# A new approach to anti-neutrino running in long baseline neutrino oscillation experiments


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work done in collaboration with

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arXiv:1005.4055[hep-ph]

# Then and Now

**Then (1930): Pauli**

**I have hit upon a desperate remedy to save the exchange theorem and the conservation of energy. Namely, the possibility that there could exist electrically neutral spin $\frac{1}{2}$ particles of small mass ....**

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## Now (2004): APS Neutrino Study Group

Much of what we know about neutrinos we have learned in the last six years. .... We have so many new questions, ... We are most certain of one thing : neutrinos will continue to surprise us ....

# Neutrino : “NU” Horizons

Solar, atmospheric, reactor and accelerator neutrino oscillation experiments over the last four decades have firmly established the phenomenon of neutrino oscillation

Neutrino oscillation happens only if there is a mass difference between at least two neutrinos, an observation of this effect proves that at least one non-zero neutrino mass exists

Neutrinos are strictly massless in the Standard Model and the finite neutrino masses required by the experimental data provide the first hint for physics beyond the Standard Model, and make an extension of the theory necessary

# Neutrino : “NU” Horizons

LHC is running and we hope that the light of new discoveries will break apart our long-held picture of the Standard Model

Recent discoveries on neutrinos might provide unique information on a more complete theory of elementary particles

Sensitivity of neutrino experiments to very tiny mass scales might provide the scope to learn something about physics at very high energy scales (i.e., at very small distances), which will never be accessible in particle accelerator experiments

Precision neutrino physics is very important and complementary to LHC and it may provide a key to a so-called Grand Unified Theory

# Present Status

| Parameter | Best fit | $3\sigma$ (1 d.o.f) |
|---|---|---|
| $\Delta m^2_{21}$ $[10^{-5}\ eV^2]$ | **7.59** | **7.03–8.27** |
| $\lvert\Delta m^2_{31}\rvert$ $[10^{-3}\ eV^2]$ | **2.4** | **2.07–2.75** |
| $\sin^2\theta_{12}$ | **0.318** | **0.27–0.38** |
| $\sin^2\theta_{23}$ | **0.50** | **0.36–0.67** |
| $\sin^2\theta_{13}$ | **0.013** | $\leq$ **0.053** |

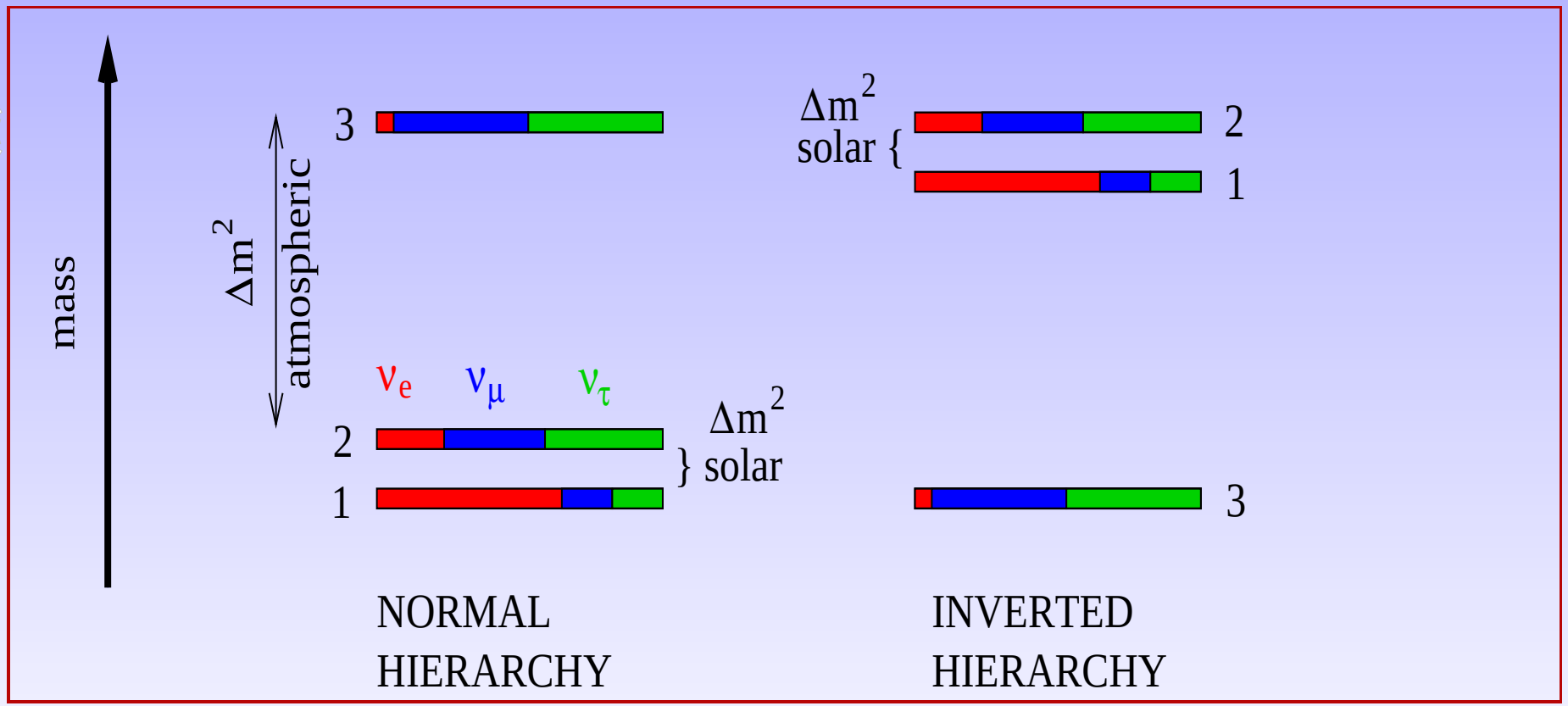
T. Schwetz, M.A. Tortola, J.W.F. Valle, arXiv:0808.2016v3

**Best-fit values under 3 flavour scheme**

**Data from Solar + Atmospheric + Reactor (KamLAND and CHOOZ) + Accelerator (K2K and MINOS) expts**

# Unsolved Issues & Motivations

- **The sign of $\Delta m^2_{31}$ $(m_3^2 - m_1^2)$ is not known.**
  **Neutrino mass spectrum can be normal or inverted hierarchical**



# Importance of $sgn(\Delta m^2_{31})$

- It dictates the structure of the neutrino mass matrix
- Could give vital clues towards the underlying theory of neutrino masses and mixing
- If $\Delta m^2_{31} < 0$, and yet no neutrino-less double beta-decay is observed even in the very far future experiments, that would be a strong hint that the neutrinos are not Majorana particles

# Unsolved Issues & Motivations

**Only an upper limit on**

$\sin^2 2\theta_{13}$ ($\leq 0.2$ **at** $3\sigma$) **exists**

**CHOOZ and Palo Verde play crucial role**

**Recent review on $\theta_{13}$ : Mezzetto, Schwetz, arXiv:1003.5800 [hep-ph]**

# Why $\theta_{13}$ is so important?

- Discovery of a non-zero value for $\theta_{13}$ would open up the possibility of observing CP-violation in the neutral lepton sector
- Non-zero $\theta_{13}$ also brings in the possibility of large Earth matter effects for GeV energy accelerator neutrinos traveling over long distances
- It acts as a powerful discriminator between various neutrino mass models

# Unsolved Issues & Motivations

**The Dirac CP phase ($\delta_{CP}$) is unconstrained**

**CP-odd asymmetries :**

$$\Delta P_{ab} \equiv P(\nu_a \to \nu_b;\, t) - P(\bar{\nu}_a \to \bar{\nu}_b;\, t)$$

$$\Delta P_{e\mu} = \Delta P_{\mu\tau} = \Delta P_{\tau e} = 4 s_{12}\, c_{12}\, s_{13}\, c_{13}^2\, s_{23}\, c_{23}\, \sin\delta \times \left[\sin\left(\frac{\Delta m_{12}^2}{2E} t\right) + \sin\left(\frac{\Delta m_{23}^2}{2E} t\right) + \sin\left(\frac{\Delta m_{31}^2}{2E} t\right)\right]$$

**Two large mixing angles + the relative oscillation frequencies open the possibility to test CP violation if $\theta_{13}$ and $\delta_{CP}$ are not vanishingly small**

# Why CP phases are crucial?

- The low energy CP violation in the neutral lepton sector might be related with the observed matter anti-matter asymmetry (baryon asymmetry) in the universe

- It plays a crucial role in making distinctions between various neutrino mass models

# Upcoming experiments

## Upcoming superbeam and reactor experiments

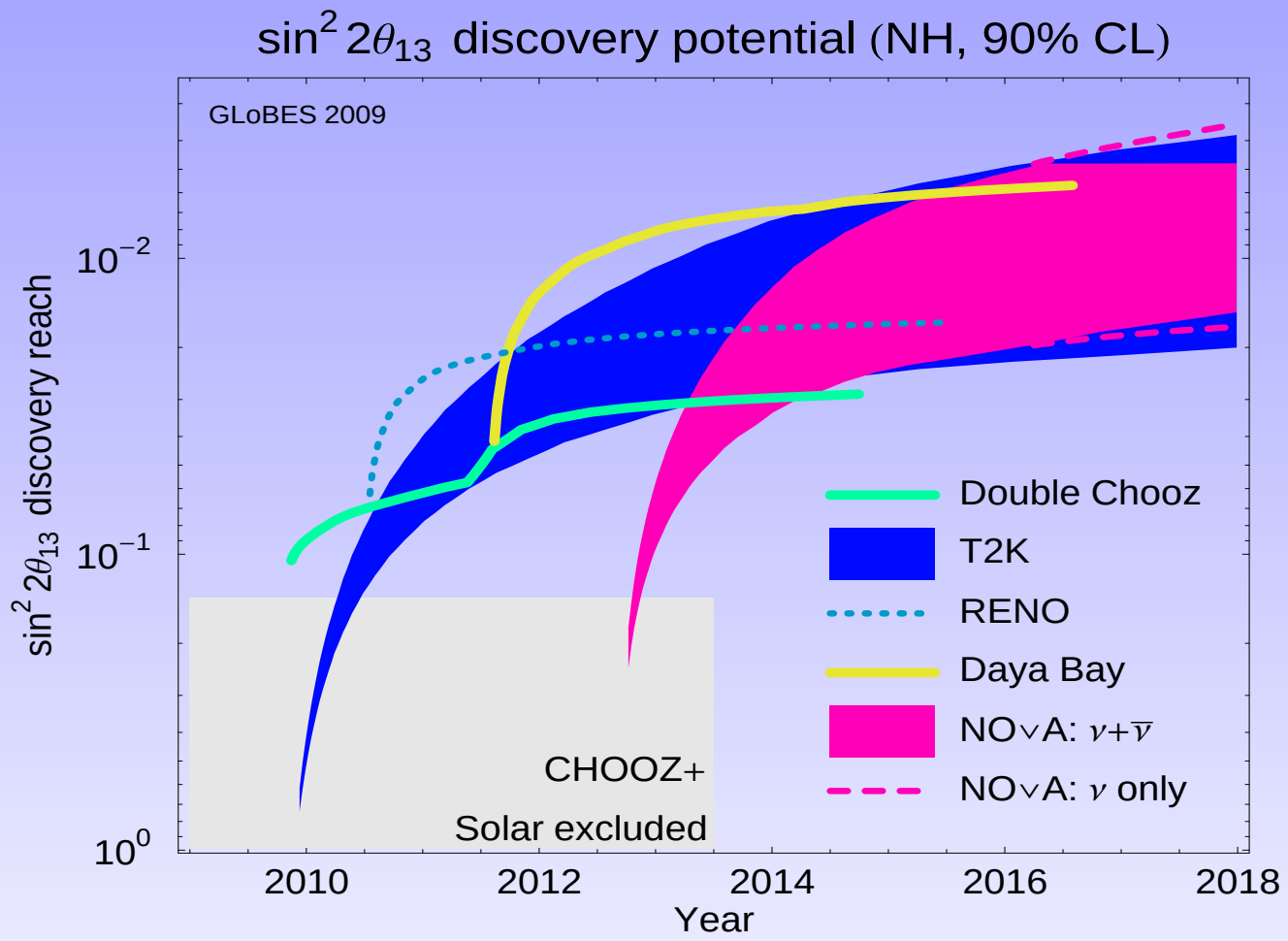
| Setup | $t_\nu$ [yr] | $t_{\bar{\nu}}$ [yr] | $P_{\rm Th}$ or $P_{\rm Target}$ | $L$ [km] | Detector tech | $m_{\rm Det}$ |
|---|---|---|---|---|---|---|
| Double Chooz | - | 3 | 8.6 GW | 1.05 | Liquid scint | 8.3 t |
| Daya Bay | - | 3 | 17.4 GW | 1.7 | Liquid scint | 80 t |
| RENO | - | 3 | 16.4 GW | 1.4 | Liquid scint | 15.4 t |
| T2K | 5 | - | 0.75 MW | 295 | Water Cerenkov | 22.5 kt |
| NO$\nu$A | 3 | 3 | 0.7 MW | 810 | TASD | 15 kt |

