Collider Verification of the Neutrino Mass Matrix in Two Scenarios

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* If the origin of neutrino mass is at the TeV scale, collider experiments may in fact <u>map out</u> all the elements of the 3×3 neutrino mass matrix, up to an overall scale.

* Two examples are
  (I) E. Ma, M. Raidal, U. Sarkar, PRL <u>85</u>, 3769 (2000); hep-ph/0012101;
  (II) E. Ma, PRL <u>86</u>, xxxx (2001).

Standard Model with one Higgs doublet

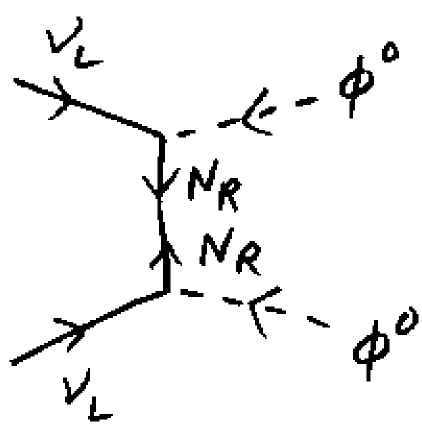
$\Phi = (\phi^+, \phi^0)$ and $L = (\nu_e, e)_L$, e_R only

$\Rightarrow$ m_ν comes from [Weinberg (79)]

$$\frac{1}{\Lambda} L L \Phi \Phi = \frac{1}{\Lambda} (\nu_e \phi^0 - e \phi^+)^2 .$$

* Canonical seesaw mechanism :

[Gell-Mann, Ramond, Slansky (79);
Yanagida (79); Mohapatra, Senjanovic (80)]



$$\Rightarrow \quad m_\nu = \frac{f^2 v^2}{m_N}$$

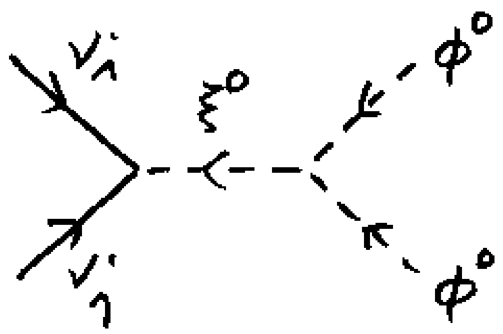
Lepton number is violated in the <u>denominator</u>.

* $m_\nu \sim \left(\frac{f}{1.0}\right)^2 \left(\frac{10^{13}\,\mathrm{GeV}}{m_N}\right) \mathrm{eV}$.

* Triplet Higgs mechanism:

[Schechter, Valle (80); Ma, Sarkar (98)]

$$\mathcal{L}_{int} = f_{ij}\left[\xi^0 \nu_i \nu_j + \xi^+\left(\frac{\nu_i l_j + l_i \nu_j}{\sqrt{2}}\right) + \xi^{++} l_i l_j\right]$$
$$+ \mu\left(\bar{\xi}^0 \phi^0 \phi^0 - \sqrt{2}\, \xi^- \phi^+ \phi^0 + \xi^{--} \phi^+ \phi^+\right) + h.c.$$



$$\Rightarrow m_\nu = \frac{2 f_{ij} \mu v^2}{m_\xi^2} = 2 f_{ij} \langle \xi^0 \rangle$$

<u>Note</u>: $L_i L_j \Phi \Phi = \nu_i \nu_j \phi^0 \phi^0 - (\nu_i l_j + l_i \nu_j) \phi^+ \phi^0 + l_i l_j \phi^+ \phi^+$.

Lepton number is violated in the <u>numerator</u>.

If $f_{ij} \sim 1$, then $\frac{\mu}{m_\xi^2} \lesssim 10^{-13}\ \mathrm{GeV}^{-1}$.

* Hence $m_\xi \sim 1$ TeV is possible, if $\mu \lesssim 100$ eV.

