
NNN05 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} ?

Introduction

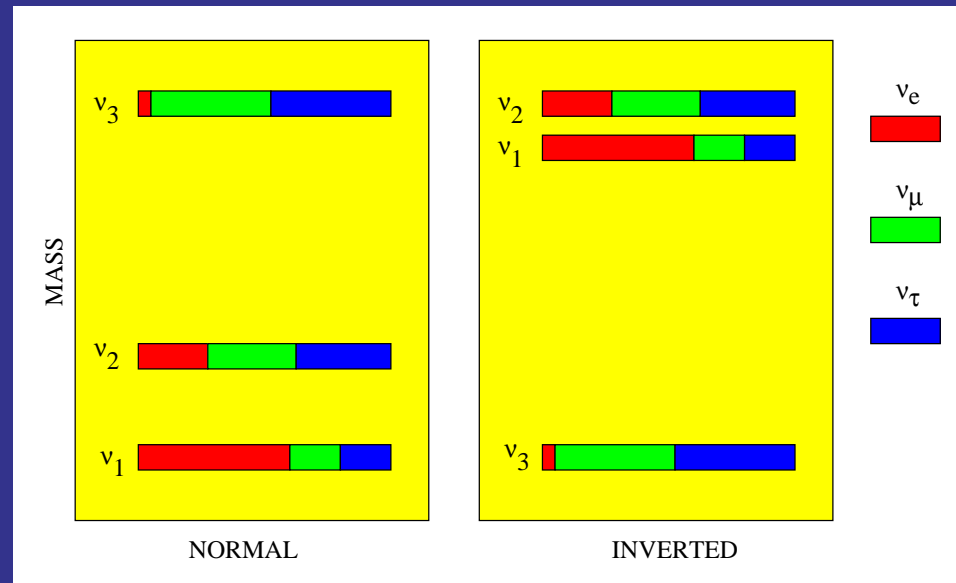
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- What is the value of the CP phase δ_{CP} ?

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



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 $(\delta_{\text{CP}}, \theta_{13})$ degeneracy

J. Burguet-Castell et al., Nucl. Phys. B608 (2001) 301

several solutions in the $(\delta_{\text{CP}}, \theta_{13})$ plane

$$P_{\mu e} \simeq \sin^2 2\theta_{13} \sin^2 \theta_{23} \sin^2 \Delta_{31} + \alpha^2 \sin^2 2\theta_{12} \cos^2 \theta_{23} \Delta_{31}^2 \\ + \alpha \sin 2\theta_{12} \sin 2\theta_{13} \sin 2\theta_{23} \Delta_{31} \sin \Delta_{31} \cos(\Delta_{31} \pm \delta_{\text{CP}})$$

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ν_{μ} -disappearance channel 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)
$\nu_\mu \rightarrow \nu_e$ signal	21 300	16 000
$\nu_\mu \rightarrow \nu_e$ background	2 140	3 260
$\nu_\mu \rightarrow \nu_\mu$ signal	73 200	75 600
$\nu_\mu \rightarrow \nu_\mu$ background	340	320

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

$$\Delta m_{21}^2 = 8.1 \times 10^{-5} \text{ eV}^2, \Delta m_{31}^2 = 2.2 \times 10^{-3} \text{ eV}^2$$

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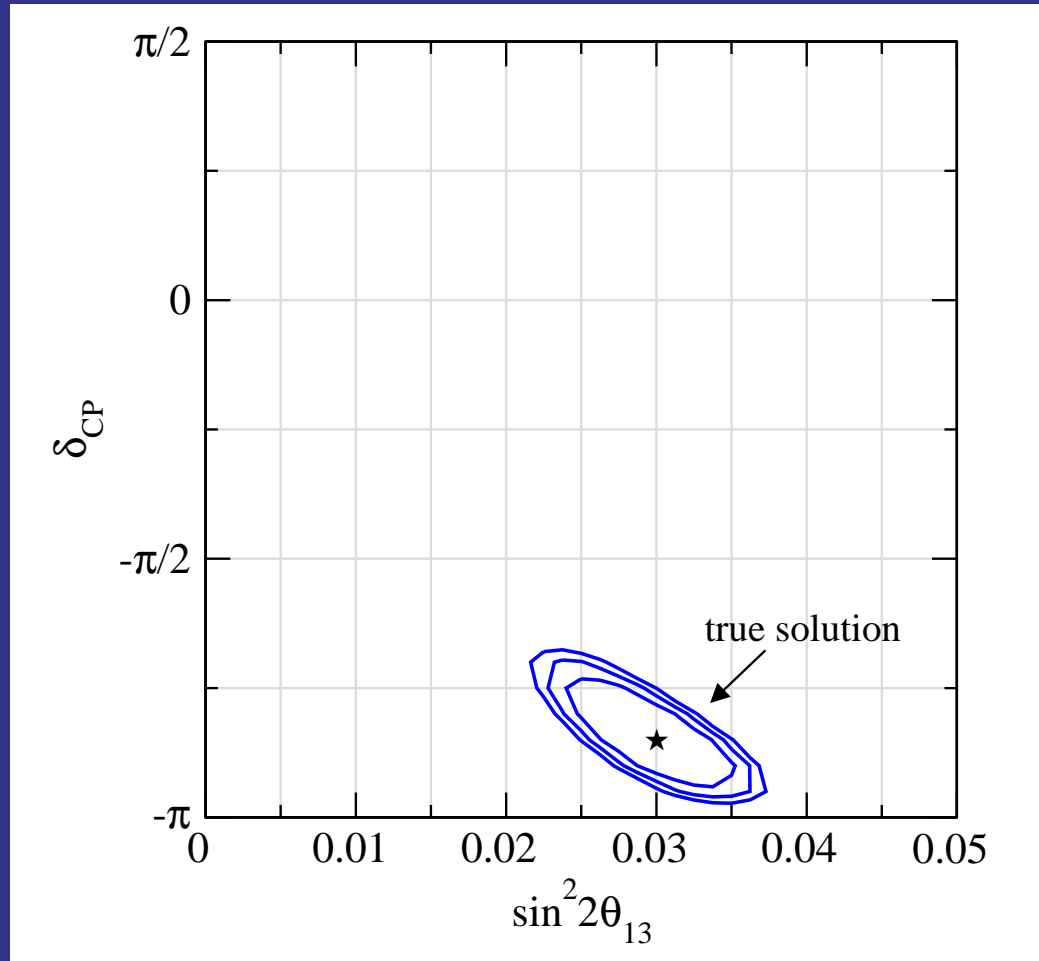
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GLoBES software

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

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

Degeneracies and T2K-II



True values:

