CMSSM WITH GENERALIZED YUKAWA QUASI-UNIFICATION: AN UPDATE

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BASED ON

- N. KARAGIANNAKIS, G. LAZARIDES AND C. P., PHYS. REV D **87**, 055001 (2013) [arXiv:1212.0517];
- N. KARAGIANNAKIS, G. LAZARIDES AND C. P., TO APPEAR.

OUTLOOK

- EMBEDDING THE MINIMAL SUPERSYMMETRIC (**SUSY**) STANDARD MODEL (**MSSM**) IN A PATI-SALAM (**PS**) SUSY GRAND UNIFIED THEORY (**GUT**)
- CONFRONTING THE RESULTING CONSTRAINED MSSM (**CMSSM**) WITH LHC, PLANCK & LUX
- RESULTS: STAU-COANNIHILATION VS FOCUS-POINT REGION
- CONCLUSIONS

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SUPER-FIELDS	REPRESENTATIONS UNDER $G_{\rm PS}$	DECOMPOSITIONS UNDER $G_{\rm SM}$	GLOBAL CHARGES R	PQ	$\mathbb{Z}_2^{\rm mp}$
		MATTER SUPERFIELDS			
F_i	$(\mathbf{4},\mathbf{2},\mathbf{1})$	$Q_{ia}(\mathbf{3},\mathbf{2},1/6)$	1	−1	1
		$L_i(\mathbf{1},\mathbf{2},-1/2)$			
F^c_i	$(\bar{\mathbf{4}},\mathbf{1},\mathbf{2})$	$u^c_{ia}(\bar{\mathbf{3}},\mathbf{1},-2/3)$	1	0	−1
		$d^c_{ia}(\bar{\mathbf{3}},\mathbf{1},1/3)$			
		$\nu^c_i(\mathbf{1},\mathbf{1},0)$			
		$e^c_i(\mathbf{1},\mathbf{1},1)$			
		HIGGS SUPERFIELDS			
H^c	$(\bar{\mathbf{4}},\mathbf{1},\mathbf{2})$	$u^c_{Ha}(\bar{\mathbf{3}},\mathbf{1},-2/3)$	0	0	0
		$d^c_{Ha}(\bar{\mathbf{3}},\mathbf{1},1/3)$			
		$\nu^c_H(\mathbf{1},\mathbf{1},0)$			
		$e^c_H(\mathbf{1},\mathbf{1},1)$			
$\bar{H}^c$	$(\mathbf{4},\mathbf{1},\mathbf{2})$	$\bar{u}^c_{Ha}(\mathbf{3},\mathbf{1},2/3)$	0	0	0
		$\bar{d}^c_{Ha}(\mathbf{3},\mathbf{1},-1/3)$			
		$\bar{\nu}^c_H(\mathbf{1},\mathbf{1},0)$			
		$\bar{e}^c_H(\mathbf{1},\mathbf{1},-1)$			
S	$(\mathbf{1},\mathbf{1},\mathbf{1})$	$S(\mathbf{1},\mathbf{1},0)$	2	0	0
G	$(\mathbf{6},\mathbf{1},\mathbf{1})$	$\bar{g}^c_{a}(\mathbf{3},\mathbf{1},-1/3)$	2	0	0
		$g^c_{a}(\bar{\mathbf{3}},\mathbf{1},1/3)$			
h	$(\mathbf{1},\mathbf{2},\mathbf{2})$	$\bar{H}(\mathbf{1},\mathbf{2},1/2)$	0	1	0
		$H(\mathbf{1},\mathbf{2},-1/2)$			
P	$(\mathbf{1},\mathbf{1},\mathbf{1})$	$P(\mathbf{1},\mathbf{1},0)$	1	−1	0
$\bar{P}$	$(\mathbf{1},\mathbf{1},\mathbf{1})$	$\bar{P}(\mathbf{1},\mathbf{1},0)$	0	1	0

THE INITIAL SUPERPOTENTIAL

WE FOCUS ON THE PS AND PQ-INVARIANT SUPERPOTENTIAL

$$W_1 = W_{\rm MSSM} + W_{\rm PQ} + W_{\rm HPS} \quad \text{WHERE}$$

- $W_{\rm MSSM} = y_{ij}F_i\boldsymbol{h}F^c_j = y_{ij}F_i\begin{pmatrix}\bar{H} & H\end{pmatrix}F^c_j =$

$$y_{ij}\left(H^{\mathsf{T}}\boldsymbol{\varepsilon}L_ie^c_j - \bar{H}^{\mathsf{T}}\boldsymbol{\varepsilon}L_i\nu^c_j + H^{\mathsf{T}}\varepsilon Q_{ia}d^c_{ja} - \bar{H}^{\mathsf{T}}\varepsilon Q_{ia}u^c_{ja}\right),$$

WITH $\varepsilon = \begin{pmatrix}0 & 1\\ -1 & 0\end{pmatrix}$, $Q_{ia} = \begin{pmatrix}u_{ia}\\ d_{ia}\end{pmatrix}$ AND $L_i = \begin{pmatrix}\nu_i\\ e_i\end{pmatrix}$.

Super-fields	Represe-ntations under $G_{\rm PS}$	Decompo-sitions under $G_{\rm SM}$	R	PQ	$\mathbb{Z}_2^{\rm mp}$
		Matter Superfields			
F_i	$(\mathbf{4},\mathbf{2},\mathbf{1})$	$Q_{ia}(\mathbf{3},\mathbf{2},1/6)$	1	-1	1
		$L_i(\mathbf{1},\mathbf{2},-1/2)$			
F^c_i	$(\bar{\mathbf{4}},\mathbf{1},\mathbf{2})$	$u^c_{ia}(\bar{\mathbf{3}},\mathbf{1},-2/3)$	1	0	-1
		$d^c_{ia}(\bar{\mathbf{3}},\mathbf{1},1/3)$			
		$\nu^c_i(\mathbf{1},\mathbf{1},0)$			
		$e^c_i(\mathbf{1},\mathbf{1},1)$			
		Higgs Superfields			
H^c	$(\bar{\mathbf{4}},\mathbf{1},\mathbf{2})$	$u^c_{Ha}(\bar{\mathbf{3}},\mathbf{1},-2/3)$	0	0	0
		$d^c_{Ha}(\bar{\mathbf{3}},\mathbf{1},1/3)$			
		$\nu^c_H(\mathbf{1},\mathbf{1},0)$			
		$e^c_H(\mathbf{1},\mathbf{1},1)$			
$\bar{H}^c$	$(\mathbf{4},\mathbf{1},\mathbf{2})$	$\bar{u}^c_{Ha}(\mathbf{3},\mathbf{1},2/3)$	0	0	0
		$\bar{d}^c_{Ha}(\mathbf{3},\mathbf{1},-1/3)$			
		$\bar{\nu}^c_H(\mathbf{1},\mathbf{1},0)$			
		$\bar{e}^c_H(\mathbf{1},\mathbf{1},-1)$			
S	$(\mathbf{1},\mathbf{1},\mathbf{1})$	$S(\mathbf{1},\mathbf{1},0)$	2	0	0
G	$(\mathbf{6},\mathbf{1},\mathbf{1})$	$\bar{g}^c_{\rm a}(\mathbf{3},\mathbf{1},-1/3)$	2	0	0
		$g^c_{\rm a}(\bar{\mathbf{3}},\mathbf{1},1/3)$			
h	$(\mathbf{1},\mathbf{2},\mathbf{2})$	$\bar{H}(\mathbf{1},\mathbf{2},1/2)$	0	1	0
		$H(\mathbf{1},\mathbf{2},-1/2)$			
P	$(\mathbf{1},\mathbf{1},\mathbf{1})$	$P(\mathbf{1},\mathbf{1},0)$	1	-1	0
$\bar{P}$	$(\mathbf{1},\mathbf{1},\mathbf{1})$	$\bar{P}(\mathbf{1},\mathbf{1},0)$	0	1	0

The Initial Superpotential

We Focus on the PS and PQ-invariant Superpotential

$$W_1 = W_{\rm MSSM} + W_{\rm PQ} + W_{\rm HPS} \quad \text{Where}$$

- $W_{\rm MSSM} = y_{ij}F_i\boldsymbol{h}F^c_j = y_{ij}F_i\left(\bar{H}\quad H\right)F^c_j =$
$y_{ij}\left(H^{\sf T}\boldsymbol{\varepsilon}L_ie^c_j - \bar{H}^{\sf T}\boldsymbol{\varepsilon}L_i\nu^c_j + H^{\sf T}\varepsilon Q_{ia}d^c_{ja} - \bar{H}^{\sf T}\varepsilon Q_{ia}u^c_{ja}\right),$
With $\varepsilon = \begin{pmatrix}0 & 1\\ -1 & 0\end{pmatrix}$, $Q_{ia} = \begin{pmatrix}u_{ia}\\ d_{ia}\end{pmatrix}$ and $L_i = \begin{pmatrix}\nu_i\\ e_i\end{pmatrix}$.
- $W_{\rm MSSM}$ Leads To Yukawa Unification **(YU)**, I.e.,

$$\boxed{h_t(M_{\rm GUT}) = h_b(M_{\rm GUT}) = h_\tau(M_{\rm GUT}) = y_{33}}$$

Super-fields	Represe-ntations under G_{PS}	Decompo-sitions under G_{SM}	Global Charges R	Global Charges PQ	Global Charges $\mathbb{Z}_2^{mp}$
Matter Superfields					
F_i	$(\mathbf{4},\mathbf{2},\mathbf{1})$	$Q_{ia}(\mathbf{3},\mathbf{2},1/6)$	1	−1	1
		$L_i(\mathbf{1},\mathbf{2},-1/2)$			
F_i^c	$(\bar{\mathbf{4}},\mathbf{1},\mathbf{2})$	$u^c_{ia}(\bar{\mathbf{3}},\mathbf{1},-2/3)$	1	0	−1
		$d^c_{ia}(\bar{\mathbf{3}},\mathbf{1},1/3)$			
		$\nu^c_i(\mathbf{1},\mathbf{1},0)$			
		$e^c_i(\mathbf{1},\mathbf{1},1)$			
Higgs Superfields					
H^c	$(\bar{\mathbf{4}},\mathbf{1},\mathbf{2})$	$u^c_{Ha}(\bar{\mathbf{3}},\mathbf{1},-2/3)$	0	0	0
		$d^c_{Ha}(\bar{\mathbf{3}},\mathbf{1},1/3)$			
		$\nu^c_H(\mathbf{1},\mathbf{1},0)$			
		$e^c_H(\mathbf{1},\mathbf{1},1)$			
$\bar{H}^c$	$(\mathbf{4},\mathbf{1},\mathbf{2})$	$\bar{u}^c_{Ha}(\mathbf{3},\mathbf{1},2/3)$	0	0	0
		$\bar{d}^c_{Ha}(\mathbf{3},\mathbf{1},-1/3)$			
		$\bar{\nu}^c_H(\mathbf{1},\mathbf{1},0)$			
		$\bar{e}^c_H(\mathbf{1},\mathbf{1},-1)$			
S	$(\mathbf{1},\mathbf{1},\mathbf{1})$	$S(\mathbf{1},\mathbf{1},0)$	2	0	0
G	$(\mathbf{6},\mathbf{1},\mathbf{1})$	$\bar{g}^c_a(\mathbf{3},\mathbf{1},-1/3)$	2	0	0
		$g^c_a(\bar{\mathbf{3}},\mathbf{1},1/3)$			
h	$(\mathbf{1},\mathbf{2},\mathbf{2})$	$\bar{H}(\mathbf{1},\mathbf{2},1/2)$	0	1	0
		$H(\mathbf{1},\mathbf{2},-1/2)$			
P	$(\mathbf{1},\mathbf{1},\mathbf{1})$	$P(\mathbf{1},\mathbf{1},0)$	1	−1	0
$\bar{P}$	$(\mathbf{1},\mathbf{1},\mathbf{1})$	$\bar{P}(\mathbf{1},\mathbf{1},0)$	0	1	0

