

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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Going beyond the MSSM

Higgs couplings in the MSSM $\sim$ SM-like,
especially when other new particle masses $\gg$ electroweak scale, **but :**
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) $\rightarrow$ **new tree-level contribution** to m_h
 $\rightarrow$ 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],...)

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

E₆ 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** :

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

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

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

- * **Superpotential** :

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

- * **As the NMSSM, this model solves the μ -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' , α_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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- * **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
- * **Sfermion sector** : New D-terms $\Delta_F = \frac{1}{2} g_1'^2 Q_F' \left(Q_{H_d}' v_d^2 + Q_{H_u}' v_u^2 + Q_S' v_s^2 \right)$
 - * 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** :

$$m_{h_1}^2 (\text{tree}) \simeq M_{Z_0}^2 \cos^2 2\beta + \frac{1}{2} \lambda^2 v^2 \sin^2 2\beta + g_1'^2 v^2 \left(Q_{H_d}' \cos^2 \beta + Q_{H_u}' \sin^2 \beta \right)^2$$

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

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	μ, 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
θ_{E_6}	$[-\pi/2, \pi/2]$ rad	$m_{\tilde{F}_i}, m_{\tilde{\nu}_j}$	[0, 4] TeV
α_Z	$[-10^{-3}, 10^{-3}]$ rad	m_t	173.34 ± 1 GeV Tevatron+LHC

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

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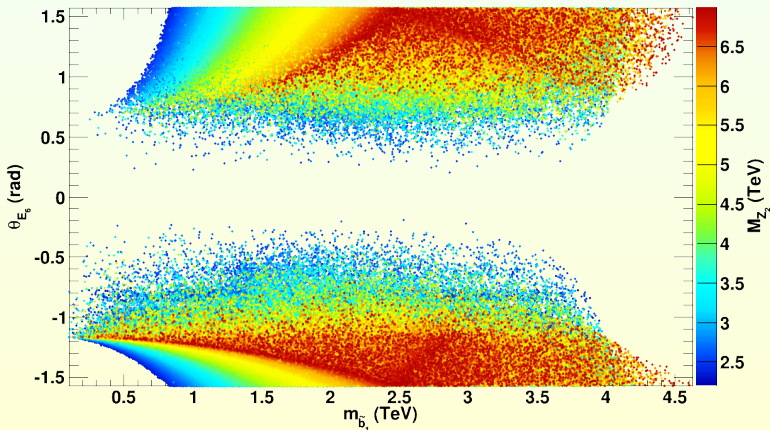
Constraints :

- * $\tilde{\nu}_{\tau R}$ or χ_1^0 is the **LSP**
- * **LEP** constraints on $\tilde{\chi}^{0,\pm}$ and $\tilde{f}$
- * **Z'** : **ATLAS + CMS** but for $Z' \rightarrow SM$
 $\rightarrow$ limits **weakened in the UMSSM**
but still important
 $\rightarrow$ **h₂** mostly doublet-like
- * **Higgs** : $m_{h_1} = 125.1 \pm 3$ GeV
HiggsBounds + HiggsSignals
+ NMSSMTools routines
 $\rightarrow$ 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
ΔM_s	$[17.805, 17.717]$ ps ⁻¹ HFAG
ΔM_d	$[0.504, 0.516]$ ps ⁻¹ HFAG
δa_μ	$[7.73, 42.14] \times 10^{-10}$ E821

First results

- * Points allowed by δa_μ 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

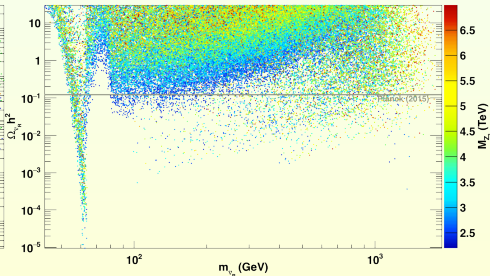
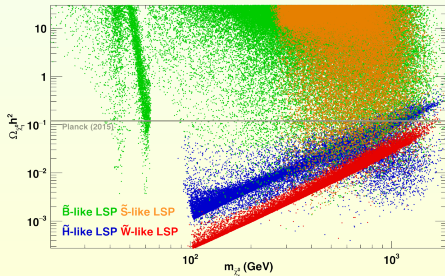


