MSSM Electroweak Baryogenesis vs LHC data

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DESY, 26/11/2012

Based on:

M. Carena, G.N., M. Quirós, C.E.M. Wagner
arXiv:0806.4297; arXiv:0809.3760; arXiv:1207.6330.

Outline

The Question: Why this asymmetry?

The Universe is matter dominated. Natural $\bar{p}$ in the cosmic rays, but compatible with secondary production.
BBN and CMB furnish independently:

$$\eta \equiv \frac{n_B - n_{\bar{B}}}{n_\gamma} = (6.11 \pm 0.19) \times 10^{-10}$$

Why this number?

Possible mechanisms attempting to produce η must contain the ingredients [Sakharov,1967]

1. B violation
2. C and CP violation
3. Departure form thermal equilibrium

An answer: EWBG in the SM

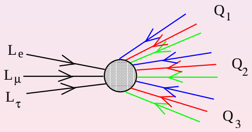
Kuzmin et al.,85; ...

Kuzmin, Rubakov and Shapshnikov, Phys.Lett.B155:36,1985;
....

Some EWBG reviews:
M. Quirós, hep-ph/9901312
A. Riotto, hep-ph/9807454
J. Cline, hep-ph/0609145

The SM contains the Sakharov conditions:

1. B number is non-perturbative violated at $T \neq 0$ (sphalerons) ['t Hooft,76]
2. CKM matrix contains CP violation
3. EWPT (when of 1^{st} order) proceeds by bubble nucleation. Expanding bubbles break the thermal equilibrium.



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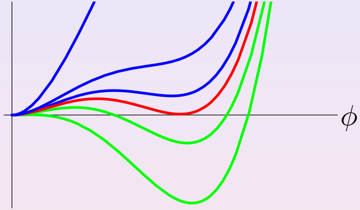

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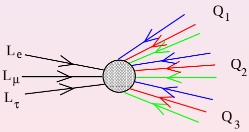

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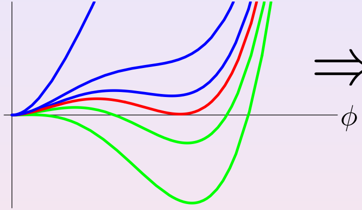
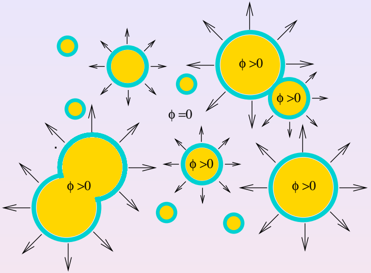


$\Longrightarrow$



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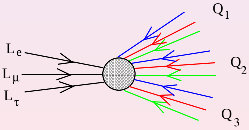

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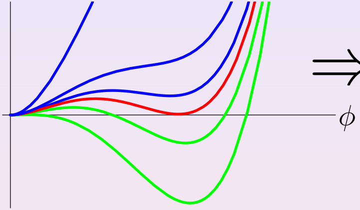
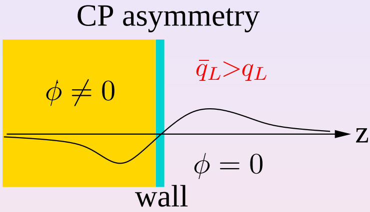


$\Rightarrow$



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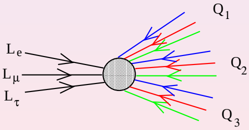

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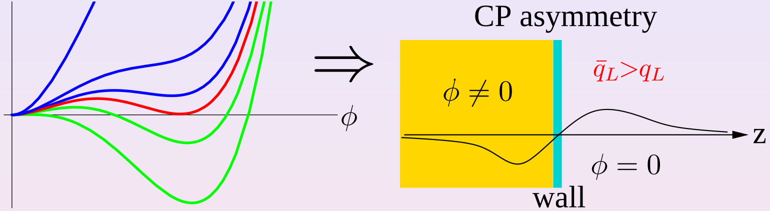

In front of the wall CP asymm. generates temporally $\bar{q}_L > q_L$
$\Rightarrow$ There are more sphalerons $B\uparrow$ than those $B\downarrow$
$\Rightarrow$ Temporally B asymm. is present beyond the wall $\Rightarrow$ The wall expansion accumulates $B > 0$ inside the bubble, where

If broken-phase sphalerons are in therm. equilibrium, $B \to 0$.
Otherwise *(strong EWPT)* WE HAVE PRODUCED $B \neq 0$.

