Complementarity between long-baseline and atmospheric neutrino experiments:

Implications for the European neutrino program

Sushant Raut

Physical Research Laboratory, India

based on work in progress with

Monojit Ghosh, Pomita Ghoshal, Srubabati Goswami

EPS HEP 2013
Stockholm
19 July 2013

Neutrino physics today

- Solar parameters: known with better than 5% precision
- θ_{13} : already measured to 10% accuracy by reactor experiments, expected to improve to 5% in a few years
- Atmospheric parameters: $|\Delta_{atm}|$ and $\sin^2 2\theta_{atm}$ known to better than 10% accuracy

Still unknown:

- sgn(Δ_{atm}): mass hierarchy
- sgn(θ_{atm}-45°): octant
- δ_{CP}

Current and upcoming expts:

- NOvA : hierarchy, octant, CPV
- T2K : hierarchy, octant, CPV
- ICAL@INO : hierarchy, octant

Measuring the unknowns

- Other proposals:
  - LBNE
  - LBNO
  - IceCube/PINGU
  - HK, T2HK

Measuring the unknowns

- Other proposals:
  - LBNE
  - LBNO
  - IceCube/PINGU
  - HK, T2HK

"Sorry, we're going down!"

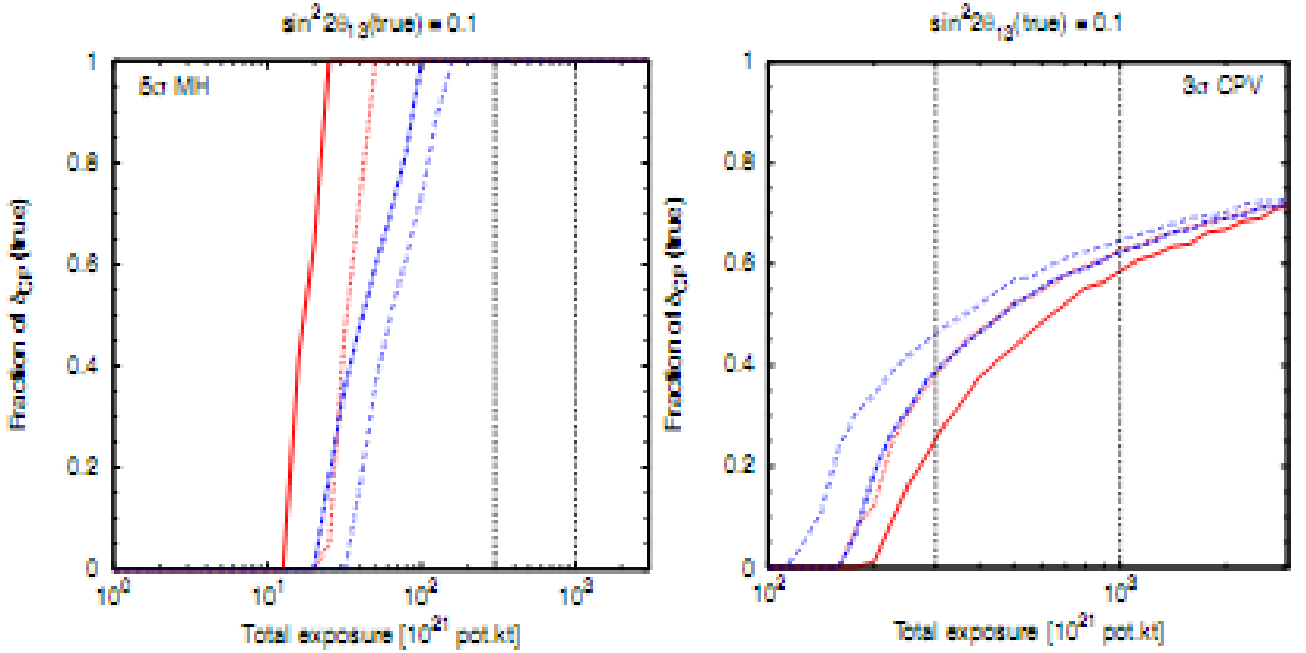
Measuring the unknowns practically

- Other proposals:
  - LBNE
  - LBNO
  - IceCube/PINGU
  - HK, T2HK

Given the fact that NOvA, T2K and INO will collect a certain amount of data, what is the **minimum exposure** required for **LBNO** in order to determine the unknowns?

LBNO capabilities

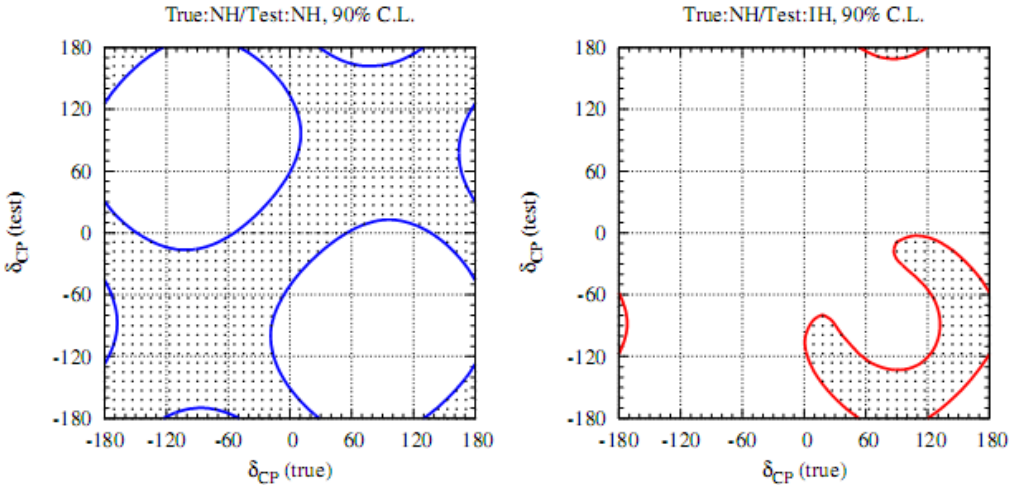
- Many previous studies on the capabilities of the various possible LBNO setups:



Agarwalla, Li, Rubbia: 1109.6526

Pre-LBNO: NOvA, T2K, INO

- It is difficult to measure CPV without knowledge of the hierarchy

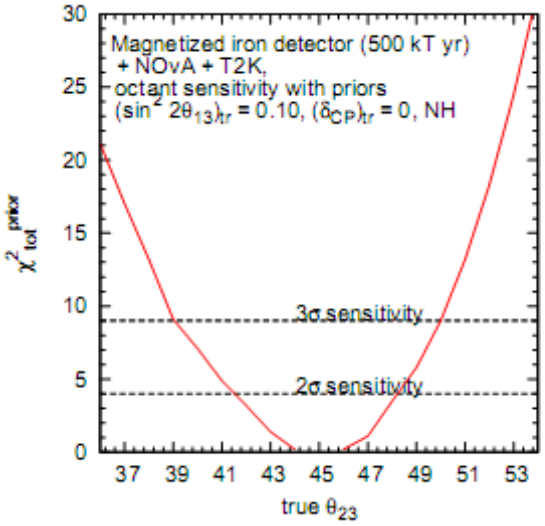


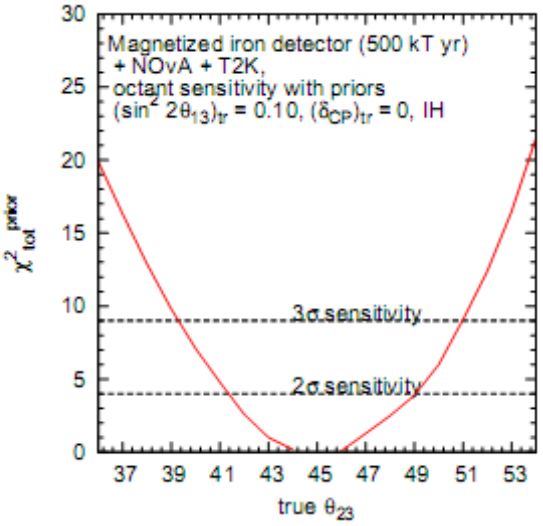
Prakash, SR, UmaSankar: 1201.6485

- But knowledge of the hierarchy itself is a strong function of δ_{CP} for long-baseline expts, giving rise to favourable and unfavourable combinations of parameter values.
- On the other hand, atmospheric neutrino experiments themselves do not have much sensitivity to δ_{CP}
- Thus, the hierarchy determining ability of NOvA + T2K is improved (even for unfavourable combinations) by adding information from INO.

Blennow, Schwetz: 1203.3388
Choubey, Ghosh, Thakore: 1212.1305

Pre-LBNO : NOvA, T2K, INO



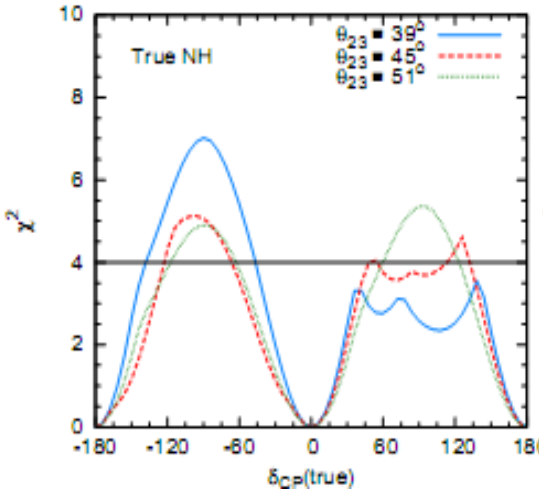


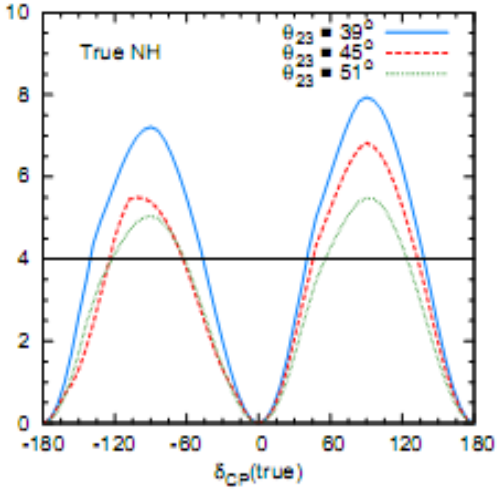
Similarly, NOvA + T2K + INO has good sensitivity to the octant, even though the individual sensitivities are not impressive.

Chatterjee, Ghoshal, Goswami, SR: 1302.1370

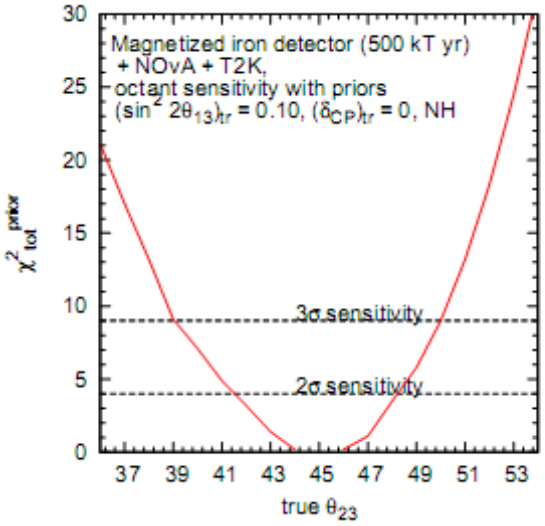
Even for CPV discovery, the inclusion of INO data (which by itself is CP independent) helps to exclude the degenerate solution and improves the CPV discovery potential of NOvA + T2K.

