LHC Searches with b-jets Versus Rare B-decays in SUSY GUTs

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Based on work with C. Kao

Supersymmetric Higgs

Higgs content of the Standard Model is minimal: one SU(2) doublet charged under U(1).
More complicated models can be easily constructed.

Natural extension: two doublets (2HDM).
Often constructed with one "up-type" and one "down-type" to avoid FCNCs.

$$\phi_u = (\mathbf{2}, \frac{1}{2}), \qquad \phi_d = (\mathbf{2}, -\frac{1}{2})$$
$$\mathscr{L} = Y_u Q \phi_u u^c + Y_d Q \phi_d d^c + Y_e L \phi_d e^c$$

Supersymmetry requires 2 doublets in minimal model (MSSM). $\rightarrow$ Important signal at LHC.

The 2HDM

Both doublets acquire vevs to break $SU(2) \times U(1)$:

$$\langle \phi_u \rangle = \begin{pmatrix} 0 \\ v_2 \end{pmatrix}, \quad \langle \phi_d \rangle = \begin{pmatrix} v_1 \\ 0 \end{pmatrix}.$$

This leaves five fields: $h^o, H^o, A^o, H^{\pm}$.

- h^0, H^0: "standard model" and heavy neutral scalars.
- A^0: neutral pseudoscalar
- H^+, H^-: charged scalar.

Two free parameters:m_A and $\tan\beta \equiv \frac{v_2}{v_1}$.

Phenomenology

For $m_A \gtrsim 125$ GeV, $m_A \simeq m_H \to A$ and H^0 are indistinguishable at LHC.

If $m_A \lesssim 125$ GeV, h^0 and A become indistinguishable.

$$d\bar{d}A^0 \propto \frac{g m_d \tan\beta}{2 m_W} \text{ (similar for } H^0 \text{ at high } m_A\text{.)}$$

At high $\tan\beta$, couplings of A, H^0 to b quark and τ become large.

- For $\tan\beta < 5$, $gg \to \phi$ is leading source of inclusive Higgs production.
- For $\tan\beta > 7$, $b\bar{b} \to \phi$ becomes dominant.
- At large $\tan\beta$, the branching fraction $B(H^0, A \to b\bar{b}) \simeq 0.89$.

Higgs in Association with b-Quarks

Generally, ϕ decays to two b-quarks at high p_T.

We work in a 5-flavor scheme. Use b-quark distribution functions to sum over large logarithms arising from collinear, low p_T quarks.

- For inclusive Higgs production, LO is $b\bar{b} \to \phi \to b\bar{b}$. Unfortunately swamped by QCD background.
- For two associated high-p_T b's, LO is $gg, q\bar{q} \to b\bar{b}\phi \to bb\overline{bb}$. Takes advantage of b-tagging but greatly reduced signal. (Dai, Gunion & Vega, '94 & '96; Richter-Was and Froidevaux, '97; Balazs, Diaz-Cruz, He,Tait & Yuan, 99)
- We choose an intermediate approach: LO is $bg \to b\phi \to bb\bar{b}$. Appropriate for 3 b-tagged jets at high p_T. (Campbell, Ellis, Maltoni & Willenbrock, '03; Huang and Zhu, '99)

Signal

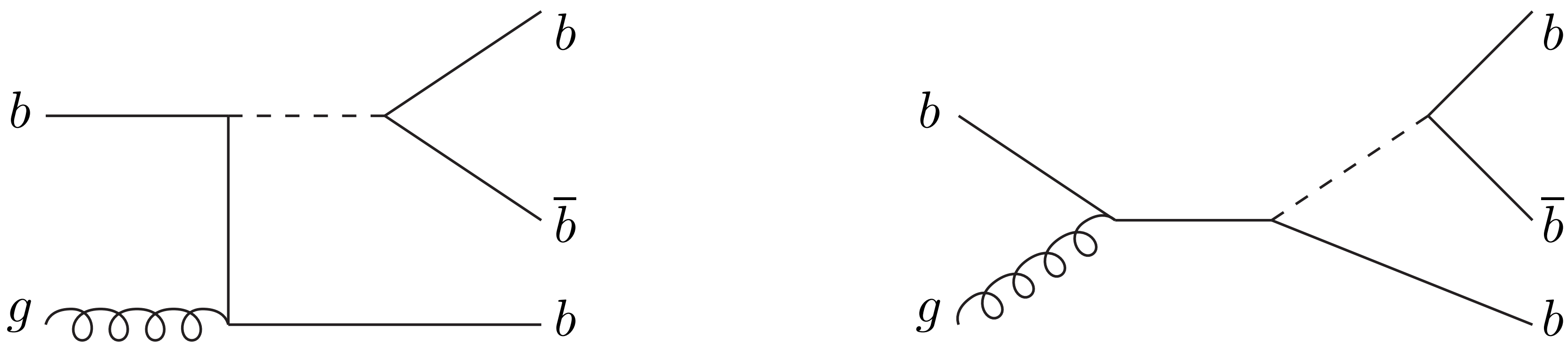
We generate a 3 b-quark signal using the above processes in a Monte Carlo program using amplitudes calculated by MadGraph.

