BENE workshop

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

Thomas Schwetz

SISSA, Trieste

based on:

P. Huber, M. Maltoni, TS, hep-ph/0501037

Outline

- Introduction
- Parameter degeneracies in LBL experiments
- Three-flavour effects in ATM experiments
- Resolving the degeneracies by a combined LBL and ATM analysis
  - simulation of the T2K-II experiment
  - preliminary analysis of CERN-Frejus experiments
- Concluding remarks

Introduction

3-flavour neutrino oscillation parameters:

$$\Delta m^2_{31} \qquad \Delta m^2_{21}$$

$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & e^{-i\delta} s_{13} \\ 0 & 1 & 0 \\ -e^{i\delta} s_{13} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

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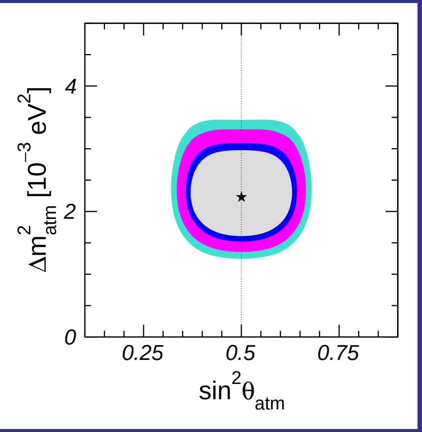
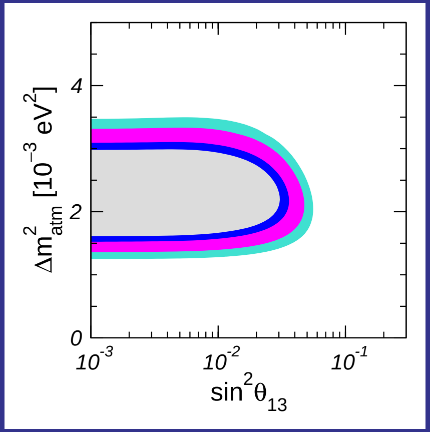
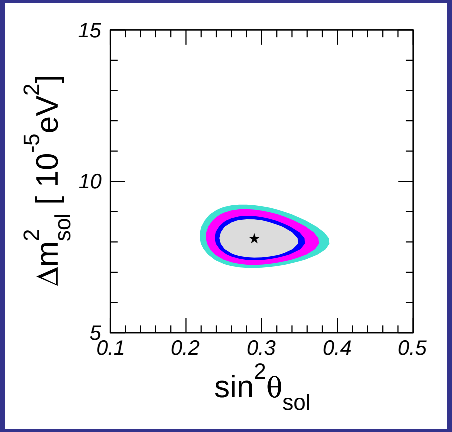


atmospheric + K2K



CHOOZ



solar + KamLAND

Maltoni, Schwetz, Tortola, Valle, hep-ph/0405172

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$$\frac{|\Delta m^2_{31}|}{10^{-3}\,\mathrm{eV}^2} = 2.2^{+0.37}_{-0.27}$$

(14%)

$$\sin^2\theta_{23} = 0.50^{+0.06}_{-0.05}$$

(11%)

atmospheric + K2K

$$\sin^2\theta_{13} < 0.05\,(3\sigma)$$

CHOOZ

$$\frac{|\Delta m^2_{21}|}{10^{-5}\,\mathrm{eV}^2} = 7.9 \pm 0.3$$

(4%)

$$\sin^2\theta_{12} = 0.30^{+0.03}_{-0.02}$$

(9%)

solar + KamLAND

Maltoni, Schwetz, Tortola, Valle, hep-ph/0405172

Introduction

Open questions:

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

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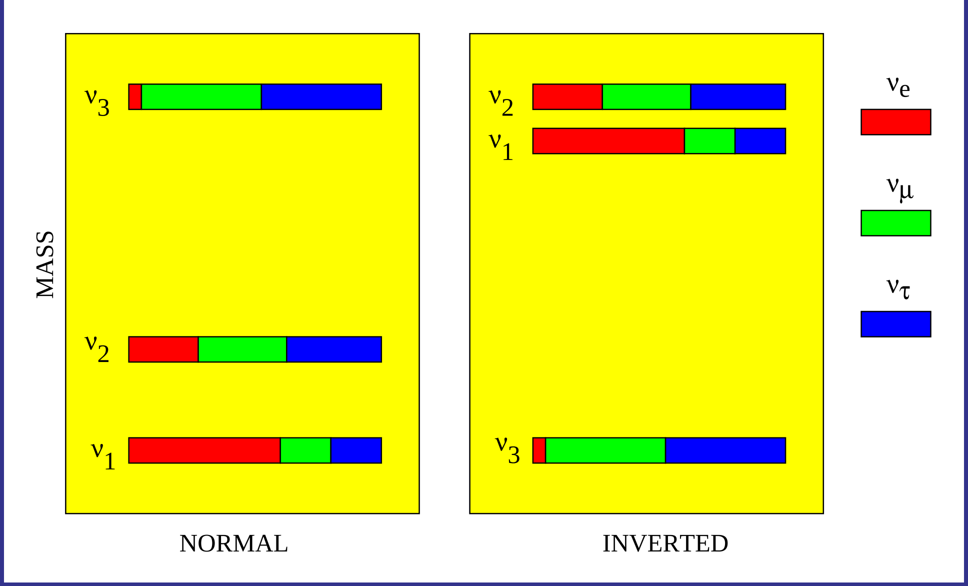
- How small is θ_{13}?
- What is the value of the CP phase $\delta_{\rm CP}$?
- Type of the neutrino mass ordering (sign of Δm^2_{31})



Parameter degeneracies in LBL experiments

M. Koike, T. Ota, J. Sato, Phys. Rev. D65 (2002) 053015
J. Burguet-Castell et al., Nucl. Phys. B608 (2001) 301
H. Minakata, H. Nunokawa, JHEP 10 (2001) 001
G.L. Fogli, E. Lisi, Phys. Rev. D54 (1996) 3667
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
A.Donini, D.Meloni, S.Rigolin, JHEP **0406** (2004) 011

and many more (I appologize for omissions)

The $\nu_\mu \to \nu_e$ oscillation probability

$P_{\mu e}$ in vacuum to leading order in $\sin^2 2\theta_{13}$ and α

$$\begin{aligned} P_{\mu e} \;\simeq\;& \sin^2 2\theta_{13} \sin^2\theta_{23} \sin^2\Delta_{31} \\ +\;& \alpha\, \sin 2\theta_{12} \sin 2\theta_{13} \sin 2\theta_{23} \Delta_{31} \sin\Delta_{31} \cos(\Delta_{31} \pm \delta_{\mathrm{CP}}) \\ +\;& \alpha^2\, \sin^2 2\theta_{12} \cos^2\theta_{23} \Delta_{31}^2 \end{aligned}$$

with

$$\alpha \equiv \frac{\Delta m^2_{21}}{\Delta m^2_{31}}\,, \qquad \Delta_{31} \equiv \frac{\Delta m^2_{31} L}{4E_\nu}$$

The 8-fold degeneracy

- The intrinsic or $(\delta_{\rm CP}, \theta_{13})$ degeneracy

  M. Koike, T. Ota, J. Sato, Phys. Rev. D65 (2002) 053015

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

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

$$
\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})
\end{aligned}
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- The hierarchy or $\mathrm{sgn}(\Delta m^2_{31})$ degeneracy

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  solutions for both signs of Δm^2_{31} (affects mainly δ_{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

Analysis method

Calculation of event rates for given experiment:

$$N_i(\alpha) = \Phi \cdot \sigma \cdot R \cdot \epsilon \cdot P(\hat{\boldsymbol{\theta}})$$

Φ: neutrino flux

σ: detection cross section

R: energy resoltion

ϵ: efficiencies

$P(\hat{\boldsymbol{\theta}})$: 3-flavour osc. prob., $\hat{\boldsymbol{\theta}} = (\Delta m^2_{21}, \Delta m^2_{31}, \theta_{12}, \theta_{23}, \theta_{13}, \delta)$

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simulate data for "true values" $\hat{\boldsymbol{\theta}}^{\rm true}$: $N_i(\hat{\boldsymbol{\theta}}^{\rm true})$

$\chi^2(\hat{\boldsymbol{\theta}}; \hat{\boldsymbol{\theta}}^{\rm true}) \quad \rightarrow$ allowed regions for $\hat{\boldsymbol{\theta}}$

including systematical errors, correlations, degeneracies

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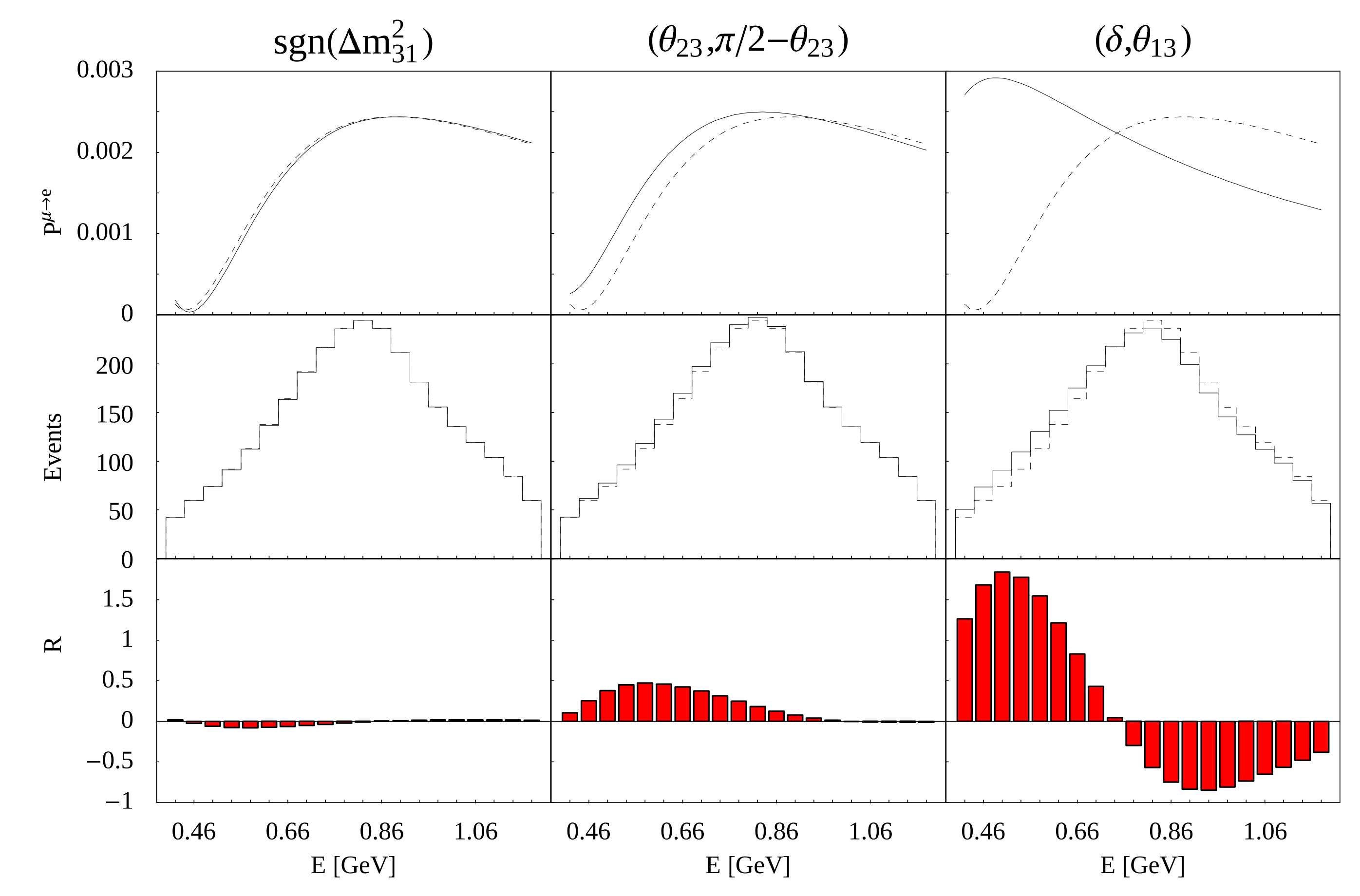
GLoBES software P. Huber, M. Lindner, W. Winter, hep-ph/0407333

