Constraining new physics scenarios in neutrino oscillations

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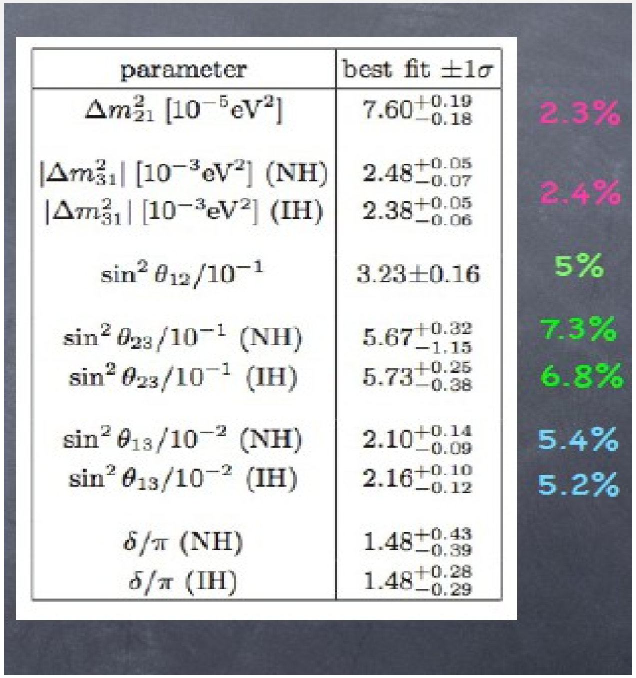
Searching for New Physics

Neutrino oscillation physics is entering a precision era:

- Good knowledge of mixing angles and mass differences
- First hints of a non-vanishing CP phase
- Sum of the neutrino masses bounded

  from above (around 0.2 eV)

Mariam's talk



parameter	best fit $\pm 1\sigma$	
Δm^2_{21} [10^{-5}eV^2]	$7.60^{+0.19}_{-0.18}$	2.3%
$\lvert\Delta m^2_{31}\rvert$ [10^{-3}eV^2] (NH)	$2.48^{+0.05}_{-0.07}$	2.4%
$\lvert\Delta m^2_{31}\rvert$ [10^{-3}eV^2] (IH)	$2.38^{+0.05}_{-0.06}$	
$\sin^2\theta_{12}/10^{-1}$	3.23 ± 0.16	5%
$\sin^2\theta_{23}/10^{-1}$ (NH)	$5.67^{+0.32}_{-1.15}$	7.3%
$\sin^2\theta_{23}/10^{-1}$ (IH)	$5.73^{+0.25}_{-0.38}$	6.8%
$\sin^2\theta_{13}/10^{-2}$ (NH)	$2.10^{+0.14}_{-0.09}$	5.4%
$\sin^2\theta_{13}/10^{-2}$ (IH)	$2.16^{+0.10}_{-0.12}$	5.2%
δ/π (NH)	$1.48^{+0.43}_{-0.39}$	
δ/π (IH)	$1.48^{+0.28}_{-0.29}$	

It is time to devote serious efforts to the search of New Physics in the lepton sector, using neutrinos

Two (three) different items

Main message of this talk:

Neutrinos can be used as probes for some New Physics scenarios

Discussing new results in details for two examples to show how New Physics shows up in the ν sector

- Sterile neutrinos
- Large Extra Dimensions
- (Non Standard Interactions)

