A brief theory overview on Neutrino Physics

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Evidences for ν oscillations: ν deficits

ν flux deficits have been observed in a large variety of experiments:

- Solar ν: Homestake, Sage, Gallex, SuperKamiokande, SNO, Borexino...

  p-p expt?, Be_7 expt?,...

- Atmospheric ν: SuperKamiokande,...

  Icecube, Antares, INO?, HyperK?...

- Beam ν: K2K, Minos

  Miniboone, OPERA, T2K, T2HyperK?, ν factory?, β beam?...

- Reactor ν: Kamland,...

  DoubleChooz, Daya Bay?...

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  ν_μ deficit in far detector with respect to near detector

- Beam ν: K2K, Minos

  Miniboone, OPERA, T2K, T2HyperK?, ν factory?, β beam?...

- Reactor ν: Kamland,...

  DoubleChooz, Daya Bay?...

Neutrino oscillations

ν flux deficits can be explained if the neutrino have a mass

example: $\nu_\mu - \nu_\tau$ system: $M_\nu = \begin{pmatrix} m_{\mu\mu} & m_{\mu\tau} \\ m_{\tau\mu} & m_{\tau\tau} \end{pmatrix}$

$$\begin{pmatrix} \nu_1 \\ \nu_2 \end{pmatrix} = \begin{pmatrix} \cos\theta & -\sin\theta \\ \sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} \nu_\mu \\ \nu_\tau \end{pmatrix} \leftarrow \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} m_{\nu_1} & 0 \\ 0 & m_{\nu_2} \end{pmatrix} \begin{pmatrix} \cos\theta & -\sin\theta \\ \sin\theta & \cos\theta \end{pmatrix}$$

mass eigenstates

neutrino mixing matrix

flavour states

neutrino masses

$$\Rightarrow \quad P(\nu_\mu \to \nu_\tau) = \sin^2(2\theta)\, \sin^2\left(\frac{\Delta m^2}{4}\frac{L}{E}\right) \quad \leftarrow \quad \Delta m^2 = m_{\nu_2}^2 - m_{\nu_1}^2$$

$$P(\nu_\mu \to \nu_\mu) = 1 - P(\nu_\mu \to \nu_\tau)$$

The 3 neutrino picture

$\nu_e,\ \nu_\mu,\nu_\tau$ system:

$$M_\nu = \begin{pmatrix} m_{e-e} & m_{e-\mu} & m_{e-\tau} \\ m_{\mu-e} & m_{\mu-\mu} & m_{\mu-\tau} \\ m_{\tau-e} & m_{\tau-\mu} & m_{\tau-\tau} \end{pmatrix}$$

$$||$$

$$U^T \cdot \begin{pmatrix} m_{\nu_1} & 0 & 0 \\ 0 & m_{\nu_2} & 0 \\ 0 & 0 & m_{\nu_3} \end{pmatrix} \cdot U$$

3 neutrino masses

$m_{\nu_{1,2,3}}$

mixing matrix: - 3 angles: $\theta_{23},\ \theta_{12},\ \theta_{13}$

- 3 CP violating phases: $\delta,\ \phi_{1,2}$

Data constraints on the 3 massive neutrino picture

(3σ)

$$\Delta m^2_{21} = m^2_{\nu_2} - m^2_{\nu_1} = 7.67^{+0.67}_{-0.61} \cdot 10^{-5}\,\mathrm{eV}^2$$

$$\theta_{12} = \left(34.5^{+4.8}_{-4.0}\right)^\circ$$

solar + Kamland

$$\Delta m^2_{31} = m^2_{\nu_3} - m^2_{\nu_1} = +2.46^{+0.47}_{-0.42} \cdot 10^{-3}\,\mathrm{eV}^2$$ (normal)

$$\Delta m^2_{31} = m^2_{\nu_3} - m^2_{\nu_1} = -2.37^{+0.43}_{-0.46} \cdot 10^{-3}\,\mathrm{eV}^2$$ (inverted)

$$\theta_{23} = \left(42.3^{+11.3}_{-7.7}\right)^\circ$$

atmospheric + K2K

$\theta_{13} < 12.9^\circ$ ← Chooz (+solar, atmosheric, Kamland, K2K)

δ *????*

$\phi_{1,2}$ *????*

m_{ν_3} *????*

C. Gonzalez-Garcia, M. Maltoni ‘07

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$\theta_{13} \longleftarrow$ Minos, DoubleChooz, T2K, NuMI, β beams, ν factories

$\delta \longleftarrow$ T2K, β beams, ν factories

$\phi_{1,2} \longleftarrow$ m_{ee} : neutrinoless double beta decay

$m_{\nu_3} \longleftarrow$ Katrin ($>$ 0.3 eV)

