TeVPA/IDM conference

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Global status of neutrino oscillations

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Outline

Introduction

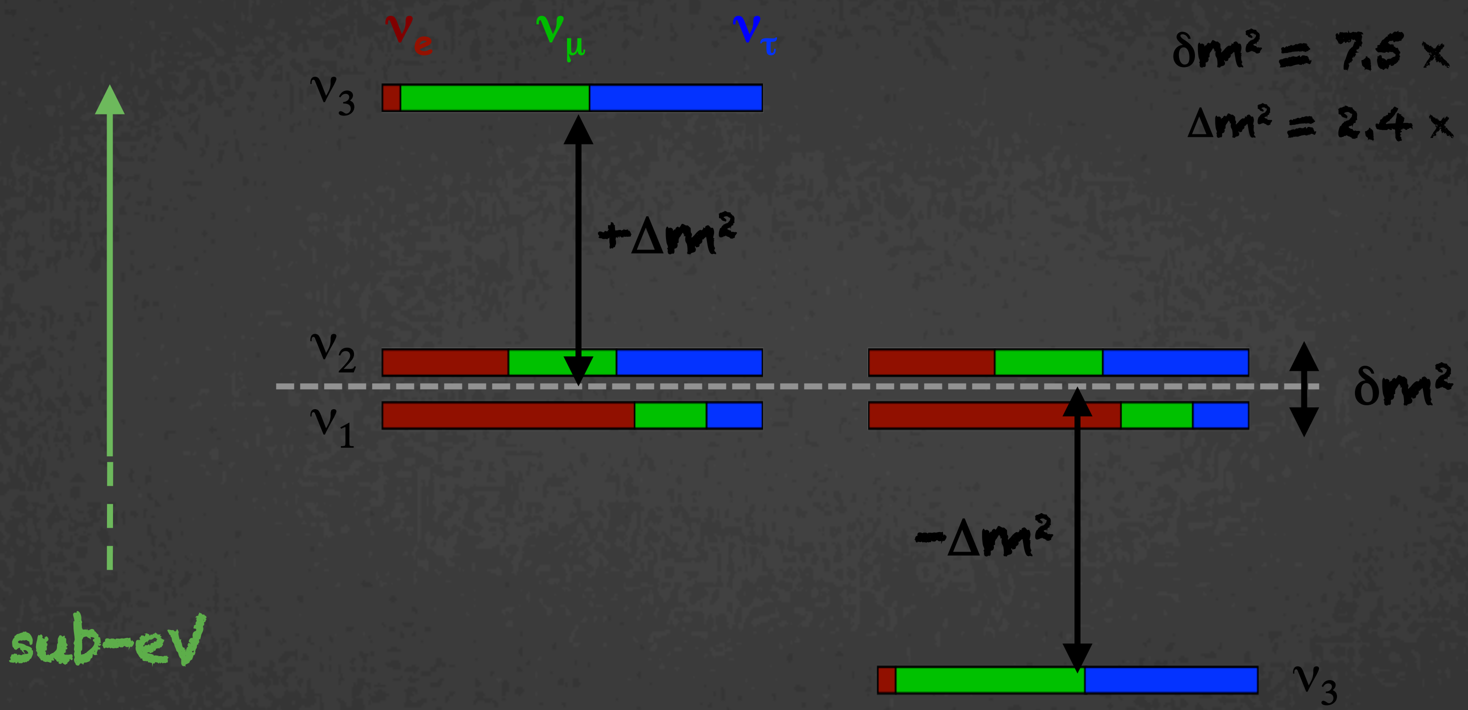
Pre-post Neutrino 2014 comparison

Focus on the "hottest" parameters δ & θ_{23}

Conclusions

The 3ν mass spectrum

NH or IH ?



$\delta m^2 = 7.5 \times 10^{-5}$ eV^2

$\Delta m^2 = 2.4 \times 10^{-3}$ eV^2

NMH and absolute mass at the center of investigation

The 3ν mixing matrix

$$|\nu_\alpha\rangle = \sum_{i=1}^{3} U^*_{\alpha i}|\nu_i\rangle$$

$$U = O_{23}\Gamma_\delta O_{13}\Gamma^\dagger_\delta O_{12}$$

$$\Gamma_\delta = \mathrm{diag}(1, 1, e^{+i\delta})$$

$$\delta \in [0, 2\pi]$$

Dirac CP-violating phase δ

U is non-real if δ ≠ (0, π)

Explicit form

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

$\theta_{23} \sim 41^\circ$ $\theta_{13} \sim 9^\circ$ $\theta_{12} \sim 34^\circ$

Three non-zero θ_{ij}: Way open to CPV searches

Precondition for leptonic CPV
(together with two non-zero mass-splittings)

The Jarlskog invariant gives a parameterization-independent measure of the CP violation induced by the non-reality of U

$$J = \Im[U_{\mu 3} U_{e2} U^*_{\mu 2} U^*_{e3}]$$

In the standard parameterization the expression of J is:

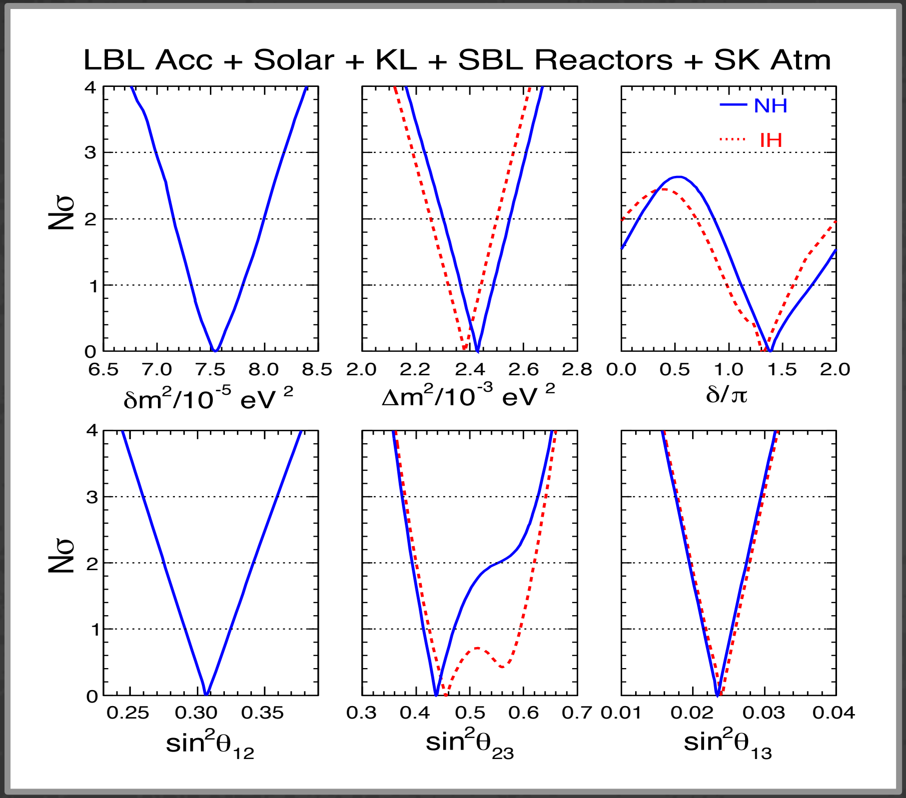
$$J = \frac{1}{8} \sin 2\theta_{12} \sin 2\theta_{23} \sin 2\theta_{13} \cos \theta_{13} \sin \delta$$

