Signals for New Physics in Rare Decays

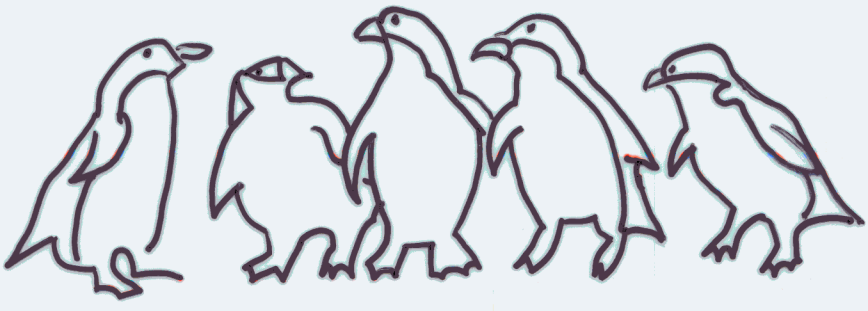
Overview ... For details see:

M. Misiak : SM $B \to X_s \gamma$ computations

G. Burdman : Exclusive $B \to K/K^* \ell^+\ell^-$

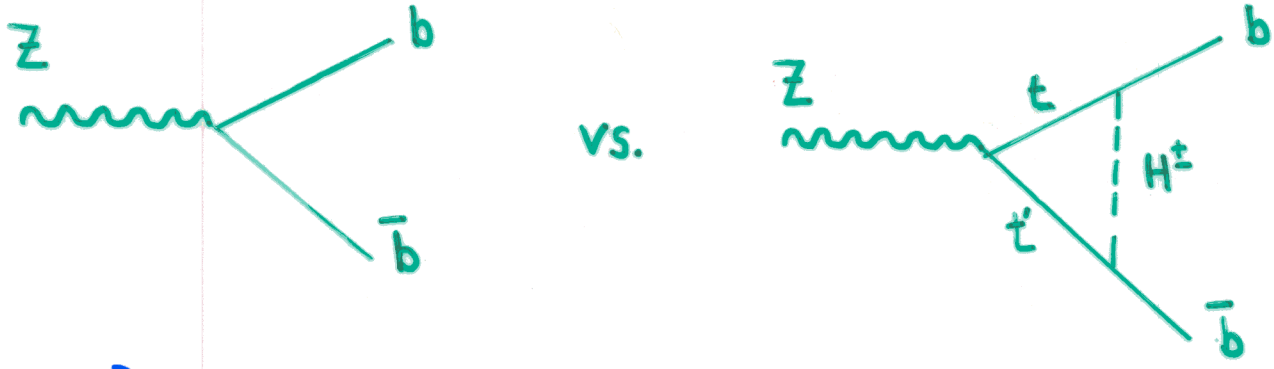
G. Hiller : Inclusive $B \to X_s \ell^+\ell^-$

J. Hewett
SLAC '02



FCNC have longstanding history of providing strong model building constraints

Precision EW:



Rare Decays:

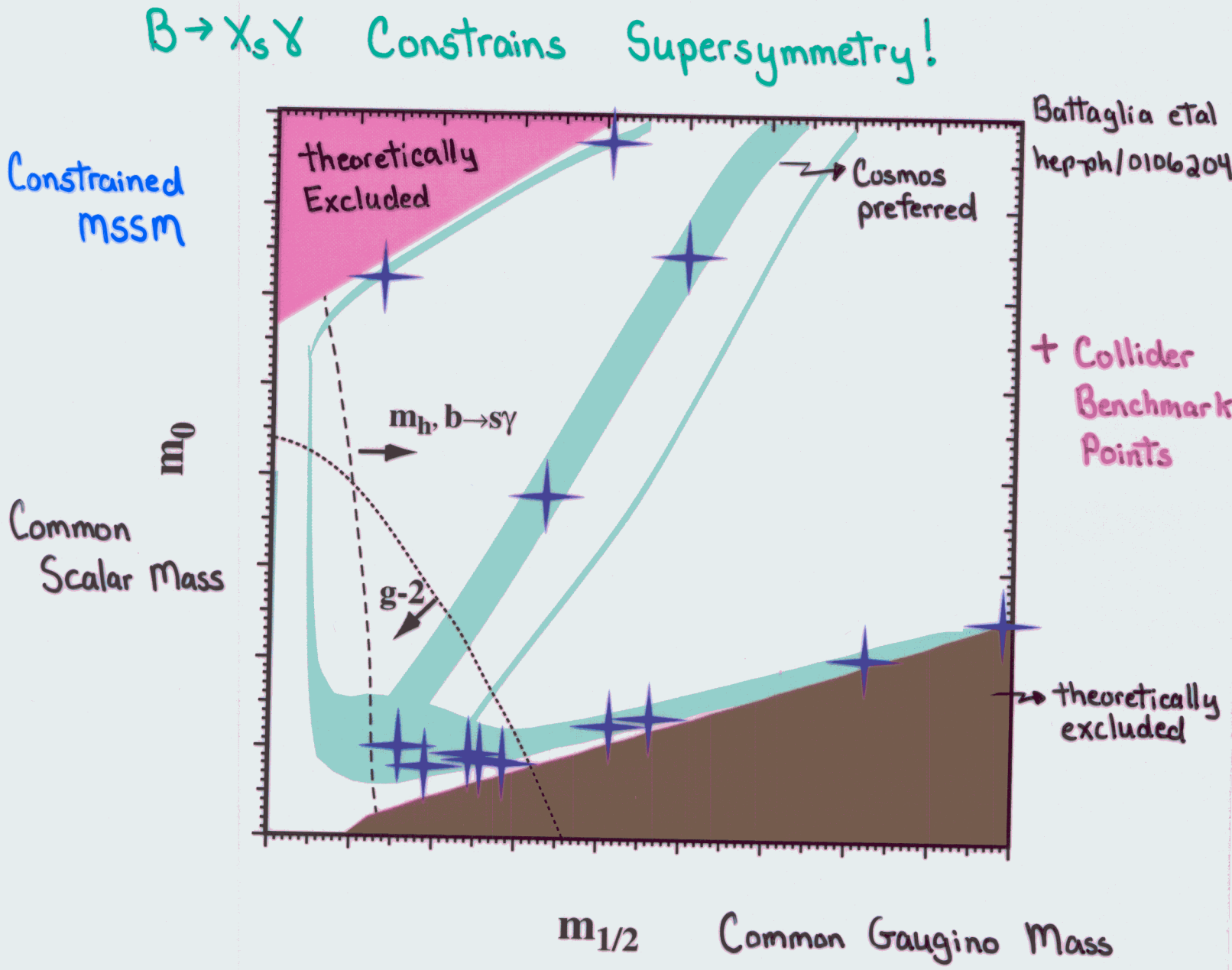
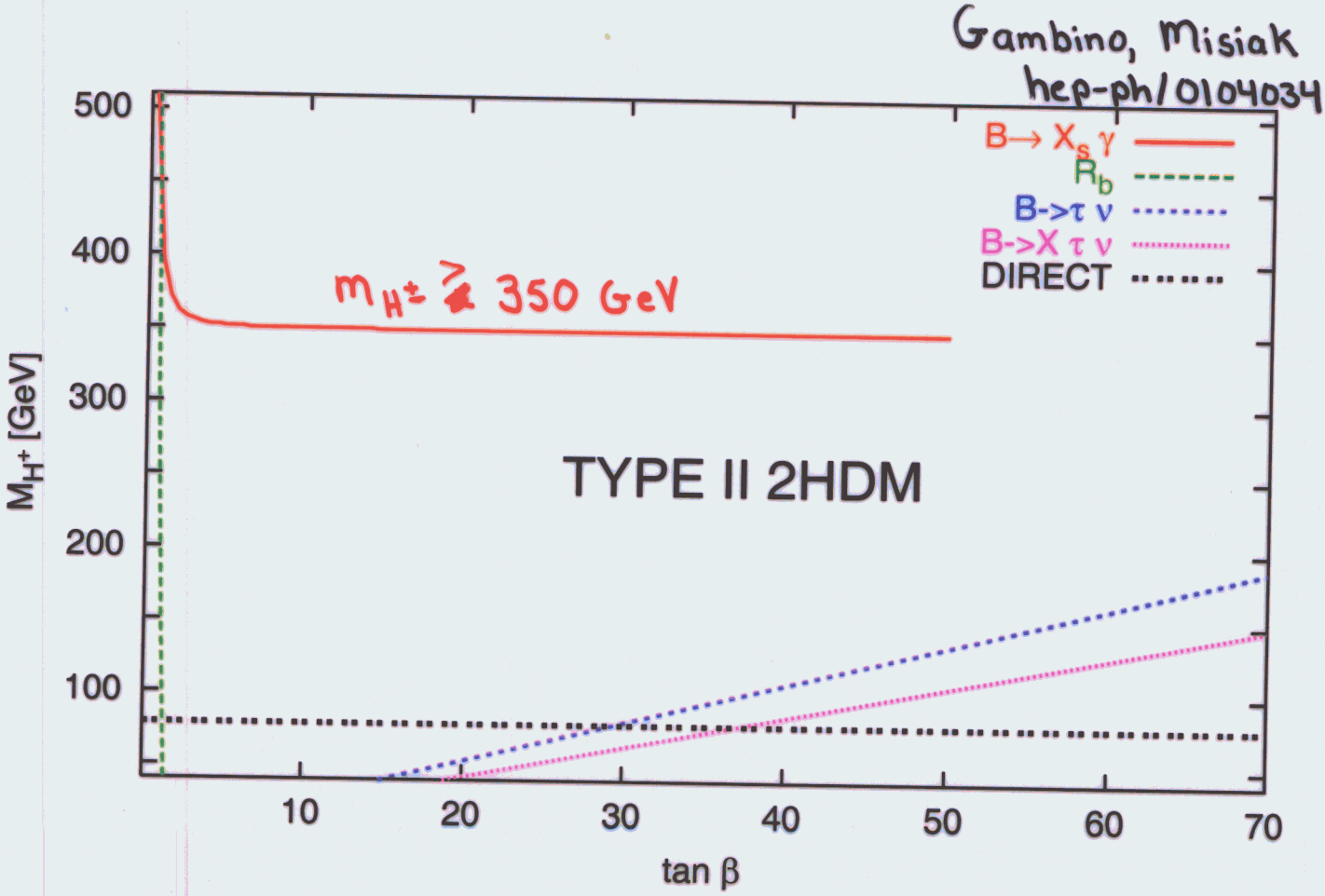


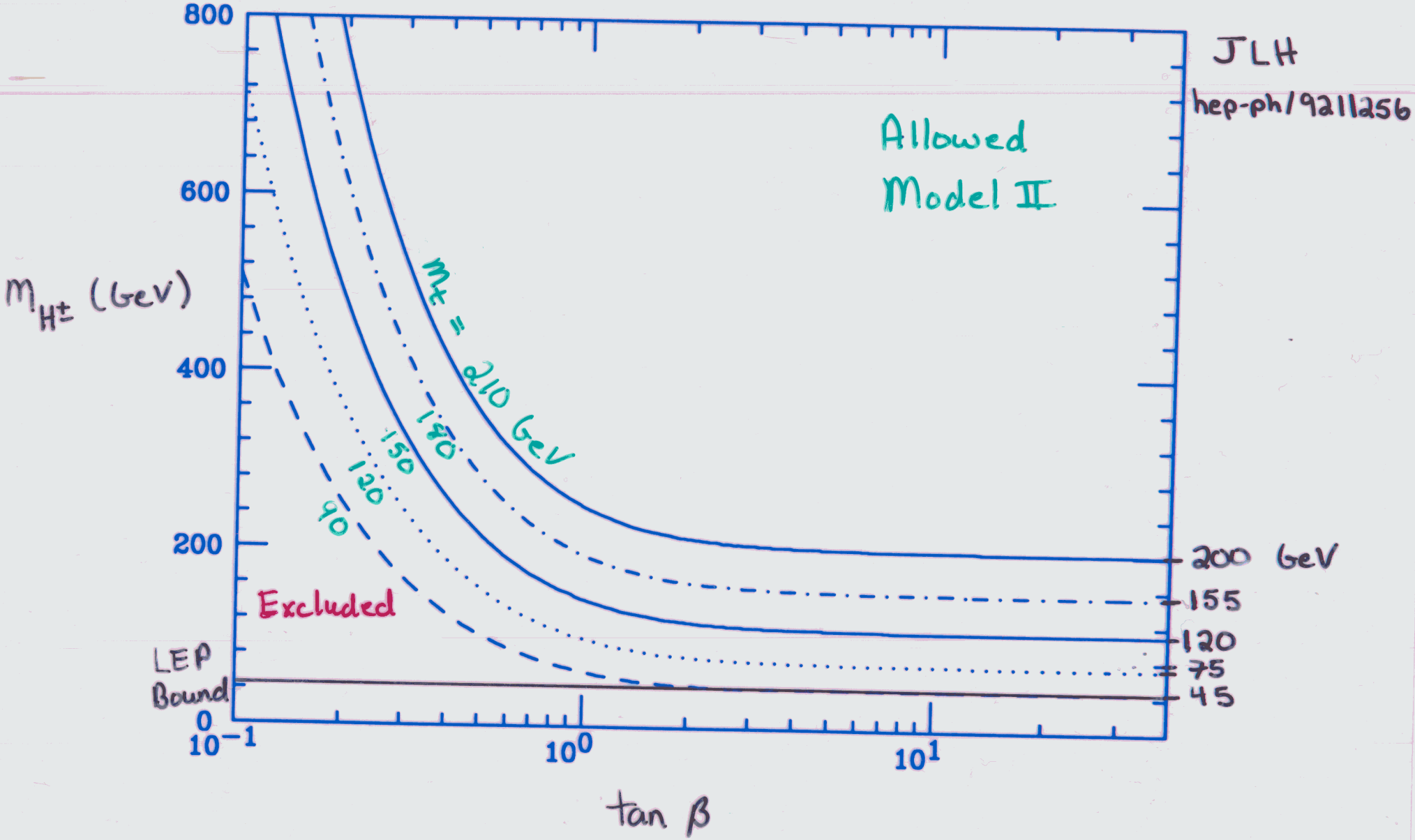
Figure 1: *Qualitative overview of the locations of our proposed benchmark points in a generic* $(m_{1/2}, m_0)$ *plane. The light (turquoise) shaded area is the cosmologically preferred region with* $0.1 \leq \Omega_\chi h^2 \leq 0.3$*, whose exact shape depends on the value of* $\tan\beta$*, and to some extent on the Standard Model inputs* m_t*,* m_b *and* α_s*. In the dark (brick red) shaded region at bottom right, the LSP is the charged* $\tilde{\tau}_1$*, so this region is excluded. Electroweak symmetry breaking is not possible in the dark (pink) shaded region at top left. The LEP experimental constraints, in particular that on* m_h*, and measurements of* $b \to s\gamma$ *exert pressure from the left side. The BNL E821 measurement of* $g_\mu - 2$ *favours relatively low values of* m_0 *and* $m_{1/2}$ *for* $\mu > 0$*. The CMSSM benchmark points we propose are indicated roughly by the (blue) crosses. We propose points in the 'bulk' region at bottom left, along the coannihilation 'tail' extending to larger* $m_{1/2}$*, in the 'focus-point' region at large* m_0*, and in the rapid-annilation 'funnel' that may appear at intermediate* $m_0/m_{1/2}$ *for large* $\tan\beta$*.*

Constraints on Two-Higgs Doublet Models



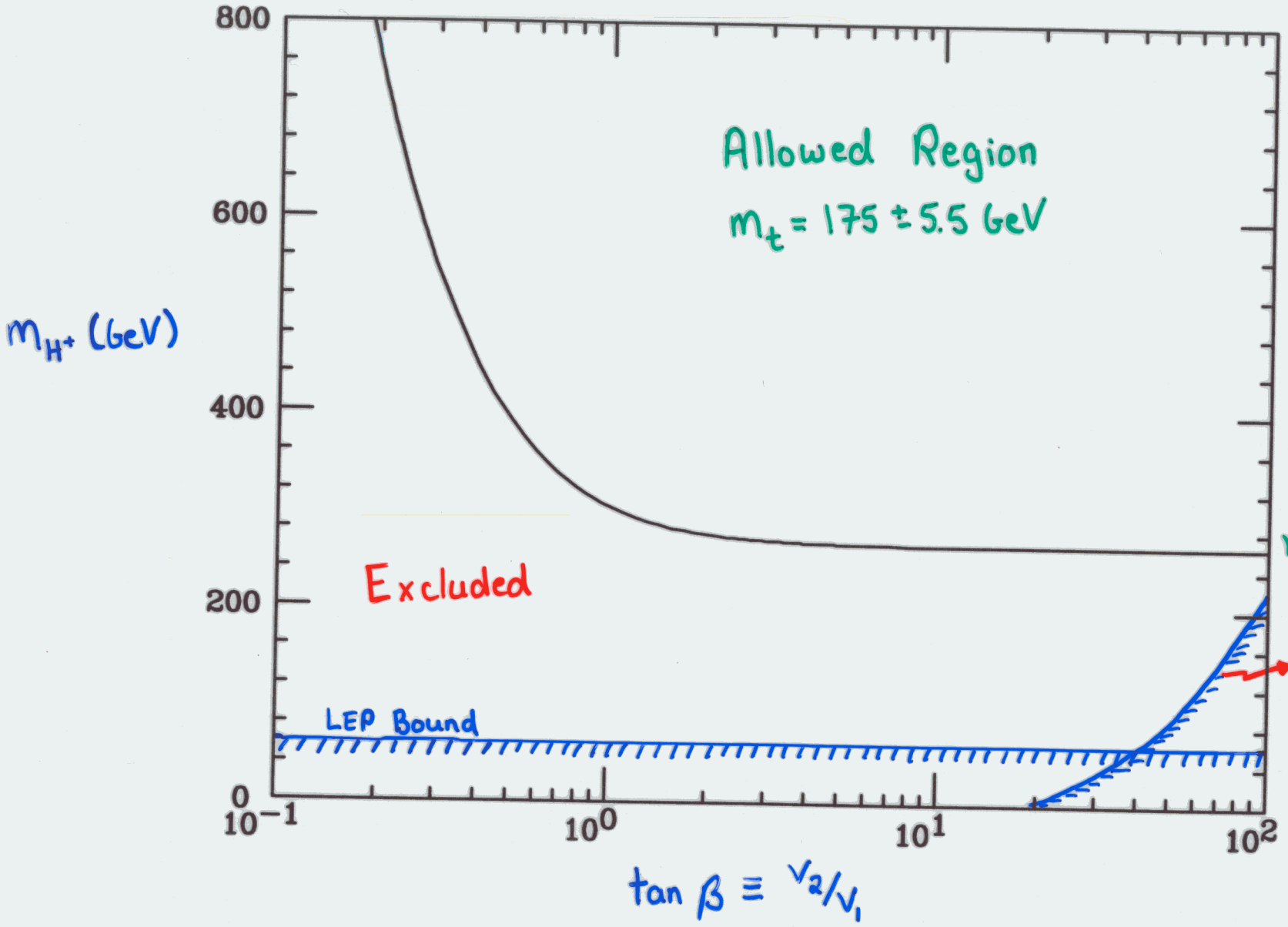
Circa '01

$B(b \to s\gamma) < 8.4 \times 10^{-4}$



$H^\pm$ bounds circa 1992 : Naive LO calculation

H^+ Constraints from $B \to X_s \gamma$ – New 95% C.L. CLEO Bounds



Surpasses Collider Reach!

