Supersymmetric quarkonia

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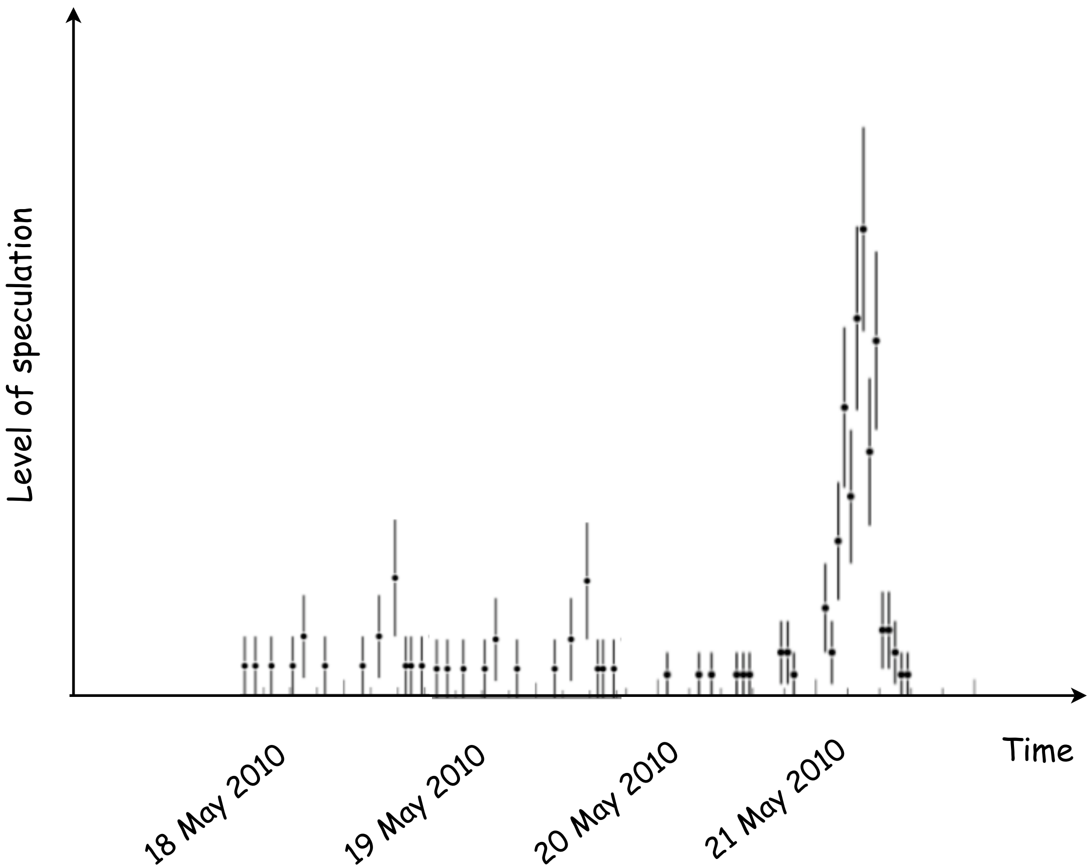
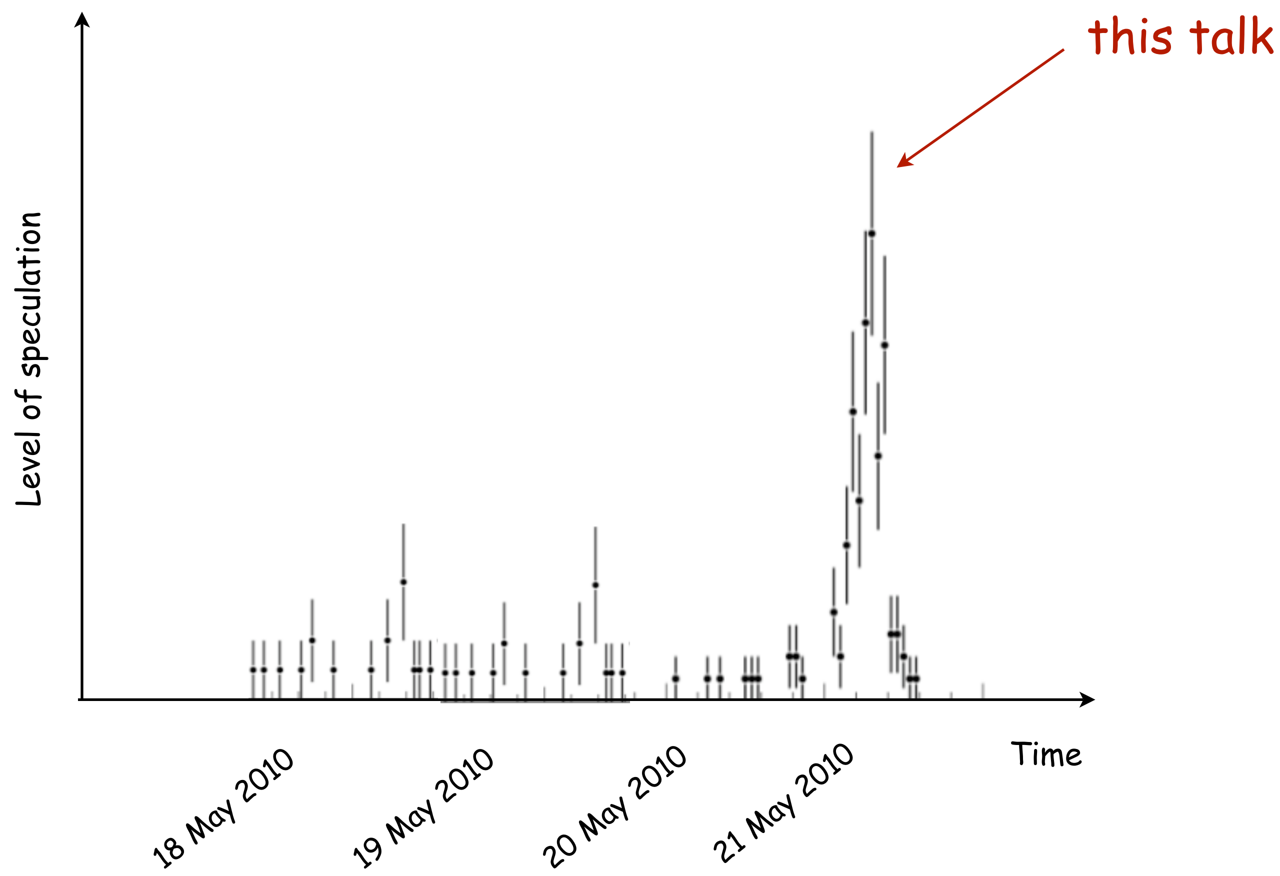
QWG-2010 presentations: level of speculation