## Standard set-ups at their nominal luminosities

P. Huber *et al.*, arXiv:0907.1896 [hep-ph]

# $\sin^2 2\theta_{13}$ discovery

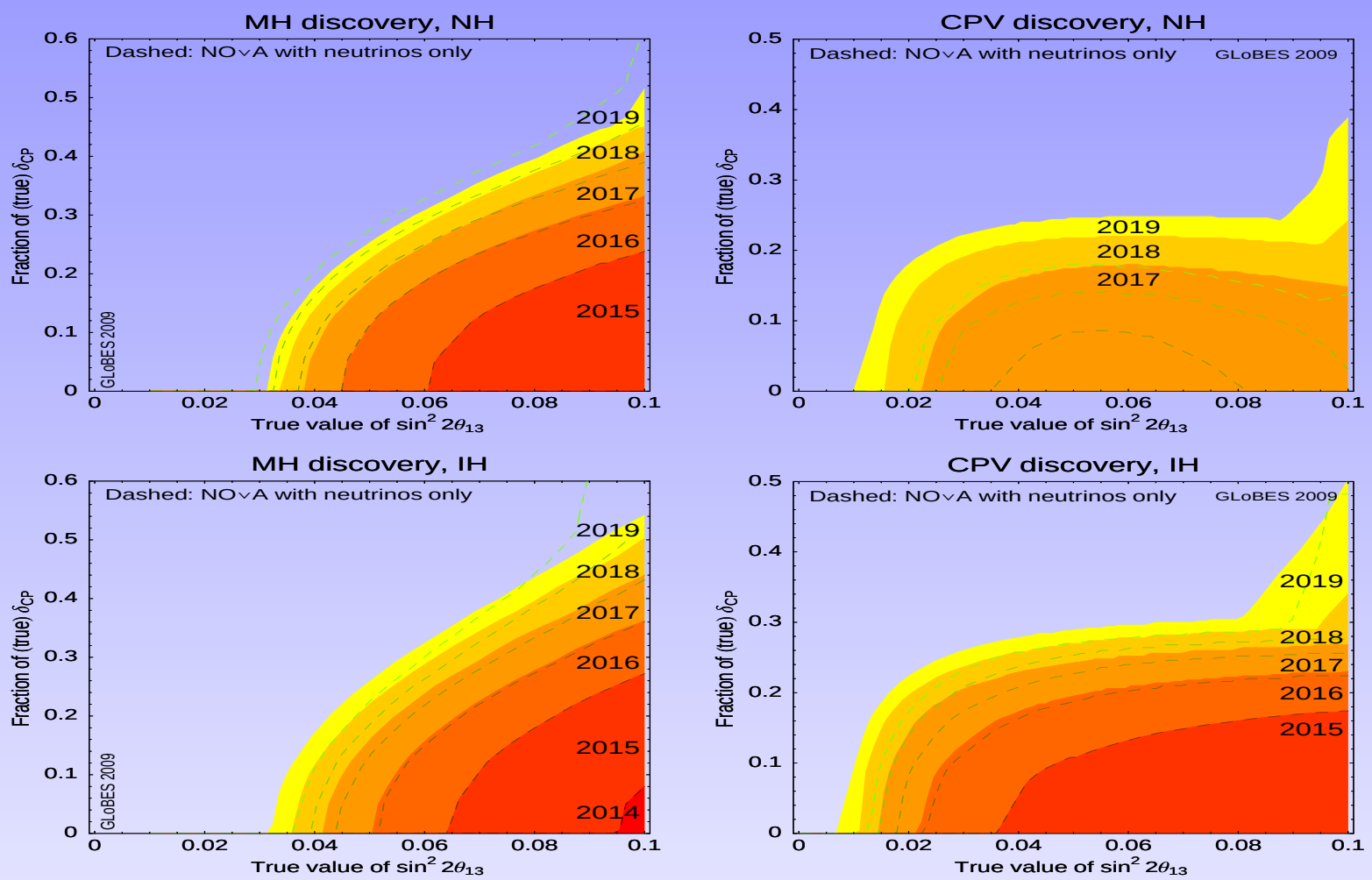
## Time evolution of physics reach




**Bands reflect the (unknown) true value of $\delta_{CP}$**

P. Huber *et al.*, arXiv:0907.1896 [hep-ph]

# MH & CPV discovery




**MH & CPV discovery at 90% C.L. with T2K, NO$\nu$A and reactor data**

P. Huber *et al.*, arXiv:0907.1896 [hep-ph]

# Ultimate Message

- Global sensitivity to CPV and the MH of all experiments with nominal exposures is marginal
- For the largest allowed values of $\theta_{13}$, typically a hint at 90% CL can be obtained for about 25% to 50% of all possible values of $\delta_{CP}$, while almost nothing can be said at $3\sigma$
- Minor upgrades of existing facilities may provide a non-negligible sensitivity to CP violation and the mass hierarchy
- High risk associated with this strategy, since for about 75% of all possible values for $\delta_{CP}$ no discovery will be possible at the $3\sigma$ level

# What we need?

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- Large Statistics

  Intense, powerful, clean neutrino beams with known energy spectrum

  Large, efficient, smart Mton class detectors with good energy resolution and background rejection capability

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  Intense, powerful, clean neutrino beams with known energy spectrum

  Large, efficient, smart Mton class detectors with good energy resolution and background rejection capability

- **Right choice of channel or combinations**

  Golden ($\nu_e \to \nu_\mu$ and $\bar{\nu}_e \to \bar{\nu}_\mu$)
  Silver ($\nu_e \to \nu_\tau$ and $\bar{\nu}_e \to \bar{\nu}_\tau$)
  Platinum ($\nu_\mu \to \nu_e$ and $\bar{\nu}_\mu \to \bar{\nu}_e$)

# What we need?

- Reduced Systematical Uncertainties

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  Near-far two detector set-up is very useful

- Low Backgrounds
  - Intrinsic beam backgrounds can be reduced by careful design of the beam stop or using mono-flavor beam
  - Detector backgrounds coming mainly from NC interactions and mis-id of particles, can be reduced by imposing suitable cuts
  - Atmospheric neutrino backgrounds can be suppressed using timing and directionality

# Platinum Channel ($P_{\mu e}$)

**The appearance probability** $(\nu_\mu \to \nu_e)$ **in matter, upto second order in the small parameters** $\alpha \equiv \Delta m^2_{21}/\Delta m^2_{31}$ **and** $\sin 2\theta_{13}$**,**

$$
\begin{aligned}
P_{\mu e} \simeq & \sin^2 2\theta_{13} \sin^2\theta_{23} \frac{\sin^2[(1-\hat{A})\Delta]}{(1-\hat{A})^2} \\
- & \alpha \sin 2\theta_{13}\, \xi \sin\delta_{CP} \sin(\Delta) \frac{\sin(\hat{A}\Delta)}{\hat{A}} \frac{\sin[(1-\hat{A})\Delta]}{(1-\hat{A})} \\
+ & \alpha \sin 2\theta_{13}\, \xi \cos\delta_{CP} \cos(\Delta) \frac{\sin(\hat{A}\Delta)}{\hat{A}} \frac{\sin[(1-\hat{A})\Delta]}{(1-\hat{A})} \\
+ & \alpha^2 \cos^2\theta_{23} \sin^2 2\theta_{12} \frac{\sin^2(\hat{A}\Delta)}{\hat{A}^2};
\end{aligned}
$$

**where** $\Delta \equiv \Delta m^2_{31} L/(4E)$**,** $\xi \equiv \cos\theta_{13} \sin 2\theta_{21} \sin 2\theta_{23}$**,**
**and** $\hat{A} \equiv \pm(2\sqrt{2} G_F n_e E)/\Delta m^2_{31}$

**Freund, Huber, Lindner, hep-ph/0105071**

# Eight-fold Degeneracy

- $(\theta_{13}, \delta_{CP})$ **intrinsic degeneracy**

  Burguet-Castell, Gavela, Gomez-Cadenas, Hernandez, Mena, hep-ph/0103258

- $(sgn(\Delta m^2_{31}), \delta_{CP})$ **degeneracy**

  Minakata, Nunokawa, hep-ph/0108085

- $(\theta_{23}, \pi/2 - \theta_{23})$ **degeneracy**

  Fogli, Lisi, hep-ph/9604415

**Severely deteriorates the sensitivity**

# Problem & Solution

Degeneracies create "Clone" Solutions

Barger, Marfatia, Whisnant, hep-ph/0112119

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Barger, Marfatia, Whisnant, hep-ph/0112119

$P_{\mu e} \Rightarrow$ SuperBeam

$P_{e\mu} \Rightarrow$ Beta Beam

$P_{e\mu} \Rightarrow$ Neutrino Factory

Need smart ideas to play with these channels

# Solutions

- Combine data from appearance expts at different $L$ and/or different $E$

Barger, Marfatia, Whisnant, hep-ph/0206038

Barger, Marfatia, Whisnant, hep-ph/0210428

Burguet-Castell et al, hep-ph/0103258

Huber, Lindner, Winter, hep-ph/0211300

Mena and Parke, hep-ph/0408070

and there are others also ...

