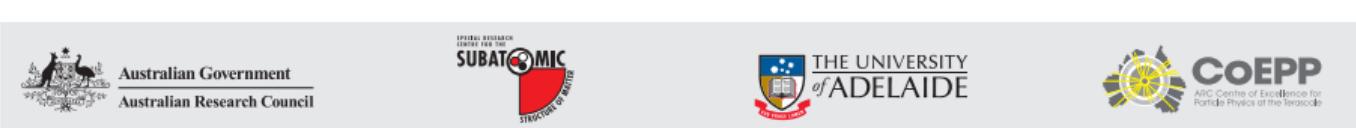


# Mass Spectrum and Dark Matter in the CSE<sub>6</sub>SSM

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Based on arXiv:1512.07040

July 4, 2016



## $E_6$ Inspired Models

- ▶ Tree-level MSSM:  $m_{h_1}^2 \leq M_Z^2 \cos^2 2\beta < 125.09$  GeV  $\Rightarrow$  little hierarchy problem
- ▶  $U(1)$  extensions  $\Rightarrow$  larger  $m_{h_1}$  via extra  $D$ - and  $F$ -terms
- ▶ Extra  $U(1)$  at low energies:

$$\begin{aligned} E_6 &\longrightarrow SO(10) \times U(1)_\psi \\ &\longrightarrow SU(5) \times U(1)_\psi \times U(1)_\chi \\ &\longrightarrow SU(3)_C \times SU(2)_L \times U(1)_Y \times U(1)_\psi \times U(1)_\chi \\ &\longrightarrow SU(3)_C \times SU(2)_L \times U(1)_Y \times U(1)' \end{aligned}$$

- ▶ Resulting  $U(1)' = U(1)_\chi \cos \theta_{E_6} + U(1)_\psi \sin \theta_{E_6}$
- ▶ Matter content fills complete **27** representations
  - ▶  $\Rightarrow$  exotic states potentially observable (e.g. see talk by R. Nevzorov, Tue 14:40)
- ▶ Break  $U(1)'$  with singlet  $\Rightarrow$  dynamically generate  $\mu$  term (solves  $\mu$  problem), massive  $Z'$

# The E<sub>6</sub>SSM

- $\tan \theta_{E_6} = \sqrt{15} \Rightarrow U(1)_N$  under which right-handed neutrinos are uncharged [1]
- Extra  $\hat{L}_4$ ,  $\hat{\bar{L}}_4$  from incomplete  $\mathbf{27}'$ ,  $\overline{\mathbf{27}}'$  for gauge unification
- Low-energy matter content from  $\mathbf{27}$ -plet:

$$(\hat{Q}_i, \hat{u}_i^c, \hat{d}_i^c, \hat{L}_i, \hat{e}_i^c) + (\hat{D}_i, \hat{\bar{D}}_i) \\ + (\hat{S}_i) + (\hat{H}_i^u) + (\hat{H}_i^d)$$

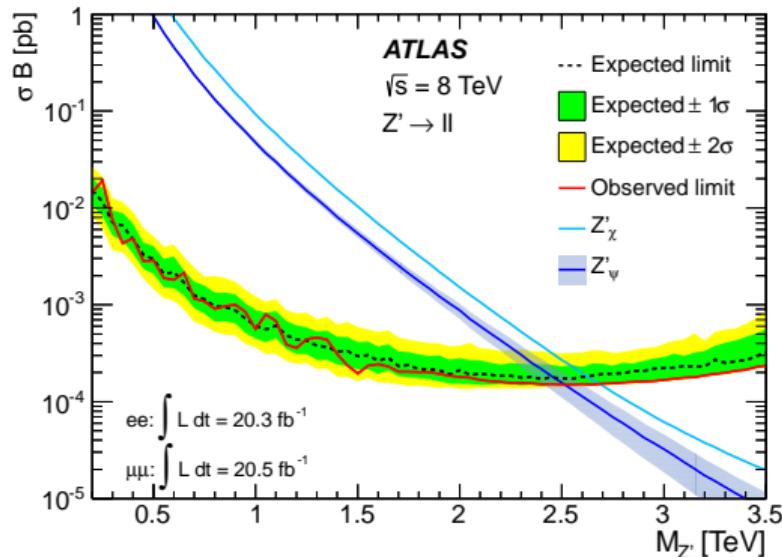
- Higgs doublets  $\hat{H}_3^d$ ,  $\hat{H}_3^u$  and one singlet  $\hat{S}_3$  get VEVs ( $\Rightarrow$  EWSB and break  $U(1)_N$ )

	$SU(3)_C$	$SU(2)_L$	$\sqrt{\frac{5}{3}} Q_i^Y$	$\sqrt{40} Q_i^N$
$\hat{Q}_i$	<b>3</b>	2	$\frac{1}{6}$	1
$\hat{u}_i^c$	<b>3</b>	1	$-\frac{2}{3}$	1
$\hat{d}_i^c$	<b>3</b>	1	$\frac{1}{3}$	2
$\hat{L}_i$	<b>1</b>	2	$-\frac{1}{2}$	2
$\hat{e}_i^c$	<b>1</b>	1	1	1
$\hat{S}_i$	<b>1</b>	1	0	5
$\hat{H}_i^u$	<b>1</b>	2	$\frac{1}{2}$	-2
$\hat{H}_i^d$	<b>1</b>	2	$-\frac{1}{2}$	-3
$\hat{D}$	<b>3</b>	1	$-\frac{1}{3}$	-2
$\hat{\bar{D}}$	<b>3</b>	1	$\frac{1}{3}$	-3
$\hat{L}_4$	<b>1</b>	2	$-\frac{1}{2}$	2
$\hat{\bar{L}}_4$	<b>1</b>	<b>2</b>	$\frac{1}{2}$	-2

