Stoponia & Higgs Bosons

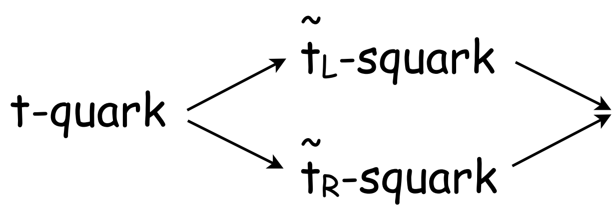
Andrew Blechman
Wayne State University
PHENO 2012, May 8

Based on work done with Prof. Alexey Petrov, WSU

Outline

- Review of stoponium physics
- Effective Field Theory of scalar fields
- Mixing with scalar (Higgs???) bosons
- Stoponium 2- and 3-body decays
- Discussion

Stoponium



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

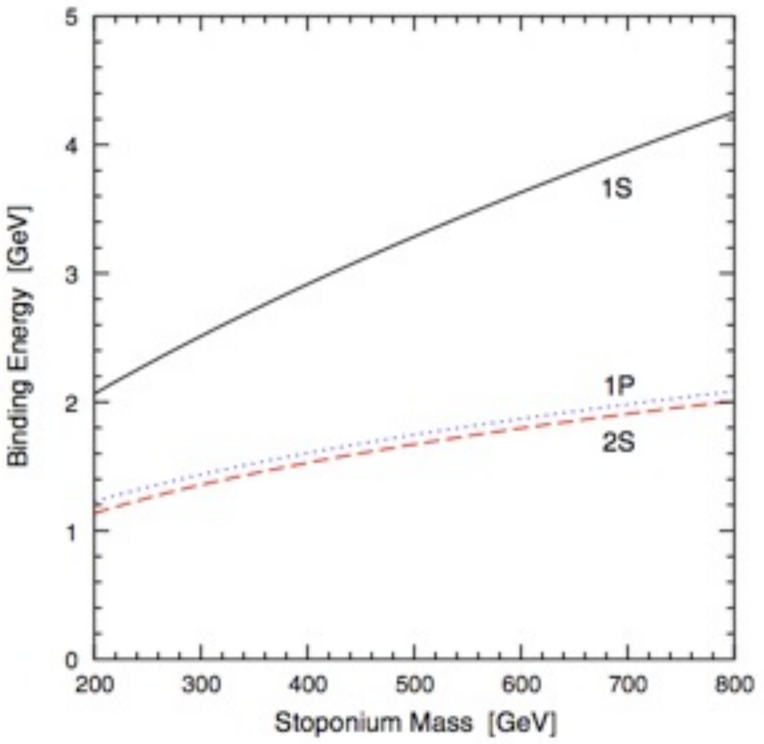
- Squarks are color (anti)triplet, scalars - can they hadronize??
- Perhaps, but like the top quark, they typically decay too quickly. For example, $\tilde{t} \to b\tilde{\chi}^+,\ t\tilde{\chi}^0$. Note the presence of the (unobserved) final state SUSY particle!
- Standard scenarios have m_t > 640 GeV to increase mass of the Higgs boson, making above decays very prompt, so no bound states.
- But stops can be lighter in extended SUSY models, and if stable they can form bound states (c.f.: Csaki Plenary Talk).

Stoponium

Assuming $m_{\tilde{t}_1} \ll m_{\tilde{t}_2}$, spectrum is simple. Spin of state tracks relative angular momentum of squarks. Lightest state is 0^{++} state $\eta_{\tilde{t}_1}$.

Spectrum computed by S. Martin (right) assuming QCD binding potential.

We will focus on light stops (~ 100 GeV) for a stoponium mass near 200 GeV.



NonRelativistic Scalar Effective Theory (NRSET)

Feshbach & Villars, 1958

Break a (real or complex) scalar field into *positive* and *negative* energy components:

$$\phi(x) = \frac{1}{\sqrt{2m}} e^{-imt} \begin{pmatrix} \varphi \\ \chi \end{pmatrix} \begin{matrix} \longleftarrow \text{positive energy} \\ \longleftarrow \text{negative energy} \end{matrix}$$

In terms of these components, the Klein-Gordan Lagrangian can be written as:

$$\mathcal{L} = \varphi^* \left[iD_0 + \frac{\mathbf{D}^2}{2m} \right] \varphi + \varphi^* \frac{\mathbf{D}^2}{2m} \chi + \chi^* \frac{\mathbf{D}^2}{2m} \varphi - \chi^* \left[iD_0 - \frac{\mathbf{D}^2}{2m} + 2m \right] \chi$$

χ has a "mass" of 2m and can be integrated out:

$$\chi = \left(1 - \frac{iD_0}{2m} + \frac{\mathbf{D}^2}{(2m)^2} \right)^{-1} \frac{\mathbf{D}^2}{(2m)^2} \varphi$$

After multipole expanding this generates power corrections in agreement with previous work.

