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,
JHEP 09 (2015) 151, arXiv:1505.06243

Outline

Motivations - description of the model

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
$\rightarrow$ Constrain stop sector, increase fine-tuning and moderate to large $\tan\beta$ preferred

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],...)
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],...)

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

E_6 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** :

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

- **MSSM fields + RH (s)neutrinos + new gauge boson (gaugino) + new singlet (singlino) + $\mathcal{O}$(TeVs) = 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	-1	3	3	-5	-1	2	-2	0	$\Rightarrow \theta_{E_6} = 0$
$\sqrt{24}\mathcal{Q}'_\psi$	1	1	1	1	1	1	-2	-2	4	$\Rightarrow \theta_{E_6} = \pi/2$

- **Superpotential** :

$$\mathcal{W}_{UMSSM} = \mathcal{W}_{MSSM}|_{\mu=0} + \lambda S H_u H_d + \tilde{\nu}_R^* y_\nu \widetilde{L} H_u + \mathcal{O}(TeVs)$$

- 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**

$$Z_1 = \cos\alpha_Z Z^0 + \sin\alpha_Z Z' \qquad Z_2 = -\sin\alpha_Z Z^0 + \cos\alpha_Z Z'$$
$$\tan\beta = f(\theta_{E_6}, \alpha_Z, M_{Z_1}, M_{Z_2})$$

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

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- **Dark Matter sector** : 6 neutralinos in the basis $(\widetilde{B}, \widetilde{W}^3, \widetilde{H}_d^0, \widetilde{H}_u^0, \widetilde{S}, \widetilde{B'})$ + 3 RH sneutrinos
- **Sfermion sector** : New D-terms $\Delta_F = \frac{1}{2} {g_1'}^2 \mathcal{Q}'_F \left(\mathcal{Q}'_{H_d} v_d^2 + \mathcal{Q}'_{H_u} v_u^2 + \mathcal{Q}'_S v_s^2 \right)$
  - 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 :

$$m_{h_1}^2(\text{tree}) \simeq M_{Z^0}^2 \cos^2 2\beta + \frac{1}{2}\lambda^2 v^2 \sin^2 2\beta + g_1'^2 v^2 \left(\mathcal{Q}'_{H_d} \cos^2\beta + \mathcal{Q}'_{H_u} \sin^2\beta \right)^2$$
$$- \frac{\lambda^4 v^2}{g_1'^2 \mathcal{Q}_S'^2} \left(1 - \frac{A_\lambda \sin^2 2\beta}{\sqrt{2}\lambda v_s} + \frac{g_1'^2}{\lambda^2} \left(\mathcal{Q}'_{H_d} \cos^2\beta + \mathcal{Q}'_{H_u} \sin^2\beta \right) \mathcal{Q}'_S \right)^2$$

First set of constraints

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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 $\pm$ 1 GeV Tevatron+LHC

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

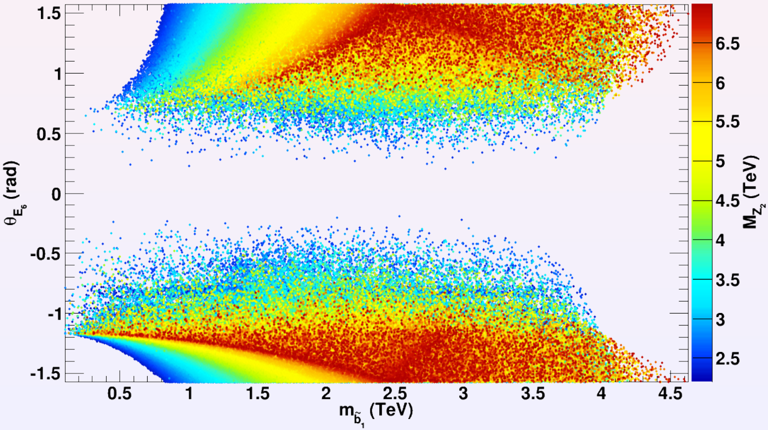
Constraints :

- $\tilde{\nu}_{\tau R}$ **or** χ_1^0 **is the LSP**
- **LEP constraints on** $\tilde{\chi}^{0,\pm}$ **and** $\tilde{f}$
- **Z′ : ATLAS + CMS at 8 TeV**
  but for Z′ → 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_4.2.3

