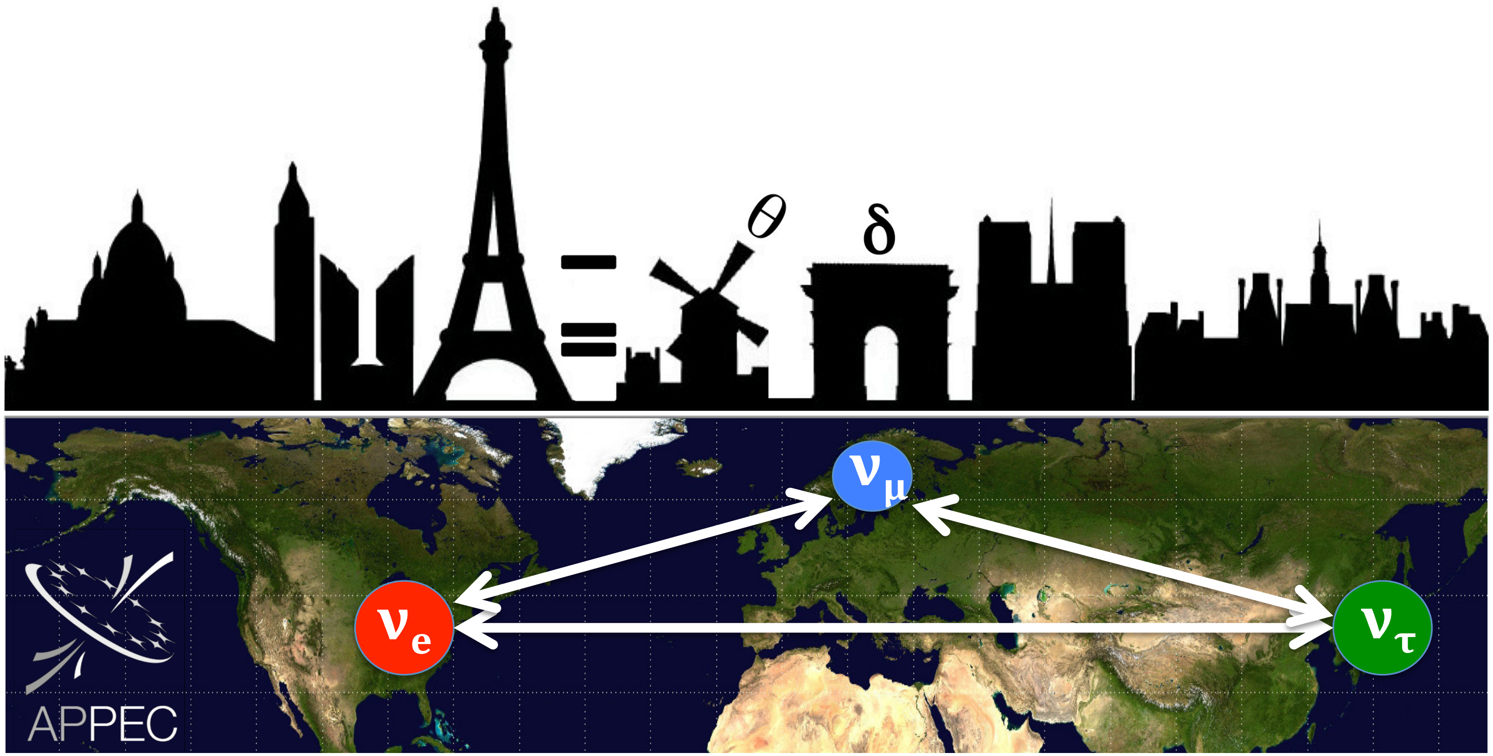
Analysis of 3ν mass-mixing parameters: 2014 status



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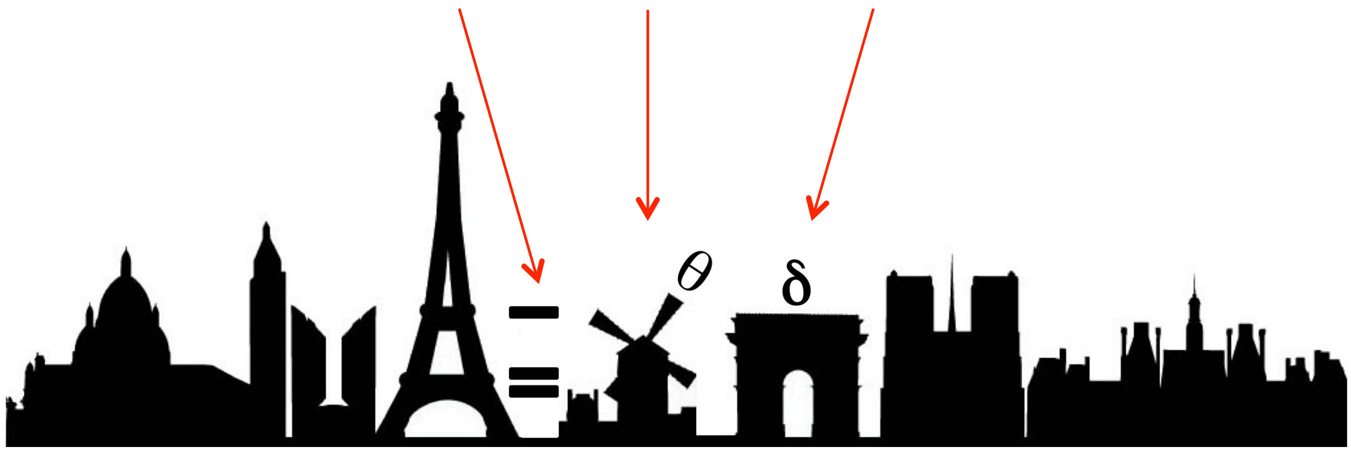
Outline:

- Intro: data, notation, methodology
- **Status just before "Neutrino 2014"**
- Impact of (some) ν2014 new data
- **Absolute neutrino mass observables**

Emphasis: hierarchy, θ_{23} octant, CP phase (unkowns)



Based on arXiv:1312.2878v2 + work done in collaboration with:
F. Capozzi, G.L. Fogli, D. Montanino, A. Marrone, A. Palazzo

2014 Data sets:

LBL Accelerators	=	K2K + T2K + MINOS
Solar	=	All Solar experiments
KL	=	KamLAND reactor expt
SBL Reactors	=	DChooz + RENO + DB
SK Atm	=	Super-K Atmospheric

3ν oscillation parameters: Notation

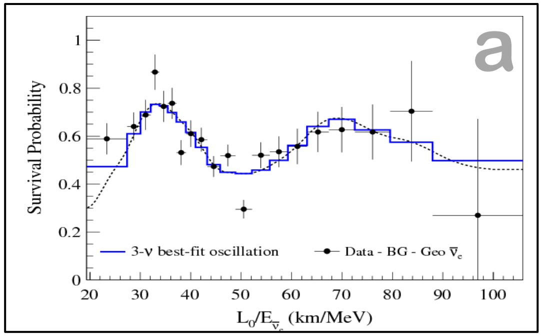
δm^2	=	Δm^2_{21}
$\theta_{12}, \theta_{23}, \theta_{13}, \delta$	=	as in PDG
δ range	=	$[0, 2\pi]$ (others prefer $[-\pi, +\pi]$)
Δm^2	=	$(\Delta m^2_{31} + \Delta m^2_{32})/2$

(All parameters free to float in the global fit)

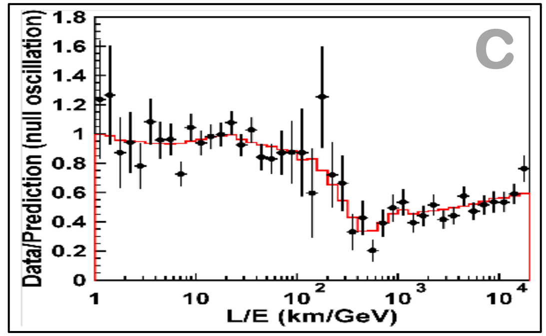
2014: 1σ error on $\Delta m^2 \approx 6 \times 10^{-5}$ eV^2 $<$ δm^2 !

$\alpha \rightarrow \beta$ transitions and dominant oscillation parameters probed so far:

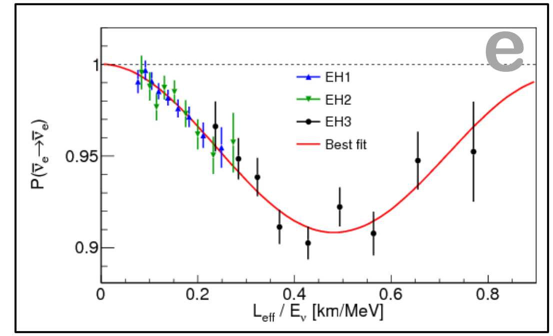
e→e (δm^2 , θ_{12})



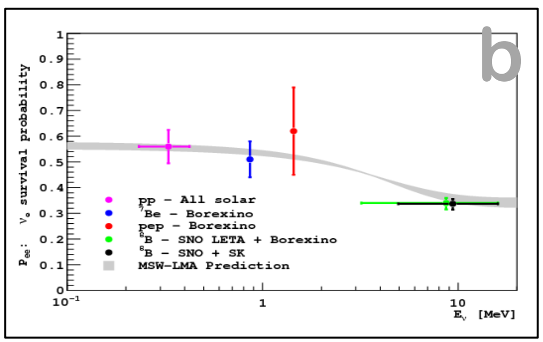
μ→μ (Δm^2 , θ_{23})



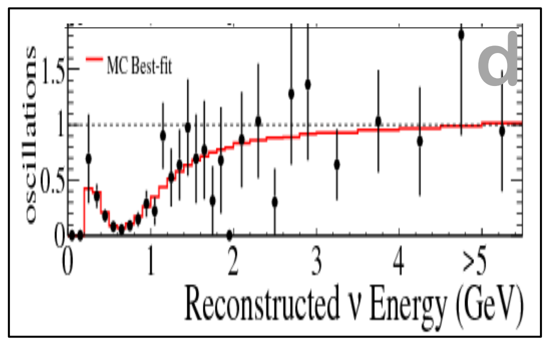
e→e (Δm^2 , θ_{13})



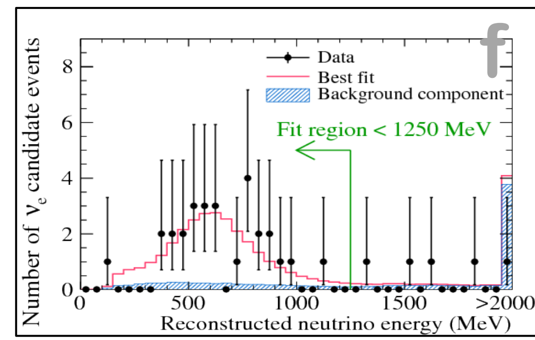
e→e (δm^2 , θ_{12})



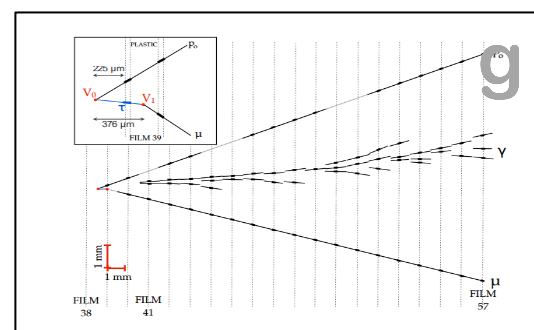
μ→μ (Δm^2 , θ_{23})



μ→e (Δm^2 , θ_{13} , θ_{23})



μ→τ (Δm^2 , θ_{23})



Data from various types of neutrino experiments: (a) solar, (b) long-baseline reactor, (c) atmospheric, (d) long-baseline accelerator, (e) short-baseline reactor, (f,g) long baseline accelerator (and, in part, atmospheric).

(a) KamLAND [plot]; (b) Borexino [plot], Homestake, Super-K, SAGE, GALLEX/GNO, SNO; (c) Super-K atmosph. [plot], MACRO, MINOS etc.; (d) T2K (plot), MINOS, K2K; (e) Daya Bay [plot], RENO, Double Chooz; (f) T2K [plot], MINOS; (g) OPERA [plot], Super-K atmospheric.

See also other talks at this Meeting.

Combined analysis of data sets: Methodology

LBL Accelerator data are dominantly sensitive to (Δm^2, θ_{23}, θ_{13}). But, accurate constraints on these parameters do need (δm^2, θ_{12}) input from **Solar + KL** to compute sub-dominant effects.

It makes sense to combine from the start: **LBL Acc + Solar + KL**. Note: Solar + KL data carry a preference ("hint") for $\sin^2\theta_{13}$~0.02

Combined analysis of data sets: Methodology

Analysis includes increasingly rich data sets:

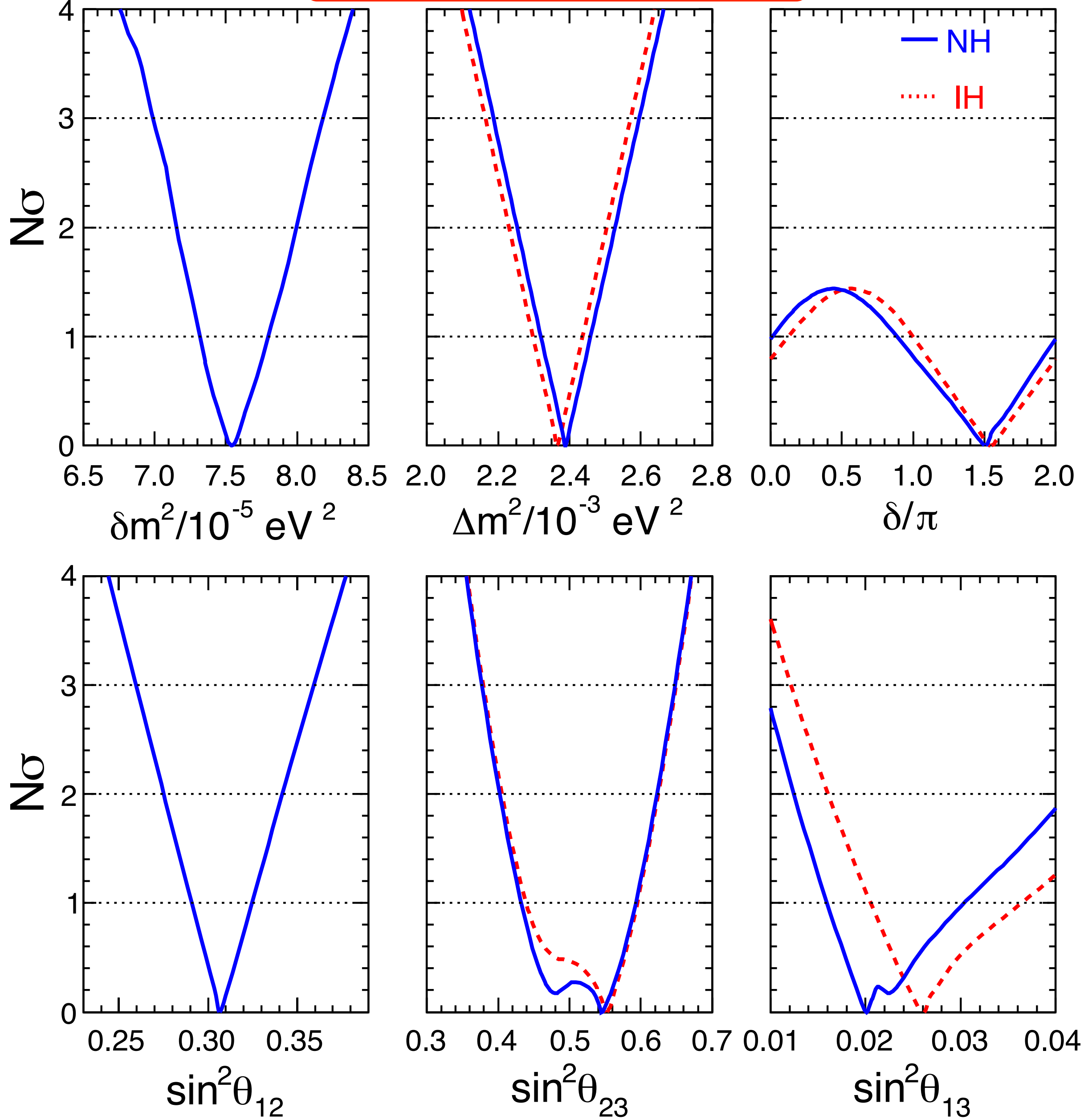
LBL Acc + Solar + KL
LBL Acc + Solar + KL + SBL Reactor
LBL Acc + Solar + KL + SBL Reactor + SK Atm.