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

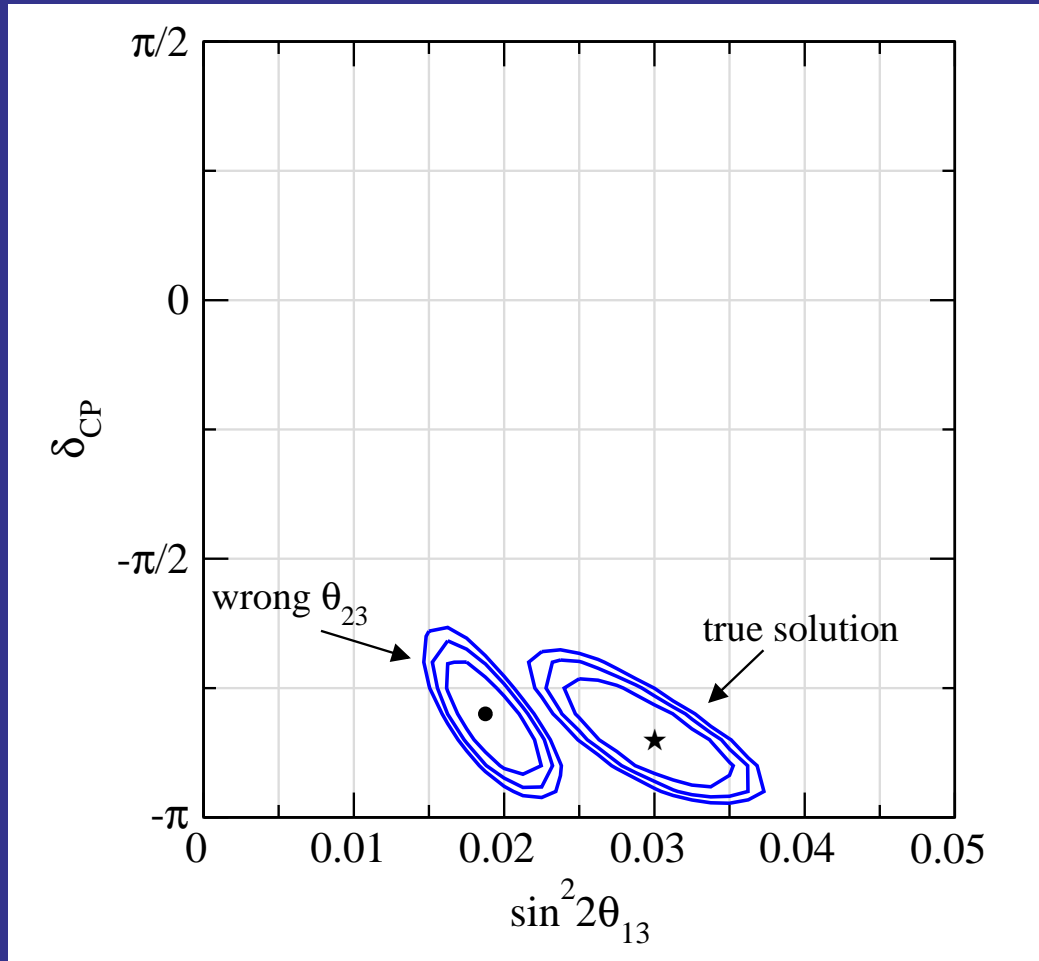
$$\delta_{CP} = -0.85\pi$$

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

$$\Delta m_{31}^2 = 2.2 \times 10^{-3} \text{eV}^2$$

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

Degeneracies and T2K-II



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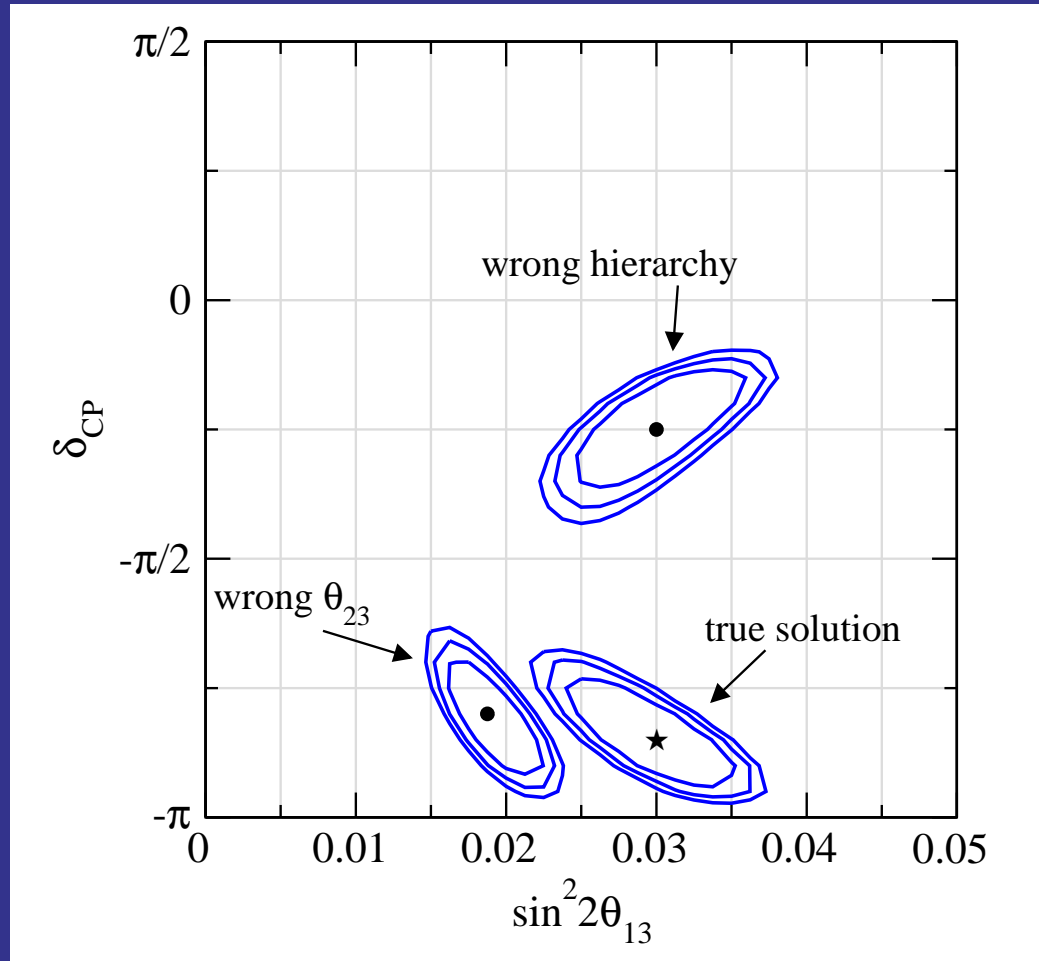
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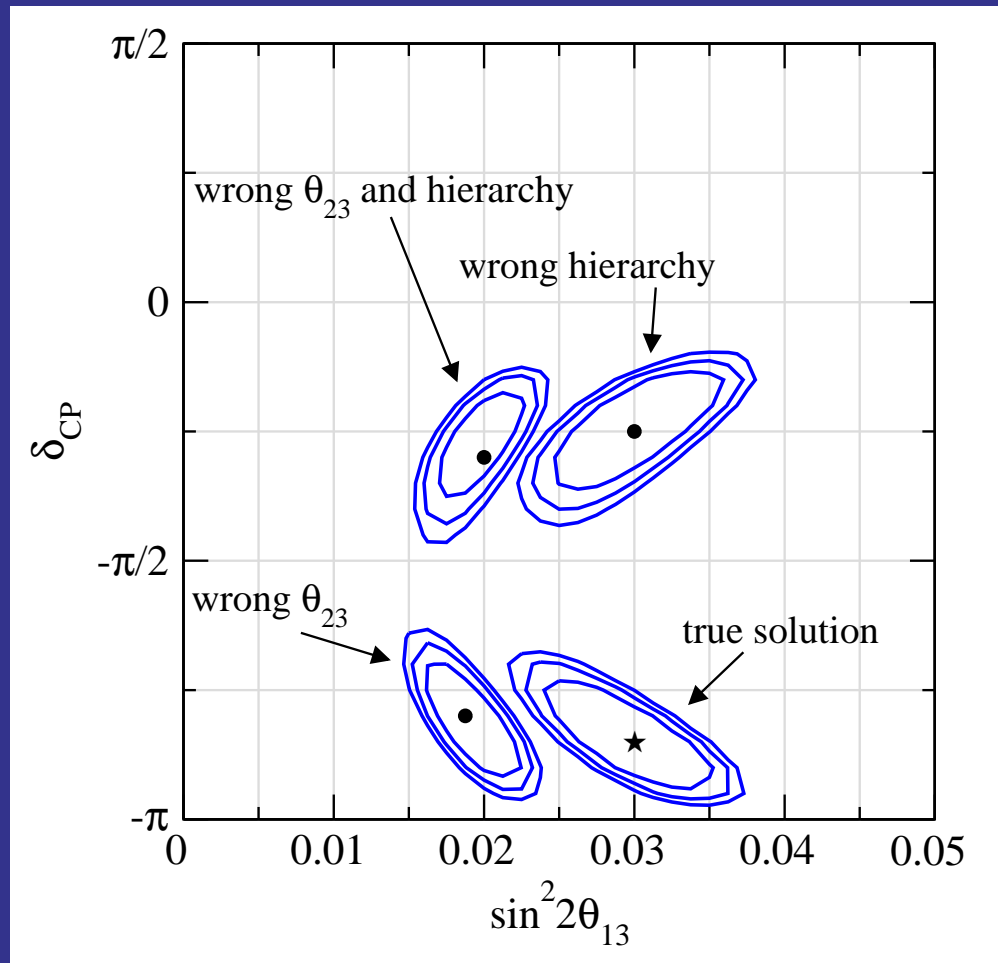
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ambiguities in θ_{13} and δ_{CP}
no information on the hierarchy

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

see also talk of T. Kajita

3-flavour effects in atmospheric neutrinos

excess of electron-like events:

$$\begin{aligned} \frac{N_e}{N_e^0} - 1 &\simeq (r s_{23}^2 - 1) P_{2\nu}(\Delta m_{31}^2, \theta_{13}) && \theta_{13}\text{-effects} \\ &+ (r c_{23}^2 - 1) P_{2\nu}(\Delta m_{21}^2, \theta_{12}) && \Delta m_{21}^2\text{-effects} \\ &- 2s_{13}s_{23}c_{23} r \operatorname{Re}(A_{ee}^* A_{\mu e}) && \text{interference: } \delta_{\text{CP}} \end{aligned}$$

$$r = r(E_\nu) \equiv \frac{F_\mu^0(E_\nu)}{F_e^0(E_\nu)} \quad \begin{array}{l} r \approx 2 \quad (\text{sub-GeV}) \\ r \approx 2.6 - 4.5 \quad (\text{multi-GeV}) \end{array}$$

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

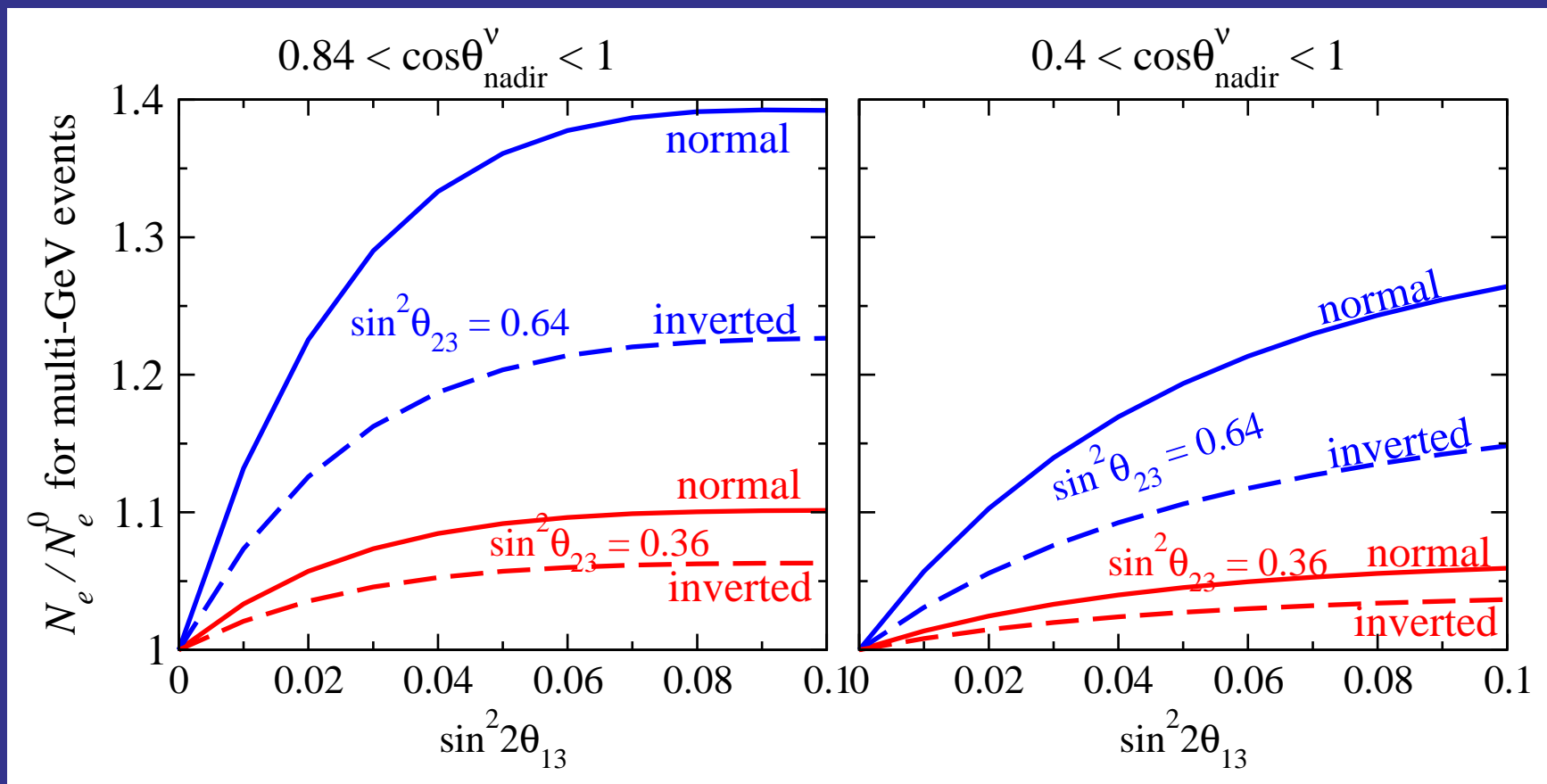
inverted hierarchy: enhancement for anti-neutrinos

