# WG1 Summary (I): Theory/Pheno

Sandhya Choubey

(Thomas Schwetz, Chris Walter)

11th International Workshop on Neutrino Factories,
Superbeams and Beta Beams, NuFact09,
July 25, 2009

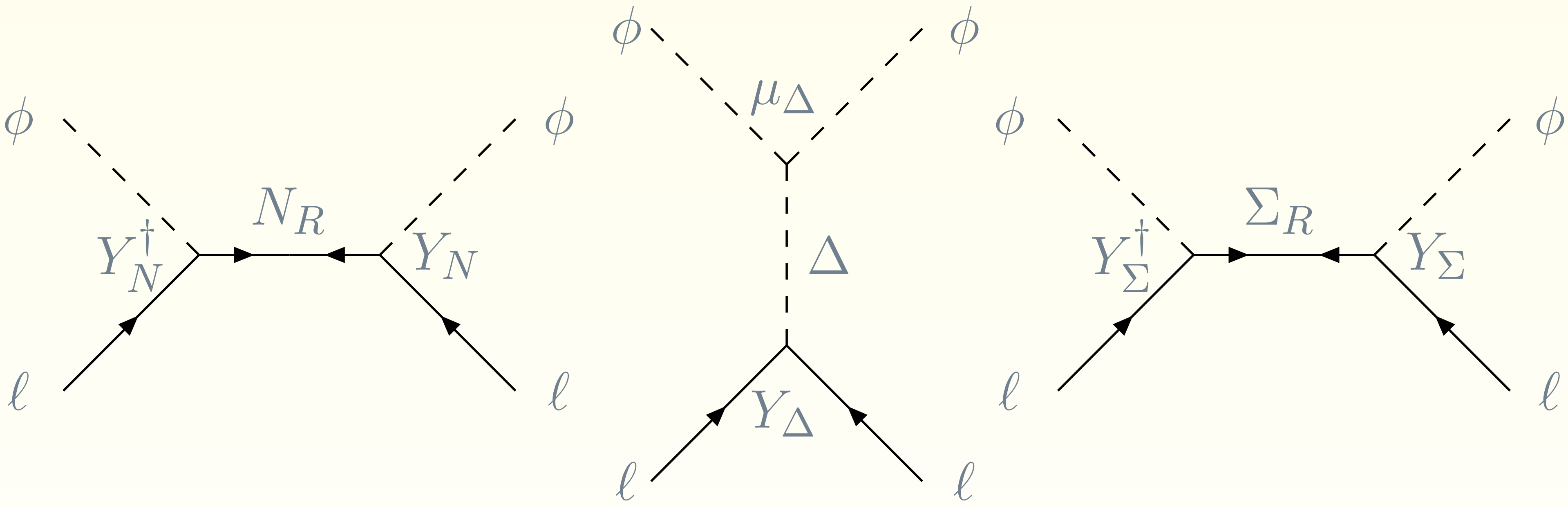
# Neutrino Masses: Beyond the Standard Model

- Neutrinos are massless in the Standard Model:
  - No right handed neutrinos $\Rightarrow$ no Dirac mass term
  - No triplet scalar $\Rightarrow$ no Majorana mass term

- Introduce right handed neutrinos by hand:
  - $m_\nu = Y_\nu v \Rightarrow Y_\nu \sim 10^{-12}$
  - Makes the already existing problem with understanding flavors even worse

# The Seesaw Mechanism

- Three variants of the seesaw mechanism




**Type I**

$\mathbf{m}_\nu = -v^2 Y_\nu^T M_N^{-1} Y_\nu$

**Type II**

$\mathbf{m}_\nu = -v^2 Y_\Delta \frac{\mu}{M_\Delta^2}$

**Type III**

$\mathbf{m}_\nu = -v^2 Y_\Sigma^T M_\Sigma^{-1} Y_\Sigma$

- Smass masses explained; flavor structure needs more

# Seesaw at LHC

- Is the seesaw mechanism testable at LHC?
- YES, if:
  - "Heavy" seesaw mediating particles (singlets or triplets) are "light" enough to be produced at LHC ($\Rightarrow$ less than TeV)
  - The signal/background ratio is large ($\Rightarrow$) one should be careful with the collider channels chosen

F. del Aguila

- LHC reach for testing:
  - Type I seesaw: $M_N \lesssim 100$ GeV
  - Type II seesaw: $M_\Delta \lesssim 600 - 800$ GeV
  - Type III seesaw: $M_\Sigma \lesssim 750$ GeV

# Seesaw and Leptogenesis

W. Rodejohann

- Lepton Asymmetry is $\propto$:

$$\epsilon_1 = \frac{1}{8\pi v^2} \frac{1}{(m_D m_D^\dagger)_{11}} \sum_{j=2,3} \text{Im}(m_D m_D^\dagger)^2_{1j} f(M_j^2/M_1^2) \quad \textbf{unflavored}$$

- In the Casas-Ibarra parametrization:

$$m_D = i\sqrt{M_N} R \sqrt{m_\nu^{\text{diag}}} U^\dagger \quad \text{where} \quad RR^T = 1$$

- The relevant quantity for leptogenesis is then

$$m_D m_D^\dagger = \sqrt{M_N} R \sqrt{m_\nu}^{\text{diag}} U^\dagger U \sqrt{m_\nu}^{\text{diag}} R^\dagger \sqrt{M_N}$$

- Leptogenesis is not necessarily related to low E $\delta_{CP}$ if $U$ is unitary

# Seesaw and Leptogenesis

W. Rodejohann

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- The relevant quantity for leptogenesis is then

$$m_D m_D^\dagger = \sqrt{M_N} R \sqrt{m_\nu^{\text{diag}}} N^\dagger N \sqrt{m_\nu^{\text{diag}}} R^\dagger \sqrt{M_N}$$

- But direct connection between low E osc params and leptogenesis if mixing matrix is non-unitary
- Showed that with inverse seesaw this was possible

