Phenomenology of the Righted Strange-Bottom Squark

LCWS 2004

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Outline

- Motivation from the Belle $B \to \phi K_S$ discrepancy
- Near-maximal mixing in the $2-3$ sector RH squarks
- Production of strange-beauty squark at hadronic Colliders
- Decay and detection at the Tevatron
- Prospect for the e^+e^- linear colliders

Motivations: $S_{\phi K_S}$ Sign Anomaly

- World average: $\sin(2\beta) = 0.734 \pm 0.055$, using $B \to J/\psi K_S$
- 2003 using $B \to \phi K_S$,

$$\text{Belle}: \ \sin(2\beta) = -0.96 \pm 0.50 \ ^{+0.09}_{-0.11}$$

$$\text{BaBar}: \ \sin(2\beta) = 0.45 \pm 0.43 \pm 0.07$$

both data are in 2.1σ disagreement

Average: $S_{\phi K_S} = -0.15 \pm 0.33$ still 2.7σ from world average

- Call for new physics in $b \to s$ CPV effect
  - Large $b - s$ mixing
  - New CPV phase
  - Right-handed interaction

Abelian flavor symmetry ⊕ SUSY

- Abelian flavor symmetry gives strong RH $s - b$ mixing (Nir-Seiberg PLB'93, Leurer-Nir-Seiberg NPB'94)

$$\hat{M}_u = \frac{M_u}{m_t} \sim \begin{bmatrix} \lambda^7 & \lambda^5 & \lambda^3 \\ \lambda^6 & \lambda^4 & \lambda^2 \\ \lambda^4 & \lambda^2 & 1 \end{bmatrix}, \quad \hat{M}_d = \frac{M_d}{m_b} \sim \begin{bmatrix} \lambda^4 & \lambda^3 & \lambda^3 \\ \lambda^3 & \lambda^2 & \lambda^2 \\ \lambda & 1 & 1 \end{bmatrix}$$

Ansatz: $M_{ij} M_{ji} \approx M_{ii} M_{jj}$

Focus on $s - b$ sector only.

Bring in the $2-3$ squark sector

Assume a heavy soft SUSY scale $\tilde{m} \sim$ TeV

AFS not far above the SUSY scale.

- $(\widetilde{M}_d^2)_{LL}$ is constrained by CKM
- $(\widetilde{M}_d^2)_{LR} \sim m_q$ suppressed by small m_q
- Only the $(\widetilde{M}_d^2)_{RR}$ has the freedom to allow maximal $2-3$ sector mixing:

$$\left(\widetilde{M}_d^2\right)_{RR} \sim \tilde{m} \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 1 \\ 0 & 1 & 1 \end{bmatrix}$$

Near-Maximal 2-3 Squark Mixing

The mass matrix is given by

$$\mathcal{L} = -(\tilde{s}_R^* \; \tilde{b}_R^*) \begin{pmatrix} \widetilde{m}_{22}^2 & \widetilde{m}_{23}^2 e^{-i\sigma} \\ \widetilde{m}_{23}^2 e^{i\sigma} & \widetilde{m}_{33}^2 \end{pmatrix} \begin{pmatrix} \tilde{s}_R \\ \tilde{b}_R \end{pmatrix} .$$

Diagonalized by a rotation

$$\begin{pmatrix} \tilde{s}_R \\ \tilde{b}_R \end{pmatrix} = R \begin{pmatrix} \widetilde{sb}_1 \\ \widetilde{sb}_2 \end{pmatrix} = \begin{pmatrix} \cos\theta_m & \sin\theta_m \\ -\sin\theta_m e^{i\sigma} & \cos\theta_m e^{i\sigma} \end{pmatrix} \begin{pmatrix} \widetilde{sb}_1 \\ \widetilde{sb}_2 \end{pmatrix} ,$$

Then

$$\mathcal{L} = -(\widetilde{sb}_1^* \; \widetilde{sb}_2^*) \begin{pmatrix} \widetilde{m}_1^2 & 0 \\ 0 & \widetilde{m}_2^2 \end{pmatrix} \begin{pmatrix} \widetilde{sb}_1 \\ \widetilde{sb}_2 \end{pmatrix} .$$

$\widetilde{m}_1$ can be small due to a strong cancellation.

The scenario

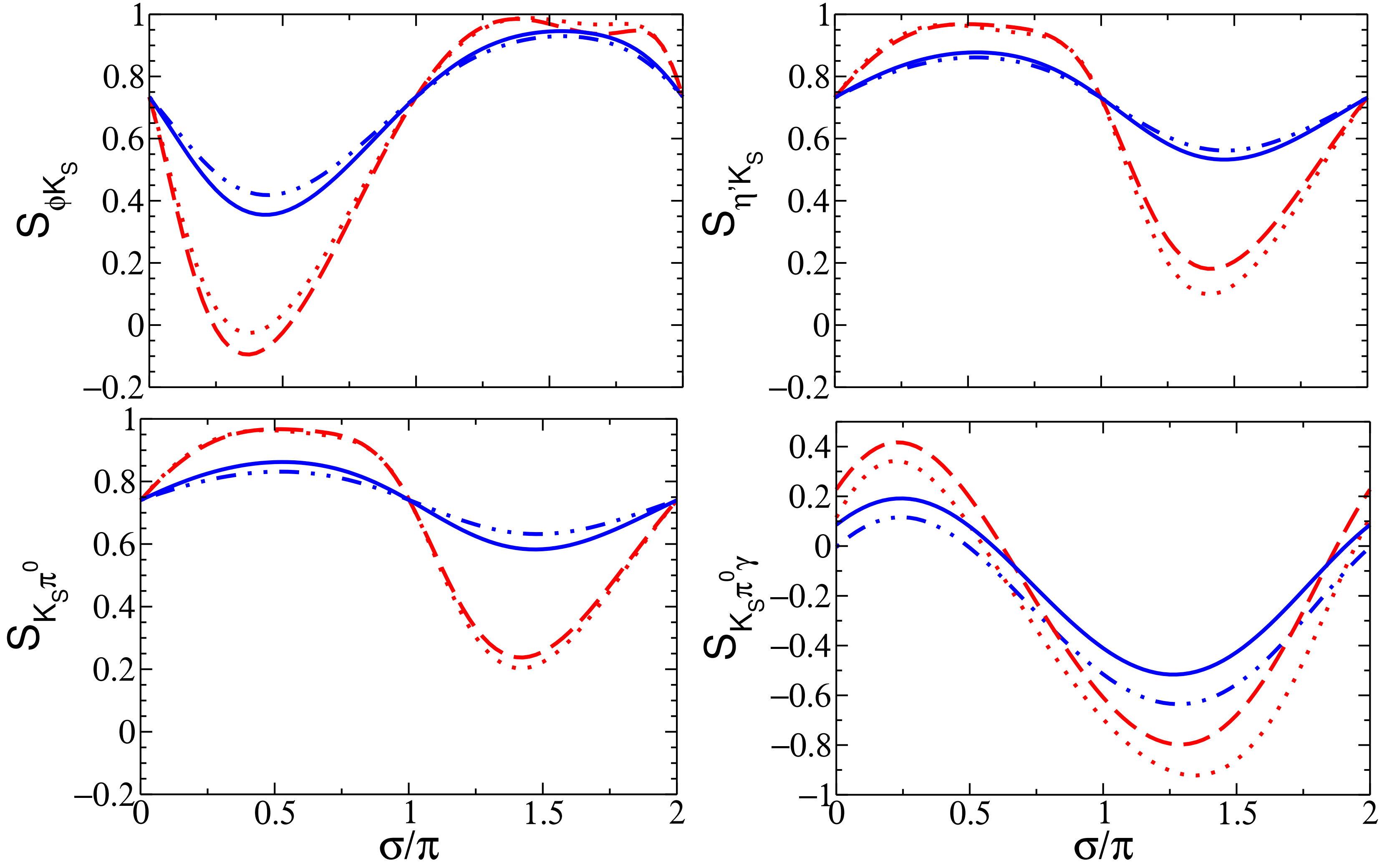
- Soft SUSY scale $\sim$ TeV
- A RH strange-beauty squark as light as 200 GeV
- Also need a relatively light gluino ~ 500 GeV, that goes together in the gluino-squark loop.

