

# NEUTRINOS: THEORY UPDATE/REVIEW

Concha Gonzalez-Garcia

*(YITP Stony Brook & ICREA U. Barcelona )*



# NEUTRINOS: THEORY

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## OUTLINE

Introduction

Determination of Lepton Flavour Parameters

Neutrino Mass Scale

Sterile Neutrinos

Some Implications

Conclusions

*Not covered due to time (my apologies):*

*Neutrino Cross Sections [talks by Hill, (Lopez, Ravonel, Snider, Soderberg)]*

*Sensitivity at Future Facilities [Di Luise, Long, Paley, Prakash, Sekiya, Sioli]*

## Conclusions at ICHEP02

- Big experimental effort: flavor conversion proved

Solar  $\nu$ 's : Verification of Flavour Conversion  $\nu_e$  to  $\nu_\mu$  or  $\nu_\tau$  at  $5\sigma$

Atmospheric  $\nu_\mu$ 's disappear ( $> 15\sigma$ ) most likely to  $\nu_\tau$

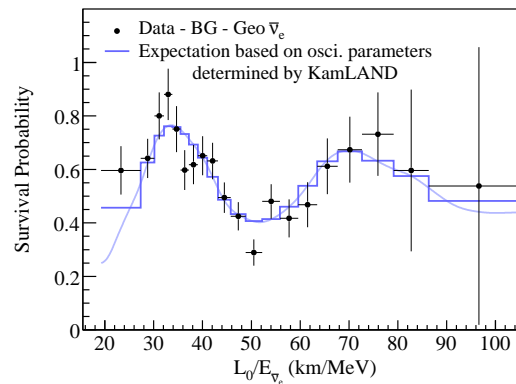
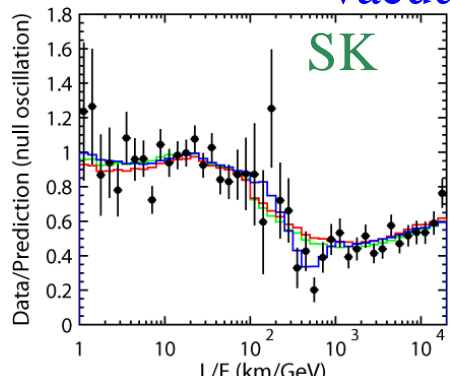
- Most likely explanation is neutrino oscillation  
and soon this will be tested with “man-made”  
neutrino beams from reactor and accelerators
- $\nu$  masses imply physics beyond the standard model
- Further advance requires more and more precise data

- By 2012 we have observed with high (or good) precision:

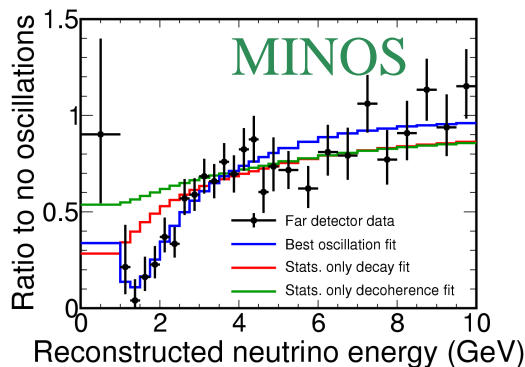
- \* Atmospheric  $\nu_\mu$  &  $\bar{\nu}_\mu$  disappear most likely to  $\nu_\tau$  (**SK**, MINOS)
- \* Accelerator  $\nu_\mu$  &  $\bar{\nu}_\mu$  disappear at  $L \sim 250$ [700] Km (K2K, T2K, [**MINOS**])
- \* Some accelerator  $\nu_\mu$  appear as  $\nu_e$  at  $L \sim 250$ [700] Km (**T2K**, [MINOS])
- \* Solar  $\nu_e$  convert to  $\nu_\mu/\nu_\tau$  (Cl, Ga, **SK**, **SNO**, **Borexino**)
- \* Reactor  $\bar{\nu}_e$  disappear at  $L \sim 200$  Km (**KamLAND**)
- \* Reactor  $\bar{\nu}_e$  disappear at  $L \sim 1$  Km (D-Chooz, **Daya-Bay**, **Reno**) [**NEW 2012**]

- We have confirmed:

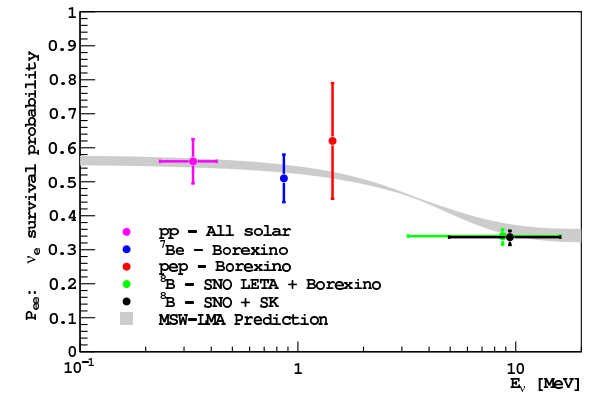
Vacuum oscillation  $L/E$  pattern



**KamLAND**



MSW conversion in Sun



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All this implies that neutrinos are massive  
and There is Physics Beyond SM

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All this implies that neutrinos are massive  
and There is Physics Beyond SM

- The *important* question:  
What is the BSM theory?
- The *difficult* path:  
Detailed determination of the new low energy parametrization

## $\nu$ in the SM

The SM is a gauge theory based on the symmetry group

$$SU(3)_C \times SU(2)_L \times U(1)_Y \Rightarrow SU(3)_C \times U(1)_{EM}$$

$(1, 2)_{-\frac{1}{2}}$	$(3, 2)_{\frac{1}{6}}$	$(1, 1)_{-1}$	$(3, 1)_{\frac{2}{3}}$	$(3, 1)_{-\frac{1}{3}}$
$\begin{pmatrix} \nu_e \\ e \end{pmatrix}_L$	$\begin{pmatrix} u^i \\ d^i \end{pmatrix}_L$	$e_R$	$u^i_R$	$d^i_R$
$\begin{pmatrix} \nu_\mu \\ \mu \end{pmatrix}_L$	$\begin{pmatrix} c^i \\ s^i \end{pmatrix}_L$	$\mu_R$	$c^i_R$	$s^i_R$
$\begin{pmatrix} \nu_\tau \\ \tau \end{pmatrix}_L$	$\begin{pmatrix} t^i \\ b^i \end{pmatrix}_L$	$\tau_R$	$t^i_R$	$b^i_R$

There is no  $\nu_R$

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There is no  $\nu_R$



Accidental global symmetry:  $B \times L_e \times L_\mu \times L_\tau$



$\nu$  strictly massless

# The New Minimal Standard Model

- Minimal Extensions to give Mass to the Neutrino:

- \* Introduce  $\nu_R$  AND impose  $L$  conservation  $\Rightarrow$  Dirac  $\nu \neq \nu^c$ :

$$\mathcal{L} = \mathcal{L}_{SM} - M_\nu \overline{\nu}_L \nu_R + h.c.$$

- \* NOT impose  $L$  conservation  $\Rightarrow$  Majorana  $\nu = \nu^c$

$$\mathcal{L} = \mathcal{L}_{SM} - \frac{1}{2} M_\nu \overline{\nu}_L \nu_L^C + h.c.$$

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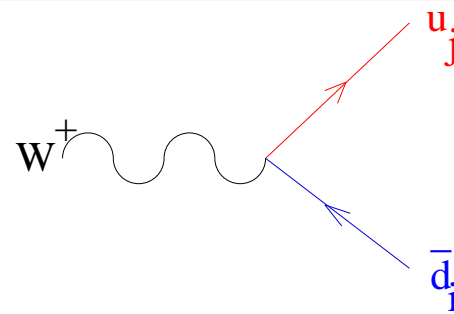
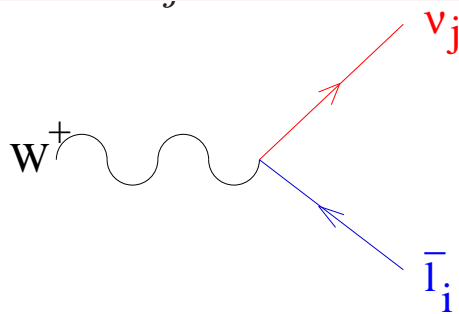
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$$\mathcal{L} = \mathcal{L}_{SM} - \frac{1}{2} M_\nu \bar{\nu}_L \nu_L^C + h.c.$$

- The charged current interactions of leptons are not diagonal (same as quarks)

$$\frac{g}{\sqrt{2}} W_\mu^+ \sum_{ij} (U_{\text{LEP}}^{ij} \bar{\ell}^i \gamma^\mu L \nu^j + U_{\text{CKM}}^{ij} \bar{U}^i \gamma^\mu L D^j) + h.c.$$

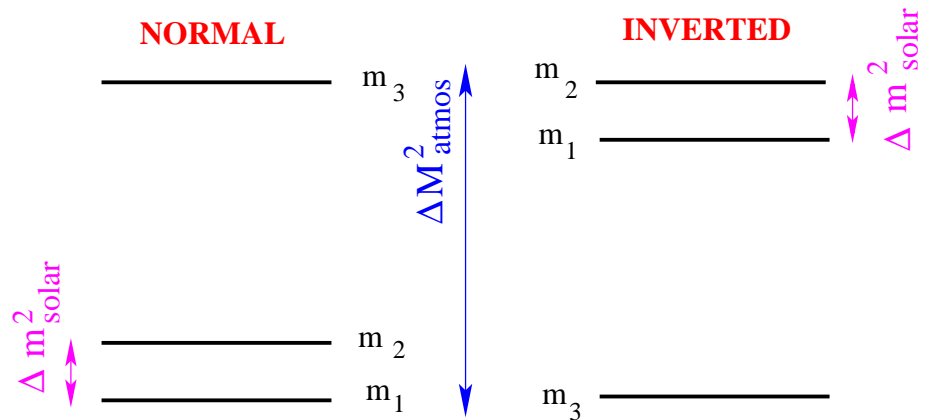


# 3ν Flavour Parameters

- For 3 ν's : 3 Mixing angles + 1 Dirac Phase + 2 Majorana Phases

$$U_{\text{LEP}} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{i\delta_{\text{CP}}} \\ 0 & 1 & 0 \\ -s_{13}e^{-i\delta_{\text{CP}}} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{21} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} e^{i\eta_1} & 0 & 0 \\ 0 & e^{i\eta_2} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

- Two Possible Orderings

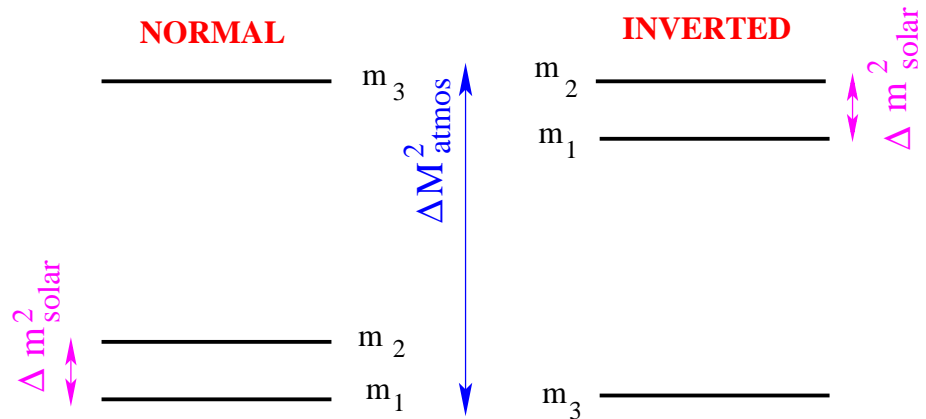


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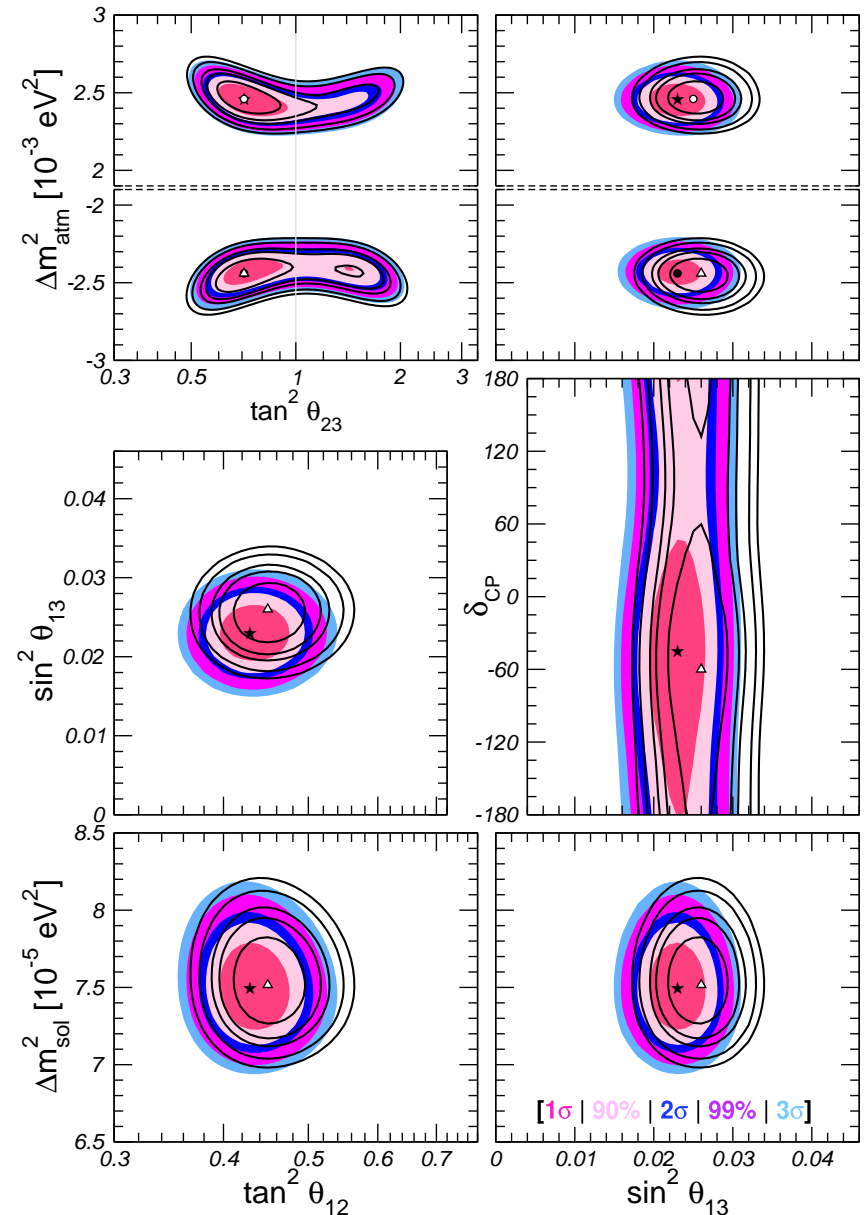
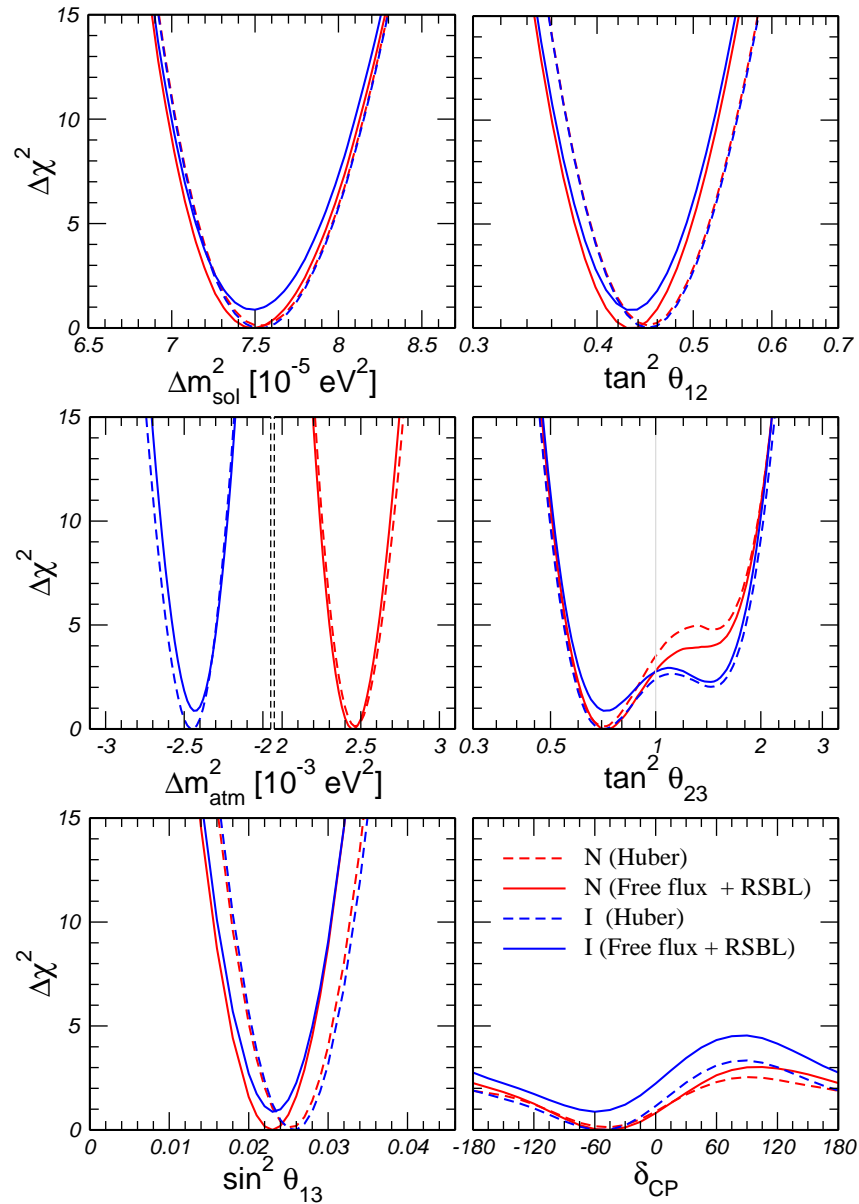
- Two Possible Orderings



