# Higgs signatures of MSSM Electroweak Baryogenesis

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May 21st, 2009

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 $n_\gamma$ is the number density of photons. WMAP '06

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

# Outline

1) The Mechanism of Electroweak Baryogenesis:
   a) The Electroweak phase transition at finite temperature
   b) Bubble Nucleation
   c) Baryon Production
   d) Sphalerons
2) Realizing Electroweak Baryogenesis
   a) Electroweak Baryogenesis in the Standard Model
   b) Electroweak Baryogenesis in the MSSM
   c) The EWBG MSSM parameter space.
3) Collider implications of EWBG MSSM
   a) Light stop searches at the Tevatron and LHC
   b) Searches for Stoponium
   c) Indirect Higgs Searches
4) Summary and Outlook

# 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

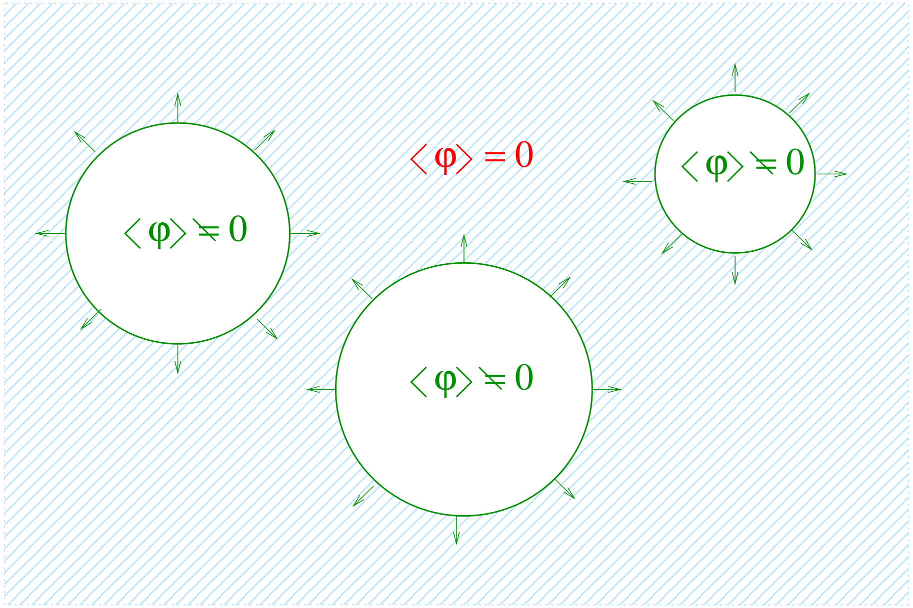
# The Electroweak Baryogenesis Scenario

• 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.