Relic abundance - SMS constraints

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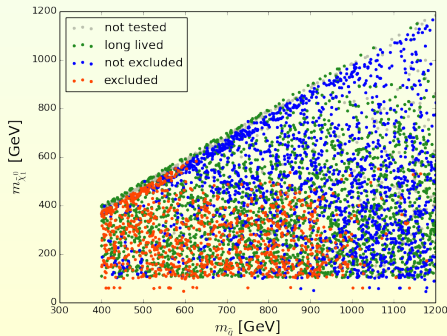
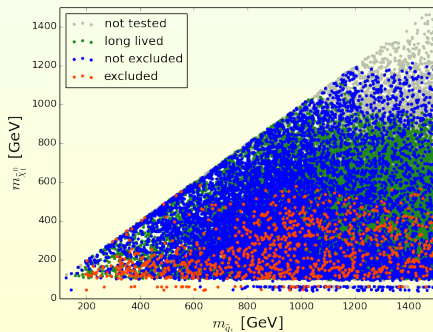
Dark Matter relic abundance

- ✳ $\Omega_{\text{LSP}} h^2 < 0.1208$ (2σ 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 1st and 2nd 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 $\tilde{\chi}_1^0 \rightarrow \nu_R \tilde{\nu}_R^*$ ($\bar{\nu}_R \tilde{\nu}_R$)

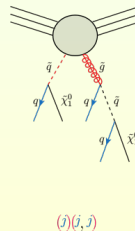
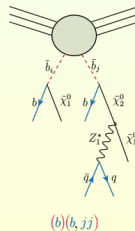
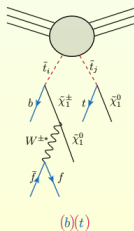
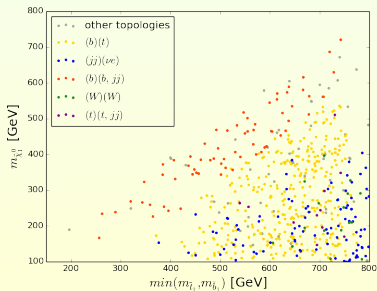


Signatures unconstrained by current SMS

* Several interesting missing topologies

⇒ $\tilde{\chi}_1^0$ LSP

- * **$bt + \text{MET}$, “ $(b)(t)$ ”** from $\tilde{t}(\tilde{b})$ pair production with **asymmetric decays**, $\tilde{\chi}_1^\pm$ **nearly degenerate** with $\tilde{\chi}_1^0 \rightarrow$ **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 $\rightarrow$ **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

⇒ $\tilde{\chi}_1^0$ LSP

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

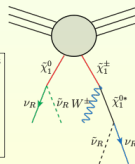
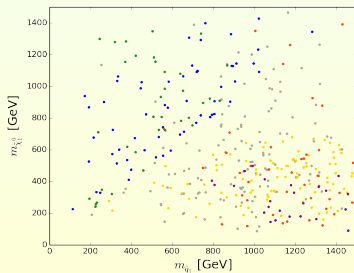
⇒ $\tilde{\nu}_R$ LSP

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

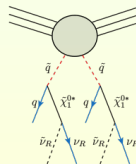
* dijets + MET, “(νj)(νj)” from $\tilde{q}$ pair production where $m_{\tilde{q}} < m_{\tilde{\chi}_1^0}$

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

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



(inv)(Wν)



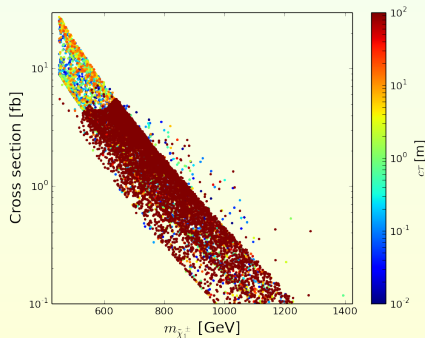
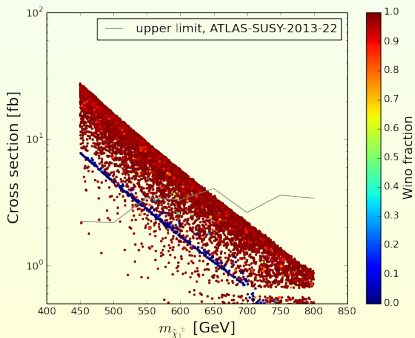
(jν)(jν)