Experiment	Dominant Dependence	Important Dependence
Solar Experiments	→ $\theta_{12}$	$\Delta m_{21}^2$ , $\theta_{13}$
Reactor LBL (KamLAND)	→ $\Delta m_{21}^2$	$\theta_{12}$ , $\theta_{13}$
Reactor MBL (Daya-Bay, Reno, D-Chooz)	→ $\theta_{13}$	$\Delta m_{\text{atm}}^2$
Atmospheric Experiments	→ $\theta_{23}$	$\Delta m_{\text{atm}}^2$ , $\theta_{13}$ , $\delta_{\text{CP}}$
Accelerator LBL $\nu_{\mu}$ Disapp (Minos)	→ $\Delta m_{\text{atm}}^2$	$\theta_{23}$
Accelerator LBL $\nu_e$ App (Minos, T2K)	→ $\delta_{\text{CP}}$	$\theta_{13}$ , $\theta_{23}$

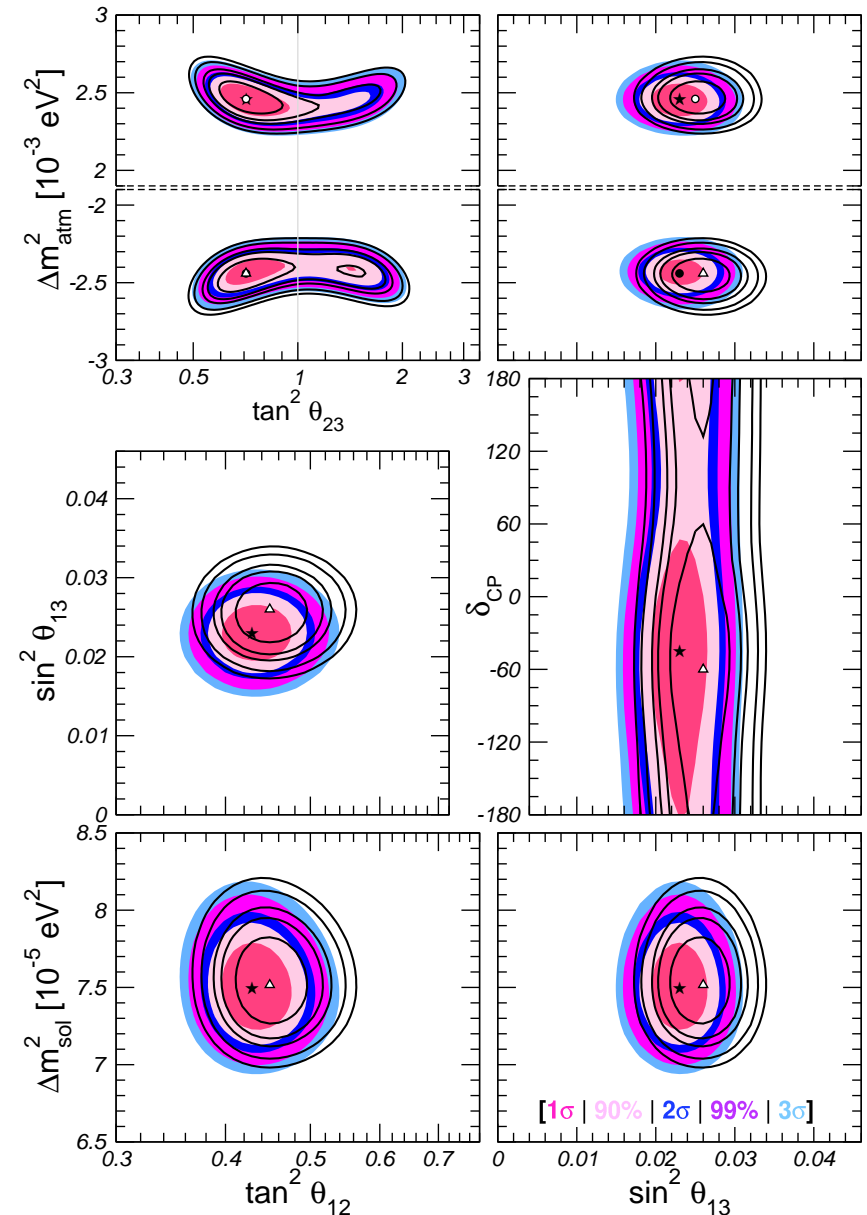
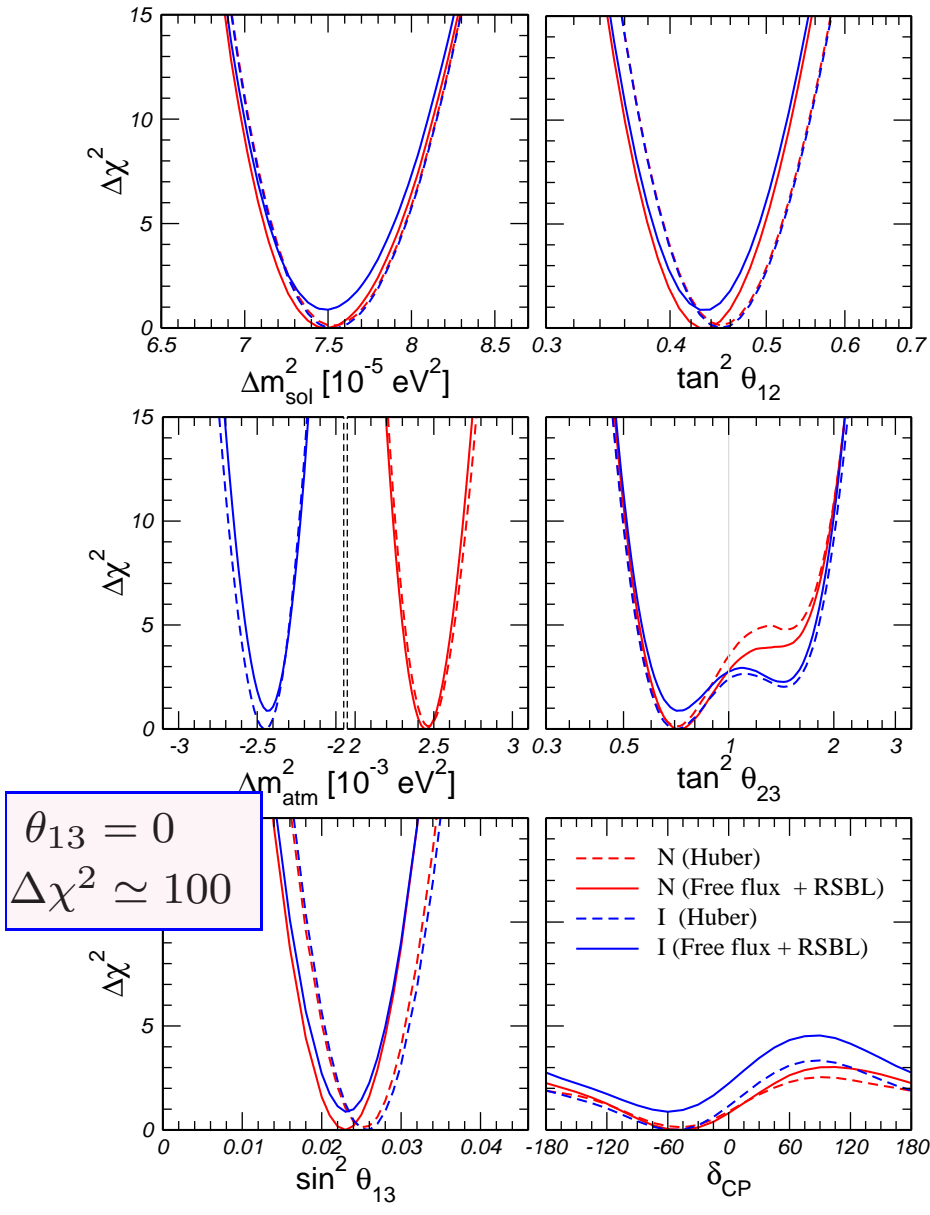
# Flavour Parameters: Present Status

Global 6-parameter fit post  $\nu 2012$   
 Maltoni, Schwetz, Salvado, MCGG



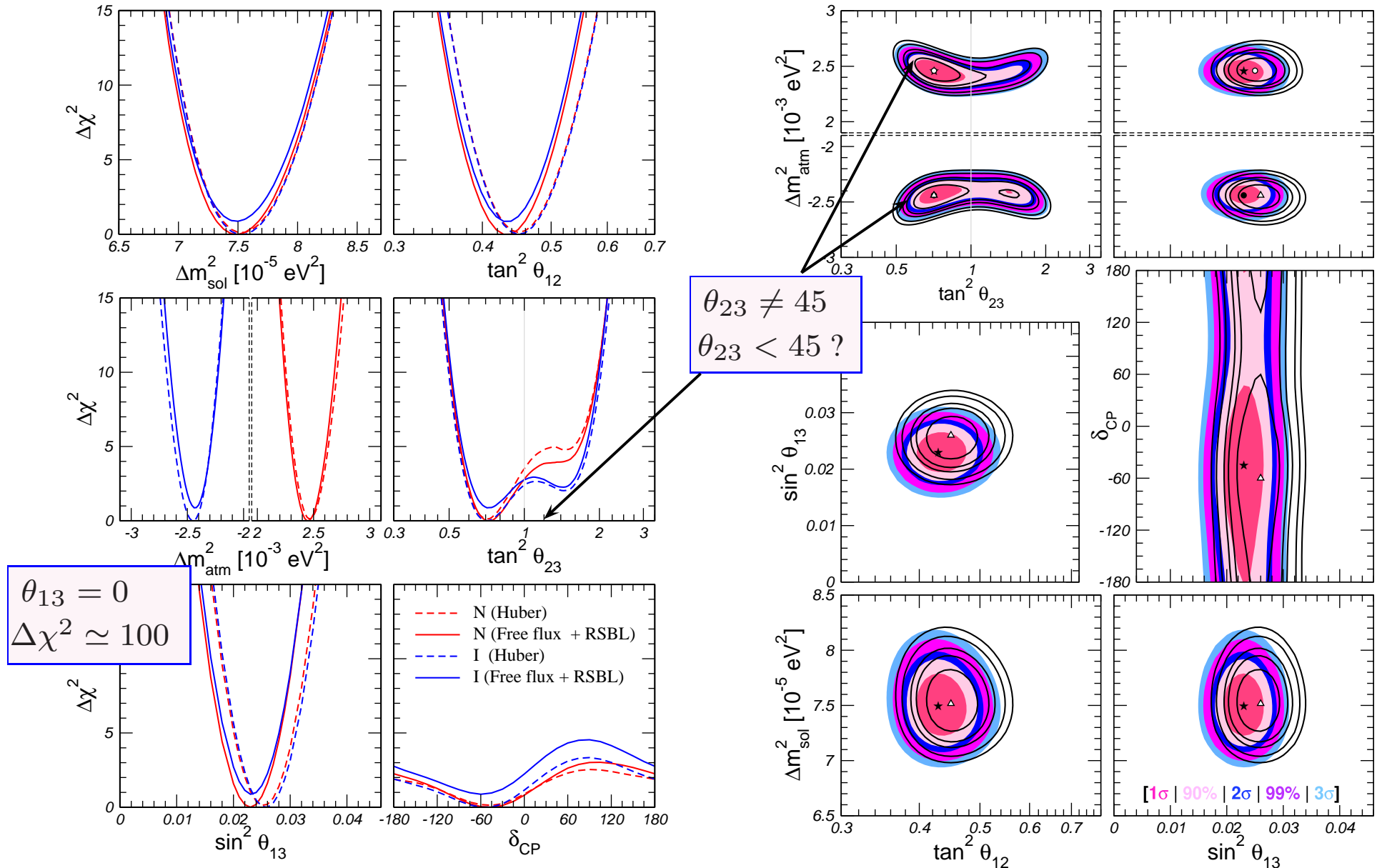
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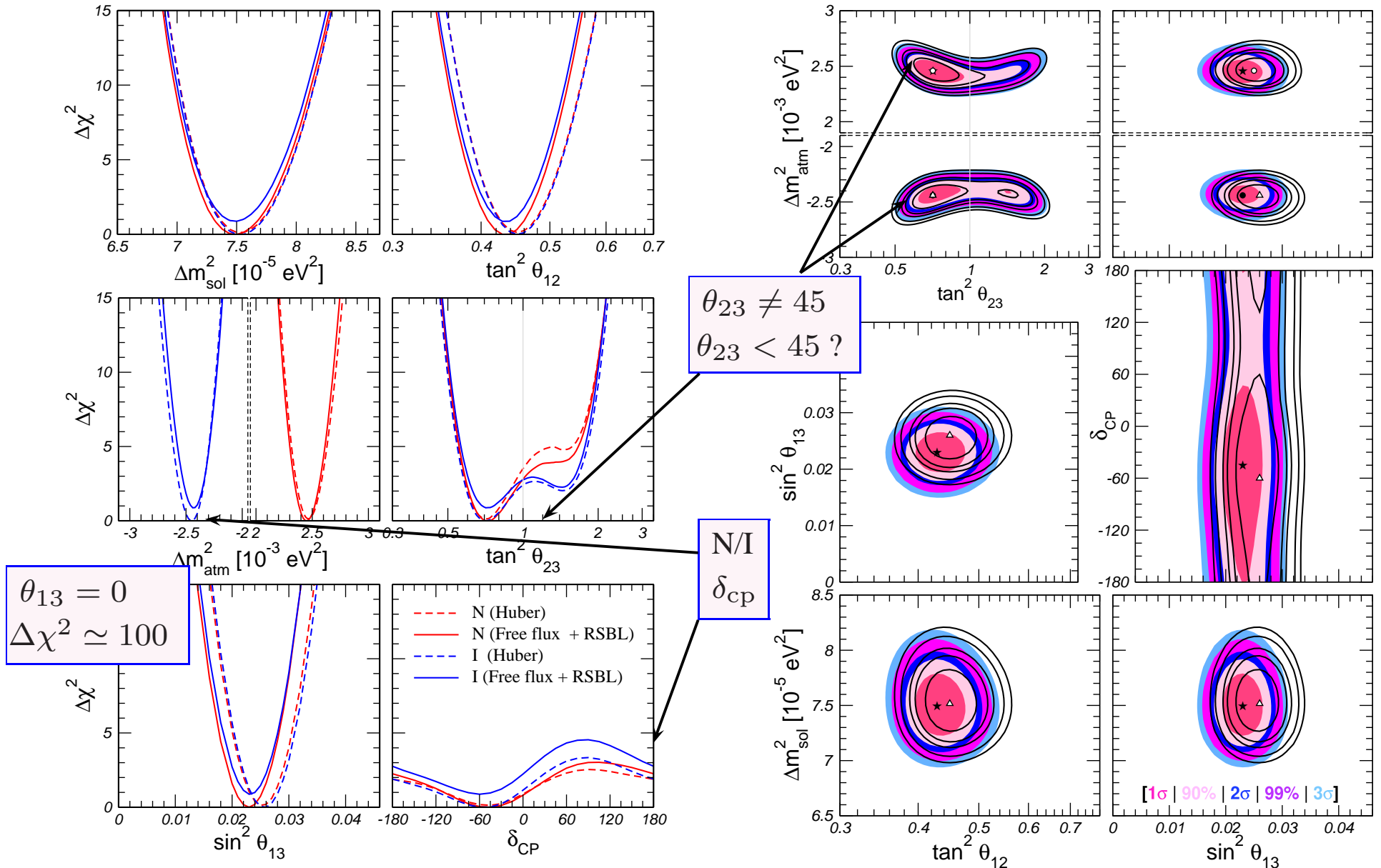
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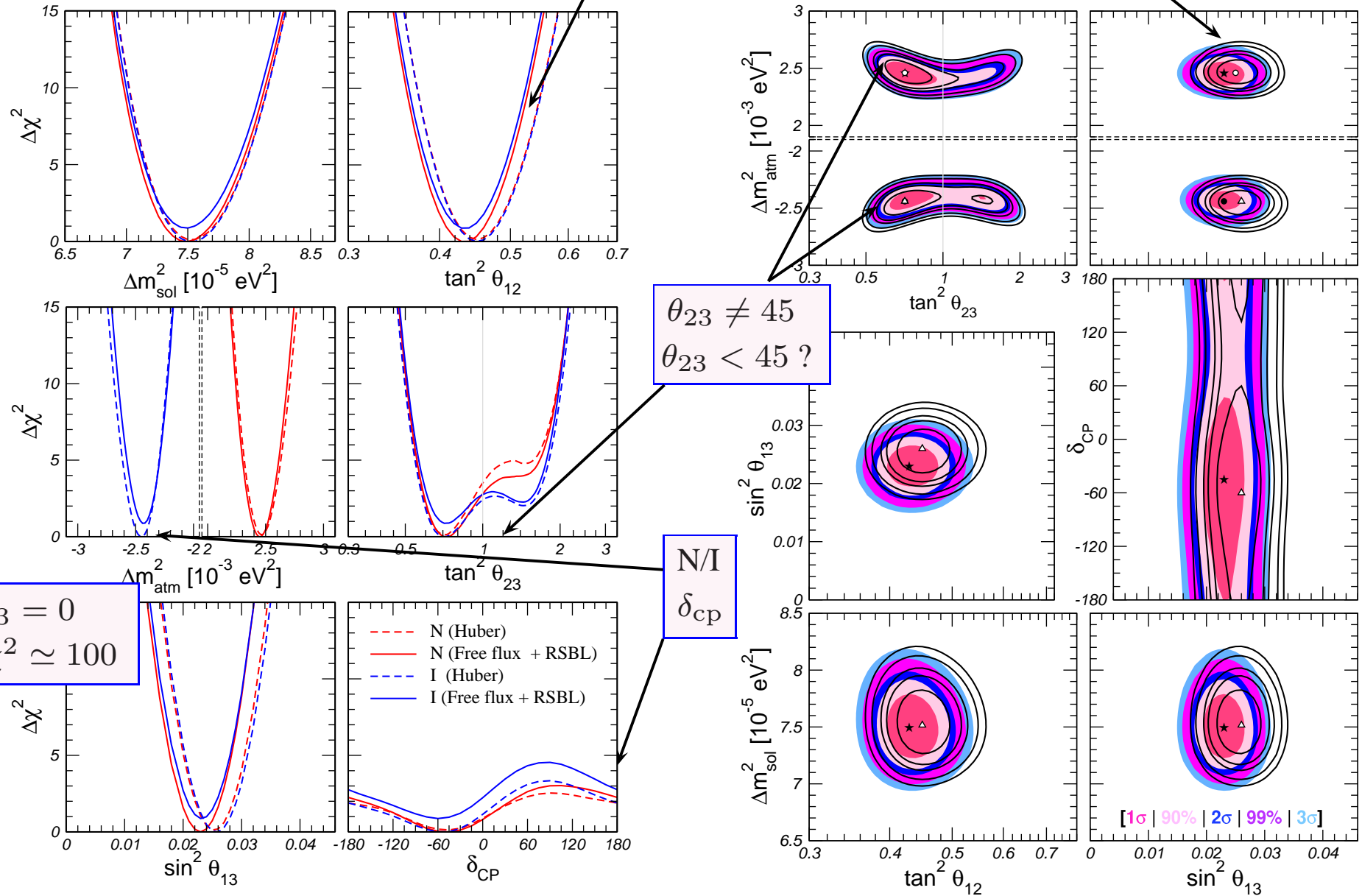
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Curves = uncertainty on reactor fluxes