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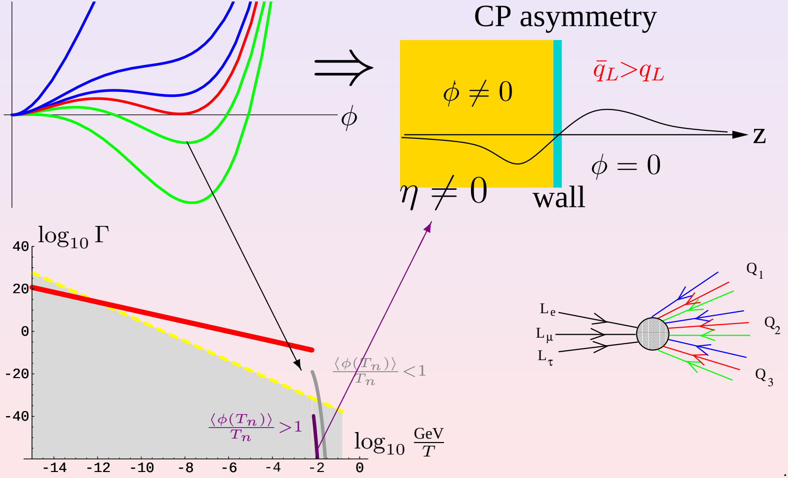
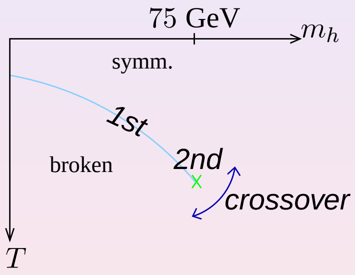


Another answer: EWBG in the MSSM

Unluckily, EWBG in the SM does not work: the EWPT is not strong enough ($\frac{\langle\phi(T_n)\rangle}{T_n} < 1$) for $m_h > 114.4$ GeV [LEP].

[Kajantie et al.,97]



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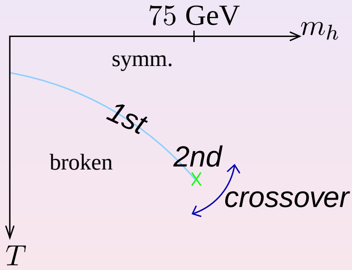

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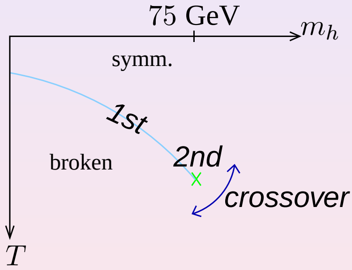

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MSSM Light Stop Scenario

[Carena et al.,96;Delepine et al.,96;Cline et al.,98] showed that the Light Stop Scenario is the most favorable MSSM framework to get a strong EWPT.

Increasing the Higgs mass weakens the EWPT but for $m_h \approx 126$ GeV it is still strong [Carena,G.N.,Quiros,Wagner ,08]. In such a case:

- Fermions are at the EW scale (gluino a bit heavier)
- The $\tilde{t}_R$ is lighter than the top quark
- The other scalars $m_Q \simeq m_A \simeq ... \equiv \tilde{m} \gg few\ TeV$
- $A_t \ll m_Q$ (motivated by the strength of the EWPT)
- $\tan\beta \lesssim 15$ (motivated by EDM and BAU)

(A sort of light-stop scenario in SS)

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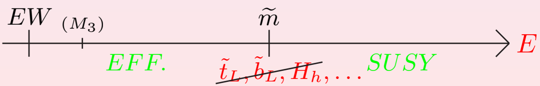
LE Lagrangian

