NOW2008

Physics Potential of Future Atmospheric Neutrino Searches

Thomas Schwetz-Mangold

CERN

We have learned a lot from atm. neutrinos

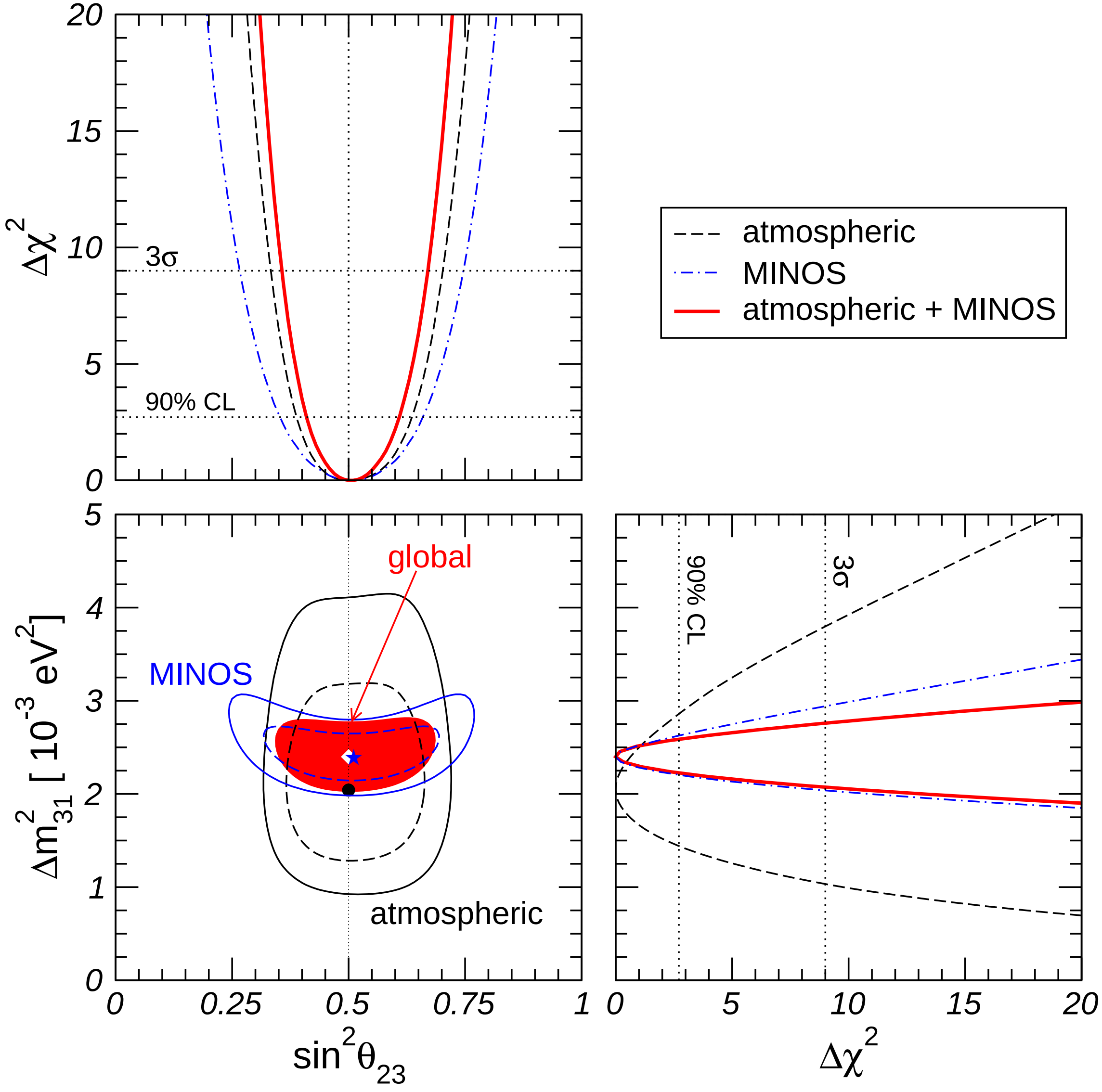
VOLUME 81, NUMBER 8 PHYSICAL REVIEW LETTERS 24 AUGUST 1998

Evidence for Oscillation of Atmospheric Neutrinos

Y. Fukuda,[1] T. Hayakawa,[1] E. Ichihara,[1] K. Inoue,[1] K. Ishihara,[1] H. Ishino,[1] Y. Itow,[1] T. Kajita,[1] J. Kameda,[1] S. Kasuga,[1] K. Kobayashi,[1] Y. Kobayashi,[1] Y. Koshio,[1] M. Miura,[1] M. Nakahata,[1] S. Nakayama,[1] A. Okada,[1] K. Okumura,[1] N. Sakurai,[1] M. Shiozawa,[1] Y. Suzuki,[1] Y. Takeuchi,[1] Y. Totsuka,[1] S. Yamada,[1] M. Earl,[2] A. Habig,[2] E. Kearns,[2] M.D. Messier,[2] K. Scholberg,[2] J.L. Stone,[2] L.R. Sulak,[2] C.W. Walter,[2] M. Goldhaber,[3] T. Barszczxak,[4] D. Casper,[4] W. Gajewski,[4] P.G. Halverson,[4,*] J. Hsu,[4] W.R. Kropp,[4] L.R. Price,[4] F. Reines,[4] M. Smy,[4] H.W. Sobel,[4] M.R. Vagins,[4] K.S. Ganezer,[5] W.E. Keig,[5] R.W. Ellsworth,[6] S. Tasaka,[7] J.W. Flanagan,[8,†] A. Kibayashi,[8] J.G. Learned,[8] S. Matsuno,[8] V.J. Stenger,[8] D. Takemori,[8] T. Ishii,[9] J. Kanzaki,[9] T. Kobayashi,[9] S. Mine,[9] K. Nakamura,[9] K. Nishikawa,[9] Y. Oyama,[9] A. Sakai,[9] M. Sakuda,[9] O. Sasaki,[9] S. Echigo,[10] M. Kohama,[10] A.T. Suzuki,[10] T.J. Haines,[11,4] E. Blaufuss,[12] B.K. Kim,[12] R. Sanford,[12] R. Svoboda,[12] M.L. Chen,[13] Z. Conner,[13,‡] J.A. Goodman,[13] G.W. Sullivan,[13] J. Hill,[14] C.K. Jung,[14] K. Martens,[14] C. Mauger,[14] C. McGrew,[14] E. Sharkey,[14] B. Viren,[14] C. Yanagisawa,[14] W. Doki,[15] K. Miyano,[15] H. Okazawa,[15] C. Saji,[15] M. Takahata,[15] Y. Nagashima,[16] M. Takita,[16] T. Yamaguchi,[16] M. Yoshida,[16] S.B. Kim,[17] M. Etoh,[18] K. Fujita,[18] A. Hasegawa,[18] T. Hasegawa,[18] S. Hatakeyama,[18] T. Iwamoto,[18] M. Koga,[18] T. Maruyama,[18] H. Ogawa,[18] J. Shirai,[18] A. Suzuki,[18] F. Tsushima,[18] M. Koshiba,[19] M. Nemoto,[20] K. Nishijima,[20] T. Futagami,[21] Y. Hayato,[21,§] Y. Kanaya,[21] K. Kaneyuki,[21] Y. Watanabe,[21] D. Kielczewska,[22,4] R.A. Doyle,[23] J.S. George,[23] A.L. Stachyra,[23] L.L. Wai,[23,‖] R.J. Wilkes,[23] and K.K. Young[23]
(Super-Kamiokande Collaboration)

3000+ citations

We have learned a lot from atm. neutrinos...



Schwetz, Tortola, Valle, 0808.2016

... but LBL experiments are taking over (MINOS, T2K, NOvA)

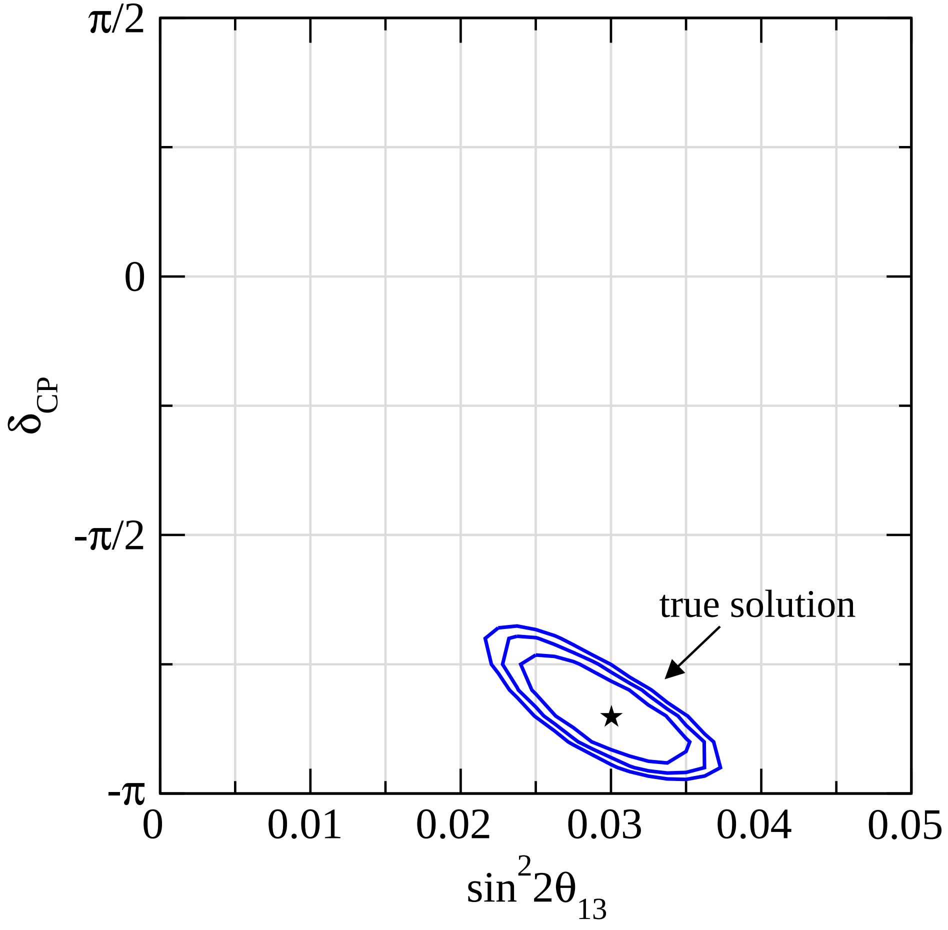
Can we learn something more from atmospheric neutrinos in the era of precision neutrino oscillation experiments?

Can we learn something more from atmospheric neutrinos in the era of precision neutrino oscillation experiments?

