Experimental tests for the Babu-Zee model

Based on: Experimental tests for the Babu-Zee two-loop model of Majorana neutrino masses. D. Aristizabal and M. Hirsch. [hep-ph/0609307].

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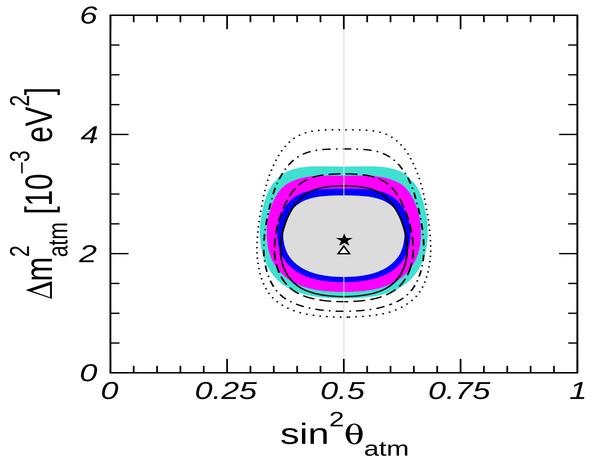
Motivation

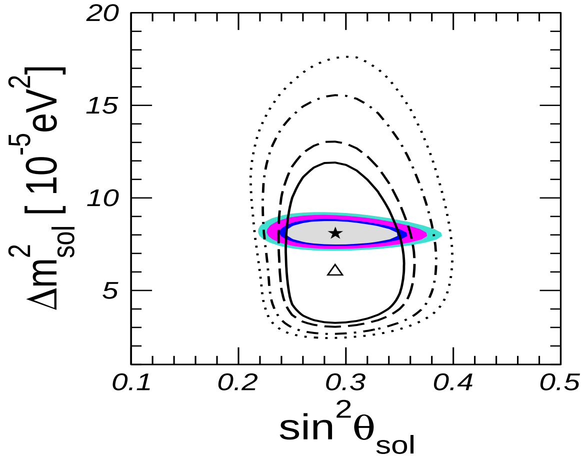
Standard model vs Experiment

In the standard model neutrinos are massless

From Neutrino oscillation experiments nowadays we know that neutrinos oscillate and that therefore they are massive

M. Maltoni *et. al.*, New J. Phys. **6**, 122 (2004)





Neutrino masses implies physics beyond the standard model

Massive neutrinos

- The “orthodox” approach is to add new fermions, ν_R, to the standard model which implies neutrino masses *a la* see-saw.

Smallness of neutrino masses (ν_L) are due to heavy R-H neutrinos (ν_R)

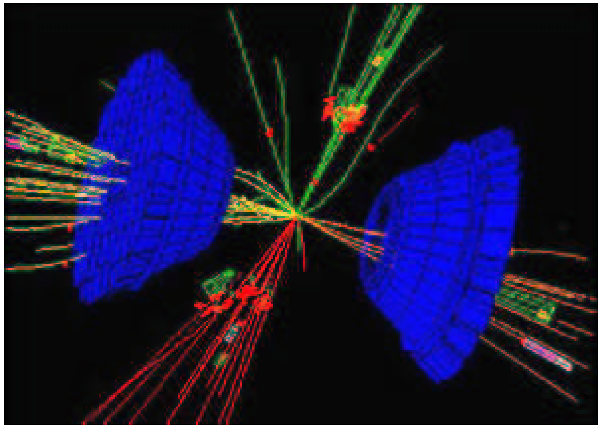
J. W. F. Valle, hep-ph/0608101

Direct experimental tests are not possible

- Another approach is the radiative mass generation mechanism. The smallness of neutrino masses come from loop suppression factors.

