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Workshop on the original of P, CP and T Violation

2 - 5 July 2008

How to measure CP violation in the lepton sector

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CPT @ ICTP

How to measure CP violation in the lepton sector

more appropriate title:

How to measure complex phases in the lepton sector

Thomas Schwetz

CERN

Outline

- Dirac vs Majorana phases
- Dirac CPV and oscillation experiments
  What is really measured in oscillation exps.?
- Majorana phases and neutrino-less DBD
- A specific model: Majorana phases @ LHC

I am not going to discuss “high-scale” phases and their effects in Leptogenesis, but restrict myself to the phenomenology of “low-scale” phases.

Outline

- Dirac vs Majorana phases
- Dirac CPV and oscillation experiments
  What is really measured in oscillation exps.?
- Majorana phases and neutrino-less DBD
- A specific model: Majorana phases @ LHC

Disclaimer: This talk is not supposed to be a general review (see extensive literature).

Instead I will give some (hopefully interesting) personal comments on the topic.

I appologize for being very sloppy with citations.

Lepton mixing

$$\mathcal{L}_{\rm CC} = -\frac{g}{\sqrt{2}} W^\rho \sum_{\alpha=e,\mu,\tau} \sum_{i=1}^{3} \bar{\nu}_{iL} \boxed{U^*_{\alpha i}} \gamma_\rho \ell_{\alpha L} + \text{h.c.}$$

$$\mathcal{L}_{\rm M} = -\frac{1}{2} \sum_{i=1}^{3} \nu^T_{iL} C^{-1} \nu_{iL} m_i^\nu - \sum_{\alpha=e,\mu,\tau} \bar{\ell}_{\alpha R} \ell_{\alpha L} m^\ell_\alpha + \text{h.c.}$$

The unitary lepton mixing matrix:

$$(U_{\alpha i}) \equiv U_{\rm PMNS} = V^{\rm Dirac}\, D^{\rm Maj}$$

$$D^{\rm Maj} = \text{diag}(e^{i\alpha_i/2})$$

Complex phases in $U_{\rm PMNS}$

there is one Dirac phase:

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

atmospheric+LBL   Chooz   solar+KamLAND

and two physical Majorana phases:

$$D^{\rm Maj} = {\rm diag}(e^{i\alpha_1/2}, e^{i\alpha_2/2}, e^{i\alpha_3/2})$$

only phase differences are physical $\Rightarrow$ can set one $\alpha_i = 0$

if $m^\nu_{\rm lightest} = 0$ there is only one physical Majorana phase

CPV in neutrino oscillations

Neutrino oscillations

Effective Hamiltonian for neutrino propagation:

$$H_{\text{eff}} = \underbrace{U\,\text{diag}\left(0, \frac{\Delta m^2_{21}}{2E_\nu}, \frac{\Delta m^2_{31}}{2E_\nu}\right) U^\dagger}_{H_{\text{vac}}} + \underbrace{\text{diag}(\sqrt{2}G_F N_e, 0, 0)}_{V^{\text{eff}}}$$

$N_e(x)$: electron density along the neutrino path

Remember: $U = V^{\text{Dirac}} D^{\text{Maj}}$

$\Rightarrow$ Majorana phases do not show up in oscillations

Neutrino oscillations in vacuum

$$P_{\nu_\alpha\to\nu_\beta} = \sum_{jk} U^*_{\alpha j} U_{\beta j} U_{\alpha k} U^*_{\beta k} \, e^{-i\Delta m^2_{jk} L/2E}$$

$$P_{\bar\nu_\alpha\to\bar\nu_\beta} = \sum_{jk} U_{\alpha j} U^*_{\beta j} U^*_{\alpha k} U_{\beta k} \, e^{-i\Delta m^2_{jk} L/2E}$$

“weak phase”: Arg$(U^*_{\alpha j} U_{\beta j} U_{\alpha k} U^*_{\beta k})$

“strong phase”: $\Delta m^2_{jk} L/2E$

Neutrino oscillations in vacuum

$$P_{\nu_\alpha\to\nu_\beta} = \sum_{jk} U^*_{\alpha j} U_{\beta j} U_{\alpha k} U^*_{\beta k} \, e^{-i\Delta m^2_{jk} L/2E}$$

$$P_{\bar\nu_\alpha\to\bar\nu_\beta} = \sum_{jk} U_{\alpha j} U^*_{\beta j} U^*_{\alpha k} U_{\beta k} \, e^{-i\Delta m^2_{jk} L/2E}$$

$$\Delta P^{CP} \equiv P_{\nu_\alpha\to\nu_\beta} - P_{\bar\nu_\alpha\to\bar\nu_\beta} \propto \mathrm{Im}(U_{\alpha j} U^*_{\beta j} U^*_{\alpha k} U_{\beta k}) \propto \sin\delta$$

$\Rightarrow$ need $\alpha \neq \beta,\ i \neq k$

only the appearance channel shows explicit CPV

CPV measurement - idealized

perform an oscillation search for

$$\nu_\alpha \longrightarrow \nu_\beta \qquad \text{and} \qquad \bar{\nu}_\alpha \longrightarrow \bar{\nu}_\beta$$

and compare the neutrino and anti-neutrino oscillation probabilities

$$\Delta P^{CP} \equiv P_{\nu_\alpha \to \nu_\beta} - P_{\bar{\nu}_\alpha \to \bar{\nu}_\beta}$$

Unfortunately, this is not the end of the story...

Realistic exps are performed in matter

$$H^{\nu}_{\text{eff}} = U\,\text{diag}\left(0, \frac{\Delta m^2_{21}}{2E_\nu}, \frac{\Delta m^2_{31}}{2E_\nu}\right) U^\dagger + \text{diag}(\sqrt{2}G_F N_e, 0, 0)$$

$$H^{\bar\nu}_{\text{eff}} = U^*\text{diag}\left(0, \frac{\Delta m^2_{21}}{2E_\nu}, \frac{\Delta m^2_{31}}{2E_\nu}\right) U^T - \text{diag}(\sqrt{2}G_F N_e, 0, 0)$$

matter potential changes sign for ν and $\bar\nu$

$\Rightarrow$ for oscillation experiments in matter:

$$P_{\nu_\alpha \to \nu_\beta} \neq P_{\bar\nu_\alpha \to \bar\nu_\beta}$$

even for real U

What is measured in an oscillation exp?

$$N_\beta^{\nu(\bar\nu)} \propto \int dE\, \Phi_\alpha^{\nu(\bar\nu)}(E)\, P_{\alpha\to\beta}^{\nu(\bar\nu)}(E)\, \sigma_\beta^{\nu(\bar\nu)}(E)$$

- neutrino fluxes Φ are different for ν and $\bar\nu$
- detection cross sections σ are different for ν and $\bar\nu$

systematic uncertainties on Φ and σ can have a dramatic impact on the CPV sensitivity Huber, Mezzetto, Schwetz, 07

- $P_{\alpha\to\beta}$ is affected by matter effects

What is measured in an oscillation exp?

In order to "establish CPV" in neutrino oscillations one

- has to input a lot of prior knowledge on fluxes, cross sections,...,
- assumes that the matter effect is known,
- assumes standard unitary 3-flavour mixing,

and then extracts information on δ by performing a parametric fit to (spectral) data.

What is measured in an oscillation exp?

