Left-right supersymmetry at the LHC

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Based on works with:
- A. Alloul, M. Frank & M. Rausch [JHEP 1310 (2013) 033]
- A. Alloul, L. Basso, M. Krauss & W. Porod [in arXiv:1405.1617]

SUSY 2014 @ Manchester

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Motivations for studying left-right supersymmetry

✦ Why supersymmetry?

- ✤ Supersymmetry naturally arises from Nœther and spin-statistics theorems
- ✤ Unifies internal and external symmetries
- ✤ Elegant solution to the hierarchy problem
- ✤ Provide (in general) a dark matter candidate
- ✤ Gauge coupling unify at higher scales

✦ Why left-right symmetry?

- ✤ Explanation for neutrino mass generation
- ✤ Possible embedding in grand-unified theories
- ✤ Possible solution to the strong CP problem

✦ Why left-right supersymmetry?

- ✤ Merging the advantages of both supersymmetry and left-right symmetry
- ✤ Less constrained by current data

Interesting questions - outline

✦ How disentangling left-right supersymmetric signals from usual MSSM ones

- ✤ Doubly-charged Higgs bosons & higgsinos
  Huitu *et al.* ('97); Chacko & Mohapatra ('98); Dutta & Mohapatra ('99); Raidal & Zerwas ('99); Godfrey, Kalyniak & Romanenko ('02); Muhlleitner & Spira ('03); Azuelos, Benslama & Ferland ('06); Mukhopadhyaya & Rai ('06); Han, Mukhopadhyaya & Si ('07); Ren & Xing ('08); Frank, Huitu & Rai ('08); Demir *et al.* ('08-'09); Akeroyd & Chiang ('09); Ma ('09); Chen, Geng, & Zhuridov ('09); Akeroyd, Chiang & Gaur ('10); Alloul, Frank, BF & Rausch de Traubenberg ('13); *etc.*
- ✤ Sneutrinos
  Hisano *et al.* ('96); Deppish *et al.* ('03); Arganda & Herrero ('06); Petcov, Shindou & Takanishi ('06); Antusch *et al.* ('06); Paradisi ('06); Hirsch *et al.* ('08-'13); Biggio & Calibbi ('10); Abada *et al.* ('10-'11); Esteves *et al.* ('11); Cannoni *et al.* ('13); Krauss *et al.* ('14); *etc.*
- ✤ Extra gauginos / higgsinos
- ✤ Extra gauge bosons (in the left-right supersymmetric context)
  Frank, Hayreter & Turan ('11)

✦ Singly-charged and neutral gauginos and higgsinos [Alloul, Frank, BF & Rausch de Traubenberg ('13)]

- ✤ Strong superpartners must be heavy (no observation)
  - ➢ Light electroweakinos could still be a viable option (appealing for 8 TeV analyses)
- ✤ Their number varies according to the theory realization
  - ➢ They can cascade decay to each other
  - ➢ Lepton-enriched signals (assuming not too heavy sleptons)

✦ Extra gauge bosons [Alloul, Basso, BF, Krauss & Porod ('14)]

- ✤ Special role of the W' (Z' could be related to extra U(1)'s)
- ✤ Present W' bounds could be evaded in the supersymmetric context

Model description

✦ Field content and representation under SU(3)$_c$ x SU(2)$_L$ x SU(2)$_R$ x U(1)$_{B-L}$

✤ Matter sector: SU(2)$_L$ and SU(2)$_R$ doublets of (s)fermions

$$(Q_L) = \begin{pmatrix} u_L \\ d_L \end{pmatrix} = (\underset{\sim}{\mathbf{3}}, \underset{\sim}{\mathbf{2}}, \underset{\sim}{\mathbf{1}}, \tfrac{1}{3}) \qquad (Q_R) = \begin{pmatrix} u_R^{\mathbf{c}} & d_R^{\mathbf{c}} \end{pmatrix} = (\underset{\sim}{\bar{\mathbf{3}}}, \underset{\sim}{\mathbf{1}}, \underset{\sim}{\mathbf{2}^*}, -\tfrac{1}{3})$$

$$(L_L) = \begin{pmatrix} \nu_L \\ \ell_L \end{pmatrix} = (\underset{\sim}{\mathbf{1}}, \underset{\sim}{\mathbf{2}}, \underset{\sim}{\mathbf{1}}, -1) \qquad (L_R) = \begin{pmatrix} \nu_R^{\mathbf{c}} & \ell_R^{\mathbf{c}} \end{pmatrix} = (\underset{\sim}{\mathbf{1}}, \underset{\sim}{\mathbf{1}}, \underset{\sim}{\mathbf{2}^*}, 1)$$

✤ Gauge sector:

$$SU(3)_c \to (\tilde{g}, g_\mu) \qquad SU(2)_L \to (\tilde{W}_L, W_{L\mu}) \qquad SU(2)_R \to (\tilde{W}_R, W_{R\mu}) \qquad U(1)_{B-L} \to (\tilde{\hat{B}}, \hat{B}_\mu)$$

