The race for the neutrino mass hierarchy

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WIN13
Natal, Brazil
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Current status in neutrino oscillations

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

Atmospheric — Interference — Solar

Known:

$$\begin{aligned} \theta_{12} &= 33.36^\circ \\ \theta_{23} &= 40^\circ/50.4^\circ \\ \theta_{13} &= 8.66^\circ \\ \Delta m^2_{21} &= 7.5 \times 10^{-5}\mathrm{eV}^2 \\ \Delta m^2_{31} &= 2.47 \times 10^{-3}\mathrm{eV}^2 (\text{for NH}) \end{aligned}$$

Unknown

$$\delta \neq 0, \pi?$$

$$m_3 \gtrless m_2?$$

$$\theta_{23} \gtreqless 45^\circ?$$

Gonzalez-Garcia, Maltoni, Salvado, Schwetz, 1209.3023 [hep-ph]

(See Gonzalez-Garcia's plenary talk on Monday)

The unknowns

Unknown

$$\delta \neq 0, \pi?$$

$$m_3 \gtrless m_2?$$

$$\theta_{23} \gtreqless 45^\circ?$$

The measured parameter which currently holds the largest uncertainty.

Important for the flavor puzzle:

- bimaximal, tri-bimaximal, etc
- golden ratio
- quark-lepton complementarity

...

The unknowns

Unknown

$$\delta \neq 0, \pi ?$$

$$m_3 \gtrless m_2 ?$$

$$\theta_{23} \gtreqless 45^\circ ?$$

- Is CP violated only in the quark sector?
- Is leptogenesis viable?
- Model building

...

Note that an appearance experiment is needed to observe CP violation

The unknowns

Unknown

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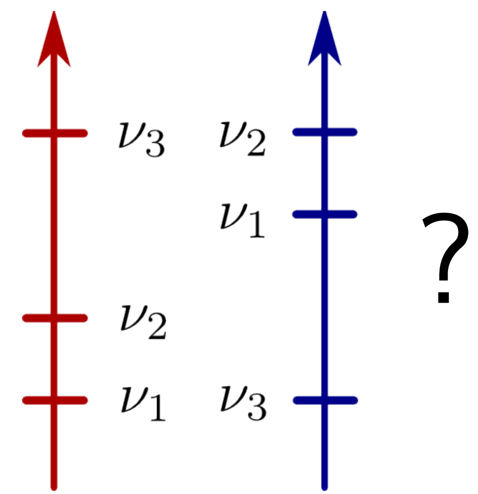

The unknowns

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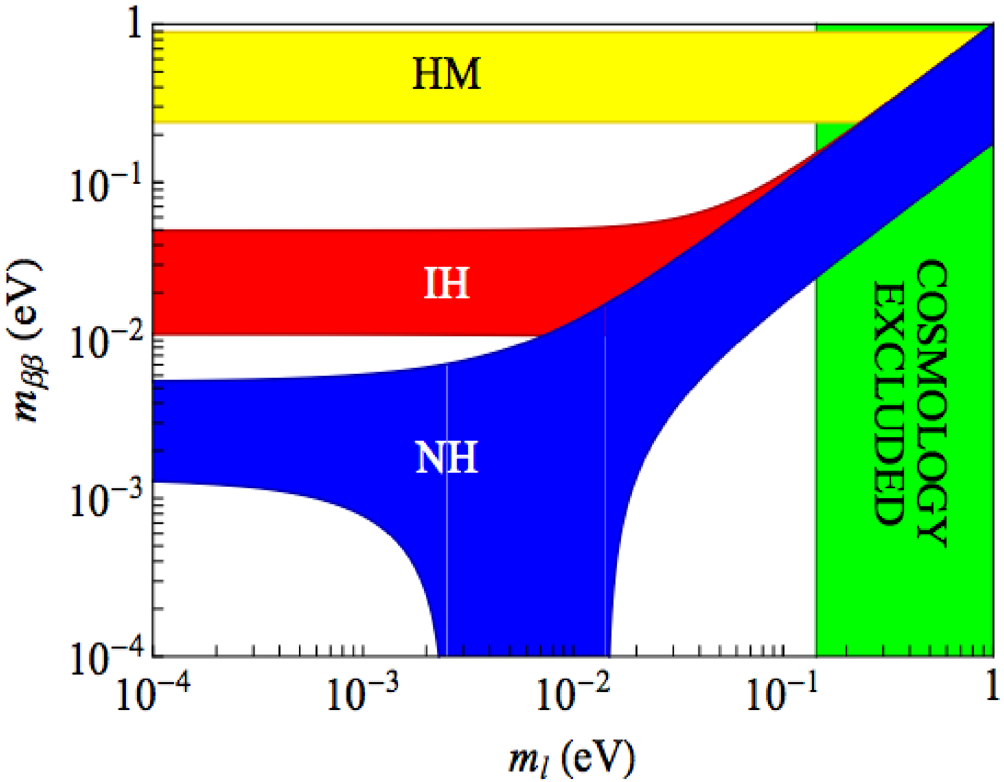


An independent measurement of the hierarchy is extremely useful as a double-check of $0\nu\beta\beta$

(see, for instance, Blennow et al, 1005.3240 [hep-ph])

The unknowns

Unknown

$$\delta \neq 0, \pi?$$

$$m_3 \gtrless m_2?$$

$$\theta_{23} \gtreqless 45°?$$

An unknown hierarchy usually leads to a reduced ability to observe CP violation

Minakata, Nunokawa, hep-ph/0108085

Barger, Marfatia, Whisnant, hep-ph/0112119

$$P^{\pm}_{e\mu}(\theta_{13}, \delta) = X_{\pm} \sin^2 2\theta_{13}$$

$$+ Y_{\pm} \cos\theta_{13} \sin 2\theta_{13} \cos\left(\pm\delta - \frac{\Delta m^2_{31} L}{4E}\right)$$

$$+ Z$$

Ways to measure the hierarchy

A large θ_{13} opens many ways to measure the hierarchy:

i. Matter effects

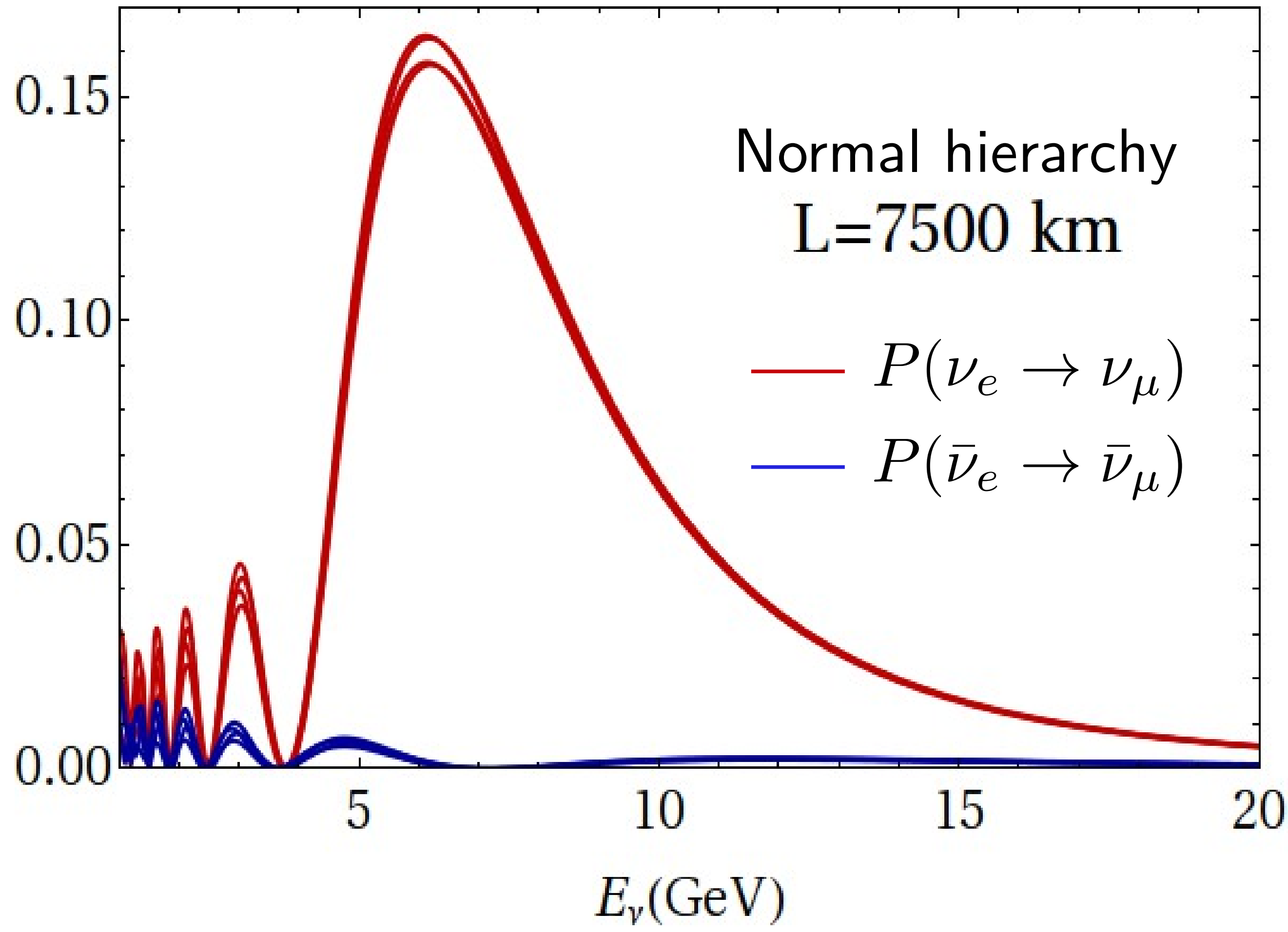
- In appearance $\rightarrow$ beams (at lower energies)
- In disappearance $\rightarrow$ atmospheric neutrinos

ii. Interference effects between solar and atmospheric oscillations $\rightarrow$ reactors at medium baselines

iii. Precise measurement of the two squared mass splittings

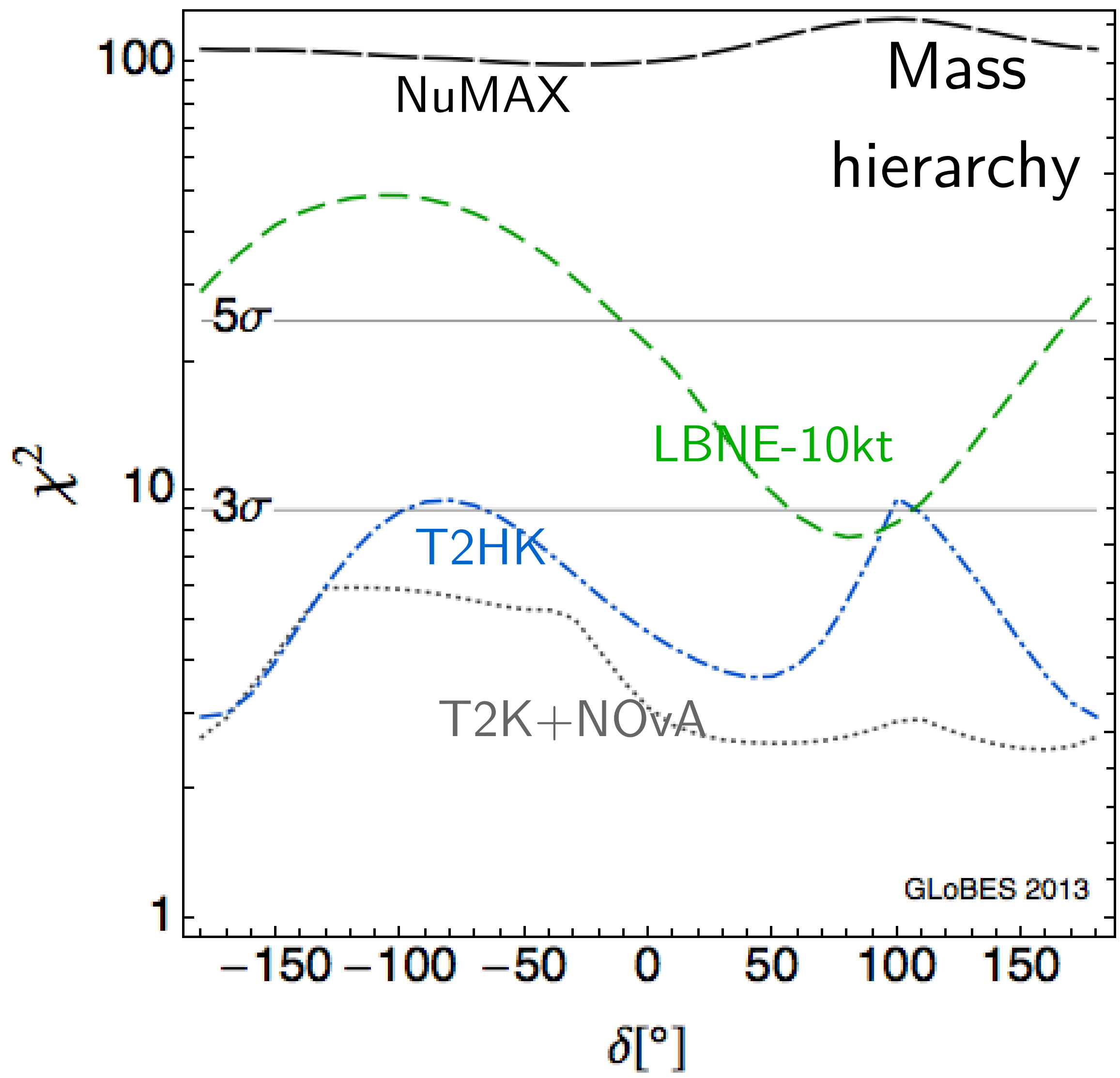
Additional possible ways are cosmology and supernovae (see Chakraborty's talk this morning), but I will not cover them in this talk

