Athanasios Dedes

University of Bonn, Germany

XIV Workshop, Beyond the Standard Model, March 11 - 14, 2002,
Bad Honnef, Germany

$B_s \to \mu^+\mu^-$ in the Minimal Supergravity Scenario

In collaboration with:

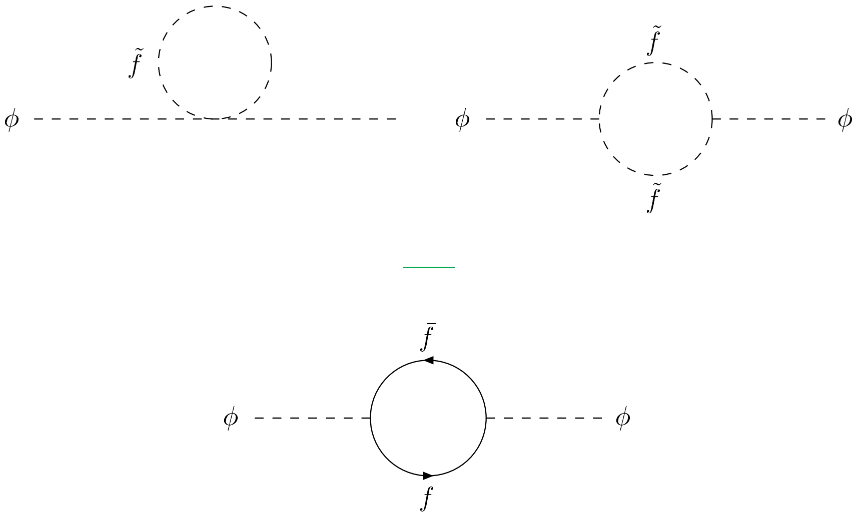
H. Dreiner and U. Nierste, Phys. Rev. Lett. **87**, 251804 (2001),
`hep-ph/0108037`

1. mSUGRA scenario (definitions)
2. The light Higgs boson mass
3. Muon anomalous magnetic moment, $(g-2)_\mu$
4. The decay $B_s \to \mu^+\mu^-$
5. Results
6. Work in progress.....
7. Conclusions

Supersymmetry

• Supersymmetry is a symmetry which relates particles of different spins. It has a virtue of allowing non trivial interactions between fermions and bosons.

• It is possible for the quadratic divergences to cancel between the bosonic and fermionic loops. To insure that this cancellation persists to all orders we need Supersymmetry.



• Supersymmetry is certainly not a symmetry in nature: for example, there is certainly no bosonic particle with the mass and charge of the electron. Supersymmetry must be broken at a scale of the electroweak symmetry breaking in order to keep in touch with the solution of the hierarchy problem.

Minimal SuperSymmetric Standard Model

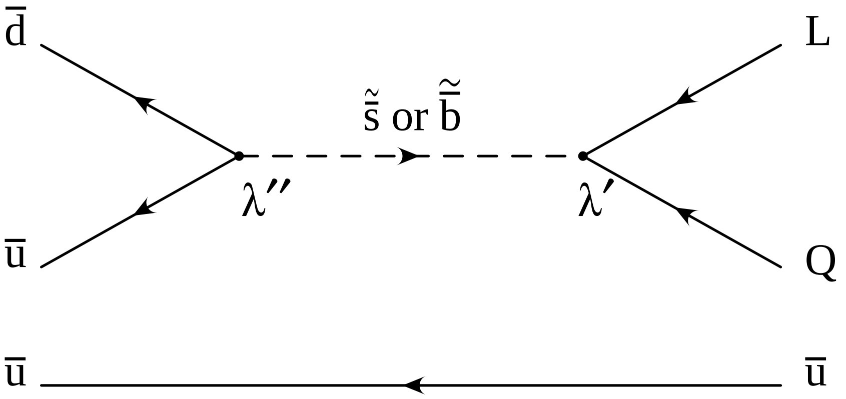
Superfields	$SU(3)_C \times SU(2)_L \times U(1)_Y$	Components
$Q_r^{i,\alpha}$	$(\mathbf{3}, \mathbf{2}, \frac{1}{6})$	$\begin{pmatrix} \tilde{u} \\ \tilde{d} \end{pmatrix}_L , \begin{pmatrix} u \\ d \end{pmatrix}_L$
$D^c_{r,\alpha}$	$(\bar{\mathbf{3}}, \mathbf{1}, \frac{1}{3})$	$\tilde{d}^c \ , \ d^c$
$U^c_{r,\alpha}$	$(\bar{\mathbf{3}}, \mathbf{1}, -\frac{2}{3})$	$\tilde{u}^c \ , \ u^c$
L_r^i	$(\mathbf{1}, \mathbf{2}, -\frac{1}{2})$	$\begin{pmatrix} \tilde{\nu}_e \\ \tilde{e} \end{pmatrix}_L , \begin{pmatrix} \nu_e \\ e \end{pmatrix}_L$
E_r^c	$(\mathbf{1}, \mathbf{1}, 1)$	$\tilde{e}^c \ , \ e^c$
H_1^i	$(\mathbf{1}, \mathbf{2}, -\frac{1}{2})$	$\begin{pmatrix} \tilde{H}_1^0 \\ \tilde{H}_1^- \end{pmatrix} , \begin{pmatrix} H_1^0 \\ H_1^- \end{pmatrix}$
H_2^i	$(\mathbf{1}, \mathbf{2}, \frac{1}{2})$	$\begin{pmatrix} \tilde{H}_2^+ \\ \tilde{H}_2^0 \end{pmatrix} , \begin{pmatrix} H_2^+ \\ H_2^0 \end{pmatrix}$

Superfields	$SU(3)_C \times SU(2)_L \times U(1)_Y$	Components
$V_3^{(R)}$	$(\mathbf{8}, \mathbf{1}, 0)$	$\tilde{G}^{(R)} \ , \ G_\mu^{(R)}$
$V_2^{(\Gamma)}$	$(\mathbf{1}, \mathbf{3}, 0)$	$\tilde{W}^{(\Gamma)} \ , \ W_\mu^{(\Gamma)}$
V_1	$(\mathbf{1}, \mathbf{1}, 0)$	$\tilde{B} \ , \ B_\mu$

Superpotential

$$
\begin{aligned}
W \;=\; & \epsilon_{ab}\left[(\mathbf{Y}_E)_{ij} L_i^a H_1^b \bar{E}_j + (\mathbf{Y}_D)_{ij} Q_i^{ax} H_1^b \bar{D}_{jx} + (\mathbf{Y}_U)_{ij} Q_i^{ax} H_2^b \bar{U}_{jx}\right] \\
& + \epsilon_{ab}\, \mu H_1^a H_2^b \\
& + \epsilon_{ab}\left[\frac{1}{2}\lambda_{ijk} L_i^a L_j^b \bar{E}_k + \lambda'_{ijk} L_i^a Q_j^{xb} \bar{D}_{kx}\right] \qquad \to \not{L} \text{ violation} \\
& + \frac{1}{2}\epsilon_{xyz}\lambda''_{ijk} \bar{U}_i^x \bar{D}_j^y \bar{D}_k^z \qquad \to \not{B} \text{ violation} \\
& + \epsilon_{ab}\left[\kappa^i L_i^a H_2^b\right] \qquad \to \not{L} \text{ violation.}
\end{aligned}
$$

$$\Downarrow$$



Proton Decay!