Only if all three $\theta_{ij} \neq 0$ the CP symmetry can be violated

- quarks: $J_{CKM} \sim 3 \times 10^{-5}$, much smaller than $|J|_{max} = \frac{1}{6\sqrt{3}} \sim 0.1$
- leptons: $|J|$ may be as large as 3×10^{-2}

It will depend on δ ... it seems ν physicists are lucky ...

Status of global 3ν oscillation analysis
(Just before Neutrino 2014)



Weak preference for $\delta \in [\pi, 2\pi]$ ($\sin\delta < 0$)

Some preference for first octant of θ_{23} but weaker in IH

No sensitivity to neutrino mass hierarchy

Capozzi, Fogli, Lisi, Marrone, Montanino, A.P.
PRD 89, 093018 (2014) [arXiv:1312.2878v2]

News from Neutrino 2014

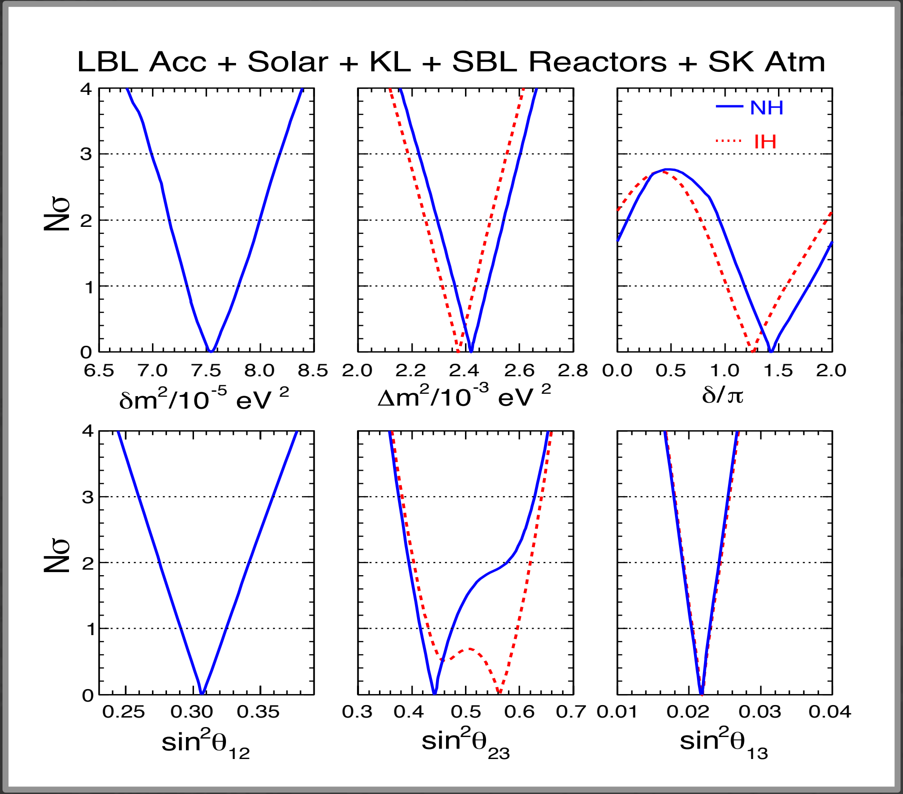
- New reactor data (Daya-Bay, RENO, D-CHOOZ)
- RENO & D-CHOOZ show excess around 5 MeV
- Rumors about similar findings in Daya-Bay
- 5 MeV bump does not affect θ_{13} (near/far ratios)
- New data from ICECUBE, MINOS+, SK-IV ATM

Daya-Bay has the most important impact on the fit
On θ_{13} (direct) & on [δ, θ_{23}] via correlation with θ_{13}

Our preliminary post ν-2014 global fit includes the new Daya-Bay & RENO. Inclusion of other data sets (having a minor impact) is in progress.

Status of global 3ν oscillation analysis

(After Neutrino 2014)



Preference for
$\delta \in [\pi, 2\pi]$ ($\sin\delta < 0$)
NH: stable
IH: enhanced

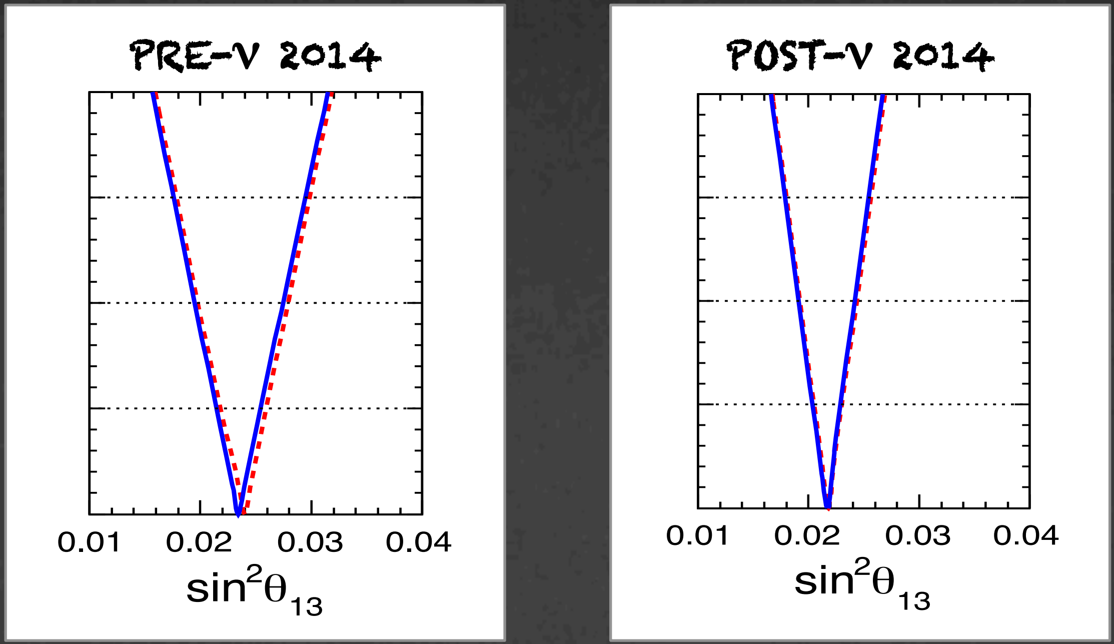
Preferred θ_{23} octant swaps with NH <–> IH

