Studying the impact of neutrino cross-section mismodelling on the T2K oscillation analysis

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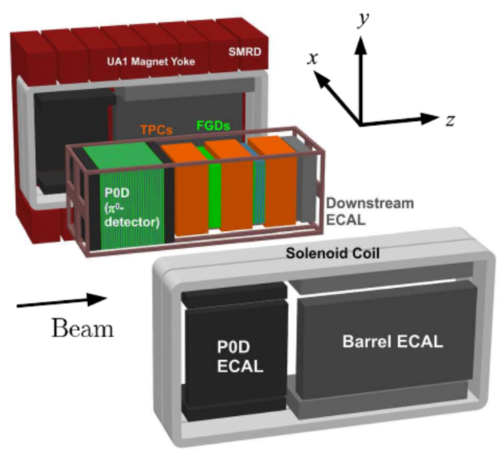
on behalf of the T2K Collaboration

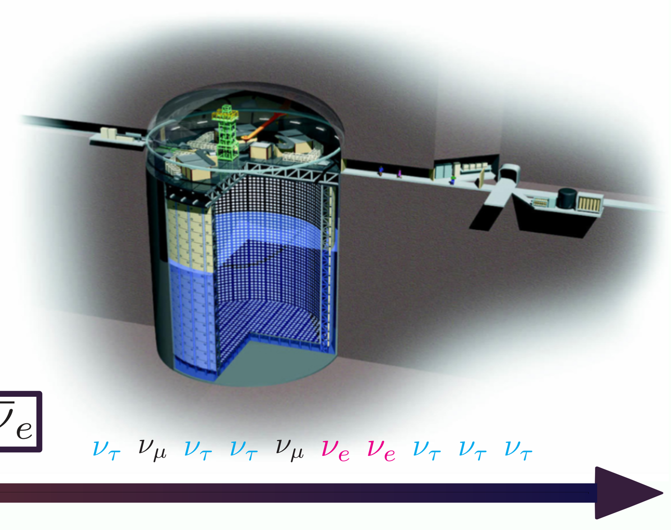
The T2K experiment

- Tokai-To-Kamioka (T2K) : long baseline neutrino oscillation experiment in Japan [1].
- High intensity muon (anti)neutrino beam produced at J-PARC (Tokai).
- Near detector (ND280) located at 280m from production target
- Far detector Super-Kamiokande (SK), 50kt water Cherenkov detector at 295 km.



- Off-axis : near and far detectors at 2.5° of the beam's axis, narrow band beam, peaked at 0.6 GeV.
- Main goal : measure θ_{23}, Δm^2_{32}, and δ_{CP} with muon (anti)neutrino disappearance and electron (anti)neutrino appearance in the muon (anti)neutrino beam.

$\nu_\mu \rightarrow \nu_\mu$ $\nu_\mu \rightarrow \nu_e$ $\overline{\nu}_\mu \rightarrow \overline{\nu}_\mu$ $\overline{\nu}_\mu \rightarrow \overline{\nu}_e$



External data
Build flux and cross-section models with external datasets

ND280 data
Those models are tuned and constrained with muon neutrino CC interactions in ND280

SK data
In order to extract the oscillation parameters the flux and cross-section models are fitted to the SK data

Cross-section mismodelling study

1. Cross section models

- T2K oscillation analysis based on **flux and cross-section models** :

$$N^{FD}_{\nu_\beta}(E_\nu) = \Phi^{FD}_{\nu_\beta}(E_\nu) \times \sigma^{FD}_{\nu_\beta}(E_\nu) \times \varepsilon^{FD}(E_\nu) \times P_{\nu_\alpha \to \nu_\beta}(E_\nu)$$