- B number is violated by 9 λ''_{ijk} couplings
- L bumber is violated by 9 λ_{ijk} + 27 λ'_{ijk} + 3 κ_i couplings

Minimal Supergravity Scenario

• Since the most general parametrization of SUSY breaking introduces more than 100 parameters a construction of a model with few parameters is needed : mSUGRA seems the most elegant!

• Supergravity $\to$ local SUSY transformations

Supergravity Scalar Potential :

H. P. Nilles '82,

A. Chamseddine, R. Arnowitt, P. Nath, '82

R. Barbieri, S. Ferrara, C. Savoy, '82

L. Hall, J. Lykken, S. Weinberg, '83

S. K. Soni, H. A. Weldon, '83

$$\mathcal{V} = e^{\left(\frac{Z_A^\dagger Z_A}{M^2}\right)} \left[F_A^\dagger F_A - 3\frac{f^\dagger f}{M^2}\right] + \frac{1}{2} D^\alpha D^\alpha ,$$

$\surd$ $\mathcal{V}$ not positive definite! so it could be spontaneous SUSY breaking : $< F_A > \neq 0$ with zero vacuum energy, $V = 0$

$\to$ New terms arive!

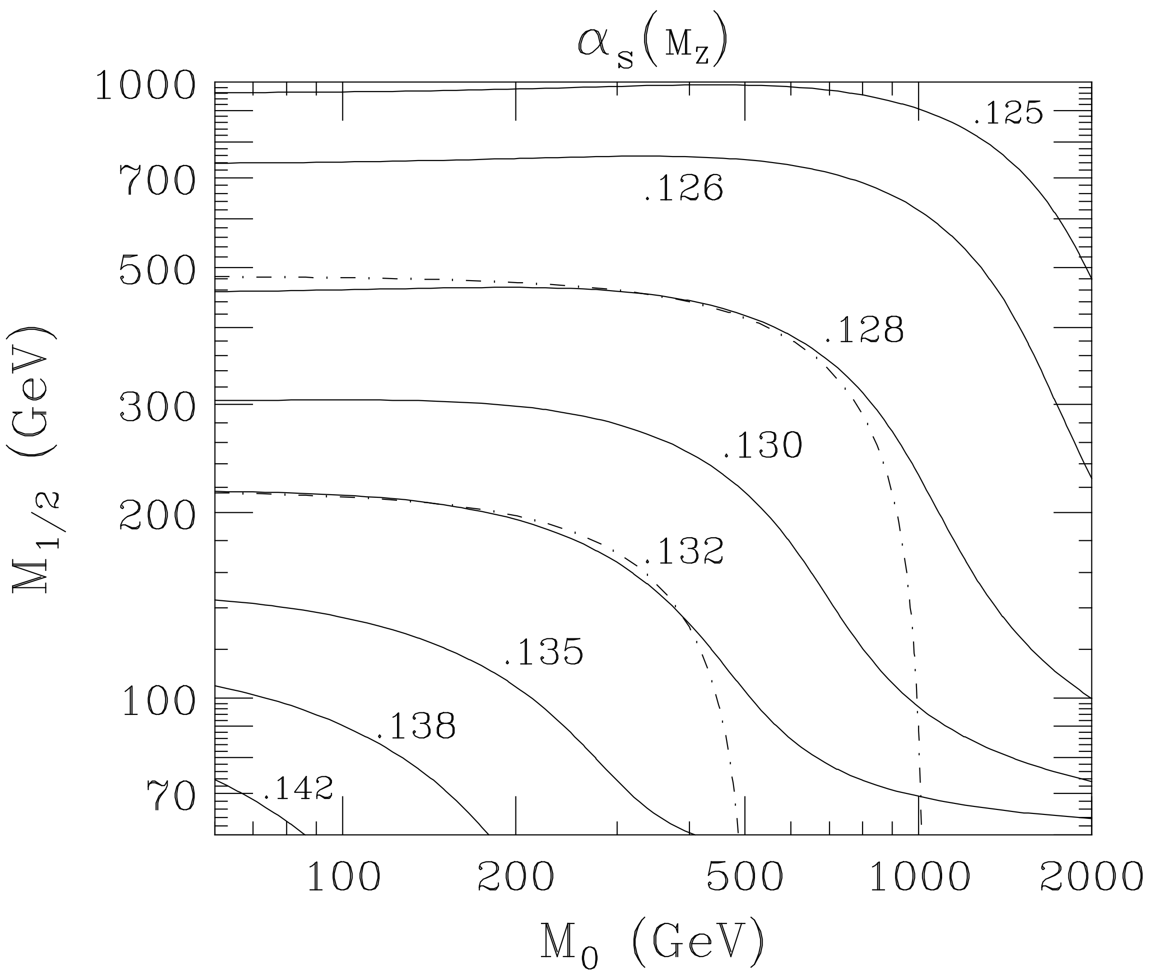
• $m_{ij}^2 = M_0^2 \, \delta_{ij}$, • $M_1 = M_2 = M_3 = M_{1/2}$

• $A_{ijk} = A_0^2$, • ϕ_{A_0}

• $B_{ij} = B_0 \, \delta_{ij}$, • ϕ_{B_0}

Gauge coupling Unification in the MSSM

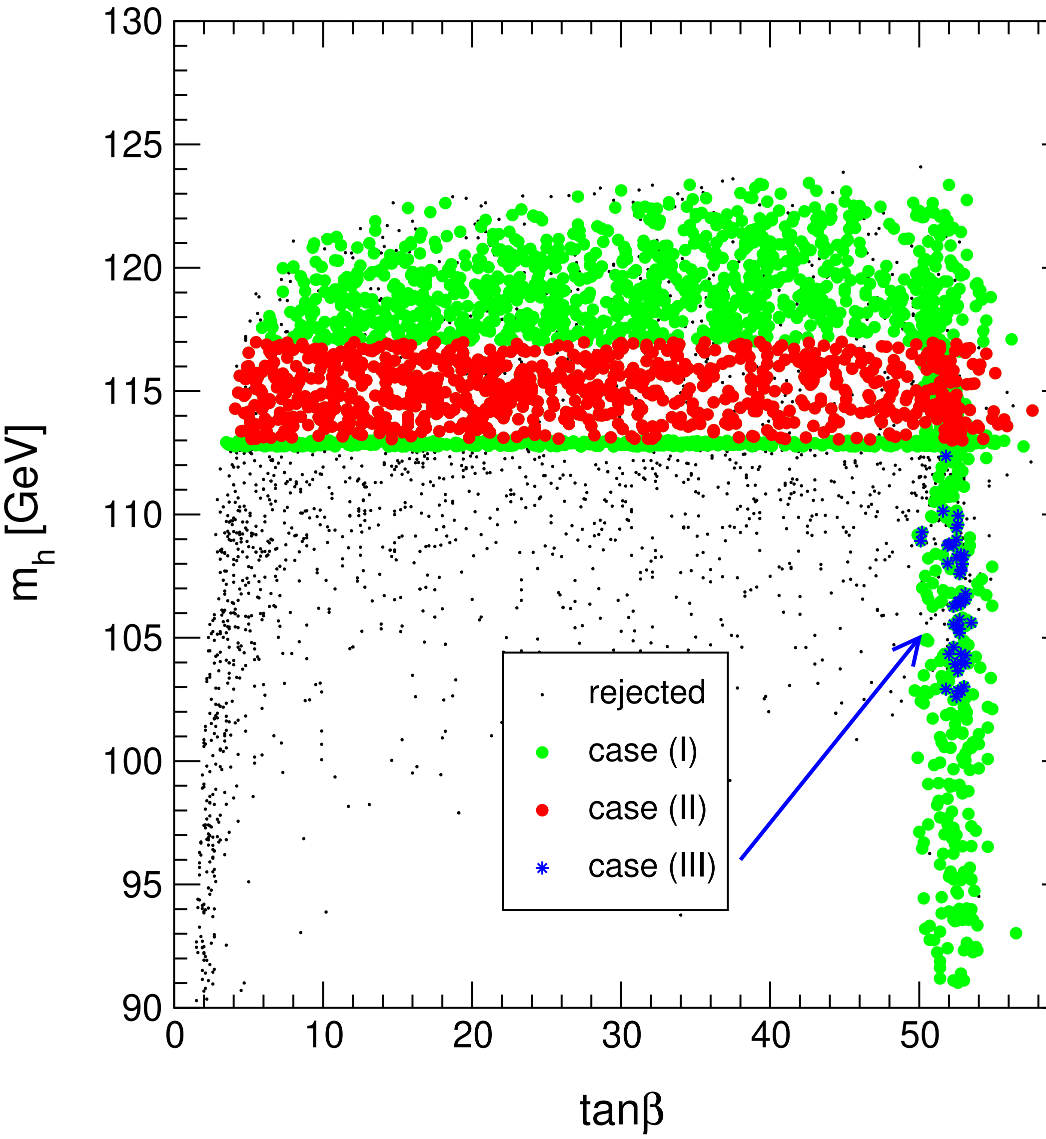
- 2 loop + thresholds from SUSY particles