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

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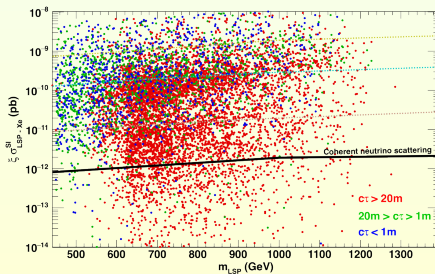
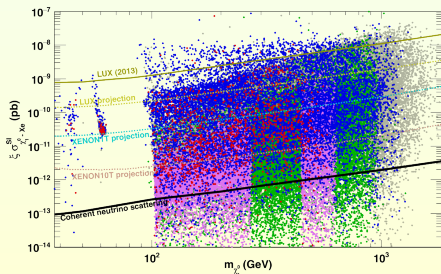
Long-lived $\tilde{\chi}^\pm$

- 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 ν background**



Conclusions

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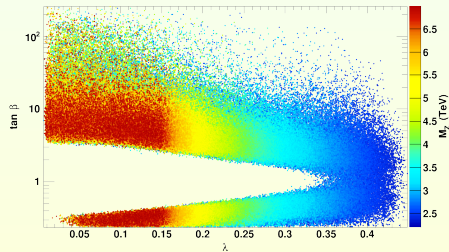
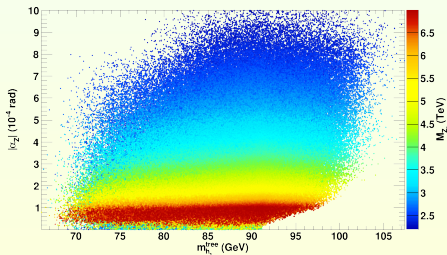
Conclusions

- ✱ 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**
- ✱ δa_μ constraint can be easily satisfied for **some regions of θ_{E_6}**
- ✱ χ_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

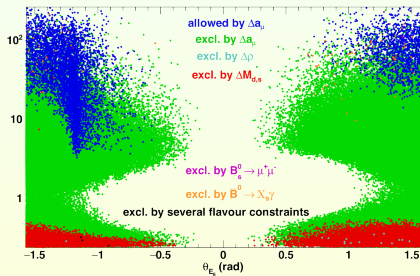
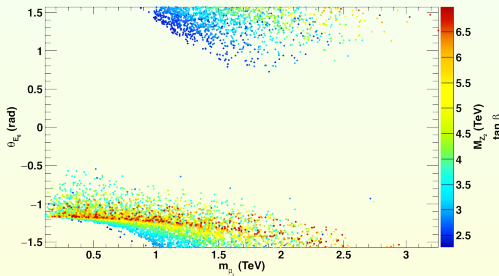
BACKUP

- Maximum tree-level mass for h_1 reaches ≈ 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 λ sufficiently large and Z_2 not too heavy



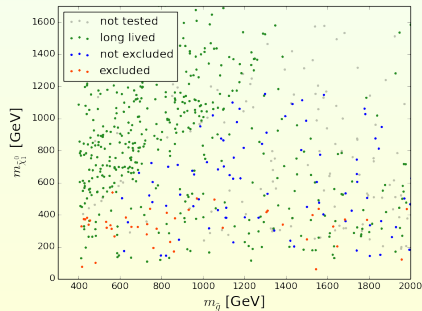
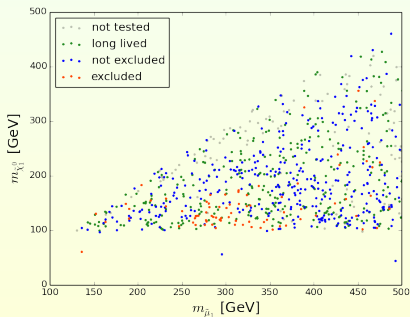
BACKUP

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



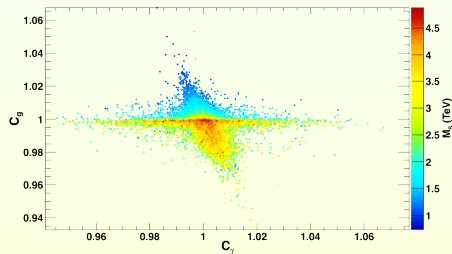
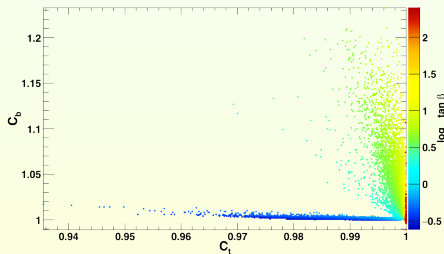
BACKUP

- ✱ Exclusions of δa_μ -allowed points weaker than at LHC Run I because $\tilde{t} \rightarrow \nu_L^i \tilde{\chi}_1^+$ also observed, not only $\tilde{t} \rightarrow t \tilde{\chi}_1^0$
- ✱ 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_γ) 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

