Lepton Number Violation
in Decays of Supersymmetric Particles

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- Sources flavour violation in supersymmetric models

- Lepton flavour violating decays of supersymmetric particles, MSSM

- Implications for LHC observables

- R-parity violation

Experimental Information

Large mixing angles in neutrino sector

$$|\tan\theta_{atm}|^2 \simeq 1$$
$$|\tan\theta_{sol}|^2 \simeq 0.4$$
$$|U_{e3}|^2 \lesssim 0.05$$

Small flavour and CP violation violation in charged lepton sector

$BR(\mu \to e\gamma) \lesssim 1.2 \cdot 10^{-11}$ $\quad BR(\mu^- \to e^- e^+ e^-) \lesssim 10^{-12}$

$BR(\tau \to e\gamma) \lesssim 3.4 \cdot 10^{-7}$ $\quad BR(\tau \to \mu\gamma) \lesssim 3.3 \cdot 10^{-7}$

$BR(\tau \to l l l') \lesssim O(10^{-6})$ $(l, l' = e, \mu)$

$$|d_e| \lesssim 10^{-27}\ e\ cm,\ |d_\mu| \lesssim 1.5 \cdot 10^{-18}\ e\ cm,\ |d_\tau| \lesssim 1.5 \cdot 10^{-16}\ e\ cm$$

possible SUSY contributions to magnetic moments of leptons

$$|\Delta a_e| \leq 10^{-12},\ \ 0 \leq \Delta a_\mu \leq 43 \cdot 10^{-10},\ \ |\Delta a_\tau| \leq 0.058$$

Sources of Flavour Violation

Sleptons:

$$M^2_{\tilde{l}} = \begin{pmatrix} M^2_{L,ij} + \frac{v_d^2 Y^{E*}_{ki} Y^E_{kj}}{2} + D_L \delta_{ij} & \frac{v_d A_{ij} - \mu v_u (Y^E_{ij})^*}{\sqrt{2}} \\ \frac{v_d A^*_{ij} - \mu v_u Y^E_{ij}}{\sqrt{2}} & M^2_{E,ij} + \frac{v_d^2 Y^E_{ik} Y^{E*}_{jk}}{2} + D_R \delta_{ij} \end{pmatrix}$$

Sneutrinos:

$$M^2_{\tilde{\nu}} = M^2_{L,ij} + D_\nu \delta_{ij}$$

where

$$D_L = \frac{\left(g'^2 - g^2\right)(v_d^2 - v_u^2)}{8}, \qquad D_R = \frac{g'^2 (v_d^2 - v_u^2)}{4}$$

$$D_\nu = \frac{\left(g^2 + g'^2\right)(v_d^2 - v_u^2)}{8}$$

Without loss of generality: $Y^E_{ij} = Y^E_i \delta_{ij}$, Y^E_i real

Lepton flavour violating SUSY decays

Lepton flavour violating couplings:

- $\tilde{l}_i - l_j - \tilde{\chi}^0_k \Rightarrow \tilde{l}_i \to l_j \, \tilde{\chi}^0_k, \; \tilde{\chi}^0_k \to l_j \, \tilde{l}_i$
- $\tilde{\nu}_i - l_j - \tilde{\chi}^+_k$
- $\tilde{l}_i - \tilde{\nu}^\dagger_j - W, \; \tilde{l}_i - \tilde{\nu}^\dagger_j - H^+$
- $\tilde{l}_i - \tilde{l}^\dagger_j - Z, \; \tilde{l}_i - \tilde{l}^\dagger_j - (h^0, \; H^0, \; A^0)$
- $\tilde{\nu}_i - \nu_j - \tilde{\chi}^0_k, \; \tilde{l}_i - \nu_j - \tilde{\chi}^+_k$

General MSSM

Motivation:

See-saw mechanism implies additional contributions to RGEs :

$$16\pi^2 \dot{A}_e = \ldots + 2Y_\nu A_\nu$$
$$16\pi^2 \dot{M}_L^2 = \ldots + M_L^2 Y_\nu^\dagger Y_\nu + Y_\nu^\dagger Y_\nu M_L^2$$

These are matrix equations.

