Stoponium at the LHC

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Classic collider signatures for SUSY:

Invisible LSPs $\longrightarrow$ Missing Energy $\longrightarrow$ No Mass Peaks

A possible exception:

Stoponium $= \eta_{\tilde{t}} =$ s-wave $\tilde{t}_1^* \tilde{t}_1$ bound state

- will be produced at hadron colliders.
- decays by annihilation to gg, $\gamma\gamma$, WW, ZZ, $Z\gamma$, $t\bar{t}$, $b\bar{b}$, $\tilde{N}_1 \tilde{N}_1$.

Drees and Nojiri 1994: $\gamma\gamma$ final state may be detectable

The process

$$pp \longrightarrow \eta_{\tilde{t}} \longrightarrow \gamma\gamma$$

is clearly NOT a discovery mode for supersymmetry.

Importance is that it will give a uniquely precise measurement of the top-squark mass, which then serves as a “standard candle” for the other superpartner masses.

For Stoponium to form, need: decay width $\ll$ binding energy.

Possible flavor-preserving 2-body top-squark decays:

$$\tilde{t}_1 \rightarrow t\tilde{N}_1$$
$$\tilde{t}_1 \rightarrow b\tilde{C}_1$$

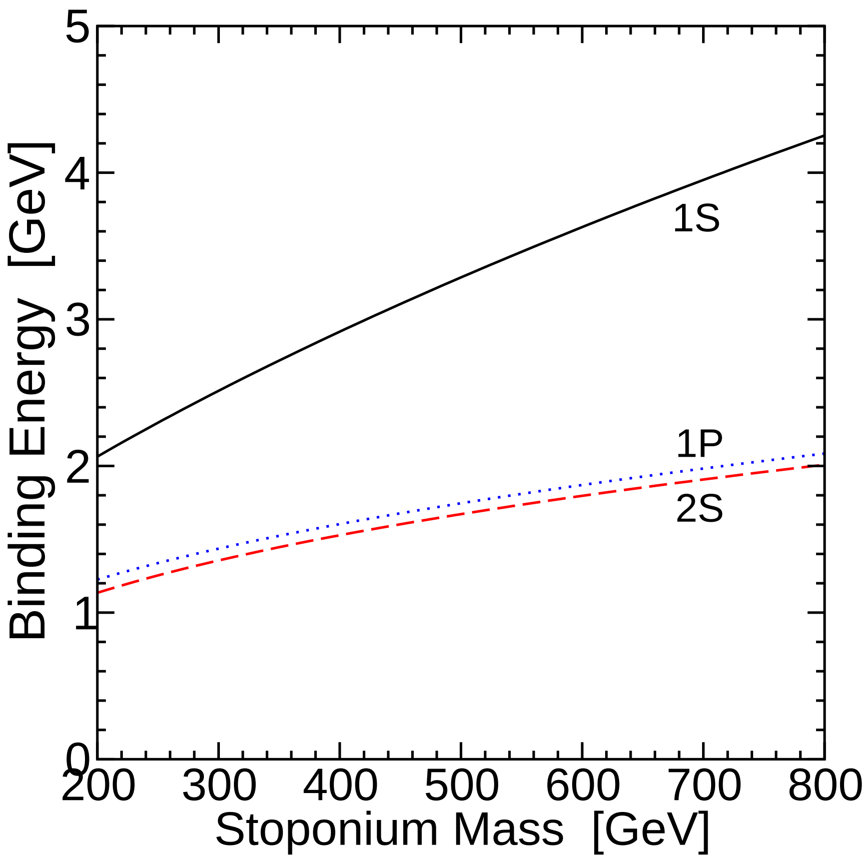
If open, will not allow Stoponium to form.

But, if these are kinematically forbidden, then Stoponium will form, because the 3-body (or 4-body) and flavor-violating 2-body decays:

$$\tilde{t}_1 \rightarrow W^{(*)}b\tilde{N}_1$$
$$\tilde{t}_1 \rightarrow c\tilde{N}_1$$

have tiny partial widths $\ll$ Stoponium binding energy.

Binding energies for Stoponium states



(Hagiwara et al 1990 potential model)

In contrast, gg annihilation partial width is dominant in many models, ~ 2 MeV.

Model-independent partial widths:

$$\begin{aligned}\Gamma(\eta_{\tilde{t}} \to gg) &= \frac{4}{3}\alpha_S^2 |R(0)|^2 / m_{\eta_{\tilde{t}}}^2, \\ \Gamma(\eta_{\tilde{t}} \to \gamma\gamma) &= \frac{32}{27}\alpha^2 |R(0)|^2 / m_{\eta_{\tilde{t}}}^2,\end{aligned}$$

where $R(0)$ = wavefunction at origin.

Then:

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

where $\tau = m_{\eta_{\tilde{t}}}^2 / s$.

The crucial unknowns are $m_{\eta_{\tilde{t}}}$ and $\mathrm{BR}(\eta_{\tilde{t}} \to gg)$. In many models, the gg final state dominates, so take $\mathrm{BR}(\eta_{\tilde{t}} \to gg) \approx 1$ as a useful idealized limit.

