BSM and the early LHC

IPNL, December 16th 2010

Slepton mass-splittings and LFV at the LHC

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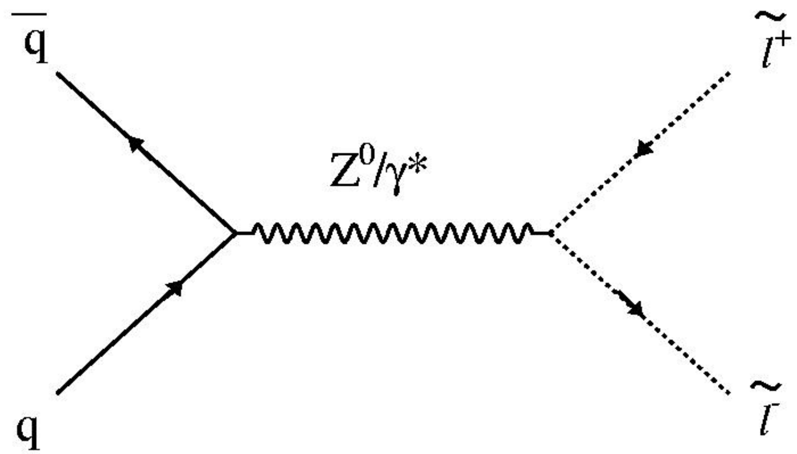
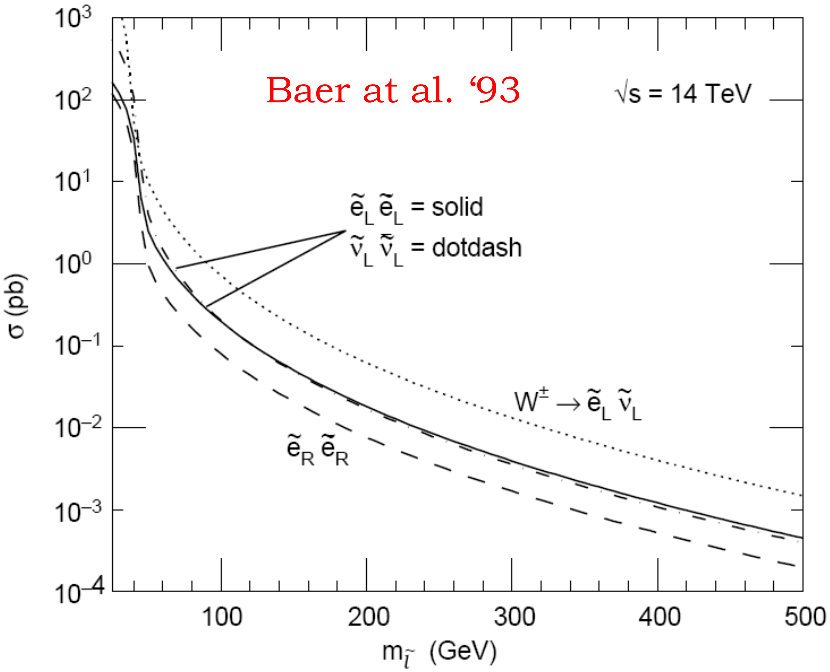
mainly based on

A. J. Buras, L.C., P. Paradisi, arXiv:0912.1309 [hep-ph]

- Direct production (Drell-Yan):





Low cross-section and large SM bg ⟹ detection up to $m_{\tilde{\ell}}$ ~ 200-300 GeV

Difficult to extract information on the slepton masses

Slepton production and mass measurement at the LHC

- Indirect production (cascade decays):

$$\tilde{q}_L \to q_L \, \tilde{\chi}_2^0 \to q_L \, \tilde{\ell}^{\pm} \ell^{\mp}$$

Wino-like $\tilde{\chi}_2^0$:

$$\mathrm{BR}(\tilde{q}_L \to q_L \, \tilde{\chi}_2^0) \simeq 1/3$$

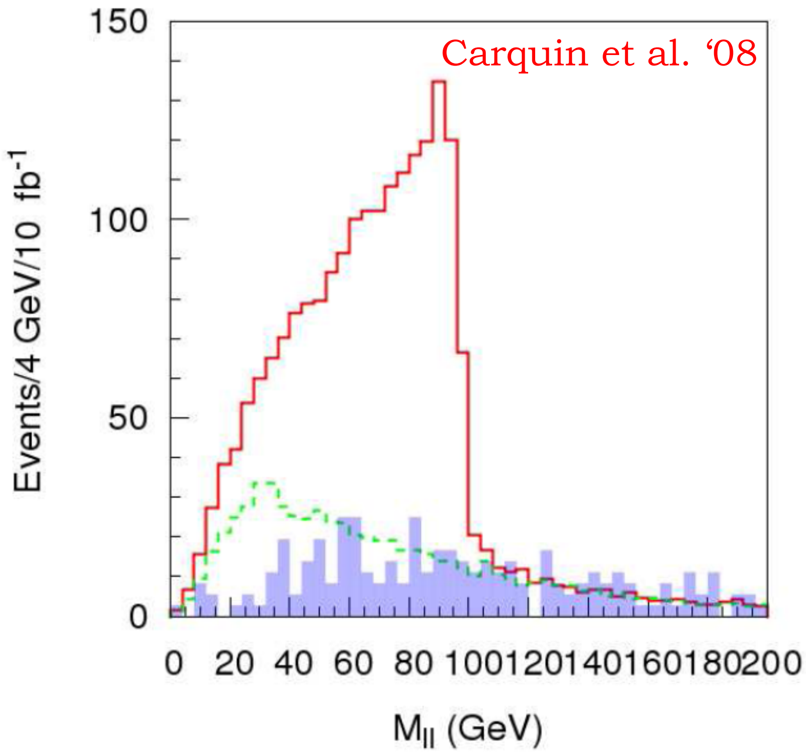
Kinematic end-point:

$$\tilde{\chi}_2^0 \to \tilde{\ell}^{\pm} \ell^{\mp} \to \tilde{\chi}_1^0 \ell^{\pm} \ell^{\mp}$$

$m_{\tilde{\chi}_2^0} > m_{\tilde{\ell}}$

$$m_{ll}^2 = \frac{(m_{\tilde{\chi}_2^0}^2 - m_{\tilde{\ell}}^2)(m_{\tilde{\ell}}^2 - m_{\tilde{\chi}_1^0}^2)}{m_{\tilde{\ell}}^2}$$

Paige '96; Hinchliffe et al. '96



Can the measurement of the kinematic edges of the *e*-*e* and *μ*-*μ* invariant mass distributions resolve a mass difference between selectron and smuon?

$$\frac{\Delta m_{\tilde{\ell}}}{m_{\tilde{\ell}}} \quad \Longrightarrow \quad \frac{\Delta m_{ll}}{m_{ll}} = \frac{\Delta m_{\tilde{\ell}}}{m_{\tilde{\ell}}} \left(\frac{m^2_{\tilde{\chi}^0_1} m^2_{\tilde{\chi}^0_2} - m^4_{\tilde{\ell}}}{(m^2_{\tilde{\chi}^0_2} - m^2_{\tilde{\ell}})(m^2_{\tilde{\ell}} - m^2_{\tilde{\chi}^0_1})} \right)$$

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It can be measured at the LHC with precision below the percent level!

Allanach et al. '08

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Allanach et al. '08

- Is a measurable selectron-smuon splitting possible within the CMSSM?
- If not, such observation could point towards non-minimal effects (e.g. LFV)
- Alternatively, it can be due to non-degeneracy already at the SUSY breaking scale in models with alignment

Feng et al. '07, '09

Slepton mass matrix in absence of flavour mixing:

$$m^2_{\tilde{\ell}} = \begin{pmatrix} m^2_{\tilde{\ell}_L} + m^2_\ell + \mathcal{O}(m^2_Z) & m_\ell(A^*_\ell - \mu\tan\beta) \\ m_\ell(A_\ell - \mu\tan\beta) & m^2_{\tilde{\ell}_R} + m^2_\ell + \mathcal{O}(m^2_Z) \end{pmatrix}$$

$$\Longrightarrow \quad m^2_{\tilde{\ell}_{1,2}} = \frac{(m^2_{\tilde{\ell}_L} + m^2_{\tilde{\ell}_R})}{2} \mp \frac{\sqrt{(m^2_{\tilde{\ell}_L} - m^2_{\tilde{\ell}_R})^2 + 4(\Delta^{\tilde{\ell}\tilde{\ell}}_{RL})^2}}{2}$$

$$\Delta^{\tilde{\ell}\tilde{\ell}}_{RL} = m_\ell(A_\ell - \mu\tan\beta)$$

In the CMSSM, from the RGEs, we approximately have:

$$m^2_{\tilde{\ell}_L} \approx m^2_0(1 - |c|y^2_\ell) + 0.5M^2_{1/2} \qquad m^2_{\tilde{\ell}_R} \approx m^2_0(1 - 2|c|y^2_\ell) + 0.15M^2_{1/2}$$