LBL experiments suffer from degeneracies

- octant degeneracy:
  cannot distinguish between θ_{23} and $(\pi/2 - \theta_{23})$
- hierarchy degeneracy:
  cannot determine the sign of Δm^2_{31}

Hierarchy and octant degeneracies in T2HK



allowed regions at

2σ, 99%, 3σ CL

true values:

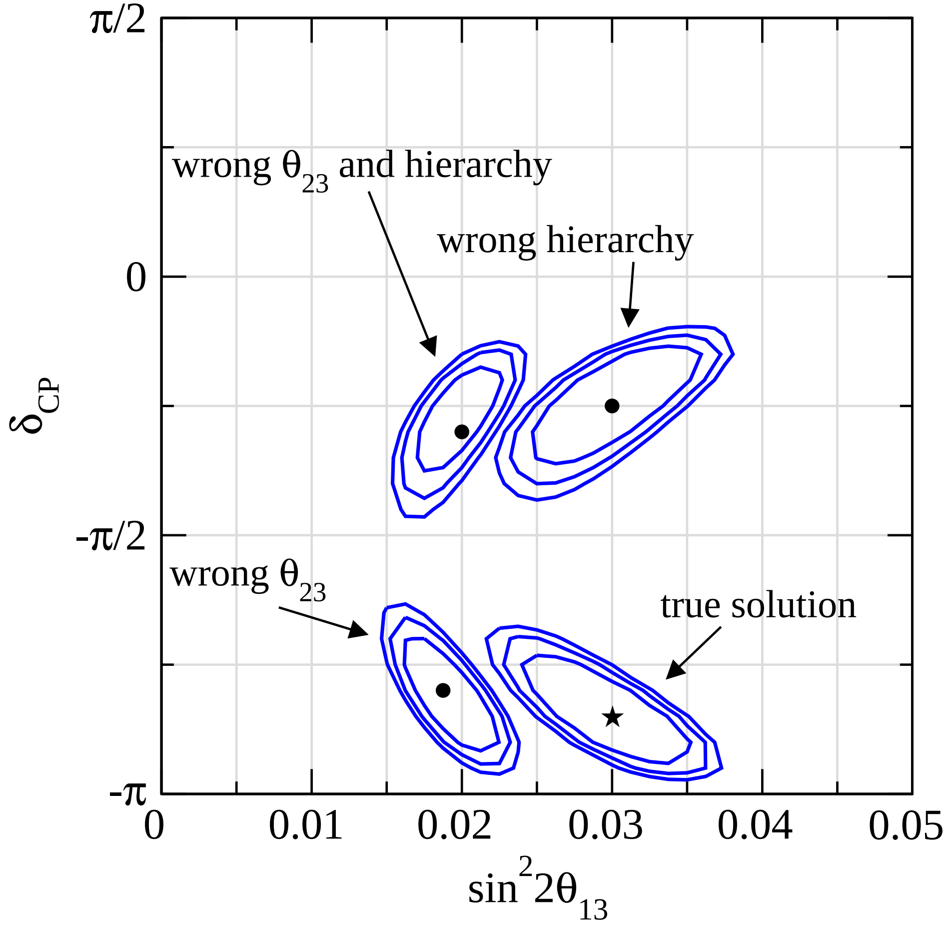
$\sin^2 2\theta_{13} = 0.03$

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

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

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

Hierarchy and octant degeneracies in T2HK



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

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

no information on θ_{23} octant and sgn(Δm^2_{31})

Resolving the degeneracies

several possibilities to resolve the degeneracies are known:

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

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- combining information from detectors at different baselines
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- spectral information (broadband beam)
- adding information on θ_{13} from a reactor experiment
- ...

or

use the atmospheric neutrinos in the same detector

Huber, Maltoni, Schwetz, PRD71, 053006 (2005) [hep-ph/0501037]

3-flavour effects in atmospheric neutrinos

Incomplete list:

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; Peres, Smirnov, Phys. Lett. B456, 204 (1999), hep-ph/9902312; Bernabeu, Palomares-Ruiz, Perez, Petcov, Phys. Lett. B531, 90 (2002), hep-ph/0110071; Gonzalez-Garcia, Maltoni, Eur. Phys. J. C26, 417 (2003), hep-ph/0202218; Bernabeu, Palomares-Ruiz, Petcov, Nucl. Phys. B669, 255 (2003), hep-ph/0305152; Peres, Smirnov, Nucl. Phys. B680, 479 (2004), hep-ph/0309312; Gonzalez-Garcia, Maltoni, Smirnov, Phys. Rev. D70, 093005 (2004), hep-ph/0408170; Fogli, Lisi, Marrone, Palazzo, hep-ph/0506083; Huber, Maltoni, Schwetz, Phys. Rev. D71, 053006 (2005), hep-ph/0501037; T. Kajita (Super-K), see e.g. talks at NuFact05, NuInt05; Petcov, Schwetz, Nucl. Phys. B740, 1 (2006) 1, hep-ph/0511277; S. Choubey, hep-ph/0609182; E. K. Akhmedov, M. Maltoni and A. Y. Smirnov, JHEP 0705 (2007) 077, hep-ph/0612285; R. Gandhi, P. Ghoshal, S. Goswami, P. Mehta, S. U. Sankar and S. Shalgar, Phys. Rev. D 76 (2007) 073012, 0707.1723; E. K. Akhmedov, M. Maltoni and A. Y. Smirnov, JHEP 0806 (2008) 072, 0804.1466.

Oscillation signal in atm neutrino exps

atmosphere provides a multi-flavour neutrino flux containing ν_μ and ν_e:

$$N_\mu = (\phi_\mu P_{\nu_\mu \to \nu_\mu} + \phi_e P_{\nu_e \to \nu_\mu})\sigma_\mu \quad = \quad \phi_\mu (P_{\nu_\mu \to \nu_\mu} + \frac{1}{r} P_{\nu_e \to \nu_\mu})\sigma_\mu$$

$$N_e = (\phi_\mu P_{\nu_\mu \to \nu_e} + \phi_e P_{\nu_e \to \nu_e})\sigma_e \quad = \quad \phi_e \underbrace{\left(r P_{\nu_\mu \to \nu_e} + P_{\nu_e \to \nu_e}\right)}_{P_{\text{eff}}} \sigma_e$$

$$r = r(E_\nu) \equiv \frac{\phi_\mu(E_\nu)}{\phi_e(E_\nu)}$$

only a combination of probabilities can be measured

3-flavour effects in atmospheric neutrinos

excess of electron-like events:

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

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

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

$$r = r(E_\nu) \equiv \frac{\phi_\mu(E_\nu)}{\phi_e(E_\nu)}$$

$r \approx 2$ (sub-GeV)

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

θ_{13}-effects

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

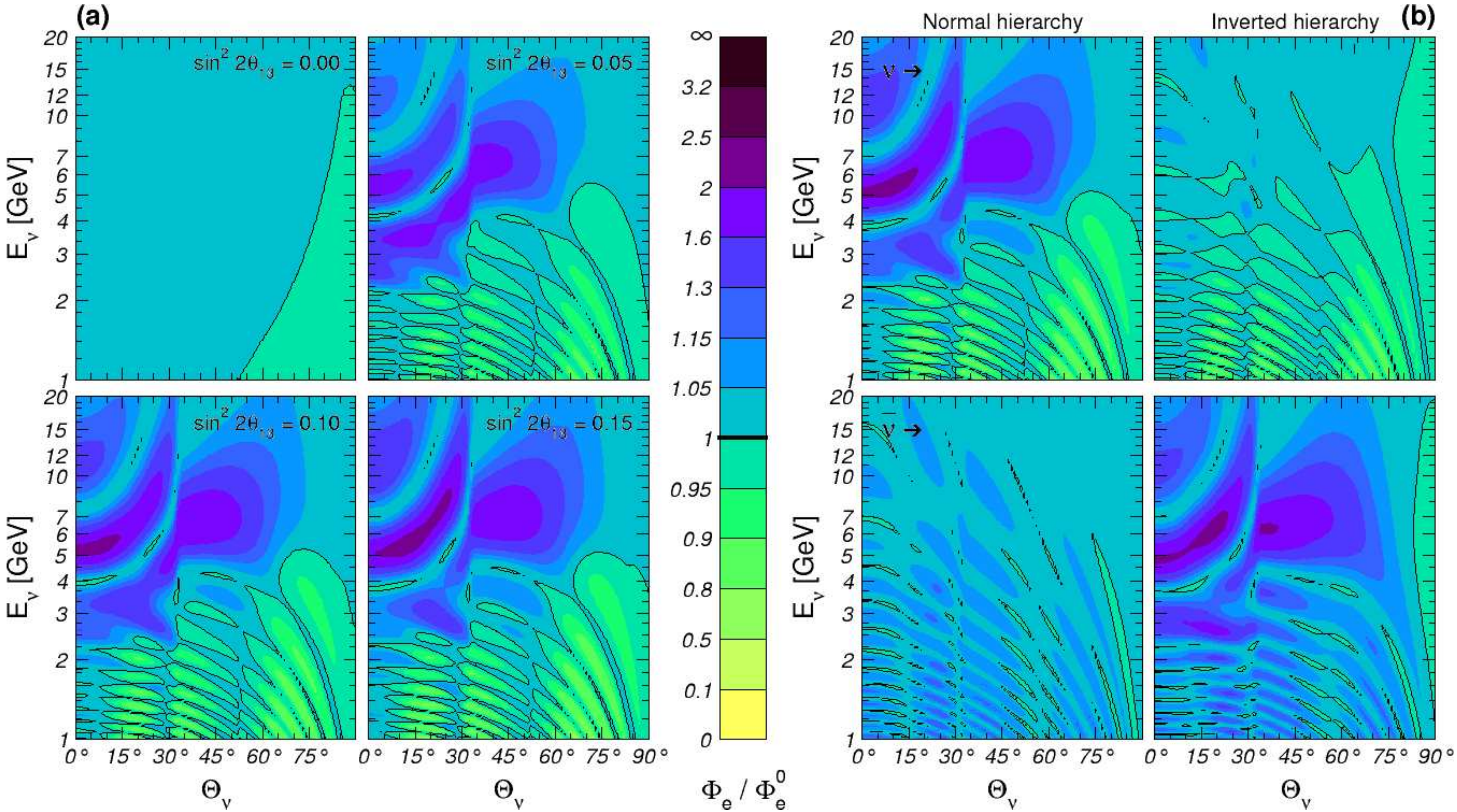
resonant matter effect in $P_{2\nu}(\Delta m_{31}^2, \theta_{13})$
for multi-GeV events ($r \approx 2.6 - 4.5$)

