}} & \frac{1}{\sqrt{3}} & 0 \\
-\frac{1}{\sqrt{6}} & \frac{1}{\sqrt{3}} & \frac{1}{\sqrt{2}} \\
\frac{1}{\sqrt{6}} & -\frac{1}{\sqrt{3}} & \frac{1}{\sqrt{2}} \\
\end{pmatrix}
\]

to still fit data, obviously corrections are needed – predictivity?
Sum rules

\[ \theta_{12} = 35^\circ + \theta_{13} \cos \delta \]
\[ \theta_{12} = 32^\circ + \theta_{13} \cos \delta \]
\[ \theta_{23} = 45^\circ + \sqrt{2} \theta_{13} \cos \delta \]
\[ \theta_{23} = 45^\circ - \frac{1}{\sqrt{2}} \theta_{13} \cos \delta \]
\[ \theta_{12} = 45^\circ + \theta_{13} \cos \delta \]

Antusch, King

3 \sigma resolution of 15° distance requires 5° error. NB – smaller error on \( \theta_{12} \) requires dedicated experiment like Daya Bay II

P. Huber – VT-CNP – p. 9
What we want to learn

In the context of neutrino oscillation experiments

- $\delta_{CP}$
- mass hierarchy
- $\theta_{23} = \pi/4$, $\theta_{23} < \pi/4$ or $\theta_{23} > \pi/4$?
- Resolution of LSND and the other short-baseline anomalies
- New physics?

Given the current state of the theory of neutrinos we cannot say with confidence that any one quantity is more fundamental than any other.
Phenomenology of $3 \times 3$ active oscillations
CP violation

Like in the quark sector mixing can cause CP violation

\[ P(\nu_\alpha \rightarrow \nu_\beta) - P(\bar{\nu}_\alpha \rightarrow \bar{\nu}_\beta) \neq 0 \]

The size of this effect is proportional to

\[ J_{CP} = \frac{1}{8} \cos \theta_{13} \sin 2\theta_{13} \sin 2\theta_{23} \sin 2\theta_{12} \sin \delta \]

but the asymmetry

\[ \frac{P(\nu_\alpha \rightarrow \nu_\beta) - P(\bar{\nu}_\alpha \rightarrow \bar{\nu}_\beta)}{P(\nu_\alpha \rightarrow \nu_\beta) + P(\bar{\nu}_\alpha \rightarrow \bar{\nu}_\beta)} \propto \frac{1}{\sin 2\theta_{13}} \]

The experimentally most suitable transition to study CP violation is \( \nu_e \leftrightarrow \nu_\mu \).
Matter effects

The charged current interaction of $\nu_e$ with the electrons creates a potential for $\nu_e$

$$A = \pm 2\sqrt{2} G_F \cdot E \cdot n_e$$

where $+$ is for $\nu$ and $-$ for $\bar{\nu}$.

This potential gives rise to an additional phase for $\nu_e$ and thus changes the oscillation probability. This has two consequences

$$P(\nu_\alpha \rightarrow \nu_\beta) - P(\bar{\nu}_\alpha \rightarrow \bar{\nu}_\beta) \neq 0$$

even if $\delta = 0$, since the potential distinguishes neutrinos from anti-neutrinos.
Matter effects

The second consequence of the matter potential is that there can be a resonant conversion – the MSW effect. The condition for the resonance is

\[ \Delta m^2 \simeq A \iff E_{\text{res}}^{\text{Earth}} = 6 - 8 \text{ GeV} \]

Obviously the occurrence of this resonance depends on the signs of both sides in this equation. Thus oscillation becomes sensitive to the mass ordering

<table>
<thead>
<tr>
<th>( \Delta m^2 )</th>
<th>( \nu )</th>
<th>( \bar{\nu} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \Delta m^2 &gt; 0 )</td>
<td>MSW</td>
<td>-</td>
</tr>
<tr>
<td>( \Delta m^2 &lt; 0 )</td>
<td>-</td>
<td>MSW</td>
</tr>
</tbody>
</table>
Consequences for experiments

• need to measure 2 out of $P(\nu_\mu \rightarrow \nu_e)$, $P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e)$, $P(\nu_e \rightarrow \nu_\mu)$ and $P(\bar{\nu}_e \rightarrow \bar{\nu}_\mu)$
• need more than 1 energy and/or 1 baseline
• matter resonance at $6 - 8$ GeV
• matter effects sizable for $L > 1000$ km
• large $\theta_{13}$ implies small CP asymmetries $\Rightarrow$ need for small systematics
Are new experiments still necessary?
Status quo

Fogli, et al., arXiv:1205.5254

NB – 1σ range for δ = 30 – 35°
CPV without new experiments?