L violation at the EW scale
The phenomenology of the new scalars is at the EW scale

J. F. Gunion *et. al.*, eConf **C960625**, LTH096 (1996)



The Model

Neutrino mass matrix in the BZ model

- Apart from the Higgs doublet the model contains a single charged and a doubly charged (h^+, k^{++}) $SU(2)$ gauge singlets scalars.

$$\mathcal{L} = f_{\alpha\beta}(L^{Ti}_{\alpha L} C L^{j}_{\beta L})\epsilon_{ij} h^{+} + h'_{\alpha\beta}(e^{T}_{\alpha R} C e_{\beta R}) k^{++} + \text{H.c.}$$

⋆ f is antisymmetric
⋆ h' is symmetric

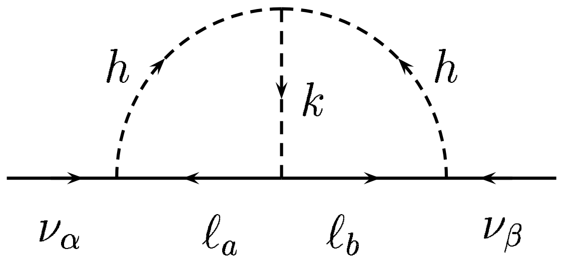
$L(h^-) = L(k^{--}) = 2 \Rightarrow \mathcal{L}$ conserves L
L cannot be spontaneously broken.

- h^+ and k^{++} can be used to drive L breaking from the leptonic to the scalar sector

$$V \supset \mu k^{++} h^- h^-$$

L explicitly broken by two units
Neutrino Majorana masses

- Majorana neutrino masses arise at the two-loop level



$$\mathcal{M}^{\nu}_{\alpha\beta} = \frac{8\mu}{(16\pi^2)^2 m_h^2} f_{\alpha a}\omega_{ab} f_{b\beta}\mathcal{I}\left(\frac{m_k^2}{m_h^2}\right)$$

Constraints from neutrino physics

Neutrino physics constraints

- Apart from m_k and m_h the model has 10 parameters. What is the region of parameter space allowed by neutrino data?
- To address this question the parameters of the model have to be related with atmospheric and solar scales and mixing angles.

$$R^T \mathcal{M}^\nu R = \widehat{\mathcal{M}}^\nu$$

$$R = R(\theta_{23}) R(\theta_{13}, \delta) R(\theta_{12})$$

$$\widehat{\mathcal{M}}^\nu = \text{diag}(m_{\nu_1}, m_{\nu_2}, m_{\nu_3})$$

$$\mathcal{M}^\nu = \underbrace{R \widehat{\mathcal{M}}^\nu R^T}_{\widetilde{\mathcal{M}}^\nu}$$

- In general this is not possible there are 6 independent equations each of them of order three in the parameters... but

$$f = -f^T \Rightarrow \det(\mathcal{M}^\nu) = 0$$

The eigenvalue equation $\widetilde{\mathcal{M}}^\nu v_0 = 0$ allows to relate ν observables with M^ν parameters

- Taking the entries of $\widetilde{\mathcal{M}}^\nu$ as m_{ij} the ratios $\epsilon = f_{13}/f_{23}$ and $\epsilon' = f_{12}/f_{23}$ can be written

$$\epsilon = \frac{m_{12} m_{33} - m_{13} m_{23}}{m_{22} m_{33} - m_{23}^2} \qquad \epsilon' = \frac{m_{12} m_{23} - m_{13} m_{22}}{m_{22} m_{33} - m_{23}^2}$$

- Different relations arise depending on the neutrino spectrum (normal or inverse).