In E_6 models one gets also additional contributions to M_E^2.

Strategy

Variations around the Snowmass point SPS1a

$M^2_{L,11} = M^2_{L,22} = 202.3^2$ GeV^2, $M^2_{L,33} = 201.5^2$ GeV^2

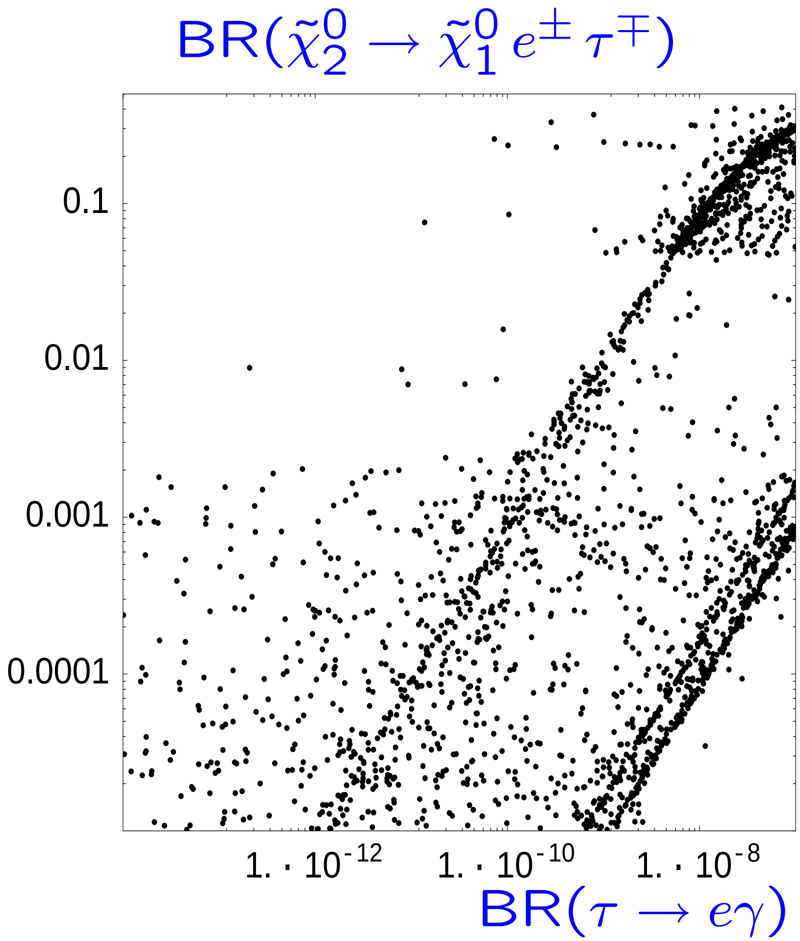
$M^2_{E,11} = M^2_{E,22} = 138.7^2$ GeV^2, $M^2_{E,33} = 136.3^2$ GeV^2