QWG-2010 presentations: level of speculation



1. Introduction: SUSY and QCD bound states

- SUSY is one of the viable (best?) models for physics beyond the Standard Model
  - solves naturalness problem/provides Dark Matter candidate/etc.
  - doubles particle spectrum

t-quark → $\tilde{t}_L$-squark, $\tilde{t}_R$-squark →

$$\begin{cases} \tilde{t}_1 = \quad \tilde{t}_L \cos\theta_t + \tilde{t}_R \sin\theta_t \\ \tilde{t}_2 = -\tilde{t}_L \sin\theta_t + \tilde{t}_R \cos\theta_t \end{cases}$$

- Squarks are color-triplet scalars: bound states?
  - Higgs mass prediction in MSSM:

$$m_h^2 = m_Z^2 \cos^2(2\beta) + \frac{3}{4\pi^2} y_t^4 \sin^4\beta \log\left(\frac{m_{\tilde{t}_1} m_{\tilde{t}_2}}{m_t^2}\right)$$

  - top quarks do not form bound states (top decays too fast!!!)

What is the story with MSSM?

Introduction: SUSY and QCD bound states

- SUSY is broken; masses of sparticles are not known
  - various scenarios can be considered, for example,

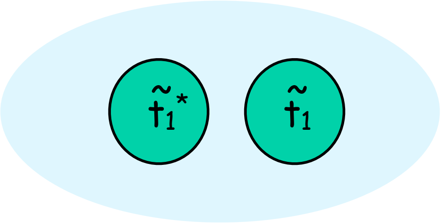
S. Martin
M. Drees & M. Nojiri

$$m_{\tilde{t}_1} - m_{\widetilde{C}_1} < m_b \text{ and } m_{\tilde{t}_1} - m_{\widetilde{N}_1} < m_t$$

then, $\tilde{t}_1 \to b\widetilde{C}_1$, $\tilde{t}_1 \to t\widetilde{N}_1$ are forbidden

