physics reach of rare b-decays

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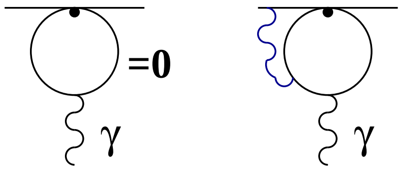
- $b \to s\gamma$ *status & future*
- $b \to s\ell^+\ell^-$ *status & opportunities* *
- *indirect signals of new physics*
  - *flavor and CP in models of EWK symmetry breaking*
  - *top 10 observables beyond* $\mathcal{B}(b \to s\gamma)$

* *A.Ali,C.Greub,G.H.,E.Lunghi, hep-ph/0112300, to appear in PRD*

$b \to s\gamma$ **status**

$b \to s\gamma$: theor & exp well studied, NLO complete; important model constraint; strong dependence of 2-loop matrix element on m_c/m_b



$\mathcal{B}(B \to X_s\gamma)_{SM} = (3.35 \pm 0.30) \cdot 10^{-4}$ if pole mass $m_c/m_b = 0.29 \pm 0.02$

$\mathcal{B}(B \to X_s\gamma)_{SM} = (3.73 \pm 0.30) \cdot 10^{-4}$ if $\bar{m}_c(\mu)/m_b = 0.22 \pm 0.04$

large uncertainty related to charm hep-ph/0104034

we cannot resolve: $\mathcal{B}(B \to X_s\gamma)_{SM} = (3.54 \pm 0.49) \cdot 10^{-4}$ (combined)

theory error exceeds experimental one

$\mathcal{B}(B \to X_s\gamma)_{worldave-winter2002} = (3.22 \pm 0.40) \cdot 10^{-4}$ Cleo,Aleph,Belle

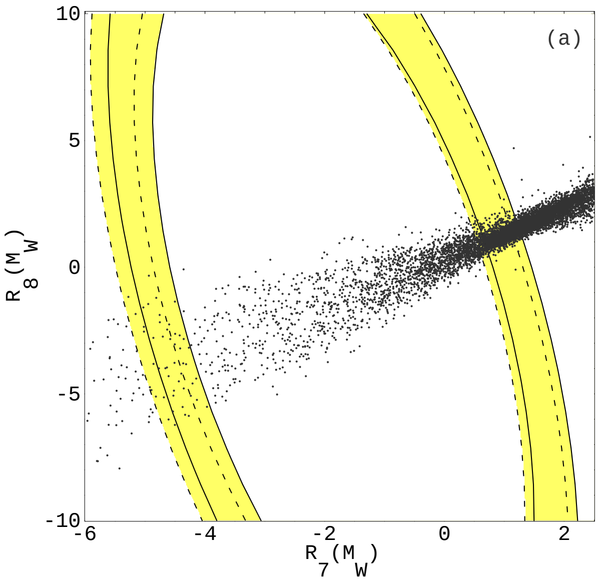
unless there is progress in theory[a], we cannot establish new physics with the $B \to X_s\gamma$ branching ratio alone

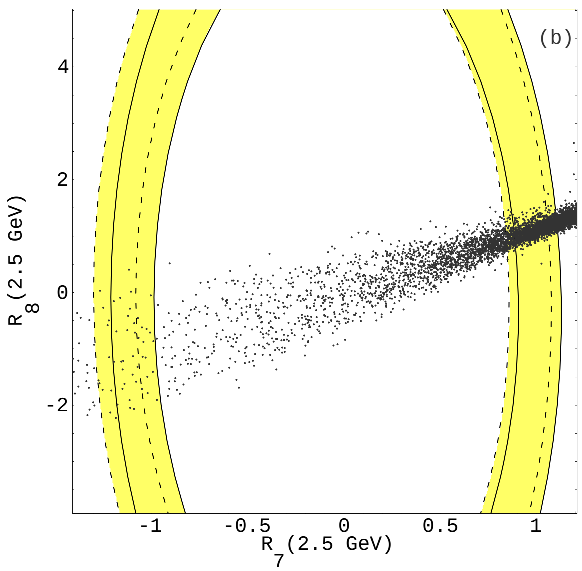
[a](or the exp central value moves a lot)

model independent analysis $\mathcal{H}_{eff} = -4G_F/\sqrt{2} V_{tb} V_{ts}^* \sum C_i O_i$

