Looking for lepton flavour violation in supersymmetry at the LHC

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Hidden Sector
(Break SUSY)

Messengers

Visible Sector
(MSSM)

It is clear that supersymmetry, if it exists, must be broken at some scale

Question

How is it broken?
(what scale)

What is the mediation mechanism

Soft breaking terms (RPC)

$$\begin{aligned}\mathcal{L}_{\rm soft}^{\rm MSSM} \;=\; & -\frac{1}{2}\left(M_3\widetilde{g}\widetilde{g} + M_2\widetilde{W}\widetilde{W} + M_1\widetilde{B}\widetilde{B} + \text{c.c.}\right) \\ & -\left(\widetilde{\overline{u}}\,\mathbf{a_u}\,\widetilde{Q}H_u - \widetilde{\overline{d}}\,\mathbf{a_d}\,\widetilde{Q}H_d - \widetilde{\overline{e}}\,\mathbf{a_e}\,\widetilde{L}H_d + \text{c.c.}\right) \\ & -\widetilde{Q}^\dagger\,\mathbf{m^2_Q}\,\widetilde{Q} - \widetilde{L}^\dagger\,\mathbf{m^2_L}\,\widetilde{L} - \widetilde{\overline{u}}\,\mathbf{m^2_{\overline{u}}}\,\widetilde{\overline{u}}^\dagger - \widetilde{\overline{d}}\,\mathbf{m^2_{\overline{d}}}\,\widetilde{\overline{d}}^\dagger - \widetilde{\overline{e}}\,\mathbf{m^2_{\overline{e}}}\,\widetilde{\overline{e}}^\dagger \\ & - m^2_{H_u}H_u^*H_u - m^2_{H_d}H_d^*H_d - (bH_uH_d + \text{c.c.})\,.\end{aligned}$$

$$m^2 = c_{ij}\tilde{m}^2$$

Is proportional to unity in GMSB,AMSB etc.

But in Planck scale mediation generically $c_{ij} = \mathcal{O}(1)\ \forall\ i,j$

Is there a flavour problem in SUGRA models?

Addressing the fermion flavour problem in SUSY can lead to flavourful soft masses (Supergravity)

$$W = \epsilon^{q_i+u_j+h_u}(Y^U_{ij} + A^U_{ij}X)Q_iU_jH_u + \epsilon^{q_i+d_j+h_d}(Y^D_{ij} + A^D_{ij}X)Q_iD_jH_d$$
$$+\epsilon^{l_i+e_j+h_d}(Y^E_{ij} + A^E_{ij}X)L_iE_jH_d$$
$$K = Q_i^\dagger Q_i + C_{ij}\epsilon^{q_i+q_j}X^\dagger X Q_i^\dagger Q_j \cdots \ .$$

This can arise in..

Strong WFR models $\longleftrightarrow$ Warped extradimensional models with SUSY

Soft breaking masses in such models become

$$\tilde{m}^2_{ij} \simeq \epsilon^{c_i+c_j}\tilde{m}^2_{3/2}$$

Other Examples where flavourful soft terms can arise

See-saw extensions of SUSY

(Borzumati Masiero, Hall Kostelecky Raby, Masiero Vempati Vives)

Messenger-Matter Mixing in GMSB (extended due to small A terms)

Fuks Herrman Klassen, Shadmi Szabo, Calibbi Paradisi Ziegler

Supersymmetric FN models (Similar to WFR models)