Cira '96
Partial NLO

Strong Interplay Between Theory and Experiment!

New Physics Searches require:

Precision Theory

+

Precision Experiment

Standard Model Computations

$B \to X_s \gamma$: NLO

$B \to X_s \ell^+ \ell^-$: NNLL

HUGE Effort from large theoretical community!

QCD Corrections - Via Operator Mixing

Gilman + Wise

Operator Product Expansion

$$\mathcal{H}_{eff} = \frac{-4G_F}{\sqrt{2}} V_{q'Q} V^*_{q'q} \sum_{i=1}^{n} C_i(\mu)\, O_i(\mu)$$

$C_i(\mu)$: short distance, perturbative physics

$O_i(\mu)$: non-pert. physics

Calculate C_i at $\mu = m_W$ $\Rightarrow$ matching conditions

Use RGE to evole to $\mu \to m_b \to m_c \to m_K$

$$\mu \frac{d}{d\mu} \mathcal{H} = 0 \quad \Rightarrow \quad \mu \frac{d}{d\mu} C_j(\mu) = \gamma^T_{ij}(g_s)\, C_i(\mu)$$

γ^T_{ij}: anomalous dimension matrix

Complete set of operators governing $\Delta Q = 1$ transitions

$$O_1 = (\bar{q}_{\alpha} \gamma_\mu P_L q'_\beta)(\bar{q}'_\beta \gamma^\mu P_L Q_\alpha) \qquad O_2 = (\bar{q}_\alpha \gamma_\mu P_L q'_\alpha)(\bar{q}'_\beta \gamma^\mu P_L Q_\beta)$$

$$O_3 = (\bar{q}_\alpha \gamma_\mu P_L Q_\alpha) \sum_{q'} (\bar{q}'_\beta \gamma^\mu P_L q'_\beta) \qquad O_4 = (\bar{q}_\alpha \gamma_\mu P_L Q_\beta) \sum_{q'} (\bar{q}'_\beta \gamma^\mu P_L q'_\alpha)$$

$$O_5 = (\bar{q}_\alpha \gamma_\mu P_L Q_\alpha) \sum_{q'} (\bar{q}'_\beta \gamma^\mu P_R q'_\beta) \qquad O_6 = (\bar{q}_\alpha \gamma_\mu P_L Q_\beta) \sum_{q'} (\bar{q}'_\beta \gamma^\mu P_R q'_\alpha)$$

$$O_7 = \frac{e}{16\pi^2} m_Q (\bar{q}_\alpha \sigma_{\mu\nu} P_R Q_\alpha) F^{\mu\nu} \qquad O_8 = \frac{g_s}{16\pi^2} m_Q (\bar{q}_\alpha \sigma_{\mu\nu} T^a_{\alpha\beta} P_R Q_\beta) G^{a\mu\nu}$$

$$O_9 = \frac{e^2}{16\pi^2} (\bar{q}_\alpha \gamma_\mu P_L Q_\alpha)(\bar{l} \gamma^\mu l) \qquad O_{10} = \frac{e^2}{16\pi^2} (\bar{q}_\alpha \gamma_\mu P_L Q_\alpha)(\bar{l} \gamma^\mu \gamma_5 l)$$

$B \to X_s \gamma$ at LO + NLO:

Wilson Coeff: NLO Matching Conditions — Buras et al, Lin, Liu, Yao, Greub, Hurth

LO Anomalous Dimension Matrix — Ciuchini et al, Cella et al, Misiak

NLO Anomalous Dimension Matrix — Chetyrkin, Misiak, Münz

Matrix Element: NLO Virtual Corrections — Greub, Hurth, Wyler, Buras et al

Bremsstrahlung Corrections — Ali, Greub, Pott

Electroweak: 2-loop resummation — Czarnecki, Marciano, Baranowski, Misiak

E_γ Spectrum: Bremsstrahlung Corrections — Ali, Greub

Scale Dependence — Neubert, Kagan

Resummation of Threshold Logs — Leibovich, Rothstein

SM Predictions:

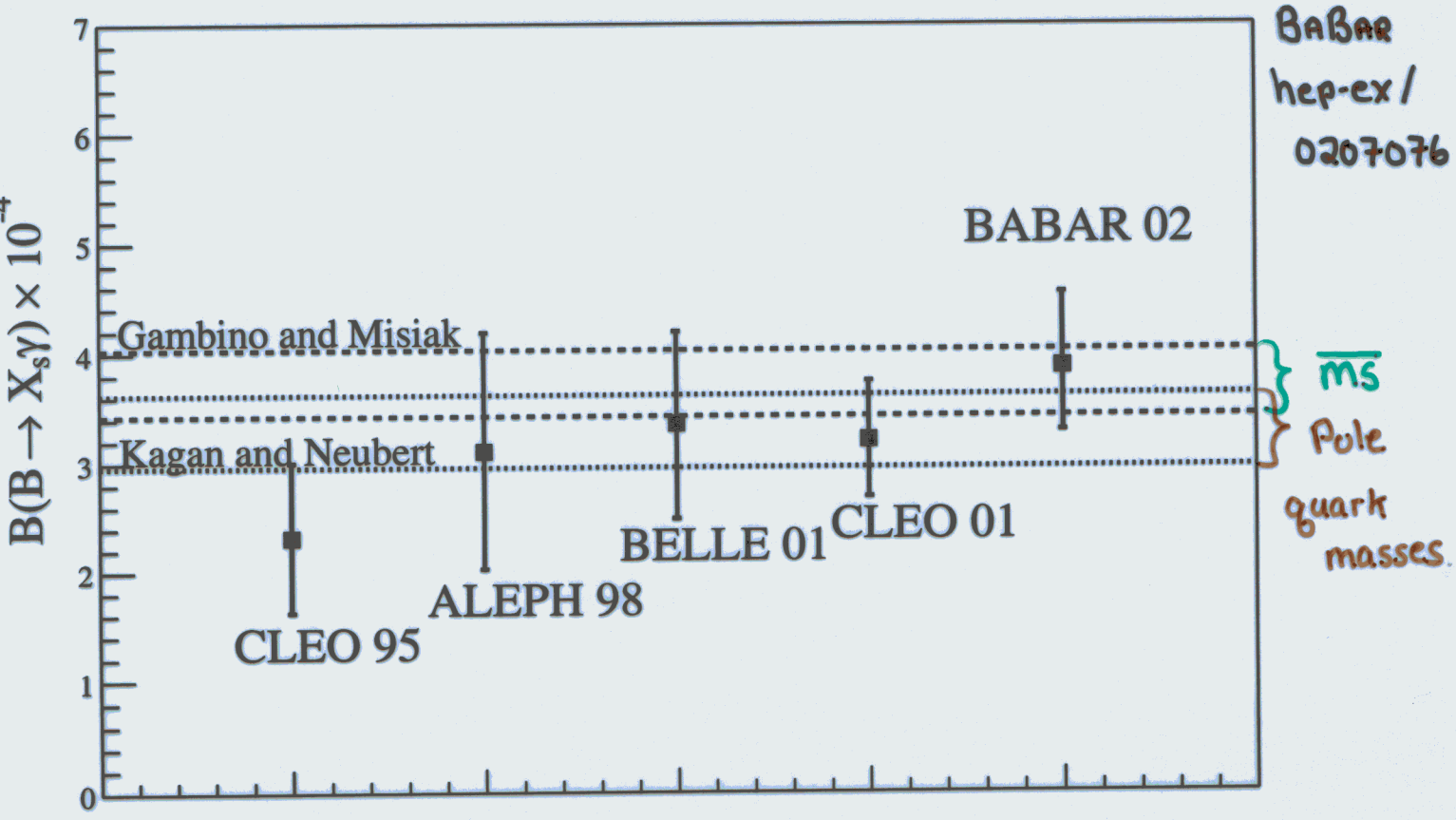
$$\mathcal{B}(B \to X_s \gamma) = \begin{cases} (3.35 \pm 0.30) \times 10^{-4} & \text{pole quark masses} \\ (3.73 \pm 0.30) \times 10^{-4} & \overline{\text{MS}} \text{ quark masses} \end{cases}$$

Gambino, Misiak

Present theoretical error larger than usually assumed

A Tour de Force Effort!!

Comparison with Experiment



More

3-loop calculations have begun ....

See Misiak

CKM Fits

hep-ph/0206242

Ali ICHEP02

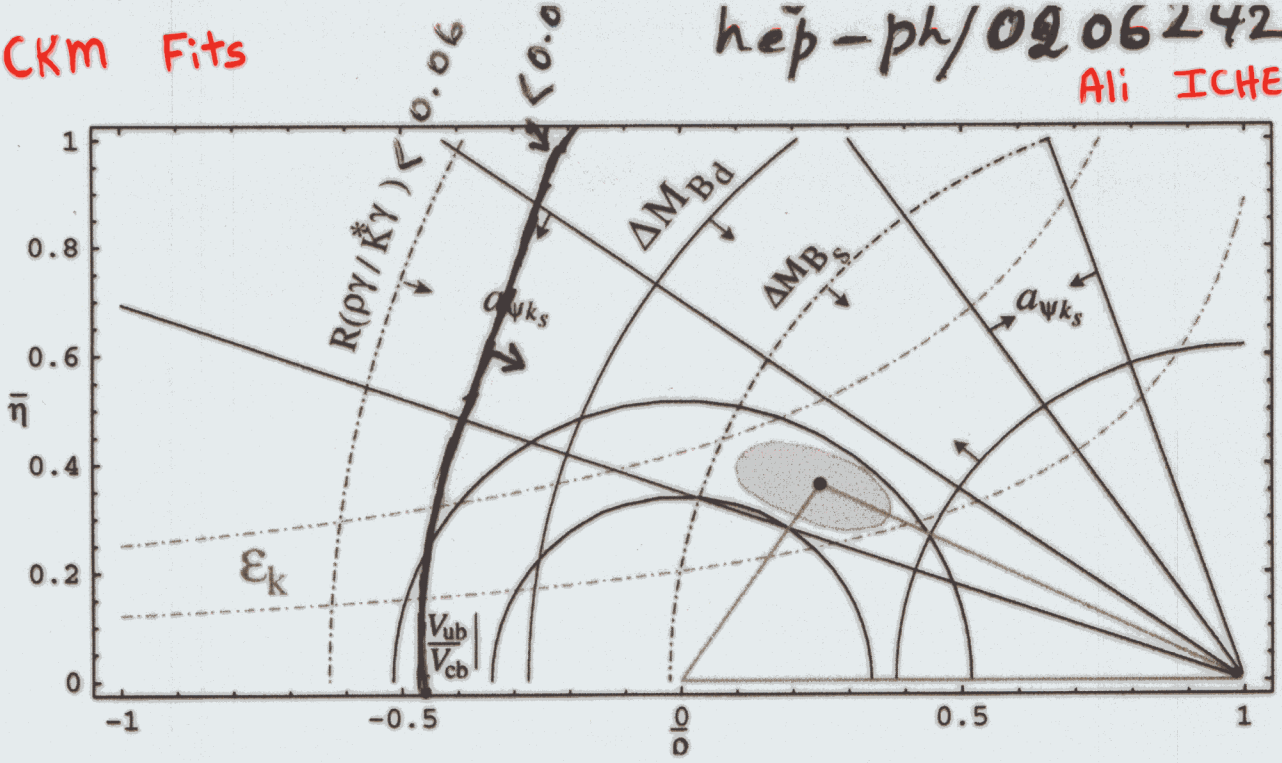


Figure 1: *Unitary triangle fit in the SM and the resulting 95% C.L. contour in the $\bar{\rho}$ - $\bar{\eta}$ plane. The impact of the $R(\rho\gamma/K^*\gamma) < 0.06$ constraint is also shown.*

Theoretical Uncertainties

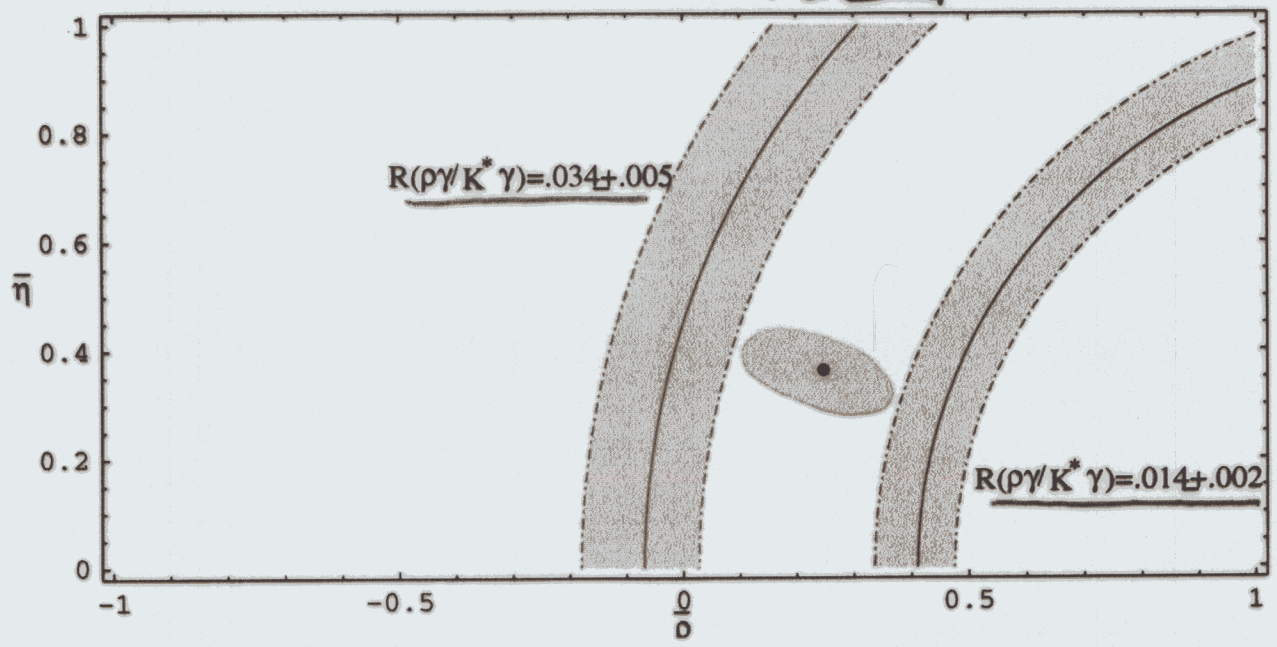
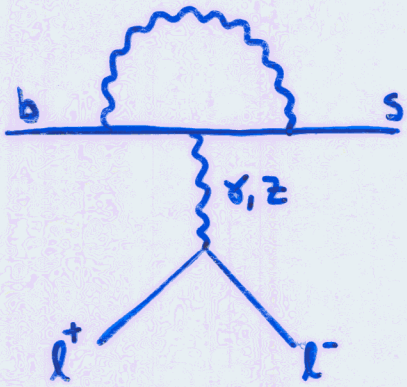


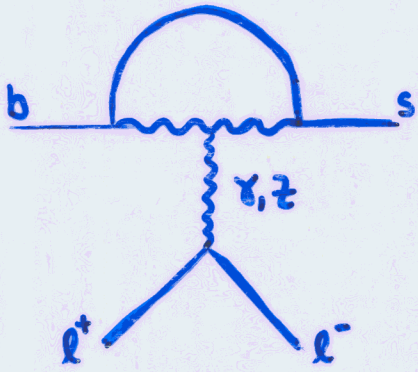
Figure 2: *Extremal values of $R(\rho\gamma/K^*\gamma)$ that are compatible with the SM unitarity triangle analysis.*

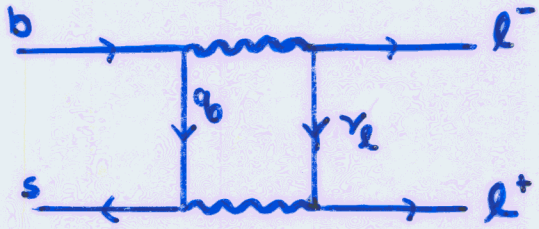
Need to reduce theoretical Uncertainty

@ present $\delta\left(\frac{V_{td}}{V_{tc}}\right) \approx O(15\%)$

$B \to X_s \ell^+ \ell^-$







Computed to NLO

$$\mathcal{M} = \frac{\sqrt{2}\, G_F \alpha}{\pi} V_{tb} V_{ts}^* \left[C_9^{eff}\, \bar{s}_L \gamma_\mu b_L\, \bar{\ell} \gamma^\mu \ell + C_{10}\, \bar{s}_L \gamma_\mu b_L\, \bar{\ell} \gamma^\mu \gamma_5 \ell - 2 C_7 m_b\, \bar{s}_L\, i \sigma_{\mu\nu} \frac{q^\nu}{q^2} b_R\, \bar{\ell} \gamma^\mu \ell \right]$$

q^2 = momentum transfer to $\ell^+\ell^-$ $\quad (\hat{s} = q^2/m_b^2)$

Long distance resonance contributions

$B \to K^{(*)} \psi^{(\prime)}$, $\psi^{(\prime)} \hookrightarrow \ell^+\ell^-$ peaks at $q^2 = m^2_{\psi^{(\prime)}}$

$\Rightarrow$ Effective $(\bar{s}_L \gamma_\mu b_L)(\bar{\ell} \gamma^\mu \ell)$ interaction

$$C_9^{eff}(\mu) = C_9(\mu) + Y(\mu, \hat{s}) - \frac{3\pi}{\alpha^2 m_b^2} \sum_{\psi_i, \psi'} \frac{m_{V_i}\, \Gamma(V_i \to \ell^+\ell^-)}{\left(\hat{s} - \frac{m_{V_i}^2}{m_b^2}\right) + i \frac{\Gamma_{V_i}}{m_b^2} m_{V_i}}$$

$Y(\mu, \hat{s})$: contribution from c + light-quarks

Kinematic Distributions - Requires high statistics!

