Physics reach of ESSnuSB

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TAUP 2021
IFIC, Valencia, Spain (Online)
26 August - 3 September, 2021

Based on: A. Alekou *et al.* [ESSnuSB], 2107.07585

Neutrino Oscillation

- Neutrino oscillation: transition from one flavor to another

  time=0; time=t;

  ν_e; $\longrightarrow$ distance=L; $\longrightarrow$ ν_e, ν_μ, ν_τ;

- This is because ν_e, ν_μ, ν_τ are combinations of ν_1, ν_2, ν_3;

$$|\nu_e\rangle = U_{e1}|\nu_1\rangle + U_{e2}|\nu_2\rangle + U_{e3}|\nu_3\rangle$$

- U is 3×3 matrix
- The transition probability $\nu_\alpha \to \nu_\beta$:

$$P_{\alpha\beta} = |\langle \nu_\beta | \nu_\alpha(t) \rangle|^2$$

where α, β are e, μ or τ

Neutrino oscillation in 3 generation

Full three flavour vacuum probability formula:

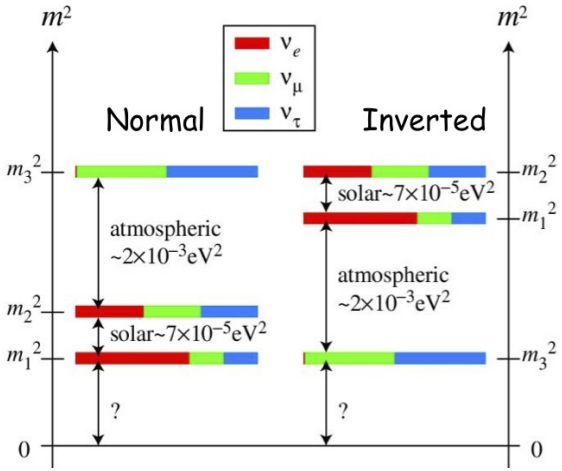
$$P_{\alpha\beta} = \delta_{\alpha\beta} - 4\sum_{i<j} Re[U^*_{\alpha i}U^*_{\beta j}U_{\beta i}U_{\alpha j}]sin^2\frac{\Delta_{ij}L}{4E} + 2\sum_{i<j} Im[U^*_{\alpha i}U^*_{\beta j}U_{\beta i}U_{\alpha j}]sin2\frac{\Delta_{ij}L}{4E}$$

$$\Delta_{ij} = m_i^2 - m_j^2$$

Parameters of neutrino oscillation:

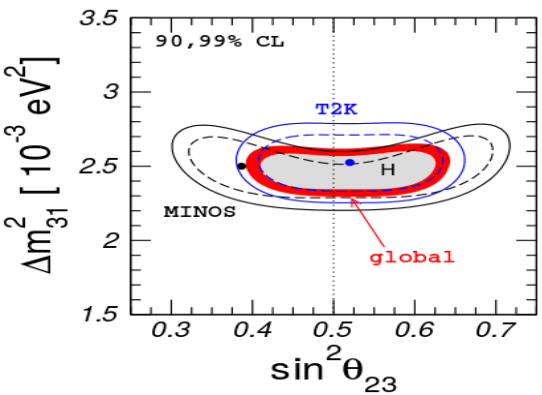
- Elements of U: Three mixing angles and one Dirac phase θ_{12}, θ_{23}, θ_{13}, δ_{CP}
- Two mass squared differences: Appears in $P_{\alpha\beta}$ $\Delta_{21} = m_2^2 - m_1^2$, $\Delta_{31} = m_3^2 - m_1^2$
- L and E

Unknowns



- The sign of Δm^2_{31} i.e.
  $\Delta m^2_{31} > 0 \Rightarrow$ Normal Hierarchy (NH)
  or
  $\Delta m^2_{31} < 0 \Rightarrow$ Inverted Hierarchy (IH).

- The octant of θ_{23} i.e.
  $\theta_{23} > 45^\circ \Rightarrow$ Higher Octant (HO) or
  $\theta_{23} < 45^\circ \Rightarrow$ Lower Octant (LO).



- δ_{CP} (violation and precision)

The ESSnuSB experiment

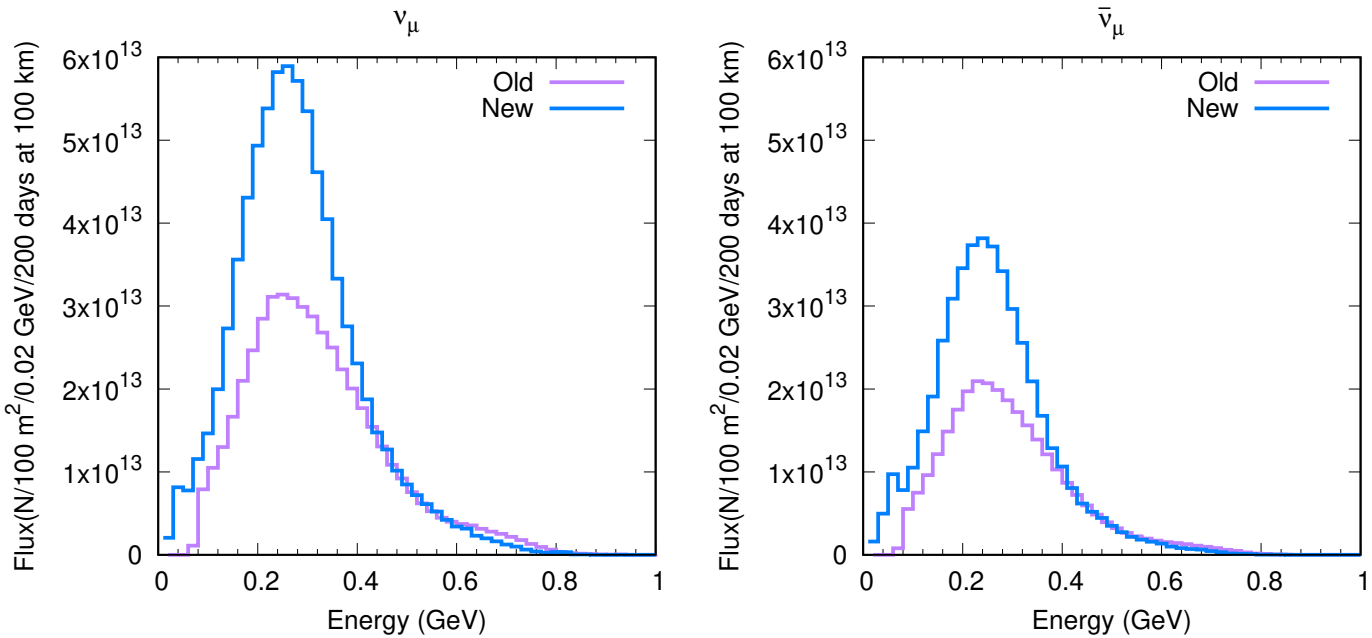
- L = 540 km/360 km
- E = 0.35 GeV
- 538 kt WC detector
- Unique: Probes Second oscillation maximum