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

detection cross sections are different for neutrinos and anti-neutrinos

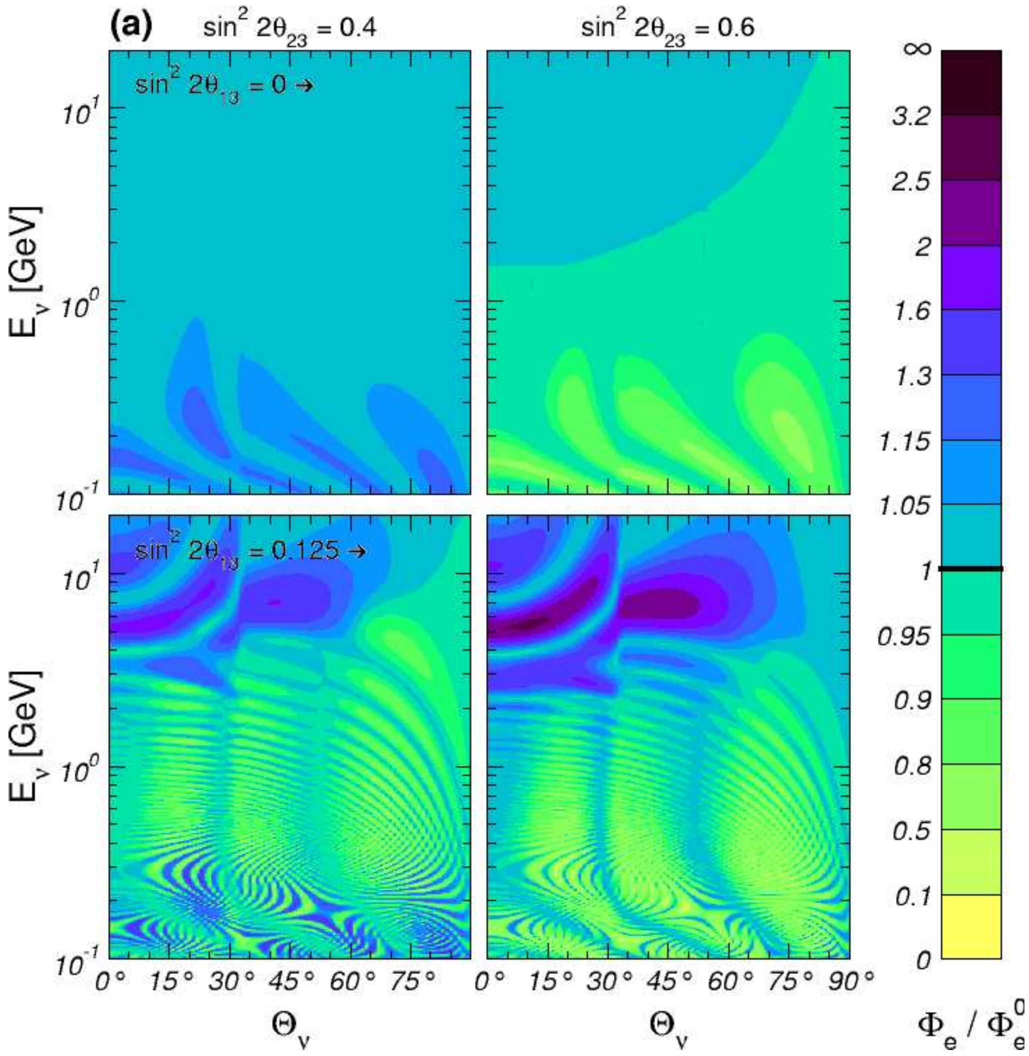
sensitivity to the neutrino mass hierarchy

θ_{13}-effects



M. Maltoni, arXiv:0707.1218

Δm^2_{21}-*effects*



$$\frac{N_e}{N_e^0} - 1 \simeq$$

$$(r\, c^2_{23} - 1)\, P_{2\nu}(\Delta m^2_{21}, \theta_{12})$$

relevant for sub-GeV events

sensitivity to the octant of θ_{23} due to "flux factor" $(r\, c^2_{23} - 1)$

note oposite θ_{23} dependence of multi-GeV θ_{13} features: $(r\, s^2_{23} - 1)$

M. Maltoni, arXiv:0707.1218

A megaton water Cerenkov detector

- Many proposed long-baseline experiments rely on a Mt-scale water Cerenkov detector

  US-WBB $\longrightarrow$ DUSEL, T2K $\longrightarrow$ HK
  CERN BB/SPL $\longrightarrow$ MEMPHYS

- high statistics atmospheric neutrino data come “for free”

- combine LBL and atmospheric data

  Huber, Maltoni, Schwetz, hep-ph/0501037

A megaton water Cerenkov detector

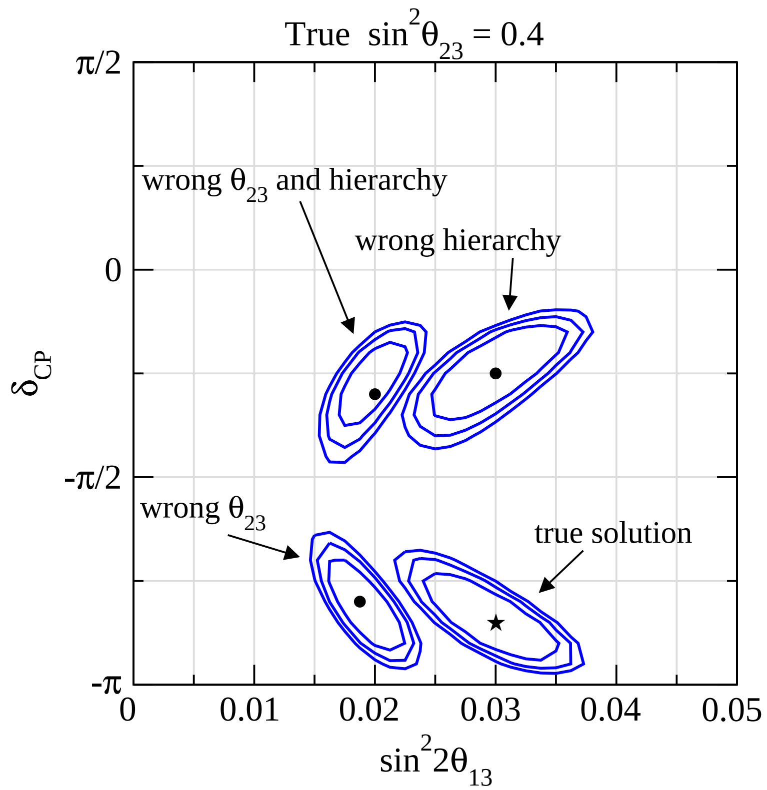
Consider $\sim 5\,\mathrm{Mt\,yr}$ atmospheric neutrino data in a water Cerenkov detector:

	ν	$\bar{\nu}$
e-like sub-GeV	$\sim 10^5$	$\sim 3 \times 10^4$
e-like multi-GeV	$\sim 3 \times 10^4$	$\sim 10^4$
μ-like sub-GeV	$\sim 10^5$	$\sim 3 \times 10^4$
μ-like multi-GeV	$\sim 5 \times 10^4$	$\sim 2 \times 10^4$
upward going μ	$\sim 6 \times 10^4$	$\sim 3 \times 10^4$

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

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

Resolving the degeneracies - ex.: T2HK



solid curves: LBL only

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

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

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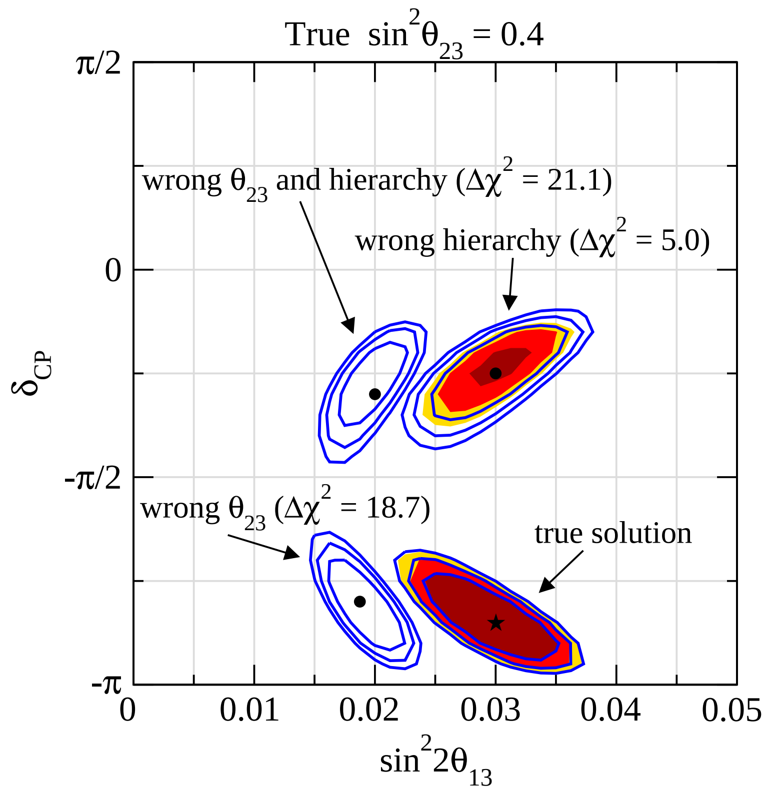