Stoponium signal:

$$pp \longrightarrow \eta_{\tilde{t}} \longrightarrow \gamma\gamma$$

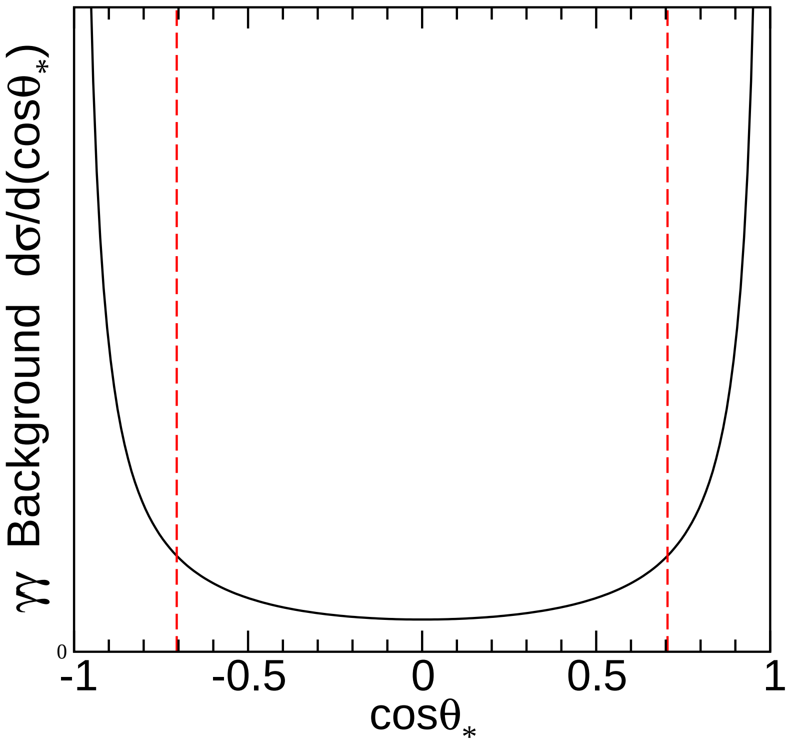
gives a narrow (few MeV) diphoton mass peak against a smoothly falling background.

The experimental width is determined by electromagnetic calorimeter resolution, of order 1% for CMS and ATLAS.

The irreducible physics backgrounds at leading order are:

$$q\overline{q} \quad \longrightarrow \quad \gamma\gamma \qquad \text{(tree-level)}$$
$$gg \quad \longrightarrow \quad \gamma\gamma \qquad \text{(1-loop)}$$

In the COM frame, the Stoponium signal is isotropic, but irreducible backgrounds are peaked forward/backward:



$\theta_* =$ angle with respect to beam in COM frame.

Optimal cut for $S/\sqrt{B}$ (independent of stoponium mass) is:

$$|\cos\theta_*| < 0.705$$

I use angular cuts:

$$|\cos\theta_*| < 0.7 \qquad \text{(COM frame)}$$

$$|\cos\theta| < 0.95 \qquad \text{(Lab frame)}$$

Note photons then automatically have high p_T for large $m_{\eta_{\tilde{t}}}$.

Lab frame cut ensures photons are isolated from beam remnant jets.

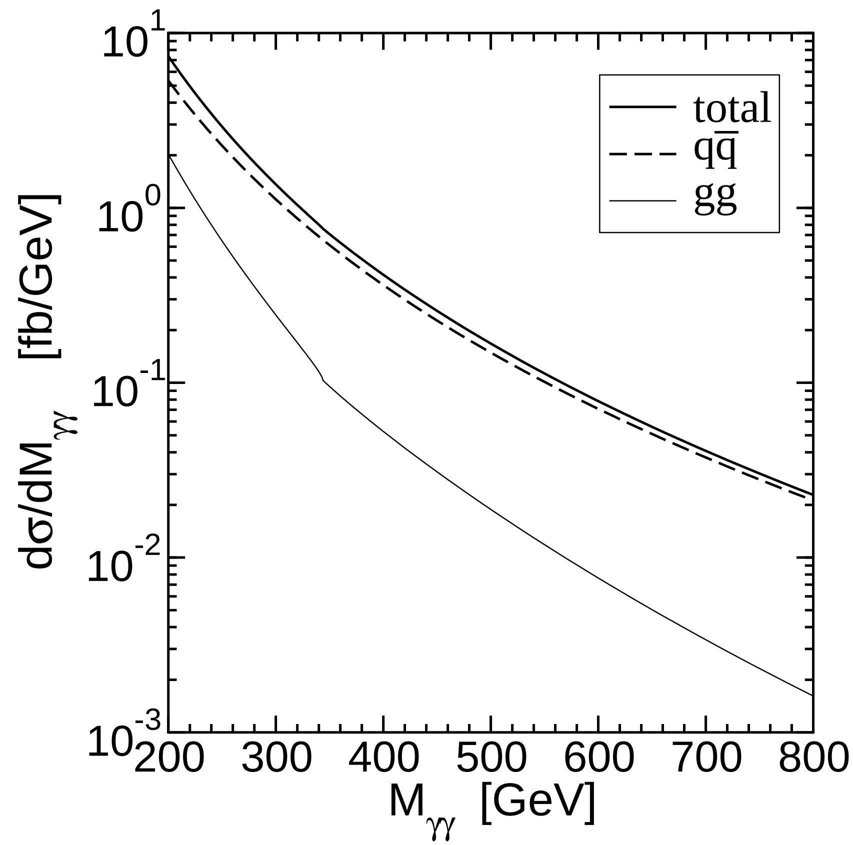
Must also require photons isolated from hadronic activity, and no additional hard jets. This reduces higher-order backgrounds from:

$$qg \to \gamma\gamma q$$

$$qg \to \gamma q \qquad \text{(with photon from jet fragmentation)}$$

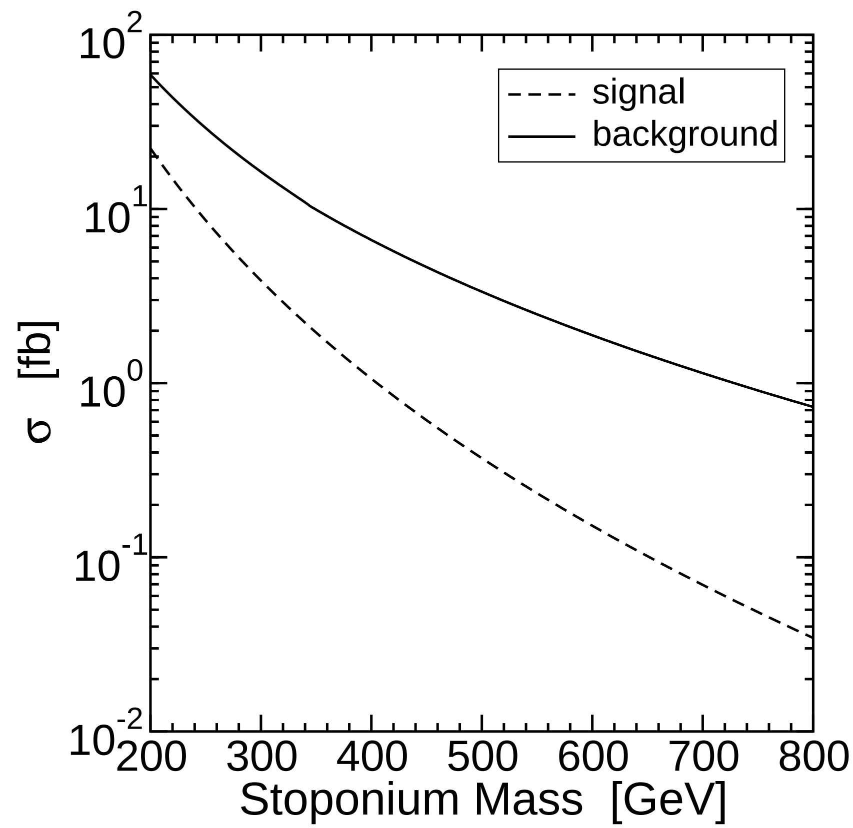
which can be as large or larger than the irreducible backgrounds. I do not include these higher-order corrections to background; higher-order corrections to signal are not known, so impact of cuts cannot be evaluated at present.

Backgrounds at LHC, at leading order, after cuts:



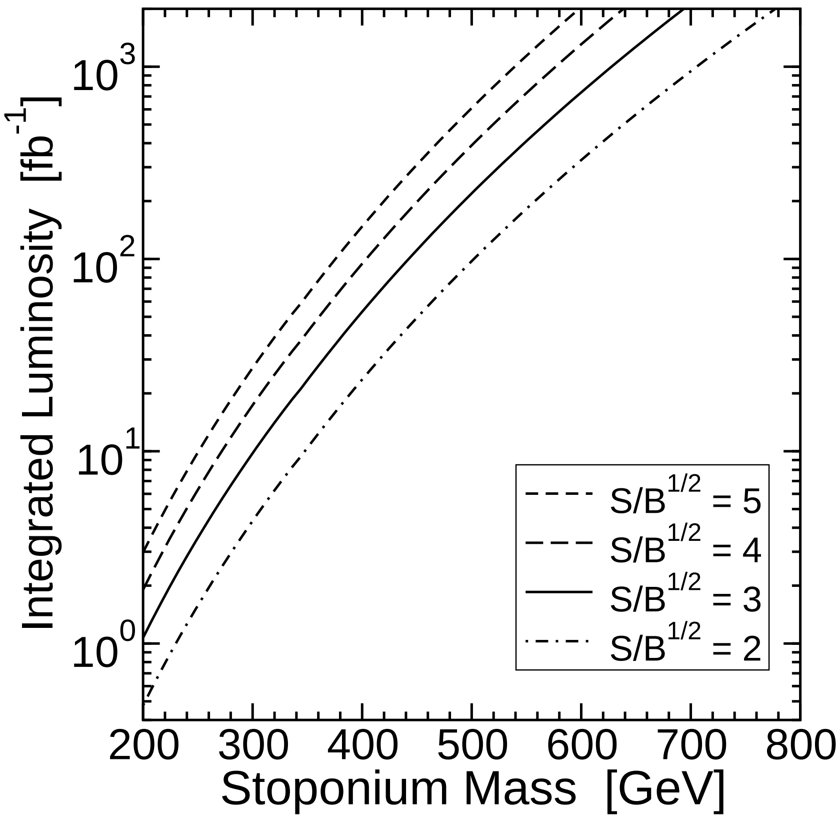
Note: actual background will be obtained from LHC data!