detection cross sections are different for neutrinos
and anti-neutrinos

sensitivity to the neutrino mass hierarchy

θ_{13} -effects

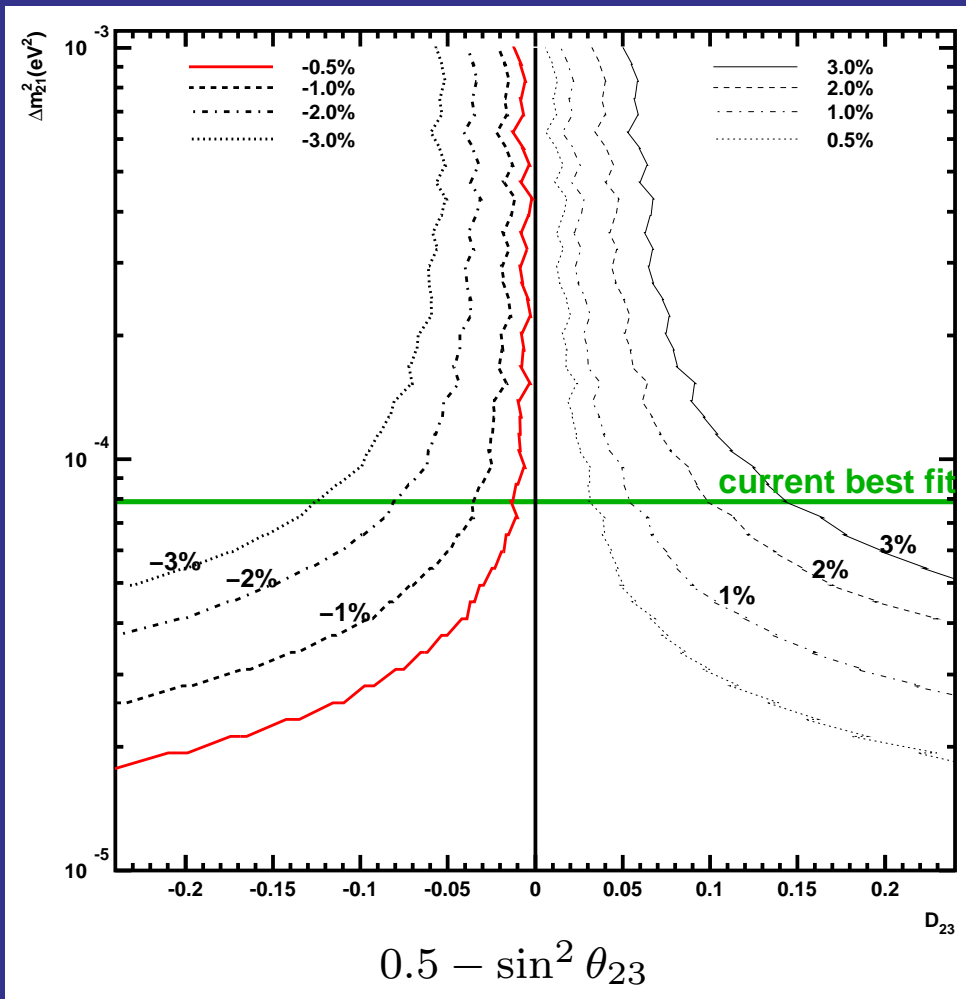
$$\frac{N_e}{N_e^0} - 1 \simeq (r s_{23}^2 - 1) P_{2\nu}(\Delta m_{31}^2, \theta_{13})$$



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

Δm_{21}^2 -effects

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



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}

The **HK** atmospheric neutrino experiment

assume 9 Mt yrs ATM data (100 × SK-I data)

	zenith angle	ν	$\bar{\nu}$
<i>e</i> -like sub-GeV	10 bins	239 000	58 000
<i>e</i> -like multi-GeV	10 bins	52 700	18 100
μ -like sub-GeV	10 bins	232 000	66 200
μ -like multi-GeV	10 bins	108 000	49 100
upward going μ	$10_{\text{thr}} + 5_{\text{st}}$	127 000	65 400

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- same binning (zenith angle, energy) as SK-I

The ATM analysis

- **Full numerical three-flavour analysis**
 - both Δm_{31}^2 and Δm_{21}^2 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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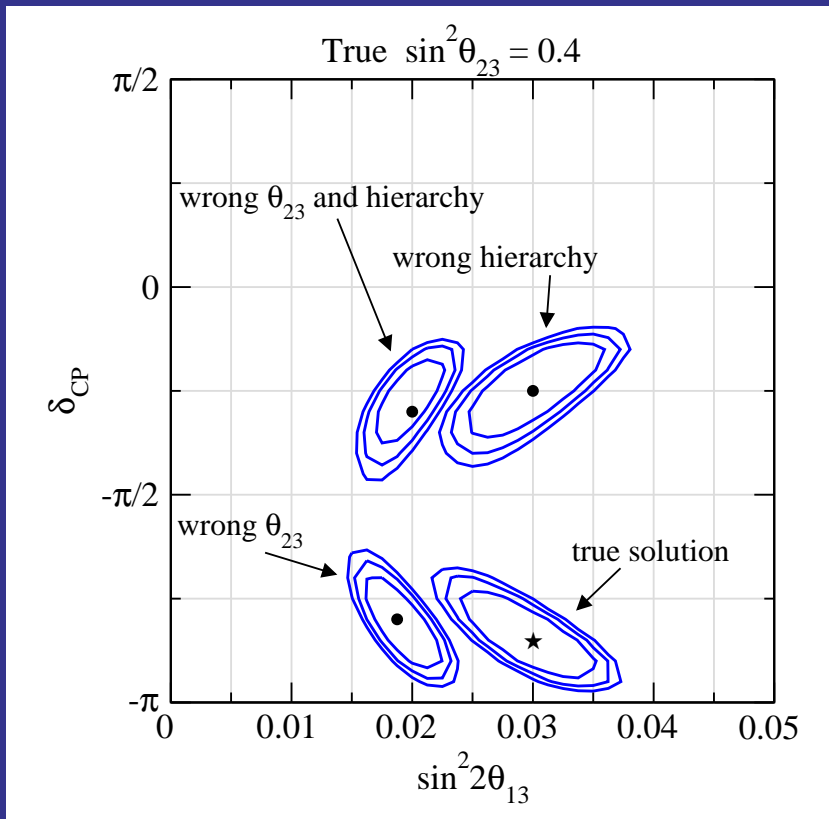
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- Combined with LBL data by using a generalized version of the GLoBES software