Hoang, Ruiz-Femenia, 2006
Hill, Solon, 2012

NRSET and the MSSM

Now let us apply this to the stops and a real scalar field:

$$\tilde{t}_1(x) = \frac{1}{\sqrt{2m_{\tilde{t}_1}}}\left[e^{-im_{\tilde{t}_1}t}\varphi(x) + e^{+im_{\tilde{t}_1}t}\overline{\varphi}(x)\right]$$

$$H(x) = \frac{1}{\sqrt{2M_H}}e^{-iM_H t}\tilde{H}(x)$$

Our Lagrangian contains a term:

$$\Delta\mathcal{L} = -g_H(\tilde{t}_1^*\tilde{t}_1)H = -\left(\frac{g_H}{2m_{\tilde{t}_1}\sqrt{2M_H}}\right)(\overline{\varphi}^*\varphi)\tilde{H}e^{-i(2m_{\tilde{t}_1}-M_H)t} + \text{ h.c.}$$

If $m_{\tilde{t}_1}$ M_H the phase vanishes, leading to a mixing term.
Note that g_H has dimensions of mass.

Matching NRSET to pNRQCD

Brambilla, et al., 2000.

We wish to match the stops onto a stoponium field: $\langle 0|S(x)|\eta_{\tilde{t}}(p)\rangle = e^{-ipx}$

The EFT that describes this is pNRQCD. We will match the definition of the stoponium decay constant:

$$f_{\eta_{\tilde{t}}} = \langle 0|(\tilde{t}_1^* \tilde{t}_1)_{\mathbf{1}}|\eta_{\tilde{t}}\rangle = \frac{\sqrt{2m_{\eta_{\tilde{t}}}}}{2m_{\tilde{t}}}\langle 0|(\overline{\varphi}^*\varphi + \overline{\varphi}\varphi^*)|\eta_{\tilde{t}}\rangle$$
$$= C\langle 0|(S(0) + S(0)^\dagger)|\eta_{\tilde{t}}(p)\rangle$$

This matching allows us to identify S(x) up to power and QCD corrections:

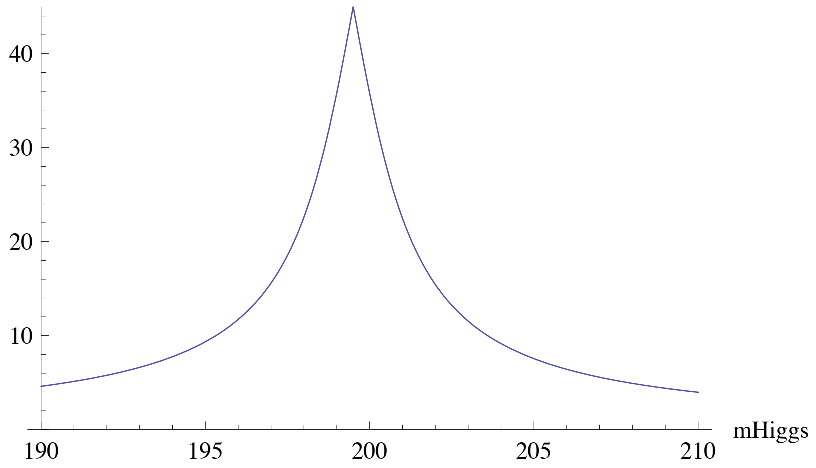
$$\varphi(x)U(x,y)\overline{\varphi}(y) \ = \left(\frac{2m_{\tilde{t}_1} f_{\eta_{\tilde{t}}}}{\sqrt{2m_{\eta_{\tilde{t}}}}}\right)\sqrt{Z_s(r)}S(R,T)$$

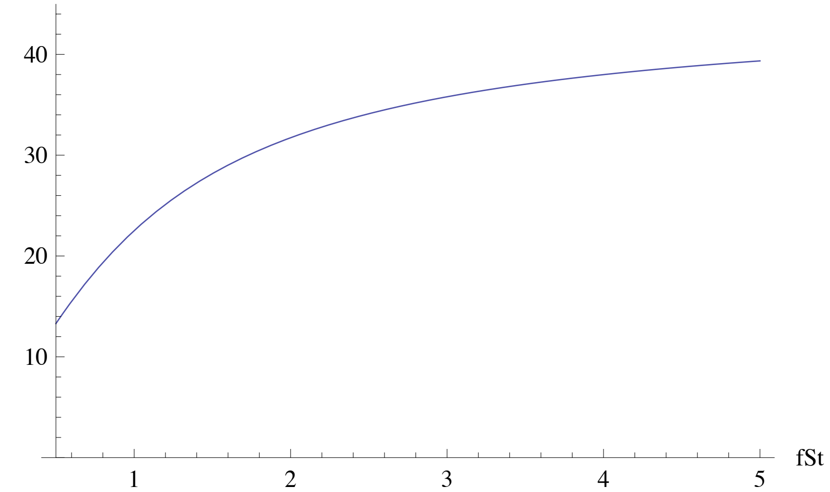
Stoponium Mixing

Applying this to the stop-H interaction term gives:

$$\Delta\mathcal{L} \supset - \left(\frac{g_H f_{\eta_{\tilde{t}}}}{2m_H}\right)\left[S^\dagger \tilde{H} + \tilde{H}^\dagger S\right]$$

As expected, the H scalar can mix with the stoponium!

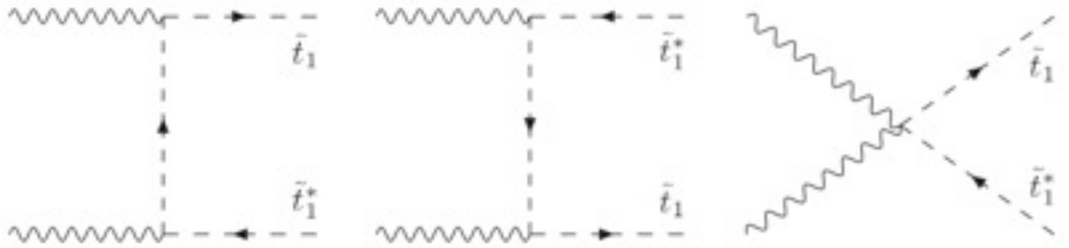




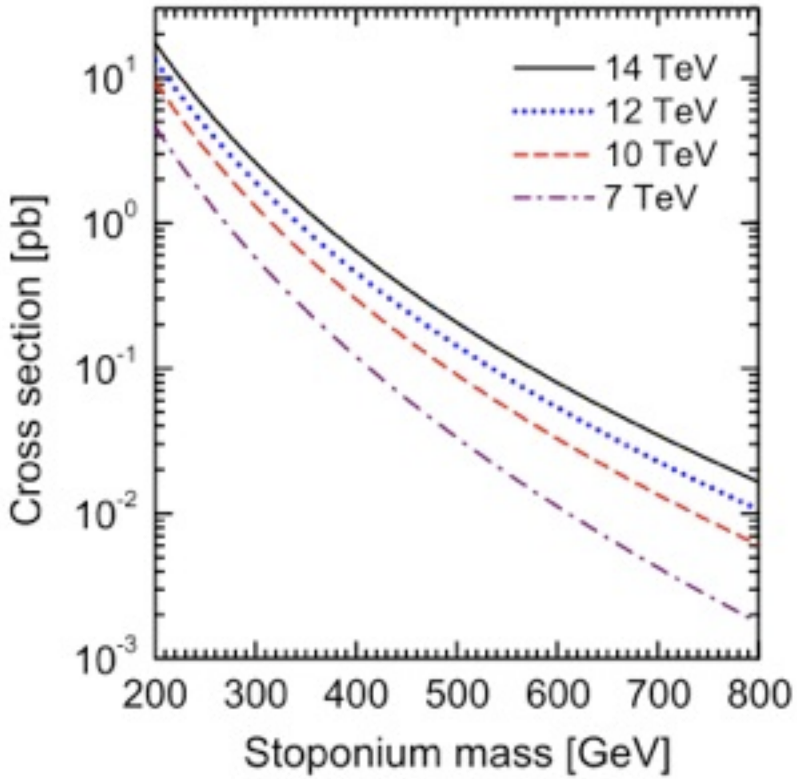
PRELIMINARY

Stoponium Production

Production occurs mostly through gluon fusion at LHC.



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



Stoponium 2-Body Decays

Decays typically go through $gg,\ \gamma\gamma,\ \gamma Z,\ WW,\ ZZ,\ b\bar{b},\ t\bar{t},\ hh$

When they can.

Typical point in parameter space:

$$\Gamma(\eta_{\tilde{t}} \to gg) = 24\ \text{MeV}$$

← Dominant channel

$$\Gamma(\eta_{\tilde{t}} \to \gamma\gamma) = 101\ \text{keV}$$
$$\Gamma(\eta_{\tilde{t}} \to \gamma Z) = 35.6\ \text{keV}$$

NO LSP!!!

