



# Neutrinos Have Mass:

## A tribute to the 2015 Nobel Prize in Physics

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Elvio Lisi  
INFN  
Bari  
IT

Madrid Xmas  
Workshop 2015

**Many thanks to the Xmas Workshop organizers!**

**I'm very happy to be here, for two reasons:**

# Many thanks to the Xmas Workshop organizers!

I'm very happy to be here, for two reasons:

1<sup>st</sup>: I attended your 2002 edition, and then exported your idea (on a small scale...) in Bari, since 2011

**Bari Theory Xmas Workshop 2011**  
Thursday, December 22, 2011, Aula Multimediale

**Bari Theory Xmas Workshop 2012**  
Thursday, December 20, 2012, Aula Multimediale

**Bari Theory Xmas Workshop 2013**  
Monday, December 23, 2013, Aula Multimediale

**Bari Theory Xmas Workshop 2014**  
Monday, December 22, 2014, Aula Multimediale

<http://agenda.infn.it/event/barixmasworkshop2015>

## Bari Theory Xmas Workshop 2015

22 December 2015 Bari, Sezione INFN e Dipartimento Interateneo di Fisica  
Europe/Rome timezone

### Overview

Scientific programme

Timetable

**Dates:** 22 December 2015 (09:30-17:20)

**Timezone:** Europe/Rome

**Location:** Bari, Sezione INFN e Dipartimento Interateneo di Fisica

Room: Aula multimediale

**Additional info:**



[Photograph credits: [http://www.sifb.it/congressobari\\_6.html](http://www.sifb.it/congressobari_6.html)]

This one-day Workshop will present an overview of the research activities of young theorists who are working - or have worked - here in Bari. It will be an opportunity to learn new physics and to get together in a relaxed atmosphere.

All students and members of the Department of Physics and INFN section are welcome.

Previous Editions:

2014 [http://www.ba.infn.it/~nicotri/Bari\\_Xmas\\_Theory\\_Workshop\\_2014](http://www.ba.infn.it/~nicotri/Bari_Xmas_Theory_Workshop_2014)

2013 [http://www.ba.infn.it/~nicotri/Bari\\_Xmas\\_Theory\\_Workshop\\_2013](http://www.ba.infn.it/~nicotri/Bari_Xmas_Theory_Workshop_2013)

2012 [http://www.ba.infn.it/~nicotri/Theory\\_2012](http://www.ba.infn.it/~nicotri/Theory_2012)

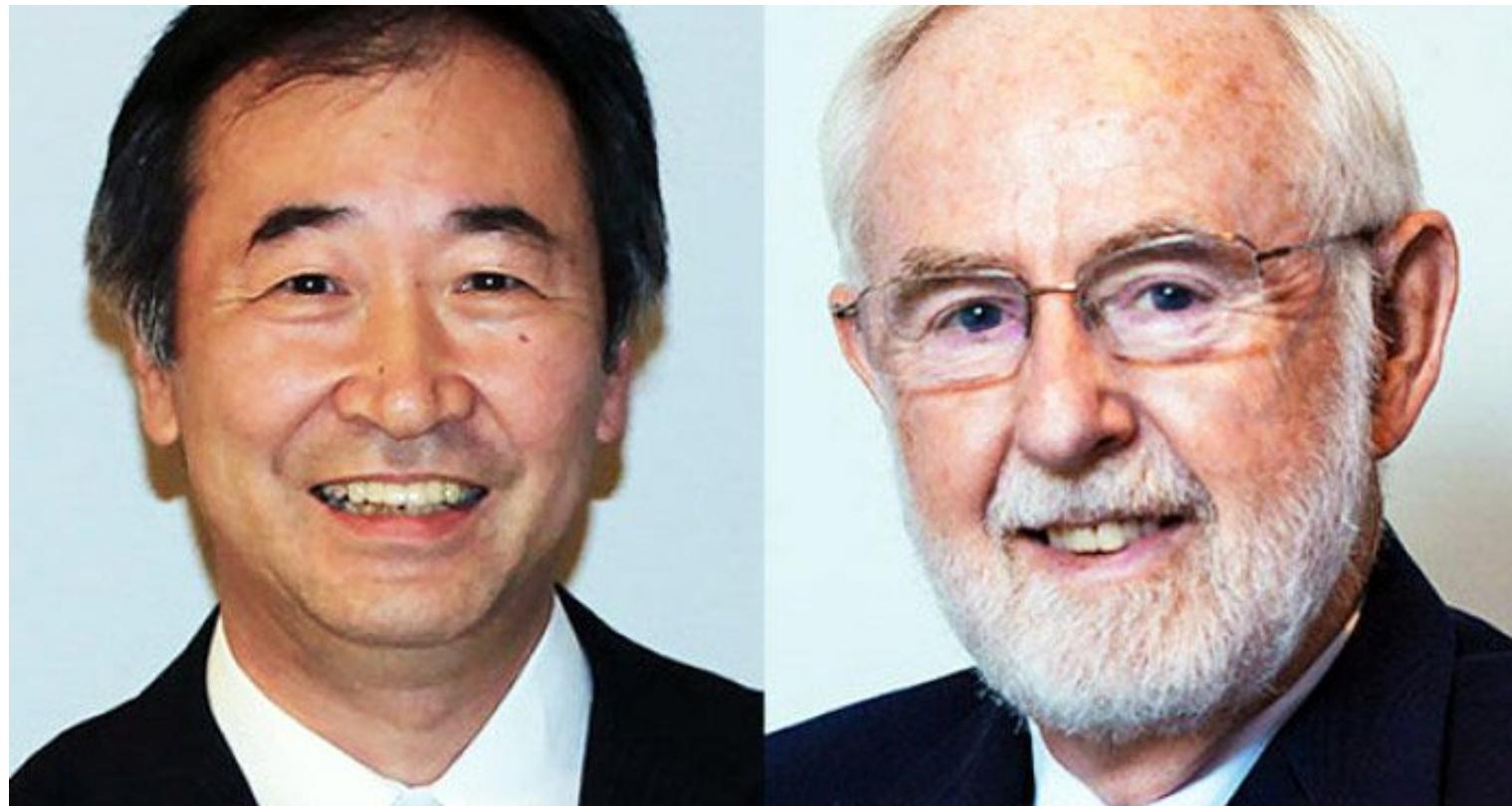
2011 [http://www.ba.infn.it/~nicotri/Theory\\_2011](http://www.ba.infn.it/~nicotri/Theory_2011)

Contact: [elilio.lisi@ba.infn.it](mailto:elilio.lisi@ba.infn.it)

**Thank you for the inspiration!**

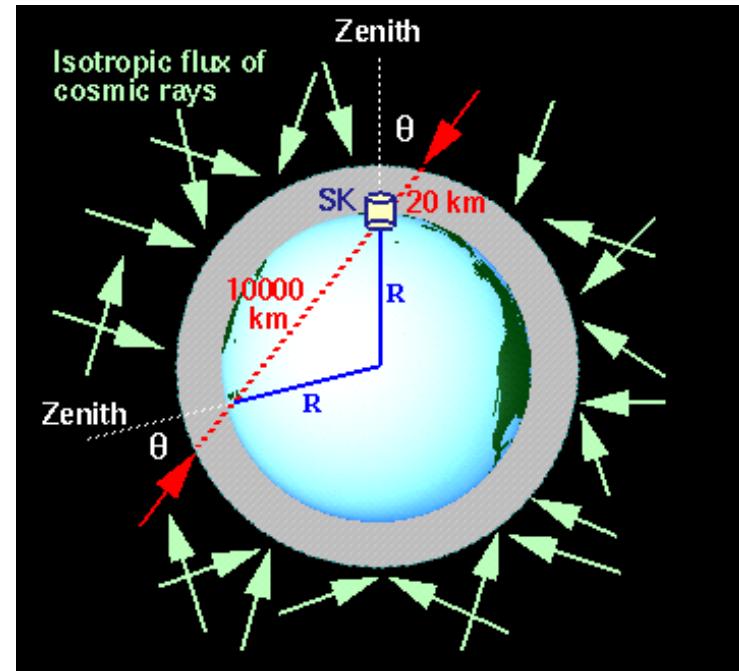
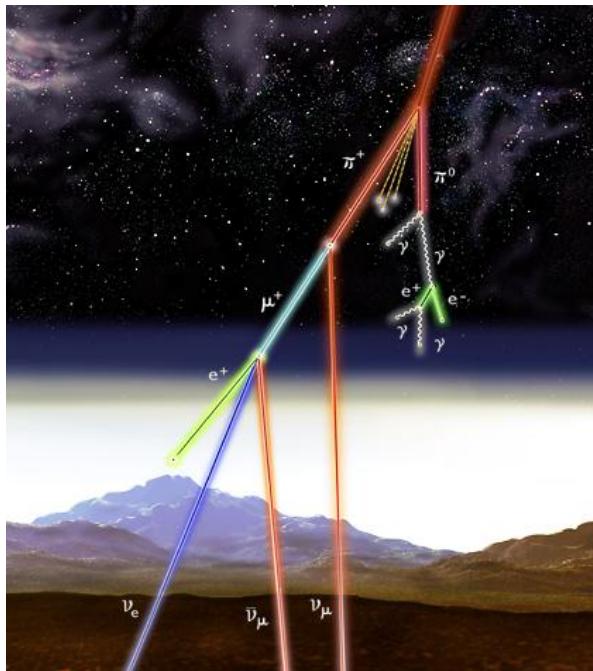
**2<sup>nd</sup>:** This is a great week for neutrino physics! 2590 km from here, the *Nobel Award Week* is taking place. Nobel laureates Takaaki Kajita and Art McDonald, tomorrow afternoon, will receive the 2015 prize for...

***“...the discovery of neutrino oscillations,  
which shows that neutrinos have mass”***



# The discovered effects were big, $\sim O(1)$ !

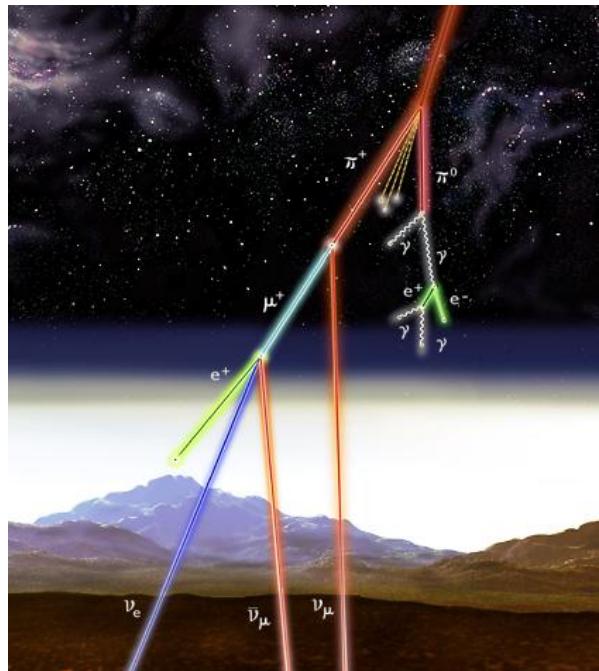
In Kamioka, atmospheric neutrinos were initially studied as “noise” to a Nucleon Decay Experiment (KamiokaNDE). **Expected features:**



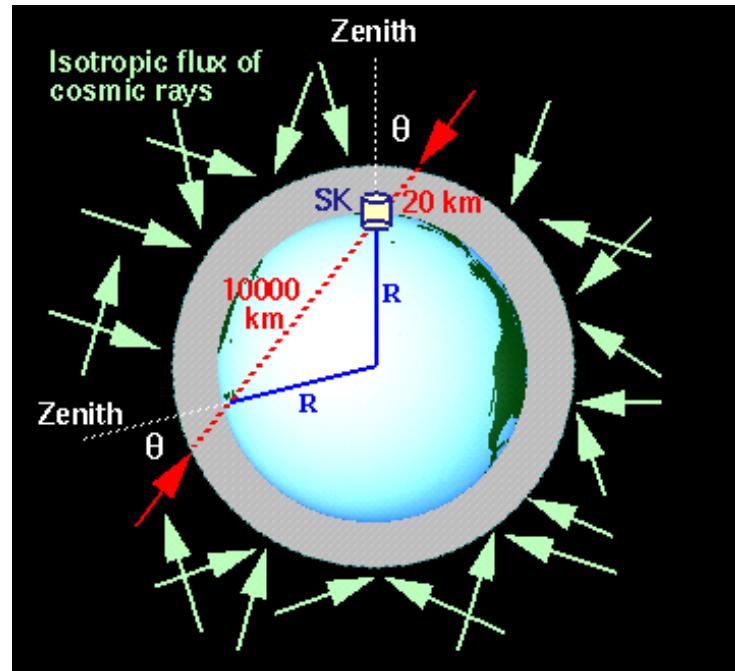
$$\text{Flux}(\nu_\mu) \sim 2 \text{ Flux}(\nu_e)$$

$$\text{Flux}(\nu_\alpha)_{\text{UP}} \sim \text{Flux}(\nu_\alpha)_{\text{DOWN}}$$

**...but, the KamiokaNDE data suggested something different!**  
[with Kajita-san playing a prominent role in the observations]



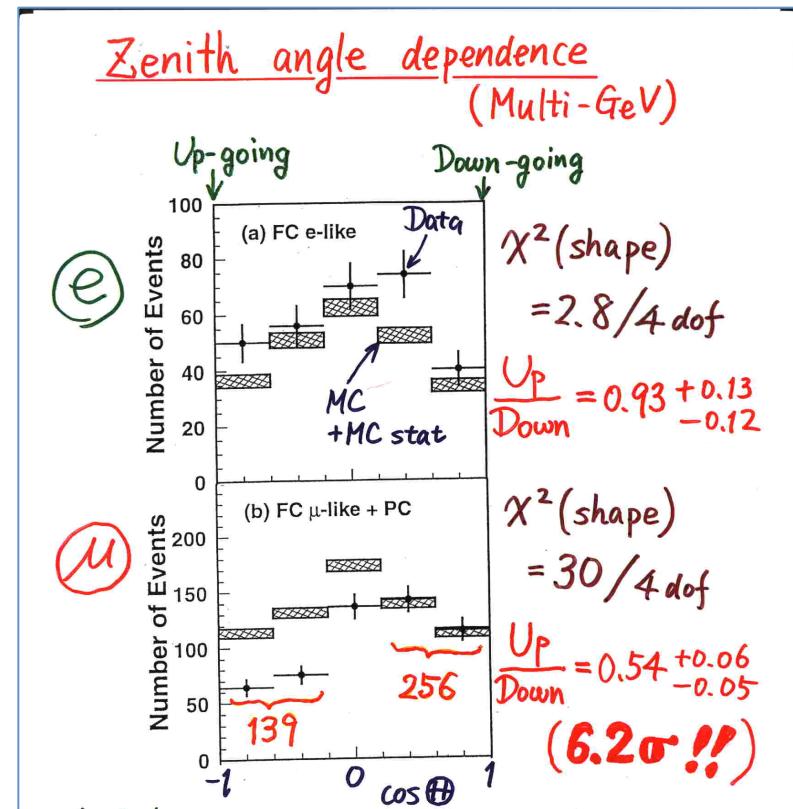
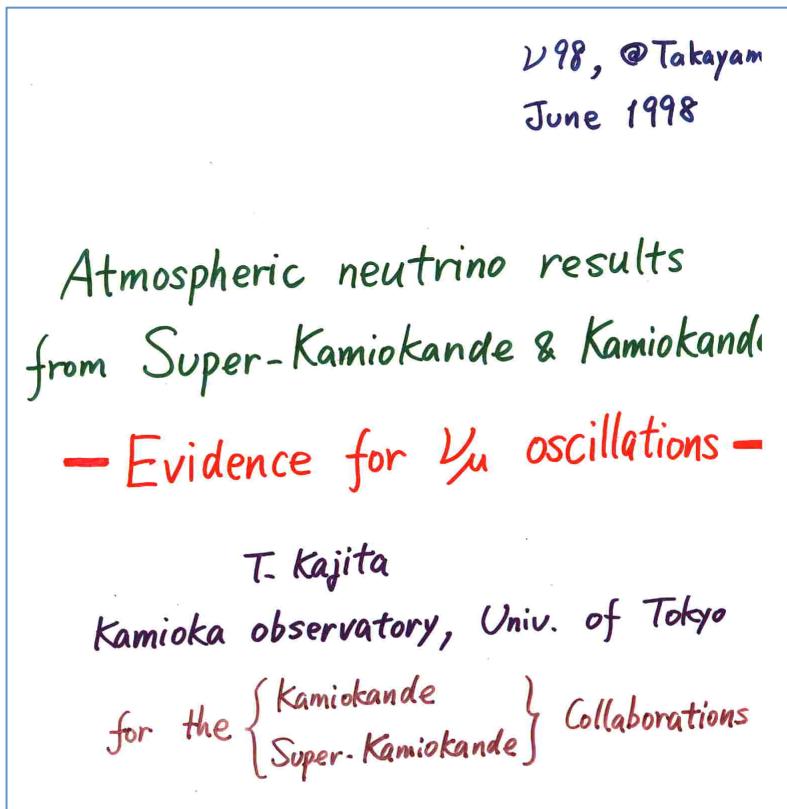
$$\text{Flux}(\nu_\mu) \sim \text{Flux}(\nu_e)$$



Up-down muon asymmetry

Atmospheric “noise” hiding a neutrino oscillation signal?

It took >10 year of further research and a much larger detector (Super-Kamiokande) to prove this hypothesis at  $>6\sigma$  in 1998:

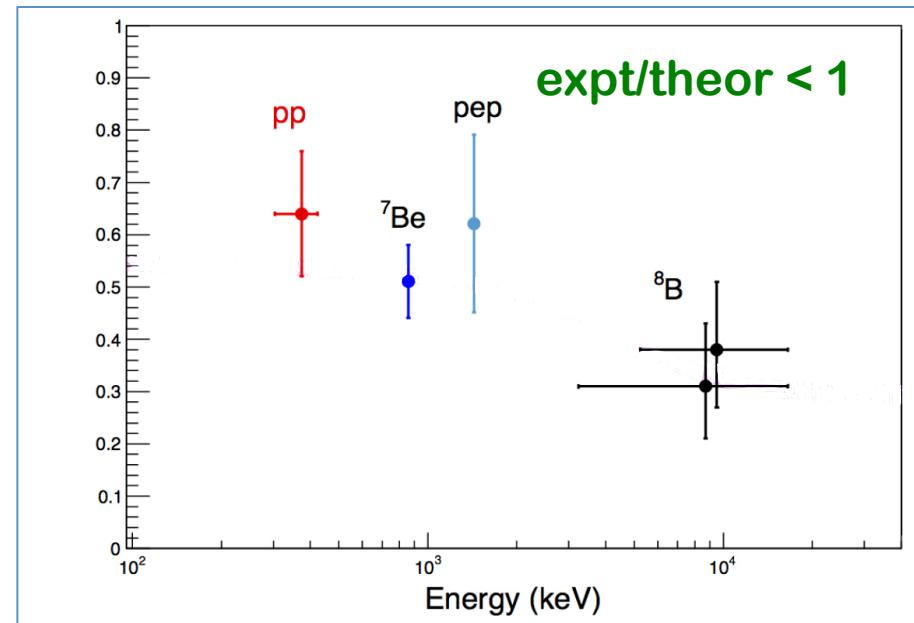
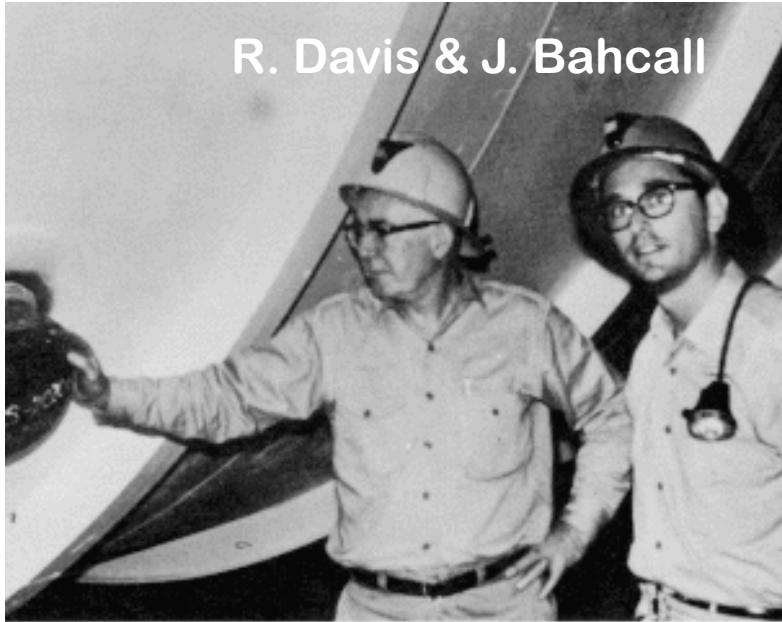


Disappearance of upgoing  $\nu_\mu$  [while  $\nu_e \sim \text{OK}$ ], therefore:  
dominant  $\nu_\mu \rightarrow \nu_\tau$  oscillations  $\rightarrow (\Delta m^2, \theta_{23})$  parameters

Independently, the solar neutrino problem was unfolding...

Theory: flux of  $\nu_e$  calculable with good accuracy...

Exp'ts: observed fluxes of  $\nu_e$  less than expected!

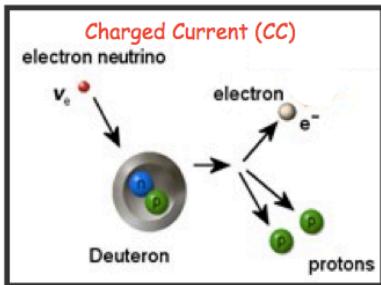


Are solar models and/or experiments **wrong?**

Are they both right, but  $\nu_e$  transform into  $\nu_{\mu,\tau}$ ?

Need a model-independent approach!

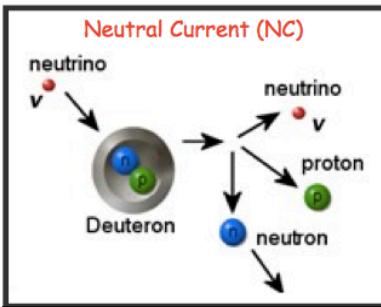
$\nu$  interactions on deuterium offered a unique possibility...



**CC interactions:**

count only solar  $\nu_e$ , not  $\nu_{\mu,\tau}$

$$\rightarrow \Phi_{cc} = \Phi_e \text{ flux}$$



**NC interactions:**

count all  $\nu_{e,\mu,\tau}$  from the Sun,

$$\rightarrow \Phi_{nc} = \Phi_e + \Phi_\mu + \Phi_\tau \text{ flux}$$

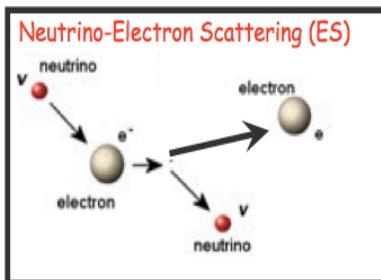
If  $\Phi_{cc} < \Phi_{nc}$ , then some  $\nu_e$  must have changed into  $\nu_{\mu,\tau}$

In addition: “bonus” ES interaction for cross-check!