$O_7 \propto \bar{s}_L \sigma_{\mu\nu} b_R F^{\mu\nu}$, $O_8 \propto \bar{s}_L \sigma_{\mu\nu} b_R G^{\mu\nu}$ $\mathcal{B}(b \to s\gamma)_{LO} \sim |C_7(m_b)|^2$

ratios $R(\mu) \equiv \frac{C^{SM}(\mu)+C^{NP}(\mu)}{C^{SM}(\mu)}$ NLO update @90%C.L. hep-ph/0112300





theory errors μ and charm mass solid:pole, dashed:$\overline{\text{MS}}$ prospects: 2005 B-factories have $500 fb^{-1}$, $\sigma(stat, sys)_{b\to s\gamma} = 1.8\%, 3\%$ hep-ex/0112041

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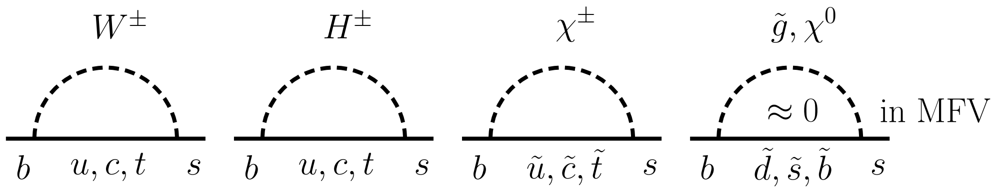
$b \to s\gamma$ in minimal flavor violating MSSM

minimal flavor violation (MFV) $=$ no more flavor violation than in SM, i.e. in the Yukawas; $A-$ terms $\propto Y$, squark masses $\propto 1$

condition on SUSY breaking, classify MFV vs non MFV

in MFV MSSM: no tree level FCNC, thus $C_7 = C_7^W + C_7^H + C_7^{\chi^\pm}$

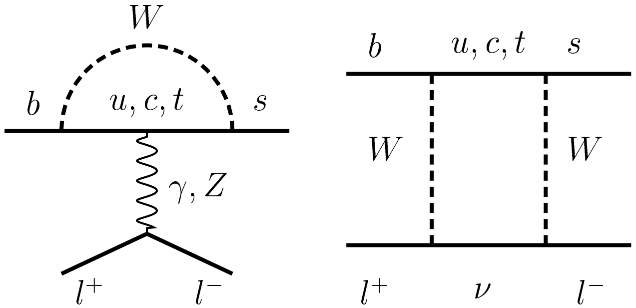


MFV scatter plot: $m_{\tilde{t}}, m_\chi > 90$ GeV $m_{H^\pm} > 78.6$ GeV $|\mu|, M_2 < 1$ TeV $2.3 < \tan\beta < 50$ $|\Theta_{\tilde{t}}| < \pi/2$ strong correlation between C_7 and C_8

non-SM branch $C_7 > 0$ needs large chargino-stop contribution, since both $C_7^W, C_7^H < 0$, large $\tan\beta$ and/or light stop required; run II reach of stops up to $300-360$GeV hep-ph/0206167

2 branches allowed, SM is $R \equiv 1$ how to distinguish them ?

structures in SM



additional operators: $O_9 \propto (\bar{s}_L \gamma_\mu b_L)(\bar{\ell}\gamma^\mu \ell)$, $O_{10} \propto (\bar{s}_L \gamma_\mu b_L)(\bar{\ell}\gamma^\mu \gamma_5 \ell)$

$\star\star\star$ recently first observation of exclusive decay $\star\star\star$ ok with SM

$\mathcal{B}(B \to K\ell^+\ell^-)_{SM} = 0.35 \pm 0.12 \cdot 10^{-6}$ NNLO,QCD fact. hep-ph/0112300

$\mathcal{B}(B \to K\ell^+\ell^-) = 0.75^{+0.25}_{-0.21} \pm 0.09 \cdot 10^{-6}$ Belle, hep-ex/0109026

$\mathcal{B}(B \to K\ell^+\ell^-) = 0.84^{+0.30+0.10}_{-0.24-0.18} \cdot 10^{-6}$ BaBar 2002

inclusive mode	branch fraction Belle'02	signif.	upper bound Belle'01
$B \to X_s \mu^+\mu^-$	$8.9^{+2.3+1.6}_{-2.1-1.7} \cdot 10^{-6}$	4.4σ	$< 19.1 \cdot 10^{-6}$ @ 90% C.L.
$B \to X_s e^+e^-$	$5.1^{+2.6+1.3}_{-2.4-1.2} \cdot 10^{-6}$	2.1σ	$< 10.1 \cdot 10^{-6}$ @ 90% C.L.

