

# Probing U(1) extensions of the MSSM at the LHC Run I and in dark matter searches

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In collaboration with G. Bélanger, U. Laa and A. Pukhov,  
arXiv:1505.06243, to appear in JHEP

# Outline

- 1 Motivations - description of the model
- 2 Scan - first constraints
- 3 Relic abundance - SMS constraints
- 4 Long-lived  $\tilde{\chi}^\pm$  - DM searches
- 5 Conclusions

# Motivations - description of the model

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Higgs couplings in the MSSM  $\sim$  SM-like,

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Higgs boson mass at 125 GeV needs large contributions from 1-loop diagrams involving stops

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New singlet scalar (e.g. the NMSSM) → new tree-level contribution to  $m_h$

→ easier to get  $m_h \sim 125$  GeV (U. Ellwanger and C. Hugonie, [JHEP 1408 (2014) 046],...)

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In U(1) extended gauge symmetry, also motivated in GUTs, superstring models,...,  
new  $D$ -terms can further increase  $m_h$  (V. Barger, P. Langacker, H.-S. Lee, and G.  
Shaughnessy, [Phys. Rev. D73 (2006) 115010],...)

One of the most analysed U(1) extension originates from a string-inspired  $E_6$  grand unified  
gauge group (P. Langacker and J. Wang, [Phys. Rev. D58 (1998) 115010], S.F. King, S.  
Moretti and R. Nevzorov, [Phys. Rev. D73 (2006) 035009],...)

$$E_6 \rightarrow SU(3)_c \times SU(2)_L \times U(1)_Y \times U(1)_X \times U(1)_\psi$$

# E<sub>6</sub> inspired model

- \* Low energy gauge symmetry considered :  $SU(3)_c \times SU(2)_L \times U(1)_Y \times U(1)'$   
 Coupling constants :  $g_3, g_2, g_Y$  and  $g'_1 = \sqrt{\frac{5}{3}}g_Y$

- \* U(1)' charge :

$$\mathcal{Q}' = \cos \theta_{E_6} \mathcal{Q}'_\chi + \sin \theta_{E_6} \mathcal{Q}'_\psi, \quad \theta_{E_6} \in [-\pi/2, \pi/2]$$

- \* MSSM fields + RH (s)neutrinos + new gauge boson (gaugino) + new singlet (singlino) +  $\mathcal{O}(\text{TeV})$  = UMSSM

$\mathcal{Q}'_Q$	$\mathcal{Q}'_u$	$\mathcal{Q}'_d$	$\mathcal{Q}'_L$	$\mathcal{Q}'_\nu$	$\mathcal{Q}'_e$	$\mathcal{Q}'_{H_u}$	$\mathcal{Q}'_{H_d}$	$\mathcal{Q}'_S$	
$\sqrt{40}\mathcal{Q}'_\chi$	-1	3	3	-5	-1	2	-2	0	$\Rightarrow \theta_{E_6} = 0$
$\sqrt{24}\mathcal{Q}'_\psi$	1	1	1	1	1	-2	-2	4	$\Rightarrow \theta_{E_6} = \pi/2$

- \* Superpotential :

$$\mathcal{W}_{\text{UMSSM}} = \mathcal{W}_{\text{MSSM}}|_{\mu=0} + \lambda \mathbf{SH_u H_d} + \tilde{\nu}_R^* \mathbf{y}_\nu \tilde{\mathbf{L}} \mathbf{H_u} + \mathcal{O}(\text{TeV})$$

- \* As the NMSSM, this model solves the  $\mu$ -problem :  $\mu = \lambda \frac{v_s}{\sqrt{2}}$

# Relevant sectors

- \* **Gauge sector** : Physical abelian gauge bosons :  $Z_1$  and  $Z_2$ , mixing between the  $Z^0$  of the SM and the  $Z'$ ,  $\alpha_Z$  is the mixing angle  $\Rightarrow \tan \beta$  constrained

$$Z_1 = \cos \alpha_Z Z^0 + \sin \alpha_Z Z' \quad Z_2 = -\sin \alpha_Z Z^0 + \cos \alpha_Z Z'$$

$$\tan \beta = f(\theta_{E_6}, \alpha_Z, M_{Z_1}, M_{Z_2})$$

- \* **Dark Matter sector** : 6 neutralinos in the basis  $(\tilde{B}, \tilde{W}^3, \tilde{H}_d^0, \tilde{H}_u^0, \tilde{S}, \tilde{B}')$  + 3 RH sneutrinos