$\Rightarrow$ but $\alpha_s^{exp} = 0.118 \pm 0.002 \Rightarrow$ We need a GUT model !!

- Minimal SU(5) model : Large $\alpha_s > 0.13$
- Missing Doublet model based on SU(5) gauge group : Small $\alpha_s < 0.12$
- Flipped SU(5) and SO(10) correct values of α_s

The Light Higgs Boson in mSUGRA



$$50 \text{ GeV} \leq M_0 \leq 1 \text{ TeV}$$

$$50 \text{ GeV} \leq M_{1/2} \leq 1 \text{ TeV}$$

$$-3 \text{ TeV} \leq A_0 \leq 3 \text{ TeV}$$

$$1.5 \leq \tan\beta \leq 60$$

$$\mu = \pm 1$$

S. Ambrosanio, A. Dedes, S. Heinemeyer, S. Su and G. Weiglein '01

$(g-2)_\mu$: Before November 2001...

• Based on Davier-Höcker calculation for the Hadronic contributions to the muon $g-2$, BNL reports a 2.6σ deviation from the SM

There are four possible interpretations of this discrepancy :

- a statistical fluctuation with 0.9% probability.
- something is "wrong" with the experiment
- something is "wrong" with the theoretical analysis of the hadronic and/or the light by light contribution to the muon anomalous magnetic moment.
- the by far most exciting possibility:

there is "New Physics" BSM

$$21.5 \times 10^{-10} \lesssim \delta a_\mu \lesssim 63.7 \times 10^{-10} \quad @90\%\ \mathrm{CL}$$

- δa_μ is positive
- δa_μ is of the same order of the EW contributions, $\delta a_\mu^{NP} \propto \frac{G_F m_\mu^2}{4\pi^2\sqrt{2}}$

• mSUGRA

$$(\delta a_\mu)_{SUSY} \propto \tan\beta \, \frac{f(M_0)}{M_{1/2}^2}$$

invites large $\tan\beta \gtrsim 10$ and $M_{1/2} \lesssim 750$ GeV

$(g-2)_\mu$: After November 2001...

M. Knecht, A. Nyffeler, M. Perrottet and E. De Rafael Nov. '01

M. Hayakawa and T. Kinoshita, Dec. '01

- : A mistake on the light by light scattering calculation :

$$-4.2 \times 10^{-10} \lesssim \delta a_\mu \lesssim 41.3 \times 10^{-10} \quad @90\%\ \mathrm{CL}$$

$\to$ only just above 1σ significance...

$\surd$ A more definite claim is waiting for a more precise a_μ measurement...

$\to$ one ideally wishes to study other observables whose sensitivity to supersymmetric loop corrections is correlated with δa_μ.

$B_s \to \mu^+\mu^-$ vs. $B \to X_s\gamma$

- SUSY modifies B-meson observables if $\tan\beta$ is large [$\Rightarrow Y_b$ large]
- Especially sensitive observables : $B \to X_s\gamma, B \to l^+l^-$
  - $B \to X_s\gamma$: relies on a cancelation between $H^\pm - t$ and $\tilde{\chi} - \tilde{t}$ loops.
  - In mSUGRA the low energy value for the trilinear term A_t is dominated by $M_{1/2}$, $A_t \simeq -2M_{1/2}$. Then $\mu > 0$ implies that the charged-Higgs-top loop and the chargino-stop loop tend to cancel in $\mathcal{B}(B \to X_s\gamma)$, so that the sensitivity to mSUGRA corrections is weakened.
  - $B \to l^+l^-$: large for large $\tan\beta$, almost independent from the sign of μ. No accidental cancelation required!
  - Since $\mathcal{B}(B \to \ell^+\ell^-) \propto m_\ell^2$, the branching ratio is largest for $\ell = \tau$: hard to detect!
  - branching ratios of B_d mesons are smaller by a factor of $|V_{td}/V_{ts}|^2 \lesssim 0.06$.
  - BaBar and BELLE could look for $B_d \to \tau^+\tau^-$?

K. S. Babu and C. Kolda, '99,

C. Huang, W. Liao and Q. Yan, '99

P. H. Chankowski and L. Slawianowska, '01,

C. Bobeth, T. Ewerth, F. Kruger and J. Urban, '01

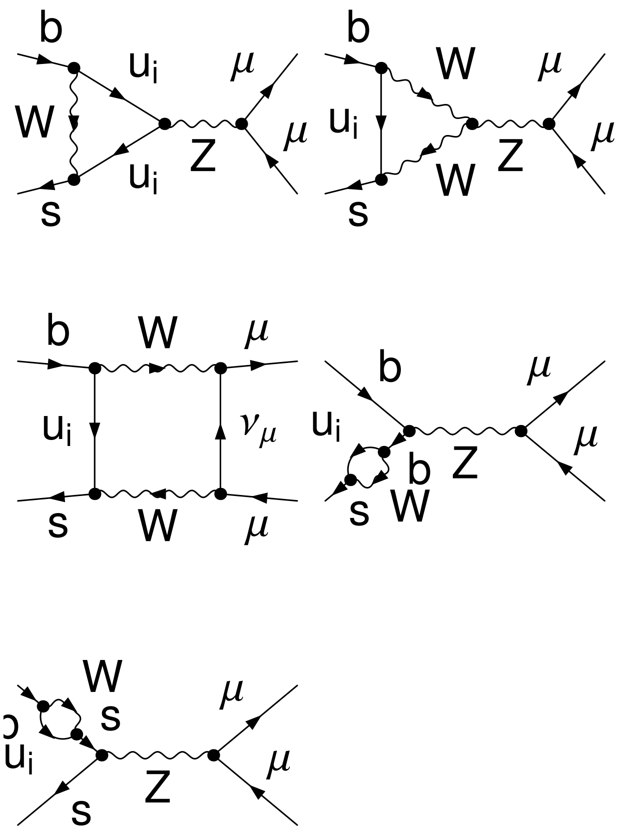
G. Isidori, A. Retico, '01.

