# Measuring Stop Mass through Bound State Decays

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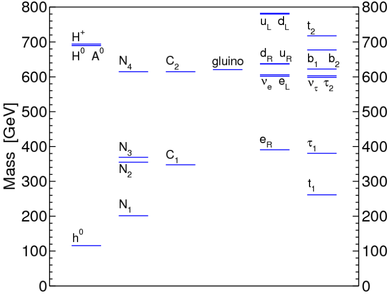
- Two models that contain stoponium: Compressed Supersymmetry and Electroweak Baryogenesis

# Scenarios Containing Stoponium Bound States




- $\tilde{t}_1$ lives long enough to form stoponium if $m_{\tilde{t}_1} - m_{\tilde{g}} < m_t$, $m_{\tilde{t}_1} - m_{\tilde{N}_1} < m_t$, and $m_{\tilde{t}_1} - m_{\tilde{C}_1} < m_b$.

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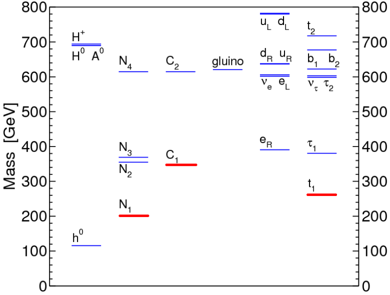


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- Compressed SUSY:

$$m_{\tilde{N}_1} + 25GeV < m_{\tilde{t}_1} < m_{\tilde{N}_1} + 100GeV$$

EW Baryogenesis:

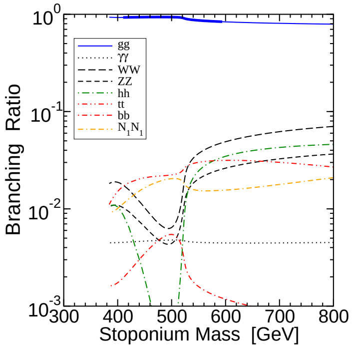
$$m_{\tilde{t}_1} < m_t$$

- Relatively slow flavor-violating and 4-body decays allow stop hadronization (Hikasa, Kobayashi, 1987)

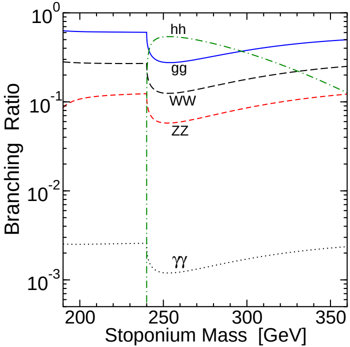
# Comparison of Binding Energy and Partial Widths

- Binding energy of stoponium on the order of a few GeV over a wide range of stop masses.
- Leading order decay rate of stoponium a few MeV.
- Kinematically-allowed top decays from a few eV to 100 keV, depends strongly on the amount of flavor violation in the model.
- In models where stop decays to top and bottom kinematically forbidden, stop will live long enough to hadronize and will form a bound state at threshold.
- Difference between top and stoponium widths cause stoponium to decay through annihilation.

# Branching Ratios




Compressed SUSY




Electroweak Baryogenesis

# Computation of LO Cross-Sections

- Decay rate of s-wave bound state related to cross-section and radial wavefunction at origin: (Hagiwara, Kim, Yoshino 1980)

$$\Gamma(\eta_{\tilde{t}} \to X) = v\sigma(\eta_{\tilde{t}} \to X)|R(0)|^2/(4\pi)$$

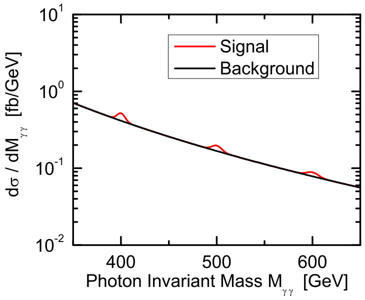
- Narrow-width approximation for stoponium cross-section:

$$\sigma(pp \to \eta_{\tilde{t}} \to \gamma\gamma) = \frac{\pi^2}{8m_{\eta_{\tilde{t}}}^3} BR(\eta_{\tilde{t}} \to gg)\Gamma(\eta_{\tilde{t}} \to \gamma\gamma) \int_\tau^1 dx \frac{\tau}{x} g(x, Q^2) g(\tau/x, Q^2)$$

