

Higgs signatures of MSSM Electroweak Baryogenesis

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Based on work with:

David E. Morrissey, [arXiv:0903.3038]

Motivation: Baryon Asymmetry of Universe

- Baryon density of the Universe:

$$\eta = \frac{n_B}{n_\gamma} = (6.5 \pm 0.3) \times 10^{-10}$$

where n_B is the excess number density of baryons and n_γ is the number density of photons. WMAP '06

- Baryon asymmetry of the Universe cannot be explained within the Standard Model.

The Sakharov Conditions for Baryon Asymmetry

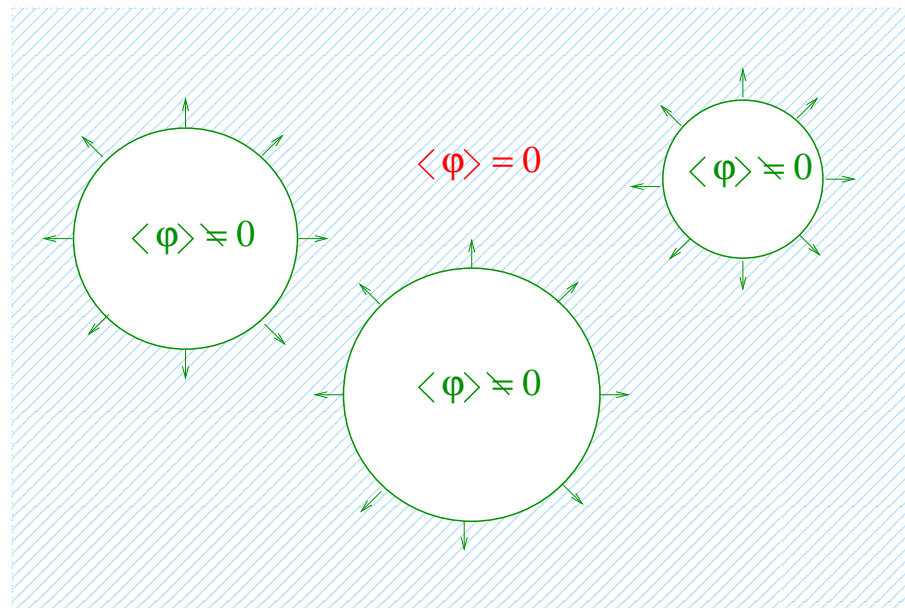
- Necessary conditions for generating baryon asymmetry (BAU) are:
 - 1) Baryon number B violation
 - 2) CP violation
 - 3) Violation of thermal equilibrium
- B violation clearly necessary for generating BAU
- B is odd under C and CP \Rightarrow BAU
- B is also odd under T \Rightarrow BAU

The Electroweak Baryogenesis Scenario

- Baryon production occurs at the electroweak phase transition.

[Kuzmin, Rubakov, Shaposhnikov '85]

- Electroweak symmetry breaking occurs as universe cools nucleating bubbles of broken phase.
- Baryon production occurs near the walls of the expanding bubbles.



The Electroweak Phase Transition

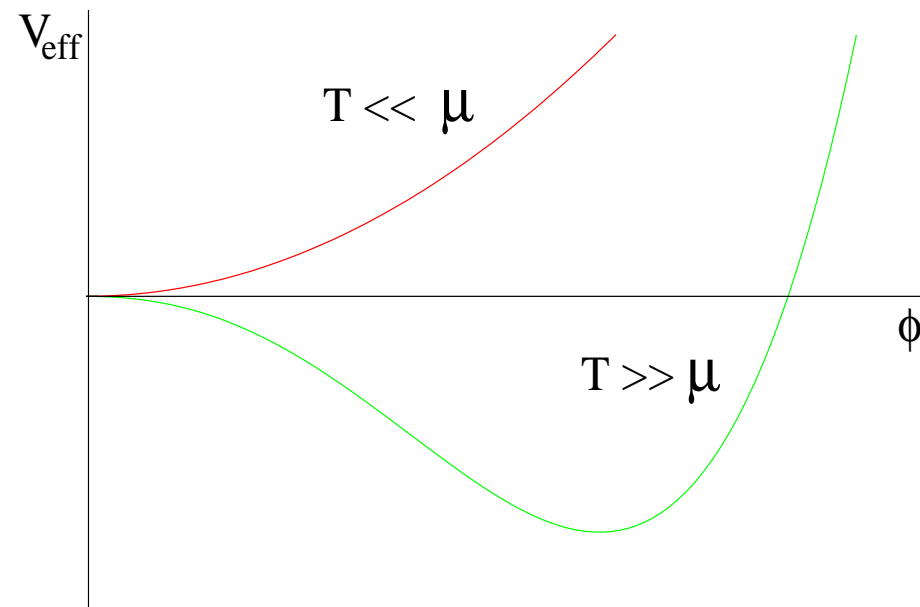
- The Higgs VEV $\langle \phi \rangle$ is the order parameter

