Synergies and complementarities between proposed future neutrino projects

Sushant Raut

기초과학연구원
Institute for Basic Science

IBS - Center for Theoretical Physics of the Universe, Daejeon, South Korea

NuFact 2017, Uppsala
28 September 2017

Neutrino Oscillations

- Standard three-flavour oscillation framework:

$$\mathbf{U} = \mathbf{U_{23}} \times \mathbf{U_{13,\delta}} \times \mathbf{U_{12}}$$
$$= \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_{23} & \sin\theta_{23} \\ 0 - \sin\theta_{23} & \cos\theta_{23} & \end{pmatrix} \begin{pmatrix} \cos\theta_{13} & 0 & e^{i\delta}\sin\theta_{13} \\ 0 & 1 & 0 \\ -e^{i\delta}\sin\theta_{13} & 0 & \cos\theta_{13} \end{pmatrix} \begin{pmatrix} \cos\theta_{12} & \sin\theta_{12} & 0 \\ -\sin\theta_{12} & \cos\theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

Atmospheric + LBL **Reactor + LBL** **Solar + reactor**

Δm^2_{31} Δm^2_{21}

- Three mixing angles, two independent mass-squared differences, one CP-violating phase

Known measurements

parameter	best fit ± 1σ	2σ range	3σ range
Δm^2_{21} $[10^{-5}\text{eV}^2]$	7.56±0.19	7.20–7.95	7.05–8.14
$\lvert\Delta m^2_{31}\rvert$ $[10^{-3}\text{eV}^2]$ (NO)	2.55±0.04	2.47–2.63	2.43–2.67
$\lvert\Delta m^2_{31}\rvert$ $[10^{-3}\text{eV}^2]$ (IO)	2.49±0.04	2.41–2.57	2.37-2.61
$\sin^2\theta_{12}/10^{-1}$	$3.21^{+0.18}_{-0.16}$	2.89–3.59	2.73–3.79
$\theta_{12}/°$	$34.5^{+1.1}_{-1.0}$	32.5–36.8	31.5–38.0
$\sin^2\theta_{23}/10^{-1}$ (NO)	$4.30^{+0.20}_{-0.18}$ [a]	3.98–4.78 & 5.60–6.17	3.84–6.35
$\theta_{23}/°$	41.0±1.1	39.1–43.7 & 48.4–51.8	38.3–52.8
$\sin^2\theta_{23}/10^{-1}$ (IO)	$5.96^{+0.17}_{-0.18}$ [b]	4.04–4.56 & 5.56–6.25	3.88–6.38
$\theta_{23}/°$	50.5±1.0	39.5–42.5 & 48.2–52.2	38.5–53.0
$\sin^2\theta_{13}/10^{-2}$ (NO)	$2.155^{+0.090}_{-0.075}$	1.98–2.31	1.89–2.39
$\theta_{13}/°$	$8.44^{+0.18}_{-0.15}$	8.1–8.7	7.9–8.9
$\sin^2\theta_{13}/10^{-2}$ (IO)	$2.140^{+0.082}_{-0.085}$	1.97–2.30	1.89–2.39
$\theta_{13}/°$	$8.41^{+0.16}_{-0.17}$	8.0–8.7	7.9–8.9
δ/π (NO)	$1.40^{+0.31}_{-0.20}$	0.85–1.95	0.00–2.00
$\delta/°$	252^{+56}_{-36}	153–351	0–360
δ/π (IO)	$1.44^{+0.26}_{-0.23}$	1.01–1.93	0.00–0.17 & 0.79–2.00
$\delta/°$	259^{+47}_{-41}	182–347	0–31 & 142–360

1708.01186: de Salas, Forero, Ternes, Tortola, Valle

Known measurements

parameter	best fit $\pm 1\sigma$	2σ range	3σ range
Δm^2_{21} [10^{-5}eV^2]	7.56±0.19	7.20–7.95	7.05–8.14
$\|\Delta m^2_{31}\|$ [10^{-3}eV^2] (NO)	2.55±0.04	2.47–2.63	2.43–2.67
$\|\Delta m^2_{31}\|$ [10^{-3}eV^2] (IO)	2.49±0.04	2.41–2.57	2.37-2.61
$\sin^2\theta_{12}/10^{-1}$	$3.21^{+0.18}_{-0.16}$	2.89–3.59	2.73–3.79
$\theta_{12}/°$	$34.5^{+1.1}_{-1.0}$	32.5–36.8	31.5–38.0
$\sin^2\theta_{23}/10^{-1}$ (NO)	$4.30^{+0.20}_{-0.18}$ [a]	3.98–4.78 & 5.60–6.17	3.84–6.35
$\theta_{23}/°$	41.0±1.1	39.1–43.7 & 48.4–51.8	38.3–52.8
$\sin^2\theta_{23}/10^{-1}$ (IO)	$5.96^{+0.17}_{-0.18}$ [b]	4.04–4.56 & 5.56–6.25	3.88–6.38
$\theta_{23}/°$	50.5±1.0	39.5–42.5 & 48.2–52.2	38.5–53.0
$\sin^2\theta_{13}/10^{-2}$ (NO)	$2.155^{+0.090}_{-0.075}$	1.98–2.31	1.89–2.39
$\theta_{13}/°$	$8.44^{+0.18}_{-0.15}$	8.1–8.7	7.9–8.9
$\sin^2\theta_{13}/10^{-2}$ (IO)	$2.140^{+0.082}_{-0.085}$	1.97–2.30	1.89–2.39
$\theta_{13}/°$	$8.41^{+0.16}_{-0.17}$	8.0–8.7	7.9–8.9
δ/π (NO)	$1.40^{+0.31}_{-0.20}$	0.85–1.95	0.00–2.00
$\delta/°$	252^{+56}_{-36}	153–351	0–360
δ/π (IO)	$1.44^{+0.26}_{-0.23}$	1.01–1.93	0.00–0.17 & 0.79–2.00
$\delta/°$	259^{+47}_{-41}	182–347	0–31 & 142–360

1708.01186: de Salas, Forero, Ternes, Tortola, Valle

Known measurements

parameter	best fit ± 1σ	2σ range	3σ range
Δm^2_{21} [10^{-5}eV^2]	7.56±0.19	7.20–7.95	7.05–8.14
$\|\Delta m^2_{31}\|$ [10^{-3}eV^2] (NO)	2.55±0.04	2.47–2.63	2.43–2.67
$\|\Delta m^2_{31}\|$ [10^{-3}eV^2] (IO)	2.49±0.04	2.41–2.57	2.37–2.61
$\sin^2\theta_{12}/10^{-1}$	$3.21^{+0.18}_{-0.16}$	2.89–3.59	2.73–3.79
$\theta_{12}/°$	$34.5^{+1.1}_{-1.0}$	32.5–36.8	31.5–38.0
$\sin^2\theta_{23}/10^{-1}$ (NO)	$4.30^{+0.20}_{-0.18}$ [a]	3.98–4.78 & 5.60–6.17	3.84–6.35
$\theta_{23}/°$	41.0±1.1	39.1–43.7 & 48.4–51.8	38.3–52.8
$\sin^2\theta_{23}/10^{-1}$ (IO)	$5.96^{+0.17}_{-0.18}$ [b]	4.04–4.56 & 5.56–6.25	3.88–6.38
$\theta_{23}/°$	50.5±1.0	39.5–42.5 & 48.2–52.2	38.5–53.0
$\sin^2\theta_{13}/10^{-2}$ (NO)	$2.155^{+0.090}_{-0.075}$	1.98–2.31	1.89–2.39
$\theta_{13}/°$	$8.44^{+0.18}_{-0.15}$	8.1–8.7	7.9–8.9
$\sin^2\theta_{13}/10^{-2}$ (IO)	$2.140^{+0.082}_{-0.085}$	1.97–2.30	1.89–2.39
$\theta_{13}/°$	$8.41^{+0.16}_{-0.17}$	8.0–8.7	7.9–8.9
δ/π (NO)	$1.40^{+0.31}_{-0.20}$	0.85–1.95	0.00–2.00
$\delta/°$	252^{+56}_{-36}	153–351	0–360
δ/π (IO)	$1.44^{+0.26}_{-0.23}$	1.01–1.93	0.00–0.17 & 0.79–2.00
$\delta/°$	259^{+47}_{-41}	182–347	0–31 & 142–360

NH or IH?

1708.01186: de Salas, Forero, Ternes, Tortola, Valle

LO or HO?

δ_{CP}=?

Beyond standard oscillations

$$\begin{pmatrix} U_{e1} & U_{e2} & U_{e3} & U_{e4} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} & U_{\mu 4} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} & U_{\tau 4} \\ U_{s1} & U_{s2} & U_{s3} & U_{s4} \end{pmatrix}$$

Sterile neutrinos: Additional 3 angles, 2 phases, 1 mass-squared difference

Non-standard propagation (Matter NSIs): Additional 6 amplitudes, 3 phases

$$V_{SM}\begin{pmatrix} 1+\varepsilon_{ee}^{m} & \varepsilon_{e\mu}^{m} & \varepsilon_{e\tau}^{m} \\ & \varepsilon_{\mu\mu}^{m} & \varepsilon_{\mu\tau}^{m} \\ h.c. & & \varepsilon_{\tau\tau}^{m} \end{pmatrix}$$

Beyond standard oscillations

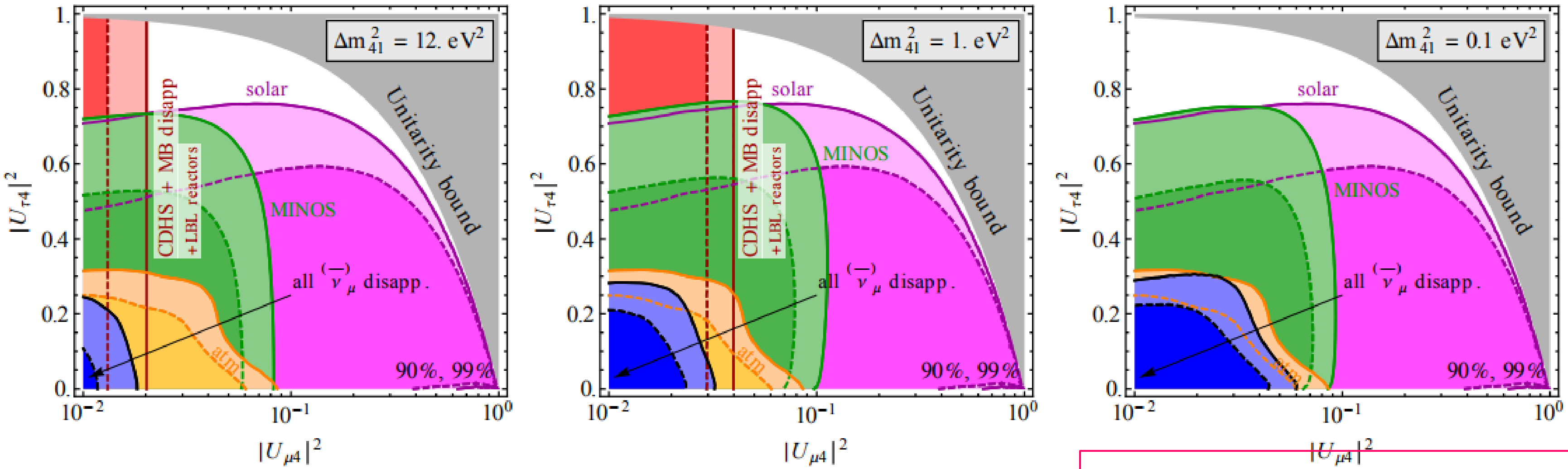
$$\begin{pmatrix} \nu_e^{s/d} \\ \nu_\mu^{s/d} \\ \nu_\tau^{s/d} \end{pmatrix} = \begin{pmatrix} 1+\varepsilon_{ee}^{s/d} & \varepsilon_{e\mu}^{s/d} & \varepsilon_{e\tau}^{s/d} \\ \varepsilon_{\mu e}^{s/d} & 1+\varepsilon_{\mu\mu}^{s/d} & \varepsilon_{\mu\tau}^{s/d} \\ \varepsilon_{\tau e}^{s/d} & \varepsilon_{\tau\mu}^{s/d} & 1+\varepsilon_{\tau\tau}^{s/d} \end{pmatrix} \begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix}$$

Non-standard production/detection (Source/detector NSIs): Additional 9+9 amplitudes, 9+9 phases

Other 'exotic' scenarios: Decoherence, neutrino decay, extra dimensions, extra gauge interactions...

Current bounds

Sterile neutrinos:



1303.3011: Kopp, Machado, Maltoni, Schwetz
Also see 1602.00671: Collin, Arguelles, Conrad, Shaevitz

Non-unitarity:

$$\begin{aligned} \epsilon_{ee} &= -0.0012 \pm 0.0006 & |\epsilon_{e\mu}| &< 0.7 \times 10^{-5} \\ |\epsilon_{\mu\mu}| &< 0.00023 & |\epsilon_{e\tau}| &< 0.00135 \\ \epsilon_{\tau\tau} &= -0.0025 \pm 0.0017 & |\epsilon_{\mu\tau}| &< 0.00048\,, \end{aligned}$$

1407.6607: Antusch, Fischer

Current bounds

Matter NSIs:

$$|\varepsilon^{\oplus}_{\alpha\beta}| < \begin{pmatrix} 4.2 & 0.33 & 3.0 \\ 0.33 & 0.068 & 0.33 \\ 3.0 & 0.33 & 21 \end{pmatrix}$$

Source/detector NSIs:

$$|\varepsilon^{ud}_{\alpha\beta}| < \begin{pmatrix} 0.041 & 0.025 & 0.041 \\ \begin{matrix} 1.8\cdot 10^{-6} \\ 0.026 \end{matrix} & 0.078 & 0.013 \\ \begin{matrix} 0.087 \\ 0.12 \end{matrix} & \begin{matrix} 0.013 \\ 0.018 \end{matrix} & 0.13 \end{pmatrix}$$

0907.0097: Biggio, Blennow, Fernandez-Martinez

Also see 1605.09284: Khan

Measuring the unknowns

$$P_{\mu e} = 4\sin^2\theta_{13}\sin^2\theta_{23}\frac{\sin^2((1-\hat{A})\Delta)}{(1-\hat{A})^2} + \alpha^2\sin^2 2\theta_{12}\cos^2\theta_{23}\frac{\sin^2(\hat{A}\Delta)}{\hat{A}^2}$$

$$+2\alpha\sin\theta_{13}\sin 2\theta_{12}\sin 2\theta_{23}\cos(\Delta+\delta_{CP})\frac{\sin((1-\hat{A})\Delta)}{(1-\hat{A})}\frac{\sin(\hat{A}\Delta)}{\hat{A}}$$

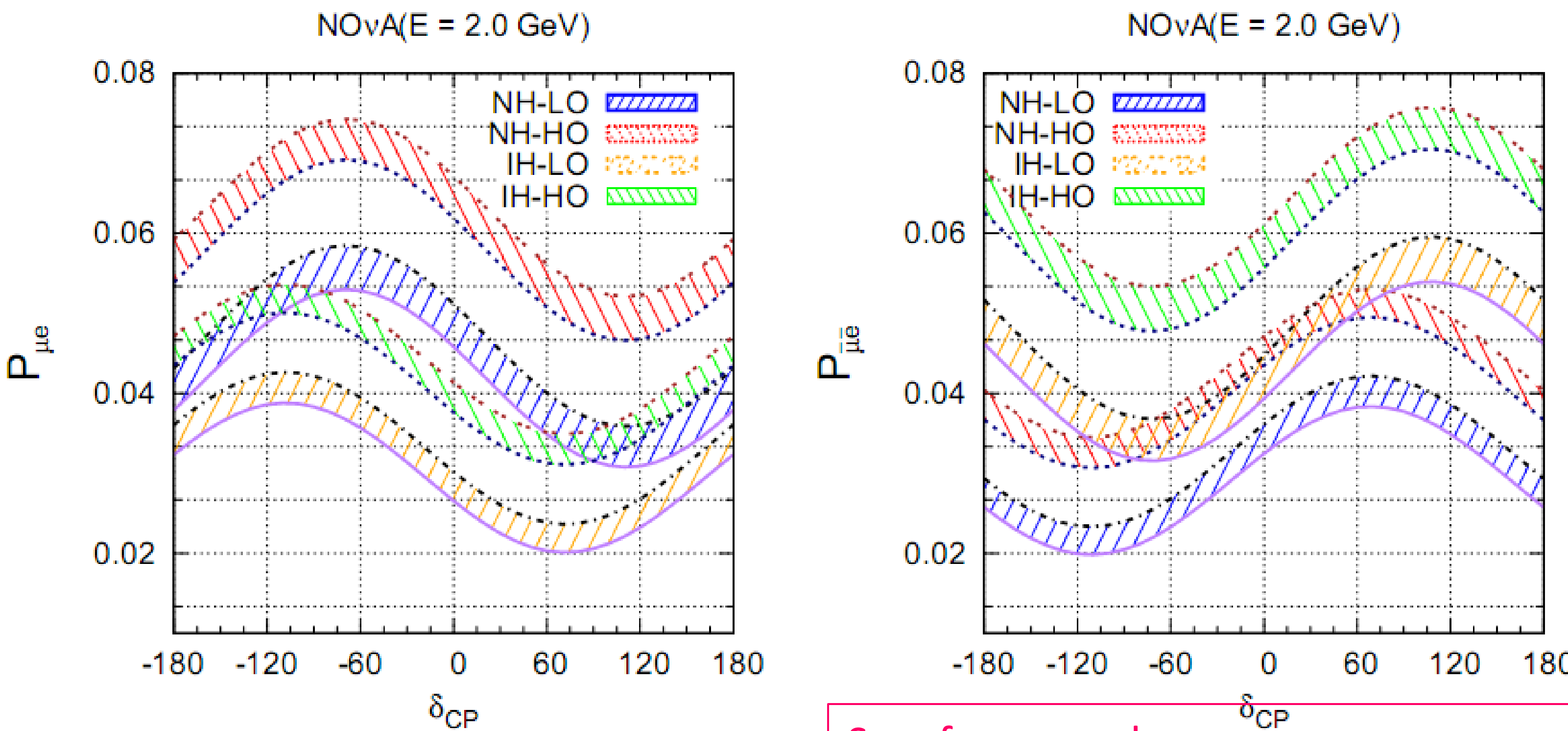
$$\text{where } \alpha = \Delta m^2{}_{21}/\Delta m^2{}_{31},\ \ \Delta = \Delta m^2{}_{31}L/4E,\ \ \hat{A} = A/\Delta m^2{}_{31}$$

Measurements of the **mass hierarchy**, octant of θ_{23} and δ_{CP} are affected by parameter degeneracies

Why do we not know what we don't know?