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$y_{ij}\left(H^{\sf T}\boldsymbol{\varepsilon}L_ie_j^c - \bar{H}^{\sf T}\boldsymbol{\varepsilon}L_i\nu_j^c + H^{\sf T}\varepsilon Q_{ia}d_{ja}^c - \bar{H}^{\sf T}\varepsilon Q_{ia}u^c_{ja}\right)$,
With $\varepsilon = \begin{pmatrix}0 & 1\\ -1 & 0\end{pmatrix}$, $Q_{ia} = \begin{pmatrix}u_{ia}\\ d_{ia}\end{pmatrix}$ and $L_i = \begin{pmatrix}\nu_i\\ e_i\end{pmatrix}$.
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- $$W_{\rm PQ} = \lambda_{\rm PQ}\frac{P^2\bar{P}^2}{M_{\rm S}} - \underbrace{\lambda_\mu\frac{P^2}{2M_{\rm S}}{\rm Tr}\left(\boldsymbol{h}\varepsilon\boldsymbol{h}^{\sf T}\varepsilon\right)},$$
to Generate $\mu = \lambda_\mu f_a^2/M_{\rm S} \sim 1$ TeV
- $$W_{\rm HPS} = \lambda S\left(\bar{H}^cH^c - M^2\right) + \underbrace{\lambda_{i\nu^c}\frac{\left(\bar{H}^cF_i^c\right)^2}{M_{\rm S}}}$$
to Generate Masses for RHNs

SUPER-FIELDS	REPRESENTATIONS UNDER $G_{\rm PS}$	DECOMPOSITIONS UNDER $G_{\rm SM}$	GLOBAL CHARGES R	PQ	$\mathbb{Z}_2^{\rm mp}$
MATTER SUPERFIELDS					
F_i	$({\bf 4},{\bf 2},{\bf 1})$	$Q_{ia}({\bf 3},{\bf 2},1/6)$	1	-1	1
		$L_i({\bf 1},{\bf 2},-1/2)$			
F^c_i	$(\bar{\bf 4},{\bf 1},{\bf 2})$	$u^c_{ia}(\bar{\bf 3},{\bf 1},-2/3)$	1	0	-1
		$d^c_{ia}(\bar{\bf 3},{\bf 1},1/3)$			
		$\nu^c_i({\bf 1},{\bf 1},0)$			
		$e^c_i({\bf 1},{\bf 1},1)$			
HIGGS SUPERFIELDS					
H^c	$(\bar{\bf 4},{\bf 1},{\bf 2})$	$u^c_{Ha}(\bar{\bf 3},{\bf 1},-2/3)$	0	0	0
		$d^c_{Ha}(\bar{\bf 3},{\bf 1},1/3)$			
		$\nu^c_H({\bf 1},{\bf 1},0)$			
		$e^c_H({\bf 1},{\bf 1},1)$			
$\bar H^c$	$({\bf 4},{\bf 1},{\bf 2})$	$\bar u^c_{Ha}({\bf 3},{\bf 1},2/3)$	0	0	0
		$\bar d^c_{Ha}({\bf 3},{\bf 1},-1/3)$			
		$\bar\nu^c_H({\bf 1},{\bf 1},0)$			
		$\bar e^c_H({\bf 1},{\bf 1},-1)$			
S	$({\bf 1},{\bf 1},{\bf 1})$	$S({\bf 1},{\bf 1},0)$	2	0	0
G	$({\bf 6},{\bf 1},{\bf 1})$	$\bar g^c_{\rm a}({\bf 3},{\bf 1},-1/3)$	2	0	0
		$g^c_{\rm a}(\bar{\bf 3},{\bf 1},1/3)$			
h	$({\bf 1},{\bf 2},{\bf 2})$	$\bar H({\bf 1},{\bf 2},1/2)$	0	1	0
		$H({\bf 1},{\bf 2},-1/2)$			
P	$({\bf 1},{\bf 1},{\bf 1})$	$P({\bf 1},{\bf 1},0)$	1	-1	0
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- $$W_{\rm PQ} = \lambda_{\rm PQ}\frac{P^2\bar P^2}{M_{\rm S}} - \underbrace{\lambda_\mu\frac{P^2}{2M_{\rm S}}{\rm Tr}\left(\boldsymbol{h}\varepsilon\boldsymbol{h}^{\sf T}\varepsilon\right)}$$,

TO GENERATE $\mu = \lambda_\mu f_a^2/M_{\rm S} \sim 1$ TeV

- $$W_{\rm HPS} = \lambda S\left(\bar H^cH^c - M^2\right) + \underbrace{\lambda_{i\nu^c}\frac{\left(\bar H^cF^c_i\right)^2}{M_{\rm S}}}$$

TO GENERATE MASSES FOR RHNs

$$+ \underbrace{\lambda_H H^{c\,\sf T}G\varepsilon H^c + \lambda_{\bar H}\bar H^c\bar G\varepsilon\bar H^{c\,\sf T}}$$

TO GENERATE MASSES FOR $d^c_H, \bar d^c_H$

WITH $G = \begin{pmatrix}\varepsilon_{\rm abc}g^c_{\rm c} & \bar g^c_{\rm a}\\ -\bar g^c_{\rm a} & 0\end{pmatrix} \Rightarrow \bar G = \begin{pmatrix}\varepsilon_{\rm abc}\bar g^c_{\rm c} & g^c_{\rm a}\\ -g^c_{\rm a} & 0\end{pmatrix}$

Soft SUSY Breaking Terms

Working in the Context of **CMSSM**, We Adopt **Universal** Initial Conditions At $M_{\rm GUT} \simeq 2\times 10^{16}$ GeV:

- A Common Mass $M_{1/2}$ For **Gauginos**:

$$M_1(M_{\rm GUT}) = M_2(M_{\rm GUT}) = M_3(M_{\rm GUT}) = M_{1/2}$$

$$\Rightarrow\;\; M_1(M_{\rm SUSY}) < M_2(M_{\rm SUSY}) < M_3(M_{\rm SUSY}).$$

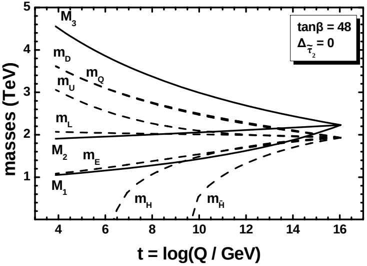
- A Common Mass m_0 For Scalars:
  - **Sleptons**, $m_L(M_{\rm GUT}) = m_E(M_{\rm GUT}) = m_0$
  - **Squarks**,

$$m_Q(M_{\rm GUT}) = m_U(M_{\rm GUT}) = m_D(M_{\rm GUT}) = m_0,$$

  - **Higgs**, $m_H(M_{\rm GUT}) = m_{\bar H}(M_{\rm GUT}) = m_0$.

- A Common Trilinear Coupling Constant, A_0:

$$A_t(M_{\rm GUT}) = A_b(M_{\rm GUT}) = A_\tau(M_{\rm GUT}) = A_0.$$



The Minimization of the Tree Level Effective Potential at an Optimal Scale $M_{\rm SUSY} = \sqrt{m_{\tilde t_1} m_{\tilde t_2}}$ Gives:

$$\mu^2(M_{\rm SUSY}) \simeq \frac{m_H^2(M_{\rm SUSY}) - m_{\bar H}^2(M_{\rm SUSY})\tan^2\beta}{\tan^2\beta - 1} - \frac{1}{2}M_Z^2 \cdot \;\; \Big(\textbf{Naturality}\text{ Entails: } \mu \sim m_{H,\bar H} \sim M_Z\Big)$$

Free Parameters Of **CMSSM**: $M_{1/2},\ m_0,\ A_0,\ \tan\beta = \langle \bar H\rangle/\langle H\rangle,\ {\rm sign}\mu$.

[1] B.C. Allanach (2002); G. Belanger, F. Boudjema, A. Pukhov, and A. Semenov, http://lapth.in2p3.fr/micromegas

SOFT SUSY BREAKING TERMS

WORKING IN THE CONTEXT OF **CMSSM**, WE ADOPT **UNIVERSAL** INITIAL CONDITIONS AT $M_{\rm GUT} \simeq 2\times 10^{16}$ GeV:

- A COMMON MASS $M_{1/2}$ FOR **GAUGINOS**:

$$M_1(M_{\rm GUT}) = M_2(M_{\rm GUT}) = M_3(M_{\rm GUT}) = M_{1/2}$$

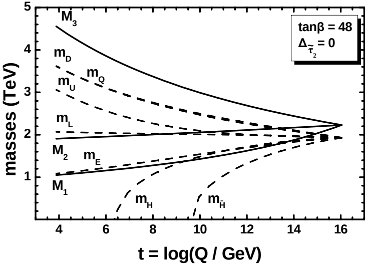
$$\Rightarrow\ M_1(M_{\rm SUSY}) < M_2(M_{\rm SUSY}) < M_3(M_{\rm SUSY}).$$

- A COMMON MASS m_0 FOR SCALARS:
  - **SLEPTONS**, $m_L(M_{\rm GUT}) = m_E(M_{\rm GUT}) = m_0$
  - **SQUARKS**,

$$m_Q(M_{\rm GUT}) = m_U(M_{\rm GUT}) = m_D(M_{\rm GUT}) = m_0,$$

  - **HIGGS**, $m_H(M_{\rm GUT}) = m_{\bar H}(M_{\rm GUT}) = m_0$.
- A COMMON TRILINEAR COUPLING CONSTANT, A_0:

$$A_t(M_{\rm GUT}) = A_b(M_{\rm GUT}) = A_\tau(M_{\rm GUT}) = A_0.$$



THE MINIMIZATION OF THE TREE LEVEL EFFECTIVE POTENTIAL AT AN OPTIMAL SCALE $M_{\rm SUSY} = \sqrt{m_{\tilde t_1} m_{\tilde t_2}}$ GIVES:

$$\mu^2(M_{\rm SUSY}) \simeq \frac{m_H^2(M_{\rm SUSY}) - m_{\bar H}^2(M_{\rm SUSY})\tan^2\beta}{\tan^2\beta - 1} - \frac{1}{2}M_Z^2\,.\quad \left(\textbf{NATURALITY}\ \text{ENTAILS:}\ \mu\sim m_{H,\bar H}\sim M_Z\right)$$

FREE PARAMETERS OF **CMSSM**: $M_{1/2},\ m_0,\ A_0,\ \tan\beta = \langle\bar H\rangle/\langle H\rangle,\ {\rm sign}\mu$.

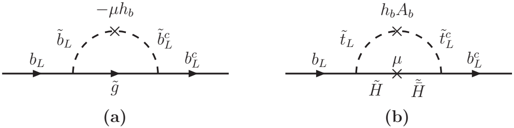
SOFTWARE USED FOR THE ANALYSIS OF THE PARAMETER SPACE OF CMSSM

- `Mathematica` FOR SOLVING THE RGEs (GAUGE AND YUKAWA CONSTANTS AND SOFT SUSY MASSES AND TRILINEARS);
- `SOFTSUSY`[1] FOR THE CALCULATION OF SUSY SPECTRUM;
- `micrOMEGAs2.4.5`[1] FOR THE COMPUTATION OF THE VARIOUS COSMOPHENOMELOGICAL CONSTRAINTS.