This Work

Calculated updated physics performance with

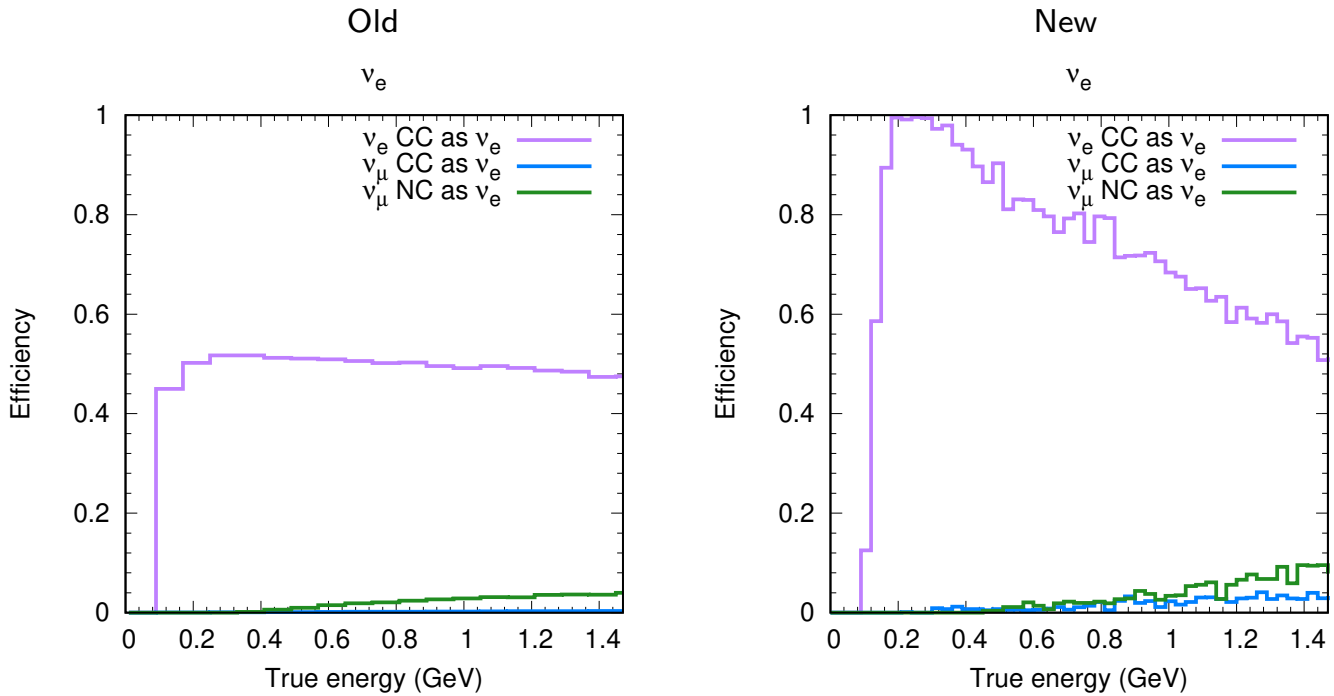
updated flux and updated event selection

Updated flux



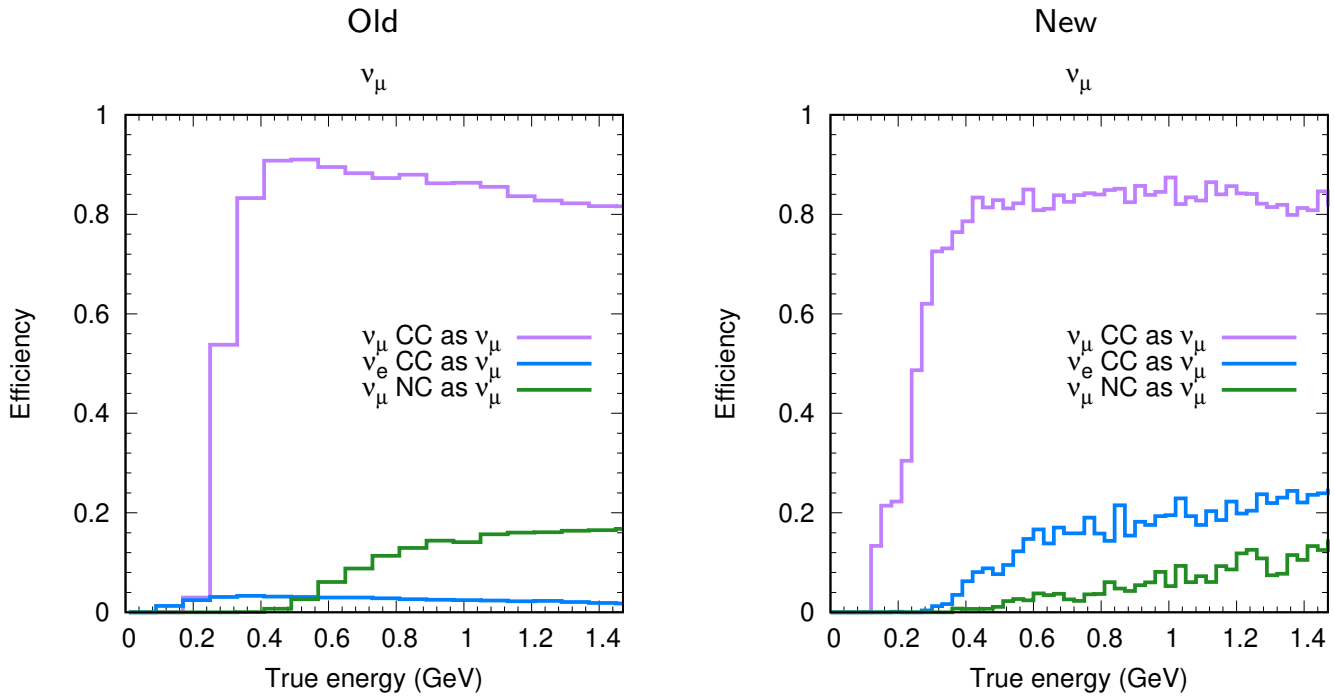
- Old flux was from the MEMPHYS project
- Significant improvement in the new flux

