ESSnuSB Physics Reach

The ESSνSB Workshop

UHH-Barenfeld-DESY 8/10/2020

Salvador Rosauro-Alcaraz, on behalf of working package 6

Instituto de Física Teórica UAM-CSIC

Universidad Autónoma de Madrid

Status of ν oscillations

What we know (at 1σ)

I. Esteban *et al.* 2007.14792 www.nu-fit.org

Solar sector $\begin{cases} \sin^2\theta_{12} = 0.304^{+0.012}_{-0.012} \\ \Delta m^2_{21} = 7.42^{+0.21}_{-0.20} \cdot 10^{-5} eV^2 \end{cases}$

Atm. sector $\begin{cases} \sin^2\theta_{23} = 0.573^{+0.016}_{-0.020} \\ |\Delta m^2_{31}| = 2.517^{+0.026}_{-0.028} \cdot 10^{-3} eV^2 \end{cases}$

$$\sin^2\theta_{13} = 0.02219^{+0.00062}_{-0.00063}$$

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What we do not know (yet)

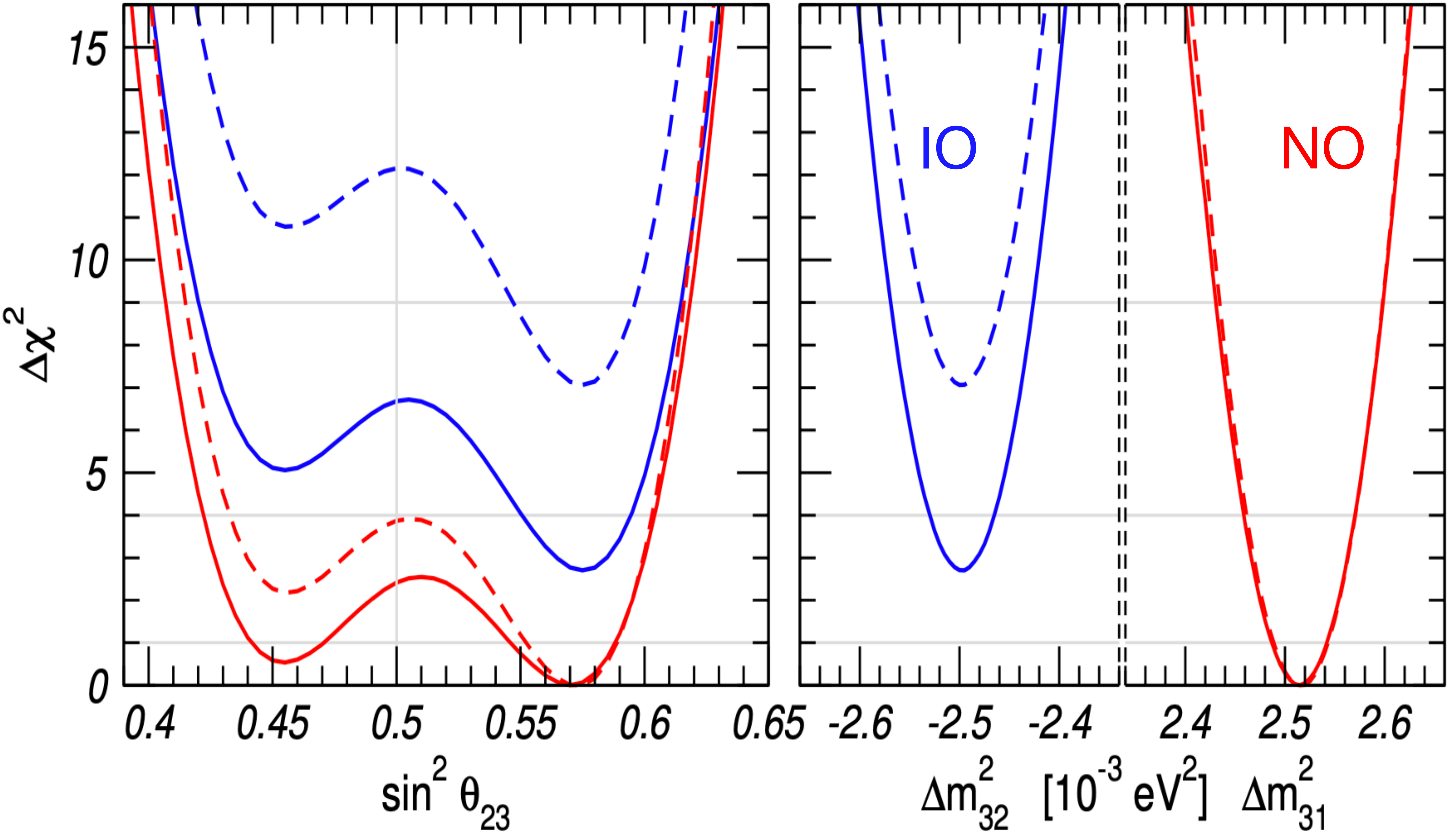
Is there leptonic CP violation, i.e., $\delta \neq 0, \pi$?

Mass ordering: $sign(\Delta m^2_{31})$

Octant of θ_{23}

Status of ν oscillations

NO is only preferred at 1.6σ (2.7σ)



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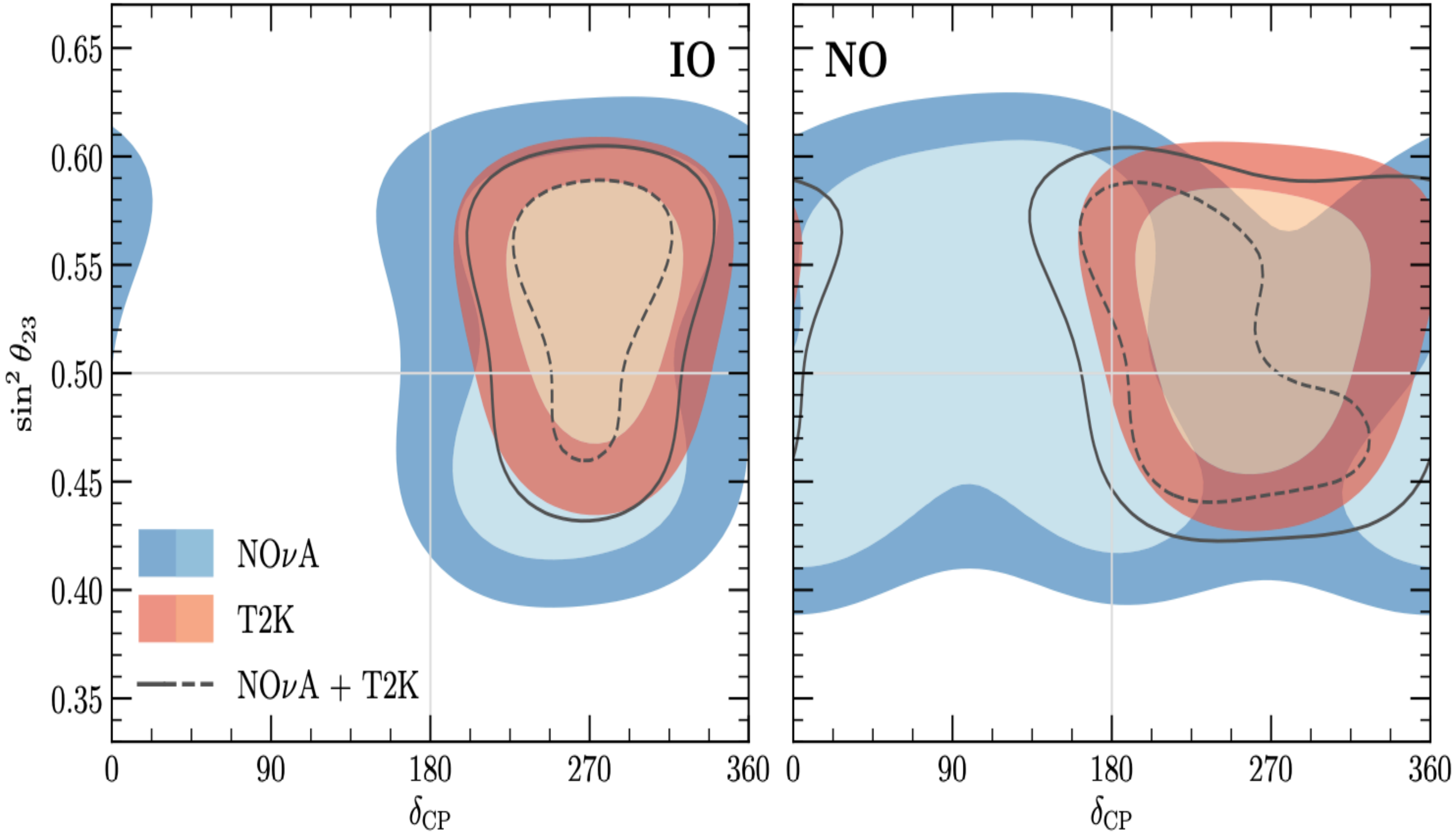
Status of ν oscillations



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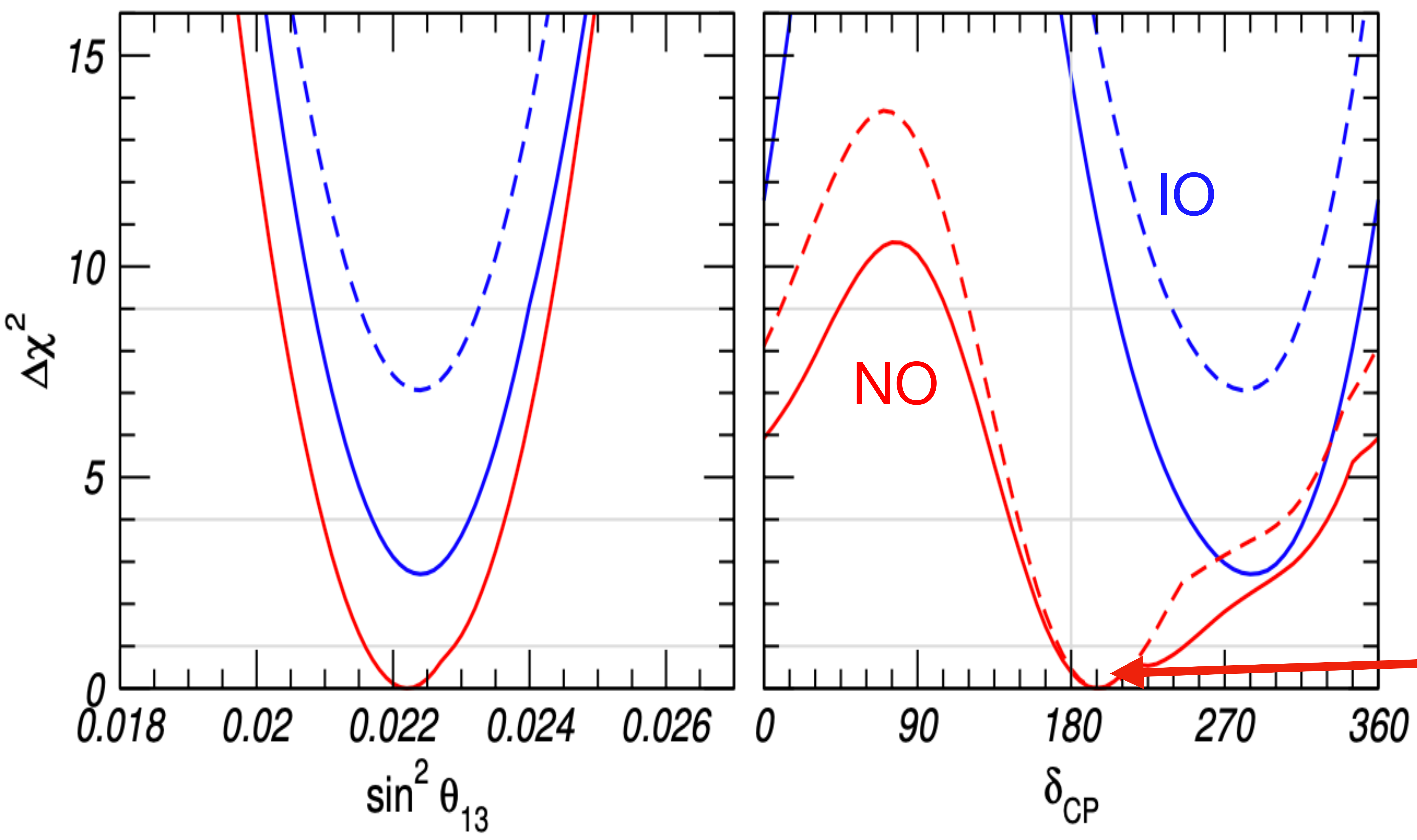

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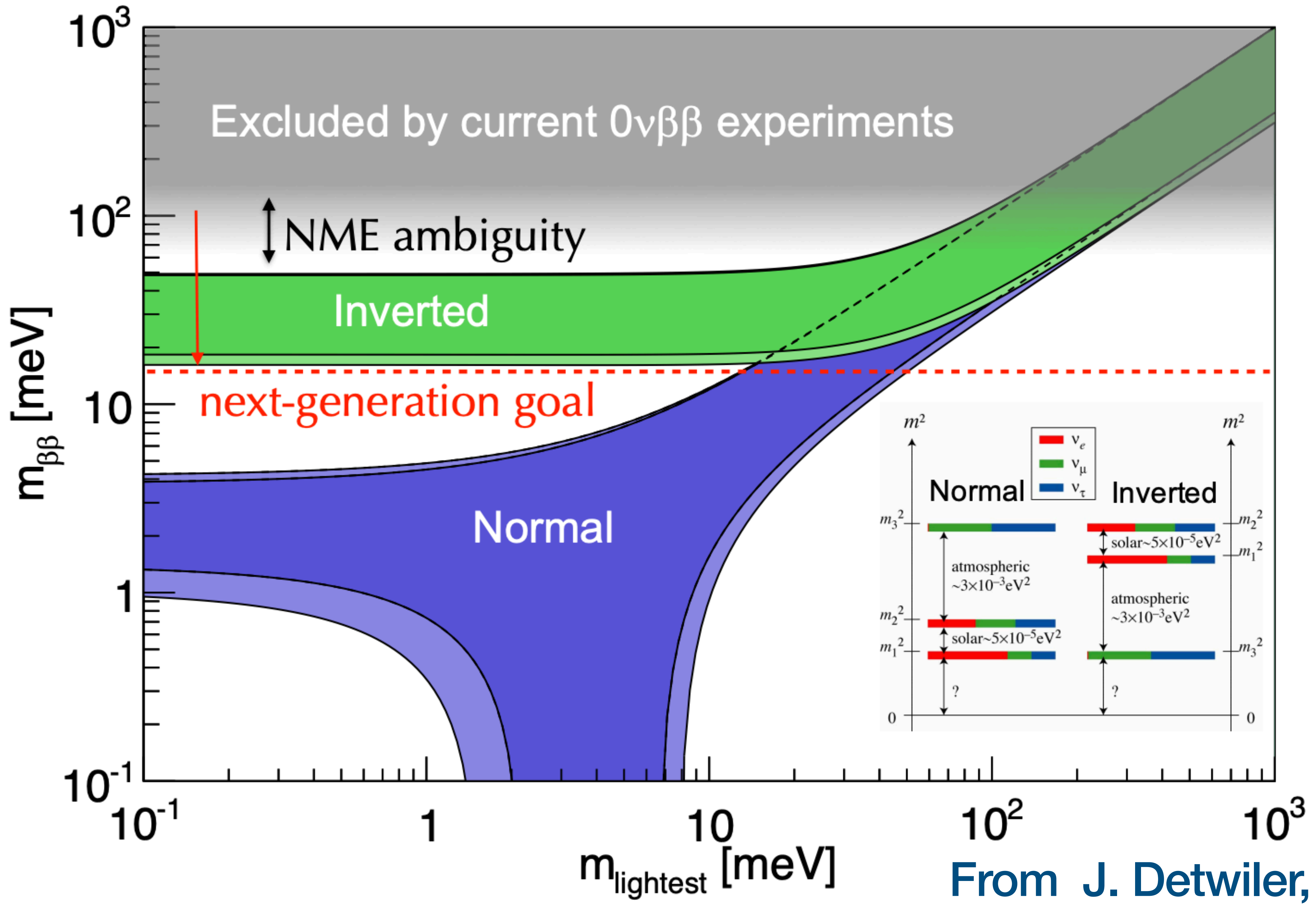
CP conservation still possible for NO

From I. Esteban *et al.* 2007.14792 www.nu-fit.org

Non-oscillation parameters

Are neutrinos Dirac or Majorana particles?

$$m_{\beta\beta} = |\, m_1 c_{12}^2 c_{13}^2 + m_2 s_{12}^2 c_{13}^2 e^{2i\alpha_1} + m_3 s_{13}^2 e^{2i\alpha_2} \,|$$



From J. Detwiler, Neutrino2020

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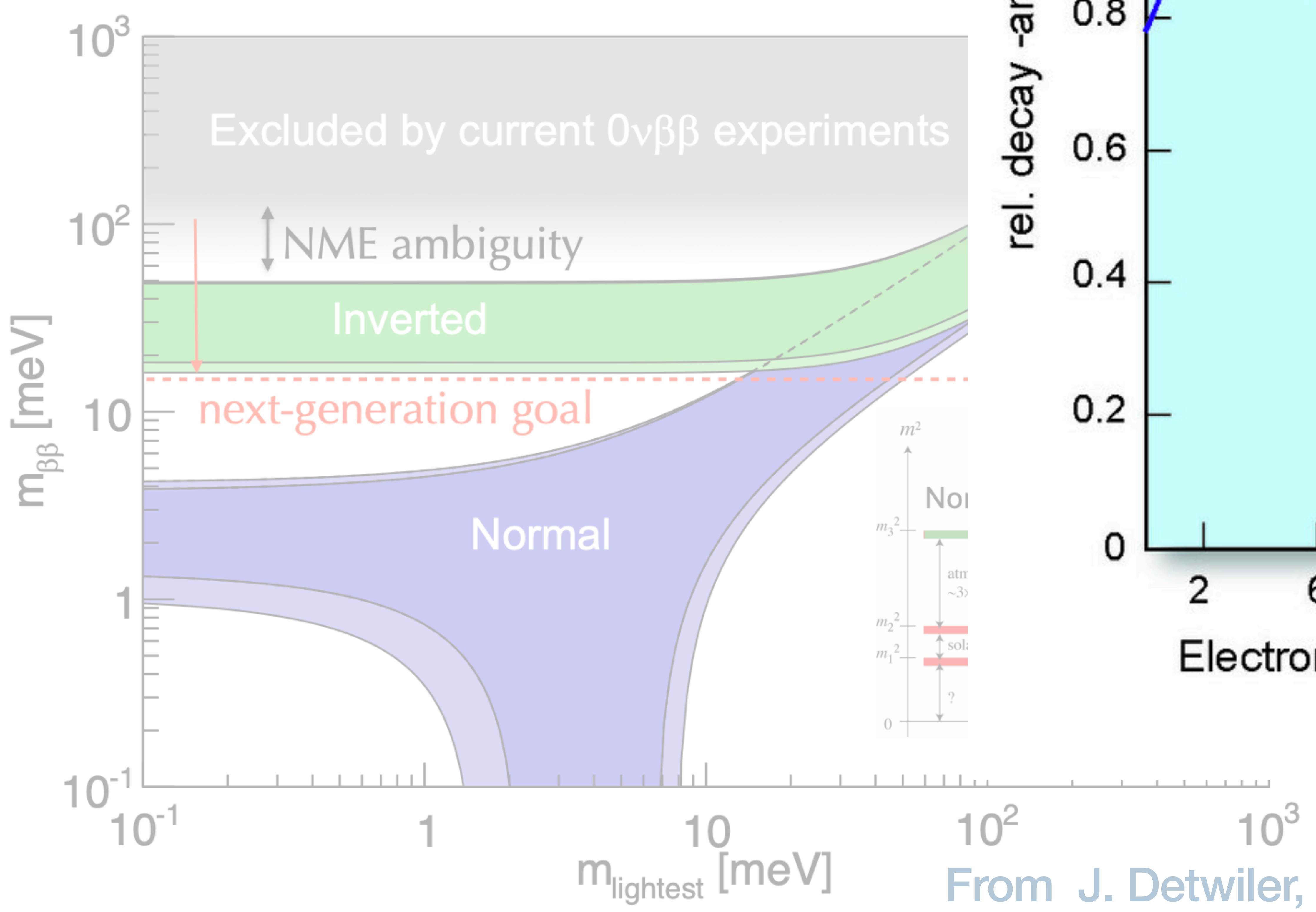
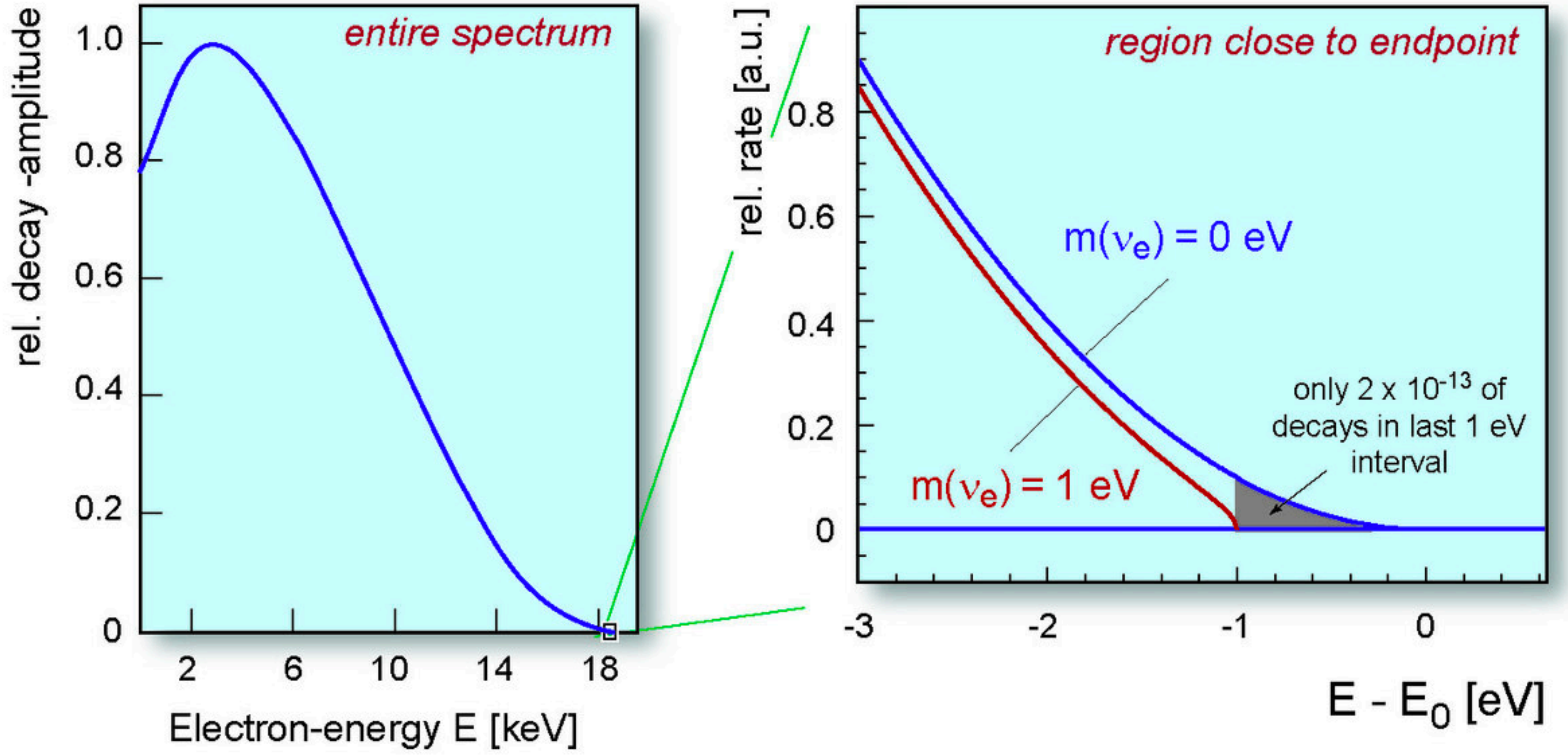