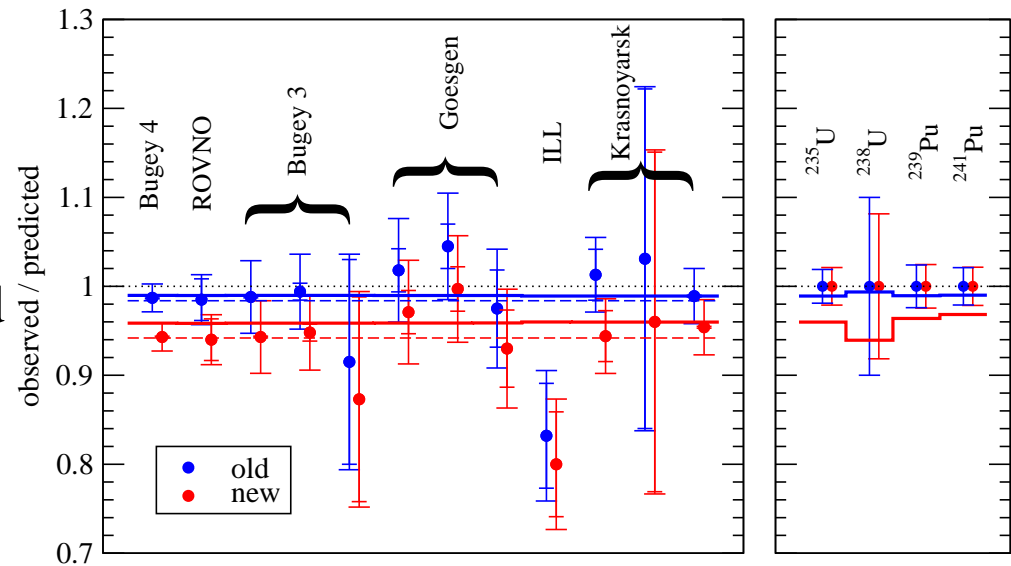
# Some Issues in $3 \nu$ Analysis: Reactor Anomaly

- Recently the reactor  $\bar{\nu}_e$  fluxes have been recalculated

T.A. Mueller et al., [arXiv:1101.2663].; P. Huber, [arXiv:1106.0687].

- Both reevaluations find higher fluxes by about 3.5 %

- So *negative* reactor experiments at short baselines (RSBL) indeed *observed a deficit*



- If due to oscillations  $\Delta m^2 \sim \text{eV}^2 \Rightarrow$  sterile  $\nu$ 's (more soon)

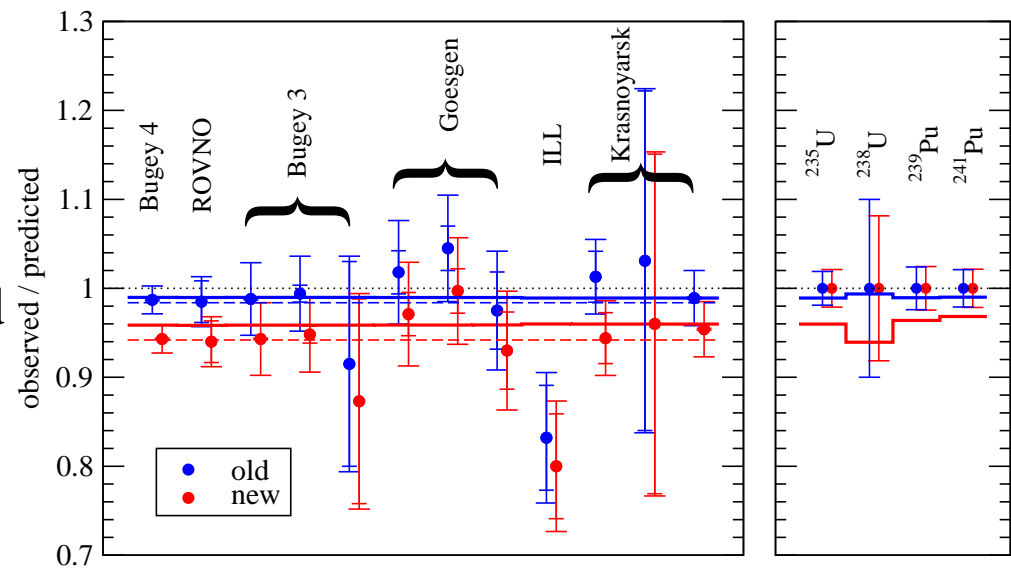
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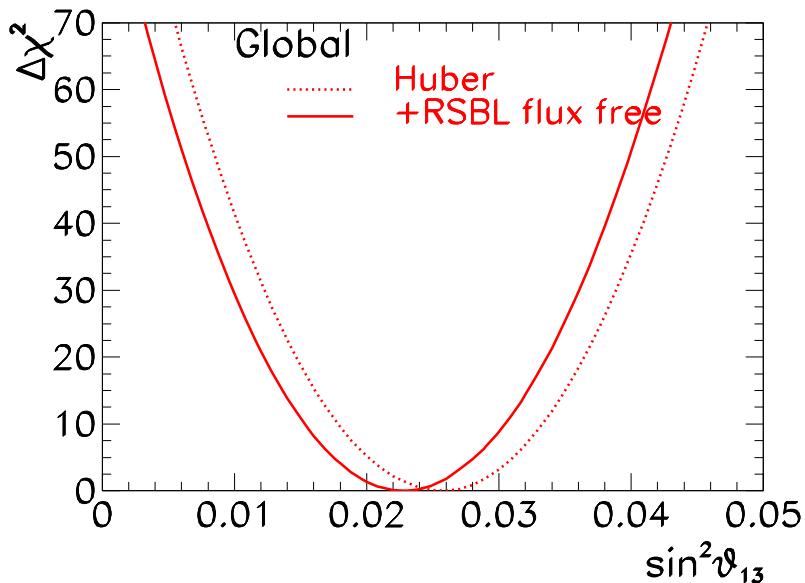
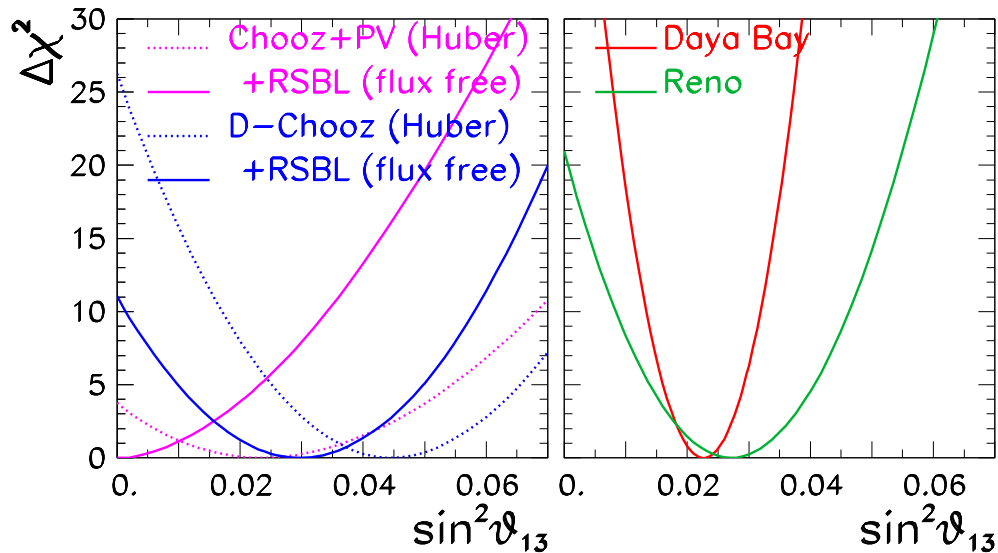
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- For  $3\nu$  analysis a consistent approach (T. Schwetz et. al. [arXiv:1103.0734]):
  - Fit oscillation parameters and reactor fluxes simultaneously
  - Use theoretical calculation and/or RSBL data as priors

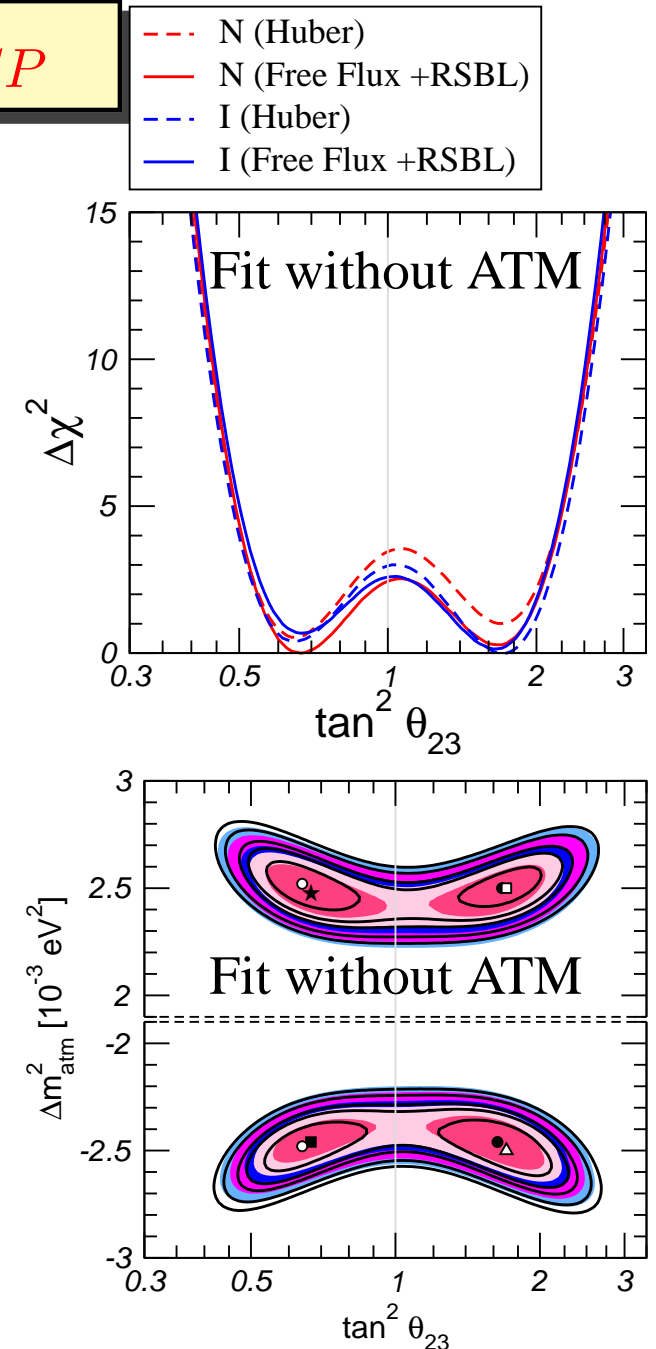
# 3 $\nu$ Analysis: Reactor Anomaly and $\theta_{13}$



- Experiments without near detector (CHOOZ, Palo-Verde, D-CHOOZ) sensitive to the flux assumptions
- **DAYA-BAY** and **RENO**  
Near-Far comparison  
⇒ results flux independent
- Two extreme priors :  
Use fluxes from **Huber 1106.0687** without RSBL data  
 $\theta_{13} = 9.2^\circ \pm 0.46^\circ$   
Leave flux free and include RSBL  
 $\theta_{13} = 8.7^\circ \pm 0.45^\circ$   
**Shift at the  $1\sigma$  level**