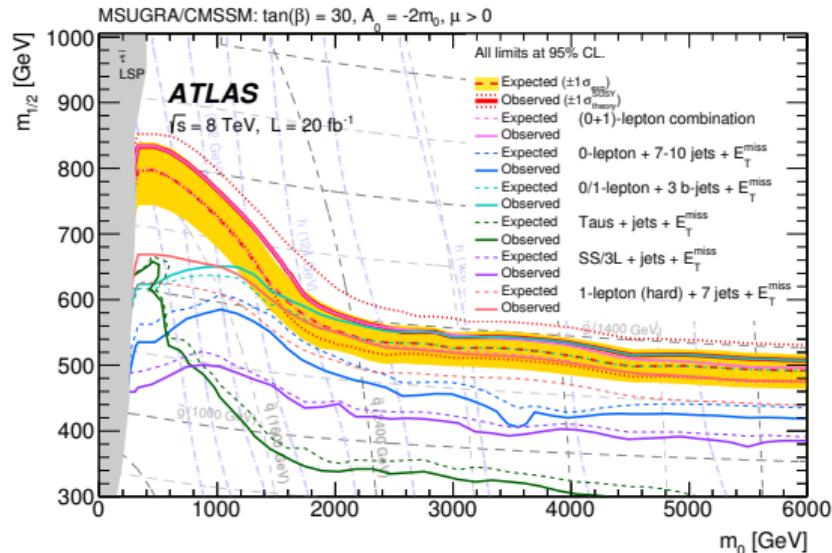
$$W_{E_6SSM} \approx y_\tau \hat{L}_3 \cdot \hat{H}_3^d \hat{e}_3^c + y_b \hat{Q}_3 \cdot \hat{H}_3^d \hat{d}_3^c + y_t \hat{H}_3^u \cdot \hat{Q}_3 \hat{u}_3^c + \lambda_i \hat{S}_3 \hat{H}_i^d \cdot \hat{H}_i^u + \kappa_i \hat{S}_3 \hat{D}_i \hat{\bar{D}}_i + \mu_L \hat{L}_4 \cdot \hat{\bar{L}}_4$$

[1] S. F. King, S. Moretti, and R. Nevzorov, Phys. Rev. D **73**, 035009 (2006) (hep-ph/0510419)

# $E_6$ SSM: $M_{Z'} \sim M_S$



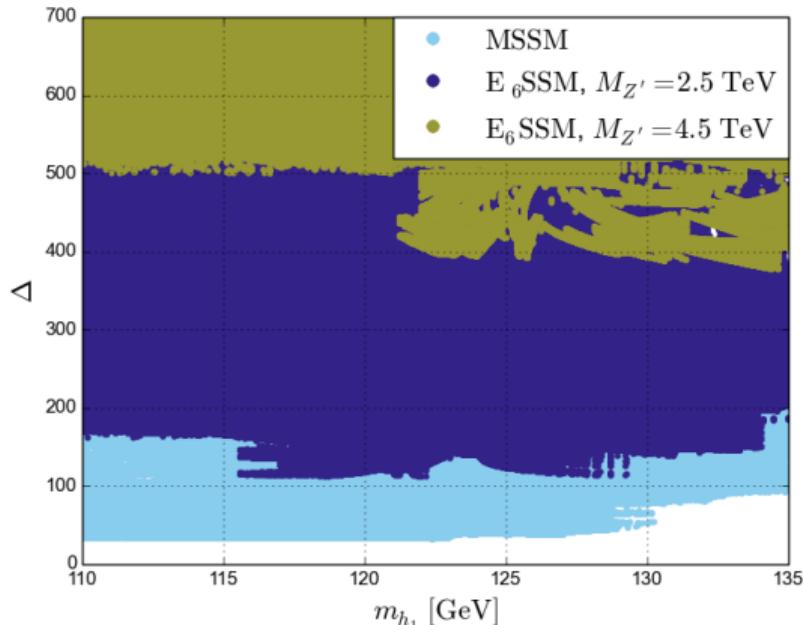
[PRD 90 (2014) 052005 (arXiv:1405.4123)]



[JHEP 10 (2015) 054 (arXiv:1507.05525)]

# Other Issues in the E<sub>6</sub>SSM

$$\overbrace{c(\tan \beta)}^{O(1)} \frac{M_{Z'}^2}{2} \approx -\lambda^2 \langle S_3 \rangle^2 + \frac{m_{H_d}^2 - m_{H_u}^2 \tan^2 \beta}{\tan^2 \beta - 1} + d(\tan \beta) \frac{M_{Z'}^2}{2}$$



[PRD 91 (2015) 115024 (arXiv:1503.08929)]

- ▶ Fine-tuning?
  - ▶  $M_{Z'} \gtrsim 2.5$  TeV  $\Rightarrow$  large traditional  $\Delta_{BG}$
- ▶ Multiple discrete symmetries required
  - ▶  $B, L$  violating interactions  $\Rightarrow$  exact  $Z_2^L$  or  $Z_2^B$
  - ▶ Unacceptable FCNCs  $\Rightarrow$  approximate  $Z_2^H$
- ▶ Light exotics could explain  $\Omega h^2 \approx 0.1187$ , but  $\text{BR}(h_1 \rightarrow \text{exotics})$ ,  $\sigma_{SI}$  too large
- ▶ Viable DM  $\Rightarrow$  another exact  $Z_2^S$

# The $SE_6$ SSM

- $E_6$  inspired model arising from 5D or 6D orbifold GUT [2]

- Extra  $\mathbf{27}'$ ,  $\overline{\mathbf{27}}'$ -plets, including

- doublets  $\hat{H}_u$ ,  $\hat{H}_d$  (and  $\hat{\bar{H}}_u$ ,  $\hat{\bar{H}}_d$ )
  - singlets  $\hat{S}$ ,  $\hat{\bar{S}}$

- $U(1)_\psi \times U(1)_\chi \rightarrow U(1)_N \times Z_2^M$  at intermediate scale  $\Rightarrow$  automatically conserved  $Z_2^M = (-1)^{3(B-L)}$

- Dangerous  $B$ ,  $L$  violating operators, FCNCs forbidden by single exact  $\tilde{Z}_2^H$

