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# LIGHT BOTTOM SQUARK PHENOMENOLOGY

Edmond L. Berger

Argonne National Laboratory

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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 on $\widetilde{b}$'s and $\widetilde{g}$'s from Other Processes
4. Implications and Expectations
5. Light Higgs Boson Decay Branching Fractions
6. Summary

gate.hep.anl.gov/berger/seminars/KIAS2003.ps

E. Berger, B. Harris, D. Kaplan, Z. Sullivan, T. Tait, and C. Wagner, Phys.Rev.Lett. 86,4231 (2001) [hep-ph/0012001]

E. Berger, C.-W. Chiang, J. Jiang, T. Tait, and C. Wagner, Phys. Rev. D66, 095001 (2002) [hep-ph/0205342] and references therein

# 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 the Tevatron ($p\bar{p} \to b\bar{b}X$) [$\to$ 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 $\tilde{g}$:

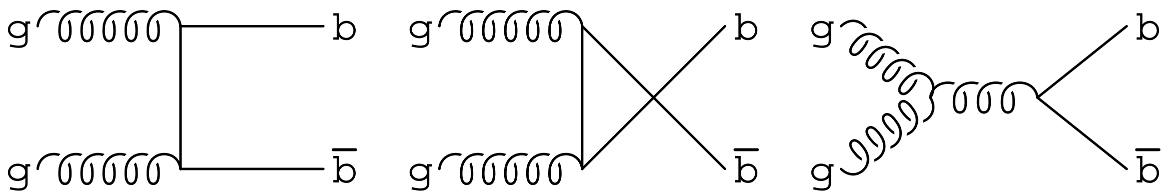
$$p + \bar{p} \to \tilde{g} + \tilde{g} + X,$$

$$\tilde{g} \to b + \tilde{b}^* \; or \; \tilde{g} \to \bar{b} + \tilde{b}$$ 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
- $\tilde{b}$ is the lightest SUSY particle; other than $\tilde{b}$ and $\tilde{g}$, masses of most other SUSY particles may be arbitrarily large; $m_{\tilde{t}} \simeq m_t$; this scenario is NOT mSUGRA, GMSB,.....
- Consistent with all constraints from precise data at the $Z$, from low-energy $e^+e^-$ experiments, etc.; ALEPH analysis requires the lifetime $\tau_{\tilde{b}} < 1$ ns Heister *et al.* hep-ex/0305071

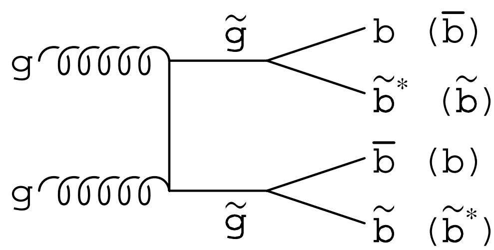
# Production Processes

- Pair production of $b\bar{b}$ via $gg$ scattering in LO QCD:
  ($q\bar{q}$ initial state makes a small contribution at the Tevatron for the masses we consider but is included in our numerical calculations) Nason, Dawson, Ellis; Beenakker, Kuijif, van Neerven, Meng, Smith; Mangano, Nason, Ridolfi




- QCD NLO calculation of inclusive $b$ cross section with CTEQ4M parton densities; SUSY-QCD contributions to $b$ production are not included — not available yet (in progress)

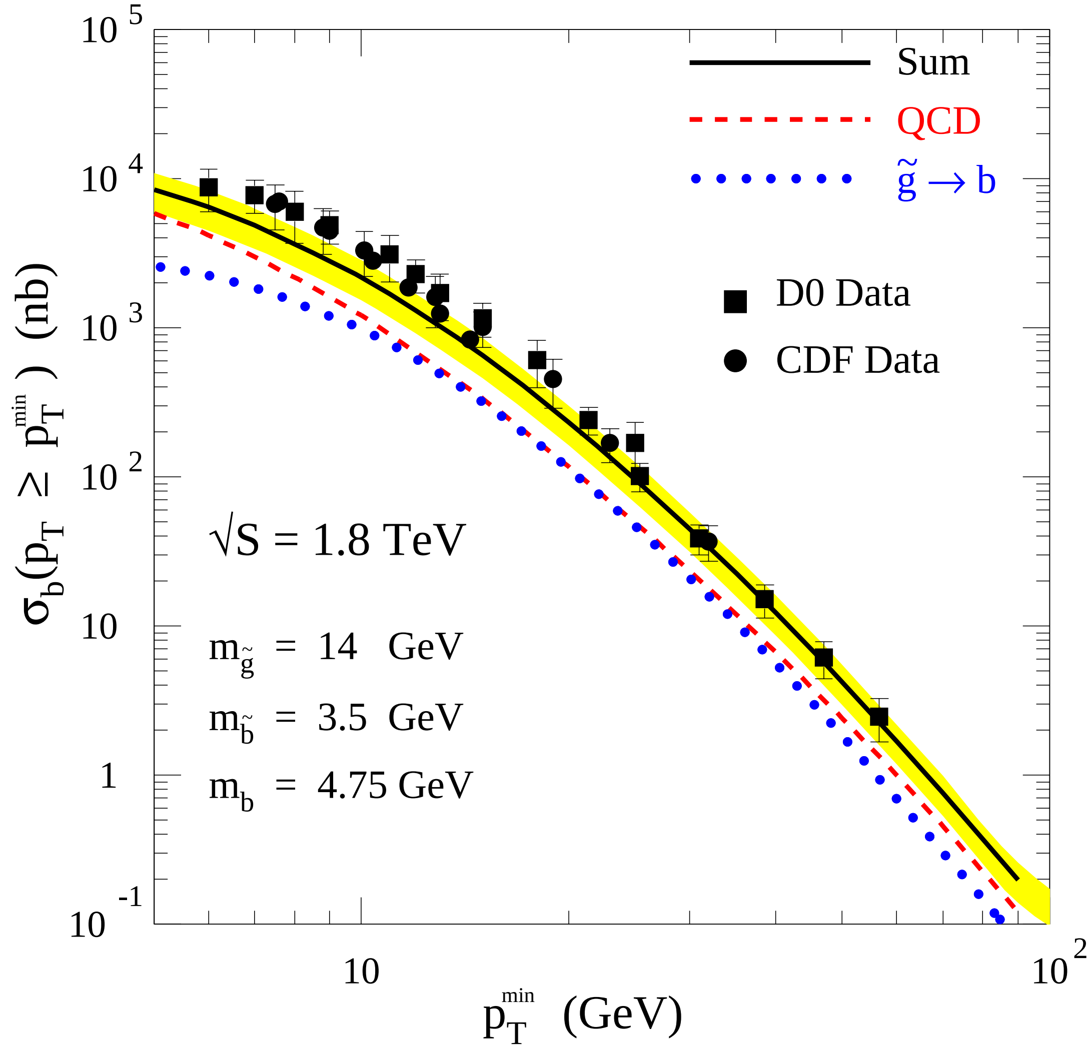
- LO SUSY QCD process, e.g., via gluino exchange
  $gg \to \tilde{g}\tilde{g} \to b\bar{b}\tilde{\bar{b}}\tilde{b}^*, bb\tilde{b}^*\tilde{b}^*, \bar{b}\bar{b}\tilde{b}\tilde{b}$:




- Fully differential NLO calculation of $\tilde{g}$ pair production and decay $\tilde{g} \to b + \tilde{b}$ does not exist; $\tilde{g}$ contribution computed at LO and multiplied by an overall NLO enhancement ($K$) factor

- $g + b \to \tilde{g} + \tilde{b}$ contributes less than 2% of $\sigma_{b\bar{b}}^{\rm QCD}$

# 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 $p_{Tb}^{\rm min} \simeq m_{\tilde{g}}$ 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 $\mu$, the $b$ mass, and the parton densities

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

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

# 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 leads to $bb$ and $\bar{b}\bar{b}$ pairs as well as $b\bar{b}$
  - 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
  - $\Rightarrow$ potential increase in like-sign lepton pairs, and apparent increased rate of $B\bar{B}$ mixing
- 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 SM $b\bar{b}$ pair production

    $\to LS_{\rm SM} = 2\bar{\chi}(1 - \bar{\chi})$
- New expression

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

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

## New expression

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

- World average value (PDG) : $\bar{\chi} = 0.118 \pm 0.005$

  Take this PDG value to represent $\bar{\chi}_{\rm SM}$

- Predict:

$$\bar{\chi}^{\rm th}_{\rm eff} = 0.17 \pm 0.02, m_{\tilde{g}} = 14\,{\rm GeV}$$

$$\bar{\chi}^{\rm th}_{\rm eff} = 0.16 \pm 0.02, m_{\tilde{g}} = 16\,{\rm GeV}$$

- CDF
  - 20% run-I data and only $\mu\mu$ PRD 55, 2546 (1997)

$$\bar{\chi}^{\rm exp}_{\rm eff} = 0.131 \pm 0.020 \pm 0.016$$

  - new analysis of full run-I sample, both $\mu\mu$ and $e\mu$: Acosta *et al.* hep-ex/0309030

$$\bar{\chi}^{\rm exp}_{\rm eff} = 0.152 \pm 0.007 \pm 0.011$$

- SUSY contribution means that $\bar{\chi}^{\rm th}_{\rm eff}$ should change with $p_{Tb}$ – run-II data

# Could the answer be hiding in QCD?

- NLO QCD contributions are roughly the same size as the LO terms. Maybe NNLO terms are very important? No full NNLO calculation exists, but it is unlikely that NNLO contributions could be large enough (the new process in NLO involves gluon exchange in $gg$ scattering)

- Peterson fragmentation does not work for $b$'s

  M. Cacciari and P. Nason, PRL 89, 122003 (2002)

- Small $x \sim \frac{m_b}{\sqrt{S}}$ resummation at hadron colliders?

  J. Collins, R. K. Ellis, NP B360 (1991) 3;

  R. Ball, R. K. Ellis, JHEP 0105 (2001) 053

- 

Most of these effects appear to go in the same direction. None would predict like sign $b$'s or a larger time-averaged mixing parameter $\bar{\chi}$

Without a compelling QCD solution, we consider the discrepancy with the $b$ production cross section an invitation to try something new. . . and explore the consequences in other reactions

## 3. Are these SUSY masses and couplings excluded?

- The light $\widetilde{g}$ and light $\widetilde{b}$ model is an ad-hoc SUSY breaking model. It is not mSUGRA, GMSB, AMSB, .... Here, $\widetilde{g}$ decays to $b\widetilde{b}$. $\widetilde{b}$ is the LSP, and $\widetilde{g}$ is the NLSP

- $\widetilde{b}$
  - Exclusion by CLEO of a light $\widetilde{b}$ with mass $3.5$ – $4.5$ GeV does not apply since the analysis focuses on lepton-number R-parity violating decays $\tilde{b} \to cl\tilde{\nu}$ 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 $s$
  - ALEPH searched for *stable* hadronizing $\tilde{q}$, $\tilde{g}$ near the $Z$ (*e.g.*, from $g \to \tilde{q}\tilde{q}^*$, $g \to \tilde{g}\tilde{g}$) and for *stable* $\tilde{q}$ via $e^+e^- \to \tilde{q}\tilde{q}^*$ at LEP-II

    ALEPH A. Heister *et al* hep-ex/0305071

    $\to m_{\tilde{b}} > 92$ GeV if stable

    (also $m_{\tilde{g}} > 25.6$ GeV if stable)

    No limitation on $m_{\tilde{b}}$ if $\tau_{\tilde{b}} < 1$ ns

# Quantum numbers of bottom squarks

- Spin zero, electric charge -1/3, color triplet
- Under charge-conjugation, squark($\tilde{q}$) $\rightarrow$ antisquark($\tilde{q}^*$)
- Let $|\tilde{b}_R\rangle$ and $|\tilde{b}_L\rangle$ be the SUSY partners of the right-handed ($R$) and left-handed ($L$) bottom quarks
- Mass eigenstates are $|\tilde{b}_1\rangle$ and $|\tilde{b}_2\rangle$. In terms of a mixing angle $\theta_{\tilde{b}}$:

$$|\tilde{b}_1\rangle = \sin\theta_{\tilde{b}}|\tilde{b}_L\rangle + \cos\theta_{\tilde{b}}|\tilde{b}_R\rangle$$
$$|\tilde{b}_2\rangle = \cos\theta_{\tilde{b}}|\tilde{b}_L\rangle - \sin\theta_{\tilde{b}}|\tilde{b}_R\rangle$$

- States of definite parity, the $J^P = 0^+$ scalar and $J^P = 0^-$ pseudo-scalar

$$|0^+\rangle = \frac{1}{\sqrt{2}}(|\tilde{b}_R\rangle + |\tilde{b}_L\rangle)$$
$$|0^-\rangle = \frac{1}{\sqrt{2}}(|\tilde{b}_R\rangle - |\tilde{b}_L\rangle)$$

- Express the mass eigenstate $\tilde{b}_1$ as

$$|\tilde{b}_1\rangle = \frac{1}{\sqrt{2}}(\cos\theta_{\tilde{b}} + \sin\theta_{\tilde{b}})|0^+\rangle + \frac{1}{\sqrt{2}}(\cos\theta_{\tilde{b}} - \sin\theta_{\tilde{b}})|0^-\rangle$$

