Earlier Resolution of Neutrino Mass Ordering?

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Based on the work by A. Cabrera et al, arXiv: 2008.11280 [hep-ph]

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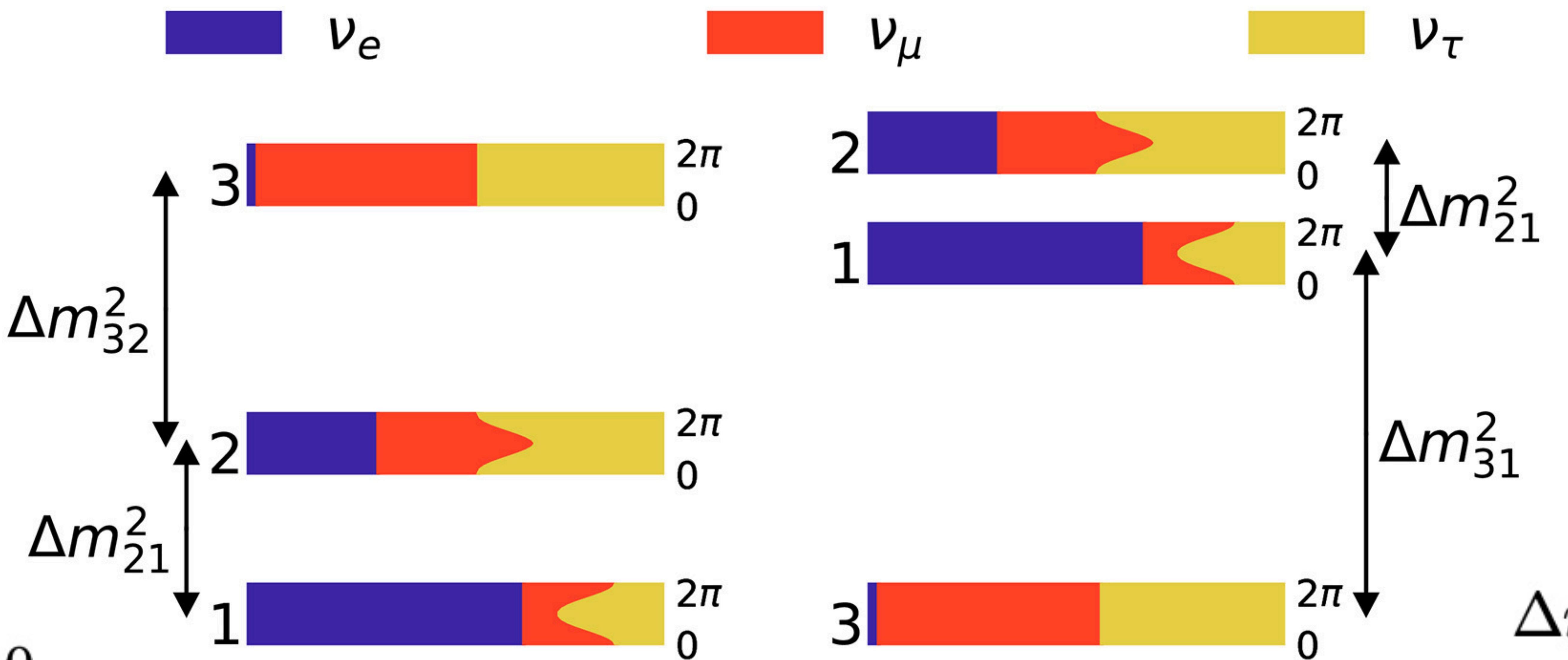
Outline

- Introduction
- Methods to determine Mass Ordering (MO) in vacuum
- MO determination boosting by Reactor + Accelerator
- Discussions
- Summary

If the neutrino Mass Ordering (MO) is normal or inverted is one of the fundamental open questions in neutrino physics

normal inverted

$$\Delta m^2_{ij} \equiv m^2_i - m^2_j$$



$\Delta m^2_{31}(\text{or } \Delta m^2_{32}) > 0$

$\Delta m^2_{31}(\text{or } \Delta m^2_{32}) < 0$

Salas et al, FASS 5, 36(2018)

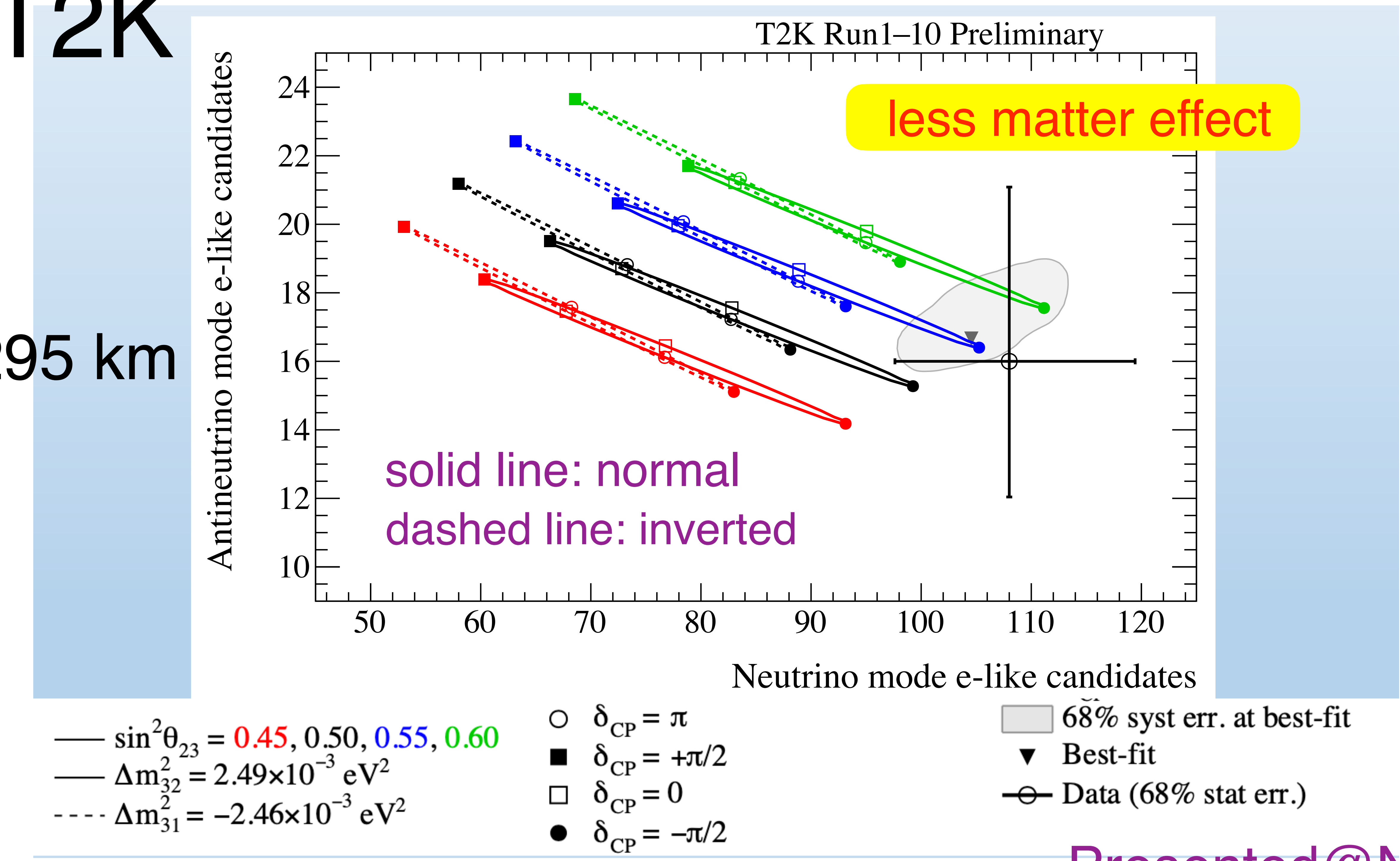
Since it is a “binary” (YES or NO) type question, to be sure, we want to answer the question with ~5σ CL or more

