European Strategy for Future Neutrino Physics

Neutrino Phenomenology

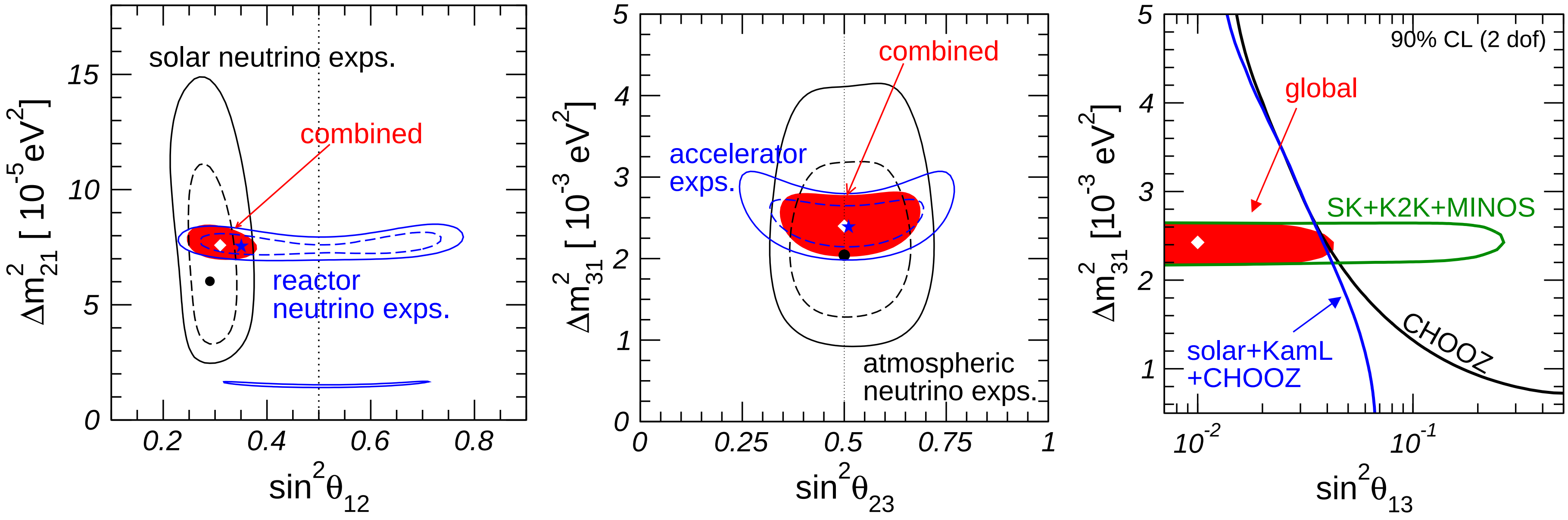
Thomas Schwetz

Max-Planck-Institute for Nuclear Physics, Heidelberg

I will not talk about. . .

Phenomenology of present oscillation experiments

TS, Tortola, Valle, 08; talk by A. deGouvea



I will also not talk about…

the LSND and MiniBooNE puzzels

- recent studies indicate that not even n sterile neutrinos ($n \geq 2$) can provide a good fit to the global data

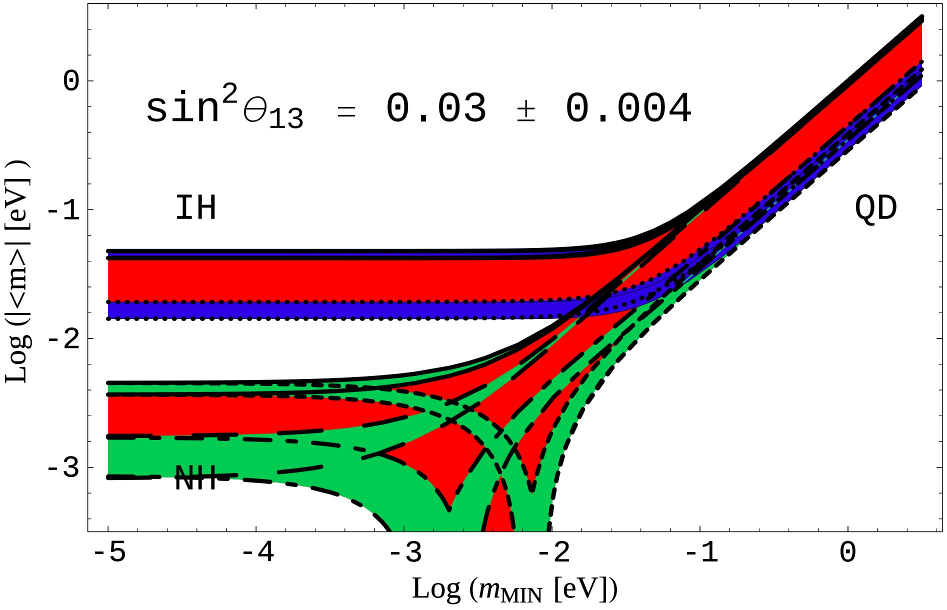
  Maltoni, Schwetz, 0705.0107; Karagiorgi et al, 0906.1997

- many VERY exotic models have been proposed, many of them cannot explain ALL data

I want to talk a little bit about...

Absolute neutrino mass phenomenology

- neutrinoless double beta decay $|\sum U_{ei}^2 m_i|$
  CUORE, EXO, GERDA, Majorana, MOON, XMASS



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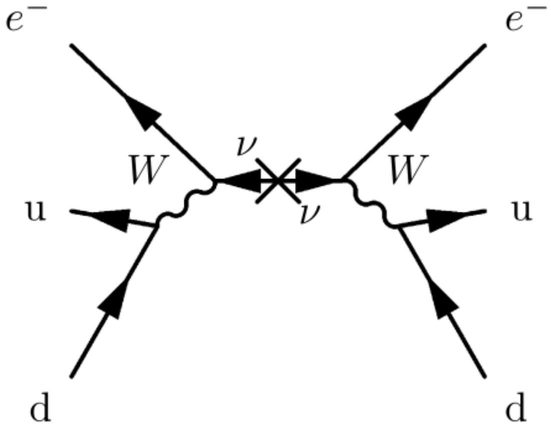
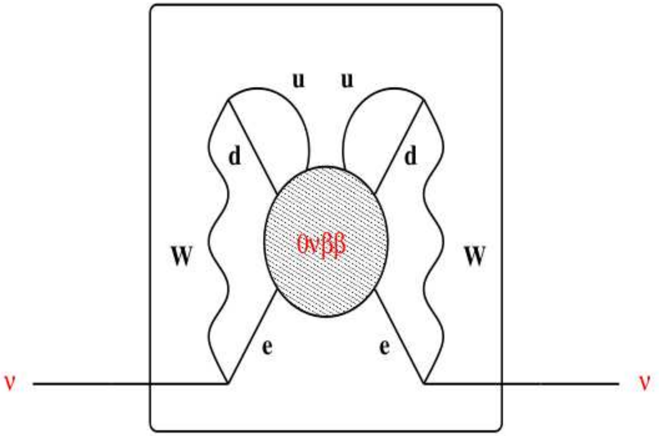
Absolute neutrino mass phenomenology

- neutrinoless double beta decay $|\sum U_{ei}^2 m_i|$
  CUORE, EXO, GERDA, Majorana, MOON, XMASS
  prove Majorana nature of neutrinos

  Schechter, Valle, 1982; Takasugi, 1984





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Absolute neutrino mass phenomenology

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- kinematical mass measurment $\sum |U_{ei}|^2 m_i$
  KATRIN, MARE: 0.2 eV $\rightarrow$ degenerate mass region
  new ideas required to go beyond this scale

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- neutrino mass from cosmology $\sum m_i$
  see talk of S. Hannestad

Ideally we would like to have signals from all three!

From now on I focus on. . .