* The "shining" mechanism of extra large dimensions : [Arkani-Hamed, Dimopoulos (98)]

Let χ be a singlet scalar in the bulk carrying lepton number $L = -2$, then

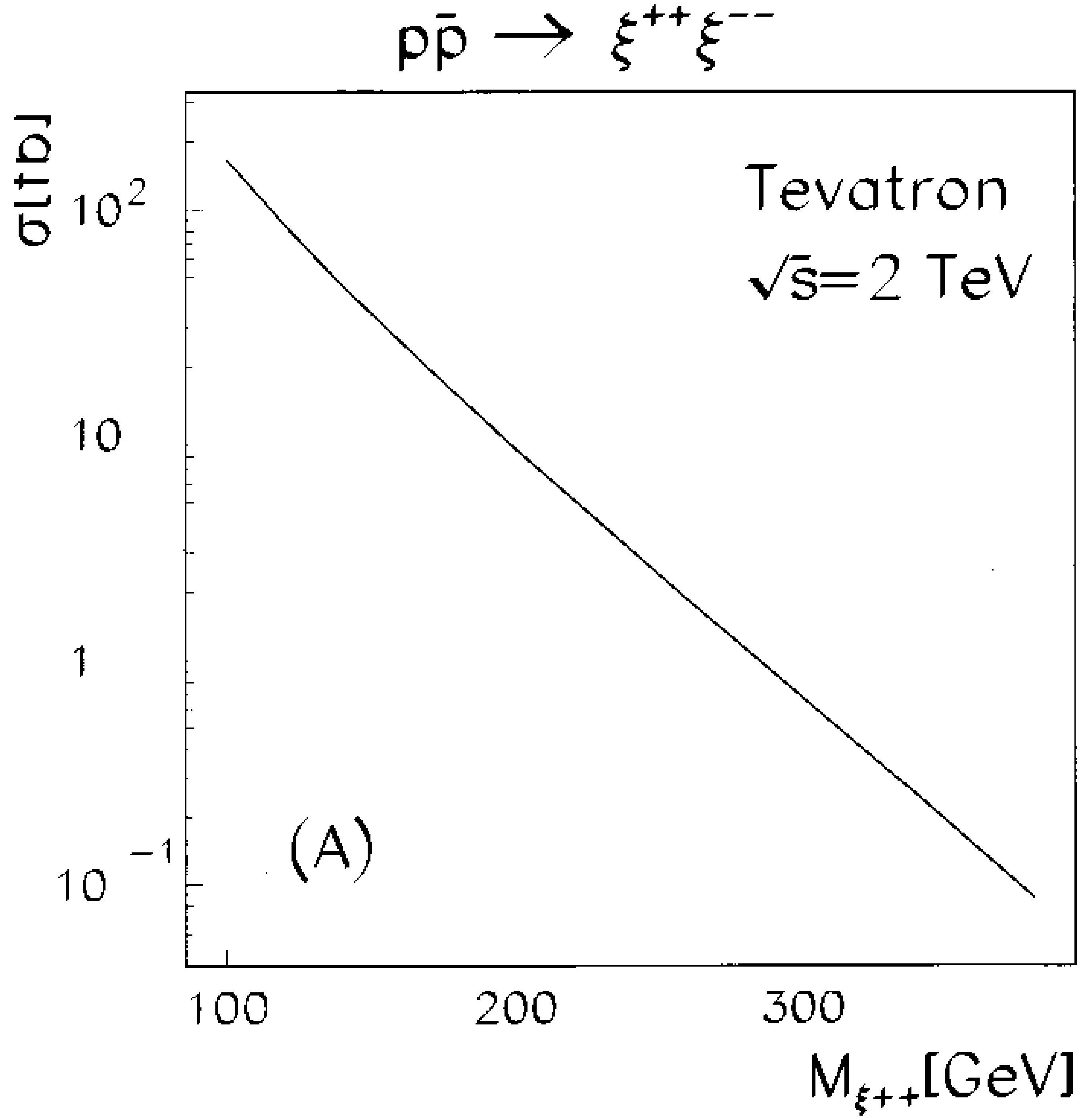
$$\langle \chi \rangle \sim \frac{\Gamma\left(\frac{n-2}{2}\right)}{4\pi^{\frac{n}{2}}} M_* \left(\frac{M_*}{M_P}\right)^{2-\frac{4}{n}} .$$