Testing further the 3 massive neutrino picture

requires: -to measure better and better: $\Delta m^2_{21},\ \Delta m^2_{31},\ \theta_{12},\ \theta_{23}$

-to measure new parameters: $\theta_{13},\ m_{ee},\ \delta,\ m_{\nu_3}$

$\Downarrow$

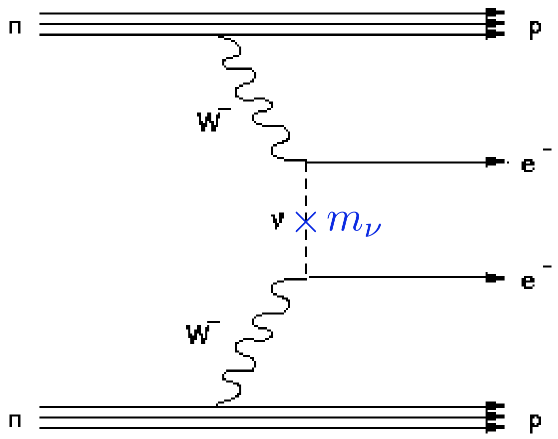
validating it further or invalidating it at least partially

$\Downarrow$

- new long range force?
- non standard neutrino interaction?
- ......?

$\Longrightarrow$ ultimately the hope is to check the unitarity of the neutrino mixing matrix: requires to measure at least: $\theta_{13},\ \delta,$ and m_{ν_3} or m_{ee}

Special role played by the $0\nu2\beta$ decay



$\Longrightarrow$ its observation would establish

that neutrino have Majorana masses

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Lepton Number is violated

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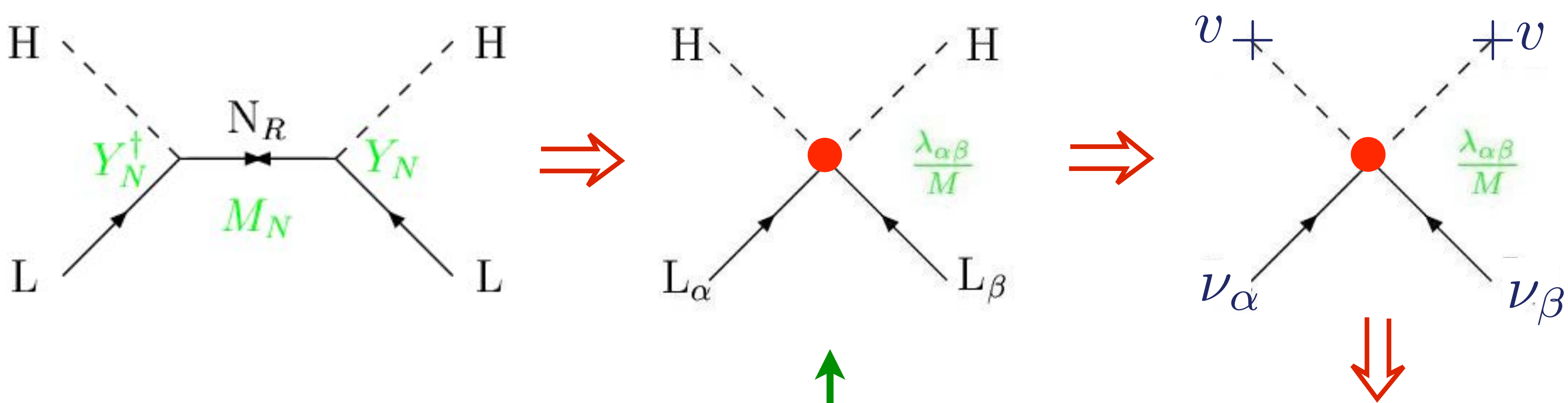
crucial information for beyond the

Standard Model physics

Origin of Neutrino Masses?

- neutrino masses require new fields beyond the Standard Model

- most straightforward possibility: heavy right-handed neutrinos: N_R



$\frac{\lambda_{\alpha\beta}}{M_N} L_\alpha L_\beta H H$ interaction

$$\left(\frac{\lambda}{M_N} = Y_N^T \frac{1}{M_N} Y_N \right)$$

$$\boxed{M_\nu = Y_N^T \frac{1}{M_N} Y_N \, v^2}$$

$\Longrightarrow$ could we confirm this ν mass origin from ν experiments?