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- \* **Sfermion sector** : New D-terms  $\Delta_F = \frac{1}{2} g_1'^2 Q'_F (Q'_{H_d} v_d^2 + Q'_{H_u} v_u^2 + Q'_S v_s^2)$ 
  - \* Light d-squark and LH slepton for  $-\tan^{-1}(3\sqrt{3/5}) < \theta_{E_6} < 0$
  - \* Light u-squark and RH slepton for  $0 < \theta_{E_6} < \tan^{-1}(\sqrt{3/5})$
  - \* Light LH smuon for  $\theta_{E_6} = -\tan^{-1}(3\sqrt{3/5}) \approx -1.16 \rightarrow$  significant contribution to the anomalous magnetic moment of the muon
- \* **Higgs sector** : MSSM fields + 1 singlet  $\Rightarrow$  3 CP-even Higgs bosons  $h_i, i \in \{1, 2, 3\}$   
 $\rightarrow$  New D-terms for the SM-like Higgs boson  $h_1$  :

$$m_{h_1}^2 (\text{tree}) \simeq M_{Z^0}^2 \cos^2 2\beta + \frac{1}{2} \lambda^2 v^2 \sin^2 2\beta + g_1'^2 v^2 (Q'_{H_d} \cos^2 \beta + Q'_{H_u} \sin^2 \beta)^2$$

$$- \frac{\lambda^4 v^2}{g_1'^2 Q'_S^2} \left( 1 - \frac{A_\lambda \sin^2 2\beta}{\sqrt{2} \lambda v_s} + \frac{g_1'^2}{\lambda^2} (Q'_{H_d} \cos^2 \beta + Q'_{H_u} \sin^2 \beta) Q'_S \right)^2$$

# Scan - first constraints

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# Scan - first constraints

Scanning the UMSSM parameter space using micrOMEGAs :

Parameter	Range	Parameter	Range
$m_{\tilde{\nu}_{\tau R}}$	[0, 2] TeV	$\mu, M_1$	[-2, 2] TeV
$M_{Z_2}$	[2.2, 7] TeV	$M_2, A_\lambda, A_t, A_b, A_l$	[-4, 4] TeV
$M'_1$	[-20, 20] TeV	$M_3$	[0.4, 12] TeV
$\theta_{E_6}$	[- $\pi/2$ , $\pi/2$ ] rad	$m_{\tilde{F}_i}, m_{\tilde{\nu}_j}$	[0, 4] TeV
$\alpha_Z$	$[-10^{-3}, 10^{-3}]$ rad	$m_t$	$173.34 \pm 1$ GeV Tevatron+LHC

$F \in \{Q, u, d, L, e\}$ ,  $i \in \{1, 2, 3\}$ ,  $j \in \{1, 2\}$  and where  $m_{\tilde{F}_2} = m_{\tilde{F}_1}$ ,  $m_{\tilde{\nu}_2} = m_{\tilde{\nu}_1}$

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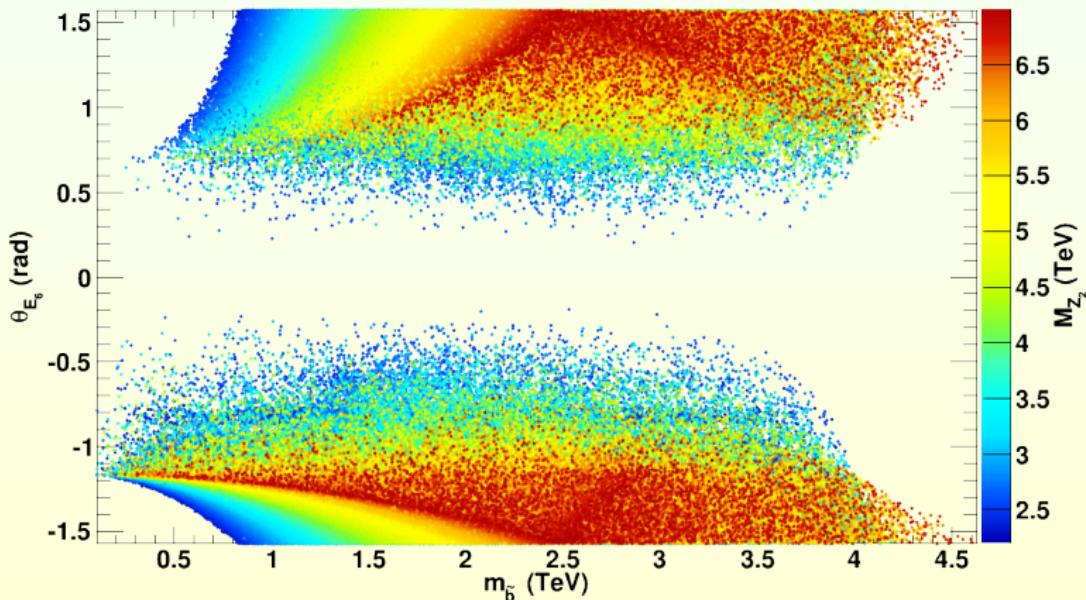
Constraints :