$$|c| \approx (3 + a^2_0)\ln(M_X/M_Z)/(4\pi)^2$$

Lepton flavour conserving case

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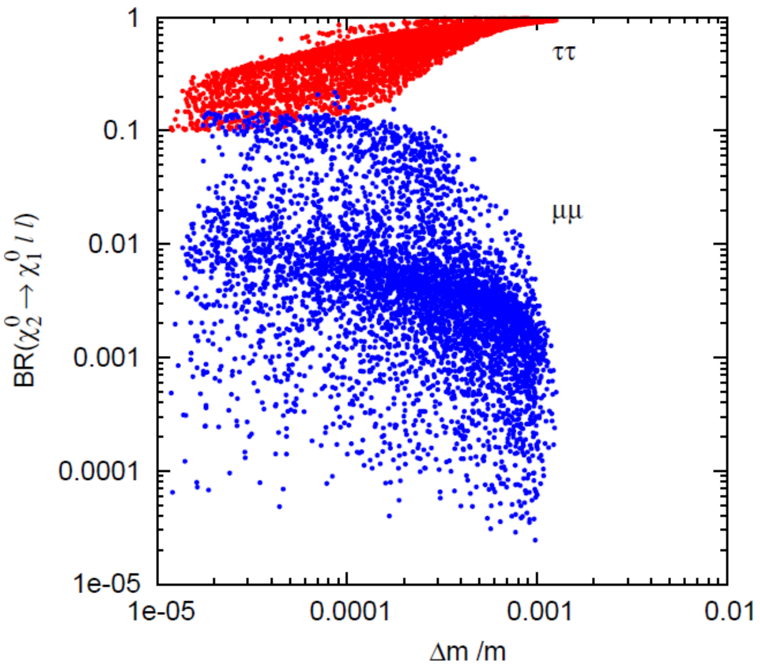
Lepton flavour conserving case

We get for smuons and selectrons:

$$\frac{\Delta m_{\tilde{\ell}}}{m_{\tilde{\ell}}} \simeq \frac{m_{\tilde{e}_R} - m_{\tilde{\mu}_R}}{m_{\tilde{\ell}}} + \frac{(\Delta^{\tilde{\mu}\tilde{\mu}}_{RL})^2}{m^2_{\tilde{\ell}}(m^2_{\tilde{\mu}_L} - m^2_{\tilde{\mu}_R})}$$

~ 0.1 %, even for large tanβ



$$m_0, M_{1/2} \leq 1 \text{ TeV}$$

$$-3 \leq a_0 \leq +3$$

$$\tan\beta \leq 50$$

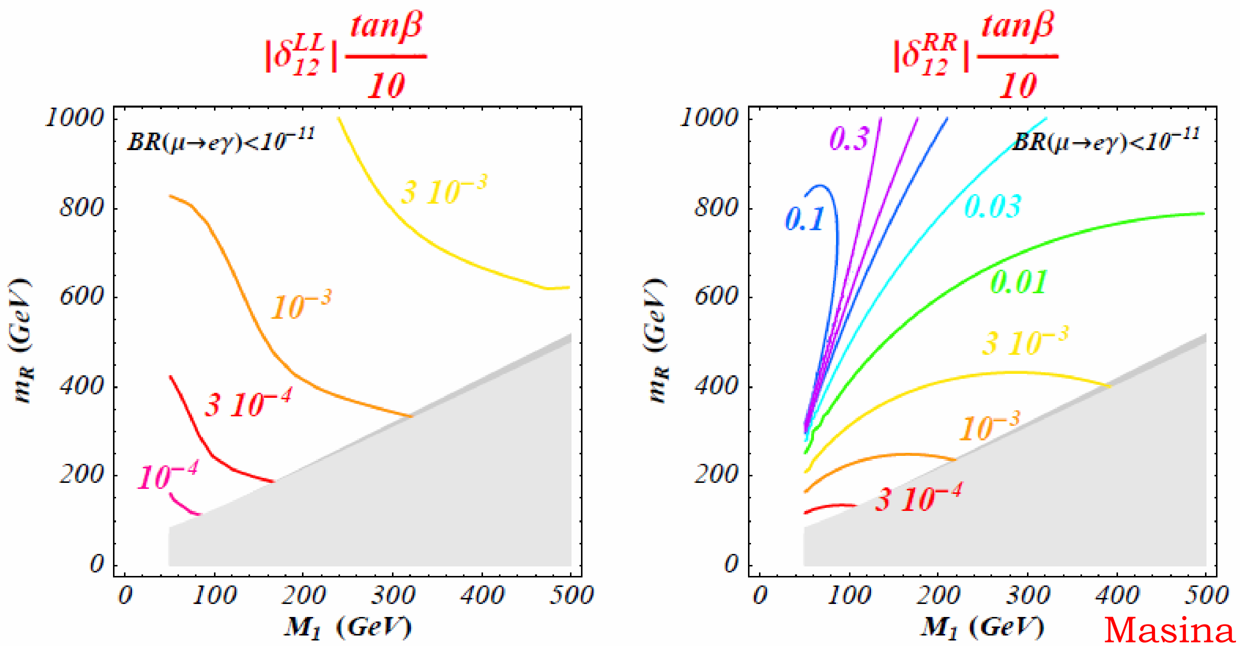
⇨ not measurable at the LHC

If $\Delta m_{\tilde{\ell}}/m_{\tilde{\ell}}$ induced by LFV → correlation with low-energy LFV, $\ell_i \to \ell_j \gamma$

- LFV sources in the 1-2 sector:

$$\left|\frac{\Delta m_{\tilde{\ell}}}{m_{\tilde{\ell}}}\right| \simeq |\delta^e_{12}| \qquad\qquad (\delta^e_{\rm XY})_{ij} \equiv \frac{(\tilde{m}^2_{\rm XY})_{ij}}{m^2_{\tilde{\ell}}}$$

Strong constraints from $\mathrm{BR}(\mu \to e\gamma)$ (< 1.2 x 10^{-11}) :



Masina and Savoy. '02

Lepton flavour violating case

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Hisano et al. '02, '08

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Hisano et al. '02, '08

- What about LFV in the 2-3 sector? (or 1-3, but not at same time)

$(\delta_{\mathrm{LL}})_{32}$ ⇒ $\tilde{e}_L - \tilde{\mu}_L$ splitting

$(\delta_{\mathrm{RR}})_{32}$ ⇒ $\tilde{e}_R - \tilde{\mu}_R$ splitting

$$\left|\frac{\Delta m_{\tilde{\ell}}}{m_{\tilde{\ell}}}\right| \simeq \frac{|\delta_{32}|}{2}$$

Clearly splitting is induced also between stau and smuon, but stau masses are also affected by possibly large RG effects, LR mixing …

Lepton flavour violating case

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$$\left|\frac{\Delta m_{\tilde{\ell}}}{m_{\tilde{\ell}}}\right| \simeq \frac{|\delta_{32}|}{2}$$

⇒ Possible hints of (2-3) LFV from flavour conserving processes such:

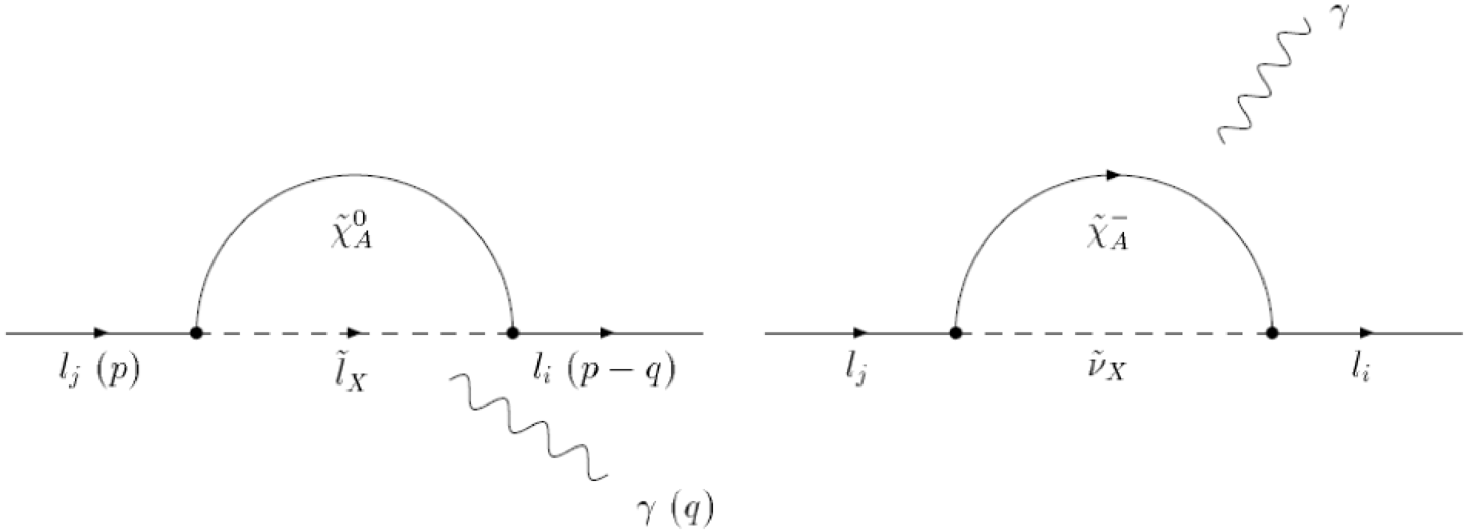
$$\tilde{\chi}^0_2 \to \tilde{\chi}^0_1 \mu^+ \mu^- / \tilde{\chi}^0_1 e^+ e^-$$

If δ_{32} is the origin of a selectron-smuon mass splitting, LFV processes are clearly unavoidable.