Phenomenology of future oscillation experiments

3-flavour oscillations

$$\begin{array}{cccc} & \Delta m^2_{31} & & \Delta m^2_{21} \\ U = & \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} & \begin{pmatrix} c_{13} & 0 & e^{-i\delta} s_{13} \\ 0 & 1 & 0 \\ -e^{i\delta} s_{13} & 0 & c_{13} \end{pmatrix} & \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \\ & \text{atmospheric+LBL} & \text{Chooz} & \text{solar+KamLAND} \end{array}$$

dominant oscillations are well described by effective two-flavour oscillations

3-flavour effects are suppressed because $\Delta m^2_{21} \ll |\Delta m^2_{31}|$ and $\theta_{13} \ll 1$

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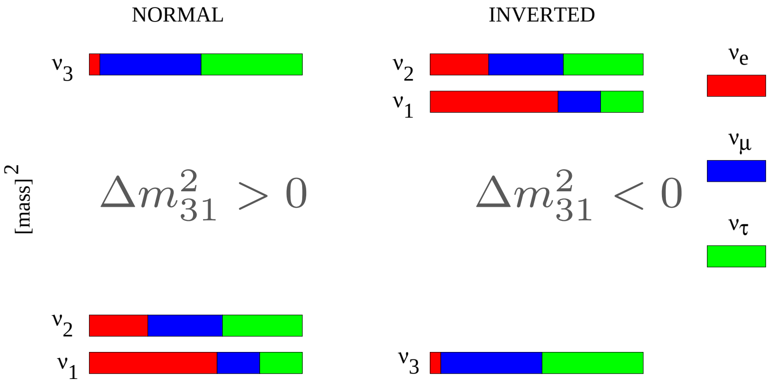
- search for θ_{13}
- CP violation in neutrino oscillations
- mass hierarchy sign(Δm^2_{31})



Upcoming oscillation experiments

and the race for θ_{13}

Upcoming oscillation experiments

Reactor experiments with near and far detectors:

Off-axis superbeams:

see talks this morning

Upcoming oscillation experiments

	baseline	power	FD mass	channel
Reactor experiments with near and far detectors:				
D-Chooz	$1.05\,\mathrm{km}$	$8.6\,\mathrm{GW_{th}}$	$8.3\,\mathrm{t}$	$\bar\nu_e \to \bar\nu_e$
RENO	$1.4\,\mathrm{km}$	$16.4\,\mathrm{GW_{th}}$	$15.4\,\mathrm{t}$	$\bar\nu_e \to \bar\nu_e$
Daya Bay	$1.7\,\mathrm{km}$	$17.4\,\mathrm{GW_{th}}$	$80\,\mathrm{t}$	$\bar\nu_e \to \bar\nu_e$
Off-axis superbeams:				

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Off-axis superbeams:				
T2K	$295\,\mathrm{km}$	$0.75\,\mathrm{MW}$	$22.5\,\mathrm{kt}$	$\nu_\mu \to \nu_e, \nu_\mu$
NOνA	$812\,\mathrm{km}$	$0.7\,\mathrm{MW}$	$15\,\mathrm{kt}$	$\nu_\mu \to \nu_e, \nu_\mu$

see talks this morning

Measuring θ_{13}

two complementary approaches towards θ_{13}:

- $\bar\nu_e \to \bar\nu_e$ disappearance reactor experiments with near and far detectors: **D-Chooz, Daya Bay, RENO**

  "clean" measurement of θ_{13}:

$$P_{ee} \approx 1 - \sin^2 2\theta_{13} \, \sin^2 \frac{\Delta m^2_{31} L}{4E_\nu} + \mathcal{O}\left(\frac{\Delta m^2_{21}}{\Delta m^2_{31}}\right)^2$$

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- LBL $\nu_\mu \to \nu_e$ appearance exp.: **T2K, NOνA**

  $P_{\mu e}$ is a complicated function of various parameters

  θ_{13} is correlated with other parameters
  (CP-phase δ, sign of Δm^2_{31})

The LBL appearance oscillation probability

$$
\begin{aligned}
P_{\mu e} \simeq\ & \sin^2 2\theta_{13}\ \sin^2\theta_{23}\ \frac{\sin^2(1-A)\Delta}{(1-A)^2} \\
+\ & \sin 2\theta_{13}\ \hat{\alpha}\ \sin 2\theta_{23}\ \frac{\sin(1-A)\Delta}{1-A}\frac{\sin A\Delta}{A}\ \cos(\Delta+\delta_{\mathrm{CP}}) \\
+\ & \hat{\alpha}^2\ \cos^2\theta_{23}\ \frac{\sin^2 A\Delta}{A^2}
\end{aligned}
$$

with

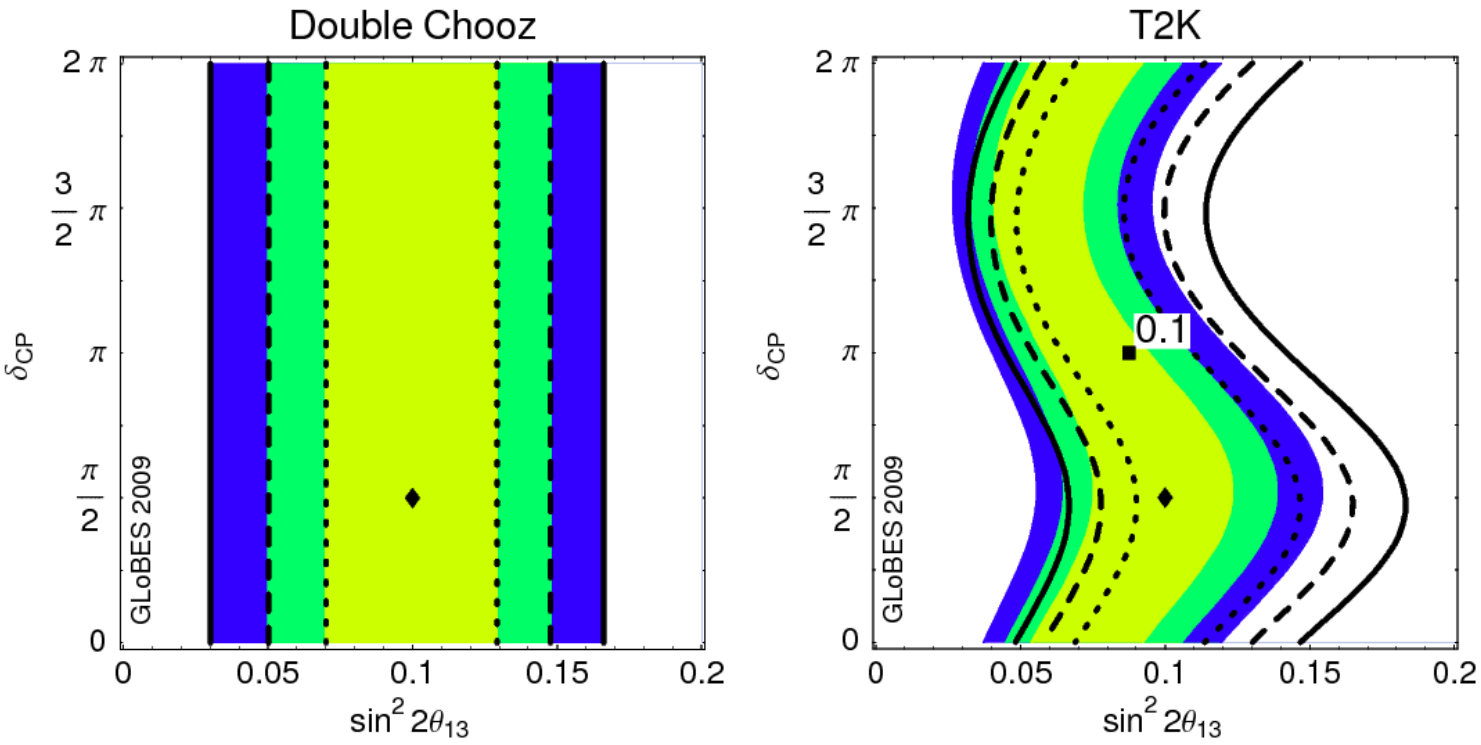
$$\Delta \equiv \frac{\Delta m^2_{31} L}{4E_\nu}\,, \qquad \hat{\alpha} \equiv \frac{\Delta m^2_{21}}{\Delta m^2_{31}}\sin 2\theta_{12}\,, \qquad A \equiv \frac{2E_\nu V}{\Delta m^2_{31}}$$

anti-ν: $\delta_{\mathrm{CP}} \to -\delta_{\mathrm{CP}}$, $A \to -A$, $\quad P_{e\mu}$: $\delta_{\mathrm{CP}} \to -\delta_{\mathrm{CP}}$