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

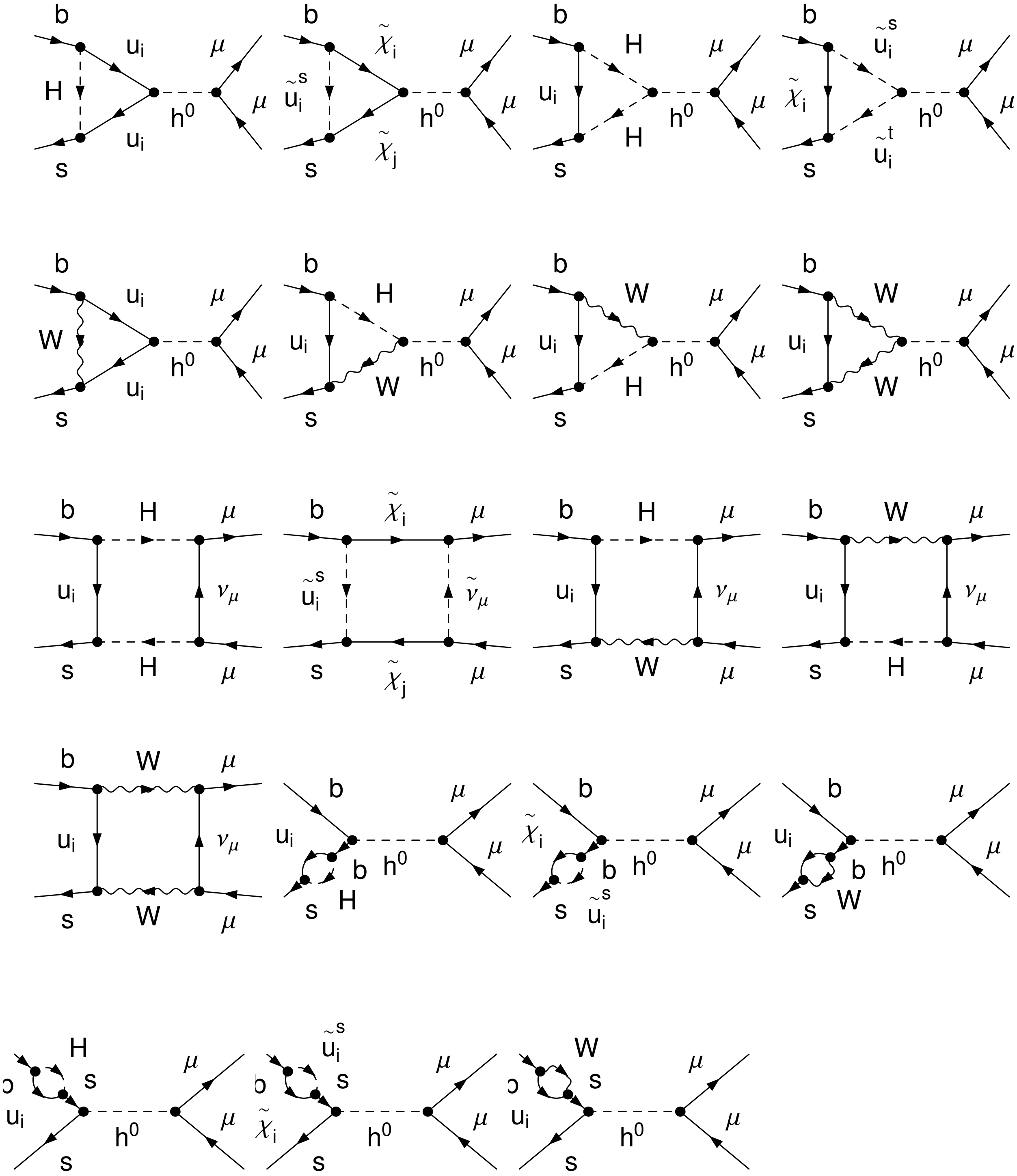
$$\mathcal{H}_{eff} = -\frac{4G_F}{\sqrt{2}} V_{tb} V_{ts}^* [c_{10}\mathcal{O}_{10} + c_S \mathcal{O}_S + c_P \mathcal{O}_P]$$

$$\begin{aligned}
\mathcal{O}_{10} &= \frac{e^2}{16\pi^2} (\bar{s}\gamma^\mu P_L b)(\bar{l}\gamma_\mu \gamma_5 l) \\
\mathcal{O}_S &= \frac{e^2}{16\pi^2} m_b (\bar{s} P_R b)(\bar{l} l) \\
\mathcal{O}_P &= \frac{e^2}{16\pi^2} m_b (\bar{s} P_R b)(\bar{l}\gamma_5 l)
\end{aligned}$$