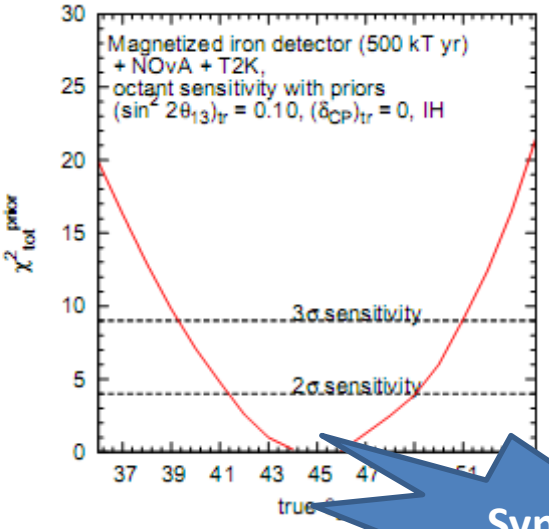
Ghosh, Ghoshal, Goswami, SR: 1306.2500





Pre-LBNO : NOvA, T2K, INO





Similarly, NOvA + T2K + INO has good sensitivity to the octant, even though the individual sensitivities are not impressive.

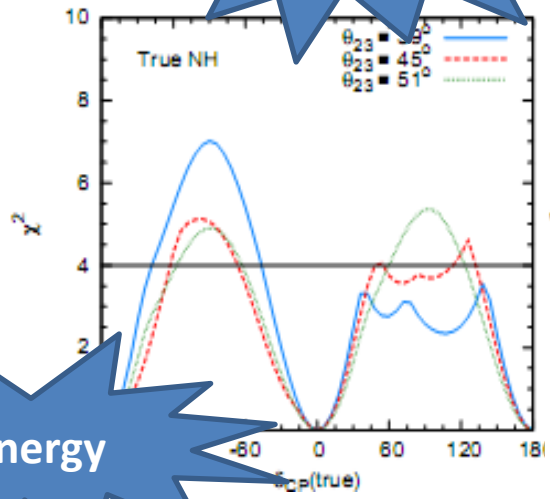
Chatterjee, Ghoshal, Goswami, SR: 1302.1370

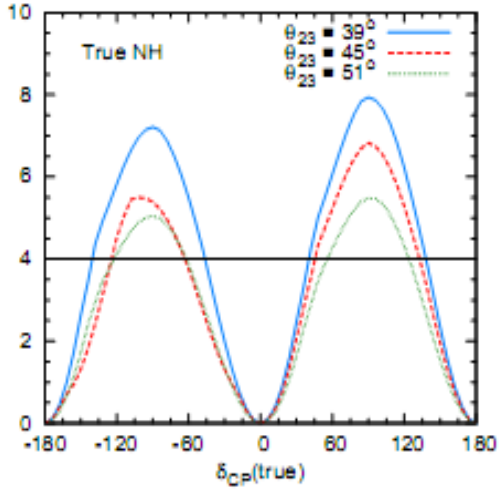
Synergy

Even for CPV discovery, the inclusion of INO data (which by itself is CP independent) helps to exclude the degenerate solution and improves the CPV discovery potential of NOvA + T2K.

Ghosh, Ghoshal, Goswami, SR: 1306.2500

Synergy





Philosophy of this work

- Thanks to synergies between the parameters and channels in various experiments, the combination of NOvA + T2K + INO is capable of providing some sensitivity to determining the hierarchy and octant and discovering CPV

- Question: How small (in terms of exposure*) can we make LBNO to determine the unknown parameters, given the sensitivity that NOvA + T2K + INO will bring to the table?

*exposure (pot kt) = beam intensity (pot/yr) x detector mass (kt) x runtime (yr) (in each, ν and anti-ν)

Eg. 15 x 10e20 pot kt can translate to 15e20 pot/yr x 5 kt x (2ν+2anti-ν yr)

Simulations

- Optimized NOvA (5+5) and T2K (3+0) setups
- Standard INO setup (500 kt yr)

- Three possible LBNO options:
  - 2290 km (CERN-Pyhäsalmi) with a non-magnetized LArTPC
  - 1540 km (CERN-Slanic) with a non-magnetized LArTPC
  - 130 km (CERN-Fréjus) with a WC detector

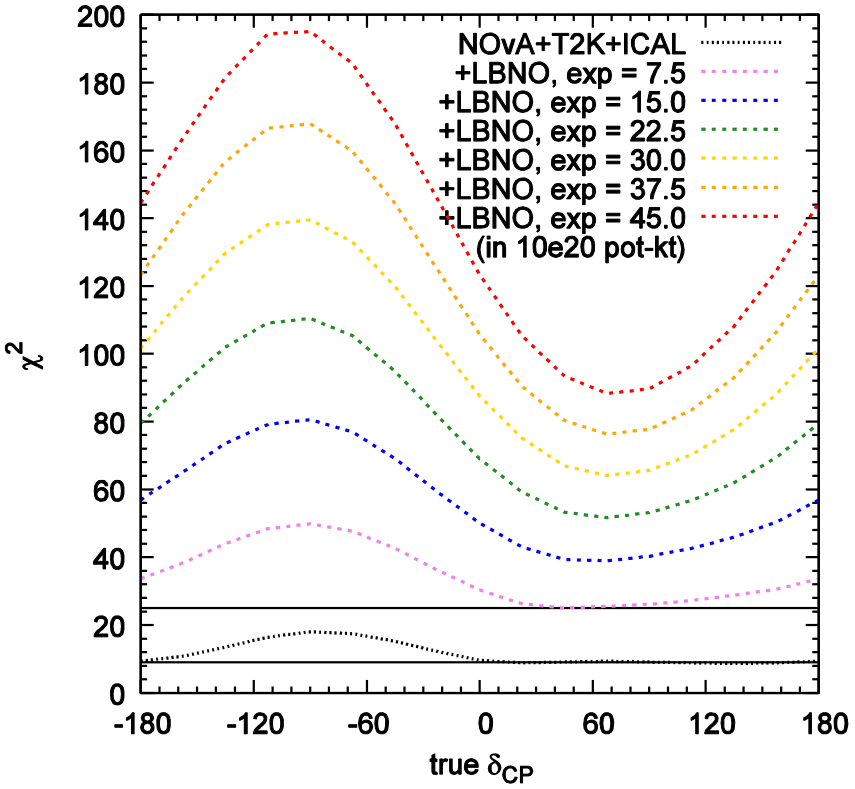
Agarwalla, Li, Rubbia: 1109.6526;
Campagne, Maltoni, Mezzetto, Schwetz: 0607026

- All long-baseline expts simulated using GLoBES

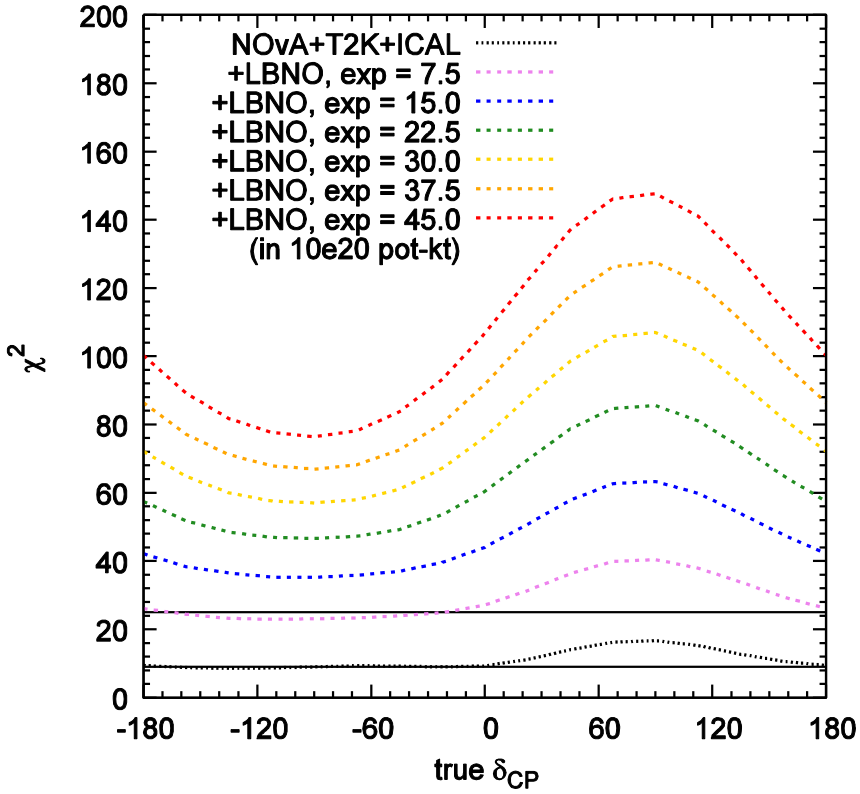
- Hierarchy, octant and CPV sensitivity determined for various exposures
- We require that hierarchy and octant be determined at 5σ, while CPV be discovered at 3σ by the full combination of NOvA + T2K + INO + LBNO