Feng Lester Nir Shadmi

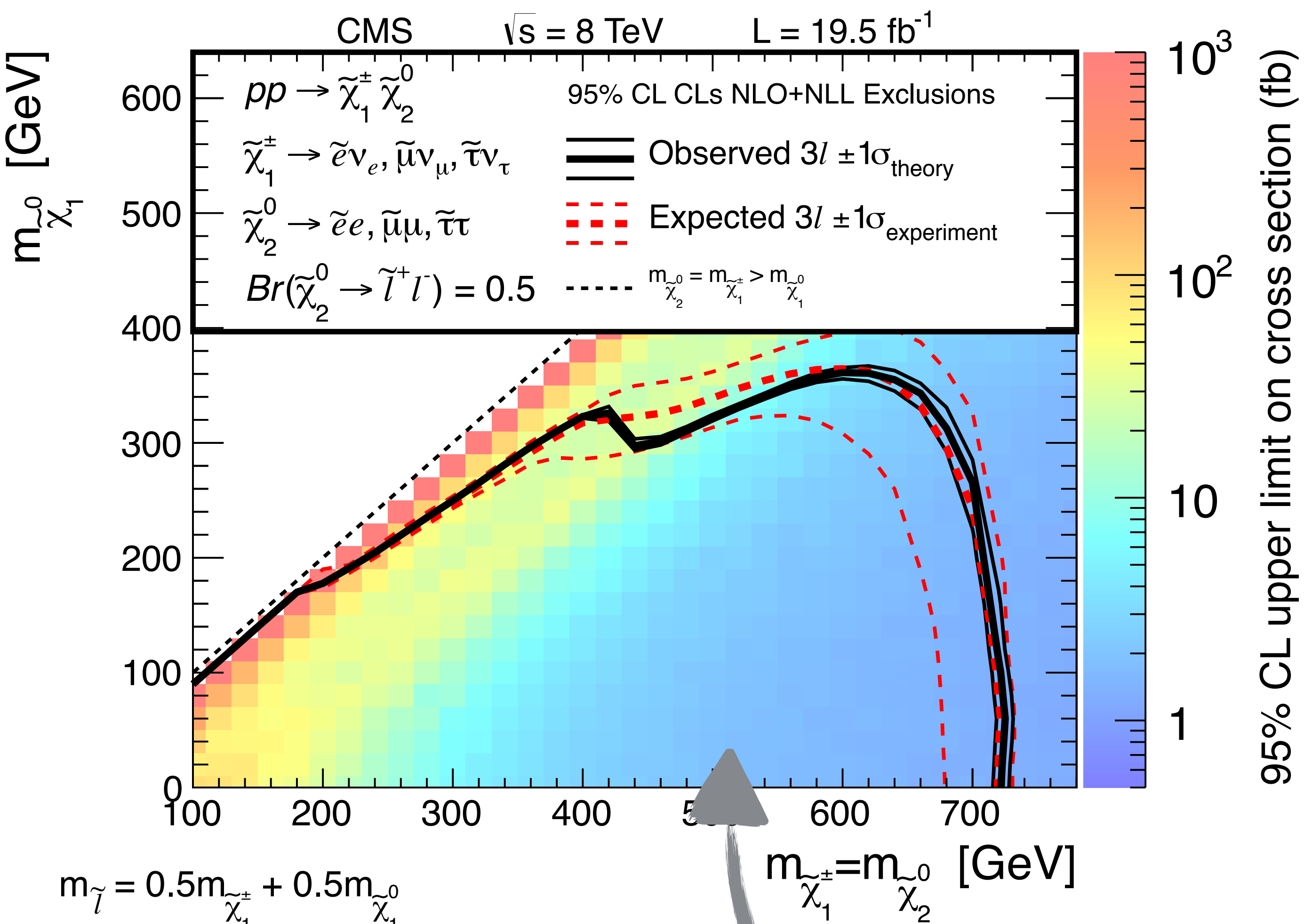
Extra-dimensional models

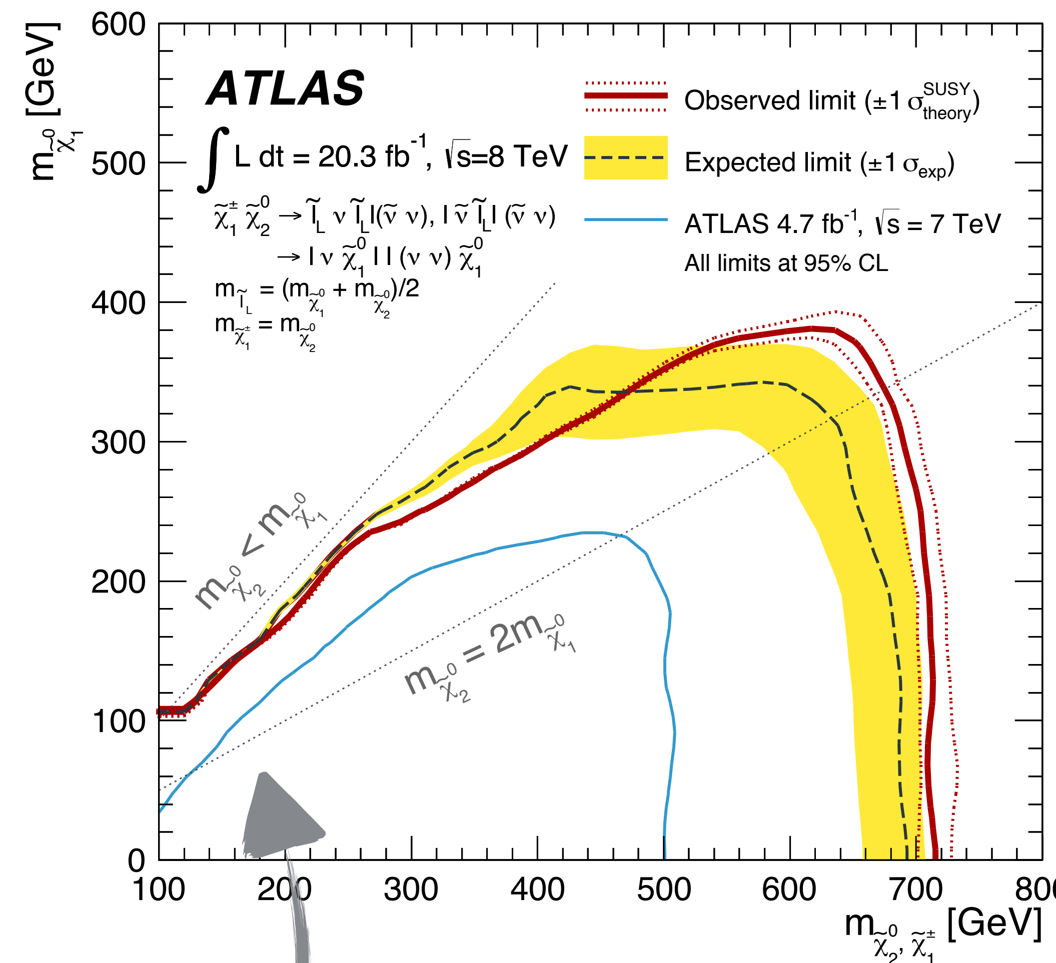
Nomura Papucci Stolarski

To find LFV in SUSY we must first find leptons

But where are the sleptons?

Before we hope to see a flavour violating decay we must first see a flavour conserving decay of sleptons.





(a) $\tilde{\ell}_L$-mediated simplified model

Not here!!

Slepton mass matrix in the basis $l_F \equiv (\tilde{e}_F, \tilde{\mu}_F)$ is given as

$$\tilde{m}^2 = \begin{bmatrix} m^2_{L_{11}} & m^2_{L_{12}} \\ m^2_{L_{12}} & m^2_{L_{22}} \end{bmatrix},$$

The flavour violating parameter is defined

$$\delta_{12} = \frac{m^2_{L_{12}}}{\sqrt{m^2_{L_{11}} m^2_{L_{22}}}}.$$

This is an accurate description of flavour violation in the Mass Insertion Approximation (MIA)

In the MIA the flavour violating parameter is

$$\delta_{12} = \frac{\sin 2\theta (m^2_{L_2} - m^2_{L_1})}{2m^2_L}$$

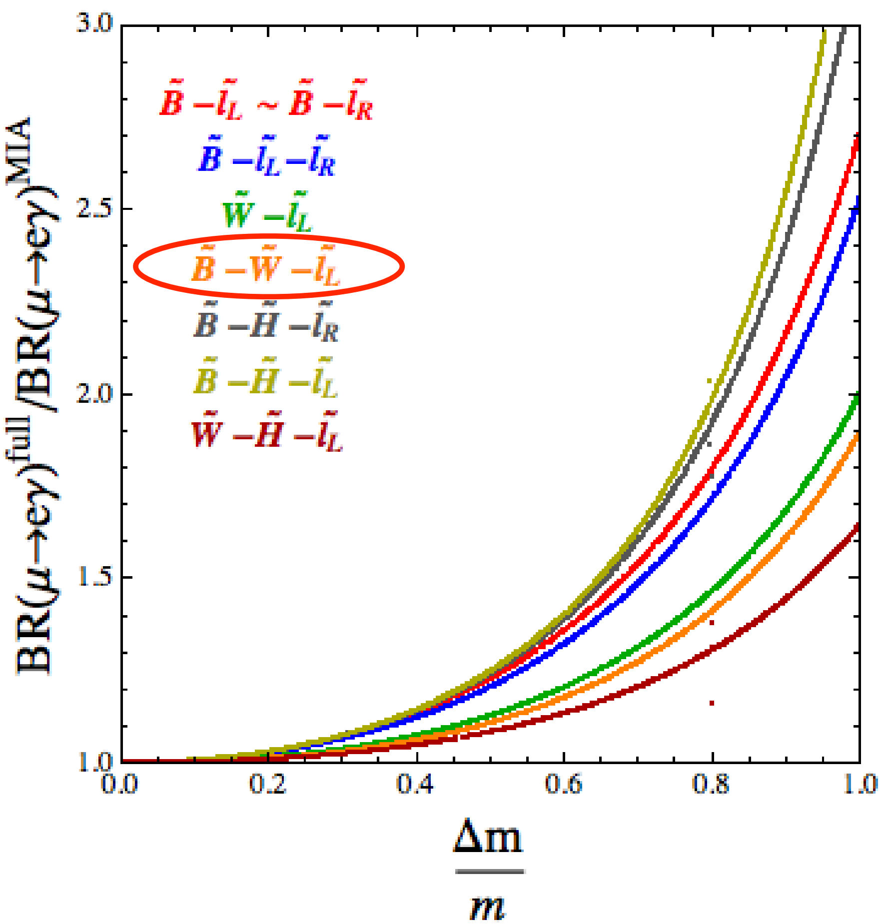
Rotates sleptons from flavour basis to mass basis