Signal and background in a bin taken to include essentially all of the signal: $|M_{\gamma\gamma} - m_{\eta_{\tilde{t}}}| < 0.02 m_{\eta_{\tilde{t}}}$



Signal assumes idealized case BR$(gg \to \gamma\gamma) \approx 1$.

Luminosity needed for expected significances
$S/\sqrt{B} = 2, 3, 4, 5.$



Signal assumes idealized case BR$(gg \to \gamma\gamma) \approx 1.$

Consider Compressed SUSY models in which the thermal relic abundance of dark matter is determined by top-squark-mediated LSP annihilations:

$$\tilde{N}_1 \tilde{N}_1 \rightarrow t\bar{t}.$$

This follows from a small gluino/wino mass ratio $M_3/M_2 \sim 1/3$ at the unification scale (SPM, hep-ph/0703097).

Also ameliorates the SUSY little hierarchy problem; Kane+King hep-ph/9810374.

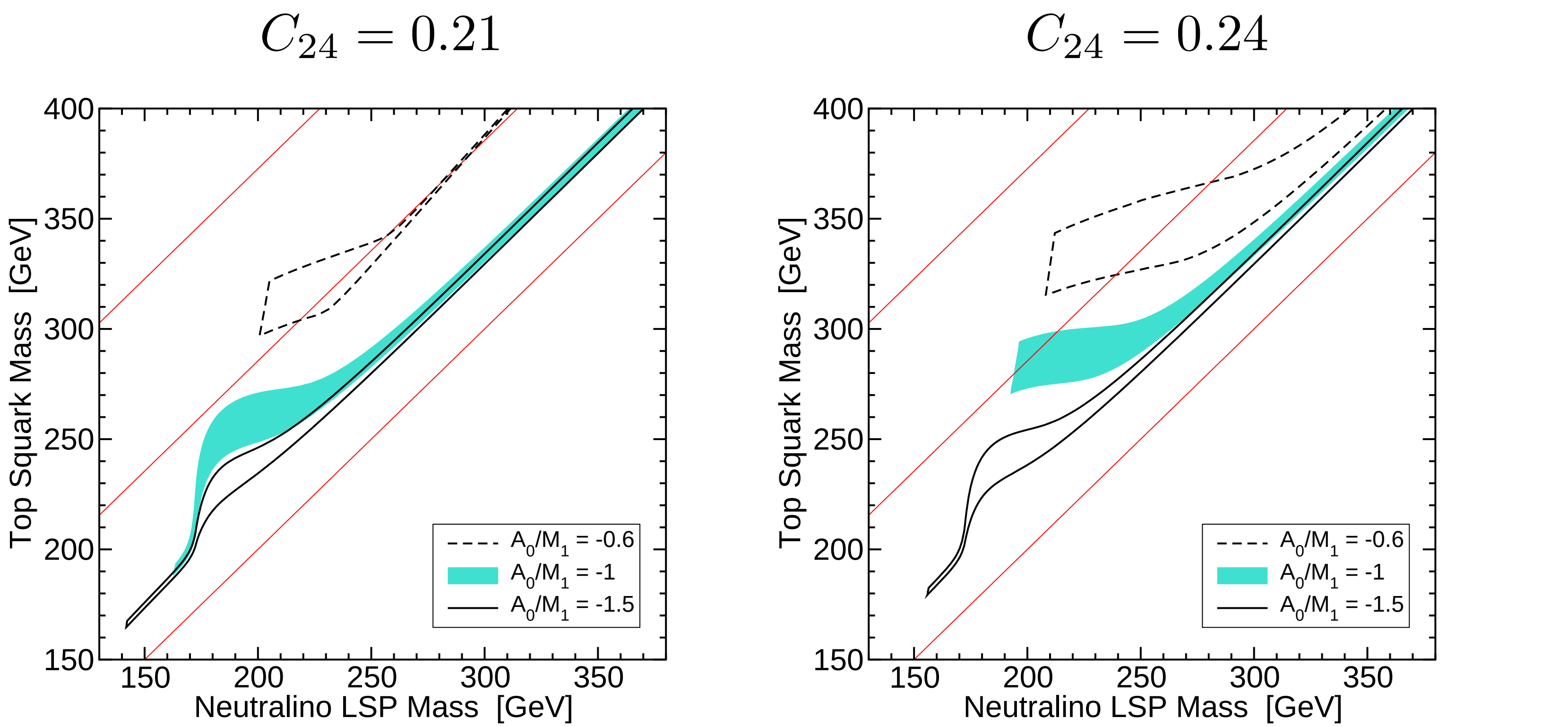
To be specific, assume that at the GUT scale:

$$\begin{aligned} M_1 &= m_{1/2}(1 + C_{24}), \\ M_2 &= m_{1/2}(1 + 3C_{24}), \\ M_3 &= m_{1/2}(1 - 2C_{24}), \end{aligned}$$

where $C_{24} = 0$ would recover the usual mSUGRA.

Instead, $0.15 \lesssim C_{24} \lesssim 0.28$ allows natural top-squark-mediated Dark Matter annihilation.