The effective Lagrangian is

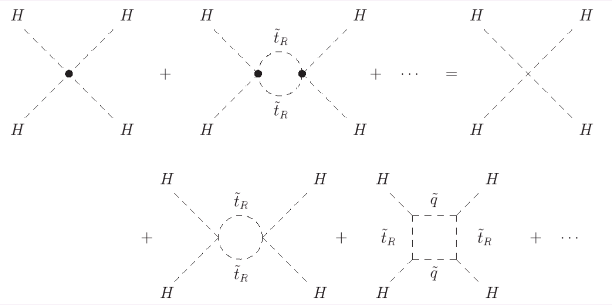
$$\begin{aligned}\mathcal{L}_{eff} =\; & m^2 H^\dagger H - \frac{\lambda}{2}\left(H^\dagger H\right)^2 - h_t\left[\bar{q}_L \epsilon H^* t_R\right] + Y_t\left[\overline{\tilde{H}}_u \epsilon q_L \tilde{t}_R^*\right] \\ & -\sqrt{2} G\, \Theta_{\tilde{g}}\, \tilde{t}_R \tilde{g}^a \overline{T}^a \bar{t}_R + \sqrt{2} J\, \tilde{t}_R^* \tilde{B} t_R - \frac{1}{6} K \tilde{t}^*_{R_\omega} \tilde{t}_{R_\omega}\, \tilde{t}^*_{R_\gamma} \tilde{t}_{R_\gamma} - Q \left|\tilde{t}_R\right|^2 |H|^2 \\ & + \frac{H^\dagger}{\sqrt{2}}\left(g_u \sigma^a \tilde{W}^a + g'_u \tilde{B}\right)\tilde{H}_u + \frac{H^T \epsilon}{\sqrt{2}}\left(-g_d \sigma^a \tilde{W}^a + g'_d \tilde{B}\right)\tilde{H}_d + \text{h.c.} \\ & -\frac{M_3}{2}\Theta_{\tilde{g}}\, \tilde{g}^a \tilde{g}^a - \frac{M_2}{2}\tilde{W}^A \tilde{W}^A - \frac{M_1}{2}\tilde{B}\tilde{B} - \mu \tilde{H}_u^T \epsilon \tilde{H}_d - M_U^2\, \tilde{t}_R^* \tilde{t}_R\end{aligned}$$

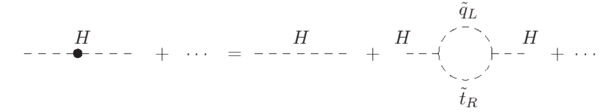


Matching conditions at $\widetilde{m}$

(*One–loop:* $\overline{MS}$ *- dim. regular. - Landau gauge - 4-dim. ops.*)

$$\lambda(\tilde{m}) - \Delta\lambda = \frac{g^2(\tilde{m}) + g'^2(\tilde{m})}{4} \cos^2 2\beta \left(1 - \frac{1}{2}\Delta Z_\lambda\right)$$

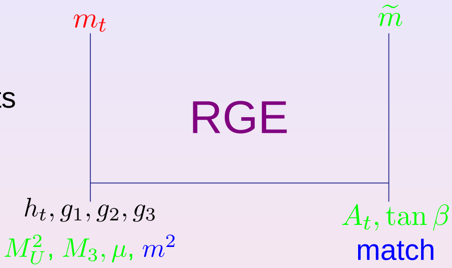




Higgs mass calculation

INPUTS:

- Experimental LE inputs
- Theoretical inputs
- Free parameters



HIGGS MASS:

by the 1-loop effective potential in the LE theory improved by the 1-loop RGE resummation (necessary to resum large logs for large values of M_Q)

KEY POINT: $M_U^2 < 0$! Why? [Carena et al.96;Delepine et al.,96]

To obtain a strong 1^{st} order EW transition ($\langle\phi(T_n)\rangle > T_n$), the Higgs potential ($V(\phi,T) \simeq m\phi^2 + E\phi^3 + \lambda\phi^4$) has to develop a large barrier ($E\uparrow$), increased by the "cubic term" produced by bosons.

Unlike in the SM (developing a small cubic term), in our LE theory the Stop could strengthen the EW transition. Its spurious cubic term appears as

$$\left[M_U^2 + \frac{Q}{2}\phi^2 + \Pi(T)\right]^{3/2} \qquad Q \sim h_t^2(1 - \tilde{A}_t^2/\widetilde{m}^2)$$

$$\Downarrow$$

To strengthen the transition $M_U^2 \approx -\Pi(T_c)$ so that $[\cdots]^{3/2} \sim E\phi^3$

$$\Downarrow$$

The theory then has two minima!