- Low-energy LFV:

$$\frac{\mathrm{BR}(\tau \to \mu\gamma)}{\mathrm{BR}(\tau \to \mu\nu_\tau\bar{\nu}_\mu)} = \frac{48\pi^3\alpha}{G_F^2}(|A_L^{32}|^2 + |A_R^{32}|^2)$$

$$A_L^{32} \simeq \frac{\alpha_2}{60\pi}\frac{\tan\beta}{\tilde{m}^2}(\delta_{\rm LL})_{32}\,, \qquad A_R^{32} \simeq -\frac{\alpha_1}{4\pi}\frac{\tan\beta}{\tilde{m}^2}\frac{(\delta_{\rm RR})_{32}}{60}\,.$$



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Process	Present Bound	Future Bound	Future Exp.
$\mathrm{BR}(\tau \to \mu\,\gamma)$	4.4×10^{-8}	$\mathcal{O}(10^{-8})$	SuperB [32]
$\mathrm{BR}(\tau \to \mu\,\mu\,\mu)$	3.2×10^{-8}	$\mathcal{O}(10^{-8})$	LHCb [33]
$\mathrm{BR}(\tau \to \mu\,e\,e)$	2.0×10^{-8}	$\mathcal{O}(10^{-8})$	SuperB [32]

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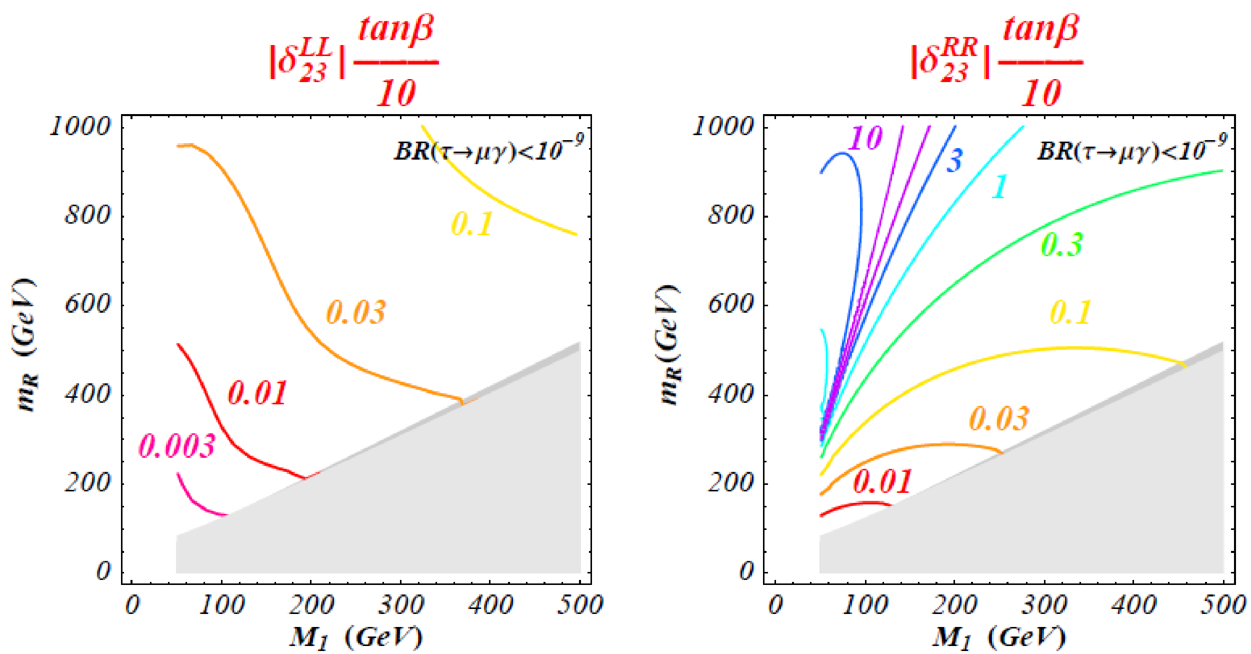

Masina and Savoy. '02

$$\left|\frac{\Delta m_{\tilde{\ell}}}{m_{\tilde{\ell}}}\right| \simeq \frac{|\delta_{32}|}{2}$$

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- High-energy LFV:

$$\boxed{\tilde{\chi}_2^0 \to \tilde{\chi}_1^0 \tau^{\pm} \mu^{\mp}}$$

Arkani-Hamed et al. '96, '97
Hinchliffe and Paige '00
Carvalho et al.'02, Carquin et al. '08
...

$$\mathrm{BR}(\tilde{\chi}_2^0 \to \ell_i \ell_j \tilde{\chi}_1^0) = \left[\mathrm{BR}(\tilde{\chi}_2^0 \to \ell_i \tilde{\ell}_\alpha)\mathrm{BR}(\tilde{\ell}_\alpha \to \ell_j \tilde{\chi}_1^0) + \mathrm{BR}(\tilde{\chi}_2^0 \to \ell_j \tilde{\ell}_\alpha)\mathrm{BR}(\tilde{\ell}_\alpha \to \ell_i \tilde{\chi}_1^0)\right]$$

$$\Gamma(\tilde{\chi}_K^0 \to \tilde{\ell}_\alpha \ell_i) = \frac{\alpha_2}{16} m_{\tilde{\chi}_K^0} \left(1 - \frac{m_{\tilde{\ell}_\alpha}^2}{m_{\tilde{\chi}_K^0}^2}\right)^2 \left(\left|L_{i\alpha}^K\right|^2 + \left|R_{i\alpha}^K\right|^2\right)$$

$$\Gamma(\tilde{\ell}_\alpha \to \tilde{\chi}_K^0 \ell_i) = \frac{\alpha_2}{8} m_{\tilde{\ell}_\alpha} \left(1 - \frac{m_{\tilde{\chi}_K^0}^2}{m_{\tilde{\ell}_\alpha}^2}\right)^2 \left(\left|L_{i\alpha}^K\right|^2 + \left|R_{i\alpha}^K\right|^2\right)$$

If δ_{32} is the origin of a selectron-smuon mass splitting, LFV processes are clearly unavoidable.

- High-energy LFV:

$$|\tilde{e}\rangle = +\cos\theta|1\rangle + \sin\theta|2\rangle$$
$$|\tilde{\mu}\rangle = -\sin\theta|1\rangle + \cos\theta|2\rangle$$

$$\begin{aligned}|\psi(t)\rangle &= \cos\theta e^{-\frac{\Gamma}{2}t-im_1t}|1\rangle + \sin\theta e^{-\frac{\Gamma}{2}t-im_2t}|2\rangle \\ &= (\cos^2\theta e^{-\frac{\Gamma}{2}t-im_1t} + \sin^2\theta e^{-\frac{\Gamma}{2}t-im_2t})|\tilde{e}\rangle \\ &\quad - \sin\theta\cos\theta(e^{-\frac{\Gamma}{2}t-im_1t} - e^{-\frac{\Gamma}{2}t-im_2t})|\tilde{\mu}\rangle\end{aligned}$$

$$\Longrightarrow \quad \begin{aligned}P(\tilde{e}\to f_\mu) &= \frac{\int_0^\infty dt|\langle\tilde{\mu}|\psi(t)\rangle|^2}{\int_0^\infty dt\langle\psi(t)|\psi(t)\rangle} \times B(\tilde{\mu}\to f_\mu) \\ &= 2\sin^2\theta\cos^2\theta\frac{(\Delta m^2)^2}{4\bar{m}^2\Gamma^2 + (\Delta m^2)^2} \times B(\tilde{\mu}\to f_\mu)\ ,\end{aligned}$$

Arkani-Hamed et al. ’96

while:

$$\mathrm{BR}(\ell_i \to \ell_j\gamma) \propto \frac{1}{\bar{m}^4}\left(\sin\theta\cos\theta\frac{\Delta m^2}{\bar{m}^2}\right)^2$$

