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LIGHT BOTTOM SQUARK PHENOMENOLOGY

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1. Bottom Squarks ($\widetilde{b}$) and Gluinos ($\widetilde{g}$) with Small Mass
2. Bottom Quark Hadronic Production: Cross Section,Mixing
3. Restrictions from Other Processes
4. Bottomonium $\Upsilon(nS)$ and $\chi_b(J^P) \rightarrow \tilde{b}\tilde{b}^*$ Decays
5. Higgs Boson Decays $\rightarrow \tilde{b}\tilde{b}^*$
6. Summary

E. Berger, B. Harris, D. Kaplan, Z. Sullivan, T. Tait, and C. Wagner,

Phys.Rev.Lett. 86,4231 (2001) [hep-ph/0012001];

E. Berger and L. Clavelli, Phys.Lett. B512,115-120 (2001) [hep-ph/0105147];

E. Berger and J. Lee, Phys. Rev D65, 114003 (2002) [hep-ph/0203092];

E. Berger, hep-ph/0201229, Int J. Mod Phys A, in press;

E. Berger, C.-W. Chiang, J. Jiang, T. Tait, and C. Wagner, hep-ph/0205342;

E. Berger, G. Bodwin, and J. Lee, hep-ph/0206115

1. Supersymmetry and Bottom Quark Production

- Motivation: Cross section for bottom quark production exceeds the central value of predictions of NLO QCD by a factor of 2 to 3 at Tevatron ($p\bar{p} \to b\bar{b}X$) [→ Fig.]
- New Physics: within the minimal supersymmetric standard model (MSSM), assume the existence of a low-mass color-octet, spin-1/2 gluino ($\tilde{g}$) and a low-mass color-triplet spin-0 bottom squark ($\tilde{b}$) Pair production of $\tilde{g}$:

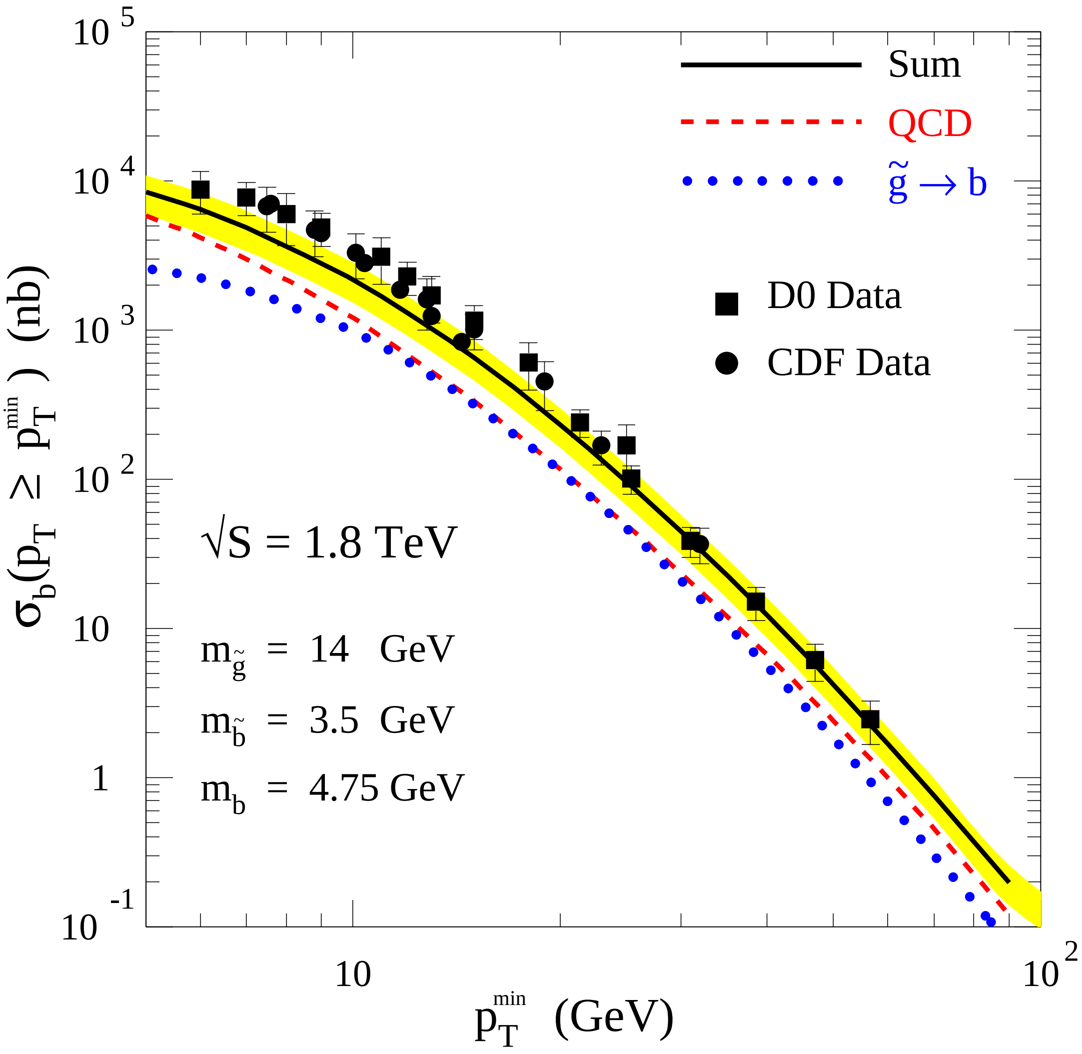
$$p + \bar{p} \to \tilde{g} + \tilde{g} + X,$$

