INSIGHTS ON ν MASSES FROM LFV

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PLAN

- Upper limits on $BR(\tau \to \mu \gamma)$, $BR(\mu \to e \gamma)$ can be translated into upper limits on a certain combination of y_D, M_R

- possibility of discriminating between seesaw models by improving the exp. sensitivity on those BR's?

STARTING POINT

$m_\nu \ll m_{q,e}$
$\theta_{atm} \simeq \pi/4$ $\longrightarrow$ mech. responsible for m_ν different from the one at work for $m_{q,e}$

MAYBE ν = Majorana, $\not{L}$

SEE-SAW $(+\nu^c)$: elegant explanation

$$m^\nu_{eff} = y_D^T \frac{1}{M_R} y_D v^2$$

CONVENTIONS :
- $\bar{R}\, m_D L$
- basis where M_R, M_e = diag

if $y_D \sim O(1) \to M_R \doteq M_{\not{L}} \lesssim M_{g.c.u.\,MSSM}$

BUT even if we precisely knew $m^\nu_{eff} = U^*_{MNS}\, \mathrm{diag}(m_1, m_2, m_3)\, U^+_{MNS}$ it wouldn't be possible TO DISENTANGLE y_D and M_R

E.G. (unlike quarks) NO ACCESS TO Left-mixing in y_D from m^ν_{eff}.

$$m^\nu_{eff} = V_L^* d_D U_R^T \frac{1}{M_R} \underbrace{U_R d_D V_L^+}_{y_D}$$

$V_L = U_{MNS}$ ONLY IF $U_R = \mathbb{1}$ and/or $M_R \propto \mathbb{1}$

NEVERTHELESS from present knowledge on m^ν_{eff}
- identify the phen. acceptable PATTERNS of y_D, M_R
- useful criterion to classify them.

IN ORDER TO PROCEED ?

$\Rightarrow$ ADDITIONAL INFORMATIONS NEEDED

CAN LFV PROVIDE ADDITIONAL INFORMATIONS ?

$BR(\mu \to e\gamma) < 1.2 \; 10^{-11} \overset{?}{\cdots\to} 10^{-14}$

$BR(\tau \to \mu\gamma) < 1.1 \; 10^{-6} \overset{?}{\cdots\to} 10^{-9}$

3 o.of.m. improvement UNDER STUDY
→ direct searches
→ slepton decays

→ IT HAS BEEN SHOWN (also in connection with susy p.s. for a_μ) some simple realization of the see-saw predict $\mu \to e\gamma$, $\tau \to \mu\gamma$ at HAND

[King et al, Buchmuller et al, Ellis et al, Casas et al, Carvalho et al, Sato et al, Hisano et al, Blazek et al, ...]

✱ IS IT A GENERAL FEATURE OF THE SEE-SAW ?

→ I WILL ILLUSTRATE

- expected improvements ARE ABLE to provide the desired additional informations ?
- susy < TeV, $\tau \to \mu\gamma$ a PROMISING TOOL to (hopefully) learn whether

y_D possesses small ← quarks / large ← light ν left mixings

... **NOT** an ACADEMIC distinction !

BR($l_i \to l_j \gamma$)

- **SM** BRs $\ll$ present bounds and NEGLIGIBLE due to $m_\nu \ll m_q$
- **MSSM** MAJOR PROBLEM: justify that **FV** has not already been found at a rate substantially larger than in SM

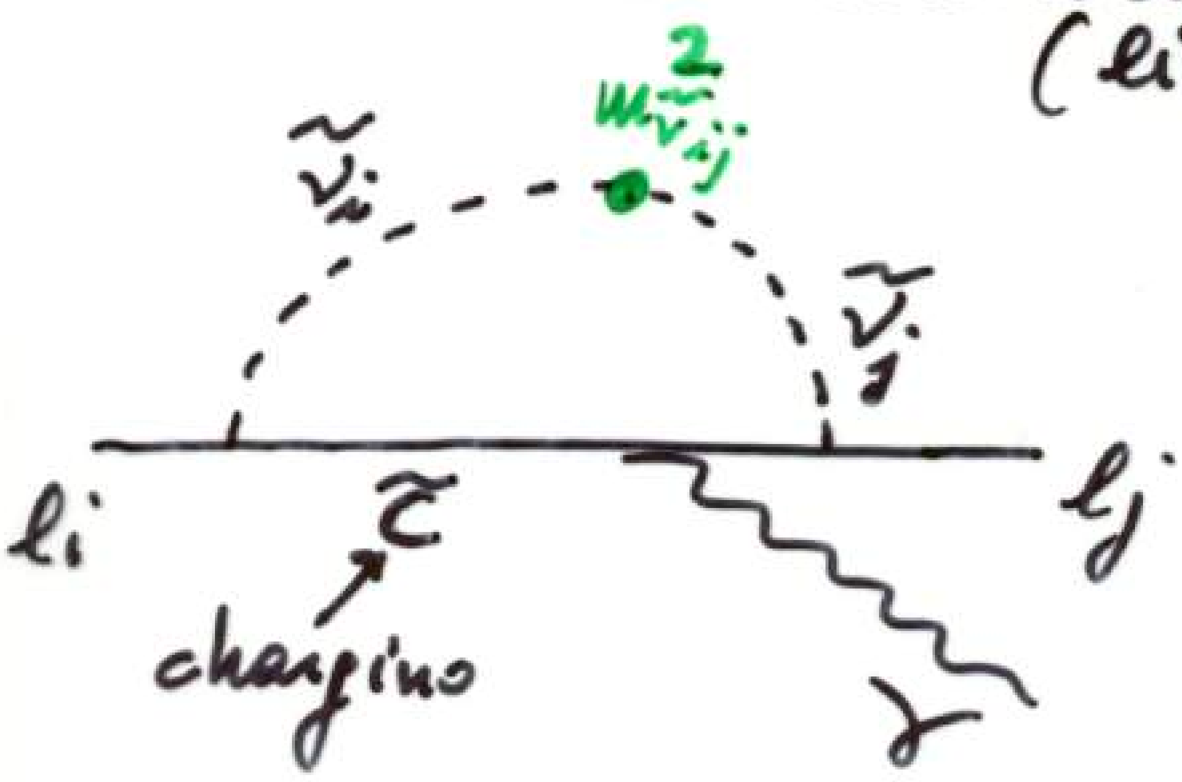
flavour dependence in soft terms $\longrightarrow$ loops with $\tilde{\ell}$ give rise to LFV because of mixing in $m^2_{\tilde{\ell}}$

$\downarrow$

$m^2_{\tilde{e}\,ij}$ $i \neq j$ STRONGLY BOUNDED by exp.