$$m_{\widetilde{sb}_1} \sim 200 \text{ GeV}, \quad m_{\tilde{g}} \sim 500 \text{ GeV}$$

- Can account for $S_{\phi K_S}$, but not affect the others.
- This $\widetilde{sb}_1$ can be produced directly at the Tevatron, LHC, and LC.

$S_{\phi K_S}$, $S_{\eta' K_S}$, $S_{K_S \pi^0}$, $S_{K_S \pi^0 \gamma}$

(Chua-Hou-Nagashima PRL'04)



Interactions

Gluino-squark-quark:

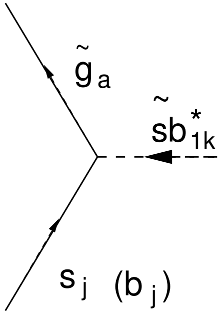
$$\mathcal{L} = -\sqrt{2} g_s T^a_{kj} \Big[-\overline{\tilde{g}_a} P_R s_j \widetilde{sb}^*_{1k} \cos\theta_m + \overline{\tilde{g}_a} P_R b_j \widetilde{sb}^*_{1k} \sin\theta_m e^{-i\sigma}$$

$$-\overline{\tilde{g}_a} P_R s_j \widetilde{sb}^*_{2k} \sin\theta_m - \overline{\tilde{g}_a} P_R b_j \widetilde{sb}^*_{2k} \cos\theta_m e^{-i\sigma} + \text{h.c.} \Big] \, .$$

Squark-squark-gluon:

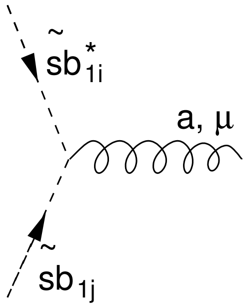
$$\mathcal{L} = -i g_s A^a_\mu T^a_{ij} \left(\widetilde{sb}^*_{1i} \overleftrightarrow{\partial}_\mu \widetilde{sb}_{1j} + \widetilde{sb}^*_{2i} \overleftrightarrow{\partial}_\mu \widetilde{sb}_{2j} \right)$$

$$+ g_s^2 (T^a T^b)_{ij} A^{a\mu} A^b_\mu \left(\widetilde{sb}^*_{1i} \widetilde{sb}_{1j} + \widetilde{sb}^*_{2i} \widetilde{sb}_{2j} \right)$$

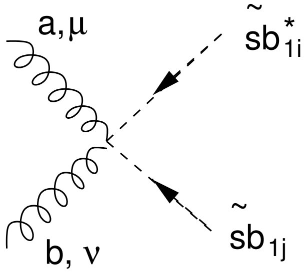


$$i\sqrt{2}\, g_s T^a_{kj} \cos\theta_m \frac{1+\gamma_5}{2}$$

$$\left(-i\sqrt{2}\, g_s T^a_{kj} \sin\theta_m e^{-i\sigma} \frac{1+\gamma_5}{2} \right)$$



$$-i\, g_s T^a_{ij} \,(p - p_*)_\mu$$



$$i\, g_s^2 \left(\frac{1}{3}\, \delta_{ab} 1_{ij} + d_{abc} T^c_{ij} \right) g_{\mu\nu}$$

Squark, gluino, gluon interactions

Hadronic Production

Possible Channels:

1) $q\bar{q}$ and gg fusion

$$q\bar{q},\ gg \to \widetilde{sb}_1\, \widetilde{sb}_1^*$$

If $s\bar{s}$ or $b\bar{b}$ in the initial state, there is an additional contribution from the t-channel gluino exchange diagram.

$b\bar{s} \to \widetilde{sb}_1\, \widetilde{sb}_1^*$ via t-channel gluino exchange only.

2) $ss, bb, \bar{s}\bar{s}, \bar{b}\bar{b}, sb, \bar{s}\bar{b}$ initial state scattering via t- and u-channel gluino exchange diagrams

$$ss,\ sb,\ bb \to \widetilde{sb}_1\, \widetilde{sb}_1, \quad \bar{s}\bar{s},\ \bar{s}\bar{b},\ \bar{b}\bar{b} \to \widetilde{sb}_1^*\, \widetilde{sb}_1^*\,,$$

3) Feed down from gluino pair production

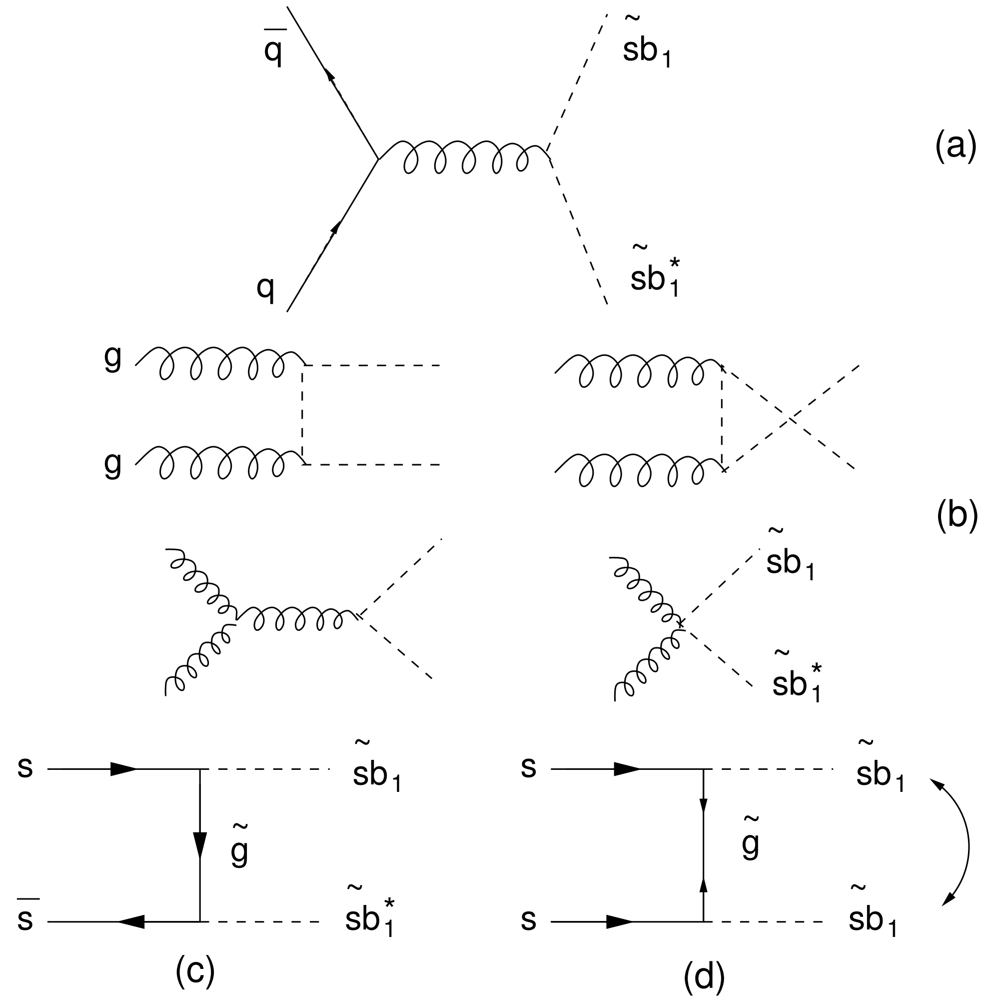
$$q\bar{q}, gg \to \tilde{g}\tilde{g}; \quad \tilde{g} \to s\widetilde{sb}_1^*,\ b\widetilde{sb}_1^*,\ \bar{s}\widetilde{sb}_1,\ \bar{b}\widetilde{sb}_1\ .$$

