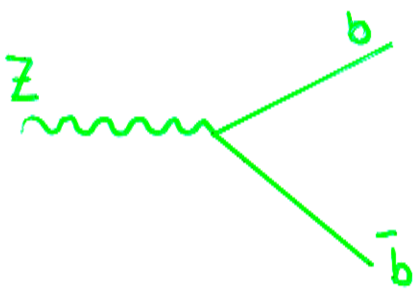
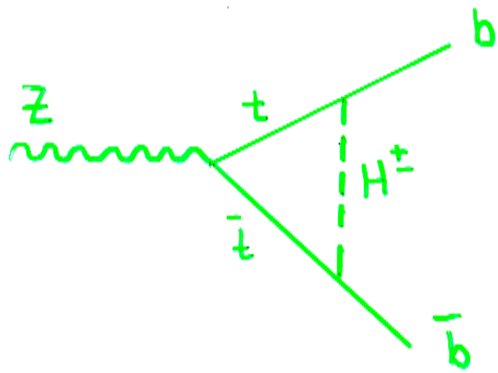
Signals for New Physics in Rare Decays

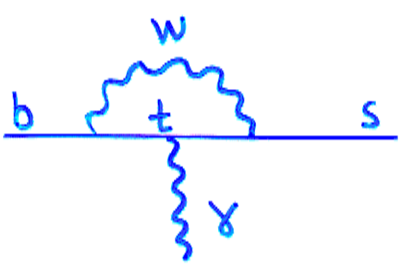
Precision EW:



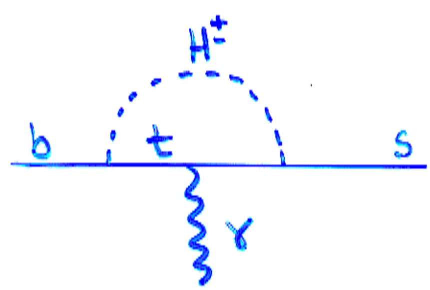
vs.



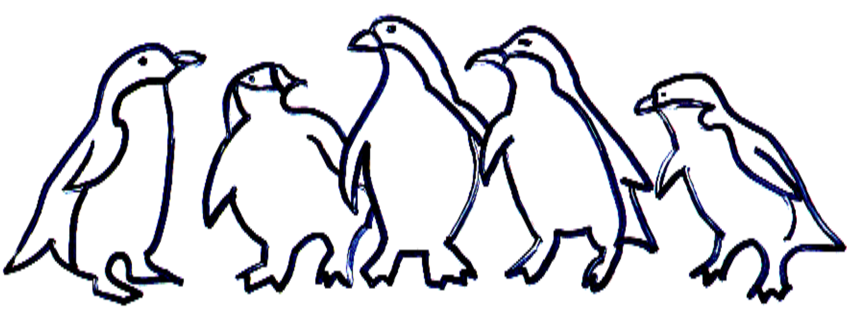
Rare Decays:



vs.



FNAL / Feb '00



Motivation

- Within Standard Model – theoretically under control
  - Tests SM at quantum level
  - $$\frac{\mathcal{B}(B \to X_d \ell^+ \ell^-)}{\mathcal{B}(B \to X_s \ell^+ \ell^-)} \propto \frac{|V_{td}|^2}{|V_{ts}|^2}$$ allows for clean determination!

- New Physics – complementary to $b \to s\gamma$
  - Sensitive to virtual effects of new particles + interactions – in different set of diagrams
  - Leptonic final state allows determination of various kinematic distributions ⇒ increased sensitivity to N.P.
  - together with $b \to s\gamma$ allows for model independent probe of new physics + structure of Operator Product Expansion ⇒ ultimate goal!

- 1ST Observation – is within BaBar's grasp!

  if PEP-II delivers $\mathcal{L}$

  CDF + CLEO have candidate events ...

Right-Handed $b \to c$ Transitions Revisited

Rizzo '98
Voloshin '97
Gronau, Wakaizumi '92

Semi-Leptonic Decay:

$$\mathcal{H}_{s\ell} = \frac{4G_F}{\sqrt{2}} V_{cb} \left[(\bar{c}_L \gamma_\mu b_L) + \zeta (\bar{c}_R \gamma_\mu b_R) \right] (\bar{\ell}_L \gamma^\mu \nu_L)$$

$\zeta = |\zeta| e^{i\Delta}$ = relative strength of RH coupling

$$\Gamma(b \to c \ell \nu) \sim |V_{cb}|^2 f(x) \eta \left[1 + |\zeta|^2 + 2 \,\mathrm{Re}\, \zeta \frac{g(x)}{f(x)} \right]$$

$$\Rightarrow |V_{cb}|_{eff} = |V_{cb}| \left[\quad \text{''} \quad \right]^{1/2}$$

CLEO: $B \to D^* \ell \nu$ – Rate (V_{cb}), A_{FB}^{ℓ}, Γ_L / Γ_T D^* Polarization

Form Factors: $V \to V(1+\zeta)$
$A_{1,2} \to A_{1,2}(1-\zeta)$

L3: Inclusive $b \to c \ell \nu$, p_ℓ + $\not{p}_T$ spectra

LEP/ADO: Λ_b polarization in Z decay

HQET + SM: $P = -(0.69 \pm 0.06)$ Falk, Peskin

ALEPH: $P = -0.29^{+0.19}_{-0.09}$

DELPHI: $P = -0.08^{+0.35}_{-0.29}{}^{+0.18}_{-0.17}$

OPAL: $P = -0.56^{+0.20}_{-0.13} \pm 0.09$

LEP Combined:
$P = -0.44^{+0.14}_{-0.12}$

95% C.L. Allowed Region

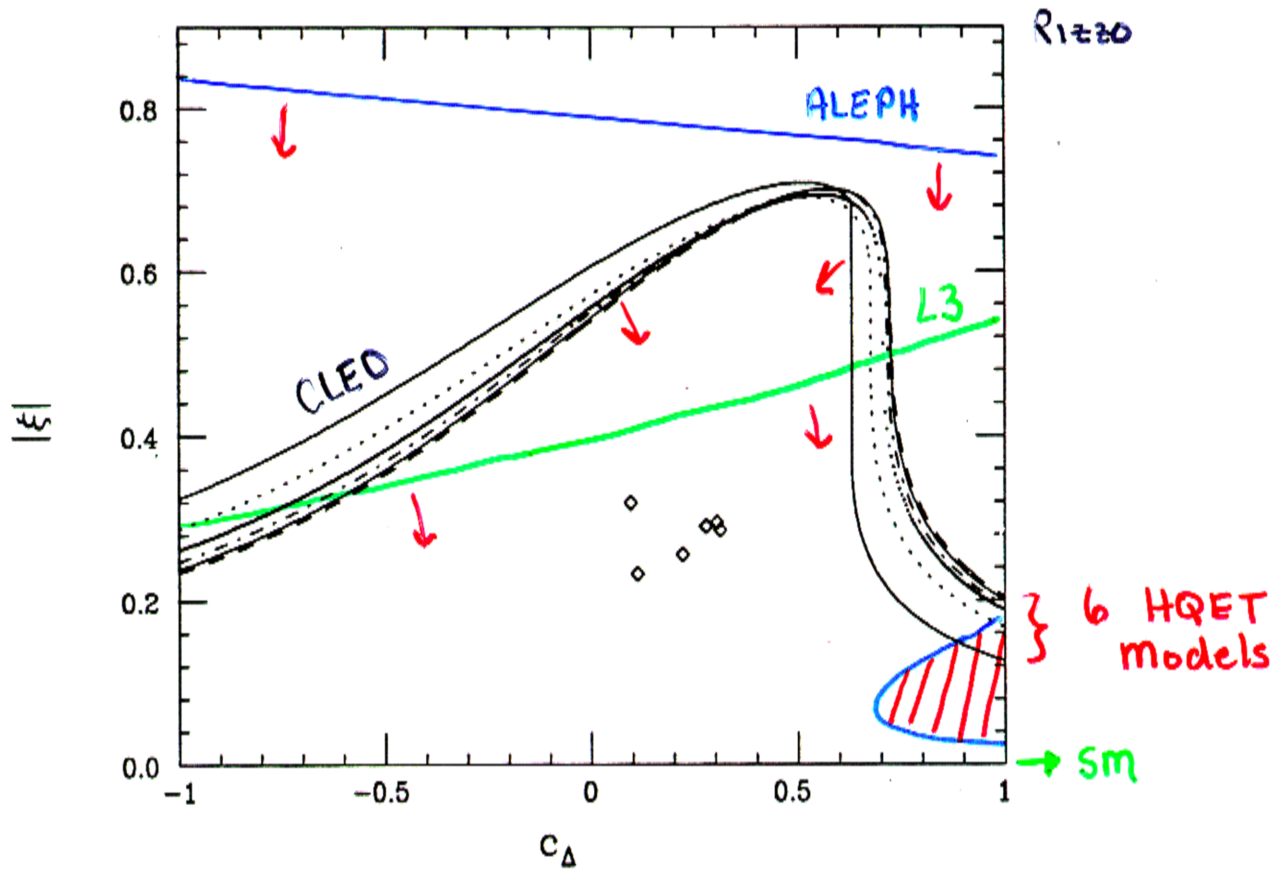
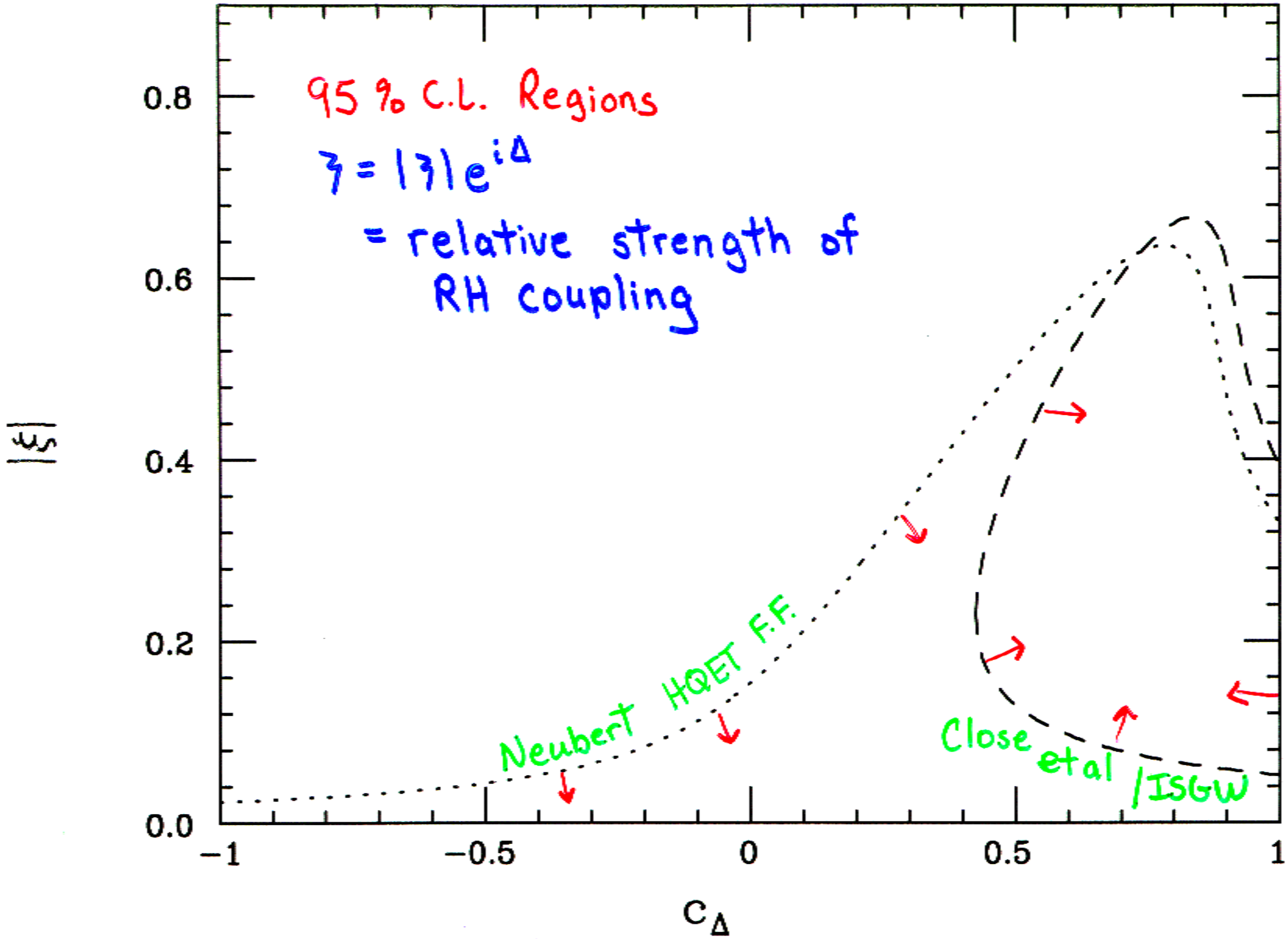


Figure 1: 95% CL allowed region (below the curves) in the $|\xi| - c_\Delta$ plane obtained from a fit to CLEO data as well as the experimental value of the ratio $V_{cb}^{exc}/V_{cb}^{inc}$. Each of the six curves corresponds to a unique choice of $R_{1,2}$ and h. The SM lies along the x-axis. The locations of the six χ^2 minima are also shown for completeness.

Best fit $|\xi| \sim 0.25 - 0.35$

$B \to D^* \ell \nu$ χ Distribution (CLEO)

with Right-Handed Currents



χ = ∡ between decay planes of W + D* in B rest frame

$$\mathcal{H}_{SL} = \frac{4G_F}{\sqrt{2}} V_{cb} \left[(\bar{c}_L \gamma_\mu b_L) + \zeta (\bar{c}_R \gamma_\mu b_R) \right] (\bar{\ell}_L \gamma^\mu \nu_L)$$

Generalize!

Goldberger
hep-ph/9902311

Most general Lorentz + SM invariant interaction

$$\mathcal{H} = \mathcal{H}_{SM} + \frac{4G_F}{\sqrt{2}} V_{cb} \sum_{\gamma,\mu,\epsilon} g^{\gamma}_{\mu\epsilon} [\bar{c}\,\Gamma^{\gamma} b_{\mu}][\bar{\ell}_{\epsilon}\,\Gamma^{\gamma} \nu_{\ell}] + \text{h.c.}$$

γ summed over S, V, T $\Rightarrow$ 12 g's [allows for ν_R]
μ, ϵ " L, R

expect $g \sim m_W^2/M^2$

5 can interfere w/ SM : $2\,\mathrm{Re}[\, g^{V}_{LL}, g^{V}_{RL}, \underbrace{g^{S}_{LR}, g^{S}_{RR}, g^{T}_{LR}}_{\text{effects} \propto m_\ell}]$

Remaining 7 enter as g^2

- Compute effects in $B \to D^{(*)} \ell\nu$, $X \ell\nu$
- Check Consistency i) V_{cb} from $B \to D/D^{*} \ell\nu$
  ii) E_ℓ spectrum in $B \to X\ell\nu$

Present data constrains g's to 10-20%

Radiative Penguin - $b \to s\gamma$

QCD corrections ala Gilman + Wise

Operator Product Expansion

$$\mathcal{H}_{eff} = \frac{-4G_F}{\sqrt{2}} V_{ts}^* V_{tb} \sum_{i=1}^{8} C_i(\mu)\, O_i(\mu)$$

$$\mathcal{M}^{LO}(b \to s\gamma) = \frac{-4G_F}{\sqrt{2}} V_{ts}^* V_{tb}\, C_7^{eff}(\mu) \langle s\gamma | O_7(\mu) | b \rangle$$

→ magnetic dipole operator

$$\mathcal{B}(b \to s\gamma) = \frac{\Gamma(b \to s\gamma)}{\Gamma(B \to X \ell \nu)}\, \mathcal{B}(B \to X \ell \nu)$$

$$C_7^{eff}(\mu) = F_1(\alpha_s)\, C_7(m_W) + F_2(\alpha_s)\, C_8(m_W) + F_3(\alpha_s)$$

NLO:

$$C_7^{eff}(\mu)_{LO} \to D = C_7^{eff}(\mu)_{NLO} + \frac{\alpha_s(m_b)}{4\pi}\left[C_i^{(0)eff}(\mu)\, \gamma_{i7}^{(0)eff} \log\frac{m_b}{\mu} + C_i^{(0)eff}\, r_i \right]$$

Radiative Penguin - $b \to s\gamma$ at NLO!

NLO: matrix element - QCD bremsstrahlung corrections
1-loop $\langle s\gamma g | O_i | b \rangle$ — Ali, Greub, Pott

- Virtual Corrections — Greub, Hurth, Wyler
2-loop $\langle s\gamma | O_i | b \rangle$

Wilson coeff - $O(\alpha_s)$ terms in matching conditions — Lin, Liu, Yao; Greub, Hurth

- $O(\alpha_s^2)$ anomalous dimension matrix used in RGE — Chetyrkin, Misiak, Münz

E_γ Spectrum - Consistent treatment of Fermi motion in HQET — Kagan, Neubert

- Resummation of threshold logs — Leibovich + Rothstein

Electroweak - 2-loop EW Corrections — Czarnecki + Marciano

$$\Rightarrow \quad \boxed{\mathcal{B}(B \to X_s\gamma) = (3.29 \pm 0.33) \times 10^{-4}}$$

ALEPH: $\mathcal{B}(B \to X_s\gamma) = (3.11 \pm 0.80 \pm 0.72) \times 10^{-4}$

CLEO: $\mathcal{B}(B \to X_s\gamma) = (3.15 \pm 0.35 \pm 0.32 \pm 0.26) \times 10^{-4}$

CKM Determination

$$\frac{|V_{tb} V_{ts}^*|}{|V_{cb}|} = 0.93 \pm 0.09_{exp} \pm 0.03_{th}$$

Taking $|V_{tb}| = 0.99 \pm 0.15$ (CDF)

$|V_{cb}| = 0.0393 \pm 0.0028$ $(B \to X_c \ell \nu)$

$$\Rightarrow \quad |V_{ts}| = 0.037 \pm 0.007$$

$B \to X_d \gamma$

$$6.0 \times 10^{-6} \leq \mathcal{B}(B \to X_d \gamma) \leq 2.6 \times 10^{-5}$$

$$\Rightarrow \quad 0.017 \leq \frac{\mathcal{B}(B \to X_d \gamma)}{\mathcal{B}(B \to X_s \gamma)} \leq 0.074$$

New Physics in $b \to s\gamma$

- Provides important model building constraints!