# Seesaw and Non-Unitarity

W. Rodejohann, H. Zhang

$$M = \begin{pmatrix} 0 & m_D^T \\ m_D & M_R \end{pmatrix} \quad U = \begin{pmatrix} N & S \\ T & V \end{pmatrix}$$ Type I/III seesaw

$$M = \begin{pmatrix} 0 & m_D^T & 0 \\ m_D & 0 & M_R^T \\ 0 & M_R & \mu \end{pmatrix} \quad U' = \begin{pmatrix} N & S & A \\ T & V & D \\ B & E & W \end{pmatrix}$$ Inverse Seesaw

$$\mathcal{L}_{CC} = \frac{g}{\sqrt{2}} W_\mu^- \bar{l}_L \gamma^\mu N \nu_{m_L} + \ldots$$

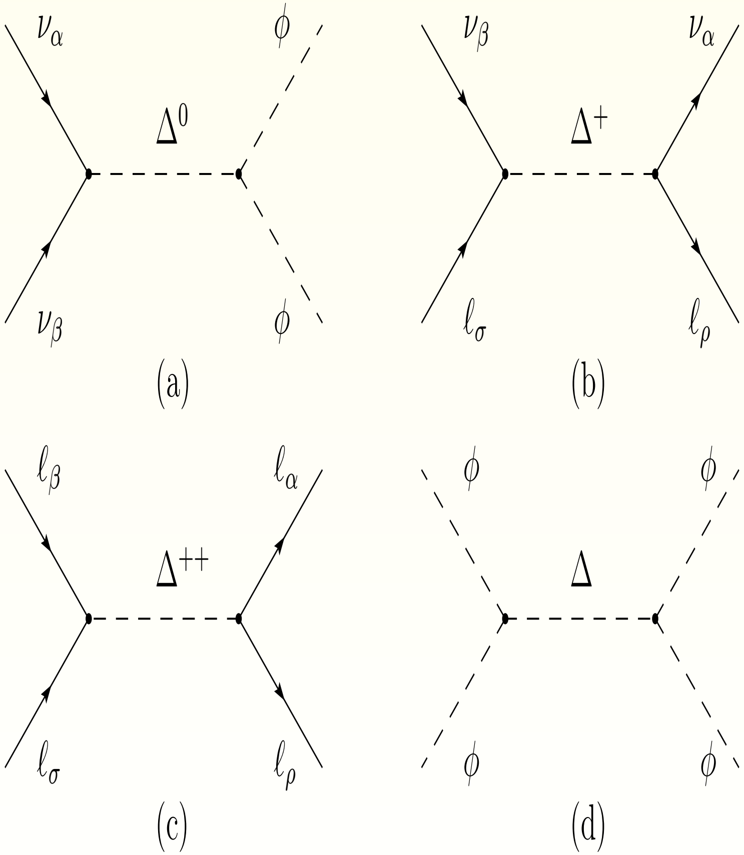
- Non-Unitarity $\sim m_D/M_R \sim m_\nu/M_R$ for Type I and III
  $\sim m_\nu/\mu$ for inverse seesaw

- Non-Unitarity for inverse seesaw is large and might be probed in neutrino factories

# Seesaw and Non Standard Interactions (NSI)

**H. Zhang**

$$\mathcal{L}_{\rm NSI} = -2\sqrt{2}G_F\epsilon^{ff'}_{\alpha\beta}\left(\bar{\nu}_\alpha\gamma^\mu P_L\nu_\beta\right)\left(\bar{f}\gamma_\mu P_{L,R}f'\right)$$




- Type II seesaw
- Contribution to neutrino propagation in matter
- Contribution to LFV processes – synergy
- Collider signatures – synergy

# Measuring NSI at LBL Experiments

**T. Ota**

- Optimizing neutrino factory for NSI
  - IDS baseline design of 4000+7500 kms optimal also for NSI
  - Silver channel (as in IDS-NF) not important
  - NSI parameters cause only very small difference to the HENF performance for the standard oscillation parameters
  - $\epsilon^m_{ee} \sim 10^{-1}$, $\epsilon^m_{\mu\tau}$ and $\epsilon^m_{\tau\tau} 2\times \sim 10^{-2}$, and $\epsilon^m_{e\tau} \sim 6 \times 10^{-3}$ can be probed

**R. Zukanovich-Funchal**

- NSI and CPV
  - Additional CP phases due to NSI can be probed at HENF
  - SM CPV search not affected
  - NSI couplings down to $10^{-3} - 10^{-4}$ can be probed
- Note the difference between the sensitivity reaches

# Theoretical Bounds on NSI

$$\mathcal{L}_{\rm NSI} = -2\sqrt{2}G_F\epsilon^{ff'}_{\alpha\beta}\left(\bar{\nu}_\alpha\gamma^\mu P_L\nu_\beta\right)\left(\bar{f}\gamma_\mu P_C f'\right)$$