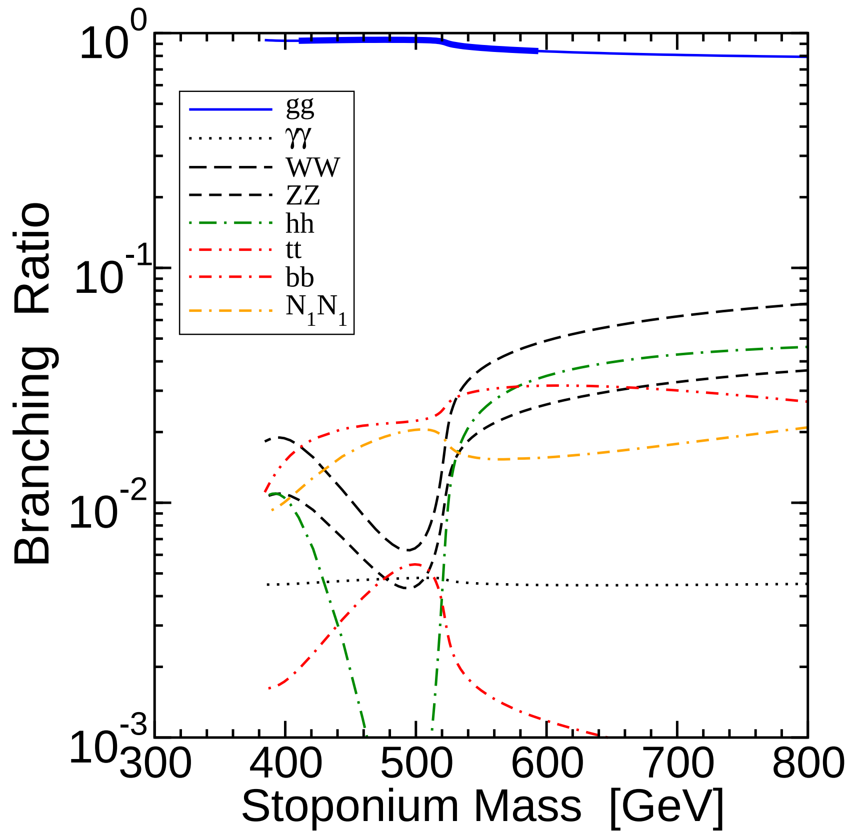
Regions in the stop-LSP mass plane with $m_h > 114$ GeV and $0.09 < \Omega_{\rm DM} h^2 < 0.13$



Stoponium must be kinematically stable in this scenario!

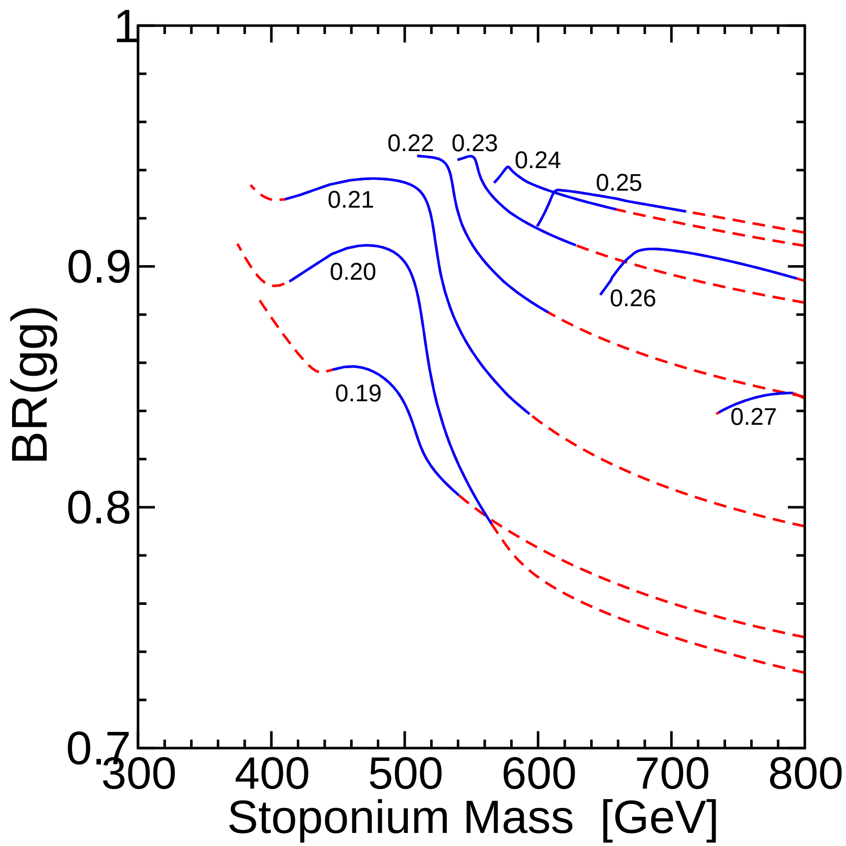
What do these models predict about BR$(\eta_{\tilde{t}} \to gg)$?