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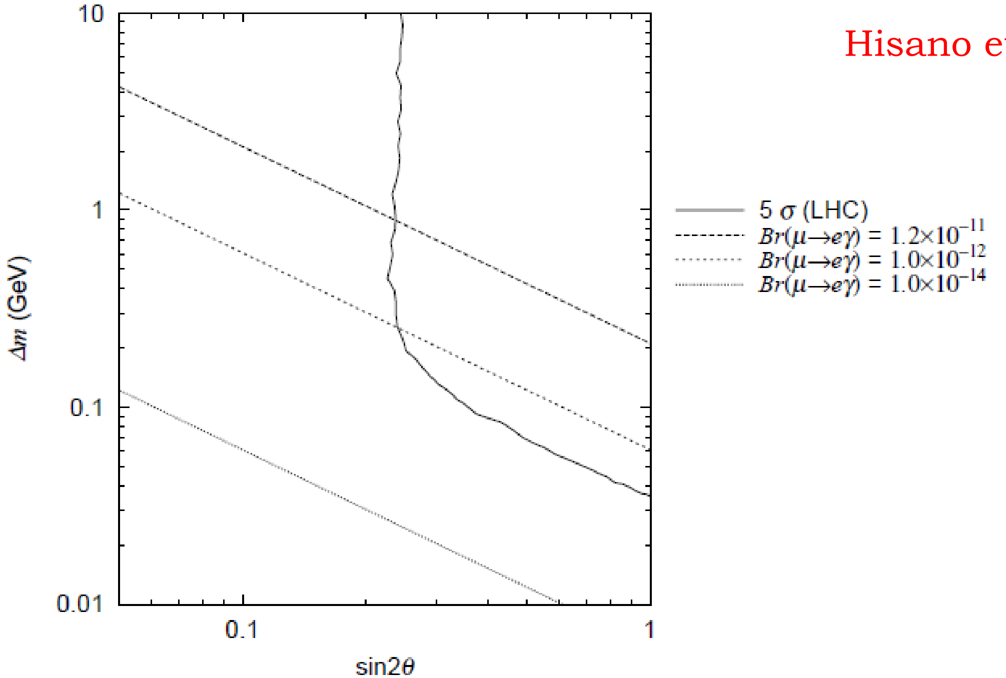
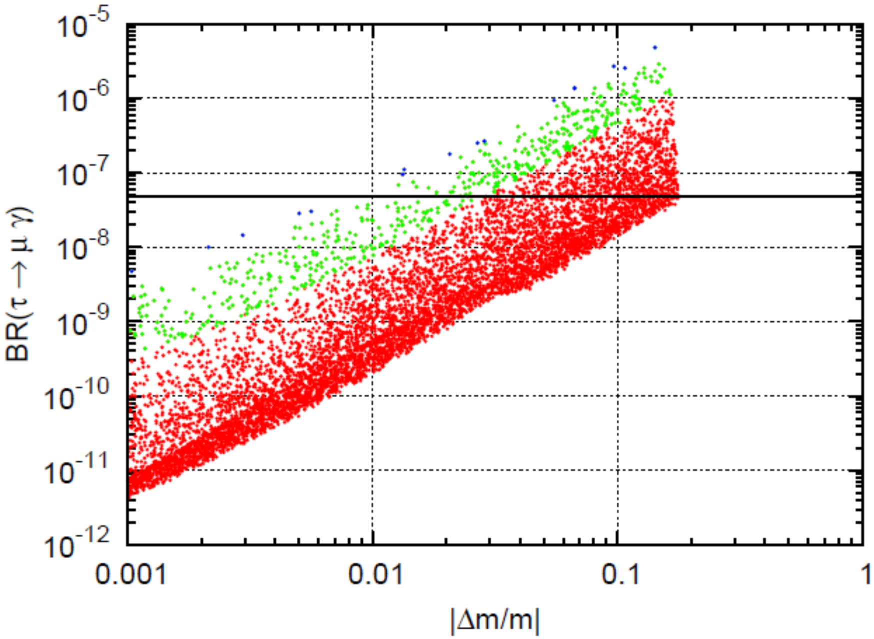
- High-energy LFV:



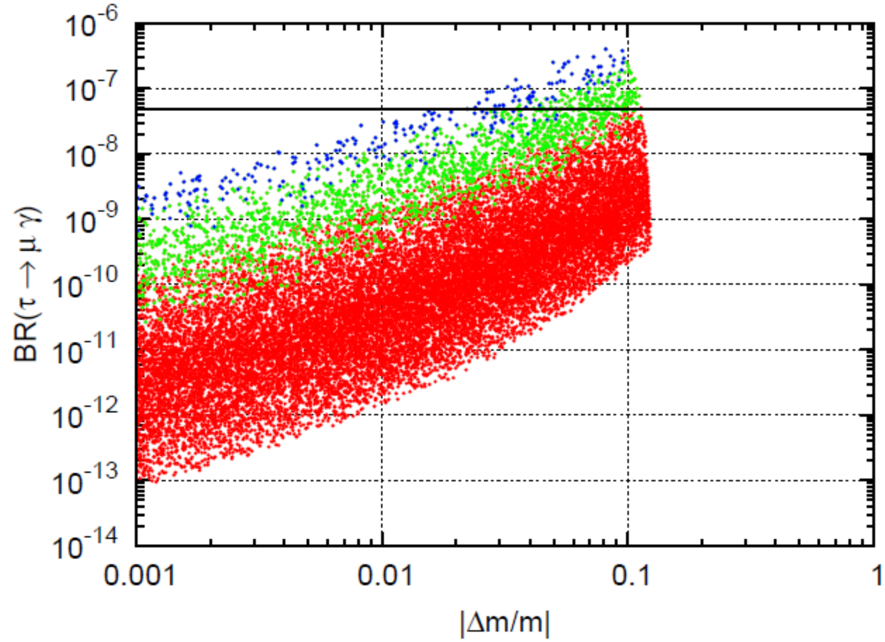
Hisano et al. '02

Figure 8: The LHC reach and the line of the constant $Br(\mu \to e\gamma)$ in the MSUGRA model are shown. Here, $\tan\beta = 10$, $A = 0$, $m = 100$ GeV, and $M = 300$ GeV.

