NuFact05 workshop

Resolving parameter degeneracies in long-baseline experiments with atmospheric neutrino data

Thomas Schwetz

SISSA, Trieste

based on:

P. Huber, M. Maltoni, TS, PRD 71 (2005) 053006 [hep-ph/0501037]

Introduction

Goals for future neutrino oscillation experiments:

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- How small is θ_{13}?

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- What is the value of the CP phase $\delta_{\rm CP}$?

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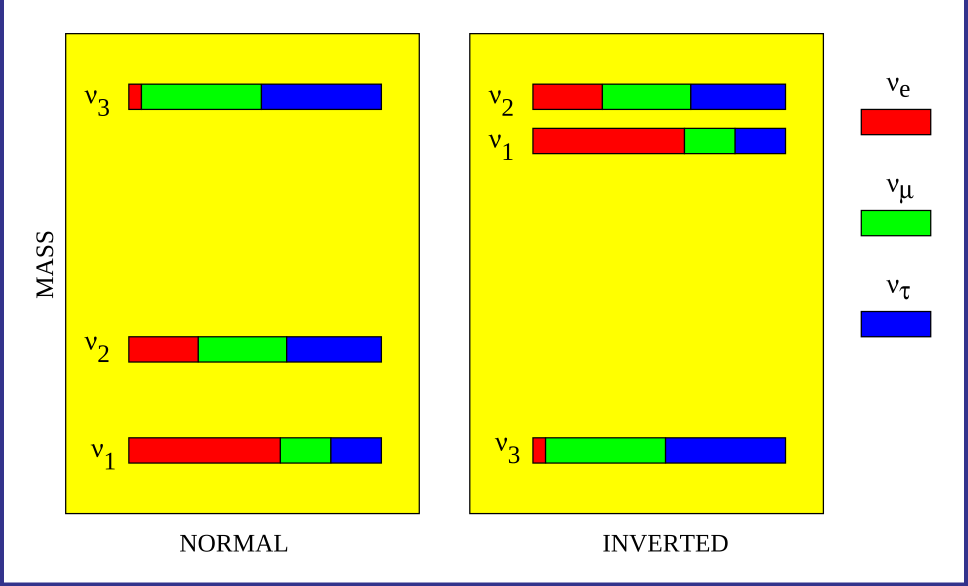
Goals for future neutrino oscillation experiments:

- How small is θ_{13}?
- What is the value of the CP phase δ_{CP}?
- Type of the neutrino mass ordering (sign of Δm^2_{31})



Parameter degeneracies in LBL experiments

G.L. Fogli, E. Lisi, Phys. Rev. D54 (1996) 3667
J. Burguet-Castell et al., Nucl. Phys. B608 (2001) 301
M. Koike, T. Ota, J. Sato, Phys. Rev. D65 (2002) 053015
H. Minakata, H. Nunokawa, JHEP 10 (2001) 001
V.Barger, D.Marfatia, K.Whisnant, Phys. Rev. D65 (2002) 073023; D66 (2002) 053007
P.Huber, M.Lindner, W.Winter, Nucl. Phys. B645 (2002) 3; Nucl. Phys. B654 (2003) 3
J. Burguet-Castell et al., Nucl.Phys. B646 (2002) 301
O. Yasuda, New J. Phys. 6 (2004) 83
A.Donini, D.Meloni, S.Rigolin, JHEP **0406** (2004) 011

and many more (I appologize for omissions)

The 8-fold degeneracy

- The intrinsic or $(\delta_{\rm CP}, \theta_{13})$ degeneracy
  J. Burguet-Castell et al., Nucl. Phys. B608 (2001) 301
  several solutions in the $(\delta_{\rm CP}, \theta_{13})$ plane

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\begin{aligned}
P_{\mu e} \quad \simeq & \quad \sin^2 2\theta_{13} \sin^2 \theta_{23} \sin^2 \Delta_{31} + \alpha^2 \sin^2 2\theta_{12} \cos^2 \theta_{23} \Delta_{31}^2 \\
+ & \quad \alpha \sin 2\theta_{12} \sin 2\theta_{13} \sin 2\theta_{23} \Delta_{31} \sin \Delta_{31} \cos(\Delta_{31} \pm \delta_{\rm CP})
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  ν_μ-disappearance chanel gives only $\sin^2 2\theta_{23}$
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overall an 8-fold degeneracy

V.Barger, D.Marfatia, K.Whisnant, Phys. Rev. D65 (2002) 073023

The T2K-II *long-baseline experiment*

4 MW superbeam at JPARC
mean neutrino energy: 0.76 GeV (2° OA)
1 Mt Cherenkov detector at Kamioka
baseline: 295 km

	ν (2 Mt yrs)	$\bar{\nu}$ (6 Mt yrs)
$\nu_\mu \to \nu_e$ signal	21 300	16 000
$\nu_\mu \to \nu_e$ background	2 140	3 260
$\nu_\mu \to \nu_\mu$ signal	73 200	75 600
$\nu_\mu \to \nu_\mu$ background	340	320

$\sin^2 2\theta_{13} = 0.05$, $\sin^2\theta_{23} = 0.5$, $\sin^2\theta_{12} = 0.3$, $\delta_{\rm CP} = 0$,
$\Delta m^2_{21} = 8.1 \times 10^{-5}$ eV^2, $\Delta m^2_{31} = 2.2 \times 10^{-3}$ eV^2

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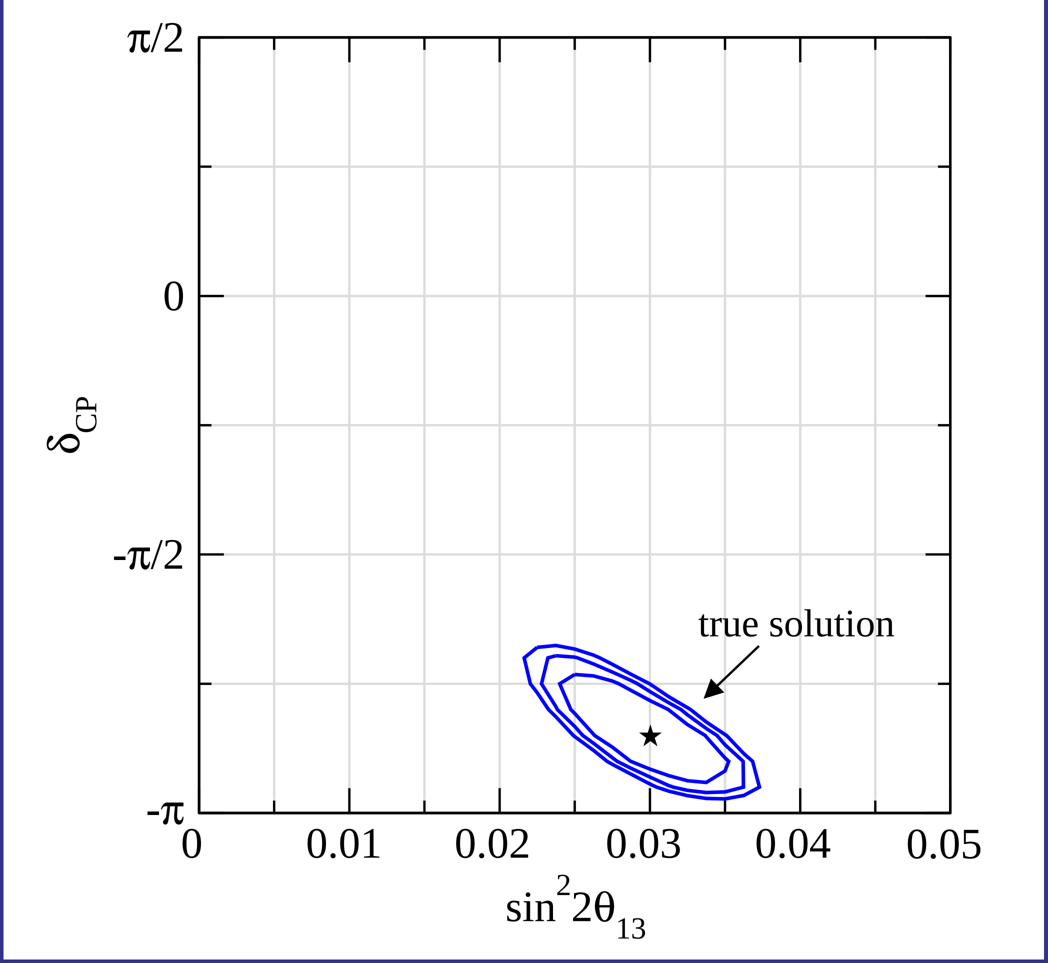
GLoBES software P. Huber, M. Lindner, W. Winter, hep-ph/0407333

http://www.ph.tum.de/~globes/

Degeneracies and T2K-II



allowed regions at 2σ, 99%, 3σ CL

true values:

$\sin^2 2\theta_{13} = 0.03$

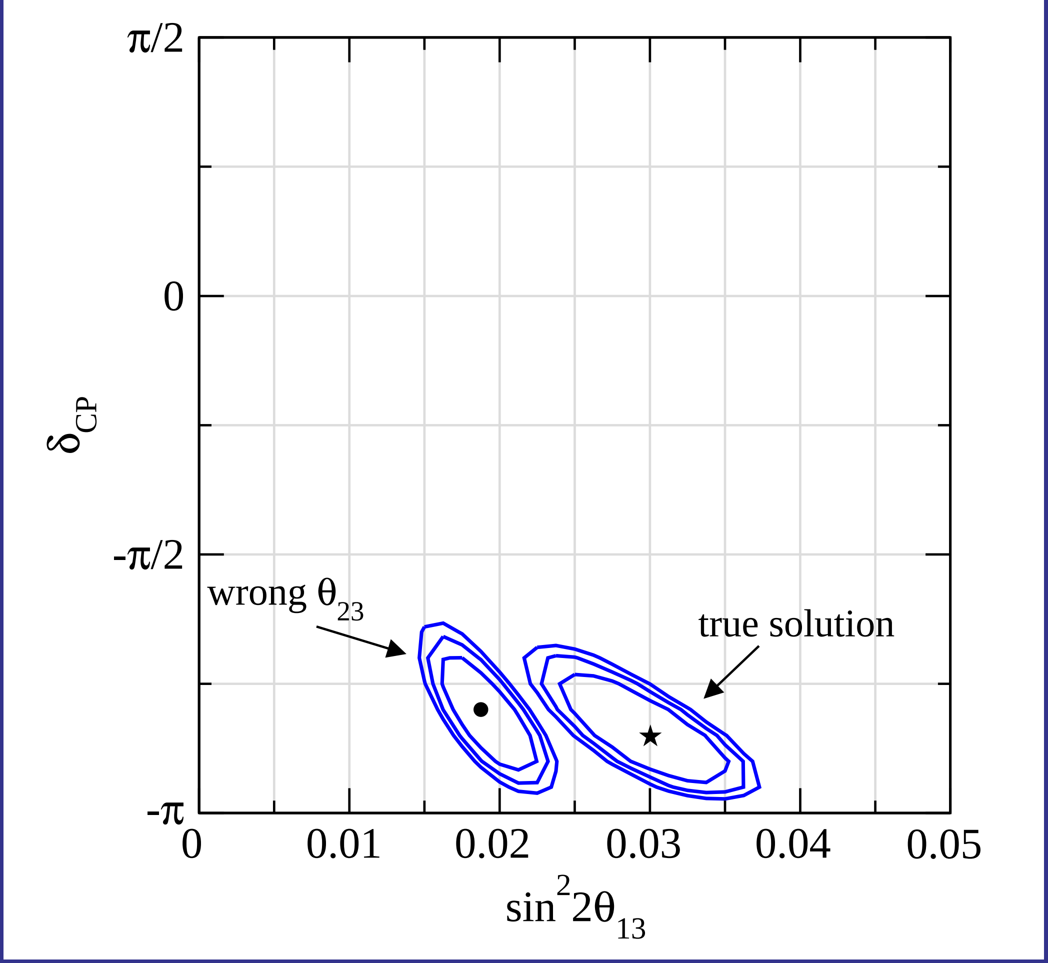
$\delta_{\rm CP} = -0.85\pi$

$\sin^2 \theta_{23} = 0.4$

$\Delta m^2_{31} = 2.2 \times 10^{-3} {\rm eV}^2$

The $(\delta_{\rm CP}, \theta_{13})$ degeneracy is not present for T2K-II because of spectral information