- $\tilde{b}_1$ is a pure $J^P = 0^+$ scalar only if $\sin\theta_{\tilde{b}} = \cos\theta_{\tilde{b}} = \frac{1}{\sqrt{2}}$

# 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 $\theta_{\tilde{b}}$

$$|\tilde{b}_1\rangle = \sin\theta_{\tilde{b}}|\tilde{b}_L\rangle + \cos\theta_{\tilde{b}}|\tilde{b}_R\rangle$$
$$|\tilde{b}_2\rangle = \cos\theta_{\tilde{b}}|\tilde{b}_L\rangle - \sin\theta_{\tilde{b}}|\tilde{b}_R\rangle$$

- Coupling to the $Z$ boson $g_{Z\tilde{b}_1\tilde{b}_1^*} \sim [T_3\, s_{\tilde{b}}^2 - Q_{\tilde{b}}\, s_W^2]$ ($T_3 = -1/2$; $Q_{\tilde{b}} = -1/3$ ; $s_W^2 = \sin^2\theta_{\mathrm{W}}$)
- Tree-level coupling to $Z$ vanishes for $s_{\tilde{b}}^2 \sim 1/6$ [$0.3 < |s_{\tilde{b}}| < 0.45$]

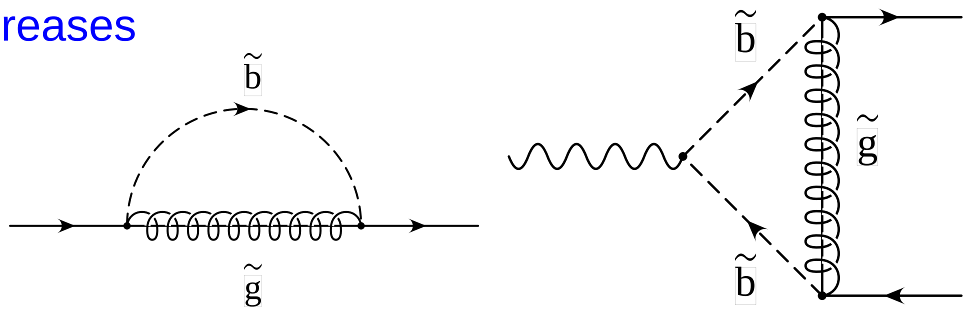
  (Carena, Heinemeyer, Wagner, and Weiglein, PRL 86, 4463 (2001))
- If the light bottom squark is an appropriate mixture of left-handed and right-handed bottom squarks, tree-level coupling to the $Z$ can be made small (in general $\neq 0$)
- $Z - \widetilde{b}_1 - \widetilde{b}_2$, $Z - \widetilde{b}_2 - \widetilde{b}_2$ couplings survive. Require constraints on $m_{\widetilde{b}_2}$, depending on decay signatures, to avoid $e^+e^- \to Z^* \to \widetilde{b}_1 + \widetilde{b}_2$
- The light $\tilde{b}_1 = \tilde{b}$ is primarily right handed

# Loop Corrections to $Z$-$b$-$\bar{b}$

- Precise measurements of $R_b$ and $A^b_{fb}$ at the $Z$ pole constrain new physics contributions to the $Z$-$b$-$\bar{b}$ couplings at loop as well as at tree level

$$R_b = 0.21664 \pm 0.00068$$
$$A^b_{fb} = 0.0982 \pm 0.0017$$

- Loops of light $\widetilde{g}$, $\widetilde{b}_1$ and $\widetilde{b}_2$ could induce unacceptably large corrections that grow in magnitude as $m_{\widetilde{b}_2}$ increases




- Cao, Xiong, and Wang PRL 88, 111802 (2002) claim that $R_b$ constrains $m_{\tilde{b}_2} < 125$ GeV ($2\sigma$ level)

  also Cho, PRL 89,091801(2002); Baek, PL B541,161 (2002)

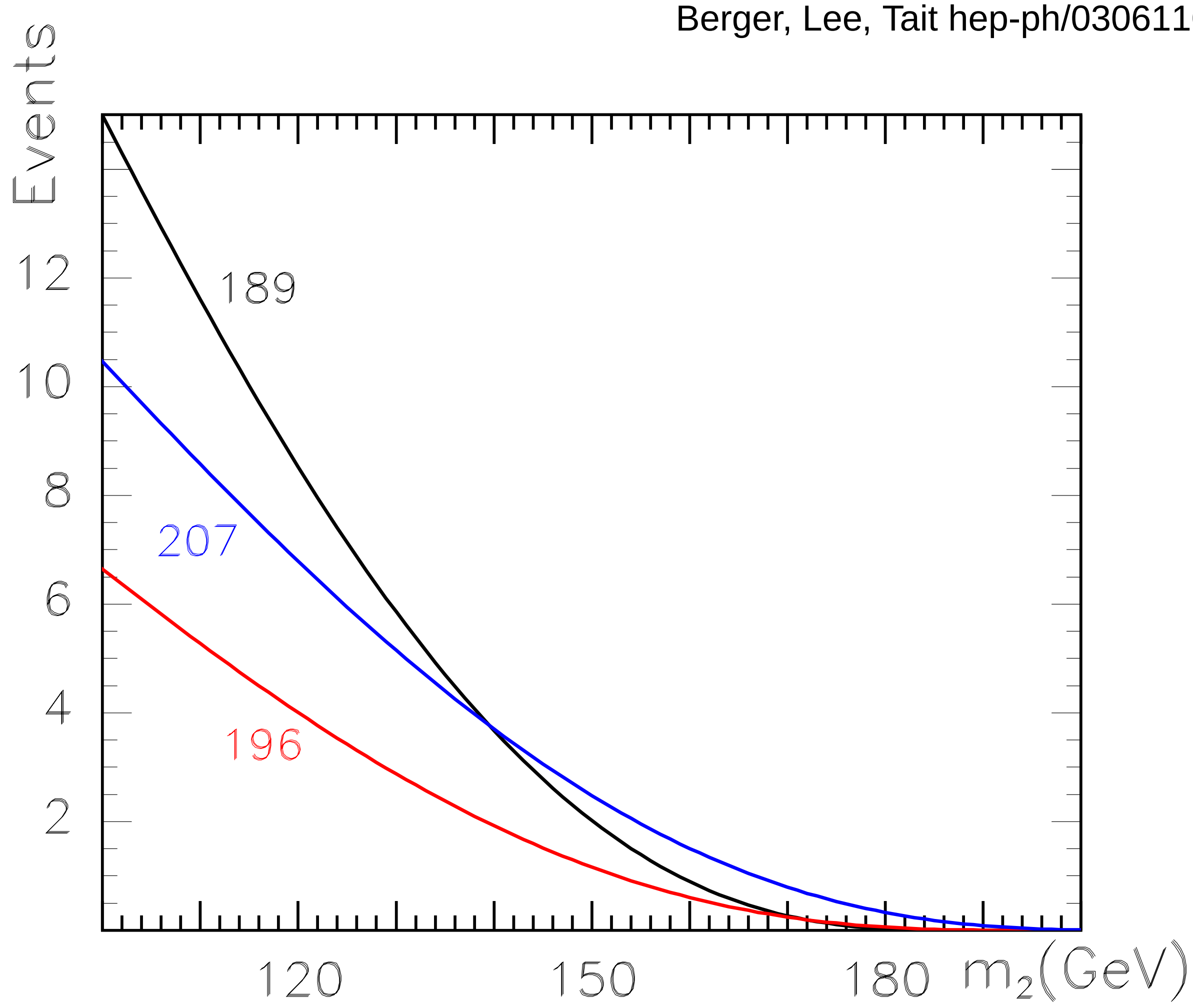
- Real decays, e.g., $Z \to \tilde{b}_1 \bar{b} \tilde{g} + \tilde{b}_1^* b \tilde{g}$, make a positive contribution to $R_b$ and soften the bound to, e.g., 155 (275) GeV at the $2\sigma$ ($3\sigma$) level Luo and Rosner, hep-ph/0306022