Conventional way to determine Neutrino Mass Ordering

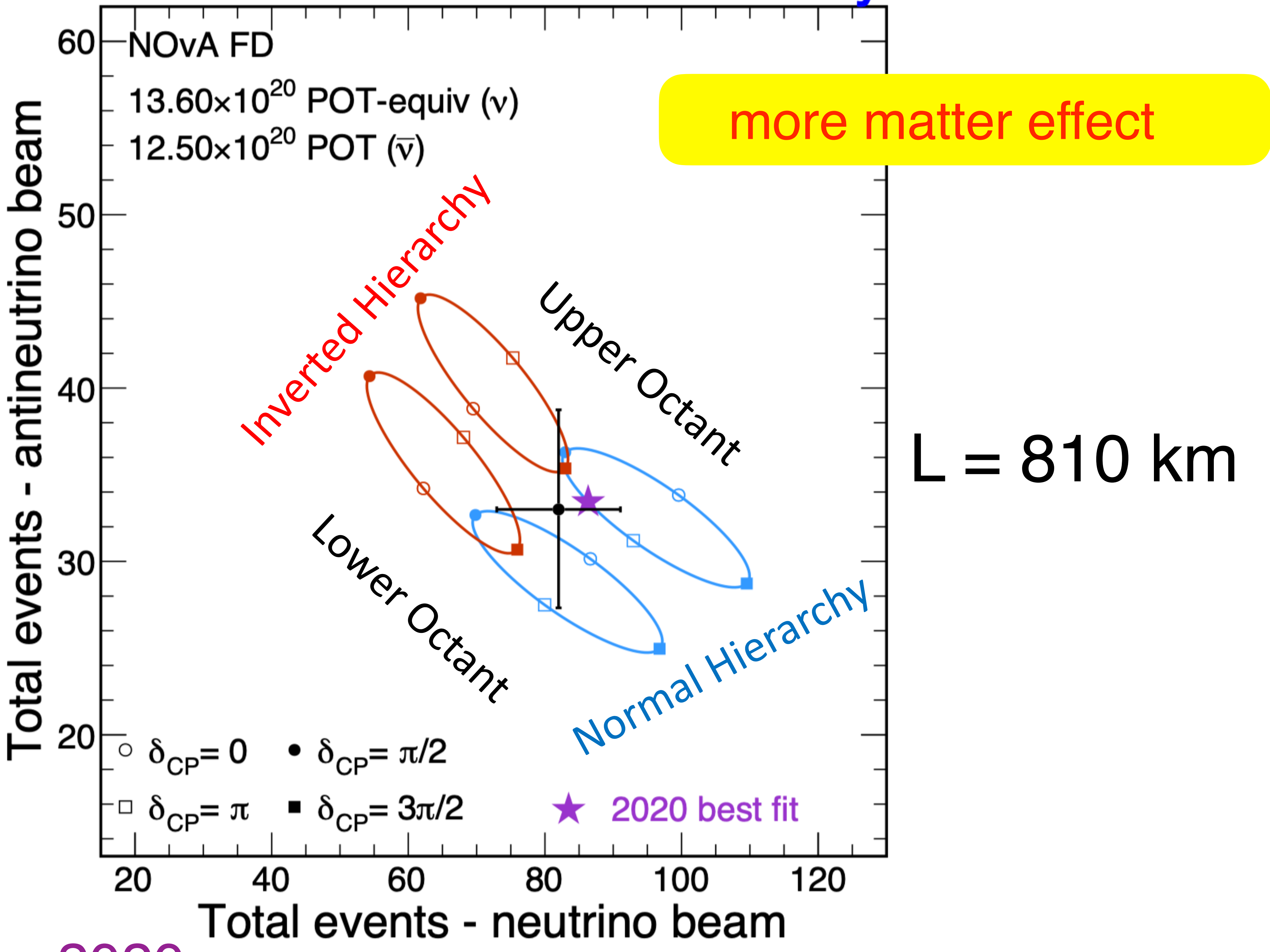
Neutrino Oscillation with matter effect

T2K

L = 295 km



NOvA Preliminary



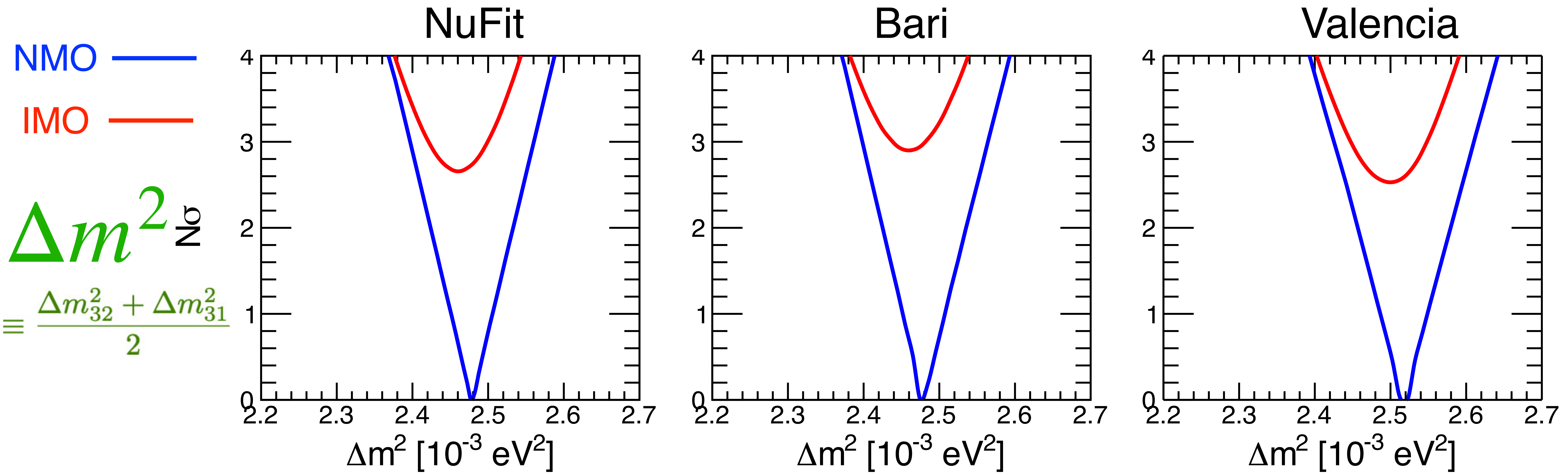
L = 810 km

Presented@Neutrino 2020

$P(\nu_\mu \to \nu_e)$ tends to be enhanced (suppressed) for normal (inverted) MO around 1st Osc. Max

$P(\bar{\nu}_\mu \to \bar{\nu}_e)$ tends to be enhanced (suppressed) for inverted (normal) MO around 1st Osc. Max.

We still do not know if the MO is normal or inverted



$\Delta m^2 \equiv \frac{\Delta m^2_{32} + \Delta m^2_{31}}{2}$

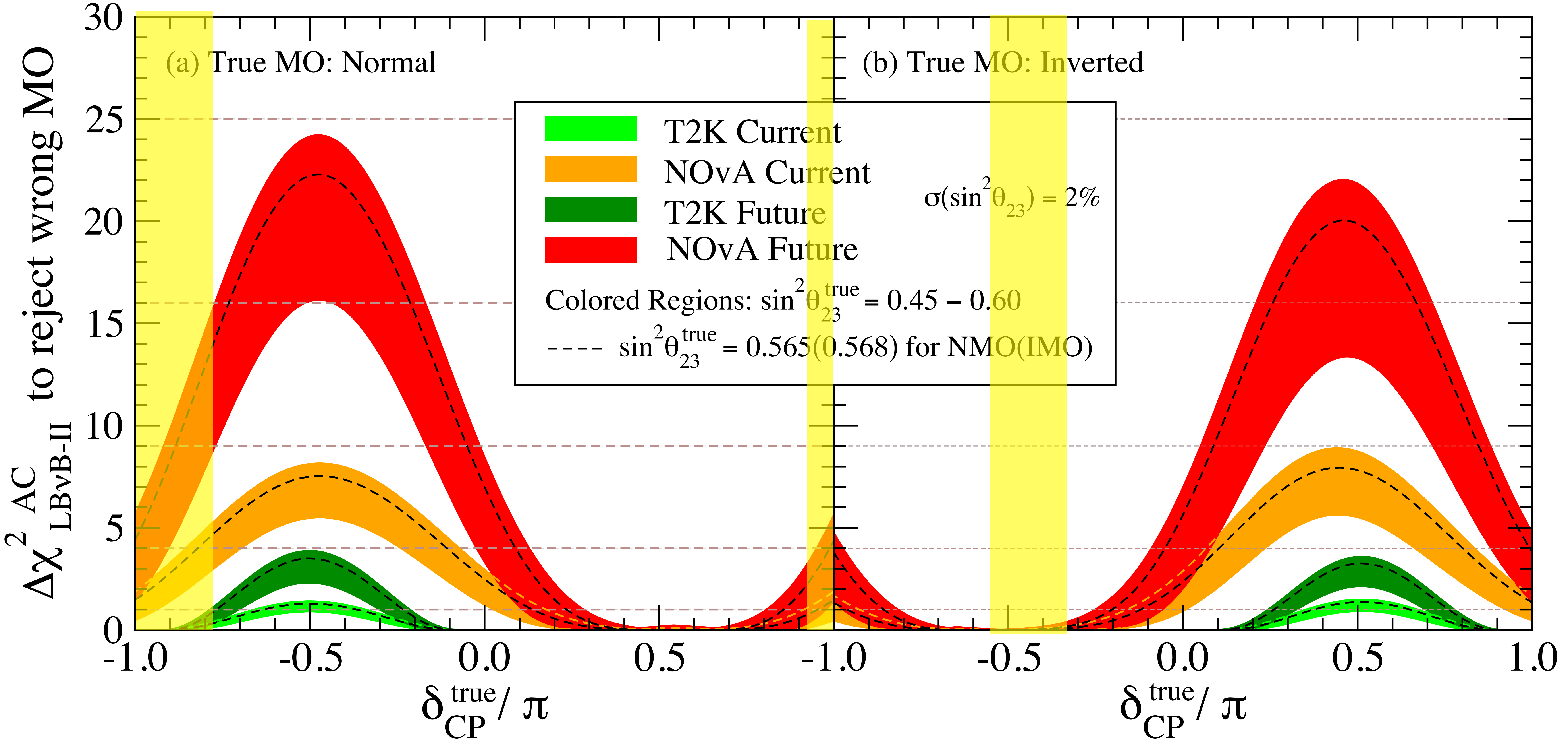
Talk by A. Marrone in this workshop on Feb. 23

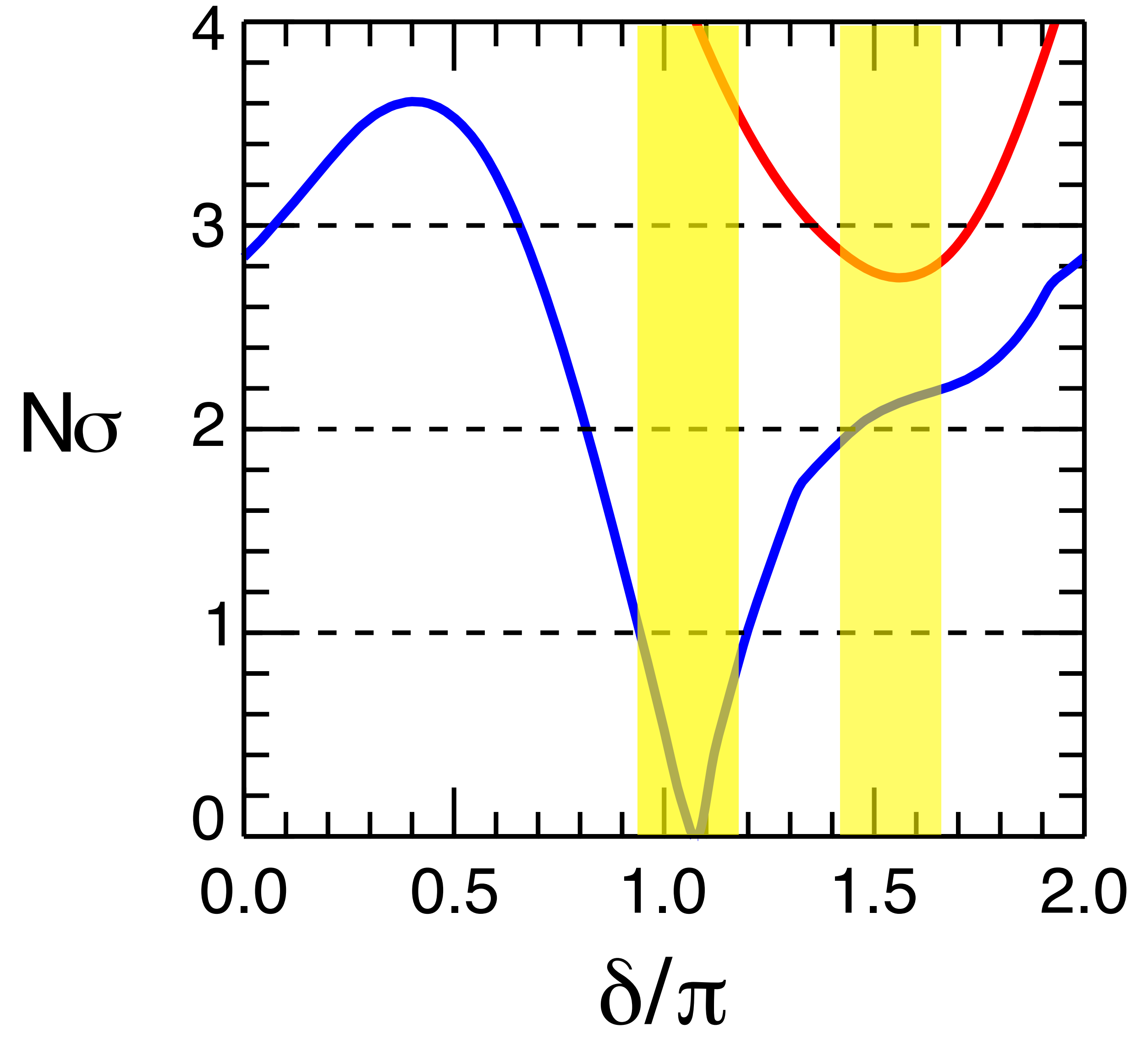
NuFit: 2007.14792 Bari: 2003.08511+update Valencia: 2006.11237v2

Currently, Normal Ordering favored at $\lesssim 3\sigma$

How much we can expect from on-going long-baseline ν beam (LBνB) experiments?