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

Degeneracies and T2K-II



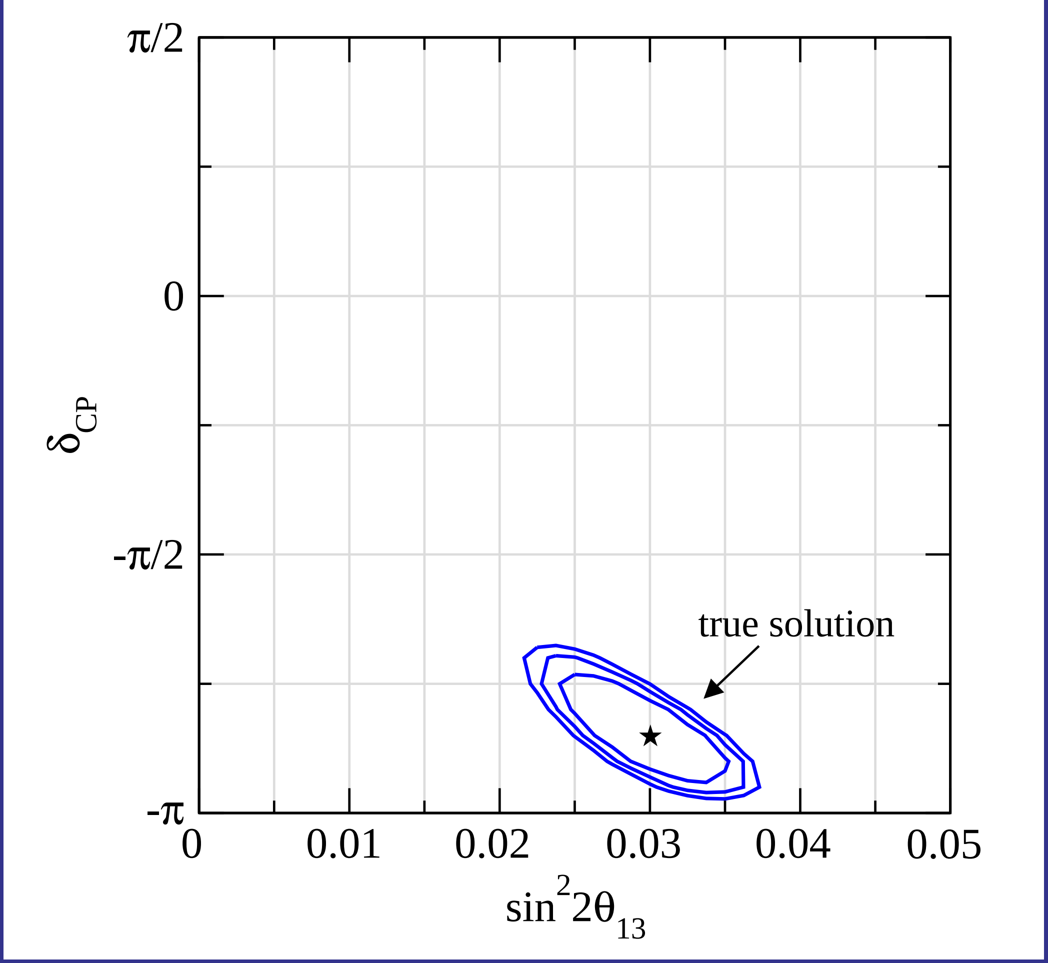
$$\sin^2 2\theta_{13} = 0.01$$
$$\delta_{CP} = \pi/4$$
$$\sin^2 \theta_{23} = 0.3$$

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

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

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

Degeneracies and T2K-II



True values:

$$\sin^2 2\theta_{13} = 0.03$$
$$\delta_{\rm CP} = -0.85\pi$$
$$\sin^2 \theta_{23} = 0.4$$
$$\Delta m^2_{31} = 2.2 \times 10^{-3} \mathrm{eV}^2$$

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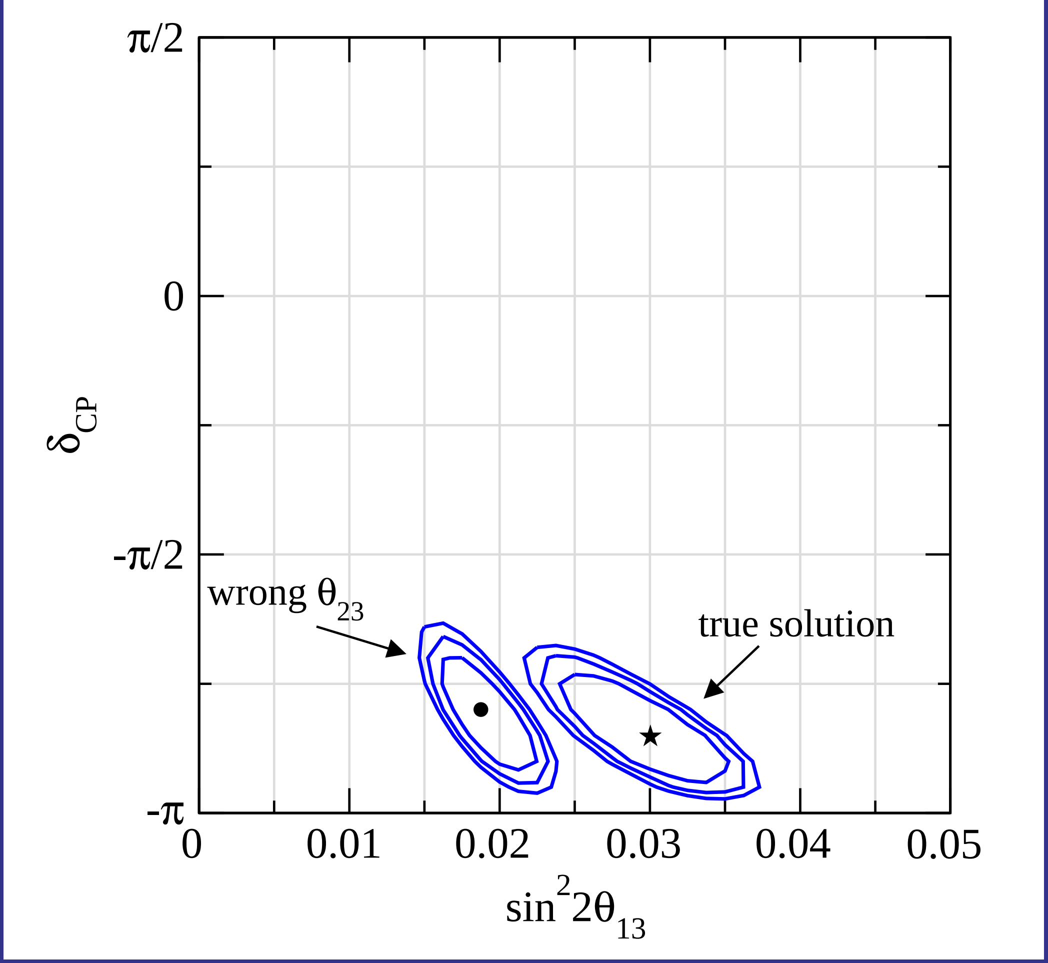

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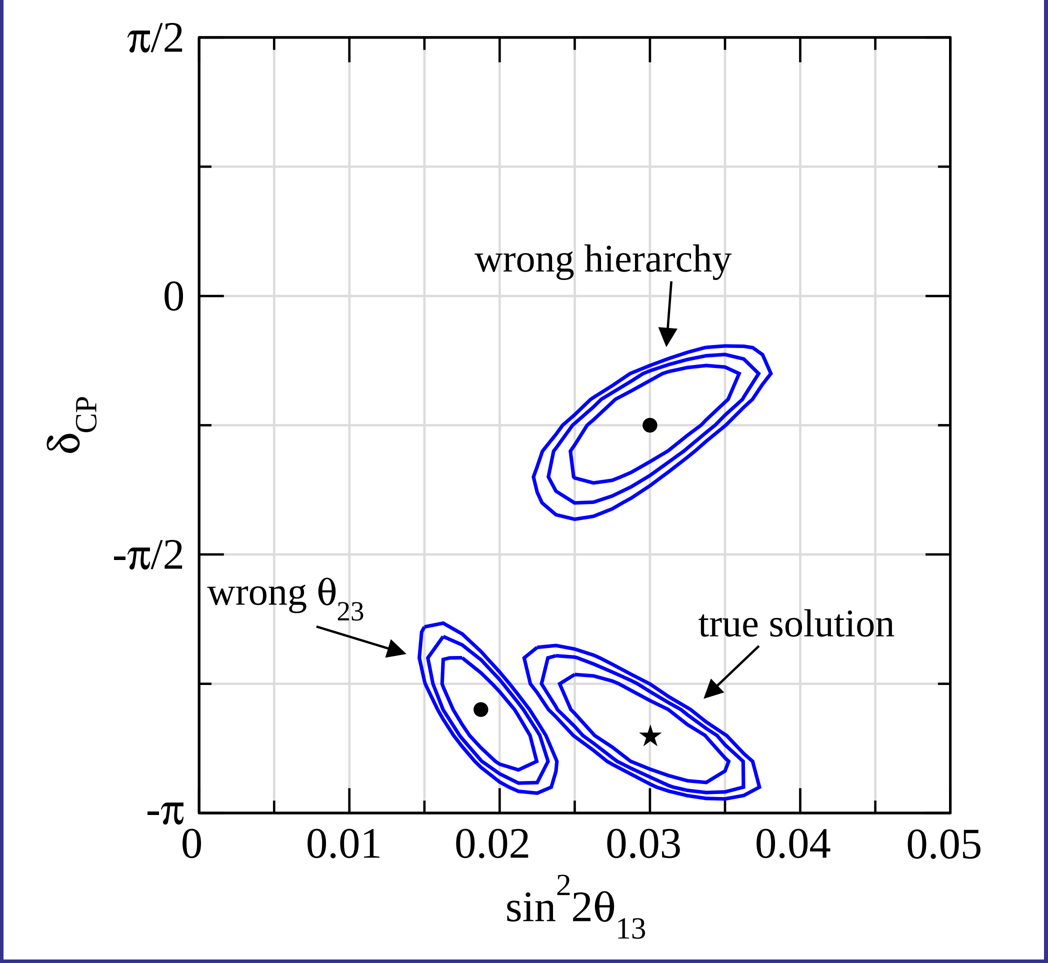