- Viability of the light bottom squark scenario can be questioned on the grounds that a $\tilde{b}_2$ with $m_{\tilde{b}_2} < 155$ GeV should have been produced (and detected?) at LEP-II in associated production $e^+e^- \to \widetilde{b}_1 \widetilde{b}_2^*$

# Event rates for $\widetilde{b}_1 \widetilde{b}_2^*$ at LEP-II

- Searches for SUSY particles are model-dependent and a search of LEP-II data for a $\tilde{b}_2$ in the light bottom squark scenario has not yet been undertaken
- Can we discover $\widetilde{b}_2$ at LEP-II?
- Predicted event rates ($\sigma$ times luminosity) for $\tilde{b}_1 \tilde{b}_2^*$ at LEP-II energies vs $m_2$ ($m_1 = 3.5$ GeV, $\sin^2\theta_b = 1/6$)

Berger, Lee, Tait hep-ph/0306110




- Below $\sqrt{s} = 189$ GeV, the integrated luminosities at LEP-II were too small to have produced enough events

## Signal/Background Analysis for $e^+e^- \to \widetilde{b}_1\widetilde{b}_2^*$

- $4$ parton final state: $2$ "$b$" jets and $2$ light $\widetilde{b}_1$ jets ($\widetilde{b}_2 \to b\widetilde{g}$; $\widetilde{g} \to b\widetilde{b}_1$)
- Take $\sqrt{s} = 207$ GeV at LEP-II
- Simulate the $4$-jet background with MADGRAPH
- After acceptance cuts, backgrounds $B >> $ signal $S$
- Demand that 3 jets reconstruct hypothesized $\widetilde{b}_2$ mass within $\Gamma(\widetilde{b}_2) \simeq 10$ GeV
- $B$ is reduced to the manageable levels of $20$ fb ($43$ fb) for $m_2 = 120$ GeV ($150$ GeV)
- Resulting signal significances about $5\sigma$ ($0.4\sigma$) at $m_2 = 120$ GeV ($150$ GeV)
- Conclude: Should be able to discover $\widetilde{b}_2$ in existing LEP-II data but only if its mass is less than 120 GeV.
  If no signal is observed, masses less than 130 GeV can be excluded at the $95\%$ CL

# Effects on $\Gamma_Z^{\rm tot}$ and other Observables

- Precise measurments of electroweak observables (e.g., $\Gamma_Z$, $R_\ell$, $\sigma_{\rm had}$, $R_b$,...) agree with the SM expectations
- New physics process can alter theoretical predictions; e.g., through vacuum polarization diagrams
- Model independent 95% CL limit $\Delta\Gamma_{\rm had} < 3.9$ MeV can be set on the partial width of any purely hadronic contribution from new physics to $Z$ decays [$< 6.3$ MeV (3 $\sigma$); $< 11.1$ MeV (5 $\sigma$)] (Janot, PL B564, 183 (2003))
- Light $\tilde{b}$ leads to an order $\alpha_s$ process $Z \to \bar{b}b^* \to \bar{b}\tilde{g}\tilde{b} \to \bar{b}b\tilde{b}\tilde{b}^*$ (plus CC) It supplies $\Delta\Gamma_{\rm had} = 2.5$ to $8.0$ MeV, depending upon the sign of $\sin 2\theta_{\tilde{b}}$ (Cheung and Keung, PRD67, 015005 (2003))
- Calculation of the order $\alpha_s^2$ process $e^+e^- \to q\bar{q}\tilde{g}\tilde{g}$ vs. $m_{\tilde{g}}$ (Baer, Cheung, and Gunion, PRD 59, 075002 (1999))
  $\Delta\Gamma_{\rm had} < 3.9$ MeV implies $m_{\tilde{g}} > 6.3$ GeV @ 95% CL
  $\Delta\Gamma_{\rm had}^Z = 0.20$ to $0.74$ MeV for $m_{\tilde{g}} = 12$ to $16$ GeV
- $Z \to b\bar{b}\tilde{g}\tilde{g}$ contributes to $Z \to b\bar{b}b\bar{b}$, via $\tilde{g} \to b\tilde{b}^*$
  $R_{4b}^{\rm exp} = 5.2 \pm 1.9 \times 10^{-4}$
  $R_{4b}^{\rm SM} + R_{b\tilde{g}} = 3.3$ to $7.3 \times 10^{-4}$, depending upon $m_{\tilde{g}}$ and $\theta_{\tilde{b}}$ (Malhotra and Dicus, PR D67, 097703 (2003))