Recent theoretical developments:

- E_γ spectrum – New Physics affects normalization only – not shape! Kagan, Neubert

- NLO matching conditions

  Two-Higgs Doublet Models — Borzumati, Greub; Ciuchini et al.

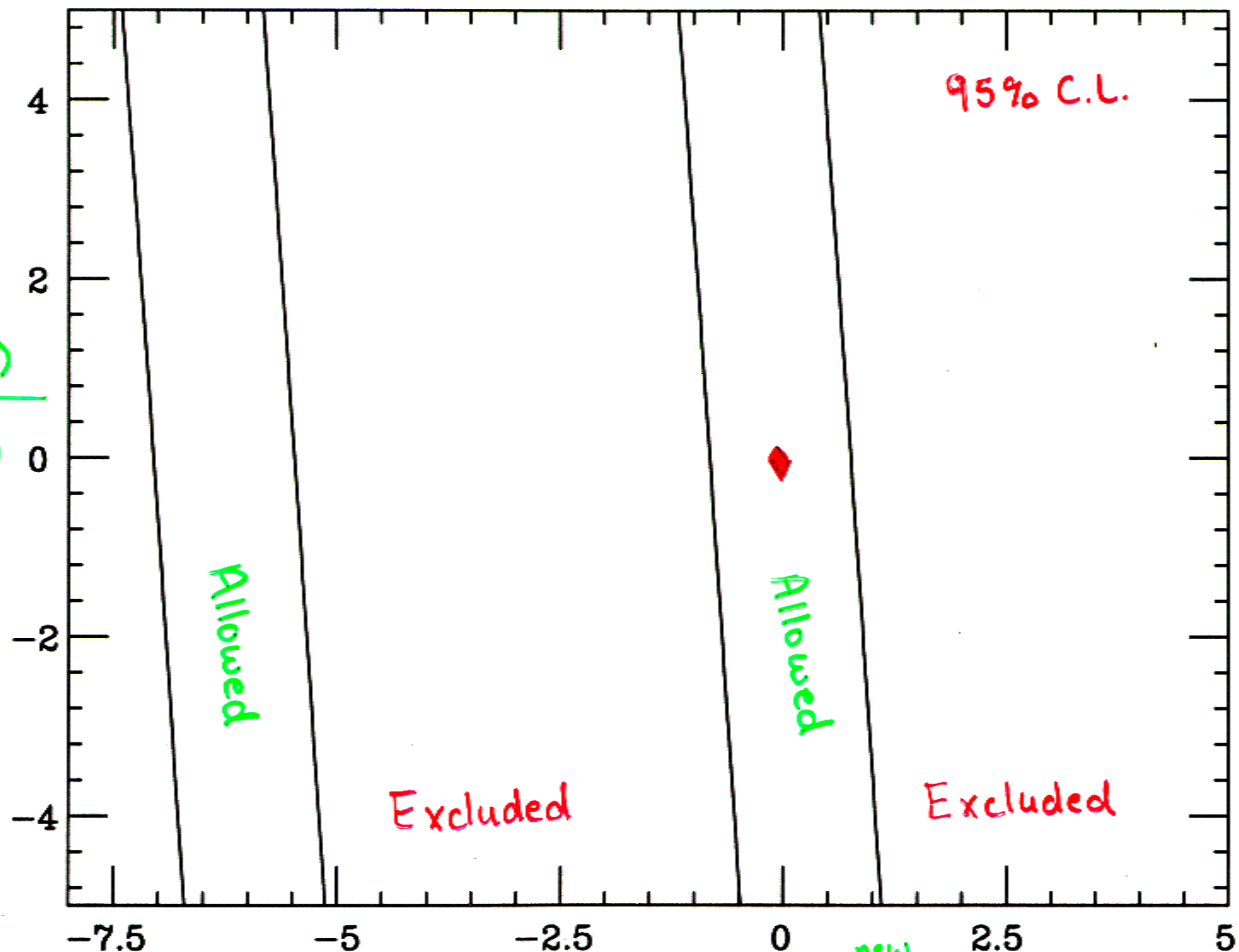
  SUSY — Ciuchini et al.

- Model Independent Constraints

$$R_i \equiv \frac{C_i^{new}(m_W)}{C_i^{sm}(m_W)}$$

Model Independent Constraints from $b \to s\gamma$ - new CLEO data

Hewett



$$R_8 = \frac{C_8^{new}(m_W)}{C_8^{sm}(m_W)}$$

$$R_7 = \frac{C_7^{new}(m_W)}{C_7^{sm}(m_W)}$$

$b \to sg$ constraint

$|R_8| < 8.9$

from

$B(b \to sg) < 0.068$

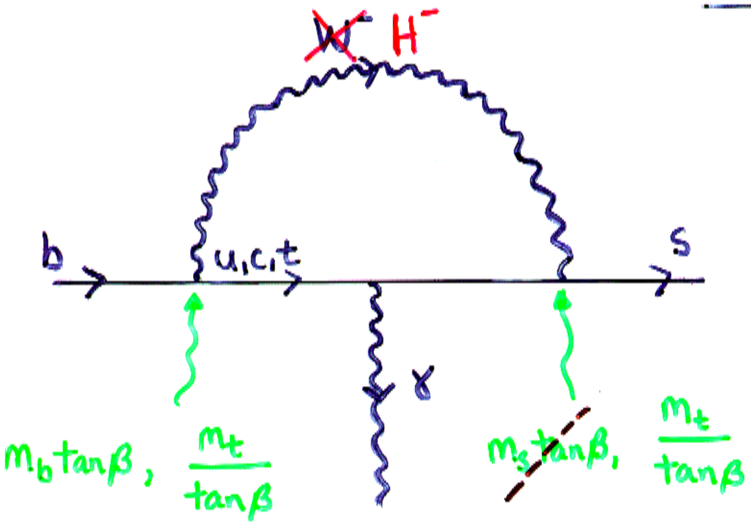
[CLEO]

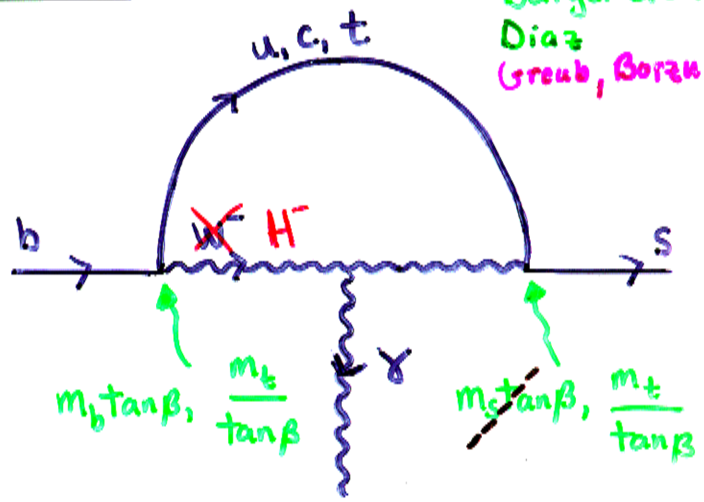
All theory + exp't errors included - 'scanning' method

Radiative b Decays - Two-Higgs Doublet Models

- Model II

JLH
Barger et al
Diaz
Greub, Borzumati





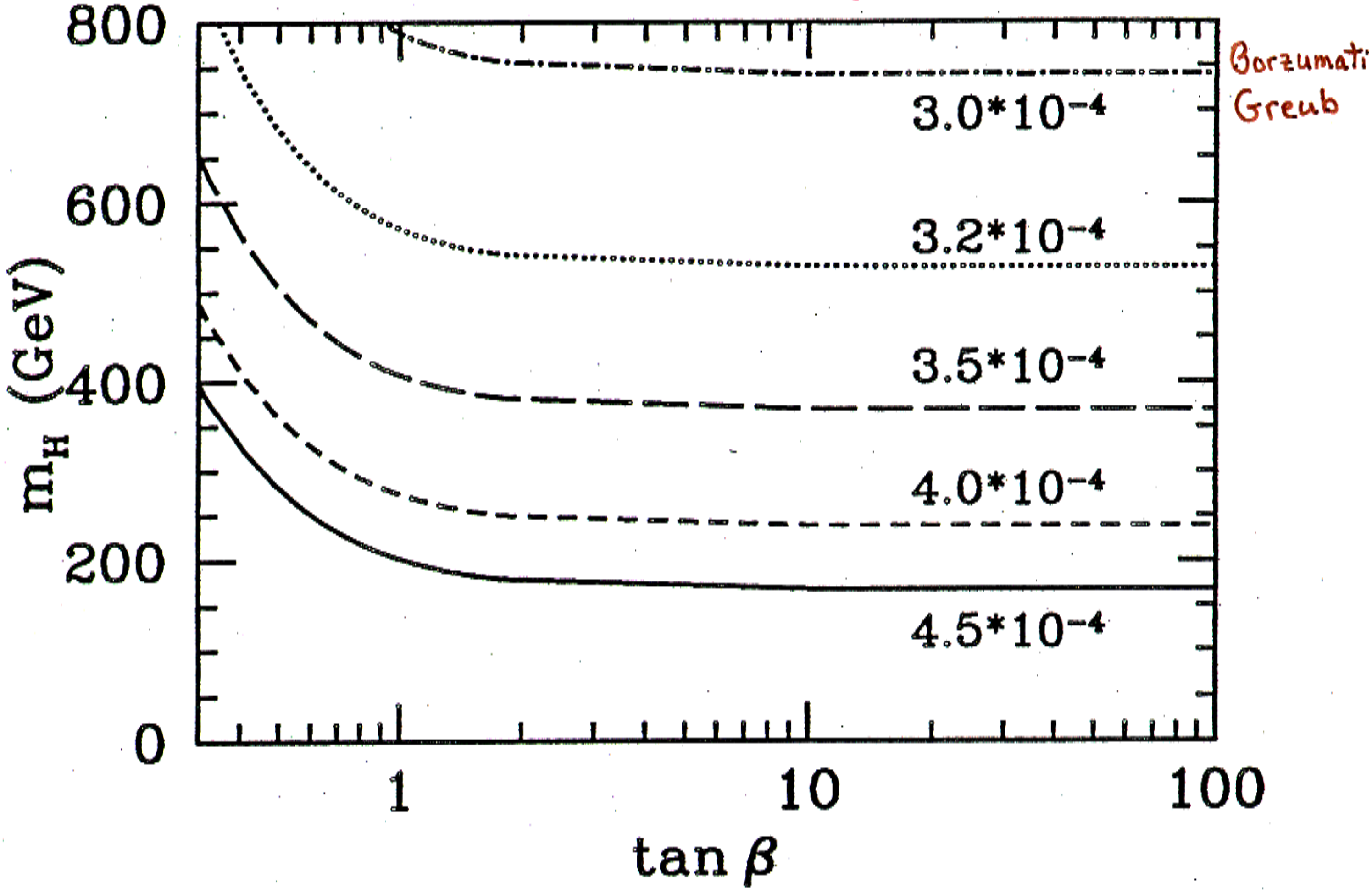
$$C_{7,8}(m_W) = G^{SM}_{7,8}\left(m_t^2/m_W^2\right) + G^{H_1}_{7,8}\left(m_t^2/m_{H^\pm}^2\right) + \frac{1}{\tan^2\beta}\, G^{H_2}_{7,8}\left(m_t^2/m_{H^\pm}^2\right)$$

$\tan\beta$ indepedent
$\Rightarrow$ Always > sm!

enhancement
for small $\tan\beta$

$$\mathcal{L} \sim V_{ij}\left[m_{u_i} \cot\beta\, \bar{u}_i (1-\gamma_5) d_j + m_{d_j} \tan\beta\, \bar{u}_i (1+\gamma_5) d_j \right] H^\pm$$

$B(B \to X_s \gamma)$ - Two Higgs Doublets - NLO



CLEO: $2.0 \times 10^{-4} \leq B(B \to X_s \gamma) \leq 4.5 \times 10^{-4}$ @ 95% CL

<u>Excludes</u>:

$m_{H^\pm} \leq$ 280 GeV,		$\tan\beta = 0.5$
200 GeV,		1.0
170 GeV,		5.0

Stop Mixing Matrix

$$\mathcal{M}^2_{\tilde{t}} = \begin{bmatrix} m^2_{\tilde{Q}} + m_t^2 + m_Z^2 c_{2\beta}(1/2 - x_W Q_t) & \underline{m_t}\left(A_t - \frac{\mu}{\tan\beta}\right) \\ \underline{m_t}\left(A_t - \frac{\mu}{\tan\beta}\right) & m^2_{\tilde{u}} + m_t^2 + m_Z^2 c_{2\beta} x_W Q_t \end{bmatrix}$$

Mixing can be large!

$$\tilde{t}_1 = \cos\theta_t\, \tilde{t}_L - \sin\theta_t\, \tilde{t}_R$$
$$\tilde{t}_2 = \sin\theta_t\, \tilde{t}_L + \cos\theta_t\, \tilde{t}_R$$

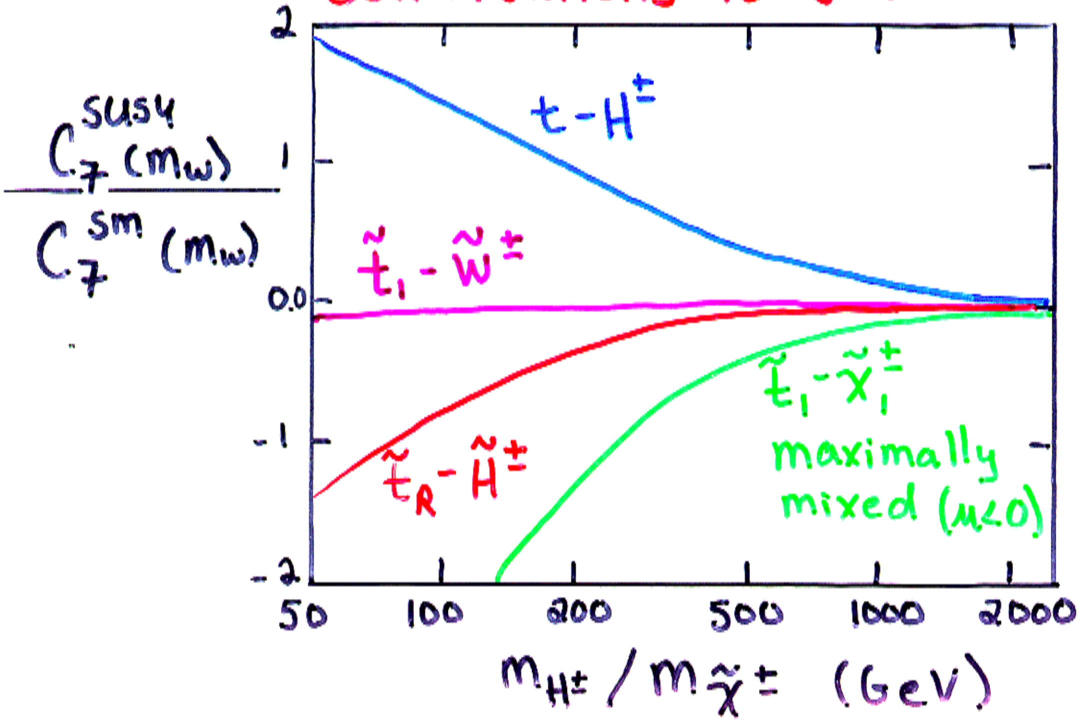
$\Rightarrow \tilde{t}_1$ can be light – exception to degenerate $\tilde{q}$'s

Phenomenological Consequences – $t \to \tilde{t} + \tilde{\chi}^0_1$

increase R_b

$b \to s\gamma$

Contributions to $b \to s\gamma$



$B(b \to s\gamma) \sim |C_7(\mu)|^2$

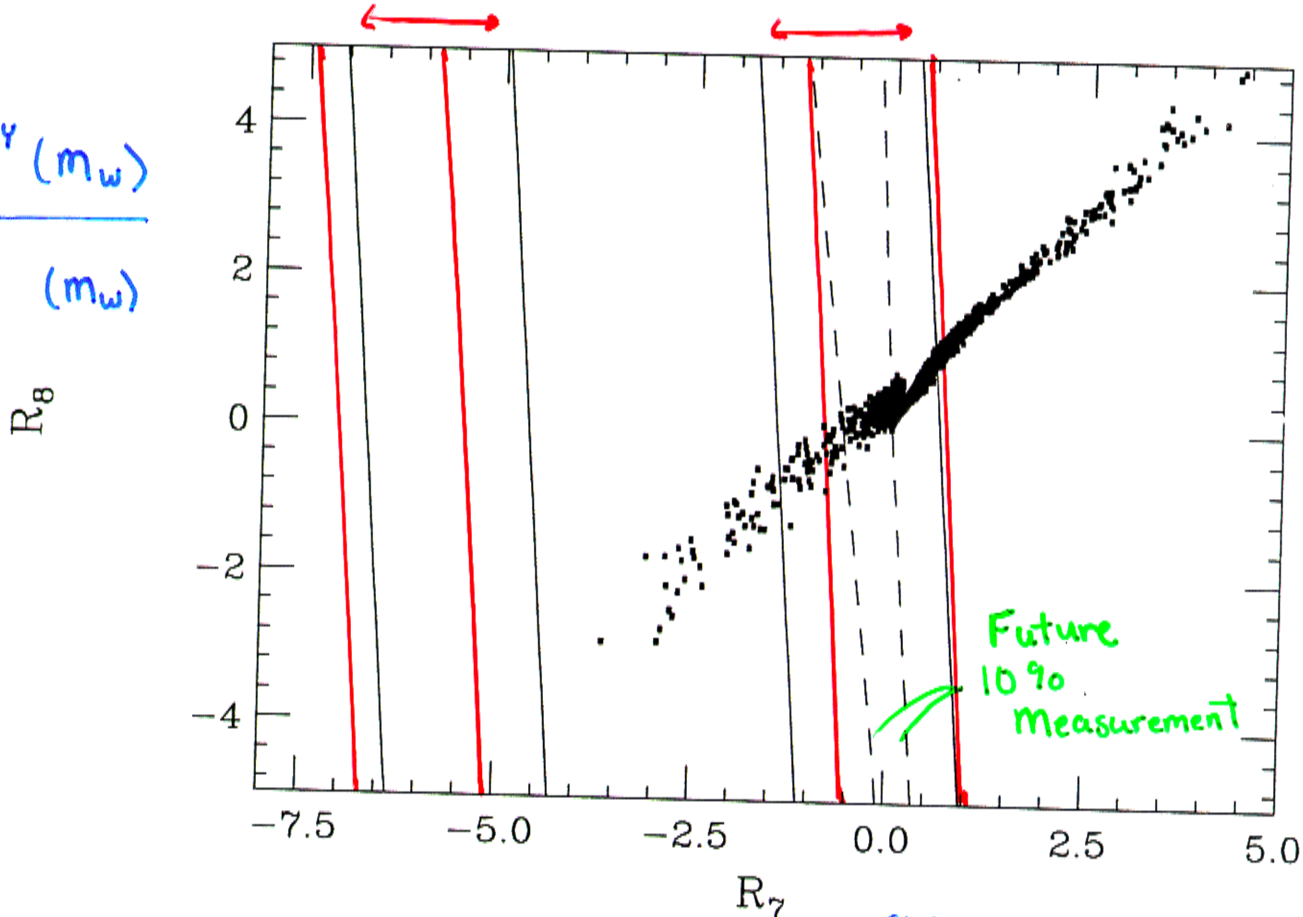
JLH, Wells

SUSY + Unification + Radiative Breaking = MSSM

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

present constraints (CLEO) - new analysis!