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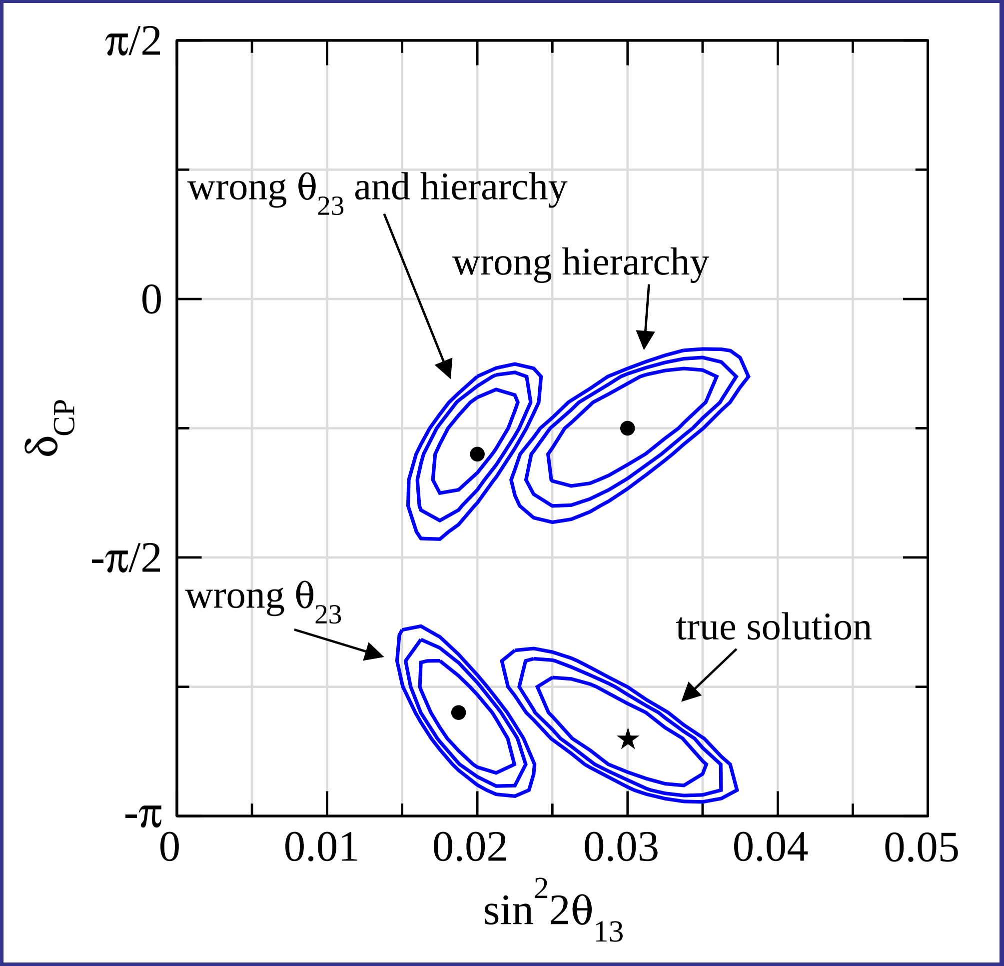

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ambiguities in θ_{13} and $\delta_{\rm CP}$

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

3-flavour effects in atmospheric neutrinos

excess of electron-like events:

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

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

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

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

$r \approx 2$ (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

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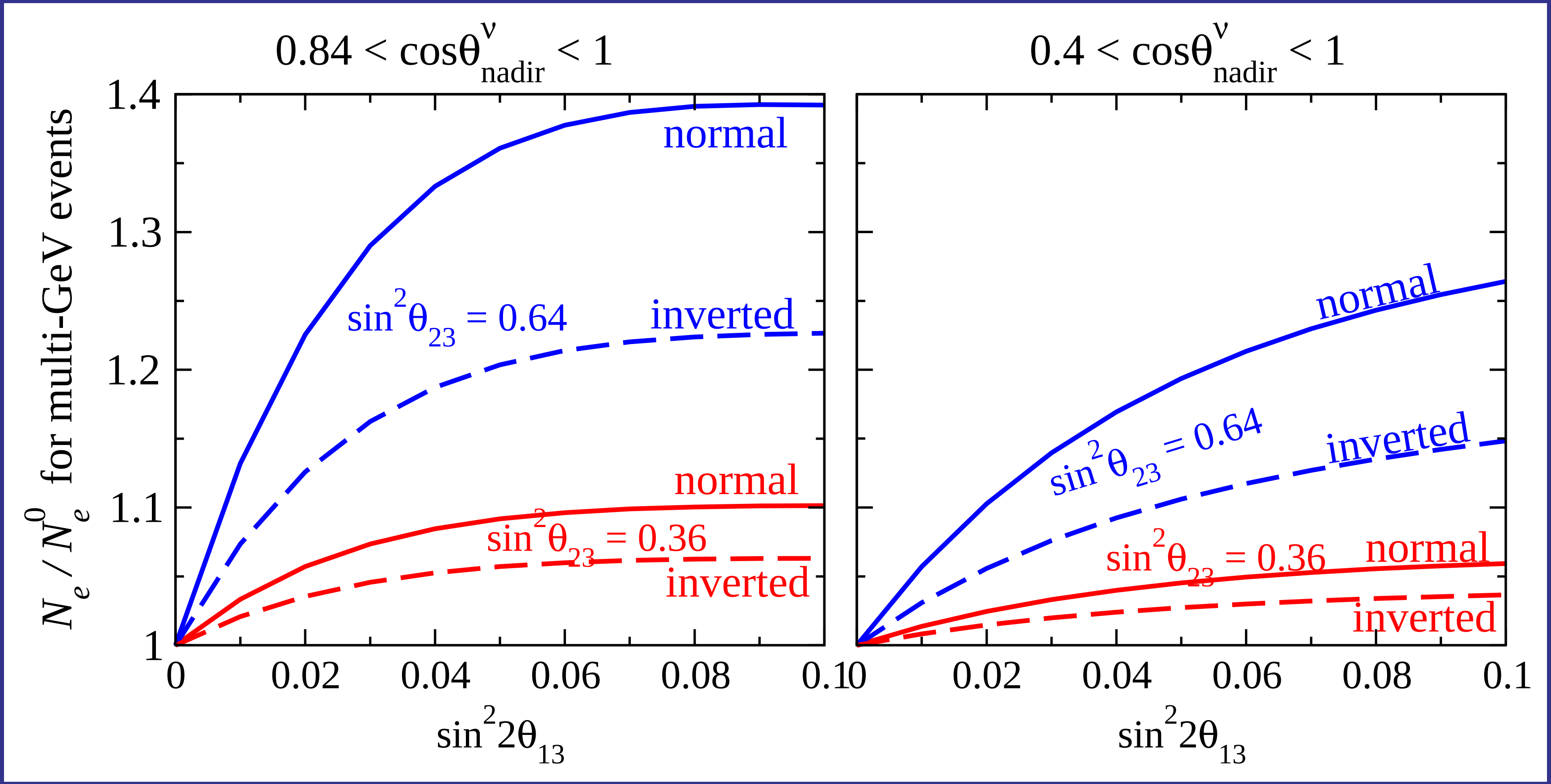
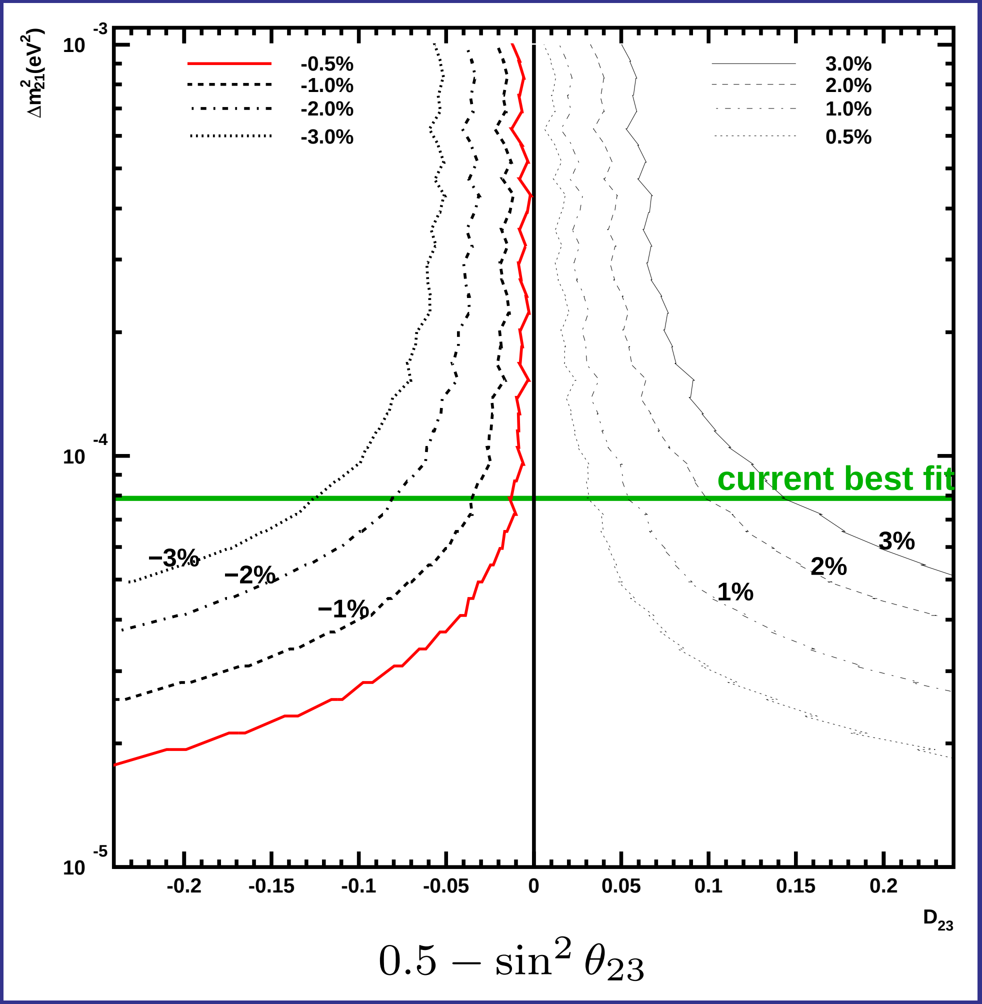


Bernabeu, Palomares-Ruiz, Petcov, Nucl. Phys. B669, 255 (2003), hep-ph/0305152

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}

Mega ton atmospheric neutrino experiments

projects for Mt water Cherenkov detectors
(SK: 22.5 kt)

UNO (US), Hyper-K (Japan), Frejus (Europe)

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multi-purpose experiments:

- far-detector for LBL experiments
- solar and atmospheric neutrinos
- supernova neutrinos
- proton decay
- . . .