For $n=3$, $M_* \sim 1$ TeV, $M_P = 2.4 \times 10^{18}$ GeV,

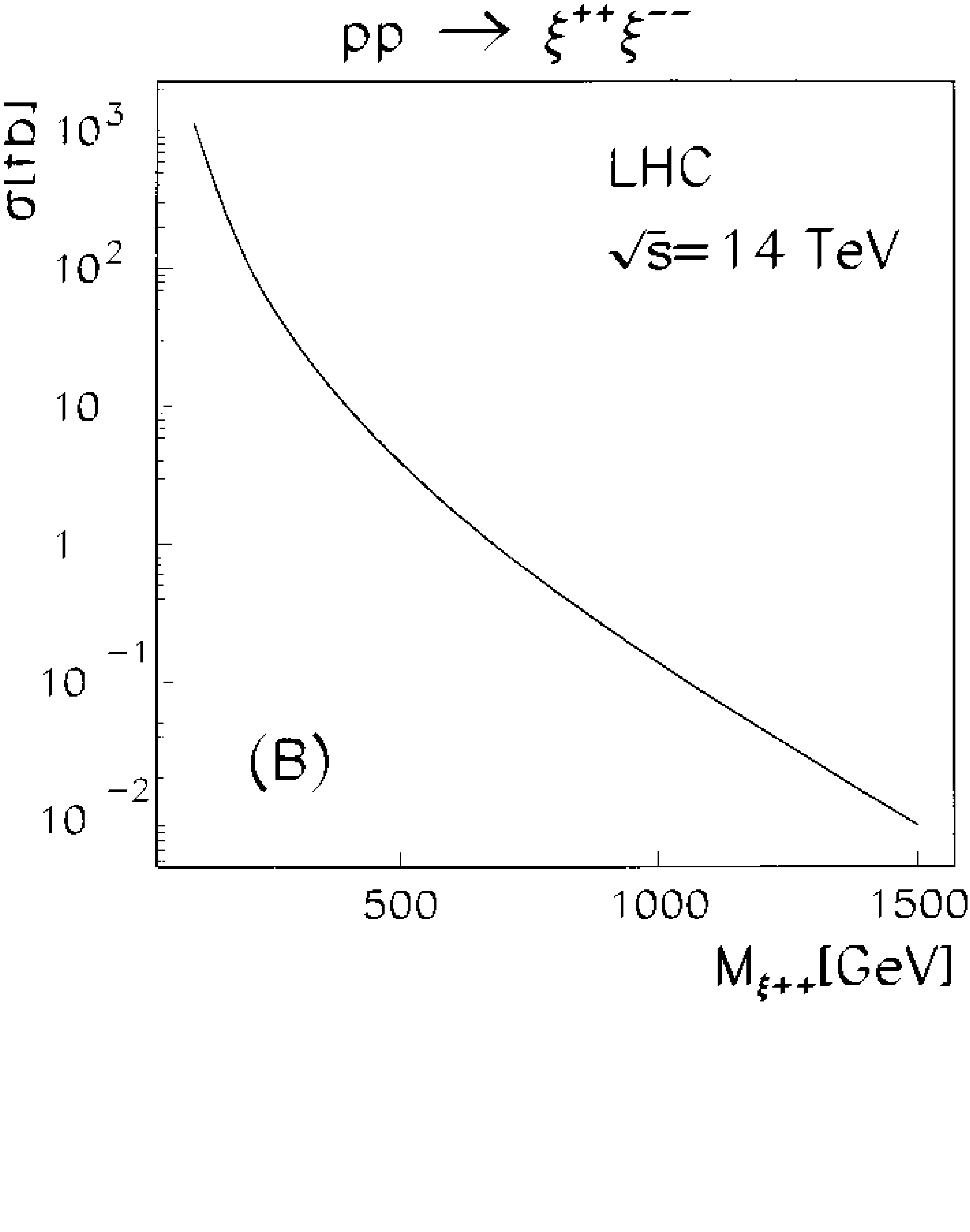
$\langle \chi \rangle \sim 4.4$ eV .

