Testing the Babu-Zee model with collider experiments

***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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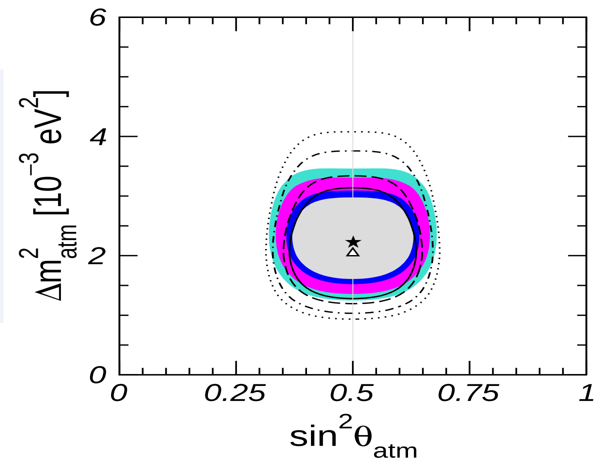
Motivation

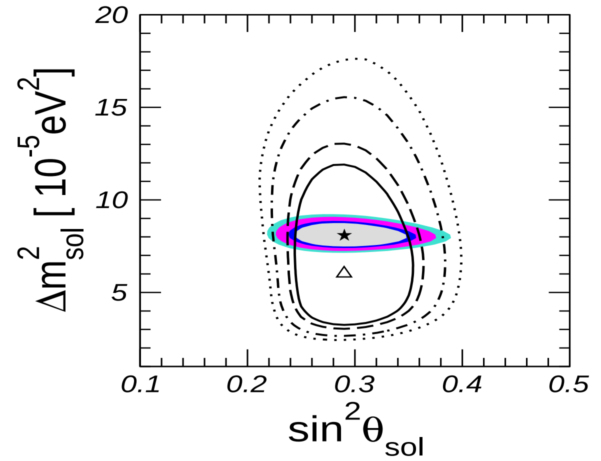
Standard model vs Experiment

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.

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

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

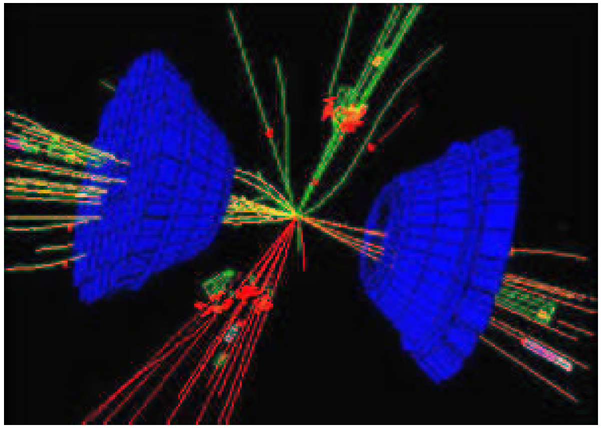
Direct experimental tests are not possible

- 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

- 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

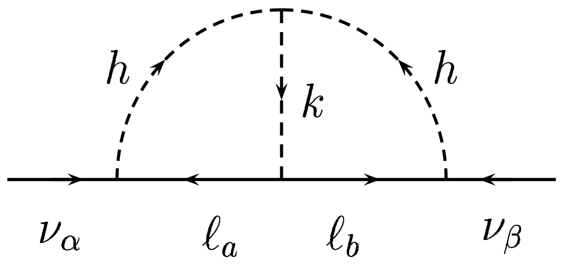
$L(h^-) = L(k^{--}) = 2 \Rightarrow \mathcal{L}$ conserves L
L cannot be spontaneously broken.