  - top squark's lifetime is longer than formation time for the QCD bound state

→ can form stoponium



- Why study stoponium?
  - HEP phenomenology:
    - precise determination of squark masses
  - Quarkonium-like physics
    - physics of bound states in new environment
    - new sources of binding (Higgs exchange, point-like interactions)

Concentrate on the lightest state (stoponium)

2. Properties of stoponium

- **Assuming $m_{t1} \ll m_{t2}$, the spectroscopy of stoponium is boring**
  - stops are spin-0: spin of bound states tracks relative angular momentum
  - lowest energy state is a 0^{++} scalar

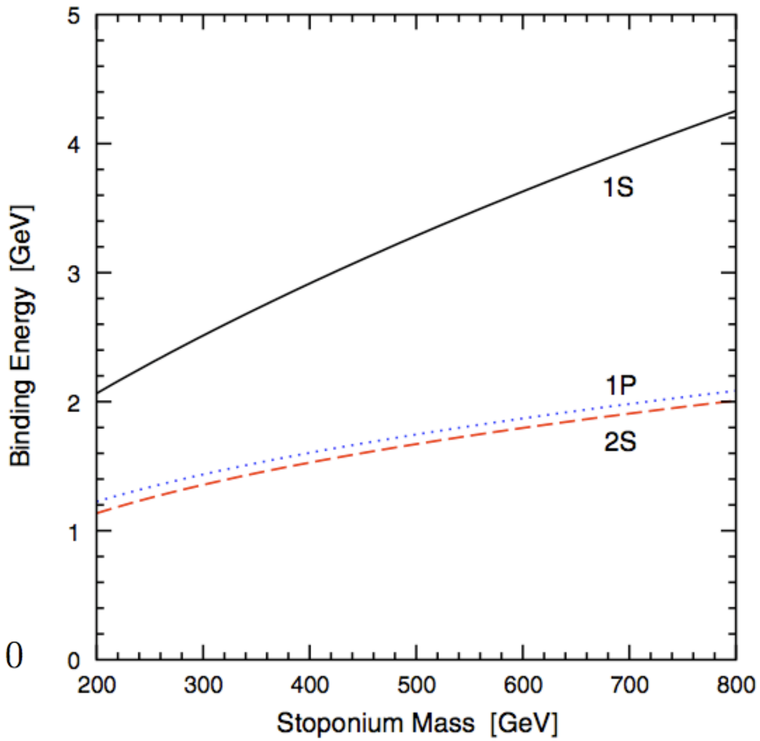
- **What is the spectrum?**
  - strongly-interacting heavy particles
    - Coulomb dominated potential

$$V_{\rm QCD}^{(C)} = -\frac{3\alpha_s}{2r} + \kappa r$$

  - if similar to ordinary quarkonia
    - binding energy B and wave function

$$\left[-\frac{\hbar^2}{m_{\tilde{t}_1}} \left(\frac{d^2}{dr^2} + \frac{2}{r}\frac{d}{dr} \right) + V_{\rm eff}(r) + \mathcal{B} \right] \psi(\mathbf{r}) = 0$$

where $V_{\rm eff}(r) = V_{\rm QCD}(r)$ for l=0



S. Martin

In SUSY there are also other contributions to the potential

Comments on the mass spectrum

- **Other contributions to potential**
  - there are at least three Higgs states (h^0, H^0, and A^0)
    - more important for heavier squarks
    - induce Yukawa interaction term
  - there is a term inducing point quartic squark interactions
    - induces delta-function interaction term

$$V_{\text{eff}}(r) = -\left(\frac{g_h e^{-m_h r}}{r} + \frac{g_H e^{-m_H r}}{r} + \frac{g_A e^{-m_A r}}{r} \right) + V_{\text{QCD}}(r) + \mathcal{A}\, \delta^{(3)}(\mathbf{r})$$

$$\mathcal{A} = \frac{1}{6} g_s^2 + y_t^2 \sin^2\theta_{\tilde{t}} \cos^2\theta_{\tilde{t}}$$

positive!