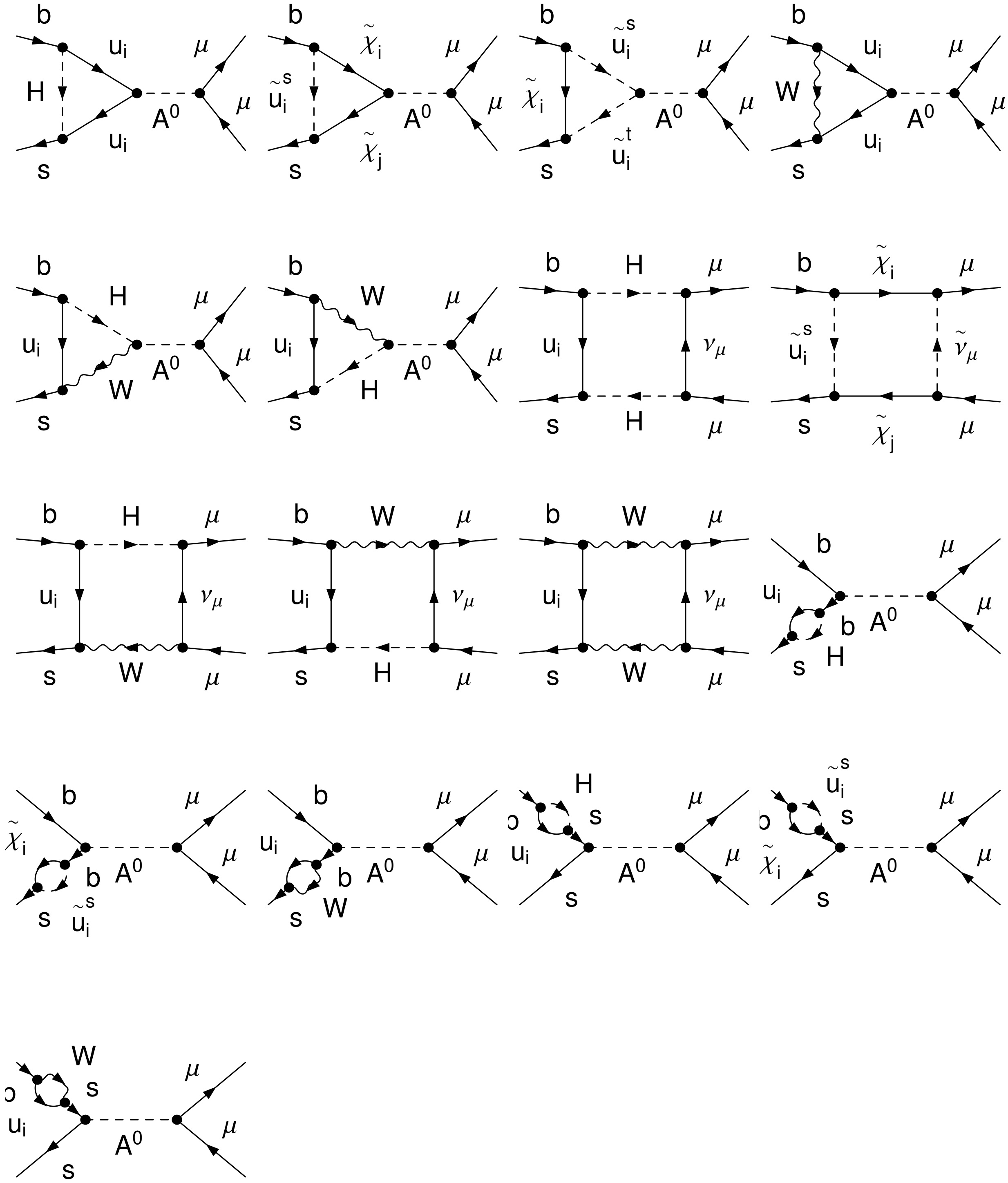
- SM $\to \mathcal{O}_{10}$



- $\text{MSSM} \to \mathcal{O}_S$



- MSSM $\to \mathcal{O}_P$



- Branching Ratio :

$$\mathcal{B}(B_s \to \mu^+\mu^-) = \frac{G_F^2 \alpha^2 M_{B_s}^3 \tau_{B_s} f_{B_s}^2}{64\pi^3} |V_{tb}^* V_{ts}|^2 \sqrt{1 - \frac{4m_\mu^2}{M_{B_s}^2}}$$

$$\times \ \{(1 - \frac{4m_\mu^2}{M_{B_s}^2})|\frac{M_{B_s}}{m_b + m_s} C_S|^2 + |\frac{2m_\mu}{M_{B_s}} C_{10} - \frac{M_{B_s}}{m_b + m_s} C_P|^2\}$$

- Standard Model :

G. Buchalla and A. J. Buras, '94

M. Misiak and J. Urban, '99

$$\mathcal{B}(B_s \to \mu^+\mu^-) = (3.7 \pm 1.2) \times 10^{-9}$$

- MSSM : Large $\tan\beta \gtrsim 40$

$$C_{S,P} \simeq \pm \frac{m_\mu}{4 s_W^2 M_W^2} \times \tan^3\beta \times \frac{\mu A_t}{M_A^2} \times C_0(\mu, m_{\tilde{t}_1}, m_{\tilde{t}_2})$$

- MSUGRA : Large $\tan\beta \gtrsim 40$

$$\mathcal{B}(B_s \to \mu^+\mu^-) \propto \tan^6\beta / M_{1/2}^4 \quad \text{for} \quad M_{1/2} \gg M_0$$

- For large $\tan\beta$, higher order corrections can be large

• $\tan\beta$-enhanced supersymmetric QCD corrections have been summed to all orders in perturbation theory.

M. Carena, D. Garcia, U. Nierste and C. E. Wagner, '00

• We have incorporated these dominant higher order corrections by simply replacing the b Yukawa coupling $h_b \propto m_b \tan\beta$ with $h_b^{\text{eff}} = h_b/(1+\Delta m_b)$

• QCD corrections to $B_s \to \mu^+\mu^-$ in the MSSM have been recently calculated.

C. Bobeth, A. J. Buras, F. Kruger and J. Urban, Dec. '01

• Experiment

• Only an experimental bound from CDF Run I

$$\mathcal{B}(B_s \to \mu^+\mu^-) < 2.6 \times 10^{-6}, \qquad \text{at } 95\% \text{ C.L.}$$

• Near Future experiment: CDF Run IIa and IIb

$\to$ Single event sensitivity $(\mathcal{S})$: Branching ratio for which we would expect to observe one event in 2 fb^{-1}

$$\mathcal{S}(B_s \to \mu^+\mu^-) = 1.0 \times 10^{-8} \times \frac{2\ \text{fb}^{-1}}{\int \mathcal{L}}$$

$\to$ 5×10^{-7} for 50 events with luminosity 2 fb^{-1}

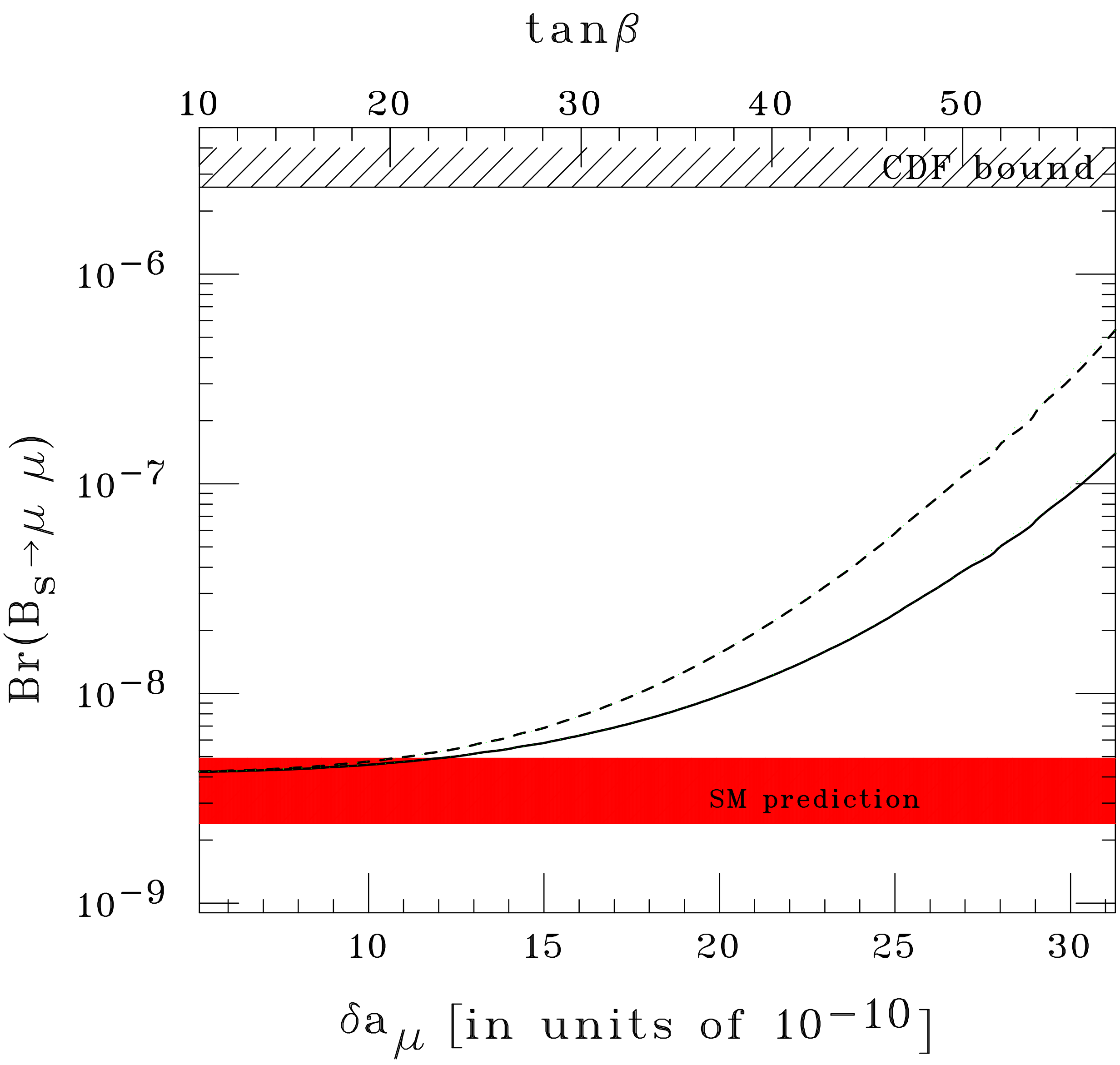
$\to$ 5×10^{-7} for 250-500 events with luminosity 10-20 fb^{-1}