$10^{-3} < (\delta_{LL})_{32} < 0.3$



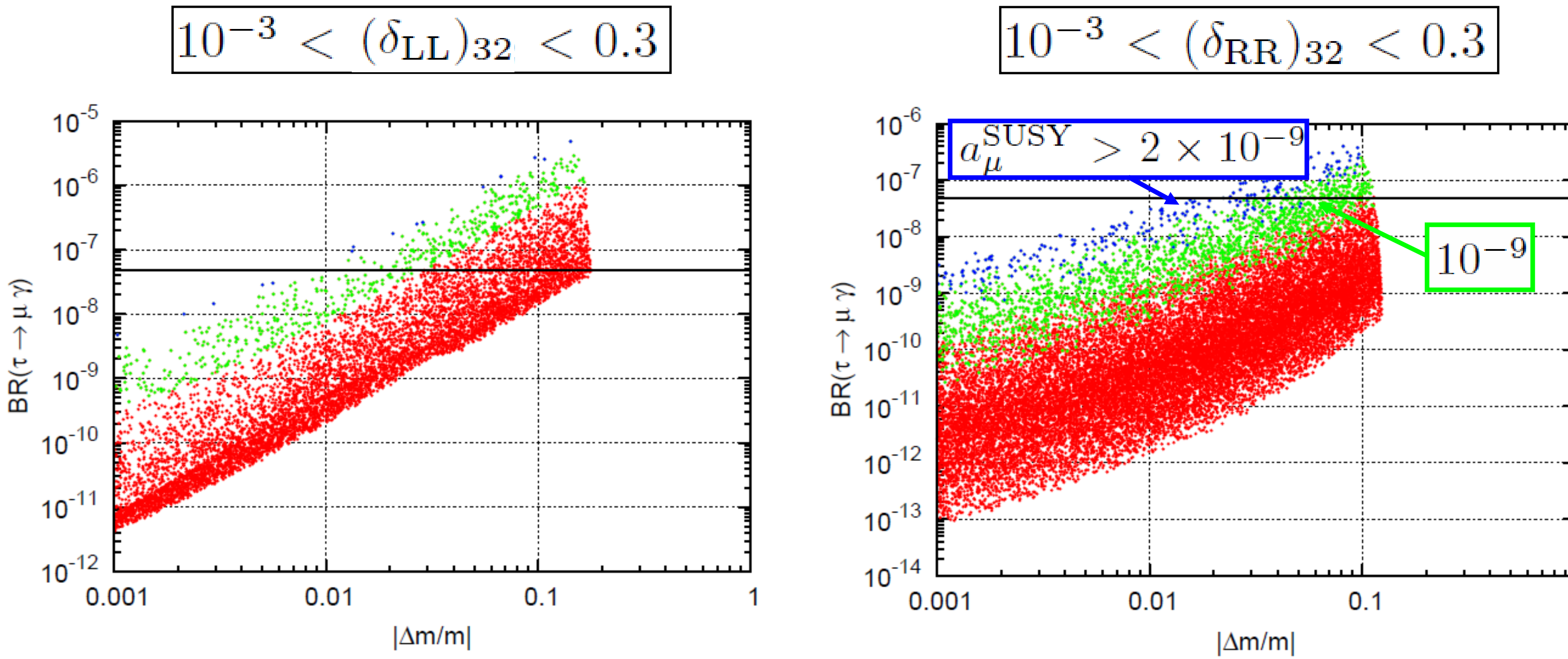
$10^{-3} < (\delta_{RR})_{32} < 0.3$



$$\tan\beta = 10, \; A_0 = 0 \quad m_0, M_{1/2} \leq 1 \text{ TeV}$$

$$m_{\tilde{e}}, m_{\tilde{\mu}} < m_{\tilde{\chi}_2^0}$$

Results



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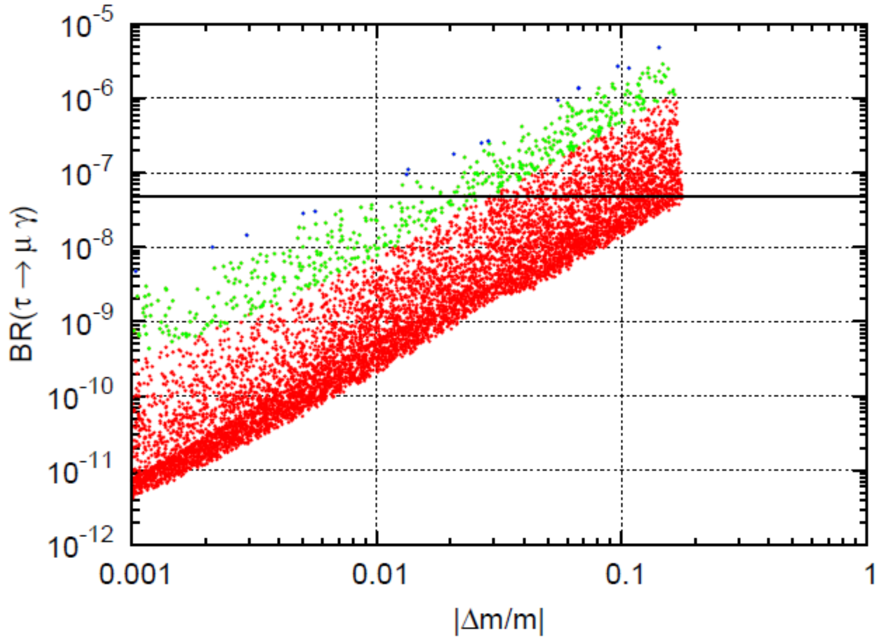

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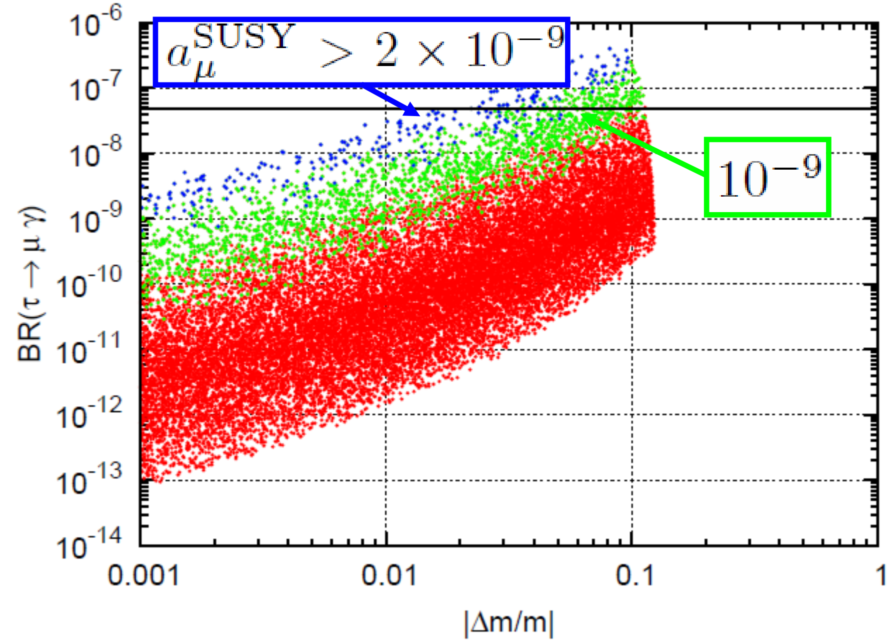

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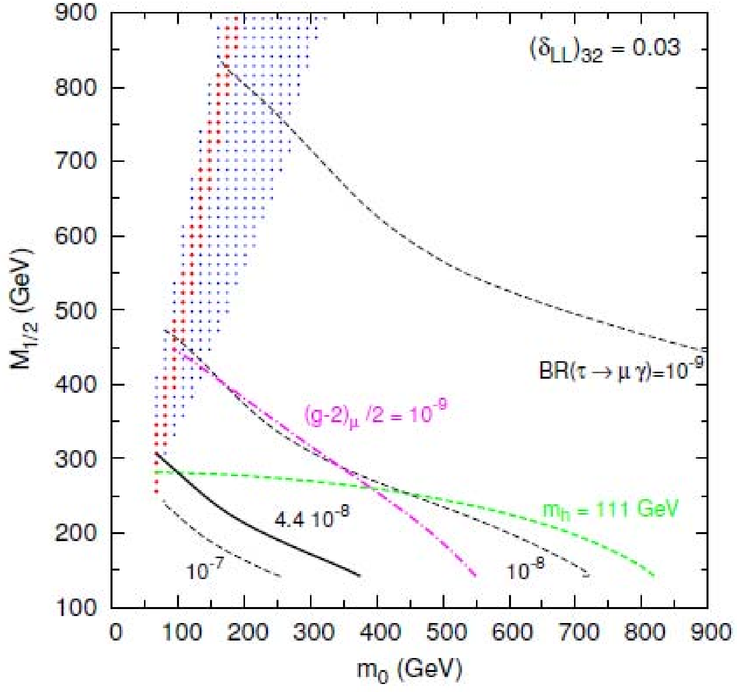
Enhancement factor in the edge splitting:

- always enhanced (*at least* ~3) in the LL case
- enhancement or suppression in the RR case