Perturbative approach

- $\sin^2 2\theta_{13}$ is a small parameter

⇓

- New effects in oscillations must be even smaller

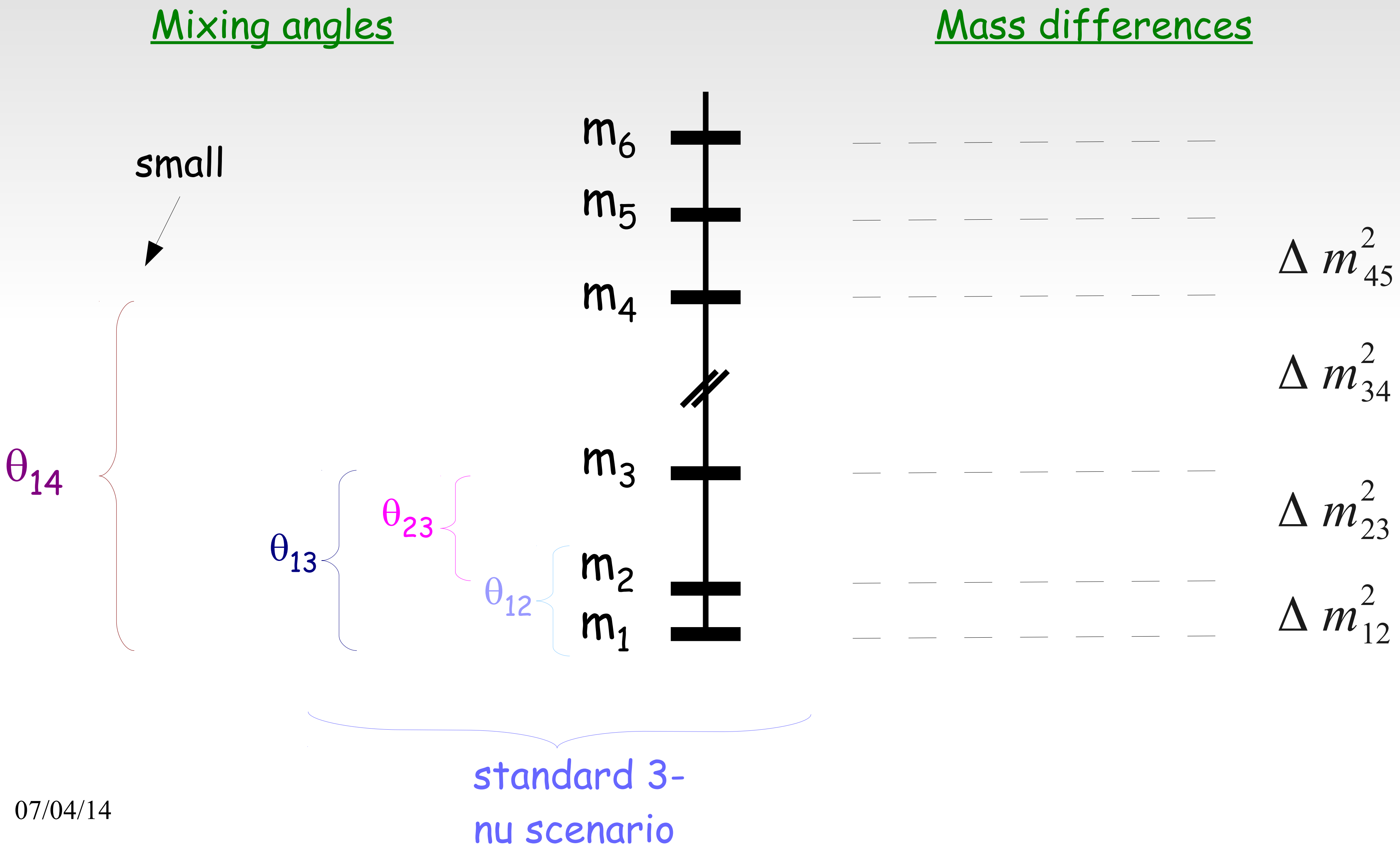
$$A(\nu_\alpha \to \nu_\beta) = A^{SM} \underbrace{(\nu_\alpha \to \nu_\beta) + \delta\, A_{\alpha\beta}}_{\text{interference}}$$

From the interference term one can:
(δ^2 is generally too small)

- set strong bounds on δ if the data are precise and very well described by SM physics
- "measure" δ if the data are precise and NOT well described by SM physics

Ex: $\sin^2 2\theta^{eff}_{13} = \sin^2 2\theta^{SM}_{13}\ (1+\delta)$

The case of sterile neutrinos



The case of sterile neutrinos

$$U = \underbrace{R_{34}\,R_{24}\,R_{14}}_{\text{perturbations}}\,R_{23}\,R_{13}\,R_{12}$$

Example: $\nu_e \rightarrow \nu_e$ transition

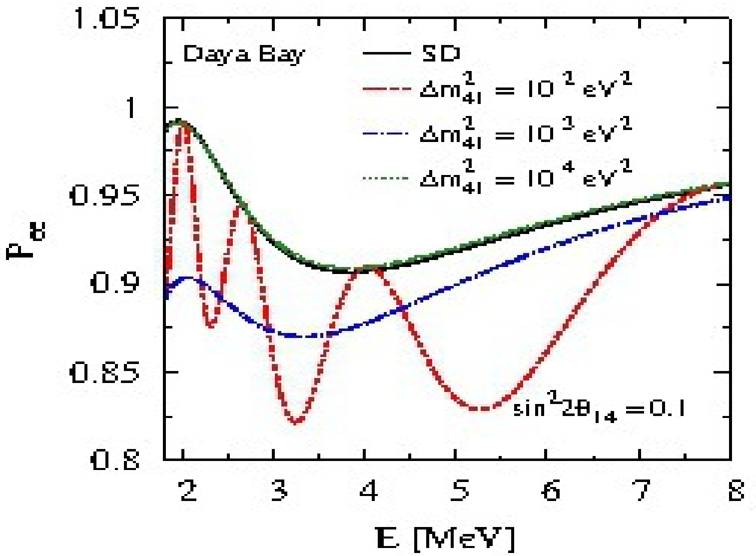
$$P_{ee} \sim 1 - s_{12}\sin^2 2\theta_{13}\sin^2\left(\frac{\Delta m^2_{32} L}{4E_\nu}\right) - c^2_{12}\sin^2 2\theta_{13}\sin^2\left(\frac{\Delta m^2_{31} L}{4E_\nu}\right) \quad \Rightarrow \quad \text{Standard}$$

$$- s_{12}\sin^2 2\theta_{14}\sin^2\left(\frac{\Delta m^2_{42} L}{4E_\nu}\right) - c^2_{12}\sin^2 2\theta_{14}\sin^2\left(\frac{\Delta m^2_{41} L}{4E_\nu}\right) \quad \Rightarrow \quad \text{Interference}$$