Barely reaches $3\sigma$ for mass hierarchy, and this is the most favorable $\delta_{CP}$!
CPV without new experiments?

MH discovery, NH (3σ CL)

CPV discovery, NH (3σ CL)

Includes Project X and T2K running at 1.7 MW.
Short baseline anomalies
$\mathcal{P}(\bar{\nu}_\mu \rightarrow \bar{\nu}_e) \simeq 0.003$

Tension between neutrino and antineutrino signals?
Reactor anomaly

6% deficit of $\bar{\nu}_e$ from nuclear reactors at short distances

- 3% increase in reactor neutrino fluxes
- decrease in neutron lifetime
- inclusion of long-lived isotopes (non-equilibrium correction)
Reactor antineutrino fluxes

Shift with respect to ILL results, due to
a) different effective nuclear charge distribution
b) branch-by-branch application of shape corrections
Non-equilibrium corrections

Mueller, et al., RRC 83 (2011) 054615

Extra shift due to long-lived isotopes

a) small nuclear physics uncertainty in $\beta$-decay
b) depends on detailed fuel history

only 2 dozen isotopes with $t_{1/2} > 12 \text{h}$ above inverse $\beta$-decay threshold
Neutron lifetime

range used in past reactor analyses

lifetime data from Wietfeldt & Greene, Rev. Mod. Phys. 83 (2011) 1173

IBD cross section change [%]

neutron lifetime [s]

PDG 2012

year
Gallium anomaly

<table>
<thead>
<tr>
<th></th>
<th>GALLEX</th>
<th>SAGE</th>
</tr>
</thead>
<tbody>
<tr>
<td>k source</td>
<td>G1 $^{51}\text{Cr}$</td>
<td>G2 $^{51}\text{Cr}$</td>
</tr>
<tr>
<td>$R_B^k$</td>
<td>0.953 ± 0.11</td>
<td>0.812 $^{+0.10}_{-0.11}$</td>
</tr>
<tr>
<td>$R_H^k$</td>
<td>0.84 $^{+0.13}_{-0.12}$</td>
<td>0.71 $^{+0.12}_{-0.11}$</td>
</tr>
<tr>
<td>radius [m]</td>
<td>1.9</td>
<td></td>
</tr>
<tr>
<td>height [m]</td>
<td>5.0</td>
<td></td>
</tr>
<tr>
<td>source height [m]</td>
<td>2.7</td>
<td>2.38</td>
</tr>
</tbody>
</table>

25% deficit of $\nu_e$ from radioactive sources at short distances

- effect depends on nuclear matrix element
- interpretation as sterile neutrino is in conflict with large scale structure neutrino mass bounds over a large fraction of the parameter space
Astrophysics

\[ N_{\text{eff}} \simeq 4 \] from relativistic energy density

**BUT**

\[ m_s \lesssim 1 \text{ eV} \] from large scale structure

Future data (PLANCK) will help to address this tension
Absence of effects in
- atmospheric
- Bugey
- CDHS
- MINOS
- ...

data creates considerable tension in 3+N sterile neutrino models

More details can be found in the sterile neutrino white paper, arXiv:1204.5379.
Sterile oscillation

In general, in a 3+N sterile neutrino oscillation model one finds that the energy averaged probabilities obey the following inequality

\[ P(\nu_\mu \to \nu_e) \leq 4P(\nu_e \to \nu_e)P(\nu_\mu \to \nu_\mu) \]

independent of CP transformations. Therefore, a stringent test of the model is to measure

