Radiative B Decays – “Standard Candles” of Flavor Physics

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Matthias Neubert – Cornell University

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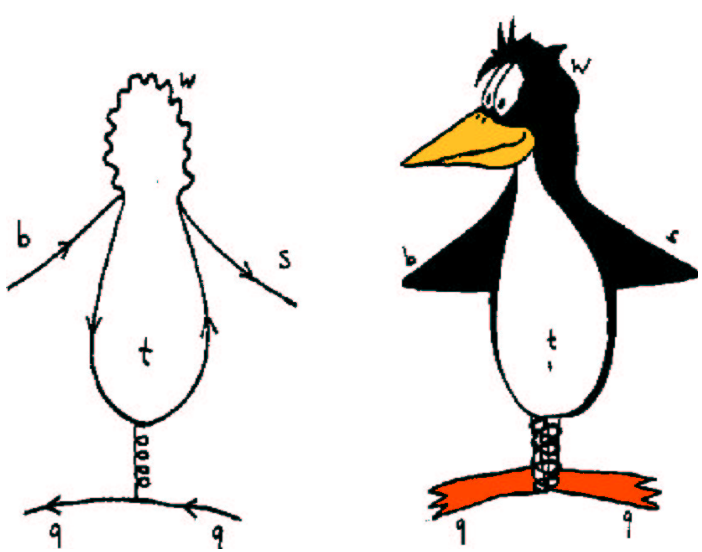
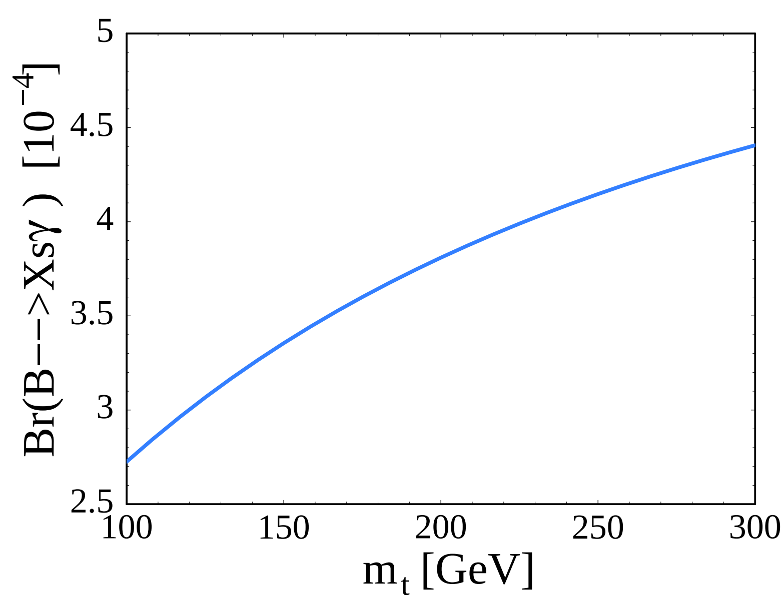
Outline

- Introduction
- Inclusive $B \to X_s\gamma$ Decay Rate
- Implications for New Physics
- Inclusive CP Violation and Photon Polarization
- $B \to X_s\gamma$ Photon Spectrum and $|V_{ub}|$
- Exclusive $B \to K^*\gamma$ and $B \to \rho\gamma$ Decays
- Conclusions

1. Introduction

- $b \to s\gamma$ transitions are the prime example of flavor-changing neutral currents (FCNCs), which are forbidden in the Standard Model at tree level
- sensitivity to heavy particles in loops (penguins)





excellent probe for physics beyond the Standard Model (SM), since:

- SM rate is small, yet well measured experimentally
- SM rate can be calculated with high precision
- large generic sensitivity to non-standard sources of flavor violation and CP violation

$\Rightarrow$ powerful constraints on many New Physics scenarios, including SUSY

2. Inclusive $B \to X_s\gamma$ Decay Rate

starting point of the most sophisticated calculation in flavor physics is the effective weak Hamiltonian:

$$H_{\text{eff}} = -\frac{G_F}{\sqrt{2}} V_{tb} V_{ts}^* \sum_i C_i(\mu)\, Q_i(\mu)$$

NLO calculation of Wilson coefficients requires:

- 3-loop anomalous dimensions [Chetyrkin, Misiak, Munz (96)]

2. Inclusive $B \to X_s\gamma$ Decay Rate

$$\hat{\gamma}^{(1)} = \begin{pmatrix} -\frac{355}{9} & -\frac{502}{27} & -\frac{1412}{243} & -\frac{1369}{243} & \frac{134}{243} & -\frac{35}{162} & -\frac{818}{243} & \frac{3779}{324} \\ -\frac{35}{3} & -\frac{28}{3} & -\frac{416}{81} & \frac{1280}{81} & \frac{56}{81} & \frac{35}{27} & \frac{508}{81} & \frac{1841}{108} \\ 0 & 0 & -\frac{4468}{81} & -\frac{31469}{81} & \frac{400}{81} & \frac{3373}{108} & \frac{22348}{243} & \frac{10178}{81} \\ 0 & 0 & -\frac{8158}{243} & -\frac{59399}{243} & \frac{269}{486} & \frac{12899}{648} & -\frac{17584}{243} & -\frac{172471}{648} \\ 0 & 0 & -\frac{251680}{81} & -\frac{128648}{81} & \frac{23836}{81} & \frac{6106}{27} & \frac{1183696}{729} & \frac{2901296}{243} \\ 0 & 0 & \frac{58640}{243} & -\frac{26348}{243} & -\frac{14324}{243} & -\frac{2551}{162} & \frac{2480344}{2187} & -\frac{3296257}{729} \\ 0 & 0 & 0 & 0 & 0 & 0 & \frac{4688}{27} & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & -\frac{2192}{81} & \frac{4063}{27} \end{pmatrix}$$

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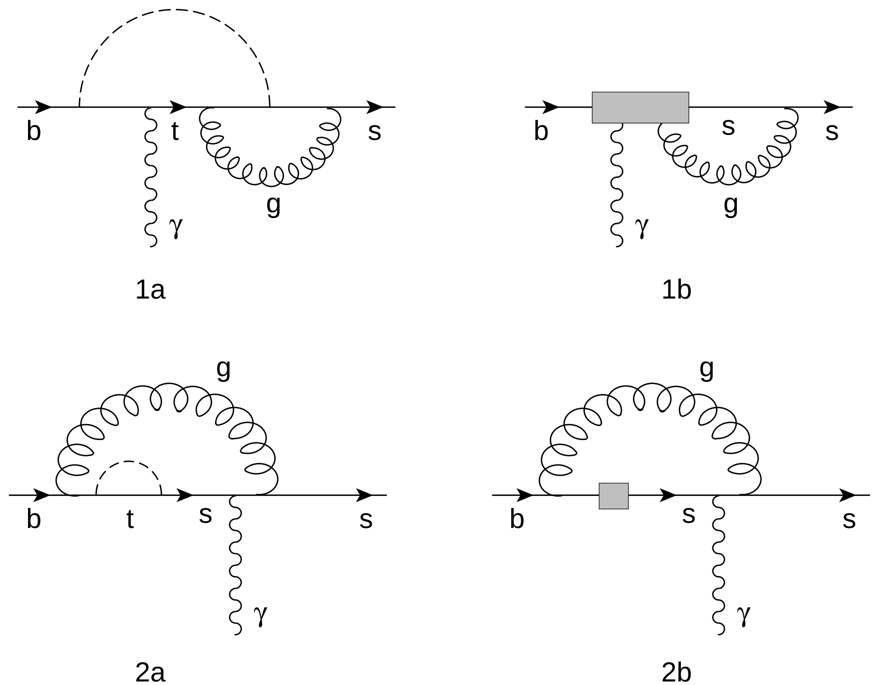
- 3-loop anomalous dimensions [Chetyrkin, Misiak, Munz (96)]
- electroweak radiative corrections
  [Czarnecki, Marciano (98); Kagan, Neubert (98); Gambino, Haisch (01)]

