LHC Signals of

MSSM Electroweak Baryogenesis

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Baryons, not Anti-Baryons

- Baryon density of the universe: [WMAP '08]

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

where $n_B = (\#\ baryons) - (\#\ anti{-}baryons)$.

- Only baryons, not anti-baryons.

  $\rightarrow$ Baryon Asymmetry of the Universe.

- No Standard Model (SM) explanation.

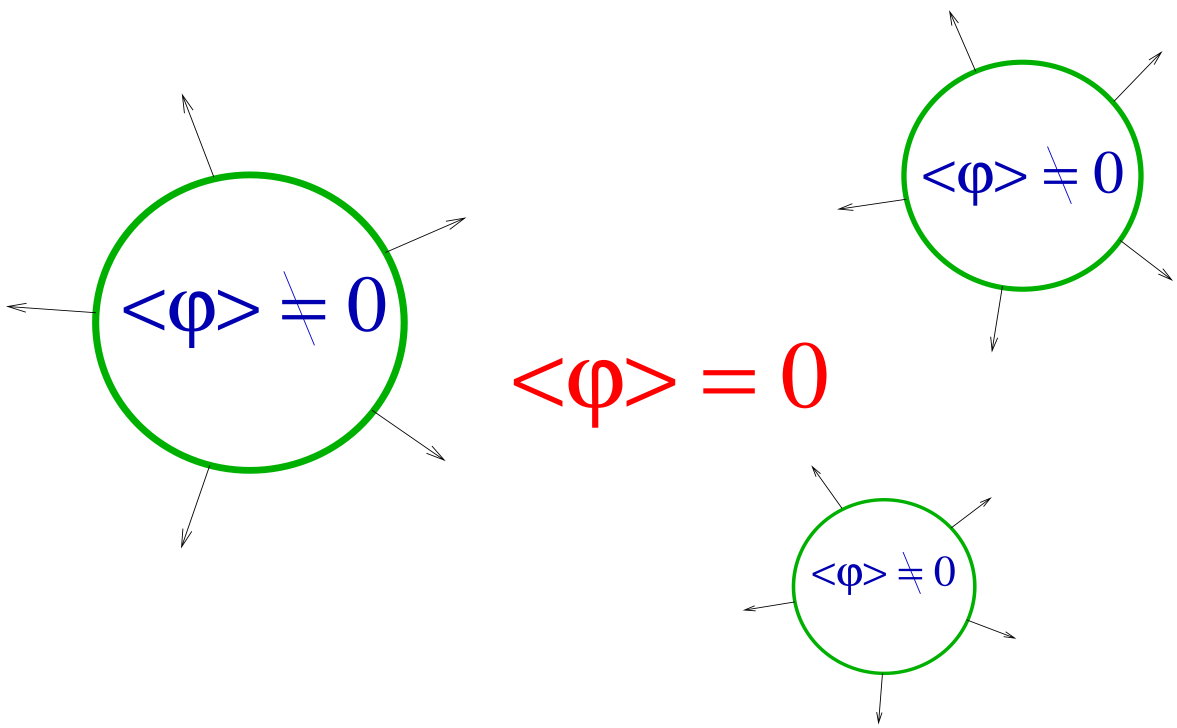
- Supersymmetric SM (MSSM) $\rightarrow$ Electroweak Baryogenesis

Electroweak Baryogenesis (EWBG)

[Kuzmin,Rubakov,Shaposhnikov '85]

- $SU(2)_L \times U(1)_Y \rightarrow U(1)_{em}$ as the universe cools.

- First-order phase transition $\Rightarrow$ bubbles of broken phase.

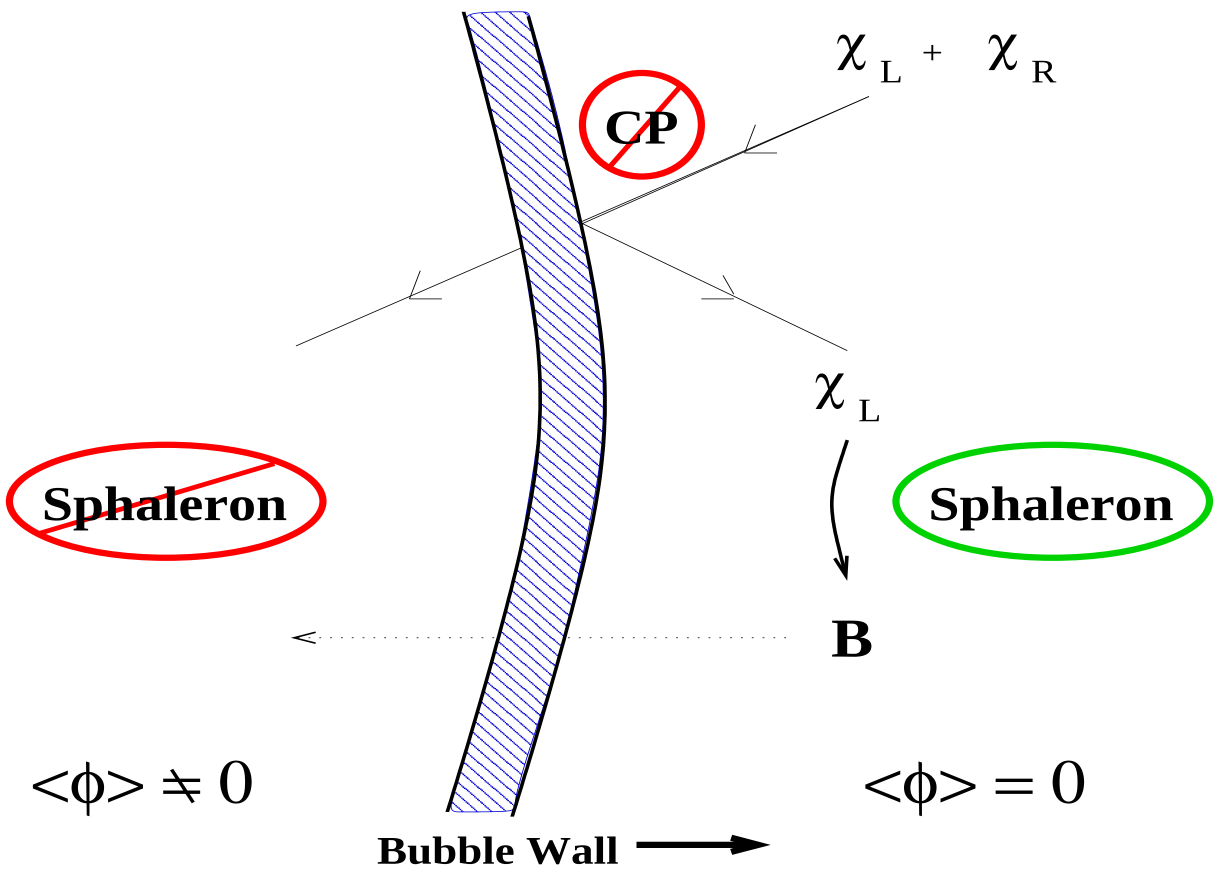


Electroweak Baryogenesis (EWBG)

- CP violation in the bubble wall creates a chiral asymmetry.

- Sphalerons transform the chiral charge into baryons.

- These baryons are swept up into the bubbles.



EWBG in the MSSM

- SM Problem #1: No First-Order Phase Transition

- The MSSM scalar top can make the transition first-order if:

  – It is very light and mostly right-handed

$$125\,\text{GeV} \lesssim m_{\tilde{t}_1} \lesssim 170\,\text{GeV}$$

  – Large stop-Higgs coupling:

$$g_{h\tilde{t}_1\tilde{t}_1{}^*} \simeq |y_t|^2\,(1 - \frac{|X_t|^2}{m_{Q_3}^2}) \leq |y_t|^2$$

- The other stop must be very heavy for $m_h > 114\,\text{GeV}$,

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

EWBG in the MSSM

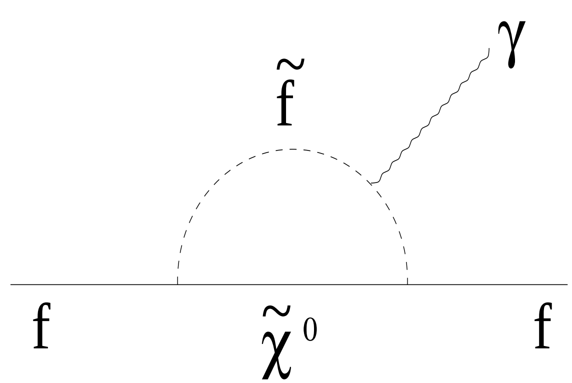
- SM Problem #2: Not Enough CP Violation
- Main MSSM source: Higgsinos and Gauginos.

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

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

$$\mu,\ M_{1,2} \lesssim 400\,\mathrm{GeV}$$

- New CP violation $\longrightarrow$ electric dipole moments (EDM)



$+ \ \ldots$

- EDM bounds $\Rightarrow$ $m_{\tilde{f}_{1,2}} \gtrsim 5\,\mathrm{TeV}$ (unless cancellations)

MSSM EWBG at the Tevatron?

- A visible light stop since $m_{\tilde{t}_1} < m_t$?

