PINGU and JUNO synergy for mass ordering determination

Mattias Blennow
emb@kth.se

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Based on arXiv:1306.3988, MB and T. Schwetz

1 Introduction

Current parameter knowledge

The oscillation parameter status

$$\begin{cases} \sin^2\theta_{12} = 0.302\,^{+0.013}_{-0.012} \\ \sin^2\theta_{13} = 0.0227\,^{+0.0023}_{-0.0024} \\ \sin^2\theta_{23} = 0.413\,^{+0.037}_{-0.025} \,/\, 0.594\,^{+0.021}_{-0.022} \end{cases} \qquad \begin{cases} \Delta m^2_{21}/10^{-5} = 7.50\,^{+0.18}_{-0.19}\,\mathrm{eV}^2 \\ \Delta m^2_{31}/10^{-3} = 2.473\,^{+0.070}_{-0.067}\,\mathrm{eV}^2\,(\mathrm{NH}) \\ \Delta m^2_{32}/10^{-3} = -2.427\,^{+0.042}_{-0.065}\,\mathrm{eV}^2\,(\mathrm{IH}) \end{cases}$$

Gonzalez-Garcia, Maltoni, Salvado, Schwetz, arXiv:1209.3023

We will use (unless stated otherwise):

$$|\Delta m^2_{31}| = 2.4 \cdot 10^{-3}\ \mathrm{eV}^2\,, \qquad \Delta m^2_{21} = 7.59 \cdot 10^{-5}\ \mathrm{eV}^2\,,$$

$$\sin^2 2\theta_{13} = 0.09\,, \quad \sin^2 2\theta_{23} = 1\,, \quad \sin^2\theta_{12} = 0.302\,, \quad \delta = 0\,.$$

What is left?

- The sign of Δm^2_{31} (neutrino mass ordering)
- The value of δ (CP violation)
- The octant of θ_{23} (for non-maximal mixing)

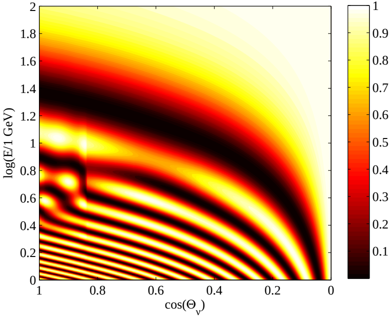
I will concentrate on the first of these in this talk

Atmospherics

Several proposals exist

- Indian Neutrino Observatory (INO)
- Hyper-Kamiokande
- PINGU
- Far detector for LBNE/LBNO

$P(\nu_\mu \to \nu_\mu)$ NO



MB, Smirnov, arXiv:1306.2903

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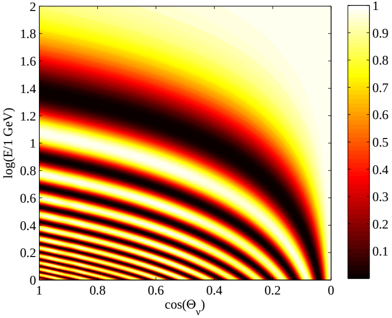
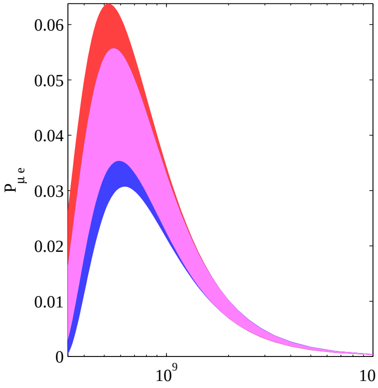


MB, Smirnov, arXiv:1306.2903

Long baseline experiments

295 km

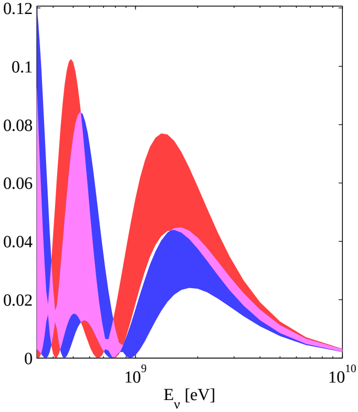


- Must be long to give large matter effect
- Compare with CP-violation, which prefers shorter baseline
- LBNE / LBNO
- T2HK too short

MB, Smirnov, arXiv:1306.2903

Long baseline experiments

810 km



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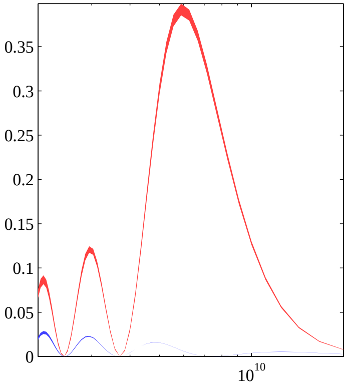
MB, Smirnov, arXiv:1306.2903

Long baseline experiments

7500 km



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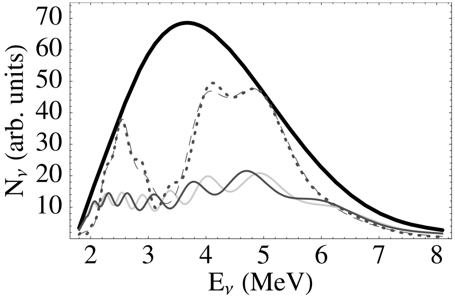
Reactors

- Have been very successful in determining θ_{13}
- Proposals have longer baseline
- Aim to detect wiggles in high frequency oscillations
- JUNO (Daya Bay II)
- RENO50



Petcov, Piai, hep-ph/0112074v2

WARNING: Huge Δm^2_{21}

What about synergy effects?