Resolving the degeneracies

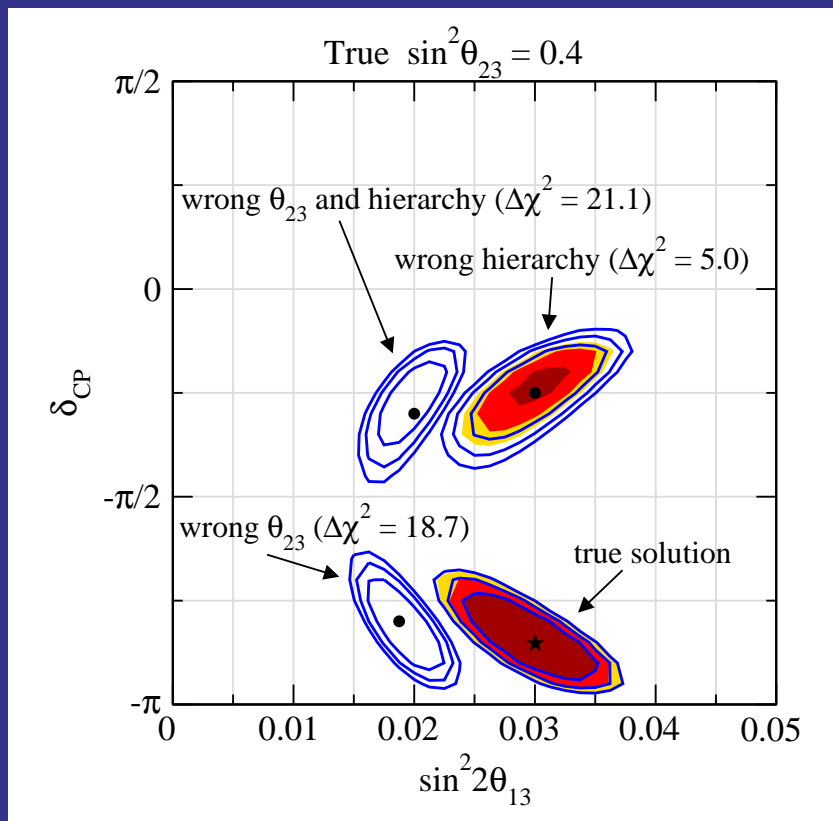
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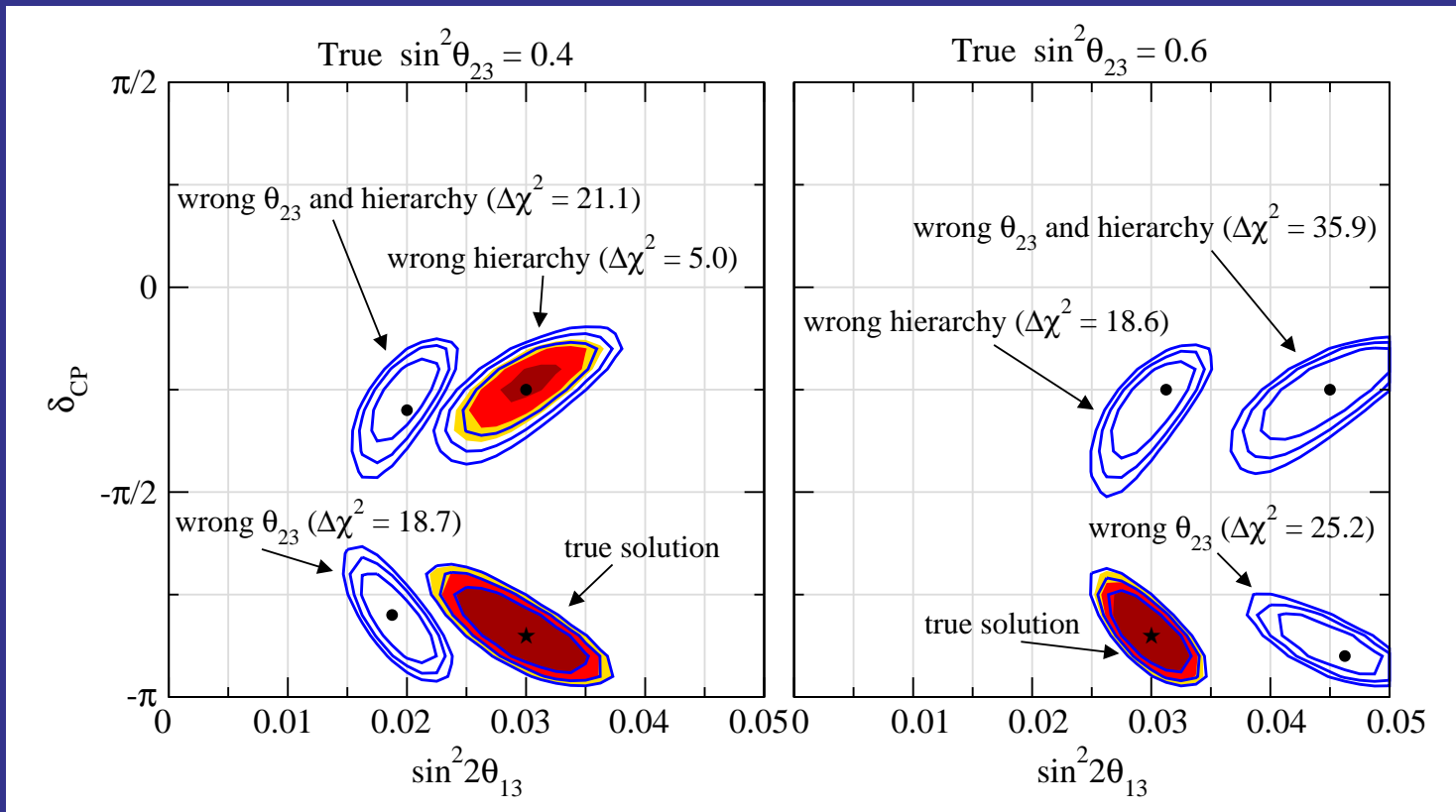
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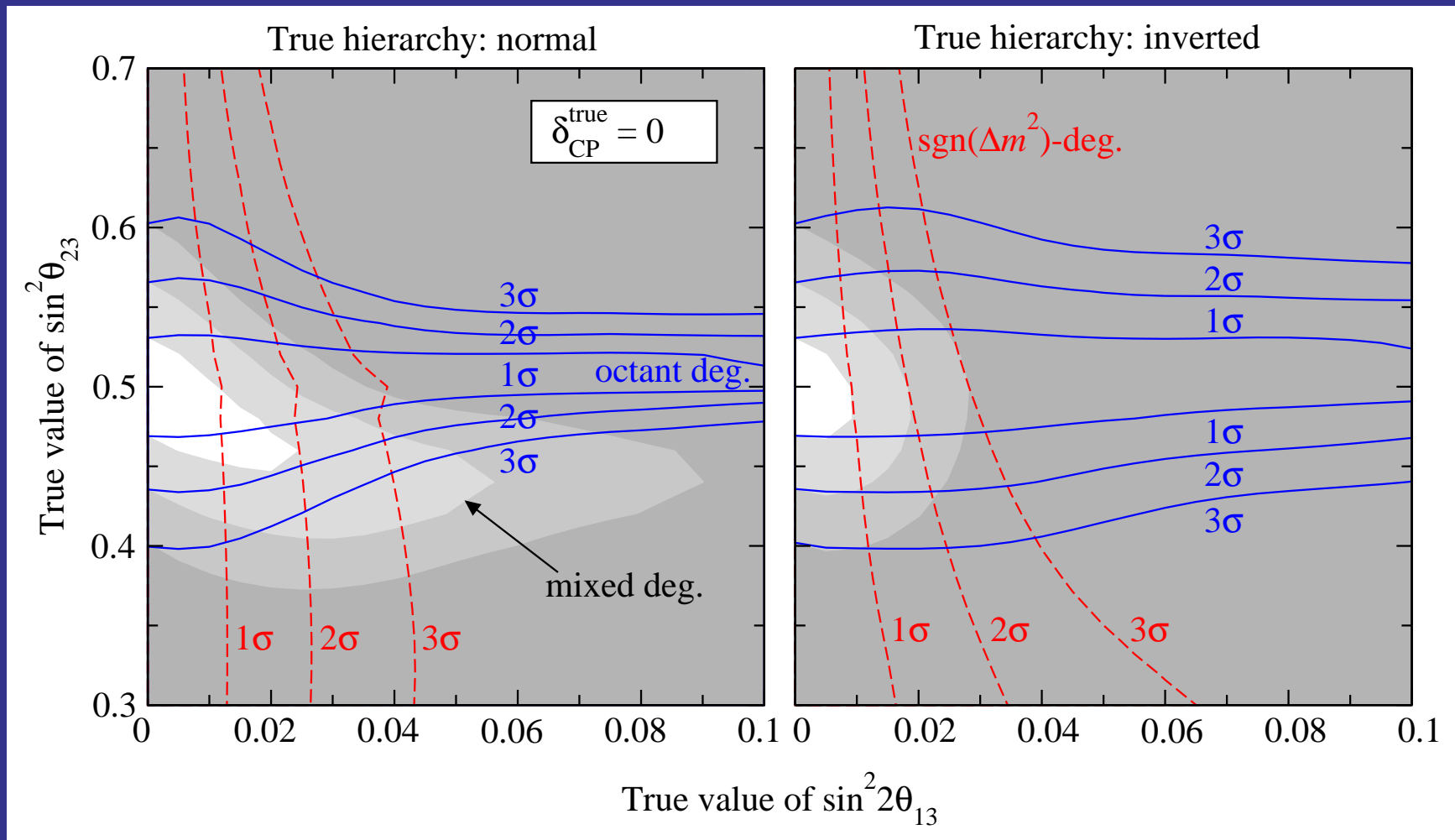
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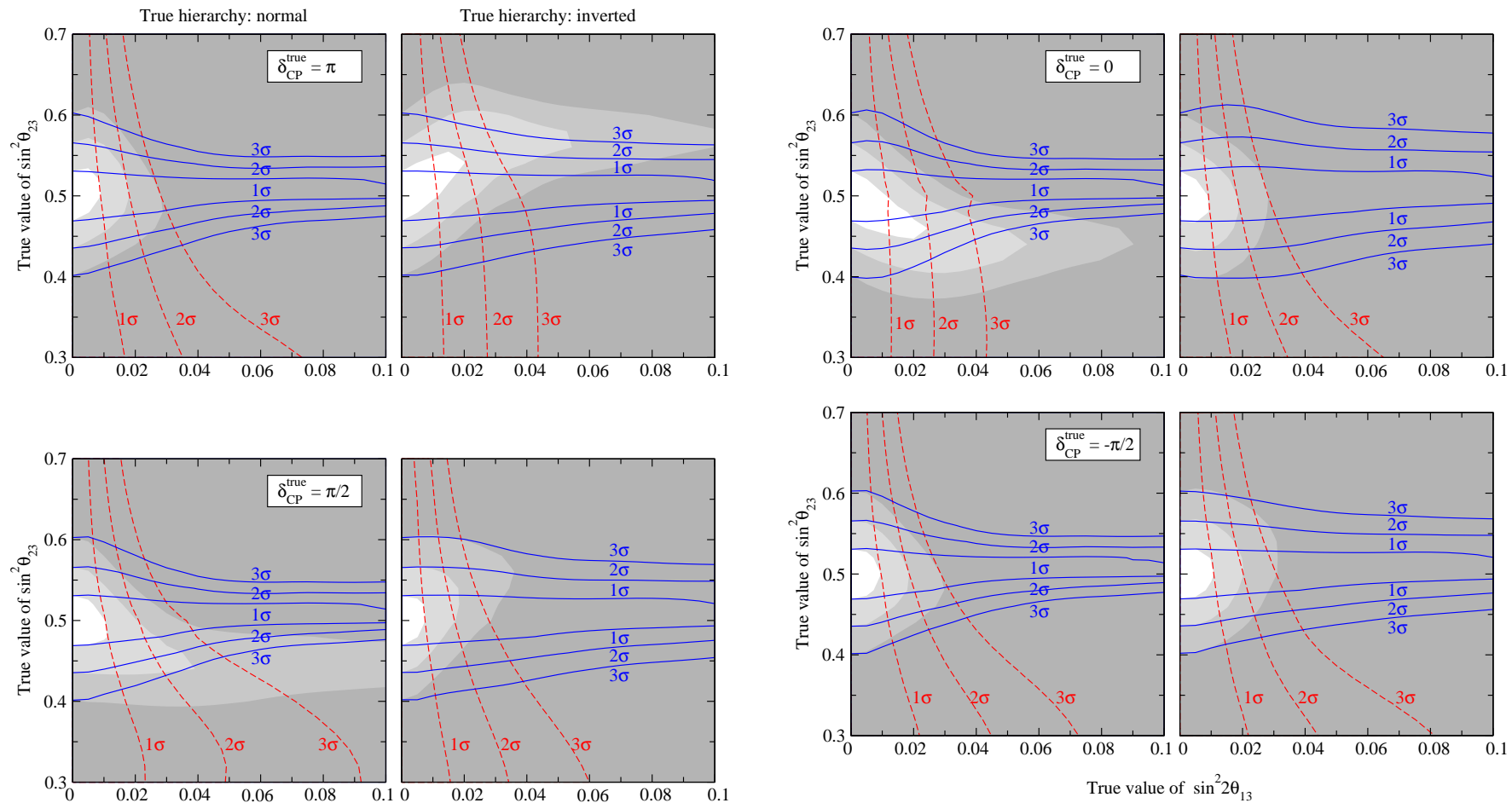
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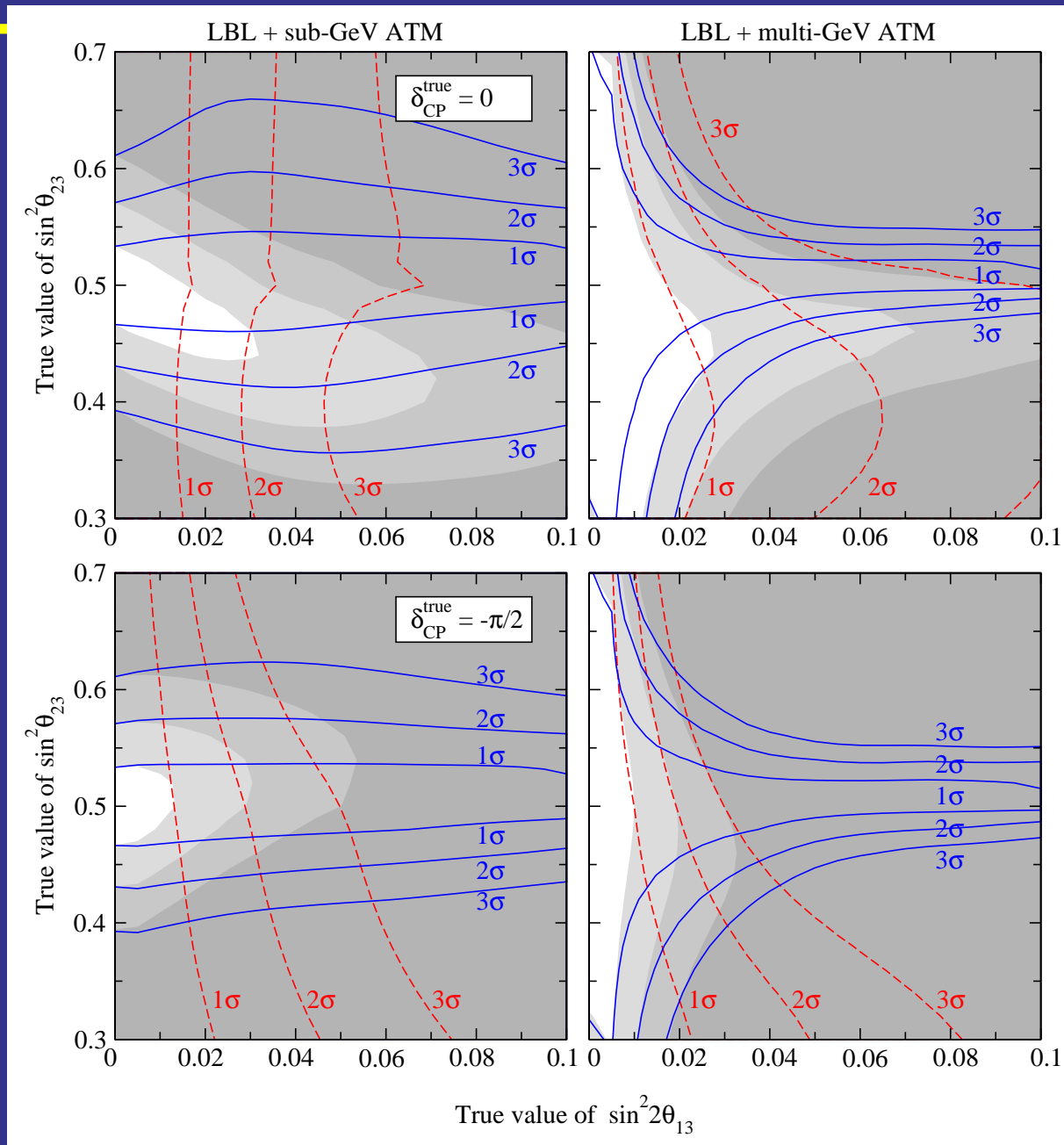
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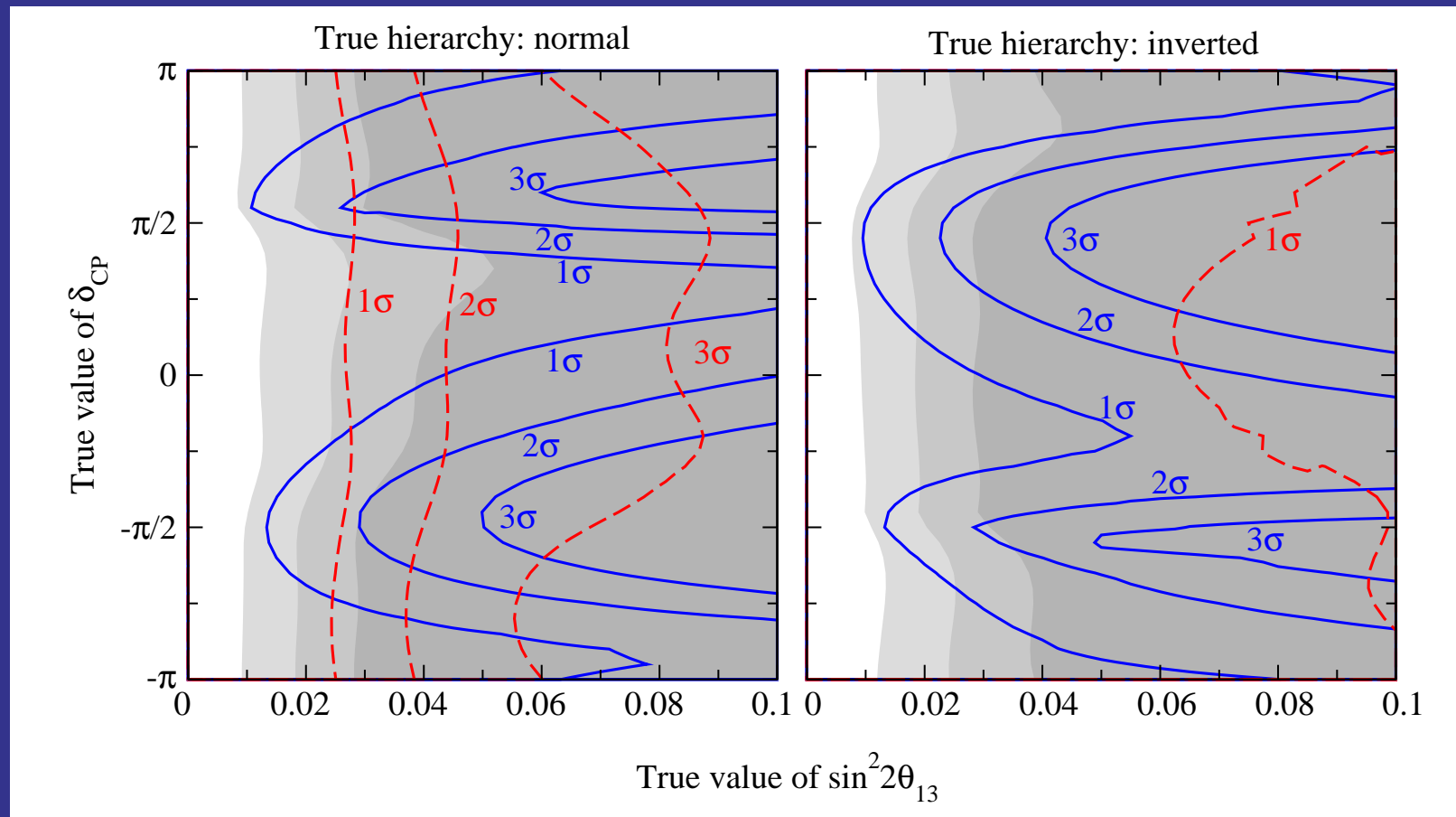


