Funded by the Horizon 2020 Framework Programme of the European Union

HIDDeν
Hunting Invisibles: Dark sectors, Dark matter and Neutrinos

Instituto de Física Teórica UAM-CSIC

Physics Potential of the ESSnuSB

NuFact 2021

Cagliari, Italy 09/09/2021

Salvador Rosauro-Alcaraz

ESS NEUTRINO SUPER BEAM

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

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

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

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

What we do not know (yet)

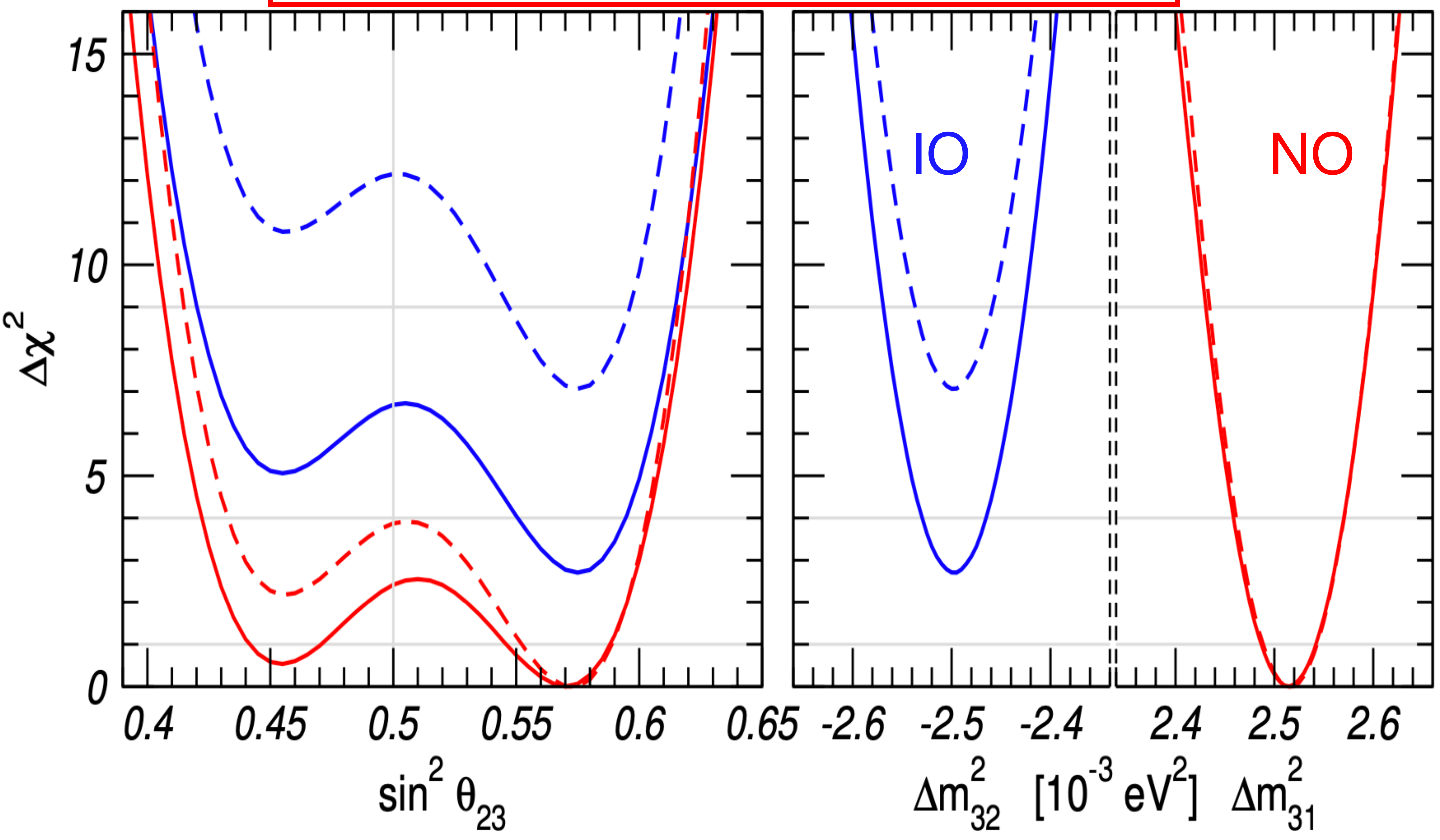
Is there leptonic CP violation, i.e., $\delta \neq 0, \pi$?

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

Octant of θ_{23}

Status of ν oscillations

NO is only preferred at 1.6σ (2.7σ)



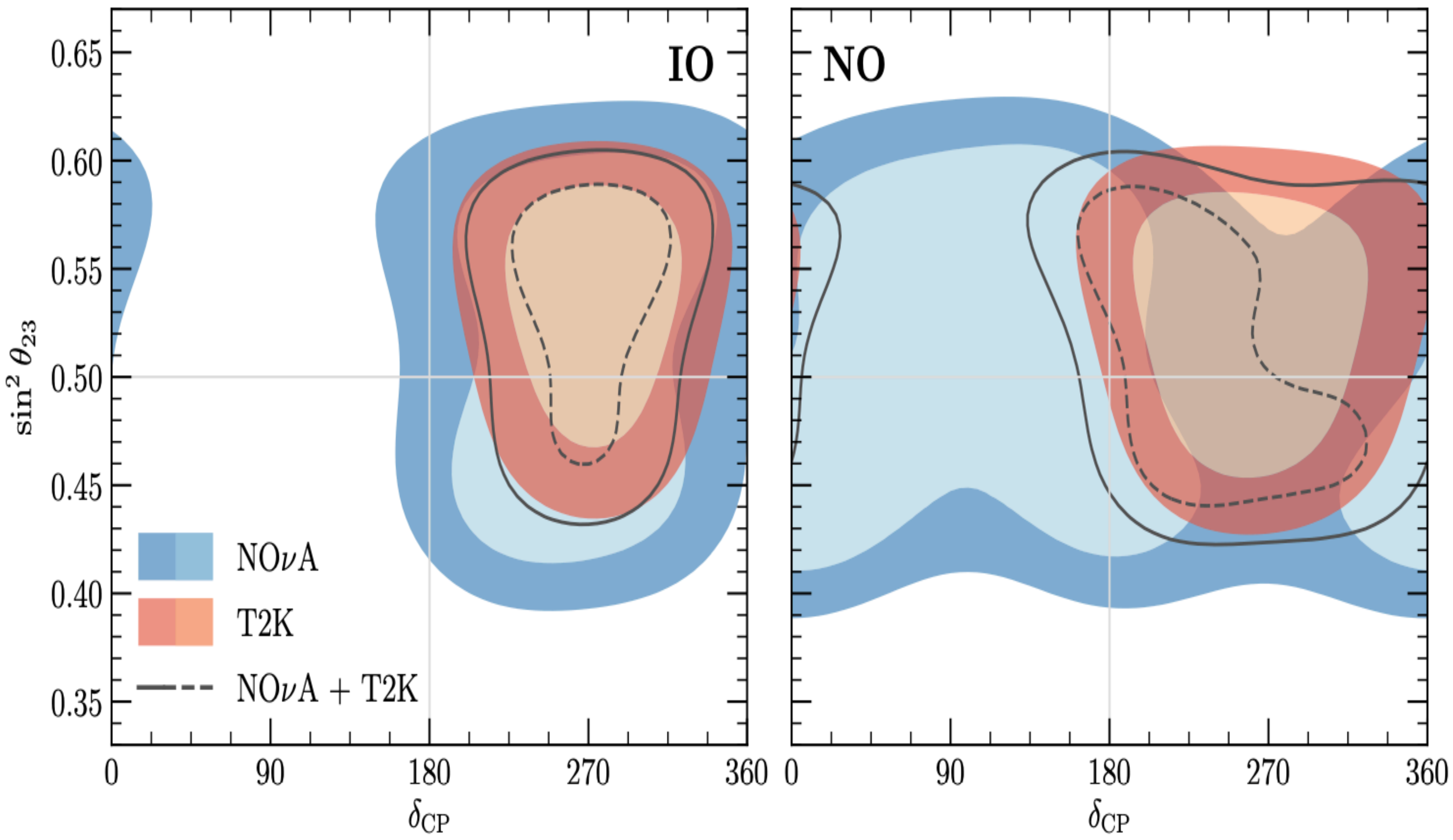
What we do not know (yet)

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

Octant of θ_{23}

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

Status of ν oscillations

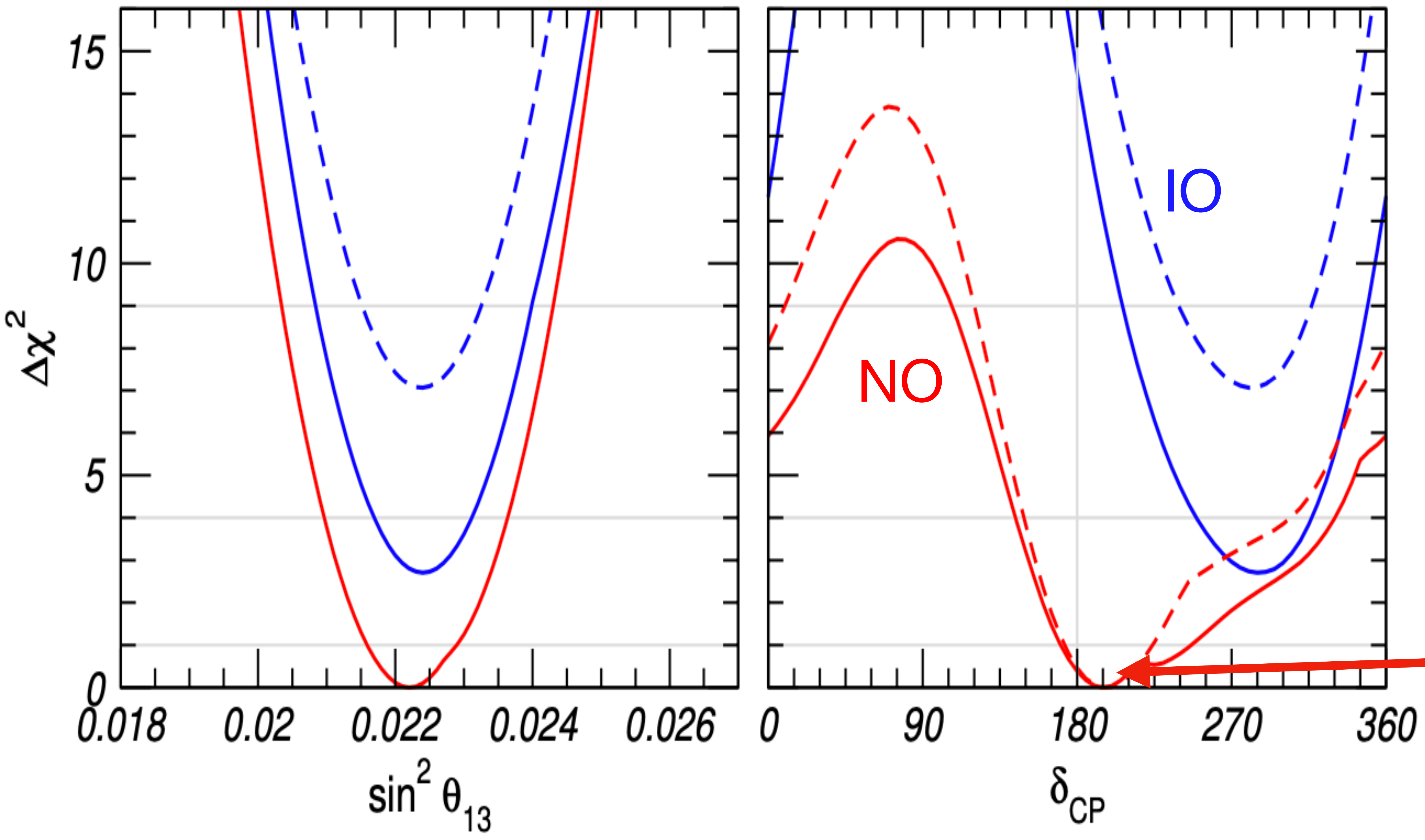


What we do not know (yet)

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

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

Status of ν oscillations



What we do not know (yet)

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

CP conservation still possible for NO

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

CP violation in ν oscillations

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

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

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

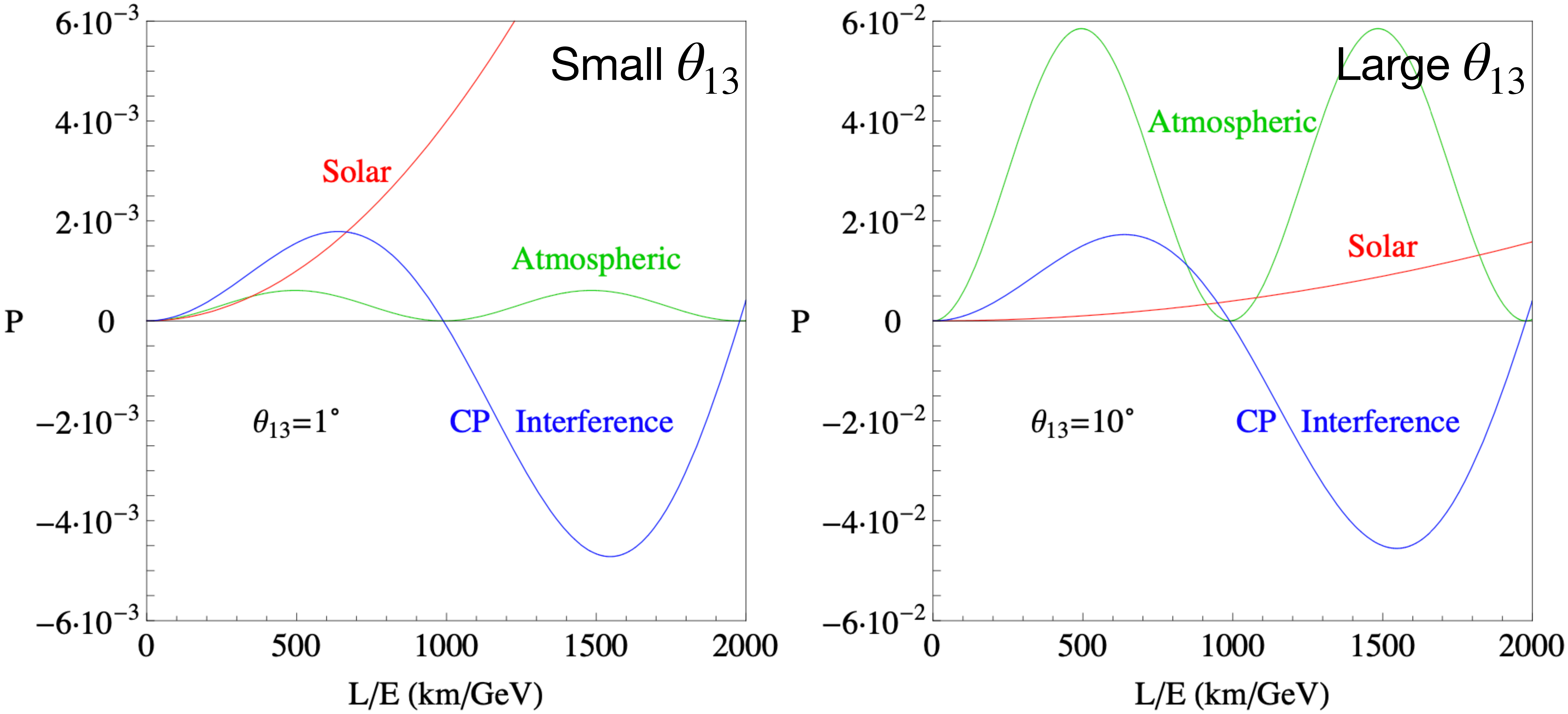
Interference

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

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

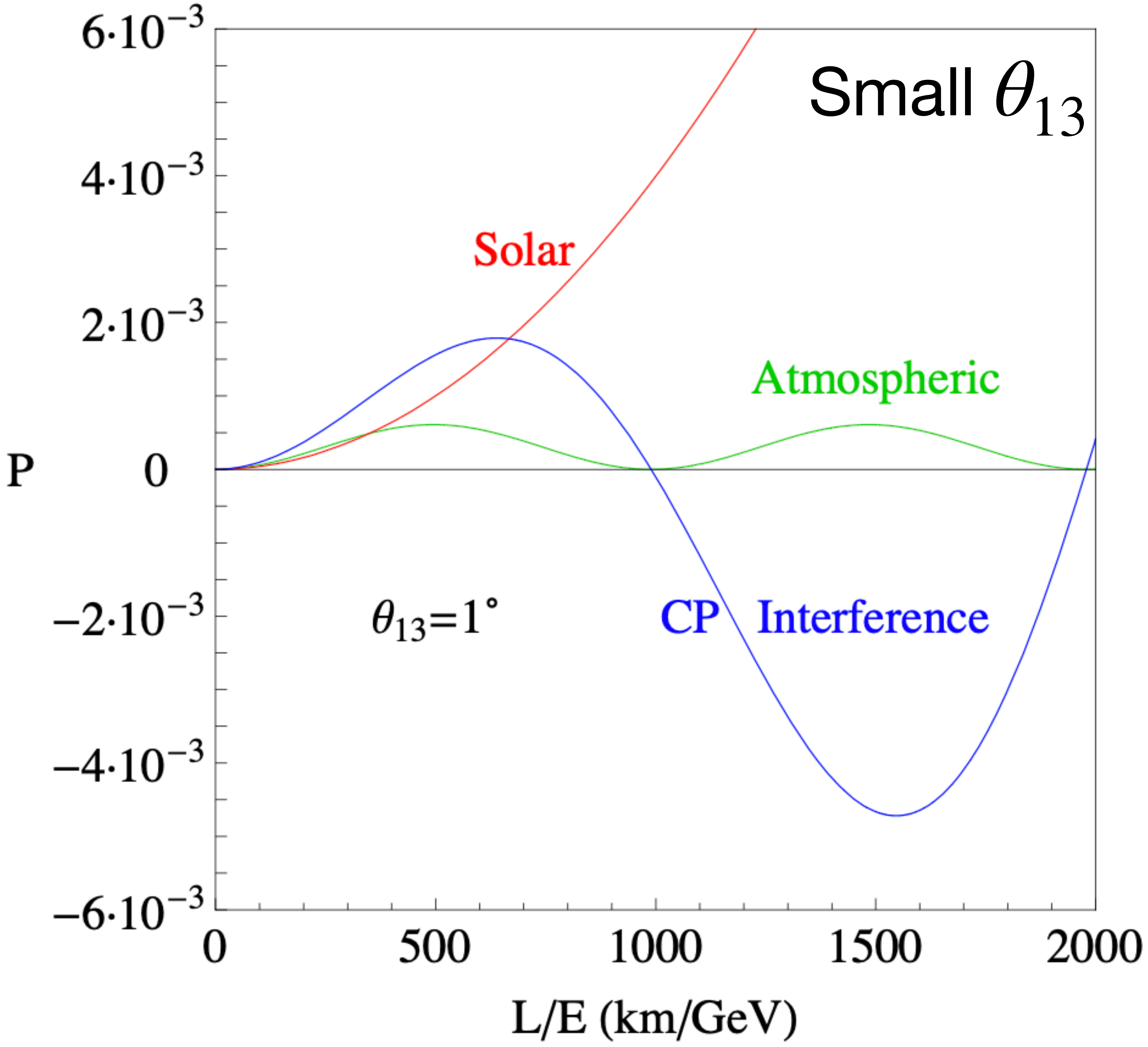
Impact of θ_{13}

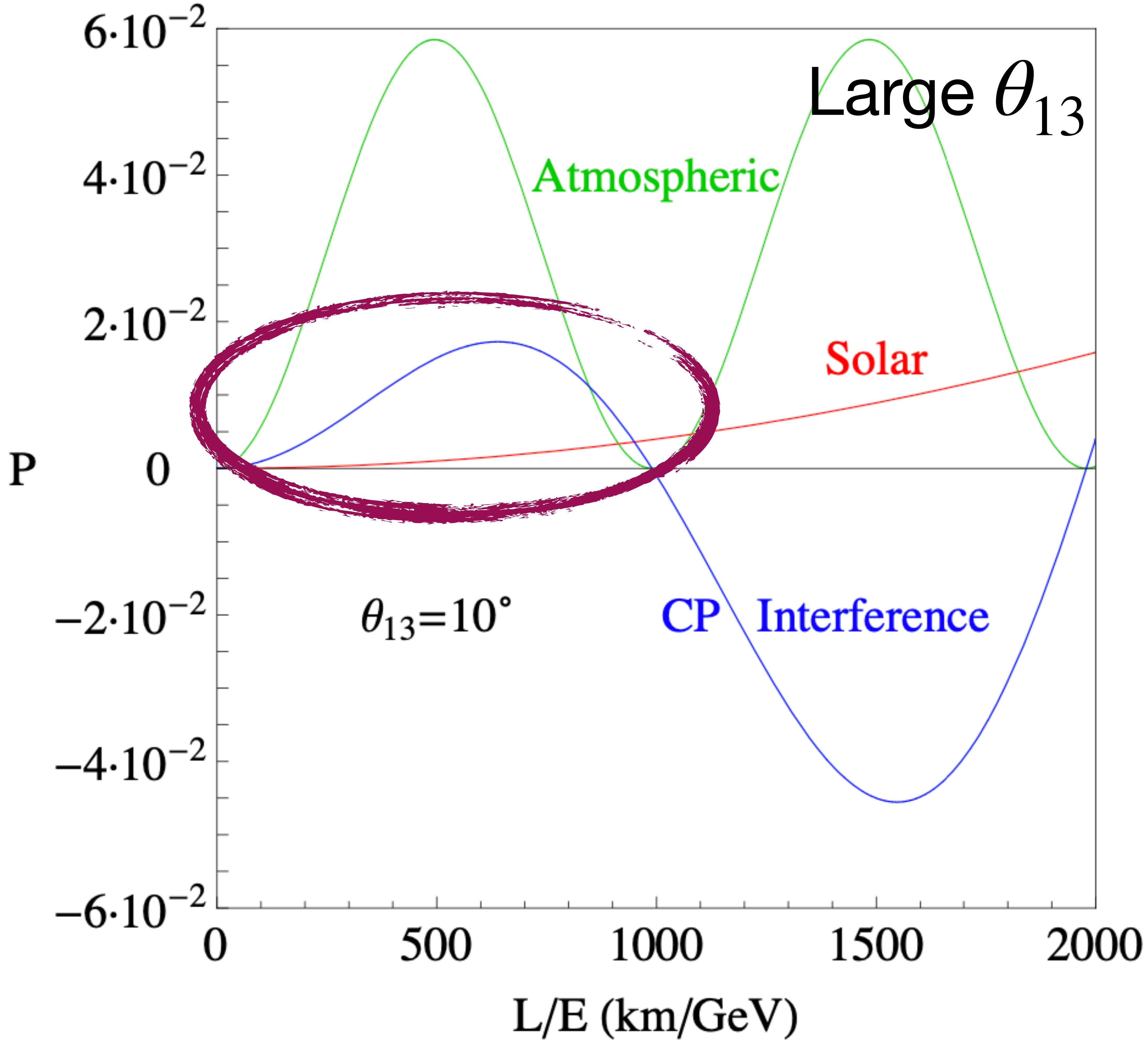
P. Coloma & E. Fernandez-Martinez, 1110.4583