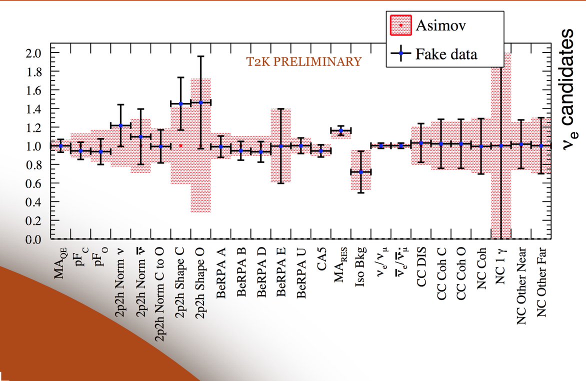
- **Flux** models built with measurements from T2K beam line and NA61/SHINE experiment [2].
- **Cross-section** models in NEUT [3] tuned to external data sets (MINERνA [4], MiniBooNE [5], bubble chambers experiments [6]...)
  - Interactions simulated in T2K, including nuclear effects :

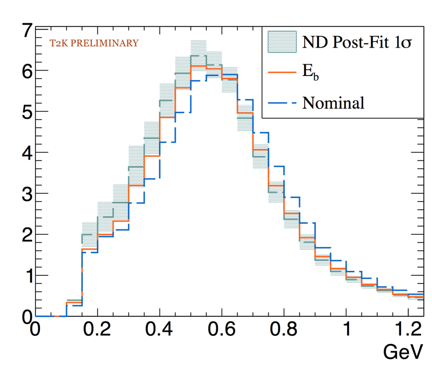
  CCQE | 2p2h | CC-Res | CC-Coh | CC-Other | NC-π^0 | NC-$\pi^\pm$ | NC-Coh | NC-1γ | NC-Other

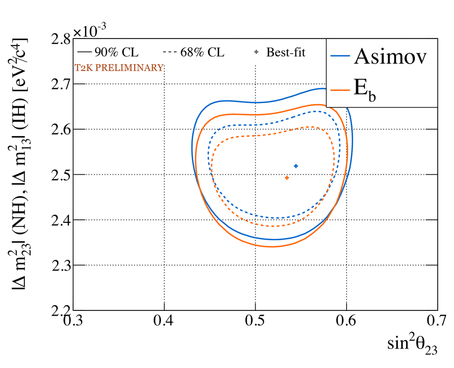
  - Nominal CCQE model : RFG + BeRPA + Nieves 2p2h [7,8,9].
- Evaluate the effect of cross-section mismodelling : **alternative models produce simulations** fitted as pseudo data.
  - Different CCQE, 2p2h, CC-Res, nuclear models.
  - Here : **modified binding energy** E_b (largest one).

$$E^C_b = 25 \rightarrow 43\ MeV \qquad E^O_b = 27 \rightarrow 45\ MeV$$

2. Procedure







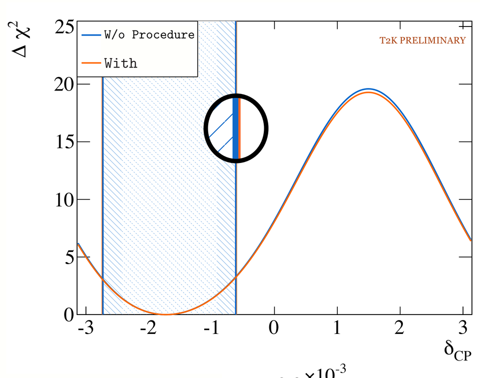
Same procedure as the oscillation analysis with near and far detector fits :

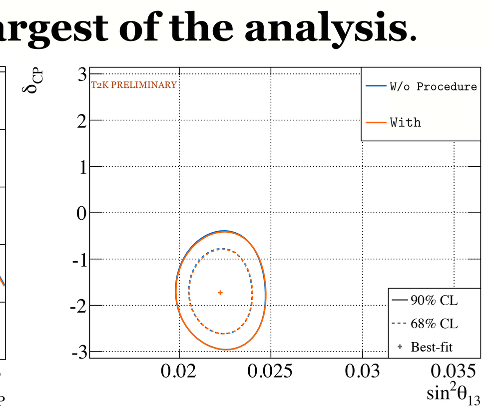
1. **Pseudo data** built at ND280 and SK.
2. **ND280** nominal model fitted to the pseudo data.
3. Tuned models passed to **SK** for SK simulated data fit.
4. **Compare** resulting $\Delta\chi^2$ surfaces for oscillation parameters with an Asimov fit (nom. MC).