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
μ-like multi-GeV	10 bins	108 000	49 100
upward going μ	10_{thr} + 5_{st}	127 000	65 400

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

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

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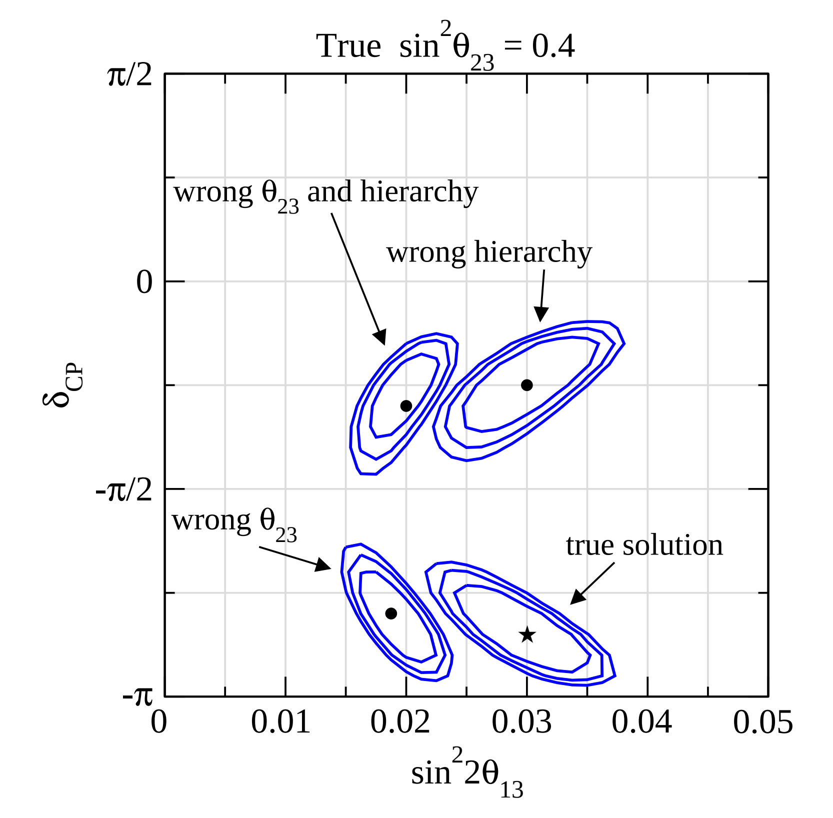
Maltoni, TS, Tortola, Valle, Phys. Rev. D **67** (2003) 013011 [hep-ph/0207227]

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

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

Resolving the degeneracies

Resolving the degeneracies



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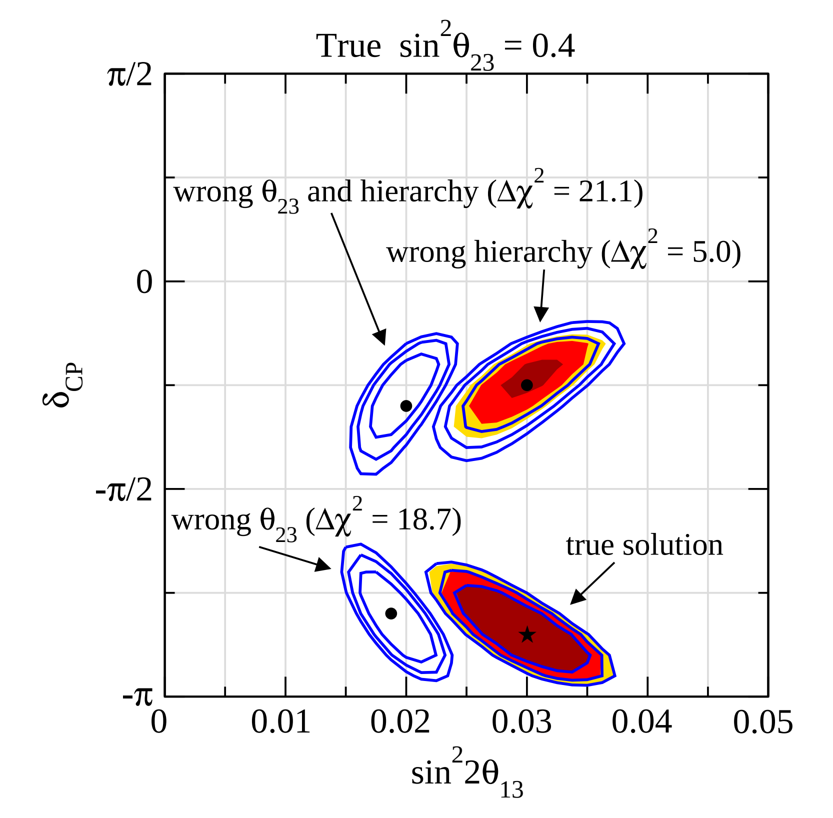
Resolving the degeneracies



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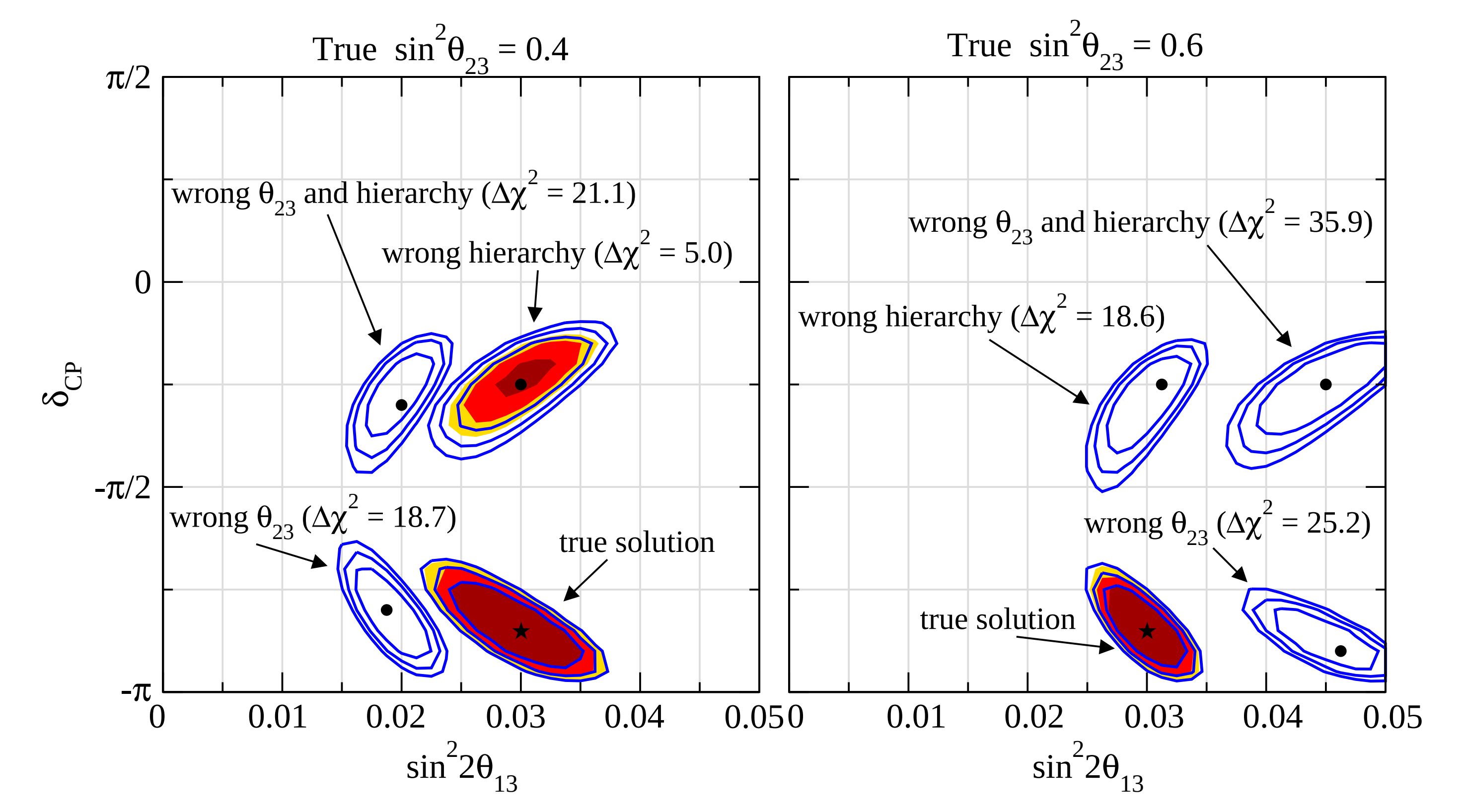

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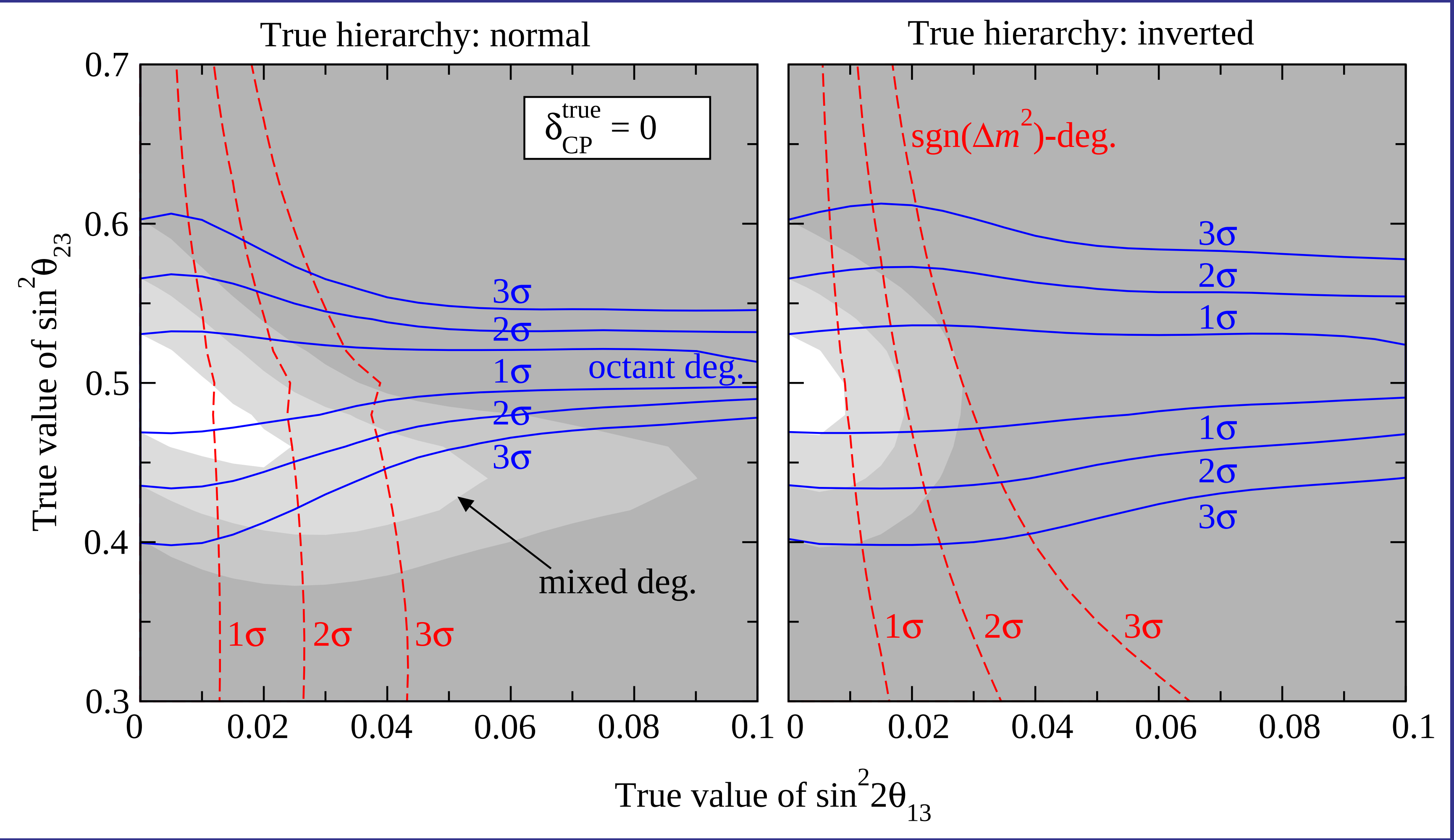