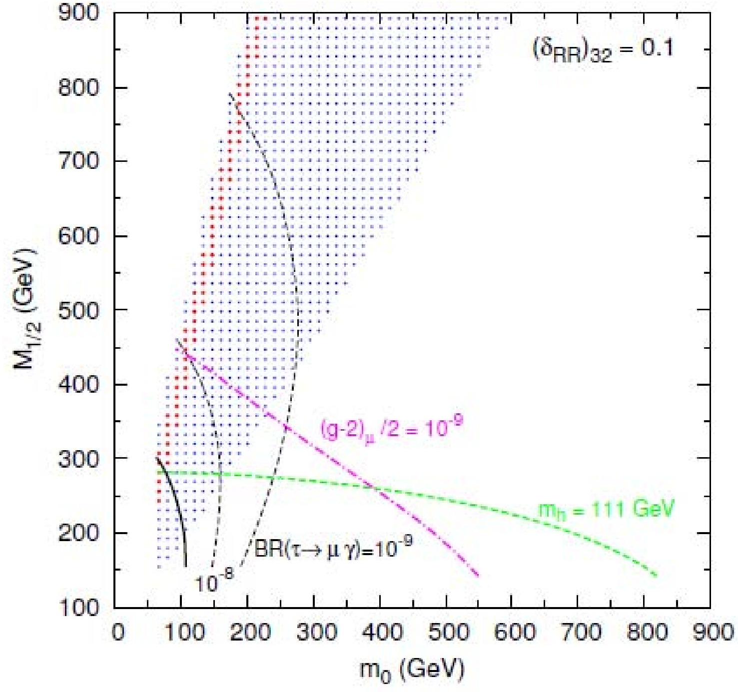
$(\delta_{\rm LL})_{32} = 0.03$

$(\Delta m_{\tilde{\ell}}/m_{\tilde{\ell}})_L$ around 1-1.5 %



$(\delta_{\rm RR})_{32} = 0.1$

$2\% \lesssim (\Delta m_{\tilde{\ell}}/m_{\tilde{\ell}})_R \lesssim 4\%$



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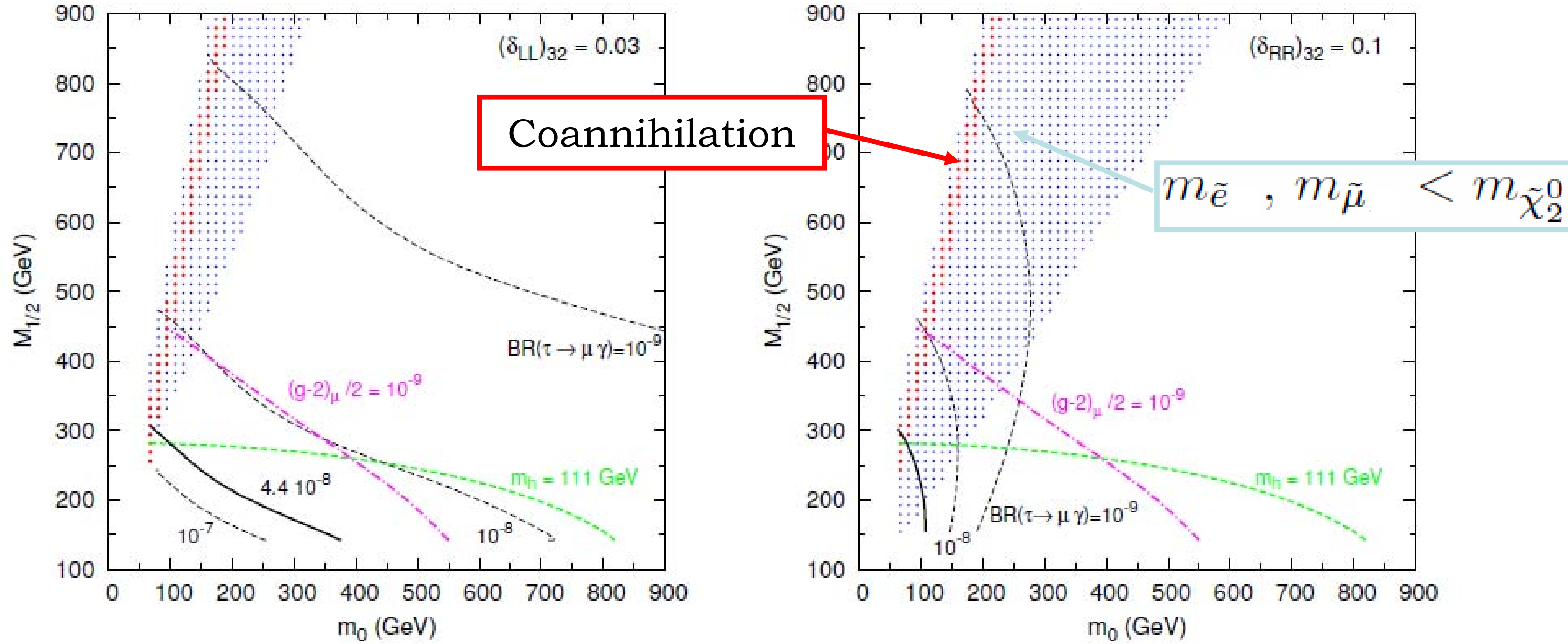

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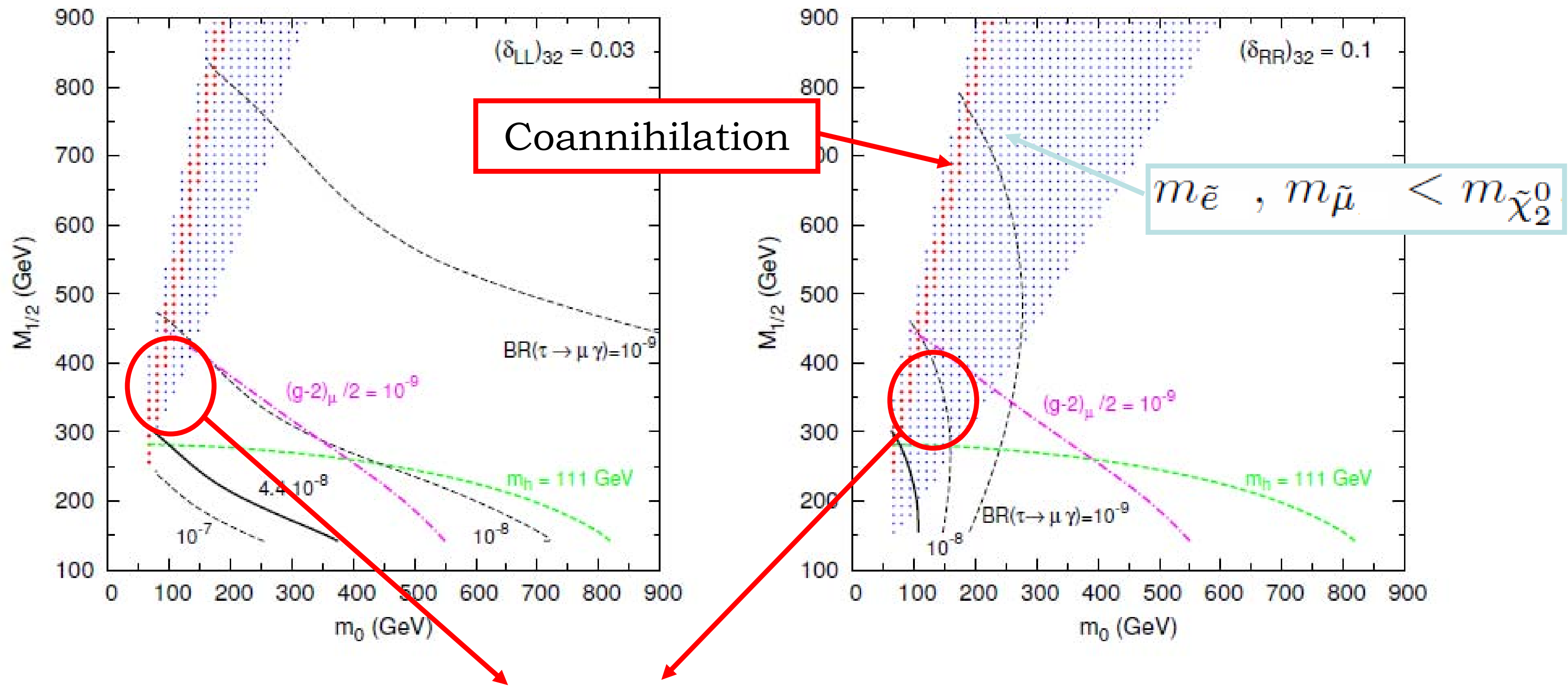
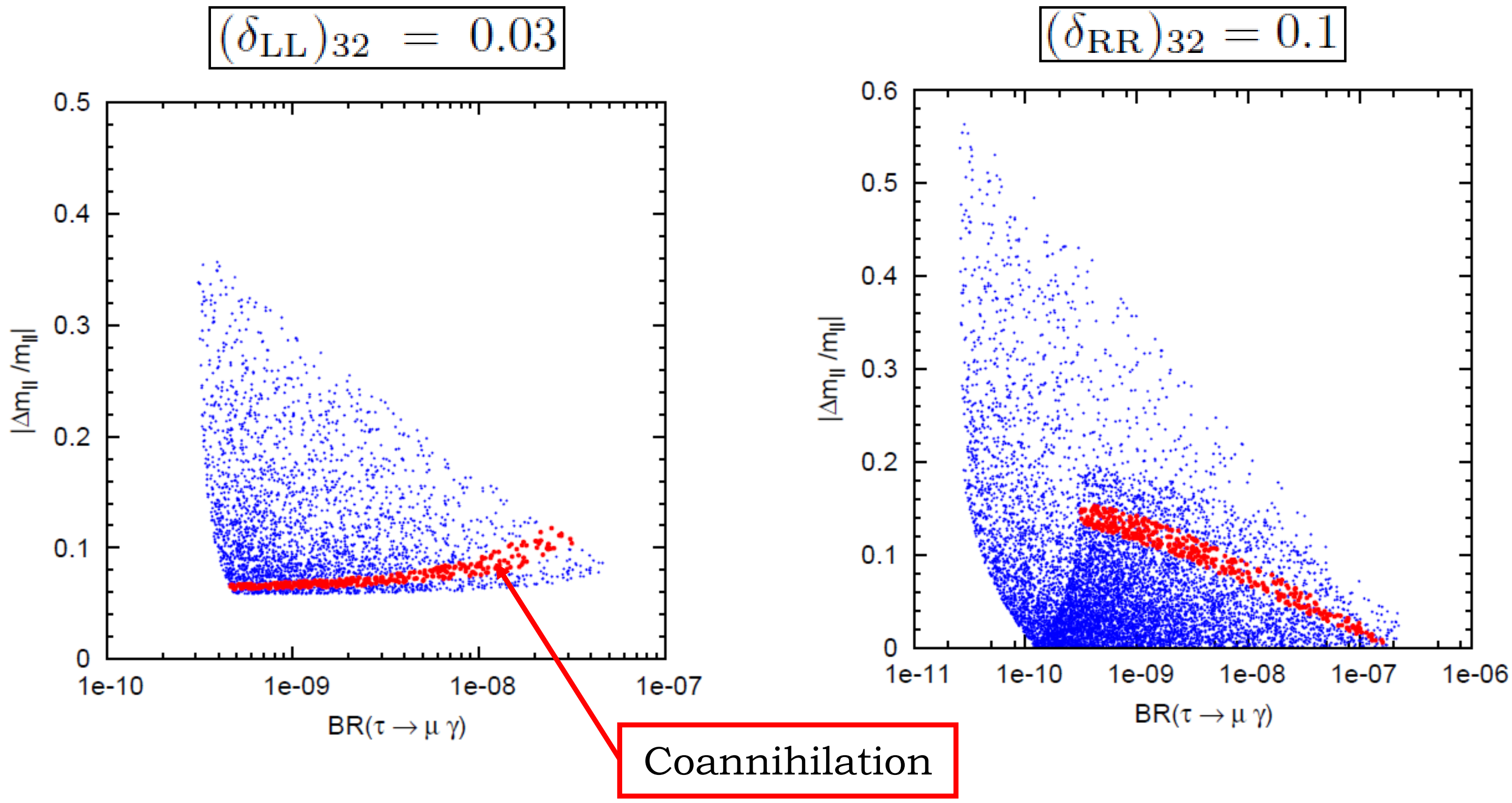