We choose $\mu_F = \mu_R = m_H/4$ to minimize NLO corrections. (Maltoni, Sullivan & Willenbrock, 2003)

Program allows for potentially complicated cuts. In general we impose the following:

- Minimum p_T cuts on 1^{st},2^{nd}, 3^{rd} jets ordered by p_T.
- Three jets also required to pass maximum η.
- Three jets required to be well separated, $\Delta R > \Delta R_{min}$.
- At least one pair of jets satisfies $|M_{bb} - M_H| < \Delta M$.
- Veto events with missing E_T above some threshold.
- May impose cuts on $\Delta\phi$ angle between jets.

Feynman Graphs



NWA is generally good.

At high m_A and high $\tan\beta$:

$$\frac{m_A}{\Gamma_A} \sim 4\%$$
$$|\sigma_{NWA} - \sigma_{BWR}| \sim 10\%$$

For completeness we do all computations in a full Breit-Wigner treatment.

Backgrounds

We consider backgrounds from the following processes: Irreducible

- $bg \to bb\bar{b}$ (QCD)

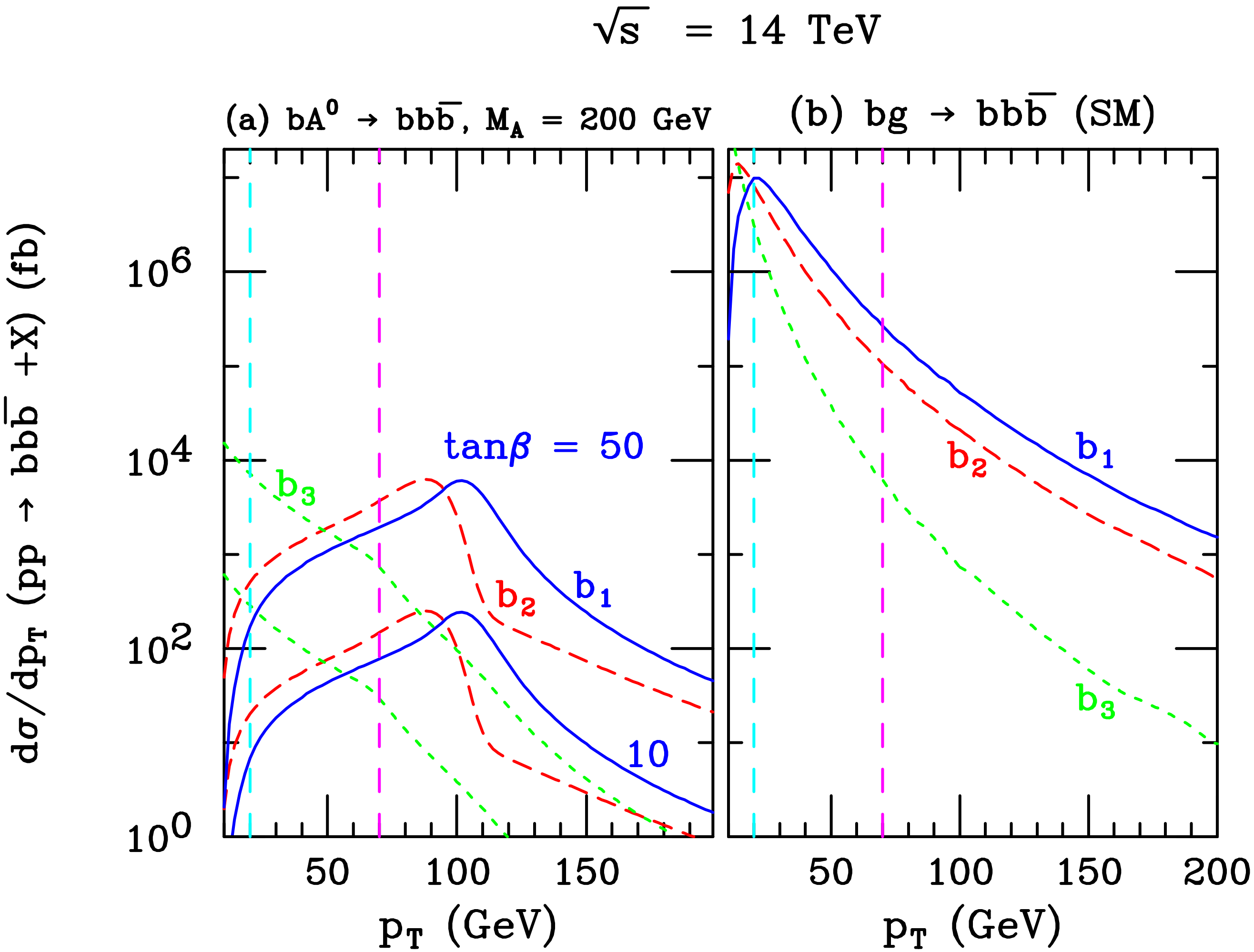
One or more mis-tagged particles

- $cg \to cb\bar{b}$
- $gg, qq \to gb\bar{b}$
- $qg \to qb\bar{b}$
- $pp \to tt \to be^{-}\nu\bar{b}d\bar{u}$ (or $c\bar{s}$)
- $pp \to tt \to bu\overline{db}d\bar{u}$