Impact of θ_{13}

P. Coloma & E. Fernandez-Martinez, 1110.4583

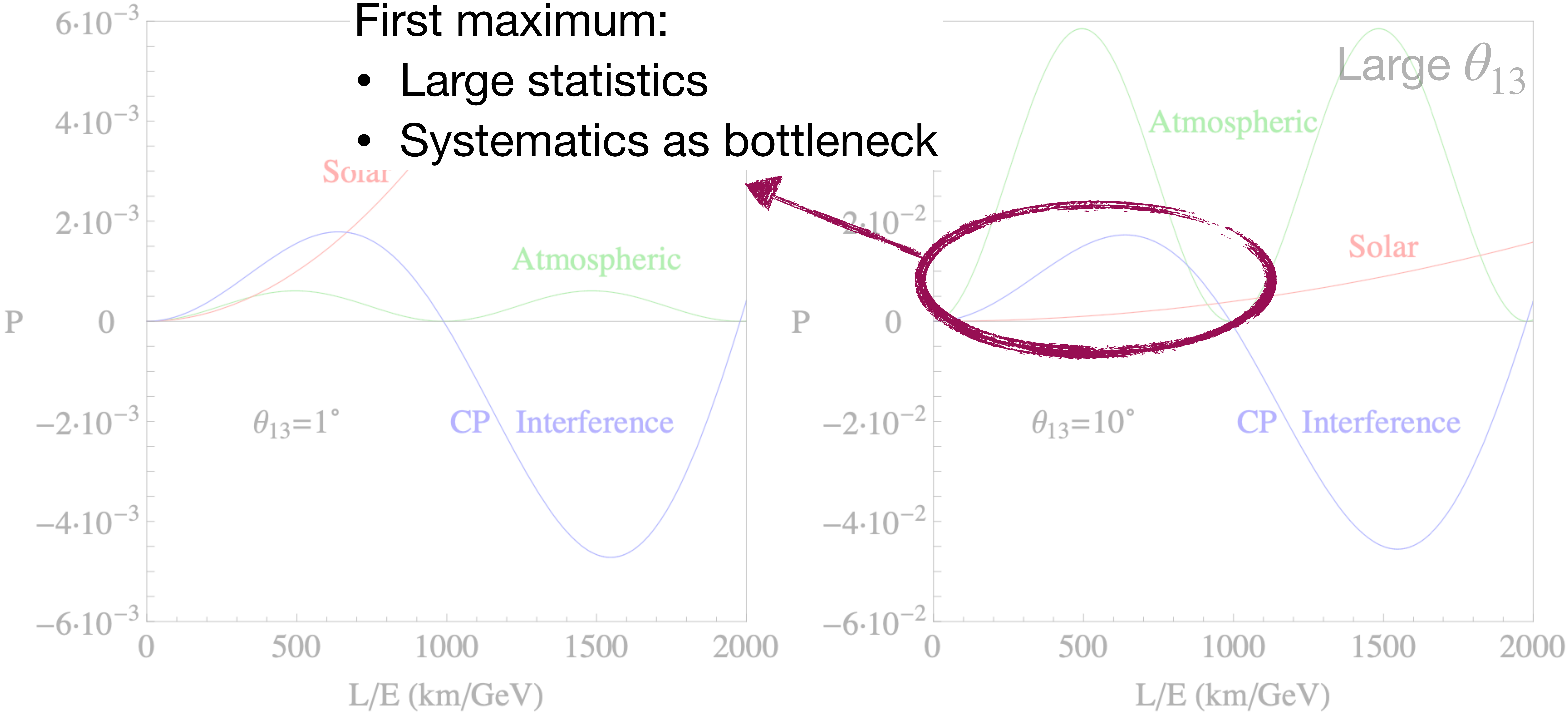




Impact of θ_{13}

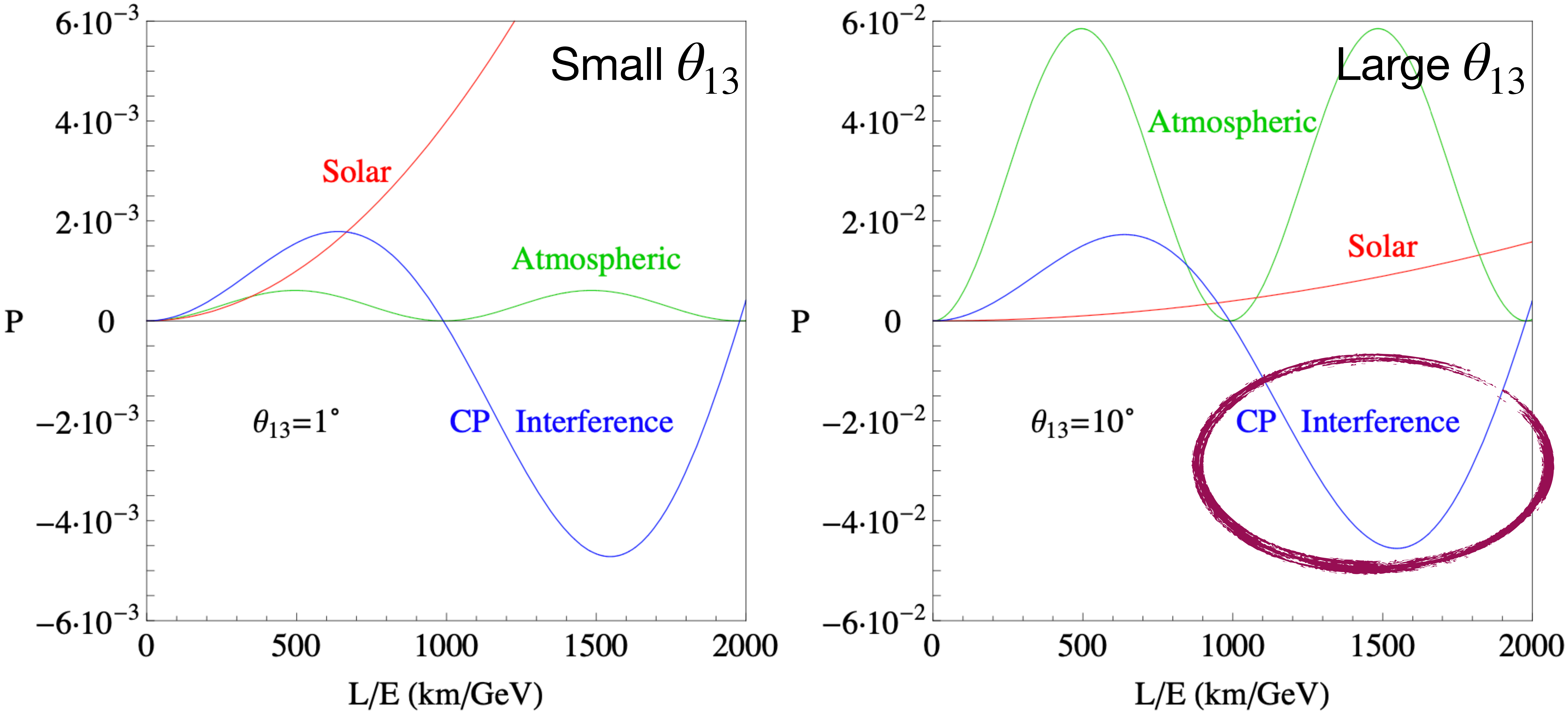
P. Coloma & E. Fernandez-Martinez, 1110.4583

First maximum:
- Large statistics
- Systematics as bottleneck



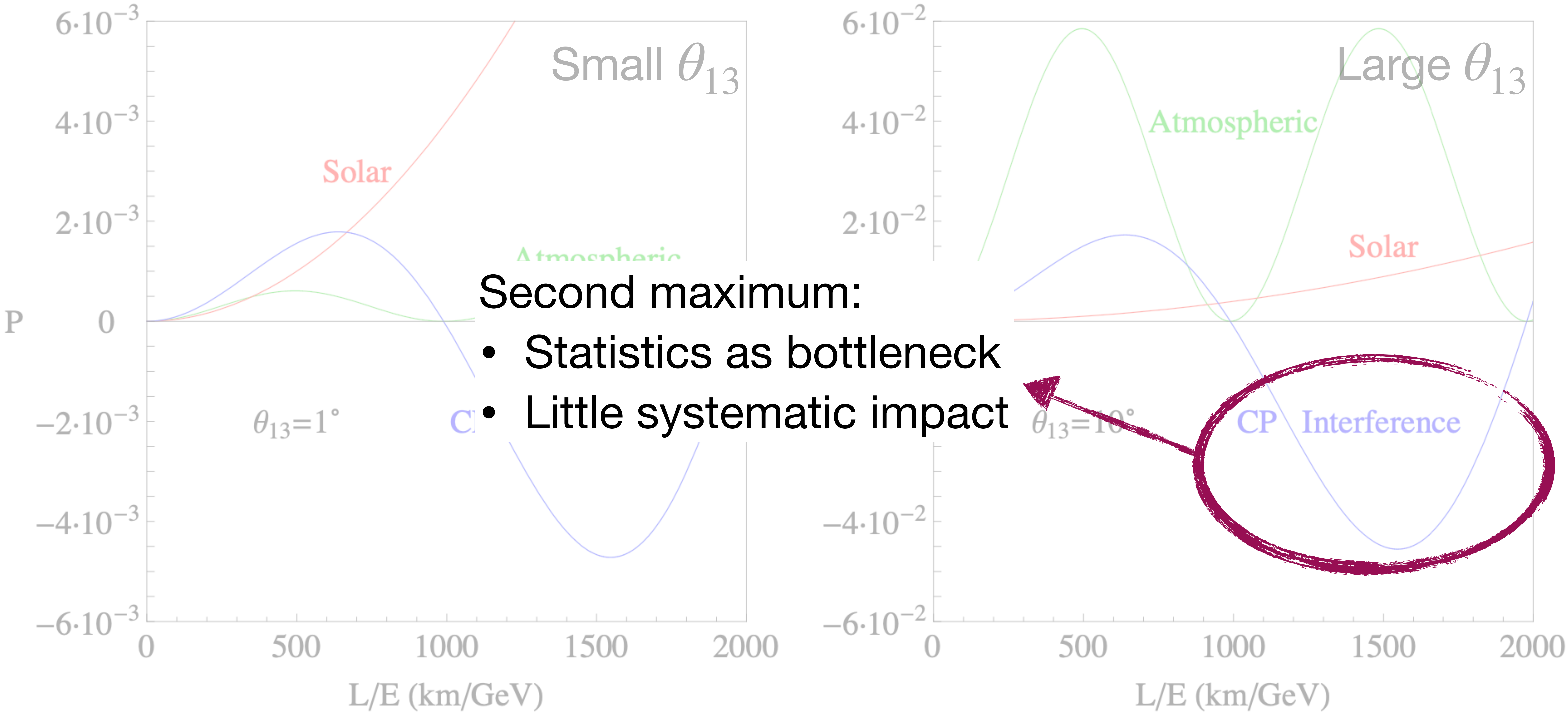
Impact of θ_{13}

P. Coloma & E. Fernandez-Martinez, 1110.4583



Impact of θ_{13}

P. Coloma & E. Fernandez-Martinez, 1110.4583



Second maximum:

- Statistics as bottleneck
- Little systematic impact

ESSnuSB

E. Baussan *et al.* 1309.7022

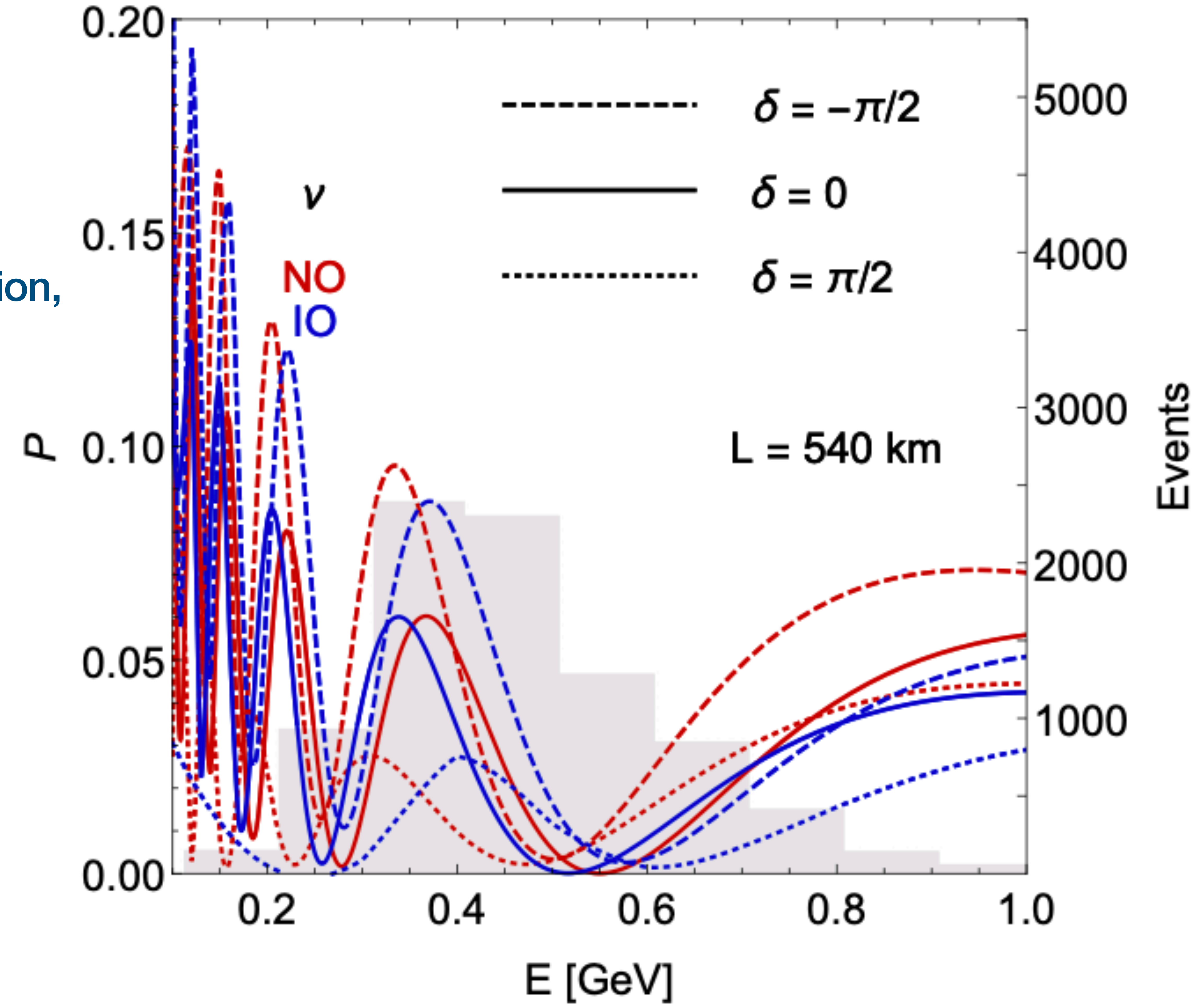
- Modify ESS linac to produce neutrinos
- 5 MW at 2.5 GeV proton beam
- Memphis-like WC detector:
  - 538 kt fiducial volume MEMPHYS Collaboration, 1206.6665
  - Best locations at 540 km and 360 km

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:
  - 538 kt fiducial volume
  - Best locations at 540 km and 360 km

MEMPHYS Collaboration, 1206.6665



M. Blennow *et al.* 1912.04309

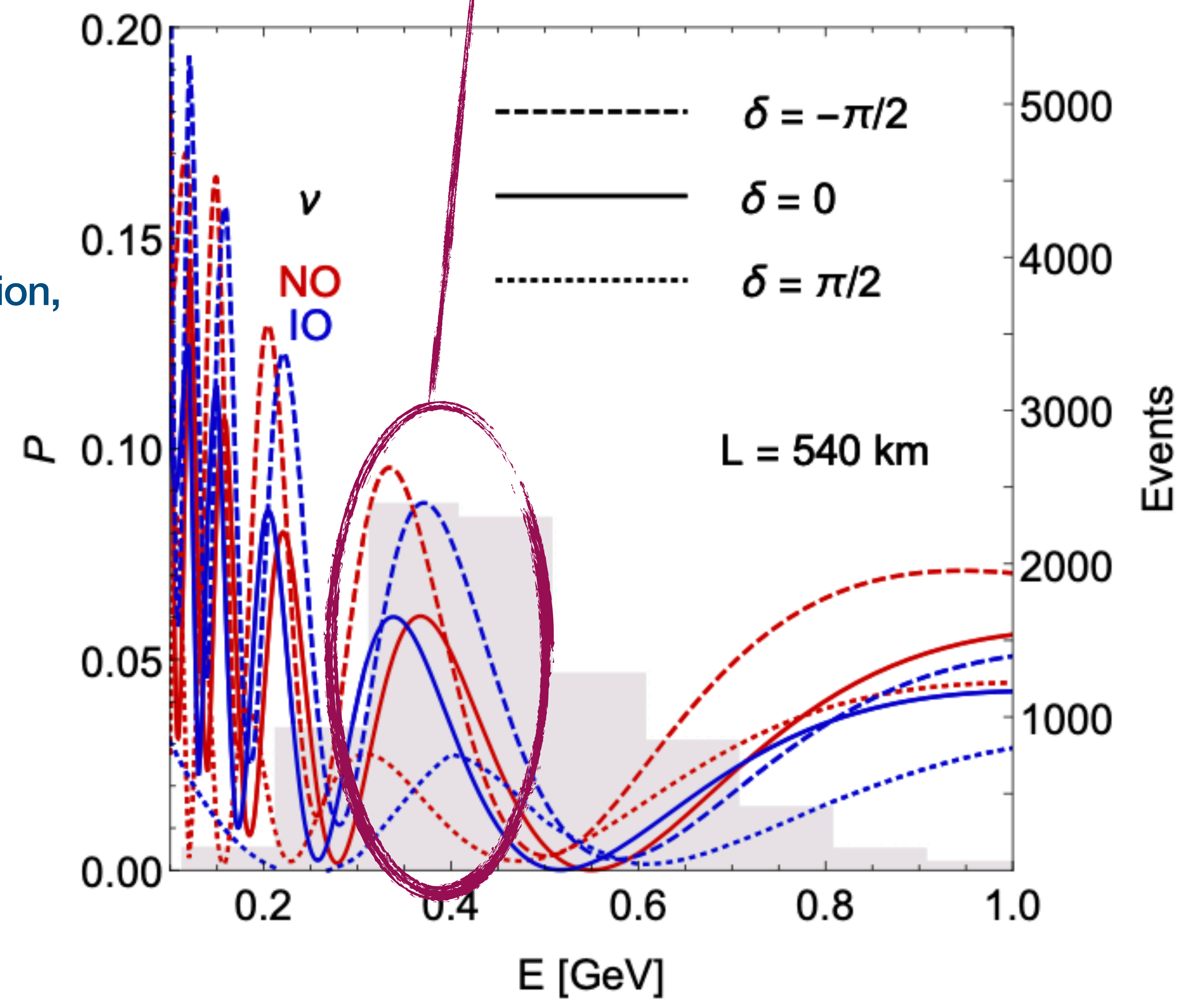
ESSnuSB

E. Baussan *et al.* 1309.7022

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

MEMPHYS Collaboration, 1206.6665

$E_\nu \sim 300$ MeV



M. Blennow *et al.* 1912.04309

ESSnuSB

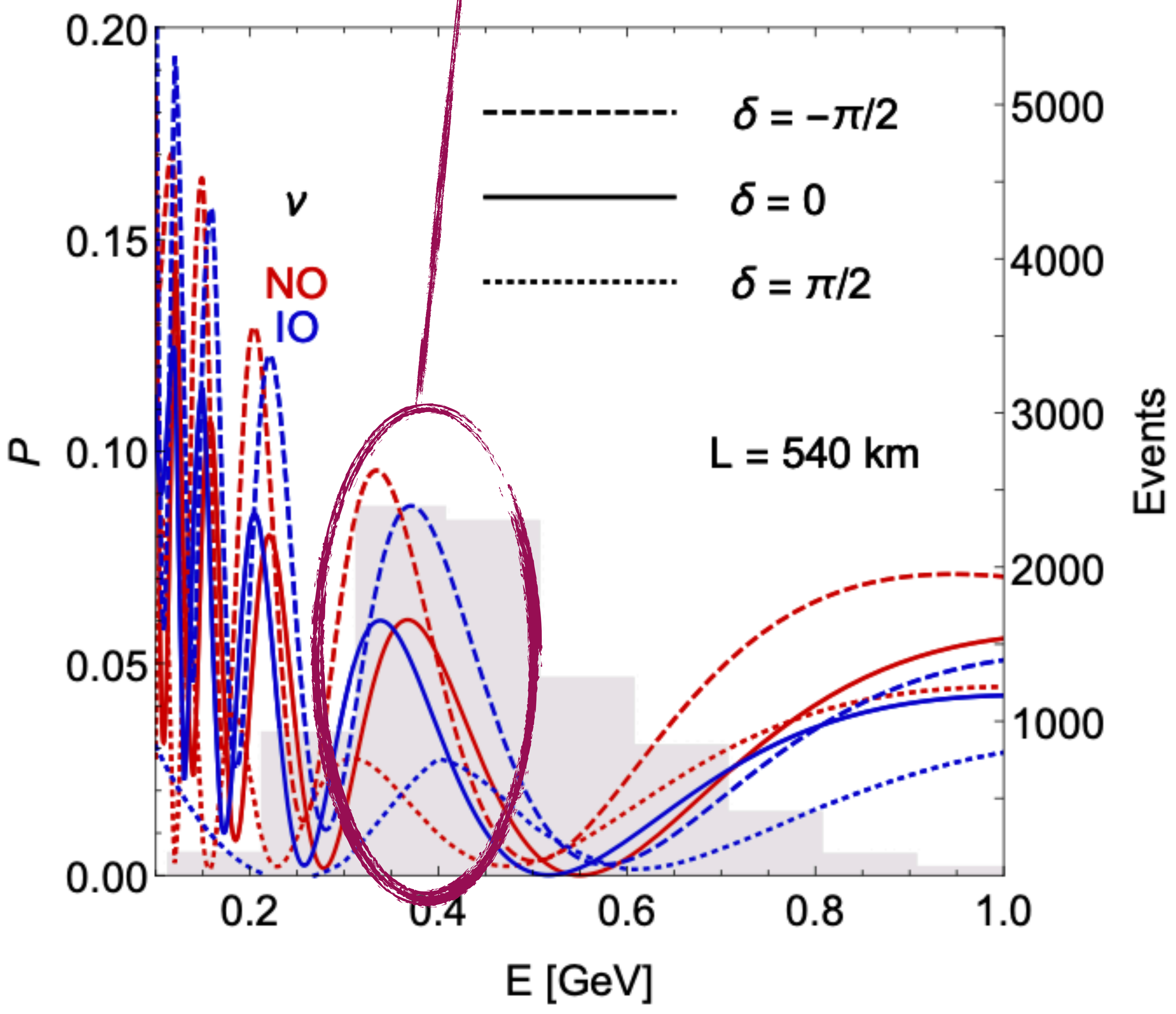
E. Baussan *et al.* 1309.7022

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

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

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

$E_\nu \sim 300$ MeV

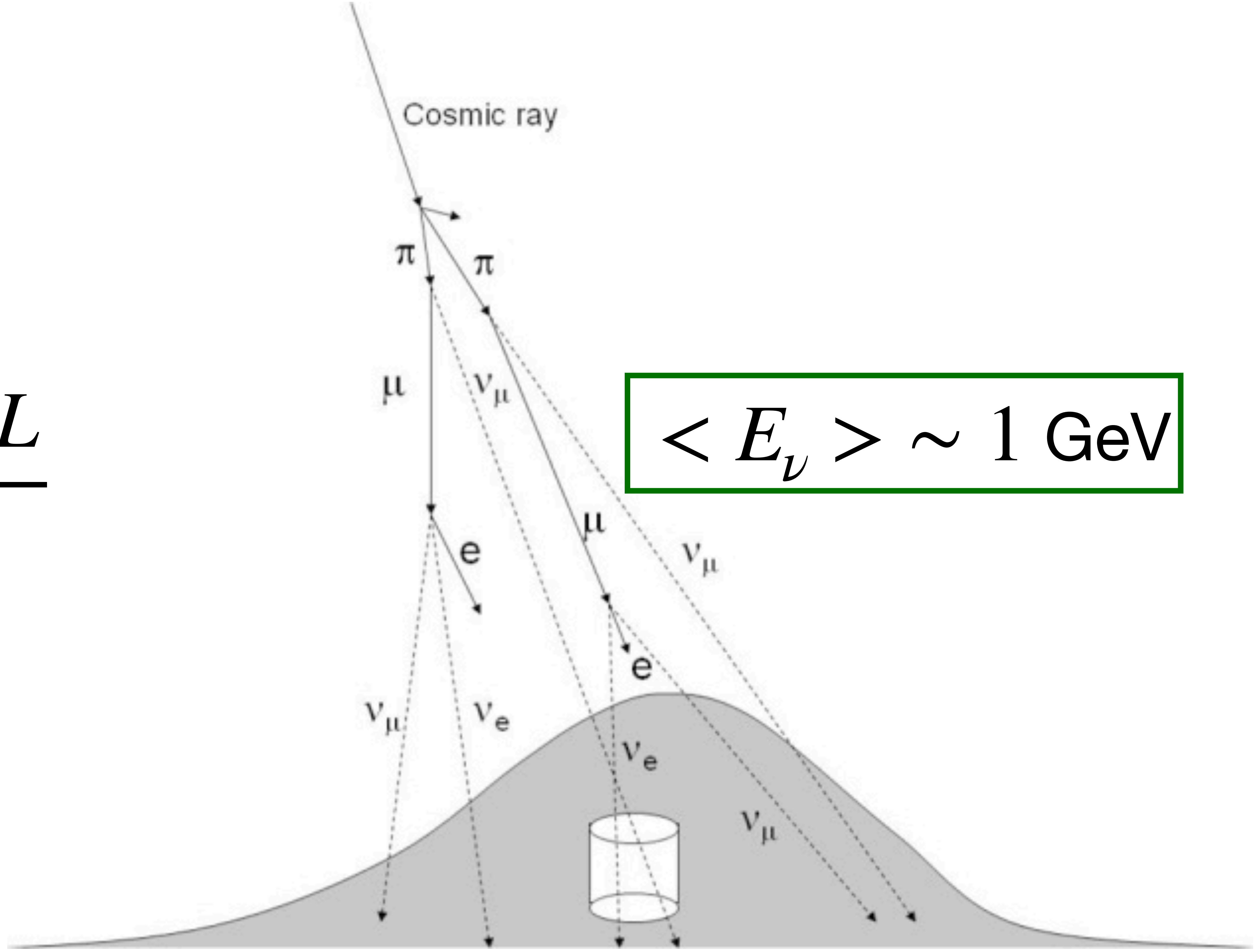


M. Blennow *et al.* 1912.04309

Atmospheric neutrinos at ESSnuSB

500 kt Water-Cerenkov detector

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



$< E_\nu > \sim 1$ GeV

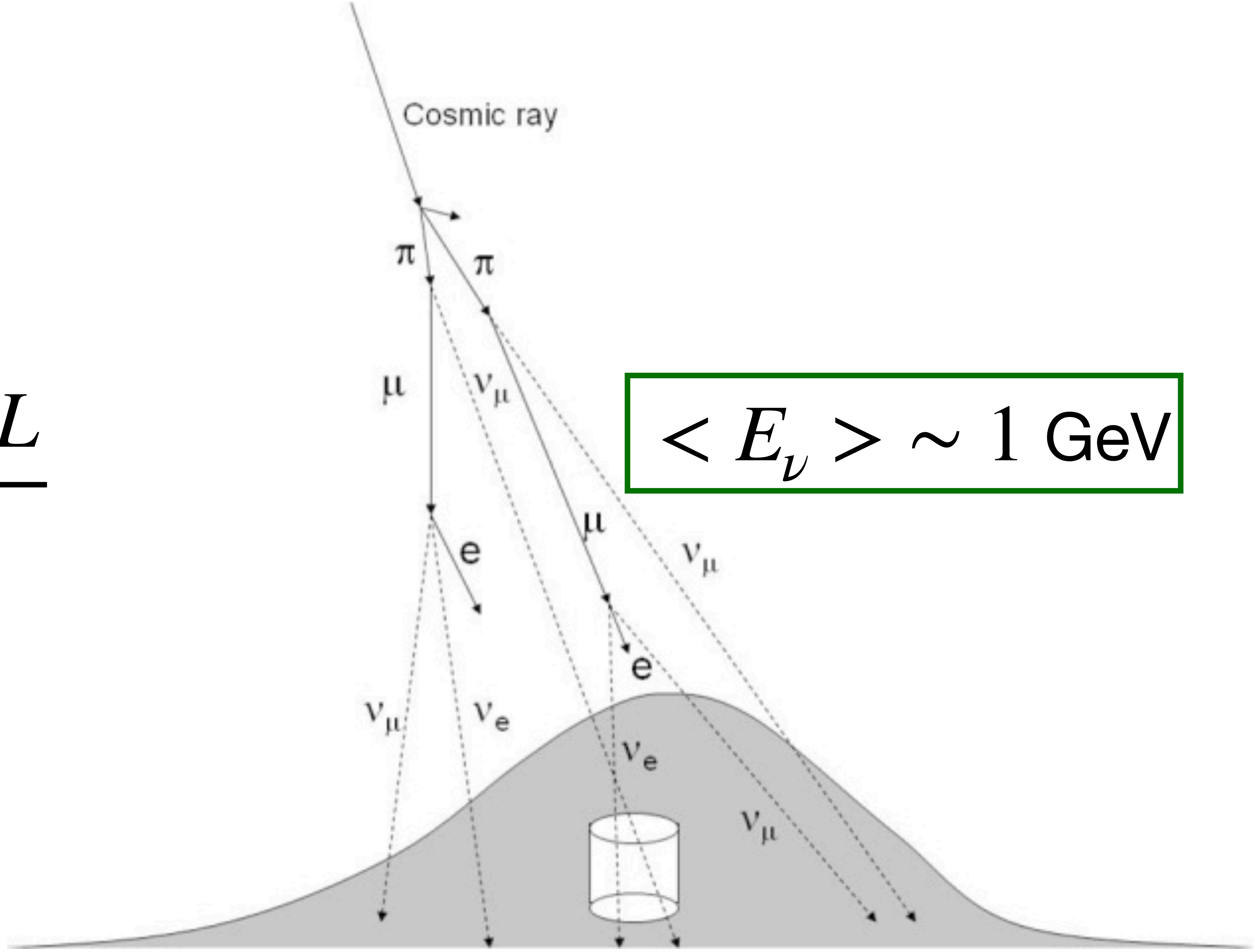
https://neutrinos.fnal.gov/sources/atmospheric-neutrinos/