- 2-loop matching coefficients at the weak scale, known for:
  - SM [Adel, Yao (94); Greub, Hurth (97)]



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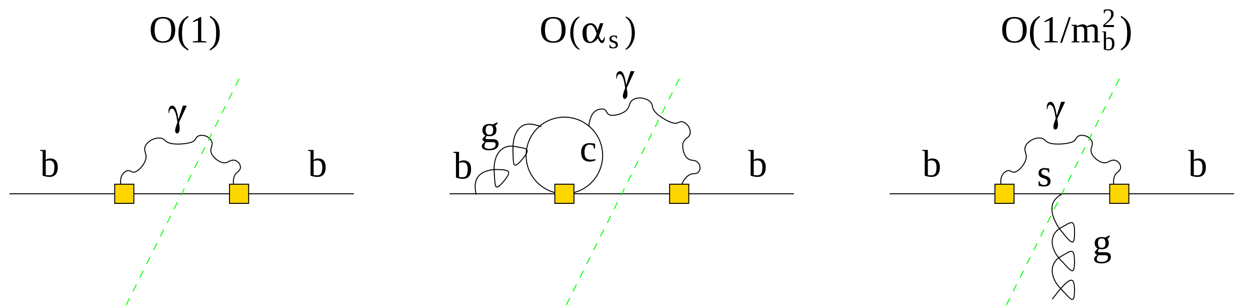
  - constrained MSSM with large $\tan\beta$
    [Degrassi, Gambino, Giudice (00); Carena et al. (00)]

matrix elements for the total inclusive rate are calculated using the operator product expansion:



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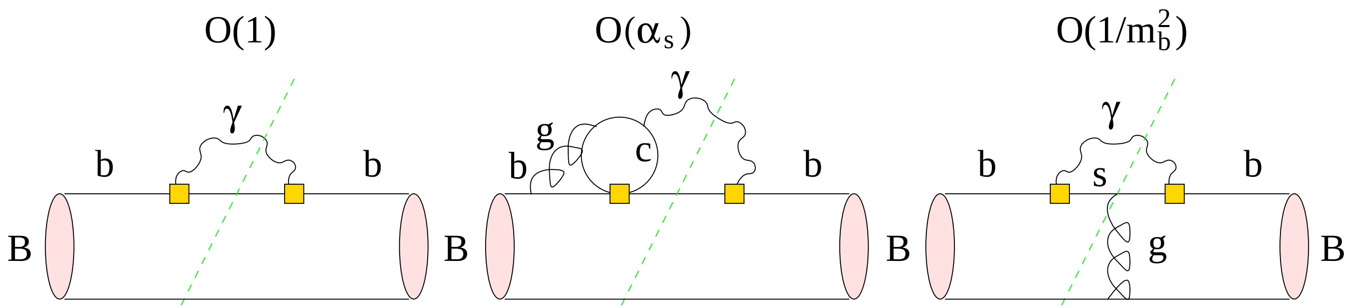
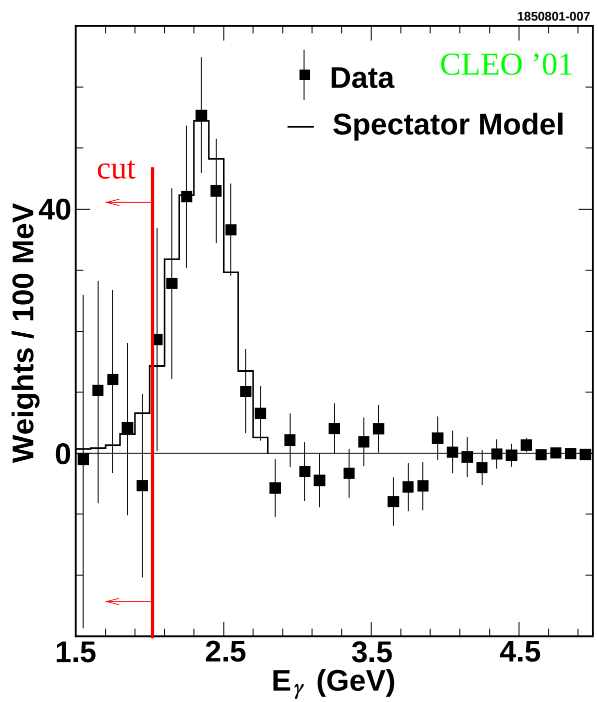


- needs 2-loop matrix elements of four-quark operators [Greub, Hurth, Wyler (96); Buras et al. (01)]
- power corrections calculable using heavy-quark effective theory [Falk, Luke, Savage (93); Voloshin (96)]

- photon-energy cut $E_\gamma > 2.0$ GeV introduces sensitivity to the shape of the photon spectrum (“Fermi motion”), which can be analysed using the twist expansion
[Neubert (93); Bigi et al. (93)]



contained fraction = (91+3−6)%
(sometimes included as part of the experimental uncertainty)

Recent Improvements

- use of running charm-quark mass $m_c(\mu)$ (rather than pole mass) in charm-penguin diagrams
  [Gambino, Misiak (01)]
  $\Rightarrow$ sizeable enhancement by about 10% (!)
- reduction of renormalization-scale dependence by keeping $m_b(m_W)$ in the top sector normalized at a high scale [Gambino, Misiak (01)]
- completion of two-loop matrix elements for penguin operators (tiny effect) [Buras et al. (02)]
- avoid normalization to semileptonic rate (using $m_b^{\rm pole} \to m_b^{1S}$ conversion) [Becher et al. (02)]

Results for total branching ratio

energy cut $E_\gamma > 1.6$ GeV:

$$\text{Br}(B \to X_s\gamma) = \begin{cases} (3.57 \pm 0.30) \cdot 10^{-4}\,; & \text{[Buras et al. (02)]} \\ (3.54 \pm 0.30) \cdot 10^{-4}\,; & \text{[Becher et al. (02)]} \end{cases}$$

extrapolation to $E_\gamma > 2.0$ GeV: [Becher et al. (02)]

$$\text{Br}(B \to X_s\gamma) = (3.26 \pm 0.27\,^{+0.09}_{-0.18}) \cdot 10^{-4}$$

- compares well with CLEO measurement of $(2.94 \pm 0.39 \pm 0.25) \cdot 10^{-4}$

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$$\text{Br}(B \to X_s\gamma) = (3.64 \pm 0.31) \cdot 10^{-4}$$

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excellent agreement with the experimental results indicates that there is not much room for New Physics!

3. Implications for New Physics

Models with minimal flavor violation:

- CKM matrix is the only source of quark-flavor mixing (e.g., type-II 2HDM, CMSSM, . . .)
- typically only moderate FCNC effects allowed after constraints from EW precision data are included
- phenomenologically “preferred”, since data show no evidence for non-standard flavor (or CP) violation
- theoretically somewhat ad hoc (naturalness?)