  No! Many decay modes are hard to see.

- $\tilde{t}_1 \to c\,\tilde{\chi}_1^0$

  Requires flavor violation.

  $(m_{\tilde{t}_1} - m_{\chi_1^0}) < 30\,\text{GeV} \Rightarrow$ soft charm

  [Balázs,Carena,Wagner '04]

- $\tilde{t}_1 \to b\,W^+\,\chi_1^0, \quad \tilde{t}_1 \to b\,\tilde{\chi}_1^+$

  Often kinematically impossible.

  Swamped by background for $m_{\chi_1^0} > 35\,\text{GeV}$. $(4\,fb^{-1})$

  [Demina, Lykken, Matchev, Nomerotski '99]

MSSM EWBG at the LHC

- $\tilde{t}_1$ are produced copiously but are hard to see.

- Same-sign tops ($\tilde{t}_1 \to c\chi_1^0$) [Kraml+Raklev '05,'06]

  $\tilde{g}\,\tilde{g} \to t\,t\,\tilde{t}_1^*\,\tilde{t}_1^* \to b\,b\,\ell^+\ell^+ + (jets) + \not{E}_T$

  $\Rightarrow$ same sign tops $\to$ same-sign leptons

  Discovery with 30 fb^{-1} for $m_{\tilde{g}} < 1000\,\text{GeV}$

- Stoponium? $\tilde{t}_1\,\tilde{t}_1^* \to \eta_{\tilde{t}_1} \to \gamma\gamma$ [Martin '08]

- Other scalars are very heavy. ($\tilde{b}_R$, $\tilde{\tau}_R$?)

- Challenging electroweak-ino decays: [Carena+Freitas '06]

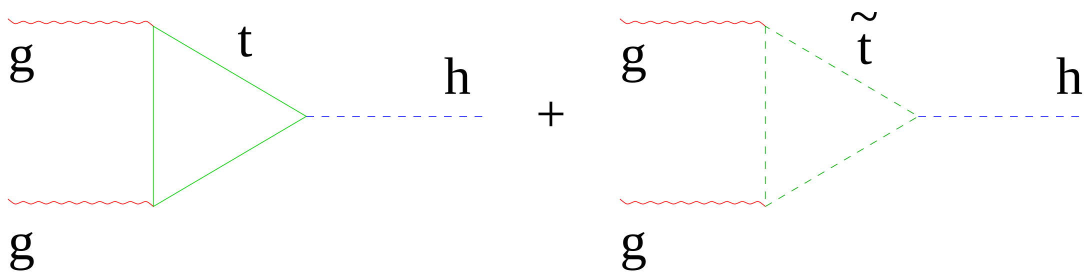
LHC Higgs Signals of MSSM EWBG

- A light stop can modify Higgs production and decay.

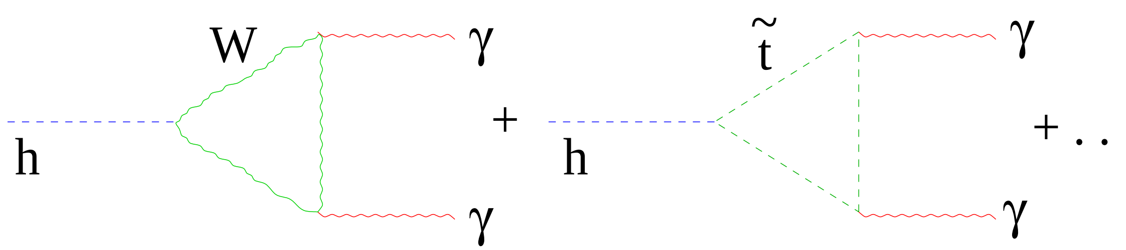
  [Kane,Kribs,Martin,Wells '95; Dawson,Djouadi,Spira '96;Djouadi '98;Dermisek+Low '07

- $h\,\tilde{t}_1\,\tilde{t}_1^*$ coupling: $g_{h\tilde{t}_1\tilde{t}_1} \simeq |y_t|^2 \left(1 - \frac{|X_t|^2}{m^2_{\tilde{Q}_3}}\right) \xrightarrow{EWBG} |y_t|^2$

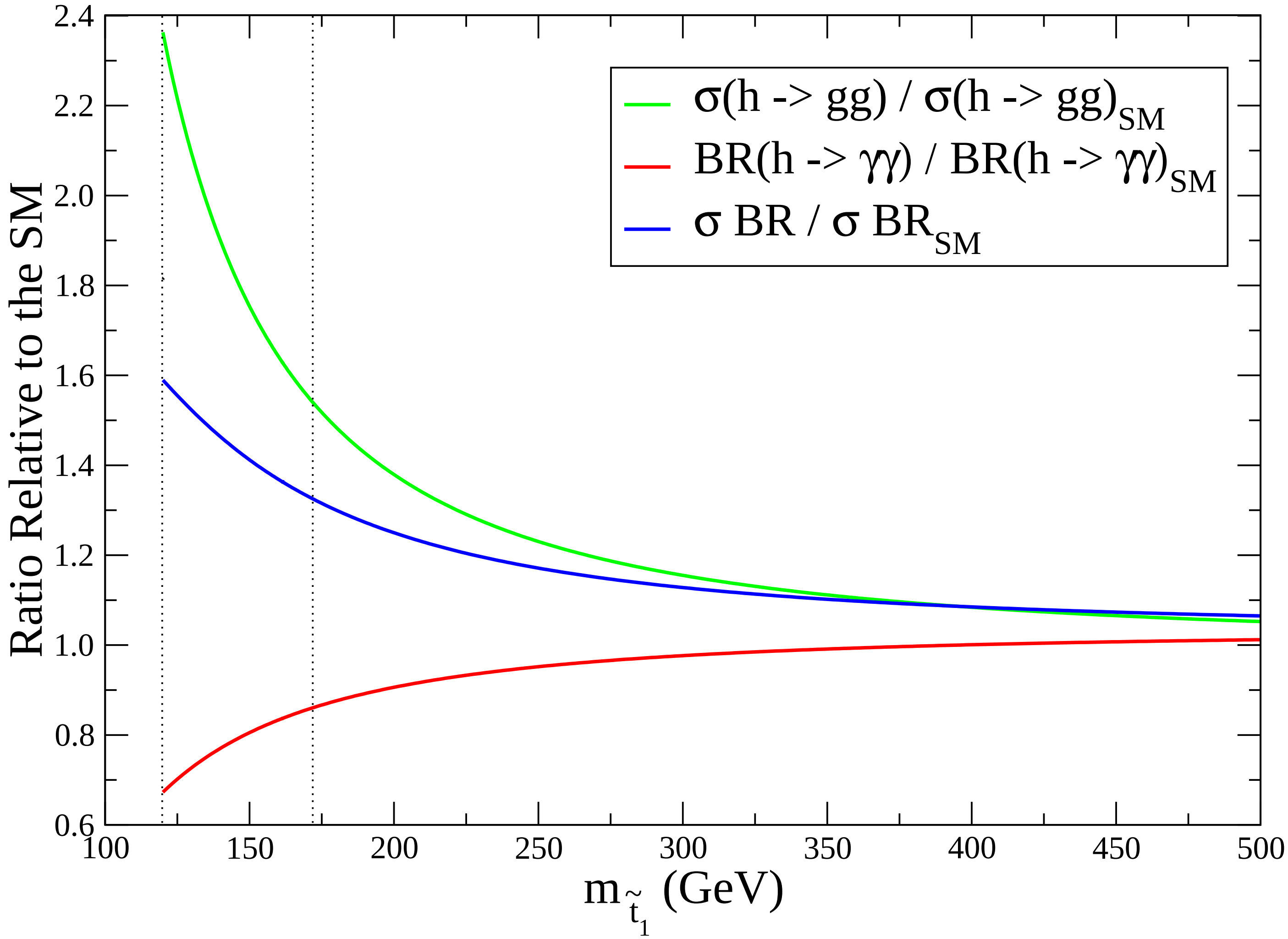
- $\sigma(gg \to h)$ is enhanced.



- $\Gamma(h \to \gamma\gamma)$ is suppressed.



- $|X_t| \simeq 0$, $\tan\beta = 10$, $M_a =$ large, $m_h = 120\,\mathrm{GeV}$



- $\Delta\sigma/\sigma \lesssim 30\%$, $\Delta BR/BR \lesssim 20\%$, $\Delta\sigma BR/\sigma BR \lesssim 15\%$

[Zeppenfeld '02]

Summary

- On top of everything else, the MSSM can account for the baryon asymmetry.
- Baryon production $\longrightarrow$ electroweak baryogenesis.
- EWBG requires a light stop, light -inos, heavy scalars.
- This scenario can be challenging at the LHC.
- Higgs boson production and decay gives an indirect probe.
- Connection between colliders and cosmology!?

Extra Slides

Sphalerons

- $B + L$ is a symmetry of the classical SM and MSSM Lagrangians.

  This symmetry is broken by quantum effects.

- The only processes that violate $B + L$ are transitions between topologically inequivalent $SU(2)_L$ gauge vacua.

- Each transition produces $\Delta B = \Delta L = n_g = \#generations$.