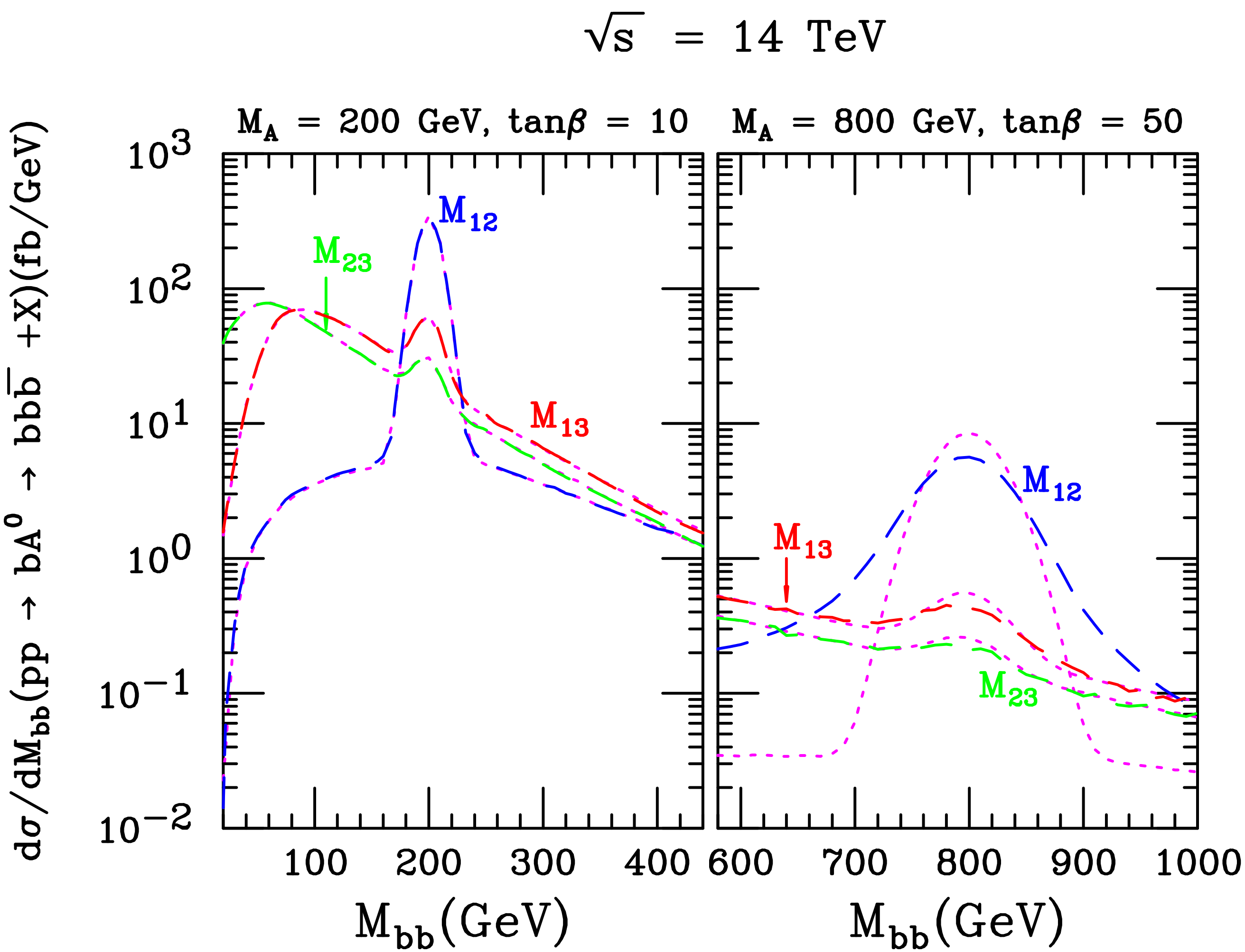
The latter are subjected to additional cuts:

- 4-jet veto for jets above some $p_{T min}$ and within $|\eta_{max}|$.
- Veto events with charged leptons above p_T threshold.

P_T Distributions



Mass Distributions



Cuts

We assume the b-tag efficiency $b_{eff} = 0.6$ for running at the LHC.
We take the mistag rates as $c_{mis} = 0.1; u, d, s, g_{mis} = 0.01$.

We impose the following cuts:

- $\eta < 2.5$
- Leading 3 jets pass $p_T > 70$ GeV (CMS TDR 2007; ATLAS TDR 1999,2003)
- $\Delta R > 0.7$ for 3 accepted jets.
- At least one $b\bar{b}$ pair has invariant mass $|M_{bb} - M_A| < \Delta M$.
  $\Delta M = 0.15$.
- $E^T_{miss} < 40 GeV$
- Veto more than 3 jets with $\eta < 2.5$ and $p_T > 15$ GeV.
- No cuts on ϕ or E_{lepton}.