(i-a) Matter effects in appearance (beams)

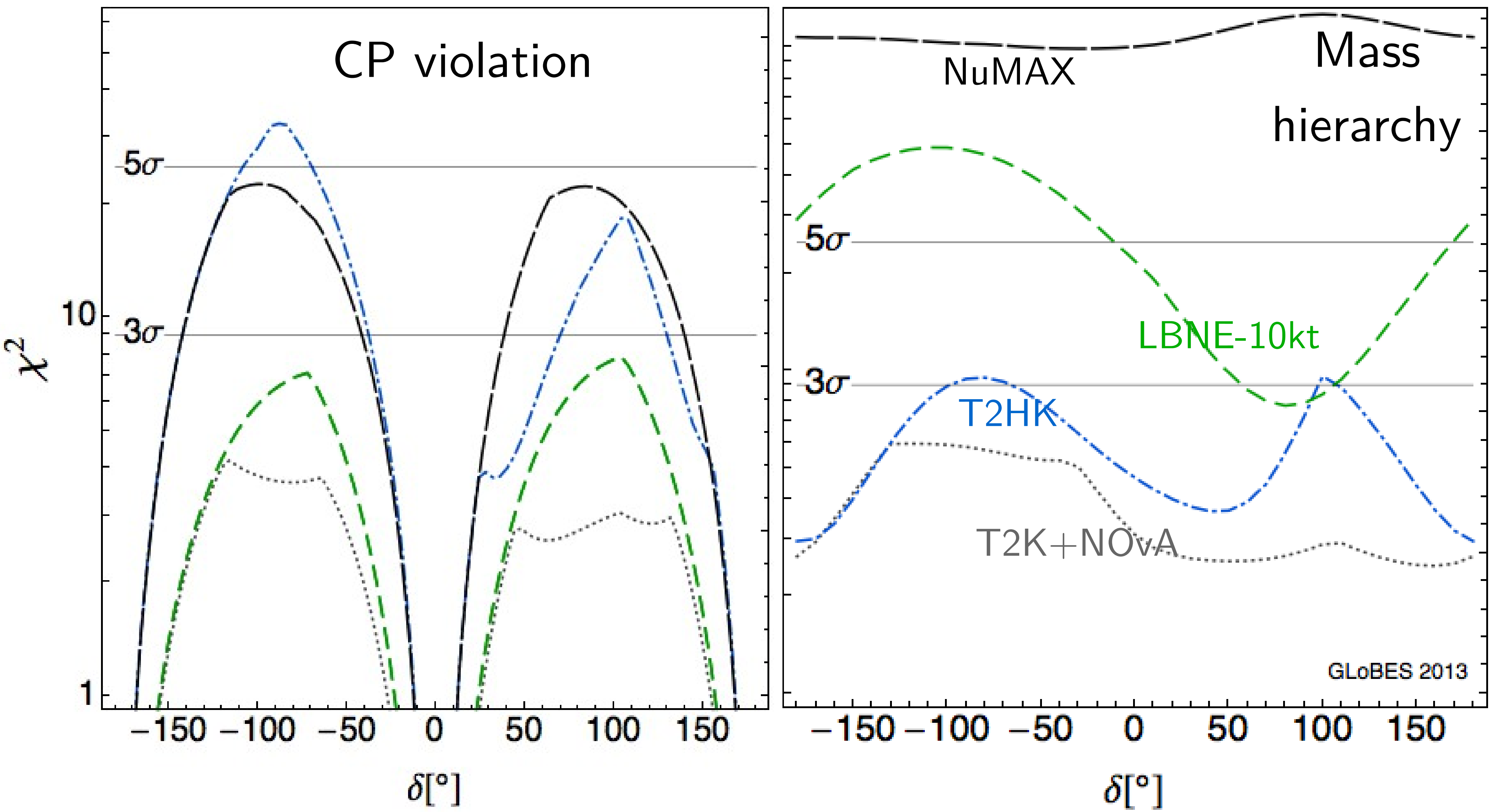


Wolfenstein ('78), Barger et al ('80),
Mikheev and Smirnov ('85)

(i-a) Matter effects in appearance (beams)



(i-a) Matter effects in appearance (beams)

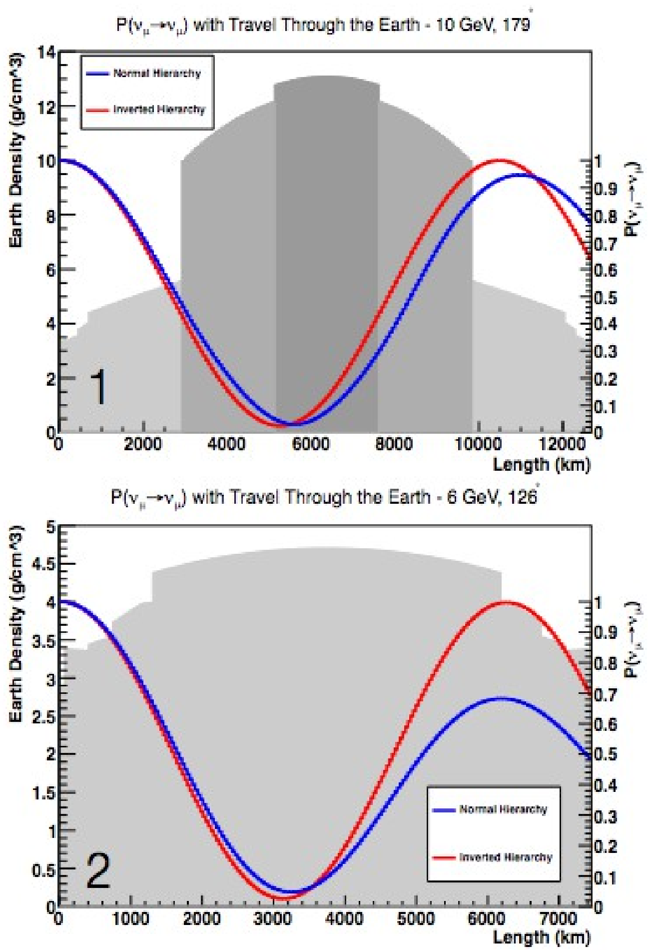


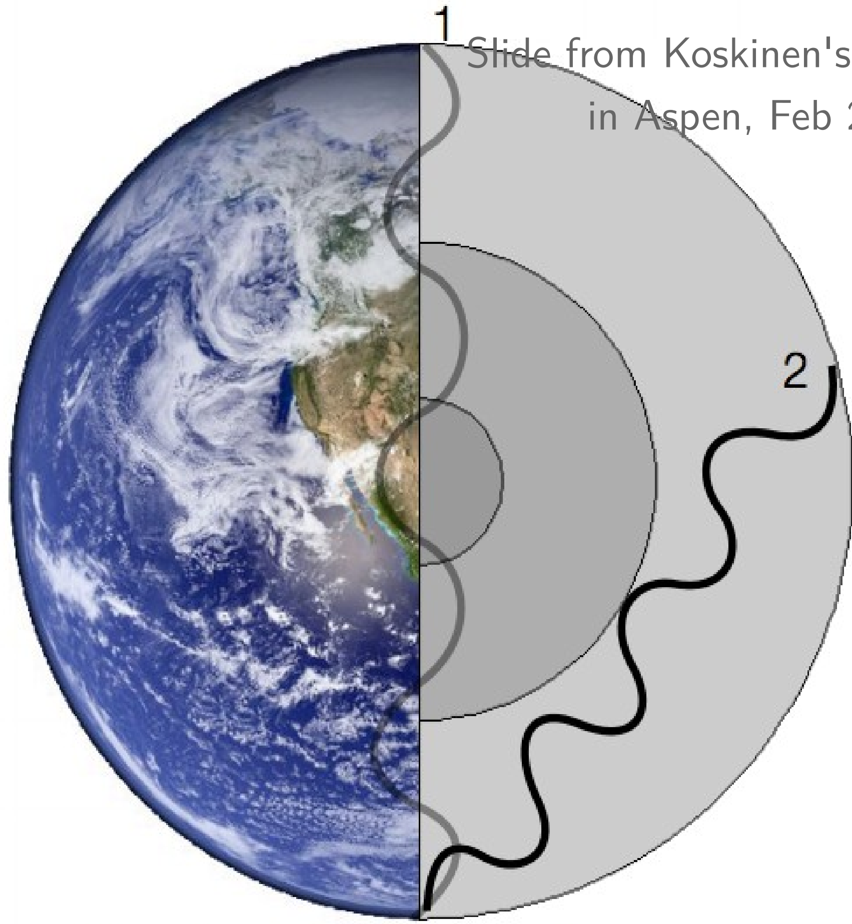
(i-b) Matter effects in disappearance

Bañuls, Barenboim, Bernabéu, hep-ph/0102184

Bernabéu, Palomares-Ruiz,Pérez,Petcov, hep-ph/0110071

$$P^{\pm}_{\mu\mu}(\theta_{13},\delta) = 1 - \chi_{\pm}\sin^2 2\theta_{13} - \psi_{\pm}\sin 2\theta_{13}\cos\delta - \omega$$