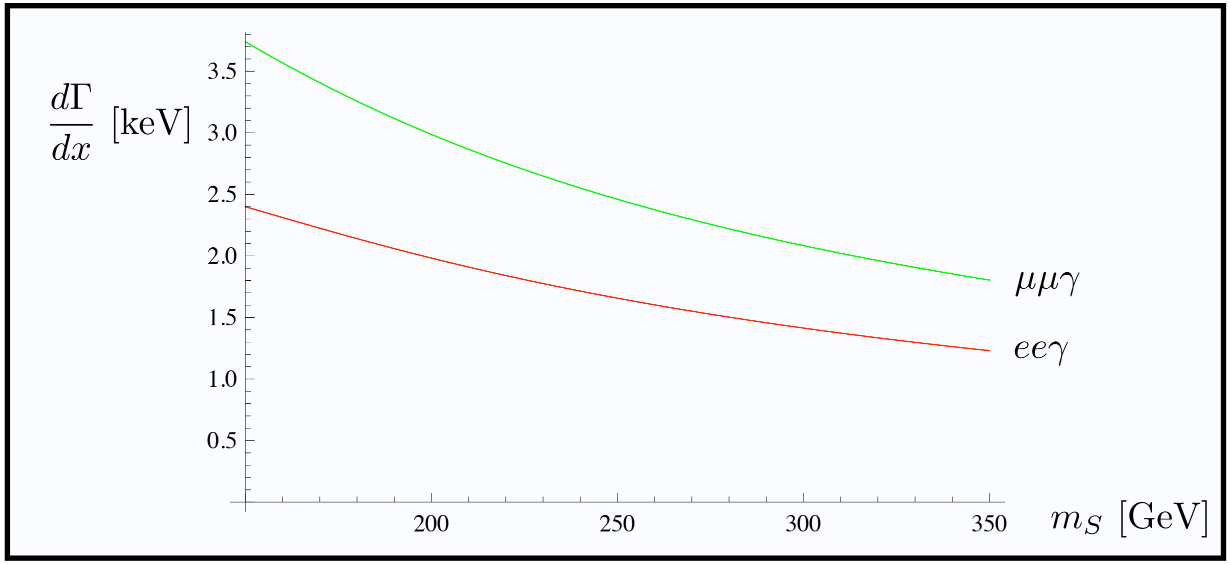
- Bosonic 2 body decays dominate, but have poor detector efficiencies.
- Leptonic 2 body decays are clean, but mass suppressed and very small.
- Three-body lepton decays are not mass suppressed (although there is still gauge coupling suppression).

Stoponium 3-Body Decays

$$\frac{d\Gamma}{dx} = \frac{Q_{\tilde{t}}^2 \alpha^3}{\pi} \left(\frac{2\pi f_S^2}{m_S} \right) \left(\frac{1-x}{x} \right) \left[\left| Q_{\tilde{t}} + B(x) c_V \right|^2 + |B(x)|^2 c_A^2 \right]$$

where $B(x) = \frac{Q_Z^{11}}{c_W^2 s_W^2} \frac{x}{x - x_Z + i\gamma_Z \sqrt{x_Z}}$ and x is the dilepton mass squared in units of m_S^2.

Thus: if stoponium mixes with the Higgs, it could enhance the three body lepton channels (which are still mass suppressed in Higgs decays).



Discussion

- NRSET is nontrivial, especially with real scalar fields that have no antiparticles.
- Formalism can be used to study scalars produced at LHC, including Higgs and superpartners, but also other extensions of the Standard Model.
- Stoponium can affect Higgs decaying to leptons, which are a clean signal and could help to study Higgs boson properties.

Extra Slides

Binding Potential

In addition to QCD, there are two other sources of binding potential for stops:

1. Higgs Exchange (h, H, A) - relevant for squarks related to heavy fermions.
2. Contact Interactions - coming from scalar potential.

Higgs Generates a Yukawa interaction of the form: $V_\phi(r) = \frac{g_\phi^2}{4\pi}\frac{e^{-m_\phi r}}{r}$

It is known that Yukawa potentials will only admit a bound state if:

$$\left(\frac{m_{\tilde{t}_1}}{m_\phi}\right)\frac{g_\phi^2}{4\pi} \geq 2.7$$

For light stoponium, none of the Higgs Yukawa potentials allow a bound state. We therefore treat these effects as perturbations on top of QCD.

Contact terms are mass suppressed, but could be relevant in general:

$$V_c(r) = \mathcal{A}\,\delta^{(3)}(\mathbf{r}), \qquad \mathcal{A} = \frac{1}{4m_{\tilde{t}}^2}\left[\frac{1}{6}g_s^2 + y_t^2 \sin^2\theta\cos^2\theta\right] + \cdots$$