Degeneracies and **T2K-II**



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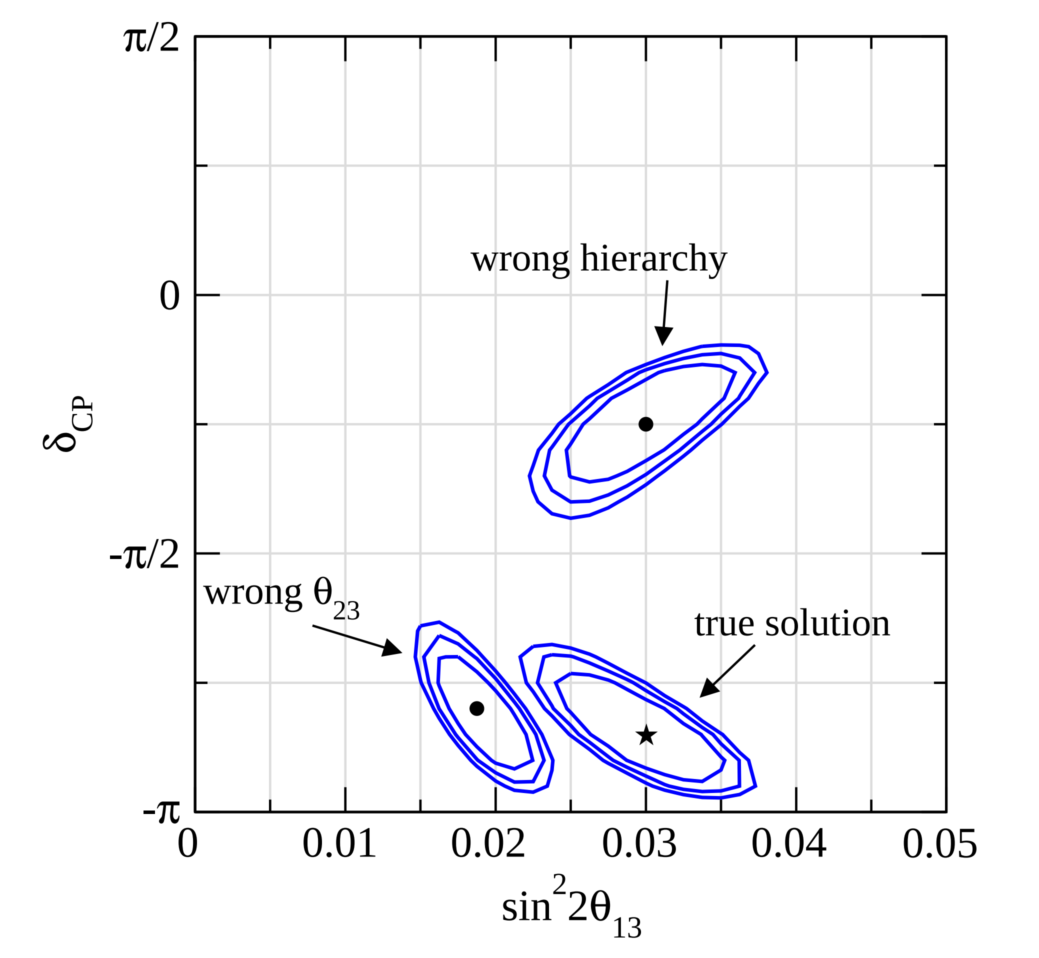

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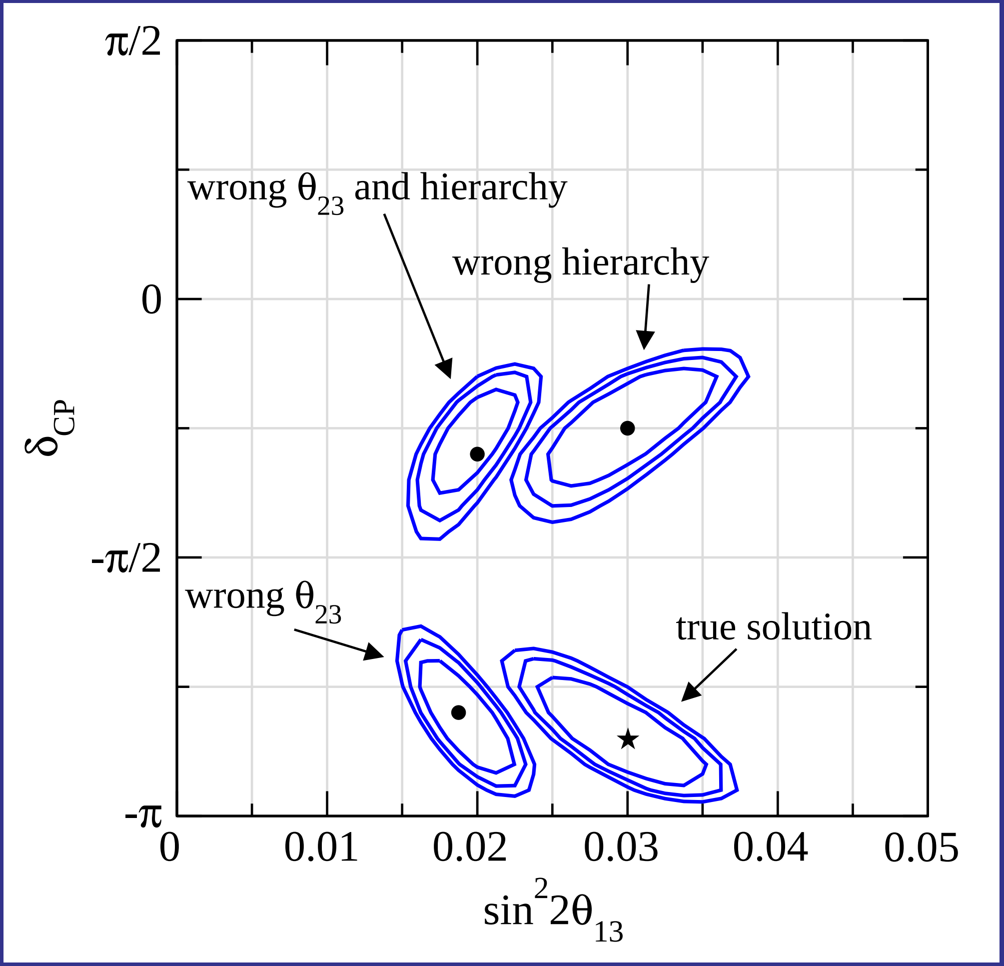

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ambiguities in θ_{13} and δ_{CP}

no information on the hierarchy

Resolving the degeneracies

several possibilities to resolve the degeneracies are known:

- combining information from detectors at different baselines
- using additional oscillation chanels ($\nu_e \longrightarrow \nu_\tau$)
- spectral information (broadband beam)
- adding information on θ_{13} from a reactor experiment
- ...

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we propose a new method based on ...

3-flavour effects in atmospheric neutrinos

Petcov, Phys. Lett. B434, 321 (1998), hep-ph/9805262
Akhmedov, Nucl. Phys. B538, 25 (1999), hep-ph/9805272
Akhmedov, Dighe, Lipari, Smirnov, Nucl. Phys. B542, 3 (1999), hep-ph/9808270
Kim, Lee, Phys. Lett. B444, 204 (1998), hep-ph/9809491
Bernabeu, Palomares-Ruiz, Perez, Petcov, Phys. Lett. B531, 90 (2002), hep-ph/0110071
Bernabeu, Palomares-Ruiz, Petcov, Nucl. Phys. B669, 255 (2003), hep-ph/0305152
Peres, Smirnov, Phys. Lett. B456, 204 (1999), hep-ph/9902312
Peres, Smirnov, Nucl. Phys. B680, 479 (2004), hep-ph/0309312
Gonzalez-Garcia, Maltoni, Eur. Phys. J. C26, 417 (2003), hep-ph/0202218
Gonzalez-Garcia, Maltoni, Smirnov, Phys. Rev. D70, 093005 (2004), hep-ph/0408170

again I appologize for omissions

3-flavour effects in atmospheric neutrinos

excess of electron-like events:

$$\frac{N_e}{N_e^0} - 1 \simeq \quad (r\, s_{23}^2 - 1)\, P_{2\nu}(\Delta m_{31}^2, \theta_{13}) \qquad \theta_{13}\text{-effects}$$

$$+ \quad (r\, c_{23}^2 - 1)\, P_{2\nu}(\Delta m_{21}^2, \theta_{12}) \qquad \Delta m_{21}^2\text{-effects}$$

$$- \quad 2 s_{13} s_{23} c_{23}\, r\, \mathrm{Re}(A_{ee}^* A_{\mu e}) \qquad \text{interference: } \delta_{\mathrm{CP}}$$

$$r = r(E_\nu) \equiv \frac{F_\mu^0(E_\nu)}{F_e^0(E_\nu)}$$

$r \approx 2$ (sub-GeV)

$r \approx 2.6 - 4.5$ (multi-GeV)

θ_{13}-effects

$$\frac{N_e}{N_e^0} - 1 \simeq (r\, s_{23}^2 - 1)\, P_{2\nu}(\Delta m_{31}^2, \theta_{13})$$

resonant matter effect in $P_{2\nu}(\Delta m_{31}^2, \theta_{13})$
for multi-GeV events ($r \approx 2.6 - 4.5$)

normal hierarchy: enhancement for neutrinos
inverted hierarchy: enhancement for anti-neutrinos