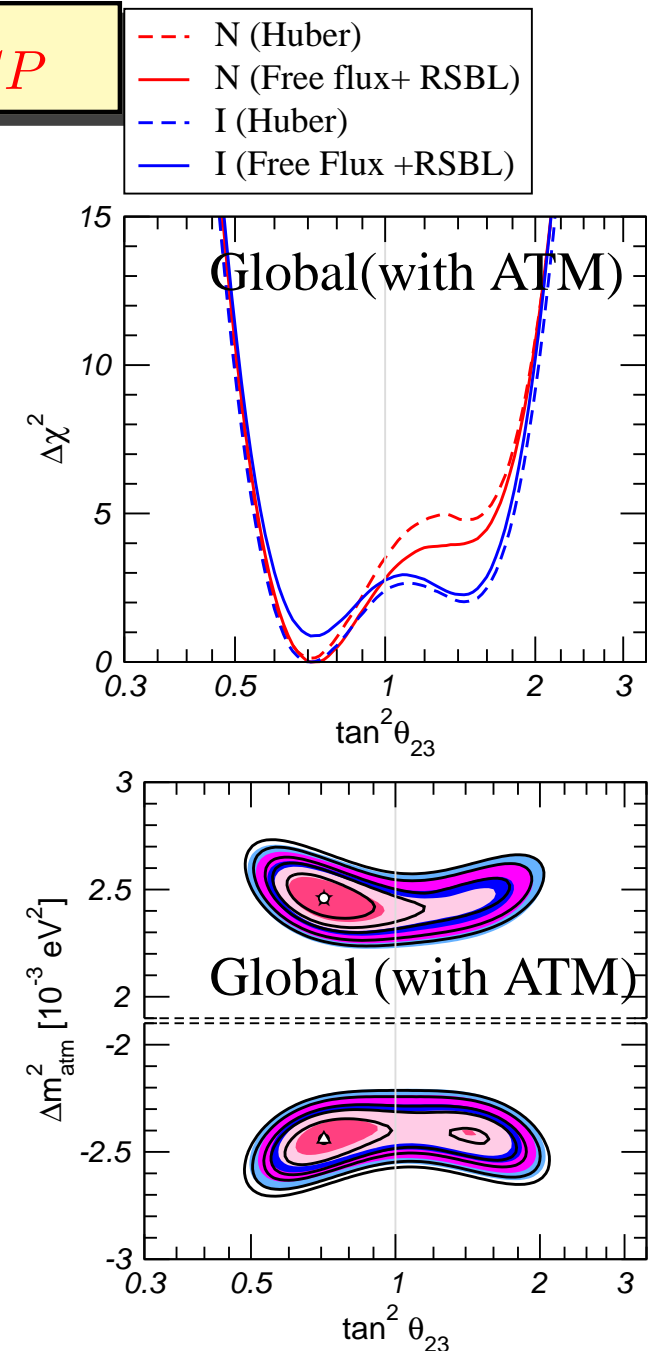
# $\theta_{23}$ , Mass Ordering, $\delta_{CP}$

- $\theta_{23}$  determination in global analysis:
  - Maximal  $\theta_{23} = 45^\circ$  Disfavoured at  $1.6\text{--}2\sigma$  level
  - Now mostly driven by MINOS  $\nu_\mu$  DIS



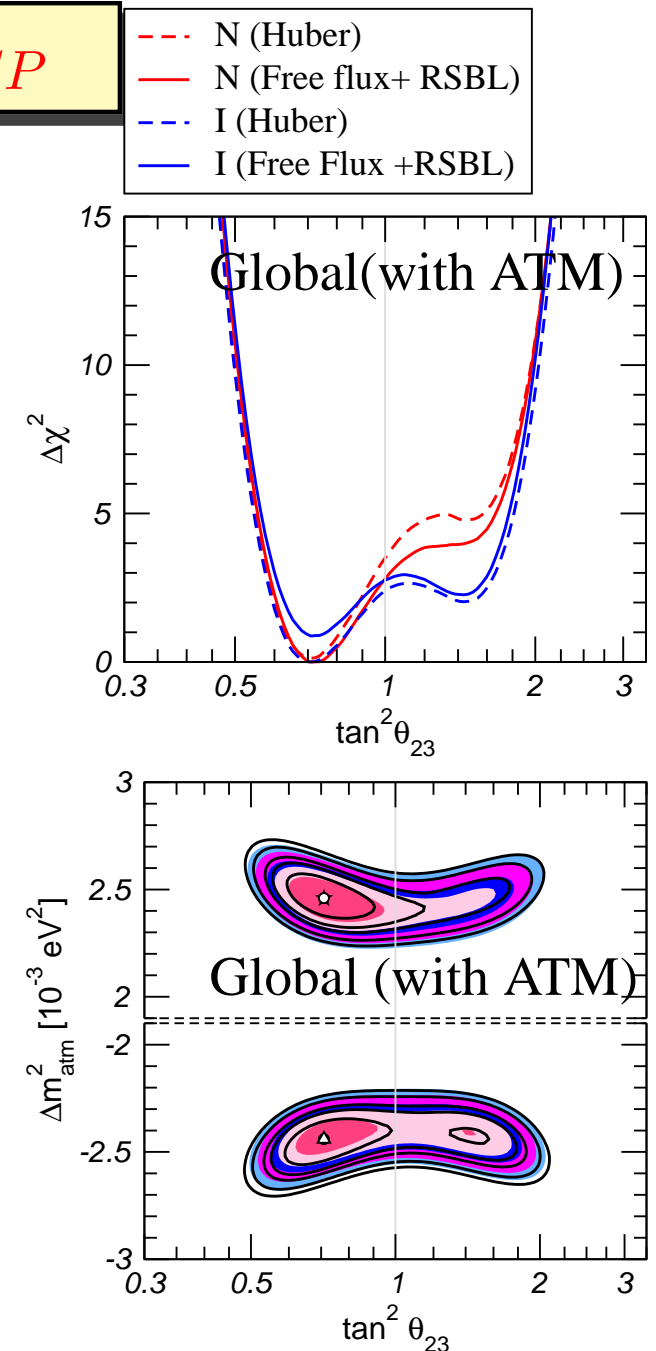
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  - First octant  $\theta_{23} < 45$  Favoured at 1.6–2  $\sigma$  level  
Driven by SK I–III ATM Sub-GeV  $\nu_e$  excess  
It seems to be reduced in SK-IV analysis



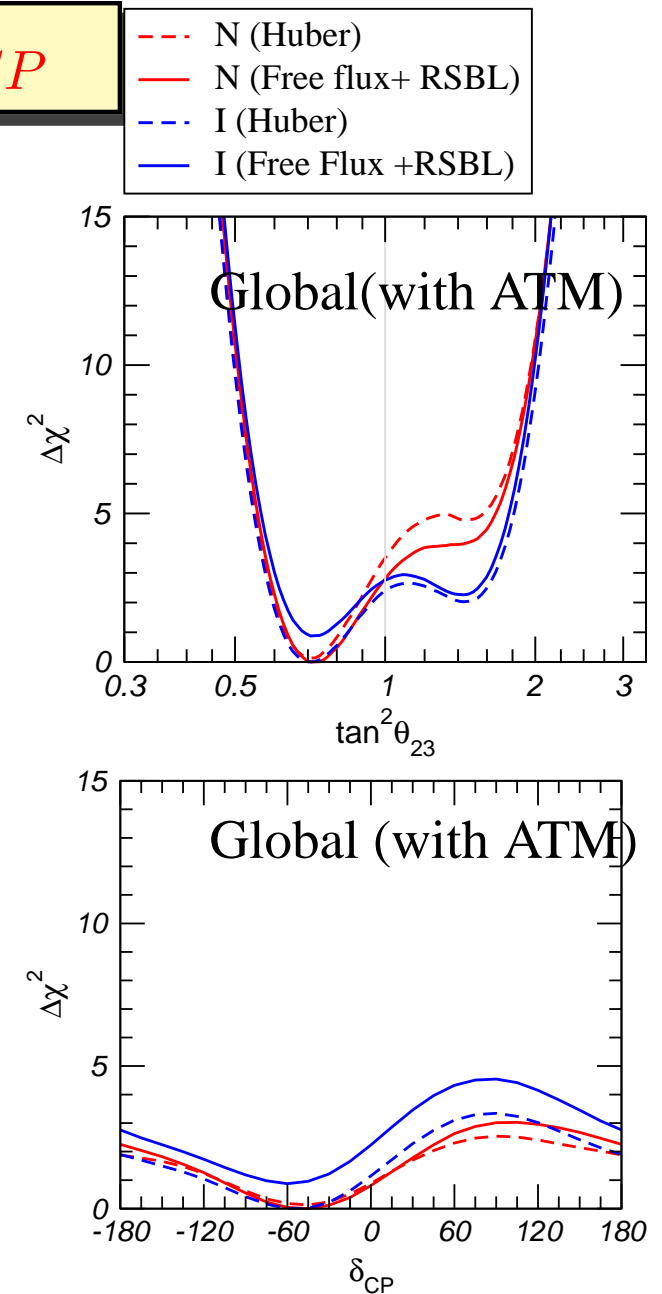
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- $\text{sign}(\Delta m_{\text{atm}}^2)$  determination in global analysis:
  - No significant difference Normal versus Inverted  
Driven by SK ATM



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- $\text{sign}(\Delta m_{\text{atm}}^2)$  determination in global analysis:
  - No significant difference Normal versus Inverted  
Driven by SK ATM
- $\delta_{CP}$  determination in global analysis:
  - Signal at most at 1.7  $\sigma$  level  
Driven mostly by SK ATM (slight LBL  $\nu_e$  app)



# $\theta_{23}$ , Mass Ordering, $\delta_{CP}$

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- Maximal  $\theta_{23} = 45$  Disfavoured at  $1.6-2 \sigma$  level

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- First octant  $\theta_{23} < 45$  Favoured at  $1 \sigma$

Driven by SK I-III ATM Sub.

It seems to be reduced in

- $\text{sign}(\Delta m_{atm}^2)$  determination in global analysis:

- No significant difference between Normal versus Inverted

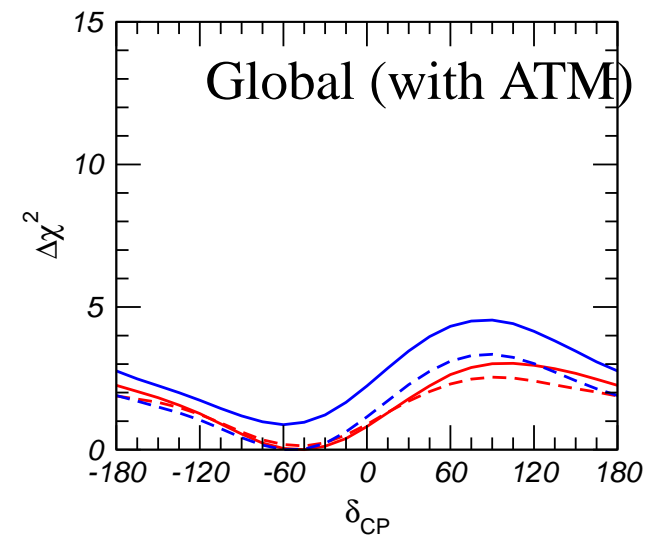
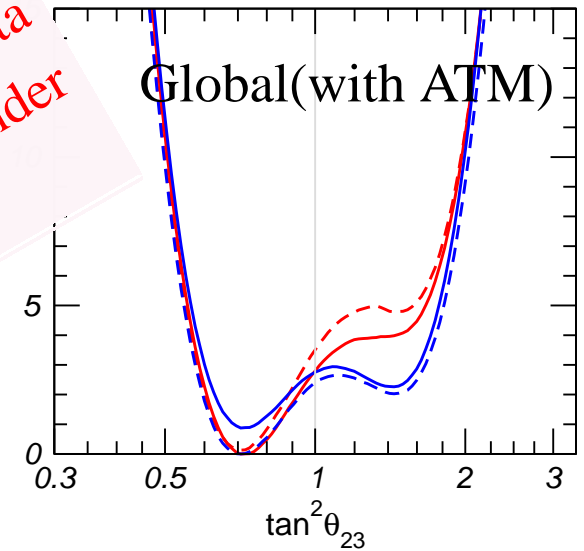
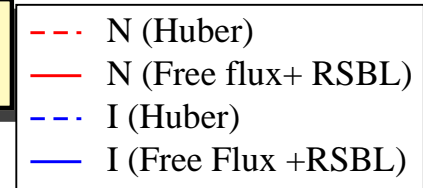
Driven

**Warning:** Statistical Significance of these small effects in ATM data depends on details of ATM data analysis which can only be done under simplifications outside SK

- $\delta_{CP}$  determination in global analysis:

- Not significant at most at  $1.7 \sigma$  level

Driven mostly by SK ATM (and slight LBL  $\nu_e$  app)



# Flavour Parameters: Present Status

- The derived ranges for the six parameters at  $1\sigma$  ( $3\sigma$ ):

$$\begin{aligned}
 \Delta m_{21}^2 &= 7.5 \pm 0.19 \begin{pmatrix} +0.59 \\ -0.50 \end{pmatrix} \times 10^{-5} \text{ eV}^2 & \theta_{12} &= 32.4^\circ \pm 0.8^\circ \begin{pmatrix} +2.5^\circ \\ -1.9^\circ \end{pmatrix} \\
 \Delta m_{31}^2(\text{N}) &= 2.45_{-0.071}^{+0.067} \begin{pmatrix} +0.22 \\ -0.20 \end{pmatrix} \times 10^{-3} \text{ eV}^2 & \theta_{23} &= 40.4^\circ_{-1.8^\circ}^{+0.8^\circ} \begin{pmatrix} +13.9^\circ \\ -4.8^\circ \end{pmatrix} \\
 |\Delta m_{32}^2|(\text{I}) &= 2.43 \pm 0.068 \begin{pmatrix} +0.22 \\ -0.20 \end{pmatrix} \times 10^{-3} \text{ eV}^2 & \theta_{13} &= 8.7^\circ \pm 0.45^\circ \begin{pmatrix} +1.3^\circ \\ -1.5^\circ \end{pmatrix} \\
 & & \delta_{\text{CP}} &= \begin{cases} (\text{N}) & -48^\circ_{-59^\circ}^{+53^\circ} \begin{pmatrix} +228^\circ \\ -132^\circ \end{pmatrix} \\ (\text{I}) & -59^\circ_{-60^\circ}^{+49^\circ} \begin{pmatrix} +239^\circ \\ -121^\circ \end{pmatrix} \end{cases}
 \end{aligned}$$

$$|U|_{\text{LEP}(3\sigma)} = \begin{pmatrix} 0.795 \rightarrow 0.841 & 0.517 \rightarrow 0.584 & 0.141 \rightarrow 0.179 \\ 0.213 \rightarrow 0.543 & 0.425 \rightarrow 0.728 & 0.575 \rightarrow 0.802 \\ 0.213 \rightarrow 0.541 & 0.411 \rightarrow 0.720 & 0.576 \rightarrow 0.802 \end{pmatrix}$$

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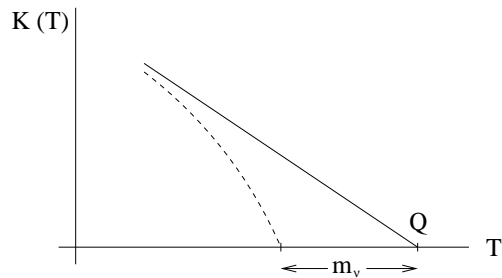
$$|U|_{\text{LEP}(3\sigma)} = \begin{pmatrix} 0.795 \rightarrow 0.841 & 0.517 \rightarrow 0.584 & 0.141 \rightarrow 0.179 \\ 0.213 \rightarrow 0.543 & 0.425 \rightarrow 0.728 & 0.575 \rightarrow 0.802 \\ 0.213 \rightarrow 0.541 & 0.411 \rightarrow 0.720 & 0.576 \rightarrow 0.802 \end{pmatrix}$$

- Good progress but still precision very far from:

$$|V|_{\text{CKM}} = \begin{pmatrix} 0.97427 \pm 0.00015 & 0.22534 \pm 0.0065 & (3.51 \pm 0.15) \times 10^{-3} \\ 0.2252 \pm 0.00065 & 0.97344 \pm 0.00016 & (41.2_{-5}^{+1.1}) \times 10^{-3} \\ (8.67_{-0.31}^{+0.29}) \times 10^{-3} & (40.4_{-0.5}^{+1.1}) \times 10^{-3} & 0.999146_{-0.000046}^{+0.000021} \end{pmatrix}$$

# Neutrino Mass Scale

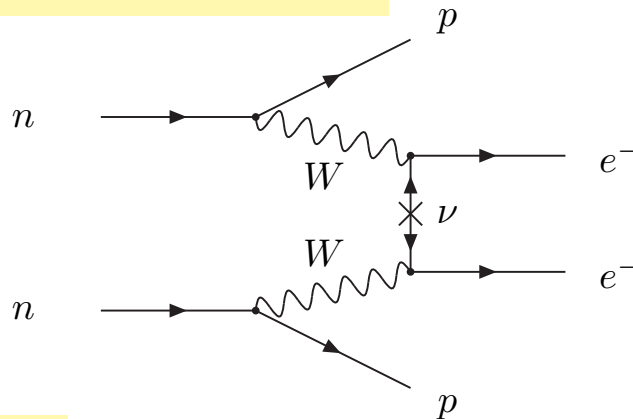
Single  $\beta$  decay : Dirac or Majorana  $\nu$  mass modify spectrum endpoint



$$m_{\nu_e}^2 = \sum m_j^2 |U_{ej}|^2 = c_{13}^2 c_{12}^2 m_1^2 + c_{13}^2 s_{12}^2 m_2^2 + s_{13}^2 m_3^2$$