A. Blechman, A.A.P

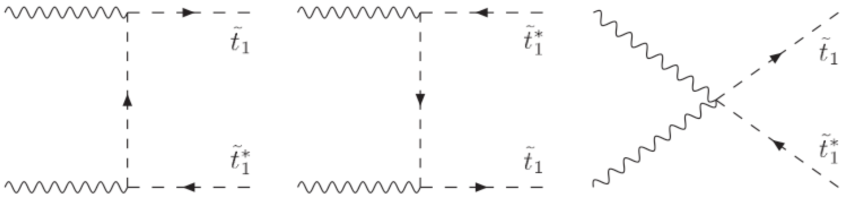
- **Stoponium has the same quantum numbers as Higgs boson(s)**
  - if close in mass, strong mixing is possible (level repulsion)

$$m_\pm^2 = \frac{1}{2}\left[(m_1^2 + m_2^2) \pm \sqrt{(m_1^2 - m_2^2)^2 + 4\Delta^2} \right]$$

(mixed stoponium-Higgs state)

3. Production & decays of stoponia

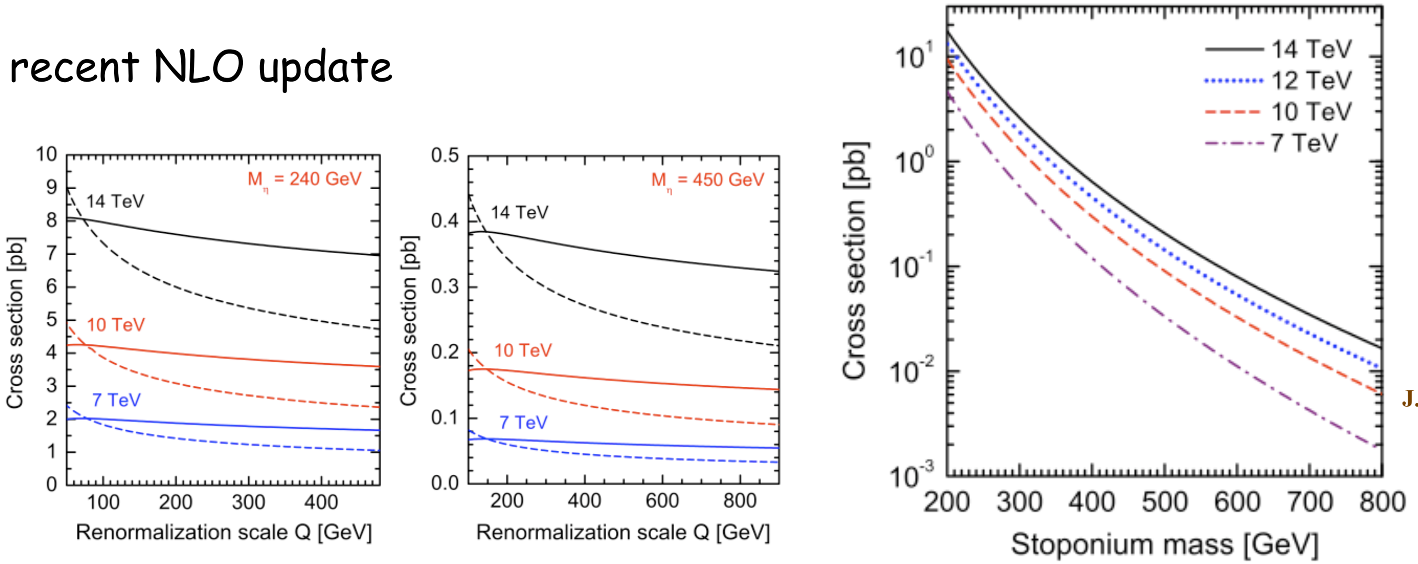
- Stoponium might be produced at the LHC
  - leading contribution is gg fusion