✦ Complicated Higgs sector (depends on the symmetry-breaking mechanism)

✤ Two pairs of SU(2) triplets (parity preservation, anomaly cancellation, *etc.*)
✤ Two Higgs bidoublets (necessary for non-trivial quark mixings)
✤ One gauge singlet (R-parity conservation)

$$S = (\underset{\sim}{\mathbf{1}}, \underset{\sim}{\mathbf{1}}, \underset{\sim}{\mathbf{1}}, 0)$$

$$(\Phi_1) = \begin{pmatrix} \Phi_1^0 & \Phi_1^+ \\ \Phi_1^- & \Phi_1'^0 \end{pmatrix} = (\underset{\sim}{\mathbf{1}}, \underset{\sim}{\mathbf{2}}, \underset{\sim}{\mathbf{2}^*}, 0) \qquad (\Phi_2) = \begin{pmatrix} \Phi_2'^0 & \Phi_2^+ \\ \Phi_2^- & \Phi_2{}^0 \end{pmatrix} = (\underset{\sim}{\mathbf{1}}, \underset{\sim}{\mathbf{2}}, \underset{\sim}{\mathbf{2}^*}, 0)$$

$$(\Delta_{1L}) = \begin{pmatrix} \frac{\Delta_{1L}^-}{\sqrt{2}} & \Delta_{1L}^0 \\ \Delta_{1L}^{--} & \frac{-\Delta_{1L}^-}{\sqrt{2}} \end{pmatrix} = (\underset{\sim}{\mathbf{1}}, \underset{\sim}{\mathbf{3}}, \underset{\sim}{\mathbf{1}}, -2) \qquad (\Delta_{1R}) = \begin{pmatrix} \frac{\Delta_{1R}^-}{\sqrt{2}} & \Delta_{1R}^0 \\ \Delta_{1R}^{--} & \frac{-\Delta_{1R}^-}{\sqrt{2}} \end{pmatrix} = (\underset{\sim}{\mathbf{1}}, \underset{\sim}{\mathbf{1}}, \underset{\sim}{\mathbf{3}}, -2)$$

$$(\Delta_{2L}) = \begin{pmatrix} \frac{\Delta_{2L}^+}{\sqrt{2}} & \Delta_{2L}^{++} \\ \Delta_{2L}^0 & \frac{-\Delta_{2L}^+}{\sqrt{2}} \end{pmatrix} = (\underset{\sim}{\mathbf{1}}, \underset{\sim}{\mathbf{3}}, \underset{\sim}{\mathbf{1}}, 2) \qquad (\Delta_{2R}) = \begin{pmatrix} \frac{\Delta_{2R}^+}{\sqrt{2}} & \Delta_{2R}^{++} \\ \Delta_{2R}^0 & \frac{-\Delta_{2R}^+}{\sqrt{2}} \end{pmatrix} = (\underset{\sim}{\mathbf{1}}, \underset{\sim}{\mathbf{1}}, \underset{\sim}{\mathbf{3}}, 2)$$

LHC simulation setup

0. Model implementation (most general Lagrangian) in FEYNRULES [Christensen & Duhr ('09); Duhr & BF ('11)] [Alloul, Christensen, Degrande, Duhr & BF ('14)]

Generation of a UFO library [Degrande, Duhr, BF, Grellscheid, Mattelaer & Reiter ('12)]

1. Event generation with MADGRAPH5_aMC@NLO [Alwall *et al.* ('14)]
    - ✤ Both signal and backgrounds at leading order
    - ✤ Precision in the normalization: (N)NLO+(N)NLL inclusive results (if available)

2. Parton showering & hadronization with PYTHIA [Sjostrand, Mrenna & Skands ('06; '08)]
    - ✤ Precision in the shapes: multiparton matrix-element MLM merging techniques [Mangano *et al.* ('07)]

3. Fast detector simulation with DELPHES (when used) [de Favareau *et al* ('13)]

4. Event analysis with MADANALYSIS 5 [Conte, BF & Serret ('13); Conte, Dumont, BF & Wymant ('14)]
    - ✤ Parton-level and reconstructed-level analyses

Benchmark scenarios for electroweakino production

✦ Many parameters: simplified scenarios focusing on the electroweakino sector

- Z_3 symmetry on the superpotential and the soft terms (no linear and bilinear terms)
- Constraints on the various Higgs vevs
  - ★ Very large singlet vev
  - ★ Larger right-handed vevs (heavy W' and Z')
  - ★ Negligible left-handed vevs (neutrino masses)
  - ★ Negligible bidoublet v'; no CP phases (W/W' and kaon mixing; CP constraints)

$$v_s \gg v_{1R}, v_{2R} \gg v_2, v_1 \gg v_1' = v_2' = v_{1L} = v_{2L} \approx 0$$