# $R$ 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)

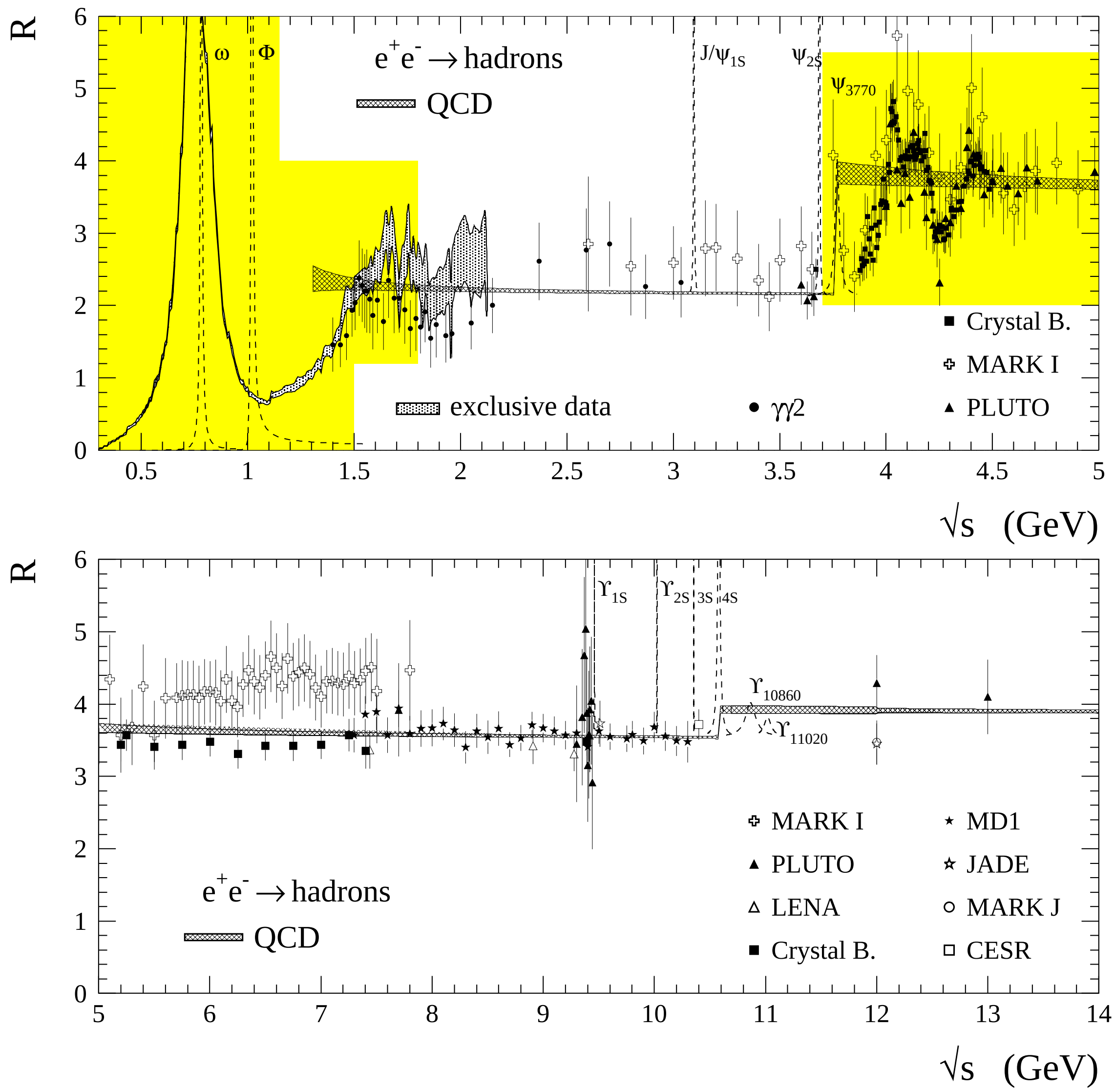
- Compared to "everything else" $\tilde{b}$ contributes

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

- Data must be accurate to $1$ to $2\%$ to discriminate.
  BES at 2 to 5 GeV accurate to $\sim 6\%$ PRL 88, 101802 (2002)
  CLEO at 10.52 GeV accurate to $\sim 2\%$ PRD 57, 1350 (1998)

- Angular distributions are potentially more powerful, $\sin^2\theta$ vs. $(1+\cos^2\theta)$; CELLO data PL B183, 400 (1987) at 14.0 to 46.8 GeV are not inconsistent with a single pair of charge-$1/3$ squarks along with $5$ flavors of $q\bar{q}$ pairs; $(1+\alpha\cos^2\theta)$, with $\alpha \simeq 0.92$

# Compilation of data on the ratio $R$




M. Davier and A. Höcker, Phys.Lett.B **419**,419 (1998)

- Note the small theoretical step in $R$ at open $b\bar{b}$ threshold
- Expected step in $R$ even smaller for $\tilde{b}\tilde{b}^*$
- $R = 3.56 \pm 0.01 \pm 0.07$ (2%) at $E_{cm} = 10.52$ GeV

  CLEO, PR D57, 1350 (1998)

# Are these SUSY masses and couplings excluded?

- $\widetilde{g}$
  - UA1 analysis excludes a $\tilde{g}$ with $4 < m_{\tilde{g}} < 53$ GeV if there is a lighter $\chi_1^0$. 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) & ALEPH 2001-042, CONF 2001-026
  - DELPHI studied energy evolution of event shape distributions with data from LEP1 and LEP2. The analysis relies heavily on the RGI approach. The $\beta$-function of strong interactions is determined: $\beta_0 = 7.86 \pm 0.32 \to n_f = 4.75 \pm 0.44$, consistent with 5, not 8. This result would seem to exclude a light $\tilde{g}$. However, a full study should be done, for different $m_{\tilde{g}}$, of the expected effects of light a $\tilde{g}$ and light $\tilde{b}$ on both final state event shapes and SUSY-QCD corrections to theoretical expressions

    DELPHI 2001-062, CONF 490 & K. Hamacher, Amsterdam ICHEP02 talk QCDH-6-5

# Running of the Strong Coupling Strength

- Evolution of the strong coupling strength $\alpha_s$:

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

- $\beta$ 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 $\sim 0.007$ 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. Predictions and Implications

- Bottomonium decays: $\Upsilon \to \tilde{b}^* \, \tilde{b}$. If the $\tilde{b}$ is light enough, expect an increase of the hadronic widths of $\Upsilon(nS)$.
  - $BR(\Upsilon(1S) \to \tilde{b}\tilde{b}^*) \simeq 10\%$ for $m_{\tilde{g}} \simeq 16$ GeV and $m_{\tilde{b}} \simeq 4$ GeV

    Berger and Clavelli, Phys.Lett. B512, 115 (2001)

- If $\tilde{b}$ is relatively stable, $\tilde{b}\tilde{b}^*$ *bound states* can exist. Suppose $\tilde{b}$ is stable enough that $\tilde{S} = S$-wave bound state exists; $\tilde{S} \to gg$ ($\Gamma_{\rm had} < 10$ MeV). $\tilde{S}$ could be produced in radiative decays: $\Upsilon \to \gamma \tilde{S}$. Branching fraction $\sim 10^{-4}$ Berger, Bodwin, and Lee, Phys. Lett. B552, 223 (2003)