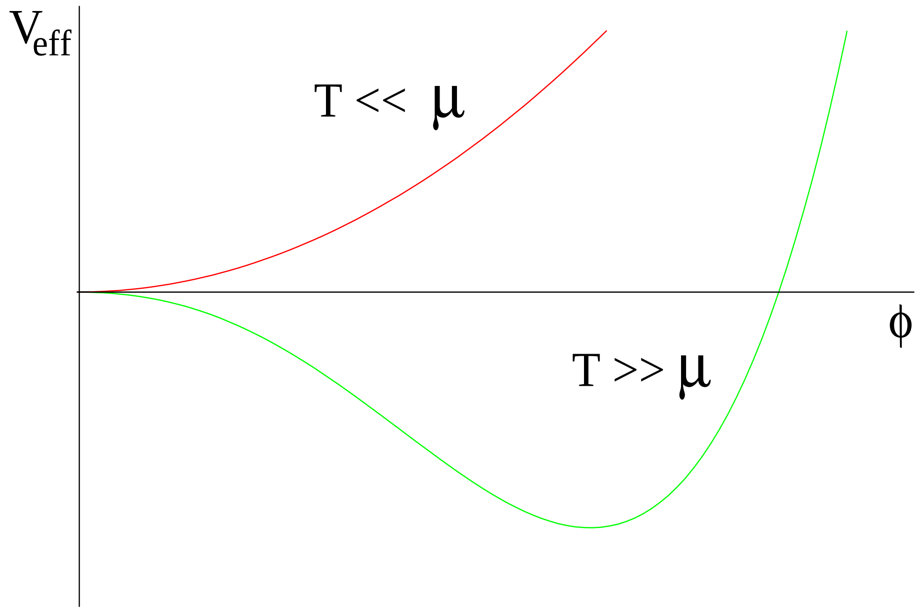
# The Electroweak Phase Transition

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

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

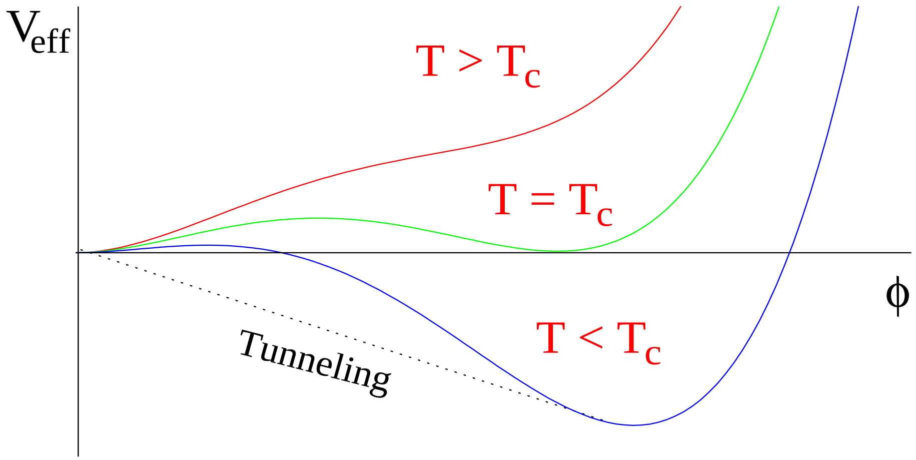
- Effective potential at finite temperature $T$