P. Moxhay & R. Robinett
M. Drees & M. Nojiri

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

  - recent NLO update

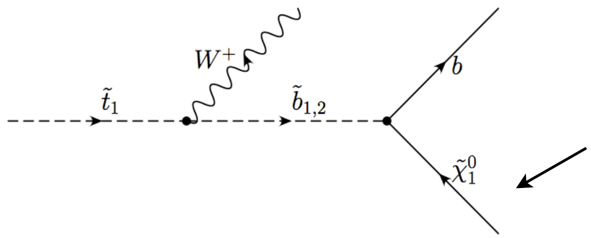


J. Younkin & S. Martin

Decays of stoponia

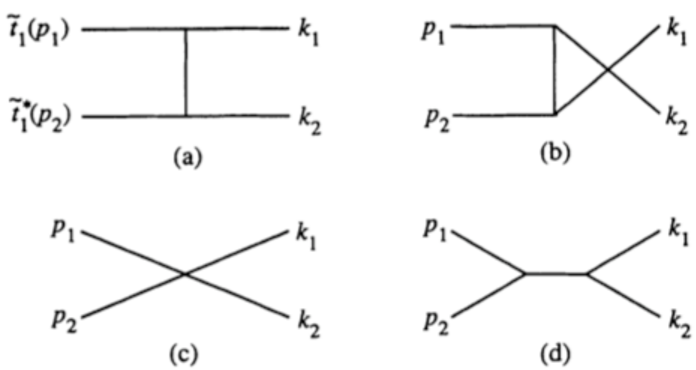
- Stoponia decay to Standard Model particles only
  - no missing energy signatures with LSP in the final state, e.g.

single stop decay



neutralino (missing energy)

- Possible 2-body decay channels of stoponia
  - bosonic final states:
    - γγ, γZ, ZZ, WW, gg
  - fermionic final states:
    - $t\bar{t}$, $b\bar{b}$, $\mu\mu$, etc.



2-body decays of stoponium

- Master formula for 2-body decays

$$\Gamma(\eta_{\tilde{t}} \to AB) = \frac{3\lambda^{1/2}(1, m_A^2/m_{\eta_{\tilde{t}}}^2, m_B^2/m_{\eta_{\tilde{t}}})}{32\pi^2(1+\delta_{AB})} \left(\frac{2\pi f_{\eta_{\tilde{t}}}^2}{m_{\eta_{\tilde{t}}}}\right) \langle |\mathcal{M}(AB)|^2 \rangle$$

with $\lambda(x,y,z) = x^2 + y^2 + z^2 - 2xy - 2yz - 2xz$

- for bosonic final states

$$\langle |\mathcal{M}(gg)|^2 \rangle = \frac{16}{9} g_s^4 \,,$$
$$\langle |\mathcal{M}(\gamma\gamma)|^2 \rangle = \frac{128}{81} e^4 \,,$$
$$\langle |\mathcal{M}(\gamma Z)|^2 \rangle = \frac{8}{9} e^2 (g^2 + g'^2)(\cos^2\theta_{\tilde{t}} - 4 s_W^2/3)^2$$

- gg final state is by far the dominant

$$\Gamma(\eta_{\tilde{t}} \to gg) = 73 \text{ MeV}$$
$$\Gamma(\eta_{\tilde{t}} \to \gamma\gamma) = 303 \text{ keV}$$
$$\Gamma(\eta_{\tilde{t}} \to \gamma Z) = 106 \text{ keV}$$

(for m_η=100 GeV)

2-body decays of stoponium

- Master formula for 2-body decays

$$\Gamma(\eta_{\tilde{t}} \to AB) = \frac{3\lambda^{1/2}(1, m_A^2/m_{\eta_{\tilde{t}}}^2, m_B^2/m_{\eta_{\tilde{t}}})}{32\pi^2(1+\delta_{AB})} \left(\frac{2\pi f_{\eta_{\tilde{t}}}^2}{m_{\eta_{\tilde{t}}}}\right) \langle |\mathcal{M}(AB)|^2 \rangle$$

with $\lambda(x,y,z) = x^2 + y^2 + z^2 - 2xy - 2yz - 2xz$

- for fermionic final states, e.g.

M. Drees & M. Nojiri

$$\mathcal{M}(\tilde{t}_1\tilde{t}_1^* \to b\bar{b}) = -\delta_{h\bar{h}} 2\sqrt{3}\sqrt{m_{\tilde{t}_1}^2 - m_b^2}$$
$$\times \left\{ \sum_{i=1}^{2} \frac{1}{3} \frac{m_{\tilde{W}_1}(c_i^2 - d_i^2) + m_b(c_i^2 + d_i^2)}{m_b^2 - m_{\tilde{t}_1}^2 - m_{\tilde{W}_i}^2} + \frac{g m_b}{2 m_W \cos\beta} \left[-\frac{c_{\tilde{t}_1}^{(1)} \cos\alpha}{4m_{\tilde{t}_1}^2 - m_{H_1}^2} + \frac{c_{\tilde{t}_1}^{(2)} \sin\alpha}{4m_{\tilde{t}_1}^2 - m_{H_2}^2} \right] \right\}$$

chargino exchange ↗   Higgs exchange ↗

- for quarks this is totally overwhelmed by QCD backgrounds
- only the second term is present for the $\mu\mu$ (or ee or $\tau\tau$) final states - small!