No sensitivity to neutrino mass hierarchy

Capozzi, Fogli, Lisi, Marrone, Montanino, A.P.

PRELIMINARY

Pre-post ν 2014 comparison: θ_{13}

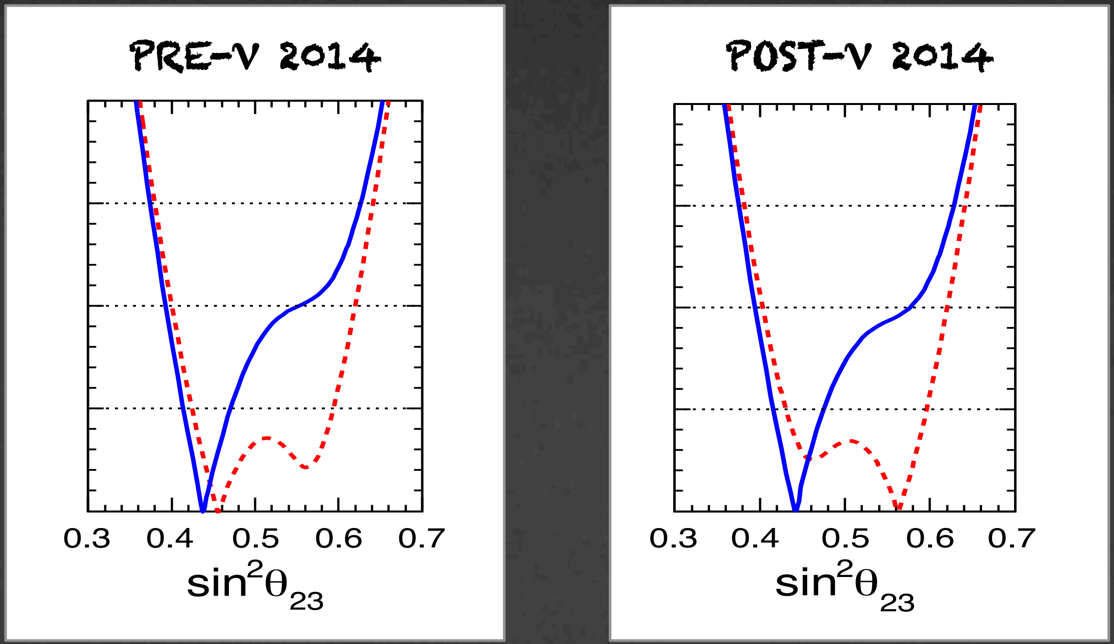


Improvement in precision (8.5% → 6%)

Best fit value sensibly lower (0.0237 → 0.0217)