A typical model line :



($C_{24} = 0.21$, $A_0/M_1 = -1$, $\tan\beta = 10$, $\mu > 0$, varying m_0)

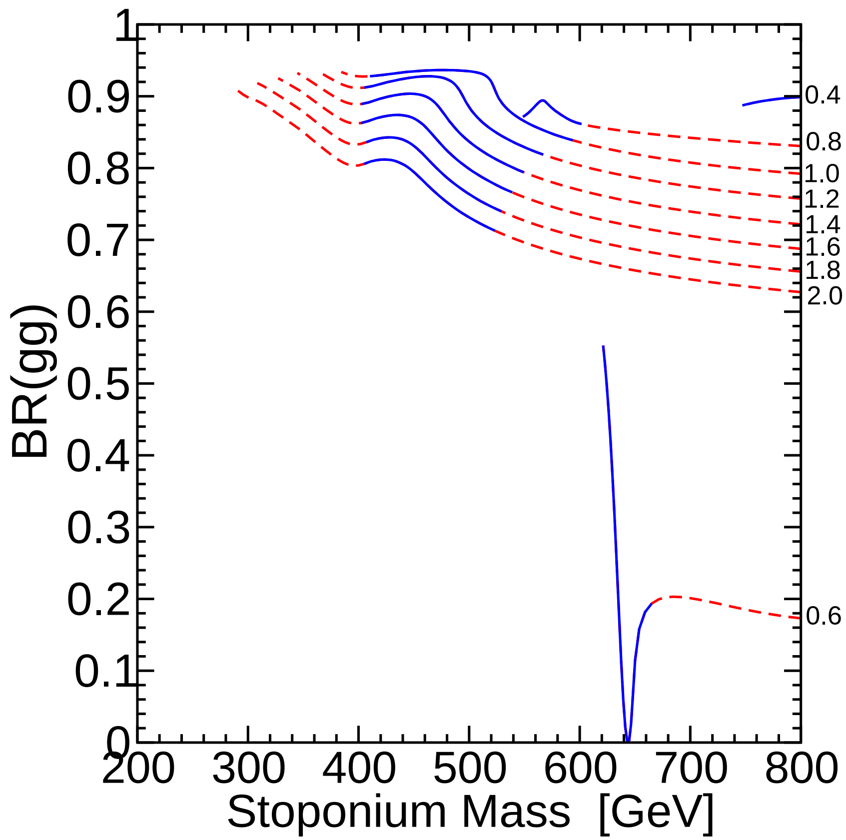
More generally, for various $0.19 \leq C_{24} \leq 0.27$



($A_0/M_1 = -1$,
$\tan\beta = 10$,
$\mu > 0$,
varying m_0)

Compared to the “idealized” case, the luminosity required for detection scales like $1/[\mathrm{BR}(\eta_{\tilde{t}} \rightarrow gg)]^2$

Other slices through parameter space, $0.4 \leq -A_0/M_1 \leq 2.0$



$C_{24} = 0.21$,

$\tan\beta = 10$,

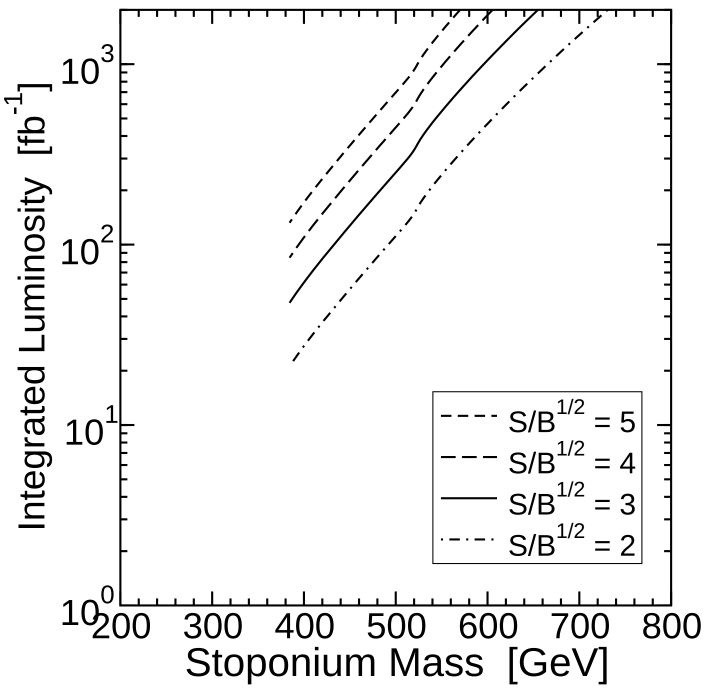
$\mu > 0$,

varying m_0

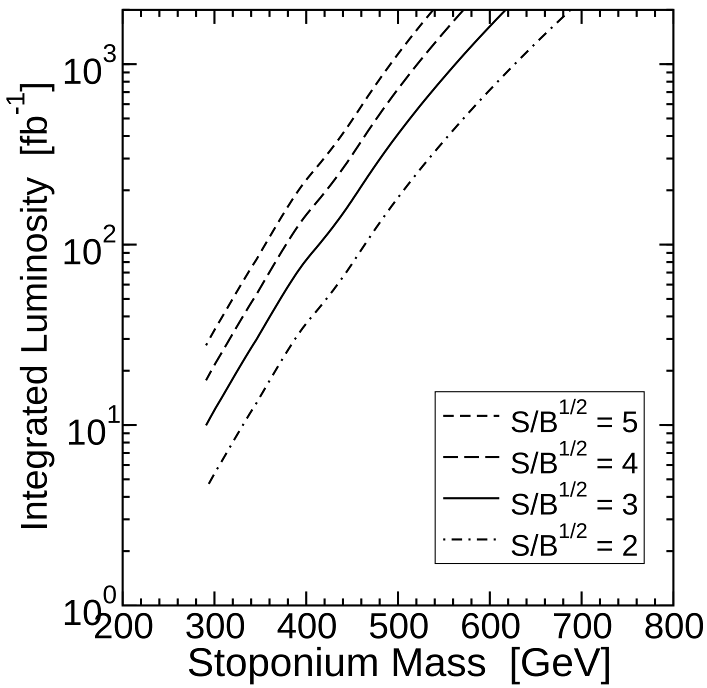
The $-A_0/M_1 = 0.6$ case is special: resonant Stoponium annihilation to $b\bar{b}$ and $t\bar{t}$ through H^0 in the s-channel can spoil the $\gamma\gamma$ signal.

