Lepton Flavor Violation at LHC

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In collaboration with J. Hisano and M. M. Nojiri, arXiv:0812.4496

Introduction & Motivation

- The LFV processes are important discovery channels of BSM.
- Current experimental upper bounds on LFV processes:

$$Br(\mu \to e\gamma) < 1.2 \times 10^{-11} \quad \text{MEGA}, \tag{1}$$
$$Br(\tau \to \mu\gamma) < 4.5(6.8) \times 10^{-8} \quad \text{Belle(BaBar)}, \tag{2}$$
$$Br(\tau \to e\gamma) < 1.2(1.1) \times 10^{-7} \quad \text{Belle(BaBar)}. \tag{3}$$

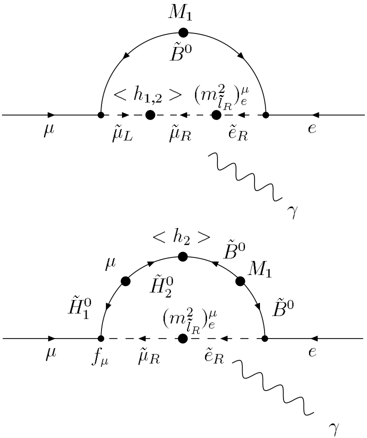
- Prospects:

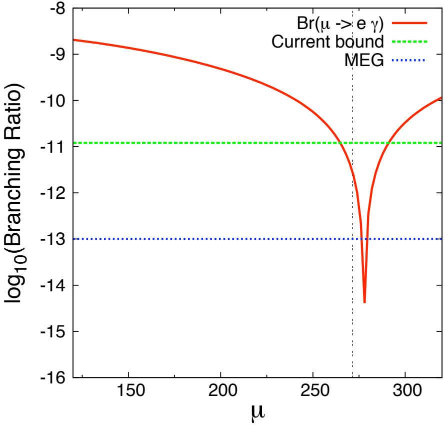
$$Br(\mu \to e\gamma) \sim 10^{-13} \quad \text{MEG}, \tag{4}$$
$$Br(\tau \text{ decay}) \sim 10^{-9} - 10^{-10} \quad \text{superB factory}. \tag{5}$$

- LHC plays a complementary role to identify new physics and determine LFV parameters. $\Leftarrow$ esp. in light slepton scenario

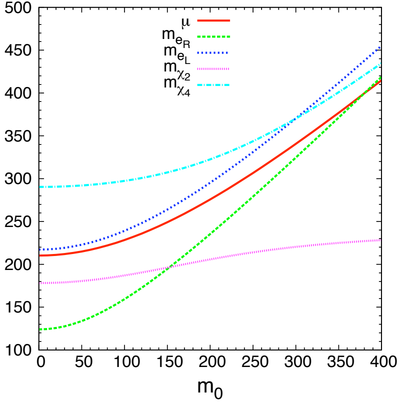
$\mu \rightarrow e\gamma$

Right-handed LFV $\Rightarrow$ Cancellation among dominant diagrams





J. Hisano, T. Moroi, K. Tobe, M. Yamaguchi, Phys. Lett. B 391, 341 (1997)



At the cancellation point,

$$\frac{1}{2\overline{m}^2_{\tilde{l}_L}} - \frac{1}{\overline{m}^2_{\tilde{l}_R}} f_1\left(\frac{\mu^2}{\overline{m}^2_{\tilde{l}_R}}\right) \sim 0. \qquad (6)$$

In the plot,

i) $m_{1/2} = 300\ \mathrm{GeV}, \tan\beta = 10$

ii) mSUGRA-like relations are assumed among M_1, M_2, and slepton masses

iii) μ is free (NUHM)

- $\mu \sim m_{\tilde{l}_L}$ along the cancellation line
- μ is smaller as m_0 decreases $\Rightarrow$ DM relic density is small and $\tilde{\chi}^0_4 \longrightarrow \tilde{e}_L$ and $\tilde{\chi}^0_2 \longrightarrow \tilde{e}_R$ are always kinematically allowed.