$$\tilde{g} \to b + \tilde{b}$$ 100% BR

- Masses obtained by "fit" to the hadron collider b data:
  - $m_{\tilde{g}} \simeq 12$ to 16 GeV; $m_{\tilde{b}} \simeq 2$ to 5.5 GeV
- Z^0 decays: Light $\widetilde{b}$ is excluded unless its coupling to the Z is small. Tree-level coupling vanishes for squark mixing angle $\sin^2\theta_{\tilde{b}} \sim (2/3)\sin^2\theta_W \sim 1/6$

  (Carena, Heinemeyer, Wagner, and Weiglein, PRL 86, 4463 (2001))
- $\tilde{b}$ is the lightest SUSY particle; other than $\tilde{b}$ and $\tilde{g}$, masses of all other SUSY particles are arbitrarily large
- $\tilde{b}$ can be long-lived on the scale of colliders or decay promptly (hadronically) via R-parity violation; lifetime less than the cosmological time scale – no contribution to the dark matter density

2. Comparison of b-Quark Cross Section with Data



- Values of $m_{\tilde{g}} \simeq 12$ to 16 GeV produce p_{Tb} spectra that are enhanced near $p_{Tb}^{\min} \simeq m_{\tilde{g}}$ where data deviate most from pure QCD; light $\tilde{g}$ is necessary to obtain a b cross section comparable to the pure QCD rate
- Theoretical uncertainty of roughly $\pm 30\%$ (yellow band) may be assigned to the final curve from variations of the renormalization and factorization scales μ, the b mass, and the parton densities

Larger Apparent B^0–$\bar{B}^0$ Mixing at Hadron Colliders

- Majorana $\tilde{g}$'s decay into b or $\bar{b}$
  - $\tilde{g}\tilde{g}$ pair production generates bb and $\bar{b}\bar{b}$ pairs as well as $b\bar{b}$ pairs ⇒ potential increase in like-sign lepton pairs, and apparent increased rate of $B\,\bar{B}$ mixing
  - Cuts chosen in Tevatron Run I produce principally unpolarized $\tilde{g}$'s and thus, at production,

    $N_{\tilde{g}}(bb+\bar{b}\bar{b}) \simeq N_{\tilde{g}}(b\bar{b})$

    Should see B^+B^+, B^-B^- events at Run II
- The SUSY contribution affects the (time-averaged mixing) parameter $\bar{\chi}$:
  - $\bar{b} \to B^o, B_s, \Lambda_b, B^+$

    $\to \ell^+$, “right sign”, with probability $1-\bar{\chi}$

    $\to \ell^-$, “wrong sign”, with probability $\bar{\chi}$
  - Define LS, like-sign lepton fraction
  - Conventional $b\bar{b}$ pair production

    $\to LS_C = 2\bar{\chi}(1-\bar{\chi})$
- New expression

$$LS = \frac{1}{2}\frac{\sigma_{\tilde{g}\tilde{g}}}{\sigma_{\tilde{g}\tilde{g}}+\sigma_{\rm QCD}} + LS_C\frac{\sigma_{\rm QCD}}{\sigma_{\tilde{g}\tilde{g}}+\sigma_{\rm QCD}} \equiv 2\bar{\chi}_{\rm eff}(1-\bar{\chi}_{\rm eff})$$

- Predict: $\bar{\chi}^{\rm th}_{\rm eff} = 0.16 \pm 0.02, m_{\tilde{g}} = 16\,{\rm GeV}$
- CDF data $\bar{\chi}^{\rm exp}_{\rm eff} = 0.131 \pm 0.020 \pm 0.016$
- World average value from PDG : $\bar{\chi} = 0.118 \pm 0.005$

3. Are these SUSY masses and couplings excluded?

- UA1 analysis excludes a $\tilde{g}$ with $4 < m_{\tilde{g}} < 53$ GeV if there is a lighter χ_1^0. Then $\tilde{g} \to q\bar{q} + \not{E}_T$ PLB 198, 261 (1987). Our model has no such decay since $\tilde{b}$ is the LSP