detection cross sections are different for neutrinos and anti-neutrinos

sensitivity to the neutrino mass hierarchy

θ_{13}-*effects*

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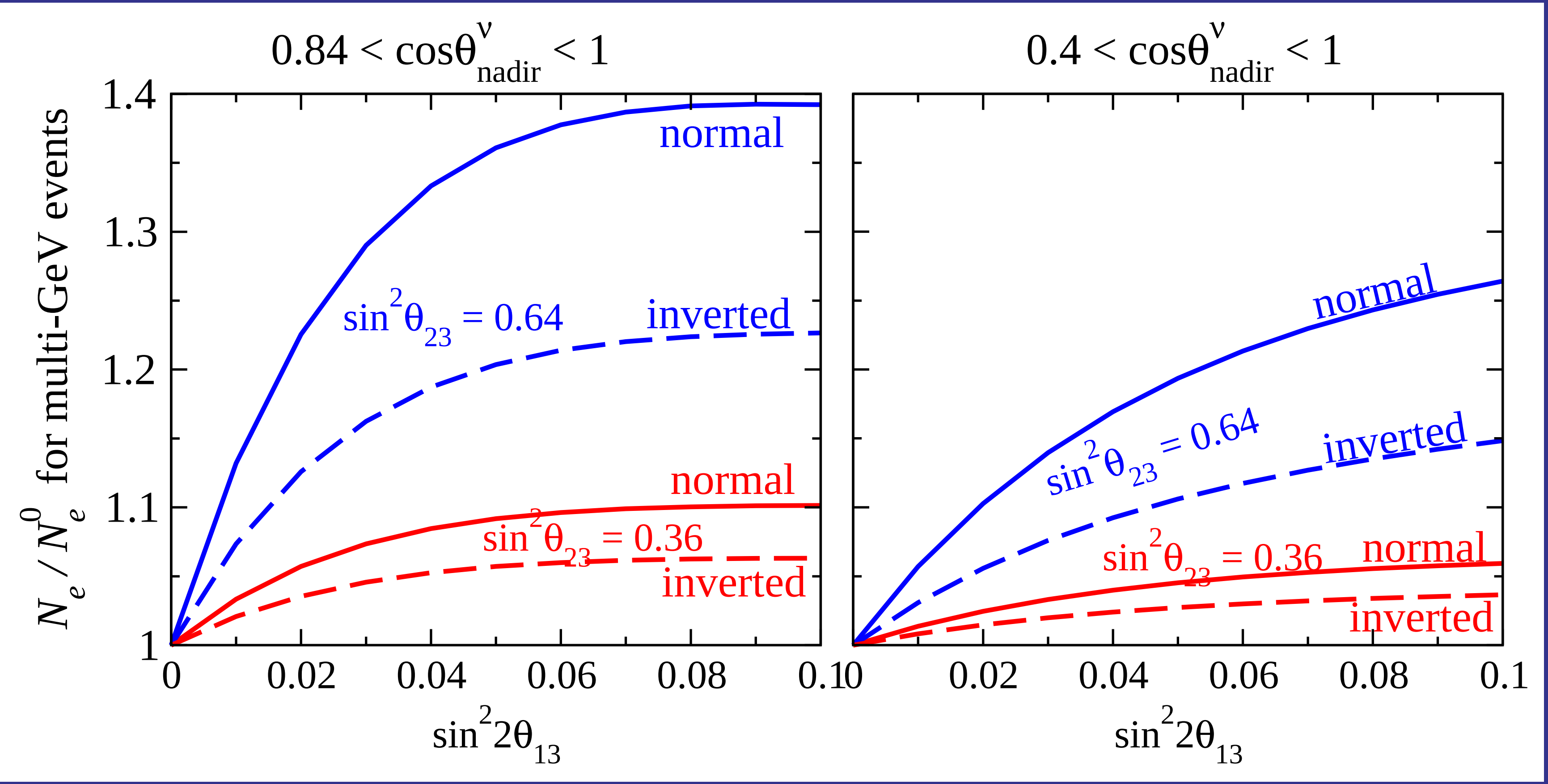
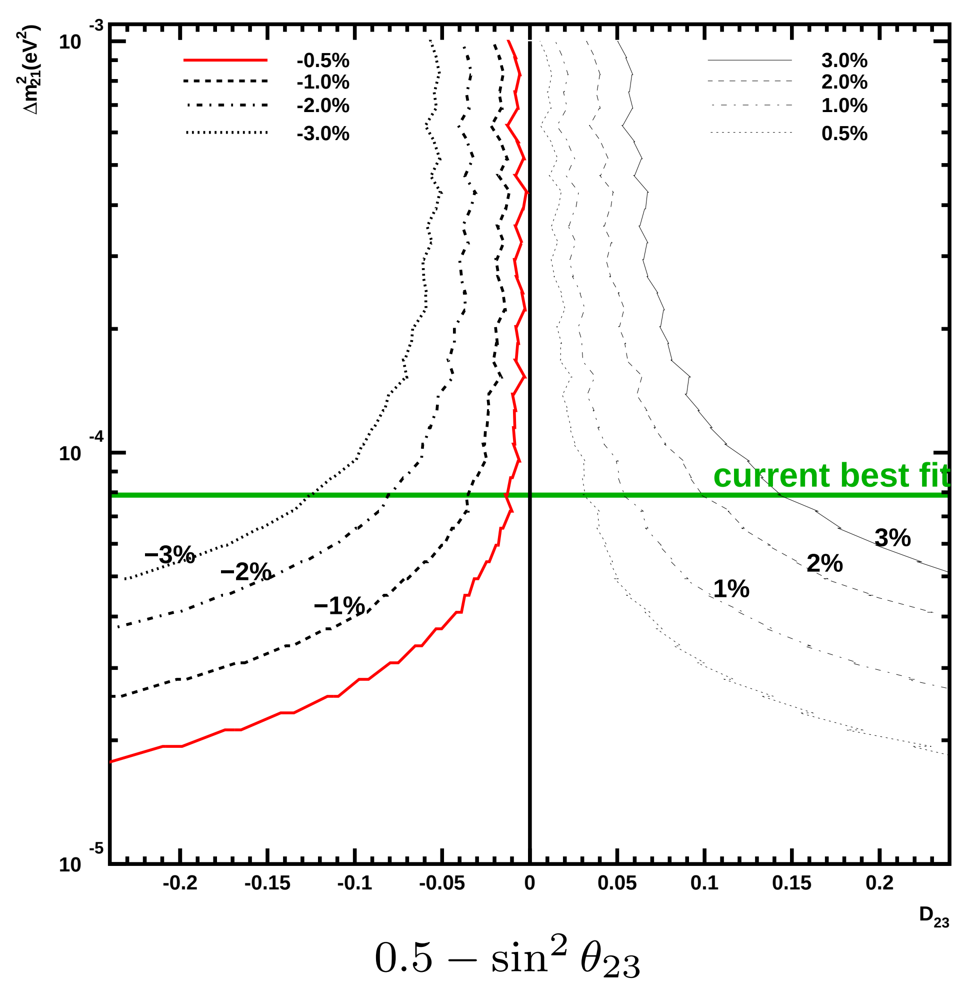


Bernabeu, Palomares-Ruiz, Petcov, Nucl. Phys. B669, 255 (2003), hep-ph/0305152

Δm^2_{21}-*effects*

$$\frac{N_e}{N_e^0} - 1 \simeq (r\, c_{23}^2 - 1)\, P_{2\nu}(\Delta m^2_{21}, \theta_{12})$$



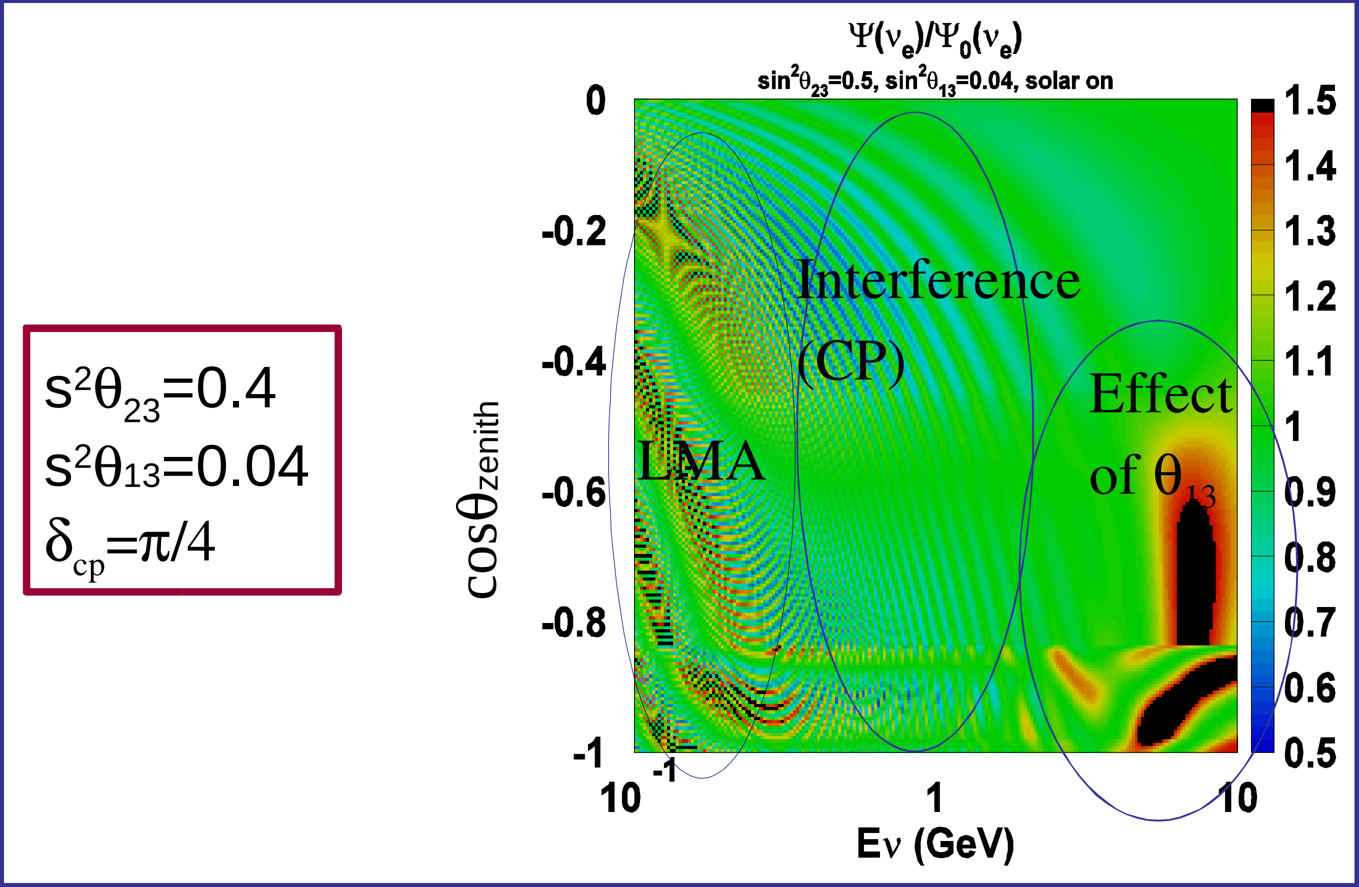
Peres, Smirnov, hep-ph/0309312

contours of $\frac{N_e}{N_e^0} - 1$

relevant for sub-GeV events

sensitivity to the octant of θ_{23}

3-flavour effects in atmospheric neutrinos



plot from T. Kajita

The **HK** *atmospheric neutrino experiment*

assume 9 Mt yrs ATM data (100 $\times$ SK-I data)

	zenith angle	ν	$\bar{\nu}$
e-like sub-GeV	10 bins	239 000	58 000
e-like multi-GeV	10 bins	52 700	18 100
μ-like sub-GeV	10 bins	232 000	66 200
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upward going μ	$10_{\rm thr}$ + $5_{\rm st}$	127 000	65 400

$\sin^2 2\theta_{13} = 0.05$, $\sin^2\theta_{23} = 0.5$, $\sin^2\theta_{12} = 0.3$, $\delta_{\rm CP} = 0$,
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WARNING:

- same systematics as SK-I
- same binning (zenith angle, energy) as SK-I
- only single-ring events

The ATM analysis

- Full numerical three-flavour analysis
  - both Δm^2_{31} and Δm^2_{21} taken into account
  - realistic treatment of earth matter effects

based on:

Gonzalez-Garcia, Maltoni, Pena-Garay, Valle, Phys. Rev. D **63** (2001) 033005

Gonzalez-Garcia, Maltoni, Eur. Phys. J. C **26** (2003) 417 [hep-ph/0202218]

Maltoni, TS, Tortola, Valle, Phys. Rev. D **67** (2003) 013011 [hep-ph/0207227]

Gonzalez-Garcia, Maltoni, Smirnov, Phys. Rev. D **70** (2004) 093005 [hep-ph/0408170]

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- Combined with LBL data by using a generalized version of the GLoBES software

Resolving the degeneracies

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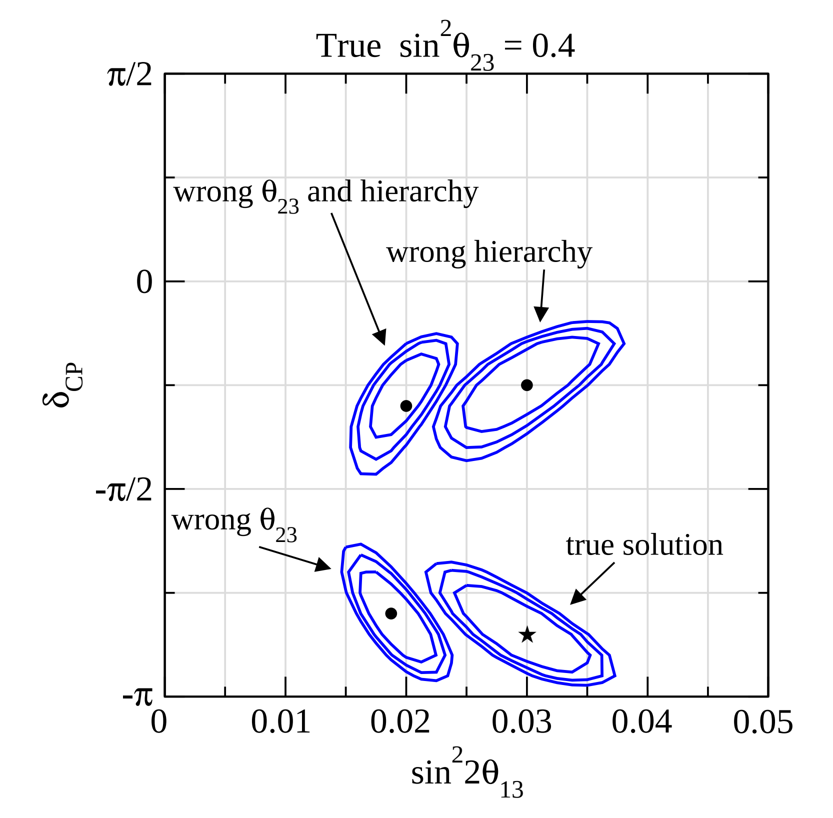

solid curves: LBL only

allowed regions at 2σ, 99% and 3σ CL (2 dof)

true values: $\sin^2 2\theta_{13} = 0.03$, $\delta_{\mathrm{CP}} = -0.85\pi$, $\Delta m^2_{31} = 2.2 \cdot 10^{-3}\mathrm{eV}^2$