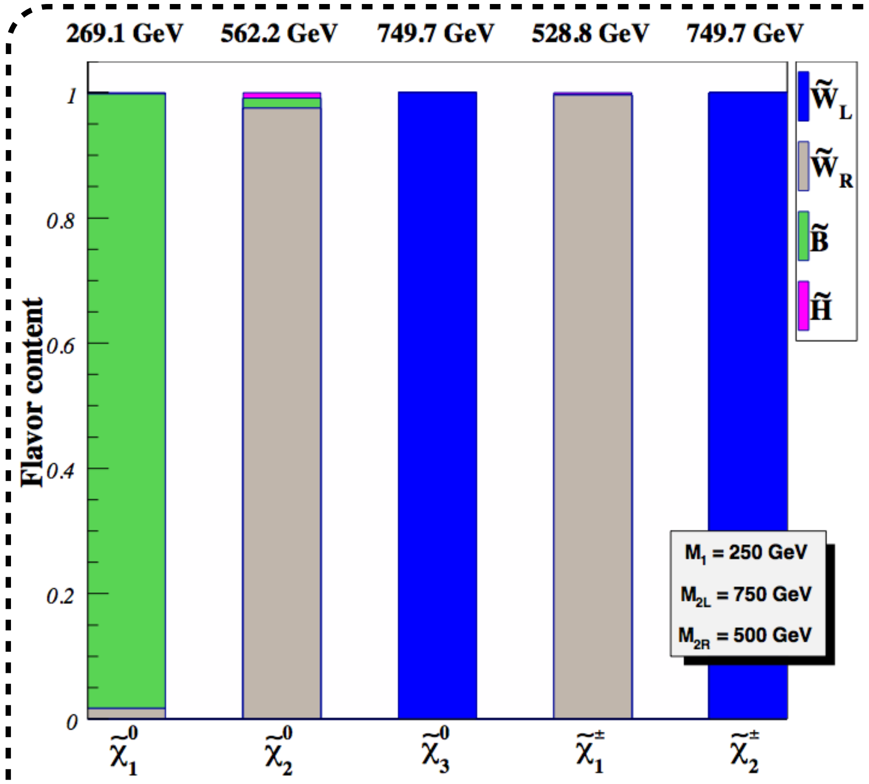
- Left-right symmetry of the coupling constants: $g_L = g_R$ (not specially restrictive)

✦ Constraints on the superpartner masses and the Higgs boson

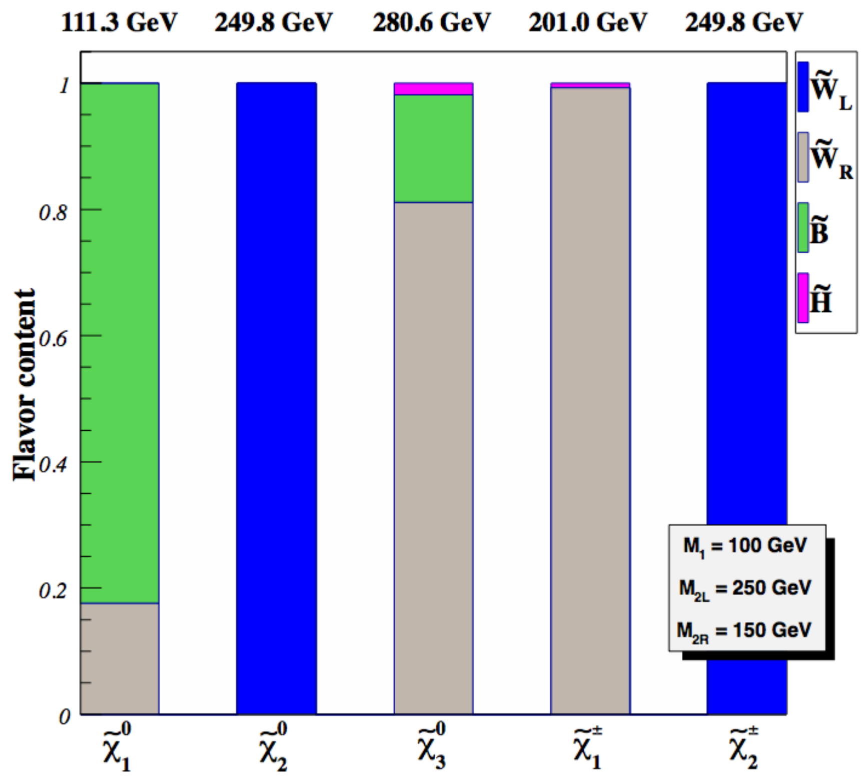
- No squark and gluino observation at the LHC: decoupling
  - ★ Sleptons and sneutrinos can still be light
- The lightest neutralino is a dark matter candidate
- A 125 GeV Higgs boson must be present
- The higgsinos turn out to be very heavy (*cf.* vev setup)

