Phenomenological aspects of the UMSSM

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G. Bélanger, JDS, U. Laa and A. Pukhov, in preparation

Outline

Motivations

Drawbacks of the MSSM

125 GeV Standard Model (SM)-like Higgs boson discovery by ATLAS and CMS collaborations + no other new particles found at LHC Run 1 $\rightarrow$ narrow window for new physics at the TeV scale

The Higgs couplings in the Minimal Supersymmetric Standard Model (MSSM) are to a large extent SM-like especially when other new particle masses $\gg$ electroweak scale

Challenges of the MSSM :

Drawbacks of the MSSM

125 GeV Standard Model (SM)-like Higgs boson discovery by ATLAS and CMS collaborations + no other new particles found at LHC Run 1 $\rightarrow$ narrow window for new physics at the TeV scale

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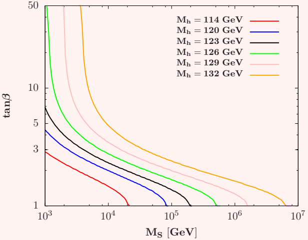
Challenges of the MSSM :

- Explain Higgs boson mass at 125 GeV $\rightarrow$ large contributions from 1-loop diagrams involving stops
- $\rightarrow$ Constrain stop sector
- Very small $\tan\beta$, i.e. $\approx 1 \Rightarrow$ tricky :
  TeV-scale SUSY–breaking parameter M_S + SM-like Higgs boson $\approx$ 125 GeV
  $\Rightarrow$ Higgs boson mass of 125 GeV requires large $\tan\beta$



$\Rightarrow$ **Going beyond the MSSM**

A. Djouadi, J. Quevillon, JHEP 10 (2013) 028

The model

E$_6$ inspired model

- Models with extended gauge symmetries are well motivated within the context of Beyond the Standard model (GUT scale models, extra-dimension motivations, superstring models, strong dynamics models, little Higgs models,...)
- 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],...)
  $E_6 \to SU(3)_c \times SU(2)_L \times U(1)_Y \times U(1)_\chi \times U(1)_\psi$

E_6 inspired model

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  $E_6 \to SU(3)_c \times SU(2)_L \times U(1)_Y \times U(1)_\chi \times U(1)_\psi$
- 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	$\Rightarrow \theta_{E_6} = \pi/2$

Content

- **Superpotential :**

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

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

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

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

$$\cos^2\beta = \frac{1}{\mathcal{Q}'_{H_d} + \mathcal{Q}'_{H_u}} \left(\frac{\sin 2\alpha_Z (M_{Z_1}^2 - M_{Z_2}^2)}{v^2 g'_1 \sqrt{g_Y^2 + g_2^2}} + \mathcal{Q}'_{H_u} \right)$$

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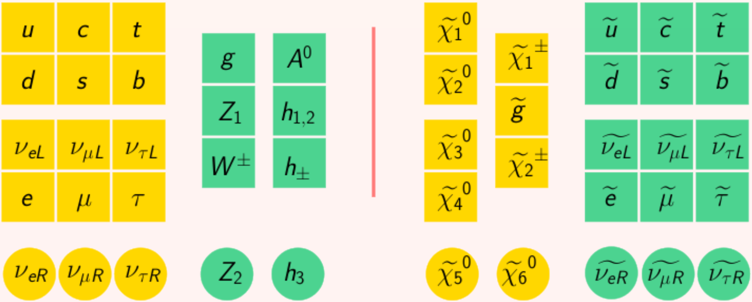
- **Gauginos sector : 6 neutralinos in the basis $(\widetilde{B}, \widetilde{W}^3, \widetilde{H}_d^0, \widetilde{H}_u^0, \widetilde{S}, \widetilde{B'})$**
- **Sfermion sector : New D-terms $\Delta_F = \frac{1}{2} {g'_1}^2 \mathcal{Q}'_F \left(\mathcal{Q}'_{H_d} v_d^2 + \mathcal{Q}'_{H_u} v_u^2 + \mathcal{Q}'_S v_s^2 \right)$, where $F \in \{Q, u, d, L, e, \nu\}$**
  - **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 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 properties