- ALEPH LEP determination of color factor ratios from an analysis of 4 jet events excludes a $\tilde{g}$ with $m_{\tilde{g}} < 6.3$ GeV, but not gluinos in the mass range of interest to us. Light $\widetilde{b}$ is not excluded by 4 jet analysis

  Z. Phys C76, 1 (1997)

- Exclusion by CLEO of a light $\widetilde{b}$ with mass 3.5 – 4.5 GeV does not apply since their analysis focuses on $\tilde{b} \to cl\tilde{\nu}$ and $\tilde{b} \to cl$ PRD 63, 051101 (2001). A long-lived $\tilde{b}$ or one that decays via baryon-number R-parity violating couplings would evade CLEO's limitation. CLEO might wish to look for $\tilde{b} \to cq$, $q = d$, or s

LEP Constraints on Bottom Squark Couplings

- Light $\widetilde{b}$ would be ruled out by LEP 1 data unless its coupling to the Z boson is small
- Squark couplings to the Z depend on the mixing angle $\theta_{\tilde{b}}$
- Let $s_{\tilde{b}} = \sin\theta_{\tilde{\mathrm{b}}}$ be the left-handed component of the lightest $\widetilde{b}$ mass eigenstate; $s_W^2 = \sin^2\theta_{\mathrm{W}}$
- Coupling $g_{Z\tilde{b}_1\tilde{b}_1} \sim [T_3\, s_{\tilde{b}}^2 - Q_{\tilde{b}}\, s_W^2]$ ($T_3 = -1/2$; $Q_{\tilde{b}} = -1/3$)
- Tree-level coupling to Z vanishes for $s_{\tilde{b}}^2 \sim 1/6$

  (Carena, Heinemeyer, Wagner, and Weiglein, PRL 86, 4463 (2001)
- Thus, if the light bottom squark is an appropriate mixture of left-handed and right-handed bottom squarks, tree-level coupling to the Z can be made small (in general $\neq 0$)
- $Z - \widetilde{b}_1 - \widetilde{b}_2$, $Z - \widetilde{b}_2 - \widetilde{b}_2$ couplings survive in this limit
- Perhaps require $m_{\widetilde{b}_2} \gtrsim 200$ GeV , depending on decay signatures, to avoid $e^+e^- \to Z^* \to \widetilde{b}_1 + \widetilde{b}_2$

R and Angular Distributions in $e^+e^- \to \mathrm{jets}$

- Deviations of R from SM expectations?

$$R = \frac{e^+e^- \to \mathrm{hadrons}}{e^+e^- \to \mu^+\mu^-}$$

- Scalars are produced in a p-wave coupled to the intermediate photon
  - Thresholds turn on slowly
  - Cross sections are small ($\sim 1/4$ a fermion of the same charge)
- Compared to “everything else” $\widetilde{b}$ contributes

$$\left(\frac{1}{3}\right)^2 \frac{1}{4} \quad \mathrm{vs.} \quad 2\left(\frac{2}{3}\right)^2 + 3\left(\frac{1}{3}\right)^2$$
$$\frac{1}{36} \quad \mathrm{vs.} \quad \frac{11}{9}$$

- Data must be accurate to 1 to 2% to discriminate.

  BES measurement gets down to ~ 6 to 7%

  Phys.Rev.Lett. 88, 101802 (2002)

- Angular distributions are potentially more powerful, $\sin^2\theta$ vs. $(1+\cos^2\theta)$; data are consistent with a single pair of charge-$1/3$ squarks along with 5 flavors of $q\bar{q}$ pairs; $(1+\alpha\cos^2\theta)$, with $\alpha \simeq 0.92$

Running of the Strong Coupling Strength

- Evolution of the strong coupling strength α_s:

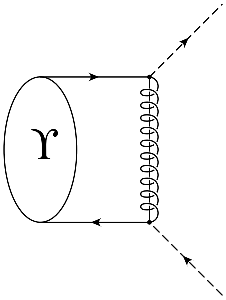
$$Q^2 d\alpha_s(Q^2)/dQ^2 = \beta(\alpha_s(Q^2))$$

- β function of (SUSY) QCD above gluino threshold:

$$\beta(\alpha_s) = \frac{\alpha_s^2}{2\pi}\left(-11 + \frac{2}{3}n_f + \frac{1}{6}n_s + 2\right) + O(\alpha_s^3)$$