- At $T = 0$, these transitions proceed by tunnelling (instantons).

$$\Gamma \propto e^{-16\pi^2/g^2} \sim 10^{-160}.$$

- At $T \neq 0$, these can go via thermal fluctuations.

  $\Rightarrow$ sphaleron transitions.

  The transition rate (per unit volume) is [Arnold+McLerran '87]

$$\Gamma_{sp} \sim \begin{cases} T^4 \, e^{-4\pi\langle\phi\rangle/g\,T} & \langle\phi\rangle \neq 0 \\ \alpha_w^4 \, T^4 & \langle\phi\rangle = 0. \end{cases}$$

- The net rate of B violation due to the sphalerons is

$$\frac{dn_B}{dt} = -\frac{\Gamma_{sp}}{T^3}\left[\mathcal{A}\sum_{i=1}^{n_g}(3\,n_{q_L^i} + n_{l_L^i}) + \mathcal{B}\,n_B\right],$$

for positive dimensionless constants $\mathcal{A}$ and $\mathcal{B}$.

- The first term corresponds to the chiral fermion charge:

  e.g. n_{q_L} = (# left-handed quarks) - (# right-handed antiquarks).

- In the absence of this asymmetry, baryon number relaxes to zero as

$$n_B(t) = n_B(0)\,e^{-\mathcal{B}\,(\Gamma_{sp}/T^3)\,t}.$$

- When non-zero, the chiral charge acts as a source for baryon production.

Electroweak Baryogenesis

1. The Electroweak Phase Transition

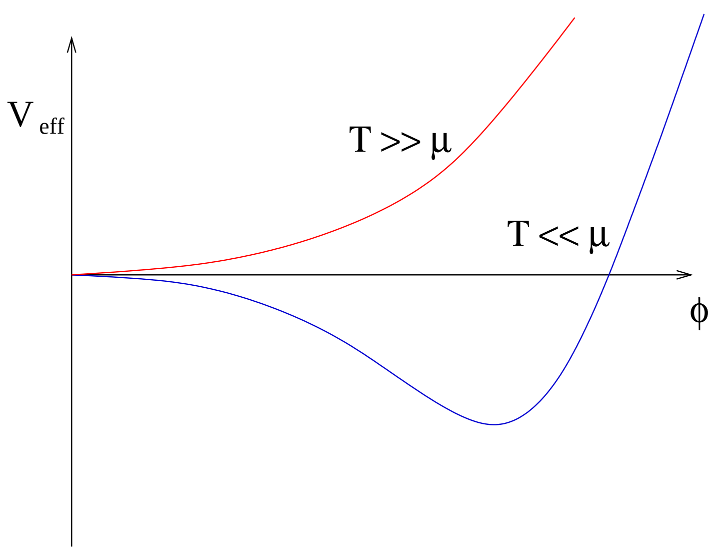
- Order parameter = Higgs VEV $\langle\phi\rangle$:

$$\langle\phi\rangle = 0 \Rightarrow SU(2)_L \times U(1)_Y \text{ is unbroken.}$$

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

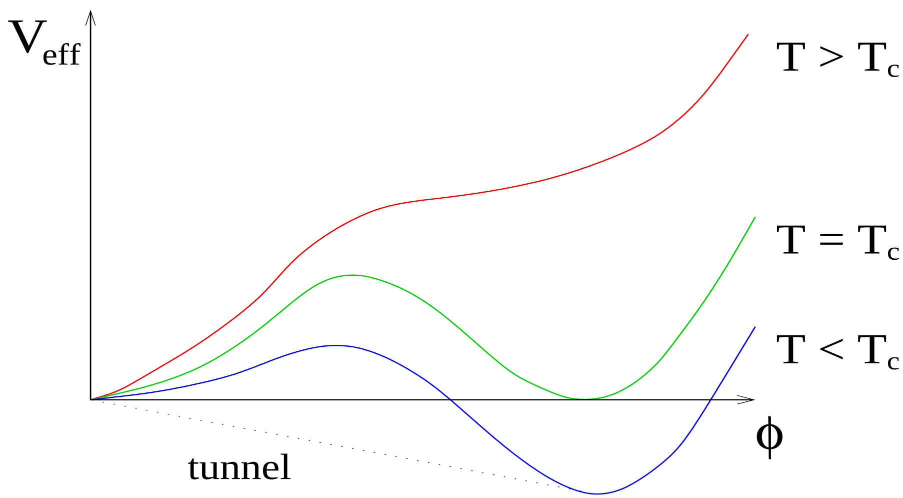
- Effective potential:

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

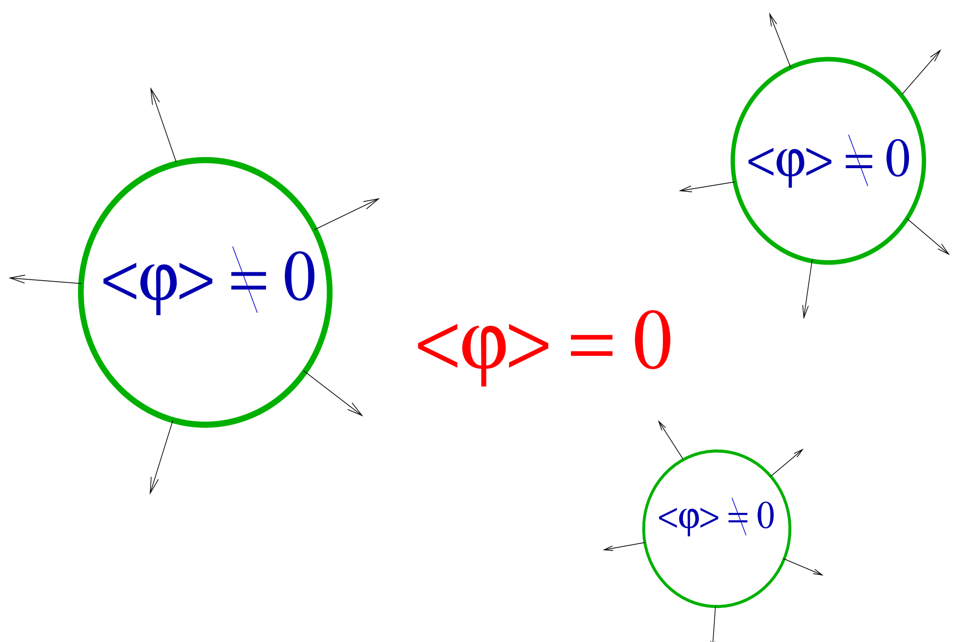


2. Bubble Nucleation

- First order phase transition:



- Bubbles of broken phase are nucleated at $T < T_c$.



Aside: Sphalerons

- $B + L$ is $SU(2)_L$ anomalous in the SM (and MSSM).

- Transitions between topologically distinct $SU(2)_L$ vacua:

  $\Delta B = \Delta L = n_g = \#\ generations$. ['t Hooft '76]

- $T = 0 \Rightarrow$ tunnelling (instantons).

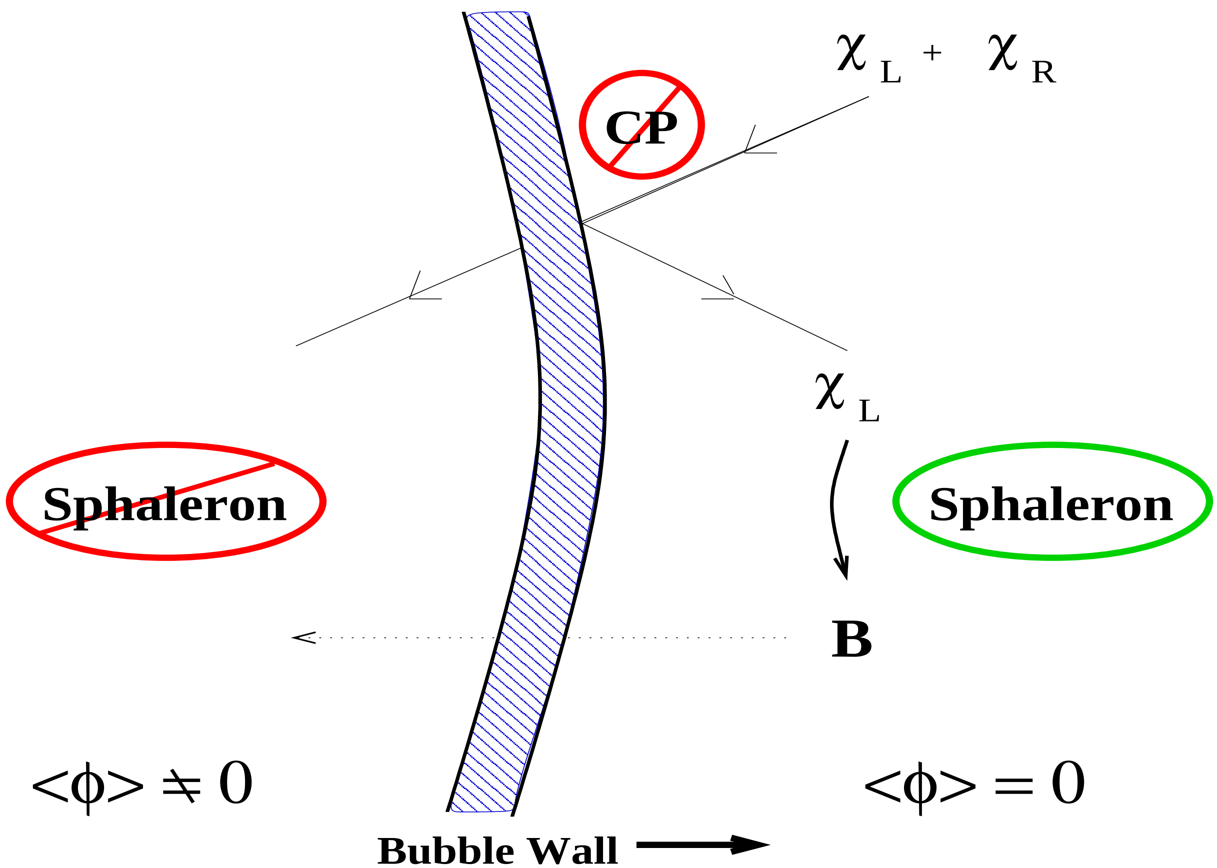
$$\Gamma_{inst} \propto e^{-16\pi^2/g_2^2} \simeq 10^{-320}$$