$$\langle \phi \rangle = 0 \Rightarrow SU(2) \times U(1)_Y \text{ Unbroken}$$

$$\langle \phi \rangle \neq 0 \Rightarrow SU(2) \times U(1)_Y \rightarrow U(1)_{em}$$

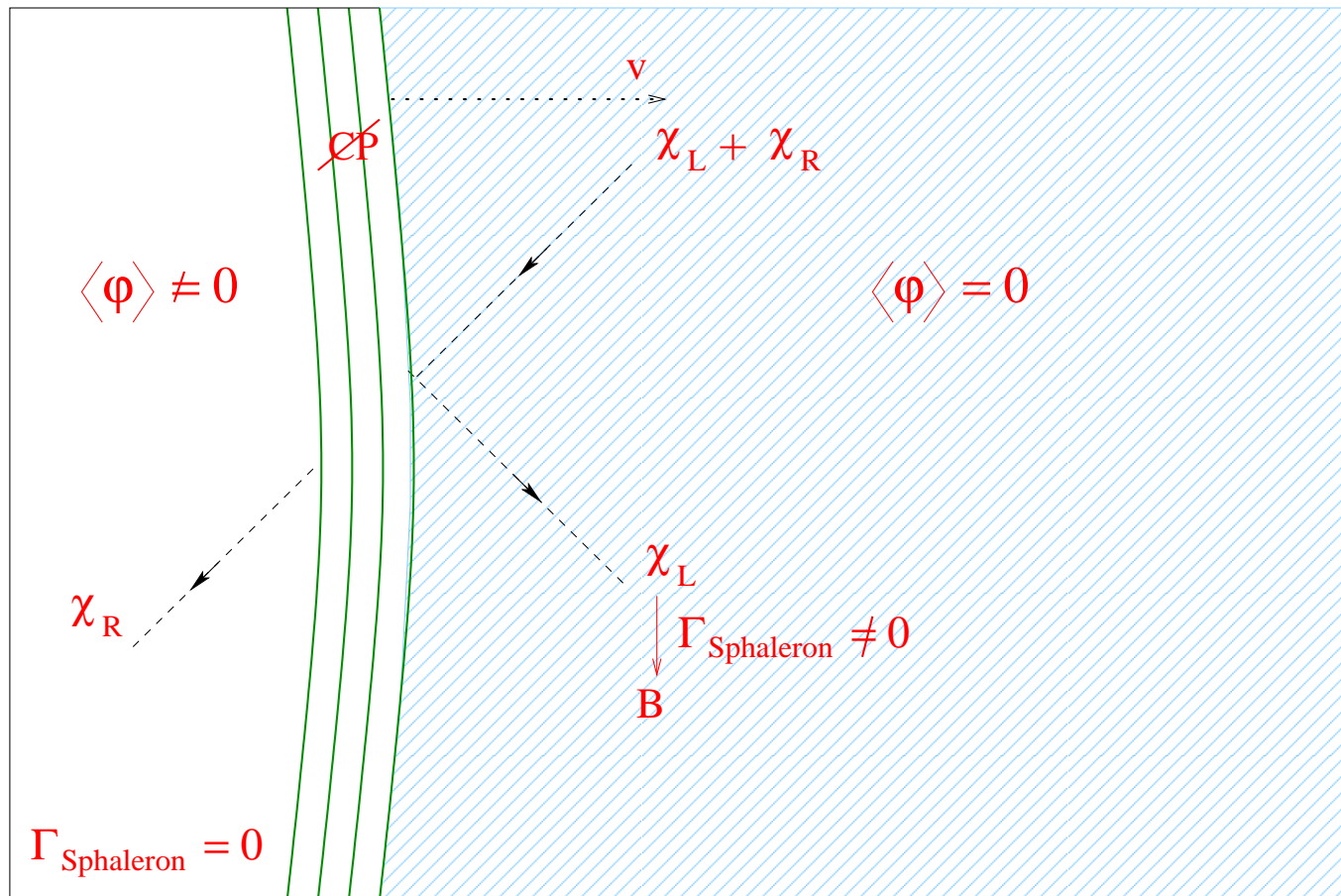
- Effective potential at finite temperature T

$$V_{eff} = (-\mu^2 + \alpha T^2)\phi^2 - \gamma T\phi^3 + \frac{\lambda}{4}\phi^4 + \dots$$



