

# Neutrino physics beyond $\theta_{13}$ at $\nu$ -factories and $\beta$ -beams

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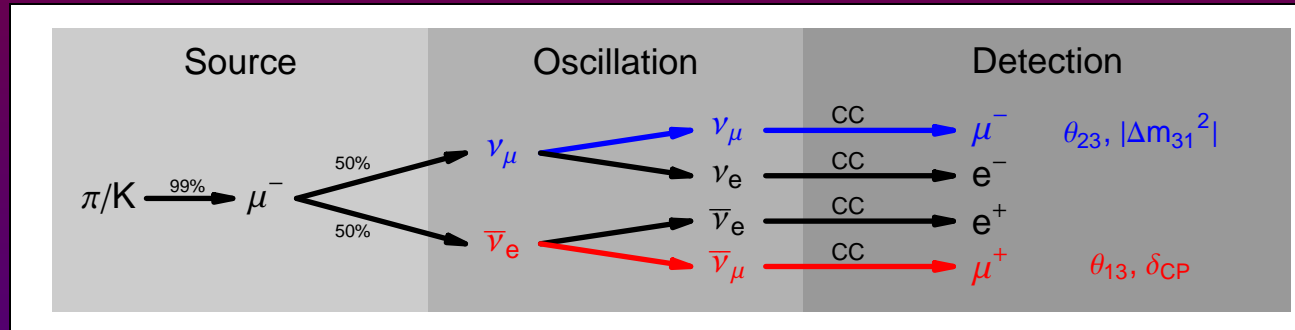
in collaboration with P. Huber, M. Lindner, and W. Winter

# Outline

- Concept of  $\nu$ -factories and  $\beta$ -beams
- Appearance channels
  - Parameter correlations
  - Degeneracies
- Performance indicators
  - Sensitivity to  $\sin^2 2\theta_{13}$
  - Sensitivity to maximal CP violation
  - Sensitivity to the sign of  $\Delta m_{31}^2$
- Silver channel and platinum channel at a  $\nu$ -factory

# $\nu$ -factories and $\beta$ -beams

- Concept of a  $\nu$ -factory: neutrino beam from decaying muons



- Concept of a  $\beta$ -beam: neutrino beam from beta decaying isotopes



Golden channel for both cases:  $\nu_e(\bar{\nu}_e) \rightarrow \nu_\mu(\bar{\nu}_\mu)$

- no muon CID needed for  $\beta$ -beams
- $\beta$ -beam cannot measure leading atmospheric parameters

# Appearance channels

Golden channel at  $\nu$ -factories and  $\beta$ -beams:

Expanding in the small parameters  $\sin 2\theta_{13}$  and  $\alpha \equiv \frac{\Delta m_{21}^2}{\Delta m_{31}^2} \sim \pm 0.04$ :

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

$$\text{with } \Delta \equiv \frac{\Delta m_{31}^2 L}{4 E_\nu} \text{ and } \hat{A} \equiv \frac{2\sqrt{2}G_F n_e E}{\Delta m_{31}^2}$$

Cervera et al. 2000; Freund,Huber,Lindner, 2000; Freund, 2001

# Correlations and degeneracies

Golden appearance channel suffers from:

- parameter correlations
- degeneracies:

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

Burguet-Castell et al., 2001

$$(\theta_{13}, \delta_{CP}) \rightarrow (\theta'_{13}, \delta'_{CP})$$

- Sign-degeneracy

Minakata, Nunokawa, 2001

$$\Delta m_{31}^2 \rightarrow -\Delta m_{31}^2 \text{ (exactly compensated by } \delta_{CP} \rightarrow -\delta_{CP} \text{ in vacuum)}$$

- $\theta_{23}$ -degeneracy

Fogli, Lisi, 1996

$$\theta_{23} \rightarrow \pi/2 - \theta_{23}$$

# Strategies to resolve degeneracies

$\nu$ -factory and  $\beta$ -beam:

- neutrino and anti-neutrino running:  $\nu_e \rightarrow \nu_\mu$  and  $\bar{\nu}_e \rightarrow \bar{\nu}_\mu$

$$P_{\bar{e}\bar{\mu}} = P_{e\mu}(\delta_{CP} \rightarrow -\delta_{CP}, \hat{A} \rightarrow -\hat{A})$$

only at  $\nu$ -factory:

- add magic baseline (2nd detector)

$$L \sim 8000 \text{ km} \rightarrow \sin(\hat{A}\Delta) = 0$$

- add silver channel:  $\nu_e \rightarrow \nu_\tau$

$$P_{e\tau} = P_{e\mu}(s_{23}^2 \leftrightarrow c_{23}^2, \sin 2\theta_{23} \rightarrow -\sin 2\theta_{23})$$

- add platinum channel:  $\nu_\mu \rightarrow \nu_e$

$$P_{\mu e} = P_{e\mu}(\delta_{CP} \rightarrow -\delta_{CP})$$

# Performance indicators

All results have been calculated using the **GLOBES** software

P. Huber, M. Lindner, W. Winter, *Comput. Phys. Commun.*, 167 (2005) 195

- **Sensitivity limit to  $\sin^2 2\theta_{13}$ :**

Largest fit value of  $\sin^2 2\theta_{13}$  which fits an assumed true value  $\sin^2 2\theta_{13} = 0$  at the chosen confidence level (systematics, correlations, and degeneracies included).