$\nu$ -less Double- $\beta$  decay:  $\Leftrightarrow$  Majorana  $\nu$ 's sensitive to Majorana phases

If  $m_\nu$  only source of  $\Delta L$   $(T_{1/2}^{0\nu})^{-1} \propto (m_{ee})^2$



$$m_{ee} = \left| \sum U_{ej}^2 m_j \right|$$

$$= \left| c_{13}^2 c_{12}^2 m_1 e^{i\eta_1} + c_{13}^2 s_{12}^2 m_2 e^{i\eta_2} + s_{13}^2 m_3 e^{-i\delta_{CP}} \right|$$

COSMO Neutrino mass (Dirac or Majorana) modify the growth of structures

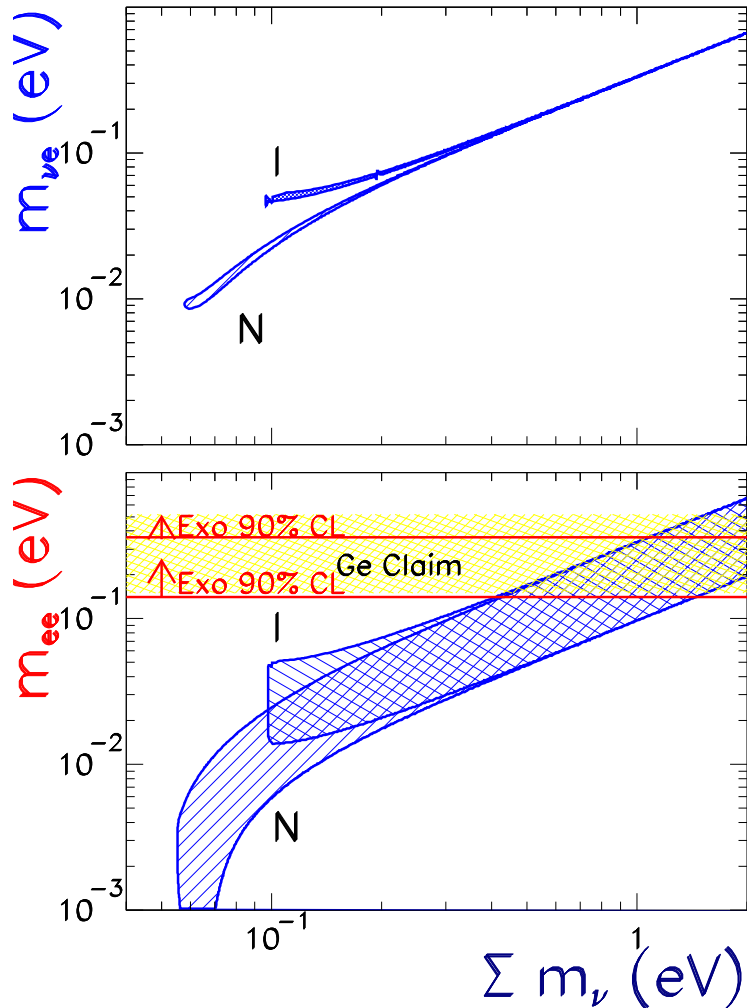
$$\sum m_i$$

# Neutrino Mass Scale: The Cosmo-Lab Connection

## Global oscillation analysis

⇒ Correlated ranges for  $m_{\nu_e}$ ,  $m_{ee}$  and  $\Sigma m_\nu$   
(Fogli *et al* (04))

Update Maltoni, Schwetz, Salvado, MCGG (95%)

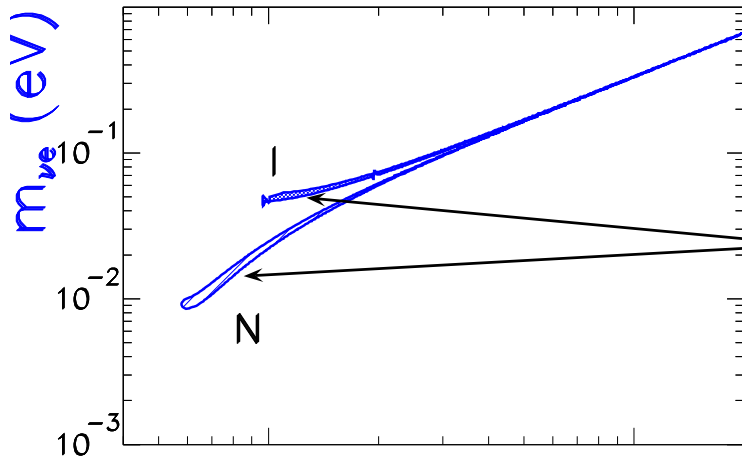


# Neutrino Mass Scale: The Cosmo-Lab Connection

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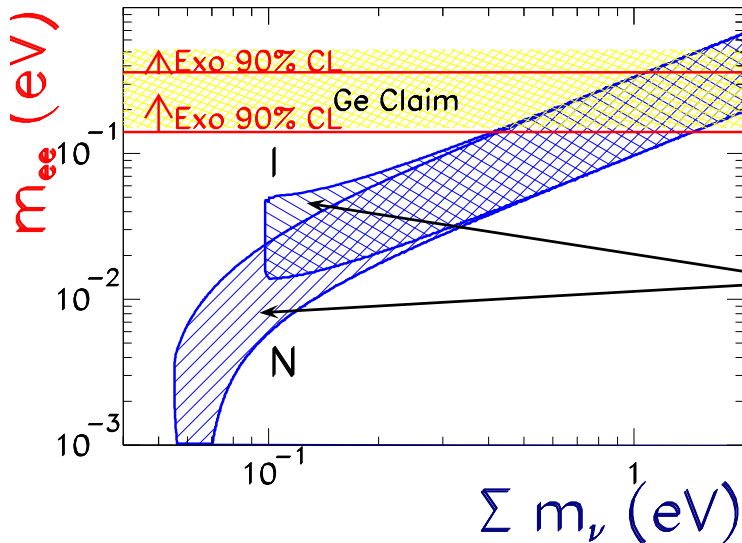
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Update Maltoni, Schwetz, Salvado, MCGG (95%)



Width due to range in oscillation parameters very narrow

High precision determination of  $m_{\nu_e}$  and  $\sum m_i$  can give information on ordering



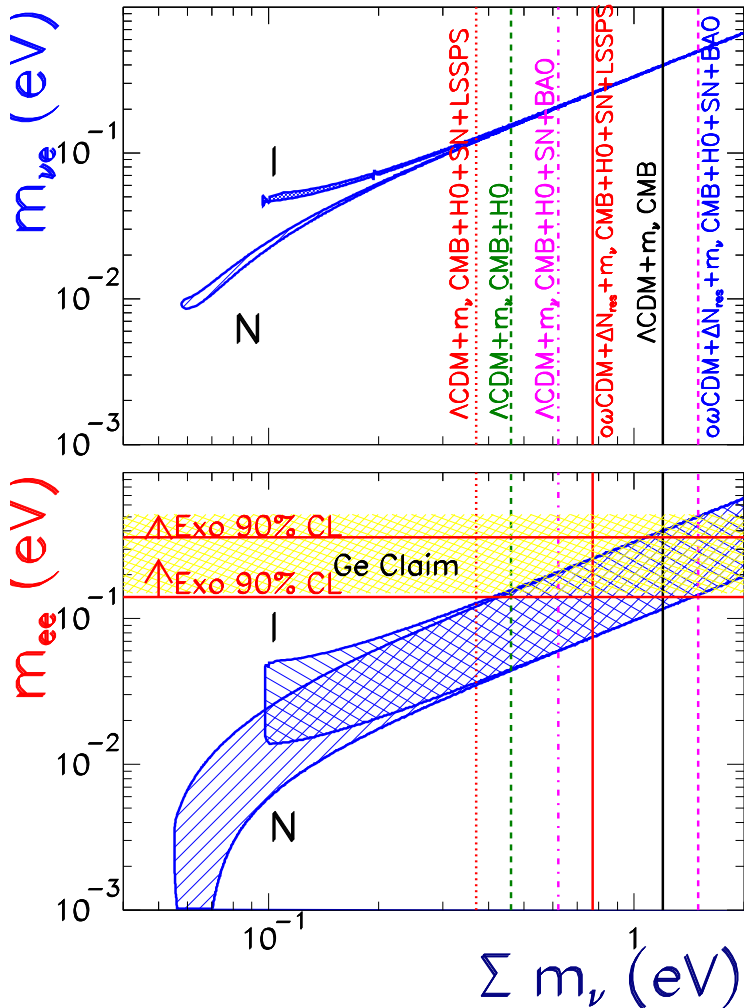
Wide band due to unknown Majorana phases

# Neutrino Mass Scale: The Cosmo-Lab Connection

## Global oscillation analysis

⇒ Correlated ranges for  $m_{\nu_e}$ ,  $m_{ee}$  and  $\sum m_\nu$   
(Fogli *et al* hep-ph/0408045)

Our update post  $\nu$ 2012 (95% CL)



## Analysis of Cosmological data

Bound on  $\sum m_\nu$  changes with:  
cosmo parameters fix in analysis  
cosmo observables considered

Model	Observables	$\sum m_\nu$ (eV) 95% Bound
$\omega\Lambda$ CDM + $\Delta N_{\text{rel}}$ + $m_\nu$	CMB+H0+SN+BAO	$\leq 1.5$
$\omega\Lambda$ CDM + $\Delta N_{\text{rel}}$ + $m_\nu$	CMB+H0+SN+LSSPS	$\leq 0.76$
$\Lambda$ CDM + $m_\nu$	CMB+H0+SN+BAO	$\leq 0.61$
$\Lambda$ CDM + $m_\nu$	CMB+H0+SN+LSSPS	$\leq 0.36$
$\Lambda$ CDM + $m_\nu$	CMB (+SN)	$\leq 1.2$
$\Lambda$ CDM + $m_\nu$	CMB+BAO	$\leq 0.75$
$\Lambda$ CDM + $m_\nu$	CMB+LSSPS	$\leq 0.55$
$\Lambda$ CDM + $m_\nu$	CMB+H0	$\leq 0.45$

Table from MCG-G, Maltoni, Salvado 1006.3795

⇒  $\sum m_\nu \leq 0.36 \rightarrow 0.75 \rightarrow 1.5$  eV (95%)

Also: Thomas *et al*, Reid *et al*, Giusarma *et al*,  
dePutter *et al*, Hannestad *et al*. ...

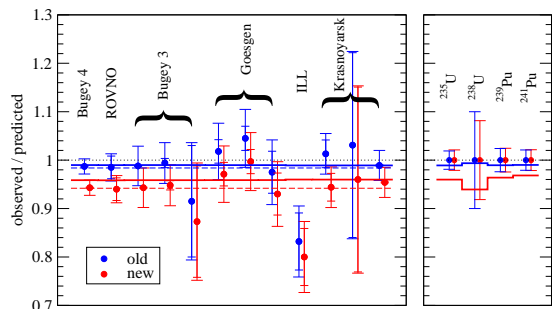
# Light Sterile Neutrinos

- Several Observations which can be Interpreted as Oscillations with  $\Delta m^2 \sim \text{eV}^2$

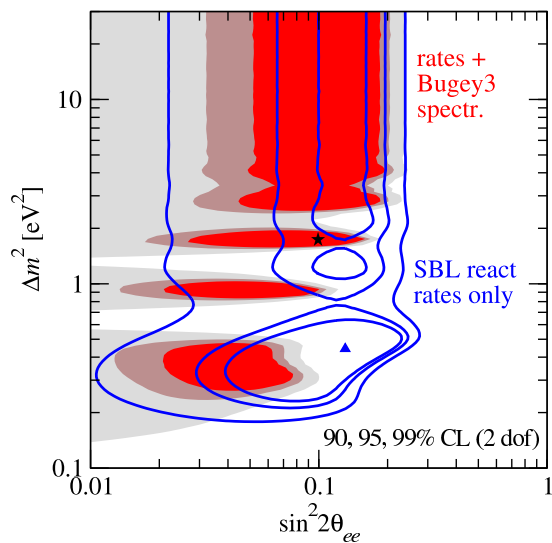
## Reactor Anomaly

New reactor flux calculation

$\Rightarrow$  Deficit in data at  $L \lesssim 100$  m



Explained as  $\nu_e$  disappearance



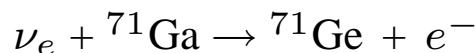
T.Schwetz, talk  $\nu$ 2012

## Gallium Anomaly

Acero, Giunti, Laveder, 0711.4222  
Giunti, Laveder, 1006.3244

Radioactive Sources ( $^{51}\text{Cr}$ ,  $^{37}\text{Ar}$ )

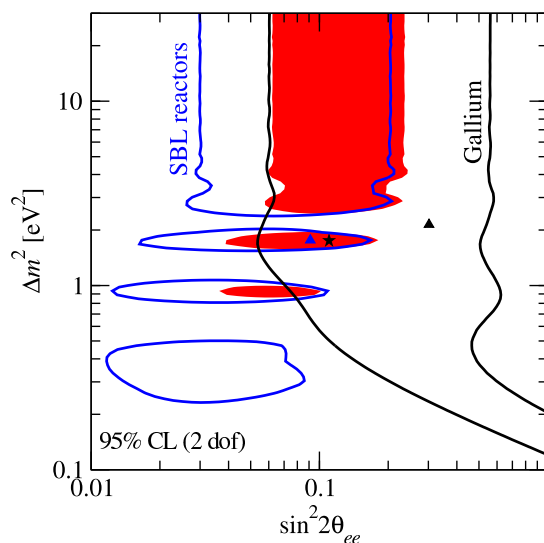
in calibration of Ga Solar Exp;



Give a rate lower than expected

$$R = \frac{N_{\text{obs}}}{N_{\text{Bahc}}^{\text{th}}} = 0.86 \pm 0.05 \quad (2.8\sigma)$$

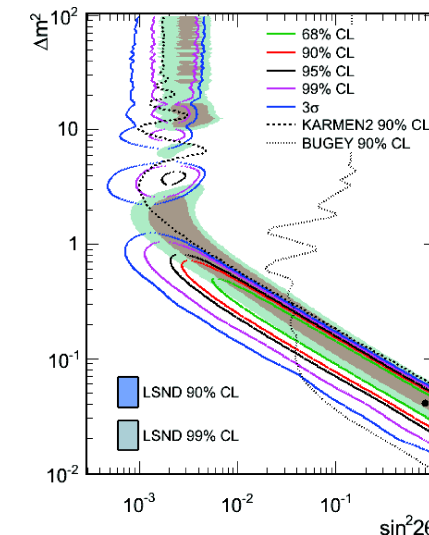
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T.Schwetz, talk  $\nu$ 2012

## LSND, MiniBoone

$\nu_\mu \rightarrow \nu_e$  and  $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$



# Light Sterile Neutrinos

- These explanations require  $3+N_s$  mass eigenstates  $\rightarrow N_s$  sterile neutrinos

$\nu_e \rightarrow \nu_e$  disappearance at SBL

- Problem is to fit together  $\nu_\mu \rightarrow \nu_e$  appearance at SBL

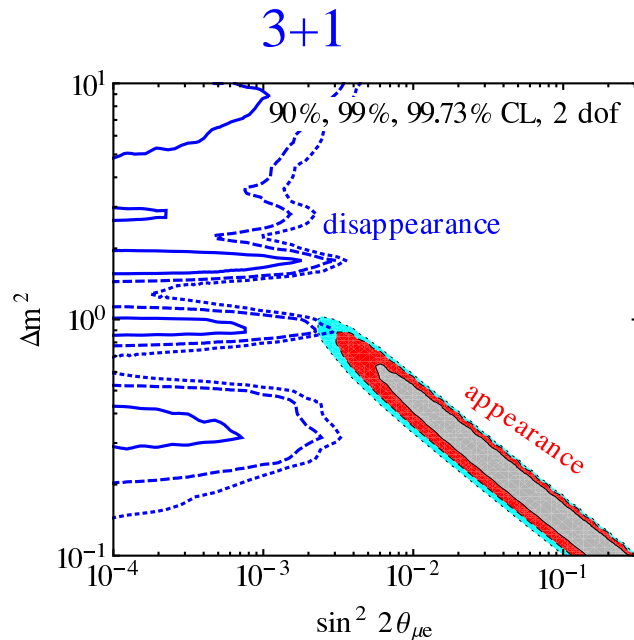
$\nu_\mu \rightarrow \nu_\mu$  no-disappearance at SBL (CDHS,ATM,MINOS)

- Generically:  $P(\nu_e \rightarrow \nu_\mu) \sim |U_{ei}^* U_{\mu i}|$  [ $i$  =heavier state(s)]