Larger δ_{12} are compatible with larger masses since

$$B.R.(\mu \to e\gamma) \propto \frac{\delta_{12}}{\tilde{m}^4_L}$$

Large masses are however accompanied by corresponding reduction in production cross-section

Validity of the mass insertion approximation



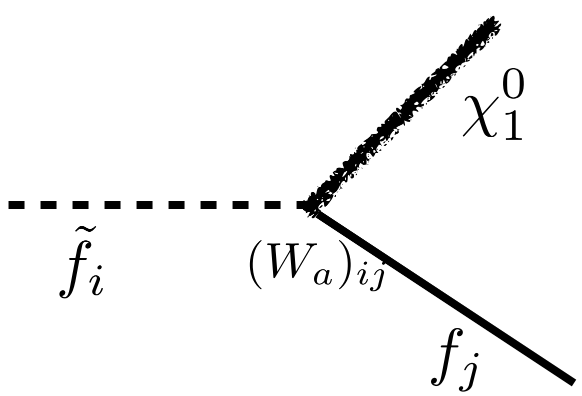
$$\delta_{12} = \sin 2\theta \frac{\Delta m}{m_L} \text{ where}$$

$$\Delta m = m_{L_2} - m_{L_1}$$

FIG. 1. The full vs. MIA results for $\mathrm{BR}(\mu \to e\gamma)$ in the simplified models considered in this paper as a function of the normalized mass-splitting $\Delta m/m$.

Physics of lepton flavour oscillations

In the presence of additional scalars there are seven additional scalar mixing matrices. $(W_a)_{ij}$



This vertex can contribute to direct and indirect processes .

A non zero $(W_a)_{ij}(i \neq j)$ opens up the possibility of slepton flavour oscillations

Mass Eigenstates

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

Mixing angle

Arkani Hamed, Cheng, Feng, Hall. 1996

Gauge eigenstate slectron $\tilde{e}$

produced at t=0

$$|\Psi(0)\rangle = \tilde{e}$$

evolves to $|\psi(t)\rangle = \cos\theta e^{-\frac{\Gamma}{2}t - im_1 t}|1\rangle + \sin\theta e^{-\frac{\Gamma}{2}t - im_2 t}|2\rangle$

The probability of a selectron decaying into a final state with muon is

$$P(\tilde{e} \to f_\mu) = \frac{\int_0^\infty dt |\langle\tilde{\mu}|\psi(t)\rangle|^2}{\int_0^\infty dt \langle\psi(t)|\psi(t)\rangle} \times B(\tilde{\mu} \to f_\mu)$$

$$= \sin^2 2\theta \frac{(\Delta m^2)^2}{4m_L^2\Gamma^2 + (\Delta m^2)^2} BR(\tilde{\mu} \to \mu),$$

Flavour violating factor $\mathcal{B}_{LFV}$

This factor is ~ 1 for $m_L\Gamma \ll \Delta m^2$

We work in this limit to \`maximise' the oscillation probability

Question#1: What is the mixing angle required to get the desired sensitivity to this decay and consistent with flavour bounds.

Answer later!!

In a model with flavour violation the slepton can decay in

flavour conserving mode

could act as

flavour violating mode

Standard techniques employed to distinguish SM background from the slepton discovery signal may not be very effective

Agashe, Graesser '99, Hisano et al.'99

Slepton production in Drell Yan process

$$p\, p(\text{or }\bar{p}) \xrightarrow{\gamma,Z} \tilde{l}^*\tilde{l} \to l^+l^-\chi_1^0\chi_1^0.$$

The SM backgrounds can be reduced using kinematic cuts on leptons and jet veto

SUSY Background: $pp \to \chi^+\chi^- \to W^+W^-\chi_1^0\chi_1^0.$

Reduction is model dependent

zero for charginos!!

Asymmetries like $A_F = N(e^+e^- + \mu^+\mu^-) - N(e^+\mu^- + \mu^+e^-)$

could be useful but depends on chargino production cross-section

Slepton production in Cascade decays

$$pp \to \tilde{g}\tilde{g}, \tilde{g}\tilde{q} \to \tilde{q}\tilde{q}$$

$$\to \chi_{EW}\chi'_{EW} + X$$ (Cascade or direct)

with χ_{EW}, χ'_{EW} one of $\chi^0_{1,2}$, $\chi_1^{+,-}$.

$\chi^+\chi^0_2$

Dilepton events

$$e\mu + 2\ j + p_T^{miss}$$

$\chi^+\chi^-$ background

$\chi^0_2\chi^0_2$

4 lepton events

$$(3e + \mu \text{ or } 3\mu + e) + 2j + p_T^{miss}$$

$\chi^+\chi^0_2$

3 lepton events

Our scenario!

direct production

No jets and OFOS and SFSS

Simplified model is composed of electro-weakinos, left handed sleptons

Rest of spectrum is considered to the very massive.

No jets and large Missing energy

Events are characterised by 3 leptons in the final state

Sleptons are produced from cascade in direct $\chi_2^0/\chi_1^\pm$ production

The μ term is ~ 1 TeV to make the $\chi_2^0/\chi_1^\pm$ predominantly gaugino like and reduce the higgsino component

This model affects the L-L mixing in the lepton sector.

Simplified Model

Mass Parametrisation

The mass of χ_2^0 is M_2 (Predominantly Wino like)

The LSP is χ_1^0 with mass $M_1 = \frac{M_2}{2}$
(Predominantly Bino like)

The slepton masses are chosen such that they are always produced on-shell $M_1 < \tilde{m}_L < M_2$

$\tilde{m}_L$ is defined to be arithmetic mean of the slepton mass eigenstates

Valid approximation in the MIA

Constraints from flavour experiments

Mixing between the first two generation leptons is constrained due to non-observation of $\mu \to e\gamma$

Prospects of observing the flavour violating decay should be consistent with the current bounds on the non-observation of the rare process(es)

$$\mathcal{L}_{FV} = e\frac{m_l}{2}\ \bar{e}\ \sigma_{\alpha\beta}\left(A_L P_L + A_R P_R\right)\ \mu\ F^{\alpha\beta},$$

$$BR(\mu \to e\gamma) = \frac{48\pi^3}{G_F^2}\left(|A_L|^2 + |A_R|^2\right). < 5.7 \times 10^{-13}$$