EWB	CB
$\langle h,\tilde{t}\rangle = (v,0)$	$\langle h,\tilde{t}\rangle = (0,u)$

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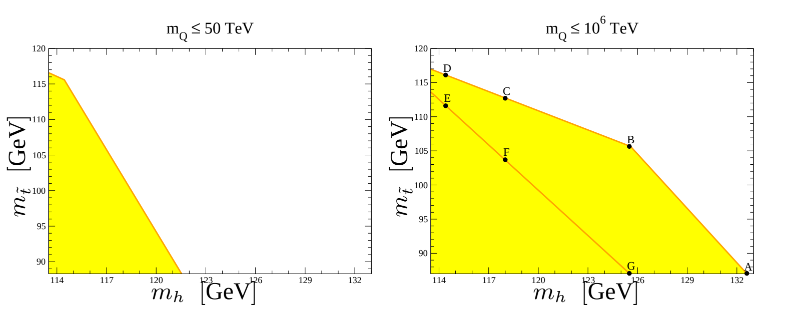
Light Right-Handed Stop

$$m_{\tilde{t}_1} = \sqrt{M_U^2 + \tfrac{Q}{2}v^2} \sim \sqrt{M_U^2 + m_t^2} < m_t \quad \text{[for } A_t \sim 0\text{]}$$

Higgs-Stop window $\langle\phi(T_n)\rangle/T_n > 1$ $(\mu = 100, M_3 = 800$ GeV)



Based on effect. parameters. g_3, h_t 2-loops $T \neq 0$ at g_3, h_t approx

EWBG bounds (for $m_h \approx 125$ GeV):

$m_{\tilde{t}_L} \gg 50$ TeV $\qquad m_{\tilde{t}_R} \lesssim 110$ GeV

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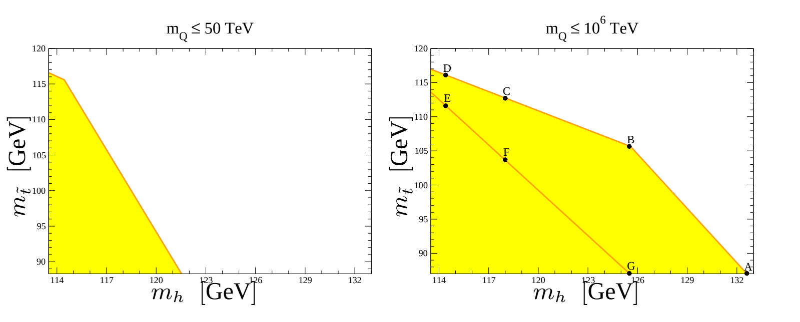

Roughly confirmed on the lattice
[M.Laine,G.N.,K.Rummukainen, 12 (to appear)]

Maybe LSS is the effective theory of non-MSSM
and m_Q can be much smaller [A.Delgado,G.N.,M.Quiros,12]

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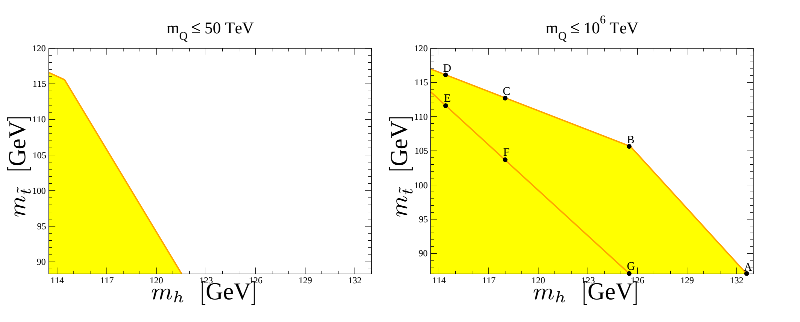


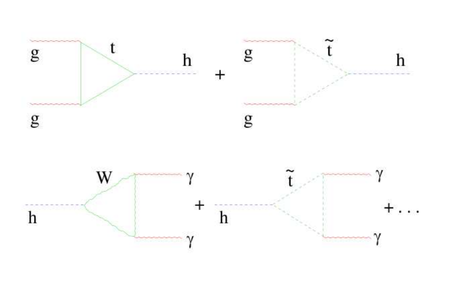
Point	A	B	C	D	E	F	G
$\lvert A_t/m_Q \rvert$	0.5	0	0	0	0.3	0.4	0.7
$\tan\beta$	15	15	2.0	1.5	1.0	1.0	1.0

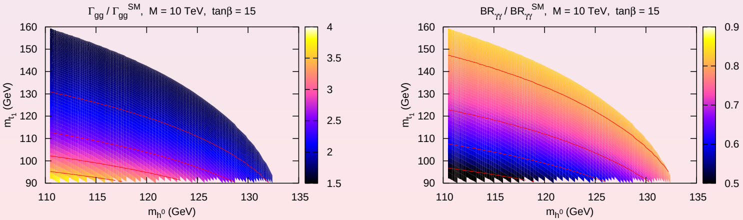
LSS and LHC

(in Higgs searches)