Baryon Production

- CP violation in bubble wall \Rightarrow chiral flux into the unbroken phase.
- Sphaleron transitions in the unbroken phase converts the chiral flux into baryons.
- Baryons produced at the bubble wall, enter the bubble as it expands.



EWBG MSSM: First Order Phase Transition

- For a first order phase transition for

$$V_{eff} = (-\mu^2 + \alpha T^2)\phi^2 - \gamma T\phi^3 + \frac{\lambda}{4}\phi^4 + \dots$$

we need

$$\frac{\langle\phi(T_c)\rangle}{T_c} \simeq \frac{\gamma}{\lambda} > 1$$

- γ is generated bosonic loops and the dominant contribution in the MSSM is from a light mostly right-handed stop. [Carena, Quiros, Wagner]
- Larger stop mass \Rightarrow large $\lambda \Rightarrow$ larger m_h .

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- The finite temperature effective Higgs potential in the MSSM has a term

$$V_{eff}^{MSSM} \subset -\frac{N_c T}{6\pi} (m_{\tilde{t}}^2 + \Pi_R(T)^2)^{3/2}$$

where $\Pi_R(T)^2$ is the positive self energy contribution and

$$m_{\tilde{t}}^2 \sim m_{U_3}^2 + y_t^2 \phi^2 \left(1 - \frac{|X_t|^2}{m_{Q_3}^2} \right)$$

- Generating a ϕ^3 term needed for a first order phase transition $\Rightarrow m_{U_3}^2$ cancels $\Pi_R(T)^2$ and $X_t \ll m_{Q_3}$.

EWBG MSSM: Light Stop Implications

- $\Delta\rho$ limits \Rightarrow light stop mass must be mostly right handed.
- For a strong first order phase transition and to avoid color breaking minima

$$\begin{aligned} -(100\text{GeV})^2 \lesssim m_{U_3}^2 \lesssim 0; \quad X_t/m_{Q_3} \lesssim 0.5 \\ \Rightarrow 120 \lesssim m_{\tilde{t}_1} \lesssim 170\text{GeV}. \end{aligned}$$

- Avoiding LEP limit on Higgs mass:

$$\begin{aligned} m_{Q_3} \gtrsim 2\text{TeV}; \quad M_A \gtrsim 200\text{GeV}; \quad 5 < \tan\beta < 10 \\ \Rightarrow m_h \lesssim 125\text{GeV} \end{aligned}$$

- Light stop search limits for $m_{\tilde{t}_1} \leq m_t$:

$$(m_{\tilde{t}_1} - m_{Wimp}) \lesssim 30\text{GeV}.$$

as decay products are soft and difficult to find.

- Light stop coannihilations with Bino LSP \Rightarrow viable Ωh^2 for $m_{\tilde{t}_1} - m_{Wimp} \lesssim 30\text{ GeV}$. [Balazs,Carena,A.M.,Morrissey,Wagner '05].

EWBG MSSM: CP Violation

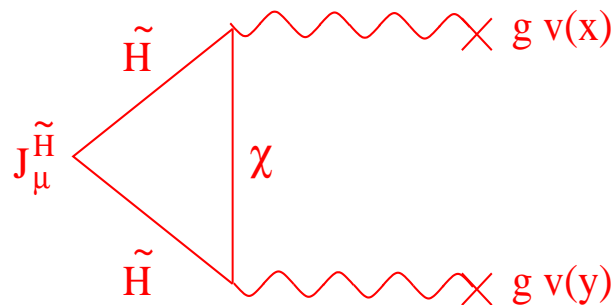
- Higgsino is an important source of MSSM CP violation phase

$$M_{\tilde{\chi}^\pm} \sim \begin{pmatrix} |M_2| & g_2 v_u(z) \\ g_2 v_d(z) & e^{i\phi} |\mu| \end{pmatrix}$$

where ϕ is the $Arg(\mu M_2)$.