From J. Detwiler, Neutrino2020

Absolute neutrino mass

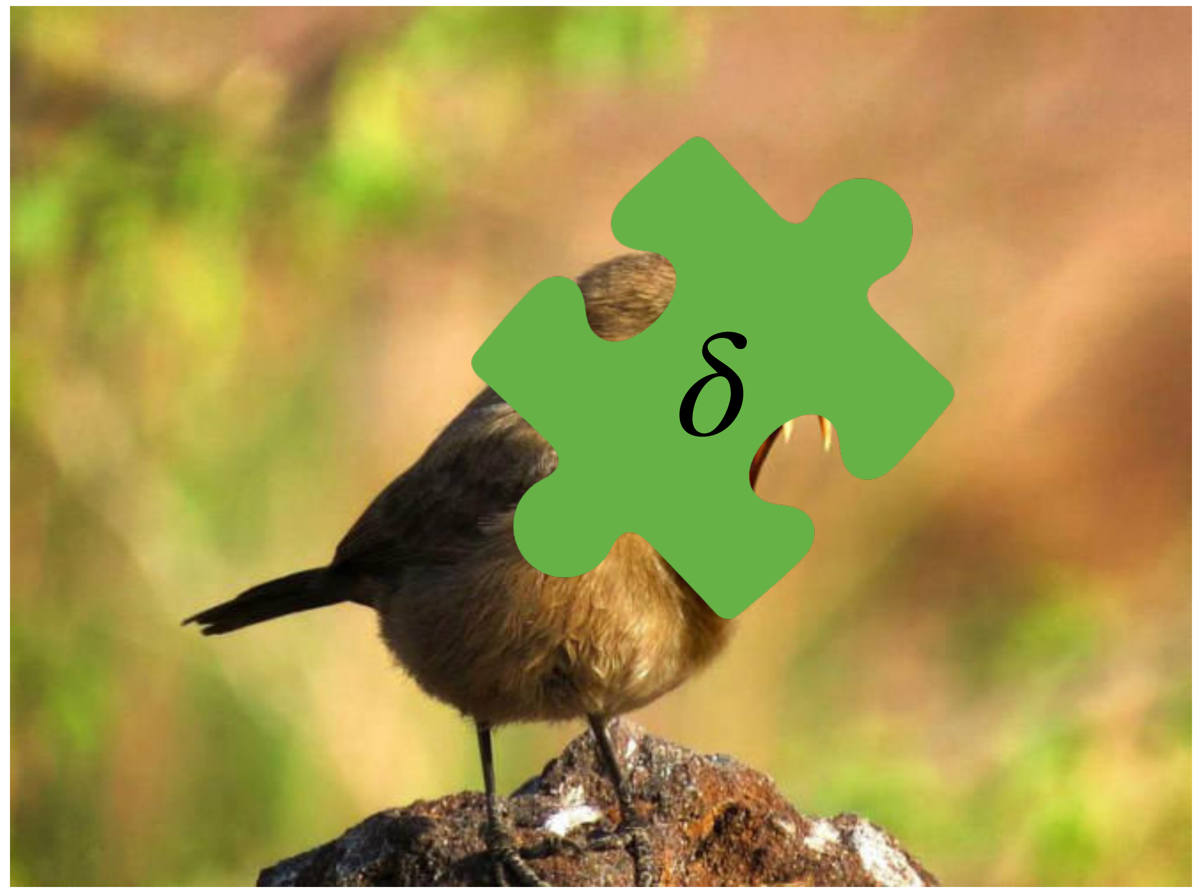
https://www.katrin.kit.edu/79.php



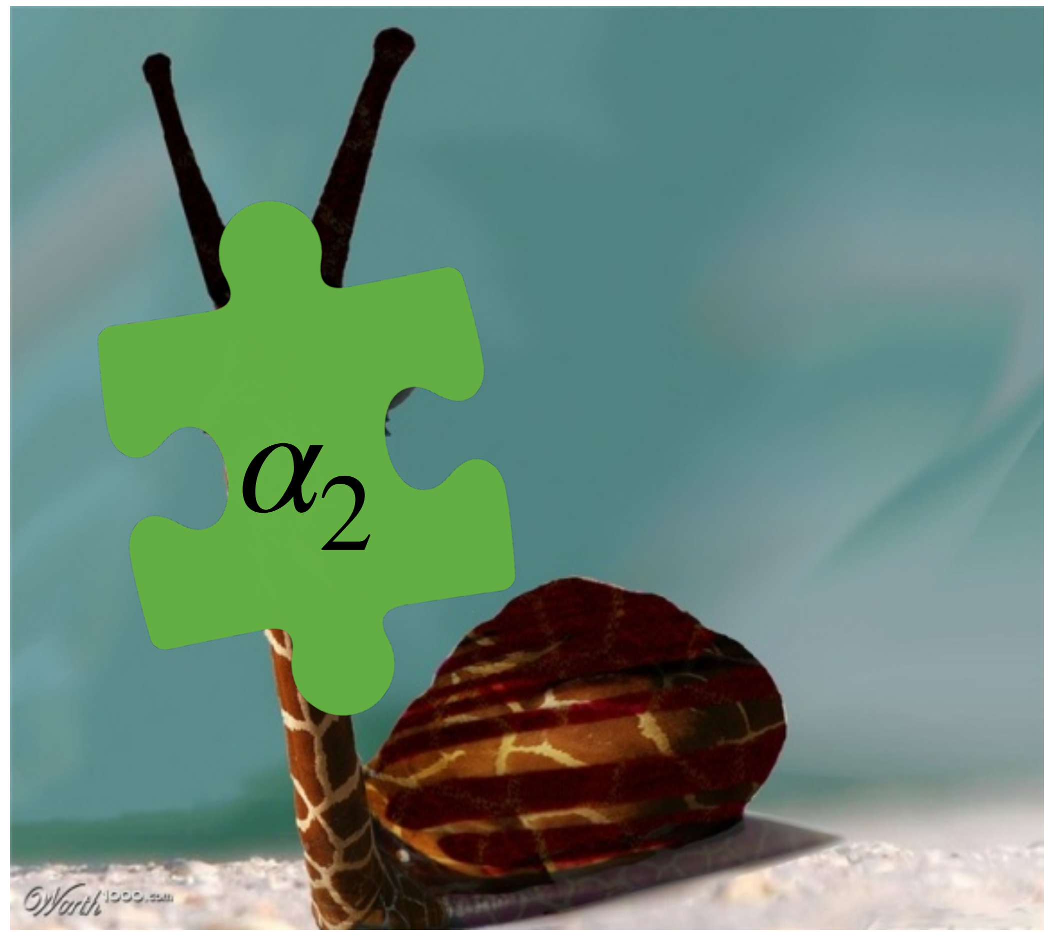
$m_\nu < 1.1\ eV$

KATRIN Collaboration, 1909.06048

Why care?



Courtesy of
Enrique Fernandez-Martinez



Why care?

We could find some surprises

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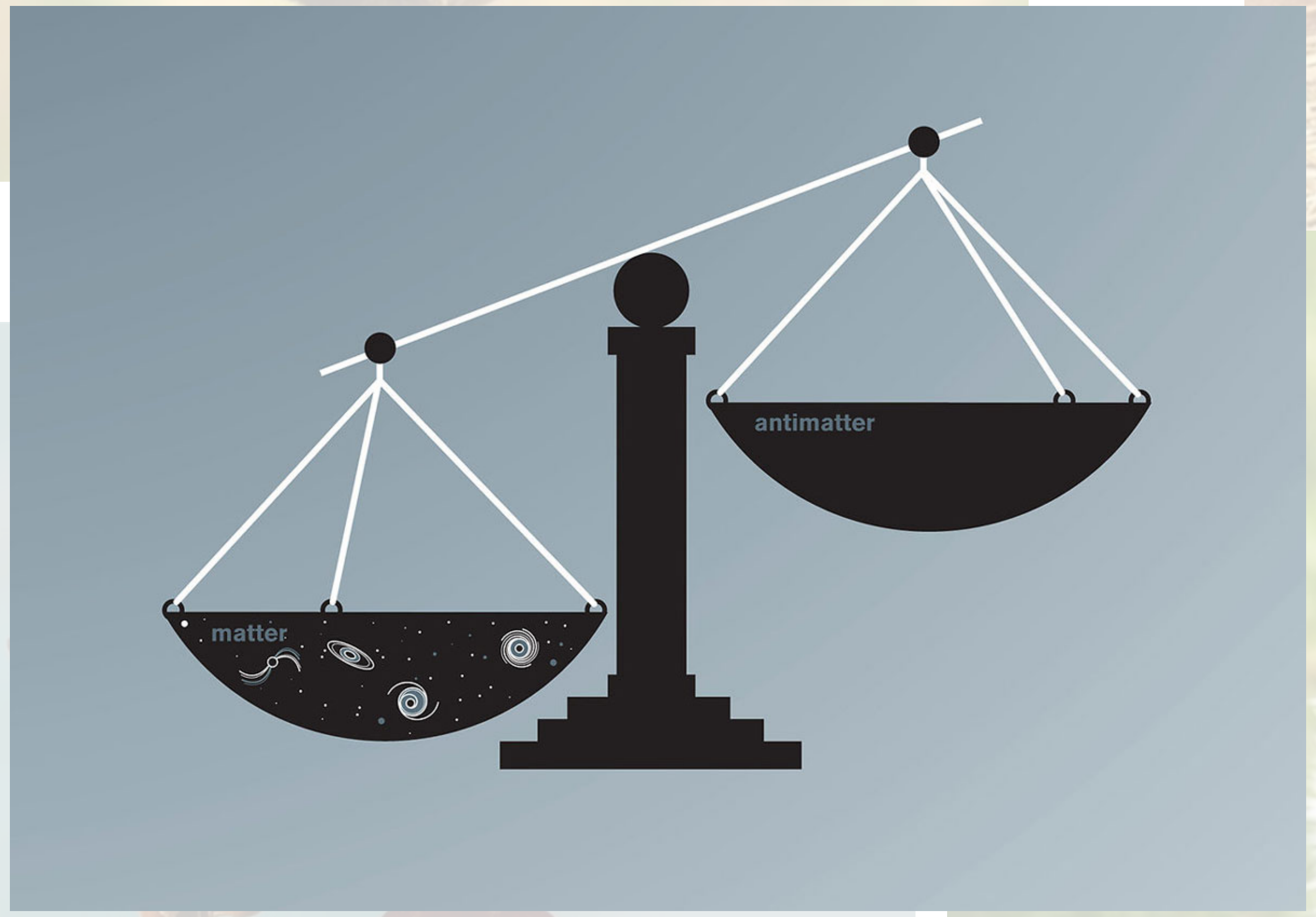
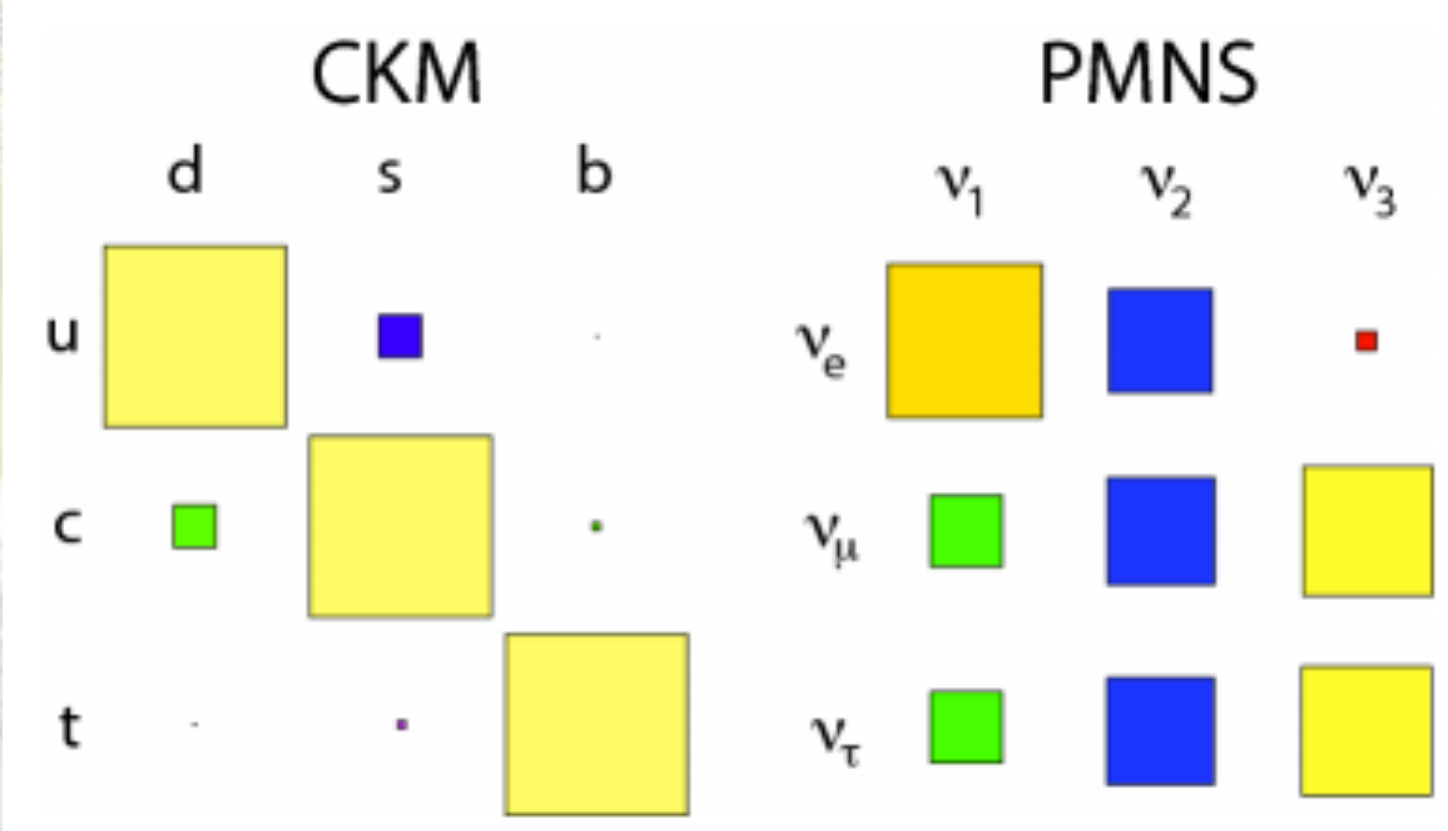
We could find some surprises

Baryon asymmetry



Flavour puzzle



CP violation in ν oscillations

A. Cervera *et al.* hep-ph/0002108

$$P^{\pm}_{\mu\to e} = s_{23}^2 \sin^2 2\theta_{13} \left(\frac{\Delta_{31}}{\tilde{B}_{\mp}}\right)^2 \sin^2 \frac{\tilde{B}_{\mp} L}{2} \quad \text{Atmospheric}$$

$$+ c_{23}^2 \sin^2 2\theta_{12} \left(\frac{\Delta_{21}}{A}\right)^2 \sin^2 \frac{AL}{2} \quad \text{Solar}$$

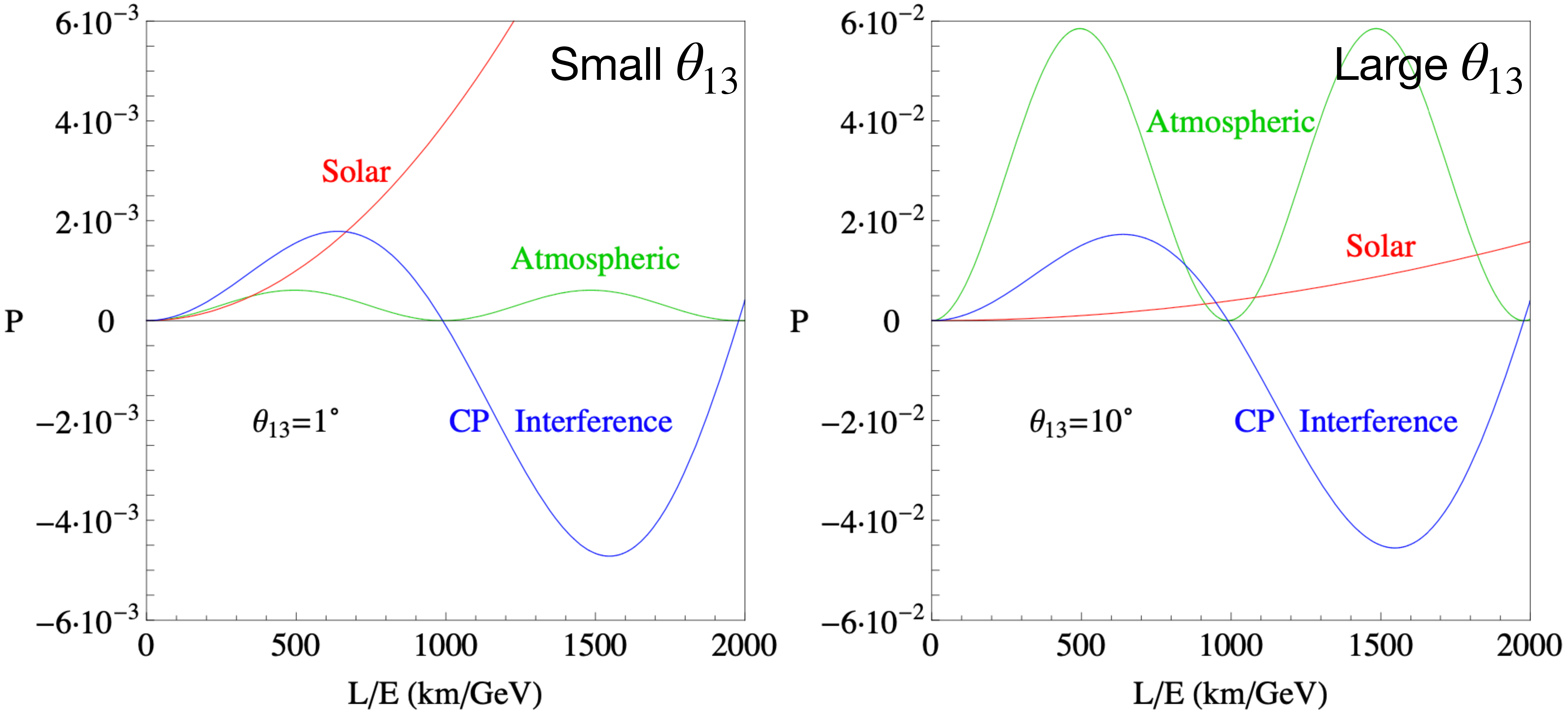
Interference

$$+ \tilde{J} \frac{\Delta_{21}}{A} \frac{\Delta_{31}}{\tilde{B}_{\mp}} \sin\left(\frac{AL}{2}\right) \sin\left(\frac{\tilde{B}_{\mp} L}{2}\right) \cos\left(\pm\delta + \frac{\Delta_{31} L}{2}\right)$$

$$\tilde{J} = c_{13} \sin 2\theta_{13} \sin 2\theta_{12} \sin 2\theta_{23} \quad \Delta_{ij} = \Delta m_{ij}^2/(2E) \quad A = \sqrt{2} G_F n_e \quad \tilde{B}_{\mp} = |A \mp \Delta_{31}|$$

Impact of θ_{13}

P. Coloma & E. Fernandez-Martinez, 1110.4583



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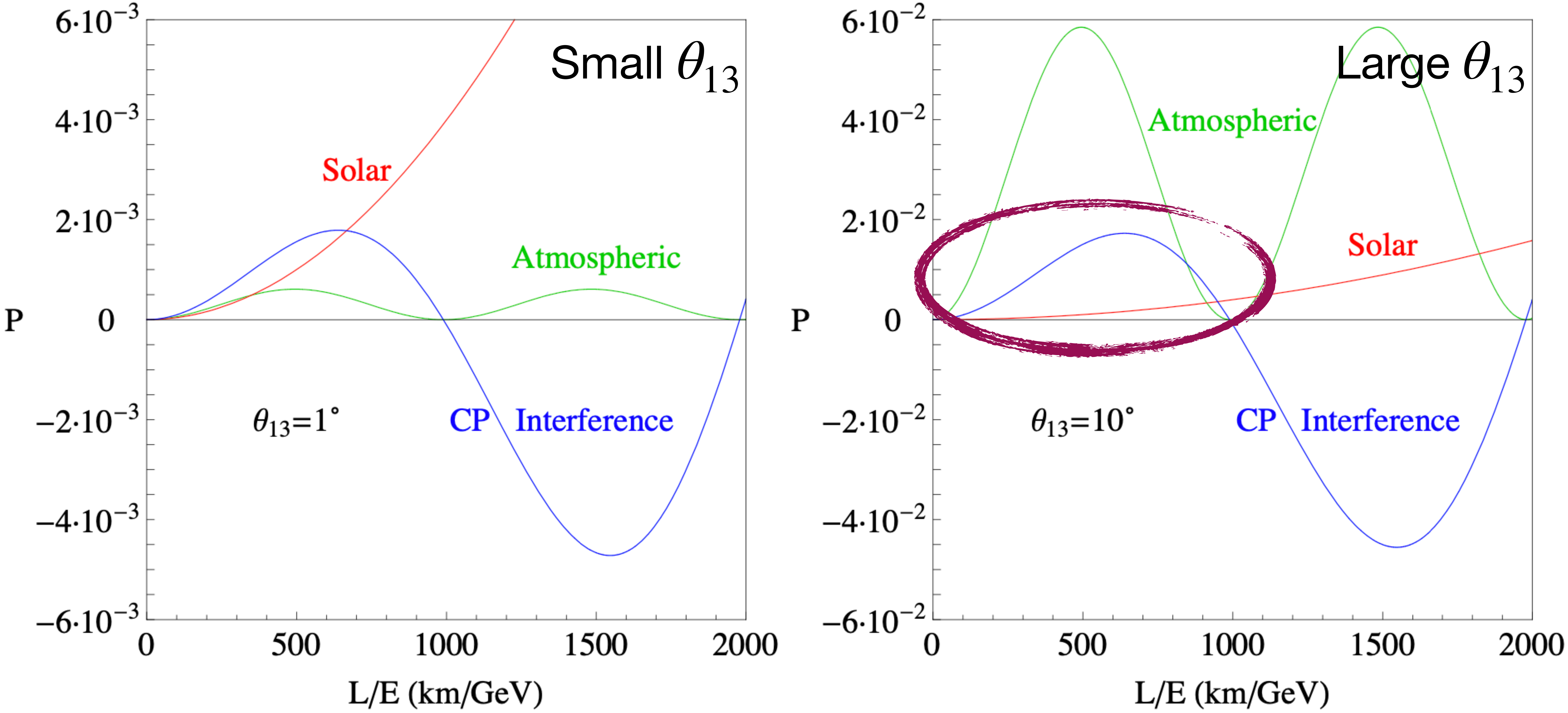