- In DIS or in photoproduction at HERA, and in $\gamma\gamma$ processes at LEP, the processes $g + g \to \widetilde{g} + \widetilde{g}$ and $q + \bar{q} \to \widetilde{g} + \widetilde{g}$ require large hadronic energy and feed from the resolved component of the real or virtual $\gamma$. There should therefore be much less excess rate of $b\bar{b}$ at HERA and in $\gamma\gamma$ processes with respect to NLO QCD

- Higgs boson decays primarily to hadronic jets Berger, Chiang, Jiang, Tait, and Wagner, Phys. Rev. D66, 095001 (2002)

## $R$-Parity Violating Decay of $\widetilde{b}$

- $R$-parity conservation in SUSY 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 $\lambda''$ 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 $\tilde{b}^* \to u + s$, $\tilde{b}^* \to c + d$, $\tilde{b}^* \to c + s$ (and, possibly, $\tilde{b}^* \to u + d$)

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

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

- Unless all $\lambda''_{ij3}$ are small, the $\widetilde{b}$ will decay quickly.
- $\tau_{\tilde{b}} \lesssim 1$ ns $\to |\lambda''_{ij3}| \gtrsim 10^{-7}$ a lower limit
- Since the neutralino $\widetilde{\chi}^0$ couples to a (off-shell) $\widetilde{q}$, $\not R_p$ decay means that $\widetilde{\chi}^0$ cannot be a dark matter candidate

Berger and Sullivan, hep-ph/0310001

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

- There is a direct tree-level coupling $h \, \widetilde{b} \, \widetilde{b}^*$
- Within the MSSM, light $\widetilde{b}$ is obtained most readily for large $\tan\beta$, ratio of Higgs vacuum expectation values $v_2/v_1$
- Work in the large $\tan\beta$ region and in the decoupling regime (large pseudo-scalar Higgs mass $m_A >> m_Z$)
- $g_{h\tilde{b}^*\tilde{b}} \propto \mu \tan\beta$

  $\mu$ is the Higgsino mass parameter; $|\mu| > m_h$
- Higgs couplings to SM particles are not enhanced in the limit of large $\tan\beta$ and $m_A$

Upshot: In the decoupling regime and at large $\tan\beta$

- Ratio of Higgs partial widths into $\widetilde{b}^* \, \widetilde{b}$ and $\bar{b} \, b$ is enhanced:

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

- decay to $\widetilde{b}^* \, \widetilde{b}$ 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 $\widetilde{b}$ loop interferes constructively with the standard top quark loop

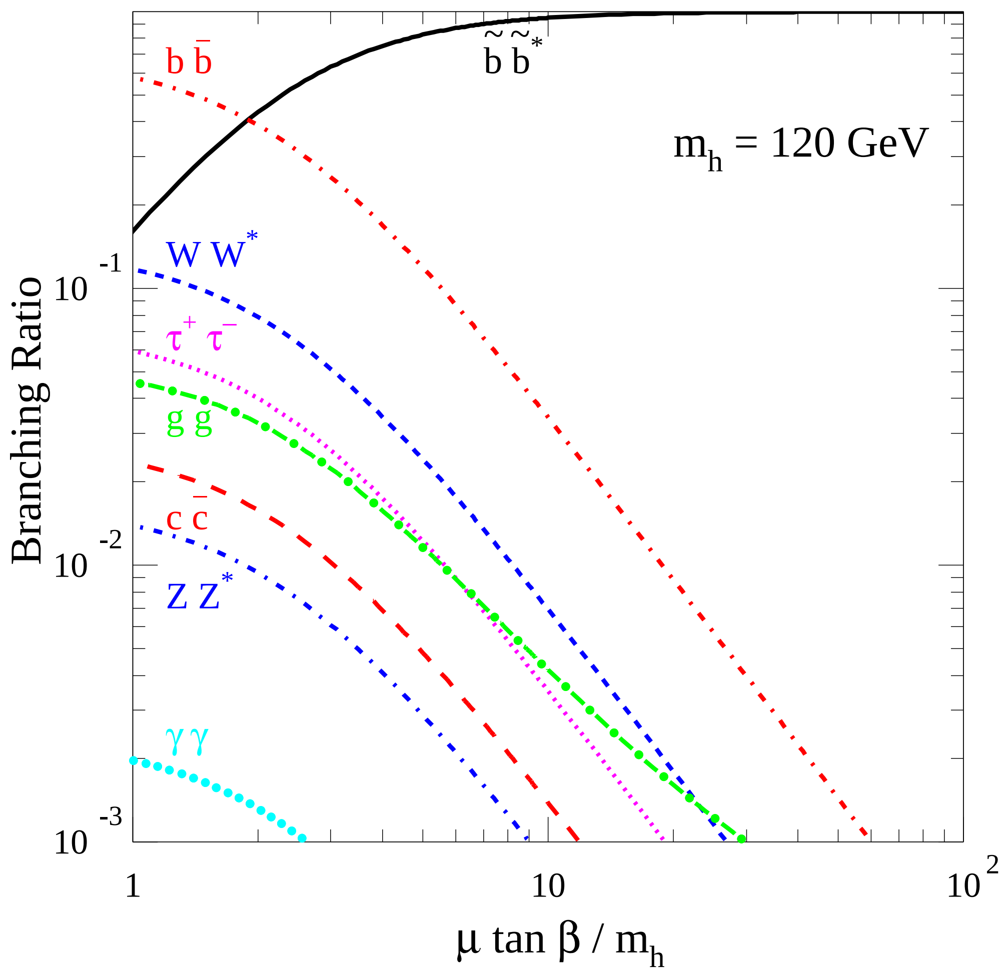
# Higgs Boson Total Width and Branching Fractions

- What happens to the prospects for observation of the Higgs boson?
  - New total width of Higgs boson $\Gamma_h \simeq \Gamma_h^{\rm SM} + \Gamma_h^{\tilde{b}^*\tilde{b}}$
    - $\Gamma_h$ grows with $(\mu \tan\beta/m_h)^2$
    - e.g., $\Gamma_h \simeq 66$ MeV for $\mu \tan\beta/m_h = 10$ vs. $\Gamma_h^{\rm SM} \simeq 3.3$ MeV; $m_h = 120$ GeV
  - Branching fractions to SM particles fall as $(\mu \tan\beta/m_h)^2$ grows [$\rightarrow$ Fig.]
    - at $m_h = 120$ GeV $BR(h^0 \rightarrow b\bar{b})$ drops to $\sim 3.4\%$ for $\mu \tan\beta/m_h = 10$, vs $\simeq 69\%$ in SM

- What about the new decay mode?
  - $\tilde{b}$ carries color; it will materialize as a jet $j$ of hadrons, without necessarily any special flavor content

- Generalize away from the light bottom squark model: Take $\mu \tan\beta/m_h$ as a parameter that measures the rate for $h \rightarrow jj$