[1] *B.C. Allanach (2002); G. Belanger, F. Boudjema, A. Pukhov, and A. Semenov,* `http://lapth.in2p3.fr/micromegas`

SUSY Corrections to the Fermion Masses

- **(a) Sbottom-Gluino** And **(b) Stop-Higgsino** Loops Give Rise to Sizable (20%) **SUSY** Corrections [2] to b-Quark Mass:



$$\Delta m_b \simeq \frac{g_3^2}{6\pi^2} m_{\tilde{g}} \mu \tan\beta \, I\left(m_{\tilde{g}}, m_{\tilde{b}_1}, m_{\tilde{b}_2}\right) + \frac{h_t^2}{16\pi^2} A_t \mu \tan\beta \, I\left(\mu, m_{\tilde{t}_1}, m_{\tilde{t}_2}\right)$$

Where $I(x, y, z)$ is a Dimensionless Function Which Arises From the Loop Computation.

[2] L. Hall, R. Rattazzi and U. Sarid (1994); M. Carena et al. (1994); D. Pierce et al. (1997); S.F. King and M. Oliveira (2000).

SUSY Corrections to the Fermion Masses

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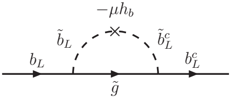
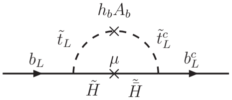


(a)

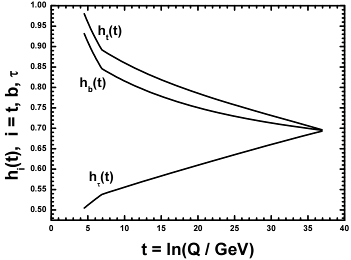


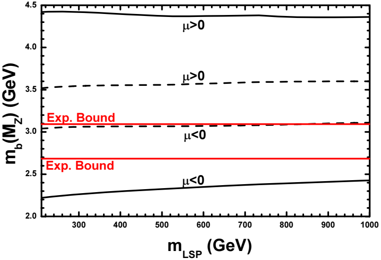
(b)

$$\Delta m_b \simeq \frac{g_3^2}{6\pi^2} m_{\tilde{g}} \mu \tan\beta \, I\left(m_{\tilde{g}}, m_{\tilde{b}_1}, m_{\tilde{b}_2}\right) + \frac{h_t^2}{16\pi^2} A_t \mu \tan\beta \, I\left(\mu, m_{\tilde{t}_1}, m_{\tilde{t}_2}\right)$$

Where $I(x,y,z)$ is a Dimensionless Function Which Arises From the Loop Computation.

- We Require $m_t(\text{physical}) = 173$ GeV $\Leftrightarrow$ $m_t(m_t) = 164.6$ GeV, $m^c_\tau(M_Z) = m_\tau(M_Z)\,(1 + \Delta m_\tau) = 1.748$ GeV





With Given $m_t(m_t)$ and m^c_τ YU Leads to an **Unacceptable** $m^c_b(M_Z) = m_b(M_Z)\,(1 + \Delta m_b)$ in the Context of CMSSM.

[2] L. Hall, R. Rattazzi and U. Sarid (1994); M. Carena et al. (1994); D. Pierce et al. (1997); S.F. King and M. Oliveira (2000).

Super-fields	Represen-tasions under G_{PS}	Trasfor-mations under G_{PS}	Global Charges R	PQ	$\mathbb{Z}_2^{mp}$
Extra Higgs Fields					
h'	$(\mathbf{15},\mathbf{2},\mathbf{2})$	$U_c^* U_L h' U_R^{\mathsf{T}} U_c^{\mathsf{T}}$	0	1	0
$\bar{h}'$	$(\mathbf{15},\mathbf{2},\mathbf{2})$	$U_c U_L \bar{h}' U_R^{\mathsf{T}} U_c^{\dagger}$	1	−1	0
ϕ	$(\mathbf{15},\mathbf{1},\mathbf{3})$	$U_c U_R \phi U_R^{\dagger} U_c^{\dagger}$	0	0	0
$\bar{\phi}$	$(\mathbf{15},\mathbf{1},\mathbf{3})$	$U_c U_R \bar{\phi} U_R^{\dagger} U_c^{\dagger}$	1	0	0
ϕ'	$(\mathbf{15},\mathbf{1},\mathbf{1})$	$U_c \phi' U_c^{\dagger}$	0	0	0
$\bar{\phi}'$	$(\mathbf{15},\mathbf{1},\mathbf{1})$	$U_c \bar{\phi}' U_c^{\dagger}$	1	0	0

The Additional Superpotential Terms

- We **Add** the Pati-Salam and Peccei-Quinn (**PQ**) Invariant Superpotential Terms

$$W_2 = W_H + W_m + W_{MSSM'} \quad \text{Where}$$

- $$W_H = m\phi\bar{\phi} + m'\phi'\bar{\phi}' - S\left(\beta\phi^2 + \beta'\phi'^2\right) + (\lambda\bar{\phi} + \lambda'\bar{\phi}')H^c\bar{H}^c,$$

- From the Scalar Potential We Find That The **SUSY Vacuum** Lies At
$\langle H^c\bar{H}^c\rangle \sim \langle\phi\rangle^2 \sim \langle\phi'\rangle^2 \sim M_{GUT}^2, \langle S\rangle = \langle\bar{\phi}\rangle = \langle\bar{\phi}'\rangle = 0$

- W_m Is The Part of W Which Is Responsible For The **Mixing** of the Doublets in h and h'

$$W_m = M_{h}\bar{h}'h' + \lambda_3\phi\bar{h}'h + \lambda_1\phi'\bar{h}'h = M_{h}\bar{h}_1'^{\mathsf{T}}\varepsilon\left(h_2' + \alpha_2 h_2\right) + M_{h}\left(h_1'^{\mathsf{T}} + \alpha_1 h_1^{\mathsf{T}}\right)\varepsilon\bar{h}_2' + \cdots, \quad \text{With} \quad \alpha_{1,2} = F(\langle\phi\rangle, \langle\phi'\rangle) \sim 1$$

- Models With Only ϕ and $\bar{\phi}$ ($\alpha_1 = -\alpha_2$) Or ϕ' and $\bar{\phi}'$ ($\alpha_1 = \alpha_2$) Have Been Excluded[3] Within **CMSSM**.
- We Obtain Two Pairs Of Superheavy Doublets With Mass M_{h} and One Pair Which Remains **Massless** At The GUT Scale:

$$\bar{h}_1', \; H_2' \;\text{ and }\; H_1', \; \bar{h}_2', \quad \text{Where} \quad H_r' = \frac{h_r' + \alpha_r h_r}{\sqrt{1 + |\alpha_r|^2}}, \; r = 1,2 \;\Rightarrow\; H_r = \frac{-\alpha_r^* h_r' + h_r}{\sqrt{1 + |\alpha_r|^2}}, \quad (1)$$

Which Can Be Identified With The **Electroweak Doublets** $H_1 := H$ and $H_2 := \bar{H}$ And Are Orthogonal to the H_r'.

[3] M.E. Gómez, G. Lazarides & C.P. (2003); N. Karagiannakis, G. Lazarides & C.P. (2013)

Super-fields	Represen-tasions under G_{PS}	Trasfor-mations under G_{PS}	Global Charges R	PQ	$\mathbb{Z}_2^{mp}$
		Extra Higgs Fields			
h'	$(\mathbf{15},\mathbf{2},\mathbf{2})$	$U_c^* U_L h' U_R^{\mathsf{T}} U_c^{\mathsf{T}}$	0	1	0
$\bar{h}'$	$(\mathbf{15},\mathbf{2},\mathbf{2})$	$U_c U_L \bar{h}' U_R^{\mathsf{T}} U_c^{\dagger}$	1	-1	0
ϕ	$(\mathbf{15},\mathbf{1},\mathbf{3})$	$U_c U_R \phi U_R^{\dagger} U_c^{\dagger}$	0	0	0
$\bar{\phi}$	$(\mathbf{15},\mathbf{1},\mathbf{3})$	$U_c U_R \bar{\phi} U_R^{\dagger} U_c^{\dagger}$	1	0	0
ϕ'	$(\mathbf{15},\mathbf{1},\mathbf{1})$	$U_c \phi' U_c^{\dagger}$	0	0	0
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The Additional Superpotential Terms

- We **Add** the Pati-Salam and Peccei-Quinn (**PQ**) Invariant Superpotential Terms

$$W_2 = W_{\rm H} + W_{\rm m} + W_{\rm MSSM'} \quad \text{Where}$$

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$$W_{\rm m} = M_{h}\bar{h}'h' + \lambda_3\phi\bar{h}'h + \lambda_1\phi'\bar{h}'h = M_{h}\bar{h}_1'^{\mathsf{T}}\varepsilon\left(h_2' + \alpha_2 h_2\right) + M_{h}\left(h_1'^{\mathsf{T}} + \alpha_1 h_1^{\mathsf{T}}\right)\varepsilon\bar{h}_2' + \cdots, \quad \text{With} \quad \alpha_{1,2} = F\left(\langle\phi\rangle, \langle\phi'\rangle\right) \sim 1$$

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$$\bar{h}_1',\ H_2' \ \text{and}\ H_1',\ \bar{h}_2', \quad \text{Where} \quad H_r' = \frac{h_r' + \alpha_r h_r}{\sqrt{1+|\alpha_r|^2}},\ r = 1,2 \ \Rightarrow\ H_r = \frac{-\alpha_r^* h_r' + h_r}{\sqrt{1+|\alpha_r|^2}}, \qquad (1)$$

Which Can Be Identified With The **Electroweak Doublets** $H_1 := H$ and $H_2 := \bar{H}$ And Are Orthogonal to the H_r'.
- The **Yukawa Interactions** Of The 3Rd Family Of Fermions Are Described By The Following **Two** Superpotential Terms

$$W_{\rm MSSM} + W_{\rm MSSM'} = y_{33}F_3 h F_3^c + 2y_{33}'F_3 h' F_3^c = y_{33}F_3\left(h_2 + 2\rho h_2' \quad h_2 + 2\rho h_2'\right)F_3^c$$

With $\rho := y_{33}'/y_{33}$ and $h' \sim T_c^{15}$ and Solving Eq. (1) w.r.t. h_r and h_r', We Obtain

$$h_r = (H_r + \alpha_r^* H_r')/\left(\sqrt{1+|\alpha_r|^2}\right) \ \text{and}\ h_r' = (-\alpha_r H_r + H_r')/\left(\sqrt{1+|\alpha_r|^2}\right).$$

[3] M.E. Gómez, G. Lazarides & C.P. (2003); N. Karagiannakis, G. Lazarides & C.P. (2013)

Yukawa Quasi-Unification Conditions

- We Can Readily Derive The Superpotential Terms of the MSSM – Except for the μ Term:

$$W_{\rm MSSM} + W_{\rm MSSM'} = -h_t \bar{H}^{\sf T} \varepsilon Q_3 u_3^c + h_b H^{\sf T} \varepsilon Q_3 d_3^c + h_\tau H^{\sf T} \varepsilon L_3 e_3^c - h_{\nu_\tau} \bar{H}^{\sf T} \varepsilon L_3 \nu_3^c$$

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- Where The h_t, h_b and h_τ Must Obey The Following Set of **Generalized Yukawa Quasi-Unification Conditions**:

$$h_t(M_{\rm GUT}) : h_b(M_{\rm GUT}) : h_\tau(M_{\rm GUT}) = \left|\frac{1-\rho\alpha_2/\sqrt{3}}{\sqrt{1+|\alpha_2|^2}}\right| : \left|\frac{1-\rho\alpha_1/\sqrt{3}}{\sqrt{1+|\alpha_1|^2}}\right| : \left|\frac{1+\sqrt{3}\rho\alpha_1}{\sqrt{1+|\alpha_1|^2}}\right|$$

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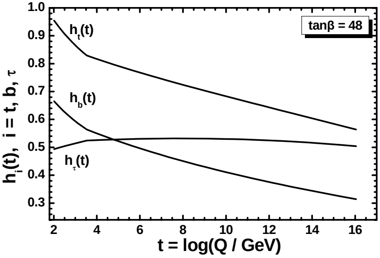
- For ρ, α_1 and $\alpha_2 \sim 1$, We Expect That $h_m/h_n \sim 1$ with $m, n = t, b, \tau$.