- \*  $\tilde{\nu}_{\tau R}$  or  $\chi_1^0$  is the LSP
- \* LEP constraints on  $\tilde{\chi}^{0,\pm}$  and  $\tilde{f}$
- \*  $Z'$  : ATLAS + CMS but for  $Z' \rightarrow SM$   
 → limits weakened in the UMSSM  
 but still important  
 →  $h_2$  mostly doublet-like
- \* Higgs :  $m_{h_1} = 125.1 \pm 3$  GeV  
 HiggsBounds + HiggsSignals  
 + NMSSMTools routines  
 → UMSSMTools in micrOMEGAs\_4.2.?

Observable	Value
$\mathcal{B}(B^\pm \rightarrow \tau^\pm \nu_\tau)$	$[0.70, 1.58] \times 10^{-4}$ HFAG
$\mathcal{B}(\bar{B}^0 \rightarrow X_s \gamma)$	$[2.99, 3.87] \times 10^{-4}$ HFAG
$\mathcal{B}(B_s^0 \rightarrow \mu^+ \mu^-)$	$[1.6, 4.2] \times 10^{-9}$ CMS+LHCb
$\Delta M_s$	$[17.805, 17.717] \text{ ps}^{-1}$ HFAG
$\Delta M_d$	$[0.504, 0.516] \text{ ps}^{-1}$ HFAG
$\delta a_\mu$	$[7.73, 42.14] \times 10^{-10}$ E821

# First results

- \* Points allowed by  $\delta a_\mu$  mostly around  $\theta_{E_6} \approx -1.16$  as expected  
→ Probing  $Z'$  at LHC Run II → scenarios  $\theta_{E_6} > 0$  could be severely constrain
- \* Light squarks still allowed → add more constraints



# Relic abundance - SMS constraints

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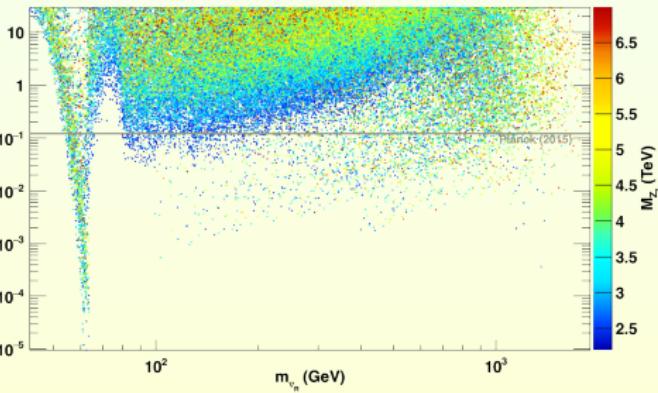
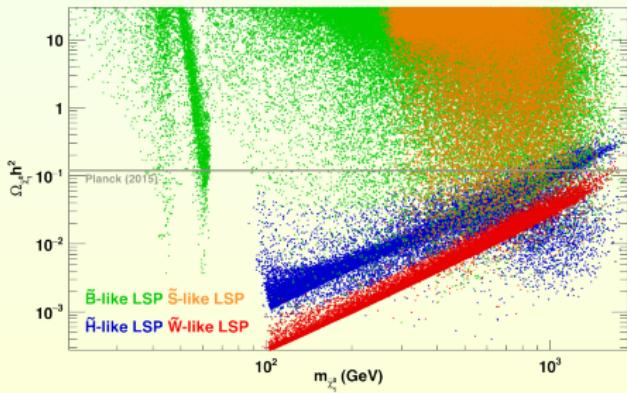
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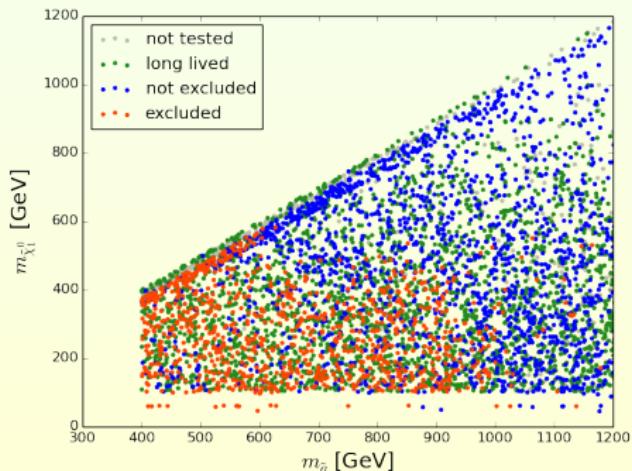
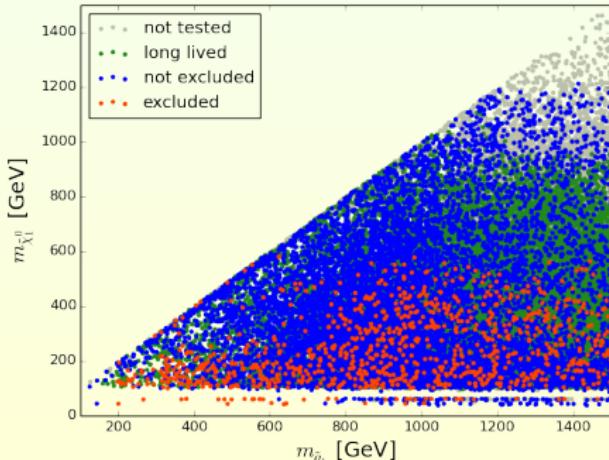
# Dark Matter relic abundance