- The QCD running of $\alpha_s(\mu)$ is slowed.
  - $\widetilde{b}$ (color triplet scalar) contributes little to the running (equivalent to $1/4$ of a new flavor)
  - $\widetilde{g}$ (color octet fermion) much more significant (equivalent to 3 new flavors of quarks)
- Precise determination of $\beta(\alpha_s)$ best way to exclude light gluino
- In SM, global fit to $\alpha_s(\mu)$ extracted from all observables provides $\alpha_s(M_Z) = 0.1184 \pm 0.006$ under SM running. With inclusion of a light gluino, there is a shift of ~ 0.007 to $\alpha_s(M_Z) \simeq 0.125$, within the range of uncertainty, but towards the upper end
- But, presence of a light gluino, with or without a light bottom squark, requires reanalysis of all extractions of $\alpha_s(\mu)$ to take SUSY production processes into account and to include SUSY-QCD contributions to the theoretical expressions. Smaller $\alpha_s(\mu)$ under slower evolution can lead to the same $\alpha_s(M_Z)$ as the SM

4. Bottomonium Decays: $\Upsilon \to \tilde{b}^* \, \tilde{b}$



- If the $\tilde{b}$ is light enough, expect an increase of the hadronic widths of
  - $\Upsilon(nS)$ ($n = 1, 2, 3$)
  - $\chi_b(J^{PC})$ ($J^{PC} = 0^{++}, 1^{++}, 2^{++}$)
- Large data samples at the $\Upsilon(4S)$ from CLEO, BaBar, BELLE; large samples at $\Upsilon(nS)$ from 2002 CLEO runs
  - fix $m_{\tilde{g}} = 14$ GeV, predict, e.g.,

$$BR(\Upsilon(4S) \to \tilde{b}^* \, \tilde{b}) = 10^{-3}, m_{\tilde{b}} = 2.50\,\mathrm{GeV}$$

  - as many as 10K events at CLEO?
  - signals could be distinctive
- $BR(\Upsilon(1S) \to \tilde{b}\tilde{b}^*) \simeq 10\%$ for $m_{\tilde{g}} \simeq 16$ GeV and $m_{\tilde{b}} \simeq 4$ GeV
- For $\Upsilon(nS)$, $n = 1$ to 3, calculate $R^{\Upsilon}_{\tilde{b}\tilde{b}^*} = \Gamma_{\tilde{b}\tilde{b}^*}/\Gamma_{\ell\bar{\ell}}$
- Current experimental uncertainty on hadonic widths:
  - for $\Upsilon(1S)$, about size of $\Gamma_{\ell\bar{\ell}}$
  - for $\Upsilon(2S)$ and $\Upsilon(3S)$, about $10\times\,\Gamma_{\ell\bar{\ell}}$
- $R^{\Upsilon}_{\tilde{b}\tilde{b}^*} < 10$ is satisfied easily for masses favored by collider data: $m_{\tilde{g}} \simeq 12 - 16$ GeV; $m_{\tilde{b}} \simeq 2 - 5.5$ GeV
- Smaller $R^{\Upsilon}_{\tilde{b}\tilde{b}^*}$ requires larger $m_{\tilde{b}}$,$m_{\tilde{g}}$. Bounds on $R^{\Upsilon}_{\tilde{b}\tilde{b}^*}$ → important lower bounds on $m_{\tilde{b}}$,$m_{\tilde{g}}$

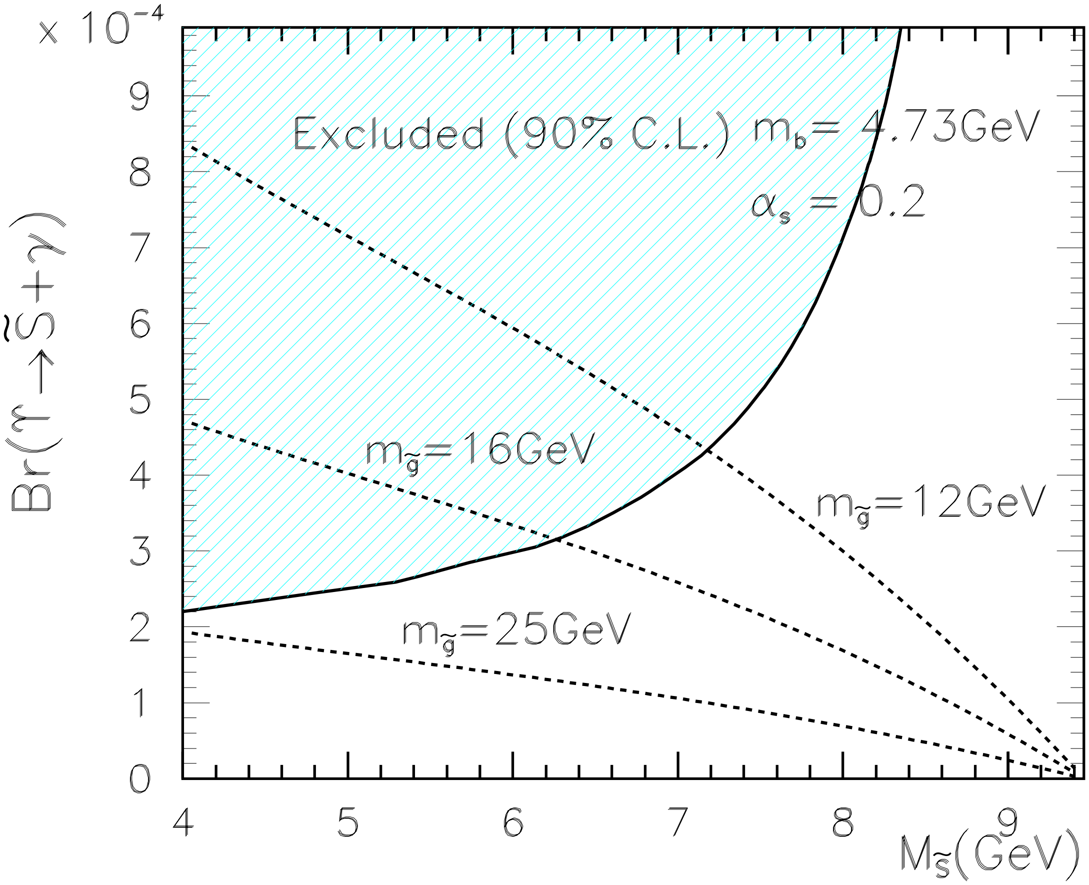
Bottomonium Decays: $\Upsilon \to \gamma\tilde{S}$ and $\chi_b \to \tilde{b}^* \; \tilde{b}$

