ASSOCIATED PRODUCTION OF Higgs WITH SQUARKS ($\tilde{t}$) at future e^+e^- colliders

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MOTIVATIONS / SUMMARY :

<u>SM</u> Higgs production in association with $t\bar{t}$ [in pp or e^+e^-]:

+ . . .

Djouadi, Kalinowski, Zerwas '92
Dittmaier et al '98
Dawson, Reina '98

NOT dominant % $e^+e^- \to Z \to Zh$, $WW \to h$;

BUT further background reduction possibilities
(lepton tagging $t \to Wb$
$\hookrightarrow \ell\nu$)

•• MSSM "analogous": associated (lighter) h_0 production:

+ etc

(NB: Simplified picture in "decoupling" regime: $m_{h_0} \ll M_{H_0} \simeq M_A \simeq M_{H^\pm}$)

MAYBE A PRIORI COMPETITIVE (DOMINANT?)
especially for large (maximal?) $\tilde{\theta}_t$ mixing scenario

$$\begin{pmatrix} M_{Q_L}^2 + D + m_t^2 & m_t(A_t - \mu/\tan\beta) \\ m_t(A_t - \mu/\tan\beta) & M_{t_R}^2 + \bar{D} + m_t^2 \end{pmatrix} \to m_{\tilde{t}_1}^2 \ll m_{\tilde{t}_2}^2, \quad m_{\tilde{t}_1} \lesssim m_t \quad \Big| \text{ for } \tilde{\theta}_t \text{ "max" } |\tilde{\theta}_t| \simeq \frac{\pi}{4}$$

→ obvious phase space enhancement of $\sigma(\tilde{t}\tilde{t}h)$;
but also because $g_{\tilde{t}_1\tilde{t}_1 h_0} \uparrow$ for $\underbrace{(A_t - \mu/\tan\beta)}_{\equiv \tilde{A}_t}$ large enough

→ pp study quite promising (Djouadi, Moultaka, JLK PRL80(1998) hep-ph/9711244)

WHAT ABOUT e^+e^- ?

$\phi\phi, \phi\phi\phi, \phi\phi\phi\phi$ F, D terms + SOFT-BREAKING TERMS

$$\rightarrow M^2_{\tilde{t}} = \begin{pmatrix} M^2_{Q_L} + m_t^2 + (\frac{1}{2} - \frac{2}{3}s_W^2) m_Z^2 \cos 2\beta & m_t(A_t - \mu/\tan\beta) \\ m_t(A_t - \mu/\tan\beta) & M^2_{t_R} + m_t^2 + \frac{2}{3}s_W^2 m_Z^2 \cos 2\beta \end{pmatrix}$$

$$\rightarrow m^2_{\tilde{t}_1, \tilde{t}_2} = m_t^2 + \frac{1}{2}\left[M^2_{Q_L} + M^2_{t_R} + \frac{m_Z^2}{2}\cos 2\beta \mp \sqrt{\left(M^2_{Q_L} - M^2_{t_R} + (\tfrac{1}{2} - \tfrac{4}{3}s_W^2) m_Z^2 \cos 2\beta\right)^2 + 4m_t^2 (A_t - \mu/\tan\beta)^2}\right]$$

$$\tilde{\theta}_t \equiv \frac{1}{2} \mathrm{Atan}\left[\frac{2m_t(A_t - \mu/\tan\beta)}{(M^2_{Q_L} - M^2_{t_R}) + D..}\right] \qquad \left(\tan\beta = \frac{v_u}{v_d}\right)$$

and physical $h\tilde{t}_1\tilde{t}_1$, etc couplings obtained from

$$\begin{pmatrix}\tilde{t}_L \\ \tilde{t}_R\end{pmatrix} = \begin{pmatrix}\cos\tilde{\theta}_t & -\sin\tilde{\theta}_t \\ \sin\tilde{\theta}_t & \cos\tilde{\theta}_t\end{pmatrix}\begin{pmatrix}\tilde{t}_1 \\ \tilde{t}_2\end{pmatrix} \quad ; \quad \begin{pmatrix}H_d \\ H_u\end{pmatrix} \equiv \begin{pmatrix}\cos\alpha & -\sin\alpha \\ \sin\alpha & \cos\alpha\end{pmatrix}\begin{pmatrix}H \\ h\end{pmatrix}$$