Stops in the Higgs searches [Menon et al.,09]

$\sigma(gg \to h^0)$ and $\Gamma(h^0 \to \gamma\gamma)$





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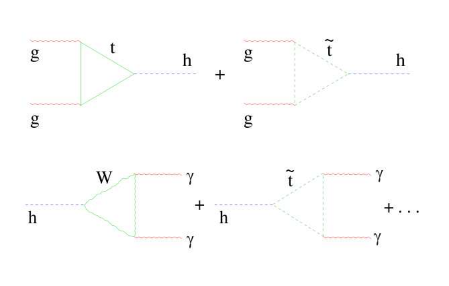

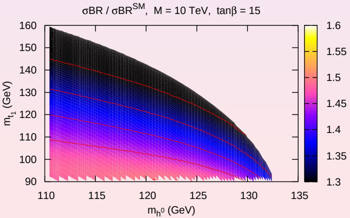

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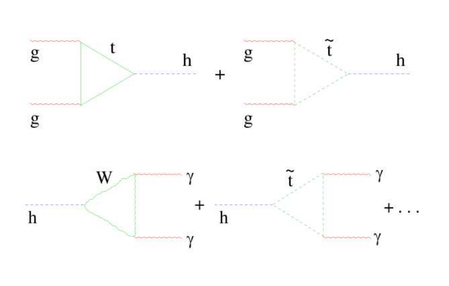

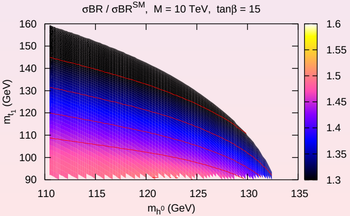

Stops in the Higgs searches [Curtin et al.,12, Cohen et al.,12]

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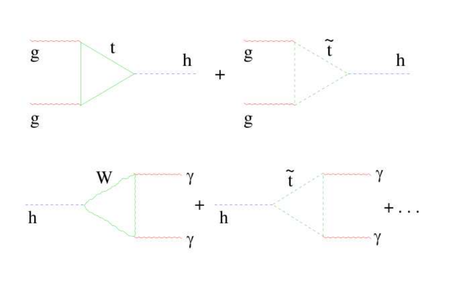
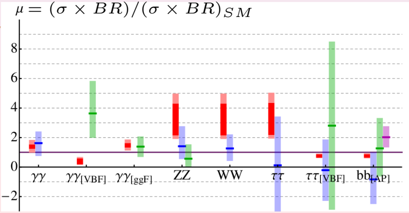


$A_t = 0$, $m_h = 125$ GeV
$80 < m_{\tilde{t}}/\text{GeV} < 115$
$\tan\beta = 15$
LHC data < 5 fb^{-1}



Stops and Light Neutralinos [Carena,G.N.,Quiros,Wagner,12]

Overproduction of weak boson vectors. Tension with data...

...but only under the assumption $\Gamma(h \to \text{inv}) \simeq 0$!!!!

In the MSSM indeed $m_{\chi_1^0} < m_h/2 \Rightarrow \Gamma(h \to \text{inv}) > 0$

$m_{\chi_1^0} \gtrsim \mathcal{O}(1\,\text{GeV})$ is allowed [H.K. Dreiner et al.,09]

Lightest-Higgs invisible decay

$$\Gamma(h \to \chi_1^0 \chi_1^0) = \frac{G_F m_W^2}{2\sqrt{2}\pi} m_h \left(1 - \frac{4m_{\chi_1^0}^2}{m_h^2}\right)^{3/2} g_{h11}^2$$

$$g_{h11} = (N_{12} - \tan\theta_W N_{11})(\sin\beta N_{1u} - \cos\beta N_{1d})$$

$\text{BR}_{95\%\text{CL}}(h \to \chi_1^0 \chi_1^0) \lesssim 0.85$ [Djouadi et al.,12; atlas-conf-2012-170]

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In the MSSM indeed $m_{\chi_1^0} < m_h/2 \Rightarrow \Gamma(h \to \text{inv}) > 0$

$m_{\chi_1^0} \gtrsim \mathcal{O}(1$ GeV) is allowed [H.K. Dreiner et al.,09]