**Elastic Scattering on electrons:**

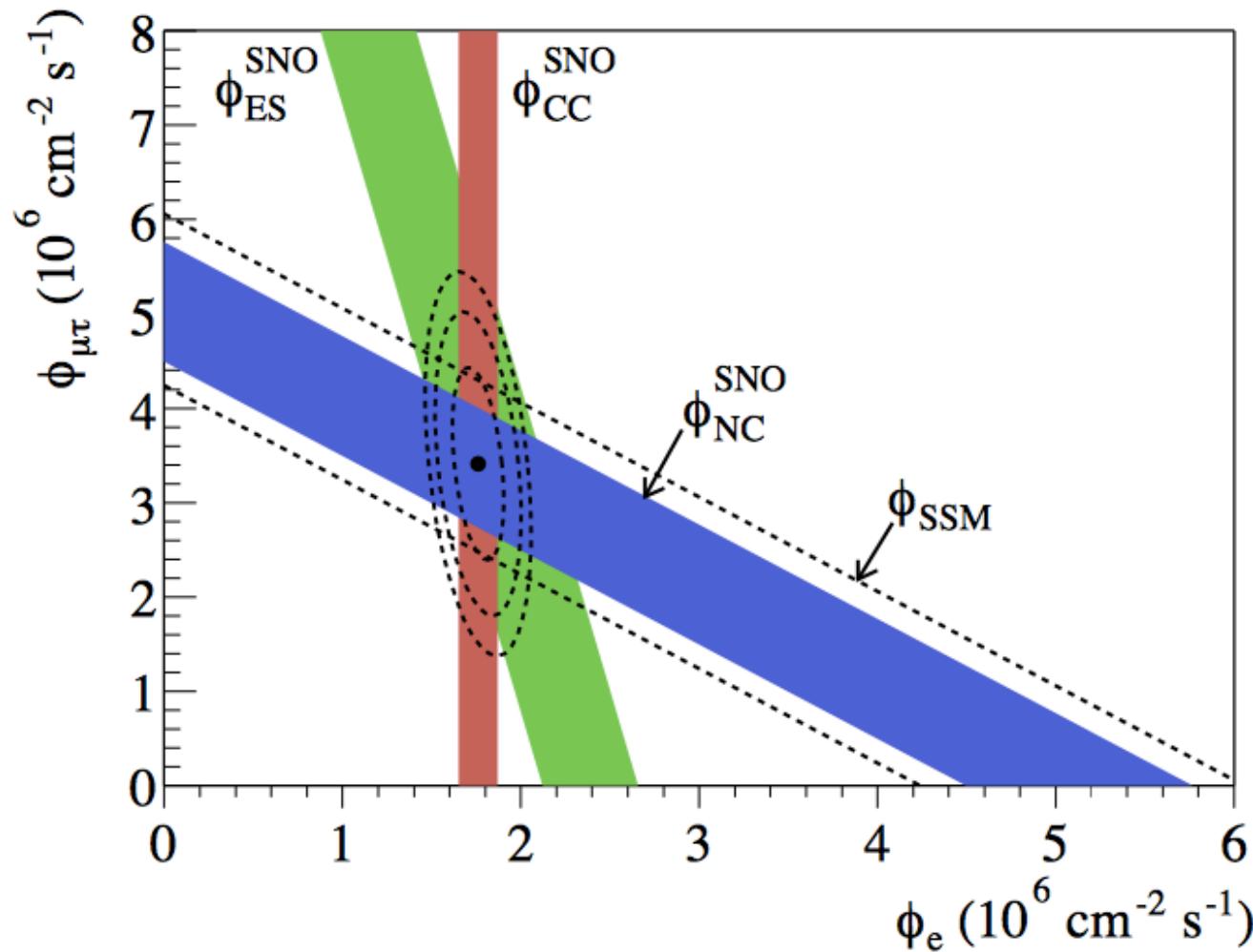
count mostly  $\nu_e$ , but also  $\nu_{\mu,\tau}$

$$\rightarrow \Phi_{es} \sim \Phi_e + 0.15 \Phi_{\mu,\tau}$$



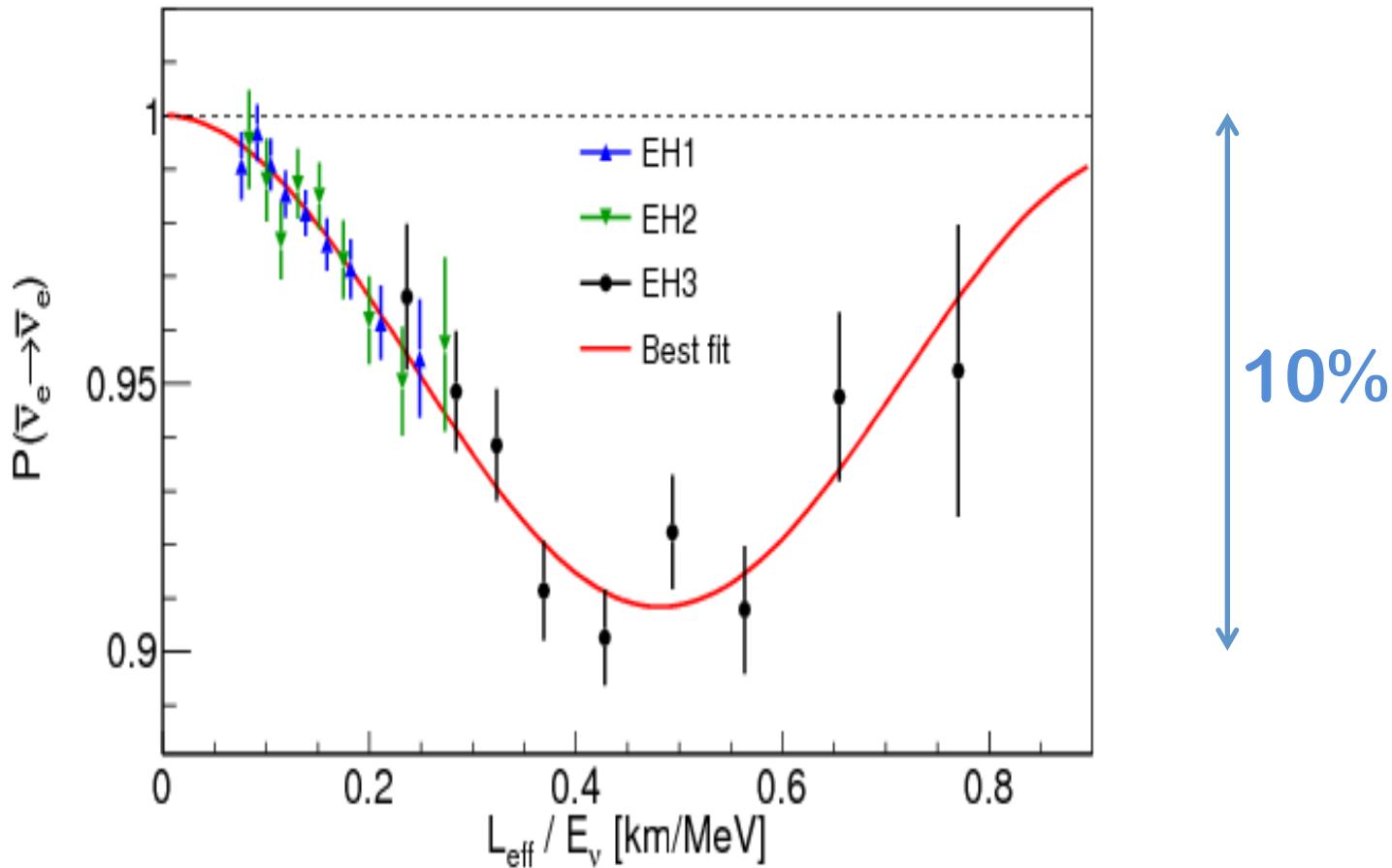
# Sudbury Neutrino Observatory, 2002: a textbook plot!

[with Art McDonald playing a prominent role in the experiment]



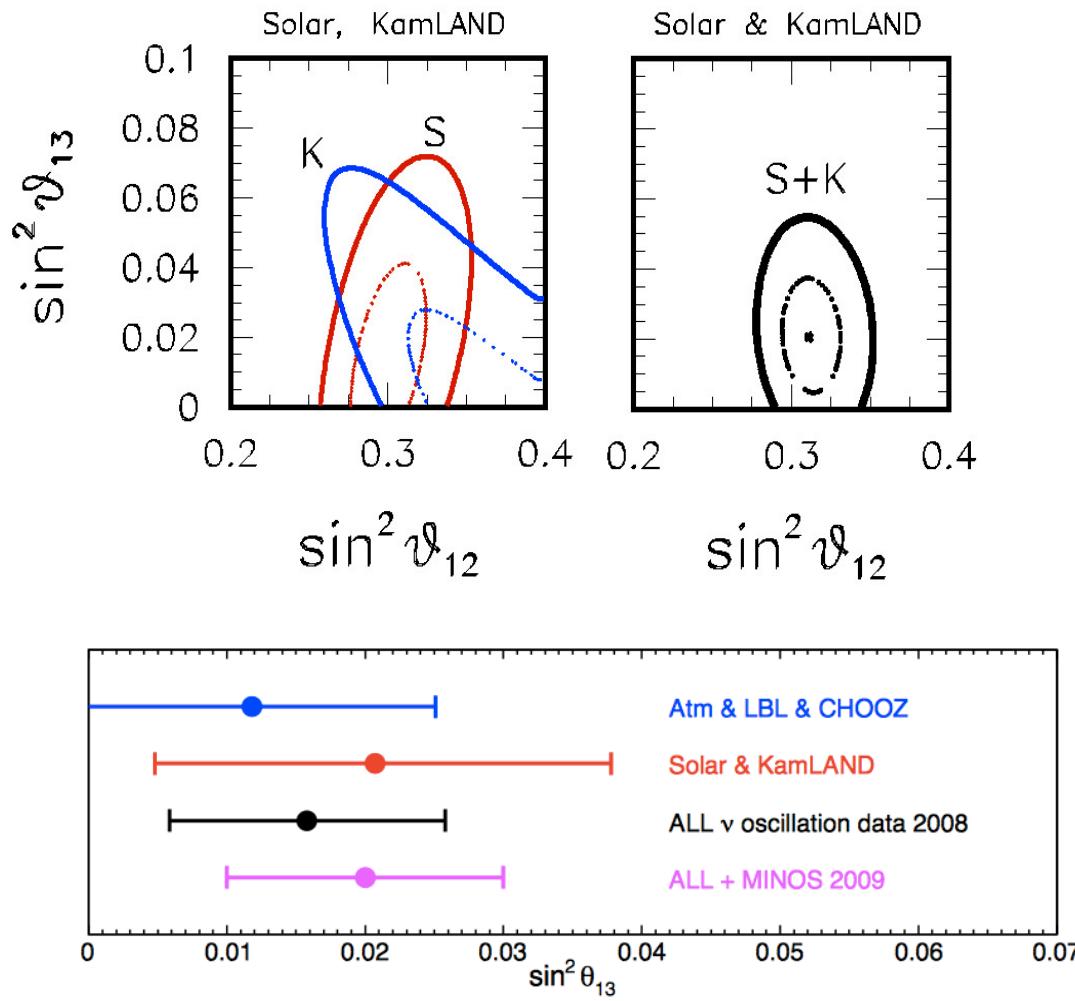
$\nu_e \rightarrow \nu_{\mu,\tau}$  oscillations  $\rightarrow (\delta m^2, \theta_{12})$  parameters

That was presumably the end of O(1) oscillation effects...  
the next “large one” has shown up at O(10%) in 2012:



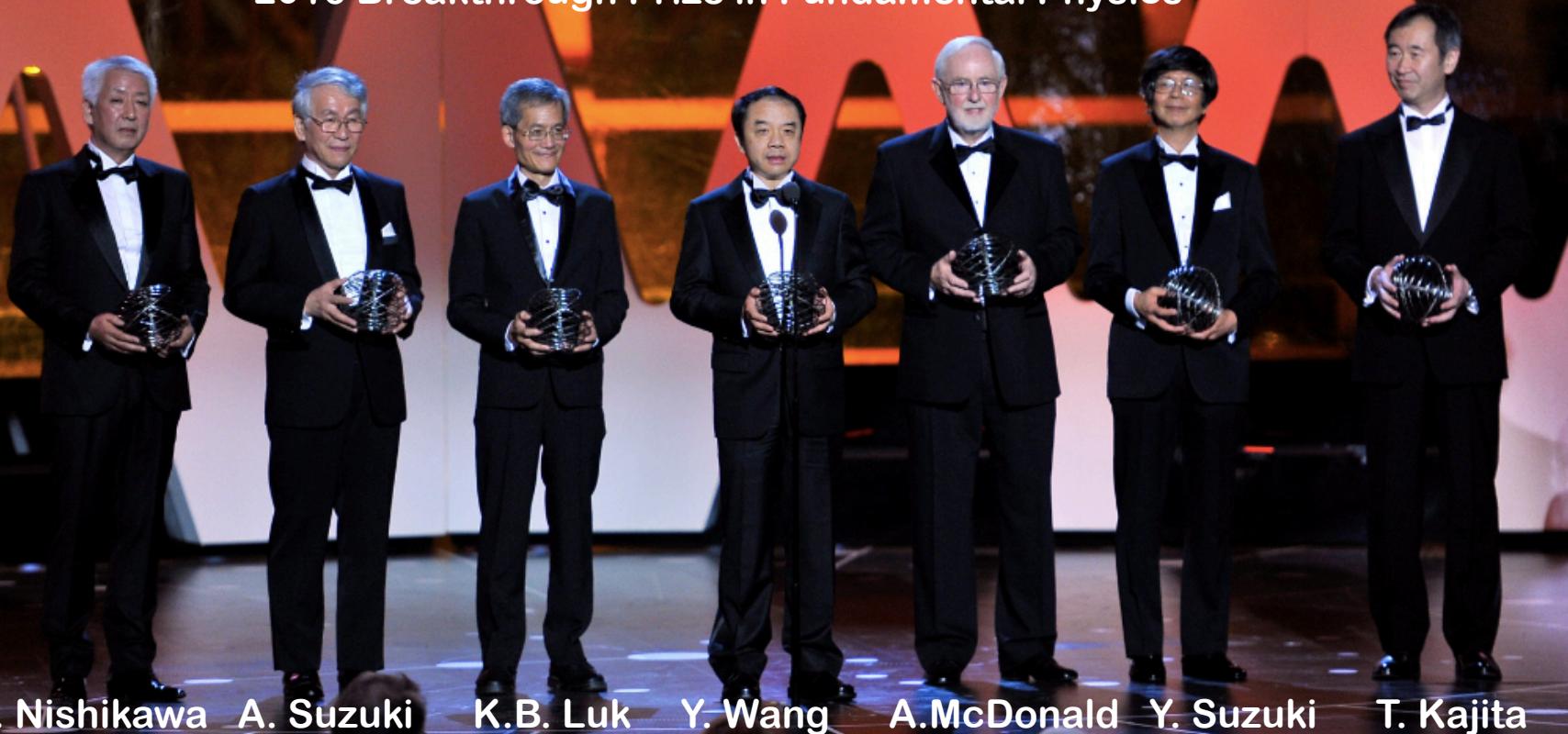
$\nu_e$  disappearance at reactors →  $\theta_{13}$  parameter

$\theta_{13}$  large enough to be glimpsed in pre-discovery global data analyses (Bari group, 2008 - 2011)



# We've got a nice picture of $\nu$ masses and mixings...

2016 Breakthrough Prize in Fundamental Physics



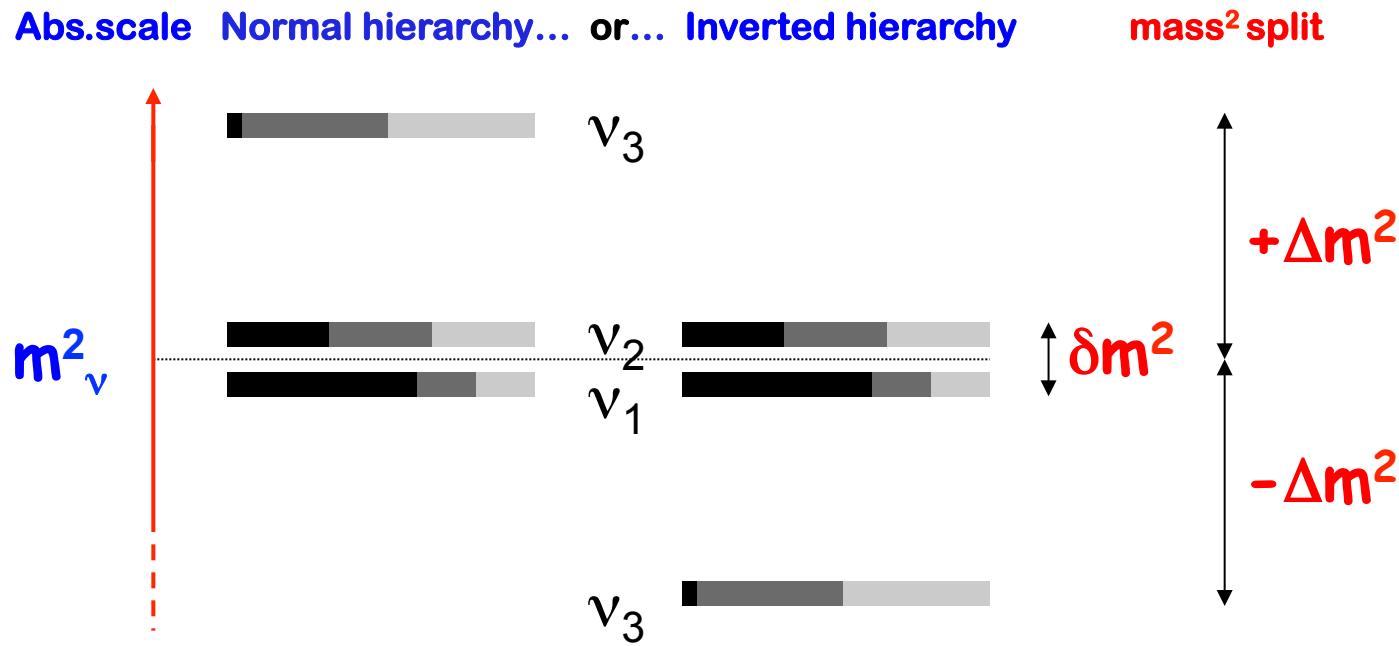
K. Nishikawa A. Suzuki K.B. Luk Y. Wang A. McDonald Y. Suzuki T. Kajita

that is, however, still incomplete ...

In the spirit of this Xmas Workshop, we've got just  
½ of the answers to the ultimate neutrino questions!

# Current 3 $\nu$ picture in just one slide (with 1-digit accuracy)

Flavors = e  $\mu$   $\tau$



$\frac{1}{2}$  Terra Cognita:

$$\begin{aligned}\delta m^2 &\sim 8 \times 10^{-5} \text{ eV}^2 \\ \Delta m^2 &\sim 2 \times 10^{-3} \text{ eV}^2 \\ \sin^2 \theta_{12} &\sim 0.3 \\ \sin^2 \theta_{23} &\sim 0.5 \\ \sin^2 \theta_{13} &\sim 0.02\end{aligned}$$

$\frac{1}{2}$  Terra Incognita:

$$\begin{aligned}&\delta (\text{CP}) \\ &\text{sign}(\Delta m^2) \\ &\text{octant}(\theta_{23}) \\ &\text{absolute mass scale} \\ &\text{Dirac/Majorana nature}\end{aligned}$$

## **WARNING**

**Pioneering era in “Terra Cognita” is over!**

**Effects we are seeking in “Terra Incognita”  
will be either small (few percent) or rare...**

**(Global) neutrino data analyses may provide  
some guidance in this difficult enterprise**

**... but they will face unprecedented challenges**

# Global analysis 2014 and status of unknowns

Analysis includes increasingly rich oscill. data sets:

LBL Acc + Solar + KL

LBL Acc + Solar + KL + SBL Reactor

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

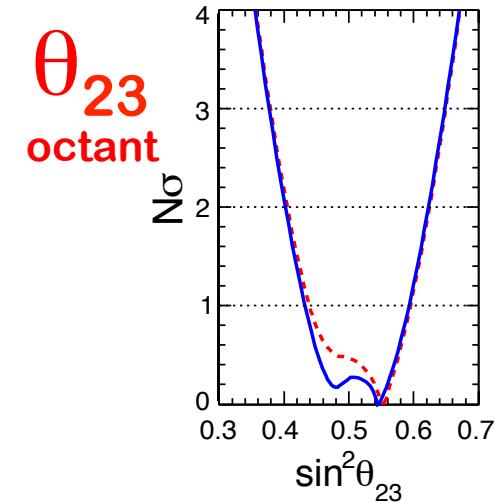
Parameters not shown are marginalized away.

C.L.'s refer to  $N\sigma = \sqrt{\Delta\chi^2} = 1, 2, 3, \dots$

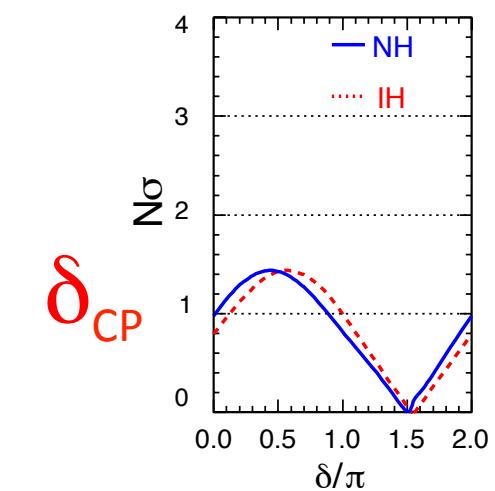
Results from Capozzi et al., arXiv:1312.2878, updated with “Reactor 2014”  
[See also: Forero et al., 1405.7540; Gonzalez-Garcia et al., 1409.5439]

2014

LBL+Sol+KL



$\Delta\chi^2$   
(IH-NH)  
-1.4

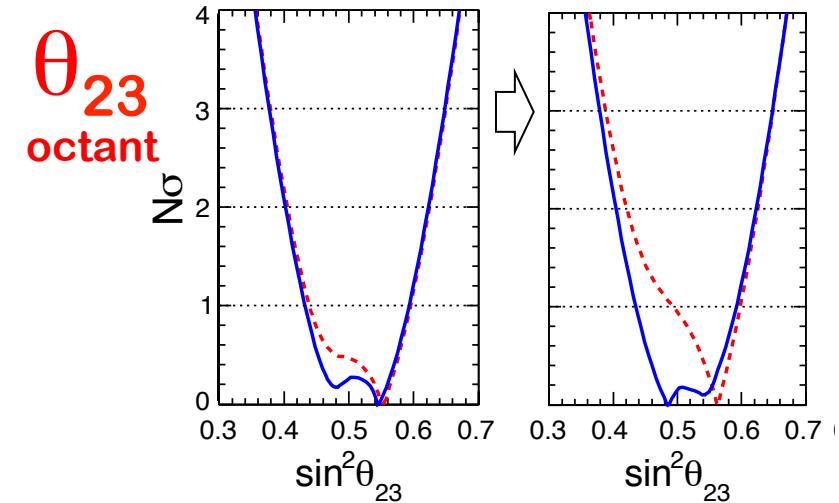


2014

2014

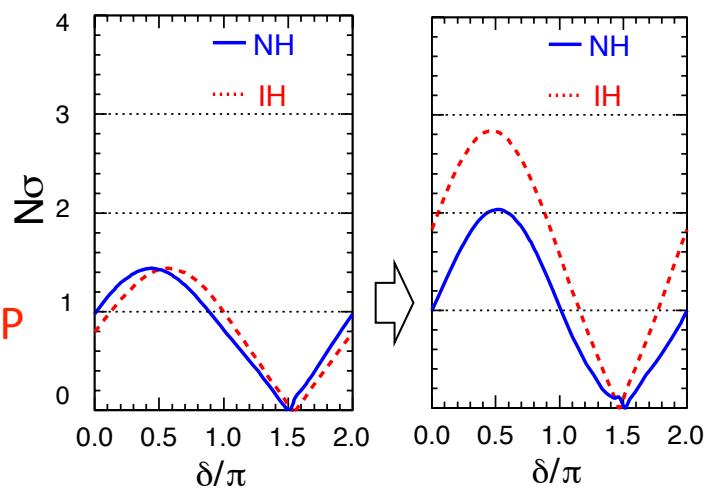
LBL+Sol+KL

+SBL Reac


 $\Delta\chi^2$   
(IH-NH)

-1.4

-0.9



2014

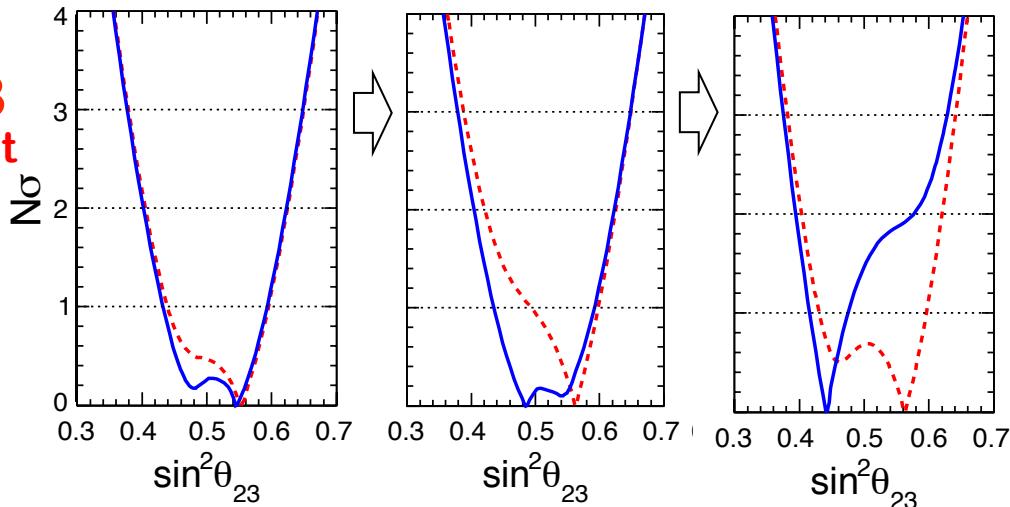
2014

2014

LBL+Sol+KL

+SBL Reac

+SK atm

 $\theta_{23}$   
octant


rather  
unstable,  
fragile

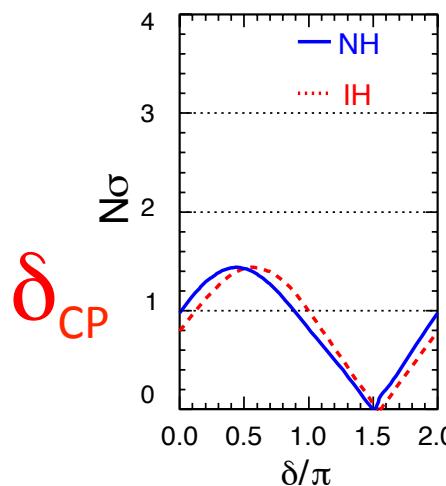
 $\Delta\chi^2$   
(IH-NH)