This is very different from direct CPV in meson decays:

$$\mathcal{A}_{\rm CP} = \frac{\Gamma(M \to f) - \Gamma(\bar{M} \to \bar{f})}{\Gamma(M \to f) + \Gamma(\bar{M} \to \bar{f})}$$

Such a model independent measurement of CPV seems not to be possible in the lepton sector.

How to define CPV in the presence of NP?

Example:

There might be new interactions of neutrinos, affecting production, propagation and detection, including also additional CP phases

Gonzalez-Garcia, Grossman, Gusso, Nir, 01; and many more

see also talk of M. Lindner

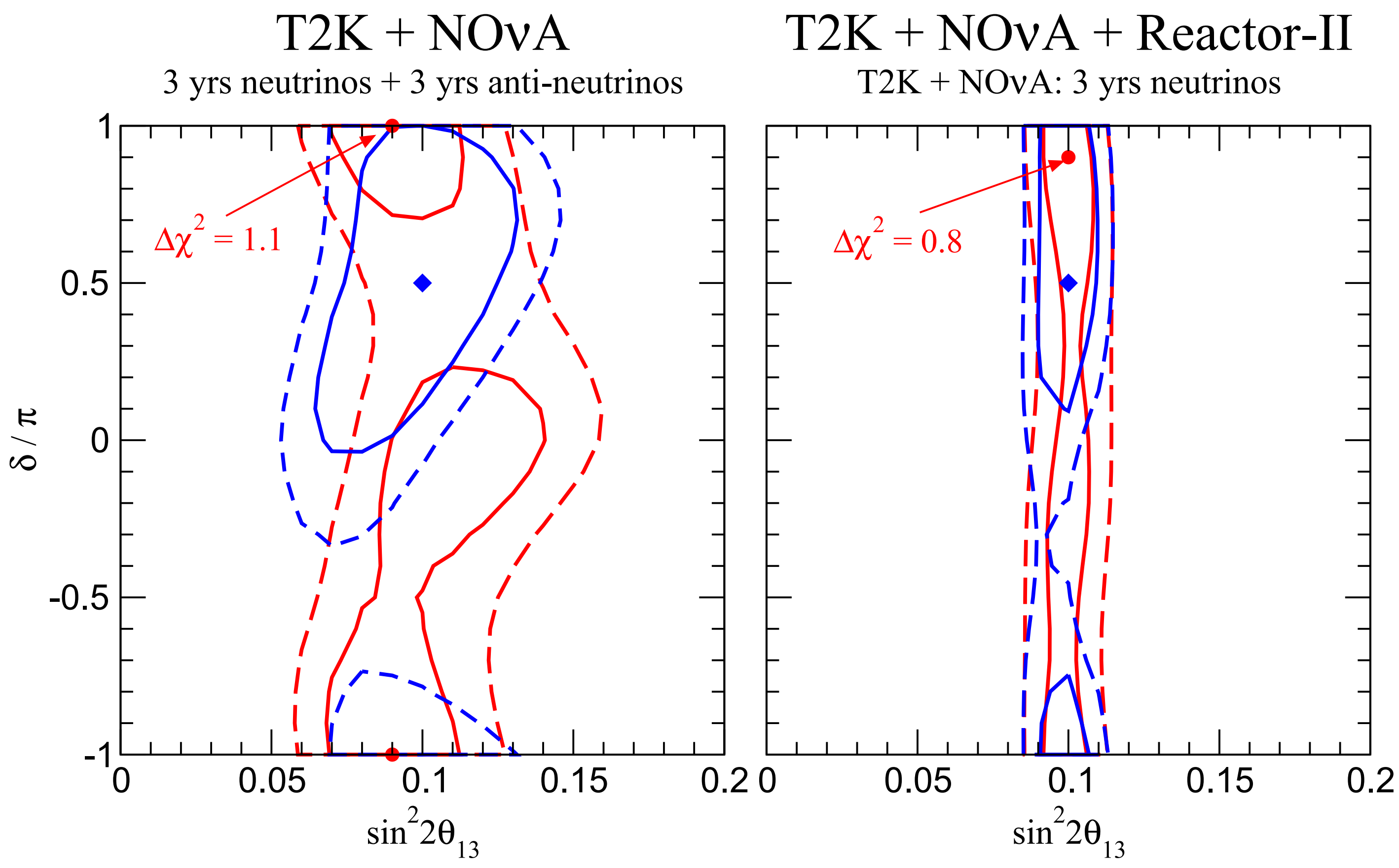
It seems difficult to define an observable in order to establish CPV in a model independent way allowing for unspecified new physics.

NP may change matter effect in intrinsically CP conserving way.

Assuming standard 3-flavour oscillations...

Upcoming experiments?

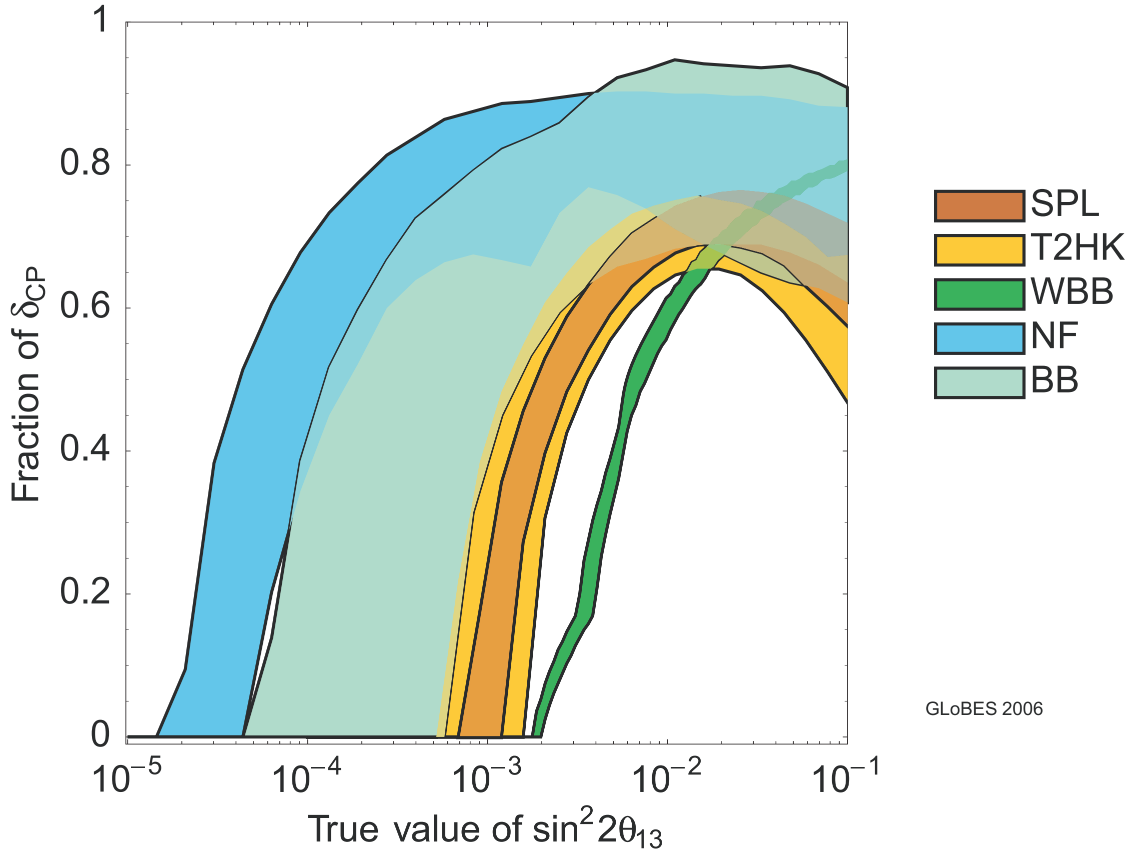
even for $\sin^2 2\theta_{13} = 0.1$ upcoming experiments (T2K, NOνA, D-Chooz, Daya Bay) cannot establish CPV