Combination dominated by Daya-Bay

Pre-post ν 2014 comparison: θ_{23}

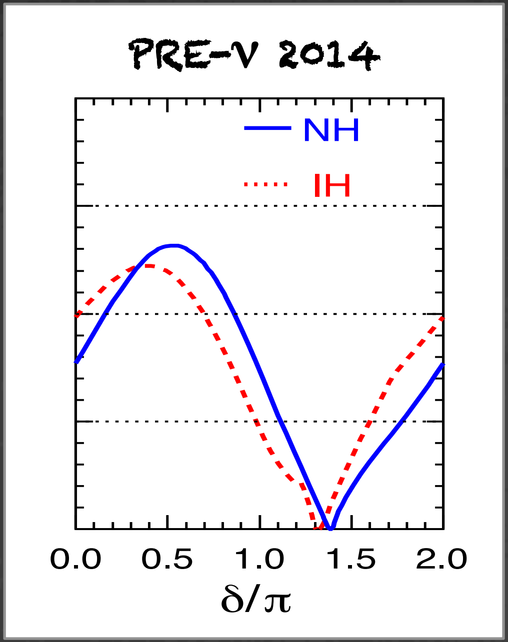


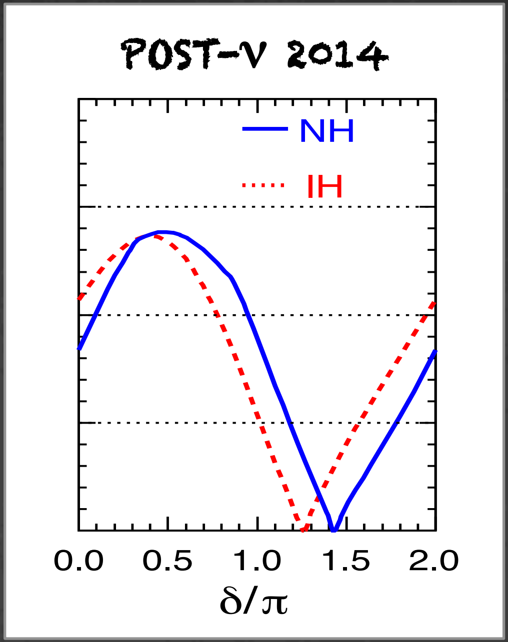
Situation almost unaltered

In IH now it is preferred the second octant

In NH second octant less disfavored than before

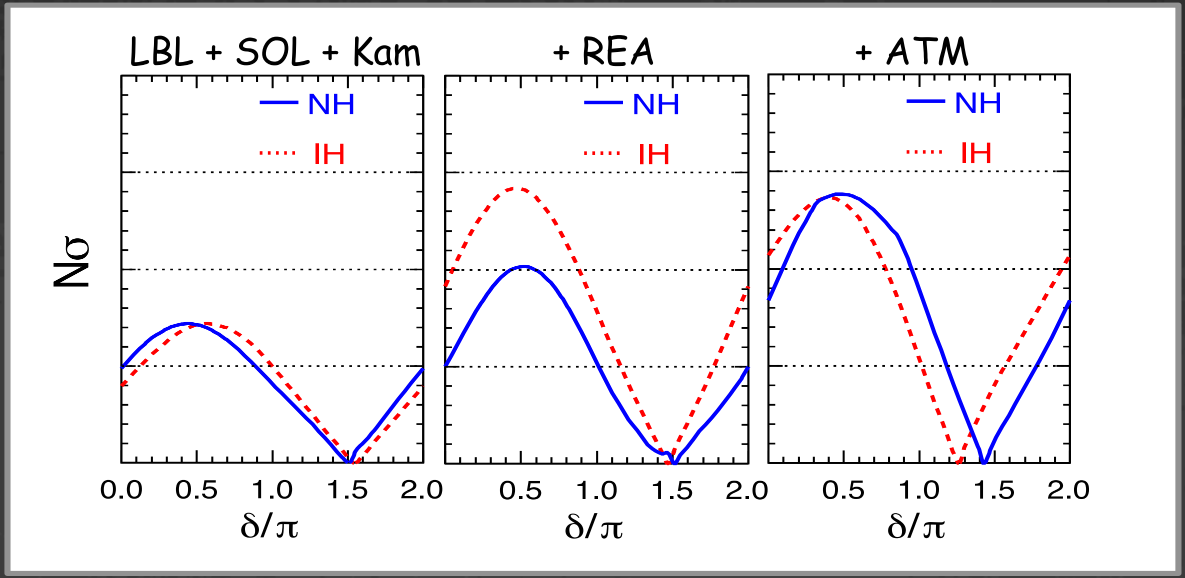
Pre-post ν 2014 comparison: δ





Preference for sin δ < 0 slightly enhanced

Is the hint of sin δ < 0 robust ?

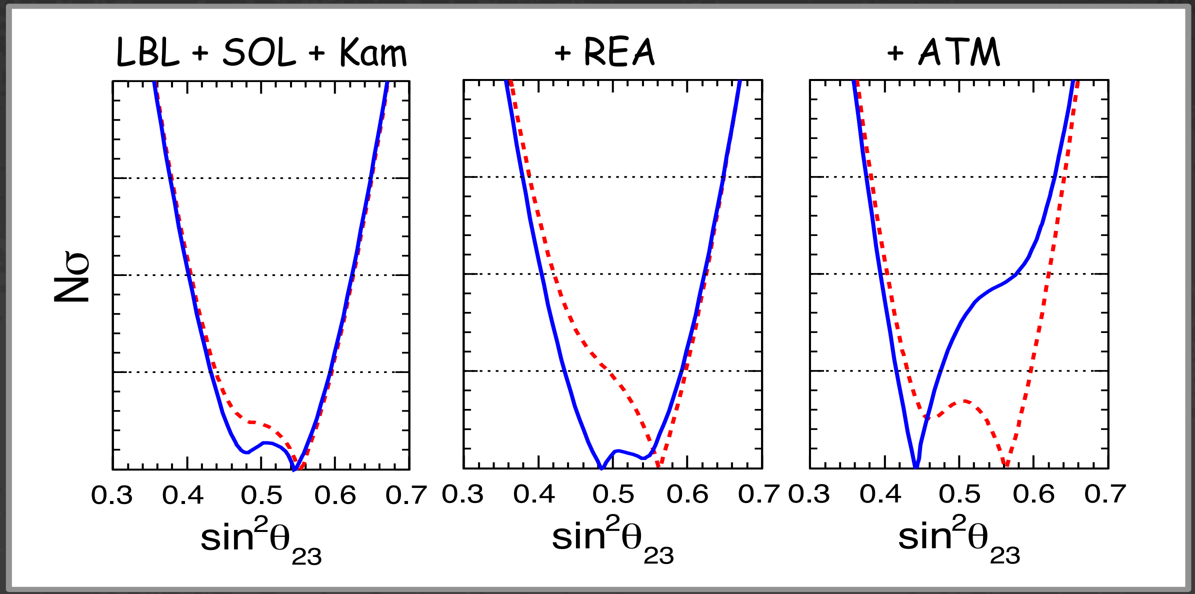


Reinforced for increasingly rich data sets

But mostly driven by "large" T2K ν_e signal
(real o statistical over-fluctuation?)

In part due to ATM (delicate analysis)

Situation much different for θ_{23}



In NH slight preference for first octant emerges totally driven by SK ATM

In IH different data sets prefer opposite octants no global octant preference emerges

Estimate of θ_{23} octant is currently very fragile

A few basic observations

LBL ν_e appearance

T2K

$P_{\mu e} = P^{ATM} + P^{INT} + \cancel{P^{SOL}}$

$P^{ATM} \propto \sin^2\theta_{13} \sin^2\theta_{23} (1+2v)$

$P^{INT} \propto -|J| \sin\delta$

$v = 2VE/\Delta m^2 = 0.05$

NH, $v>0$, $P_{\mu e} \uparrow$ $\quad \frac{\Delta P}{P} \sim 20\%$
IH, $v<0$, $P_{\mu e} \downarrow$

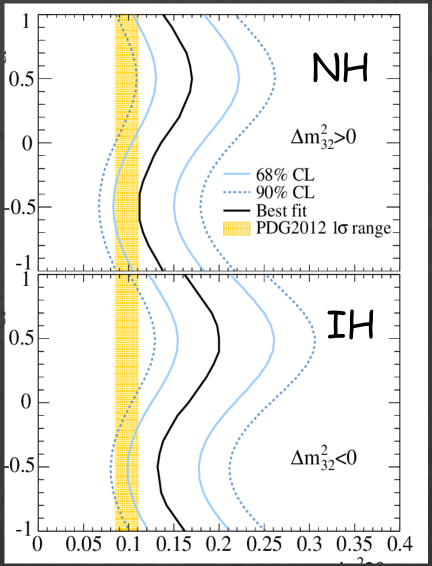
- θ_{13}, θ_{23} anti-correlated
- MSW $\rightarrow$ NH: $\theta_{13}\downarrow$ IH: $\theta_{13}\uparrow$
- $\delta = -\pi/2 \rightarrow$ max $P^{INT} > 0$

