Long baseline neutrino oscillation phenomenology

Enrique Fernández Martínez

νProbes
Oscillation Parameters

What we already know ($1\sigma$)

- Solar sector
  \[
  \begin{align*}
  \Delta m_{21}^2 &= 7.49^{+0.19}_{-0.17} \cdot 10^{-5} \text{eV}^2 \\
  \sin^2 \theta_{12} &= 0.308^{+0.013}_{-0.012}
  \end{align*}
  \]

- Atm. sector
  \[
  \begin{align*}
  \left|\Delta m_{31}^2\right| &= 2.484^{+0.045}_{-0.048} \cdot 10^{-3} \\
  \sin^2 \theta_{23} &= 0.574^{+0.026}_{-0.144}
  \end{align*}
  \]

- $\sin^2 \theta_{13} = 0.0229^{+0.002}_{-0.0019}$

What we still don’t know

- $\delta = ?$

- Mass hierarchy $s_{atm} = \text{sign}(\Delta m_{31}^2)$

- Octant of $\theta_{23}$

M. C. Gonzalez-Garcia, M. Maltoni, J. Salvado, T. Schwetz 1512.06856 www.nu-fit.org
Neutrinos and the flavour puzzle

The $\nu$ sector is, at least, half of the **flavour puzzle** and we are still **missing several pieces!!** (that we know of)
Neutrinos and the flavour puzzle

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Status with present experiments

From M. C. Gonzalez-Garcia, M. Maltoni, J. Salvado, T. Schwetz 1512.06856 www.nu-fit.org
Status with present experiments

From F. Capozzi, E. Lisi, A. Marrone, D. Montanino and A. Palazzo 1601.07777
Sensitivities to CPV

\[
\chi^2
\]

\( \delta_{CP} \) (°)

\(~2020\)  T2K+NOvA

5σ

3σ

Courtesy of P. Coloma
To plot these: compute $\Delta \chi^2 = \chi^2(\delta = 0, \pi) - \chi^2_{\text{min}}$ for a given "true" $\delta$

If $\Delta \chi^2 > 1, 4, 9, 25$ then CP conservation excluded at 1, 2, 3, 5 $\sigma$
Is it a $\chi^2$?

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Why 1, 4, 9, 25?

Wilk’s theorem says $\Delta \chi^2$ should be distributed as $\chi^2$ with 1 dof
Is it a $\chi^2$?

Wilk’s theorem assumes linearity of the observables to have a $\chi^2$

But $\delta$ is cyclic $\rightarrow$ line becomes a segment or an ellipse...
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And degeneracies will also violate linearity...

No guarantee that the test statistics will follow a $\chi^2$ distribution

M. Blennow, P. Coloma and EFM 1407.3274
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We have generated $10^5$ realizations of each experiment and computed the test statistics $\chi^2(\delta=0, \pi)-\chi^2_{\text{min}}$ for each of them for CP conserving values of $\delta$.

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Others slightly above the $\chi^2$.
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T2HK degeneracies induce further deviations.

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Others slightly above the $\chi^2$.
Present hint Significance

2D contour closer to $\chi^2$ approximation

From J. Elevant and T. Schwetz 1506.07685
Sensitivities to CPV

New generation facilities to reach the 5$\sigma$ mark

Syst: $\sim$2% signal
$\sim$5% background

The Golden channel in matter

\[ P(\overline{\nu}_e \rightarrow \overline{\nu}_\mu) = s_{23}^2 \sin^2 2\theta_{13} \left( \frac{\Delta_{atm}}{\tilde{B}_\mp} \right)^2 \sin \left( \frac{\tilde{B}_\mp L}{2} \right) \]

\[ + c_{23}^2 \sin^2 2\theta_{13} \left( \frac{\Delta_{sol}}{A} \right)^2 \sin^2 \left( \frac{AL}{2} \right) \]

“interference” \[ + \tilde{J} \frac{\Delta_{sol}}{A} \frac{\Delta_{atm}}{\tilde{B}_\mp} \sin \left( \frac{AL}{2} \right) \sin \left( \frac{\tilde{B}_\mp L}{2} \right) \cos \left( \pm \delta - \frac{\Delta_{atm} L}{2} \right) \]