$$\frac{C_8^{susy}(m_W)}{C_8^{sm}(m_W)}$$



JLH, Wells

$$\frac{C_7^{susy}(m_W)}{C_7^{sm}(m_W)}$$

Pick $\tilde{m}_0$, $\tilde{m}_{1/2}$, A_0, sign (μ), $\tan\beta$ at GUT scale + RGE evolve to EW/TeV scale

SUSY NLO matching conditions

Ciuchini et al
hep-ph/9806308

$m_{H^+} = 100$ GeV

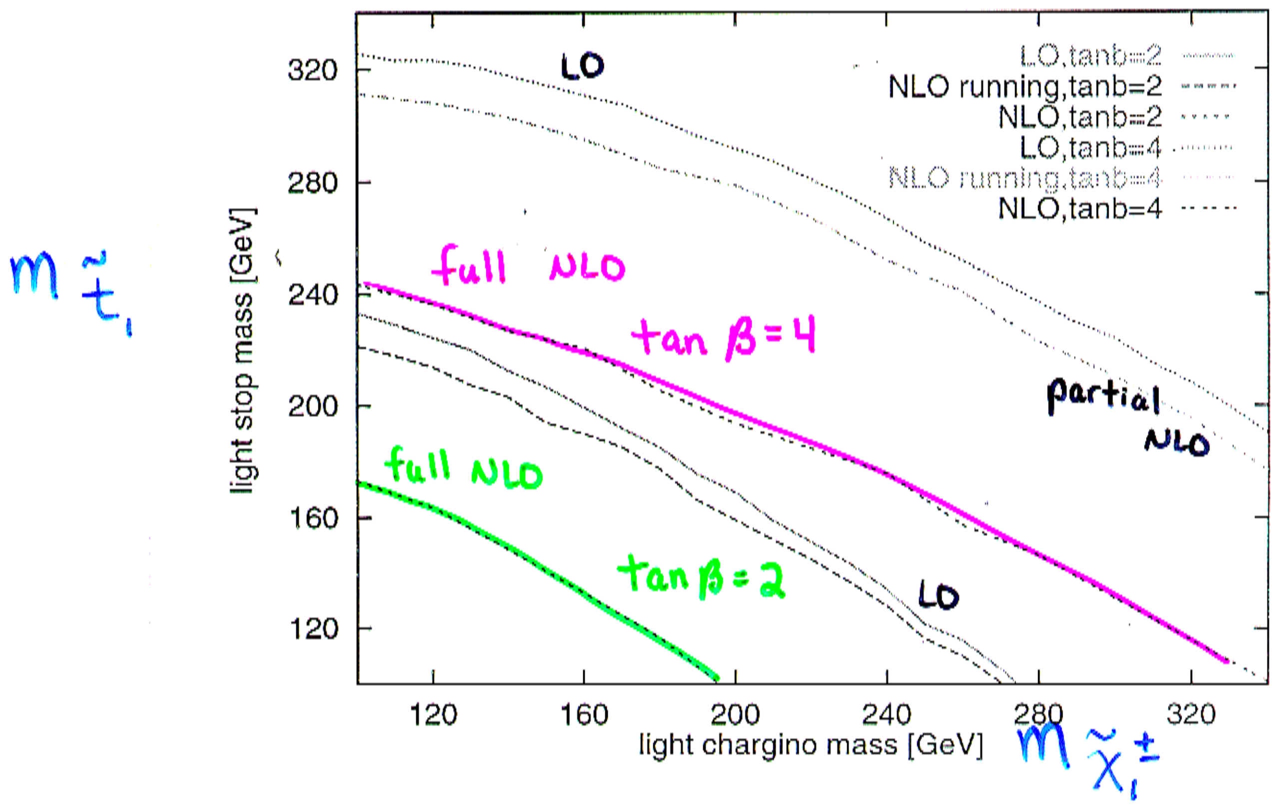


Figure 2: Upper bounds on the lighter chargino and stop masses from the CLEO 95% CL limit on $\mathrm{BR}(B \to X_s \gamma)$ in the case $M_{H^\pm} = 100$ GeV. We have taken $|\theta_{\tilde{t}}| < \pi/10$, $|\mu| < 500$ GeV, $A_b = A_t$, and set all heavy masses to 1 TeV. For $\tan\beta = 2$ and 4 we show the results of the LO and NLO calculations. The result of neglecting the new NLO supersymmetric contributions to the Wilson coefficients is labelled as "NLO running".

Contours of Constant $B(b \to s\gamma)$ - MSUGRA - Excluded

Baer, Brhlik

$m_{1/2}$

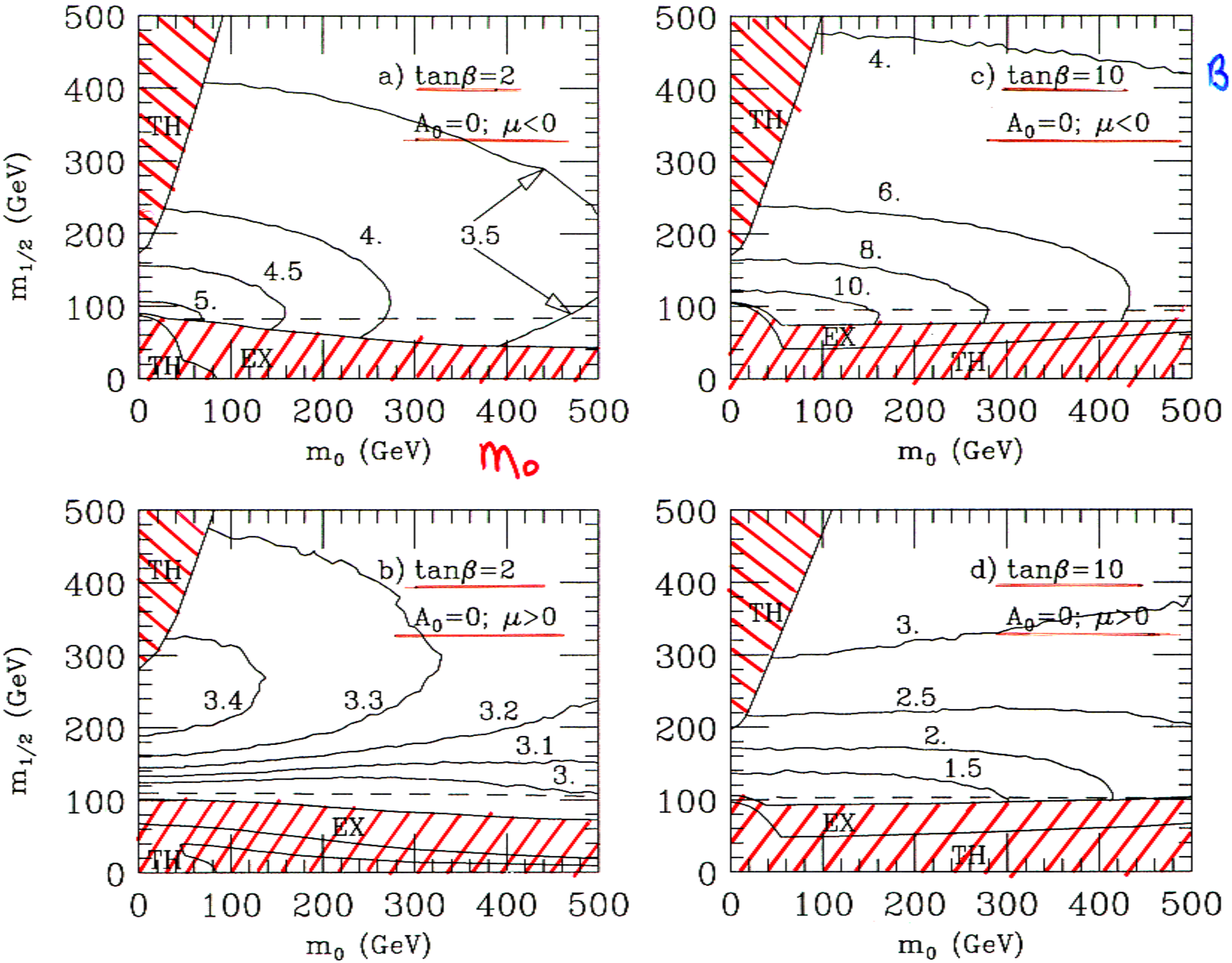
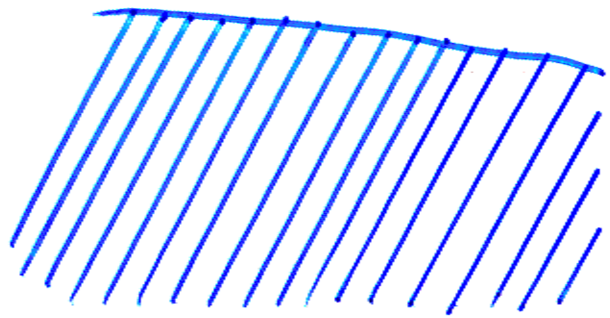


Fig. 4

by $b \to s\gamma$



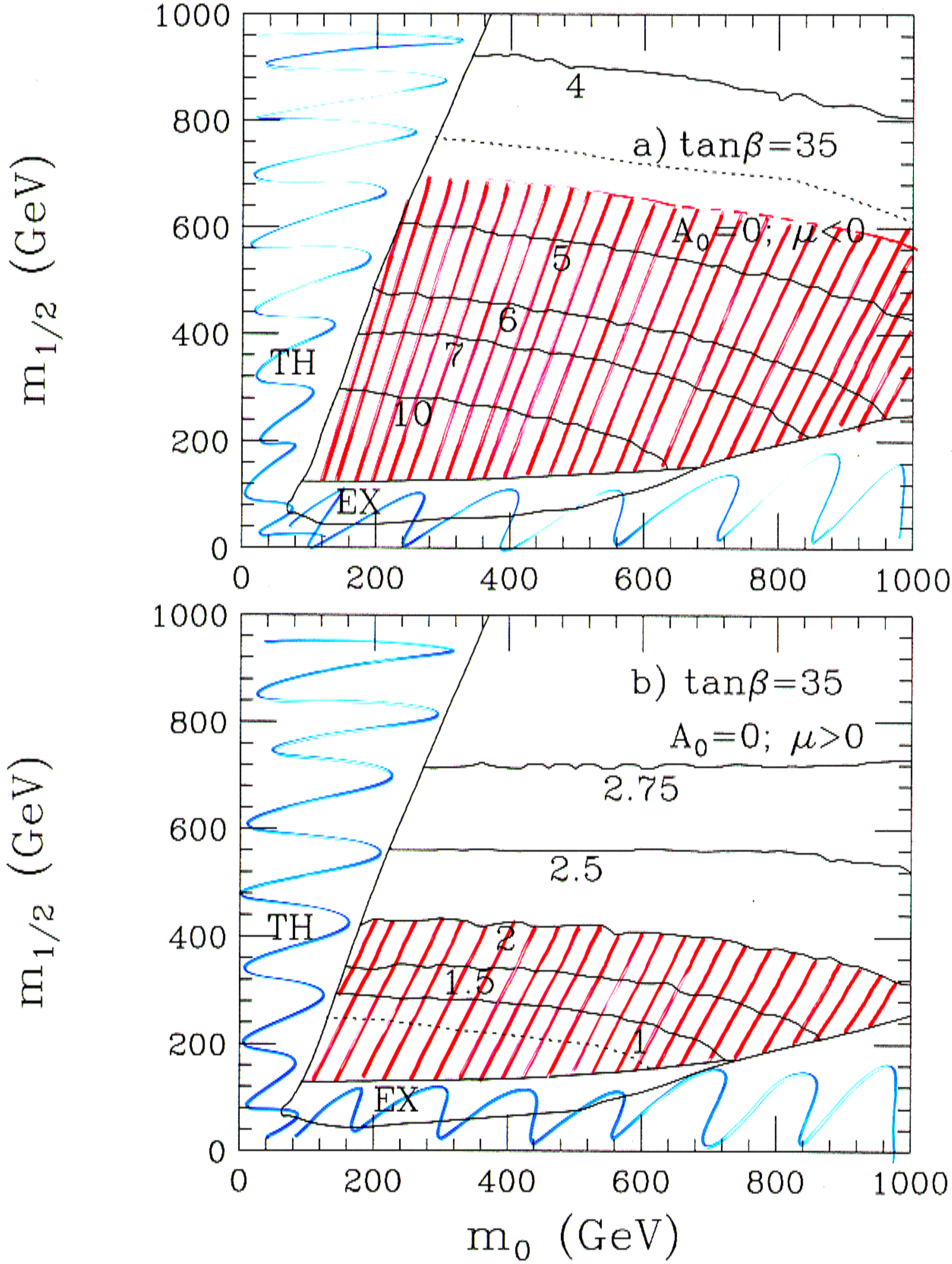
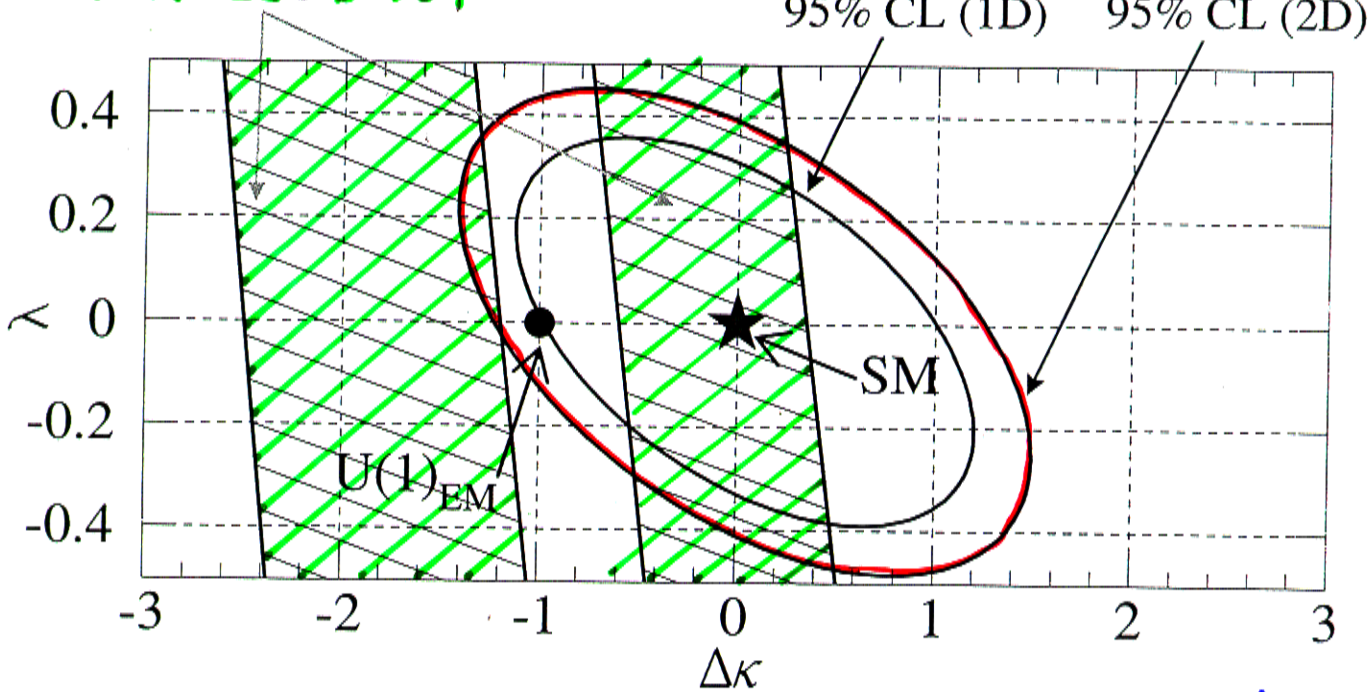
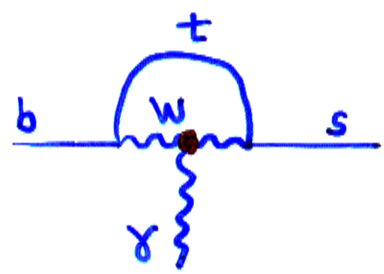

1000
800
600
400
200
0
0
200
400
600
800
1000
$m_{1/2}$ (GeV)
4
a) $\tan\beta=35$
$A_0=0;\ \mu<0$
5
6
7
10
TH
EX
b) $\tan\beta=35$
$A_0=0;\ \mu>0$
2.75
2.5
2
1.5
1
m_0 (GeV)

Fig. 3

Limits on the WWγ Anomalous Couplings

- DØ Web Page





D0 Limits at 95% CL (single DOF):

$$-0.98 < \Delta\kappa < 1.01 \text{ (for } \lambda = 0)$$
$$-0.33 < \lambda < 0.31 \text{ (for } \Delta\kappa = 0)$$

Fermilab-Pub-96-434-E

Excluded:

1) The *W* boson has zero magnetic dipole and electric quadrupole moments

   ➨ **ruled out at the 99% CL**

2) The photon couples only to the U(1) electric charge of the *W* boson

   ➨ **ruled out at the 88% CL (95% CL if assume λ = 0)**

The DØ Collaboration

Direct CP Asymmetry in $B \to X_s \gamma$

$A_{CP}^{b\to s\gamma} \lesssim 1\%$ in SM $\Rightarrow$ Clean signal for N.P.!