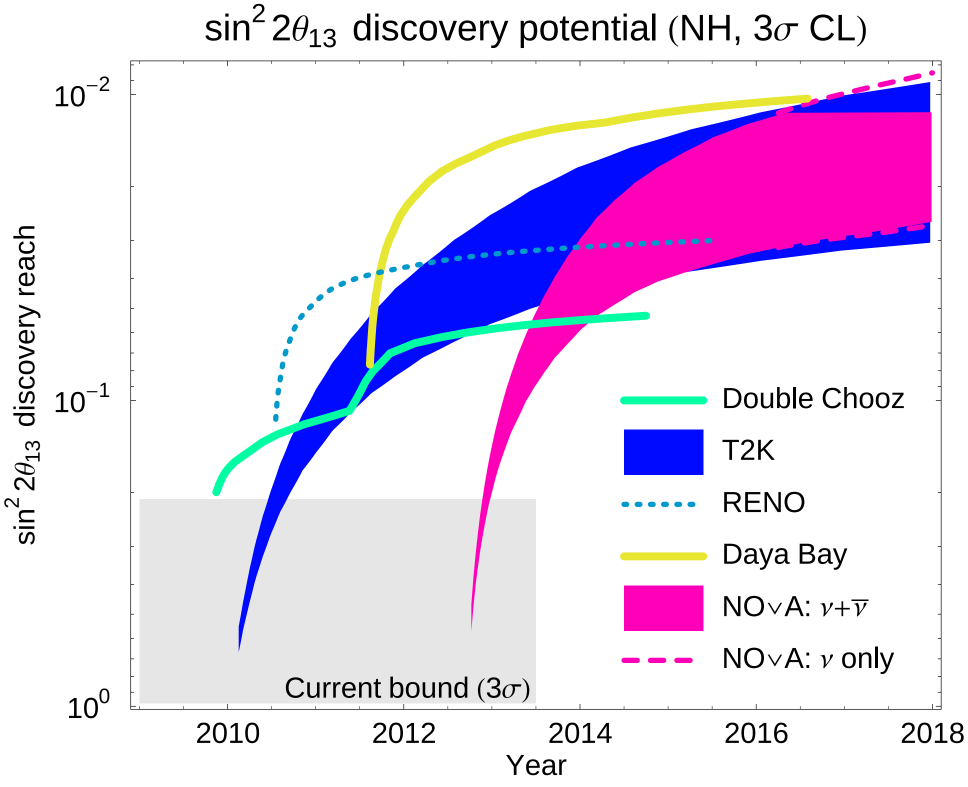
other hierarchy: $\Delta \to -\Delta$, $A \to -A$, $\hat{\alpha} \to -\hat{\alpha}$

Reactor vs Beam

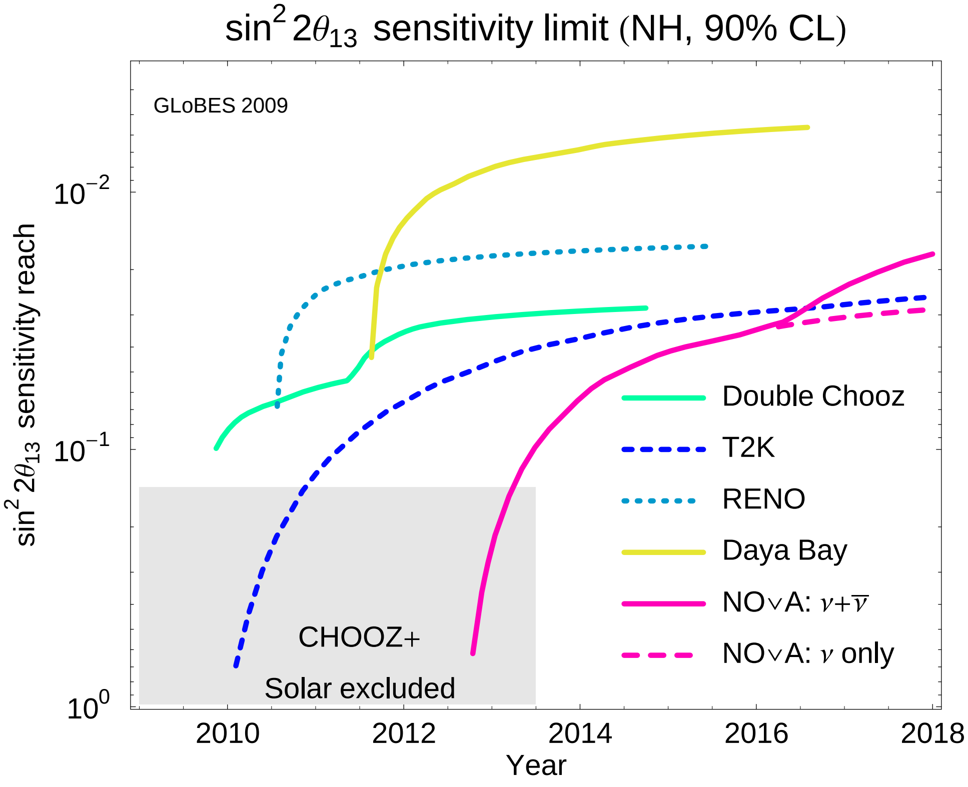
assume $\sin^2 2\theta_{13} = 0.1,\ \delta = \pi/2$



The race for θ_{13}



$\sin^2 2\theta_{13}$ discovery potential (NH, 3σ CL)



$\sin^2 2\theta_{13}$ sensitivity limit (NH, 90% CL)

Huber, Lindner, TS, Winter, 0907.1896

The ultimate goals*

- measure the value of $\delta_{\rm CP}$
  establish CP violation
- determine the neutrino mass hierarchy
  i.e., sgn(Δm^2_{31})

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*Slightly different “ultimate goals” than defined this morning by Andre deGouvea

CP violation

In theory: measure $P_{\nu_\alpha\to\nu_\beta}$ vs $P_{\bar\nu_\alpha\to\bar\nu_\beta}$
In practice:

- cross section and fluxes are different for ν and $\bar\nu$
- matter effect is CP violating

or: measure $P_{\nu_\alpha\to\nu_\beta}$ vs $P_{\nu_\beta\to\nu_\alpha}$

- need two completely different neutrino sources

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perform a parametric fit to δ

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Assume standard 3-flavour oscillations
perform a parametric fit to δ

Is there a model-independent way to establish CP violation in the lepton sector?

Determination of the mass hierarchy

the vacuum oscillation probability is invariant under

$$\Delta m^2_{31} \to -\Delta m^2_{31} \qquad \delta_{\rm CP} \to \pi - \delta_{\rm CP}$$

$\longrightarrow$ the key to resolve the hierarchy degeneracy is the matter effect

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$\longrightarrow$ the key to resolve the hierarchy degeneracy is the matter effect

resonance condition for $\nu_\mu \to \nu_e$ oscillations:

$$\pm \frac{2EV}{\Delta m^2_{31}} = \cos 2\theta_{13} \approx 1$$

can be fulfilled for

neutrinos if $\Delta m^2_{31} > 0$ (normal hierarchy)

anti-neutrinos if $\Delta m^2_{31} < 0$ (inverted hierarchy)

The size of the matter effect

$$A \equiv \left|\frac{2EV}{\Delta m^2_{31}}\right| \simeq 0.09 \left(\frac{E}{\mathrm{GeV}}\right)\left(\frac{|\Delta m^2_{31}|}{2.5\times 10^{-3}\,\mathrm{eV}^2}\right)^{-1}$$

for experiments at the 1st osc. max, $|\Delta m^2_{31}|L/2E \simeq \pi$, and

$$A \simeq 0.02 \left(\frac{L}{100\,\mathrm{km}}\right)$$

need $L \gtrsim 1000$ km and $E_\nu \gtrsim 3$ GeV in order to reach the regime of strong matter effect $A \gtrsim 0.2$.