Expected MO resolution sensitivity by T2K and NOvA





A. Marrone in this workshop

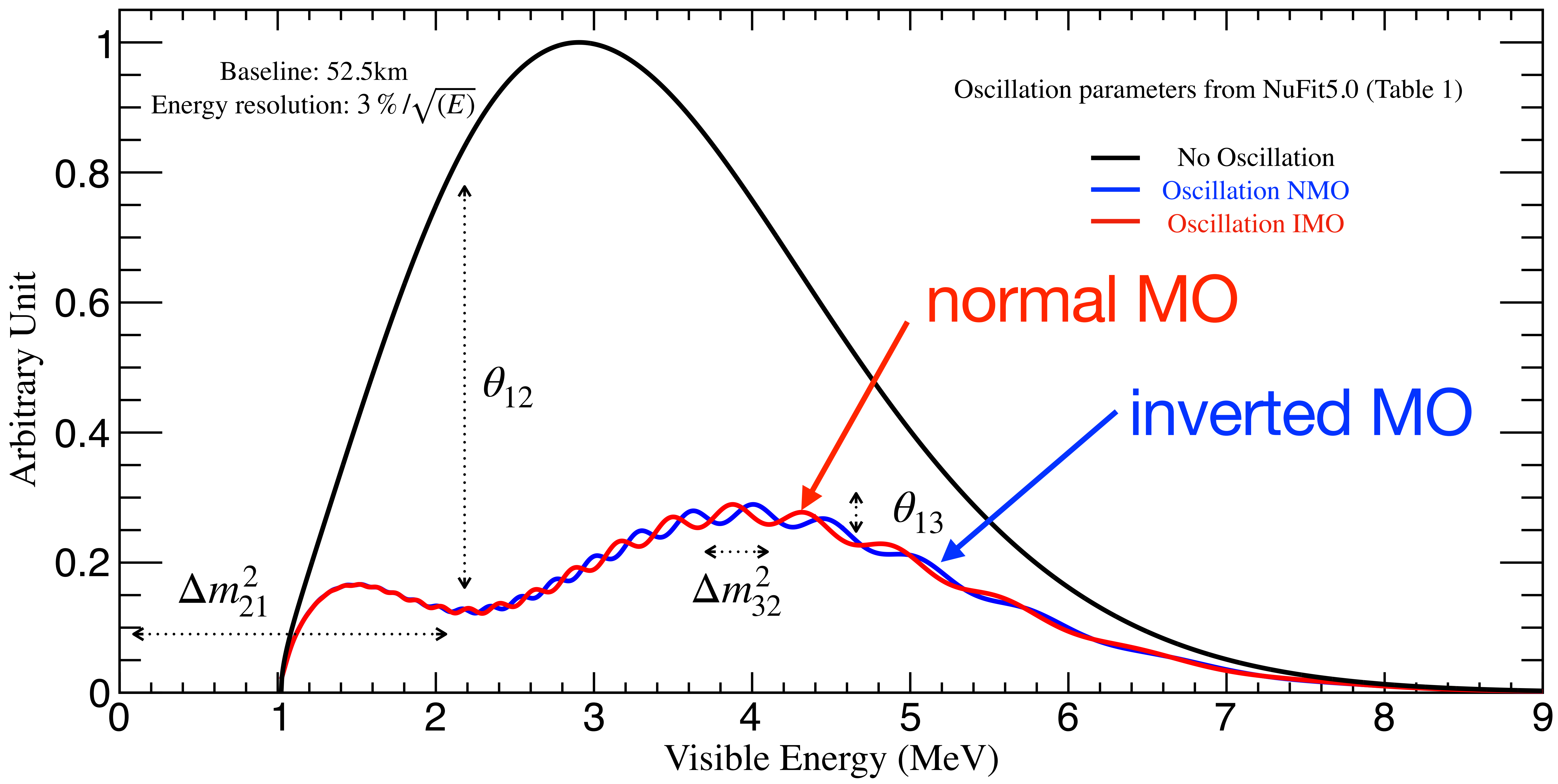
currently preferred δ_{CP}

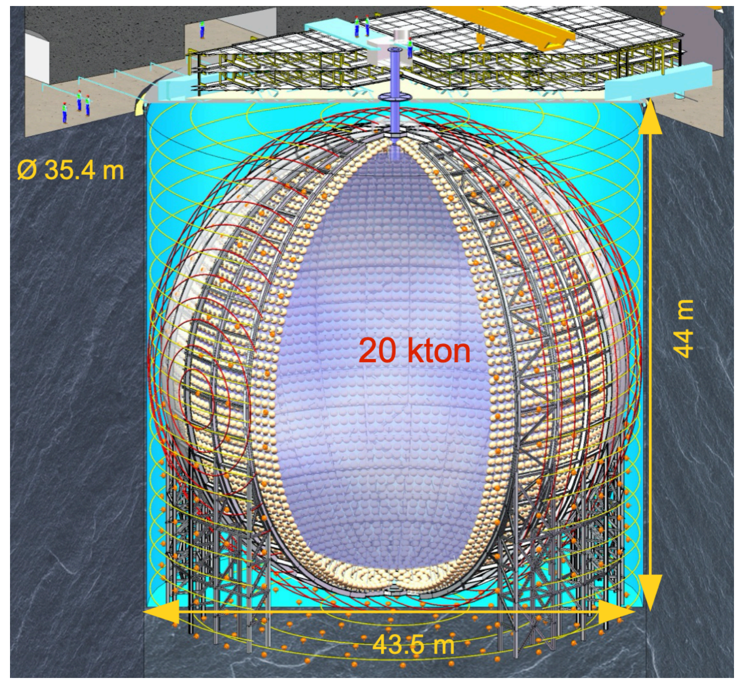
NOvA is significantly more powerful than T2K because of larger matter effect

T2K and NOvA (alone or together) can not reach 5σ for currently preferred δ_{CP}

(Unconventional) Method to determine MO in vacuum

JUNO aims to determine MO by observing the interference of essentially vacuum oscillation driven by 2 independent mass squared differences





expected JUNO MO sensitivity ~ 3σ

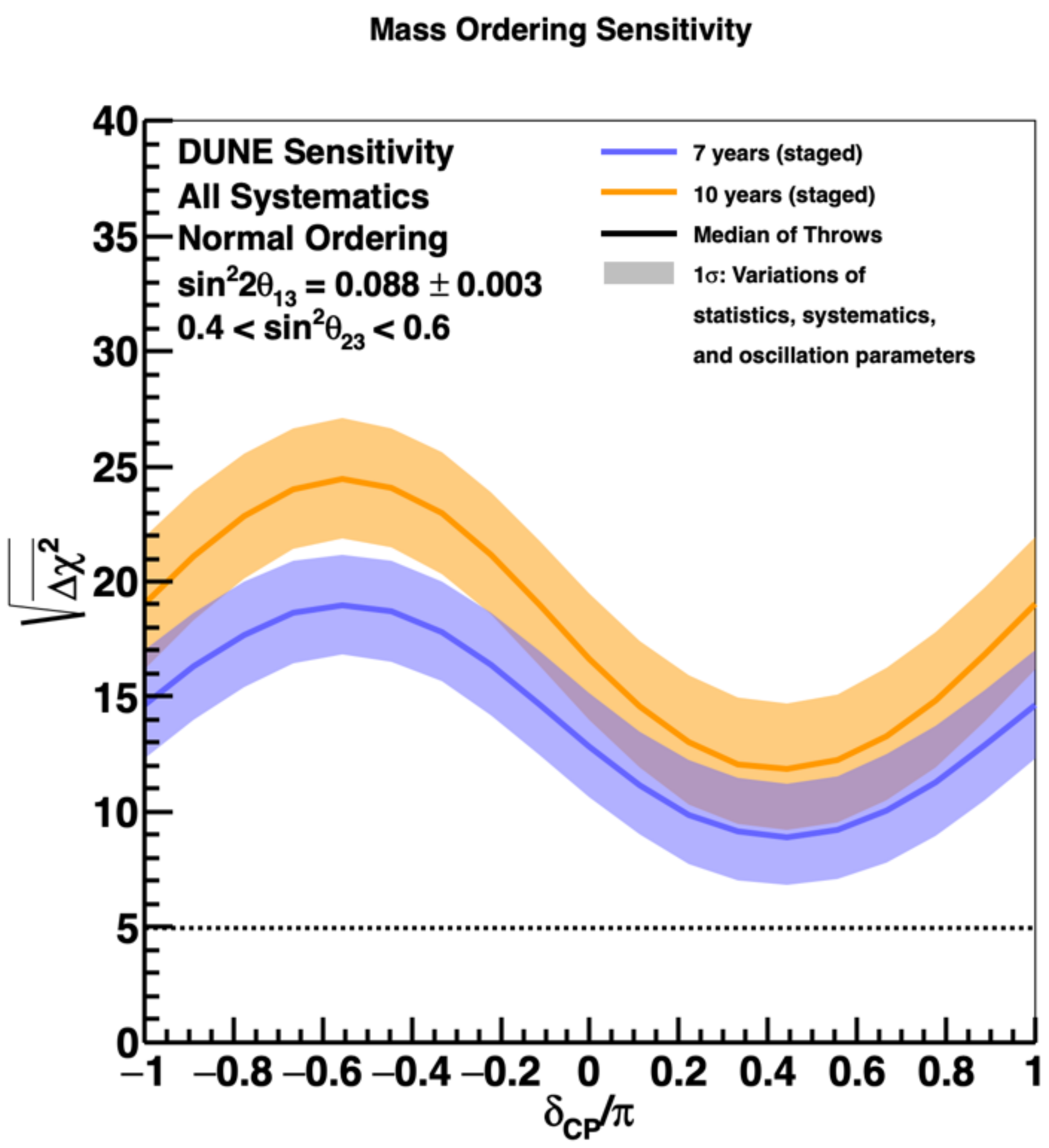
An et al (JUNO collab.), J. Phys. G43, 030401 (2016)