A_L is a function of gauging mass M_2 and slepton mass m_L

The contributions to $\mu \to e\gamma$ chargino neutralino and bino mediation

For the given model since the right handed leptons are massive $A_R \sim 0$

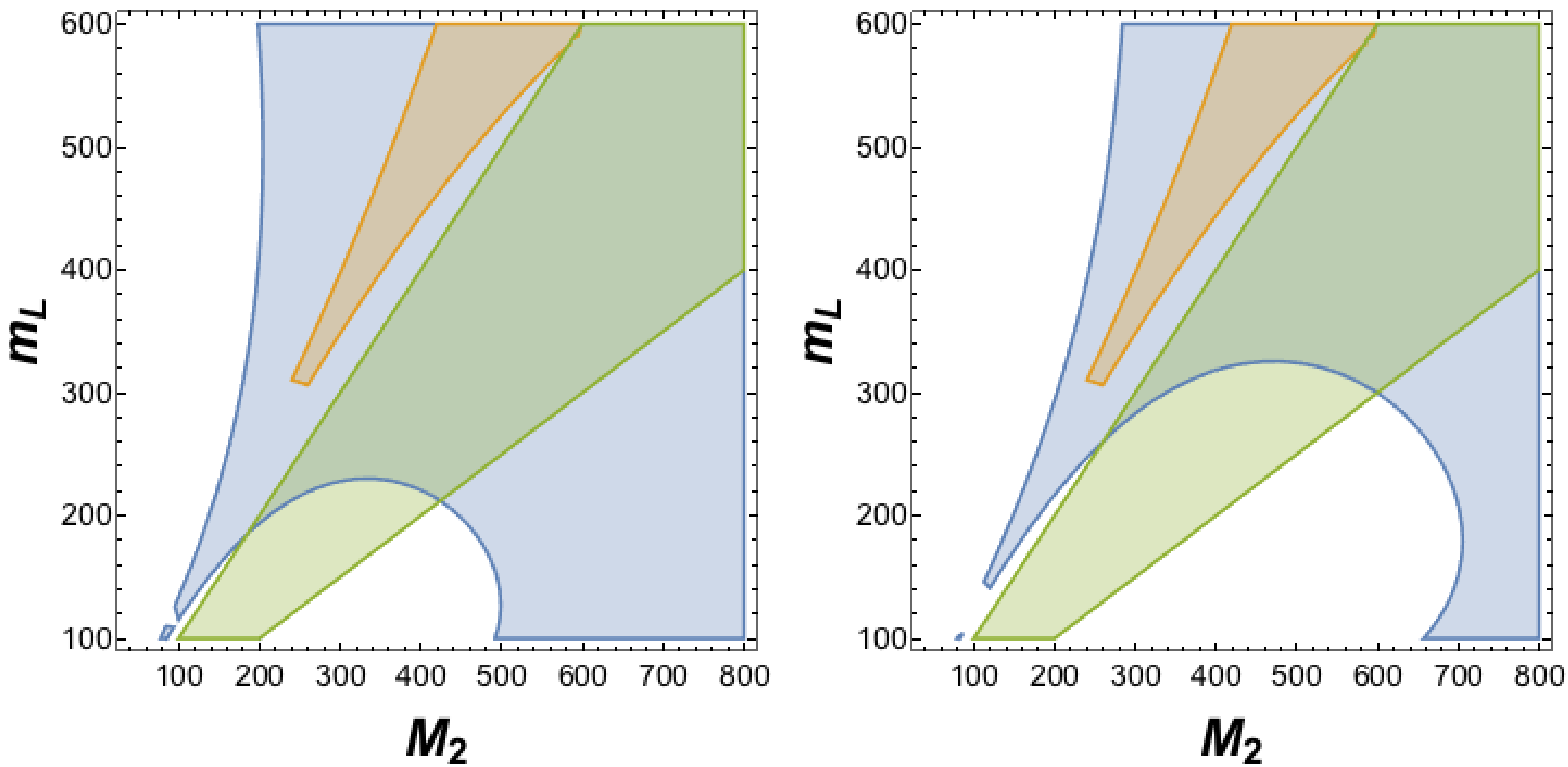
The left handed amplitude A_L due to the three contributions is given as

$$A_L = \frac{\delta_{12}}{m_L^2}\left(\frac{\alpha_Y}{4\pi} f_n\left(\frac{M_1^2}{m_L^2}\right) + \frac{\alpha_Y}{4\pi} f_n\left(\frac{M_1^2}{m_L^2}\right) + \frac{\alpha_2}{4\pi} f_c\left(\frac{M_2^2}{m_L^2}\right)\right)$$

In this model chirality flip occurs only on the external lines!!

NO μ or $\tan\beta$ dependance

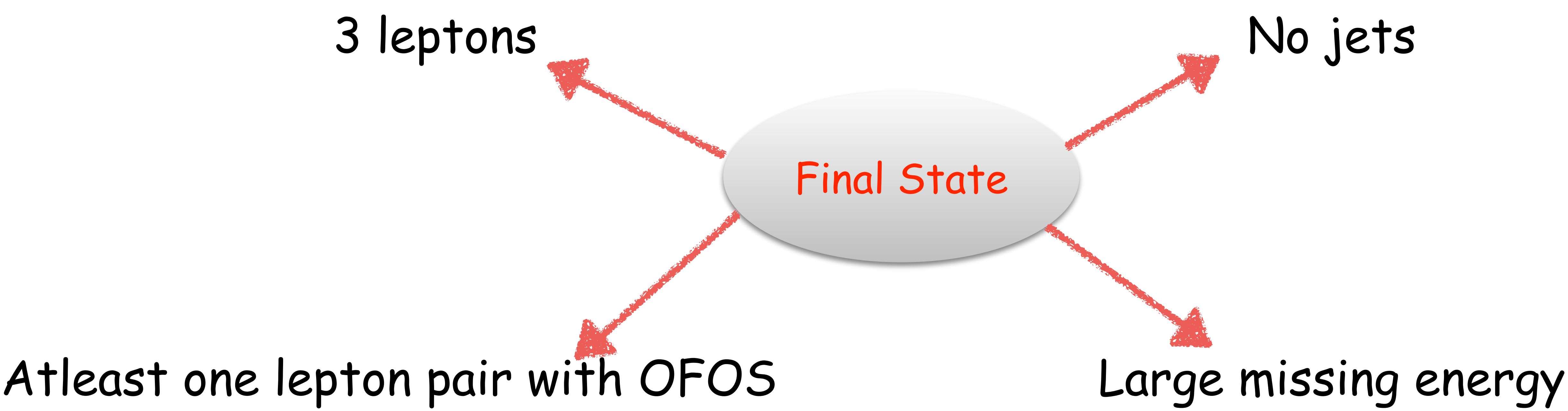
Region constrained by $\mu \to e\gamma$



Signal Characteristics

Signal Characteristics

$$pp \to \begin{cases} \chi_2^0 \to l_i^\pm \tilde{l}_i^\mp \to l_i^\pm l_j^\mp \chi_1^0, \quad i \neq j, \\ \chi_1^\pm \to l_i^\pm \nu \chi_1^0, \end{cases}$$