Normal and inverted hierarchy

- Normal hierarchy case:

$$\begin{aligned} \epsilon &= \tan\theta_{12}\frac{\cos\theta_{23}}{\cos\theta_{13}} + \tan\theta_{13}\sin\theta_{23}e^{-i\delta} \\ \epsilon' &= \tan\theta_{12}\frac{\sin\theta_{23}}{\cos\theta_{13}} - \tan\theta_{13}\cos\theta_{23}e^{-i\delta} \end{aligned}$$

- Inverse hierarchy case:

$$\begin{aligned} \epsilon &= -\cot\theta_{13}\sin\theta_{23}e^{-i\delta} \\ \epsilon' &= \cot\theta_{13}\cos\theta_{23}e^{-i\delta} \end{aligned}$$

- Since $m_e \ll m_\mu, m_\tau$, in general ν physics do not put any constraint on $h_{ee}, h_{e\mu}, h_{e\tau}$. However, the requirement of a large θ_{23} implies in both, the normal as well as in the inverse case.

$$h_{\tau\tau} \simeq (\frac{m_\mu}{m_\tau})h_{\mu\tau} \simeq (\frac{m_\mu}{m_\tau})^2 h_{\mu\mu}$$

Yukawa couplings are constrained by neutrino physics.
These constraints have experimental consequences

Lepton Flavour Violation (LFV) processes

Lower bounds on $\mu \to e\gamma$

- Due to the flavour off-diagonal couplings of the charged scalars to SM leptons the model has non standard flavour violating charged lepton decays. The most important within this model $\mu \to e\gamma$.
- Requiring that the largest eigenvalue of M^ν fits the present values for $\sqrt{\Delta m^2_{\rm Atm}}$ it is possible to place sizeable lower bounds on $Br(\mu \to e\gamma)$.

$$Br(\mu \to e\gamma) \sim 4.5 \cdot 10^{-10} \left(\frac{\epsilon^2}{h^2_{\mu\mu}\mathcal{I}(r)^2}\right) \left(\frac{m_\nu}{0.05\ \rm eV}\right)^2 \left(\frac{100\ \rm GeV}{m_h}\right)^2$$

- Lower bounds for $\tau \to e\gamma$ and $\tau \to \mu\gamma$ are of $\mathcal{O}(10^{-13})$, far below near-future experimental sensitivities.
- From the experimental upper bound on $Br(\tau \to 3\mu)$

$$h_{\mu\tau}\left(\frac{m_\tau}{m_\mu}\right) = h_{\mu\mu} = 1 \Rightarrow m_k \gtrsim 770\ \text{GeV}$$

which allows to fix the maximum allowed value of $\mathcal{I}(r)$.

- Setting $h_{\mu\mu} = 1$ it is possible to find lower bounds for $Br(\mu \to e\gamma)$ as function of m_h or neutrino mixing angles.

$\mu \to e\gamma$ vs m_h

$Br(\mu \to e\gamma)$:

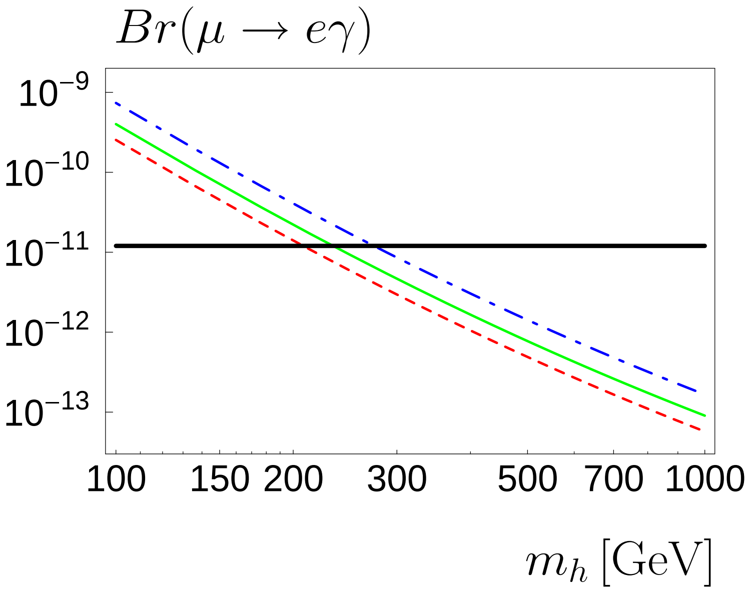
$\sin^2\theta_{23} = 0.5$

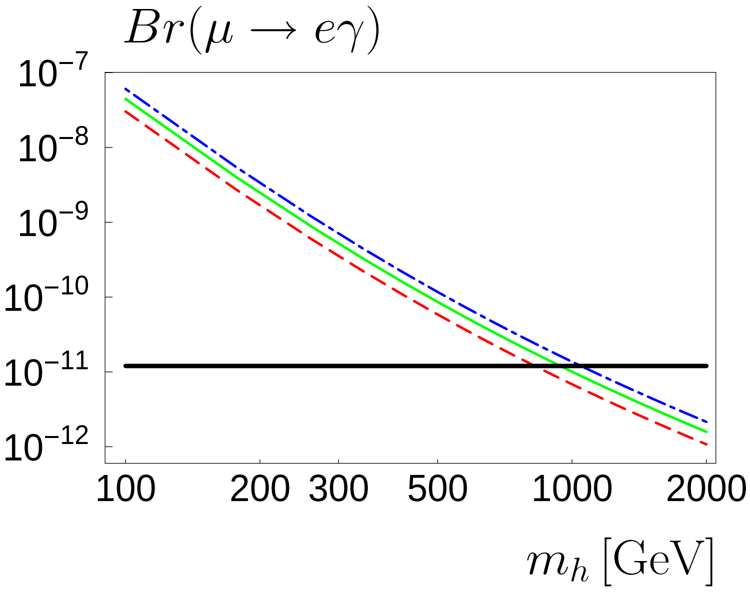
$\sin^2\theta_{13} = 0.040$

$\Delta m^2_{\mathrm{Atm}} = 2.0 \cdot 10^{-3}$ eV^2

$\sin^2\theta_{12} = 0.24, 0.30, 0.40$

$\delta = \pi$





NH: $m_h \lesssim 1$ TeV

$Br(\mu \to e\gamma) \gtrsim 10^{-13}$

IH: $m_h \lesssim 2$ TeV

$Br(\mu \to e\gamma) \gtrsim 10^{-12}$

The model predicts a lower bound for $\mu \to e\gamma$ accesible to the MEG experiment

$\mu \to e\gamma$ vs mixing angles

Motivation
The Model
Constraints from neutrino physics
Lepton Flavour Violation (LFV) processes
● Lower bounds on $\mu \longrightarrow e\gamma$
● $\mu \longrightarrow e\gamma$ vs m_h
● $\mu \longrightarrow e\gamma$ vs mixing angles
Charged scalars collider signatures

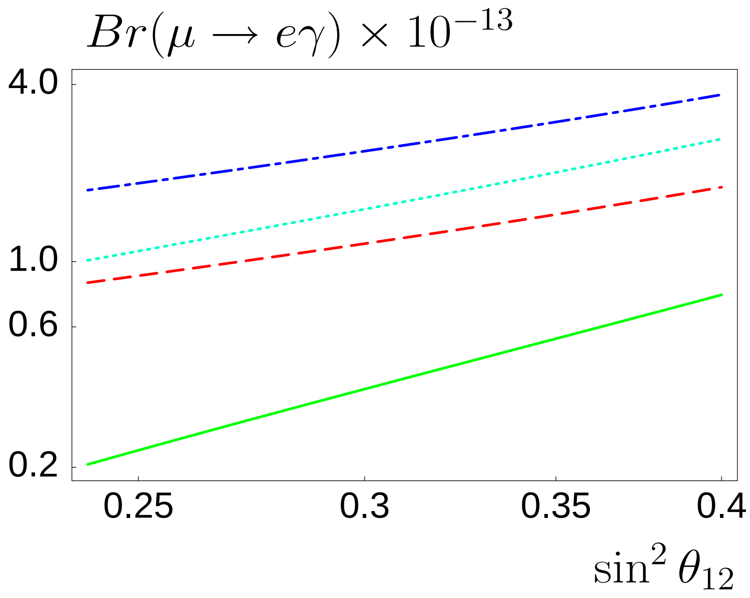
$Br(\mu \to e\gamma)$:

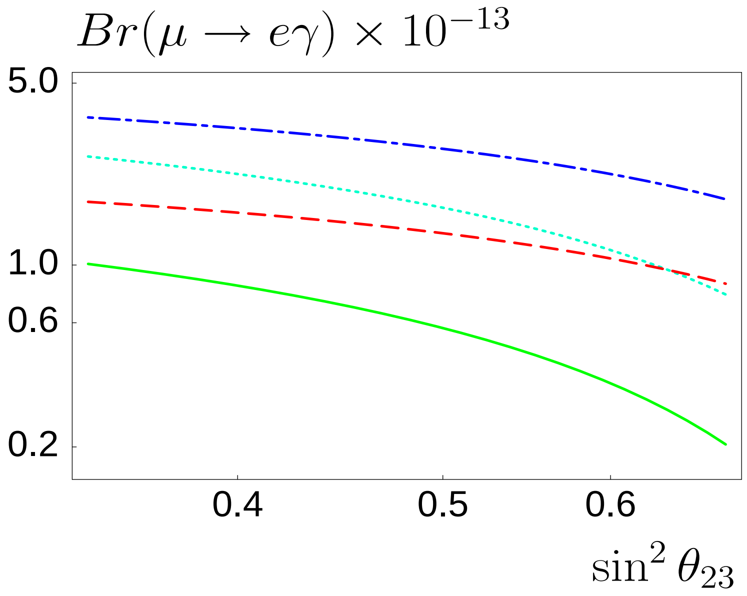
$s^2_{23} = 0.68$, ($s^2_{13} = 0, 0.04$)

$s^2_{23} = 0.34$, ($s^2_{13} = 0, 0.04$)

$\Delta m^2_{\text{Atm}} = 2.0 \cdot 10^{-3}$ eV^2

$m_h = 1$ TeV, $\delta = \pi$





$Br(\mu \to e\gamma)$:

$s^2_{12} = 0.4$, ($s^2_{13} = 0, 0.04$)

$s^2_{12} = 0.24$, ($s^2_{13} = 0, 0.04$)

$\Delta m^2_{\text{Atm}} = 2.0 \cdot 10^{-3}$ eV^2

$m_h = 1$ TeV, $\delta = \pi$

Smaller ranges for ν mixing angles lead to stringent bounds for $\mu \to e\gamma$

Charged scalars collider signatures

Single charged signatures

- The h^+ will decay to leptons and neutrinos. These decays are controlled by the $f_{\alpha\beta}$ couplings which implies that $Br(h^+ \to l_\alpha \sum_\beta \nu_\beta)$ are completely determined by neutrino mixing angles

$$
\begin{aligned}
Br(h^+ \to e \textstyle\sum_\beta \nu_\beta) &= \frac{\epsilon^2+\epsilon'^2}{2(1+\epsilon^2+\epsilon'^2)} \\
Br(h^+ \to \mu \textstyle\sum_\beta \nu_\beta) &= \frac{1+\epsilon'^2}{2(1+\epsilon^2+\epsilon'^2)} \\
Br(h^+ \to \tau \textstyle\sum_\beta \nu_\beta) &= \frac{1+\epsilon^2}{2(1+\epsilon^2+\epsilon'^2)}
\end{aligned}
$$

Using the current 3σ range for neutrino mixing angles $Br(h^+ \to l_\alpha \sum_\beta \nu_\beta)$ can be predicted

$$
\begin{aligned}
Br(h^+ \to e \textstyle\sum_\beta \nu_\beta) &= [0.13, 0.22]([0.48, 0.50]) \\
Br(h^+ \to \mu \textstyle\sum_\beta \nu_\beta) &= [0.31, 0.50]([0.17, 0.34]) \\
Br(h^+ \to \tau \textstyle\sum_\beta \nu_\beta) &= [0.31.0.50]([0.18, 0.50])
\end{aligned}
$$