Non-universal Higgs Mass Model (NUHM)

H. Baer, A. Mustafayev, S. Profumo, A. Belyaev, X. Tata, Phys. Rev. D71, 095008 (2005).
J. Ellis, K. A. Olive, Y. Santoso, Phys. Lett. B539, 107 (2002).
M. Drees *et al.*, Phys. Rev. D63, 035008 (2001).
J. Hisano, R. Kitano, M. M. Nojiri, Phys. Rev. D65:116002 (2002).

We took $m_{H_U} > m_{H_D} = m_0$, particularly with $M_1 < M_2 < \mu \sim m_{1/2}$ and dark matter relic density consistent with observations.

Moreover, we took the choice $m_{\tilde{\chi}_1^0} < m_{\tilde{e}_R} < m_{\tilde{\chi}_2^0} < m_{\tilde{e}_L} < m_{\tilde{\chi}_4^0}$ when both left- and right-handed sleptons can be directly produced via neutralino decay.

LFV Model

J.L. Feng, C.G. Lester, Y. Nir, Y. Shadmi, arXiv:0712.0674

Consider a horizontal $U(1) \times U(1)$ symmetry where each $U(1)$ is explicitly broken by a scalar singlet spurion carrying the corresponding charge -1.

$\Rightarrow$ Slepton masses:

$$M_{\tilde{L}}^2 = m_{\tilde{L}}^2 + x m_0^2 X'_{\tilde{L}}, \qquad M_{\tilde{e}}^2 = m_{\tilde{e}}^2 + x m_0^2 X'_{\tilde{e}}, \tag{7}$$

where

$$X'_{\tilde{L}} \sim \begin{pmatrix} 0 & \epsilon^4 & \epsilon^8 \\ \epsilon^4 & 0 & \epsilon^4 \\ \epsilon^8 & \epsilon^4 & 0 \end{pmatrix}, \qquad X'_{\tilde{e}} \sim \begin{pmatrix} 0 & \epsilon^2 & \epsilon^4 \\ \epsilon^2 & 0 & \epsilon^2 \\ \epsilon^4 & \epsilon^2 & 0 \end{pmatrix}, \tag{8}$$

and $\epsilon =$ symmetry breaking parameter $\sim |V_{us}| \sim 0.2$

Contents

1. A model point with correct DM relic density $\Rightarrow$ the cancellation point
2. Sparticle masses and parameters determination from endpoint information
3. Flipping solution exercises

   Key observables:

   - 2 jets + missing E_T
   - relative edge heights
   - charge asymmetry

4. LFV and DM density

MC Study

ISAJET v7.75 + HERWIG 6.5 + AcerDet

# of generated events $= 5 \times 10^6 \rightarrow \sim 300\ fb^{-1}$ of integrated luminosity

point A:

m_0	100	$m_{1/2}$	300
m_{H_D}	100	m_{H_U}	380
A_0	0	$\tan\beta$	10

$\Rightarrow$ $\mu = 271$ GeV, $\Omega_{\rm DM} h^2 = 0.1179$

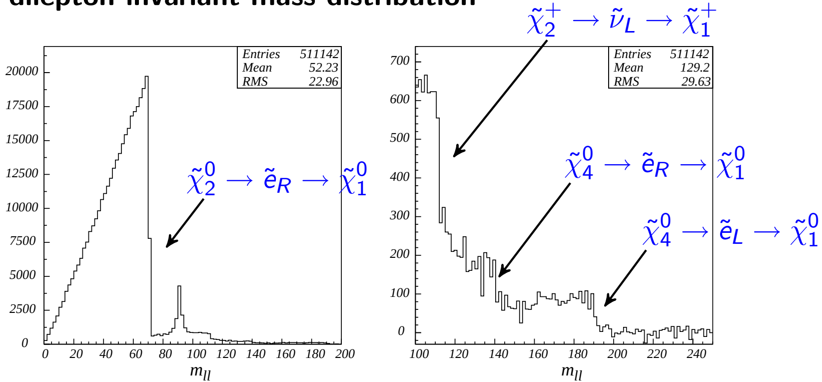
	A	mSUGRA		A	mSUGRA
$\tilde{u}_L \rightarrow \tilde{\chi}_2^0$	25.4	31.6	$\tilde{\chi}_2^0 \rightarrow \tilde{e}_R$	13.5	3.1
$\tilde{u}_L \rightarrow \tilde{\chi}_4^0$	7.8	1.3	$\tilde{\chi}_4^0 \rightarrow \tilde{e}_R$	0.7	0.3
$\tilde{u}_L \rightarrow \tilde{\chi}_2^+$	13.1	1.8	$\tilde{\chi}_4^0 \rightarrow \tilde{e}_L$	2.3	1.0
			$\tilde{\chi}_2^+ \rightarrow \tilde{\nu}_L$	7.4	2.1

($\mu = 397.3$ GeV for mSUGRA point)

$\Rightarrow$ For point A, $\tilde{\chi}_4^0$ and $\tilde{\chi}_2^+$ have more Wino component.

$\Rightarrow$ Enhancement in $Br(\tilde{u}_L \rightarrow \tilde{\chi}_4^0/\tilde{\chi}_2^+)$ by at least factor 6.

OSSF dilepton invariant mass distribution



- Including m_{jll}^{max}, m_{jl}^{max}, m_{jl}^{min}, one can resolve $m_{\tilde{q}_L}$, $m_{\tilde{\chi}_4^0}$, $m_{\tilde{\chi}_2^0}$, $m_{\tilde{\chi}_1^0}$, $m_{\tilde{e}_L}$, $m_{\tilde{e}_R}$.
- A study of four-lepton (2OSSF) events reveals $m_{ll}^{max}(\tilde{\chi}_4^0 \to \tilde{e}_L \to \tilde{\chi}_2^0)$.
- $m_{\tilde{e}_L} - m_{\tilde{\chi}_1^0} = 124.92\ ^{+0.65}_{-0.65}$ GeV, $m_{\tilde{e}_R} - m_{\tilde{\chi}_1^0} = 15.68\ ^{+0.45}_{-0.49}$ GeV

Flipping Solutions

(1) $M_1 < M_2 < \mu$ (point A)

(2) $M_1 < \mu < M_2$ (point A2)

(3) $\mu < M_1 < M_2$ (point A3)

$m_{\tilde{u}_L}, m_{\tilde{\chi}^0_4}, m_{\tilde{\chi}^0_2}(m_{\tilde{\chi}^0_3}$ for A3$), m_{\tilde{\chi}^0_1}, m_{\tilde{e}_L}, m_{\tilde{e}_R}$ are degenerate between three points
$\Rightarrow$ endpoints from their cascade decay will be the same

We investigate whether three solutions can be discriminated @ the LHC.

For point A2,

- $\tilde{\chi}^0_4$ and $\tilde{\chi}^+_2$ have more Wino component $\Leftarrow$ Branching ratios
- $\tilde{\chi}^0_2$ has less Wino component $\Leftarrow$ Charge asymmetry

For point A3,

- $\tilde{\chi}^0_1$ is Higgsino-like $\Leftarrow$ 2 jets + missing E_T

2 jets + missing E_T

C. G. Lester and D. J. Summers, Phys. Lett. B463, 99 (1999)
A. Barr, C. Lester and P. Stephens, J. Phys. G29, 2343 (2003)

$$Br(\tilde{q}_R \to \tilde{\chi}_1^0) = \begin{cases} 0.94 & \text{point A} \\ 0.89 & \text{point A2} \\ 0.16 & \text{point A3} \end{cases}$$

For $pp \to \tilde{q}_R\tilde{q}_R \to q\tilde{\chi}_1^0 q\tilde{\chi}_1^0$ events, their signature is two high-p_T jets +large $\not{E}_T$.