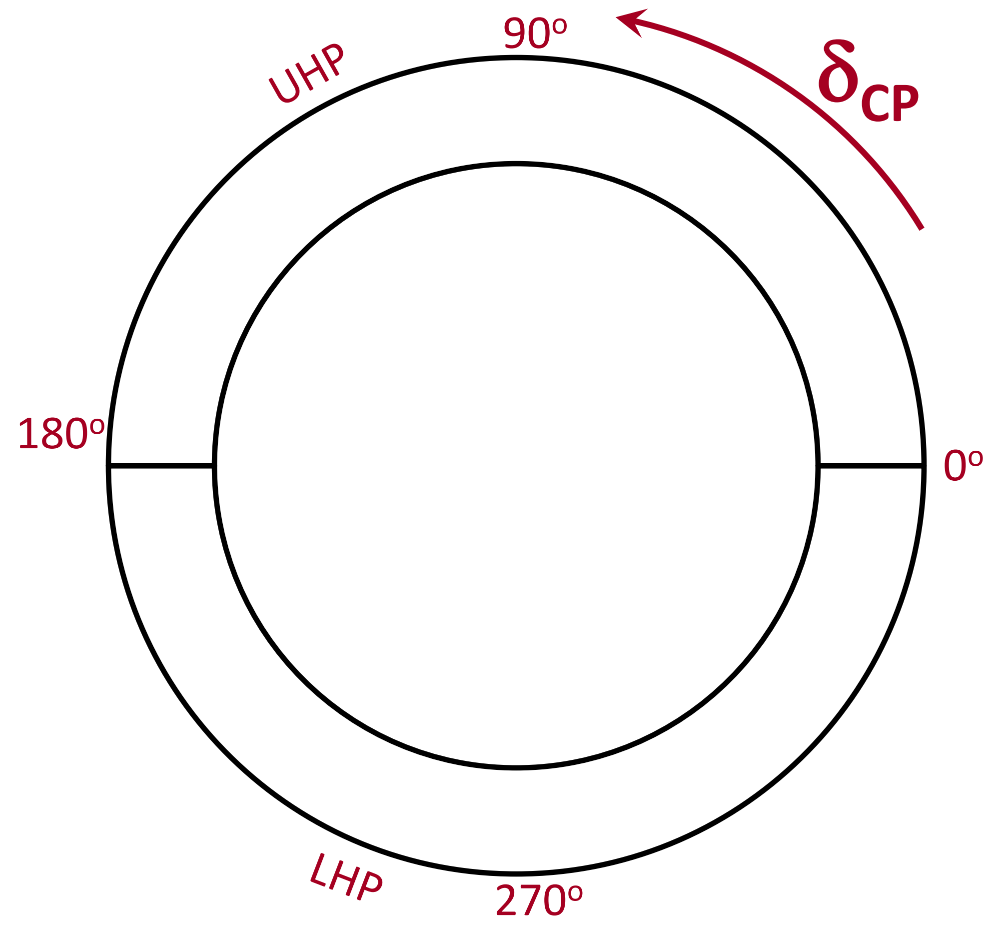
- Parameter degeneracies:

$P(NH, \delta_{CP}) = P(IH, \delta_{CP}')$; $P(\theta_{23}) = P(90\text{-}\theta_{23})$

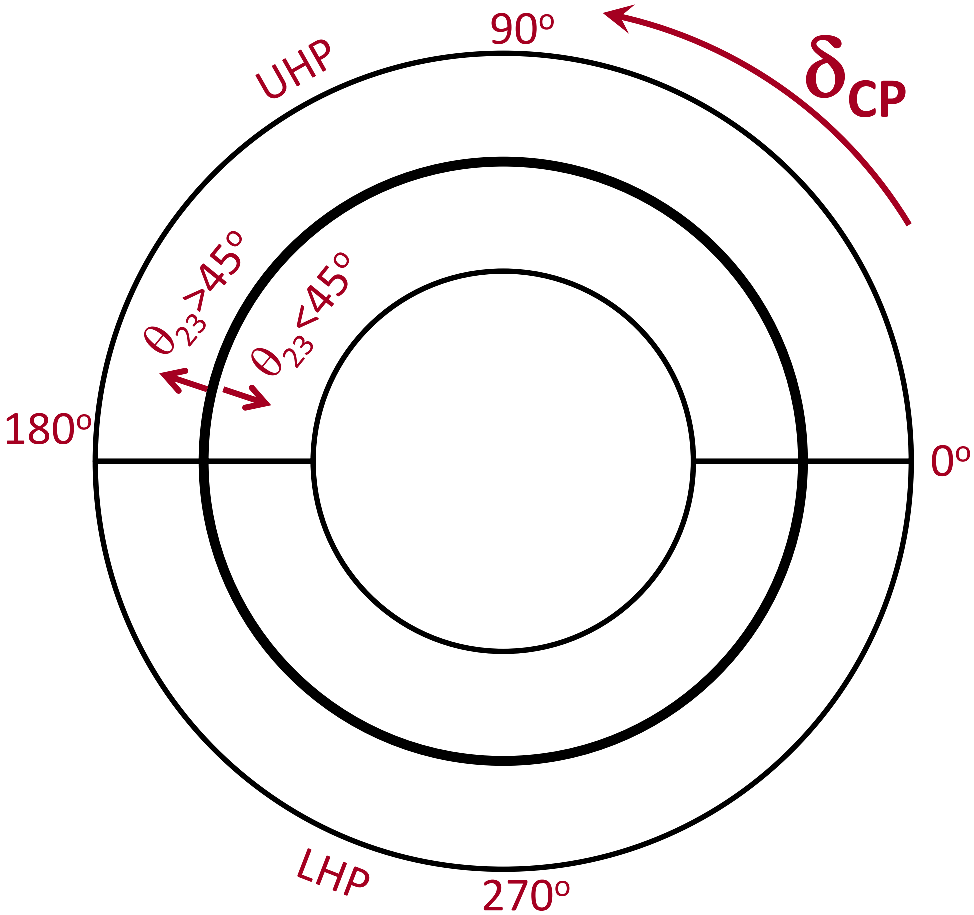


See, for example:
1504.06283: Ghosh, Ghoshal, Goswami, Nath, SR
1406.2551: Coloma, Minakata, Parke

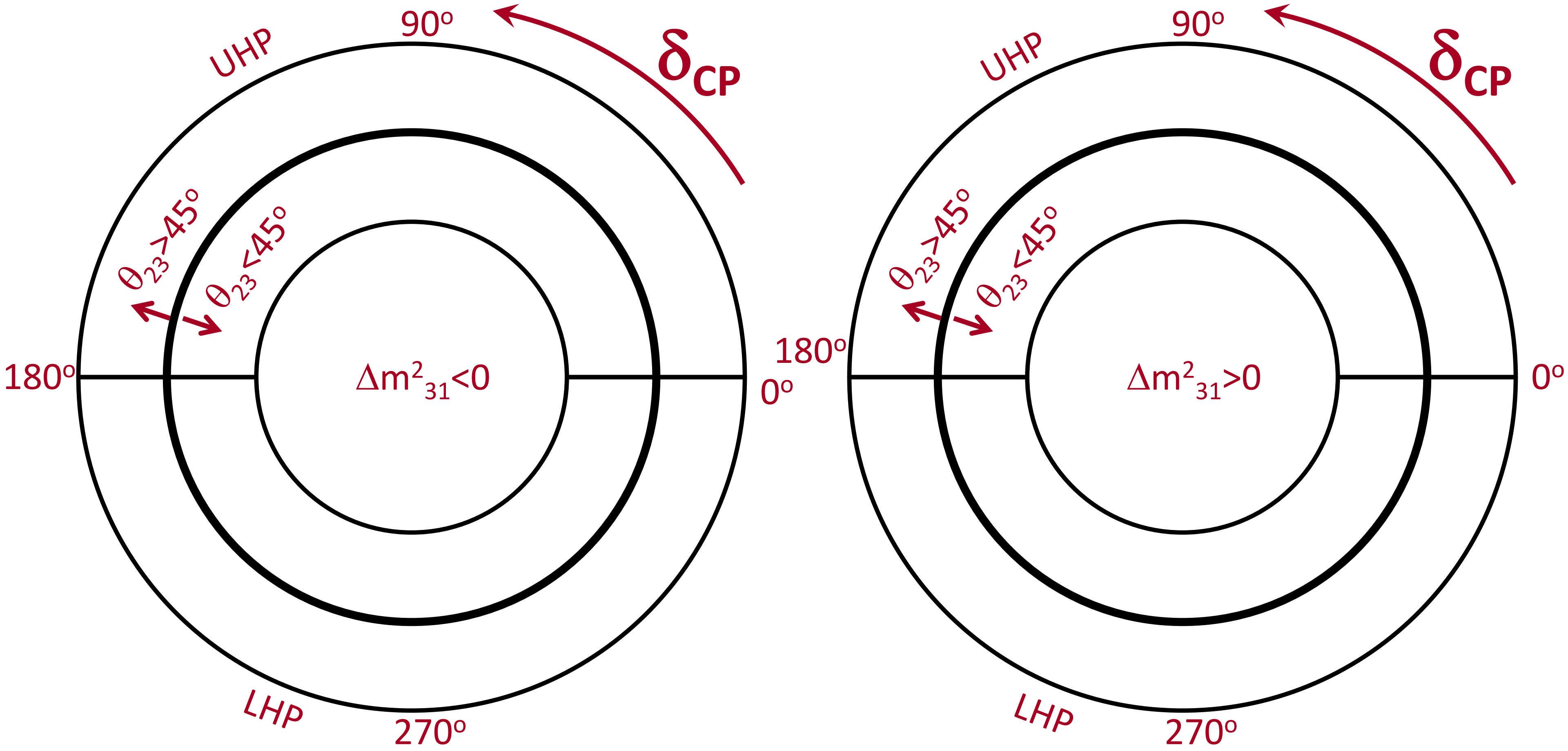
Degeneracies in neutrino parameter space



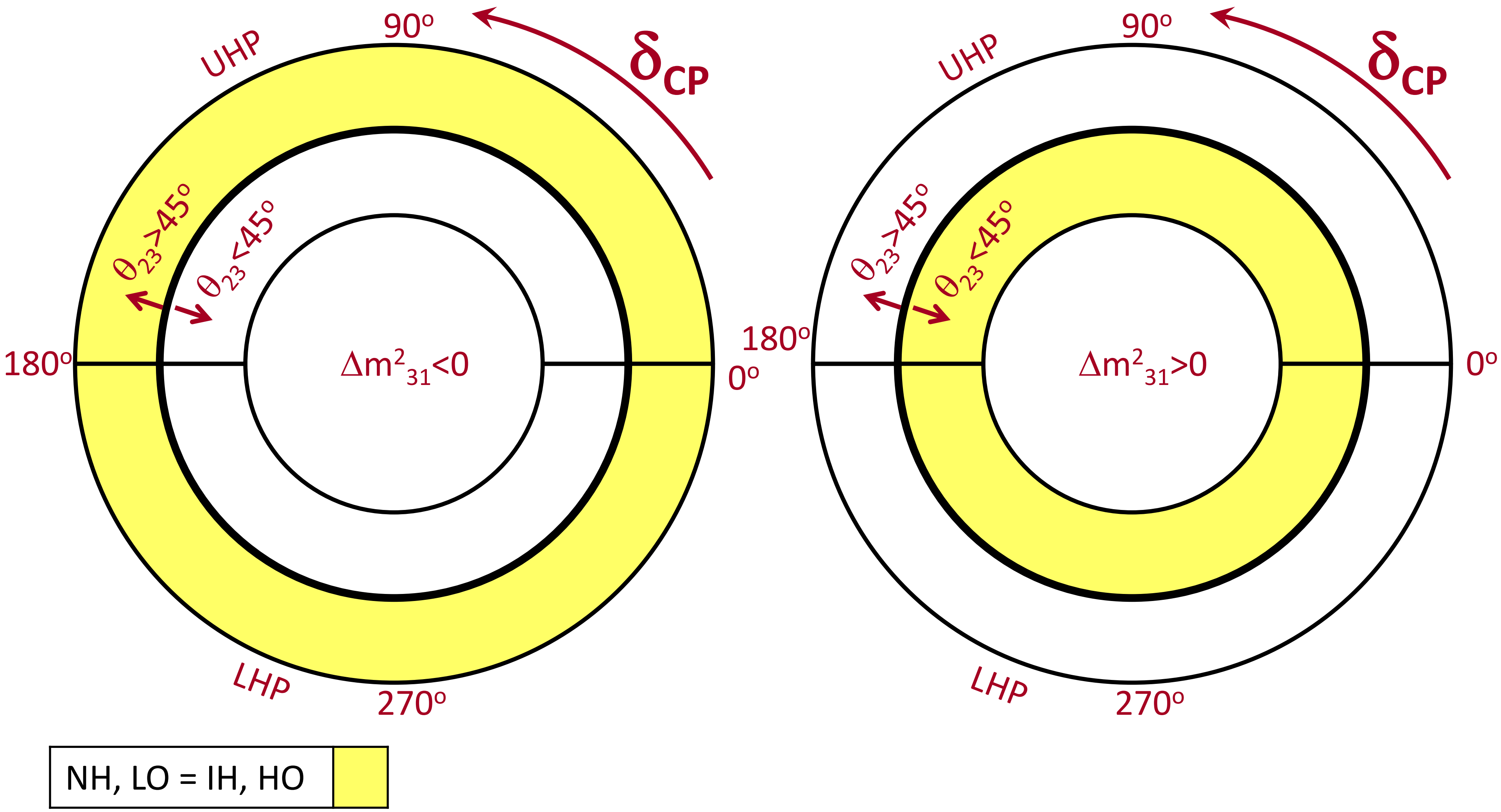
Degeneracies in neutrino parameter space



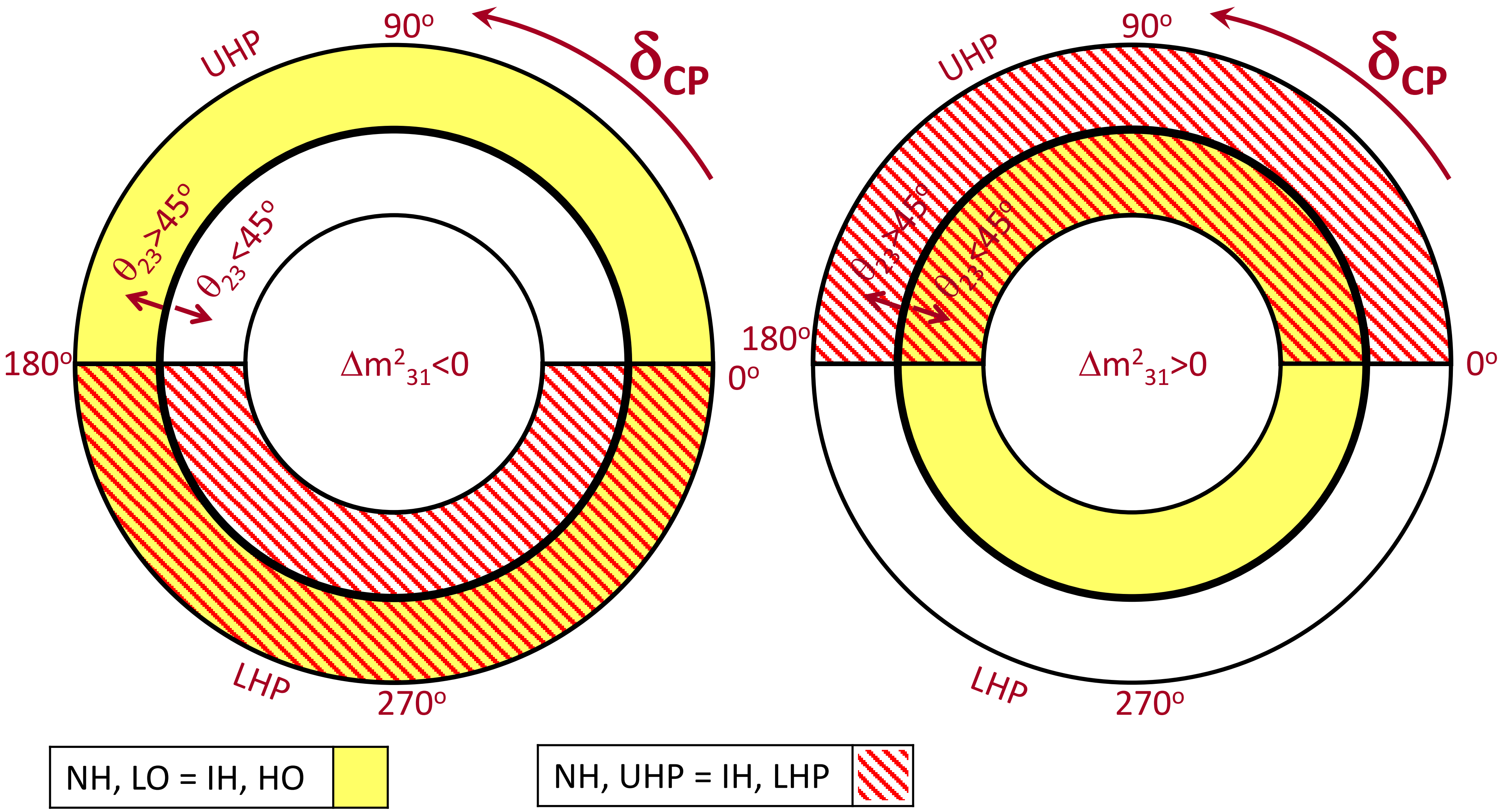
Degeneracies in neutrino parameter space