  - **Stau-Coannihilation Region**



- E.g. For $\tan\beta = 48$, $\Delta_{\tilde{\tau}_2} \simeq 0$, $A_0/M_{1/2} = -1.4$ and $M_{1/2} = 2.2$ TeV we Find $h_t/h_\tau(M_{\rm GUT}) = 1.117$ $h_b/h_\tau(M_{\rm GUT}) = 0.623$ and $h_t/h_b(M_{\rm GUT}) = 1.792$.

YUKAWA QUASI-UNIFICATION CONDITIONS

- WE CAN READILY DERIVE THE SUPERPOTENTIAL TERMS OF THE MSSM – EXCEPT FOR THE μ TERM:

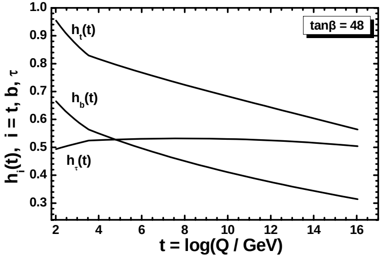
$$W_{\rm MSSM} + W_{\rm MSSM'} = -h_t \bar{H}^{\sf T} \varepsilon Q_3 u_3^c + h_b H^{\sf T} \varepsilon Q_3 d_3^c + h_\tau H^{\sf T} \varepsilon L_3 e_3^c - h_{\nu_\tau} \bar{H}^{\sf T} \varepsilon L_3 \nu_3^c$$

- WHERE THE h_t, h_b AND h_τ MUST OBEY THE FOLLOWING SET OF **GENERALIZED YUKAWA QUASI-UNIFICATION CONDITIONS**:

$$h_t(M_{\rm GUT}) : h_b(M_{\rm GUT}) : h_\tau(M_{\rm GUT}) = \left|\frac{1-\rho\alpha_2/\sqrt{3}}{\sqrt{1+|\alpha_2|^2}}\right| : \left|\frac{1-\rho\alpha_1/\sqrt{3}}{\sqrt{1+|\alpha_1|^2}}\right| : \left|\frac{1+\sqrt{3}\rho\alpha_1}{\sqrt{1+|\alpha_1|^2}}\right|$$

- FOR ρ, α_1 AND $\alpha_2 \sim 1$, WE EXPECT THAT $h_m/h_n \sim 1$ WITH $m, n = t, b, \tau$.

- **STAU-COANNIHILATION REGION**



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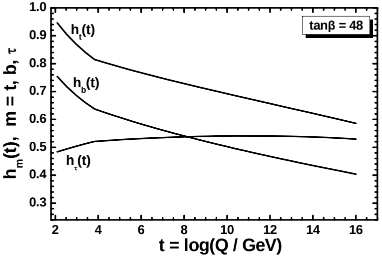
- **FOCUS-POINT REGION**



- E.G. FOR $\tan\beta = 48$, $M_{1/2} = 2.9$ TeV, $A_0/M_{1/2} = -1.5$ AND $m_0 = 8.8$ TeV WE FIND $h_t/h_\tau(M_{\rm GUT}) = 1.107$ $h_b/h_\tau(M_{\rm GUT}) = 0.763$ AND $h_t/h_b(M_{\rm GUT}) = 1.45$.

Cosmo-Phenomenological Requirements: Preliminaries

Phenomenological Requirements

1. Mass Of the **Lighter CP- Even Higgs** Boson:

$$122 \lesssim m_h/\mathrm{GeV} \lesssim 129.2.$$

2. The **Branching Ratios** of The Rare B decays:

- $\mathrm{BR}\,(B_s \to \mu^+\mu^-) \lesssim 4.2\times 10^{-9}$ or
  $1.1 \lesssim \mathrm{BR}\,(B_s \to \mu^+\mu^-)/10^{-9} \lesssim 6.4.$;
- $2.84\times 10^{-4} \lesssim \mathrm{BR}\,(b \to s\gamma) \lesssim 4.2\times 10^{-4}$;
- $0.52 \lesssim \mathrm{R}\,(B_u \to \tau\nu) \lesssim 2.04.$

3. The Bounds on the **Masses of Sparticles**;
   Most Notably $m_{\chi^\pm} \geq 103.5$ GeV and $m_{\tilde{g}} \geq 1.4$ TeV.

4. **Muon Anomalous Magnetic Moment** of μ, a_μ:

$$7.5\times 10^{-10} \lesssim \delta a_\mu = a_\mu^{\rm exp} - a_\mu^{\rm SM} \lesssim 42.3\times 10^{-10}.$$

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Cosmological Considerations

• To Avoid the **Proton Decay** Via Terms

$$UDD,\ Q^{\mathsf{T}}\varepsilon LD,\ L^{\mathsf{T}}\varepsilon LE,\ L^{\mathsf{T}}\varepsilon H,$$

We Require that $\mathcal{L}_{\text{MSSM}}$ Is Invariant Under A Multiplicative Quantum Number Defined As Follows:

$$R = \begin{cases} +1 & \text{For SM Particles and Higgs} \\ -1 & \text{For Sparticles} \end{cases}$$

With The Following Consequences:

- In Every Term of $\mathcal{L}_{\text{MSSM}}$ There is **Even** Number of Sparticles.
- The Sparticles Can Be Produced in Pairs;
- The Heavier Sparticles Decay to the Lighter;
- The Lightest SUSY Particle (**LSP**) Is Stable.
- The LSP Is Weakly Interacting (I.e., It Interacts Via The Exchange of a Heavier Sparticle)

• The LSP Can Act As A **Viable** CDM Candidate if

$$\Omega_{\text{LSP}}h^2 \lesssim 0.12 \quad \text{at } 95\% \text{ c.l.}$$

• The Spin-Independent **LSP-Proton** Cross Section Is To be Lower Than the LUX results.

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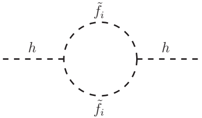
$$\boxed{?????? \quad \lesssim m_{\mathrm{LSP}}/\mathrm{GeV} \lesssim \quad ?????}$$

1. MASS OF THE LIGHTER CP- EVEN (SM-LIKE) HIGGS BOSON

- AT TREE LEVEL WE OBTAIN $m_h \leq M_Z \cos 2\beta \leq M_Z$.
- SUSY CORRECTIONS ARISE FROM SFERMIONS $\tilde{f} = \tilde{t},\ \tilde{b}$ LOOPS WHICH INCREASE m_h AS FOLLOWS[4]

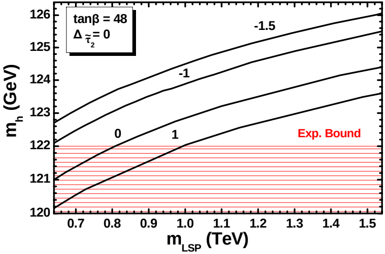


$$\Delta m_h^2 \simeq \ln \frac{M_{\rm SUSY}^2}{m_t^2} + \frac{X_t^2}{M_{\rm SUSY}^2}\left(1 - \frac{X_t^2}{12 M_{\rm SUSY}^2}\right)$$

WITH $X_t = A_t - \mu \cot\beta$ AND $M_{\rm SUSY} \simeq \sqrt{m_{\tilde{t}_1} m_{\tilde{t}_2}}$.

- THE LHC [5] DISCOVERED A BOSONIC PARTICLE WHICH FITS THE PROFILE OF THE SM HIGGS WITH MASS

$$m_h = \begin{cases} 125.3 \pm 0.4\ \text{(STAT)} \pm 0.5\ \text{(SYS) GeV} & \text{CMS} \\ 126.0 \pm 0.4\ \text{(STAT)} \pm 0.4\ \text{(SYS) GeV} & \text{ATLAS} \end{cases} \stackrel{(*)}{\Longrightarrow} 122 \lesssim m_h/\mathrm{GeV} \lesssim 129.2.$$



$(^*)$ ALLOWING FOR A THEORETICAL UNCERTAINTY OF ± 1.5 GeV.

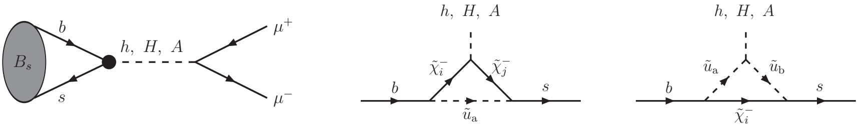
- WE PRESENT m_h VS $m_{\rm LSP}$ FOR VARIOUS $A_0/M_{1/2}$'S.
- A **LOWER** BOUND ON $m_{\rm LSP}$ CAN BE INFERRED FROM THE LOWER BOUND ON m_h
- WE REMARK THAT m_h INCREASES WITH $m_{\rm LSP}$ AND AS $A_0/M_{1/2}$ DECREASES TO VALUES LOWER THAN ZERO. THIS OCCURS SINCE X_t IS MAXIMIZED FOR $A_0/M_{1/2} < 0$.
- AS A CONSEQUENCE THE BOUND ON $m_{\rm LSP}$ FOR $A_0/M_{1/2} < 0$ IS LESS RESTRICTIVE.

[4] *M. Drees and M. Nojiri (1992); J.Ellis, G. and F. Zwirner (1991); S. Heinemeyer, W. Hollik and G. Weiglein (2000).*

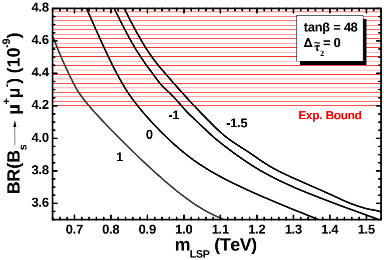
[5] *ATLAS Collaboration (2012); CMS Collaboration (2012).*

2. The Branching Ratio of $B_s \to \mu^+\mu^-$

• The SUSY Contributions Originate[6] from Neutral Higgs Bosons in **Chargino-, $H^\pm$-, and $W^\pm$-Mediated Penguins** Which are Particularly Important For Large $\tan\beta$'s:



• We Impose the Following Very Stringent Constraint $\mathrm{BR}\left(B_s \to \mu^+\mu^-\right) \sim \left|A_t \tan^3\beta / m_A\right|^2 \lesssim 4.2 \times 10^{-9}$ (95% c.l.[7]) (i) Although There is Recently a Novel Less Restrictive Bound $1.1 \lesssim \mathrm{BR}\left(B_s \to \mu^+\mu^-\right)/10^{-9} \lesssim 6.4$ (95% c.l.).