- **Sensitivity to maximal CP violation:**

Smallest true value of  $\sin^2 2\theta_{13}$  for which the CP conserving fit values  $\delta_{CP} = 0$  and  $\delta_{CP} = \pi$  can be excluded at the chosen confidence level, if true  $\delta_{CP} = \pi/2$  or  $\delta_{CP} = 3\pi/2$  is assumed (systematics, correlations, and degeneracies included).

- **Sensitivity to the sign of  $\Delta m_{31}^2$ :**

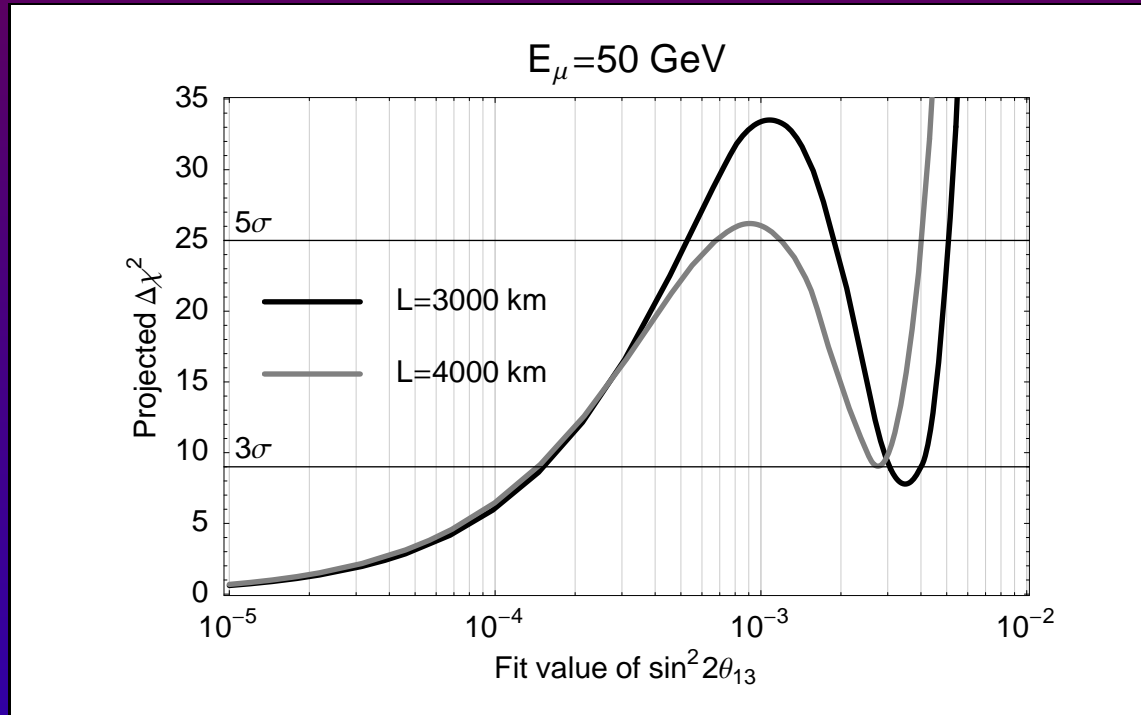
Smallest true value of  $\sin^2 2\theta_{13}$  for which the degenerate solution with  $\Delta m_{31}^2 < 0$  does not appear at the chosen confidence level if true  $\Delta m_{31}^2 > 0$  is assumed (systematics and correlations included).