- Decays to $\tilde{b}$ can increase the hadronic width of χ_{b0} by $\sim 10\%$, for $m_{\tilde{g}} \sim 16$ GeV and $m_{\tilde{b}} \sim 4$ GeV; smaller contributions in χ_{b1} and χ_{b2} cases

  Berger and Lee, Phys. Rev. D65, 114003 (2002) [hep-ph/0203092]

- If $\tilde{b}$ is relatively stable, $\tilde{b}\tilde{b}^*$ *bound states* can exist. $\tilde{S} = S$-wave bound state; $\tilde{S} \to gg$

- $\tilde{S}$ could be produced in radiative decays $\Upsilon \to \gamma\tilde{S}$; branching fraction:



Berger, Bodwin, and Lee, hep-ph/0203092

$\widetilde{b}$ Lifetime and Observability

- Suppose the $\widetilde{b}$ is relatively “stable”, what could happen?
  - $\widetilde{b}$ picks up a light $\bar{u}$ or $\bar{d}$ and becomes a $\widetilde{B}^-$ or $\widetilde{B}^0$ “mesino” with $J = 1/2$, the superpartner of the B meson, a hadron with mass $\sim 3 – 7$ GeV
  - $\Upsilon \to \tilde{B}^+\tilde{B}^-$ produces two back-to-back charged tracks in the cm; equal momentum; $1 + \cos^2\theta$ angular distribution; tracks have lower momentum than those from $\Upsilon \to \mu^+\ \mu^-$. Look in the “$\tau$ scan” events
  - The mesino has baryon number 0 but acts like a heavy $\bar{p}$ — ionization, TOF, signal in DIRC, ... consistent with heavy $\bar{p}$
  - The charged mesino is not a muon but could fake a heavy muon in hadron collider experiments if it exits the muon chambers; $\Rightarrow$ extra “muon”-like objects in a fraction of the $b\bar{b}$ event sample, with tracks that left some activity in the hadron calorimeter?
  - Detailed analyses should be done at hadron colliders to verify what ranges of $\widetilde{b}$ masses and lifetimes may be allowed/disfavored
  - Assume that the lifetime of the bottom squark is less than the cosmological time scale so that these squarks make no contribution to the dark matter density

$\widetilde{b}$ Lifetime and Observability, continued

- R-parity conservation does not permit $\widetilde{b}$ decay unless there is an even lighter LSP

- MSSM superpotential with baryon-number-violating R-parity-violating term

  $$W_{\not R_p} = \lambda''_{ijk} U^c_i D^c_j D^c_k$$

  U^c_i and D^c_i are right-handed quark-singlet chiral superfields; i, j, k are generation indices

- Limits on individual baryon-number-violating R-parity-violating couplings λ'' are weak for 3rd generation $\tilde{q}$'s: $\lambda'' < 0.5$ to 1 Allanach, Dedes, Dreiner, PRD 60, 075014 (1999)

- Possible $\not R_p$ decay channels are $123 : \tilde{b}^* \to u + s$, $213 : \tilde{b}^* \to c + d$, and $223 : \tilde{b}^* \to c + s$.

  $$\Gamma(\tilde{b} \to jj) = \frac{m_{\tilde{b}}}{2\pi} \sin^2\theta_{\tilde{b}} \sum_{j<k} |\lambda''_{ij3}|^2$$

  If $m_{\tilde{b}} = 3.5$ GeV, $\Gamma(\widetilde{b} \to ij) = 0.08|\lambda''_{ij3}|^2$ GeV