Impact of θ_{13}

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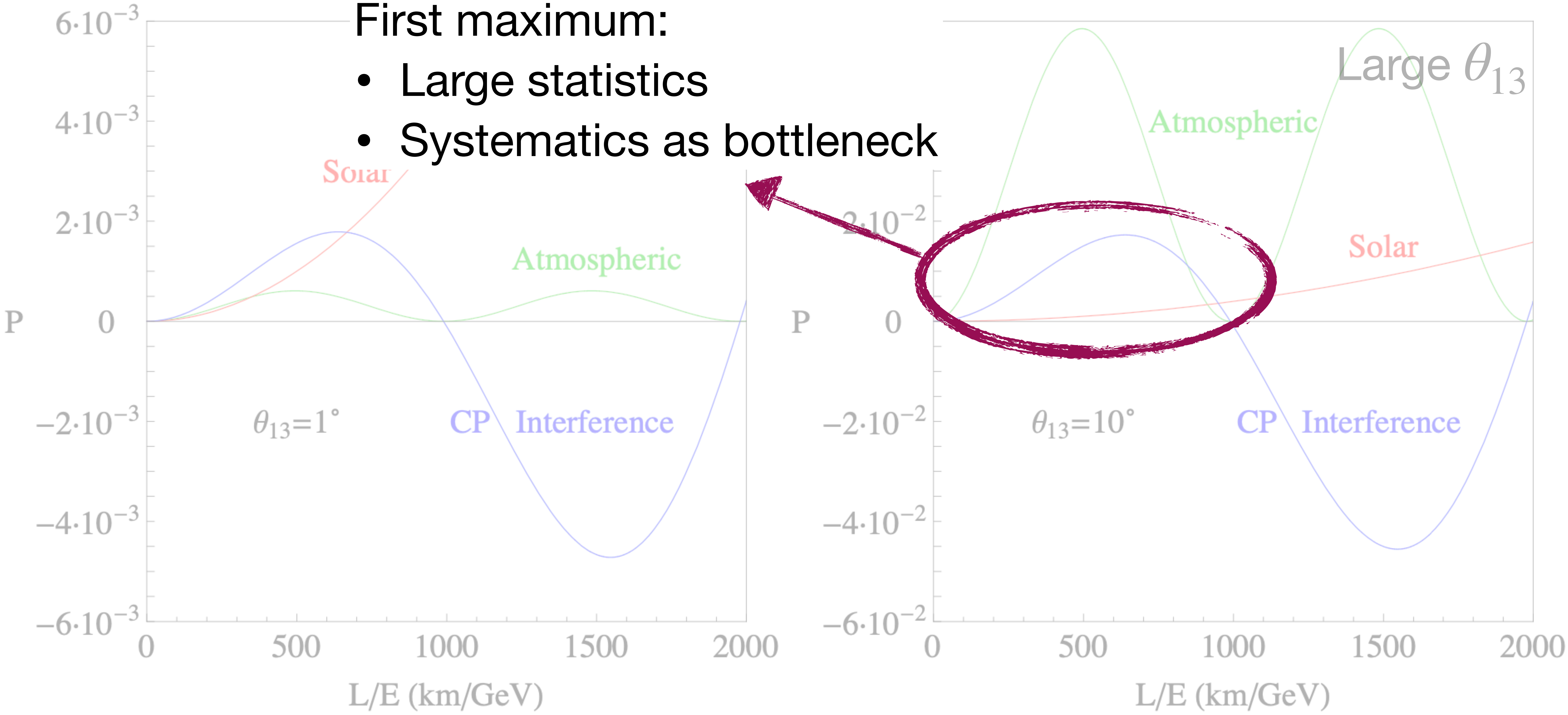
First maximum:

- Large statistics
- Systematics as bottleneck



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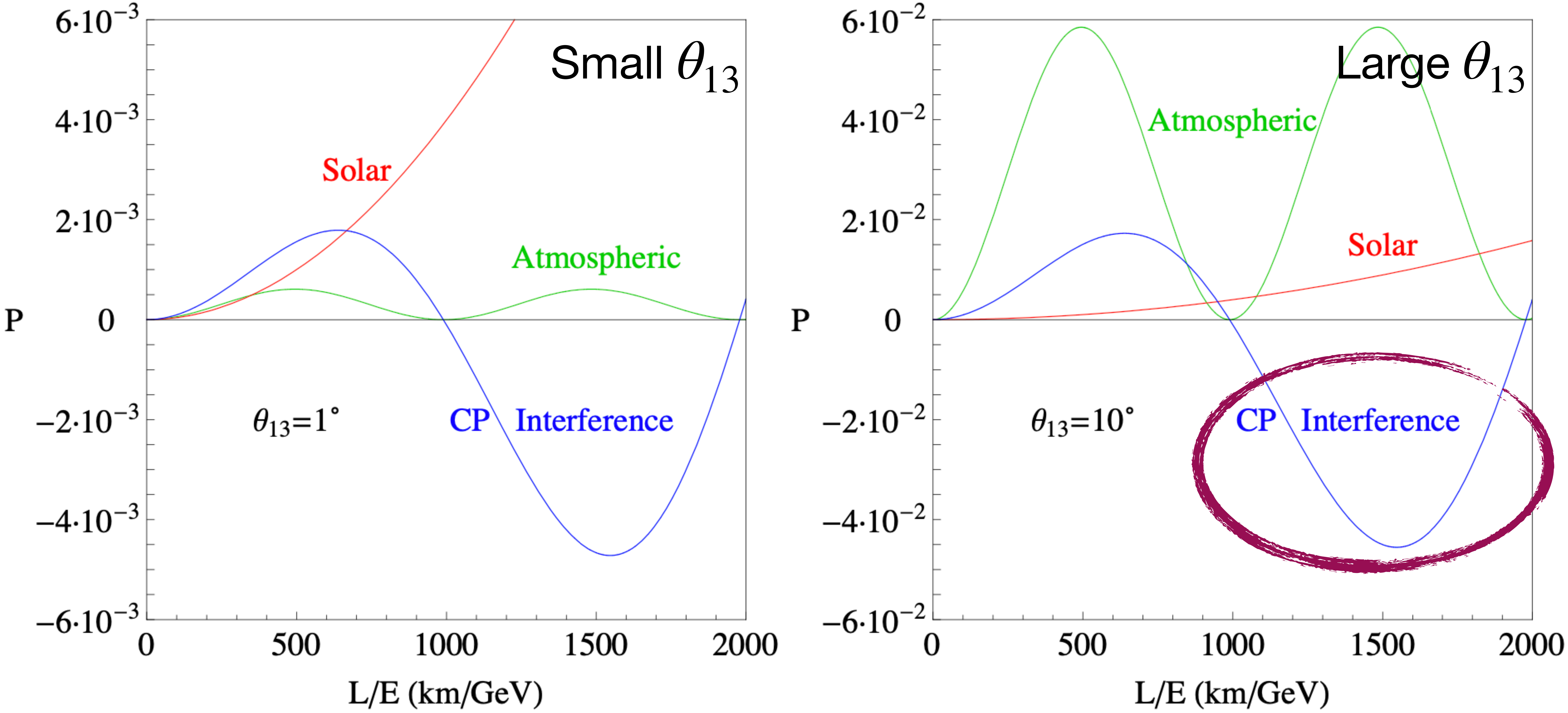

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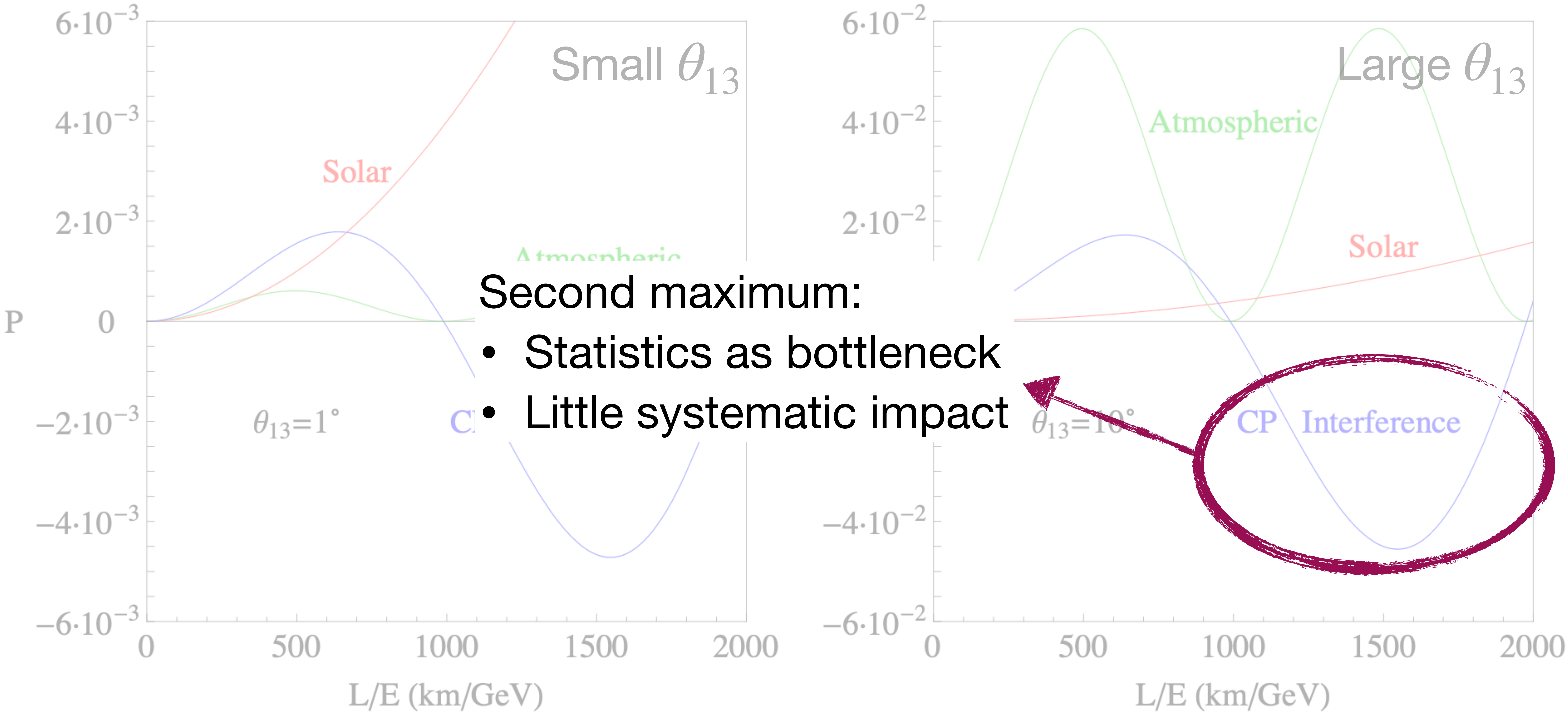

Second maximum:

- Statistics as bottleneck
- Little systematic impact

ESSnuSB

E. Baussan *et al.* 1309.7022

- Modify ESS linac to produce neutrinos
- 5 MW at 2.5 GeV proton beam
- Memphis-like WC detector:
  - 500 kt fiducial volume
  - Best locations at 540 km and 360 km

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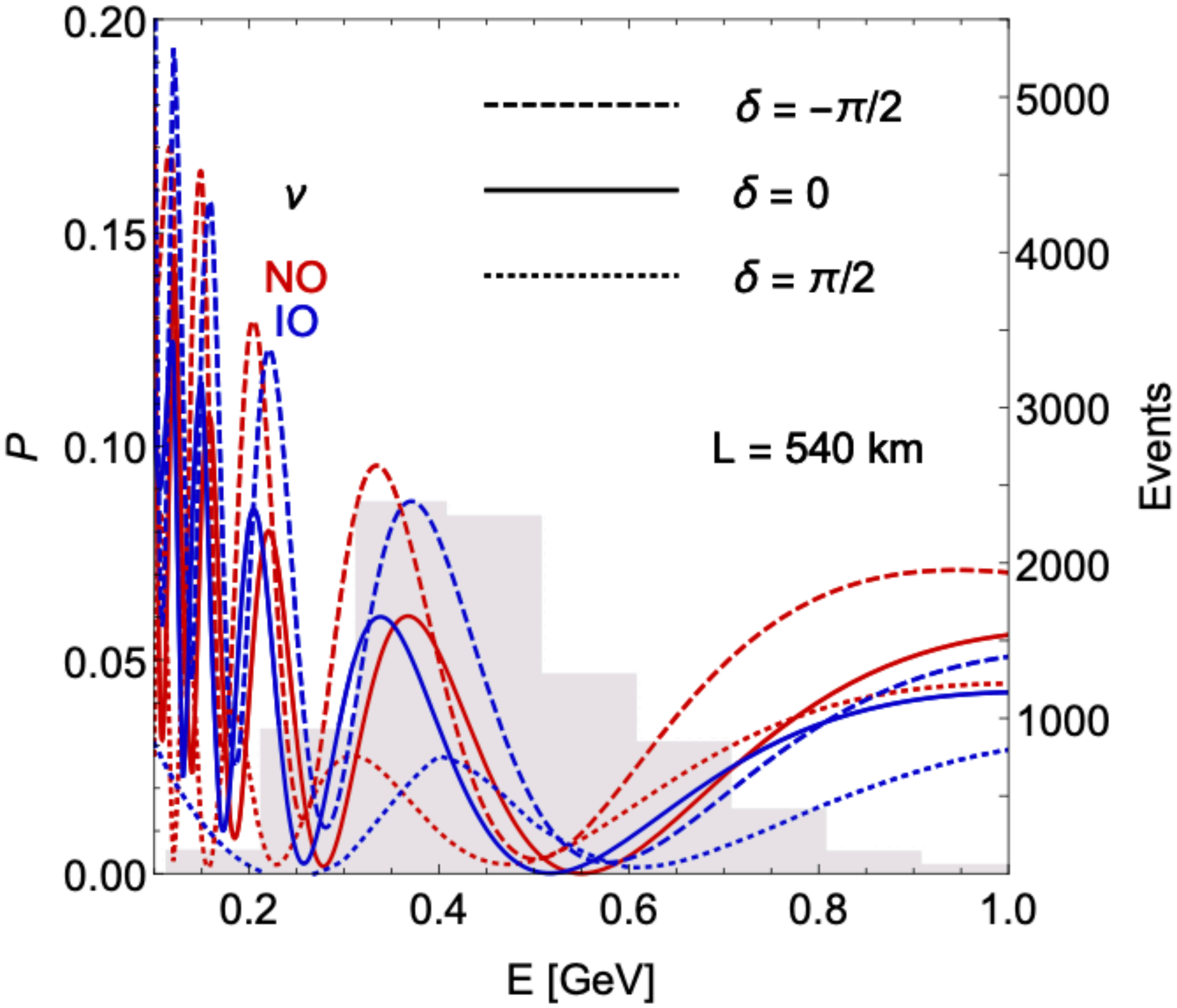

M. Blennow *et al.* 1912.04309

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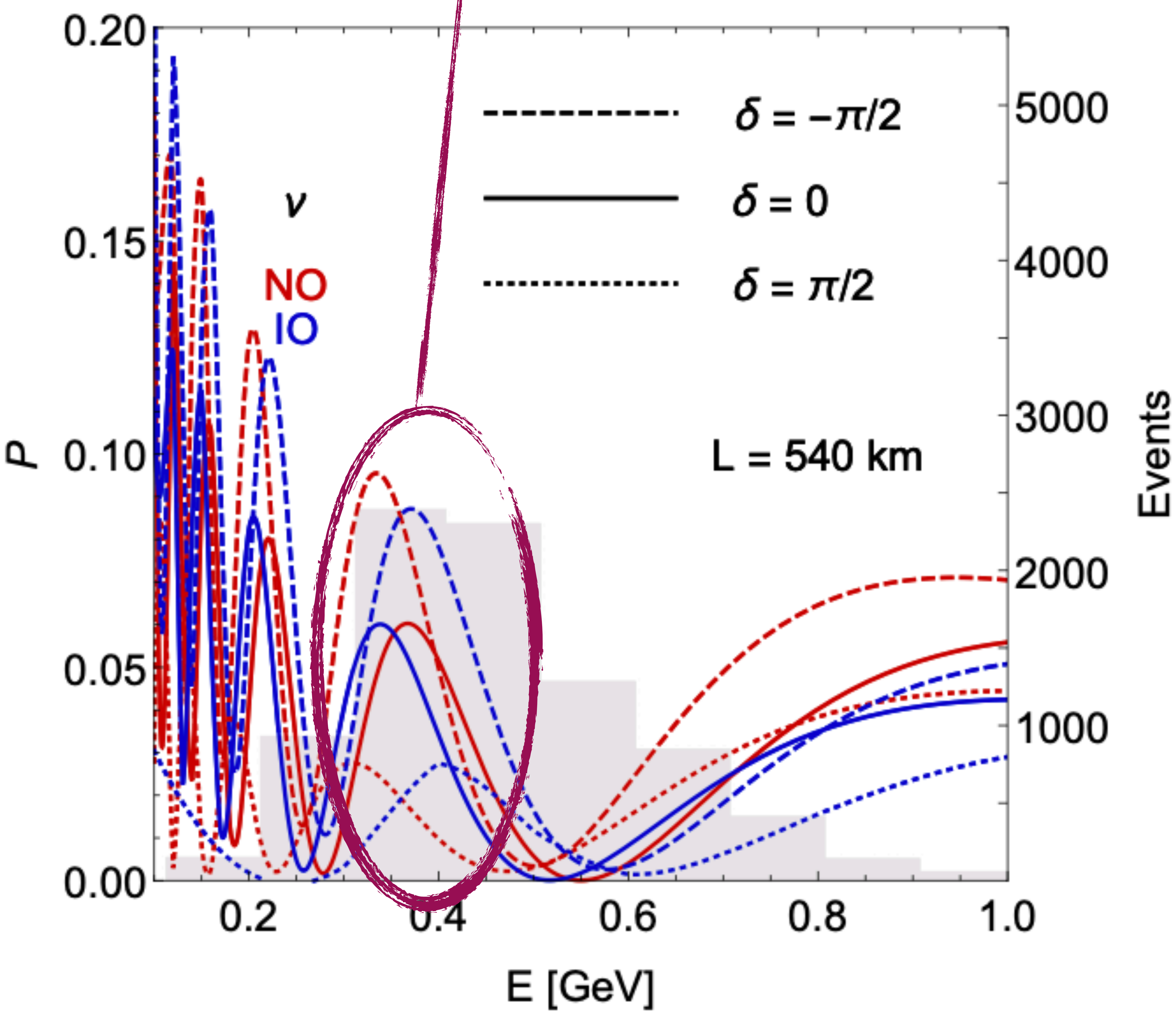
$E_\nu \sim 300$ MeV



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Matter effects are important for $E_\nu \sim \mathcal{O}(\text{GeV})$

Not very sensitive to $sign(\Delta m^2_{31})$

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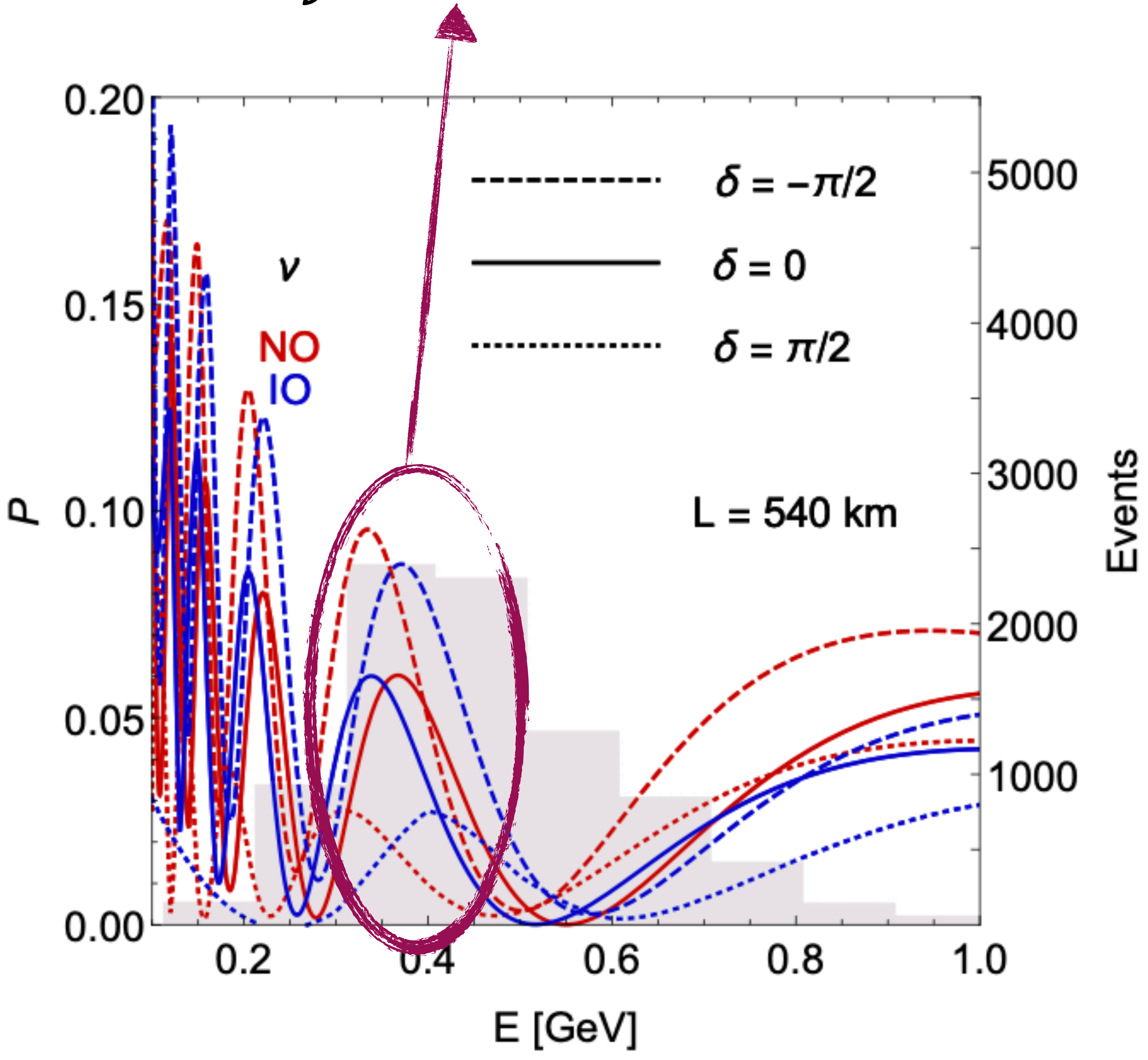