* Replace μ by $h\chi$, then $m_\xi \sim 1$ TeV is possible.

** $\xi^{\pm\pm}$ can be produced at colliders and $\xi^{++} \to l_i^+ l_j^+$ maps out f_{ij} and thus $(m_\nu)_{ij}$ up to an overall scale !



pp̄ → ξ++ξ--
σ[fb]
10²
10
1
10⁻¹
Tevatron
√s=2 TeV
(A)
100
200
300
Mξ++[GeV]



pp → ξ++ξ--
σ[fb]
LHC
√s=14 TeV
(B)
M_ξ++[GeV]

* Sample Neutrino Mass Matrix :

$$\mathcal{M}_\nu = m \begin{bmatrix} 0 & b & -bx \\ b & x^2+a & x-ax \\ -bx & x-ax & 1+ax^2 \end{bmatrix}$$

Let $m = 0.03\,\mathrm{eV}$, $x = 0.9$, $b = 0.4$, $a = 0.02$,

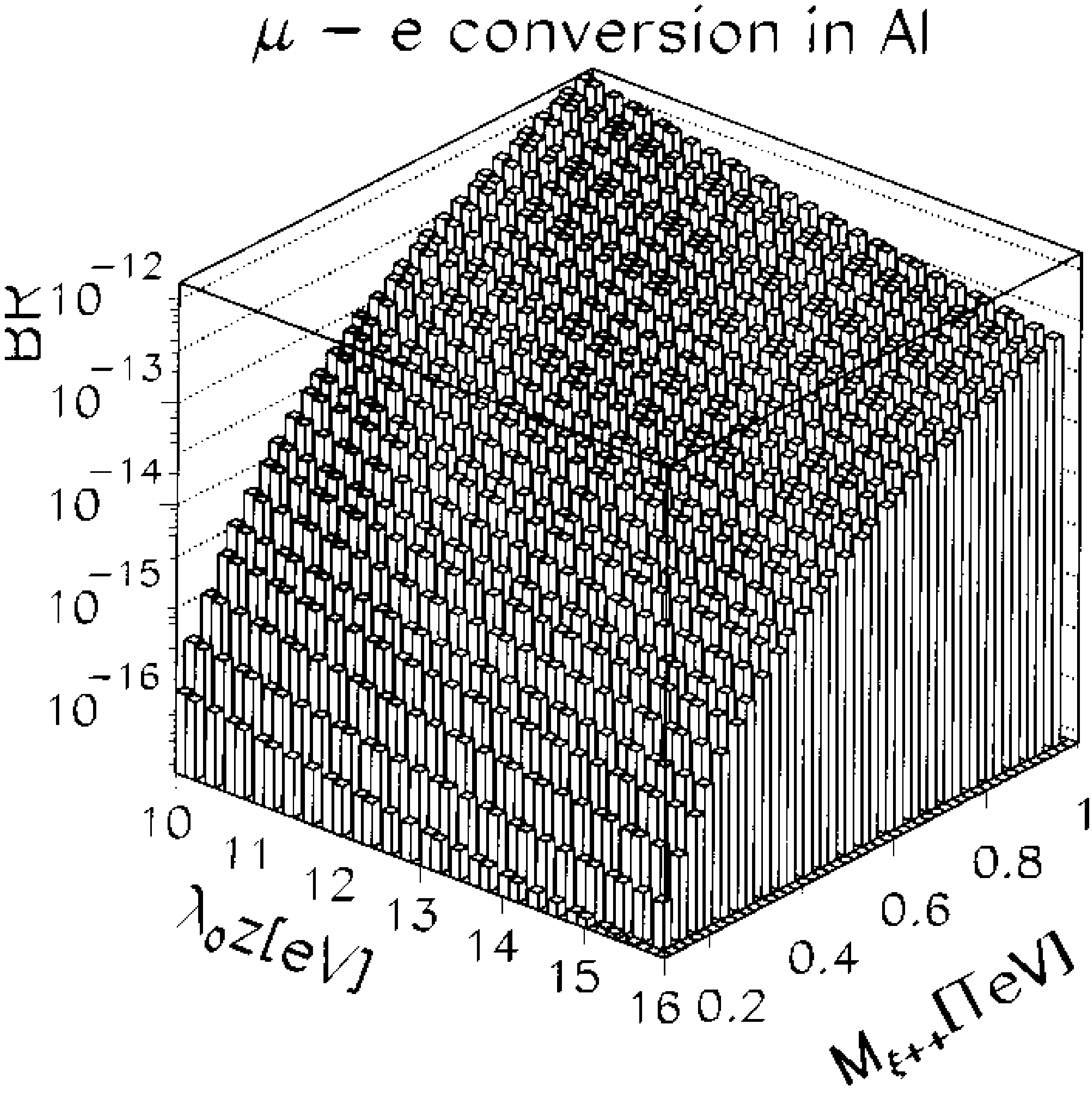
then $(\Delta m^2)_{atm} \sim 2.7 \times 10^{-3}\,\mathrm{eV}^2$,