See also the talks by Y. Malyshkin, D. Xu in this workshop

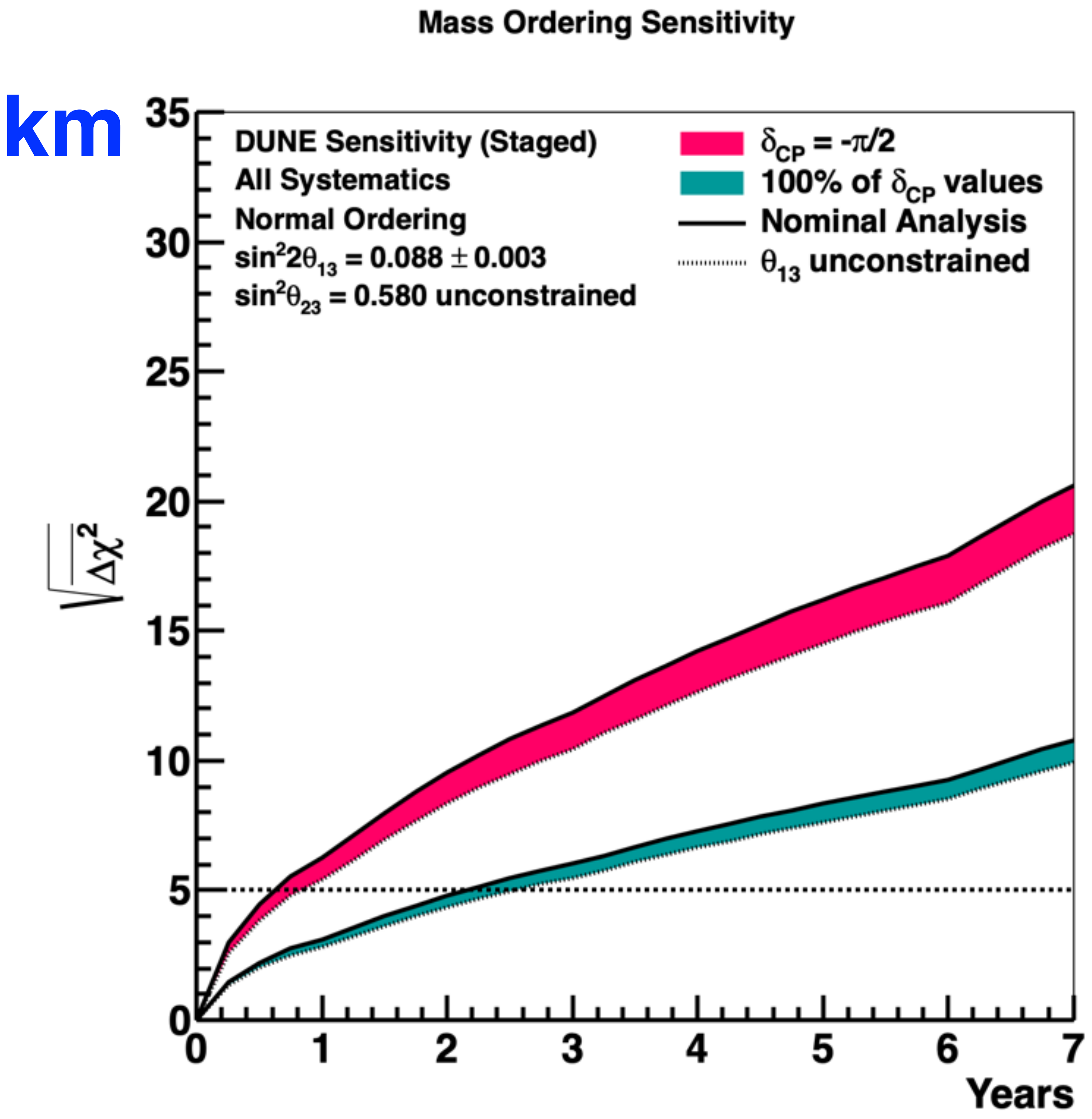
Based on the idea originally proposed in Petcov & Piai, PLB533, 94 (2002)

JUNO alone will not be able to determine MO with 5σ CL

A new generation LBvB experiment based on the conventional method, DUNE, would be very powerful to determine MO due to longer baseline, hence, larger matter effect



L = 1300km



Abi et al, DUNE Design Report , arXiv:2002.03005 [hep-ex]

See also the talk by G. Karagiorgi in this workshop

DUNE alone can determine MO at more than 5σ !

Question we want to answer

When we can determine MO at > 5σ ?

Possible to yield 5σ, complementary information to DUNE?

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When we can determine MO at > 5σ ?

Possible to yield 5σ, complementary information to DUNE?

- **We assume the standard 3 neutrino scheme without new physics beyond mass and mixing**

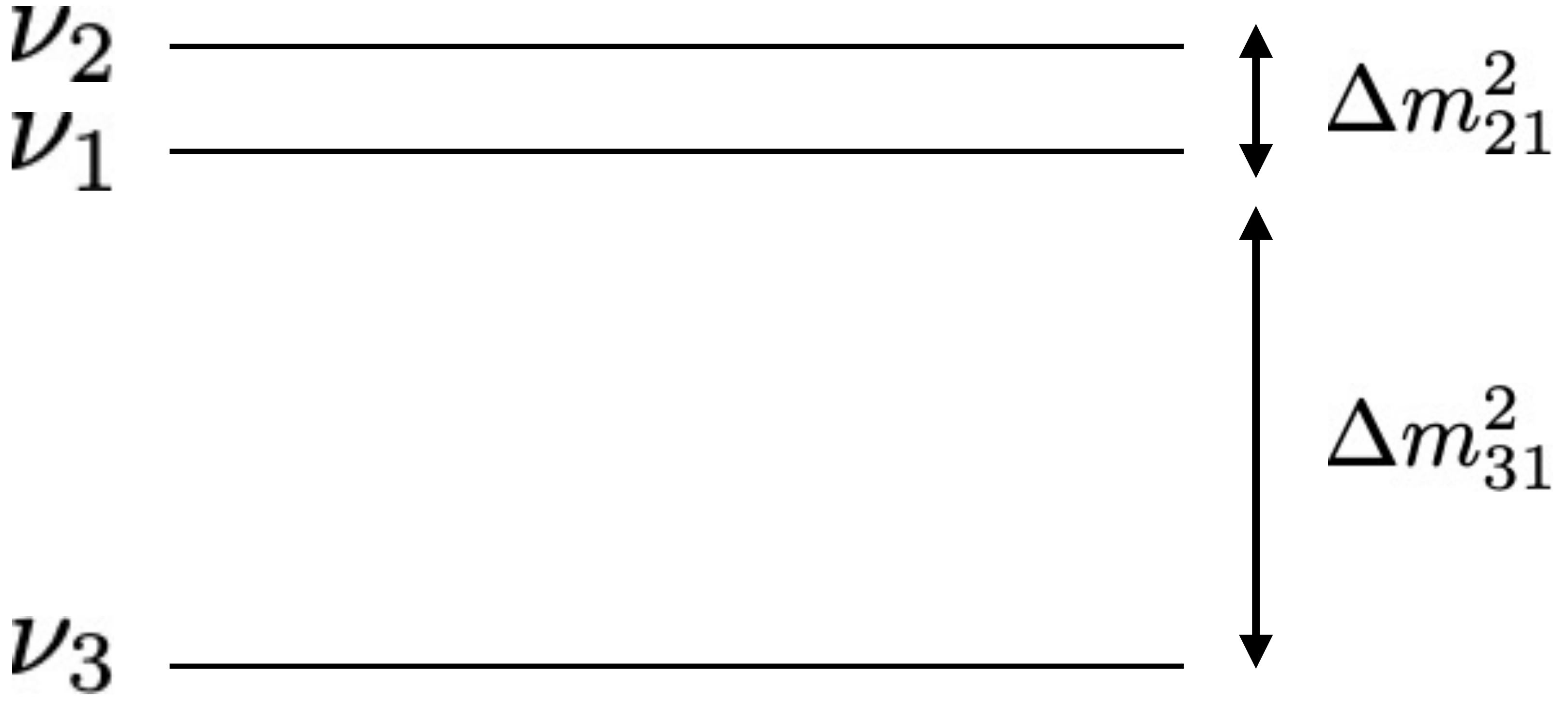
- **We consider only reactor (JUNO) and accelerator (LBνB) experiments and do not include atmospheric neutrino experiments (such as ORCA, PINGU) as the treatment is simpler and the synergy (Boosting) can be understood easily in a semi-analytic way. Hence our results would be conservative one**

For MO determination by atmospheric neutrinos (+JUNO), see the talks by A. Heijboer, N. Chau, in this workshop

Another possible way to determine MO

normal

inverted



Just from the information on $|\Delta m^2|$, we can determine MO

$|\Delta m^2_{31}| > |\Delta m^2_{32}|$ normal

$|\Delta m^2_{31}| < |\Delta m^2_{32}|$ inverted

In terms of effective mass squared differences for around 1st oscillation maximum

$$P(\nu_\alpha \to \nu_\alpha) \sim 1 - \sin^2 2\theta_{\alpha\alpha} \sin\left[\frac{\Delta m^2_{\alpha\alpha}}{4E} L\right] \quad (\alpha = e, \mu)$$