E.g.: $m^2_{\tilde{\nu}_{ij}}$ $_{i\neq j} \neq 0$

dominant contribution (like a_μ but with $m^2_{\tilde{\nu}_{ij}}$)



$\sim tg\beta$ (large $tg\beta$)

$$A_{ij} = f(m_{\tilde{\nu}}, M_2) \; \frac{m^2_{\tilde{\nu}_{ij}}}{m^2_{\tilde{\nu}}} \equiv \delta_{ij}$$

mean $m_{\tilde{\nu}}$ gaugino

WAY OUT: flavour indep. soft terms at $M_U \sim M_{Pl}$

universality

$$m_0^2 = m^2_{\tilde{L}} = \dots$$

EVEN in this case, if ν^c are present, [Borzumati Masiero] running of $m^2_{\tilde{\nu}}$ from M_U to M_R induces $m^2_{\tilde{\nu}_{ij}} \neq 0$ $_{i\neq j}$ due to y_D:

$$m^2_{\tilde{\nu}_{ij}}\Big|_{i\neq j} \approx -\frac{3}{8\pi^2} m_0^2 \left(y_D^\dagger \ln\frac{M_U}{M_R}\, y_D\right)_{ij}$$

SO $BR_{ij} \leq \mathcal{L}^{exp}_{ij}$ SUPPLIES $\left(y_D^\dagger \ln\frac{M_U}{M_R}\, y_D\right)_{ij} \leq L_{ij}(m_{\tilde{\nu}}, M_2) \propto \frac{\sqrt{\mathcal{L}^{exp}_{ij}}}{tg\beta}$

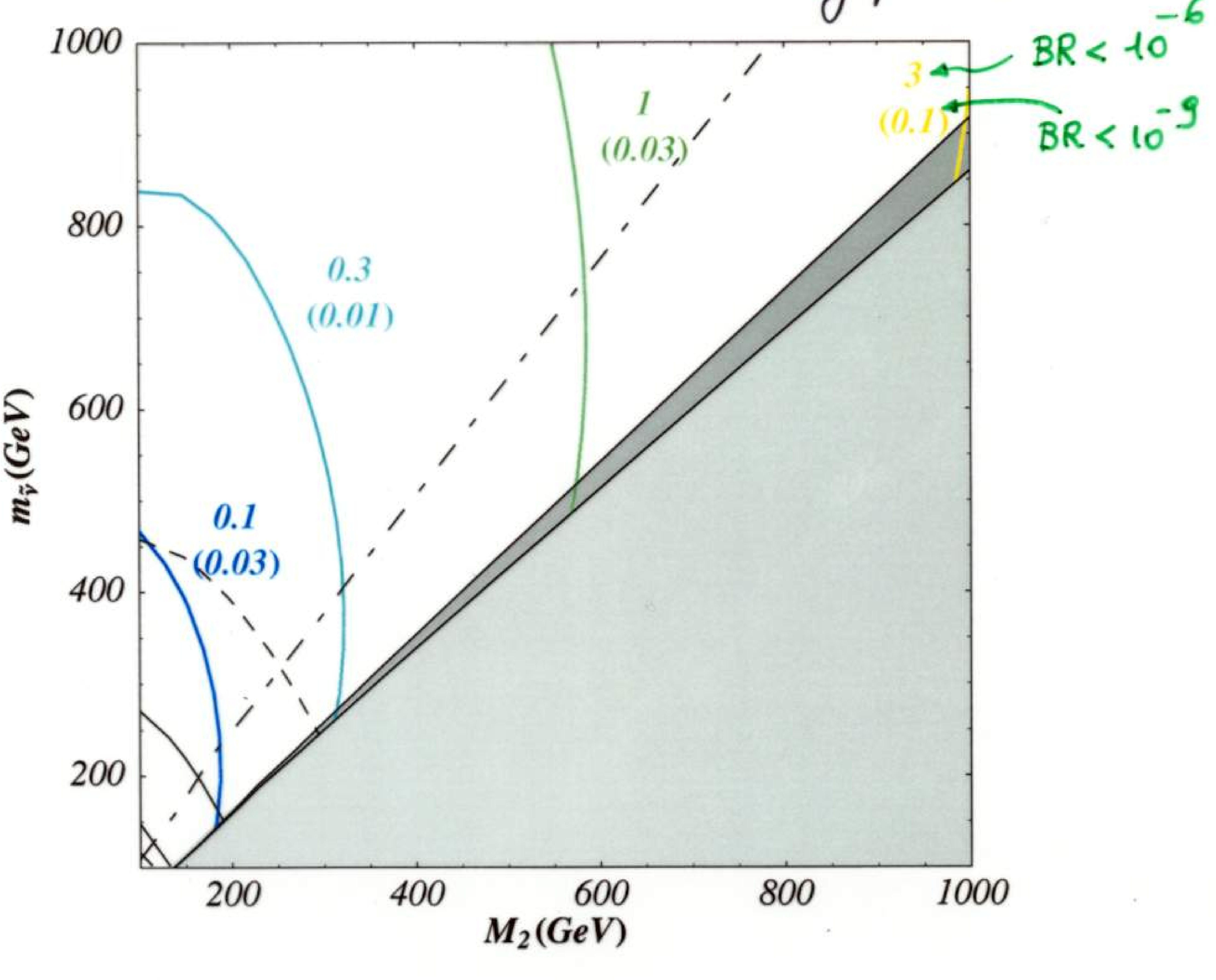
N.B. these are upper bounds: as usual assume NO CONSPIRACY with other (eventual) LFV sources (fl. dep. soft terms, rad corr in GU, unknown)