- $T \neq 0 \Rightarrow$ thermal fluctuations (sphalerons). [Klinkhamer+Manton '84]

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

3. Producing Baryons

- CP violation in the bubble wall creates a chiral asymmetry.
- Sphalerons transform the chiral charge into baryons.
- These baryons are swept up into the bubbles.



EWBG in the Standard Model

It doesn't work for two reasons:

1. The electroweak phase transition is first-order only if the Higgs boson is very light, [Kajantie *et al.* '98]

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

   LEP II experimental mass bound:

$$m_h > 114.4\,\text{GeV} \qquad (95\%\, c.l.).$$

2. There isn't enough CP violation in the SM. [Gavela *et al.* '94]

EWBG in the MSSM

- SM Problem #1: No First-Order Phase Transition
  - MSSM superpartners modify the Higgs potential.

- SM Problem #2: Not Enough CP Violation
  - Soft SUSY breaking (and μ) introduces new CPV phases:

$$Arg(\mu\, M_a),\, Arg(\mu\, A_i), \ldots$$

- EWBG can work in the MSSM!

- These requirements fix much of the MSSM spectrum.

Requirement #1: A Strong First-Order EWPT

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

- Quantitative Condition: [Shaposhnikov '88]

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

- $\gamma \neq 0$ is generated by *bosonic* loops.

- The dominant MSSM contribution comes from a light mostly right-handed stop. [Carena,Quirós,Wagner '95]

- $m_h \simeq \sqrt{\lambda}\, v$

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

$$\text{Stop Mass} = \mathcal{M}^2_{\tilde{t}} = \begin{pmatrix} m^2_{Q_3} + m^2_t + D_L & m_t X_t \\ m_t X_t & m^2_{U_3} + m^2_t + D_R \end{pmatrix}$$

- MSSM "cubic term":

$$\gamma T\phi^3 \simeq \frac{T}{4\pi}\left[m^2_{\tilde{t}_1}(\phi, T)\right]^{3/2}$$

where

$$m^2_{\tilde{t}_1}(\phi, T) \simeq y_t^2\phi^2\left(1 - \frac{|X_t|^2}{m^2_{Q_3}}\right) + \underbrace{m^2_{U_3} + \xi T^2}_{\delta m^2}.$$

- $\delta m^2 \to 0$ maximizes the "cubic term".

Implications

- A light right-handed stop:

$$-(100\,\mathrm{GeV})^2 \lesssim m_{U_3}^2 \lesssim 0, \quad |X_t|/m_{Q_3} \lesssim 0.5$$

$\Rightarrow 120\,\mathrm{GeV} \lesssim m_{\tilde{t}_1} \lesssim 170\,\mathrm{GeV} \leq m_t.$

- A heavy left-handed stop:

$$m_{Q_3} \gtrsim 2\,\mathrm{TeV}.$$

- A light SM-like Higgs:

$$M_a \gtrsim 200\,\mathrm{GeV}, \quad 5 < \tan\beta < 10.$$

$\Rightarrow m_{higgs} \lesssim 120\,\mathrm{GeV}.$

Requirement #2: New CP Violation

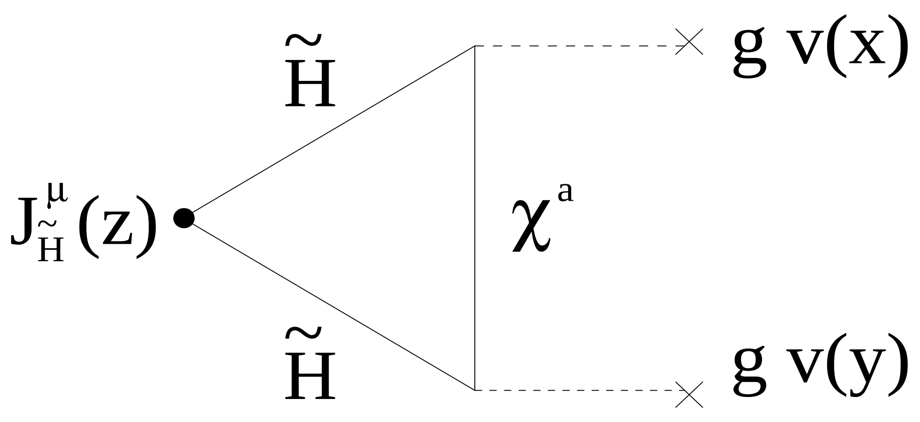
- Main source: Higgsinos.

  e.g.

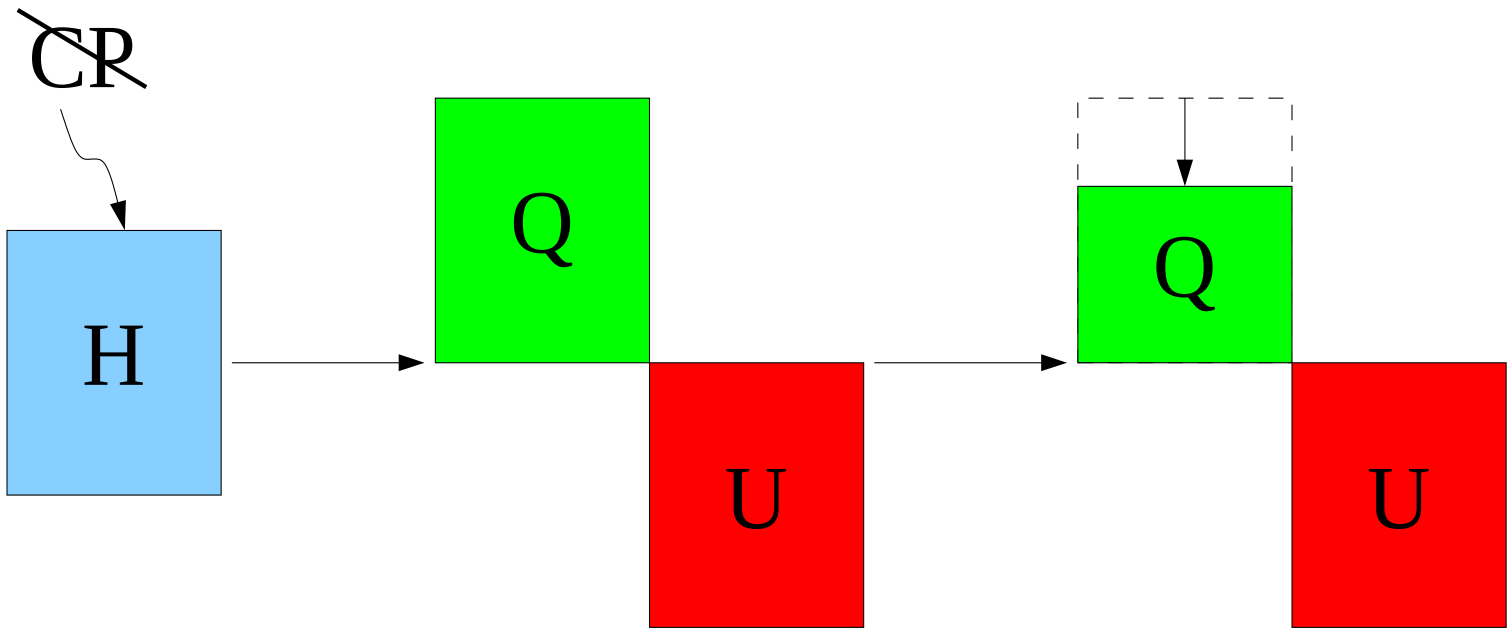
$$\mathcal{M}_{\tilde{\chi}^\pm} \sim \begin{pmatrix} |M_2| & g_2\, v_u(z) \\ g_2\, v_d(z) & e^{i\phi}\, |\mu| \end{pmatrix}, \quad \text{with } \phi = Arg(\mu\, M_2).$$

- CPV source:

$$\left\langle J^0_{\tilde{H}}(z) \right\rangle = \left\langle \bar{\tilde{H}} \gamma^0 \tilde{H} \right\rangle \propto Im(\mu\, M_2)\, \partial_z f(v_u(z),\, v_d(z))$$



- B formation cartoon:



$y_t\, QH_uU^c$ $SU(2)_L$ sphaleron

- $\mathcal{O}_{sphal} \propto \Pi_i(Q_iQ_iQ_iL_i)$ is sourced by the Q asymmetry.