3-body decays of stoponium

- **Other ways to search for stoponium?**
  - leptonic 2-body decays are suppressed by helicity ($\sim m_l^2$)
    - but have very nice decay signatures
  - bosonic 2-body decays are reasonably large
    - but have lower detection efficiencies

- **How about 3-body decays (like $\mu\mu\gamma$)?**
  - lower branching ratios than $\gamma\gamma$...
  - higher branching ratios than $\mu\mu$

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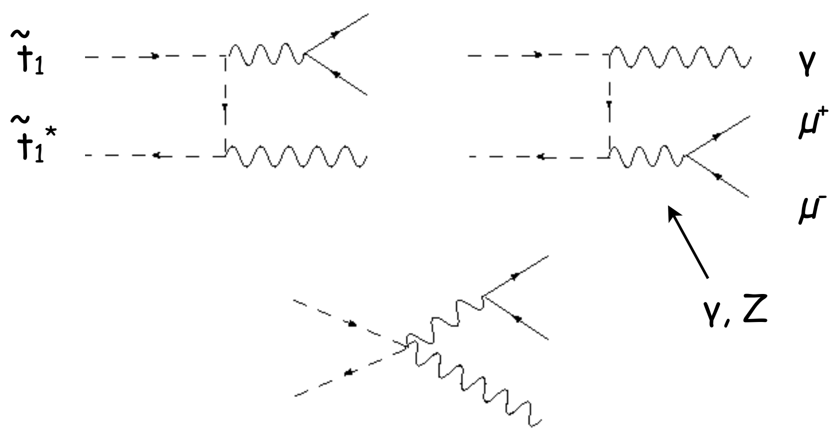

3-body decays of stoponium

- 3-body decays are not helicity-suppressed

$$\mathcal{M} = \frac{8e^3 f_{\eta_{\tilde t}}}{9m_{ll}^2}\left[\frac{p_S^\mu p_S^\nu}{m_{\eta_{\tilde t}}^2 - m_{ll}^2} - g^{\mu\nu}\right]\left[(1+Bc_V)V_\mu(k_-,k_+) + Bc_A A_\mu(k_-,k_+)\right]\varepsilon_\nu^*(q)$$

- Dalitz analyses of decays are possible

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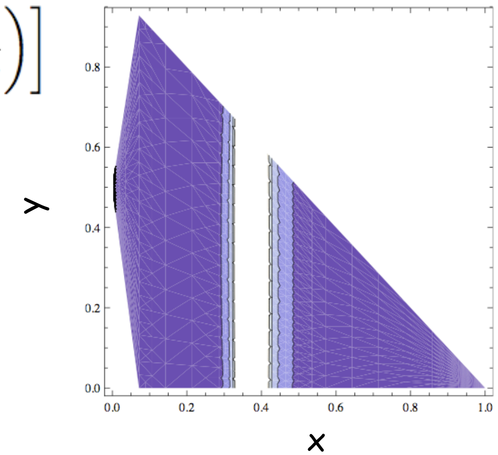
- define $x \equiv m_{ll}^2/m_{\eta_{\tilde t}}^2$ and $y \equiv (k_- + q)^2/m_{\eta_{\tilde t}}^2$

$$\frac{d^2\Gamma}{dx\,dy} = \frac{64\alpha^3 f_S^2}{81 m_S}\frac{\left|1+B(x)c_V\right|^2 + |B(x)|^2 c_A^2}{x}\left[1 + \frac{1-2x}{2(1-x)}\left(y - \frac{y^2}{1-x}\right)\right]$$

with $$B(x) = \frac{3Q_Z^{11}}{2c_W^2 s_W^2}\frac{x}{x - x_Z + i\gamma_Z\sqrt{x_Z}}$$