$\tau \to \mu\gamma$

UPPER LIMIT ON

$$\delta_{\tau\mu} \equiv \frac{m^2_{\tilde{\nu}_{32}}}{m^2_{\tilde{\nu}}}$$

$tg\,\beta = 10$

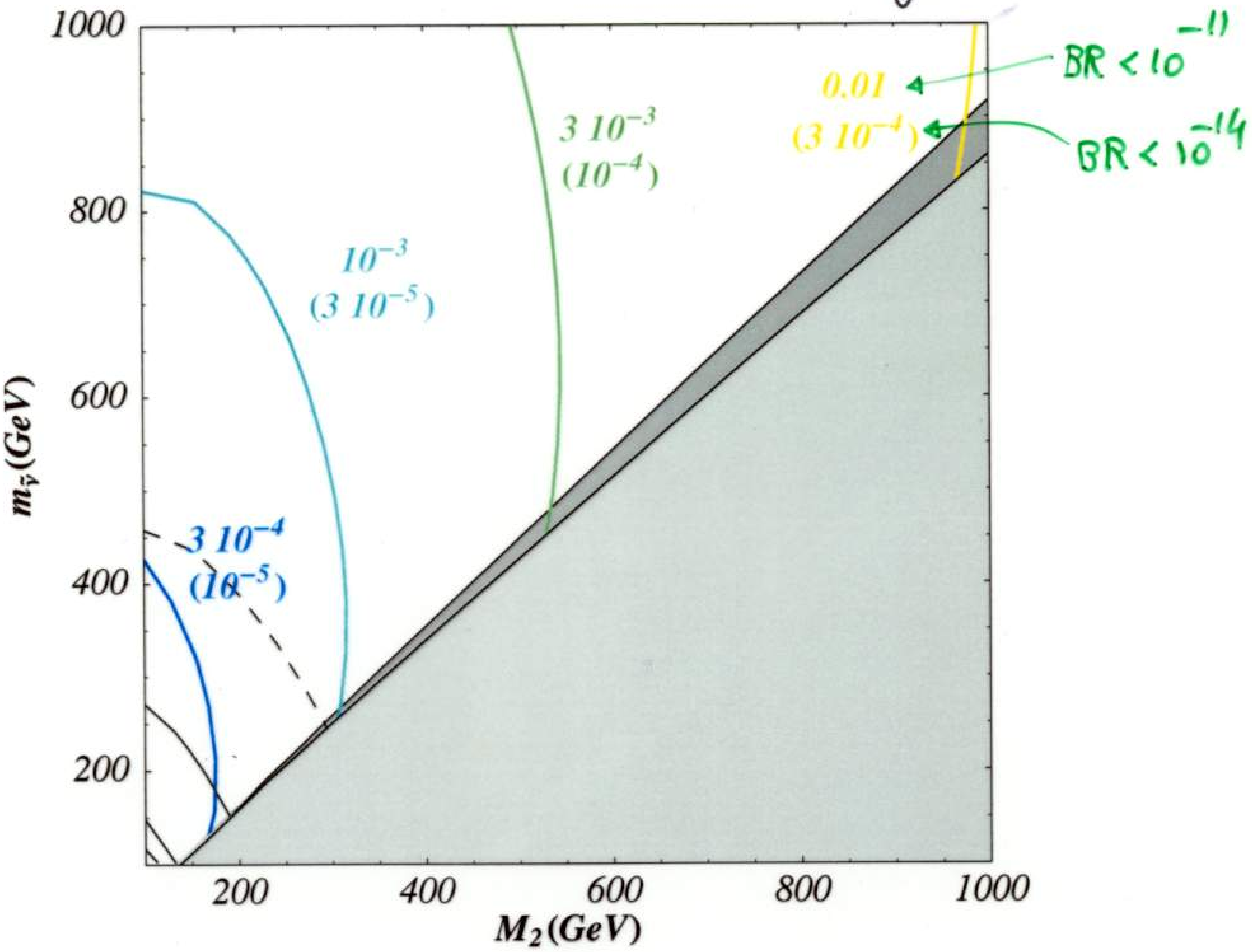


$\mu \to e\gamma$

UPPER LIMIT ON

$$\delta_{\mu e} \equiv \frac{m^2_{\tilde{\nu}_{21}}}{m^2_{\tilde{\nu}}}$$

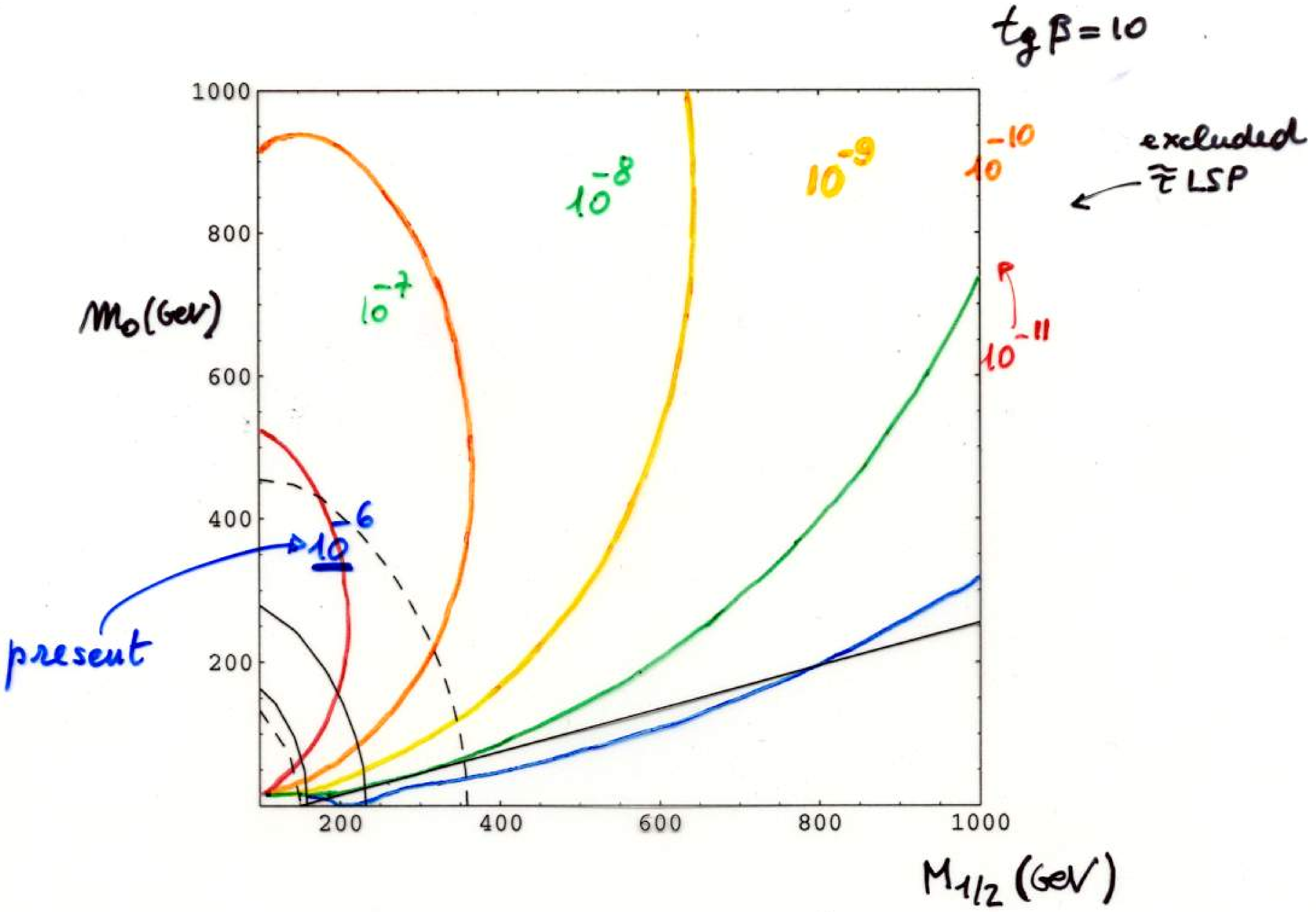