-1.4

-0.9

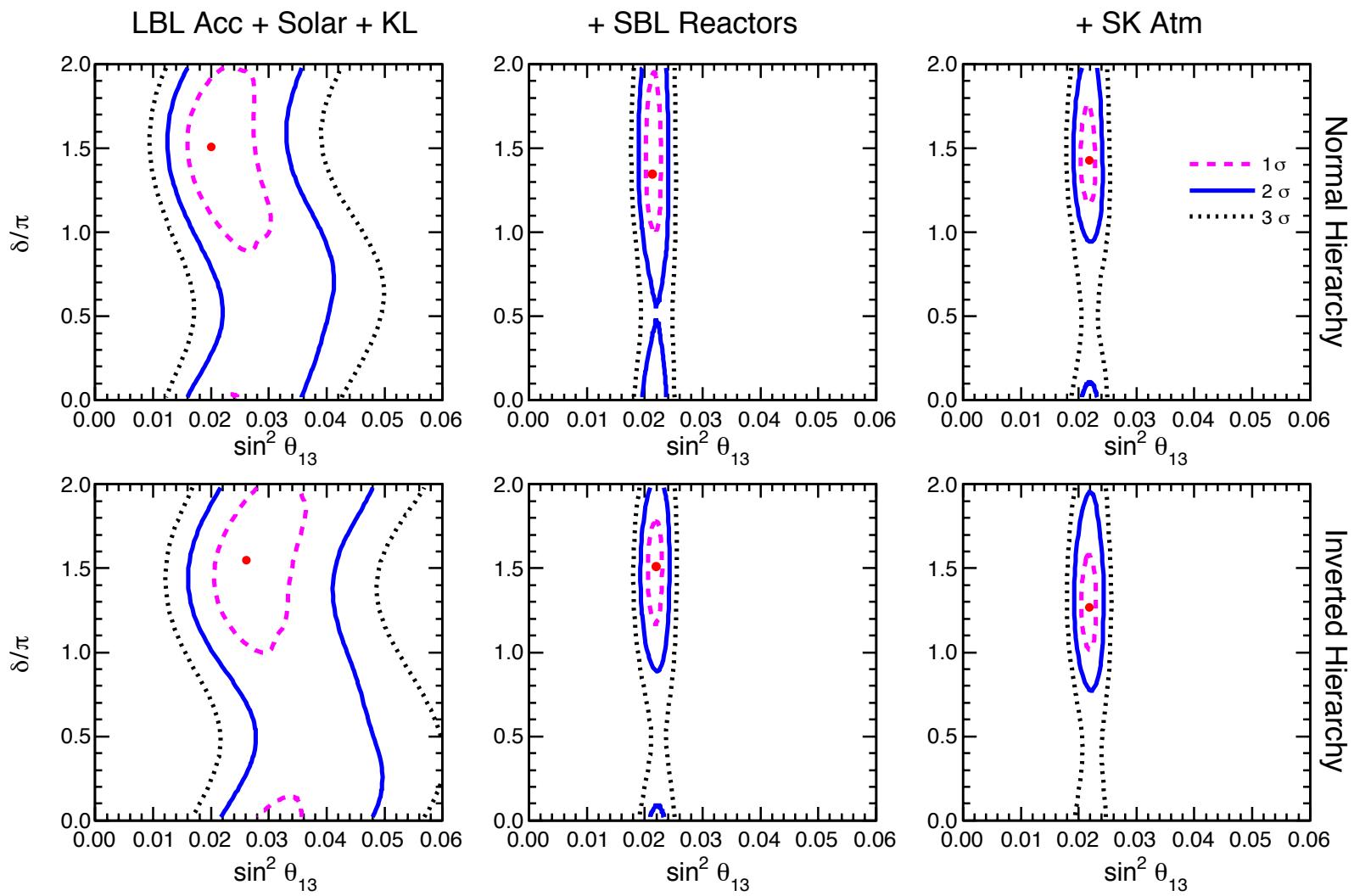
-0.1

negligible



intriguing,  
 $\sin \delta \sim -1$   
(or  $\sin \delta < 0$ )  
favored

# $\delta - \theta_{13}$ correlation 2014



# Global analysis 2015 (partial and preliminary)

Several new data in 2015:

Updated reactor (DB) & atmosph. (SK, DC) data  
(not yet included herein, work in progress)

First anti- $\nu$  data from T2K, **disapp.+app.**  
(included, preliminary)

First data from NOvA, **disapp.+app. (LID or LEM)\***  
(included, preliminary)

\*LID (Likelihood Identification) = primary NOvA analysis  
LEM (Library Event Matching) = alternative NOvA analysis

Reminder: in T2K neutrino run, appearance rate was nearly the largest, favoring  $\sin\delta \sim -1$

2014

2014

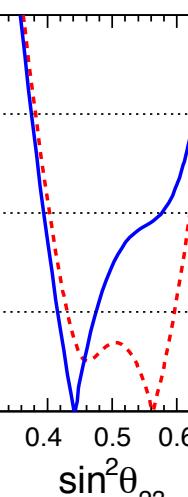
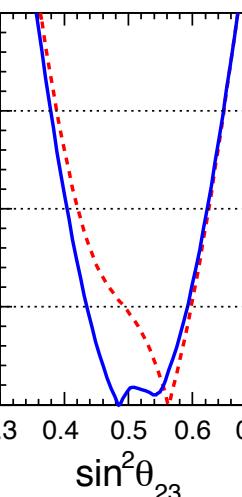
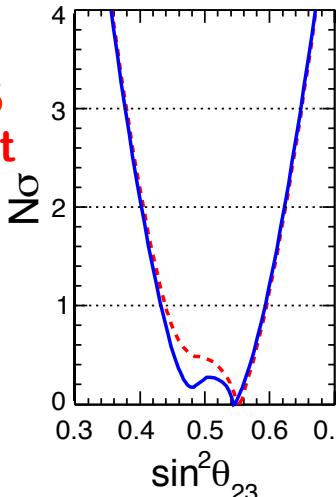
2014

LBL+Sol+KL

+SBL Reac

+SK atm

$\theta_{23}$   
octant



$\Delta\chi^2$   
(IH-NH)

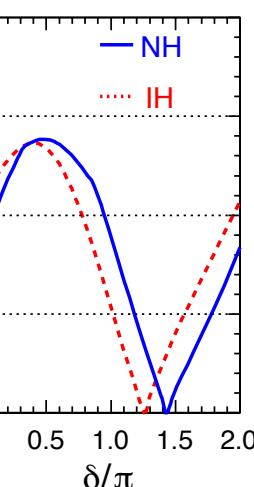
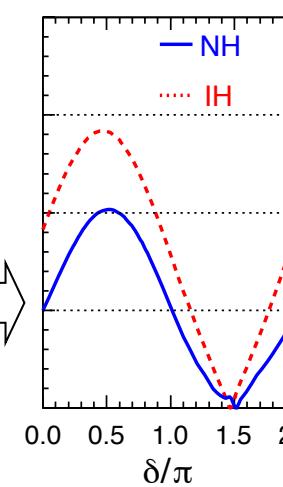
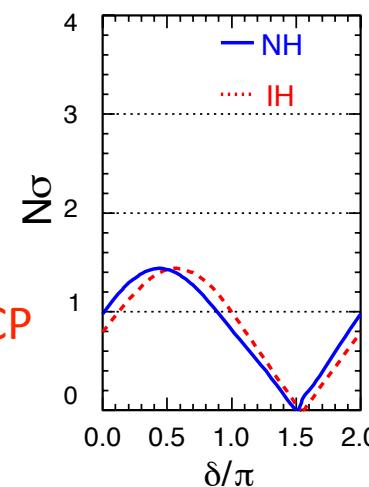
-1.4



-0.9



-0.1



In T2K antineutrino run, appearance rate is nearly the lowest, consistent with  $\sin\delta \sim -1$

2014

2014

2014

2015

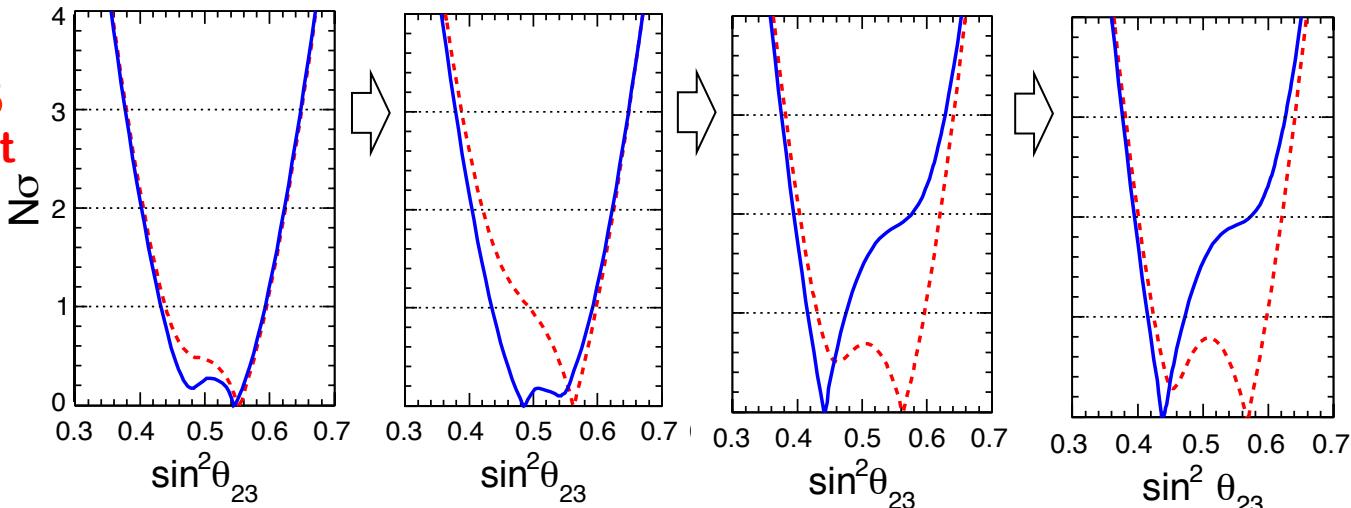
LBL+Sol+KL

+SBL Reac

+SK atm

+T2K anti- $\nu$

$\theta_{23}$   
octant



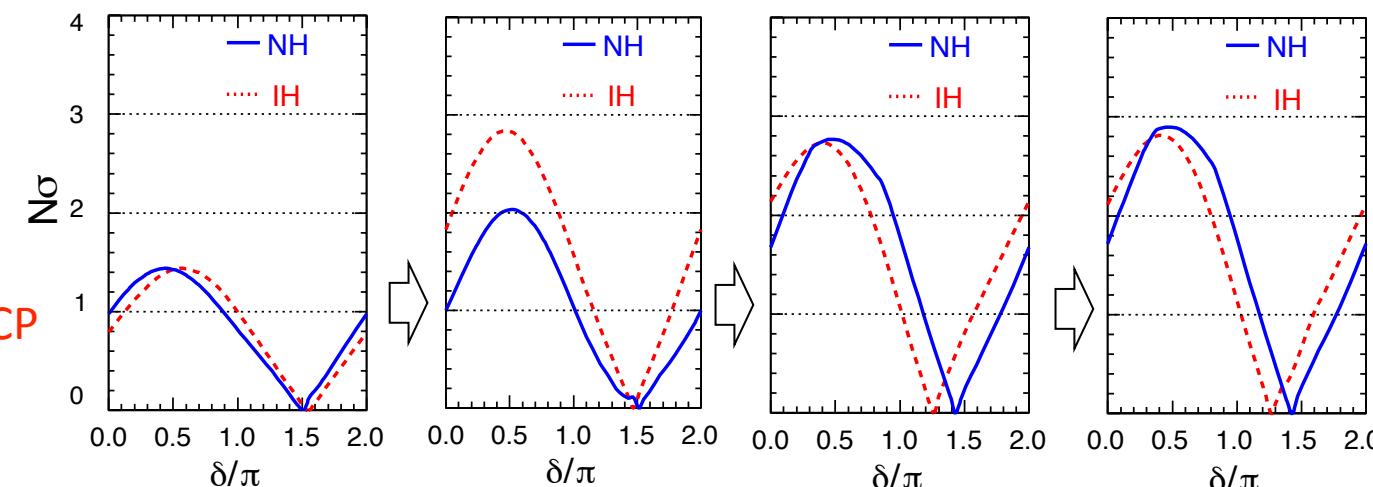
-1.4

-0.9

-0.1

+0.3

$\Delta\chi^2$   
(IH-NH)



In NOvA (neutrino) run, appearance rate is nearly the highest, consistent with  $\sin\delta \sim -1$

2014

2014

2014

2015

2015

LBL+Sol+KL

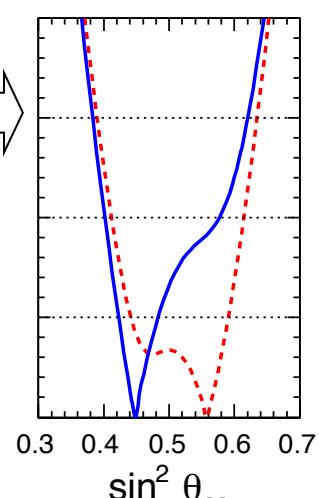
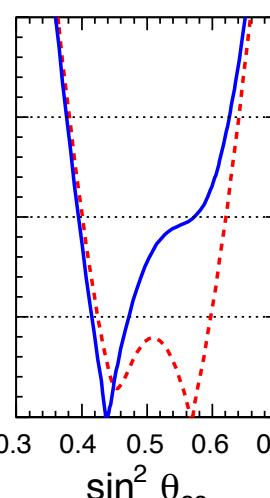
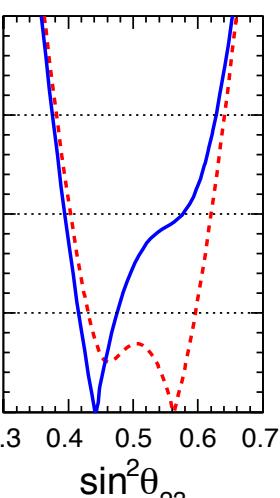
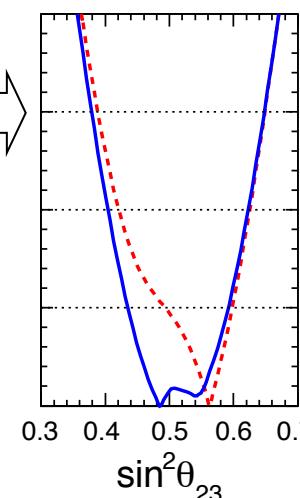
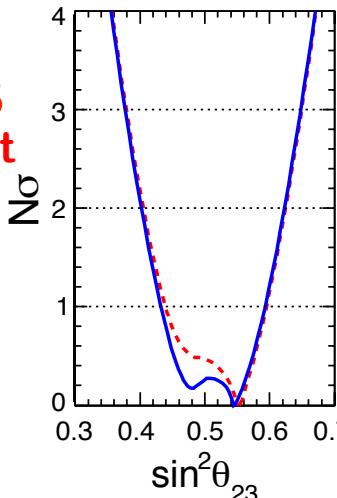
+SBL Reac

+SK atm

+T2K anti-v

+NOvA (LID)

$\theta_{23}$   
octant



-1.4

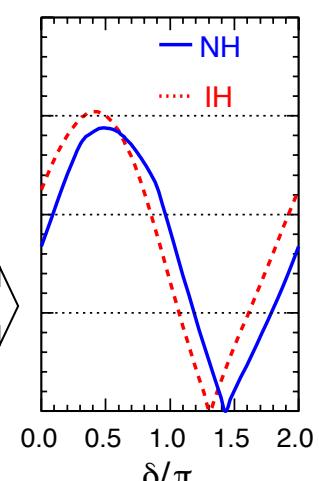
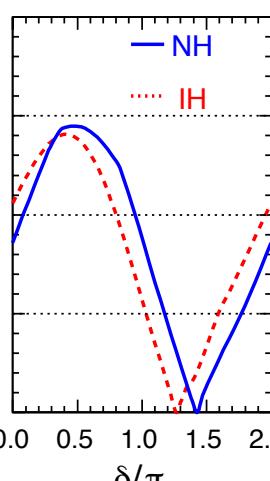
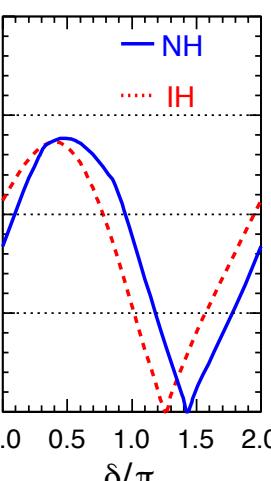
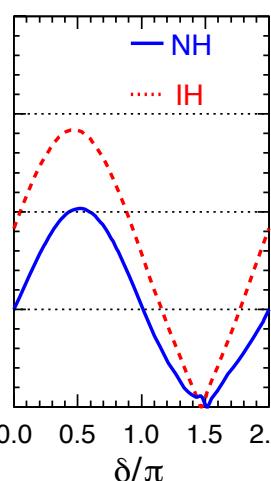
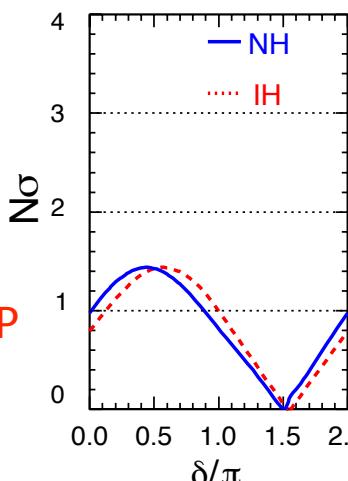
-0.9

-0.1

+0.3

+0.3

$\Delta\chi^2$   
(IH-NH)



$\delta_{CP}$

... and is even a little bit “too high” in NOvA LEM (w.r.t. LID)

2014

2014

2014

2015

2015

LBL+Sol+KL

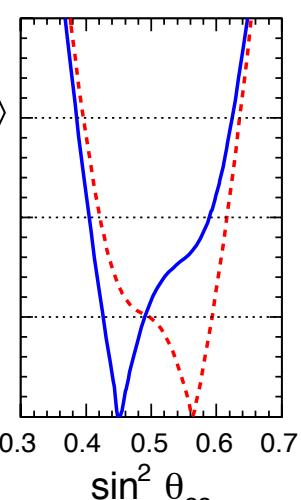
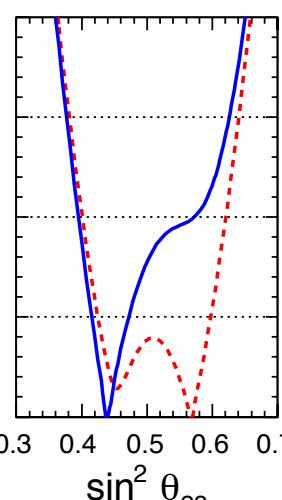
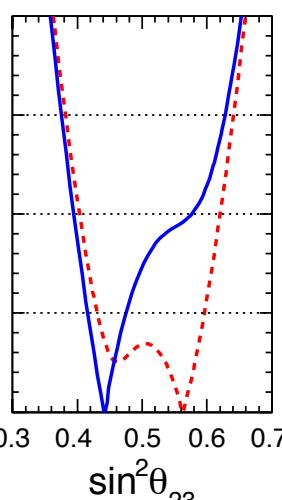
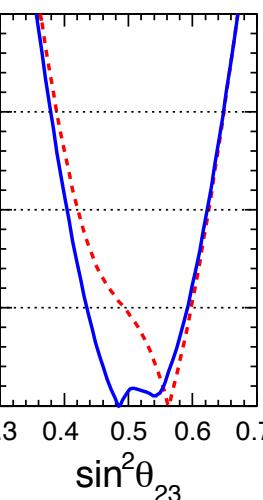
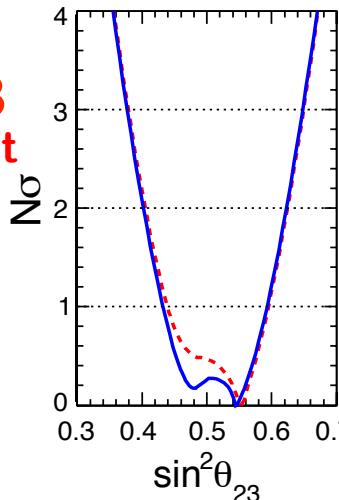
+SBL Reac

+SK atm

+T2K anti-v

+NOvA (LEM)

$\theta_{23}$   
octant



$\Delta\chi^2$   
(IH-NH)

-1.4



-0.9



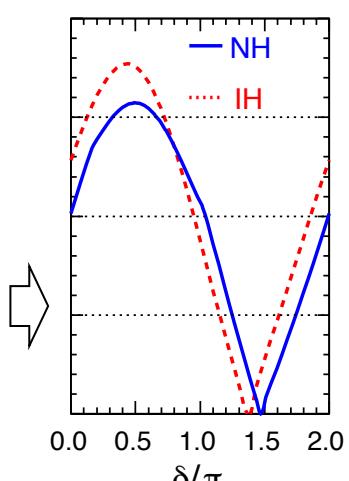
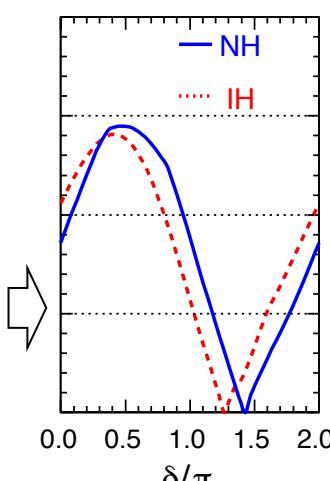
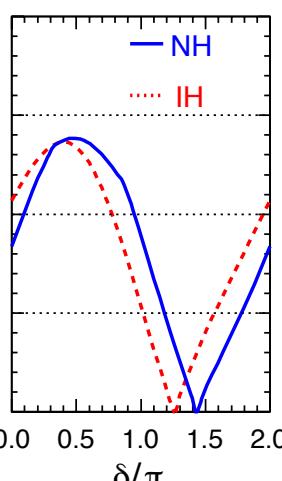
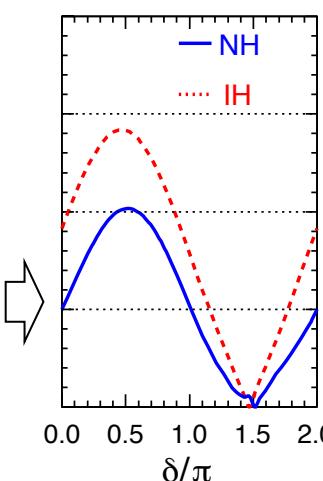
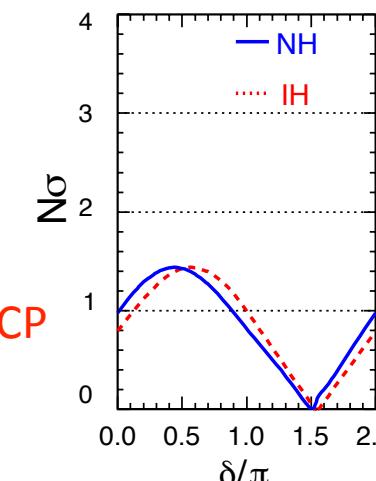
-0.1



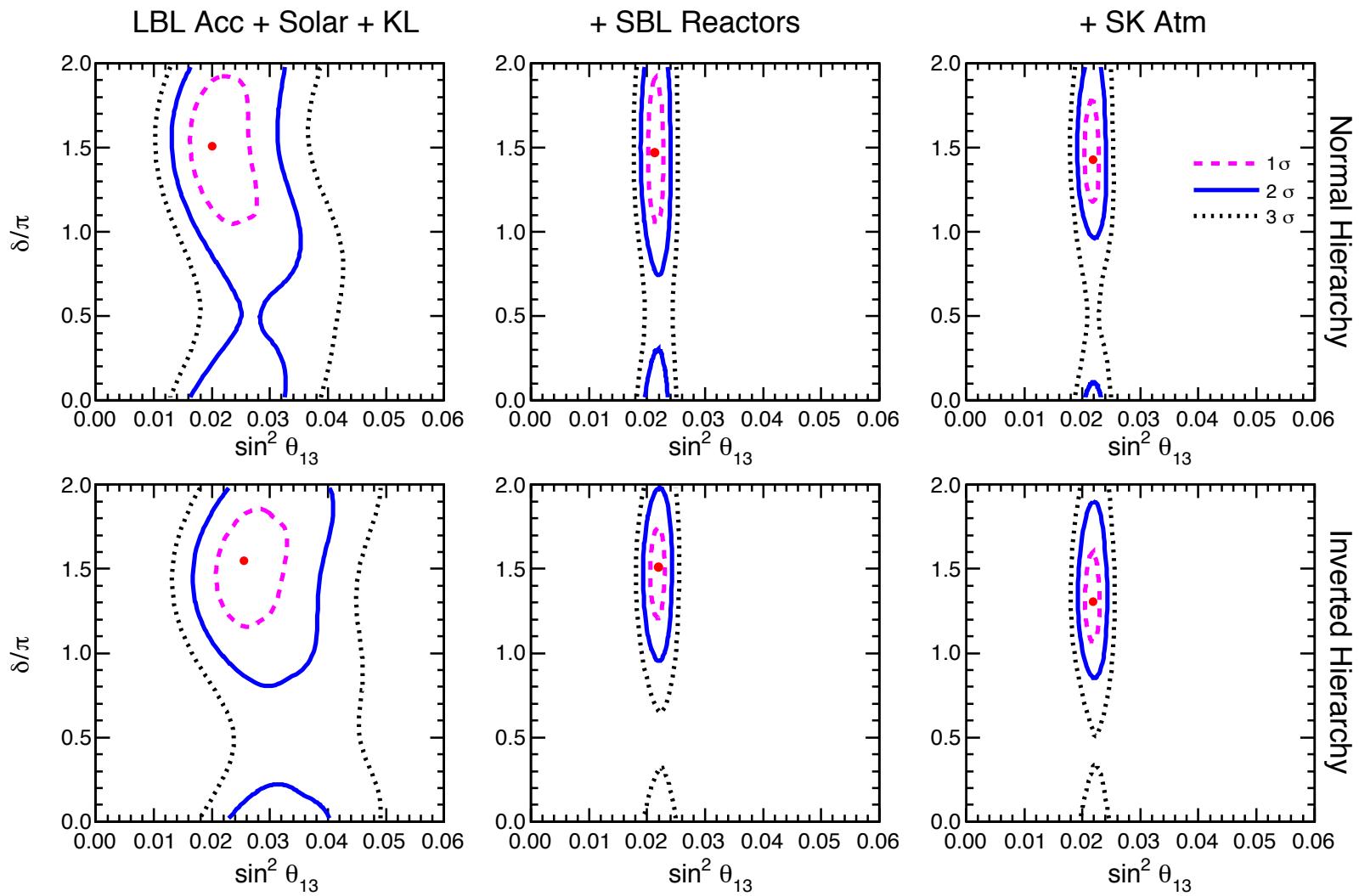
+0.3



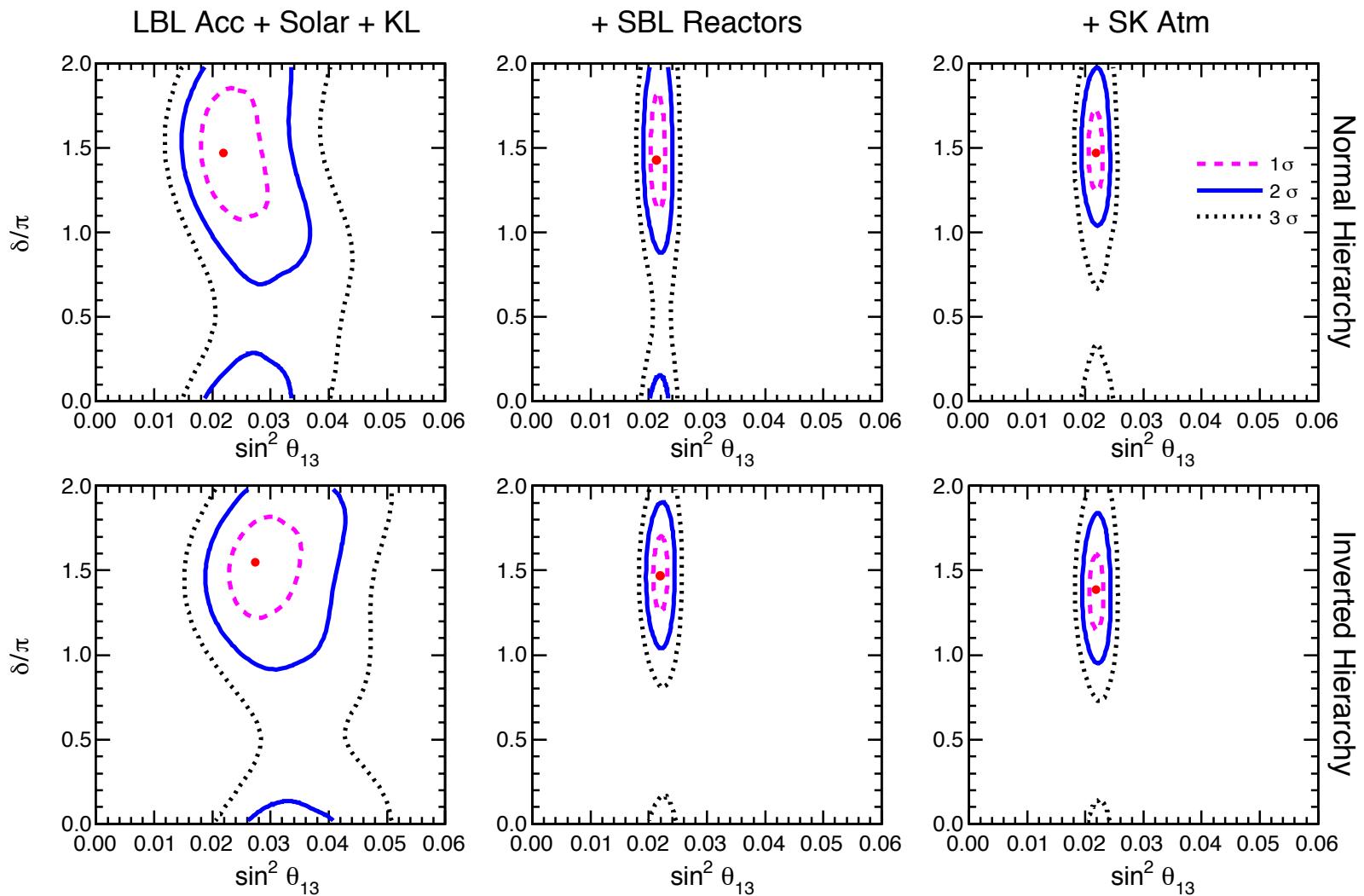
+2.2



# $\delta - \theta_{13}$ correlation 2015 (LID)



# $\delta - \theta_{13}$ correlation 2015 (LEM)



At ~90% C.L. ( $1.64\sigma$ )  
we find that...