# Light Higgs Boson Branching Fractions

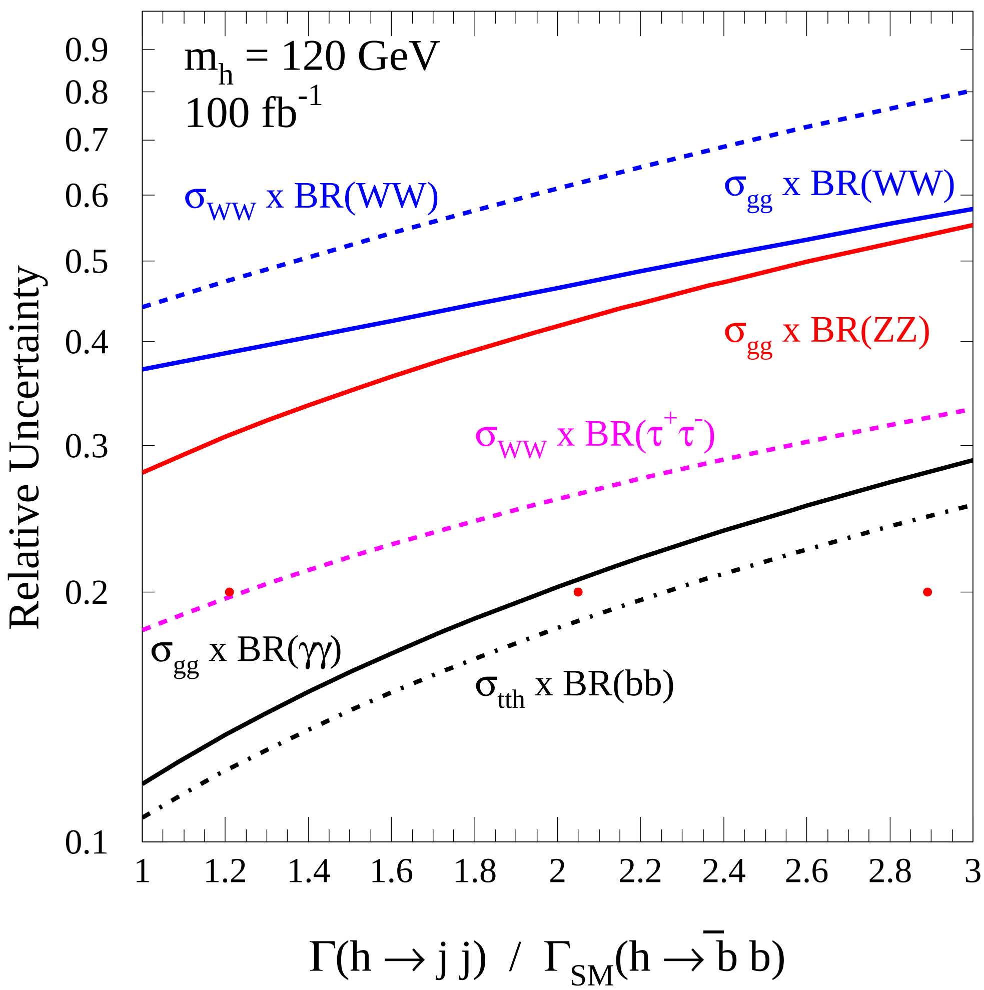



- With $m_h = 120$ GeV, $BR(h^0 \to b\bar{b}) \simeq 69\%$ in SM, and $b$-tagging plays a big role in search strategies
- $BR(h^0 \to b\bar{b})$ drops to $\sim 3.4\%$ at $\mu \tan\beta / m_h = 10$
- Decrease of SM $BR$'s by a factor of 2 to 3 (i.e., $\mu \tan\beta / m_h =$ 2.3 to 3.2) drops expected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

# Implications for LHC experiments

- At the LHC, a SM-like Higgs boson with $m_h \lesssim 135$ GeV is expected to be discovered through a variety of production processes and decay modes (ATLAS and CMS TDR's)
- Standard searches look for $h$ decays into SM particles
- New dominant decay mode into jets suppresses the BR's of SM decay modes by a factor $\sim 10$ to $\sim 100$'s
- Standard decays are suppressed, and the principal decay mode into jets suffers from enormous QCD backgrounds
- Take estimates of the backgrounds and SM signal rates presented in Cavalli *et al.*, Les Houches, 2001; Zeppenfeld *et al.*, Phys. Rev. D62, 013009 (2000). Decrease SM BR's
- Show accuracies at the LHC for $\sigma B$ (cross sections $\times$ BR's) for $g\, g \to h\, X$, with $h \to \gamma\gamma$, $W^+W^-$, $ZZ$; for $W\, W \to h\, X$, with $h \to WW$, $\tau^+\tau^-$
- Accuracies are shown as a function of the ratio of the jet-jet and the SM $b\bar{b}$ widths
  - Prospects at hadron colliders diminished; large QCD jet-jet backgrounds