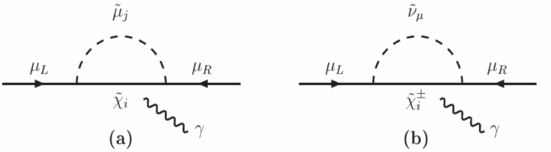


• We Present $\mathrm{BR}\left(B_s \to \mu^+\mu^-\right)$ Vs $m_{\rm LSP}$ for Various $A_0/M_{1/2}$'s.
• Eq. (i) Imposes a **Lower** Bound on $m_{\rm LSP}$
• We Remark that $\mathrm{BR}\left(B_s \to \mu^+\mu^-\right)$ Decreases As $m_{\rm LSP}$ and $A_0/M_{1/2}$ Increases.
• As A Consequence the Bound on $m_{\rm LSP}$ for $A_0/M_{1/2} < 0$, Favored by m_h Data, is More Restrictive.
• The Inclusion Of $\phi, \bar{\phi}$ **and** $\phi'\bar{\phi}'$ Assists us to Decrease $\tan\beta$ Below 50, Reducing Thereby $\mathrm{BR}\left(B_s \to \mu^+\mu^-\right)$.

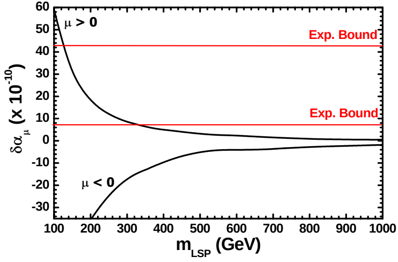
[6] *P.H. Chankowski and L. Slawianowska (2001); C.S. Huang, W. Liao, Q.S. Yan, and S.H. Zhu (2001).*
[7] *LHCb (2012).*

3. MUON ANOMALOUS MAGNETIC MOMENT OF μ, a_μ

• THERE IS A $2.9-\sigma$ **DISCREPANCY** BETWEEN THE EXPERIMENTAL VALUE OF a_μ, $a_\mu^{\rm exp}$, AND THE ONE PREDICTED BY SM, $a_\mu^{\rm SM}$, WHICH CAN BE **ATTRIBUTED** TO SUSY CORRECTIONS[8] ARISING FROM **(a) SMUON - NEUTRALINO** AND **(b) SNEUTRINO - CHARGINO** LOOPS:



(i) $7.5\times10^{-10}\lesssim\delta a_\mu$ **(ii)** $\delta a_\mu\lesssim 42.3\times10^{-10}$, e^+e^- AND τ-DATA (95% C.L)[9] WHERE: $\delta a_\mu=a_\mu^{\rm exp}-a_\mu^{\rm SM}$



• WE PRESENT δa_μ VS $m_{\rm LSP}$ FOR $A_0/M_{1/2}=0$ AND BOTH SIGNS OF μ.
• EQ. (ii) IMPOSES A **LOWER** BOUND ON $m_{\rm LSP}$ AND EQ. (i) IMPOSES AN **UPPER** BOUND ON $m_{\rm LSP}$, NOT COMPATIBLE WITH THE BOUND INFERRED BY $\Omega_{\rm LSP}h^2$ AS WE WILL SEE.
• THE $\mu<0$ CASE IS MORE **DISFAVORED** THAN THE $\mu>0$ CASE FROM THE δa_μ CONSIDERATIONS. THEREFORE, WE DECIDE TO USE $\mu>0$.

• ARE THESE LOWER LIMITS ON $m_{\rm LSP}$ **COMPATIBLE** WITH THE CANDIDACY OF LSP AS CDM PARTICLE?
• A REPLY TO THIS DILEMMA CAN BE GIVEN THE **COSMOLOGICAL** CONSIDERATION OF LSP AS A CDM CANDIDATE.

8 *J.G. Lopez, D. Nanopoulos and G. Wang (1995); T. Ibrahim and P. Nath (2000); S.P. Martin and J.D. Wells (2001).*
9 *G.W. Bennett et al. (2006); K. Hagiwara et al. (2011); T. Aoyama et al. (2012).*

The Standard Cosmological Scenario (SC)

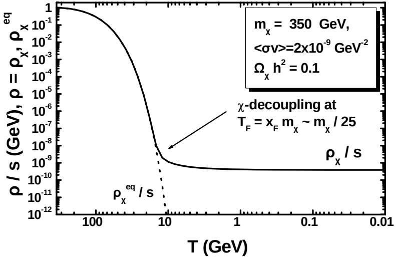
Assumptions of SC for the Decoupling of a Weekly Interacting Massive Particle (**WIMP**) χ from the Cosmic Bath:

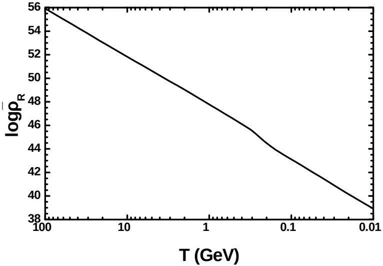
- The χ's Achieve **Kinetic And Chemical** Equilibrium. Therefore, the **Thermal Averaged Cross Section Times The Relative Velocity** of χ's is to be $\langle\sigma v\rangle \gtrsim 10^{-20}$ GeV^{-2}. Within a Specific Particle Model $\langle\sigma v\rangle$ can be Derive Self-Consistently from the (s)particle Spectrum of the Theory.
- The χ's Are Produced by **Thermal Scatterings**. The **Number Density** of χ, n_χ, Obey the **Boltzmann** Equation:

$$\dot{n}_\chi + 3Hn_\chi + \langle\sigma v\rangle\left(n_\chi^2 - n_\chi^{\rm eq2}\right) = 0 \ \text{With Initial Condition: } n_\chi(T = m_\chi) = n_\chi^{\rm eq}(x = 1) \ \ (\text{Note: } \rho_\chi = m_\chi n_\chi)$$

$$\text{Where } n_\chi^{\rm eq}(x) = \frac{g}{(2\pi)^{3/2}} m_\chi^3\, x^{3/2}\, e^{-1/x} P_2(1/x), \ \text{With } x = T/m_\chi,\ P_n(z) = 1 + (4n^2-1)/8z,\ g = 2$$

- The χ's Decouple During a **Radiation** Dominated Era, $H = \sqrt{\rho_{\rm R}}/\sqrt{3}m_{\rm P} \sim T^2$ And $sR^3 = {\rm cst} \ \Rightarrow\ TR = {\rm cst}$.





- The Relic Abundance of χ is Given By $\Omega_\chi = \rho_{\chi0}/\rho_{\rm c0} = m_\chi s_0 Y_{\chi0}/\rho_{\rm c0} \ \Rightarrow \underline{\Omega_\chi h^2 = 2.748 \cdot 10^8\ Y_{\chi0}\ m_\chi/\text{GeV}}$

Where m_χ, the Mass of WIMP χ and $Y_\chi = n_\chi/s$. Therefore $\underline{\Omega_\chi h^2 = f\left(m_\chi, \langle\sigma v\rangle\right)}$. Mostly $\underline{\Omega_\chi h^2 \sim m_\chi/\langle\sigma v\rangle}$.

The Relic Abundance of The Neutralino LSP, $\tilde{\chi}$, & the CMSSM Parameter Space

- Focusing on the Case of CMSSM, The Computation of $\langle\sigma v\rangle$ Includes **Annhilation** and **Coannihilation** Processes:

$$\langle\sigma v\rangle \sim \sigma_{\rm eff} \sim \sigma_{\rm LSP-LSP} + e^{-\Delta_{\rm NLSP}/x_{\rm F}}\sigma_{\rm LSP-NLSP} + e^{-2\Delta_{\rm NLSP}/x_{\rm F}}\sigma_{\rm LSP-NLSP^{(*)}}, \ \text{With } x_{\rm F} \sim \frac{1}{25} \text{ and } \Delta_{\rm NLSP} = \frac{m_{\rm NLSP}-m_{\rm LSP}}{m_{\rm LSP}}$$

- $\Omega_{\tilde{\chi}}h^2$ Can Be Consistent With Observations Only Into Well Localized **Portions** Of the CMSSM Parameter Space.

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1. Annihilation Processes ($\tilde{\chi}\tilde{\chi}$) - $\Delta_{\rm NLSP} \gg 0.25$

States: Initial	States: Final	Channels: Interactions
$\tilde{\chi}\tilde{\chi}$	$f\bar{f}$	$s(h)$, $s(H)$, $s(A)$, $s(Z)$
	$(f := t, \tau, b)$	$t(\tilde{f}_{1[2]})$, $u(\tilde{f}_{1[2]})$
	hh, hH, HH	$s(h)$, $s(H)$, $t(\tilde{\chi}_i^0)$, $u(\tilde{\chi}_i^0)$
	AA, ZA	$s(h)$, $s(H)$, $t(\tilde{\chi}_i^0)$, $u(\tilde{\chi}_i^0)$
	hA, HA	$s(Z)$, $s(A)$, $t(\tilde{\chi}_i^0)$, $u(\tilde{\chi}_i^0)$
	W^+W^-, H^+H^-	$s(h)$, $s(H)$, $s(Z)$, $t(\tilde{\chi}_i^\pm)$, $u(\tilde{\chi}_i^\pm)$
	H^+W^-	$s(h)$, $s(H)$, $s(A)$, $t(\tilde{\chi}_i^\pm)$, $u(\tilde{\chi}_i^\pm)$
	ZZ	$s(h)$, $s(H)$, $t(\tilde{\chi}_i^0)$, $u(\tilde{\chi}_i^0)$
	Zh, ZH	$s(A)$, $s(Z)$, $t(\tilde{\chi}_i^0)$, $u(\tilde{\chi}_i^0)$

The Relic Abundance of The Neutralino LSP, $\tilde{\chi}$, & the CMSSM Parameter Space

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$$\langle\sigma v\rangle \sim \sigma_{\rm eff} \sim \sigma_{\rm LSP-LSP} + e^{-\Delta_{\rm NLSP}/x_{\rm F}}\sigma_{\rm LSP-NLSP} + e^{-2\Delta_{\rm NLSP}/x_{\rm F}}\sigma_{\rm LSP-NLSP^{(*)}},\ \text{With } x_{\rm F} \sim \frac{1}{25} \text{ and } \Delta_{\rm NLSP} = \frac{m_{\rm NLSP} - m_{\rm LSP}}{m_{\rm LSP}}$$

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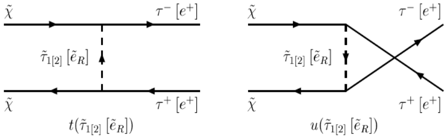
1. Annihilation Processes ($\tilde{\chi}\tilde{\chi}$) - $\Delta_{\rm NLSP} \gg 0.25$

States		Channels
Initial	Final	Interactions
$\tilde{\chi}\tilde{\chi}$	$f\bar{f}$	$s(h)$, $s(H)$, $s(A)$, $s(Z)$
	$(f := t, \tau, b)$	$t(\tilde{f}_{1[2]})$, $u(\tilde{f}_{1[2]})$
	hh, hH, HH	$s(h)$, $s(H)$, $t(\tilde{\chi}_i^0)$, $u(\tilde{\chi}_i^0)$
	AA, ZA	$s(h)$, $s(H)$, $t(\tilde{\chi}_i^0)$, $u(\tilde{\chi}_i^0)$
	hA, HA	$s(Z)$, $s(A)$, $t(\tilde{\chi}_i^0)$, $u(\tilde{\chi}_i^0)$
	W^+W^-, H^+H^-	$s(h)$, $s(H)$, $s(Z)$, $t(\tilde{\chi}_i^\pm)$, $u(\tilde{\chi}_i^\pm)$
	H^+W^-	$s(h)$, $s(H)$, $s(A)$, $t(\tilde{\chi}_i^\pm)$, $u(\tilde{\chi}_i^\pm)$
	ZZ	$s(h)$, $s(H)$, $t(\tilde{\chi}_i^0)$, $u(\tilde{\chi}_i^0)$
	Zh, ZH	$s(A)$, $s(Z)$, $t(\tilde{\chi}_i^0)$, $u(\tilde{\chi}_i^0)$

- **Bulk Region** With $m_0, M_{1/2} \ll 500$ GeV Where $\tilde{\chi}$ is Bino-like And The Dominant Processes Are



This Region Is **Excluded** by the LHC bound on m_h.