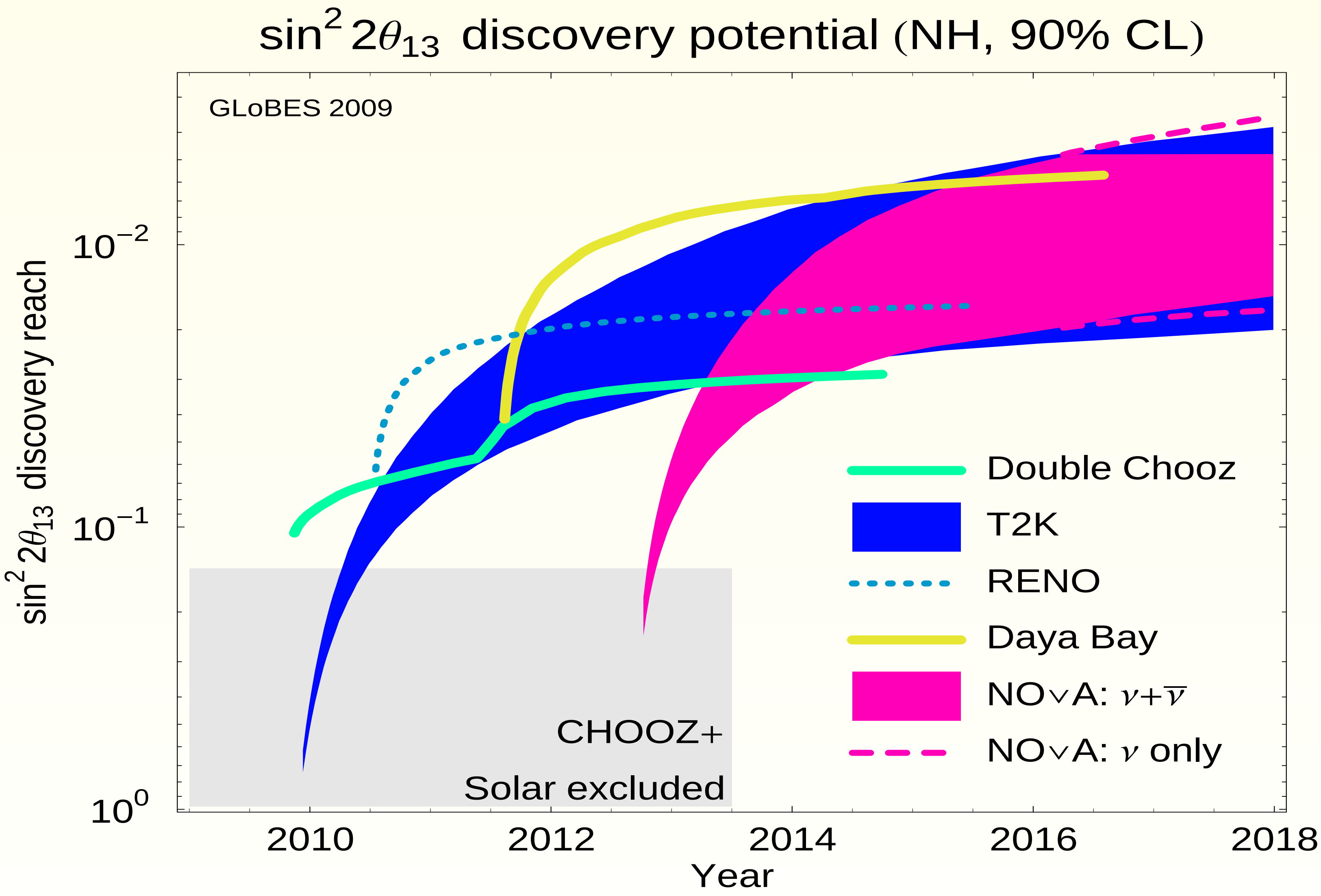
**E. Fernandez-Martinez**

- Current limits on NSI
  - NSI couplings involved in production/detection severely constrained from charged lepton sector
  - NSI in neutrino propagation are directly constrained only by neutral current scattering of neutrinos and appear to be large
  - However, gauge invariance forces them also to be very small
  - Typically, NSI couplings are “predicted” to be $\mathcal{O}(10^{-3}-10^{-2})$ theoretically
  - Might be difficult to constrain them any further using neutrino osc expts