Current upper limit:

$\sin^2 2\theta_{14} \sim 0.1$

M.C.Gonzalez-Garcia et al.,
JHEP 1212, 123 (2012)



The case of sterile neutrinos

Bounds on new parameters require experiments
with very low systematic uncertainties

Daya Bay in China:

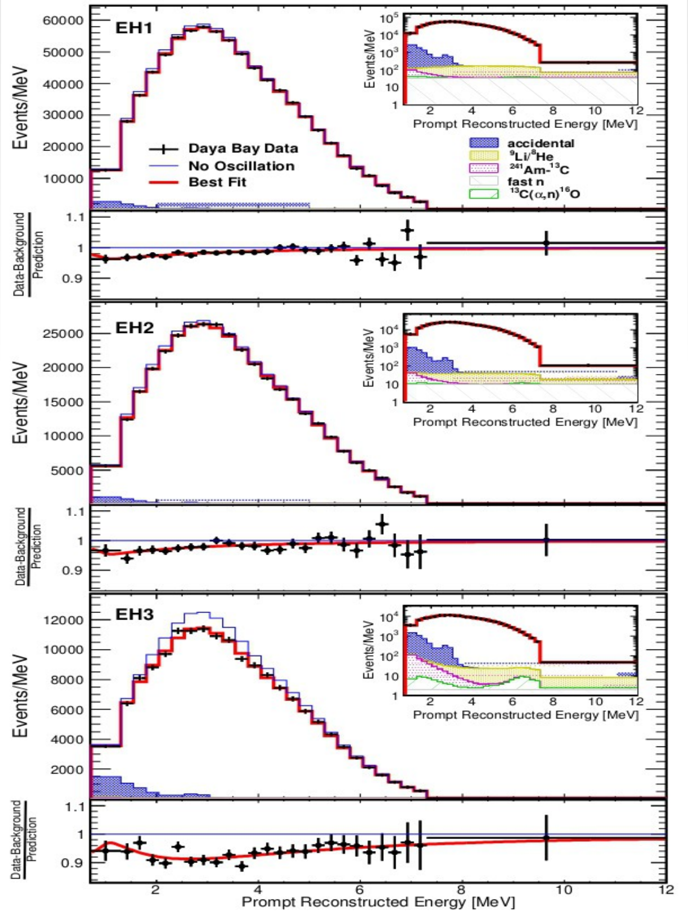
$\bar{\nu}_e \to \bar{\nu}_e$ transition

neutrinos from reactor plants

Daya Bay Collaboration,
Phys.Rev.Lett.112, 061801 (2014)

Near
Detectors

Far Hall



Standard result: $\sin^2 2\theta_{13} = 0.090\ (0.009)$

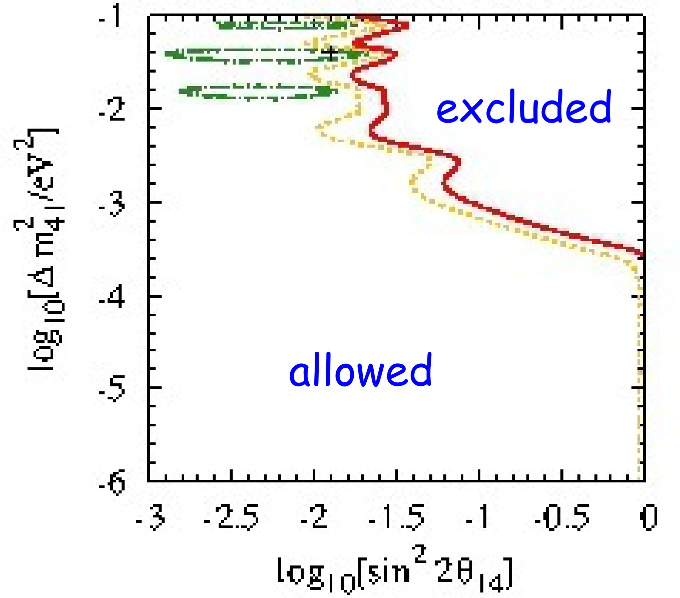
$\Delta m^2_{31} = 2.59(0.20) \times 10^{-3}\ \mathrm{eV}^2$

The case of sterile neutrinos

New results...