Results: Hierarchy

2290 km, NH

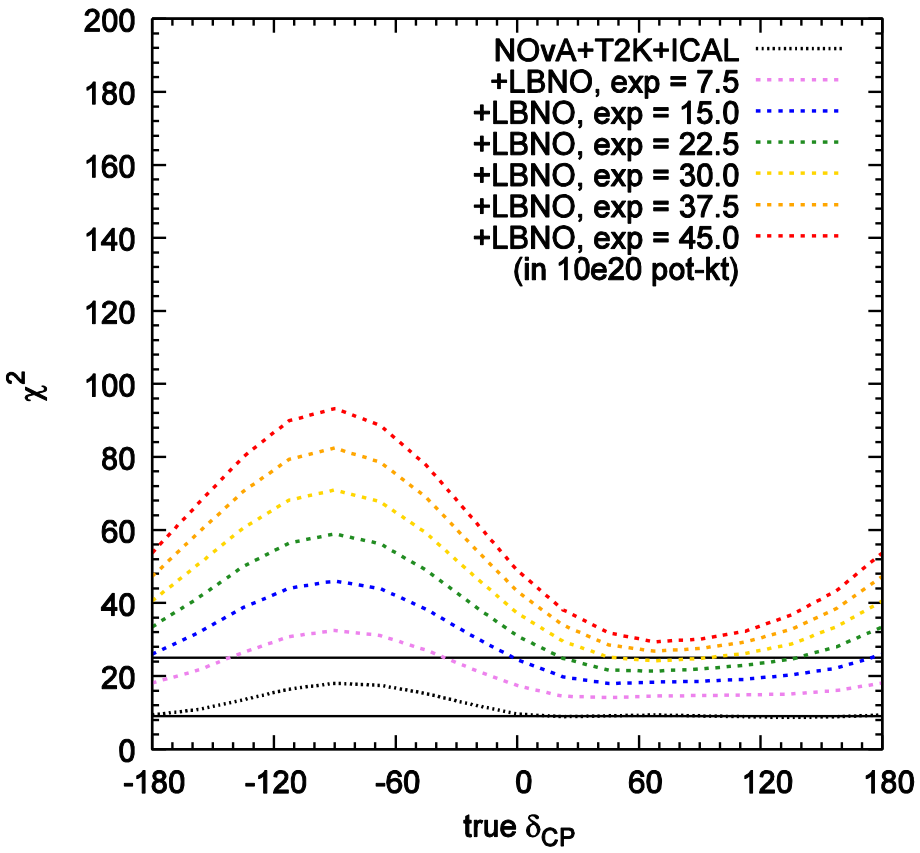


2290 km, IH

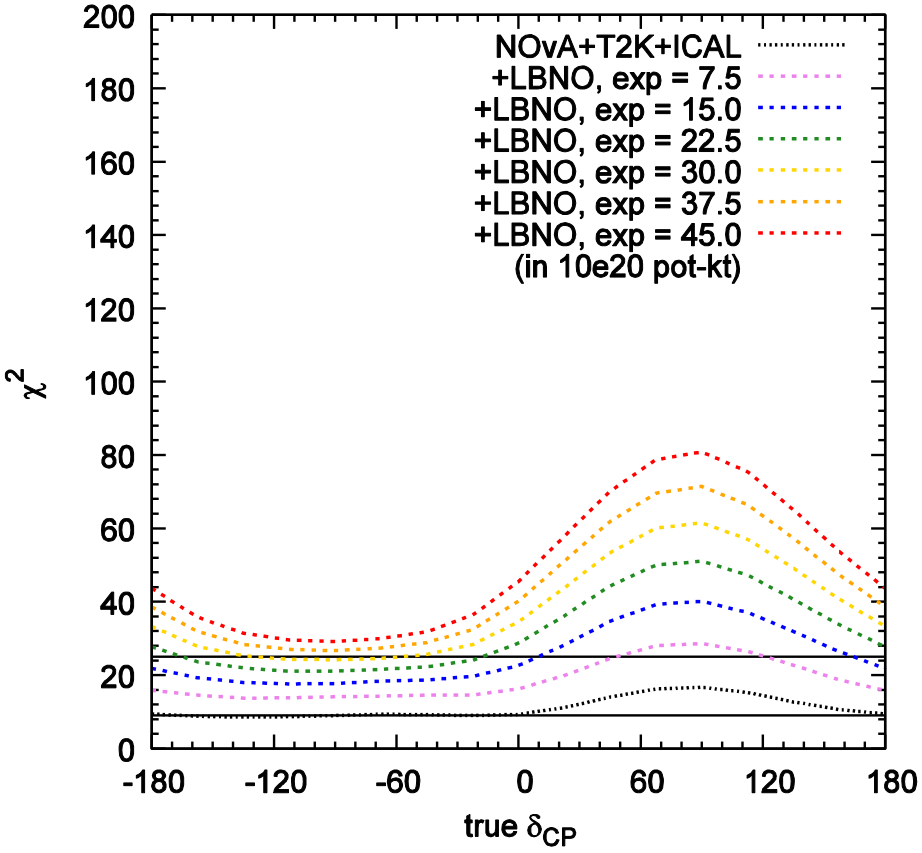


Results: Hierarchy

1540 km, NH



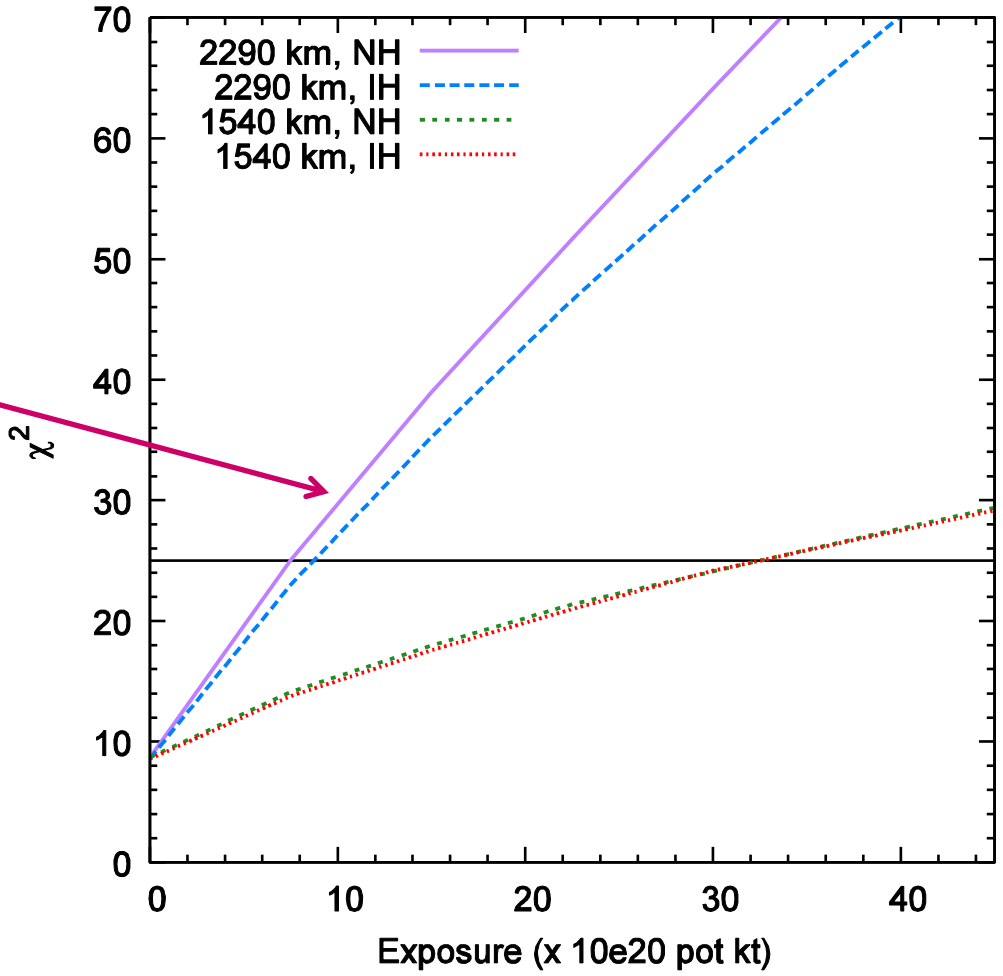
1540 km, IH



Summary: Hierarchy

Close to the bimagic baseline:

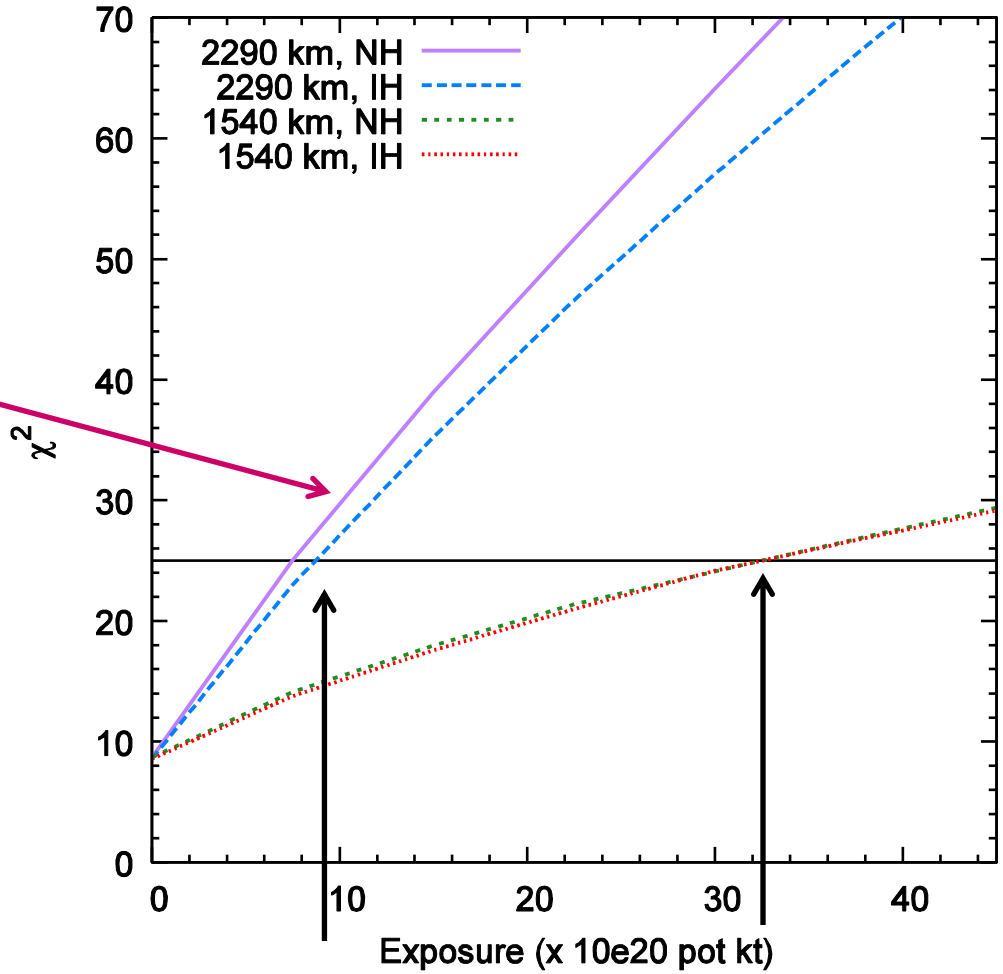
SR, Singh, UmaSankar: 0908.3741 ;
Dighe, Goswami, Ray: 1009.1093



Summary: Hierarchy

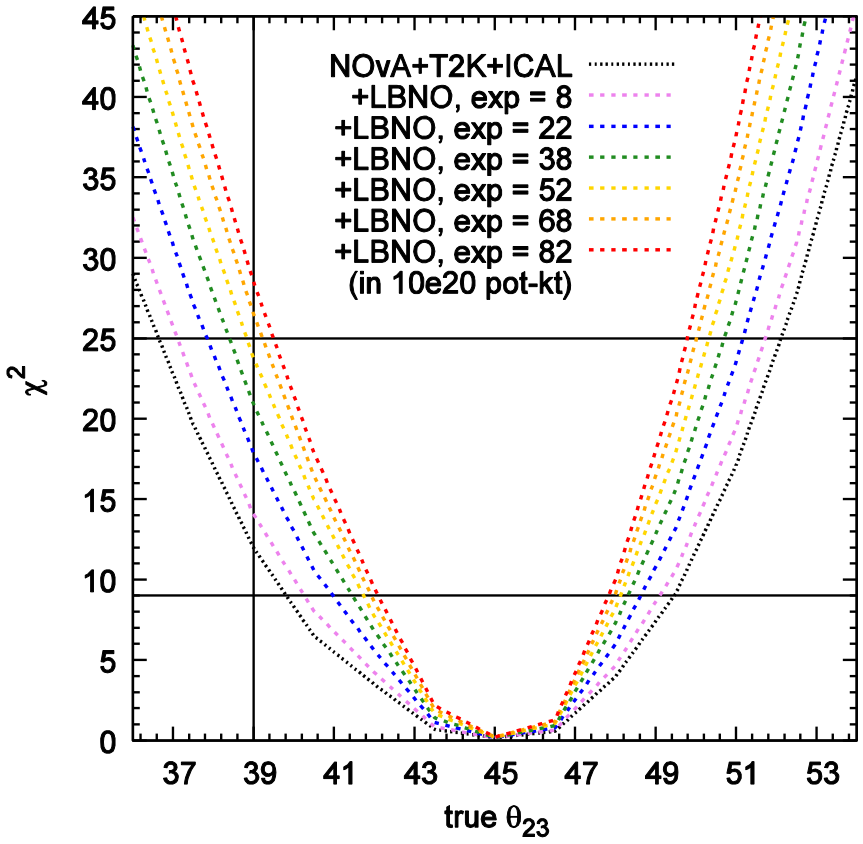
Close to the bimagic baseline:

SR, Singh, UmaSankar: 0908.3741 ;
Dighe, Goswami, Ray: 1009.1093

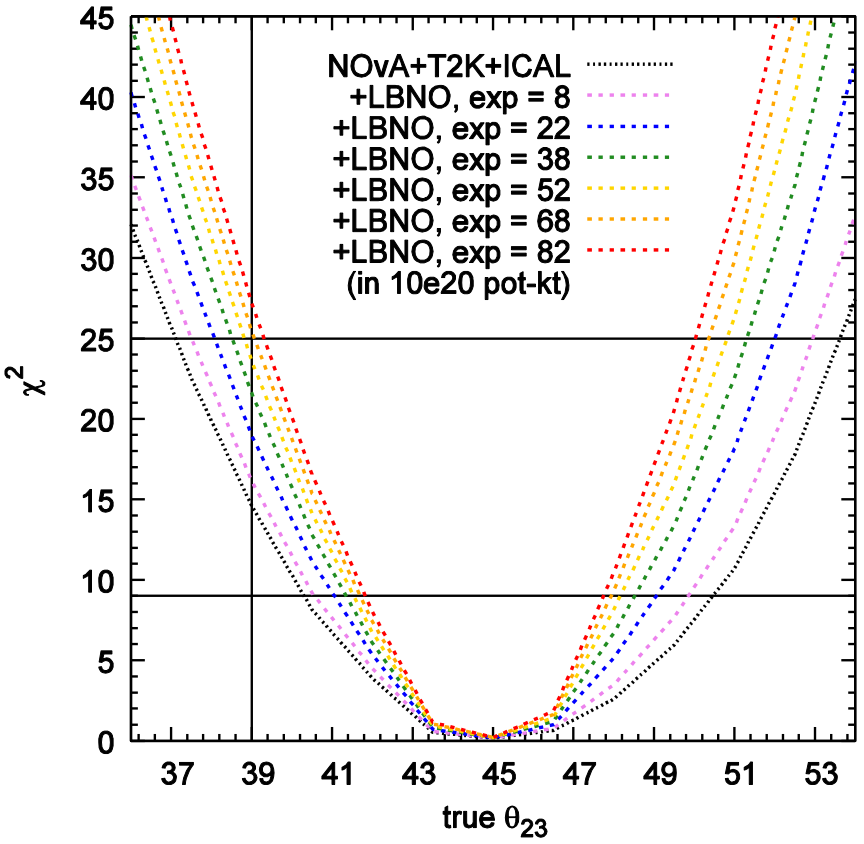


Results: Octant

2290 km, NH

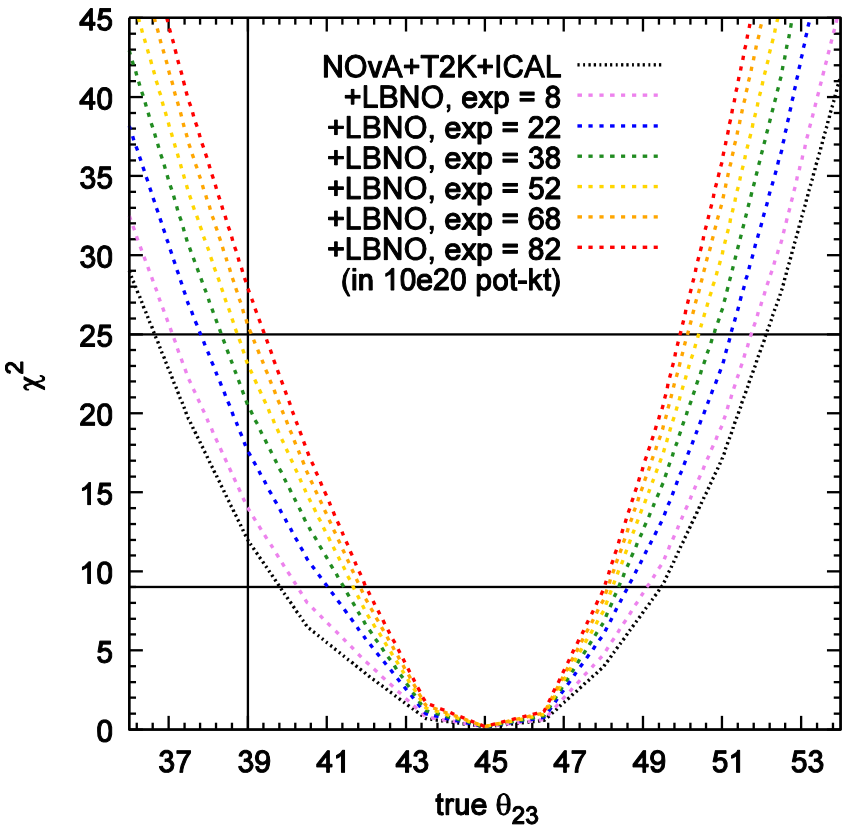


2290 km, IH

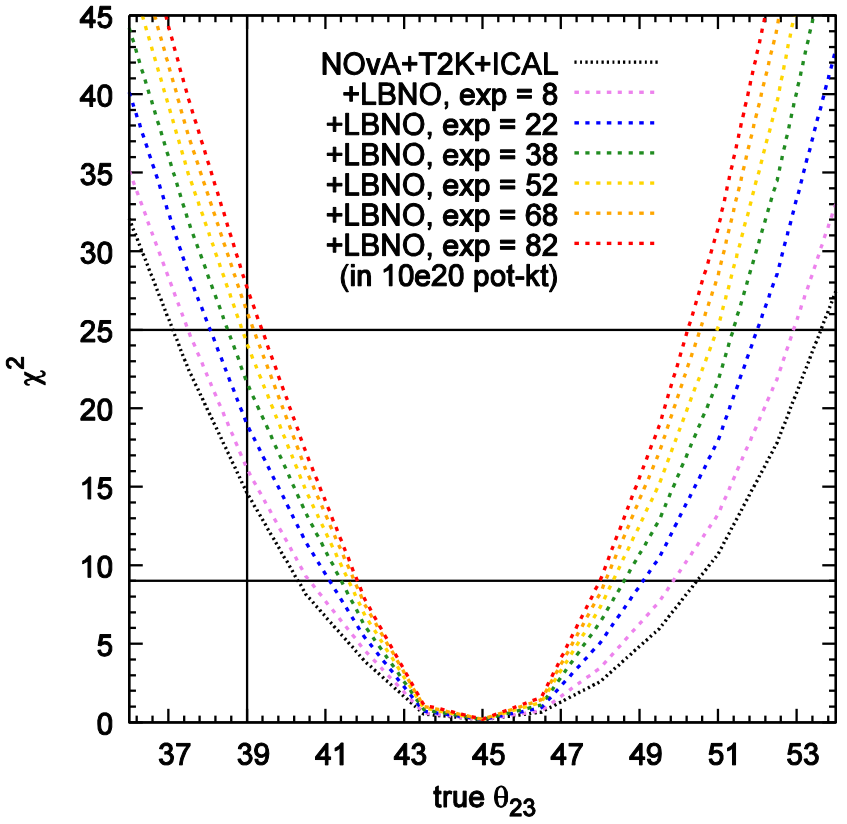


Results: Octant

1540 km, NH

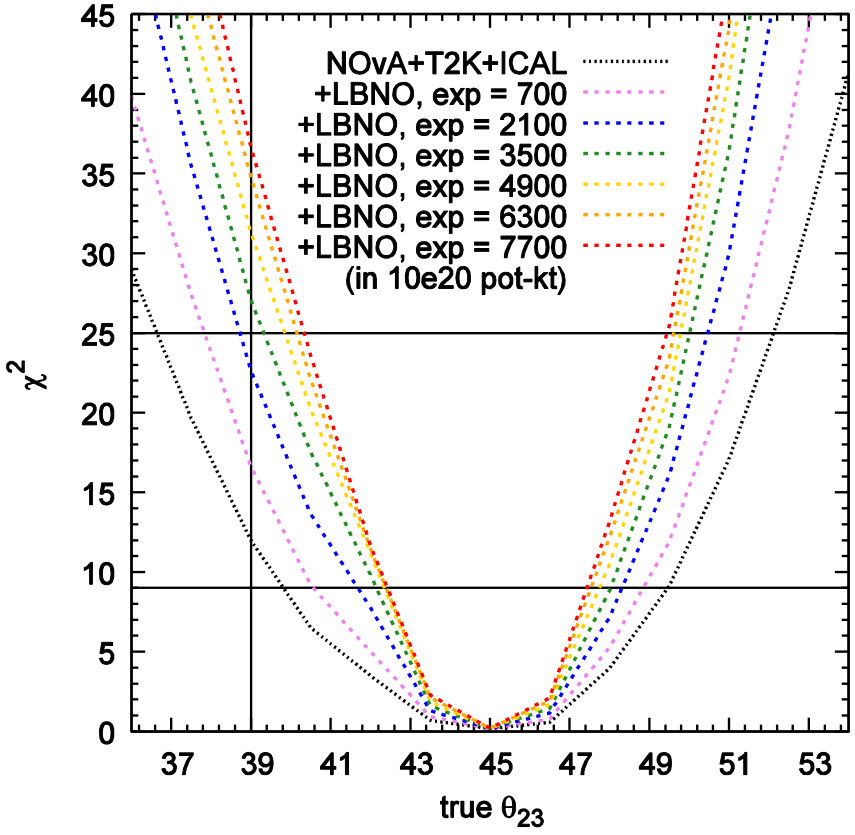


1540 km, IH

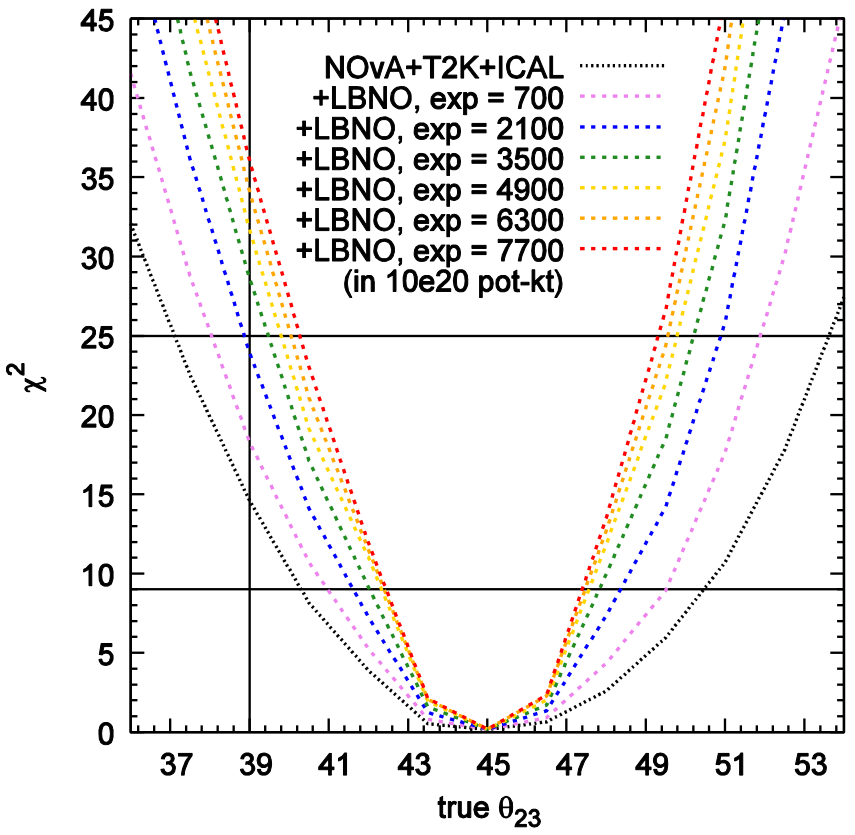


Results: Octant

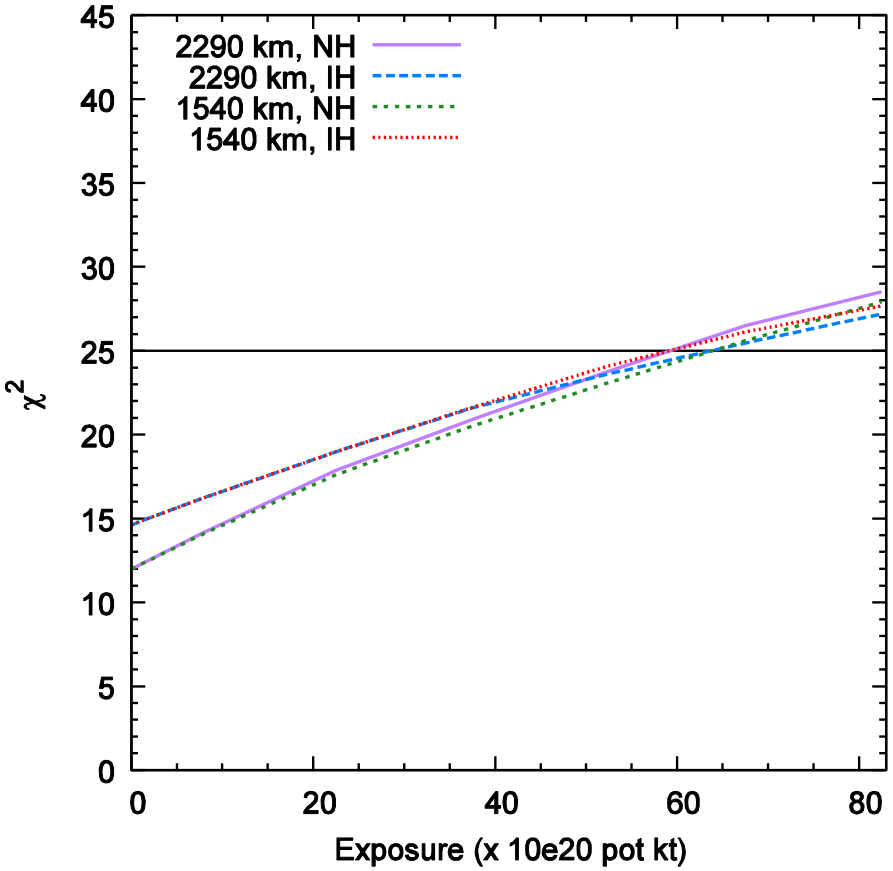
130 km, NH

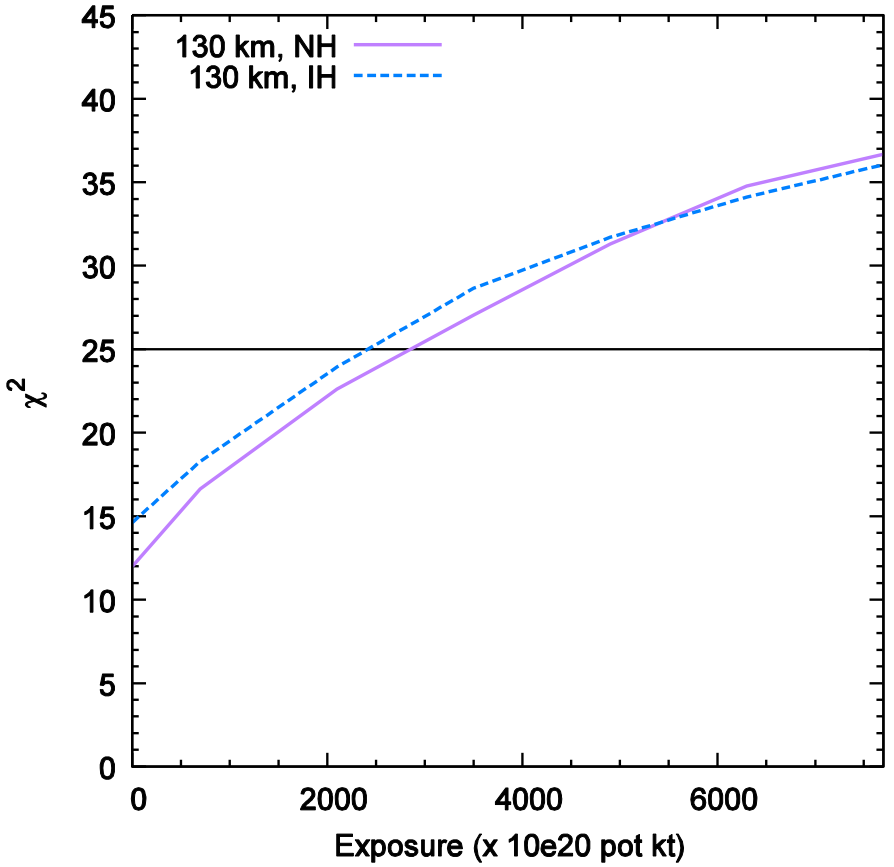


130 km, IH

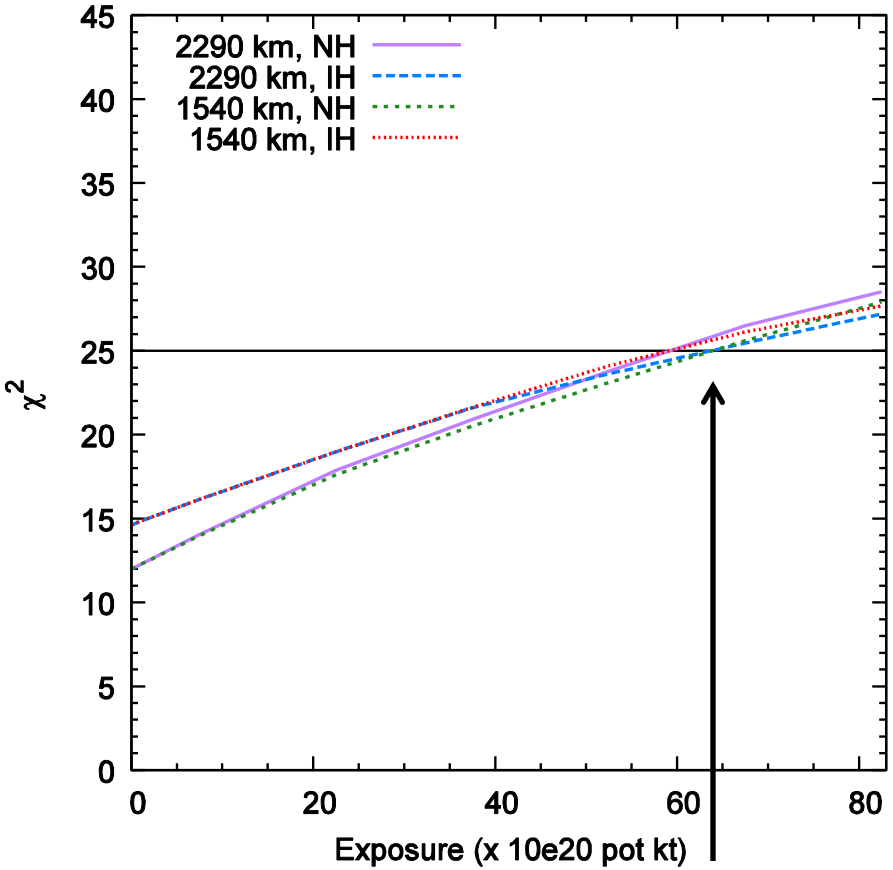


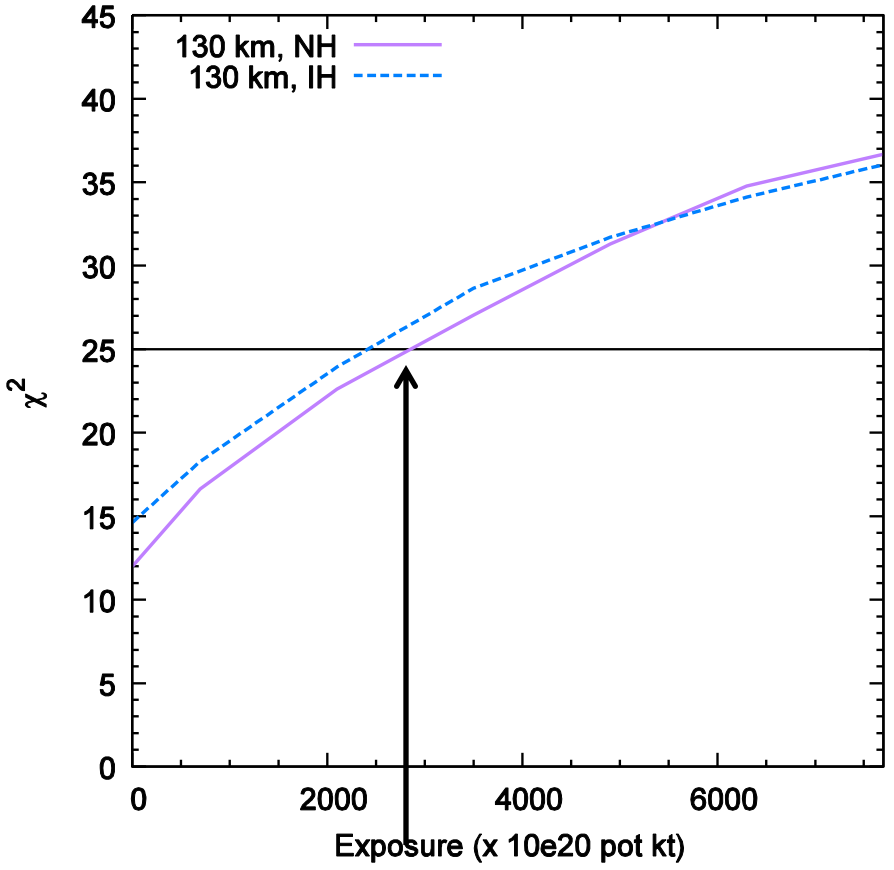