- CP violation in bubble wall modifies the transmission and reflection coefficients leading the current

$$\langle J_\mu^{\tilde{H}} \rangle \propto Im(\mu M_2)$$



- $\langle J_\mu^{\tilde{H}} \rangle$ in turn sources B violating process through sphalerons.

EWBG MSSM: Implications of CP Violation

- Generating baryon asymmetry:

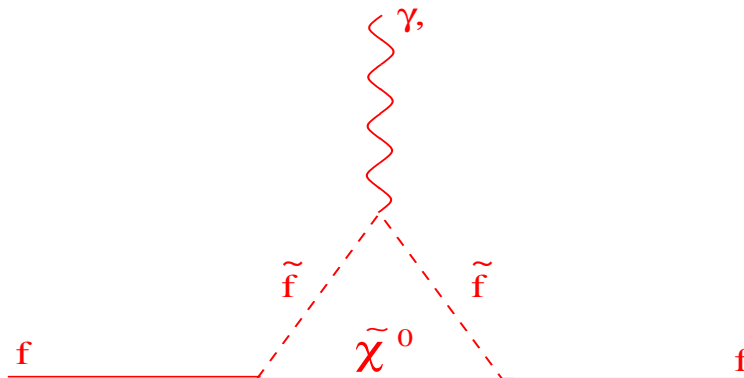
$$\begin{aligned} \text{Arg}(\mu M_{1,2}) &\gtrsim 10^{-2} \\ \mu M_{1,2} &\lesssim 400 \text{ GeV} \end{aligned}$$

[Carena, Quiros, Seco, Wagner '02, Lee, Cirigliano, Ramsey-Musolf '04]

- EDM constraints:

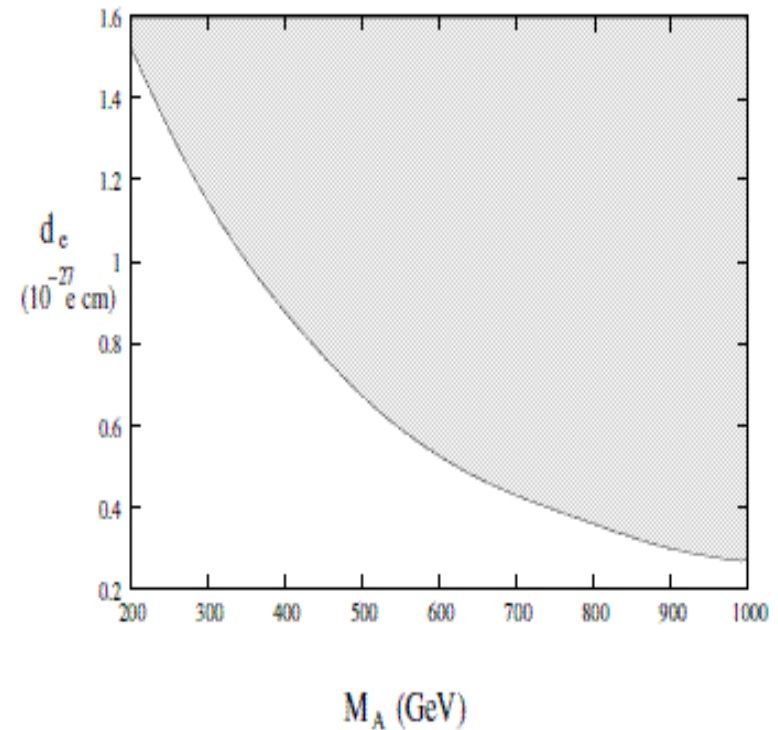
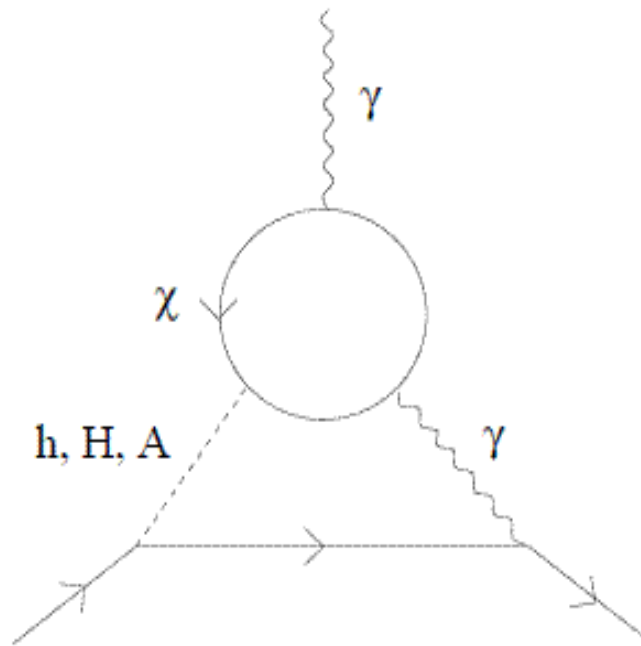
$$\begin{aligned} |d_e| &< 1.6 \times 10^{-27} \text{ e cm} && [\text{Regan et. al. '02}] \\ |d_n| &< 2.9 \times 10^{-26} \text{ e cm} && [\text{Baker et. al. '06}] \end{aligned}$$