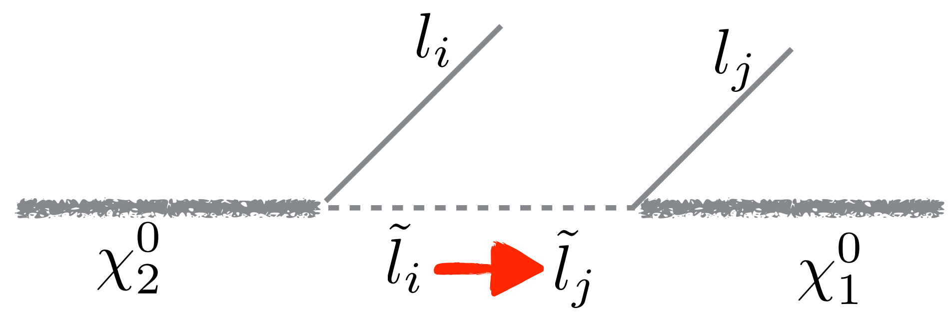
These characteristics are not enough to get a significant sensitivity of the signal over the background

The tri-lepton final state can grouped into following 8 combinations

$$e^+e^+\mu^- \;; e^-e^-\mu^+ \;; \mu^-e^+\mu^- \;; \mu^+e^-\mu^+$$

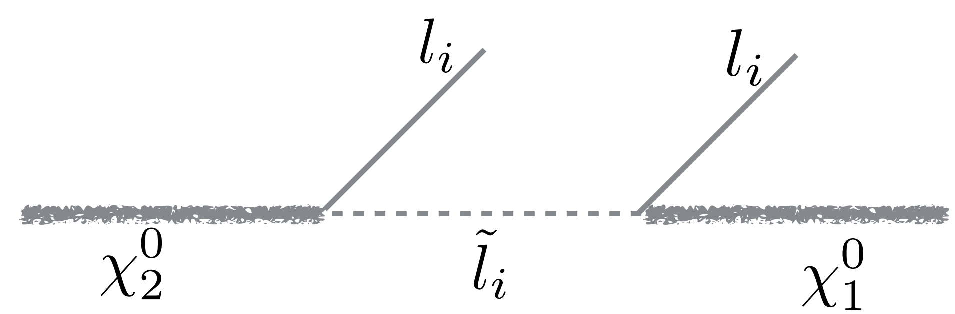
$$e^+e^-\mu^+ \;; e^-e^+\mu^- \;; \mu^+e^+\mu^- \;; \mu^-e^-\mu^+.$$

The first lepton comes from the chargino. The latter two originate from the flavour violating vertex.



Each `triplet' has one pair with OFOS

Also possible with flavour conserving decay

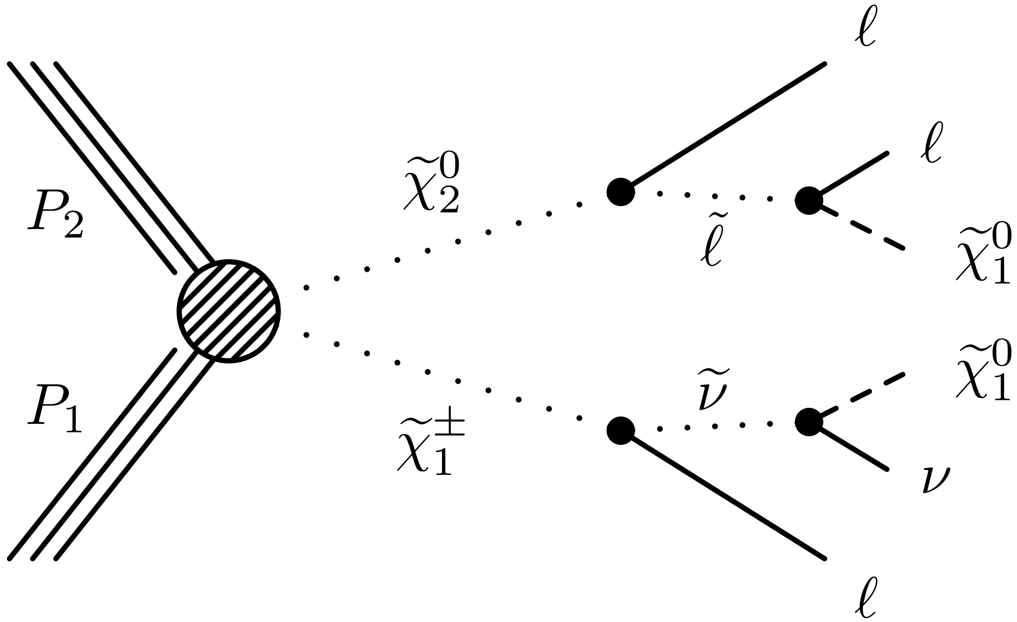


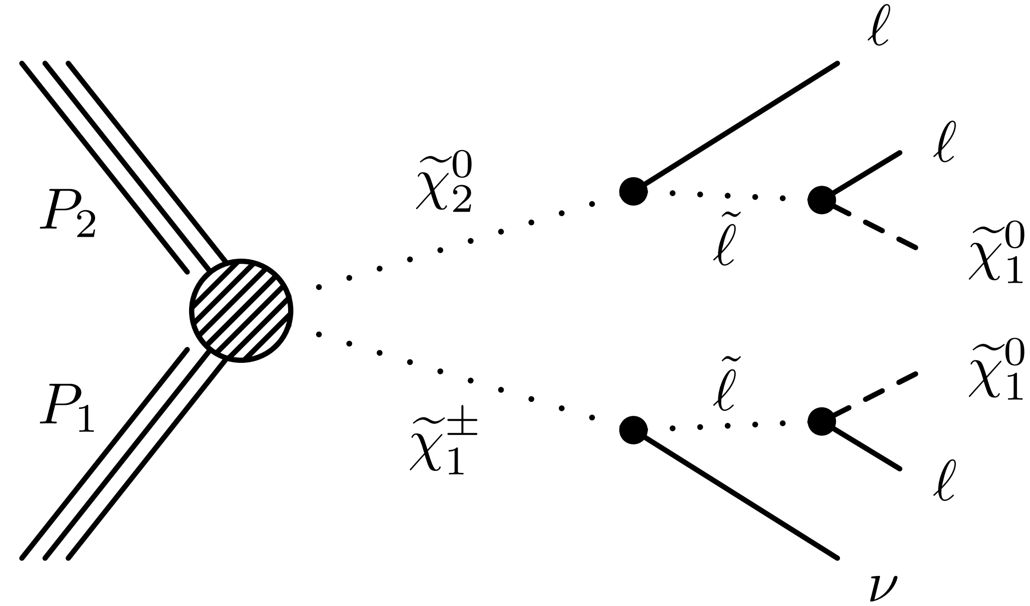
$$e^+\mu^+\mu^- \;; e^-\mu^+\mu^- \;; \mu^-e^+e^- \;; \mu^+e^+e^-$$