THE RELIC ABUNDANCE OF THE NEUTRALINO LSP, $\tilde{\chi}$, & THE CMSSM PARAMETER SPACE

- FOCUSING ON THE CASE OF CMSSM, THE COMPUTATION OF $\langle\sigma v\rangle$ INCLUDES **ANNIHILATION** AND **COANNIHILATION** PROCESSES:

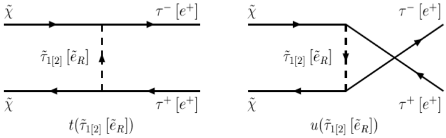
$$\langle\sigma v\rangle \sim \sigma_{\rm eff} \sim \sigma_{\rm LSP-LSP} + e^{-\Delta_{\rm NLSP}/x_{\rm F}}\sigma_{\rm LSP-NLSP} + e^{-2\Delta_{\rm NLSP}/x_{\rm F}}\sigma_{\rm LSP-NLSP^{(*)}},\ \text{WITH } x_{\rm F}\sim\frac{1}{25}\ \text{AND } \Delta_{\rm NLSP}=\frac{m_{\rm NLSP}-m_{\rm LSP}}{m_{\rm LSP}}$$

- $\Omega_{\tilde{\chi}}h^2$ CAN BE CONSISTENT WITH OBSERVATIONS ONLY INTO WELL LOCALIZED **PORTIONS** OF THE CMSSM PARAMETER SPACE.

1. ANNIHILATION PROCESSES ($\tilde{\chi}\tilde{\chi}$) - $\Delta_{\rm NLSP} \gg 0.25$

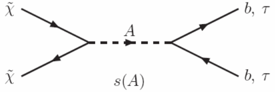
STATES: INITIAL	STATES: FINAL	CHANNELS: INTERACTIONS
$\tilde{\chi}\tilde{\chi}$	$\mathbf{f\bar{f}}$	$s(h),\ s(H),\ \mathbf{s(A)},\ s(Z)$
	$(f := t,\tau,b)$	$\mathbf{t(\tilde{f}_{1[2]}),\ u(\tilde{f}_{1[2]})}$
	$hh,\ hH,\ HH$	$s(h),\ s(H),\ t(\tilde{\chi}_i^0),\ u(\tilde{\chi}_i^0)$
	$AA,\ ZA$	$s(h),\ s(H),\ t(\tilde{\chi}_i^0),\ u(\tilde{\chi}_i^0)$
	$hA,\ HA$	$s(Z),\ s(A),\ t(\tilde{\chi}_i^0),\ u(\tilde{\chi}_i^0)$
	$\mathbf{W^+W^-},\ H^+H^-$	$\mathbf{s(h),\ s(H)},\ s(Z),\ t(\tilde{\chi}_i^\pm),\ u(\tilde{\chi}_i^\pm)$
	H^+W^-	$s(h),\ s(H),\ s(A),\ t(\tilde{\chi}_i^\pm),\ u(\tilde{\chi}_i^\pm)$
	ZZ	$s(h),\ s(H),\ t(\tilde{\chi}_i^0),\ u(\tilde{\chi}_i^0)$
	$Zh,\ ZH$	$s(A),\ s(Z),\ t(\tilde{\chi}_i^0),\ u(\tilde{\chi}_i^0)$

- **BULK REGION** WITH $m_0, M_{1/2} \ll 500$ GeV WHERE $\tilde{\chi}$ IS BINO-LIKE AND THE DOMINANT PROCESSES ARE



THIS REGION IS **EXCLUDED** BY THE LHC BOUND ON m_h.

- **THE A-FUNNEL REGION** WHERE THE PROCESS $\tilde{\chi}\tilde{\chi} \overset{s(A)}{\rightarrow} b\bar{b}$ IS **ENHANCED** IF $\Delta_A = (m_A - 2m_{\tilde{\chi}})/2m_{\tilde{\chi}} \simeq 0$ FOR $\tan\beta > 40$. THIS REGION IS ALSO **ALMOST EXCLUDED** BY THE LHC BOUND ON m_h.



The Relic Abundance of The Neutralino LSP, $\tilde\chi$, & the CMSSM Parameter Space

- Focusing on the Case of CMSSM, The Computation of $\langle\sigma v\rangle$ Includes **Annihilation** and **Coannihilation** Processes:

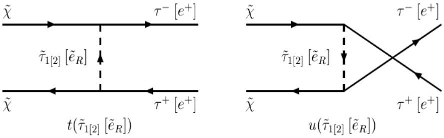
$$\langle\sigma v\rangle \sim \sigma_{\rm eff} \sim \sigma_{\rm LSP-LSP} + e^{-\Delta_{\rm NLSP}/x_{\rm F}}\sigma_{\rm LSP-NLSP} + e^{-2\Delta_{\rm NLSP}/x_{\rm F}}\sigma_{\rm LSP-NLSP^{(*)}},\quad \text{With } x_{\rm F}\sim\frac{1}{25} \text{ and } \Delta_{\rm NLSP} = \frac{m_{\rm NLSP}-m_{\rm LSP}}{m_{\rm LSP}}$$

- $\Omega_{\tilde\chi}h^2$ Can Be Consistent With Observations Only Into Well Localized **Portions** Of the CMSSM Parameter Space.

1. Annihilation Processes ($\tilde\chi\tilde\chi$) - $\Delta_{\rm NLSP} \gg 0.25$

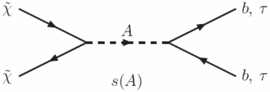
States		Channels
Initial	Final	Interactions
$\tilde\chi\tilde\chi$	$f\bar f$	$s(h),\ s(H),\ s(A),\ s(Z)$
	$(f := t,\tau,b)$	$t(\tilde f_{1[2]}),\ u(\tilde f_{1[2]})$
	$hh,\ hH,\ HH$	$s(h),\ s(H),\ t(\tilde\chi_i^0),\ u(\tilde\chi_i^0)$
	$AA,\ ZA$	$s(h),\ s(H),\ t(\tilde\chi_i^0),\ u(\tilde\chi_i^0)$
	$hA,\ HA$	$s(Z),\ s(A),\ t(\tilde\chi_i^0),\ u(\tilde\chi_i^0)$
	$W^+W^-,\ H^+H^-$	$s(h),\ s(H),\ s(Z),\ t(\tilde\chi_i^\pm),\ u(\tilde\chi_i^\pm)$
	H^+W^-	$s(h),\ s(H),\ s(A),\ t(\tilde\chi_i^\pm),\ u(\tilde\chi_i^\pm)$
	ZZ	$s(h),\ s(H),\ t(\tilde\chi_i^0),\ u(\tilde\chi_i^0)$
	$Zh,\ ZH$	$s(A),\ s(Z),\ t(\tilde\chi_i^0),\ u(\tilde\chi_i^0)$

- **Bulk Region** With $m_0, M_{1/2} \ll 500$ GeV Where $\tilde\chi$ is Bino-like And The Dominant Processes Are

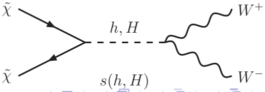


This Region Is **Excluded** by the LHC bound on m_h.

- **The A-Funnel Region** Where The Process $\tilde\chi\tilde\chi \xrightarrow{s(A)} b\bar b$ Is **Enhanced** If $\Delta_A = (m_A - 2m_{\tilde\chi})/2m_{\tilde\chi} \simeq 0$ For $\tan\beta > 40$. This Region Is Also **Almost Excluded** by the LHC bound on m_h.



- **The Hyperbolic Branch/Focus Point Region** at Large $m_0 > 5$ TeV, Where $|\mu|$ Becomes Small, and $\tilde\chi$ Develops A Significant **Higgsino** Component. The Dominant Process Is:



2. Coannihilation Processes - $\Delta_{\rm NLSP} < 0.25$

• These Processes Can Be Activated[10] For **Every** $\tan\beta$ If $\Delta_{\rm NLSP} \ll 0.25$ Since $\sigma_{\rm LSP-NLSP} + \sigma_{\rm LSP-NLSP^{(*)}} \gg \sigma_{\rm LSP-LSP}$. Can Dominate the $\langle\sigma v\rangle$ Computation. For Given $m_{\rm LSP}$, $\Omega_{\rm LSP}h^2$ **Decreases** With $\Delta_{\rm NLSP}$.

Focus-Point (FP) Coannihilations

(In the limit $m_{H,A,H^\pm} \gg m_{\tilde\chi}, m_{\tilde\chi_i^\pm}$)

States: Initial	States: Final	Channels: Interactions
$\tilde\chi\tilde\chi_j^+$	W^+h	$t(\tilde\chi_k^0),\ u(\tilde\chi_k^+),\ s(H^+),\ s(W^+)$
	W^+Z	$t(\tilde\chi_k^0),\ u(\tilde\chi_k^+),\ s(W^+)$
	γW^+	$t(\tilde\chi_j^+),\ s(W^+)$
	$u\bar d$	$t(\tilde d_{1,2}),\ u(\tilde u_{1,2}),\ s(H^+),\ s(W^+)$
	$\nu\bar\ell$	$t(\tilde\ell_{L,R}),\ u(\tilde\nu_L),\ s(H^+),\ s(W^+)$
$\tilde\chi_i^+\tilde\chi_j^+$	W^+W^+	$t(\tilde\chi_k^0),\ u(\tilde\chi_k^0)$
$\tilde\chi_i^+\tilde\chi_j^-$	ZZ	$t(\tilde\chi_k^+),\ u(\tilde\chi_k^+),\ s(h,H)$
	W^+W^-	$t(\tilde\chi_k^0),\ s(h,H),\ s(Z,\gamma)$
	$\gamma\gamma$ (for $i=j$)	$t(\tilde\chi_i^+),\ u(\tilde\chi_i^+)$
	$Z\gamma$	$t(\tilde\chi_j^+),\ u(\tilde\chi_i^+)$
	$u\bar u$	$t(\tilde d_{L,R}),\ s(h,H,A),\ s(Z,\gamma)$
	$\nu\bar\nu$	$t(\tilde\ell_{L,R}),\ s(Z)$
	$\bar d d$	$t(\tilde u_{L,R}),\ s(h,H,A),\ s(Z,\gamma)$
	$\bar\ell\ell$	$t(\tilde\nu_L),\ s(h,H,A),\ s(Z,\gamma)$

[10] J. Edsjo & P. Gondolo (1997); J. Ellis et al. (1999); M.E. Gómez, G. Lazarides and C.P. (2000, 2002); G. Bélanger et al. (micrOMEGAs) (2001).

2. Coannihilation Processes - $\Delta_{\rm NLSP} < 0.25$

• These Processes Can Be Activated[10] For **Every** $\tan\beta$ If $\Delta_{\rm NLSP} \ll 0.25$ Since $\sigma_{\rm LSP-NLSP} + \sigma_{\rm LSP-NLSP^{(*)}} \gg \sigma_{\rm LSP-LSP}$. Can Dominate the $\langle\sigma v\rangle$ Computation. For Given $m_{\rm LSP}$, $\Omega_{\rm LSP}h^2$ **Decreases** With $\Delta_{\rm NLSP}$.