- One loop EDM constraints $\Rightarrow m_{\tilde{f}}^2 > 2 - 5 \text{ TeV}$ or the first two generations are decoupled. [Nath, Ibrahim '98]



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- Two-loop contribution: $\propto \text{Im}(\mu M_2)$ [Chang, Chang, Kueng '02; Pilatfsis '02]



- EDM constraints weaker for $M_A \gtrsim 1$ TeV.

Split Stop Supersymmetry

- EDM constraints \Rightarrow large sfermion and pseudo scalar masses.

$$m_{\tilde{f}} \gtrsim 5 \text{ TeV}$$

- LEP Higgs mass limit \Rightarrow heavy mostly left-handed stop

$$m_{\tilde{t}_2} \gtrsim 2 \text{ GeV}.$$

- EWBG \Rightarrow light charginos, neutralinos and right handed stops.

$$m_{LSP} < m_{\tilde{t}_1} \lesssim m_t$$

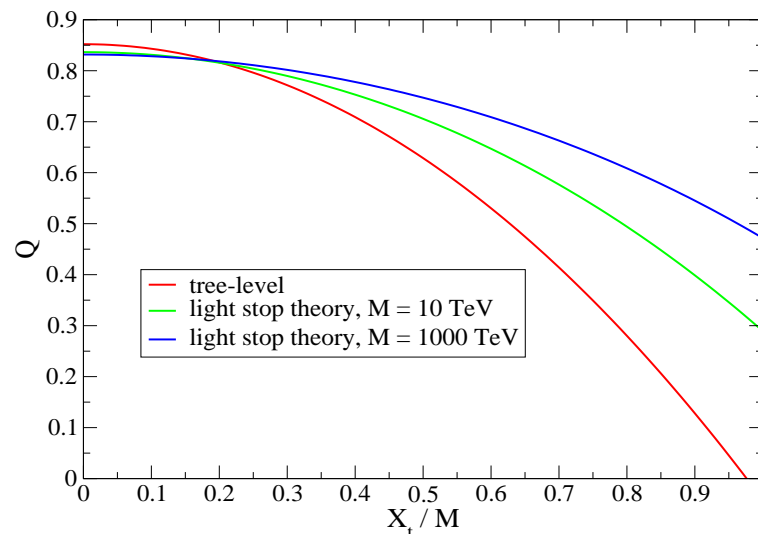
\Rightarrow Stop Split Supersymmetry. [Carena,Nardini,Quiros,Wagner '09]

Indirect light stop effects on Higgs Searches

- Light stops can modify Higgs production cross-sections.
[Kane et. al. '95; Dawson et. al. '96; Djouadi '98; Dermisek, Low '07]
- Effective light stop Higgs coupling in EWBG

$$g_{h\tilde{t}_1\tilde{t}_1} \sim m_t^2 \left(1 - \frac{|X_t|^2}{m_{Q_3}^2} \right)$$