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

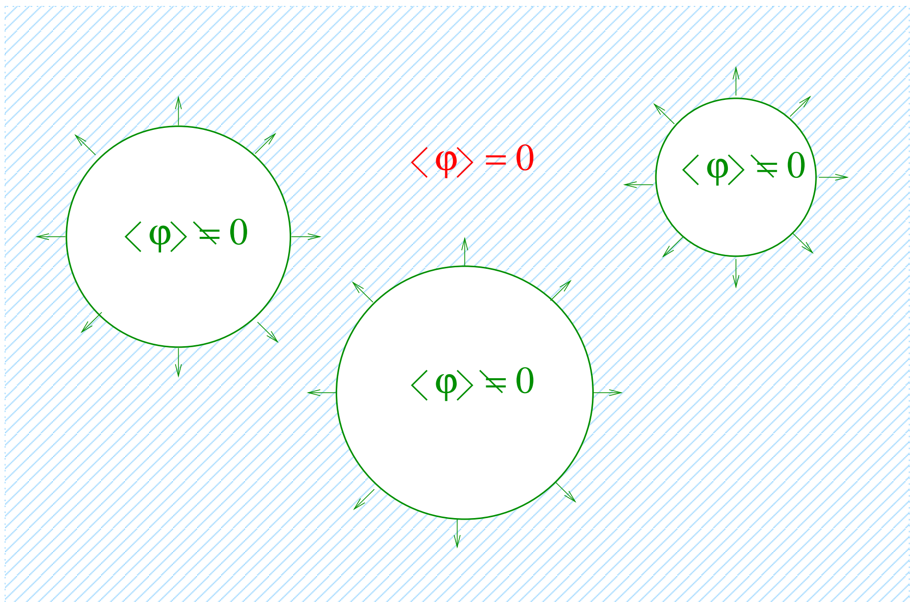


# Bubble Nucleation

- First order phase transition




- Bubbles of broken phase nucleate for $T \lesssim T_c$

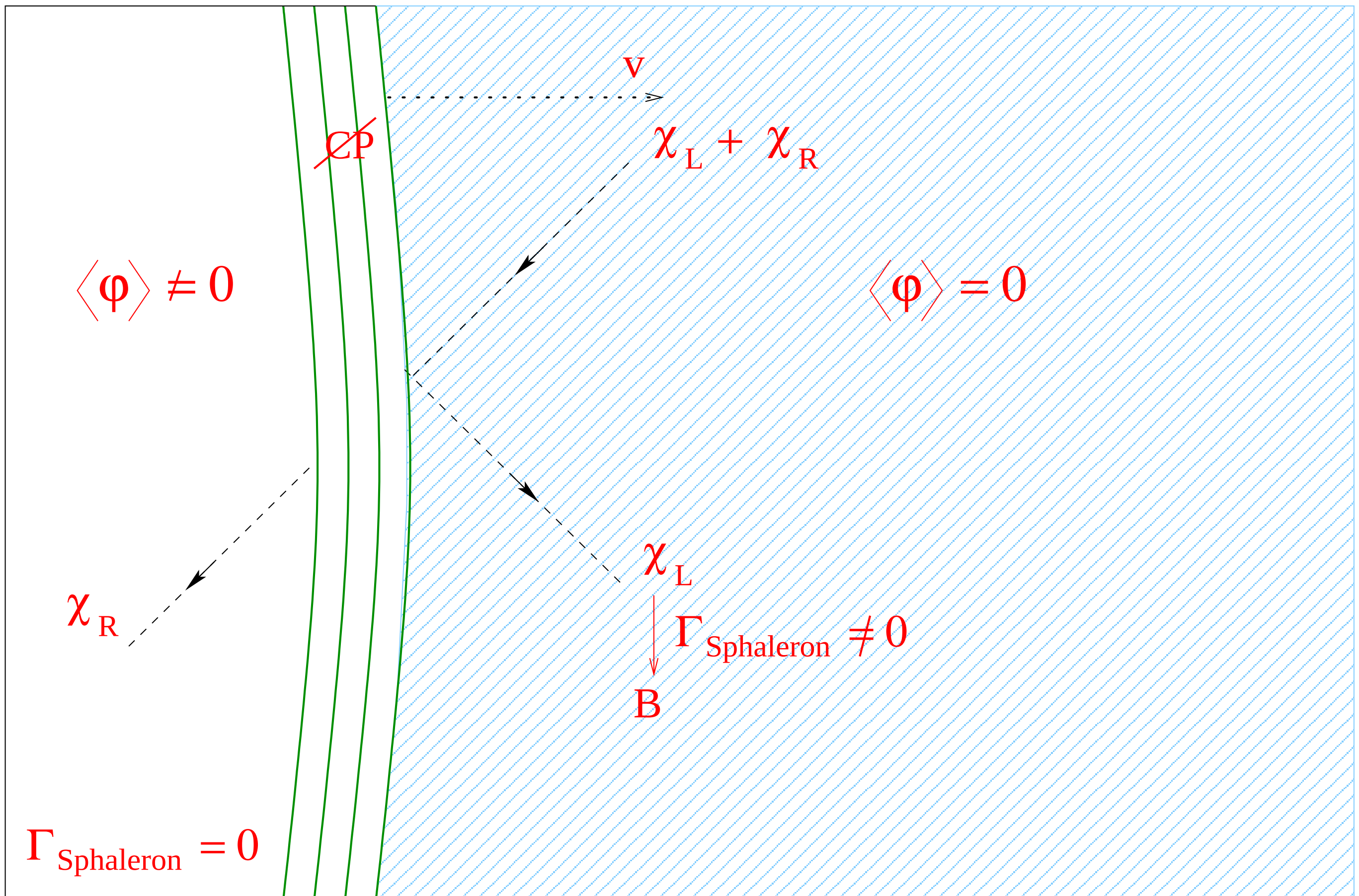


# Baryon Production

- 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.



# Sphalerons

- $U(1)_{B+L}$ is anomalous in the SM and is violated by quantum effects.

- $T = 0$ Instanton effects drive transitions

$$\Gamma \sim e^{-16\pi^2/g_2^2} \simeq 10^{-320}.$$

- $T \neq 0$ Thermal fluctuations (sphaleron) drive transitions

$$\Gamma \sim \begin{cases} T^4 e^{-4\pi\langle\phi\rangle/gT} & \langle\phi\rangle \neq 0 \quad \text{[Arnold,Mclerran '87]} \\ \alpha_w^4 T^4 & \langle\phi\rangle = 0. \quad \text{[Bodeker,Moore,Rummukainen '99]} \end{cases}$$

# EWBG in the Standard Model

- Electroweak phase transition is first-order only if [Kajantie et. al.'98]

$$m_h \lesssim 70 \text{ GeV}$$

- LEP experimental mass bound

$$m_h > 114.4 \text{ GeV}$$

- Not enough CP violation is SM [Gavela et. al. '94]

EWBG does not work in the Standard Model.

# EWBG MSSM: First Order Phase Transition

- For a first order phase transition for

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

we need

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

- $\gamma$ 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 $m_h$.

# contd...

• 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 $\phi^3$ 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

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

- Avoiding LEP limit on Higgs mass:

$$m_{Q_3} \gtrsim 2\text{TeV}; \quad M_A \gtrsim 200GeV; \quad 5 < \tan\beta < 10$$

$\Rightarrow m_h \lesssim 125\text{GeV}$

- 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 $\Omega h^2$ for $m_{\tilde{t}_1} - m_{Wimp} \lesssim 30$ GeV. [Balazs,Carena,A.M.,Morrissey,Wagner '05].

# EWBG MSSM: CP Violation

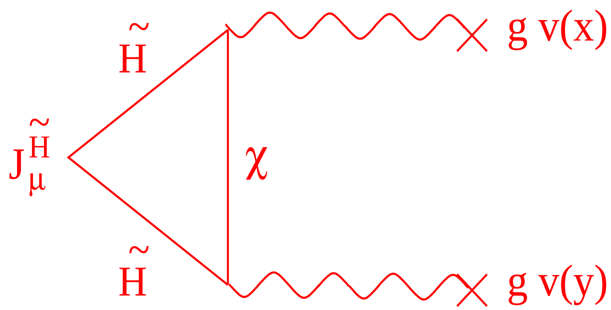
- Higgsino is an important source of MSSM CP violation phase