$(\sin^2 2\theta)_{atm} \sim 0.99$;

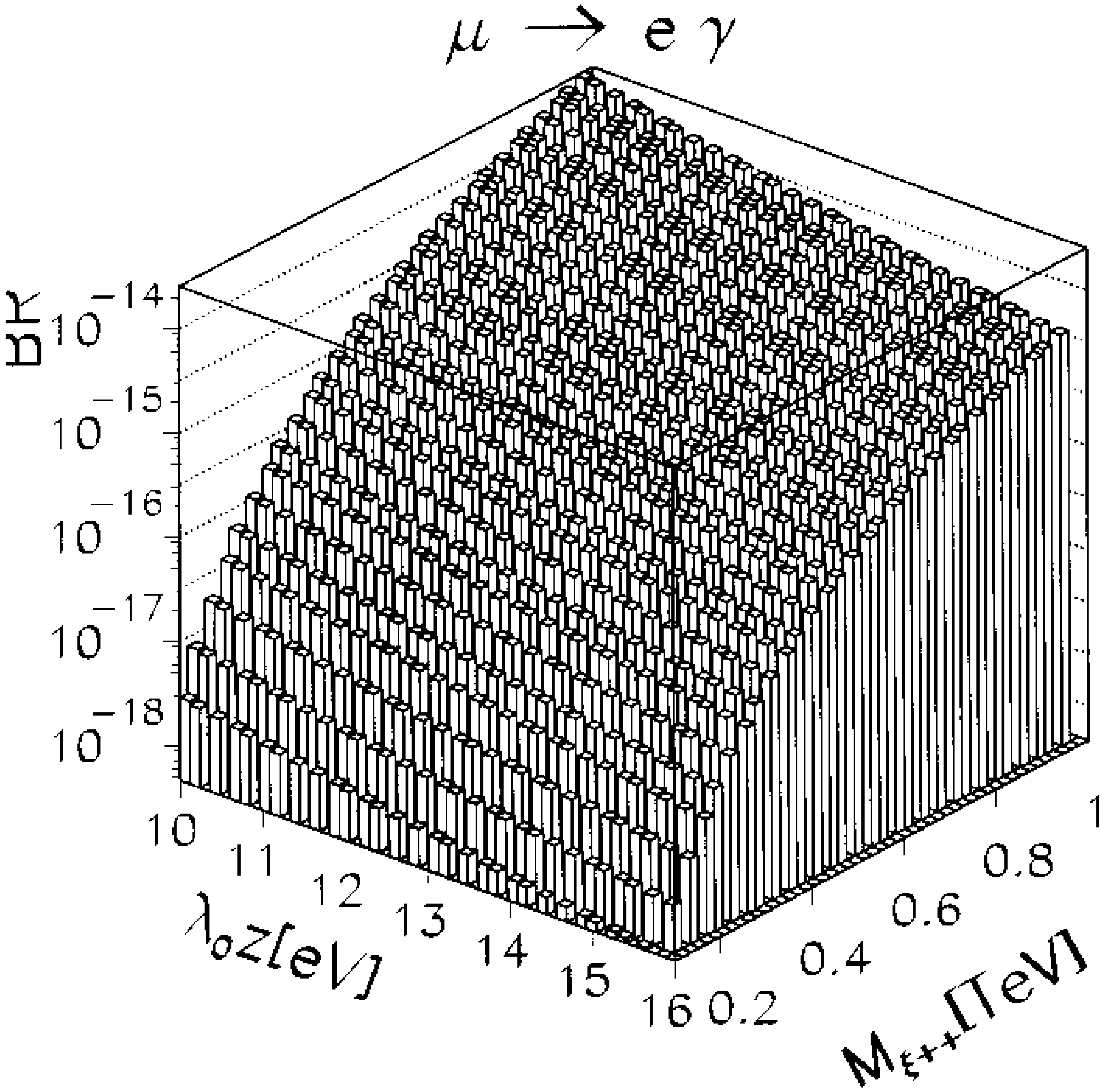
$(\Delta m^2)_{sol} \sim 3.5 \times 10^{-5}\,\mathrm{eV}^2$,