Let $$C_7(m_W) = -\tfrac{1}{2} F_2(x) + C_7^{new}(m_W)$$
$$C_8(m_W) = -\tfrac{1}{2} D(x) + C_8^{new}(m_W)$$

with $$C_7^{new}(m_W) = -K_7\, e^{i\gamma_7}$$
$$C_8^{new}(m_W) = K_8\, e^{i\gamma_8}$$

$$\zeta = \frac{C_7^{new}(m_W)}{C_8^{new}(m_W)}$$

Models with big C_8^{new}	$\lvert\zeta\rvert$	C_7^{new}	$\lvert\zeta\rvert$
Vector-like q's	1	Scalar diquark-top	5-8
$\tilde{g}-\tilde{q}$ $(m_{\tilde{g}} < m_{\tilde{q}})$	.1-1	$\tilde{g}-\tilde{q}$ $(m_{\tilde{g}} > m_{\tilde{q}})$	1-3
techni scalar	.5	H^+-top	2-4
		$\tilde{H}^+ - \tilde{t}$	3-24
		W_R-top	7

Hewett

Radiative Baryon Decays - $\Lambda_b \to \Lambda + \gamma$ - Mannel Recksiegel

$$H_{eff} = \frac{4G_F}{\sqrt{2}} V_{tb} V_{ts}^* C_7(\mu) \mathcal{O}_7(\mu)$$

$$\mathcal{O}_7(\mu) = \frac{e}{32\pi^2} m_b \bar{s} \sigma_{\mu\nu} (g_V - g_A \gamma_5) b F^{\mu\nu}$$

$$g_V^{SM} = 1 + m_s/m_b \,, \qquad g_A^{SM} = -1 + m_s/m_b$$

$$\Gamma(\Lambda_b \to \Lambda + \gamma) = \Gamma_0 (1 + \alpha\, p \cdot S_\Lambda)$$

$$\Gamma_0 \sim (C_7 g_V)^2 + (C_7 g_A)^2$$

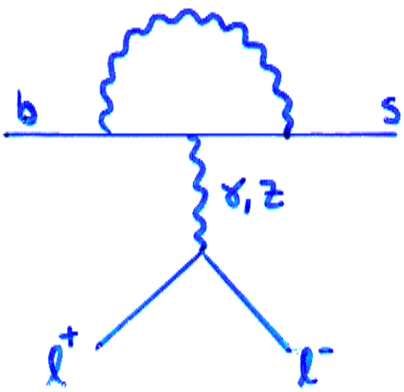
$$\alpha \sim \frac{2 g_V g_A}{g_V^2 + g_A^2}$$

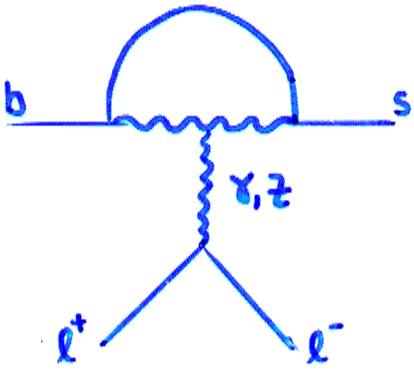
$\Rightarrow$ Polarization of Λ sensitive to new physics!

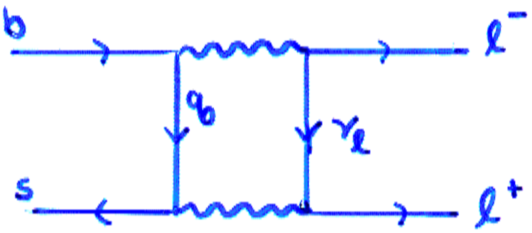
Probes helicity structure of H_{eff}

- $B(\Lambda_b \to \Lambda + \gamma) \sim (1 - 4.5) \times 10^{-5}$
- Small long distance corrections

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







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 $\ell^+\ell^-$ $\qquad (\hat{s} = q^2/m_b^2)$

Long distance resonance contributions

$$B \to K^{(*)} \psi^{(\prime)}$$
$$\quad \hookrightarrow \ell^+ \ell^-$$

peaks at $q^2 = m^2_{\psi^{(\prime)}}$

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

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

Contribution from
c + light-quarks

Kinematic Distributions - Requires high statistics!

(Lim, Morozumi, Sanda
Deshpande et al
Ali et al)

- $m_{\ell^+\ell^-}$ Distribution

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

- Forward-Backward Asymmetry of $\ell^+\ell^-$ angular distribution

(Ali et al)

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

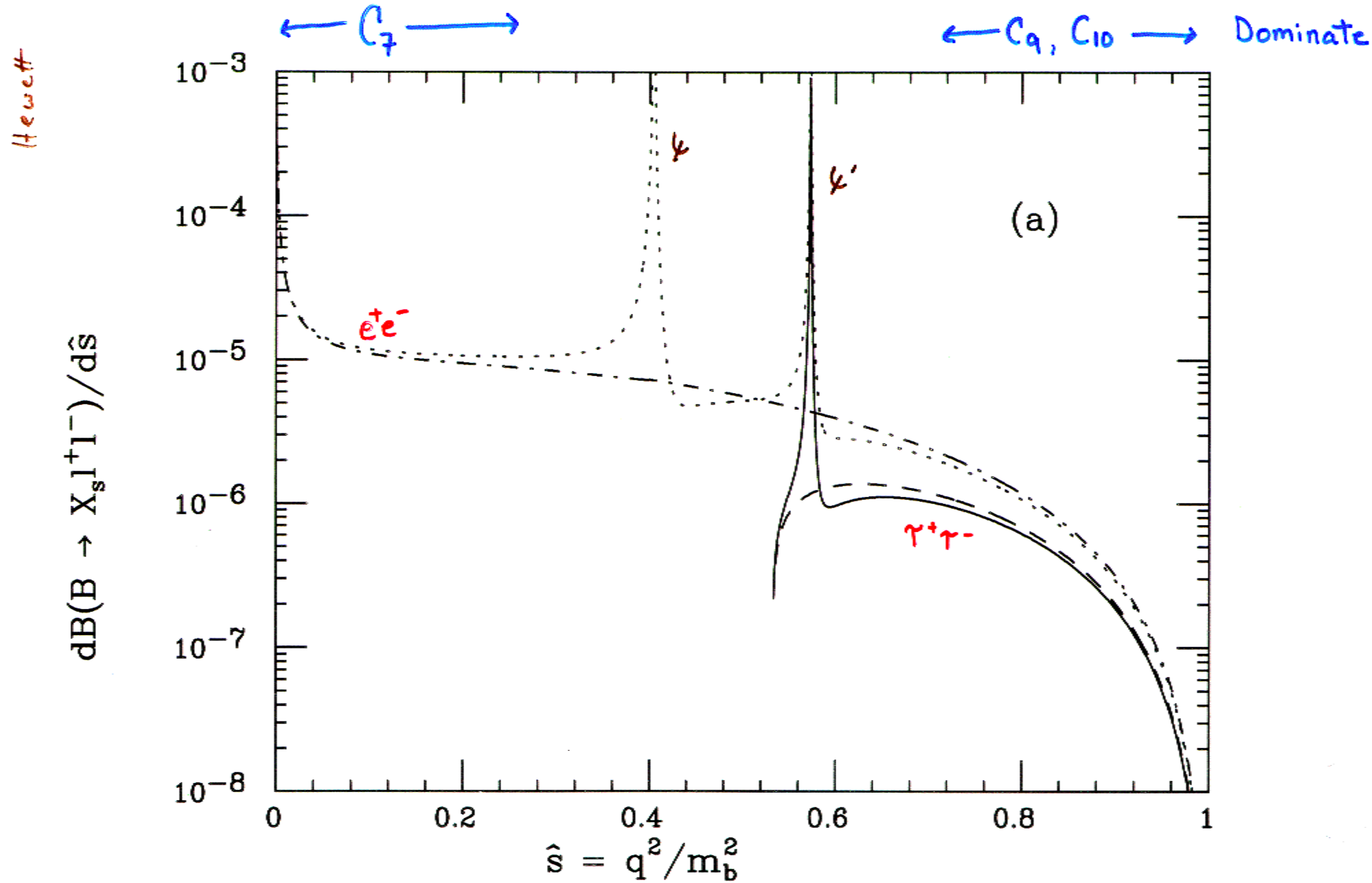
$$= -3\,C_{10}\left[\mathrm{Re}\,C_9^{eff}\,\hat{s} + 2C_7\right] \Big/ d\Gamma/d\hat{s}$$

- Tau Polarization Asymmetry in $B\to X_s\tau^+\tau^-$

(JLH
Kruger, Sehgal)

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

$$= -2C_{10}\left[\mathrm{Re}\,C_9^{eff}\,F_1(\hat{s},m_\tau) + 3C_7\,F_2(\hat{s},m_\tau)\right] \Big/ d\Gamma_\tau/d\hat{s}$$

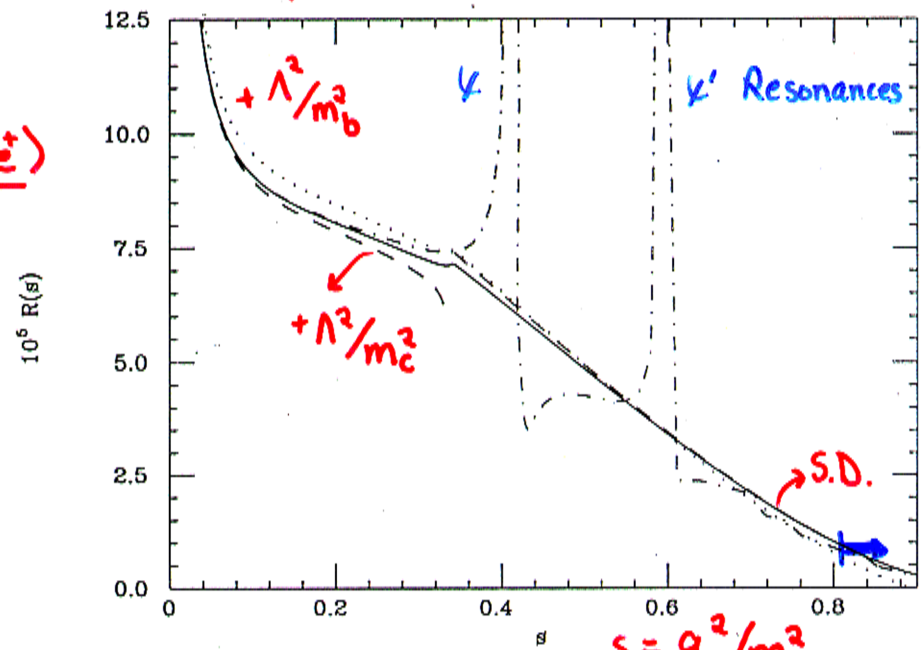


short distance + ψ/ψ' resonance contributions

$B \to X_s \ell\ell$

SD + Non-perturbative Corrections

$\frac{dB(B \to X_s e^+ e^-)}{ds}$



Buchalla, Isidori

$+\frac{\Lambda^3}{m_b^3}$ corrections

Bauer + Burrell

~ 10%

HQET breaksdown!
use χPTh.

Ali, Hiller
Buchalla, Isidori

Figure 9-14. *Dilepton invariant mass spectrum of $B \to X_s e^+ e^-$ normalized to the semileptonic rate: partonic result (full line), partonic result + $\mathcal{O}(\Lambda^2_{QCD}/m_b^2)$ corrections (dotted line), partonic result + $\mathcal{O}(\Lambda^2_{QCD}/m_c^2)$ corrections (dashed line), partonic result + factorizable resonance contributions (dash-dotted line). These results have been obtained for $\mu = m_b = 4.8$ GeV and $m_c = 1.4$ GeV.*

A_{FB} Tau Polarization Asymmetry

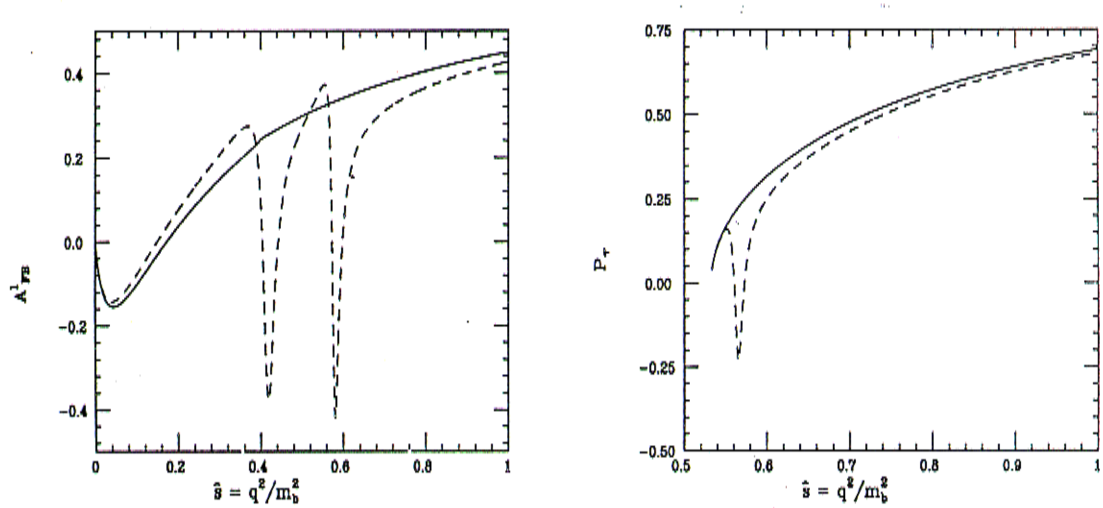


Figure 9-15. *Lepton forward-backward ($\ell = e$) and tau polarization asymmetry with and without the long distance resonance contributions.*

Numerical Results - Before + After cuts

Ali + Hiller
hep-ph/9807418

	No cuts		m_{X_s} cut		$m_{\ell\ell}$ cuts			
FM parameters $(\lambda_1, \bar{\Lambda})$ in $(\mathrm{GeV}^2, \mathrm{GeV})$	$\mathcal{B} \cdot 10^{-6}$ $\mu^+\mu^-$	$\mathcal{B} \cdot 10^{-6}$ e^+e^-	No s-cut $\mu^+\mu^-$	No s-cut e^+e^-	cut A $\mu^+\mu^-$	cut B e^+e^-	cut C $\mu^+\mu^-$	cut C e^+e^-
$(-0.3, 0.5)$ $[SD]$	5.8	8.6	83%	79 %	57%	57%	6.4%	4.5%
$(-0.1, 0.4)$ $[SD]$	5.7	8.4	93%	91 %	63%	68%	8.3%	5.8%
$(-0.14, 0.35)$ $[SD]$	5.6	8.3	92%	90 %	65%	67%	7.9%	5.5%
$(-0.3, 0.5)$ $[SD+LD]$	562.5	563.9	96%	96 %	0.8%	1.0%	0.06%	0.06%
$(-0.1, 0.4)$ $[SD+LD]$	564.0	565.6	99.7%	99.7%	0.8%	1.1%	0.08%	0.08%
$(-0.14, 0.35)$ $[SD+LD]$	566.5	568.2	99%	99 %	0.9%	1.2%	0.08%	0.08%

↑ Fermi motion parameters

Parameter	Value
m_W	80.26 (GeV)
m_Z	91.19 (GeV)
$\sin^2\theta_W$	0.2325
m_s	0.2 (GeV)
m_c	1.4 (GeV)
m_b	4.8 (GeV)
m_t	175 ± 5 (GeV)
μ	${m_b}^{+m_b}_{-m_b/2}$
$\Lambda^{(5)}_{QCD}$	$0.214^{+0.066}_{-0.054}$ (GeV)
α^{-1}	129
$\alpha_s(m_Z)$	0.117 ± 0.005
$\mathcal{B}_{sl}$	(10.4 ± 0.4) %
λ_1	-0.20 (GeV^2)
λ_2	$+0.12$ (GeV^2)

Input parameters

Introduce uncertainties

$\pm 23\%$ e^+e^-

$\pm 16\%$ $\mu^+\mu^-$

Reduced m_t dependence

Bobeth etal hep-ph/9910220

Hadronic Invariant Mass cut

$$S(t = 1.8\,\mathrm{GeV}) = \left(\int_{m^2_{X_s}}^{t^2} \frac{dB}{dS_{had}}\, dS_{had} \right) / B$$

$m_{\ell\ell}$ cuts:

A: $q^2 \leq (m_\psi - 0.1\,\mathrm{GeV})^2$

B: $q^2 \leq (m_\psi - 0.3\,\mathrm{GeV})^2$

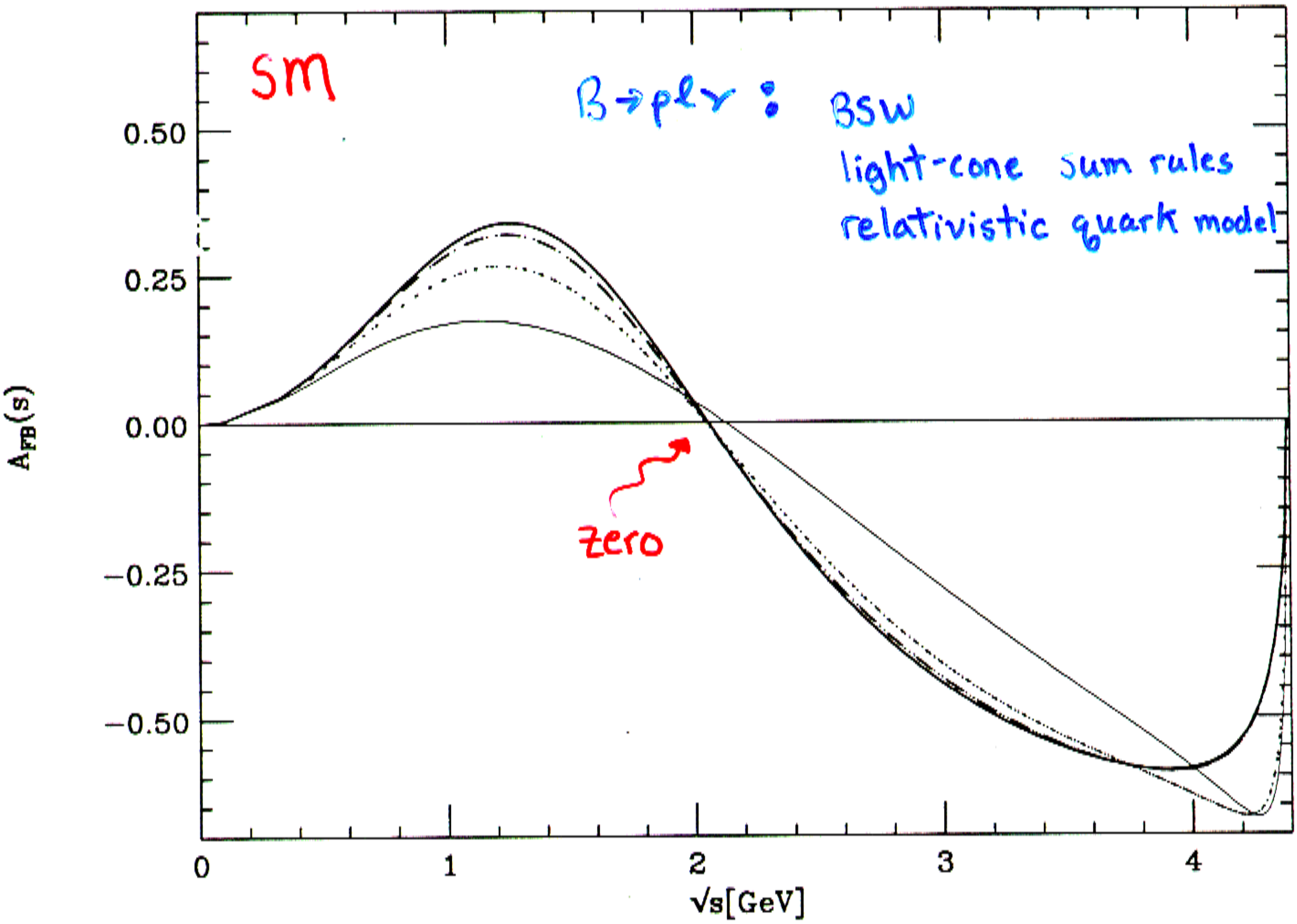
C: $q^2 \geq (m_{\psi'} + 0.1\,\mathrm{GeV})^2$

Numerical value of cuts as implemented by CLEO

$$B(B \to X_s \tau\tau)_{\substack{\text{No}\\ \text{cuts}}} = \left(3.24^{+0.44}_{-0.54}\right) \times 10^{-7}$$

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

Burdman '97

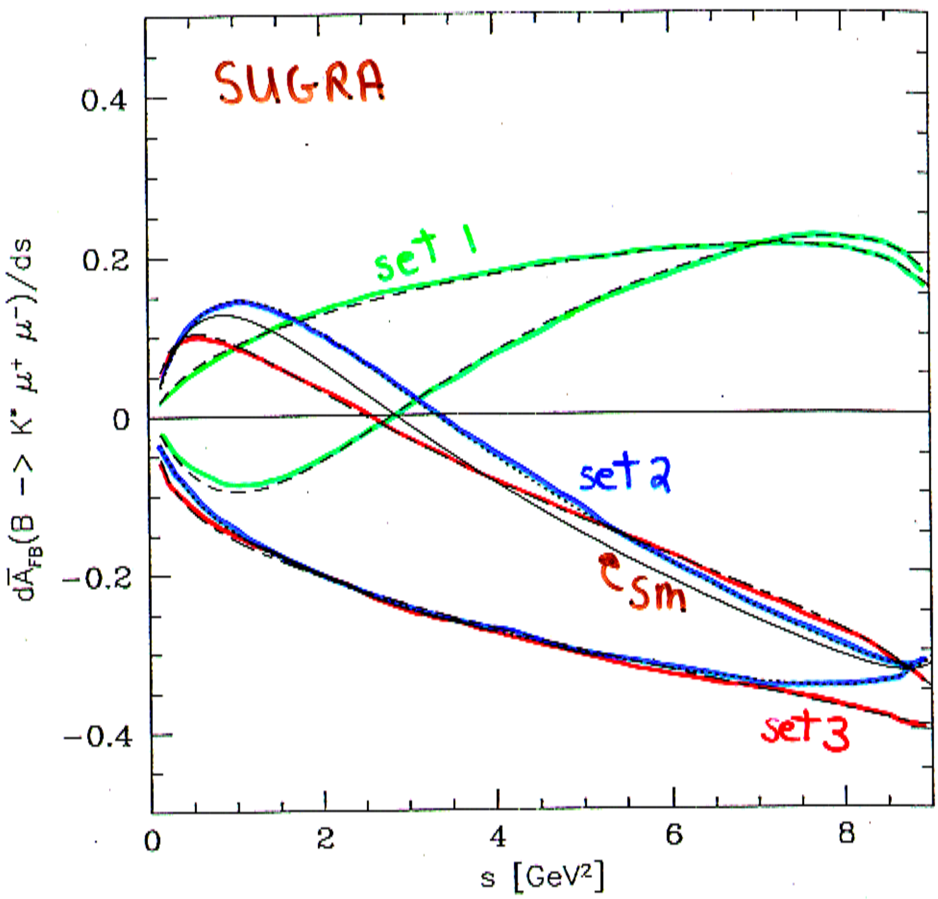


Form Factors related to $B \to \rho \ell \nu$

- Need Acurate Form Factor predictions for exclusive modes!

Hewett

Position of Asymmetry changes/vanishes with NP!



Ali, Ball, Handoko, Hiller '99

Clear indication of New Physics!

CKM Determination - Requires high statistics!

$$\Delta R = \frac{B(B \to X_d \ell^+\ell^-)}{B(B \to X_s \ell^+\ell^-)} \propto \frac{|V_{td}|^2}{|V_{ts}|^2}$$

Ali, Hiller

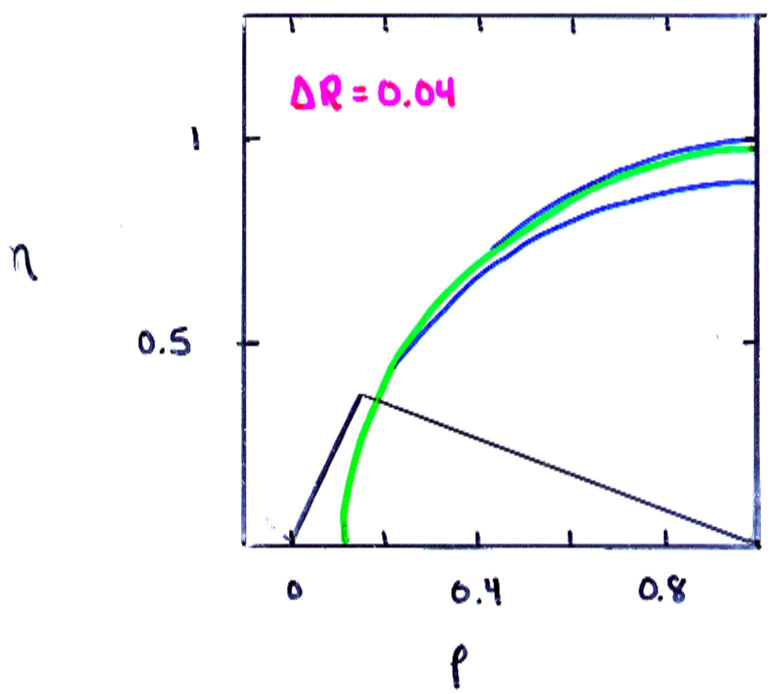
Kim, Morozumi, Sanda

Examine region $m^2_{\rho,\omega} \leq q^2 \leq m^2_{\psi}$

Major sources of uncertainty:

1) μ - dependence $\Rightarrow$ 0.6% error in ΔR

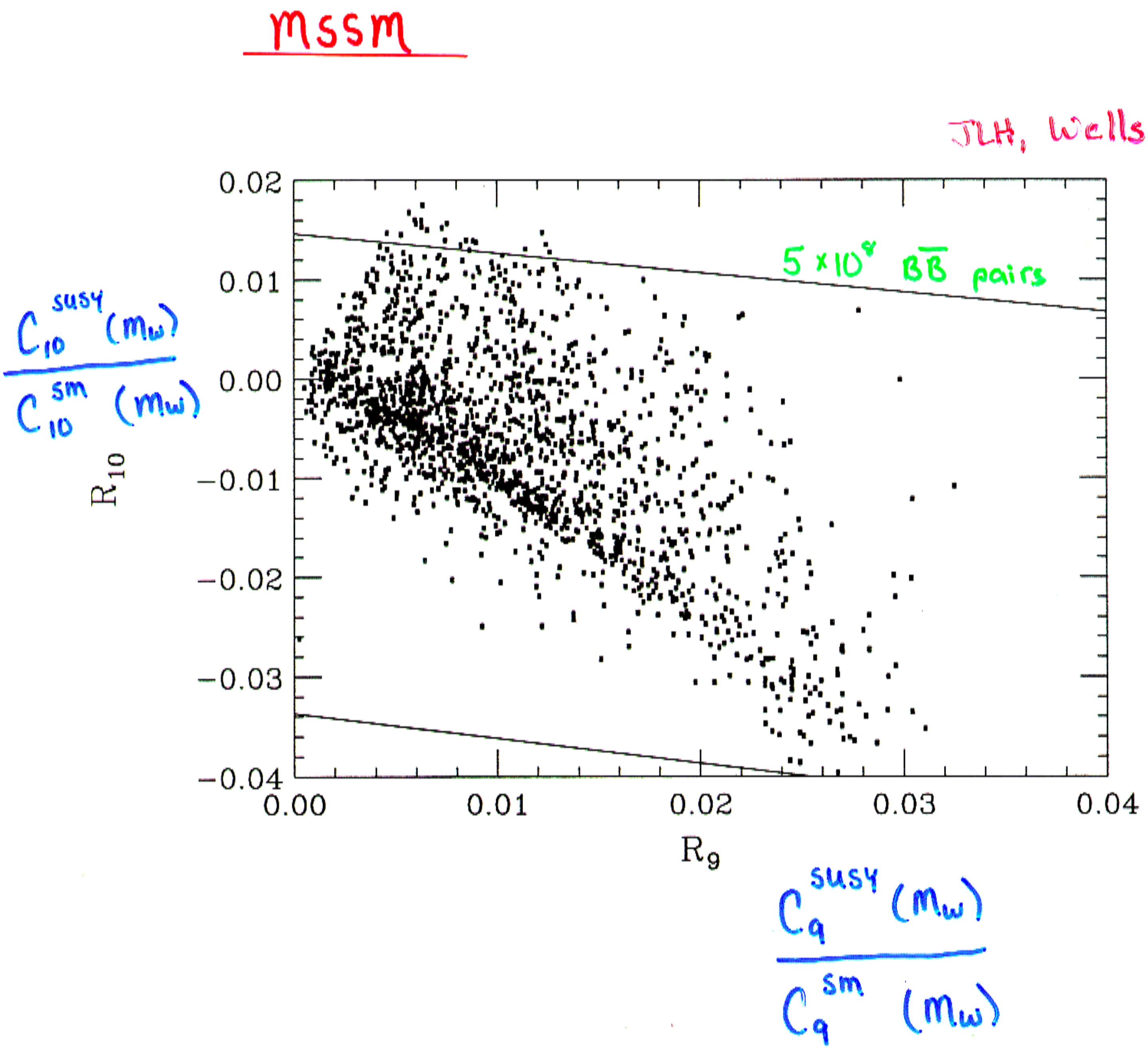
2) LD scheme dependence $\Rightarrow$ few % error in ΔR



μ-dependence = width of line!

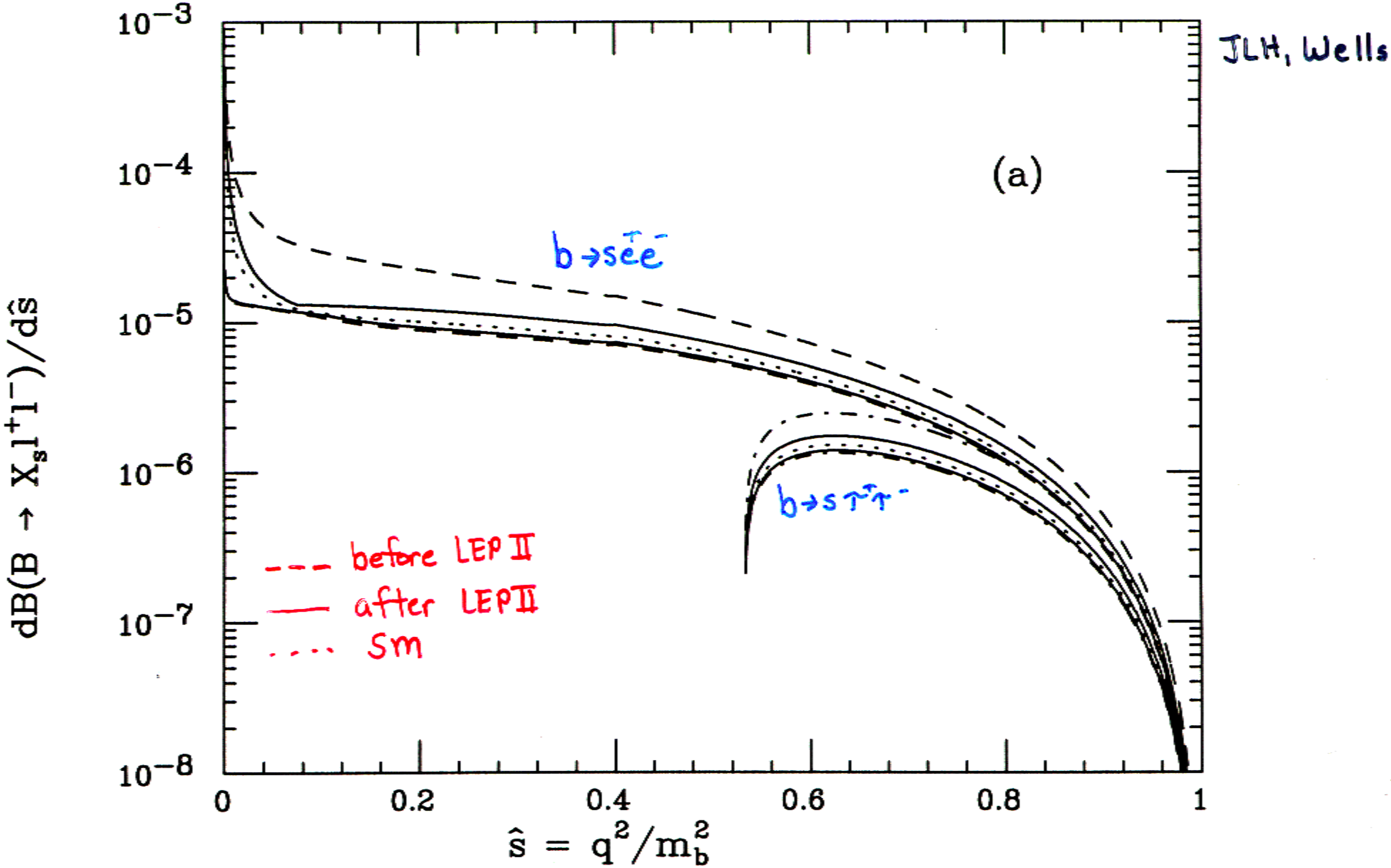
LD scheme dependence

Could yield most accurate determination of $\frac{V_{td}}{V_{ts}}$!

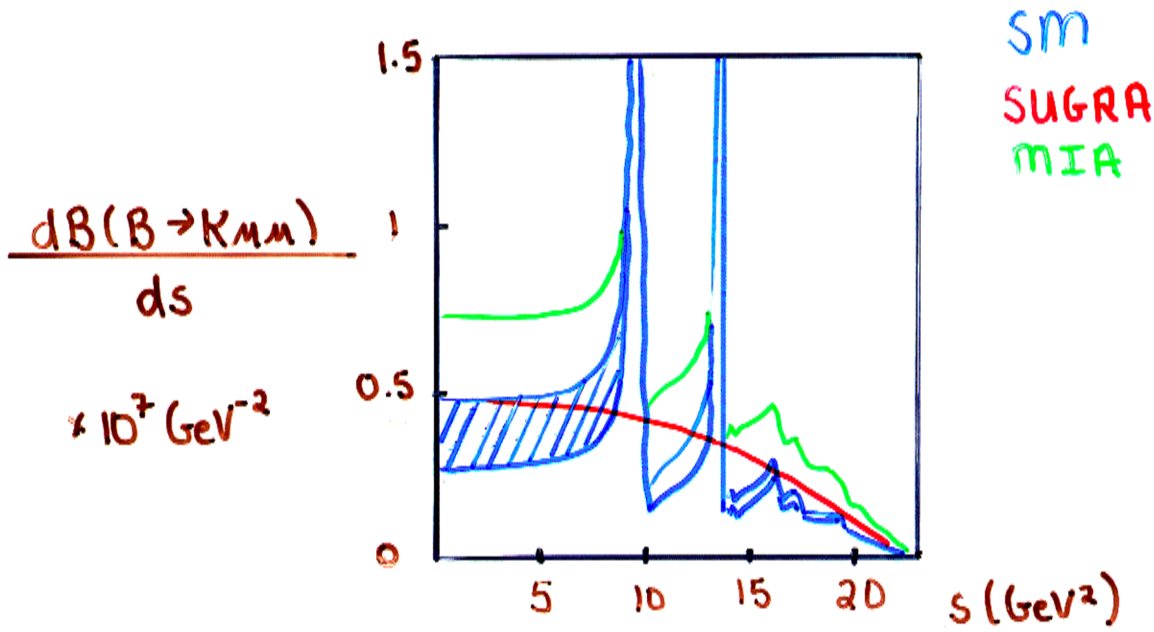


mssm
JLH, Wells
5 x 10^8 $B\bar{B}$ pairs
0.02
0.01
0.00
−0.01
−0.02
−0.03
−0.04
R_{10}
$\frac{C_{10}^{susy}(m_w)}{C_{10}^{sm}(m_w)}$
0.00
0.01
0.02
0.03
0.04
R_9
$\frac{C_9^{susy}(m_w)}{C_9^{sm}(m_w)}$