Which are the relevant ATM data samples?



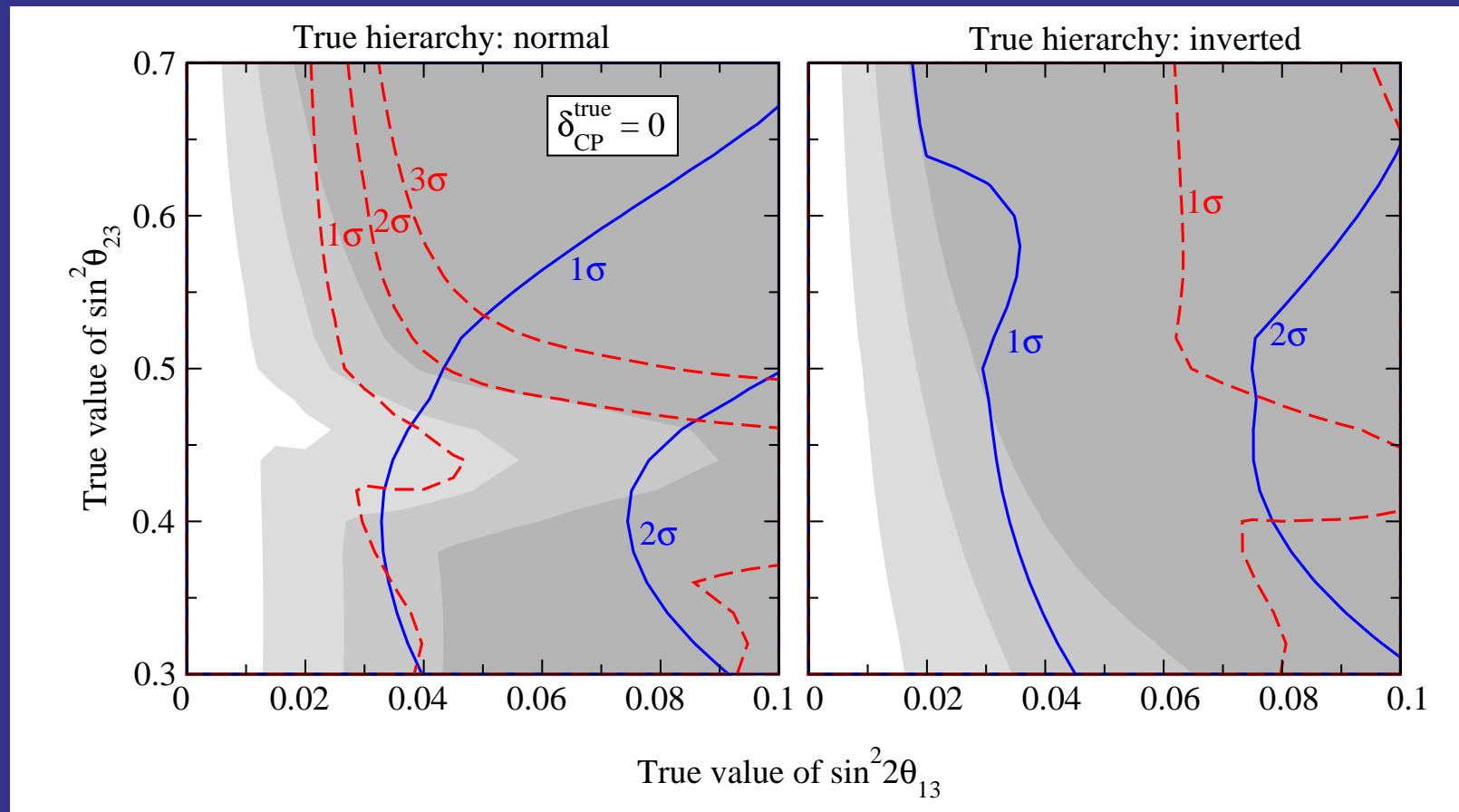
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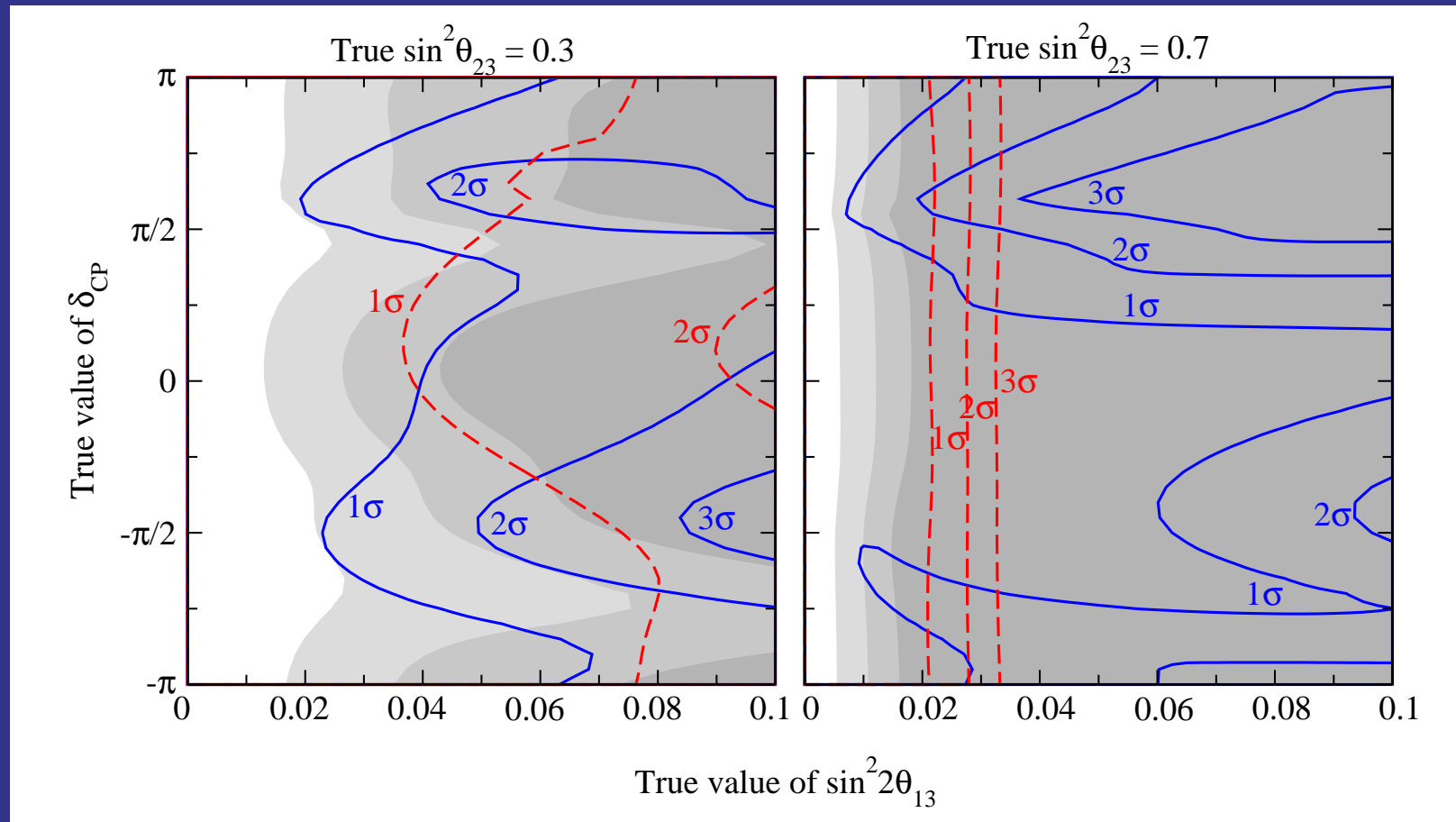
solid: LBL-only, dashed: ATM-only, shading: LBL+ATM