Updated efficiency (ν_e)



- Old selection was from the MEMPHYS project
- Significant improvement in the ν_e selection

Updated efficiency (ν_μ)



- Old selection was from the MEMPHYS project
- ν_μ selection is almost same

Systematics

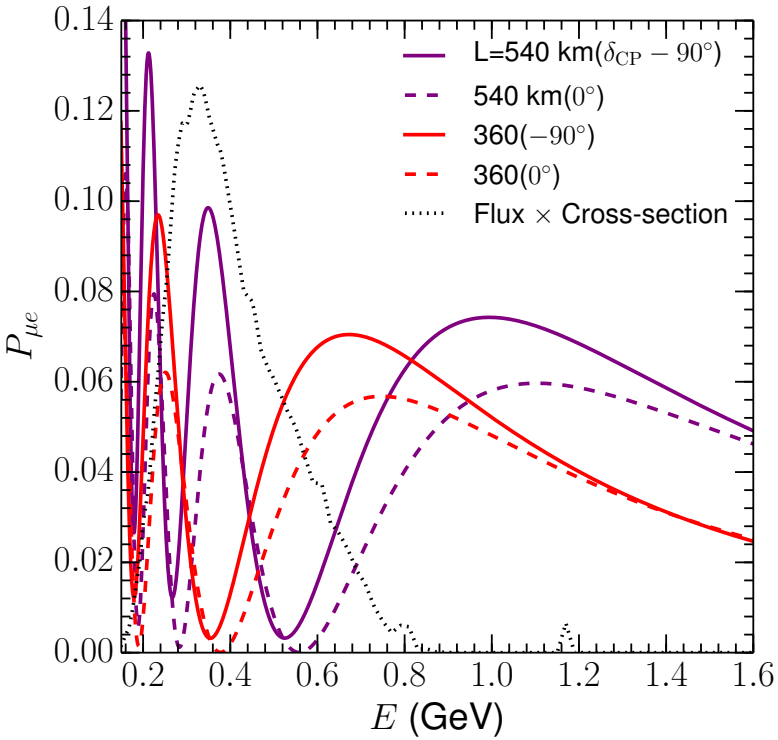
Normalization error

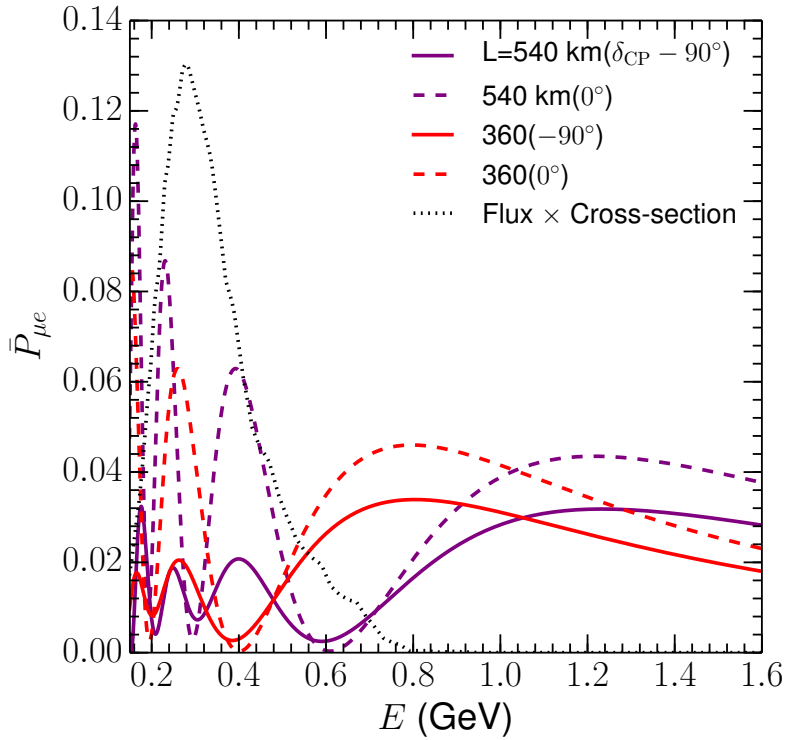
- 5% in signal
- 10% in background

Shape error

- Not included in the current analysis

Probability and Flux