- Stabilise scalar potential  $\Rightarrow$  pure singlet  $\hat{\phi}$

## Objectives

- ✓ Single discrete symmetry
- ? Decouple  $M_{Z'}$  and  $M_S$
- ? DM

$$\begin{aligned} W_{SE_6\text{SSM}} = & \lambda \hat{S}(\hat{H}_d \cdot \hat{H}_u) - \sigma \hat{\phi} \hat{S} \hat{\bar{S}} + \frac{\kappa}{3} \hat{\phi}^3 + \frac{\mu}{2} \hat{\phi}^2 \\ & + \Lambda_F \hat{\phi} + \lambda_{\alpha\beta} \hat{S}(\hat{H}_\alpha^d \cdot \hat{H}_\beta^u) + \kappa_{ij} \hat{S} \hat{D}_i \hat{\bar{D}}_j \\ & + \tilde{f}_{i\alpha} \hat{S}_i (\hat{H}_u \cdot \hat{H}_\alpha^d) + f_{i\alpha} \hat{S}_i (\hat{H}_\alpha^u \cdot \hat{H}_d) \\ & + g_{ij}^D (\hat{Q}_i \cdot \hat{L}_4) \hat{\bar{D}}_j + h_{i\alpha}^E \hat{e}_i^c (\hat{H}_\alpha^d \cdot \hat{L}_4) \\ & + \mu_L (\hat{L}_4 \cdot \hat{\bar{L}}_4) + \tilde{\sigma} \hat{\phi} (\hat{L}_4 \cdot \hat{\bar{L}}_4) \\ & + W_{\text{MSSM}}(\mu = 0) \end{aligned}$$

# EWSB in the $SE_6SSM$

- At physical minimum,

$$\langle H_d^0 \rangle = \frac{v_1}{\sqrt{2}}, \quad \langle H_u^0 \rangle = \frac{v_2}{\sqrt{2}}, \quad \langle S \rangle = \frac{s_1}{\sqrt{2}}, \quad \langle \bar{S} \rangle = \frac{s_s}{\sqrt{2}}, \quad \langle \phi \rangle = \frac{\varphi}{\sqrt{2}}$$

- $S, \bar{S}$  develop along nearly  $D$ -flat direction  $\langle S \rangle = \langle \bar{S} \rangle$  with

$$\langle S \rangle \approx \langle \bar{S} \rangle \sim \frac{M_S}{\sigma}$$

- Small  $\sigma \Rightarrow M_{Z'}^2 \sim g_1'^2 Q_S^2 (s_1^2 + s_2^2)$  far heavier than  $M_S$
- $\therefore$  can have  $M_{Z'}$  far above limits while keeping sparticles (relatively) light
- $D$ -term contribution to EW scale, i.e.  $M_{\tilde{Z}}^2$ , also suppressed ( $\sim \tilde{Q}_S (s_1^2 - s_2^2)$ )

## Objectives

- ✓ Single discrete symmetry
- ✓ Decouple  $M_{Z'}$  and  $M_S$
- ? DM

# Dark Matter Candidates

- ▶ Write  $\tilde{Z}_2^H = Z_2^M \times Z_2^E \Rightarrow$  conserved  $Z_2^E$
- ▶  $\therefore$  lightest exotic ( $\equiv Z_2^E$  odd) state is stable
- ▶  $f_{i\alpha}, \tilde{f}_{i\alpha} \sim 10^{-7} \Rightarrow$  almost massless inert singlinos  $\tilde{S}_i$
- ▶  $\tilde{S}_i$  form hot DM, negligible contribution to relic density
- ▶ Conserved  $Z_2^M$  ( $\Leftrightarrow$  R-parity)  $\Rightarrow$  second stable DM candidate

$\Rightarrow$  account for  $\Omega h^2$  with MSSM-like  $\tilde{\chi}_1^0$ ?

## Objectives

- ✓ Single discrete symmetry
- ✓ Decouple  $M_{Z'}$  and  $M_S$
- ? DM

	$\tilde{Z}_2^H$	$Z_2^M$	$Z_2^E$
$\hat{Q}_i, \hat{u}_i^c, \hat{d}_i^c, \hat{L}_i, \hat{e}_i^c, \hat{N}_i^c$	—	—	+
$\hat{H}_\alpha^u, \hat{H}_\alpha^d, \hat{S}_i, \hat{D}_i, \hat{\bar{D}}$	—	+	—
$\hat{H}_u, \hat{H}_d$	+	+	+
$\hat{S}, \hat{\bar{S}}$	+	+	+
$\hat{L}_4, \hat{\bar{L}}_4$	+	—	—

$$M_{\tilde{\chi}^0} = \begin{pmatrix} A & C^T \\ C & B \end{pmatrix}$$

# The CSE<sub>6</sub>SSM

- ▶ General model is complicated
  - ▶  $O(200)$  new parameters (assuming no new sources of CP-violation)
  - ▶ Many masses and mixings
- ▶ Consider constrained model (CSE<sub>6</sub>SSM) inspired by gravity mediated SUSY breaking
- ▶ Universal soft breaking parameters:  $M_{1/2}$ ,  $A_0$ ,  $B_0$ ,  $m_0$
- ▶ Interested in mechanism decoupling  $Z'$  from EWSB conditions  $\Rightarrow$  can have large  $s = \sqrt{s_1^2 + s_2^2}$
- ▶ Higgsino mass set by  $\mu_{\text{eff}} = \lambda s_1 / \sqrt{2} \Rightarrow$  acceptable LSP mass ( $\lesssim$  TeV) for small  $\lambda$
- ▶  $\Rightarrow$  other exotic couplings must be small, otherwise exotic states are tachyonic

## Parameter Space Scans

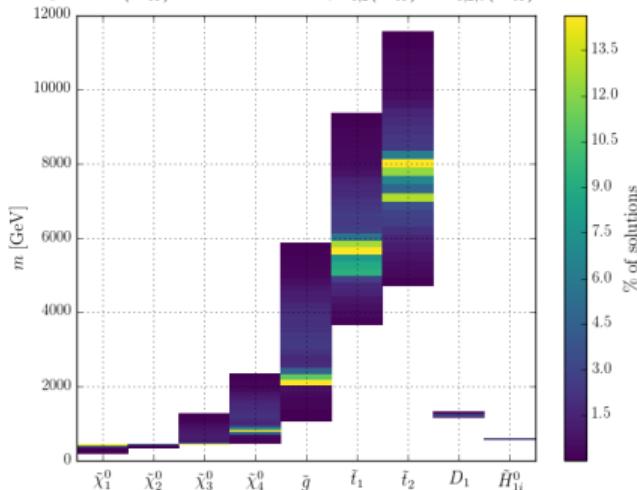
- ▶ Focus on heavy  $Z'$ ,  $s = 650$  TeV, choose fixed  $\mu_{\text{eff}}$
- ▶ Achieve using semi-analytic solutions for soft parameters:

$$M_i(Q) = p_i(Q)M_{1/2} + q_i(Q)A_0, \quad A_i(Q) = e_i(Q)A_0 + f_i(Q)M_{1/2}, \\ m_i^2(Q) = a_i(Q)m_0^2 + b_i(Q)M_{1/2}^2 + c_i(Q)A_0M_{1/2} + d_i(Q)A_0^2, \dots$$