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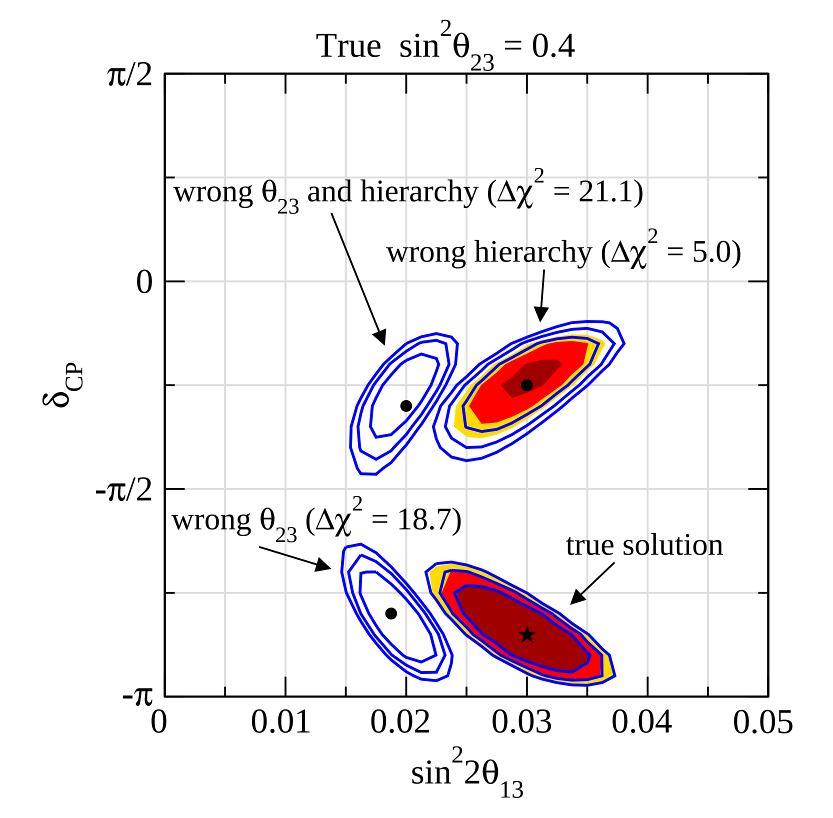

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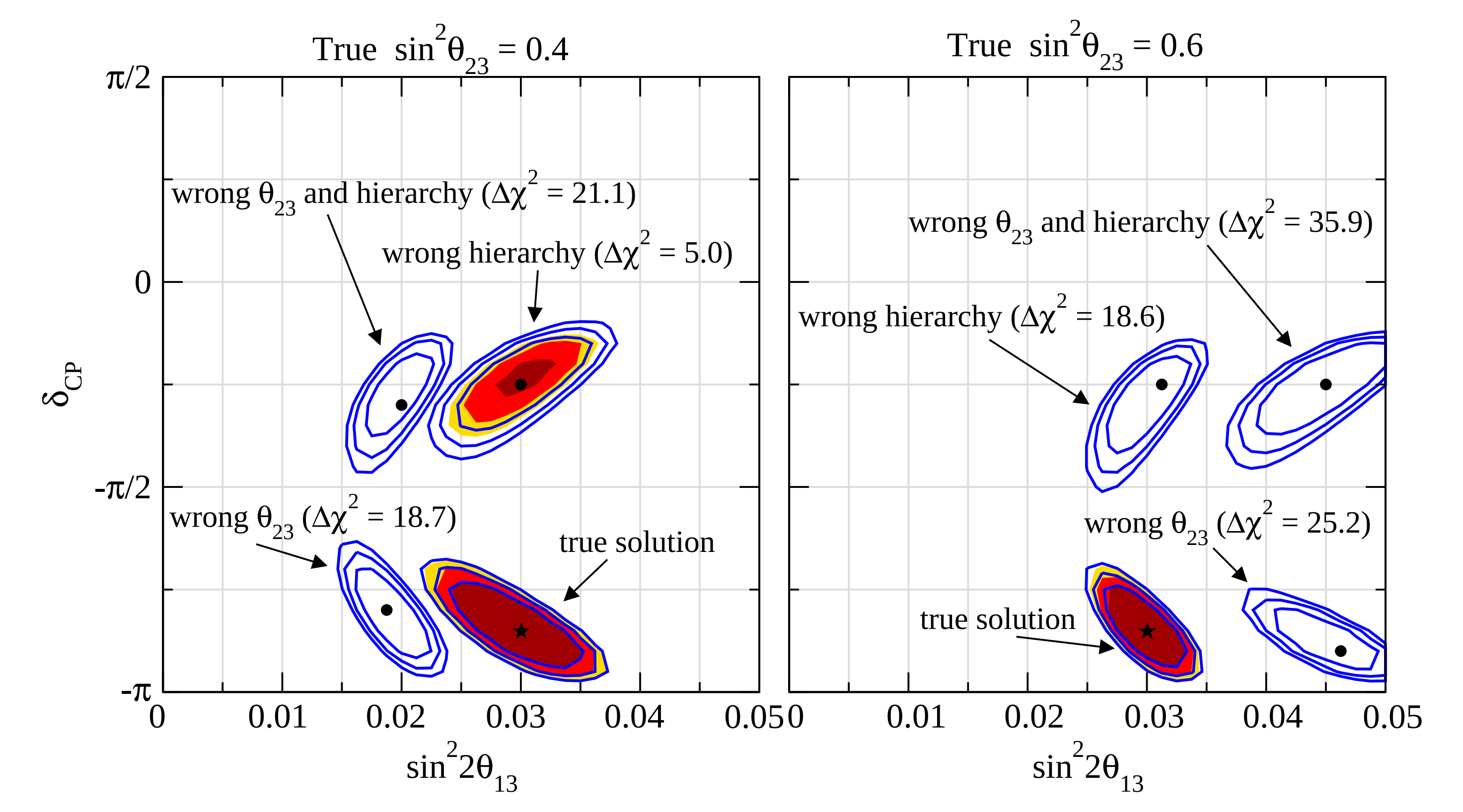

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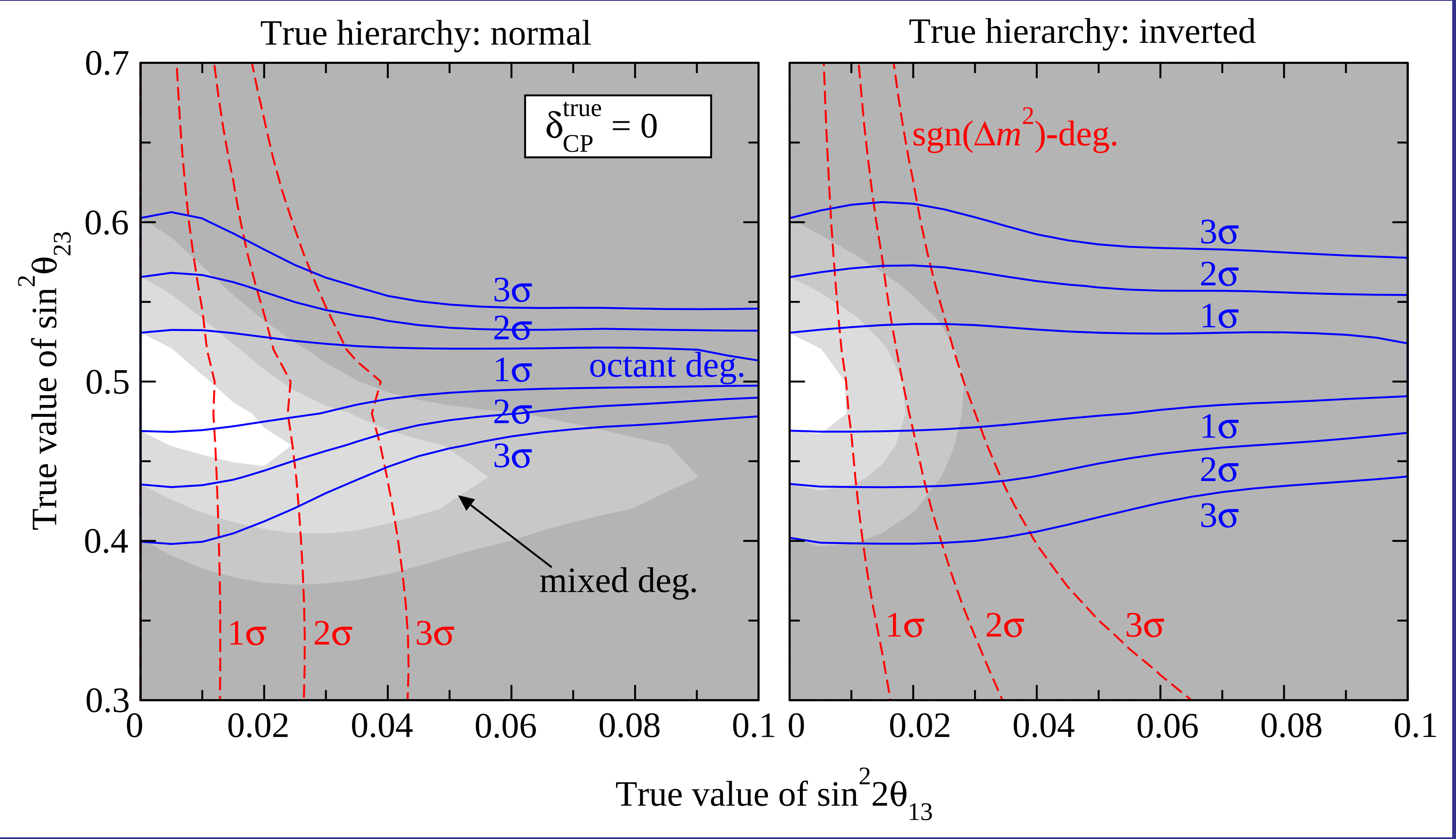