Atmospheric neutrinos at ESSnuSB

500 kt Water-Cerenkov detector

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

Sensitivity to octant



$< E_\nu > \sim 1$ GeV

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

Atmospheric neutrinos at ESSnuSB

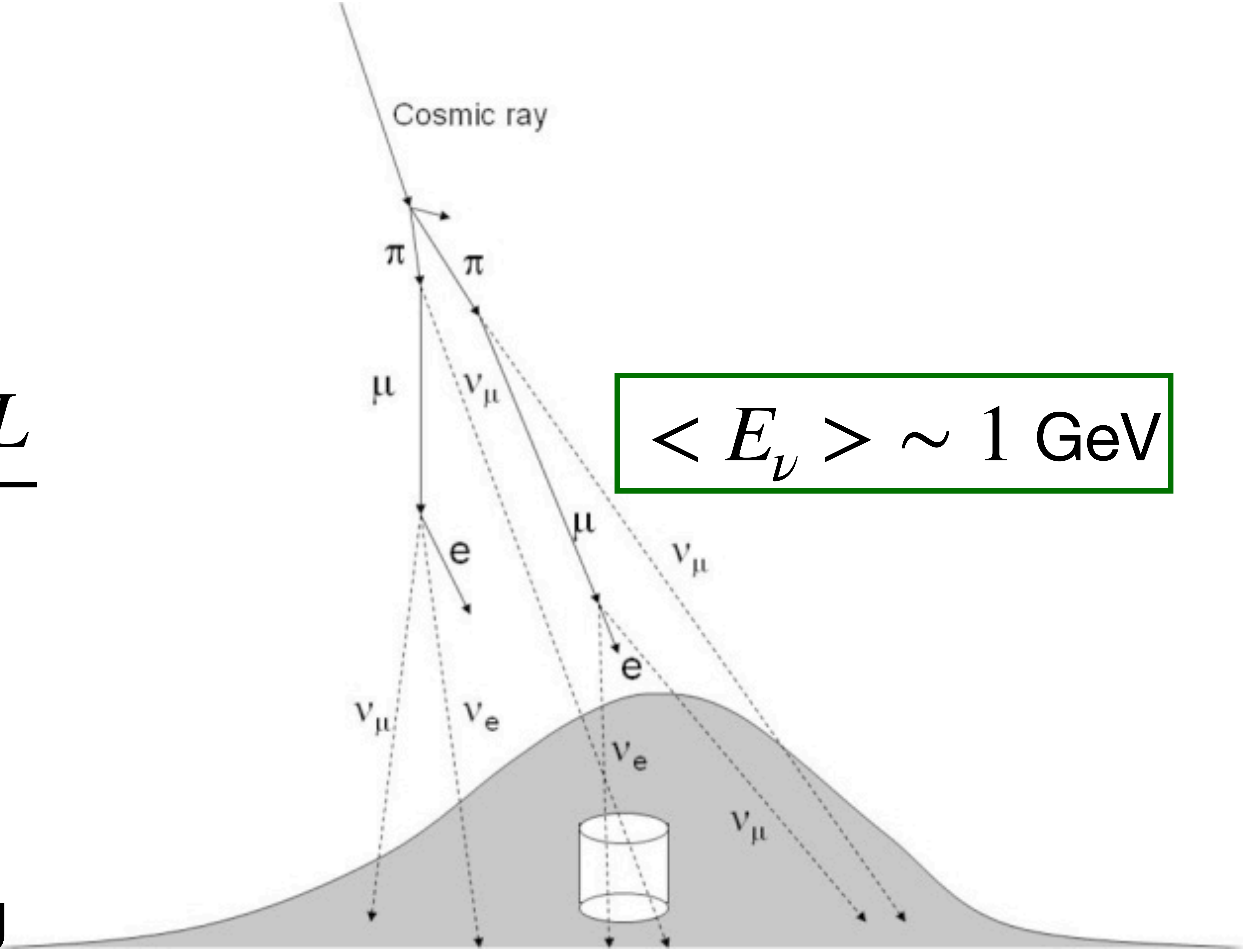
500 kt Water-Cerenkov detector

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

Sensitivity to octant

Sensitivity to mass ordering

$< E_\nu > \sim 1$ GeV



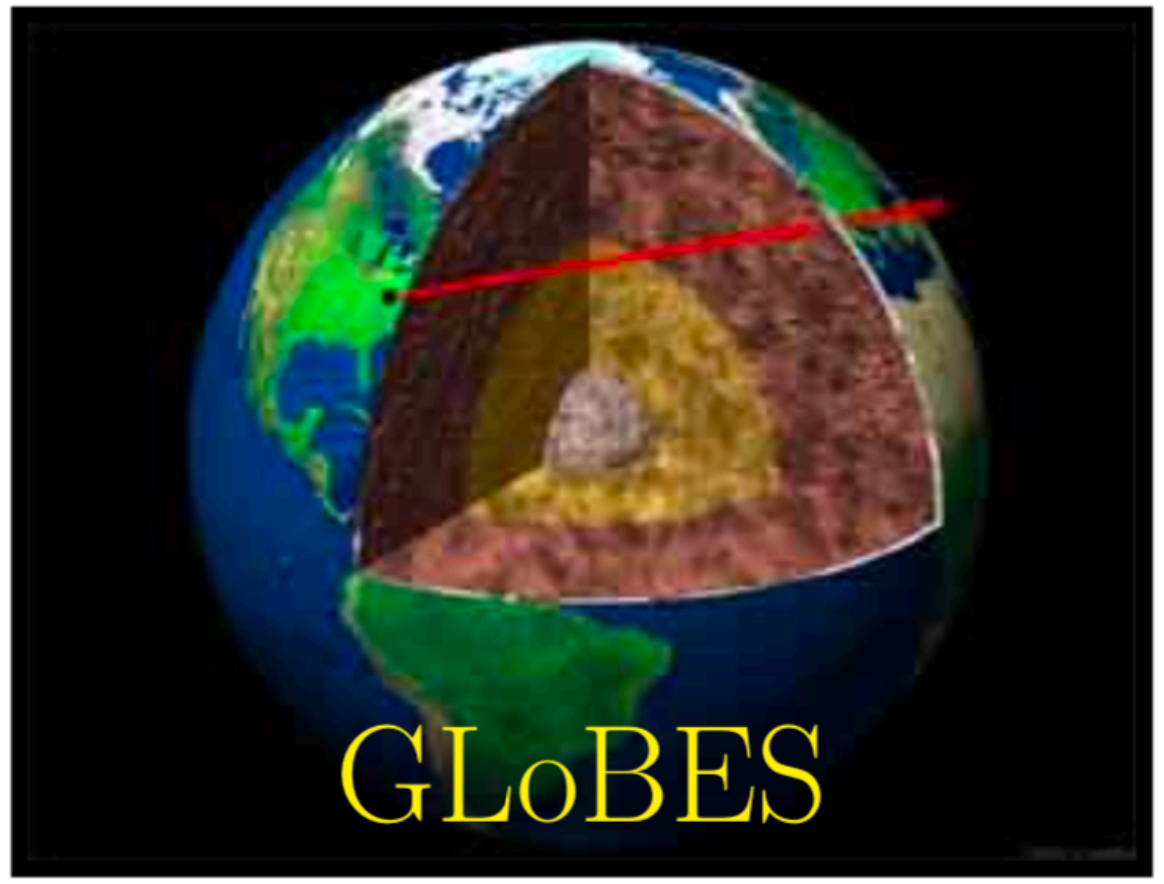
https://neutrinos.fnal.gov/sources/atmospheric-neutrinos/

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

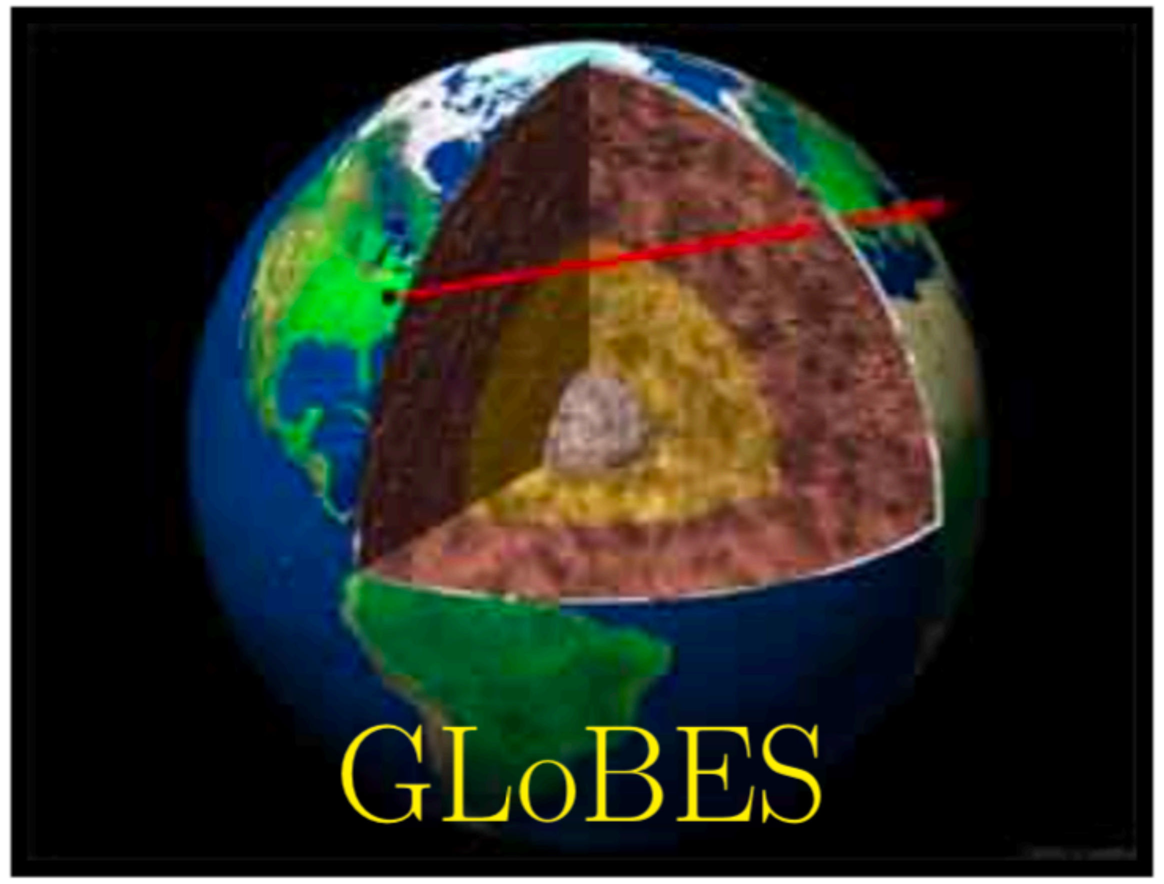


Simulation details

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



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*

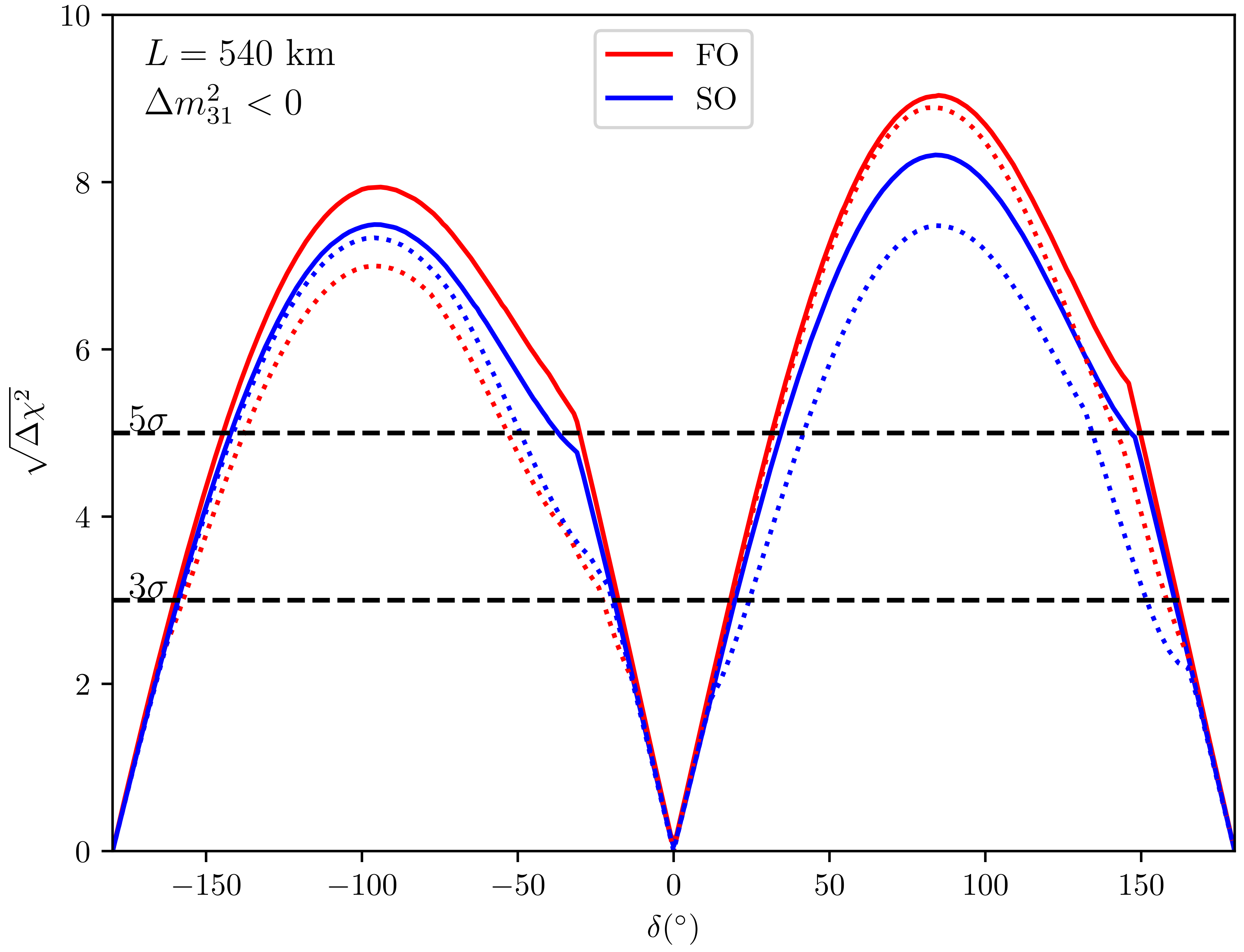
SK Collaboration, Y. Ashie *et al.* hep-ex/0501064