Slide from Koskinen's talk in Aspen, Feb 2013

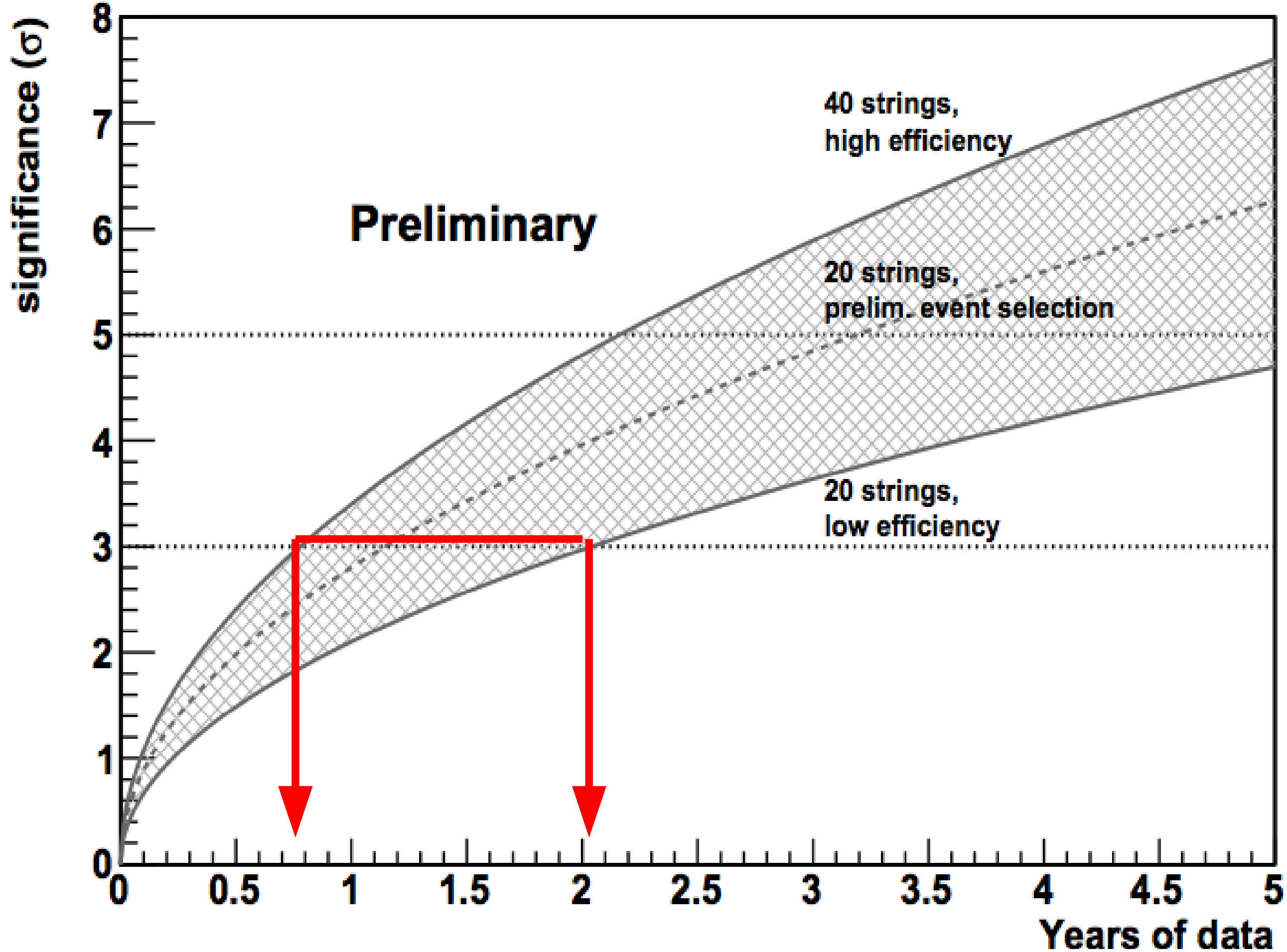
(i-b) Matter effects in disappearance

PINGU

See also:
ORCA (talk at NuFact'13);

Hyper-Kamiokande (see talk at RENO-50 workshop in June 2013);

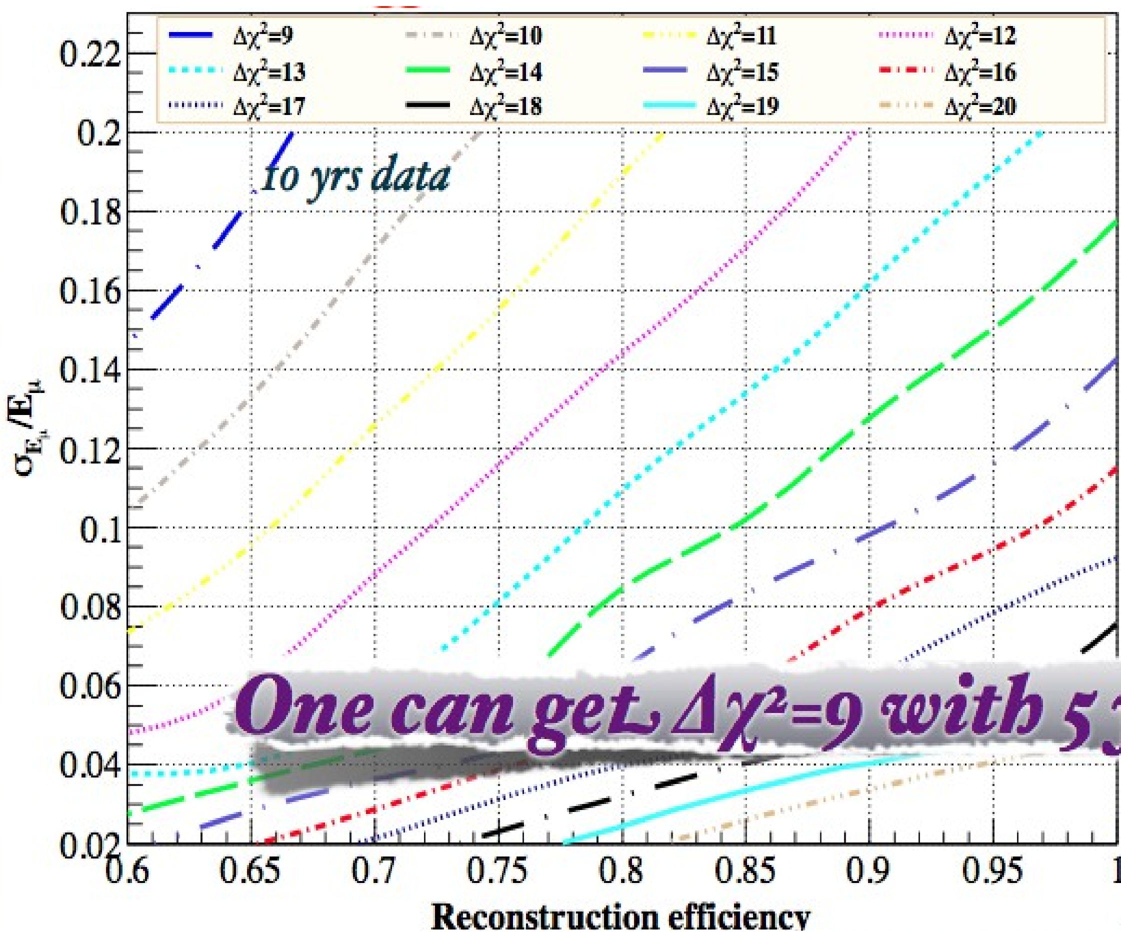
Barger et al, 1203.6012[hep-ph] (50 kt LAr det.)



PINGU coll., 1306.5846 (see also the talk by Kapess in WG4)
(see also Mena, Mocioiu, Razzaque, 0803.3044[hep-ph] and Akhmedov, Razzaque, Smirnov, 1205.7071 [hep-ph])

(i-b) Matter effects in disappearance

ICAL@INO



Results from Ghosh and Choubey, 1306.1423 [hep-ph]

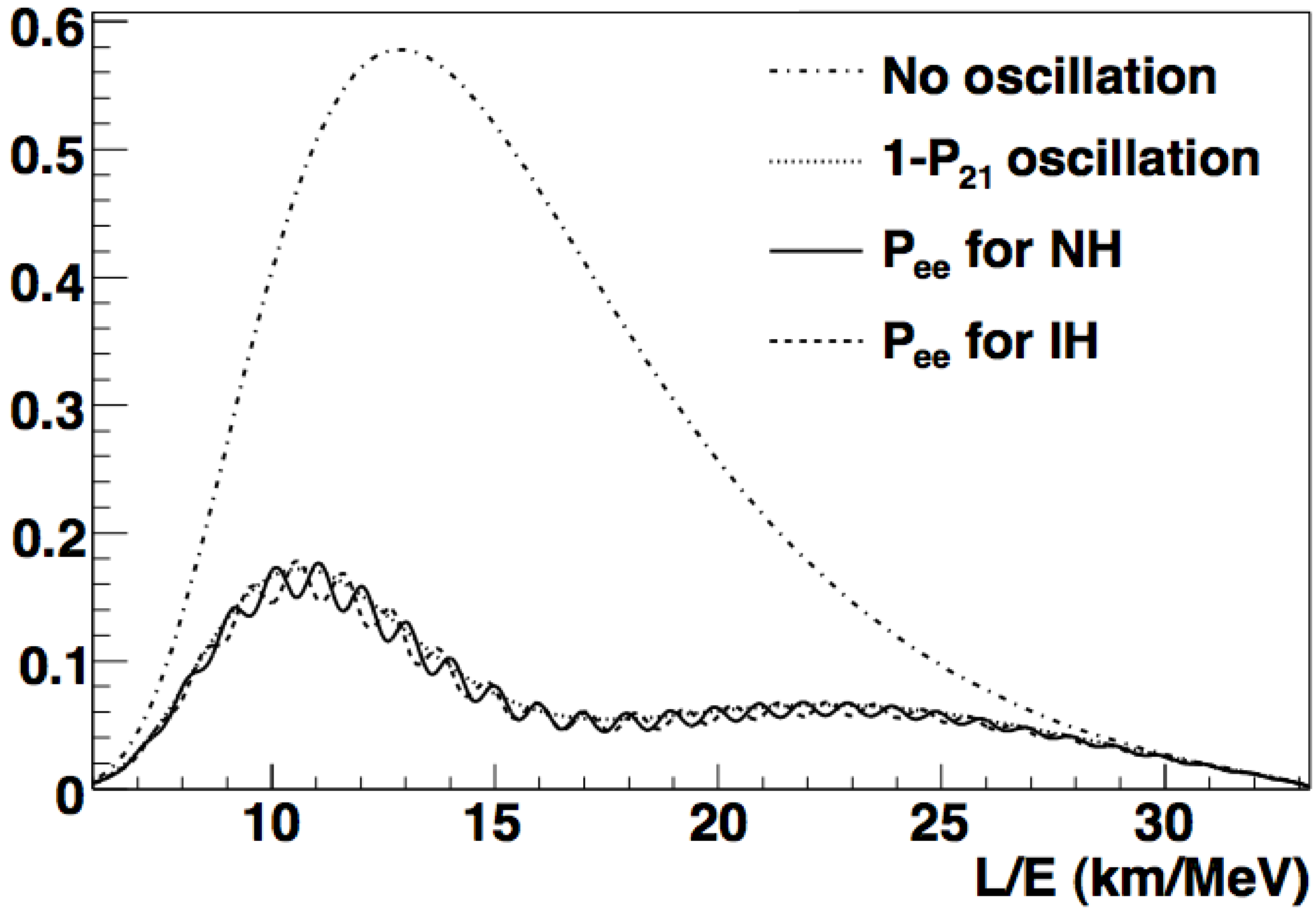
For $\sigma_E/E<4\%$ and $\varepsilon>95\%$
$\Delta\chi^2>20$ (muons+hadrons)
$\Delta\chi^2>14$ (muons)

For $\sigma_E/E<5\%$ and $\varepsilon>90\%$
$\Delta\chi^2>18$ (muons+hadrons)
$\Delta\chi^2>12$ (muons)

For $\sigma_E/E<6\%$ and $\varepsilon>85\%$
$\Delta\chi^2>16$ (muons+hadrons)
$\Delta\chi^2>10$ (muons)