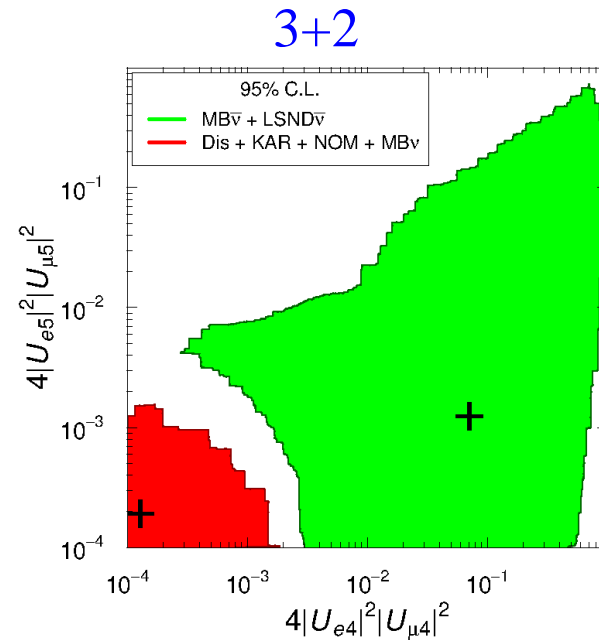
But  $|U_{ei}|$  constrained by  $P(\nu_e \rightarrow \nu_e)$  disappearance data

And  $|U_{\mu i}|$  constrained by  $P(\nu_\mu \rightarrow \nu_\mu)$  disappearance data

}  $\Rightarrow$  Severe tension



T.Schwetz, talk  $\nu$ 2012



Giunti, Laveder, 1107.1452

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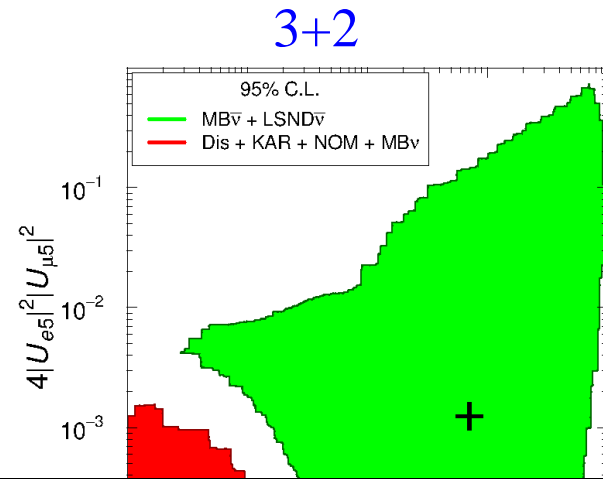
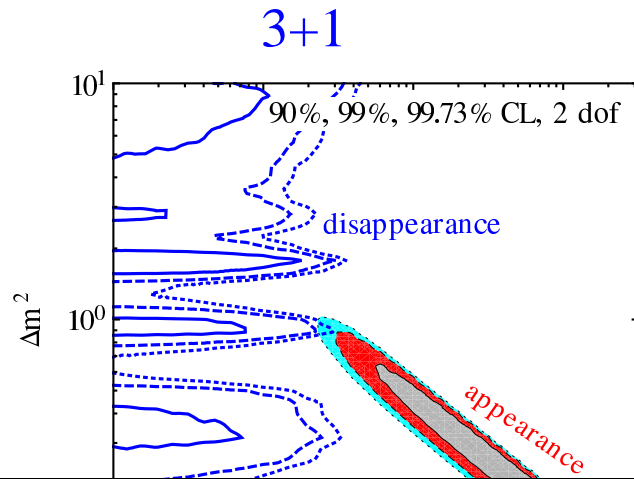
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My view: These anomalies need independent tests, but testing the combined sterile oscillation interpretation may not be the best way

# Implications

The two arising questions

- Why are neutrinos so light?

The Origin of Neutrino Mass

- Why are lepton mixing so different from quark's?

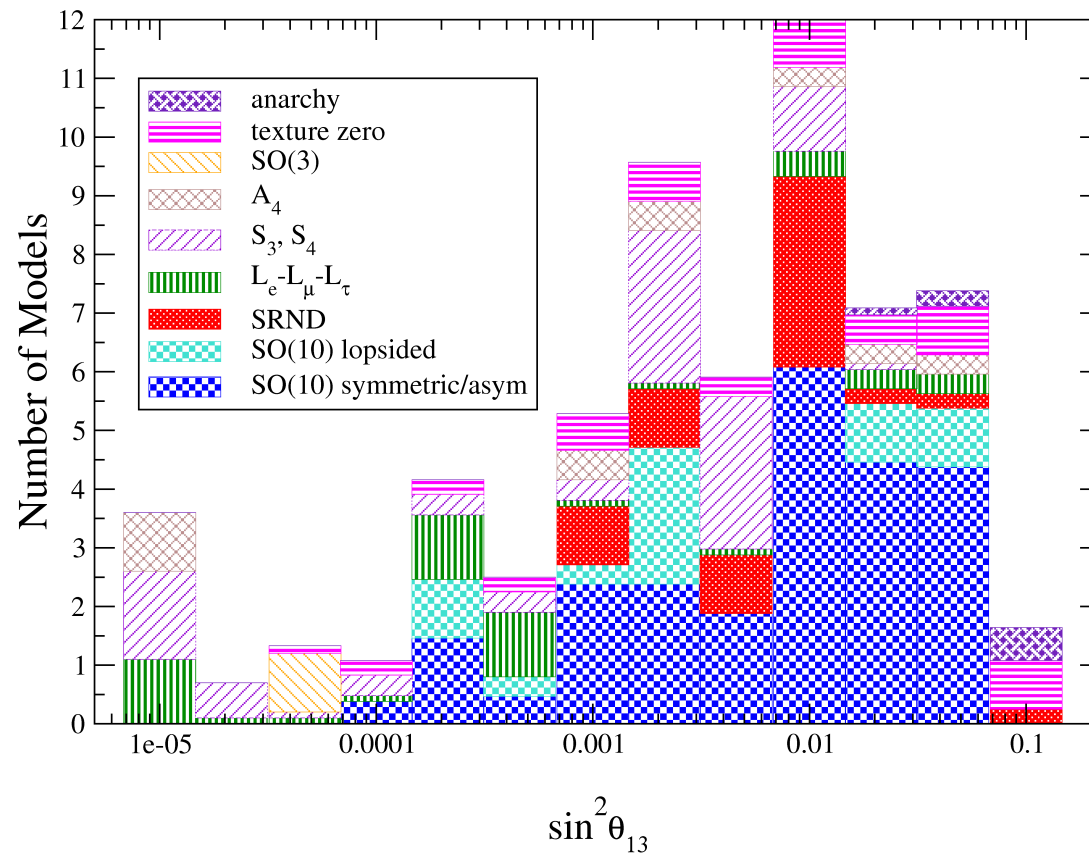
The Flavour Puzzle

Talks by S. Antusch, K.S. Babu, P.F. Harrison

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- Survey of 63  $\nu$  mass models in 2006 (Albright, M-C Chen, hep-ph/0608136)

Predictions of All 63 Models

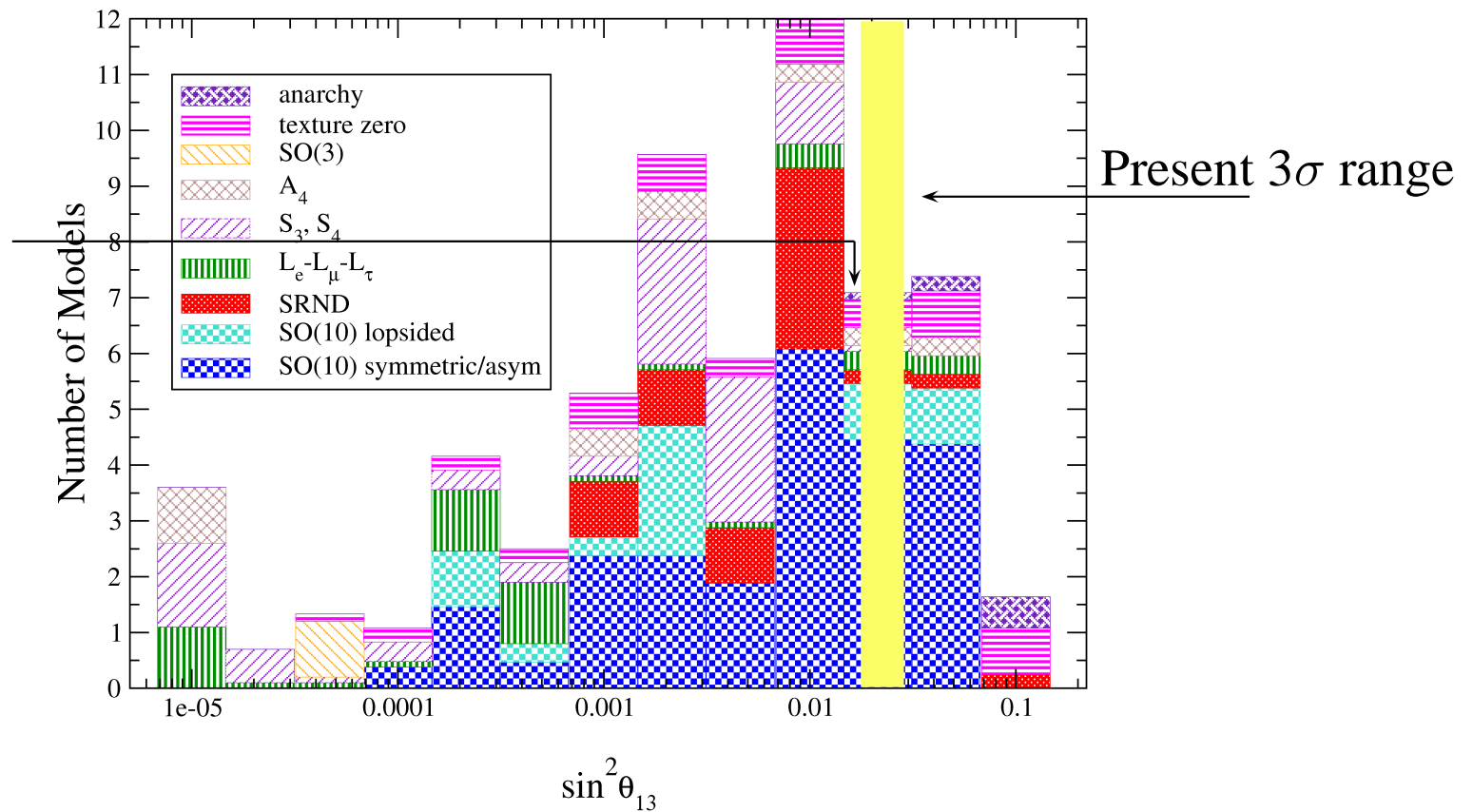


S. Antusch

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Predictions of All 63 Models



Only 7  
got it right !

S. Antusch

# Implications

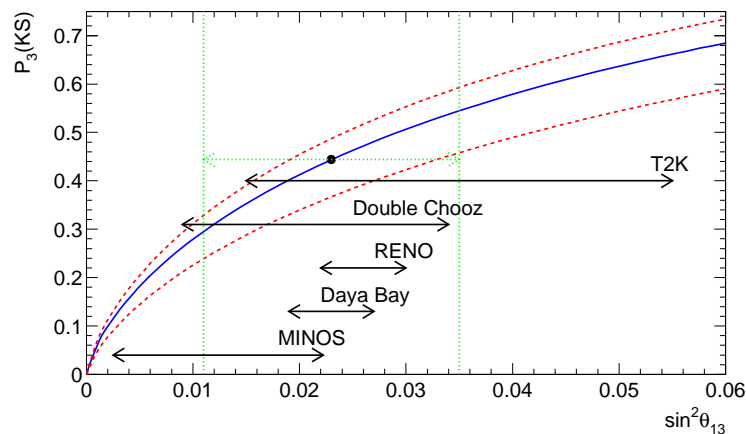
## Simplest proposals still alive

- Anarchy-Random

Hal, Murayama, Weiner (99)

⇒ large  $\theta_{13}$  OK with observed  $\theta_{13}$

de Gouvea, Murayama 1204.1249



- Quark-Lepton Complementarity

Minakata, Smirnov (94), Raidal (04)

Based on observation  $\theta_{12} + \theta_C = 45$

$$\Rightarrow \sin \theta_{13} \simeq \frac{\sin \theta_C}{\sqrt{2}} \simeq 0.026$$

Also other relations still to be tested

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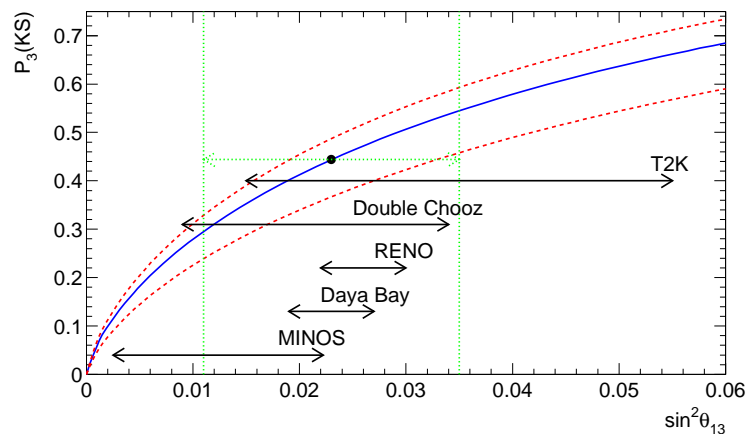
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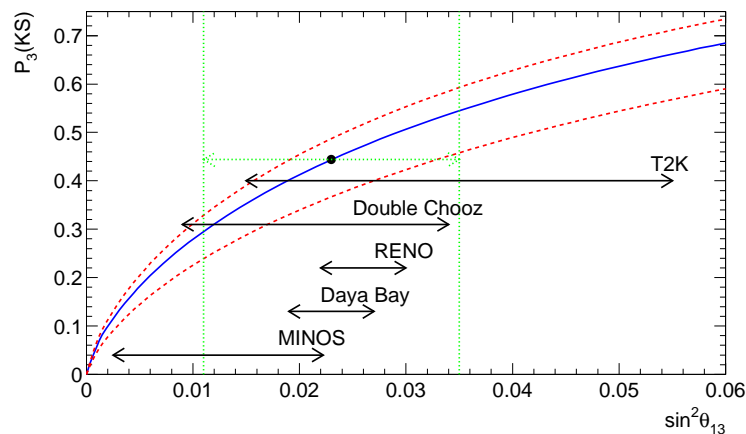
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Predicted in flavour symmetry models

(f.e. with symm groups  $A_4, S_4, A_5$ )

⇒ Consider as LO pattern corrected

f.e. by charge lepton mixing (GUTS)

⇒ Predicted sum rules with quark and

lepton angles and phases

Talk by S. Antusch

# Implications: Model Independent Approach

- If SM is an effective low energy theory, for  $E \ll \Lambda$ 
  - The same particle content as the SM and same pattern of symmetry breaking
  - But there can be non-renormalizable  
(dim > 4) operators

$$\mathcal{L} = \mathcal{L}_{\text{SM}} + \sum_n \frac{1}{\Lambda^{n-4}} \mathcal{O}_n$$

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**There is only one!**

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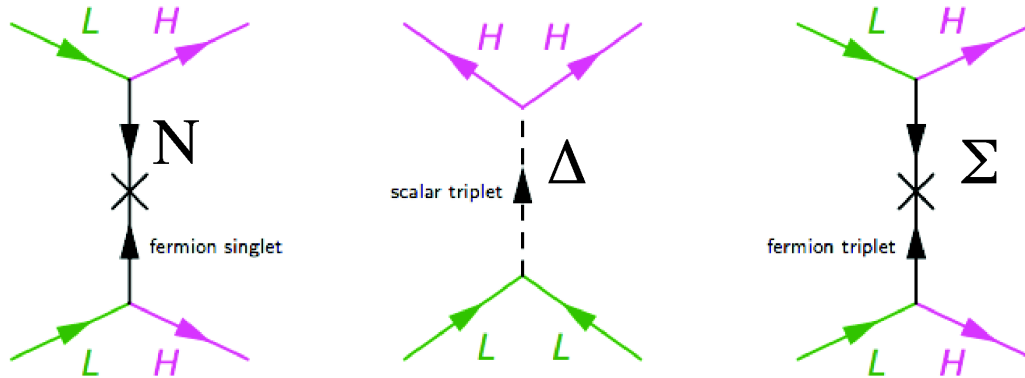
$$(M_\nu)_{\alpha\beta} = \frac{Z_{\alpha\beta}^\nu v^2}{2 \Lambda}$$