Models with new sources of flavor violation:

- e.g., generic SUSY extensions of the SM, models with new quark generations, etc.
- more “natural”, since we expect some physics beyond the SM to explain the origin of flavor
- generically, these models can have drastic effects on FCNC processes!

  (K–$\bar{K}$ mixing, $B \to X_s\gamma$, $K \to \pi\nu\bar{\nu}$, ...)

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SUSY flavor problem

A Caveat

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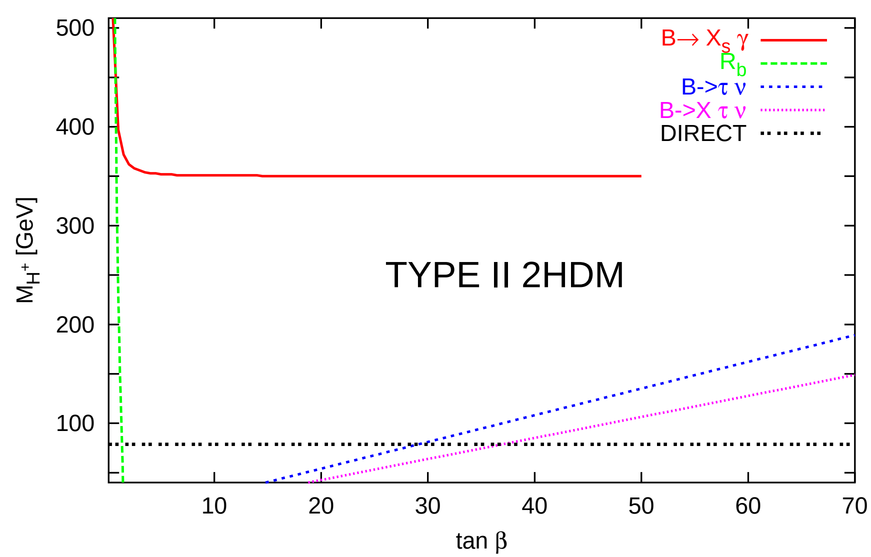
- in a generic model, each flavor-changing process receives its own, characteristic New-Physics effects
- adjusting flavor parameters in an ad hoc way leads to correlations between observables that are strongly model dependent

$$(K\text{–}\bar{K} \;\leftrightarrow\; B\to X_s\gamma \;\leftrightarrow\; K\to\pi\nu\bar{\nu} \;\leftrightarrow\; \dots)$$

Type-II 2HDM

- charged-Higgs contribution adds constructively to SM contribution $\Rightarrow$ obtain a strong bound on m_{H^+}
- complete NLO analysis [Ciuchini et al. (97); Borzumati, Greub (98)]
- most recent update yields $m_{H^+} > 350$ GeV at 99% CL [Gambino, Misiak (01)]



- more generally, expect constructive or destructive interference with SM contribution: [Kagan, Neubert (98)]

$$10^4\,\text{Br}(B\to X_s\gamma)\approx 3.26+1.40\,\text{Re}\,\xi_7+0.14\,\text{Re}\,\xi_8$$
$$+0.37\left(|\xi_7|^2+|\xi_7^R|^2\right)+0.08\,\text{Re}\left(\xi_7\xi_8^*+\xi_7^R\xi_8^{R*}\right)$$

where the New Physics contributions are

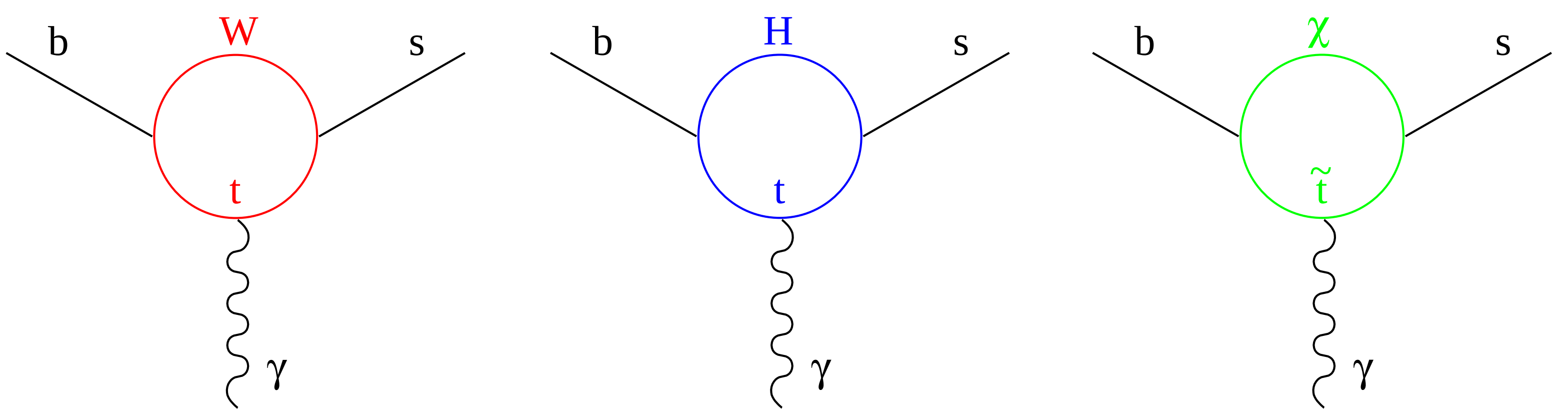
$$\xi_{7,8}=\frac{C_{7,8}^{\rm NP}(m_W)}{C_{7,8}^{\rm SM}(m_W)}\,,\qquad \xi_{7,8}^R=\frac{C_{7,8}^{R,\rm NP}(m_W)}{C_{7,8}^{\rm SM}(m_W)}$$

- possible to have large New Physics contributions if $\text{Re}\,\xi_{7,8}<0$ (destructive interference), and if one is willing to accept some fine-tuning

CMSSM with minimal flavor violation

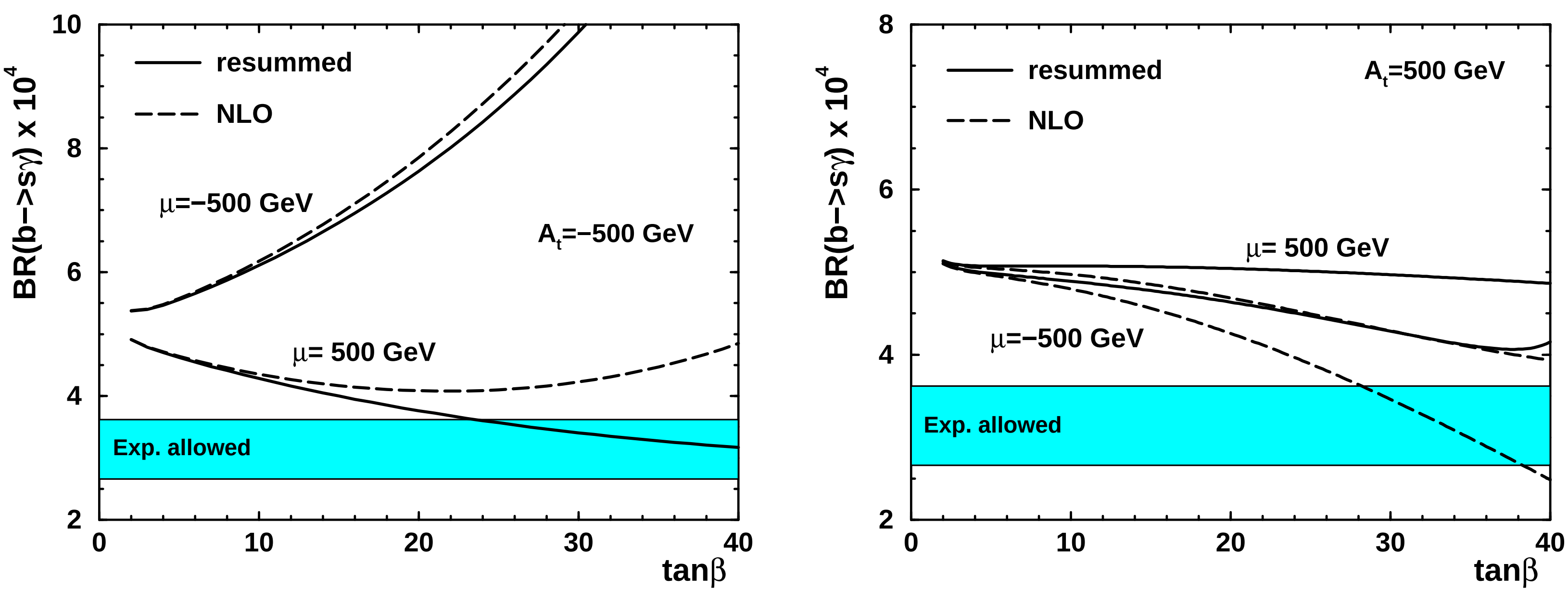
three types of contributions:

$$C_{7,8}(m_W) = \underbrace{C_{7,8}^{\rm SM}(m_W)}_{\text{SM}} + \underbrace{C_{7,8}^{\rm H}(m_W)}_{\text{type-II 2HDM}} + \underbrace{C_{7,8}^{\chi}(m_W)}_{\text{chargino-stop}}$$



- several recent analyses, including novel higher-order terms enhanced by large $\tan\beta$:

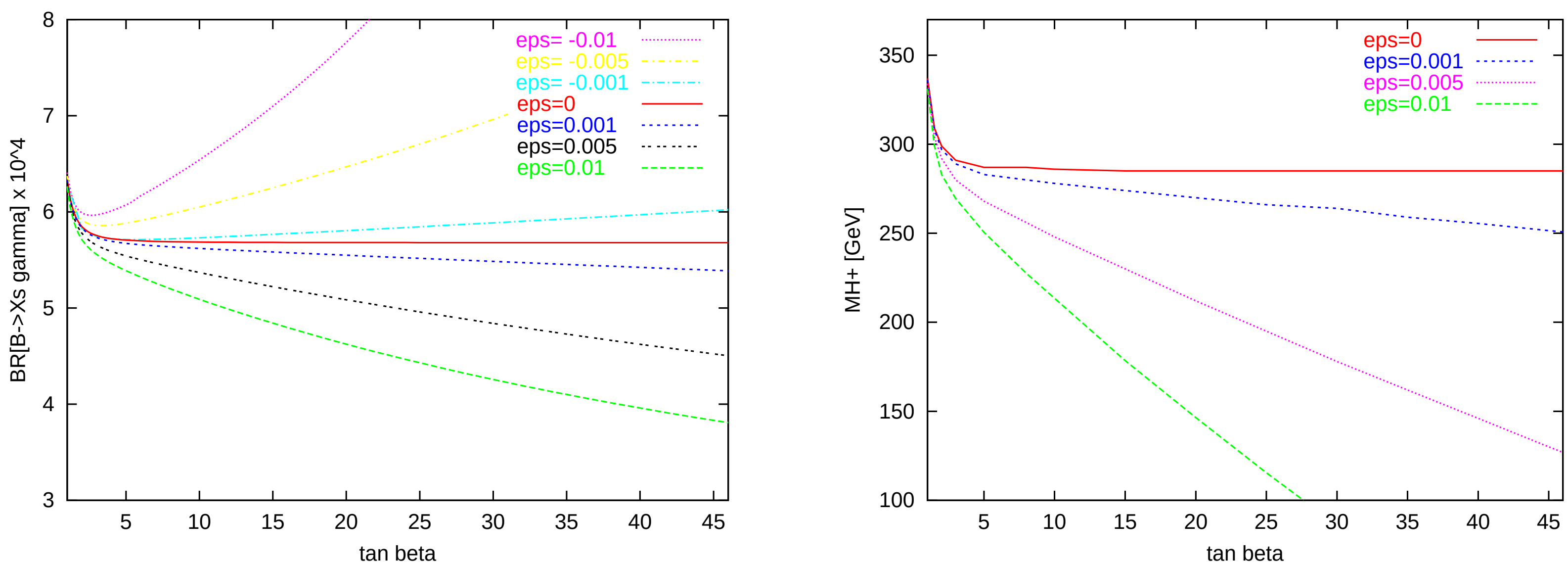
  [Carena et al. (00); Degrassi et al. (00); Demir, Olive (01); Boz, Pak (02)]



$\Rightarrow$ strongly favors negative values of $\mu\, A_t$ (with positive μ preferred)

- important finding that large-$\tan\beta$ corrections can weaken the bound on the charged Higgs mass even in the decoupling limit:

[Degrassi, Gambino, Giudice (00); Carena et al. (00)]



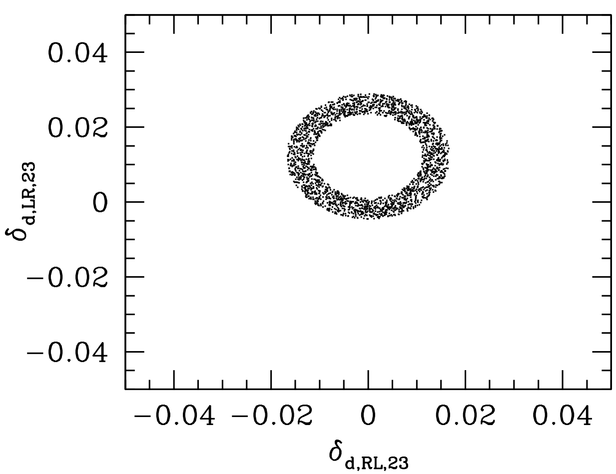
Unconstrained MSSM

- new SUSY flavor-changing quark-squark-gluino couplings can be parameterized in terms of off-diagonal entries in the squark mass matrix, e.g.

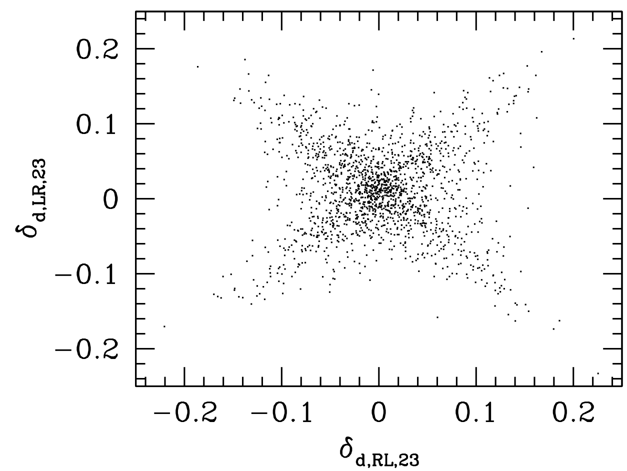
$$\delta_{23}^{LR} = \frac{(m_{LR}^2)_{23}}{m_{\tilde{q}}} \quad \text{etc.} \quad (\text{naively of } O(1))$$

- many analyses based on the mass insertion approximation [Gabbiani et al. (96); Hagelin, Kelley, Tanaka (94); . . .]