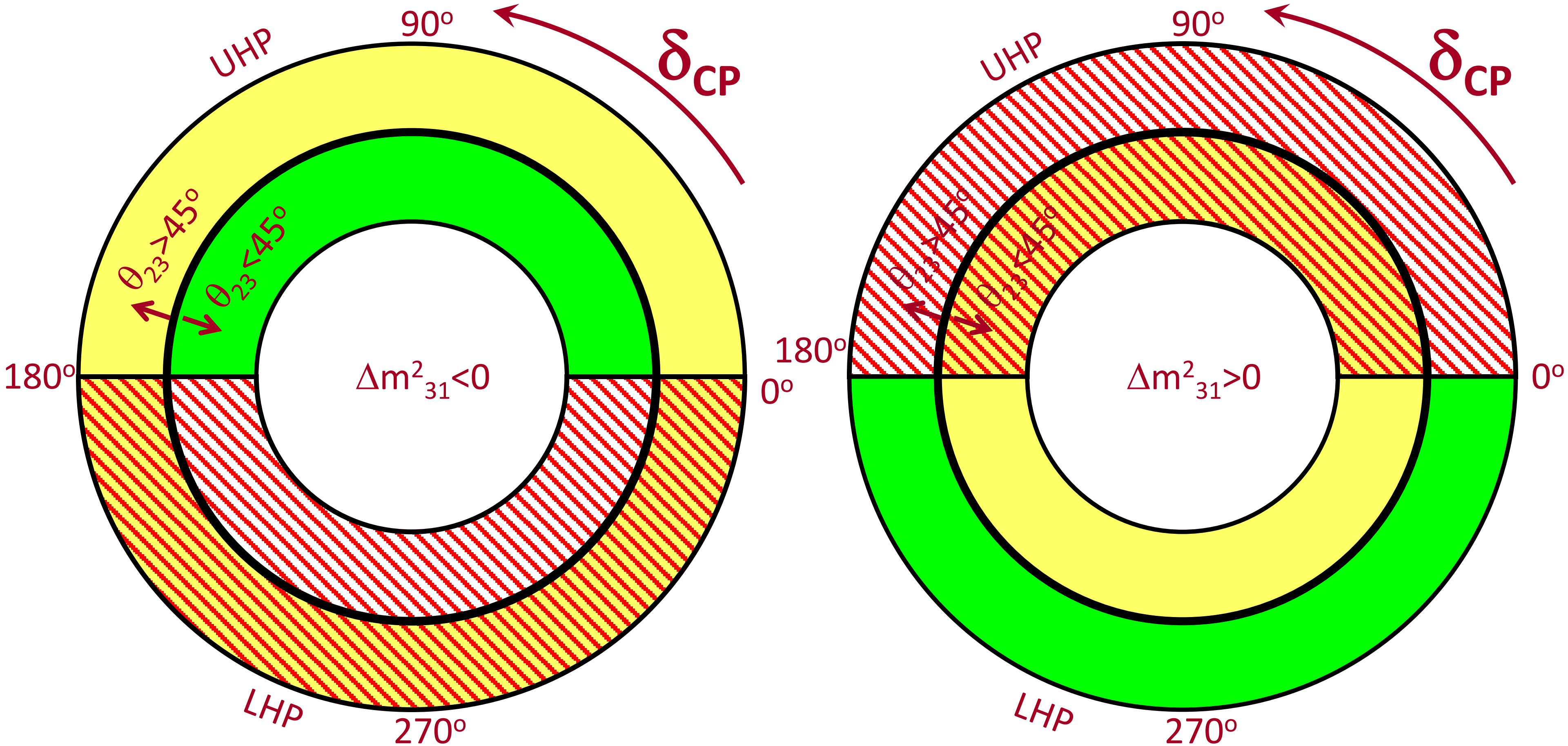
Degeneracies in neutrino parameter space



Degeneracies in neutrino parameter space

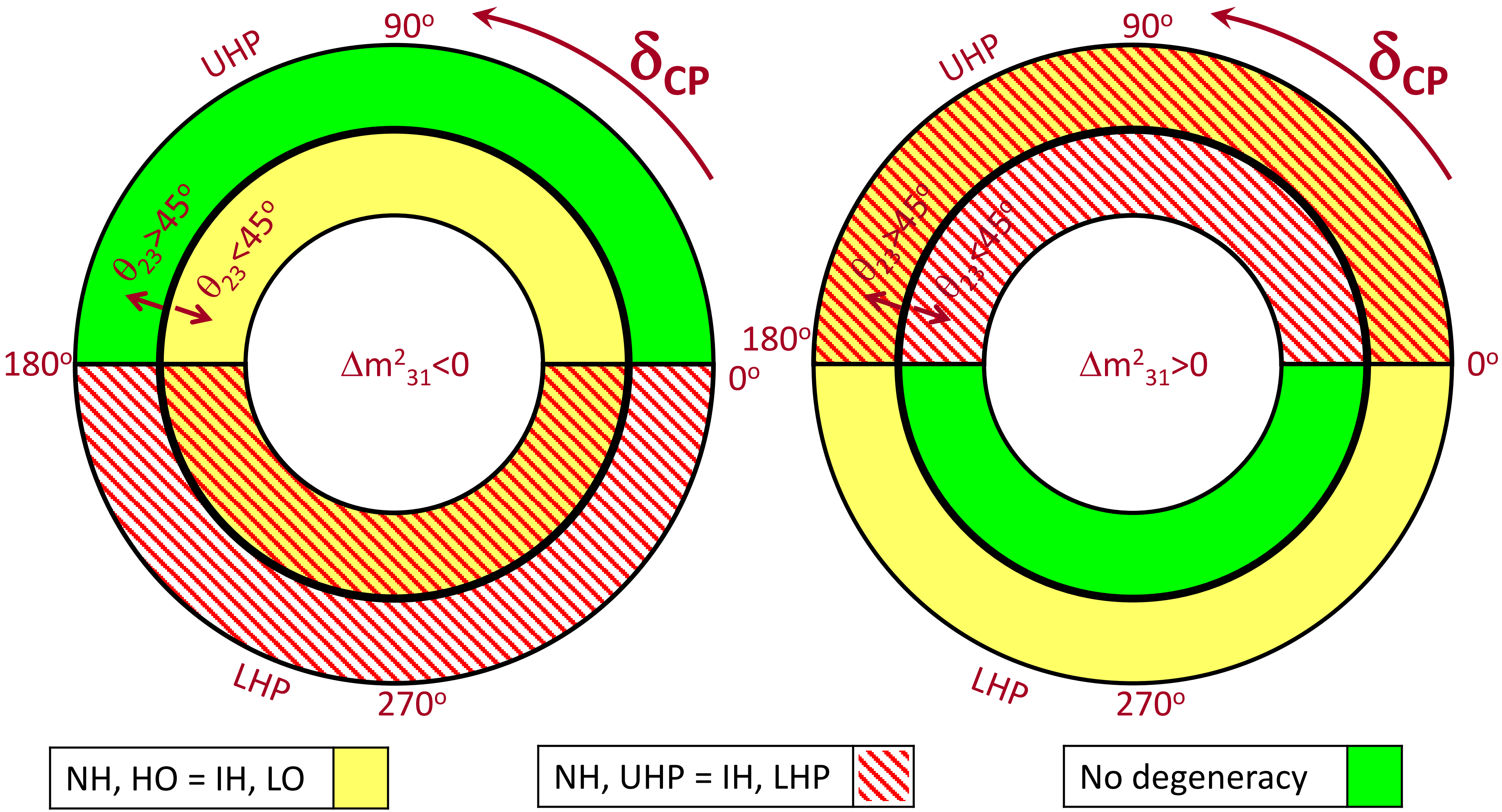


Degeneracies in neutrino parameter space



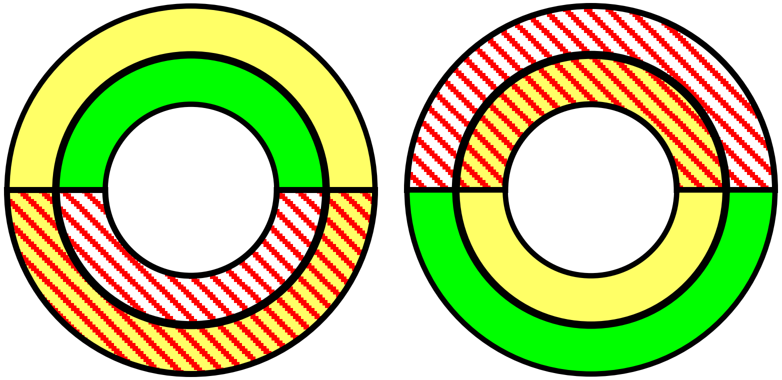
NH, LO = IH, HO	
NH, UHP = IH, LHP	
No degeneracy	

Degeneracies in antineutrino parameter space

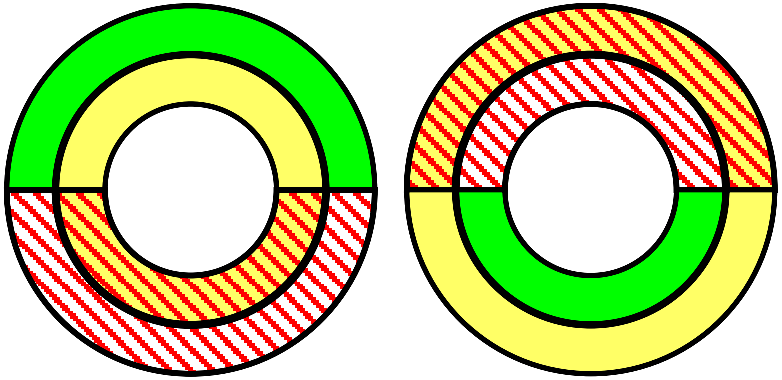


Summary of degeneracies

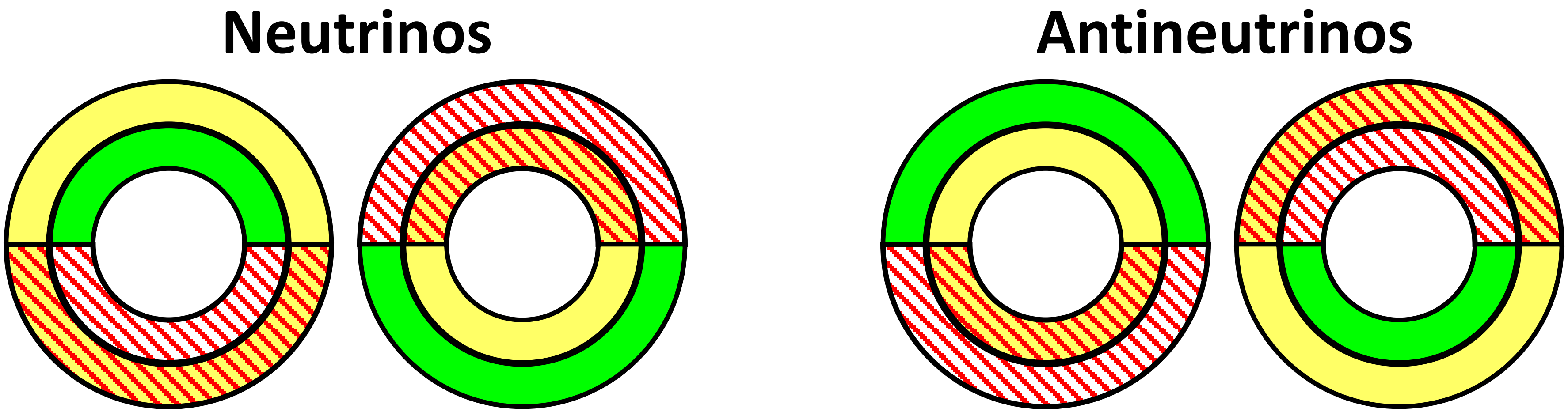
Neutrinos



Antineutrinos

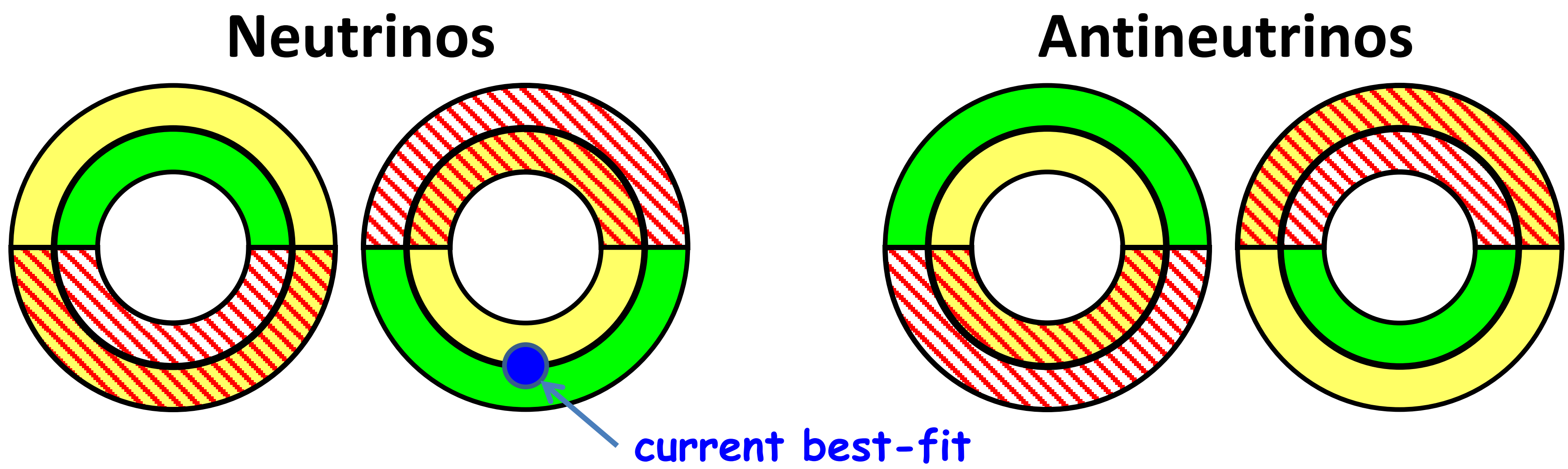


Summary of degeneracies



0. If the best-fit value is in the 'green' area, we are lucky
1. If we end up in the yellow unshaded area, lift the octant degeneracy by collecting data with the opposite polarity
2. If we are in the shaded area, we need to resolve the hierarchy degeneracy. This can only be done in conjunction with another experiment that measures δ_{CP} or is insensitive to δ_{CP} .

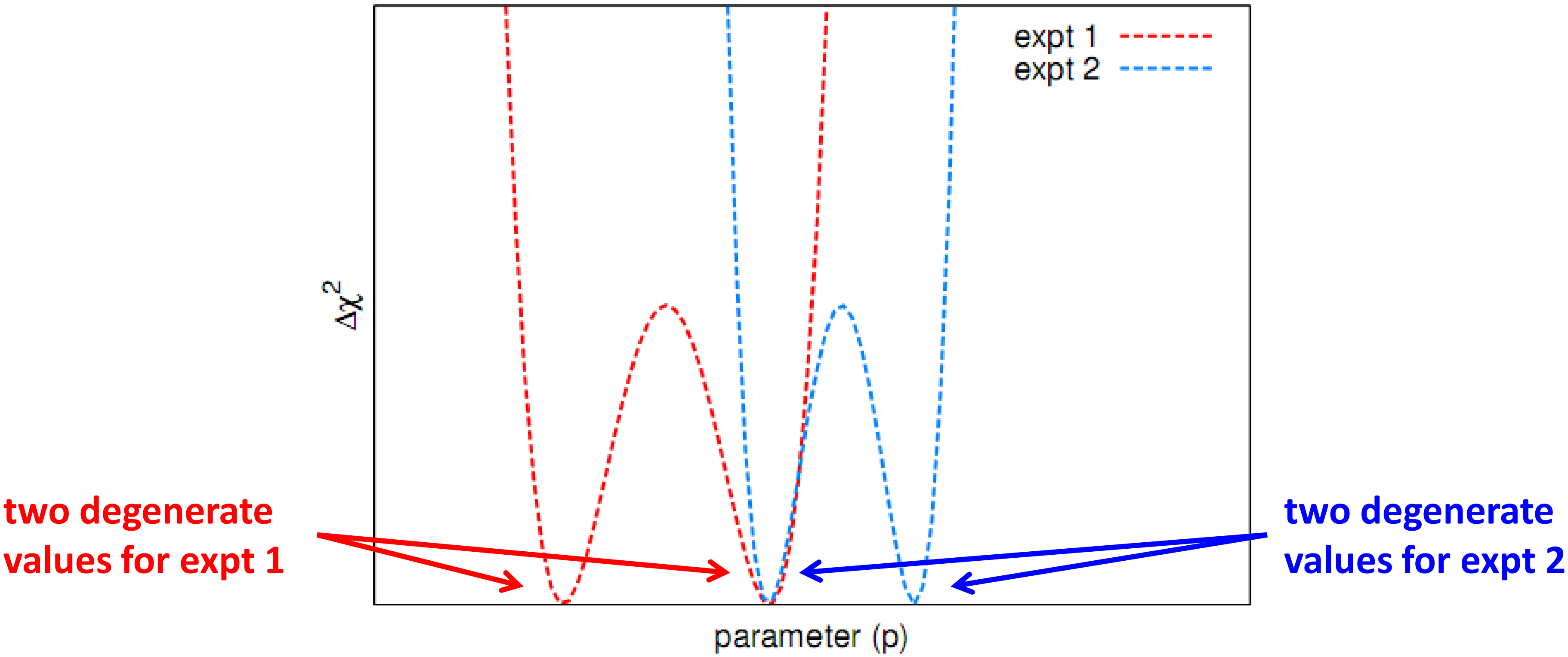
Summary of degeneracies



0. If the best-fit value is in the 'green' area, we are lucky
1. If we end up in the yellow unshaded area, lift the octant degeneracy by collecting data with the opposite polarity
2. If we are in the shaded area, we need to resolve the hierarchy degeneracy. This can only be done in conjunction with another experiment that measures δ_{CP} or is insensitive to δ_{CP} .