Expanded in

\[ \sin 2\theta_{13} \sim 0.3 \]

\[ \left( \frac{\Delta_{sol} L}{2} \right) \approx 0.05 \]

where

\[ \tilde{J} = \cos \theta_{13} \sin 2\theta_{13} \sin 2\theta_{12} \sin 2\theta_{23} \]

\[ \Delta_{atm} = \frac{\Delta m_{23}^2}{2E} \]

\[ \Delta_{sol} = \frac{\Delta m_{12}^2}{2E} \]

\[ A = \sqrt{2} G_F n_e \quad \tilde{B}_\mp = \left| A \mp \Delta_{atm} \right| \]

A. Cervera et al. hep-ph/0002108
Optimization of facilities for large $\theta_{13}$

Signal **systematics** and not stats become the bottleneck for large $\theta_{13}$, explore **second peak**?  
P. Coloma and EFM 1110.4583
Systematics (mainly xsec) have huge impact in sensitivity
Systematics

Systematics (mainly xsec) have huge impact in sensitivity.

With broad spectrum and good energy resolution the effect is much reduced.
Importance of energy reconstruction

Energy reconstruction from LArSoft simulation by M. Sorel

V. De Romeri, EFM and M. Sorel 1607.00293
Importance of energy reconstruction

Better reconstruction of the second oscillation peak

DUNE

V. De Romeri, EFM and M. Sorel 1607.00293
Importance of energy reconstruction

**CPV discovery potential**

- NH
- This work
- CDR-like

\[ \sqrt{\chi^2} \]

\[ \delta_{CP} \ (\degree) \]

**Mass hierarchy discovery potential**

- NH
- This work
- CDR

\[ \sqrt{\chi^2} \]

\[ \delta_{CP} \ (\degree) \]

**Improvement on the CPV and mass hierarchy measurements**

V. De Romeri, EFM and M. Sorel 1607.00293
Conclusions

- **T2K** and **NOνA** will provide the first $\sim 2-3 \sigma$ indications over the next years. In order to reach a $5 \sigma$ discovery, upgraded or new facilities will be needed.

- Deviations from $\chi^2$ in present facilities: necessary to carefully calibrate the $\chi^2$ when assessing present hint from T2K+Daya Bay+Nova. $\chi^2$ underestimates its significance!

- Sensitivity to CPV and mass hierarchy very dependent on $\theta_{23}$.

- The optimization strategy for CPV changes for large $\theta_{13}$: importance of systematic errors and the second oscillation peak over statistics and backgrounds. Few percent control of systematics necessary for $5 \sigma$ goal.
Sensitivities to CPV

New generation facilities to reach the $5\sigma$ mark


Syst: $\sim 2\%$ signal
$\sim 5\%$ background
For T2HK 0.87% nu and 2.1% antinu
Importance of energy reconstruction

Maximal Mixing Rejection Potential

Octant Sensitivity

Improvement on $\theta_{23}$

V. de Romeri, EFM and M. Sorel 1606.XXXXX
Importance of energy reconstruction

 Improvement on the CP measurement

V. de Romeri, EFM and M. Sorel 1606.XXXX
Importance of energy reconstruction

DUNE-like facility: underestimation of missing E

Calorimetric Method
Realistic Resolution

- Correct Result
- $90\%$ ($\chi^2_{6dof}/dof=0.3/106$)
- $80\%$ ($\chi^2_{6dof}/dof=1.4/106$)
- $70\%$ ($\chi^2_{6dof}/dof=3.7/106$)

Contours for $\Delta \chi^2 = 2.3$
Wide Band Beam, $L=1300$ km

A. M. Ankowski, P. Coloma, P. Huber, C. Mariani and E. Vagnoni 1507.08561
Importance of cross sections sys

T2K-like disappearance measurement

(a) No calibration error
\[ \chi^2_{\text{min}} / \text{dof} = 47.64 / 16 \]