$tg\,\beta = 10$



$\tau \to \mu\gamma$

fix $\left(y_D^\dagger \ln\frac{M_U}{M_R} y_D\right)_{32} \simeq \ln(2'000) \sim 7$

and plot $BR(\tau \to \mu\gamma)$

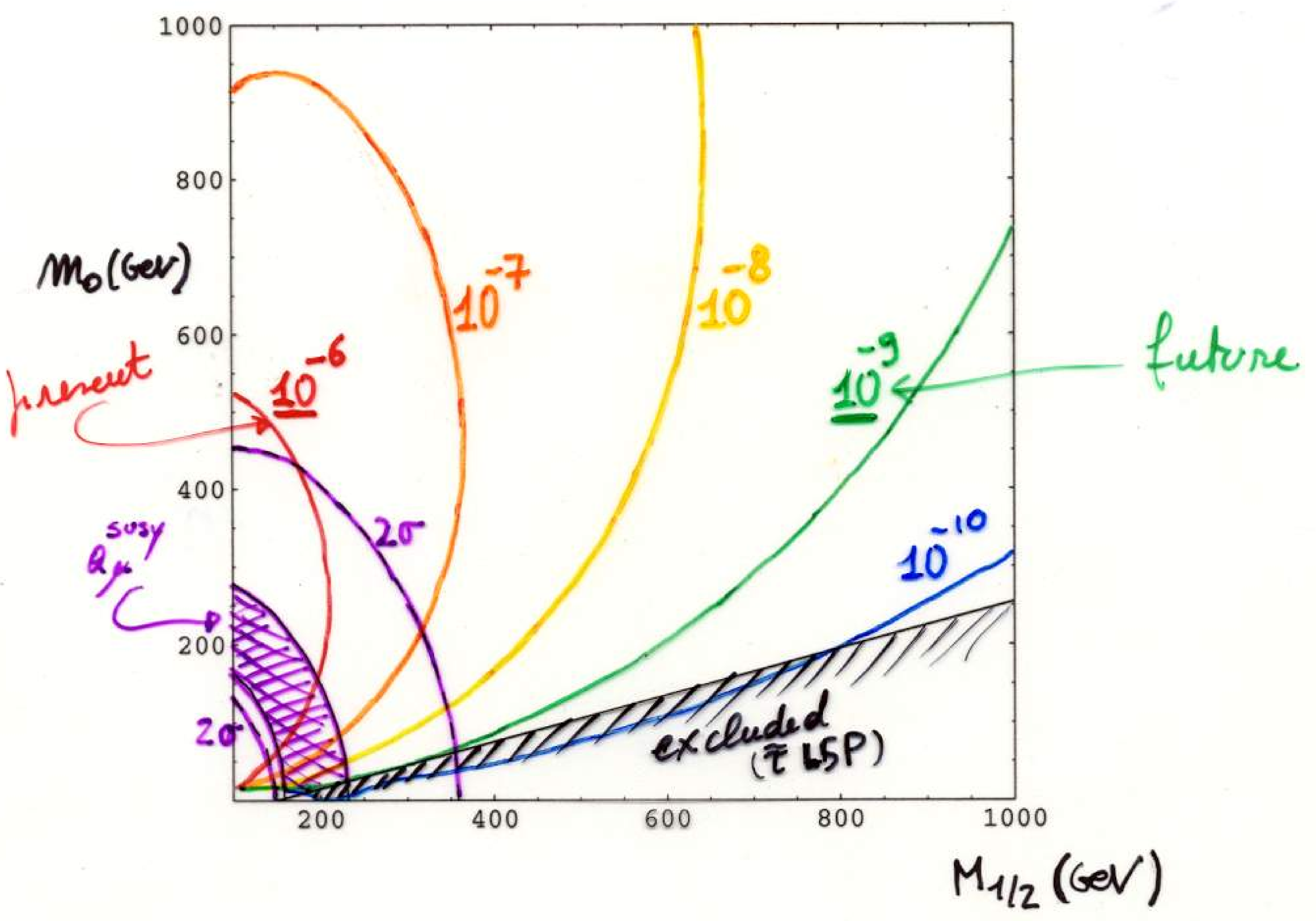


$\tau \to \mu\gamma$

fix $\left(y_D^\dagger \ln \frac{M_U}{M_R} y_D \right)_{32} \approx \ln(2\,10^3)$, $\tan\beta = 10$