- **MSSM fields + 1 singlet $\Rightarrow$ 3 CP-even Higgs bosons $h_i, i \in \{1,2,3\}$**
- **New D-terms for the SM-like Higgs boson mostly h_1 :**

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

- **To sum up :**



Results : Higgs and squark sectors

Scan and first constraints

Scanning the UMSSM parameter space with the `micrOMEGAs` code :

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}	[-π/2, π/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

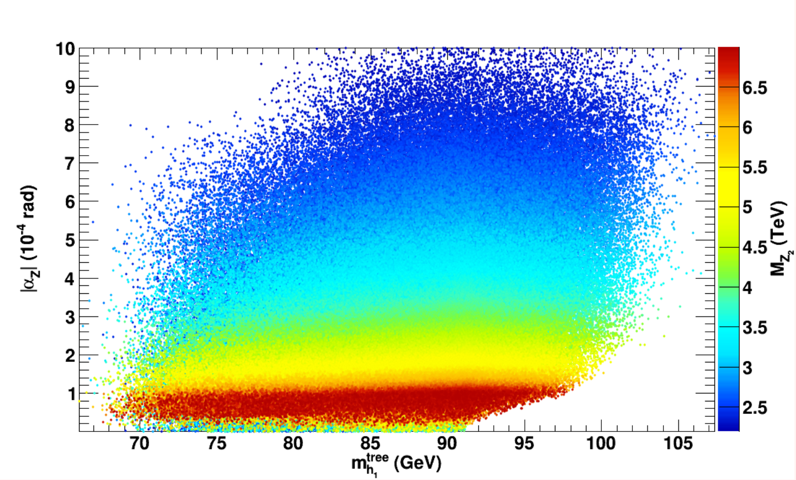
$F \in \{Q, u, d, L, e\}$, $i \in \{1, 2, 3\}$, $j \in \{1, 2\}$ and where $m_{\tilde{F}_2} = m_{\tilde{F}_1}$, $m_{\tilde{\nu}_2} = m_{\tilde{\nu}_1}$

Constraints :

- $\tilde{\nu}_{\tau R}$ **or** χ_1^0 **is the Lightest Supersymmetric Particle (LSP)**
- **LEP constraints on neutralinos, charginos, sleptons and squarks**
- **Z' : ATLAS + CMS : $M_{Z_2} > 2.57$ TeV for $\theta_{E_6} = \theta_\psi$ assuming only SM decay modes $\rightarrow$ limits weakened in the UMSSM but still important so that heavy singlet-like Higgs boson $\rightarrow$ h_2 mostly doublet-like**
- **Higgs : $m_{h_1} = 125.1 \pm 3$ GeV, `HiggsBounds-4.1.3` and `HiggsSignals-1.2.0`**
- **Higgs search in the $\tau^+\tau^-$ mode and other Higgs constraints through a modification of the `NMSSMTools` code : `UMSSMTools`**