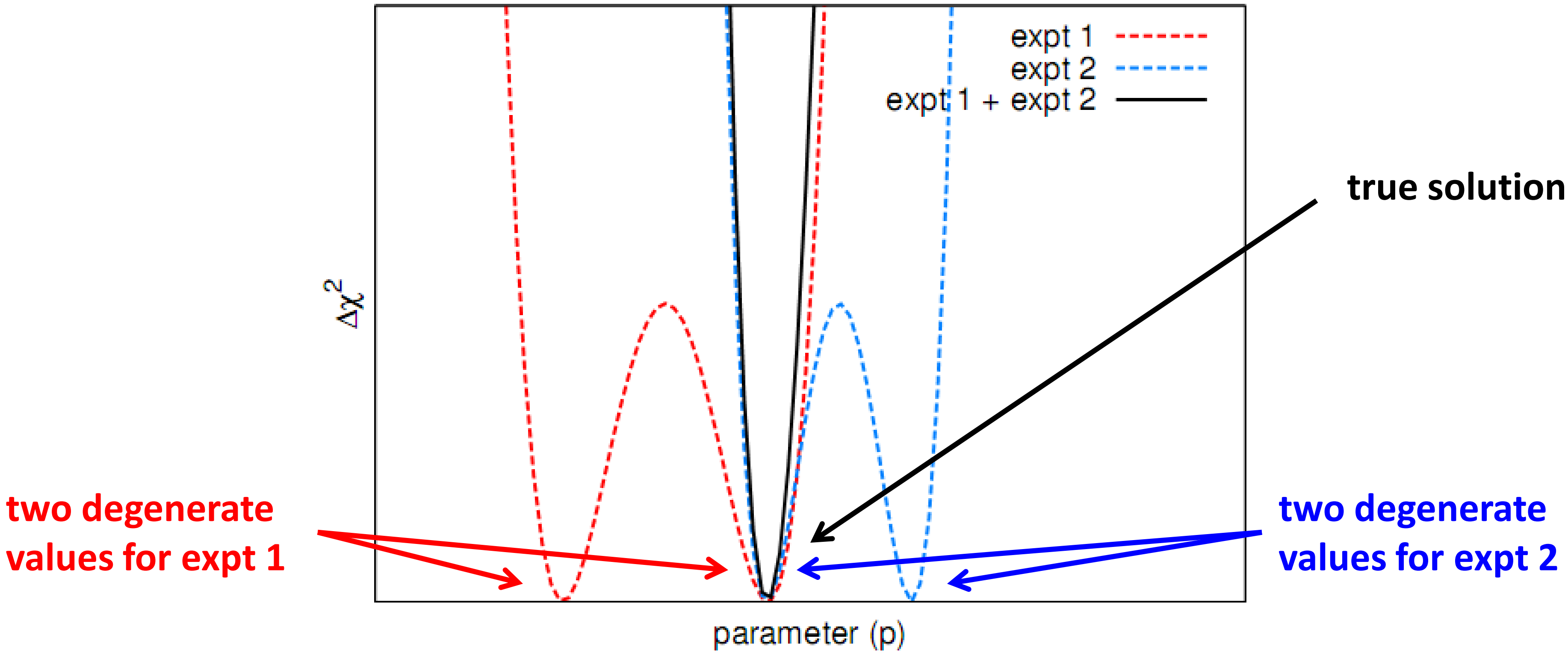
Synergies between experiments

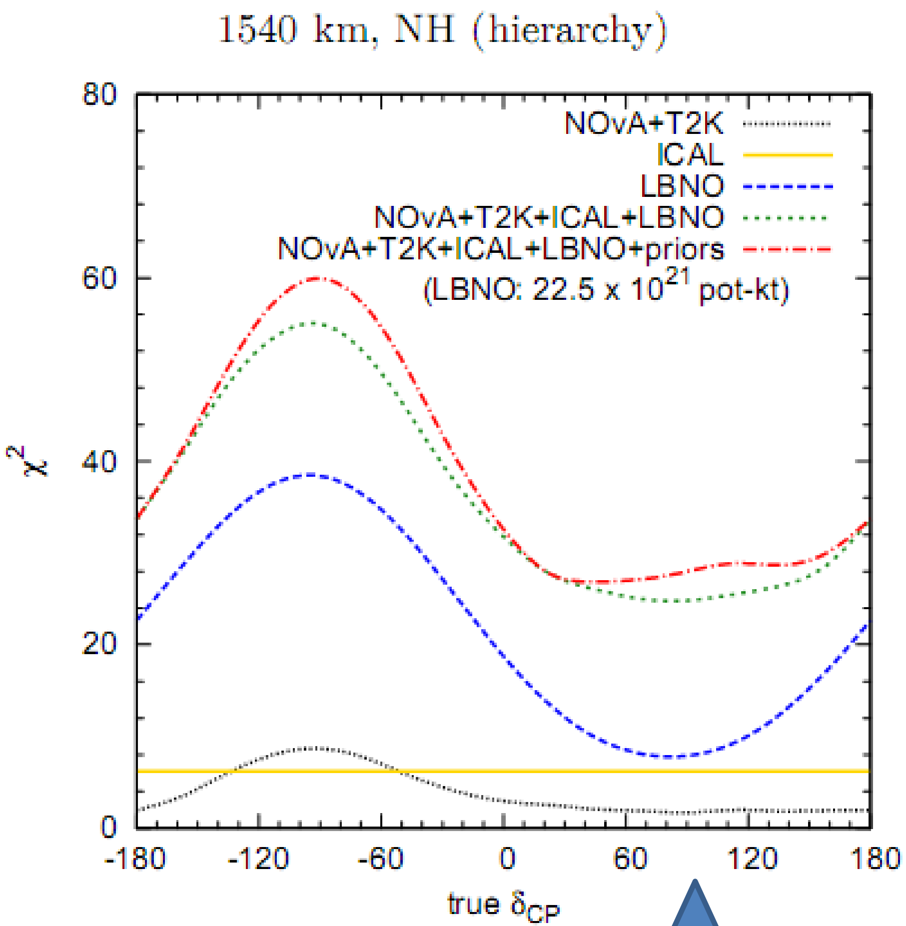
Different experiments have different L,E dependence, therefore their functional dependence on a given parameter p is different.



Synergies between experiments

Different experiments have different L,E dependence, therefore their functional dependence on a given parameter p is different.





1308.5979: Ghosh, Ghoshal, Goswami, SR

Combined χ^2 much higher than sum of the individual χ^2 : Synergy!

Future experiments

T2HK

T2HKK

ESSνSB

DUNE

JUNO

HK

ICAL@INO

PINGU

μDAR

MOMENT

Future experiments

<~20 km

μDAR

200-2000 km

T2HK

T2HKK

DUNE

ESSνSB

20-200 km

JUNO

MOMENT

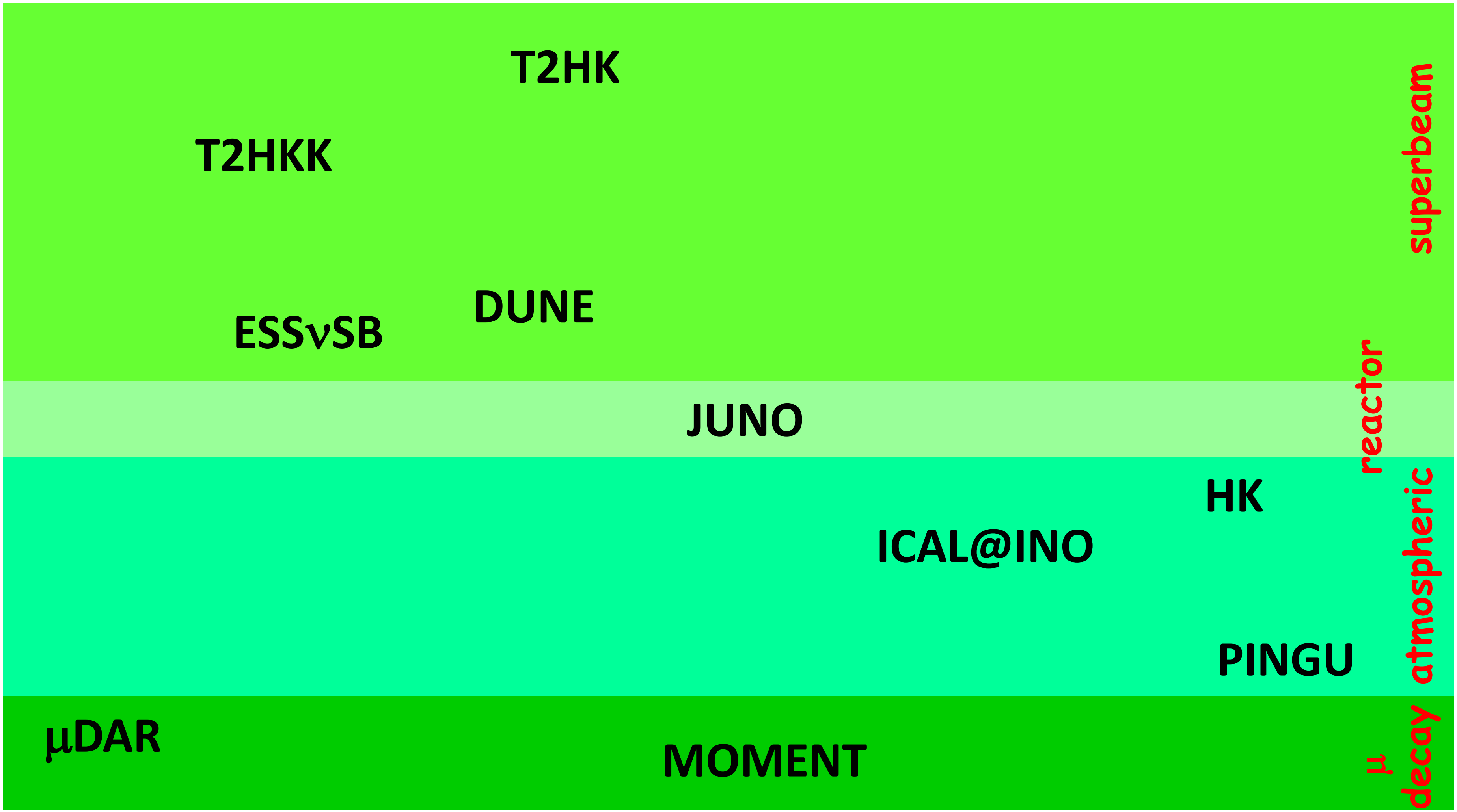
O(1000-10000 km)