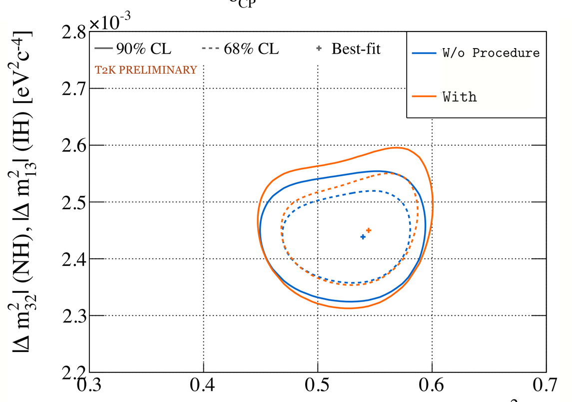
Differences can be interpreted as biases.

5. Effect on the data fit

Full procedure mainly affects the disappearance data fit contour $\boldsymbol{\theta_{23}}$ **-** $\boldsymbol{\Delta m^2_{32}}$.
Impact non negligible : the additional uncertainty is now **one of the largest of the analysis**.



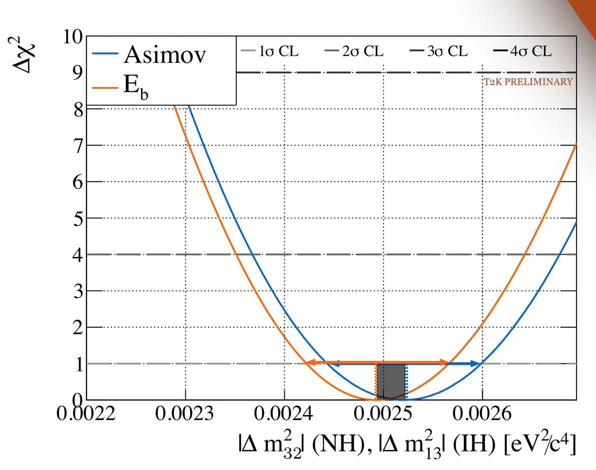




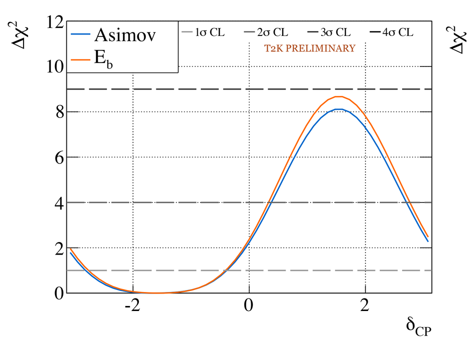
3. Impact of cross-section mismodelling

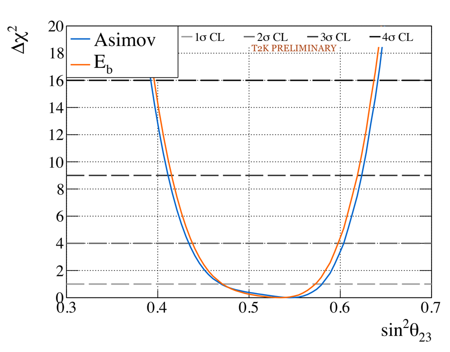
- 2D contours (θ_{23} Δm^2_{32}) and (δ_{CP} θ_{13}) of pseudo data and Asimov compared.
- **Quantify** the effect : compare 1D likelihood for θ_{23}, Δm^2_{32}, and δ_{CP} .
- Bias defined as the difference between pseudo data and Asimov 1σ interval means over the size of 1σ of the Asimov.