Huber, Lindner, Rolinec, Schwetz, Winter, 04

CPV sensitivities of future projects

ability to exclude $\delta = 0, \pi$ at 3σ, based on the observation of $\nu_\mu \to \nu_e$ (or $\nu_e \to \nu_\mu$) for ν and $\bar{\nu}$



Future oscillation facilities:

Superbeams (T2K, SPL, WBB)

Beta Beams

Neutrino factories

ISS Physics Working Group 0710.4947

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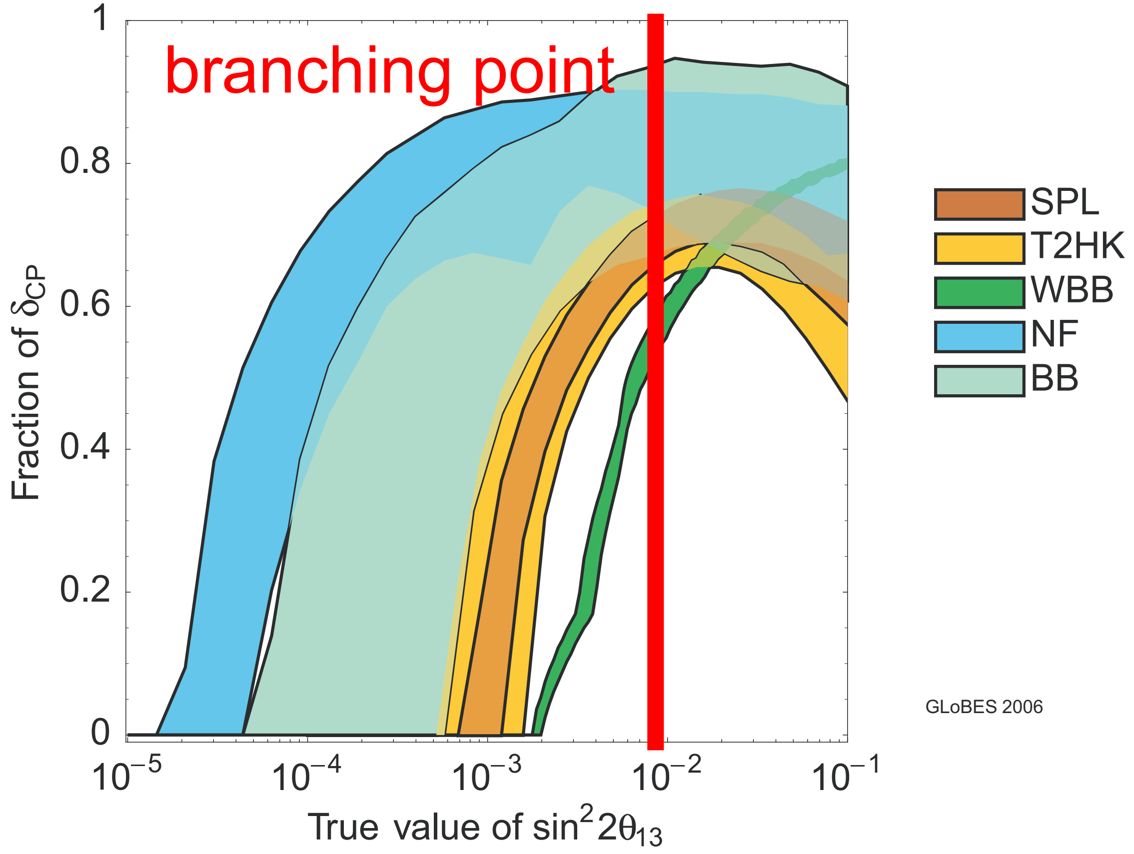

Future oscillation facilities:

Superbeams (T2K, SPL, WBB)

Beta Beams

Neutrino factories

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Can we use CP + T = CPT ?

T-violation in theory

In vacuum: $P_{\nu_\alpha\to\nu_\beta} = P_{\bar\nu_\beta\to\bar\nu_\alpha}$ (CPT)

for symmetric matter profile:

$$P_{\nu_\alpha\to\nu_\beta}(\delta) = P_{\nu_\beta\to\nu_\alpha}(-\delta)$$

hence:

$$\Delta P^T \equiv P_{\nu_\alpha\to\nu_\beta} - P_{\nu_\beta\to\nu_\alpha}$$

is not affected by matter effect!

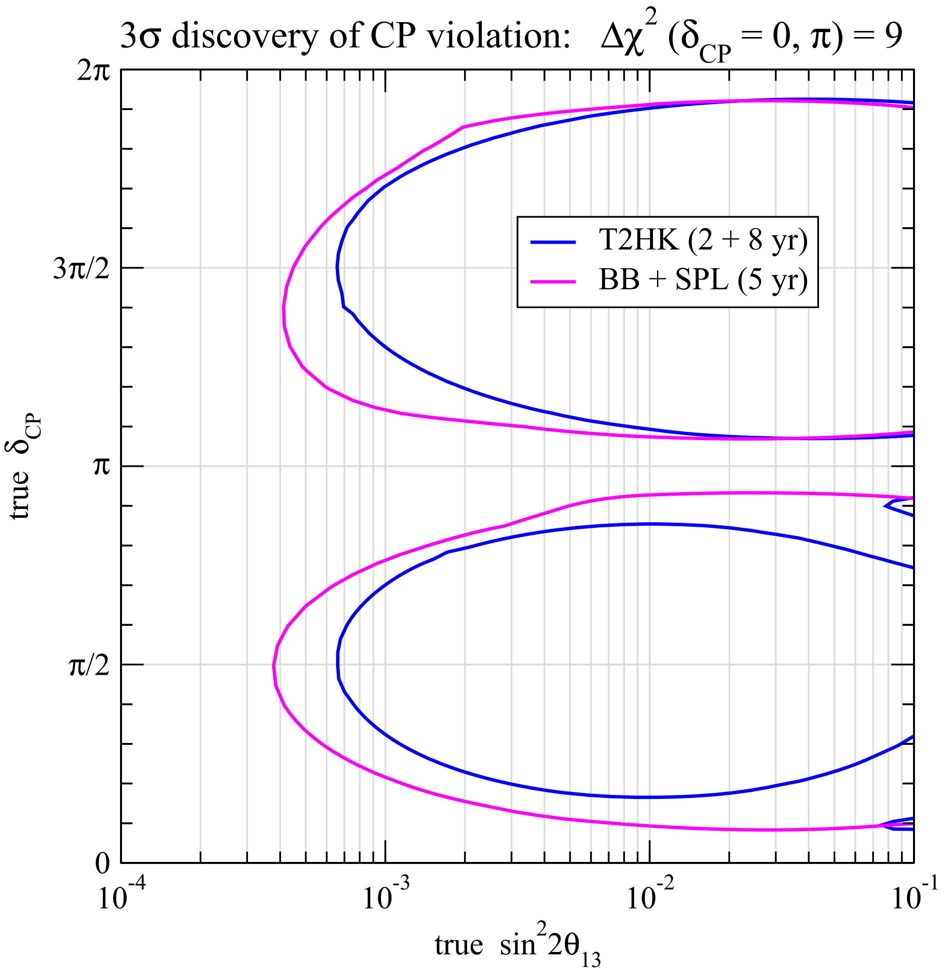
T-violation in practice

- need intense sources of ν_μ AND ν_e, and a detector capable of measuring ν_e AND ν_μ, using the same baseline
- have to compare two completely different experiments (problem of systematics)