solid curves: LBL only, colored regions: LBL+ATM

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

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

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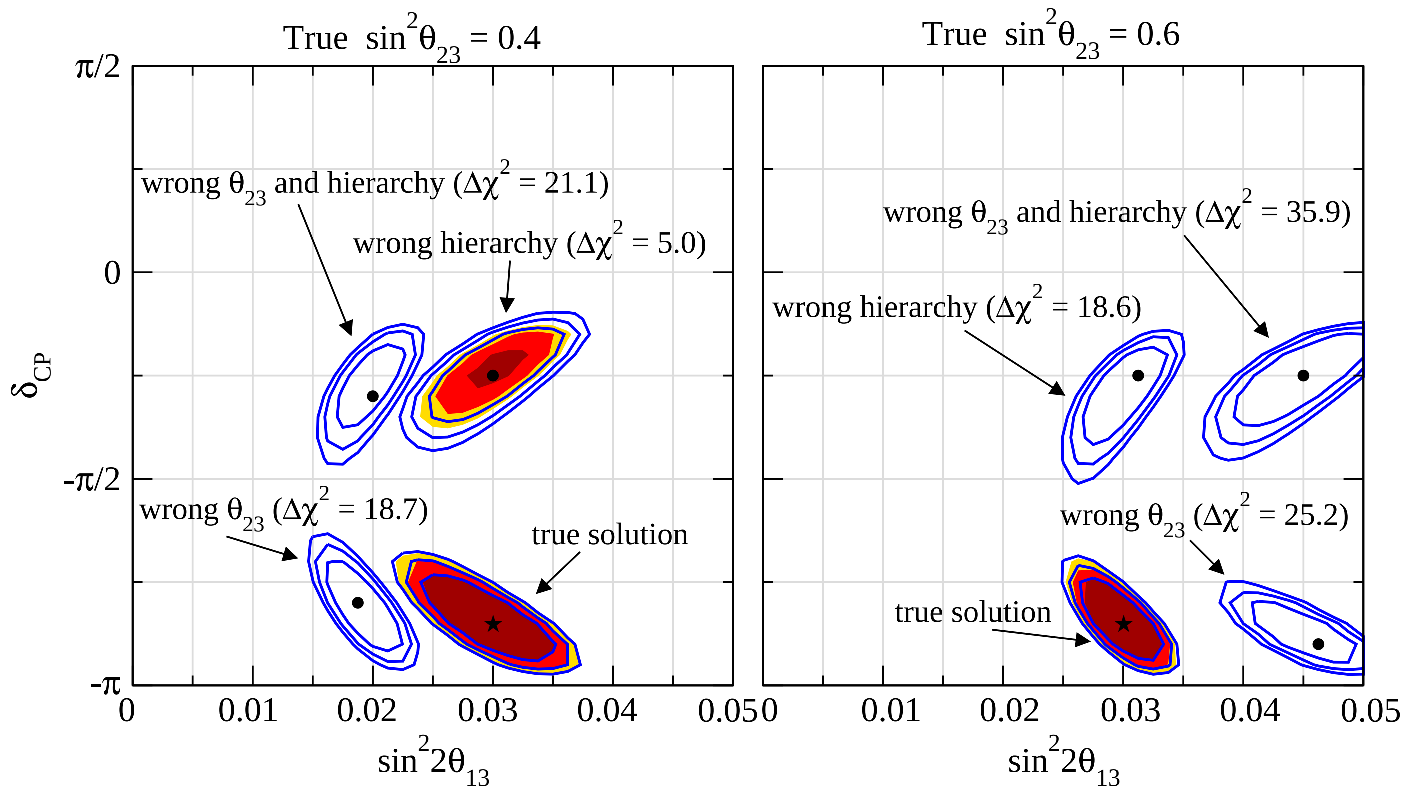

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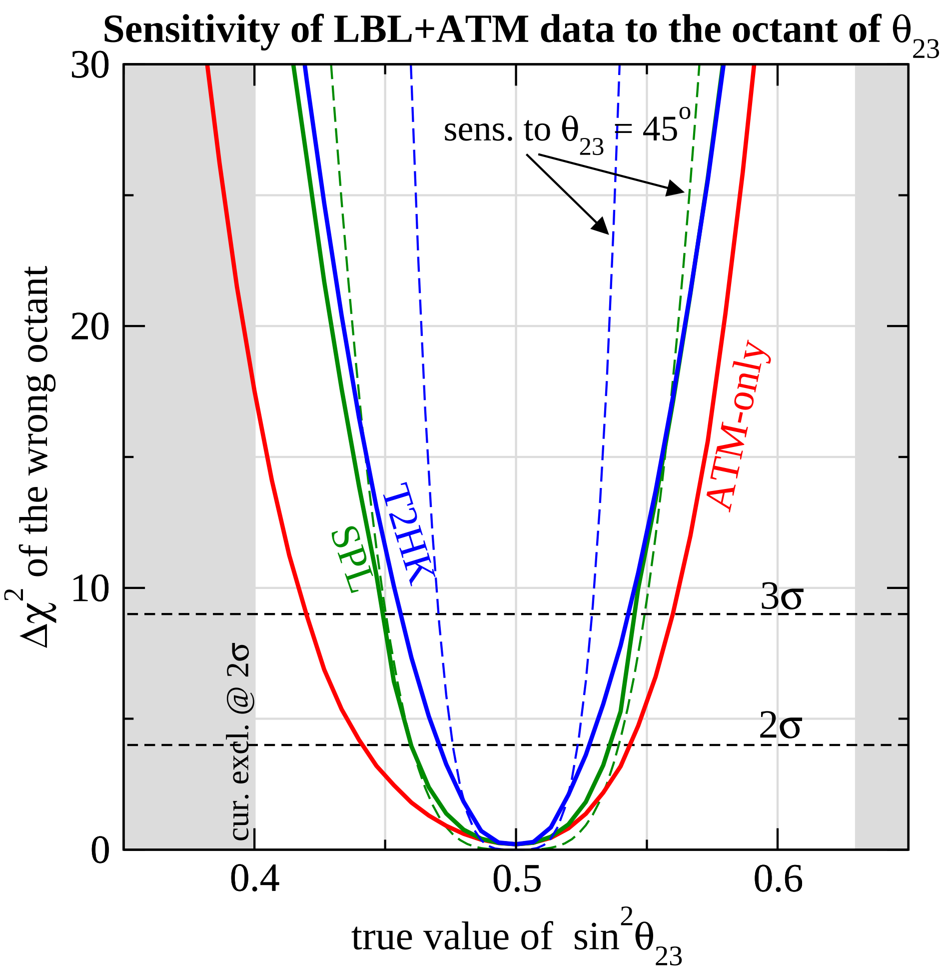
true values: $\sin^2 2\theta_{13} = 0.03$, $\delta_{\rm CP} = -0.85\pi$, $\Delta m^2_{31} = 2.2 \cdot 10^{-3}{\rm eV}^2$

Identifying the octant of θ_{23}



ATM data from a 500 kt WC detector

quite powerful to resolve the octant degeneracy, even for $\theta_{13} = 0$

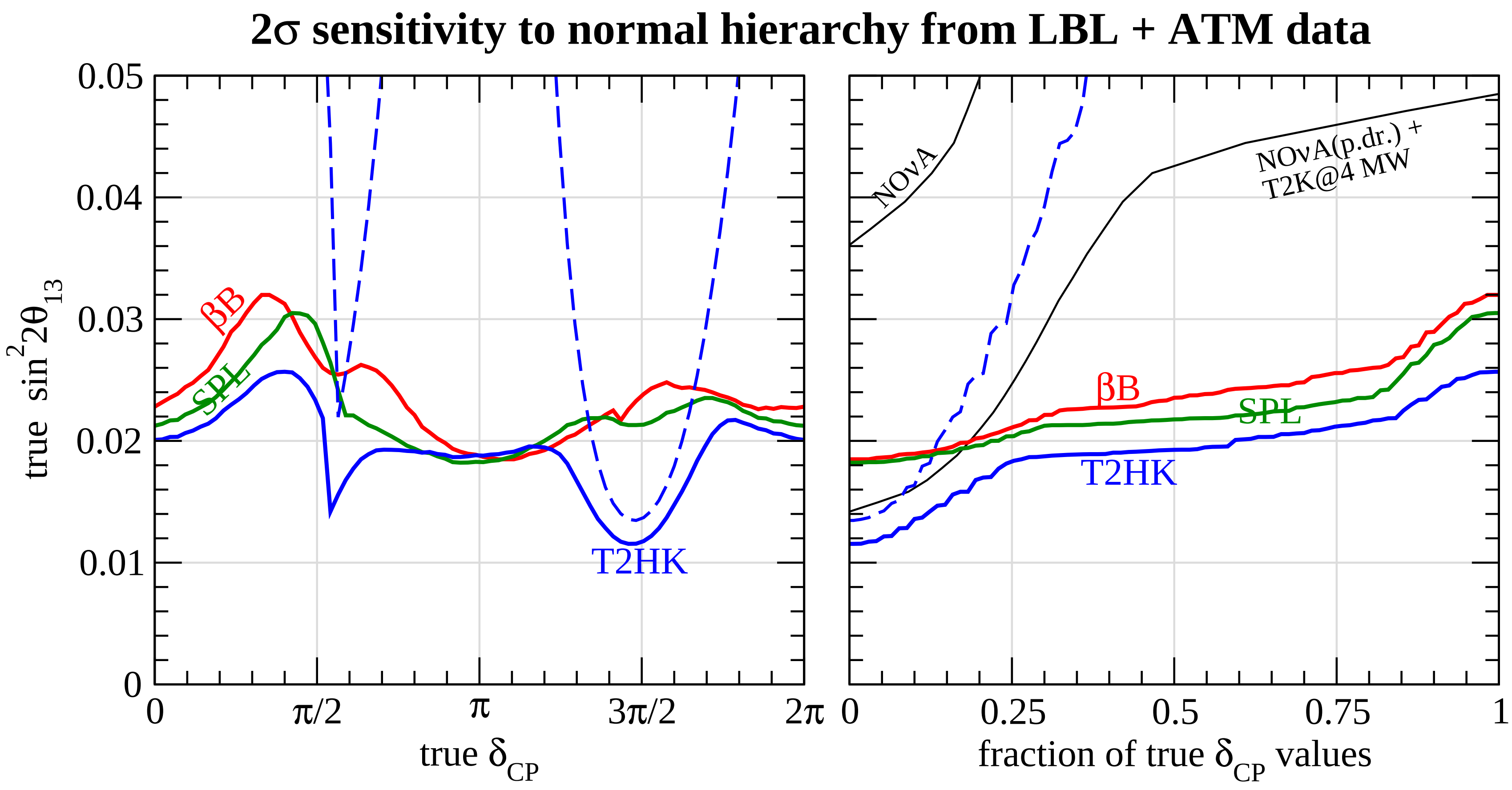
robust signature in sub-GeV e-like events

Campagne, Maltoni, Mezzetto, Schwetz, hep-ph/0603172

The hierarchy problem

Identifying the mass hierarchy

LBL + ATM data from a 500 kt WC detector:



Campagne, Maltoni, Mezzetto, Schwetz, hep-ph/0603172

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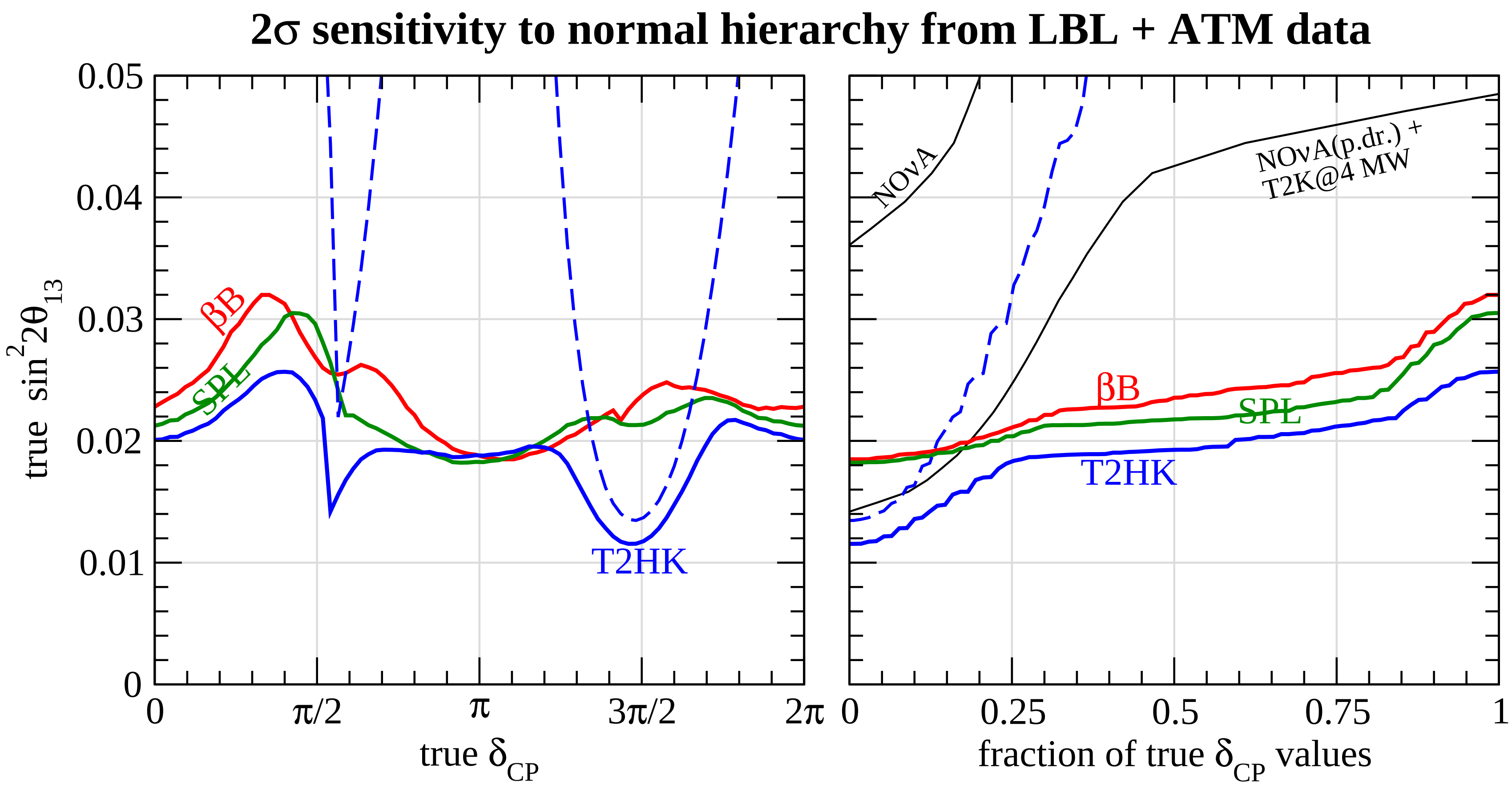

Campagne, Maltoni, Mezzetto, Schwetz, hep-ph/0603172

sensitivity improves for $\theta_{23} > 45^\circ$ because of $(r\, s_{23}^2 - 1)$ factor

Magnetized iron detectors

- Water Cerenkov:
  - sees only sum $\nu + \bar{\nu} \longrightarrow$ dilution of the effect
  + can be made very big (Mt scale)
- Magnetized iron:
  + can distinguish ν from $\bar{\nu}$ events
  - electron detection difficult $\longrightarrow$ μ-like events

Magnetized iron detectors

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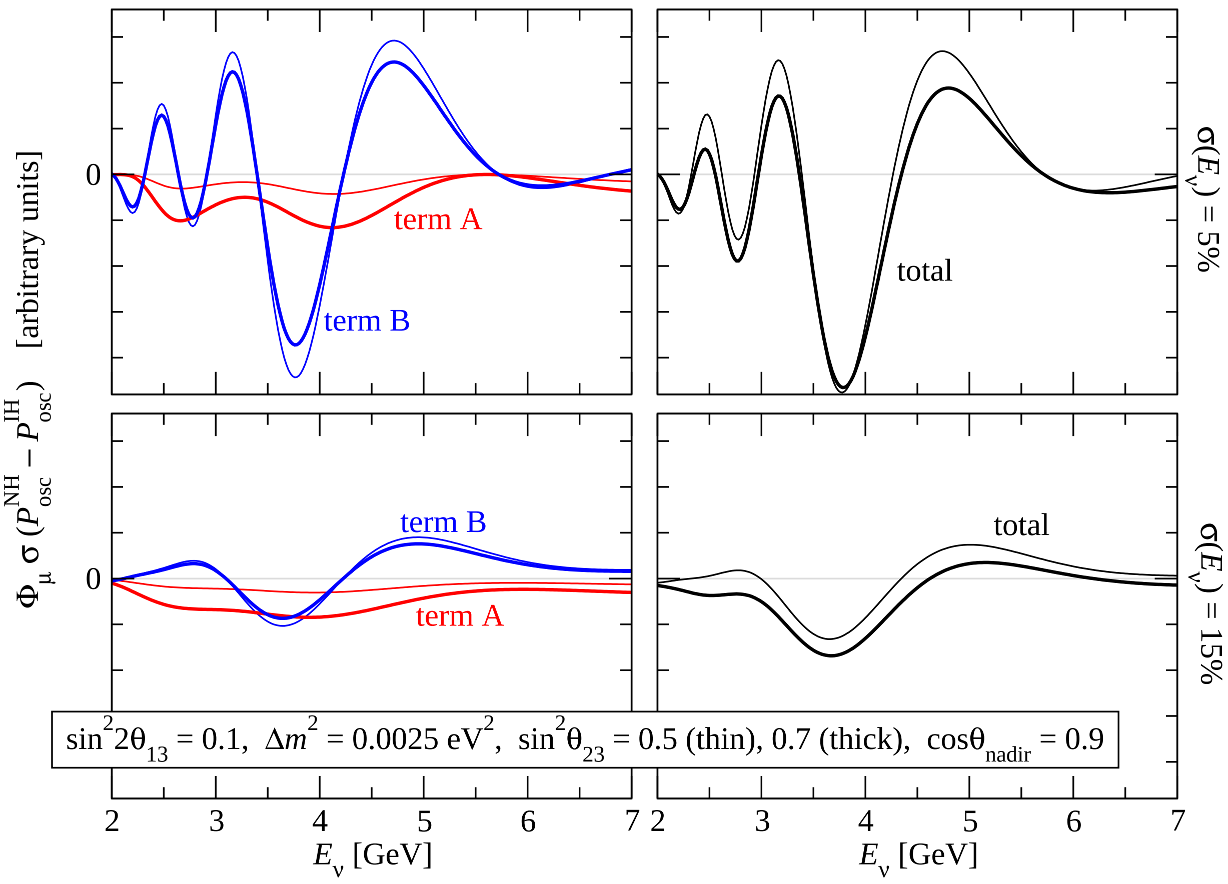
  - electron detection difficult $\to$ μ-like events

Indian Neutrino Observatory:
~ 50 kt magnetized Iron calorimeter

see also talk by S. Goswami

The mass hierarchy signal in μ-like events

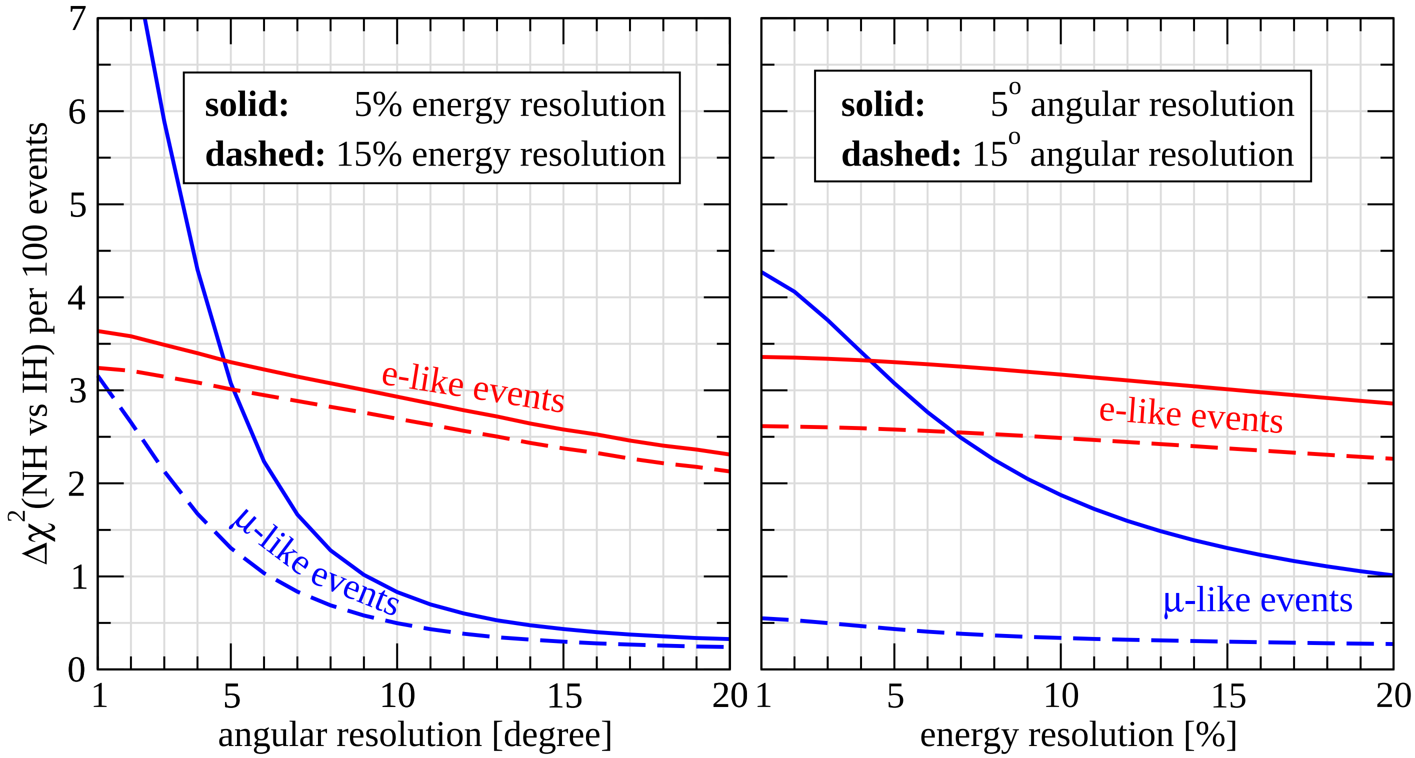
difference of the μ-like event spectra for NH and IH



$$\Delta S_\mu \propto \underbrace{\Phi_\mu \sigma \, \sin^2\theta_{23} \left(\frac{1}{r} - \sin^2\theta_{23}\right) \Delta P_{2\nu}}_{\text{term A}} + \underbrace{\Phi_\mu \sigma \, \frac{1}{2} \sin^2 2\theta_{23} \Delta \mathrm{Re}\,(A'_{33})}_{\text{term B}}$$