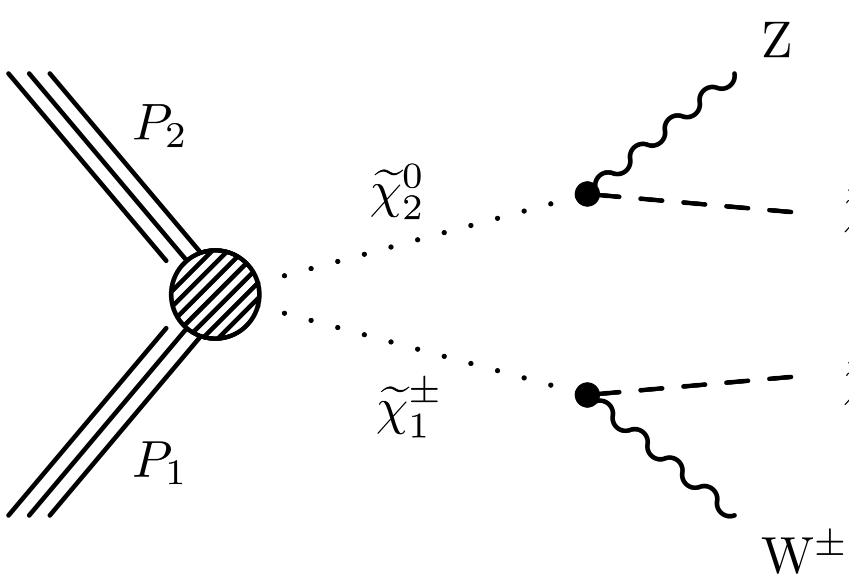
$$\mu^+\mu^+\mu^- \;; e^-e^+e^- \;; e^+e^+e^- \;; \mu^-\mu^-\mu^+$$

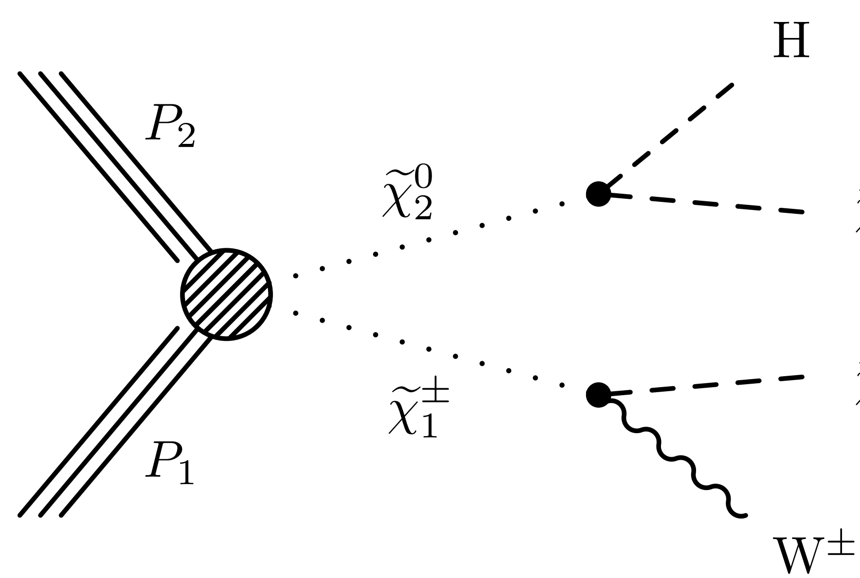
Question#2: How does one differentiate between the flavour violating and conserving decays?

SUSY Backgrounds









Answer!!

Flavour Violating (FV) vertex

$e^+e^+\mu^-$; $e^-e^-\mu^+$; $\mu^-e^+\mu^-$; $\mu^+e^-\mu^+$

$e^+e^-\mu^+$; $e^-e^+\mu^-$; $\mu^+e^+\mu^-$; $\mu^-e^-\mu^+$.

Flavour conserving (FC) vertex

$e^+\mu^+\mu^-$; $e^-\mu^+\mu^-$; $\mu^-e^+e^-$; $\mu^+e^+e^-$

$\mu^+\mu^+\mu^-$; $e^-e^+e^-$; $e^+e^+e^-$; $\mu^-\mu^-\mu^+$

The FV vertex has a unique feature → Presence of a lepton pair with same flavour and same sign (SFSS) → Absent in FC vertex

Reduces signal by half but extremely effective

SIGNAL:
OFOS+SFSS+Missing Energy

Simulations were performed using the following selections

Jet selection: Reconstructed usin anti-kt and R=0.5. The jets passing min p_T are accepted.

Lepton selection: Three isolated leptons with $p_T^{l_{1,2,3}} \geq 20, 10, 10 \text{ GeV}$

Missing Transverse Momentum: A minimum of 100 GeV for each event

b -like Jet selection: Identified through jet quark matching i.e. jets which satisfy $\Delta R(b, j) < 0.3$

Presence of OFOS +SFSS

Spectrum Characteristics	A	B	C	D	E	F
$\chi_2^0/\chi_1^\pm$	210	314	417	518	619	718
χ_1^0	95.8	144	193	241	290	339
m_L	156	229	303	377	452	526
$BR(\chi_2^0 \to \tilde{e}_L e)$	0.13	0.15	0.16	0.16	0.16	0.16
$BR(\chi_2^0 \to \tilde{\mu}_L \mu)$	0.13	0.15	0.16	0.16	0.16	0.16

TABLE I: Representative choices of SUSY parameter space. All masses are in GeV.

SIGNAL

	Signal($\chi_2^0\chi_1^\pm$)					
$M_2 \Longrightarrow$	200	300	400	500	600	700
No. of events generated	10000	10000	10000	10000	10000	10000
$p_T^{\ell_{1,2}} > 20, p_T^{\ell_3} > 10, \|\eta\| < 2.5$	1371	1752	2014	2218	2225	2342
Lepton isolation cut	1330	1669	1883	2055	2036	2112
$\not{p}_T > 100$	474	959	1326	1600	1683	1860
OFOS	470	952	1319	1581	1659	1828
Z mass veto	423	849	1218	1485	1574	1752
SFSS	223	462	640	783	804	892
Case a: jet veto	91	205	288	337	346	380
Case b: b-like jet veto	221	458	635	777	798	884
Case c: $n_j \leq 1$ and b-like veto	161	375	479	604	617	687

SUSY and SM background

	SUSY($\chi_2^0\chi_1^\pm$)						SM	
	A	B	C	D	E	F	$t\bar{t}$	WZ
$M_2 \Longrightarrow$	200	300	400	500	600	700	-	-
Cross section (fb) at 14 TeV	1.65×10^3	370.5	118.8	45.6	20.5	9.57	9.3×10^5	4.47×10^4
No. of events generated	10000	10000	10000	10000	10000	10000	10^7	3×10^6
$p_T^{\ell_{1,2}} > 20, p_T^{\ell_3} > 10, \|\eta\| < 2.5$	1299	1779	2015	2195	2245	2361	164895	23960
Lepton isolation cut	1251	1672	1874	2044	2051	2131	70233	22366
$\not{p}_T > 100$	454	967	1311	1624	1722	1872	19241	1669
OFOS	209	482	656	820	855	918	14012	858
Z mass veto	126	346	547	728	768	853	12395	122
SFSS	4	6	11	14	15	25	4598	22
Case a: jet veto	≤ 1	1	1	5	4	4	29	≤ 1
Case b: b-like jet veto	4	5	10	14	13	23	131	13
Case c: $n_j \leq 1$ and b-like veto	1	3	7	9	9	19	48	5