- \( P(\nu_\mu \to \nu_e) \) – appearance
- \( P(\bar{\nu}_\mu \to \bar{\nu}_e) \) – appearance
- \( P(\nu_\mu \to \nu_\mu) \) or \( P(\bar{\nu}_\mu \to \bar{\nu}_\mu) \) – disappearance
- \( P(\nu_e \to \nu_e) \) or \( P(\bar{\nu}_e \to \bar{\nu}_e) \) – disappearance
SBL anomalies – corollary

- All current hints are 3 $\sigma$-ish
- A lot of hidden, hard to control systematics and theory errors
- Tension in global fits
- Need for new experiments
- What would be the consequence of a discovery for LBL physics?
Neutrino sources
### Traditional beam

**Neutrino beam from \( \pi \)-decay**

<table>
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<tr>
<th>Source</th>
<th>Oscillation</th>
<th>Detection</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \pi, K )</td>
<td>( \nu_\mu )</td>
<td>( \nu_\mu \rightarrow \mu^- )</td>
</tr>
<tr>
<td>( \pi, K )</td>
<td>( \nu_e )</td>
<td>( \nu_e \rightarrow e^- )</td>
</tr>
<tr>
<td>( \pi, K )</td>
<td>( \nu_\mu )</td>
<td>( \nu_\mu \rightarrow \mu^- )</td>
</tr>
<tr>
<td>( \pi, K )</td>
<td>( \nu_e )</td>
<td>( \nu_e \rightarrow e^- )</td>
</tr>
</tbody>
</table>

- primary \( \nu_\mu \) flux constrained to 5-15%
- \( \nu_e \) component known to about 20%
- anti-neutrino beam systematically different – large wrong sign contamination
- \( \nu_e \) difficult to distinguish from NC events
Appearance experiments using a (nearly) flavor pure beam can not rely on a near detector to predict the signal at the far site!

Large $\theta_{13}$ most difficult region.

PH, M. Mezzetto, T. Schwetz
arXiv:0711.2950
Nuclear effects change the relation between true neutrino energy and lepton energy.

Inferring the CP phase from QE spectrum seems quite difficult – no quantitative analysis with respect to oscillation physics, yet.

Not obvious that near detectors alone can solve this problem.

Neutrino factory beam

This requires a detector which can distinguish $\mu^+$ from $\mu^-$ ⇒ magnetic field of around 1T

- beam known to $\%$-level or better
- muon detection very clean
- multitude of channels available
Long-baseline oscillations
MH from existing experiments

- NOvA continues running at 14 kton and 700 kW to 2025
- T2K continues running at 22.5 kton with 700 kW to 2025
- NOvA achieves a further 20% sensitivity gain
- T2K achieves a further 10% sensitivity gain

Includes Daya Bay projected final error

R. Patterson, NuFact 12
Hyper-K

Atmospheric data only
Assumes $\theta_{13}$ known from reactors
Assumes $\theta_{23}$ known from beam
Leaves $\delta$ free

Hyper-K LOI, arXiv:1109.3262
PINGU

Phased IceCube Next Generation upgrade
20 strings with $\sim 1000$ optical modules
Energy threshold of around 1 GeV

5-10 $\sigma$ for all CP phases
Cheap & fast
Feasibility under study by the IceCube collaboration

Akhmedov, Razzaque, Smirnov
arXiv:1205.7071
Indian Neutrino Observatory

40 kt magnetized iron detector (like MONOLITH)

Improved angular and energy resolution in the multi-GeV range neutrino/antineutrino separation from muon charge

Blennow, Schwetz, arXiv:1203.3388
MH from reactors

Interference of the two mass scales
Choubey, Petcov, Piai, 2003
Baseline of $\sim 60$ km and exposure of $\mathcal{O}(100)$ kt years

Daya Bay II
Question of systematics control – energy scale
Qian et al., 2012

Learned et al., hep-ex/0612022
Mass hierarchy corollary

- Given the large value of $\theta_{13}$ mass hierarchy can be done in many different ways
- PINGU, ICAL, Daya Bay 2, HK atmospheric data, ...  
- It therefore seems very likely that the mass hierarchy will be determined at some level w/o a new long baseline experiment
Mass hierarchy is no longer a distinguishing feature!
CP and systematics