1,2 and 3σ confidence level

3+1 result



L/Enu →

Δm^2 around $10^{-2/3}$ eV^2

New bound: $\sin^2 2\theta_{14}$ <~ 10^{-2}

I.Girardi, D.Meloni, T.Ohlsson, H.Zhang and S.Zhou, arXiv:1405.6540 [hep-ph].

Large Extra Dimensions

Hierarchy problem:

there exist two fundamental energy scales:

- the electroweak scale $M_D \sim 1$ TeV
- quantum gravity $M_{PL} \sim 10^{18}$ GeV

<u>A possible way-out:</u>

- there are δ compact extra dimensions of radius R and M_D is the only fundamental energy scale: $M^2_{PL} = R^\delta M^{\delta+2}_D$
- at distances less than R gravity propagates in all $4+\delta$ dimensions
- Standard Model fields are confined in our 4D world

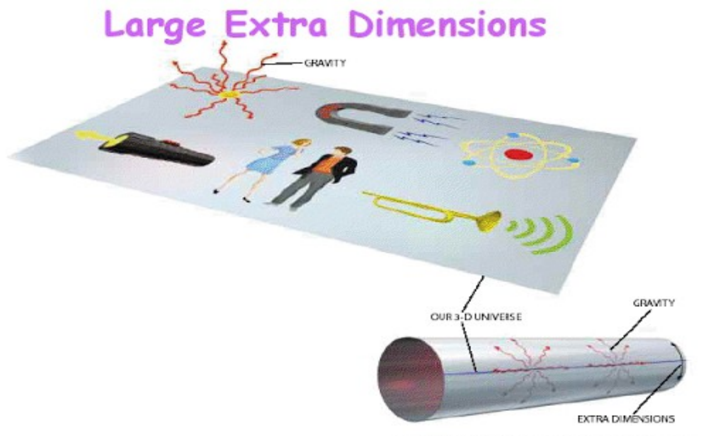


Figure from Scientific American

Right-handed neutrinos in extra dimensions

Since neutrinos are special: massless right-handed neutrinos ν_R also feel the whole 5D space

- ν_R propagated in the whole 5D
- $\nu_R = \nu_R(x^\mu, y)$

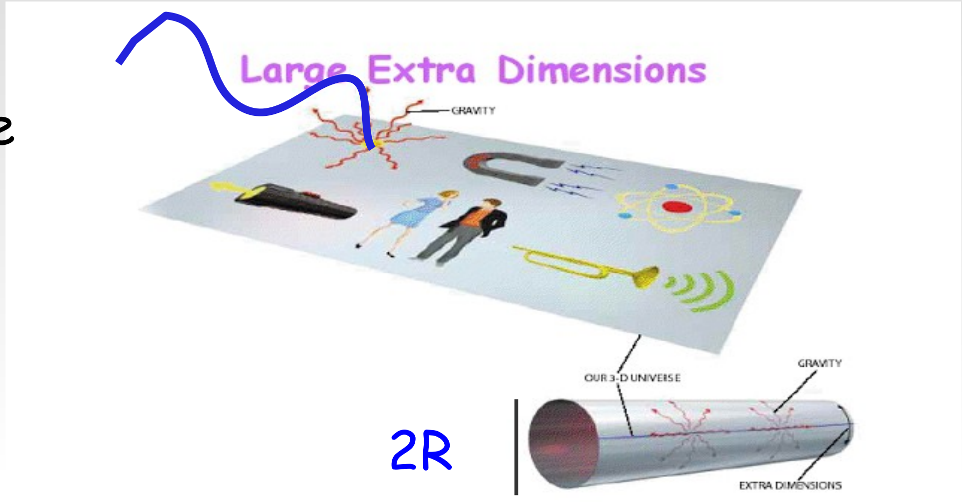


Figure from Scientific American

Imposing $y = y + 2\pi R$ on the ν_R wave function generates infinite replica of the field