Fit with wrong generator (GiBUU vs GENIE)
\[ \chi^2 / \text{dof} = 20.95 / 16 \]

True value (events from GiBUU)

P. Coloma et al 1311.4506
Importance of energy reconstruction

F. Capozzi, E. Lisi and A. Marrone 1508.01392
Importance of energy reconstruction

Spectrum/10^3 [MeV^{-1}]

osc. + norm.
+ energy scale
+ flux shape

JUNO

F. Capozzi, E. Lisi and A. Marrone 1508.01392
## Systematics

<table>
<thead>
<tr>
<th>Systematics</th>
<th>SB</th>
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<th>NF</th>
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<td>Fiducial volume FD (incl. near-far extrap.)</td>
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<td>2.5%</td>
<td>5%</td>
<td>1%</td>
<td>2.5%</td>
<td>5%</td>
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<tr>
<td>Flux error signal $\nu$</td>
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<td>7.5%</td>
<td>10%</td>
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<tr>
<td>Flux error background $\nu$</td>
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<td>Background uncertainty</td>
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<tr>
<td>Cross secs $\times$ eff. QE$^\dagger$</td>
<td>10%</td>
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<td>Effec. ratio $\nu_e/\nu_\mu$ QE$^*$</td>
<td>3.5%</td>
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<td>Effec. ratio $\nu_e/\nu_\mu$ RES$^*$</td>
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<td>Matter density</td>
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<td>5%</td>
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Importance of cross sections sys

\[ \Delta \delta \text{ at } 1\sigma \]

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Courtesy of P. Coloma

P. Coloma et al 1209.5973
Importance of cross sections sys

+NuSTORM (1% uncorrelated errors on xsecs)

Courteous of P. Coloma

P. Coloma et al 1209.5973
How to interpret it?

For low performance, distribution falls much faster than $\chi^2$
As the performance improves, first it falls slower and then
approaches asymprocically a $\chi^2$  

M. Blennow, P. Coloma and EFM 1407.3274
For low performance, distribution falls much faster than $\chi^2$. As the performance improves, first it falls slower and then approaches asymptotically a $\chi^2$. M. Blennow, P. Coloma and EFM 1407.3274.
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Statistical fluctuations around the test point ($\delta=0$) will have a characteristic size $l = sR$. For large $s$ distance to circle is larger than line $\rightarrow$ smaller difference with distance to point $\rightarrow$ smaller test stat.

M. Blennow, P. Coloma and EFM 1407.3274
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Statistical fluctuations around the test point \((\delta=0)\) will have a characteristic size \(l = sR\). For small \(s\) distance to circle is smaller than line → larger difference with distance to point → smaller test stat.

For \(s=0\) \(\chi^2\) is recovered

M. Blennow, P. Coloma and EFM 1407.3274
Is it a $\chi^2$?

Final sensitivity not very affected.
Present hint? Significance??

From J. Elevant and T. Schwetz 1506.07685
Probabilities

T2K/T2HK

Plot from the Physics Briefing Book: Input for the Strategy Group to the European Strategy for Particle Physics
Probabilities

NOνA

Plot from the Physics Briefing Book: Input for the Strategy Group to the European Strategy for Particle Physics
Probabilities

LBNE (LBNF)

Plot from the Physics Briefing Book: Input for the Strategy Group to the European Strategy for Particle Physics
Precision

θ_{13} : 3° - 10°

P. Coloma, A. Donini, EFM and P. Hernandez 1203.5651
Optimization of facilities for large $\theta_{13}$

Signal systematics and not stats becomes the bottleneck for large $\theta_{13}$, explore second peak?  P. Coloma and EFM 1110.4583
Present hint Significance

From J. Elevant and T. Schwetz 1506.07685
Plus non-oscillation searches:

\[ m_{\beta\beta} = m_1 c_{12}^2 c_{13}^2 + m_2 s_{12}^2 c_{13}^2 e^{2i\alpha_1} + m_3 s_{13}^2 e^{2i\alpha_2} \]