Implications

- This is enough to generate the baryon asymmetry if:

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

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

- New CP violation $\longrightarrow$ electric dipole moments (EDM)

- Strict constraints:

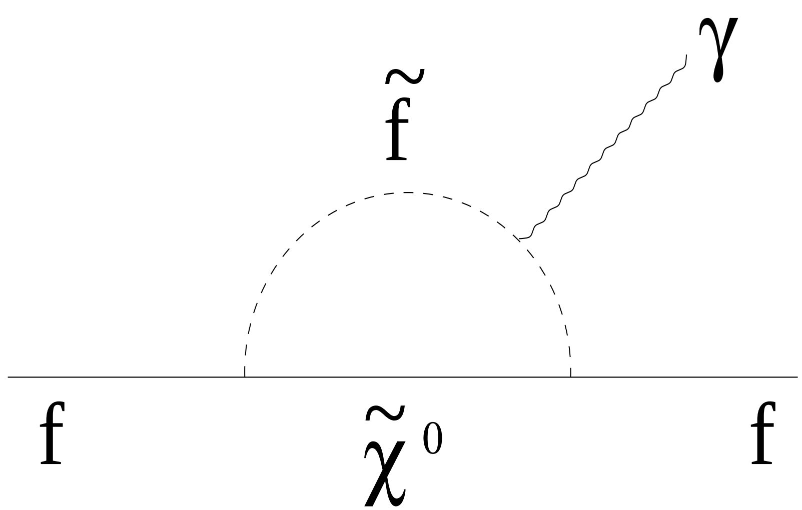
$$|d_e| < 1.6 \times 10^{-27}\ \text{e cm}$$ [Regan *et al* '02]

$$|d_n| < 2.9 \times 10^{-26}\ \text{e cm}$$ [Baker *et al* '06]

$$|d_{Hg}| < 2.1 \times 10^{-28}\ \text{e cm}$$ [Romalis *et al* '01]

- *e.g.* Electron EDM d_e

One-loop contribution: [Ibrahim+Nath '98]



$+ \ldots$

- Consistency with EWBG and EDM constraints requires

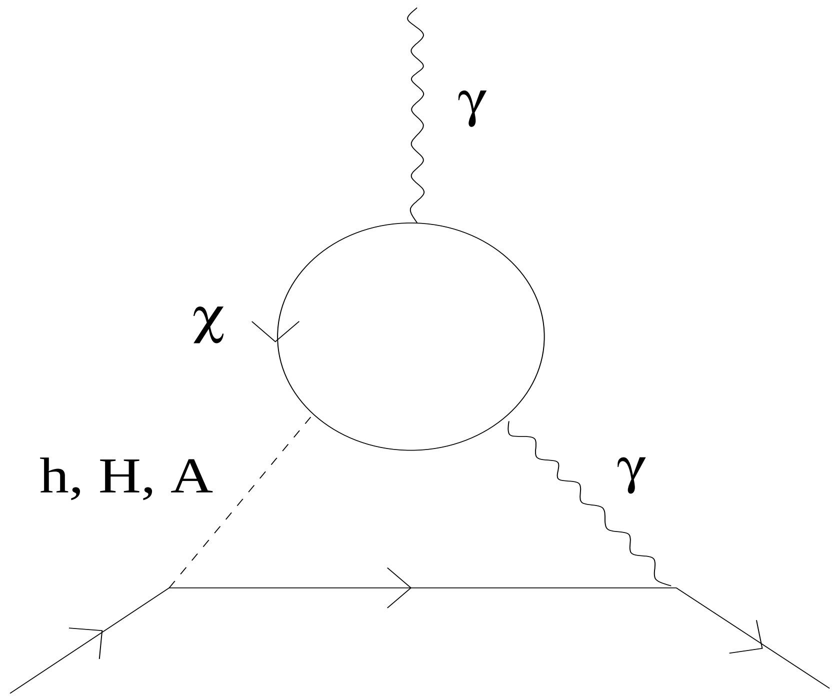
$$m_{\tilde{f}_{1,2}} \gtrsim 5-10\,\text{TeV}.$$

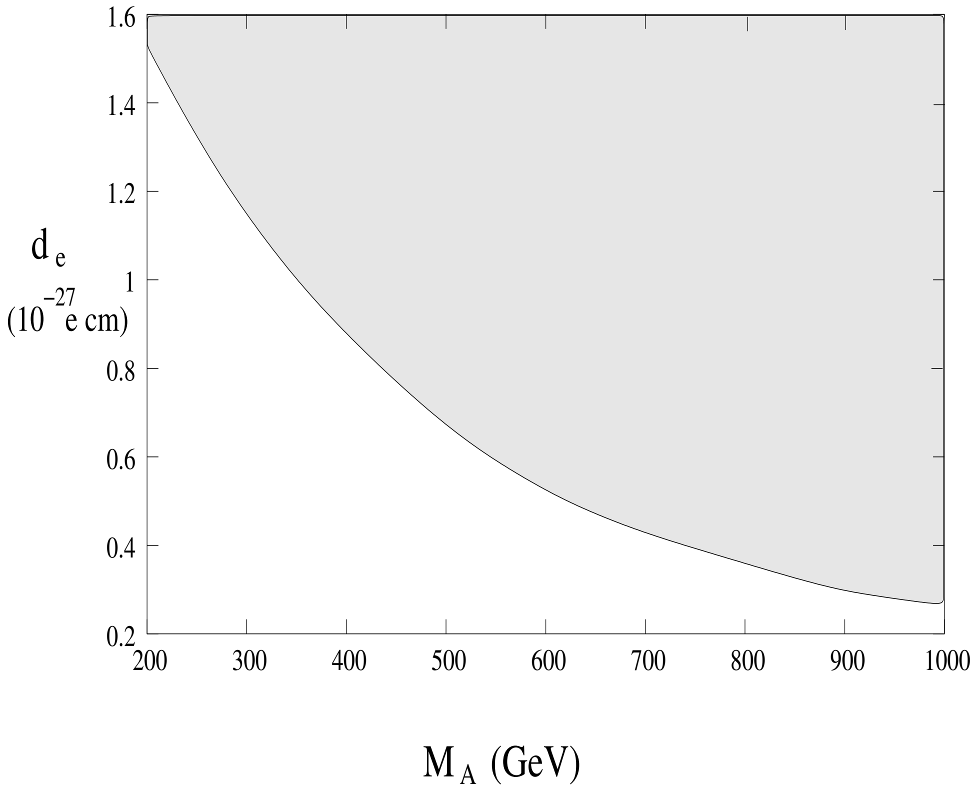
$\Rightarrow$ decouple first and second generation sfermions.

- *e.g.* Electron EDM d_e (contd. . .)

Irreducible two-loop contribution ($\propto Im(\mu M_2)$):

[Chang, Chang, Keung '02; Pilaftsis '02]





Upcoming experiments will probe the EWBG region.

[Balázs,Carena,Menon,DM,Wagner '04, Lee,Cirigliano,Ramsey-Musolf '04]

Spectrum Summary

- Light mostly right-handed stop: $m_{\tilde{t}_1} < m_t$.

- Heavy mostly left-handed stop: $m_{\tilde{t}_2} > 2\,\mathrm{TeV}$.

- Light SM-like Higgs boson: $m_h \lesssim 120\,\mathrm{GeV}$.

- Very heavy 1st and 2nd gen. sfermions: $m_{\tilde{f}_{1,2}} \gtrsim 5\,\mathrm{TeV}$.