- \*  $\Omega_{\text{LSP}} h^2 < 0.1208$  (2 $\sigma$  upper bound from **Planck combination**)
  - $\Rightarrow \tilde{B}, \tilde{H}, \tilde{W}, \tilde{S}$  can satisfy relic abundance constraint, the upper bound leads to an overabundance of  $\tilde{H}$  and  $\tilde{W}$  scenarios
  - $\Rightarrow$  Annihilation into  $W$  or  $Z_1$  pairs for  $m_{\tilde{\nu}_R} \sim 100$  GeV gives a smaller contribution than in past study (**G. Bélanger, JDS, and A. Pukhov, [JCAP 1112 (2011) 014]**) because of  $Z'$  constraints



# LHC constraints on sparticles

- \* Using SModelS v1.0.1 for interpreting simplified-model results from the LHC Run I
  - ⇒ Light squarks poorly constrained
    - \* No degeneracy between the 8 squarks of the 1<sup>st</sup> and 2<sup>nd</sup> generations because of the new  $D$ -terms in the UMSSM
    - \* Unexcluded points mostly feature  $\tilde{H}$  LSP  $\neq \tilde{B}$  LSP mostly assumed in SMS
  - ⇒ Many possible decay channels → gluino exclusion differ from SMS
  - ⇒ Many scenarios with long-lived  $\tilde{g}/\tilde{q}$  for  $\tilde{\nu}_R$  LSP exclusions as in  $\tilde{\chi}_1^0$  LSP case with  $\tilde{\chi}_1^0 \rightarrow \nu_R \tilde{\nu}_R^* (\bar{\nu}_R \tilde{\nu}_R)$

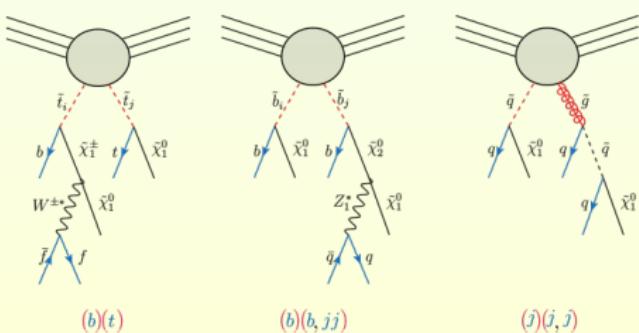
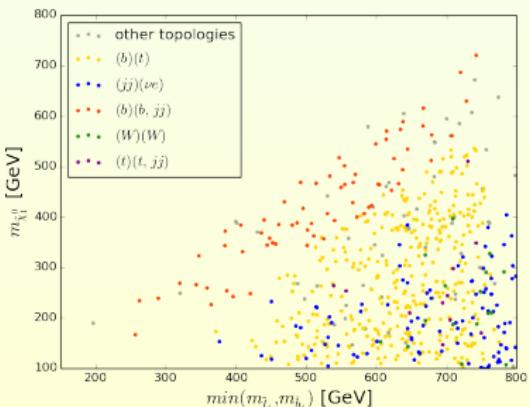