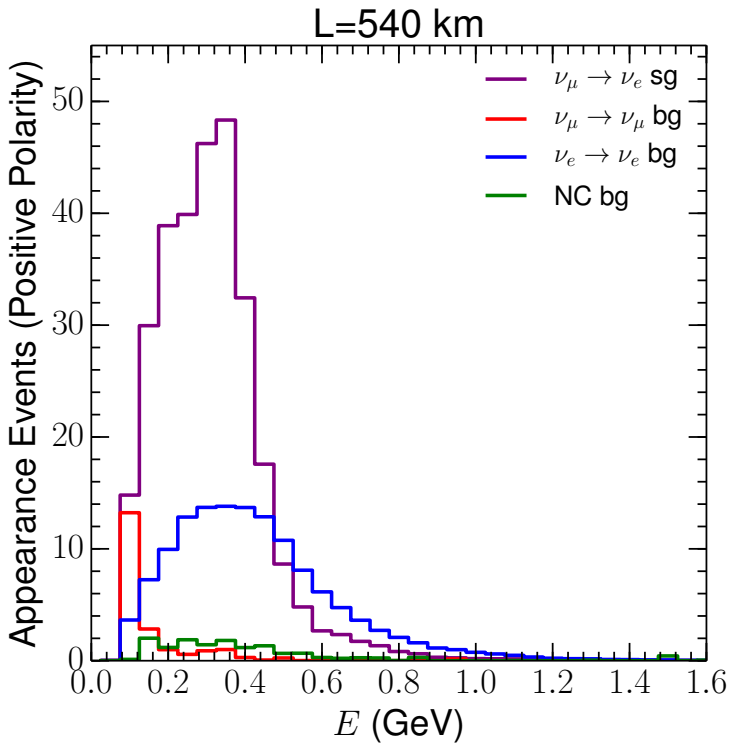


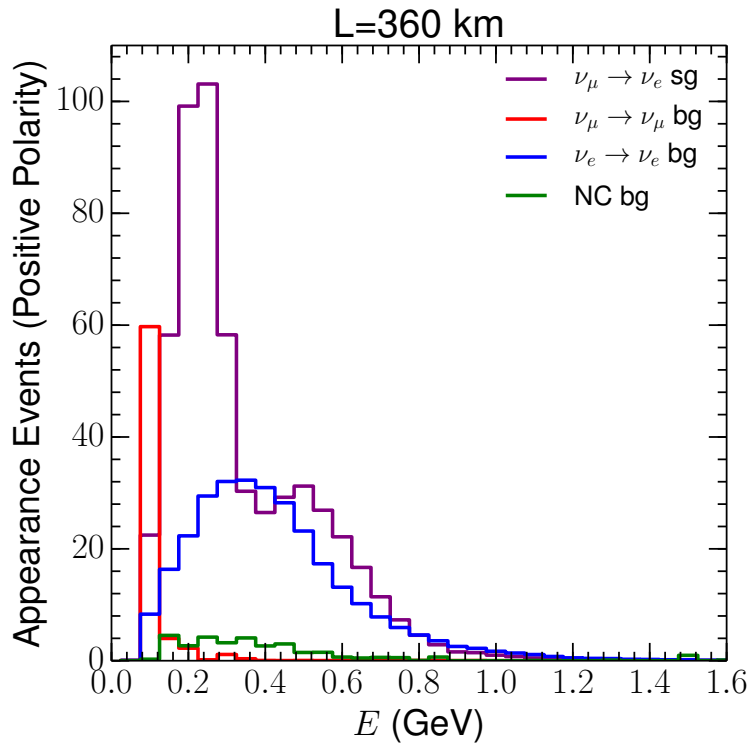


- Probes 2nd maximum
- Separation between the curves are more in 2nd maximum

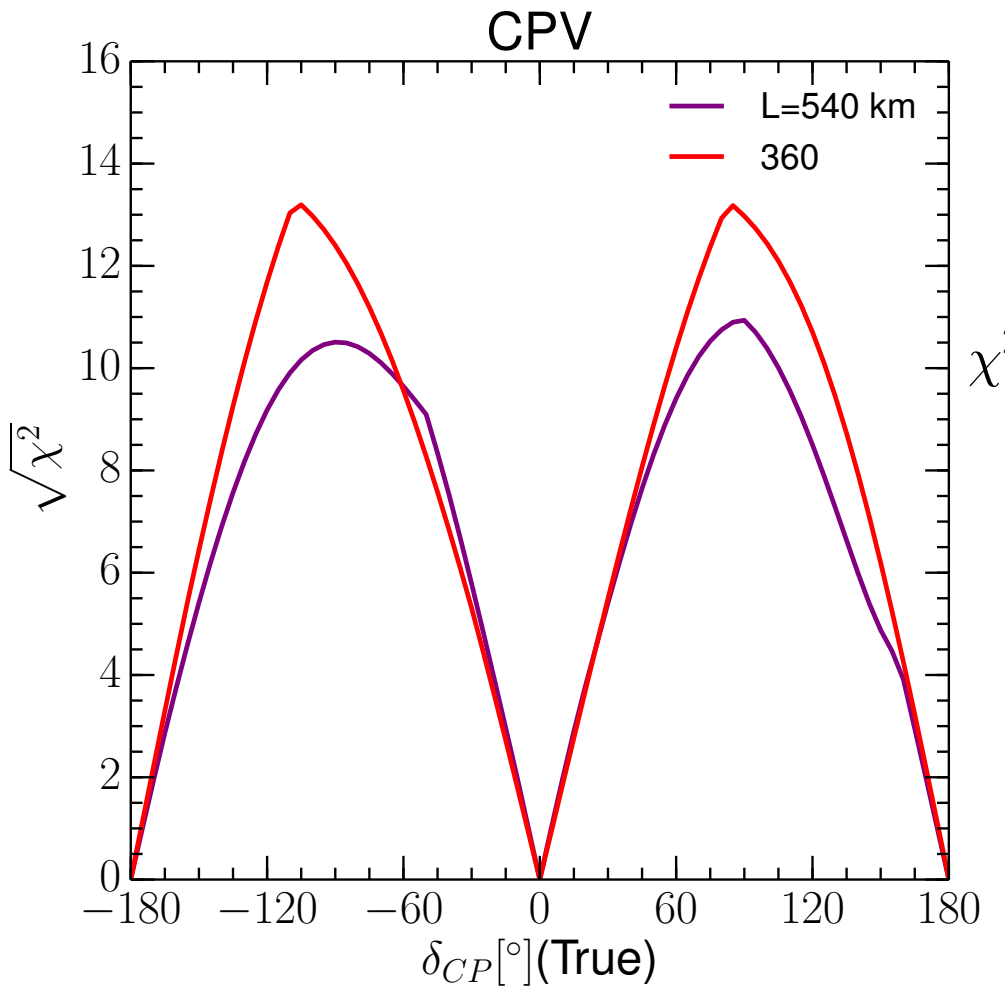
ν_e events/year

	Channel	$L = 540$ km	$L = 360$ km
Signal	$\nu_\mu \to \nu_e$ ($\bar{\nu}_\mu \to \bar{\nu}_e$)	292.77 (70.04)	557.52 (118.80)
Background	$\nu_\mu \to \nu_\mu$ ($\bar{\nu}_\mu \to \bar{\nu}_\mu$)	20.41 (4.41)	68.12 (13.81)