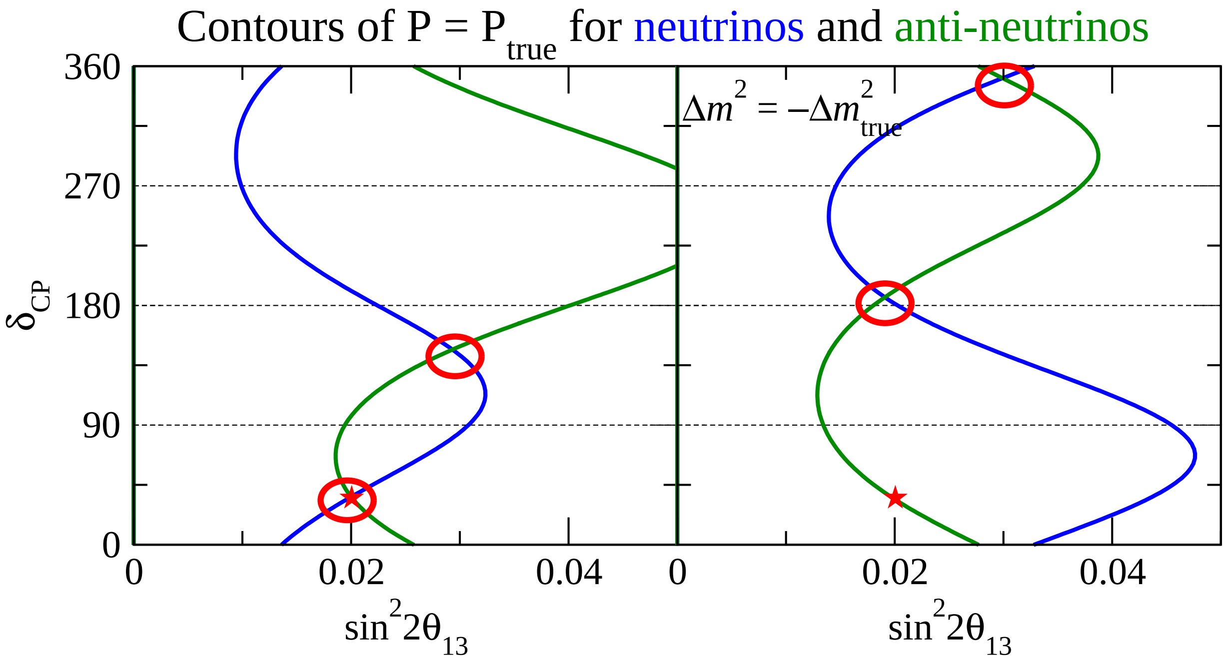
terms linear in A do not break the degeneracy → have to be sensitive to higher order terms in A TS, hep-ph/0703279

Mass hierarchy degeneracy and CPV

in matter the sign(Δm^2_{31})-degenerate solution is located at

$$\Delta m^2_{31} \to -\Delta m^2_{31} \qquad \delta_{\rm CP} \to \pi - \delta_{\rm CP} + \epsilon(A)$$

Even if the true $\delta_{\rm CP}$ has a CP violating value, the degenerate solution may be located at a CP conserving value


Contours of P = $P_{\rm true}$ for neutrinos and anti-neutrinos

ex.: $E_\nu = 2.2$ GeV
$L = 812$ km (NOvA)

MH degeneracy can destroy sensitivity to CPV

Assume “large” θ_{13}: can we measure CPV and the mass hierarchy with the upcoming generation of experiments?

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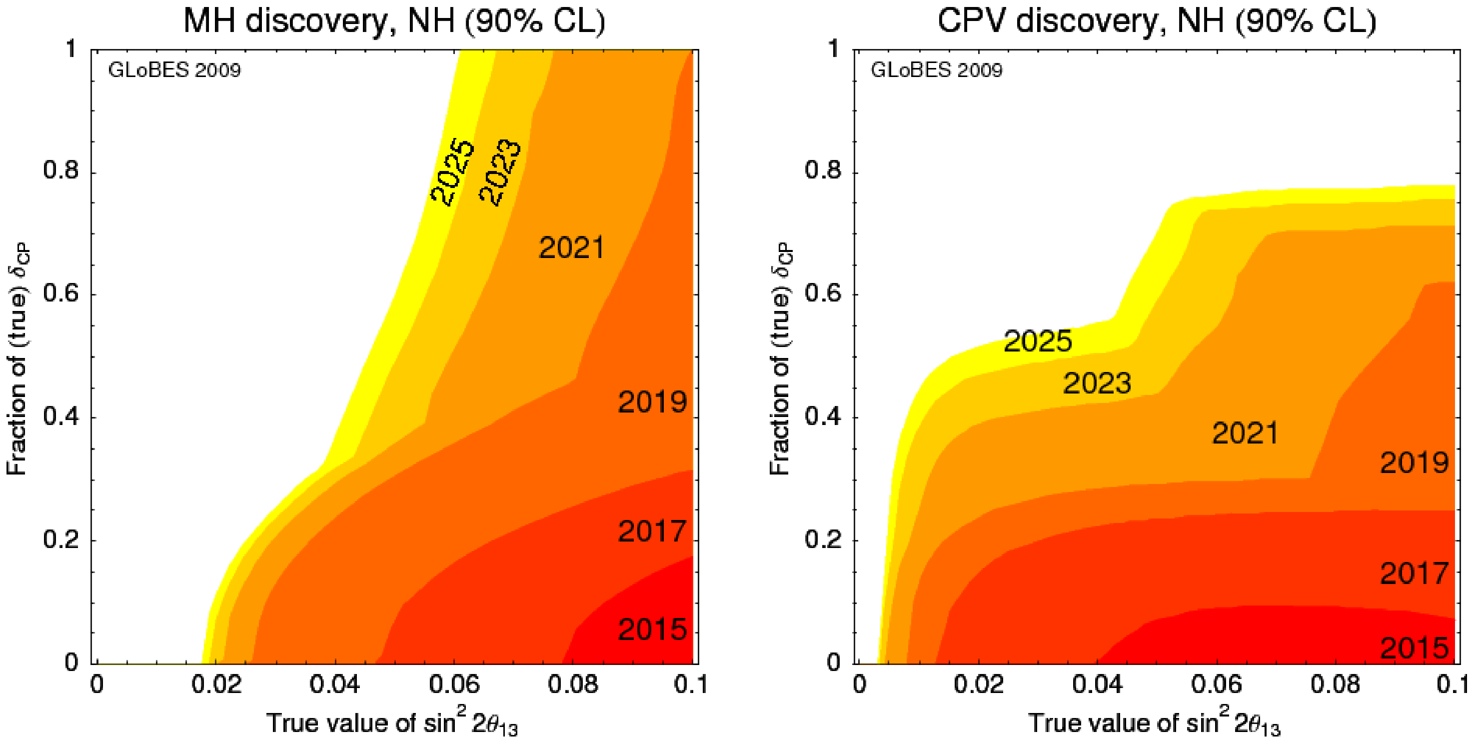
toy scenario:

- **T2K**: proton driver @ 2015: beam power $0.75 \rightarrow 1.66\,\mathrm{MW}$
- **NOνA**: project X @ 2018: beam power $0.7 \rightarrow 2.3\,\mathrm{MW}$
- combined data from **T2K**, **NOνA**, **Daya Bay**
- fully optimized $\nu/\bar{\nu}$ switching between **T2K** and **NOνA**