Focus-Point (FP) Coannihilations

(In the limit $m_{H,A,H^\pm} \gg m_{\tilde\chi}, m_{\tilde\chi_i^\pm}$)

States: Initial	States: Final	Channels: Interactions
$\tilde\chi\tilde\chi_j^+$	W^+h	$t(\tilde\chi_k^0),\ u(\tilde\chi_k^+),\ s(H^+),\ s(W^+)$
	W^+Z	$t(\tilde\chi_k^0),\ u(\tilde\chi_k^+),\ s(W^+)$
	γW^+	$t(\tilde\chi_j^+),\ s(W^+)$
	$u\bar d$	$t(\tilde d_{1,2}),\ u(\tilde u_{1,2}),\ s(H^+),\ s(W^+)$
	$\nu\bar\ell$	$t(\tilde\ell_{L,R}),\ u(\tilde\nu_L),\ s(H^+),\ s(W^+)$
$\tilde\chi_i^+\tilde\chi_j^+$	W^+W^+	$t(\tilde\chi_k^0),\ u(\tilde\chi_k^0)$
$\tilde\chi_i^+\tilde\chi_j^-$	ZZ	$t(\tilde\chi_k^+),\ u(\tilde\chi_k^+),\ s(h,H)$
	W^+W^-	$t(\tilde\chi_k^0),\ s(h,H),\ s(Z,\gamma)$
	$\gamma\gamma$ (for $i=j$)	$t(\tilde\chi_i^+),\ u(\tilde\chi_i^+)$
	$Z\gamma$	$t(\tilde\chi_j^+),\ u(\tilde\chi_i^+)$
	$u\bar u$	$t(\tilde d_{L,R}),\ s(h,H,A),\ s(Z,\gamma)$
	$\nu\bar\nu$	$t(\tilde\ell_{L,R}),\ s(Z)$
	$\bar d d$	$t(\tilde u_{L,R}),\ s(h,H,A),\ s(Z,\gamma)$
	$\bar\ell\ell$	$t(\tilde\nu_L),\ s(h,H,A),\ s(Z,\gamma)$

$\tilde\chi - \tilde\tau_2$ Coannihilations ($\tilde\tau_2$-CAs)

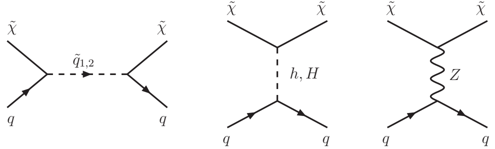
(At Low m_0 And Almost Any $M_{1/2}$)

States: Initial	States: Final	Channels: Interactions
$\tilde\chi\tilde\tau_2$	$\tau h,\ \tau H,\ \tau Z$	$s(\tau),\ t(\tilde\tau_{1,2})$
	τA	$s(\tau),\ t(\tilde\tau_1)$
	$\tau\gamma$	$s(\tau),\ t(\tilde\tau_2)$
$\tilde\tau_2\tilde\tau_2$	$\tau\tau$	$t(\tilde\chi),\ u(\tilde\chi)$
$\tilde\tau_2\tilde\tau_2^*$	$hh,\ hH,\ HH,\ ZZ$	$s(h),\ s(H),\ t(\tilde\tau_{1,2}),\ u(\tilde\tau_{1,2})$, PI
	AA	$s(h),\ s(H),\ t(\tilde\tau_1),\ u(\tilde\tau_1)$, PI
	$hZ,\ HZ$	$s(Z),\ t(\tilde\tau_{1,2}),\ u(\tilde\tau_{1,2})$
	$h\gamma,\ H\gamma$	$t(\tilde\tau_2),\ u(\tilde\tau_2)$
	$hA,\ HA$	$s(Z),\ t(\tilde\tau_1),\ u(\tilde\tau_1)$
	AZ	$s(h),\ s(H),\ t(\tilde\tau_1),\ u(\tilde\tau_1)$
	$H^+H^-,\ W^+W^-$	$s(h),\ s(H),\ s(\gamma),\ s(Z)$, PI
	H^+W^-	$s(h),\ s(H)$
	$\gamma\gamma,\ \gamma Z$	$t(\tilde\tau_2),\ u(\tilde\tau_2)$, PI
	$t\bar t,\ b\bar b$	$s(h),\ s(H),\ s(\gamma),\ s(Z)$
	$\tau\bar\tau$	$s(h),\ s(H),\ s(\gamma),\ s(Z),\ t(\tilde\chi)$
	$u\bar u,\ d\bar d,\ e\bar e$	$s(\gamma),\ s(Z)$
	$\nu\bar\nu$	$s(Z)$

[10] J. Edsjo & P. Gondolo (1997); J. Ellis et al. (1999); M.E. Gómez, G. Lazarides and C.P. (2000, 2002); G. Bélanger et al. (micrOMEGAs) (2001).

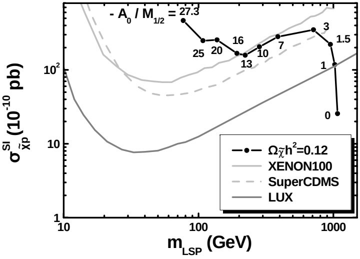
Neutralino–Proton Spin Independent (SI) Cross Section $\sigma^{\rm SI}_{\tilde\chi \rm p}$

- The Lagrangian $\mathcal{L}_{\rm eff} = \alpha^{\rm SI}_q\,(\bar{\tilde\chi}\tilde\chi)\,(\bar q q)$ for the $\tilde\chi$–Quark Elastic Scattering Takes Contributions[11] From the Processes:



- $\mathcal{L}_{\rm eff}$ Gives Rise to $\sigma^{\rm SI}_{\tilde\chi \rm p} = \frac{4}{\pi}\mu^2_{\tilde\chi \rm p} f_{\rm p}^2,$ where $\mu_{\tilde\chi \rm p} = \frac{m_{\tilde\chi} m_{\rm p}}{m_{\tilde\chi}+m_{\rm p}}$ and $f_{\rm p} = \sum_{q=u,d,s}\frac{m_{\rm p}}{m_q} f^{\rm p}_{{\rm T}q}\,\alpha^{\rm SI}_q + \frac{2}{27} f^{\rm p}_{{\rm T}G}\sum_{q=c,b,t}\frac{m_{\rm p}}{m_q}\,\alpha^{\rm SI}_q$

Where the **Hadronic Inputs** $f^p_{{\rm T}_G}$ and $f^p_{{\rm T}_q}$ Encode The Transition From **The Quark To Nucleon** Level.



- In The FP Region, Data Coming From LUX Provide **Strict Bounds** On The CMSSM Parameters Since

$$\alpha^{\rm SI}_q = \frac{g_{H\tilde\chi\tilde\chi}\, g_{Hqq}}{2m^2_H} \sim \frac{\tan\beta^2}{m^4_H}|N_{11}|^2|N_{13}|^2$$

With N the Matrix Which Diagonalizes The Neutralino Mass Matrix.

- In order to Reliably Compare data from LUX With $\sigma^{\rm SI}_{\tilde\chi \rm p}$ When $\Omega_{\tilde\chi} h^2 < 0.12$, We Use the **Scaled Quantity**:

$$\sigma^{\rm SI}_{\rm CDM-p} = \xi\sigma^{\rm SI}_{\tilde\chi \rm p},\;\; \xi = \Omega_{\tilde\chi} h^2/0.12.$$

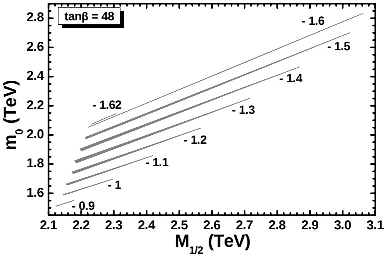
[11] M.W. Goodman and E. Witten (1985); J. Ellis and R. Flores (1988); K. Griest (1988).

Restrictions to the CMSSM Parameter Space

The Free Parameters of CMSSM are $M_{1/2},\ m_0,\ A_0,\ \tan\beta,\ \mathrm{sign}\mu \overset{\mu>0}{\Longrightarrow} M_{1/2},\ A_0/M_{1/2},\ \tan\beta,\ \Delta_{\tilde\tau_2}$ $\left(\Delta_{\tilde\tau_2}=\frac{m_{\tilde\tau_2}-m_{\tilde\chi}}{m_{\tilde\chi}}\right)$

We Present Our Results:

- In the $M_{1/2}-m_0$ Plane for Various $A_0/M_{1/2}$'s



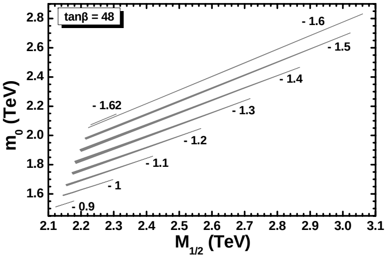
We Find $0.9 \lesssim m_{\tilde\chi}/\mathrm{TeV} \lesssim 1.4$ & $123.7 \lesssim m_h/\mathrm{GeV} \lesssim 125.9$

Restrictions to the CMSSM Parameter Space

The Free Parameters of CMSSM are $M_{1/2},\ m_0,\ A_0,\ \tan\beta,\ \mathrm{sign}\mu \ \overset{\mu>0}{\Longrightarrow}\ M_{1/2},\ A_0/M_{1/2},\ \tan\beta,\ \Delta_{\tilde\tau_2}\ \left(\Delta_{\tilde\tau_2} = \frac{m_{\tilde\tau_2} - m_{\tilde\chi}}{m_{\tilde\chi}}\right)$

We Present Our Results:

- In the $M_{1/2} - m_0$ Plane for Various $A_0/M_{1/2}$'s



We Find $0.9 \lesssim m_{\tilde\chi}/\mathrm{TeV} \lesssim 1.4$ & $123.7 \lesssim m_h/\mathrm{GeV} \lesssim 125.9$

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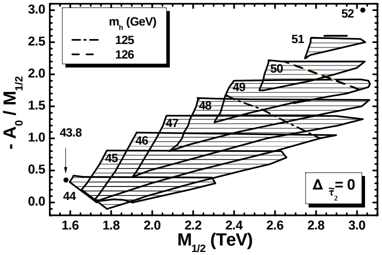

We Find $0.75 \lesssim m_{\tilde\chi}/\mathrm{TeV} \lesssim 1.4$ & $122 \lesssim m_h/\mathrm{GeV} \lesssim 127$

Restrictions to the CMSSM Parameter Space

The Free Parameters of CMSSM are $M_{1/2},\ m_0,\ A_0,\ \tan\beta,\ \mathrm{sign}\mu\ \stackrel{\mu>0}{\Longrightarrow}\ M_{1/2},\ A_0/M_{1/2},\ \tan\beta,\ \Delta_{\tilde\tau_2}\ \left(\Delta_{\tilde\tau_2}=\frac{m_{\tilde\tau_2}-m_{\tilde\chi}}{m_{\tilde\chi}}\right)$

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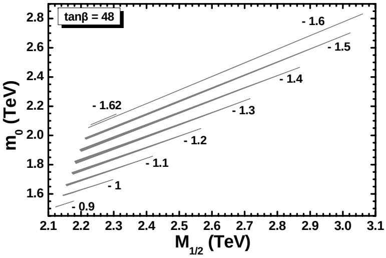

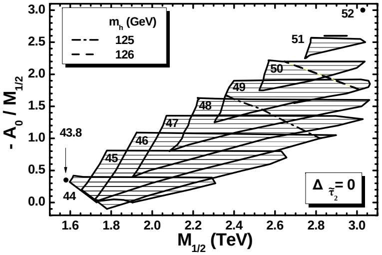

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- We Obtain a Fulfilment of All the Restrictions But This From The The Lower Bound of δa_μ.
- The **Interplay** of BR $(B_s \to \mu^+\mu^-)$ And $\Omega_\chi h^2$ Constraints Determine the allowed $m_{\tilde\chi}$'s and $\tan\beta$'s i.e., $43.8 \leq \tan\beta \leq 52$
- Since $m_{\tilde g}, m_{\tilde t_{1,2}}$ and $m_{\tilde b_{1,2}} \gtrsim 3$ TeV, their **Discovery is Very Difficult**.
- Since $\mu \gtrsim 1$ TeV, the SSB Requires Some Tuning Named "**Little Hierarchy**".
- In the Allowed Region we Obtain $h_t/h_\tau \simeq 0.98-1.29$, $h_b/h_\tau \simeq 0.60-0.65$, and $h_t/h_b \simeq 1.62-2.00$.