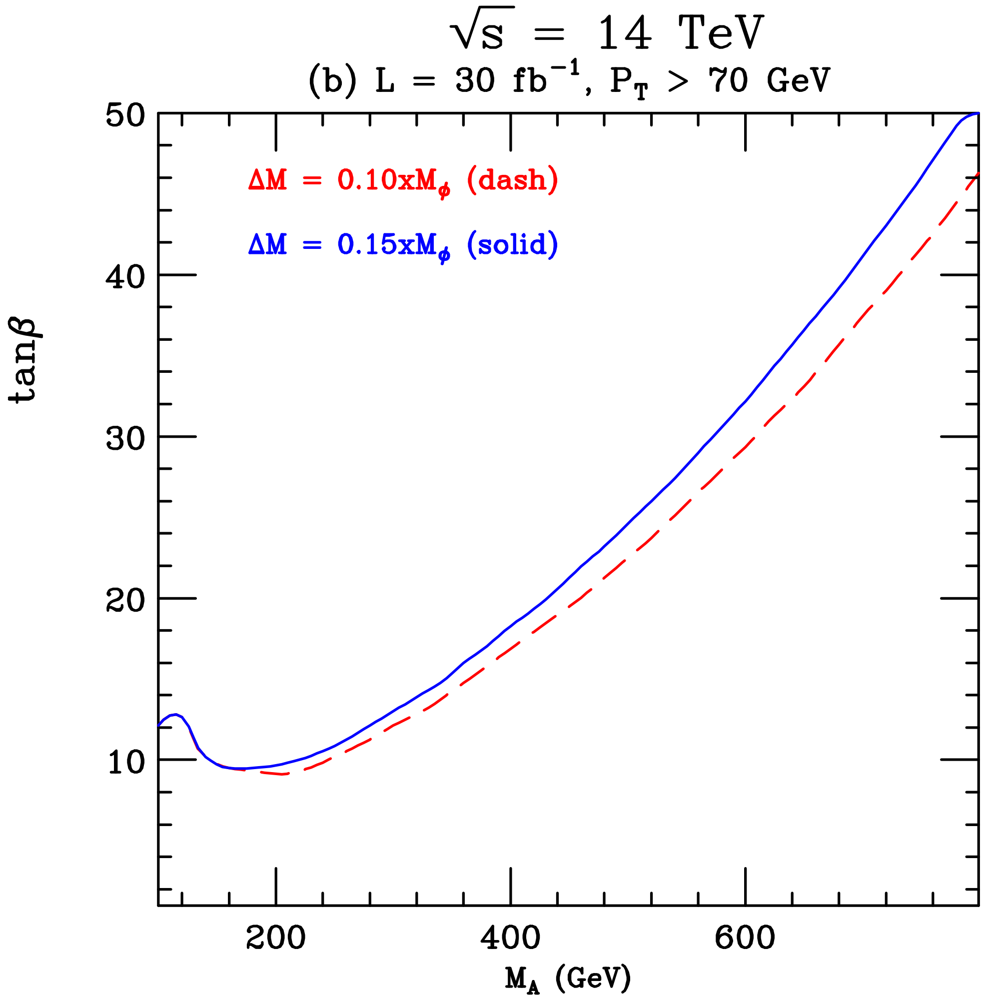
Comparison of Cross Sections

Signal	bbb	cbb	bbg	qbb
3.11×10^4	2.05×10^8	5.18×10^8	2.48×10^{10}	5.5×10^9
6.72×10^3	4.43×10^7	2.79×10^7	8.95×10^7	1.99×10^7
2.41×10^3	1.503×10^5	6.53×10^4	1.59×10^5	3.44×10^4
2.44×10^2	4.48×10^3	1.86×10^3	4.04×10^3	1.301×10^3

Minimal cuts, no tagging.
With tagging efficiencies.
Applying low cuts: $p_T > 20, 30, 50$ GeV.
Applying Level-1 (CMS) Trigger threshold: $p_T > 70$ GeV.

$pp \to t\bar{t}$ backgrounds are negligible after cuts.

MSSM Detection ($30\,fb^{-1}$)



Unified Models

We wish to work in a supersymmetric framework, but general soft SUSY-breaking terms introduce many free parameters.

$$M_i^2|\phi_i|^2, M_a\lambda_a\lambda_a, A_{ijk}\phi_i\phi_j\phi_k, B\mu HH$$

Various unified frameworks allow us to constrain our models to a few important parameters.

Parameters depend on messenger responsible for SUSY breaking, unification assumptions.

Two Minimal Models

mSUGRA

- Gravity acts as messenger between hidden sector and SM sector.
- Require unification at GUT scale, run RGEs to find low energy particle spectrum.
- Minimal set of parameters chosen as: $M_0, M_{\frac{1}{2}}, \tan\beta, A_0, sgn(\mu)$.

mAMSB

- Tree-level supergravity terms can be suppressed in higher-dimensional models. SUSY breaking terms induced by super-conformal anomaly may become dominant.
- 1st and 2nd generation soft terms proportional to gauge group beta functions $\rightarrow$ no SUSY flavor problem.
- In generic AMSB, negative scalar squared masses are generated. mAMSB adds a universal M_0^2 to generate a minimal acceptable phenomenology.
- Parameterized by: $M_0, M_{\frac{3}{2}}, \tan\beta, sgn(\mu)$.