$(\sin^2 2\theta)_{sol} \sim 0.98$.

Notation : $\mathcal{M}_\nu \simeq \frac{1}{\sqrt{2}} f_{ij} \lambda_0 z \frac{v^2}{m^2_{\xi^{++}}}$



μ − e conversion in Al
BR
10^{-12}
10^{-13}
10^{-14}
10^{-15}
10^{-16}
10
11
12
13
14
15
16
$\lambda_o Z[eV]$
0.2
0.4
0.6
0.8
1
$M_{\xi^{++}}[TeV]$



$\mu \to e\,\gamma$
BR
10^{-14}
10^{-15}
10^{-16}
10^{-17}
10^{-18}
10
11
12
13
14
15
16
$\lambda_o z[eV]$
0.2
0.4
0.6
0.8
1
$M_{\xi^{++}}[TeV]$

* Add N_R but assign it $L=0$, then $\frac{1}{2} m_N N_R^2 + h.c.$ is allowed, but $\bar{N}_R(\nu_L \phi^0 - \ell_L \phi^+)$ is forbidden by lepton number conservation. Hence $LL\Phi\Phi$ is not possible and $m_\nu = 0$.

* Add a new scalar doublet $\eta = (\eta^+, \eta^0)$ with $L=-1$, then $\bar{N}_R(\nu_L \eta^0 - \ell_L \eta^+)$ is allowed, and

  $LL\eta\eta \Rightarrow m_\nu \neq 0$ if $\langle \eta^0 \rangle \neq 0$.

* If $f\langle \eta^0 \rangle \lesssim 1$ MeV, then $m_N \sim 1$ TeV is possible!

$$V = m_1^2 \Phi^\dagger \Phi + m_2^2 \eta^\dagger \eta + \frac{1}{2}\lambda_1 (\Phi^\dagger\Phi)^2 + \frac{1}{2}\lambda_2 (\eta^\dagger\eta)^2$$
$$+ \lambda_3 (\Phi^\dagger\Phi)(\eta^\dagger\eta) + \lambda_4 (\Phi^\dagger\eta)(\eta^\dagger\Phi)$$
$$+ \underbrace{\mu_{12}^2 (\Phi^\dagger\eta + \eta^\dagger\Phi)}_{\text{breaks L softly}}$$

breaks L softly (the only possible such term)

Let $\langle\phi^0\rangle = v$, $\langle\eta^0\rangle = u$, then

$$v\left[m_1^2 + \lambda_1 v^2 + (\lambda_3+\lambda_4)u^2\right] + \mu_{12}^2 u = 0,$$
$$u\left[m_2^2 + \lambda_2 u^2 + (\lambda_3+\lambda_4)v^2\right] + \mu_{12}^2 v = 0.$$