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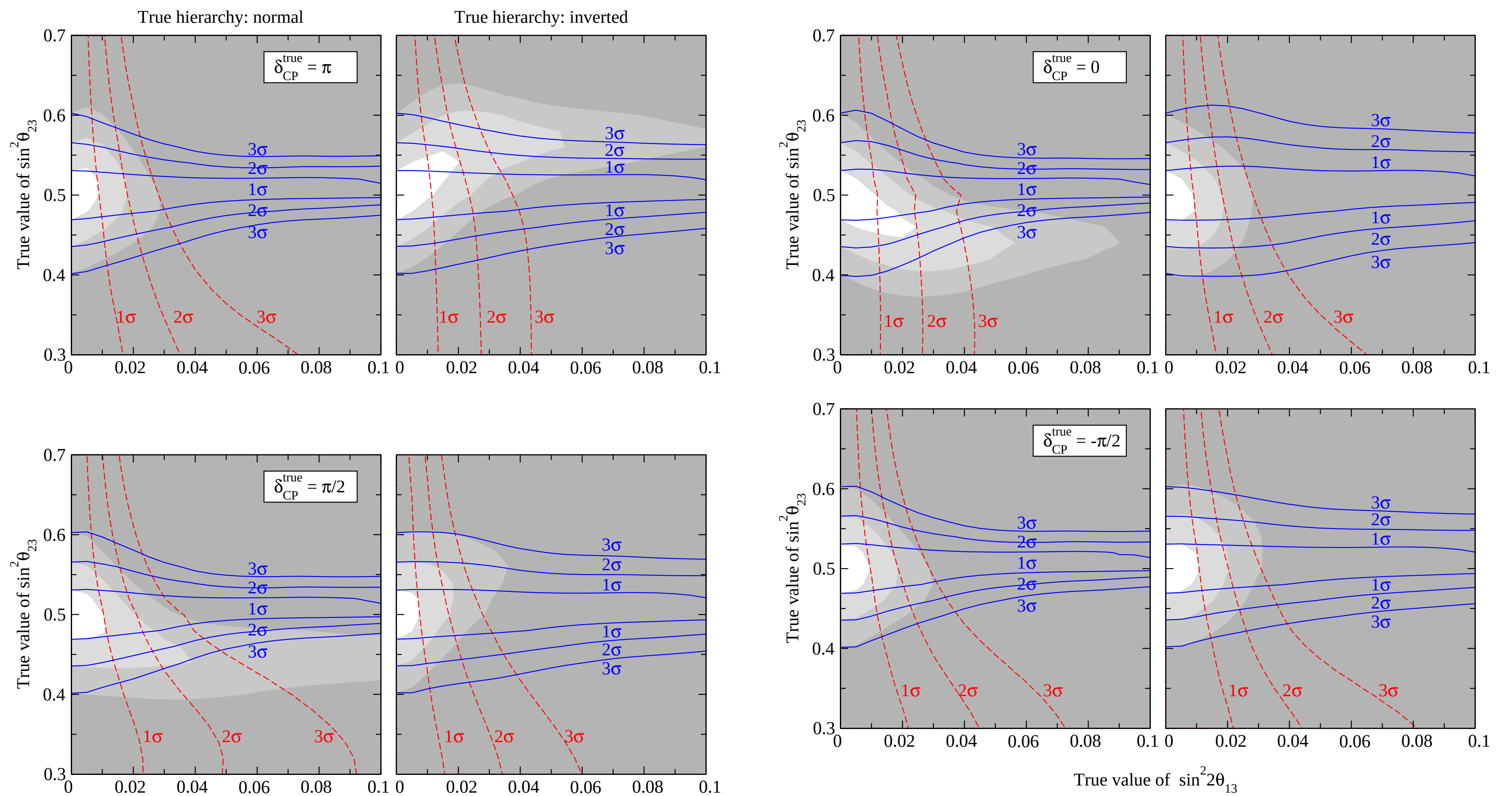
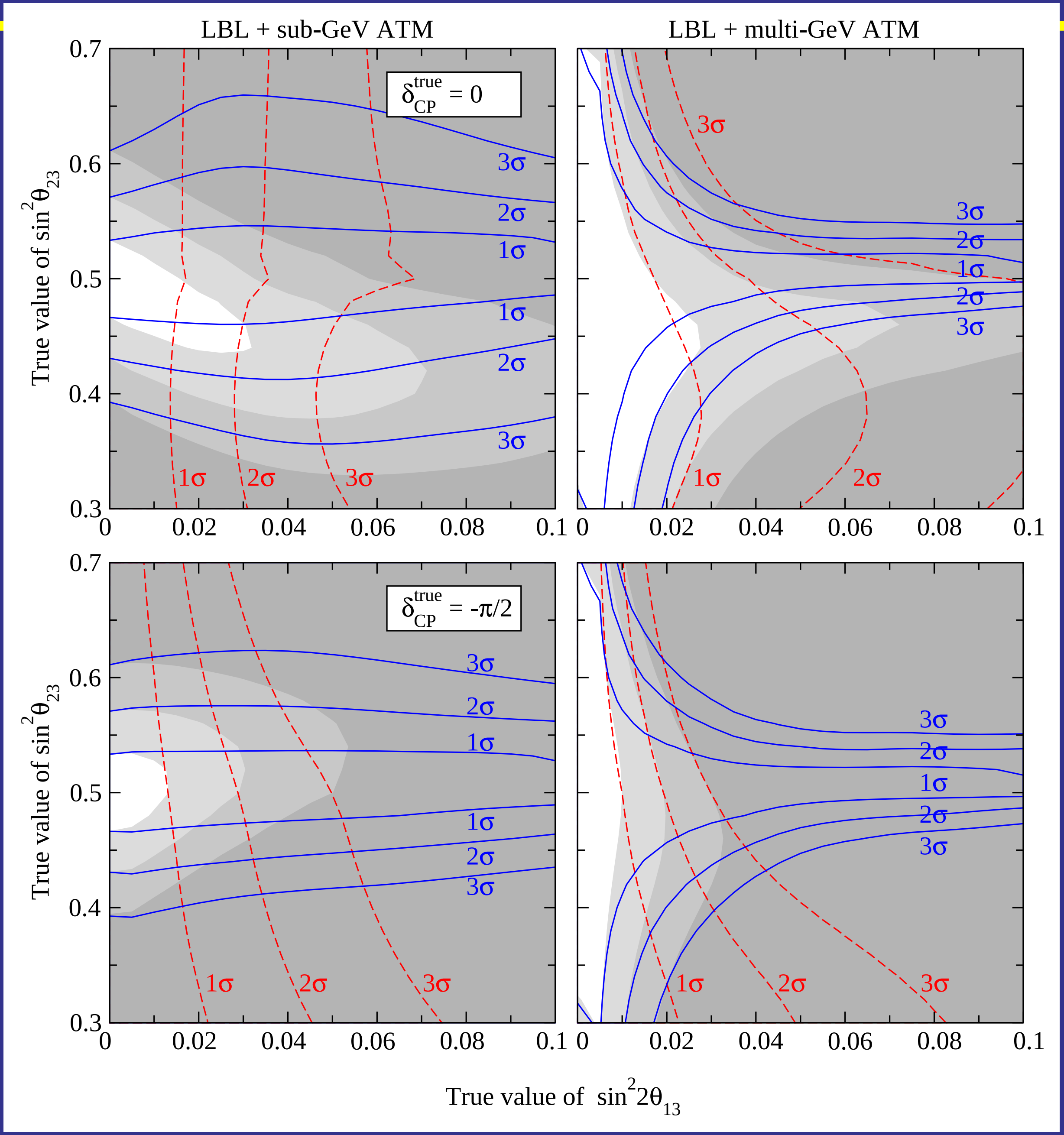


Which are the relevant ATM data samples?



Identifying the mass hierarchy

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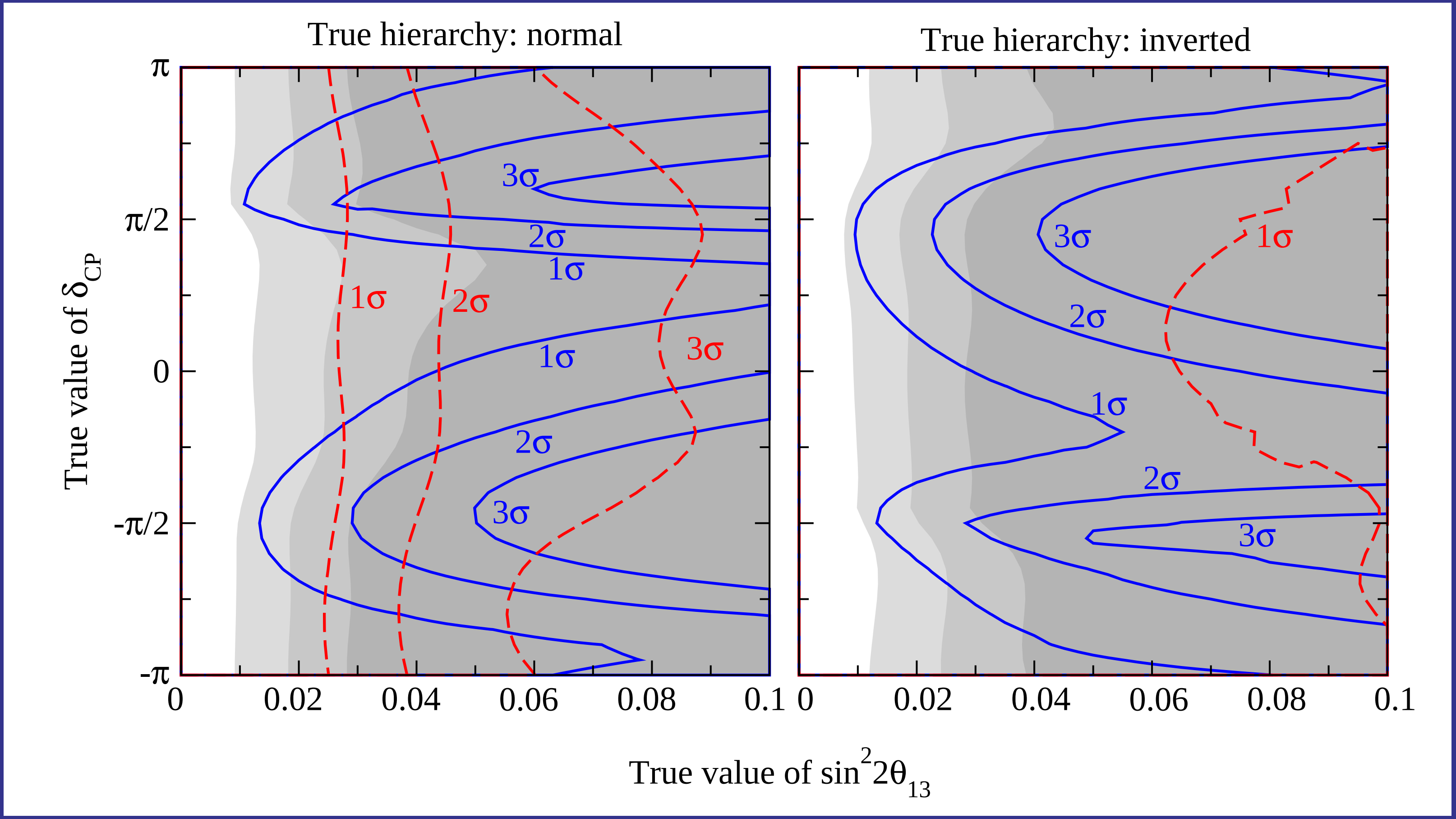