✦ Scan for different possible setups in the electroweakino sector

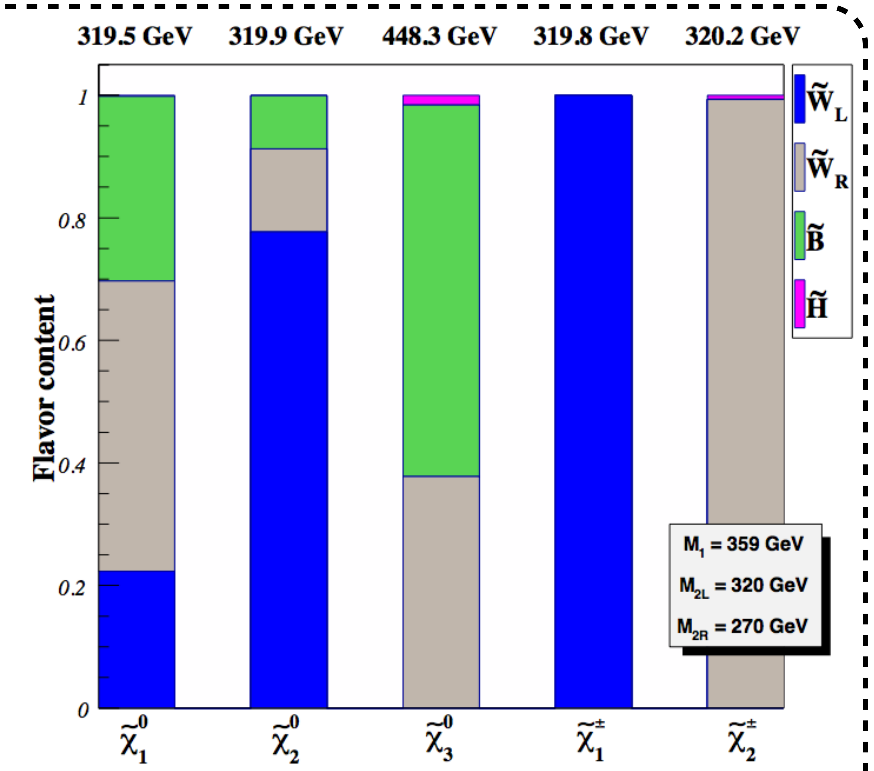
Classes of scenarios for the lightest electroweakinos



No mixing



Moderate neutralino mixing



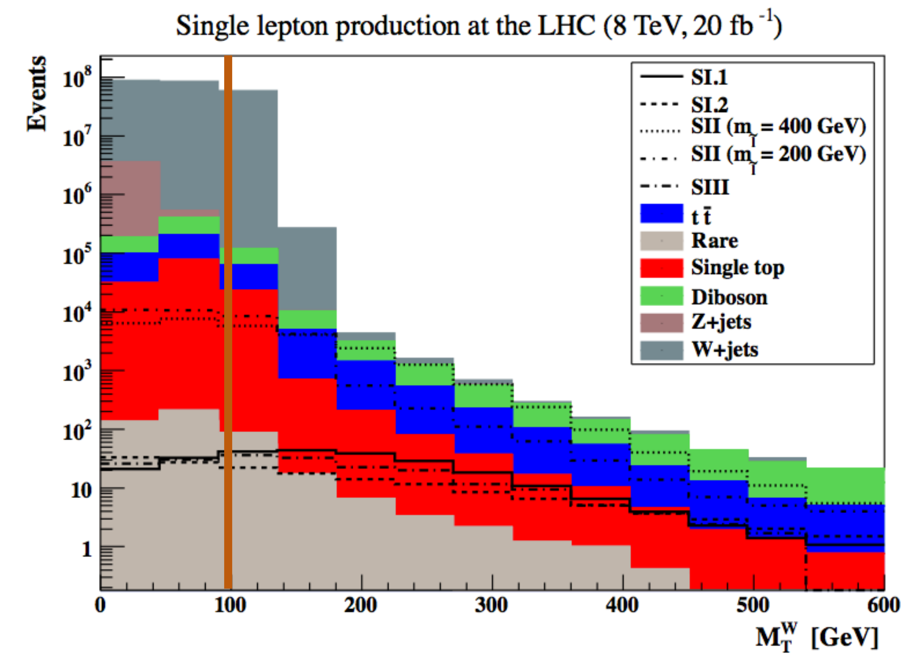
Maximal neutralino mixing: compressed spectrum