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

where $\phi$ 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:

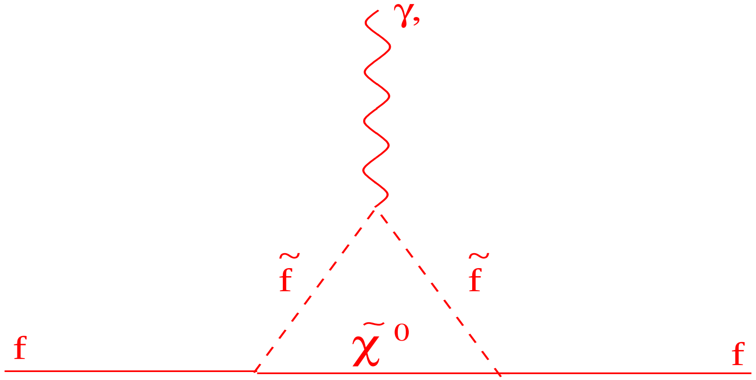
$$Arg(\mu M_{1,2}) \gtrsim 10^{-2}$$
$$\mu M_{1,2} \lesssim 400 \text{ GeV}$$

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

- EDM constraints:

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

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



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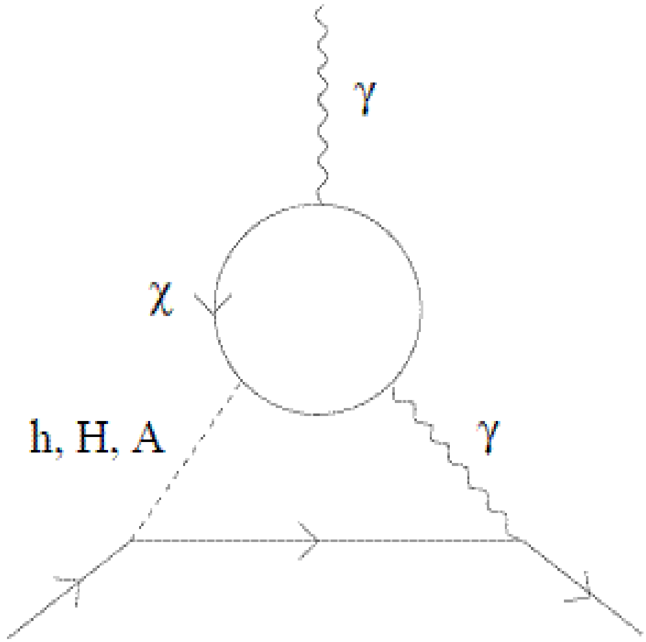
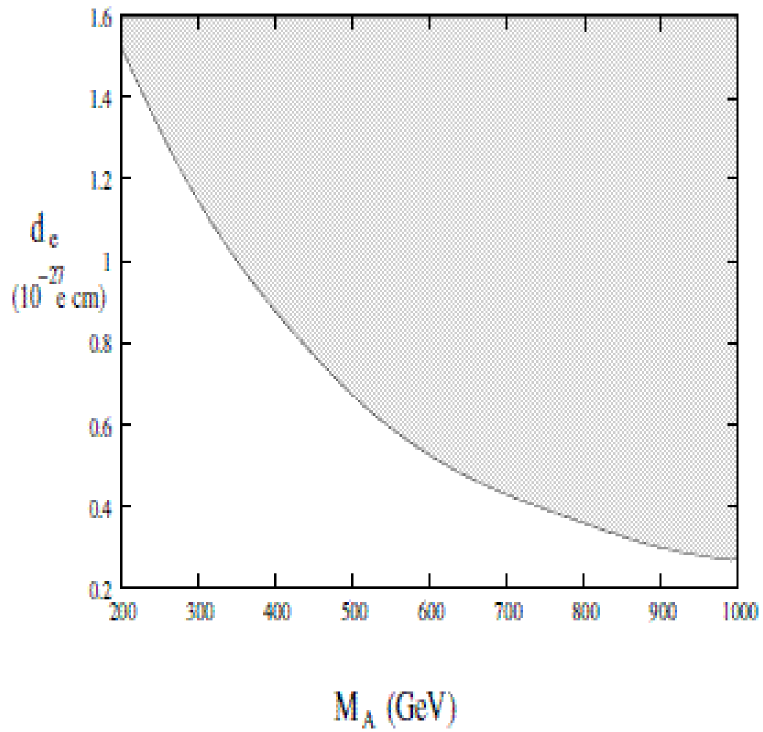
- Two-loop contribution: $\propto Im(\mu M_2)$ [Chang, Chang, Kueng '02; Pilatfsis '02]




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

# Split Stop Supersymmetry

- EDM constraints ⇒ large sfermion and pseudo scalar masses.