- recent, more complete analysis includes interplay of contributions from gluinos, neutralinos, charginos, and charged Higgs [Besmer, Greub, Hurth (01)]



only 2 flavor−violating parameters



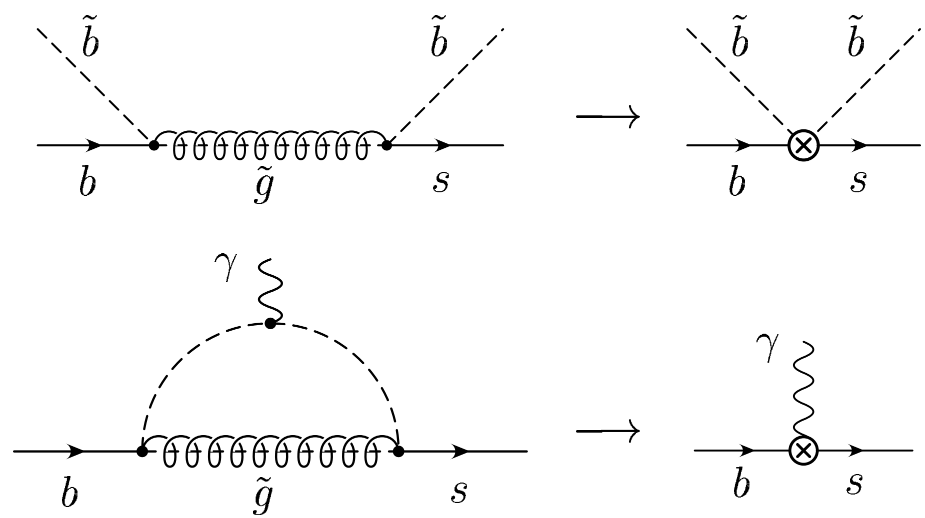
4 flavor−violating parameters

$\Rightarrow$ find that constraints on $\delta_{23}^{LR,RL}$ can be significantly relaxed due to interference effects

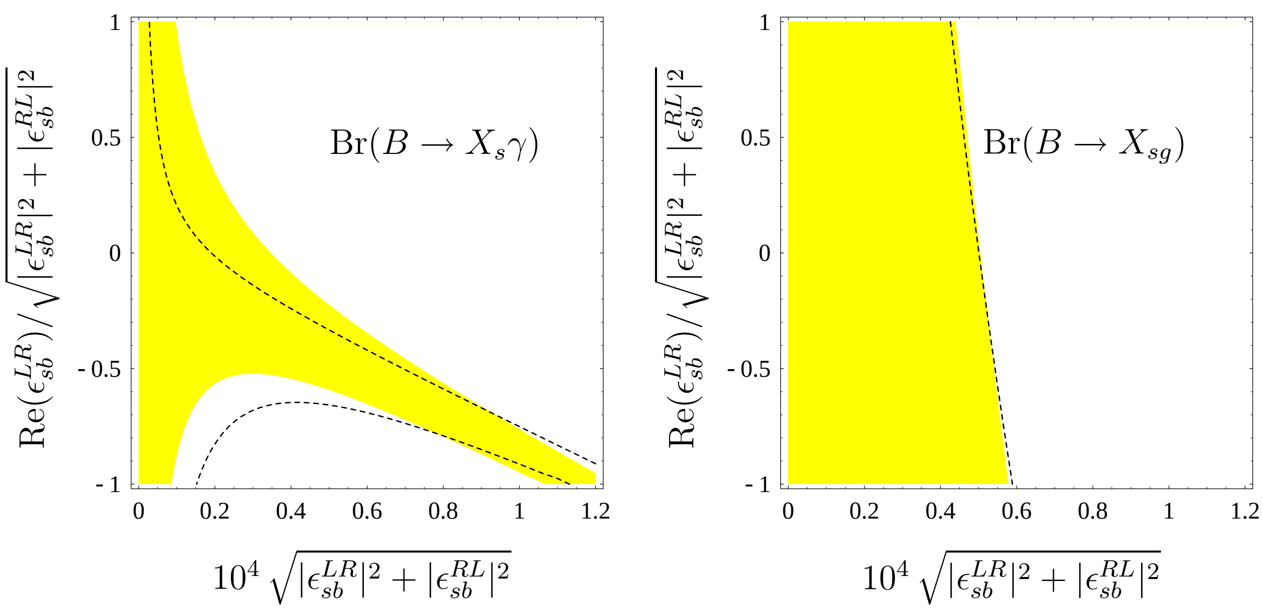
Flavor violation from light $\tilde{b}$ squarks

presence of a light $\tilde{b}$ squark (mass ~ 2–4 GeV) and gluino (mass ~ 15 GeV) could explain the observed excess of b-production at the Tevatron [Berger et al. (00)]

- this would give rise to new sources of $b \to s$ FCNC transitions



- flavor-violations can be parameterized in terms of $\epsilon_{sb}^{LR} = \Gamma_{s3}^{L\dagger}\,\Gamma_{b3}^{R}$ etc. (naively of $O(1)$)
- complete NLO analysis gives extremely tight constraints on these couplings [Becher et al. (02)]



4. CP Asymmetry in $B \to X_s\gamma$

- additional, powerful probe for New Physics
- basically a null effect in the SM, since:

  [Soares (91); Wolfenstein, Wu (94); Aliev et al. (95); Kagan, Neubert (98)]

$$A_{\rm CP}(B \to X_s\gamma) \sim \underbrace{\alpha_s(m_b)}_{\text{strong phase}} \times \underbrace{\frac{V_{ub}}{V_{cb}}}_{\text{CKM suppr.}} \times \underbrace{\frac{m_c^2}{m_b^2}}_{\text{GIM suppr.}} \approx 0.5\%$$

  and

$$A_{\rm CP}(B \to X_{s/d}\,\gamma) = 0$$

- large asymmetries are possible in extensions of the SM with new CP-violating couplings entering the Wilson coefficients

approximate expression (without new operators):