Constraints

Higgs production in association with b's becomes important at high $\tan\beta$. However, large $\tan\beta$ may induce large BSM effects in experimentally constrained phenomena.

$B_s \to \mu^+\mu^-$

SM predicts $BF(B_s \to \mu^+\mu^-) = 3.6 \times 10^{-9}$. [A.J. Buras (2009)]

Current Experimental Limits

- D0: $< 5.1 \times 10^{-8}$
- CDF:$< 4. \times 10^{-8}\star$
- CMS:$< 1.9 \times 10^{-8}$
- LHCb:$< 1.5 \times 10^{-8}$

$\star$ -CDF reports a weak signal corresponding to $BF = 1.8 \times 10^{-8}$.

LHCb was estimated to reach the SM limit with ~ 2fb^{-1} at 14 TeV. [LHCb Collaboration (2009)] Extrapolated to $BF = 7. \times 10^{-9}$ with 1fb^{-1} at 7 TeV. [Serra (2009)]

Penguin diagrams involving neutral Higgs scale as $(\tan\beta)^6$.

Measured Constraints

SUSY/Unification scenarios generally can induce Flavor-Changing effects.

$b \to s\gamma$ acts as a sensitive probe of new physics.

Experimentally measured:
BR$(B \to X_s\gamma) = (3.55 \pm 0.26) \times 10^{-4}$ [PDG (2010)]

Theory (SM):
BR $(b \to s\gamma) = (2.98 \pm 0.26) \times 10^{-4}$ [Becher & Neubert, 2007]
$= (3.15 \pm 0.23) \times 10^{-4}$ [Misiak et al., 2007]

mSUGRA favors smaller values relative to SM.

mAMSB can show enhancement.

Δa_μ

Anomalous muon magnetic moment $g-2$ acts as a precision EW probe of new physics.

Experiment: $a_\mu \equiv (g-2)/2 = (11659208.9 \pm 6.3) \times 10^{-10}$[PDG 2010]

Theory (SM): $a_\mu = (11659183.0 \pm 5.1) \times 10^{-10}$ [Teubner, Hagiwara, Liao, Martin & Nomura (2011)]

$\Delta a_\mu = (25.9 \pm 8.1) \times 10^{-10}$

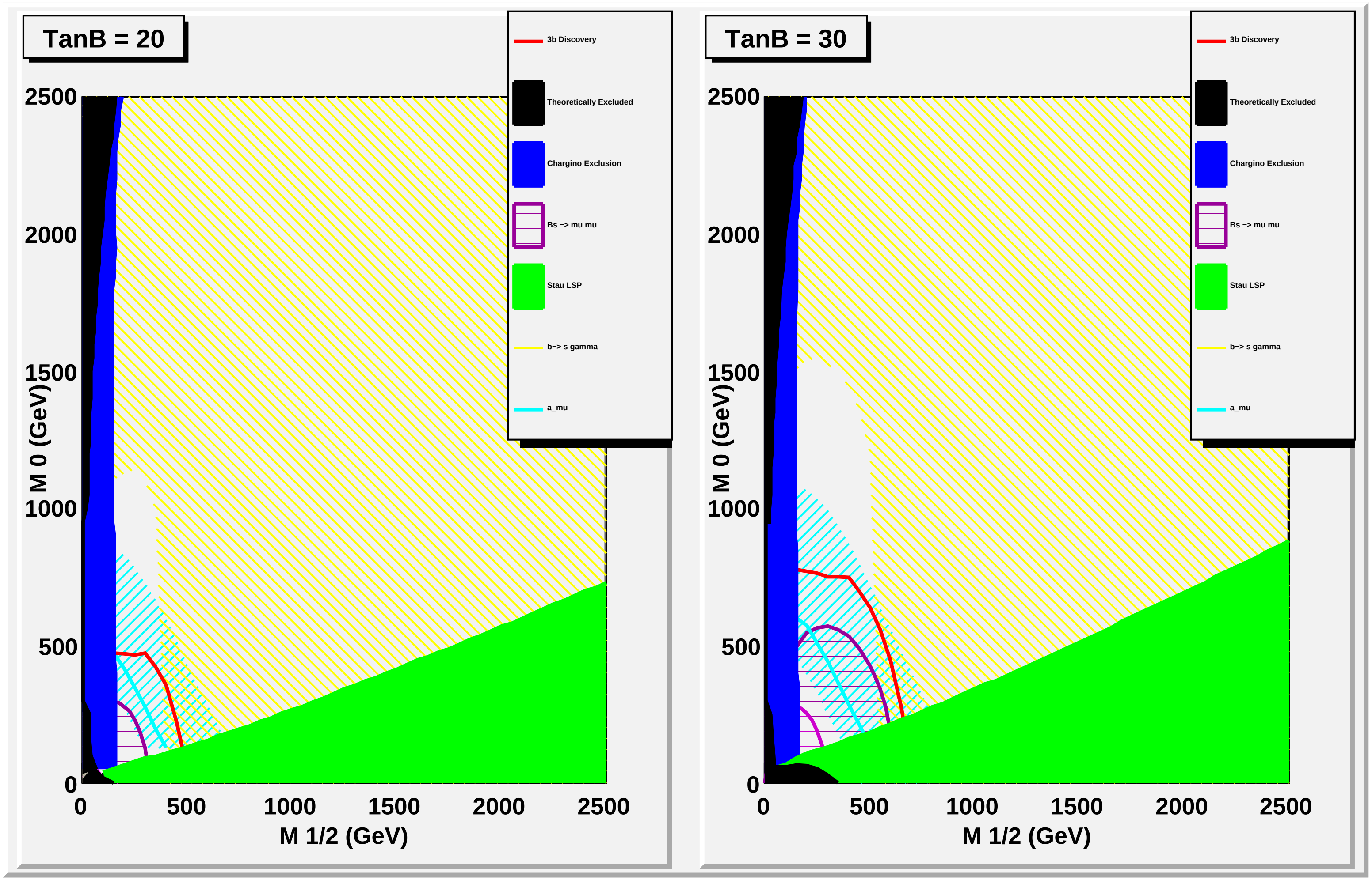
3.2σ discrepancy. Possible sign of new physics?