# Solutions

**Add data from different channels**

- **The Silver Channel, $P_{e\tau}$**

  Autiero et al, hep-ph/0305185

  Donini, Meloni, Migliozzi, hep-ph/0206034

- **The Disappearance Channel, $P_{\mu\mu}$**

  Donini, Fernandez-Martinez, Meloni, Rigolin, hep-ph/0512038

  Donini, Fernandez-Martinez, Rigolin, hep-ph/0411402

- **Adding reactor antineutrino data**

  Huber, Lindner, Schwetz, Winter, hep-ph/0303232

# Solutions

- **Adding atmospheric neutrino data**

  Huber, Maltoni, Schwetz, hep-ph/0501037

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

- **Kill the "Clones" at the "Magic" Baseline**

$$L_{\text{magic}} = 7690 \text{ km}$$

The $\delta_{CP}$ dependence disappears from $P_{e\mu}$

It enables a clean determination of $\theta_{13}$ and $sgn(\Delta m^2_{31})$

Huber, Winter, hep-ph/0301257

Smirnov, hep-ph/0610198

# Long Baseline Neutrino Experiment

New, upgraded, intense wide band beam from FNAL

towards

Very massive detector > 100 kton at DUSEL

**FNAL - DUSEL = 1300 km**

It can enhance our knowledge of neutrino oscillations well beyond what can be anticipated from ongoing and planned experiments worldwide

V. Barger *et al.*, arXiv:0705.4396 [hep-ph]

S. Raby *et al.*, arXiv:0810.4551 [hep-ph]

# Wide Band Beam

- Conventional neutrino (HFN) and anti-neutrino (HFA) beams based on the decay of horn focused pions will be sent from FNAL to a 100 - 300 kton water Cerenkov detector in DUSEL at a distance of 1300 km
- This beam is wide enough to cover the first (2.5 GeV) and second (0.8 GeV) oscillation maxima, helps to resolve the $(sgn(\Delta m^2_{31}), \delta_{CP})$ degeneracy
- 120 GeV, proton-on-target, on-axis, NuMI-like beam with 700 kW of beam power, delivers $6.2 \times 10^{20}$ protons on target per year and pions decay in a optimized 380 m decay pipe to reduce the high energy tail

**M. Diwan *et al.*, hep-ph/0303081, M. Diwan *et al.*, hep-ex/0407047**

**V. Barger *et al.*, hep-ph/0607177, M. Diwan *et al.*, hep-ex/0608023**

# Challenges with $\bar{\nu}_\mu$ run

- Production rate for $\pi^-$, the parent of $\bar{\nu}_\mu$, is lower than $\pi^+$
- Anti-neutrino charged current cross section is lower
- Background levels are higher due to the larger contamination from wrong sign pions
- Systematic errors are expected to be larger
- Overall, the event rate for anti-neutrinos is suppressed by a factor of 2-5

# Stopped pion source

Cost effective, megawatt-class $\sim$ 1 GeV cyclotron accelerators delivers $9.4 \times 10^{22}$ protons per year in a target at a beam dump at 2.5 mA during a 100 $\mu$s pulse every 500 $\mu$s

These accelerators are already being developed for Accelerator Driven Systems (ADS) for subcritical thorium-based reactors and for active interrogation for homeland security

Protons interact in a target producing both $\pi^+$ and $\pi^-$. The pions then are brought to rest in a high-Z beam stop. The $\pi^-$, and also the daughter $\mu^-$, will be captured on the high-Z nuclei. The $\pi^+$ will produce the following cascade of decays

$$\begin{aligned} \pi^+ \quad \rightarrow \quad & \mu^+ + \nu_\mu \\ & \hookrightarrow \; e^+ + \nu_e + \bar{\nu}_\mu \end{aligned}$$

# DAR Beam

It provides an equal, high-intensity, isotropic, decay at rest $\nu_\mu$, $\nu_e$ and $\bar{\nu}_\mu$ beam but no $\bar{\nu}_e$

$4 \times 10^{22}$/flavor/year of $\nu_\mu$, $\nu_e$, and $\bar{\nu}_\mu$ from each cyclotron. We use 4 cyclotrons at a distance of 20 km from DUSEL

$\bar{\nu}_\mu$ oscillates into $\bar{\nu}_e$ and they can be detected and uniquely identified by IBD, $\bar{\nu}_e + p \rightarrow e^+ + n$

Very useful coincidence tag between the prompt positron and the delayed neutron capture in a Gd dopped WC detector

Strong $\pi^-$ absorption in the target, $\bar{\nu}_e$ contamination is very small $\sim 4 \times 10^{-4}$

**Agarwalla, Huber, Link, Mohapatra, arXiv:1005.4055 [hep-ph]**

**See also, DAE$\delta$ALUS EOI, arXiv:1006.0260 [physics.ins-det]**

**J. M. Conrad *et al.*, Phys. Rev. Lett. 104, 141802 (2010)**

# Smart Idea

Combine low energy $\bar{\nu}_\mu$ from muon decay at rest (DAR) with high energy $\nu_\mu$ from a superbeam (HFN) aimed at the same Gadolinium-doped water Cerenkov detector at DUSEL

Moderately improved reach for $\theta_{13}$ and a vastly improved discovery reach for CP violation while leaving the mass hierarchy sensitivity intact

DAR marries with HFN

# What is new?

- Replace the $\bar{\nu}_\mu$ run of LBNE, with $\bar{\nu}_\mu$ from muon decay at rest (DAR) in a beam dump located at a distance of 20 km from DUSEL
- These low energy (20-60 MeV) $\bar{\nu}_\mu$'s oscillate into $\bar{\nu}_e$ and detected via IBD in a Gd-doped water Cerenkov detector at DUSEL
- This new approach yields a factor of five times larger anti-neutrino event sample

# DAR+HFN .vs. HFA+HFN

DAR+HFN: **Concurrent operation** *possible*

**Different duty factors**

HFN $\Rightarrow d < 10^{-4}$ **and** DAR $\Rightarrow d \simeq 0.1$

HFA+HFN: **Concurrent operation** *not possible*

**Horn either focuses $\pi^+$ or $\pi^-$**

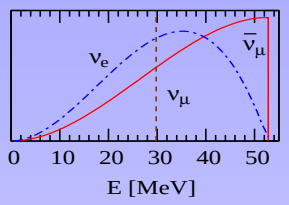
**Baselines and energies are completely different for HFN and DAR but $L/E$ is nearly the same**

**Baselines and energies are same for HFN and HFA**

**Agarwalla, Huber, Link, Mohapatra, arXiv:1005.4055 [hep-ph]**

# New Approach

**New Approach : DAR + HFN**
**LBNE : HFA + HFN**




**Proton Accelerators**
**1 MW, 1 GeV**
**Low–cost, High–power**

**DAR** $4 \,.\, 10^{22}$ neutrinos/flavor/year/accelerator

**DAR** : $\bar{\nu}_\mu \longrightarrow \bar{\nu}_e$
**0.2 – 0.6 MeV**

**20 km IBD**

**DUSEL**
**w / Gd**
**100 – 300 kton**

**FNAL**

**1300 km CC QE**

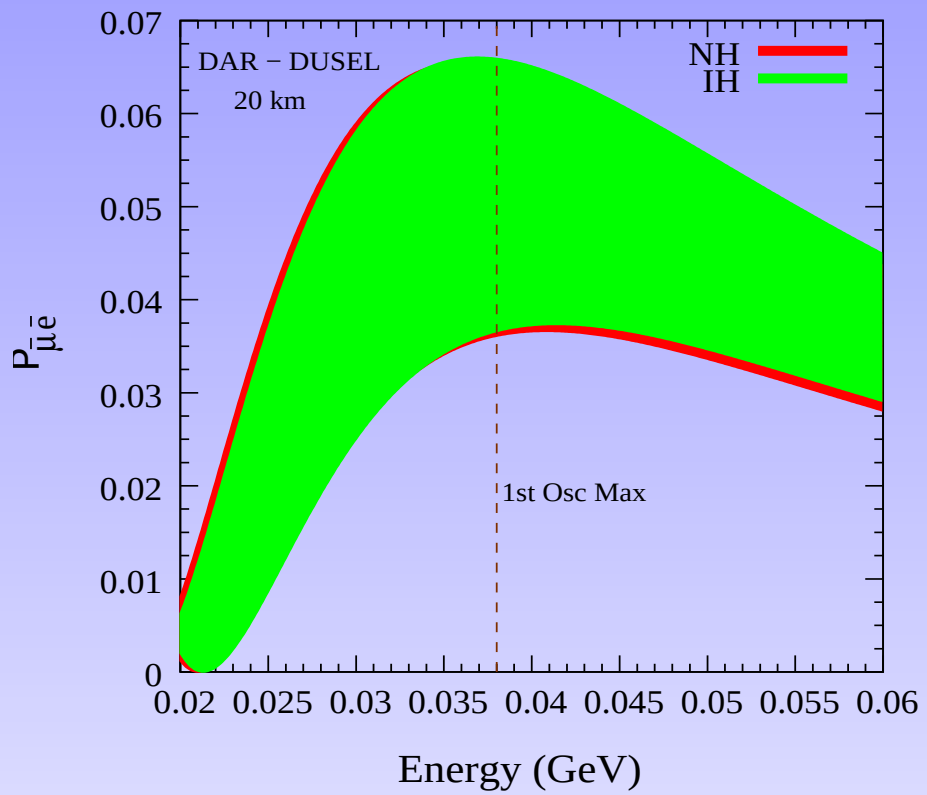
**HFN** : $\nu_\mu \longrightarrow \nu_e$
**HFA** : $\bar{\nu}_\mu \longrightarrow \bar{\nu}_e$
**0.5 – 6 GeV**

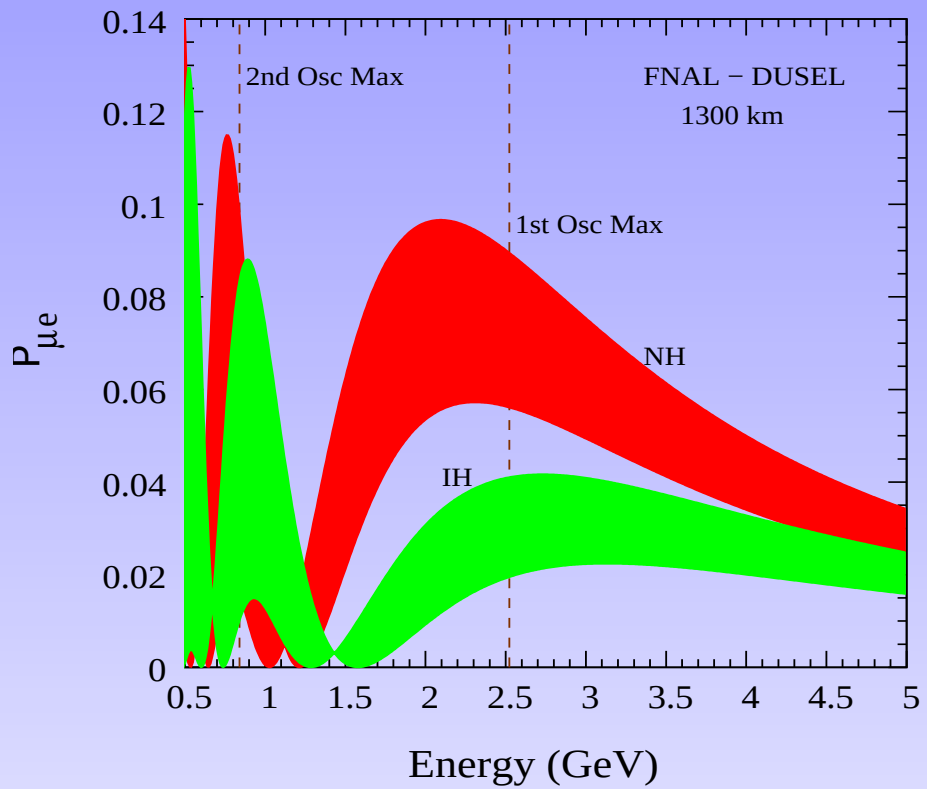
**Wide Band Beam**
**700 kW, 120 GeV**
**$6.2 \,.\, 10^{20}$ protons/year**

Agarwalla, Huber, Link, Mohapatra, arXiv:1005.4055 [hep-ph]

See also, DAE$\delta$ALUS EOI, arXiv:1006.0260 [physics.ins-det]