MH & CPV with T2K & NOvA & DayaB



Huber, Lindner, TS, Winter, 0907.1896

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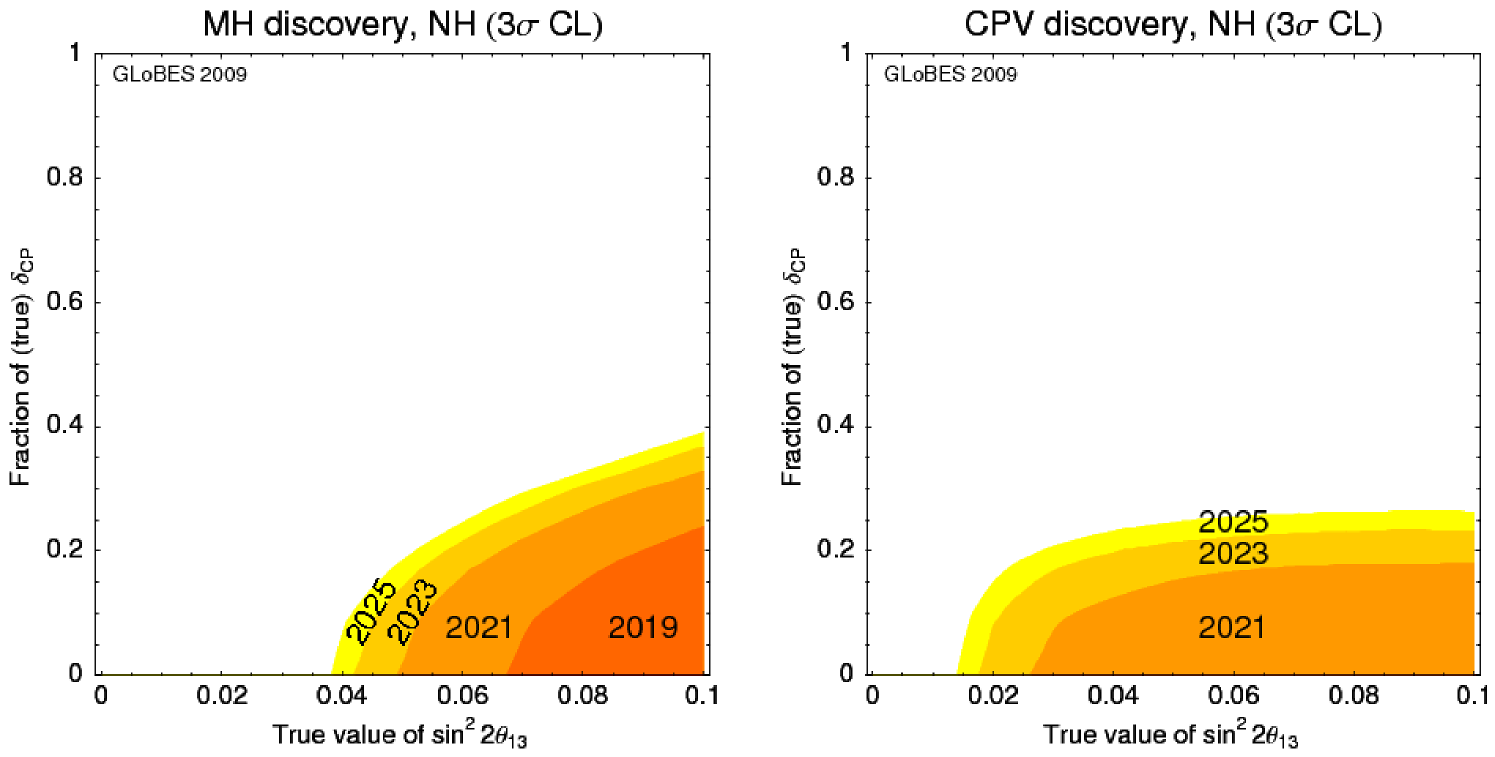

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subsequent generation of LBL experiments

- superbeam upgardes $(\nu_\mu \to \nu_e, \nu_\mu) + (\bar\nu_\mu \to \bar\nu_e, \bar\nu_\mu)$

- beta beams (**βB**) $(\nu_e \to \nu_\mu) + (\bar\nu_e \to \bar\nu_\mu)$

- neutrino factory (**NuFact**) $(\nu_e, \nu_\mu \to \nu_\mu) + (\bar\nu_e, \bar\nu_\mu \to \bar\nu_\mu)$

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  T2KK: second detector in Korea

  NOνA: proton driver, second detector

  WBB: wideband beam, $E_\nu \sim \mathrm{GeV}, L \simeq 1300\,\mathrm{km}$

  CNGS-upgrades (beam upgrade, liquid Ar detector)

  SPL: CERN to ∼Mt water Cerenkov at Frejus (130 km)

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  high γ **βB** (longer BL), mono-energetic **βB**

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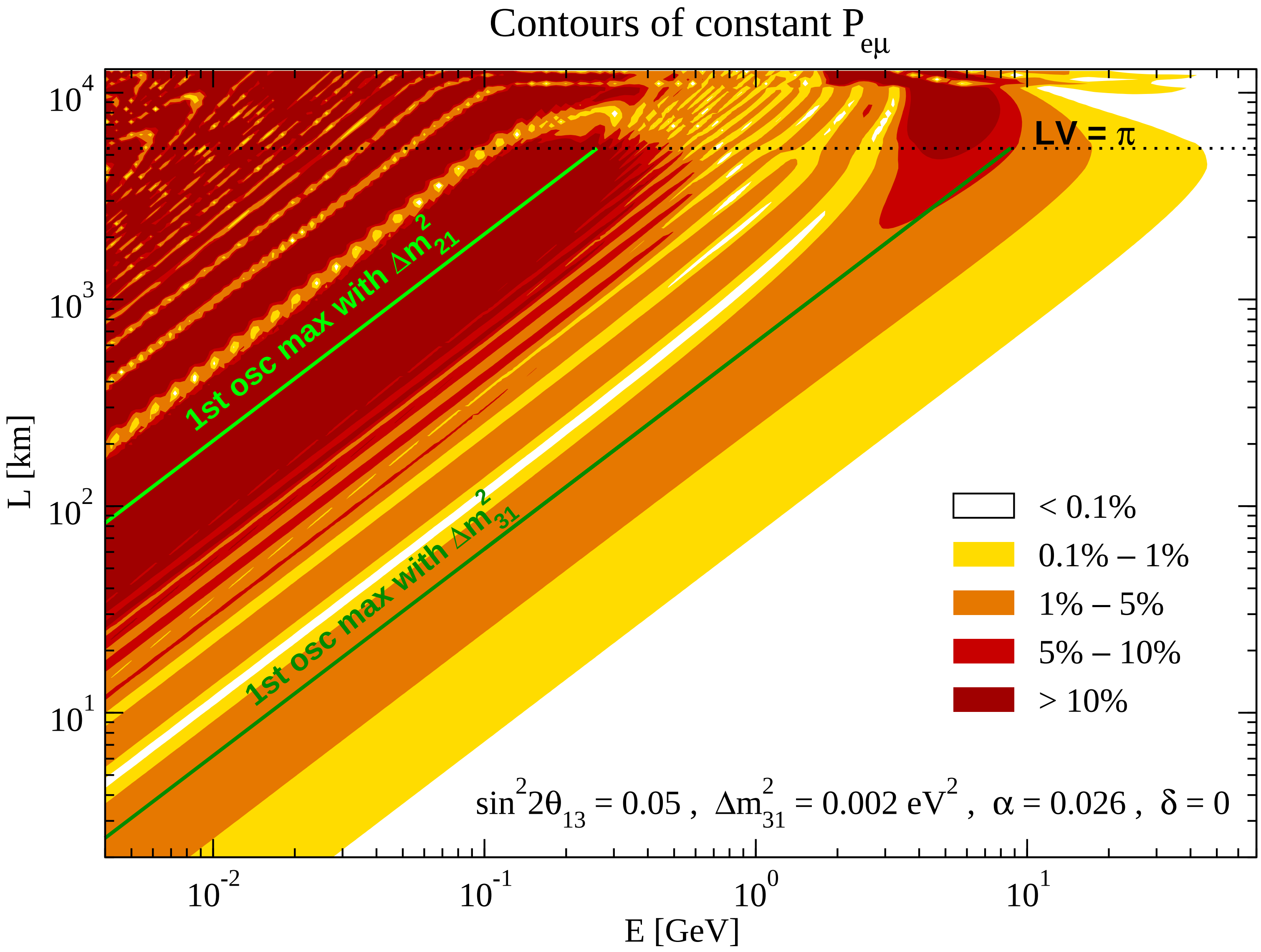
  $E_\nu \sim 20 - 50\,\mathrm{GeV},\ 1000\,\mathrm{km} \lesssim L \lesssim 7000\,\mathrm{km}$