LBL ν_μ disappearance

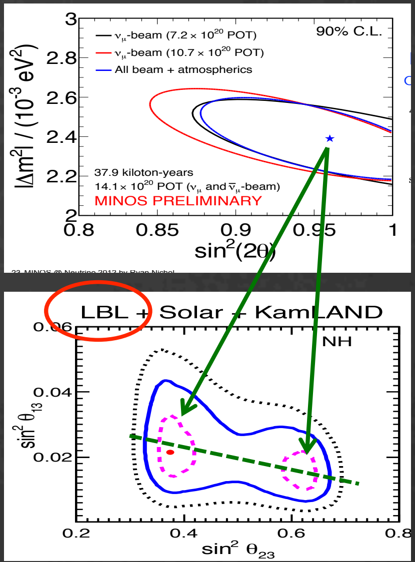
$P_{\mu\mu} \propto \sin^2 2\theta_{23}$

Mostly sensitive to octant symmetric deviations from maximal mixing

T2K ν 2014



MINOS ν 2012



* Figures shown in this slide do not necessarily contain up to date material; they are used here only for illustration purposes

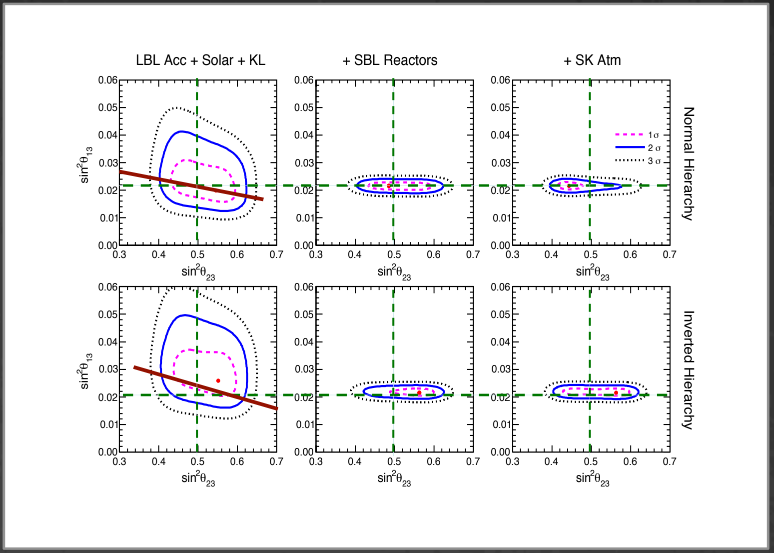
$[\theta_{23}, \theta_{13}]$ correlation plot

LBL ν_μ disappearance

Slight non-maximal preference from MINOS but T2K preference for maximal mixing dominates

LBL ν_e appearance

Strong T2K signal points to big values of θ_{13}, especially in IH, where MSW tends to suppress $P_{\mu e}$



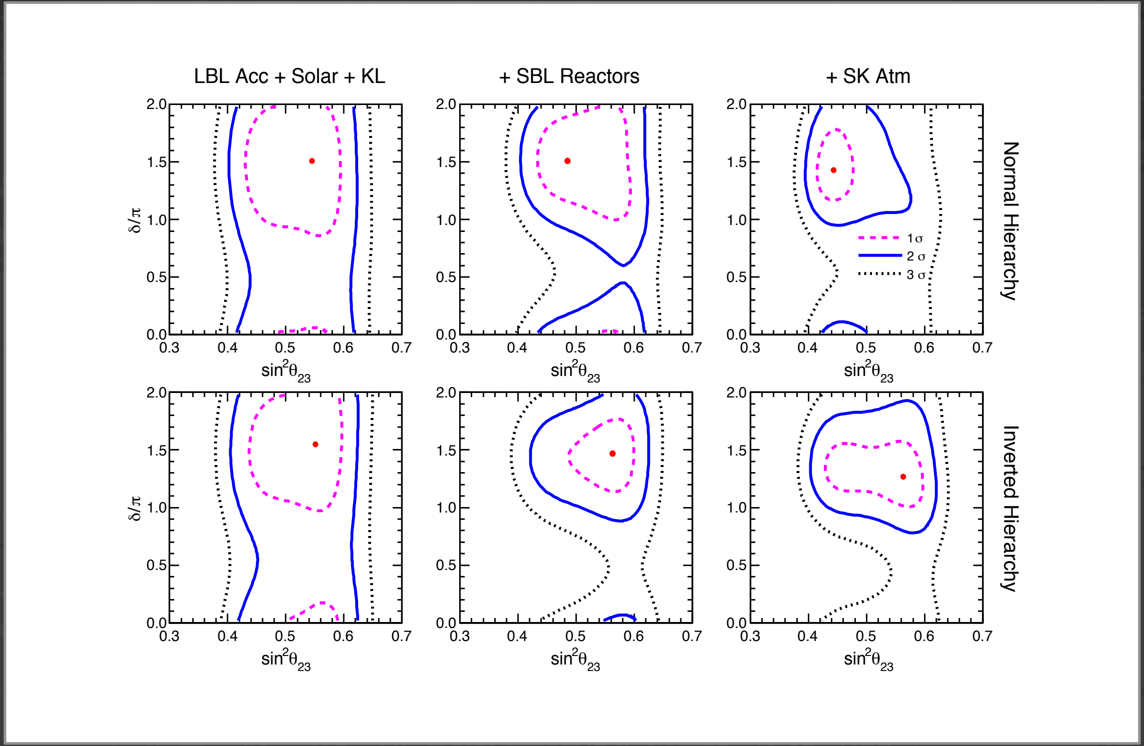
Once REA fix θ_{13} octant asymmetry may emerge

- NH: no octant asymmetry (REA lie just in the middle of LBL)
- IH: θ_{23} in 2nd octant (REA lie in the lower part of LBL region)

ATM tend to push θ_{23} in the first octant (NH & IH)

- NH: ATM easily push global θ_{23} estimate in the first octant
- IH: no global octant preference (ATM counterbalance REA+LBL)

$[\theta_{23} - \delta]$ correlation plot



Effect of SK Atm in the global δ estimate is twofold:

I) **Direct:** in SK we find a weak preference for $\delta = 1.2\ \pi$ (NH & IH)

II) **Indirect:** via $[\delta, \theta_{23}]$ anticorrelation (especially important in NH)