$\rightarrow$

$$g_{\tilde{t}_1\tilde{t}_1 h} = -\sin(\alpha+\beta)\left[\frac{\cos^2\tilde{\theta}_t}{2} - \tfrac{2}{3}s_W^2\cos(2\tilde{\theta}_t)\right] + \frac{m_t^2}{m_Z^2}\frac{\cos\alpha}{\sin\beta} + \frac{\sin(2\tilde{\theta}_t)}{2}\frac{m_t}{m_Z^2}\left(A_t\frac{c_\alpha}{s_\beta} + \mu\frac{s_\alpha}{s_\beta}\right)$$

$$g_{\tilde{t}_1\tilde{t}_2 h} = -\sin(\alpha+\beta)\left[\sin(2\tilde{\theta})\left(\tfrac{2}{3}s_W^2 - \tfrac{1}{4}\right)\right] + \frac{\cos(2\tilde{\theta}_t)}{2}\frac{m_t}{m_Z^2}\left(A_t\frac{c_\alpha}{s_\beta} + \mu\frac{s_\alpha}{s_\beta}\right)$$

$\times\left(\frac{M_W}{c_W} \cdot g\right)$

– Decoupling regime: $m_h << M_H \simeq M_A \simeq M_{H^\pm} \rightarrow \alpha \rightarrow \beta - \frac{\pi}{2}$

$$\text{So } g_{\tilde{t}_1\tilde{t}_1 h} \sim \frac{\cos 2\beta}{2}\left[\cos^2\tilde{\theta}_t - \tfrac{4}{3}s_W^2\cos(2\tilde{\theta}_t)\right] + \frac{m_t^2}{m_Z^2} + \frac{m_t}{m_Z^2}\frac{\sin(2\tilde{\theta}_t)}{2}(A_t - \mu/\tan\beta)$$

originally $\tilde{t}_L\tilde{t}_R H = c_{\tilde{\theta}}s_{\tilde{\theta}}\,\tilde{t}_1\tilde{t}_1 H + ..$

Now: "large" $\tilde{A}_t (\equiv A_t - \mu/\tan\beta)$ limit?

clearly, $m_{\tilde{t}_1} \searrow$ while $g_{\tilde{t}_1\tilde{t}_1 h} \sim \sin(2\tilde{\theta}_t)\tilde{A}_t \sim \tilde{A}_t$

$\hookrightarrow \frac{\pi}{4}$ linear growth!