C_9 is special: O_2 admixture at 1-loop without α_s-corr, so $C_9 \propto \frac{1}{\alpha_s} + \ldots$

NNLO complete for low dilepton inv mass $\hat{s}$ ⋆⋆⋆ many people ⋆⋆⋆

$$C_i^{eff} = \left[1 + \frac{\alpha_s}{\pi}\omega_i(\hat{s})\right] A_i + \frac{\alpha_s}{4\pi} C_j F_{ij}(\hat{s})$$

F_{ij}: virtual corrections

ω_i: correction of matrix element of O_i includes bremsstrahlung

$$\begin{aligned}\frac{d\Gamma(b \to s\ell^+\ell^-)}{d\hat{s}} &= \left(\frac{\alpha_{em}}{4\pi}\right)^2 \frac{G_F^2 m_{b,pole}^5 \left|V_{ts}^* V_{tb}\right|^2}{48\pi^3} (1-\hat{s})^2 \left[(1+2\hat{s})\left(\left|C_9^{eff}\right|^2 + \left|C_{10}^{eff}\right|^2\right) f_1(\hat{s})\right. \\ &+ \left. 4\,(1+2/\hat{s})\left|C_7^{eff}\right|^2 f_2(\hat{s}) + 12\mathrm{Re}\left(C_7^{eff} C_9^{eff*}\right) f_3(\hat{s}) + f_c(\hat{s})\right]\end{aligned}$$

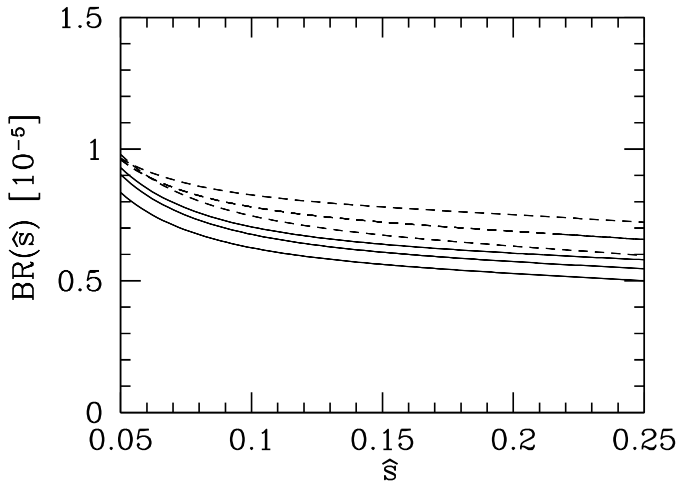
includes $1/m_c$,$1/m_b$ hqet corrections $\lambda_1 = -0.2\,\mathrm{GeV}^2$, $\lambda_2 = +0.12\,\mathrm{GeV}^2$

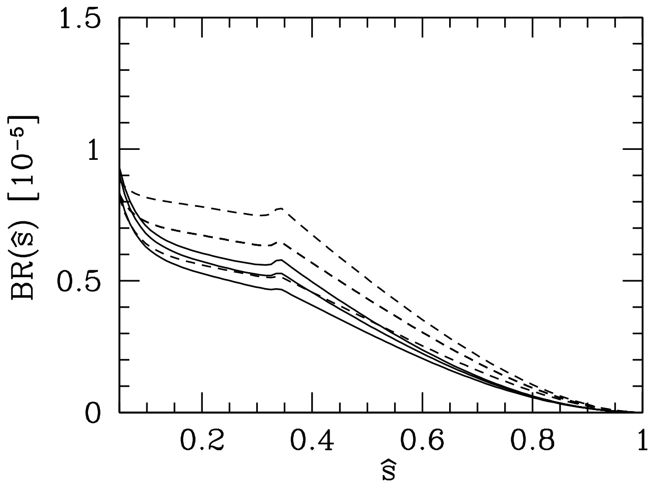
$$f_i(\hat{s}) = 1 + \frac{\mathcal{O}(\lambda_1)}{m_b^2} + \frac{\mathcal{O}(\lambda_2)}{m_b^2} \quad f_c(\hat{s}) \propto \frac{\lambda_2}{m_c^2} C_2 \left[C_9^{eff*}(2+\hat{s}) + C_7^{eff*}\frac{1+6\hat{s}-\hat{s}^2}{\hat{s}}\right]$$