and plot

$BR(\tau \to \mu\gamma)$

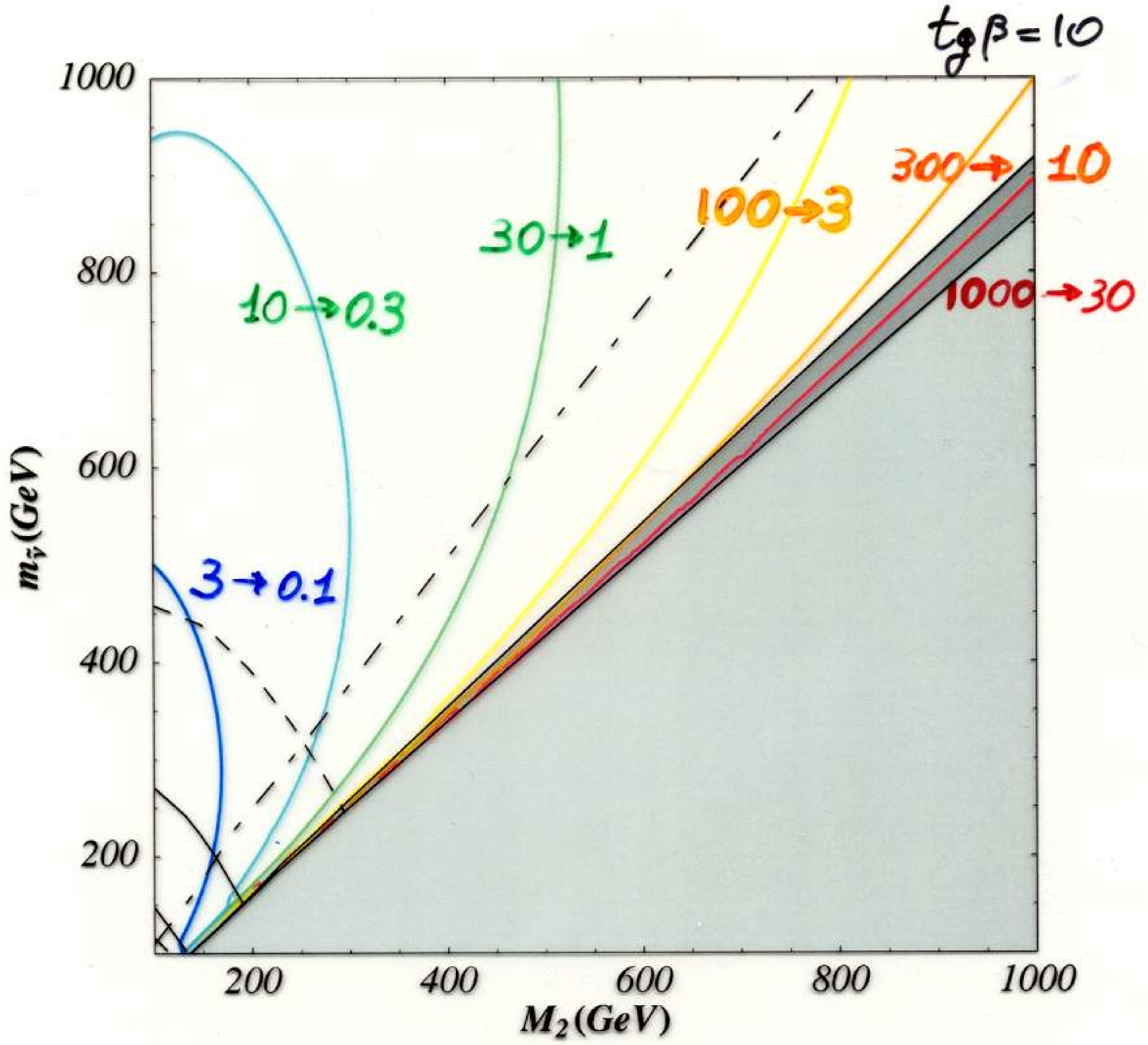


(see Ellis et al.)

$\tau \to \mu\gamma$

fix $BR(\tau \to \mu\gamma) \leq 10^{-6}$

and plot $L_{\tau\mu} \geq \left(y_D^{+} \ln \frac{M_U}{M_R} y_D\right)_{32}$



$$\boxed{\text{WHAT'S } \left(y_D^\dagger \ln\frac{M_U}{M_R}\, y_D\right)_{ij} \text{ ?}}$$

$$y_D = \begin{pmatrix} y_{D11} & y_{D12} \times & y_{D13} \times \\ y_{D12} + & y_{D22} \times & y_{D23} \times \\ y_{D13} + & y_{D32} \times & y_{D33} \times \end{pmatrix} \begin{array}{l} \ln M_U/M_1 \\ \ln M_U/M_2 \\ \ln M_U/M_3 \end{array}$$

IT CAN HAPPEN (e.g. y_D hyerarchycal) that III gen. gives the most sizeable contr.

$$\left(y_D^\dagger \ln\frac{M_U}{M_R}\, y_D\right)_{ij} \simeq y_{D_{3i}}^* \, y_{D_{3j}} \ln\frac{M_U}{M_3}$$

→ some access to V_L

HOWEVER it doesn't hold in general ...

CLASSES OF SEE-SAW MODELS

Consider $3\nu_L$ with hierarchycal spectrum $m_1 < m_2 < m_3$

$$m_3^2 \simeq \Delta m^2_{atm} \gg \Delta m^2_{sol} \simeq m_2^2$$

$\theta_{atm} \sim \pi/4$ all possible solutions

Useful CRITERION to classify the phen. allowed patterns for y_D and M_R:

which ν^c DOMINATES the 23 block of m^ν_{eff} ?

$$m_{atm} \simeq y^T_{D3i} \frac{1}{M_i} y_{i3} \; v^2 \qquad i = ?$$

$\equiv$ the contr. of the other ν^c is smaller by at least

$$\epsilon \equiv \frac{m_2}{m_3} \begin{cases} 0.1 & \text{LMA} \\ 0.04 & \text{SMA} \\ 0.006 & \text{LOW} \end{cases}$$

1) NONE

2) THE HEAVIEST, ν_3^c

3) ONE OF THE LIGHTEST, ν_1^c OR ν_2^c

CLASS 1 : NONE

E.g. 2x2

$$y_D = \begin{pmatrix} a & b \\ x & y \end{pmatrix} \qquad M_R = \begin{pmatrix} M_2 & 0 \\ 0 & M_3 \end{pmatrix} \quad \Bigg\} \quad m^\nu_{eff} = \begin{pmatrix} \frac{x^2}{M_3} + \frac{a^2}{M_2} & \frac{xy}{M_3} + \frac{ab}{M_2} \\ \frac{xy}{M_3} + \frac{ab}{M_2} & \frac{y^2}{M_3} + \frac{b^2}{M_2} \end{pmatrix} v_u^2$$

" $y_D^2 \sim M_R$ "

→ $m_2 \sim m_3$ invoke a tuning $t \sim \epsilon$

$t \simeq \{ \underset{LMA}{10\%},\ \underset{SMA}{4\%},\ \underset{LOW}{0.6\%} \}$ to have $\Delta m^2_{sol} \ll \Delta m^2_{atm}$

→ $\underline{x \simeq y}$, $a \simeq b$ for $\theta_{atm} \sim \pi/4$ ← LARGE LEFT mixing in y_D

→ $y \sim O(1) \Rightarrow M_3 \sim 5\ 10^{14}$ GeV

→ LFV : $y \sim O(1) \Rightarrow \left(y_D^\dagger \ln\frac{M_U}{M_R} y_D \right)_{32} \sim 7$ QUITE SHARP PREDICTION FOR $\tau \to \mu\gamma$

3x3

Despite t, this is an interesting class: always arises with Abelian $U(1)$ with "$q \geq 0$" (no susy zeros, ...), i.e. simplest fl. symm.
[Froggatt Nielsen, Ibanez Ross, Binétruy Lavignac Ramond, ...]