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

- LEP Higgs mass limit ⇒ heavy mostly left-handed stop

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

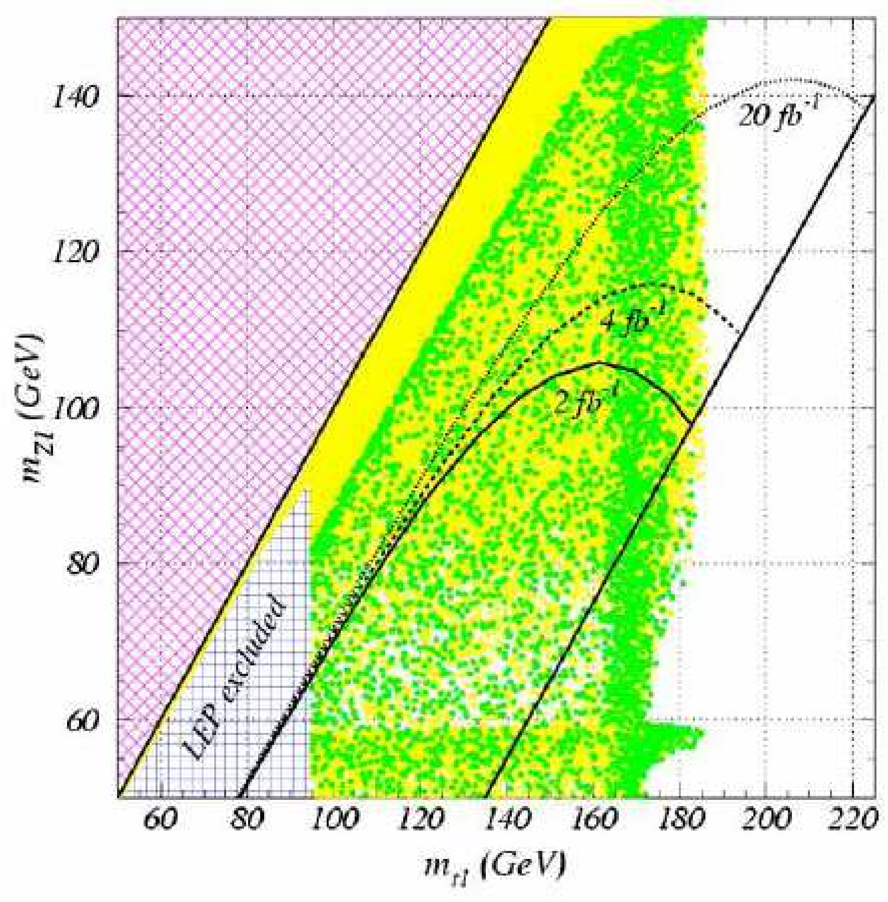
- EWBG ⇒ light charginos, neutralinos and right handed stops.

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

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

# Direct light stop searches: Tevatron

- Light stop searches the in $\tilde{t} \to c\tilde{\chi}^0$ channel: [Balazs, Carena, Wagner '04]



# Direct light stop searches: LHC

- $\tilde{t}_1$ produced copiously, but decays into soft jets so hard to find.

- Possible channels $\tilde{t}_1 \to c\chi_1^0$, $\tilde{t}_1 \to bW^*\chi_1^0$, $\tilde{t}_1 \to b\chi_1^{+*}$.

[Balazs et. al. '04; Demina et. al. '99; Hiller, Nir'08]

- Can be seen in gluino pair production and decay into same sign leptons, jets and MET with 30 $\text{fb}^{-1}$ for $m_{\tilde{g}} \lesssim 1$ TeV. [Kramel, Raklev '05,06]

- Parameter space determination is generally challenging.

# Direct light stop searches: Stoponium

- $\eta_{\tilde{t}_1} = \tilde{t}_1 \tilde{t}_1^*$ can form as $\Gamma_{\tilde{t}_1 \to c\chi_1^0} \ll$ binding energy of $\eta \tilde{t}_1$.

[Nojiri, Dress '95]

- $\eta_{\tilde{t}_1} \to \gamma\gamma$ may be observable with 100 $\text{fb}^{-1}$ for $m_{\eta \tilde{t}_1} \lesssim 250$ GeV.

[Martin '08]

Precise measurement of stoponium mass.