Sufficiently light SUSY contributions can account for observed a_μ.

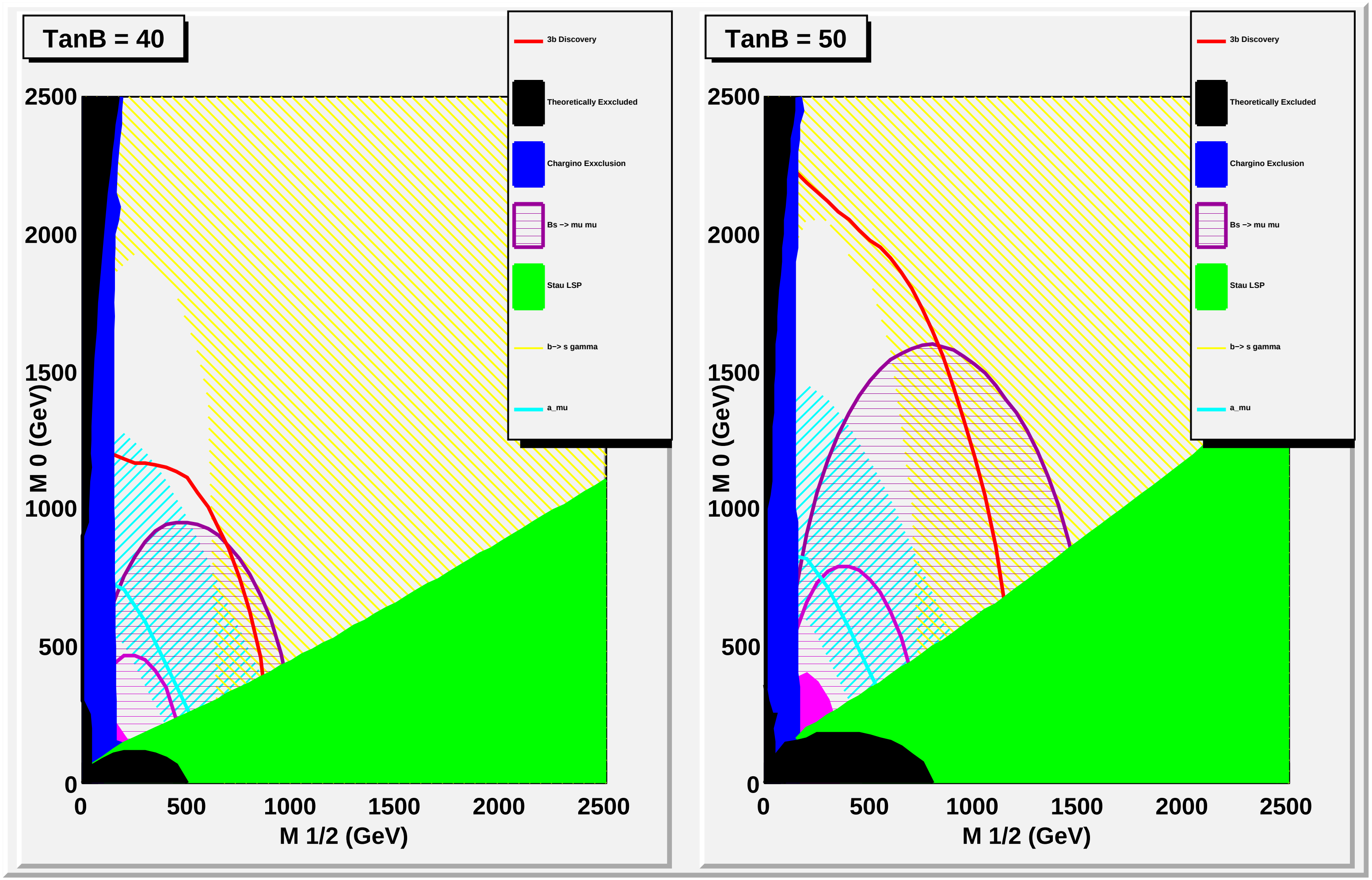
Computation Strategy

- We use ISAJET [Baer, Paige, Protopopescu & Tata] to calculate Higgs masses and decay widths as a function of unification parameters.
- Results are passed to MadGraph based Monte Carlo code for signal simulation.