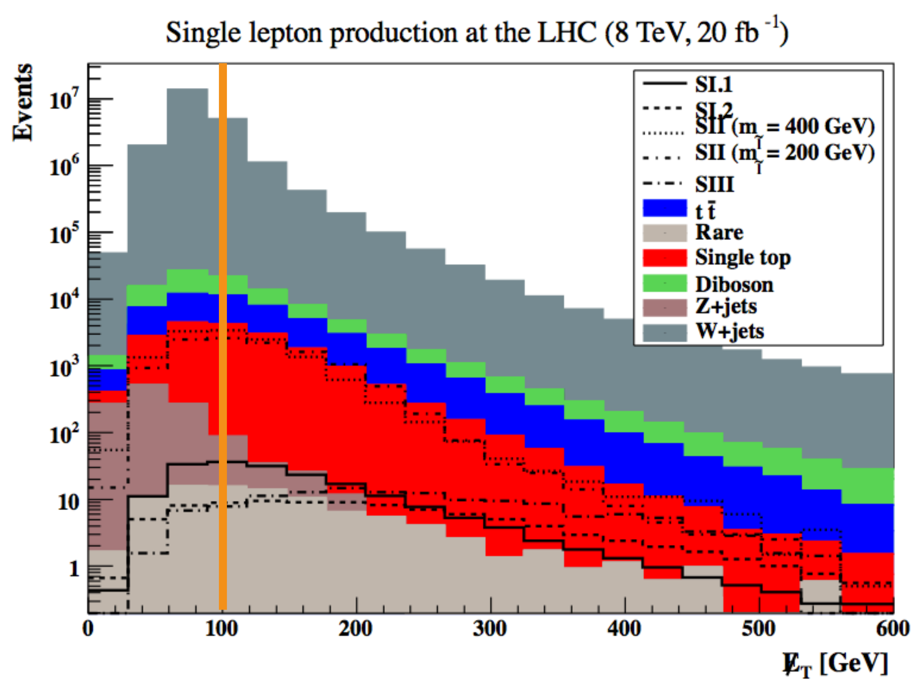
Electroweakino leptonic cascade decays (sleptons are light) ➤ Analysis of leptonic LHC signatures

Single lepton channel

✦ Signal region definition

- ✤ Small signal cross sections (including branching ratio)
  - ➢ More leptons are generally expected
- ✤ One hard isolated electron or muon
- ✤ b-jet veto
- ✤ Reconstructed W-boson transverse mass: larger for the signal
- ✤ Missing transverse energy: larger for the signal
- ✤ Hardness of the signal lepton
  - ➢ Expected to be harder in the signal case





✦ Results

Scenario	Signal (S)	Background (B)	$S/\sqrt{S+B}$
SI.1	94.9 ± 8.2		0.40 ± 0.08
SI.2	56.1 ± 7.8		0.24 ± 0.07
SII (200 GeV sleptons)	1594 ± 44	55332 ± 247	6.68 ± 0.36
SII (400 GeV sleptons)	3334 ± 63		13.8 ± 0.5
SIII	31.8 ± 6.2		0.13 ± 0.05

- ✤ Unsensitive to no mixing scenarios (**SI**)
  - ➢ Too small signal cross sections
- ✤ Very sensitive to moderate mixing scenarios (SII)
  - ➢ Better for heavier sleptons
- ✤ No sensitivity to compressed spectra (**SIII**)

Dilepton and multilepton channels

✦ Signal region definition

- Moderate signal cross sections (including branching ratio)
  - 20%-30% of the cases in for no or moderate mixings
- Two hard isolated electrons or muons
- b-jet veto; Z-boson veto
- Large missing energy requirement
- Selection on the p_T of the leptons

✦ Results

Scenario	Signal (S)	Background (B)	$S/\sqrt{S+B}$
SI.1	41.2 ± 6.8	1748.3 ± 41.7	0.97 ± 0.32
SI.2	53.9 ± 7.7		1.27 ± 0.36
SII (200 GeV sleptons)	2610 ± 56		39.5 ± 1.2
SII (400 GeV sleptons)	2686 ± 57		40.3 ± 1.2
SIII	2.6 ± 1.8		0.06 ± 0.08

- Unsensitive to no mixing scenarios (**SI**)
  - Better results than for the single lepton mode
- Very sensitive to moderate mixing scenarios (**SII**)
  - Independent of the slepton mass
- No sensitivity to compressed spectra (**SIII**)

✦ Signal region definition

- Moderate signal cross sections (including branching ratio)
  - Lower backgrounds
- At least three hard isolated electrons or muons
- b-jet veto
- Large missing energy requirement
- Selections on the two leading lepton p_T

✦ Results

Scenario	Signal (S)	Background (B)	$S/\sqrt{S+B}$
SI.1	65.4 ± 8.4	133.4 ± 11.5	4.64 ± 1.03
SI.2	108 ± 10		6.98 ± 1.09
SII (200 GeV sleptons)	259 ± 18		13.1 ± 1.3
SII (400 GeV sleptons)	289 ± 19		14.1 ± 1.3
SIII	≈ 0		-

- Sensitive to no mixing scenarios (**SI**)
- Very sensitive to moderate mixing scenarios (**SII**)
  - Independent of the slepton mass
  - Not as good as for the dilepton mode
- No sensitivity to compressed spectra (**SIII**)