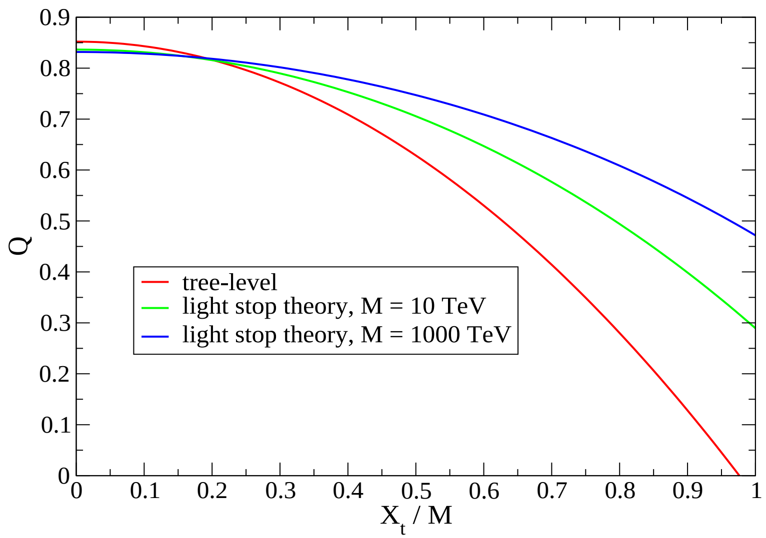
# Indirect light stop effects on Higgs Searches

- 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

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

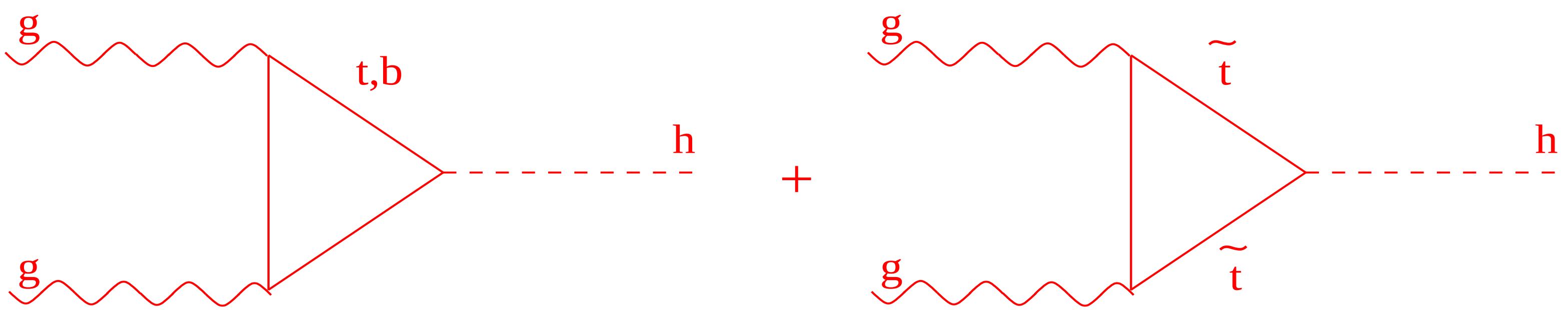
where $Q = \sqrt{2} v g_{h\tilde{t}_1\tilde{t}_1}$



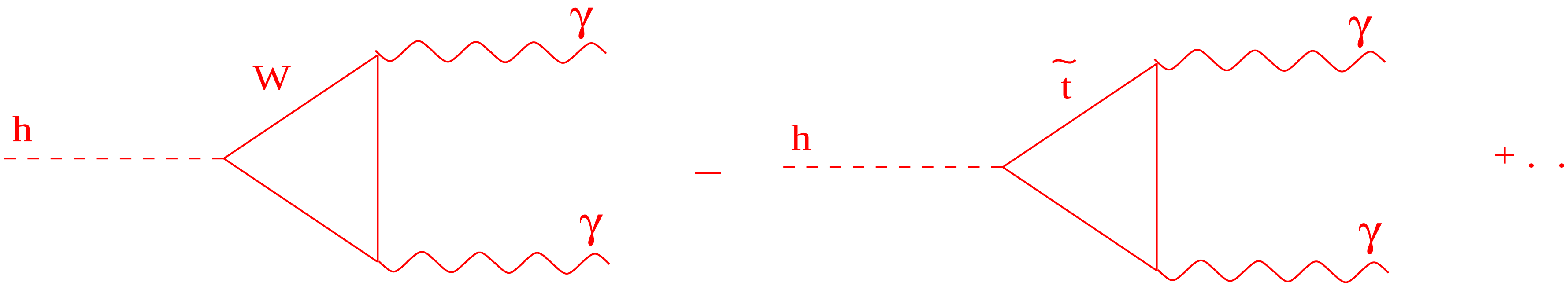

- Stronger first order EW phase transition $\Rightarrow$ larger $g_{h\tilde{t}_1\tilde{t}_1}$ coupling, if $X_t \ll m_{Q_3}$.