- can do the measurment without an anti-neutrino experiment
- can do the measurment in half of the running time

T vs CP violation

CERN SPL superbeam ($\nu_\mu \to \nu_e$) + CERN beta beam ($\nu_e \to \nu_\mu$) + 0.5 Mt water Cerenkov detector at Frejus (130 km)



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

CP-even observables

CP-even observable - 1

explore the energy dependence of $P_{\nu_\mu\to\nu_e}(\delta)$:

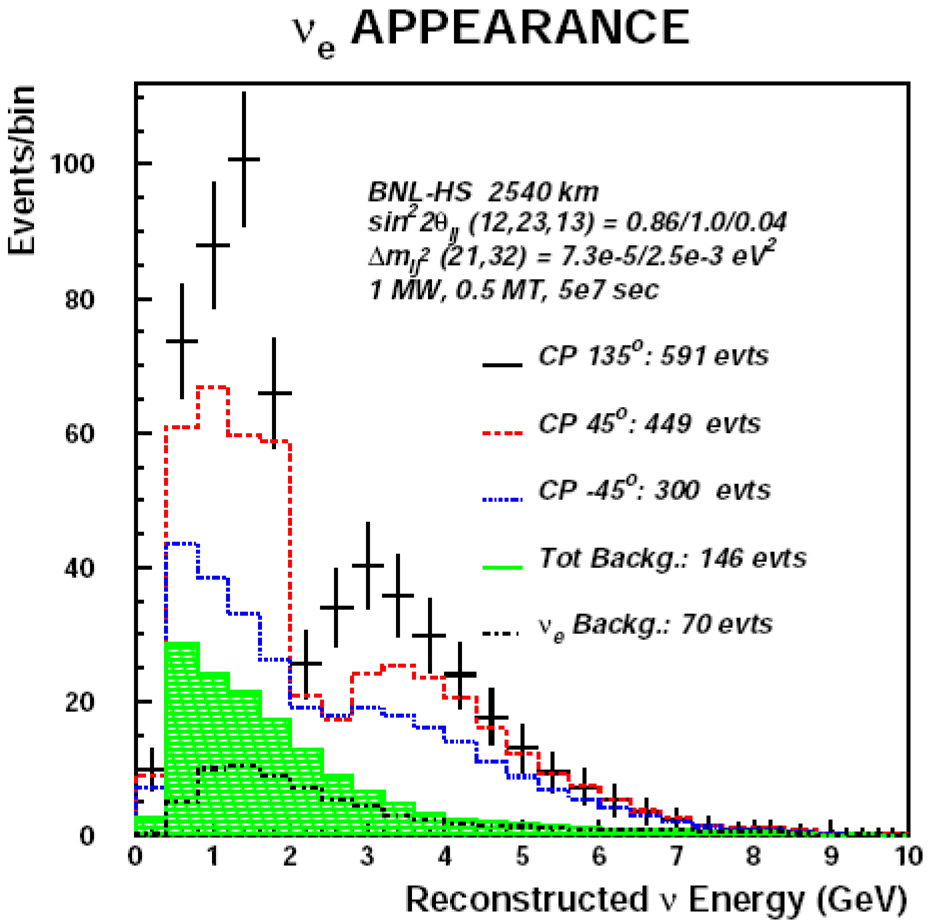
$$
\begin{aligned}
P_{\mu e} \;\simeq\;& \sin^2 2\theta_{13}\, \sin^2\theta_{23}\, \frac{\sin^2(1-A)\Delta}{(1-A)^2} \\
&+ \sin 2\theta_{13}\, \hat{\alpha}\, \sin 2\theta_{23}\, \frac{\sin(1-A)\Delta}{1-A}\, \frac{\sin A\Delta}{A}\, \cos(\Delta+\delta_{\mathrm{CP}}) \\
&+ \hat{\alpha}^2\, \cos^2\theta_{23}\,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

with

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

CP-even observable - 1

explore the energy dependence of $P_{\nu_\mu\to\nu_e}(\delta)$:



M.V. Diwan et al., hep-ph/0303081

CP-even observable - 2

leptonic unitarity triangle

Farzan, Smirnow, hep-ph/0201105

have to measure $|U_{\alpha i}|$ precisely (with acc. $\lesssim \theta_{13}$)
$\Rightarrow$ disappearance experiments

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

very difficult in practice, in particular:

to measure $|U_{\mu 1}|$ and $|U_{\mu 2}|$ seperately one has to be sensitive to Δm^2_{21} in $\nu_\mu \to \nu_\mu$ oscillations

CP-even observable - 2

ν_μ disappearance channel:

$$P_{\nu_\mu\to\nu_\mu} \text{ contains terms } \propto \frac{\Delta m^2_{21}}{\Delta m^2_{31}} \sin\theta_{13} \cos\delta$$

e.g., Kimura, Takamura, Yoshikawa, 0711.1567, 0803.0787

very difficult in practice:

to be sensitive to Δm^2_{21} in $\nu_\mu \to \nu_\mu$ oscillations
$\Rightarrow$ go to very low energies/long baselines

Is there hope to measure Majorana phases?

Majorana phases

need processes related to the Majorana nature of neutrino masses

$\Rightarrow$ neutrinoless double-beta decay

$$|\langle m\rangle| = \left|\sum_i U_{ei}^2 m_i\right| \qquad (U_{\mathrm{PMNS}} = V^{\mathrm{Dirac}} D^{\mathrm{Maj}})$$

depends on Majorana phases

- in practice only on $\alpha_{21} \equiv \alpha_2 - \alpha_1$

(α_{31} dependence is suppressed by U_{e3})

Majorana phases and neutrinoless DBD

$$|\langle m\rangle| = \left|\sum_i U_{ei}^2 m_i\right|$$ is a CP-even observable