# Signatures unconstrained by current SMS

- \* Several interesting missing topologies

$\Rightarrow \tilde{\chi}_1^0$  LSP

- \*  **$bt + \text{MET}$** , “ $(b)(t)$ ” from  $\tilde{t}(\tilde{b})$  pair production with **asymmetric decays**,  $\tilde{\chi}_1^\pm$  nearly degenerate with  $\tilde{\chi}_1^0$  → **generic feature** of models with  $\tilde{W}/\tilde{H}$  LSP
- \*  **$2b + 2 \text{ jets} + \text{MET}$** , “ $(b)(b, jj)$ ” from  $\tilde{b}$  pair production with **asymmetric decays**, also “ $(j)(j, jj)$ ” and “ $(t)(t, jj)$ ” ( $\tilde{q}$  and  $\tilde{t}$  pair production)
- \*  **$3 \text{ jets} + \text{MET}$** , “ $(j)(j, j)$ ” from  $\tilde{q}\tilde{g}$  production → **Special interest** in the UMSSM where limits are **much weaker** because **no degeneracy** between the **8 light**  $\tilde{q}$



# Signatures unconstrained by current SMS

- ★ Several interesting missing topologies

$\Rightarrow \tilde{\chi}_1^0$  LSP

• also 4 jets + MET, “ $(j,j)(j,j)$ ”, 2 jets +  $W$  + MET, “ $(j)(j,W)$ ”, ...

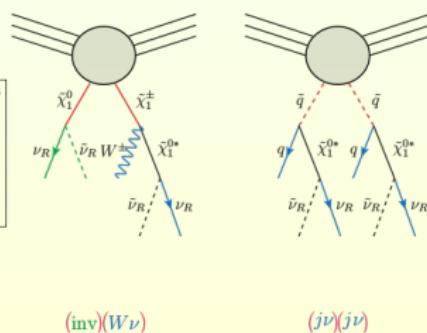
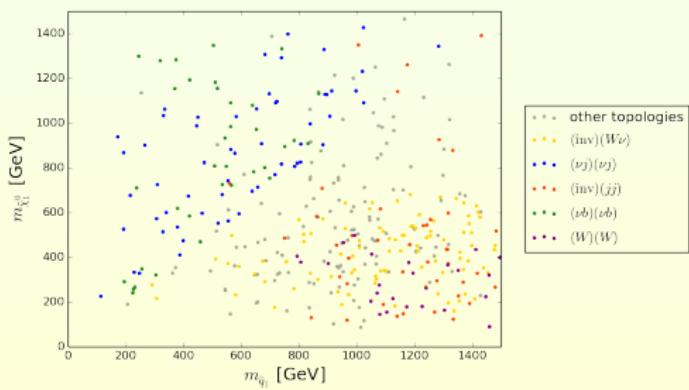
$\Rightarrow \tilde{\nu}_R$  LSP

• mono- $W$ , “(inv) $(W\nu)$ ” from  $\tilde{\chi}_1^\pm$ - $\tilde{\chi}_1^0$  production

• dijets + MET, “ $(\nu j)(\nu j)$ ” from  $\tilde{q}$  pair production where  $m_{\tilde{q}} < m_{\tilde{\chi}_1^0}$