Luminosity needed for expected significances, now including $\mathrm{BR}(\eta_{\tilde{t}} \to \gamma\gamma)$ effect:

$C_{24} = 0.21, \;\; A_0/M_1 = -1$



$C_{24} = 0.21, \;\; A_0/M_1 = -2$



Detectability for $m_{\eta_{\tilde{t}}} = 500$ GeV will require more than 100 fb^{-1}.

For $m_{\eta_{\tilde{t}}} = 300$ GeV, 10 fb^{-1} might do it.

Another scenario with stable stoponium: electroweak scale baryogenesis with a strongly first-order phase transition.

$\tilde{t}_1$ is lighter than top, mostly right-handed.

Espinosa, Quiros, Zwirner, Carena, Wagner...

Balazs, Carena, Wagner hep-ph/0403224, Carena, Menon, Morrissey, Wagner hep-ph/0412264

Carena, Nardini, Quiros, Wagner to appear.

Off-diagonal top-squark squared mass is $m_t X_t$, with

$$0.3 \;\lesssim\; |X_t|/m_{\tilde{t}_2} \;\lesssim\; 0.5$$

$m_{\tilde{t}_2}$ very large, (here 10 TeV)

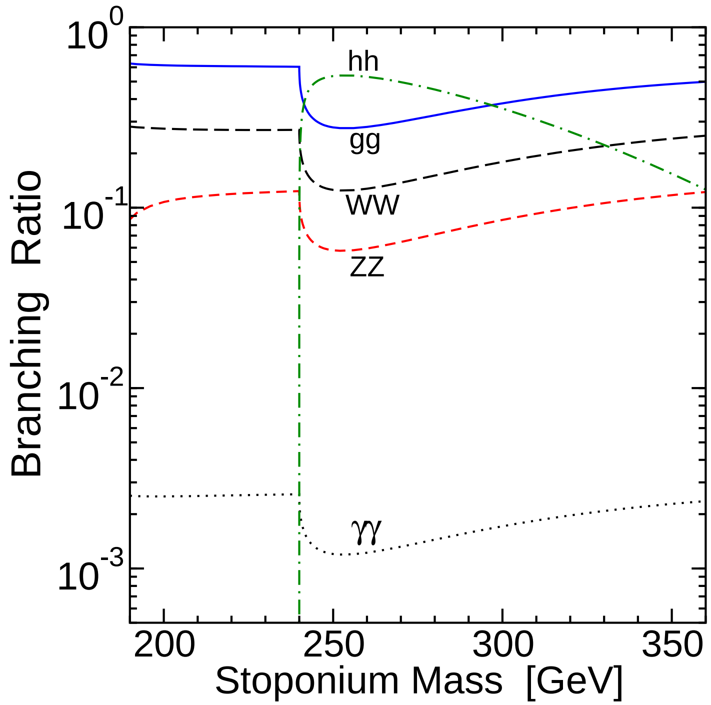
$$5 \;\lesssim\; \tan\beta \;\lesssim\; 10$$

Stoponium is stable, mass must be less than about 360 GeV.

Stoponium branching ratios in model lines motivated by electroweak-scale baryogenesis:

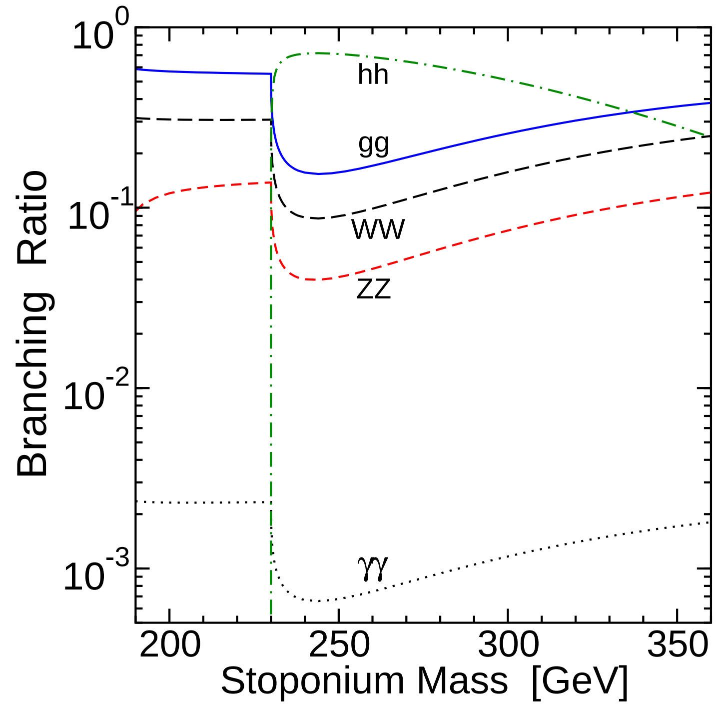
Optimistic

($m_h = 120$ GeV, $X_t/m_{\tilde{t}_2} = 0.3$)