$$A_{\rm CP} \approx 1.3\% \,\text{Im}(C_2/C_7) - 9.5\% \,\text{Im}(C_8/C_7)$$

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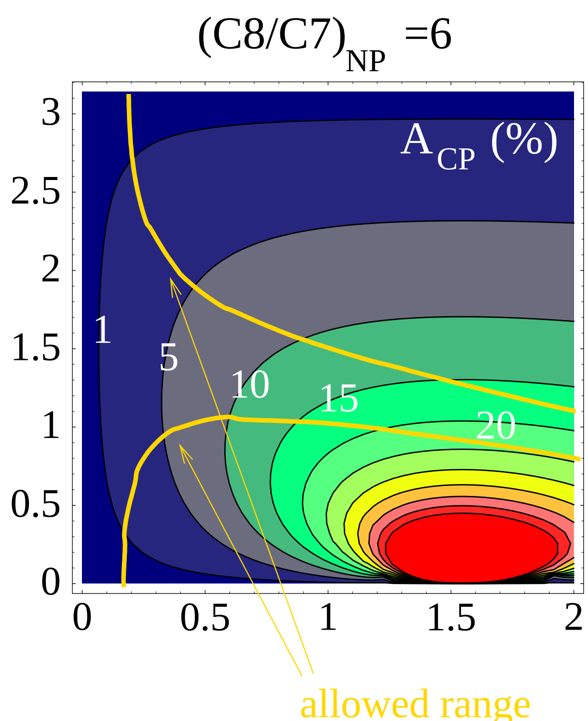
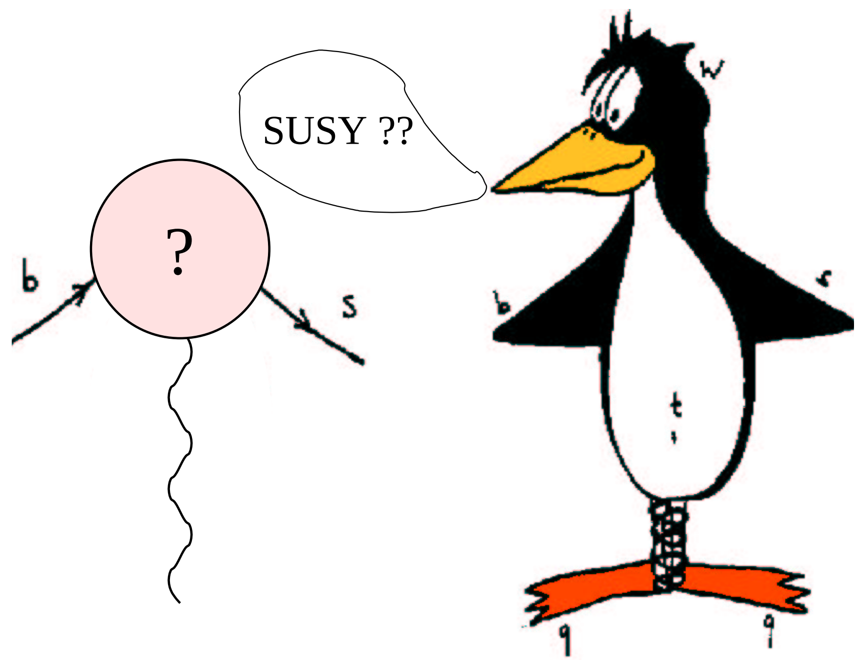
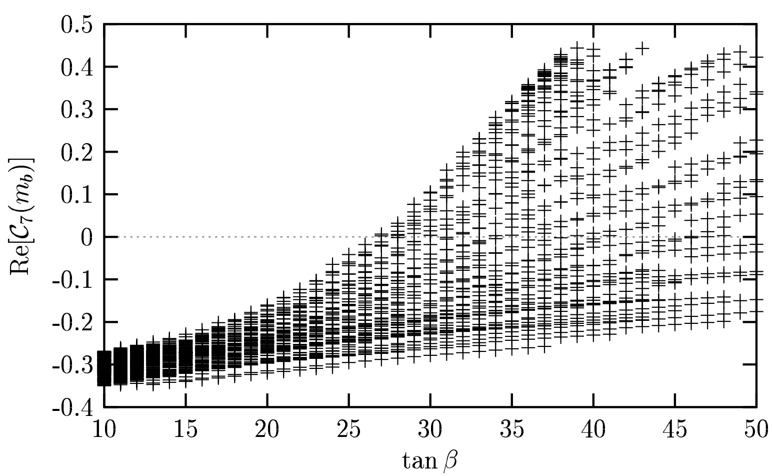
- second term is important for models with enhanced chromo-magnetic dipole transitions (C_8) and new CP-violating couplings, and can lead to CP asymmetries exceeding 10–20%

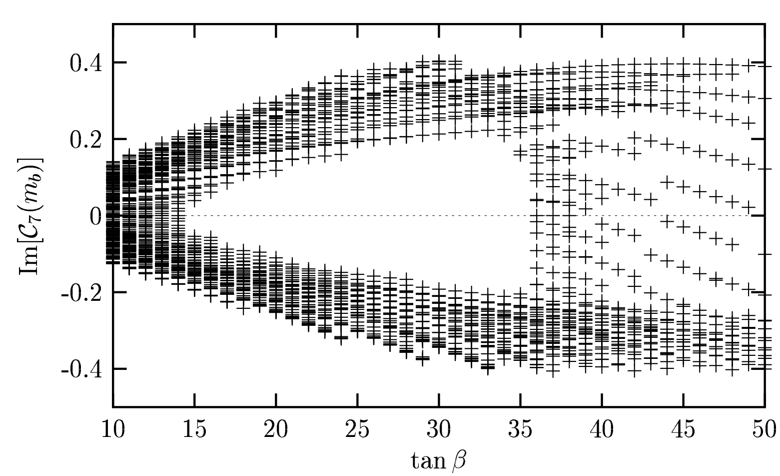
An example: [Kagan, Neubert (98)]



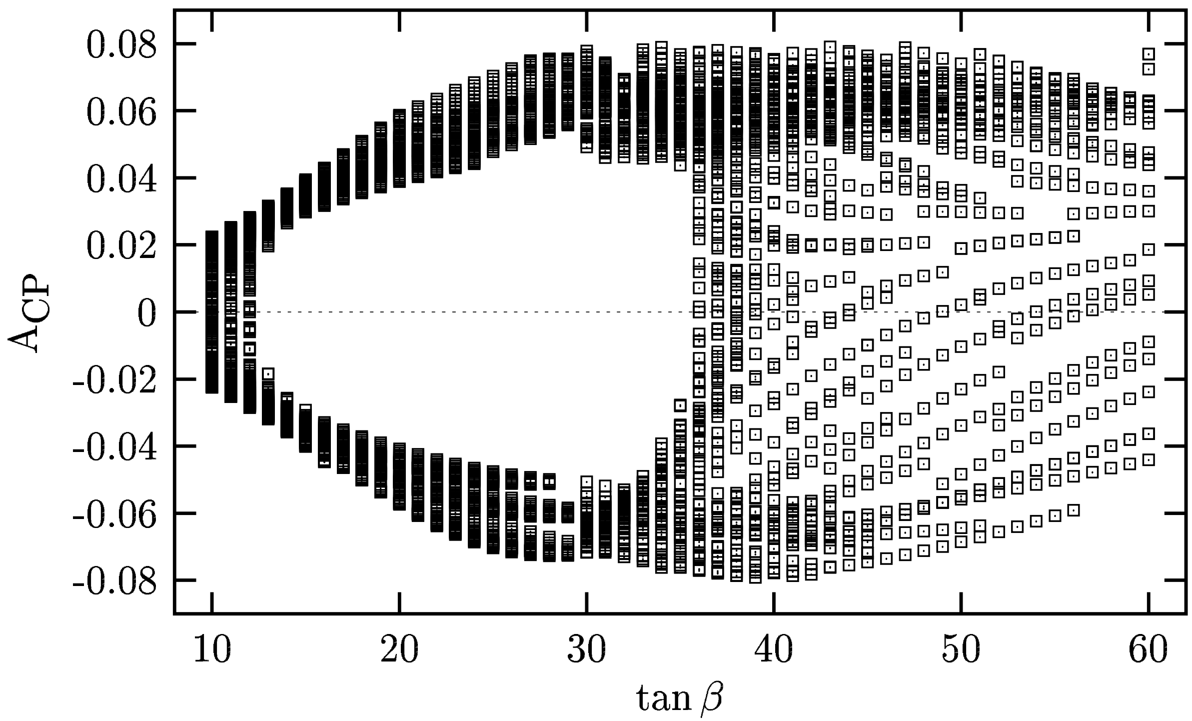


- two recent analyses in MSSM with minimal flavor violation but explicit CP violation ($\phi_\mu, \phi_A \neq 0$) [Demir, Olive (01); Boz, Pak (02)]
- including large-$\tan\beta$ enhanced contributions beyond leading order, they find significant (complex) contributions to $C_{7,8}$, e.g.:





- this can lead to $A_{\mathrm{CP}}(B \to X_s\gamma)$ of order 10% without spoiling the SM prediction for the branching ratio:



Photon Polarization

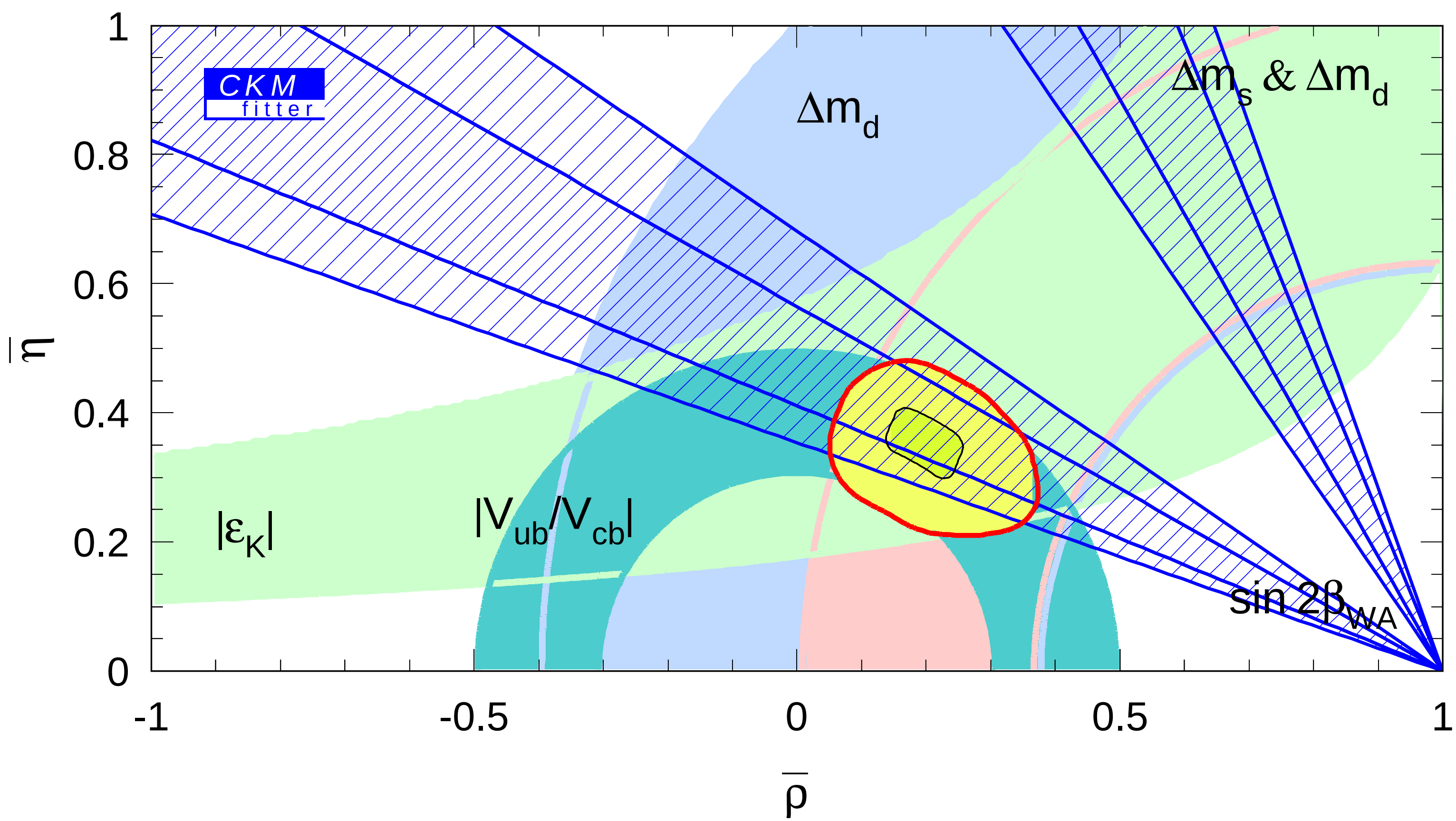
radiative B decays in the SM have helicity structure $b_R \to s_L \gamma_L$; however, in many extensions of the SM (e.g., left-right symmetric models, SUSY) there can be couplings with opposite helicity ($\to$ parameters $\xi_{7,8}^R$ above)

- photon polarization can be measured in $B \to K_{\rm res}\gamma$ decays (followed by $K_{\rm res} \to K^*\pi \to K\pi\pi$), by studying the up-down asymmetry of the photon direction relative to the $K\pi\pi$ decay plane [Gronau et al. (01)]
- asymmetry can be calculated reliably to be $(34 \pm 5)\%$ for $K_1(1400)$
- gross deviations from this prediction would signal the presence of opposite-chirality transitions from New Physics

5. Photon Spectrum as a QCD Tool

$B \to X_s\gamma$ photon energy spectrum is insensitive to New Physics and therefore a great QCD laboratory:

- moments $\langle E_\gamma \rangle$ and $(\langle E_\gamma^2 \rangle - \langle E_\gamma \rangle^2)$ provide a precise determination of the b-quark mass and other HQET parameters
  $\Rightarrow$ helps in the determination of $|V_{cb}|$
- combination of $B \to X_s\gamma$ photon spectrum and $B \to X_u l\nu$ charged-lepton spectrum provide the currently best route to measuring $|V_{ub}|$ (immensely important for unitarity-triangle physics at the B factories)



CKM fitter
Δm_d
Δm_s & Δm_d
$|\varepsilon_K|$
$|V_{ub}/V_{cb}|$
sin $2\beta_{WA}$
1
0.8
0.6
0.4
0.2
0
-1
-0.5
0
0.5
1
$\bar\eta$
$\bar\rho$

Determination of $|V_{ub}|$

non-perturbative effects in endpoint region of $B \to X_s\gamma$ and $B \to X_u l\nu$ can be related to a universal shape function (up to $1/m_b$ corrections): [Neubert (93)]

- measure the $B \to X_s\gamma$ photon spectrum $S(E_\gamma)$
- predict the fraction of events with charged-lepton energy $E_l > E_0$ via

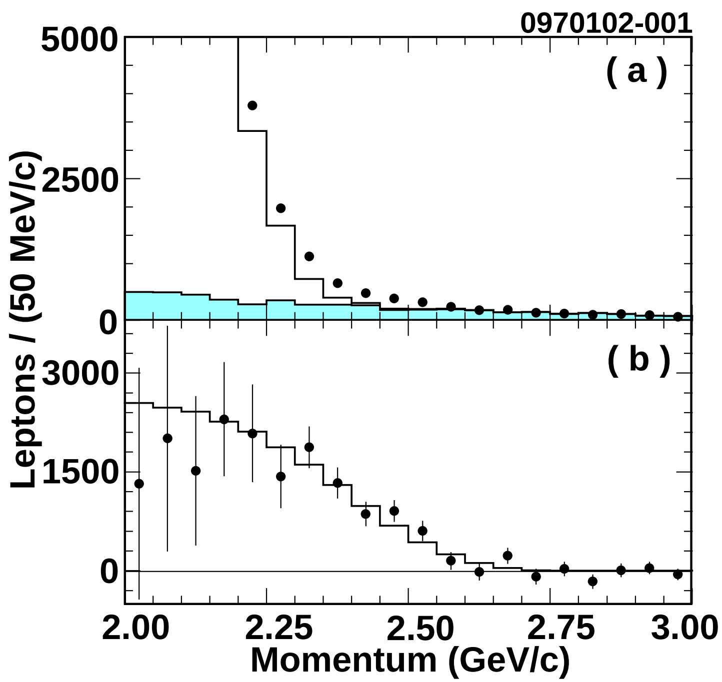
$$F_u(E_0) = \frac{4}{m_b} \int_{E_0}^{m_B/2} dE_\gamma \, w(E_\gamma, E_0) \, S(E_\gamma)$$

where the weight function $w(E_\gamma, E_0)$ is known including perturbative and $1/m_b$ corrections