# Example: correlations and degeneracies

e.g. sensitivity limit to  $\sin^2 2\theta_{13}$

calculated with the hypothesis of true  $\sin^2 2\theta_{13} = 0$

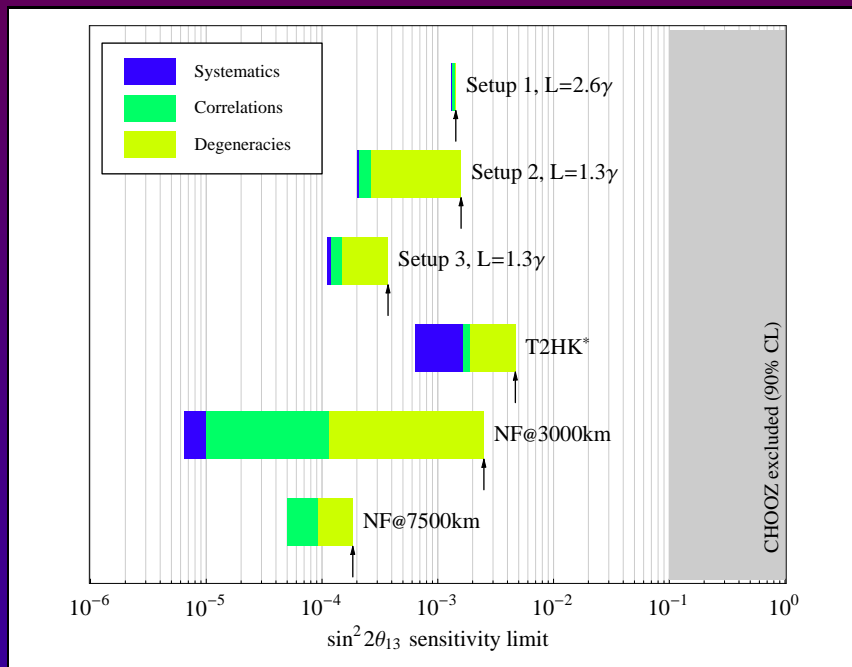
Here: golden channel at  $\nu$ -factory with  $E_{\text{max}} = 50 \text{ GeV}$  (only fitted with  $\Delta m_{31}^2 > 0$ )



The sensitivity to  $\sin^2 2\theta_{13}$  suffers from the intrinsic  $(\delta_{CP}, \sin^2 2\theta_{13})$ -degeneracy

# $\sin^2 2\theta_{13}$ sensitivity limit

at  $\nu$ -factories and  $\beta$ -beams:



- Setup 1:  $\beta$ -beam  
 $\gamma = 200$ ,  $L = 520$  km, WC (500 kt)
- Setup 2:  $\beta$ -beam  
 $\gamma = 500$ ,  $L = 650$  km, T ASD (50 kt)
- Setup 3:  $\beta$ -beam  
 $\gamma = 1000$ ,  $L = 1300$  km, T ASD (50 kt)
- T2HK\*: T2K upgrade (superbeam)  
 $L = 295$  km, WC (500 kt)
- NF@3000km:  $\nu$ -factory (golden channel)  
 $E_{\max} = 50$  GeV,  $L = 3000$  km, MID (50 kt)
- NF@7500km:  $\nu$ -factory (golden channel)  
 $E_{\max} = 50$  GeV,  $L = 7500$  km, MID (50 kt)

Figure taken from P. Huber, M. Lindner, MR, and W. Winter, Phys. Rev. D73 (2006) 053002