Rcharges (ν^c charges) disappear in m^ν_{eff} : all ν^c contribute at the same level to m^ν_{eff};
But, due to ln, ν^c_3 dominates ($y \ln y$)

LFV : $\tau \to \mu\gamma$ SHARP

$\mu \to e\gamma$ DEFINITE : having allowed for t, then:

(i) SMA $y_{31} \sim 10^{-3}$ (problems with me)

(ii) LMA $y_{31} \sim 0.1$

(iii) LOW $y_{31} \sim 0.005$

$$\left(y_D^\dagger \ln\frac{M_U}{M_R} y_D \right)_{21} \begin{cases} 7\ 10^{-3} & \text{SMA} \\ 0.7 & \text{LMA} \\ 0.04 & \text{LOW} \end{cases}$$

CLASS 2: THE HEAVIEST, ν_3^c

$$y_D = \begin{pmatrix} a & b \\ x & y \end{pmatrix}, \quad M_R = \begin{pmatrix} M_2 & 0 \\ 0 & M_3 \end{pmatrix} \Bigg\} \quad m^\nu_{eff} = \begin{bmatrix} \frac{x^2}{M_3} + \cancel{\frac{a^2}{M_2}} & \frac{xy}{M_3} + \cancel{\frac{ab}{M_2}} \\ \frac{xy}{M_3} + \cancel{\frac{ab}{M_2}} & \frac{y^2}{M_3} + \cancel{\frac{b^2}{M_2}} \end{bmatrix} v_u^2$$

" $y_D^2 > M_R$ "

→ $m_2 \ll m_3$ → $\Delta m^2_{sol} \ll \Delta m^2_{atm}$ naturally obtained

→ $\underline{x \approx y}$ for $\theta_{atm} \sim \pi/4$ ← LARGE LEFT mixing in y_D

→ $y \sim O(1)$ → $M_3 \sim 5\ 10^{14}$ GeV

→ LFV: $y \sim O(1)$ → $\left(y_D^+ \ln \frac{M_G}{M_R} y_D\right)_{32} \sim 7$ QUITE SHARP PREDICTION FOR $\tau \to \mu\gamma$

3x3

Need for a fl.-symm. more flexible than " $U(1)$ $q \geq 0$ "

E.g.: $U(1)$ $q \gtrless 0$ (susy zeros or more flavons)
[King (SRHND), Altarelli Feruglio, ...]

→ achieve SMA, LMA, LOW
but no sharp prediction for y_{31}
(→ look at single models)

LFV: $\tau \to \mu\gamma$ SHARP
$\mu \to e\gamma$ NOT DEFINITE PREDICTION

CLASS 3 : ONE OF THE LIGHTEST, ν_1^c OR ν_2^c

$$y_D = \begin{pmatrix} a & b \\ x & y \end{pmatrix} \qquad M_R = \begin{pmatrix} M_2 & 0 \\ 0 & M_3 \end{pmatrix} \Bigg\} \quad m^\nu_{eff} = \begin{pmatrix} \cancel{\frac{x^2}{M_3}} + \frac{a^2}{M_2} & \cancel{\frac{xy}{M_3}} + \frac{ab}{M_2} \\ \cancel{\frac{xy}{M_3}} + \frac{ab}{M_2} & \cancel{\frac{y^2}{M_3}} + \frac{b^2}{M_2} \end{pmatrix} v_u^2$$

"$y_D^2 < M_R$"

→ $m_2 \ll m_3$ → $\Delta m^2_{sol} \ll \Delta m^2_{atm}$ naturally obtained

→ $a \simeq b$ for $\theta_{atm} \sim \pi/4$

$x \lesssim y$ ← NO NEED FOR LARGE LEFT mixing in y_D

→ $\sqrt{\Delta m^2_{atm}} \simeq \frac{b^2}{M_2} v_u^2 \Rightarrow y \sim O(1) \quad M_3 \gtrsim M_{GUT} \sim 10^{16}\,GeV$

→ LFV : NO SHARP PREDICTION FOR $\tau \to \mu\gamma, \mu \to e\gamma$ BUT CAN BE SUPPRESSED

3x3

Need for a fl.-symm. which ensures "$y^2 < M$"

E.g. : $U(1) \times U(1)$, $U(2)$

[Altarelli Feruglio I.M., Barbieri et al, ...]

→ can achieve SMA, LMA, LOW with small y_{31}, y_{32}

EXAMPLES OF 3

U(1)
$q \gtrsim 0$

$$y_D = \begin{array}{c|ccc} & 2 & 0 & 0 \\ \hline 3 & \lambda^3 & \lambda & \lambda \\ 1 & \lambda & 0 & 0 \\ 0 & 1 & 0 & 0 \end{array} \qquad -2 \text{ from } H_U$$

$\lambda \cong \lambda_c$

$$M_R = \begin{array}{c|ccc} & 3 & 1 & 0 \\ \hline 3 & \lambda^6 & \lambda^4 & \lambda^3 \\ 1 & \lambda^4 & \lambda^2 & \lambda \\ 0 & \lambda^3 & \lambda & 1 \end{array} \; M_3$$

suitable for realistic SU(5)
[Altarelli Feruglio I.M.]

canonical form + basis where $M_R, m_\ell = \text{diag}$

$$y_D = \begin{pmatrix} \lambda^3 & \lambda & \lambda \\ \lambda & \lambda^3 & \lambda^3 \\ 1 & \lambda^2 & \lambda^2 \end{pmatrix}$$

- dominance of M_1
- $\theta_{atm} \sim \pi/4$
- LOW for solar
- $\begin{cases} M_1 \sim 10^{13}\,\text{GeV} \\ M_2 \sim 10^{16}\,\text{GeV} \\ M_3 \sim 2\,10^{17}\,\text{GeV} \end{cases}$

dominant contribution to $\tau \to \mu\gamma$

$$(y^\dagger \ln y)_{32} \approx \lambda^2 \ln \frac{M_U}{M_1}$$

U(2)

$$U(2) \xrightarrow{\epsilon} U(1) \xrightarrow{\epsilon'} \text{unity}$$

1,2 row not greater than 3

$$y_D = \begin{pmatrix} \cdot & \cdot & \cdot \\ \cdot & \cdot & \cdot \\ \epsilon' & \epsilon & 1 \end{pmatrix}$$