[Neubert (93); Leibovich, Low, Rothstein (99); Bauer, Luke, Mannel (02)]

- extract $|V_{ub}|$ from a measurement of the $B \to X_u l\nu$ decay rate in the region above 2.2 GeV
- theoretical uncertainty on $|V_{ub}|$ is of order 10% or less

experimental result (CLEO '01):



$$|V_{ub}| = (4.08 \pm 0.56_{\rm exp} \pm 0.29_{\rm th})$$

6. Exclusive Radiative Decays

- significant recent progress in theory of exclusive hadronic B decays based on QCD factorization theorems [Beneke et al. (99)]
- factorization formula for $B \to V\gamma$ ($V = K^*$ or ρ):
  [Bosch, Buchalla (01); Beneke, Feldmann, Seidel (01)]

$$\langle V\gamma(\epsilon)|Q_i|B\rangle = \left[F_{B\to V}(0)\, T_i^I + \int_0^1 d\xi\, dx\, T_i^{II}(\xi,x)\,\Phi_B(\xi)\,\Phi_V(x) \right]\cdot\epsilon^*$$

- opens up novel probes for New Physics, since e.g. CP asymmetries can be enhanced w.r.t. inclusive decays

- particularly important for $b \to d\gamma$ transitions, where inclusive measurements are hindered by the large $b \to s\gamma$ background
- SM prediction is that $b \to d\gamma$ decays are about 20 times smaller than $b \to s\gamma$ decays, but CP asymmetries are predicted to be 20 times larger!

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- expectation is supported by tight experimental bounds $\text{Br}(B^- \to \rho^-\gamma) < 2.8 \cdot 10^{-6}$ and $\text{Br}(B^0 \to \rho^0\gamma) < 1.5 \cdot 10^{-6}$, which imply (BaBar '02):

$$\frac{\text{Br}(B^- \to \rho^-\gamma)}{\text{Br}(B^- \to K^{*-}\gamma)} < 0.07\,, \qquad \frac{2\text{Br}(B^0 \to \rho^0\gamma)}{\text{Br}(B^0 \to K^{*0}\gamma)} < 0.07$$

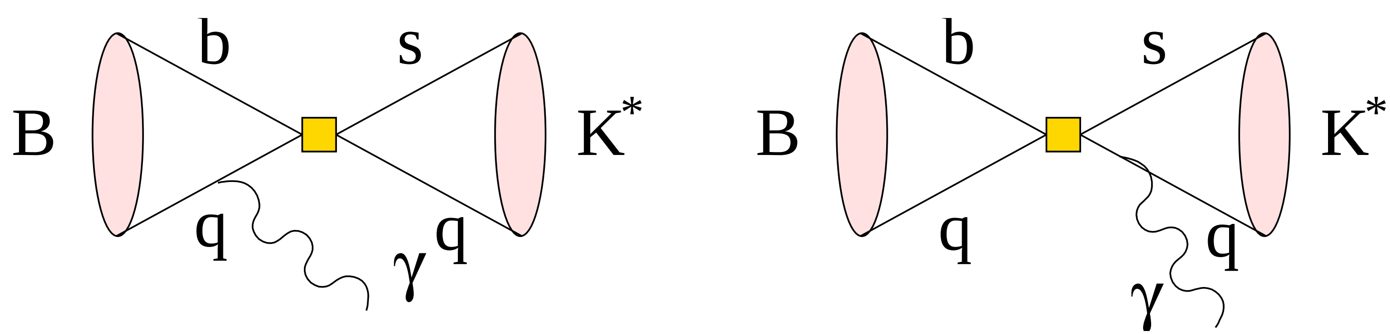
Isospin Violation in $B \to K^*\gamma$

in SM, the leading contribution to isospin asymmetry

$$\Delta_{0-} = \frac{\Gamma(B^0 \to K^{*0}\gamma) - \Gamma(B^- \to K^{*-}\gamma)}{\Gamma(B^0 \to K^{*0}\gamma) - \Gamma(B^- \to K^{*-}\gamma)} = (8 \pm 2)\%$$

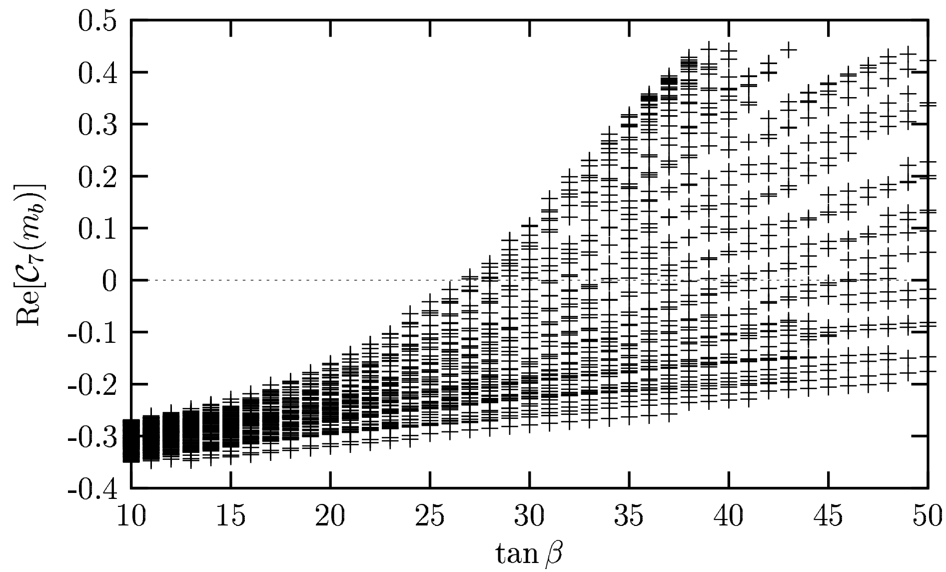
is due to the 4-quark penguin operator

$Q_6 = (\bar{s}_i b_j)_{V-A} \sum_q (\bar{q}_j q_i)_{V+A}$



$\Rightarrow$ direct probe of sign and magnitude of the ratio Re(C_6/C_7) of Wilson coefficients [Kagan, Neubert (01)]

- new window to New Physics; for instance, a positive value for the asymmetry would exclude a large region of MSSM parameter space at large $\tan\beta$, where Re$(C_7) > 0$:



- present experimental situation is inconclusive, since $\Delta_{0-} = (3 \pm 6)\%$

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- had no time to discuss related processes such as $b \to s l^+ l^-$, $b \to s\nu\bar{\nu}$, $K \to \pi\nu\bar{\nu}$, which are equally rich

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- . . . . . . while the optimist looks forward to SUSY 2003