For $s\bar{s}$, $b\bar{b}$ in the initial states there are additional t- and u-channel diagrams.

$s\bar{b}, \bar{s}b \to \tilde{g}\tilde{g}$ through the t- and u-channel diagrams.

4) Associated production of $\widetilde{sb}_1$ with gluino

$$sg,\ bg\ \to \widetilde{sb}_1\tilde{g}$$



Squark pair production channels

Cross Section Formulas

Introduce some short-hand notation.

$$\hat{t}_{\tilde{g}} = \hat{t} - m^2_{\tilde{g}}\,, \quad \hat{u}_{\tilde{g}} = \hat{u} - m^2_{\tilde{g}}\,,$$

$$\hat{t}_{sb} = \hat{t} - m^2_{\widetilde{sb}_1}\,, \quad \hat{u}_{sb} = \hat{u} - m^2_{\widetilde{sb}_1}\,, \quad \beta_{sb} = \sqrt{1 - \frac{4m^2_{\widetilde{sb}_1}}{\hat{s}}}\,,$$

$$\beta_g = \sqrt{1 - \frac{4m^2_{\tilde{g}}}{\hat{s}}}\,, \quad \beta_{sbg} = \sqrt{\left(1 - \frac{m^2_{\tilde{g}}}{\hat{s}} - \frac{m^2_{\widetilde{sb}_1}}{\hat{s}}\right)^2 - 4\frac{m^2_{\tilde{g}}}{\hat{s}}\frac{m^2_{\widetilde{sb}_1}}{\hat{s}}}$$

Direct production of $\widetilde{sb}_1 \widetilde{sb}_1^*$:

$$\frac{d\sigma}{d\cos\theta^*}(q\bar{q} \to \widetilde{sb}_1 \widetilde{sb}_1^*) = \frac{2\pi\alpha_s^2}{9\hat{s}}\beta_{sb}\left[\frac{1}{4}(1 - \beta_{sb}^2 \cos^2\theta^*) - \frac{m^2_{\widetilde{sb}_1}}{\hat{s}}\right]\,,$$

$$\frac{d\sigma}{d\cos\theta^*}(gg \to \widetilde{sb}_1 \widetilde{sb}_1^*) = \frac{\pi\alpha_s^2}{256\hat{s}}\beta_{sb}\left(\frac{64}{3} - \frac{48\hat{u}_{sb}\hat{t}_{sb}}{\hat{s}^2}\right)\left(1 - \frac{2\hat{s}m^2_{\widetilde{sb}_1}}{\hat{u}_{sb}\hat{t}_{sb}} + \frac{2\hat{s}^2 m^4_{\widetilde{sb}_1}}{\hat{u}_{sb}^2\hat{t}_{sb}^2}\right)$$

Formulas

$$\frac{d\sigma}{d\cos\theta^*}(s\bar{s}\to \widetilde{sb}_1\widetilde{sb}_1^*) = \frac{2\pi\alpha_s^2\beta_{sb}}{9\hat{s}}\left(\frac{1}{4}(1-\beta_{sb}^2\cos^2\theta^*)-\frac{m^2_{\widetilde{sb}_1}}{\hat{s}}\right) \times \left[1-\frac{1}{3}\frac{\hat{s}}{\hat{t}_{\tilde{g}}}\cos^2\theta_m+\frac{1}{2}\frac{\hat{s}^2}{\hat{t}_{\tilde{g}}^2}\cos^4\theta_m\right]$$

For $b\bar{b}\to \widetilde{sb}_1\widetilde{sb}_1^*$, replace $\cos^2\theta_m \leftrightarrow \sin^2\theta_m$.

$$\frac{d\sigma}{d\cos\theta^*}(s\bar{b}\to \widetilde{sb}_1\widetilde{sb}_1^*) = \frac{\pi\alpha_s^2\beta_{sb}}{9}\frac{\hat{s}}{\hat{t}_{\tilde{g}}^2}\cos^2\theta_m\sin^2\theta_m\left(\frac{1}{4}(1-\beta_{sb}^2\cos^2\theta^*)-\frac{m^2_{\widetilde{sb}_1}}{\hat{s}}\right)$$

Formulas

Direct production of $\widetilde{sb}_1\widetilde{sb}_1$:

Proceed via t and u gluino diagrams

$$\frac{d\sigma}{d\cos\theta^*}(ss \to \widetilde{sb}_1\widetilde{sb}_1) = \frac{\pi\alpha_s^2\beta_{sb}}{18}\,\cos^4\theta_m\, m_{\tilde g}^2 \left[\frac{1}{\hat t_{\tilde g}^2} + \frac{1}{\hat u_{\tilde g}^2} - \frac{2}{3}\frac{1}{\hat t_{\tilde g}}\frac{1}{\hat u_{\tilde g}}\right] \,,$$

For $bb \to \widetilde{sb}_1\widetilde{sb}_1$ replace $\cos^4\theta_m \leftrightarrow \sin^4\theta_m$.

For $sb \to \widetilde{sb}_1\widetilde{sb}_1$ replace $\cos^4\theta_m \leftrightarrow \cos^2\theta_m \sin^2\theta_m$.