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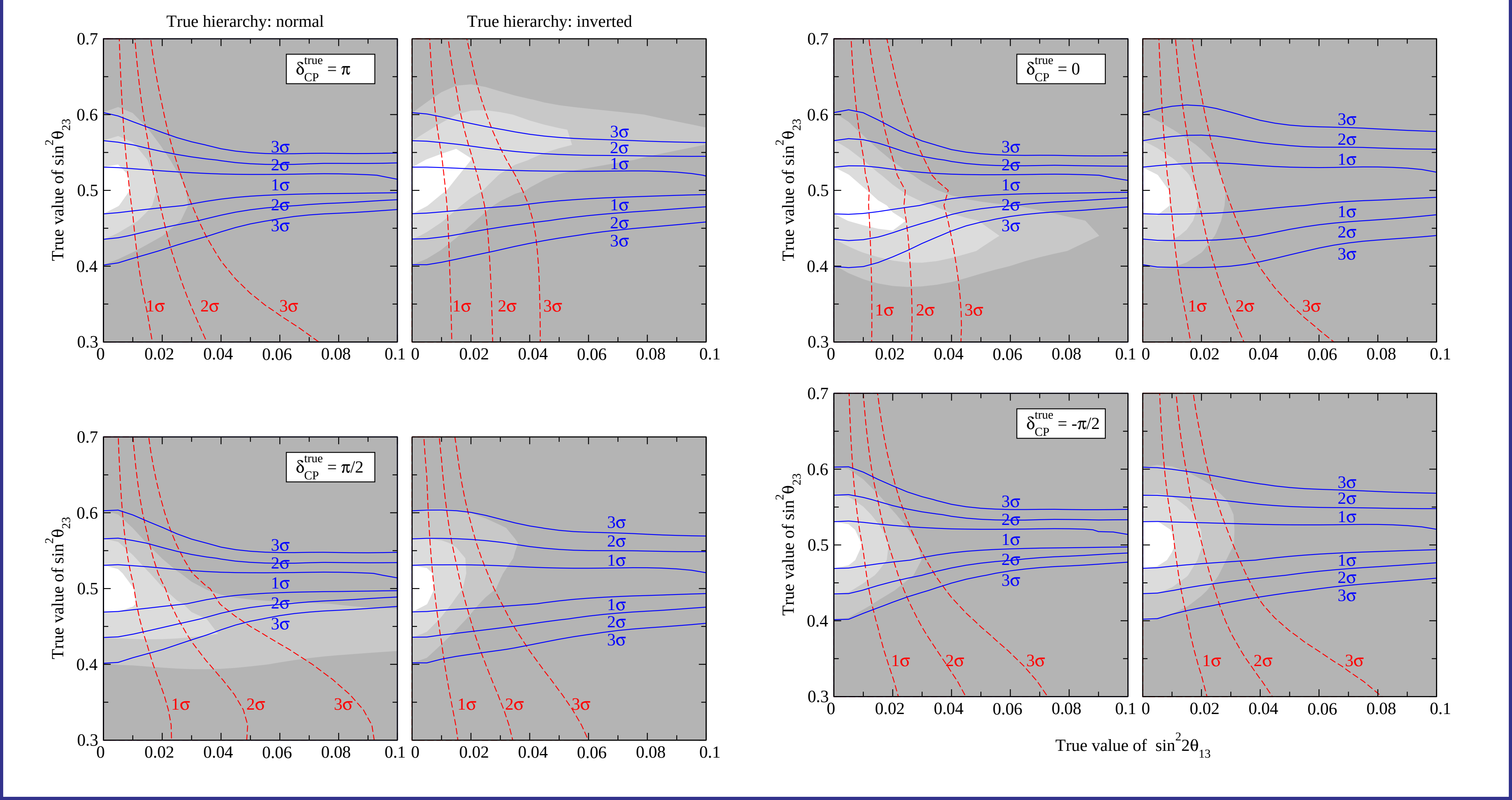
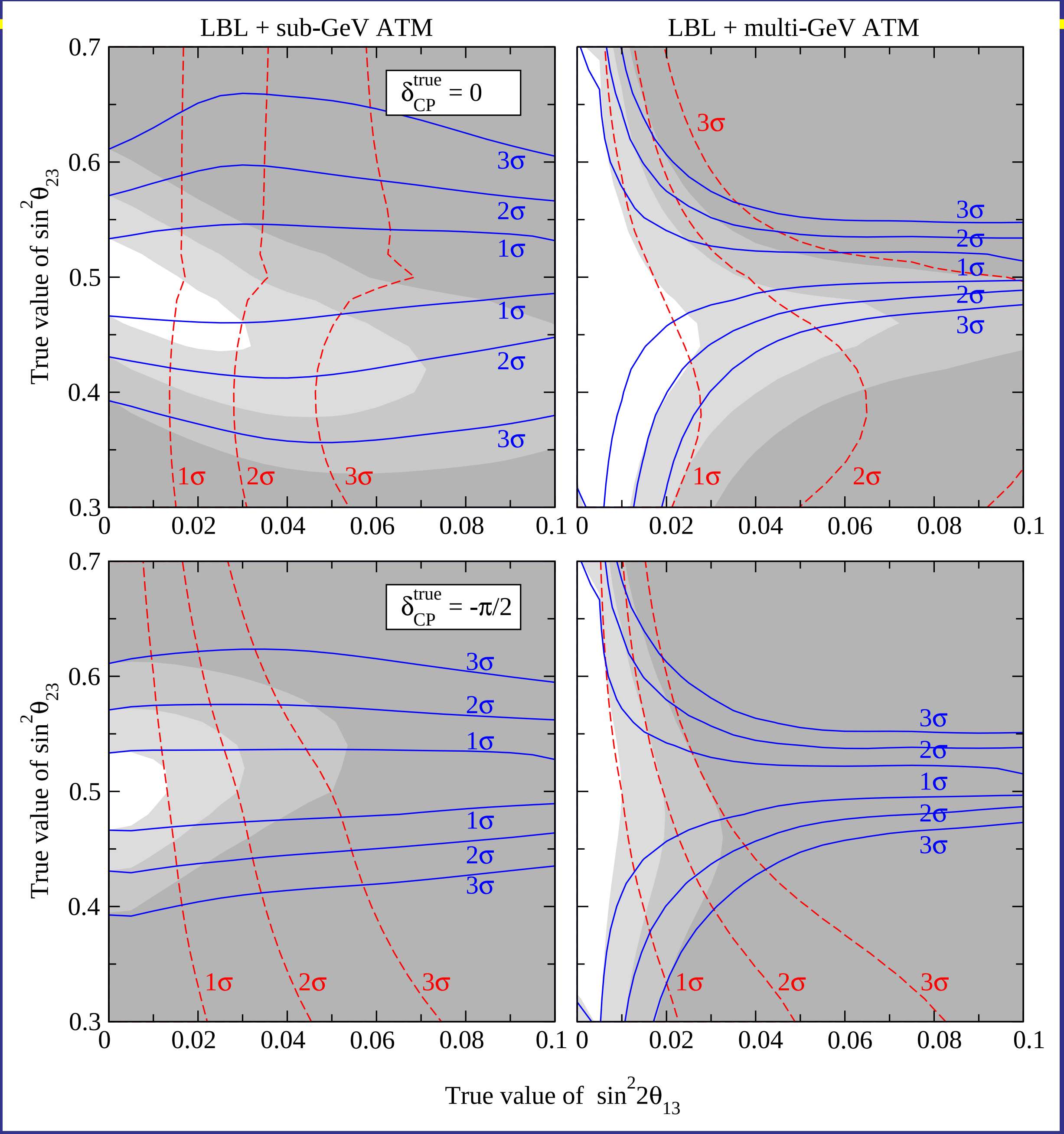


Which are the relevant ATM data samples?



Identifying the mass hierarchy

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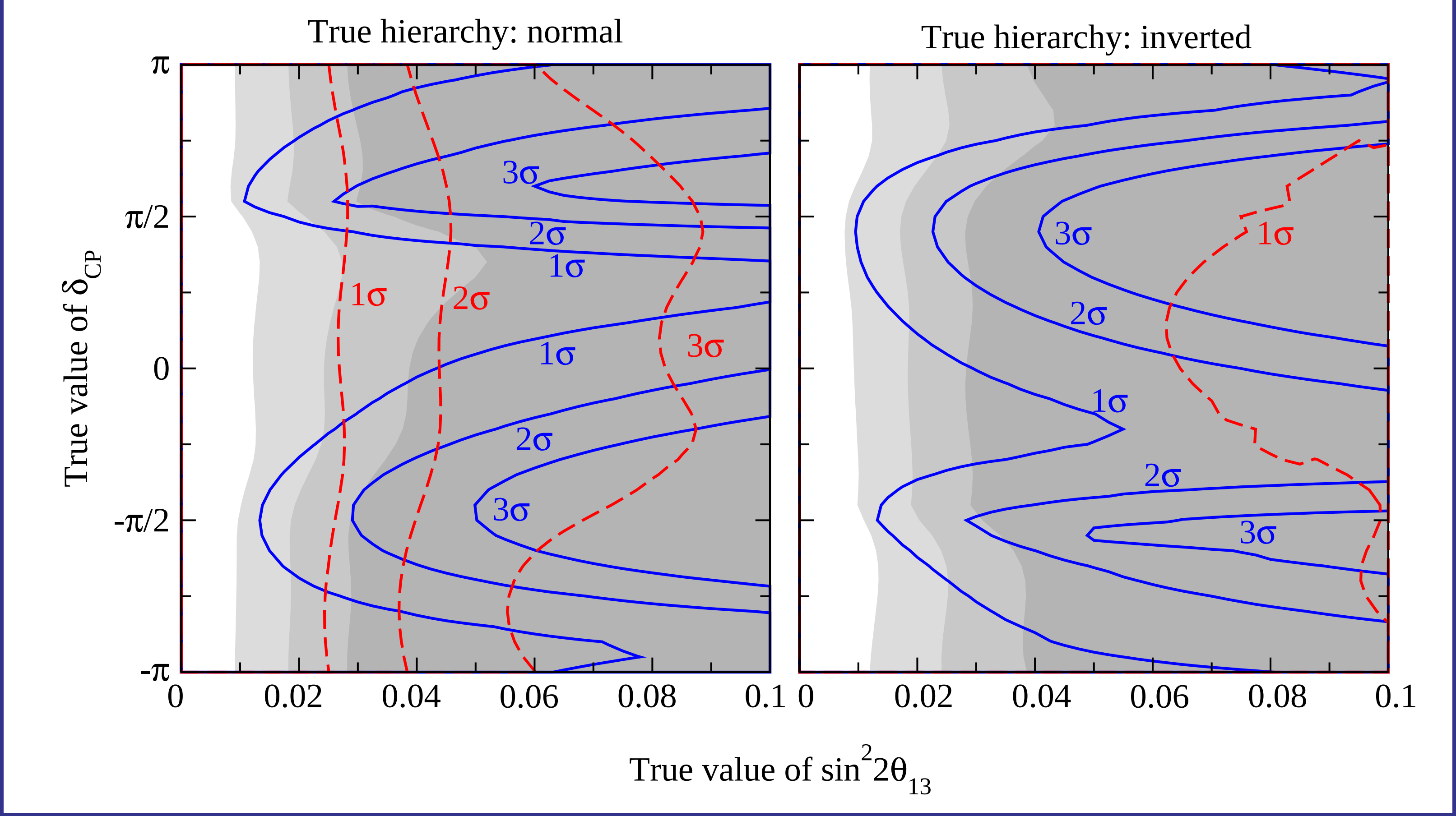

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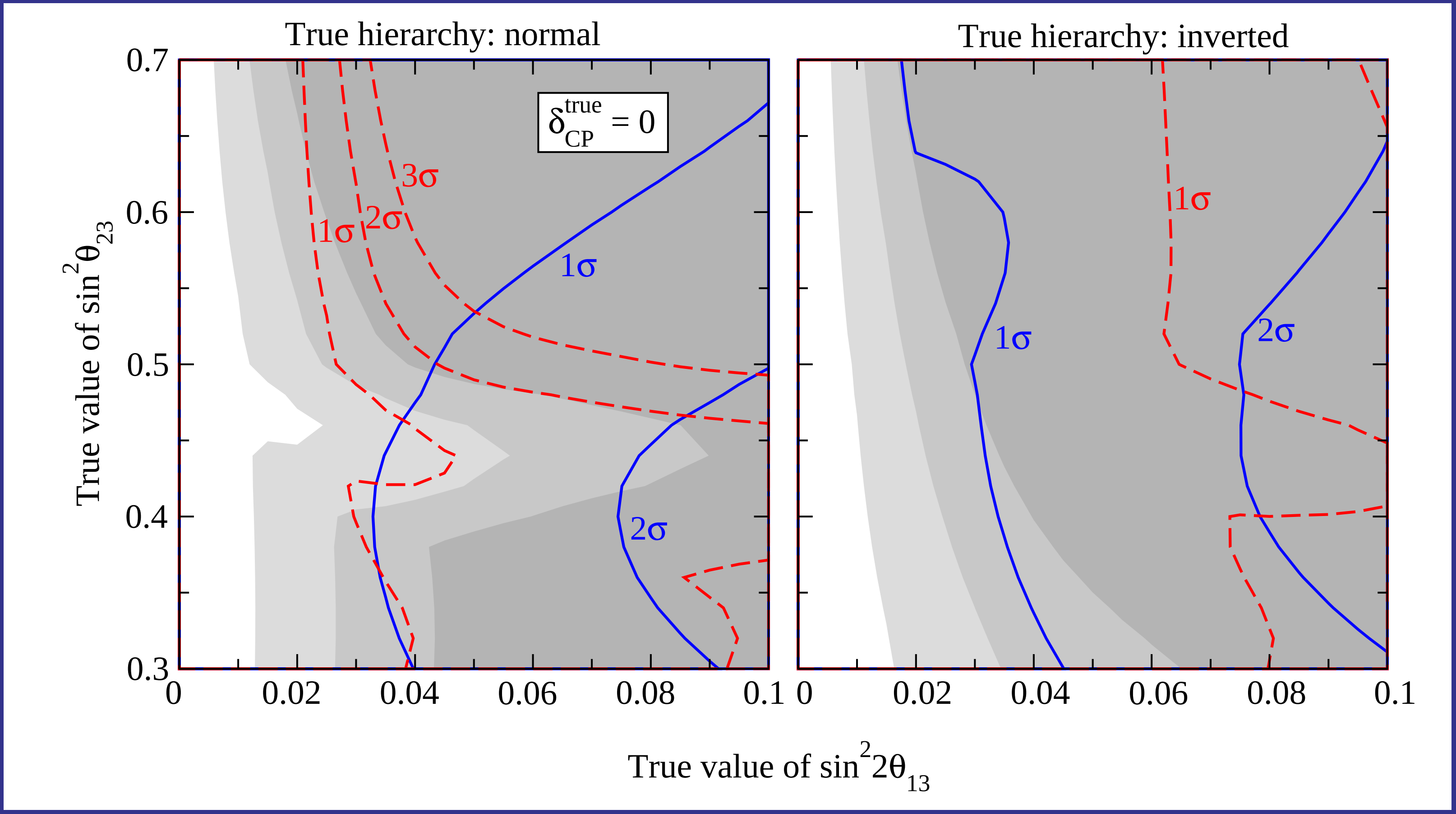