Summary: Octant





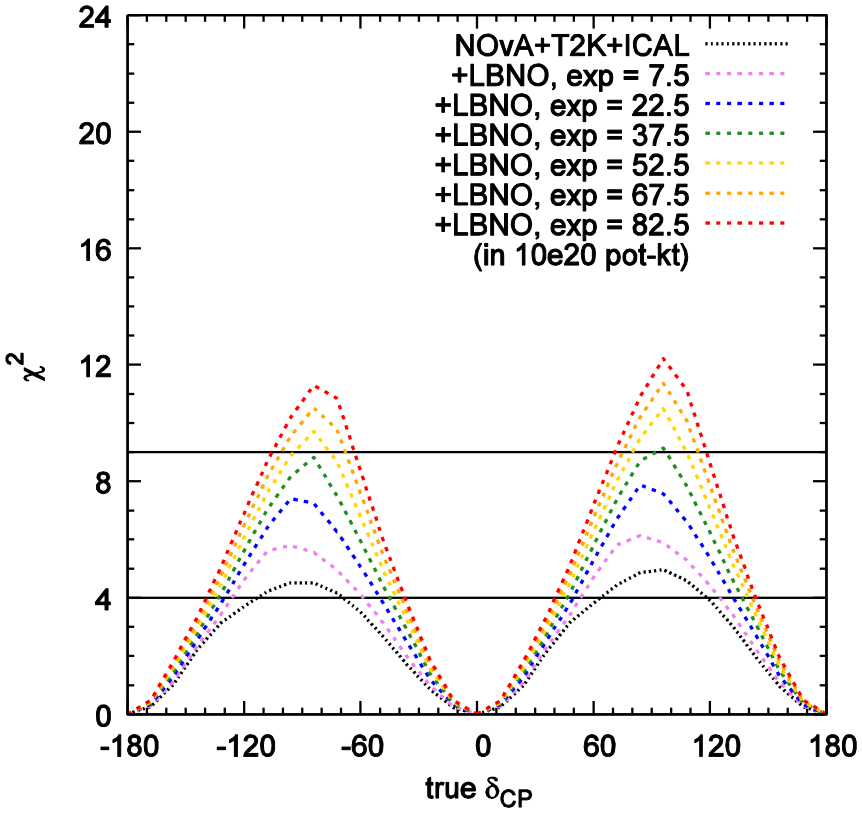
Summary: Octant



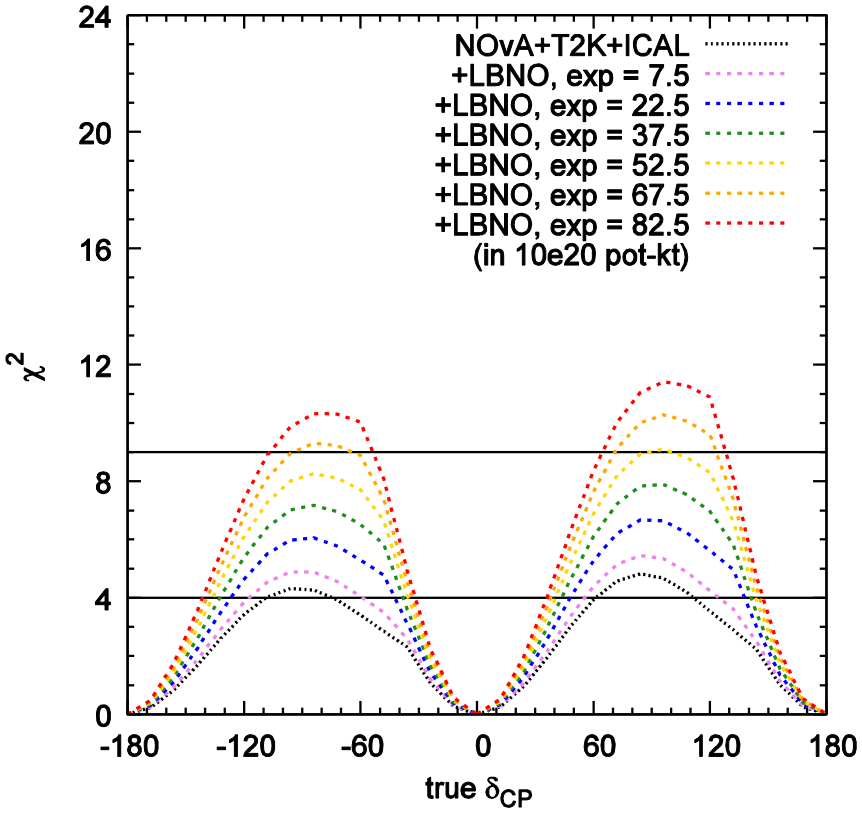


Results: CPV discovery

2290 km, NH

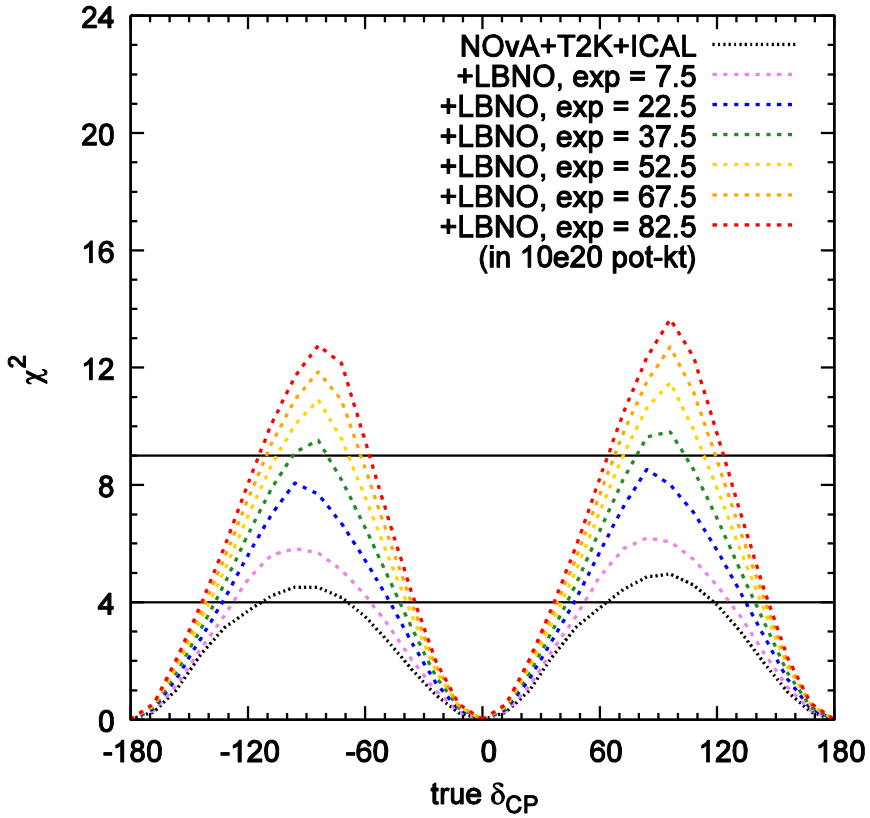


2290 km, IH

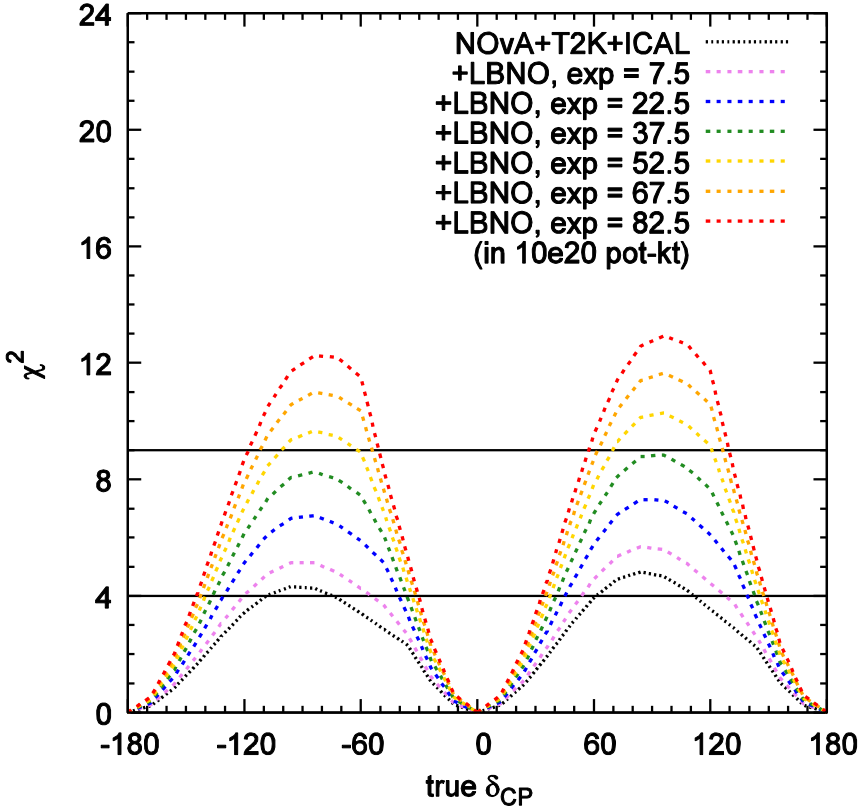


Results: CPV discovery

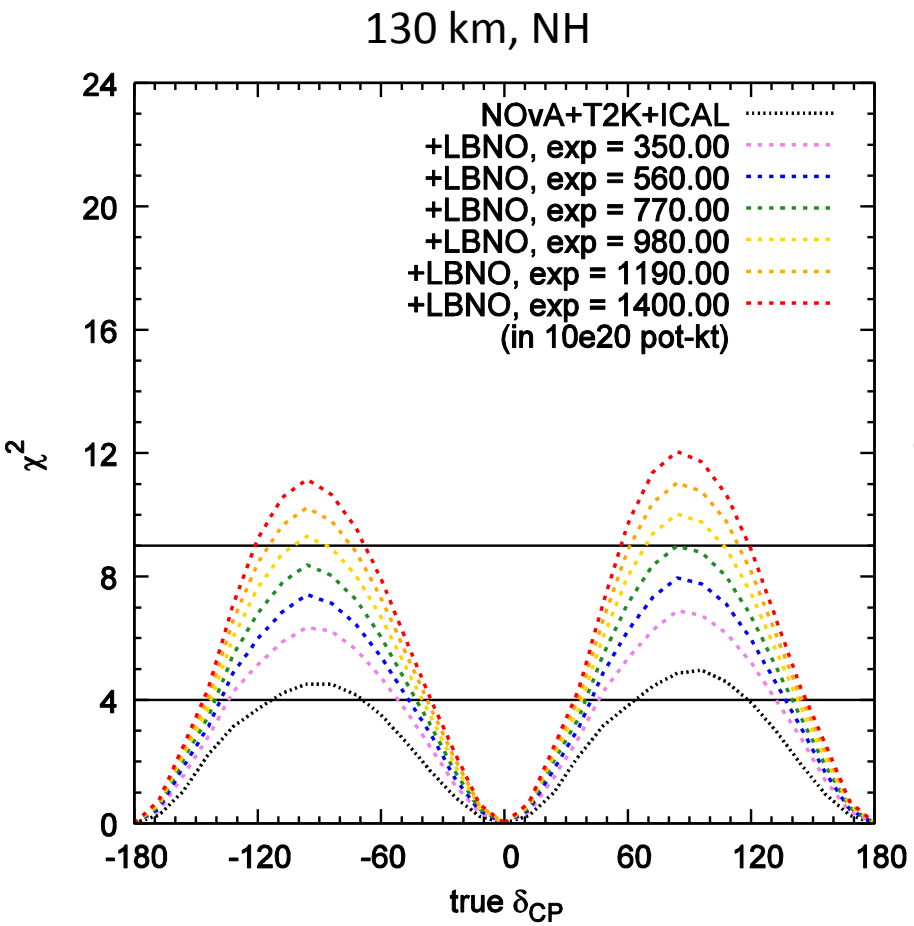
1540 km, NH

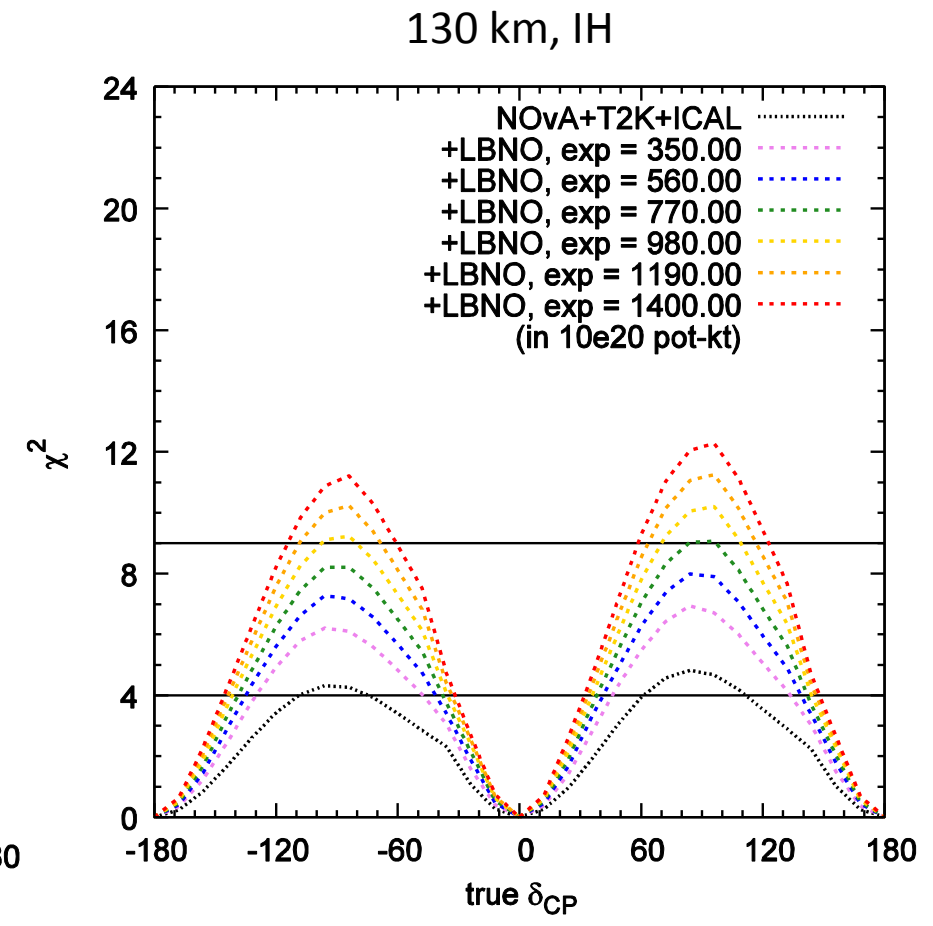


1540 km, IH



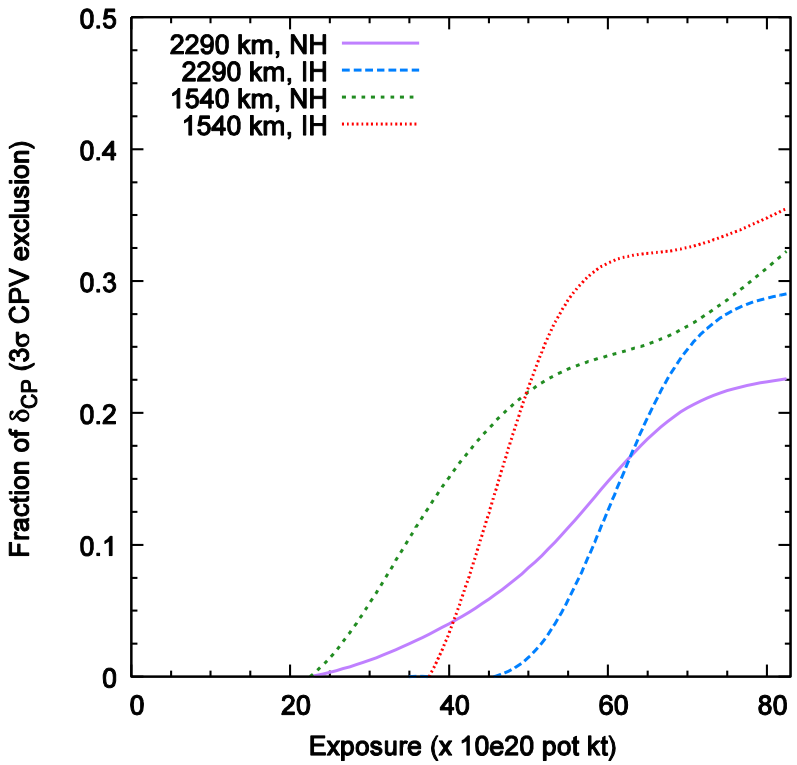
Results: CPV discovery

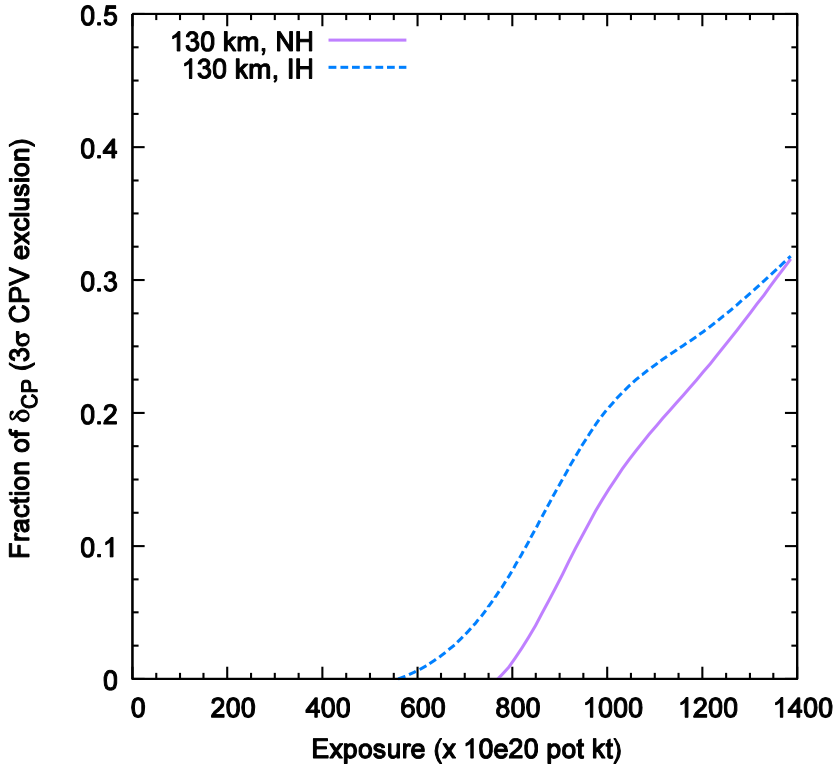




Summary: CPV discovery

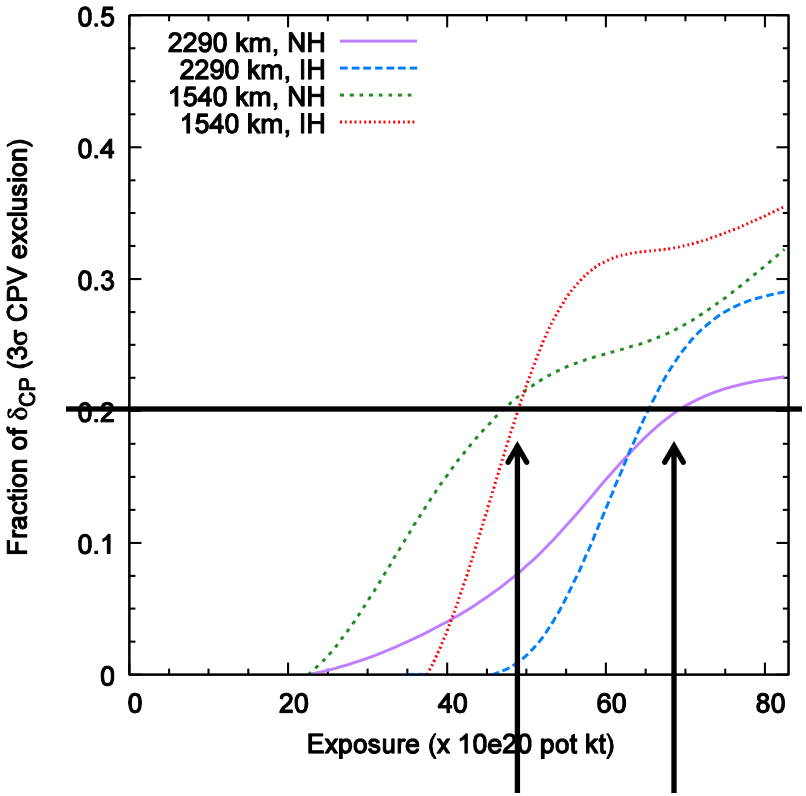