3-body decays of stoponium

- Branching ratios can be computed
  - for a particular point $(m_{\eta_{\tilde{t}}} = 100 \text{ GeV},\ f_{\eta_{\tilde{t}}} = 10 \text{ GeV},\ \cos\theta_{\tilde{t}} = 0.01)$

$$\begin{aligned} Br(gg) &= 0.99 \ , \\ Br(\gamma\gamma) &= 4.1 \times 10^{-3} \ , \\ Br(\gamma Z) &= 1.4 \times 10^{-3} \ , \\ Br(\gamma e^+ e^-) &= 0.426 \times 10^{-3} \\ Br(\gamma \mu^+ \mu^-) &= 0.423 \times 10^{-3} \end{aligned}$$

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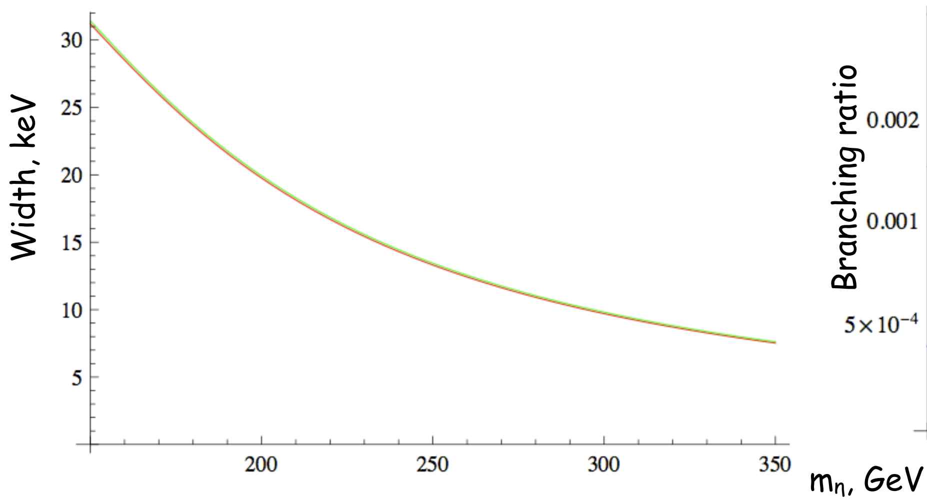
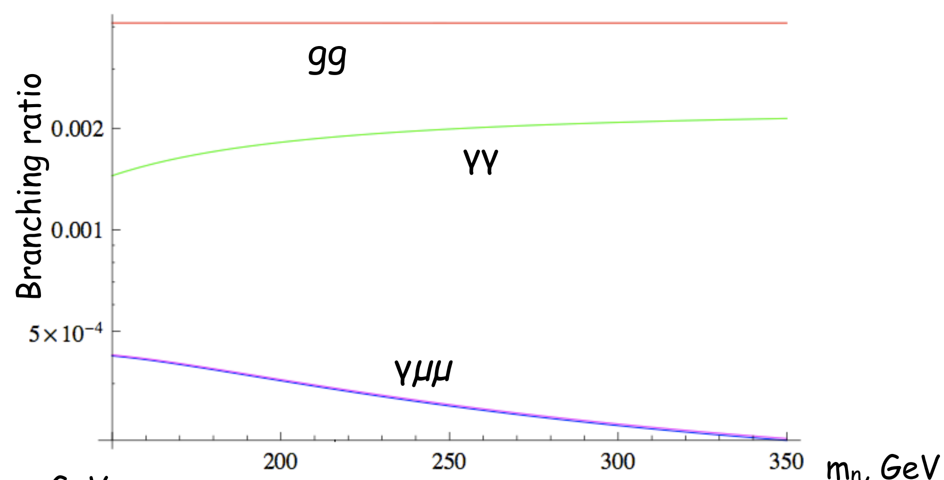
- Comparing to other decays…





Conclusions

- New Physics particles can form quarkonium-like bound states
  - can be used to extract NP particle masses
  - can be used to study QCD bound state physics in a new regime
- Interesting interplay of different effects in the bound state
  - besides QCD, there are other sources (Higgs exchange, etc) that affect properties of a bound state
- Possible observations/studies in 2- and 3-body decays
  - small decay branching ratios implies that those are NOT discovery modes, but rather tools for precision studies of properties of squarks...
  - ... provided they exist!