- $m_{\ell^+\ell^-}$ Distribution (Lim, Morozumi, Sanda; Deshpande et al; Ali et al)

$$\frac{d\Gamma(B\to X_s\ell^+\ell^-)}{d\hat{s}} \sim (1-\hat{s})^2\left[\begin{array}{l}(|C_9^{eff}|^2+|C_{10}|^2)(1+2\hat{s})\\ +4|C_7|^2\frac{2+\hat{s}}{\hat{s}}+12\,\mathrm{Re}(C_9^{eff}C_7)\end{array}\right]$$

- Forward-Backward Asymmetry of $\ell^+\ell^-$ angular distribution (Ali et al)

$$A_{FB}=\frac{\int_0^1 dz\ d\Gamma/dzd\hat{s}-\int_{-1}^0 dz\ d\Gamma/dzd\hat{s}}{\int_0^1 dz\ d\Gamma/dzd\hat{s}+\int_{-1}^0 dz\ d\Gamma/dzd\hat{s}}$$

$$=-3C_{10}\left[\mathrm{Re}\,C_9^{eff}\hat{s}+2C_7\right]/\,d\Gamma/d\hat{s}$$

- Tau Polarization Asymmetry in $B\to X_s\tau^+\tau^-$ (JLH; Kruger, Sehgal)

$$P_\tau=\frac{d\Gamma_{\lambda=-1}-d\Gamma_{\lambda=+1}}{d\Gamma_{\lambda=-1}+d\Gamma_{\lambda=+1}}$$

$$=-2C_{10}\left[\mathrm{Re}\,C_9^{eff}F_1(\hat{s},m_\tau)+3C_7F_2(\hat{s},m_\tau)\right]/\,d\Gamma_\tau/d\hat{s}$$

$B \to X_s \ell^+ \ell^-$ at NLO + NNLL

LO Estimate of $d\Gamma/d\hat{s}$ — Grinstein, Savage, Wise '89

Matching Conditions: NLL — Misiak; Buras, Munz

NNLO — Bobeth, Misiak, Urban

Matrix Elements: 2-loop virtual corrections — Asatrian, Greub, Walker; Asatryan

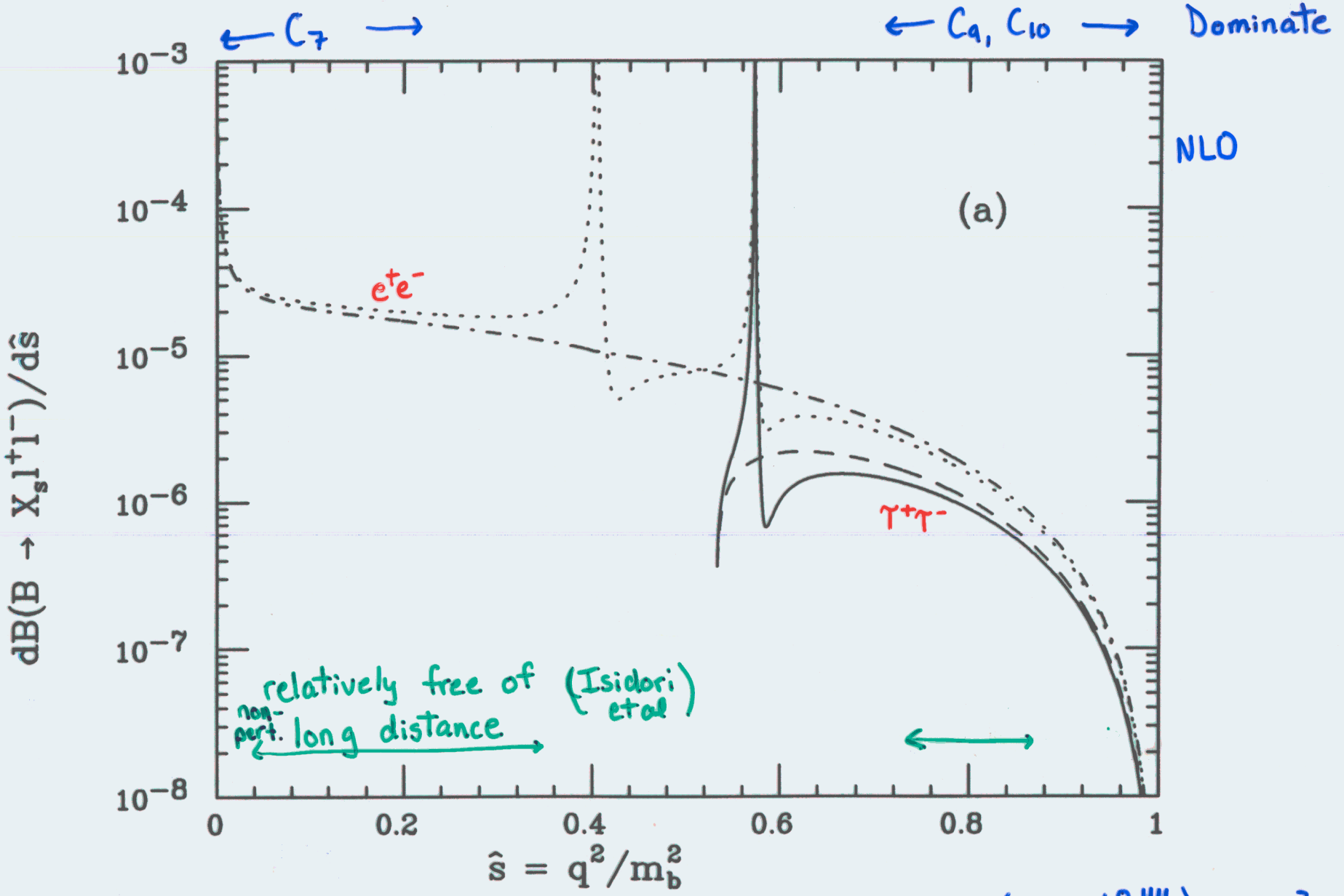
Bremsstrahlung corrections — Asatryan, Asatrian, Greub, Walker

Leading Power Corrections: $1/m_b$ — Falk, Luke, Savage; Ali, Hiller, Handoko, Morozumi; Buchalla, Isidori

$1/m_c$ — Buchalla, Isidori, Rey; Chen, Rupak, Savage

A_{FB} to NNLL — Ghinculov, Hurth, Isidori, Yao; Asatrian, Bieri, Greub, Hovhannisyan

Tour de Force Effort #2 !



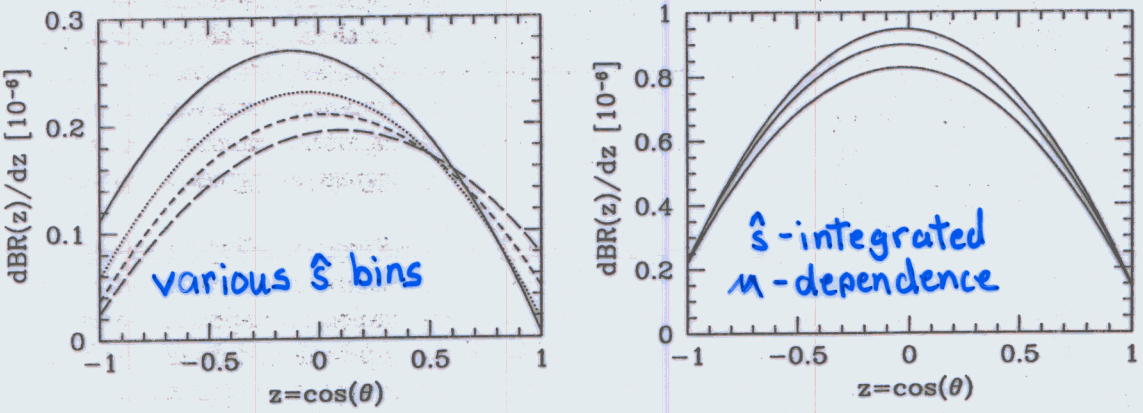
$B(B \to X_s e^+e^-) = (6.25 \pm 0.7) \times 10^{-6}$

$B(B \to X_s \mu^+\mu^-) = (4.15 \pm 1.0) \times 10^{-6}$

$B(B \to X_s \tau\tau) = (3.24^{+0.44}_{-0.54}) \times 10^{-7}$

NNLL Corrections

Angular Distributions:



Asatrian et al hep-ph/ 0209006

$\hat{s} = q^2/m_B^2$

FIG. 7. Left frame: NNLL branching ratio differential in $z = \cos\theta$ for four bins in $\hat{s}$. Bin 1: $0.05 \le \hat{s} \le 0.10$ (solid); bin 2: $0.10 \le \hat{s} \le 0.15$ (dotted); bin 3: $0.15 \le \hat{s} \le 0.20$ (short-dashed); bin 4: $0.20 \le \hat{s} \le 0.25$ (long-dashed). $m_c^{\rm pole}/m_b^{\rm pole} = 0.29$ and $\mu = 5$ GeV. Right frame: NNLL branching ratio differential in $z = \cos\theta$. $\hat{s}$ is integrated in the interval $0.05 \le \hat{s} \le 0.25$. The curves correspond to $\mu = 2.5$ GeV (lowest), $\mu = 5.0$ GeV (middle) and $\mu = 10.0$ GeV (uppermost). $m_c^{\rm pole}/m_b^{\rm pole} = 0.29$.

Forward-Backward Asymmetry

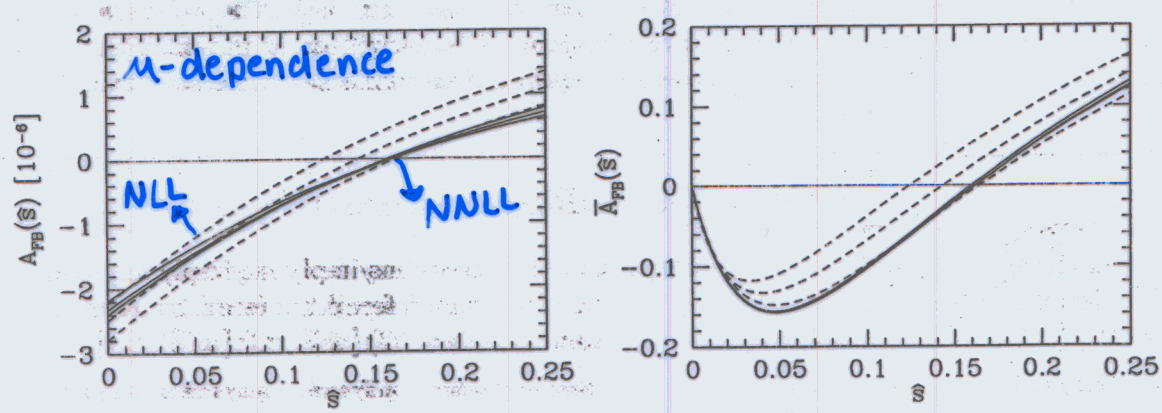


FIG. 4. Left frame: Unnormalized forward-backward asymmetry $A_{\rm FB}(\hat{s})$. The three solid lines show the NNLL prediction for $\mu = 2.5, 5.0, 10.0$ GeV, respectively. The corresponding curves in NLL approximation are shown by dashed lines. Right frame: Normalized forward-backward asymmetry $\overline{A}_{\rm FB}(\hat{s})$. The lines have the same meaning as in the left frame. $m_c/m_b = 0.29$.

Theory + Data Comparison

SM predictions at NNLO accuracy & Comparison with Data
(all in units of 10^{-6})
[A.A., Lunghi, Greub, Hiller, DESY 01-217; hep-ph/0112300]

Ali ICHEP02

Decay Mode	Theory (SM)	BELLE	BABAR
$B \to K\ell^+\ell^-$	0.35 ± 0.12	$0.75^{+0.25}_{-0.21} \pm 0.09$ (*) ~~$0.58 \pm 0.17 \pm 0.06$~~	$0.84^{+0.30+0.10}_{-0.24-0.18}$ (*) ~~$0.78^{+0.24+0.11}_{-0.20-0.18}$~~
$B \to K^*e^+e^-$	1.58 ± 0.52	< 5.1	~~$1.68^{+0.68}_{-0.58} \pm 0.28$~~
$B \to K^*\mu^+\mu^-$	1.2 ± 0.4	< 3.0	< 3.6 (*); weighted $e^+e^-, \mu^+\mu^-$ ~~$B \to K^*\ell^+\ell^-$~~
$B \to X_s\mu^+\mu^-$	4.15 ± 1.0	$8.9^{+2.3+1.6}_{-2.1-1.7}$ (*) ~~$7.9 \pm 2.1^{+2.0}_{-1.5}$~~	–
$B \to X_se^+e^-$	6.9 ± 0.70	< 11.0 (*) ~~$5.0 \pm 2.3^{+1.2}_{-1.1}$~~	–
$B \to X_s\ell^+\ell^-$	5.6 ± 0.9	$7.1 \pm 1.6^{+1.6}_{-1.2}$ (*) ~~$6.1 \pm 1.4^{+1.3}_{-1.1}$~~	–

(*) S. Nishida (ICHEP 2002)

(*) J. Richman (ICHEP 2002)

- Experiments + SM in good accord;
- Improved precision crucial to disentangle NP effects

Global Fit to the Wilson Coefficients

Ingredients:

- $B(B \to X_s \gamma)$ - Flat 10% systematic error
- $m_{\ell^+\ell^-}$ Distribution in $B \to X_s \ell^+\ell^-$
- $\ell^+\ell^-$ Forward-Backward Asymmetry in $B \to X_s \ell^+\ell^-$ [Ali '89]
- τ Polarization Asymmetry in $B \to X_s \tau^+\tau^-$ [JLH '95]

Divide $\ell\ell$ spectrum into 9 bins
stat. errors only
(randomly fluctuated)

Perform Theorist's Monte Carlo - χ^2 fit to simulated data (assuming SM)

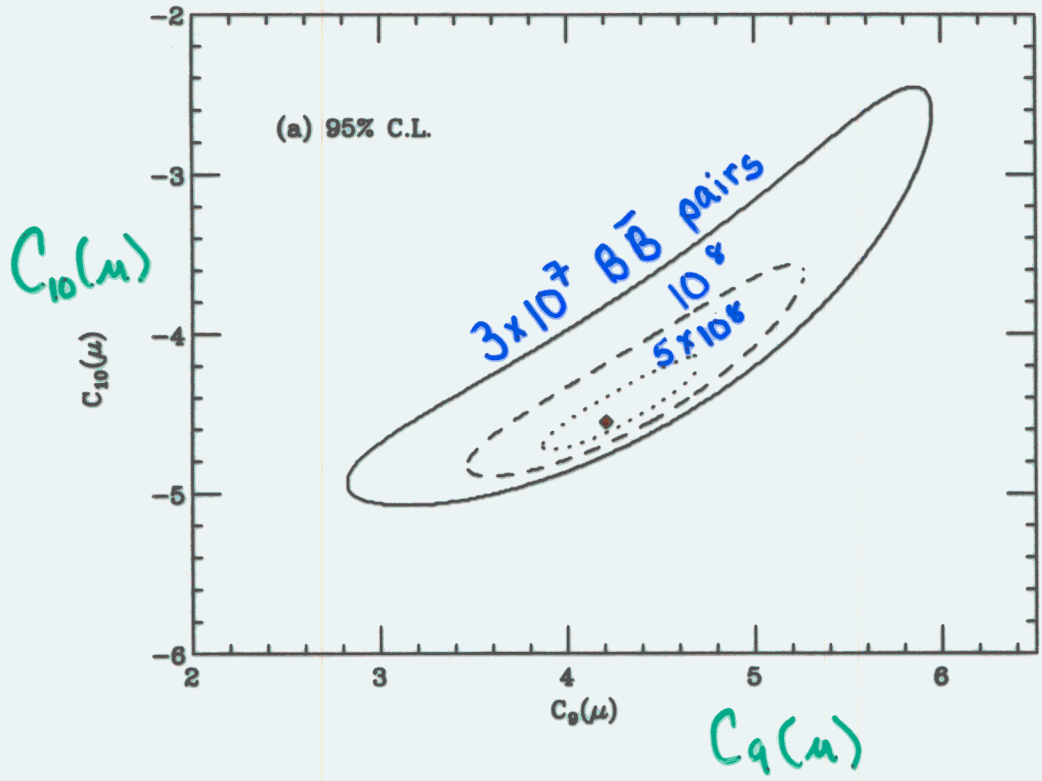
⇒ Determines magnitude + sign of

$C_7(\mu)$, $C_9(\mu)$, $C_{10}(\mu)$!

Offers precision test of New Physics

Global Fit to Wilson Coefficients

JLH, Wells '96
hep-ph/9610323

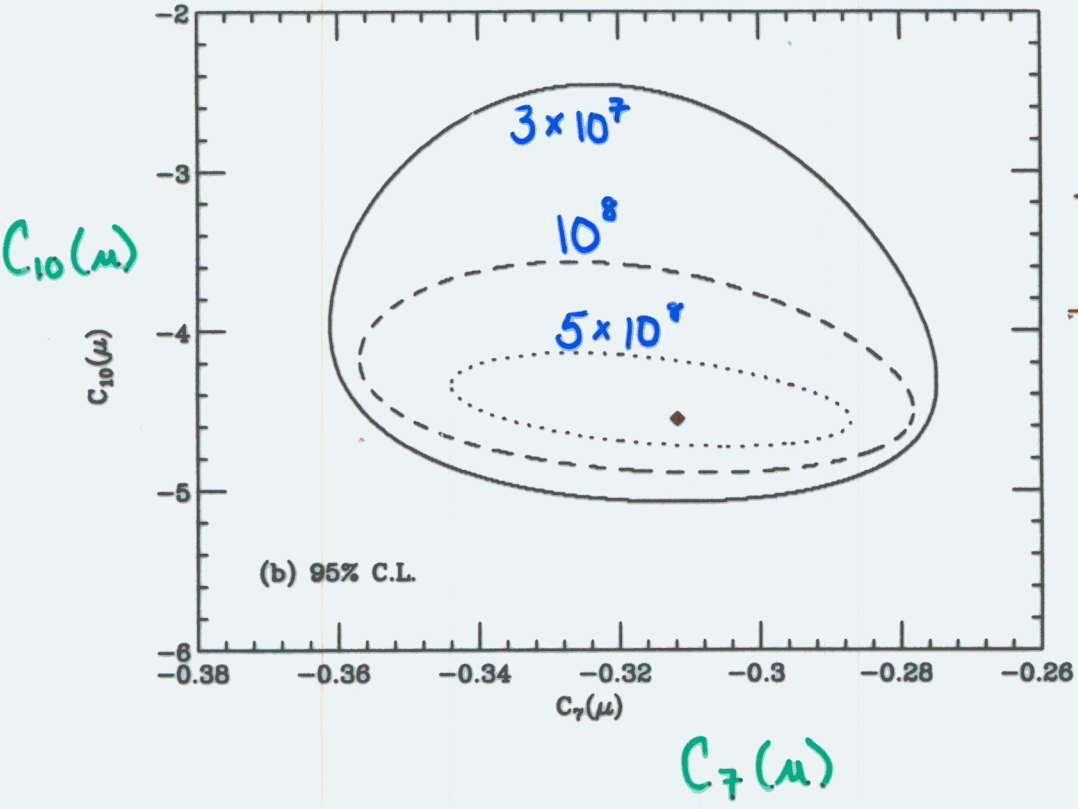


SM:

$C_7(\mu) = -0.31^{-0.06}_{+0.03}$

$C_9(\mu) = 4.2^{+0.3}_{-0.4}$

$C_{10}(\mu) = -4.55$



Event rate converter

$B\bar{B}$'s	see/SMM
3×10^7	225
10^8	750
5×10^8	3780

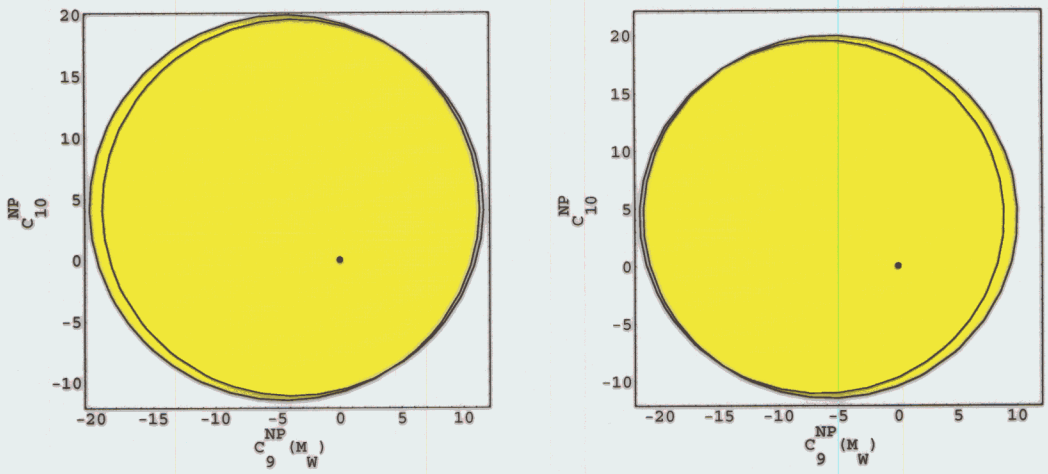
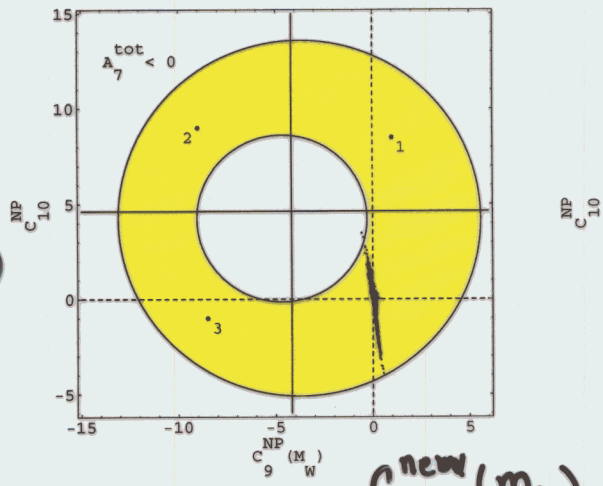


Figure 9: **NNLO Case.** *Constraints in the* $[C_9^{NP}(\mu_W), C_{10}^{NP}]$ *plane that come from the* $90\% CL$ *BELLE constraint* $\mathcal{B}(B \to K^* e^+ e^-) \leq 5.1 \times 10^{-6}$. *See Fig. 4 for further details.*

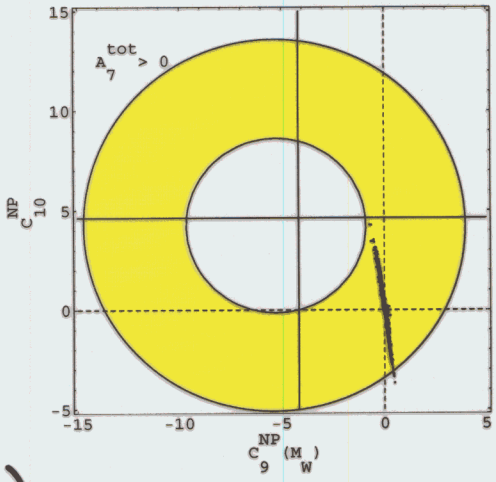
Summary of all Constraints:

$A_{FB} < 0$

$C_{10}^{new}(m_W)$



$C_9^{new}(m_W)$



$A_{FB} > 0$

Figure 10: **NNLO Case.** *Superposition of all the constraints. The plots correspond to the* $A_7^{\rm tot}(2.5\ GeV) < 0$ *and* $A_7^{\rm tot}(2.5\ GeV) > 0$ *case, respectively. The points are obtained by means of a scanning over the EMFV parameter space and requiring the experimental bound from* $B \to X_s\gamma$ *to be satisfied.*

New Physics Effects in the Global Fit:

1) Determined $C_i = C_i^{sm}$ with good χ^2

$\Rightarrow$ New Physics is decoupled

2) Good χ^2, but $C_i \neq C_i^{sm}$

$\Rightarrow$ New Physics present in loops

3) Large χ^2 for best-fit

$\Rightarrow$ Extended Operator Basis

Examples: Left-Right Symmetric Model — Rizzo

Additional 4-Fermi interactions — C.S. Kim etal

Tests of Right-handed interactions:

- Λ polarization in $\Lambda_b \to \Lambda + \gamma$ — Mannel, Recksiegal
- Angular correlations in $B \to K^* \gamma^{(*)}$ ($\gamma^{(*)} \to e^+e^-$, $K^* \to K\pi$) — Grossman, Pirjol

Effective Field Theory Approach to MFV

Ambrosio et al hep-ph/0207036

Construct complete set of gauge + CP invariant dimension-6 operators.

Scale operators as: $\pm \frac{\theta_i}{\Lambda^2}$, where Λ = New Physics scale

Minimally flavour violating dimension six operator	main observables	Λ [TeV] −	+	
$\mathcal{O}_0 = \frac{1}{2}(\bar{Q}_L \lambda_{FC} \gamma_\mu Q_L)^2$	ϵ_K, Δm_{B_d}	6.4	5.0	
$\mathcal{O}_{F1} = H^\dagger \left(\bar{D}_R \lambda_d \lambda_{FC} \sigma_{\mu\nu} Q_L\right) F_{\mu\nu}$	$B \to X_s \gamma$	9.3	12.4	
$\mathcal{O}_{G1} = H^\dagger \left(\bar{D}_R \lambda_d \lambda_{FC} \sigma_{\mu\nu} T^a Q_L\right) G^a_{\mu\nu}$	$B \to X_s \gamma$	2.6	3.5	
$\mathcal{O}_{\ell 1} = (\bar{Q}_L \lambda_{FC} \gamma_\mu Q_L)(\bar{L}_L \gamma_\mu L_L)$	$B \to (X)\ell\bar{\ell}$, $K \to \pi\nu\bar{\nu}, (\pi)\ell\bar{\ell}$	3.1	2.7	*
$\mathcal{O}_{\ell 2} = (\bar{Q}_L \lambda_{FC} \gamma_\mu \tau^a Q_L)(\bar{L}_L \gamma_\mu \tau^a L_L)$	$B \to (X)\ell\bar{\ell}$, $K \to \pi\nu\bar{\nu}, (\pi)\ell\bar{\ell}$	3.4	3.0	*
$\mathcal{O}_{H1} = (\bar{Q}_L \lambda_{FC} \gamma_\mu Q_L)(H^\dagger i D_\mu H)$	$B \to (X)\ell\bar{\ell}$, $K \to \pi\nu\bar{\nu}, (\pi)\ell\bar{\ell}$	1.6	1.6	*
$\mathcal{O}_{q5} = (\bar{Q}_L \lambda_{FC} \gamma_\mu Q_L)(\bar{D}_R \gamma_\mu D_R)$	$B \to K\pi$, $\epsilon'/\epsilon, \ldots$	~ 1		

$B \to X_s \gamma$ Constraints:

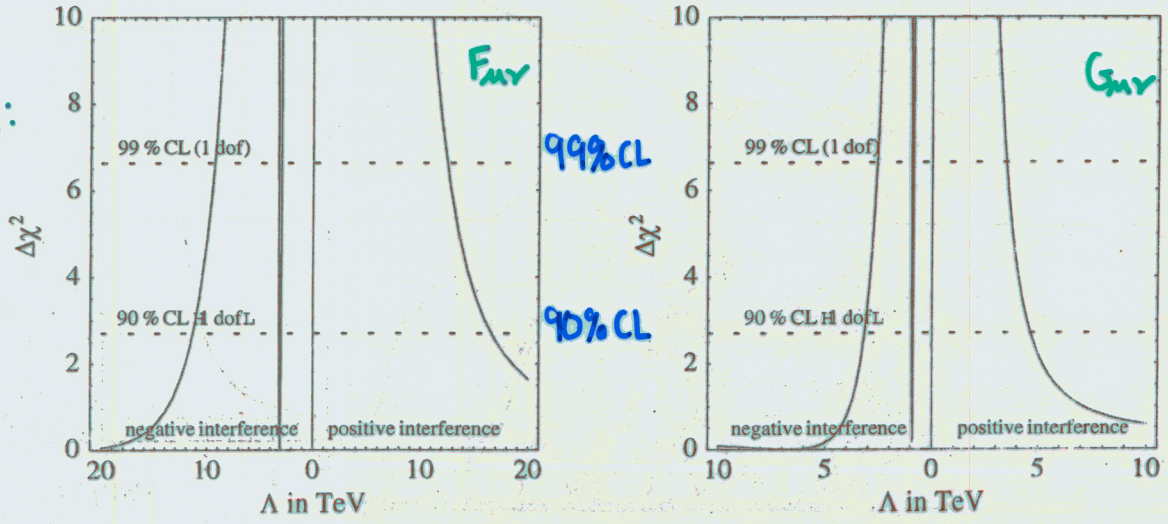


Figure 2: *Bounds on the scale of the operators $\mathcal{O}_{F1}$ (left) and $\mathcal{O}_{G1}$ (right) from $B \to X_s\gamma$.*

B → Xs γ Constraints

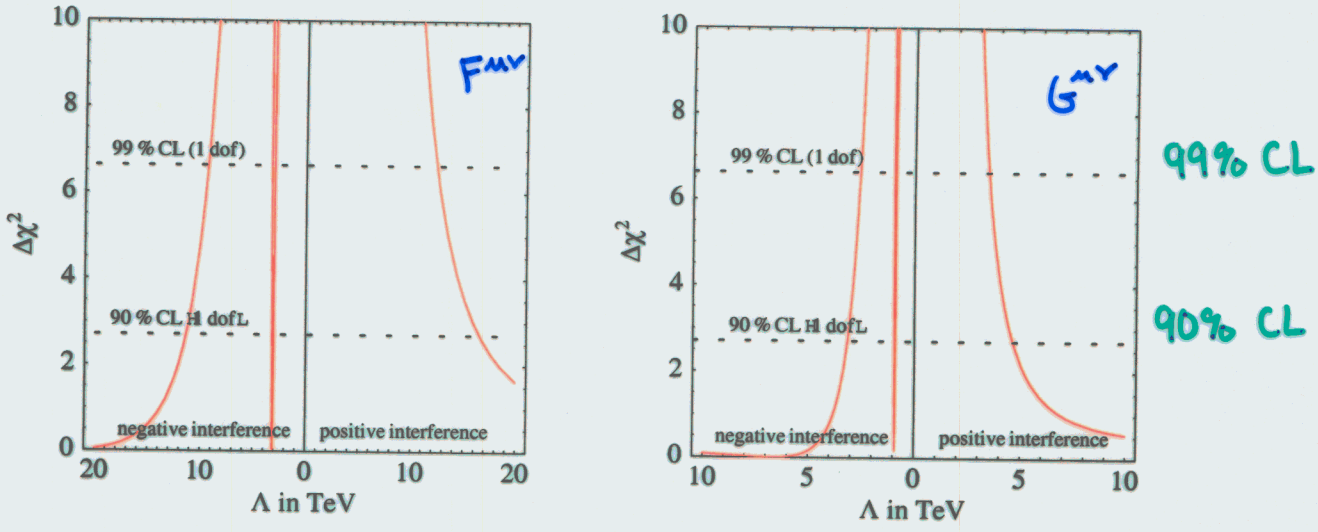


Figure 2: *Bounds on the scale of the operators $\mathcal{O}_{F1}$ (left) and $\mathcal{O}_{G1}$ (right) from $B \to X_s\gamma$.*

result [19]

$$\mathcal{B}(K^+ \to \pi^+\nu\bar{\nu}) = \left(1.57\ ^{+\ 1.75}_{-\ 0.82}\right) \times 10^{-10}\ . \tag{30}$$

leads to the 99% CL limit

$$-\ 4.8 < C_{\nu\bar{\nu}}/C^{\rm SM}_{\nu\bar{\nu}} < 4.0\ . \tag{31}$$

These bounds are still rather weak, corresponding to effective scales of the new physics operator around 1 TeV, nonetheless they already imply significant bounds on $\mathcal{B}(K_L \to \pi^0\nu\bar{\nu})$ and $\mathcal{B}(B \to X_s\nu\bar{\nu})$, as shown in table 3 (see also ref. [20]). In few years, at the end of the E949 experiment, assuming that the central value of $\mathcal{B}(K^+ \to \pi^+\nu\bar{\nu})$ will move towards the SM prediction, we can expect to probe Λ from this observable up to about 3 TeV, a sensitivity comparable to the one of electroweak precision data on the corresponding flavour-diagonal terms. At the end of the CKM experiment, with a 10% measurement of this branching ratio, the search on Λ could be pursued up to above 5 TeV. As illustrated in fig. 4, a sensitivity above 10 TeV could in principle be reached by a measurement of $\mathcal{B}(K_L \to \pi^0\nu\bar{\nu})$ with a precision of few percent around the SM value, since this rate is free from the theoretical uncertainty due to charm contributions.

The most interesting constraint on pure-leptonic decays is provided by $K_L \to \mu^+\mu^-$. The branching ratio of this decay is measured very precisely; however, this mode receives also a large long-distance amplitude by the two-photon intermediate state. Actually short- and long-distance dispersive parts cancel each other to a good extent, since the total $K_L \to \mu^+\mu^-$ rate is almost saturated by the absorptive two-photon contribution. Taking into account the recent experimental result on $\mathcal{B}(K_L \to \mu^+\mu^-)$ [21] and following the analyses of the long-distance amplitude in [22], we shall impose the conservative upper bound

$$\mathcal{B}(K_L \to \mu^+\mu^-)^{\rm short} \leq 3.0 \times 10^{-9}\ , \tag{32}$$

that we shall treat as an absolute limit. Employing the SM expression of $\mathcal{B}(K_L \to \mu^+\mu^-)^{\rm short}$ [3] and taking into account the uncertainty of the CKM fit, this information can be translated

Supersymmetry: General Features

$B \to X_s \gamma$: Large restrictions!

particularly for large $\tan\beta$, $\mu < 0$

$B \to X_s \ell^+ \ell^-$: Smaller contributions to rate

Deviations in Asymmetries

very many authors

$B_q \to \ell^+ \ell^-$: Large contributions from Higgs exchange for large $\tan\beta$

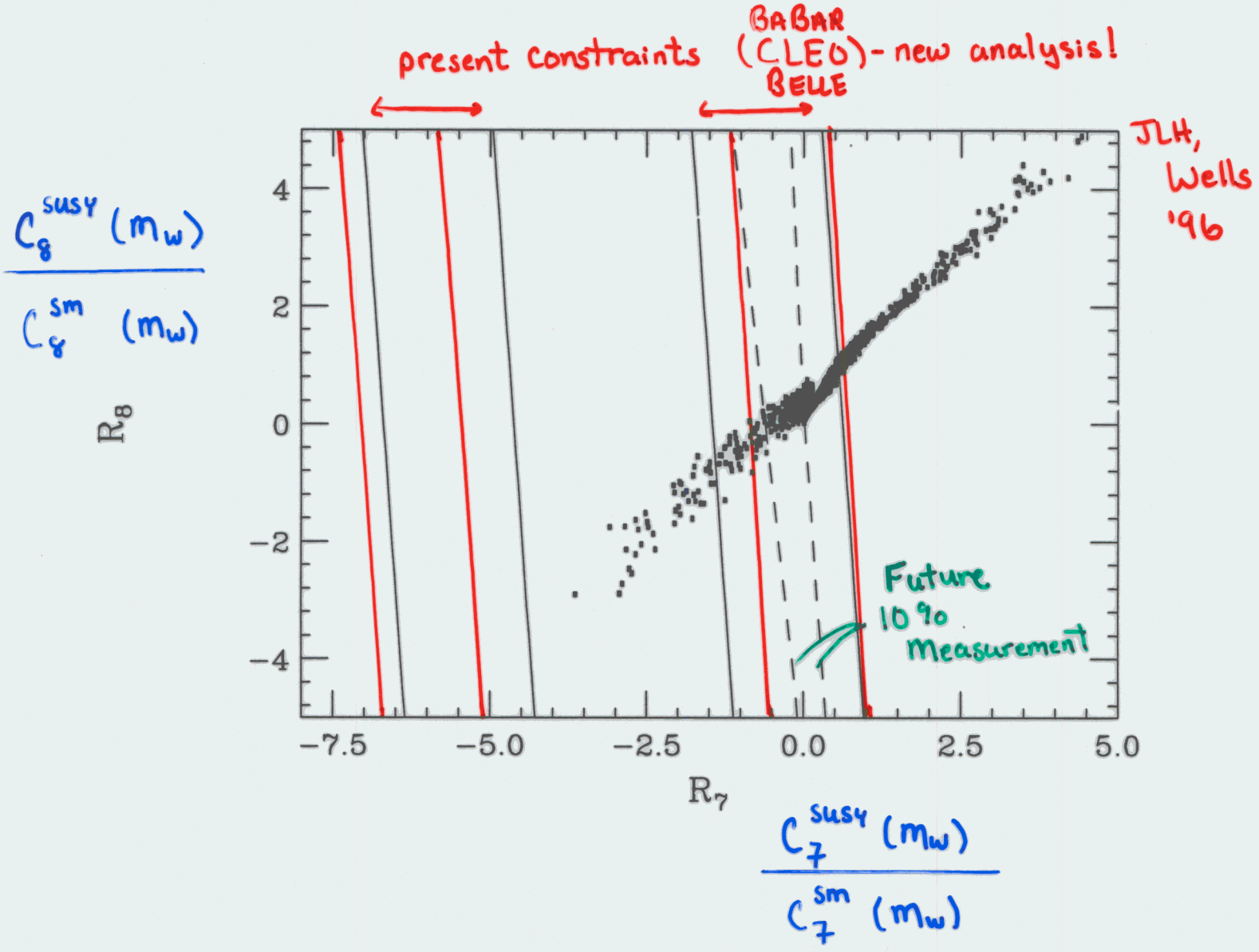
Babu, Kolda

Distinct patterns emerge for various SUSY-breaking scenarios!

Possible (if lucky) to learn about SUSY breaking from rare decays!