Let $m_1^2 < 0$, $m_2^2 > 0$, $|\mu_{12}^2| \ll m_2^2$,

then
$$v^2 \simeq -\frac{m_1^2}{\lambda_1},$$
$$u \simeq \frac{-\mu_{12}^2 v}{m_2^2 + (\lambda_3+\lambda_4)v^2}.$$

For example, if $m_2 \sim 1$ TeV, $|\mu_{12}|^2 \sim 10$ GeV^2,
then $u \sim 1$ MeV and

$$m_\nu = \left(\frac{f}{1.0}\right)^2 \left(\frac{1 \text{ TeV}}{m_N}\right) \text{ eV}$$

(I) $m_2 > m_N$

$\Rightarrow h^+ \to \ell_i^+ N_j$, then $N_j \to \ell_k^\pm W^\mp$
(via ν-N mixing)

(II) $m_N > m_2$

$\Rightarrow N_i \to \ell_j^\pm h^\mp$, then $h^+ \to t\bar{b}$
(via Φ-η mixing)

In either case, m_2 & m_N can be determined kinematically, and $|f_{ij}|$ measured up to an overall scale.

* Particle spectrum :

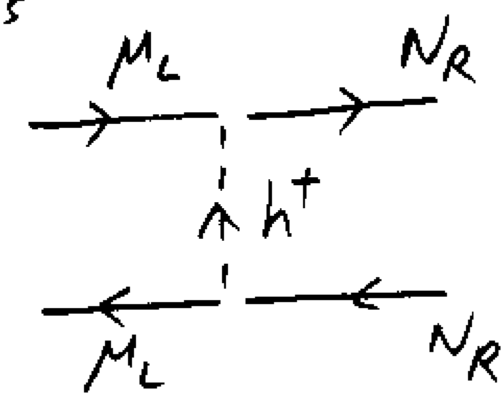
(1) Standard Model particles, including the one physical Higgs boson h_1^0 ;

(2) 3 heavy N_R's at TeV scale ;

(3) heavy scalar doublet $(h^\pm, h_2^0, A)$ of mass $\sim m_Z$.

* $h^\pm$ can be pair-produced at hadron colliders

* N_R can be produced at lepton colliders



* Lepton number violation for m_ν may occur at several different mass scales :

(1) Large : $m_N \sim 10^{13}$ GeV in the canonical seesaw mechanism ,

(2) Medium : $|\mu_{12}^2| \sim 10$ GeV^2 in the reduced seesaw mechanism with $m_N \sim 1$ TeV and a second scalar doublet ,

(3) Small : $\lambda_0 z \sim 10$ eV in the Higgs triplet scenario with a bulk singlet scalar .

** In (2) + (3) , direct experimental determination of $\mathcal{M}_\nu$ (up to an overall scale) is possible at colliders !

Muon g-2

$$\Delta a_\mu = a_\mu^{exp} - a_\mu^{SM} > 215 \times 10^{-11} \; [90\% \, CL]$$