$(g_{\tilde{t}_1\tilde{t}_2} \sim \cos(2\tilde{\theta}_t)\tilde{A}_t)$

MAINLY: $e^+e^-\,(\gamma\gamma) \rightarrow \tilde{t}_1\tilde{t}_1 h$

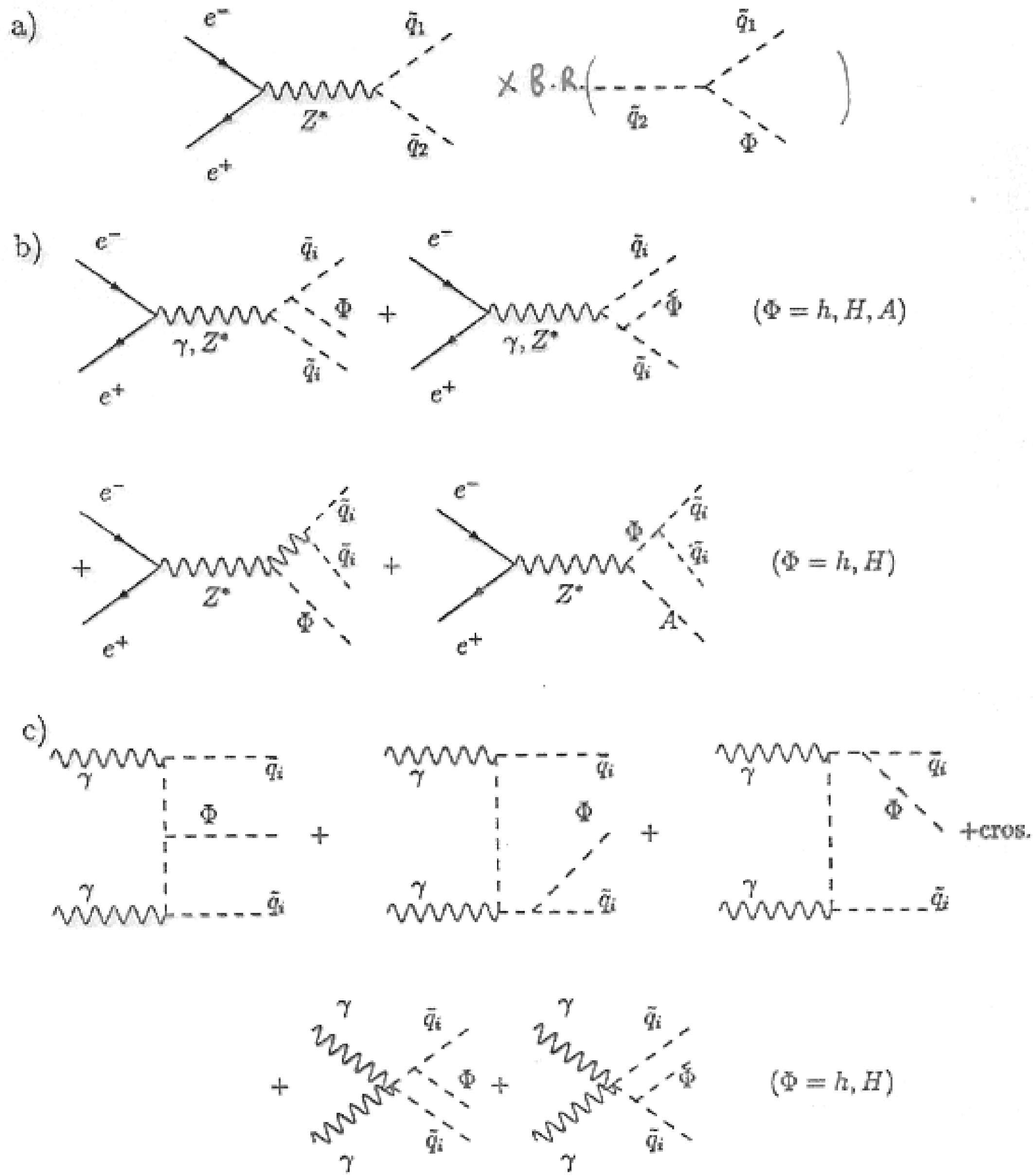

Figure 1: Feynman diagrams for the production of a Higgs boson Φ in association with a pair of squarks in e^+e^- and $\gamma\gamma$ collisions.

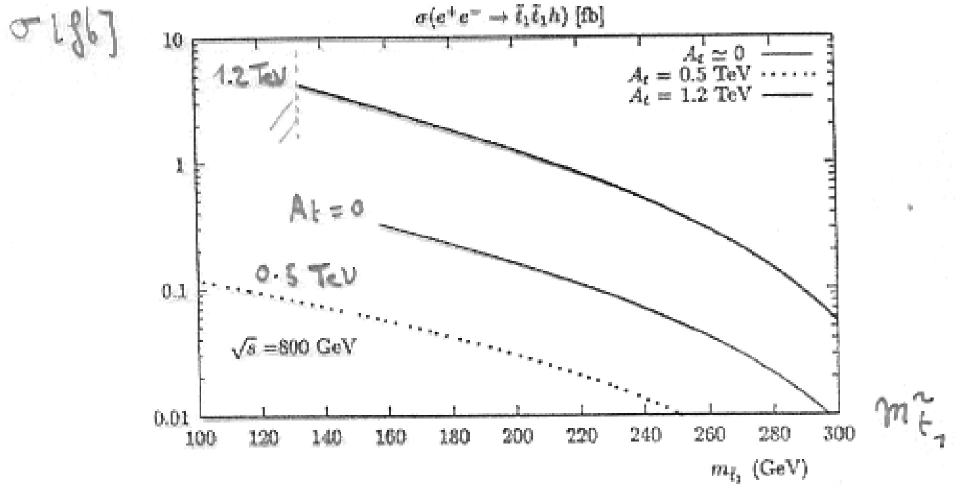

Figure 3: The cross section $\sigma(e^+e^- \to \tilde{t}_1\tilde{t}_1 h)$ [in fb] as a function of the $\tilde{t}_1$ mass and three different choices of the other parameters: $\tan\beta = 30$, $A_t = 0$ (0.5) TeV; $\tan\beta = 3$, $A_t =$ 1.2 TeV.