SUSY + Unification + Radiative Breaking = MSSM

Generate 2000 points consistent with SUSY scales above LEP II + Tevatron reach



Pick $\tilde{m}_0$, $\tilde{m}_{1/2}$, A_0, sign(μ), $\tan\beta$ at GUT scale

+ RGE evolve to EW/TeV scale

Constraints on 2-d SUSY parameter plane

MSUGRA

Baer et al
hep-ph/0205325

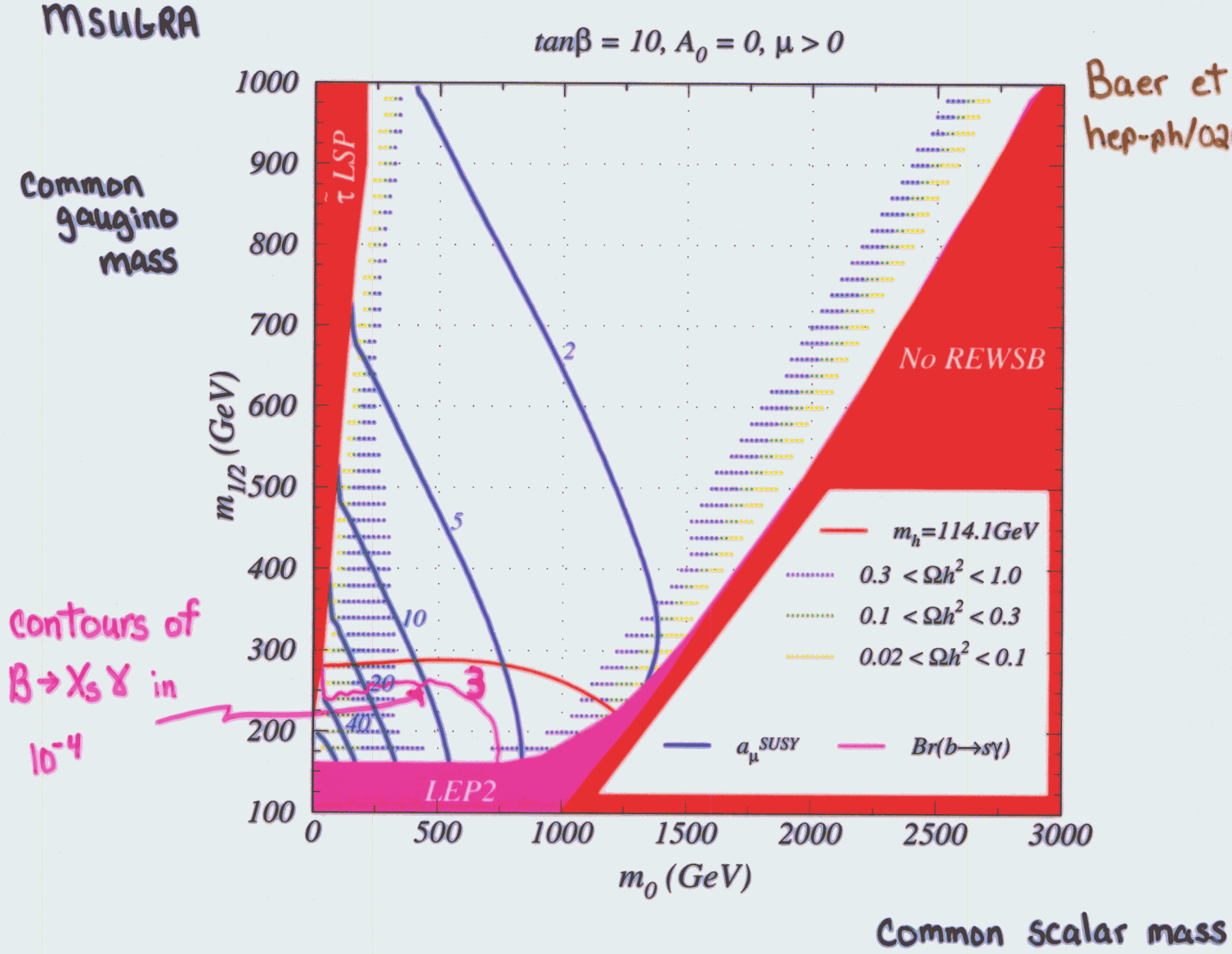


Figure 2: Same as Fig. 1, but for $\mu > 0$.

enhanced neutralino annihilation to $b\bar{b}$ and $\tau\bar{\tau}$ at large $\tan\beta$. Both lighter values of $m_{\tilde{\tau}_1}$ and $m_{\tilde{b}_1}$ and also large τ and b Yukawa couplings at large $\tan\beta$ enhance these t-channel annihilation rates through virtual staus and sbottoms. Unfortunately, the region excluded by $BF(b \to s\gamma)$ and by δa_μ (even with the conservative constraint of Ref.[43]) also expands, and most of the cosmologically preferred region is again ruled out. As before, we are left with the corridors of stau co-annihilation and the focus point scenario as the only surviving regions.

The corresponding plot is shown for $\tan\beta = 30$ but $\mu > 0$ in Figure 4. In this case, the magenta contours of $BF(b \to s\gamma)$ correspond to 2 and 3×10^{-4}. Thus, the lower left region is excluded since it leads to too *low* a value of $BF(b \to s\gamma)$. The δa_μ contours begin

mSUGRA

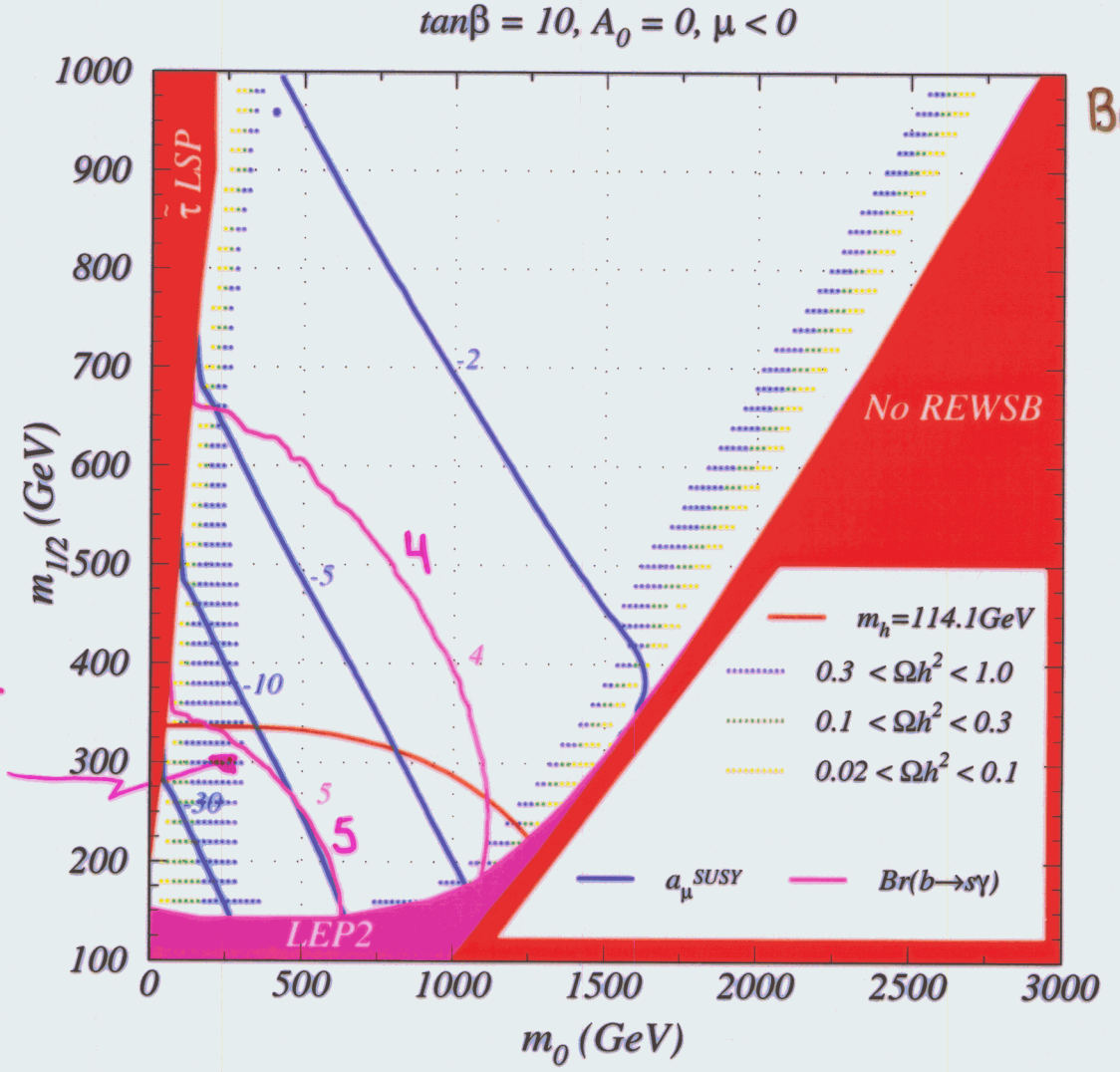


Figure 1: Plot of constraints for the mSUGRA model in the m_0 *vs.* $m_{1/2}$ plane for $\tan\beta = 10$, $A_0 = 0$ and $\mu < 0$. We show regions of CDM relic density, plus contours of $m_h = 114.1$ GeV, contours of muon anomalous magnetic moment a_μ ($\times 10^{10}$) and contours of $b \to s\gamma$ branching fraction ($\times 10^4$).

preferred value of neutralino relic density, one must again live in the stau co-annihilation region, or the focus point region. A final possibility is to be in the slepton annihilation region, but then the value of m_h should be slightly beyond the LEP2 limit; in this case, a Higgs boson signal may be detected in Run 2 of the Fermilab Tevatron[51].

We next turn to the m_0 *vs.* $m_{1/2}$ plane for $\tan\beta = 30$ and $\mu < 0$. The gray region in the bottom left corner of the plot is excluded because $m^2_{\tilde{\tau}_1} < 0$. In this case, the area of the green region of relic density in the lower-left has expanded considerably owing to

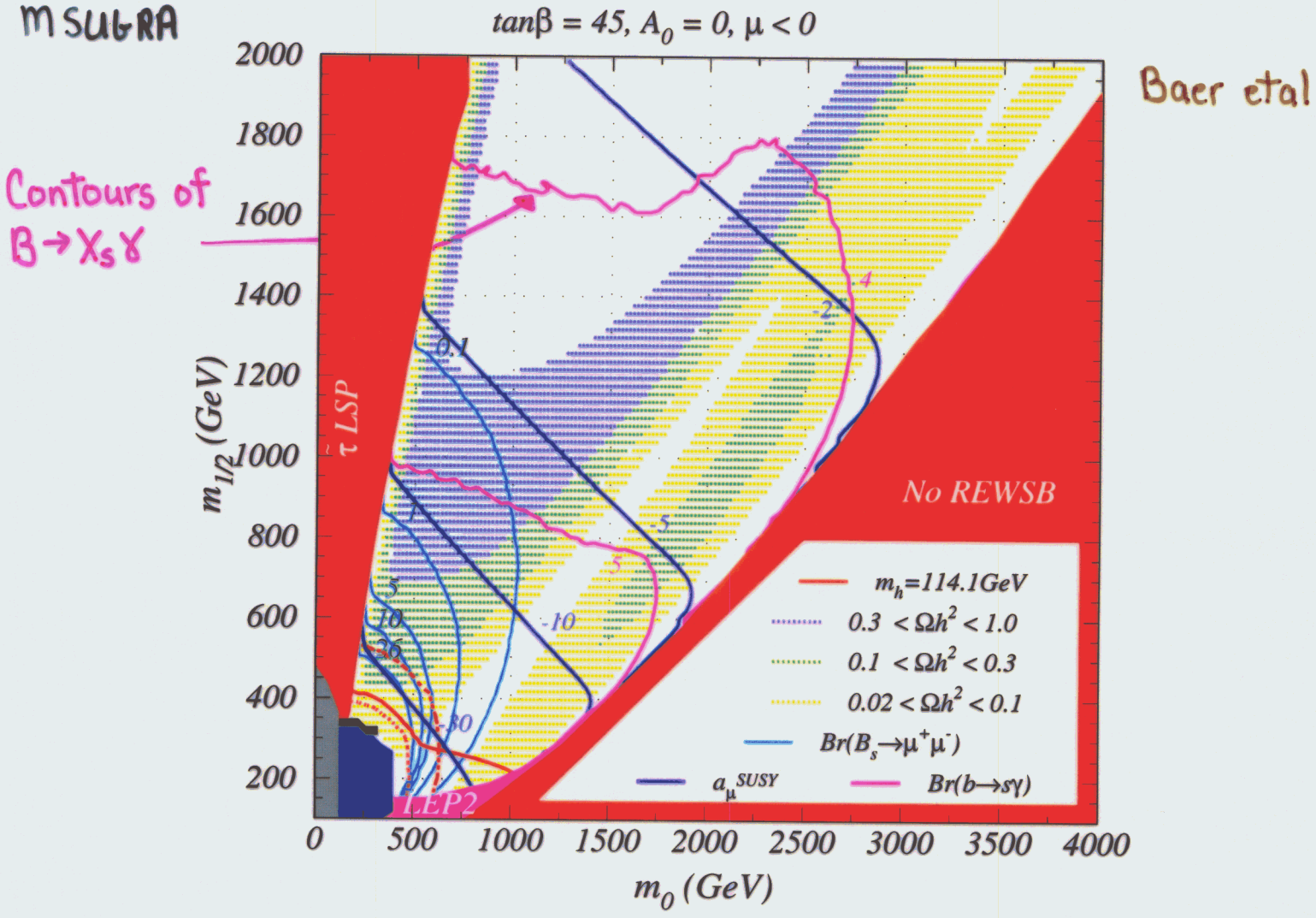
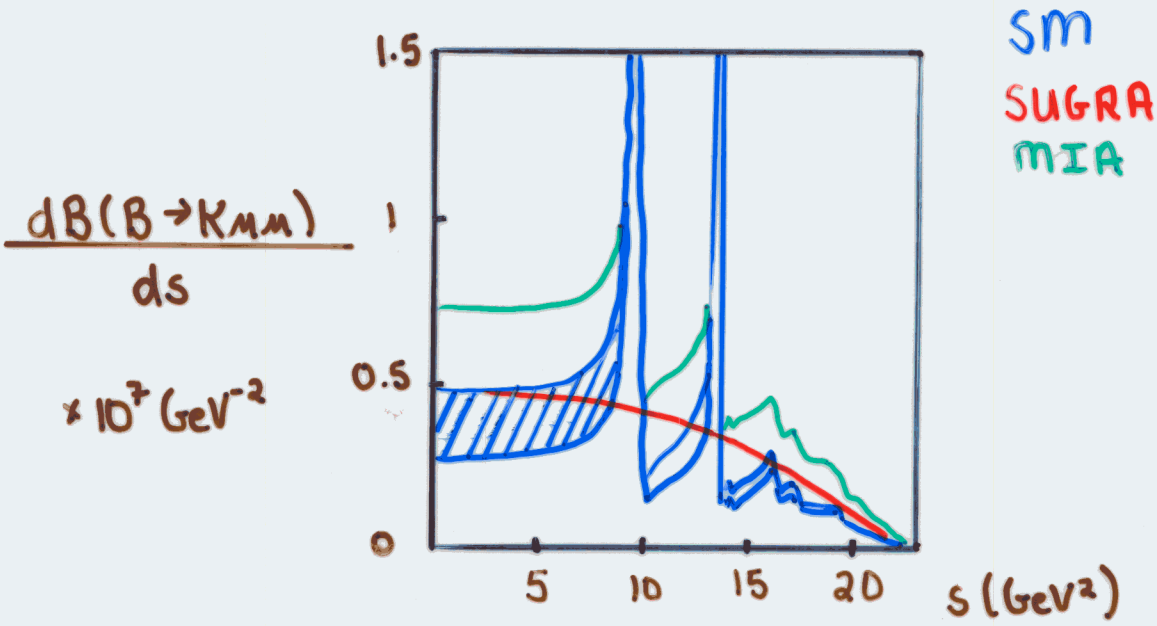


Figure 5: Same as Fig. 1, but for $\tan\beta = 45$ and $\mu < 0$. The inner and outer red dashed lines are contours of $m_A = 100$ and $m_A = 200$ GeV, respectively.

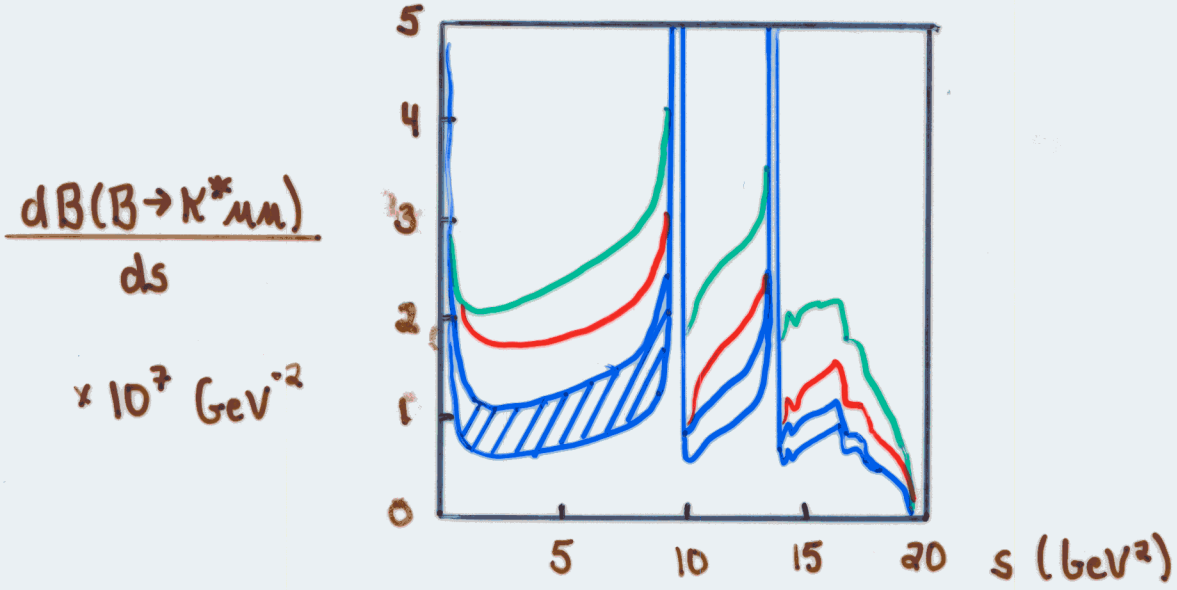
- **1.** annihilation through t-channel slepton exchange (low m_0 and $m_{1/2}$),
- **2.** the stau co-annihilation region (very low m_0 but large $m_{1/2}$),
- **3.** the focus point region (large m_0 but low to intermediate $m_{1/2}$) and
- **4.** the flanks of the neutralino s-channel annihilation via A and H corridor at large $\tan\beta$ when Γ_A and Γ_H are very large.