Fraction of δ_{CP} for which it is possible to exclude CP violation at > 3σ

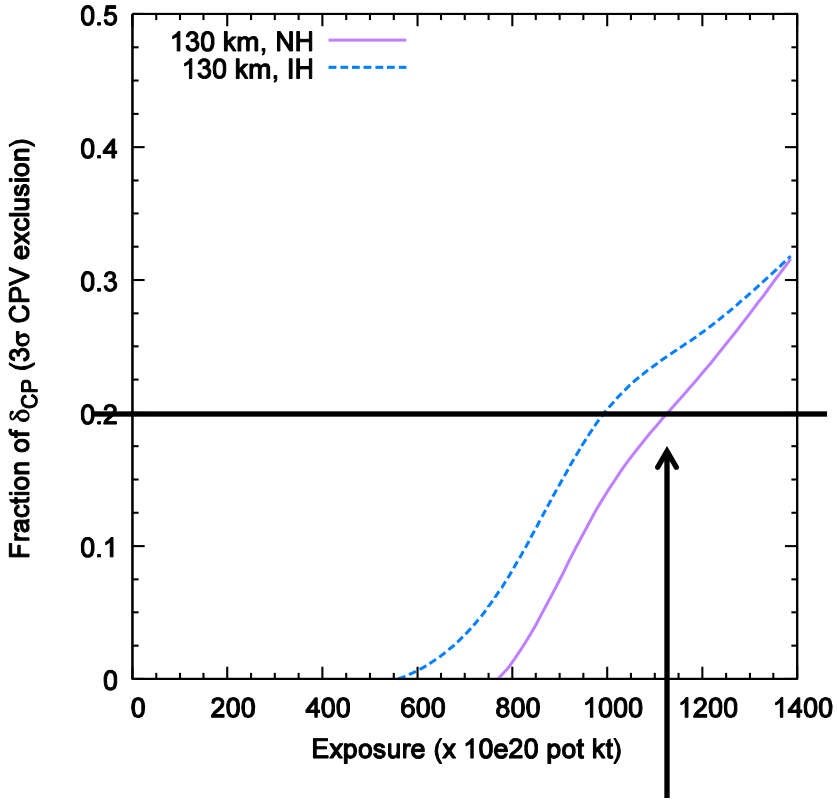




Summary: CPV discovery

Fraction of δ_{CP} for which it is possible to exclude CP violation at > 3σ





Conclusions

- There is a synergy between NOvA, T2K and INO which enhances their sensitivity to hierarchy, octant and CP.

- Because of their good combined sensitivity, it is possible to reduce the exposure (and hence cost) of LBNO, such that the combination NOvA + T2K + INO + LBNO can achieve our goals

- Minimum exposure required (in 10^{21} pot kt) for:

	2290 km	**1540 km**	**130 km**
Hierarchy (5σ)	~ 9	~ 33	-
Octant (5σ)	~ 65	~ 65	~ 3000
CPV discovery (3σ) for 20% δ_{CP} fraction	~ 70	~50	~ 1150

Backup slides

Minimum exposure required (in 10^{21} pot kt) for a lower significance of 4σ:

	2290 km	1540 km	130 km
Hierarchy (4σ)	~ 5	~ 12	-
Octant (4σ)	~ 15	~ 15	~ 600
3σ CPV discovery for 10% δ_{CP} fraction	~ 60	~45	~ 800

Corrected definitions for large θ_{13} in 3-flavour analysis

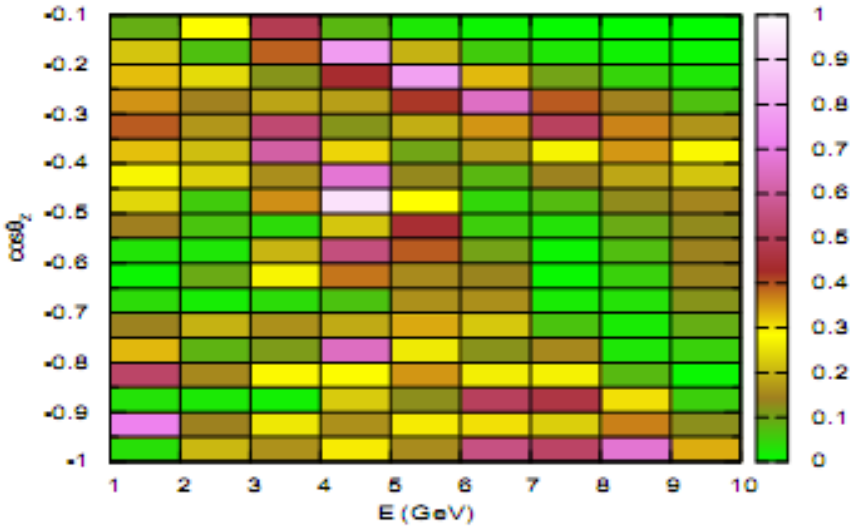
$$P_{\mu\mu} = 1 - \sin^2 2\theta_{atm} \sin^2 \frac{\Delta_{atm} L}{4E}$$