Lightest-Higgs invisible decay

$$\Gamma(h \to \chi_1^0 \chi_1^0) = \frac{G_F m_W^2}{2\sqrt{2}\pi}\, m_h \left(1 - \frac{4m_{\chi_1^0}^2}{m_h^2}\right)^{3/2} g_{h11}^2$$

$$g_{h11} = (N_{12} - \tan\theta_W N_{11})(\sin\beta N_{1u} - \cos\beta N_{1d})$$

$\mathrm{BR}_{95\%\mathrm{CL}}(h \to \chi_1^0 \chi_1^0) \lesssim 0.85$ [Djouadi et al.,12; atlas-conf-2012-170]

Stops and Light Neutralinos [Carena,G.N.,Quiros,Wagner,12]

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Z invisible decay

$$\Gamma(Z \to \chi_1^0\chi_1^0) = \frac{G_F}{\sqrt{2}\,6\pi} m_Z^3 \left(1 - \frac{4m_{\chi_1^0}^2}{m_Z^2}\right)^{3/2} g_{Z11}^2$$

$$g_{Z11} = \frac{1}{2}\left(|N_{1u}|^2 - |N_{1d}|^2\right)$$

$\Gamma_{95\%\mathrm{CL}}(Z \to \chi_1^0\chi_1^0) \lesssim 0.5\,\text{MeV}$ [LEP]

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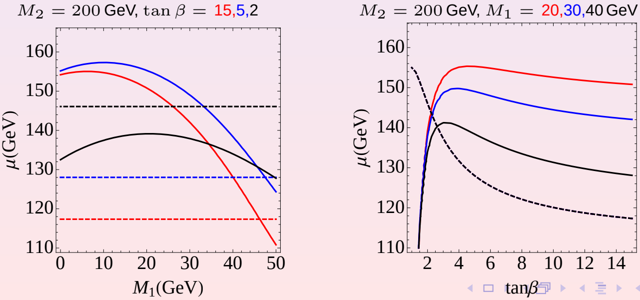

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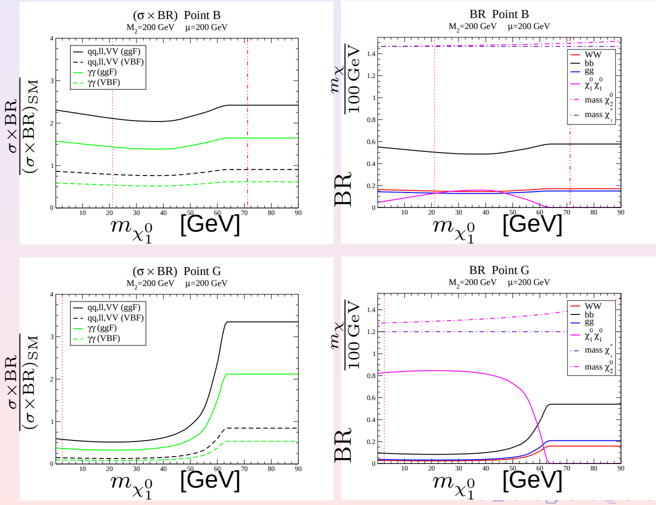

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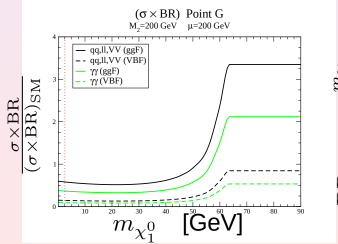
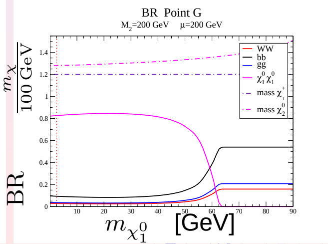
With light neutralino the LSS predictions are less restrictive

Some general predictions are still possible:

- The ratios between the LSS channels are (almost) invariant
- Diphoton channel through weak vector fusion is smaller than SM



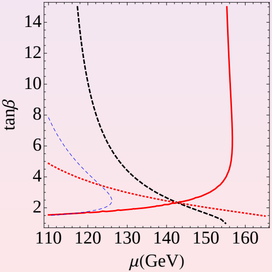


Light Neutralinos as DM [Carena,G.N.,Quiros,Wagner,12]