normal $\Delta m^2_{ee} > \Delta m^2_{\mu\mu}$

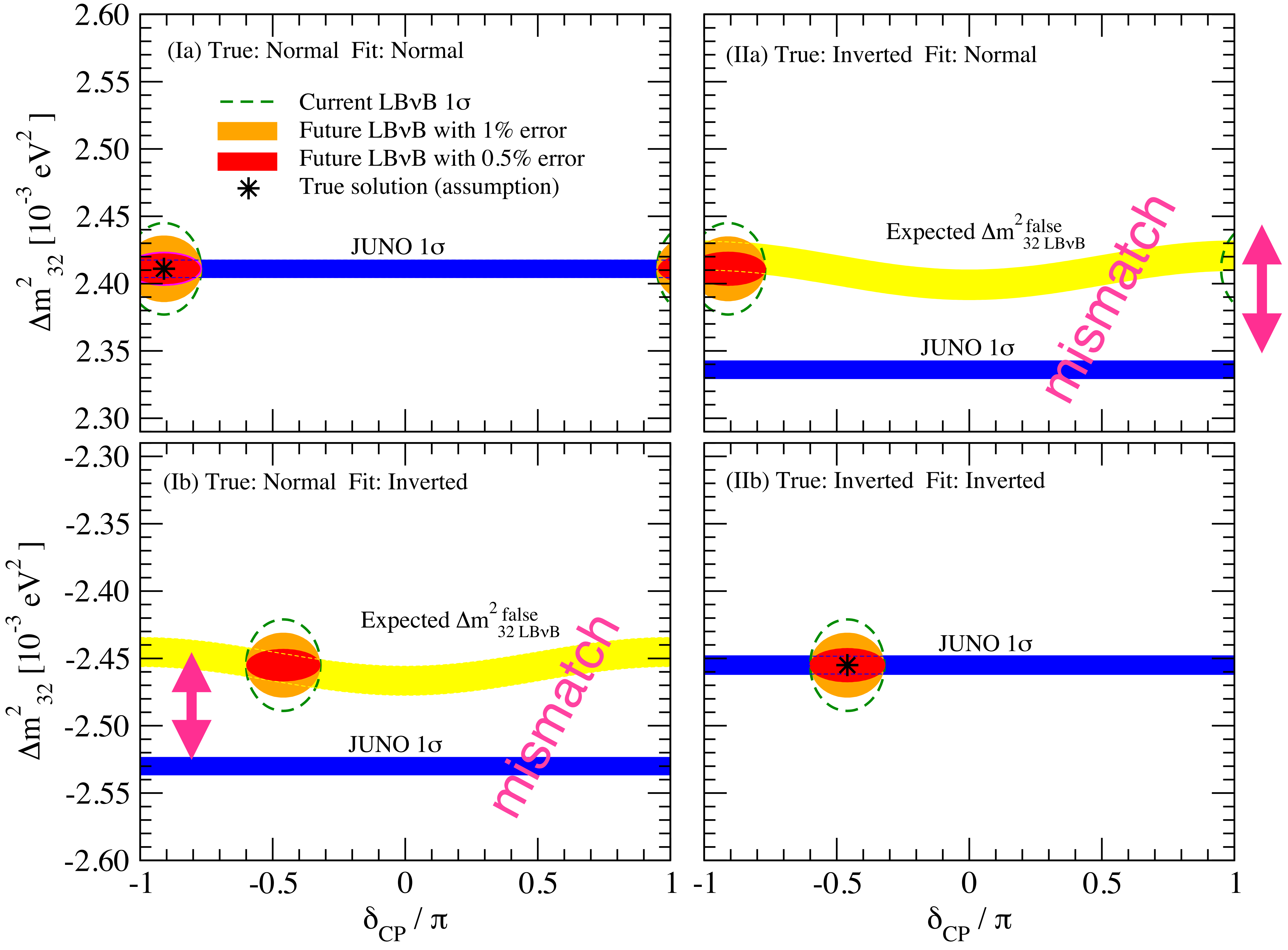
inverted $\Delta m^2_{ee} < \Delta m^2_{\mu\mu}$

HN, Parke, Zukanovich Funchal (**NPZ**), PRD72, 013009 (see also Gouvea et al, PRD71, 113009 (2005))

Synergy between Reactor and Accelerator

Li et al, PRD88, 013008 (2013) elaborated the NPZ proposal applying to JUNO (like)

schematic illustration of origin of boosting



Δm^2_{32} determined by different experiments agree (disagree) for true (false) MO

See also Blennow, Schwetz JHEP09, 89 (2013)

Origin of BOOSTING

$$\Delta\chi^2_{\rm BOOST} \sim \left(\frac{\Delta m^{2\ \ \rm false}_{32\ \rm JUNO} - \Delta m^{2\ \ \rm false}_{32\ \rm LB\nu B}}{\sigma(\Delta m^2_{32})_{\rm LB\nu B}} \right)^2.$$

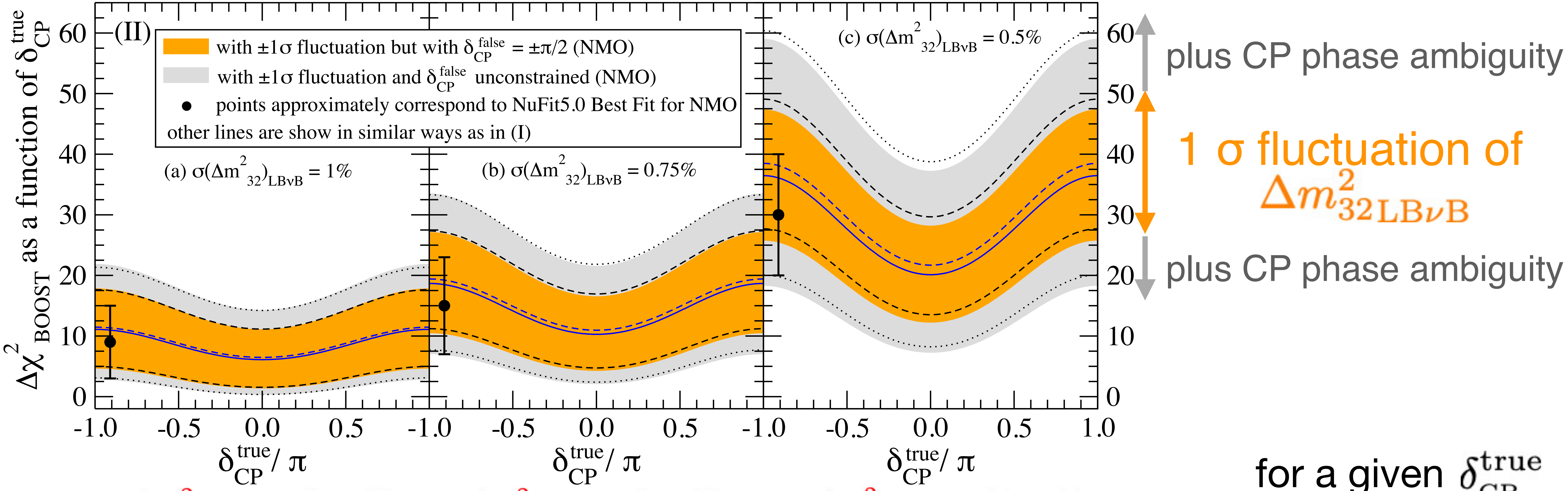
see backup slide for the definition of $\Delta\chi^2_{\rm BOOST}$

extra gain in χ^2 for MO determination, to disfavor/exclude false MO

Important Point: JUNO and LBvB experiments (each one) are expected to have 2 different solutions (values) of Δm^2_{32} corresponding to normal and inverted where one of them is FALSE one!

MO sensitivity boosting effect as a function of CP phase for $\sigma(\Delta m^2_{32})_{\mathrm{LB}\nu\mathrm{B}} = 1\%, 0.75\%$ and 0.5%

Impact of the fluctuation for the measurement of $\Delta m^2_{32\,\mathrm{LB}\nu\mathrm{B}}$



$\Delta\chi^2_{\mathrm{BOOST}} \sim 5 - 20$ $\Delta\chi^2_{\mathrm{BOOST}} \sim 8 - 32$ $\Delta\chi^2_{\mathrm{BOOST}} \sim 20 - 60$

we hope to reach this situation!

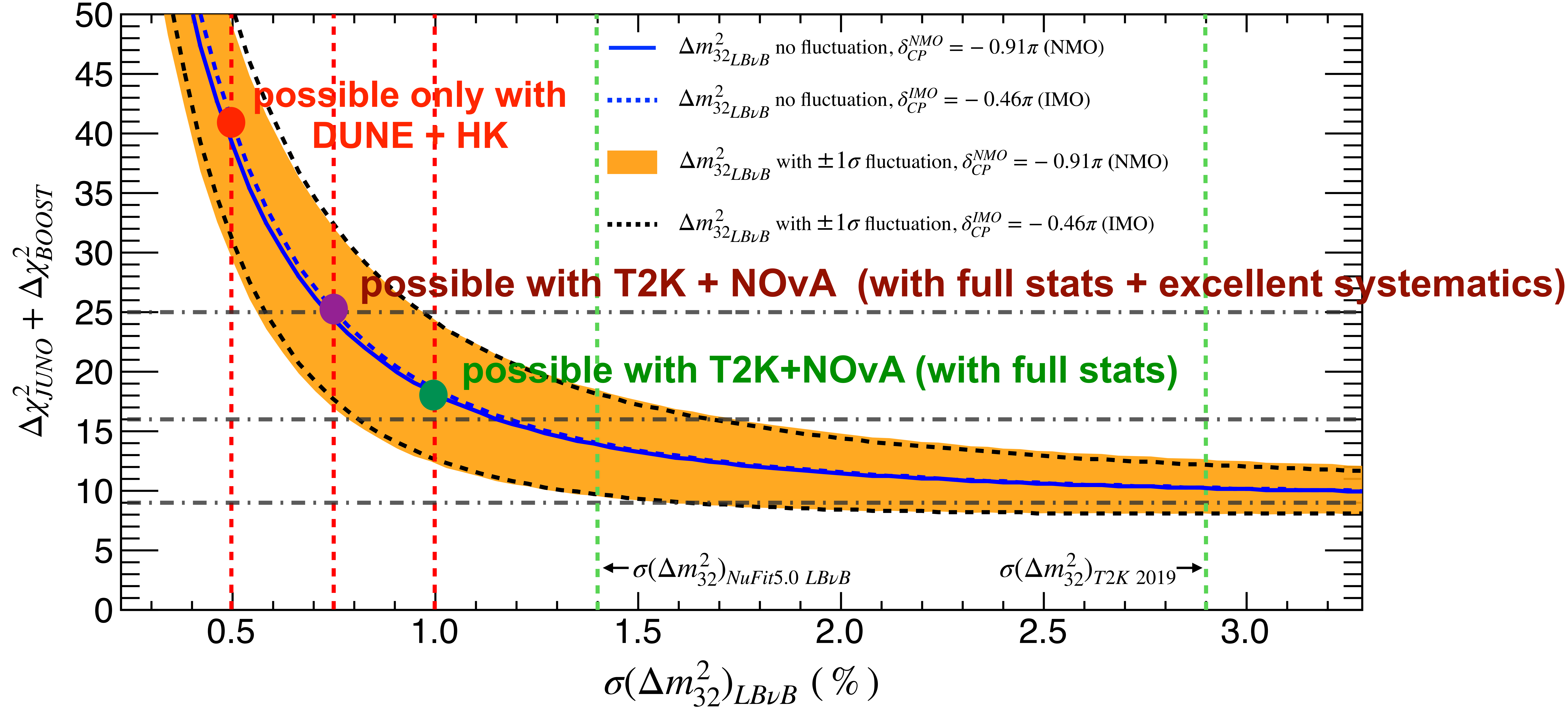
for a given $\delta_{\mathrm{CP}}^{\mathrm{true}}$

there are $\delta_{\mathrm{CP}}^{\mathrm{false}} \neq \delta_{\mathrm{CP}}^{\mathrm{true}}$

(see backup slide for detail)