Formulas

Feed down from gluino-pair production

$$\frac{d\sigma}{d\cos\theta^*}(q\bar{q}\to\tilde{g}\tilde{g}) = \frac{2\pi\alpha_s^2}{3\hat{s}}\beta_g\,\frac{\hat{t}_{\tilde{g}}^2+\hat{u}_{\tilde{g}}^2+2m_{\tilde{g}}^2\hat{s}}{\hat{s}^2},$$

$$\frac{d\sigma}{d\cos\theta^*}(gg\to\tilde{g}\tilde{g}) = \frac{9\pi\alpha_s^2}{16\hat{s}}\beta_g\left(1-\frac{\hat{t}_{\tilde{g}}\hat{u}_{\tilde{g}}}{\hat{s}^2}\right)\left(\frac{\hat{s}^2}{\hat{t}_{\tilde{g}}\hat{u}_{\tilde{g}}}-2+\frac{4m_{\tilde{g}}^2\hat{s}}{\hat{t}_{\tilde{g}}\hat{u}_{\tilde{g}}}-\frac{4\hat{s}^2m_{\tilde{g}}^4}{\hat{t}_{\tilde{g}}^2\hat{u}_{\tilde{g}}^2}\right)$$

$$\begin{aligned}\frac{d\sigma}{d\cos\theta^*}(s\bar{s}\to\tilde{g}\tilde{g}) &= \frac{2\pi\alpha_s^2}{3\hat{s}}\beta_g\left\{\frac{\hat{t}_{\tilde{g}}^2+\hat{u}_{\tilde{g}}^2+2m_{\tilde{g}}^2\hat{s}}{\hat{s}^2}+\frac{2}{9}\cos^4\theta_m\left(\frac{\hat{t}_{\tilde{g}}^2}{\hat{t}_{sb}^2}+\frac{\hat{u}_{\tilde{g}}^2}{\hat{u}_{sb}^2}\right)\right.\\ &+ \left.\frac{1}{2}\cos^2\theta_m\frac{1}{\hat{s}}\left(\frac{\hat{s}m_{\tilde{g}}^2+\hat{t}_{\tilde{g}}^2}{\hat{t}_{sb}}+\frac{\hat{s}m_{\tilde{g}}^2+\hat{u}_{\tilde{g}}^2}{\hat{u}_{sb}}\right)+\frac{1}{18}\cos^4\theta_m\frac{\hat{s}m_{\tilde{g}}^2}{\hat{u}_{sb}\hat{t}_{sb}}\right\}\end{aligned}$$

$$\frac{d\sigma}{d\cos\theta^*}(s\bar{b}\to\tilde{g}\tilde{g}) = \frac{\pi\alpha_s^2}{27\hat{s}}\beta_g\;\cos^2\theta_m\sin^2\theta_m\left\{4\left(\frac{\hat{t}_{\tilde{g}}^2}{\hat{t}_{sb}^2}+\frac{\hat{u}_{\tilde{g}}^2}{\hat{u}_{sb}^2}\right)+\frac{\hat{s}m_{\tilde{g}}^2}{\hat{u}_{sb}\hat{t}_{sb}}\right\}$$