- Implications:
  - Expected that  $\nu$  mass is the first evidence of NP
  - Explains why  $m_\nu \ll$  other fermions masses  $\sim \lambda^f v$
  - If  $Z_{\alpha\beta}^\nu \gtrsim 10^{-4}$ ,  $m_\nu > \sqrt{|\Delta m_{atm}^2|} \sim 0.05 \text{ eV} \Rightarrow \Lambda \sim 10^{10} - 10^{15} \text{ GeV}$
  - $\mathcal{O}_5$  breaks lepton number and lepton flavours

# The See-Saw Models

Minkowski; Ramond, Gell-Mann, Slansky, Yanagida; Konetschny, Kummer; Cheng, Li; Lazarides, Shafi, Wetterich; Schechter, Valle; Mohapatra, Senjanovich; Foot, Lew, He, Joshi

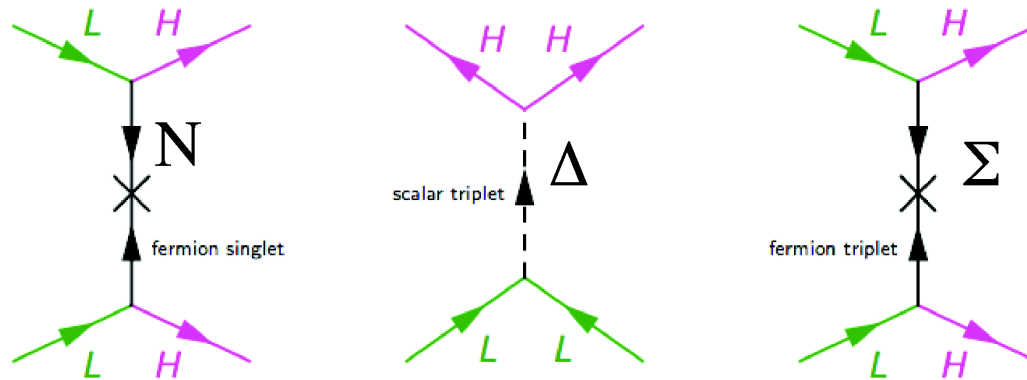
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• For fermionic see-saw

$$-\mathcal{L}_{\text{NP}} = -i\overline{N}_i \not{D} N_i + \frac{1}{2} M_{ij} \overline{N}_i^c N_j + \lambda_{\alpha j}^\nu \overline{L}_\alpha \tilde{\phi} N_j [\cdot \tau]$$

$$\Rightarrow \mathcal{O}_5 = \frac{(\lambda^{\nu T} \lambda^\nu)_{\alpha\beta}}{\Lambda} \left( \overline{L}_\alpha \tilde{\phi} \right) \left( \tilde{\phi}^T L_\beta^C \right) \text{ with } \Lambda = M$$

• For scalar see-saw

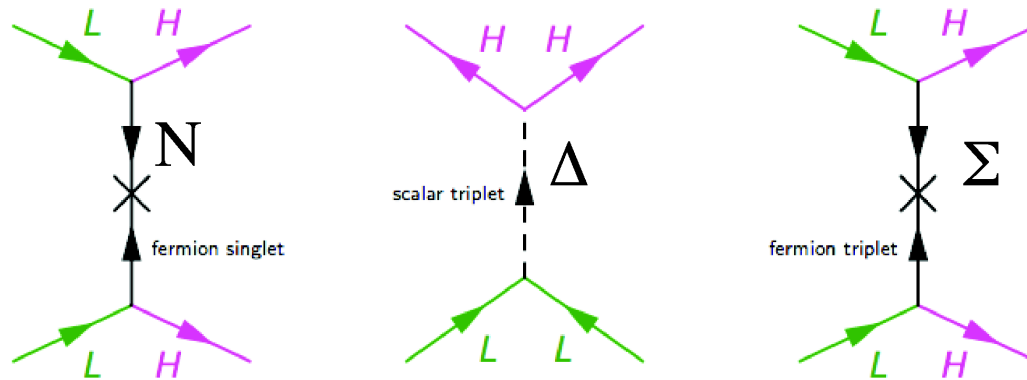
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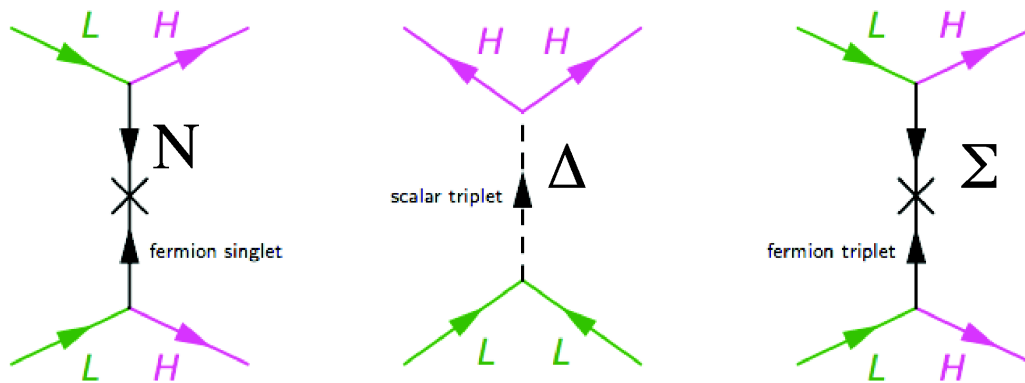
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Very different physics, but same  $\nu$  parameters: How to proceed?

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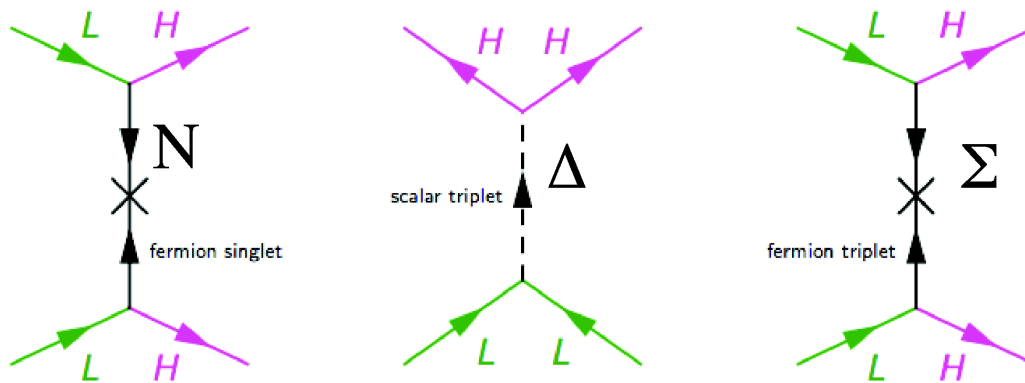
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Example: SO(10) GUT which relates quark and lepton masses and mixing [S.F. Babu](#)

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How to proceed?

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– Still Bottom-up: Hope for additional information from [charged LFV](#), [collider signals](#) ...

# Implications: LFV & Collider Signatures

- $\nu$  oscillation  $\Rightarrow$  Lepton Flavour is not conserved

If only  $\mathcal{O}_5 \Rightarrow Br(\tau \rightarrow \mu\gamma) \sim 10^{-41}$  too small!

- But dim=6 operators are LN conserving but LFV (f.e.  $\mathcal{O}_6 \sim \bar{L}_\alpha \bar{L}_\beta L_\gamma L_\rho$ ).

So may be

$$\mathcal{L} = \mathcal{L}_{SM} + \frac{c_{5\alpha\beta}}{\Lambda_{LN}} \left( \bar{L}_\alpha \tilde{\phi} \right) \left( \tilde{\phi}^T L_\beta^C \right) + \sum_i \frac{c_{6,i}}{\Lambda_{LF}^2} \mathcal{O}_{6,i}$$

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$$\mathcal{L} = \mathcal{L}_{SM} + \frac{c_{5\alpha\beta}}{\Lambda_{LN}} \left( \bar{L}_\alpha \tilde{\phi} \right) \left( \tilde{\phi}^T L_\beta^C \right) + \sum_i \frac{c_{6,i}}{\Lambda_{LF}^2} \mathcal{O}_{6,i}$$

- In general to have observable LFV one needs to decouple :

New Physics scale  $\Lambda_{LN}$  responsible for the small  $m_\nu$  from

New Physics scale  $\Lambda_{LF}$  ( $\ll \Lambda_{LN}$ ) controlling of LFV

- Collider signatures if mass of heavy states  $M \sim \Lambda_{LN} \sim \text{TeV}$  and/or  $M \sim \Lambda_{LF} \sim \text{TeV}$

If  $M \sim \Lambda_{LF} \sim \text{TeV}$  ( $\ll \Lambda_{LN}$ ) motivation of light  $\nu$  OK

Furthermore if  $c_{6,i} \propto c_5^{\text{some power}} \Rightarrow$  LFV and collider signals directly related to  $M_\nu$

# Implications: LFV & Collider Signatures

- $\nu$  oscillation  $\Rightarrow$  Lepton Flavour is not conserved

If only  $\mathcal{O}_5 \Rightarrow Br(\tau \rightarrow \mu\gamma) \sim 10^{-41}$  too small!

- But dim=6 operators are LN conserving but LFV (f.e.  $\mathcal{O}_6 \sim \bar{L}_\alpha \bar{L}_\beta L_\gamma L_\rho$ ).

So may be

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## Minimal Lepton Flavour Violation

Cirigliano, Grinstein, Isidori, Wise(05); Davidson, Palorini (06); Gavela, Hambye, Hernandez,Hernandez (09)  
Alonso, Isidori, Merlo, Munoz, Nardi(11)

# Implications: MLFV & Collider Signatures

- Minimal Flavour Violation Hypothesis: Chivukula, Georgi (87) Buras, Gambino, Gorbahn, Jager, Silvestrini,(01) d'Ambrosio, Giudice, Isidori, Strumia (02)

*Yukawas are the only source of flavour violation in and beyond SM*

Very **predictive** and **successful** to explain **quark** flavour data

For **leptons** more **subtle** since BSM fields are required to generate **majorana**  $M_\nu$

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- Scalar (Type-II) see-saw is MLFV

$$c_{5,\alpha\beta} = f_{\Delta\alpha\beta} \frac{\mu}{M_\Delta} \quad c_{6,\alpha\beta\gamma\rho} = f_{\Delta\alpha\beta}^\dagger f_{\Delta\gamma\rho}$$

- If  $M_\Delta \lesssim \text{TeV}$

$\Rightarrow$  Production of triplet scalars:  $H^{\pm\pm}, H^\pm, A_0, H_0$

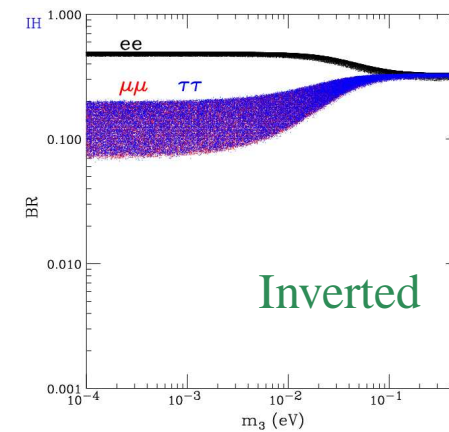
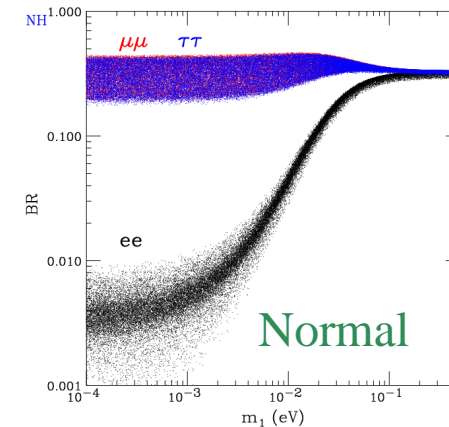
Striking Signatures

$$pp \rightarrow H^{++} H^{--}$$

$$pp \rightarrow H^{++} H^-$$

$$\Rightarrow H^{\pm\pm} l_i^\pm l_j^\pm, H^\pm \rightarrow l_i^\pm \nu_j$$

predicted by neutrino parameters



Akeroyd et al, Chao et al, Fileviez et al  
Garayoa et al, Han et al, Kadastik et al ...

# Implications: MLFV & Collider Signatures

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For **leptons** more **subtle** since BSM fields are required to generate **majorana**  $M_\nu$

- Simplest MLFV Fermionic (I or III) see-saw

→ one massless  $\nu$  & one CP phase  $\alpha$

→ Yukawas  $\lambda_{\alpha N}$  determined by  $\nu$  parameters

- If  $M_N \lesssim \text{TeV}$

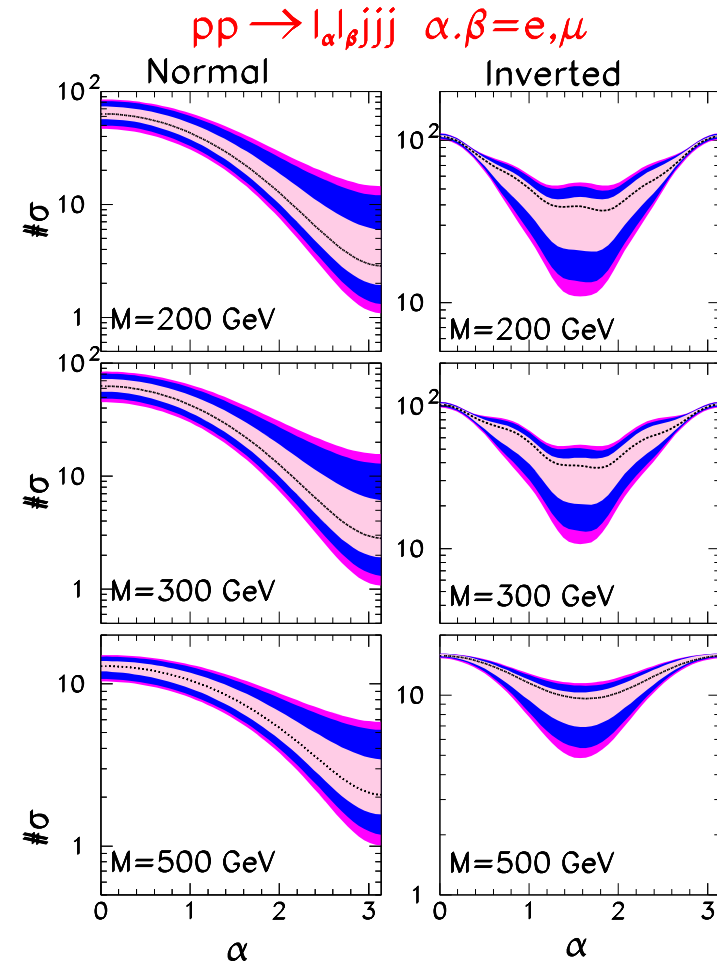
– Type-I unobservable but Type-III observable

$$pp \rightarrow F(\rightarrow \ell_\alpha X)F'(\rightarrow \ell_\beta X')$$

– **Rates predictable in terms of  $\nu$  parameters**

$$N_{\alpha\beta}^{\text{ev}} \propto |\lambda_{\alpha N}|^2 |\lambda_{\beta N}|^2$$

– **Difficult but *beatable* SM backgrounds**



Eboli, Gonzalez-Fraile, MCGG 1108.0661

# Conclusions

- First ICHEP with the three leptonic mixing angles determined (at  $\pm 3\sigma/6$ )

$$\Delta m_{21}^2 = 7.5 \times 10^{-5} \text{ eV}^2 \text{ (2.4\%)}$$

$$\Delta m_{31}^2 = 2.45 \times 10^{-3} \text{ eV}^2 \text{ (2.8\%)}$$

$$|\Delta m_{32}^2| = 2.43 \times 10^{-3} \text{ eV}^2$$

$$\sin^2 \theta_{12} = 0.3 \text{ (4\%)}$$

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Absolute  $\nu$  mass

CP violation in leptons?

Normal or Inverted Ordering?