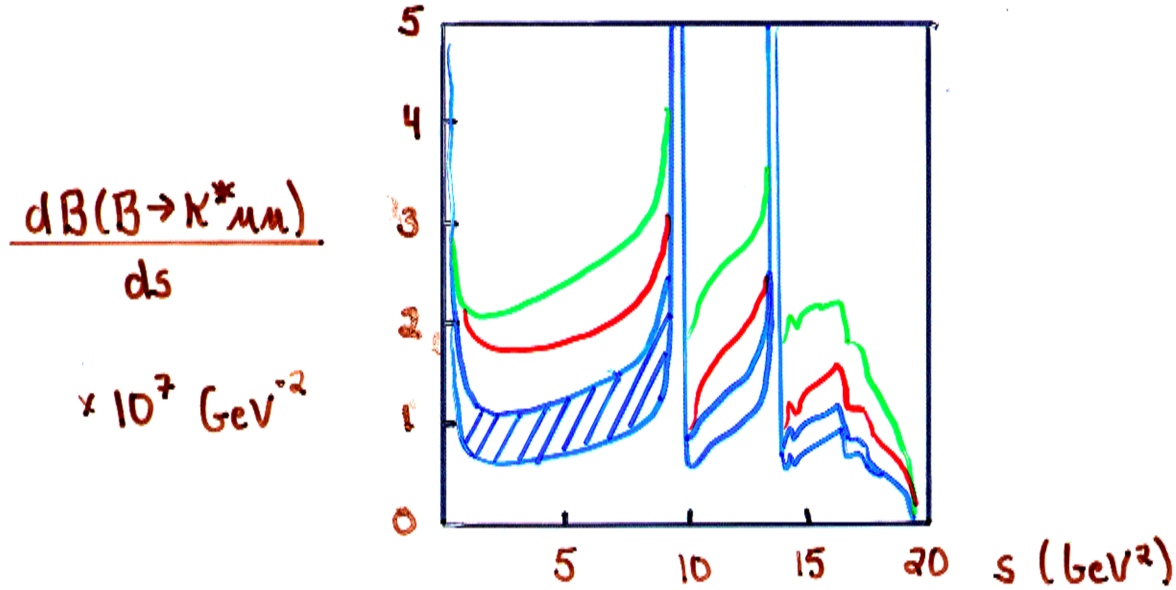
Maximal SUSY Effects - MSSM



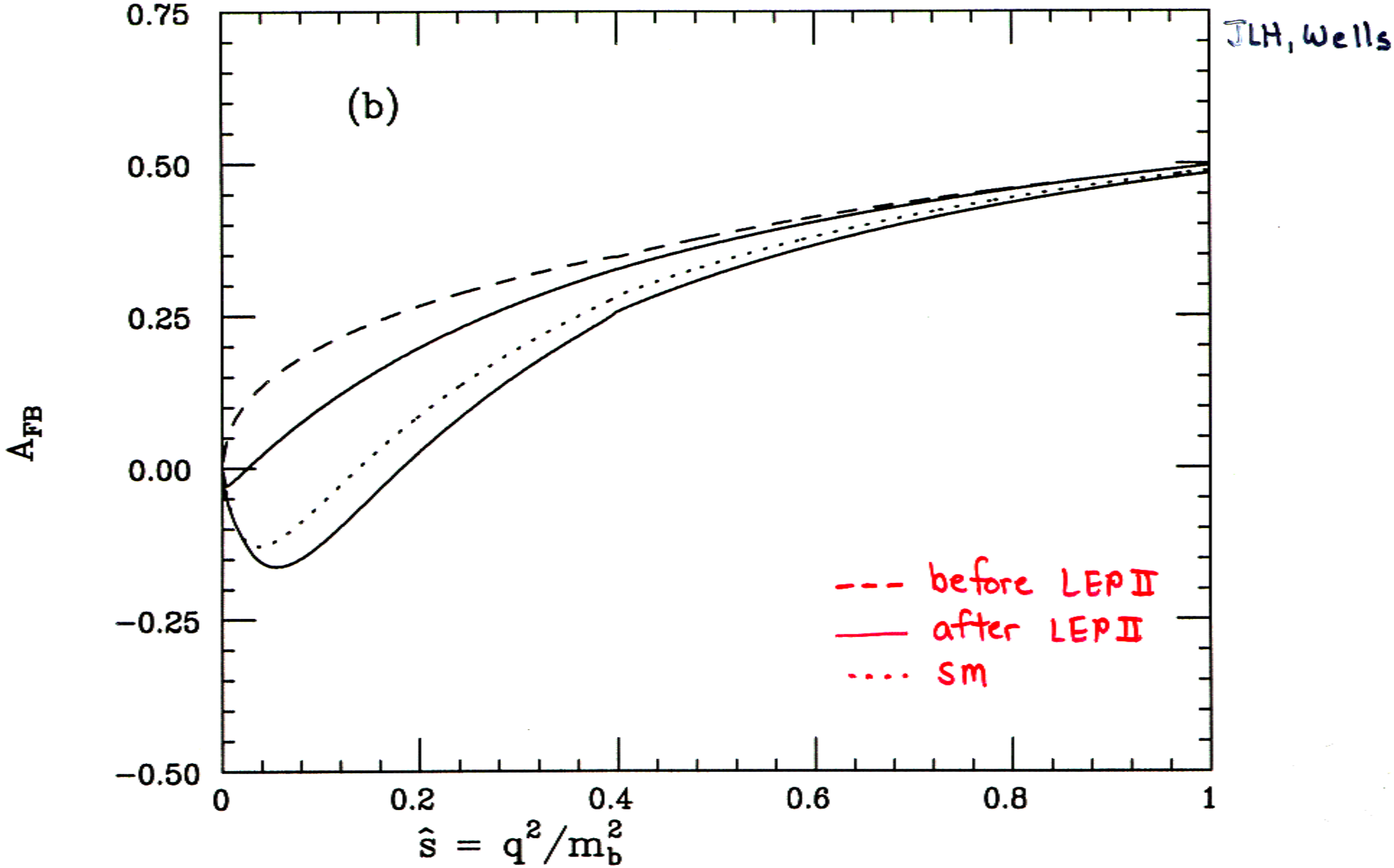
Exclusive Branching Fractions



Ali, Ball, Handoko, Hiller



Maximal SUSY Effects - mssm

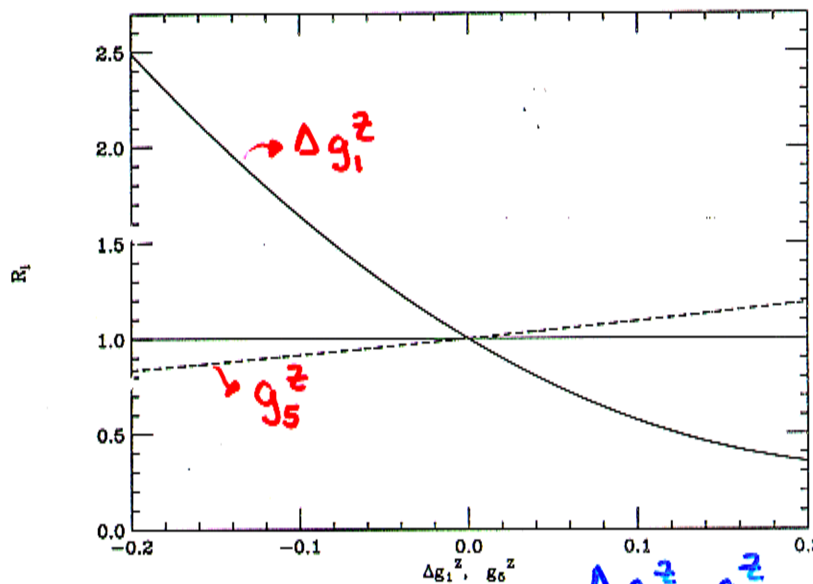


Anomalous TGV in $B \to X_s \ell^+ \ell^-$

$$\mathcal{L}_{WWV} = g_{WWV} \Big[i \kappa_V W^+_\mu W_\nu V^{\mu\nu} + i g_1^V \left(W^+_{\mu\nu} W^\mu V^\nu - W_{\mu\nu} W^{+\mu} V^\nu \right) + g_5^V \epsilon^{\mu\nu\rho\sigma} \left(W^+_\mu \partial_\rho W_\nu - W_\mu \partial_\rho W^+_\nu \right) V_\sigma \Big]$$

Burdman hep-ph/9806360

$\dfrac{BR(B \to X_s \mu\mu)}{BR|_{sm}}$

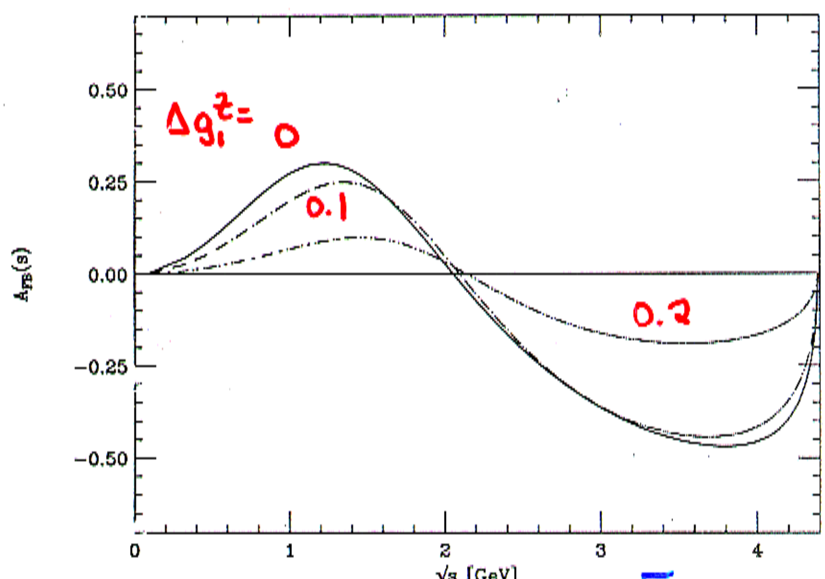


Δg_1^Z only effects C_{10}

Δg_1^Z, g_5^Z

Figure 3: *The $b \to s\ell^+\ell^+$ branching ratio, normalized to its SM value, vs. Δg_1^Z (solid line) and g_5^Z (dashed line).*

A_{FB}



$\sqrt{s}$

Figure 4: *The forward-backward asymmetry for leptons in $B \to K^*\ell^+\ell^-$, for $\Delta g_1^Z = 0$, 0.1 and 0.20 (solid, dashed, dot-dashed respectively). Although these give large effects in the branching ratio, the position of the asymmetry zero is almost unaffected.*

Global Fit to the Wilson Coefficients

Ingredients:

- $\mathcal{B}(B \to X_s \gamma)$ - 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)

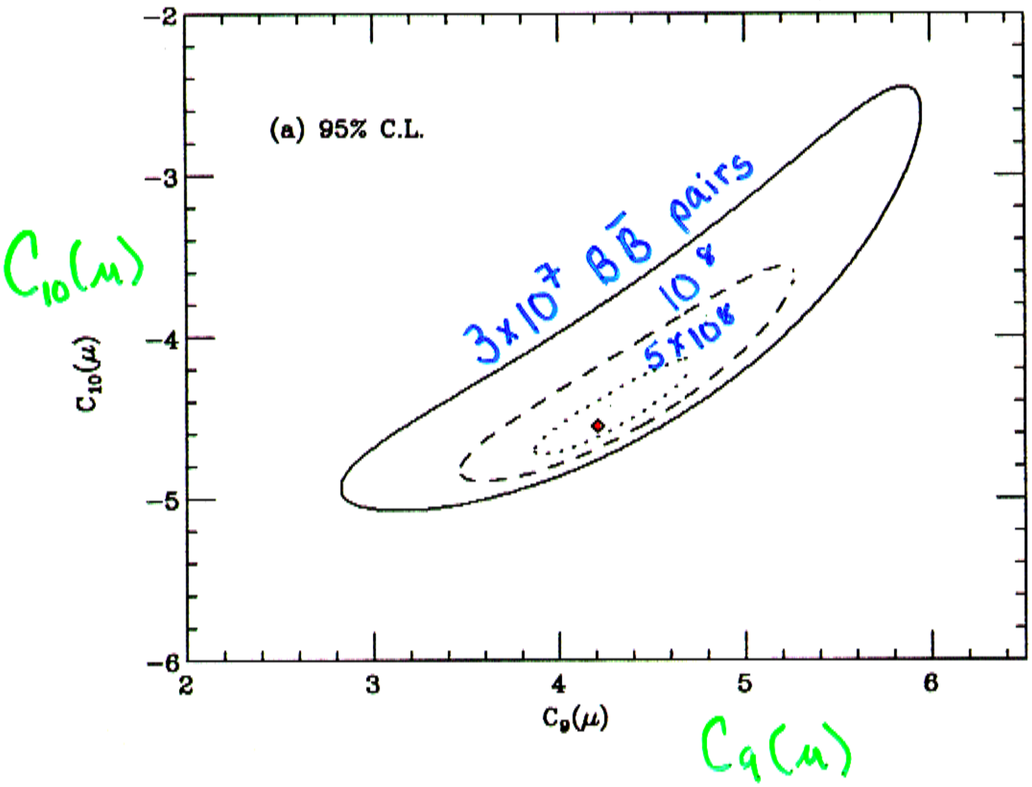
$\Rightarrow$ Determines magnitude + sign of

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

Offers precision test of New Physics

Global Fit to Wilson Coefficients

JLH, Wells '96

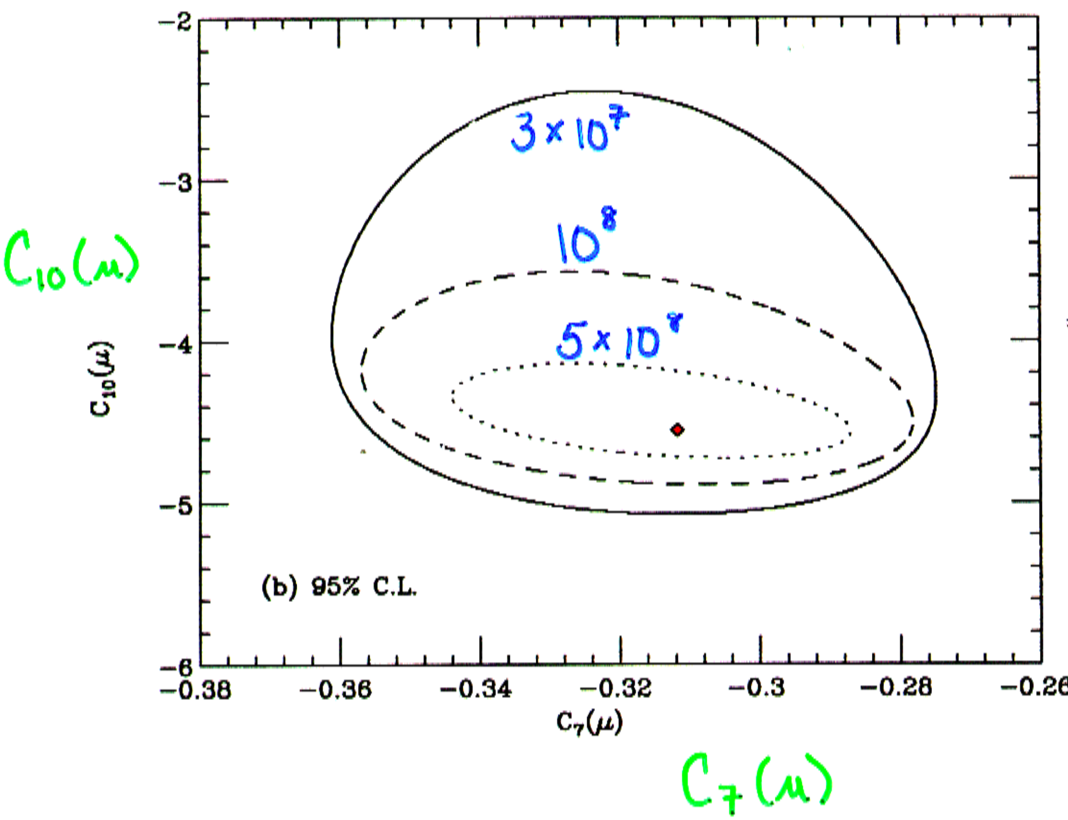


SM:

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

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

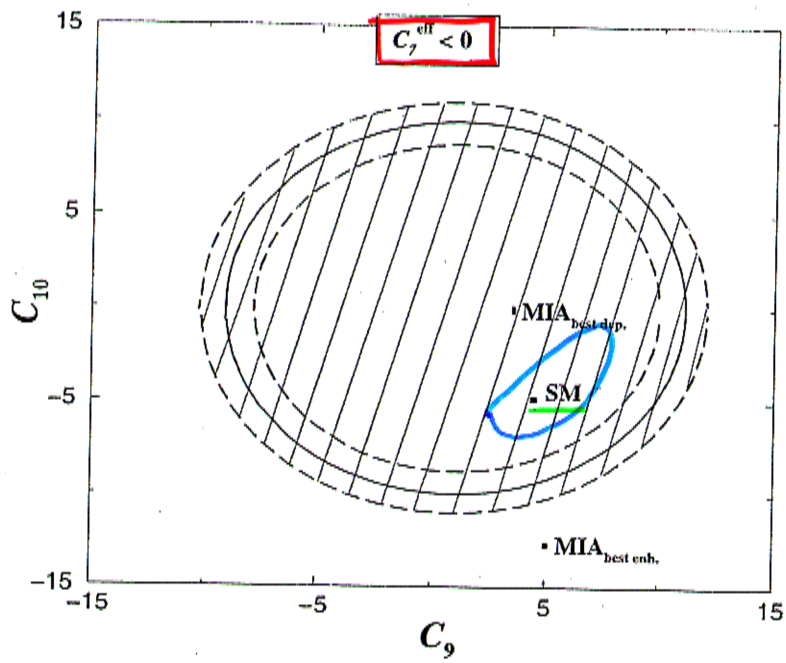
$$C_{10}(\mu) = -4.55$$



Event rate converter

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

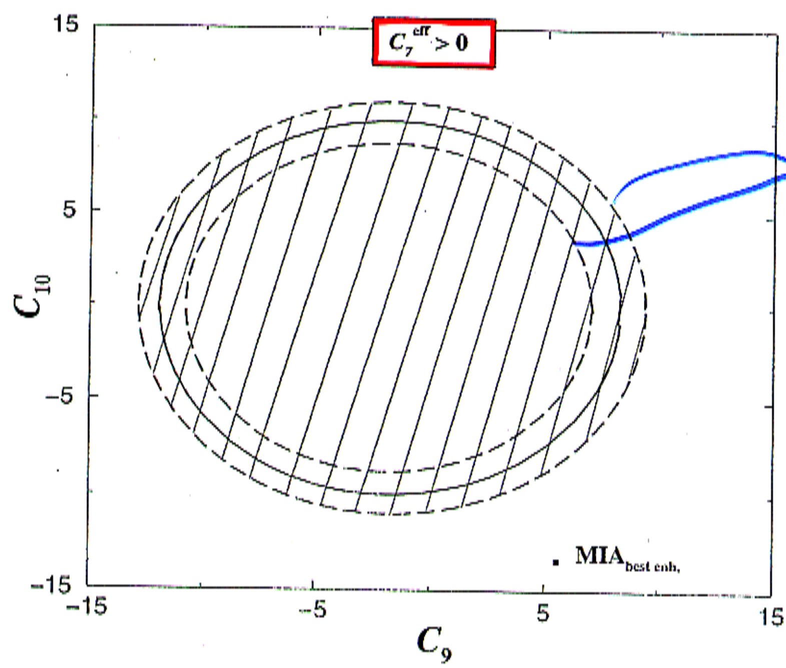
Present Global fit from CDF bound $B \to K^* \mu\mu$



Ali etal

$C_7^{\rm eff} = \pm\, C_7^{\rm eff}\big|_{sm}$

Figure 9: *Bounds on the coefficients $C_9(m_B)$ and C_{10} resulting from the experimental upper bound $\mathcal{B}(B^0 \to K^{*0}\mu^+\mu^-) < 4.0 \times 10^{-6}$ (at 90% C.L.) [34] and $C_7^{\rm eff}(\mu = 4.8\ GeV) = -0.249$ from the bounds given in Eq. (6.1).The SM-point and two representative points in the SUSY-MIA approach from Ref. [23] are also shown. The three curves correspond to using the central values of the form factors (solid curve), the minimum (outer dashed curve) and maximum (inner dashed curve) allowed values discussed in Sec. 3.*



form factor dependence

Figure 10: *The same as Fig. 9 but for the solution with $C_7^{\rm eff} = 0.249$. The point MIA_{best} corresponds to the "best enhancement scenario" of Ref. [23], discussed in the text.*

How does new physics affect the global fit?