	$\nu_e \to \nu_e$ ($\bar{\nu}_e \to \bar{\nu}_e$)	133.06 (25.13)	298.28 (57.13)
	ν_μ NC ($\bar{\nu}_\mu$ NC)	14.14 (2.27)	31.82 (5.11)





CP violation sensitivity

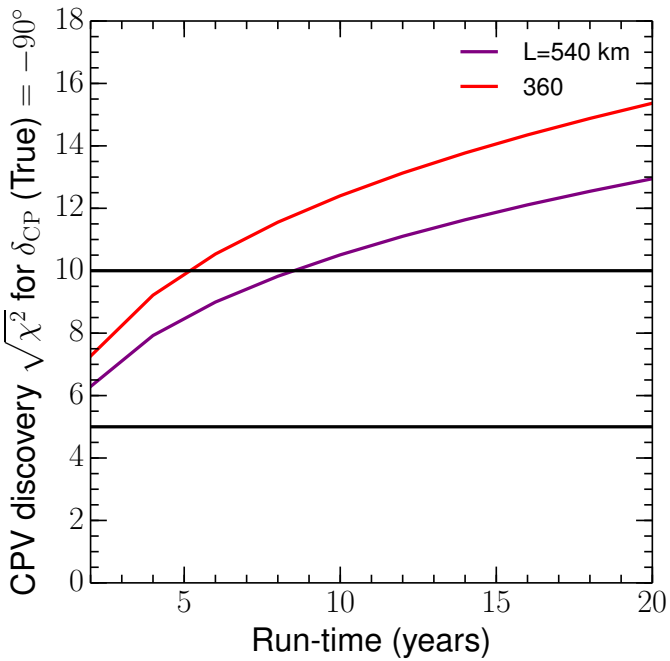


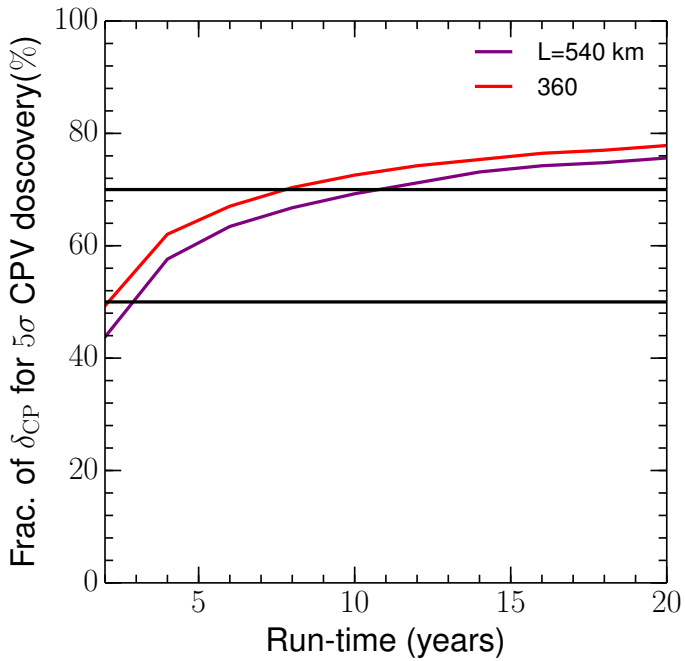
- To exlclude $\delta_{CP} = 0^\circ$ and 180°

$$\chi^2 = \frac{(N(\delta^{tr}_{CP}) - N(\delta^{test}_{CP} = 0, 180^o))^2}{N(\delta^{tr}_{CP})}$$
$$= 0 \text{ for } \delta^{tr}_{CP} = 0^\circ \text{ and } 180^\circ$$
$$\neq \text{otherwise}$$