K. Anikeev et al., "B physics at the Tevatron: Run II and beyond," arXiv:hep-ph/0201071.

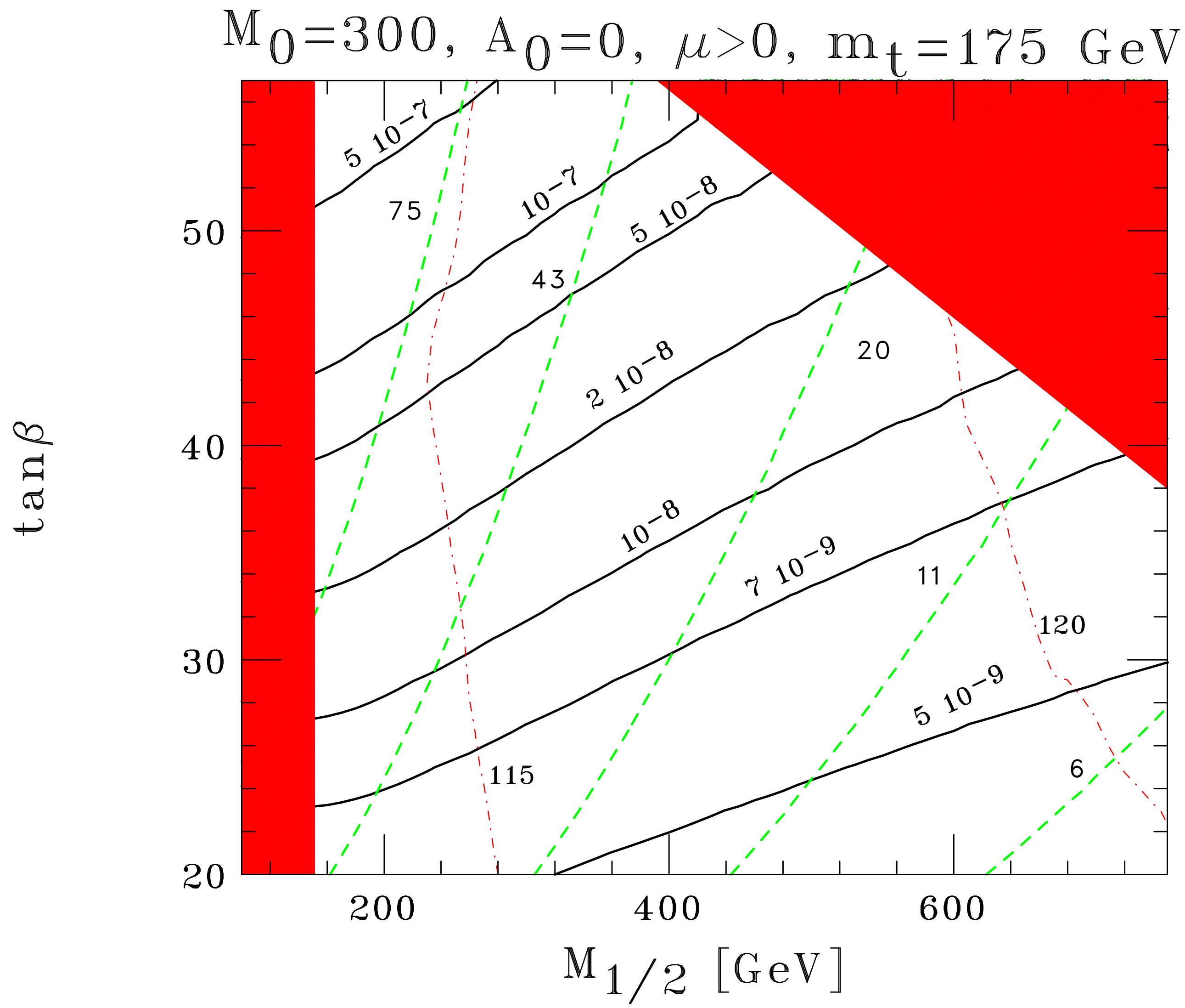
Results

- $M_{1/2} = 450, M_0 = 350, A_0 = 0, \mu > 0, m_t = 175$ GeV

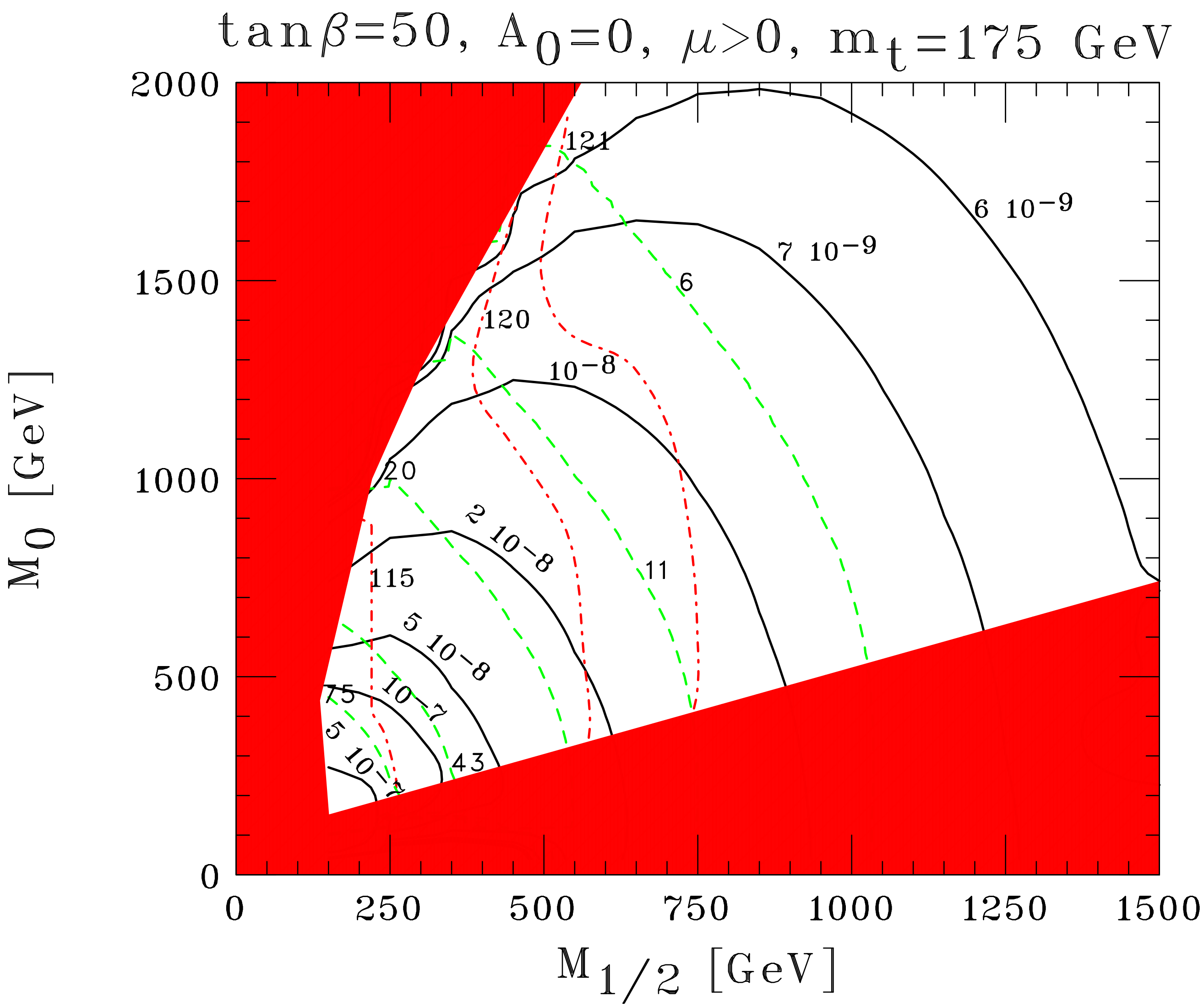
$\surd$ Fine with $b \to s\gamma$ and direct searches...