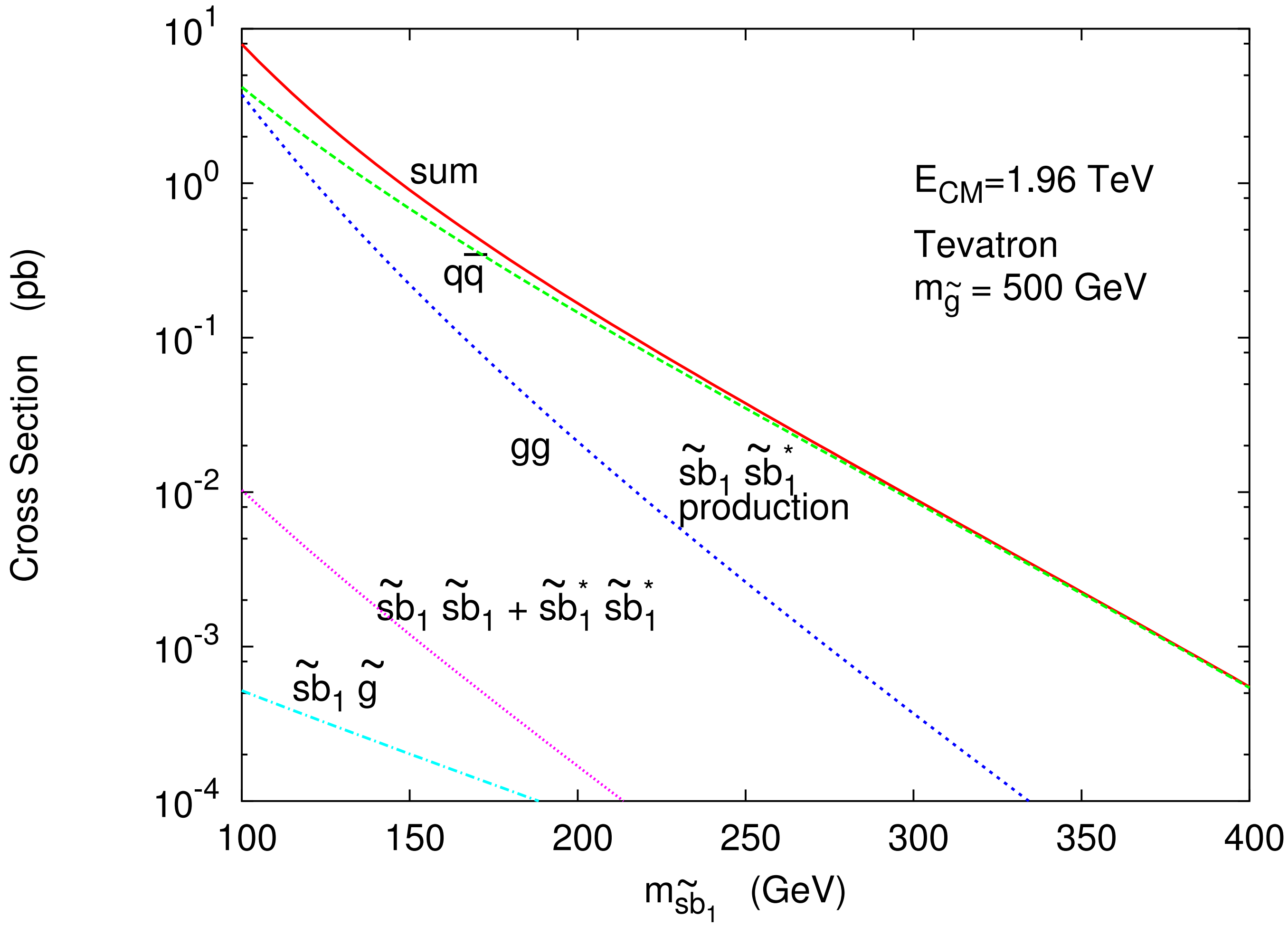
Formulas

Associated production of $\widetilde{sb}_1\tilde{g}$

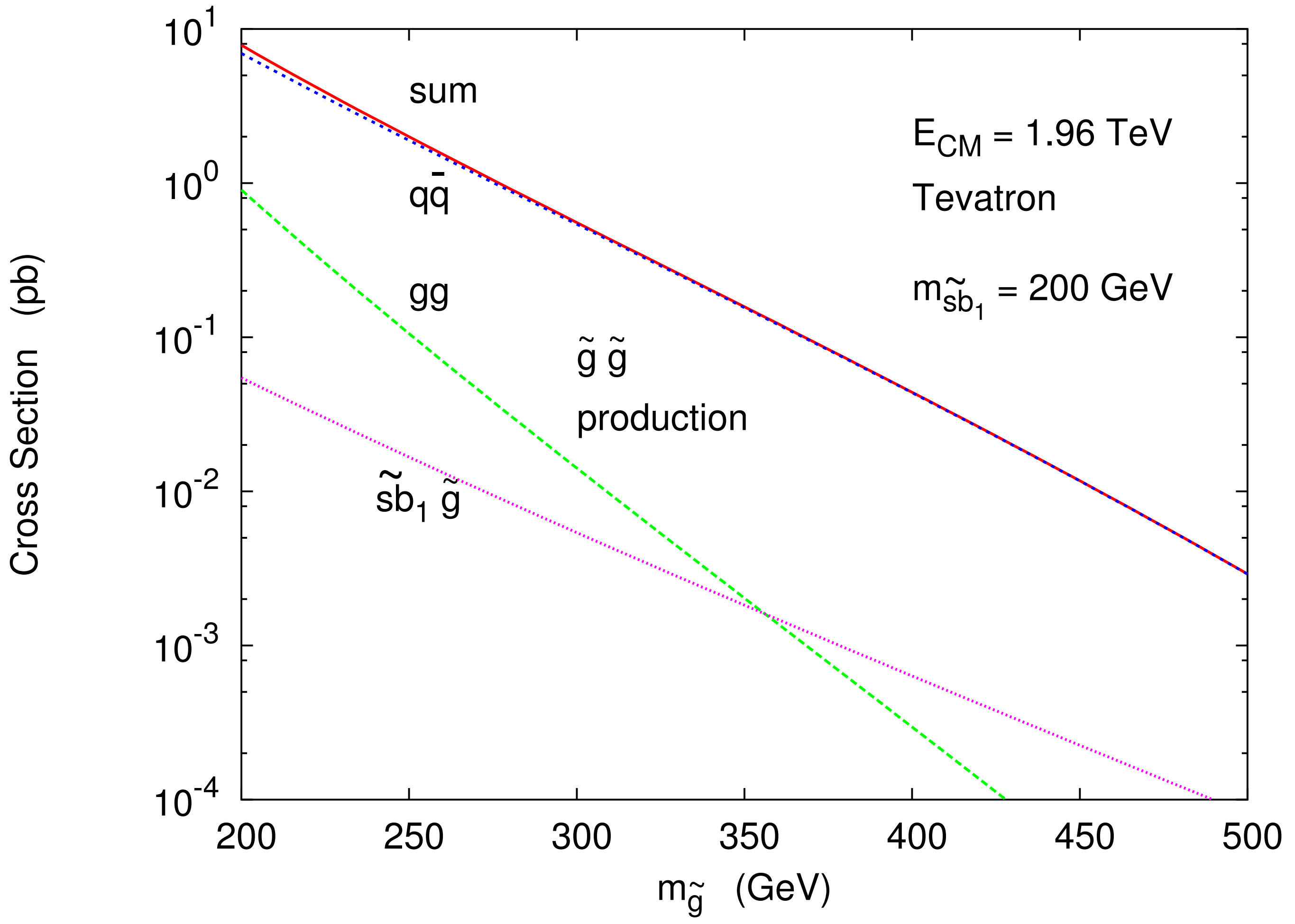
$$\frac{d\sigma}{d\cos\theta^*}(sg \to \widetilde{sb}_1\tilde{g}) = \frac{\pi\alpha_s^2}{192\hat{s}}\beta_{sbg}\cos^2\theta_m \left[24\left(1-\frac{2\hat{s}\hat{u}_{sb}}{\hat{t}_{\tilde{g}}^2}\right)-\frac{8}{3}\right] \times \left[-\frac{\hat{t}_{\tilde{g}}}{\hat{s}}+\frac{2(m_{\tilde{g}}^2-m_{\widetilde{sb}_1}^2)\hat{t}_{\tilde{g}}}{\hat{s}\hat{u}_{sb}}\left(1+\frac{m_{\widetilde{sb}_1}^2}{\hat{u}_{sb}}+\frac{m_{\tilde{g}}^2}{\hat{t}_{\tilde{g}}}\right)\right]$$

For the bg initial state, the above formula is modified by changing $\cos^2\theta_m \leftrightarrow \sin^2\theta_m$.

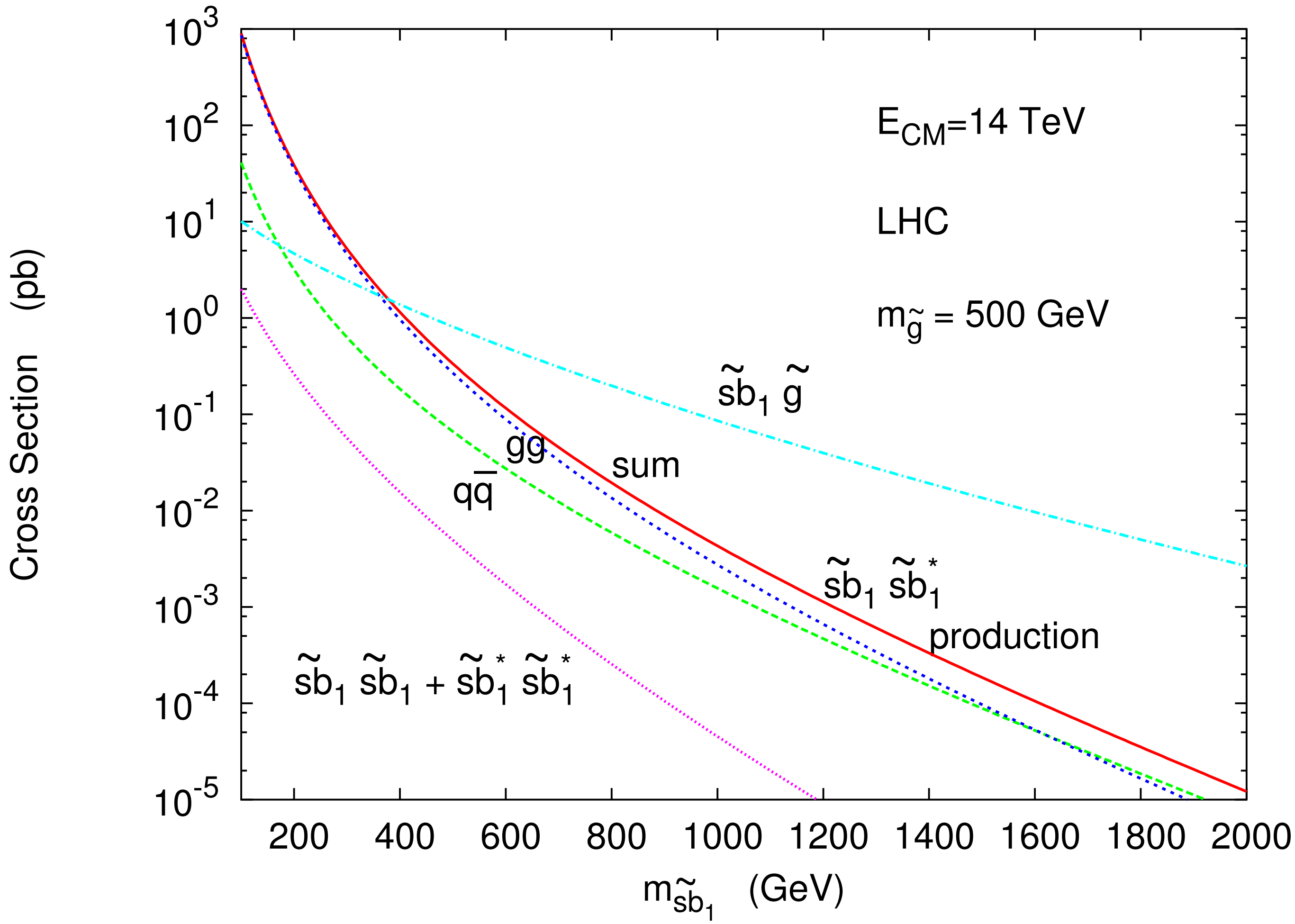
Squark pair cross section at the Tevatron