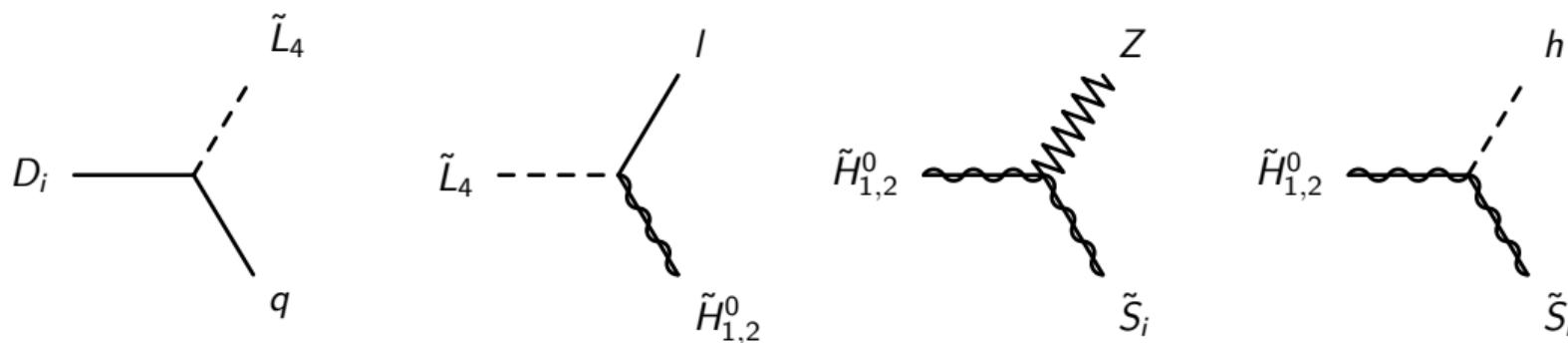
- ▶ Fix  $m_0$  from EWSB,  $m_0^2 \sim -\frac{b_{H_u}}{a_{H_u}} M_{1/2}^2 - \dots$
- ▶ Implemented in FlexibleSUSY for [full 1-loop masses and 2-loop RGEs](#)
- ▶ Require  $\Omega h^2 \leq 0.1187$  (micrOMEGAs) and  $m_{h_1} = 125.09 \pm 3$  GeV
- ▶ Compare with CMSSM for  $|\mu| \sim 300$  GeV and  $|\mu| \sim 1$  TeV

# Sparticle Mass Spectrum

CSE6SSM:  $\lambda(M_X) = 9.15181 \times 10^{-4}$ ,  $\lambda_{1,2}(M_X) = \kappa_{1,2,3}(M_X) = 10^{-3}$

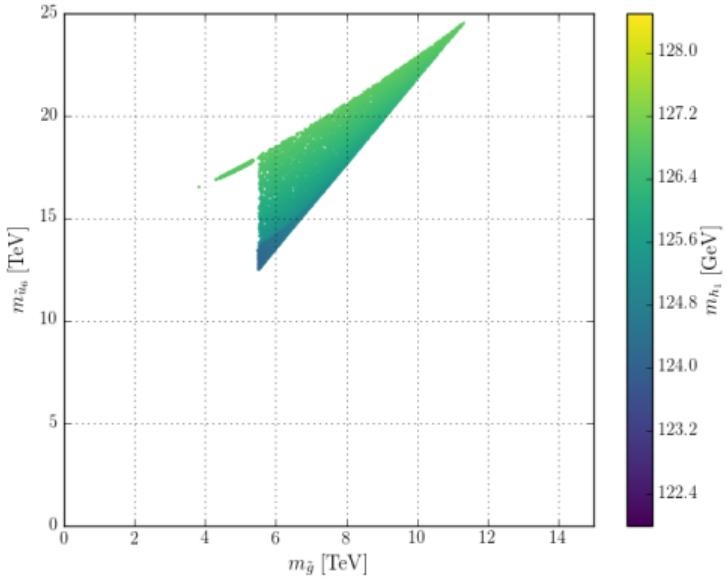


- EWSB conditions  $\Rightarrow m_0 > M_{1/2}, A_0$
- $\therefore$  MSSM sfermions out of reach of run II
- Light exotic fermions can be observable
  - Exotic leptoquarks  $D_i$ :  
 $p p \rightarrow t \bar{t} \tau^+ \tau^- + E_T^{miss} + X, p p \rightarrow b \bar{b} + E_T^{miss} + X$
  - Charged, neutral inert Higgsinos:  
 $p p \rightarrow W W/Z Z/W Z + E_T^{miss} + X$



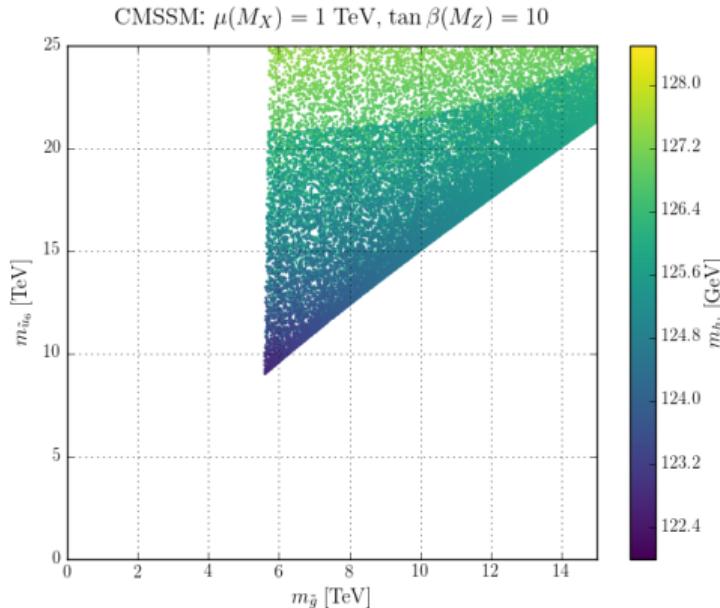
# CP-even Higgs Mass

CSE<sub>6</sub>SSM:  $\lambda(M_X) = 2.4 \times 10^{-3}$ ,  $\lambda_{1,2}(M_X) = \kappa_{1,2,3}(M_X) = 3 \times 10^{-3}$