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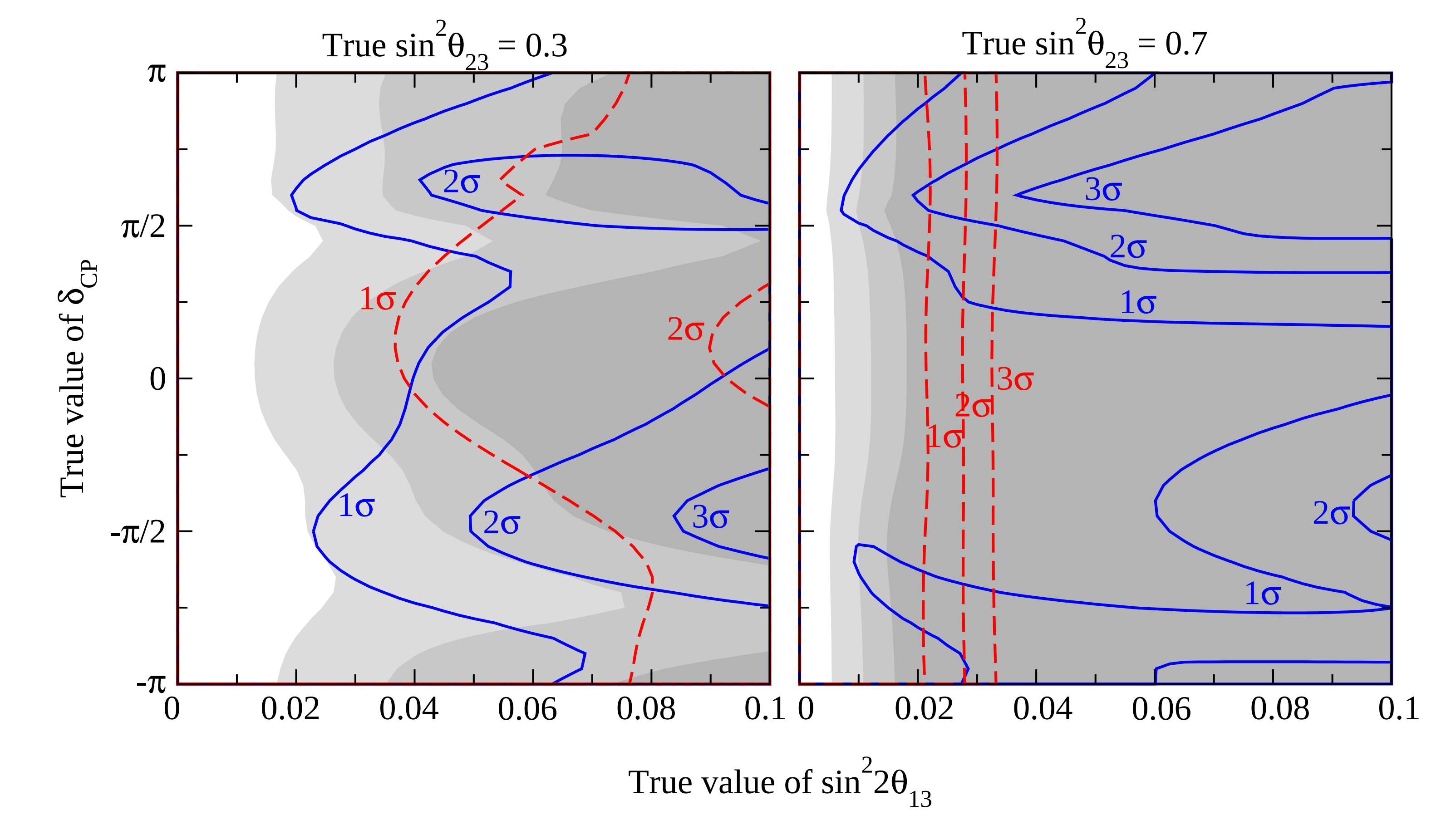

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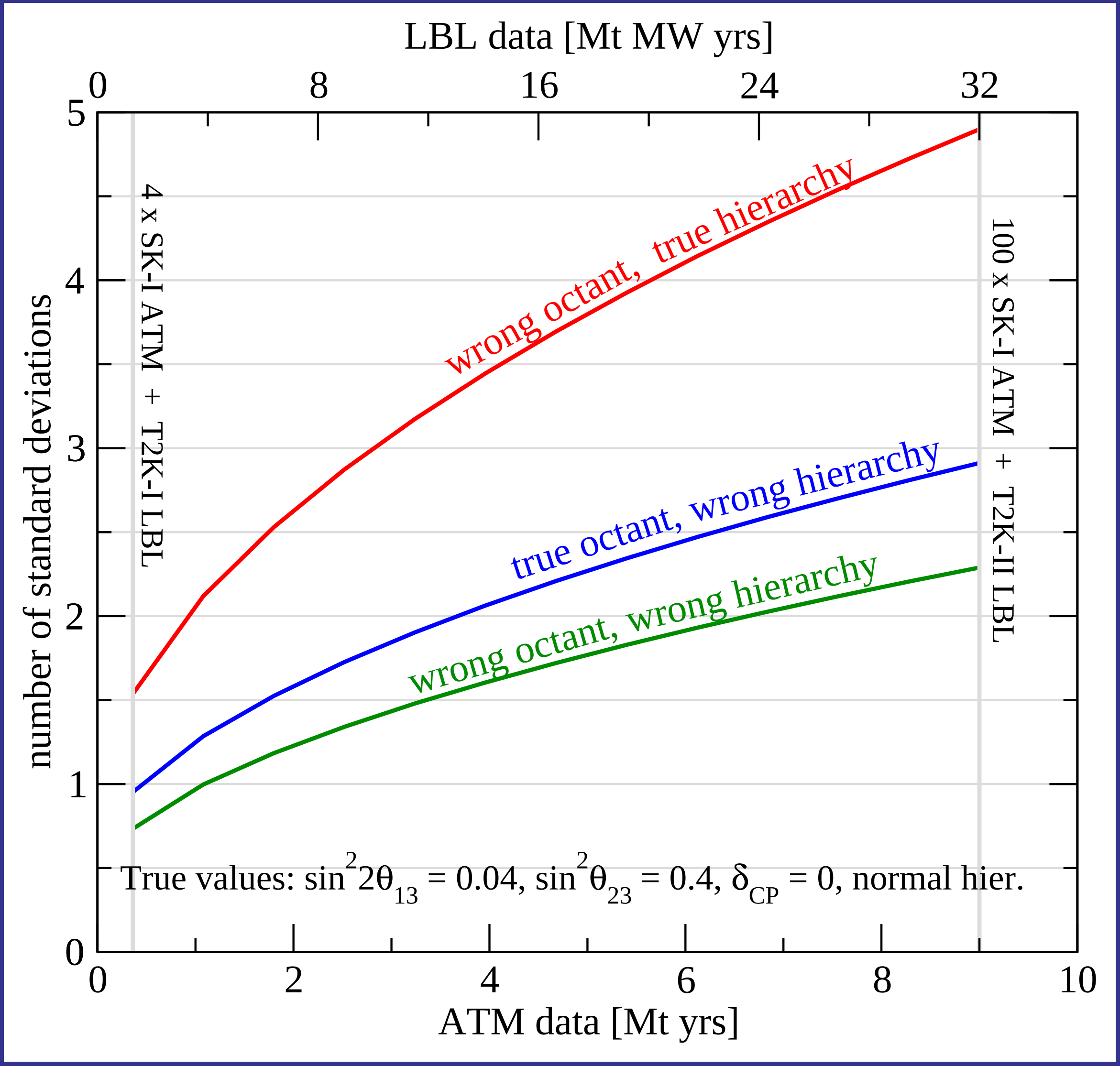
Luminosity scaling

Do we really need a Mt experiment?

Luminosity scaling



Preliminary BB/SPL analysis

CERN-Frejus LBL experiments **(PRELIMINARY)**

work in progress in collaboration with J.E. Campagne and M. Mezzetto

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  see talk of M. Mezzetto for details

  $\bar{\nu}$: ^{6}He ($\gamma = 100$), ν: ^{18}Ne ($\gamma = 100$), 10 yrs data

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  3.5 GeV proton beam from 4 MW SPL, 2 yrs ν, 8 yrs $\bar{\nu}$

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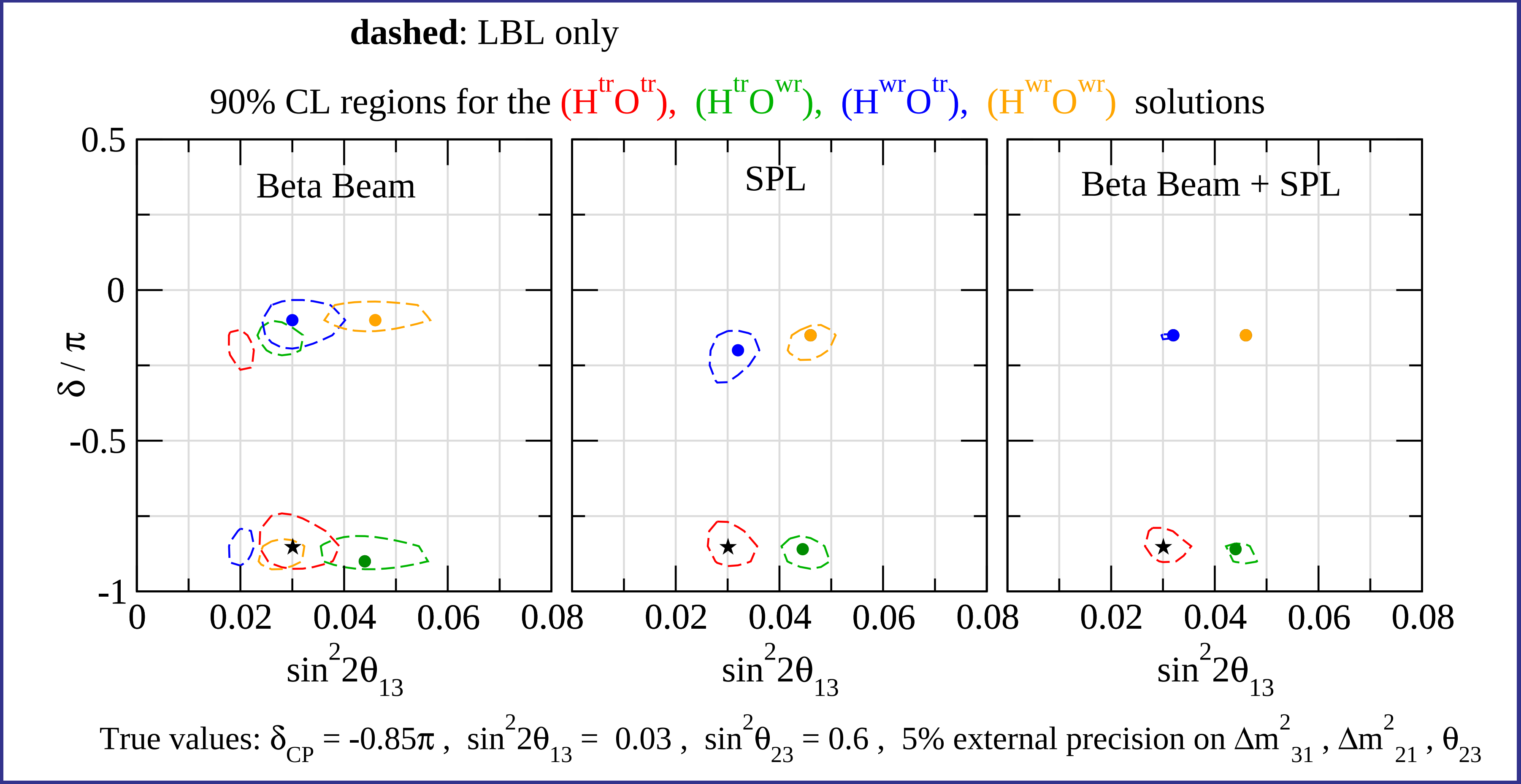
- 450 kt water Cherenkov detector at Frejus