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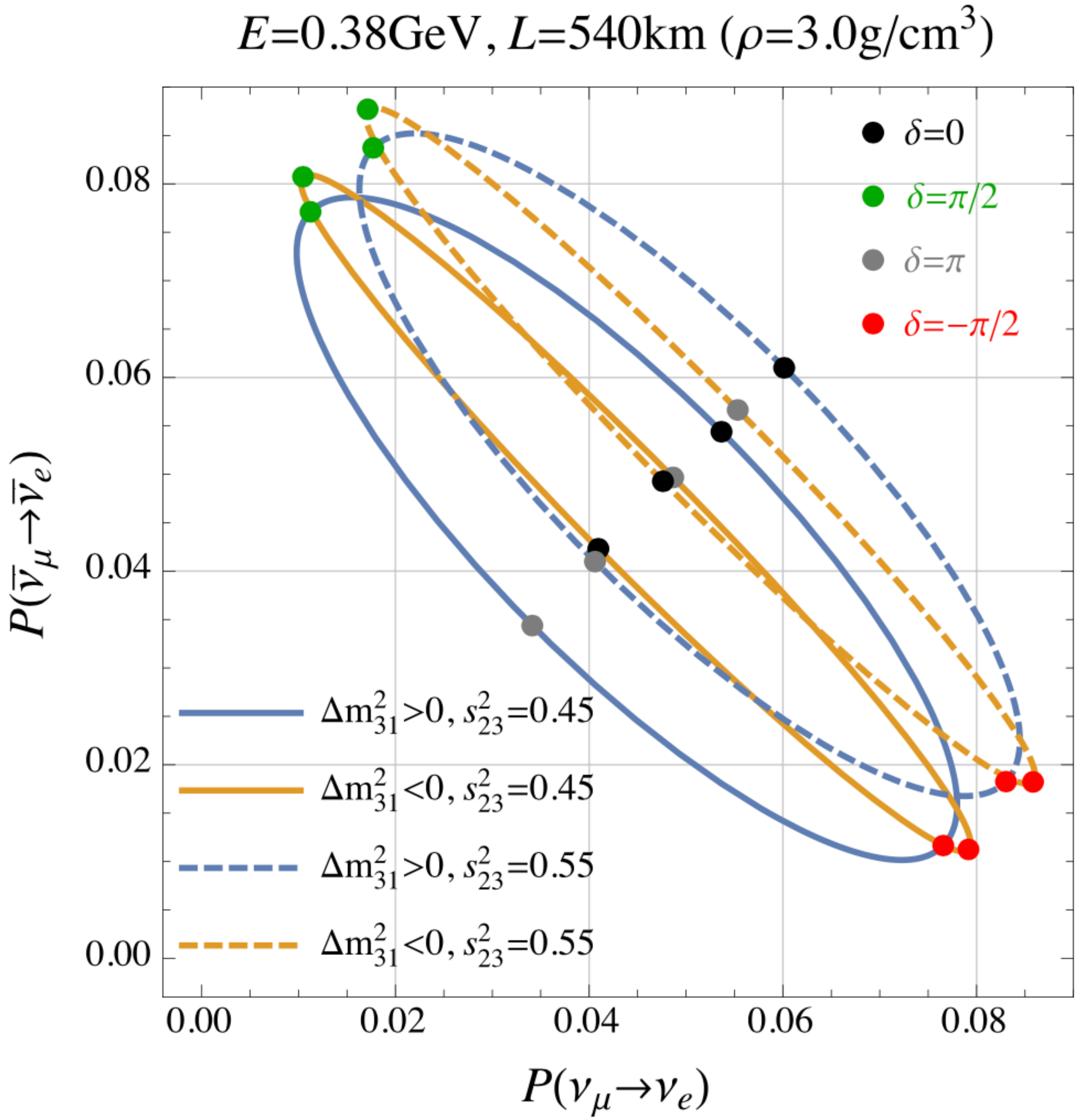
Poor determination of the ordering and the octant of θ_{23}



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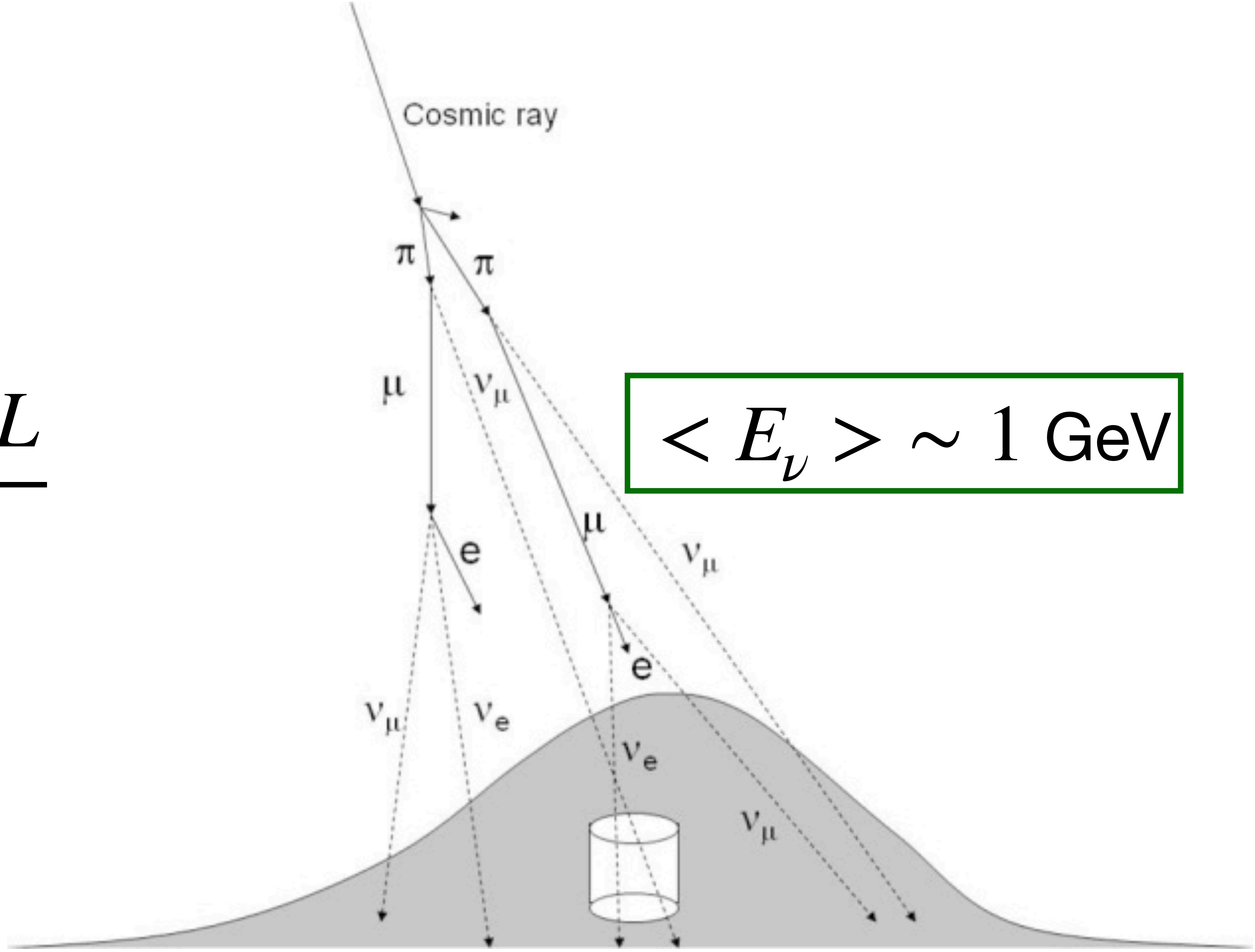
Atmospheric neutrinos at ESSnuSB

500 kt Water-Cerenkov detector

$$P_{\mu\to e} = s_{23}^2 \sin^2 2\theta_{13} \left(\frac{\Delta_{31}}{\tilde{B}_\mp}\right)^2 \sin^2 \frac{\tilde{B}_\pm L}{2}$$



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https://neutrinos.fnal.gov/sources/atmospheric-neutrinos/

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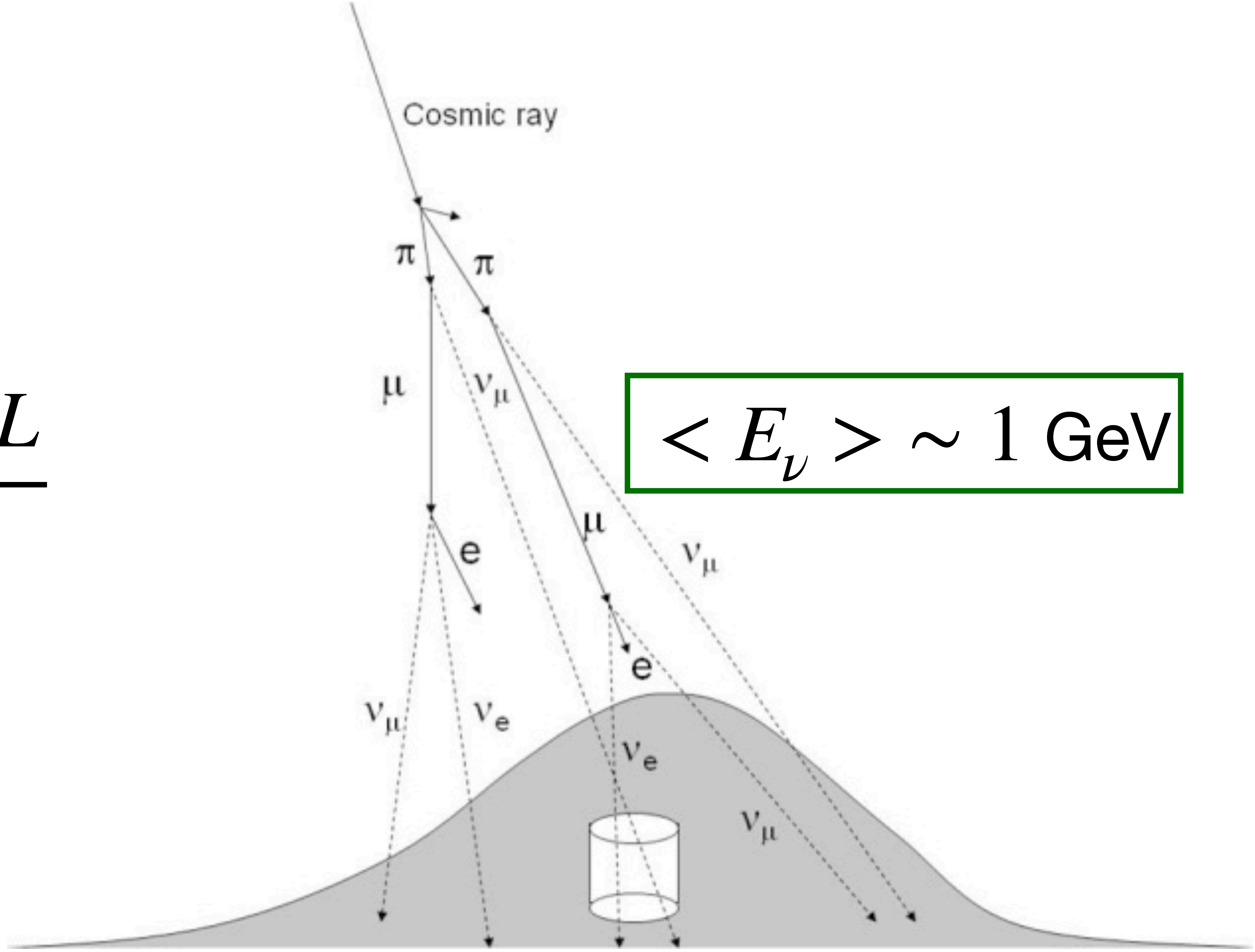
Sensitivity to octant



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Sensitivity to octant

Sensitivity to mass ordering

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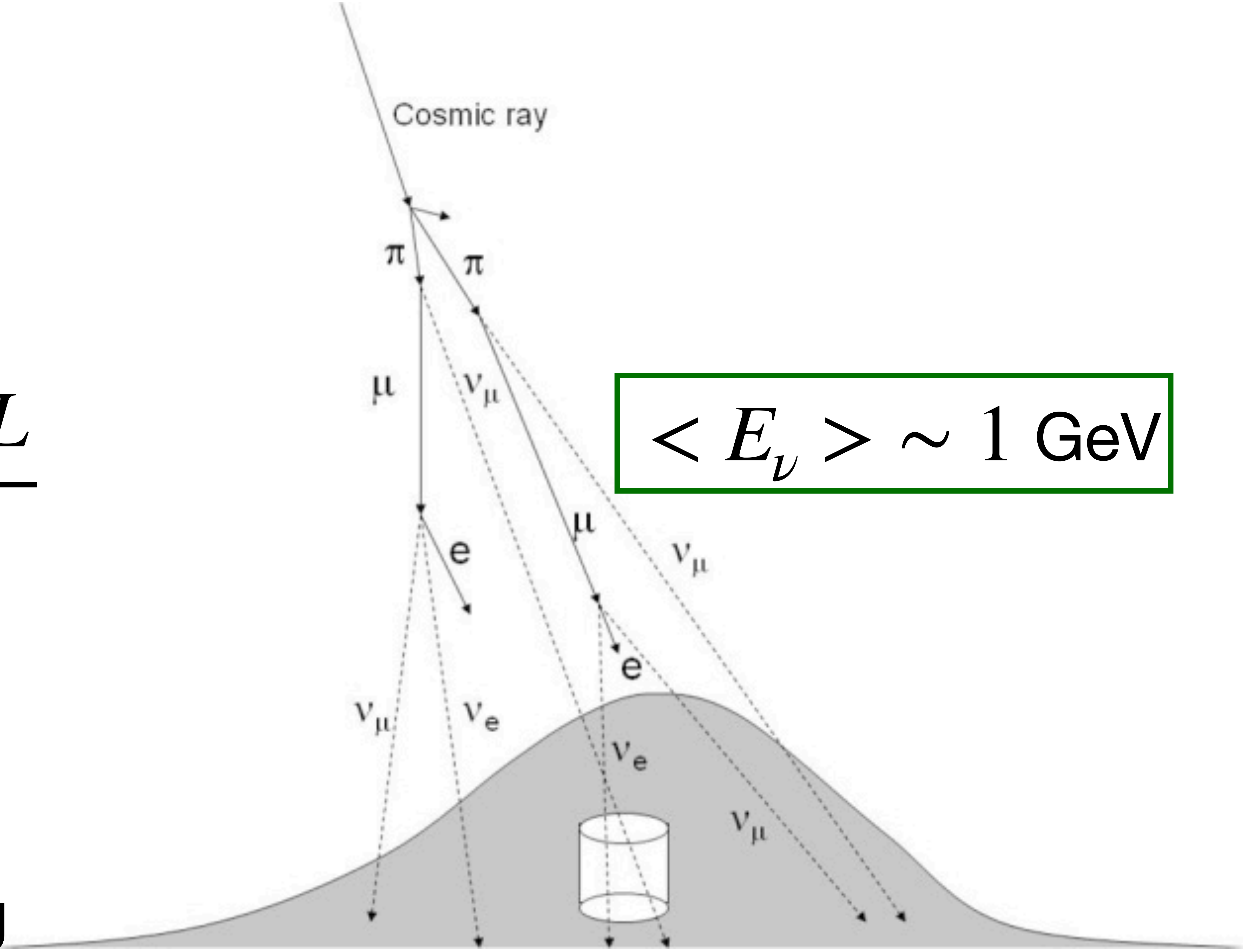

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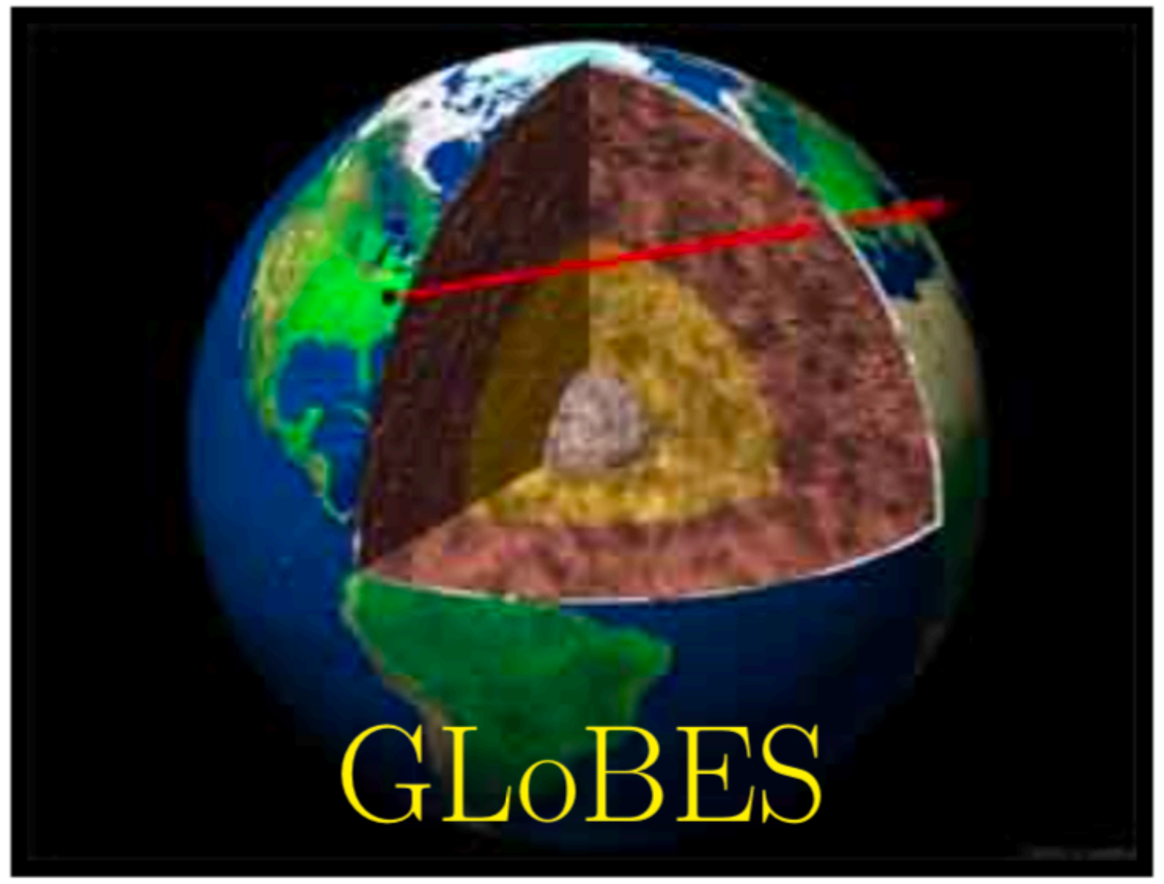
Simulation details

P. Huber *et al.* hep-ph/0701187

Implemented in GLoBES

- Explicitly simulate the ND
- 2.5 GeV proton beam
- 1 Mt WC far detector
- QE cross sections
- $t_\nu = t_{\bar{\nu}} = 5$ years



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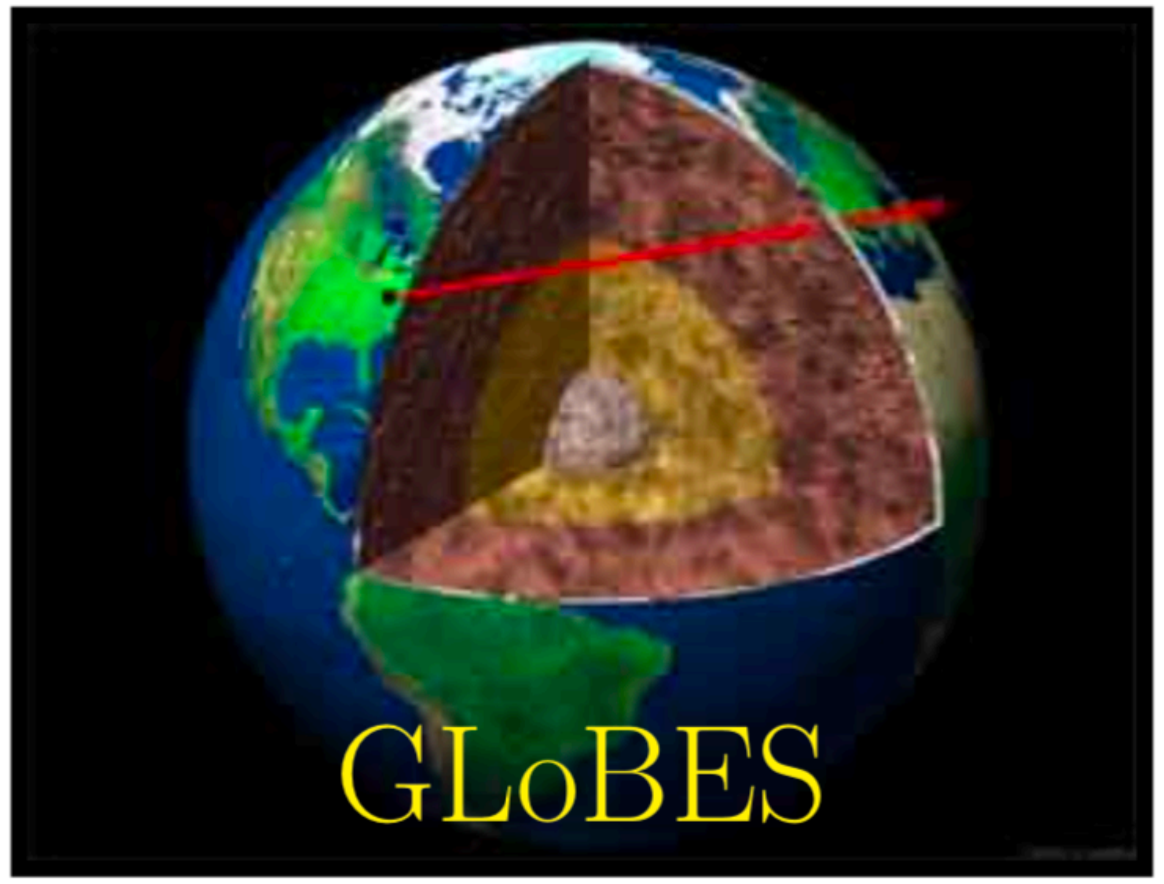

Systematic uncertainties

Systematics	Opt.	Cons.
Fiducial volume ND	0.2%	0.5%
Fiducial volume FD	1%	2.5%
Flux error ν	5%	7.5%
Flux error $\bar{\nu}$	10%	15%
Neutral current background	5%	7.5%
Cross section $\times$ eff. QE	10%	15%
Ratio ν_e/ν_μ QE	3.5%	11%

P. Coloma *et al.* 1209.5973

Simulation details

Atmospheric sample J. Campagne *et al.* hep-ph/0603172

(kindly provided by Michele Maltoni)

- Honda flux at Gran Sasso
- Expect larger fluxes at Garpenberg or Zinkgruvan
- NC contamination: Same ratio between NC and unoscillated CC events as SK