$\theta_{23}$   
octant

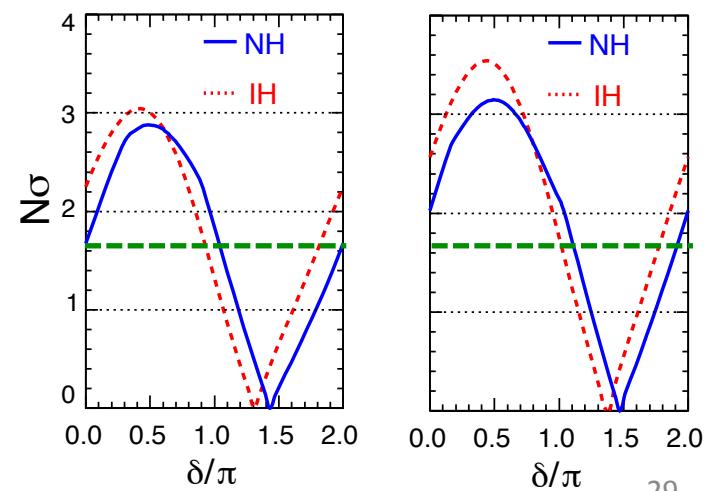
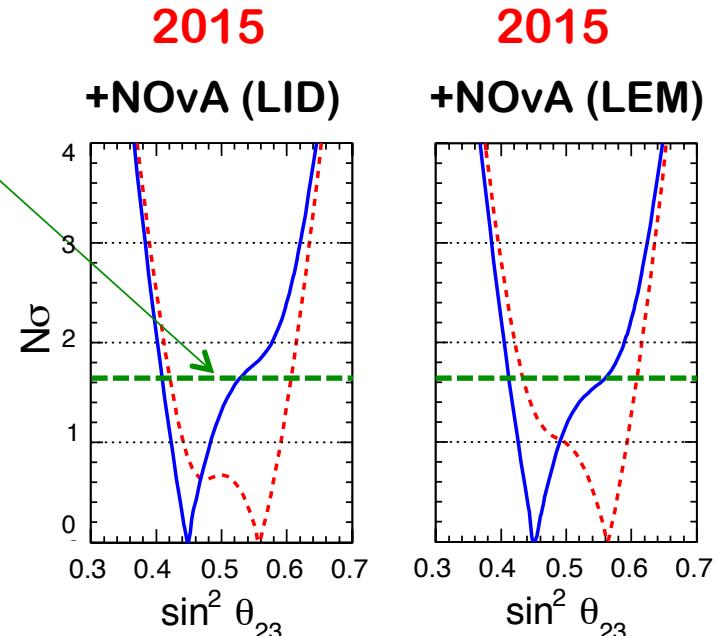
...both  $\theta_{23}$  octants,  
both NH and IH,  
both CPV and no CPV  
are still allowed...

$\Delta\chi^2$   
(IH-NH)

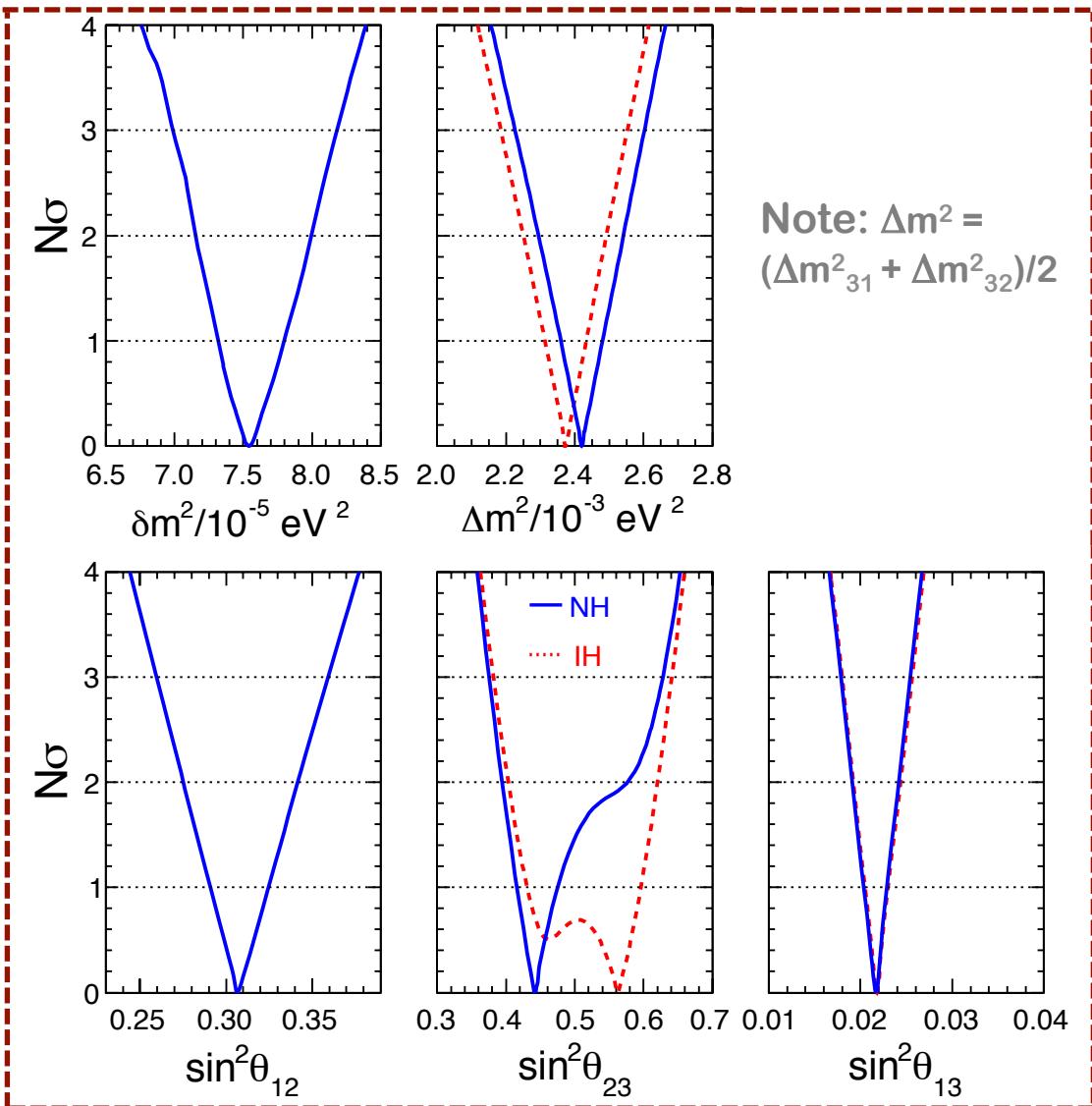
...but  $\delta \sim 3\pi/2$  is clearly  
favored over  $\delta \sim \pi/2$   
at the level of  $\sim 3\sigma$

$\delta_{CP}$

(Preliminary!)



# Terra Cognita 2014

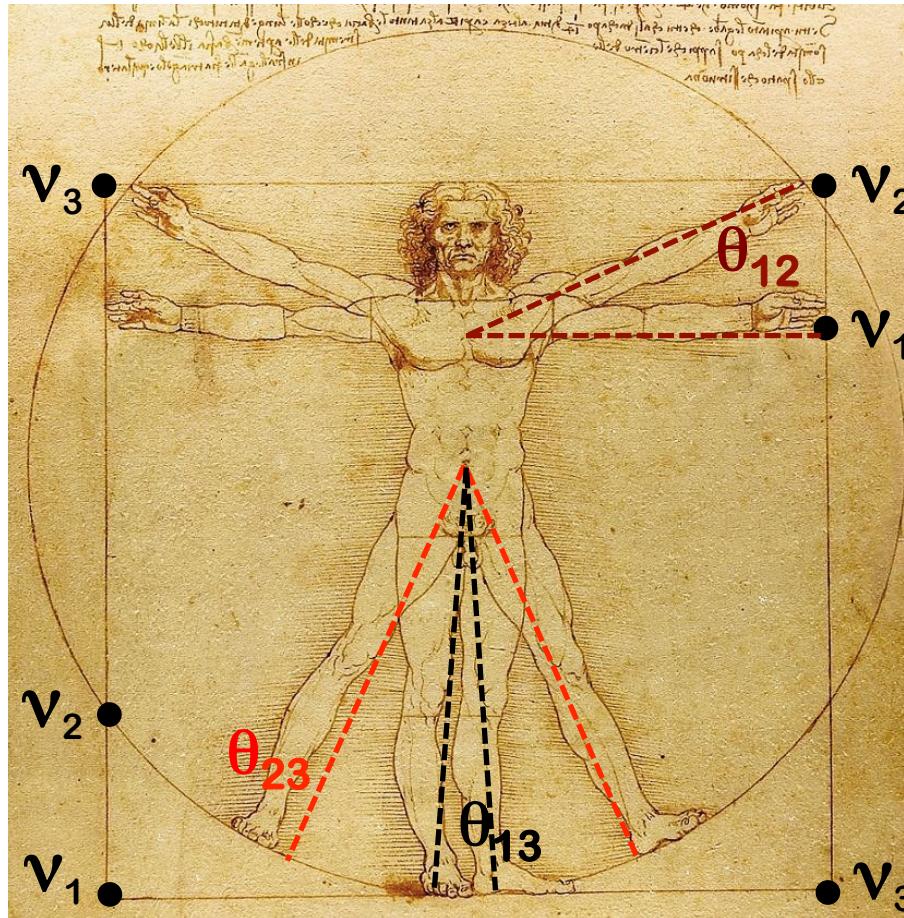


Fractional  $1\sigma$  error  
(1/6 of  $\pm 3\sigma$  range):

$\delta m^2$	2.6 %
$\Delta m^2$	2.6 %
$\sin^2 \theta_{12}$	5.4 %
$\sin^2 \theta_{13}$	5.8 %
$\sin^2 \theta_{23}$	~ 10 %

Also important as input  
to future experiments  
as well as to theoretical  
models

Neutrino flavor theory: is the current picture suggestive of some “simmetry”?  
Or the symmetry is only in our mind, and there is just randomness?  
Are there possible connections with the quark flavor sector?



Many interesting ideas, but no obvious answer/guidance so far

# Specific outcomes (a few examples from a vast literature)

No organizing principle  
("anarchy")



Discrete family symmetries  
("geometry")

linear relations between  
 $\theta_{13}\cos\delta$  and  $\theta_{12}, \theta_{23}$

Continuous flavor symmetries  
("dynamics")

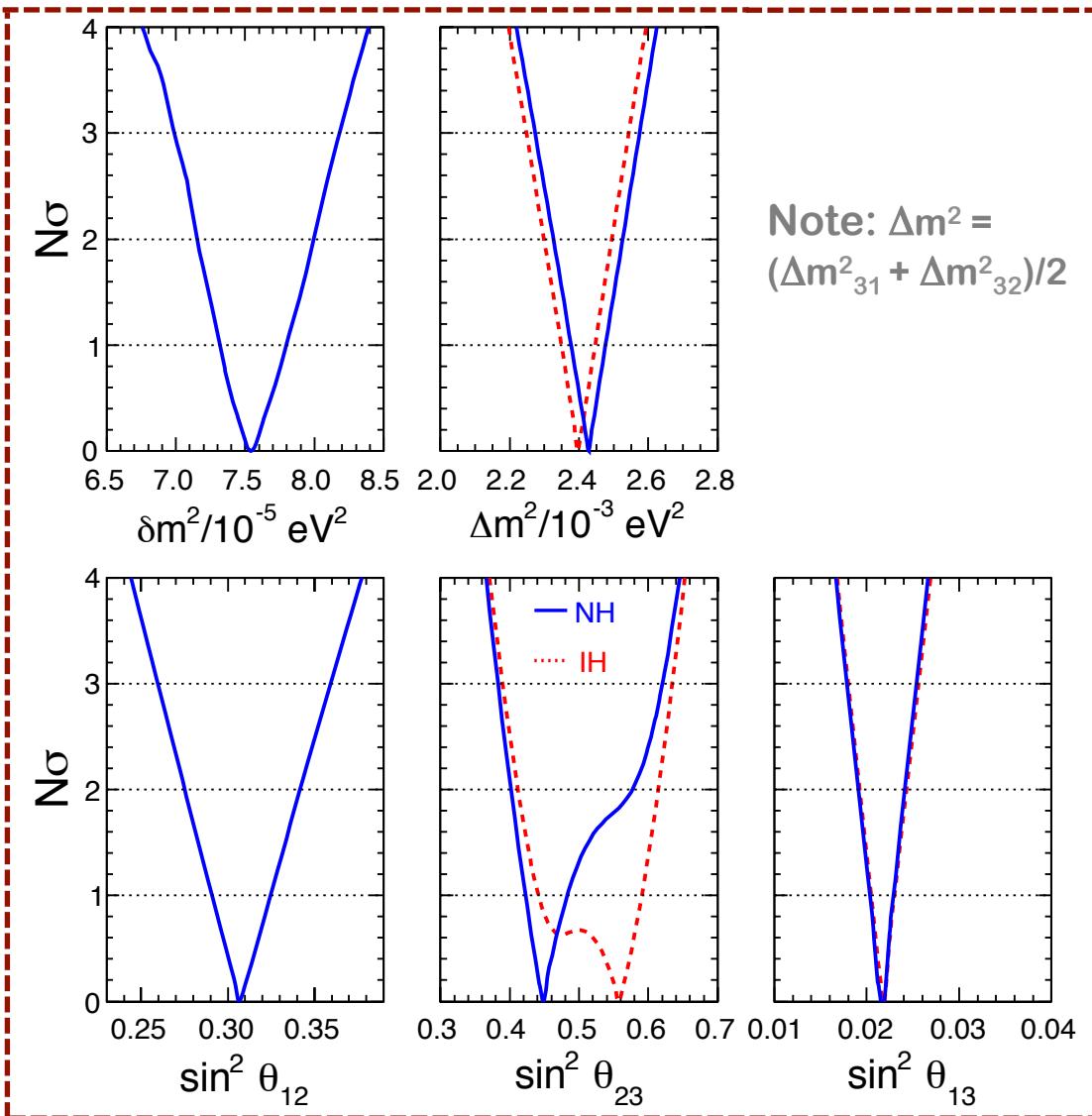
links between neutrino  
spectra/angles/phases

Common quark-lepton features  
("complementarity")

links between  
 $\theta_{13}$  and  $\theta_C$

## Model selection may benefit from higher precision

# Terra Cognita 2015 (partial, preliminary)



Fractional  $1\sigma$  error  
(1/6 of  $\pm 3\sigma$  range):

$\delta m^2$	2.6 %
$\Delta m^2$	2.6 % → 2.2 %
$\sin^2 \theta_{12}$	5.4 %
$\sin^2 \theta_{13}$	5.8 %
$\sin^2 \theta_{23}$	~10 % → ~9 %

Systematics play an increasing role, e.g.,

Can we get  $\Delta m^2$  at 1%?

Hard to improve much more on  $\Delta m^2$  with LBL:  
hitting the “floor” of Xsection systematics →

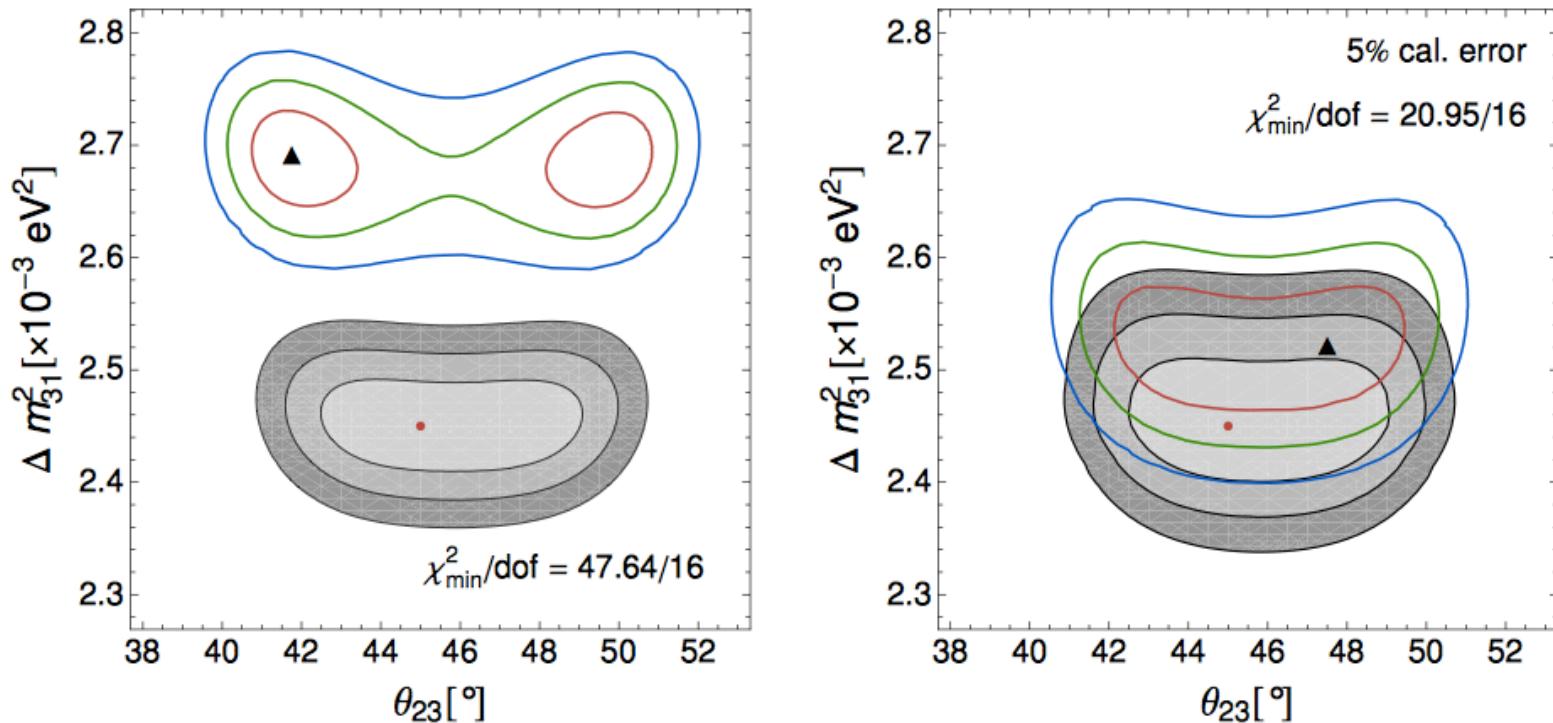


FIG. 36 (color online) Impact on the results if a different generator is used to compute the true and fitted rates in the analysis. The shaded areas show the confidence regions at 1, 2 and  $3\sigma$  that are obtained in the  $\theta_{23} - \Delta m_{31}^2$  plane if the true and fitted rates are generated using the same set of migration matrices (obtained from GiBUU, with oxygen as the target nucleus). The solid lines show the same confidence regions if the true rates are generated using matrices produced with GiBUU, but the fitted rates are computed using matrices produced with GENIE. Both sets of matrices are generated using oxygen as the target nucleus. The dot indicates the true input value, while the triangle shows the location of the best fit point. The value of the  $\chi^2$  at the best fit is also shown, together with the number of degrees of freedom. In the left panel no energy scale uncertainty is considered, while for the right panel an energy scale uncertainty of 5% is assumed, see text for details. Figure and caption adapted from [Coloma et al. \(2014\)](#)

Perhaps a bit “extreme”, but useful to get the point!

Once upon a time... all neutrino experiments were limited by stat's, and systematics could be treated as numbers (normalization, bias ...)

Now we have as many as  $O(10^6)$  events collected in SBL reactors, and we expect  $O(10^5)$  events in each of JUNO, ORCA, PINGU expt's

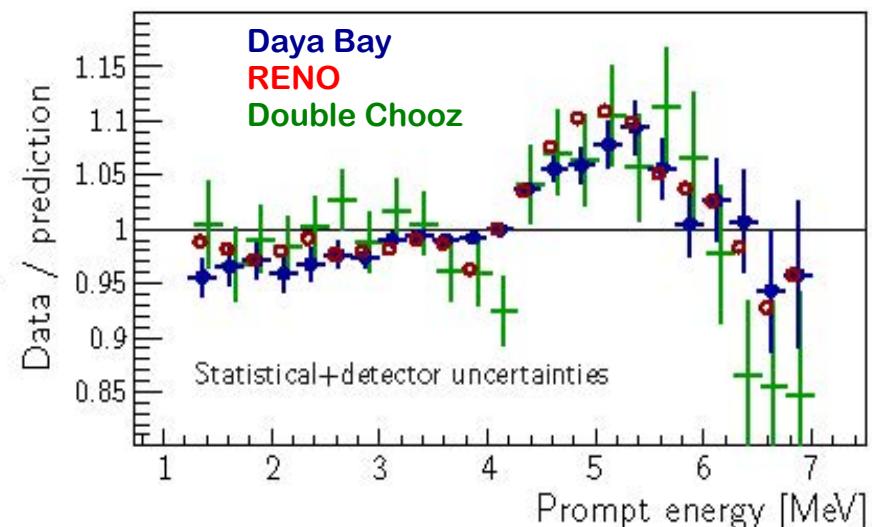
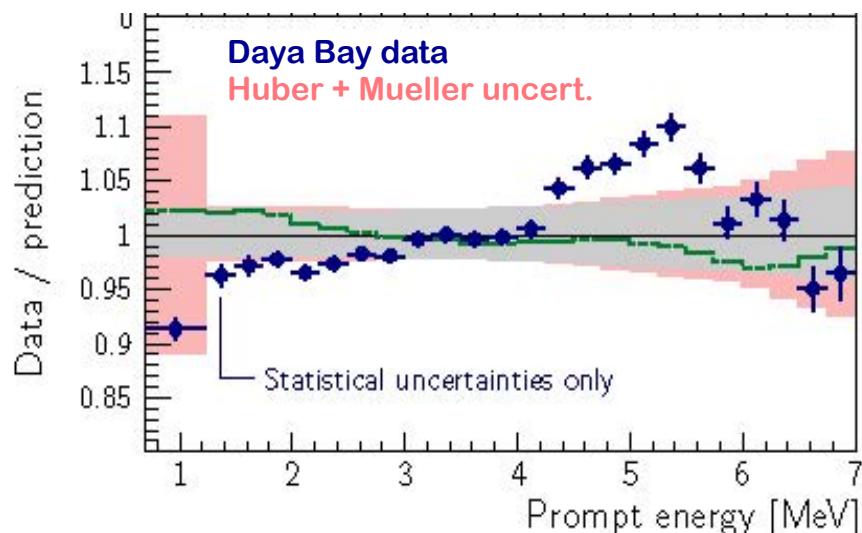
Systematic errors are no longer “numbers” but become “functions”. Dedicated approaches are needed to deal with such uncertainties.

[This transition has already taken place in other fields, such as in parton distribution function fits and precision cosmology forecasts.]

Unprecedented challenges are awaiting us in neutrino data analyses:

We must be prepared to deal with “functions” which *ideally* should be known in size, shape, correlations and probability distributions, but *in practice* may also be partly (if not completely!) unknown.