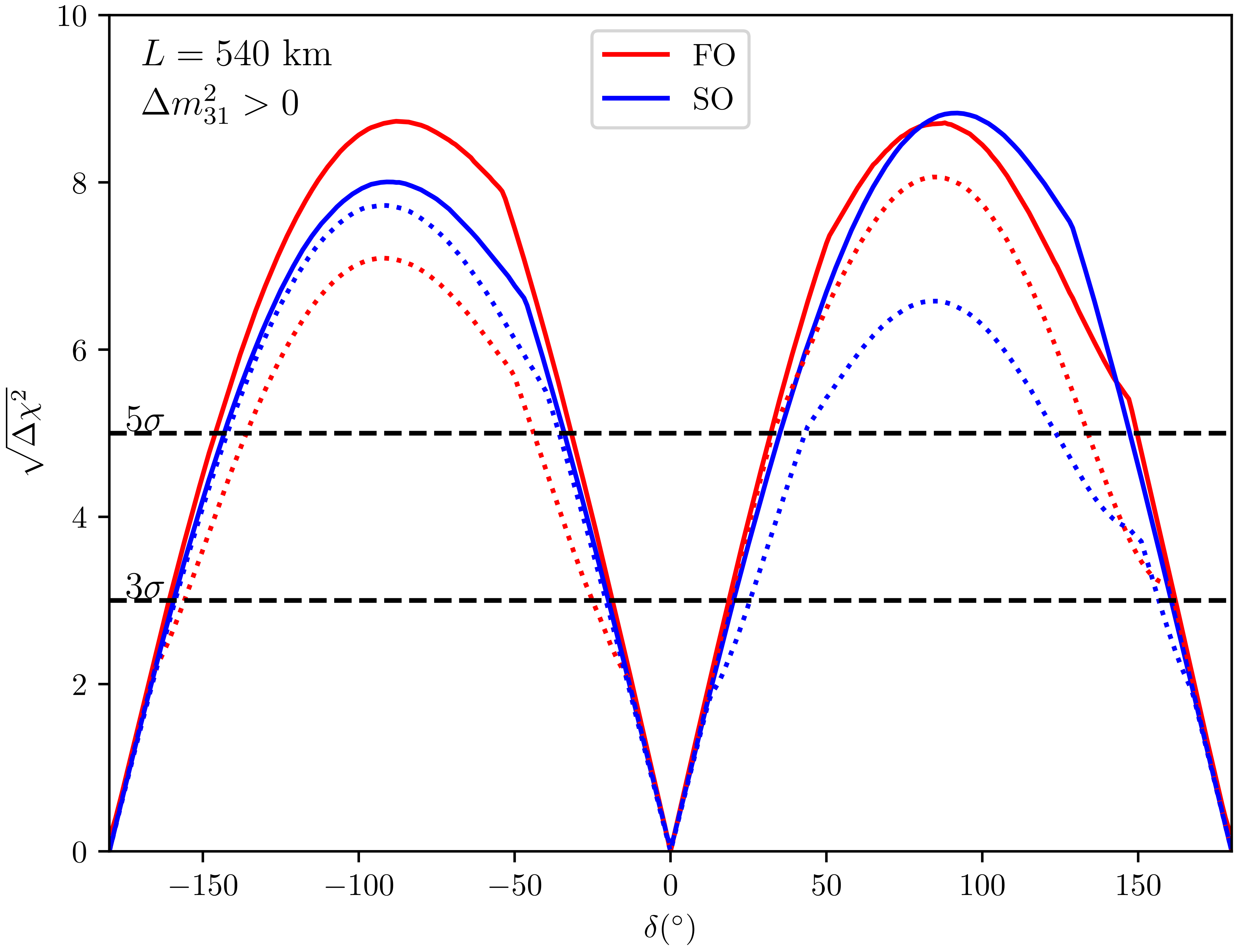
Systematic uncertainties

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

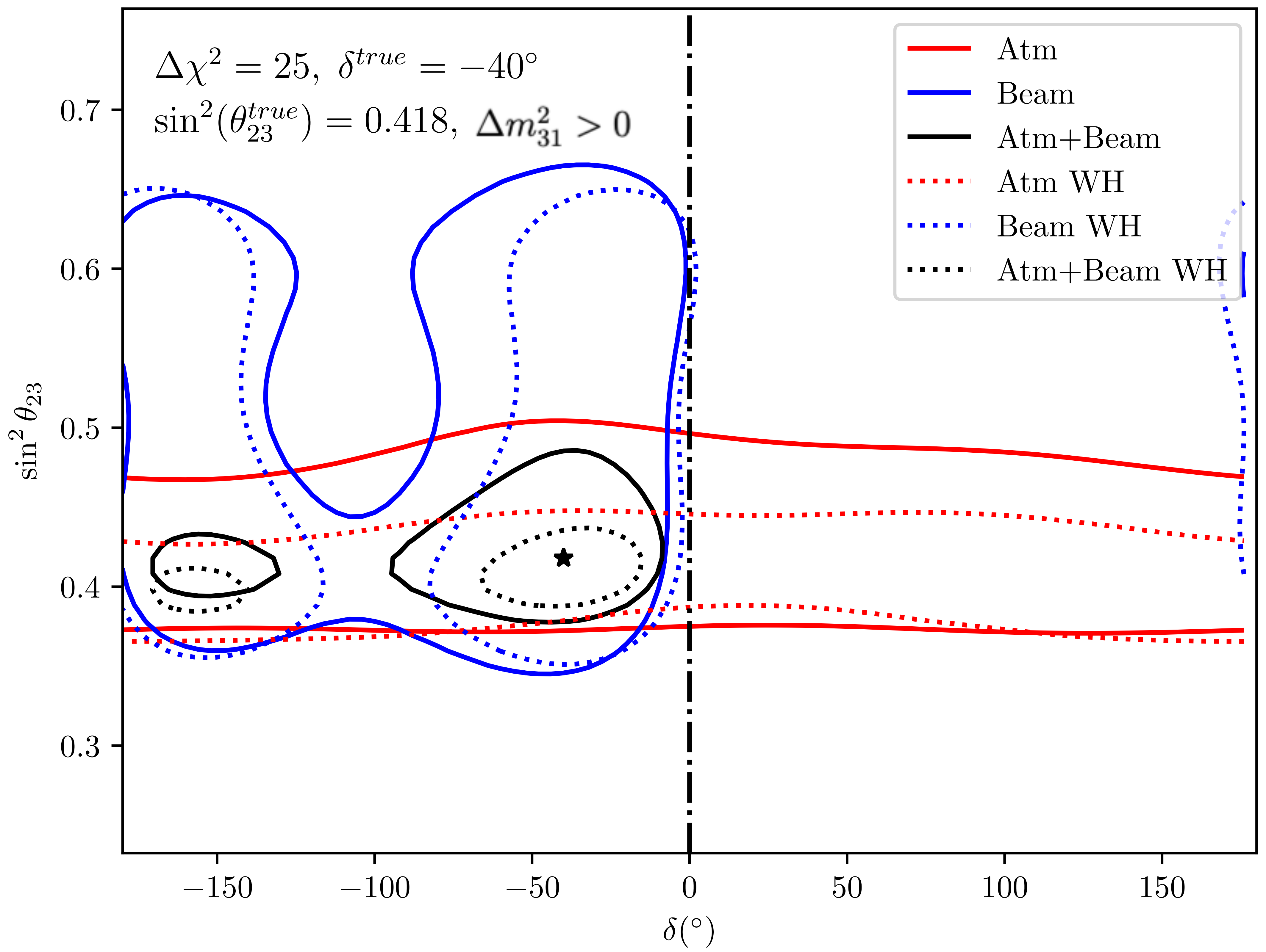
CP violation sensitivity

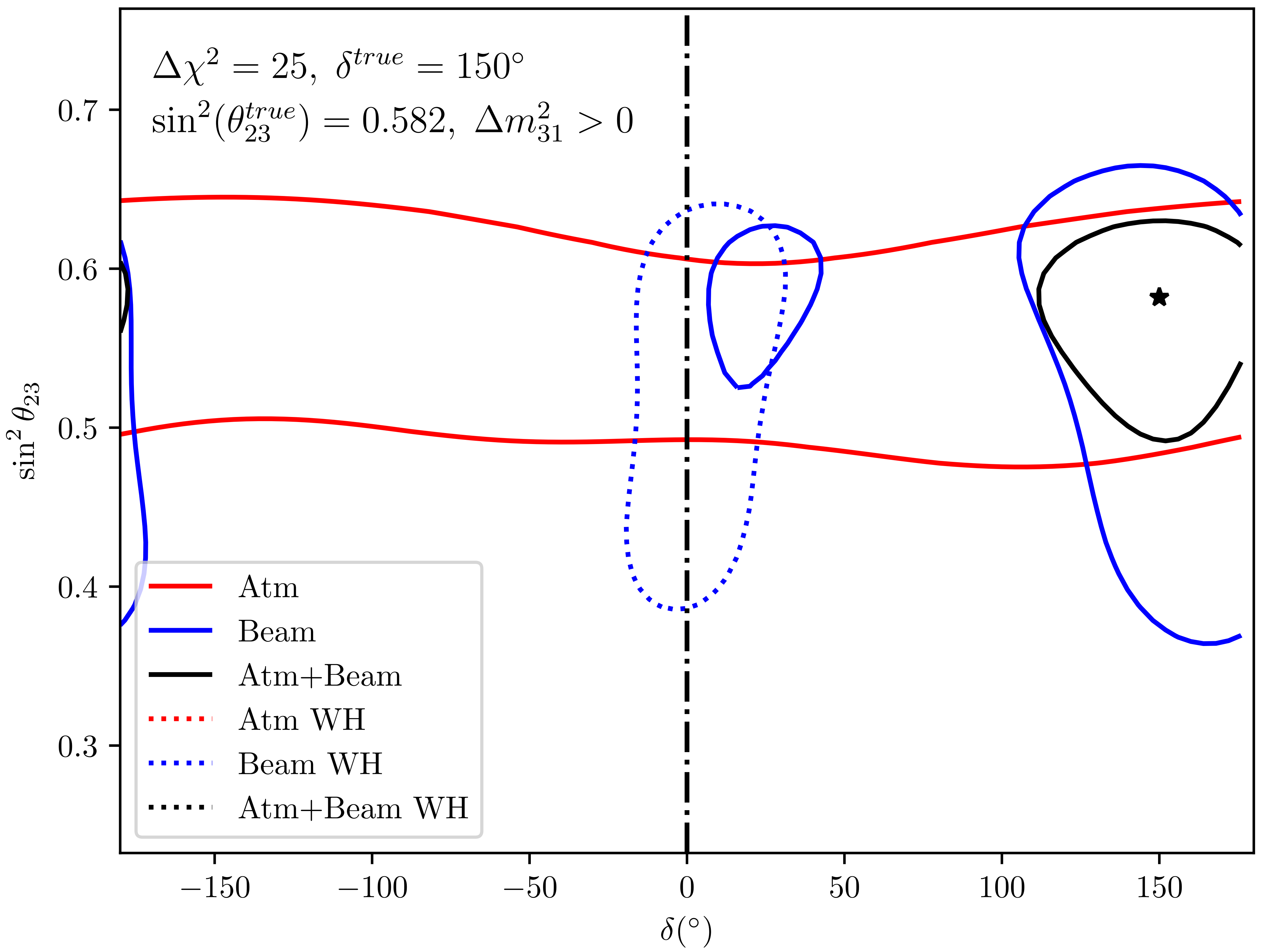




M. Blennow *et al.* 1912.04309

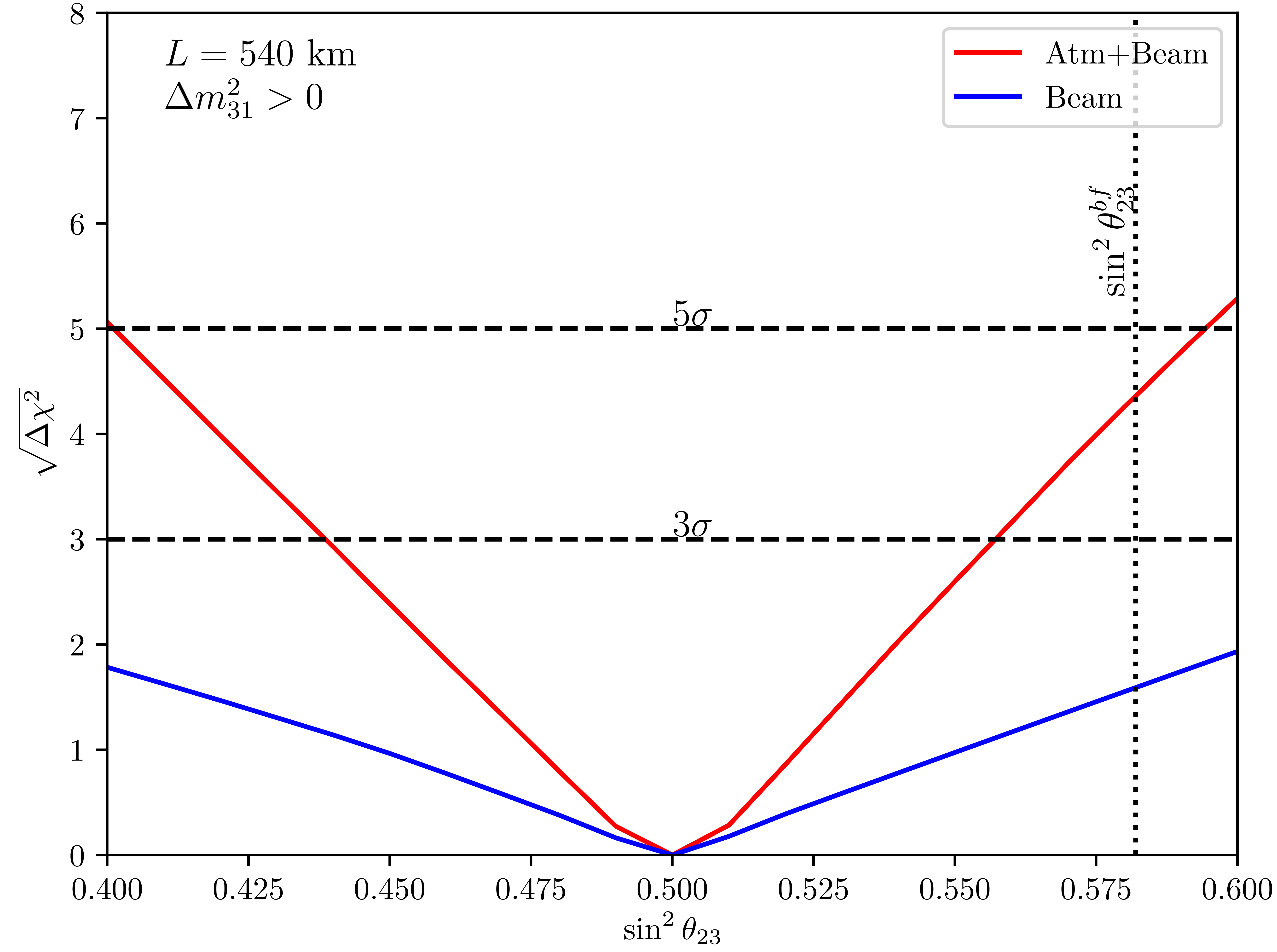
Complementarity between beam and atm





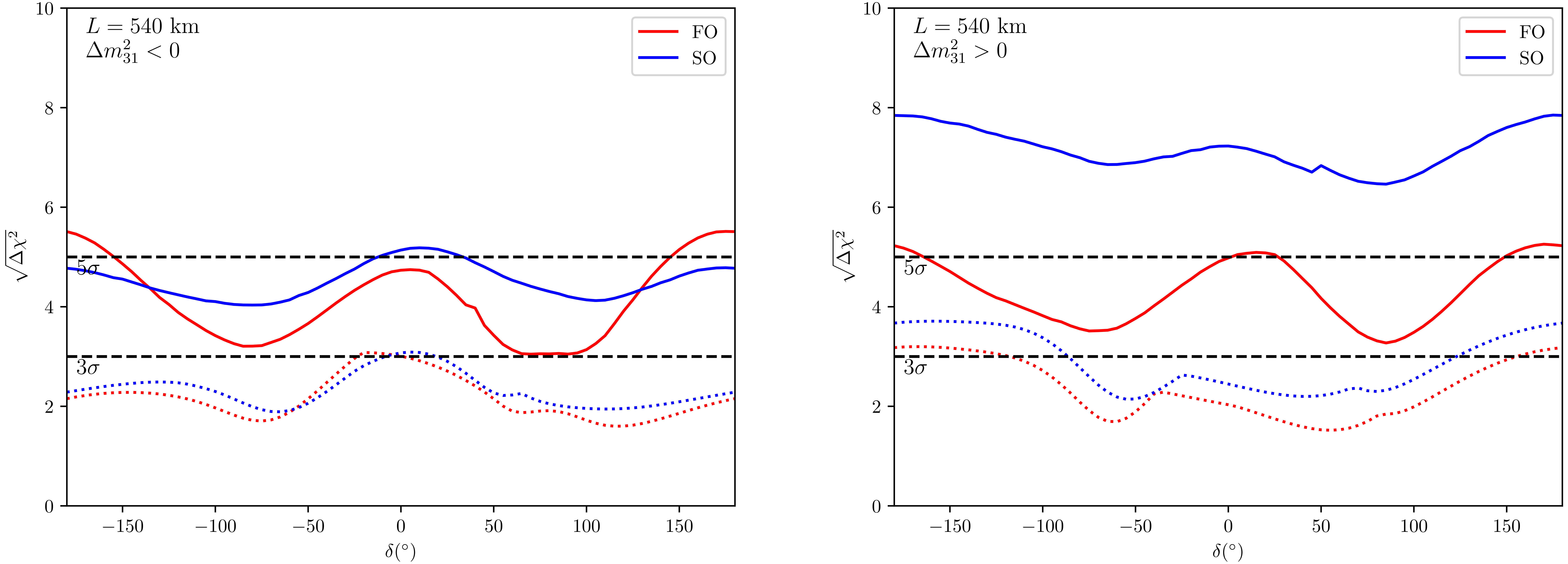
M. Blennow *et al.* 1912.04309

Octant and mass ordering



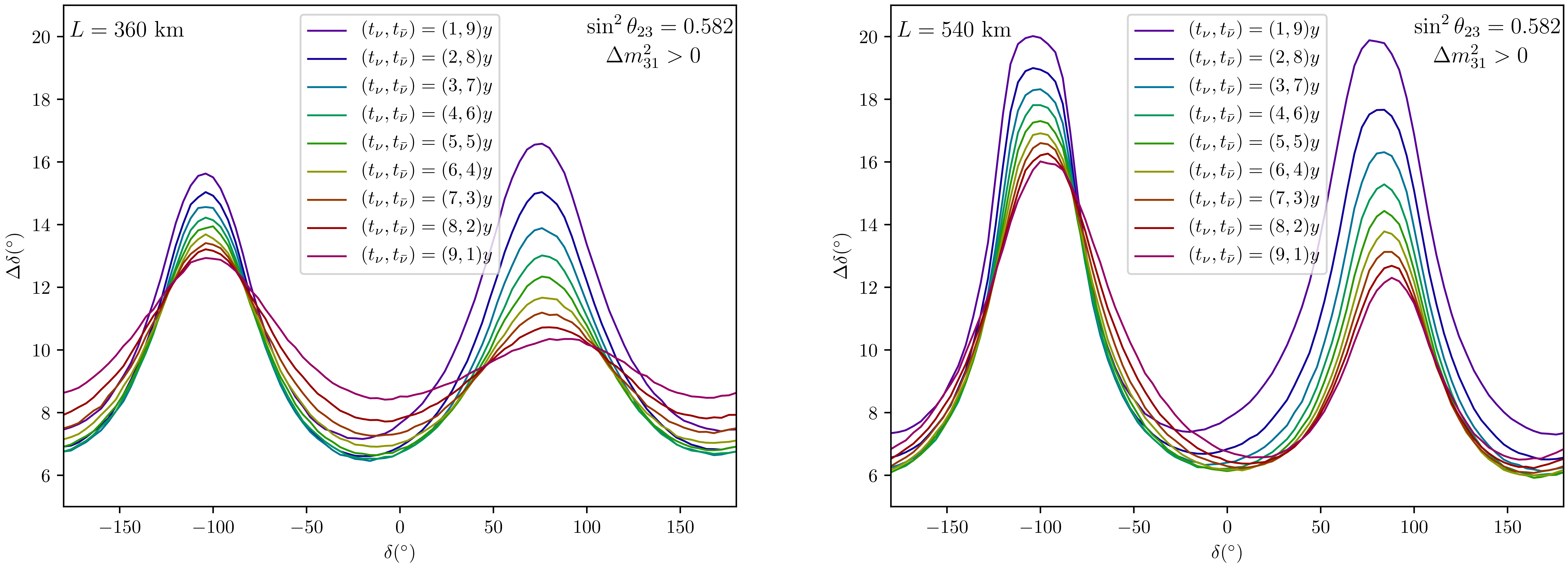
M. Blennow *et al.* 1912.04309

Octant and mass ordering



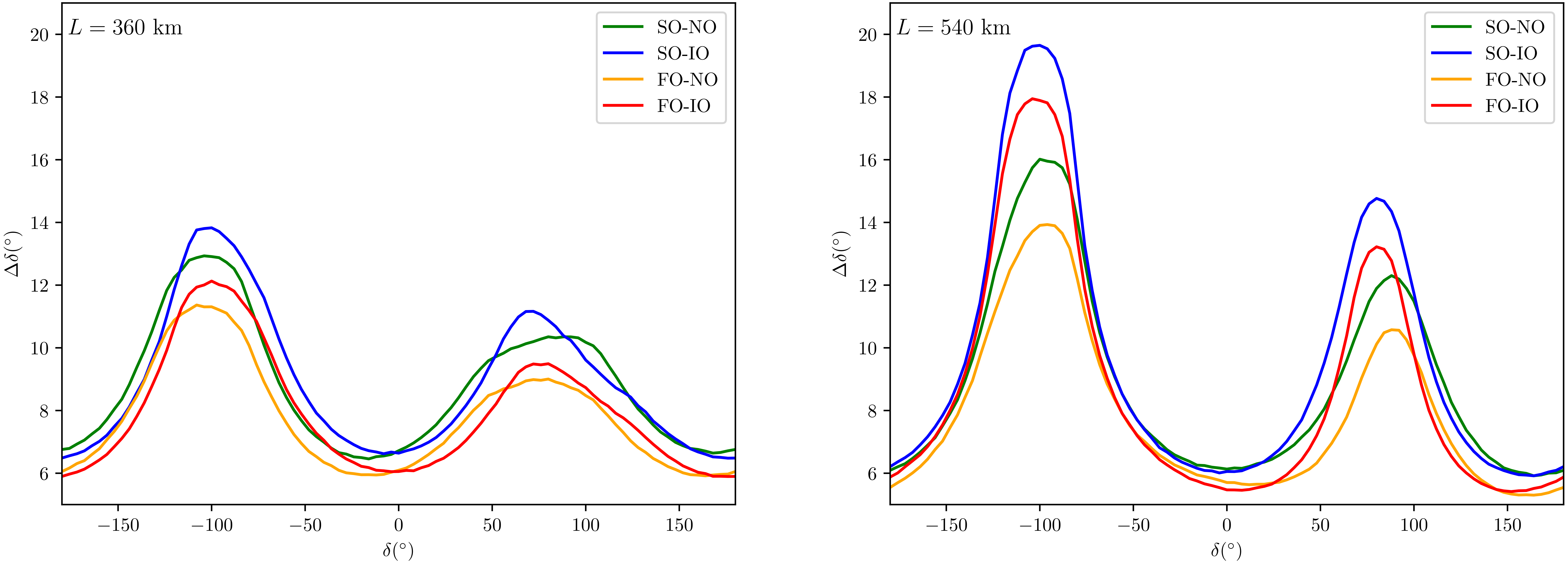
M. Blennow *et al.* 1912.04309

Precision on δ



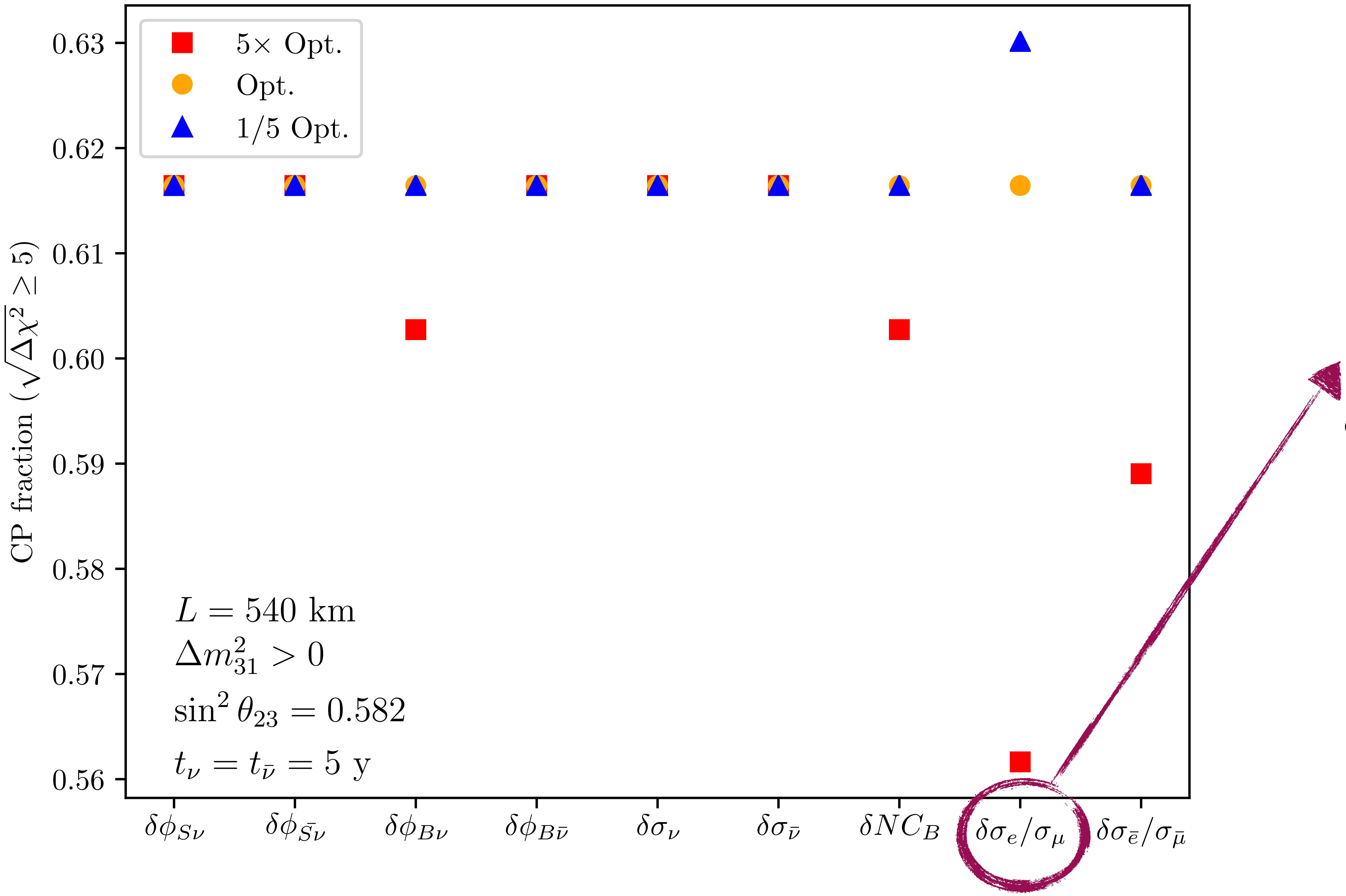
M. Blennow *et al.* 1912.04309

Precision on δ



M. Blennow *et al.* 1912.04309

Effect of systematic uncertainties

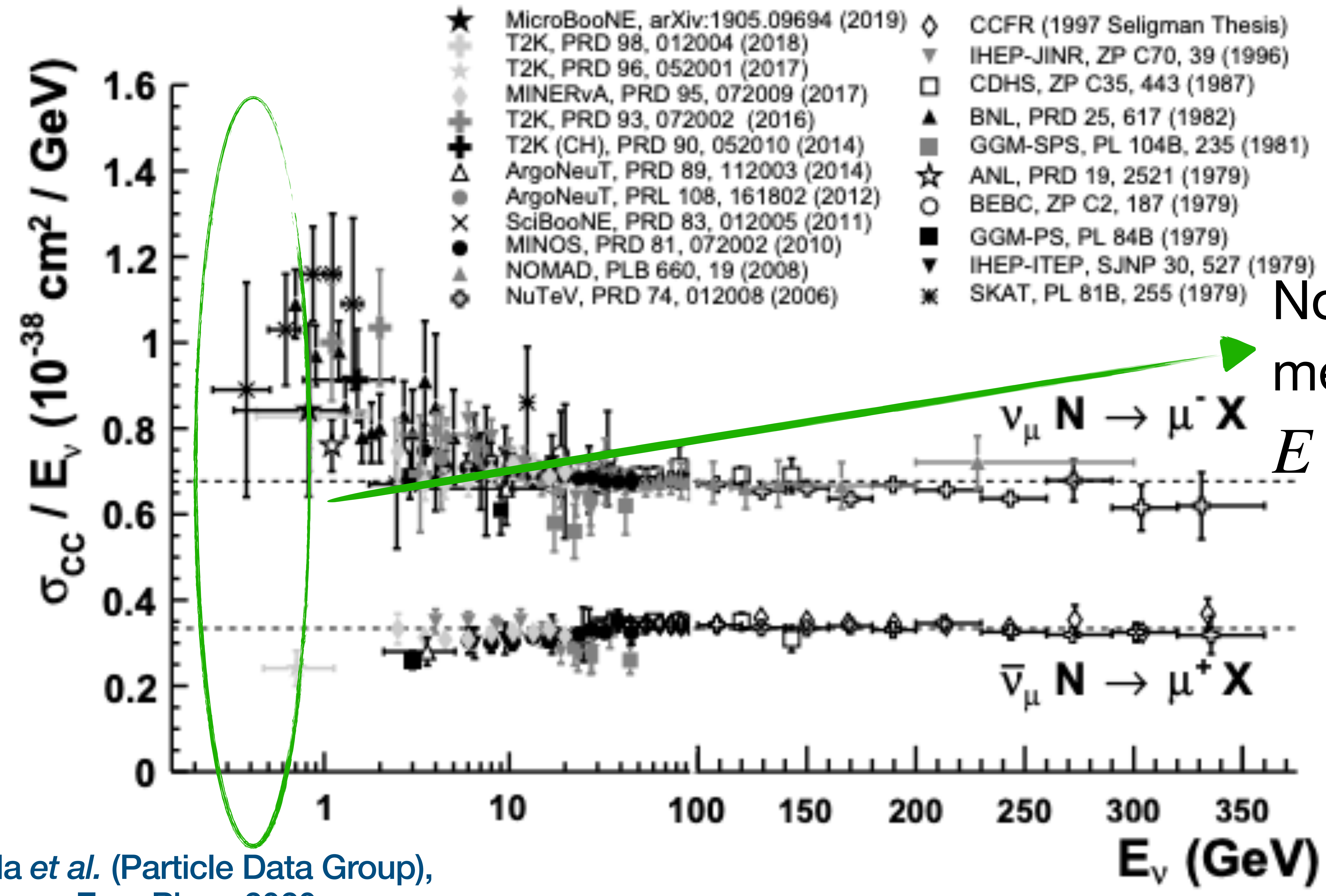


Mostly ν_μ at the ND

and ν_e at the FD

M. Blennow *et al.* 1912.04309

What about shape systematics?