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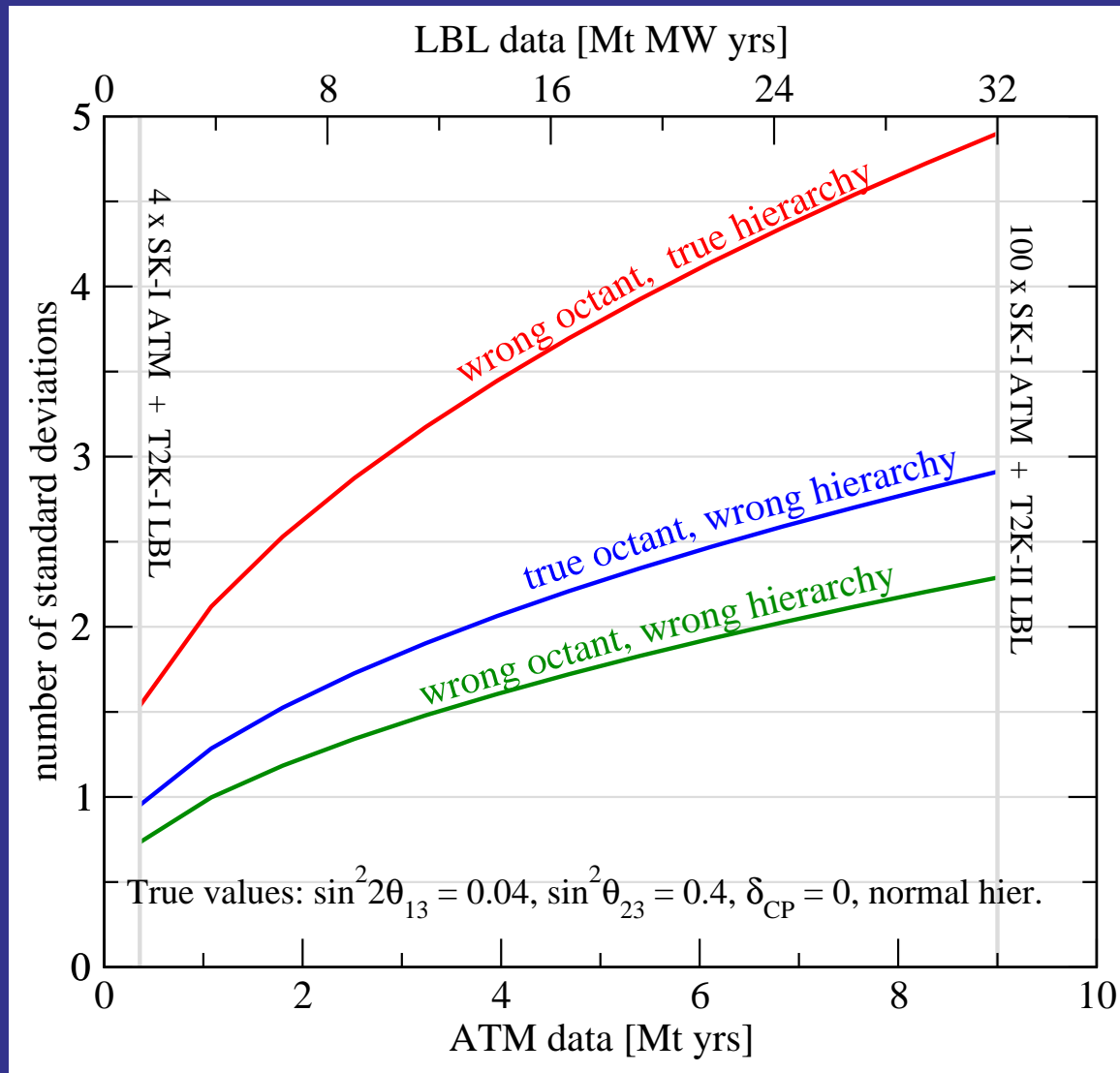


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Luminosity scaling

Do we really need a Mt experiment?

Luminosity scaling



Preliminary BB/SPL analysis

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

simulation from Huber, Lindner, Rolinec, Winter, work in progress

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- **Beta Beam**

similar to the setups from Bouchez, Lindroos, Mezzetto, hep-ex/0310059;
Burguet-Castell et al., hep-ph/0312068; Donini et al., hep-ph/0406132

$\bar{\nu}$: ${}^6\text{He}$ ($\gamma = 60, 3 \times 10^{18}$ decays/yr),

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10 yrs running

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- **SPL Superbeam**

similar to SB from Gomes-Cadenas et al., hep-ex/0105297; Donini et al., hep-ph/0406132

2.2 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**

Preliminary BB/SPL analysis

main difference to T2K:

- baseline: 130 km
- $E_\nu \simeq 0.2 - 0.3$ GeV
- no spectral information available

Preliminary BB/SPL analysis

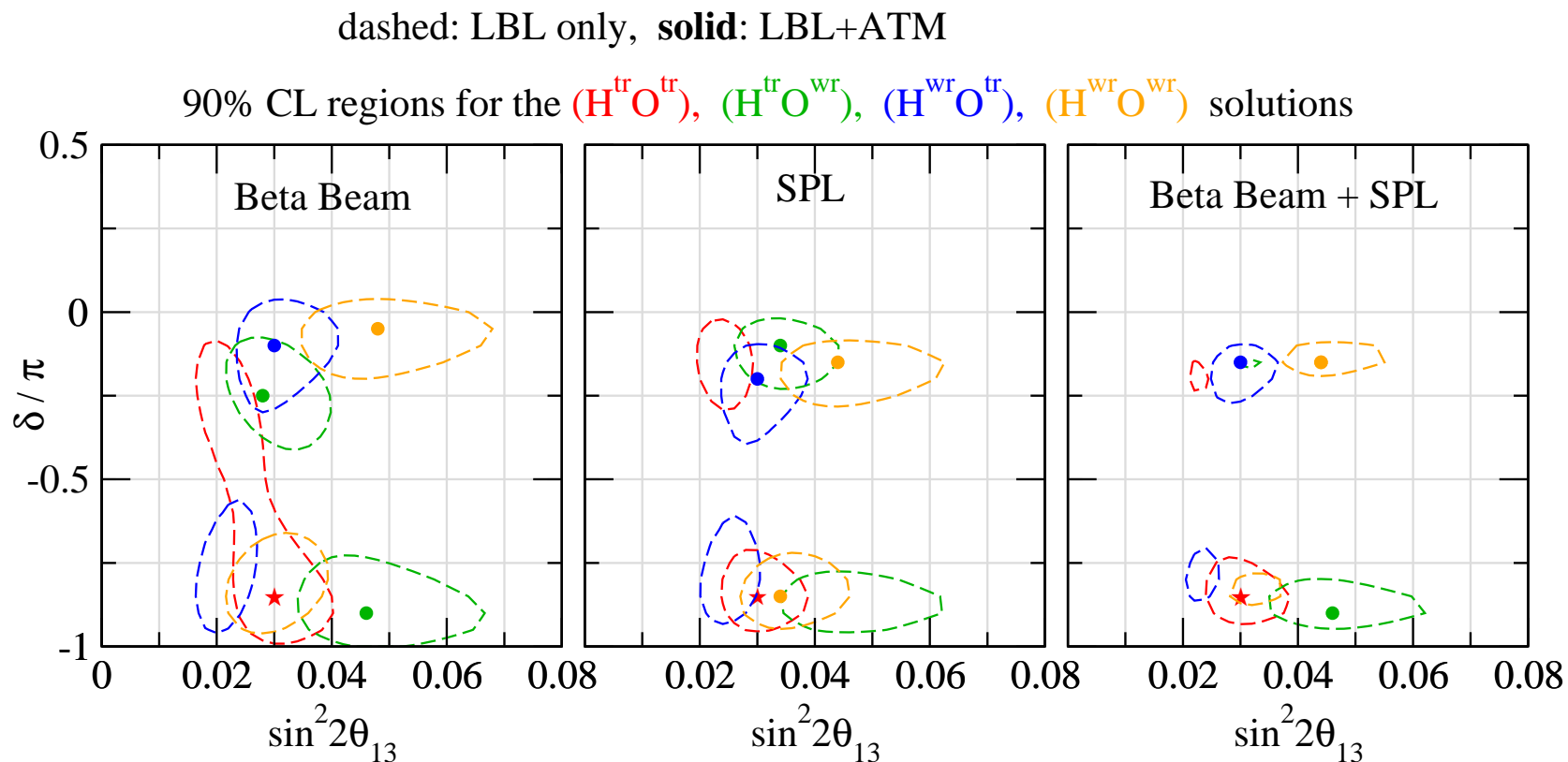
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$(\theta_{13}, \delta_{CP})$ -degeneracy cannot be resolved