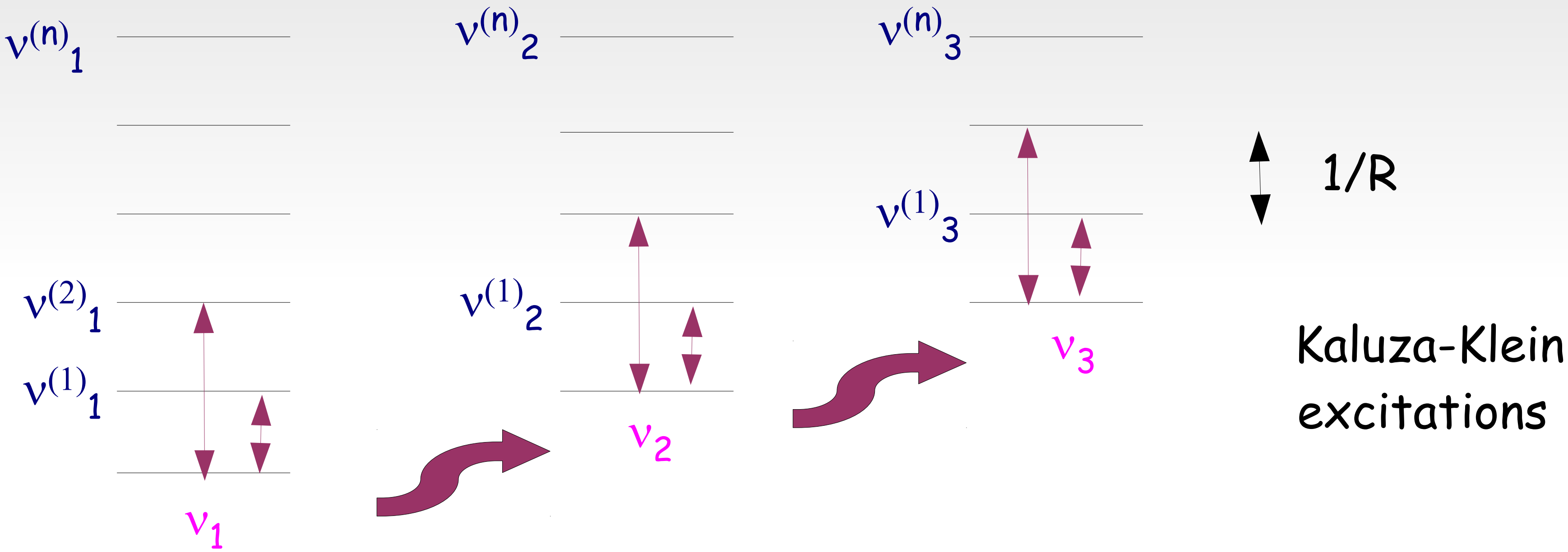
$$\nu_R(x, y) \sim \Sigma_{n=-\infty}^{+\infty} \nu_R^{(n)}(x, y) e^{\frac{iny}{R}}$$

Interaction term:

$$\lambda_{\alpha\beta} \nu_L^{\alpha}(x) \nu_R^{\beta}(x, 0) H(x)$$

Right-handed neutrinos in extra dimensions

For the mass eigenstates (normal ordering):



Oscillations can take place among active-active and active-KK (infinite) states

Right-handed neutrinos in extra dimensions

$$A(\nu_\alpha \rightarrow \nu_\beta) = \Sigma_j U_{\beta j} U^*_{\alpha j} e^{\frac{-i m_j^2 L}{2 E_\nu}} \rightarrow \Sigma_{j=1}^{3} \Sigma_{k=0}^{\infty} U_{\beta j} U^*_{\alpha j} \left|W_j^{(k)}\right|^2 e^{\frac{-i \lambda_j^{(k)2} L}{2 E_\nu R^2}}$$

D. Davoudiasl, P. Langacker and M. Perelstein, Phys. Rev. D 65, 105015 (2002)

$W_j^{(k)}$ = Transition between zero modes and KK

$\lambda_j^{(k)}$ = absolute neutrino masses

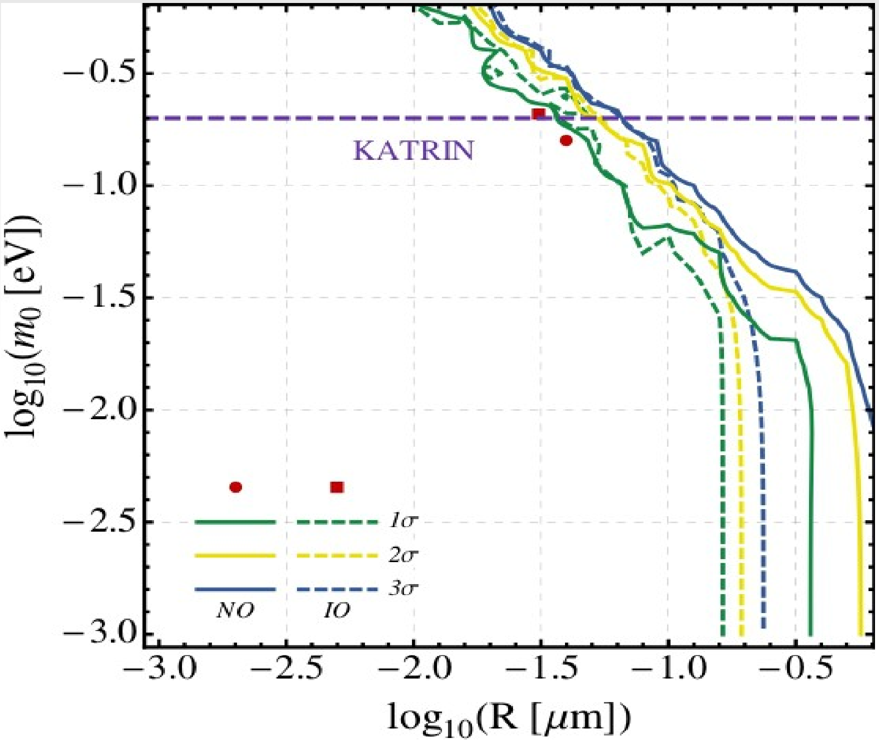
Depend on the lightest absolute neutrino mass m_0 and R