In leptonic Higgs doublet model, assume all m_N's equal with

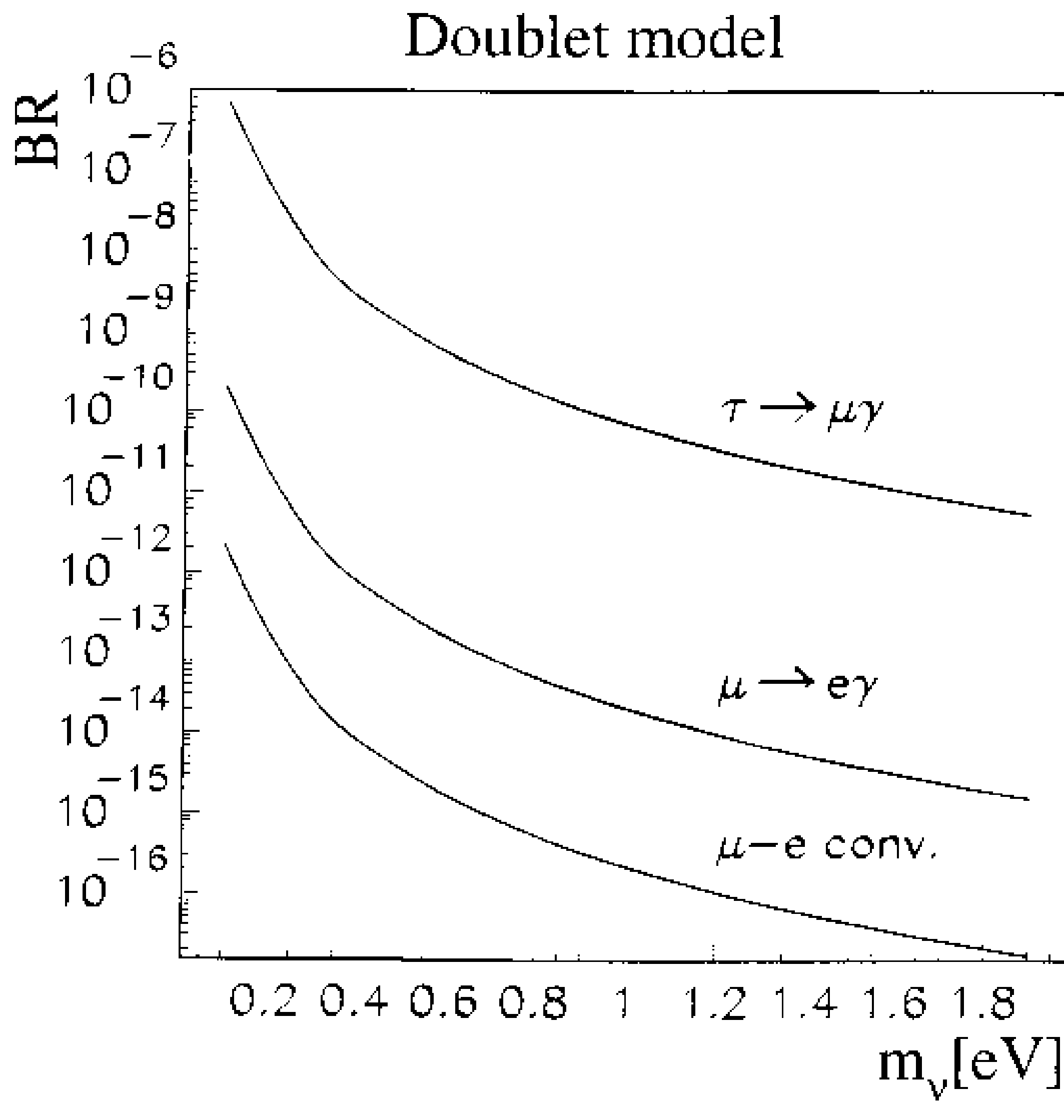
$$h_{i\eta} = \begin{bmatrix} 2ch_1 & -\sqrt{2}\, sh_1 & \sqrt{2}\, sh_1 \\ 2sh_2 & \sqrt{2}\, ch_2 & -\sqrt{2}\, ch_2 \\ 0 & \sqrt{2}\, h_3 & \sqrt{2}\, h_3 \end{bmatrix}$$

with $h_1 \le h_2 \le h_3$, we find

$$m_\eta < 371 \sqrt{\alpha_h} \text{ GeV}, \quad \text{and}$$

$$\frac{\Gamma(\mu \to e\gamma)}{m_\mu^5} : \frac{\Gamma(\tau \to e\gamma)}{m_\tau^5} : \frac{\Gamma(\tau \to \mu\gamma)}{m_\tau^5}$$

$$= 2s^2c^2(\Delta m^2)^2_{sol} : 2s^2c^2(\Delta m^2)^2_{sol} : (\Delta m^2)^2_{atm}$$



$\Rightarrow$ neutrino masses almost degenerate with common mass $m_\nu \gtrsim 0.2$ eV, assuming large-angle matter-enhanced solar ν oscillations.

[Ma, Raidal, hep-ph/0102255]