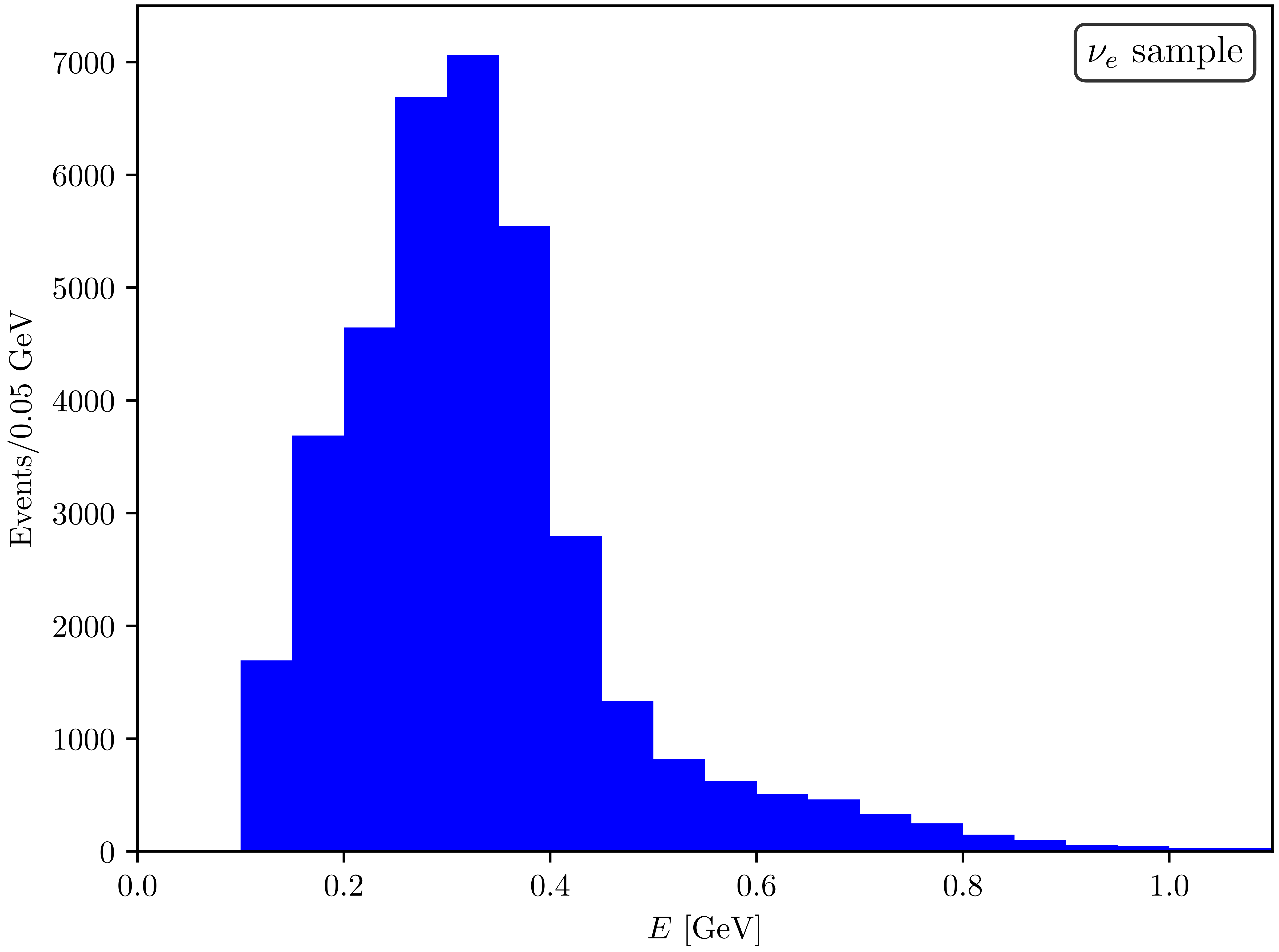


No cross section measuerement around $E \sim 300$ MeV

P. A. Zyla *et al.* (Particle Data Group), Prog. Theor. Exp. Phys. 2020

What about shape systematics?

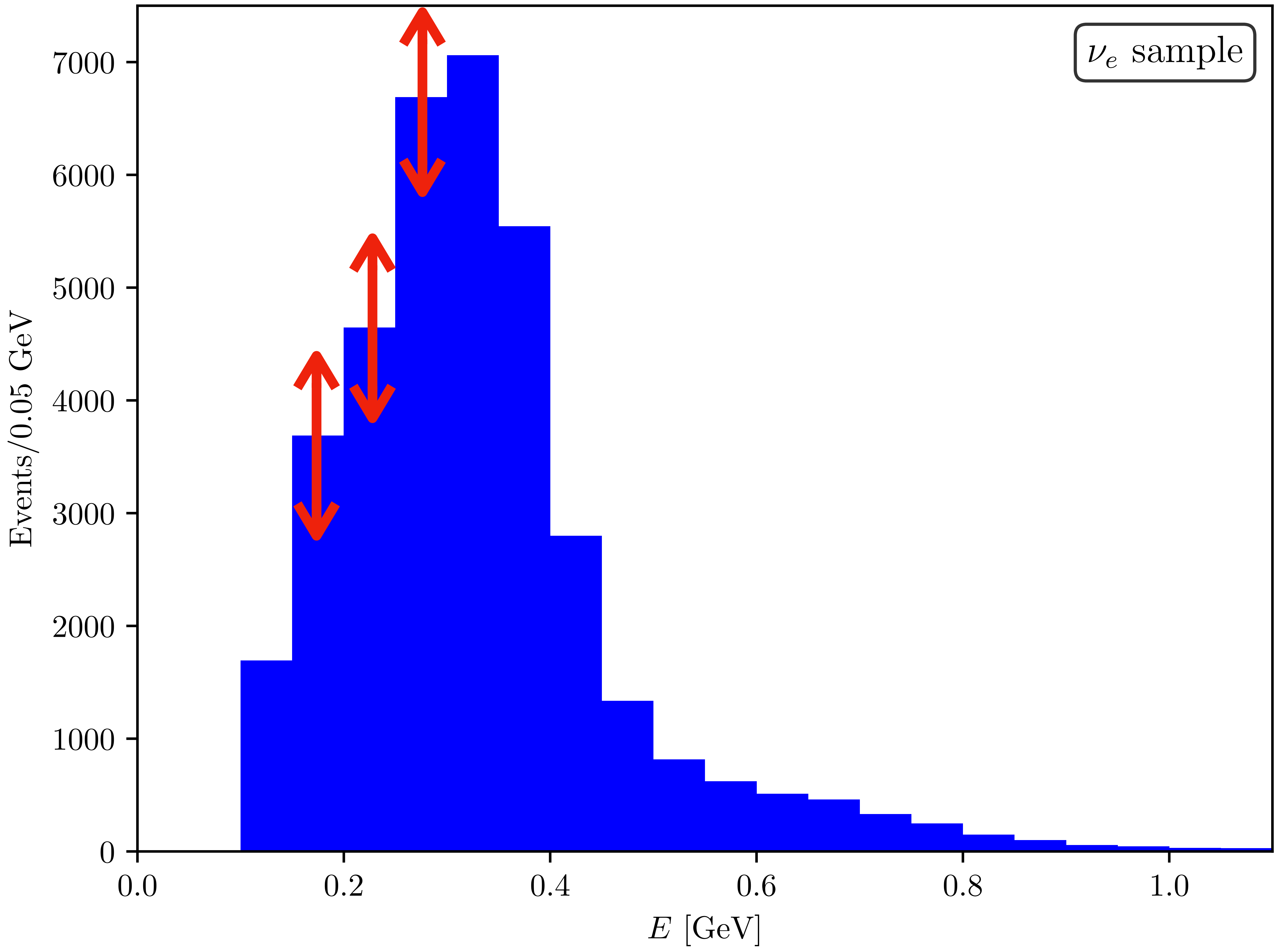
Energy-dependant uncertainties



What about shape systematics?

Energy-dependant uncertainties

Introduce uncorrelated nuisance parameters in each energy bin in GLoBES



Updated ESSnuSB description

ESSnuSB Collaboration, arXiv:2107.07585 (See talk by Budimir Klicek)

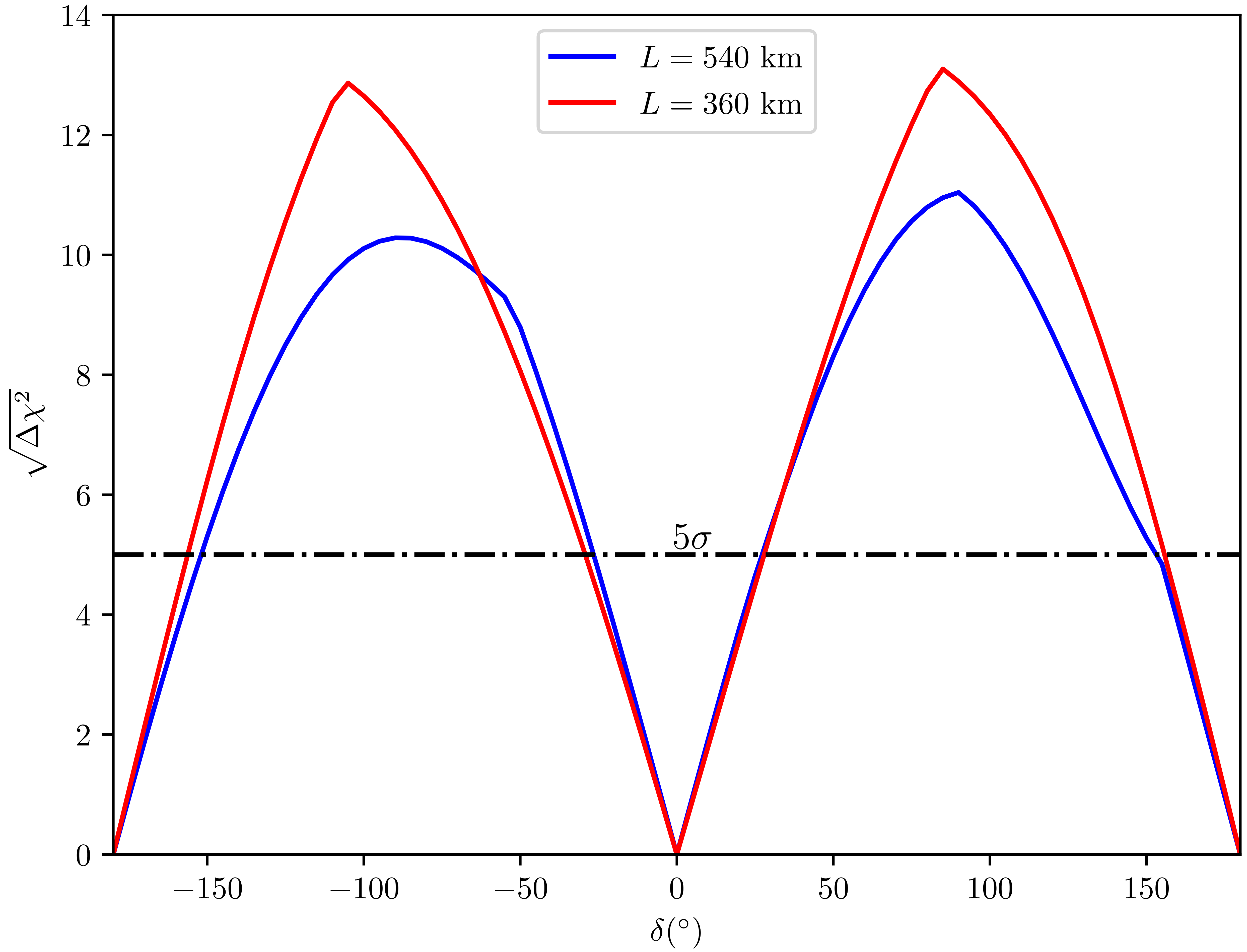
- 5 MW at 2.5 GeV proton beam
- Memphis-like WC detector:
  - 538 kt fiducial volume
  - ν flux and migration matrices calculated for ESSnuSB configuration $\rightarrow$ **Factor of 2 improvement on signal selection efficiency**
- Normalization systematics: **5% signal, 10% background**
- **Better energy resolution**
- **Only FD simulated**

Updated ESSnuSB description

ESSnuSB Collaboration, arXiv:2107.07585

- 5 MW at 2.5 GeV proton beam
- Memphis-like WC detector:
  - 538 kt fiducial volume
  - ν flux and migration matrices calculated for ESSnuSB configuration → **Factor of 2 improvement on signal selection efficiency**
- Normalization systematics: **5% signal, 10% background**
- **Better energy resolution**
- **Only FD simulated**

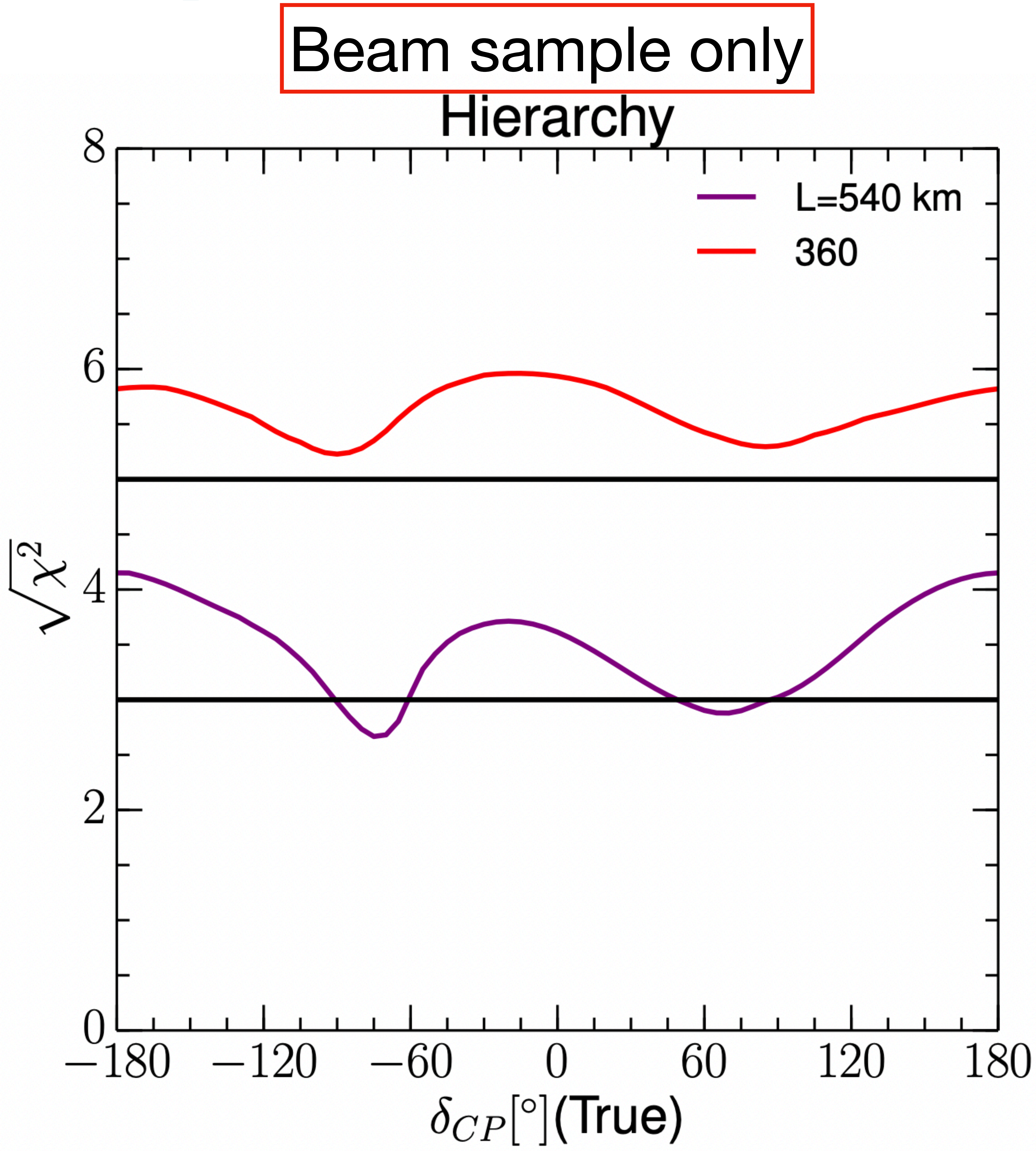
Beam sample only



Updated ESSnuSB description

ESSnuSB Collaboration, arXiv:2107.07585

- 5 MW at 2.5 GeV proton beam
- Memphis-like WC detector:
  - 538 kt fiducial volume
  - ν flux and migration matrices calculated for ESSnuSB configuration → **Factor of 2 improvement on signal selection efficiency**
- Normalization systematics: **5% signal, 10% background**
- **Better energy resolution**
- **Only FD simulated**

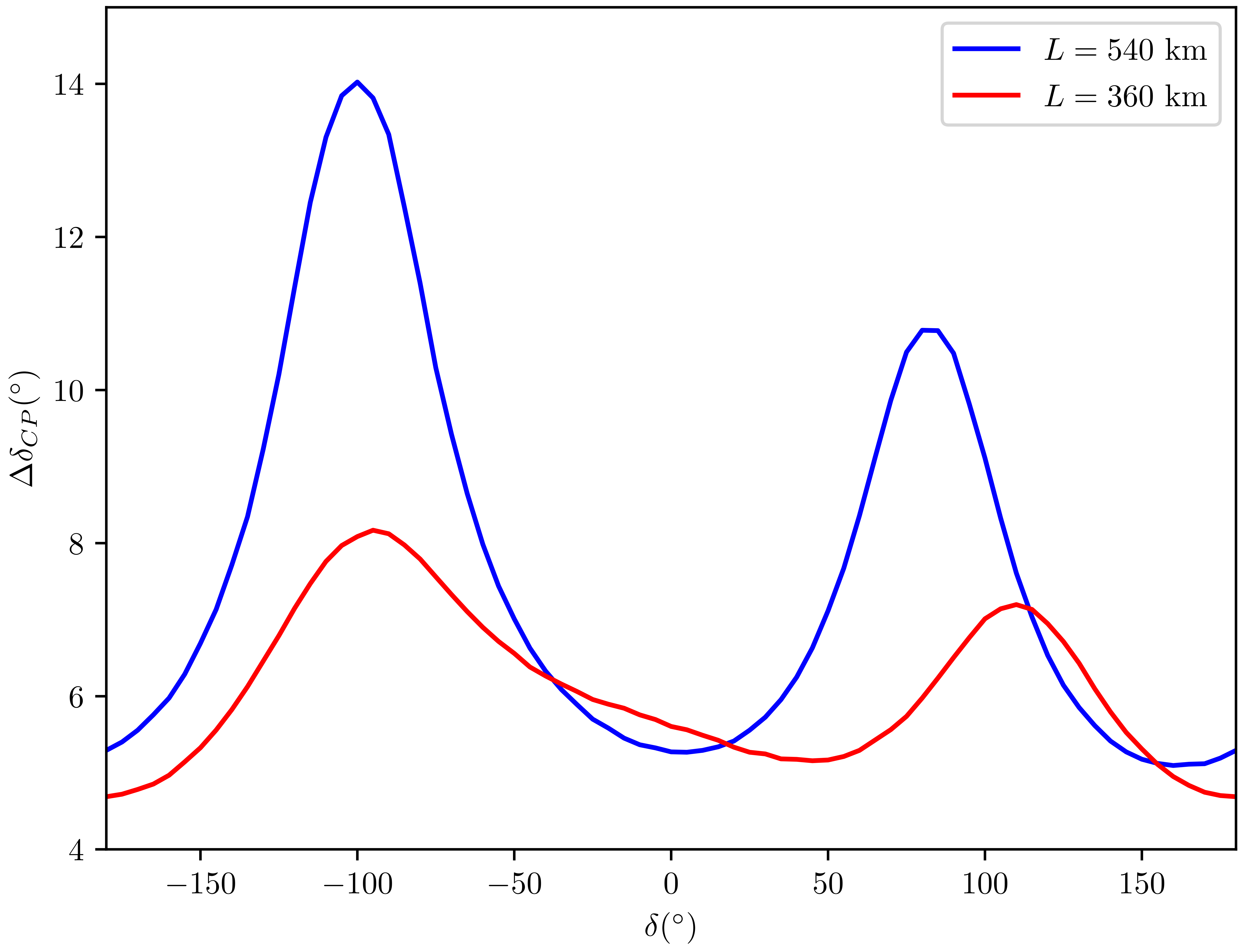


Updated ESSnuSB description

ESSnuSB Collaboration, arXiv:2107.07585

- 5 MW at 2.5 GeV proton beam
- Memphis-like WC detector:
  - 538 kt fiducial volume
  - ν flux and migration matrices calculated for ESSnuSB configuration → **Factor of 2 improvement on signal selection efficiency**
- Normalization systematics: **5% signal, 10% background**
- **Better energy resolution**
- **Only FD simulated**