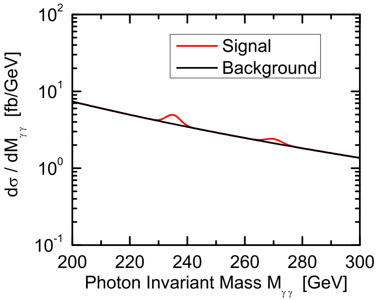
$$\Gamma(\eta_{\tilde{t}} \to \gamma\gamma) = \tfrac{32}{27}\alpha^2 |R(0)|^2/m_{\eta_{\tilde{t}}}^2 \qquad \Gamma(\eta_{\tilde{t}} \to gg) = \tfrac{4}{3}\alpha_S^2 |R(0)|^2/m_{\eta_{\tilde{t}}}^2$$

- Wavefunction amplitude at origin and binding energy taken from potential models used to parametrize quarkonium mass levels (Hagiwara, Kato, Martin, Ng 1990)

# Signal + Background in Diphoton Channel



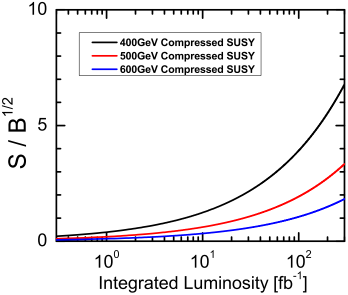

Compressed SUSY

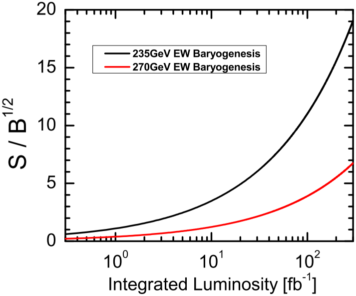



Electroweak Baryogenesis

- $\sigma = 0.01 m_{\eta_{\tilde{t}}}$ gaussians, leading-order background from $q\bar{q}/gg \to \gamma\gamma$
- Gaussians in Electroweak Baryogenesis model suppressed by $BR(\eta_{\tilde{t}} \to gg)$

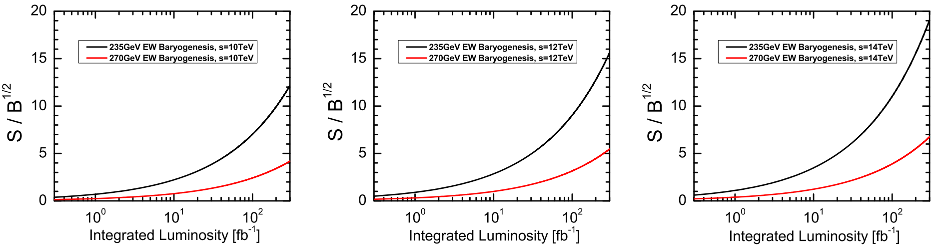
# Signal to Background Ratios



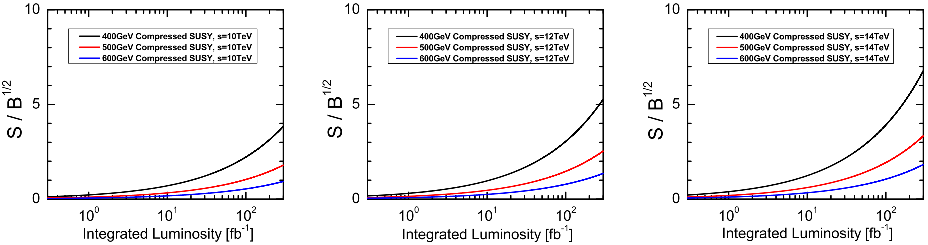

- Number of signal and background events within a 4% width bin centered on the peak
- At least 100 $\text{fb}^{-1}$ of integrated luminosity needed to distinguish Compressed SUSY stoponium peaks, but light stoponium in EW Baryogenesis might be seen after $\sim 10\ \text{fb}^{-1}$

# Electroweak Baryogenesis Scenarios at Lower Energies




- Signal-to-Background ratios for EW Baryogenesis scenarios at 10, 12, and 14 TeV center of mass energies
- Signal still distinguishable from background within reasonable integrated luminosity

# Compressed Supersymmetry Scenarios at Lower Energies




- Signal-to-Background ratios for Compressed SUSY scenarios at 10, 12, and 14 TeV center of mass energies
- May still be possible to see resonance peaks at 12 TeV

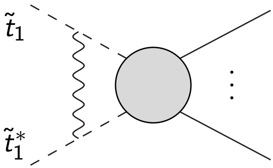
# Motivation for Calculating Radiative Corrections

- In order to make believable predictions, decay rates and total cross-section must be computed at least to NLO
- QCD corrections could potentially be quite large, even compared to tree-level result
- Follow methods used in calculating radiative corrections to toponium annihilation (Hagiwara, Kim, Yoshino, 1980)