Figures: parameters not shown are marginalized away.

Contours are drawn at $\Delta\chi^2 = 1, 4, 9$ →
$N\sigma = 1, 2, 3$ for projections over single parameters.

End of Intro. **Results on single parameters** →
[with all data available just before Nu2014]

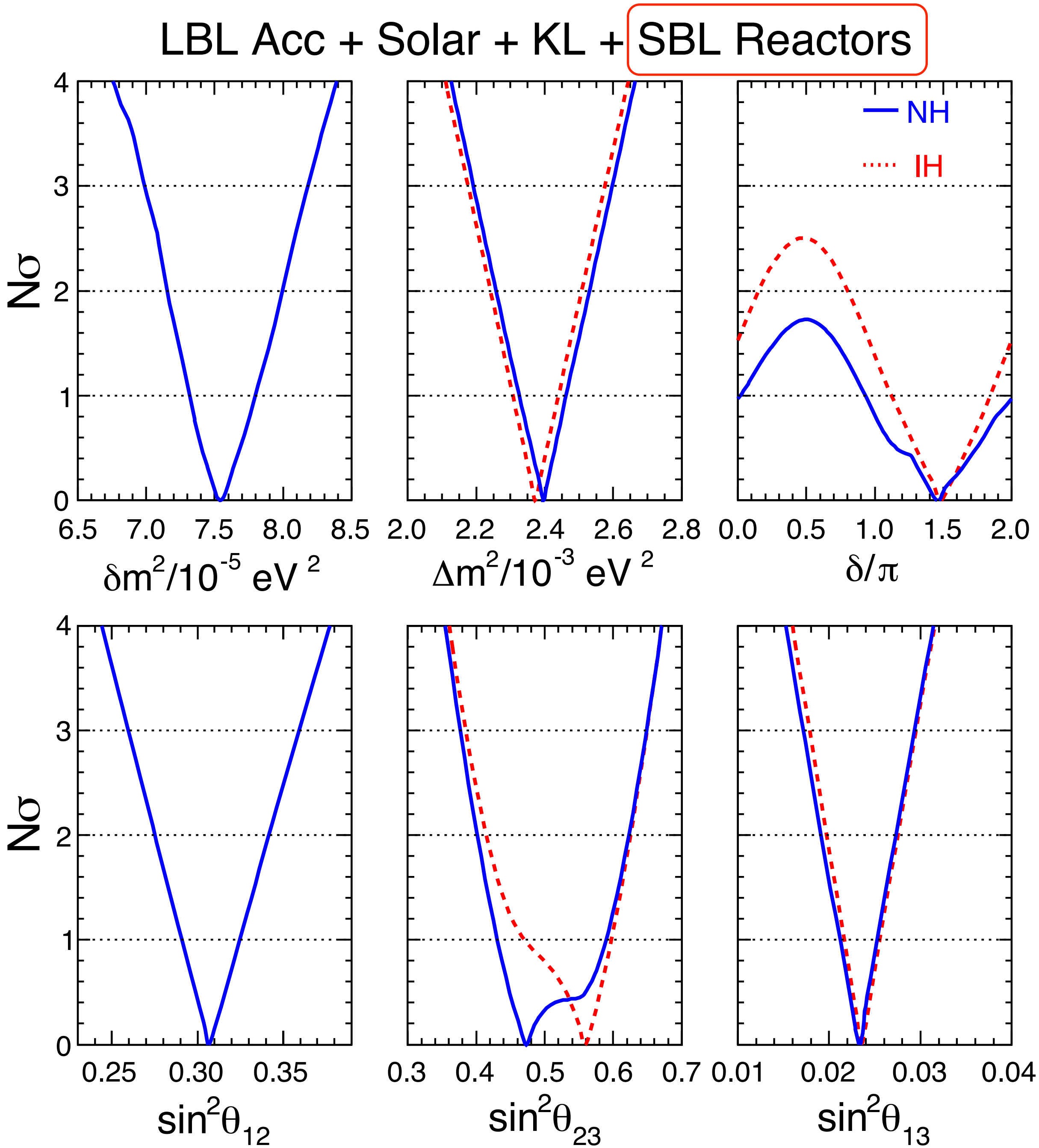
LBL Acc + Solar + KL



Upper and lower bound on all oscill. parameters but δ

Slight preference for $\delta \sim 1.5\,\pi$

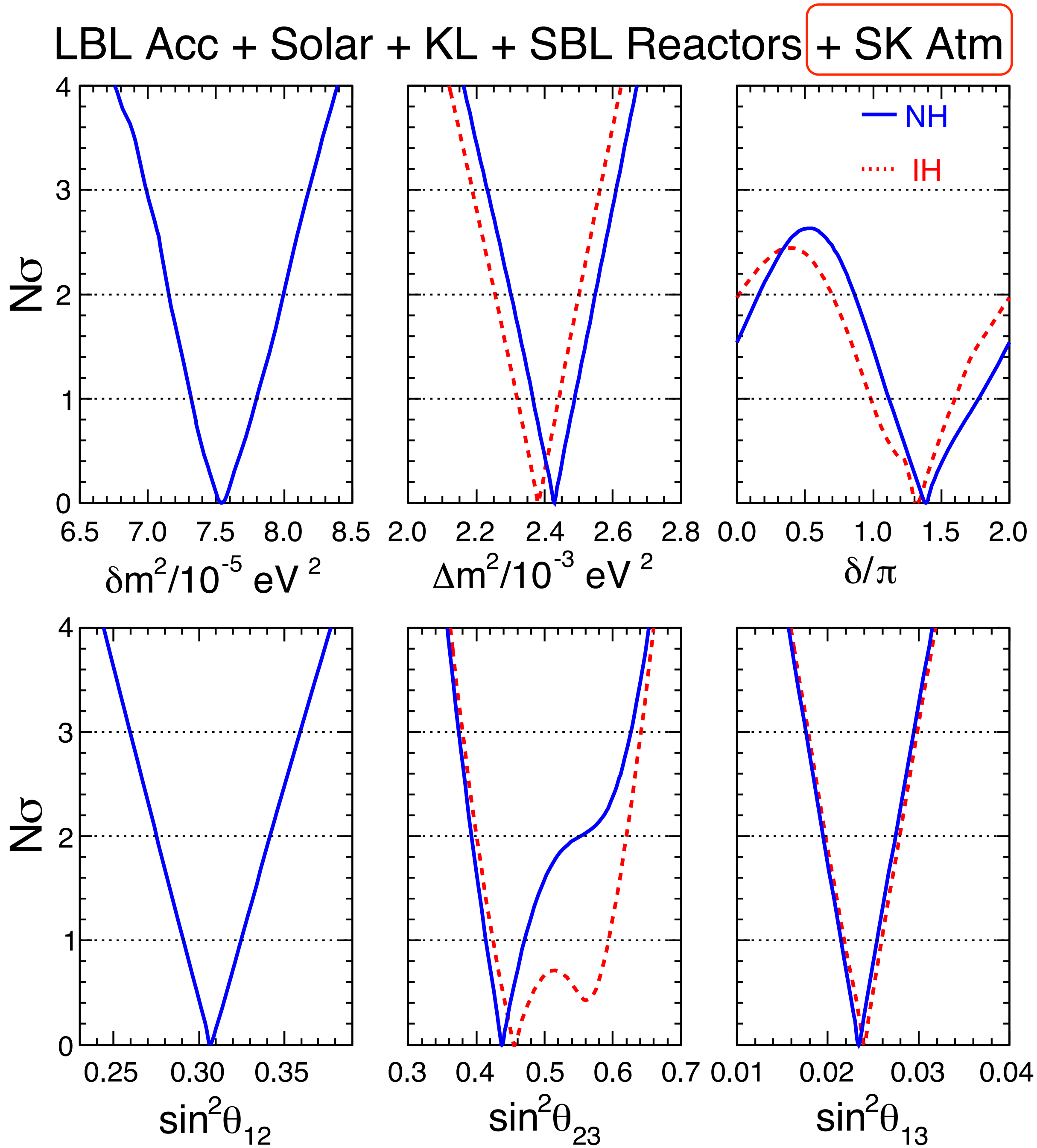
Slight preference for nonmaximal θ_{23} and for 2nd octant



Strong θ_{13} bounds

Still a preference for $\delta \sim 1.4\text{–}1.5\,\pi$

Slight preference for nonmax θ_{23} but octant flips with hierarchy



Some effects on the $\nu_\mu \to \nu_\tau$ dominant parameters (Δm^2, θ_{23})

Preference for $\delta \sim 1.4\,\pi$ and, in NH, for $1 < \delta/\pi < 2$ ($\sin\delta<0$ @90% CL)

Preference for nonmaximal θ_{23} and 1st octant in NH; much weaker in IH. Somewhat fragile.

Nσ ranges for single parameters (pre-Neutrino'14):

TABLE I: Results of the global 3ν oscillation analysis, in terms of best-fit values and allowed 1, 2 and 3σ ranges for the 3ν mass-mixing parameters. See also Fig. 3 for a graphical representation of the results. We remind that Δm^2 is defined herein as $m_3^2 - (m_1^2 + m_2^2)/2$, with $+\Delta m^2$ for NH and $-\Delta m^2$ for IH. The CP violating phase is taken in the (cyclic) interval $\delta/\pi \in [0, 2]$. The overall χ^2 difference between IH and NH is insignificant ($\Delta\chi^2_{\mathrm{I-N}} = -0.3$).

Parameter	Best fit	1σ range	2σ range	3σ range
$\delta m^2/10^{-5}$ eV^2 (NH or IH)	7.54	7.32 – 7.80	7.15 – 8.00	6.99 – 8.18
$\sin^2\theta_{12}/10^{-1}$ (NH or IH)	3.08	2.91 – 3.25	2.75 – 3.42	2.59 – 3.59
$\Delta m^2/10^{-3}$ eV^2 (NH)	2.43	2.37 – 2.49	2.30 – 2.55	2.23 – 2.61
$\Delta m^2/10^{-3}$ eV^2 (IH)	2.38	2.32 – 2.44	2.25 – 2.50	2.19 – 2.56
$\sin^2\theta_{13}/10^{-2}$ (NH)	2.34	2.15 – 2.54	1.95 – 2.74	1.76 – 2.95
$\sin^2\theta_{13}/10^{-2}$ (IH)	2.40	2.18 – 2.59	1.98 – 2.79	1.78 – 2.98
$\sin^2\theta_{23}/10^{-1}$ (NH)	4.37	4.14 – 4.70	3.93 – 5.52	3.74 – 6.26
$\sin^2\theta_{23}/10^{-1}$ (IH)	4.55	4.24 – 5.94	4.00 – 6.20	3.80 – 6.41
δ/π (NH)	1.39	1.12 – 1.77	0.00 – 0.16 $\oplus$ 0.86 – 2.00	—
δ/π (IH)	1.31	0.98 – 1.60	0.00 – 0.02 $\oplus$ 0.70 – 2.00	—

Fractional errors (defined as 1/6 of $\pm3\sigma$ ranges):

δm^2	2.6 %
Δm^2	2.6 %
$\sin^2\theta_{12}$	5.4 %
$\sin^2\theta_{13}$	8.5 %
$\sin^2\theta_{23}$	~ 10 %

No significant hierarchy preference from global fit [$\Delta\chi^2$(I-N)=-0.3]
Weak preference for first octant (more fragile after T2K 2014 data).
Intriguing hint of nonzero CP violation, with $\sin\delta < 0$ ... (*)

(*) Similar CP hint: Gonzalez-Garcia, Maltoni, Schwetz, Salvado 2013/14; SK, T2K official data analyses 2013/14.

CP violation requires genuine 3ν oscillations, distinct from 2ν limits...

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TIME REVERSAL VIOLATION IN NEUTRINO OSCILLATION

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Received 11 October 1977

We discuss the possibility of CP or T violation in neutrino oscillation CP requires $\nu_\mu \leftrightarrow \nu_e$ and $\bar{\nu}_\mu \leftrightarrow \bar{\nu}_e$ oscillations to be equal Time reversal invariance requires the oscillation probability to be an even function of time Both conditions can be violated, even drastically, if more than two neutrinos exist

CP violation requires genuine 3ν oscillations, distinct from 2ν limits…

3 mixing angles should be nonvanishing ✔

2 mass gaps should be nonvanishing ✔

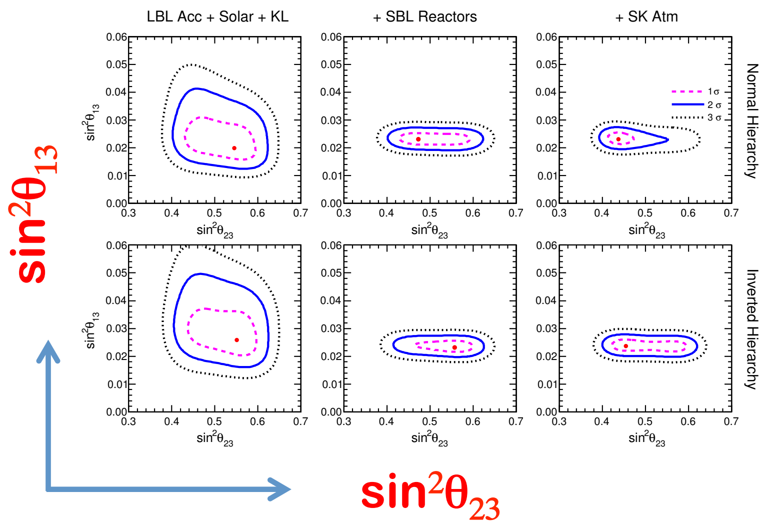
1 Dirac phase should be nonvanishing …

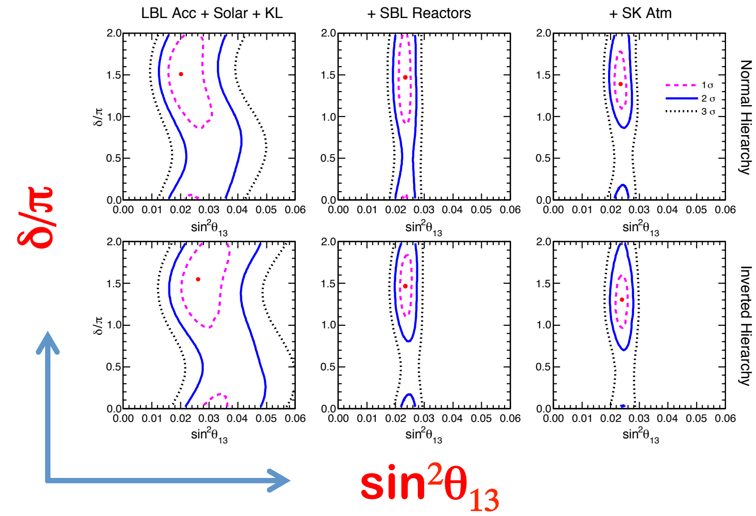
Nature has already provided us with 5 favorable conditions at **terrestrial** scales …

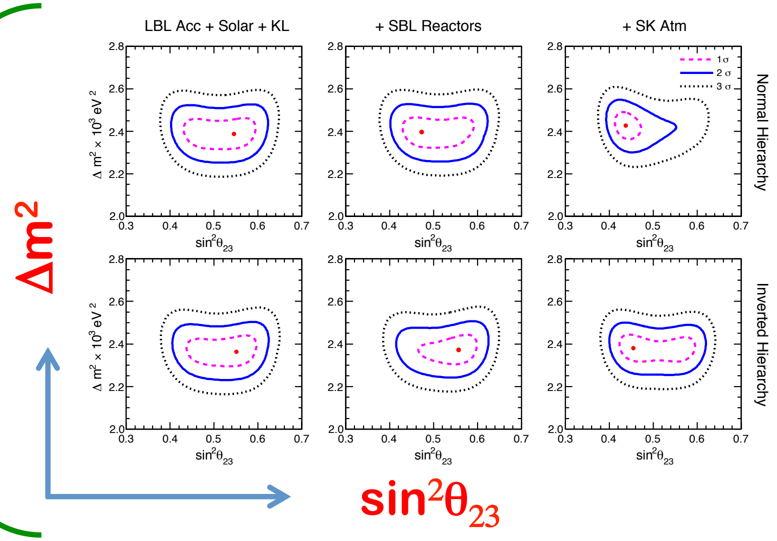
Let us hope that the 6th is also realized

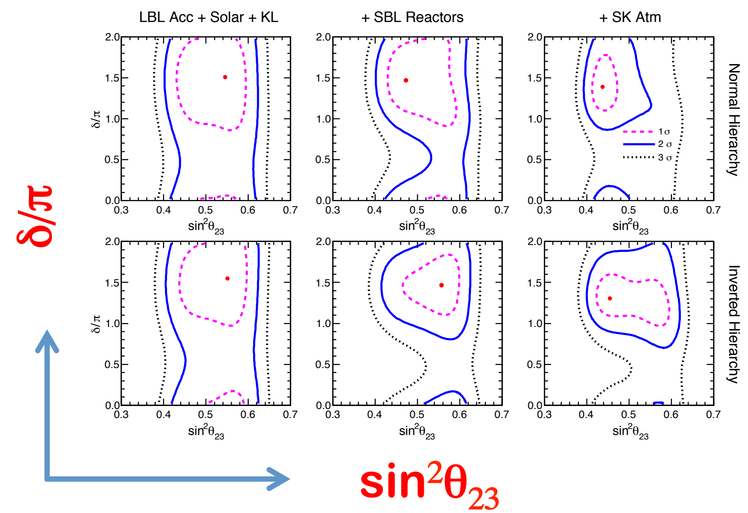
[and, if neutrinos are Majorana… CPV bonanza with 2 more phases !]