One can get $\Delta\chi^2=9$ with 5 years INO data

(ii) Reactor experiment at medium baseline



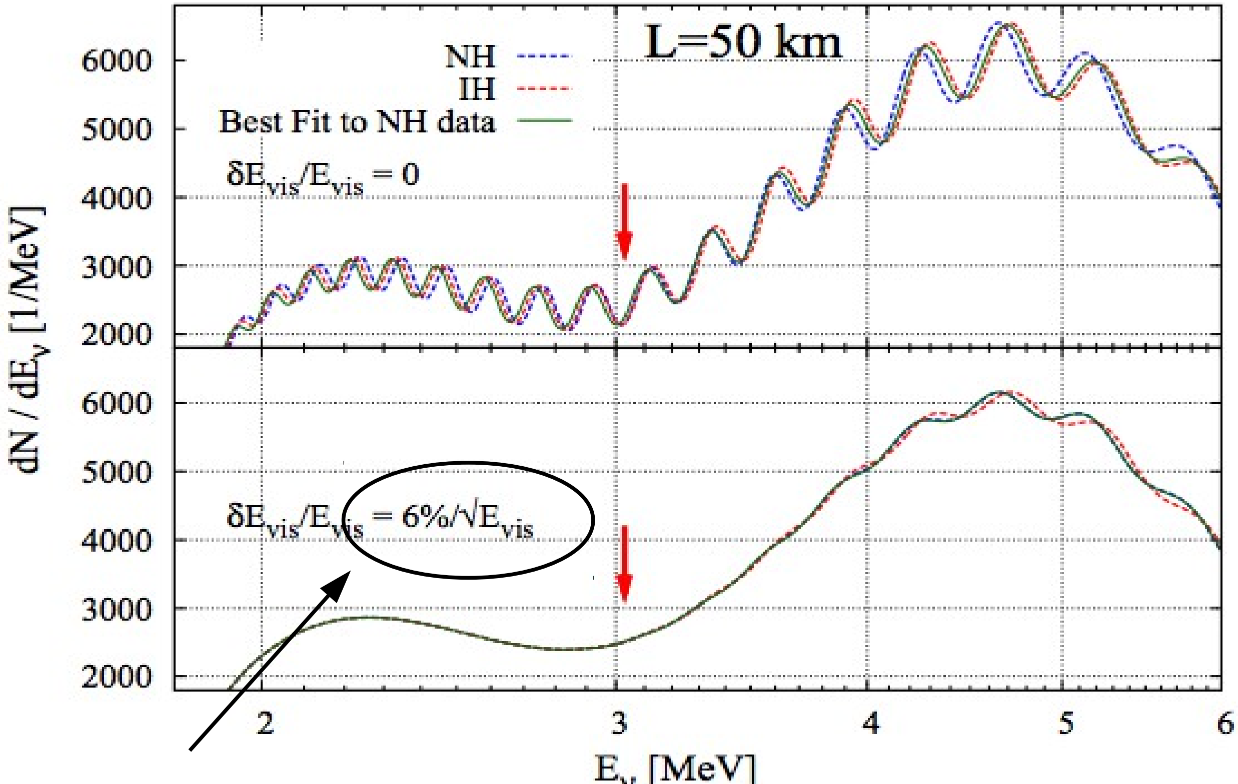
Zhan, Wang, Cao and Wen, 0807.3203 [hep-ph]

(ii) Reactor experiment at medium baseline

Two major proposals: RENO-50 and JUNO

Technical challenges:

- energy resolution
- energy non-linearity
- reactor distribution



KamLAND E_{res}
(~1 kton)

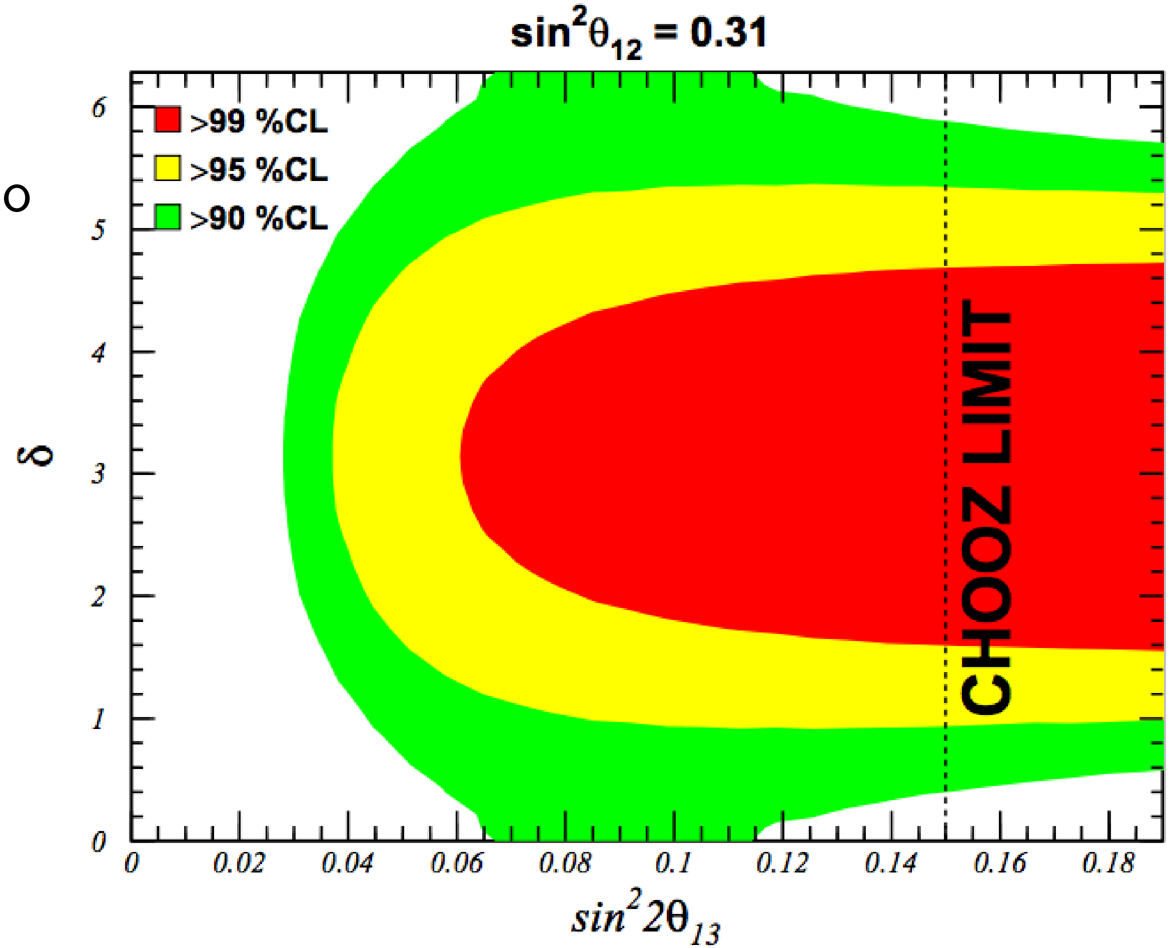
Ge, Hagiwara, Okamura, Takaesu, 1210.8141 [hep-ph]

See also:
Zhan et al, 0807.3203, 0901.2976
Qian et al, 1208.1551
Kettell et al, 1307.7419
Learned et al, hep-ex/0612022
Ciuffoli et al, 1209.2227,1308.0591
...

(iii) Precise measurements of mass splittings

The difference between the two mass splittings is due to a non-vanishing Δm^2_{21}

Assumed errors of $\sim 0.3\ (\sin^2 2\theta_{13}/0.1)\%$ on Δm^2_{ee} and 0.5% on $\Delta m^2_{\mu\mu}$



Nunokawa, Parke, Zukanovich Funchal, hep-ph/0503283

Minakata, Nunokawa, Parke, Zukanovich Funchal, hep-ph/0607284

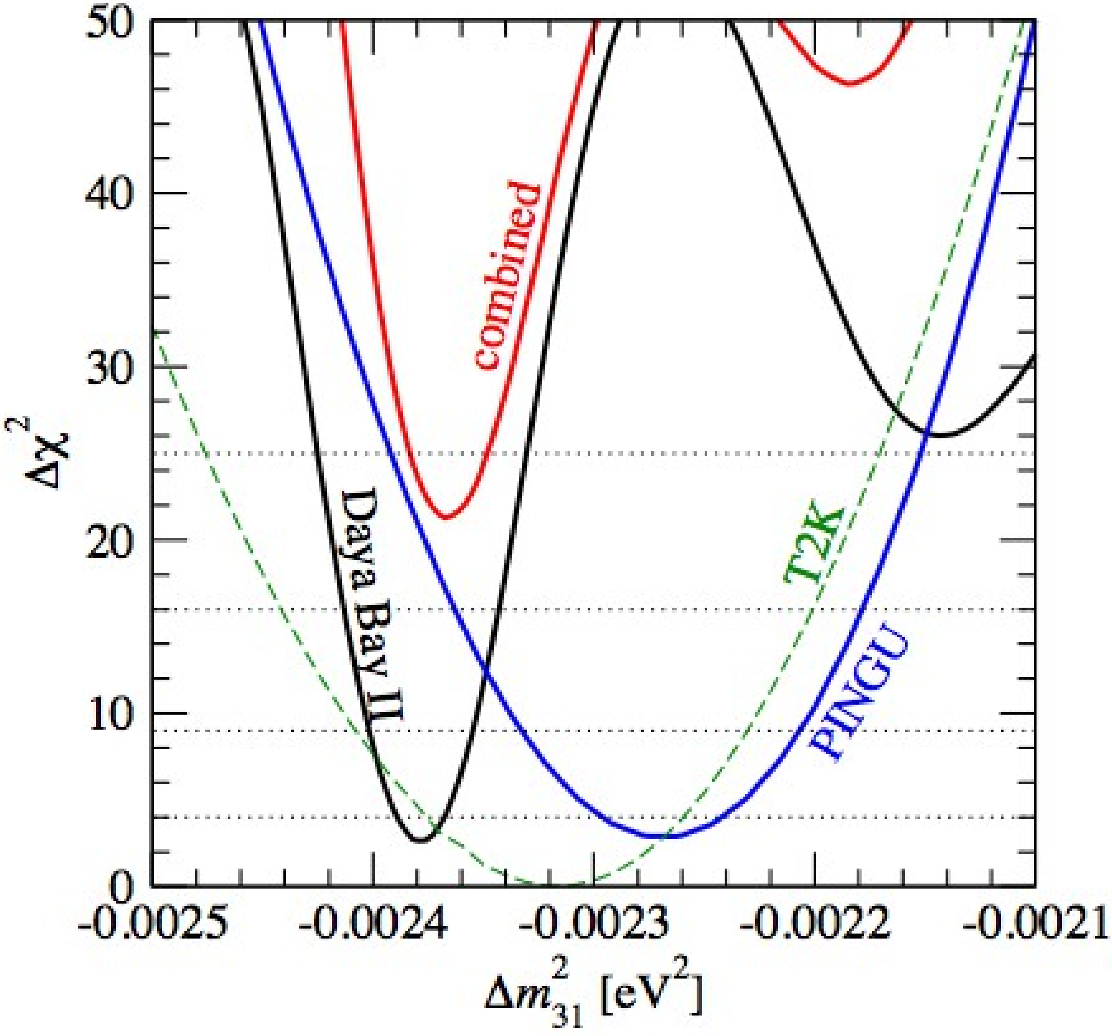
De Gouvea, Jenkins, Kayser, hep-ph/0503079

(see also Li, Cao, Wang, Zhang, 1303.6733 [hep-ph])

(iii) Precise measurements of mass splittings

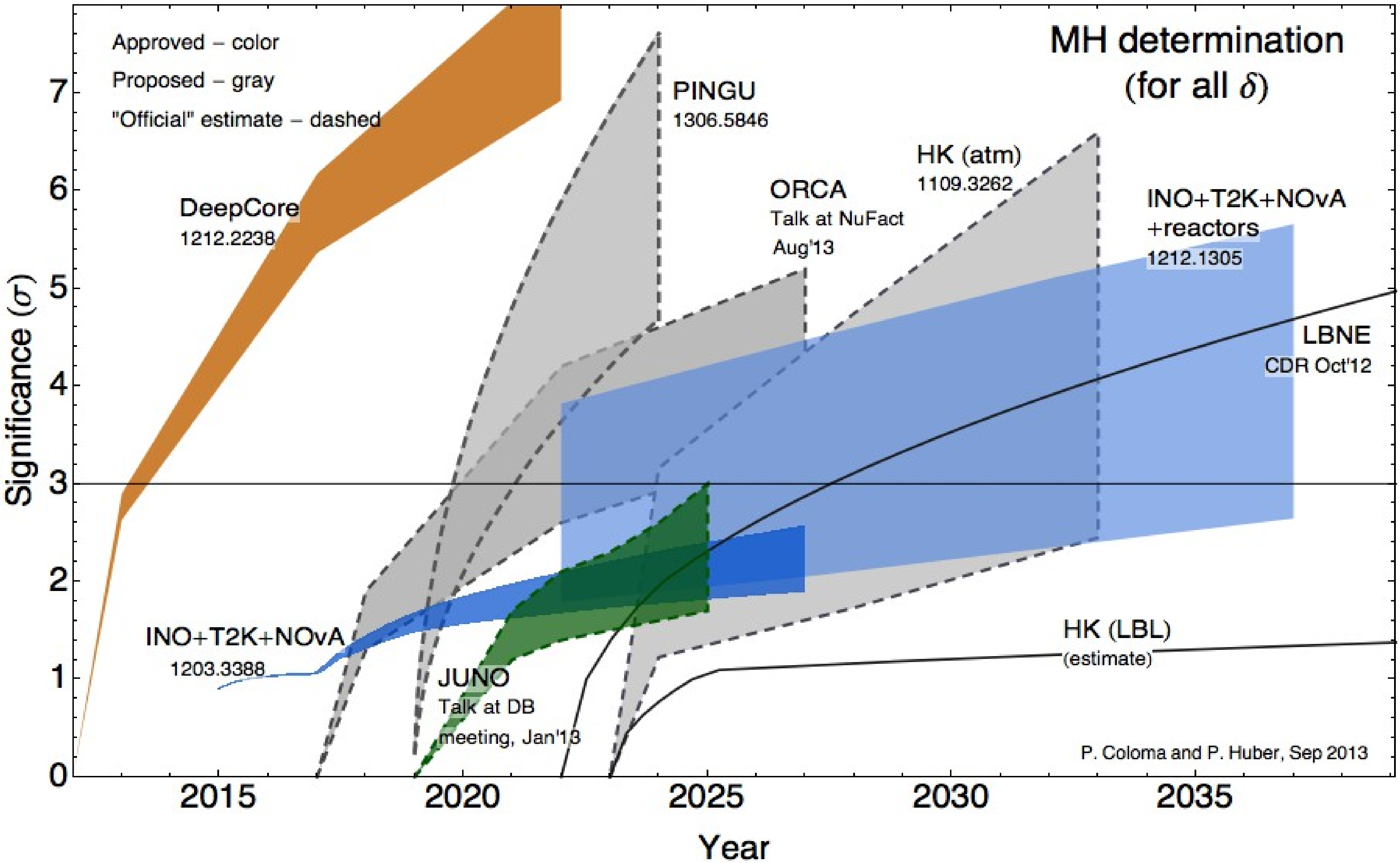
Physics in this case is more complicated, but the observable effect is similar. Effect remains even if

$$\Delta m^2_{21} = 0$$



Blennow, Schwetz, 1306.3988 [hep-ph]