M. Honda *et al. hep-ph/0404457*

SK Collaboration, Y. Ashie *et al.* hep-ex/0501064

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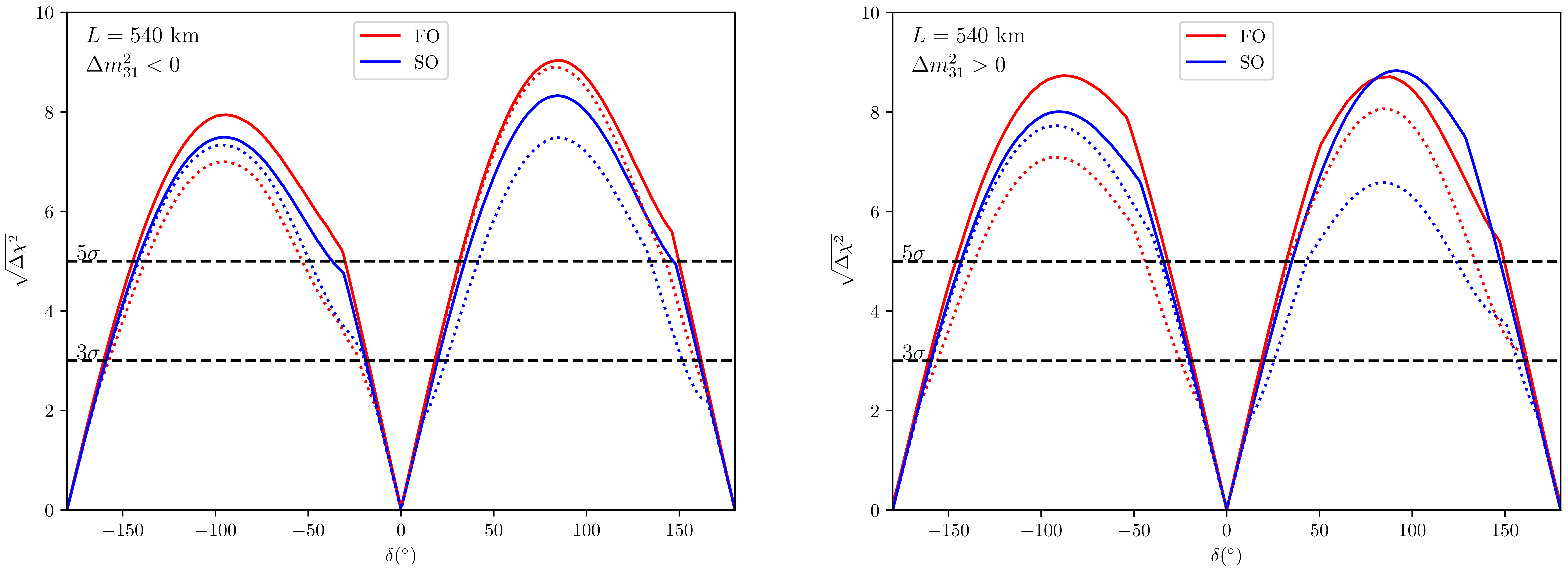
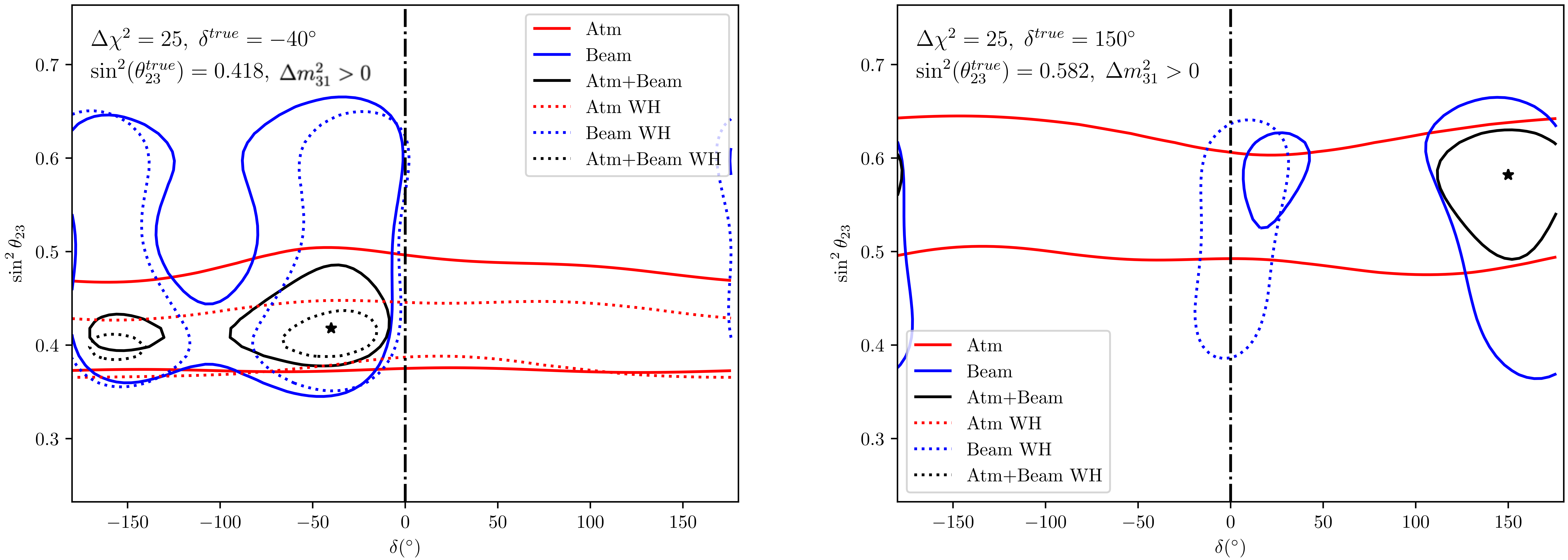
P. Coloma *et al.* 1209.5973

CP violation sensitivity



M. Blennow *et al.* 1912.04309

Complementarity between beam and atm



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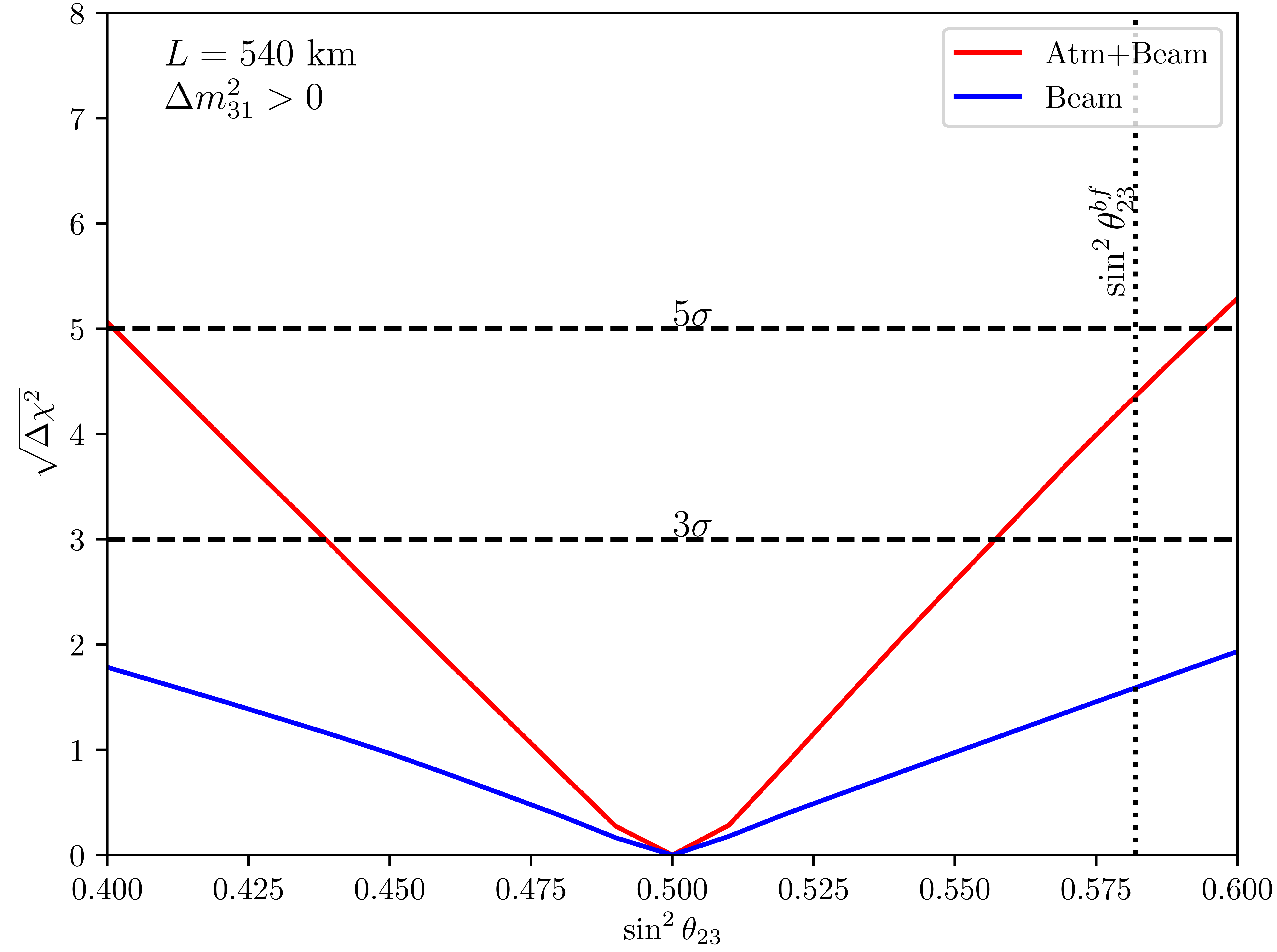
Octant and mass ordering



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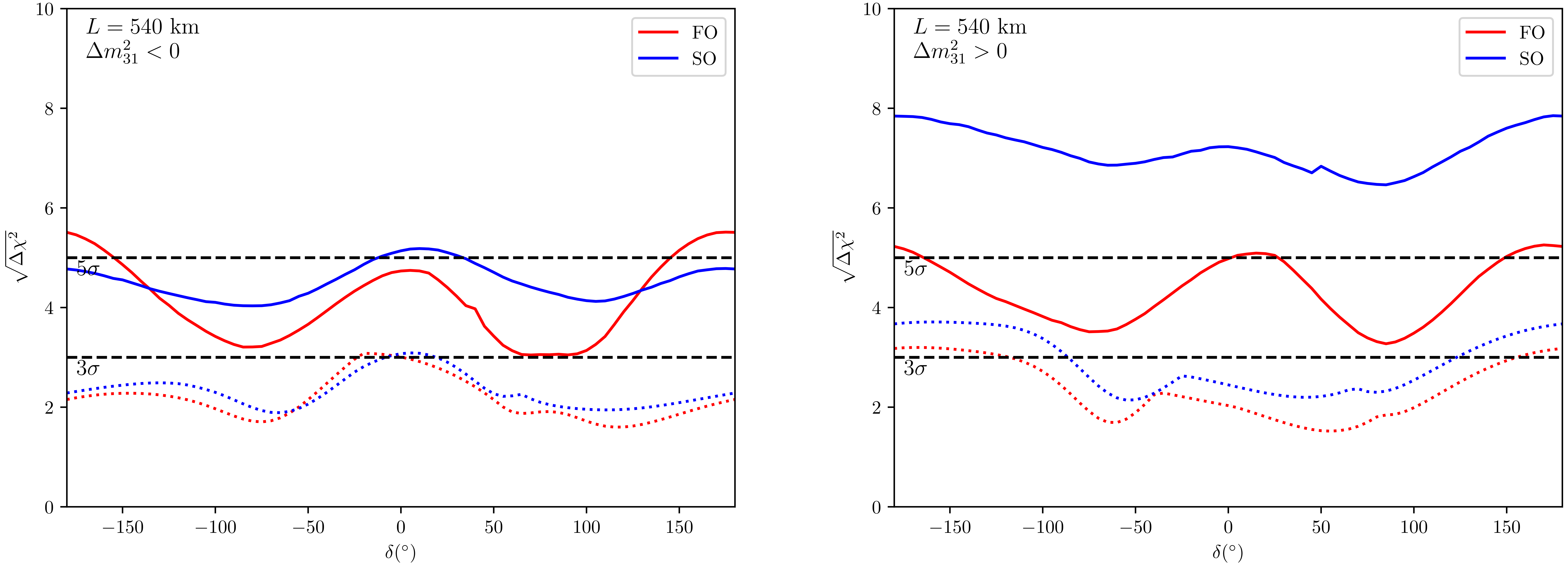

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Precision on δ

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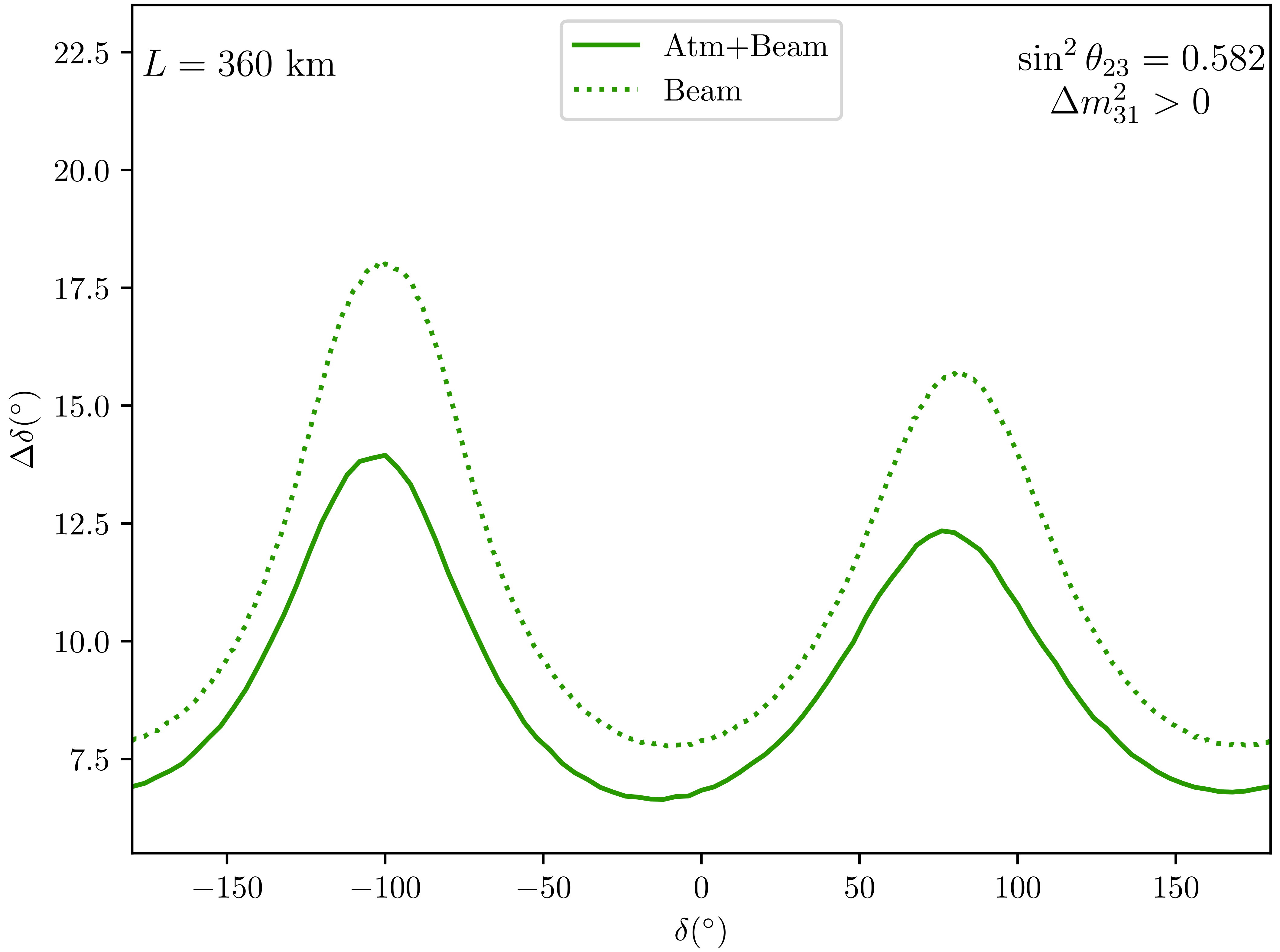

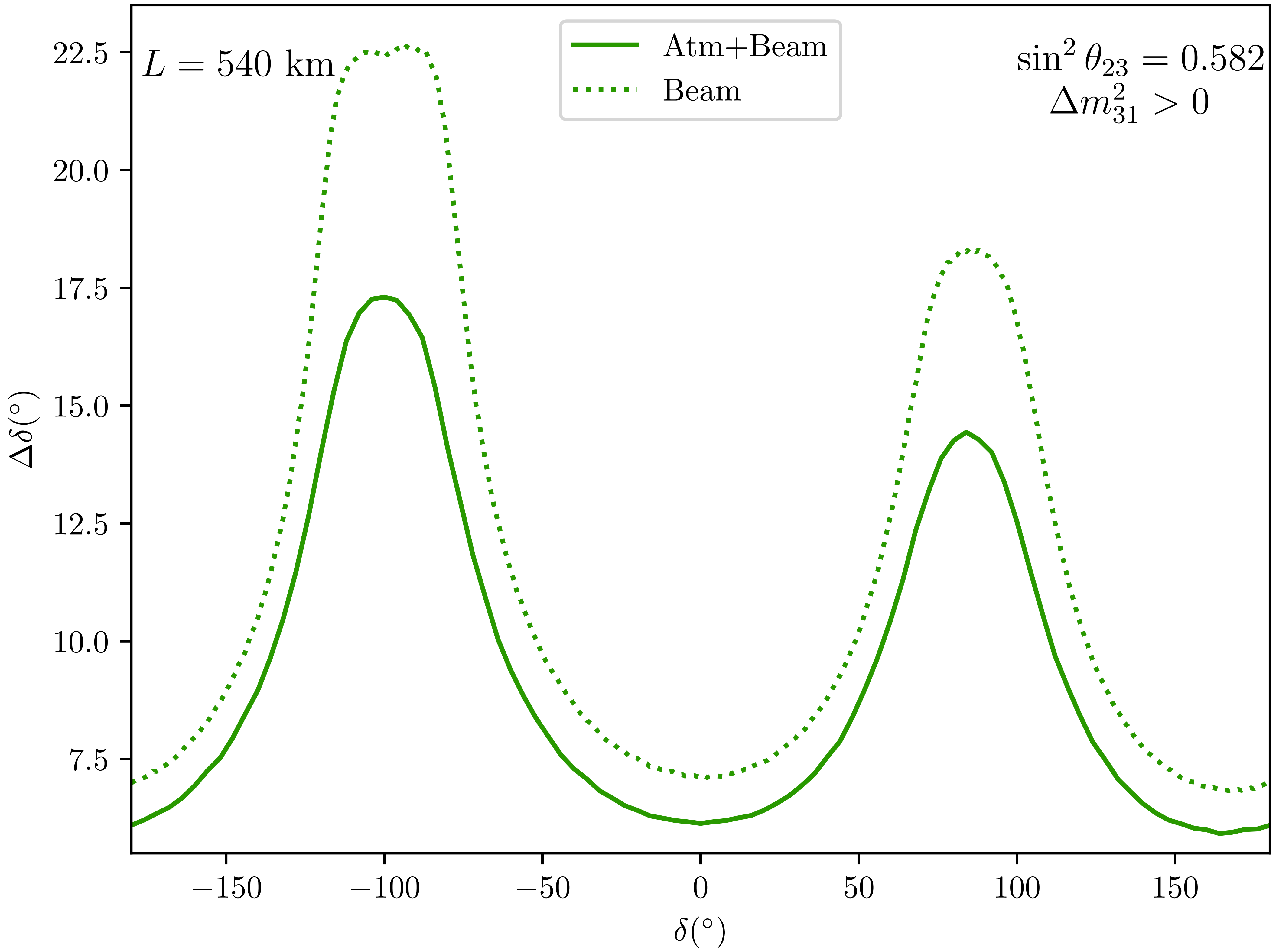

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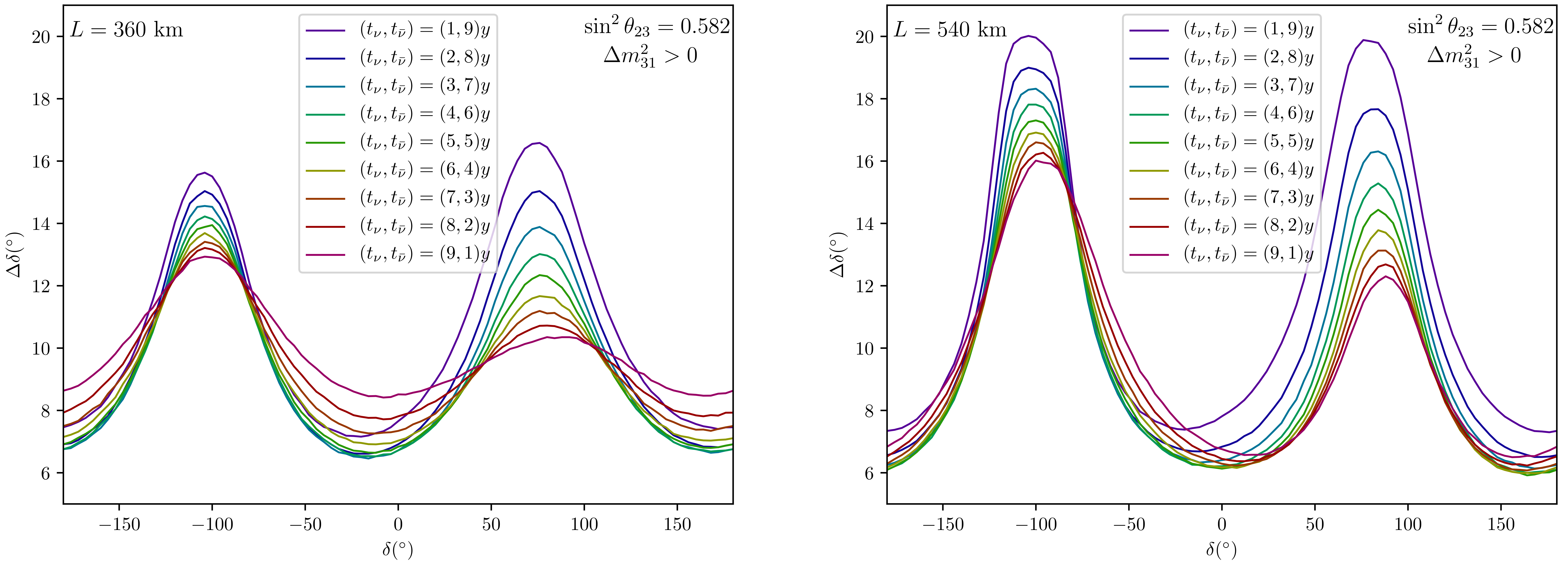

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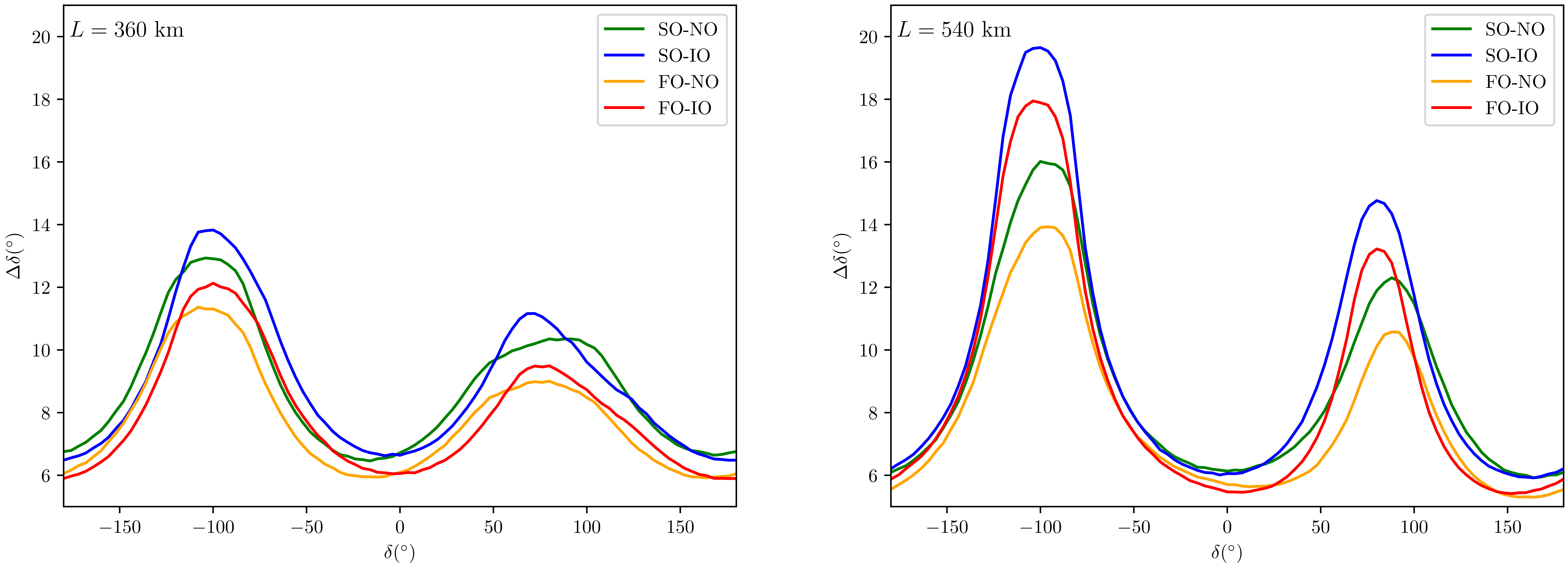