- Backgrounds simulated with MadGraph for a range of mass windows; spline interpolated. We assume a K-factor of 2.
- ISATOOLS extension used to estimate $B_s \to \mu\mu$, $b \to s\gamma$, Δa_μ.
- We choose $sgn(\mu) > 0$ and $A_0 = 0$ for the results presented here.

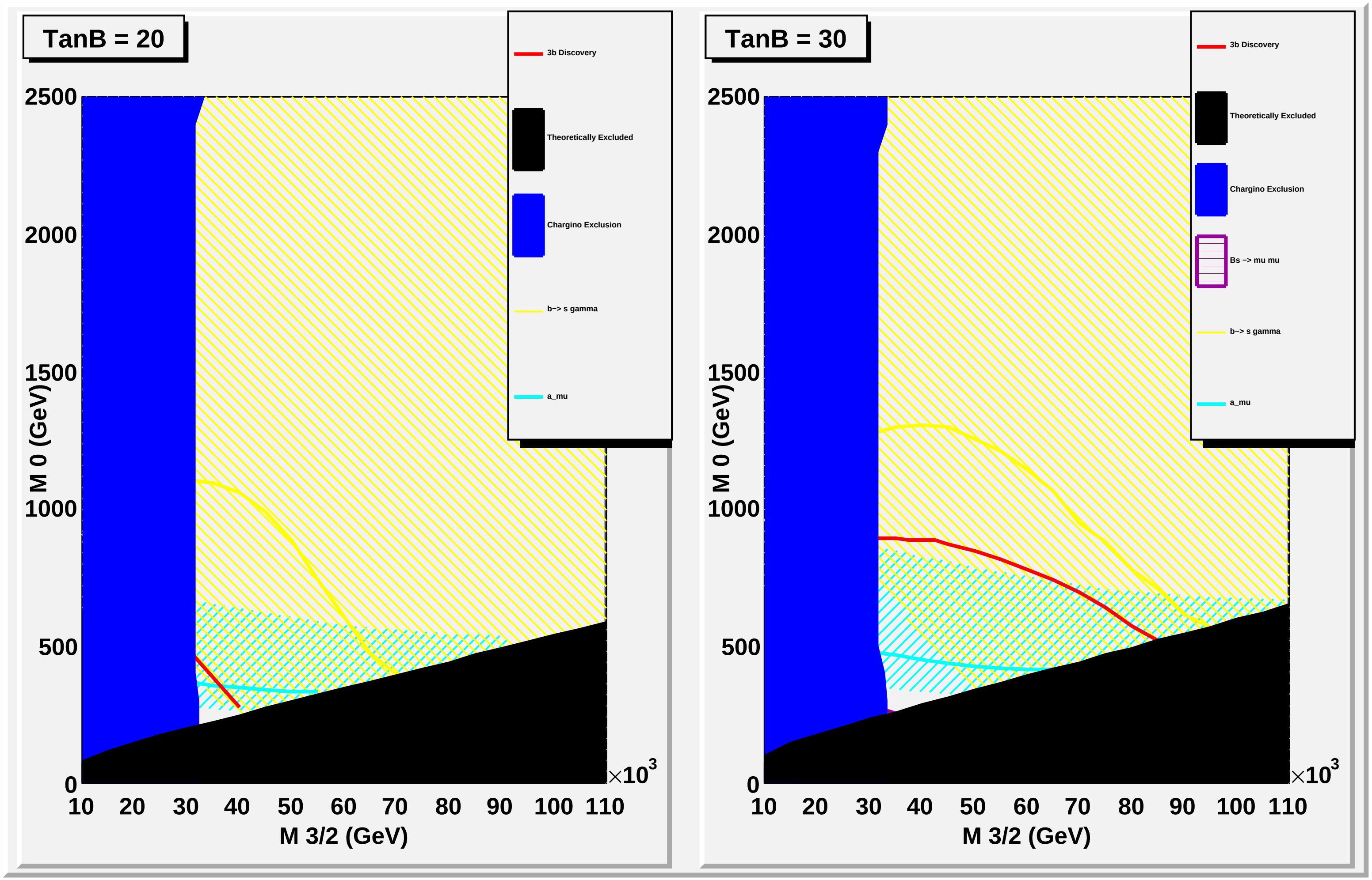
mSUGRA (mid $\tan\beta$)