How JUNO boosted MO sensitivity depends on $\sigma(\Delta m^2_{32})_{LB\nu B}$

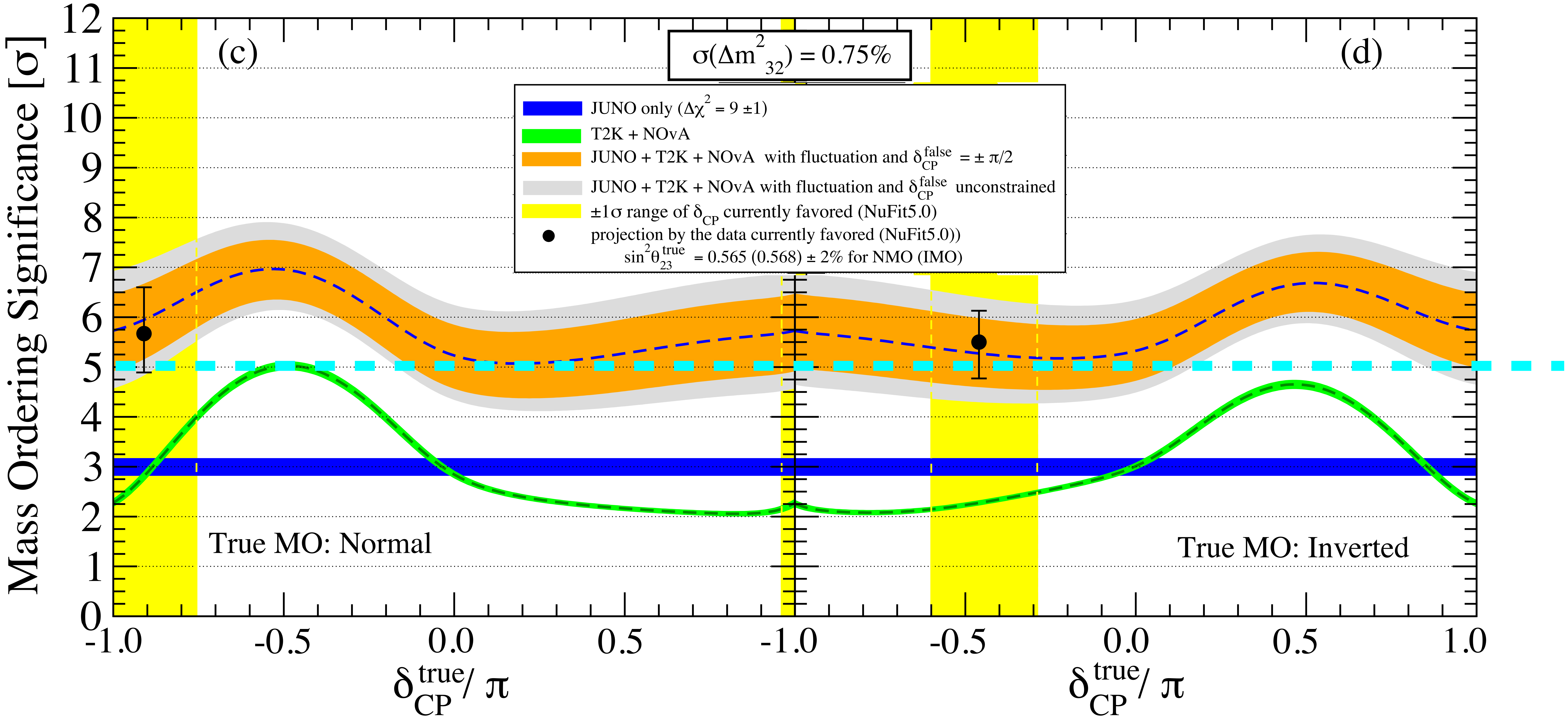
JUNO + just external information of $\Delta m^2_{32\mathrm{LB}\nu\mathrm{B}}$ ~ vacuum osc.



uncertainty of Δm^2_{32} determined by accelerator experiments

Combined MO sensitivity for $\sigma(\Delta m^2_{32})_{\mathrm{LB}\nu\mathrm{B}} = 0.75\%$

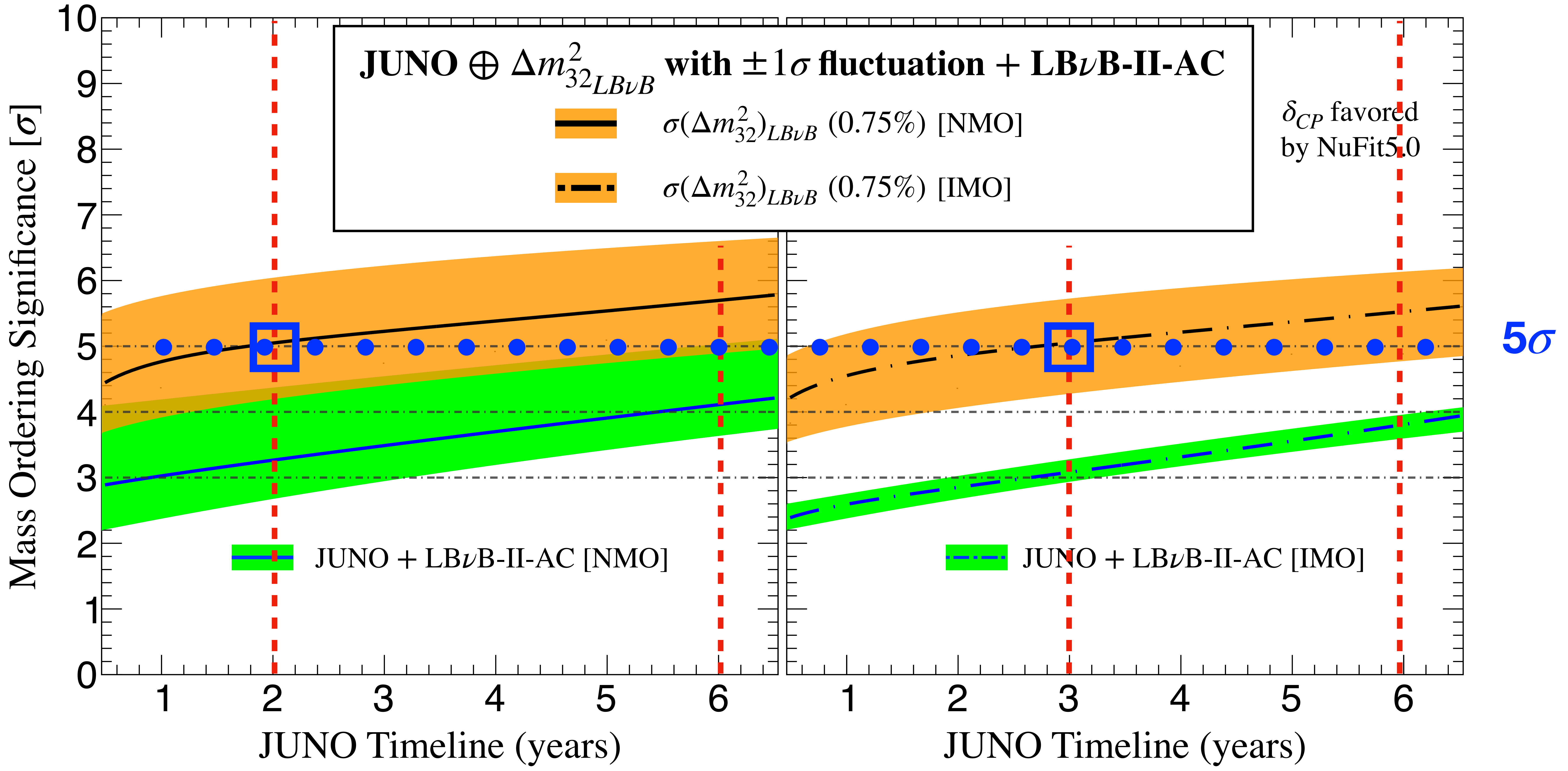
JUNO + LBvB disappearance + appearance (matter effect)



Roughly speaking, for ~ 3/4 of δ_{CP} we can reach 5σ as median sensitivity

Combined MO sensitivity as a function of time for $\sigma(\Delta m^2_{32})_{\text{LB}\nu\text{B}} = 0.75\%$

JUNO + LBvB disappearance + appearance (matter effect)

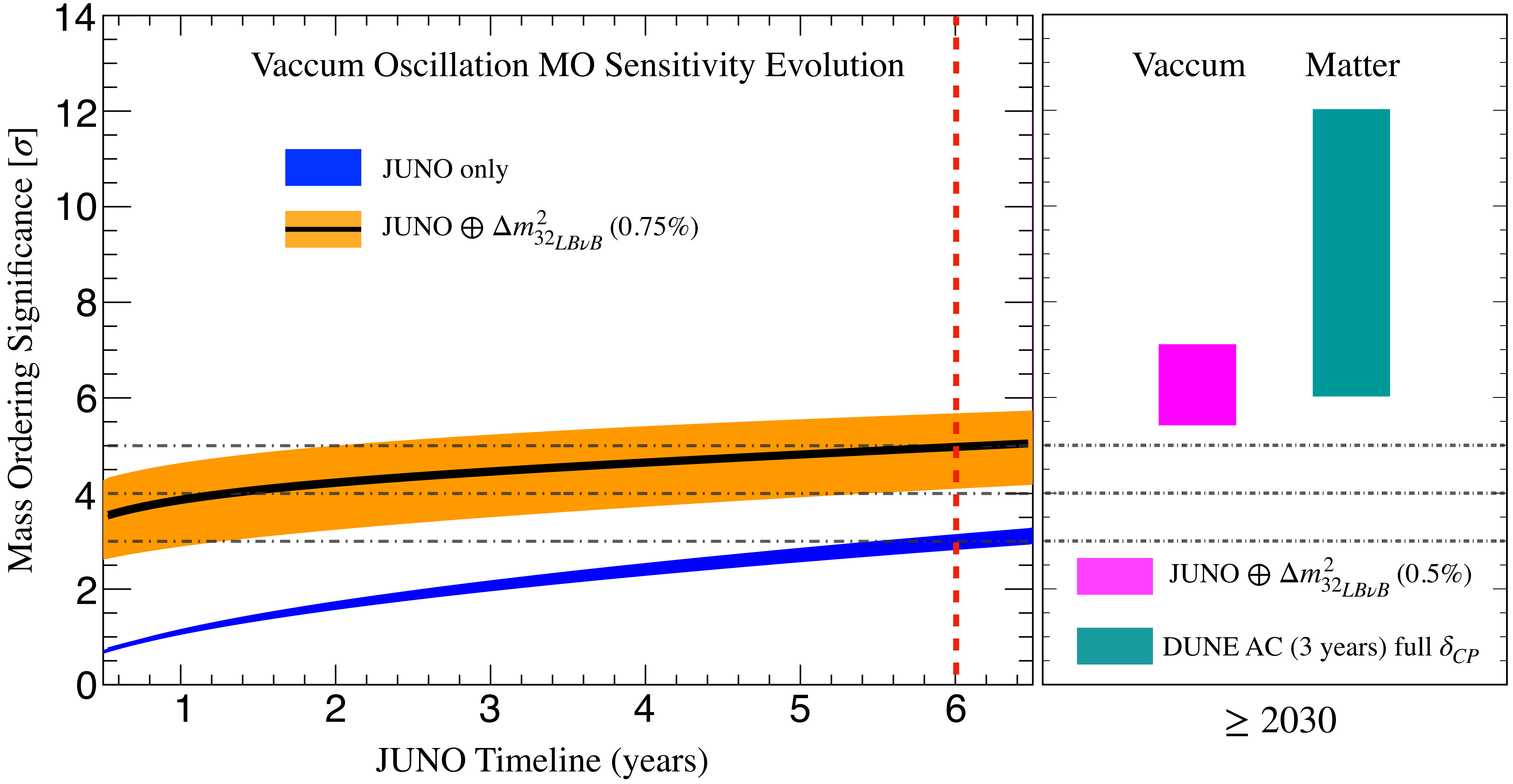


For currently favored value of CP phase, 5σ MO resolution is possible by JUNO + accelerator experiments for the median sensitivity (+ atmospheric data will only shorten required time)