$$\text{bias} = \frac{\text{mean}_{PD} - \text{mean}_{MC}}{\sigma_{MC}}$$



- Bias computed for the three parameters and all of the sets of pseudo data.
- **"Acceptable" bias : 25% of the uncertainty or 50% of the systematic uncertainty.**





Bias without any additional uncertainty

	θ_{23}	Δm^2_{32}	δ_{CP}
$1\sigma_{Stat+Syst}$	15%	90%	2%
$1\sigma_{\text{Syst}}$	40%	200%	10%

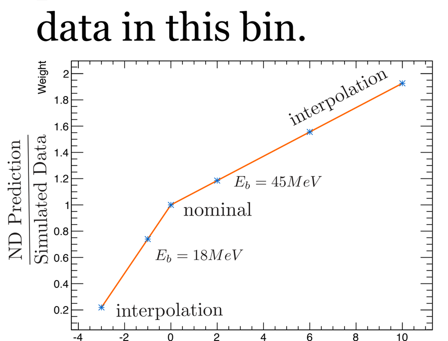
Bias with the new parameter and smearing

	θ_{23}	Δm^2_{32}	δ_{CP}
$1\sigma_{Stat+Syst}$	10%	20%	2%
$1\sigma_{\text{Syst}}$	20%	40%	5%

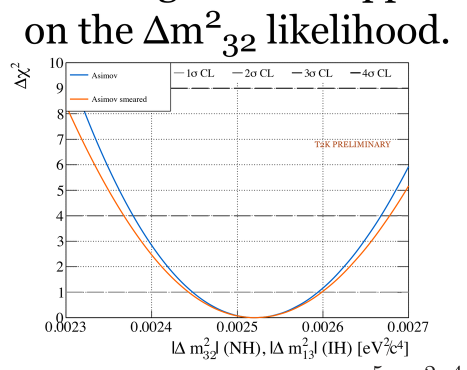
4. An additional uncertainty

- Observed biases too large : need some additional uncertainty to account for the lack of freedom of the models.
- Bias on θ_{23} reduced with a new uncertainty, via the introduction of a new parameter. To reduce bias on Δm^2_{32} smear the likelihood after the fit.

1 Spline parameter based on the E_b simulated set. Spline knots : post-ND prediction over simulated data in this bin.



2 Quadrature sum of the absolute bias of the sets with largest effect applied on the Δm^2_{32} likelihood.



smearing factor $= 4.08 \cdot 10^{-5} eV^2c^4$

Biases reduced with those new uncertainties.
The impact is **non negligible** and the additional uncertainty added is one of the largest of the analysis(~2% on the event rate of 1Rμ and ~7% on the 1Re in neutrino mode).

Final results

- Bias observed in all the sets small enough, with the addition of the new parameter and the smearing, to **fit the data**.
- T2K data from run 1 to 9, **1.47×10²¹ POT in neutrino mode and 1.12×10²¹ POT in anti-neutrino mode.**
- Reductions of the biases will come from **upgrades of the underlying cross-section models**. Work is already ongoing, in particular for CCQE, 2p2h, CC-Res, and nuclear models.