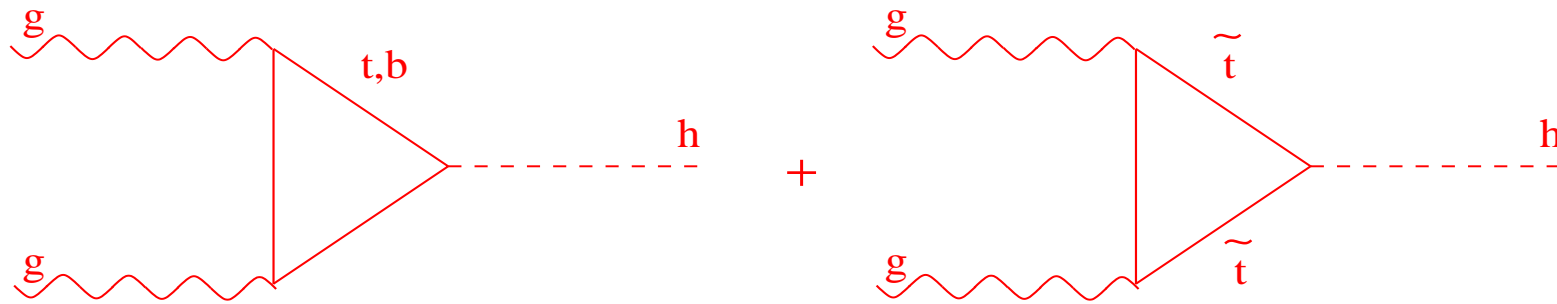
where $Q = \sqrt{2}vg_{h\tilde{t}_1\tilde{t}_1}$



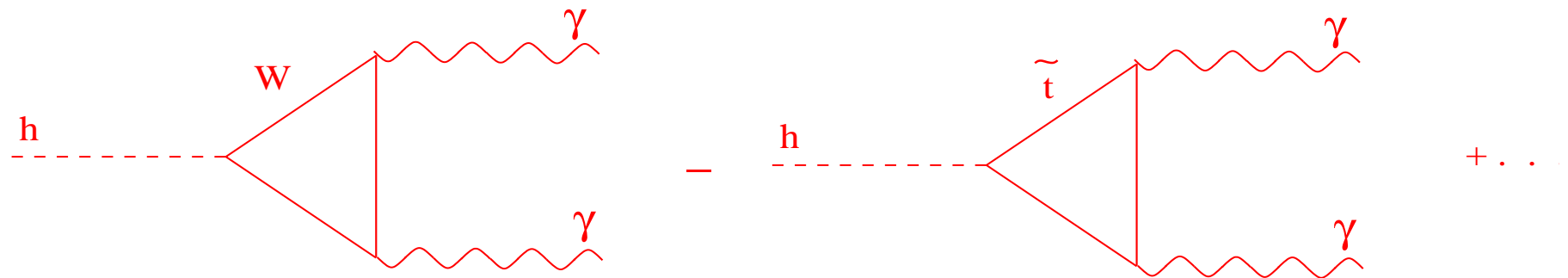
- Stronger first order EW phase transition \Rightarrow larger $g_{h\tilde{t}_1\tilde{t}_1}$ coupling, if $X_t \ll m_{Q_3}$.