- 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 on the parameters

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

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

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

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

Normal and inverted hierarchy

- Normal hierarchy case:

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

- Inverse hierarchy case:

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

- 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.
Decay patterns of charged scalars can be predicted

LFV constraints I

- While the most stringent bounds on the Yukawas come from ν physics, the most stringent bounds on m_k, m_h come from LFV.
- m_h bounds come from $Br(\mu \to e\gamma)$ requiring that the largest eigenvalue of M^ν fits the present values for $\Delta m^2_{\rm Atm}$.

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

- Bounds for m_k come from $Br(\tau \to 3\mu)$.

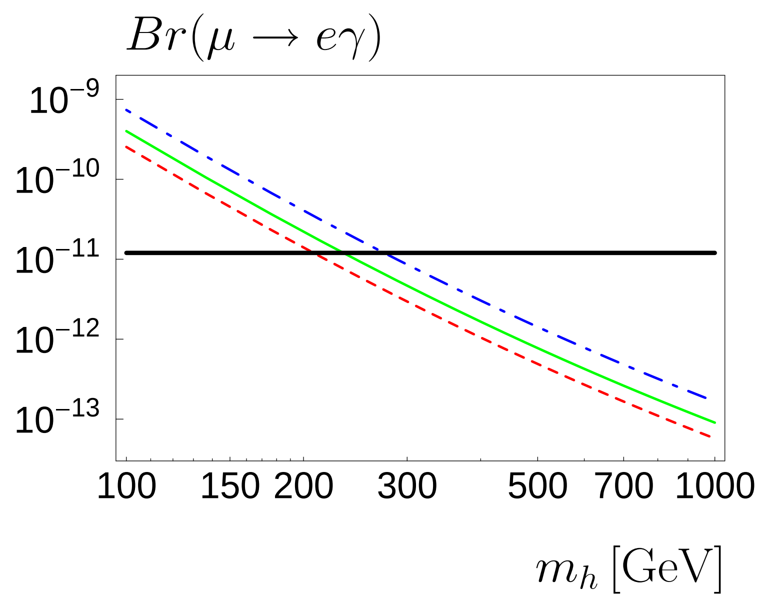
$$\frac{|h_{\mu\tau}h_{\mu\mu}|}{m_k^2} \lesssim 10^{-7}\ \ \mathrm{GeV}^{-2}.$$

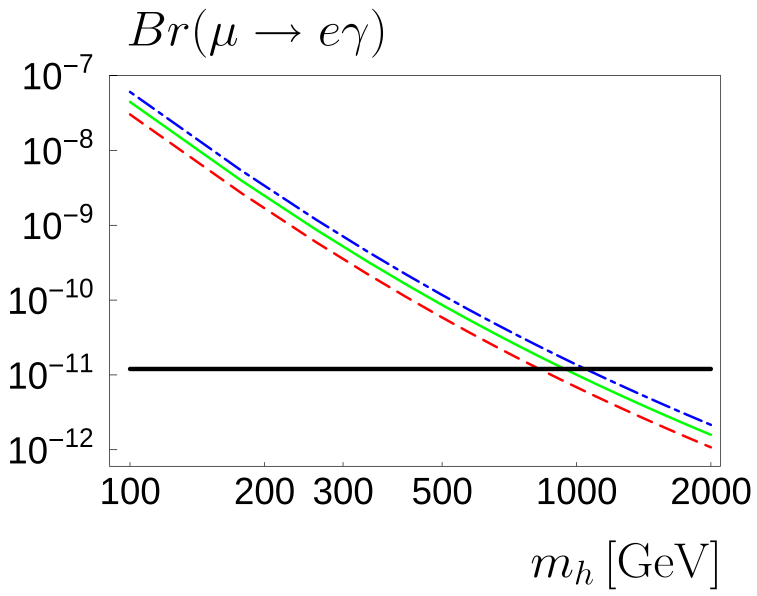
- Lower bounds from $\mu \to e\gamma$ and $\tau \to 3\mu$ can be used to find lower bounds for m_h and m_k.
- For m_k we found