- Barbieri et al: dominance of M_1 SMA

for $\tau \to \mu\gamma$

$$(y^\dagger \ln y)_{32} \sim \epsilon \ln \frac{M_U}{M_{3(2)}}$$

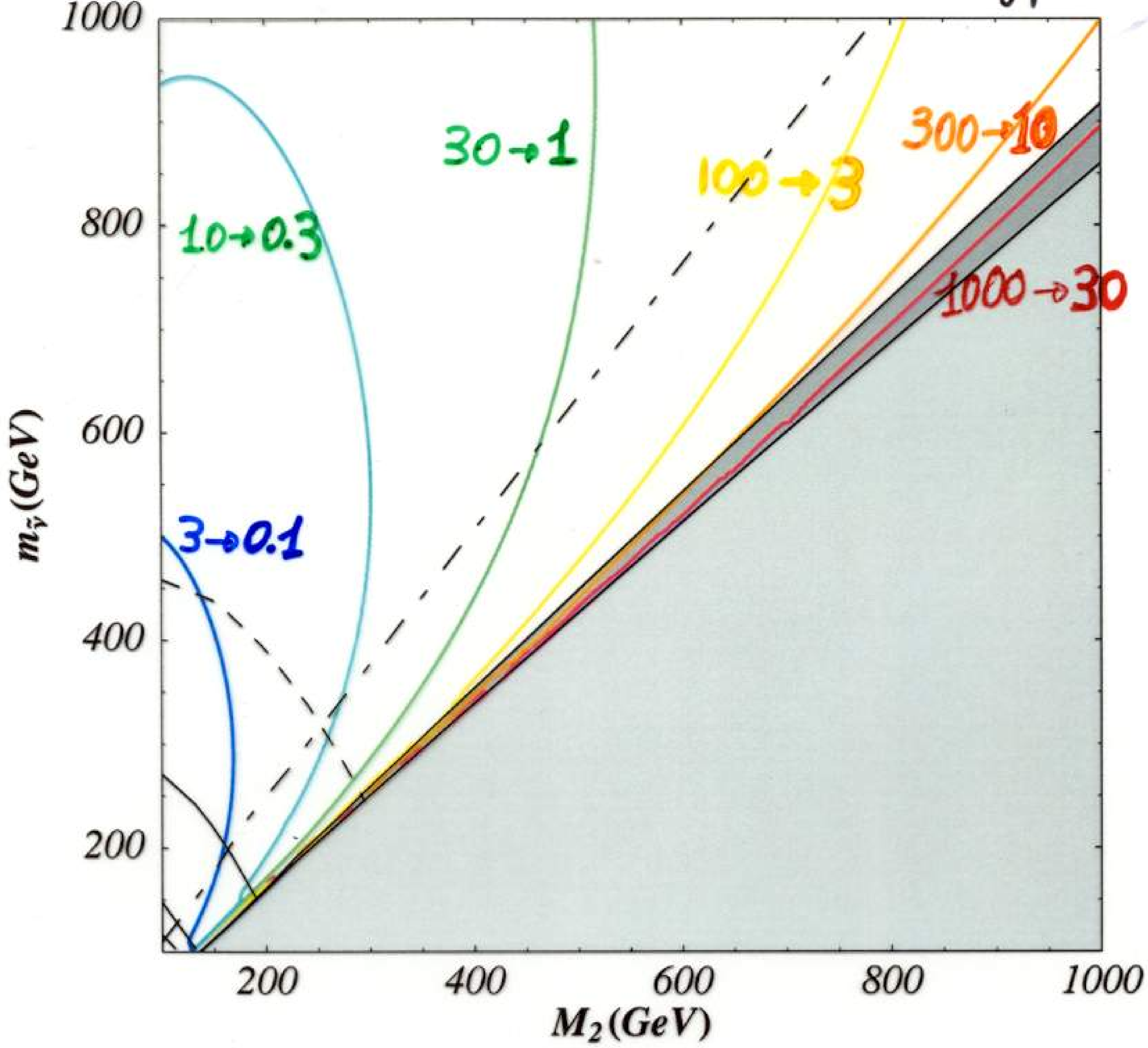
linked to $U(2) \to U(1)$

$\tau \to \mu\gamma$

fix $BR(\tau \to \mu\gamma) \lesssim 10^{-6}$ (10^{-9})

and plot $L_{\tau\mu} \gtrsim \left(y_D^\dagger \ln\frac{M_U}{M_R} y_D\right)_{32}$

$\tan\beta = 10$



$\left(y_D^\dagger \ln\frac{M_U}{M_R} y_D\right)_{32} \approx O(7)$ for class 1, 2
None M_3

$\approx O(0.4)$ in the ex. of. class 3
M_1, M_2

(If susy < TeV and)

if $\tau \to \mu\gamma$ is FOUND ($BR > 10^{-9}$) $\Rightarrow$?

Find $(m_{\tilde{\nu}}, M_2)$. If $y_{32} y_{33} \ll 1$ go back, otherwise

$y_{32} \sim y_{33} \sim O(1)$ $\Rightarrow$ V_L has LARGE 23 LEFT-MIXINGS

$\Downarrow$

UNLIKE quarks!! Maybe SU(5) and large R mixings in y_d

$\Rightarrow$ DOMINANCE of M_3 or NONE in m^{ν}_{eff}

$\Downarrow$

ν^c are NOT NECESSARILY hierarchycal

$\Downarrow$

$M_{\cancel{?}} \div M_3 \leq M_{GUT}$ (g.c.u. in MSSM) $M_3 \sim 5\ 10^{14}$ GeV

$\Rightarrow$ FLAVOUR SYMMETRY which gives y_D^2 MORE / AS hierarchycal then / as M_R

$\Downarrow$

It can be

NONE $\to$ $\cancel{\square}$ trivial : $U(1)\ q \geq 0$

M_3 $\to$ $\cancel{\square}$ non trivial : $U(1)\ q \gtrless 0$, $U(1) \times U(1)$, $U(2)$, ...