HK

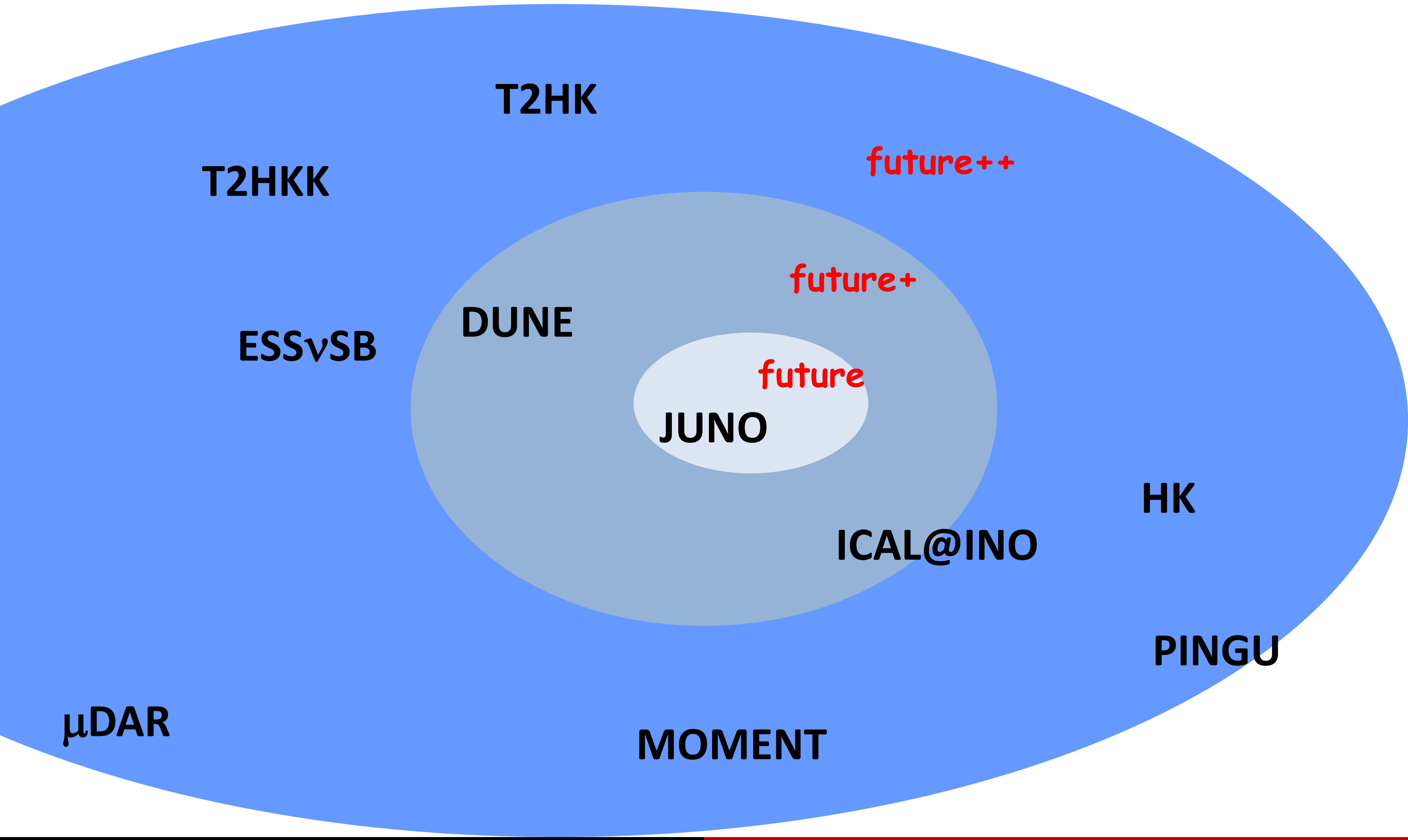
ICAL@INO

PINGU

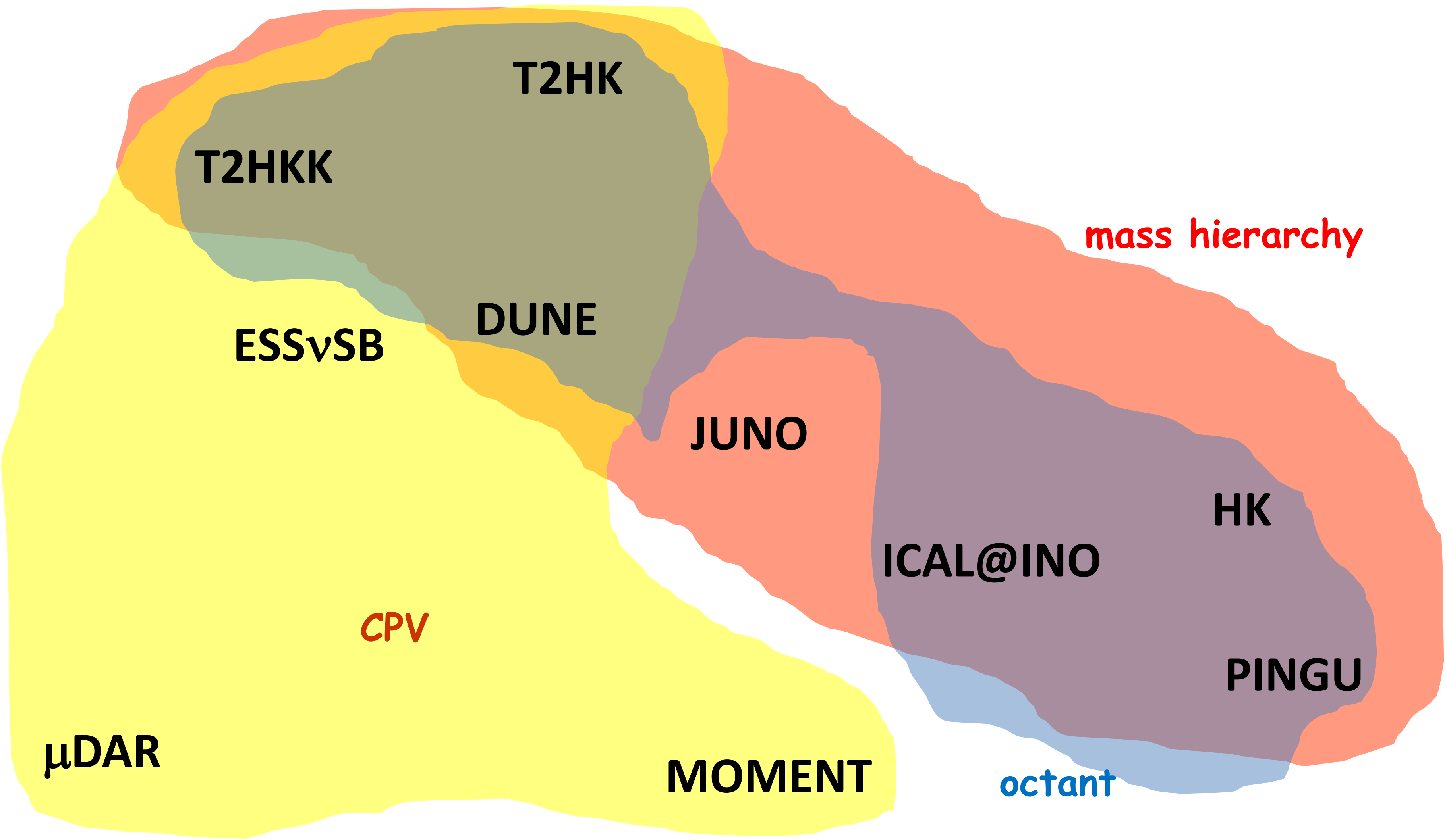
Future experiments



Future experiments



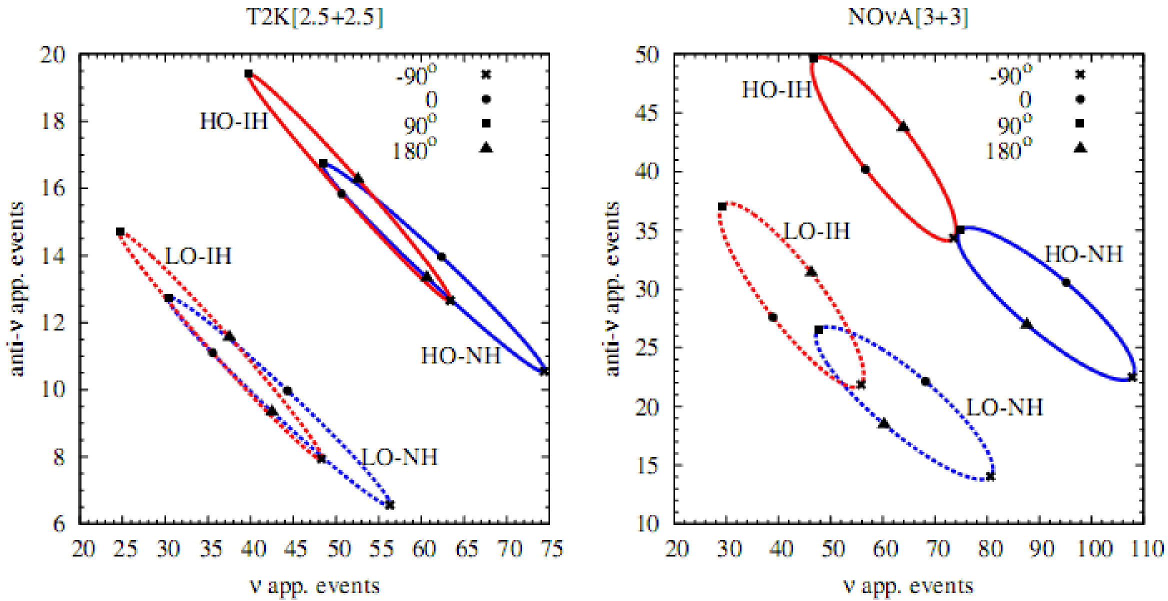
Future experiments



Mass hierarchy

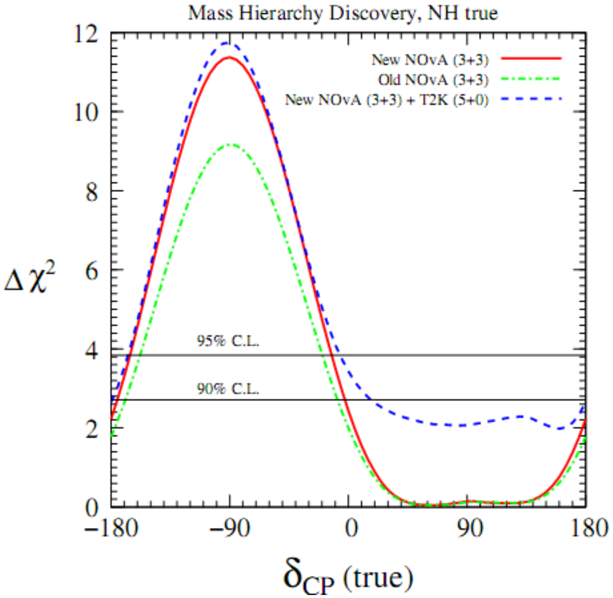
$$P_{\mu e} = 4\sin^2\theta_{13}\sin^2\theta_{23}\frac{\sin^2((1-\hat{A})\Delta)}{(1-\hat{A})^2} + \alpha^2\sin^2 2\theta_{12}\cos^2\theta_{23}\frac{\sin^2(\hat{A}\Delta)}{\hat{A}^2}$$

$$+2\alpha\sin\theta_{13}\sin 2\theta_{12}\sin 2\theta_{23}\cos(\Delta+\delta_{CP})\frac{\sin((1-\hat{A})\Delta)}{(1-\hat{A})}\frac{\sin(\hat{A}\Delta)}{\hat{A}}$$



Matter effects help to break the hierarchy-CP degeneracy

Mass hierarchy

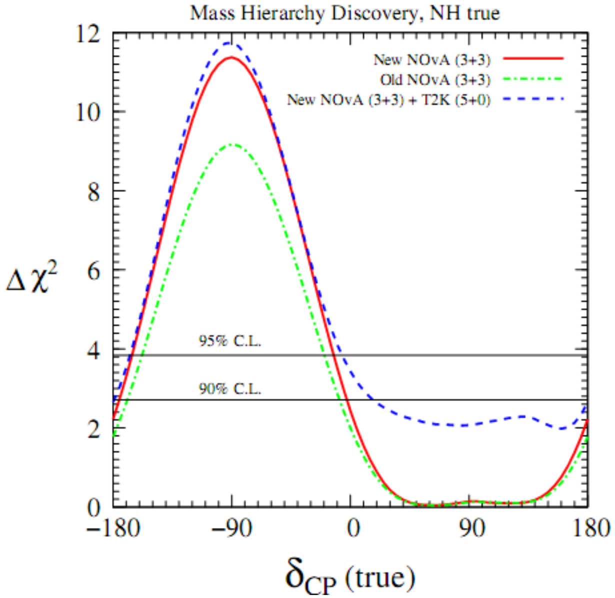


For favourable combinations of parameters, NOvA and T2K can determine the hierarchy very well

1208.3644: Agarwalla, Prakash, SR, Uma Sankar

For unfavourable combinations, we need data from an expt that is either (a) insensitive to CP, (b) has more matter effects to break the degeneracy, or (c) has negligible matter effects in order to measure CP independently of the hierarchy

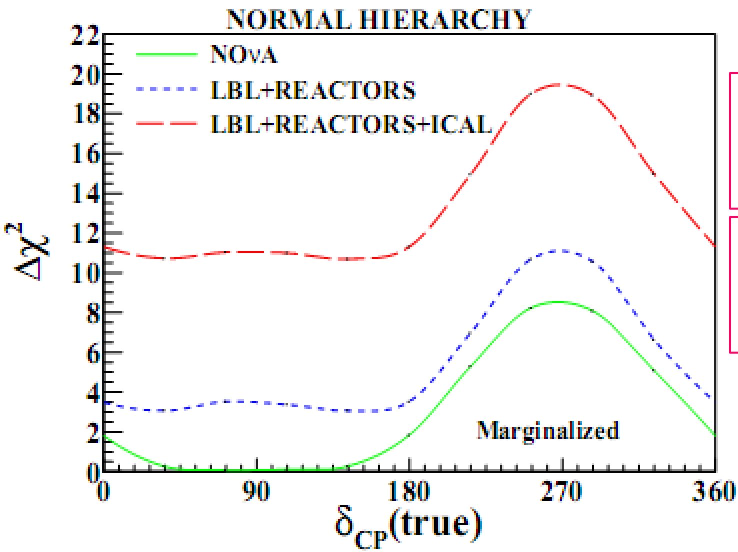
Mass hierarchy



For favourable combinations of parameters, NOvA and T2K can determine the hierarchy very well

1208.3644: Agarwalla, Prakash, SR, Uma Sankar

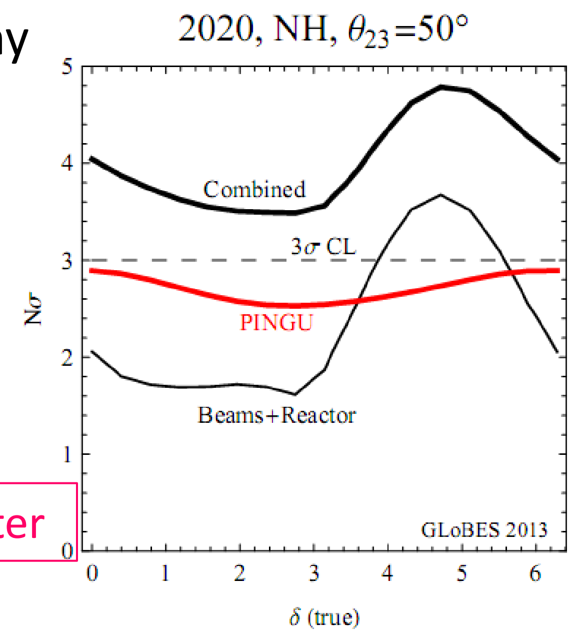
For unfavourable combinations, we need data from an expt that is either (a) insensitive to CP, (b) has more matter effects to break the degeneracy, or (c) has negligible matter effects in order to measure CP independently of the hierarchy



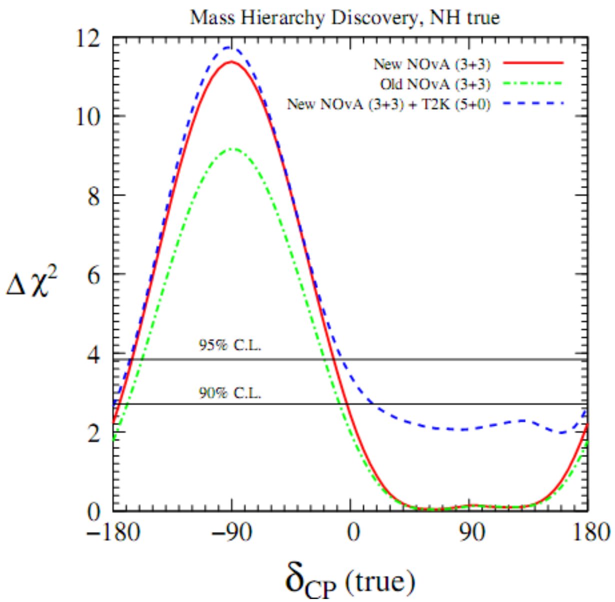
1212.1305: Choubey, Ghosh, Thakore

Also see 1203.3388: Blennow, Schwetz

1305.5539: Winter



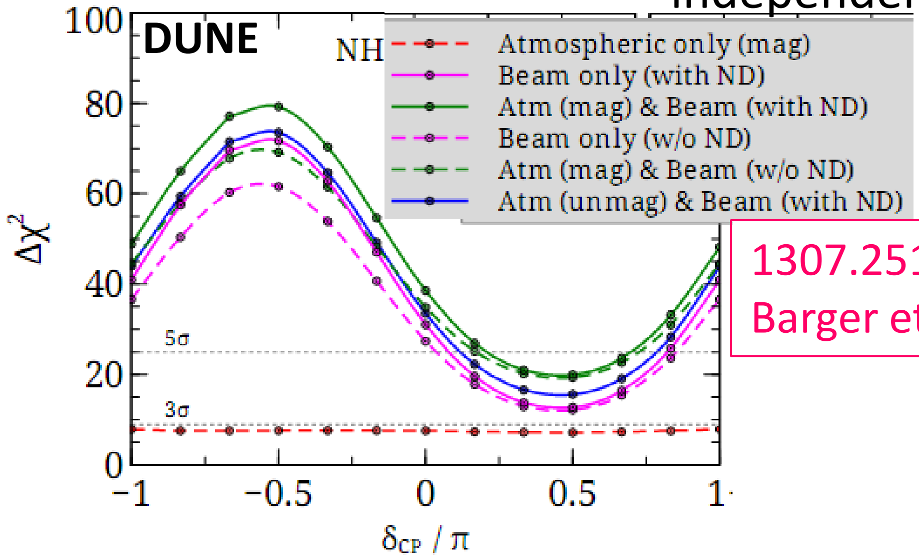
Mass hierarchy



For favourable combinations of parameters, NOvA and T2K can determine the hierarchy very well

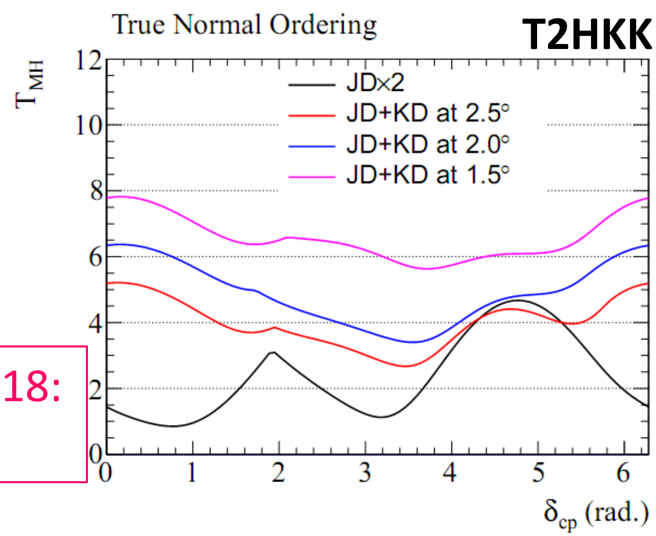
1208.3644: Agarwalla, Prakash, SR, Uma Sankar

For unfavourable combinations, we need data from an expt that is either (a) insensitive to CP, (b) has more matter effects to break the degeneracy, or (c) has negligible matter effects in order to measure CP independently of the hierarchy

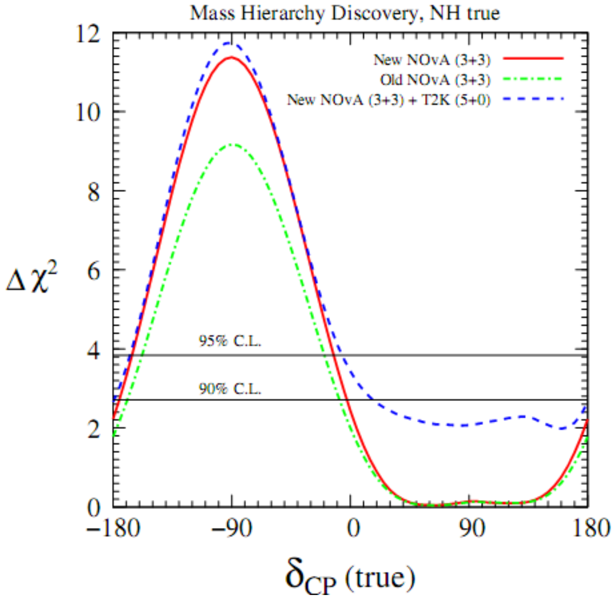


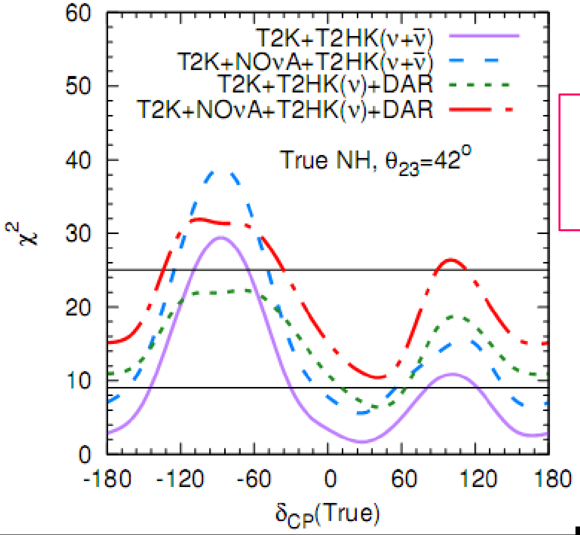
1307.2519: Barger et al.

1611.06118: Abe et al.