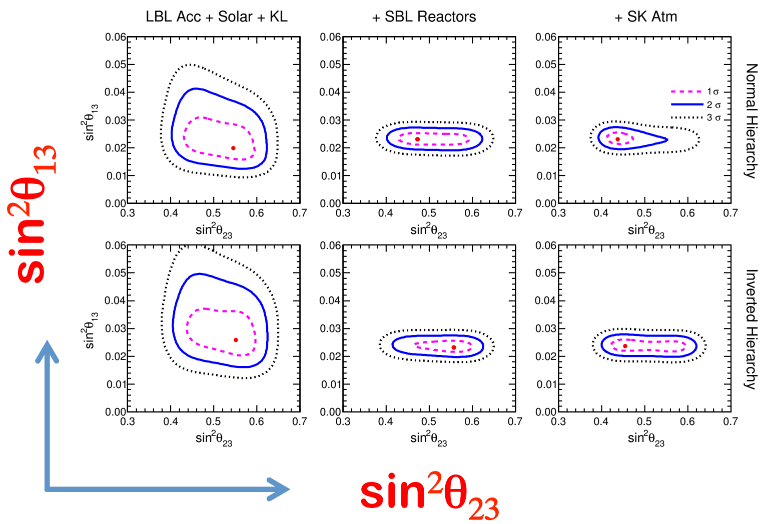
From variances to covariances: analysis of 2D plots











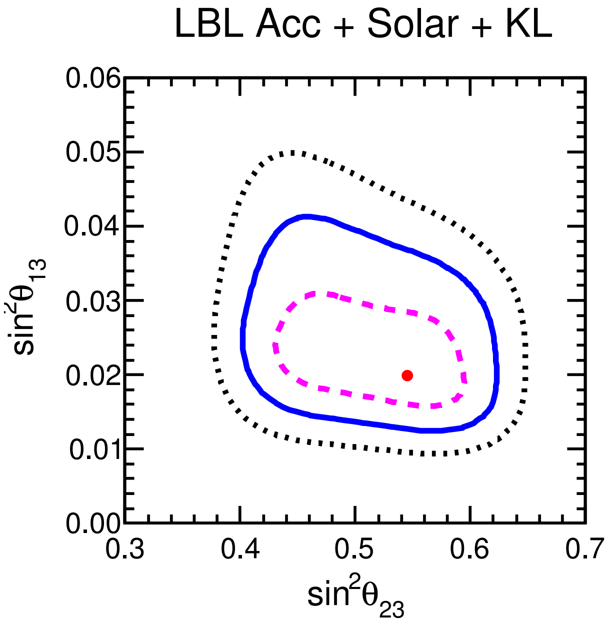
Leading appearance amplitude at LBL Acc. ~ $\sin^2\theta_{23}\,\sin^2(2\theta_{13})$

→ anticorrelates θ_{23} and θ_{13}

Leading disappearence amplitude at SBL Reac. ~ $\sin^2(2\theta_{13})$

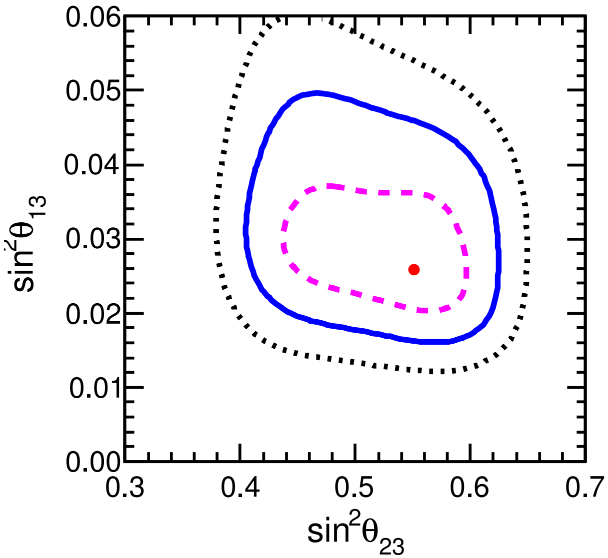
Subleading disappearence effects in Solar + KL ~ $\sin^2\theta_{13}$

→ indirectly help in selecting high/low θ_{23}



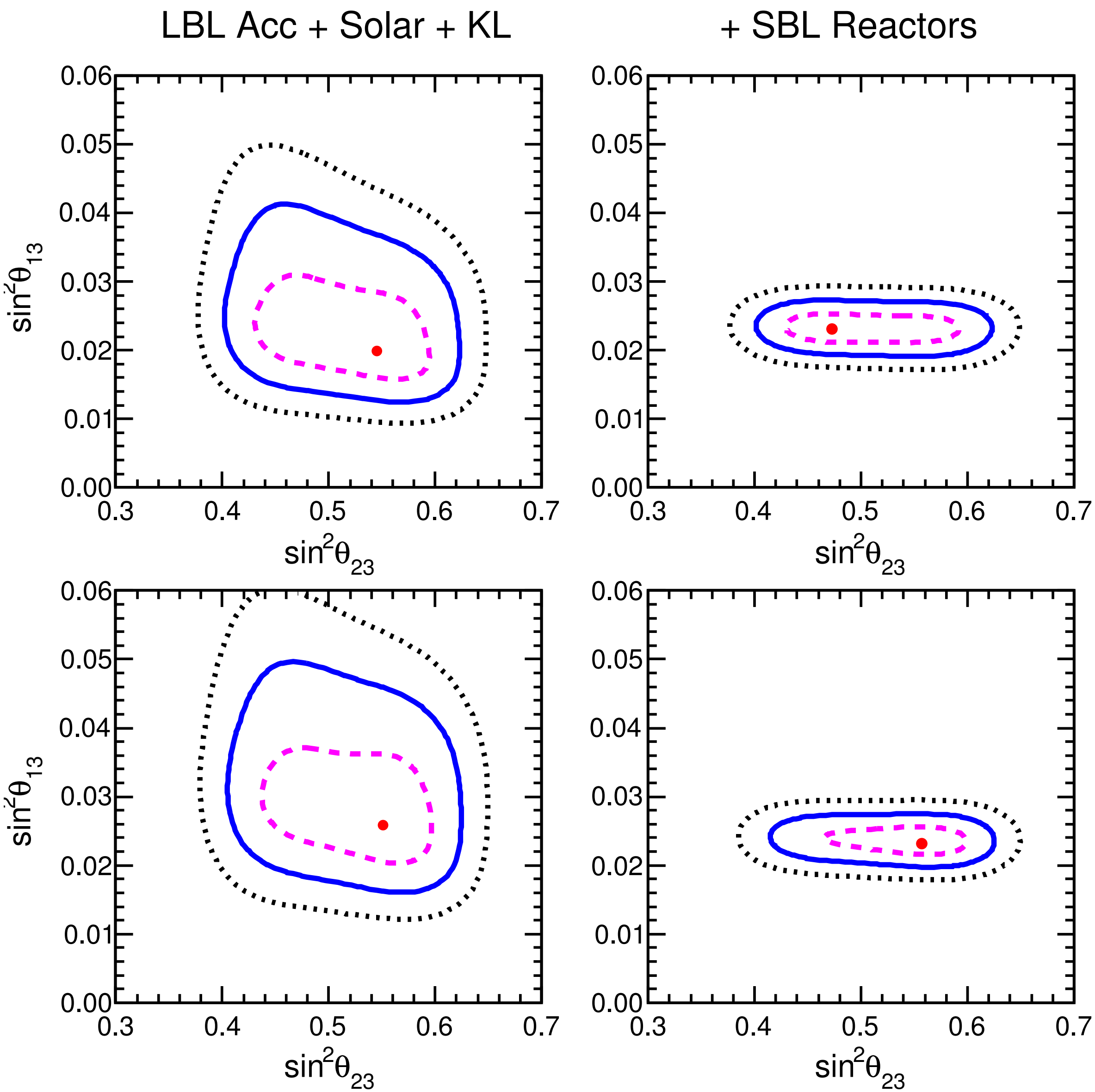
MINOS disappearance prefers nonmaximal mixing (still wins over T2K preference for ~maximal) → two degenerate minima for θ_{23}

T2K + MINOS appearance anticorrelate the minima with θ_{13}: the higher θ_{23}, the lower θ_{13}

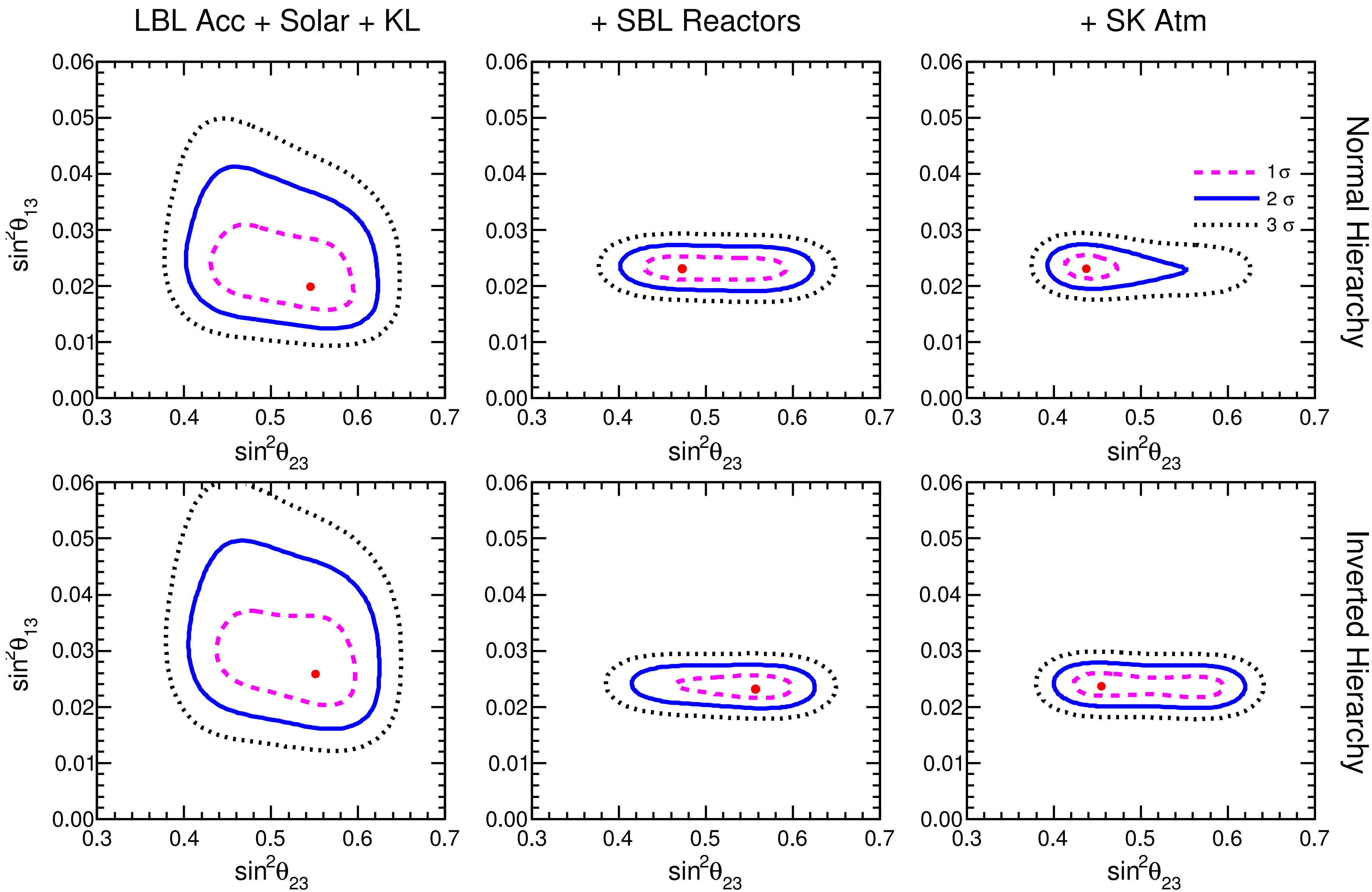


Contours extend to relatively high $\sin^2\theta_{13}$ to accommodate the relatively "strong" T2K appearance signal, especially in IH

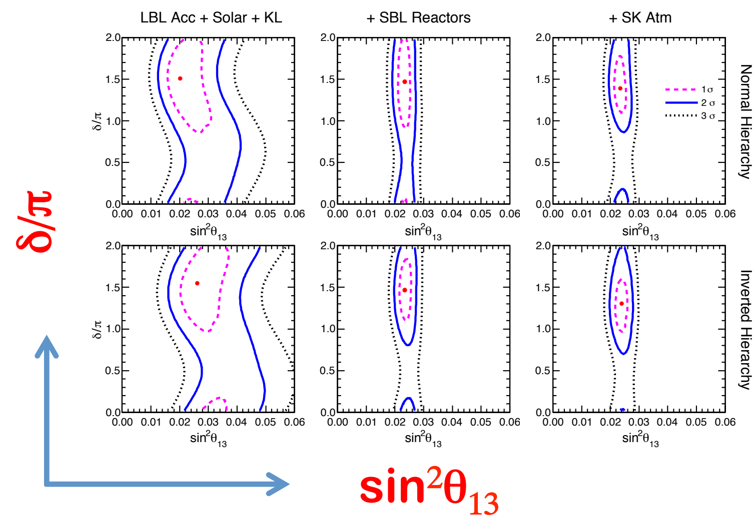
In the combination, Solar + KL data lift the degeneracy and prefer the second octant solution, associated with "low" $\sin^2\theta_{13}$~0.02



Reactor data prefer $\sin^2\theta_{13}$~0.023, slightly higher than Solar+KL: **enough to flip the octant in NH, but not enough to do so in IH.**



SK atm: In our analysis we still find an overall preference of these data for 1st octant. But, global balance for $\theta_{23}<\pi/4$ somewhat fragile