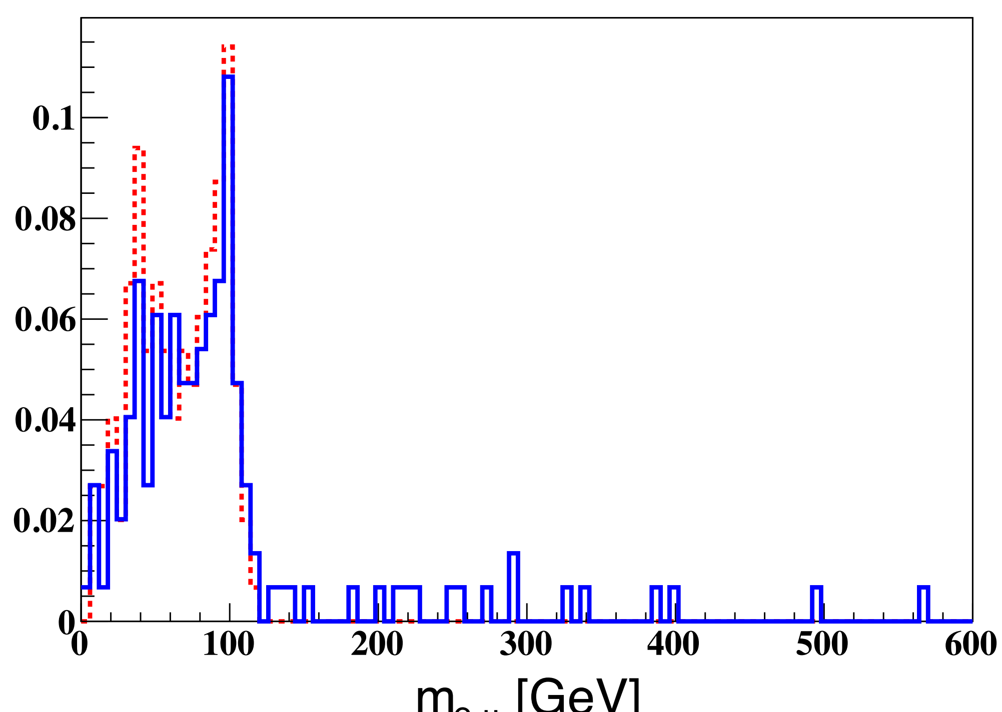
The appearance of an edge in the $m_{e\mu}$ distribution is clear indication of LFV decay → choice of SFSS is beset with a minor combinatorial problem → Identity of the leptons from the FV vertex is unclear

$$e^+e^+\mu^- \;; e^-e^-\mu^+ \;; \mu^-e^+\mu^- \;; \mu^+e^-\mu^+$$

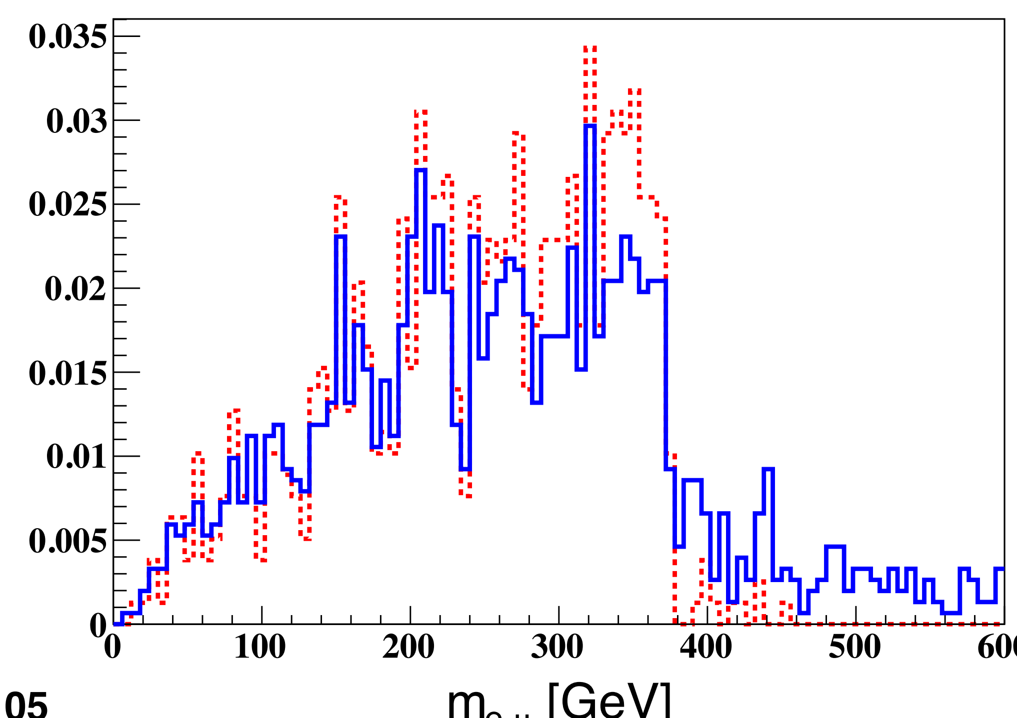
Two combinations of leptons with OFOS is possible for each tri-lepton state!!.

Not much of a problem!!

Spectrum A



Spectrum F



Results with maximum mixing $\mathcal{B}_{LFV} = \sin^2 2\theta = 1$

Properties	Signal (S)						Background (B)	
	A	B	C	D	E	F	$t\bar{t}$	WZ
Cross section (fb) at 14 TeV	1.65×10^3	370.5	118.8	45.6	20.5	9.57	9.3×10^5	4.47×10^4
Normalized cross sections								
Case a: jet veto	15.01	7.59	3.41	1.51	0.67	0.37	2.69	≤ 1
Case b: b-like veto	36.4	16.9	7.54	3.54	1.63	0.85	12.1	0.19
Case c: $n_j \leq 1$ and b-like veto	26.5	13.9	5.7	2.75	1.26	0.66	4.4	0.07
$\frac{S}{\sqrt{B}}$(@100) fb^{-1}								
Case a: jet veto	91.43	45.93	20.78	9.32	4.31	2.24	-	-
Case b: b-like veto	100.99	47.87	21.34	10.04	4.64	2.43	-	-
Case c: $n_j \leq 1$ and b-like veto	122.4	64.4	26.4	12.8	5.92	3.12	-	-

TABLE IV: Normalized cross-section (fb) and $S/\sqrt{B}$ for signal and background subject to three selection conditions

Question#1: What is the mixing angle required to get the desired sensitivity to this decay and consistent with flavour bounds.