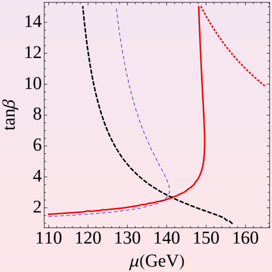
For $m_{\chi_1^0} = 35 - 40$ GeV and $g_{Z11} \approx 0.05$ lightest neutralino provides correct DM abundance [Menon et al.,04]. In such a case (with $M_2 = 200$ GeV) the LSS prediction is stronger:

$$m_{\chi_1^+} > 95\,\text{GeV} \qquad \Gamma_{95\%\text{CL}}(Z \to \chi_1^0 \chi_1^0) \lesssim 0.5\,\text{MeV}$$

$M_1 = 55$ GeV



$M_1 = 40.6$ GeV



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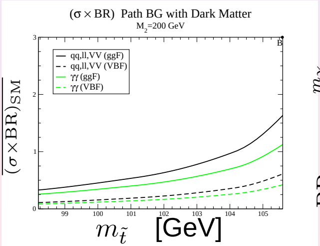
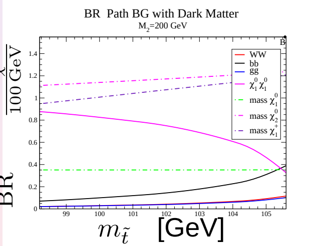




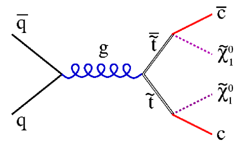
In this specific case LHC data favor $m_{\tilde{t}_R} \approx 104$ GeV

LSS and LHC

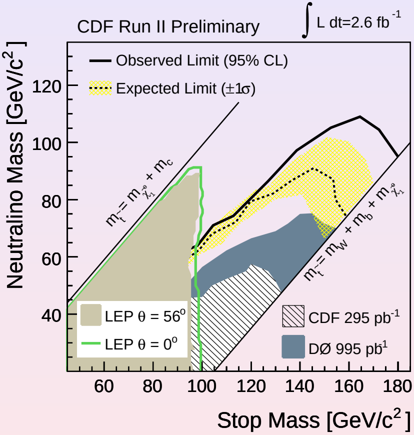
(in stop searches)

Looking for stops at LHC (with $m_{\chi_1^0} \gtrsim 65$ GeV)

- stop-neutralino coannihilation:



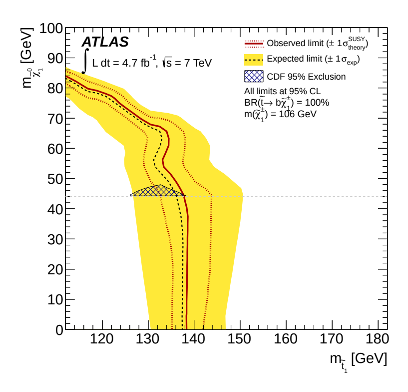
$$\Gamma_{\tilde{t}} \sim \frac{m_{\tilde{t}}}{16\pi^2}\mathcal{O}\left(\frac{m_t A_b}{m_Q^2}, \frac{m_t A_t}{m_Q^2}\right)$$

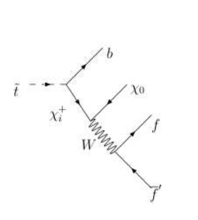


- light gluino (already disfavored by EWPT):
  $\tilde{g}\tilde{g} \to tt\tilde{t}^*\tilde{t}^* \to bbl^+l^+ + (jets) + \not{E}_T$ rules out $m_{\tilde{g}} \lesssim 700$ GeV

Looking for stops at LHC (with $m_{\chi_1^0} < 65\,$GeV)

- on-shell chargino $m_{\chi_1^+} = 106\,$GeV, 2 opposite-sign e/μ events
  $\tilde{t} \to b\chi_0^+(W^*\chi_1^0)$ [arXiv:1208.4305]:





But in the LSS, charginos are typically off-shell ($m_{\tilde{t}} < m_{\chi_1^+}$)

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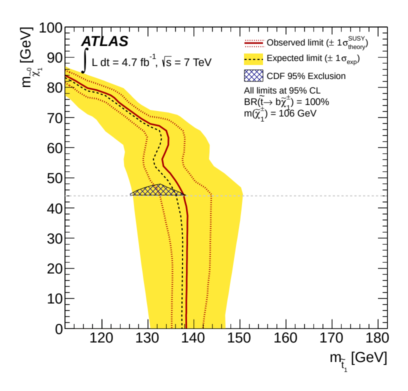