TO PROCEEDE : $\mu \to e\gamma$

Also because (III non dom. in $y_\nu y$)

$$\frac{BR(\mu \to e\gamma)}{BR(\tau \to \mu\gamma)} = \frac{100}{17} \frac{y_{31}}{y_{33}}$$

(If susy < TeV and) BR $< 10^{-9}$

if $\tau \to \mu\gamma$ is <u>NOT FOUND</u>

$\Rightarrow$ V_L has <u>SMALL</u> 23 LEFT-MIXINGS

$\Downarrow$ <u>LIKE</u> quarks! Maybe <u>LR, SO(10), ...</u>

$\Rightarrow$ DOMINANCE of <u>M_1 or M_2</u> in m^{ν}_{eff}

$\Downarrow$ ν^c are <u>STRONGLY</u> hierarchycal

$\downarrow$

$M_{1,2} \div M_3 \gtrsim M_{GUT}$ (g.c.u. in MSSM) well for SO(10)

$\Rightarrow$ FLAVOUR SYMMETRY which gives y_D^2 <u>LESS</u> hierarchycal than M_R

$\Downarrow$ It can be

☐ trivial : $U(1)$ $q \geq 0$

☒ non trivial : $U(1)$ $q \gtrless 0$, $U(1) \times U(1)$, $U(2)$, ...

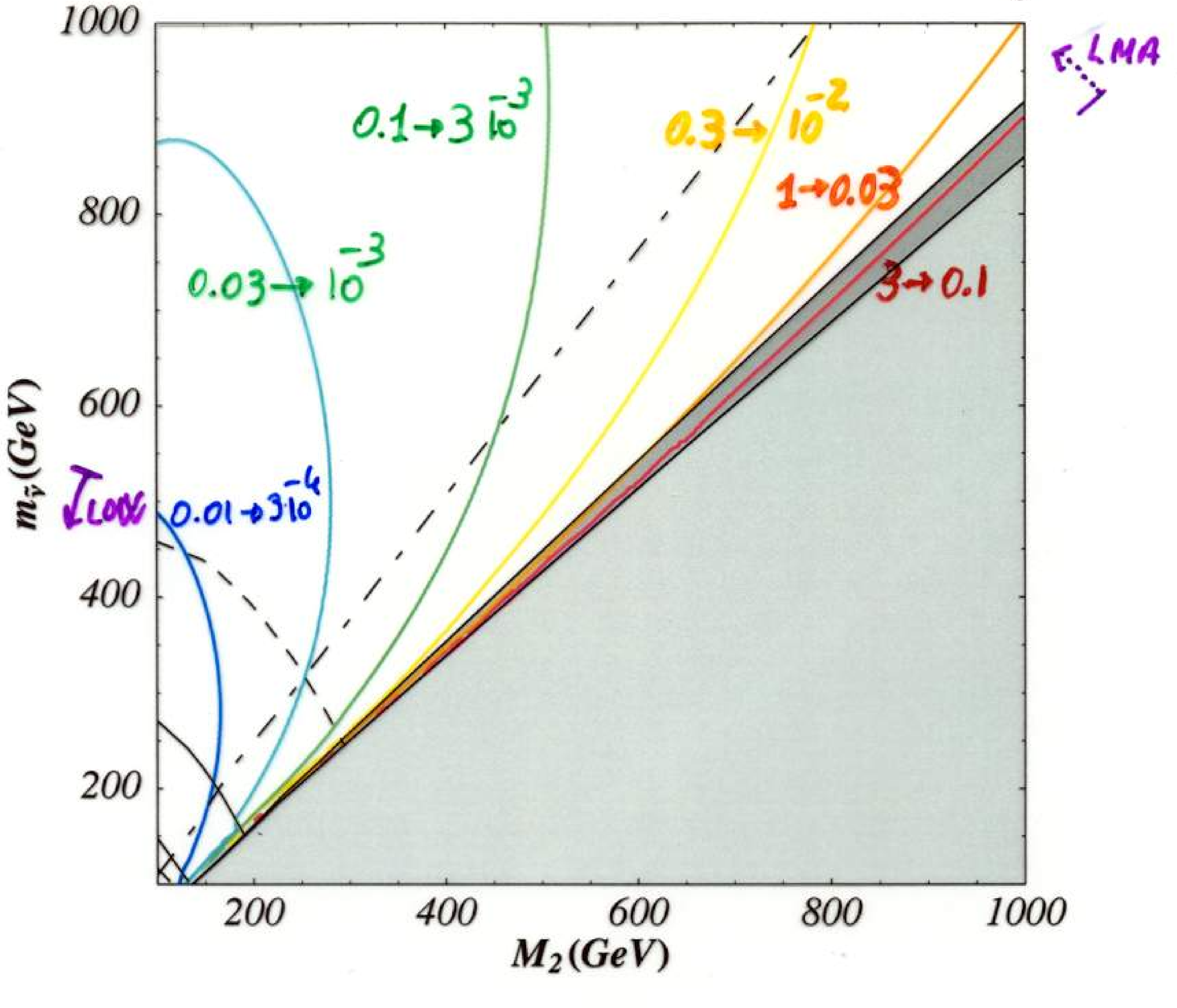
$\mu \to e\gamma$

fix $BR(\mu \to e\gamma) \leq 10^{-11}$ (10^{-14}) and plot $L_{\mu e} \geq \left(y_D^\dagger \ln \frac{M_U}{M_R} y_D\right)_{21}$

LOW

LMA

$tg\beta = 10$



simplest U(1) (NONE) : $\left(y_D^\dagger \ln \frac{M_U}{M_R} y_D\right)_{21}$ ↗ 0.7 LMA ↘ 0.04 LOW

CONCLUSIONS

- Is it possible to DISCRIMINATE SEE-SAW MODELS by improving the exp. sensitivity to ch. LFV processes?

- (hierarchical spectrum)
  CLASSIFYING the see-saw models according to THE MECHANISM WHICH GENERATES

$$\epsilon = \frac{m_2}{m_3} = \sqrt{\frac{\Delta m^2_{sol}}{\Delta m^2_{atm}}}$$

ALLOWS TO

→ characterize each class through phys. properties : flavour mixing in y_D
scale for ν^c masses

→ study the predictions for $\tau \to \mu\gamma$, $\mu \to e\gamma$

$\tau \to \mu\gamma$ PROMISING TOOL to identify the origin of $\theta_{atm} \sim \pi/4$ (y_D or seesaw?)

$\mu \to e\gamma$ more MODEL DEPENDENT

EVEN with 10^{-3} improvement,
$\tau \to \mu\gamma$, $\mu \to e\gamma$ COULD ESCAPE DETECTION
in models where Δm^2_{atm} is determined by one of the lightest ν^c.