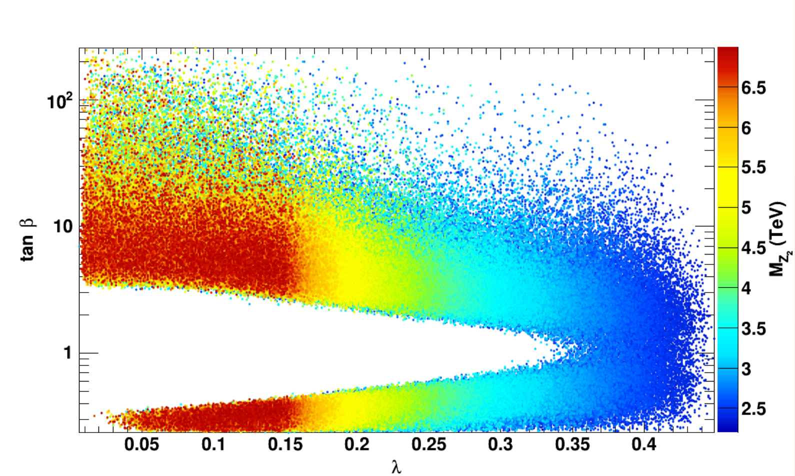
Higgs sector

- **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**



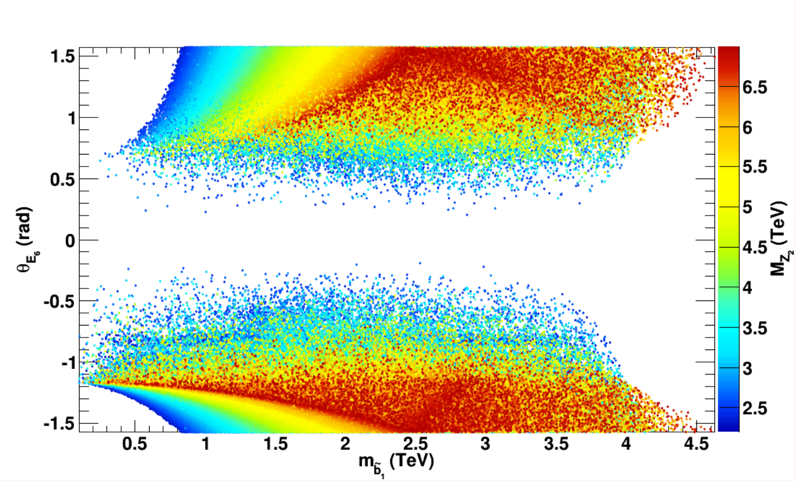
Higgs sector

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



Squarks

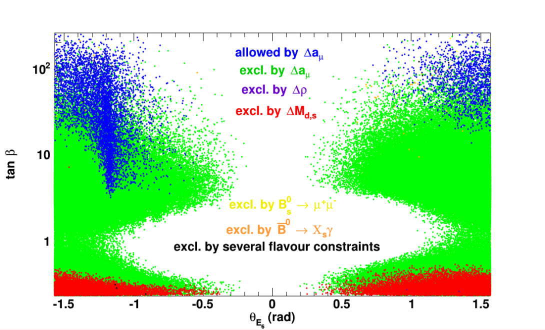
- Light squarks still allowed → add more constraints



Low energy observables

Low energy observables

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

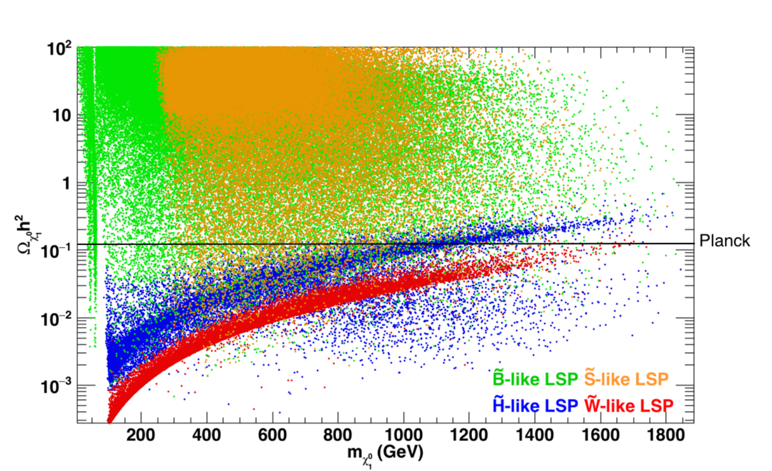


Points allowed by δa_{μ} mostly around $\theta_{E_6} \approx -1.16$ as expected

Dark Matter constraints

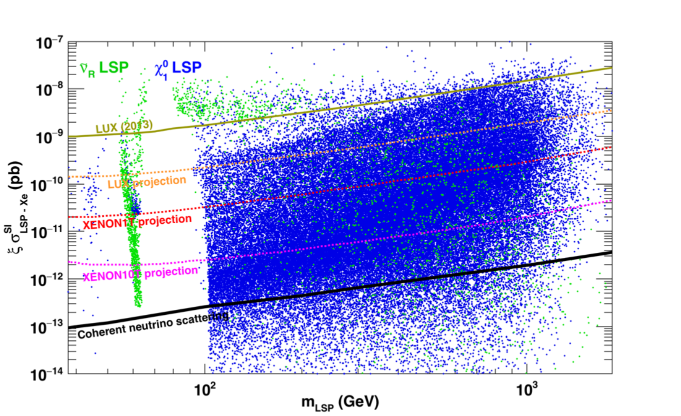
LSP abundance

- Dark Matter (DM) observables for either neutralino or RH sneutrino DM candidate :
  - $\Omega_{\rm LSP}\mathbf{h^2} < 0.1208$ (2σ upper bound from Planck combination)
    $\rightarrow \widetilde{\rm B}, \widetilde{\rm H}, \widetilde{\rm W}, \widetilde{\rm S}$ can satisfy relic abundance constraint