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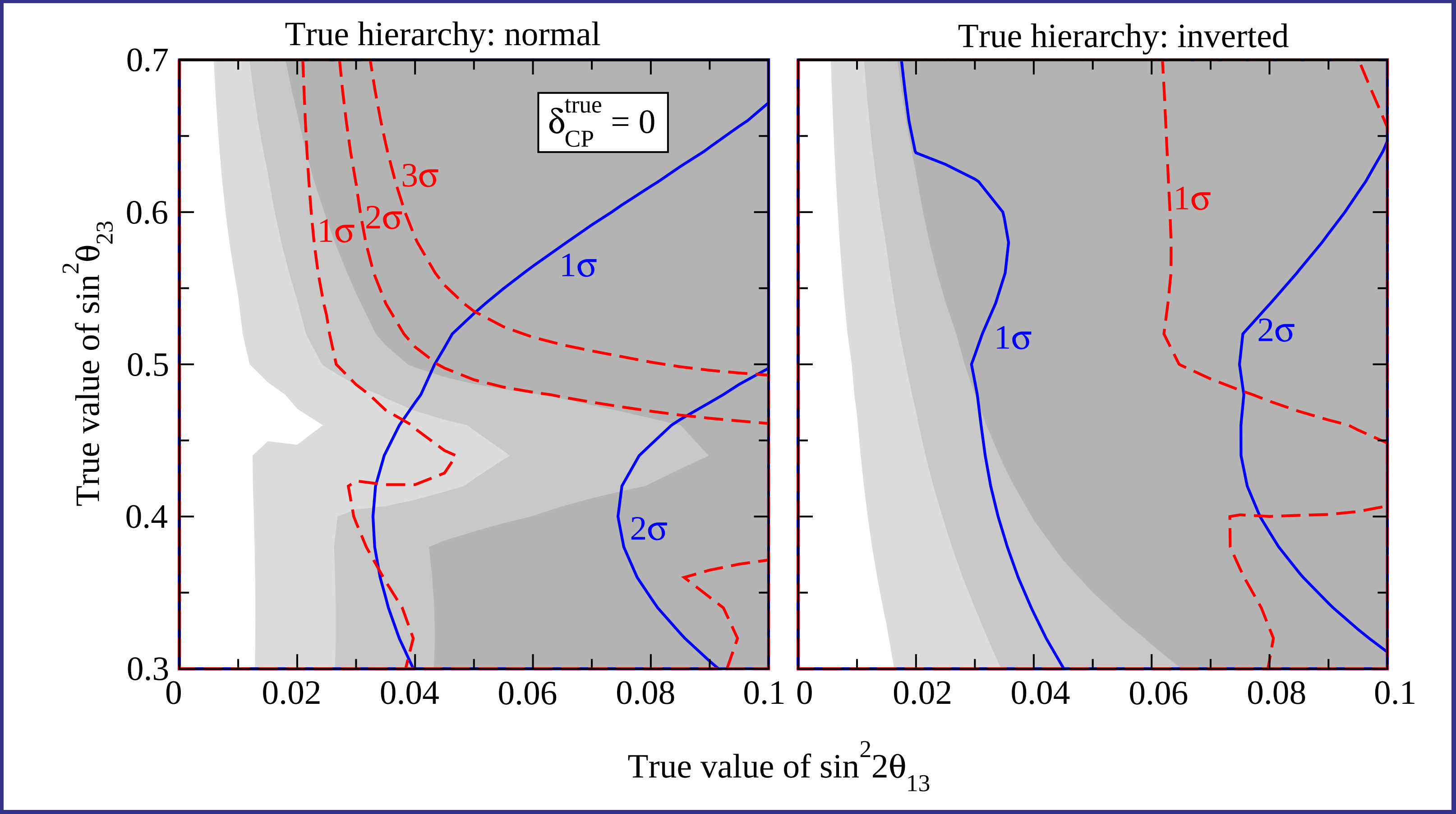

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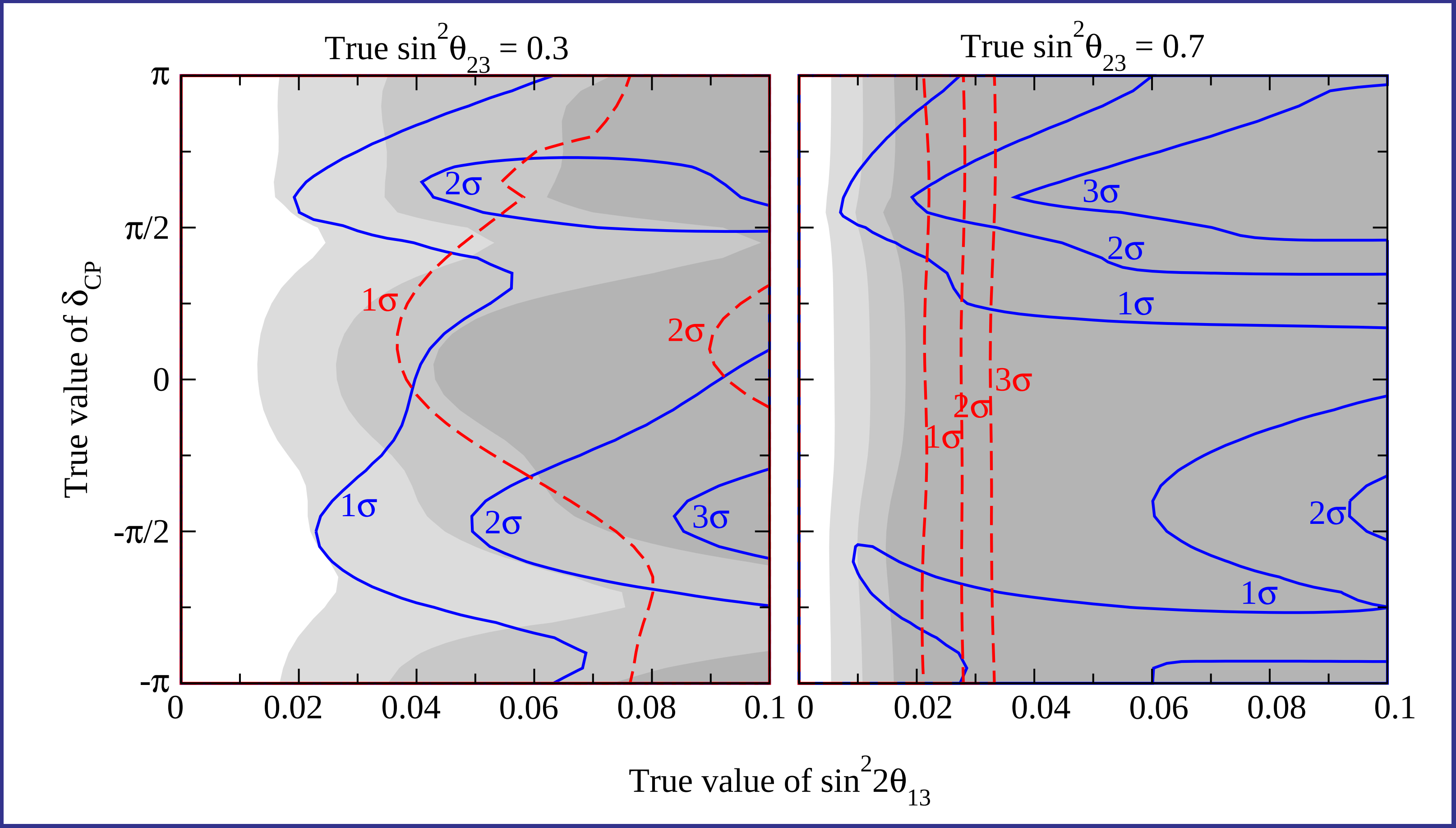

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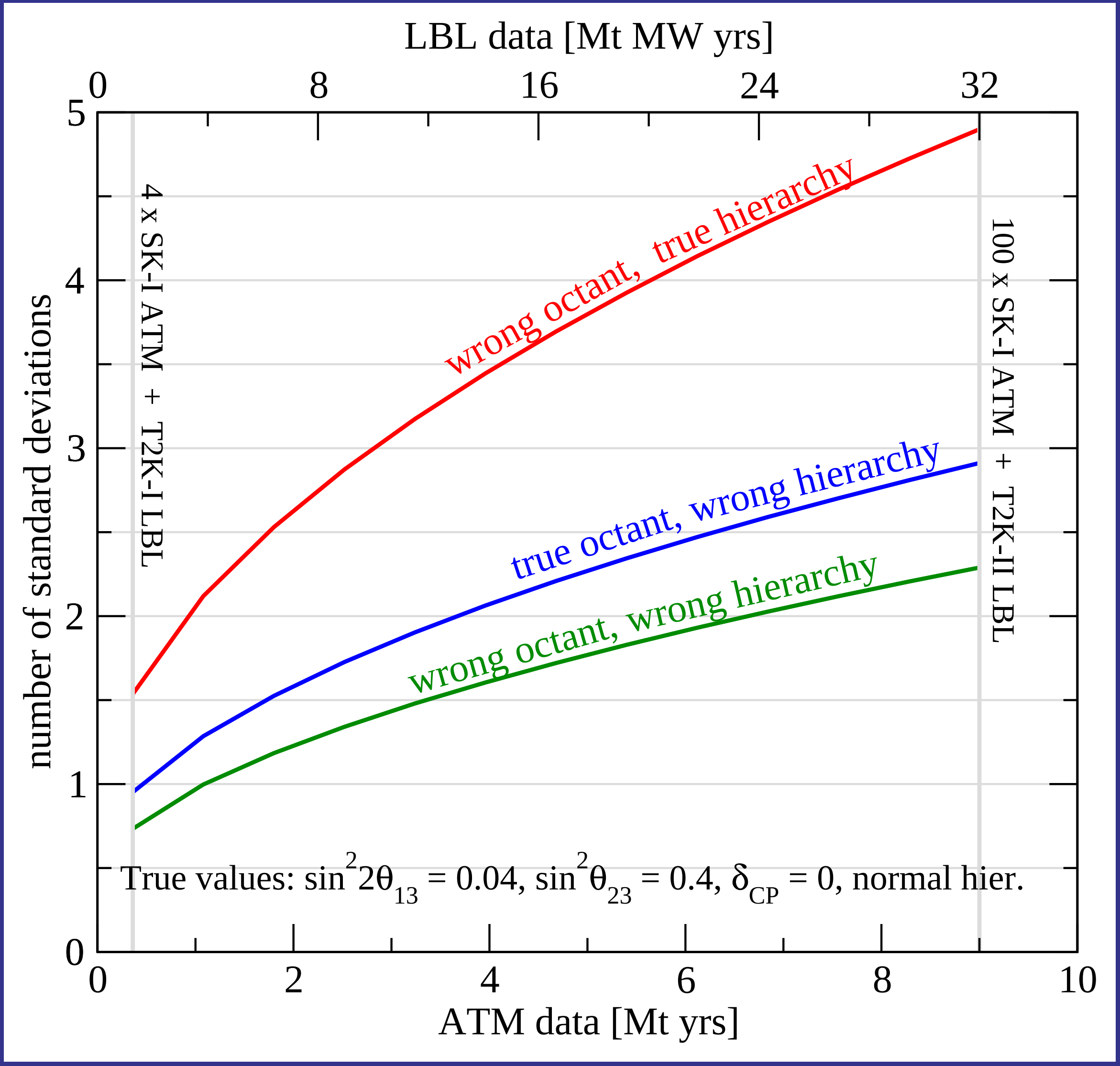
Luminosity scaling

Do we really need a Mt experiment?