# Sensitivity to CP violation

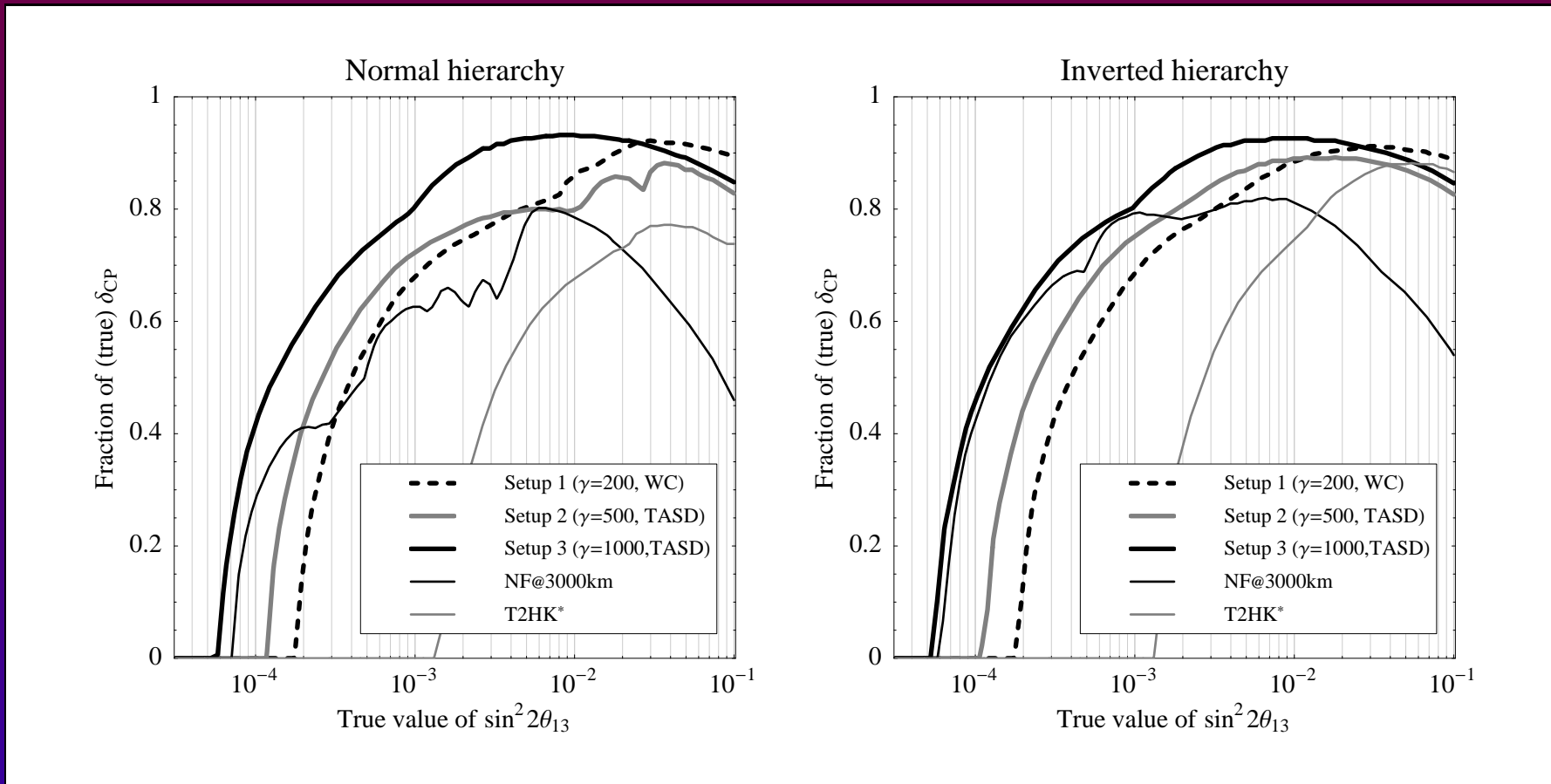


Figure taken from P. Huber, M. Lindner, MR, and W. Winter, Phys. Rev. D73 (2006) 053002