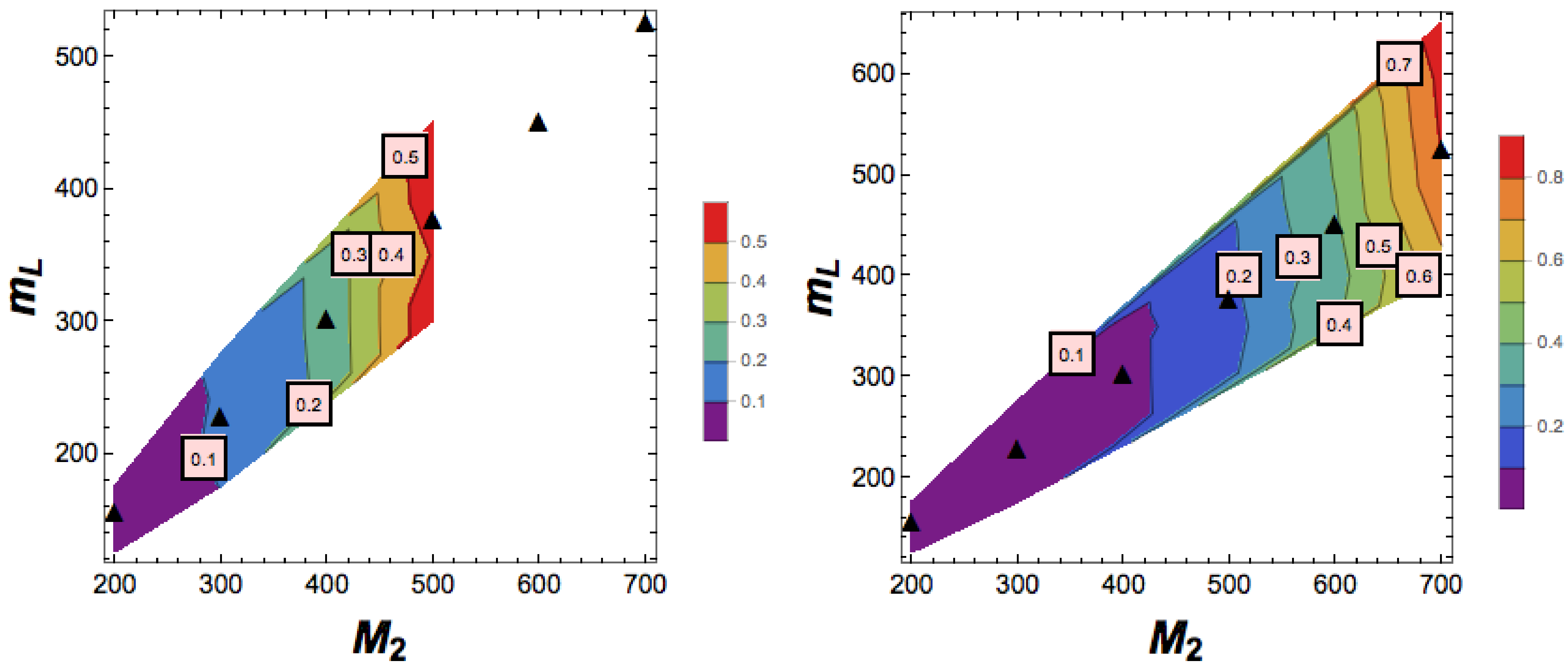
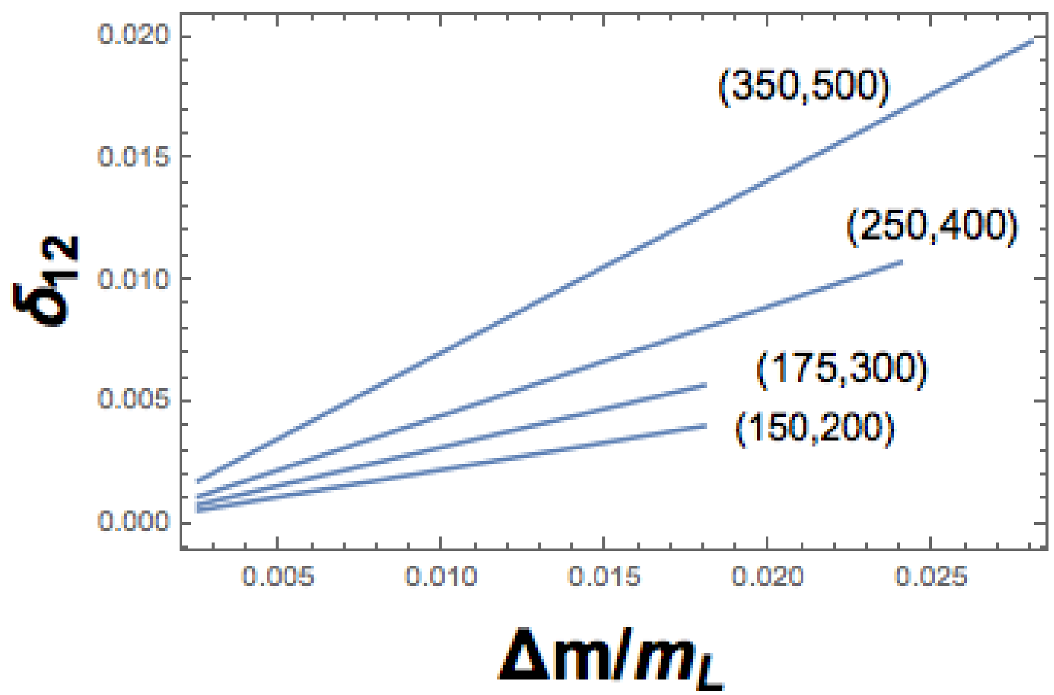


FIG. 5: Minimum value (in small box) of $\mathcal{B}_{LFV}$ for a $S/\sqrt{B} = 5$ discovery for $\mathcal{L} = 100\ fb^{-1}$ (left) and $\mathcal{L} = 1000\ fb^{-1}$ (right). The $S/\sqrt{B}$ is computed using jet veto condition. The filled triangles correspond to the representative points A-F from left to right. The plot is truncated at the point where $\mathcal{B}_{LFV} > 1$ is required to get a 5 σ sensitivity of signal for that particular luminosity. Masses are in GeV.



$$\delta_{12} = \sin 2\theta \frac{\Delta m}{m_L} \text{ where}$$
$$\Delta m = m_{L_2} - m_{L_1}$$

FIG. 6: Varition of δ_{12} as a function of $\frac{\Delta m}{m_L}$ for different choices of (m_L, M_2) $\mathcal{L} = 100\ fb^{-1}$. The plot is terminated on the right at the point where the δ_{12} exceeds the current experimental bound for the given mass.

This analysis was essentially a combinatorial game to identify the signal over the background

We identified a feature which was unique to our signal and avoids contamination with SUSY and SM backgrounds.

This analysis can be extended to the exploring 1-3 and 2-3 sectors (where τ decays leptonically)

It would be nice to check if a similar analysis could give us an estimate of the mass splitting-Possibly an upper bound on $\mu \to e\gamma$

End