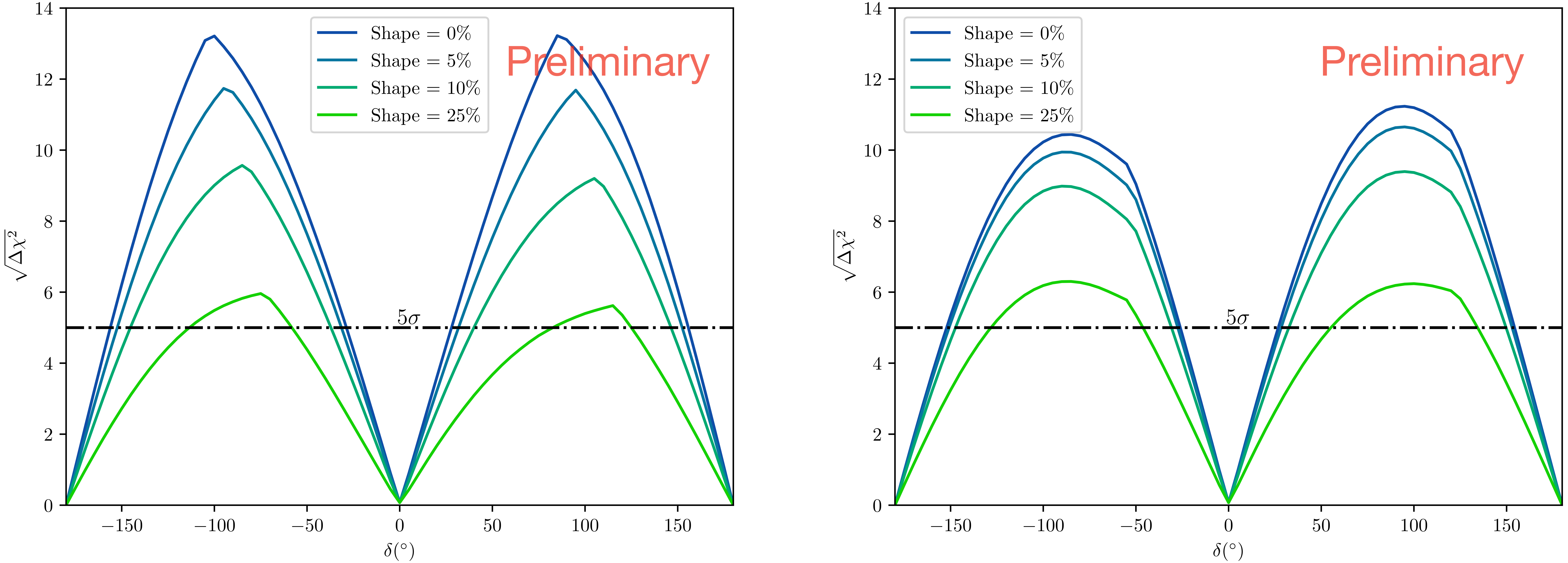
Beam sample only



Effect of shape systematics

Beam + Atmospherics

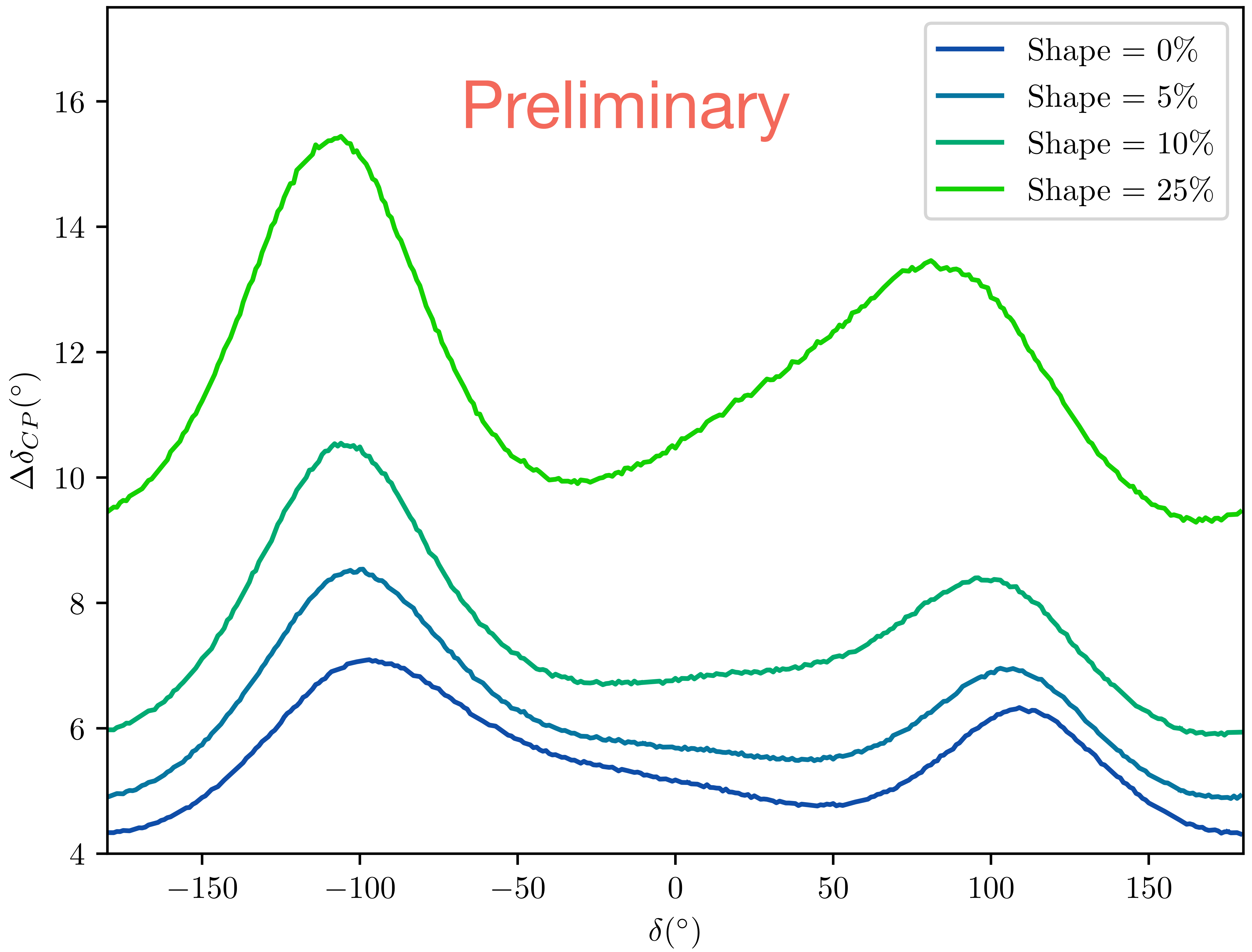
$L = 360$ km $\quad$ $L = 540$ km



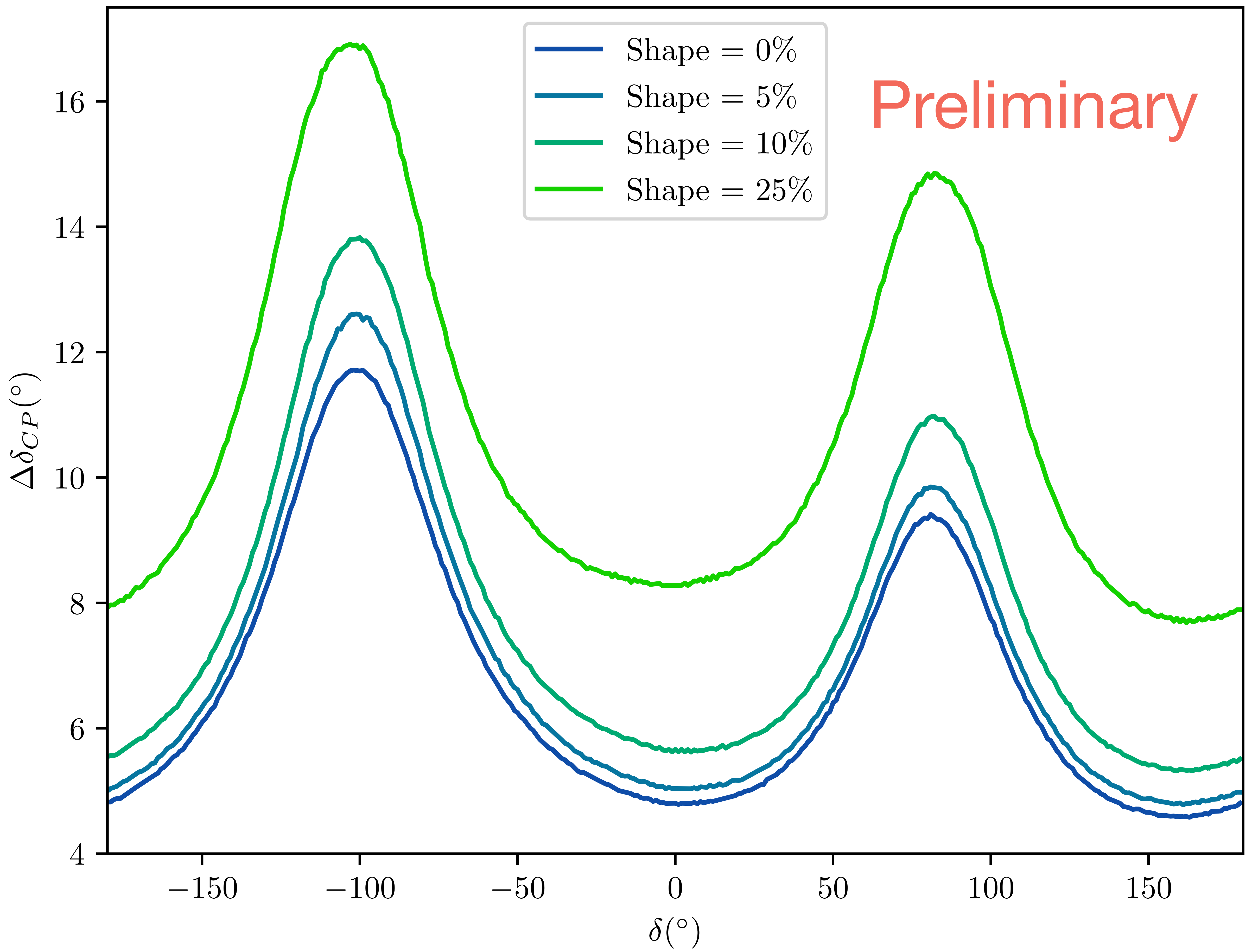
Effect of shape systematics

Beam + Atmospherics

$L = 360$ km



$L = 540$ km



Conclusions

- Combining **beam** and **atm** data particularly **enhance** the **physics reach of ESSnuSB**
- After **10 years**, the CP fraction for a 5σ discovery is >**70%**
- Optimise RT to maximise the precision on δ which can range from $\Delta\delta$~4.5º for CP conservation to $\Delta\delta$<12º ($\Delta\delta$<6º) at 540 (360) km for maximal CP violation
- Study of **spectral uncertainties** is fundamental. If they are not under control, then the **longer baseline closer to the second maximum** is **more resilient** against them.

Conclusions

- Combining **beam** and **atm** data particularly **enhance** the **physics reach of ESSnuSB**
- After **10 years**, the CP fraction for a 5σ discovery is >**70%**
- Optimise RT to maximise the precision on δ which can range from $\Delta\delta$~4.5º for CP conservation to $\Delta\delta$<12º ($\Delta\delta$<6º) at 540 (360) km for maximal CP violation
- Study of **spectral uncertainties** is fundamental. If they are not under control, then the **longer baseline closer to the second maximum** is **more resilient** against them.

Thank you!

Back up slides

Precision on δ

$$
\begin{aligned}
P^{\pm}_{\mu\to e} = {} & s_{23}^2 \sin^2 2\theta_{13} \left(\frac{\Delta_{31}}{\tilde{B}_{\mp}}\right)^2 \sin^2 \frac{\tilde{B}_{\mp} L}{2} \\
& + c_{23}^2 \sin^2 2\theta_{12} \left(\frac{\Delta_{21}}{A}\right)^2 \sin^2 \frac{AL}{2} \\
& + \tilde{J} \frac{\Delta_{21}}{A} \frac{\Delta_{31}}{\tilde{B}_{\mp}} \sin\left(\frac{AL}{2}\right) \sin\left(\frac{\tilde{B}_{\mp} L}{2}\right) \left(\cos\delta \cos\frac{\Delta_{31} L}{2} \pm \sin\delta \sin\frac{\Delta_{31} L}{2}\right)
\end{aligned}
$$

Precision on δ

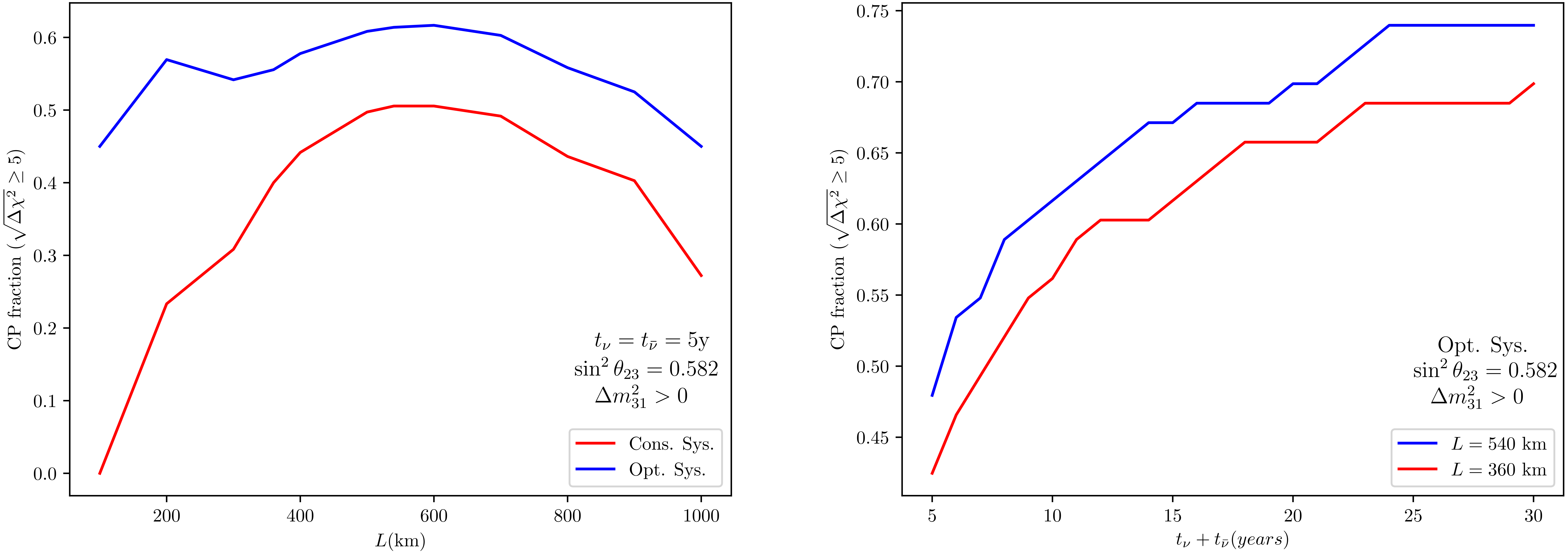
$$\frac{\partial \Delta P_{\mu\to e}}{\partial \delta} \propto -\sin\delta\cos\frac{\Delta_{31}L}{2} \pm \cos\delta\sin\frac{\Delta_{31}L}{2}$$

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

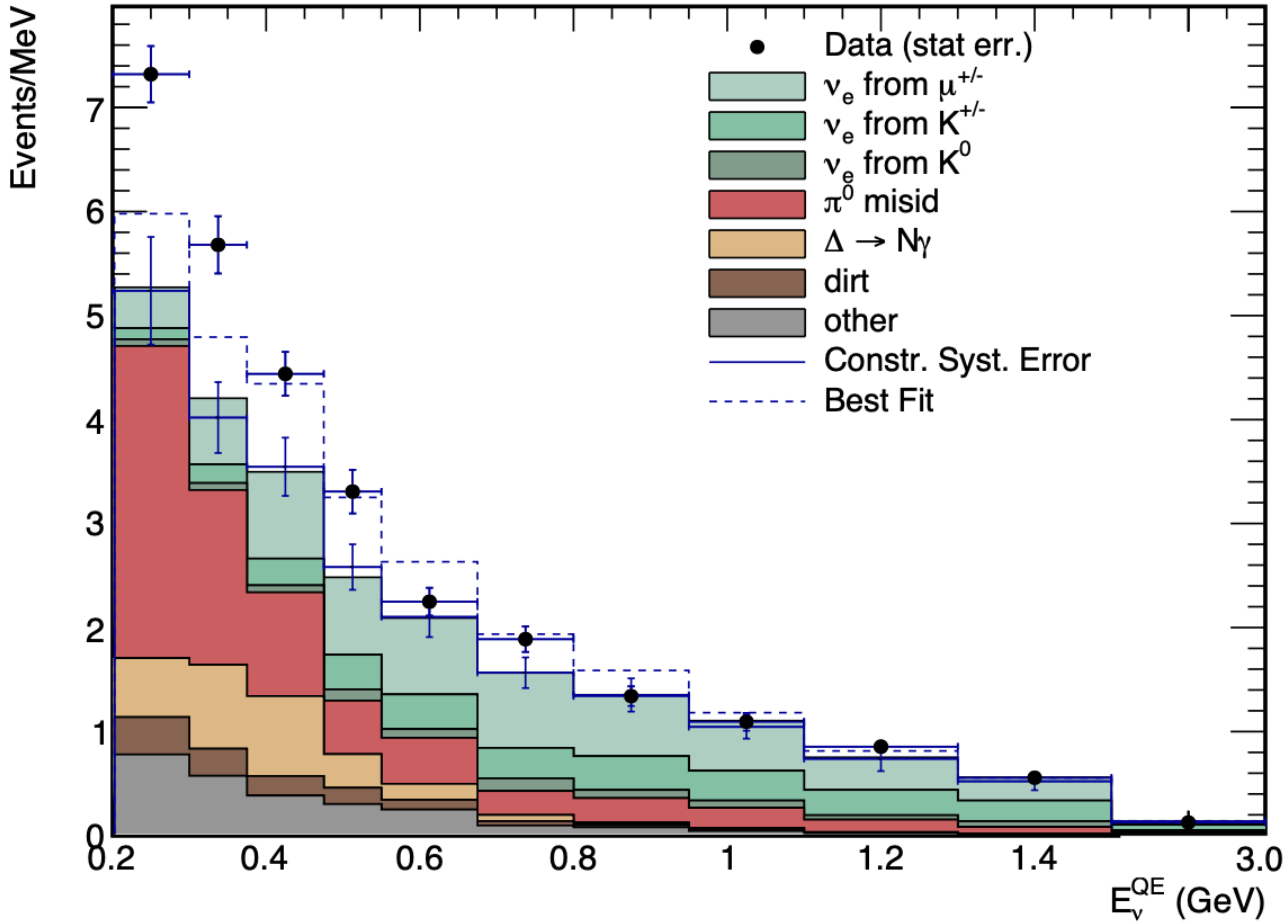
Non-standard oscillation searches

Light-sterile neutrino searches

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

ν_e appearance at SBL

MiniBooNE Collaboration 2006.16883



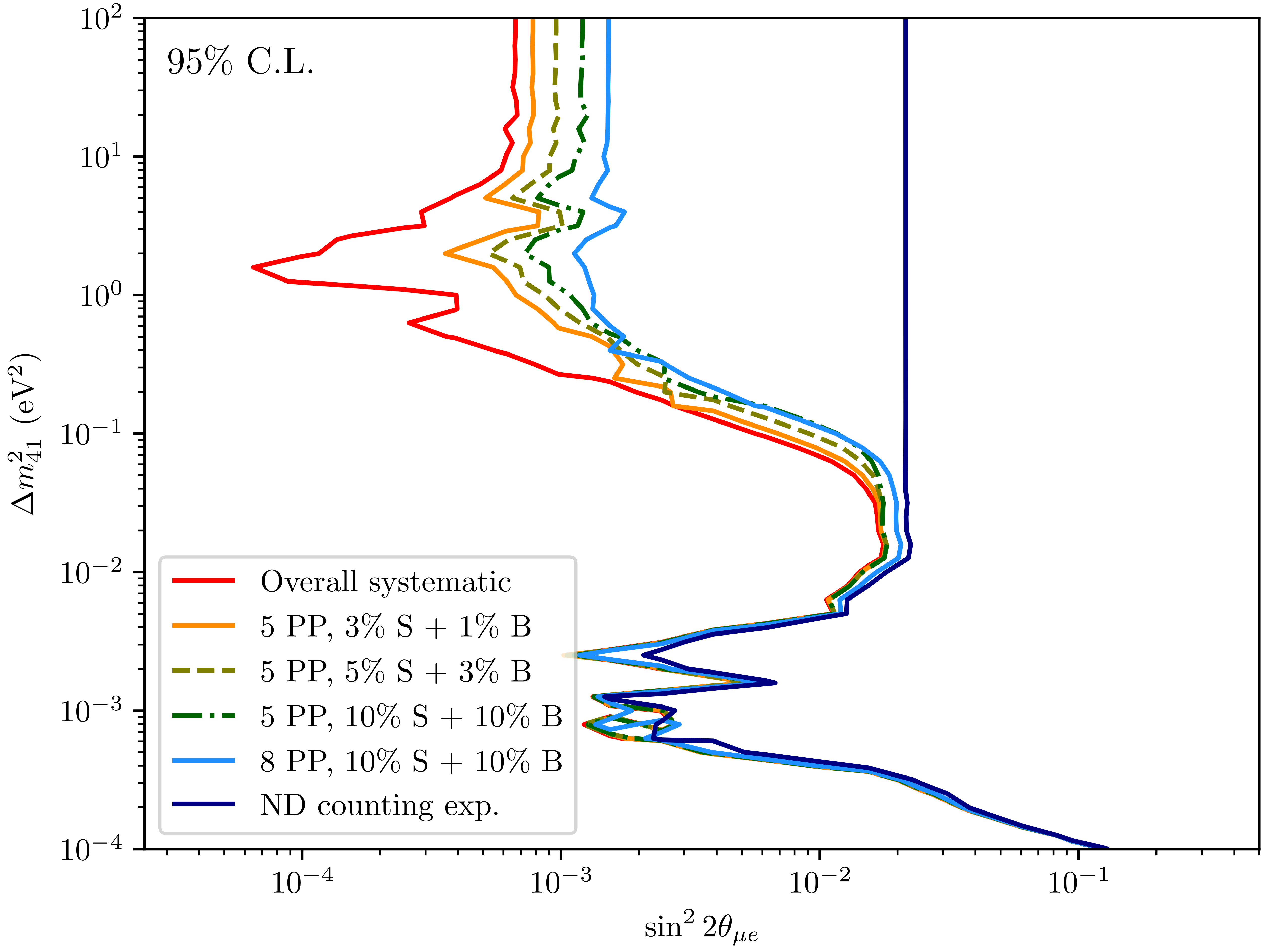
Light-sterile neutrino searches

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

Simulation details

- ND+FD analysis
- Conservative systematics

M. Gosh *et al.* 1912.10010



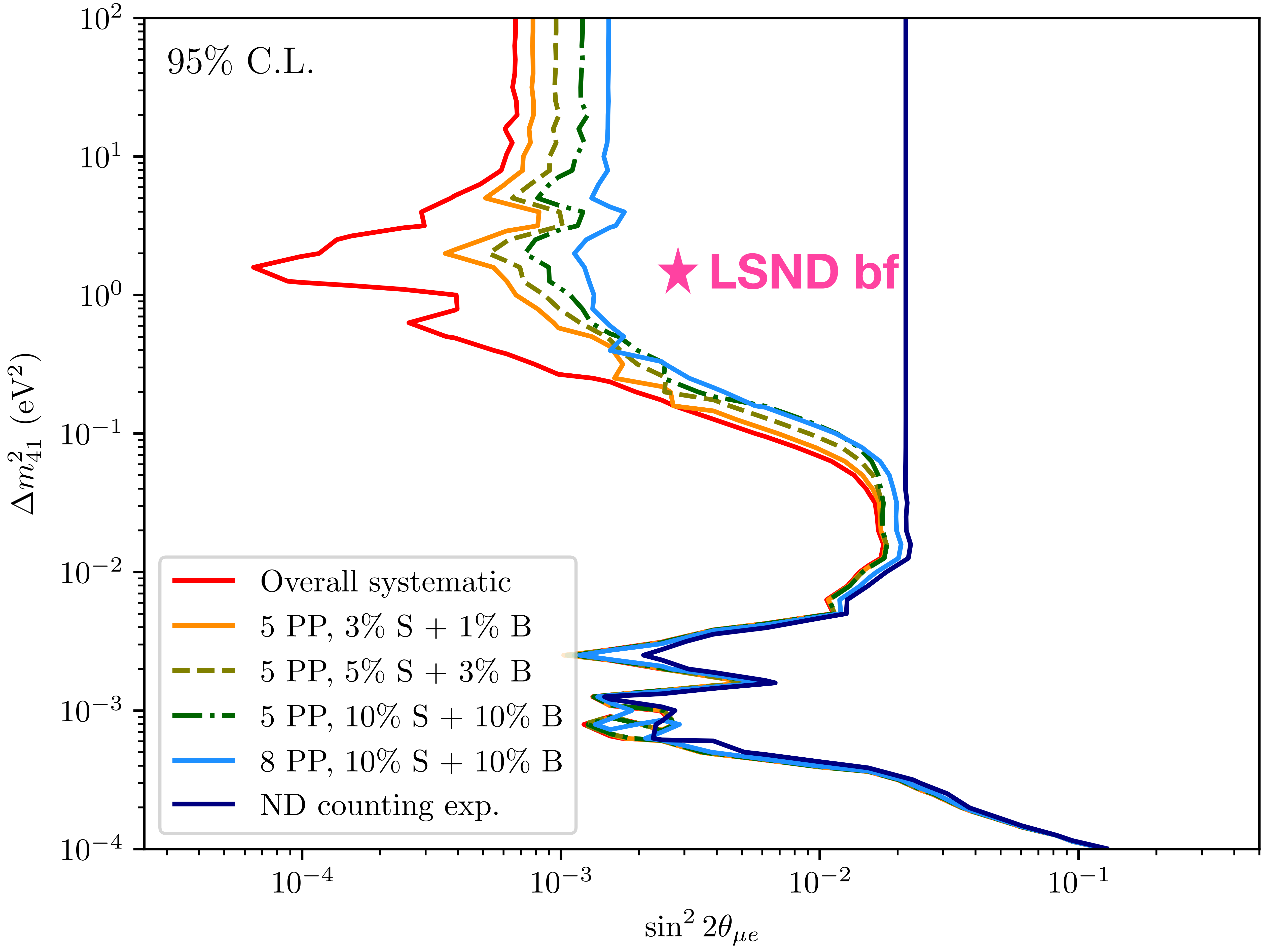
Light-sterile neutrino searches

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

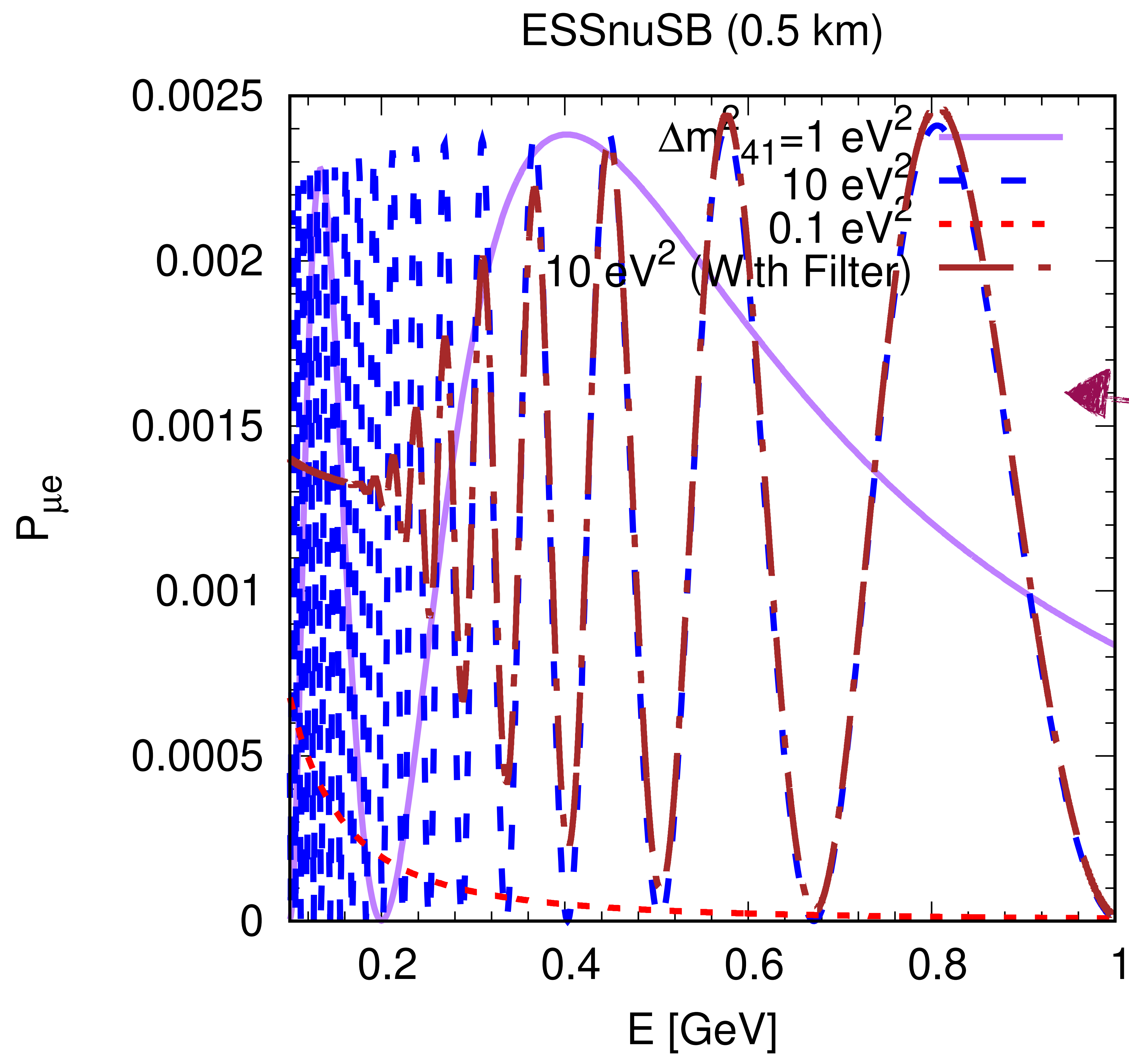
Simulation details

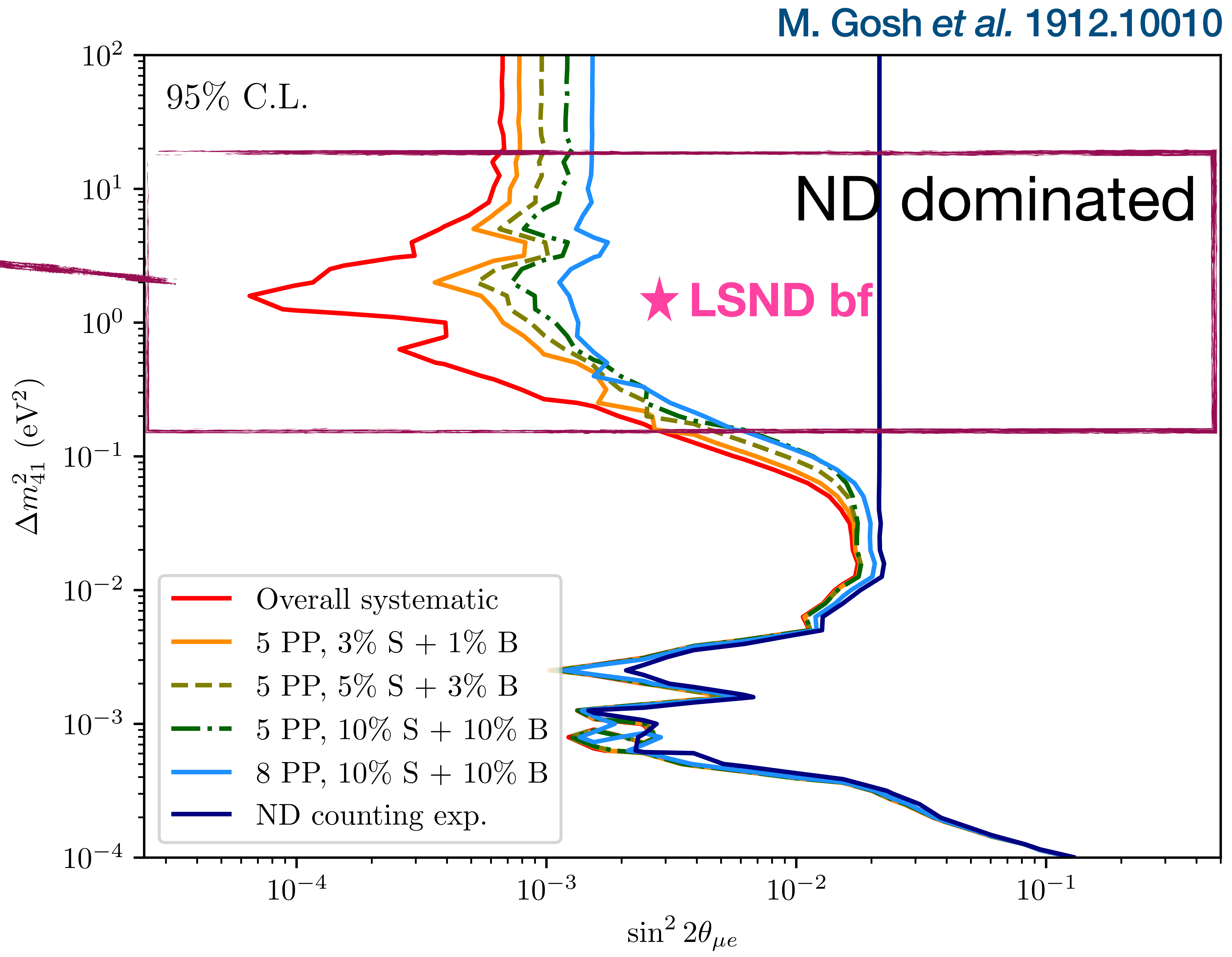
- ND+FD analysis
- Conservative systematics