$$m_{T2}(\mathbf{p}_T^{j_1}, \mathbf{p}_T^{j_2}, \not{\mathbf{p}}_T^{\rm miss}; m_{\rm test}) \equiv \min_{\not{\mathbf{p}}_T^{\alpha}+\not{\mathbf{p}}_T^{\beta}=\not{\mathbf{p}}_T^{\rm miss}} \left[\max\left\{m_T(\mathbf{p}_T^{j_1}, \not{\mathbf{p}}_T^{\alpha}; m_{\rm test}), m_T(\mathbf{p}_T^{j_2}, \not{\mathbf{p}}_T^{\beta}; m_{\rm test})\right\}\right]$$

$$m_T^2(\mathbf{p}_T^{j}, \not{\mathbf{p}}_T^{\alpha}; m_{\rm test}) \equiv m_j^2 + m_{\rm test}^2 + 2\left(E_T^j \not{E}_T^{\alpha} - \mathbf{p}_T^j \cdot \not{\mathbf{p}}_T^{\alpha}\right).$$

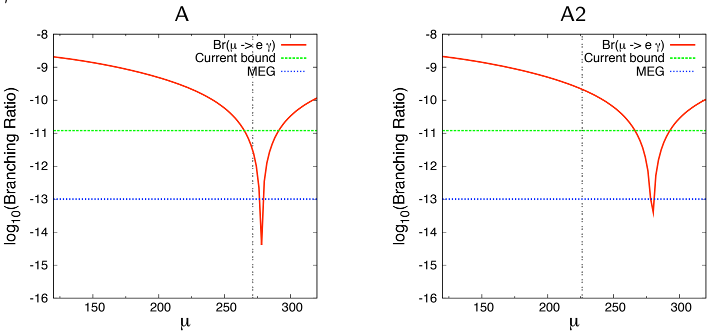
$$m_{T2}(m_{\rm test} = m_{\tilde{\chi}_1^0}) \le m_{\tilde{q}_R}$$

Point	No. of Signal	No. of SM Background	S/B_{SM}	$S/\sqrt{B_{SM}}$
A	1341	180	7.5	100.0
A3	133	180	0.7	9.9

CERN-OPEN-2008-020

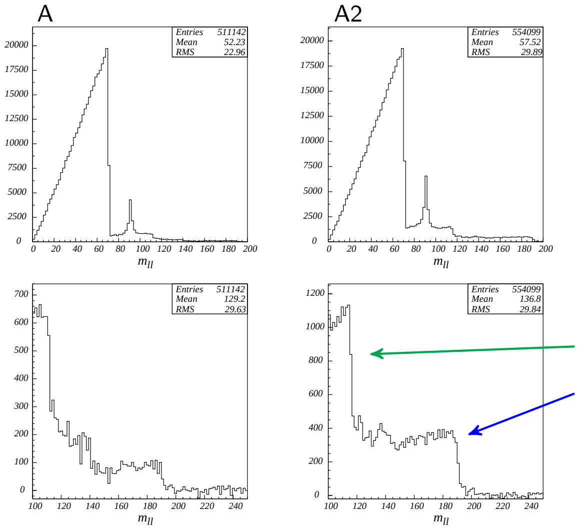
$\mu \longrightarrow e\gamma$

$x = 0.3$



- Point A and A2 have $Br(\mu \to e\gamma)$ differ by two orders of magnitude.
- Only point A is in the cancellation region and then gives $Br(\mu \to e\gamma)$ below the current experimental upper bound.
- A precise determination of μ parameter is important for determination of flavor mixing parameter.