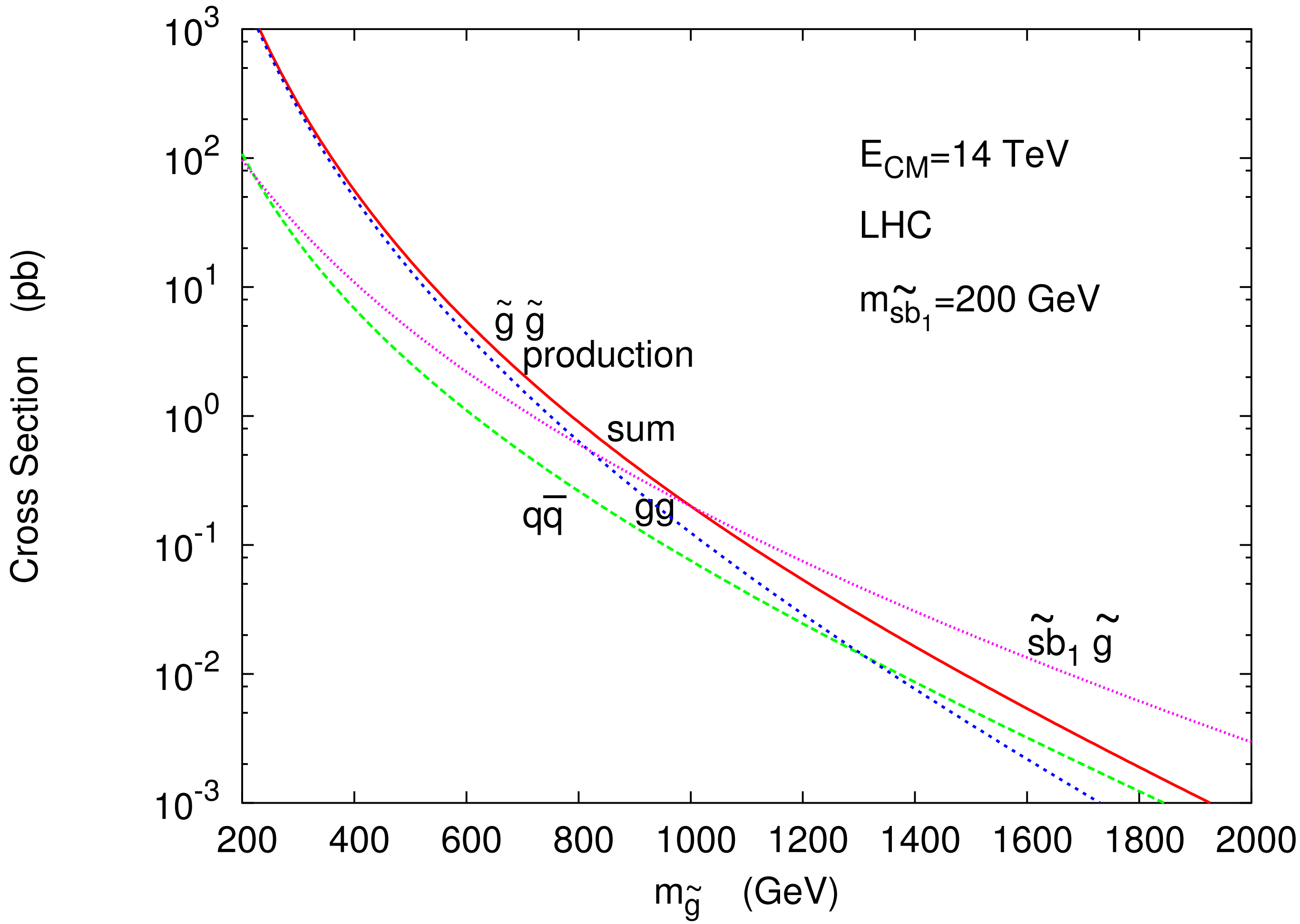
Gluino pair cross section at the Tevatron