  baseline 130 km

Preliminary BB/SPL analysis



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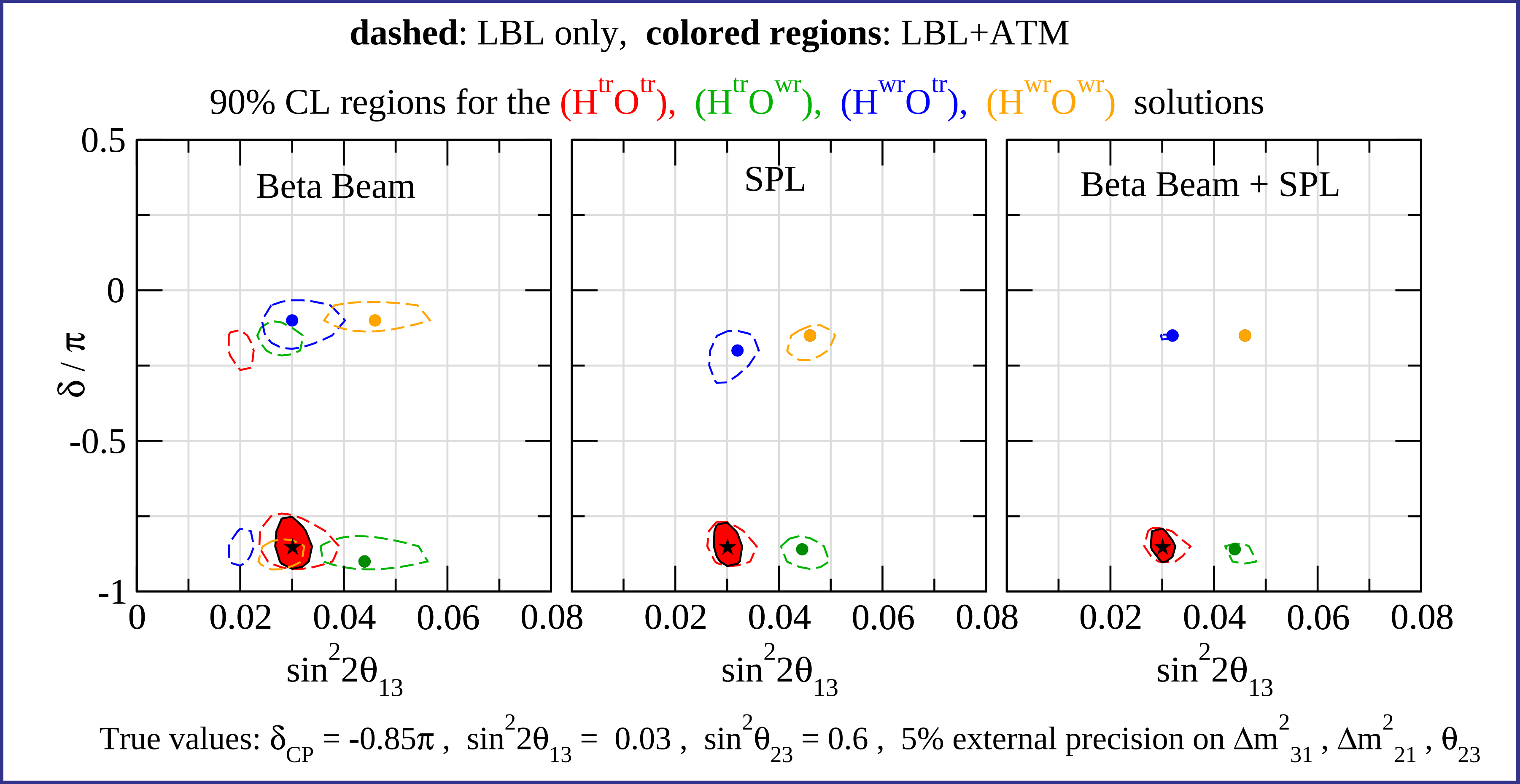
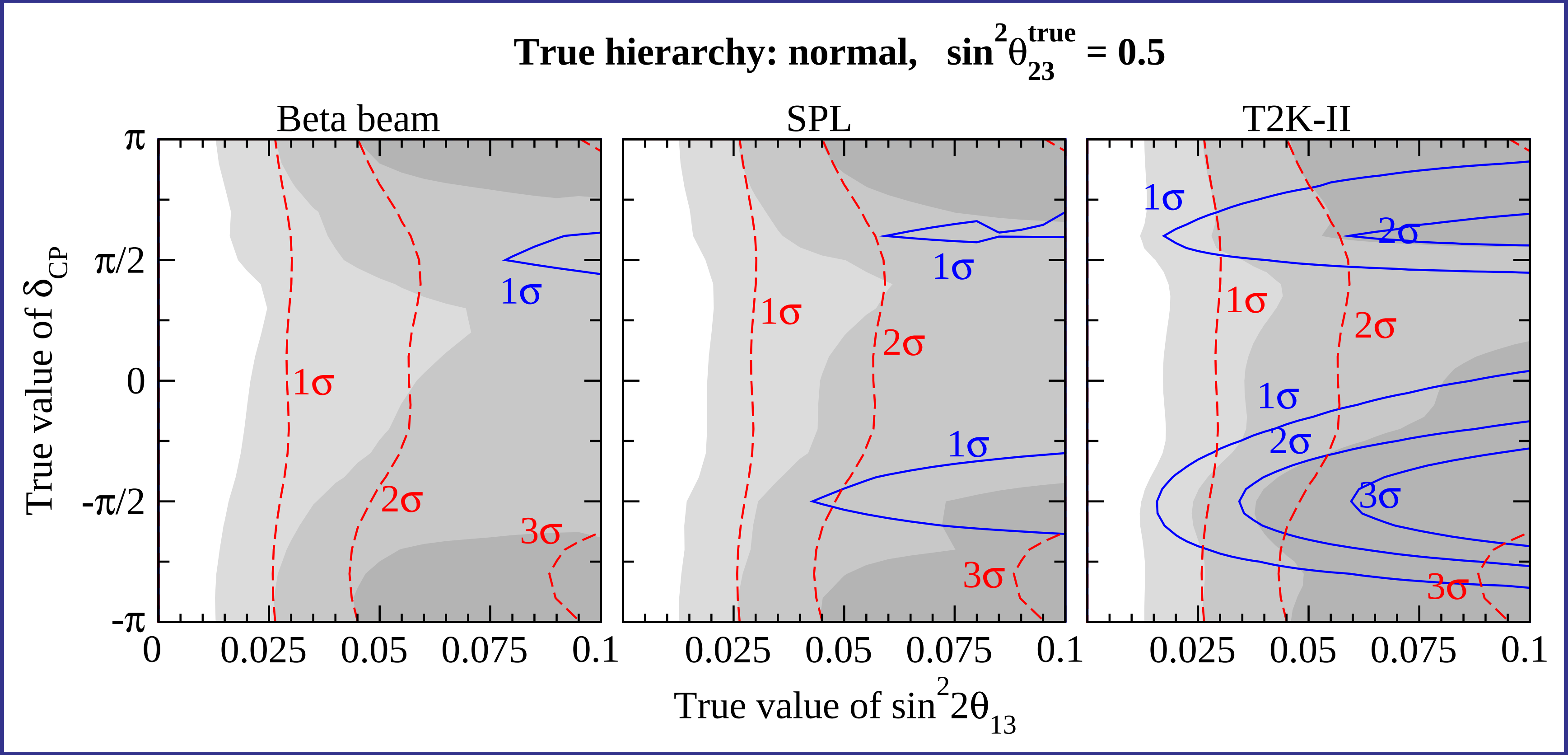


Preliminary BB/SPL analysis

sensitivity to the mass hierarchy



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given the Mt detector for the LBL experiment,
ATM data come for free!

Concluding remarks

Complementarity of LBL and ATM data:

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- Three-flavour effects in ATM data provide sensitivity to mass ordering and octant of θ_{23}

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- The determination of Δm^2_{31} and $\sin^2 2\theta_{23}$ at the sub-percent level and a constraint on $\sin^2 2\theta_{13}$ from LBL data is necessary

Concluding remarks

Complementarity of LBL and ATM data:

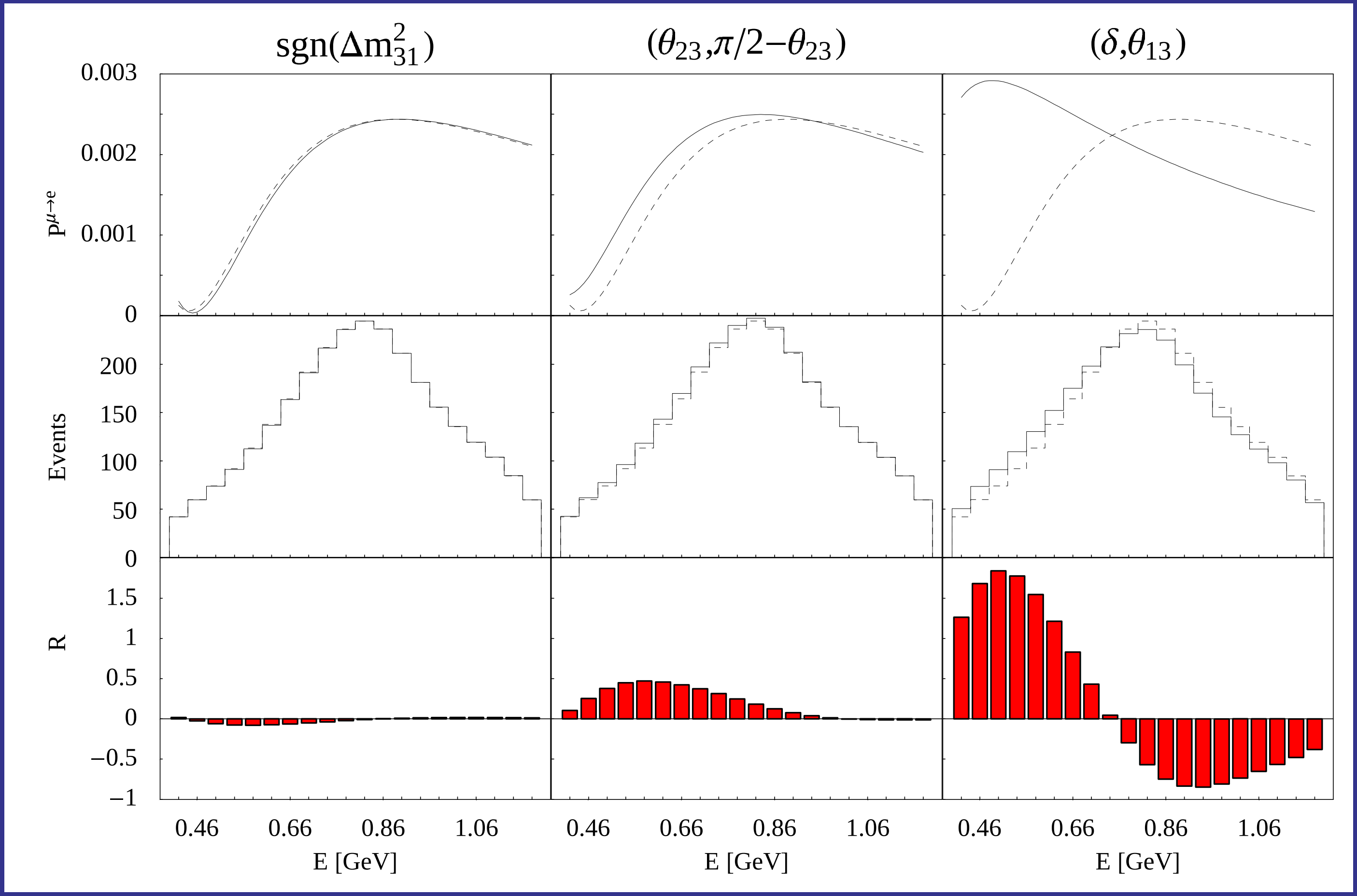
- Three-flavour effects in ATM data provide sensitivity to mass ordering and octant of θ_{23}
- The determination of Δm^2_{31} and $\sin^2 2\theta_{23}$ at the sub-percent level and a constraint on $\sin^2 2\theta_{13}$ from LBL data is necessary

Thank you for your attention!