1) Determined values $C_i = C_i^{sm}$

with good χ^2 $\Rightarrow$ New physics is decoupled

2) Good χ^2, but Determined $C_i \neq C_i^{sm}$

$\Rightarrow$ New physics in loops

3) Large χ^2 for best 3-parameter fit

$\Rightarrow$ Extended operator basis

$$\mathcal{H}_{eff} \sim \sum_i^n C_i(\mu)\, \mathcal{O}_i(\mu) \qquad n > 10$$

Examples: Left-Right Symmetric Model (Rizzo)

Model Independent Analysis (C.S. Kim et al)

- 10 local 4-fermi interactions

Snowmass SUSY common points

JLH, Wells '97

Compare Reach from Colliders + Rare Decays

Snowmass : Direct comparison of NLC, TeV33, LHC

Points 1-3, 5 based on Minimal SUGRA relations

[All points $\tan\beta < 10$ due to isajet implementations]

Models

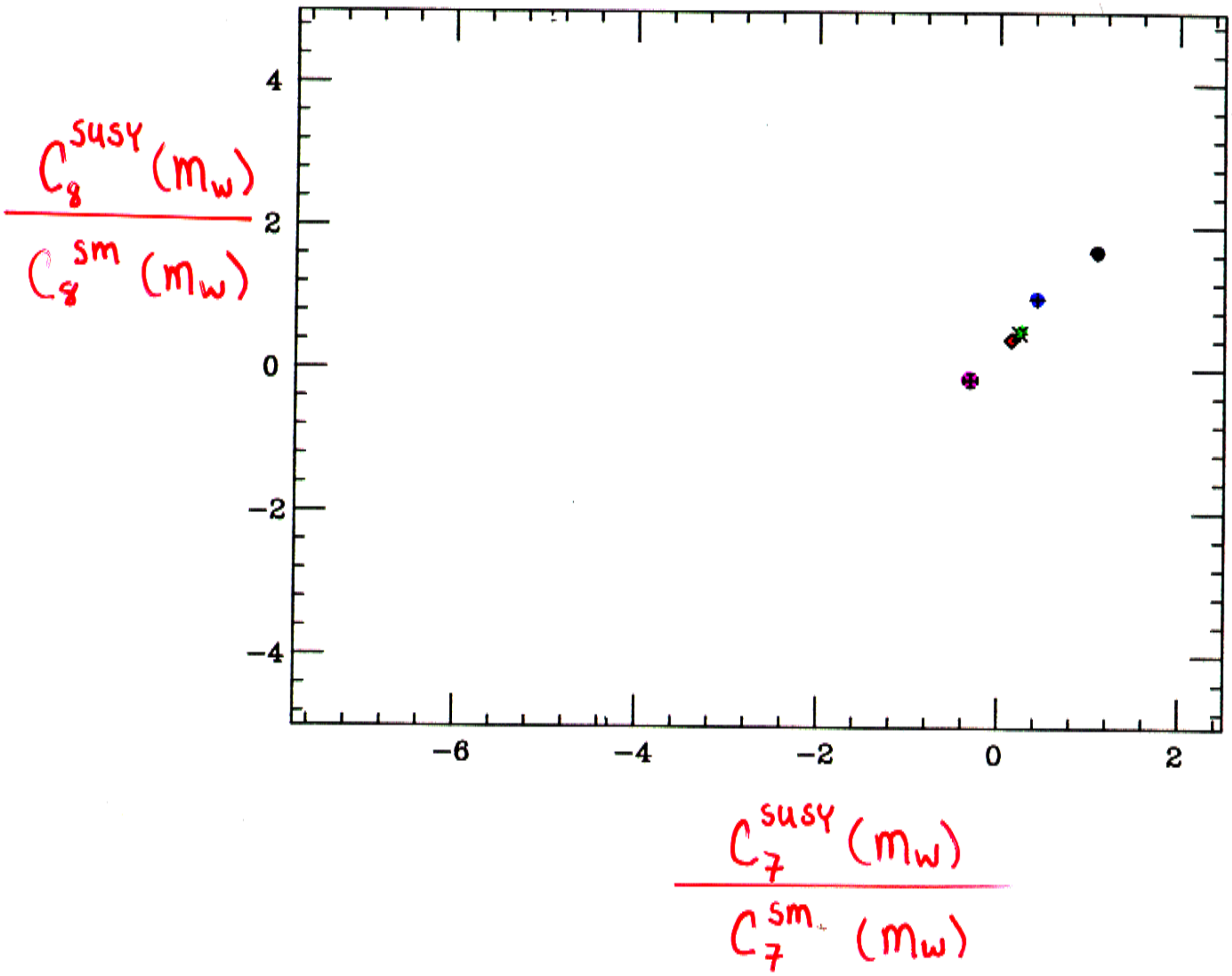
	1	2	3	4	5
m_0	400	100	200		300
$m_{1/2}$	200	300	100		150
A_0/m_0	0	0	0		-2
sign μ	-1	-1	-1		+1
$\tan\beta$	2	2	2		2

$m_t = 175$ GeV

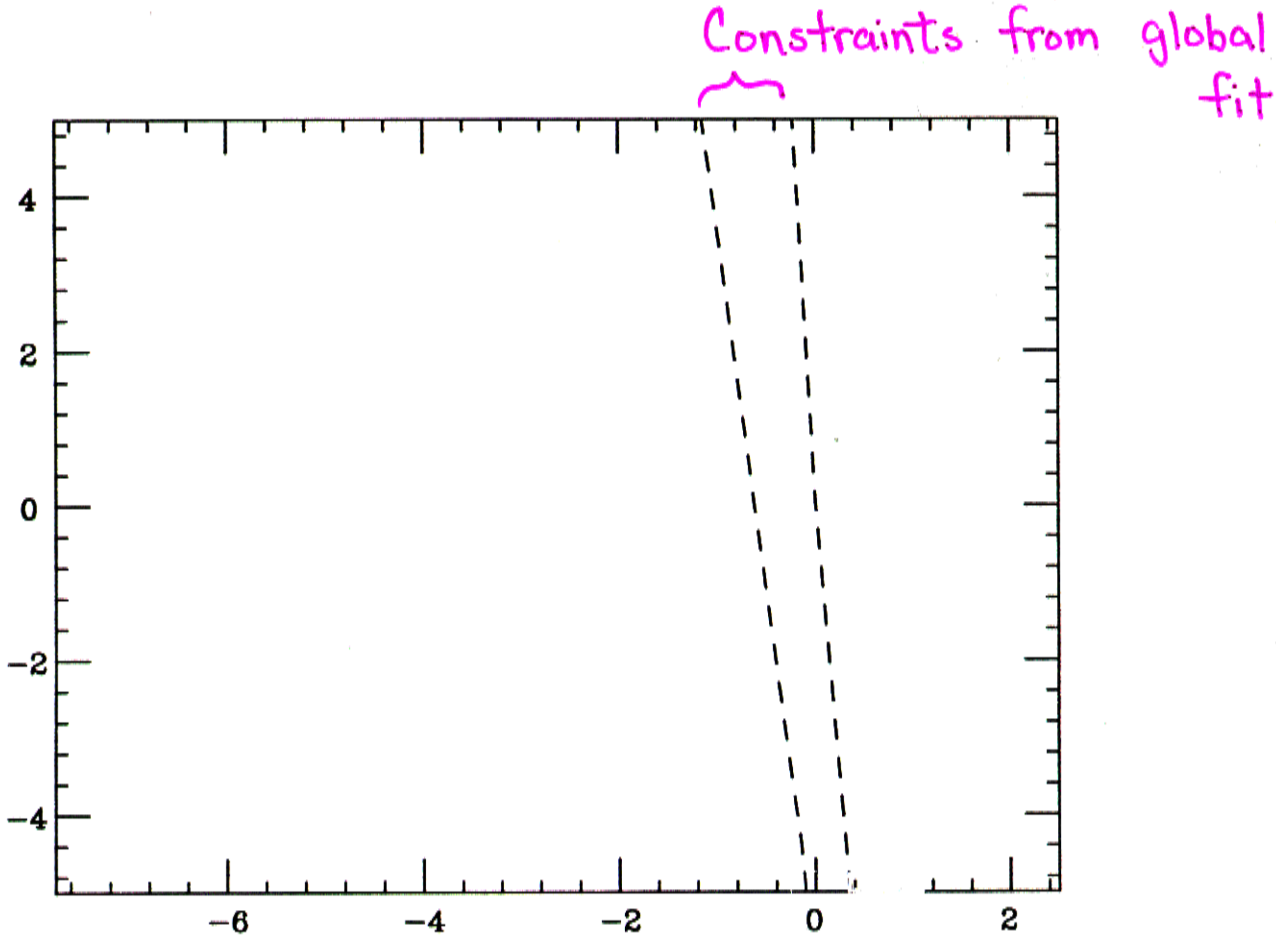
Sparticle Spectrum (in GeV)

Model	1	2	3	4	5
$H^{\pm}$	742	666	379	200	622
$\tilde{g}$	537	742	290	900	416
$\chi_1^{\pm}$	159	235	88	1000	98
$\chi_2^{\pm}$	498	532	265	1000	458
χ_1^0	81	122	42	1000	54
χ_2^0	159	235	89	1000	100
χ_3^0	490	525	249	1000	442
χ_4^0	500	532	266	1000	461
$\tilde{t}_{L/R}$	406/537	510/635	258/321	1000	136/480
$\tilde{b}_{L/R}$	511/587	602/634	273/308	1000	375/461
$\tilde{\tau}_{L/R}$	408/424	156/233	206/215	1000	305/321
$\tilde{e}_L$	424	233	215	1000	320
$\tilde{e}_R$	408	156	206	1000	307
$\tilde{\nu}_L$	420	224	206	1000	314
$\tilde{q}_L$	599	661	311	1000	460
$\tilde{q}_R$	588	686	308	1000	450

Contributions to C_7^{eff} in $b \to s\gamma$



Model 1
2
3
4
5


Constraints from global fit
4
2
0
−2
−4
−6
−4
−2
0
2

Left-Right Symmetric Model

$SU(2)_L \times U(1)_Y \Longrightarrow SU(2)_L \times SU(2)_R \times U(1)_{B-L}$

$g_L \Longrightarrow g_L\,,\quad g_R \qquad \kappa \equiv g_R/g_L$

$Z, W^\pm \Longrightarrow Z, Z', W_L^\pm, W_R^\pm$

$V_{CKM} \Longrightarrow V_L, V_R$

$\rho = m_W^2/m_Z^2\cos^2\theta_W \Longrightarrow \rho_L\,,\quad \rho_R = \dfrac{2\kappa^2(1-x_w)}{\kappa^2(1-x_w)-x_w}\,\dfrac{m_{W_R}^2}{m_{Z'}^2}$

$Z, Z' \Longrightarrow$

$$Z_1 = Z\cos\phi_Z + Z'\sin\phi_Z$$
$$Z_2 = -Z\sin\phi_Z + Z'\cos\phi_Z$$

$\phi_Z \ll 0.01$

LEP/SLD

$W_L, W_R \Longrightarrow$

$$W_1 = W_L\cos\phi + W_R\sin\phi\, e^{i\alpha}$$
$$W_2 = W_R\cos\phi - W_L\sin\phi\, e^{i\alpha}$$

Another phase!

- LRM parameter space is complicated
- Constraints are parameter dependent < K-Mixing / Tevatron

Use $b\to s\ell\ell$ / $b\to s\gamma$ as new tool to explore parameter space.

Operator Basis Extension - $B \to X_s \ell\ell$ in LRM

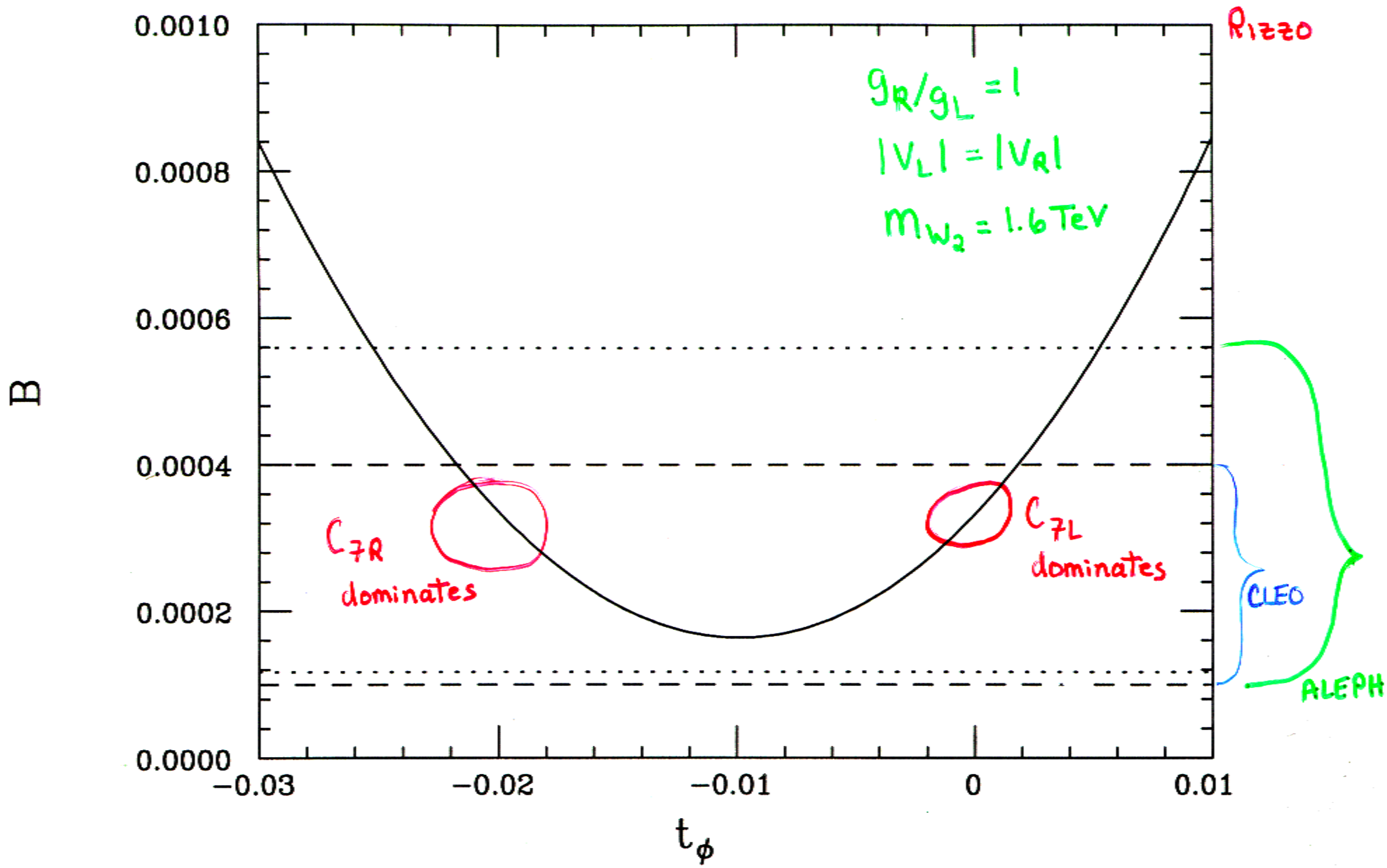
$$\mathcal{H} = \frac{4G_F}{\sqrt{2}} \sum_{i=1}^{12} C_{i\,{}^{L}_{R}}(\mu)\, \mathcal{O}_{i\,{}^{L}_{R}}(\mu)$$

- 2 new operators: $\mathcal{O}_{11L} \sim (\bar{s}_\alpha c_\beta)_R (\bar{c}_\beta b_\alpha)_L$

$\mathcal{O}_{12L} \sim (\bar{s}_\alpha c_\alpha)_R (\bar{c}_\beta b_\beta)_L$ $+ L \leftrightarrow R$