- Only upper limit on m_0 (from $\Sigma_i m_i < 0.2$ eV)
- Limits on R from experiments based on the torsion pendulum: $R < 37 \times 10^{-6}$ m (95% CL) on the largest extraD

J. Beringer et al. (Particle Data Group Collaboration), Phys. Rev. D 86, 010001 (2012)

First results...

new limits from Daya Bay



$R < 0.2\ (0.6) \times 10^{-6}$ m @2σ
for Inverted (Normal) Ordering

I. Girardi and D, Meloni, 1403.5507

Conclusions

- Neutrino physics is an active field, from both experimental and theoretical point of views
- Many and precise data are now available, which are very well described in the context of the SM theory of neutrino oscillation
- As for the hadronic sector, New Physics must pop-up as perturbations of the standard picture
- We started to investigate such tiny effects for a variety of New Physics scenarios...

Backup

The case of sterile neutrinos

χ^2 analysis

NP parameters

measured events

theoretical predictions

$$\chi^2(\vec{\theta},\vec{S},\underbrace{\alpha_r,\epsilon_d,\eta_d}_{\text{pull parameters}})=\Sigma_{d=1}^{6}\frac{\left[M_d-T_d\left(1+\Sigma_r\,\omega_r^d\,\alpha_r+\epsilon_d\right)+\eta_d\right]^2}{M_d+B_d}$$

SM parameters

pull parameters

background events

$$+\Sigma_r\frac{\alpha_r^2}{\sigma_r^2}+\Sigma_{d=1}^{6}\left[\frac{\epsilon_d^2}{\sigma_d^2}+\frac{\eta_d^2}{\sigma_{B_d}^2}\right]+priors$$

ω= the fraction of InverseBetaDecays contribution of the r-th reactor to the d-th detector

background uncertainties ~ O(1)

detector uncertainties ~ O(0.1%)

reactor uncertainties ~ O(1%)

GLoBES
P. Huber et al., Nucl. Phys. B665, 487 (2003);
P. Huber et al., Comput. Phys. Commun. 167,195 (2005).

Standard neutrino oscillations

- Neutrinos can also be described in terms of mass eigenstates ν_i

$$\downarrow$$

neutrino matrix

matrix

$$|\nu_\alpha\rangle = \Sigma_{i=1}^{3} U_{\alpha i} |\nu_i\rangle$$

- Considering time evolutions of mass eigenstates:

$$P(\nu_\alpha \rightarrow \nu_\beta) = |\langle \nu_\beta | \nu_\alpha(t) \rangle|^2 = \left| \Sigma_j U_{\beta j} U^*_{\alpha j} e^{\frac{-i m_j^2 L}{2 E_\nu}} \right|^2$$

$$U_{PMNS} = \underbrace{\begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix}}_{\text{atmospheric}} \times \underbrace{\begin{pmatrix} c_{13} & 0 & s_{13} e^{i\delta} \\ 0 & 1 & 0 \\ -s_{13} e^{-i\delta} & 0 & c_{13} \end{pmatrix}}_{\text{reactor}} \times \underbrace{\begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}}_{\text{solar}}$$