Luminosity scaling



Preliminary BB/SPL analysis

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

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

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- **450 kt water Cherenkov detector at Frejus**

Preliminary BB/SPL analysis

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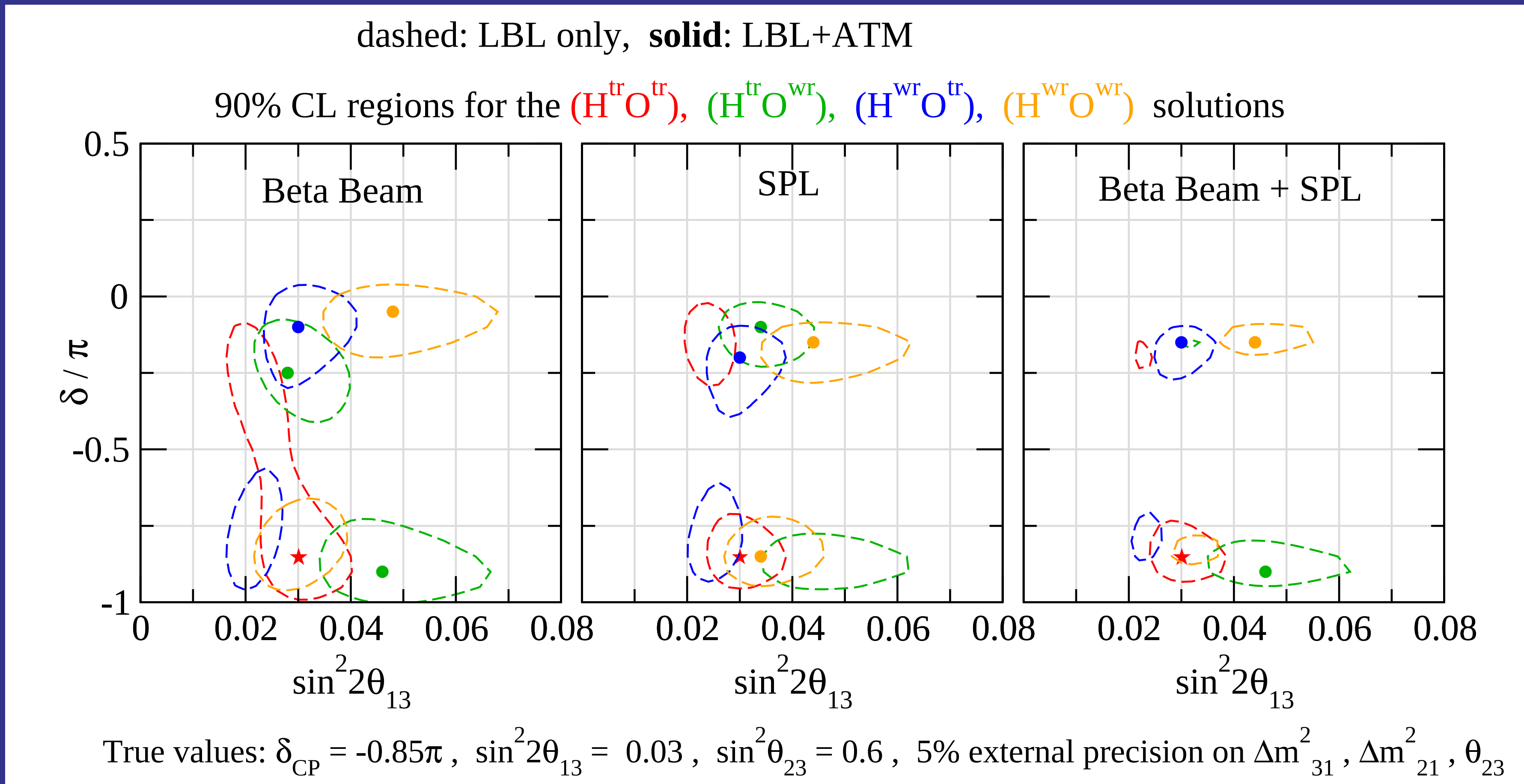
$(\theta_{13}, \delta_{\rm CP})$-degeneracy cannot be resolved

Preliminary BB/SPL analysis



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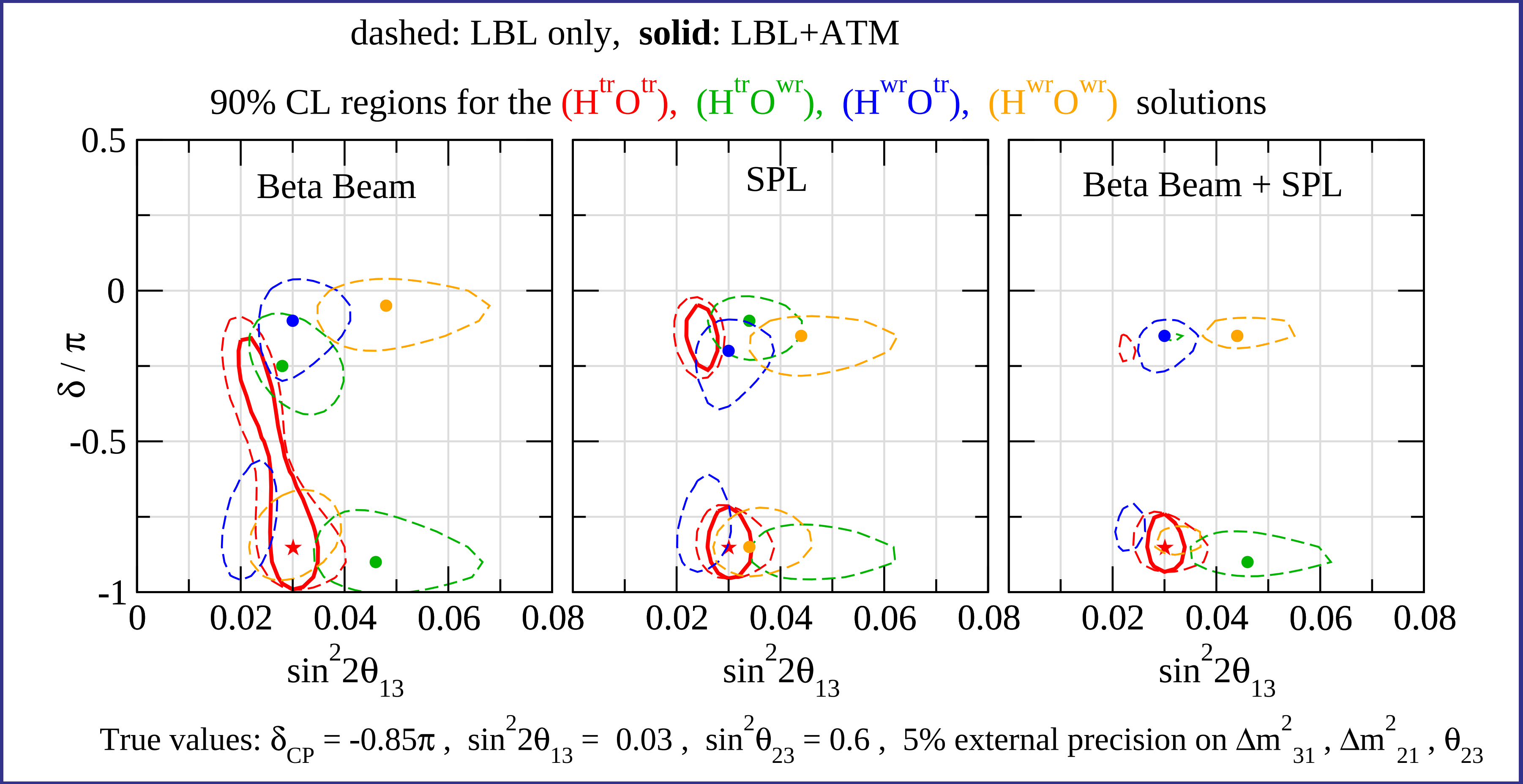

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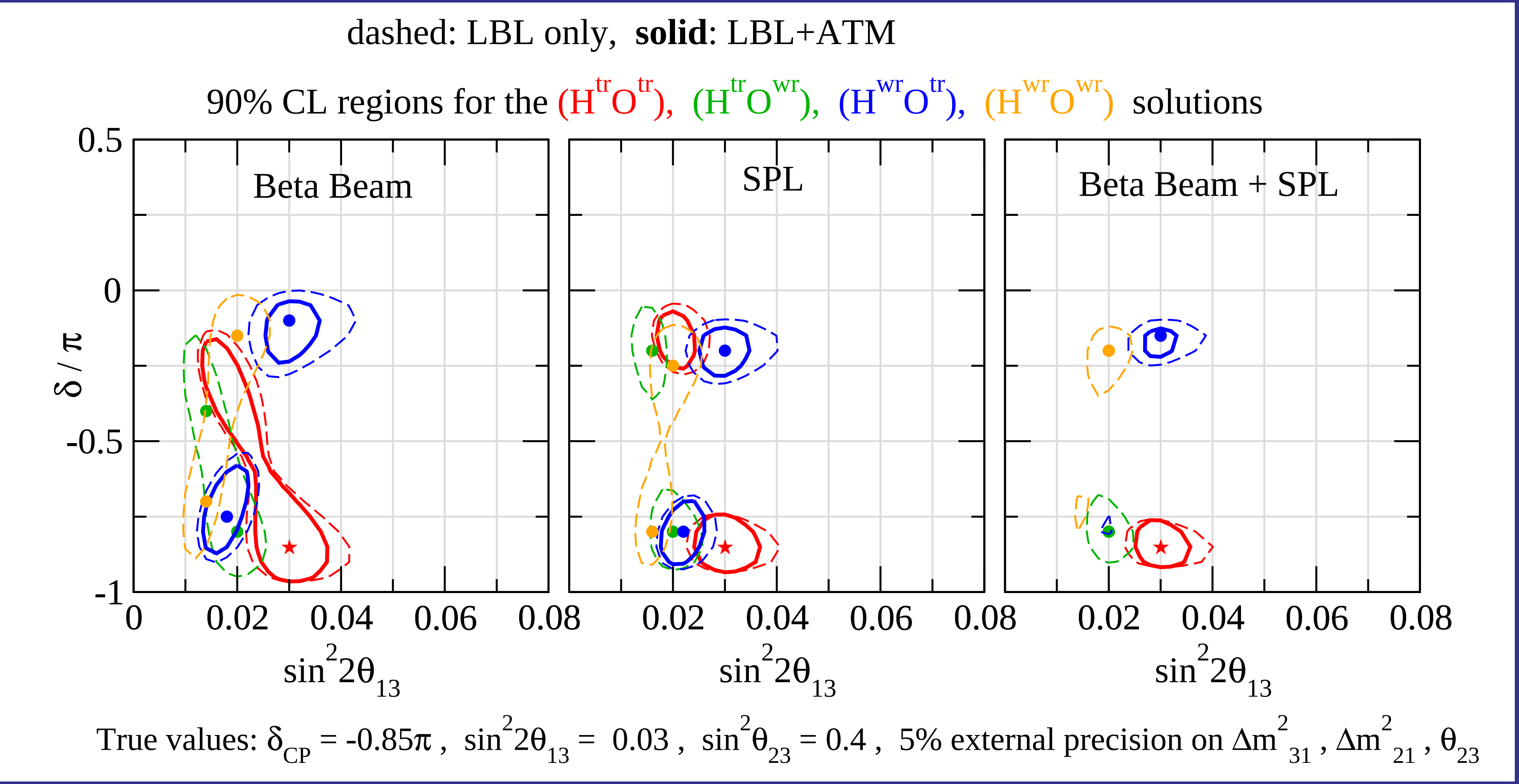

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given the Mt detector for the LBL experiment,
ATM data come for free!