left figure NLO dashed vs NNLO solid available for $\hat{s} < 0.25$

NLO $\to$ NNLO: branching ratio for $B \to X_s \ell^+\ell^-$ decreased by 12% (electrons) 20% (muons)

renorm scale $\mu = m_b/2$(lowest)$, m_b, 2m_b$





right figure partially NNLO ($F_{ij} = 0$) dashed, full NNLO solid

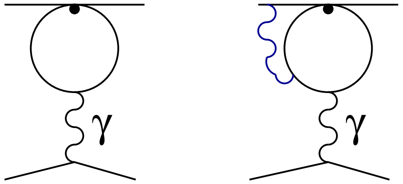
$b \to s\ell^+\ell^-$ at NNLO precision, prospects

inclusive decays @NNLO hep-ph/0112300

errors $m_b/2 < \mu < 2m_b$ $m_t^{pole} = (173.8 \pm 5)$ GeV $m_c/m_b = 0.29 \pm 0.04$

$$\mathcal{B}(B \to X_s e^+e^-)_{SM} = 6.89 \pm 0.37 \pm 0.25 \pm 0.91 \cdot 10^{-6} \quad \delta\mathcal{B}_{X_s ee} = \pm 15\%$$

$$\mathcal{B}(B \to X_s \mu^+\mu^-)_{SM} = 4.15 \pm 0.27 \pm 0.21 \pm 0.62 \cdot 10^{-6} \quad \delta\mathcal{B}_{X_s \mu\mu} = \pm 17\%$$



charm mass enters already at 1-loop

prospects at B-factories hep-ex/0112041

year	summer 2002	2005	2008
$\mathcal{L}[fb^{-1}/y]$	100	500	1000
yield $b \to s e^+e^-(\mu^+\mu^-)$	73 (57)	365 (280)	728 (565)
$\sigma(stat)[\%]$	17 (19)	7 (9)	5 (6)
$\sigma(sys)[\%]$	10 (17)	7 (12)	6 (10)

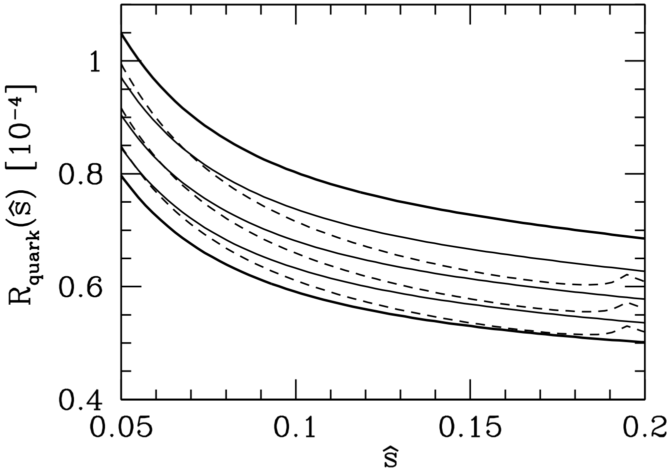
parametric dependence in rates $z = m_c/m_b$ as $\triangle(z) = \frac{\Gamma(z)-\Gamma(0.29)}{\Gamma(0.29)}$

then approx. linear $\triangle(z) \approx (0.29 - z)/0.04\ \epsilon$

	ϵ
$b \to s\ell^+\ell^-$	2%
$b \to s\gamma$	6%
$b \to c\ell^-\bar{\nu}_\ell$	16%

differences $b \to s\ell^+\ell^-$ vs $b \to s\gamma$ 1) m_c already at 1-loop 2) parametric dependence on z smaller 3) less crucial in 2002: experimental error far (~ 2005 ?) 4) richer final state: in asymmetries normalization $\Gamma(b \to c\ell^-\bar{\nu}_\ell)$ drops out