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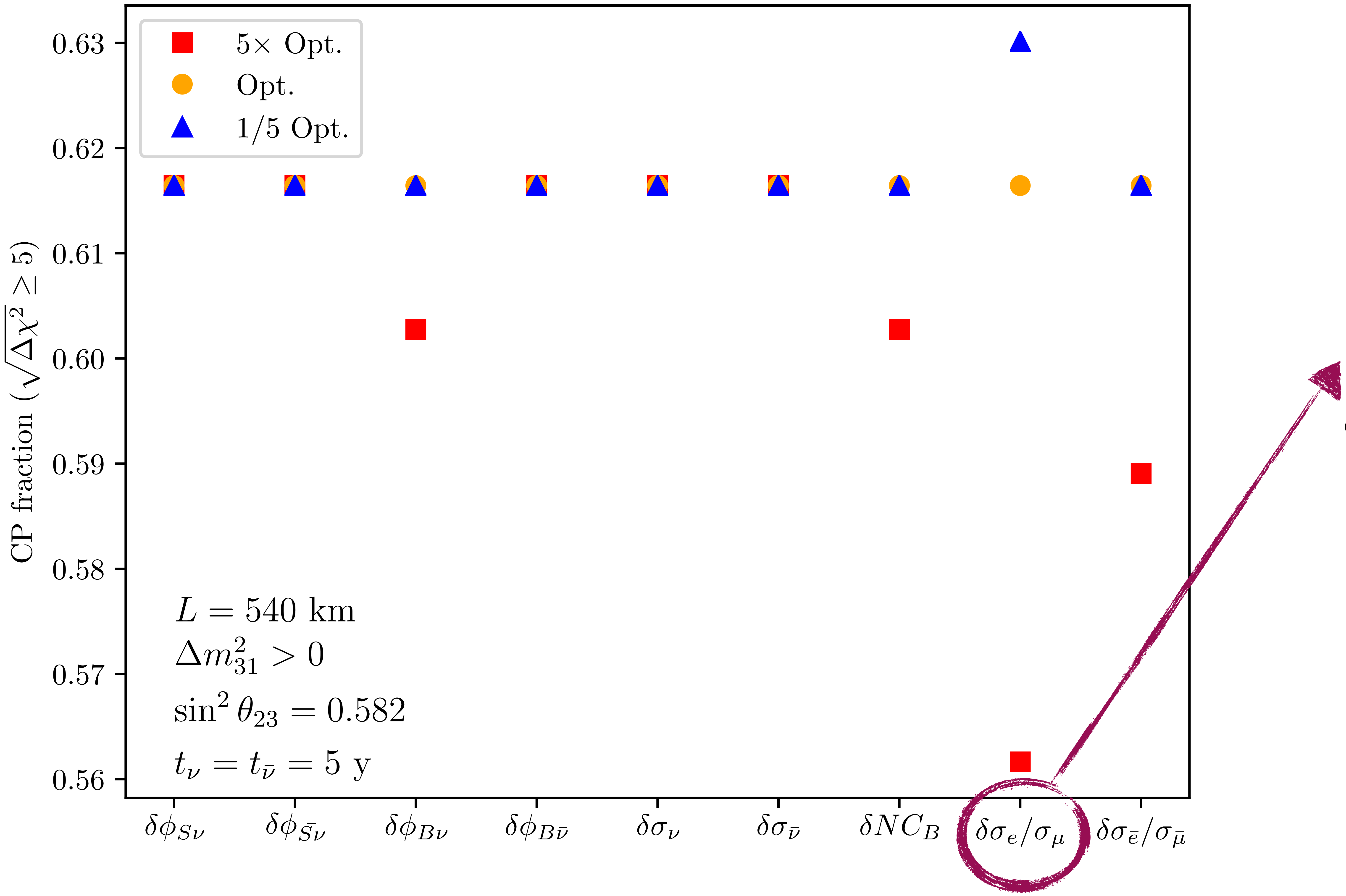
Effect of systematic uncertainties



Mostly ν_μ at the ND

and ν_e at the FD

M. Blennow *et al.* 1912.04309

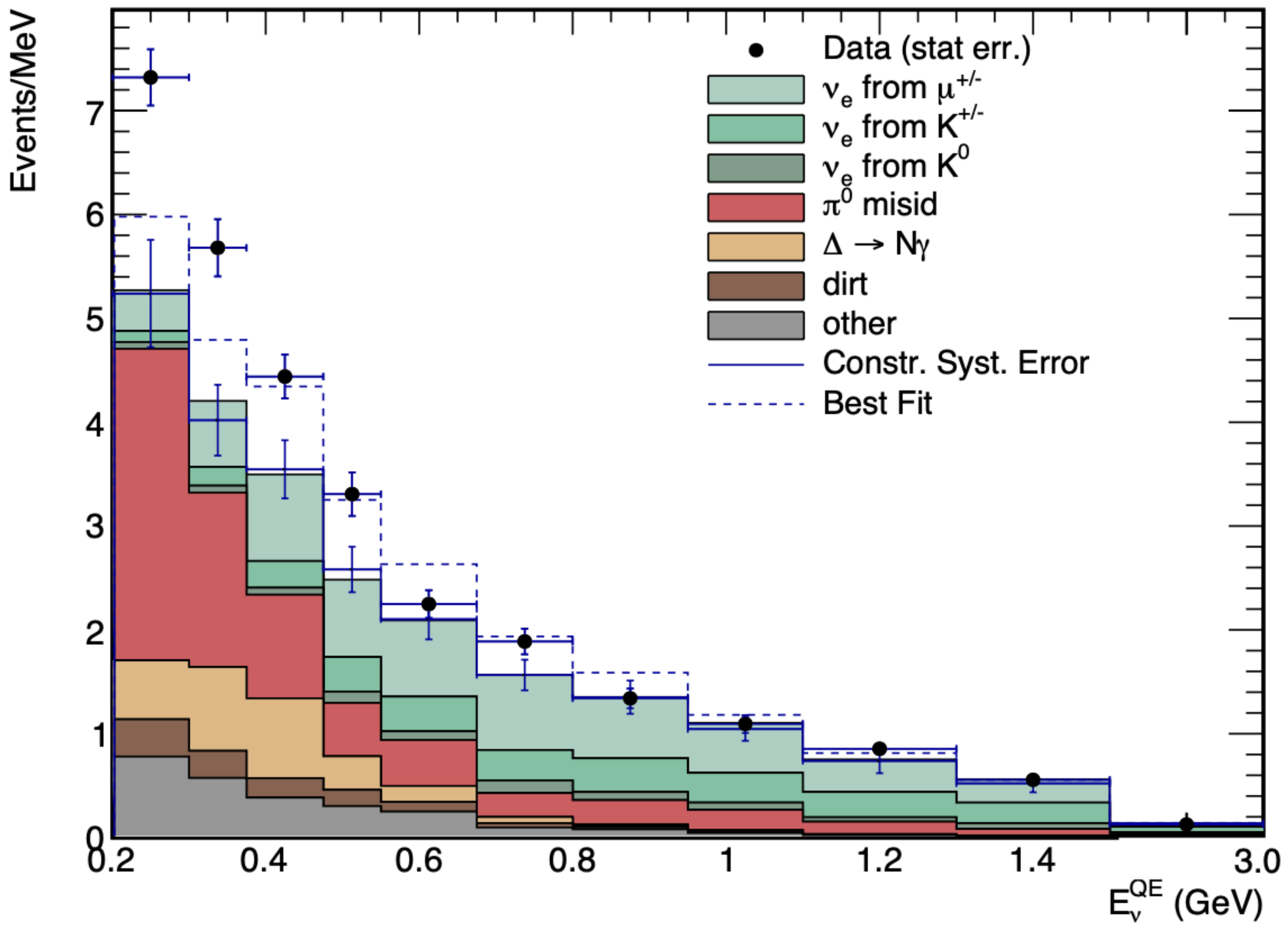
Non-standard oscillation searches

Light-sterile neutrino searches

- LSND experiment
- MiniBooNE experiment
- Gallium anomaly
- Different reactor anomalies

ν_e appearance at SBL

MiniBooNE Collaboration 2006.16883



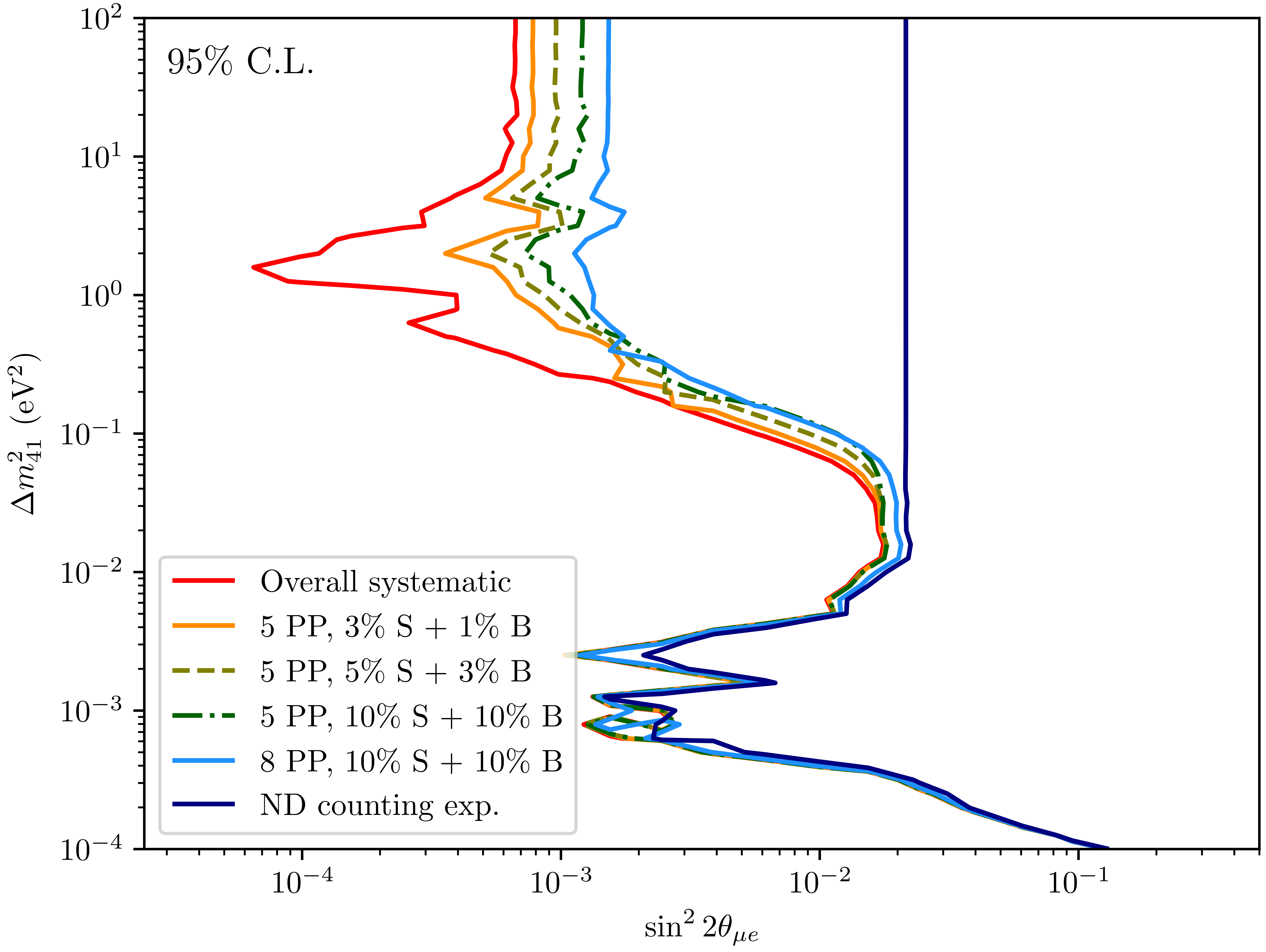
Light-sterile neutrino searches

I. Esteban *et al.* 2007.14792 www.nu-fit.org

Simulation details

- ND+FD analysis
- Conservative systematics

M. Gosh *et al.* 1912.10010



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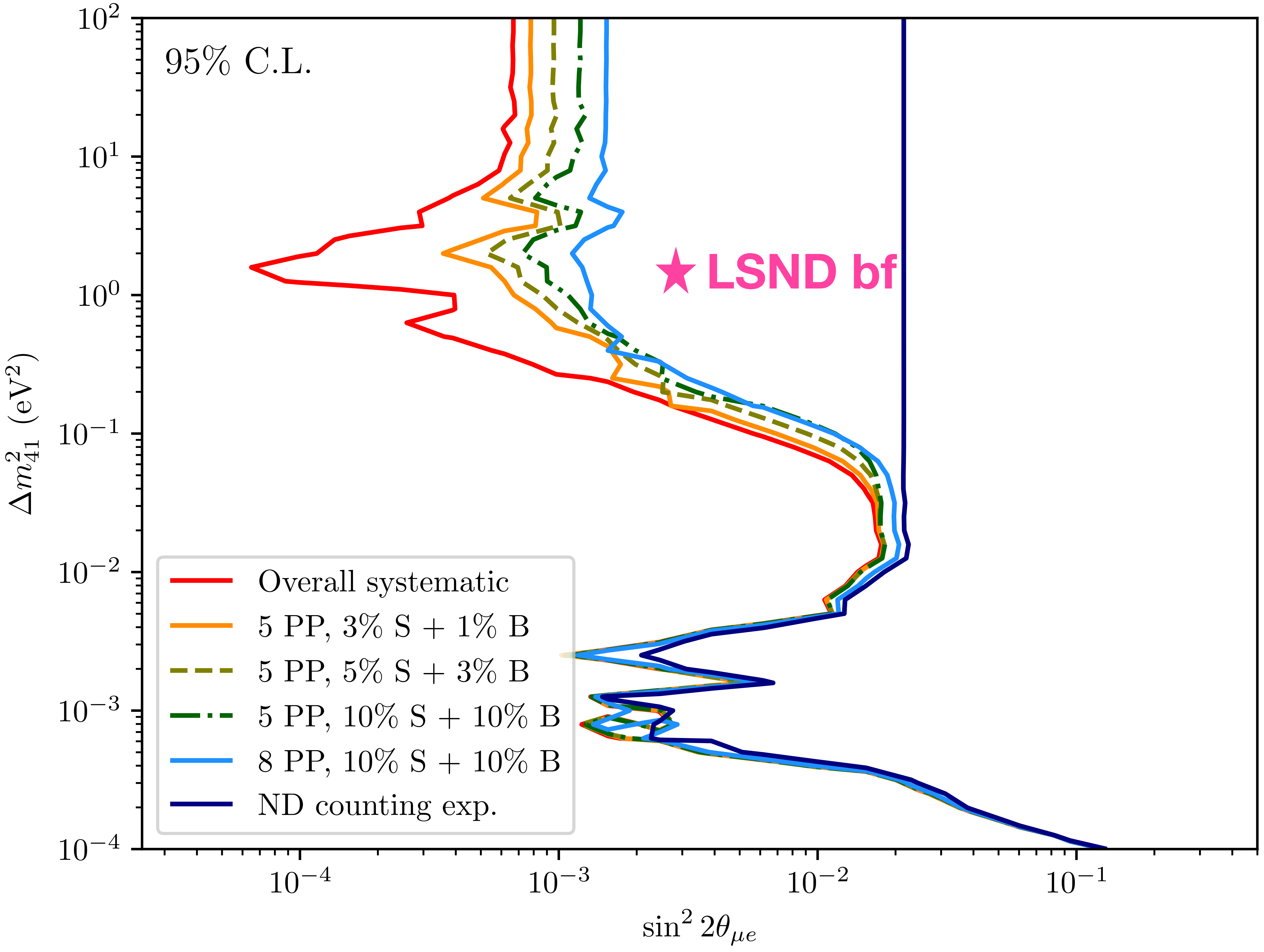

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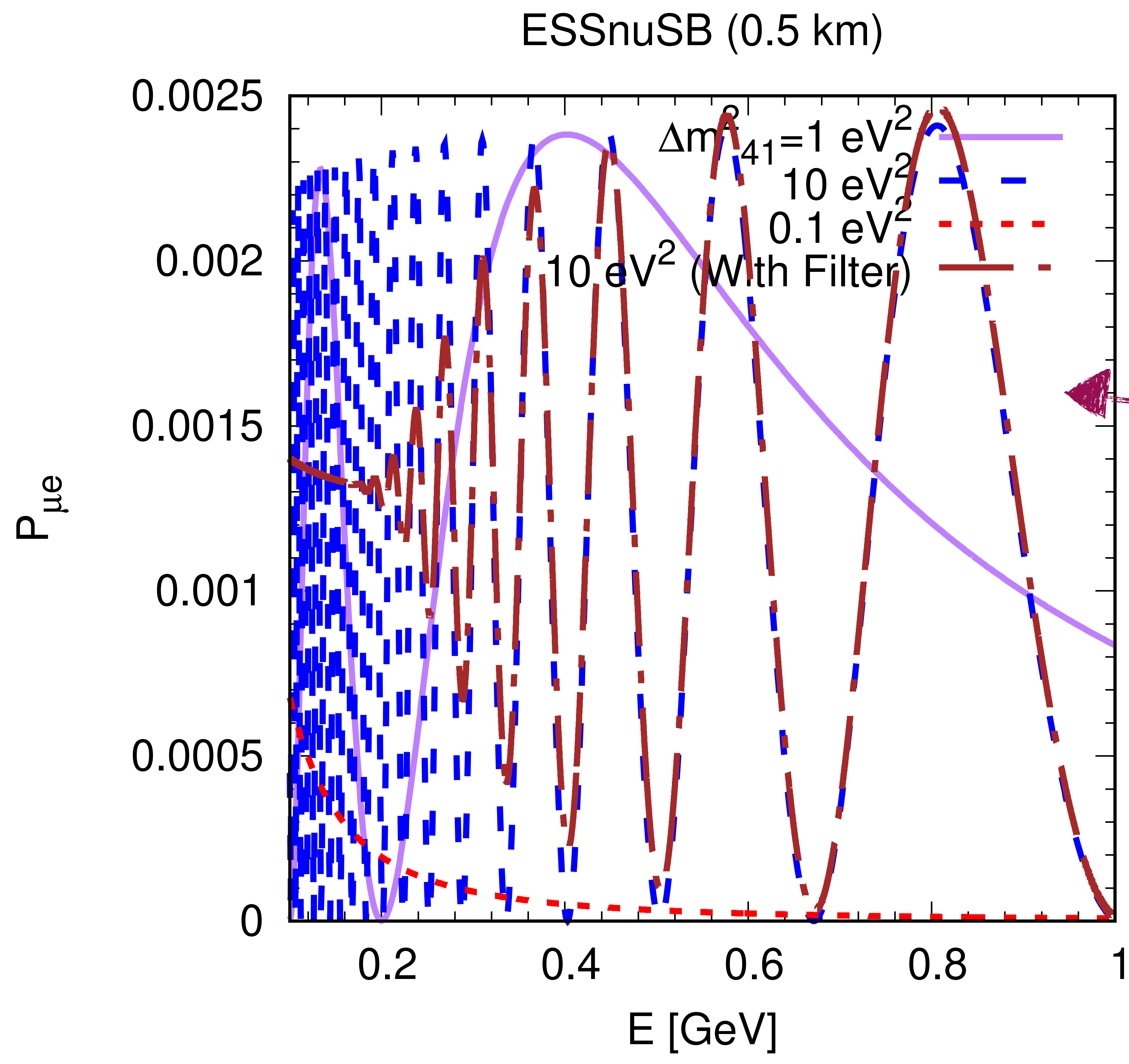
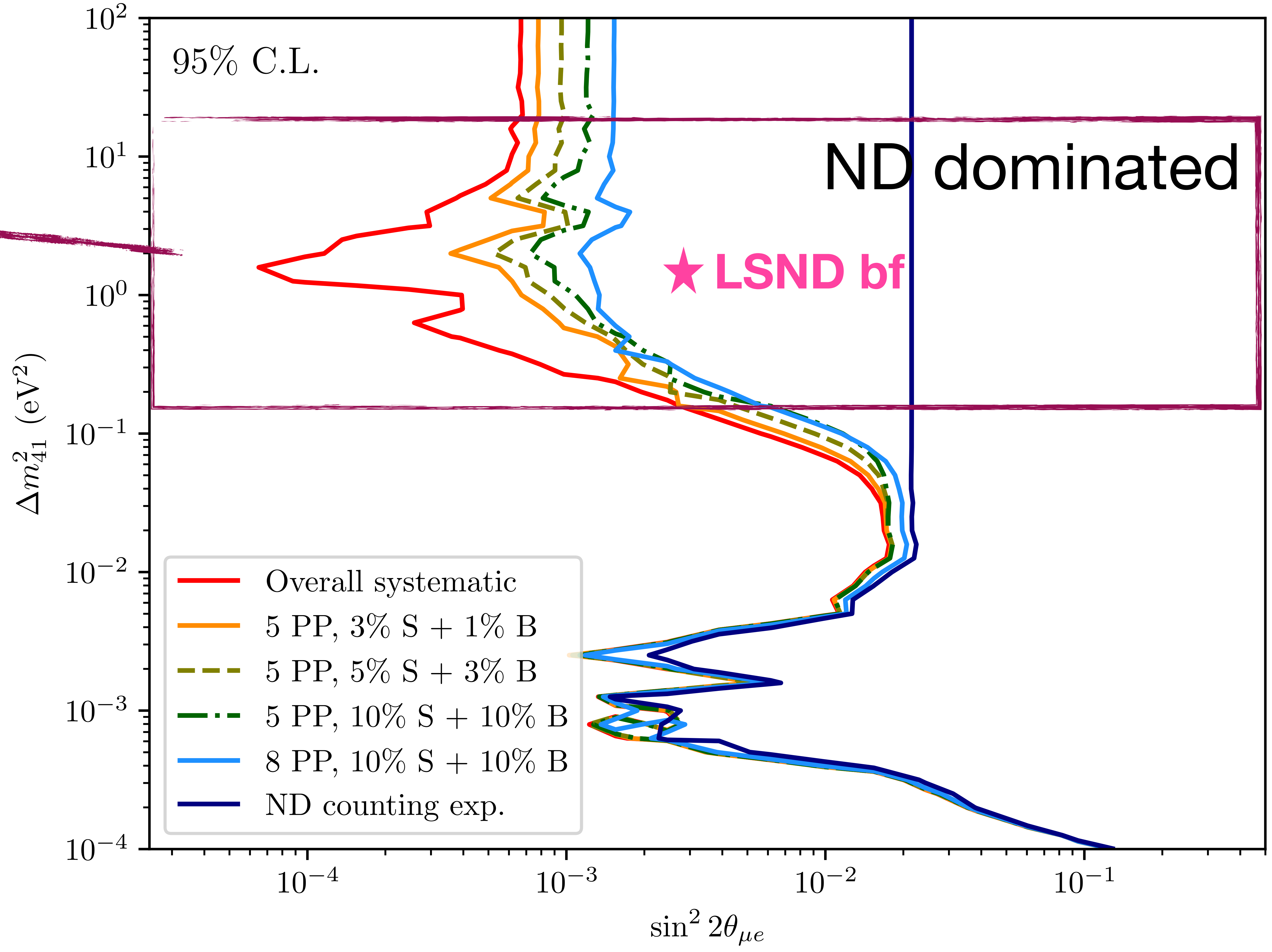