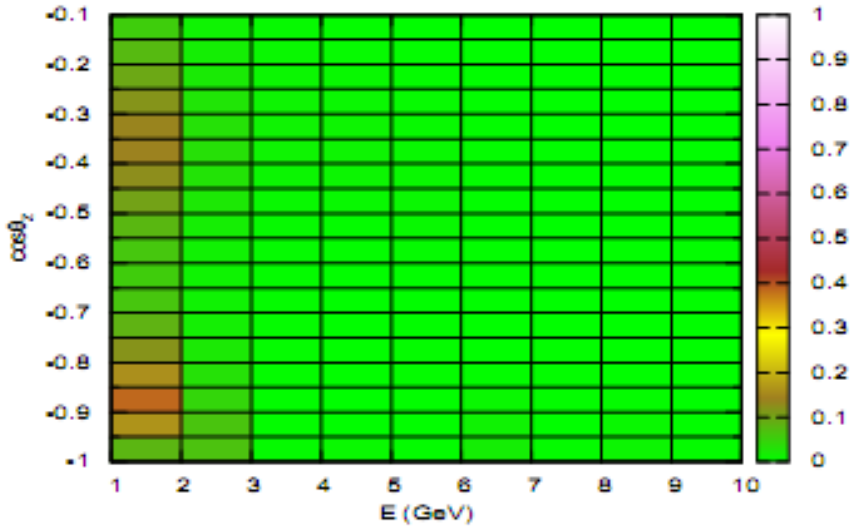
$$\Delta_{31} = \Delta_{atm} + (\cos^2 \theta_{12} - \sin\theta_{13} \sin 2\theta_{12} \tan\theta_{23} \cos\delta_{CP})\Delta_{21}$$

$$\sin\theta_{23} = \frac{\sin\theta_{atm}}{\cos\theta_{13}}$$

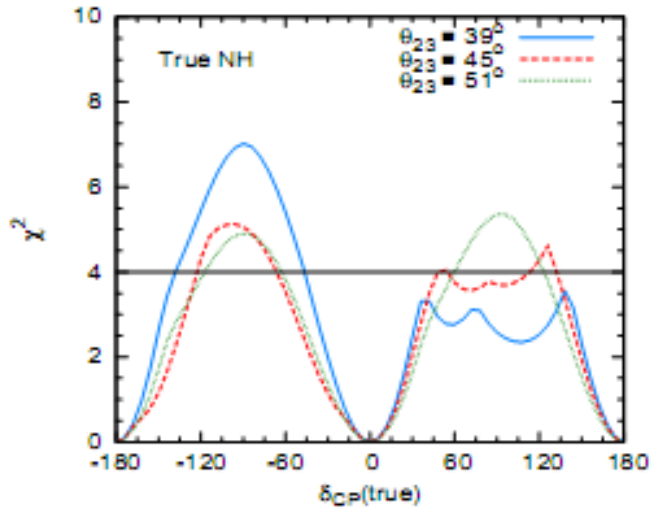
deGouvea, Jenkins, Kayser: 0503079;
Nunokawa, Parke, Zukanovich-Funchal: 0503283;
SR: 1209.5658

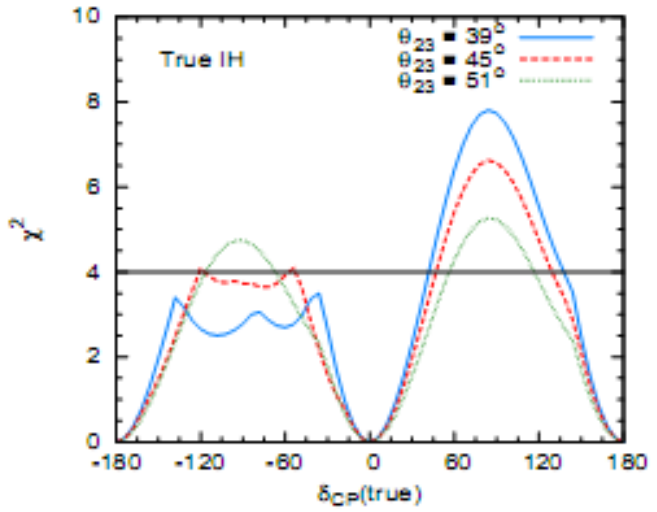
δ_{CP} independence of atmospheric neutrino sensitivity

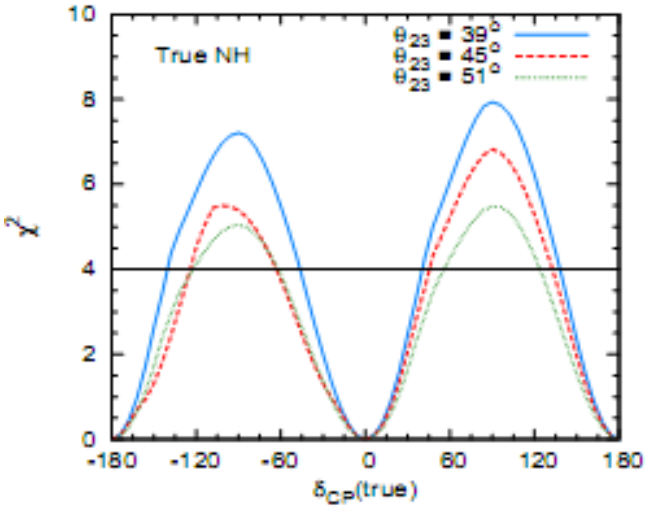


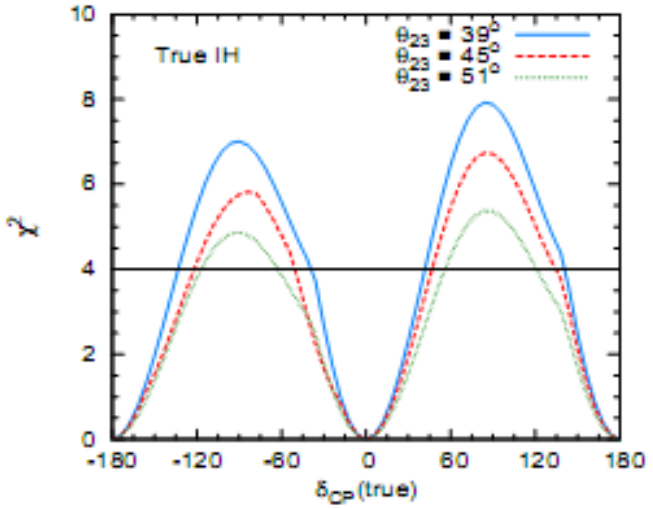


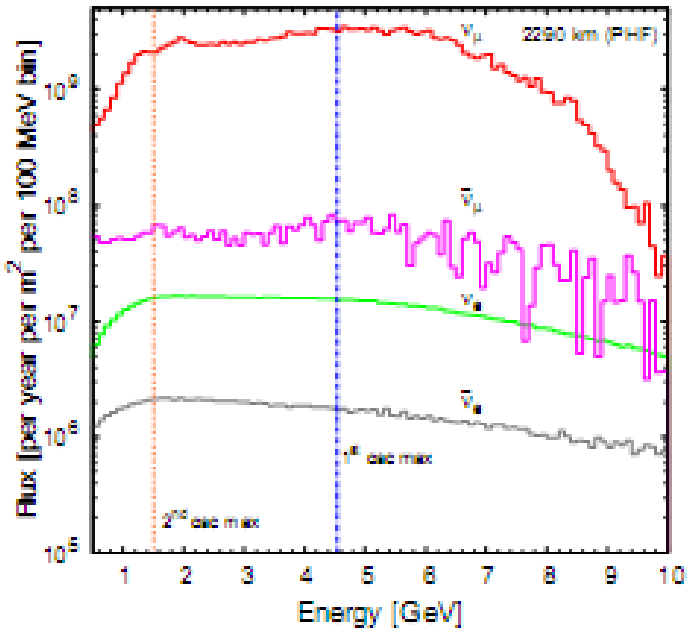
Impact of INO on CP discovery ability of NOvA+T2K

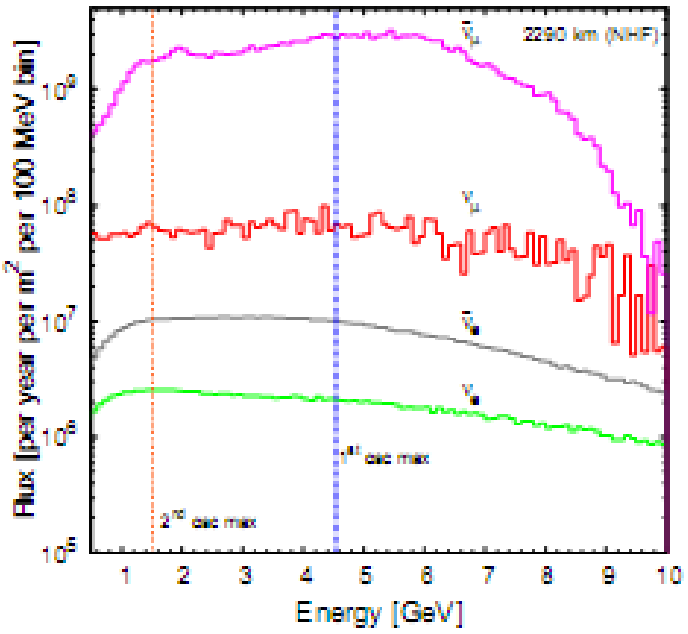


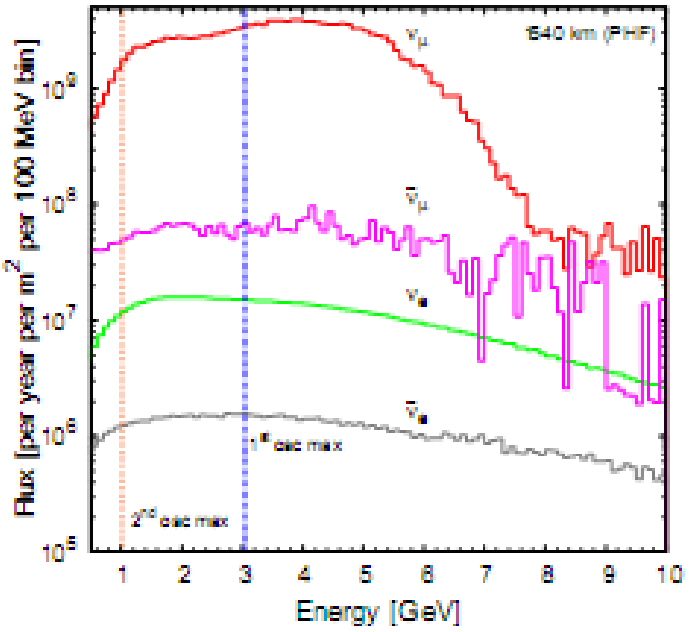


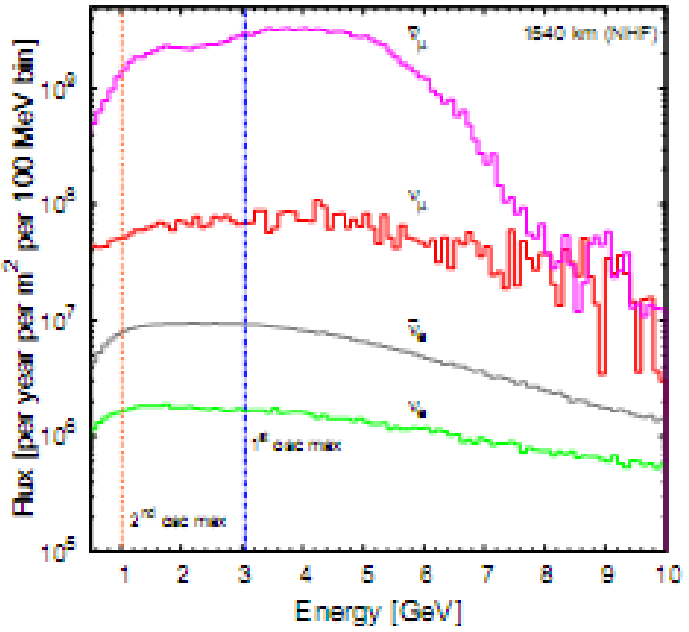





2290 km (PHF)
Flux [per year per m^2 per 100 MeV bin]
Energy [GeV]
2nd osc max
1st osc max


2290 km (NHF)
Flux [per year per m^2 per 100 MeV bin]
Energy [GeV]
2nd osc max
1st osc max


1640 km (PHF)
Flux [per year per m^2 per 100 MeV bin]
Energy [GeV]
2nd osc max
1st osc max


1640 km (NHF)
Flux [per year per m^2 per 100 MeV bin]
Energy [GeV]
2nd osc max
1st osc max