# Measuring Standard Oscillation Parameters

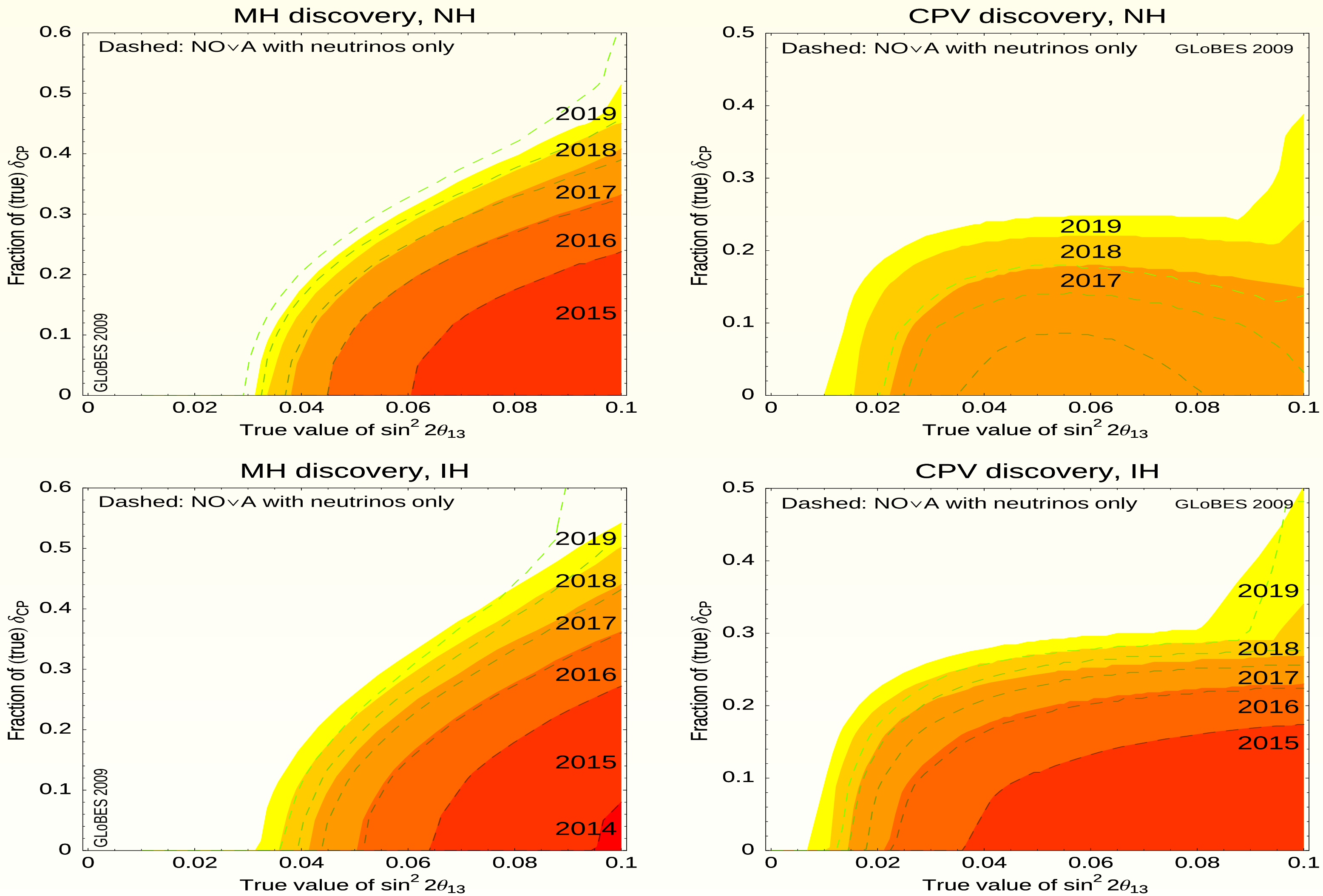
# Prospects Until 2025

P. Huber



# Prospects Until 2025

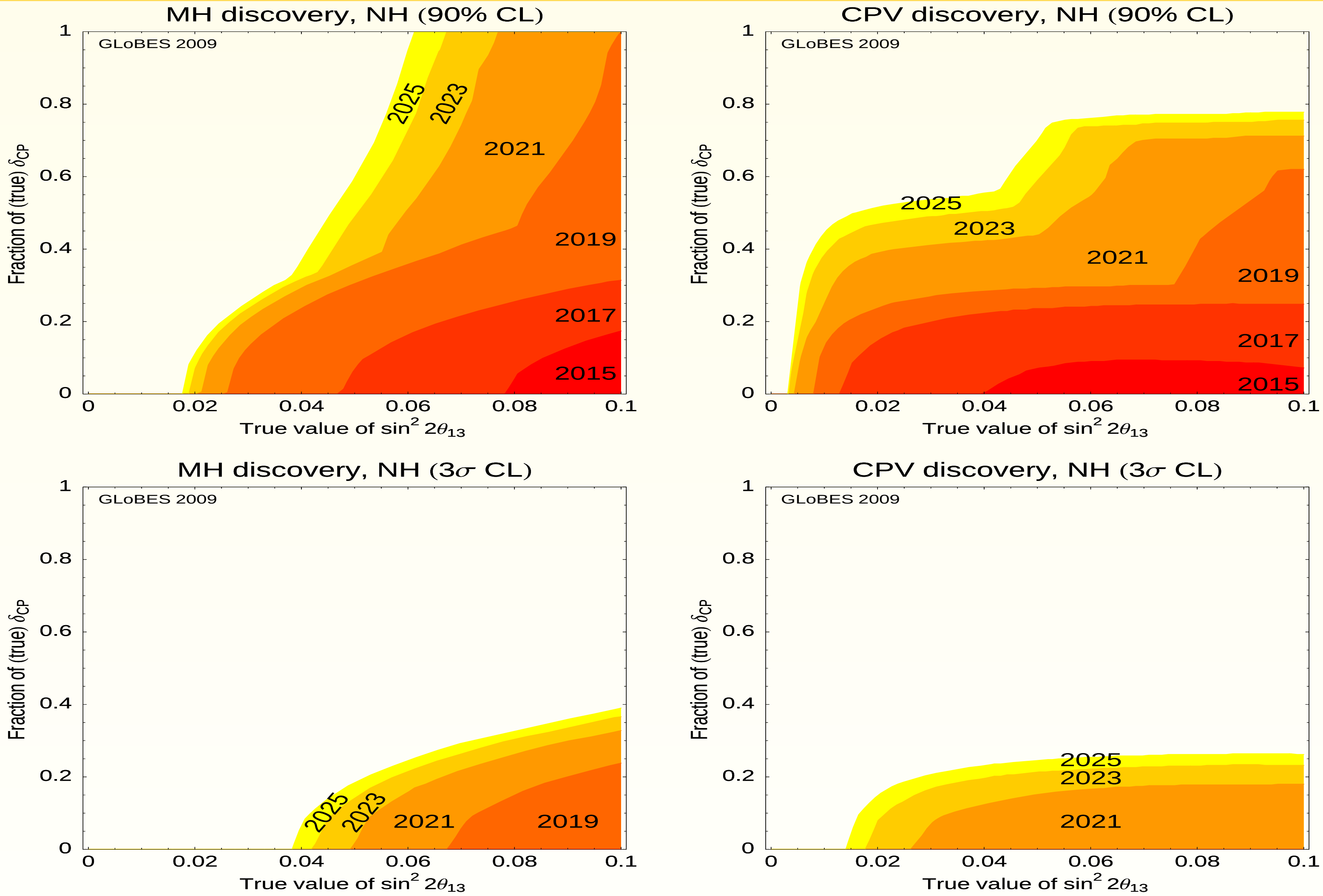
P. Huber




- Reactors+T2K+NOvA
- At 90% C.L.

# Prospects Until 2025

P. Huber




- With beam upgrades – not quite encouraging
- One needs $\sim 300$ kton detector and a WBB to have reasonable sensitivity to hierarchy and CPV

# The Low Energy Neutrino Factory

T. Li

## LENF specifications:

- $1.4 \times 10^{21}$ muon decays per year for 10 years
- $E_\mu = 4.5$ GeV
- $L = 1300$ km
- Either 20 kton magnetized TASD or 100 kton of magnetized liquid Argon

- Consider two extreme scenarios for a 100 kton LAr detector:

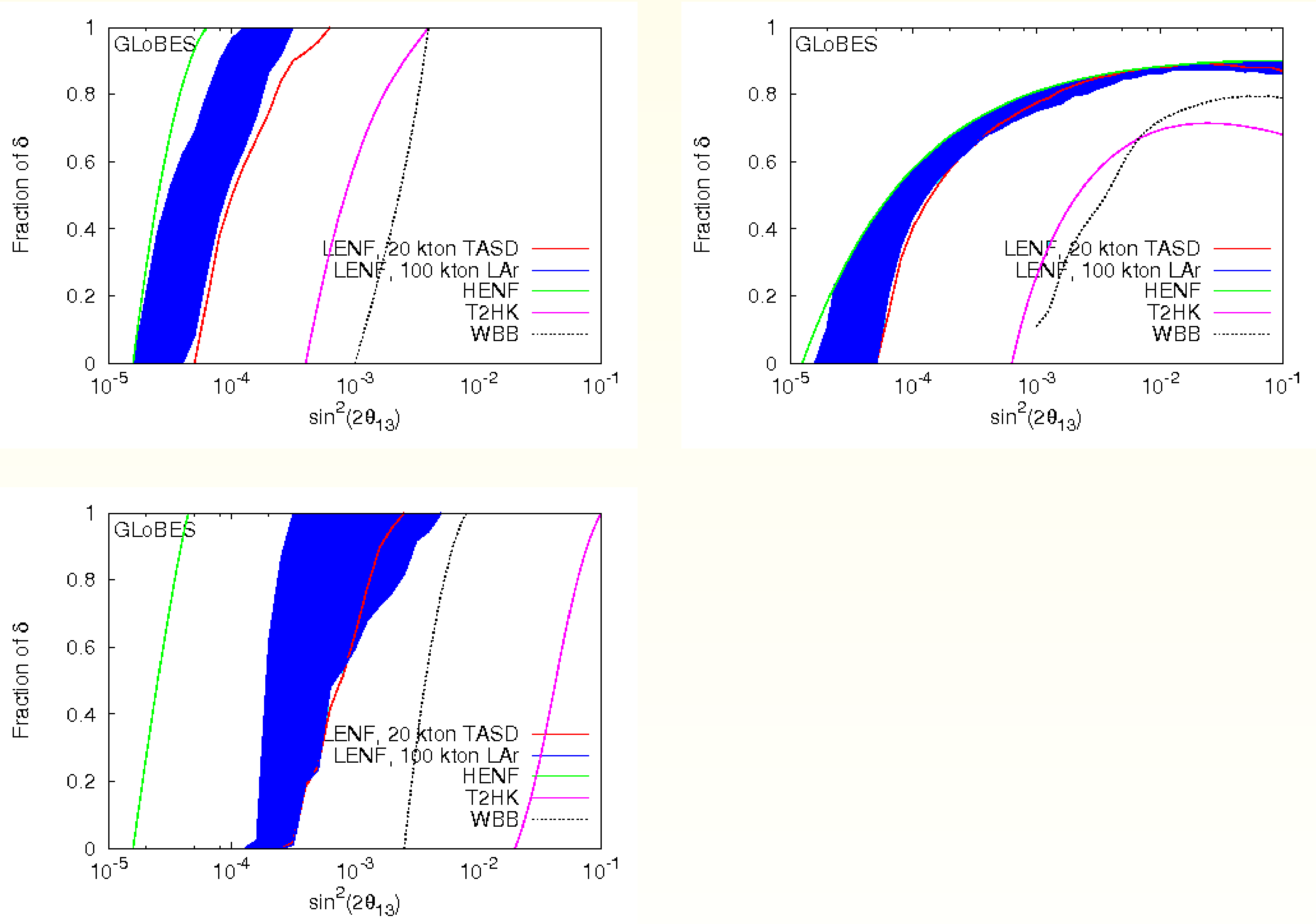
| | Conservative | Optimistic |
|---|---|---|
| Efficiency - all channels | 80% | 80% |
| Systematics | 5% | 2% |
| Energy resolution - QE events | 5% | 5% |
| Energy resolution - non-QE events | 20% | 10% |
| Background on $\nu_\mu$ (dis)appearance channels | $5 \times 10^{-3}$ | $1 \times 10^{-3}$ |
| Background on $\nu_e$ appearance channels | 0.8 | $1 \times 10^{-2}$ |

## For TASD:

- $\epsilon$: 73% (94%) for $E < 1 (> 1)$ GeV
- Bkgrd: $10^{-3}$ ($\mu$), $10^{-2}$ (e)
- $dE/E = 10\%$