Light stop loop effects on Higgs Branching Ratios

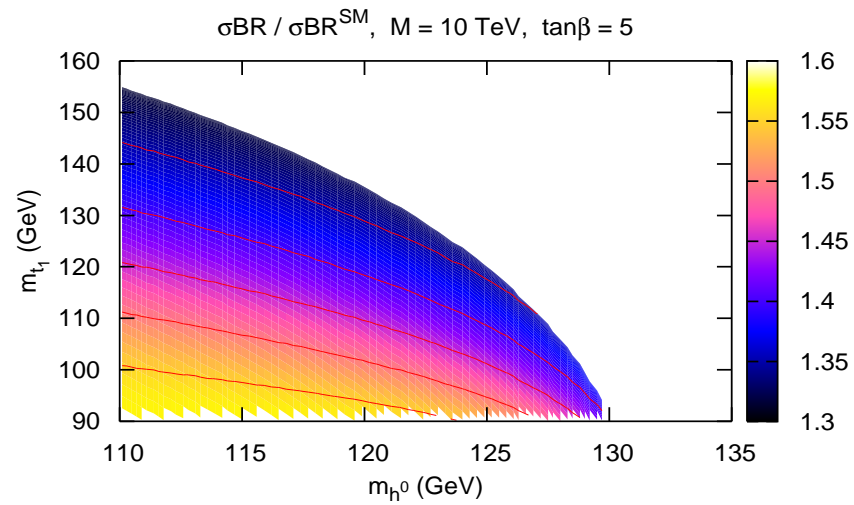
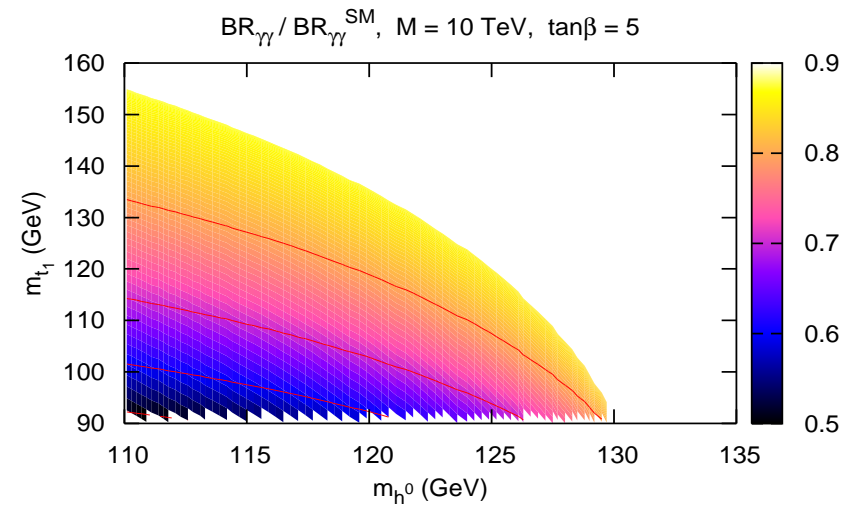
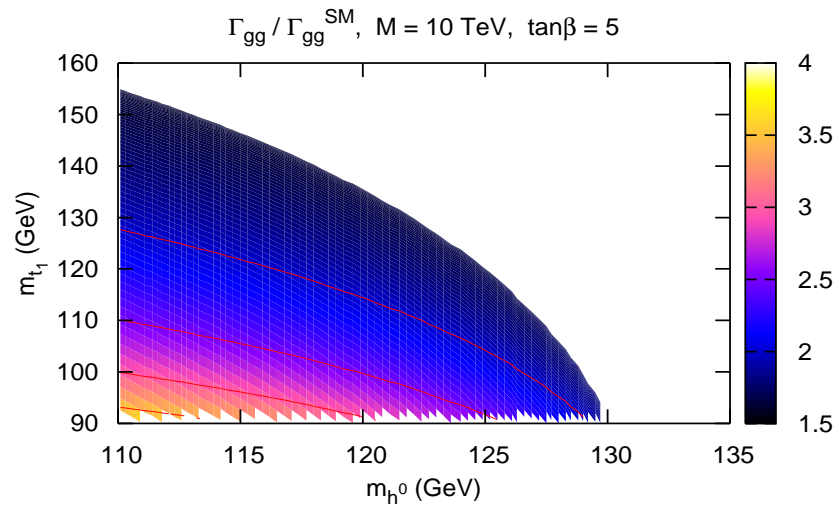
Gluon Fusion