A. Dedes, H. K. Dreiner and U. Nierste, '01



A. Dedes, H. K. Dreiner and U. Nierste, '01

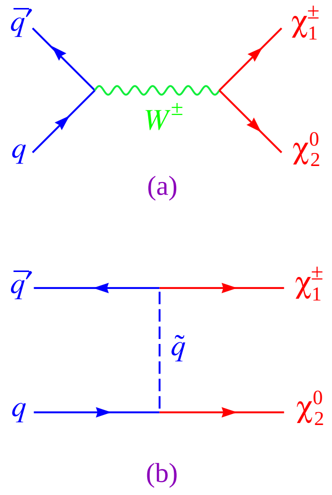


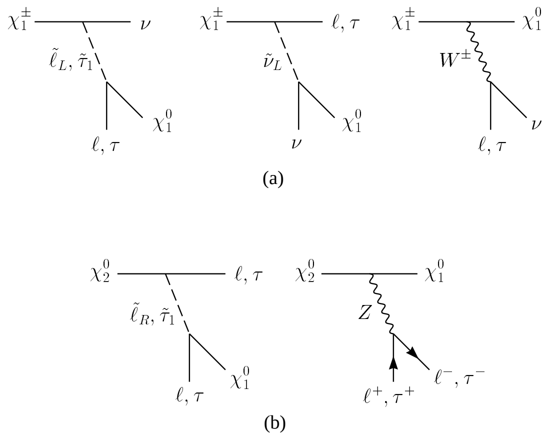
A. Dedes, H. K. Dreiner and U. Nierste, '01

Trileptons and $B_s \to \mu^+\mu^-$ at Tevatron

- The Mode

$q\bar{q}' \to \chi_1^{\pm}\chi_2^0$

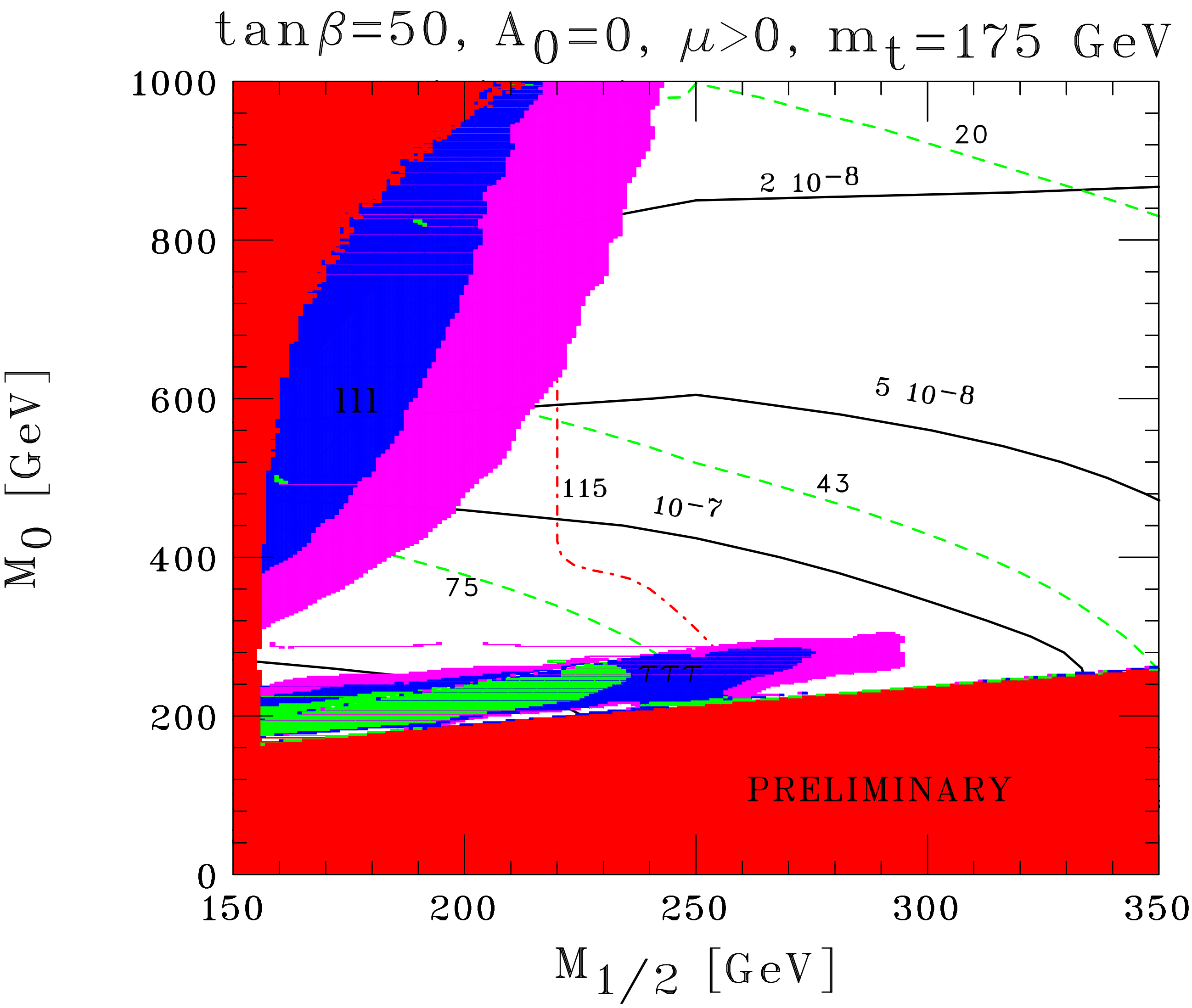




- Final State : $lll,\ l^{\pm}l^{\pm},\ l^{\pm}l^{\pm}\tau,\ l^{\pm}\tau\tau,\ \tau\tau\tau,\ \tau^{\pm}\tau^{\pm}$

Work in progress..........