The mass hierarchy signal in μ-like events

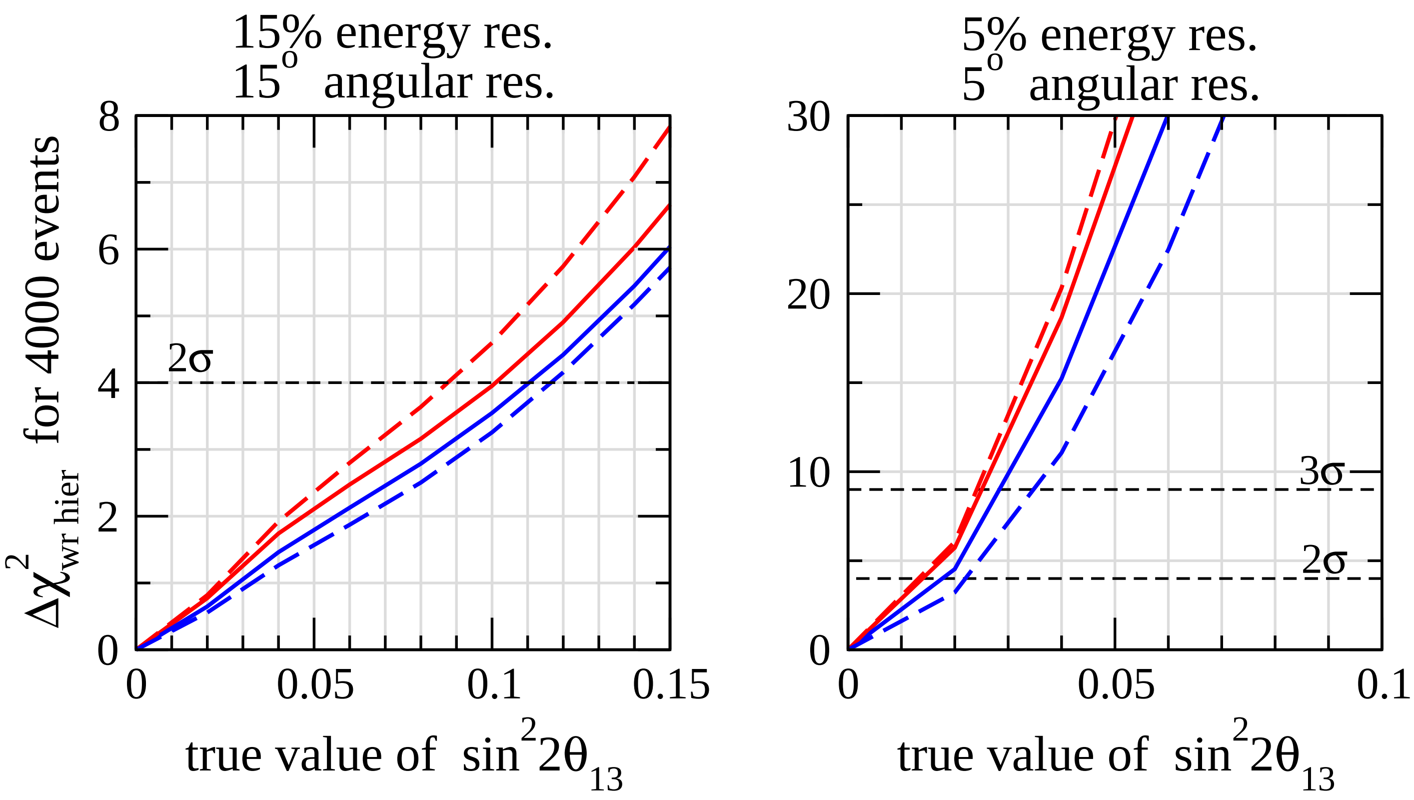
the ability to reconstruct the neutrino energy and neutrino direction is crucial



Petcov, Schwetz, NPB **740** (2006) 1 [hep-ph/0511277]

The mass hierarchy and magnetized detectors

consider 500 kty data (e.g., INO with 50 kt for 10 yrs)



osc. params. fixed, external prior information

solid: true hierarchy normal, **dashed:** true hierarchy inverted

Which type of detector?

The ideal detector should be able to

- see e-like events with charge ID (at least statistically),
- see μ-like events with charge ID,
- reconstruct neutrino energy (direction) at the level of few % (degree) for μ like events,
- and it should be VERY BIG.

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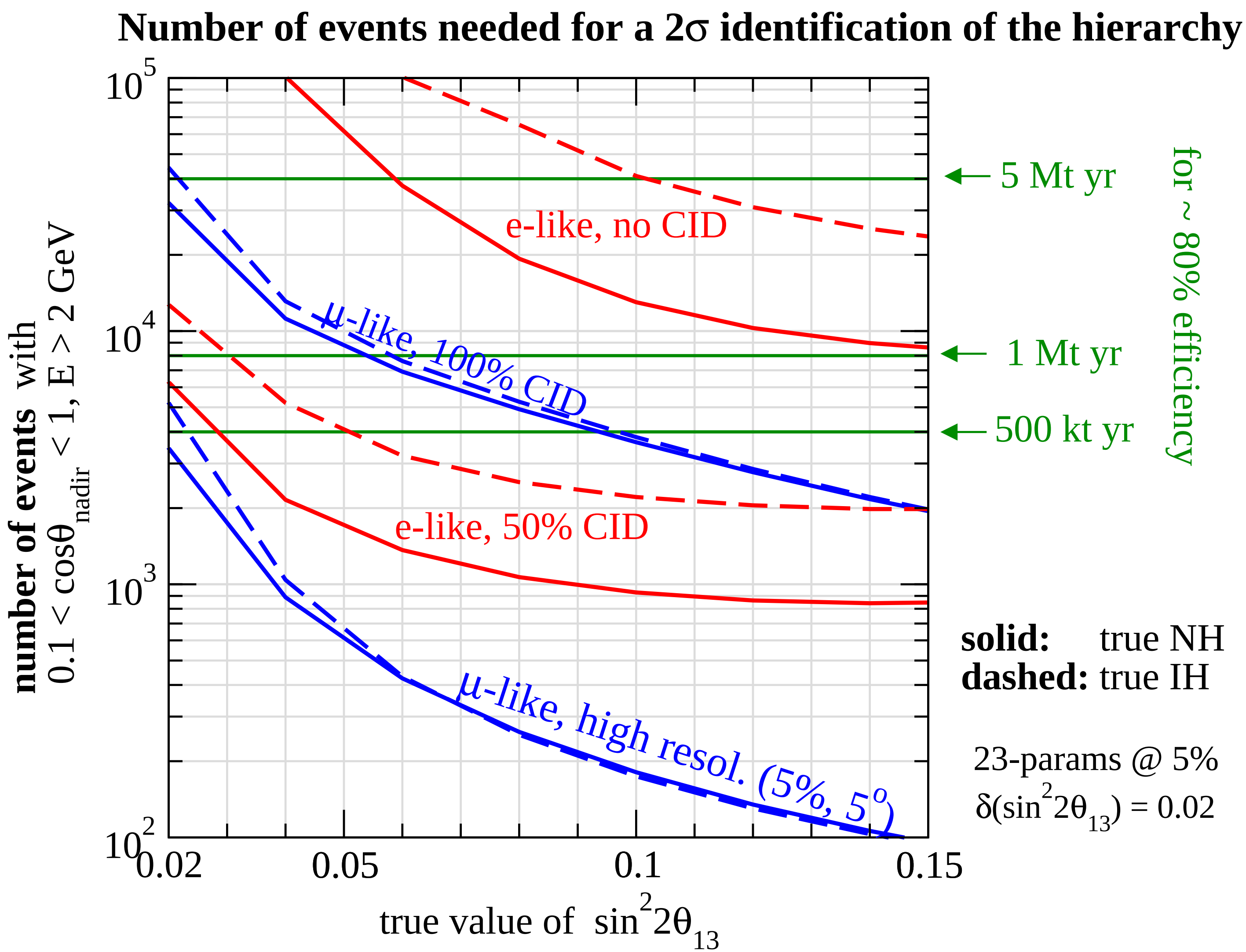
Water Cerenkov vs mag. Iron Cal. vs liquid Argon ?

Which type of detector?



Comment - 1

Separation of neutrino and anti-neutrino events (statistical or event-by-event) in 100 kt scale WC or LAr detectors would be very useful for atmospheric neutrino studies

and also in the context of a Neutrino Factory

see Huber, Schwetz, 0805.2019

n/p tagging, muon life time, single/multi-ring...??

Comment - 1

Example: single/multi-ring samples in a WC:

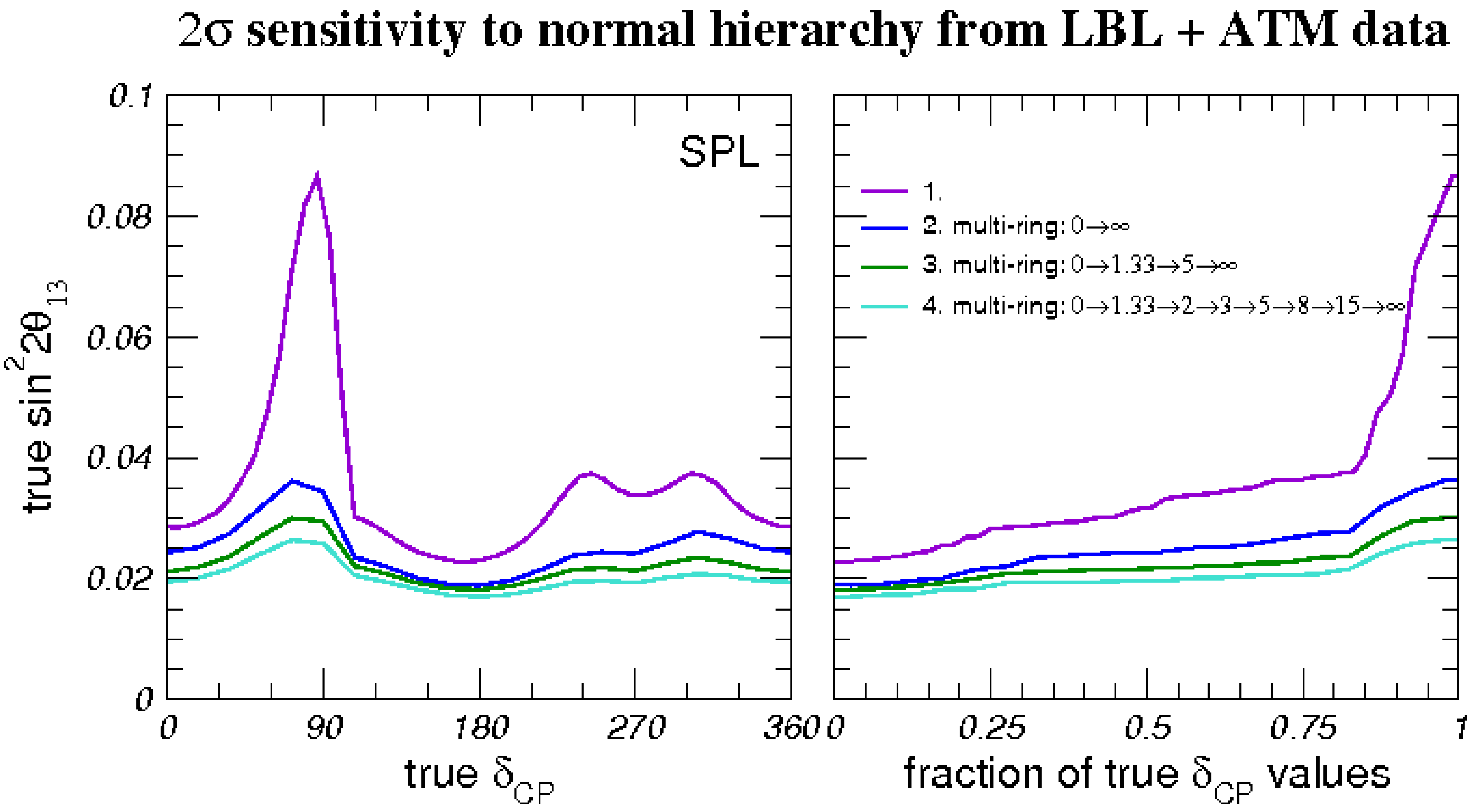
$$
\begin{aligned}
N_{\text{single}-\text{ring}} &= A N_\nu + B N_{\bar{\nu}} \\
N_{\text{multi}-\text{ring}} &= C N_\nu + D N_{\bar{\nu}}
\end{aligned}
$$