In previous years, there may have been a preference for region **1.** as offering the most natural channel for obtaining a reasonable value of relic density. However, recently much of

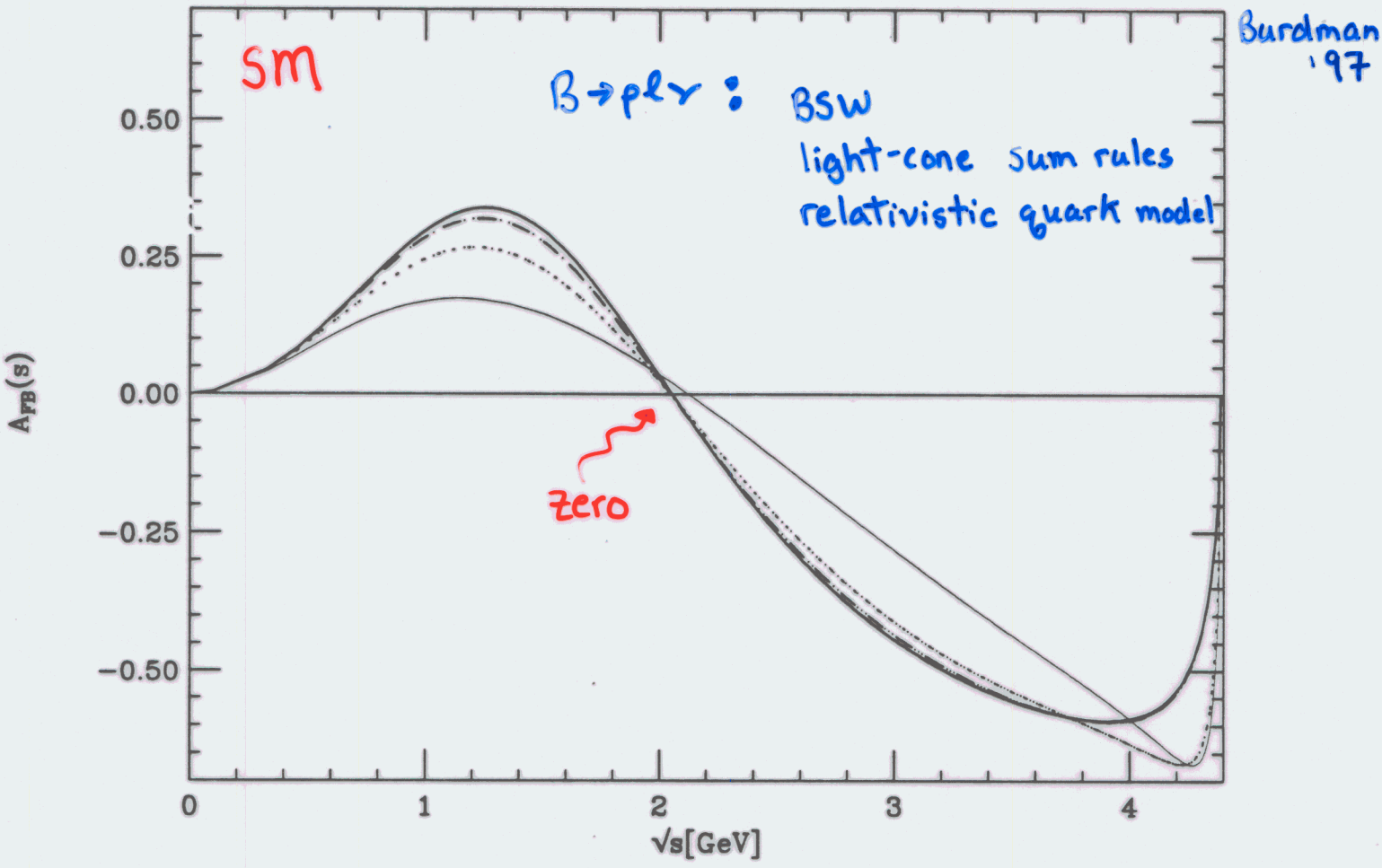
Exclusive Branching Fractions



Ali, Ball, Handoko, Hiller



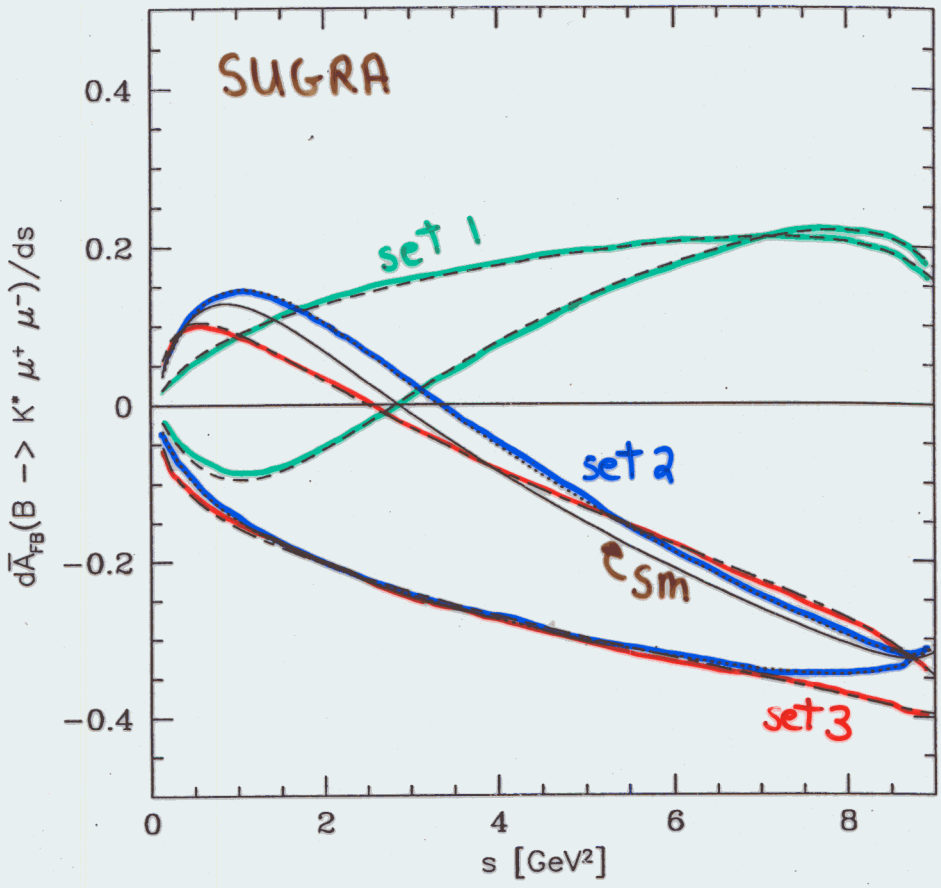
$\ell^+\ell^-$ Forward-Backward Asymmetry for $B \to K^* e^+ e^-$



Form Factors related to $B \to \rho l \nu$

- Need Acurate Form Factor predictions for exclusive modes!

Position of Asymmetry Zero ^ changes / vanishes with NP!



Ali, Ball, Handoko, Hiller '99

Clear indication of New Physics!

Correlation between $B_{s,d} \to ll$ + Δm_s : Large tan β

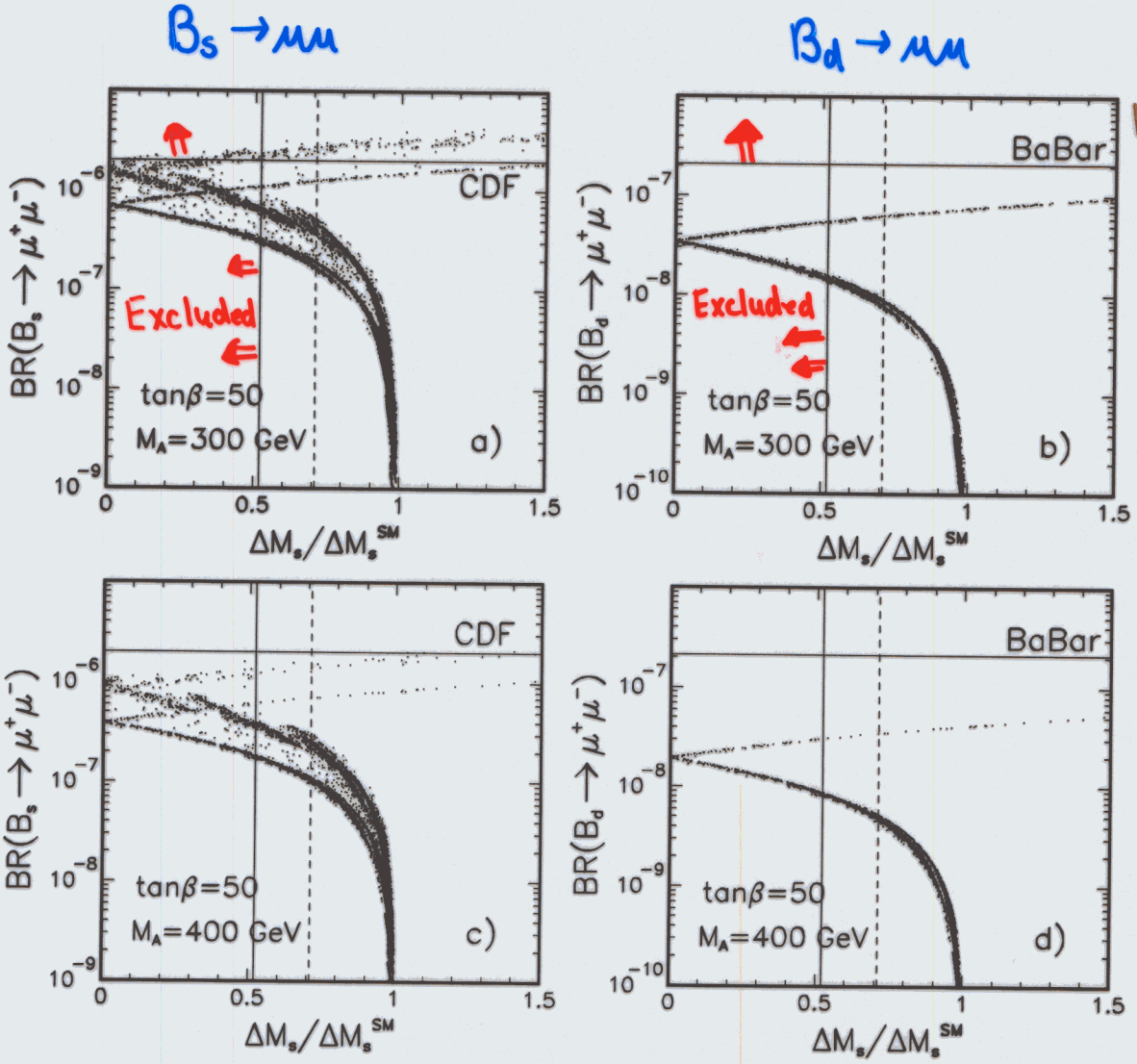


Figure 23: Correlation between $\Delta M_s/(\Delta M_s)^{\rm SM}$ and $B^0_{s,d} \to \mu^+\mu^-$ in the MSSM with flavour violation ruled by the CKM matrix. Lower (upper) branches of points correspond to $0 < 1 + f_s < 1$ ($1 + f_s < 0$). Current experimental bounds: $BR(B^0_s \to \mu^+\mu^-) < 2 \cdot 10^{-6}$ (CDF) [32] and $BR(B^0_d \to \mu^+\mu^-) < 2.1 \cdot 10^{-7}$ (BaBar) [31] are shown by the horizontal solid lines. Solid (dashed) vertical lines show the lower limit on $\Delta M_s/(\Delta M_s)^{\rm SM}$ following from eq. (7.62) with $a = 0.52$ as in ref. [20] ($a = 0.71$ as in [41]).

Patterns from SUSY-breaking mechanisms

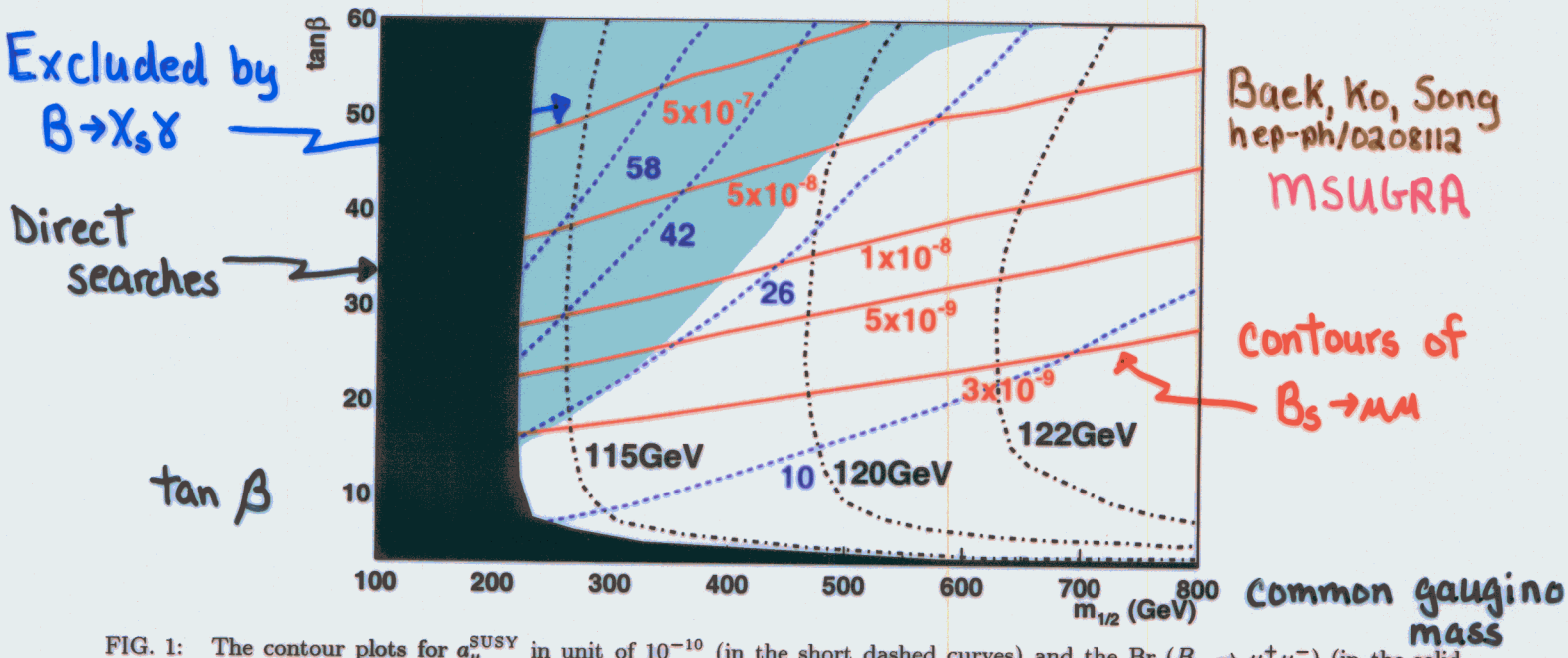
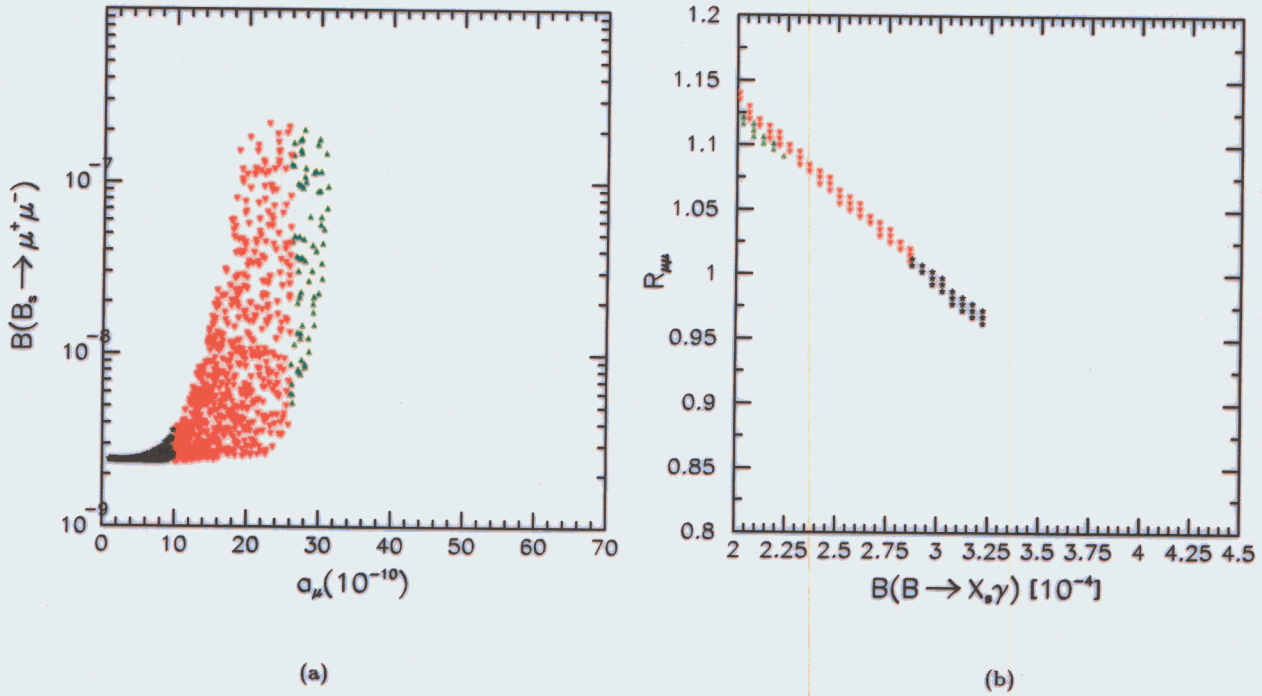


FIG. 1: The contour plots for $a_\mu^{\rm SUSY}$ in unit of 10^{-10} (in the short dashed curves) and the Br $(B_s \to \mu^+\mu^-)$ (in the solid curves) in $(M_{1/2}, \tan\beta)$ plane in the minimal SUGRA model for $m_0 = 300$ GeV and $A_0 = 0$.



(a) (b)

FIG. 2: The correlations between (a) the muon $a_\mu^{\rm SUSY}$ and $B(B_s \to \mu^+\mu^-)$, and (b) $Br(B \to X_s\gamma)$ and $R_{\mu\mu}$ in the mSUGRA model with $A_0 = 0$ and $m_0 = 300$ GeV. The regions $a_\mu^{\rm SUSY} < 10^{-10}$, $10 \times 10^{-10} < a_\mu^{\rm SUSY} < 26 \times 10^{-10}$, $26 \times 10^{-10} < a_\mu^{\rm SUSY} < 42 \times 10^{-10}$, $42 \times 10^{-10} < a_\mu^{\rm SUSY} < 58 \times 10^{-10}$, and $a_\mu^{\rm SUSY} > 58 \times 10^{-10}$ are represented by the stars (black), the inverted triangles (red), the triangles (green), the squares (blue) and the circles (yellow).