  LENF: low energy NuFact, $E_\nu \sim 5\,\mathrm{GeV},\ L \simeq 1300\,\mathrm{km}$

LBL oscillation probability



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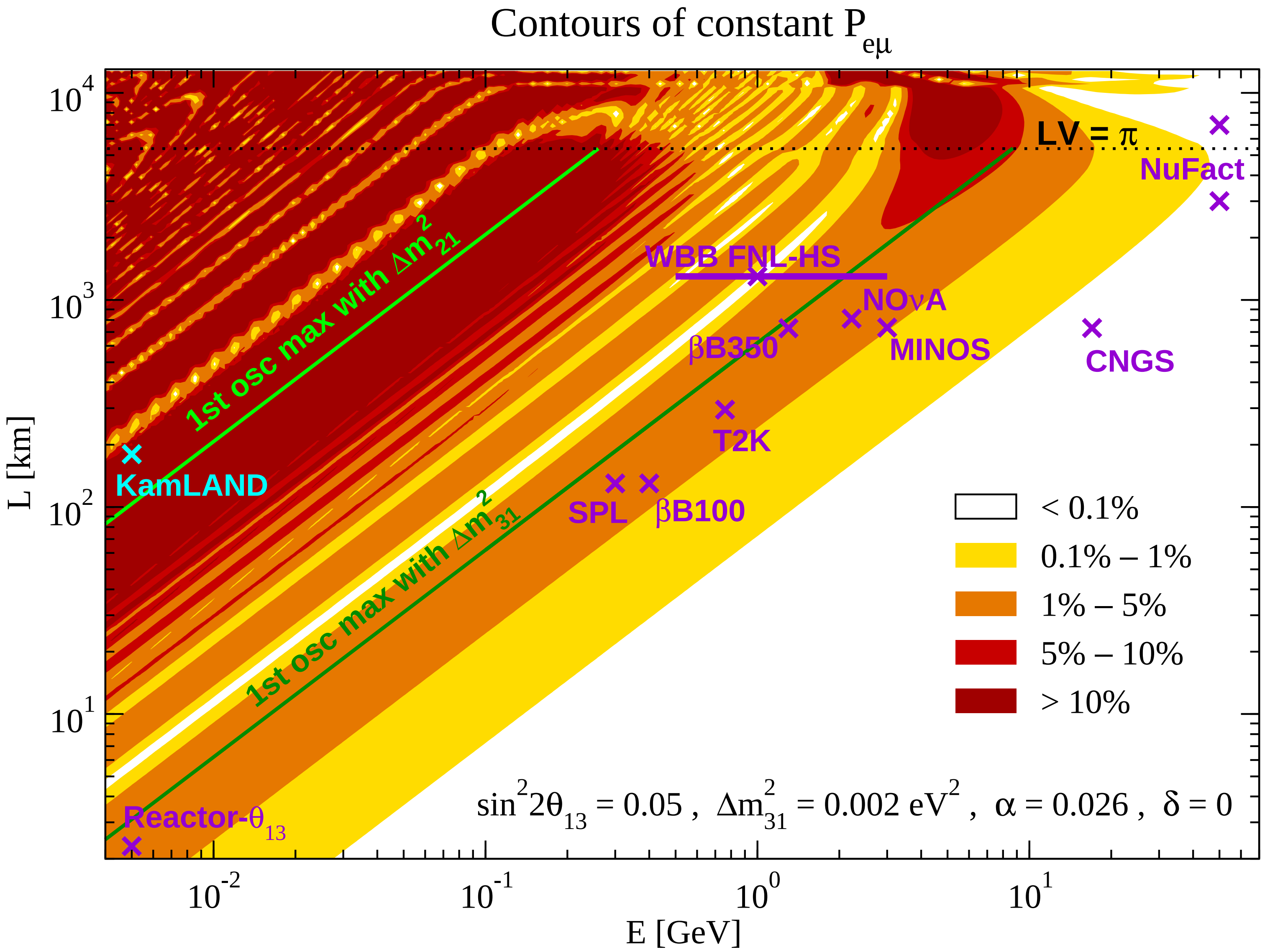
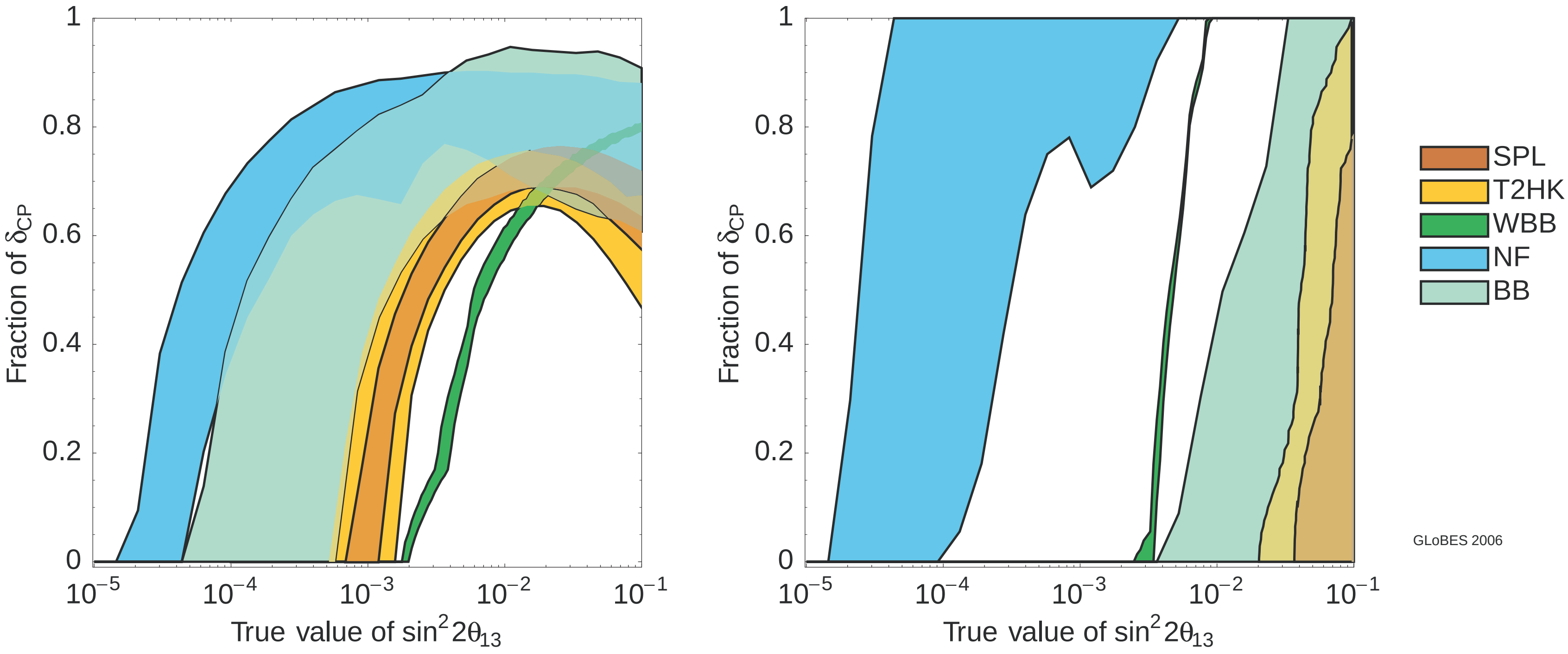


CPV & mass hierarchy sensitivities

The ISS Physics Working Group report arxiv:0710.4947



Systematics and the CPV measurment

In superbeam experiments

- we do not know the fluxes ($\sim$ 10%)
- we do not know the cross sections ($\sim$ 10%)

How can we do a precision experiment ($\lesssim$ 1%)?