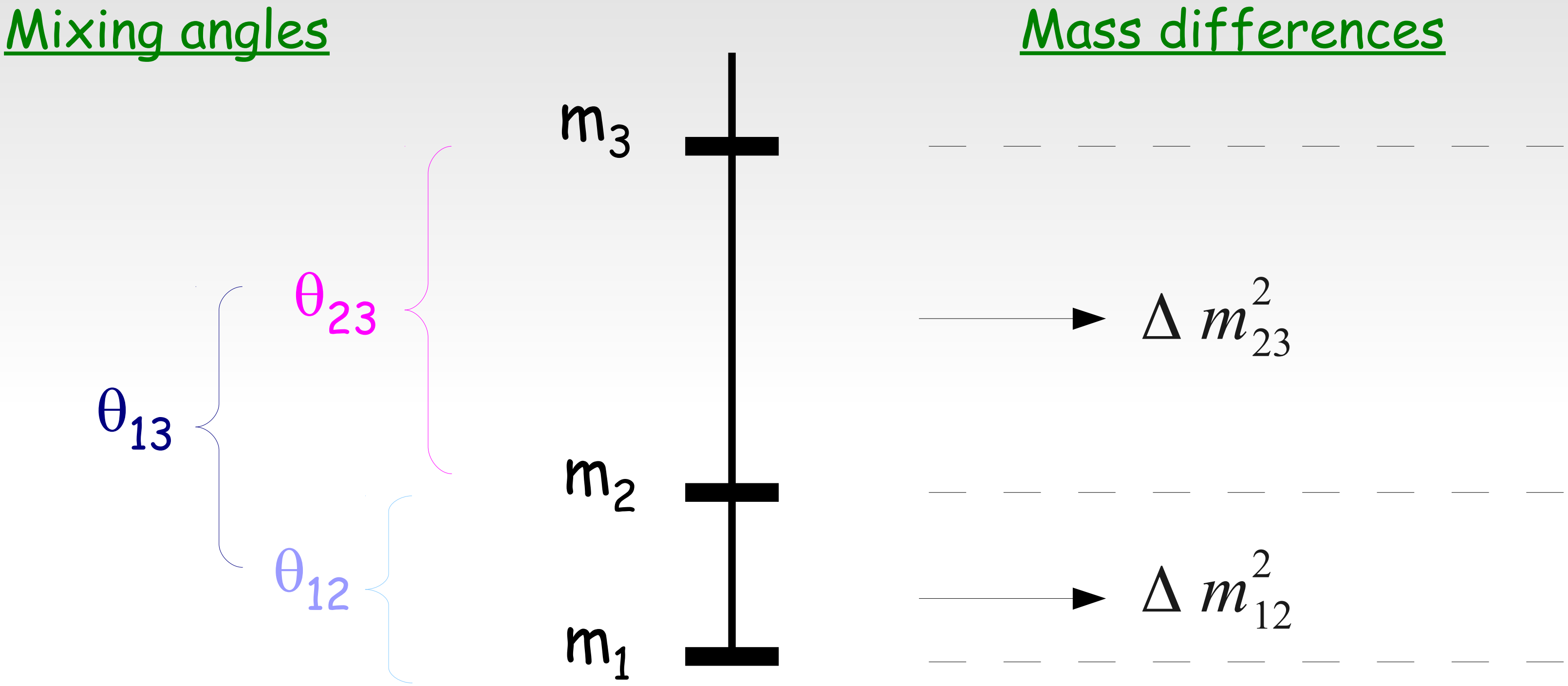
Summary of the experimental results

Gonzalez-Garcia et al. JHEP1212,(2012)123

Parameter	Fit results
θ_{12}	$33.36^{+0.81}_{-0.78}$
θ_{13}	$8.66^{+0.44}_{-0.46}$
θ_{23}	$40.0^{+2-1}_{-1.5}$
δ (?)	300^{+66}_{-138}
$(10^{-3}\,eV^2)$	$2.47^{+0.07}_{-0.07}$ Δm^2_{23}
$(10^{-5}\,eV^2)$	$7.50^{+0.18}_{-0.19}$ Δm^2_{12}

- precision era in the determination of mixing parameters

To be determined by oscillation experiments



- And: a possible CP phase δ and the absolute order of the mass eigenstates (normal or inverted hierarchy)

The case of sterile neutrinos

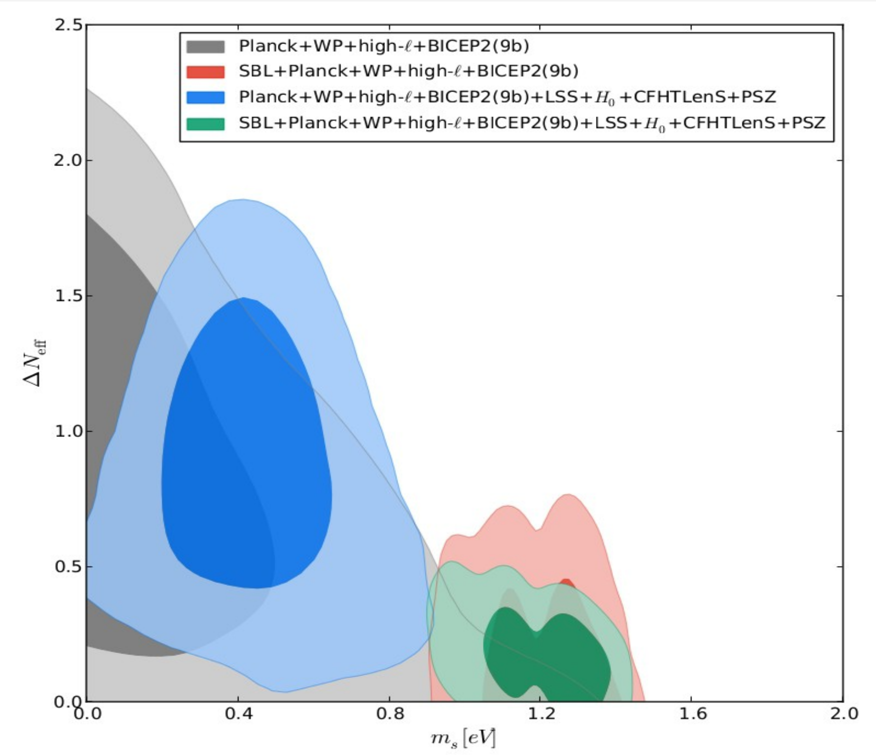
- The number of active neutrino species is fixed by the Z-boson invisible decay width: $N_\nu = 2.994 \pm 0.011$
- Extra families (if they exist) must have either very heavy neutrinos ($m_N > m_Z/2$), or no neutrinos at all