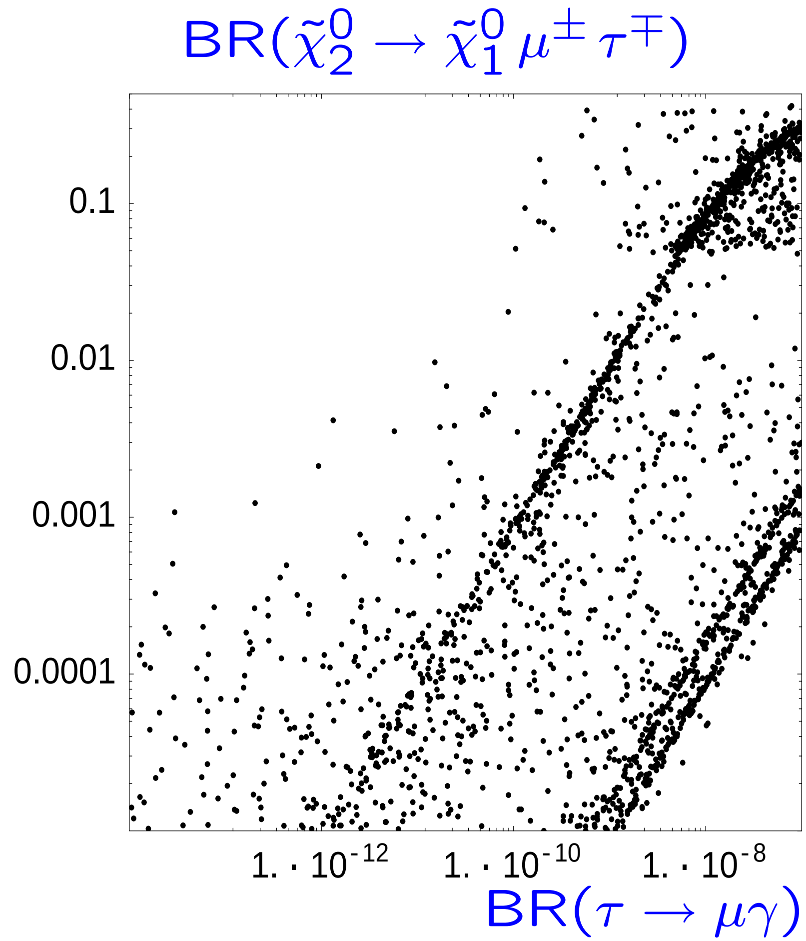
$A_{11} = -7.567 \cdot 10^{-3}$ GeV, $A_{22} = -1.565$ GeV, $A_{33} = -26.326$ GeV

$M_1 = 107.9$ GeV, $M_2 = 208.4$ GeV, $\mu = 365$ GeV, $\tan\beta = 10$

$\Delta a_e = 6.8 \cdot 10^{-14}$, $\Delta a_\mu = 2.9 \cdot 10^{-9}$, $\Delta a_\tau = 8.4 \cdot 10^{-7}$

$$\tilde{\chi}_2^0 \to \tilde{l}_i l_j \to l_k l_j \tilde{\chi}_1^0$$





Variations around SPS1a

Implications for LHC

Edge variables Magnitude changes only sightly: $\pm$(1-2) %

However, new combinations: $m_{ll}^{max} \to m_{e\mu}^{max}\ m_{e\tau}^{max}\ m_{\mu\tau}^{max}$

similarly for m_{llq}^{max} and m_{llq}^{min}

Note: BR($\tilde{\chi}_2^0 \to \tilde{\chi}_1^0\, e^\pm\, \tau^\mp$), BR($\tilde{\chi}_2^0 \to \tilde{\chi}_1^0\, \mu^\pm\, \tau^\mp$) $\simeq$ BR($\tilde{\chi}_2^0 \to \tilde{\chi}_1^0\, e^\pm\, e^\mp$)

or even larger

$\Rightarrow$ pairing of different lepton flavours necessary

Particularity of SPS1a

$\tilde{\chi}_1^+ \to \tilde{\tau}^+ \nu_\tau \to \tau^+ \nu \tilde{\chi}_1^0$

$\Rightarrow$ extremely difficult to detect if not impossible

with LFV

$\tilde{\chi}_1^+ \to \tilde{\tau}_1^+ \nu_\tau \to e^+ \nu_\tau \tilde{\chi}_1^0$ or $\tilde{\chi}_1^+ \to \tilde{\tau}_1^+ \nu_\tau \to \mu^+ \nu_\tau \tilde{\chi}_1^0$

with BR($\tilde{\chi}_1^+ \to l^+ \nu \tilde{\chi}_1^0$) up to 15%.