# Sensitivity to the sign of $\Delta m_{31}^2$

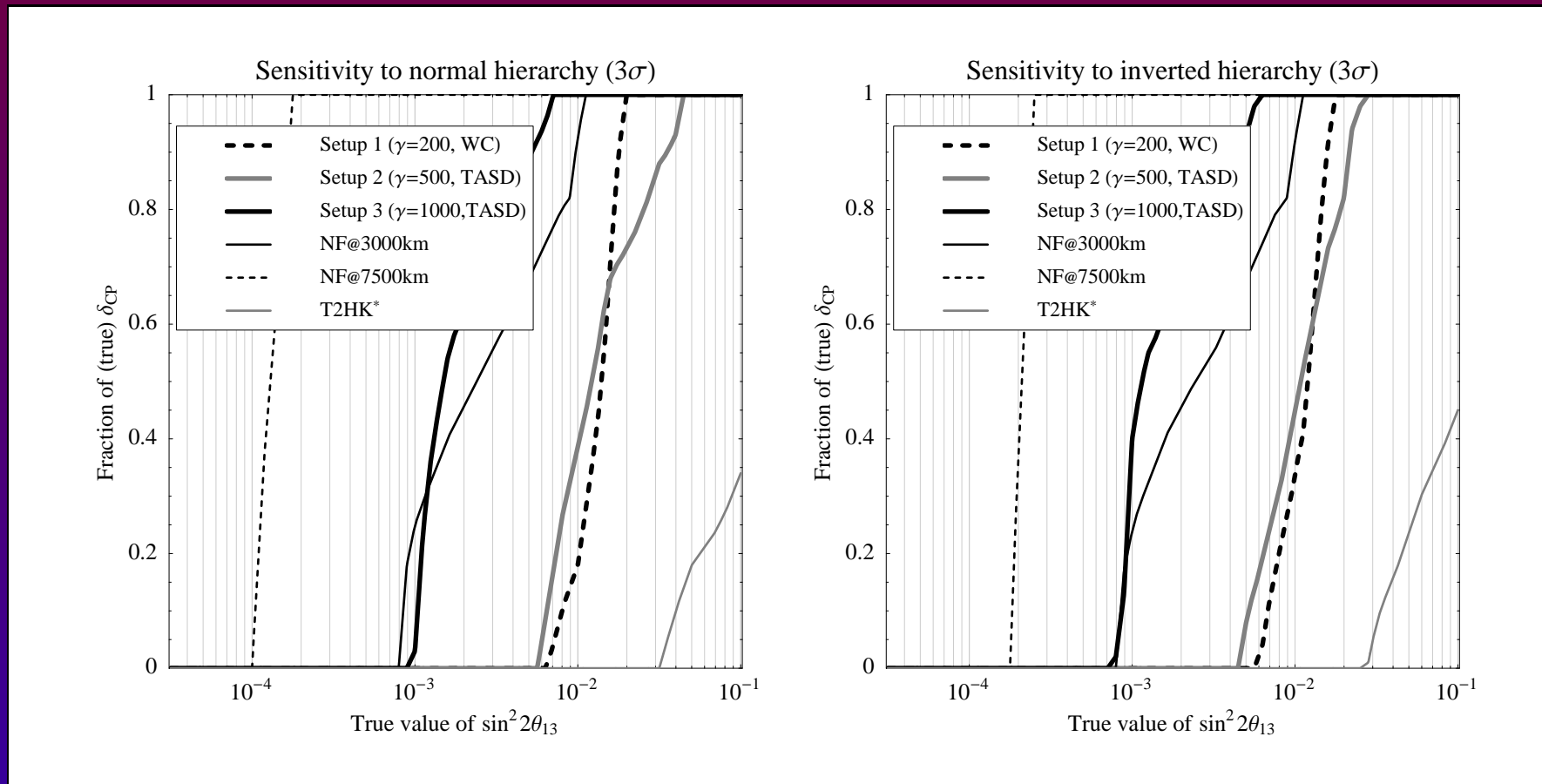


Figure taken from P. Huber, M. Lindner, MR, and W. Winter, Phys. Rev. D73 (2006) 053002