also  $b\bar{b}$  + MET, “ $(\nu b)(\nu b)$ ”,  $\tilde{b}$  pair production

→ clear feature of the model with  $\tilde{\nu}$  LSP



# Long-lived $\tilde{\chi}^\pm$ - DM searches

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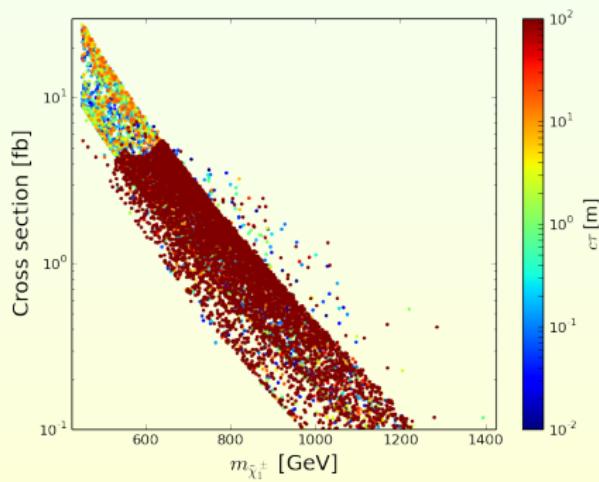
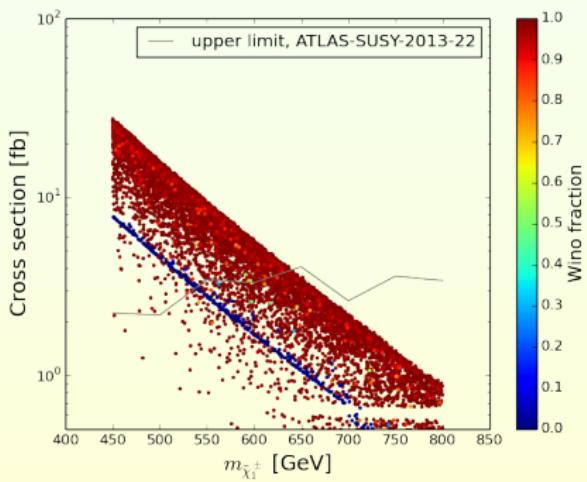
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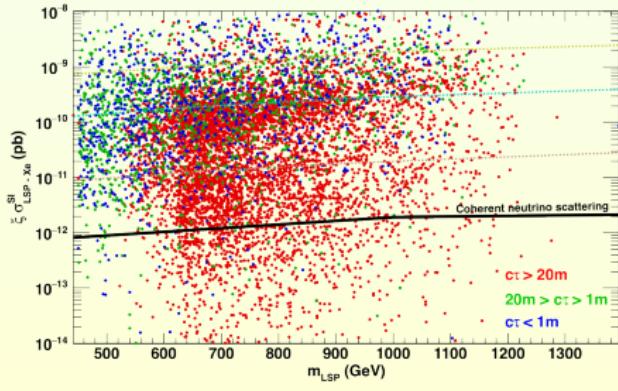
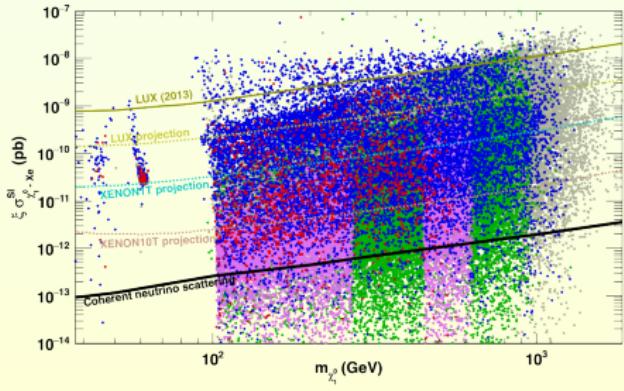
# Long-lived $\tilde{\chi}^\pm$

- Using D0 and ATLAS limits on pair production of  $\tilde{\chi}^\pm$  (or  $\tilde{\chi}^\pm$ - $\tilde{\chi}^0$  production)  
 $\rightarrow m_{\tilde{\chi}_1^\pm}$  up to 650 GeV can be excluded
- Search at 13 TeV  $\rightarrow$  large fraction of the points could be probe



# Complementarity with DM searches

- ✿ WIMP-nucleon scattering cross section limits from **LUX**  
→ DM direct detection experiments **can probe entirely** some regions, especially for  $\tilde{\nu}_R$  LSP, however **LHC helps to exclude scenarios beyond the reach of ton-scale detectors** (long-lived  $\tilde{\chi}^\pm$  points excluded shown in **pink**)
- ✿ Limits on DM annihilation from the dwarf spheroidal satellite galaxies of the Milky Way from **Fermi-LAT**  
→  $b\bar{b}$  channel **complementary** to direct detection for  $\tilde{\nu}_R$  LSP
- ✿ Long-lived  $\tilde{\chi}^\pm$  searches **could probe scenarios below  $\nu$  background**