# Light stop loop effects on Higgs Branching Ratios

Gluon Fusion




Higgs Photon coupling



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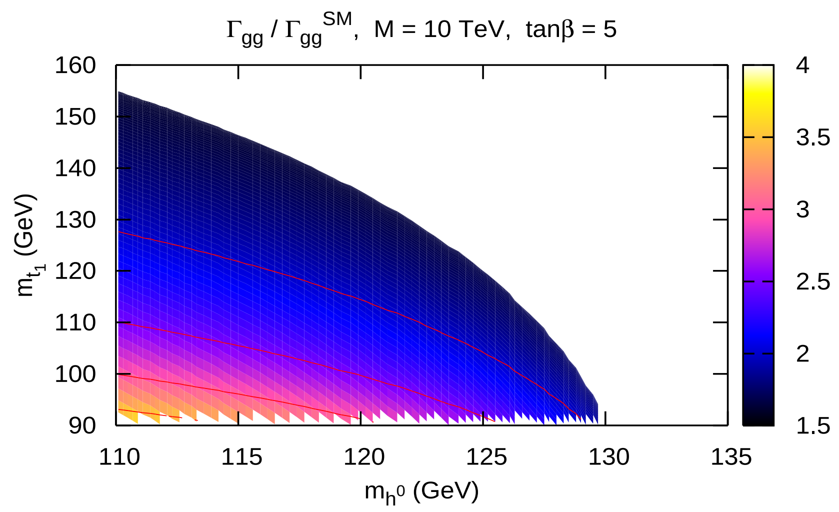
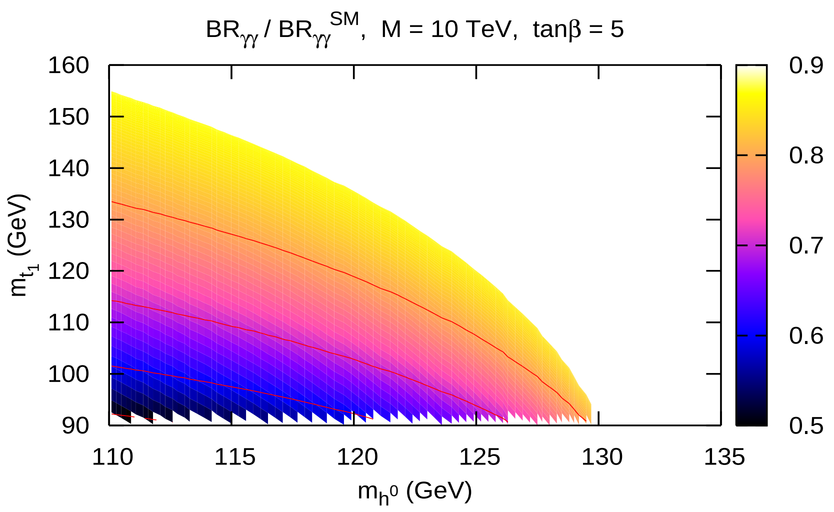
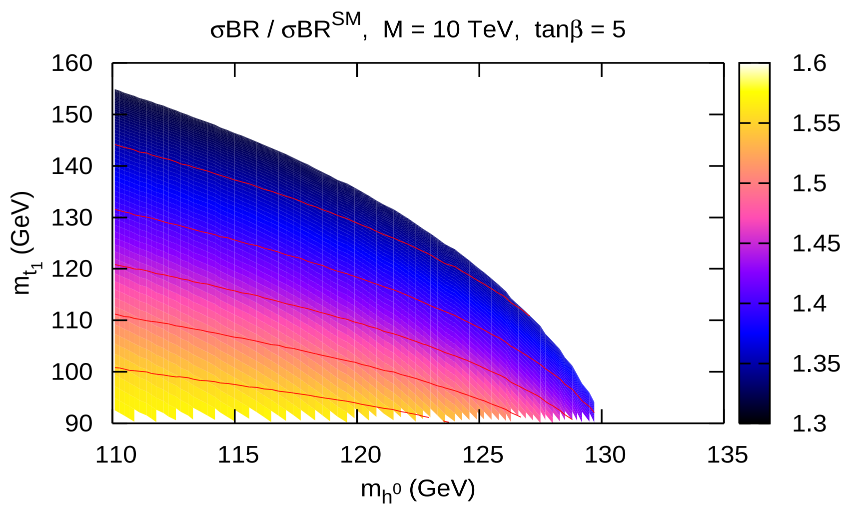


$\Gamma_{gg} / \Gamma_{gg}^{SM}$, M = 10 TeV, tanβ = 5
$m_{\tilde{t}_1}$ (GeV)
$m_{h^0}$ (GeV)
160
150
140
130
120
110
100
90
110
115
120
125
130
135
4
3.5
3
2.5
2
1.5

$BR_{\gamma\gamma} / BR_{\gamma\gamma}^{SM}$, M = 10 TeV, tanβ = 5
$m_{\tilde{t}_1}$ (GeV)
$m_{h^0}$ (GeV)
160
150
140
130
120
110
100
90
110
115
120
125
130
135
0.9
0.8
0.7
0.6
0.5