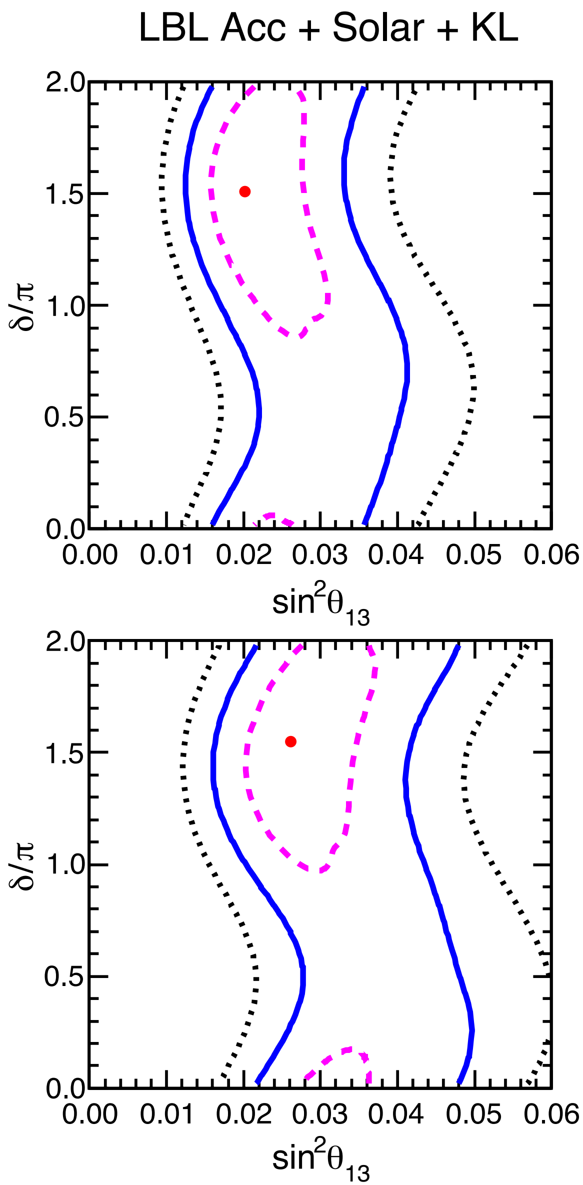


Leading appearance amplitude at LBL Acc. ~ $\sin^2\theta_{23}\sin^2(2\theta_{13})$

→ **uncertainty on θ_{23} somewhat affects subleading terms**

Subleading CPV appearance amplitude for ν ~ $-\sin\delta$

→ **T2K signal maximized for $\sin\delta \sim -1$** ($\delta \sim 1.5\pi$)

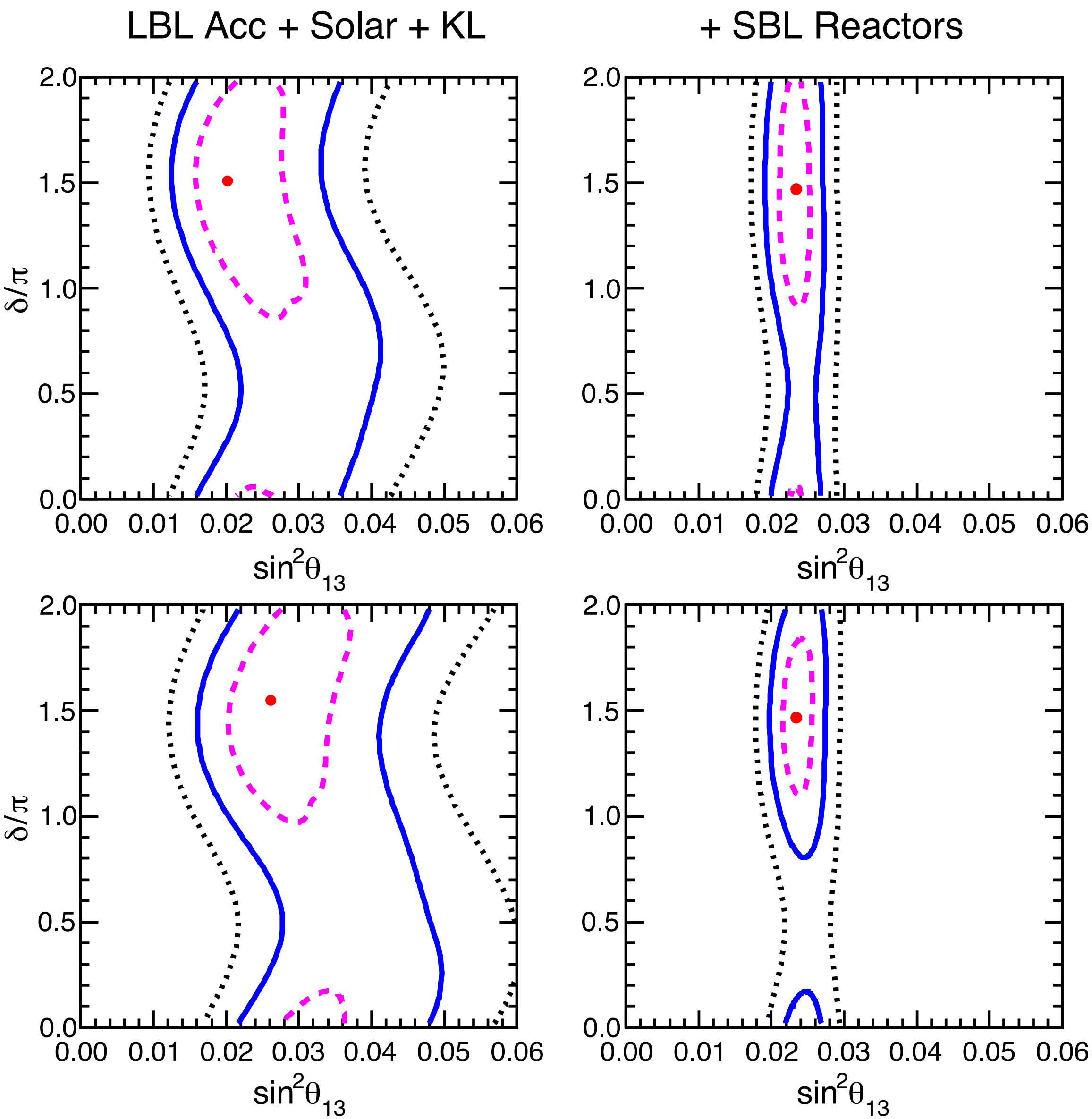


Each wavy band is in part determined by superposition of "two bands" for the two θ_{23} octants [it was more evident in previous fits]

For the relatively "low" value $\sin^2\theta_{13}$~0.02 preferred by Solar + KL data, appearance ν signal in T2K maximized by subleading CP-odd term for $\sin\delta < 0$ [i.e., $1<\delta/\pi<2$]

Best agreement with relatively "strong" T2K appearance signal is for $\delta/\pi \sim 1.5$, irrespective of the hierarchy.

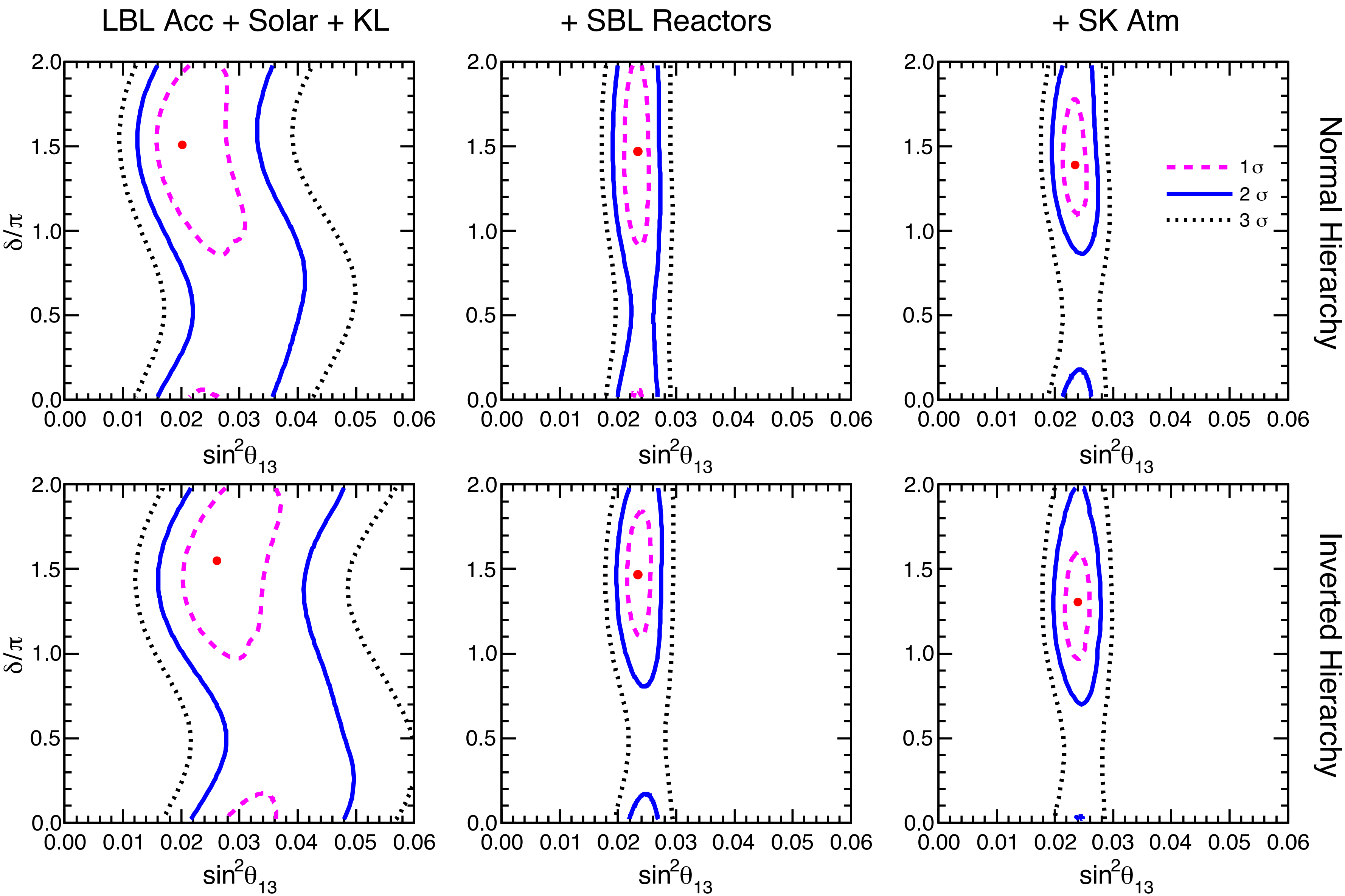
This trend wins over weaker MINOS appearence signal, which tend to prefer $\sin\delta > 0$ at best fit.



Reactor data shrink the band around $\sin^2\theta_{13} \sim 0.023$,

a bit higher than Solar+SK but still on the leftmost side of the band:

preference for $\delta/\pi \sim 1.5$ persists



SK atm: in combination, these data **further shrink the allowed regions** and slight lower the preferred value to **$\delta/\pi \sim 1.3$-1.4**

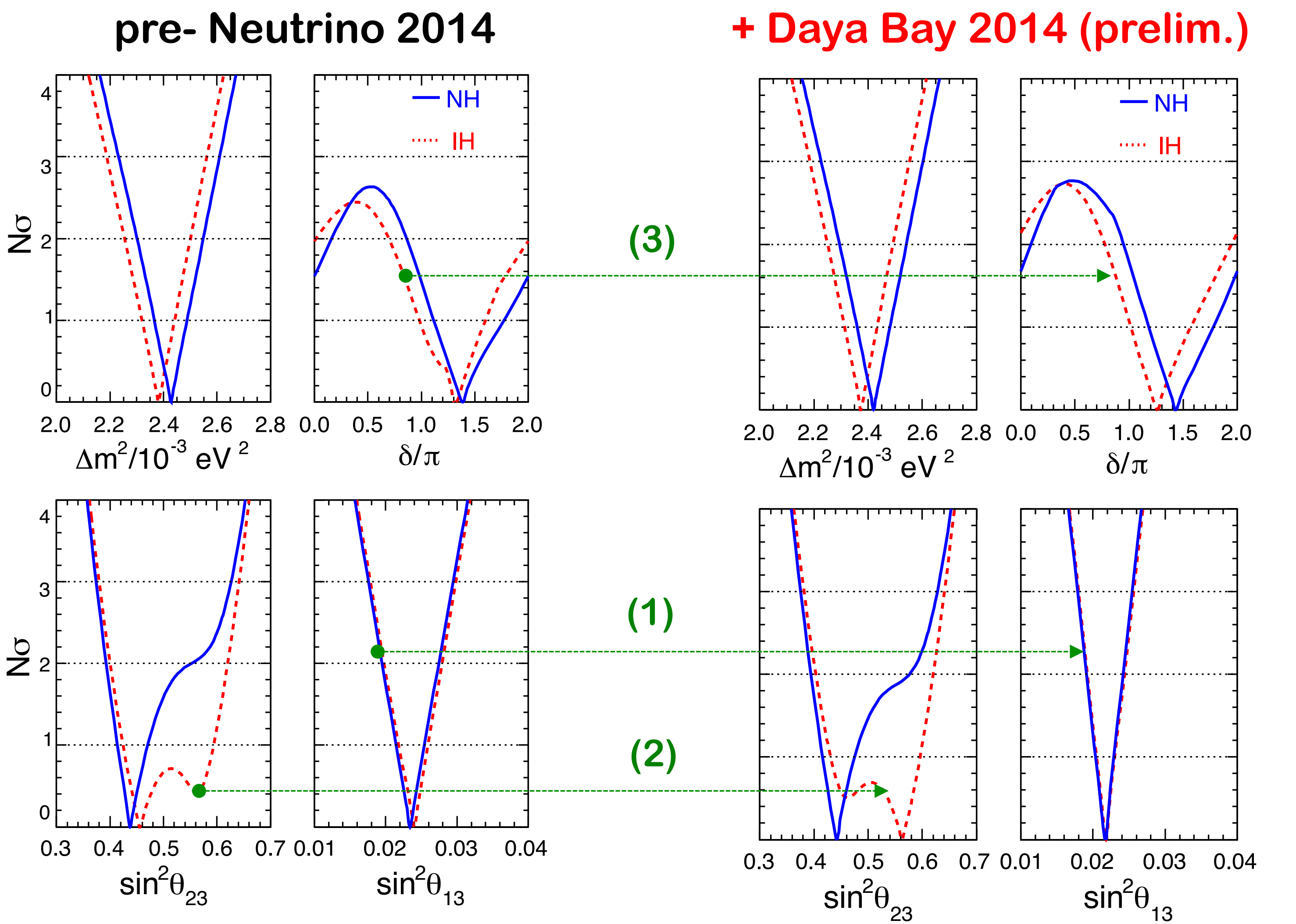
Impact of (some) "Neutrino 2014" data:
SBL reactors

Daya Bay: gives more stringent bounds on (Δm^2, $\sin^2\theta_{13}$)
In particular: $\sin^2\theta_{13} = (2.15 \pm 0.13) \times 10^{-2}$
(a bit lower and with 6.0% error, wrt 8.5% in our previous fit)

RENO: claims observation of new reactor component at ~4-6 MeV
Double Chooz: sees ~5 MeV bump but with lower significance
[Rumors: Presumably seen also by Daya Bay ? ...]

In any case: (Δm^2, $\sin^2\theta_{13}$) parameter estimate from near-far comparison seems robust under this possible new reactor comp.