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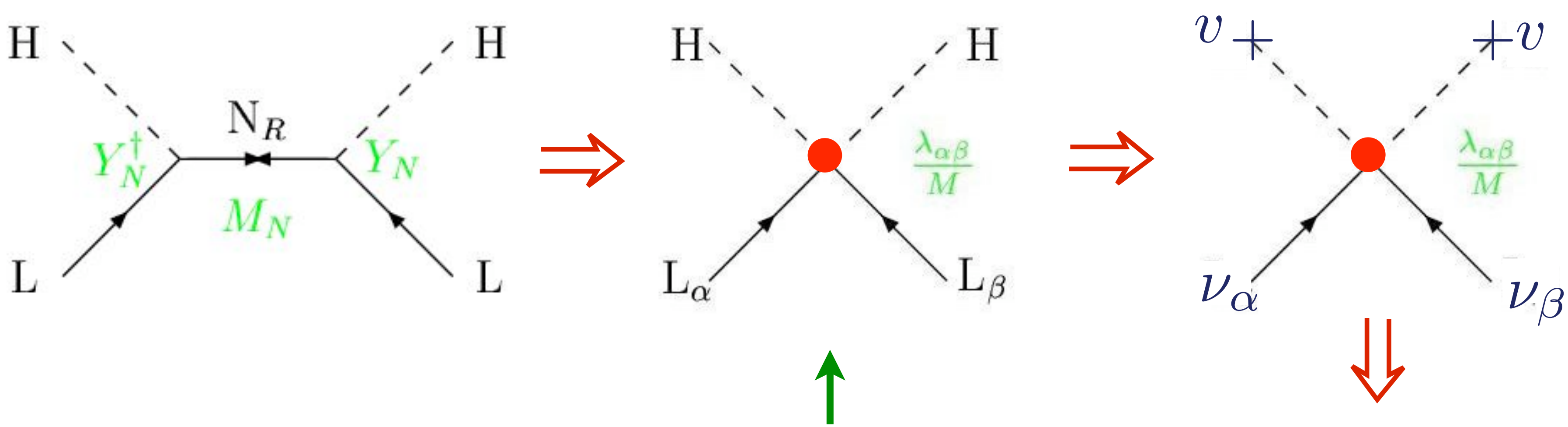

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Origin of Neutrino Masses?

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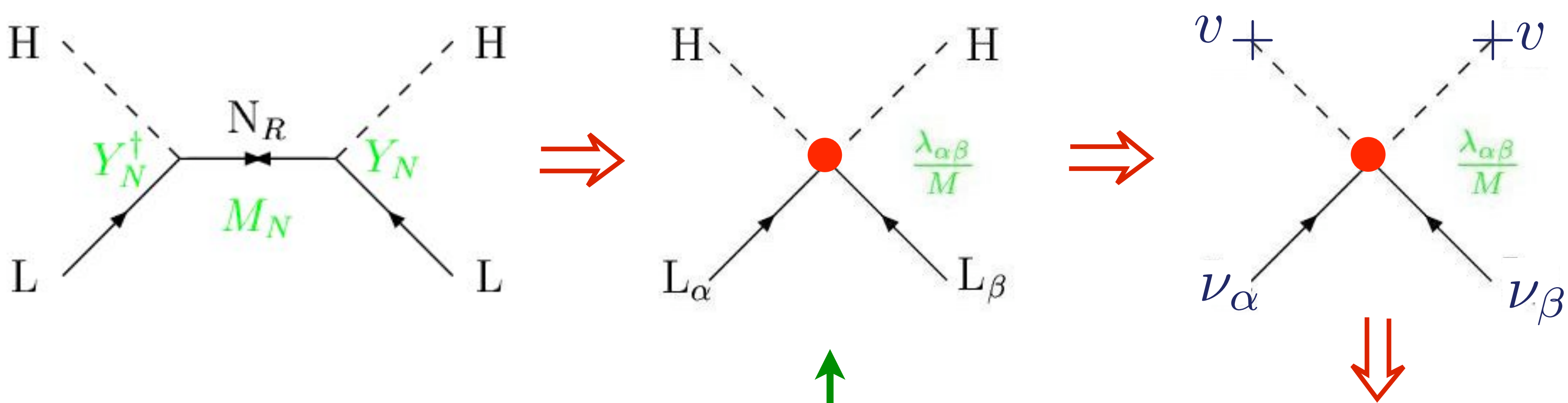
  basically an infinity of possibilities