M. Gosh *et al.* 1912.10010



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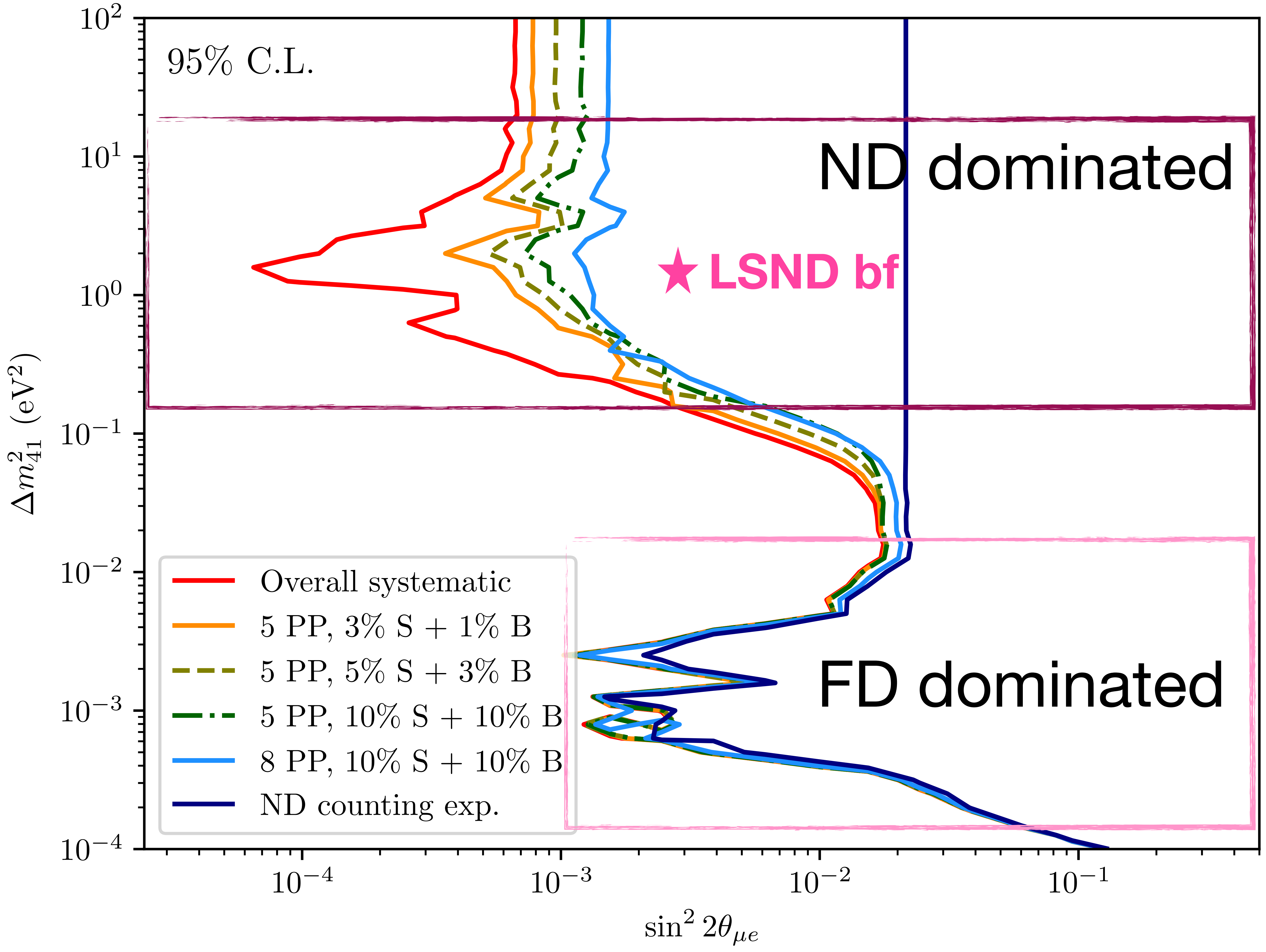
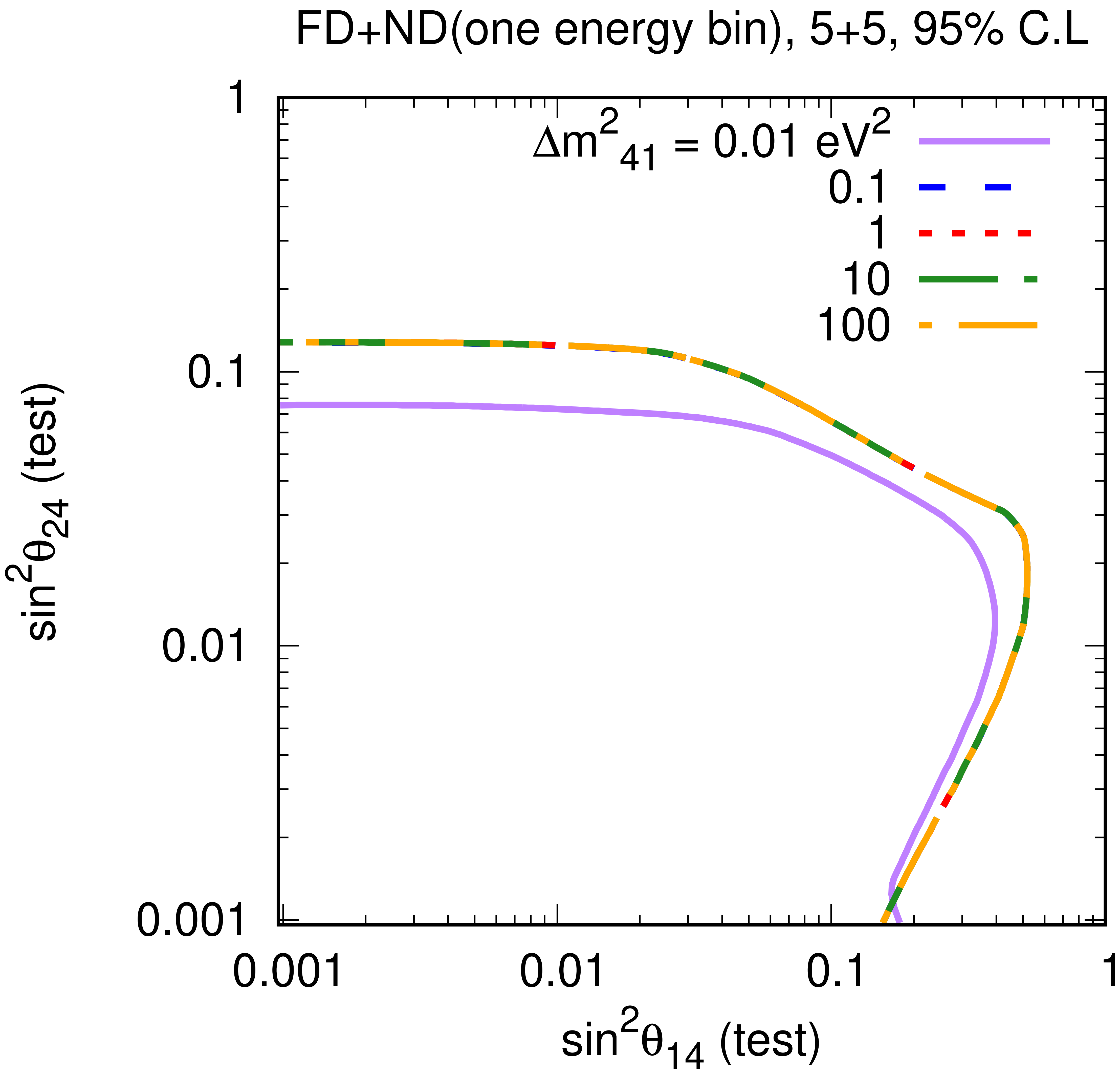
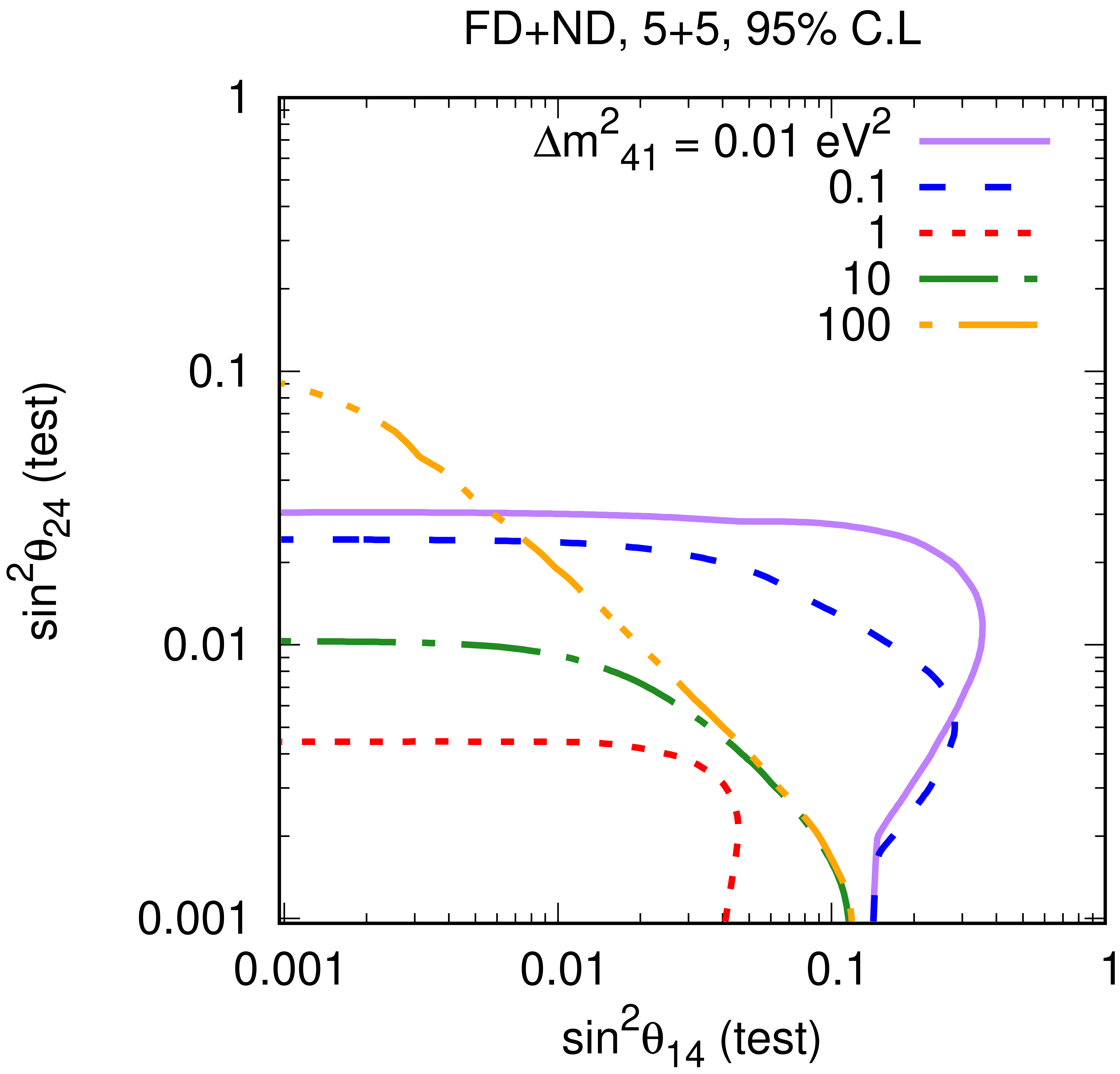


Determination of the sterile parameters



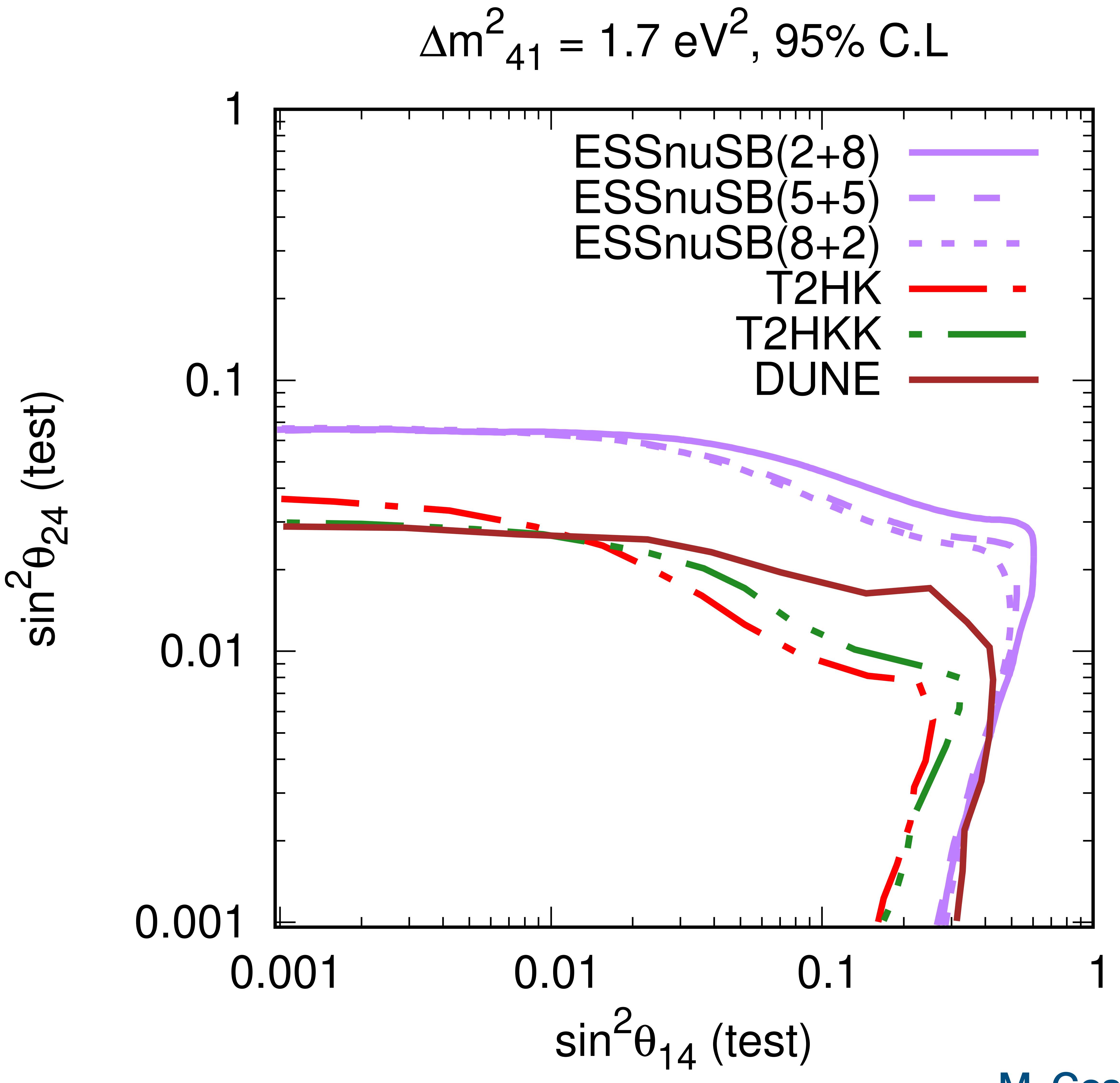


M. Gosh *et al.* 1912.10010

Determination of the sterile parameters

Systematics

- 8% signal
- 10% bkg



M. Gosh *et al.* 1912.10010

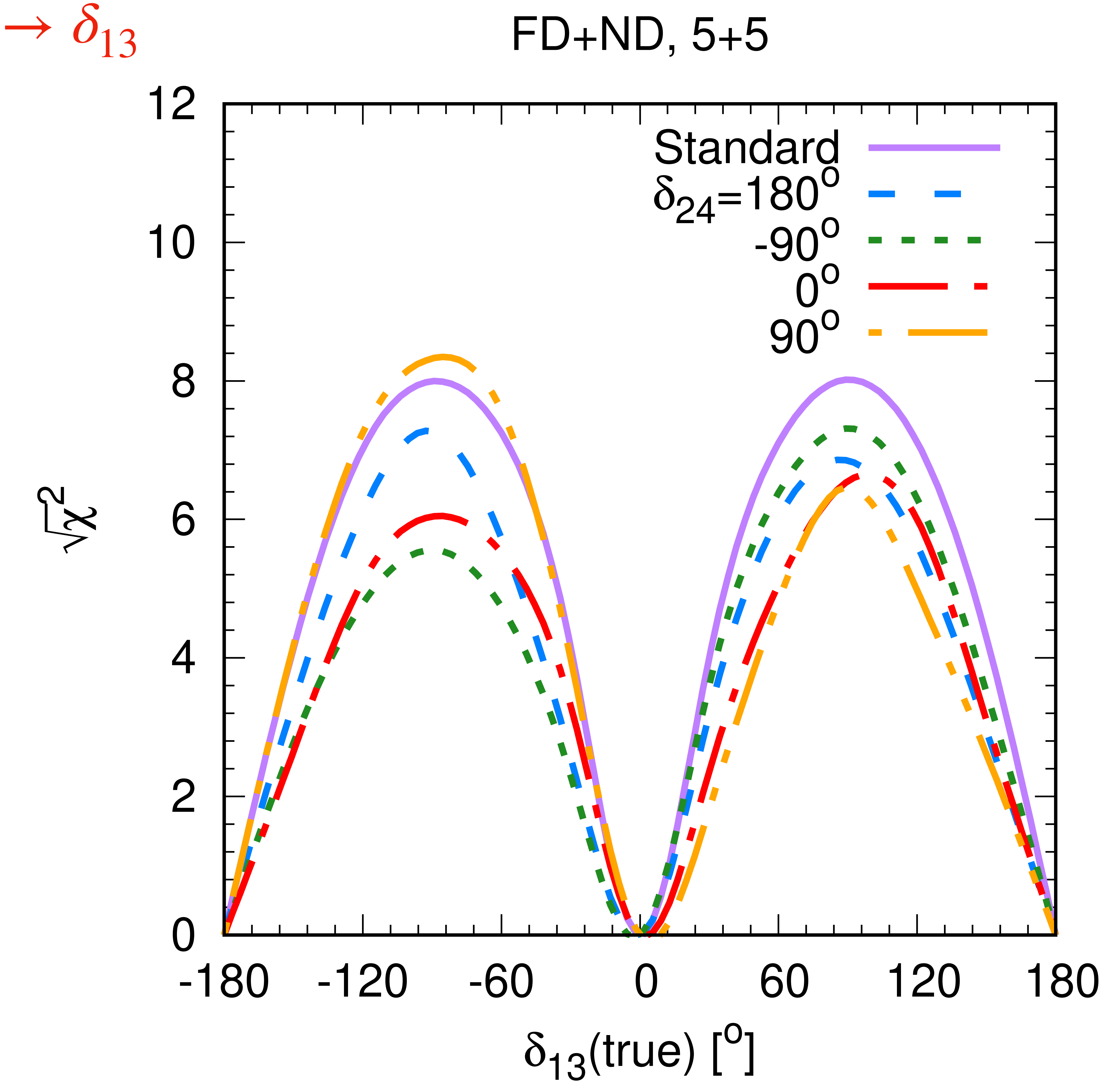
Impact of a sterile on δ

$$\sin^2\theta_{14} = \sin^2\theta_{24} = 0.025$$

$$\Delta m^2_{41} = 1eV^2$$

$$\theta_{34} = \delta_{34} = 0^\circ$$

$\delta \rightarrow \delta_{13}$



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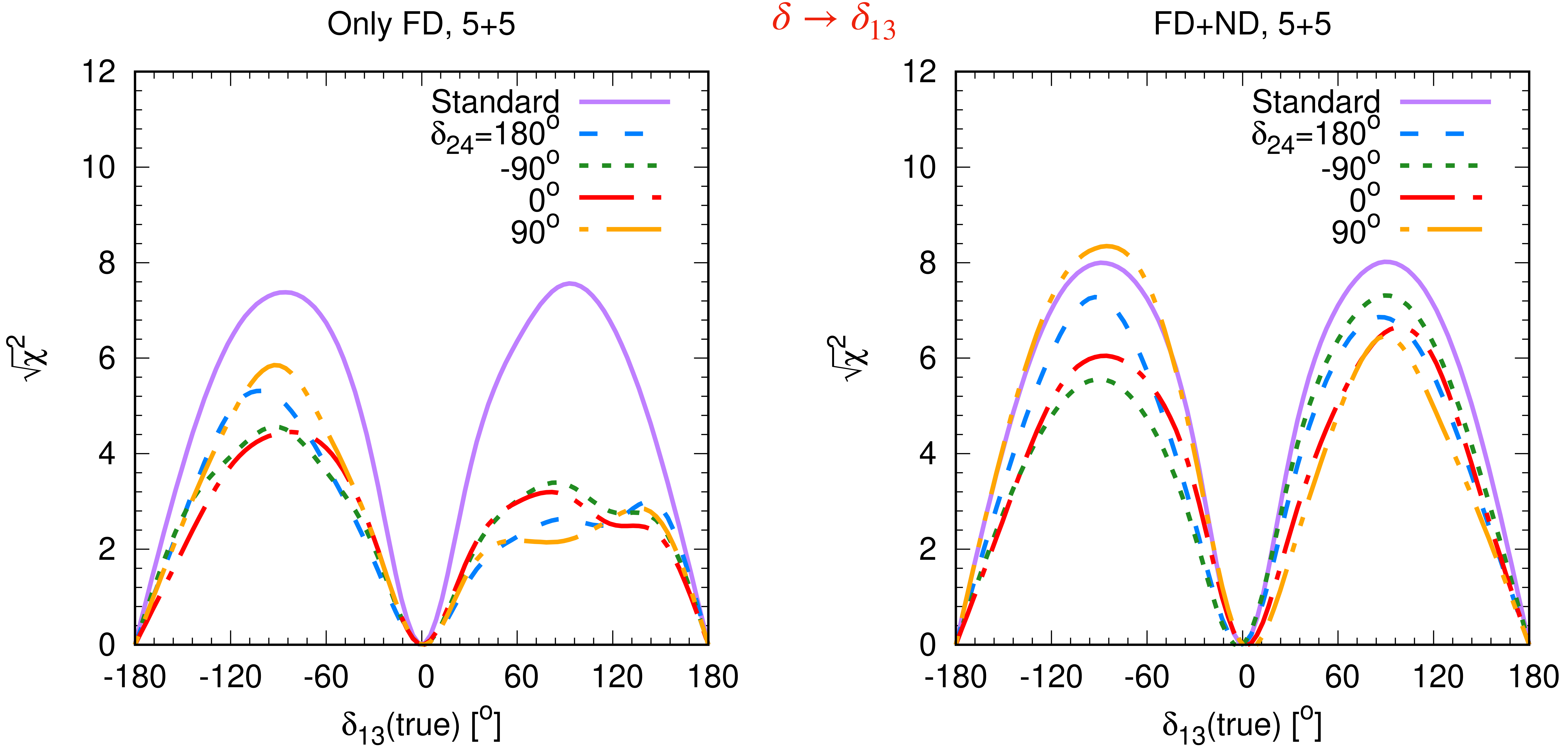
Impact of a sterile on δ

$\delta \to \delta_{13}$



M. Gosh *et al.* 1912.10010

Flavour models

PMNS mixing matrix structure → Discrete flavour symmetry

Flavour models

PMNS mixing matrix structure → Discrete flavour symmetry

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Models in agreement with oscillation data at 3σ

Flavour models

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→ One-parameter models (models 1.1–1.5)

Flavour models

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Models 1.1–1.5 → One-parameter models