# Additional channel information - I

$\nu$ -factory:

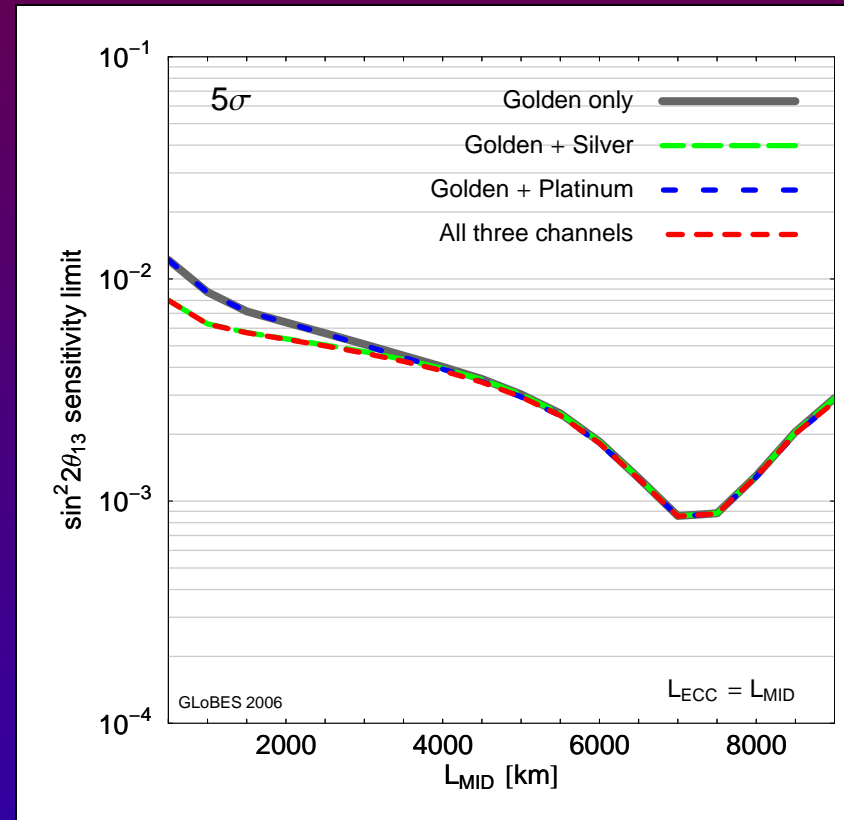
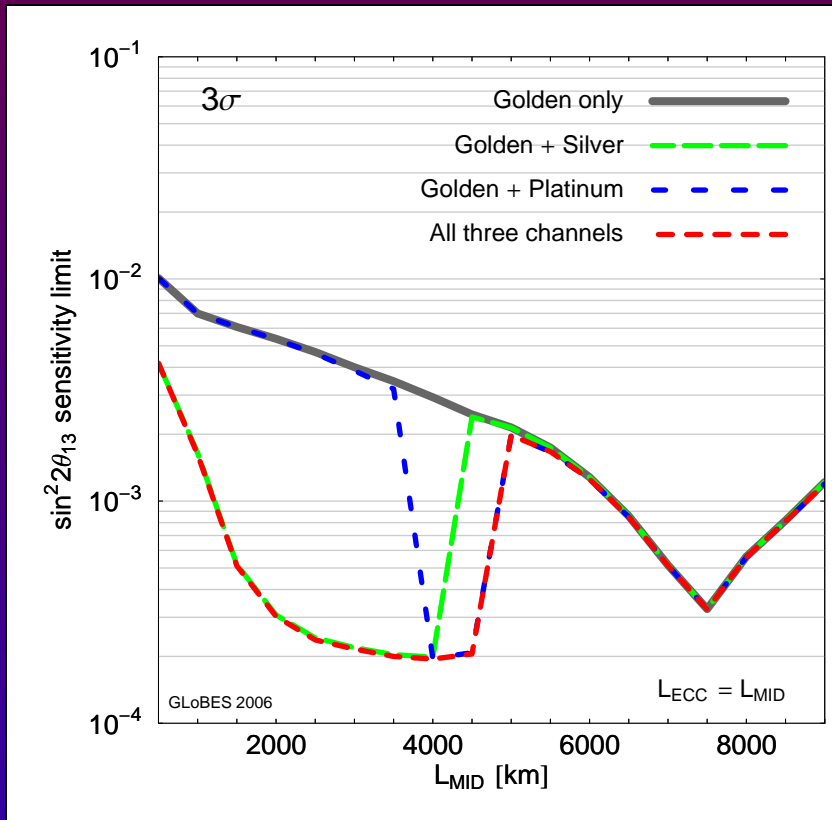
golden channel combined with silver channel and platinum channel