see also talk of M. Mezzetto

Preliminary BB/SPL analysis

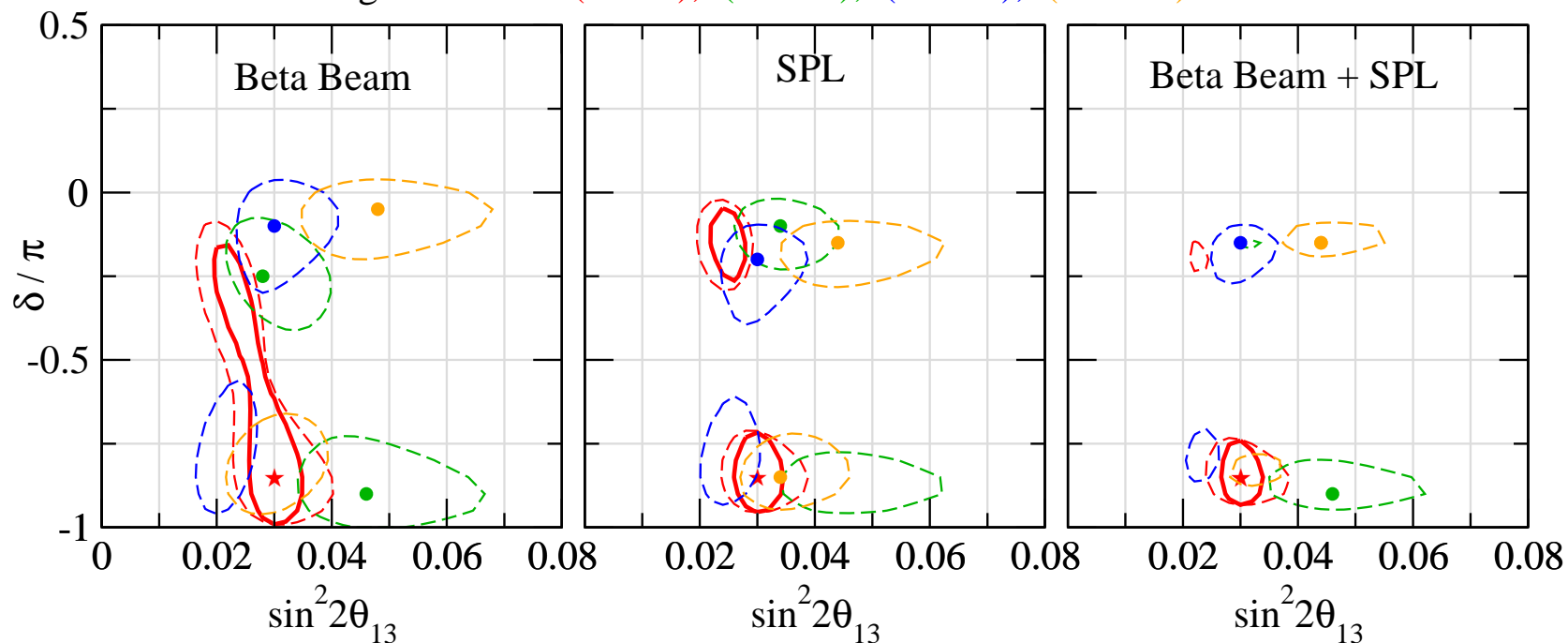


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Preliminary BB/SPL analysis

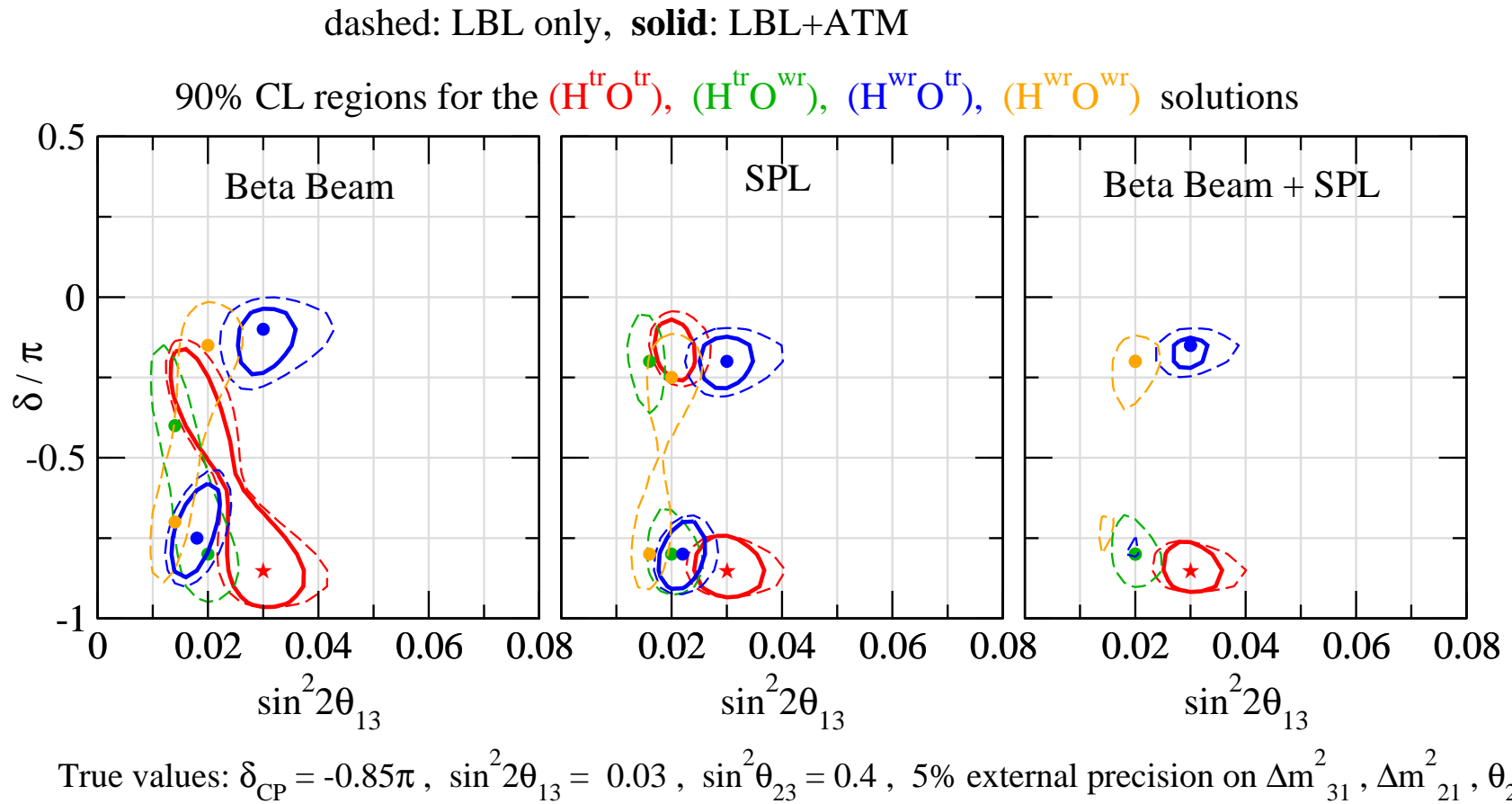
dashed: LBL only, **solid**: LBL+ATM

90% CL regions for the $(H^{tr}O^{tr})$, $(H^{tr}O^{wr})$, $(H^{wr}O^{tr})$, $(H^{wr}O^{wr})$ solutions



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

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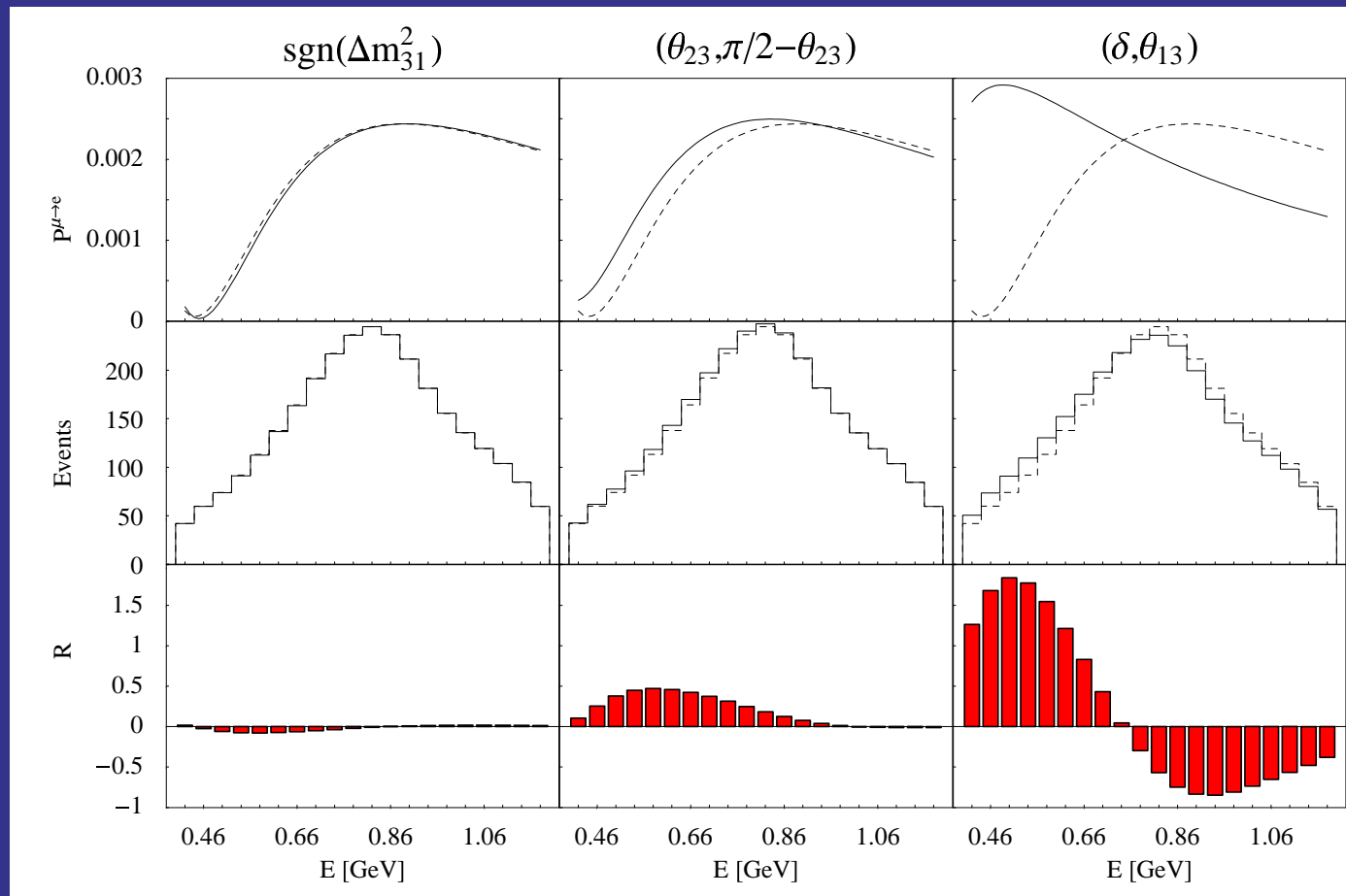
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- The determination of Δm_{31}^2 and $\sin^2 2\theta_{23}$ at the sub-percent level and a constraint on $\sin^2 2\theta_{13}$ from LBL data is necessary

Thank you for your attention!