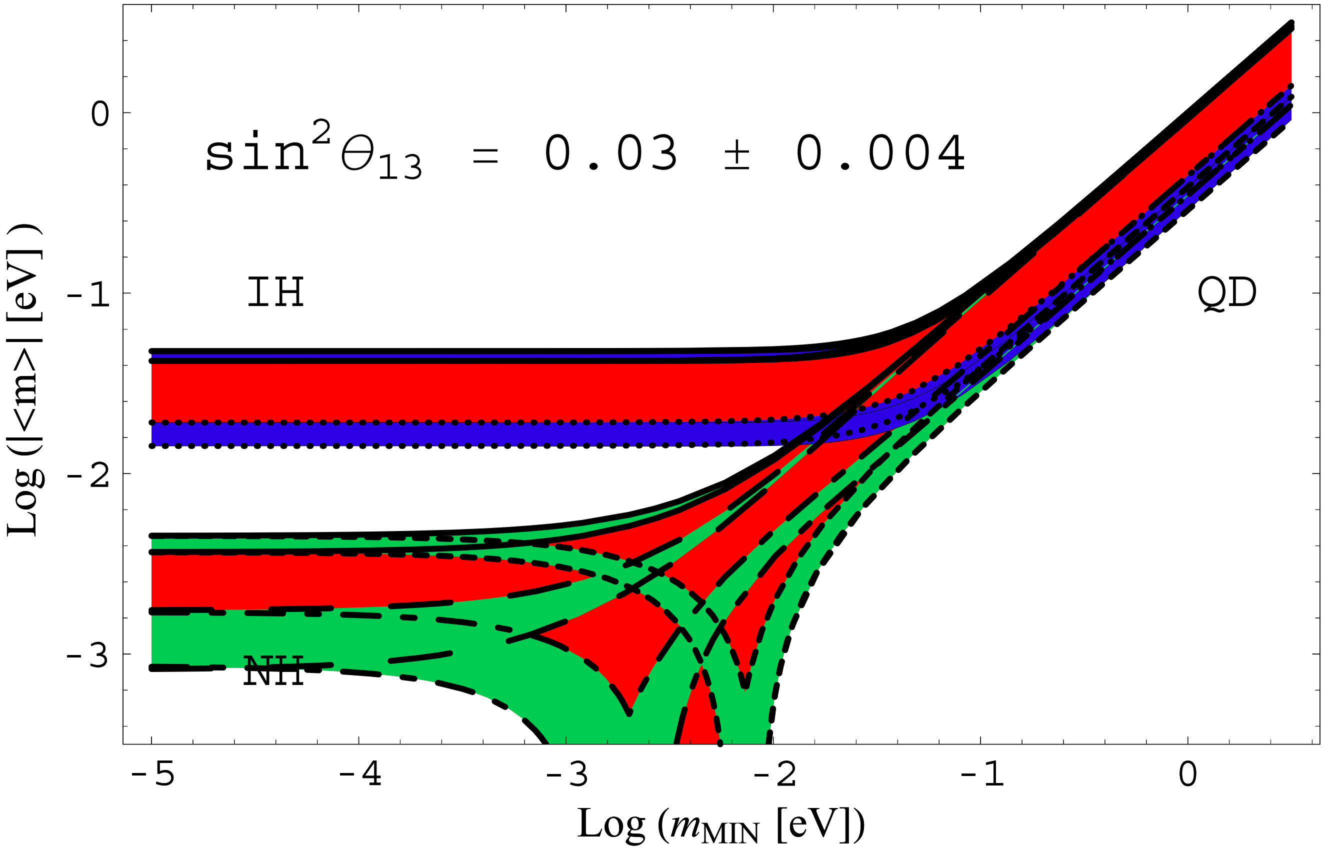
consider a hypothetical neutrinoless DBD experiment with anti-nuclei:

$$|\langle \bar m\rangle| = \left|\sum_i U_{ei}^{*2} m_i\right|$$

and hence $|\langle m\rangle| = |\langle \bar m\rangle|$ (there is no "strong phase")

deGouvea, Kayser, Mohapatra, hep-ph/0211394

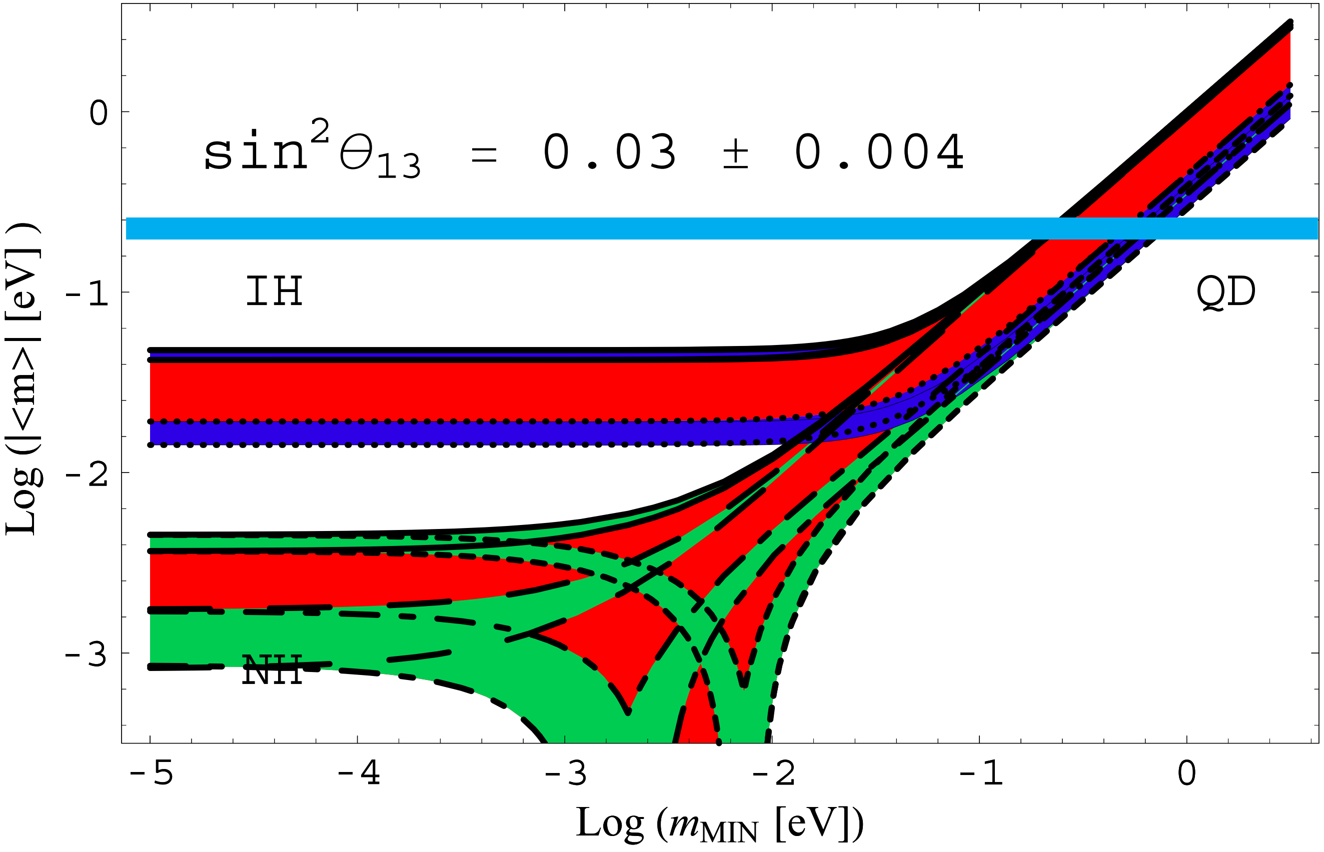
Majorana phases and neutrinoless DBD



Pascoli, Petcov, Schwetz, 05, and many more

need to establish experimentally a point within the red regions in order to prove CP violating values of α_{21}