Assumptions:

- silver channel follows D. Autiero et al., Eur. Phys. J. C33 (2004) 243
  - additional ECC detector (OPERA-like)
  - fiducial mass 10 kt (optimistic)
  - only  $\mu^+$ -stored phase (neutrinos)
  - $L_{\text{ECC}} = L_{\text{MID}}$  (matter density uncertainty correlated)
- platinum channel follows M. Diwan et al., NuMI-L-714 (2001)
  - measured at golden detector
  - matter density uncertainty correlated
  - 1% additional background from charge identification

# Additional channel information - II

$\nu$ -factory: sensitivity to  $\sin^2 2\theta_{13}$   $E_{\max} = 50\text{GeV}$

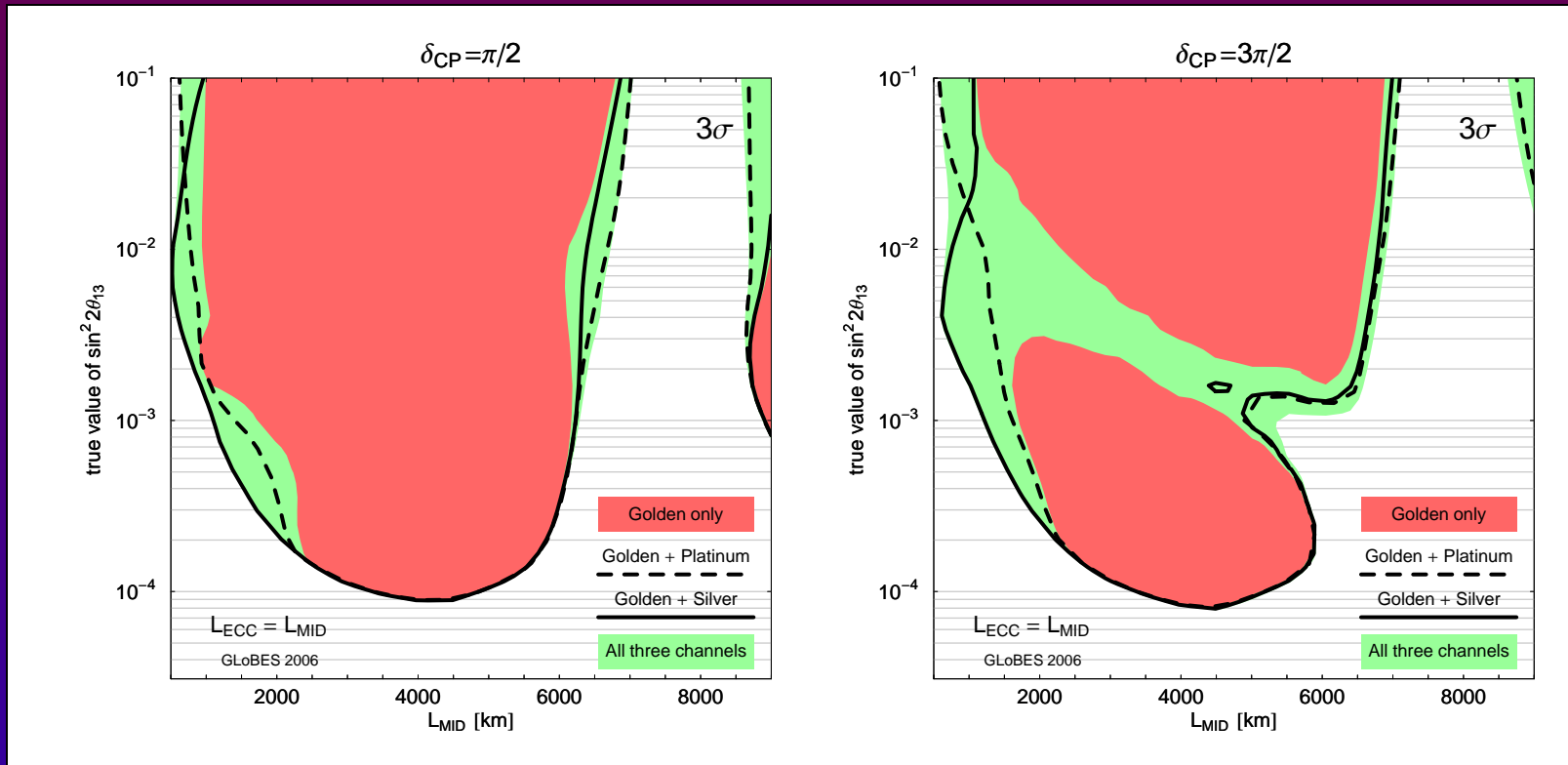


P. Huber, M. Lindner, MR, and W. Winter, to appear

# Additional channel information - III

$\nu$ -factory: sensitivity to maximal CP violation

$$E_{\max} = 50\text{GeV}$$

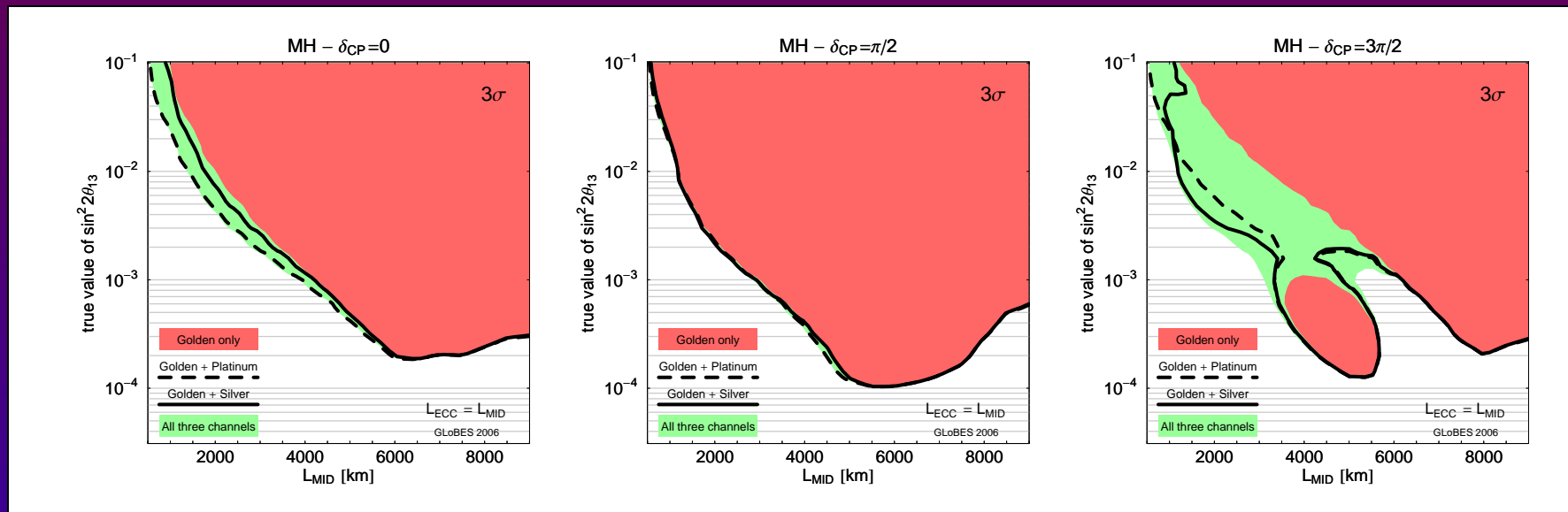


P. Huber, M. Lindner, MR, and W. Winter, to appear