Literature survey



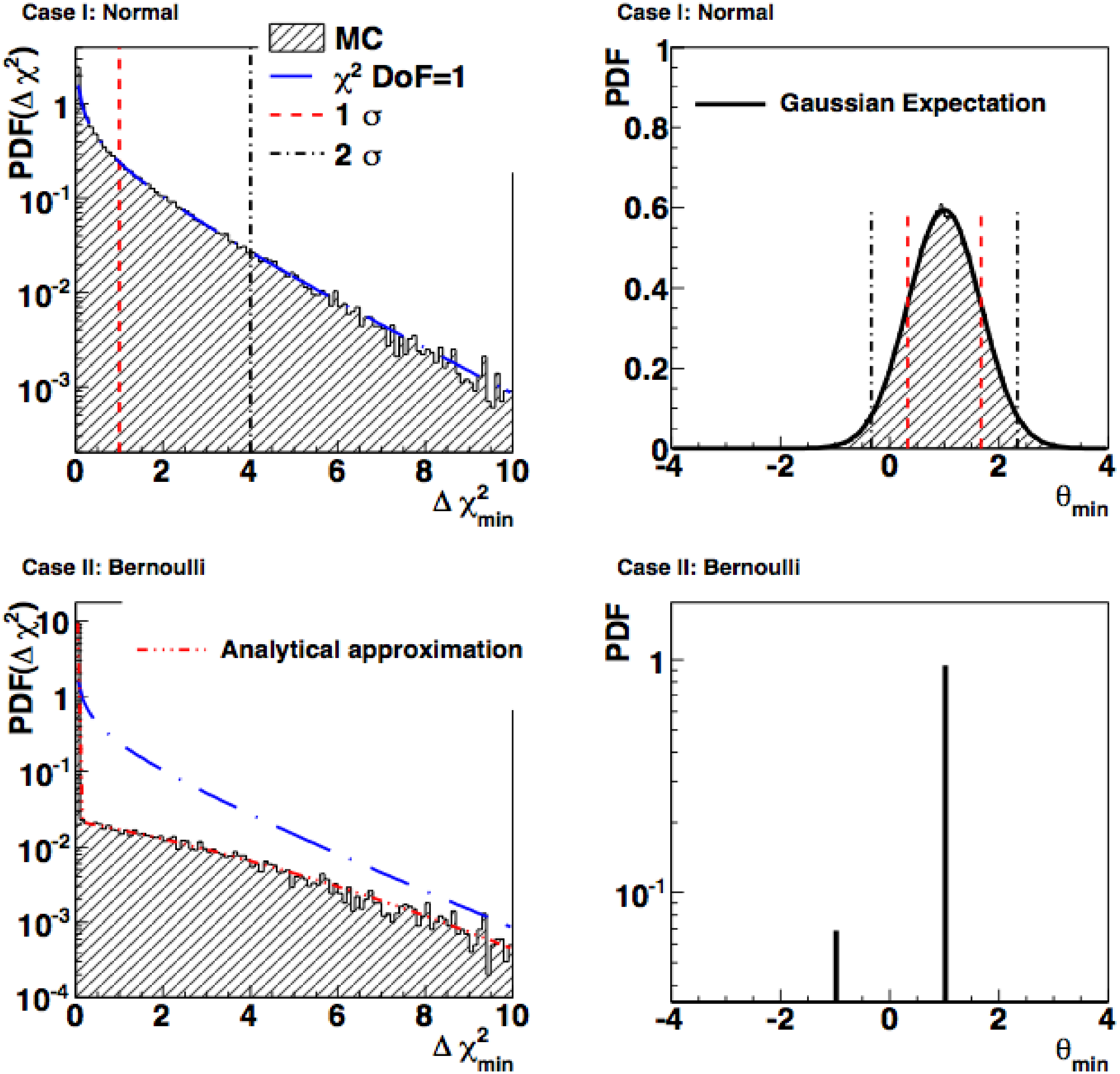
Conclusions

- The large value of θ_{13} recently measured has open a door to measure the hierarchy in many different ways
- Huge number of possibilities (short-, mid- and long-term): PINGU, ORCA, HyperK, JUNO, RENO50, ICAL, NOvA, LBNE,...
- Synergies between different proposals exist. Combinations can be very effective!
- If the hierarchy is known, we may want to optimize long baseline oscillation experiments differently

Thank you!

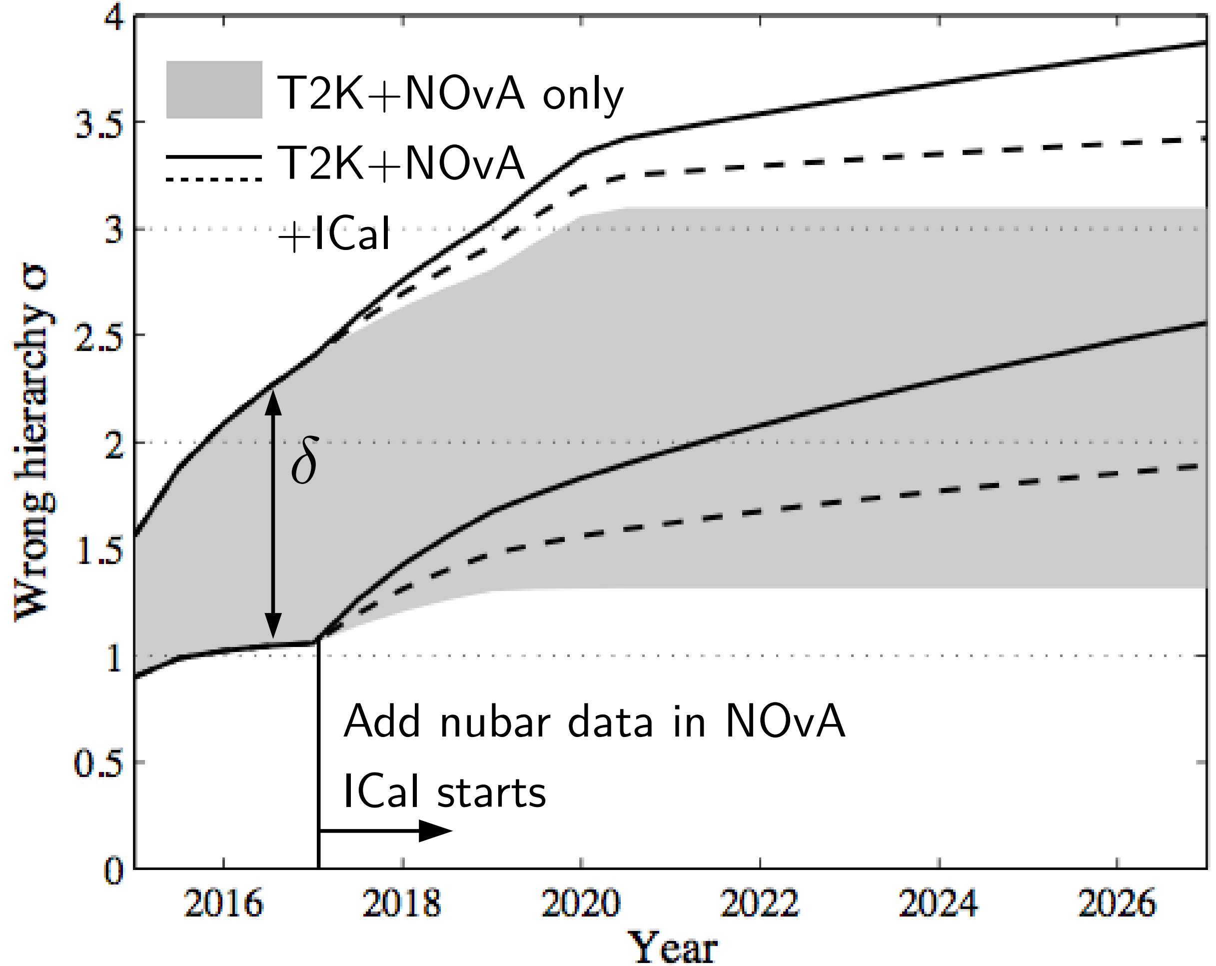
Backup

Statistical issues



Qian et al, 1210.3651 (see also Ciuffoli et al, 1305.5150)