T2K Only

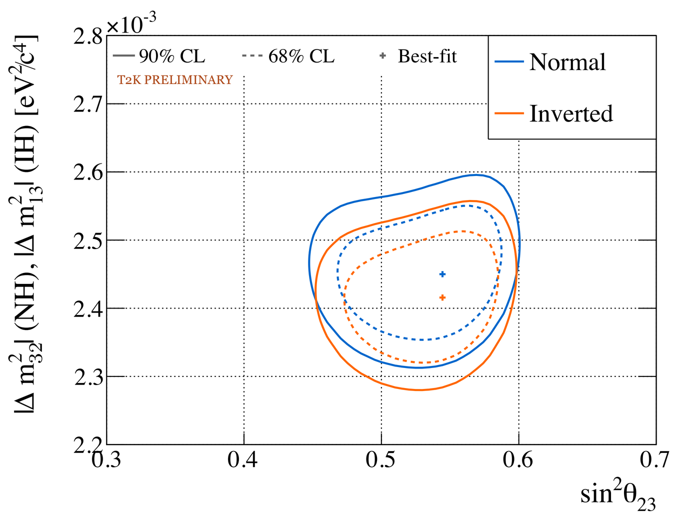
$\sin^2\theta_{23} = 0.487^{+0.064}_{-0.046}$ $\quad$ $\sin^2\theta_{13} = 0.0283^{+0.0058}_{-0.0048}$

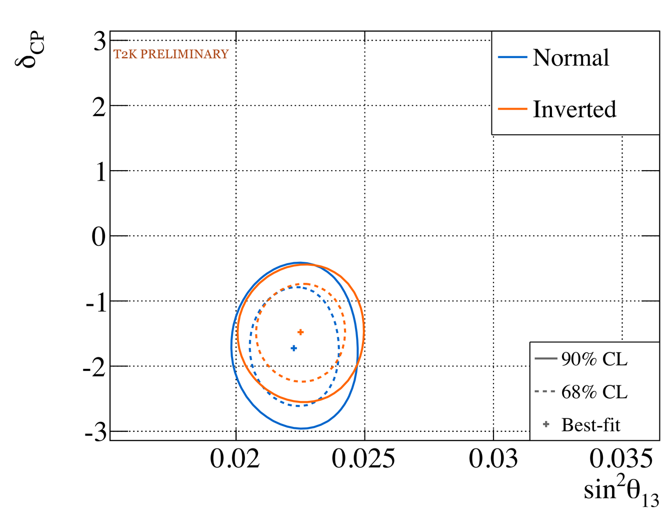
$(NH)|\Delta m^2_{32}| = 2.446^{+0.065}_{-0.063} \times 10^{-3}\text{eV}^2/c^4$ $\quad$ $\delta_{CP} = -1.71^{+0.81}_{-0.82}$

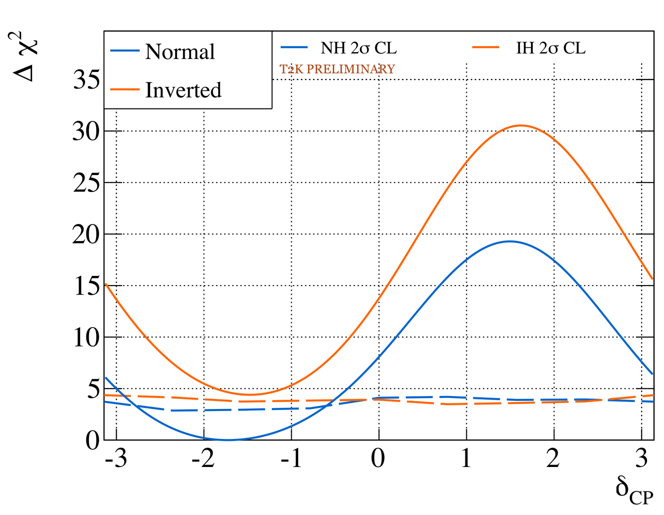
With Reactor Constraint

$\sin^2\theta_{23} = 0.543^{+0.029}_{-0.050}$ $\quad$ $\sin^2\theta_{13} = 0.0224 \pm 0.0011$

$(NH)|\Delta m^2_{32}| = 2.450^{+0.068}_{-0.065} \times 10^{-3}\text{eV}^2/c^4$ $\quad$ $\delta_{CP} = -1.69^{+0.60}_{-0.58}$







References

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