We specifically simulate near and far detectors

We use common assumptions for all experiments on

- cross sections split into QE, RES and DIS for each flavor and neutrinos and antineutrinos
- cross section ratios between e and $\mu$ flavors for QE, RES and DIS and neutrinos and antineutrinos
- fiducial volume and near/far extrapolation errors

We use experiment type specific errors for

- fluxes
- beam backgrounds
- detector backgrounds
## Setups

<table>
<thead>
<tr>
<th>Setup</th>
<th>$E_{\nu_{\text{peak}}}^L$</th>
<th>$L$</th>
<th>OA</th>
<th>Detector</th>
<th>kt</th>
<th>MW</th>
<th>Decays/yr</th>
<th>($t_{\nu}, t_{\bar{\nu}}$)</th>
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</thead>
<tbody>
<tr>
<td><strong>Benchmark</strong></td>
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<td></td>
<td></td>
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<td></td>
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</tr>
<tr>
<td>BB350</td>
<td>1.2</td>
<td>650</td>
<td>–</td>
<td>WC</td>
<td>500</td>
<td>–</td>
<td>$1.1(2.8) \times 10^{18}$</td>
<td>(5,5)</td>
</tr>
<tr>
<td>NF10</td>
<td>5.0</td>
<td>2000</td>
<td>–</td>
<td>MIND</td>
<td>100</td>
<td>–</td>
<td>$7 \times 10^{20}$</td>
<td>(10,10)</td>
</tr>
<tr>
<td>WBB</td>
<td>4.5</td>
<td>2300</td>
<td>–</td>
<td>LAr</td>
<td>100</td>
<td>0.8</td>
<td>–</td>
<td>(5,5)</td>
</tr>
<tr>
<td>T2HK</td>
<td>0.6</td>
<td>295</td>
<td>2.5°</td>
<td>WC</td>
<td>560</td>
<td>1.66</td>
<td>–</td>
<td>(1.5,3.5)</td>
</tr>
<tr>
<td><strong>Alternative</strong></td>
<td></td>
<td></td>
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<td></td>
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<td></td>
</tr>
<tr>
<td>BB100</td>
<td>0.3</td>
<td>130</td>
<td>–</td>
<td>WC</td>
<td>500</td>
<td>–</td>
<td>$1.1(2.8) \times 10^{18}$</td>
<td>(5,5)</td>
</tr>
<tr>
<td>+ SPL</td>
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<td></td>
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<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>NF5</td>
<td>2.5</td>
<td>1290</td>
<td>–</td>
<td>MIND</td>
<td>100</td>
<td>–</td>
<td>$7 \times 10^{20}$</td>
<td>(10,10)</td>
</tr>
<tr>
<td>LBNE$_{\text{mini}}$</td>
<td>4.0</td>
<td>1290</td>
<td>–</td>
<td>LAr</td>
<td>10</td>
<td>0.7</td>
<td>–</td>
<td>(5,5)</td>
</tr>
<tr>
<td>NOvA$^+$</td>
<td>2.0</td>
<td>810</td>
<td>0.8°</td>
<td>LAr</td>
<td>30</td>
<td>0.7</td>
<td>–</td>
<td>(5,5)</td>
</tr>
</tbody>
</table>

NB – neutrino/antineutrino running at NF10/NF5 is simultaneous.

The following results are taken from

Disappearance data can play the role of near detector if three flavor framework is assumed. NF10 clearly outperforms all other options.
Systematics II

Near detector crucial for new physics searches

$\text{NOvA}^+$ higher risk from systematics

Current $\Delta \delta$ is $30-35^\circ$

Fogli et al., 2012
CP precision

2020 – T2K, NO\nuA and Daya Bay nominal runs
LBNE – 1300 km, 34 kt
0.7 MW, $2 \times 10^8$ s
WBB – 2300 km, 100 kt
0.8 MW, $1 \times 10^8$ s
T2HK – 295 km, 560 kt
0.7 MW, $1.2 \times 10^8$ s
all masses are fiducial

LBNO EOI submitted to CERN –
20 kt LAr + MIND, similar beam power to above, but Finish government will not support Pyhäsalmi lab
One way forward