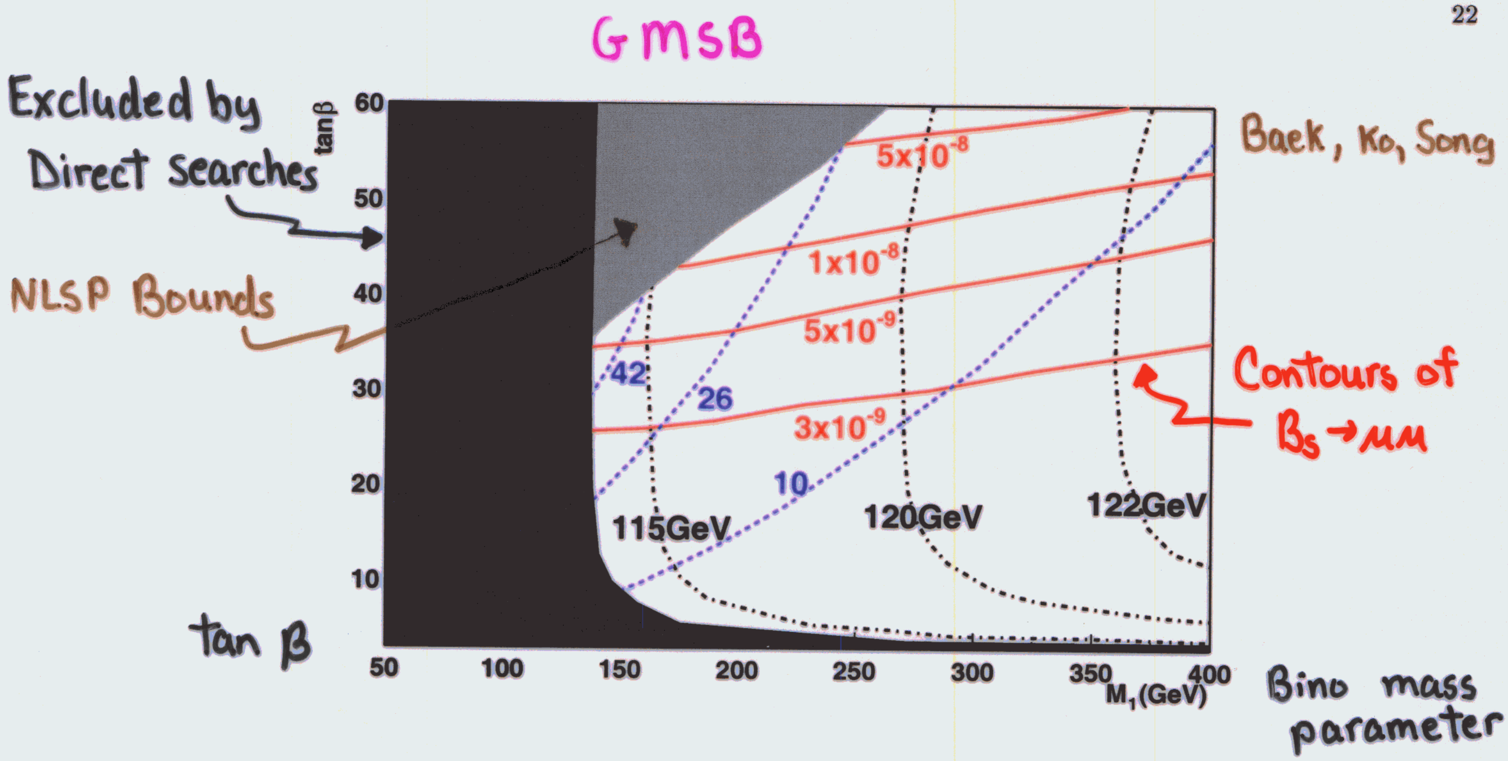


FIG. 7: The contour plots for $a_\mu^{\rm SUSY}$ in unit of 10^{-10} (in the short dashed curves) and the Br $(B_s \to \mu^+\mu^-)$ (in the solid curves) in the $(M_1, \tan\beta)$ plane for the GMSB model with $N_{\rm mess} = 5$ and $M_{\rm mess} = 10^{15}$ GeV. The gray region is excluded by the NLSP mass bound.

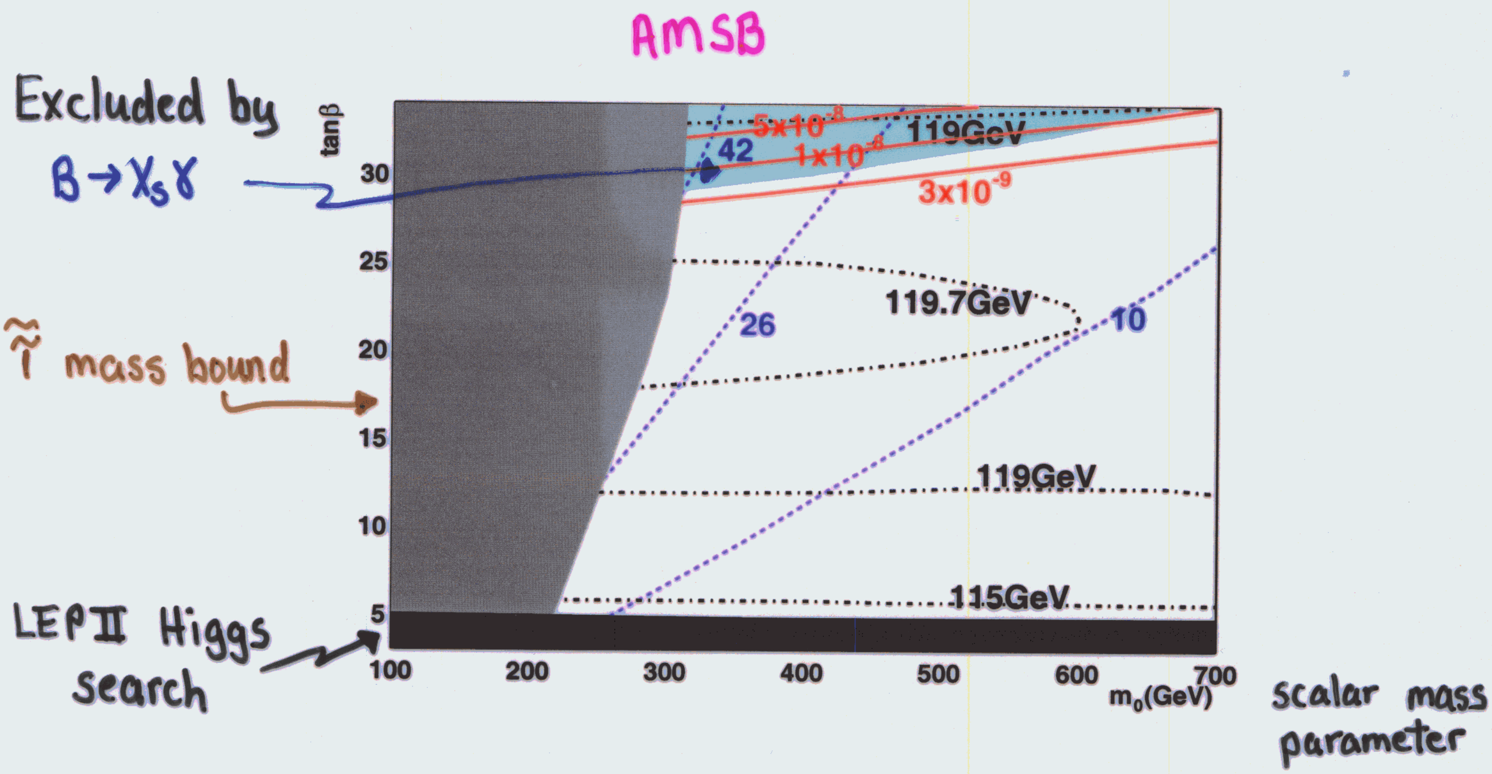
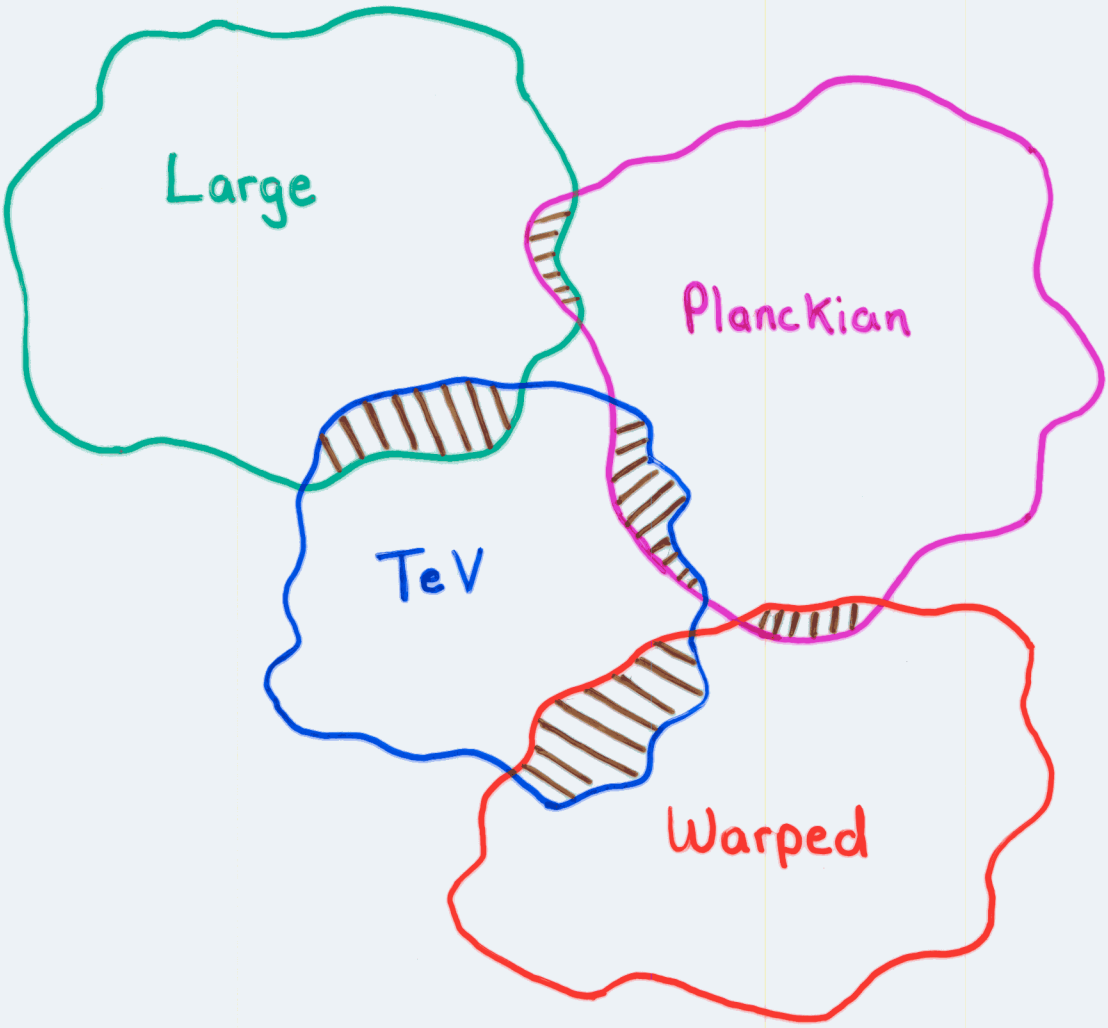


FIG. 8: The contour plots for $a_\mu^{\rm SUSY}$ in unit of 10^{-10} (in the short dashed curves) and the Br $(B_s \to \mu^+\mu^-)$ (in the solid curves) in the $(m_0, \tan\beta)$ plane for the minimal AMSB scenarios with $M_{\rm aux} = 50$ TeV and $\mu > 0$.

Extra Dimensions!



Many different types with overlap in features

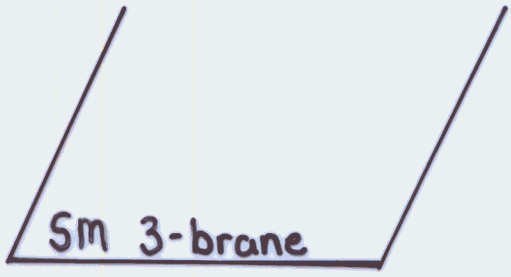
Impact on B physics just starting to be explored!

Physics of Branes: Spatial Dimensional Subspace

Our 3+1-dim subspace = 3-brane

Embedded in D = 3+6+1 space = bulk

Bulk

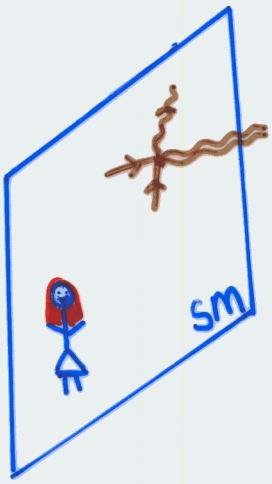


Size & geometry of bulk can vary

Large Extra Dimensions

Arkani-Hamed,
Dimopoulos, Dvali
SLAC-PUB-7801

Motivation: Solve the hierarchy problem by removing it!



SM fields confined to 3-brane

Gravity becomes strong in the bulk

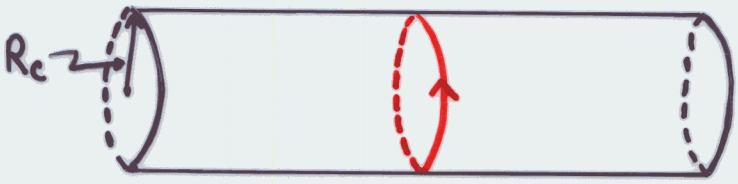
Gauss' Law: $M_{Pl}^2 = V_\delta M_D^{2+\delta}$; $V_\delta \sim R_c^\delta$

M_D = Fundamental scale in the bulk
$\simeq$ TeV

$\delta = 1$	$R_c \sim 10^{11}$ m	Excluded!
2	0.4 mm	$m_c = 1/R_c \sim 5 \times 10^{-4}$ eV
4	10^{-5} mm	20 KeV
6	30 fm	7 MeV

Compactification: Bulk Fields

Bulk fields expand into Kaluza-Klein towers



δ-d kinetic motion is quantized!

$$p_\delta^2 = \frac{\vec{n}\cdot\vec{n}}{R_c^2}$$

mode numbers $\vec{n} = (n_1, n_2, \ldots n_\delta)$
label KK excitation state

Appears as tower of massive particles in 4-d

$$\Phi(x_\mu, y_i) = \sum_{\vec{n}=0}^{\infty} \phi^{(\vec{n})}(x_\mu)\, e^{i\vec{n}\cdot\vec{y}/R_c} \cdot \frac{1}{\sqrt{V_\delta}}$$

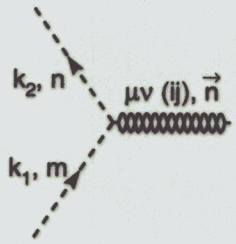
for periodic $y_i \to y_i + 2\pi R_c$ Flat space

with mass $m_{\vec{n}}^2 = \frac{\vec{n}\cdot\vec{n}}{R_c^2}$

KK tower of evenly spaced states
each with identical spin + quantum numbers

Feynman Rules - Graviton KK tower

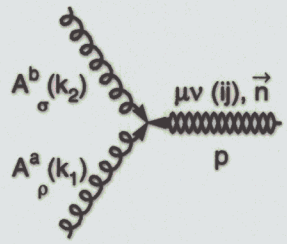
Massless 0-mode + KK states have identical coupling to matter



$\tilde{h}^{\vec{n}}_{\mu\nu}\,\Phi\Phi$: $\quad -i\,\kappa/2\,\delta_{mn}\,(m^2_\Phi\,\eta_{\mu\nu} + C_{\mu\nu,\rho\sigma}\,k_1^\rho\,k_2^\sigma)$

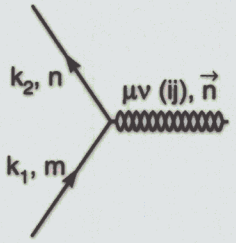
$\tilde{\phi}^{\vec{n}}_{ij}\,\Phi\Phi$: $\quad i\,\omega\,\kappa\,\delta_{ij}\,\delta_{mn}\,(k_1 \bullet k_2 - 2\,m^2_\Phi)$

$\kappa \sim \frac{1}{M_{Pl}}$



$\tilde{h}^{\vec{n}}_{\mu\nu}\,AA$: $\quad -i\,\kappa/2\,\delta^{ab}\,((m^2_A + k_1 \bullet k_2)\,C_{\mu\nu,\rho\sigma} + D_{\mu\nu,\rho\sigma}(k_1,k_2) + \xi^{-1}\,E_{\mu\nu,\rho\sigma}(k_1,k_2))$

$\tilde{\phi}^{\vec{n}}_{ij}\,AA$: $\quad i\,\omega\,\kappa\,\delta_{ij}\,\delta^{ab}\,(\eta_{\rho\sigma}\,m^2_A + \xi^{-1}\,(k_{1\rho}\,p_\sigma + k_{2\sigma}\,p_\rho))$



$\tilde{h}^{\vec{n}}_{\mu\nu}\,\psi\psi$: $\quad -i\,\kappa/8\,\delta_{mn}\,(\gamma_\mu\,(k_{1\nu} + k_{2\nu}) + \gamma_\nu\,(k_{1\mu} + k_{2\mu}) - 2\,\eta_{\mu\nu}\,(\not{k}_1 + \not{k}_2 - 2\,m_\psi))$

$\tilde{\phi}^{\vec{n}}_{ij}\,\psi\psi$: $\quad i\,\omega\,\kappa\,\delta_{ij}\,\delta_{mn}\,(3/4\,\not{k}_1 + 3/4\,\not{k}_2 - 2\,m_\psi)$

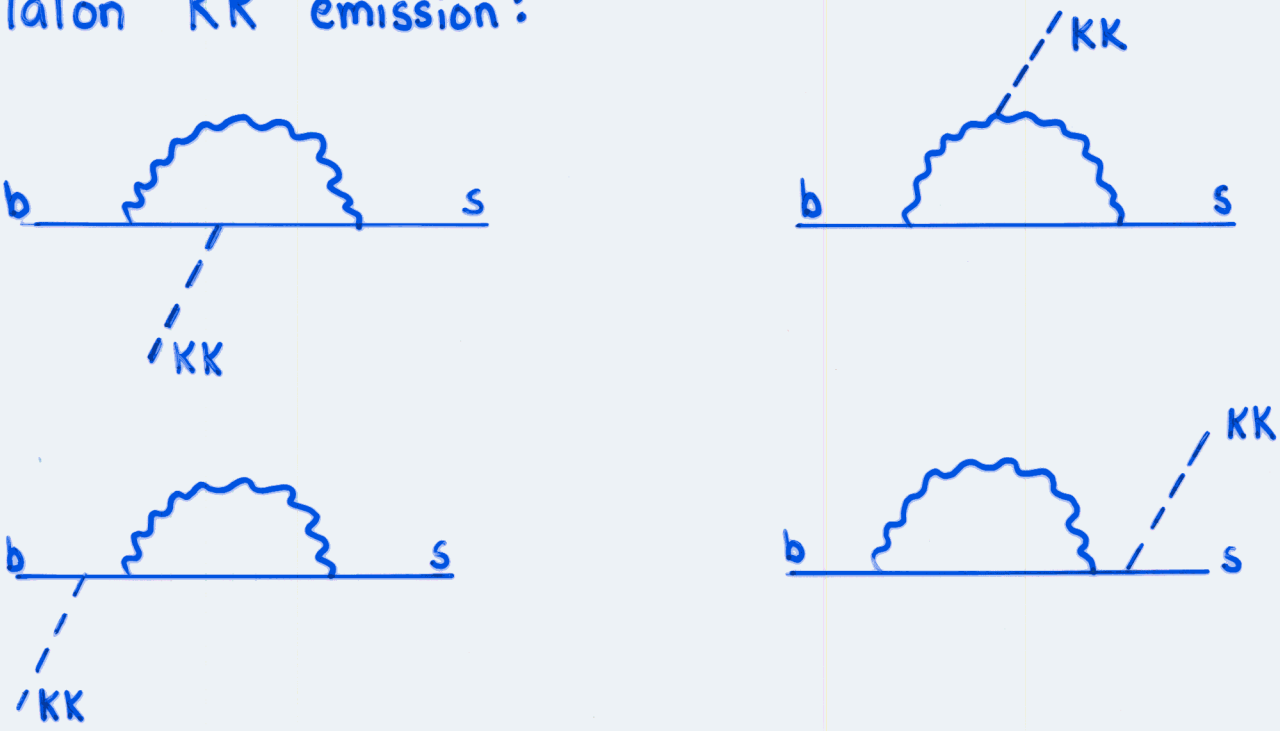
Figure 4: Three-point vertex Feynman rules. The KK states are plot in double-sinusoidal curves. The symbols $C_{\mu\nu,\rho\sigma}$, $D_{\mu\nu,\rho\sigma}(k_1,k_2)$ and $E_{\mu\nu,\rho\sigma}(k_1,k_2)$ are defined in Eqs. (A.10), (A.11) and (A.12) respectively. m_Φ, m_A and m_ψ are masses of the scalar, vector and fermion. $\omega = \sqrt{\frac{2}{3(n+2)}}$, $\kappa = \sqrt{16\pi G_N}$ and ξ is the gauge-fixing parameter.