Majorana phases and neutrinoless DBD



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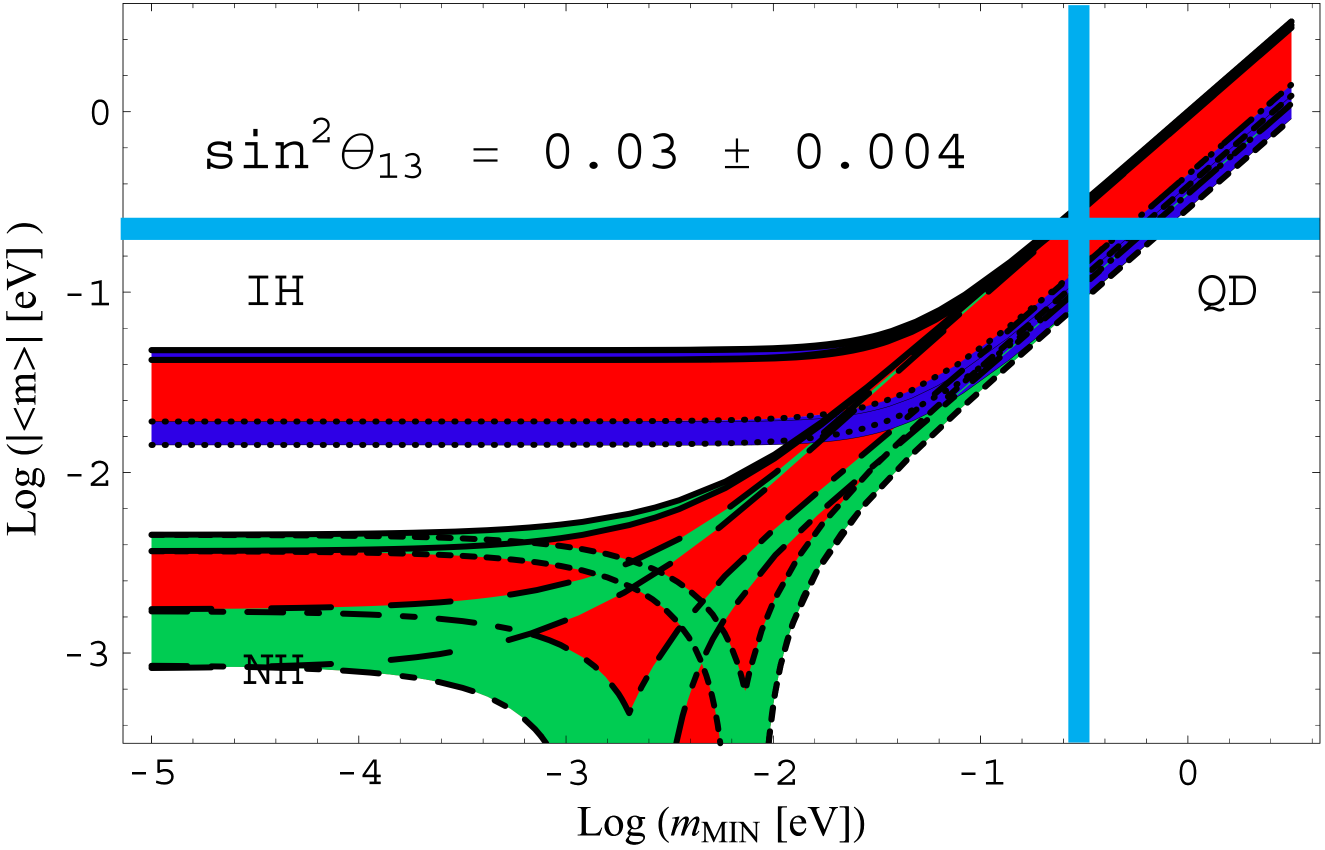
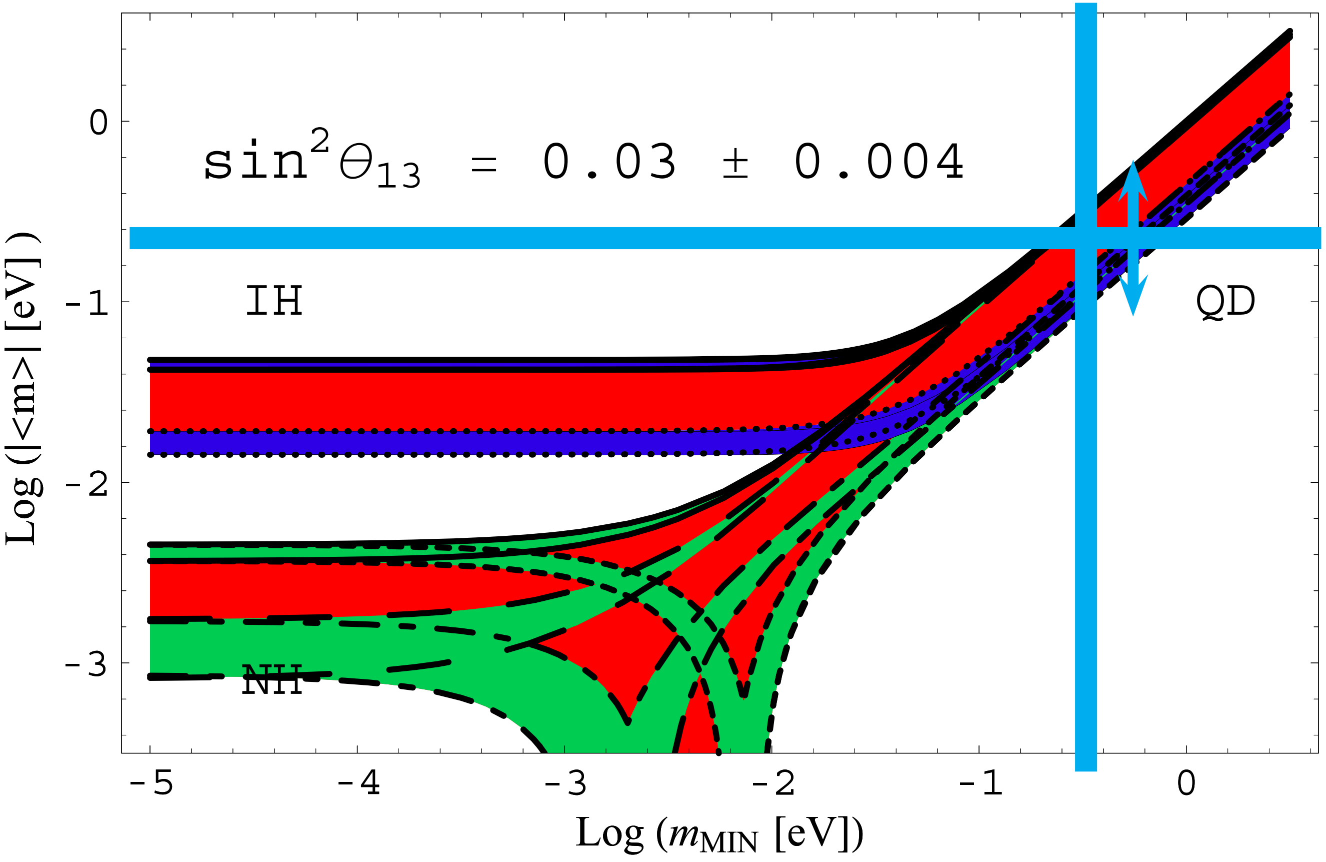
Majorana phases and neutrinoless DBD