# The Low Energy Neutrino Factory

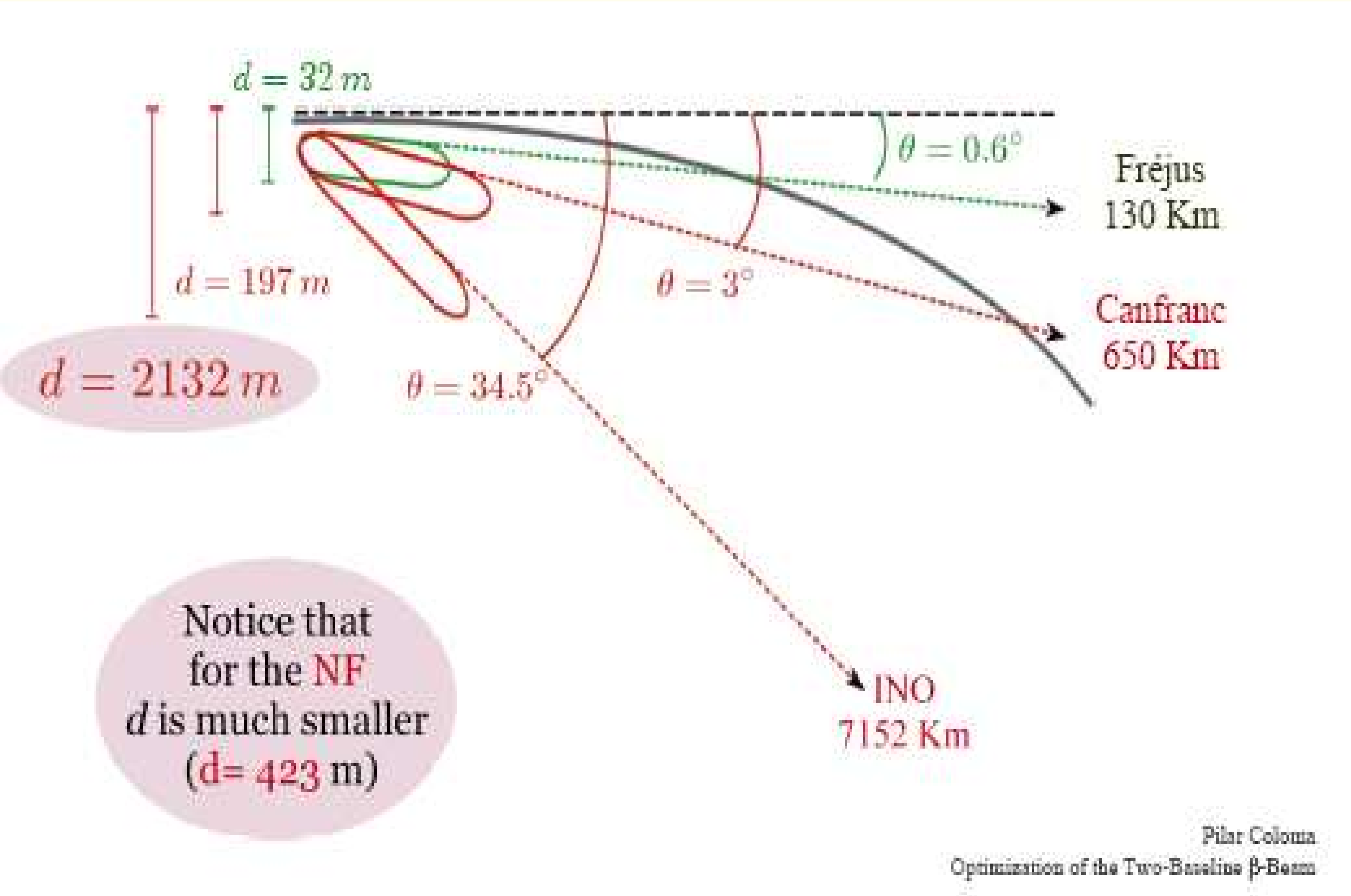
T. Li




- Very good performance with the high end 100 kton LAr

# Better Optimized Beta-Beam

P. Coloma



# Better Optimized Beta-Beam

P. Coloma

- Due to a different A/Z, we can reach higher boost factors for Li/B in the LR:

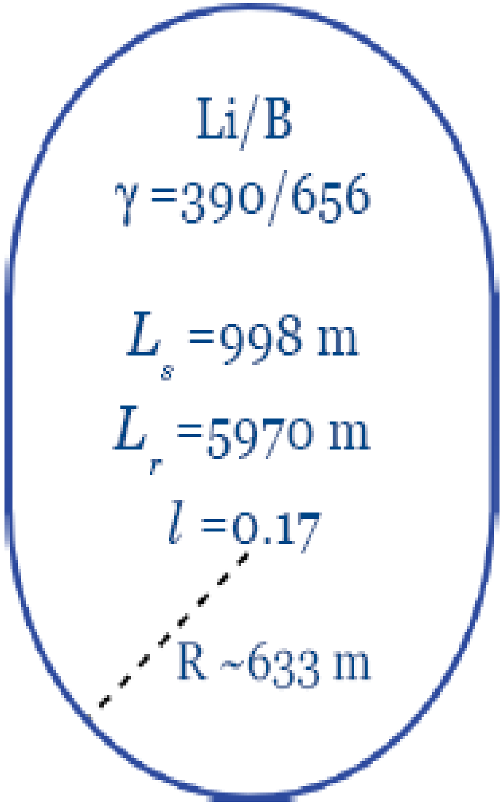
$$\gamma_{max}^{Li/B}\Big|_{Long\,Ring} = 390/656$$

- With only a 10% increase in γ, the statistics increase a 50% !

$$N_{ev}^{Li}(390) = N_{ev}^{Li}(350) \times 1.5$$

- We can use this to reduce the ring size:

$$l = 0.6 \times 0.28 \sim 0.17 \Rightarrow \begin{cases} L_s = 998\,m \\ d = 1282\,m \end{cases}$$