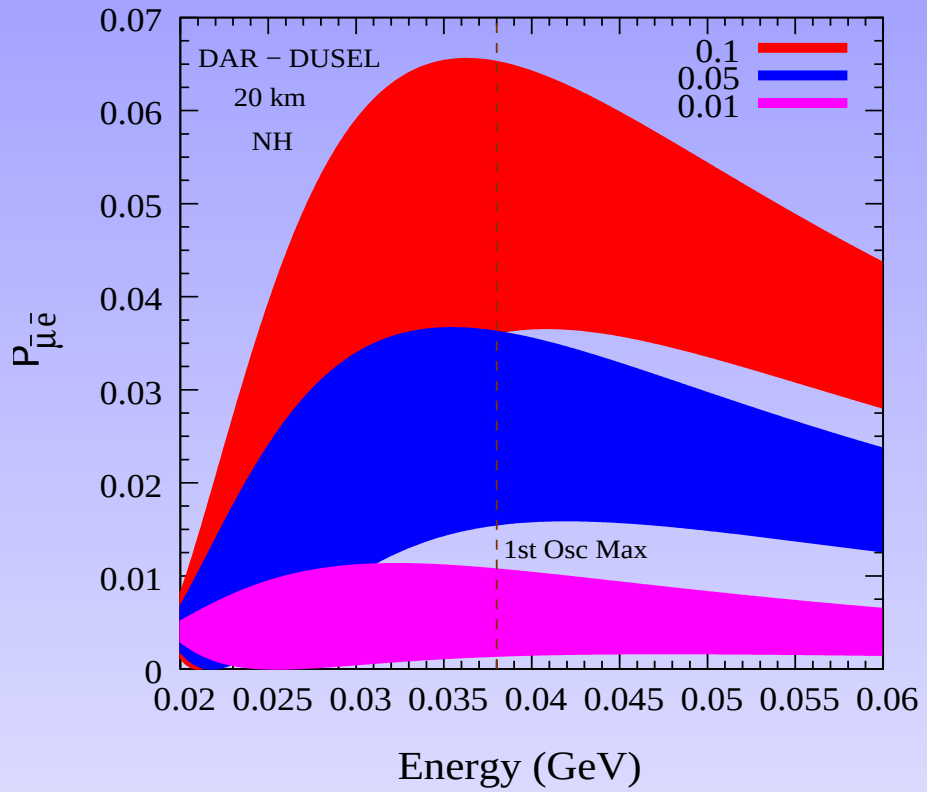
# $(\bar{\nu}_\mu \to \bar{\nu}_e)$ & $(\nu_\mu \to \nu_e)$

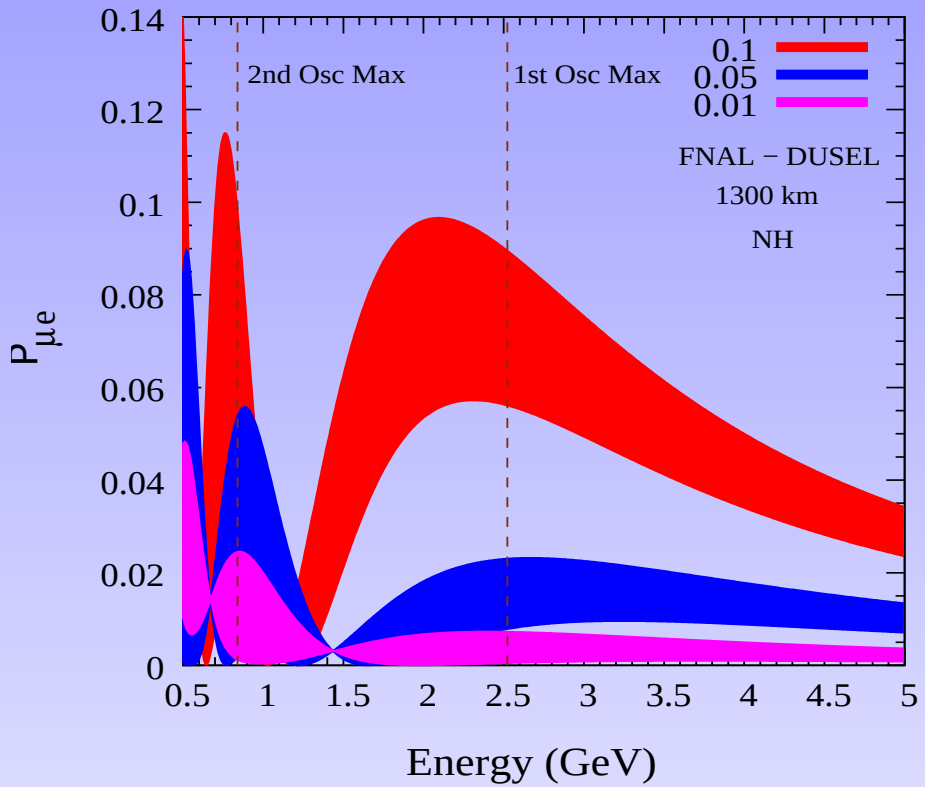



**Normal .vs. Inverted hierarchy** $\sin^2 2\theta_{13} = 0.1$

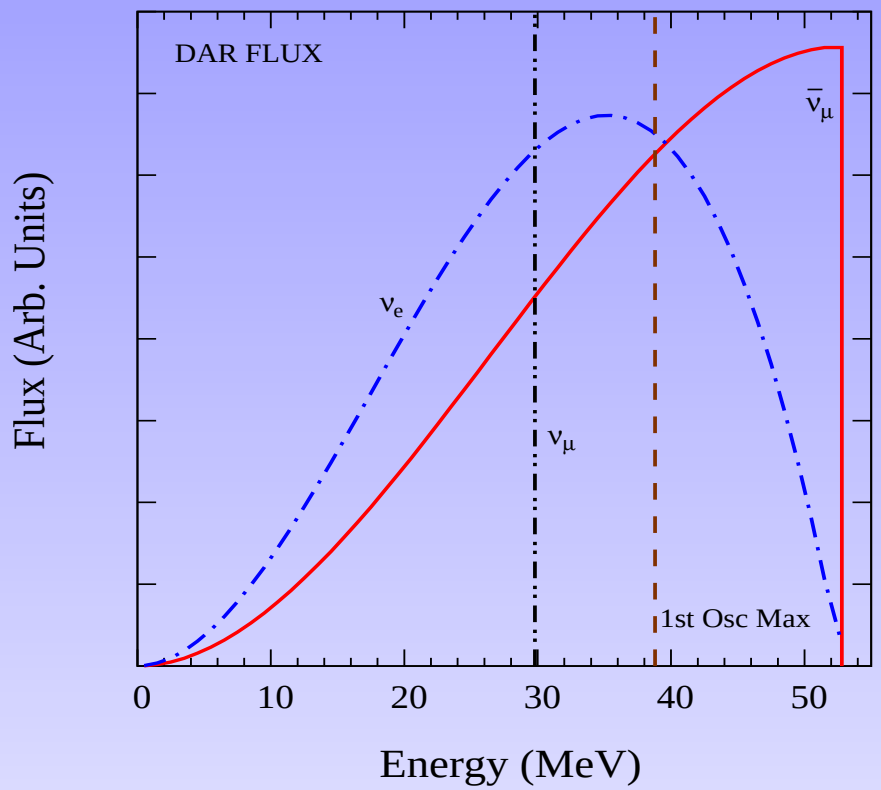
# $(\bar{\nu}_\mu \to \bar{\nu}_e)$ & $(\nu_\mu \to \nu_e)$

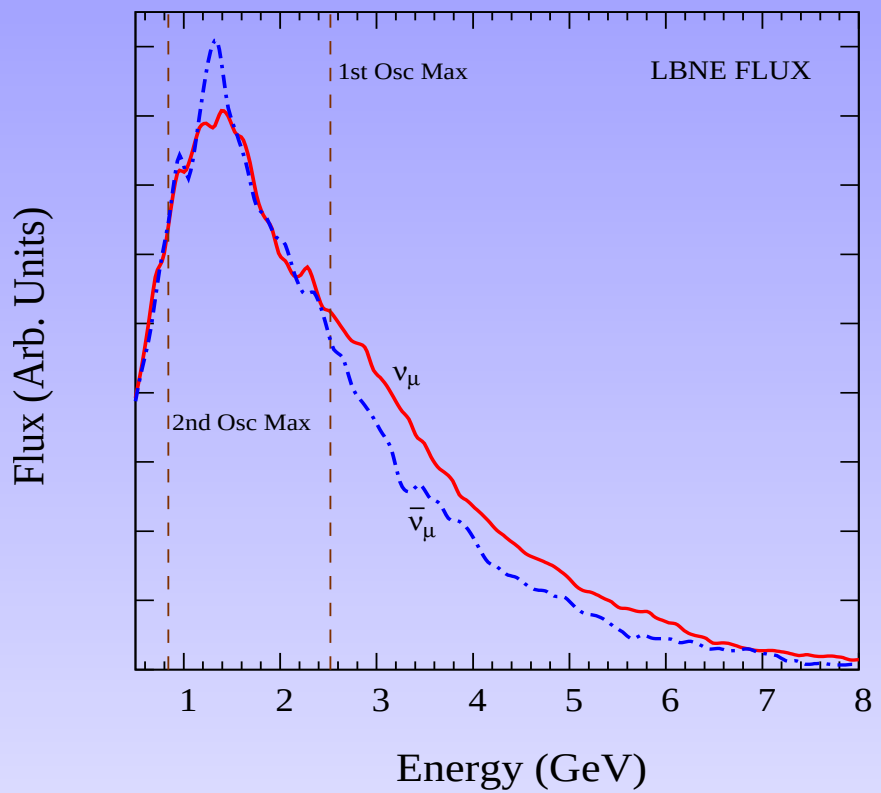



**Two different values of $\sin^2 2\theta_{13}$** | **Normal hierarchy**

# $\bar{\nu}_\mu$ (DAR) & $\nu_\mu$ (LBNE) flux




**DAR .vs. LBNE flux**

**Combination of low and high energy**

# Signal .vs. Background

| | $\bar{\nu}_\mu \to \bar{\nu}_e$ | Bkg | $\nu_\mu \to \nu_e$ | Bkg |
|---|---|---|---|---|
| DAR+HFN | 398 | 73 | 511 | 143 |
| HFA+HFN | 77 | 53 | 255 | 71 |

$\sin^2 2\theta_{13} = 0.1$, $\delta_{\rm CP} = 0^\circ$, **NH and total 6 years run**