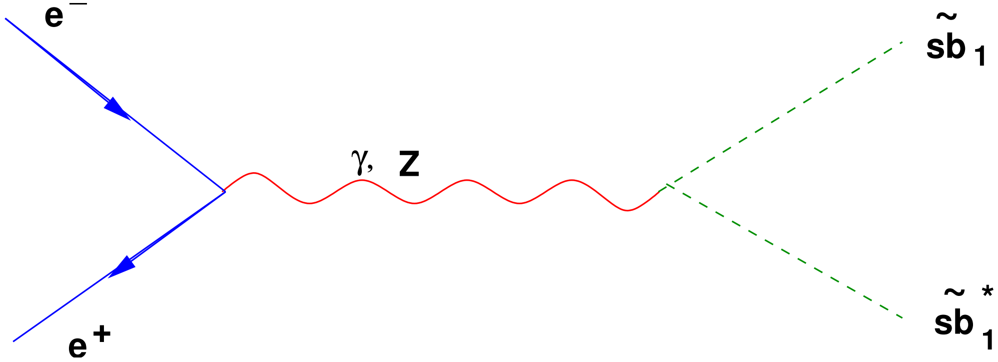
Squark pair cross section at the LHC



Gluino pair cross section at the LHC

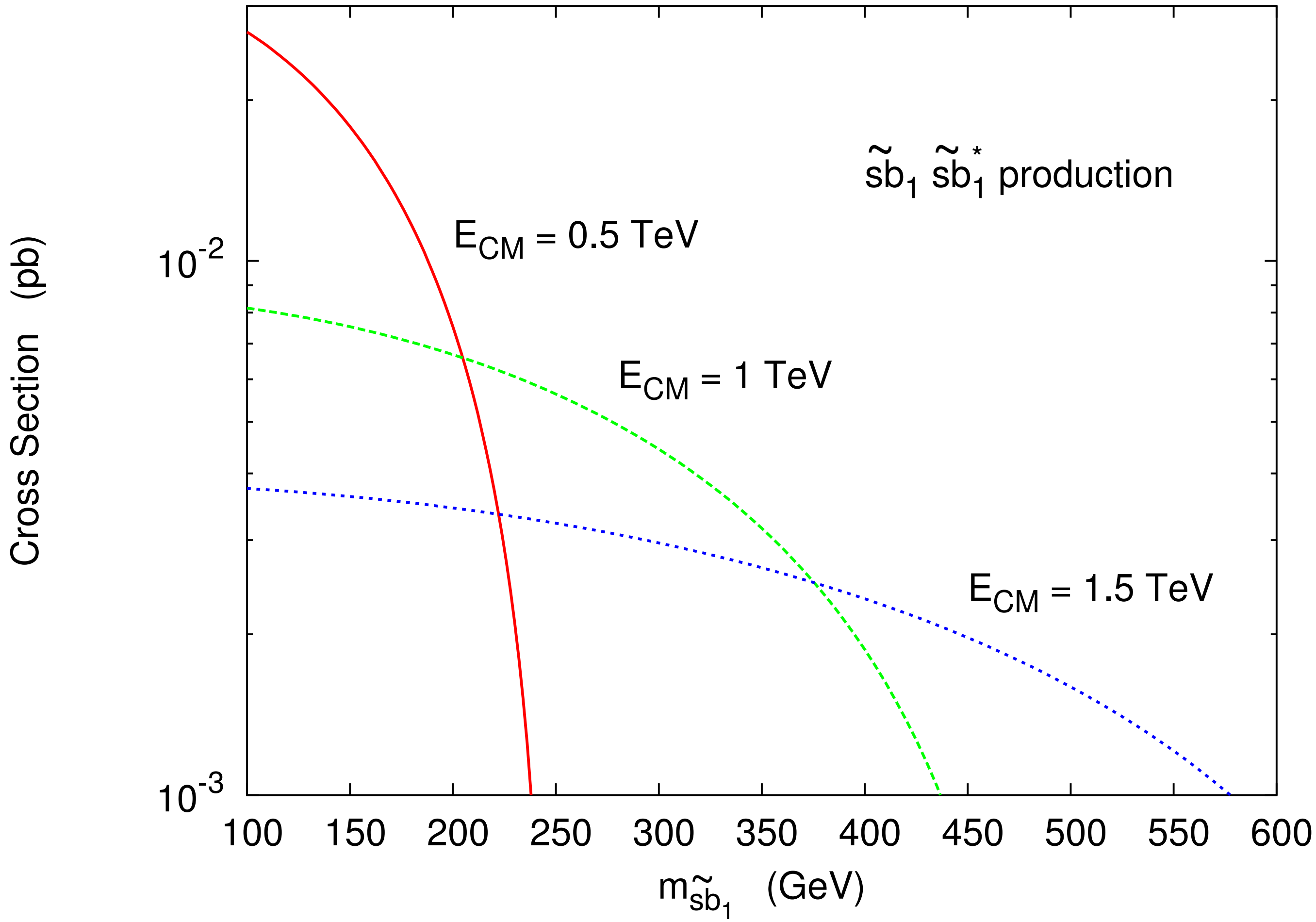


Production at e^+e^- Colliders



$$\frac{d\sigma}{d\cos\theta}(e^-e^+ \to \widetilde{sb}_1\widetilde{sb}_1^*) \quad = \quad \frac{\pi\alpha^2 s}{24}\beta^3 \ \sin^2\theta \Bigg\{ \left| \frac{1}{s} + \frac{g_L^e}{\cos^2\theta_W}\frac{1}{s-m_Z^2} \right|^2 + \left| \frac{1}{s} + \frac{g_R^e}{\cos^2\theta_W}\frac{1}{s-m_Z^2} \right|^2 \Bigg\}$$

Squark pair cross section at the LC



Decay scenarios of the strange-beauty squark pair

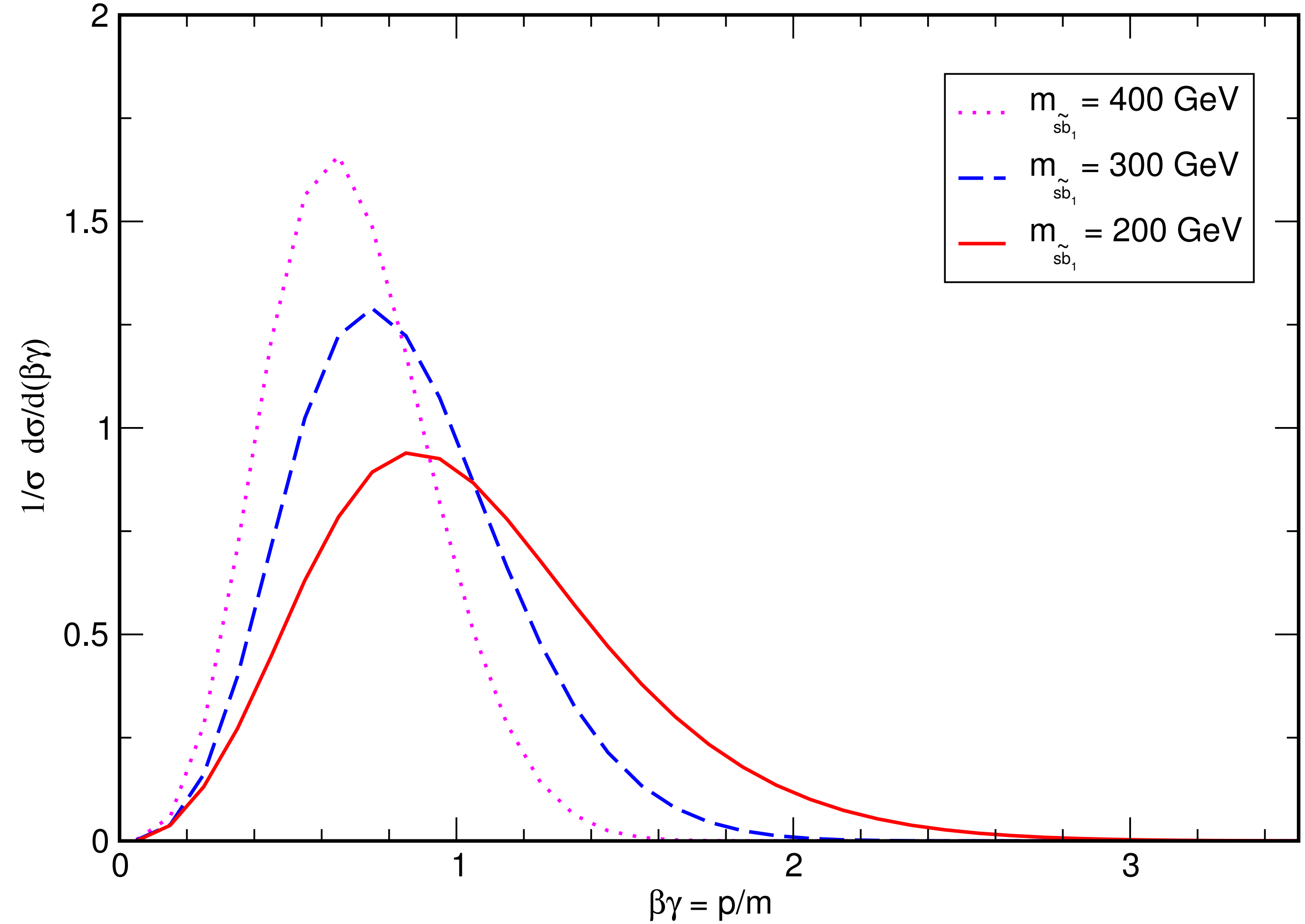
1. $\widetilde{sb}_1$ is the LSP and R-parity is conserved,
2. $\widetilde{sb}_1$ is the LSP but R-parity is violated. It decays into 2 jets or 1 lepton plus 1 jet,
3. $\widetilde{sb}_1$ is the NLSP, decay into neutralino (in SUGRA) or gravitino (gauge-mediated) and b/s quark.