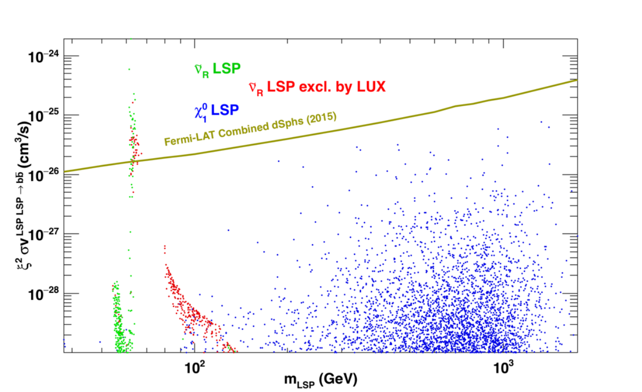
Direct detection

- **Dark Matter (DM) observables for either neutralino or RH sneutrino DM candidate :**
  - $\Omega_{\rm LSP}\mathbf{h}^2 < 0.1208$ **(**2σ **upper bound from Planck combination)**
  - **WIMP-nucleon scattering cross section limits from LUX**
    $\rightarrow$ **DM direct detection experiments can probe entirely some regions, especially for** $\tilde{\nu}_{\rm R}$ **LSP**



Indirect detection

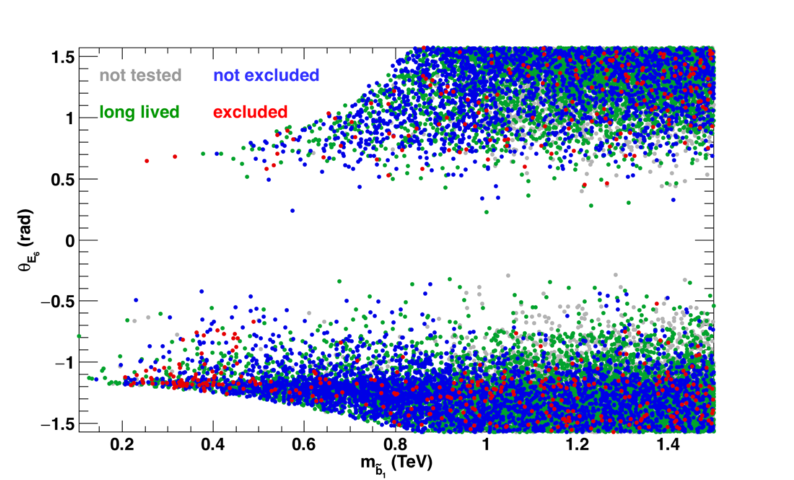
- Dark Matter (DM) observables for either neutralino or RH sneutrino DM candidate :
  - $\Omega_{\rm LSP}h^2 < 0.1208$ (2σ upper bound from Planck combination)
  - WIMP-nucleon scattering cross section limits from LUX
  - Limits on DM annihilation from the dwarf spheroidal satellite galaxies of the Milky Way from Fermi-LAT
    $\to b\bar{b}$ channel complementary to direct detection for $\tilde{\nu}_R$ LSP



LHC constraints on sparticles

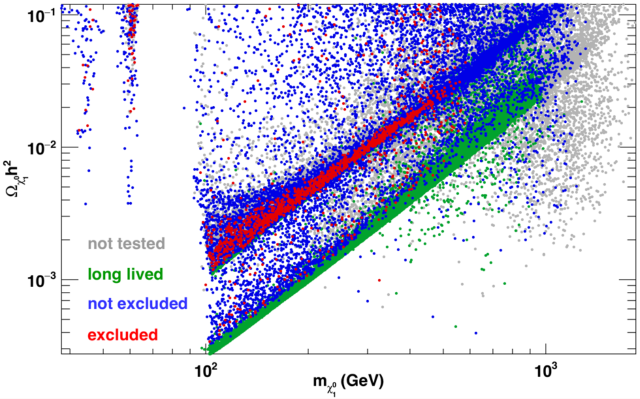
SModelS

- Using `SModelS` for interpreting simplified-model results from the LHC
- Some regions with light squarks remain unconstrained