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

additional slides

Degeneracies and T2K-II



$$\sin^2 2\theta_{13} = 0.01$$

$$\delta_{\text{CP}} = \pi/4$$

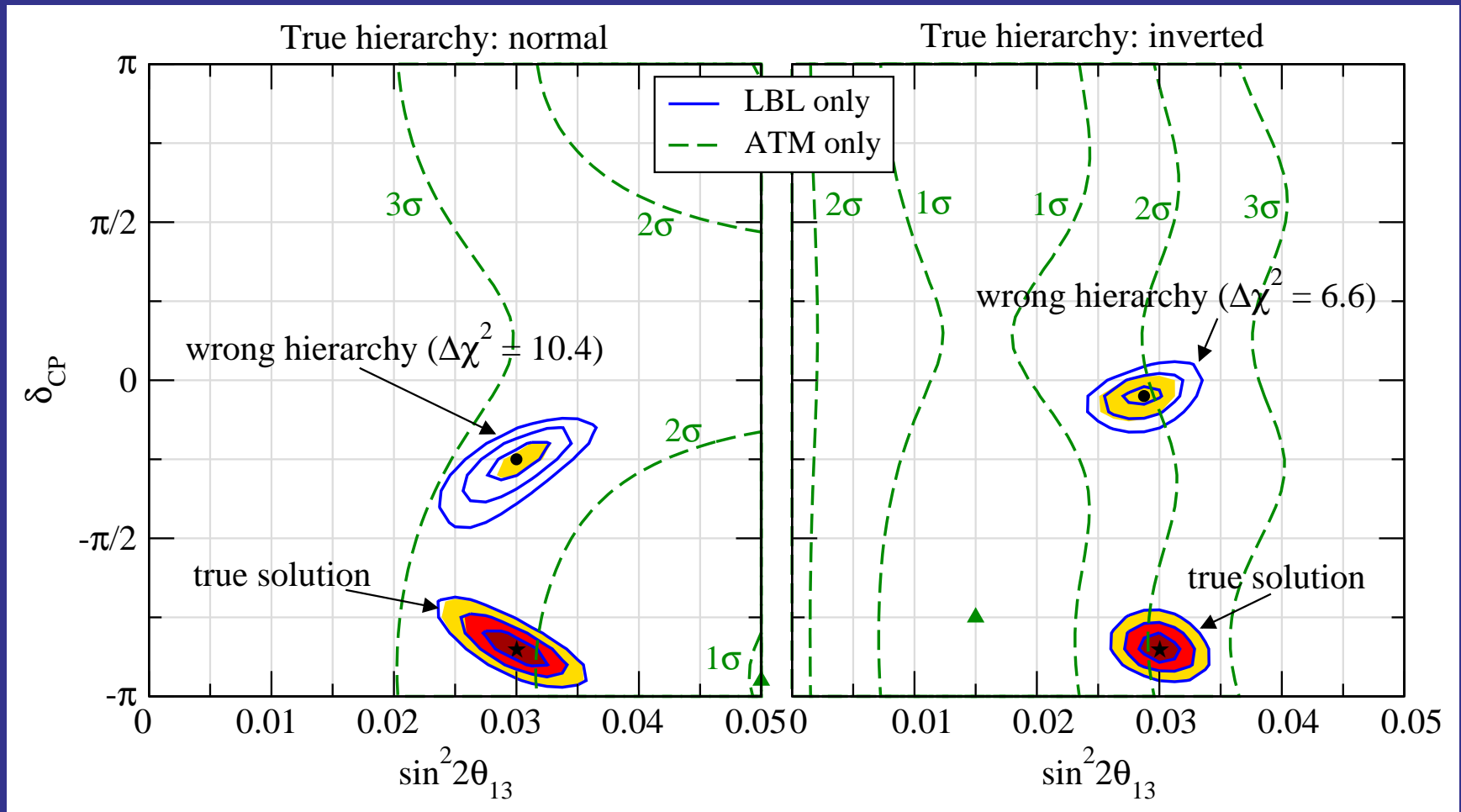
$$\sin^2 \theta_{23} = 0.3$$

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

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

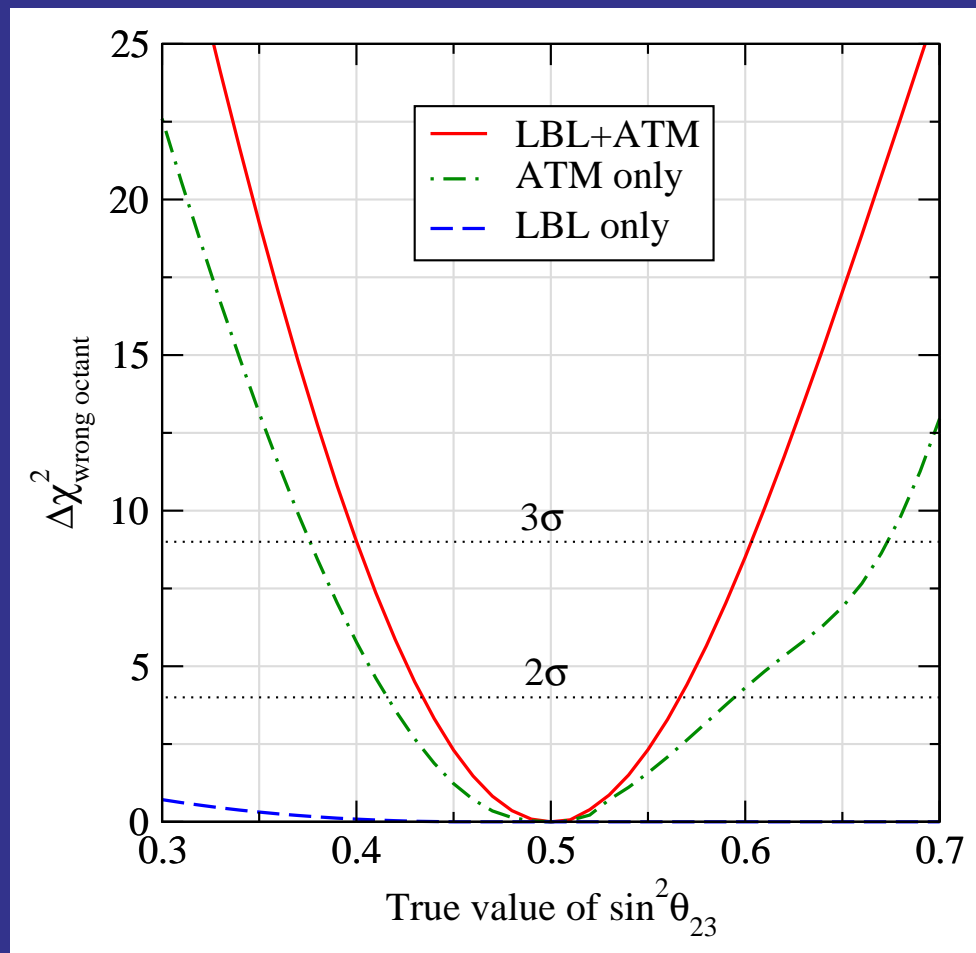
The intrinsic degeneracy is absent for T2K-II

Additional slides



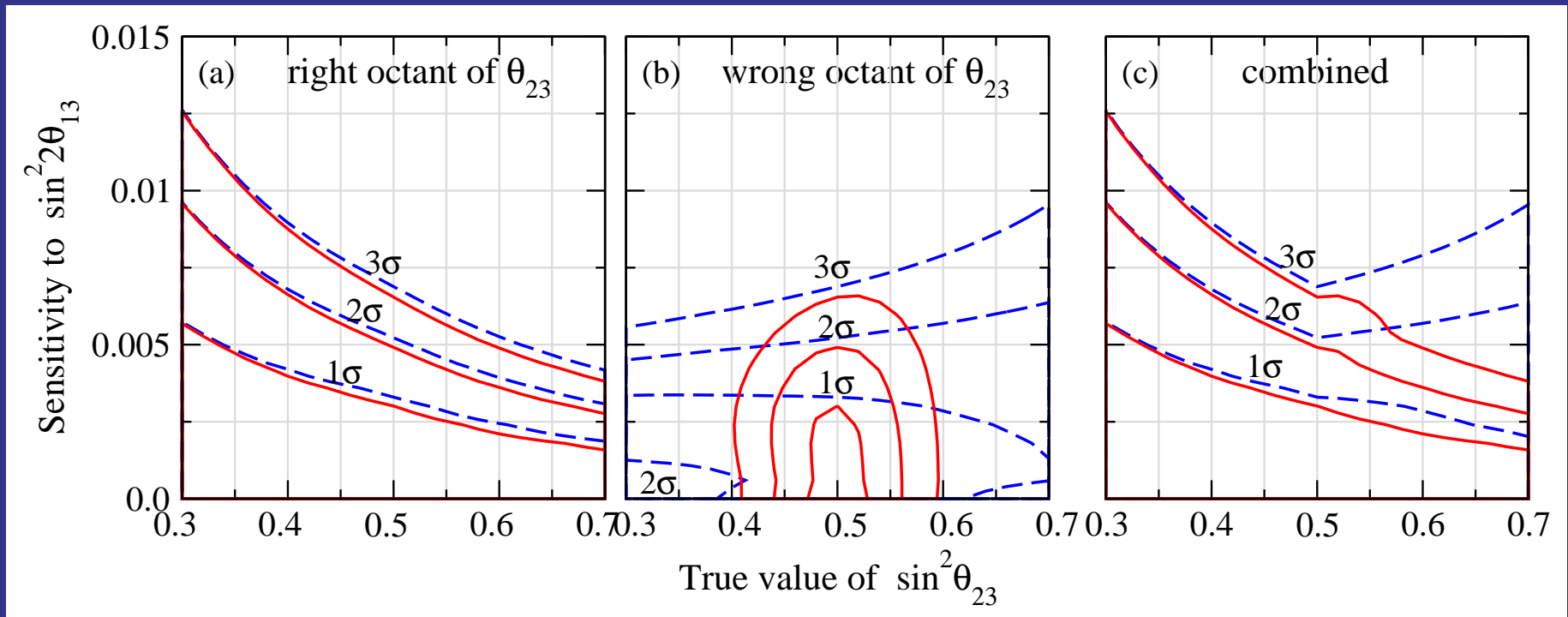
$$\text{True } \theta_{13} = 0$$

Resolving the octant-degeneracy:



True $\theta_{13} = 0$

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



dashed: LBL only, solid: LBL+ATM

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