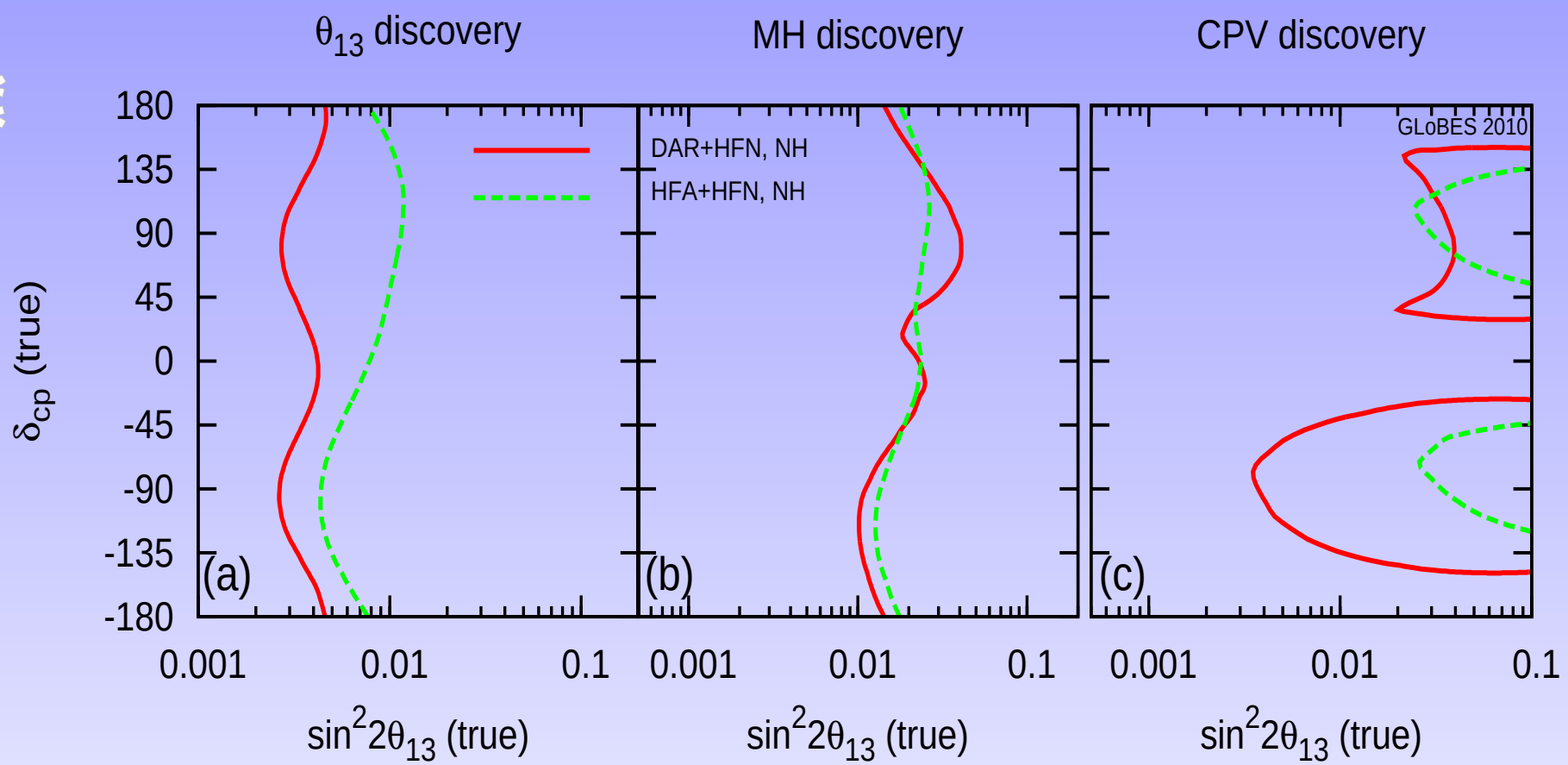
DAR+HFN: **6 years of *simultaneous* running of neutrinos and anti-neutrinos**

HFA+HFN: **3 years of *consecutive* running of neutrinos and anti-neutrinos**

DAR+HFN: ***twice* the statistics in the neutrino mode and *five times* as much statistics with a five times better sig/bkg ratio in the anti-neutrino mode**

**Agarwalla, Huber, Link, Mohapatra, arXiv:1005.4055 [hep-ph]**

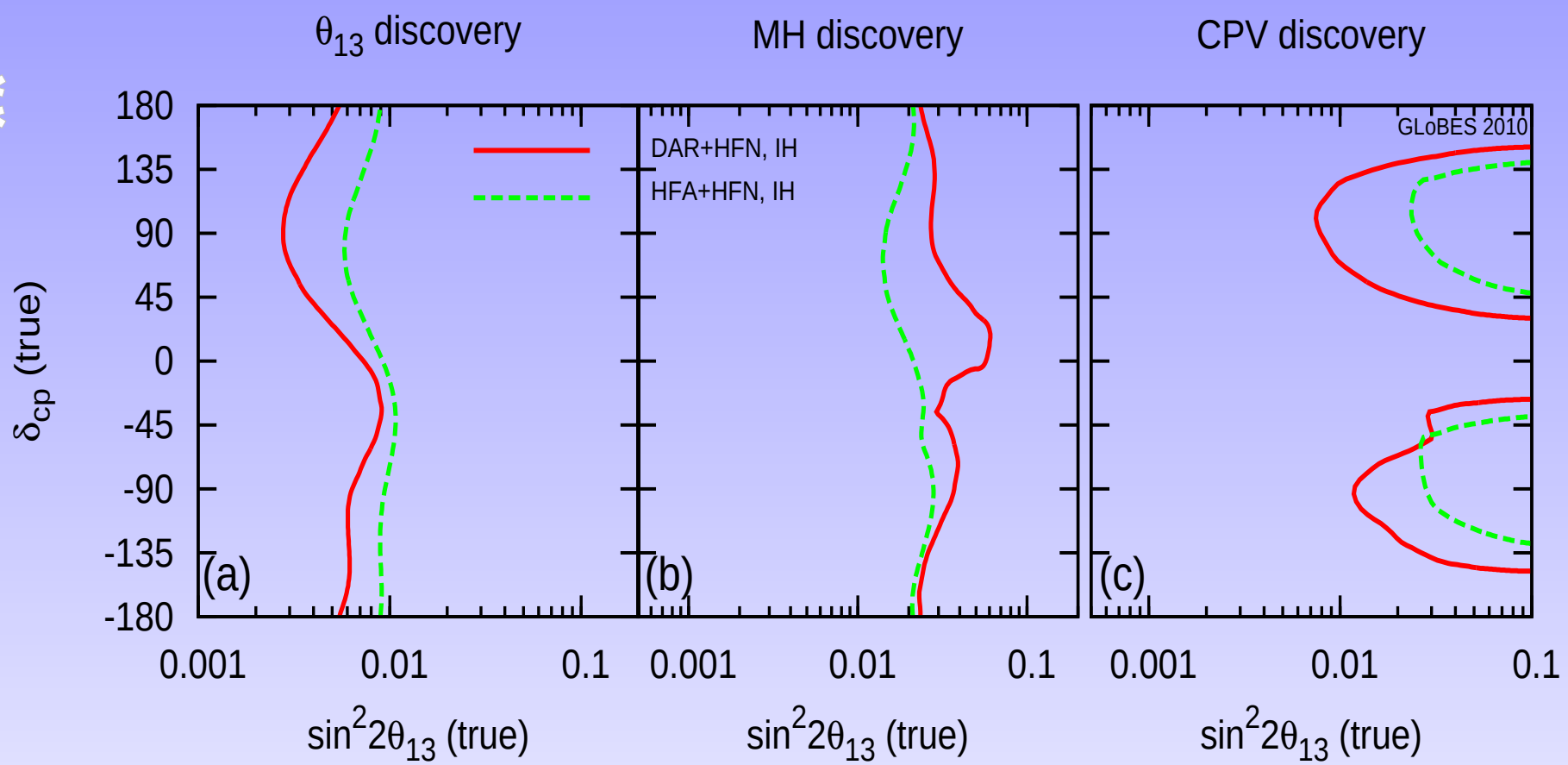
# 100 kton & NH




Agarwalla, Huber, Link, Mohapatra, arXiv:1005.4055 [hep-ph]

**Discovery reaches at $3\sigma$ confidence level**

# 100 kton & IH




Agarwalla, Huber, Link, Mohapatra, arXiv:1005.4055 [hep-ph]

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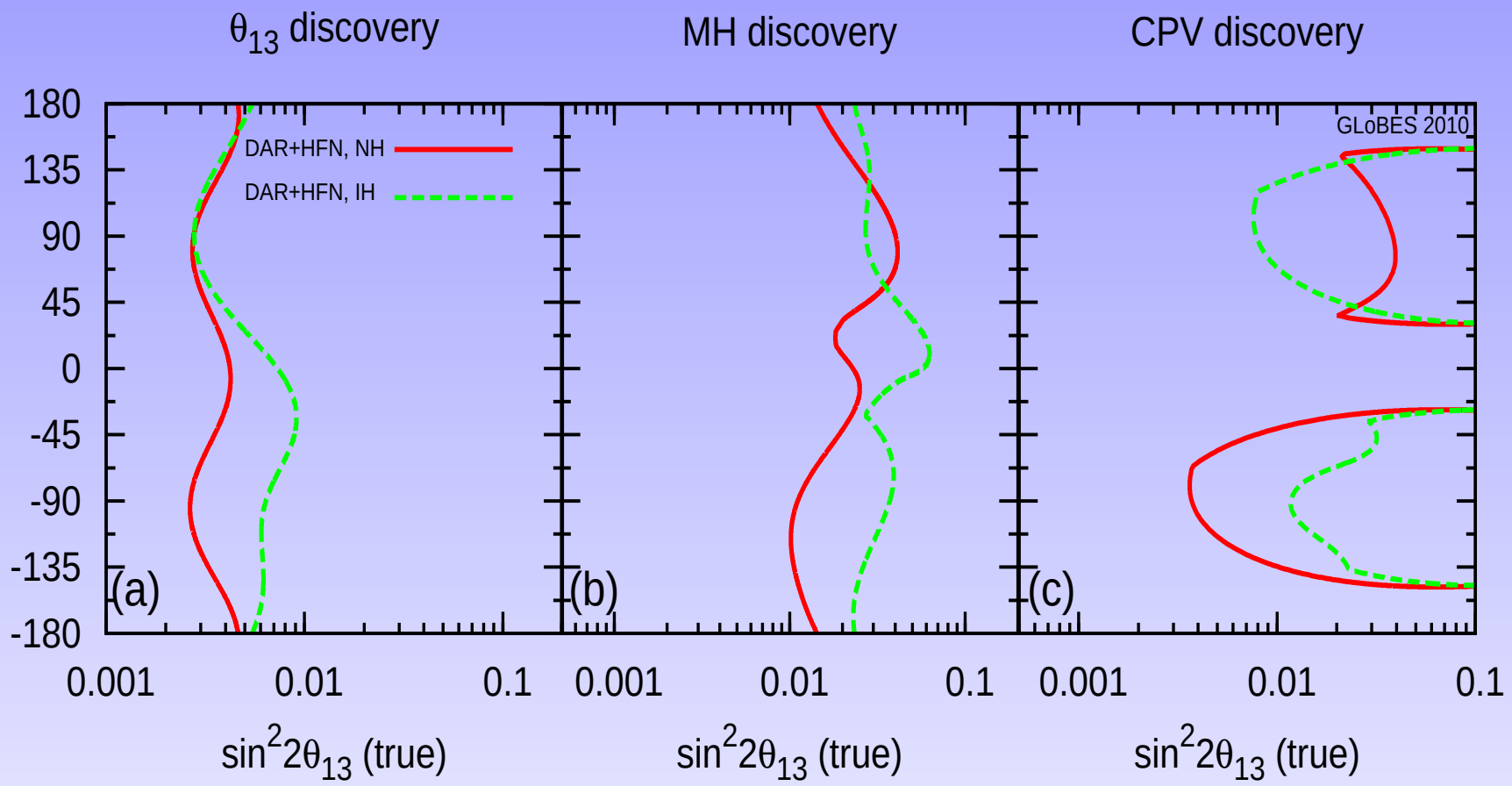
# 100 kton, NH & IH




Agarwalla, Huber, Link, Mohapatra, arXiv:1005.4055 [hep-ph]