Bilinearly broken R-parity

Is defined as MSSM $+ \epsilon_i \widehat{L}_i \widehat{H}_u + B_i \epsilon_i \widetilde{L}_i H_u$

Induced mixings: (leptons, charginos), (neutrinos, neutralinos), (Higgs bosons, sleptons)

Solves neutrino problems:
Atmospheric at tree level, solar at loop level

Negligible flavour violating decays of leptons:
BR($\mu \to e\gamma$) $< 10^{-17}$, BR($\tau \to e\gamma, \mu\gamma$) $< 10^{-18}$.

Leads to predictions for collider physics

Neutralino Mass Matrix

basis $\psi^{0T} = (-i\lambda', -i\lambda^3, \widetilde{H}_d^1, \widetilde{H}_u^2, \nu_e, \nu_\mu, \nu_\tau)$ we get:

$$M_N = \begin{bmatrix} \mathcal{M}_{\chi^0} & m^T \\ m & 0 \end{bmatrix}$$

with

$$\mathcal{M}_{\chi^0} = \begin{bmatrix} M_1 & 0 & -\frac{1}{2}g'v_d & \frac{1}{2}g'v_u \\ 0 & M_2 & \frac{1}{2}gv_d & -\frac{1}{2}gv_u \\ -\frac{1}{2}g'v_d & \frac{1}{2}gv_d & 0 & -\mu \\ \frac{1}{2}g'v_u & -\frac{1}{2}gv_u & -\mu & 0 \end{bmatrix}, \quad m = \begin{bmatrix} -\frac{1}{2}g'v_1 & \frac{1}{2}gv_1 & 0 & \epsilon_1 \\ -\frac{1}{2}g'v_2 & \frac{1}{2}gv_2 & 0 & \epsilon_2 \\ -\frac{1}{2}g'v_3 & \frac{1}{2}gv_3 & 0 & \epsilon_3 \end{bmatrix}$$

Approximate diagonalization as in usual seesaw mechanism gives

$$m_{\nu,eff} = \frac{M_1 g^2 + M_2 g'^2}{4\,det(\mathcal{M}_{\chi^0})} \begin{pmatrix} \Lambda_1^2 & \Lambda_1\Lambda_2 & \Lambda_1\Lambda_3 \\ \Lambda_1\Lambda_2 & \Lambda_2^2 & \Lambda_2\Lambda_3 \\ \Lambda_1\Lambda_3 & \Lambda_2\Lambda_3 & \Lambda_3^2 \end{pmatrix}$$

where

$$\Lambda_i = \mu v_i + v_d \epsilon_i$$

Parameters controlling ν-Physics

If $m_{\nu,Loop} \ll m_{\nu,Tree}$

Δm^2_{atm}	$M_2/det(\mathcal{M}_{\chi^0})\ \lvert\vec{\Lambda}\rvert^2$
$\tan^2\theta_{atm}$	$\lvert\Lambda_3/\Lambda_3\rvert^2$
CHOOZ	$\lvert\Lambda_1\rvert/\sqrt{\Lambda_2^2+\Lambda_3^2}$
$\tan^2\theta_{sol}$	$\lvert\epsilon_1/\epsilon_2\rvert^2$
m^2_{sol}/m^2_{atm}	$\lvert\vec{\epsilon}\rvert^2/\lvert\vec{\Lambda}\rvert$