$\theta_{23}$  Octant

$\Rightarrow$  New experiments beyond approved  
needed to answer these questions

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$\nu$  masses are BSM physics effects to be put together with *all other NP effects*:  
from charged LFV, Collider signals, Cosmo-astroparticle... to establish  
the Next Standard Model

# NEUTRINOS: THEORY

Concha Gonzalez-Garcia

THANK YOU

Special thanks to:

My “ $\nu$ ” Collaborators: M. Maltoni, J. Salvado, T. Schwetz, J.J. Gomez-Cadenas

My “Higgs” Collaborators: T. Corbett, J. Gonzalez-Fraile, O. Eboli

# The New Minimal Standard Model

- Minimal Extensions to give Mass to the Neutrino:

- \* Introduce  $\nu_R$  AND impose  $L$  conservation  $\Rightarrow$  Dirac  $\nu \neq \nu^c$ :

$$\mathcal{L} = \mathcal{L}_{SM} - M_\nu \bar{\nu}_L \nu_R + h.c.$$

- \* NOT impose  $L$  conservation  $\Rightarrow$  Majorana  $\nu = \nu^c$

$$\mathcal{L} = \mathcal{L}_{SM} - \frac{1}{2} M_\nu \bar{\nu}_L \nu_L^C + h.c.$$

- The charged current interactions of leptons are not diagonal (same as quarks)

$$\frac{g}{\sqrt{2}} W_\mu^+ \sum_{ij} (U_{\text{LEP}}^{ij} \bar{\ell}^i \gamma^\mu L \nu^j + U_{\text{CKM}}^{ij} \bar{U}^i \gamma^\mu L D^j) + h.c.$$

- To fully determine the lepton flavour sector we want to know:

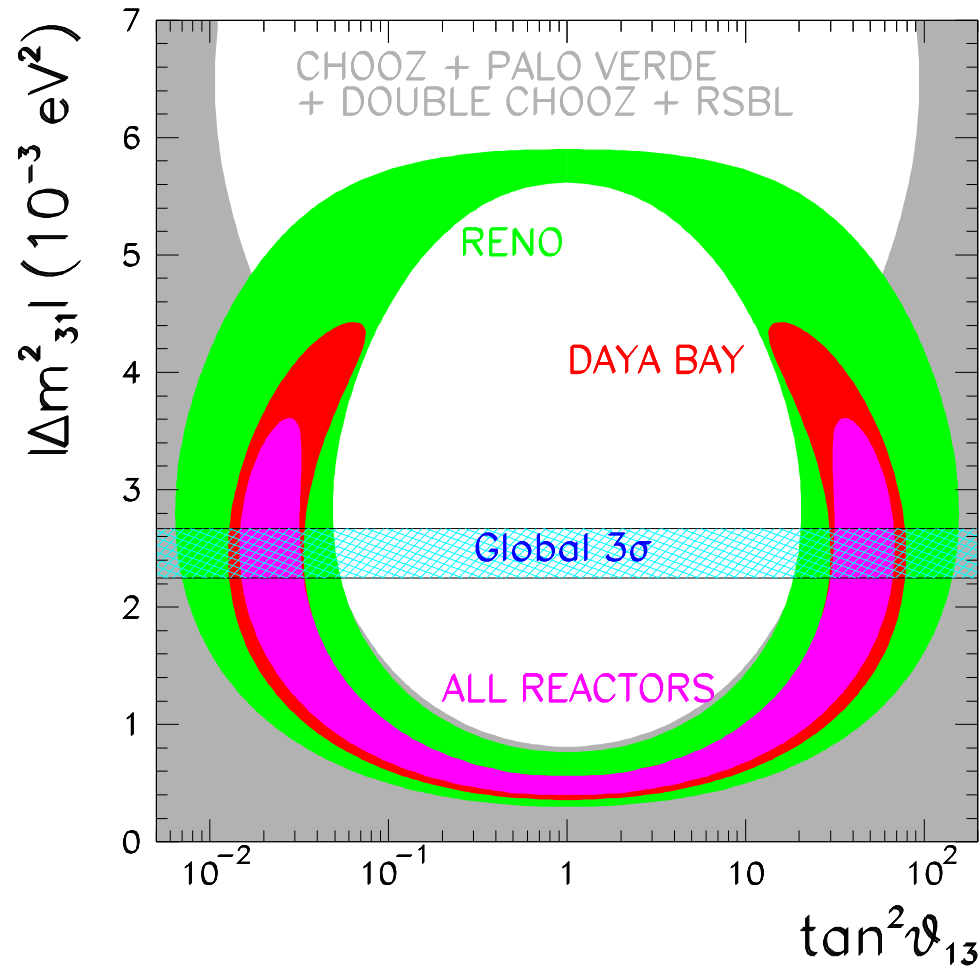
- \* How many,  $N$ , massive  $\nu_i$  and their masses  $m_i$

- \* Their mixing and CP properties (angles and phases in  $U_{\text{LEP}}$ )

- \* Their nature: Dirac neutrino  $\Rightarrow$  If  $L$  is conserved

- Majorana neutrino  $\Rightarrow$  If  $L$  is violated (and extra phases)

# 3 $\nu$ Analysis: Reactor Data and $\Delta m_{31}^2$



$3\sigma$  regions 2dof

- Due to different baselines the combination of reactors provides independent determination of the largest mass splitting
- Expected to improve with Daya-Bay and Reno spectrum

# Lepton Mixing Unitarity

- Previous results assume  $U_{\text{LEP}}$  to be unitary
- If  $\nu_L$  mixed with  $m$  extra states  $U_{\text{LEP}} = (K_l, K_h)$  Schechter, Valle (1980)  
And  $U_{\text{LEP}} U_{\text{LEP}}^\dagger = I_{3 \times 3}$  but in general  $U_{\text{LEP}}^\dagger U_{\text{LEP}} \neq I_{(3+m) \times (3+m)}$
- If  $m$  states are heavy ( $M \gg E_\nu$ ) oscillations measure  $K_L, 3 \times 3$  (not unitary)

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Flavour Changing Neutral Currents

- But this **unitarity violation**  $\Rightarrow$  Flavour Violation in Charged Lepton Processes  
Universality Violation of Charge Current ...

- Constraints on these processes limit leptonic unitarity violation to

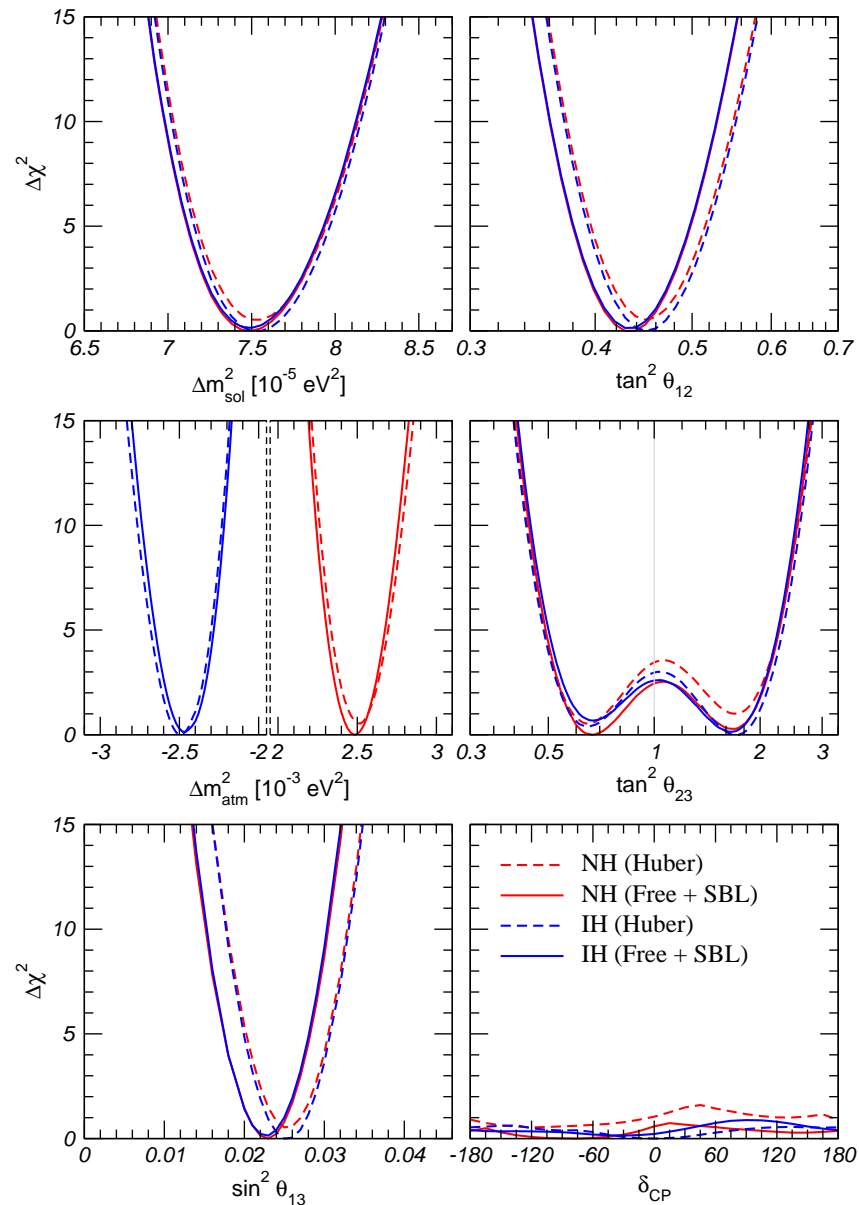
$$|K_l K_l^\dagger| = \begin{pmatrix} 0.994 \pm 0.005 & < 7.0 \times 10^{-5} & < 1.6 \times 10^{-2} \\ < 7.0 \times 10^{-5} & 0.995 \pm 0.005 & < 1.0 \times 10^{-2} \\ < 1.6 \times 10^{-2} & < 1.0 \times 10^{-2} & 0.995 \pm 0.005 \end{pmatrix}$$

Antusch *et al* hep-ph/0607029

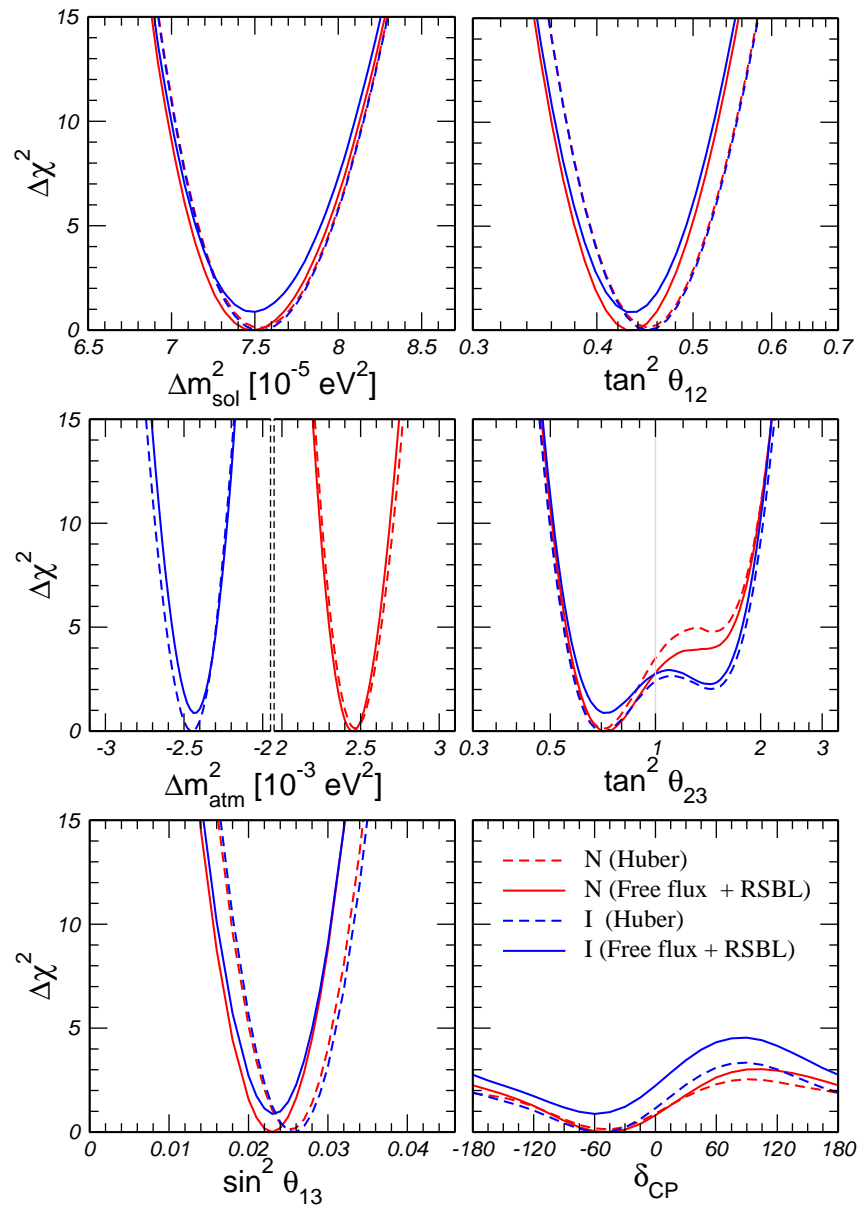
or equivalently  $K_l \simeq (I + \epsilon)U(\theta_{ij}, \delta, \eta_i)$  with  $|\epsilon_{\alpha j}| \leq \text{few} \times 10^{-3}$  while  $K_h \sim \mathcal{O}(\epsilon)$

# Flavour Parameters: Status without/with ATM

Without ATM



With ATM



# 3-flavor effects in atmospheric neutrinos

Peres, Smirnov, 99;  
Gonzalez-Garcia, Maltoni, Smirnov, 04

excess in electron-like events:

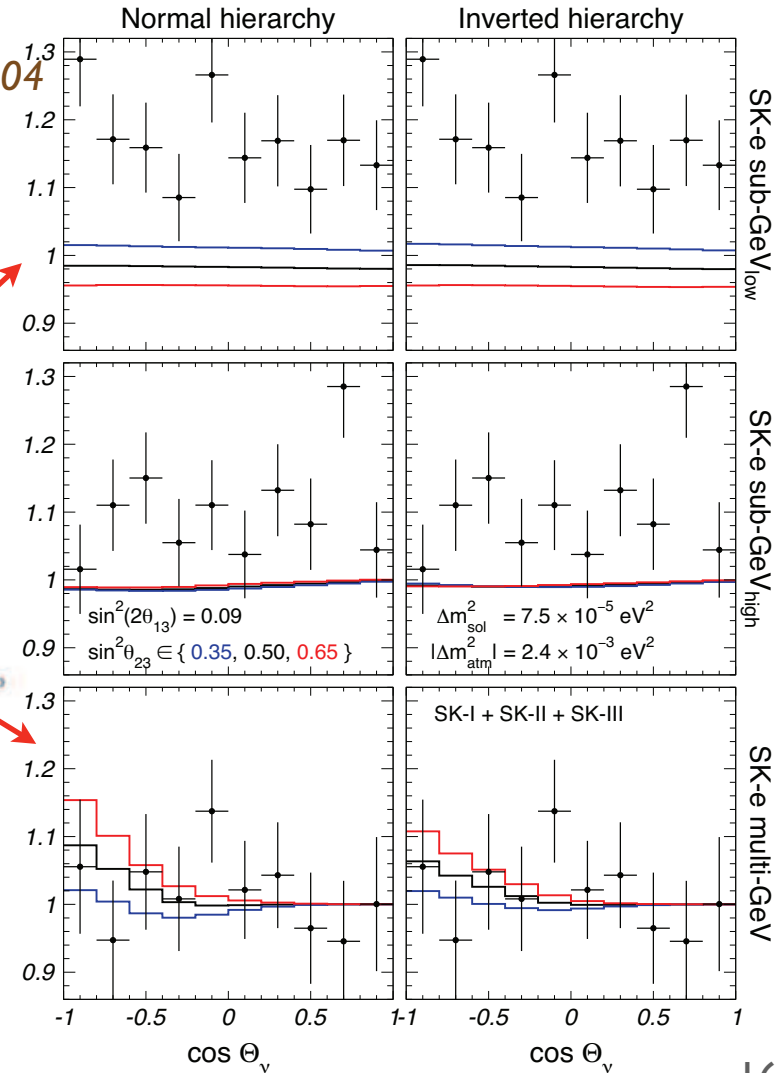
$$\frac{N_e}{N_e^0} - 1 \simeq (r s_{23}^2 - 1) P_{2\nu}(\Delta m_{31}^2, \theta_{13}) \quad \theta_{13}\text{-effects}$$

$$+ (r c_{23}^2 - 1) P_{2\nu}(\Delta m_{21}^2, \theta_{12}) \quad \Delta m_{21}^2\text{-effects}$$

$$- 2s_{13}s_{23}c_{23} r \operatorname{Re}(A_{ee}^* A_{\mu e}) \quad \text{interference: } \delta_{\text{CP}}$$

$$r = r(E_\nu) \equiv \frac{F_\mu^0(E_\nu)}{F_e^0(E_\nu)}$$

$r \approx 2$  (sub-GeV)  
 $r \approx 2.6 - 4.5$  (multi-GeV)



T. Schwetz