Han, Lykken, Zhang
Giudice, Rattazzi, Wells

$B \to X_s$ + Missing : Graviton Emission

Mahajan
hep-ph/0211255

Dilaton KK emission:



Induces new operators:

$$O_{Dilaton} \sim \bar{s}(1 \pm \gamma_5) b \, \Phi$$

$$O_{Graviton} \sim \bar{s} \gamma_m p_\nu(b)(1-\gamma_5) b \, h^{\mu\nu}$$

$$\mathcal{M}(b \to s \Phi) = \frac{i G_F \omega \kappa}{16\pi^2} \ln \frac{\Lambda^2}{m_W^2} \sum_t m_t^2 \frac{m_b}{3} \left[18 \frac{m_s^2}{m_b^2 - m_s^2} - 1 \right] \bar{s}(1+\gamma_5) b$$

($\kappa \sim \frac{1}{m_{Pl}}$)

Perform sum over KK tower:

$$\Gamma \sim \frac{1}{m_{Pl}^2} (m_b R_c)^\delta \rightarrow \frac{1}{m_D^2} \left(\frac{m_b}{m_D}\right)^\delta$$

$B(B \to X_s \Phi)$	δ	m_D (TeV)
1.28×10^{-3}	2	1
2.25×10^{-6}	3	1
4.93×10^{-9}	4	1
5.50×10^{-6}	2	5
1.93×10^{-9}	3	5
8.45×10^{-13}	4	5

$B(B \to X_s \nu\bar{\nu})_{sm} \sim 5 \times 10^{-5}$

$B(B \to X_s \nu\bar{\nu})_{exp} < 6.2 \times 10^{-4}$ @ 90% CL

LEP Bound: Graviton emission

$\delta = 2$, $m_D > 1.28$ TeV

$\Rightarrow$ $B \to X_s \Phi$ is comparable to collider searches!

Flavor Physics in Extra Dimensions - Basic Ingredients

String / M-Theory $\Rightarrow$ $n = 6, 7$

Let $R^n = R_1^p R_2^{n-p}$ with $R_1 \sim$ large

$R_2 \sim$ small $\sim 1/\text{TeV} \sim 1/m_*$

$\Rightarrow M_{Pl}^2 = R_1^p m_*^{p-n} m_*^{n+2}$

$= R_1^p m_*^{p+2}$ with $2 \leq p \leq 6$

SM fields can propagate in small R_2^{n-p} dimensions

Consider 5DSM : 1 extra $1/\text{TeV}$ dimension (Antoniadis)

flat, factorizable geometry

(x^μ, y) with y compactified on S^1/Z_2 orbifold

S^1: circle of radius R

Z_2: folded over $y \to -y$, with $0 \leq y \leq \pi R$

3D branes located at orbifold fixed points

Examine 5-D Action

$$S_5 = \int d^4x \int dy \, [\, S_{SMGF} + S_{Higgs} + S_{fermions} \,]$$

↑ integrate to get 4-D effective theory

KK excitations of gauge fields

γ_n, Z_n, W_n, g_n

$m_n = n/R$

- degenerate (up to mixing)
- equally spaced states
- $\alpha_{(n)} = 2\,\alpha_{(0)}$

Contribute to EW precision observables

$\Rightarrow$ $M_c \sim 1/R \gtrsim 2\text{-}5$ TeV

Rizzo, Wells

Can lead to drastic lowering of GUT scale via ~power-like running of couplings

Dienes, Dudas, Ghergetta

Universal Extra Dimensions

Appelquist etal

Full SM is in the bulk!

and expands into KK towers...

Branes need not be present ⇒ translational invariance perserved in full spacetime.

Conservation of KK parity $(-1)^n$

KK states ocurr in pairs in production & in loops

Drastic reduction in precision EW constraints:

$$R_c^{-1} \gtrsim 400\text{-}500 \text{ GeV}$$

KK Contributions to $B \to X_s \gamma$

Agashe, Deshpande, Wu

W-top KK loops:

$$C_7(m_W) \sim \sum_n \frac{m_t^2 m_W^2}{(n/R_c)^4}$$

Goldstone Boson-top KK loops:

$$C_7(m_W) \sim \sum_n \left[1 + \frac{m_t^2}{(n/R)^2}\right]\left[A\left(m_t^2/(n/R)^2\right) - \tfrac{1}{6} B\left(m_t^2/(n/R)^2\right)\right]$$

loop integrals

No new operators are induced

Comparison with data:

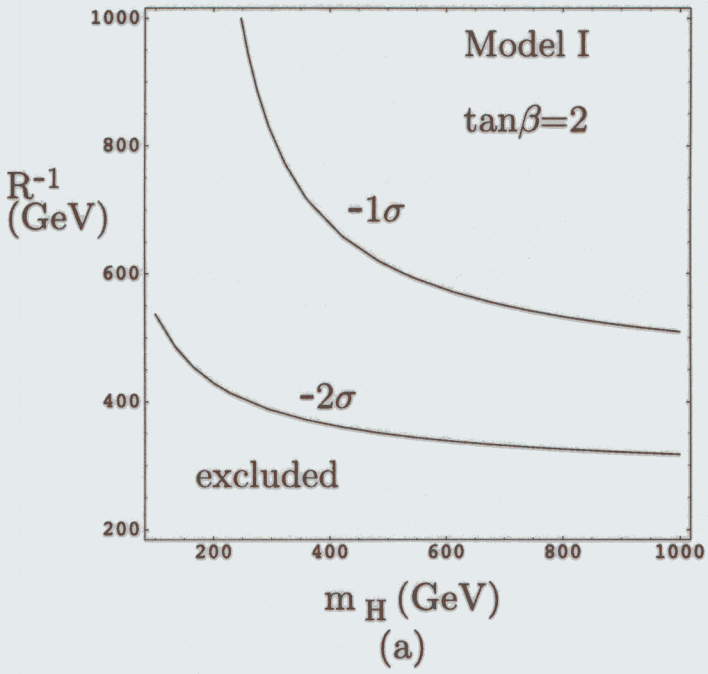
$$R_c^{-1} \gtrsim 280 \text{ GeV}$$

Comparable to precision EW constraints!

Two Higgs Doublets in the bulk:

Constraints from $B \to X_s \gamma$

Agashe, Deshpande, Wu



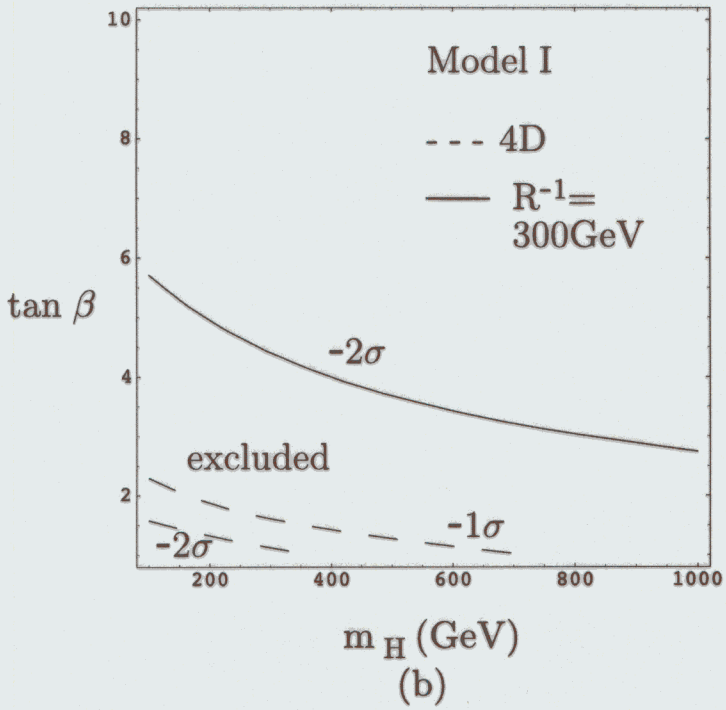


Figure 2: The deviation of the rate of $b \to s\gamma$ from the SM prediction in model I as a function of size of one extra dimension (R^{-1}) and charged Higgs mass (m_H) for $\tan\beta = 2$ (figure (a)) and as a function of $\tan\beta$ and m_H for $R^{-1} = 300$ GeV (figure (b)). In figure (b), the dashed lines are the result in $4D$. The 1σ deviation corresponds to 18%.

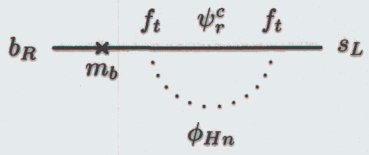
Supersymmetric Extra Dimensions

Barbieri + Hall

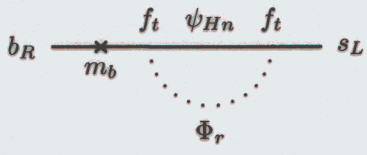
5D SUSY compactified on $S^1/Z_2 \times Z_2'$

Double orbifolding breaks EW symmetry !!

$B \to X_s \gamma$:

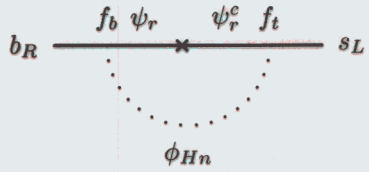


(a)



(b)

+ attached γ

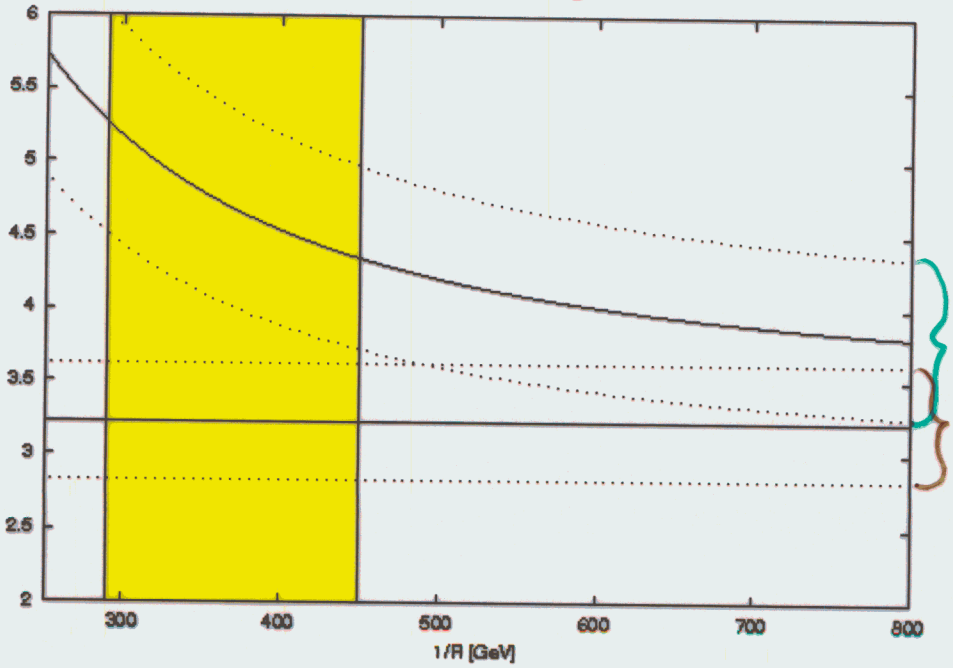


(c)

(d)

Barbieri, Cacciapaglia, Romito

$B(B \to X_s \gamma) \times 10^{-4}$ vs $1/R$ (GeV)



Shaded region: theoretically favored to obtain light Higgs

prediction

Exp

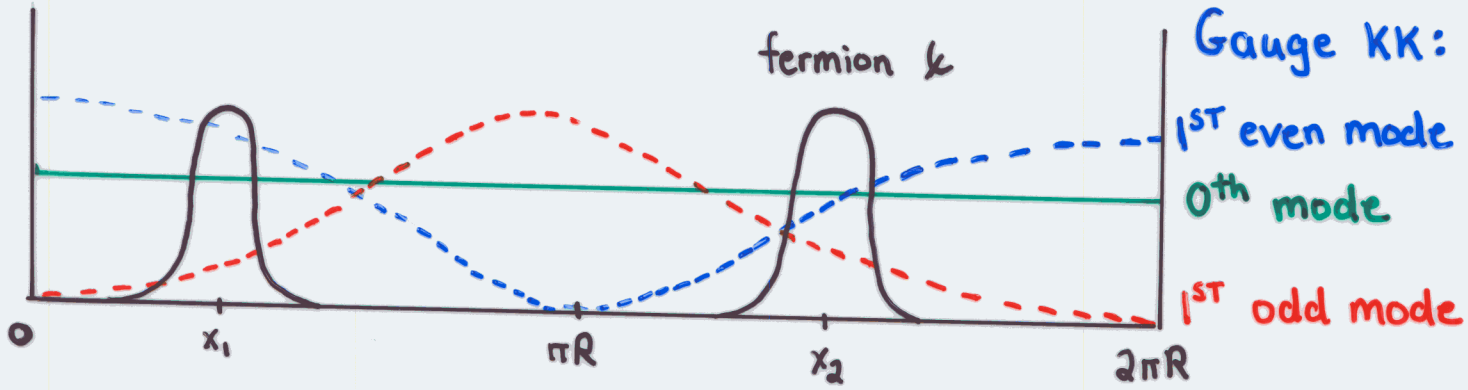
Fat Branes - SM lives in a thick brane

Antoniadis

One Scenario:
- SM gauge fields live throughout
- SM fermions localized at specific points within brane

Motivations:
- suppress proton decay
- achieve gauge coupling unification
- generate fermion mass hierarchy

Precision EW Data constrains $R_c^{-1} \gtrsim 2\text{-}5$ TeV



Arkani-Hamed, Schmaltz

$$\chi^n(\theta) = \begin{cases} 1/\sqrt{2\pi}, & n=0 \\ \dfrac{\cos n\theta}{\sqrt{\pi}}, & n\neq 0 \end{cases}$$

Fermion mixing induces FC KK interactions

Wavefunction Overlap:

$$x_i = \int d\theta\, \bar{f}_i(\theta)\, f_i(\theta)\, \chi^n(\theta) \quad ; \quad f(\theta) = \text{narrow Gaussian}$$

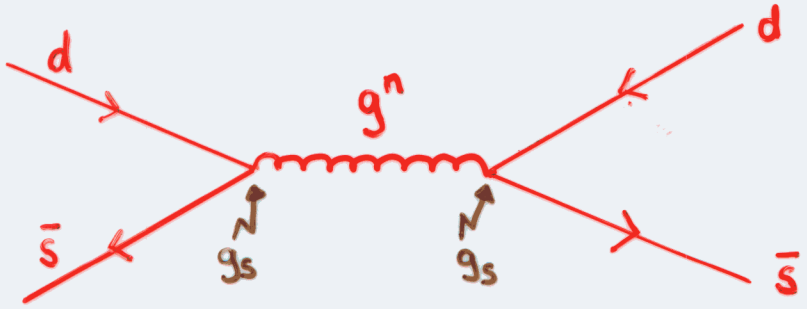
$$\simeq \cos n\theta_i \qquad \text{in weak basis}$$

In mass eigenstate basis:

$$X_{ij} = (U^\dagger)_{ik}\, x_k\, \delta_{ak}\, U_{aj}$$

leads to flavor changing couplings!

K-$\bar{K}$ mixing:



Tree-level FCNC with strong couplings!

$$1/R_c \gtrsim 400\ \text{TeV} \left[\frac{\sum_n X_{sd}/n}{0.3} \right]$$

Delgado, Pomarol, Quiros
hep-ph/9911252

Poses a threat to the model! Further study needed...

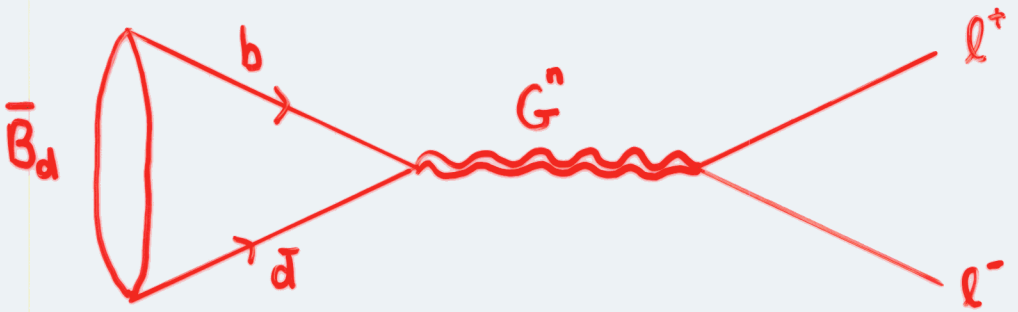
$AdS_5 \times S^1/Z_2$

Davoudiasl, JLH, Rizzo
hep-ph/0211377

Attempt to embed Randall-Sundrum model of localized gravity within string theory

TeV scale KK gravitons with TeV^{-1} couplings

Fermion mixing induces FC KK graviton interactions!



$$\Gamma(B_q \to \ell^+\ell^-) \sim \frac{f_B^2 m_B^5 m_\ell^2}{\Lambda_\pi^4 m_{10}^4} \left| \sum_{n,m} \frac{x_{10}^2 [X_L^{qb} - X_R^{qb}][x_L^\ell - x_R^\ell]}{x_{nm}^2} \right|^2$$

⇒ is highly suppressed!

Further study needed...

Model Dependent New Physics Summary

Table 13–6. *Model dependent effects of new physics in various processes.*

Model	*CP* Violation		Rare Decays	$D^0 - \bar{D}^0$ Mixing
	$B_d^0 - \bar{B}_d^0$ Mixing	Decay Amplitude		
MSSM	$\mathcal{O}(20\%)$ SM Same Phase	No Effect	$B \to X_s\gamma$ – yes $B \to X_s l^+ l^-$ – no	No Effect
SUSY – Alignment	$\mathcal{O}(20\%)$ SM New Phases	$\mathcal{O}(1)$	Small Effect	Big Effect
SUSY – Approx. Universality	$\mathcal{O}(20\%)$ SM New Phases	$\mathcal{O}(1)$	No Effect	No Effect
R-Parity Violation	Can Do	Everything	Except Make	Coffee
MHDM 2HDM	$\sim$ SM/New Phases $\sim$ SM/Same Phase	Suppressed Suppressed	$B \to X_s\gamma$, $B \to X_s\tau\tau$ $B \to X_s\gamma$	Big Effect No Effect
Quark Singlets Fourth Generation	Yes/New Phases $\sim$ SM/New Phases	Yes Yes	Saturates Limits Saturates Limits	$Q = 2/3$ Big Effect
LRM – $V_L = V_R$ – $V_L \neq V_R$	No Effect Big/New Phases	No Effect Yes	$B \to X_s\gamma$, $B \to X_s l^+ l^-$ $B \to X_s\gamma$, $B \to X_s l^+ l^-$	No Effect No Effect
DEWSB	Big/Same Phase	No Effect	$B \to X_s\ell\ell$, $B \to X - s\nu\bar{\nu}$	Big Effect

+ Extra Dimensions! + Little Higgs!