- most straightforward possibility: heavy right-handed neutrinos: N_R



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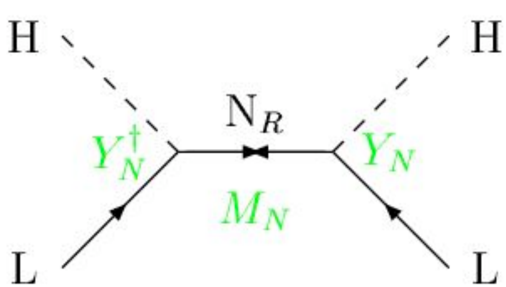
The 3 basic seesaw models

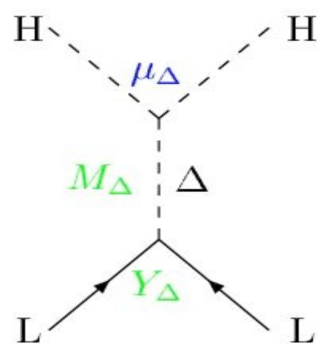
i.e. tree level ways to generate the dim 5 $\frac{\lambda}{M} LLHH$ operator

Right-handed singlet:
(type-I seesaw)



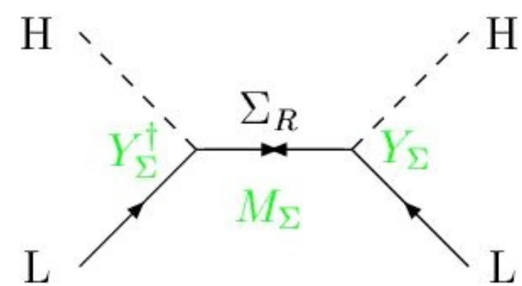
$$m_\nu = Y_N^T \frac{1}{M_N} Y_N v^2$$

Scalar triplet:
(type-II seesaw)



$$m_\nu = Y_\Delta \frac{\mu_\Delta}{M_\Delta^2} v^2$$

Fermion triplet:
(type-III seesaw)



$$m_\nu = Y_\Sigma^T \frac{1}{M_\Sigma} Y_\Sigma v^2$$

$\Rightarrow$ all these models can give any ν mass matrix which could be observed

Number of parameters: model vs ν mass matrix

$\hookrightarrow$ more parameters in the model than in the neutrino mass matrix

Example: 3 right-handed neutrinos:

18 parameters

3 masses of the N

15 parameters in Yukawa matrix $\rightarrow$ 9 real parameters, 6 phases

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Number of parameters: model vs ν mass matrix

more parameters in the model than in the neutrino mass matrix

Example: 3 right-handed neutrinos

18 parameters $\Leftarrow$ to be compared with 9 parameters in M_ν

- 3 masses of the N
- 15 parameters in Yukawa matrix
  - 9 real parameters
  - 6 phases

$\Rightarrow$ to distinguish the ν mass models we need to have access to the other parameters from non neutrino experiments $\rightarrow$

	$\mu \to eee$	
$\mu \to e\gamma$	$\tau \to eee$	$Z \to \mu e$
$\tau \to e\gamma$	$\tau \to \mu ee$	$Z \to \tau e$
$\tau \to \mu\gamma$	$\tau \to \mu\mu e$	$Z \to \tau\mu$
	$\tau \to \mu\mu\mu$	....

Why other effects associated to the same ν physics are e.g. expected very suppressed (1)

- Writing down the possible low energy effects involving SM fermions which could be induced by any kind of new heavy physics at a scale M:

  - the $\frac{\lambda}{M} LLHH$ effect turns out to be the only possible one in $\frac{1}{M}$

    → neutrino masses

  - all other possible effects are in $\frac{1}{M^2}, \frac{1}{M^3}, \ldots$

$\Longrightarrow$ special status of ν masses

Why other effects associated to the same ν physics are e.g. expected very suppressed (II)

- Neutrino masses are very tiny: $m_\nu < 2.2\,\mathrm{eV}$

$\downarrow$

so tiny that even $M = 10^{15}\,\mathrm{GeV}$ can give them

$\downarrow$

bad news for other effects in $\frac{1}{M^2}, \frac{1}{M^3}, \cdots$

- So tiny ν mass effects could be observed because they are very long distance processes unlike other effects like $\mu \to e\gamma, \ldots.$

$\Rightarrow$ $\mu \to e\gamma, \ldots.$ e.g. very suppressed (but not necessarily always)

Summary

- It is important to measure better the already known oscillation parameters as well as new neutrino mass parameters $\theta_{13},\ \delta,\ m_{\nu_3},\ m_{ee}$

  to test further the neutrino mass pattern

  $\theta_{13},\ \delta,\ m_{\nu_3}$: simply because they are new parameters of nature

  m_{ee} : would bring an essential ingredient: Dirac or Majorana

- Important to keep in mind that ν experiments alone cannot distinguish between the neutrino mass models