Mass hierarchy





For favourable combinations of parameters, NOvA and T2K can determine the hierarchy very well

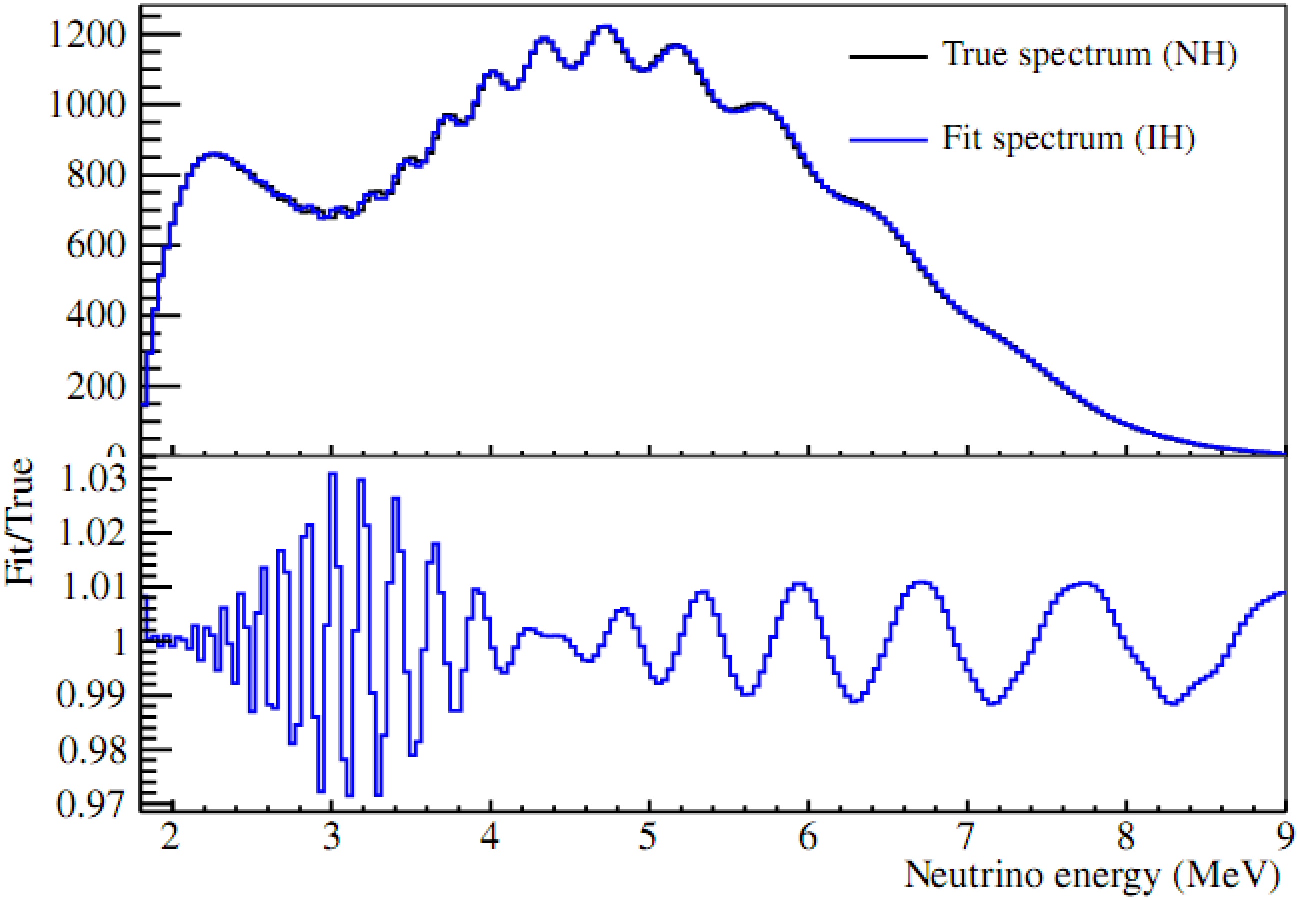
1208.3644: Agarwalla, Prakash, SR, Uma Sankar

For unfavourable combinations, we need data from an expt that is either (a) insensitive to CP, (b) has more matter effects to break the degeneracy, or (c) has negligible matter effects in order to measure CP independently of the hierarchy

1704.06116: Agarwalla, Ghosh, SR

See poster #64

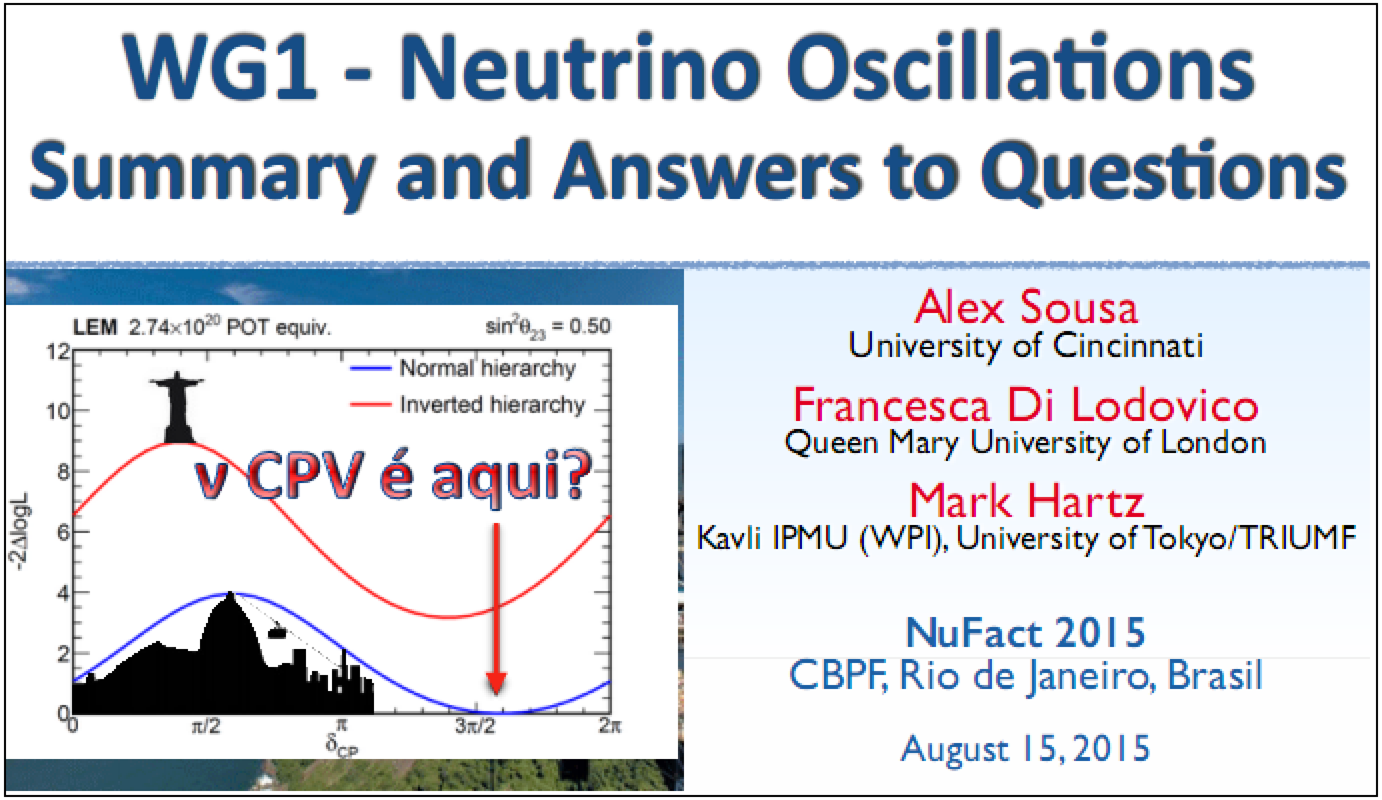
Mass hierarchy



JUNO: Mass hierarchy determination through spectral effects at L/E ~ solar mass-sq diff

1508.07166 (JUNO CDR)

CP violation

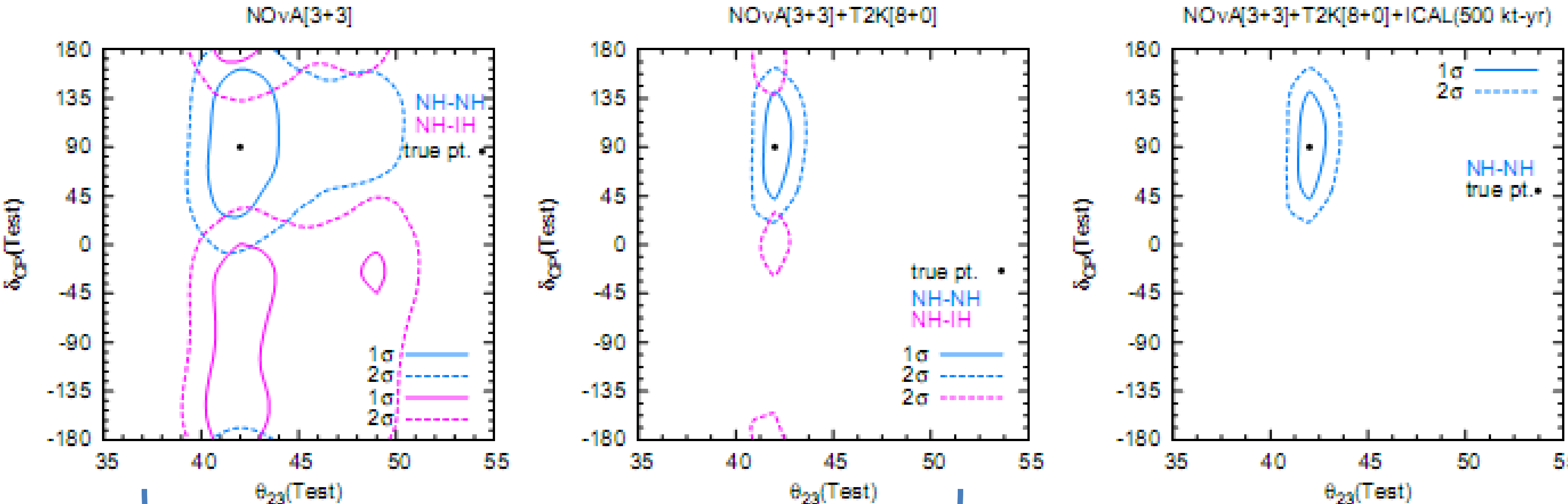


Alex Sousa, at NuFact 2015 in Rio

Hint from T2K and NOvA for δ_{CP} around -90^o

Favourable part of the parameter space if the hierarchy is normal

CP violation



Synergy between NOvA and T2K helps constrain the wrong-hierarchy solution

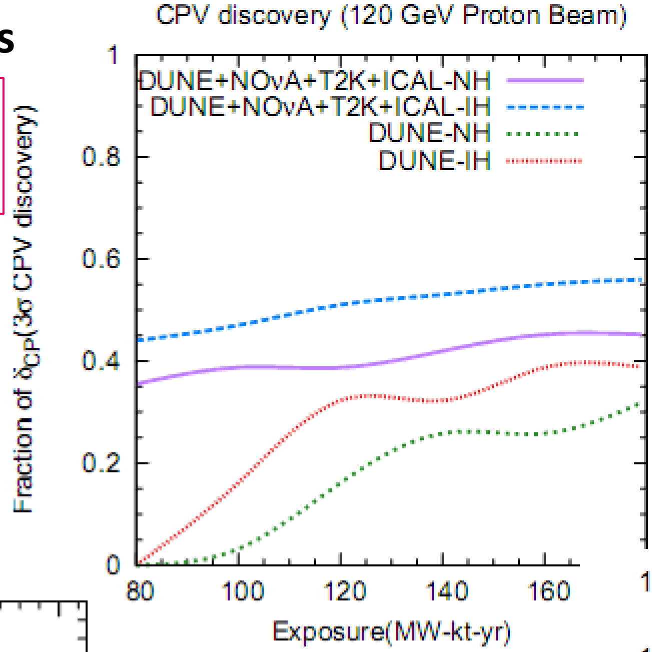
1504.06283: Ghosh, Ghoshal, Goswami, Nath, SR

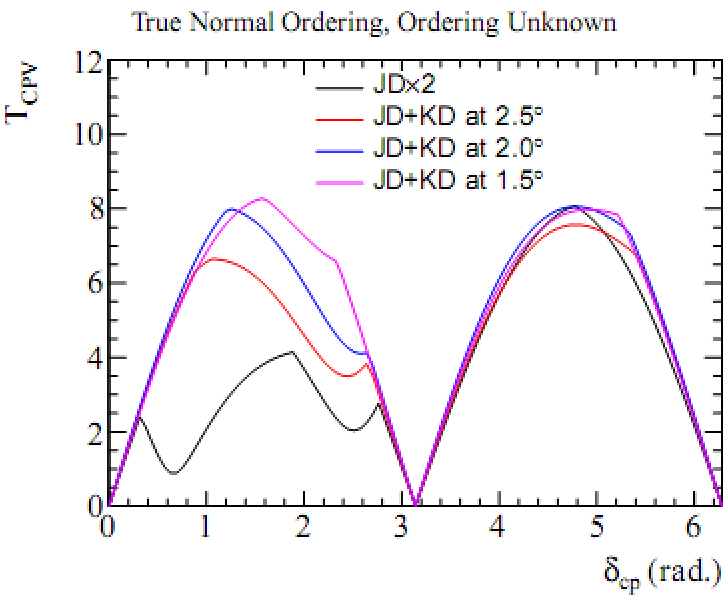
Atmospheric neutrino expts which are typically insensitive to CP, can also improve CP measurement further by eliminating the wrong-hierarchy solution

CP violation

DUNE + NOvA + T2K + atmos

1412.1744: Ghosh, Goswami, SR

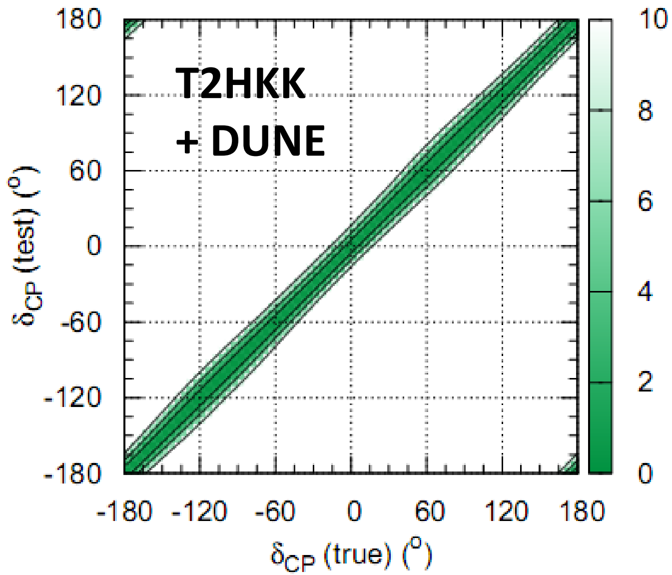




T2HK/ T2HKK

1611.06118: Abe et al.

1703.07136: SR

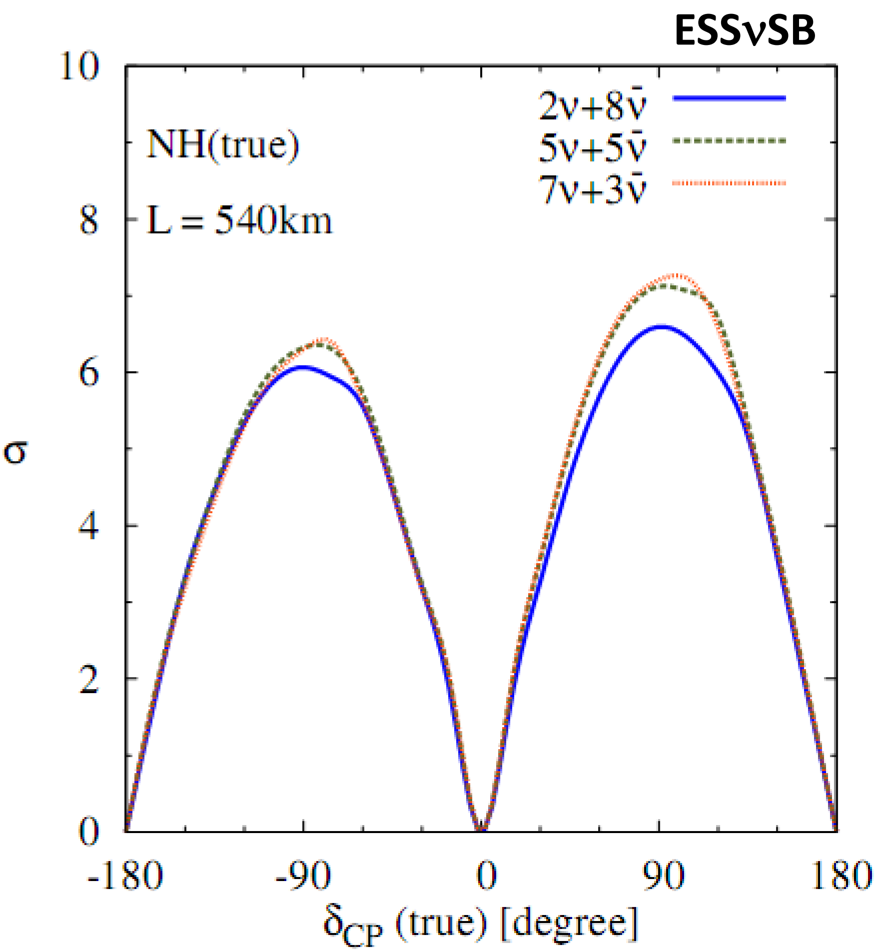


CP violation

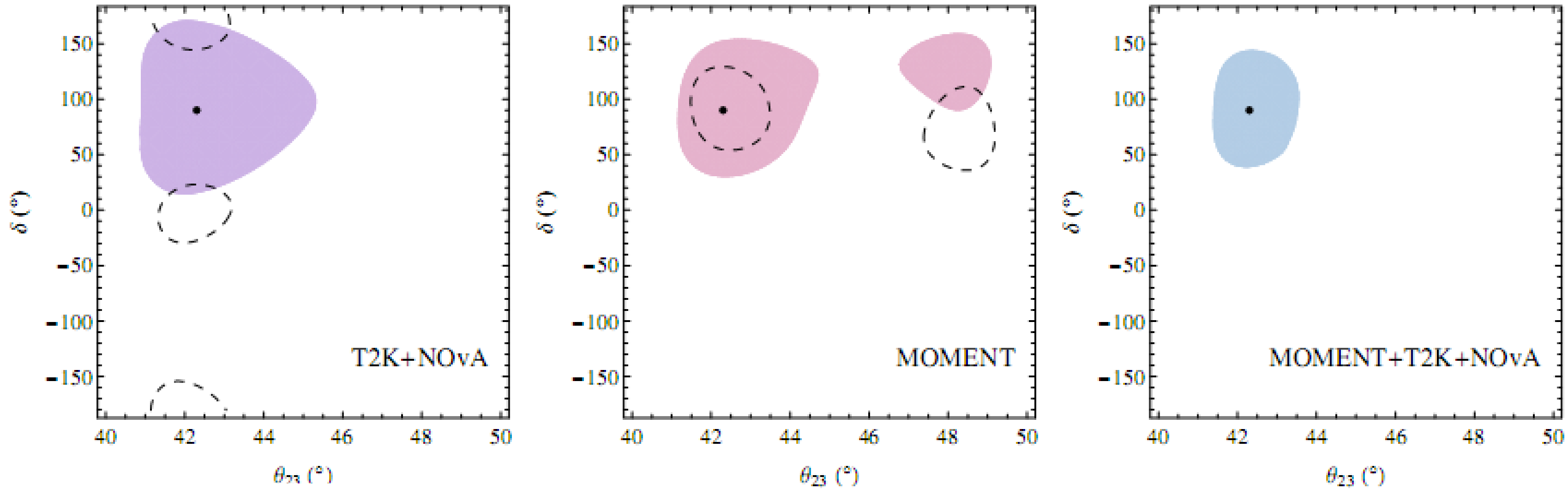
$$\lim_{\hat{A}\to 0} \frac{dP_{\mu e}}{d\delta_{CP}} \propto \Delta \sin\Delta \sin(\Delta + \delta_{CP})$$