Hard lesson learned from SBL reactor experiments:  
**An unknown systematic error source (function)  $\delta\Phi(E)$ , well beyond supposedly-known shape uncertainties!**



From S. Jetter (TAU 2014) & J. Cao (TAUP 2015)

Now we know its shape, and can correct for it, but residuals do remain:

**energy-scale uncertainties**

**flux-shape uncertainties**

$E \rightarrow E'(E)$

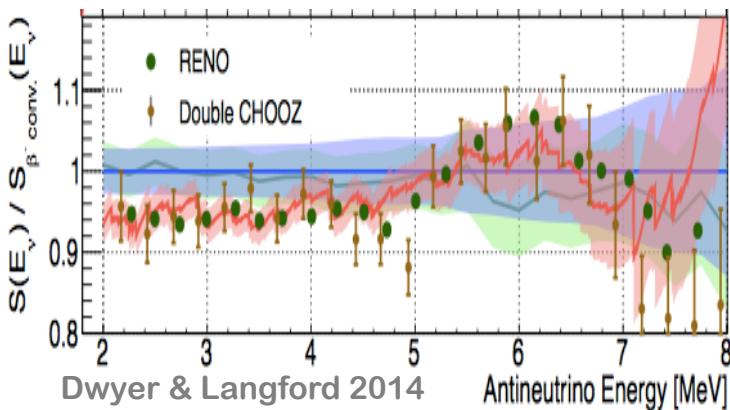
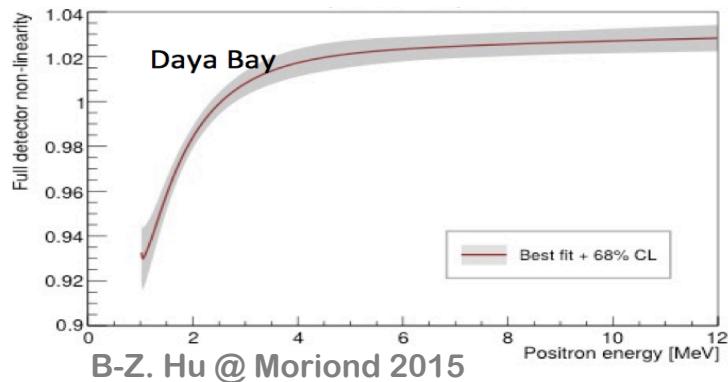
$\Phi(E) \rightarrow \Phi'(E)$

(x-axis “stretch”)

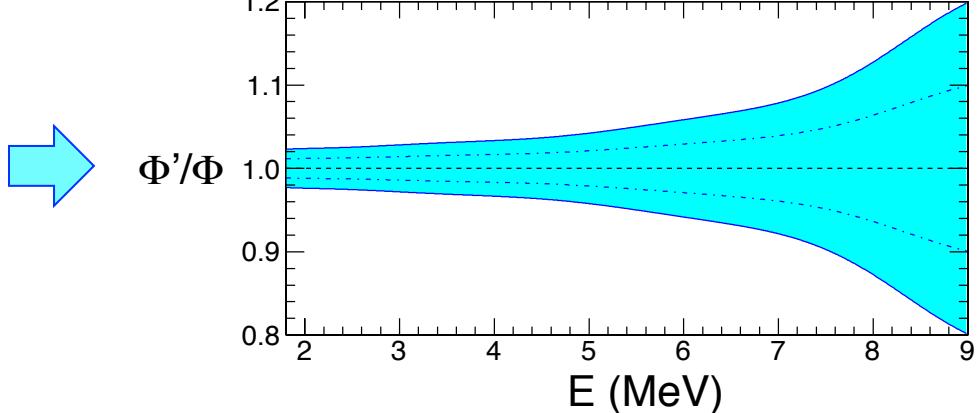
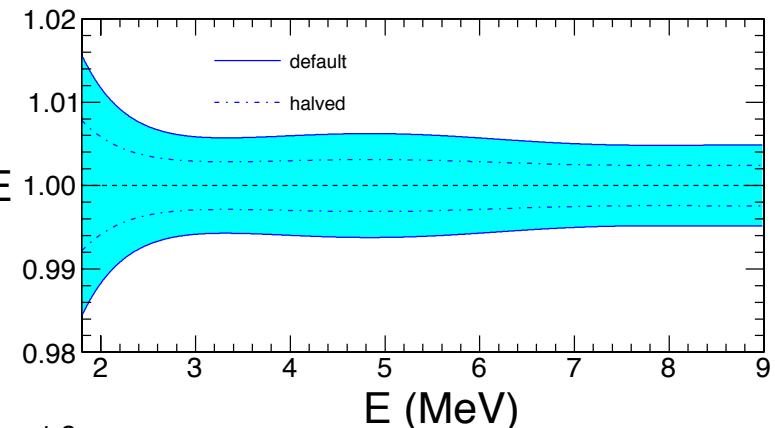
(y-axis “stretch”)

# Recent evaluations of energy-scale and flux-shape errors

## $E'(E)$ and $\Phi'(E)$ models



## Relative $1\sigma$ error bands



Now, allow smooth deviations

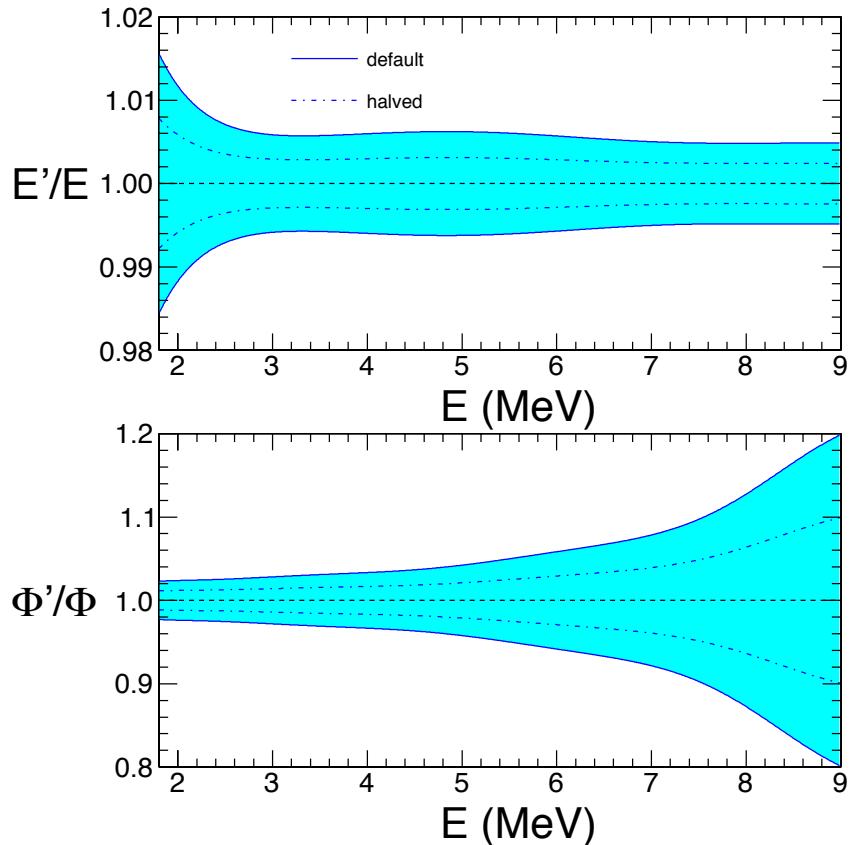
$E \rightarrow E'(E)$  and  $\Phi(E) \rightarrow \Phi'(E)$

within the above error bands.

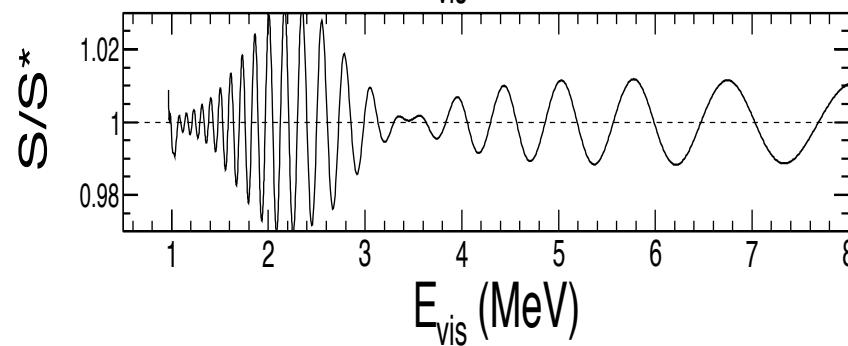
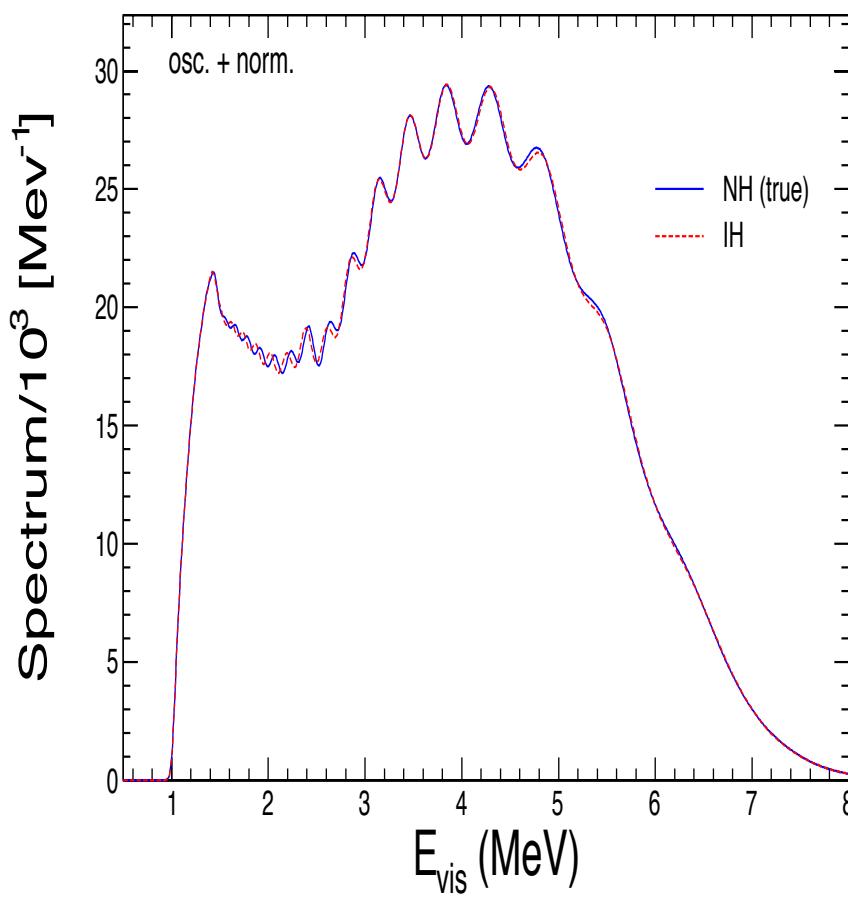
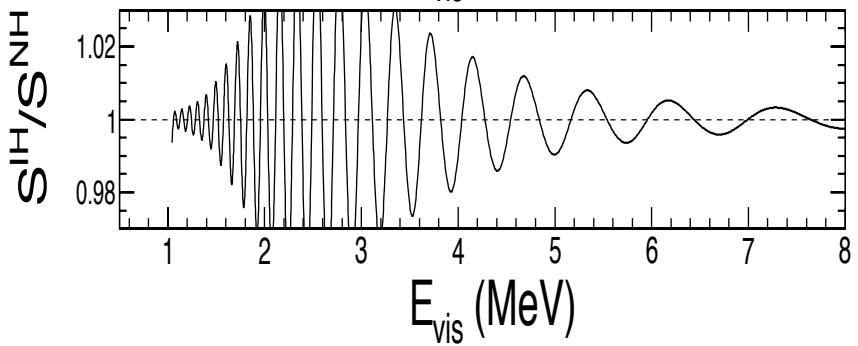
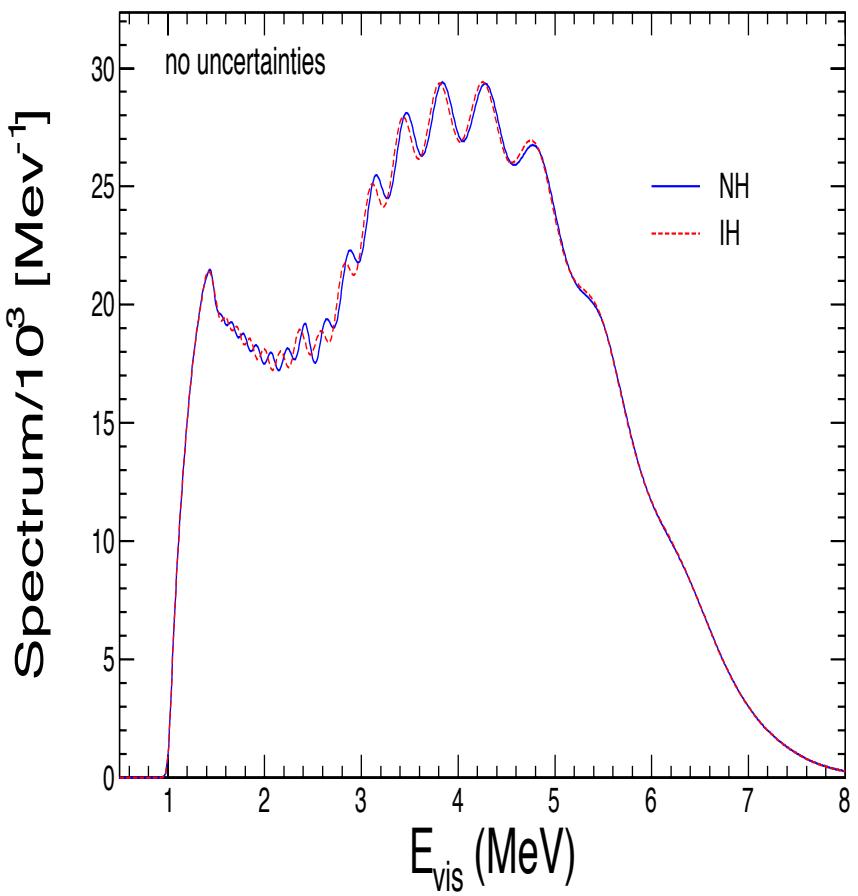
How will these uncertainties  
affect the hierarchy sensitivity  
in a medium-baseline reactor  
experiment such as JUNO?

[in addition to “usual” oscillation  
and normalization uncertainties]

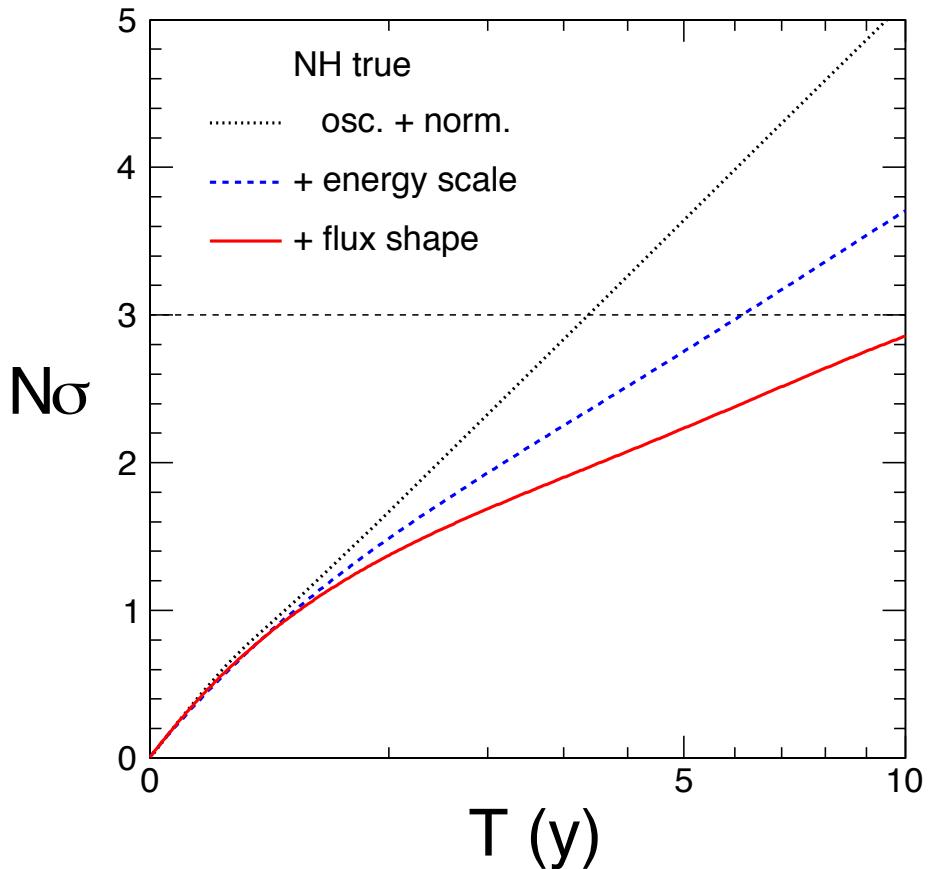
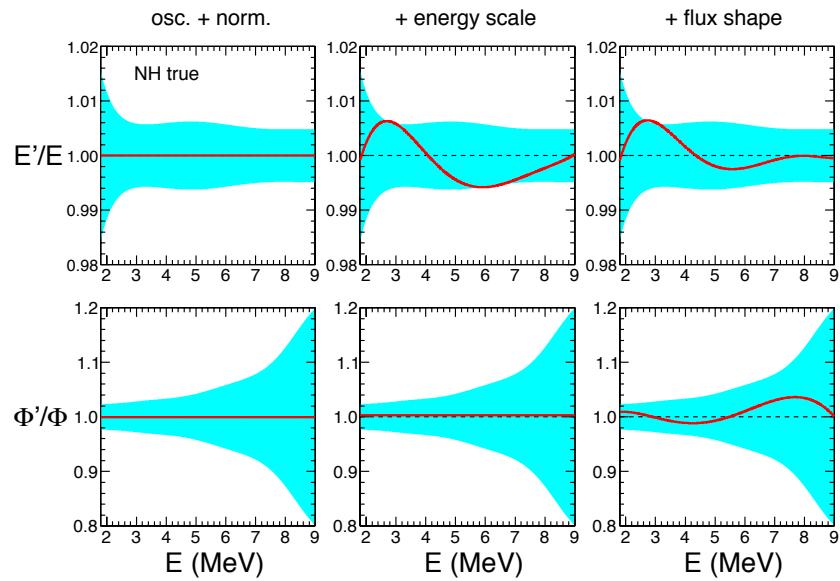
Relative  $1\sigma$  error bands



Details in hep-ph 1508.01391



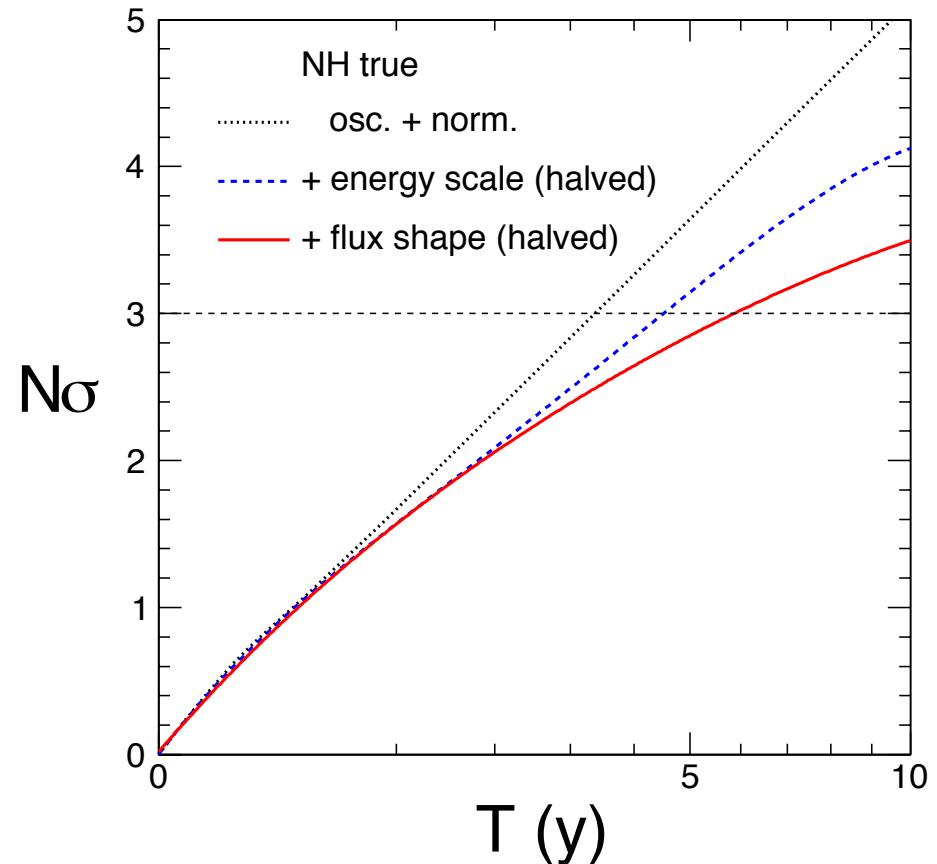
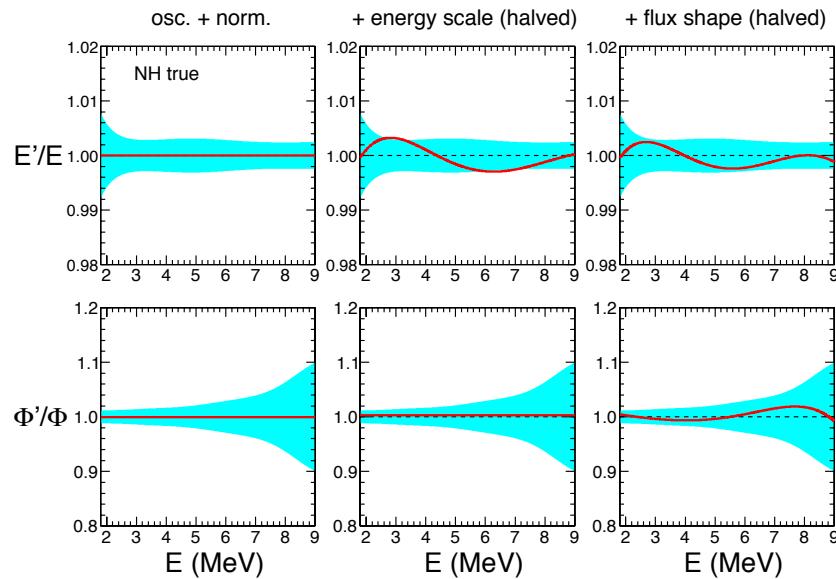
# Energy-scale and flux-shape errors with constrained “size” but unconstrained “shape” can bring the JUNO sensitivity below $3\sigma$



(Note abscissa prop. to  $\sqrt{T}$ )

Roughly need halving their size to bring JUNO above  $3\sigma$  in  $\sim 5$  years

[similar results for the case of true IH, see 1508.01391]

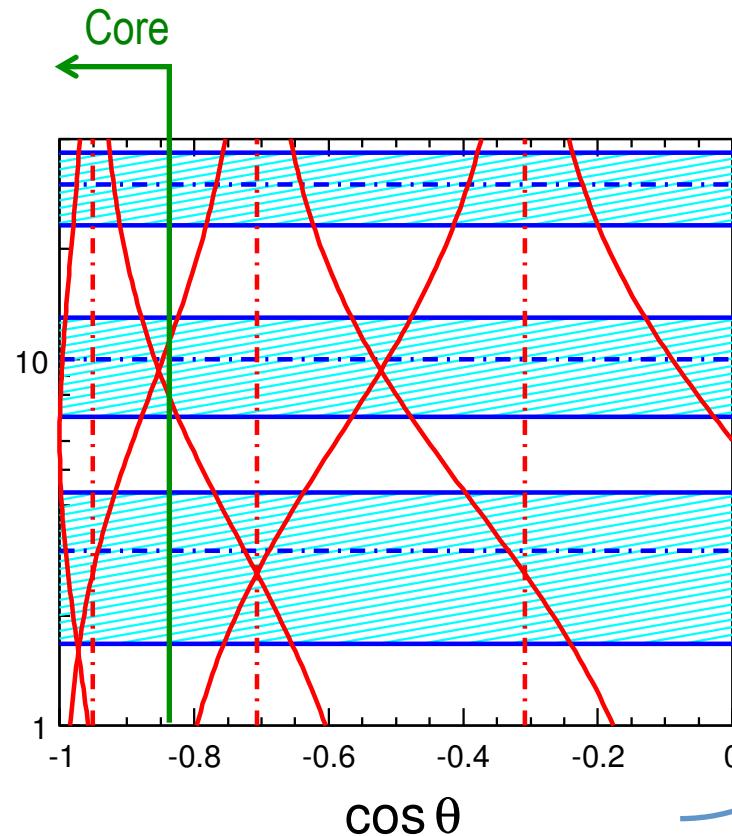
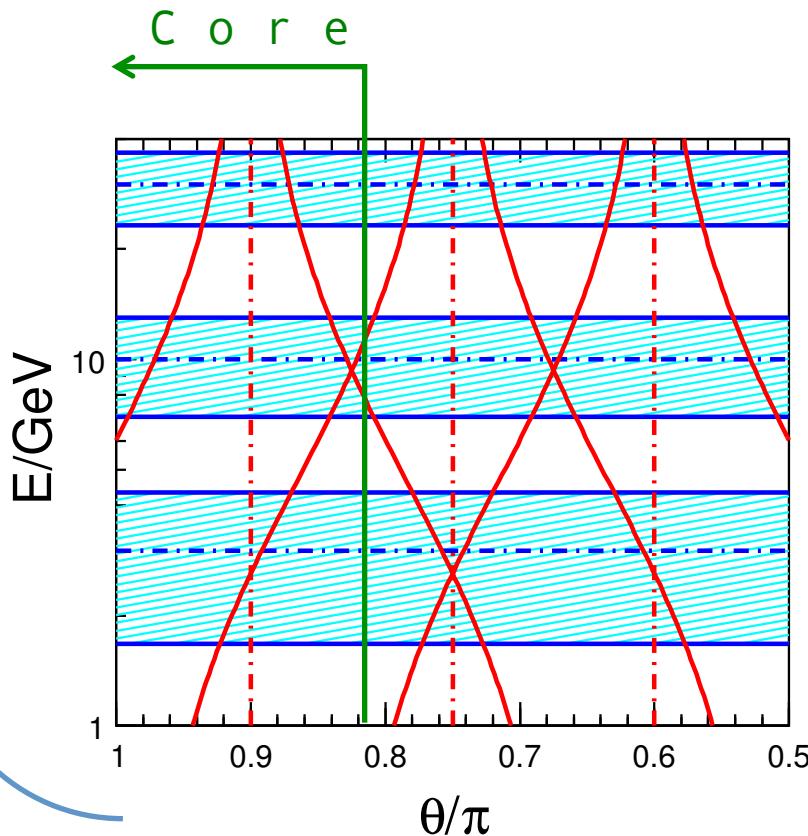