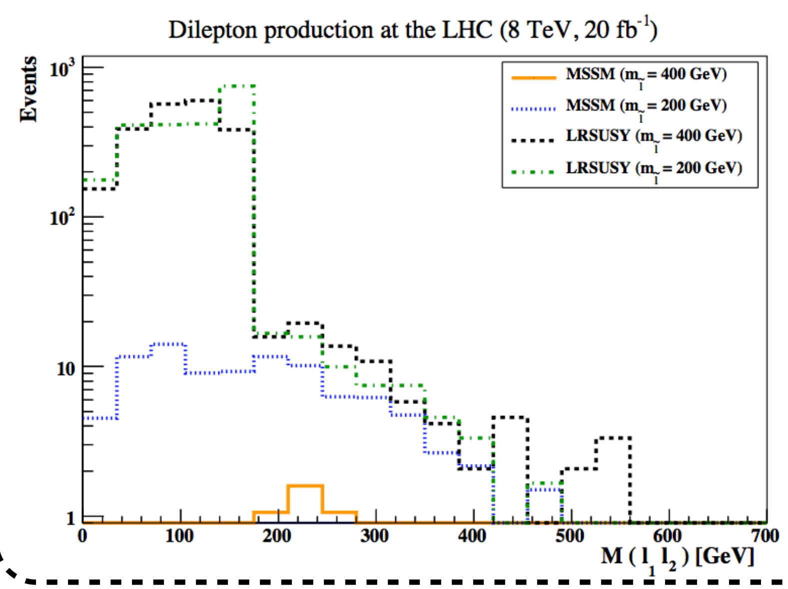
Comparing with the MSSM

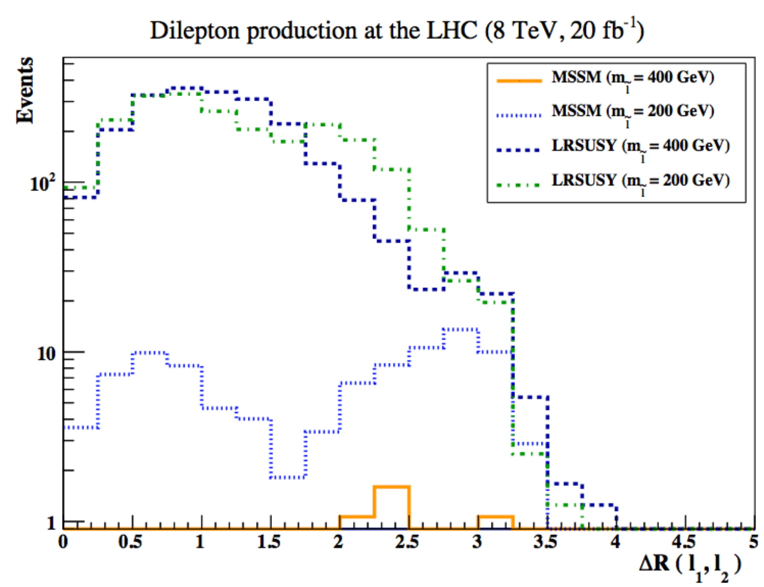
✦ Benchmark definition (our choice)

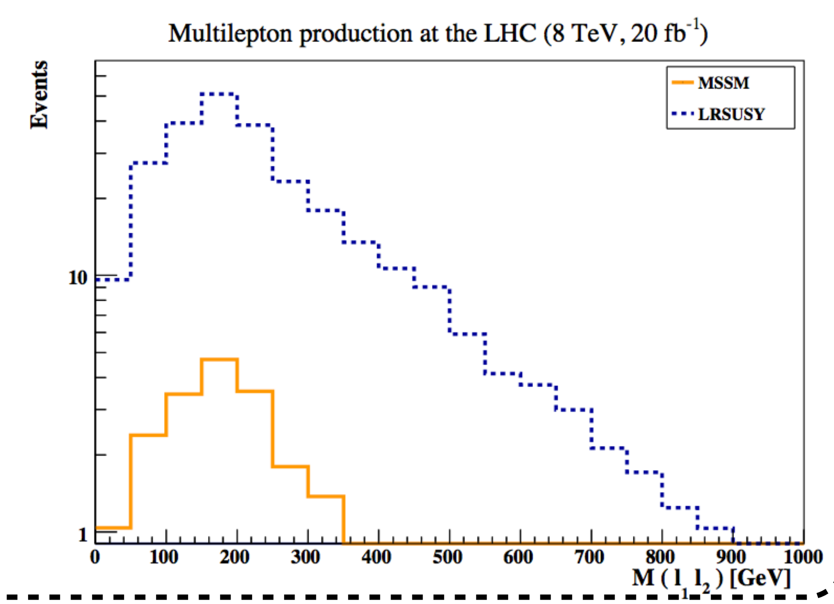
- Starting from a left-right supersymmetric scenario
- Removal of the two electroweakinos with the largest right-handed wino components
- Remaining states: we neglect their right-handed wino components
- Masses constrained to have the same values in both cases
  - ➢ This fixes the mixing parameters
- MSSM: decoupling of all Higgsino states

✦ Same event selections in both cases - analysis of the obtained distributions

- Comparison of various observables (in the dilepton and multilepton case)
- Large differences are expected
  - ➢ Mainly rate effects for the multilepton channel; also shapes for the dilepton case
  - ➢ Possible handles on the realized scenarios







Extra charged gauge bosons ($W' = W_R$)

✦ Particularities of the left-right supersymmetric case

- If the extra gauge bosons are heavy enough, they can decay into superpartner pairs
- Reduction of the existing bounds on the W', that assume specific branchings

How are existing searches constraining left-right supersymmetric models?