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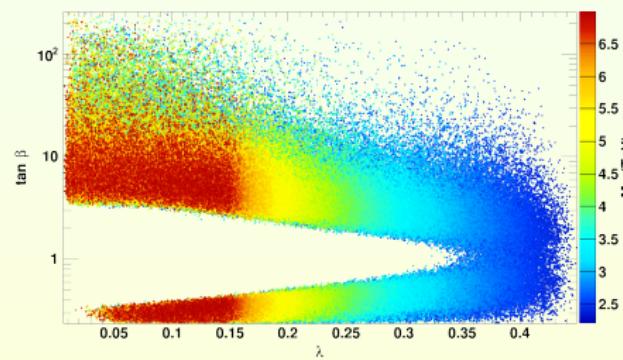
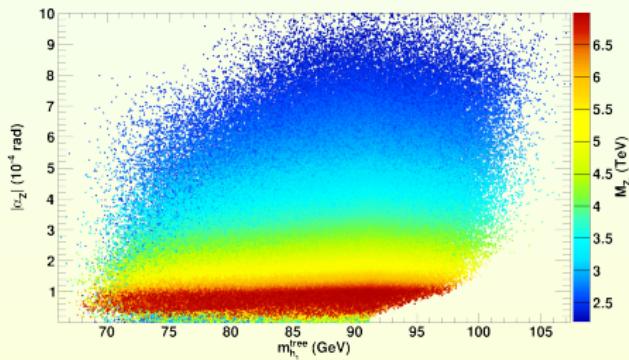
# Conclusions

- ✿ New D-terms in the UMSSM  $\Rightarrow$  low  $\tan\beta$  values still allowed for TeV-scale  $M_S$  to get a 125 Higgs boson  
 $\Rightarrow$  sfermion sector impacted
- ✿  $\delta a_\mu$  constraint can be easily satisfied for some regions of  $\theta_{E_6}$
- ✿  $\chi_1^0$  or  $\tilde{\nu}_R$  LSP that does not overclose the Universe exclude a large region of the parameter space
- ✿ Suggestions for future LHC searches about interesting signatures obtained in this study which are not yet covered in SMS results
- ✿ Forthcoming direct detection experiments would probe entirely some scenarios
- ✿ Complementarity between direct and indirect detection of DM, especially for  $\tilde{\nu}_R$  LSP
- ✿ Complementarity between direct detection of DM and long-lived  $\tilde{\chi}^\pm$  searches
- ✿ Importance of  $Z'$  searches to probe/exclude large parts of the UMSSM sectors

# BACKUP

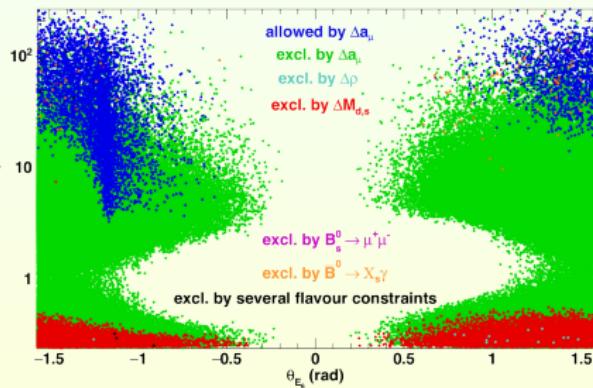
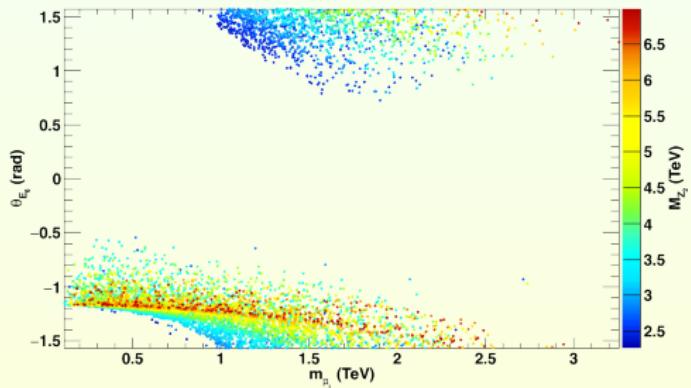
# BACKUP

- Maximum tree-level mass for  $h_1$  reaches  $\approx 107$  GeV and above the  $Z^0$  mass for mixing angles  $\alpha_Z > 2 \times 10^{-5}$  rad
- $\tan \beta \approx 1$  gives expected  $m_{h_1}$  if  $\lambda$  sufficiently large and  $Z_2$  not too heavy