At the same time:

- selectrons and smuons produced in cascade decays
- $\mathrm{BR}(\tau \to \mu\gamma) > 10^{-8}$ (Super-KEK-B)
- $(g\text{-}2)_\mu$ tension below 2σ
- WMAP bound from neutralino-stau coannihilation

Splitting of the di-muon and di-electron distributions edges:



$$(m_{\tilde{\chi}_2^0} - m_{\tilde{e},\,\tilde{\mu}}) \geq 10\,\mathrm{GeV},\ (m_{\tilde{e},\,\tilde{\mu}} - m_{\tilde{\chi}_1^0}) \geq 10\,\mathrm{GeV}$$

Results

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$(\Delta m_{\tilde{\ell}}/m_{\tilde{\ell}})_L$ around 1-1.5 %

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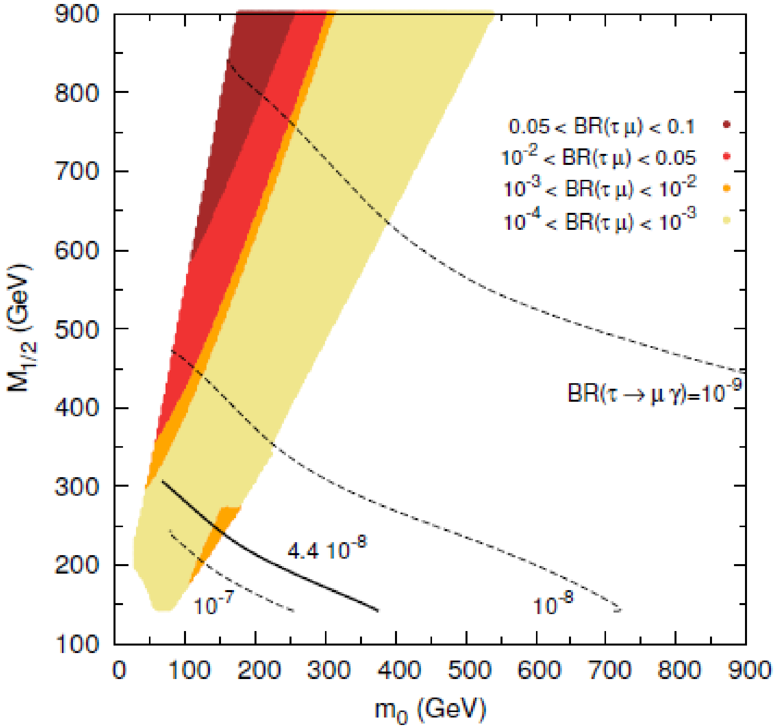
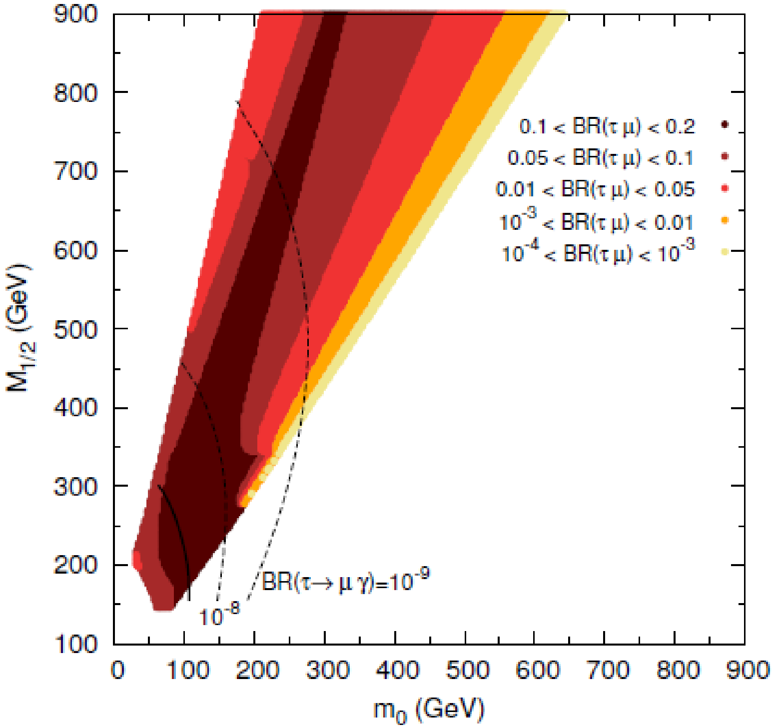
$$\mathrm{BR}(\tilde{\chi}_2^0 \to \tilde{\chi}_1^0 \tau^{\pm} \mu^{\mp})$$





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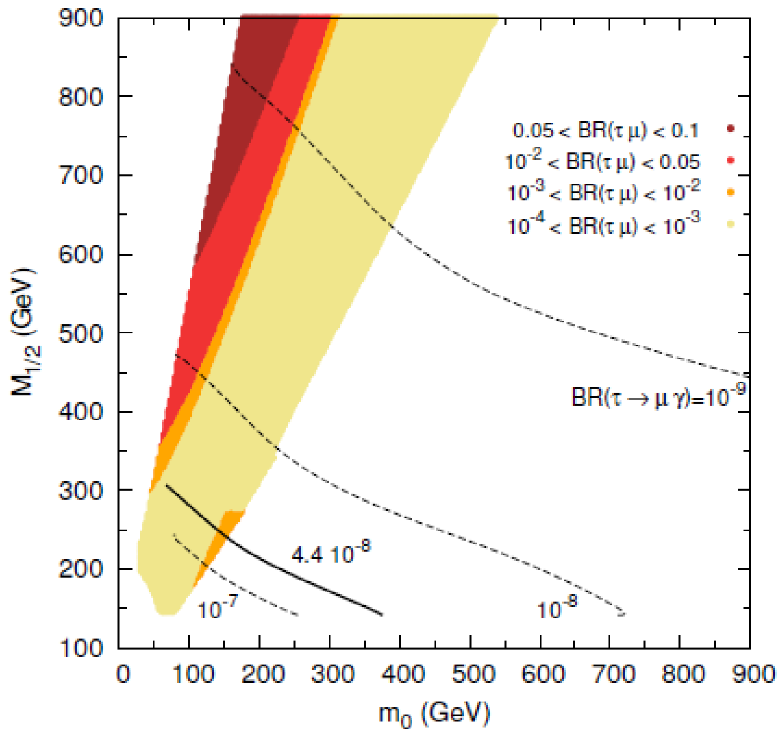
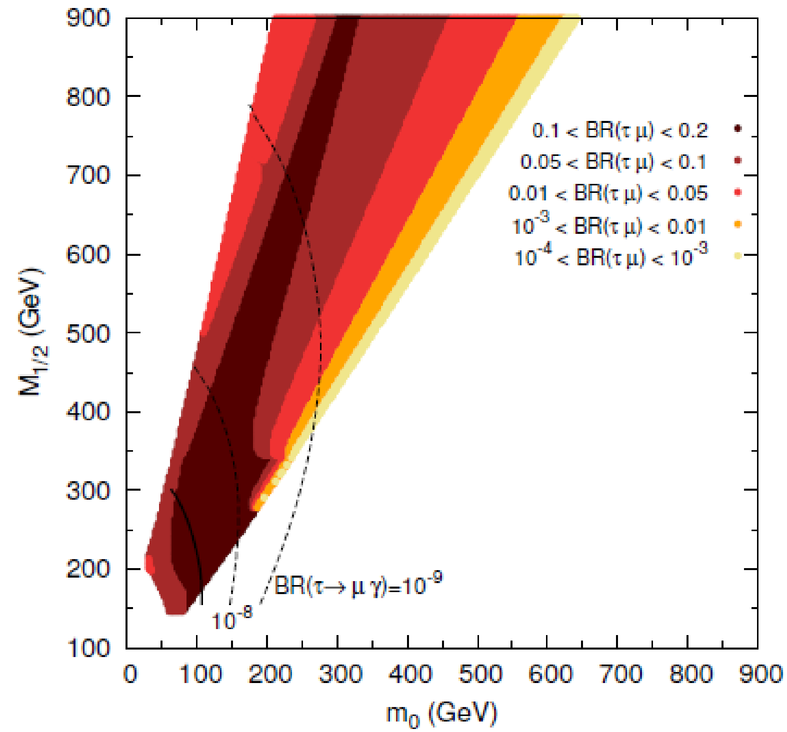
$$\mathrm{BR}(\tilde{\chi}^0_2 \to \tilde{\chi}^0_1 \tau^\pm \mu^\mp)$$