✦ Focusing on other W' searches relevant for left-right supersymmetric models

- CMS PAS-EXO-12-059: dijet resonances
- CMS PAS-B2G-12-010: top-bottom production
- CMS PAS-EXO-12-017: decay to right-handed neutrinos further decaying into a ljj system

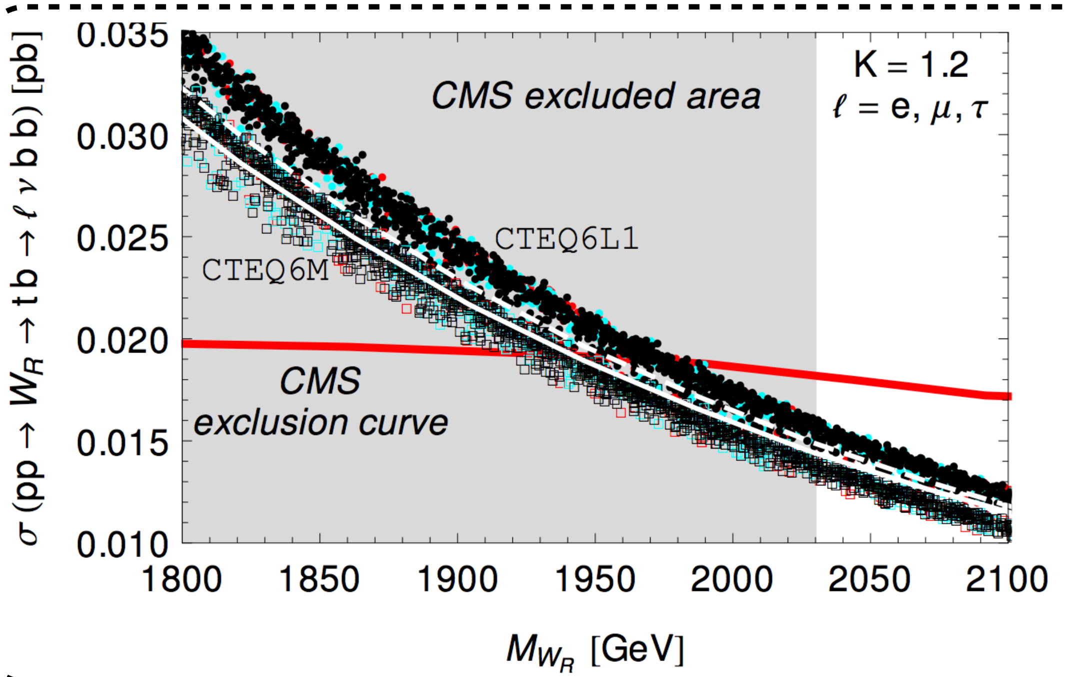
Two-body decays of the W_R

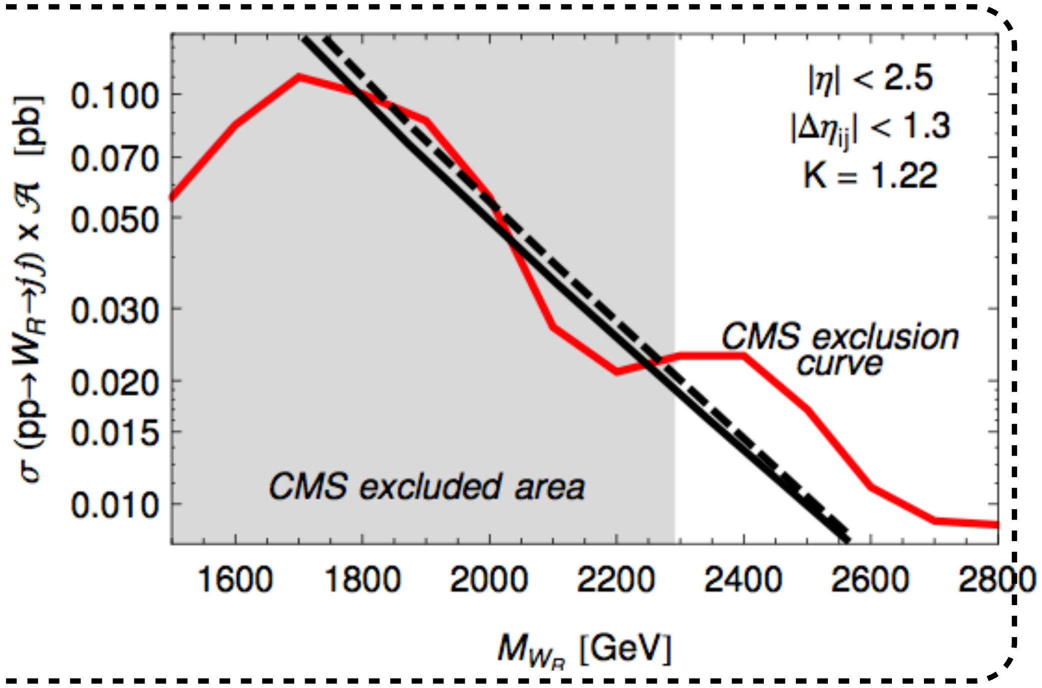
✦ Top-bottom channel: CMS PAS-B2G-12-010