- Smaller baseline: More events at 360 km

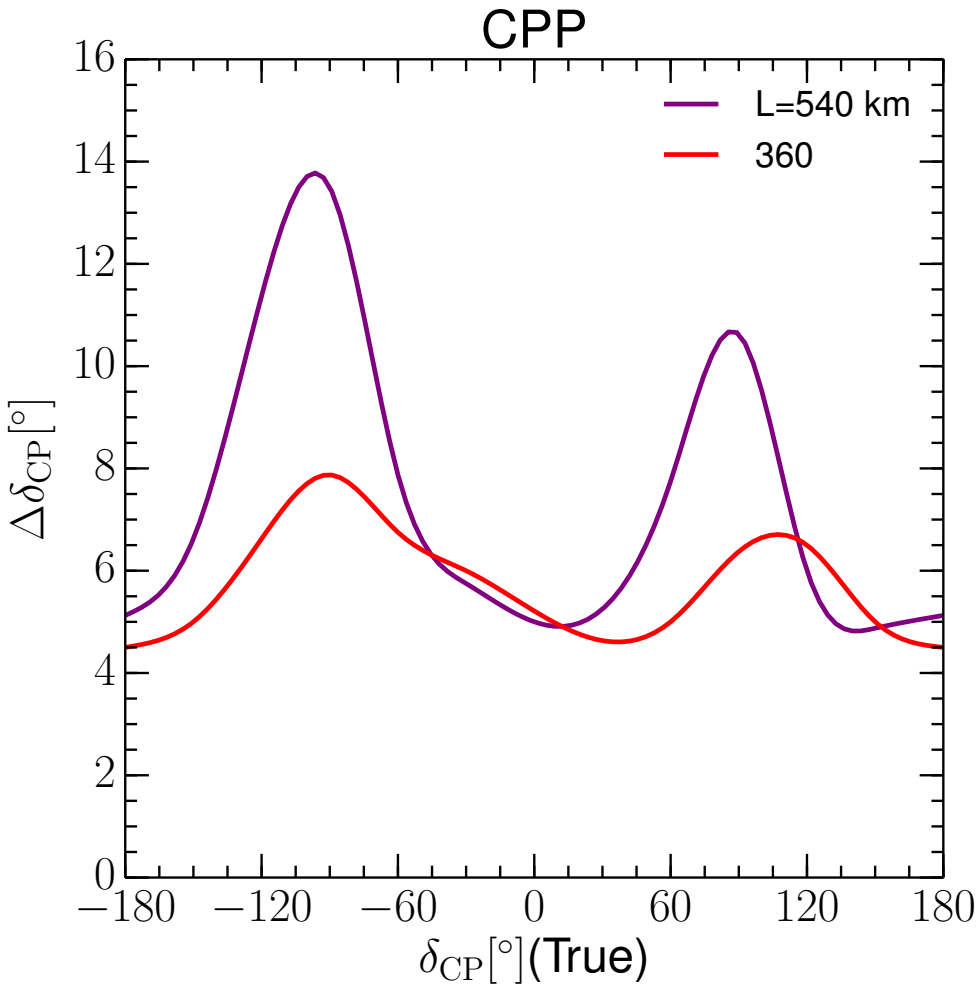
CPV vs run-time





- Left: same χ^2 but for $\delta_{\rm CP} = -90°$
- Right: Fraction of $\delta_{\rm CP}$ for which $\chi^2 \geq 25$

CP precision sensitivity

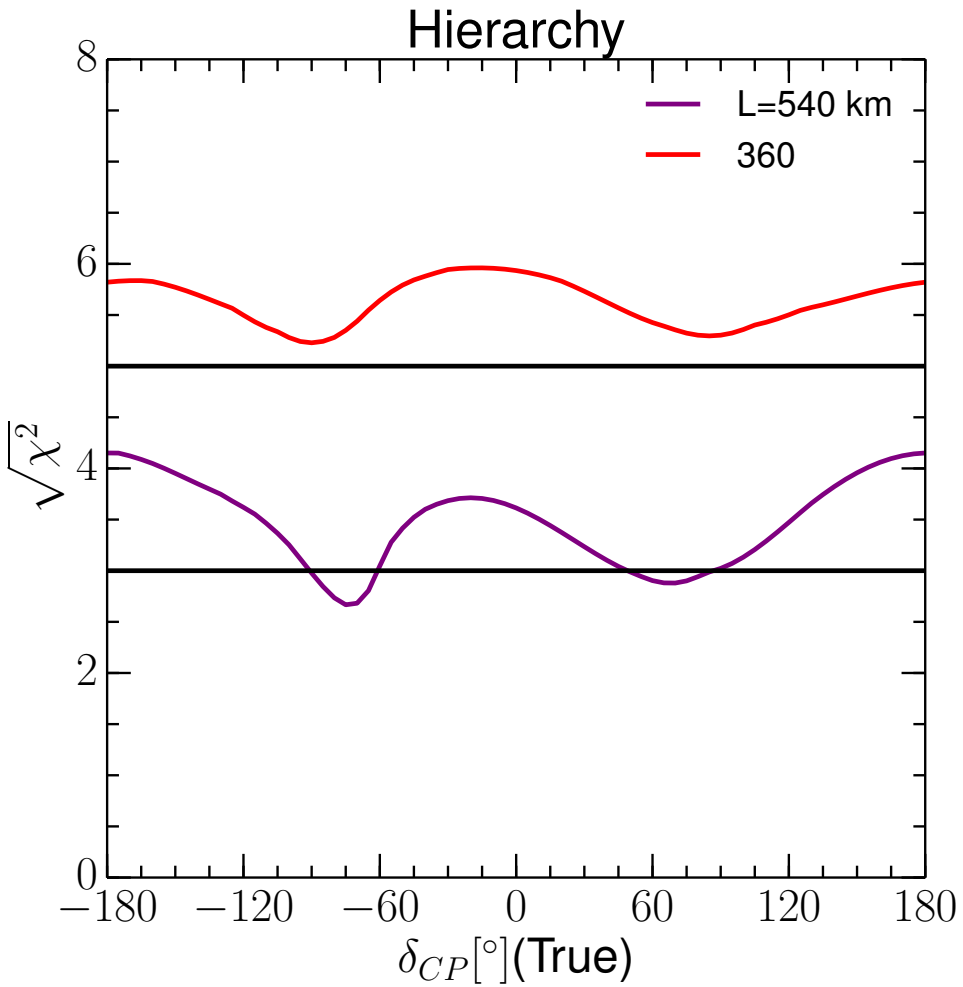


- To precisely measure $\delta_{\rm CP}$

$$\begin{aligned} \chi^2 &= \frac{(N(\delta^{tr}_{CP}) - N(\delta^{test}_{CP}))^2}{N(\delta^{tr}_{CP})} \\ &= 0 \text{ for } \delta^{tr}_{CP} = \delta^{test}_{CP} \\ &\neq \text{otherwise} \end{aligned}$$