Standard Model singlets allowed:

sterile neutrinos

Renewed interest after the recent Planck and BICEP2 results

M.Archidiacono et al., arXiv:1404.1794 [astro-ph.CO]

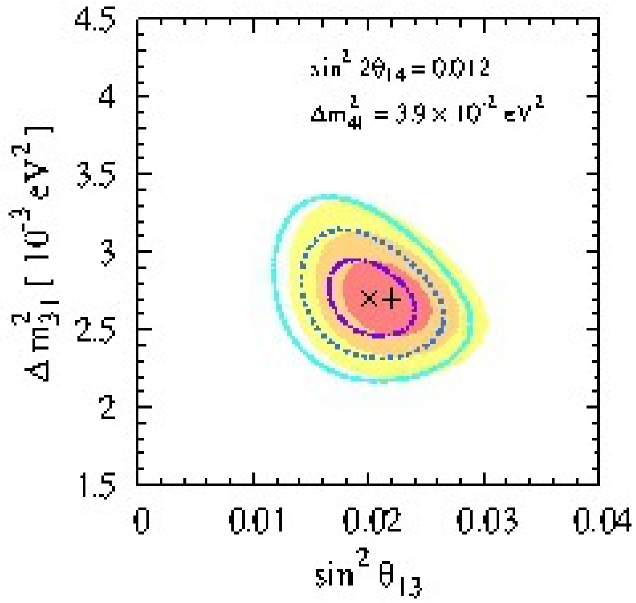


extra species

Mass of the extra species

The case of sterile neutrinos

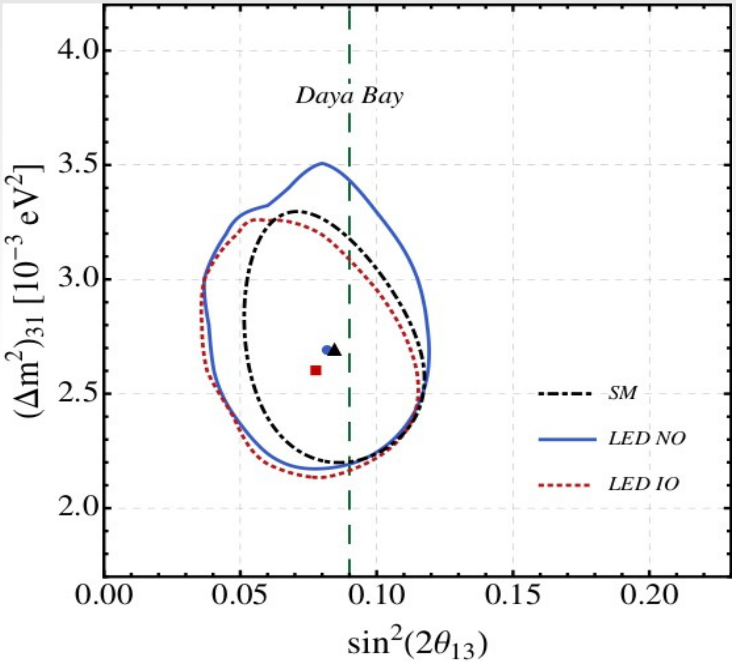
Effects on the standard parameters



small perturbations on top of the standard results

First results...

Effects of New Physics



standard results are robust...

I. Girardi and D, Meloni, 1403.5507

Matrix elements

$$\xi_j \equiv \sqrt{2} R m_j, \qquad j = 1, 2, 3$$

$$\lambda_j^{(0)} = \frac{\xi_j}{\sqrt{2}} \left[1 - \frac{\pi^2 \xi_j^2}{12} + \mathcal{O}(\xi_j^3) \right]$$

$$\lambda_j^{(k \geq 1)} = k + \frac{\xi_j^2}{2k} + \mathcal{O}(\xi_j^3).$$

$$W_j^{(00)} = 1 - \frac{\pi^2 \xi_j^2}{12} + \mathcal{O}(\xi_j^4)$$

$$W_j^{(0k \geq 1)} = \frac{\xi_j}{k} + \mathcal{O}(\xi_j^2)$$