Pilar Coloma
Optimization of the Two-Baseline β-Beam

# Better Optimized Beta-Beam

P. Coloma

## First attempt at optimizing the BB storage ring

**He/Ne @ WC**

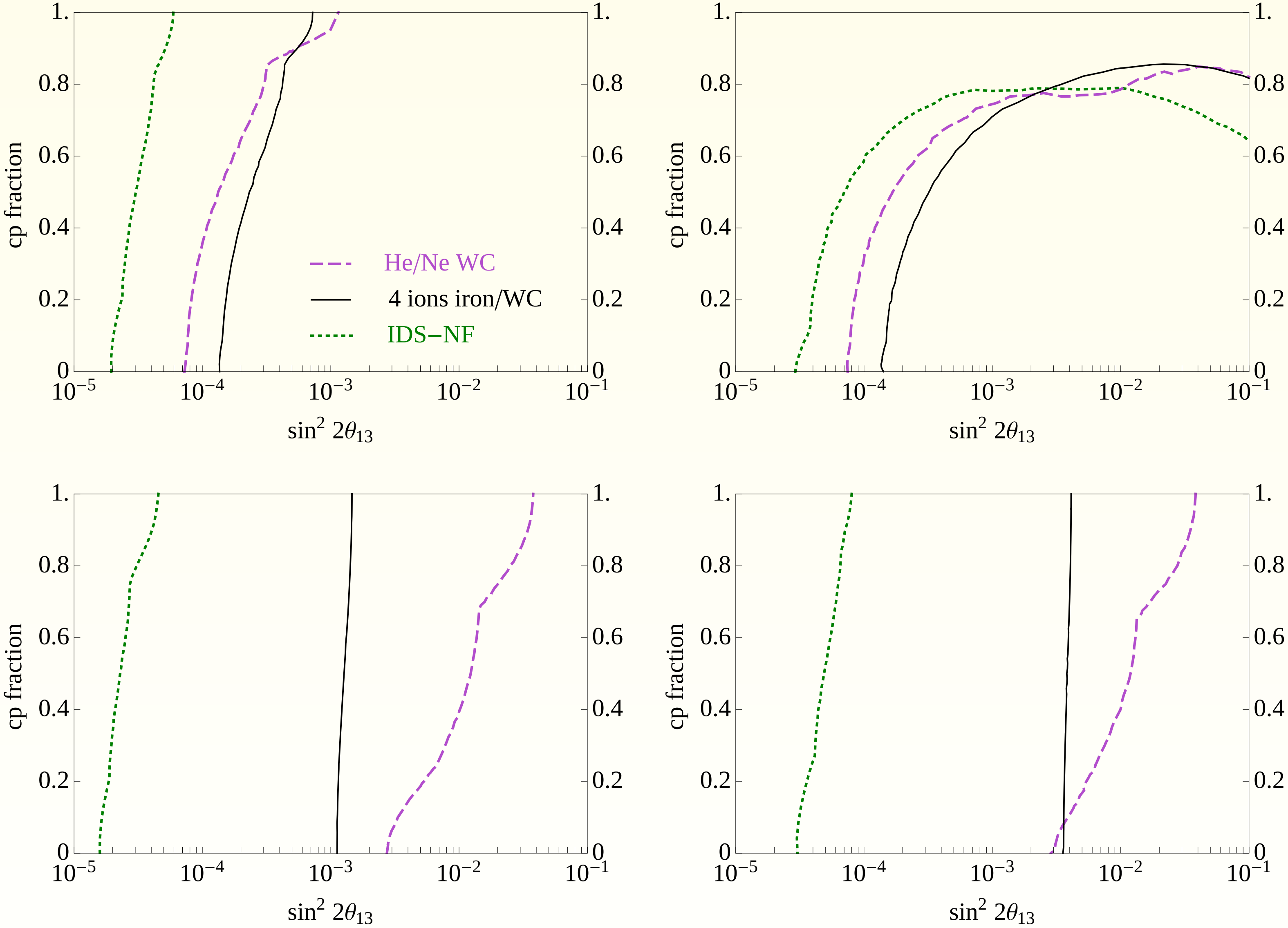
- $\gamma = 350$;
- 500 kton;
- $L = 650$ km (first osc peak);
- 2.5 years/ion;
- $3 \times 10^{18}$ useful decays/year;
- Migration matrices (hep-ph/0503021);
- Uncorr syst errors of 5% and 2.5%;

**Li/B @ MI**

- $\gamma = 350$*(A/Z);
- 50 kton;
- $L = 7000$ km (matter effects);
- 2.5 year/ion;
- $1.7 \times 10^{18}$ useful decays/year;
- MIND Effeciency (IDS-NF);
- Energy resoln = 55%/$\sqrt{E(\mathrm{GeV})}$;
- Uncorr syst errors of 5% and 2.5%;