where

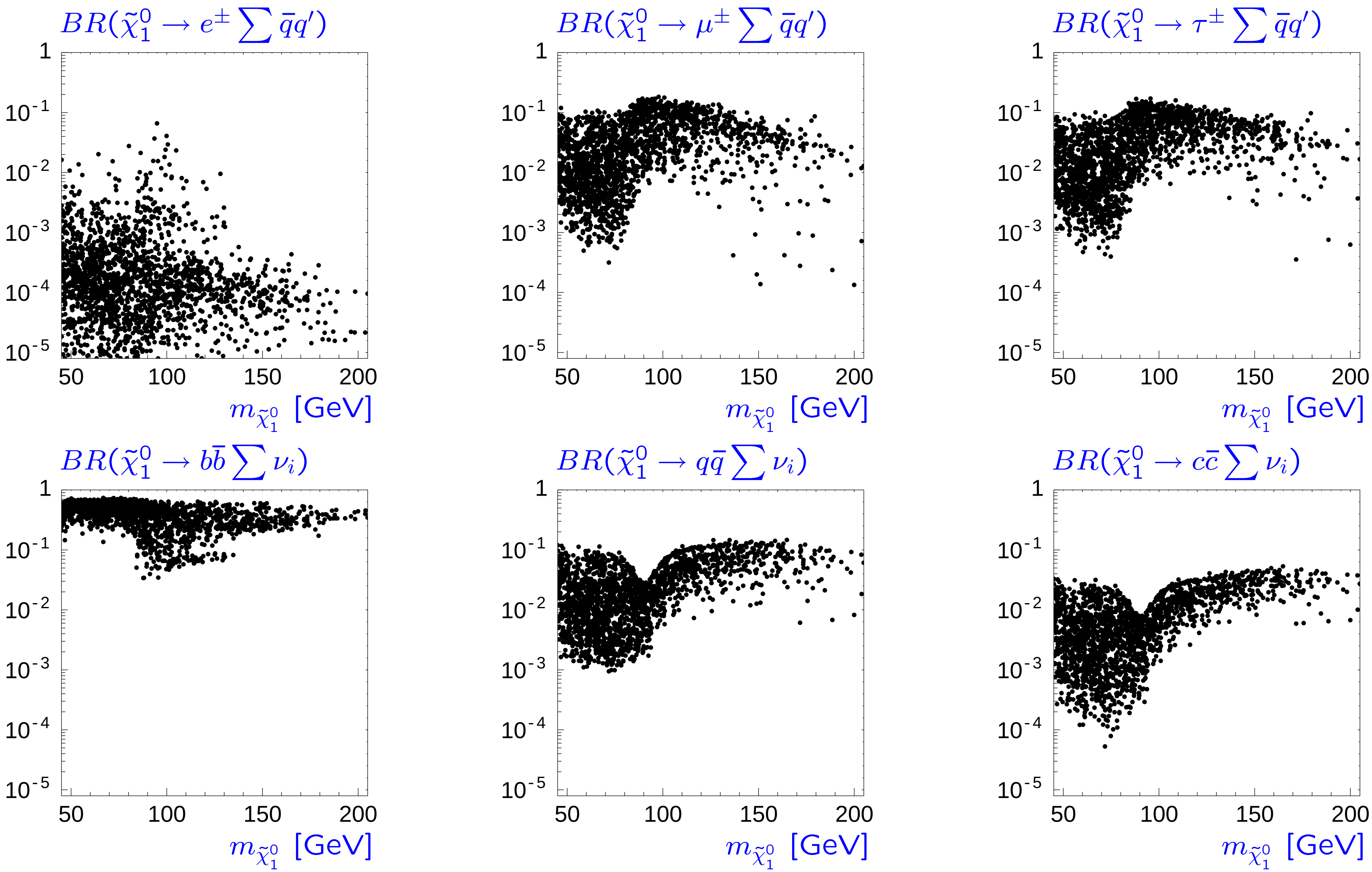
$$\Lambda_i = \mu v_i + v_d \epsilon_i$$