JUNO & RENO-50 involve a 1D spectrum. PINGU and ORCA provide a more challenging 2D spectrum, in terms of energy  $E$  and direction  $\theta \rightarrow$

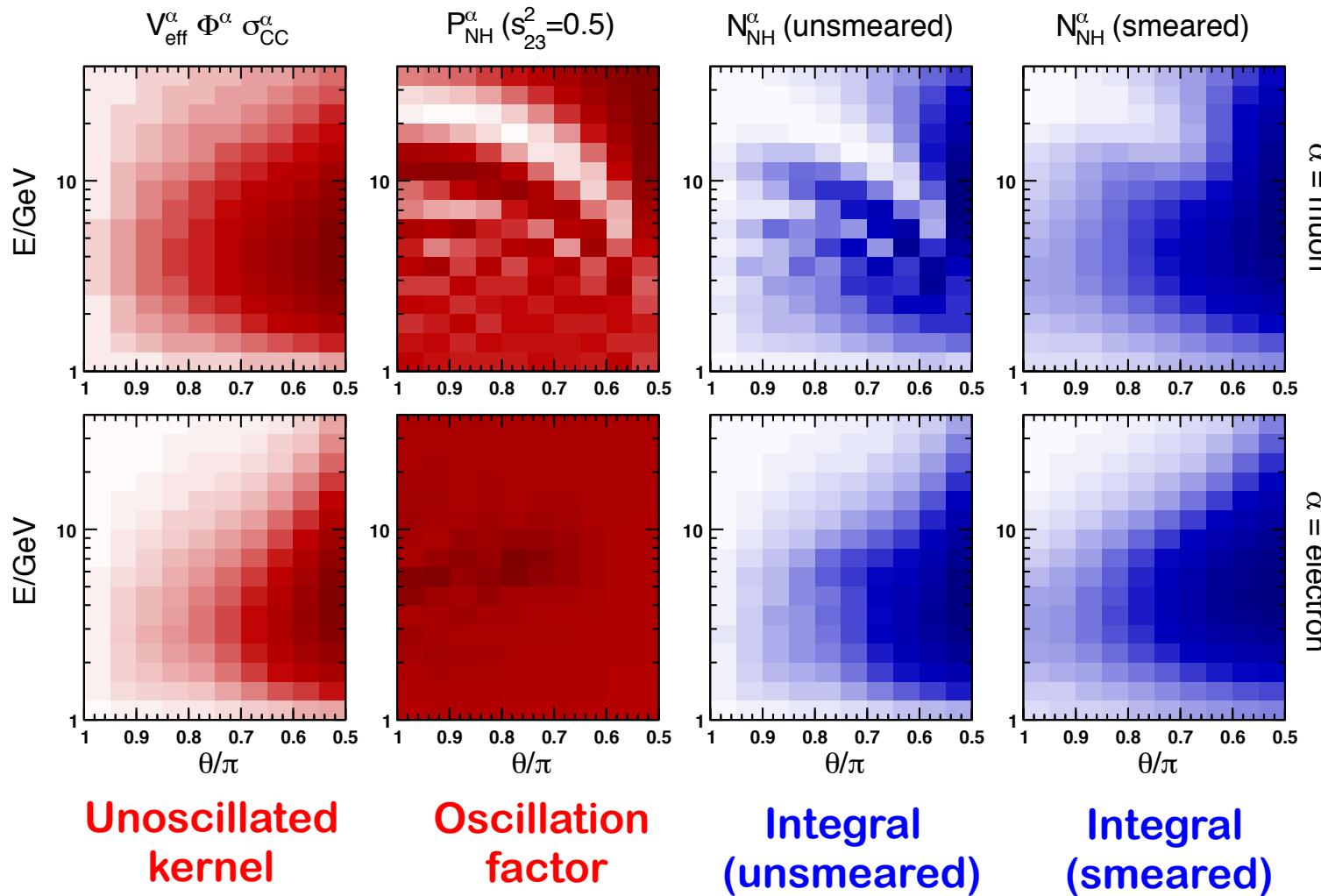
# Analysis of a PINGU-like experiment [1503.01999]: seeking the hierarchy via matter effects on atm. $\nu$

Note: we use  $(E, \theta)$ , not  $(E, \cos\theta)$ . Reasons:

- (1)  $\theta$  resolution width is asymmetric in  $\cos\theta$ ;
- (2)  $\cos\theta$  squeezes the interesting core region.



Observable (lepton) spectra come out from multiple integrations over unobservable (neutrino) kernels

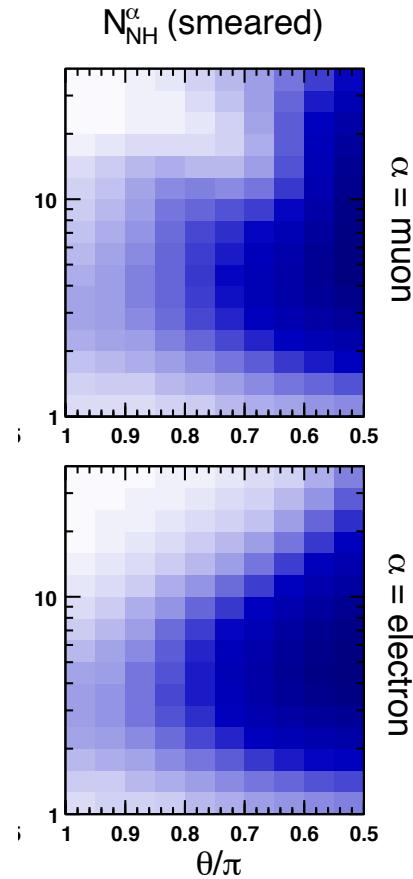


**This is what we can observe.**

**By eye, you would not notice  
any difference from NH to IH**

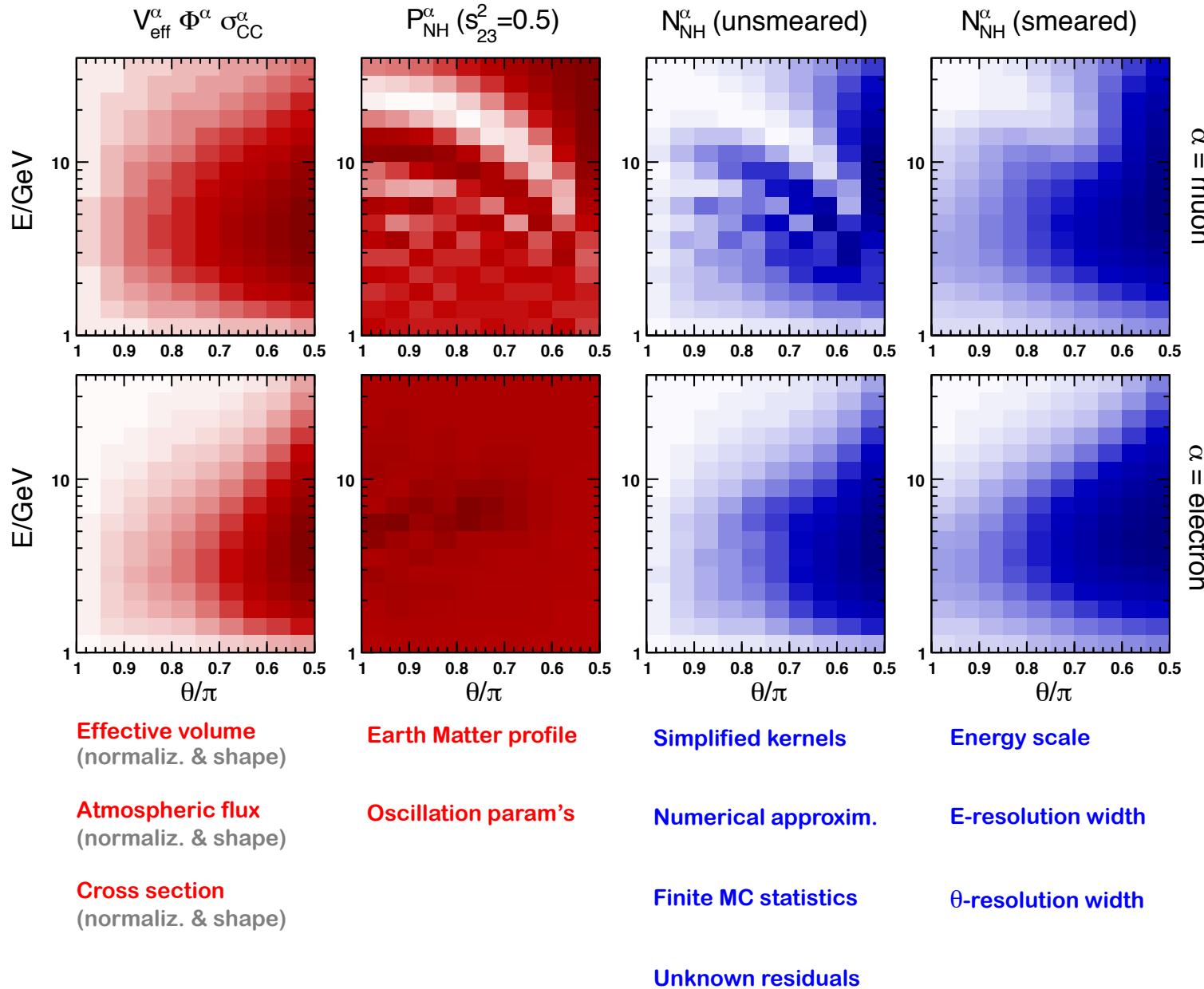
(typically, few % variations in each  
bin, smaller than color ladder step)

**Crucial to control systematic  
errors at (few) percent level.**

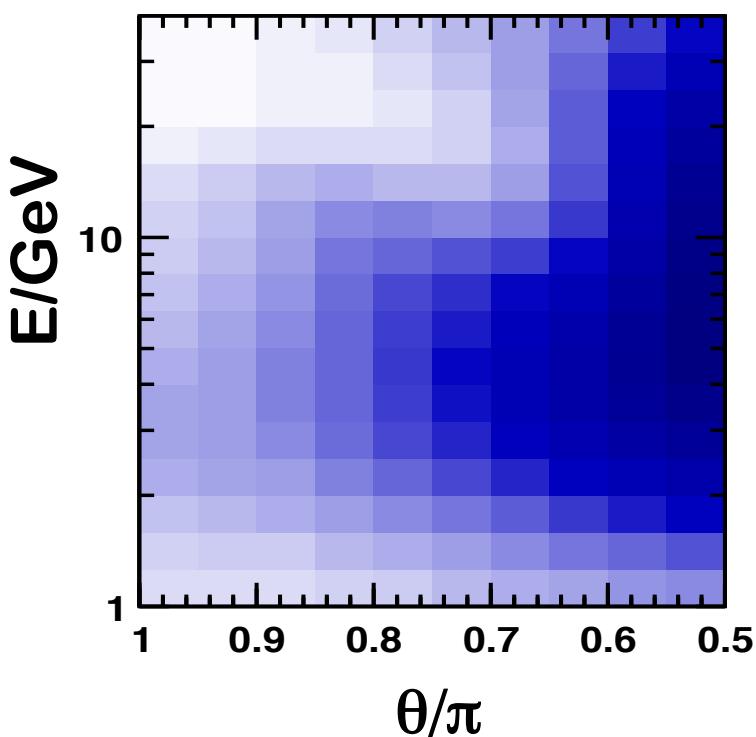


**Integral  
(smeared)**

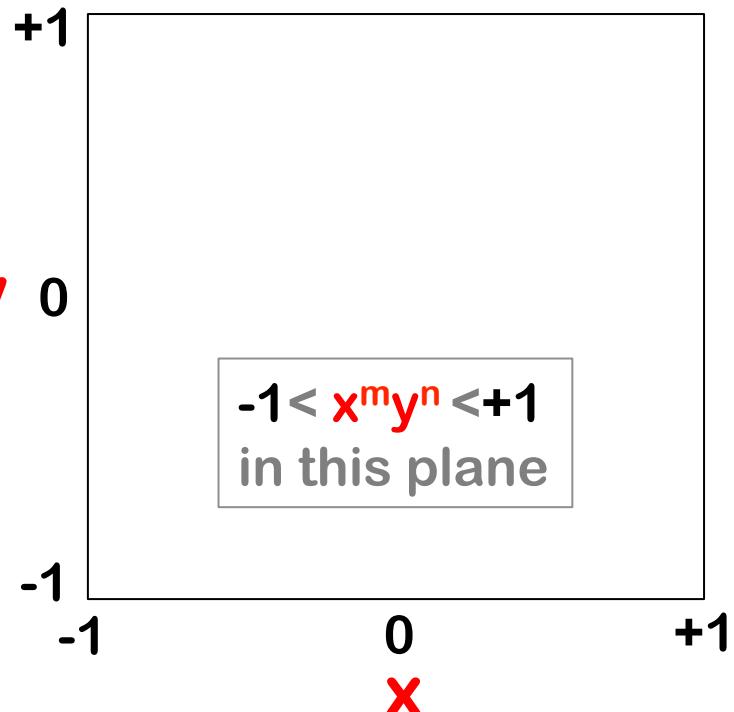
# Sources of systematic errors (list probably incomplete!)



$N_{\text{NH}}^{\alpha}$  (smeared)



change coordinates



Assume generic 2D polynomial deformations  $1 + \sum c_{nm} x^m y^n$

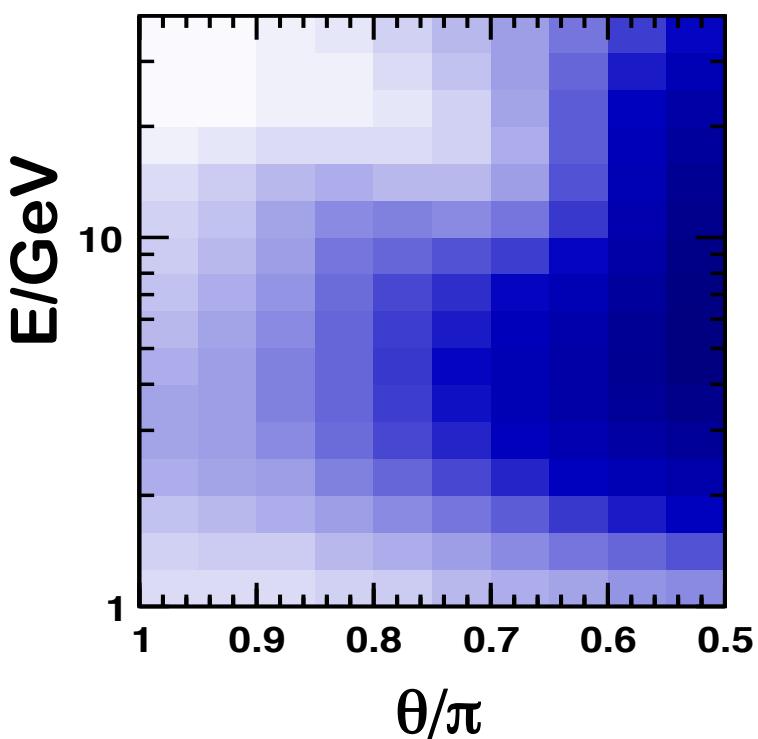
$n=0=m$ : recover normalization errors

$n+m=1$ : recover tilt error on  $x$  or  $y$

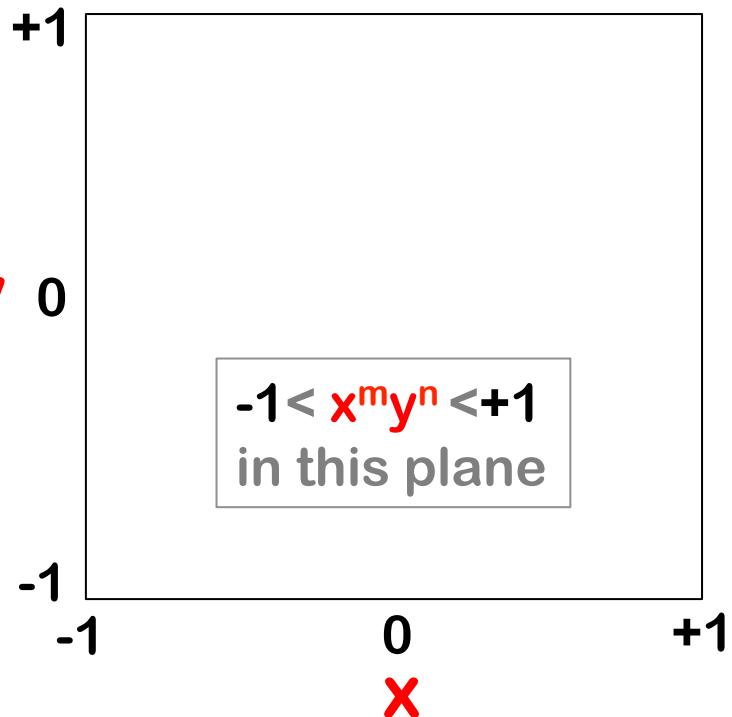
$n+m>1$ : nonlinear 2D shape errors (quadratic, cubic, quartic ...)

[Stopping at  $n+m=4$  is enough: we find stable results for  $n+m>4$ ]

$N_{\text{NH}}^{\alpha}$  (smeared)



change coordinates



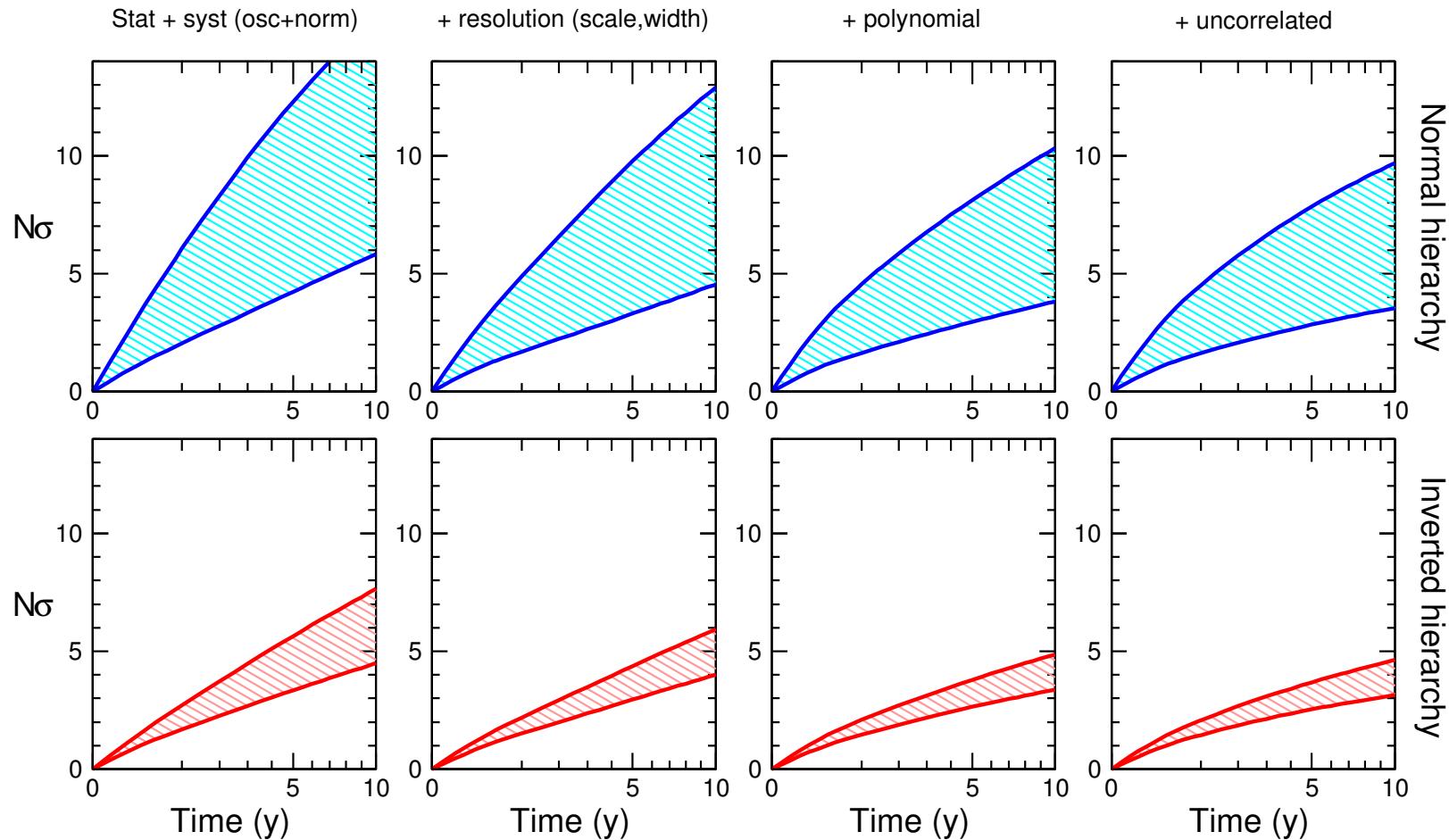
Add quadratic penalties in  $\chi^2$ , corresponding to  $\sigma(c_{nm}) = p\%$

Then, at  $1\sigma$ , each polynomial term is bounded by  $|c_{nm} x^m y^n| < p\%$

3 cases studied:  $p=1.5$  (default),  $p=3.0$  (doubled),  $p=0.75$  (halved)

Finally, we also add uncorrelated syst. errors at the same  $p\%$  level

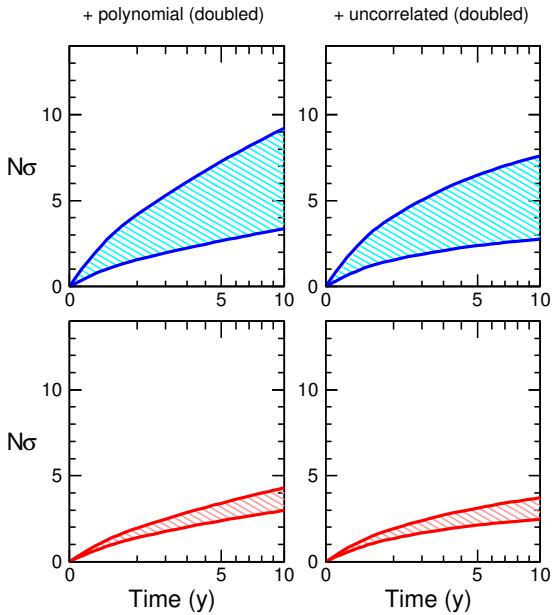
## Results for default case: nonnegligible reduction of sensitivity



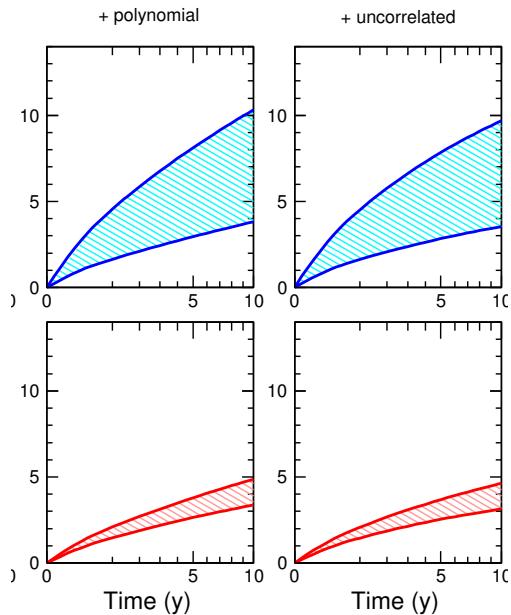
Bands correspond to  $\sin^2\theta_{23}$  spanning the range [0.4, 0.6]  
Note abscissa scaling as  $\text{sqrt}(T)$

[Details in 1503.01999]