Observable	Value
$\mathscr{B}(B^\pm \to \tau^\pm \nu_\tau)$	[0.70, 1.58]$\times 10^{-4}$ HFAG
$\mathscr{B}(\bar{B}^0 \to X_s \gamma)$	[2.99, 3.87]$\times 10^{-4}$ HFAG
$\mathscr{B}(B_s^0 \to \mu^+ \mu^-)$	[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

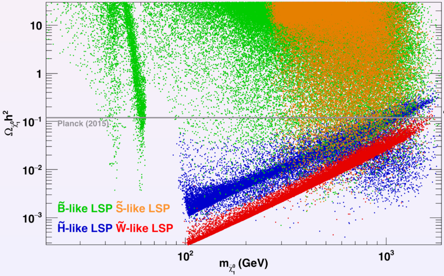
- Points allowed by δa_μ mostly around $\theta_{\mathrm{E_6}} \approx -1.16$ as expected
  $\rightarrow$ Probing Z' at LHC Run II $\rightarrow$ scenarios $\theta_{\mathrm{E_6}} > 0$ could be severely constrain
- Light squarks still allowed $\rightarrow$ add more constraints

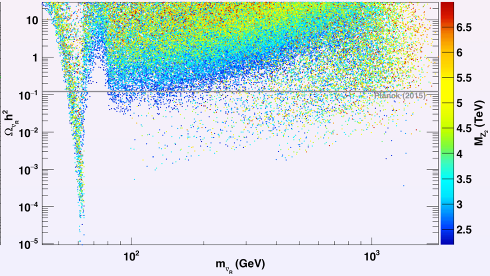


Relic abundance - SMS constraints

Dark Matter relic abundance

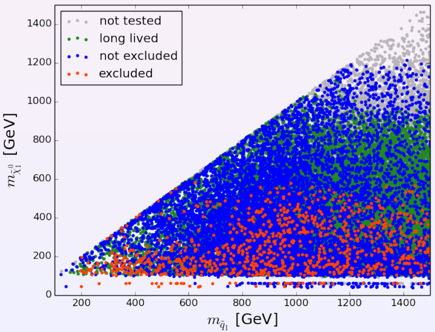
- $\Omega_{\rm LSP}\mathbf{h^2} < 0.1208$ (2σ **upper bound from Planck combination**)
  - $\Rightarrow$ $\tilde{\mathbf{B}}, \tilde{\mathbf{H}}, \tilde{\mathbf{W}}, \tilde{\mathbf{S}}$ **can satisfy relic abundance constraint, the upper bound leads to an overabundance of $\tilde{\mathbf{H}}$ and $\tilde{\mathbf{W}}$ 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**

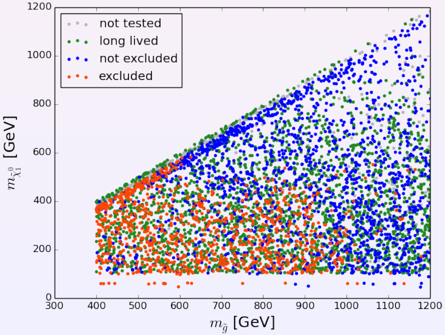




LHC constraints on sparticles

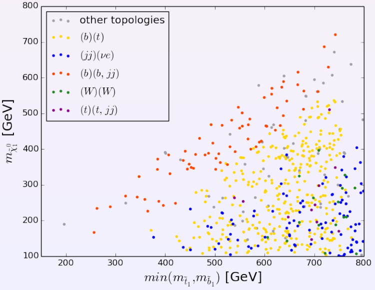
- **Using** `SModelS v1.0.1` **for interpreting simplified-model results from the LHC Run I**
  - $\Rightarrow$ **Light squarks poorly constrained**
    - **No deneracy between the 8 squarks of the 1^{st} and 2^{nd} generations because of the new D-terms in the UMSSM**
    - **Unexcluded points mostly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

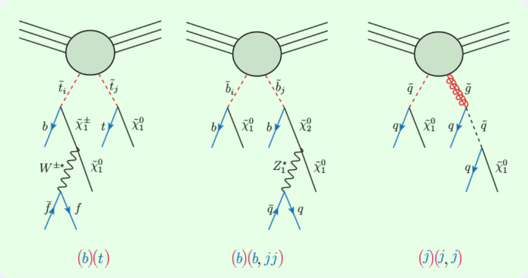




Signatures unconstrained by current SMS

- Several interesting missing topologies
  - $\Rightarrow$ $\tilde{\chi}_1^0$ LSP
    - bt + 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 jets + 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 jets + 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 $\tilde{q}$