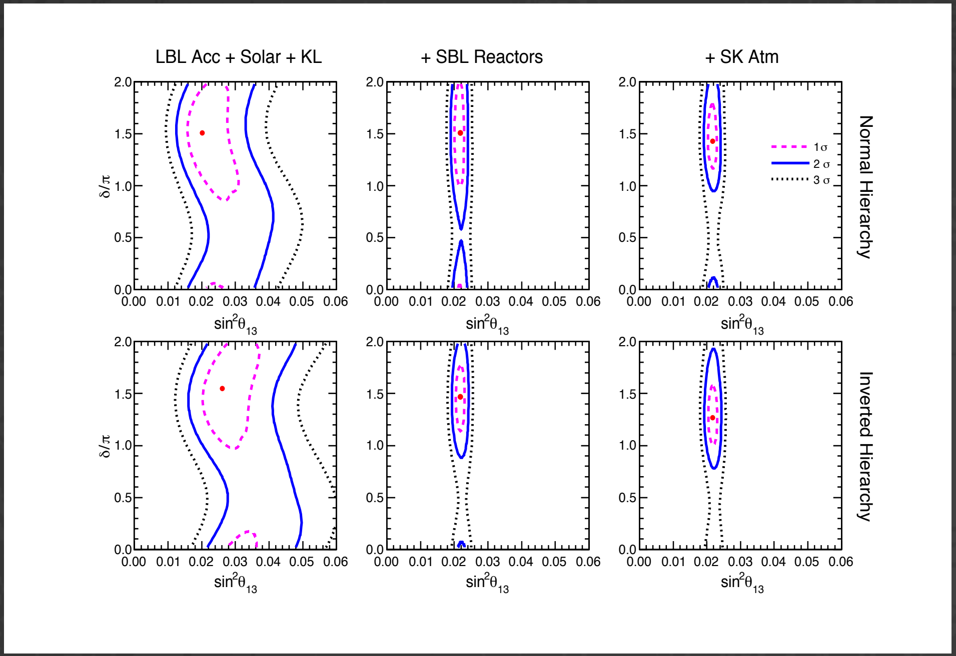
Summary

- 3-flavor scheme describes all data (except VSBL)
- Intriguing indication in favor of $\sin\delta < 0$
- Preference for octant of θ_{23} is very fragile
- No sensitivity to neutrino mass hierarchy
- Be ready to surprises to come from new data

Thank you for your attention!

Backup slides

[θ_{13} – δ] correlation plot



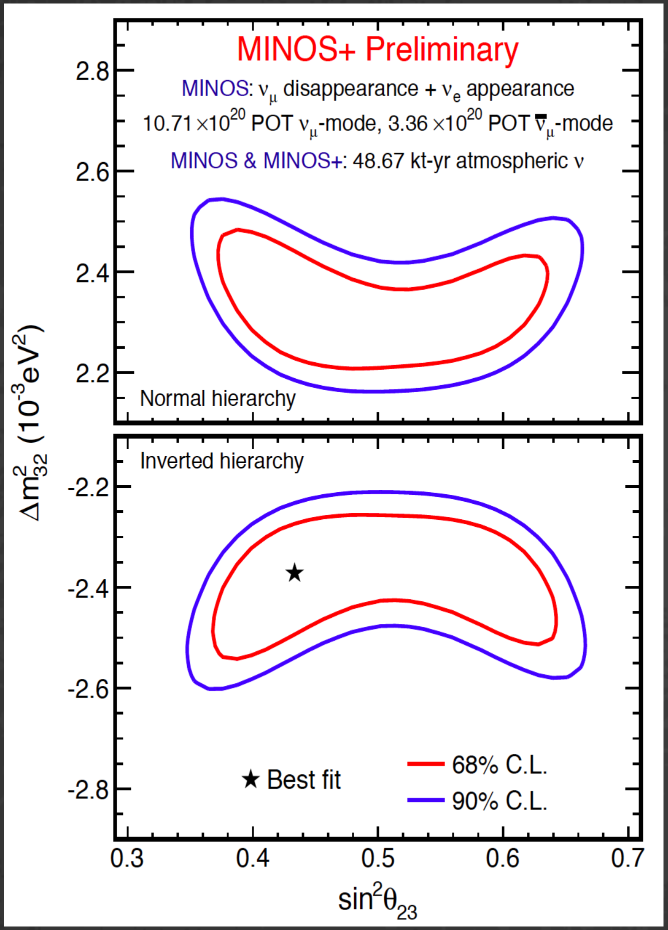
LBL + Sol + KL almost insensitive to δ

Sensitivity emerges once reactors fix θ_{13}

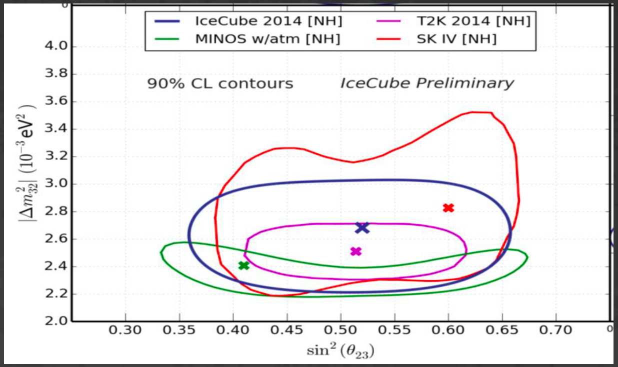
SK Atmospheric slightly reinforce $\sin\delta < 0$

Other data presented at Neutrino 2014*

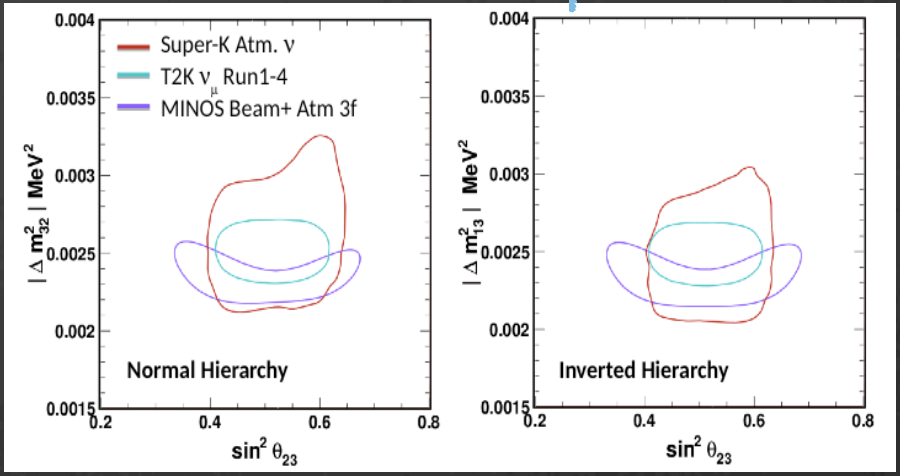
MINOS+



IceCUBE



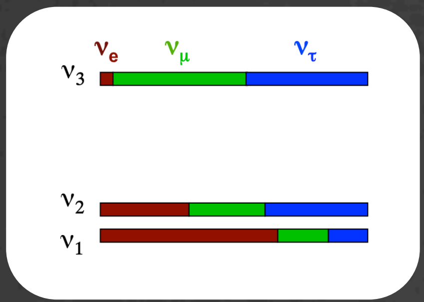
SK-IV ATM update



* To be included in our global analysis; work in progress.