- Width is the error
- $\delta_{CP} = 0^\circ > \delta_{CP} = \pm 90^\circ$

Hierarchy sensitivity

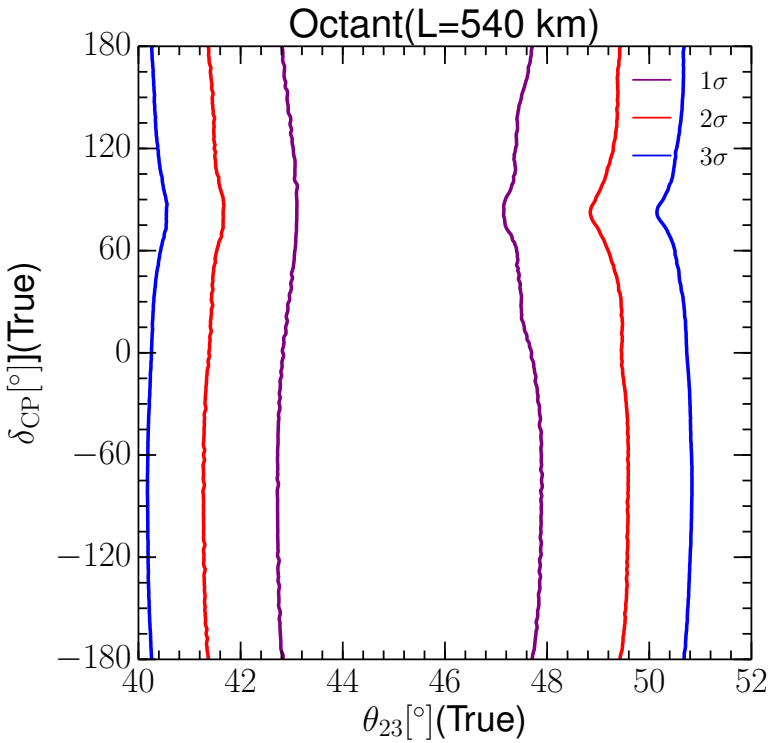


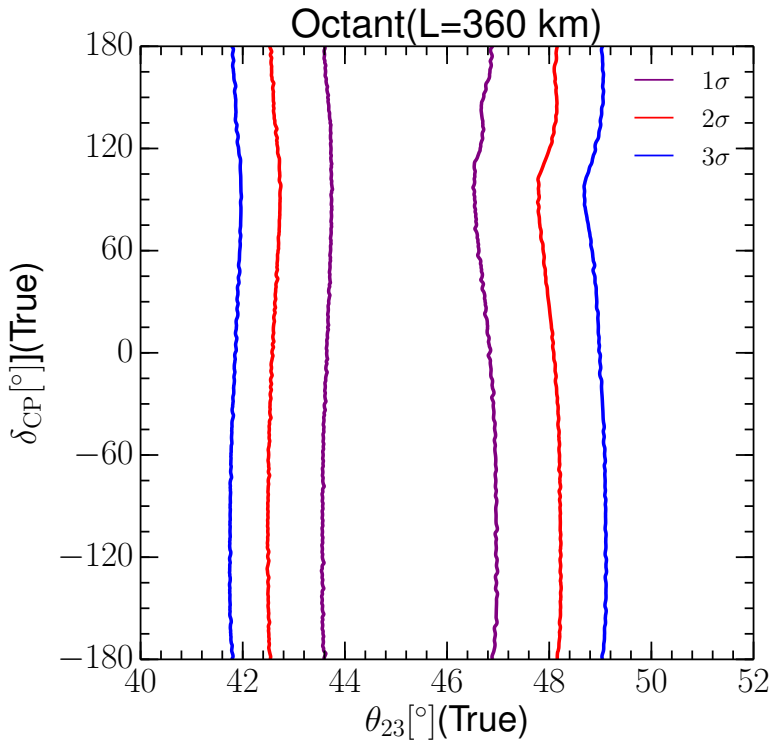
- To exclude wrong hierarchy

$$\chi^2 = \frac{(N(\Delta_{31}) - N(-\Delta_{31}))^2}{N(\Delta_{31})}$$

- More events and more matter effect for 360 km
- Matter effect $\sim E$ which is higher for 360 km