the ν and $\bar{\nu}$ content of single and multi-ring events are different

can solve for N_ν and $N_{\bar{\nu}}$ from a measurement of $N_{\text{single}-\text{ring}}$ and $N_{\text{multi}-\text{ring}}$

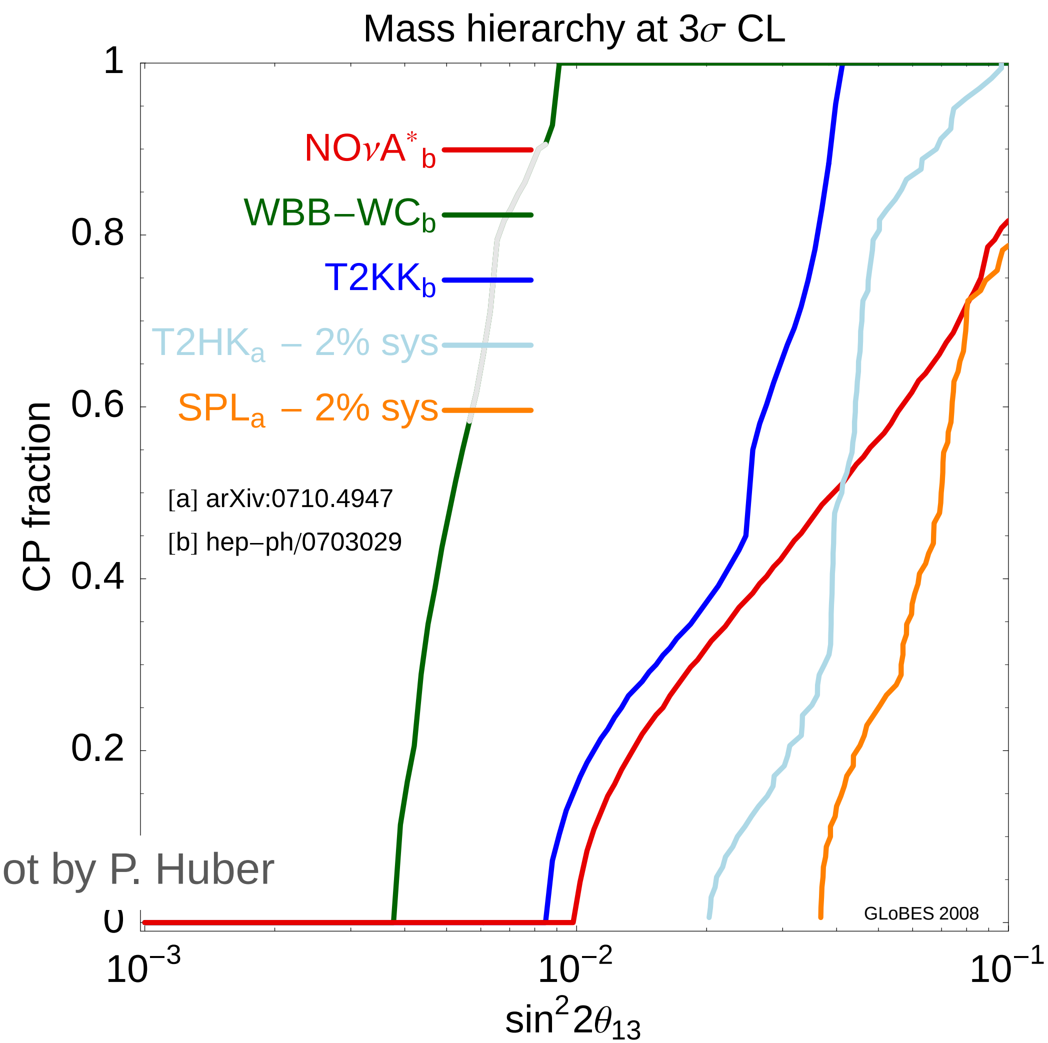
Comment - 1

Example: single/multi-ring samples in a WC



Comment - 2

Atmospheric ν can solve the hierarchy problem for large θ_{13}, but cannot compete with (very-)LBL experiments for small θ_{13}



plot by P. Huber

SPL (130 km) and T2HK (295 km) include 5 Mt yr WC atm neutrino data

NOνA*:

100 kt LAr @ 820 km

3 yr ν, 3 yr $\bar{\nu}$ @ 1.1 MW

T2KK:

270 kt WC @ 295 & 1050 km

4 yr ν, 4 yr $\bar{\nu}$ @ 4 MW

WBB:

300 kt WC @ 1290 km

5yr ν @ 1 MW, 5yr $\bar{\nu}$ @ 2 MW

Beyond oscillations

Earth tomography using oscillations?

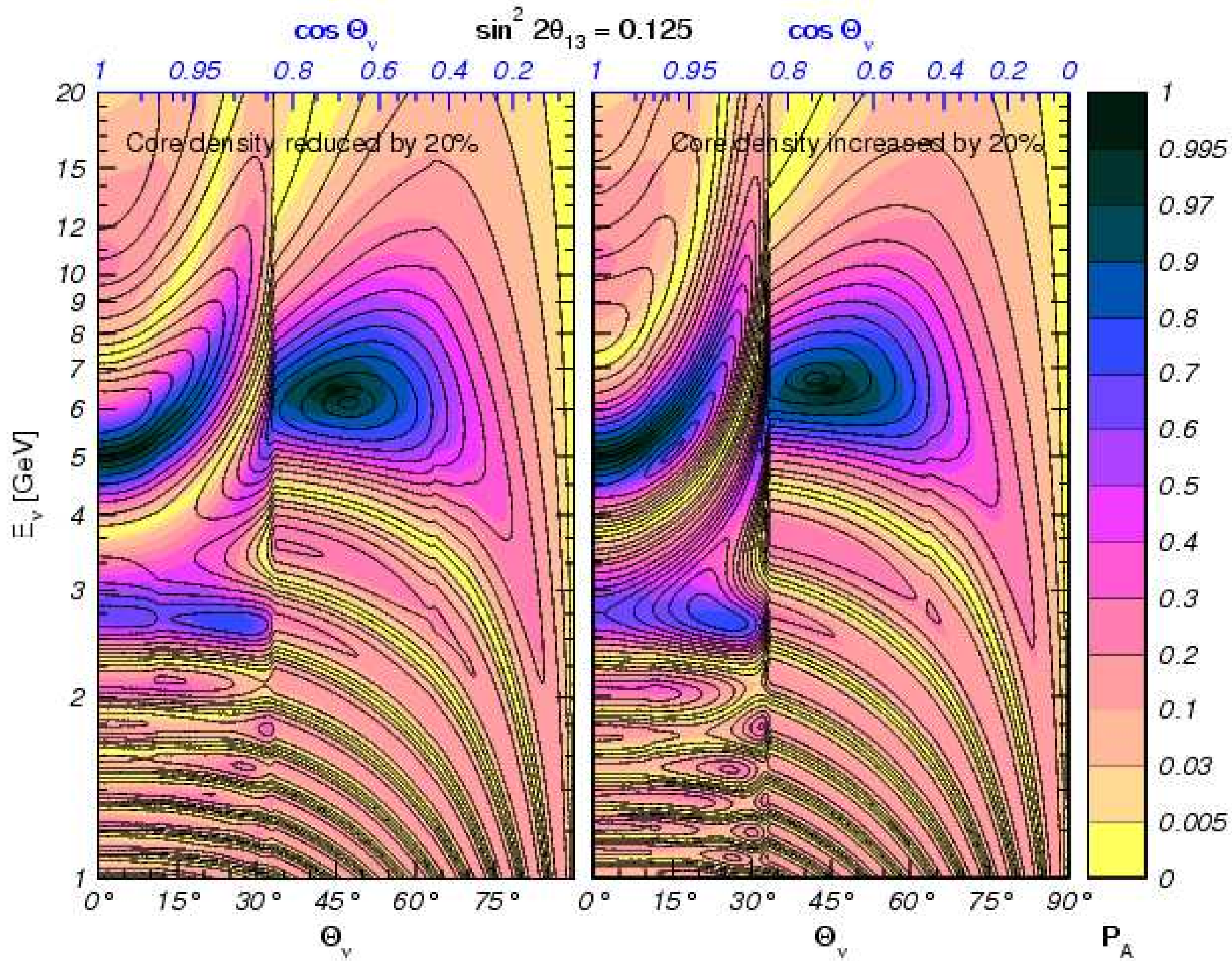
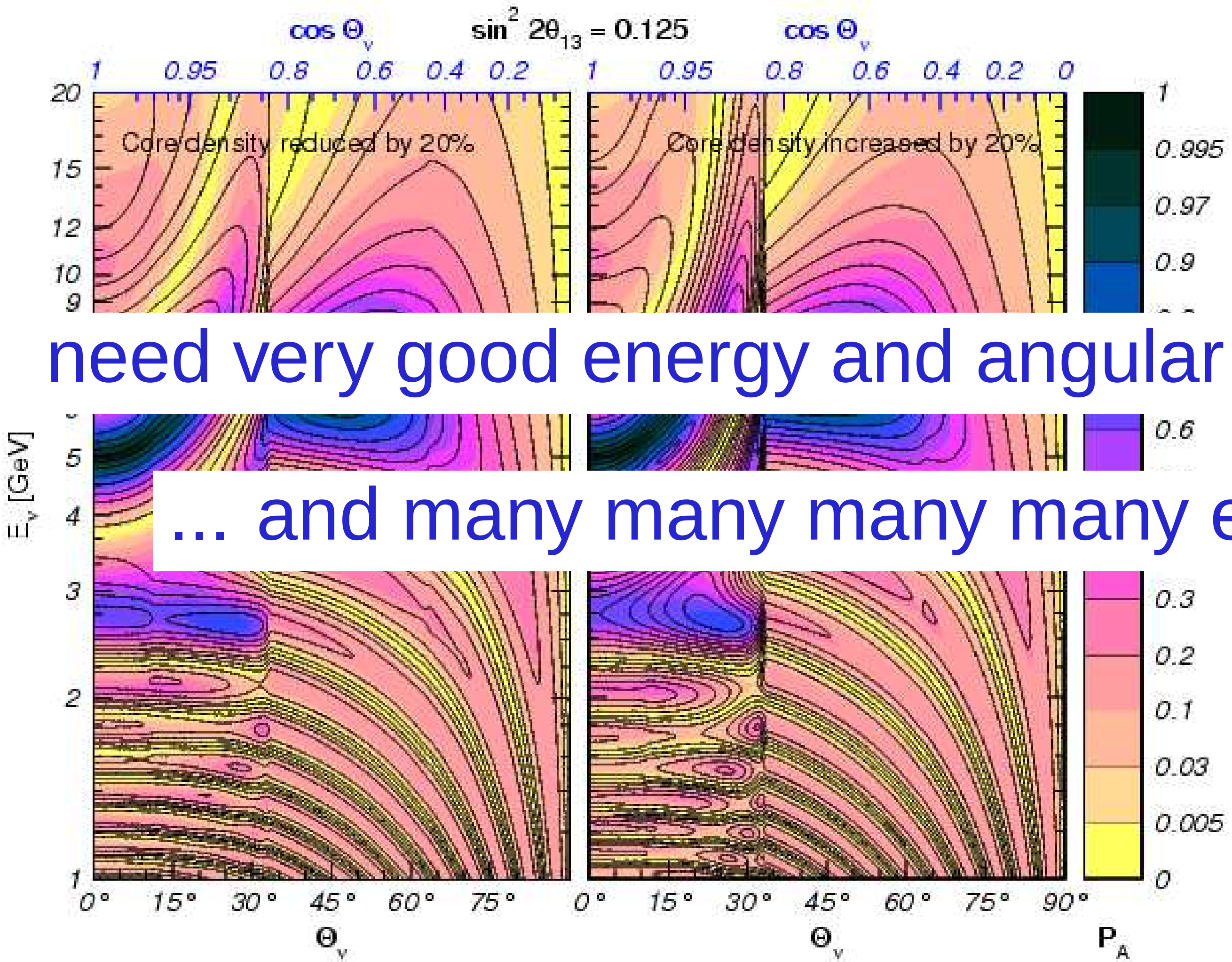