A staged, muon based program

- $\nu$STORM – resolve the SBL anomalies and if discovery, precise measurements of NP, necessary to control systematics in superbeam experiments
- Low luminosity neutrino factory (700kW beam, no cooling, 10 kt detector) – better than mini-LBNE
- Full neutrino factory – ultimate precision provides excellent, unique physics in each phase!
νSTORM

Low energy, low luminosity muon storage ring, based on existing technology. Provides with $1.7 \times 10^{18}$ $\mu^+$ stored, the following oscillated event numbers

\[
\begin{align*}
\nu_e &\rightarrow \nu_\mu \text{ CC} \quad 330 \\
\bar{\nu}_\mu &\rightarrow \bar{\nu}_\mu \text{ NC} \quad 47000 \\
\nu_e &\rightarrow \nu_e \text{ NC} \quad 74000 \\
\bar{\nu}_\mu &\rightarrow \bar{\nu}_\mu \text{ CC} \quad 122000 \\
\nu_e &\rightarrow \nu_e \text{ CC} \quad 217000
\end{align*}
\]

and each of these channels has a more than 10 $\sigma$ difference from no oscillations

With more than 2000 000 $\nu_e$ CC events in the near detector a %-level $\nu_e$ cross section measurement should be possible
νSTORM – νμ appearance

\[ \Delta m^2_{41} \quad \text{[eV}^2] \]

\[ \begin{align*}
\text{3 \sigma} & \\
\text{5 \sigma} & \\
\text{10 \sigma} & \\
\end{align*} \]

99% MBν/LSND

arXiv:1205.6338
Wrong-sign μ

10^{21} \text{ POT}

\[ \chi^2_{\text{stats}} \]
Low energy, low luminosity NF

1300 km baseline
700 kW proton beam power
5 GeV muon storage ring
no muon cooling
10 kt magnetized (!) LAr detector
includes $\nu_e$ appearance

NB – LBNE’s sensitivity is lower than in the CDR since we use $\theta_{23} = 45^\circ$

Coloma, Christensen, PH, in preparation

L3NF – still all existing technology.
Summary

• New facilities are indispensable to fully exploit the discovery of neutrino oscillation and to study the short-baseline anomalies

• Mass hierarchy at large $\theta_{13}$ is no longer a main decision criterion

• CP violation is never easy to measure – especially for the largest values of $\theta_{13}$

• muon based options clearly outperform any other technology both for short- and long-baseline physics

• attractive staging scenario – $\nu$STORM, L3NF, full neutrino factory, …
Backup Slides
# Systematics – detailed inputs

<table>
<thead>
<tr>
<th>Systematics</th>
<th>SB</th>
<th></th>
<th></th>
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<th></th>
<th></th>
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<tr>
<td>Fiducial volume ND</td>
<td>0.2%</td>
<td>0.5%</td>
<td>1%</td>
<td>0.2%</td>
<td>0.5%</td>
<td>1%</td>
<td>0.2%</td>
</tr>
<tr>
<td>Fiducial volume FD</td>
<td>1%</td>
<td>2.5%</td>
<td>5%</td>
<td>1%</td>
<td>2.5%</td>
<td>5%</td>
<td>1%</td>
</tr>
<tr>
<td>(incl. near-far extrap.)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>Flux error signal $\nu$</td>
<td>5%</td>
<td>7.5%</td>
<td>10%</td>
<td>1%</td>
<td>2%</td>
<td>2.5%</td>
<td>0.1%</td>
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<tr>
<td>Flux error background $\nu$</td>
<td>10%</td>
<td>15%</td>
<td>20%</td>
<td>correlated</td>
<td></td>
<td></td>
<td>correlated</td>
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<tr>
<td>Flux error signal $\bar{\nu}$</td>
<td>10%</td>
<td>15%</td>
<td>20%</td>
<td>1%</td>
<td>2%</td>
<td>2.5%</td>
<td>0.1%</td>
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<tr>
<td>Flux error background $\bar{\nu}$</td>
<td>20%</td>
<td>30%</td>
<td>40%</td>
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<td></td>
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<td>Background uncertainty</td>
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<td>7.5%</td>
<td>10%</td>
<td>5%</td>
<td>7.5%</td>
<td>10%</td>
<td>10%</td>
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<td>Cross secs $\times$ eff. QE$^\dagger$</td>
<td>10%</td>
<td>15%</td>
<td>20%</td>
<td>10%</td>
<td>15%</td>
<td>20%</td>
<td>10%</td>
</tr>
<tr>
<td>Cross secs $\times$ eff. RES$^\dagger$</td>
<td>10%</td>
<td>15%</td>
<td>20%</td>
<td>10%</td>
<td>15%</td>
<td>20%</td>
<td>10%</td>
</tr>
<tr>
<td>Cross secs $\times$ eff. DIS$^\dagger$</td>
<td>5%</td>
<td>7.5%</td>
<td>10%</td>
<td>5%</td>
<td>7.5%</td>
<td>10%</td>
<td>5%</td>
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<tr>
<td>Ratio $\nu_e/\nu_\mu$ QE$^*$</td>
<td>3.5%</td>
<td>11%</td>
<td>–</td>
<td>3.5%</td>
<td>11%</td>
<td>–</td>
<td>3.5%</td>
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<td>Ratio $\nu_e/\nu_\mu$ RES$^*$</td>
<td>2.7%</td>
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<td>–</td>
<td>2.7%</td>
<td>5.4%</td>
<td>–</td>
<td>2.7%</td>
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<td>Ratio $\nu_e/\nu_\mu$ DIS$^*$</td>
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<td>5.1%</td>
<td>–</td>
<td>2.5%</td>
<td>5.1%</td>
<td>–</td>
<td>2.5%</td>
</tr>
<tr>
<td>Matter density</td>
<td>1%</td>
<td>2%</td>
<td>5%</td>
<td>1%</td>
<td>2%</td>
<td>5%</td>
<td>1%</td>
</tr>
</tbody>
</table>
### L3NF – Detector assumptions