Stable strange-beauty squark

- Stable $\widetilde{sb}_1$ hadronize into neutral or charged particles.
- Neutral stable particle escapes detection easily
- Charged stable particle ionizes in central tracking and in muon chamber, so behaves like a "heavy muon".
- Selection cuts:

$$p_T(\widetilde{sb}_1) > 20 \text{ GeV}\,, \qquad |y(\widetilde{sb}_1)| < 2.0\,, \qquad 0.25 < \beta\gamma < 0.85\,.$$

$\beta\gamma \equiv p/m_{\widetilde{sb}_1}$ spectrum



Cross sections (fb) for stable $\widetilde{sb}_1$ pair production at Tevatron

$m_{\widetilde{sb}_1}$ (GeV)	$\sigma_{1\mathrm{MCP}}$ (fb)	$\sigma_{2\mathrm{MCP}}$ (fb)	$\sigma_{\geq 1\mathrm{MCP}}$ (fb)
200	41 (0.46)	9.3 (0.02)	50 (0.48)
250	10.9 (0.96)	2.8 (0.14)	14 (1.1)
300	3.1 (1.2)	0.91 (0.3)	4.0 (1.5)
350	0.87 (1.3)	0.29 (0.43)	1.2 (1.8)
400	0.23 (1.4)	0.088 (0.48)	0.32 (1.8)
450	0.058 (1.4)	0.024 (0.51)	0.082 (1.9)

() feed down from gluino pair production

R-parity violating decay of $\widetilde{sb}_1$

- $\lambda'' U^c D^c D^c$ only gives multijet decay.
- Choose the $\lambda' L Q D^c$ coupling, such that

$$\widetilde{sb}_1 \to e^- u \quad \text{or} \quad \mu^- c$$

  with λ'_{ii3} and λ'_{ii2} couplings, $i = 1, 2$.

- $\widetilde{sb}_1$ then behaves like a scalar leptoquark.
- Current best limit on the first generation LQ:

  $M_{LQ} \gtrsim 260$ GeV prelim. from combined CDF, DØ Runs I, II

- Our estimate for a 2 fb^{-1} RunII will give a sensitivity up to 300 GeV, and for 20 fb^{-1} can be up to 350 GeV.

$\widetilde{sb}_1$ NLSP

- $\widetilde{sb}_1$ will decay promptly into a b/s quark plus a neutralino in SUGRA.
- $\widetilde{sb}_1$ will decay into a b/s quark plus a gravitino (or via an intermediate neutralino into gravitino and photon) in gauge-mediated models.

$$1/\sqrt{F_{SUSY}} \lesssim 10^7 GeV$$

otherwise behaves like a stable particle within the detector.

- For $\widetilde{sb}_1$ pair production, or feed down from gluino production, multi b/s jets plus $\not{E}_T$ in the final state.

Event rates for $\widetilde{sb}_1$ NLSP

- Note that

$$\widetilde{sb}_1 \to b\, \widetilde{\chi}^0_1 \qquad \text{scales with } \sin^2\theta_m$$

- Selection cuts

$$p_{Tj} > 15 \text{ GeV}\,, \qquad |\eta_j| < 2.0\,, \qquad \not{p}_T > 40 \text{ GeV},$$
$$\epsilon_{btag} = 0.6\,, \qquad \epsilon_{mis} = 0.05\,.$$

- Most events pass the jet cuts if

$$m_{\widetilde{sb}_1} - m_{\widetilde{\chi}^0_1} > 50 \text{ GeV}$$

- If we choose $B(\widetilde{sb}_1 \to b\widetilde{\chi}^0_1) = 1\,(0.5)$, the ratio of $0:1:2$ B-tagged events

$$16:48:36 \qquad (49:42:9)$$

Event rates (fb) for $\widetilde{sb}_1$ at Tevatron

$m_{\widetilde{sb}_1}$	0 b-tag	1 b-tag	2 b-tag	0 b-tag	1 b-tag	2 b-tag
(GeV)	$\sin^2\theta_m = 1$			$\sin^2\theta_m = 0.75$		
150	115(0.11)	288(0.54)	175(2.2)	190(0.29)	284(0.89)	104(1.6)
200	26(0.091)	70(0.49)	47(2.2)	44(0.27)	70(0.85)	28(1.7)
250	6.1(0.090)	17(0.49)	11(2.2)	11(0.27)	17(0.85)	6.8(1.7)
300	1.5(0.090)	4.2(0.49)	2.9(2.2)	2.6(0.27)	4.2(0.85)	1.7(1.7)
350	0.38(0.090)	1.1(0.49)	0.72(2.2)	0.66(0.27)	1.1(0.86)	0.43(1.7)
	$\sin^2\theta_m = 0.5$			$\sin^2\theta_m = 0.25$		
150	283(0.66)	243(1.2)	51(1.0)	395(1.3)	165(1.1)	17(0.40)
200	68(0.63)	61(1.1)	14(1.0)	96(1.3)	42(1.1)	4.6(0.42)
250	16(0.62)	15(1.1)	3.3(1.0)	23(1.3)	10(1.1)	1.1(0.42)
300	4.0(0.63)	3.7(1.1)	0.84(1.0)	5.8(1.3)	2.5(1.1)	0.28(0.42)
350	1.0(0.63)	0.93(1.1)	0.21(1.0)	1.4(1.3)	0.64(1.1)	0.071(0.43)

() feed down from gluino pair production

Summary

- The Belle $B \to \phi K_S$ anomaly calls for strong right-handed strange-beauty mixing.
- A near-maximal mixing in the $2-3$ squark sector gives a relatively light right-handed strange-beauty squark.
- It is feasible to search for $\widetilde{sb}_1$ at Tevatron Run II.
- We studied 3 decay scenarios:
  1. stable $\widetilde{sb}_1$
  2. RPV decay of $\widetilde{sb}_1$, like leptoquark
  3. $\widetilde{sb}_1 \to b/s\widetilde{\chi}_1^0$
- In general, the sensitivity is up to 300 GeV at Run II with 2 fb^{-1}.
- At 0.5 TeV LC with 100 fb^{-1} can cover slight above 200 GeV. At 1 TeV LC with 100 fb^{-1} can easily cover up to 400 GeV.