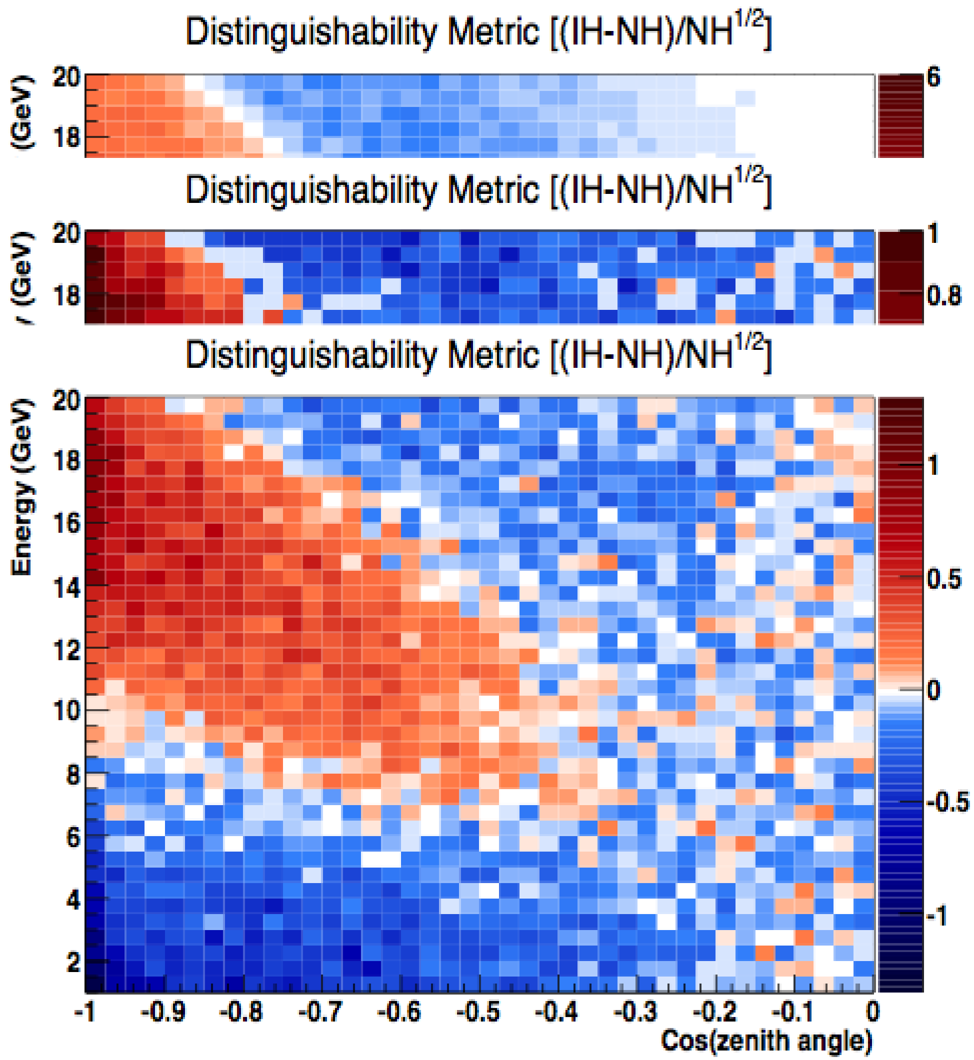
(i-a+b) Combining different experiments



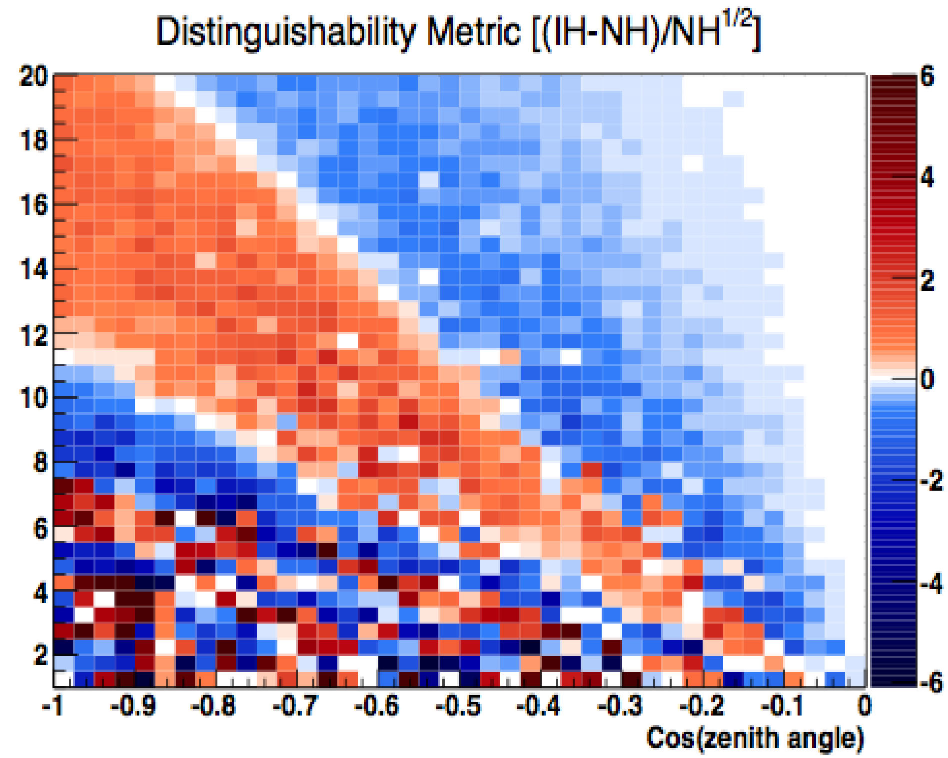
Blennow, Schwetz, 1203.3388 [hep-ph]

(see also Ghosh, Thakore, Choubey, 1212.1305 [hep-ph])

PINGU



Zenith resolution: 12.5° Energy resolution 3 GeV

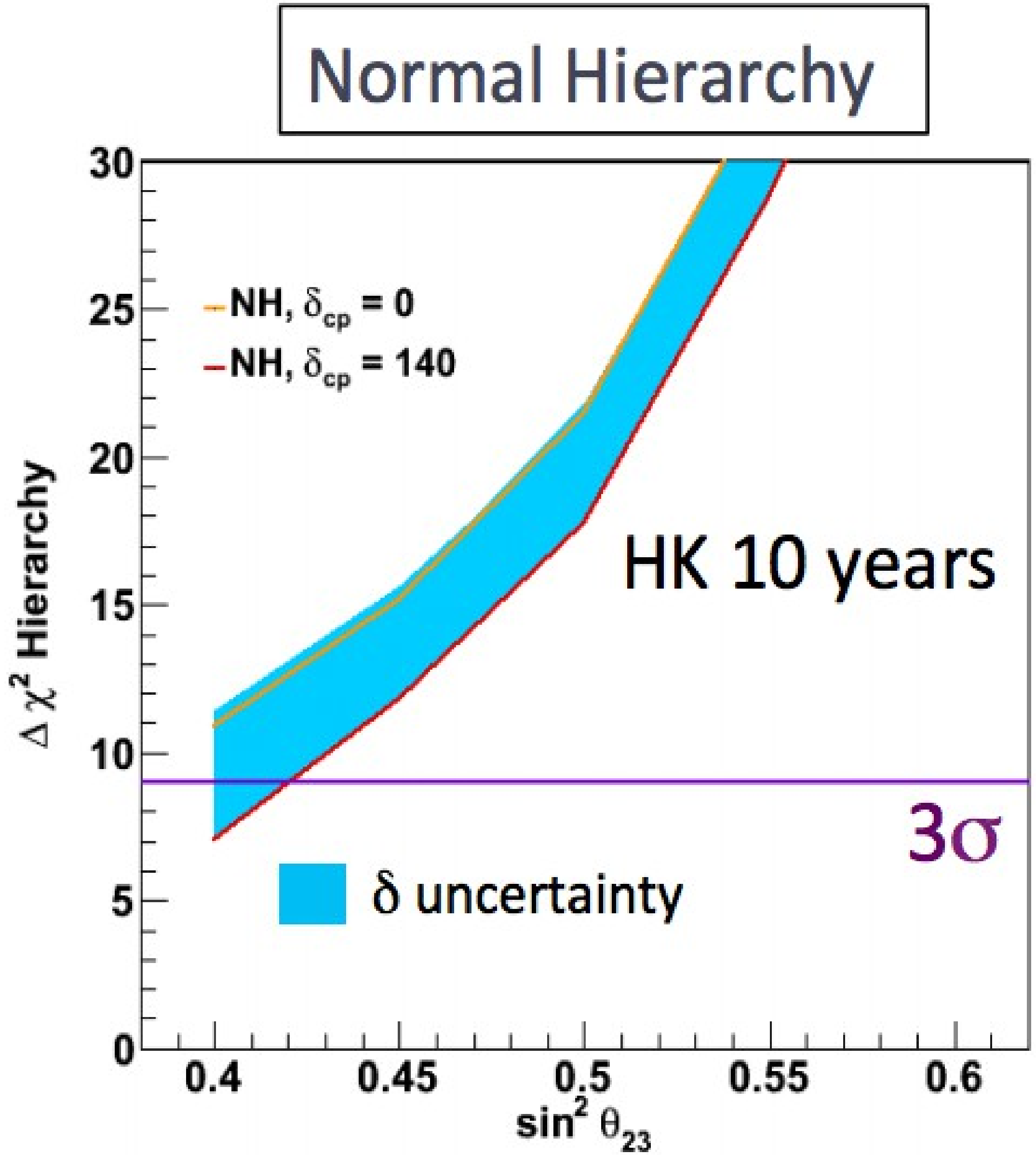


Perfect detector resolution

K Clark, talk at NuFact'13

Hyper-K

Data taking could start in 2023. Combination with long baseline data would further enhance the sensitivity



(See Shoei Nakayama talk at "International workshop on RENO-50 towards Neutrino Mass Hierarchy", June 2013)

(ii) Reactor experiment at medium baseline

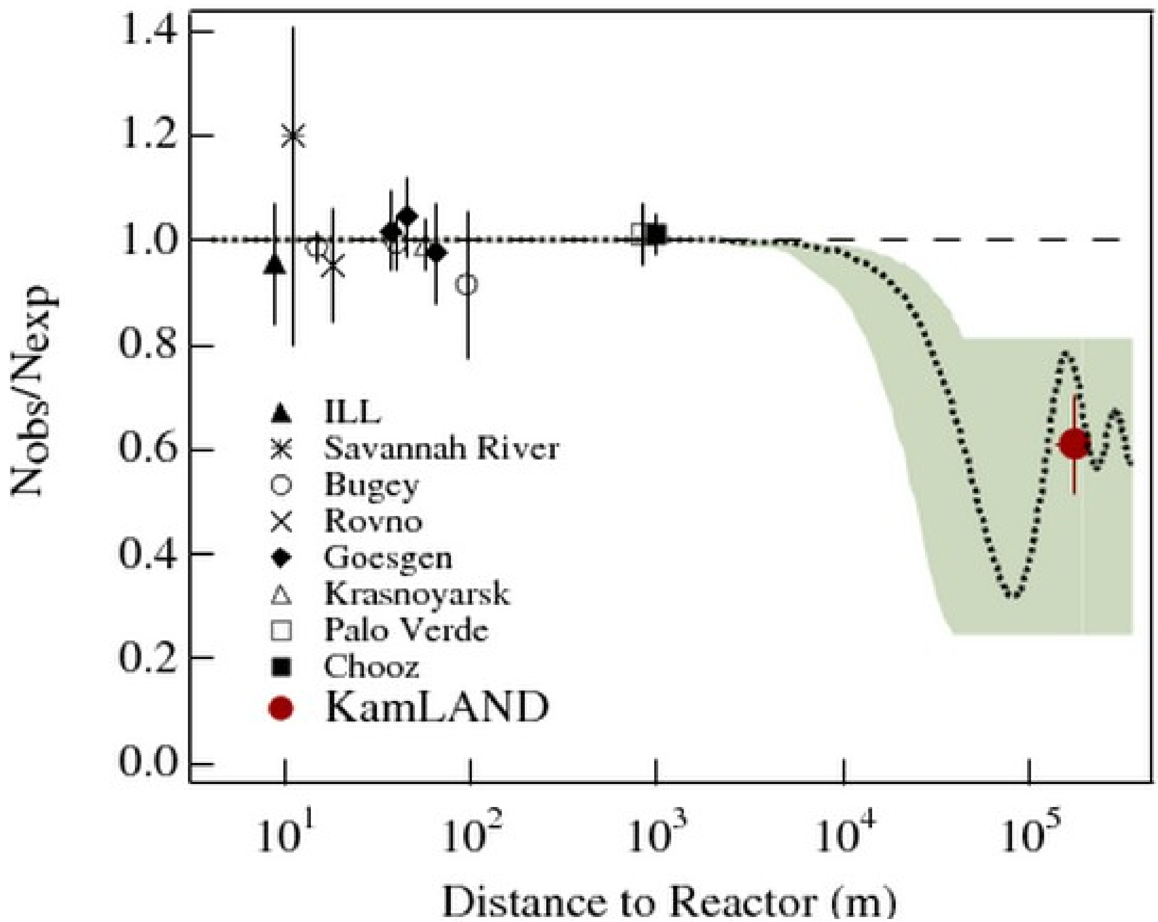
Petcov, Piai, hep-ph/01102074
Choubey, Petcov, Piai, hep-ph/0306017

$$\begin{aligned} P_{ee} \quad = \quad & 1 - \cos^4\theta_{13}\sin^2 2\theta_{12}\sin^2\Delta_{21} \\ & - \sin^2 2\theta_{13}\sin^2\Delta_{31} \\ & - \sin^2\theta_{12}\sin^2 2\theta_{13}\sin^2\Delta_{21}\cos 2\Delta_{31} \\ & \pm \frac{1}{2}\sin^2\theta_{12}\sin^2 2\theta_{13}\sin 2\Delta_{21}\sin 2\Delta_{31} \end{aligned}$$

Ge, Hagiwara, Okamura, Takaesu, 1210.8141 [hep-ph]

$$\Delta_{ij} \equiv \frac{|\Delta m_{ij}^2| L}{4E}$$

(ii) Reactor experiment at medium baseline



KamLAND coll., hep-ex/0212021

RENO50

10 Kton liquid scintillator

L~47 km (very close to optimal)