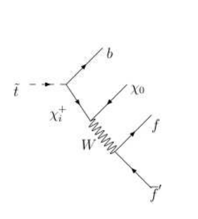

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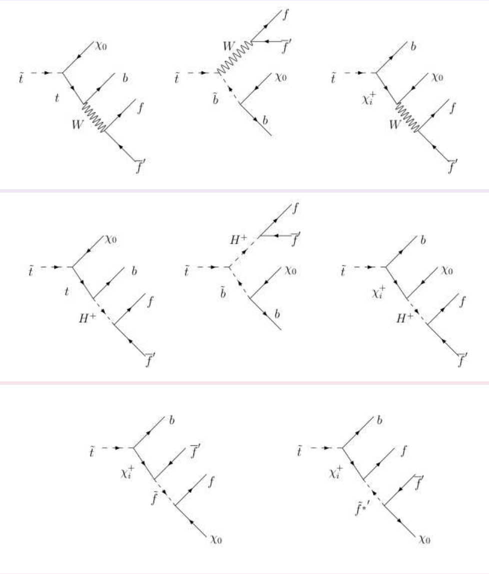
Looking for stops at LHC (with $m_{\chi_1^0} < 65\,$GeV)



Looking for stops at LHC (model dependent)

For $m_{\chi_1^+} < m_{\tilde{t}_R}$:

- $\tilde{t} \to b\chi_1^+(W\chi_1^0)$ rules out $m_{\tilde{t}_R} \lesssim 130$ GeV
- $\tilde{t} \to b\chi_1^+(\tau\nu_\tau\chi_1^0)$ (via light $\tilde{\tau}/\tilde{\nu}_\tau$) Allowed

For $m_{\chi_1^+} > m_{\tilde{t}_R}$:

- as above but with χ_1^+ off-shell. Allowed
- $\tilde{t} \to c\chi_1^0$ (disfavored by Higgs searches)

If different channels have similar widths, more difficult

Conclusions

- There exists a parameter window providing strong EWPT with $m_h \simeq 126$ GeV (and able to reproduce the BAU):

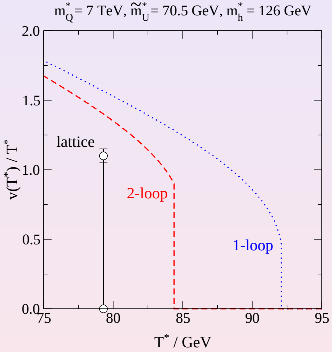
LSS bounds for EWBG in the MSSM:

$m_Q \gg 50$ TeV $\qquad m_{\tilde{t}_R} \lesssim 110$ GeV

- Direct stop detection requires specific analyses
- LHC data on Higgs search favor $m_{\chi_1^0} \lesssim 60$ GeV
- The ratios between Higgs (visible) decay widths are quite fixed
- LHC data are compatible with LSS but better precision is required to probe the model

Open questions (1)

In lattice simulations the phase transition is stronger than in perturbation theory [Laine,GN,Rummukainen, to appear]

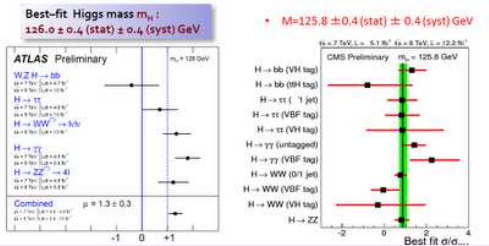


The stop mass seems to be much larger.
Smaller departure from the SM Higgs rates.

Open questions (2)

In UV extensions of the MSSM including triplet $Y = \pm 1$ (and a mixture of gauge mediation and gravity mediation), it is possible to reproduce the LSS at low energy. It alleviates the hierarchy problem and enhances the diphoton decay channel (there are extra gauginos)[Delgado,GN,Quiros, arXiv:1201.5164, arXiv:1207.6596]

Can it qualitatively modify the tension between the LSS and LHC data?


Best–fit Higgs mass m_H :
126.0 ± 0.4 (stat) ± 0.4 (syst) GeV
ATLAS Preliminary
W,Z H → bb
H → ττ
H → WW → lνlν
H → γγ
H → ZZ → 4l
Combined
μ = 1.3 ± 0.3
-1
0
+1
M=125.8 ± 0.4 (stat) ± 0.4 (syst) GeV
CMS Preliminary
H → bb (VH tag)
H → bb (ttH tag)
H → ττ (VBF tag)
H → ττ (VH tag)
H → γγ (untagged)
H → γγ (VBF tag)
H → WW (0/1 jet)
H → WW (VBF tag)
H → WW (VH tag)
H → ZZ
-2
0
2
4