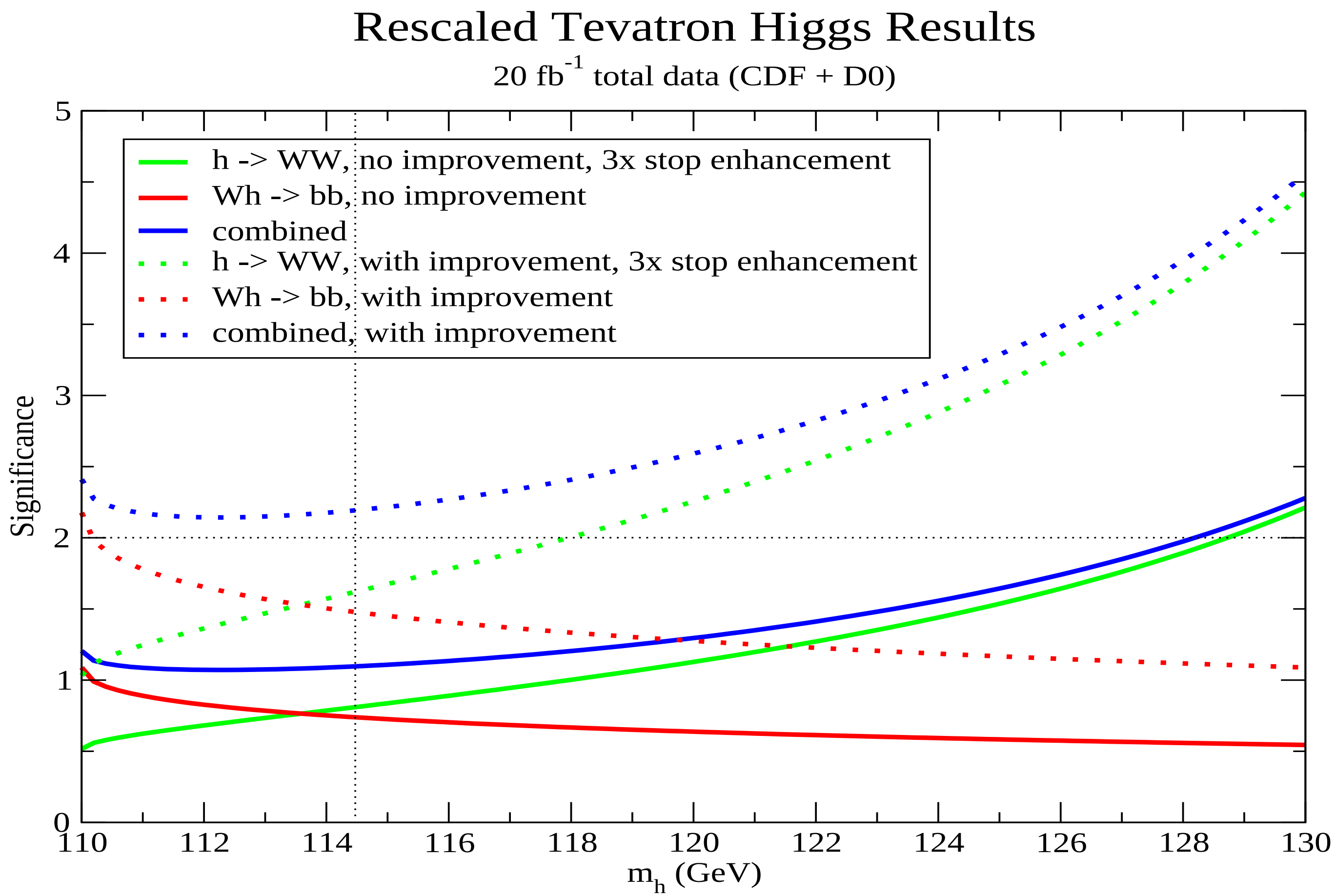



$\sigma BR / \sigma BR^{SM}$, M = 10 TeV, tanβ = 5
$m_{\tilde{t}_1}$ (GeV)
$m_{h^0}$ (GeV)
160
150
140
130
120
110
100
90
110
115
120
125
130
135
1.6
1.55
1.5
1.45
1.4
1.35
1.3

# Light stop effects on Higgs searches at the Tevatron

- For $m_h \lesssim 135$ GeV: Associated Higgs production $Wh \to Wb\bar{b}$ is dominant

- For $m_h \gtrsim 135$ GeV: $gg \to h \to WW^*$ dominant.




Improvements in analysis $\Rightarrow 2-3\sigma$ observation of the Higgs?

# Light stop and Higgs searches at LHC

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

- 30 % error in $\Gamma_{hgg}$ 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 $\Gamma_{hgg}$ in EWBG $\Rightarrow$ deviations in $\Gamma_{ggh}/(\Gamma_{ggh})_{SM}$ should be observable with 200fb$^{-1}$ at $3\sigma$.

- 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

• Stoponium 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.