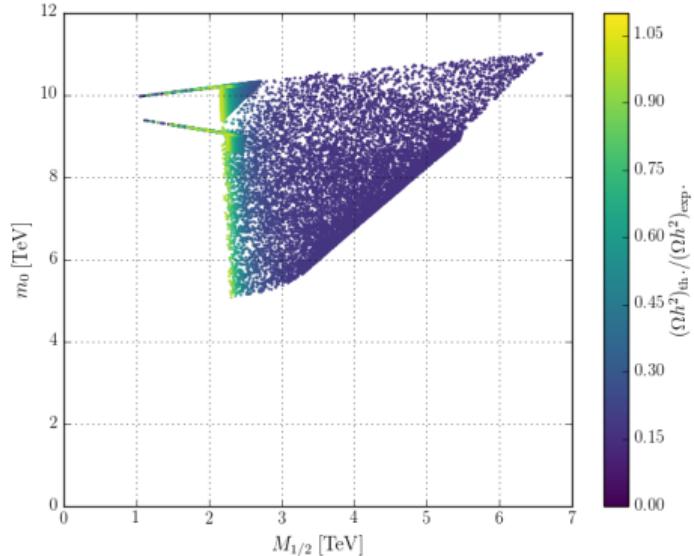
$m_{h_1} \lesssim 130$  GeV  
(i.e. bounded from above, as usual)

- ▶ Split spectrum  $\Rightarrow$  large logarithms contribute
- ▶ Exotic contributions small, mainly  $\tilde{t}$ 's
- ▶ Use EFT calculation of  $m_{h_1}$  (SUSYHD)
  - ▶ cross-checked with prototype FlexibleHiggs (see talk by P. Atron, Tue 16:30)

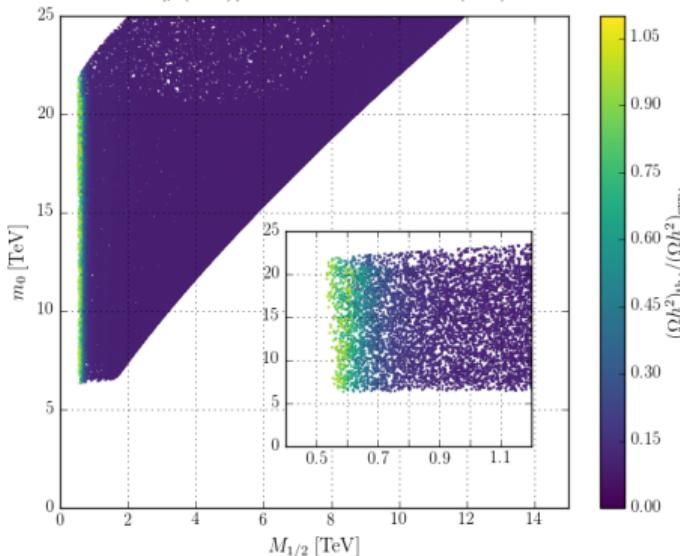


# DM Relic Abundance: $|\mu_{\text{eff}}| \sim 300$ GeV

CSE6SSM:  $|\lambda(M_X)| = 9.15181 \times 10^{-4}$ ,  $\lambda_{1,2}(M_X) = \kappa_{1,2,3}(M_X) = 10^{-3}$



CMSSM:  $|\mu(M_X)| = 297.434$  GeV,  $\tan \beta(M_Z) = 10$

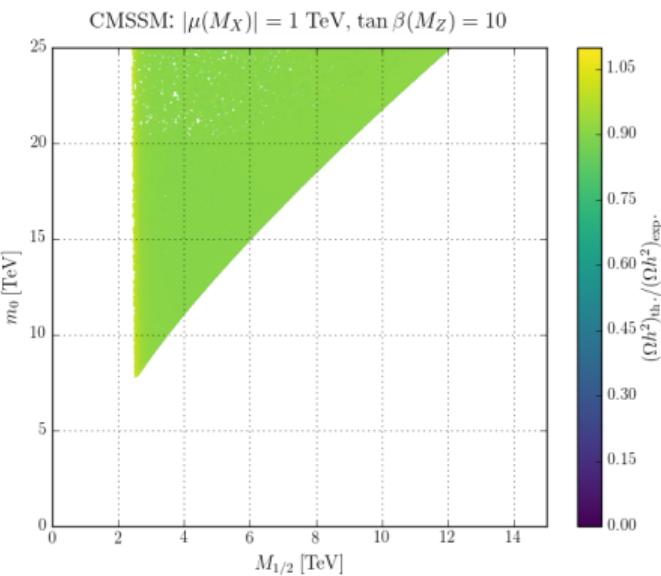
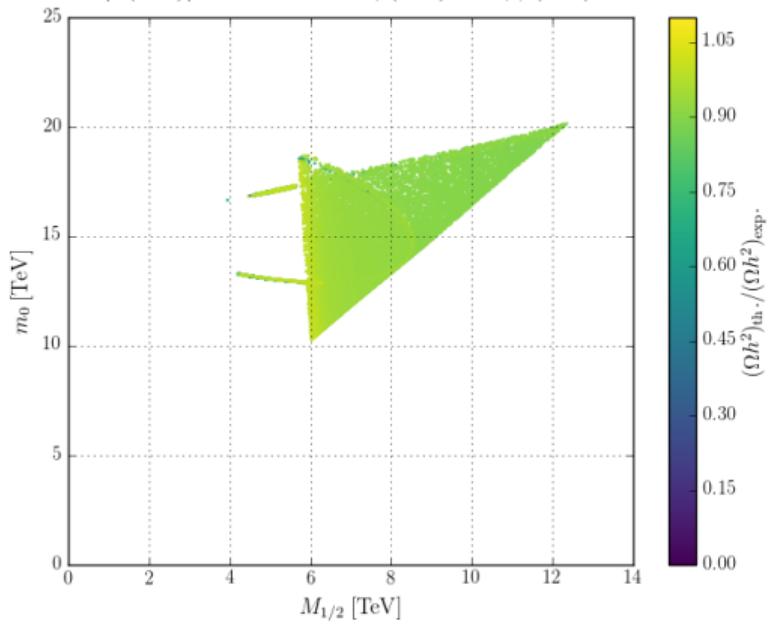