Pragmatic attitude:
While waiting for a clarification of the ~5 MeV "bump" origin,
let us take the dominant Daya Bay 2014 bounds at face value →



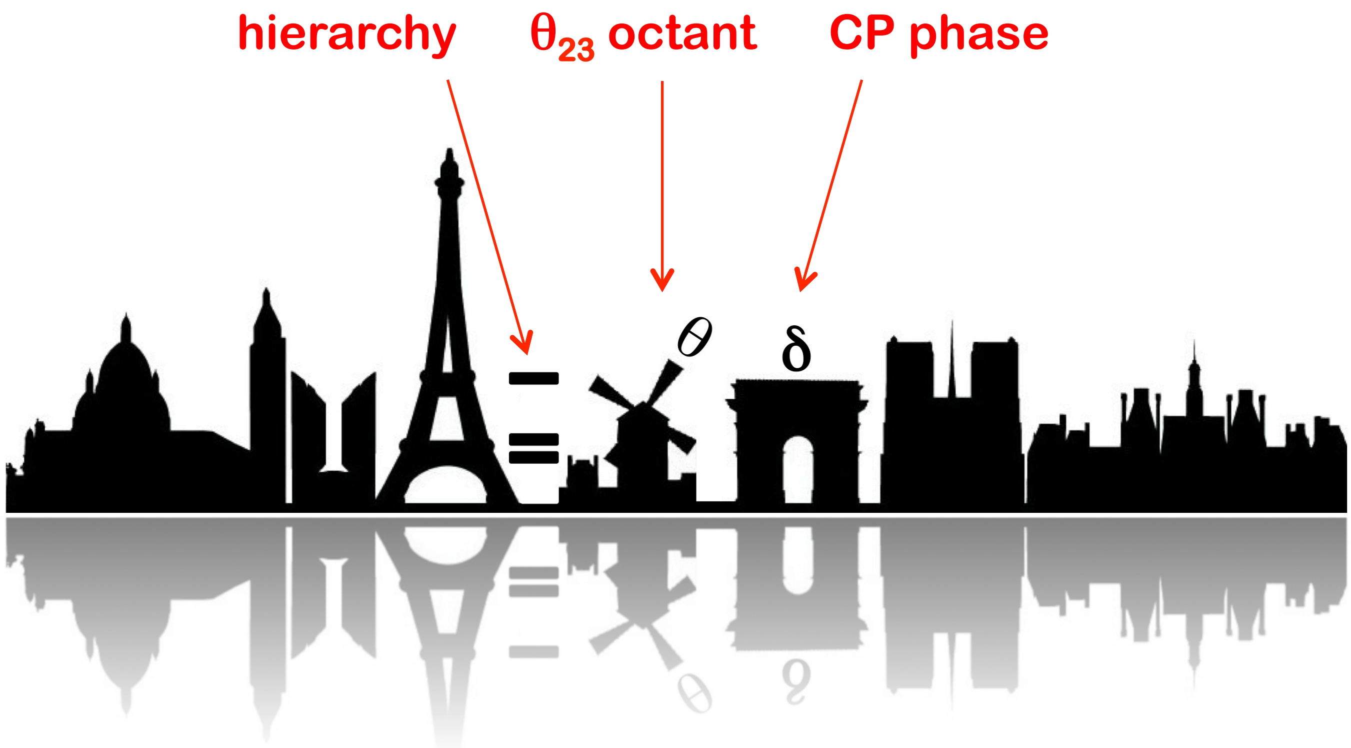
(1) Significantly more precise (and slightly lower) $\sin^2\theta_{13}$

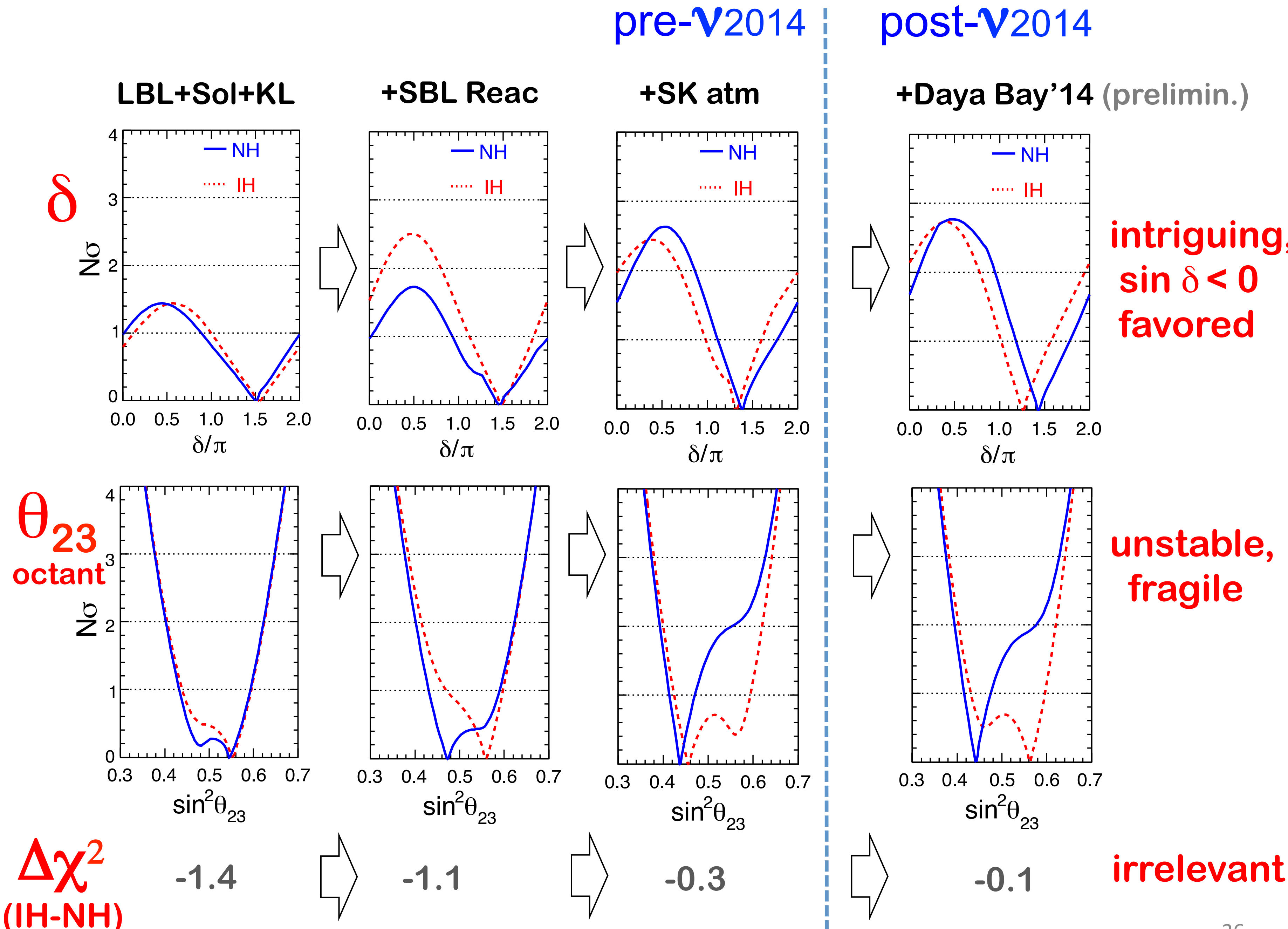
(2) 2nd octant of θ_{23} : less disfavored in NH, favored in IH, via anticorr. with θ_{13}

(3) Slightly sharper bounds on δ, via interplay of SBL reac. with LBL accel.

(4) NH/IH: no hint, $\Delta\chi^2$(I-N)=+0.1

Recap of hints on unknowns →

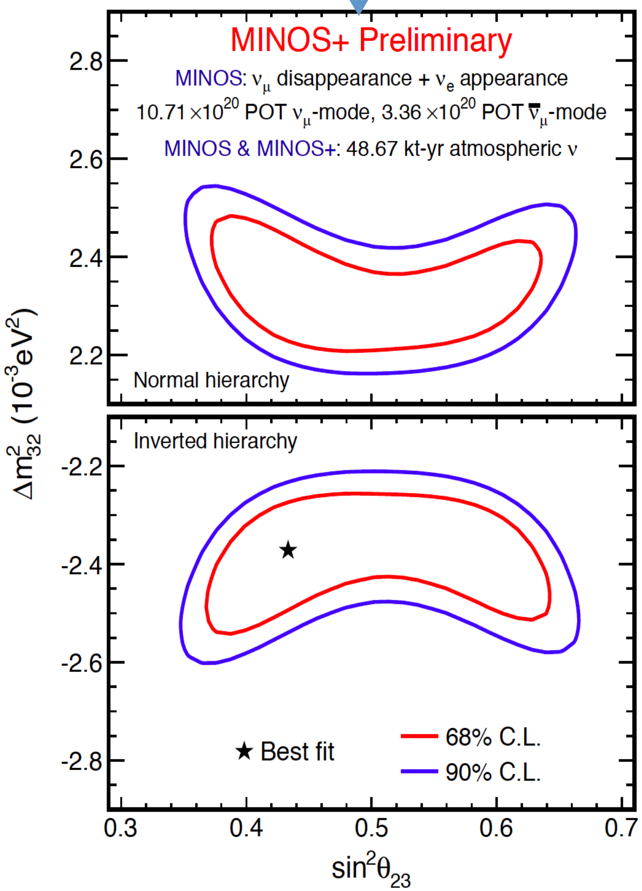


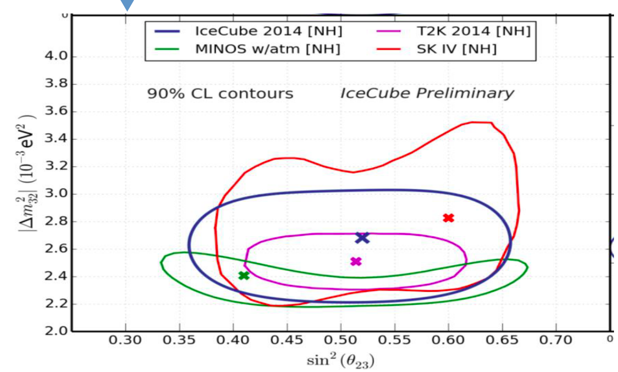

pre-ν2014
post-ν2014
LBL+Sol+KL
+SBL Reac
+SK atm
+Daya Bay'14 (prelimin.)
δ
Nσ
NH
IH
δ/π
intriguing, sin δ < 0 favored
θ23 octant
sin²θ23
unstable, fragile
Δχ² (IH-NH)
-1.4
-1.1
-0.3
-0.1
irrelevant

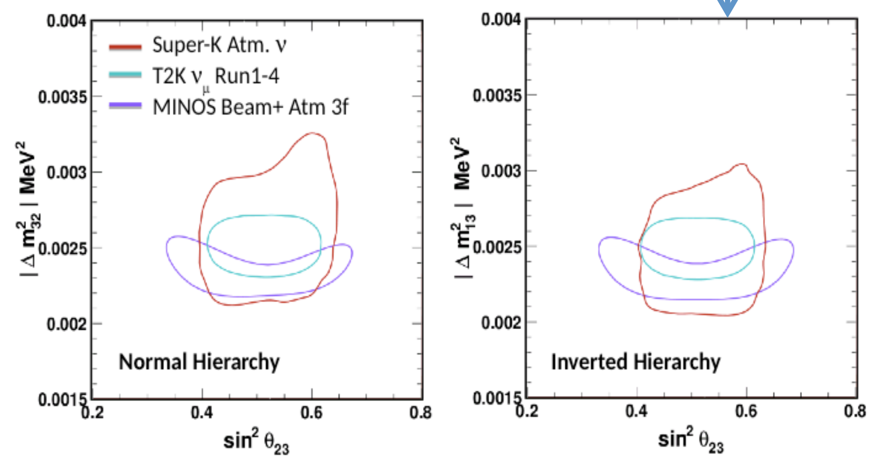
Current **instability of octant** (best fit) reflected in other new data presented at Neutrino 2014:

MINOS+, IceCube atm., SK atm update (*)

<π/4 ~π/4 >π/4







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

Status of absolute ν mass observables → (m_β, $m_{\beta\beta}$, Σ)

In the 3ν framework:

β **decay**, sensitive to the "effective electron neutrino mass":

$$m_\beta = \left[c_{13}^2 c_{12}^2 m_1^2 + c_{13}^2 s_{12}^2 m_2^2 + s_{13}^2 m_3^2\right]^{\frac{1}{2}}$$

0νββ **decay**: only if Majorana. "Effective Majorana mass":

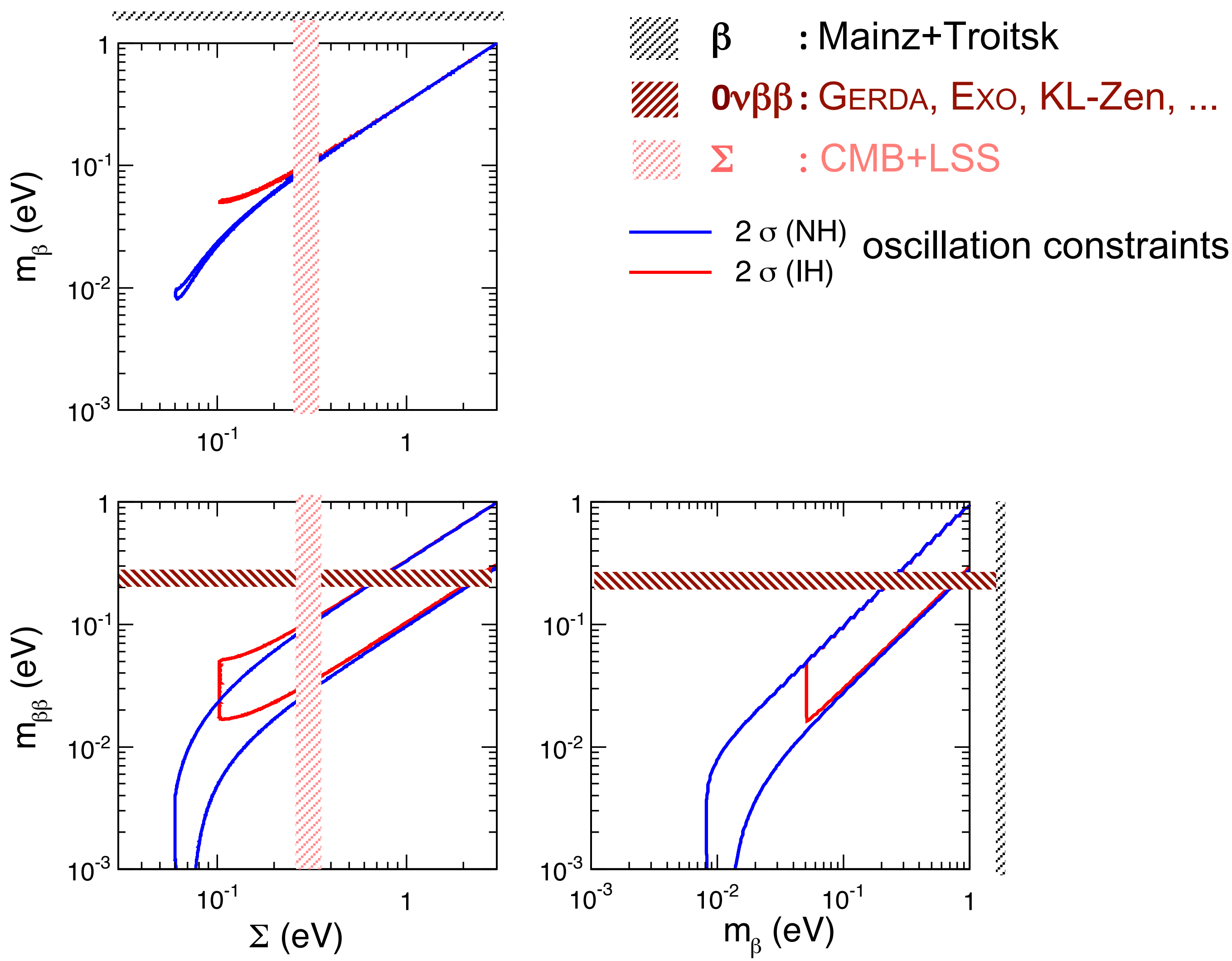
$$m_{\beta\beta} = \left|c_{13}^2 c_{12}^2 m_1 + c_{13}^2 s_{12}^2 m_2 e^{i\phi_2} + s_{13}^2 m_3 e^{i\phi_3}\right|$$