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

LFV constraints II

$Br(\mu \to e\gamma)$:
$\sin^2\theta_{23} = 0.5$
$\sin^2\theta_{13} = 0.040$
$\Delta m^2_{\rm Atm} = 2.0 \cdot 10^{-3}$ eV^2
$\sin^2\theta_{12} = 0.24, 0.30, 0.40$
$\delta = \pi$





NH: $m_h \geq 200$ GeV
In the interesting region for ILC

IH: $m_h \geq 900$ GeV out of reach for ILC

Predictions within the NH case can be tested in ILC

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Charged scalars production and decays

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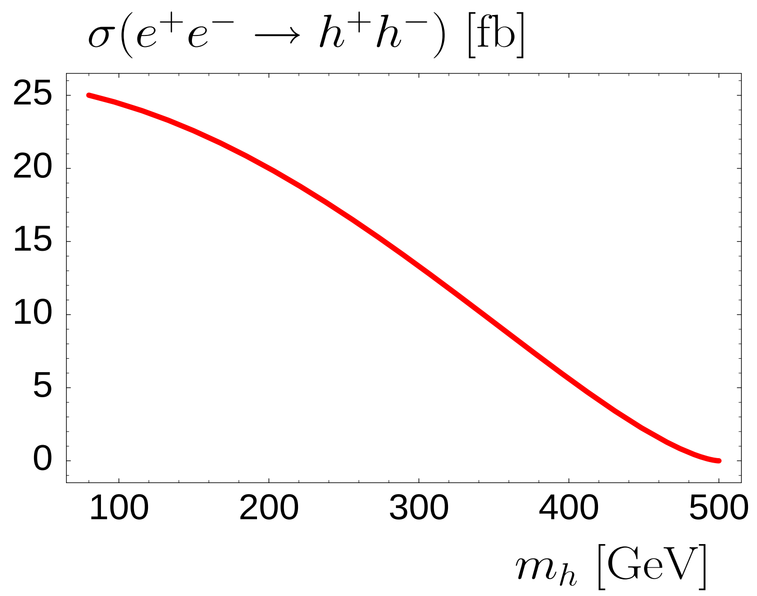
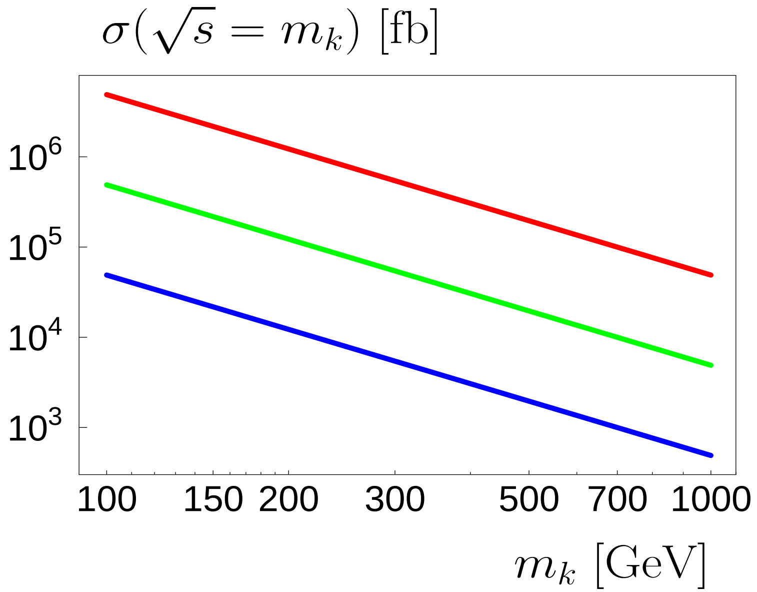
Production Cross sections