Measurements of these branching ratios can be used to determine normal or inverse hierarchy spectrum

Measuring any branching ratio outside these ranges would rule out the model

Doubly charged scalar signatures I

- $h_{e\alpha}$ couplings are constrained by LFV processes

For $m_k \leq 1$ TeV
$\mu^+ e^- \to \mu^- e^+ : h_{ee} \lesssim 0.2$
$\mu \to e\gamma : h_{e\mu} \lesssim 2.6 \times 10^{-3}$
$h_{e\tau} \lesssim 4.4 \times 10^{-2}$

Of the final states containing e^- Br_k^{ee} larger than $Br_k^{e\mu}$ and $Br_k^{e\tau}$

- For $k^{--} \to h^- h^-$ is kinematically forbidden: the hierarchy $h_{\mu\mu} : h_{\mu\tau} : h_{\tau\tau} \simeq 1 : m_\mu/m_\tau : (m_\mu/m_\tau)^2$ implies

$$Br(k^{--} \to \mu^- \mu^-)/Br(k^{--} \to \mu^- \tau^-) \simeq (m_\tau/m_\mu)^2$$
$$Br(k^{--} \to \mu^- \mu^-)/Br(k^{--} \to \tau^- \tau^-) \simeq (m_\tau/m_\mu)^4$$

$k^{--} \to \mu^- \mu^-$ will be the dominant mode although e^- pairs can also be expected

- If $k^{--} \to h^- h^-$ is kinematically allowed ($m_k \geq 2m_h$). The L violating coupling μ can be measured through the measurement of $Br(k^{--} \to h^- h^-)$. For $h_{ee} \ll h_{\mu\mu}$

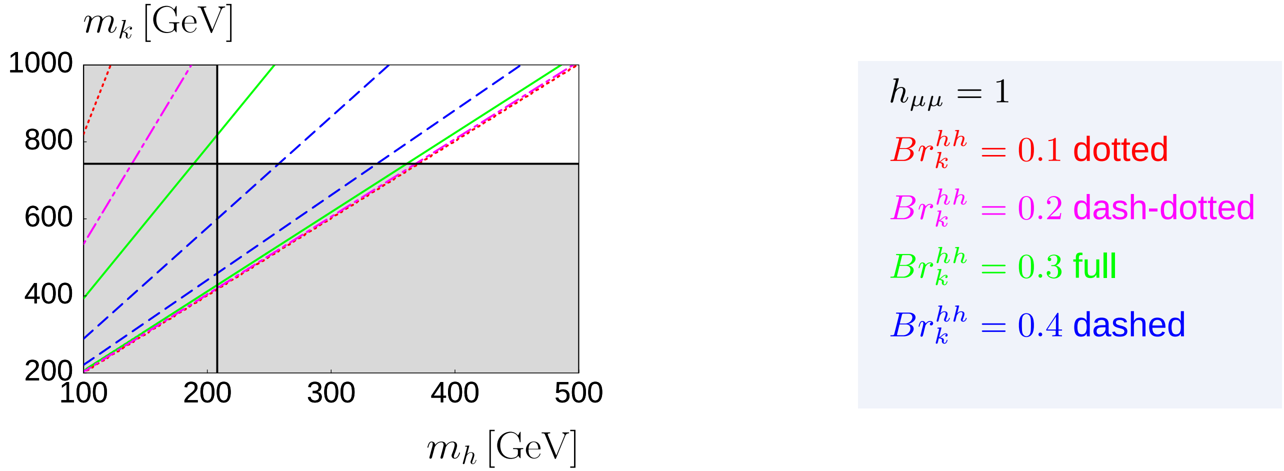
$$Br(k^{--} \to h^- h^-) \simeq \frac{\mu^2 \beta}{m_k^2 h_{\mu\mu}^2 + \mu^2 \beta}$$