Higgs Photon coupling

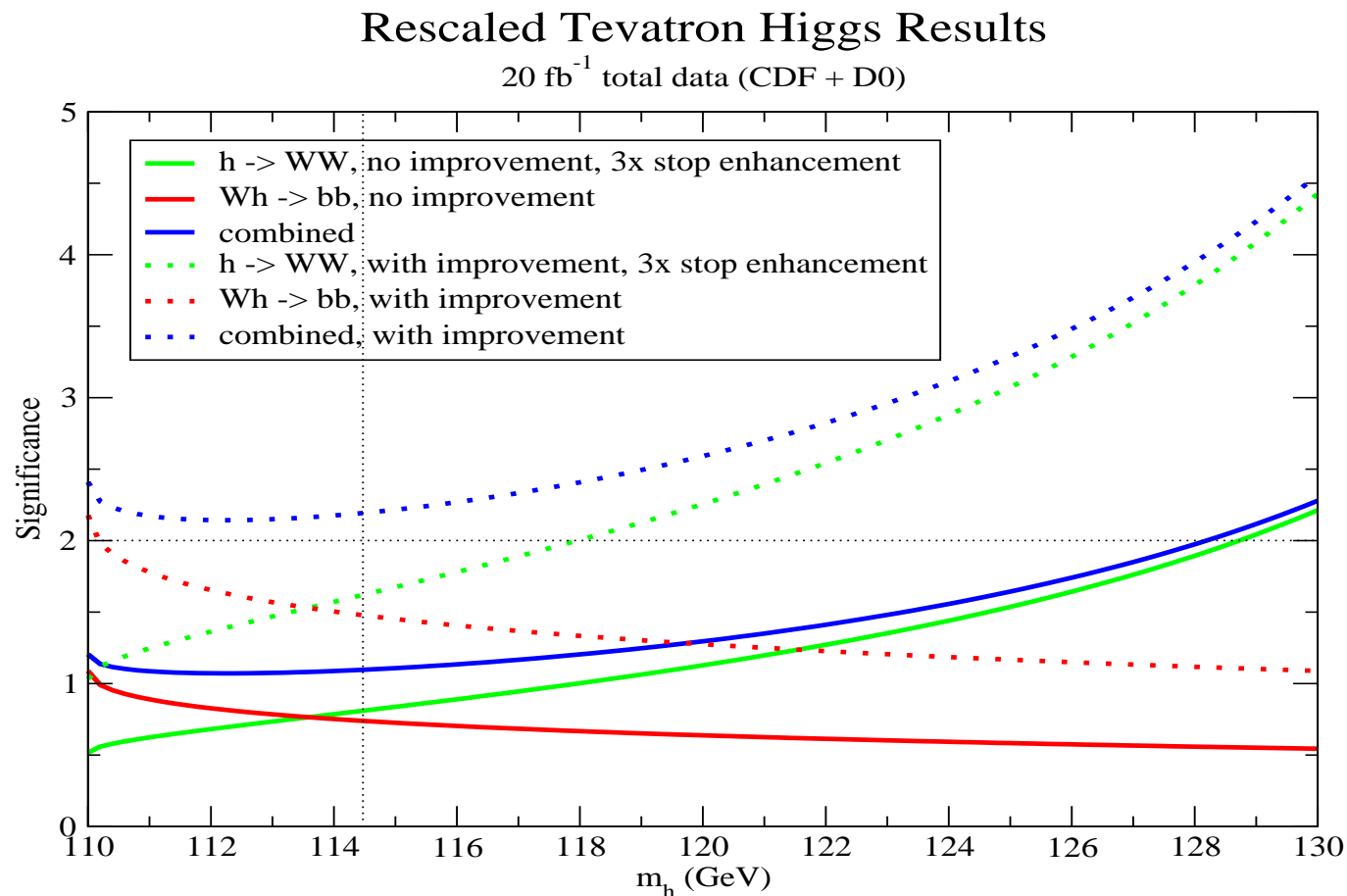


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Light stop effects on Higgs searches at the Tevatron

- For $m_h \lesssim 135$ GeV: Associated Higgs production $Wh \rightarrow Wb\bar{b}$ is dominant
- For $m_h \gtrsim 135$ GeV: $gg \rightarrow h \rightarrow WW^*$ dominant.



Improvements in analysis \Rightarrow 2 – 3 σ observation of the Higgs?

Light stop and Higgs searches at LHC

- 5σ Higgs discovery in $gg \rightarrow h \rightarrow \gamma\gamma$ with 30fb^{-1} and error in Higgs mass 0.2 GeV . [ATLAS Collaboration'09; CMS Collaboration '07]

- 30 % error in Γ_{hgg} with 200fb^{-1} of data.

[Zeppenfeld et. al. '00,02; Belyaev, Reina '02; Duhrssen et. al. '04]

- 20 % error in $\Gamma_{h\gamma\gamma}$ with 200fb^{-1} of data.

[Zeppenfeld et. al. '00,02; Belyaev, Reina '02; Duhrssen et. al. '04]

Large enhancements of Γ_{hgg} in EWSB \Rightarrow deviations in $\Gamma_{ggh}/(\Gamma_{ggh})_{SM}$ should be observable with 200fb^{-1} at 3σ .

- Finding deviations in $\Gamma_{h\gamma\gamma}$ is more challenging.

Summary

- EWBG MSSM is a very predictive scenario \Rightarrow stop split SUSY - light stop, charginos and neutralinos with the remaining scalars being heavy.
- Observing this scenario at the LHC is very challenging.
- Higgs branching fractions are a potential indirect probe of this scenario and could lead to an enhancement of the signal significance at the Tevatron.

Future avenues

- Stopped quarkonium decays into leptons are velocity suppressed but lower backgrounds in this channel may make it a viable channel at the LHC.
- Light charginos and neutralino decays involving intermediate stops could be an additional way of probing this scenario at the LHC.