HOWEVER, TH. + EXP. CONSTRAINTS on large A_t :

1) Charge & Color non-breaking constraint(s) :

$$A_t^2 < 3\,(m^2_{Q_L} + m^2_{t_R} + \mu^2 + m^2_{\bar{E}v}) \quad \text{(at EWSB scale)}$$

2) The (in)famous most "new physics killer" :

$\Delta\rho = \varepsilon_1 \simeq$  $-$  [mainly; + also other oblique corrections]

measuring SU(2) "custodial" breaking

MS: large $(m_t^2 - m_b^2) \times G_F$ contribution

MSSM: additional SU(2)-breaking sources!

- $\tilde{m}_{t_L}, \tilde{m}_{t_R} \neq \tilde{m}_{b_R}$
- $m_t \tilde{A}_t \neq m_b \tilde{A}_b$

$$\Delta\rho^{(\tilde{t},\tilde{b})}_{MSSM} \simeq \frac{3\,G_F}{8\pi^2\sqrt{2}} \Big[c^2_{\tilde{\theta}_t} \big(c^2_{\tilde{\theta}_b} |m^2_{\tilde{t}_1} - m^2_{\tilde{b}_1}| + s^2_{\tilde{\theta}_b} |m^2_{\tilde{t}_1} - m^2_{\tilde{b}_2}| \big)$$
$$+ s^2_{\tilde{\theta}_t} \big(c^2_{\tilde{\theta}_b} |m^2_{\tilde{t}_2} - m^2_{\tilde{b}_1}| + s^2_{\tilde{\theta}_b} |m^2_{\tilde{t}_2} - m^2_{\tilde{b}_2}| \big)$$
$$- \underbrace{c^2_{\tilde{\theta}_t} s^2_{\tilde{\theta}_t}}_{\propto \sin^2(2\theta)} |m^2_{\tilde{t}_1} - m^2_{\tilde{t}_2}| - c^2_{\tilde{\theta}_b} s^2_{\tilde{\theta}_b} |m^2_{\tilde{b}_1} - m^2_{\tilde{b}_2}| \Big]$$

Barbieri, Maiani '83

Drees Hagiwara '90

$\delta(\Delta\rho) \gtrsim 2\text{-}3 \cdot 10^{-3}$ (1-2 σ) e.g. Altarelli's reviews '97 '98

3) + direct limits:

$m_h \gtrsim 90$ GeV (decoupling regime) (LEP2)

$m_{\tilde{t}_1} \gtrsim 80 - 120$ GeV (LEP2, CDF)

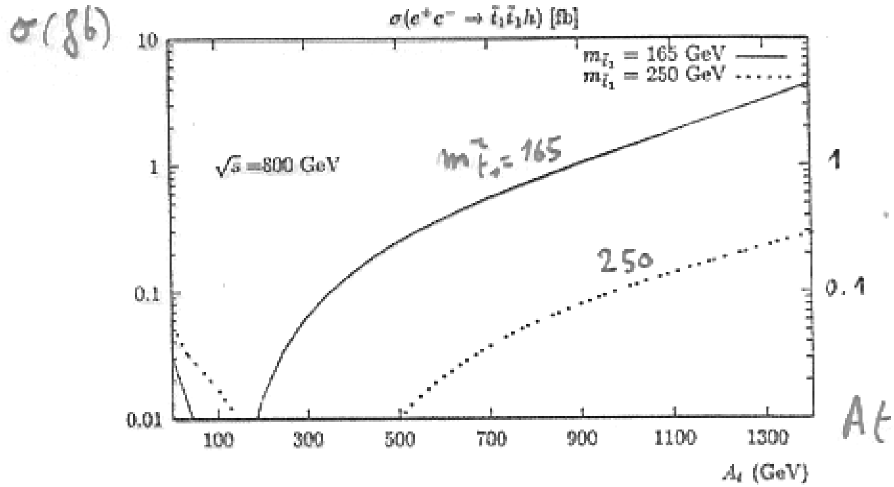

Figure 4: The cross section $\sigma(e^+e^- \to \tilde{t}_1\tilde{t}_1 h)$ [in fb] as a function of A_t for fixed $m_{\tilde{t}_1} = 165$ ($\tan\beta = 3$); and 250 GeV ($\tan\beta = 30$).