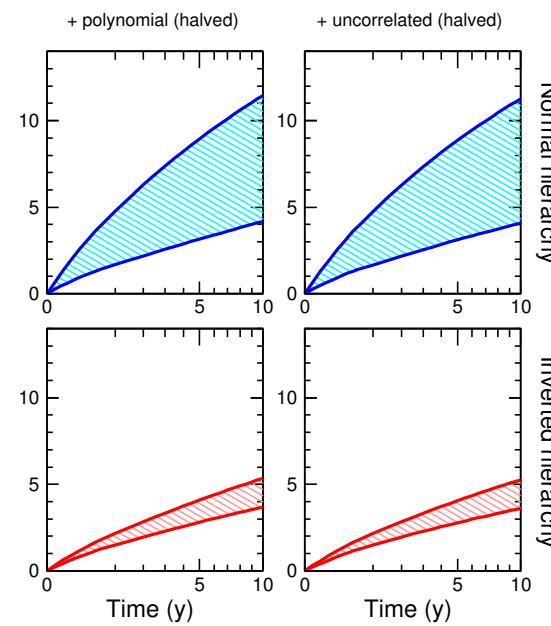
**doubled (3%)**



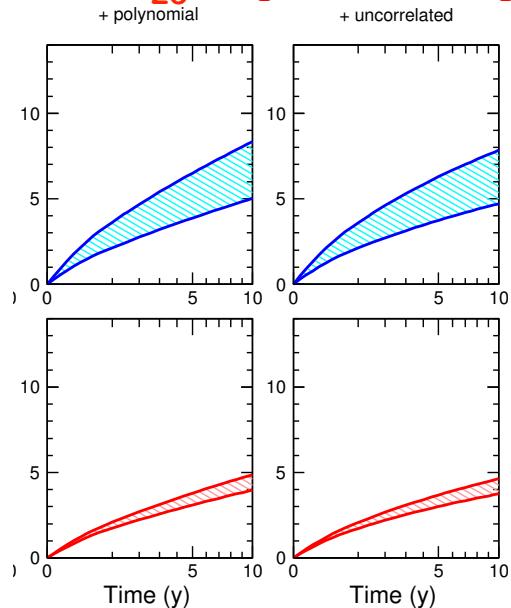
**default (1.5%)**



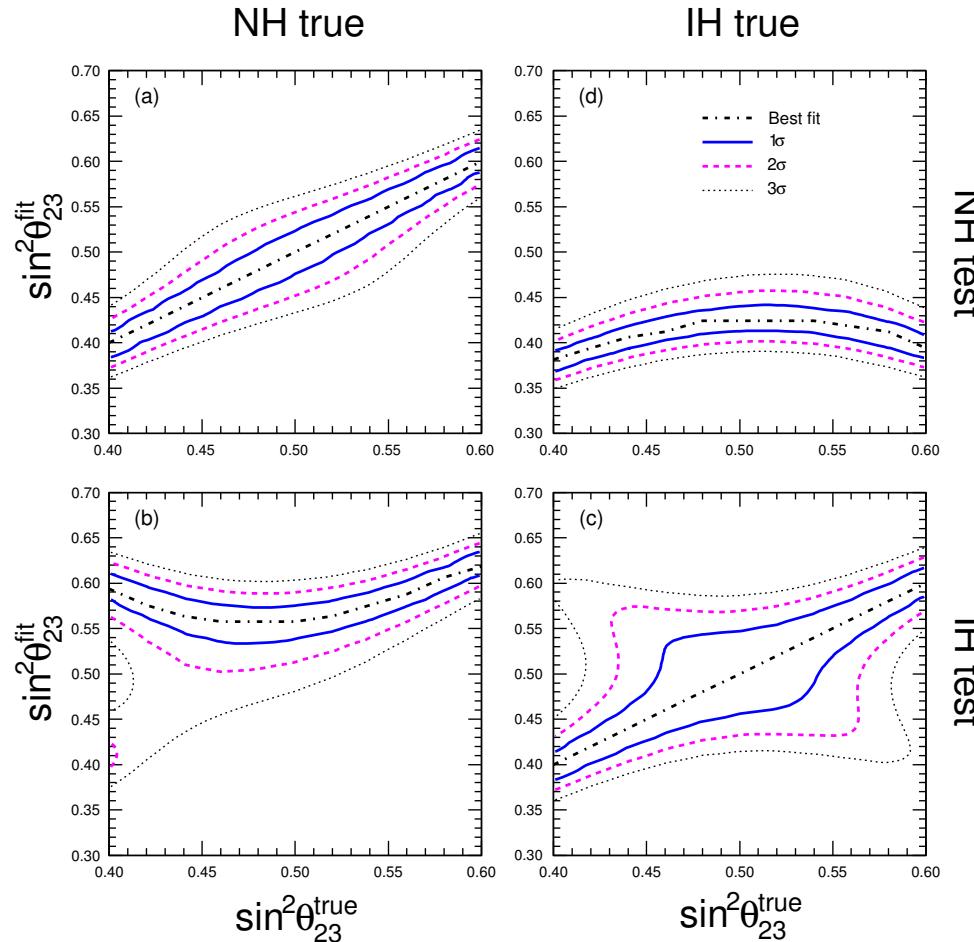
**halved (0.75%)**



**$\sin^2\theta_{23}$  in [0.45, 0.55]**

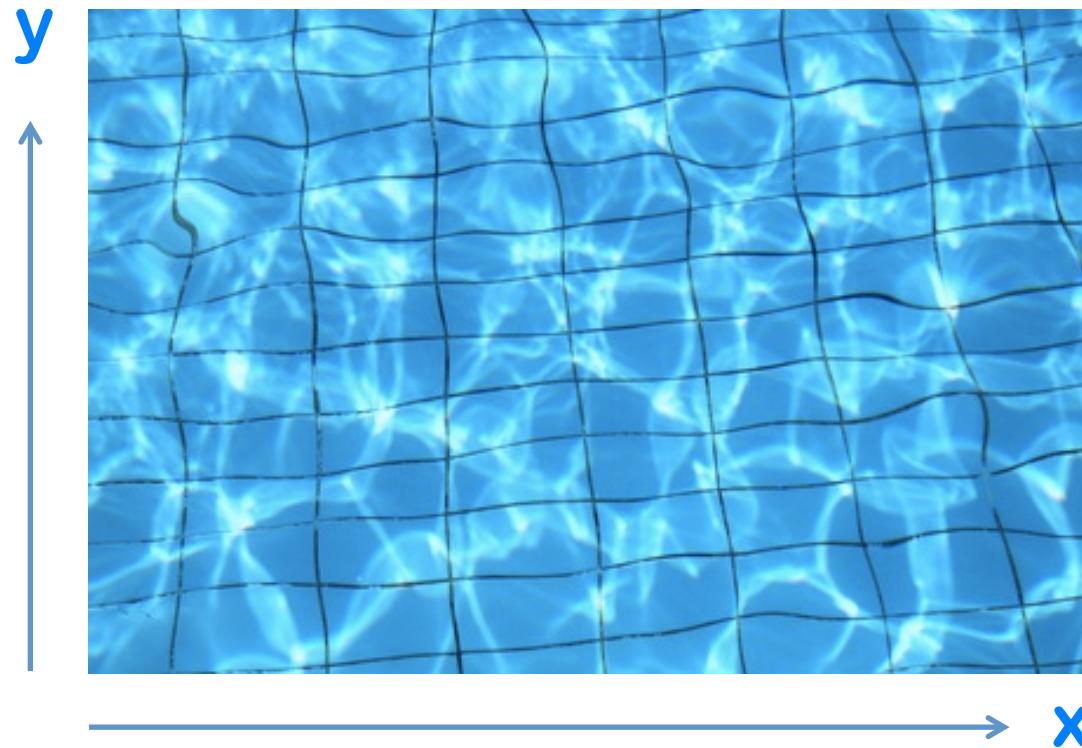


PINGU itself can better constrain  $\theta_{23}$ , but with **strong bias** if hierarchy is unknown (so  $\theta_{23}$  and hierarchy must be determined at the same time)



Note: Most of the previous comments apply also to ORCA (and HK, INO, ...)

**Message: nonlinear deformations of 1D and 2D spectra will be relevant in future high-statistics oscillation experiments.**



**Must find ways to break down, estimate and include them, allowing extra room for poorly known effects. Challenging!**

# More Terra Incognita... (absolute mass observables)

( $m_\beta$ ,  $m_{\beta\beta}$ ,  $\Sigma$ )

In the 3ν framework:

$\beta$  decay, sensitive to the “effective electron neutrino mass”:

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

Ov $\beta\beta$  decay: only if Majorana. “Effective Majorana mass”:

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

Cosmology: Dominantly sensitive to sum of neutrino masses:

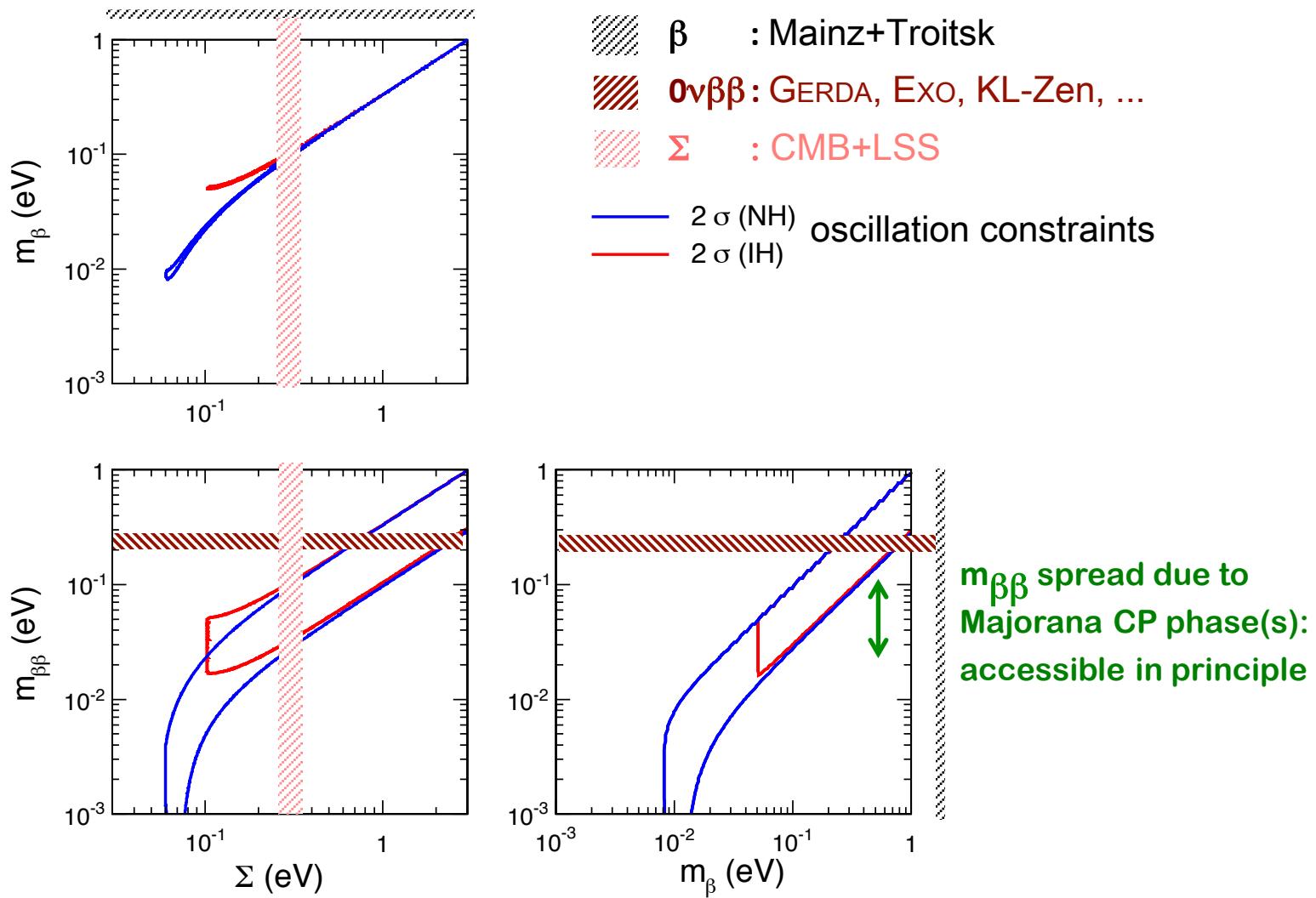
$$\Sigma = m_1 + m_2 + m_3$$

Note 1: These observables may provide handles to distinguish NH/IH.

Note 2: Majorana case gives a new source of CPV (unconstrained)

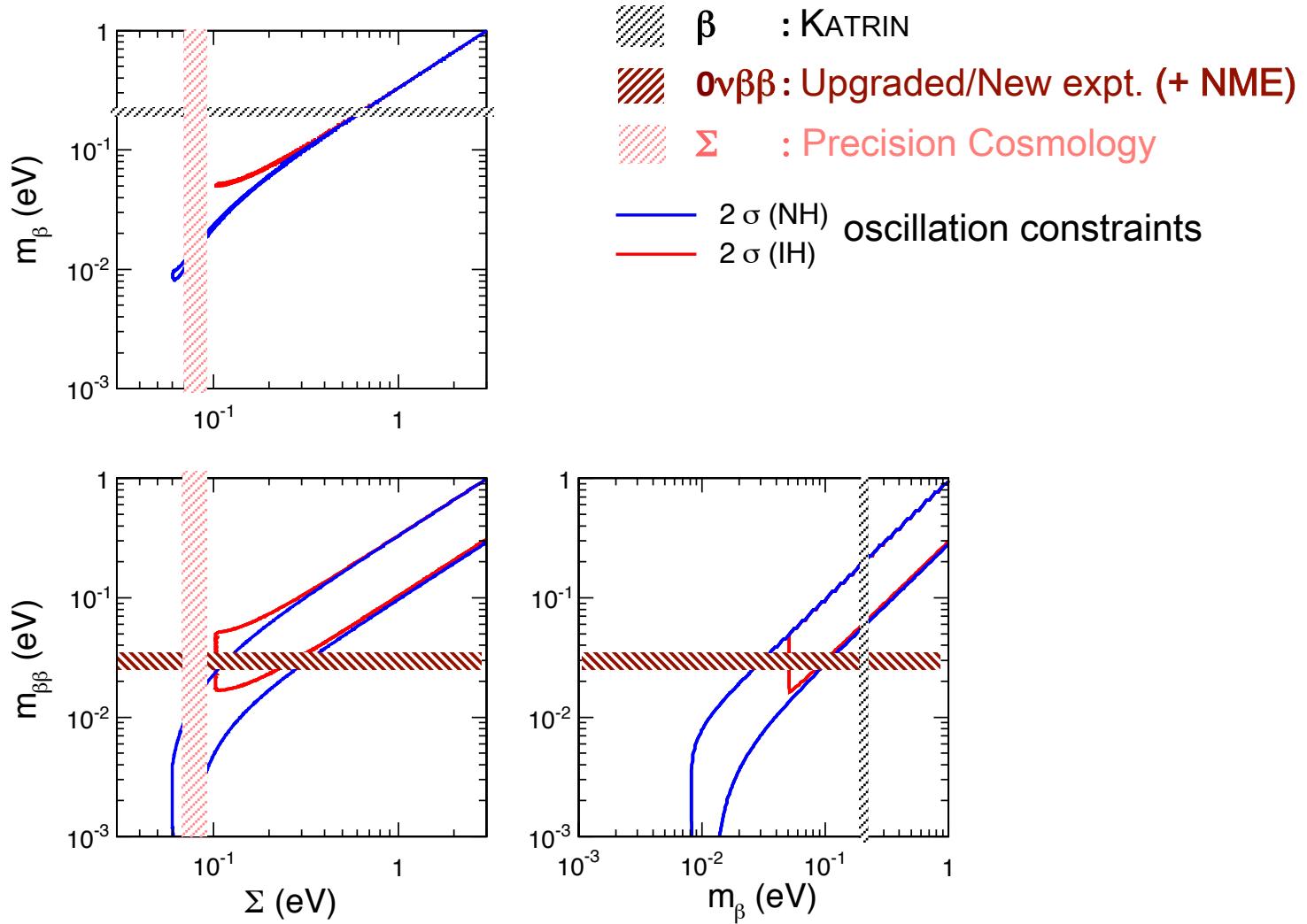
Note 2: The three observables are correlated by oscillation data →

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



[Clearly, the inverted hierarchy case would make life easier...]

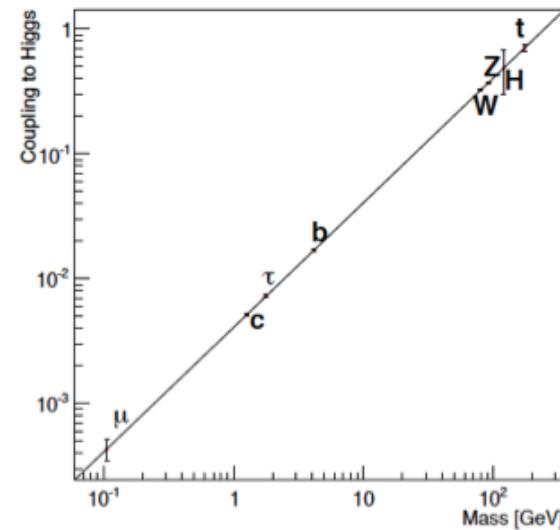
# Upper limits on $m_\beta$ , $m_{\beta\beta}$ , $\Sigma$ in ~10 years ?



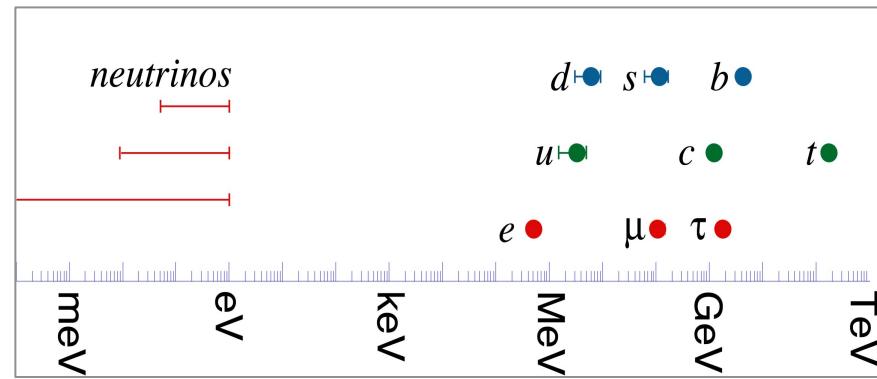
Large phase space for discoveries about  $\nu$  mass and nature,  
also beyond the standard 3-neutrino framework!

Think big! Linking two fundamental research lines:

## 1. Test Higgs sector

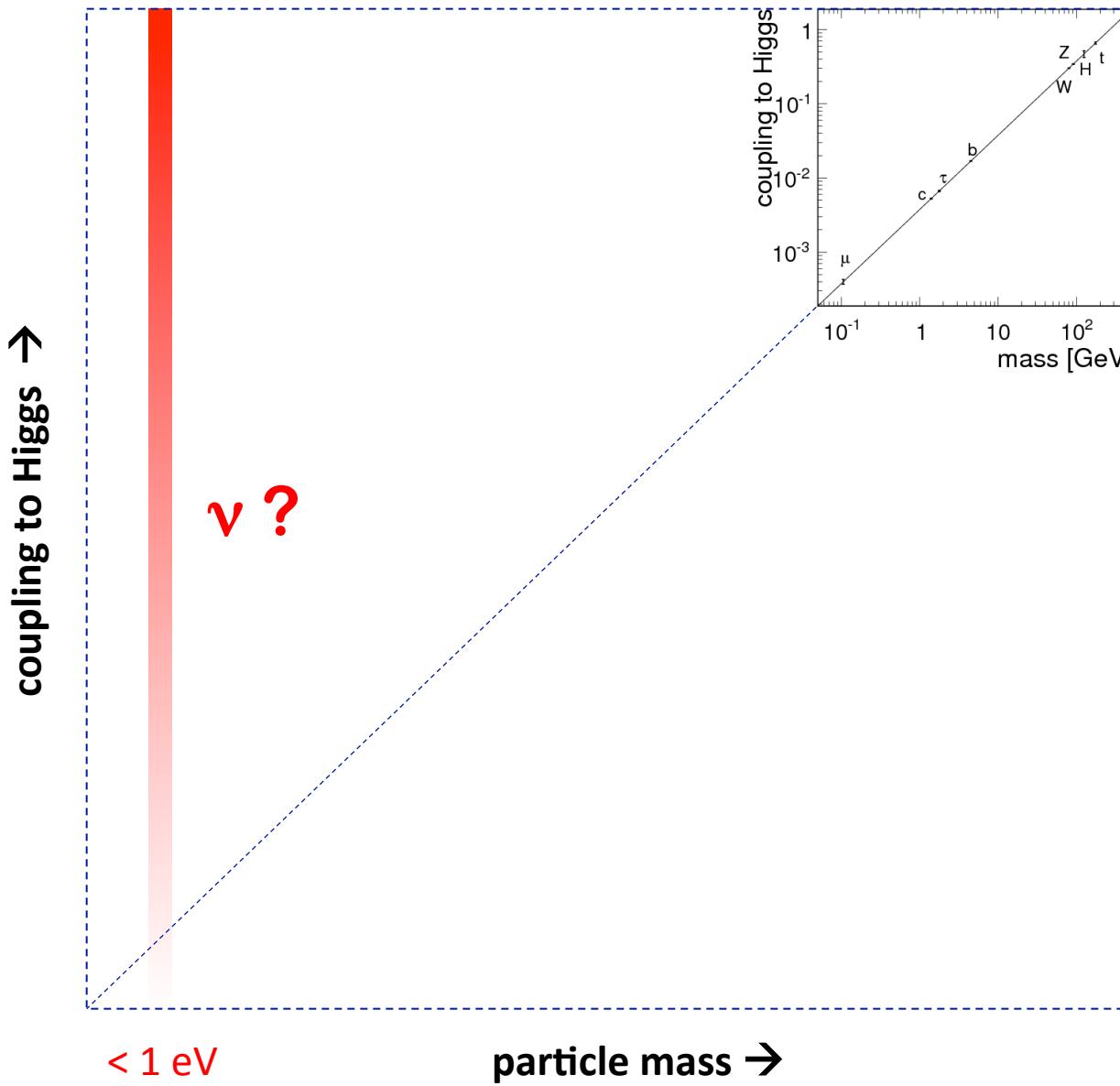


## 2. Find $\nu$ masses



**1 + 2**

Where are the  $\nu$ 's on this plot? Why are they so light?



# Options:

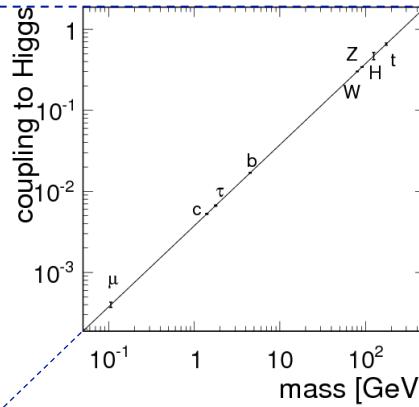
coupling to Higgs →

$\nu$

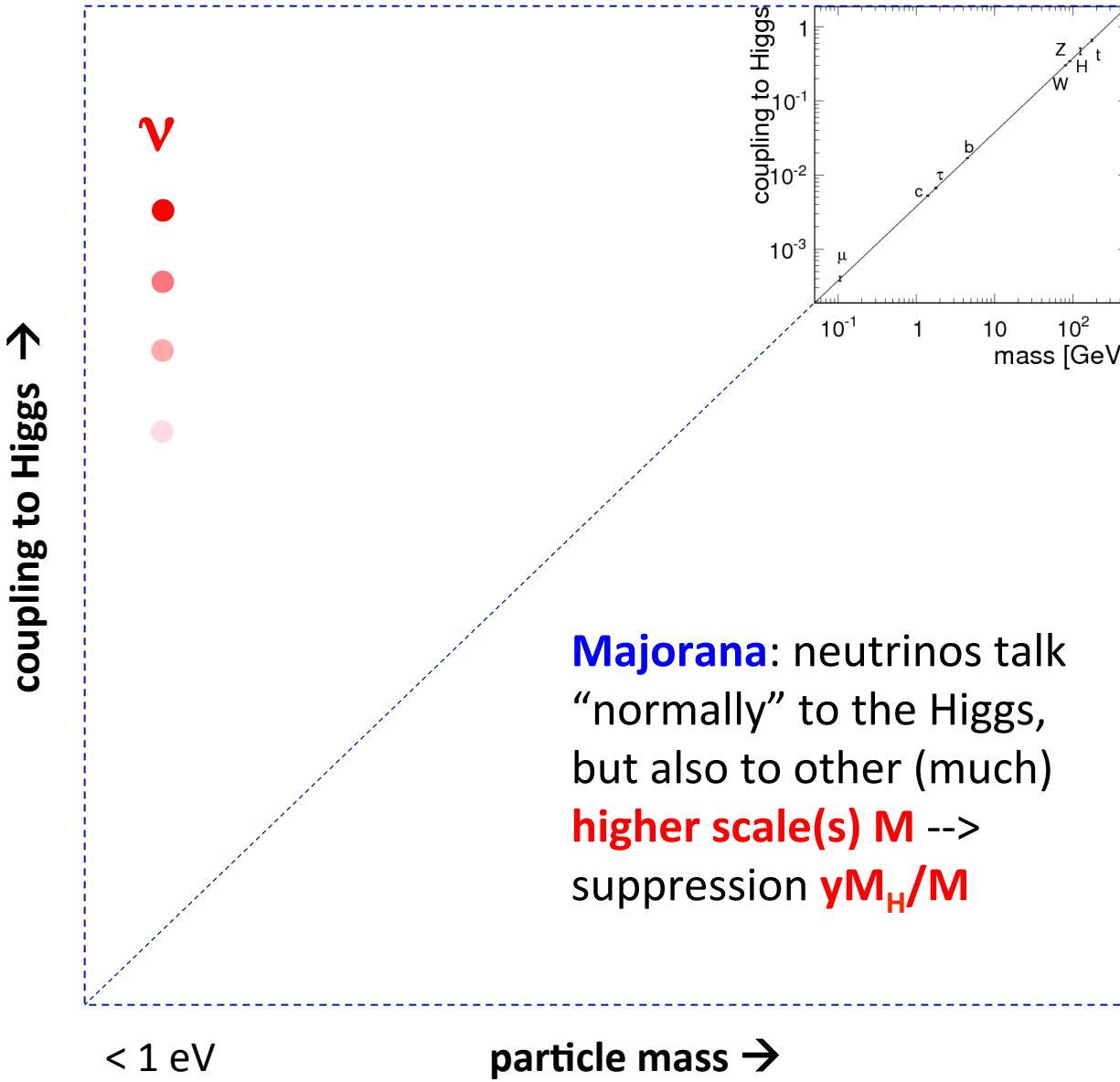
< 1 eV

particle mass →

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



# Options:



**Neutrinos masses** may offer  
a great opportunity to jump  
**beyond the EW framework**  
via see-saw ...

M  
•  
•  
•  
•



... and to address fundamental physics issues, such as:

- new sources of CP violation at low and high energies
- lepton number violation and associated phenomena
- matter-antimatter asymmetry of the universe ...

CP-violating decays of heavy neutrinos at scale  
 $M$  may generate lepton asymmetry (leptogenesis):  
Discovery of leptonic CP violation and of Majorana nature (+ proton decay?) would be important steps towards this scenario.

- 
- 
- 
-

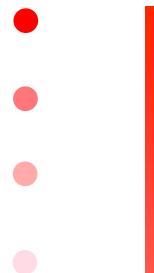
CP-violating decays of heavy neutrinos at scale  $M$  may generate lepton asymmetry (leptogenesis).  
Discovery of leptonic CP violation and of Majorana nature (+ proton decay?) would be important steps towards this scenario.