# Uncertainties in Cross Section × Branching Fractions for Higgs Boson Production at the LHC



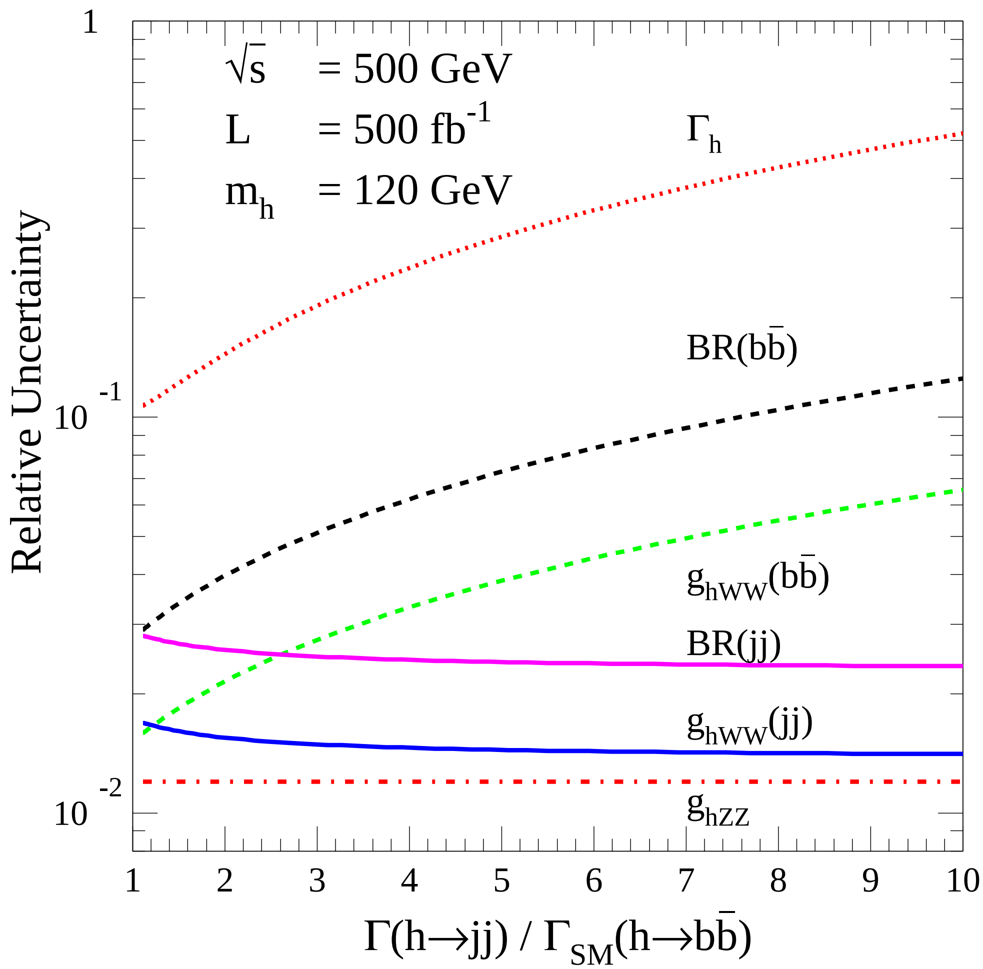

- Uncertainty is $\sqrt{S+B}/S$. Plotted vs. ratio of jet-jet width divided by SM $b\bar{b}$ width (jet jet defined as $\tilde{b}\tilde{b}^*$, $b\bar{b}$, $gg$, $c\bar{c}$)

- 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 $WW \to hX$, $h \to \tau^+\tau^-, WW^*$

# Implications for LC Experiments

- The dominant production process is $e^+e^- \to Zh^0$. Once the $Z$ is identified, $h^0$ is discovered in the missing mass distribution. The $hZZ$ coupling strength is measured independently of the Higgs boson decay products
- Measurement of the $hWW$ coupling is necessary to test the $SU(2)$ relationship between $hWW$ and $hZZ$. The usual method relies of the process $e^+e^- \to \nu\bar{\nu}h$, plus knowledge of at least one $h$ branching fraction. Full analysis of signals and backgrounds for the $h \to b\bar{b}$ case is reported in Desch and Meyer, LC-PHSM-2001-25 and Brau, Potter, Iwasaki, Snowmass 2001. Situation for the $h \to b\bar{b}$ case deteriorates as $\Gamma(jj)$ grows since the uncertainty on the $b\bar{b}$ branching fraction dominates the overall uncertainty
- However, we use the Desch and Meyer, LC-PHSM-2001-25 analysis after removing the "$b$-tags", and show that $h$ can be discovered in the $h \to \mathrm{jet\ jet}$ channel in $e^+e^- \to \nu\bar{\nu}h$ even at large $\mu \tan\beta/m_h$. The jet-jet mode allows a good determination of $hWW$ [$\to$ Fig.]

# 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 SM $b\bar{b}$ width
- Starts at SM values from Snowmass '01 study
- Contrast: at the LHC $\Gamma(\mathrm{h} \to \mathrm{jj})/\Gamma(\mathrm{h} \to \mathrm{b\bar{b}}) \sim 3$ drops $\sqrt{S+B}/S < 5$. At the LC, even an increase of the ratio to 10 is tolerable

# Implications for LC Experiments (continued)

- Knowledge of $hWW$ coupling strength along with $m_h$ allows one to compute the partial width $\Gamma_W$. If an independent measurement of $\mathrm{BR}(h \to WW^*)$ is also available, the Higgs boson total width $\Gamma_h$ is obtained: $\Gamma_h = \Gamma_W / \mathrm{BR}(h \to WW^*)$. Accuracy deteriorates with the increase of $\Gamma(\mathrm{jet\ jet})$ [$\to$ Fig.]

- Direct measurment of $\Gamma_h$?
  - Best estimate of the expected jet-jet invariant mass resolution is $\sim 2$ GeV LC Resource Book, Snowmass, 2001
  - Predicted total width exceeds 2 GeV if $\mu \tan\beta / m_h > 56$

- Measure $h\tilde{b}\tilde{b}^*$ coupling in $e^+e^- \to h\tilde{b}\tilde{b}^*$, with $h \to \tilde{b}\tilde{b}^*$?

  Despite $\tan\beta$ enhancement, the rate remains below $10^{-3}$ fb for energies below 1 TeV

# 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 experimental and theoretical constraints
- This SUSY scenario helps to resolve the longstanding discrepancy between data and predictions for the magnitude and shape of the $b$-quark $p_T$ distribution
  - 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
- Light bottom squarks $\widetilde{b}_1$ escape detection at LEP-I because their mixing angle is such that their diagonal coupling to the $Z$ cancels
- A dedicated analysis of existing LEP-II data should make it possible to discover heavy bottom squarks $\widetilde{b}_2$ at the $5\sigma$ level for masses as large as 120 GeV. If no signal is observed, exclusion limits at the $95\%$ CL should be feasible for masses of the order of 130 GeV and less
- 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 uncover new physics (or 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 very viable; prospects at hadron colliders more challenging

  Berger, Chiang, Jiang, Tait, and Wagner, Phys. Rev. D66, 095001 (2002) [hep-ph/0205342] and references therein

## Alternative Scenarios

- Suppose only the $\widetilde{b}$ is light
  - Assume $\widetilde{b}$ decay products (e.g., $\tau c$ via R-parity violation) are similar to those in $b$ decay
  - $\sigma_{\tilde{b}\bar{\tilde{b}}} \simeq \sigma_{b\bar{b}}$ for $m_{\tilde{b}} \simeq 3$ GeV
  - Fails: excess in $J/\Psi$ channel not produced, and $p_{Tb}$ spectrum not reproduced
- Light $\widetilde{b}$ and light $\tilde{g}$, with $m_{\tilde{b}} + m_b > m_{\tilde{g}}$ but $m_b < m_{\tilde{b}} < m_{\tilde{g}}$
  - $\tilde{g} \to \widetilde{b}s$ or $\tilde{g} \to \widetilde{b}d$; $\widetilde{b} \to b\tilde{\chi}^0$ (light $\tilde{\chi}^0$)
  - Requires FV coupling $\tilde{g} - \widetilde{b} - s$ to suppress $\tilde{g} \to g\tilde{\chi}^0$
  - Killer: $\sigma(b + \bar{b} + \not{E}_T)$ much too large; excluded at run I