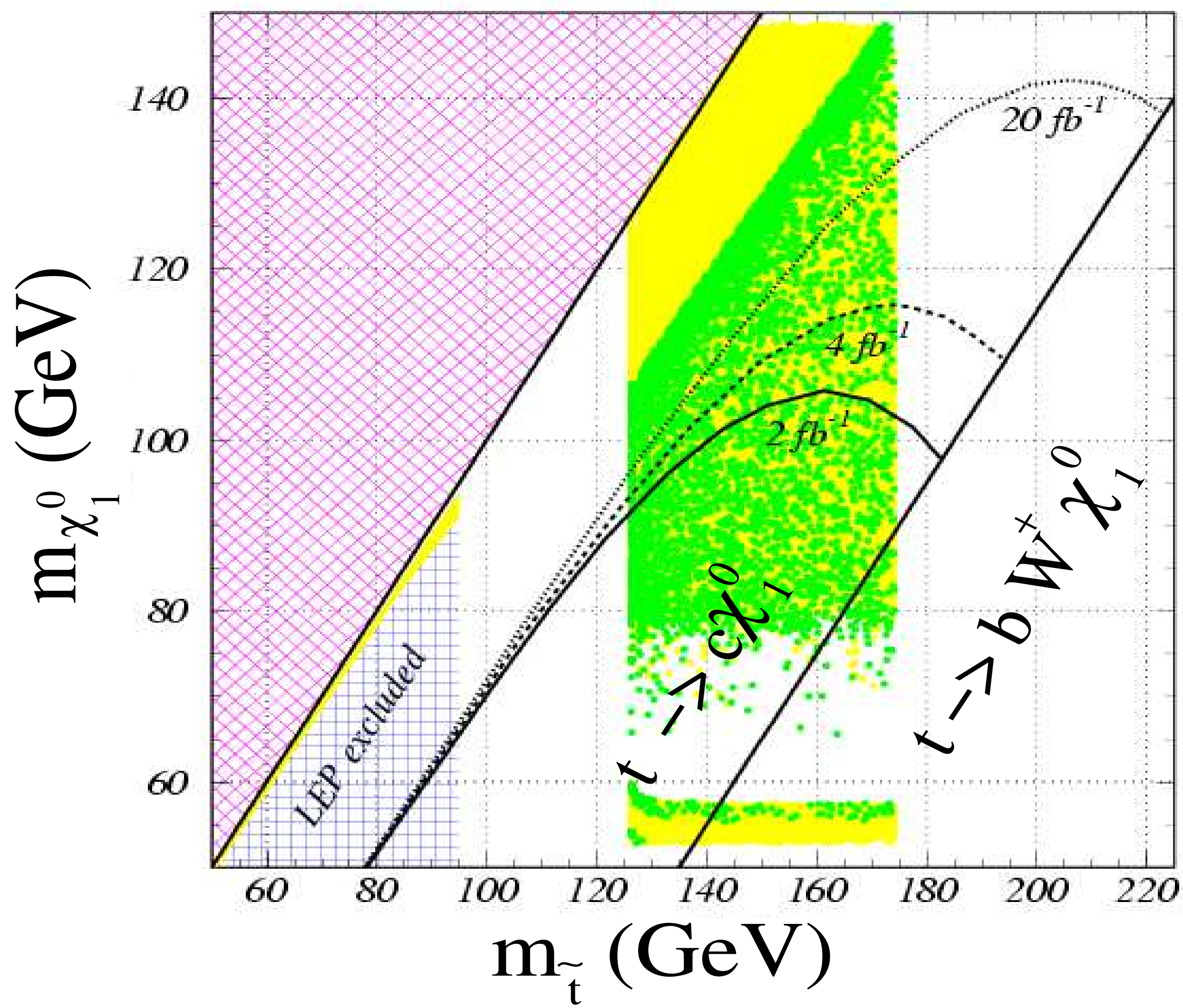
- Light charginos and neutralinos: $M_{1,2},\ \mu \lesssim 400\,\mathrm{GeV}$.

MSSM EWBG at the LHC

MSSM EWBG at the Tevatron?

- A visible light stop since $m_{\tilde{t}_1} < m_t$?

  [Balázs,Carena,Wagner '04]



Light Stop Decay Modes

- $\tilde{t}_1 \to c\,\tilde{\chi}_1^0$

  Requires flavor violation.

  $(m_{\tilde{t}_1} - m_{\chi_1^0}) < 30\,\text{GeV} \Rightarrow$ soft charm

- $\tilde{t}_1 \to b\,W^+\,\chi_1^0, \quad \tilde{t}_1 \to b\,\tilde{\chi}_1^+$

  Often kinematically impossible.

  Swamped by background for $m_{\chi_1^0} > 35\,\text{GeV}$. $(4\,fb^{-1})$

  [Demina, Lykken, Matchev, Nomerotski '99]

- Metastable $\tilde{t}_1$ ($\to$ gravitino)

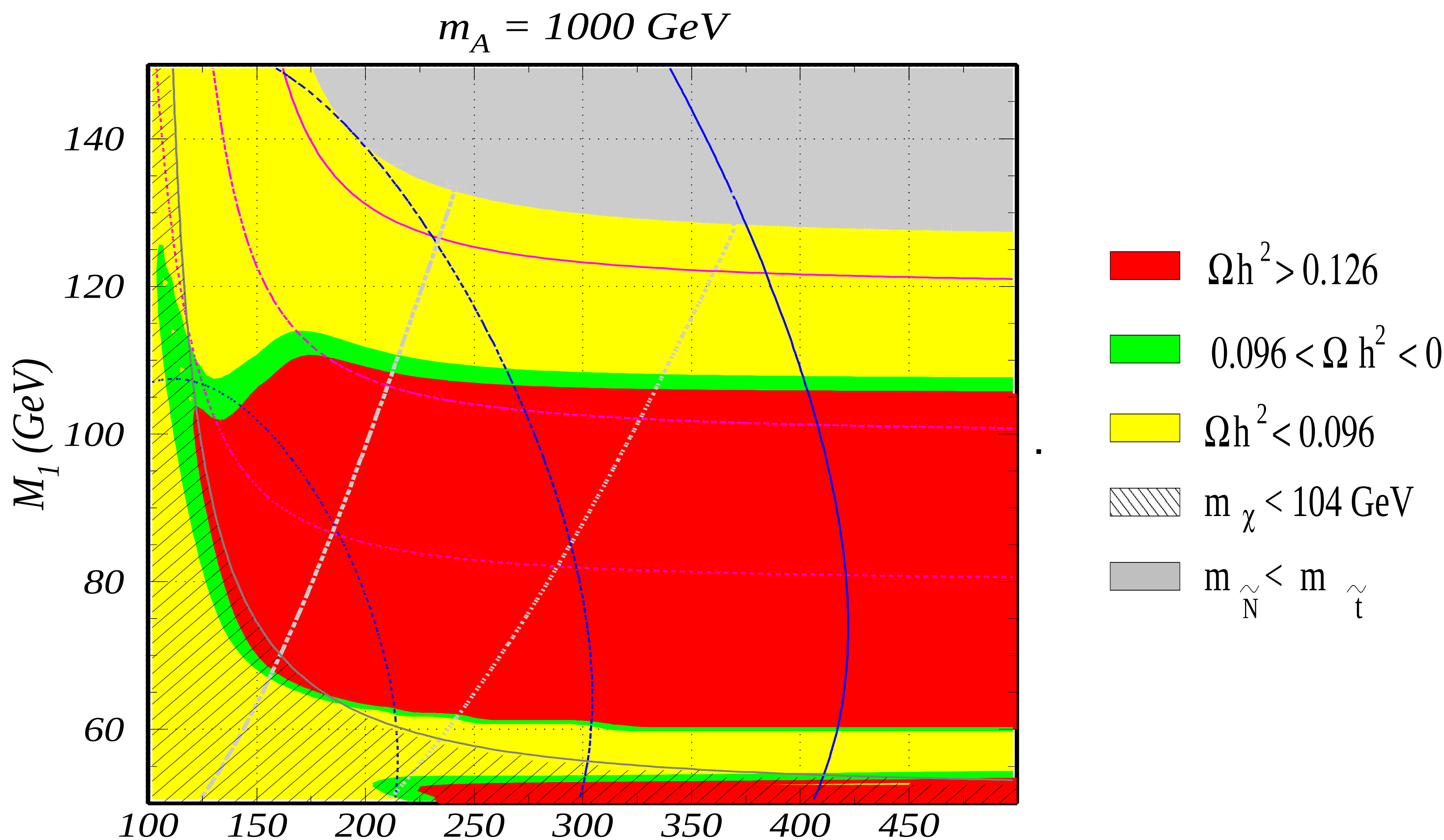
  Tevatron CHAMP searches imply $m_{\tilde{t}_1} > 220\,\text{GeV}$.

  [CDF '06; Diaz-Cruz, Ellis, Olive, Santoso '07]

$\tilde{t}_1 \to c\,\chi_1^0$ and Dark Matter

- Stop coannihilation with a Bino LSP:

  [Balázs,Carena,Menon,DM,Wagner '04]



LHC Picture ($\tilde{t}_1 \to c\chi_1^0$)

A bit glum . . .

- $\tilde{t}_1 \to c\,\chi_1^0$ is difficult to trigger on.
- Other scalars are very heavy. ($\tilde{b}_R,\ \tau_R$?)
- $\tilde{g} \to \bar{t}\,\tilde{t}_1,\ t\,\tilde{t}_1^*$ dominates.
- Challenging electroweak-ino decays: [Carena+Freitas '06]

$$\chi^{\pm}_{1,2} \;\to\; \tilde{t}_1\,b \quad \text{(if possible)}$$
$$\chi^0_{(i>1)} \;\to\; Z\,\chi^0,\ h\,\chi^0,\ W^{\pm}\,\chi^{\mp}$$

Same Sign Stops

[Kraml+Raklev '05,'06]

- $\tilde{g}\,\tilde{g} \to t\,t\,\tilde{t}_1^*\,\tilde{t}_1^* \to b\,b\,\ell^+\ell^+ + (jets) + \not{E}_T$
  $\Rightarrow$ same sign tops $\rightarrow$ same-sign leptons

- Discovery of light stops with 30 fb^{-1} for $m_{\tilde{g}} < 1000$ GeV.

- Parameter determination is difficult.

- No c-tags. . .