It would be interesting to compare 2 fully resolved MO determinations driven by vacuum (JUNO + only boost effect) and by matter (DUNE)

Boosted JUNO with $\Delta m^2_{32_{LB\nu B}}$ (0.75%) (T2K&NOvA)

Boosted JUNO with $\Delta m^2_{32_{LB\nu B}}$ (0.5%) (HK/DUNE)



DUNE NMO is shown.
DUNE IMO is roughly ~2σ worse.

Discrepancy → **New Physics beyond SM, for example NSI?**

See the talk by A. Palazzo in this workshop

Summary

- If neutrino MO is normal or inverted is one of the fundamental open questions
- Currently, normal MO is favored at ~ 3σ level
- Only DUNE seems to be able to reach 5σ by itself, while NOvA+T2K or JUNO can reach ~3σ for currently favored CP phase
- MO determination can be boosted by Reactor + Accelerator w/o matter effect
- JUNO + Accelerator Disapp. + App. can provide 5σ MO resolution
- It would be important to compare 2 fully resolved MO determinations: vacuum driven (only JUNO boosted with $\Delta m^2_{32\mathrm{LB}\nu\mathrm{B}}$ precision at 0.5%) and matter driven (only by DUNE) for cross check (or new discovery of new physics!)

Thank you very much for your attention!

Backup Slides

Analysis Method

$$\chi^2 = {\chi^2}_{\rm JUNO} + \left(\frac{\Delta m^2_{32} - {\Delta m^2_{32}}_{\rm LB\nu B}^{\rm NMO\ or\ IMO}}{\sigma(\Delta m^2_{32})_{\rm LB\nu B}} \right)^2$$

external information

$$\Delta\chi^2_{\rm boost} \equiv \pm \left(\chi^2_{\rm IMO} - \chi^2_{\rm NMO}\right)$$

+ (-) : true MO is normal (inverted)

Δm^2_{32} to be determined by accelerator is taken into account simply as a pull term

Roughly speaking, at 1st approximation, this is mainly vacuum oscillation driven

Analytic Understanding

For JUNO,

$$P_{\bar{\nu}_e \to \bar{\nu}_e} = 1 - c_{13}^4 \sin^2 2\theta_{12} \sin^2 \Delta_{21} - \frac{1}{2} \sin^2 2\theta_{13} \left[1 - \sqrt{1 - \sin^2 2\theta_{12} \sin^2 \Delta_{21}} \cos(2|\Delta_{ee}| \pm \phi) \right]$$

$$\Delta_{ij} \equiv \Delta m_{ij}^2 L/4E \qquad \Delta m_{ee}^2 \equiv c_{12}^2 \Delta m_{31}^2 + s_{12}^2 \Delta m_{32}^2 = \Delta m_{32}^2 + c_{12}^2 \Delta m_{21}^2$$

$$c_{ij} \equiv \cos\theta_{ij} \text{ and } s_{ij} \equiv \sin\theta_{ij} \qquad \tan\phi = \frac{c_{12}^2 \sin(2 s_{12}^2 \Delta_{21}) - s_{12}^2 \sin(2 c_{12}^2 \Delta_{21})}{c_{12}^2 \sin(2 s_{12}^2 \Delta_{21}) + s_{12}^2 \sin(2 c_{12}^2 \Delta_{21})}$$

JUNO is expected to provide 2 different values of Δm_{32}^2 corresponding to NMO (normal mass ordering) and IMO (inverted mass ordering) which are related to each other as

$$\Delta m_{32}^2 {}_{\text{JUNO}}^{\text{IMO}} \simeq -\Delta m_{32}^2 {}_{\text{JUNO}}^{\text{NMO}} - 2 c_{12}^2 \delta m_{21}^2 - \delta m_\phi^2$$

where

$$\delta m_\phi^2 \equiv \frac{4E}{L}\phi \simeq 2.1 \times 10^{-5} \left(\frac{E}{4\ \text{MeV}} \right) \text{eV}^2$$

Analytic Understanding

Like JUNO, LBvB based accelerator experiments also are expected to provide 2 different values of Δm^2_{32} corresponding to NMO (normal mass ordering) and IMO (inverted mass ordering) which are related to each other as

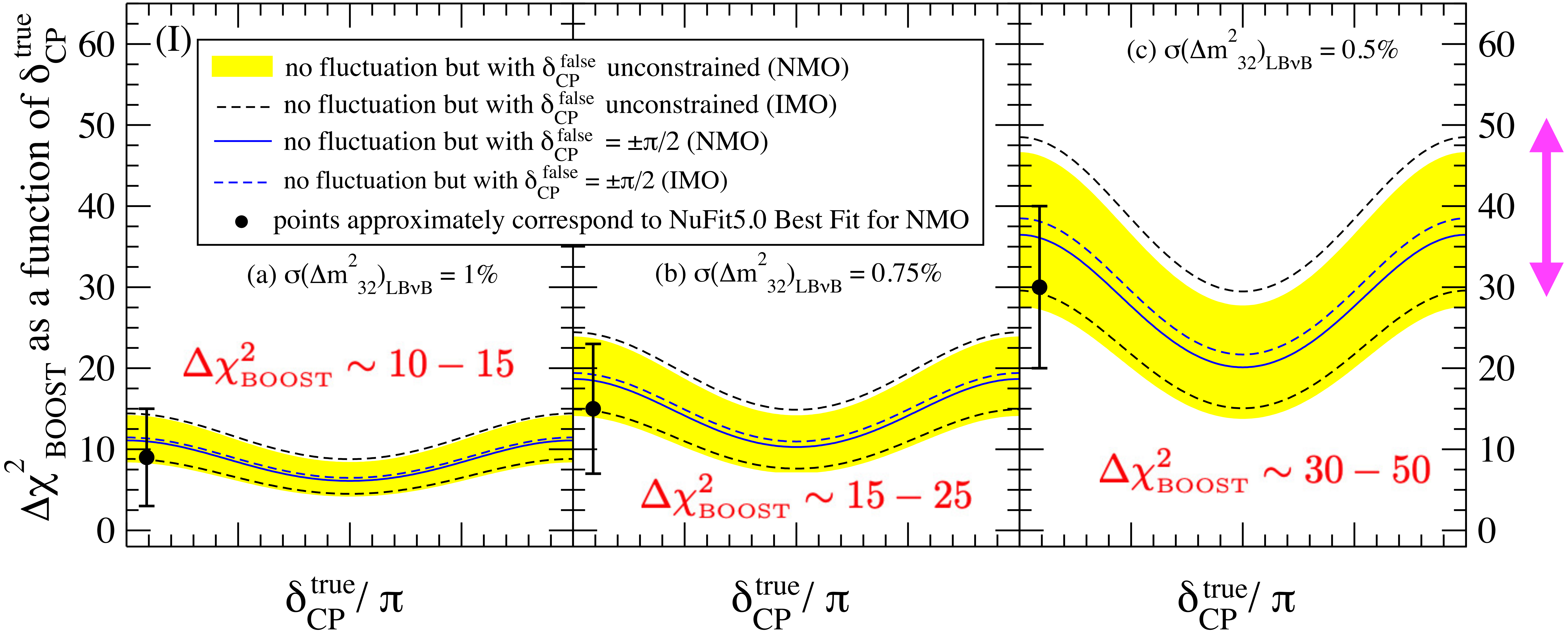
$$
\begin{aligned}
\Delta m^{2\ \mathrm{IMO}}_{32\,\mathrm{LB}\nu\mathrm{B}} &= -\Delta m^{2\ \mathrm{NMO}}_{32\,\mathrm{LB}\nu\mathrm{B}} - \delta m^2_{21}\left\{2s^2_{12} + \sin 2\theta_{12}\left(\cos\delta^{\mathrm{NMO}}_{\mathrm{CP}}\, s^{\mathrm{NMO}}_{13}\tan\theta^{\mathrm{NMO}}_{23} + \cos\delta^{\mathrm{IMO}}_{\mathrm{CP}}\, s^{\mathrm{IMO}}_{13}\tan\theta^{\mathrm{IMO}}_{23}\right)\right\} \\
&\simeq -\Delta m^{2\ \mathrm{NMO}}_{32\,\mathrm{LB}\nu\mathrm{B}} - \delta m^2_{21}\left\{2s^2_{12} + \sin 2\theta_{12}\, s_{13}\tan\theta_{23}\left(\cos\delta^{\mathrm{NMO}}_{\mathrm{CP}} + \cos\delta^{\mathrm{IMO}}_{\mathrm{CP}}\right)\right\}
\end{aligned}
$$

a set of parameters correspond either to NMO or to IMO are false!

a mismatch of false values of Δm^2_{32} between JUNO and LBvB experiments is the origin of the boost (synergy) effect

MO sensitivity boosting effect as a function of CP phase for $\sigma(\Delta m^2_{32})_{\mathrm{LB}\nu\mathrm{B}} = 1\%, 0.75\%$ and 0.5%