On systematics in a superbeam experiment

Let’s use the near detector:

beam	ND	FD
ϕ_{ν_μ}	$N_\mu^{\rm ND} \propto \phi_{\nu_\mu}\sigma_{\nu_\mu}$	$\phi_{\nu_\mu}\sigma_{\nu_\mu}P_{\nu_\mu\to\nu_\mu}$
ϕ_{ν_e}	$N_e^{\rm ND} \propto \phi_{\nu_e}\sigma_{\nu_e}$	$\phi_{\nu_\mu}\sigma_{\nu_e}P_{\nu_\mu\to\nu_e} + \phi_{\nu_e}\sigma_{\nu_e}$

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dis.: $f N_\mu^{\rm ND} \quad P_{\nu_\mu\to\nu_\mu}$

app.: $f N_\mu^{\rm ND} \frac{\sigma_{\nu_e}}{\sigma_{\nu_\mu}} P_{\nu_\mu\to\nu_e} + f N_e^{\rm ND}$

$$f = \frac{M_F}{M_N}\,\frac{L_N^2}{L_F^2}\,\frac{\epsilon_F}{\epsilon_N}$$

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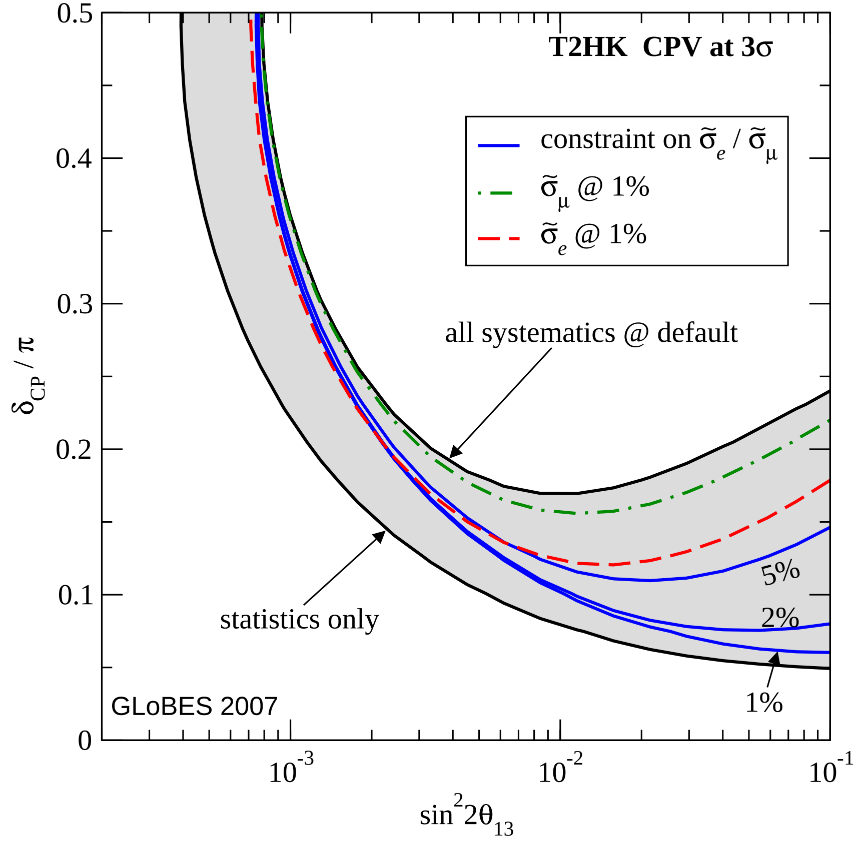
$$f = \frac{M_F}{M_N}\,\frac{L_N^2}{L_F^2}\,\frac{\epsilon_F}{\epsilon_N}$$

no information on $\dfrac{\epsilon_F^e \cdot \sigma_{\nu_e}}{\epsilon_N^\mu \cdot \sigma_{\nu_\mu}}$

Systematics in superbeam experiments

For “large” θ_{13}: rely on external information on $\sigma_{\nu_e}/\sigma_{\nu_\mu}$, cannot be obtained within the experiment itself.



Huber, Mezzetto, Schwetz, arXiv:0711.2950

Some questions

- How precisely can (total) cross sections be measured?

  Current Xsec experiments (MiniBooNE, MINERνA) are still based on convential beams with large flux uncertainties
- How to measure ν_e cross sections?

  Do we need a beta beam?
- Do we want to base our results on theoretical calculations of the ratio $\sigma_{\nu_e}/\sigma_{\nu_\mu}$?

Some questions

At beta beam and NuFact the flux is known to good precision.

- How does it look like for a beta beam?
  measure σ_{ν_e} at ND, but still need σ_{ν_μ} for appearance signal
- Combine a beta beam and a super beam?
  cross correlations to eliminate cross section errors

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  all cross sections can be measured at ND! (except σ_{ν_τ})
  very long baselines: think about matter density uncertainty

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More dedicated studies along these lines are needed

Huber, Mezzetto, Schwetz, 0711.2950; Tang, Winter, 0903.3039

Determination of the mass hierarchy

matter effect becomes large for BL $\gtrsim 1000$ km

- $\sin^2 2\theta_{13} \sim 10^{-2}$: LBL experiments with BL $\simeq 1000$ km
  WBB or **LENF**: FNL to DUSEL, 1290 km; or **T2KK**, 1050 km

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- $\sin^2 2\theta_{13} \ll 10^{-2}$: need BL of several 1000 km
  NuFact (e.g., 3000 & 7000 km) or very LBL β**B**

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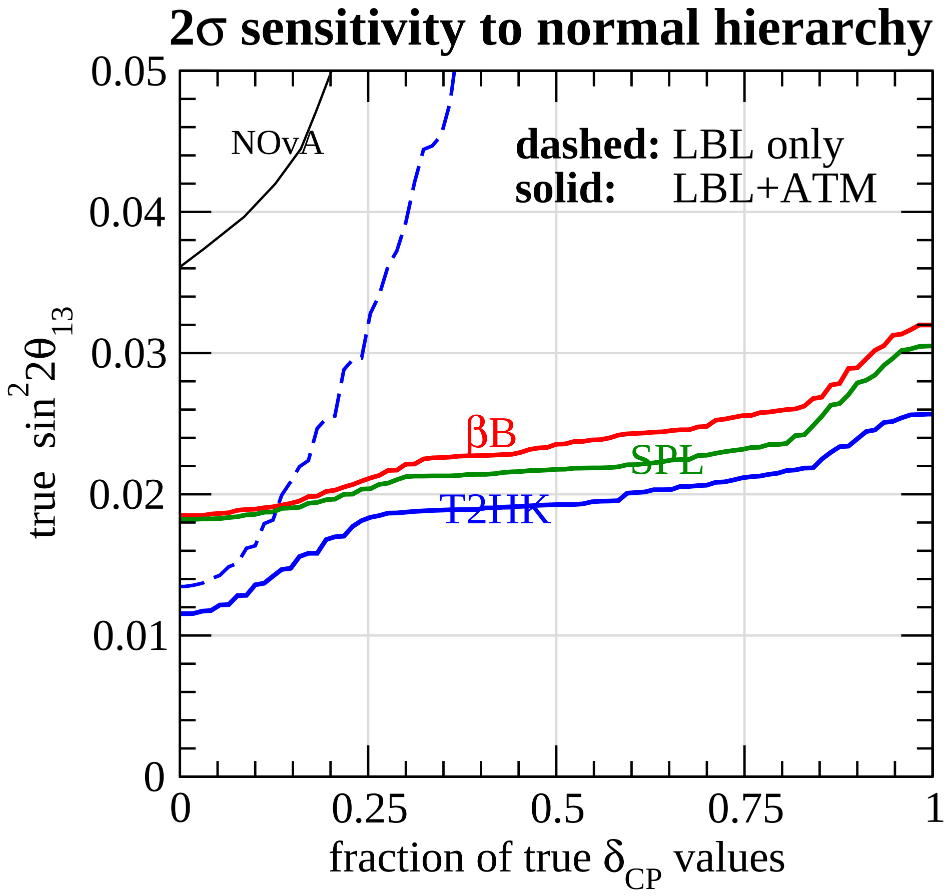
- $\sin^2 2\theta_{13} \sim 10^{-2}$: LBL experiments with BL $\simeq 1000$ km
  WBB or **LENF**: FNL to DUSEL, 1290 km; or **T2KK**, 1050 km
- $\sin^2 2\theta_{13} \ll 10^{-2}$: need BL of several 1000 km
  NuFact (e.g., 3000 & 7000 km) or very LBL **βB**
- $\sin^2 2\theta_{13} \gtrsim 2 \times 10^{-2}$:
  - Atmospheric neutrinos: Mt WC atm+LBL combination or magnetized detector, μ only (**INO** experiment)
  - Combination of superbeam and beta beam works even at relatively short baselines (130 km)