- ▶ “Well-tempered” scenario: require  $M_1 \sim \mu_{\text{eff}}$
- ▶ Pair annihilations  $\tilde{\chi}_1^0 \tilde{\chi}_1^0 \rightarrow \bar{f} f$
- ▶ MSSM-like nature of neutralino sector clear – almost identical behaviour
- ▶ Low  $M_{1/2} \Rightarrow \tilde{g} \sim 1.5 - 2$  TeV (and  $\tilde{\chi}^0$ ,  $\tilde{\chi}^\pm$ ) observable

# DM Relic Abundance: $|\mu_{\text{eff}}| \sim 1 \text{ TeV}$

Higgsino LSP:  $\Omega h^2 \approx (\Omega h^2)_{\text{obs}} \left( \frac{\mu_{\text{eff}}}{1 \text{ TeV}} \right)^2$

CSE<sub>6</sub>SSM:  $|\lambda(M_X)| = 2.4 \times 10^{-3}$ ,  $\lambda_{1,2}(M_X) = \kappa_{1,2,3}(M_X) = 3 \times 10^{-3}$

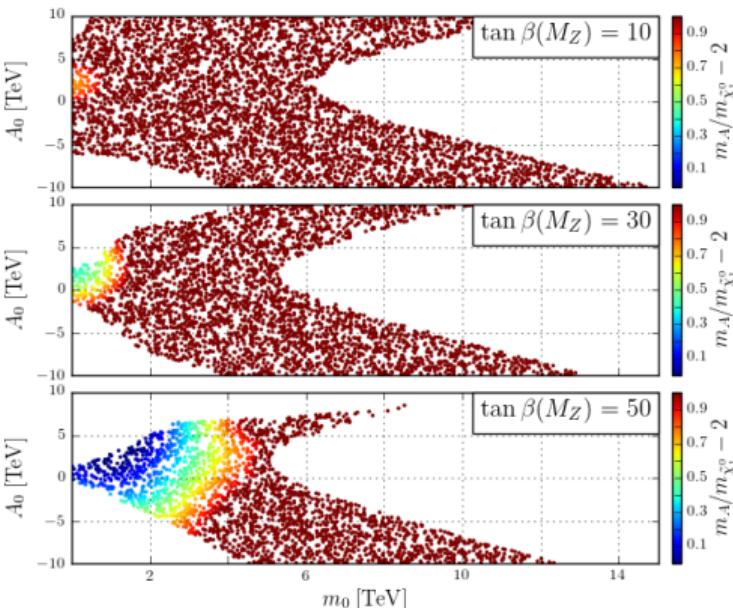


- ▶ Mainly  $\tilde{\chi}_i^0 \tilde{\chi}_1^\pm \rightarrow \bar{f}_1 f_2$ ,  $\tilde{\chi}_1^0 \tilde{\chi}_2^0 \rightarrow \bar{f} f$
- ▶ Suppress  $\tilde{B}$  fraction  $\Rightarrow$  large  $M_{1/2}$
- ▶  $\therefore$  all gauginos are heavy ( $m_{\tilde{g}} \gtrsim 5 \text{ TeV}$ )
- ▶ Naturalness of  $\mu_{(\text{eff})} \sim 1 \text{ TeV}$ ?

# A-funnel in the $SE_6$ SSM

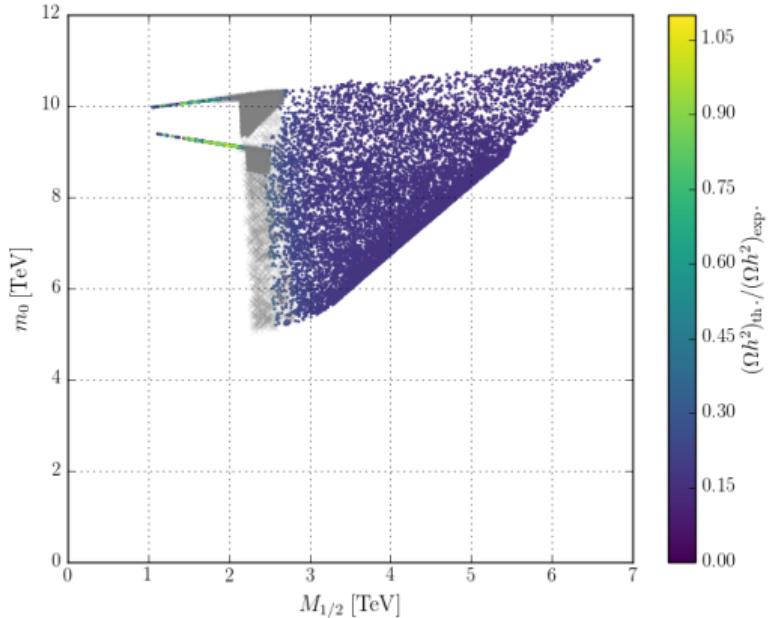
- ▶ Solutions at lower  $M_{1/2}$  due to  $m_{A_1} \sim 2m_{\tilde{\chi}_1^0}$
- ▶ CMSSM: A-funnel requires  $\tan \beta \gtrsim 40$
- ▶ CSE<sub>6</sub>SSM: tune  $A_0$  for given  $\tan \beta$ ,  $M_{1/2}$  to that  $m_{A_1} \rightarrow 0$ , keeping  $m_{\tilde{\chi}_1^0} \sim$  fixed
- ▶ Lightest state  $A_1$  mixture of singlets for  $s \gg M_S \gg v$  ( $\tan \delta \approx \frac{s_1 s_2}{\varphi \sqrt{s_1^2 + s_2^2}}$ ):

$$m_{A_1}^2 \approx \cos^2 \delta \left( -2B\mu - 3 \frac{\kappa A_\kappa}{\sqrt{2}} \varphi - \sqrt{2}\xi \frac{\Lambda}{\varphi} + \frac{9}{2} \sigma \kappa s_1 s_2 + 2\sqrt{2} \frac{\sigma \mu s_1 s_2}{\varphi} + \frac{\sigma s_1 s_2 \Lambda}{\varphi^2} \right)$$