**$M \sim \text{low scale}$**

At the other end of the spectrum, low-scale (e.g. EW) see-saw may also generate (at the price of fine-tuning) additional interesting phenomenology: dark matter candidates, di-lepton and heavy lepton events in HEP

CP-violating decays of heavy neutrinos at scale  
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**Discovery of leptonic CP violation and of Majorana nature (+ proton decay?) would be important steps towards this scenario.**



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In principle, several sterile states might even be split among different (light?) energy scales, and contribute to various phenomena in (astro)particle physics.

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In principle, several sterile states might even be split  
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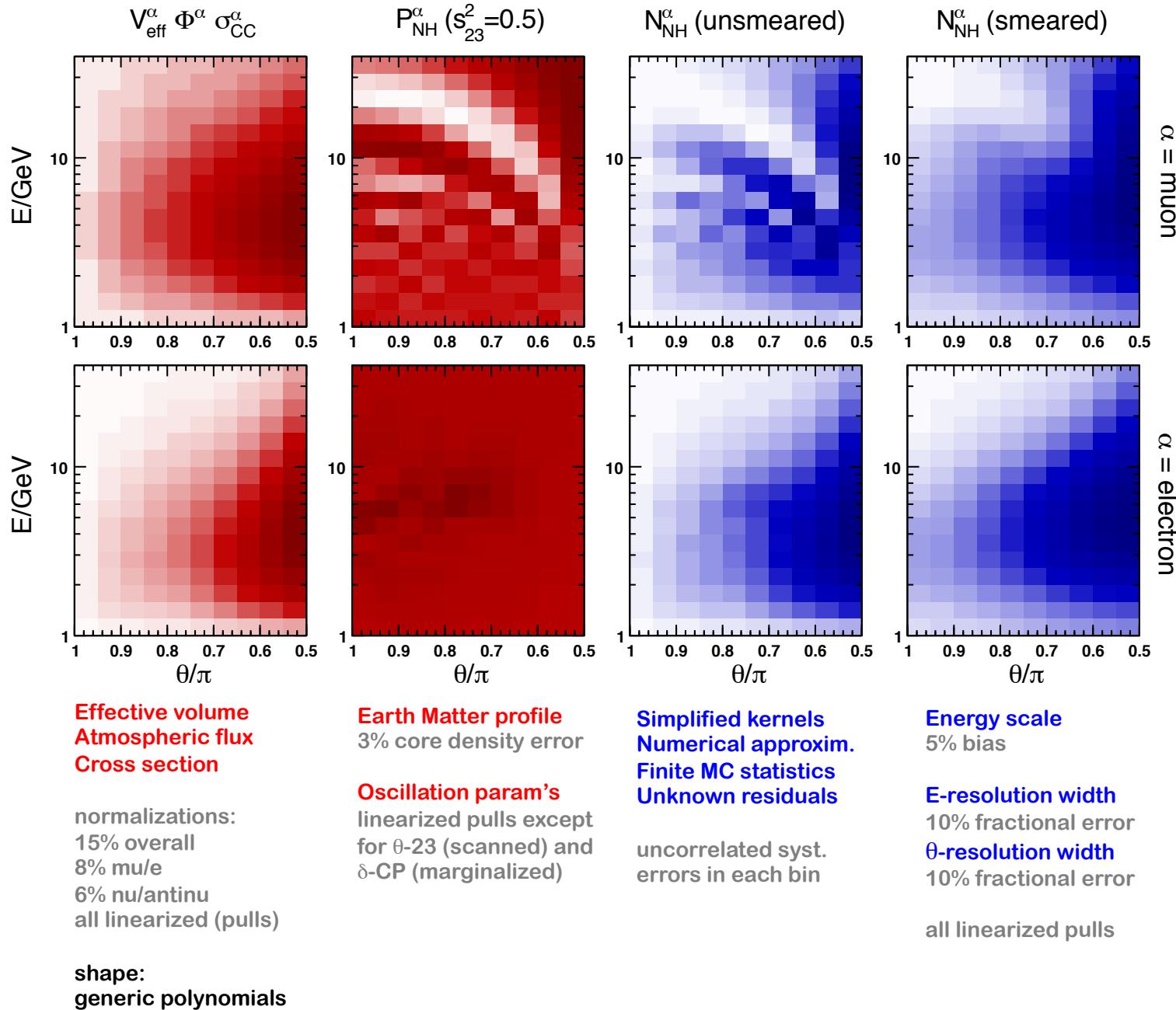
½ of the ultimate  $\nu$  answers are still out there, waiting  
for more Xmas Workshops and... Nobel prizes!

A large, glowing golden pyramid structure with a globe at the top and a Nobel Prize medal in the foreground.

Thank you for  
your attention!

# Extra slides

# Our implementation of systematic errors



## Comments

(1) oscillation + normalization errors: most obvious and known sources.  
Must scan in  $\theta_{23}$  and  $\delta$ -CP

(2) resolution errors: less obvious but quite relevant

(3) shape errors: poorly known at present (at South Pole)

(4) uncorrelated systematics: mostly unknown “by definition”

### (1) oscillation + normalization errors

Effective volume  
Atmospheric flux  
Cross section

normalizations:  
15% overall  
8% mu/e  
6% nu/antine  
all linearized (pulls)

Earth Matter profile  
3% core density

Oscillation param's  
all linearized (pulls)  
but  $\theta_{23}$  and  $\delta$ -CP

### (4) uncorr. syst.

Simplified kernels  
Numerical approxim.  
Finite MC statistics  
Unknown residuals  
  
uncorrelated syst.  
errors in each bin

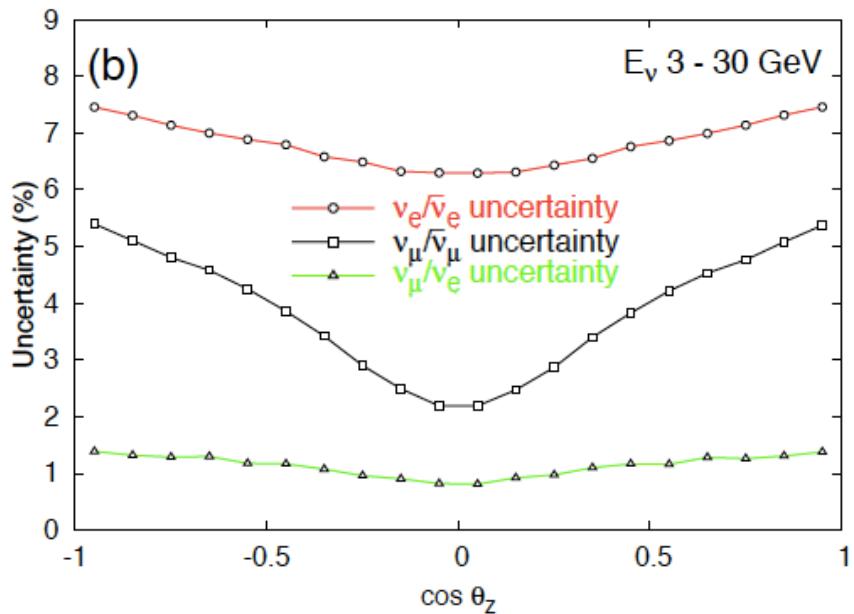
### (2) resolution err.

Energy scale  
5% bias  
  
E-resolution width  
10% fractional error  
θ-resolution width  
10% fractional error  
  
all linearized (pulls)

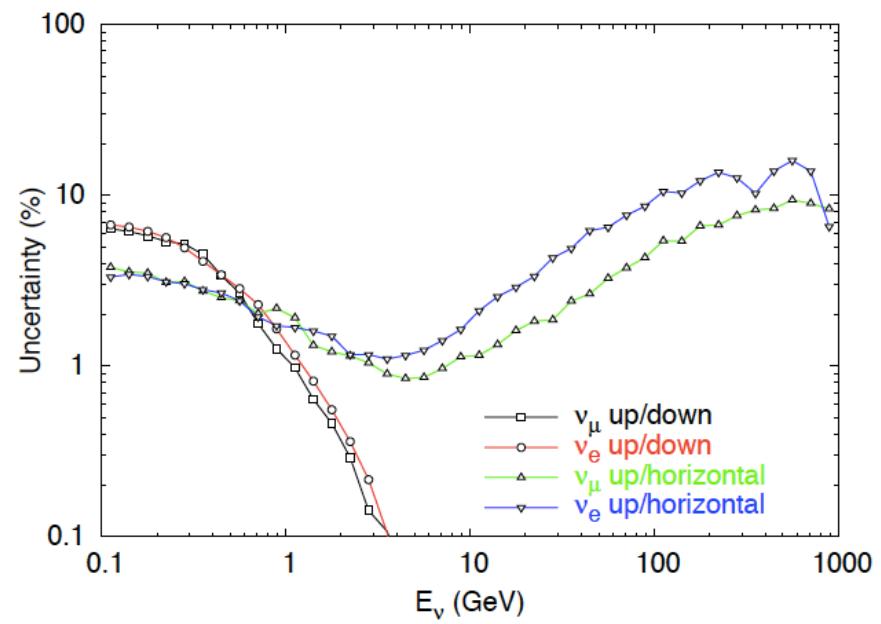
shape:  
generic polynomials

### (3) 2D spectrum shape errors

relative errors depend on direction at given energy...



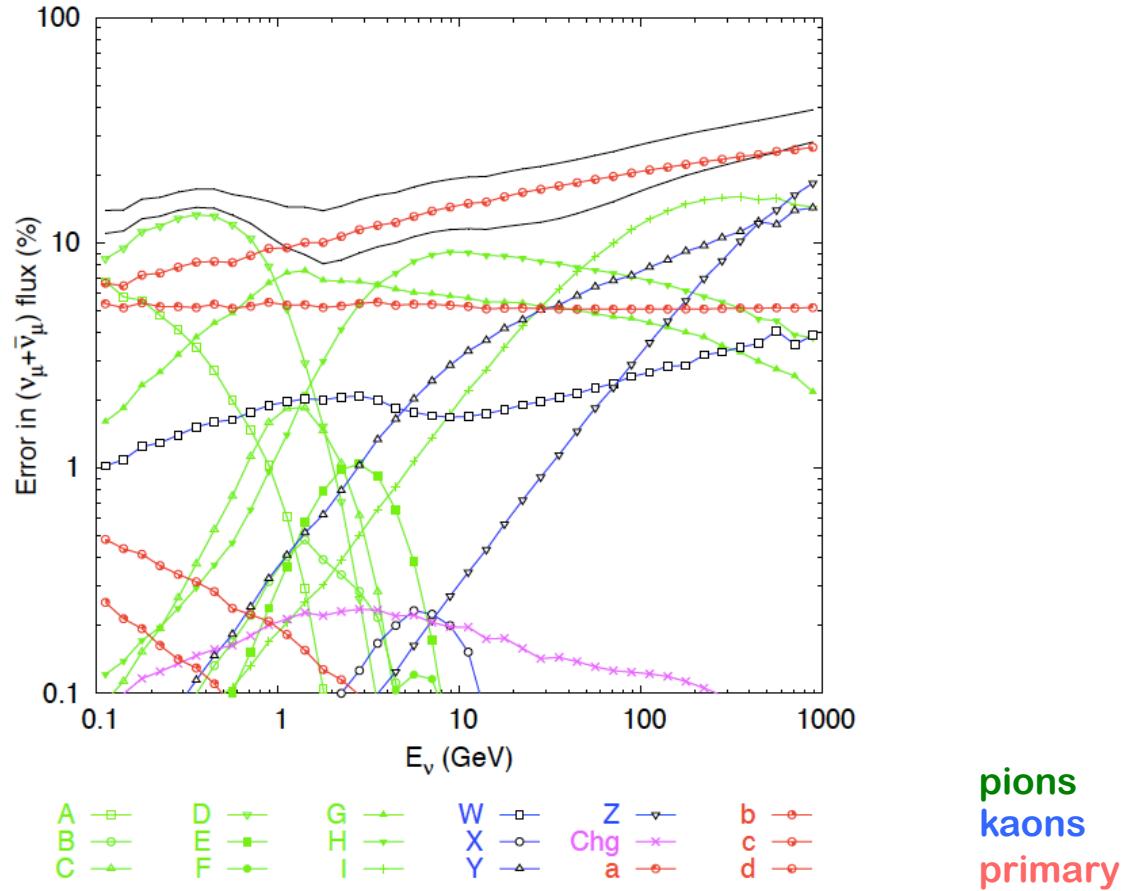
and on energy for given directions...



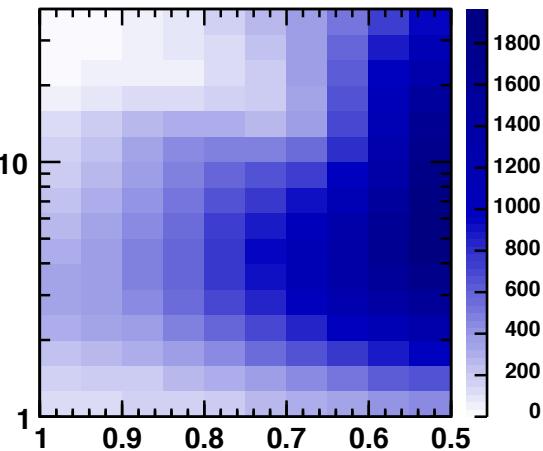
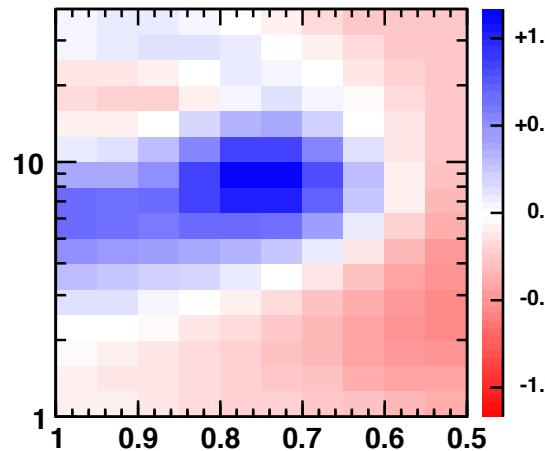
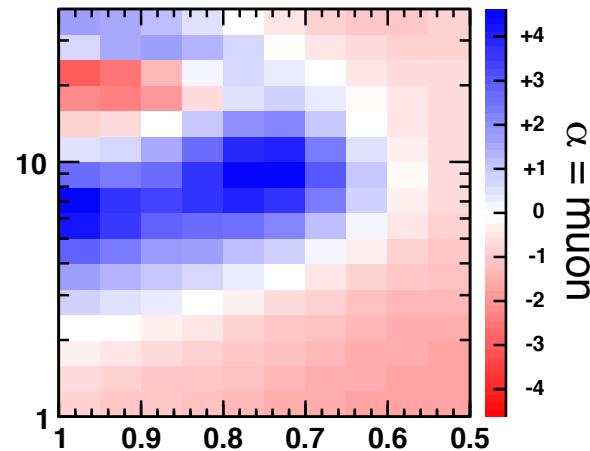
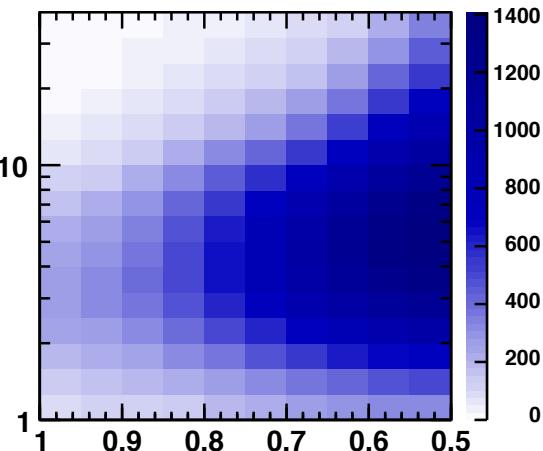
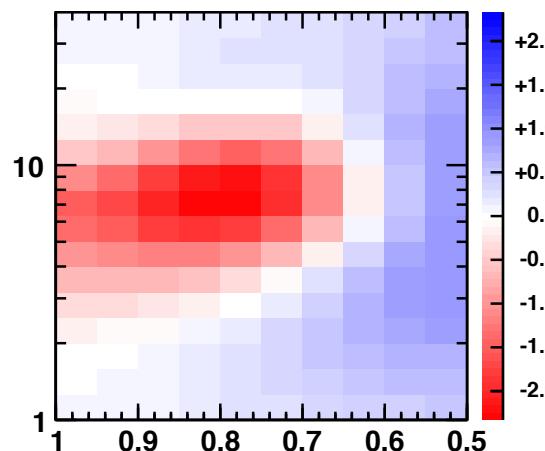
In general, 2D dependence cannot be factorized

Note typical size from O(1) to O(10) percent

## Breakdown to individual error sources (26 in Barr et al.)



Treating each source as a ``pull'' function with penalties in a  $\chi^2$  approach, the overall 2D flux spectrum would be rather “flexible” at the few % level  
**Not captured by a handful of normalization or tilt uncertainties!**

$N_{\text{NH}}^{\alpha} (s_{23}^2 = 0.6)$  $E/\text{GeV}$  $(N_{\text{IH}}^{\alpha} - N_{\text{NH}}^{\alpha}) / \sqrt{N_{\text{NH}}^{\alpha}}$  $100 \times (N_{\text{IH}}^{\alpha} - N_{\text{NH}}^{\alpha}) / N_{\text{NH}}^{\alpha}$  $E/\text{GeV}$  $\theta/\pi$  $\theta/\pi$  $\alpha = \text{muon}$  $\alpha = \text{electron}$

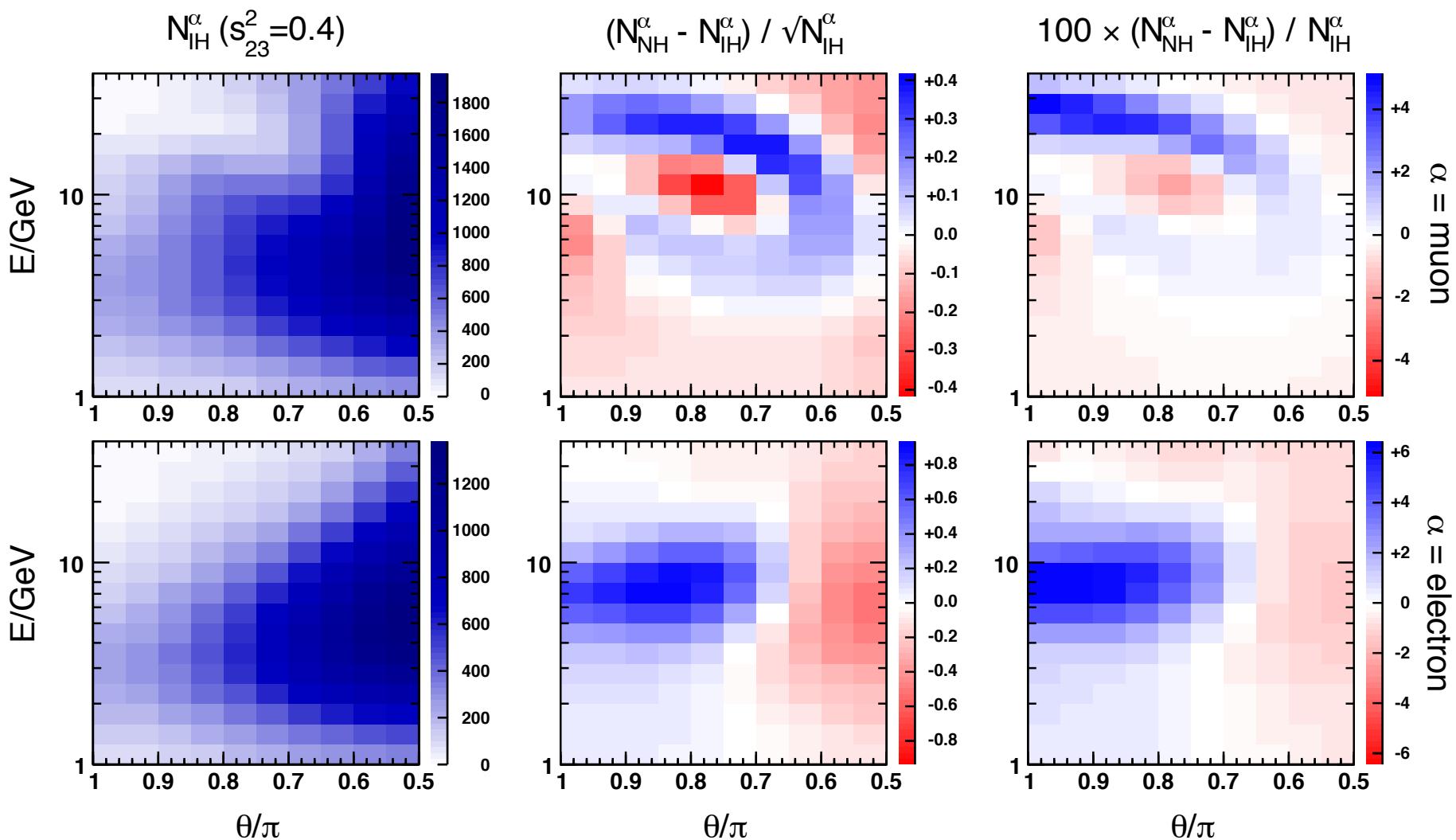


TABLE I: Reduction of the PINGU sensitivity to the hierarchy (expressed in terms of  $N_\sigma$  range for  $\sin^2 \theta_{23} \in [0.4, 0.6]$ ) due to the progressive inclusion of various shape systematics, for 5 and 10 years of exposure. Correlated polynomial and uncorrelated systematic uncertainties are taken at the default level of 1.5%. See the text for details.

Errors included in the fit	5-year sensitivity $N_\sigma$		10-year sensitivity $N_\sigma$	
	True NH	True IH	True NH	True IH
Stat. + syst (osc.+norm.)	4.23–12.3	3.34–5.64	5.82–16.1	4.49–7.64
+ resolution (scale, width)	3.31–9.76	2.95–4.37	4.54–12.9	4.00–5.94
+ polynomial (linear)	3.14–9.17	2.86–4.16	4.23–11.9	3.81–5.49
+ polynomial (quadratic)	3.01–8.29	2.69–3.88	3.93–10.6	3.47–5.05
+ polynomial (cubic)	2.98–8.26	2.67–3.84	3.87–10.5	3.42–4.94
+ polynomial (quartic)	2.95–8.12	2.64–3.79	3.82–10.3	3.37–4.87
+ uncorrelated systematics	2.84–7.84	2.54–3.68	3.55–9.69	3.14–4.63
Total $N_\sigma$ reduction from 1st row	33–36%	24–35%	39–40%	30–39%

# Pontecorvo-Maki-Nakagawa-Sakata (PMNS) matrix

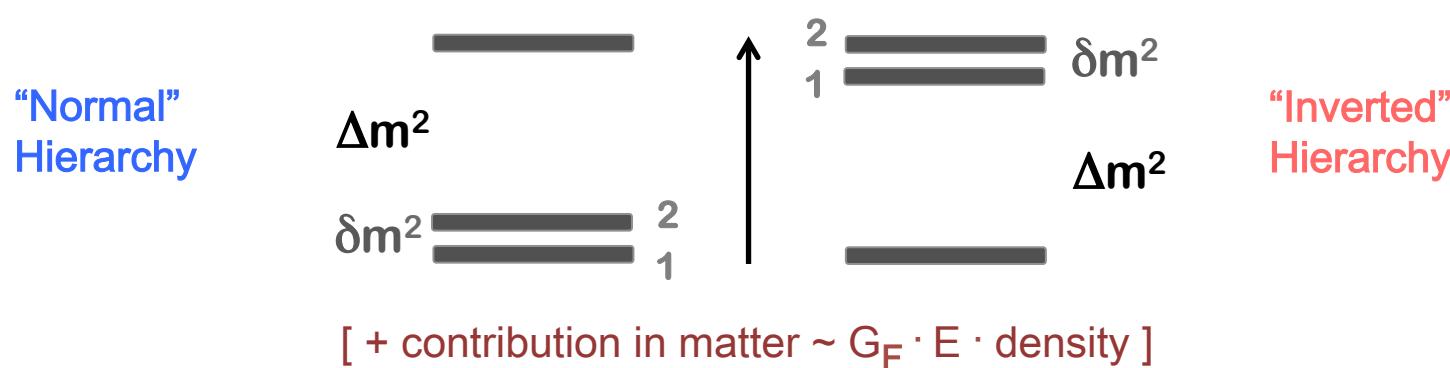
$$U_{\alpha i} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{bmatrix} \begin{bmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{bmatrix} \begin{bmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{bmatrix}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

[ only if Majorana ]

Mixing angles  $\theta_{23}$ ,  $\theta_{13}$ ,  $\theta_{12}$ : known ✓

CP-violat. phase(s)  $\delta$  ( $\alpha$ ,  $\beta$ ) : unknown ✗

## Mass-squared spectrum (up to absolute scale)



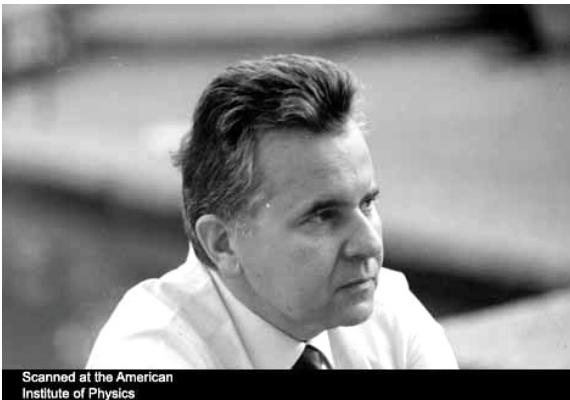
$\delta m^2$ ,  $\Delta m^2$ : known ✓

Matter effects (solar  $\nu$ ): ✓

Hierarchy : unknown ✗

Is there new physics beyond (or behind) three neutrinos?

# CP (or T) violation requires genuine $3\nu$ oscillations, distinct from $2\nu$ limits...



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## TIME REVERSAL VIOLATION IN NEUTRINO OSCILLATION

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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 (or T) violation requires genuine  $3\nu$  oscillations,  
distinct from  $2\nu$  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...

**...and maybe also with the 6<sup>th</sup> condition!**