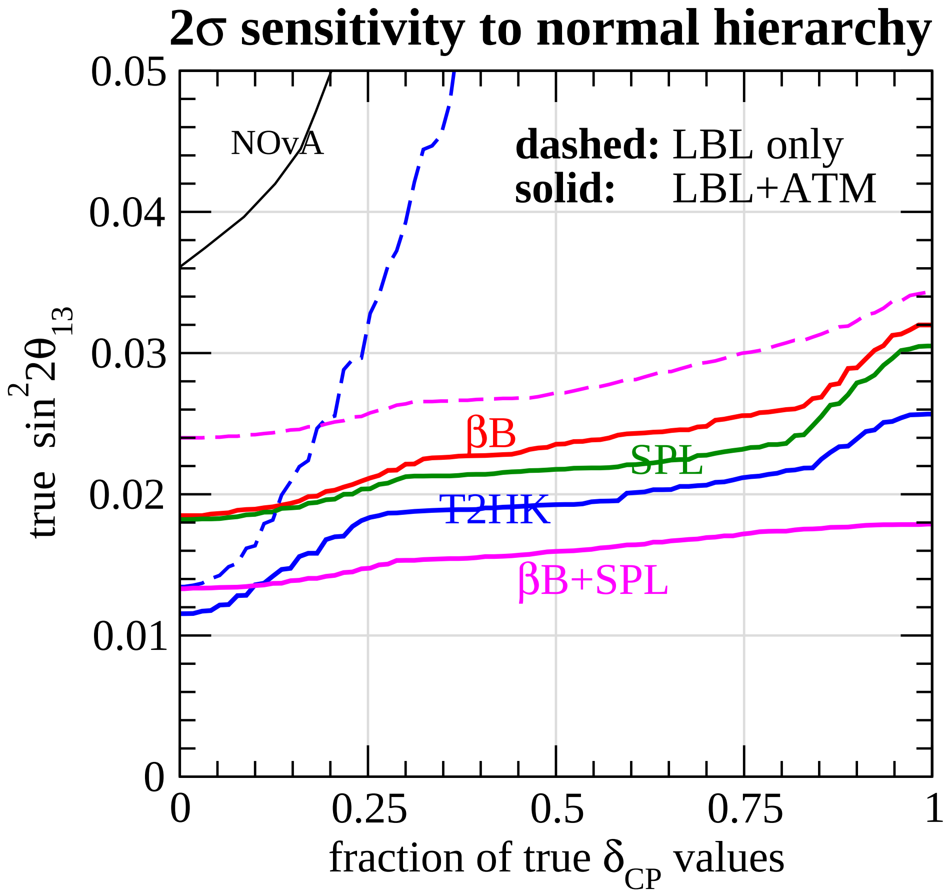
Mass hierarchy for large θ_{13}



Huber, Maltoni, TS, hep-ph/0501037; Campagne, Maltoni, Mezzetto, TS, hep-ph/0603172

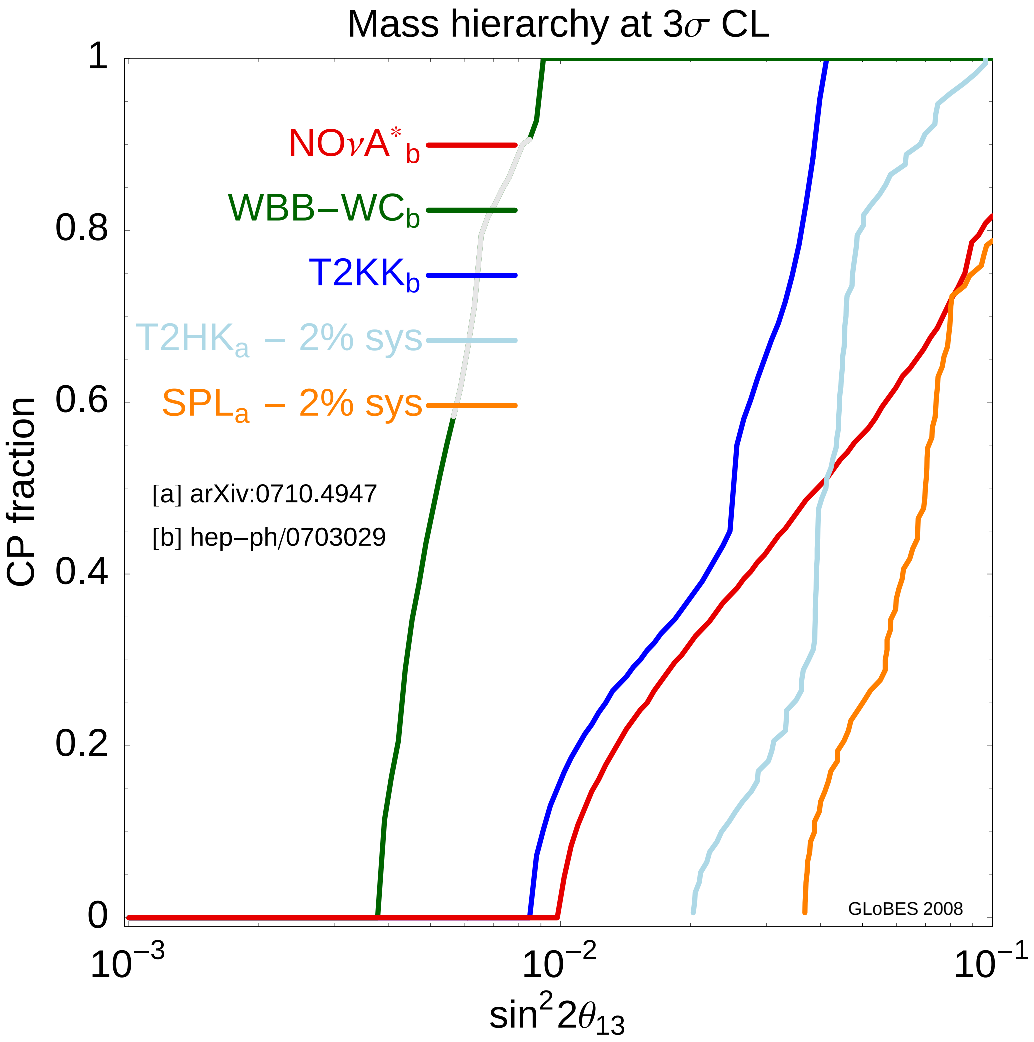
synergy of LBL data and atmospheric neutrinos in (the same!)
Mt-scale multi-purpose detector (WC, LAr)

Mass hierarchy for large θ_{13}



CP+T-conjugated channels $\nu_\mu \to \nu_e, \bar{\nu}_\mu \to \bar{\nu}_e, \nu_e \to \nu_\mu, \bar{\nu}_e \to \bar{\nu}_\mu$ (SB+BB) provide sensitivity to MH Schwetz, hep-ph/0703279

Comparison with 1290 km WBB



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

The ultimate goals[*]

Overconstraining the system

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[*] According to Andre deGouvea's definition

Can we do a unitarity triangle measurment?

$$U = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix}$$

$$U_{e1}U_{\mu 1}^* + U_{e2}U_{\mu 2}^* + U_{e3}U_{\mu 3}^* = 0$$

Have to measure absolute values of $U_{ei}, U_{\mu i}$, and check whether the area of the triange is consistent with the measurment of δ

Farzan, Smirnov, hep-ph/0201105

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Farzan, Smirnov, hep-ph/0201105

- $|U_{ei}|$: can be measured at reactors
  need reactor experiment at 50-60 km
- $|U_{\mu i}|$: need accurate ν_μ disappearance exps.
  I do not know of a realistic possibility to measure $|U_{\mu 1}|$ and $|U_{\mu 2}|$ (need ν_μ disappearance at the "solar scale" $\Delta m^2_{21} \to$ very low E_ν and long baselines)

Summary

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Thank you for your attention!