# Direct Detection Limits: $|\mu_{\text{eff}}| \sim 300$ GeV

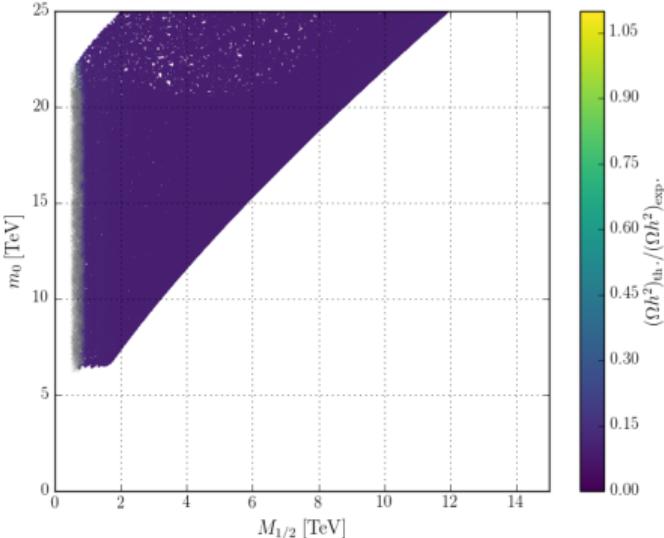
CSE<sub>6</sub>SSM:  $|\lambda(M_X)| = 9.15181 \times 10^{-4}$ ,  $\lambda_{1,2}(M_X) = \kappa_{1,2,3}(M_X) = 10^{-3}$



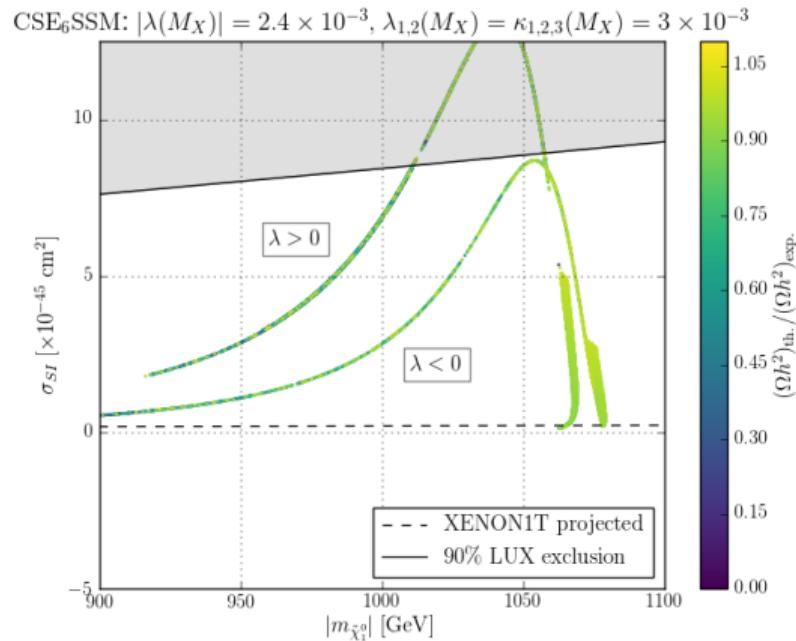
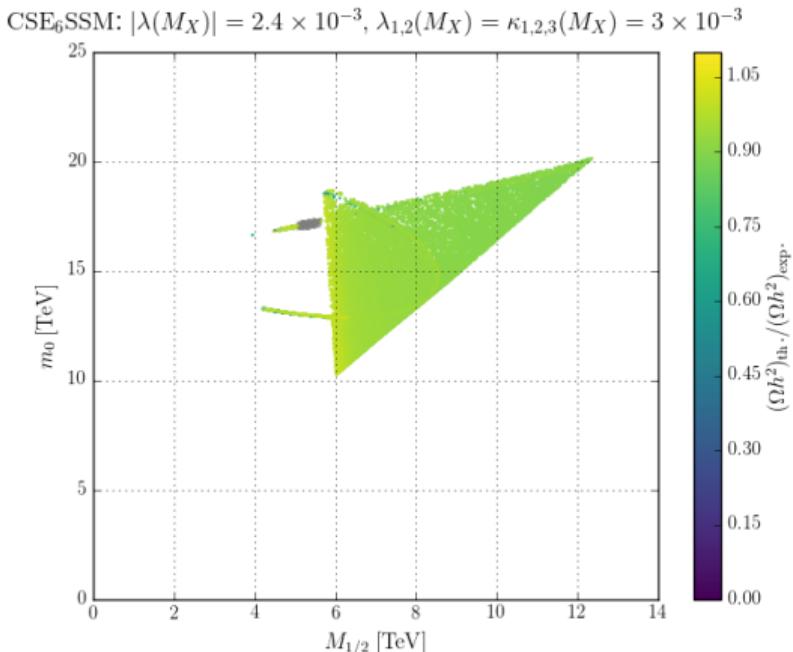
Grey points:  $\sigma_{SI}^p \geq \frac{(\Omega h^2)_{\text{obs.}}}{(\Omega h^2)_{\text{th.}}} \times (90\% \text{ LUX exclusion})$

- ▶ Stringent constraint on parameter space
- ▶ Large mixings  $\Rightarrow$  (almost) all points with  $\Omega h^2 \sim 0.1187$  excluded
- ▶ SD limits (LUX, IceCube) can also be relevant