Cosmology: Dominantly sensitive to sum of neutrino masses:

$$\Sigma = m_1 + m_2 + m_3$$

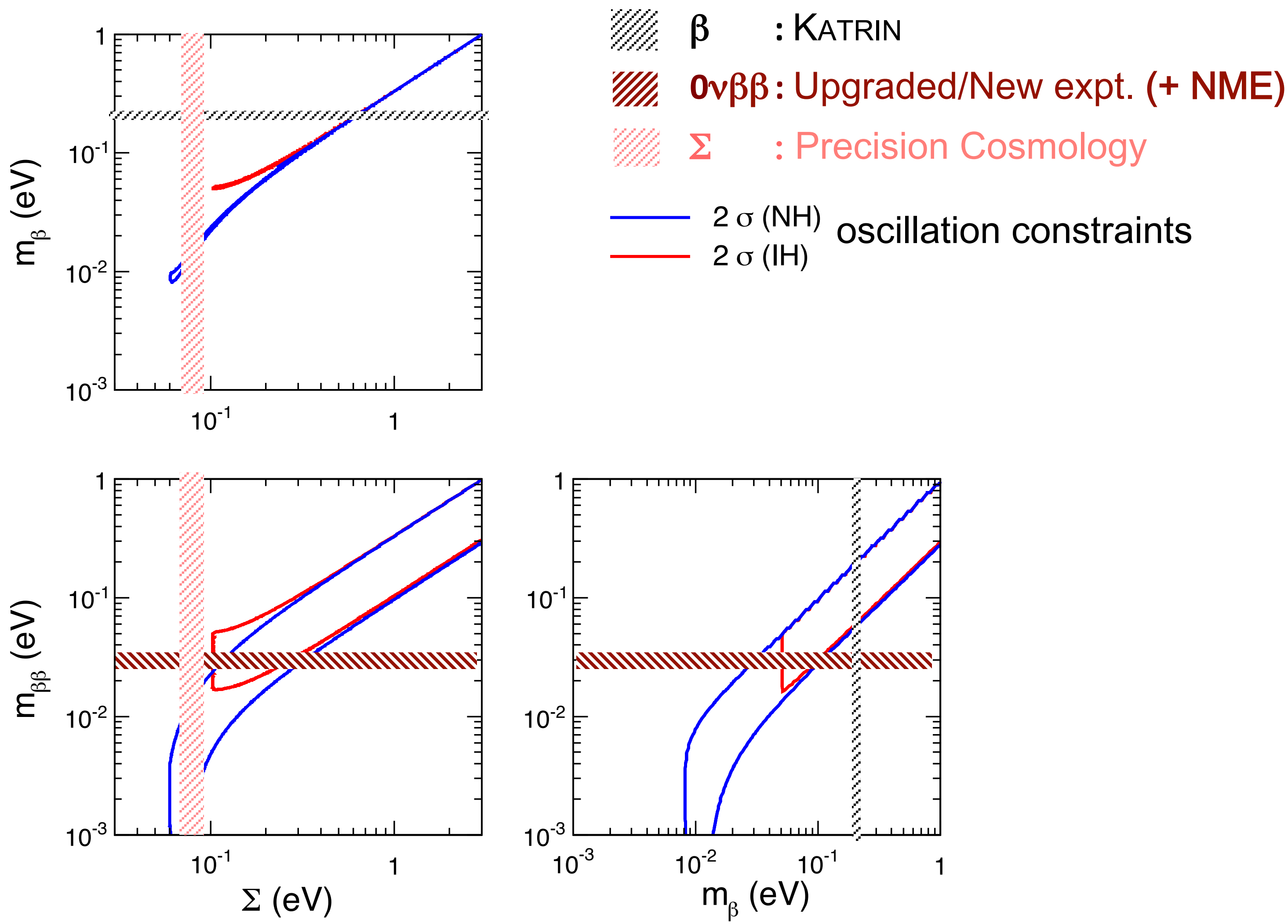
Note 1: These observables may provide handles to distinguish NH/IH.
Note 2: Majorana case gives a new source of CPV (unconstrained)
Note 2: The three observables are correlated by oscillation data→

Upper limits on m_β, $m_{\beta\beta}$, Σ (up to some syst.) + osc. constraints*



*arXiv:1205.5254 by Fogli, Lisi, Marrone, Montanino, Palazzo, Rotunno

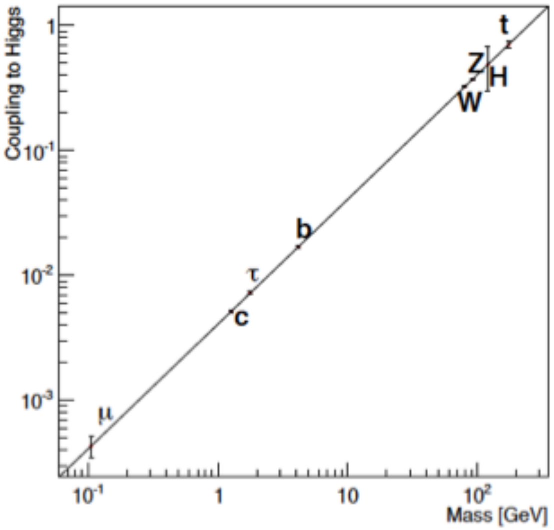
Upper limits on m_β, $m_{\beta\beta}$, Σ in ~10 years ?



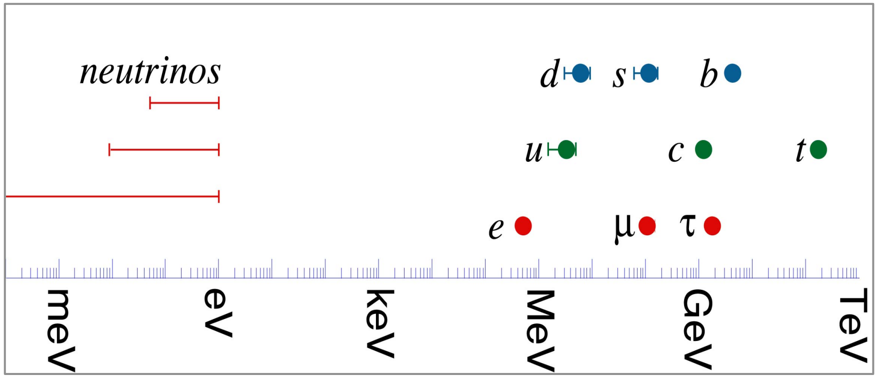
Large phase space for discoveries about ν mass and nature.

Towards a bigger picture…

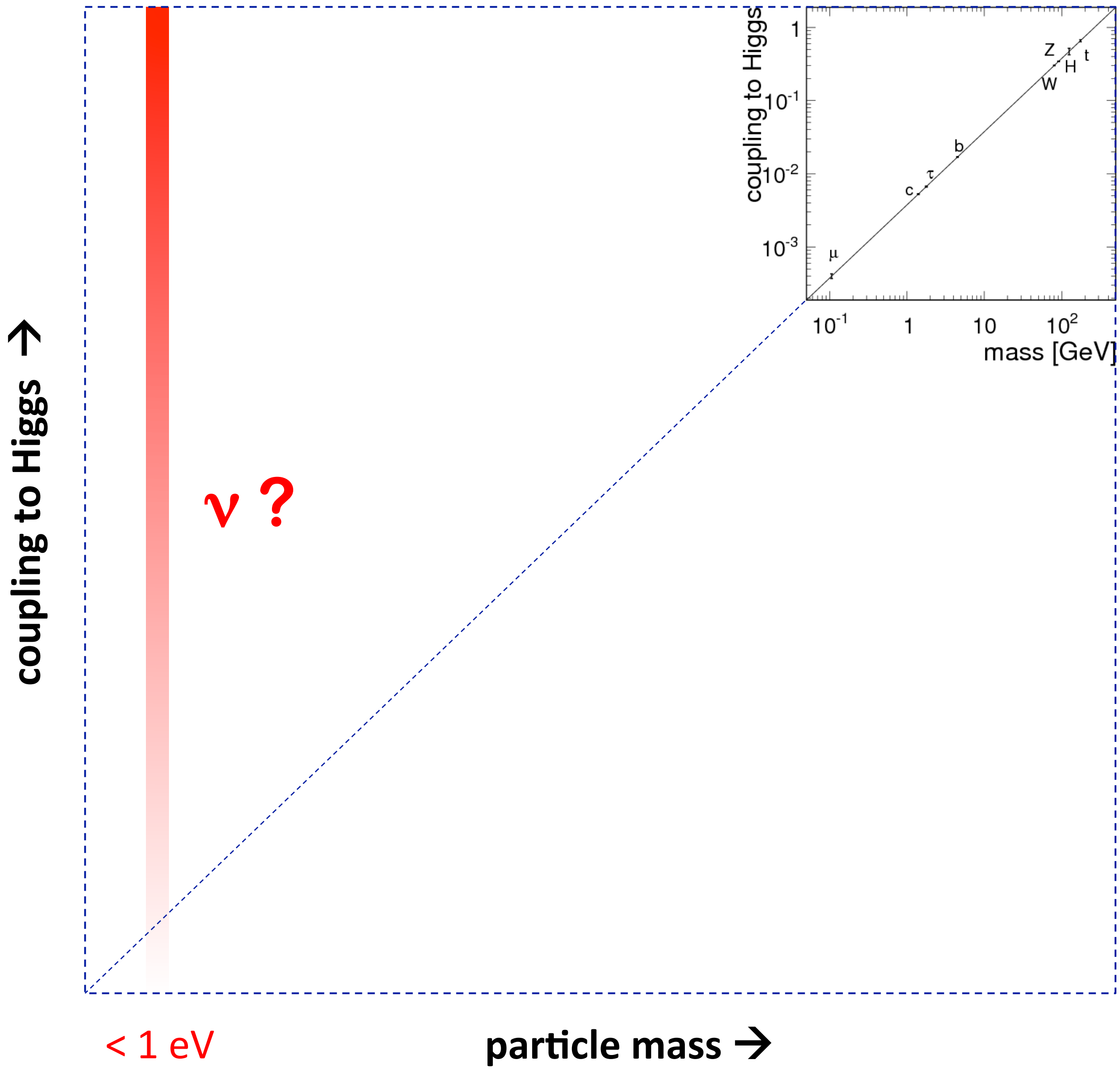
1. Test Higgs sector



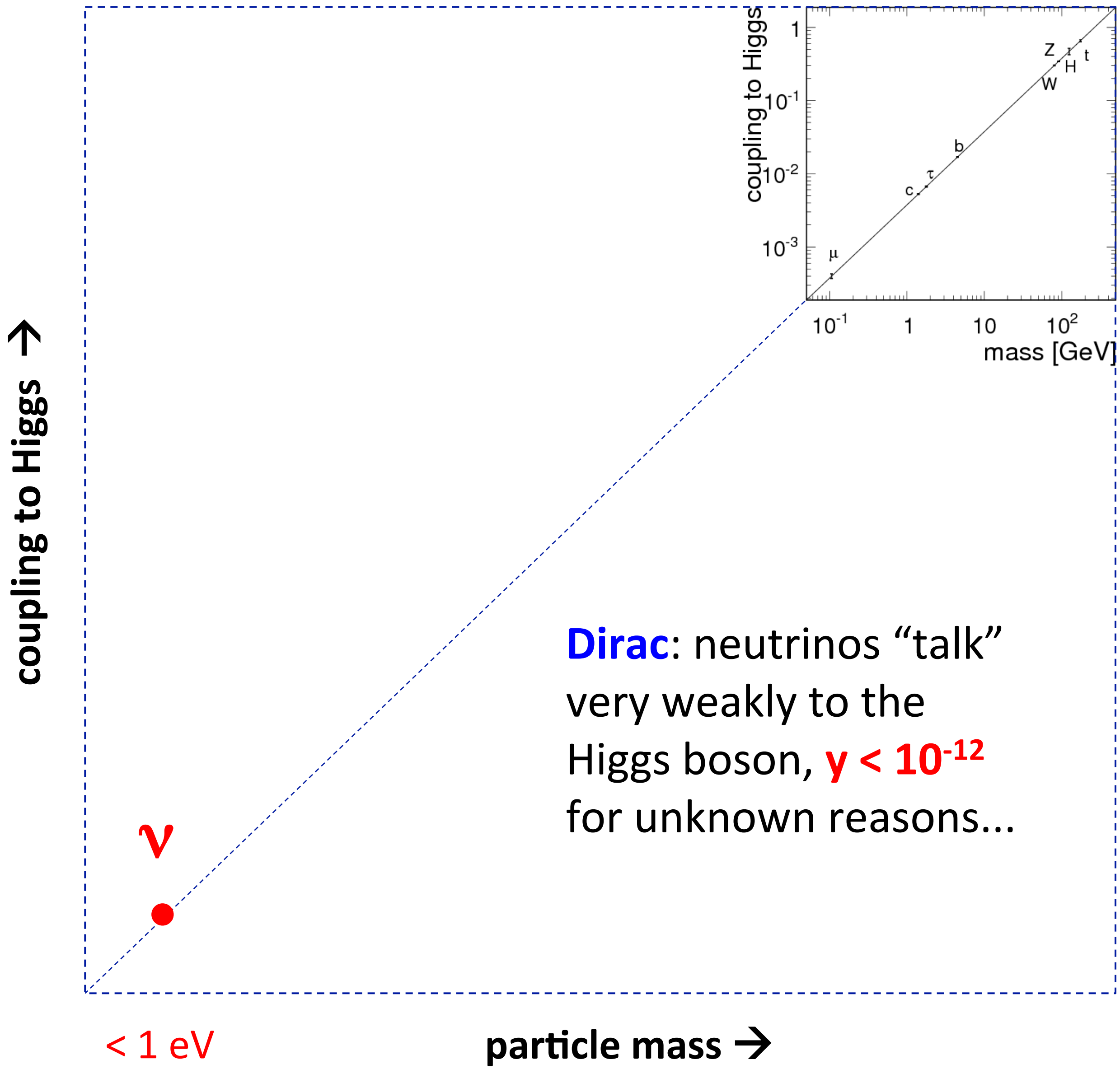
2. Find ν masses



1 + 2 Where are the ν's on this plot? Why are they so light?

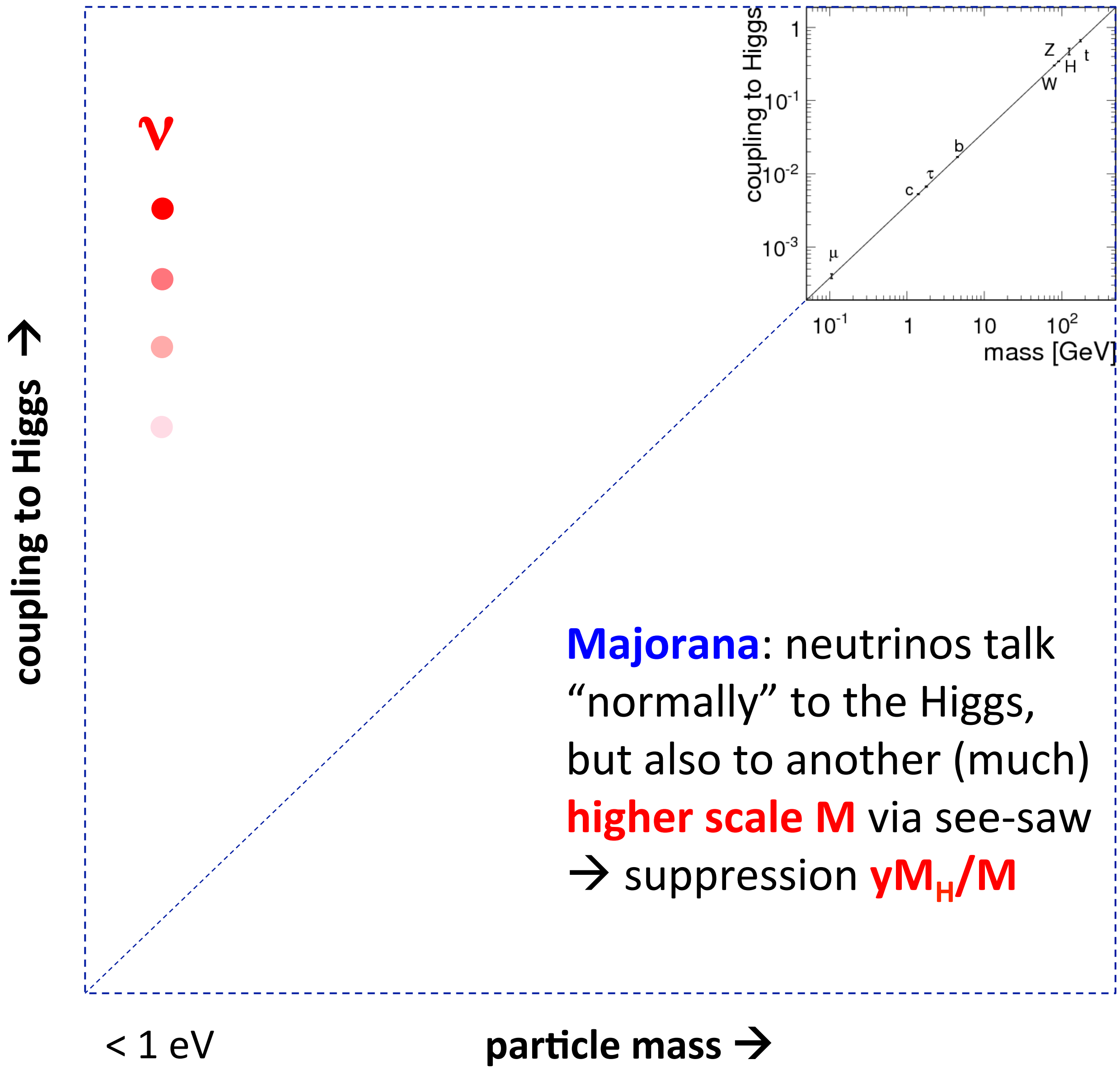


Options:



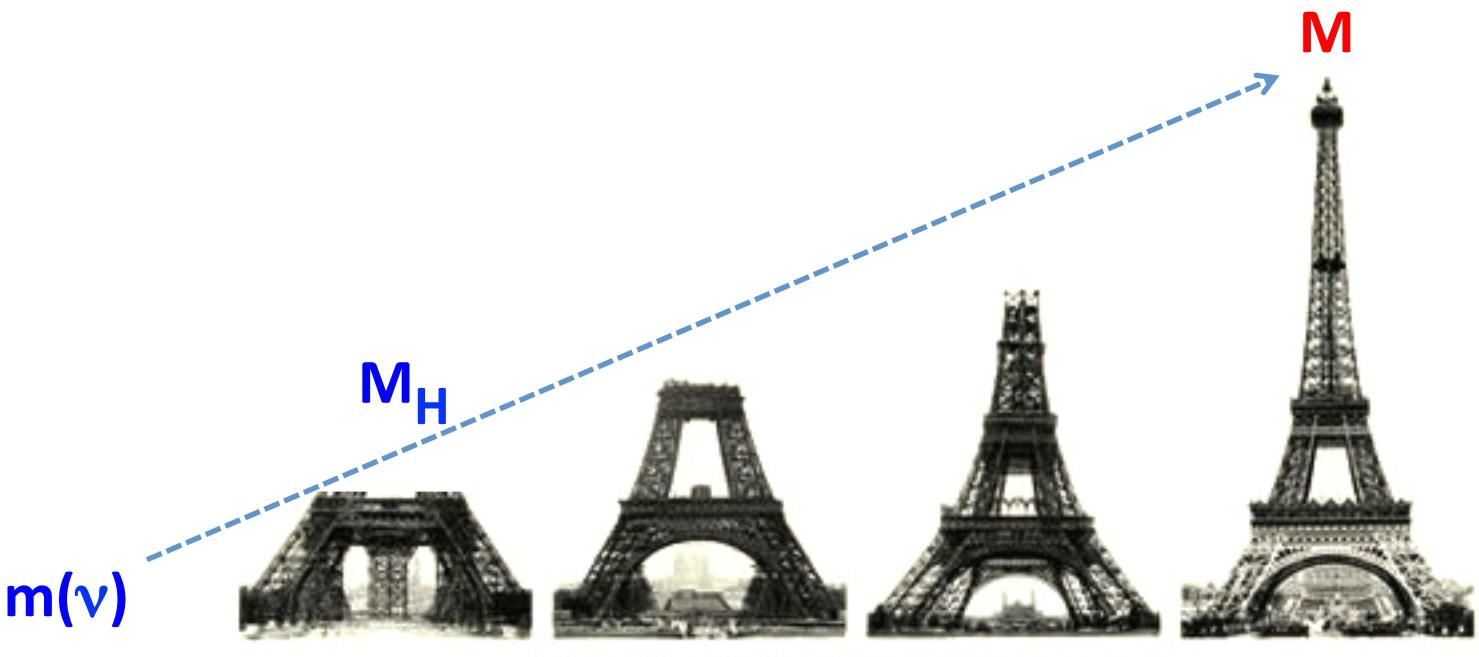
Dirac: neutrinos "talk" very weakly to the Higgs boson, **$y < 10^{-12}$** for unknown reasons...

Options:

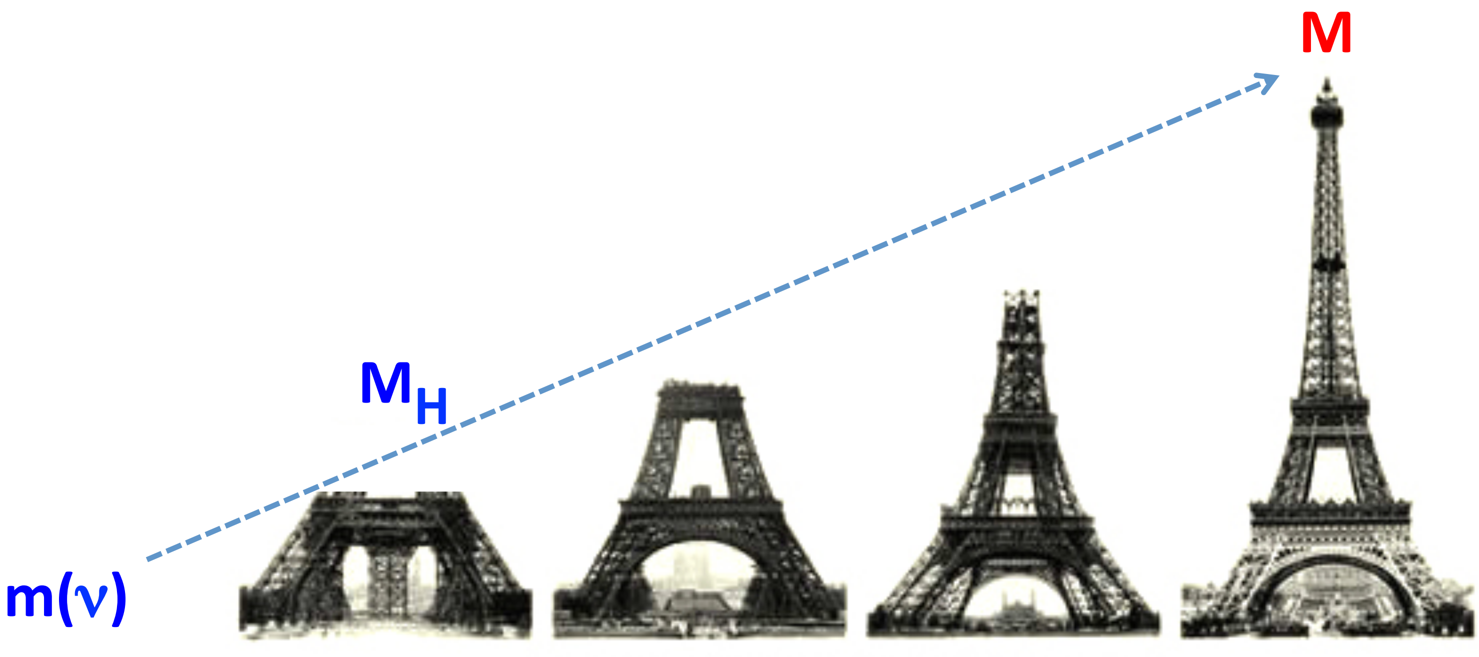


Majorana: neutrinos talk "normally" to the Higgs, but also to another (much) **higher scale M** via see-saw → suppression $\mathbf{yM_H/M}$

The ν flavor sector (masses, mixings and phases) may thus offer a great opportunity to probe new physics beyond the EW scale ...

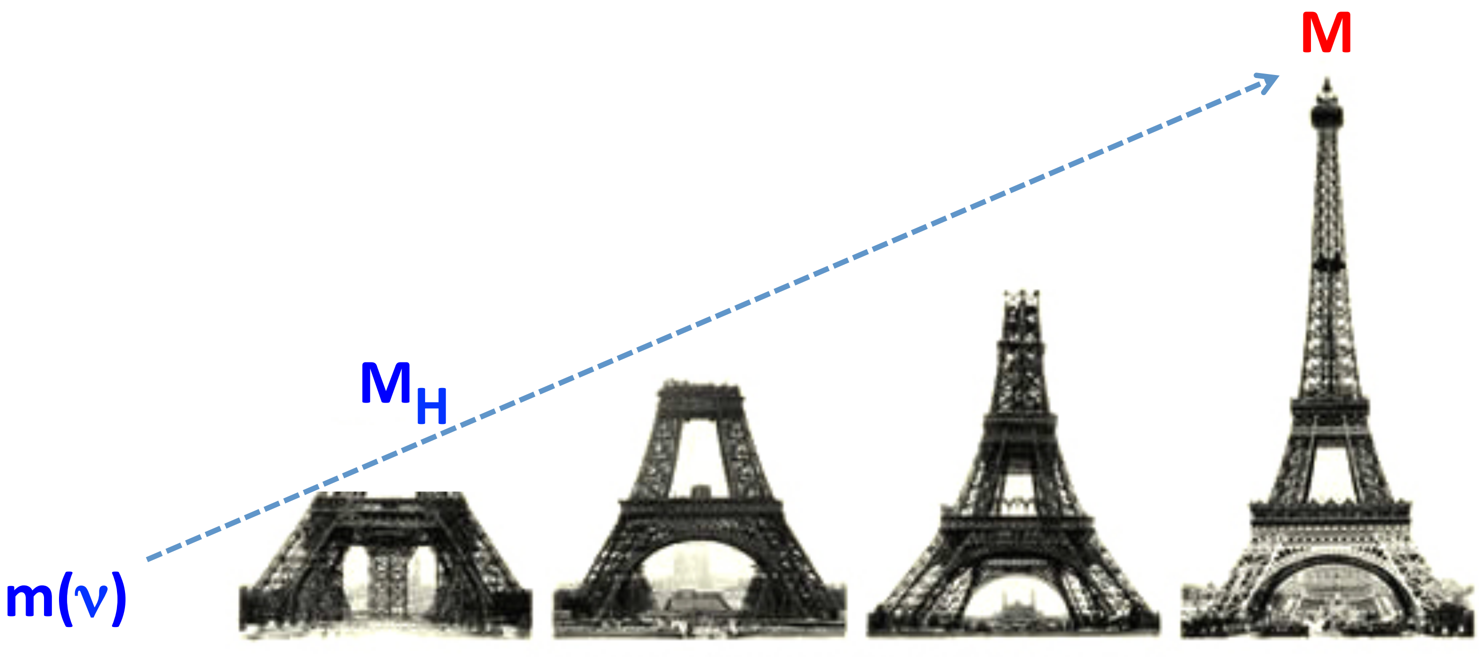


The ν flavor sector (masses, mixings and phases) may thus offer a great opportunity to probe new physics beyond the EW scale ...



... with the help of increasingly large infrastructures!

The ν flavor sector (masses, mixings and phases) may thus offer a great opportunity to probe new physics beyond the EW scale ...



... with the help of increasingly large infrastructures!

Thank you for your attention.

Backup slides

Pontecorvo-Maki-Nakagawa-Sakata (PMNS) matrix

$$U_{\alpha i} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{bmatrix} \begin{bmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{bmatrix} \begin{bmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} 1 & 0 & 0 \\ 0 & e^{i\alpha/2} & 0 \\ 0 & 0 & e^{i\beta/2} \end{bmatrix}$$

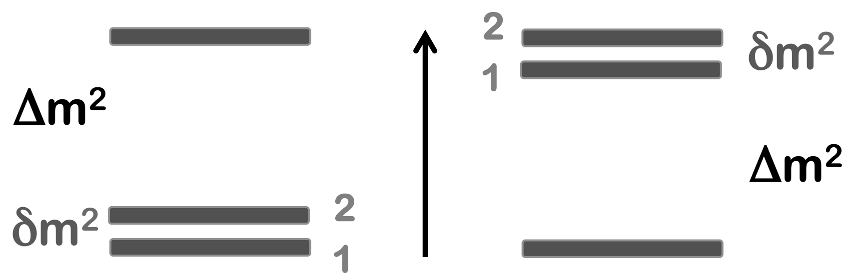
[only if Majorana]

Mixing angles θ_{23}, θ_{13}, θ_{12} : known ✔

CP-violat. phase(s) δ (α, β) : unknown ✗

Mass-squared spectrum (up to absolute scale)

"Normal" Hierarchy



"Inverted" Hierarchy

[+ contribution in matter ~ $G_F \cdot E \cdot$ density]

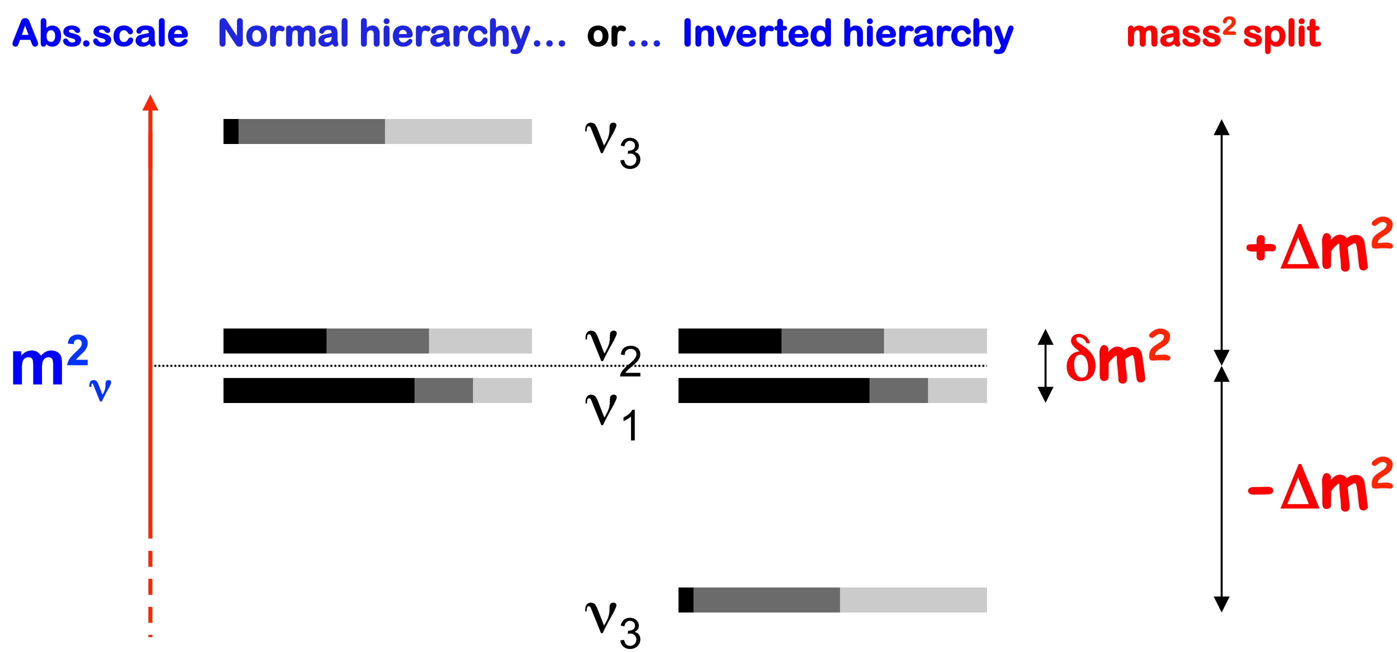
δm^2, Δm^2: **known ✔**

Matter effects (solar ν): ✔

Hierarchy : unknown ✗

Current 3ν picture in just one slide (with 1-digit accuracy)