OSSF Dilepton Invariant Mass Distribution



A2: $\tilde{\chi}_4^0$ and $\tilde{\chi}_2^+$ have more Wino component

$\Rightarrow$ Enhancement in edges from

$\tilde{\chi}_2^+ \to \tilde{\nu}_L \to \tilde{\chi}_1^0$ (factor 2)

and

$\tilde{\chi}_4^0 \to \tilde{e}_L \to \tilde{\chi}_1^0$ (factor 4)

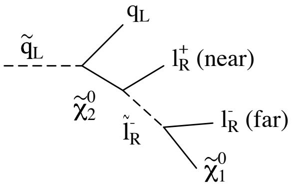
relative to edge of

$\tilde{\chi}_2^0 \to \tilde{e}_R \to \tilde{\chi}_1^0$

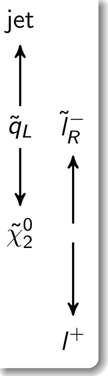
Charge Asymmetry

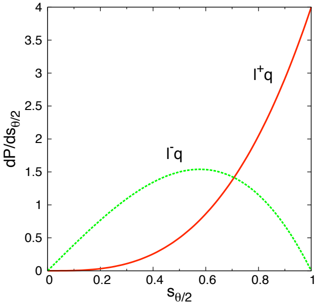
A. J. Barr, Phys. Lett. B596, 205 (2004)
T. Goto, K. Kawagoe, M. M. Nojiri , Phys. Rev. D70, 075016 (2004)
J. M. Smillie, B. R. Webber, JHEP 0510:069,2005.

Example



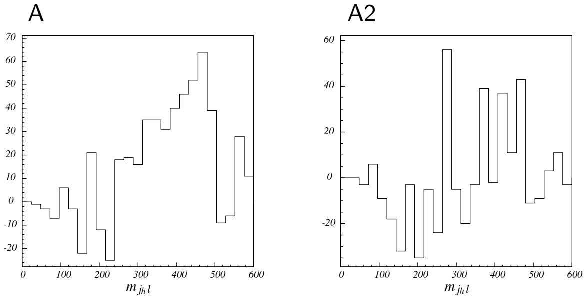
θ = angle between quark and lepton in the $\tilde{\chi}_2^0$ rest frame





$\Rightarrow$ positive charge asymmetry

Spin correlation in Herwig, G. Corcella *et al*, arXiv:hep-ph/0011363v3.

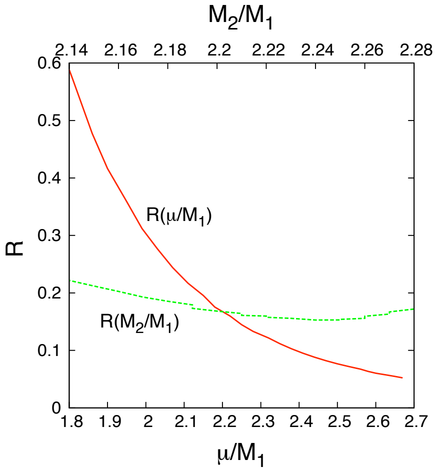


The difference between $m_{j_h l^+}$ and $m_{j_h l^-}$ distributions as a function of $m_{j_h l}$ (j_h is defined by $m_{j_h ll} \equiv \max(m_{j_1 ll}, m_{j_2 ll})$)

Assuming that L-R slepton mixing is negligible, the flatness of charge asymmetry distribution suggests the contribution from $\tilde{q}_R \longrightarrow \tilde{\chi}_2^0$ decay.

$\Rightarrow$ $\tilde{\chi}_2^0$ for point A2 must have smaller Wino component.

$\Rightarrow M_1 < \mu < M_2$



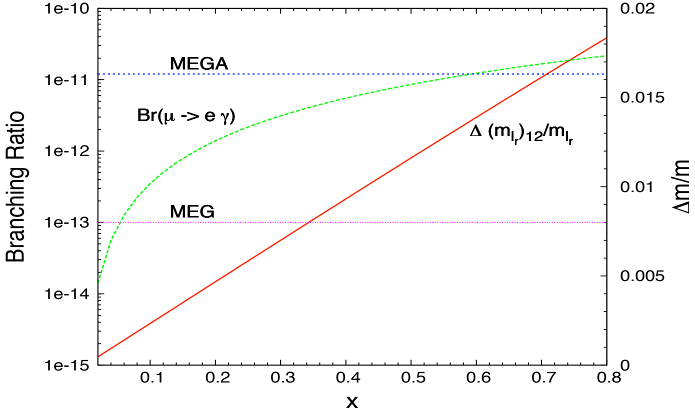
$$R \equiv \frac{Br(\tilde{u}_R \to \tilde{\chi}_2^0)}{Br(\tilde{u}_L \to \tilde{\chi}_2^0)}$$

⇒The ratio R depends on μ/M_1 stronger than on M_2/M_1.