NB : to compare, $\sigma(t\bar{t}h)|_{SM} \simeq 2$ fb ($M_h \simeq 130$ GeV)

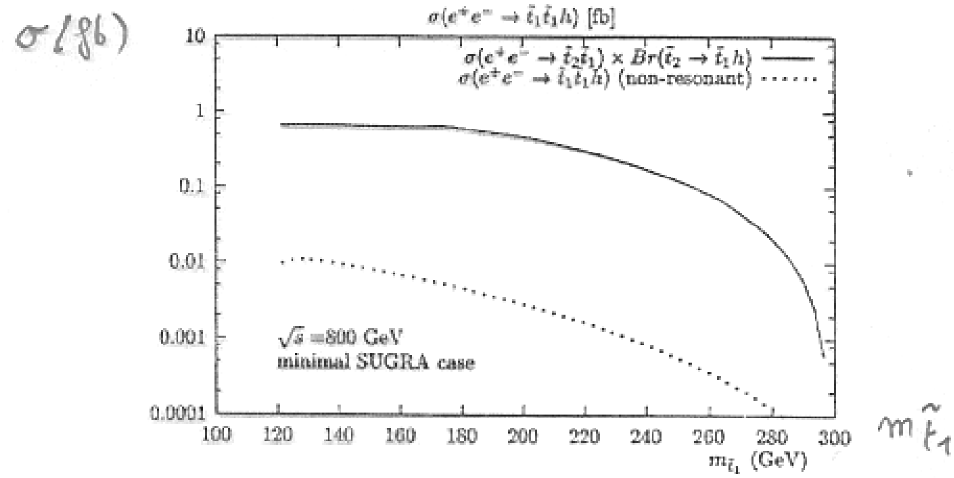

Figure 2: The production cross section $\sigma(e^+e^- \to \tilde{t}_1\tilde{t}_1 h)$ [in fb] as a function of $m_{\tilde{t}_1}$ in the mSUGRA case; $\tan\beta = 30$, $m_{1/2} = 100$ GeV and $A_0 = -600$ GeV.

(i.e. moderate mixing case)

NB : $Z\tilde{t}_1\tilde{t}_2 \sim \sin(2\tilde{\theta}_t)$

$\tilde{t}_2\tilde{t}_1 h \simeq \cos 2\beta\left(\frac{2}{3}s_W^2 - \frac{1}{4}\right)\sin(2\theta) + \frac{m_t}{2m_Z^2}\tilde{A}_t\cos(2\tilde{\theta}_t)$

can't be too large in most of the parameter space

$\Rightarrow \sigma^{\text{resonant}} \simeq \sin 2\tilde{\theta}_t \cos 2\tilde{\theta}_t$

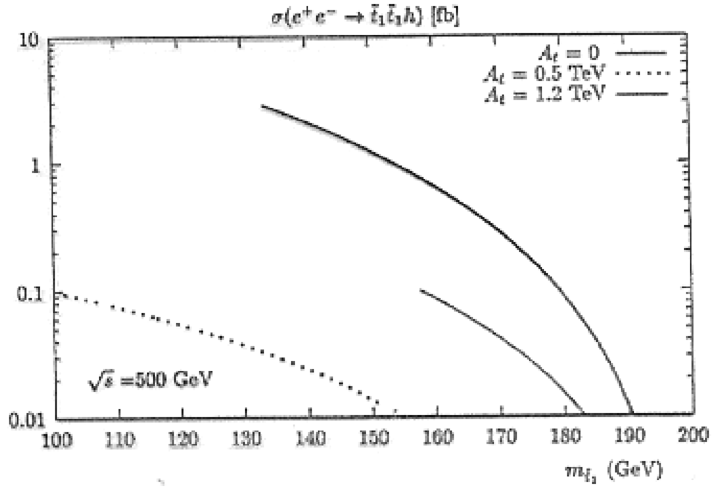

Figure 5: Same as Fig. 8 but with $\sqrt{s} = 500$ GeV.