- Experiments are studying different channels/energies/baselines
- Sensitivity in different parts of parameter space
- Will exclude different regions for the same true values
- It may happen that only the combined fit excludes a specific ordering

1 Introduction

2 Synergy effects

3 PINGU+JUNO

4 Summary and conclusions

Two flavor approximations

$$P_{\alpha\beta} = \sin^2(2\theta_{\alpha\beta})\sin^2\left(\frac{\Delta m^2_{\alpha\beta} L}{4E}\right), \quad P_{\alpha\alpha} = 1 - \sin^2(2\theta_{\alpha\alpha})\sin^2\left(\frac{\Delta m^2_{\alpha\alpha} L}{4E}\right)$$

- What $\Delta m^2_{\alpha\beta}$ should be inserted in the two-flavor approximations?
- Typically, we see $\Delta m^2_{\alpha\beta} \simeq \Delta m^2_{31} \simeq \Delta m^2_{32}$
- What happens when we test the two-flavor formula in an experiment with better resolution?

Looking at different channels

- Based on the oscillation maximum:

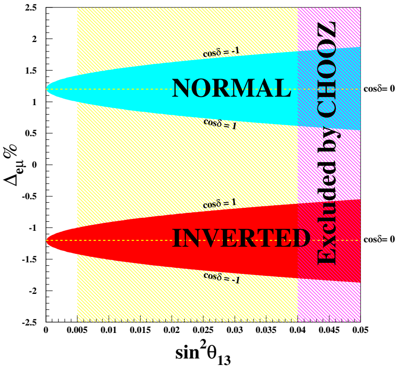
  Nunokawa, Parke, Funchal, hep-ph/0503283

$$\begin{aligned}
\Delta m^2_{ee} &= c^2_{12}\Delta m^2_{31} + s^2_{12}\Delta m^2_{32} \\
\Delta m^2_{\mu\mu} &= s^2_{12}\Delta m^2_{31} + c^2_{12}\Delta m^2_{32} + c_\delta s_{13}\sin(2\theta_{12})\tan(\theta_{23})\Delta m^2_{21} \\
\Delta m^2_{\tau\tau} &= s^2_{12}\Delta m^2_{31} + c^2_{12}\Delta m^2_{32} - c_\delta s_{13}\sin(2\theta_{12})\cot(\theta_{23})\Delta m^2_{21}
\end{aligned}$$

- Atmospherics are trickier
  - Full spectrum of baselines and energies
  - Combination of channels

Reactors vs Long baselines

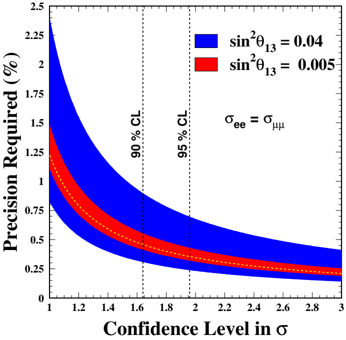
- Idea has been around for a while
- The effect is at the % level



Nunokawa, Parke, Funchal, hep-ph/0503283

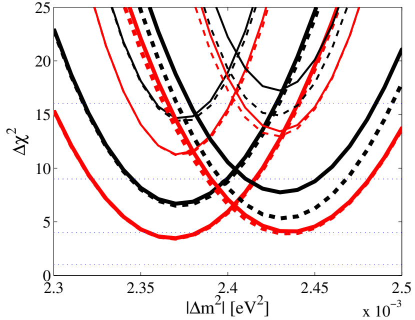
Reactors vs Long baselines

- Idea has been around for a while
- The effect is at the % level
- Both experiments must measure Δm^2_{31} with high precision



Nunokawa, Parke, Funchal, hep-ph/0503283

Atmospherics



MB, Schwetz, arXiv:1306.3988

- More complicated dependence
  - Baseline
  - Energy
  - Resolutions
- $\Delta m^2_{21} = 0$, still a difference
- Simulated $|\Delta m^2| = 2.4 \cdot 10^{-3}$ eV^2
- ← inverted, → normal true ordering

PINGU

Muon reconstruction:

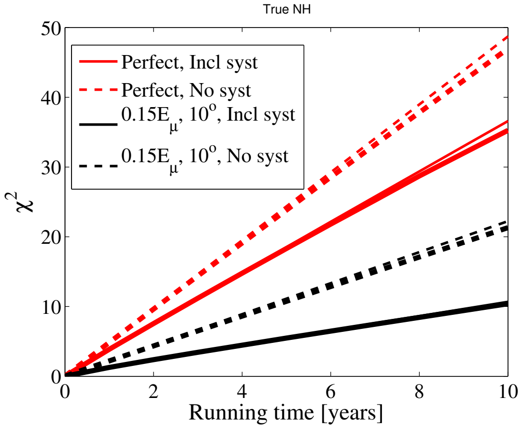
- Assume no knowledge on the hadronic part
- Just reconstruct the muon energy and direction
- See also Franco et al, arXiv:1301.4332

Neutrino reconstruction:

- Assume hadronic shower can help neutrino reconstruction
- Do the analysis in the reconstructed neutrino parameters

	σ_{E_μ}	σ_{θ_μ}	σ_{E_ν}	σ_{θ_ν}
Low	$0.15 E_\mu$	10°	2 GeV	$\sqrt{1\ \mathrm{GeV}/E_\nu}$
High	0	0	$0.2 E_\nu$	$0.5\sqrt{1\ \mathrm{GeV}/E_\nu}$

PINGU results (muon parameters)



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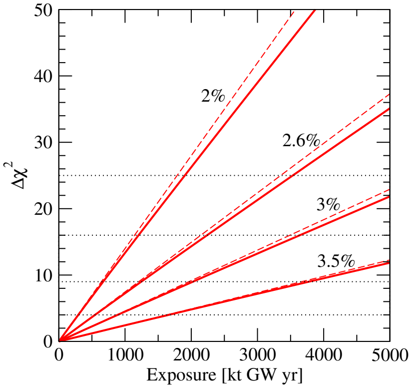
JUNO

Assumptions:

- Point-like source at 58 km
- Different assumptions on energy resolution
- Normalized to 10^5 events for 6 years running (4320 kt GW year)



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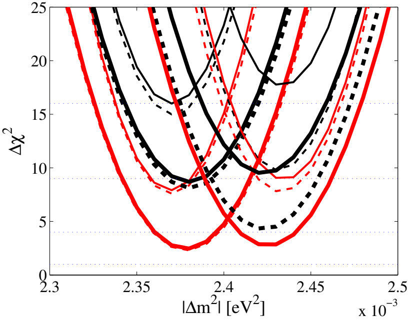
PINGU dependence on assumptions (ν reconstruction)



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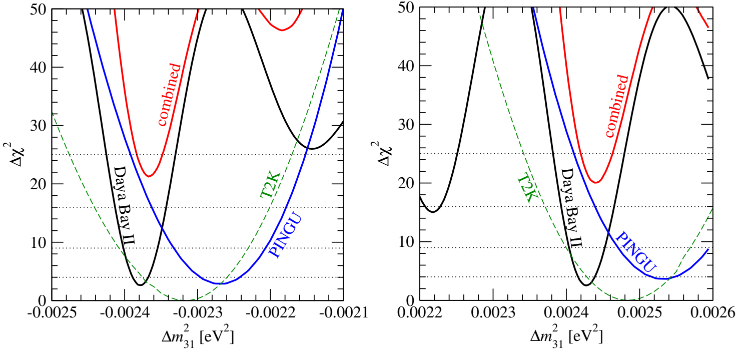
- Thin: High, Thick: Low
- Red: w syst, Black: w/o syst
- Solid: fixed, Dash: free
- $\leftarrow$ inverted, $\rightarrow$ normal true ordering

Shape mainly dependent on resolutions

Synergy results

PINGU: 1 year (High ν, no syst), JUNO: 1000 kt GW year



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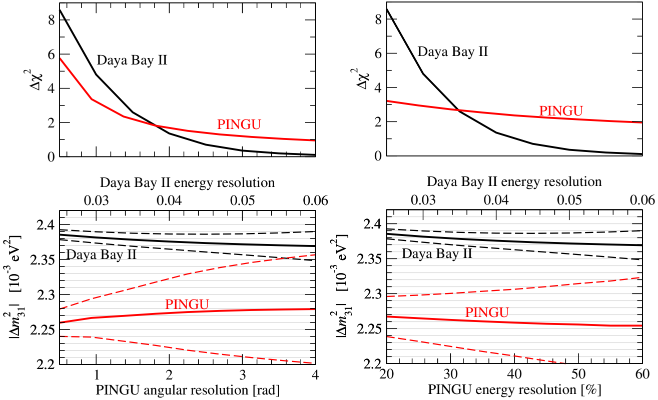
Mass squared precision

PINGU: 1 year (no syst), JUNO: 1000 kt GW year



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Summary and conclusions

- The neutrino mass ordering is one of the remaining unknowns in neutrino oscillations
- Synergies in different types of experiments may significantly increase global sensitivity
- Atmospherics and reactors provide the most separated best-fits in the wrong ordering
- Crucially dependent on resolution for Δm^2