$\sqrt{s} = 1$ TeV

Via s-channel exchange of a γ or a Z^0

$\mathcal{L} \sim 1$ ab^{-1} $\Rightarrow N \gtrsim 5 \times 10^3$

In the e^-e^- mode if $\sqrt{s} = m_k$

k^{--} is resonantly produced in the s-channel

$Br_k^{ee} = 10^{-2}$, $Br_k^{ee} = 10^{-3}$, $Br_k^{ee} = 10^{-4}$

Even for small h_{ee} coupling

Millions of k^{--} can be produced

Large statistic is expected

Decay properties of h^- and k^{--} can be studied

Single charged signatures

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

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

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

$$Br(h^+ \to e \sum_\beta \nu_\beta) = [0.13, 0.22]$$
$$Br(h^+ \to \mu \sum_\beta \nu_\beta) = [0.31, 0.50]$$
$$Br(h^+ \to \tau \sum_\beta \nu_\beta) = [0.31.0.50]$$

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^-
$k^{--} \to e^- e^-$ will be dominant

- 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

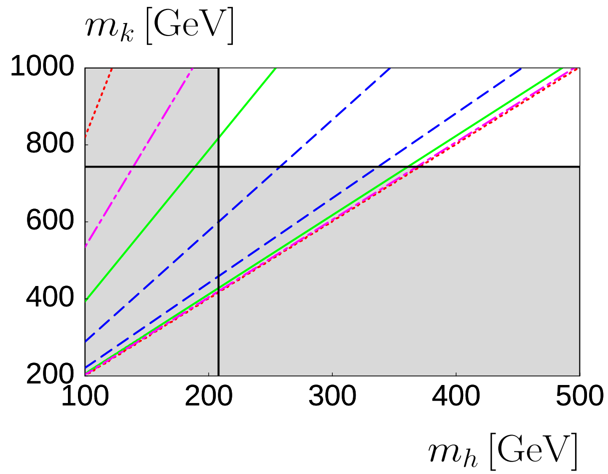
- If $k^{--} \to h^- h^-$ is kinematically allowed ($m_k \geq 2m_h$). The L violating coupling μ can be measured through the measurement of $Br(k^{--} \to h^- h^-)$. For $h_{ee} \ll h_{\mu\mu}$

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

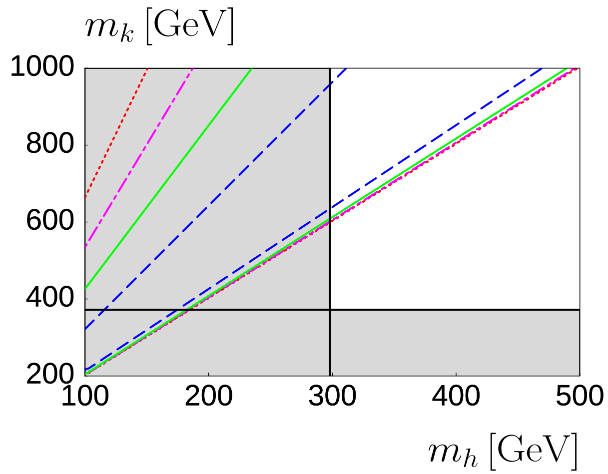
$\beta(x^2) = \sqrt{1 - 4x^2}$
kinematic factor

Doubly charged scalar signatures II

- 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.



$h_{\mu\mu} = 1$
$Br_k^{hh} = 0.1$ dotted
$Br_k^{hh} = 0.2$ dash-dotted
$Br_k^{hh} = 0.3$ full
$Br_k^{hh} = 0.4$ dashed



$h_{\mu\mu} = 0.5$
$Br_k^{hh} = 0.4$ dotted
$Br_k^{hh} = 0.5$ dash-dotted
$Br_k^{hh} = 0.6$ full
$Br_k^{hh} = 0.7$ dashed

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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.
- ILC provides a very good enviroment to measure the decay patterns of h^+ and k^{--}. In particular, the fact that k^{--} could be resonantly produced allows for a very accurate determination of the decay properties of the doubly charged Higgs.
- 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.