Flavors = e μ τ

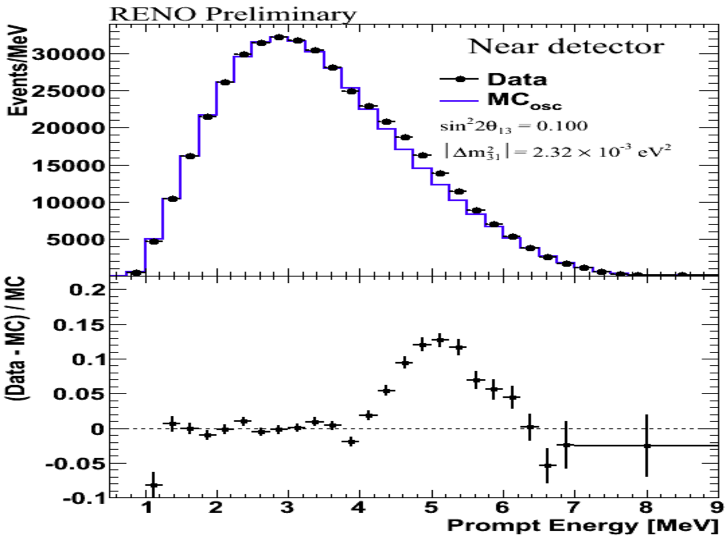


Knowns:
$\delta m^2 \sim 8 \times 10^{-5}\ eV^2$
$\Delta m^2 \sim 2 \times 10^{-3}\ eV^2$
$\sin^2\theta_{12} \sim 0.3$
$\sin^2\theta_{23} \sim 0.5$
$\sin^2\theta_{13} \sim 0.02$

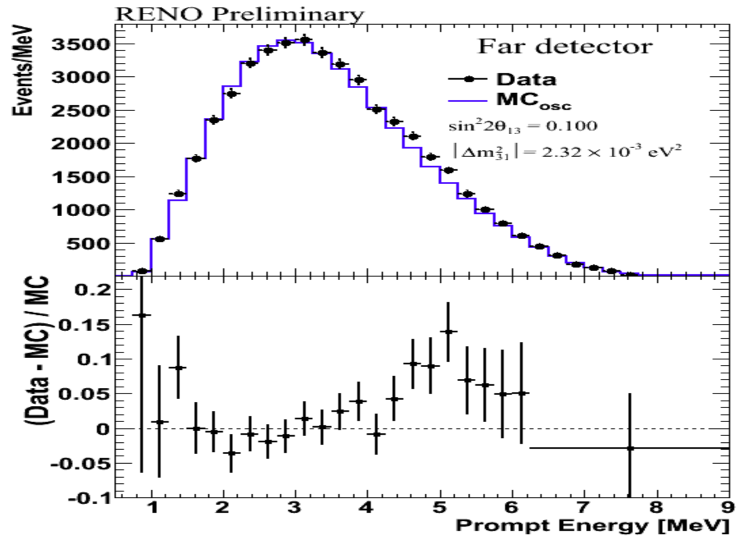
Unkowns:
δ (CP)
sign(Δm^2)
octant($\sin^2\theta_{23}$)
absolute mass scale
Dirac/Majorana nature

Reactor spectra at Neutrino 2014

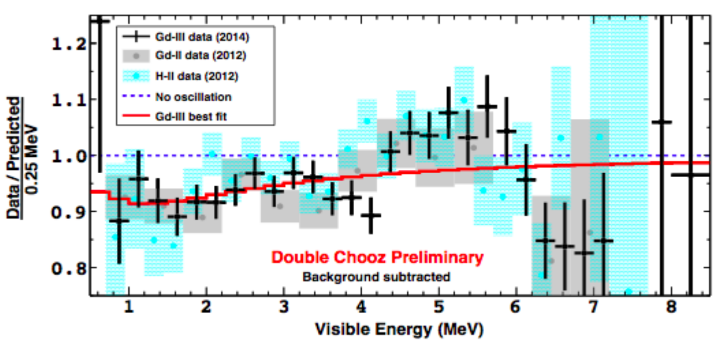
RENO near



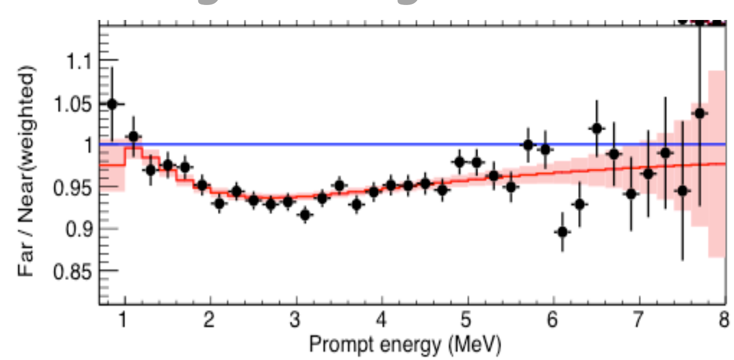
RENO far



DC far/predicted



Daya Bay far/near

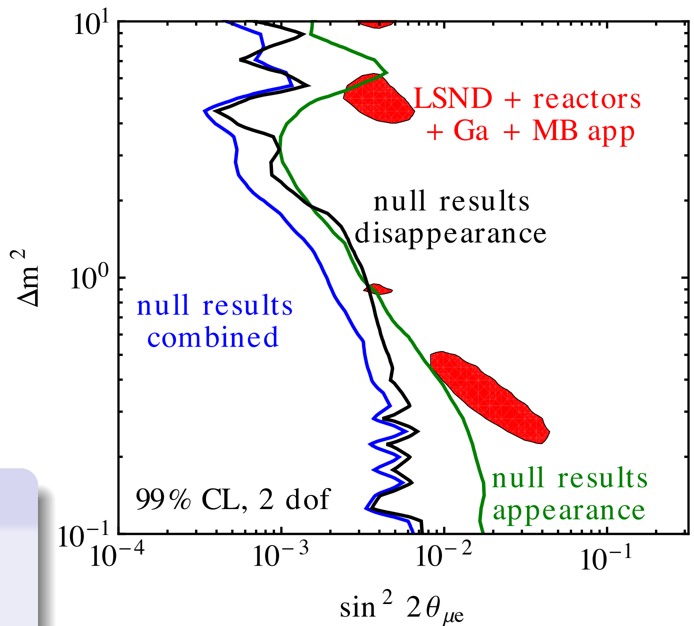


Sterile neutrinos: J. Kopp at ν 2014

The global oscillation fit

JK Machado Maltoni Schwetz, arXiv:1303.3011

3 + 1 Severe tension between appearance and disappearance and between exp's with and without a signal



Parameter goodness of fit (PG) test:

Compares χ^2_{min} from global and separate fits to test compatibility of 2 data sets

	χ^2_{min}/dof	GOF	χ^2_{PG}/dof	PG
3+1	712/(689 − 9)	19%	18.0/2	1.2×10^{-4}

Sterile neutrinos: J. Kopp summary at ν 2014

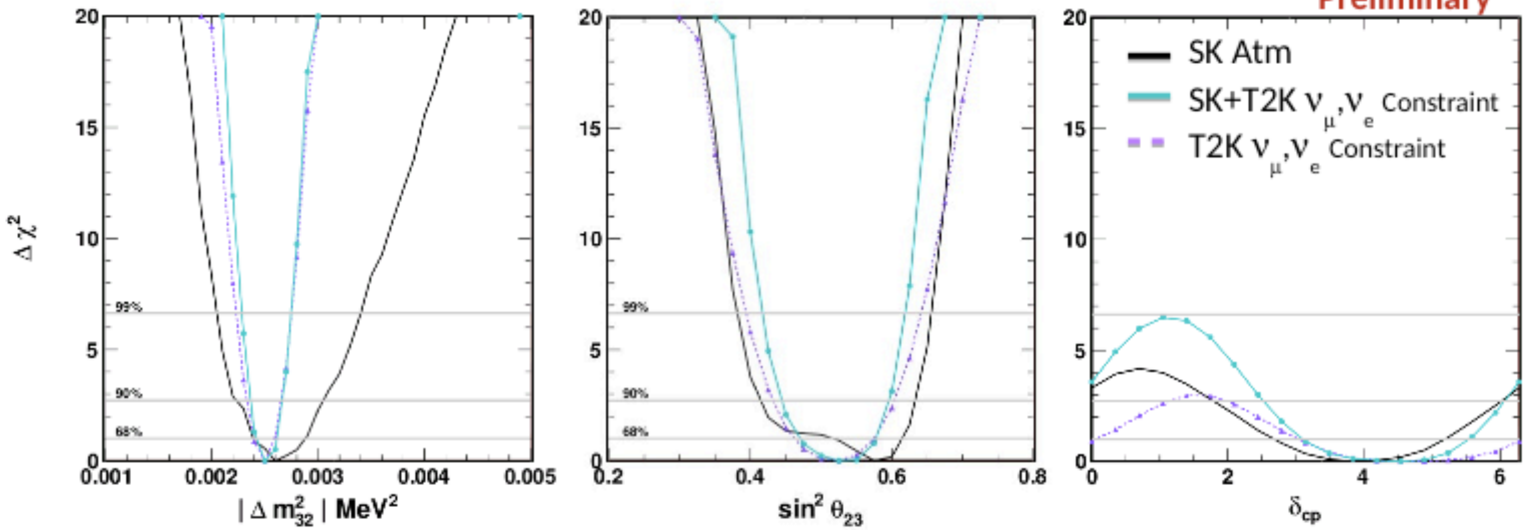
- Sterile neutrinos are theoretically well motivated and phenomenologically useful
- Tension between appearance and disappearance searches
- Neutrino 2014: several interesting new limits
  - Will increase the tension
  - Qualitative conclusions strengthened
- Cosmology disfavors $N_\nu \geq 4$, especially for $m_{\nu_s} \gtrsim 0.23$ eV.
  (if BICEP-2 is included, this conclusion would change)
- Many mechanisms for making sterile neutrinos fully consistent with cosmology
  - Example: hidden sector gauge force
  - Can additionally solve small scale structure problems if coupled also to dark matter
- Sterile neutrinos and dark matter searches
  - Direct searches: non-standard neutrino signals in DM detectors
  - Indirect searches: limits on DM annihilation in the Sun modified by active–sterile oscillations

R. Wendell – SK atmospheric at ν 2014

Theta13 **Fixed** SK + T2K ν_μ, ν_e (External Constraint) NH

19

Preliminary



Fit (543 dof)	χ^2	θ_{13}	δ_{cp}	θ_{23}	Δm_{23} ($\times 10^{-3}$)
SK + T2K (NH)	578.2	0.025	4.19	0.55	2.5
SK + T2K (IH)	579.4	0.025	4.19	0.55	2.5

- $\chi^2_{IH} - \chi^2_{NH}$ = **-1.2** (-0.9 SK only)
- CP Conservation ($\sin\delta_{cp}$ = 0) allowed at (at least) 90% C.L. for both hierarchies

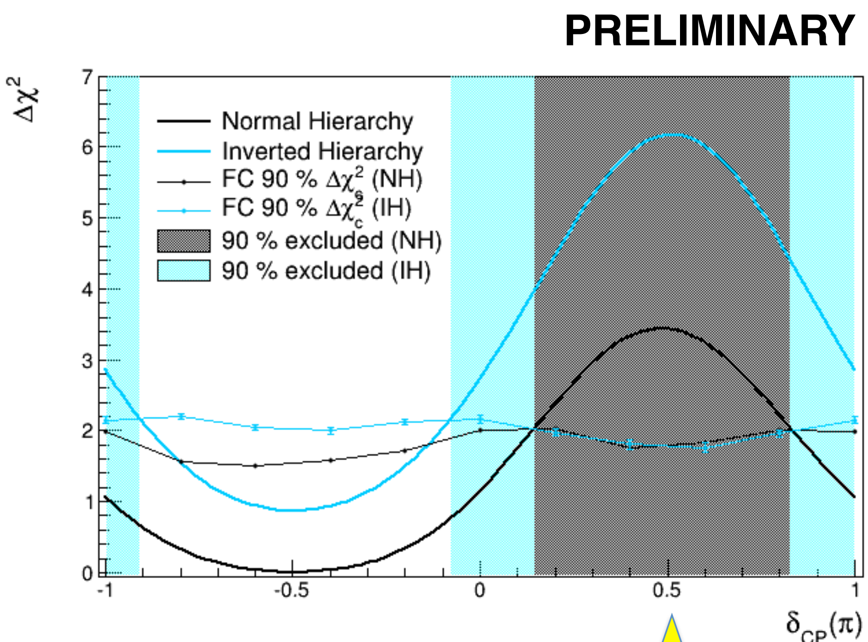
T2K: C. Walter at Neutrino 2014

T2K Joint $\nu_\mu + \nu_e$ Analysis: Constraints on δ_{CP}

Likelihood ratio fit to both $\nu_\mu + \nu_e$ event samples

Plot includes constraint from reactor experiments as given by PDG 2013.

T2K has a slight hint for the normal hierarchy with a value of δ_{CP} of $-\pi/2$

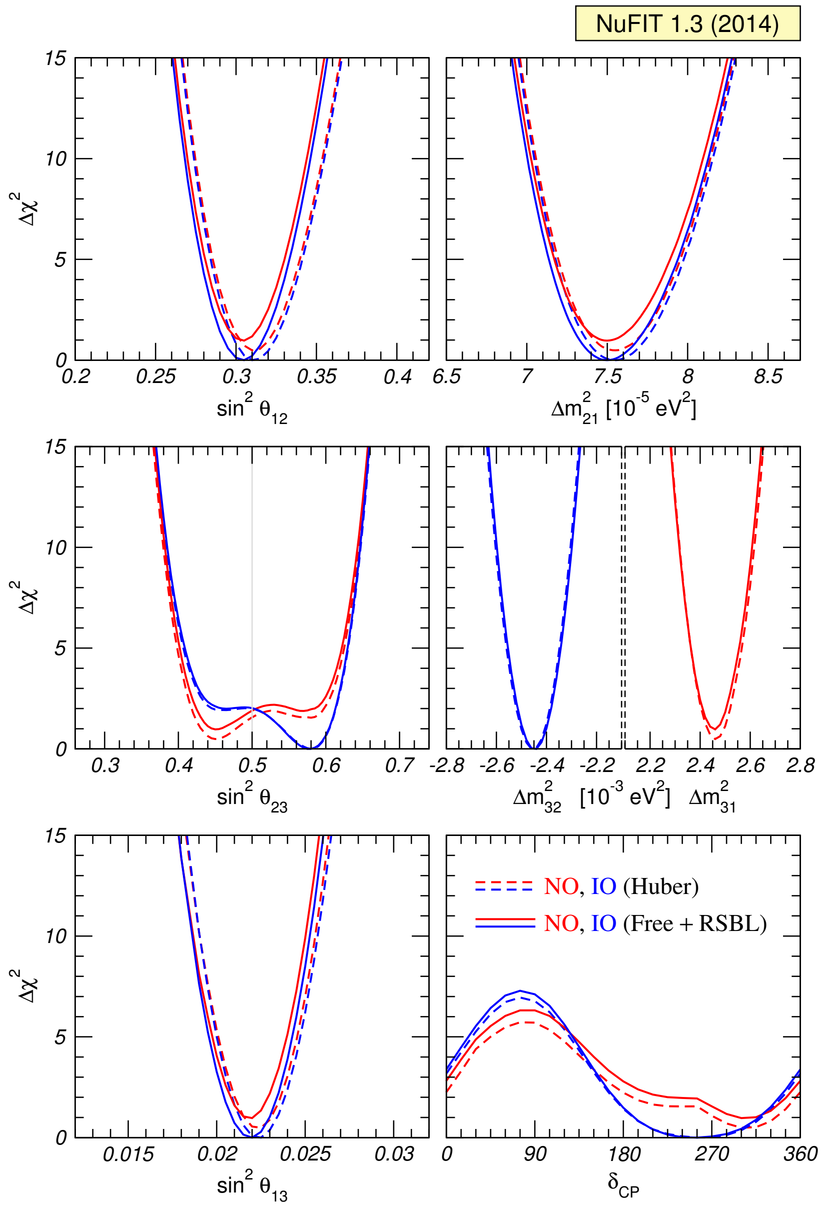


FUTURE -> Neutrino + Antineutrino running!

Poster #160!

06/04/2014 Chris Walter - Results from T2K - Neutrino2014 18

Gonzalez-Garcia, Maltoni, Salvado, Schwetz'14



Forero, Tortola, Valle ’14