Stoponium

[Drees+Nojiri '97; Martin '08]

- $\eta_{\tilde{t}_1} = \tilde{t}_1^* \, \tilde{t}_1^*$ bound state.

- $\underbrace{\Gamma_{\tilde{t}_1 \to c \chi_1^0}}_{\sim \text{eV}} \ll \underbrace{\eta_{\tilde{t}_1} \text{ binding energy}}_{\sim \text{GeV}}$.

- $\eta_{\tilde{t}_1} \to \gamma\gamma$ may be observable at the LHC

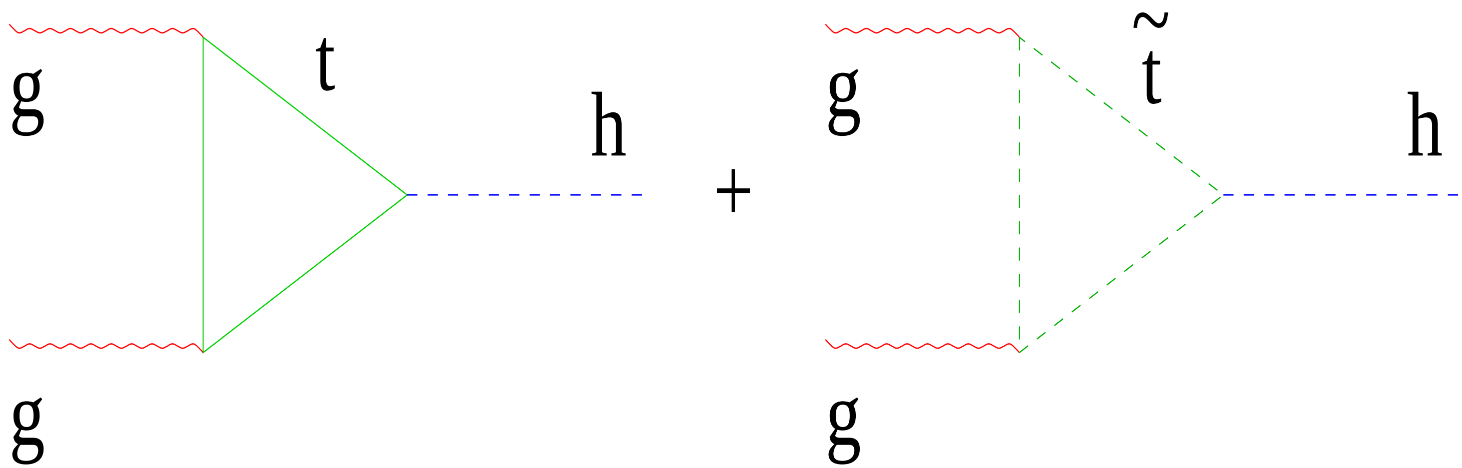
  with $< 100\, fb^{-1}$ for $m_{\eta_{\tilde{t}_1}} < 250\,\text{GeV}$. [Martin '08]

- Very good *absolute* mass measurement of $\tilde{t}_1$!

Gluon Fusion: $gg \rightarrow h$

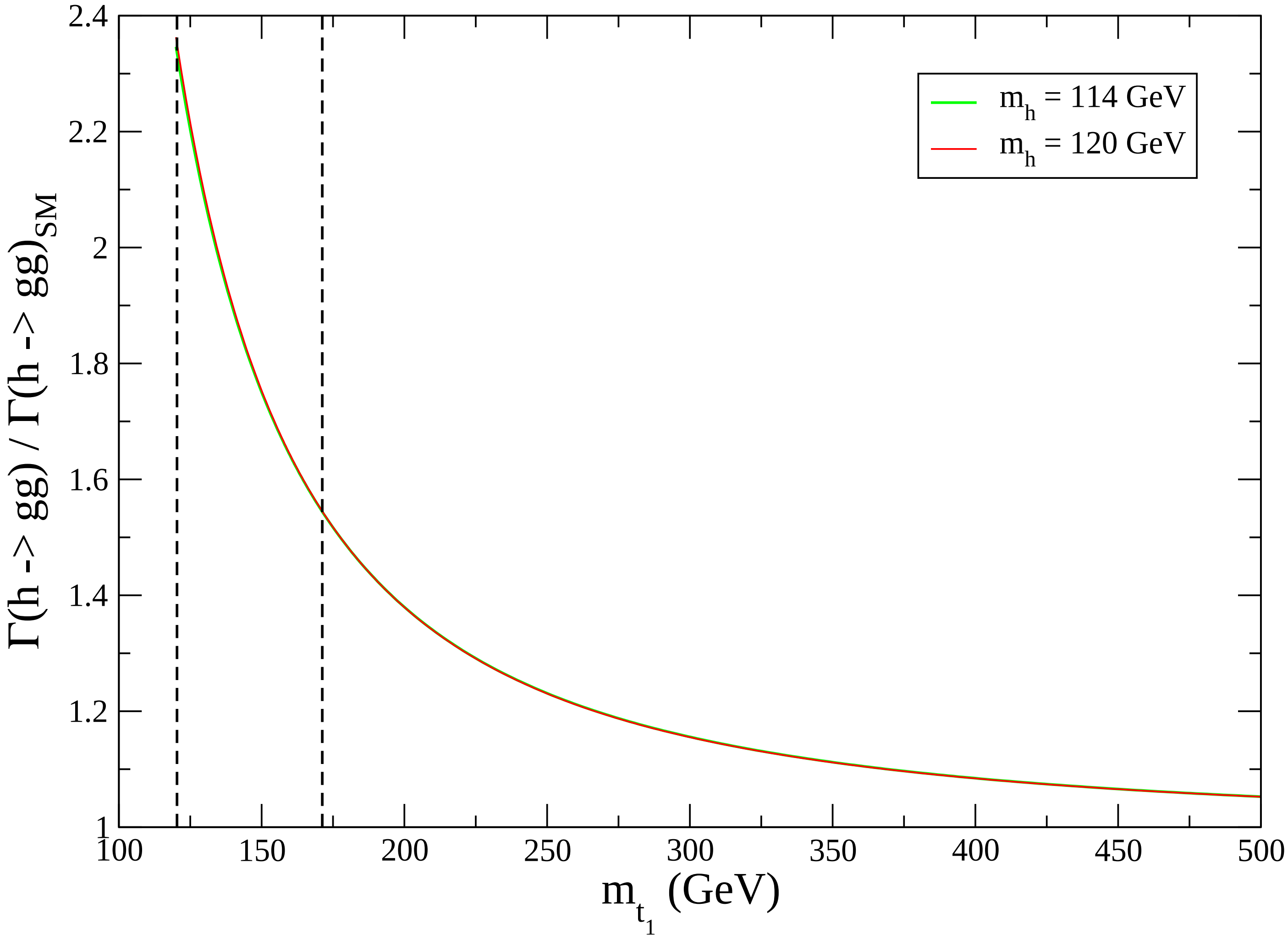
- $\sigma(gg \rightarrow h) \propto \Gamma(h \rightarrow gg)$

- Loops:



- Constructive . . .

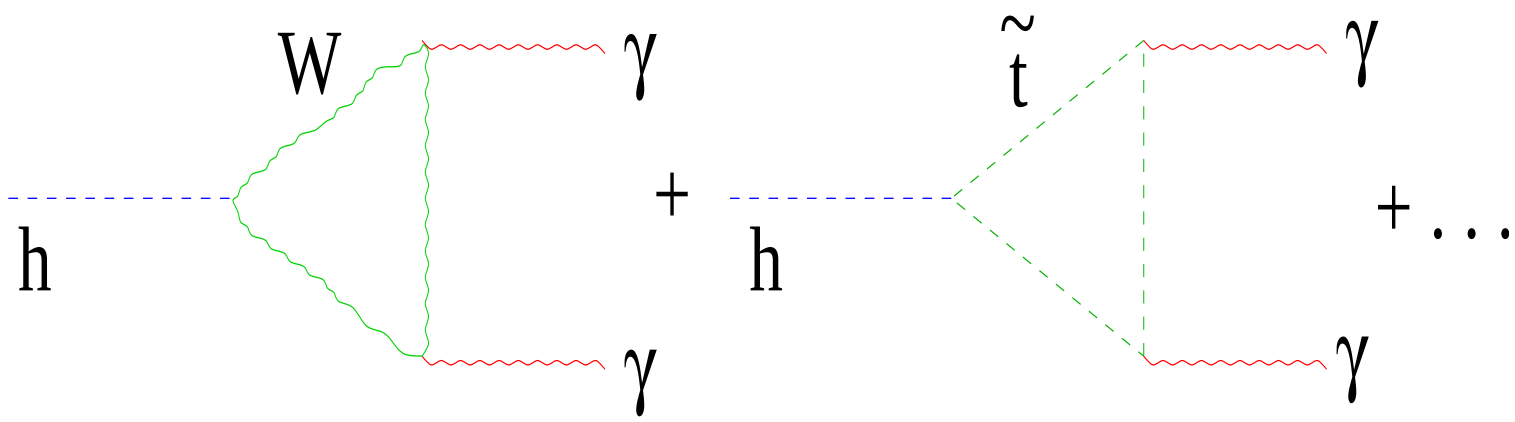
- $|X_t| \simeq 0$, $\tan\beta = 10$, $M_a =$ large
- $M_1 = 120$ GeV, $|\mu| = M_2 = 200$ GeV