γγ mode

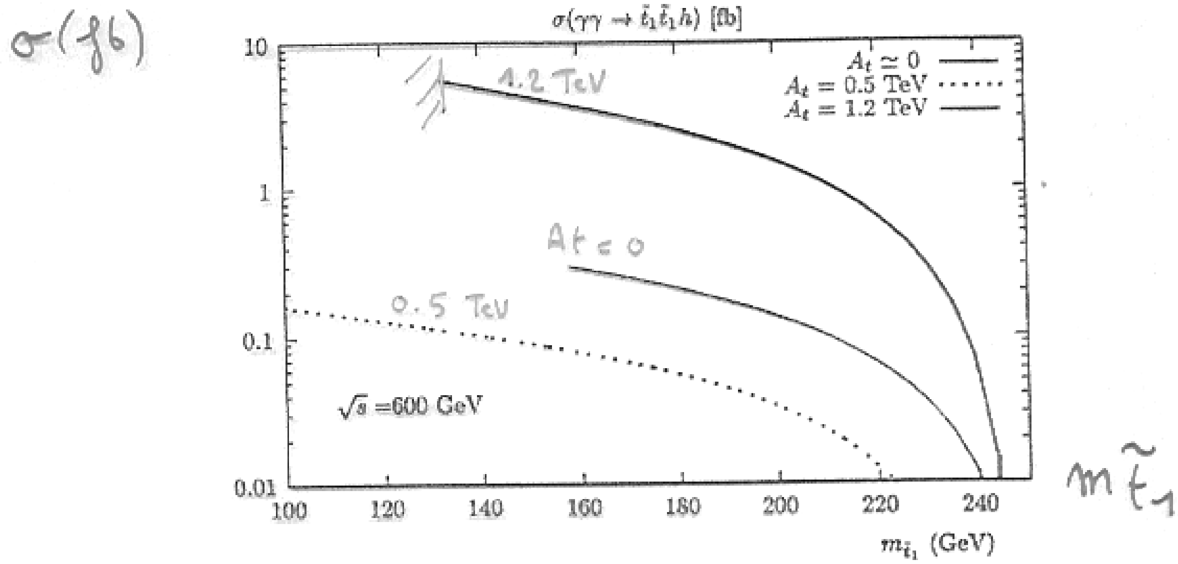

Figure 6: The cross section $\sigma(\gamma\gamma \to \tilde{t}_1\tilde{t}_1 h)$ in $\gamma\gamma$ collisions [in fb] at a center of mass energy $\sqrt{s_{\gamma\gamma}} = 600$ GeV as a function of $m_{\tilde{t}_1}$. The other parameters have the same values as in Fig. 10.

Decay properties - Possible detection modes

1 - $\tilde{t}_1 \to b\chi^+$ (if $\tilde{m}_{t_1} < m_t + m_{\chi_0}$)

2 - $\tilde{t}_1 \to t\chi_0^1$ (LSP) otherwise

(also $\underset{(1\text{-loop})}{\tilde{t}_1 \to c\chi_0}$ may compete if $m_{\tilde{t}_1} - m_{\chi_1^+} \simeq 0$.

$\Rightarrow$ $\tilde{t}_1 \to b\chi^+$ dominates where $\sigma_{\tilde{t}_1\tilde{t}_1h}$ is large

$\hookrightarrow \chi^0 W^+$

$\hookrightarrow e\nu$

$\tilde{t}_1 \to bW^+ + \not{E}$

Same topology as $t \to bW^+$

BUT $\pm$ large amount of $\not{E}$

• $h \to b\bar{b}$ dominant decay

$\to 4b + 2W$ final state $+ \not{E}$

if efficient microvertex detectors (b tagging)

should be relatively easy in clean e^+e^- environment

CONCLUSIONS

- new h production process

$\sigma(e^+e^-, \gamma\gamma \to \tilde{q}_i \tilde{q}_i \Phi)$ general expressions available
(rather simple analytical formulae)

- at e^+e^- LC, $\sqrt{s} = 500 - 800$ GeV

with $\int \mathcal{L}\, dt \sim 100 - 500\ fb^{-1}$

several hundred of events possible if $m_{\tilde{t}_1} < 250$ GeV
and A_t large enough

- Rather spectacular and clean signal

$4b\text{'s} + 2W\text{'s} + \not{E}$

- Also more th. motivations:

a possible handle to probe
the mysterious SOFT-SUSY-BREAKING sector
(if A_t large, $\tilde{t}\tilde{t}h$ potentially largest MSSM coupling!)