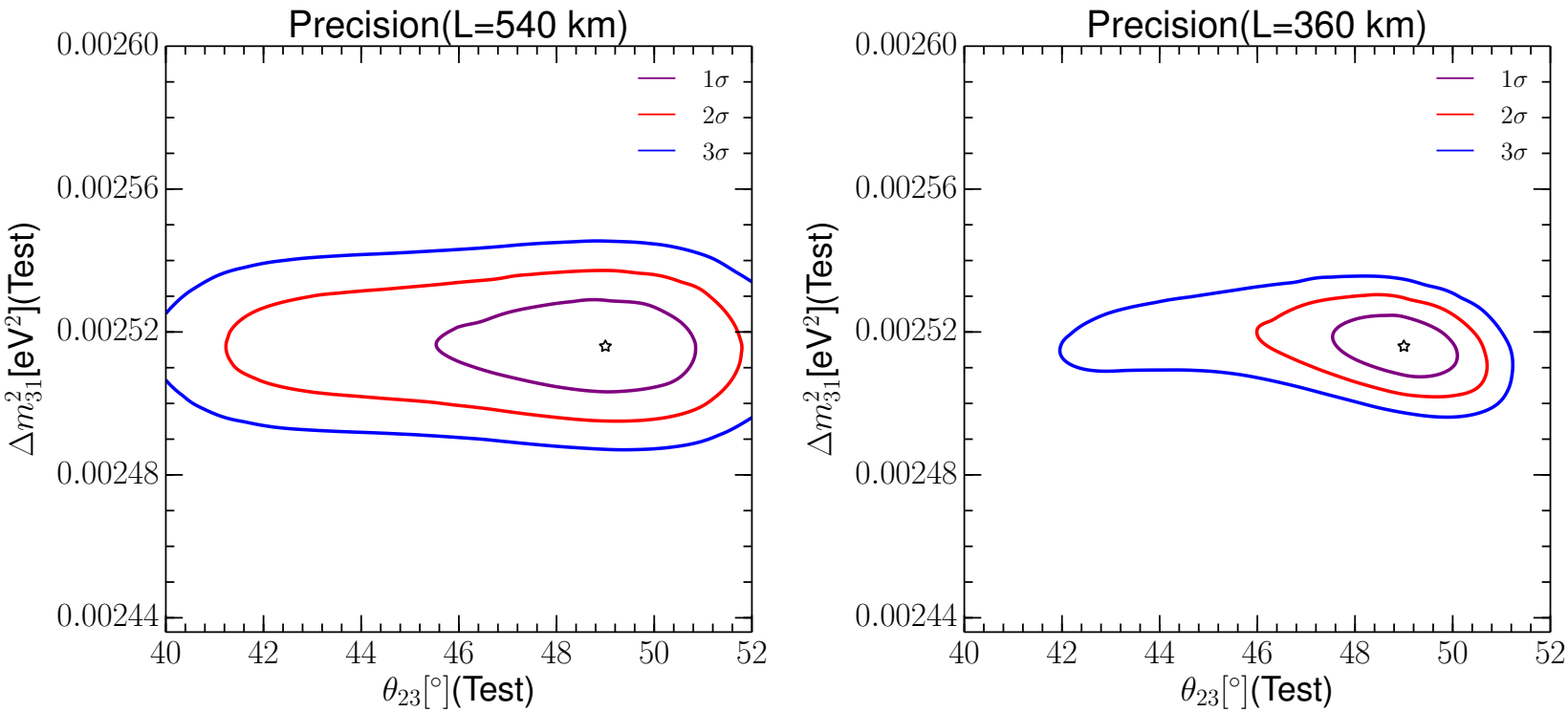
Octant sensitivity





- Limited Octant sensitivity
- 360 is better

Precision of θ_{23} - Δ_{31} sensitivity



- Current best-fit denoted by star
- 360 is better

Effect of shape systematics

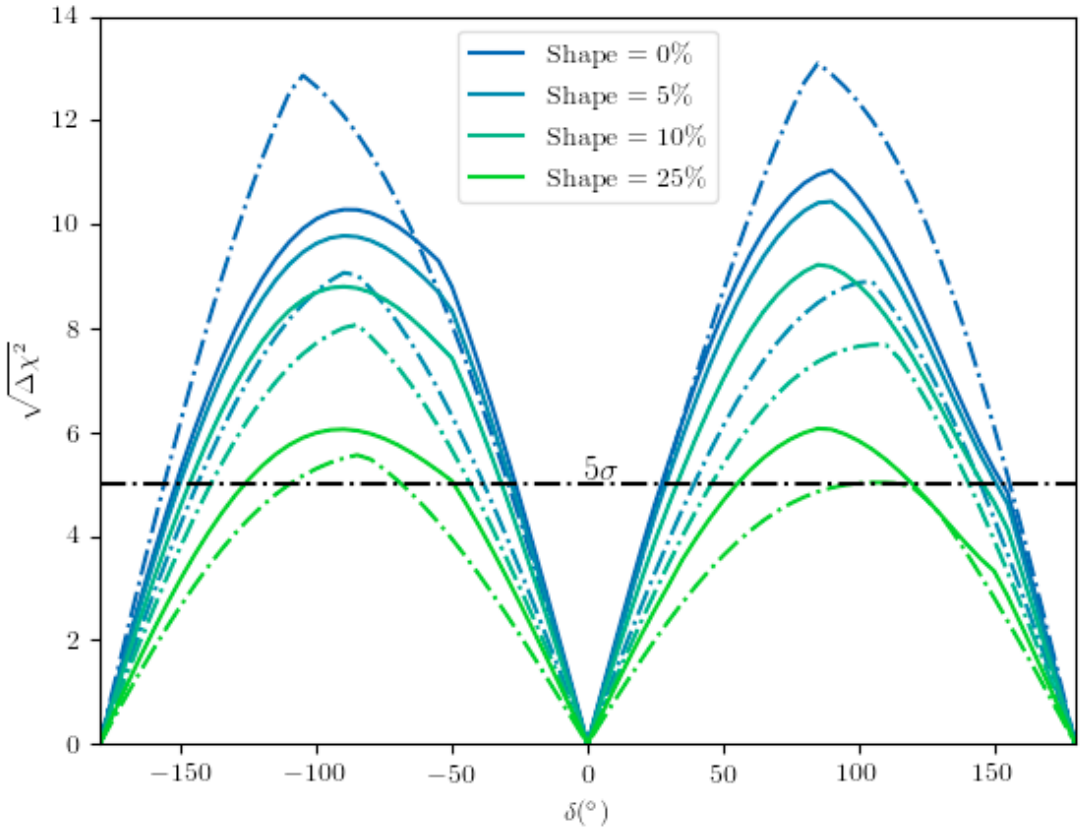


Figure by Enrique Fernandez Martinez and Salvador Rosauro Alcaraz

- Solid: 540 km
  Dashed: 360
- For 0% 360 is better
  for 5% 540 is better

Summary

- Unique experiment to probe 2nd oscillation maximum
- Excellent CP sensitivity
- 360 is better without any shape error
- 540 seems better with shape error

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- Excellent CP sensitivity
- 360 is better without any shape error
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Thank You