Diphotons: $h \to \gamma\gamma$

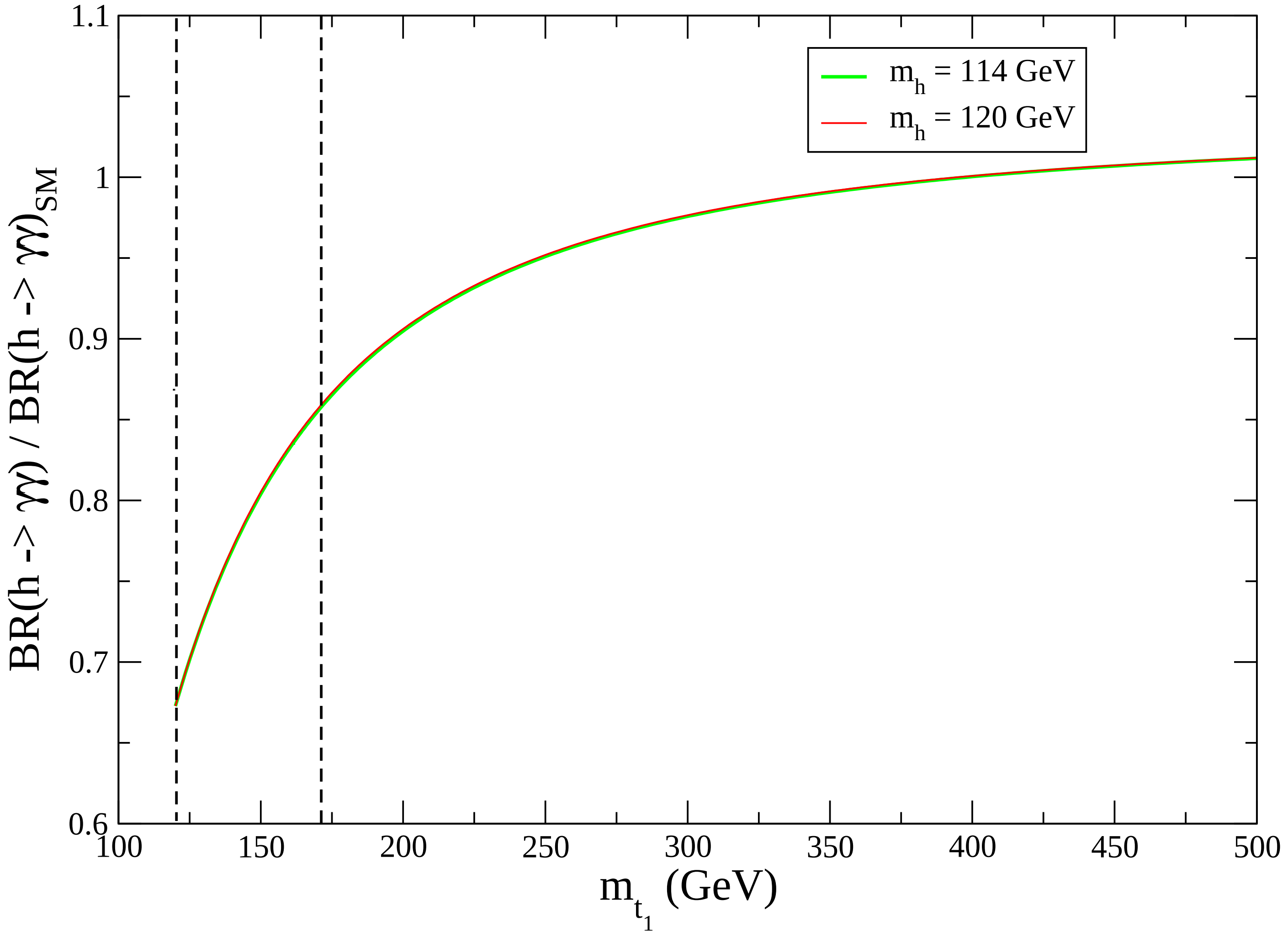
- Important search channel for a light Higgs.

- Loops:



- Destructive . . .

- $|X_t| \simeq 0$, $\tan\beta = 10$, $M_a =$ large
- $M_1 = 120$ GeV, $|\mu| = M_2 = 200$ GeV



LHC Light SM Higgs ($m_h < 120\,\text{GeV}$) Searches

[ATLAS TDR '99; CMS TDR '07]

- $(gg \rightarrow)\ h \rightarrow \gamma\gamma$

  5σ with about $10\, fb^{-1}$

  $\Delta m_h/m_h < 0.2\%$.

- $VBF \rightarrow h \rightarrow \tau\tau$

  4.0σ with $30\, fb^{-1}$, 5.5σ with $60\, fb^{-1}$

- $VBF \rightarrow h \rightarrow \gamma\gamma$

  3.1σ with $60\, fb^{-1}$

- $Wh,\ Zh \rightarrow \gamma\gamma$

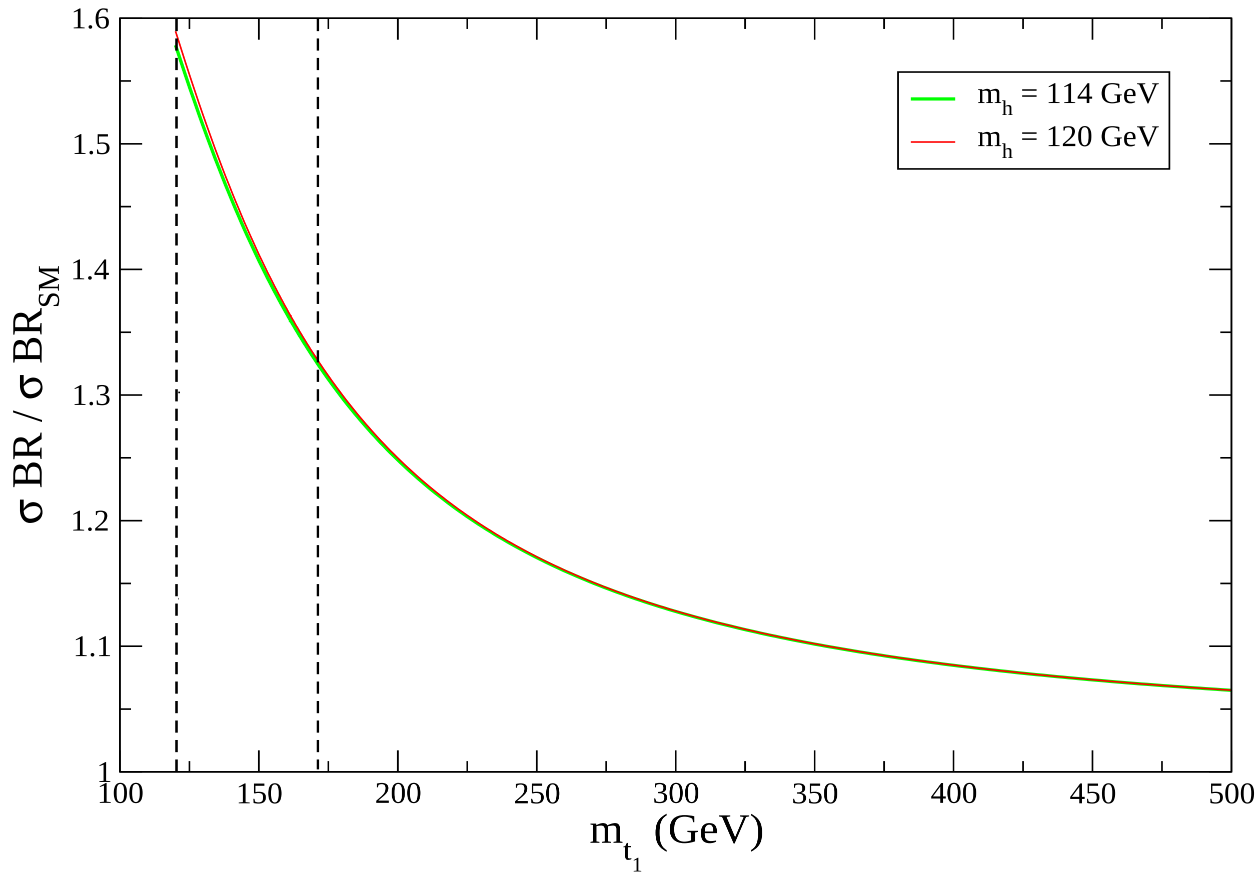
  $4.0\,\sigma$ with $100\, fb^{-1}$ (high $\mathcal{L}$)

- $(gg \rightarrow)\ h \rightarrow ZZ^*$

  $3.0\,\sigma$ with $30\, fb^{-1}$ ($m_h = 120\,\text{GeV}$)

$gg \to h \to \gamma\gamma$

- Total Rate $\propto \Gamma(h \to gg)\, BR(h \to \gamma\gamma)$



- 10–20% uncertainty on the rate with 300 fb^{-1} [Zeppenfeld '02]