A. Dedes, H. Dreiner, U. Nierste, P. Richardson



SO(10) Unification

Table 1: Five representative points of the fits. The first three are with Just So Higgs splitting and the last two are with D term splitting. All fits assume exact Yukawa unification at the GUT scale, except for 5 which has $\epsilon_b = -0.08$, $\epsilon_t = 0.02$. All fits are with one loop RG running from M_G to M_Z for dimensionful parameters, except for 3 which uses two loop running. All entries are in units of GeV to the appropriate power.

Data points		1	2	3	4	5
Input parameters						
α_G^{-1}		24.46	24.66	24.66	24.73	24.58
$M_G \times 10^{-16}$		3.36	3.07	3.07	3.13	3.16
ϵ_3		−0.042	−0.040	−0.040	−0.046	−0.039
λ		0.70	0.67	0.67	0.80	0.63
m_{16}		1500	2000	2000	2000	2000
m_{10}/m_{16}		1.35	1.35	1.35	1.20	1.33
Δm_H^2		0.13	0.13	0.12	0.07	0.05
$M_{1/2}$		250	350	350	350	300
μ		150	200	200	115	150
$\tan\beta$		51.2	50.5	50.6	54.3	51.1
A_0/m_{16}		−1.83	−1.87	−1.83	−0.37	−1.87
χ^2 observables	Exp (σ)					
M_Z	91.188 (0.091)	91.13	91.14	91.14	91.15	91.15
M_W	80.419 (0.080)	80.45	80.45	80.44	80.44	80.44
$G_\mu \times 10^5$	1.1664 (0.0012)	1.166	1.166	1.166	1.166	1.166
α_{EM}^{-1}	137.04 (0.14)	137.0	137.0	137.0	137.0	137.0
$\alpha_s(M_Z)$	0.118 (0.002)	0.1175	0.1176	0.1175	0.1161	0.1179
$\rho_{new} \times 10^3$	−0.200 (1.10)	0.696	0.460	0.437	0.035	0.265
M_t	174.3 (5.1)	175.5	174.6	174.4	177.9	174.1
$m_b(m_b)$	4.20 (0.20)	4.28	4.27	4.28	4.59	4.22
M_τ	1.7770 (0.0018)	1.777	1.777	1.777	1.777	1.777
TOTAL χ^2		1.50	0.87	0.91	5.42	0.45
h^0		116	116	117	115	116
H^0		120	121	121	117	120
A^0		110	110	111	110	110
H^+		148	148	149	146	148
$\tilde{\chi}_1^0$		86	130	130	86	99
$\tilde{\chi}_2^0$		135	190	189	126	152
$\tilde{\chi}_1^+$		123	178	177	105	131
$\tilde{g}$		661	913	898	902	787
$\tilde{t}_1$		135	222	235	1020	141
$\tilde{b}_1$		433	588	589	879	342
$\tilde{\tau}_1$		288	420	542	1173	693
$a_\mu^{SUSY} \times 10^{10}$	25.6 (16)	9.7	5.5	5.5	6.1	6.4

T. Blazek, R. Dermisek, S. Raby '02

$\to \mathcal{B}(B_s \to \mu^+\mu^-) \gtrsim 10^{-5}$ already excluded by CDF

Table 2: Four representative points of the fits. The first two are with Just So Higgs splitting and the last two are with D term splitting. All fits assume exact Yukawa unification at the GUT scale, except for 4 which has $\epsilon_b = -0.08$, $\epsilon_t = 0.02$. All fits are with one loop RG running from M_G to M_Z for dimensionful parameters. For these fits the branching ratio for $b \to s\gamma$ is included in χ^2. In addition, the CP odd Higgs mass m_A^0 is constrained to be 200 GeV. These points are thus consistent with both $B(b \to s\gamma)$ and $B_s \to \mu^+\mu^-$. In Fits 1, 2 we show the change in the $\tilde{t}_1$, $\tilde{b}_1$, $\tilde{\tau}_1$ masses if we fit $b \to s\,\gamma$ at the central value + 3σ.

Data points		1	2	3	4
Input parameters					
α_G^{-1}		24.72	24.78	24.75	24.62
$M_G \times 10^{-16}$		3.00	3.12	3.09	3.20
ϵ_3		−0.040	−0.041	−0.045	−0.043
λ		0.63	0.61	0.80	0.60
m_{16}		2000	3200	2000	2000
m_{10}/m_{16}		1.32	1.30	1.19	1.30
Δm_H^2		0.13	0.13	0.07	0.05
$M_{1/2}$		350	350	350	300
μ		200	150	115	150
$\tan\beta$		52.5	50.6	55.0	50.7
A_0/m_{16}		−1.71	−1.83	−0.05	−1.75
χ^2 observables	Exp(σ)				
M_Z	91.188 (0.091)	91.18	91.18	91.16	91.18
M_W	80.419 (0.080)	80.42	80.42	80.43	80.42
$G_\mu \times 10^5$	1.1664 (0.0012)	1.166	1.166	1.166	1.166
α_{EM}^{-1}	137.04 (0.14)	137.0	137.0	137.0	137.0
$\alpha_s(M_Z)$	0.118 (0.002)	0.1172	0.1173	0.1162	0.1167
$\rho_{new} \times 10^3$	−0.200 (1.10)	0.228	0.321	0.221	0.279
M_t	174.3 (5.1)	173.8	172.1	178.8	172.6
$m_b(m_b)$	4.20 (0.20)	4.46	4.42	4.56	4.50
M_τ	1.7770 (0.0018)	1.777	1.777	1.777	1.777
TOTAL χ^2		2.05	1.72	5.03	3.38
h^0		118	119	115	118
H^0		217	217	218	216
A^0		200	200	200	200
H^+		229	229	228	228
$\tilde{\chi}_1^0$		130	110	86	99
$\tilde{\chi}_2^0$		190	160	126	152
$\tilde{\chi}_1^+$		178	136	105	131
$\tilde{g}$		909	904	902	781
$\tilde{t}_1$		509 (−30)	511 (−27)	1067	443
$\tilde{b}_1$		749 (−42)	903 (−14)	900	550
$\tilde{\tau}_1$		459 (+47)	1001 (−25)	1173	854
$B(b \to s\gamma) \times 10^3$	0.296 (0.035)	0.297	0.297	0.297	0.297
$a_\mu^{SUSY} \times 10^{10}$	25.6 (16)	5.8	2.2	6.4	6.4

T. Blazek, R. Dermisek, S. Raby '02

!!!! Detailed analysis for $B_s \to \mu^+\mu^-$ is not done..

!!!! SO(10) predicts $B_s \to \mu^+\mu^-$ just around the corner...

Conclusions

√ Striking correlation between the muon anomalous magnetic moment a_μ and the branching ratio $\mathcal{B}(B_s \to \mu^+\mu^-)$ in mSUGRA scenarios.

√ If a reported excess on a_μ is caused by mSUGRA corrections with large $\tan\beta$, one faces more than an order of magnitude enhancement of $\mathcal{B}(B_s \to \mu^+\mu^-)$ over its SM value.

√ Well within reach of Run-II of the Tevatron.

√ The two combined measurements significantly constrain the mSUGRA parameters, allowing a determination of $\tan\beta$ and $M_{1/2}$.

√ A measurement of $\mathcal{B}(B_s \to \mu^+\mu^-)$ will further constrain the mass of the lightest Higgs boson.