Impact of the CP phase ambiguity on Boosting



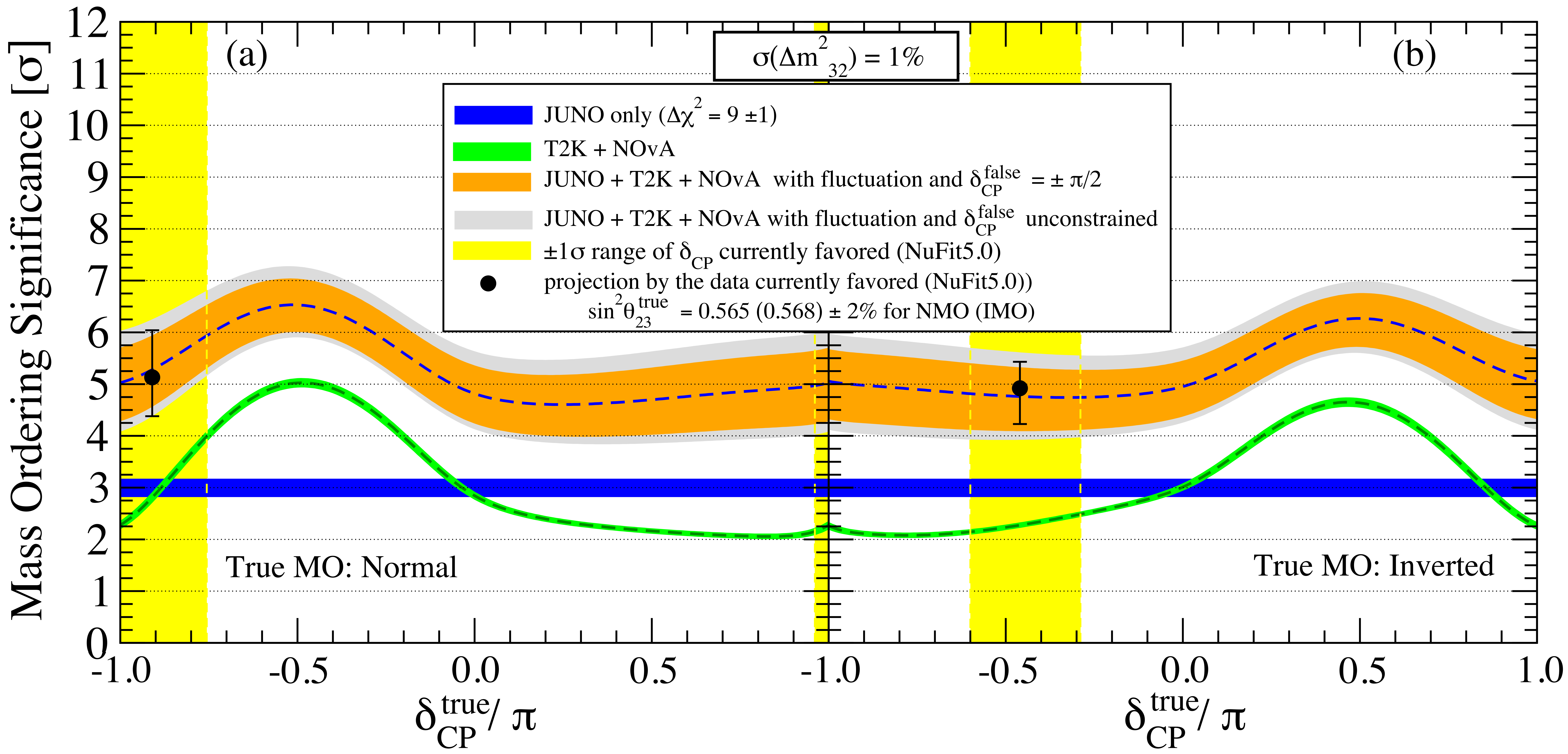
for a given $\delta_{CP}^{\mathrm{true}}$

there are $\delta_{CP}^{\mathrm{false}} \neq \delta_{CP}^{\mathrm{true}}$

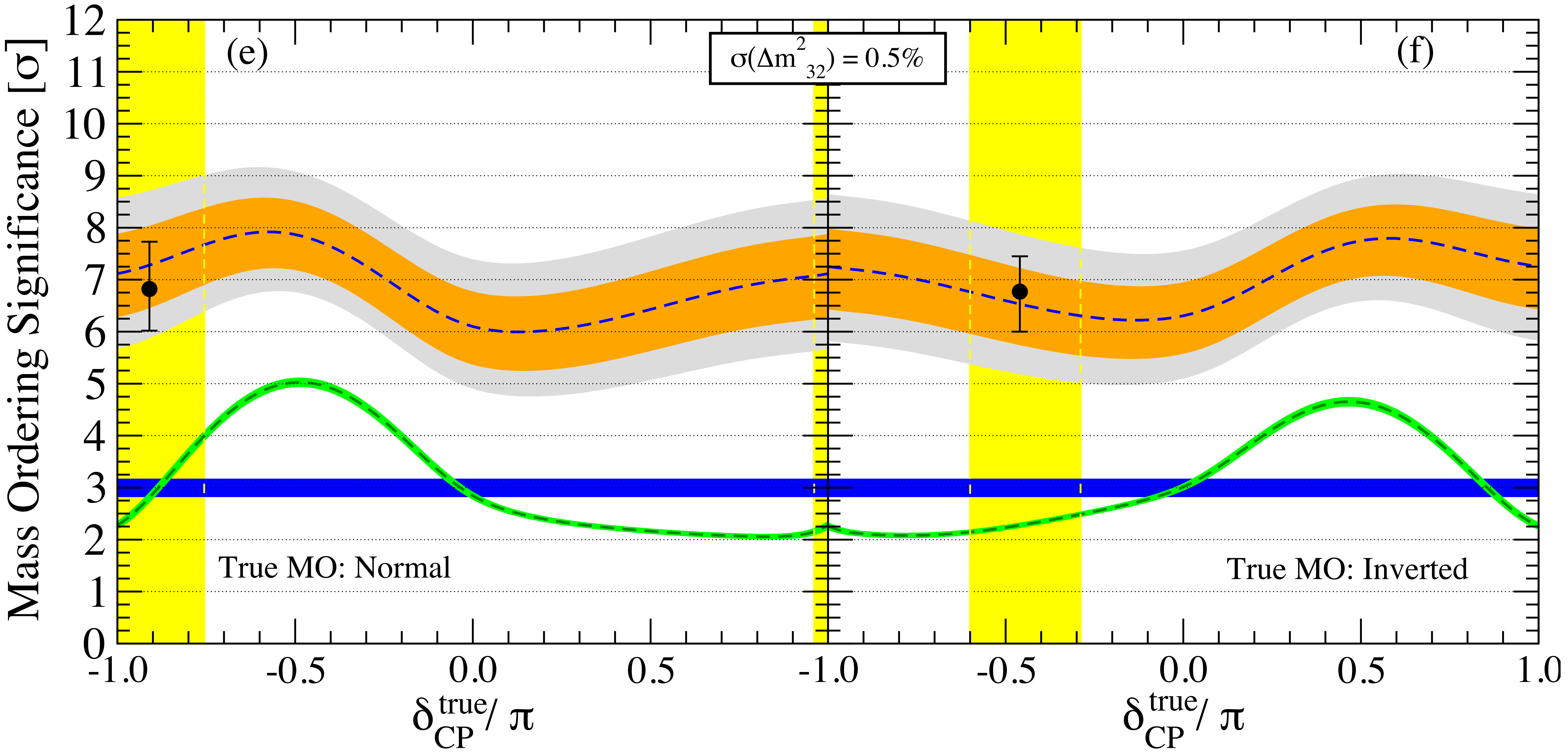
Global Analyses show that Δm^2_{32} is determined already at ~ 1% level (see the talk by A. Marrone)

CP phase dependence exists because $\Delta m^2_{32\,\mathrm{LB}\nu\mathrm{B}}$ depends on CP phase

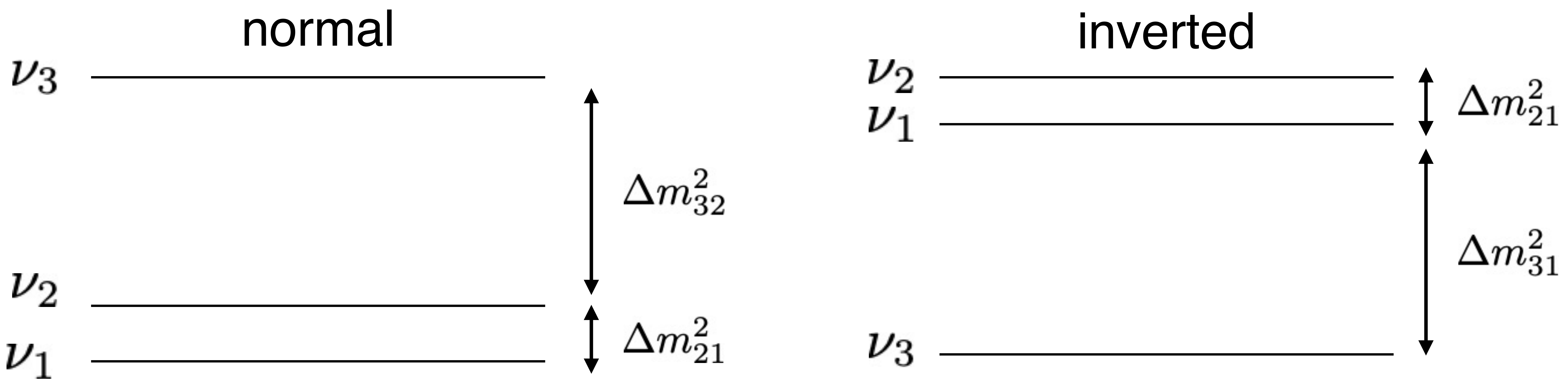
Combined MO sensitivity for $\sigma(\Delta m^2_{32})_{\mathrm{LB}\nu\mathrm{B}} = 1\%$



Combined MO sensitivity for $\sigma(\Delta m^2_{32})_{\mathrm{LB}\nu\mathrm{B}} = 0.5\%$



Another possible way to determine MO



Just from the information on $|\Delta m^2|$, we can determine MO

$|\Delta m^2_{31}| > |\Delta m^2_{32}|$ normal $\quad$ $|\Delta m^2_{31}| < |\Delta m^2_{32}|$ inverted

In terms of effective mass squared differences for around 1st oscillation maximum

normal $\Delta m^2_{ee} > \Delta m^2_{\mu\mu}$ $\quad$ inverted $\Delta m^2_{ee} < \Delta m^2_{\mu\mu}$

$$\Delta m^2_{ee} \equiv c^2_{12}\Delta m^2_{31} + s^2_{12}\Delta m^2_{32} = \Delta m^2_{32} + c^2_{12}\Delta m^2_{21}$$ ← from reactor

$$\Delta m^2_{\mu\mu} \equiv \Delta m^2_{32} + (s^2_{12} + \cos\delta_{\rm CP} s_{13} \sin 2\theta_{12} \tan\theta_{23})\Delta m^2_{21}$$ ← from accelerator

NH, Parke, Zukanovich Funchal, PRD72, 013009 (see also Gouvea et al, PRD71, 113009 (2005))