Good prospects at the LHC if: $\mathrm{BR}(\tilde{\chi}^0_2 \to \tilde{\chi}^0_1 \tau\mu)/\mathrm{BR}(\tilde{\chi}^0_2 \to \tilde{\chi}^0_1 \tau\tau) \gtrsim 0.1$

Carvalho et al.'02, Carquin et al. '08

Conclusions

• We considered a mSUGRA SUSY breaking scenario, in which selectrons and smuons are predicted to be highly degenerate (in absence of LFV)

• Any evidence of a sizeable splitting between selectron and smuon masses points towards either a different SUSY breaking mechanism or different realizations of mSUGRA: we considered the case of LFV-induced splitting

• Mixing between *second* and *third* generation sleptons can induce sizeable (and measurable at the LHC) mass-splittings between first and second generation sleptons

• Processes such as $\tau \to \mu\gamma$ and $\tilde{\chi}_2^0 \to \tilde{\chi}_1^0 \tau^\pm \mu^\mp$ can be detectable and help to shed light on the origin of the mass-splitting

⇨ nice example of the inteplay between *high-energy* and *high-intensity* (low-energy) frontier experiments

Additional transparencies

$$\sigma_{ee} \equiv \sigma(\tilde\chi_2^0 \to \tilde\chi_1^0 e^+ e^-) = \sigma_{\tilde\chi_2^0} \times \mathrm{BR}(\tilde\chi_2^0 \to \tilde\chi_1^0 e^+ e^-)$$

$$\sigma_{\mu\mu} \equiv \sigma(\tilde\chi_2^0 \to \tilde\chi_1^0 \mu^+ \mu^-) = \sigma_{\tilde\chi_2^0} \times \mathrm{BR}(\tilde\chi_2^0 \to \tilde\chi_1^0 \mu^+ \mu^-)$$

$$\sigma_{\tau\mu} \equiv \sigma(\tilde\chi_2^0 \to \tilde\chi_1^0 \tau^\pm \mu^\mp) = \sigma_{\tilde\chi_2^0} \times \mathrm{BR}(\tilde\chi_2^0 \to \tilde\chi_1^0 \tau^\pm \mu^\mp)$$

	$\sigma_{\rm SUSY}$	σ_{ee}	$\sigma_{\mu\mu}$	$\sigma_{\tau\mu}$	$\lvert\Delta m_{\tilde\ell}/m_{\tilde\ell}\rvert$	$\lvert\Delta m_{ll}/m_{ll}\rvert$	$a_\mu^{\rm SUSY}$	$\mathrm{BR}(\tau\to\mu\gamma)$
Point A	5.2 pb	63 fb	43 fb	24 fb	1.1 %	10 %	1.2×10^{-9}	1.7×10^{-8}
Point B	1.8 pb	32 fb	18 fb	15 fb	1.3 %	7.6 %	8.0×10^{-10}	7.3×10^{-9}
Point C	9.7 pb	62 fb	49 fb	110 fb	2.7 %	4.9 %	1.5×10^{-9}	2.4×10^{-8}
Point D	18.2 pb	169 fb	91 fb	536 fb	3.0 %	6.2 %	1.6×10^{-9}	1.3×10^{-8}

$$S_{\ell^+\ell^-} = \sigma_{\ell\ell} \times \epsilon_\ell^2 \times \epsilon_{\rm cut} \times L$$

$$S_{\tau\mu} = 2 \times \sigma_{\tilde\chi_2^0} \times \epsilon_{\tau_h} \times \epsilon_\ell \times \epsilon_{\rm cut} \times L \times \mathrm{BR}(\tilde\chi_2^0 \to \tilde\chi_1^0 \tau\mu)\,\mathrm{BR}(\tau \to h)$$

Signals and backgrounds estimates

$$\tilde{q}_L \tilde{q}_L^* \to \tilde{\chi}_1^+ \tilde{\chi}_1^- + \cdots \longrightarrow \begin{cases} \tilde{\chi}_1^\pm \to \tilde{\nu}\, \ell^\pm \,, \\ \tilde{\chi}_1^\pm \to \tilde{\ell}^\pm \nu \to \ell^\pm \nu\, \tilde{\chi}^0 \,, \\ \tilde{\chi}_1^\pm \to W^\pm \tilde{\chi}^0 \to \ell^\pm \nu\, \tilde{\chi}^0 \,. \end{cases}$$

$$B_{\ell^+\ell^-}^{\tilde{\chi}^+\tilde{\chi}^-} = \sigma_{\tilde{\chi}^+\tilde{\chi}^-} \times \epsilon_\ell^2 \times \epsilon_{\rm cut} \times L \times \Big[{\rm BR}(\tilde{\chi}_1^\pm \to \tilde{\nu}\ell^\pm) + \tag{5.6}$$

$$+ {\rm BR}(\tilde{\chi}_1^\pm \to \tilde{\ell}^\pm \nu)\, {\rm BR}(\tilde{\ell}^\pm \to \ell^\pm \tilde{\chi}^0) + {\rm BR}(\tilde{\chi}_1^\pm \to W^\pm \tilde{\chi}^0)\, {\rm BR}(W^\pm \to \ell^\pm \nu) \Big]^2 ,$$

$$B_{\ell^+\ell^-}^{\tau\tau} = \sigma_{\tilde{\chi}_2^0} \times \epsilon_\ell^2 \times \epsilon_{2\tau_\ell} \times \epsilon_{\rm cut} \times L \times {\rm BR}(\tilde{\chi}_2^0 \to \tilde{\chi}_1^0 \tau\tau) \times \Big[{\rm BR}(\tau \to \ell \nu \bar{\nu}) \Big]^2 ,$$

	$S_{\mu^+\mu^-}$	$B^{(\tilde{\chi}^+\tilde{\chi}^-)}_{\mu^+\mu^-}$	$B^{(\tau\tau)}_{\mu^+\mu^-}$	$B^{(\tau\mu)}_{\mu^+\mu^-}$	$S_{e^+e^-}$	$B^{(\tilde{\chi}^+\tilde{\chi}^-)}_{e^+e^-}$	$B^{(\tau\tau)}_{e^+e^-}$	$S_{\tau\mu}$	$B^{(\tilde{\chi}^+\tilde{\chi}^-)}_{\tau\mu}$	$B^{(\tau\tau)}_{\tau\mu}$	$\frac{\mathrm{BR}(\tau\mu)}{\mathrm{BR}(\tau\tau)}$
Point A	850	0.65 $S_{\mu^+\mu^-}$	0.12 $S_{\mu^+\mu^-}$	0.09 $S_{\mu^+\mu^-}$	1275	0.44 $S_{e^+e^-}$	0.09 $S_{e^+e^-}$	490	1.15 $S_{\tau\mu}$	1.3 $S_{\tau\mu}$	0.12
Point B	364	0.64 $S_{\mu^+\mu^-}$	0.07 $S_{\mu^+\mu^-}$	0.14 $S_{\mu^+\mu^-}$	648	0.35 $S_{e^+e^-}$	0.04 $S_{e^+e^-}$	307	0.82 $S_{\tau\mu}$	0.53 $S_{\tau\mu}$	0.32
Point C	992	0.48 $S_{\mu^+\mu^-}$	0.19 $S_{\mu^+\mu^-}$	0.38 $S_{\mu^+\mu^-}$	1255	0.38 $S_{e^+e^-}$	0.15 $S_{e^+e^-}$	1126	0.21 $S_{\tau\mu}$	0.5 $S_{\tau\mu}$	0.34
Point D	1842	0.16 $S_{\mu^+\mu^-}$	0.45 $S_{\mu^+\mu^-}$	1.02 $S_{\mu^+\mu^-}$	3822	0.09 $S_{e^+e^-}$	0.24 $S_{e^+e^-}$	10974	0.03 $S_{\tau\mu}$	0.44 $S_{\tau\mu}$	0.38

TABLE III: Expected number of signal and background events for the relevant flavour conserving and violating channels. The estimate has been done taking for the integrated luminosity $L = 100$ fb^{-1}.