RENO used as near detector

Data taking expected to start in 2019

JUNO

20 Kton liquid scintillator

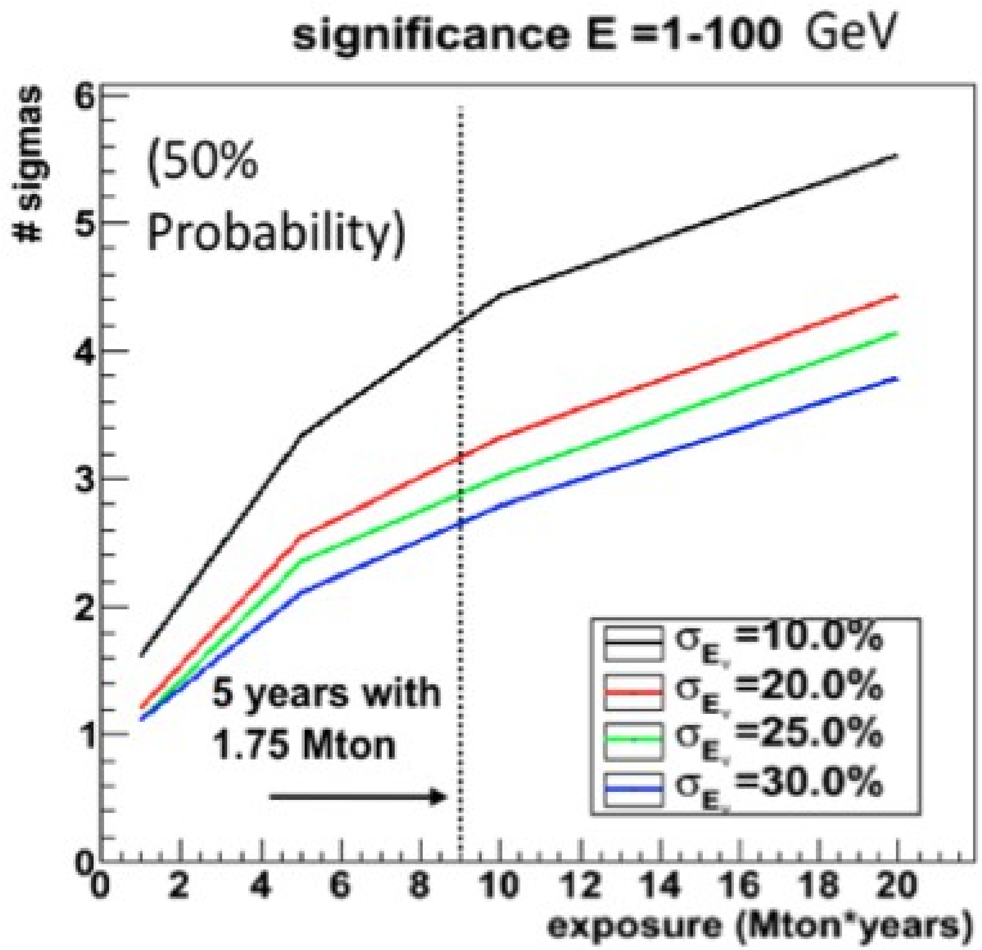
L=53 km (very close to optimal)

2 reactors, each of them with P~18 GW

Data taking expected to start in 2020

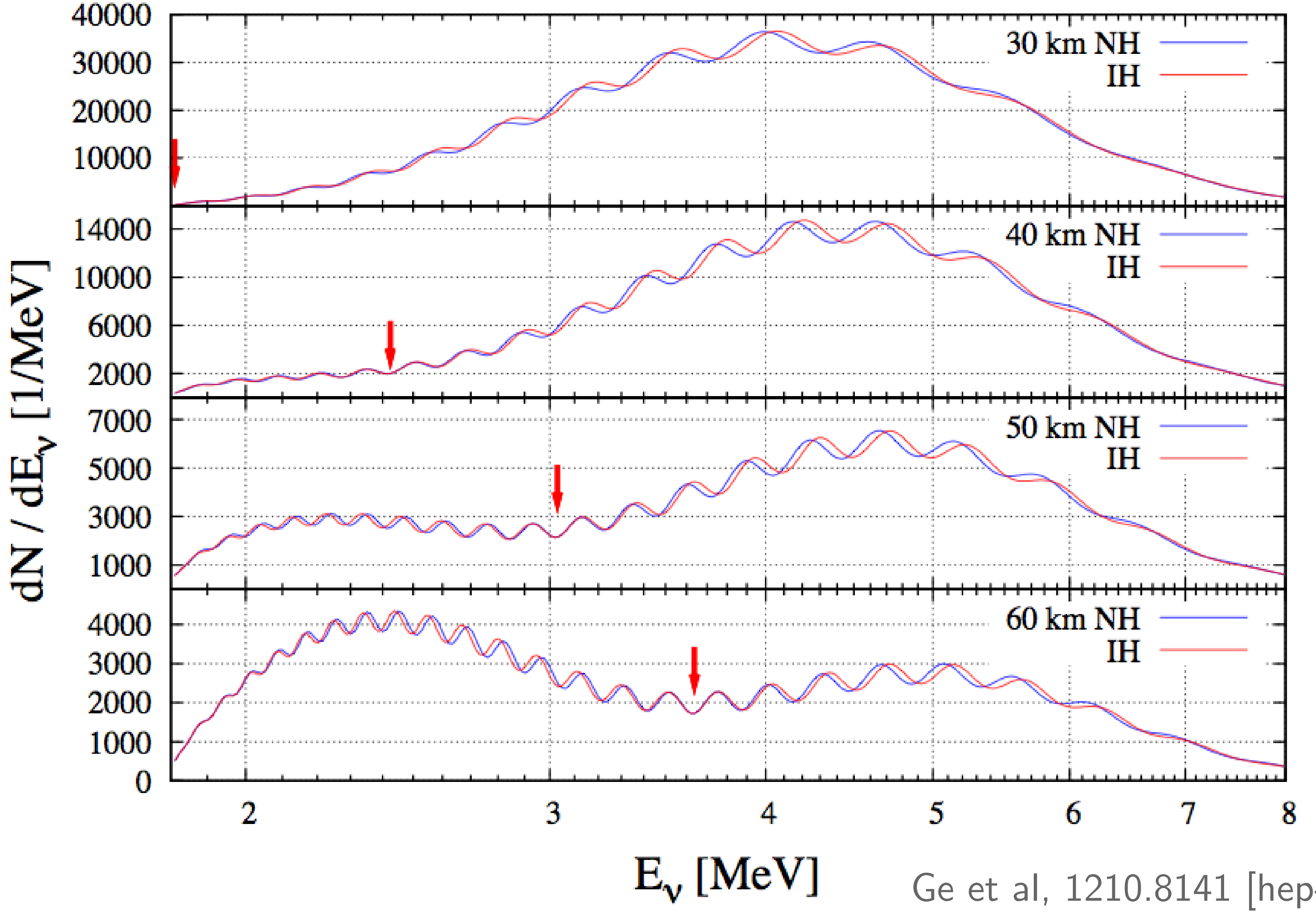
(i) Matter effects in disappearance

ORCA



Thomas Eberl, talk at NuFact'13

(ii) Reactor experiment at medium baseline



Ge et al, 1210.8141 [hep-ph]

Precise measurements of mass splittings

$$\Delta m^2(\alpha\alpha) = r_\alpha|\Delta m^2_{31}| + (1 - r_\alpha)|\Delta m^2_{32}|$$

$$r_\alpha \equiv \frac{|U_{\alpha 1}|^2}{|U_{\alpha 1}|^2 + |U_{\alpha 2}|^2}\,.$$

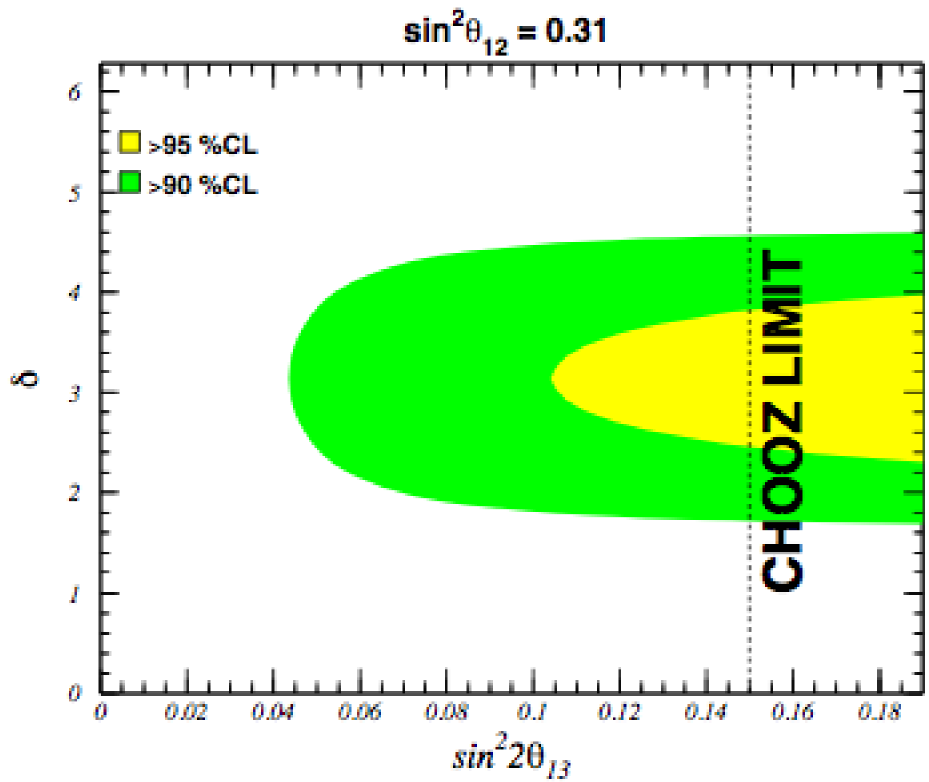
$$\Delta_{e\mu} \equiv \Delta m^2(\mathrm{ee}) - \Delta m^2(\mu\mu) = (r_e - r_\mu)(|\Delta m^2_{31}| - |\Delta m^2_{32}|).$$

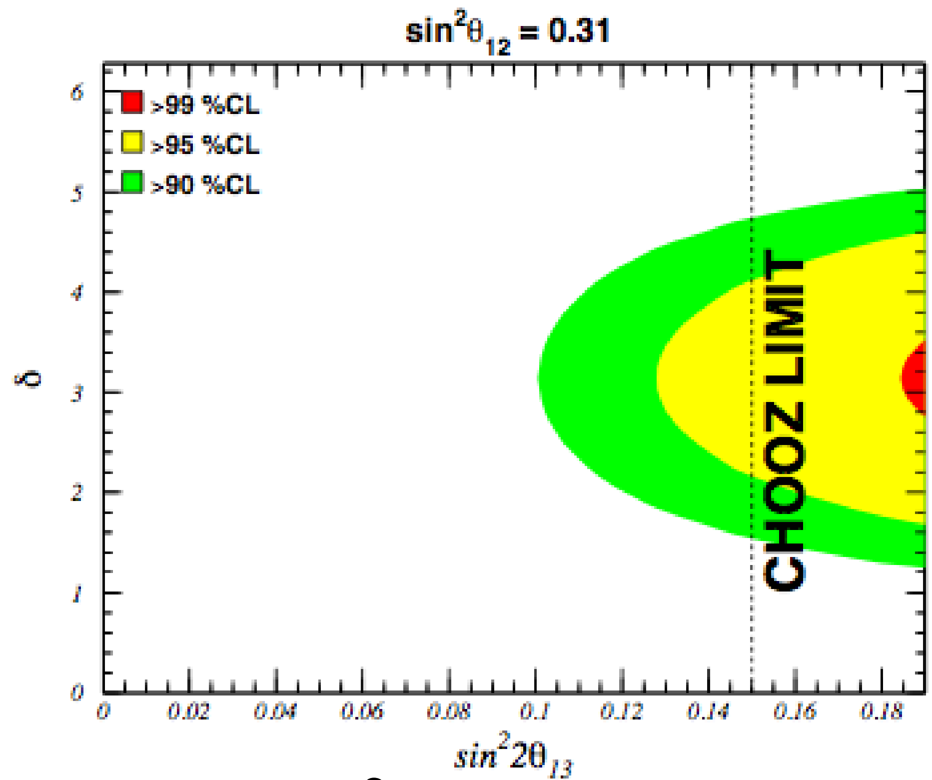
$$r_e - r_\mu = \cos 2\theta_{12} - \cos\delta \sin\theta_{13} \sin 2\theta_{12} \tan\theta_{23} + \mathcal{O}(\sin^2\theta_{13})$$