- Unless all λ''_{ij3} are extremely small, the $\widetilde{b}$ will decay quickly. In Υ decay, curious $(2q, 2\bar{q})$ spectroscopy. In hadron colliders $\tilde{b}$ will leave soft jets in the cone around the b; jets with an extra c are possibly disfavored by CDF. Detailed simulations are needed

$\widetilde{b}$-onia

- Might be seen as mesonic resonances in $\gamma\gamma$ reactions (i.e., $e^+e^- \to e^+e^-X)$ and in $p\bar{p}$ formation with masses between 4 – 10 GeV and $J^P = 0^+$, 1^-, 2^+, $\ldots$
- Could show up as narrow states in $\mu^+\mu^-$ invariant mass spectra at hadron colliders, between the J/ψ and Υ
- At an e^+e^- collider, the intermediate photon requires production of a $J^{PC} = 1^{--}$ state
  - Bound states of low mass squarks with $Q_{\tilde{q}} = 2/3$ studied by Nappi with a potential model PRD 25, 84 (1982)
    - $\Gamma_\ell \sim 24$ eV
    - $\Gamma_h \sim 18$ keV
    - $\Gamma_{1S+\gamma} \sim 65$ keV
  - The $1S$ state decays hadronically
  - Because the leptonic decay widths are too small there are no bounds for $m_{\tilde{q}} > 3$ GeV, $Q_{\tilde{q}} = 2/3$
  - For bottom squarks, the situation is even more difficult ($Q_{\tilde{q}} = -1/3$)

5. Light Higgs Boson Decay: $h^0 \to \tilde{b}^* \, \tilde{b}$

- Within the MSSM, light $\widetilde{b}$ is obtained most readily for large $\tan\beta$, ratio of Higgs vacuum expectation values v_2/v_1
- Tree-level coupling of CP-even light h to light $\widetilde{b}$ is

$$\frac{g m_b}{2 m_W \cos\beta}(\mu \cos\alpha + A_b \sin\alpha) \sin 2\theta_b + \cdots$$

  - μ is the Higgsino mass parameter; $|\mu| > m_h$
  - α is the CP-even Higgs mixing angle
  - In the decoupling regime (large pseudo-scalar Higgs mass $m_A >> m_Z$), $\cos\alpha \to \sin\beta$

- For large $\tan\beta$, the first term dominates $g_{h\tilde{b}^*\tilde{b}} \propto \mu \tan\beta$
- Higgs couplings to SM particles are not enhanced in the limit of large $\tan\beta$ and m_A
- Ratio of Higgs partial widths into $\tilde{b}^* \, \tilde{b}$ and $\bar{b} \, b$ is enhanced:

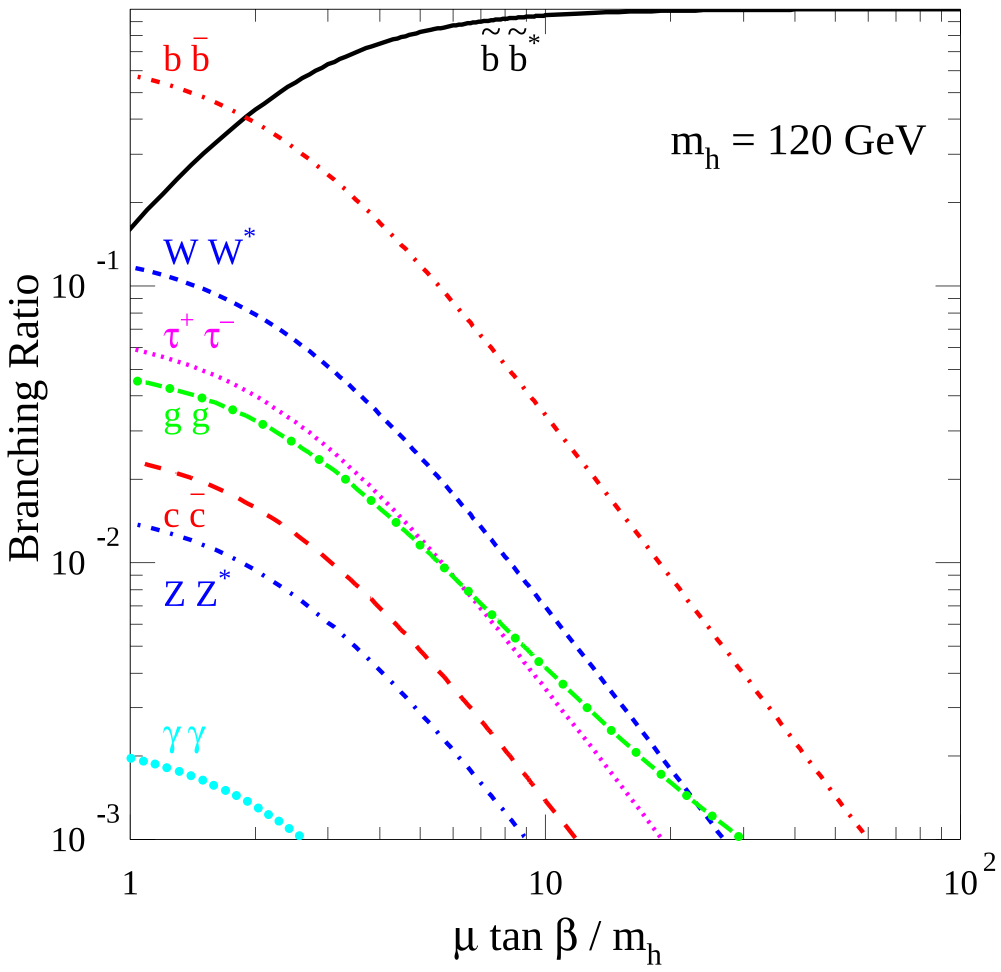
$$\frac{\Gamma_{\tilde{b}}}{\Gamma_b} \approx \frac{1}{2}\left(\frac{\mu}{m_h}\right)^2 \tan^2\beta \sin^2 2\theta_{\tilde{b}}$$