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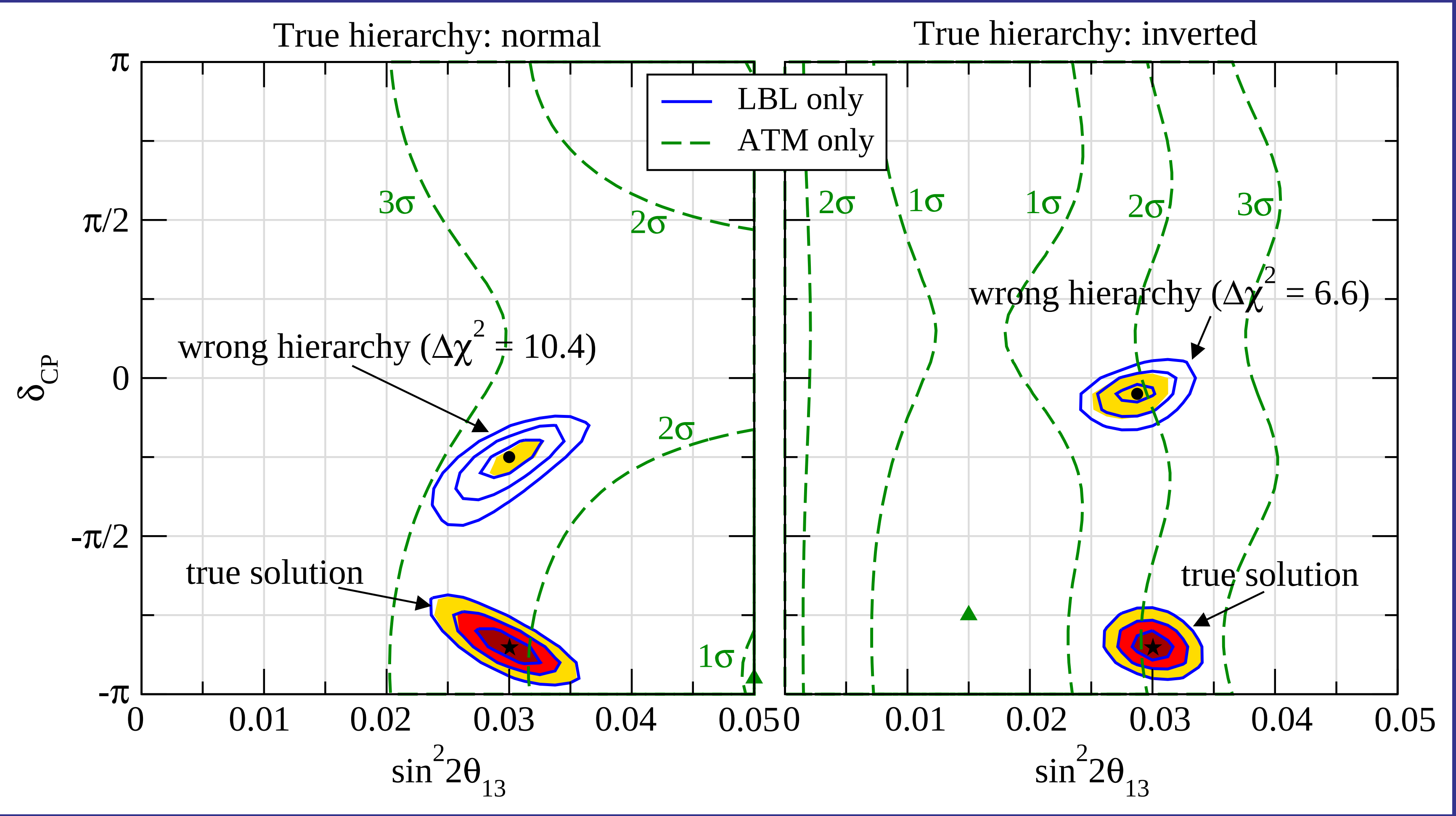
Thank you for your attention!

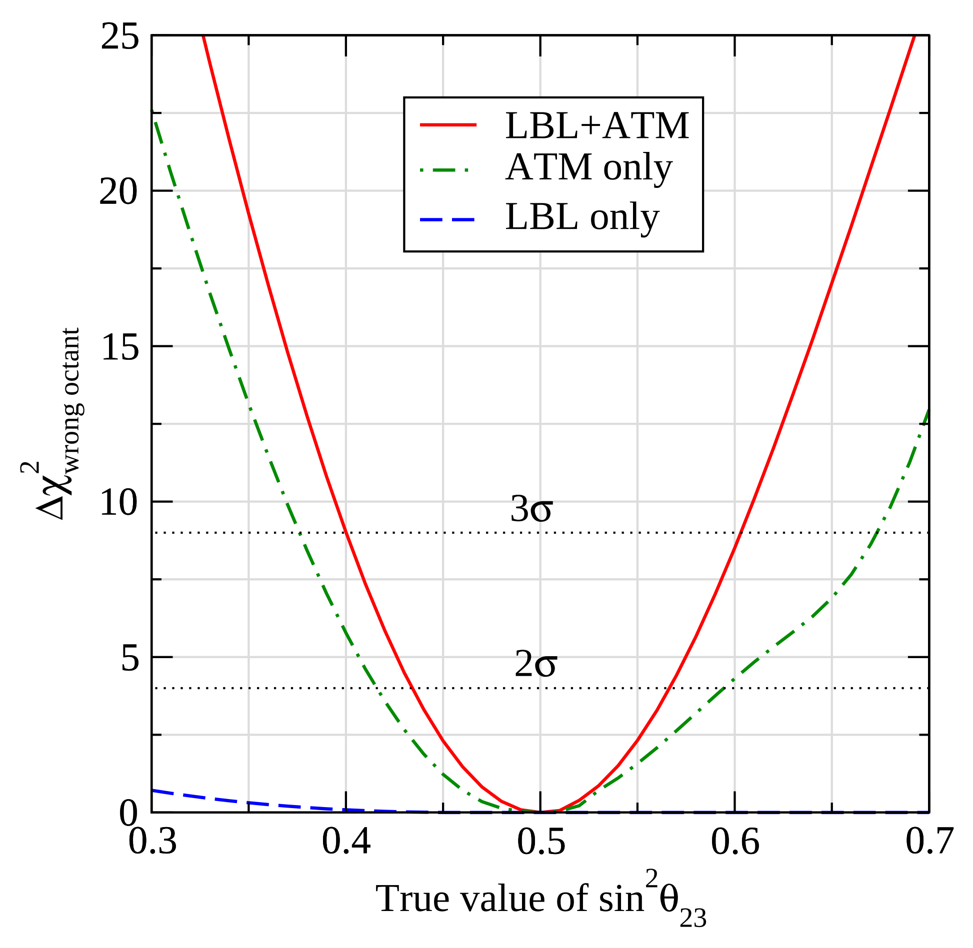
P.Huber, M.Maltoni, TS, hep-ph/0501037

Additional slides



True $\theta_{13} = 0$

Resolving the octant-degeneracy:



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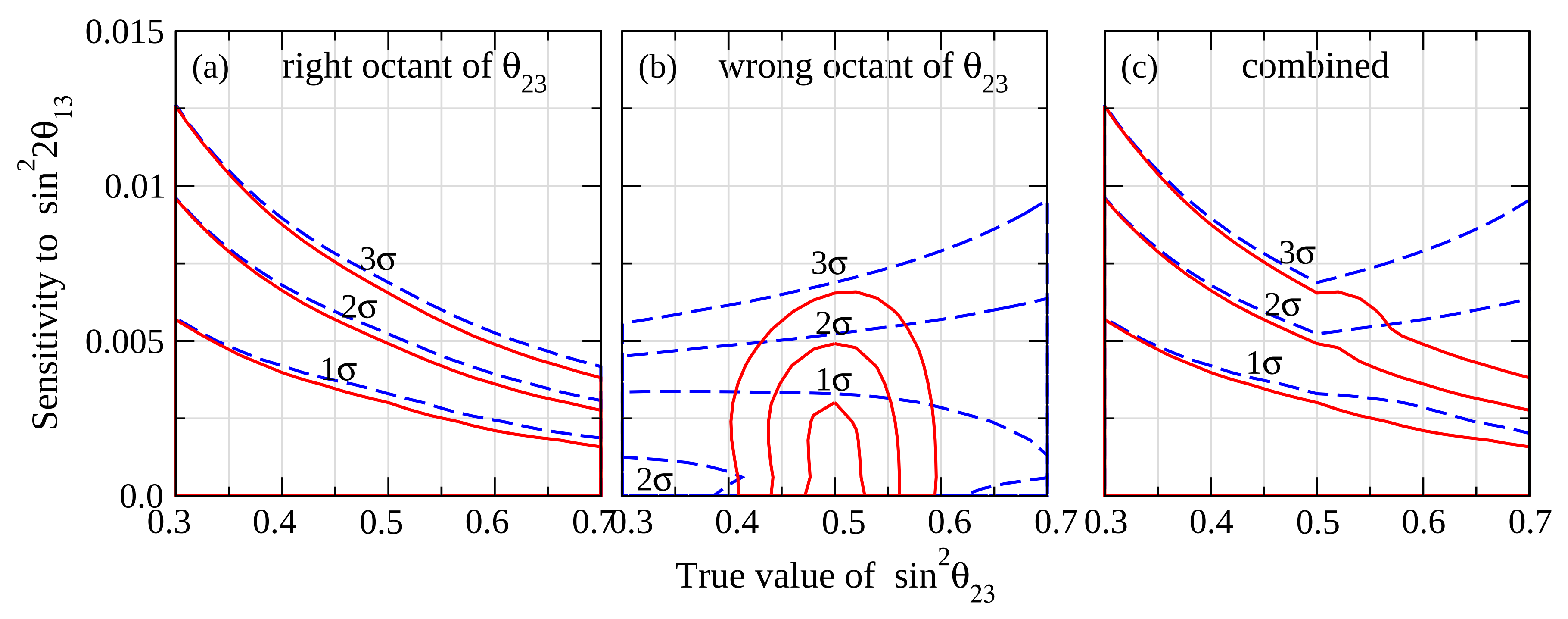
The limit on $\sin^2 2\theta_{13}$:



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