Models 2.1–2.5 → Two-parameter models

Flavour models

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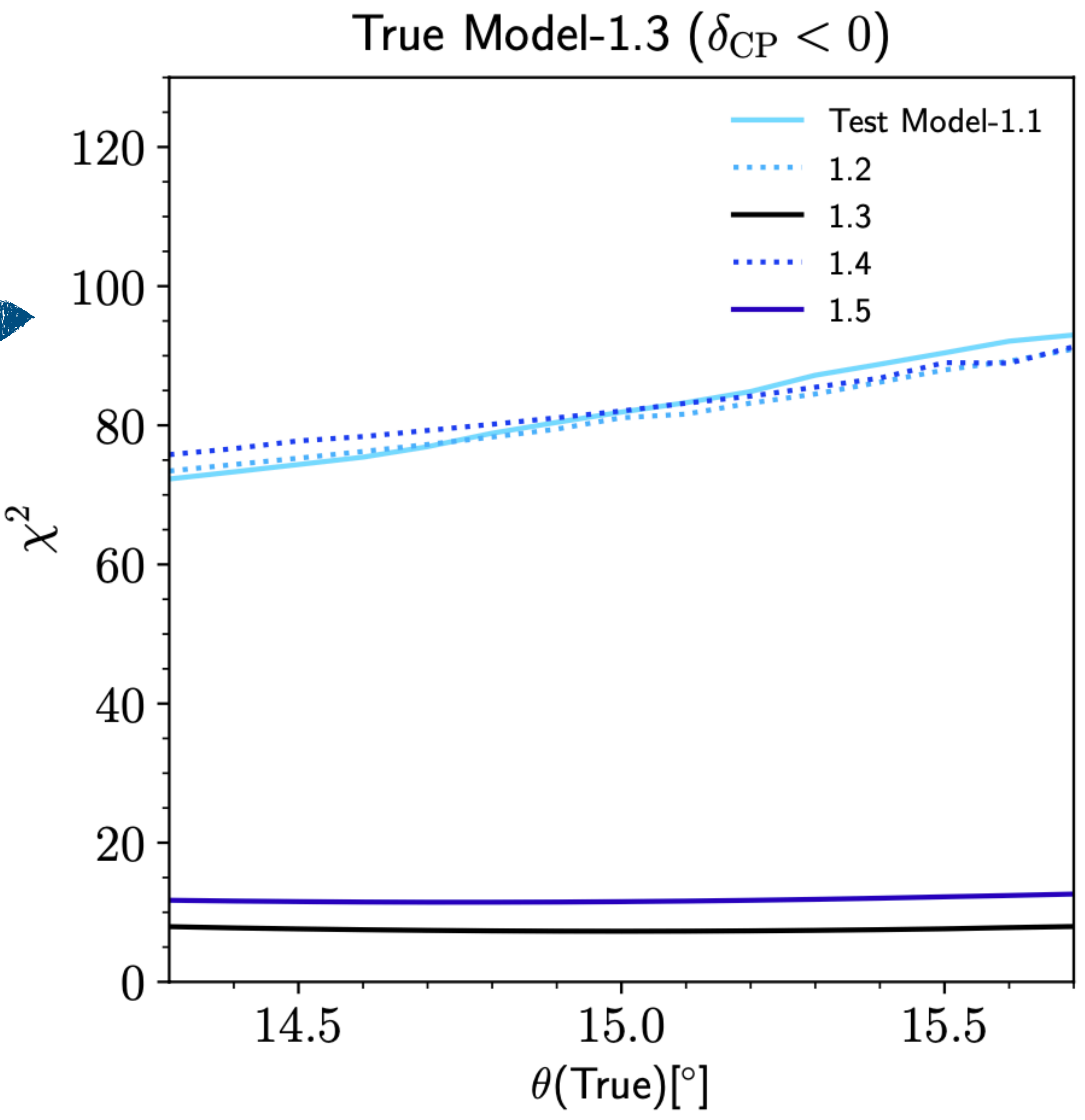

M. Blennow *et al.* 2004.00017

Flavour models

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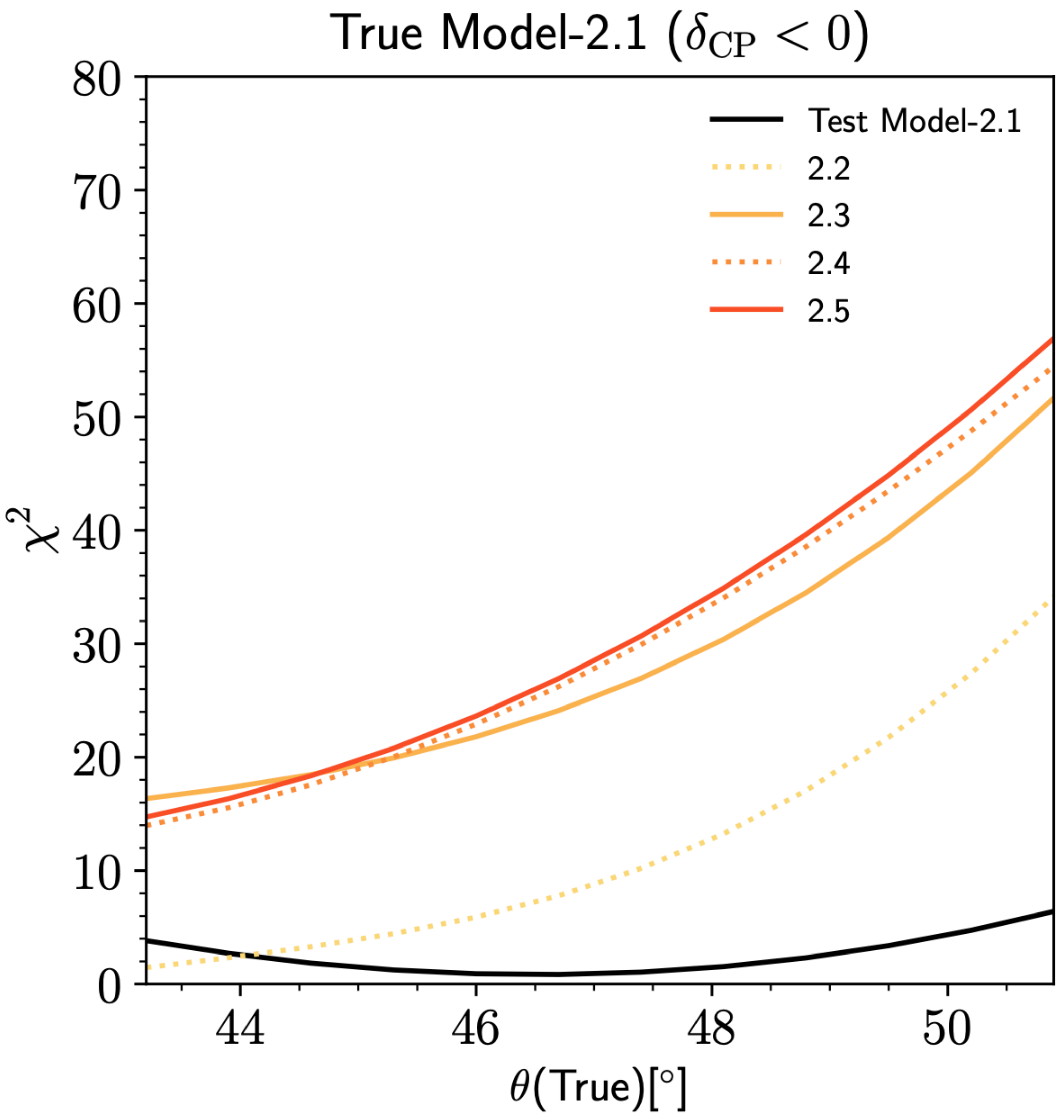

M. Blennow *et al.* 2004.00017

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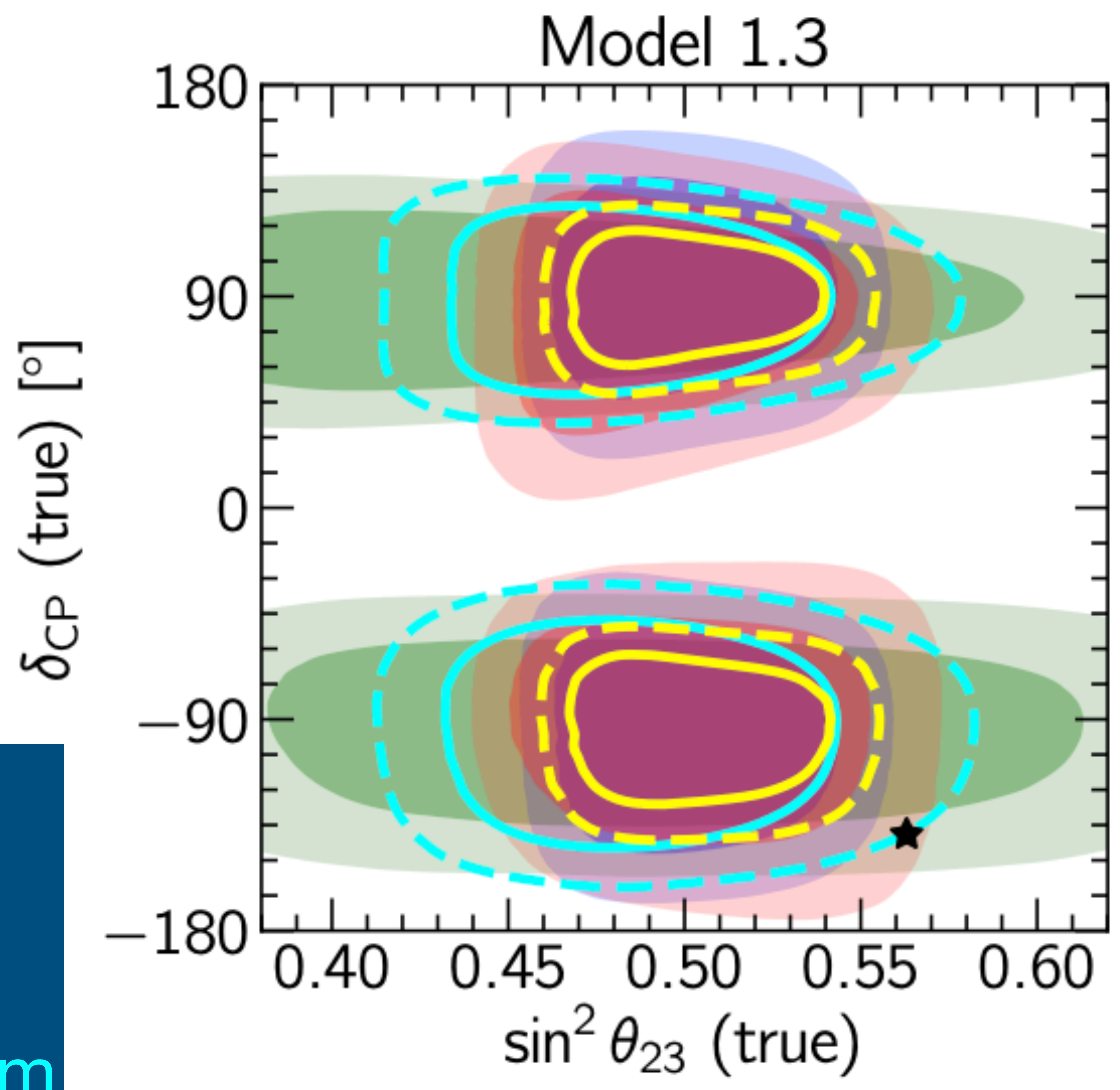
ESSnuSB
T2HK
DUNE
ESSnuSB+atm
Combination



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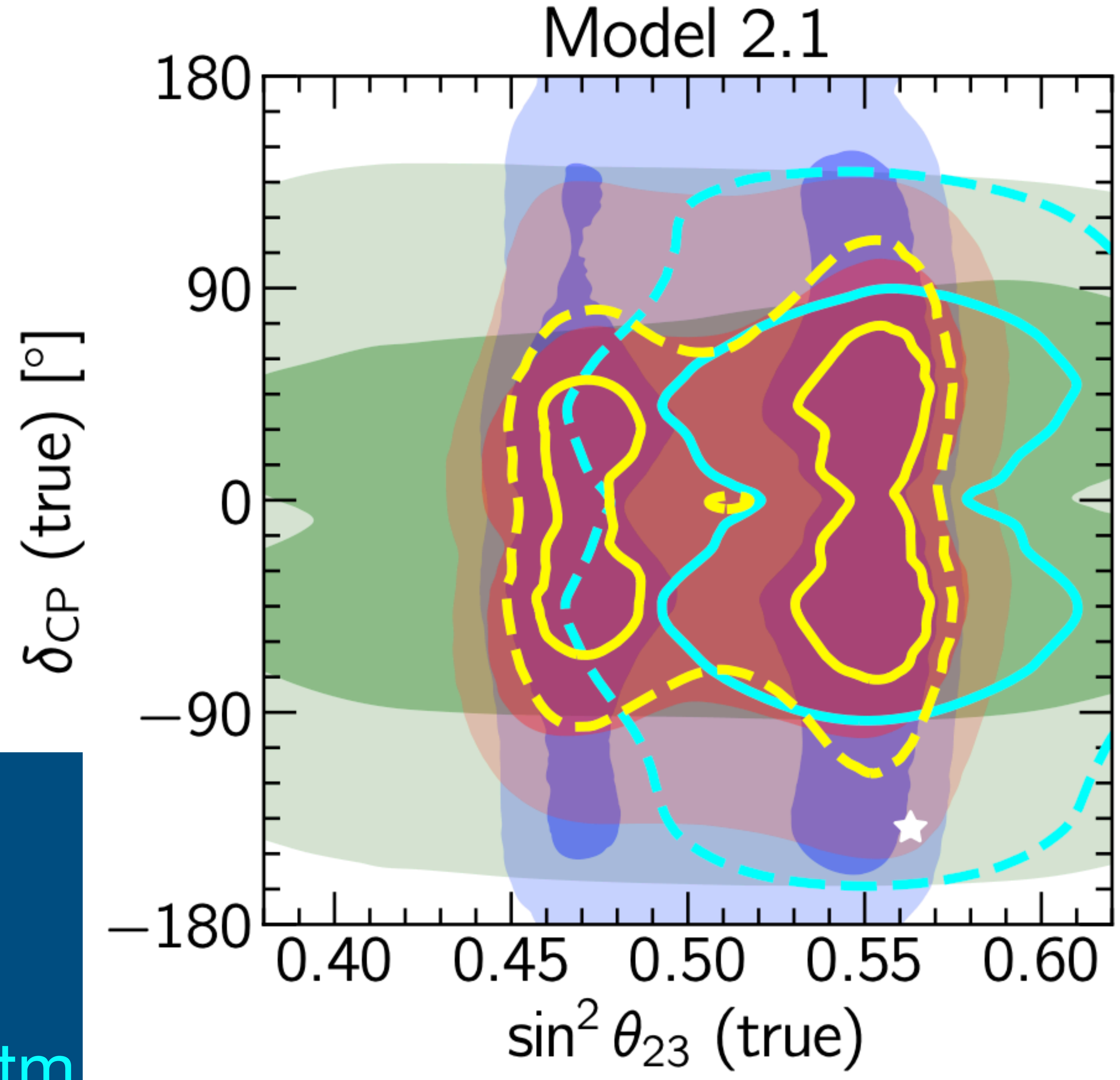

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M. Blennow *et al.* 2005.12277

Conclusions

3ν oscillation searches:

- Combining **beam** and **atm** data **enhance** the **physics reach of ESSnuSB**
- After **10 years**, the CP fraction for a 5σ discovery is **62** (56)% at **540** (360)km
- Optimise RT to maximise the precision on δ which

can range from $\Delta\delta$~6º for CP conservation to $\Delta\delta$<18º for maximal CP violation

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Beyond 3ν oscillation searches:

- **ESSnuSB** could **constrain light-steriles** and still **discover CP violation**
- **Discrete flavour models** can be tested and **constrained/ruled out**

Thank you!

Back up slides

Precision on δ

$$P^{\pm}_{\mu\to e} = s^2_{23}\sin^2 2\theta_{13}\left(\frac{\Delta_{31}}{\tilde{B}_{\mp}}\right)^2 \sin^2\frac{\tilde{B}_{\mp}L}{2}$$

$$+c^2_{23}\sin^2 2\theta_{12}\left(\frac{\Delta_{21}}{A}\right)^2 \sin^2\frac{AL}{2}$$

$$+\tilde{J}\frac{\Delta_{21}}{A}\frac{\Delta_{31}}{\tilde{B}_{\mp}}\sin\left(\frac{AL}{2}\right)\sin\left(\frac{\tilde{B}_{\mp}L}{2}\right)\left(\cos\delta\cos\frac{\Delta_{31}L}{2}\pm\sin\delta\sin\frac{\Delta_{31}L}{2}\right)$$

Precision on δ

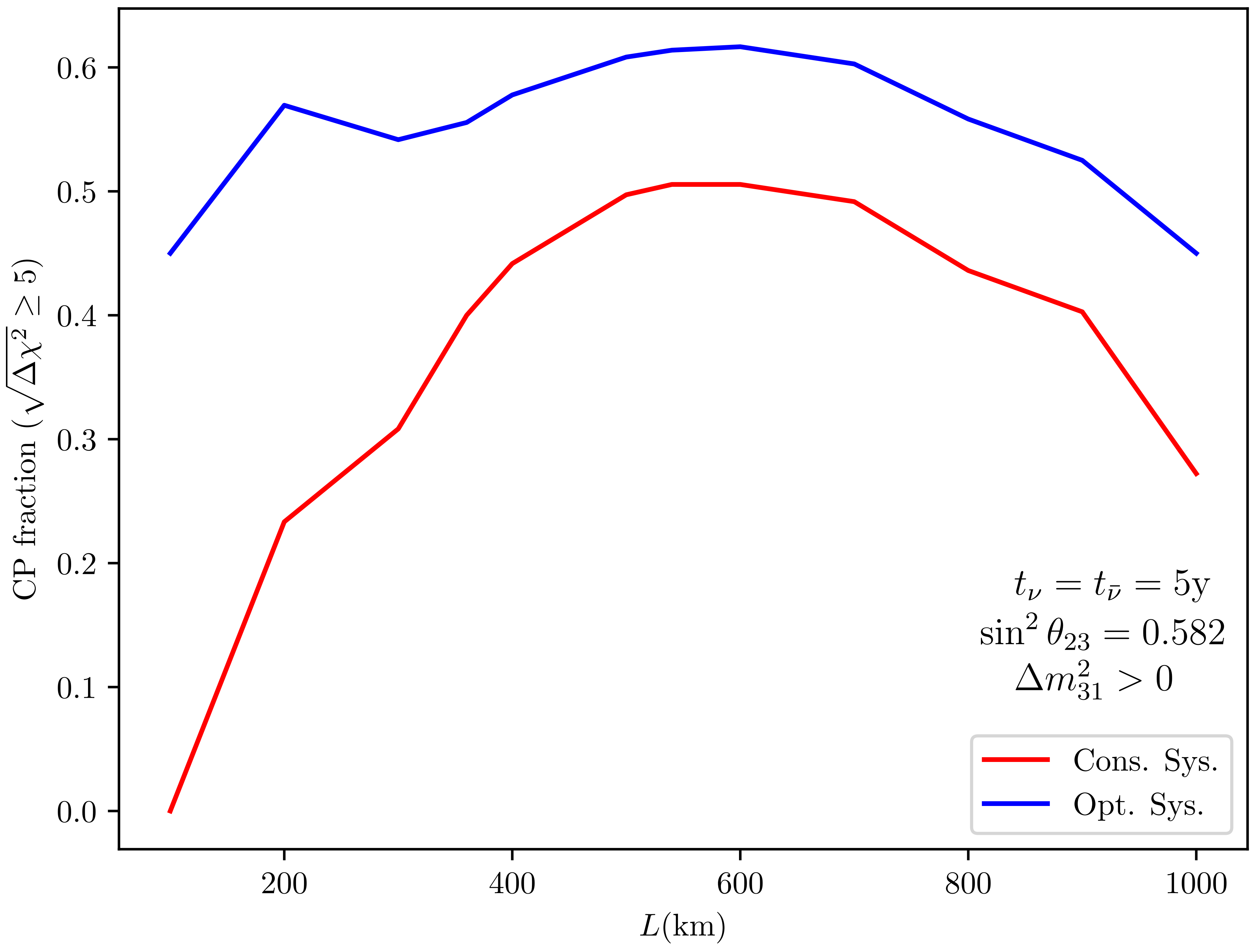
$$\frac{\partial \Delta P_{\mu\to e}}{\partial \delta} \propto -\sin\delta\cos\frac{\Delta_{31}L}{2} \pm \cos\delta\sin\frac{\Delta_{31}L}{2}$$

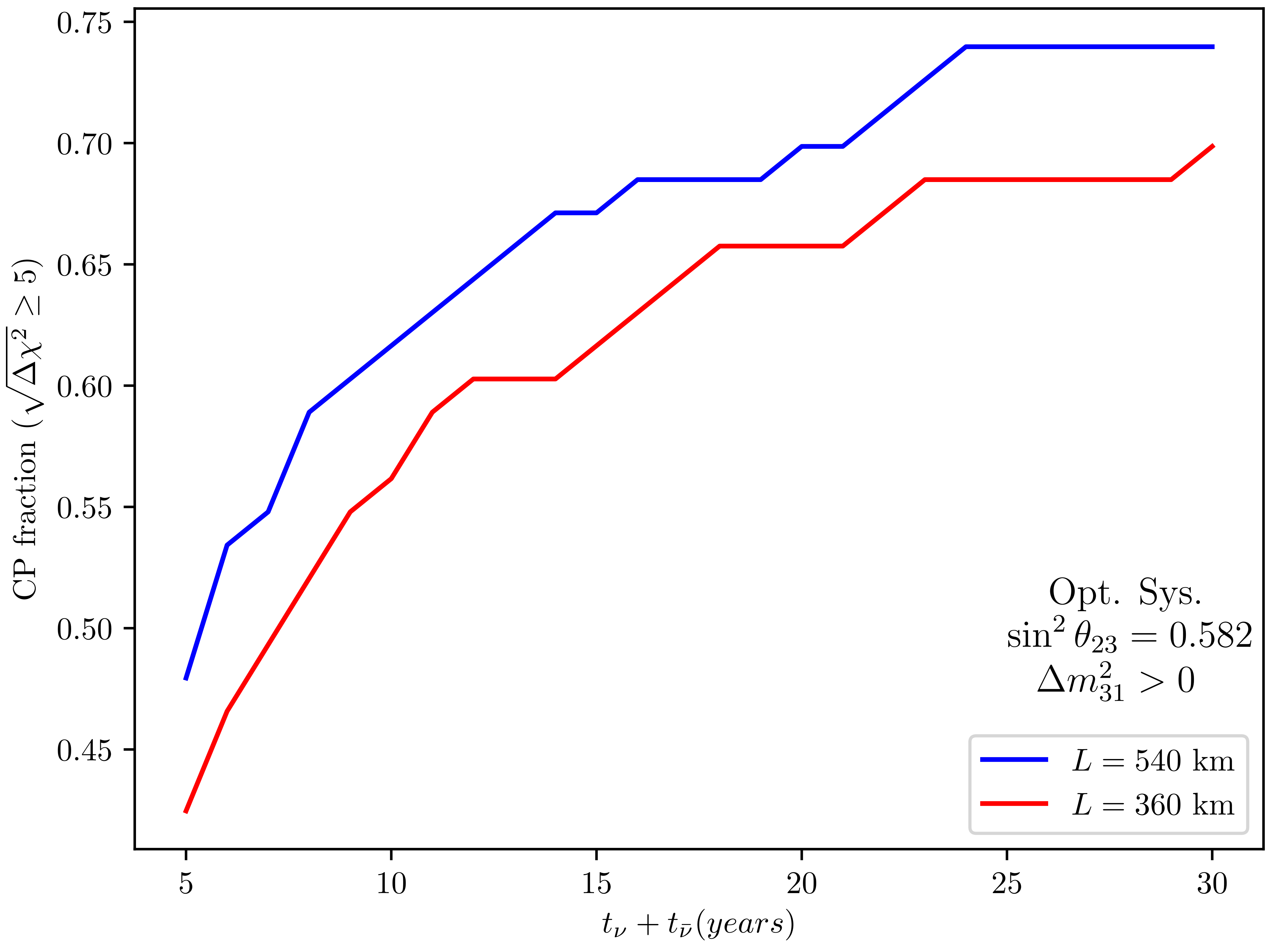
At an oscillation maximum $\rightarrow \Delta_{31}L/2 = (2n-1)\pi/2$

$$\frac{\partial \Delta P_{\mu\to e}}{\partial \delta} \propto \pm\cos\delta\sin\frac{\Delta_{31}L}{2}$$

Maximum CP violation $\rightarrow \cos\delta = 0$

Effect of systematic uncertainties





M. Blennow *et al.* 1912.04309

Sensitivity to CP violation

CP violation discovery
still possible for any δ_{24}