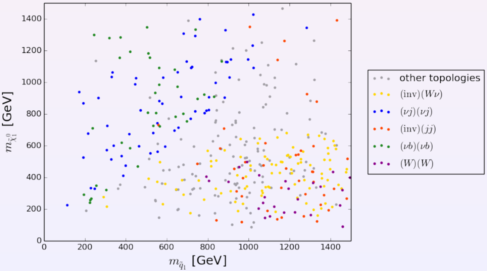


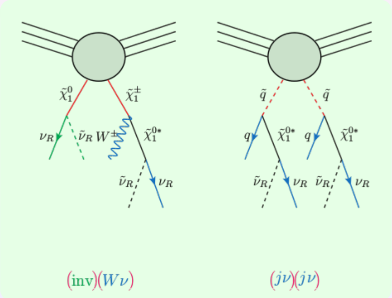
Signatures unconstrained by current SMS

- Several **interesting missing topologies**
  - $\Rightarrow$ $\tilde{\chi}_1^0$ LSP
    - also 4 jets + MET, "$(j,j)(j,j)$", 2 jets + W + MET, "$(j)(j,W)$", ...
  - $\Rightarrow$ $\tilde{\nu}_R$ LSP
    - mono-W, "$(\mathrm{inv})(W\nu)$" 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

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

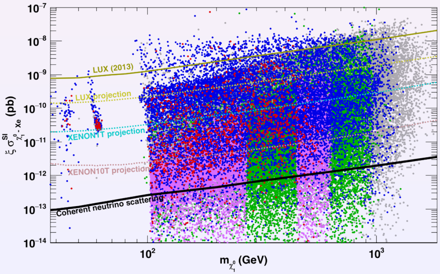


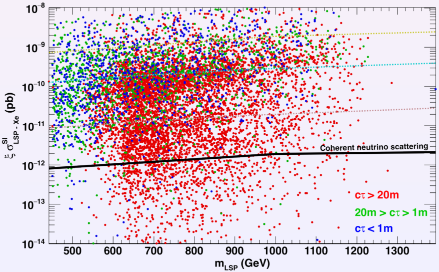


Long-lived $\tilde{\chi}^{\pm}$ - DM searches

Complementarity with DM searches

- 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
- WIMP-nucleon scattering cross section limits from LUX
  $\rightarrow$ 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
  $\rightarrow$ $b\bar{b}$ channel complementary to direct detection for $\tilde{\nu}_R$ LSP
- Long-lived $\tilde{\chi}^{\pm}$ searches could probe scenarios below ν background





Conclusions

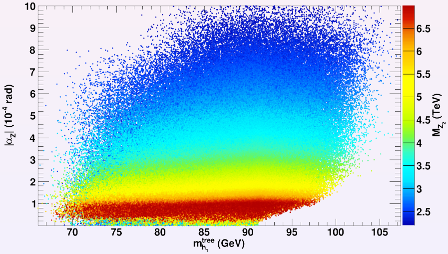
Conclusions

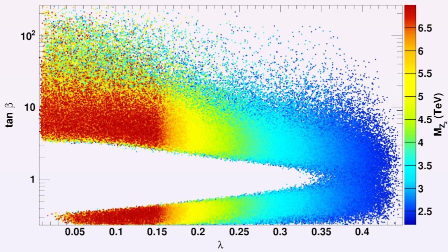
- New D-terms in the UMSSM $\Rightarrow$ low $\tan\beta$ values still allowed for TeV-scale M_S to get a 125 Higgs boson
  $\Rightarrow$ sfermion sector impacted
- δa_μ constraint can be easily satisfied for some regions of θ_{E_6}
- χ_1^0 or $\tilde{\nu}_R$ LSP that does not overclose the Universe exclude 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