Introducing a light sterile neutrino

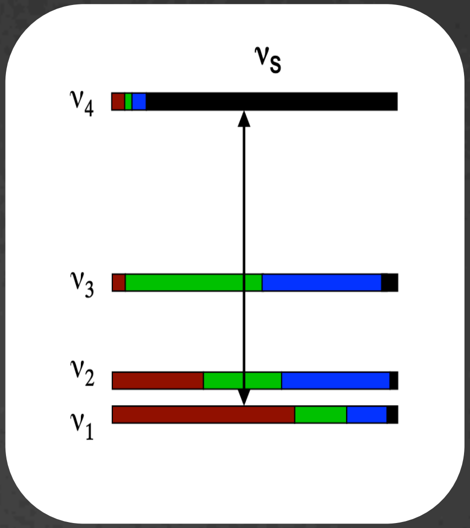
3ν



Δm^2_{atm}

Δm^2_{sol}

4ν



$|U_{s4}| \sim 1$

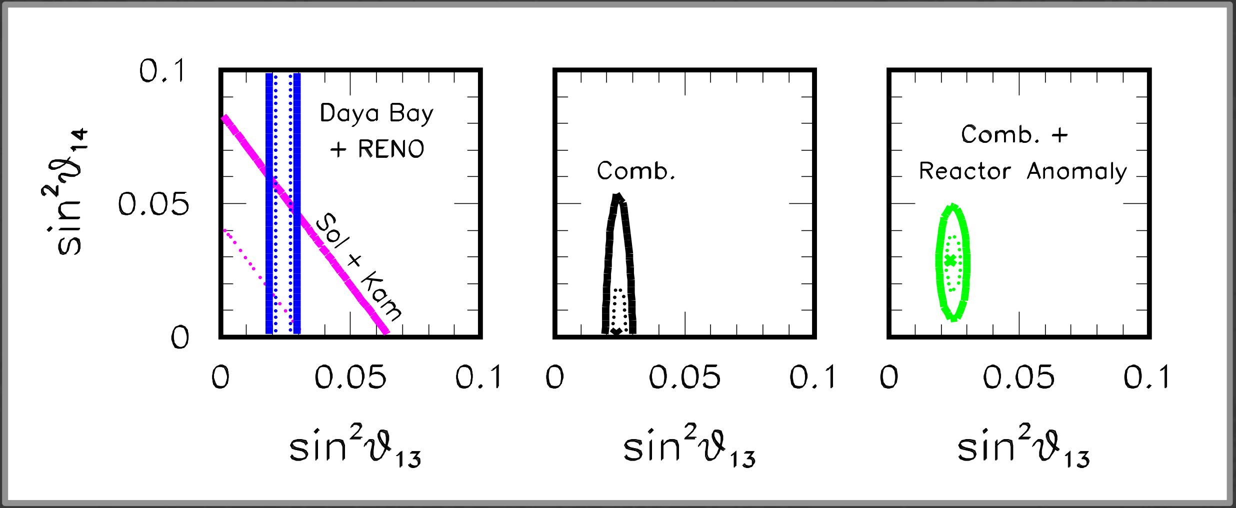
$\Delta m^2_{14} \sim 1$ eV ^{2}

Small mixing of active flavors with the 4th state

Estimate of θ_{13} in a 3+1 scheme

$\Delta m^2_{14} \sim 1 \text{ eV}^2$

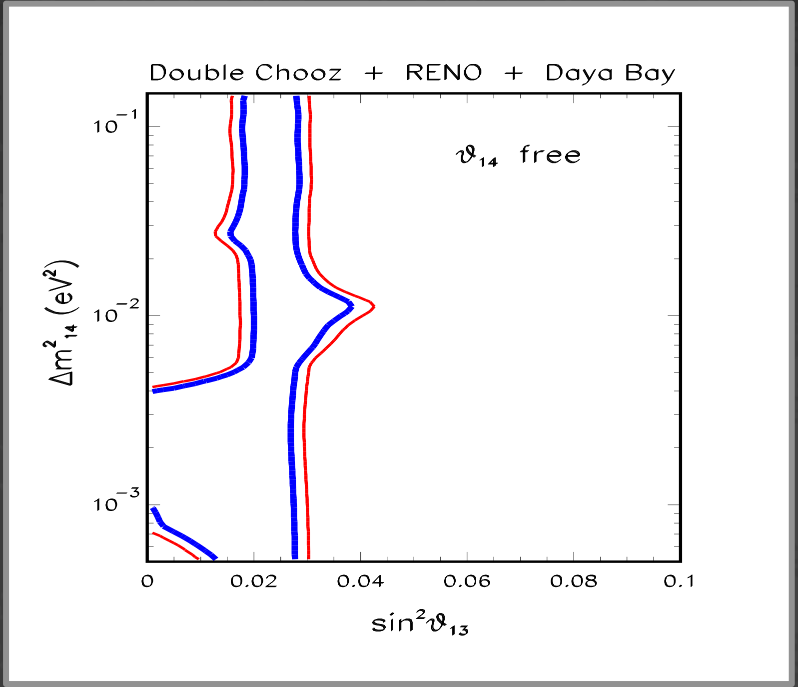
A.P., Review for Mod. Phys. Lett. A 28, 1330004 (2013)



- Solar + LBL reactors: $\sin^2\theta_{14} < 0.04 \quad (90\% \text{ C.L.})$

- Bound indep. of reactor fluxes (KamLAND only shape)