Pascoli, Petcov, Schwetz, 05, and many more

need an independent determination of lightest neutrino mass

Majorana phases and neutrinoless DBD

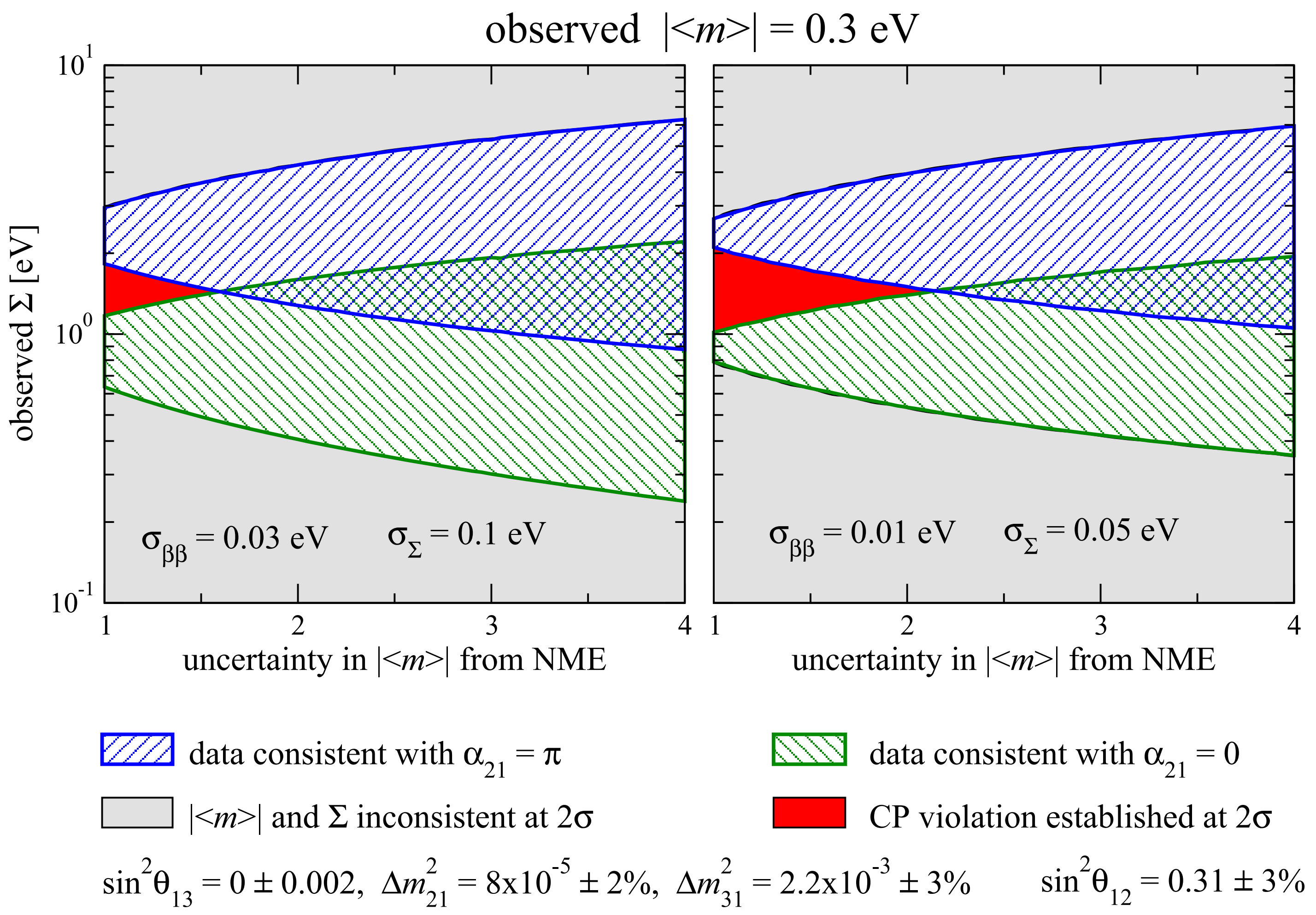


Pascoli, Petcov, Schwetz, 05, and many more

uncertainty on nuclear matrix element is crucial

Majorana phases and neutrinoless DBD

combining measurements of $|\langle m \rangle|$ and Σ from cosmology:



Pascoli, Petcov, Schwetz, 05

Majorana phases and neutrinoless DBD

- maybe there is no no-go theorem

  Barger, Glashow, Langacker, Marfatia, 02

  but it is VERY difficult!

- need to rely on nuclear matrix element calculations
- need precise complementary neutrino mass measurement
  - can we trust in cosmology at that level?
  - seems difficult to achieve the required precision with beta-decay endpoint experiments (KATRIN)

Majorana phases in a specific model

The Higgs triplet model

$$\mathcal{L}_\Delta = f_{ab}\, L_a^T C^{-1}\, i\tau_2 \Delta\, L_b + \text{h.c.} \qquad (a, b = e, \mu, \tau)$$

with the SU(2) triplet $$\Delta = \begin{pmatrix} H^+/\sqrt{2} & H^{++} \\ H^0 & -H^+/\sqrt{2} \end{pmatrix}$$

VEV of the neutral component $\langle H^0 \rangle \equiv v_T/\sqrt{2}$ induces a Majorana mass term for the neutrinos:

$$\frac{1}{2}\nu_{La}^T C^{-1} M_{ab}\, \nu_{Lb} + \text{h.c.} \qquad \text{with} \qquad M_{ab} = \sqrt{2}\, v_T\, f_{ab}\,.$$

Doubly charged scalars at the LHC

if the triplet is light enough it can be seen at LHC via like-sign lepton events:

$$q\bar{q} \to H^{++} H^{--} \to \ell^+ \ell^+ \, \ell^- \ell^-$$

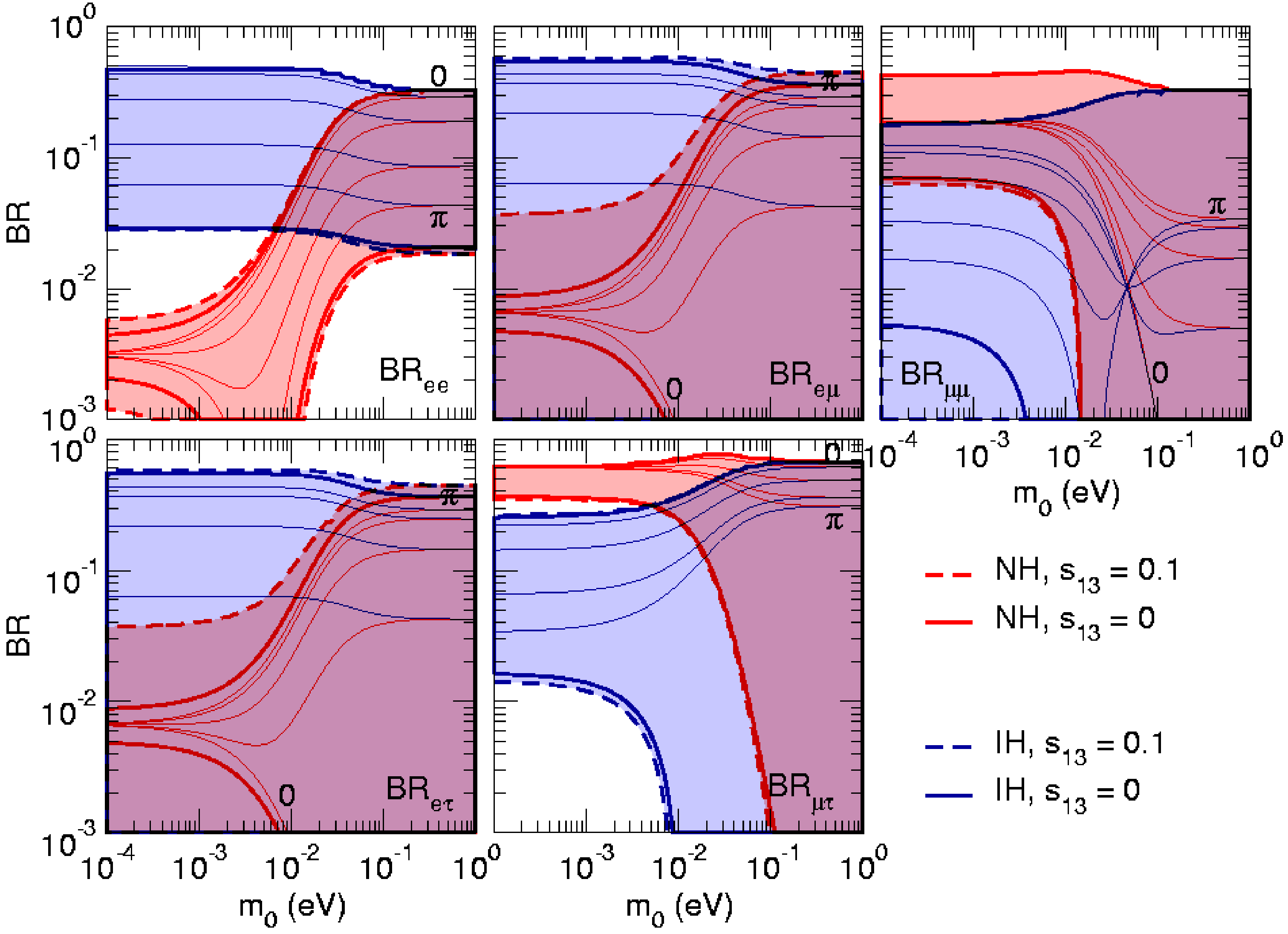
$\sigma \simeq$ 100 fb for $M_{H^{++}} = 200$ GeV $\to$ 0.1 fb for $M_{H^{++}} = 900$ GeV

e.g., Han, Mukhopadhyaya, Si, Wang, 0706.0441

decay rate is proportional to the neutrino mass matrix:

$$\Gamma(H^{++} \to \ell_a^+ \ell_b^+) = \frac{1}{4\pi(1+\delta_{ab})} |f_{ab}|^2 M_{H^{++}} \propto |M_{ab}|^2$$

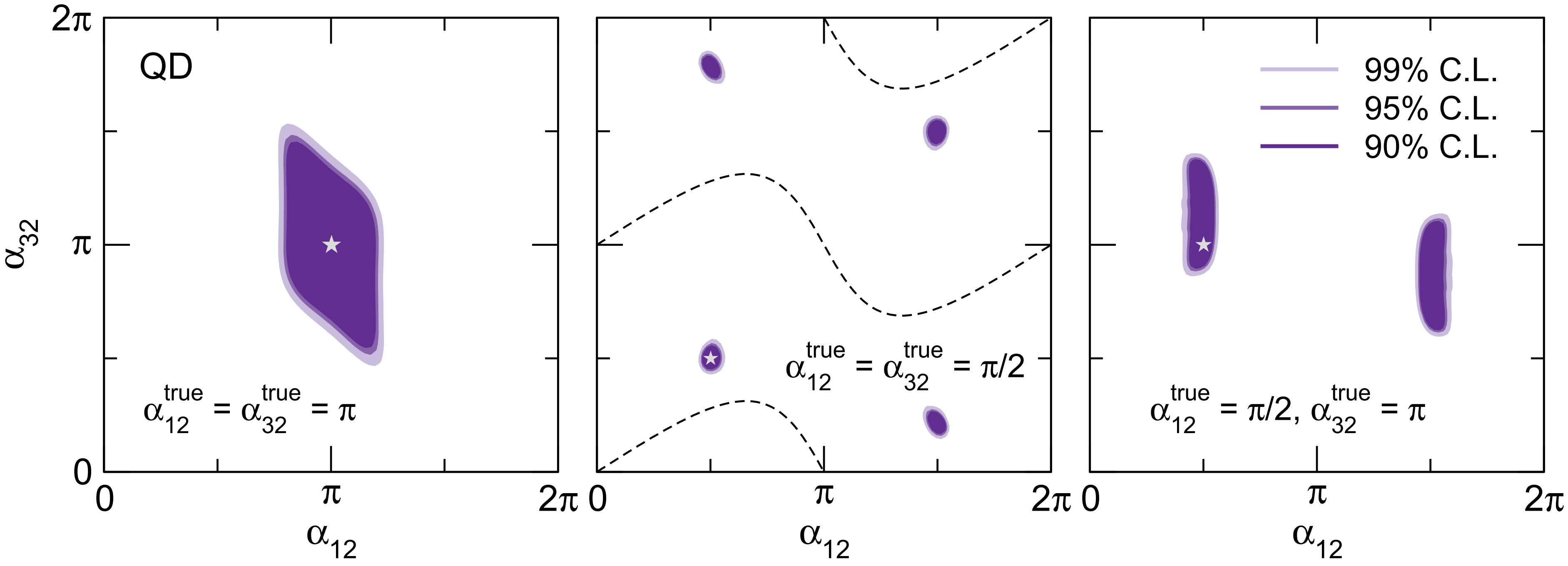
$H^{++} \rightarrow \ell_a^+ \ell_b^+$ ***branching ratios***



Measuring Majorana phases at LHC

1000 doubly charged Higgs events

QD neutrino mass spectrum ($m_0 = 0.15$ eV)



Garayoa, Schwetz, 0712.1453

see also, Akeroyd, Aoki, Sugiyama, 0712.4019; Kadastik, Raidal, Rebane, 0712.3912

Measuring Majorana phases at LHC

the decay

$$H^{\pm\pm} \to \ell_a^{\pm}\ell_b^{\pm} \qquad \propto |M_{ab}|^2$$

is CP-even! (decay at tree-level, no “strong phase”)

$\Rightarrow$ no explicit CP violation due to Majorana phases

Conclusions

Conclusions

- Dirac CPV: main goal of future oscillation facilities:
  $\sin^2 2\theta_{13} \gtrsim 0.01$: many options (SB, BB, LENF)
  $\sin^2 2\theta_{13} \lesssim 0.01$: only NuFact?
- It is very difficult to establish CPV in oscillations in a model-independent way ⇒ parametric fit for δ including a lot of assumptions
- Majorana phases (model-indep.): the only remote chance is neutrinoless double-beta decay + independent neutrino mass determination
- Majorana phases (model-dep.): specific models may provide additional observables
  Ex.: Higgs-triplet @ LHC

Thank you for your attention