- ✤ The bounds on the cross section can be immediately reapplied to our case
  - ★ (1) Leading-order matrix elements + leading order parton densities and K=1.2
  - ★ (2) Leading-order matrix elements + next-to-leading order parton densities and K=1.2
- ✤ W_R are constrained to be heavier than 1.95 TeV (similar to those on the sequential W')
  - ★ The K-factor effects are small

✦ Dijet channel: CMS PAS-EXO-12-059

- ✤ CMS bounds on the fiducial cross section apply to our case
- ✤ W_R are constrained to be heavier than 2.25 TeV (similar to those on the sequential W')
- ✤ Allowed mass window in the [1.80, 2.03] TeV range

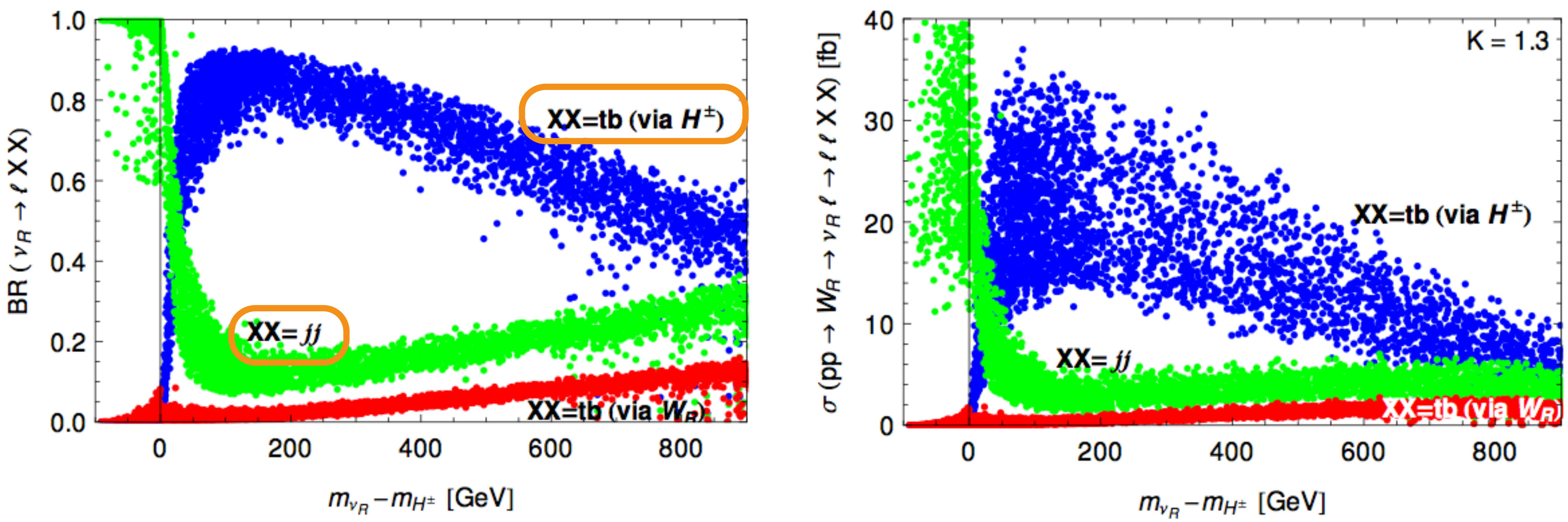




Interplay of the W_R with right-handed neutrinos

✦ Searches of right-handed neutrinos N_R: CMS PAS-EXO-12-017

- Experimental setup:
  - ★ The right-handed neutrino can only decay via an on-shell or off-shell W_R boson
  - ★ In CMS PAS-EXO-12-017: $W_R \to N_R\, l \to l\, l\, j\, j$ with BR=100%
  - ★ Bounds are derived under this very specific assumption
  - ★ Generally too restrictive for the left-right supersymmetric case
  - ★ Bounds on the W_R mass: 2.5-2.75 TeV (different assumptions on N_R flavours)
- In our setup:
  - ★ Right-handed neutrinos are connected to the $SU(2)_R$ Higgs triplet
  - ★ At least one of the charged Higgs is in general light
  - ★ Dominant decay: $N_R \to H^\pm l^\mp \to XX\, l^\mp$
  - ★ Bounds on the W_R mass drop by about 600 GeV



Summary

- ✦ We have investigated a particular left-right supersymmetric setup

- ✦ We considered multilepton signatures arising from electroweakino cascades
  - ✤ We designed analyses that could be sensitive to different setups for the electroweakino sector
    - ★ Single lepton: sensitive for large mass splittings
    - ★ Two leptons or more: sensitive to most of the (non-compressed) parameter space
  - ✤ Left-right supersymmetry is in principle distinguishable from the MSSM

- ✦ We interpreted several LHC searches in the left-right supersymmetric context
  - ✤ The bounds are in general weaker