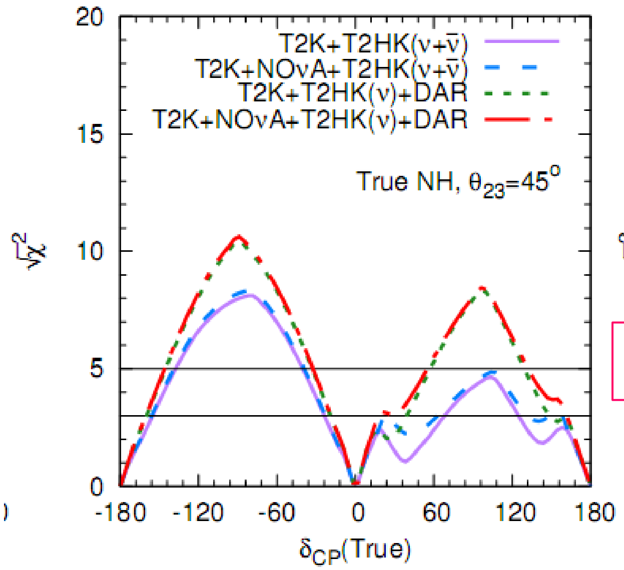
CP sensitivity is greater at the second oscillation maximum ($\Delta=3\pi/2$) than at the first one ($\Delta=\pi/2$)

1406.2219: Agarwalla, Choubey, Prakash



CP violation

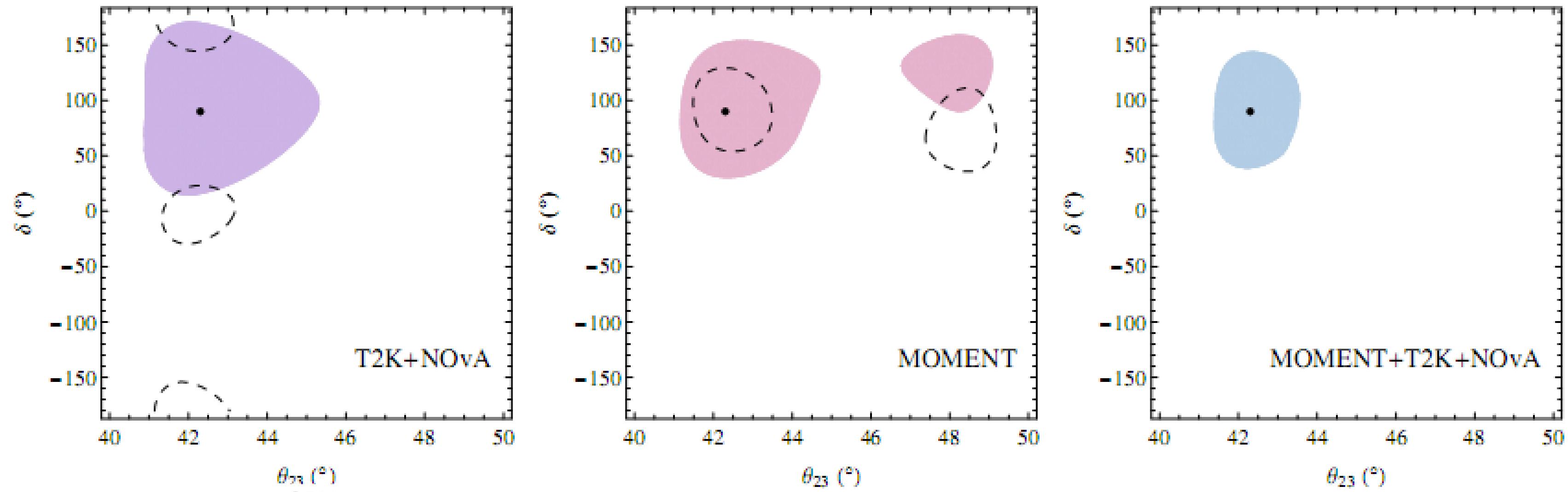


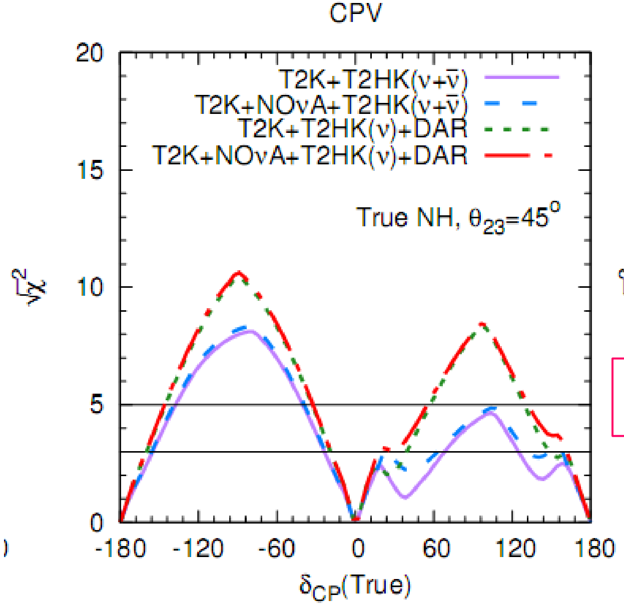


1511.02859: Blennow, Coloma, Fernandez-Martinez

1704.06116: Agarwalla, Ghosh, SR

CP violation



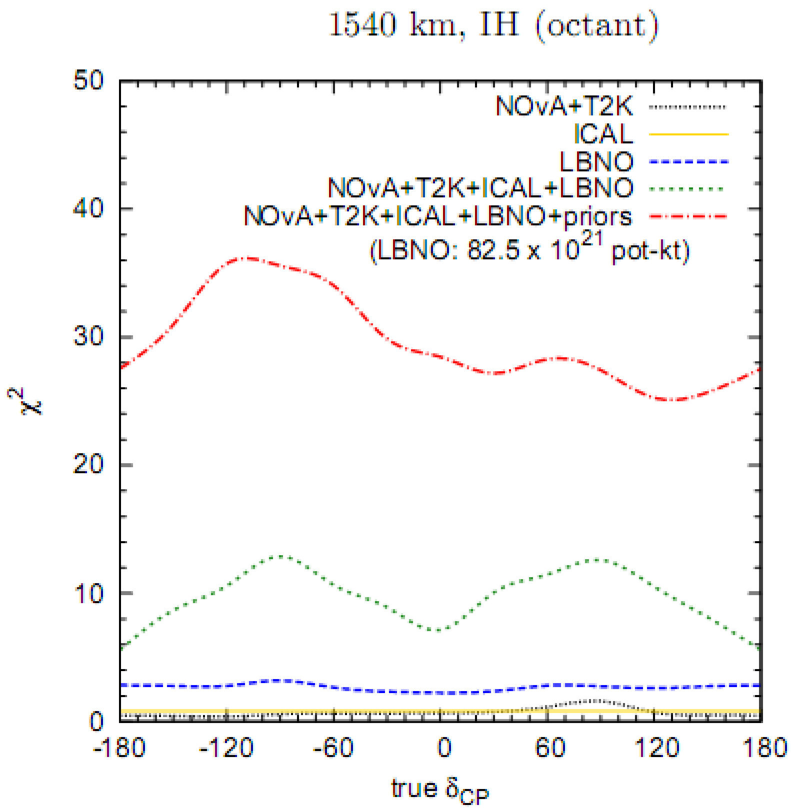


1511.02859: Blennow, Coloma, Fernandez-Martinez

Combination of neutrino and antineutrino data helps in measuring δ_{CP} by breaking the degeneracy

1704.06116: Agarwalla, Ghosh, SR

Octant of θ_{23}



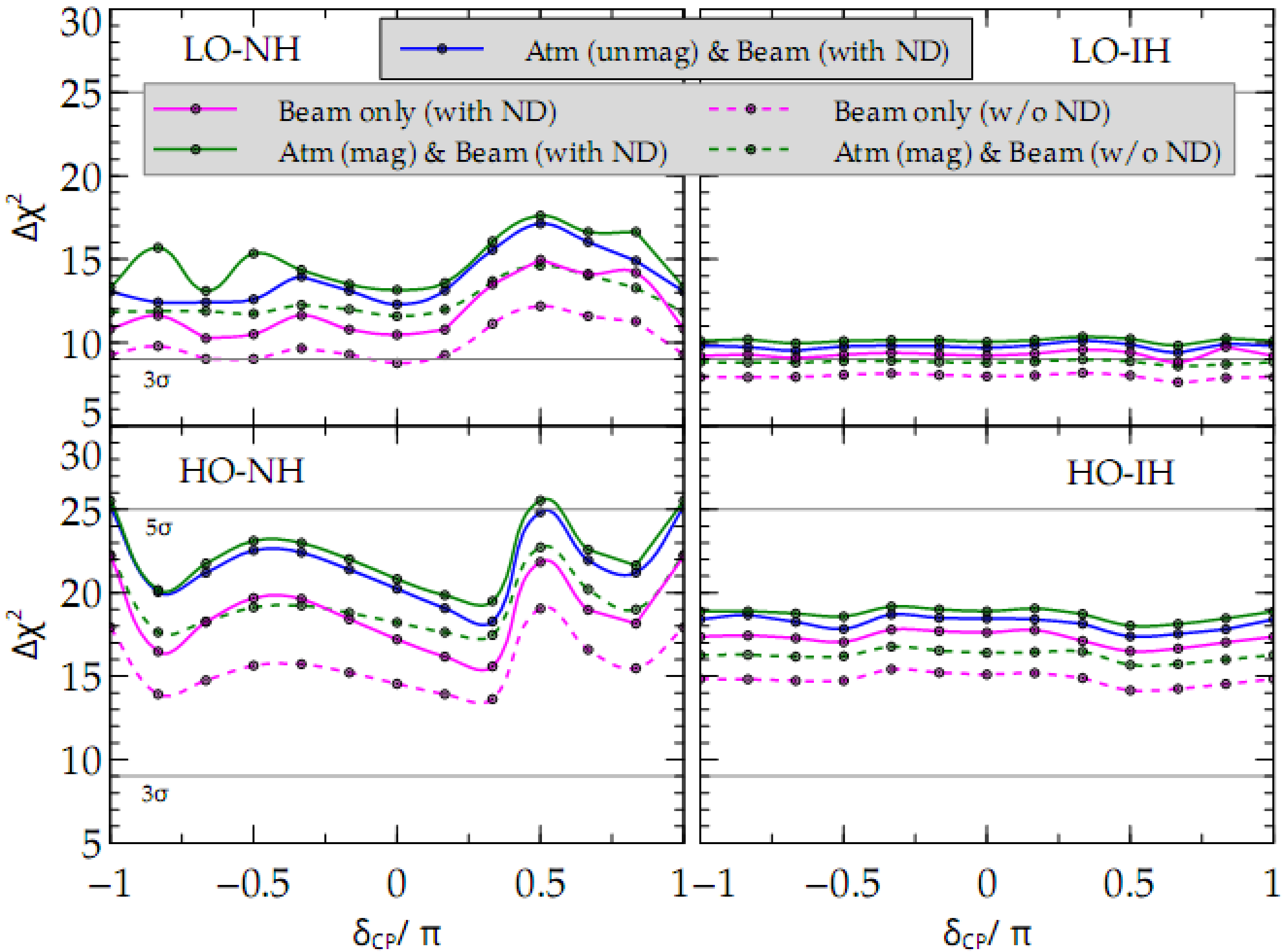
1308.5979: Ghosh, Ghoshal, Goswami, SR

Synergy in octant measurement: Note the effect of reactor data (prior on θ_{13})

$$\sin^2 2\theta_{\mu\mu} = 4|U_{\mu 3}|^2 \left(1 - |U_{\mu 3}|^2\right)$$

$$= 4\cos^2\theta_{13}\sin^2\theta_{23}(1 - \cos^2\theta_{13}\sin^2\theta_{23})$$

Octant of θ_{23}



DUNE

1307.2519:
Barger et al.


Sterile nus
hierarchy, octant,
CP measurements
CC NSIs
NC NSIs
non-unitarity
etc.

Beyond standard oscillations

Beyond standard oscillation scenarios:

CC NSIs (production/detection),

NC NSIs (propagation),

Sterile neutrinos,

Non-unitarity, ...

- Q1: How does the presence of new physics affect the measurement of the standard neutrino parameters?
- Q2: Can the new physics parameters be measured?

Beyond standard oscillations

Beyond standard oscillation scenarios:

CC NSIs (production/detection),

NC NSIs (propagation),

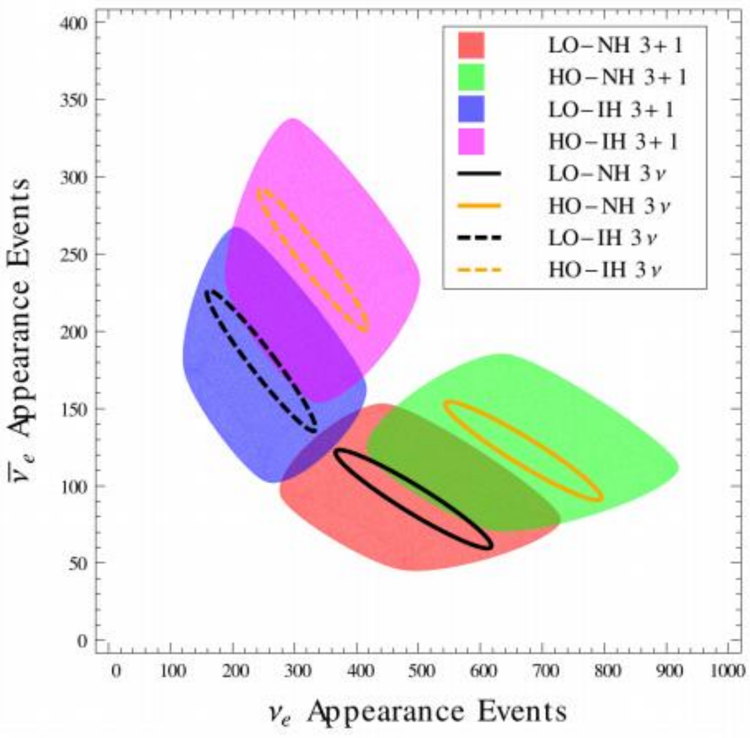
Sterile neutrinos,

Non-unitarity, ...

- Q1: How does the presence of new physics affect the measurement of the standard neutrino parameters?
- Q2: Can the new physics parameters be measured?

an opportunity to probe BSM physics!