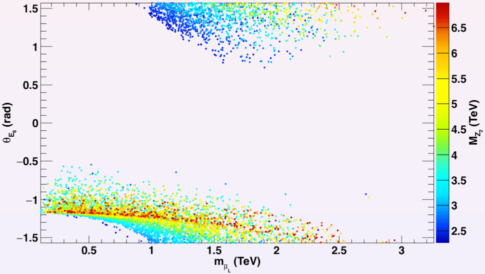
- **Maximum tree-level mass** for h_1 reaches ≈ 107 **GeV** and above the Z^0 mass for mixing angles $\alpha_Z > 2 \times 10^{-5}$ **rad**
- $\tan\beta \approx$ **1** gives expected $\mathbf{m_{h_1}}$ if λ **sufficiently large** and Z_2 **not too heavy**

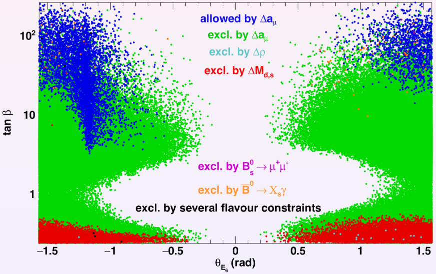




BACKUP

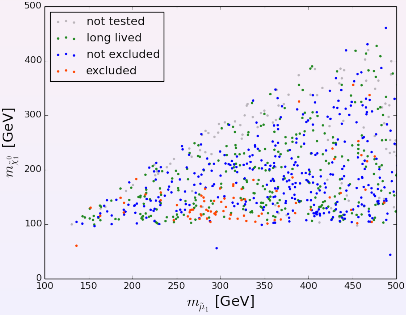
- **Importance of Z' searches on scenarios $\theta_{E_6} > 0$ for points allowed by δa_μ :**

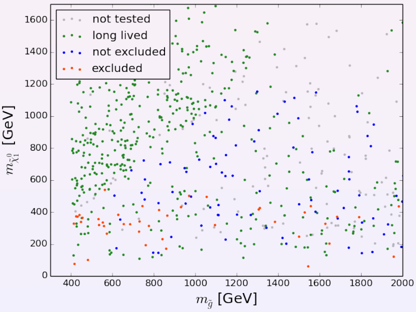




BACKUP

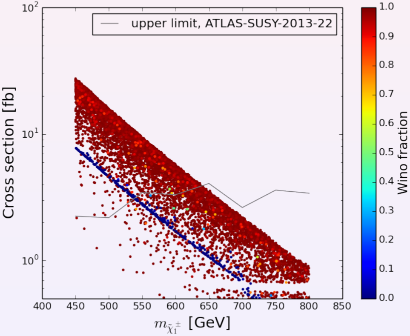
- Exclusions of δa_μ-allowed points weaker than at LHC Run I because $\tilde{l} \to \nu_L^l \tilde{\chi}_1^+$ also observed, not only $\tilde{l} \to l\tilde{\chi}_1^0$
- Case of long-lived $\tilde{g}$ for $\tilde{\nu}_R$ LSP

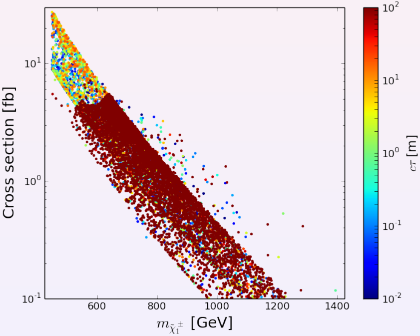




BACKUP

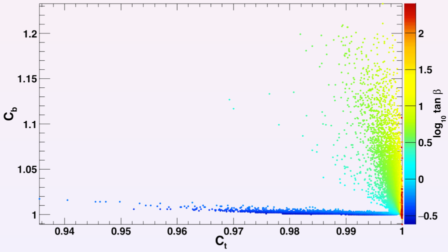
- **Long-lived $\tilde{\chi}^s\pm$: search at 13 TeV $\rightarrow$ large fraction of the points could be probed**

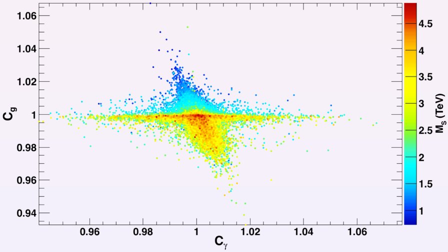




BACKUP

- **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**
  $\rightarrow$ decay into $b\bar{b}$, $\tau^+\tau^-$ at large $\tan\beta$, $t\bar{t}$ at small $\tan\beta$, generally kinematically forbidden for sfermions