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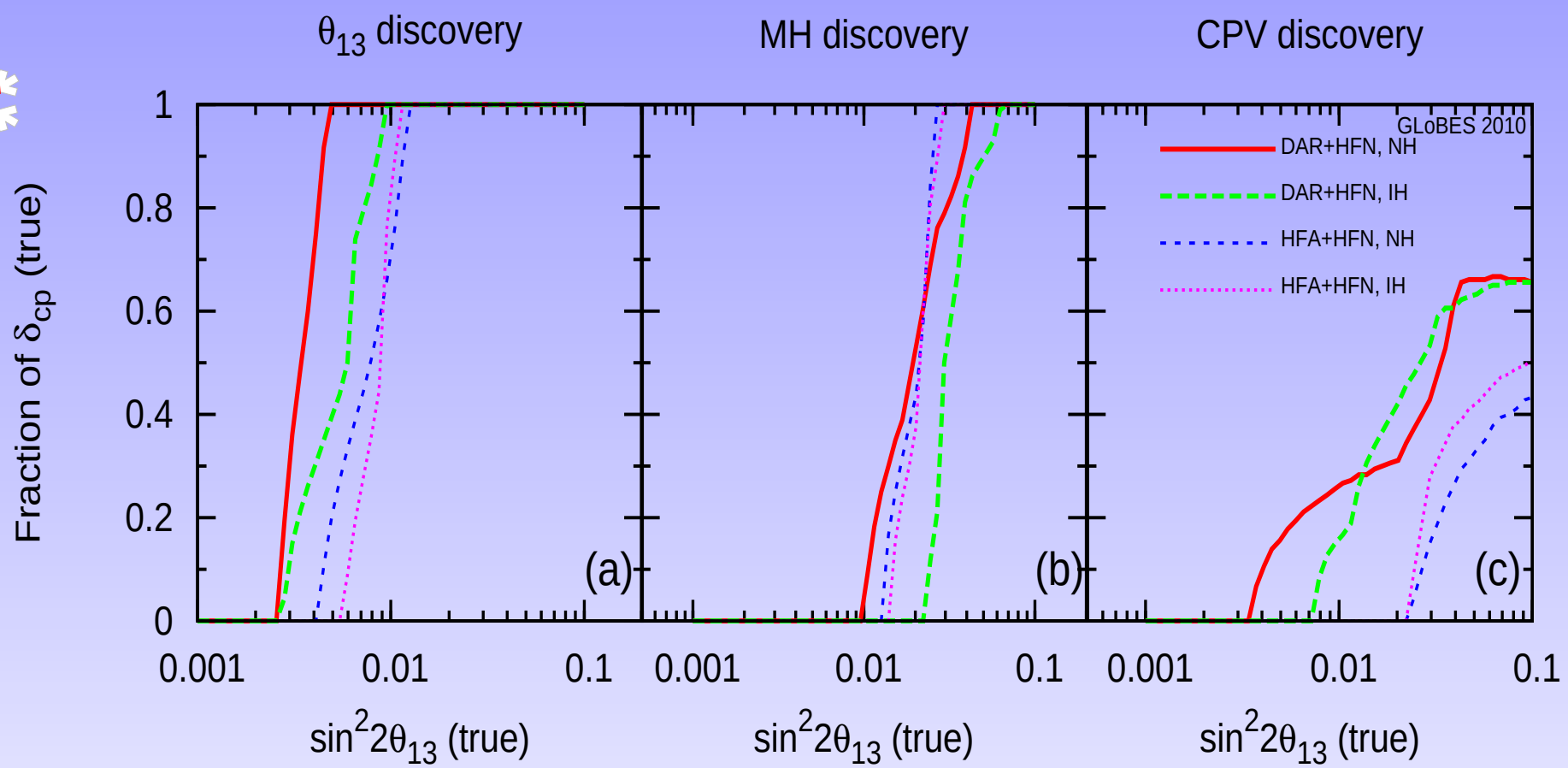
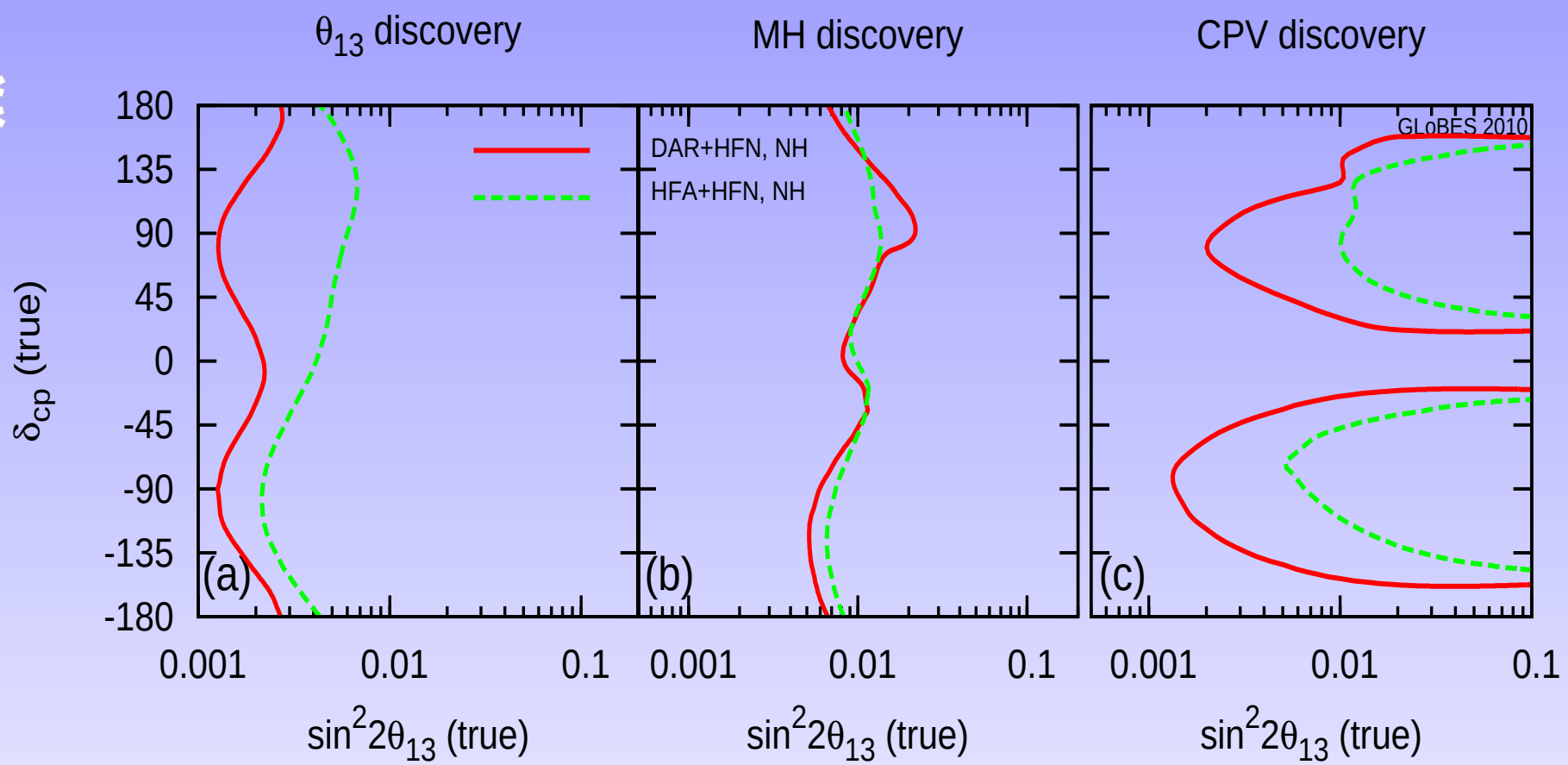



Agarwalla, Huber, Link, Mohapatra, arXiv:1005.4055 [hep-ph]

**CP fraction for which a discovery at $3\,\sigma$ confidence level is possible as a function of $\sin^2 2\theta_{13}$(true)**

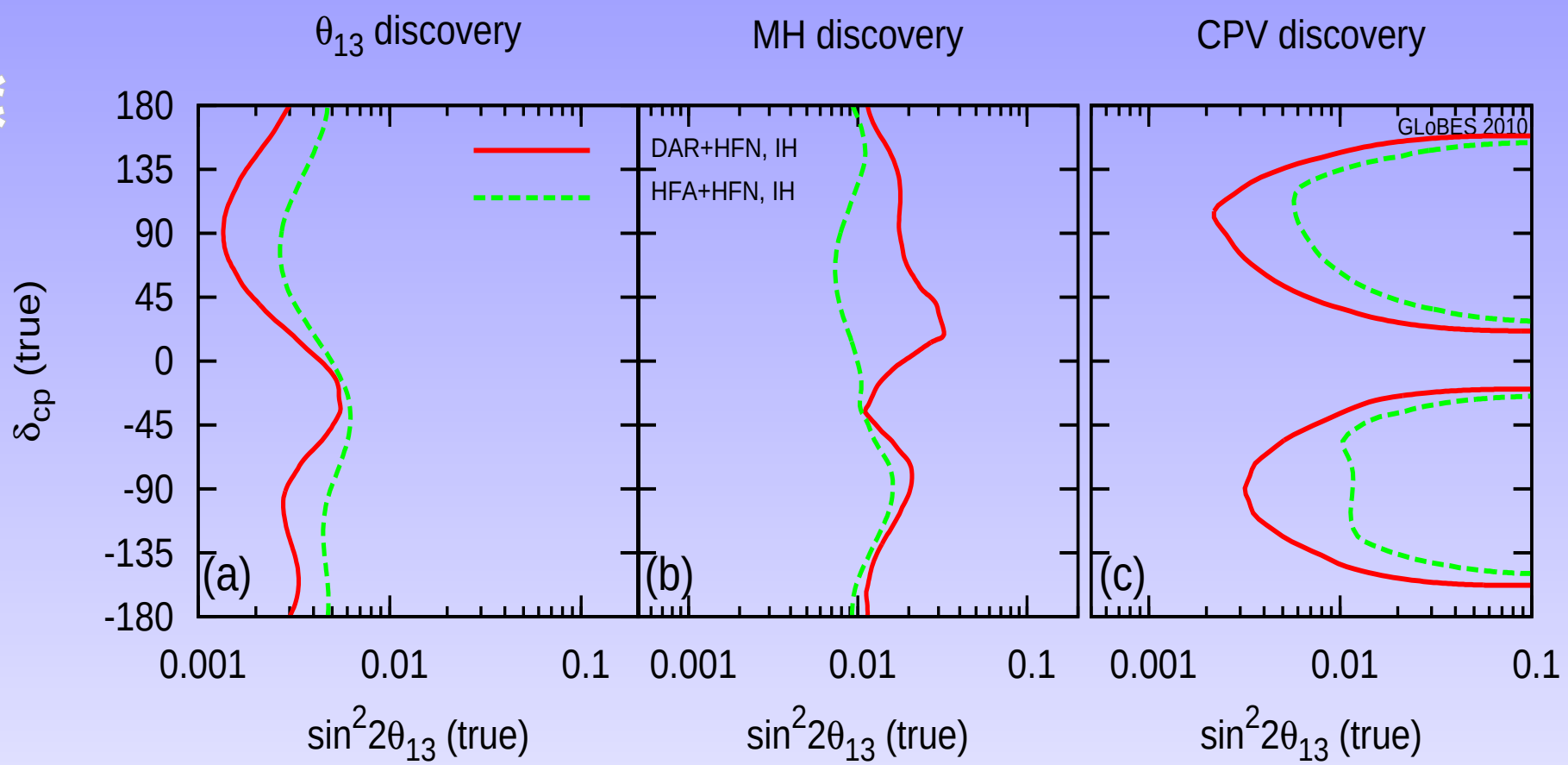
# 300 kton & NH




Agarwalla, Huber, Link, Mohapatra, arXiv:1005.4055 [hep-ph]