Figure 10: P_A oscillograms for the PREM density profile (colored regions) and for a 20% variations of the core/mantle density ratio. The total mass of the Earth is kept fixed.

P_A: effective 2ν appearance probability

E. K. Akhmedov, M. Maltoni and A. Y. Smirnov, JHEP **0705**, 077 (2007)

Earth tomography using oscillations?



need very good energy and angular resolution

... and many many many many events!

P_A: effective 2ν appearance probability

Figure 10: P_A oscillograms for the PREM density profile (colored regions) and for a 20% variations of the core/mantle density ratio. The total mass of the Earth is kept fixed.

E. K. Akhmedov, M. Maltoni and A. Y. Smirnov, JHEP **0705**, 077 (2007)

Beyond oscillations

Sensitivity of atmospheric neutrino data to new physics:

incomplete list of references:

non-standard interactions

N. Fornengo, M. Maltoni, R. T. Bayo and J. W. F. Valle, Phys. Rev. D **65**, 013010 (2002)

A. Friedland, C. Lunardini and M. Maltoni, Phys. Rev. D **70**, 111301 (2004)

A. Friedland and C. Lunardini, Phys. Rev. D **72**, 053009 (2005)

Lorentz violation, equivalence principle

G. L. Fogli, E. Lisi, A. Marrone and G. Scioscia, Phys. Rev. D **60** (1999) 053006

M. C. Gonzalez-Garcia and M. Maltoni, Phys. Rev. D **70** (2004) 033010

Quantum decoherence

G. L. Fogli, E. Lisi, A. Marrone and D. Montanino, Phys. Rev. D **67**, 093006 (2003)

Neutrino decay

G. L. Fogli, E. Lisi, A. Marrone and G. Scioscia, Phys. Rev. D **59**, 117303 (1999)

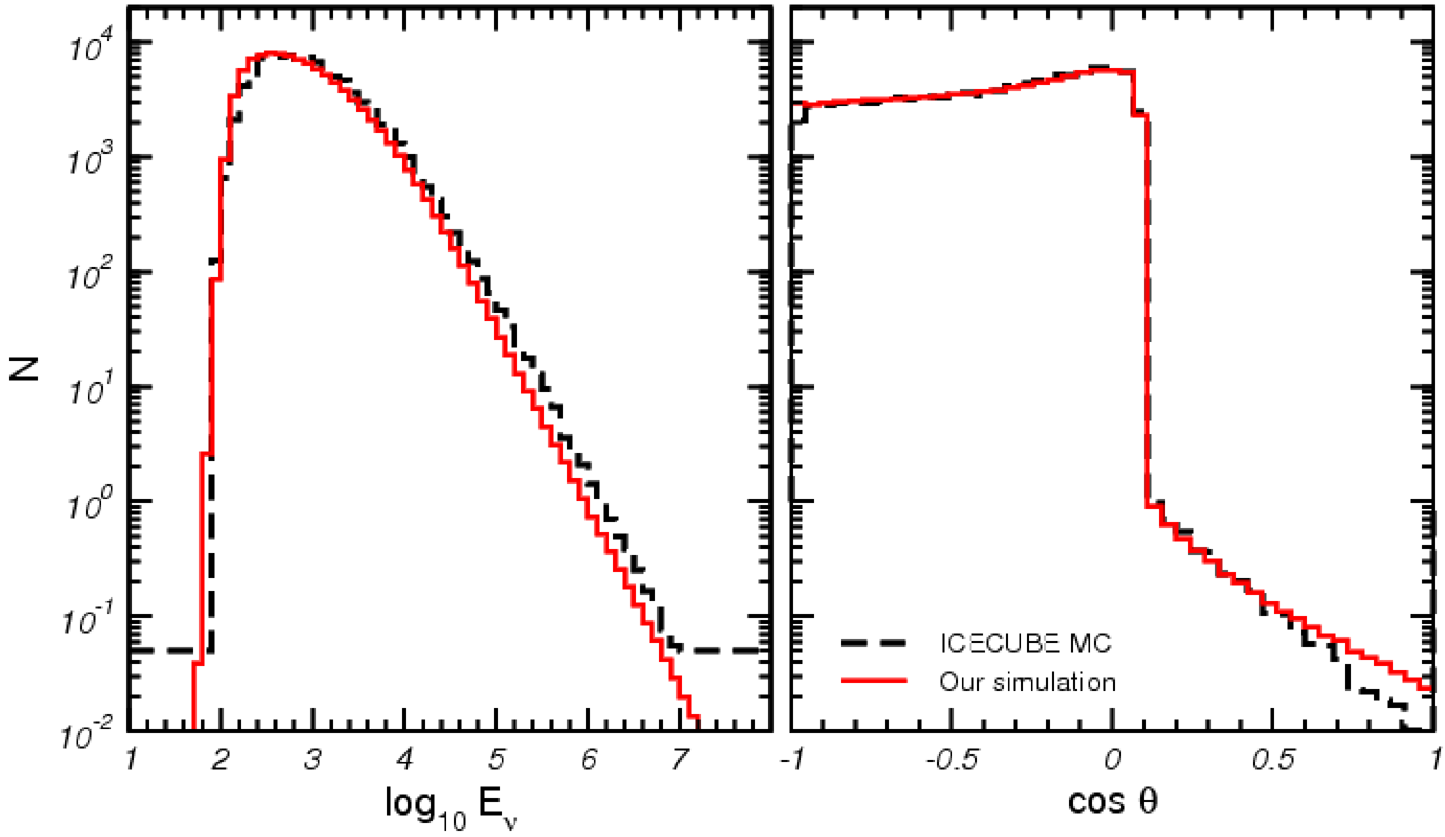
S. Choubey and S. Goswami, Astropart. Phys. **14**, 67 (2000)

V. D. Barger et al., Phys. Lett. B **462**, 109 (1999)

M. C. Gonzalez-Garcia and M. Maltoni, Phys. Lett. B **663**, 405 (2008)

TeV atmospheric neutrinos in Ice Cube

There are many atmospheric neutrino events in Ice Cube with energy $\sim$ TeV



M. C. Gonzalez-Garcia, F. Halzen and M. Maltoni, Phys. Rev. D **71**, 093010 (2005)

TeV atmospheric neutrinos in Ice Cube

Non-standard neutrino properties

M. C. Gonzalez-Garcia, F. Halzen and M. Maltoni, Phys. Rev. D **71**, 093010 (2005)

eV-scale sterile neutrinos

S. Choubey, JHEP **0712**, 014 (2007) [arXiv:0709.1937 [hep-ph]]

Earth tomography by neutrino absorption

M.C.Gonzalez-Garcia, F.Halzen, M.Maltoni, H.K.M.Tanaka, Phys.Rev.Lett. **100**, 061802 (2008)

Summary

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atmospheric neutrinos will continue to be very interesting for neutrino oscillations

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

- octant: good sensitivity of atm data
- hierarchy: sensitivity for $\sin^2 2\theta_{13} \gtrsim 0.02$

Summary

But: One needs really large detectors

- 500 kt water Cerenkov
- 100 kt liquid Argon
- 50 kt magnetized Iron calorimeter

Summary

But: One needs really large detectors

- 500 kt water Cerenkov
- 100 kt liquid Argon
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Apart from being big, the requirements are (ideally):

- good (neutrino) energy reconstruction
- good (neutrino) direction reconstruction
- $\nu/\bar{\nu}$ separation for ν_μ and ν_e
  (ev-by-ev or statistically)