⇒ As μ/M_1 is smaller, mixing between neutralino states is larger and the charge asymmetry receives more $\tilde{q}_R$ contribution.

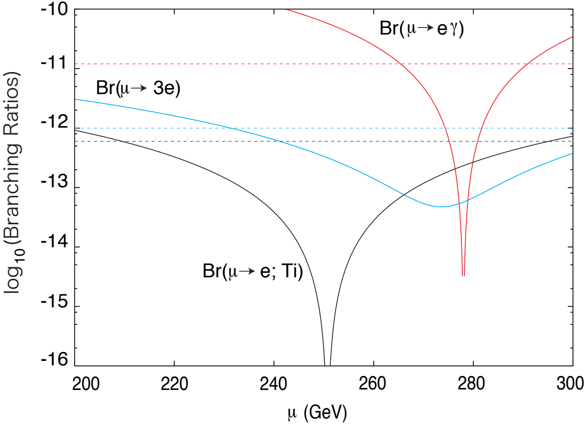
Parameters	Resolving Methods
$\mu < M_1, M_2$	m_{T2} method
$M_1 < \mu < M_2$	charge asymmetry + branching ratio
$m_{\tilde{e}_L} \leftrightarrow m_{\tilde{e}_R}$	charge asymmetry

$\mu \longrightarrow e\gamma$



Recall $m_{\tilde{e}_L} - m_{\tilde{\chi}_1^0} = 124.92\ ^{+0.65}_{-0.65}\ \mathrm{GeV},\ \ m_{\tilde{e}_R} - m_{\tilde{\chi}_1^0} = 15.68\ ^{+0.45}_{-0.49}\ \mathrm{GeV}$.

- The mass difference of order one percent, corresponding to $1 \sim 2$ GeV, is allowed by MEGA bound $(Br(\mu \to e\gamma) < 1.2 \times 10^{-11})$.



- The $\mu \to e$ conversion rate shows strong sensitivity to the SUSY parameters at different μ values from $Br(\mu \to e\gamma)$ and $Br(\mu \to 3e)$.
- $\mu = 271.33\ ^{+6.89}_{-6.81}\ \mathrm{GeV}$

Finally, precise SUSY parameter determination is also important for the determination of DM density and DM scattering cross section.

	$\Omega_{\mathrm{DM}} h^2$	$\sigma_{p\chi}^{SI} (10^{-8}\ pb)$
A	0.1179	1.6
A2	0.0817	3.2
A3	0.0096	17.5
observation/exp. upper bound	0.122 (WMAP & SDSS)	4.6 (CDMS)

Uncertainties in $\sigma_{p\chi}^{SI}$:

- nucleon matrix element of strange quark
- $\sigma_{p\chi}^{SI}|_{A-\mathrm{exchange}} \propto \left(\frac{\tan^2\beta}{m_A^4}\right)$