- decay to $\tilde{b}^* \, \tilde{b}$ much more important than decay to $\bar{b} \, b$ for $\mu \tan\beta / m_h \gtrsim 10$
- Some enhancement of gg partial width because the $\tilde{b}$ loop interferes constructively with the standard top quark loop

Implications of $h^0 \to \tilde{b}^* \, \tilde{b}$

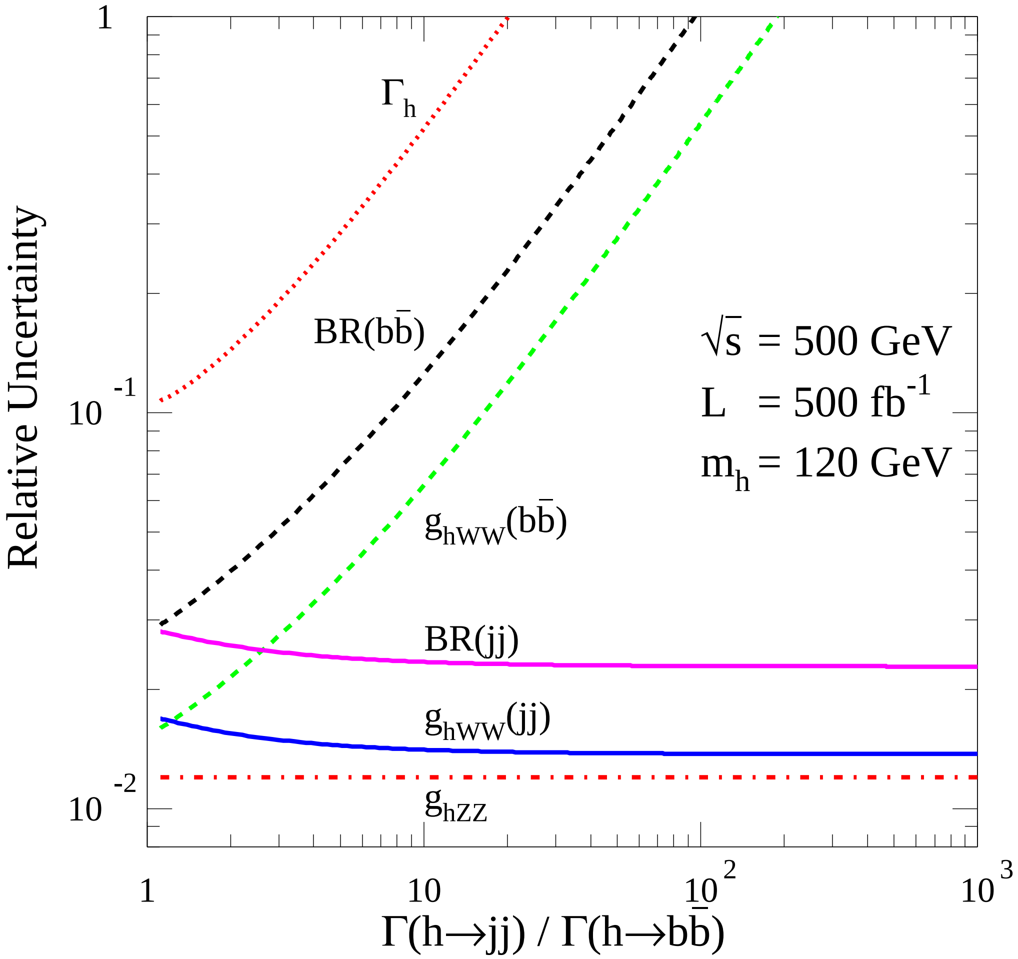
- $\tilde{b}$ carries color; it will materialize as a jet j of hadrons
- Take $\mu \tan\beta / m_h$ as a parameter that measures the rate for $h \to jj$
- What happens to the prospects for observation of the Higgs boson?
- New total width of Higgs boson $\Gamma_h \simeq \Gamma_h^{\mathrm{SM}} + \Gamma_h^{\tilde{b}^* \tilde{b}}$
  - e.g., $\Gamma_h \simeq 66$ MeV for $\mu \tan\beta / m_h = 10$ vs. $\Gamma_h^{\mathrm{SM}} \simeq 3.3$ MeV; $m_h = 120$ GeV
- Branching fractions to SM particles decreased [→ Fig.]
  - LC processes, $e^+ e^- \to Z^0 h$, $e^+ e^- \to \nu \bar{\nu} h$ remain fully viable for discovery, measurement of mass and (some) couplings ($h^0 ZZ$; $h^0 WW$, $\ldots$)
  - Prospects at hadron colliders diminished; large QCD jet-jet backgrounds