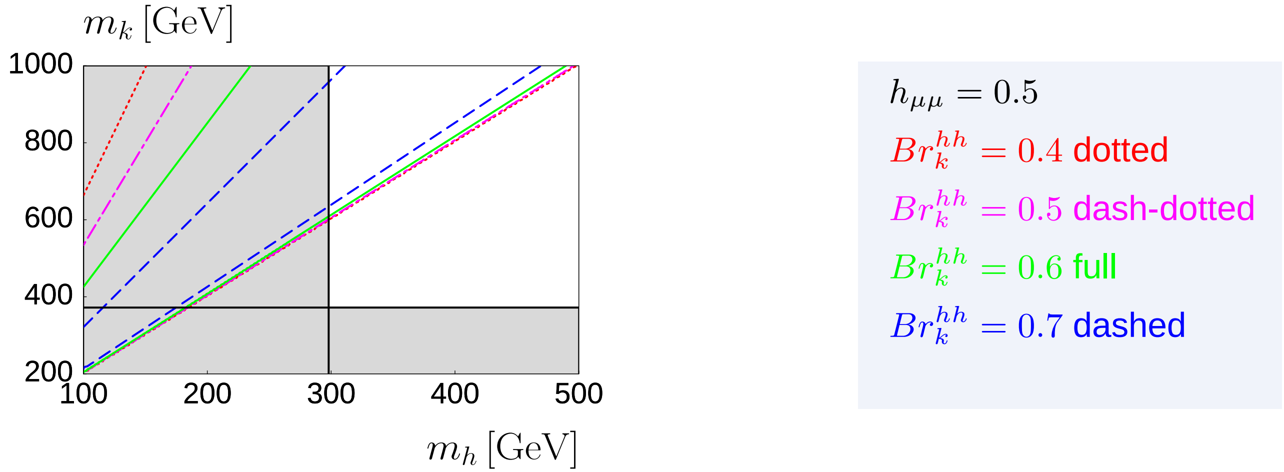
$\beta(x^2) = \sqrt{1 - 4x^2}$
kinematic factor

Doubly charged scalar signatures II

Motivation
The Model
Constraints from neutrino physics
Lepton Flavour Violation (LFV) processes
Charged scalars collider signatures
- Single charged signatures
- Doubly charged scalar signatures I
- Doubly charged scalar signatures II
- Final Remarks

- The current limit on Br$(\mu \to e\gamma)$ exclude all the points for which $m_h \lesssim 500$ GeV if $h_{\mu\mu} \lesssim 0.2$. Thus this measurement is possible only for $h_{\mu\mu} \gtrsim 0.2$
- Upper bounds for $Br_k^{hh} \Rightarrow$ can be found for any $h_{\mu\mu}$. These bounds allow to place upper bounds on neutrino masses.





Final Remarks

- Given the observed neutrino masses and angles, it turns out that the parameters of this model are very tightly constrained already today and thus it is possible to make various predictions.
- Given the bounds on $\mu \to e\gamma$ within this model one should expect that the MEG experiment will see the first evidence for this process if neutrino masses are induced through this mechanism.
- Measurements of decay patterns of h^+ and k^{--} can be used to reconstruct the parameter space of the model. Interesting for the determination of the L number violationg coupling μ will be the measurement of $Br(k^{++} \to h^+ h^+)$.
- h^+ decays are entirely controlled by neutrino mixing angles. Therefore they can be predicted in well determined ranges. Measurements outside of these ranges will rule out the model.
- k^{--} leptonic decays follow the hierarchy $Br_k^{\mu\mu} : Br_k^{\mu\tau} : Br_k^{\tau\tau} = 1 : (m_\mu/m_\tau)^2 : (m_\mu/m_\tau)^4$. Mesurements of k^{++} decays which do not obey this hierarchy will also rule out the model.