CMSSM:  $|\mu(M_X)| = 297.434$  GeV,  $\tan \beta(M_Z) = 10$



# Direct Detection Limits: $|\mu_{\text{eff}}| \sim 1 \text{ TeV}$



- ▶ 1 TeV  $\sim$  pure Higgsino, small  $\tilde{B}$  mixing
- ▶  $\therefore \sigma_{SI}^p$  (mostly) reduced below LUX

- ▶ Entire parameter space should still be probed by XENON1T

## Summary

- ▶  $E_6$  inspired models can address little hierarchy problem and  $\mu$ -problem of MSSM
- ▶ Simplest phenomenologically viable variants, e.g.  $E_6$ SSM, face several problems:  $Z'$  limits, multiple discrete symmetries, ...
- ▶  $SE_6$ SSM is a well-motivated extension with an exact custodial symmetry
- ▶ DM relic density can be fitted by MSSM-like neutralino
  - ▶ Higgsino LSP  $\Rightarrow$  heavy spectrum (except possibly exotics)
  - ▶ Mixed bino-Higgsino LSP  $\Rightarrow$  observable gauginos too
  - ▶  $A$ -funnel mechanism accessible at lower  $\tan\beta$  than in MSSM
- ▶ Strong constraints from direct detection, as in MSSM
- ▶  $\Rightarrow$  most of parameter space considered accessible at XENON1T

Thank you for listening!

## Additional Slides

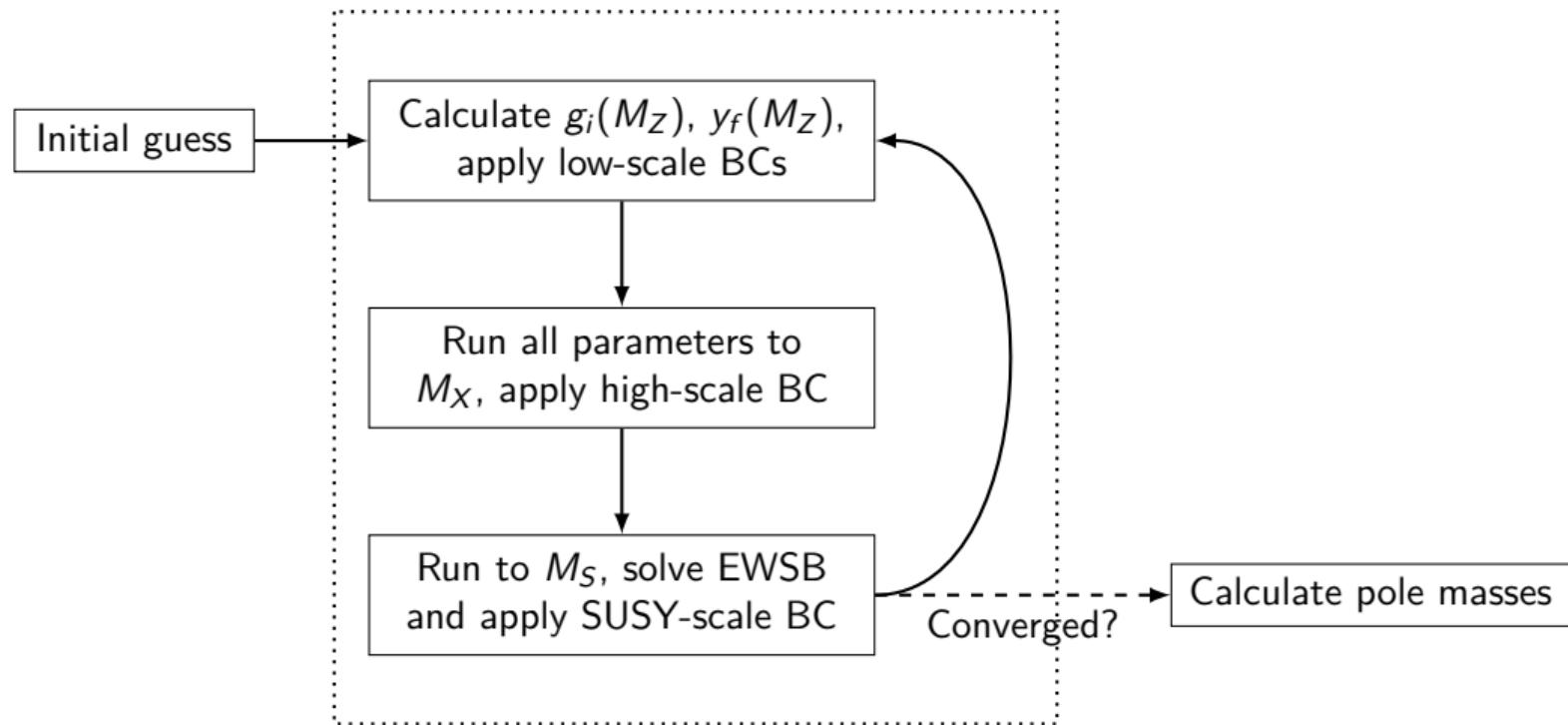
## Semi-analytic Solutions

- ▶ Useful technique for studying constrained models (e.g. CE<sub>6</sub>SSM)
- ▶ RGEs for SUSY parameters independent of soft SUSY breaking parameters (up to effects of threshold corrections)
- ▶ RGEs for SUSY breaking parameters are system of linear ODEs with variable coefficients
- ▶ Combine with boundary conditions  $\Rightarrow$  semi-analytic solutions,

$$M_i(Q) = p_i(Q)M_{1/2} + q_i(Q)A_0, \quad A_i(Q) = e_i(Q)A_0 + f_i(Q)M_{1/2}, \\ m_i^2(Q) = a_i(Q)m_0^2 + b_i(Q)M_{1/2}^2 + c_i(Q)A_0M_{1/2} + d_i(Q)A_0^2, \dots$$

- ▶ Coefficients depend only on SUSY parameters, calculated numerically
- ▶ Relate SUSY scale parameters to high-scale inputs, e.g. trade  $m_0$  for  $\mu_{\text{eff}}$ 
  - ▶ Contrast with traditional approach in CMSSM:  $\mu$  output for given  $m_0$
  - ▶ N.B. all results here are for fixed  $\mu$

## Two-scale Algorithm



# Semi-analytic Algorithm