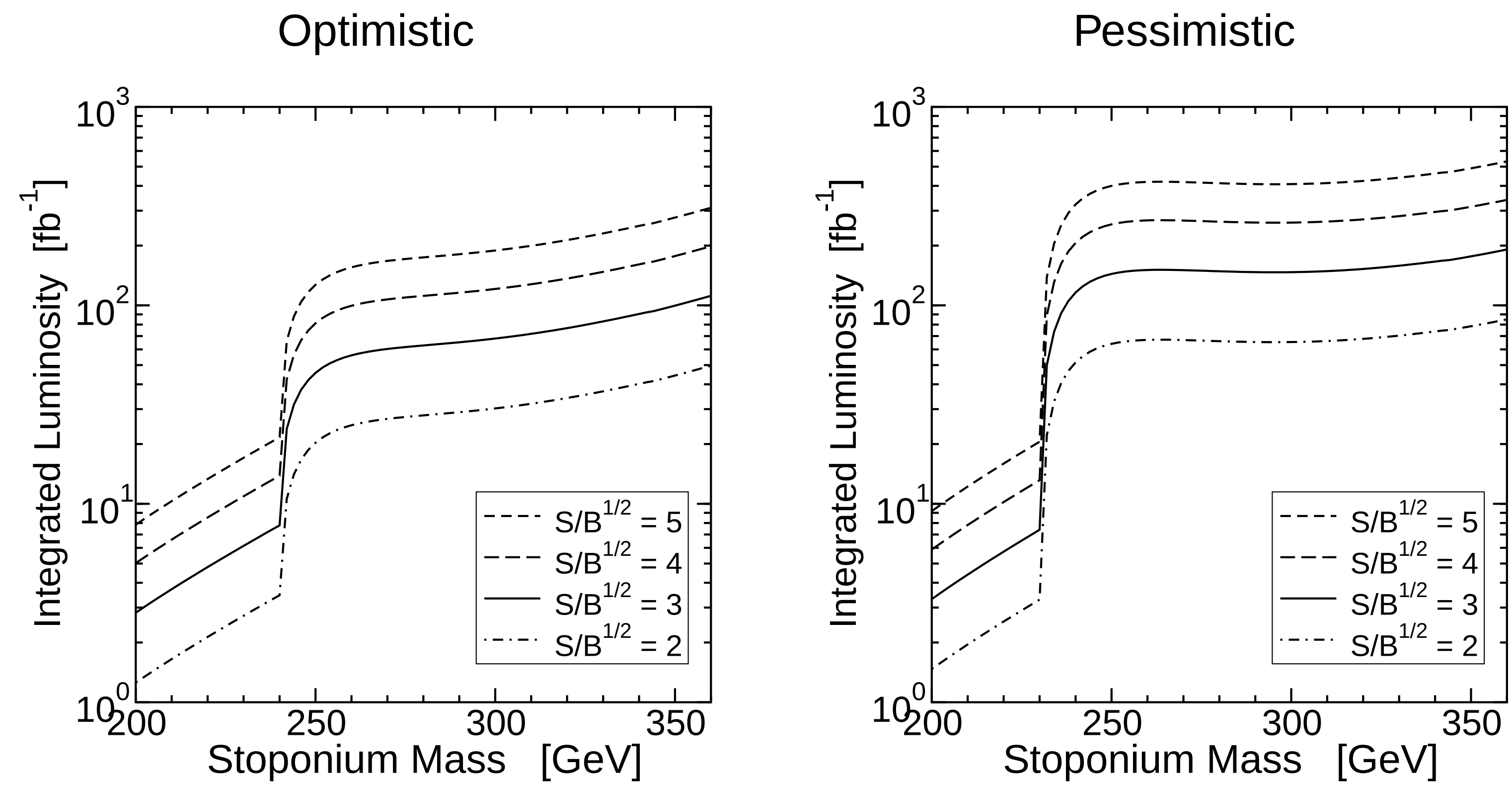
Pessimistic

($m_h = 115$ GeV, $X_t/m_{\tilde{t}_2} = 0.5$)



The spoiler mode here is $\eta_{\tilde{t}} \to h^0 h^0$, especially just above threshold.

Luminosities needed for expected $S/\sqrt{B} = 2, 3, 4, 5$



100 fb^{-1} might lead to detectability over the entire stoponium mass range in this scenario.

10 fb^{-1} might be enough, if $m_{\eta_{\tilde{t}}} < 2m_{h^0}$.

Outlook:

- Diphoton signal for Stoponium may be a viable signal at LHC
- I've updated the original Drees and Nojiri 1994 analysis:
  - Corrected factors of 2 in gg, $\gamma\gamma$ partial widths
  - More liberal angular cut, more conservative energy resolution
  - Used now-known $m_{\rm top}$, $\Omega_{DM}h^2$, LEP2 m_h limit.
  - Motivated models of dark matter and baryogenesis
- 100 fb^{-1} needed for 500 GeV Stoponium
- 10 fb^{-1} may be enough for $<$300 GeV Stoponium
- If detected, Stoponium would give a uniquely precise determination of superpartner masses