Sterile neutrinos

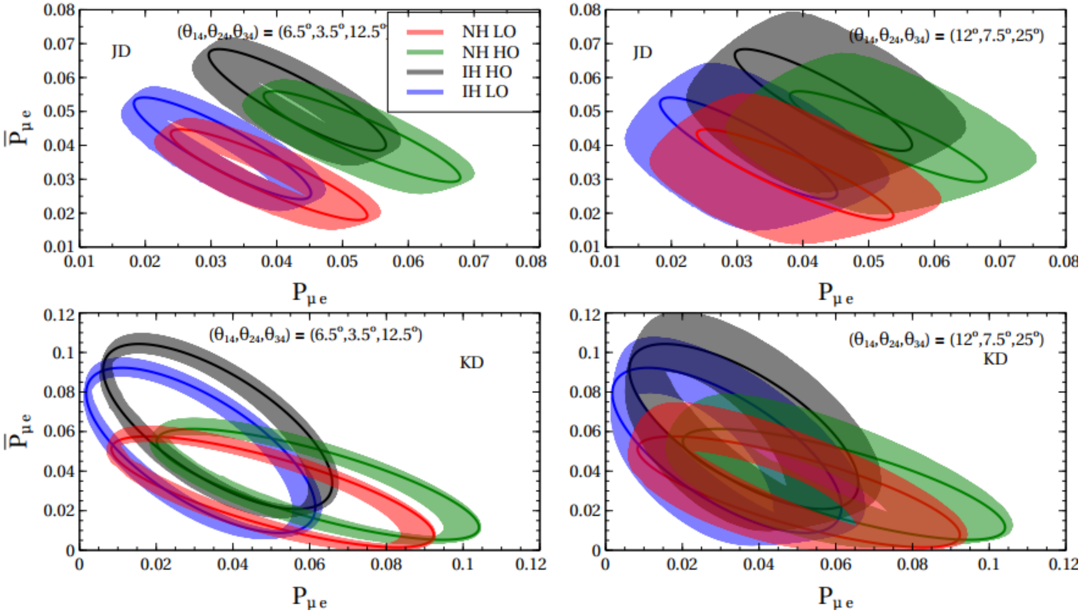


1605.04299: Agarwalla, Chatterjee, Palazzo

DUNE: Expansion of the parameter space leads to octant-δ_{CP}-δ_{14} degeneracy

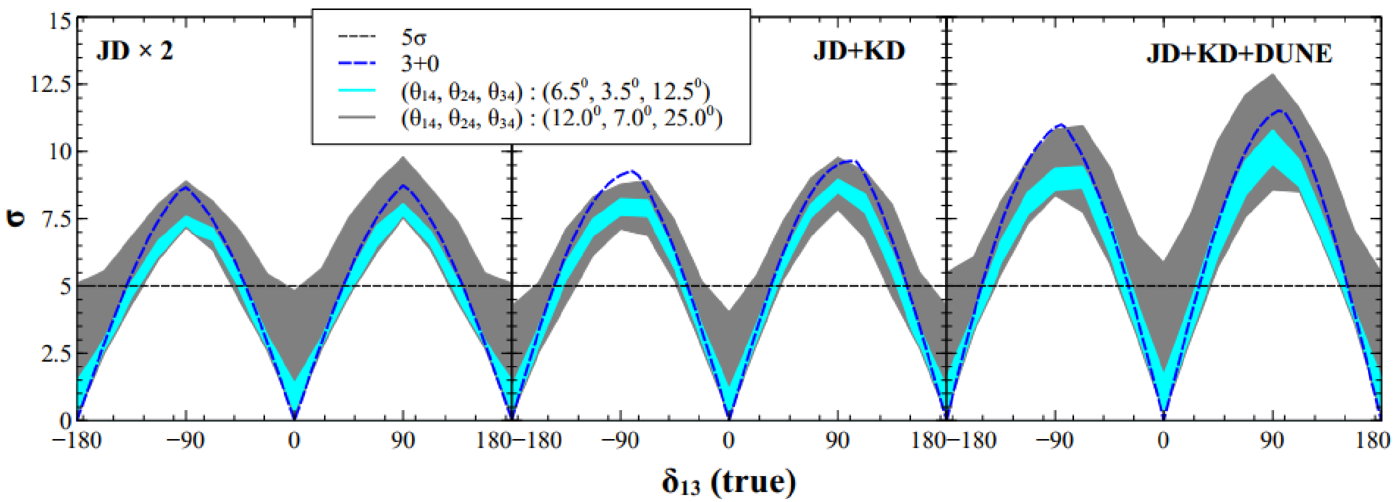
Unlike the hierarchy-δ_{14} degeneracy, the octant-δ_{14} degeneracy is more difficult to resolve, even with a combination of neutrino and antineutrino data

1704.04771: Ghosh, Gupta, Matthews, Sharma, Williams



1704.07269: Choubey, Dutta, Pramanik

Degeneracies and their possible removal at T2HKK and DUNE

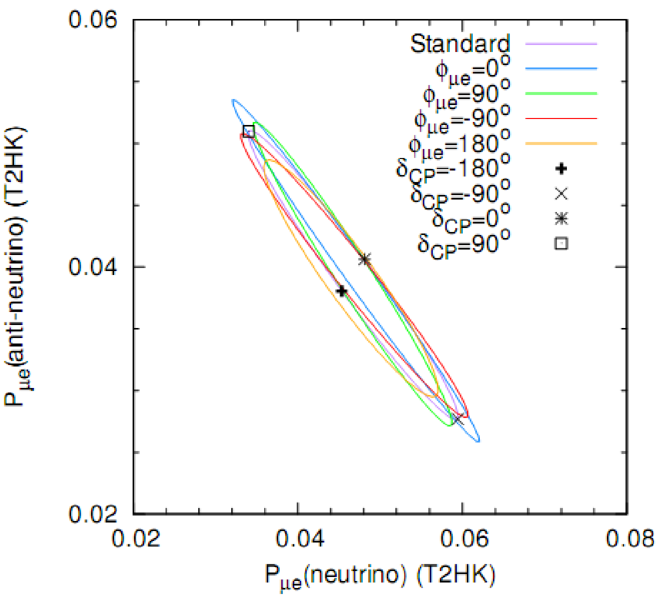


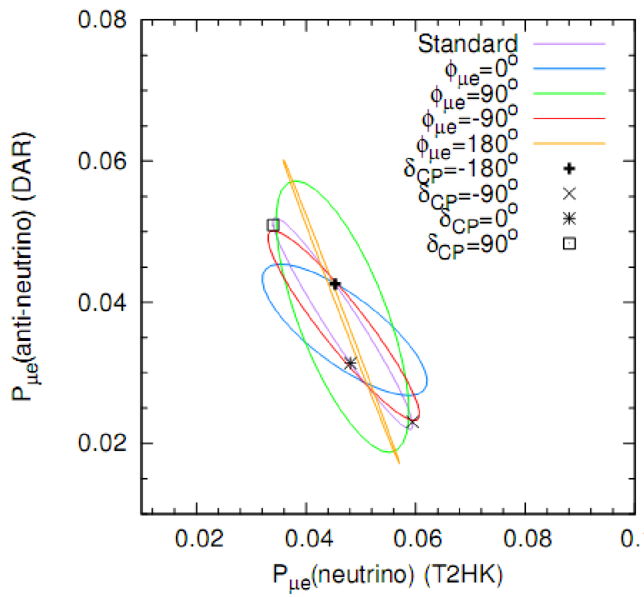
CC NSIs

To probe CC NSIs (at source and detector) without interference from the NC NSIs (in propagation), use a low-energy experiment to reduce matter effects

Eg. ESSnuSB 1507.02868: Blennow, Choubey, Ohlsson, SR

Eg. MOMENT 1705.09500: Tang, Zhang



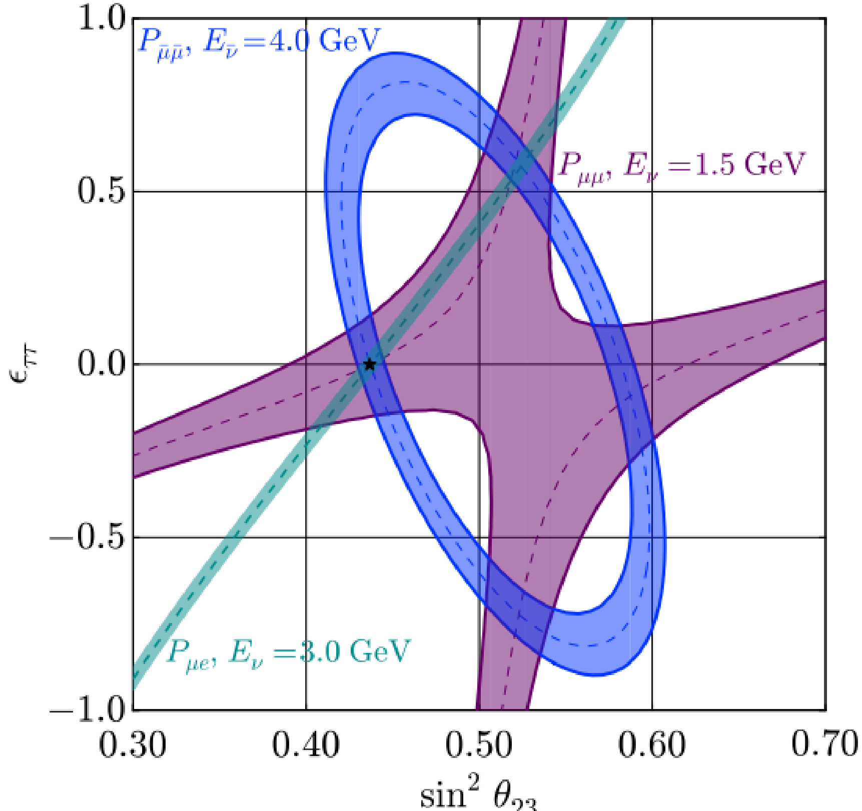


In preparation: Agarwalla, Ghosh, SR

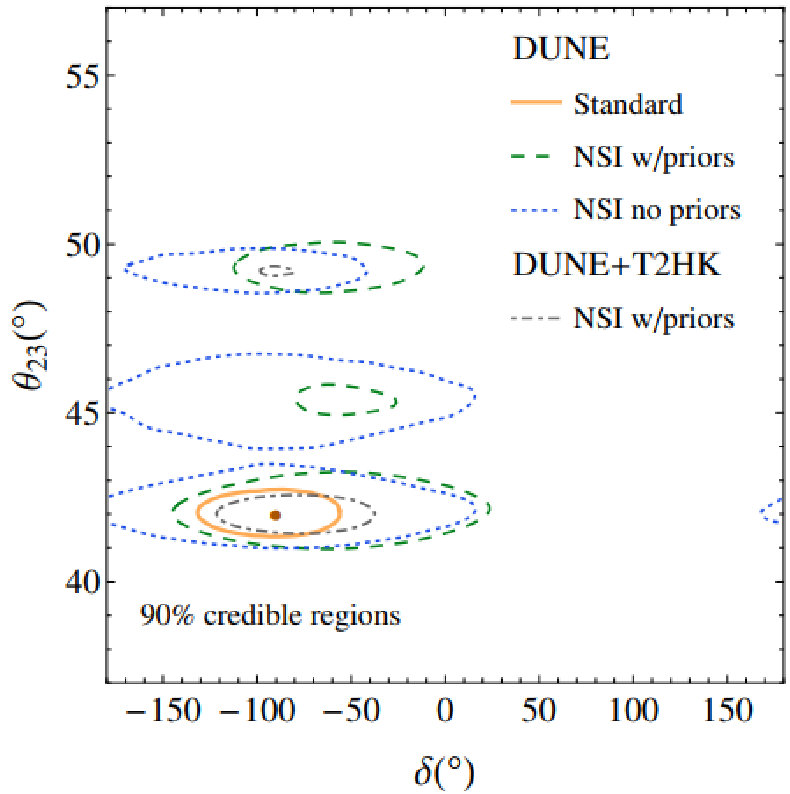
NC NSIs

NC NSIs (in propagation) are best probed with large matter effects

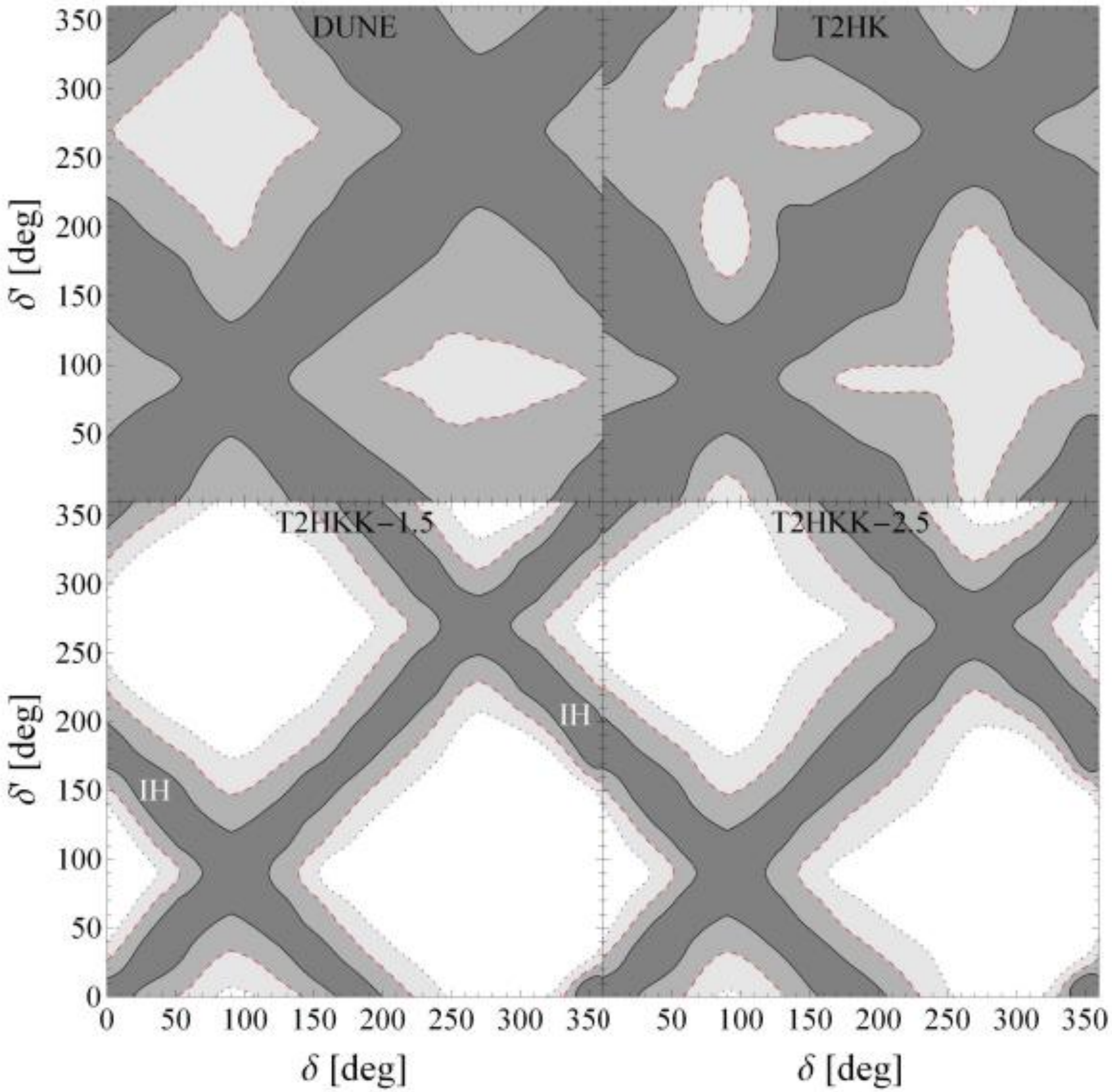
Eg. DUNE, T2HKK, atmospheric neutrino experiments



1511.05562: de Gouvea, Kelly



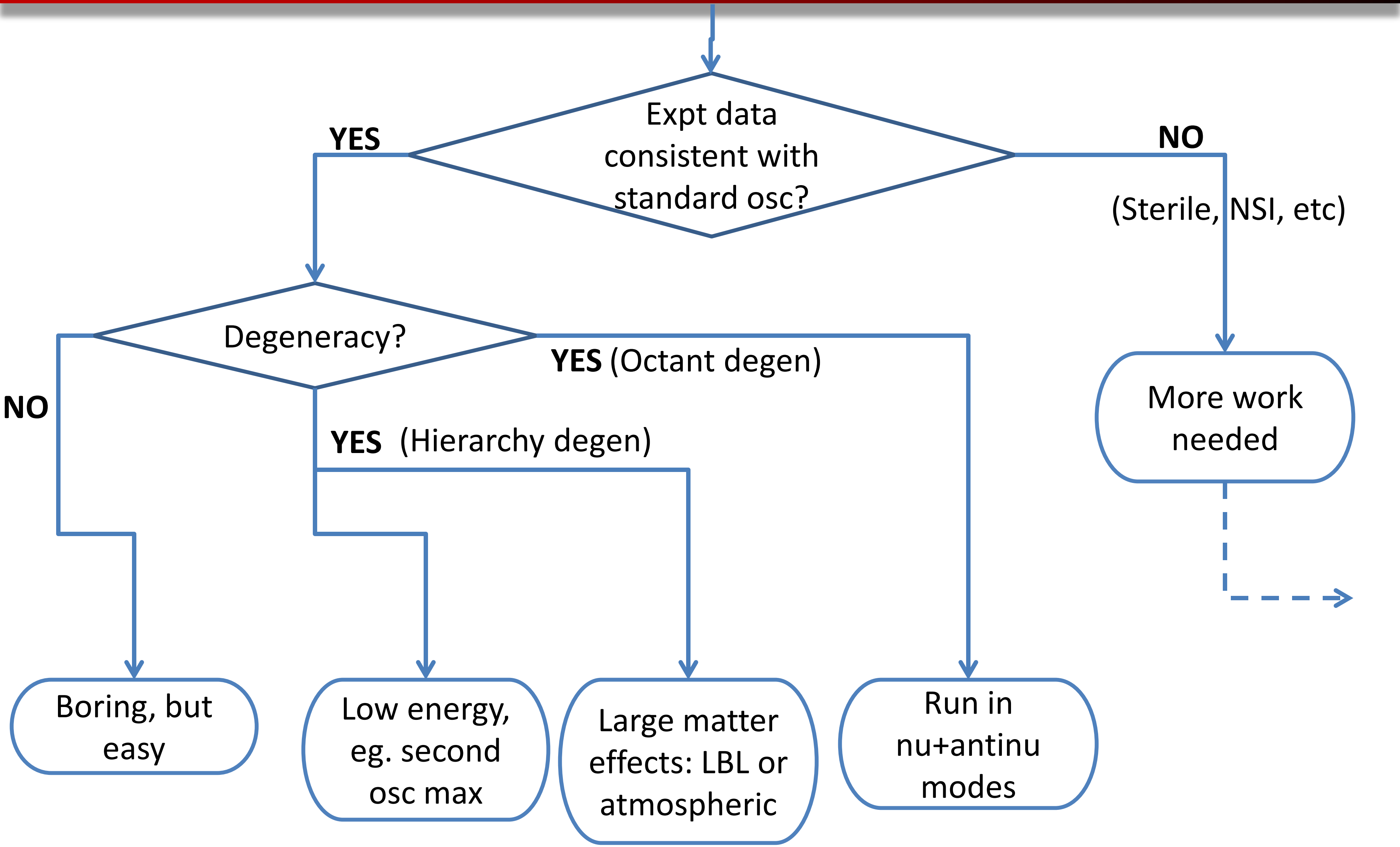
1511.06357: Coloma



Degeneracies in measuring CPV at DUNE, T2HK and T2HKK (hierarchy unknown)

1612.01443: Liao, Marfatia, Whisnant

Summary: A flowchart for the future?



THANK YOU