Nature of the LSP

- Using SModelS for interpreting simplified-model results from the LHC
- Some regions with light squarks remain unconstrained
  $\rightarrow$ Mostly because of $\widetilde{W}$ LSP
- Important signatures are not covered by existing SMS results



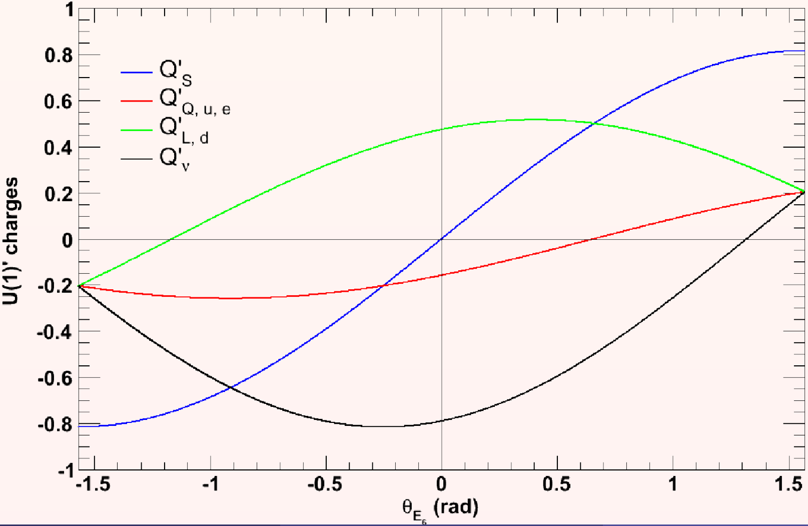
Conclusions

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**
- **Viable or excluded regions depend strongly on θ_{E_6}**
- **Forthcoming direct detection experiments would probe entirely some scenarios**
- **Complementarity between direct and indirect detection of DM, especially for $\tilde{\nu}_R$ LSP**
- **Simplified-model results from the LHC can exlude scenarios but some interesting signatures obtained in this study are not yet covered in SMS results**

BACKUP

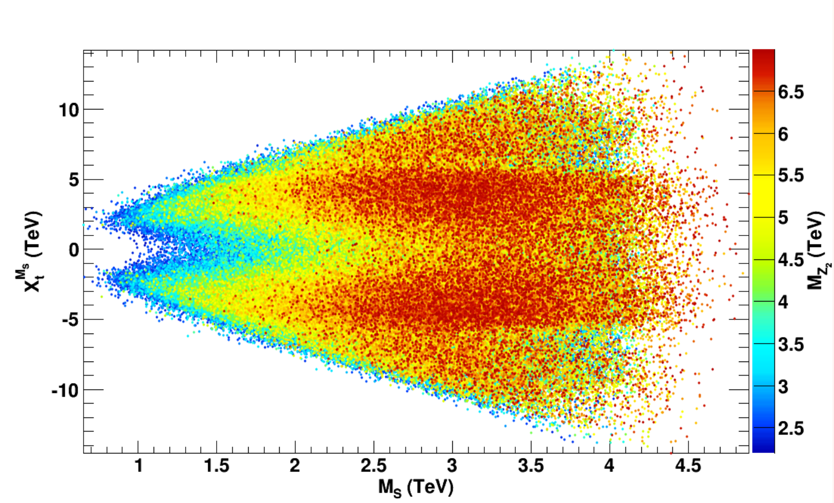
BACKUP



Q'_S
$Q'_{Q, u, e}$
$Q'_{L, d}$
Q'_ν
U(1)' charges
θ_{E_6} (rad)
1
0.8
0.6
0.4
0.2
0
-0.2
-0.4
-0.6
-0.8
-1
-1.5
-1
-0.5
0
0.5
1
1.5

BACKUP

X_t-M_S **plane :**



BACKUP

Some missing topologies with highest cross section for $\widetilde{H}$ LSP