+ 116 (!!) new 1-loop diagrams with W_R exchange

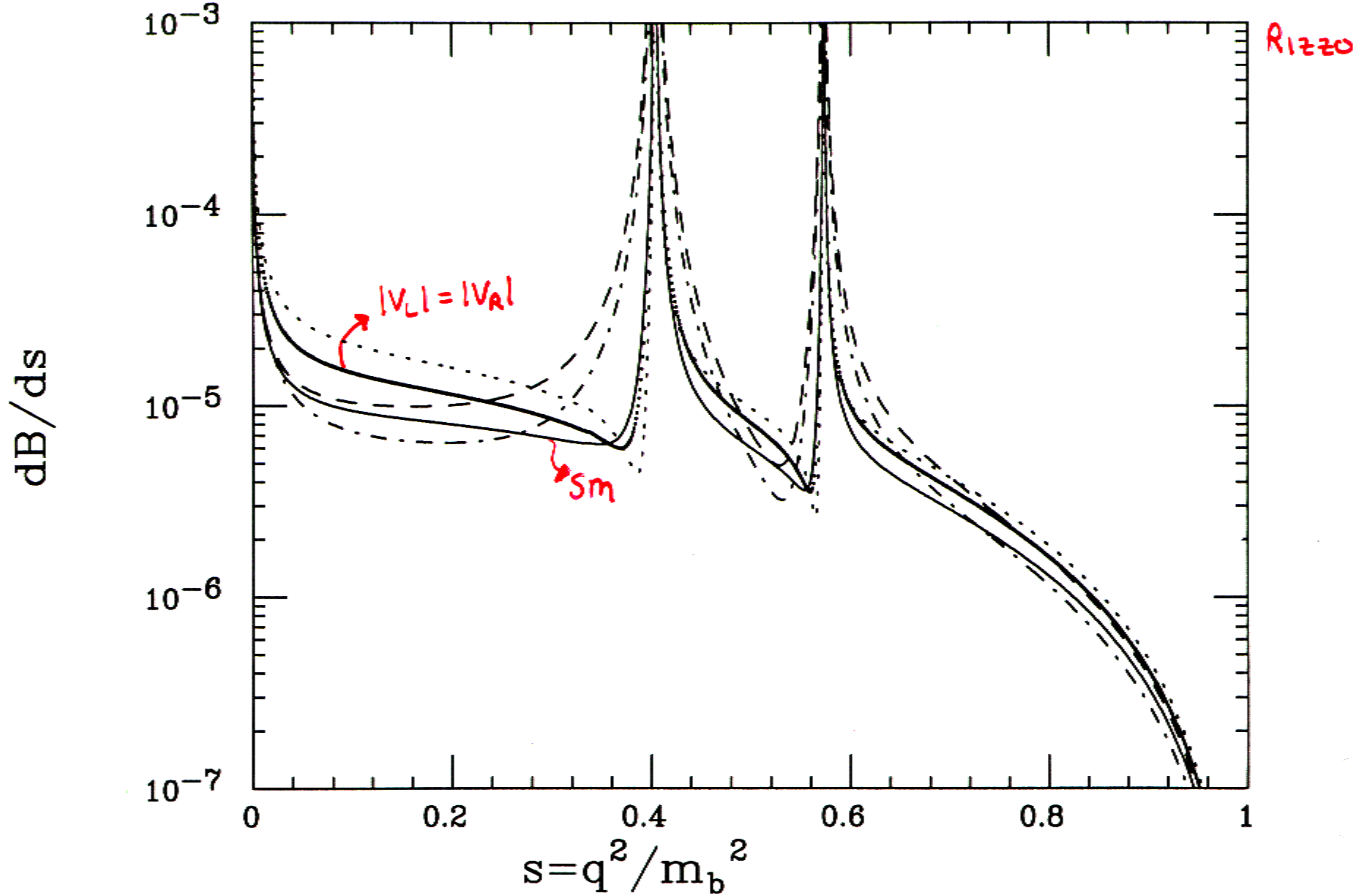
$b \rightarrow s\gamma$ at NLO in LRM



$\hookrightarrow$ W_L - W_R mixing angle

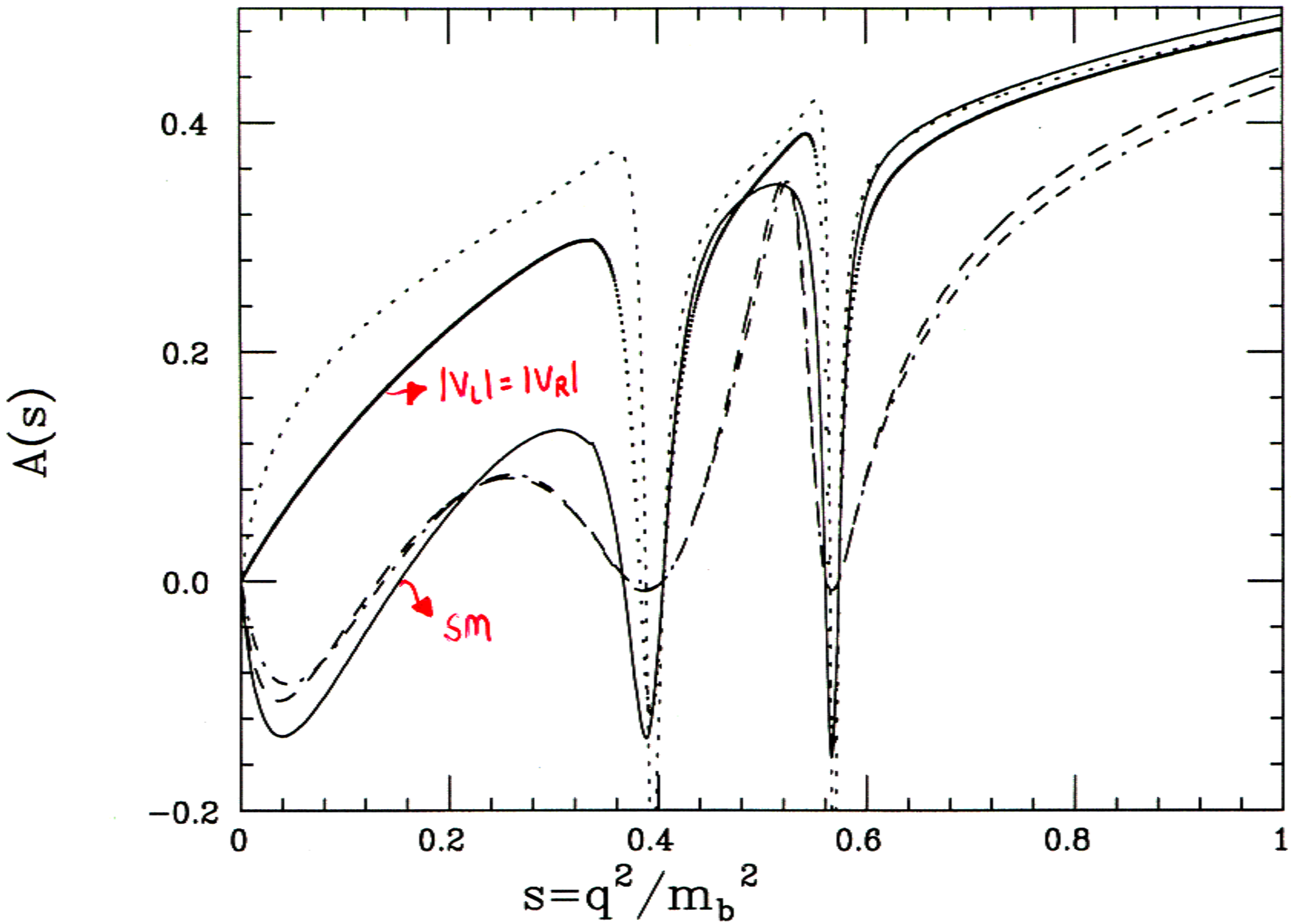
Conspiratorial region
$t_\phi \approx -0.02$

$b \to s \ell^+ \ell^-$ at NLO in LRM

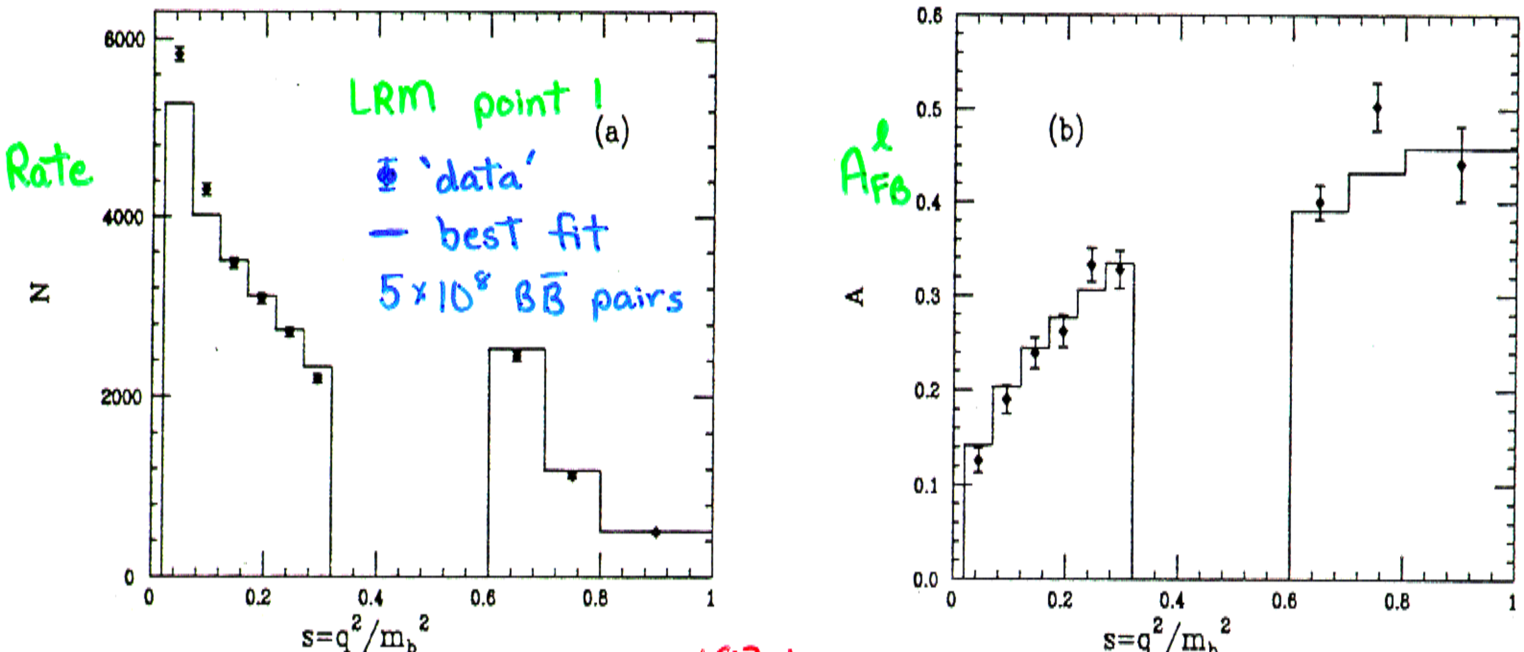


4 Representative models in LRM
where $B(b \to s \gamma)$ = SM value

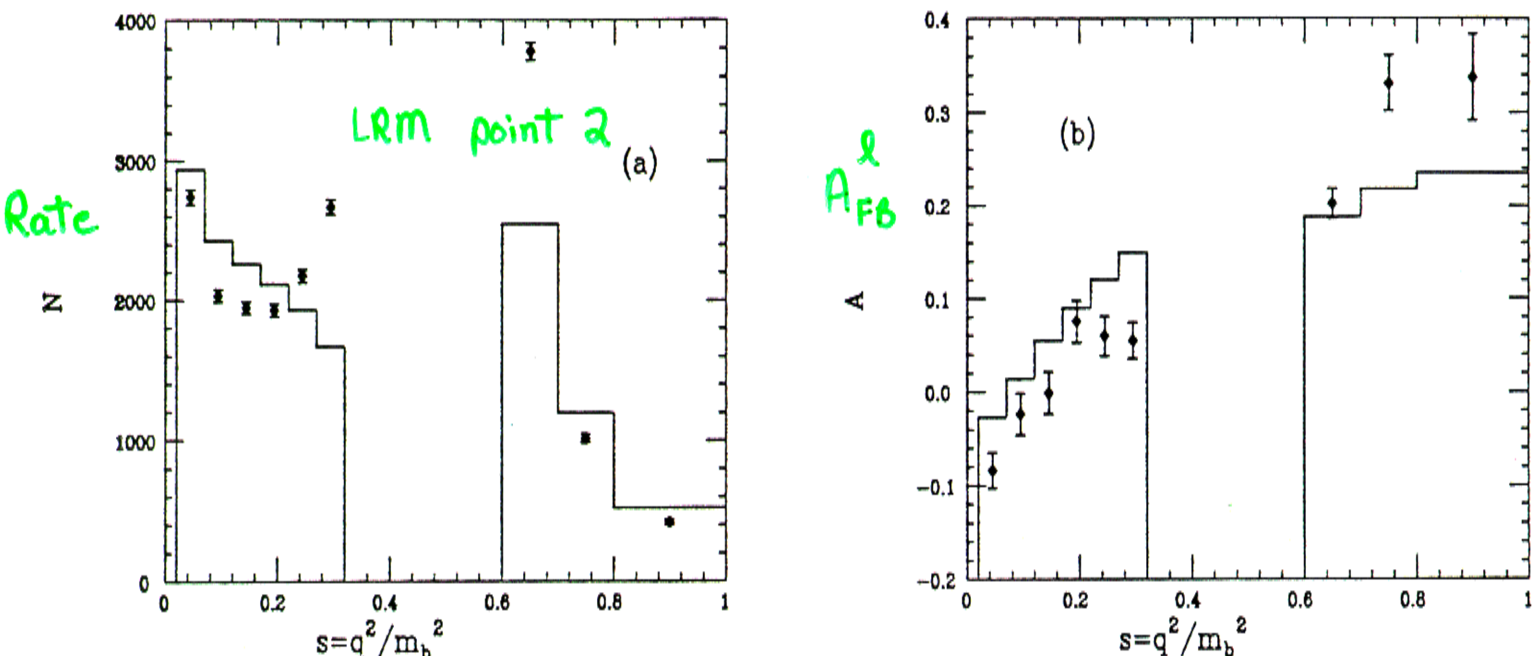
A_{FB} in $b \to s \ell^+ \ell^-$



Examples of best 3-parameter fit to data in LRM $\rightsquigarrow C_{7,9,10\,L}$



$\chi^2/\text{d.o.f.} = 187.1/25$ $P < 10^{-2}$



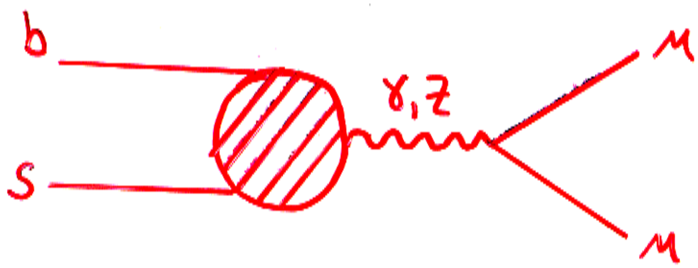
$\chi^2/\text{d.o.f.} = 1187.2/25$

Matrix	$P = 5\%$	$P = 1\%$	$P = 0.1\%$	$P = 0.01\%$
$V_L = V_R$	$\sim 39\%$	$\sim 23\%$	$\sim 11\%$	$\sim 6\%$
$A(1)$	$\sim 100\%$	$\sim 100\%$	$\sim 100\%$	$\sim 100\%$
$A(3)$	$\sim 90\%$	$\sim 76\%$	$\sim 51\%$	$\sim 30\%$
$B(2)$	$\sim 47\%$	$\sim 28\%$	$\sim 15\%$	$\sim 8\%$
$B(3)$	$\sim 92\%$	$\sim 80\%$	$\sim 56\%$	$\sim 36\%$
$D(2)$	$\sim 100\%$	$\sim 100\%$	$\sim 100\%$	$\sim 99\%$

Fraction of time extended operator basis is observable w/ 5×10^7 $B\bar{B}$ pairs

- 1000 Monte Carlo data samples

$B_s \to \mu\mu$

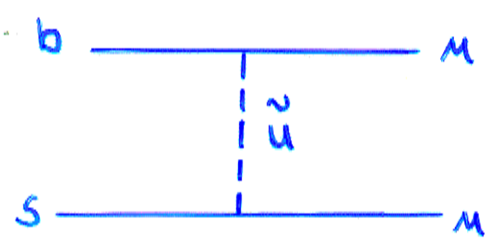


$B_{sm} \sim 4 \times 10^{-9}$

Most new physics already [will be] constrained by $b \to s\ell\ell$ / $b \to s\gamma$

Exceptions:

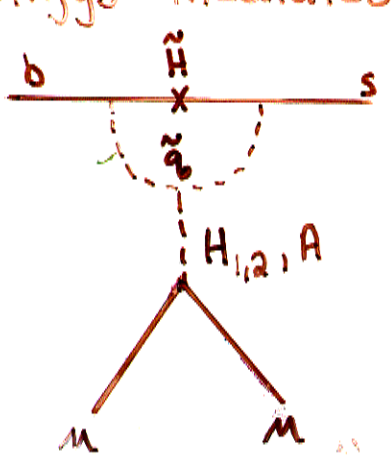
- $\cancel{R_p}$ - SUSY / Leptoquarks

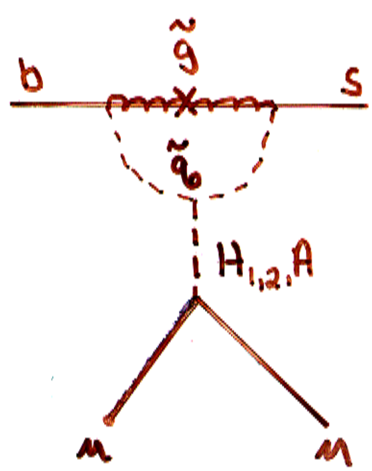


$B \sim 10^{-7}$ Nardi

- Higgs-mediated

Babu, Kolda





Already constrains

$m_A \gtrsim 175$ GeV

for large $\tan\beta$

Model Dependent New Physics Summary

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

Model	CP Violation: $B^0_d - \bar{B}^0_d$ Mixing	CP Violation: Decay Amplitude	Rare Decays	$D^0 - \bar{D}^0$ Mixing
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!