# NLO Partial Width Calculation Procedure

1. Write down all stoponium $\rightarrow X \rightarrow$ stoponium diagrams that can contribute to the decay channel (there are 40 non-zero diagrams corresponding to stoponium $\rightarrow gg$)
2. Calculate all cuts for each diagram, performing any internal loop integrals
3. Integrate each cut over phase space to get contribution to NLO cross-section $v\sigma^{(1)}$
4. Sum over all diagrams to get total cross-section
5. Renormalize result to eliminate ultraviolet divergence
6. Parton-level cross-section $v\sigma^{(1)}$ related to bound state decay rate $\Gamma^{(1)}$ through bound state wavefunction at the origin $|\Psi(0)|^2$
7. Decay rate in each channel given by $\Gamma^{(1)} = v\sigma^{(1)}|R(0)|^2/(4\pi)$

- Coulomb singularities arise in the calculation that are inversely proportional to the stop-antistop relative velocity:




- Corrections to wavefunction at origin will cancel this singularity
- All non-relativistic quantities cancelled by taking the ratio of partial widths:

$$R^{(1)} \equiv \frac{\Gamma^{(1)}(\text{stoponium} \to \gamma\gamma)}{\Gamma^{(1)}(\text{stoponium} \to gg)} = \frac{v\sigma^{(1)}(\tilde{t}_1^*\tilde{t}_1 \to \gamma\gamma)|R(0)|^2}{v\sigma^{(1)}(\tilde{t}_1^*\tilde{t}_1 \to gg)|R(0)|^2}$$

# Analytic Result

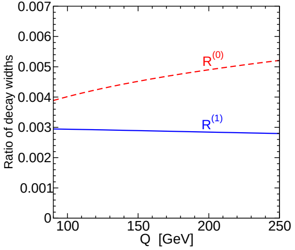
- Renormalized ratio of $\gamma\gamma$ to $gg$ partial widths for s-wave stoponium:

$$R^{(0)} = \frac{8\alpha^2}{9\alpha_S^2}$$

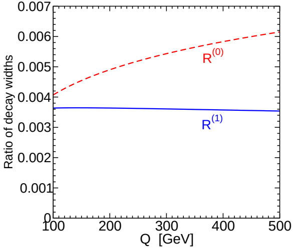
$$R^{(1)} = \frac{8\alpha^2}{9\alpha_S^2}\left\{1 + \frac{\alpha_S}{\pi}\left[-\frac{b_0}{2}\ln\left(\frac{Q^2}{4m_{\tilde{t}_1}^2}\right) + \left(\frac{13\pi^2}{24} - \frac{199}{18}\right) C_A + \left(\frac{\pi^2}{4} - 2 - 2\ln(2)\right) C_F + \left(\frac{16}{9}(n_{\mathrm{light}} + n_t) + 2n_t h(m_t^2/m_{\tilde{t}_1}^2) + \frac{1}{3} n_s \ln(2)\right) T_F\right]\right\}$$

$$h(r) = \frac{2}{9}(4-r)\sqrt{1-r} - \frac{8}{9} - \frac{2}{3}\ln(1+\sqrt{1-r}) + \frac{2}{3}\ln(2)$$

# Dependence of Ratio on Renormalization Scale



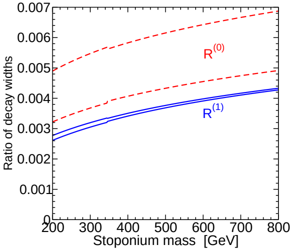

Stop mass = 120 *GeV*




Stop mass = 225 *GeV*

- Using the approximation $BR(\eta_{\tilde{t}_1} \to gg) \approx 1$, $R^{(1)}$ gives $\gamma\gamma$ branching ratio
- Greatly improved renormalization scale dependence
- Decrease in diphoton branching ratio at NLO

# Dependence of Ratio on Stoponium Mass




- Dependence of decay ratios on stop mass in different renormalization schemes
- Top Line: renormalization scale $= 1/2 \times$ stop mass
- Bottom Line: renormalization scale $= 2 \times$ stop mass

# Conclusions

- Reduction in diphoton branching ratio of approximately 30% from tree-level
- Approximately 3.5 diphoton decays for every thousand gluon-gluon decays; $\mathrm{BR}(\eta_{\tilde{t}_1} \to \gamma\gamma) \sim 3.5 \times 10^{-3}$
- Also computed Higgs partial width at NLO, which is useful in studying EW Baryogenesis scenarios, but is highly model-dependent

- Currently completing NLO calculation of production cross-section $\sigma(pp \to \eta_{\tilde{t}})$ in order to obtain full diphoton annihilation cross-section $\sigma(pp \to \eta_{\tilde{t}} \to \gamma\gamma)$ at NLO in QCD
- Previous studies of toponium production at NLO show a corresponding 30% increase in production cross-section (Kühn, Mirkes, 1992)