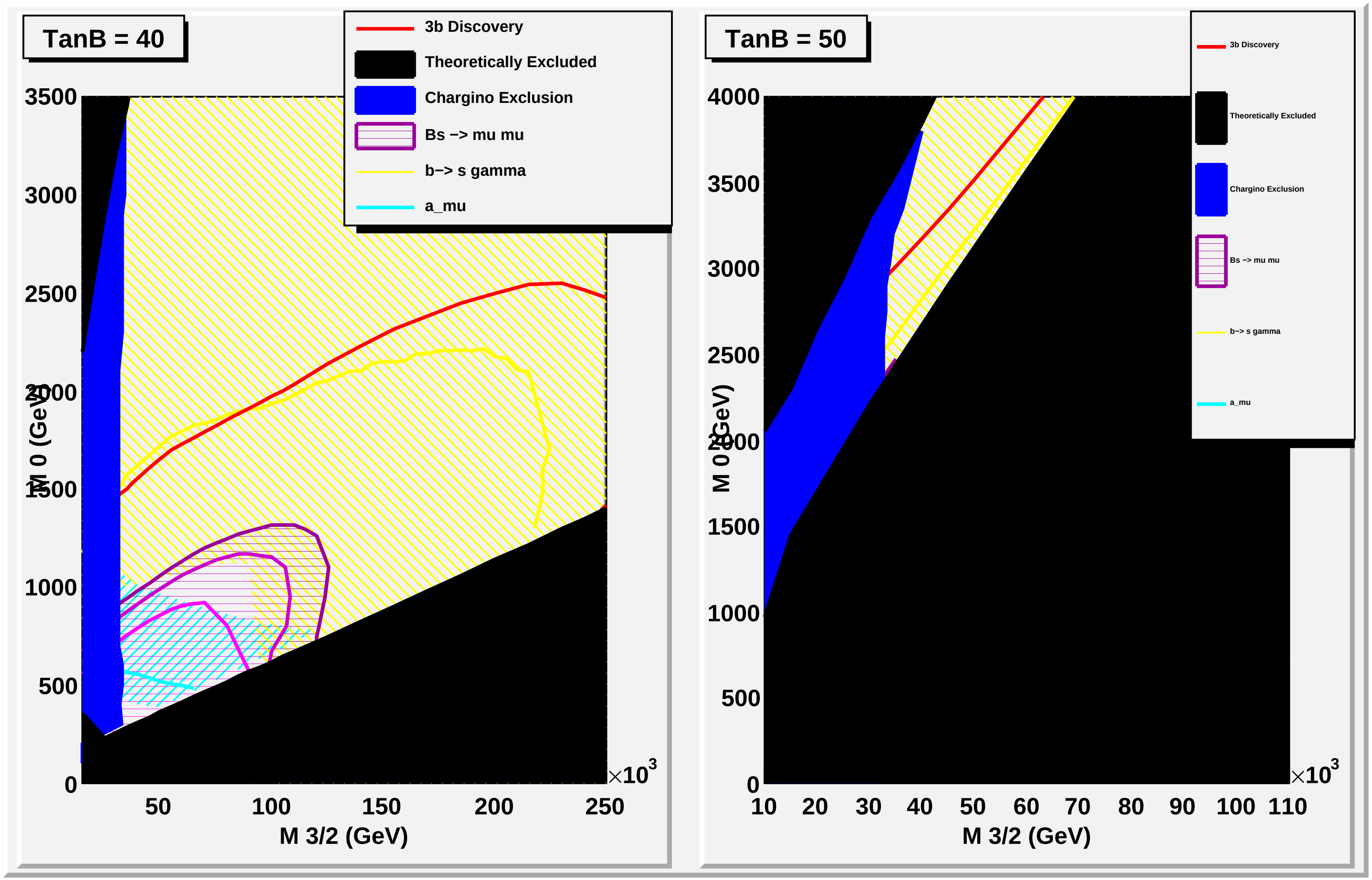
mSUGRA (high $tan\beta$)



mAMSB (mid $tan\beta$)



mAMSB (high $tan\beta$)



Conclusions

- The 3-b channel is a promising window for discovering neutral MSSM Higgs bosons in the case of high $\tan\beta$.
- QCD backgrounds are large but can be overcome with selective cuts and tight b-tagging.
- Significant parameter space covered in mSUGRA and mAMSB scenarios. Any excess for $B_s \to \mu\mu$ above SM likely corresponds to discoverable A^0, H^0.
- In mSUGRA, tension between $b \to s\gamma$ and Δa_μ leaves small windows if SUSY is to account for observed values.
- mAMSB better resolves $b \to s\gamma$ vs. Δa_μ. For $\tan\beta \gtrsim 40$, $B_s \to \mu\mu$ exclusion conflicts with Δa_μ. Theoretically disallowed regions become large for very high $\tan\beta$.
- Additional models to be considered: GMSB, mixed models, non-minimal models. Related channels $b\tau^+\tau^-$ and $b\mu^+\mu^-$, (Kao, Dicus, Malhotra & Wang, '08)