These Values can be **Motivated** by the Embedding of CMSSM in our SUSY Pati-Salam Model.

Restrictions to the CMSSM Parameter Space

The Free Parameters of CMSSM are $M_{1/2},\ m_0,\ A_0,\ \tan\beta,\ \mathrm{sign}\mu \stackrel{\mu>0}{\Longrightarrow} m_h,\ m_{\rm LSP},\ A_0/M_{1/2},\ \tan\beta\,.$

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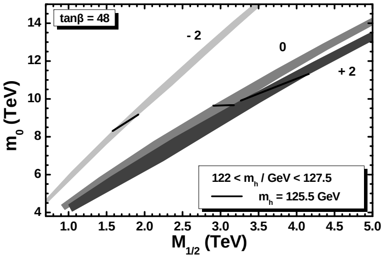

We Find $0.1 \lesssim m_{\rm LSP}/{\rm TeV} \lesssim 1.1$ & $122 \lesssim m_h/{\rm GeV} \lesssim 127$.

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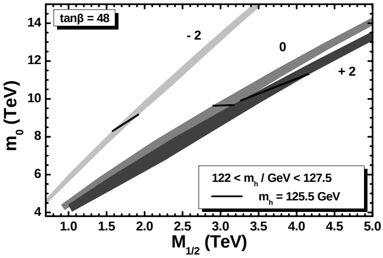

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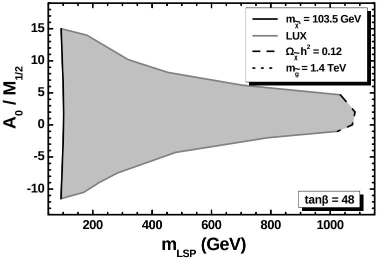
- In the $m_{\rm LSP} - A_0/M_{1/2}$ Plane for $m_h = 125.5$ GeV



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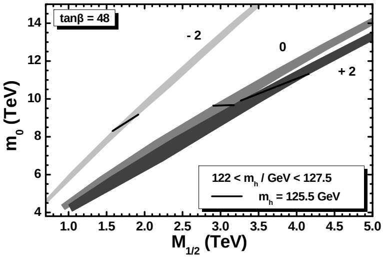

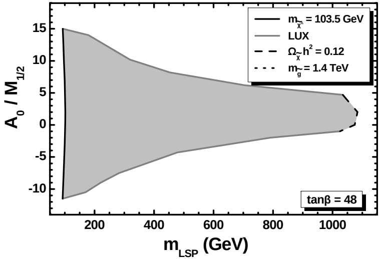

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- **Varying $40 \leq \tan\beta \leq 51$**, the Restrictions in the $m_{\rm LSP} - A_0/M_{1/2}$ Plan Remain Almost **Intact**.
- We Obtain a Fulfilment of All the Restrictions But This From The Lower Bound of δa_μ.
- The Bound $m_{\tilde\chi_i^\pm} \geq 103.5$ GeV **Implies** $m_{\rm LSP} \gtrsim 99$ GeV Whereas ${\rm BR}\left(B_s \to \mu^+\mu^-\right)$ Remains Close to its SM value.
- Since $m_{\tilde g}, m_{\tilde t_{1,2}}$ and $m_{\tilde b_{1,2}} \gtrsim$ **5 TeV**, Their **Discovery is Very Difficult**.
- For $\Omega_{\tilde\chi}h^2 \simeq 0.11$ the **Little Hierarchy** Problem Insists, But for $\Omega_{\tilde\chi}h^2 \ll 0.11$, We Obtain $\mu \simeq 0.1$ TeV
- For $40 \leq \tan\beta \leq 51$ we obtain the $h_t/h_\tau \simeq 1-1.5$, $h_b/h_\tau \simeq 0.75-0.79$, and $h_t/h_b \simeq 1.2-2.00$.

These Ratios can be **Motivated** by the Embedding of CMSSM in our SUSY Pati-Salam Model.

FP Region and Direct Detection of CDM

- In the $\tilde{\tau}_2$-CA Region, $\mathrm{BR}\left(B_s \to \mu^+\mu^-\right)$ Implies $m_{\rm LSP} \gtrsim 746.5~\mathrm{GeV}$ and Therefore the Detection of LSP Is Unlikely.

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- In the FP Region We take Constraints From LUX and Achieve Predictions for $\sigma^{\rm SI}_{\tilde{\chi}p}$.
  - For $A_0/M_{1/2} < 0$
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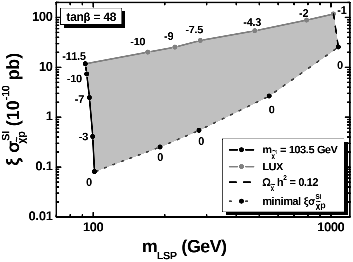

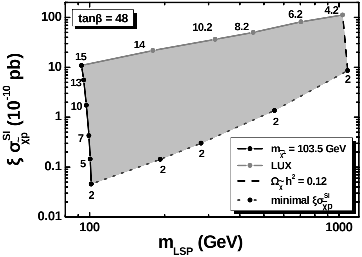

- The Upper boundary Curve Comes from the LUX data.
- The Remaining $\sigma^{\rm SI}_{\tilde{\chi}p}$'s Are Predictions Of Our Scheme.
- The Entire Allowed Region May Be Probed by XENON1T Experiment.
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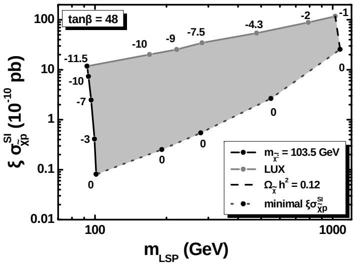

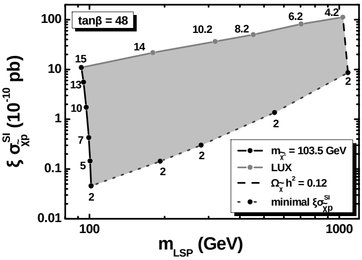

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- The Present Bounds on the Spin-Dependent $\tilde\chi-{\rm p}$ Cross Section Are not as Restrictive as Bounds from LUX
- As a Bottom Line We Could Say That the FP Region Is More Attractive Or Even Natural Than the $\tilde\tau_2$-CA Region.

Summary

CMSSM Can **Become Consistent With the Data** (Except For That of $\delta\alpha_\mu$) Within **Two** Regions Of its Parameter Space:

Comparison Of The Allowed Regions

	$\tilde{\tau}_2$-CA Region	FP Region
Model Parameters		
$M_{1/2}$/TeV	$1.6-3$	$2-4$
m_0/TeV	$1.6-3$	$4-16$
$A_0/M_{1/2}$	$0.2-(-3)$	$(-11)-15$
$\tan\beta$	$43.8-52$	$40-50$
μ/TeV	≥ 3	$0.1-1$
h_t/h_τ	$0.98-1.29$	$1-1.5$
h_b/h_τ	$0.6-0.65$	$0.75-0.79$
h_t/h_b	$1.62-2$	$1.2-2$
Spectroscopy		
LSP:	Bino	Bino-Higgsino
NLSP:	$\tilde{\tau}_2$	$\tilde{\chi}_i^{\pm}, \tilde{\chi}_i^0$
$m_{\tilde{\chi}}$/TeV	$0.75-1.4$	$0.1-1.08$
$m_{\tilde{t}_{1,2}}$/ TeV	$3-4$	$6-10$
$m_{\tilde{u},\tilde{d}}$/TeV	$4-6$	$10-12$
$m_{H,A,H^\pm}$/TeV	$2.1-2.6$	$2-6$
$m_{\tilde{g}}$/TeV	$5-6$	$5-8$
Predictions		
$\Omega_\chi h^2$ Tunings	$\Delta_{\tilde{\tau}_2}\simeq 0, \Delta_H \simeq 0$	$\Delta_{\tilde{\chi}_1^\pm} \simeq 0$
$\sigma^{SI}_{\tilde{\chi}p}$/pb $\sim$	10^{-12}	10^{-9}
$\delta a_\mu/10^{-10} \geq 7.5$	$(0.35-2.76)$	$(0.04-0.27)$

Final Remarks

1. For $\Omega_\chi h^2 \ll 0.12$, the **Naturality** of the FP Region Increases, since $\mu \sim (100 \pm 20)$ GeV.
2. The Sparticle Spectra – Besides $\tilde{\chi}$ – in the FP Region Are **More Heavy** Than the Ones in the $\tilde{\tau}_2$-CA Region.
3. The Allowed FP Region Is More **Ample & Natural** Than the $\tilde{\tau}_2$-CA Region.
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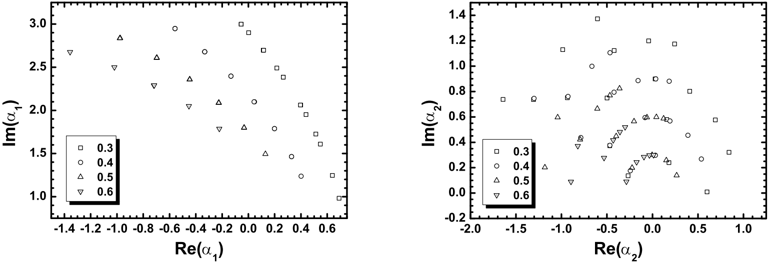
6. To Obtain a Fulfilment of the Constraints Above An **Amount Of Tuning** (μ Determination, $\Delta_{\tilde{\tau}_2} = 0$ and $\Delta_H = 0$ or $\Delta_{\tilde{\chi}_1^\pm} \simeq 0$) Is Required Which, Though, Is Significantly Lower Than The Amount Of Tuning Which Is Removed By SUSY.

[a] S. Antusch et al. (2012).

Back-up: Testing Yukawa Quasi-Unification

We Present The Complex Parameters α_1, α_2 For Various ρ's Corresponding To $h_b/h_\tau = 0.618$ and $h_t/h_\tau = 1.079$.



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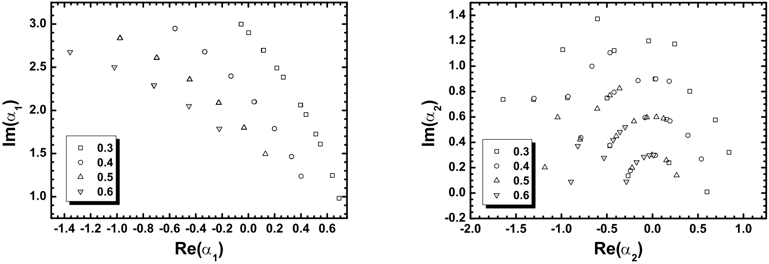

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