# Optimized Beta-Beam

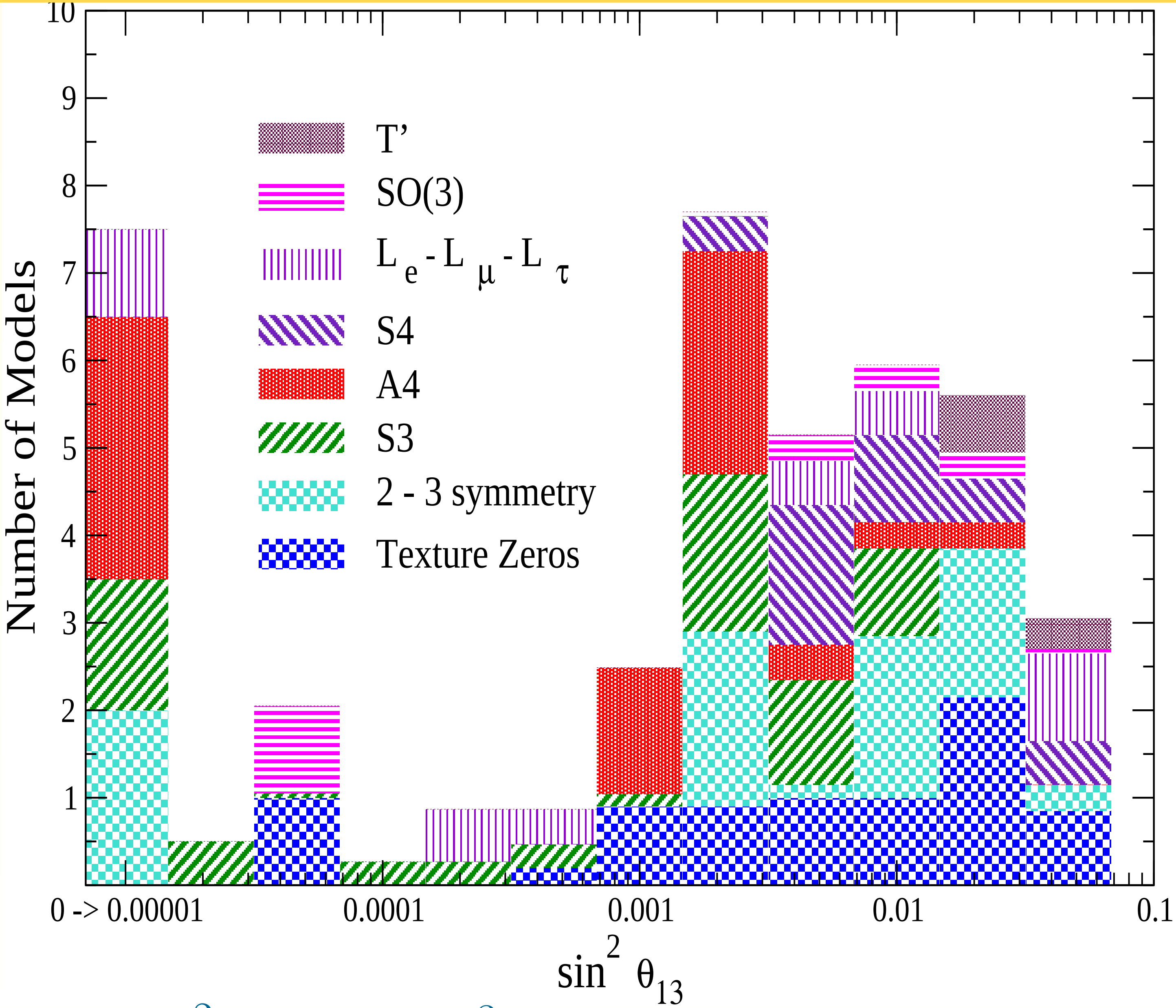
P. Coloma




- Outperforms the Neutrino Factory for $\sin^2 2\theta_{13} \gtrsim 10^{-3}$

# Model Predictions for Osc Para

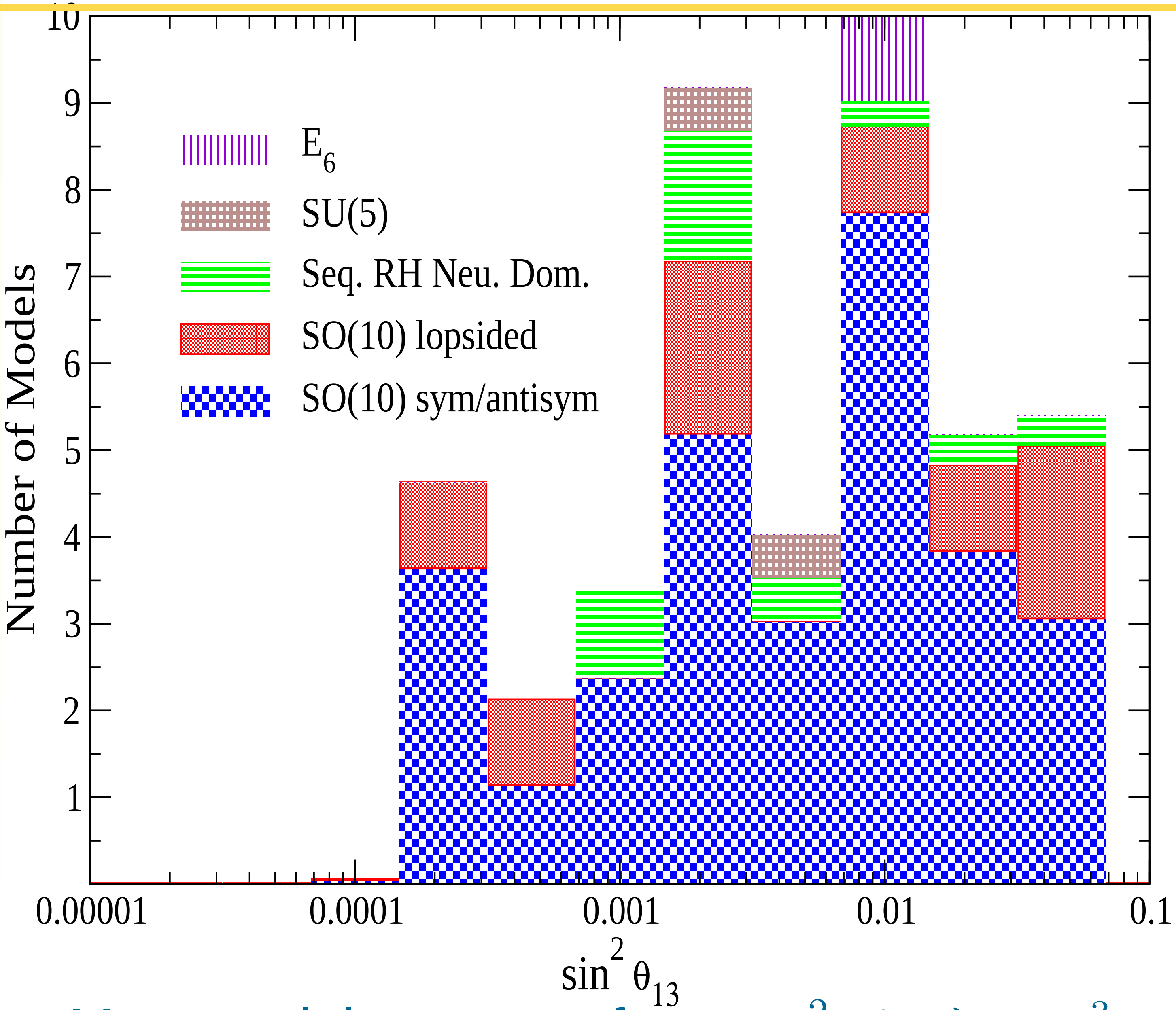
C. Albright




- Is $\sin^2 2\theta_{13} \gtrsim 10^{-3}$ more "natural"?

# Model Predictions for Osc Para

C. Albright




- Most models seem to favor $\sin^2 2\theta_{13} \gtrsim 10^{-3}$

# Near Detector at a Neutrino Factory

Questions from IDS-NF

- Study of the potential of near detectors to cancel systematical errors.
- Study of the characteristics of the near detectors, such as technology, number, *etc*.
- Study of the use of the near detectors for searches of new physics.

*reference: https://www.ids-nf.org/*

**J. Tang**

- These questions were addressed in detail by
- Results/conclusions can be found in his slides

# Also Discussed

- *Almost* all sens plots shown in WG1 were done with GLoBES
- GLoBES **P. Huber**
- MonteCUBES **M. Blennow**
- Update on T2KK (V2) **N. Okamura**
- Direct Mass Limits using BB **C. Orme**
- CPV from BB+EC nu expt **M-C. Espinoza-Hernandez**
- Constraining sterile nus with a low E BB **S. Agarwalla**
- Sterile neutrinos at a neutrino factory **J. Lopez-Pavon**
- Low E atmos nu expts **O. Peres**

# Discussion Session at this NuFact

- NuFlavor Workshop Summary and Discussions

S. Pascoli

# Questions for Next NuFact

- Is there really a synergy between Neutrino Oscillation Expts, LFV expts, Neutrino-less double beta decay expts, direct mass search experiments, SN, LHC....?
- What is the case for precision in neutrino expts? Does it lead to better theoretical understanding?
- What value of $\sin^2 2\theta_{13}$ is uninterestingly small?
- Is it really possible to measure NSI in neutrino oscillation expts?

*Thank you*