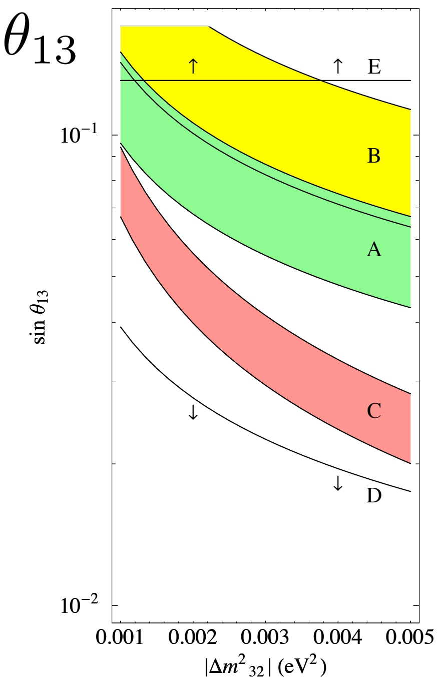
  other complementary searches are essential: $\mu \rightarrow e\gamma,\ \mu \rightarrow eee, \ldots$

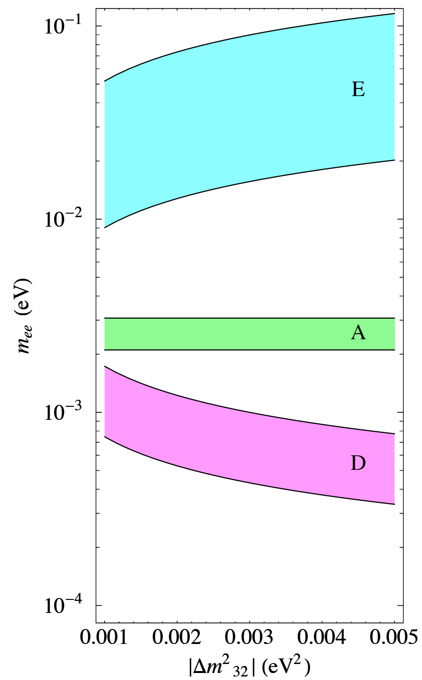
  (even if e.g. expected suppressed)

On the expected value of θ_{13}

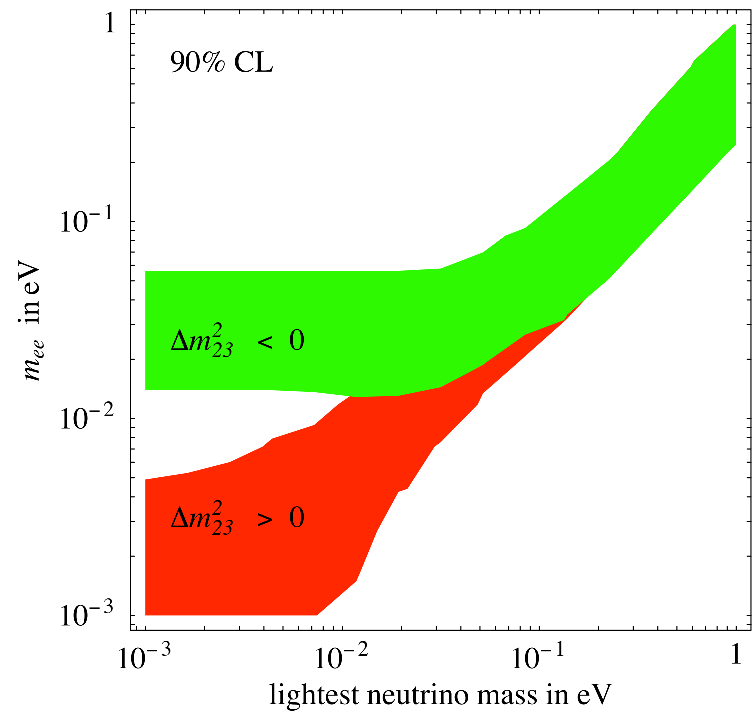
Example: determine the Yukawa and N mass matrix which can reproduce all the data with a minimum of non-negligible uncorrelated parameters

θ_{13}





m_{ee}



Barbieri, T.H., Romanino '03

Ferruglio, Strumia, Vissani '02

$(m_{ee} = 0 \text{ in case B and C})$

Importance of measuring δ for leptogenesis

wouldn't bring any definite answer for leptogenesis

$\Downarrow$

the right-handed neutrino seesaw model has 18 parameters

$\Downarrow$

6 phases

$\Downarrow$

δ is not expected to be e.g. the dominant phase