Going down with Δm^2_{14}



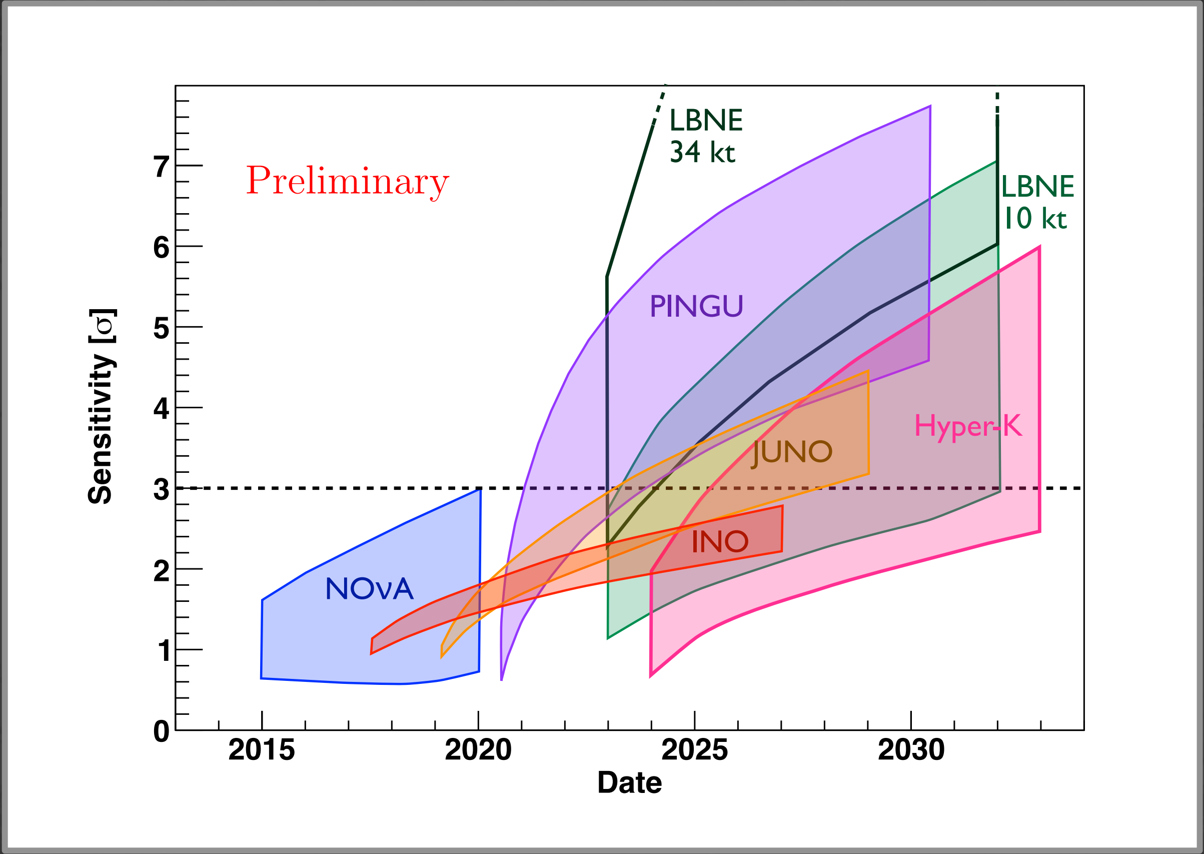
A.P. JHEP 1310, 172 (2013) [1308.5880 hep-ph]

3ν estimate robust provided that $\Delta m^2_{14} > 6 \times 10^{-3}$ eV^2

No lower bound for smaller Δm^2_{14} (θ_{13}–θ_{14} degeneracy)

However, in this region lower bound by T2K

Sensitivity to NMH of future experiments

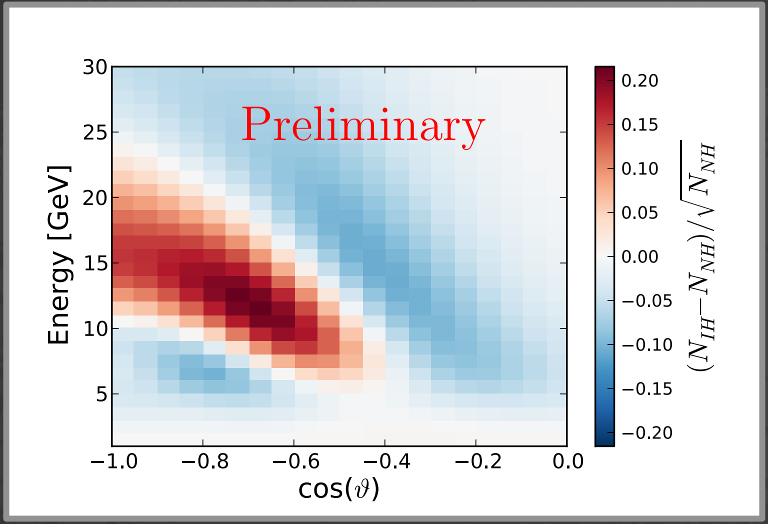


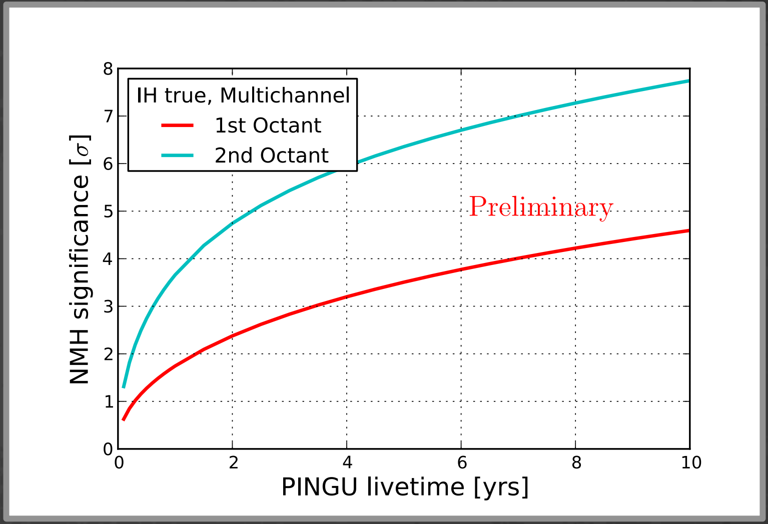
Blennow et al. 1311.1822

Reactor, Accelerators, atmospheric ν experiments

PINGU @ IceCube

Signature in the energy/zenith-angle distribution





PINGU LoI

Interference of MSW potential with atmospheric Δm^2