Light Higgs Boson Branching Fractions



- With $m_h = 120$ GeV, $BR(h^0 \to b\bar{b}) \simeq 69\%$ in SM, and b-tagging plays a big role in search strategies
- $BR(h^0 \to b\bar{b})$ drops to $\sim 3.4\%$ at $\mu \tan\beta/m_h = 10$
- Decrease of SM BR's by a factor of 2 to 3 (i.e., $\mu \tan\beta/m_h =$ 2.3 to 3.2) drops expected $S/\sqrt{B} < 5$ at LHC for $gg \to hX$, $h \to \gamma\gamma, ZZ^*, WW^*$ Likewise for $WW \to hX$, $h \to \tau^+\tau^-, WW^*$

Uncertainties in Higgs Boson Parameters at an e^+e^- Collider



- Uncertainty is $\sqrt{S+B}/S$. Plotted vs. ratio of jet-jet width divided by $b\bar{b}$ width
- Starts at SM values from Snowmass '01 study
- jet jet (jj) defined as $\tilde{b}\tilde{b}^*$, $b\bar{b}$, gg, $c\bar{c}$
- $BR(h \to jj)$ and g_{hWW} can be determined fairly well from $e^+e^- \to hZ$ and $e^+e^- \to \nu\bar{\nu}h$, with $h \to jj$

6. Summary

- Postulate the existence of light gluinos and light bottom squarks with 100% branching fraction $\widetilde{g} \to b\widetilde{b}$
  $m_{\tilde{g}} \simeq 12 – 16$ GeV; $m_{\tilde{b}} \simeq 2 – 5.5$ GeV; $\sin^2\theta_{\tilde{b}} \simeq 1/6$
- Consistent with all known experimental and theoretical constraints
- This SUSY scenario, with $\sigma_{\tilde{g}\tilde{g}}/\sigma_{\rm QCD} \simeq 1/3$, helps to resolve the longstanding discrepancy between data and predictions for the magnitude and shape of the b-quark p_T distribution at the Tevatron and UA1
  - Should see B^+B^+, B^-B^- events at Run II
  - Visible in B^0–$\bar{B}^0$ oscillation parameters at the Tevatron – larger apparent mixing
- Rare decays $\Upsilon(nS) \to \widetilde{b}\,\widetilde{b}^*$; $\Upsilon(nS) \to \gamma\,\widetilde{S}$; and $\chi_b \to \widetilde{b}\,\widetilde{b}^*$ – searches could discover (place significant limits on) $m_{\widetilde{b}}$ and/or R-parity violation
- In light Higgs boson decay, $h^0 \to \widetilde{b}\,\widetilde{b}^*$ dominates
  $\to$ light Higgs boson decays primarily to hadronic jets
  Discovery at LC still viable; prospects at hadron colliders diminished significantly
- See E. Berger, C.-W. Chiang, J. Jiang, T. Tait, and C. Wagner, hep-ph/0205342; and references therein

Further Papers

- Z-peak constraints beyond tree-level

  Cao, Xiong, and Yang, Phys.Rev.Lett. 88, 111802 (2002)

  Cho, hep-ph/0204348

  Baek, hep-ph/0205013

- Increase in the yield of $t\bar{t}b\bar{b}$ at hadron colliders from $t\bar{t}\tilde{g}\tilde{g}$

  Leibovich and Rainwater, Phys.Rev.Lett. 88, 221801 (2002)

- Constraints from radiative B meson decays

  Becher, Braig, Neubert, and Kagan, hep-ph/0205274

- Prediction of possible excess of $q\bar{q}b\bar{b}$ at LEP

  $q\bar{q}\tilde{g}\tilde{g}$ vs. $q\bar{q}g$ with $g \to b\bar{b}$

  Cheung and Keung, hep-ph/0205345