P. Huber, M. Maltoni, TS, PRD 71 (2005) 053006 [hep-ph/0501037]

additional slides

Degeneracies and **T2K-II**



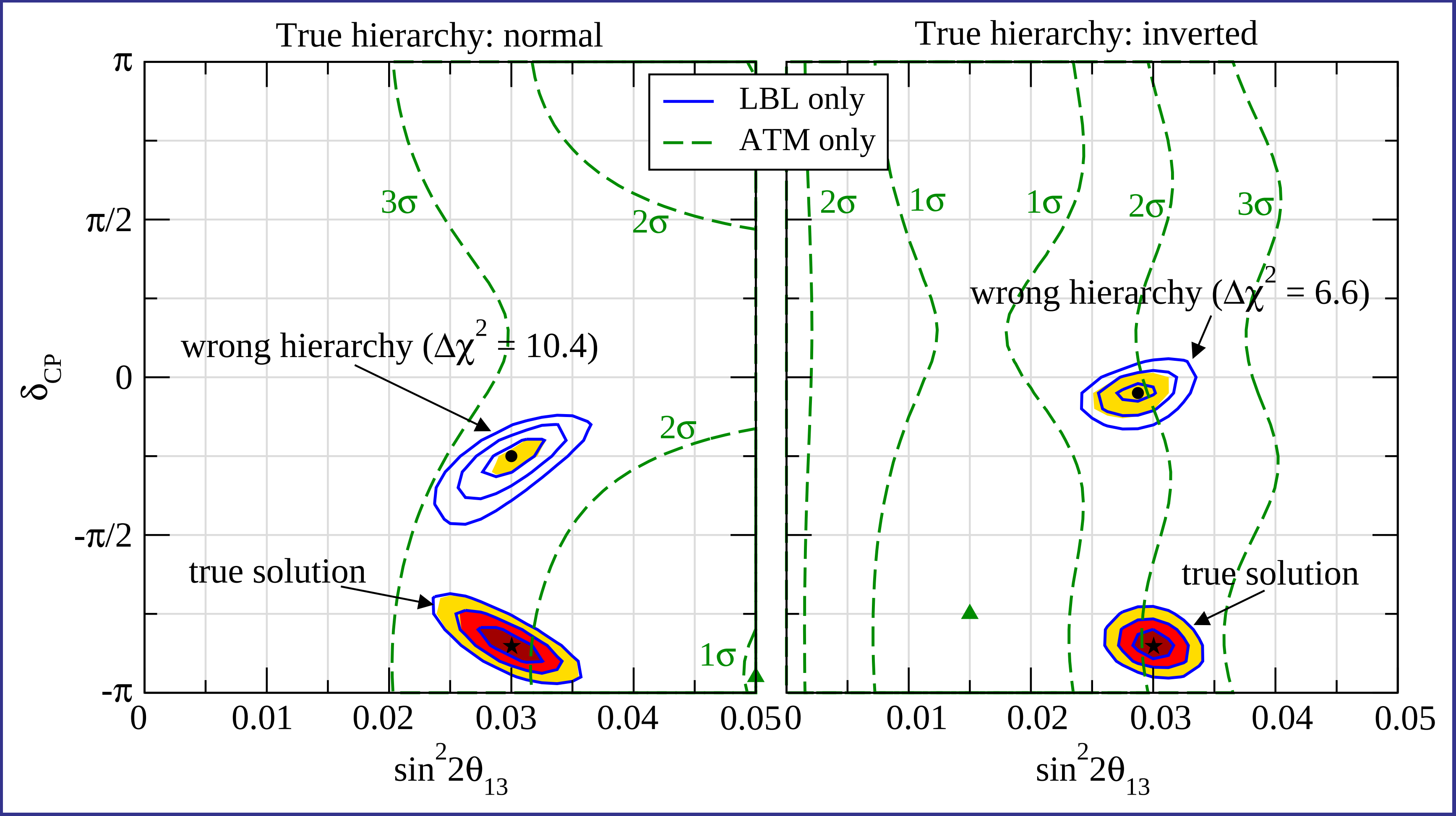
$$\sin^2 2\theta_{13} = 0.01$$
$$\delta_{CP} = \pi/4$$
$$\sin^2 \theta_{23} = 0.3$$

$$R = \frac{N_i^{tr} - N_i^{deg}}{\sqrt{(N_i^{tr} + N_i^{deg})/2}}$$

P.Huber, M.Lindner, W.Winter, Nucl. Phys. B645 (2002) 3

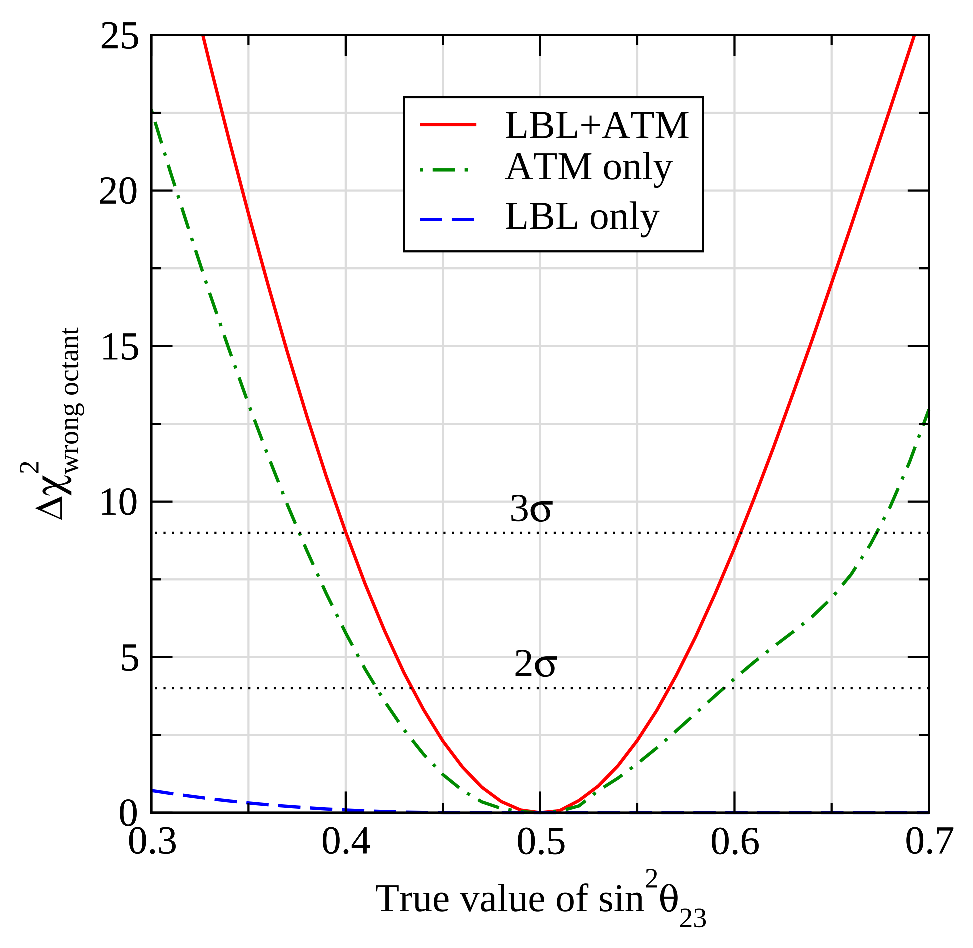
The intrinsic degeneracy is absent for **T2K-II**

Additional slides



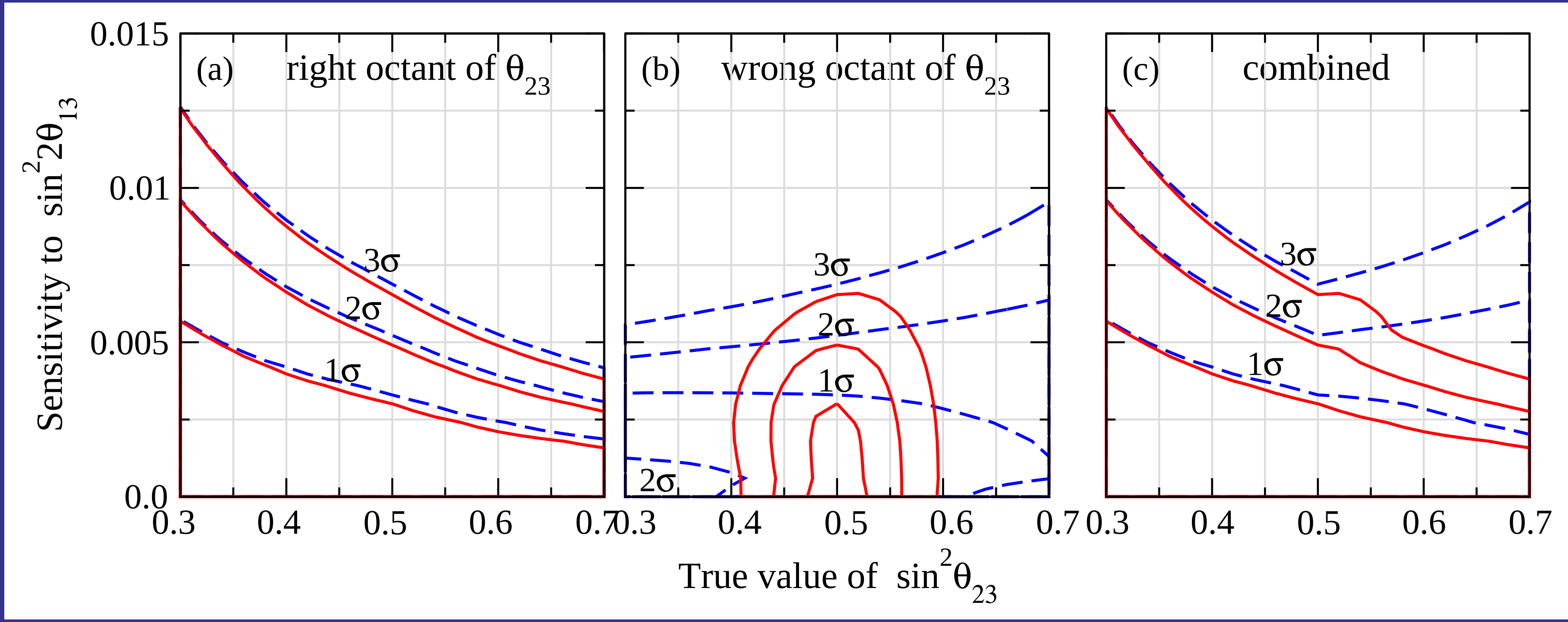
True $\theta_{13} = 0$

Resolving the octant-degeneracy:



True $\theta_{13} = 0$

The limit on $\sin^2 2\theta_{13}$:



dashed: LBL only, solid: LBL+ATM

$$P_{\mu e} \simeq \sin^2 2\theta_{13} \sin^2 \theta_{23} \sin^2 \Delta_{31} + \ldots$$