M. Gosh *et al.* 1912.10010



Light-sterile neutrino searches





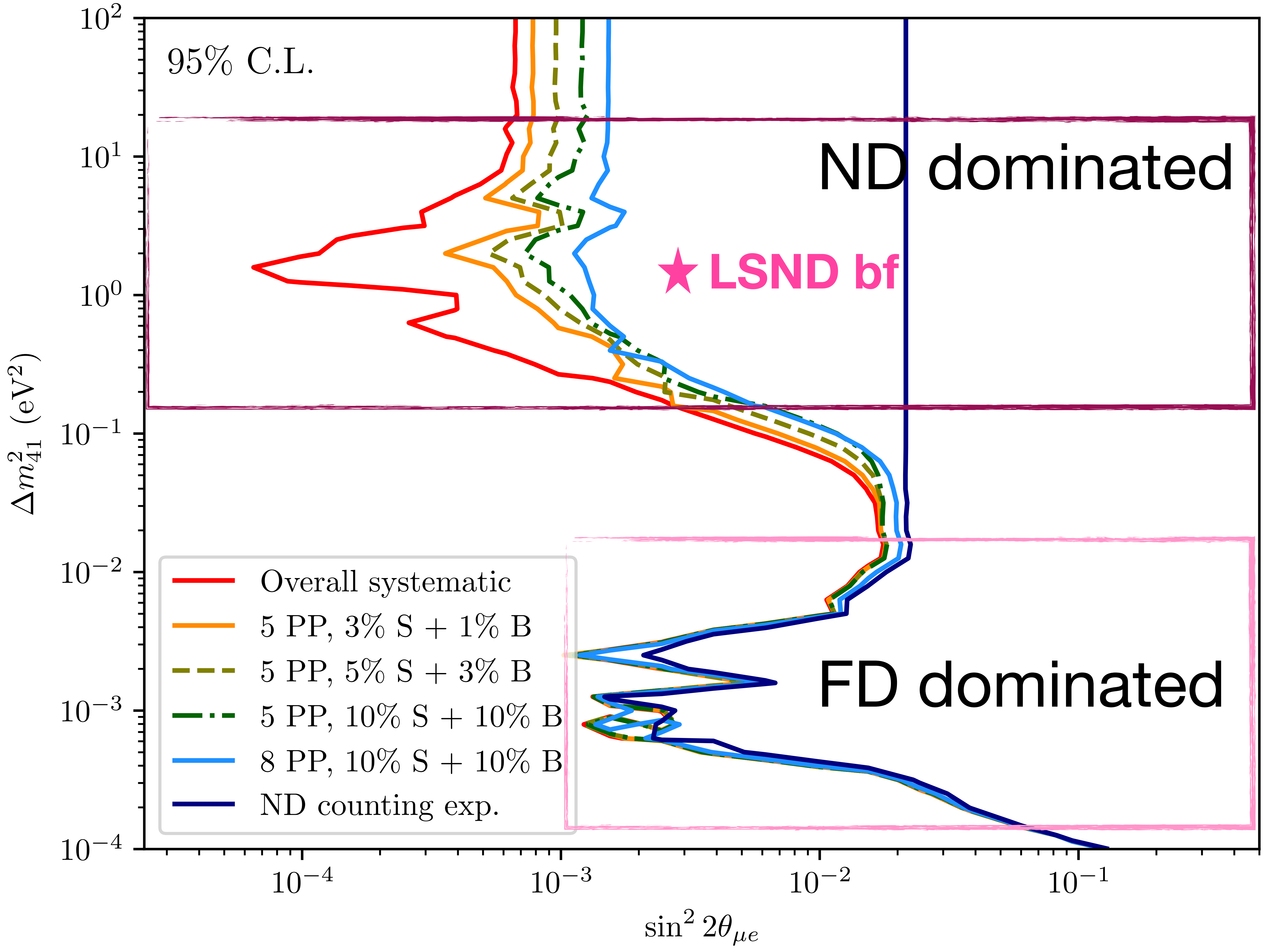
Light-sterile neutrino searches

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

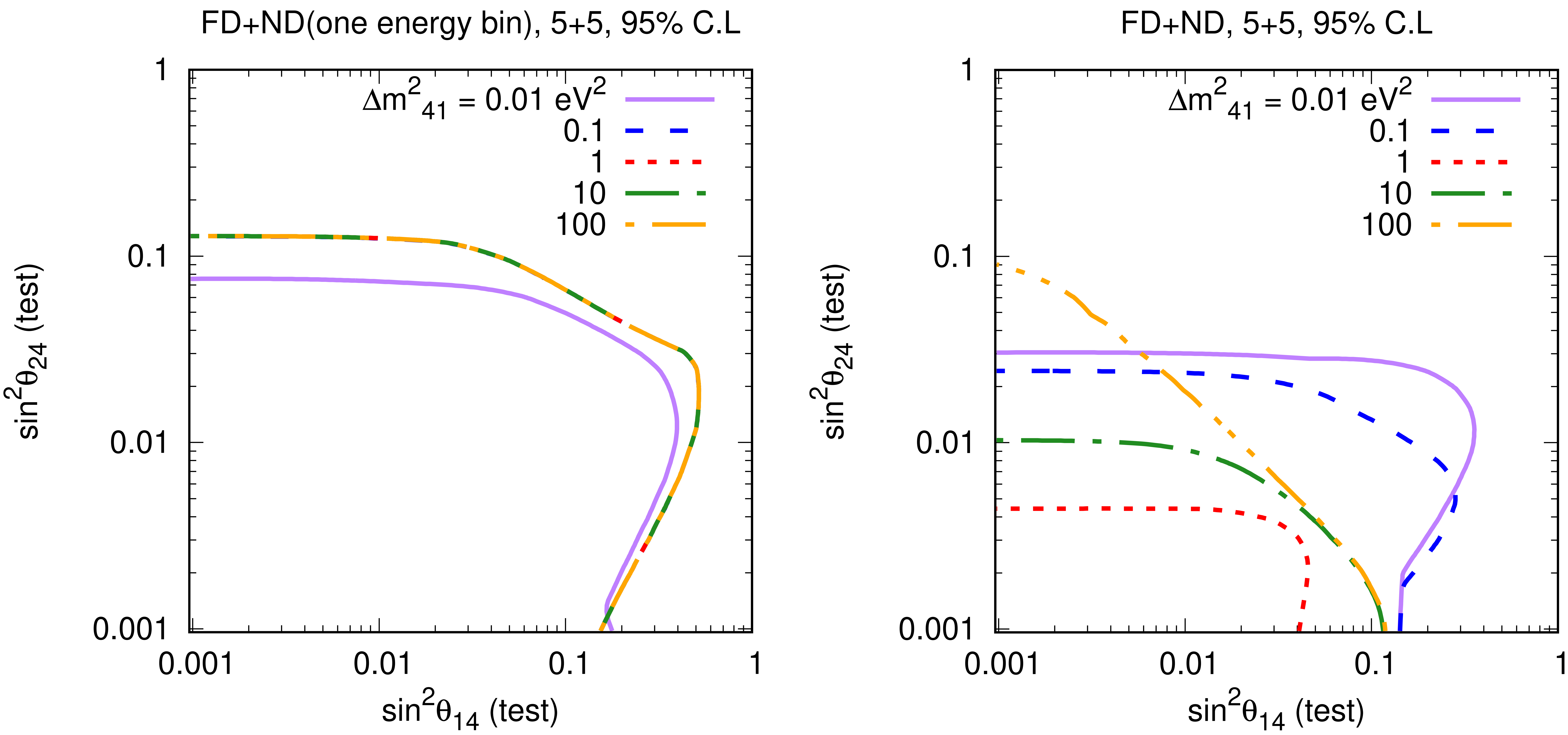
Simulation details

- ND+FD analysis
- Conservative systematics

M. Gosh *et al.* 1912.10010



Determination of the sterile parameters

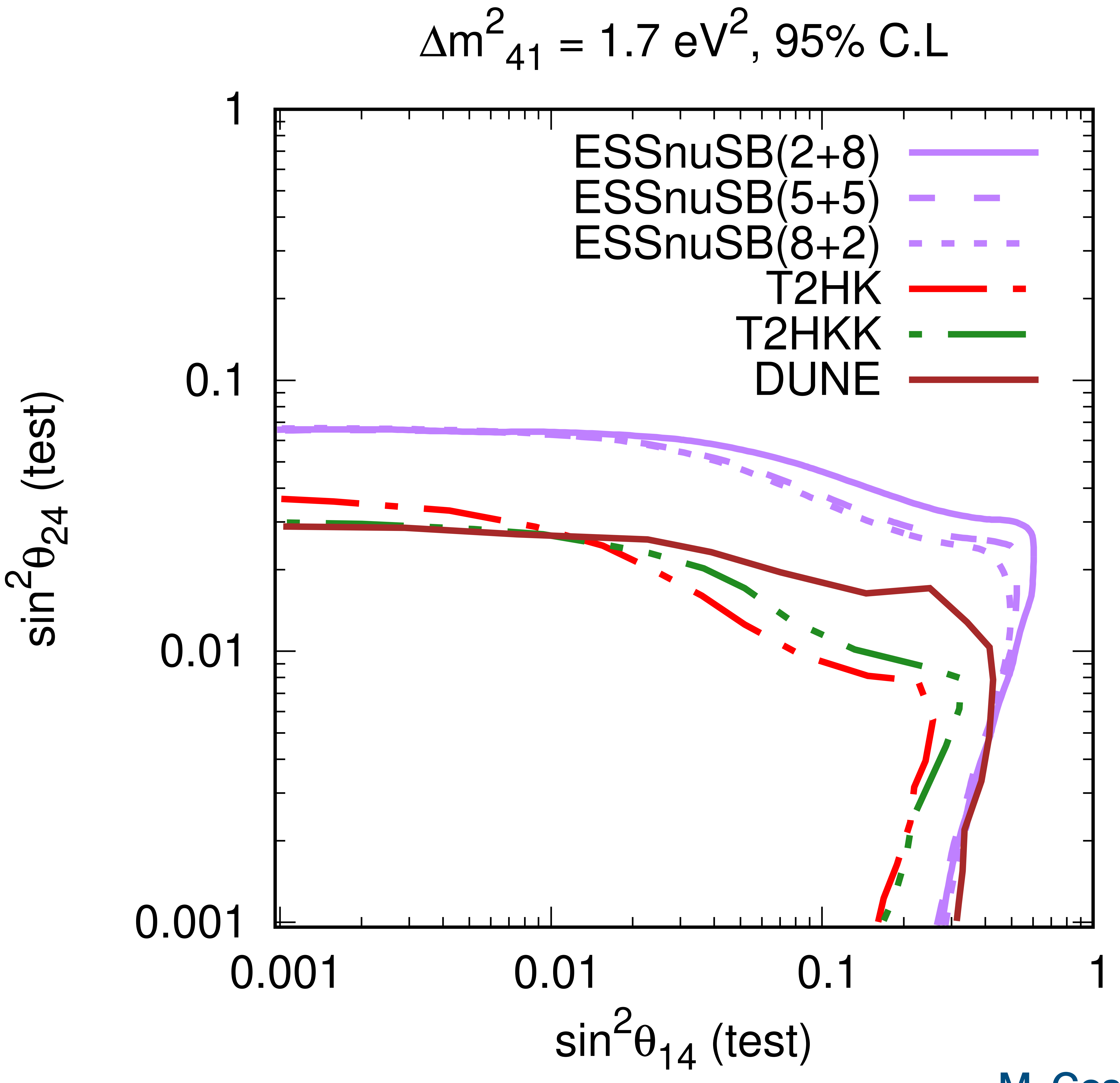


M. Gosh *et al.* 1912.10010

Determination of the sterile parameters

Systematics

- 8% signal
- 10% bkg



M. Gosh *et al.* 1912.10010

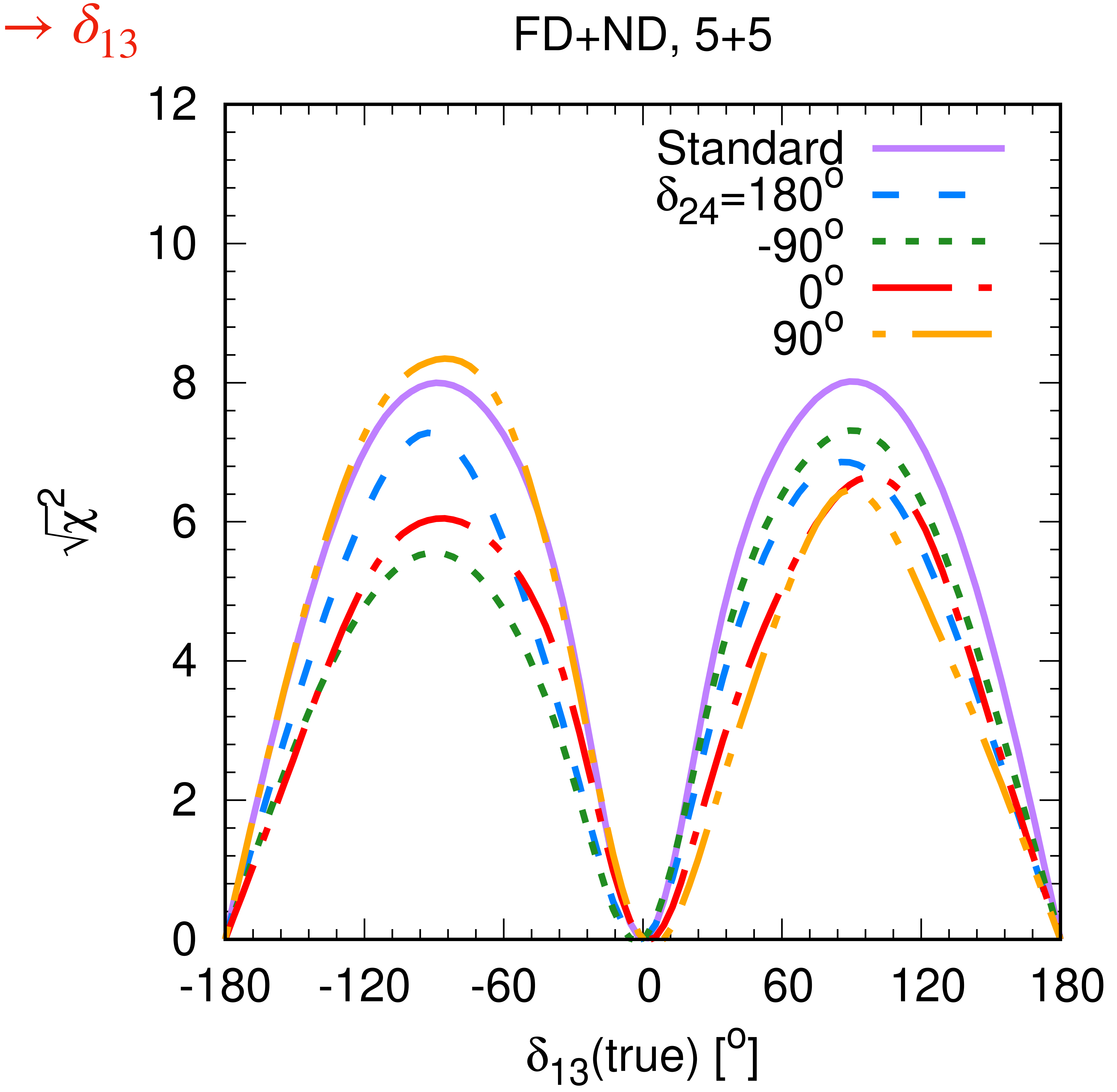
Impact of a sterile on δ

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

$$\Delta m_{41}^2 = 1 eV^2$$

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

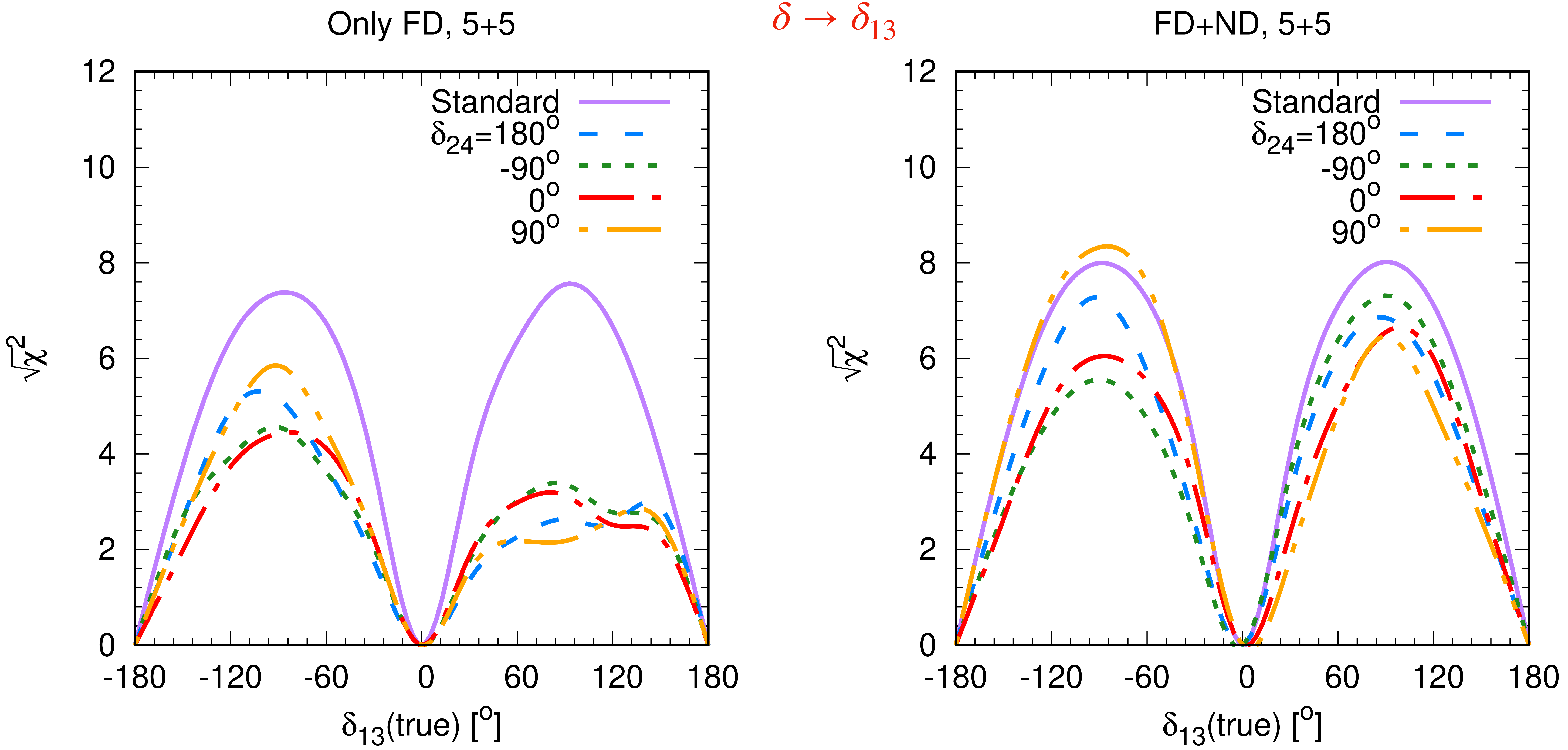
$\delta \to \delta_{13}$



M. Gosh *et al.* 1912.10010

Impact of a sterile on δ

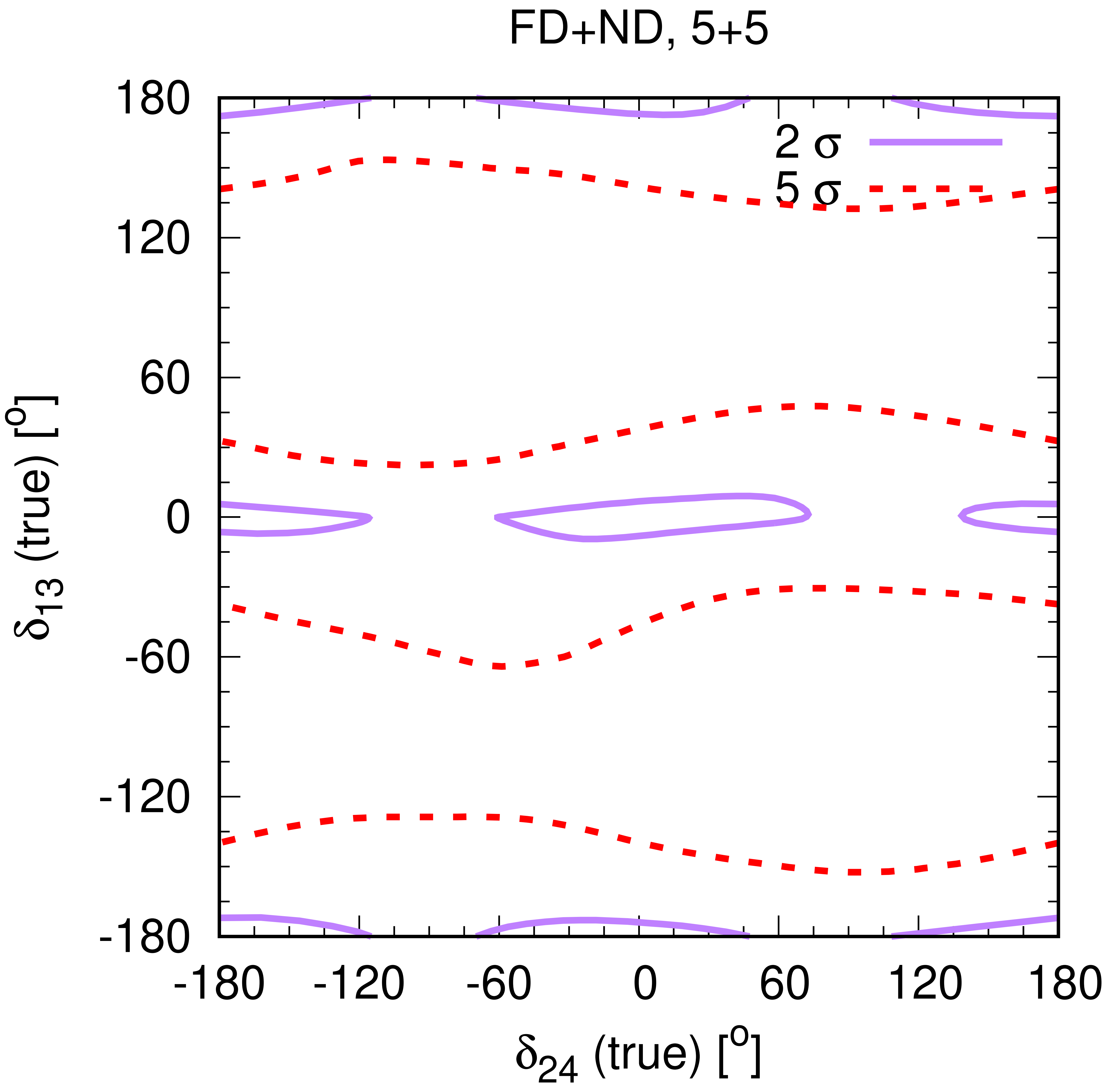
$\delta \rightarrow \delta_{13}$



M. Gosh *et al.* 1912.10010

Sensitivity to CP violation

CP violation discovery still possible for any δ_{24}



Flavour models

PMNS mixing matrix structure → Discrete flavour symmetry

Flavour models

PMNS mixing matrix structure → Discrete flavour symmetry

Can we test these models? Is it possible to differentiate among them?