# Additional channel information - IV

$\nu$ -factory: sensitivity to the sign of  $\Delta m_{31}^2$

$E_{\max} = 50\text{GeV}$

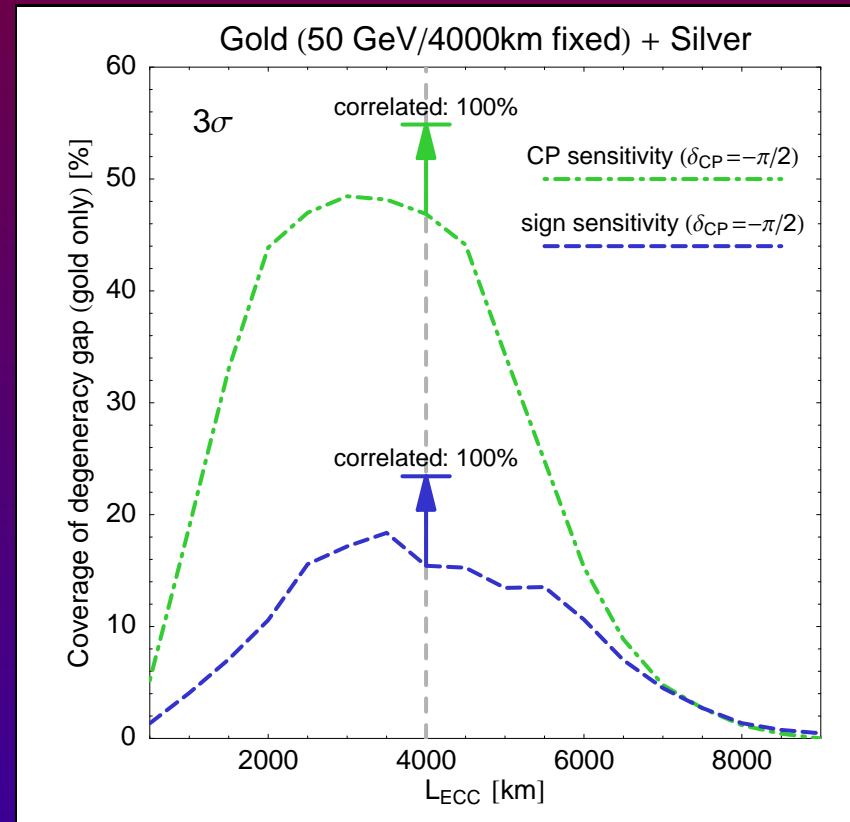
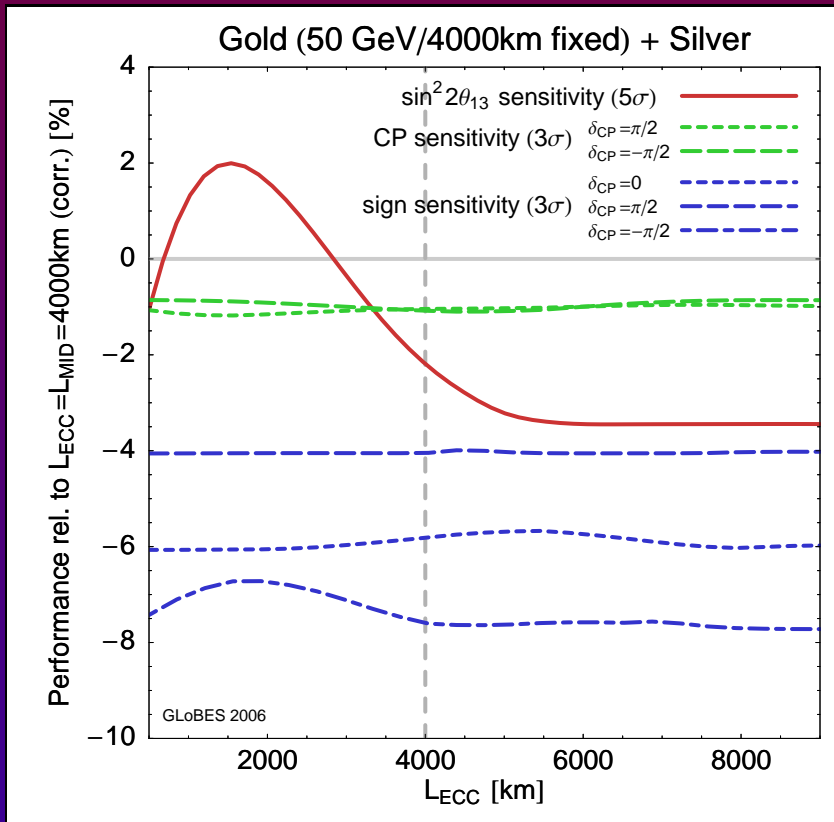


P. Huber, M. Lindner, MR, and W. Winter, to appear

# Conclusions

- $\beta$ -beams could compete with  $\nu$ -factories in measurements of  $\sin^2 2\theta_{13}$  and  $\delta_{CP}$  (especially for larger  $\sin^2 2\theta_{13}$ )
- no measurement of leading atmospheric parameters at  $\beta$ -beams
- $\nu$ -factories outperform  $\beta$ -beams in the determination of neutrino mass hierarchy
- $\nu$ -factories suffer from degeneracies (especially for true  $\delta_{CP} \sim 3\pi/2$ )
- additional silver channel and platinum channel information could help to resolve the degeneracies

# Silver channel baseline



P. Huber, M. Lindner, MR, and W. Winter, to appear