#### TASD

<table>
<thead>
<tr>
<th>Channel</th>
<th>Effs.</th>
<th>(\tau) Rej.</th>
<th>NC/CID/FID Rej.</th>
<th>(\Delta E / E)</th>
</tr>
</thead>
<tbody>
<tr>
<td>(\nu_\mu) app.</td>
<td>73%-94%</td>
<td>0%</td>
<td>99.9%</td>
<td>0.2 / (\sqrt{E})</td>
</tr>
<tr>
<td>(\nu_e) app.</td>
<td>37%-47%</td>
<td>0%</td>
<td>99%</td>
<td>0.15 / (\sqrt{E})</td>
</tr>
<tr>
<td>(\nu_\mu) dis.</td>
<td>73%-94%</td>
<td>0%</td>
<td>99.9%</td>
<td>0.2 / (\sqrt{E})</td>
</tr>
</tbody>
</table>

#### Magnetized LAr

<table>
<thead>
<tr>
<th>Channel</th>
<th>Effs.</th>
<th>(\tau) Rej.</th>
<th>NC/CID/FID Rej.</th>
<th>(\Delta E / E)</th>
</tr>
</thead>
<tbody>
<tr>
<td>(\nu_\mu) app.</td>
<td>80%</td>
<td>0%</td>
<td>99.9%</td>
<td>0.2 / (\sqrt{E})</td>
</tr>
<tr>
<td>(\nu_e) app.</td>
<td>80%</td>
<td>0%</td>
<td>99.9%</td>
<td>0.15 / (\sqrt{E})</td>
</tr>
<tr>
<td>(\nu_\mu) dis.</td>
<td>80%</td>
<td>0%</td>
<td>99.9%</td>
<td>0.2 / (\sqrt{E})</td>
</tr>
</tbody>
</table>

\(\nu_\tau\) backgrounds included and we use 2E7 s per year for ten years (like LBNE)
The $\nu_\mu \rightarrow \nu_e$ channel is the CPT conjugate of the $\bar{\nu}_e \rightarrow \bar{\nu}_\mu$ channel.

As a result matter effects effectively cancel.

This has been known for quite a while, but the effect is only relevant for large $\theta_{13}$.

NB: LBNE-mini corresponds to the LBNE CDR (CD1)
L3NF CP precision

Solid line – magnetized LAr
Dashed line – magnetized TASD

The obtainable precision is nearly everywhere better than LBNEs by about 9 degrees (1/3)

Coloma, Christensen, PH, in preparation