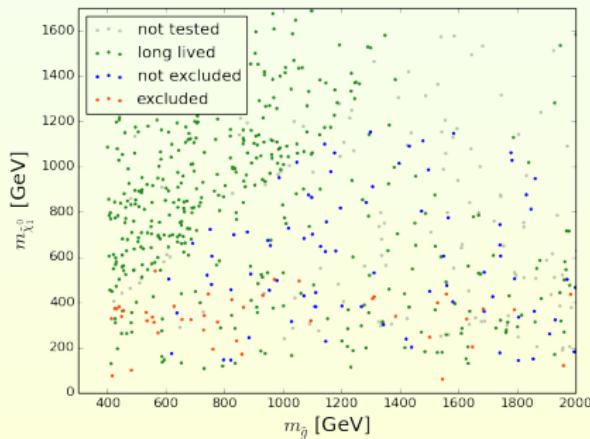
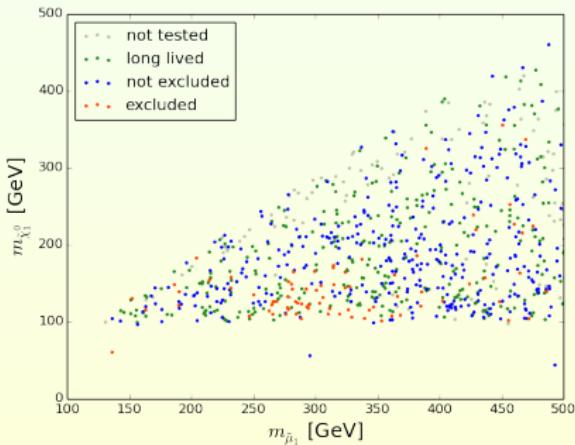
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- \* Importance of  $Z'$  searches on scenarios  $\theta_{E_6} > 0$  for points allowed by  $\delta a_\mu$  :



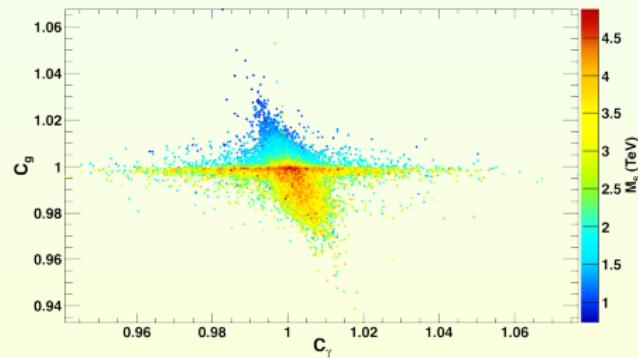
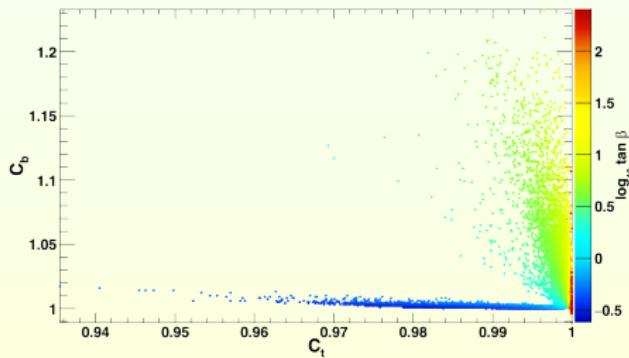
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- ✿ Exclusions of  $\delta a_\mu$ -allowed points weaker than at LHC Run I because  $\tilde{t} \rightarrow \nu_L^I \tilde{\chi}_1^+$  also observed, not only  $\tilde{t} \rightarrow l \tilde{\chi}_1^0$
- ✿ Case of long-lived  $\tilde{g}$  for  $\tilde{\nu}_R$  LSP



# BACKUP

- ✿ Reduced couplings of the light Higgs close to SM (generation universal couplings)
- ✿ Effect of squark ( $C_g$ ) and slepton/chargino ( $C_\gamma$ ) contributions below 5%



# BACKUP

- Prospects for searches of heavy Higgses below TeV scale at LHC Run II : signal strengths and preferred decays for  $h_2$   
 → decay into  $b\bar{b}$ ,  $\tau^+\tau^-$  at large  $\tan\beta$ ,  $t\bar{t}$  at small  $\tan\beta$ , generally kinematically forbidden for sfermions