Approximate Couplings

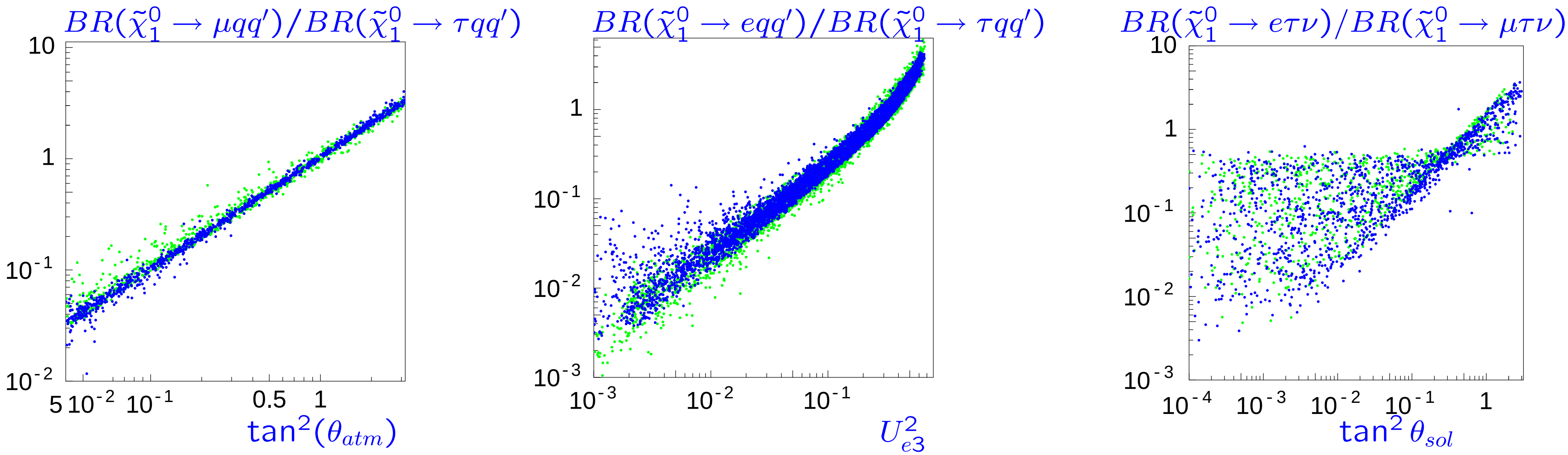
$\tilde{\chi}^0_1$-$W^\pm$-l_i couplings:

$$
\begin{aligned}
O_{Ri} &= \frac{g h^E_{ii} v_d}{2\text{Det}_+}\left[\frac{g v_d N_{12} + M_2 N_{14}}{\mu}\epsilon_i\right. \\
&+ \left. g\,\frac{\left(2\mu^2 + g^2 v_d v_u\right) N_{12} + (\mu + M_2)\, g v_u N_{14}}{2\mu\text{Det}_+}\Lambda_i\right] \\
O_{Li} &= \frac{g\Lambda_i}{\sqrt{2}}\left[-\frac{g' M_2 \mu}{2\text{Det}_0} N_{11} + g\left(\frac{1}{\text{Det}_+} + \frac{M_1\mu}{2\text{Det}_0}\right) N_{12}\right. \\
&\qquad -\frac{v_u}{2}\left(\frac{g^2 M_1 + g'^2 M_2}{2\text{Det}_0} + \frac{g^2}{\mu\text{Det}_+}\right) N_{13} \\
&\qquad \left. + \frac{v_d (g^2 M_1 + g'^2 M_2)}{4\text{Det}_0} N_{14}\right]
\end{aligned}
$$

Semi-leptonic final states



Correlations



Summing over all neutrinos.

LHC can measure $BR(\tilde\chi^0_1 \to \mu q q')/BR(\tilde\chi^0_1 \to \tau q q')$ with an accuracy of $\simeq 3$ % for SPS1a like scenarions (W.P., P. Skands, hep-ph/0401077)

Summary

- Large lepton flavour violating SUSY decays despite stringent constraints from rare lepton decays

- Impact on edge variables and chargino discovery

- R-parity violation: LHC can measure correlations between neutrino mixing angles and branching ratios of LSP