**Discovery reaches at $3\sigma$ confidence level**

# 300 kton & IH

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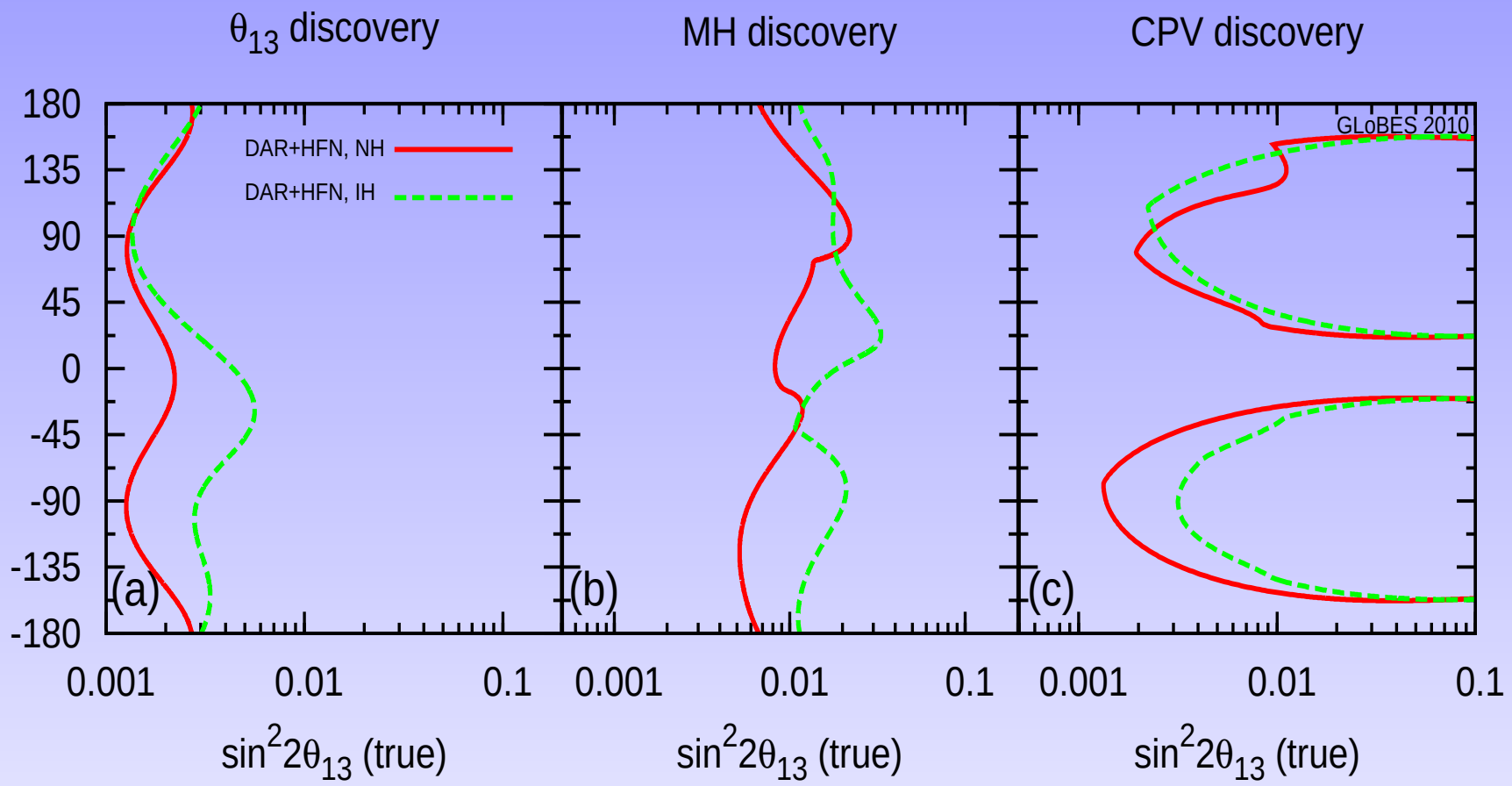
**Discovery reaches at $3\sigma$ confidence level**

# 300 kton, NH & IH

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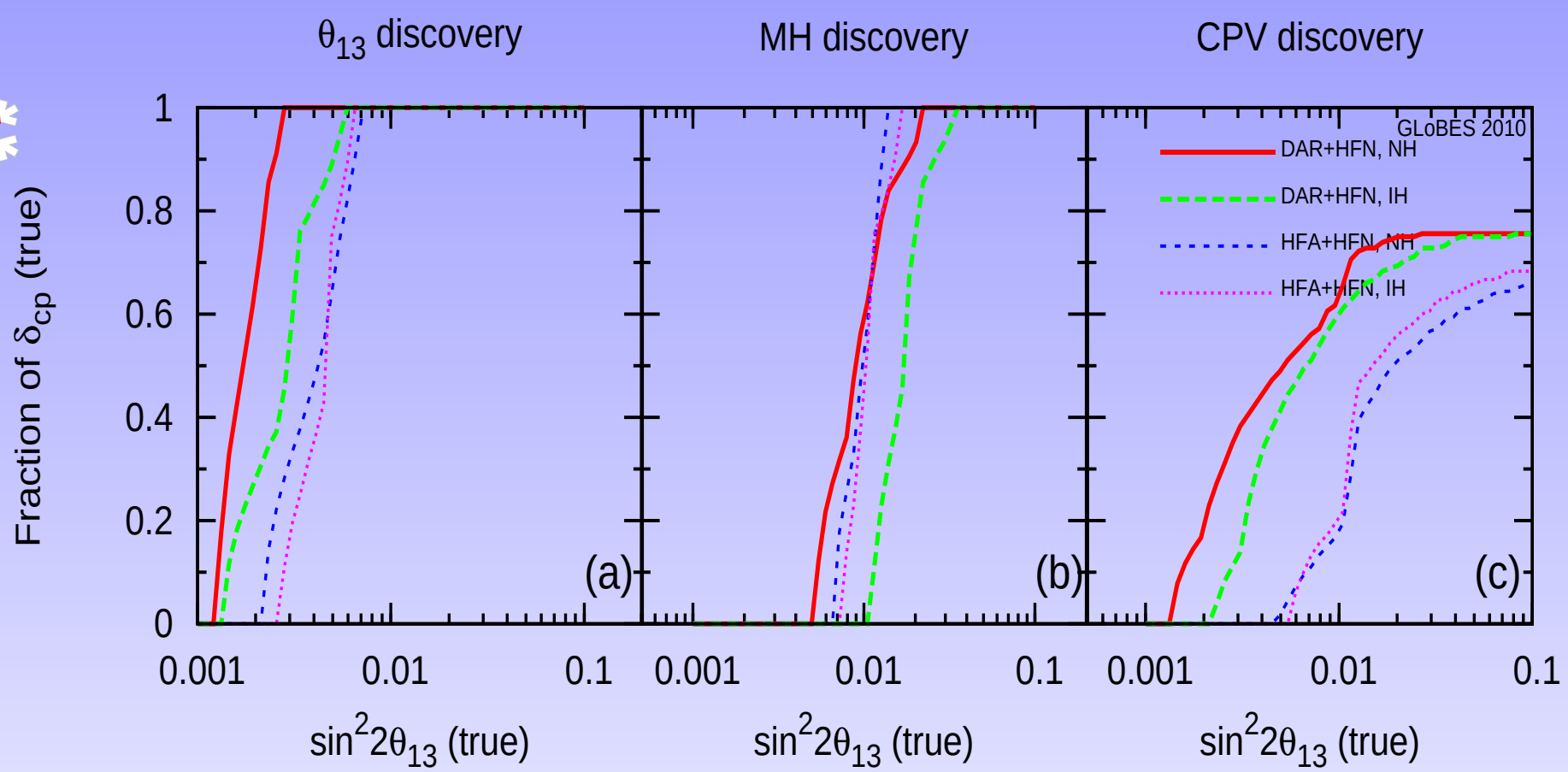
**Discovery reaches at $3\sigma$ confidence level**

# 300 kton, NH & IH




Agarwalla, Huber, Link, Mohapatra, arXiv:1005.4055 [hep-ph]

**CP fraction for which a discovery at $3\,\sigma$ confidence level is possible as a function of $\sin^2 2\theta_{13}$(true)**

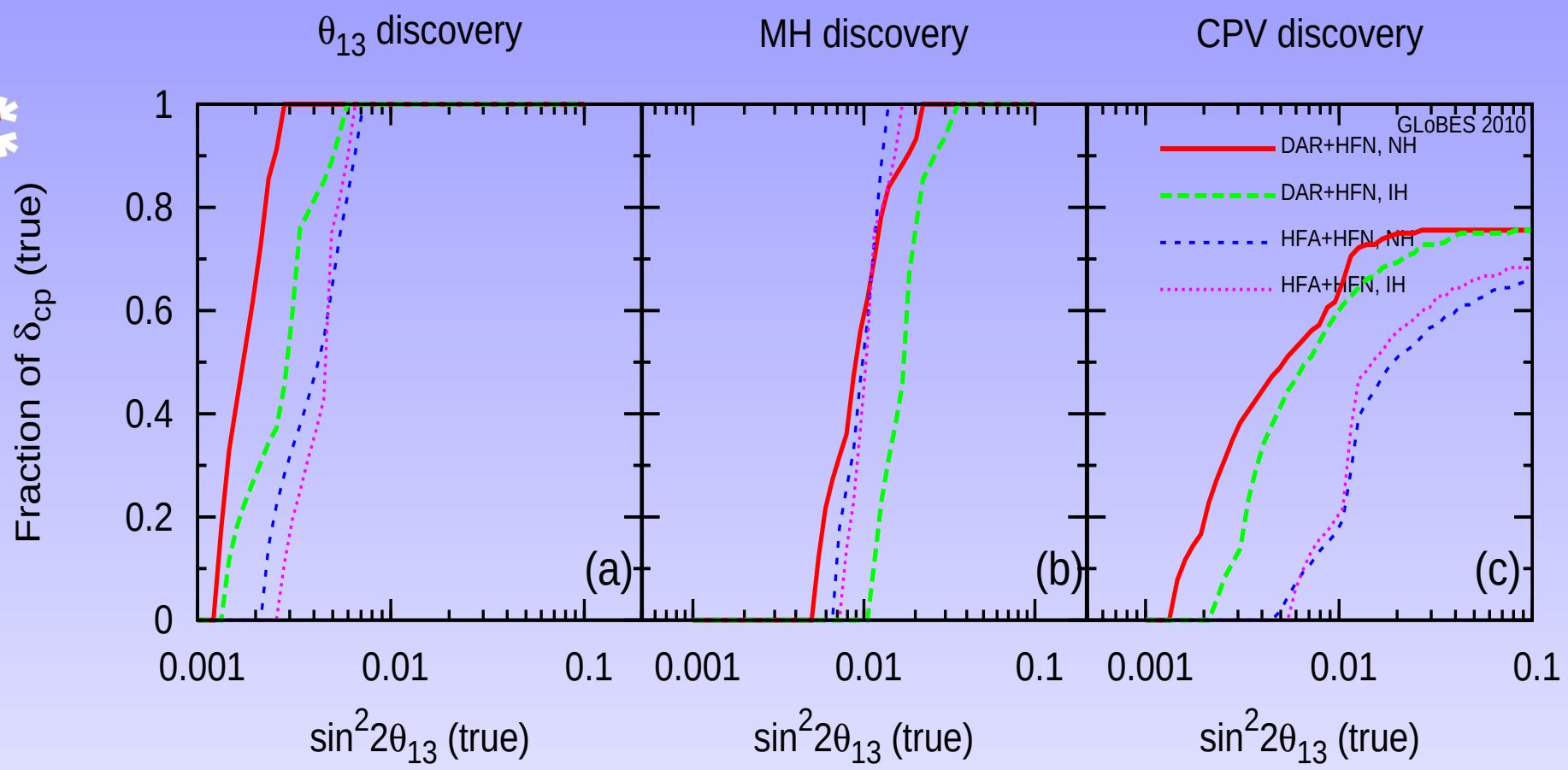
# Summary

- Precision neutrino physics is very important and complementary to LHC
- T2K and NO$\nu$A will hardly measure leptonic CP violation and mass hierarchy, even if $\theta_{13}$ is large
- LBNE can play a crucial role in this direction
- High intensity proton source and Mton class large detectors are key
- Anti-neutrino run poses a number of specific challenges : causing a suppression in event rate by factor of 2-5

# Summary

- Replace the $\bar{\nu}_\mu$ run of LBNE, with $\bar{\nu}_\mu$ from muon decay at rest (DAR) in a beam dump located at a distance of 20 km from DUSEL
- These low energy (20-60 MeV) $\bar{\nu}_\mu$'s oscillate into $\bar{\nu}_e$ and detected via IBD in a Gd-doped water Cerenkov detector at DUSEL
- Concurrent operation of $\nu_\mu$ run of LBNE and $\bar{\nu}_\mu$ run of DAR set-up is possible
- This new approach yields a factor of five times larger anti-neutrino event sample and a factor of two enhancement in the neutrino event sample