$$|\Delta m^2_{31}| - |\Delta m^2_{32}| = \pm\,\Delta m^2_{21}$$

Minakata, Nunokawa, Parke, Zukanovich Funchal, hep-ph/0607284

Precise measurements of mass splittings



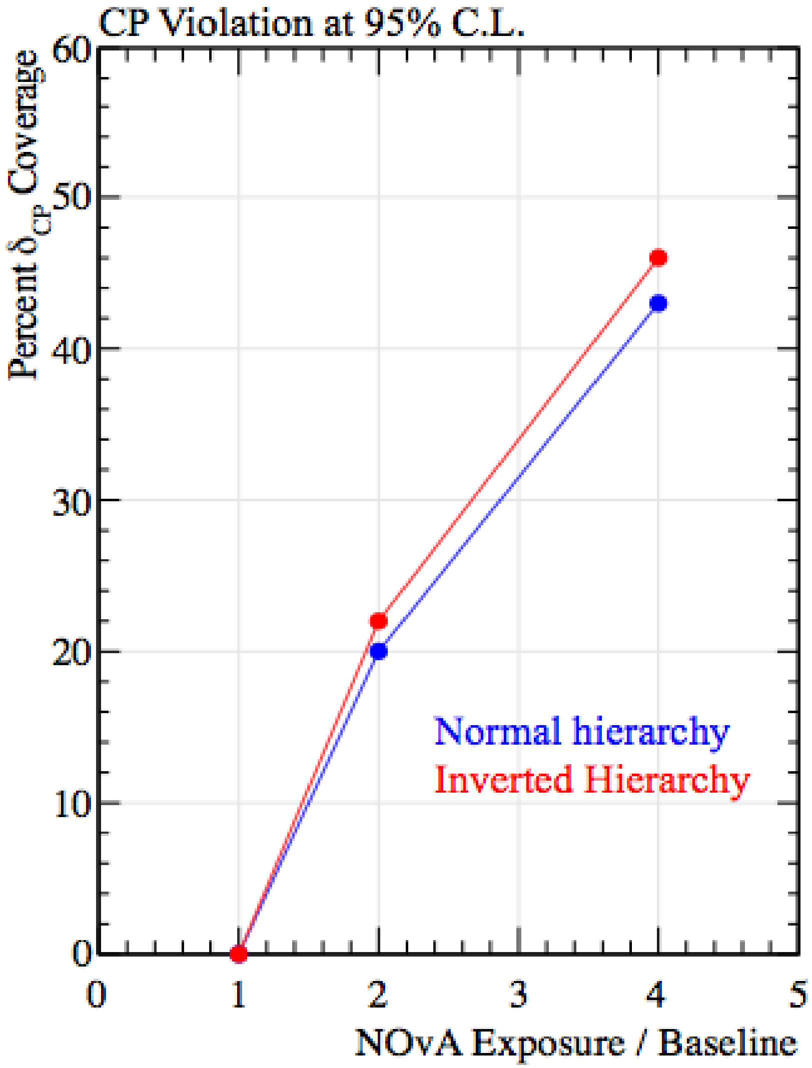


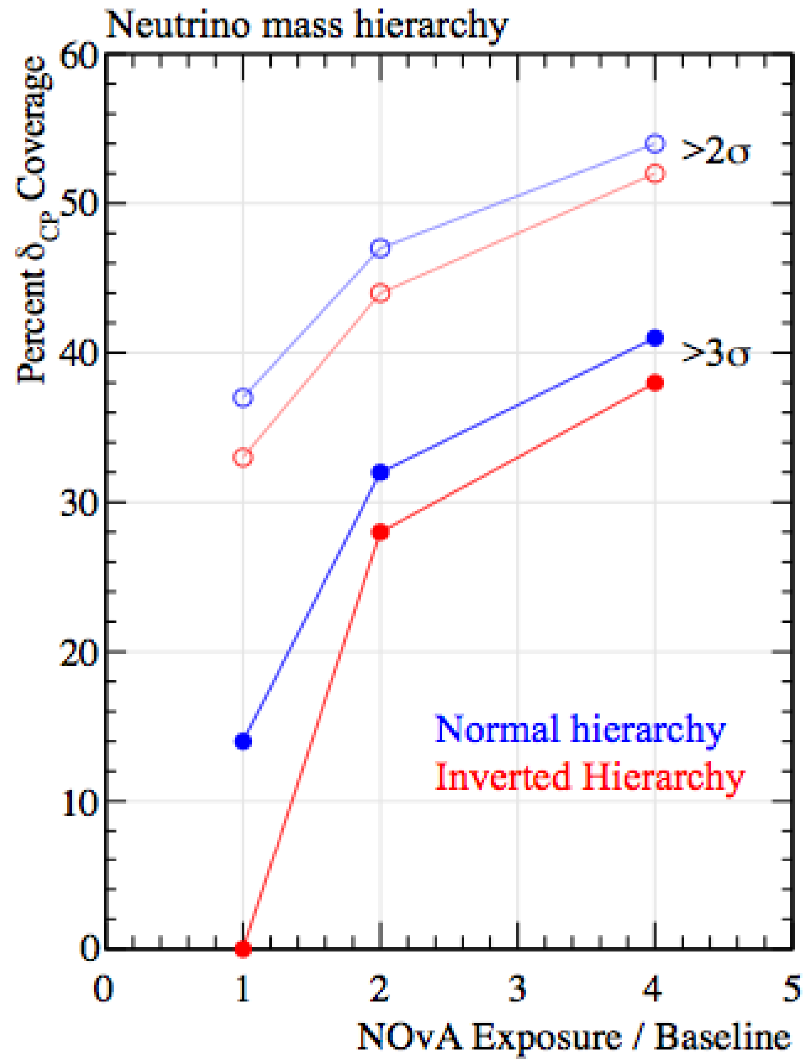
1% on $\Delta m^2_{\mu\mu}$

$\sim 1\ (\sin^2 2\theta_{13}/0.1)\%$ on Δm^2_{ee}

Minakata, Nunokawa, Parke, Zukanovich Funchal, hep-ph/0607284

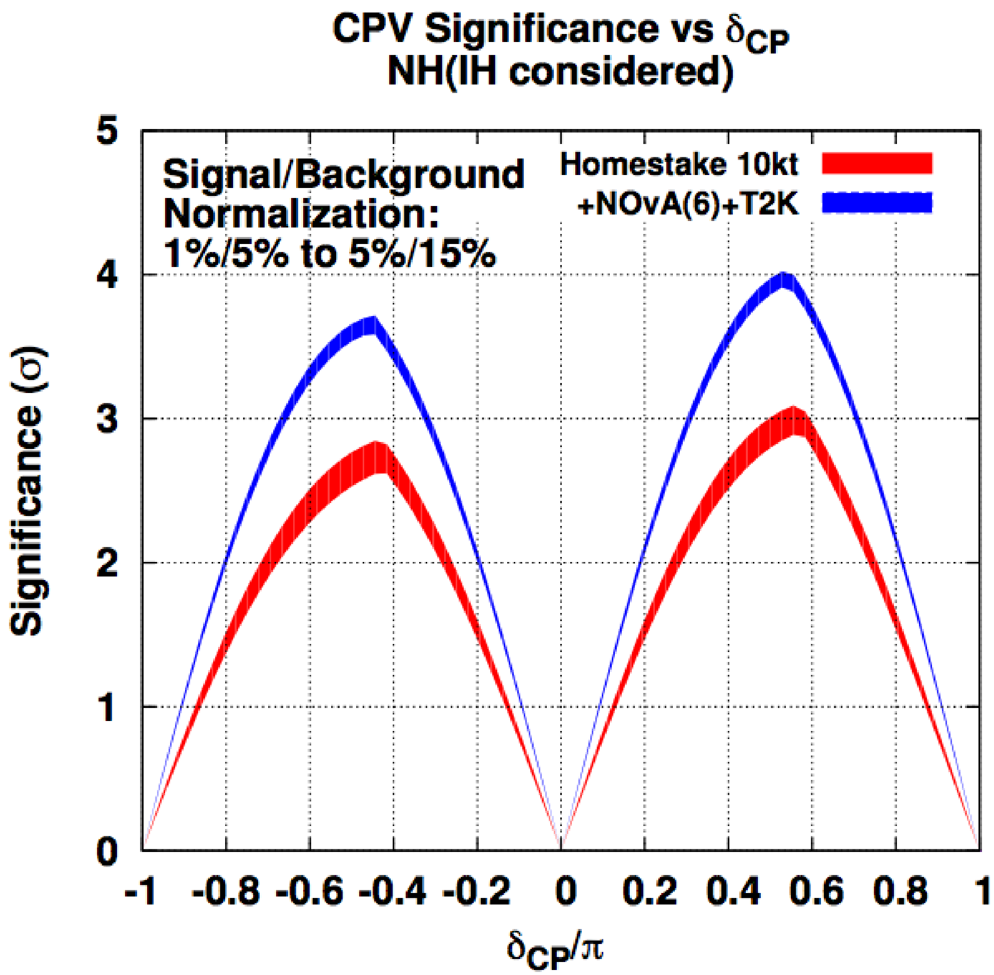
Impact on T2K/NOνA

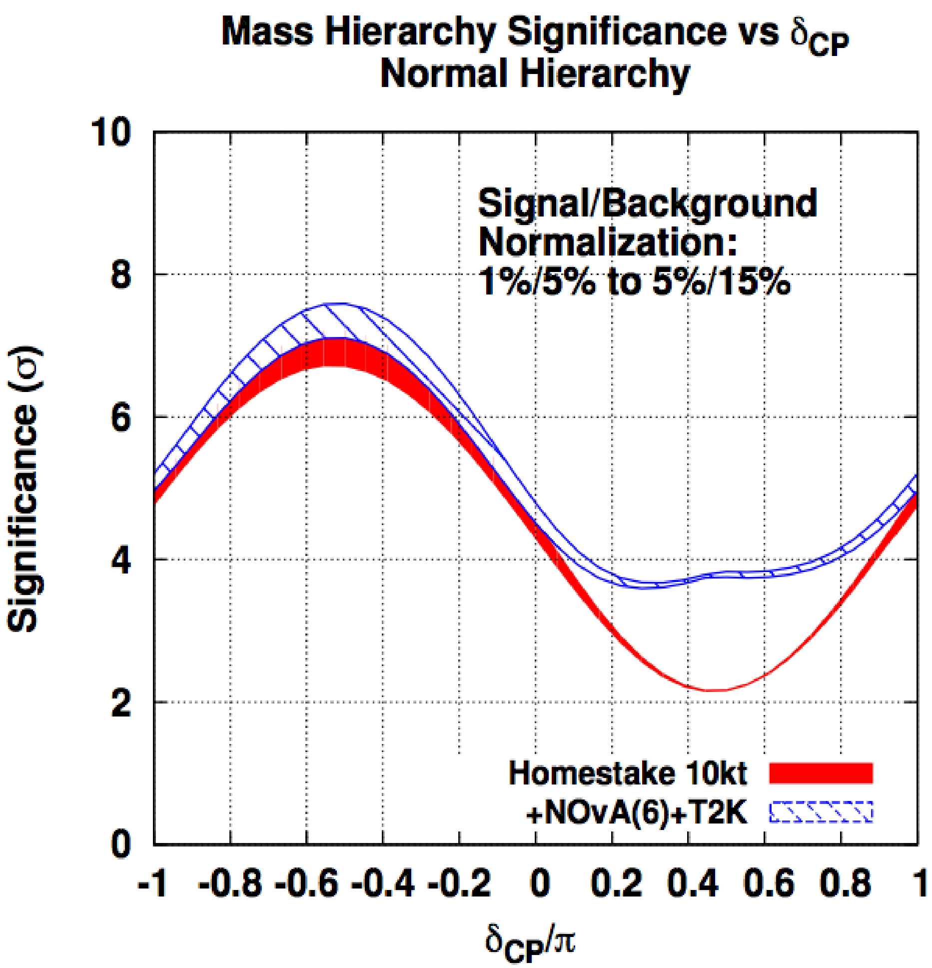




NOvA's whitepaper for SNOWMASS 2013
(See also 1201.6485 [hep-ph])

LBNE phase I





LBNE CDR from October 2012