Model	Case [Ref.]	Group	$\sin^2\theta_{12}$	$\sin^2\theta_{23}$	δ_{CP}	χ^2_{min}
1.1	VII-b [18]	$A_5 \rtimes$ CP	0.331	0.523	180°	5.37
1.2	III [18]	$A_5 \rtimes$ CP	0.283	0.593	180°	5.97
1.3	IV [17]	$S_4 \rtimes$ CP	0.318	1/2	±90°	7.28
1.4	II [17]	$S_4 \rtimes$ CP	0.341	0.606	180°	8.91
1.5	IV [18]	$A_5 \rtimes$ CP	0.283	1/2	±90°	11.3
2.1	A1 [21]	A_5	—	0.554	$f_1(\theta_{12})$	0.151
2.2	B2 [21]	S_4	0.318	—	$f_2(\theta_{23})$	0.386
2.3	B2 [21]	A_5	0.330	—	$f_3(\theta_{23})$	2.49
2.4	B1 [21]	A_5	0.283	—	$f_4(\theta_{23})$	4.40
2.5	B1 [21]	$A_4/S_4/A_5$	0.341	—	$f_5(\theta_{23})$	5.67

M. Blennow *et al.* 2005.12277

Models in agreement with oscillation data at 3σ

Flavour models

PMNS mixing matrix structure → Discrete flavour symmetry

Can we test these models? Is it possible to differentiate among them?

Model	Case [Ref.]	Group	$\sin^2\theta_{12}$	$\sin^2\theta_{23}$	δ_{CP}	χ^2_{min}
1.1	VII-b [18]	$A_5 \rtimes CP$	0.331	0.523	180°	5.37
1.2	III [18]	$A_5 \rtimes CP$	0.283	0.593	180°	5.97
1.3	IV [17]	$S_4 \rtimes CP$	0.318	1/2	±90°	7.28
1.4	II [17]	$S_4 \rtimes CP$	0.341	0.606	180°	8.91
1.5	IV [18]	$A_5 \rtimes CP$	0.283	1/2	±90°	11.3
2.1	A1 [21]	A_5	—	0.554	$f_1(\theta_{12})$	0.151
2.2	B2 [21]	S_4	0.318	—	$f_2(\theta_{23})$	0.386
2.3	B2 [21]	A_5	0.330	—	$f_3(\theta_{23})$	2.49
2.4	B1 [21]	A_5	0.283	—	$f_4(\theta_{23})$	4.40
2.5	B1 [21]	$A_4/S_4/A_5$	0.341	—	$f_5(\theta_{23})$	5.67

M. Blennow *et al.* 2005.12277

Models 1.1–1.5 → One-parameter models

Flavour models

PMNS mixing matrix structure → Discrete flavour symmetry

Can we test these models? Is it possible to differentiate among them?

M. Blennow *et al.* 2005.12277

Model	Case [Ref.]	Group	$\sin^2\theta_{12}$	$\sin^2\theta_{23}$	δ_{CP}	χ^2_{min}
1.1	VII-b [18]	$A_5 \rtimes CP$	0.331	0.523	180°	5.37
1.2	III [18]	$A_5 \rtimes CP$	0.283	0.593	180°	5.97
1.3	IV [17]	$S_4 \rtimes CP$	0.318	1/2	±90°	7.28
1.4	II [17]	$S_4 \rtimes CP$	0.341	0.606	180°	8.91
1.5	IV [18]	$A_5 \rtimes CP$	0.283	1/2	±90°	11.3
2.1	A1 [21]	A_5	—	0.554	$f_1(\theta_{12})$	0.151
2.2	B2 [21]	S_4	0.318	—	$f_2(\theta_{23})$	0.386
2.3	B2 [21]	A_5	0.330	—	$f_3(\theta_{23})$	2.49
2.4	B1 [21]	A_5	0.283	—	$f_4(\theta_{23})$	4.40
2.5	B1 [21]	$A_4/S_4/A_5$	0.341	—	$f_5(\theta_{23})$	5.67

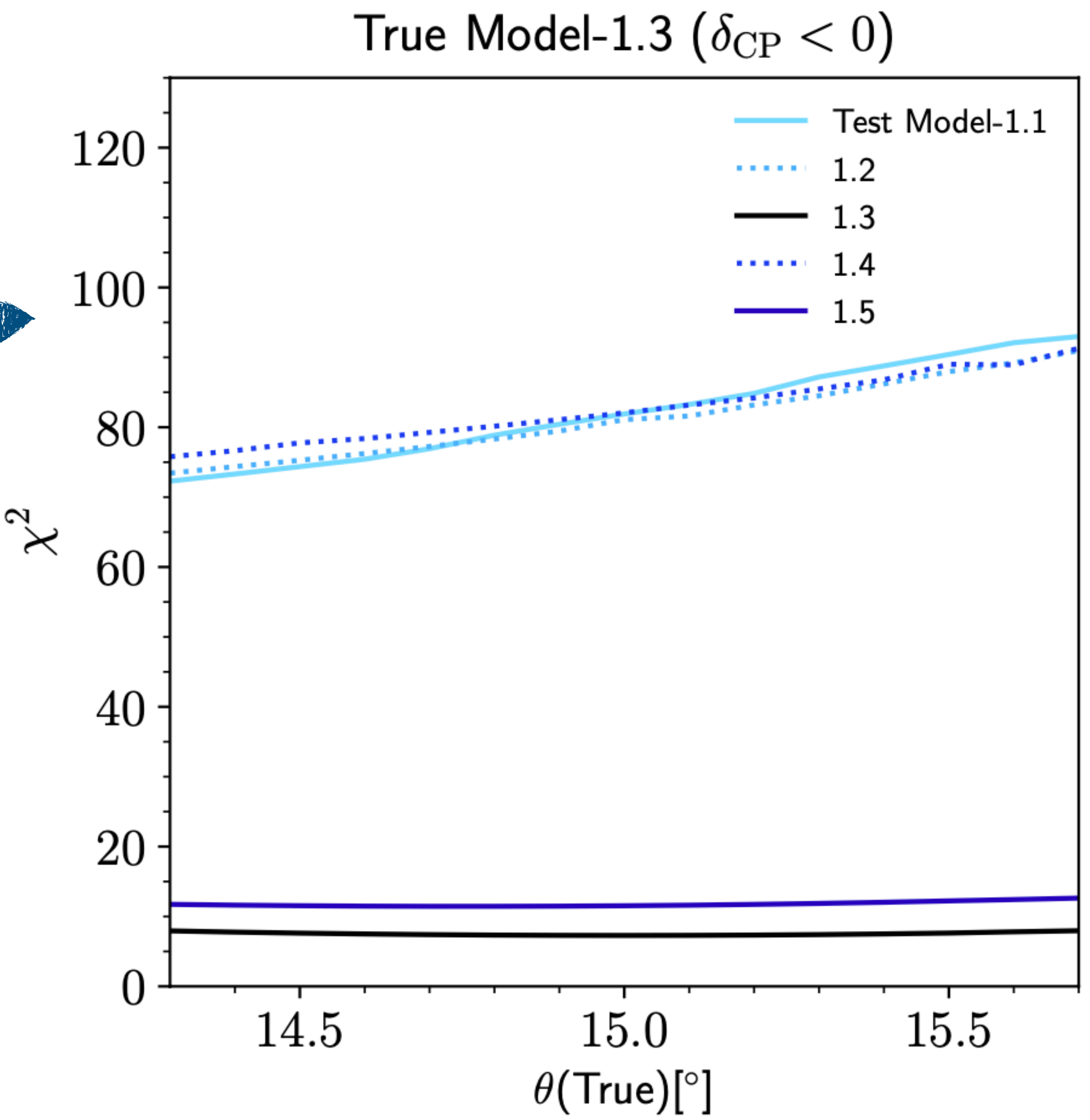
Models 1.1–1.5 → One-parameter models

Models 2.1–2.5 → Two-parameter models

Flavour models

Can we differentiate among models?

Model	Case [Ref.]	Group	$\sin^2\theta_{12}$	$\sin^2\theta_{23}$	δ_{CP}	χ^2_{min}
1.1	VII-b [18]	$A_5 \rtimes CP$	0.331	0.523	180°	5.37
1.2	III [18]	$A_5 \rtimes CP$	0.283	0.593	180°	5.97
1.3	IV [17]	$S_4 \rtimes CP$	0.318	1/2	±90°	7.28
1.4	II [17]	$S_4 \rtimes CP$	0.341	0.606	180°	8.91
1.5	IV [18]	$A_5 \rtimes CP$	0.283	1/2	±90°	11.3
2.1	A1 [21]	A_5	—	0.554	$f_1(\theta_{12})$	0.151
2.2	B2 [21]	S_4	0.318	—	$f_2(\theta_{23})$	0.386
2.3	B2 [21]	A_5	0.330	—	$f_3(\theta_{23})$	2.49
2.4	B1 [21]	A_5	0.283	—	$f_4(\theta_{23})$	4.40
2.5	B1 [21]	$A_4/S_4/A_5$	0.341	—	$f_5(\theta_{23})$	5.67

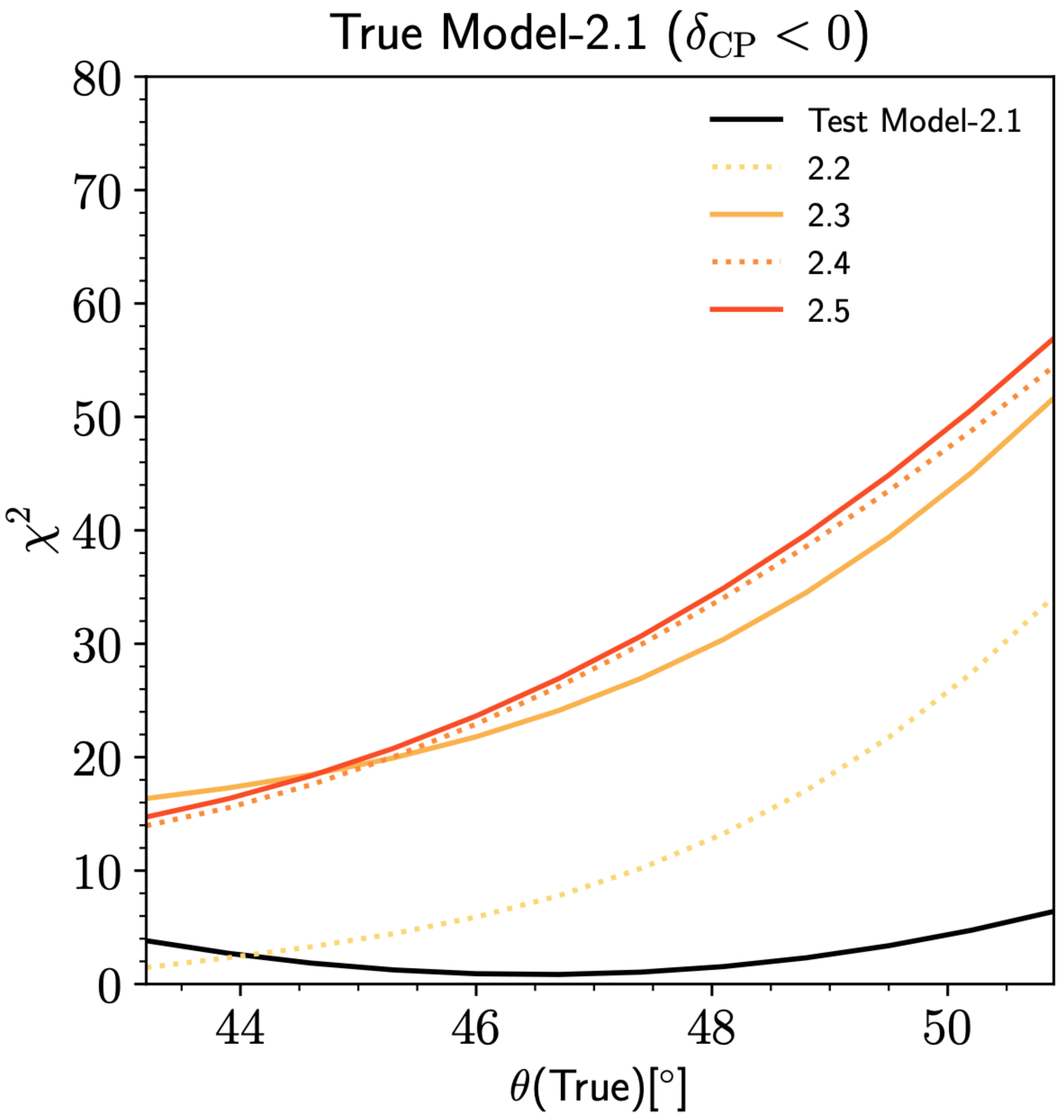


M. Blennow *et al.* 2004.00017

Flavour models

Can we differentiate among models?

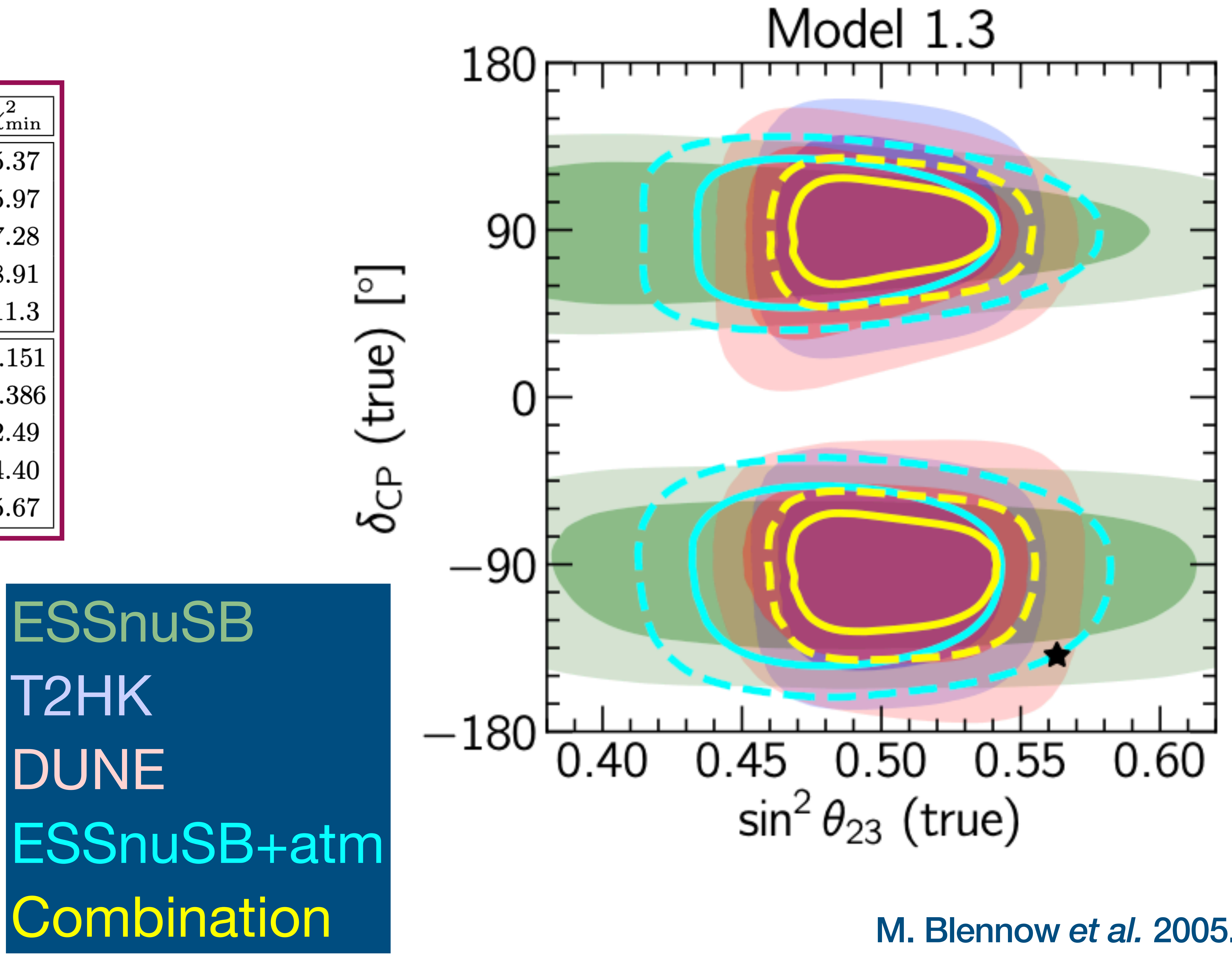
Model	Case [Ref.]	Group	$\sin^2\theta_{12}$	$\sin^2\theta_{23}$	δ_{CP}	χ^2_{min}
1.1	VII-b [18]	$A_5 \rtimes CP$	0.331	0.523	180°	5.37
1.2	III [18]	$A_5 \rtimes CP$	0.283	0.593	180°	5.97
1.3	IV [17]	$S_4 \rtimes CP$	0.318	1/2	±90°	7.28
1.4	II [17]	$S_4 \rtimes CP$	0.341	0.606	180°	8.91
1.5	IV [18]	$A_5 \rtimes CP$	0.283	1/2	±90°	11.3
2.1	A1 [21]	A_5	—	0.554	$f_1(\theta_{12})$	0.151
2.2	B2 [21]	S_4	0.318	—	$f_2(\theta_{23})$	0.386
2.3	B2 [21]	A_5	0.330	—	$f_3(\theta_{23})$	2.49
2.4	B1 [21]	A_5	0.283	—	$f_4(\theta_{23})$	4.40
2.5	B1 [21]	$A_4/S_4/A_5$	0.341	—	$f_5(\theta_{23})$	5.67



M. Blennow *et al.* 2004.00017

Future experimental sensitivities

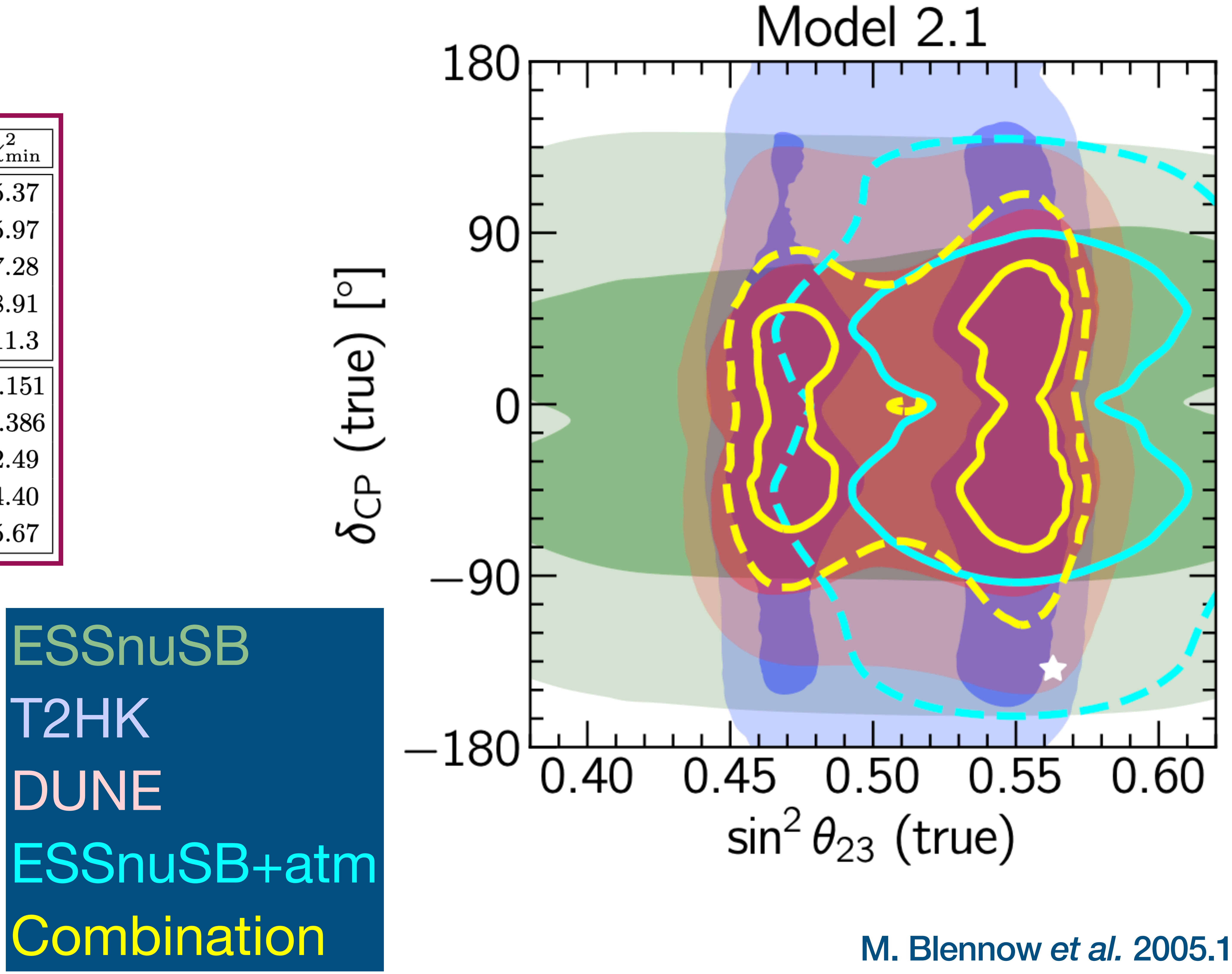
Model	Case [Ref.]	Group	$\sin^2\theta_{12}$	$\sin^2\theta_{23}$	δ_{CP}	χ^2_{min}
1.1	VII-b [18]	$A_5 \rtimes CP$	0.331	0.523	180°	5.37
1.2	III [18]	$A_5 \rtimes CP$	0.283	0.593	180°	5.97
1.3	IV [17]	$S_4 \rtimes CP$	0.318	1/2	±90°	7.28
1.4	II [17]	$S_4 \rtimes CP$	0.341	0.606	180°	8.91
1.5	IV [18]	$A_5 \rtimes CP$	0.283	1/2	±90°	11.3
2.1	A1 [21]	A_5	—	0.554	$f_1(\theta_{12})$	0.151
2.2	B2 [21]	S_4	0.318	—	$f_2(\theta_{23})$	0.386
2.3	B2 [21]	A_5	0.330	—	$f_3(\theta_{23})$	2.49
2.4	B1 [21]	A_5	0.283	—	$f_4(\theta_{23})$	4.40
2.5	B1 [21]	$A_4/S_4/A_5$	0.341	—	$f_5(\theta_{23})$	5.67



M. Blennow *et al.* 2005.12277

Future experimental sensitivities

Model	Case [Ref.]	Group	$\sin^2\theta_{12}$	$\sin^2\theta_{23}$	δ_{CP}	χ^2_{min}
1.1	VII-b [18]	$A_5 \rtimes$ CP	0.331	0.523	180°	5.37
1.2	III [18]	$A_5 \rtimes$ CP	0.283	0.593	180°	5.97
1.3	IV [17]	$S_4 \rtimes$ CP	0.318	1/2	±90°	7.28
1.4	II [17]	$S_4 \rtimes$ CP	0.341	0.606	180°	8.91
1.5	IV [18]	$A_5 \rtimes$ CP	0.283	1/2	±90°	11.3
2.1	A1 [21]	A_5	—	0.554	$f_1(\theta_{12})$	0.151
2.2	B2 [21]	S_4	0.318	—	$f_2(\theta_{23})$	0.386
2.3	B2 [21]	A_5	0.330	—	$f_3(\theta_{23})$	2.49
2.4	B1 [21]	A_5	0.283	—	$f_4(\theta_{23})$	4.40
2.5	B1 [21]	$A_4/S_4/A_5$	0.341	—	$f_5(\theta_{23})$	5.67



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 $\Delta\delta$~6° for CP conservation to $\Delta\delta$<18° for maximal CP violation

Beyond 3ν oscillation searches:

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