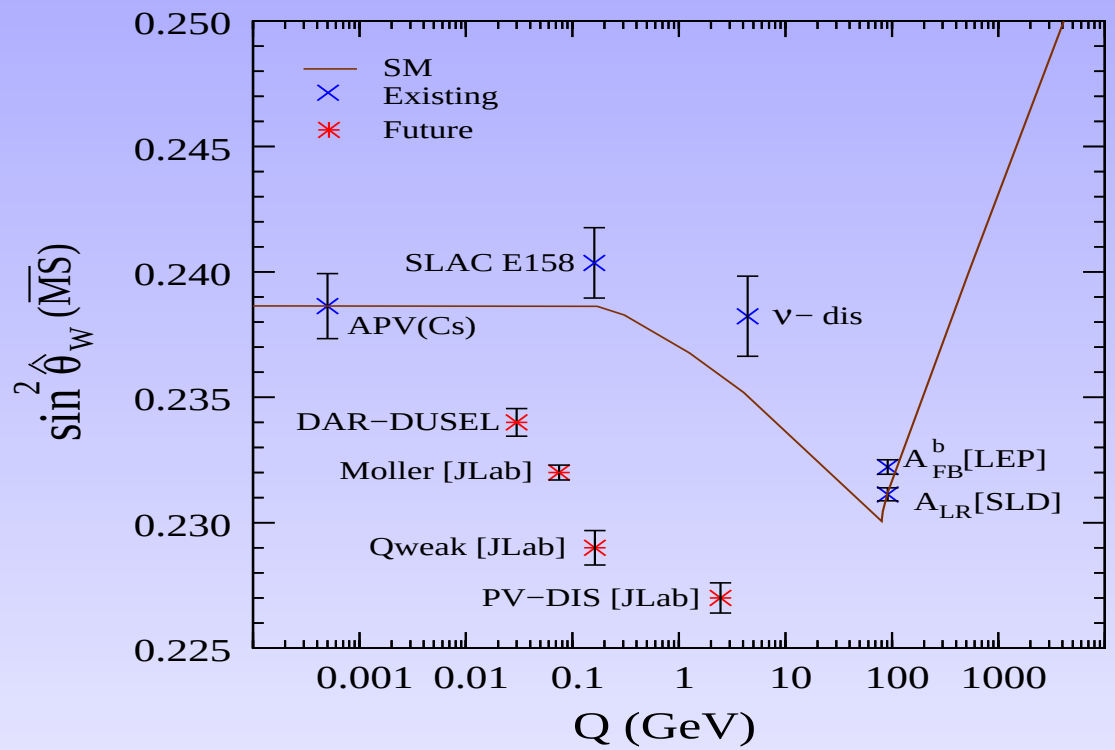
# Summary




Moderately improved reach for $\theta_{13}$ and a vastly improved discovery reach for CP violation while leaving the mass hierarchy sensitivity intact

# DAR-DUSEL

Our proposed experiment will provide a $\simeq 0.24\%$ measurement of $\sin^2\theta_W$

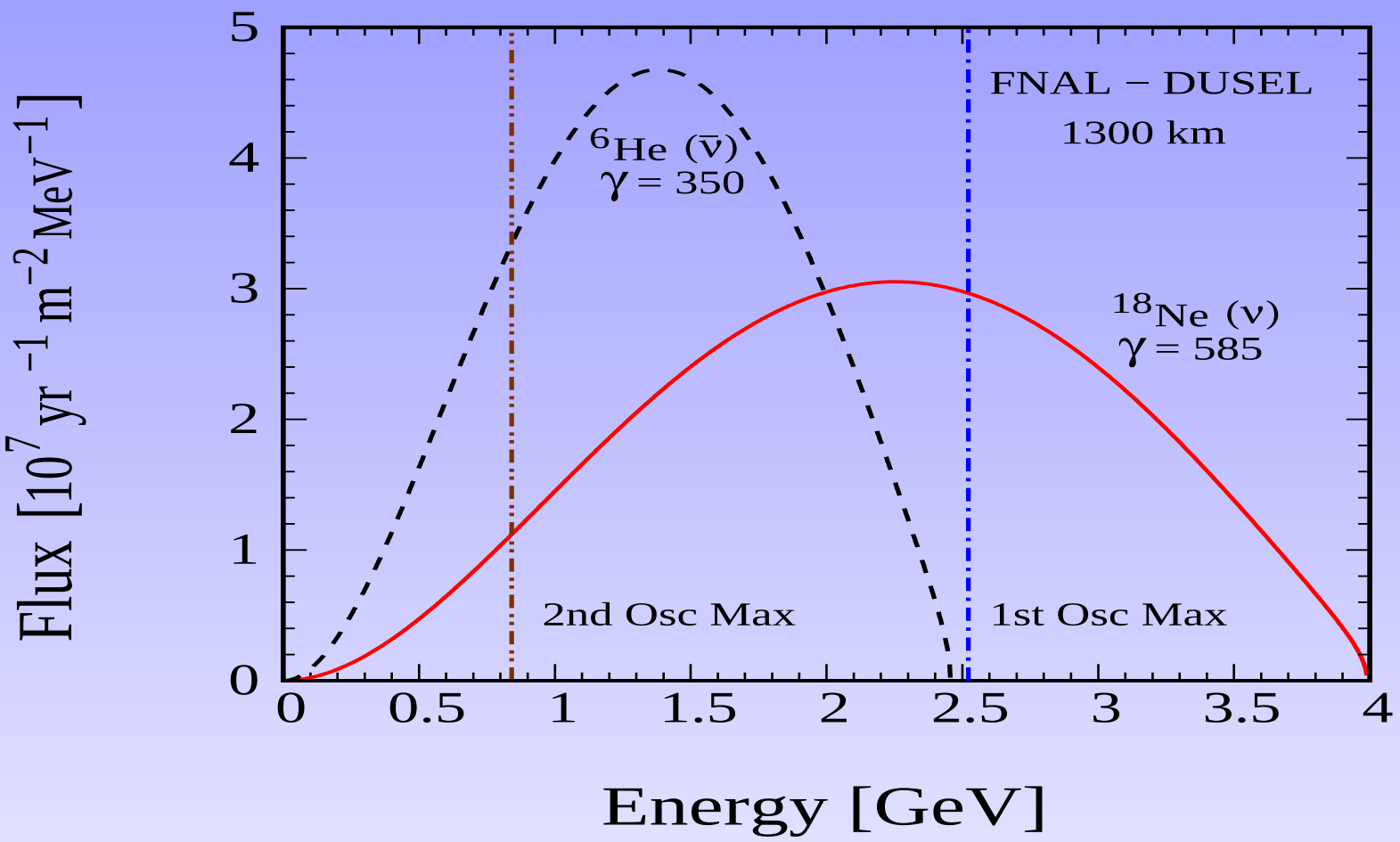



This configuration can be a natural part of the proposed physics program for DUSEL

# $\beta$-beam at FNAL

## Physics reach of $\beta$-beam with FNAL to DUSEL Baseline

# $\beta$-beam flux




Agarwalla, Huber, arXiv:0909.2257

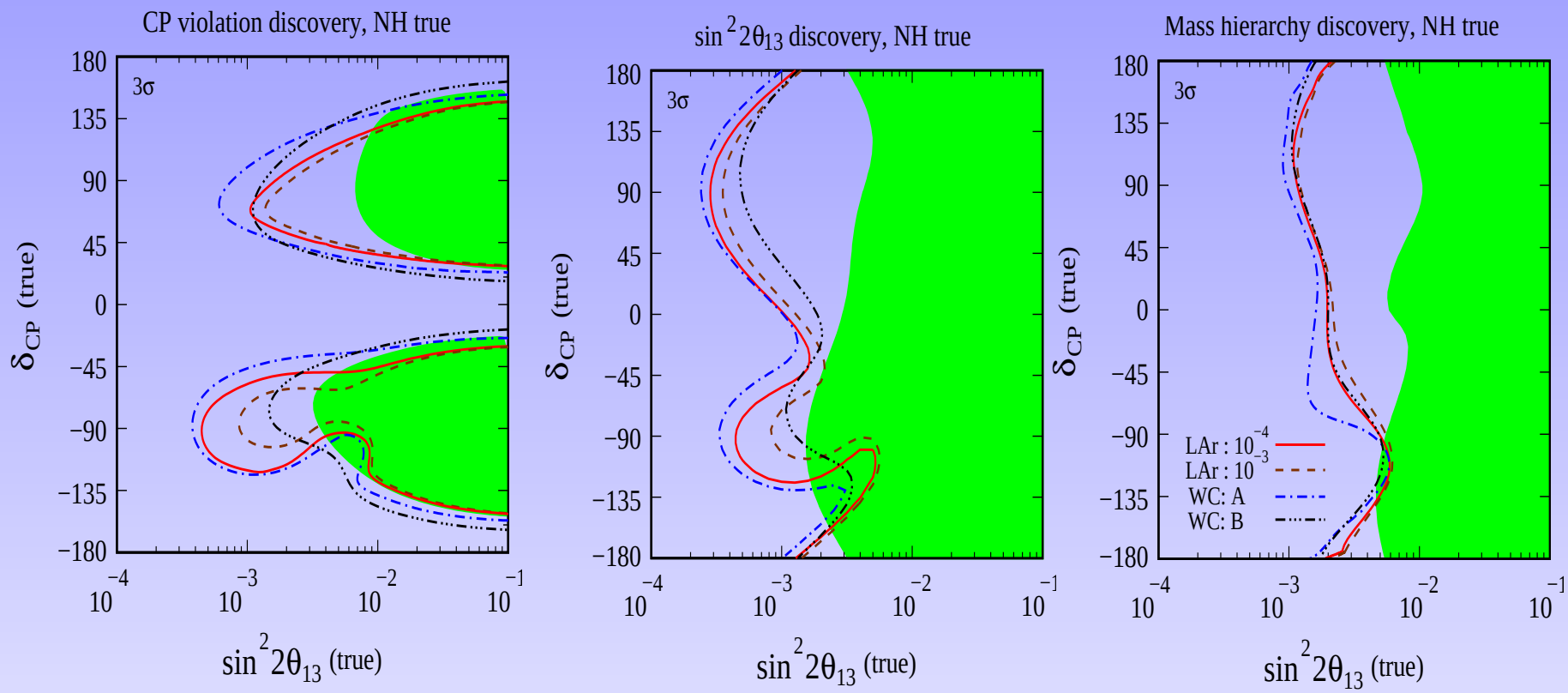
**Un-oscillated flux at DUSEL from FNAL**

# $\beta$-beam flux

| Ion | $t_{1/2}$ (s) | $E_0$ (MeV) | Useful decays | $\gamma$ (Tevatron) | Beam | $E_{lab}^{peak}$ (GeV) |
|---|---|---|---|---|---|---|
| $^{18}_{10}$Ne | 1.67 | 3.92 | $5 \cdot (1.1 \cdot 10^{18})$ | 585 | $\nu_e$ | 2.3 |
| $^{6}_{2}$He | 0.81 | 4.02 | $5 \cdot (2.9 \cdot 10^{18})$ | 350 | $\bar{\nu}_e$ | 1.4 |

**The beta-decay parameters, half-life $t_{1/2}$ and electron total end-point energy $E_0$ are shown in the first two columns. In the third column, we list the total number of useful ion decays considered in this work. The maximum $\gamma$ available for these ions using the Tevatron are mentioned in column four. The peak energies of the $\nu_e$ and $\bar{\nu}_e$ spectrum in the lab frame are shown in the last column.**

# Sensitivity Plots




Agarwalla, Huber, arXiv:0909.2257