Conclusions

- We studied the the one-parameter-extended NUHM, $m_{H_U} \neq m_{H_D} = m_0$, particularly with $M_1 < M_2 < \mu \sim m_{1/2}$ and dark matter relic density consistent with cosmological and astrophysical observations.
- We are also interested in the region where cancellation among leading contributions to $Br(\mu \to e\gamma)$ occurs in the models with right-handed LFV masses. Therefore, we took the choice $m_{\tilde{\chi}_1^0} < m_{\tilde{e}_R} < m_{\tilde{\chi}_2^0} < m_{\tilde{e}_L} < m_{\tilde{\chi}_4^0}$ when both left- and right-handed sleptons can be directly produced via neutralino decay.
- In the region when $M_1 < M_2 < \mu \sim m_{1/2}$, $\tilde{\chi}_4^0$ and $\tilde{\chi}_2^+$ are a mixed states with rather large Wino component and their various decay patterns are expectable at the LHC.
- When the relation $M_1 < M_2, \mu$ is kept, we showed three solutions with similar mass spectrum but different ordering of M_1, M_2 and μ. We showed that by looking into 2 jets + missing E_T signature, relative height of m_{ll} edges and charge asymmetry, the degeneracy can be lifted.
- We emphasized that a precise μ parameter determination is an important key for resolving cancellation point of LFV processes, determination of the LFV parameter and determination of DM density and DM scattering cross section.

Mass Spectrum (point A)

$m_{\tilde{g}}$	719.67	$m_{\tilde{\nu}}$	224.37	$m_{\tilde{\chi}_2^+}$	321.62
$m_{\tilde{u}_L}$	665.19	$m_{\tilde{e}_L}$	239.62	$m_{\tilde{\chi}_1^+}$	196.30
$m_{\tilde{d}_L}$	670.29	$m_{\tilde{e}_R}$	130.38	$m_{\tilde{\chi}_4^0}$	323.23
$m_{\tilde{u}_R}$	648.85	$m_{\tilde{\tau}_2}$	238.89	$m_{\tilde{\chi}_3^0}$	278.87
$m_{\tilde{d}_R}$	642.47	$m_{\tilde{\tau}_1}$	128.07	$m_{\tilde{\chi}_2^0}$	197.82
				$m_{\tilde{\chi}_1^0}$	114.70

Selection criteria:

- an OSSF dilepton pair where both leptons have $p_T^l > 10\ \mathrm{GeV}$ and $|\eta| < 2.5$.
- more than 4 jets with $p_{T,1}^j > 100\ \mathrm{GeV}, p_{T,2,3,4}^j > 50\ \mathrm{GeV}$.
- $M_{\mathrm{eff}} \equiv p_{T,1} + p_{T,2} + p_{T,3} + p_{T,4} + \not{E}_T > 400\ \mathrm{GeV}$.
- $\not{E}_T > \max(100, 0.2 M_{\mathrm{eff}})$.

Estimated error of sparticle masses and SUSY parameters

Sparticle Mass	Central value	Estimated error (1-σ)
$m_{\tilde{\chi}_1^0}$	114.70	$^{+6.7}_{-6.3}$
$m_{\tilde{e}_R} - m_{\tilde{\chi}_1^0}$	15.68	$^{+0.45}_{-0.49}$
$m_{\tilde{\chi}_2^0} - m_{\tilde{\chi}_1^0}$	83.12	$^{+0.75}_{-0.62}$
$m_{\tilde{e}_L} - m_{\tilde{\chi}_1^0}$	124.92	$^{+0.65}_{-0.65}$
$m_{\tilde{\chi}_4^0} - m_{\tilde{\chi}_1^0}$	208.53	$^{+0.77}_{-0.64}$
$m_{\tilde{q}_L} - m_{\tilde{\chi}_1^0}$	551.19	$^{+4.64}_{-4.47}$
$m_{\tilde{e}_R} - m_{\tilde{\mu}_R}$	1.00	$^{+0.04}_{-0.04}$
$m_{\tilde{e}_L} - m_{\tilde{\mu}_L}$	2.00	$^{+0.48}_{-0.49}$

Parameter	Central value	Estimated error (1-σ)
μ	271.33	$^{+6.89}_{-6.81}$
M_1	122.49	$^{+7.16}_{-7.17}$
M_2	230.89	$^{+6.57}_{-6.54}$
μ/M_1	2.215	$^{+0.084}_{-0.078}$
M_2/M_1	1.885	$^{+0.063}_{-0.057}$