Plot of branching ratio of $b \to s\ell^+\ell^-$ from hep-ph/0204341
solid:$m_c/m_b = 0.33$ (upper most) $m_c/m_b = 0.31, 0.29, 0.27, 0.25$ in both semileptonic decays; dashed: pole mass $m_c/m_b = 0.31, 0.29, 0.27$ in Γ_{sl},$\bar{m}_c/m_b = 0.22$ in rare decay $m_c/m_b = 0.29 \pm 0.04$ conservative



exclusive $B \to K, K^*\ell^+\ell^-$ decays: normalize to life time $\delta\tau(B) = 2\%$

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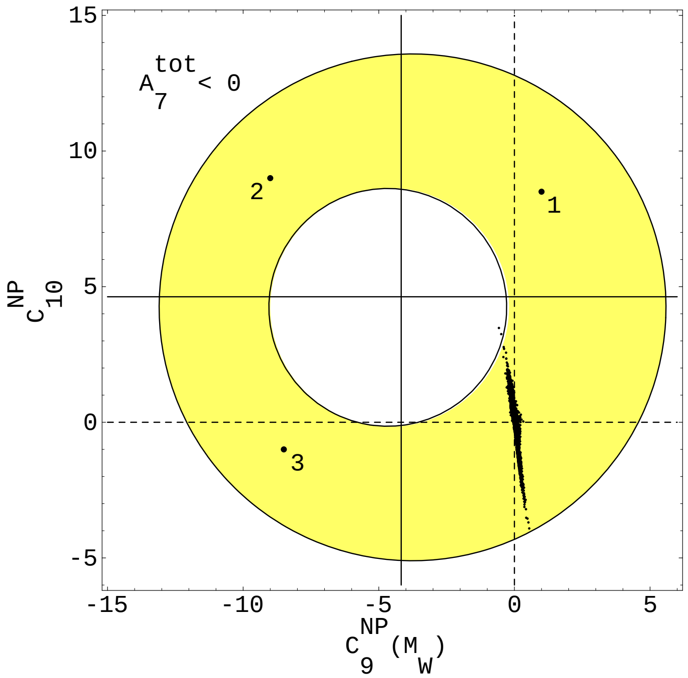
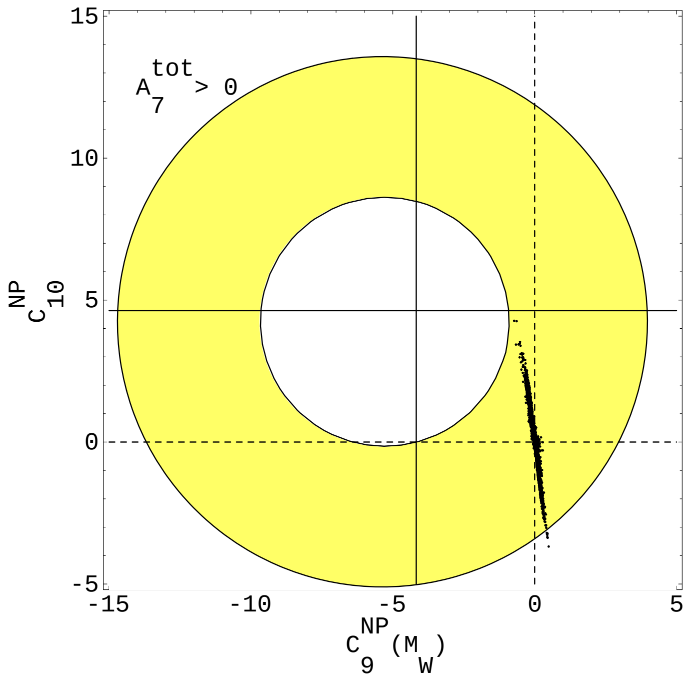
SM: $C_9(m_W) = 2.04$, $C_{10} = -4.59$, $C_7 < 0$ hep-ph/0112300

@ 90% C.L. incl data on $B \to K\mu^+\mu^-$,$B \to X_s e^+ e^-$ and $b \to s\gamma$





MSSM MFV: effects on C_9, C_{10} small, both signs of C_7 allowed

scatter plot: non MFV scenario, with up-squark mixing $\delta^U_{23,LL}, \delta^U_{23,LR}$

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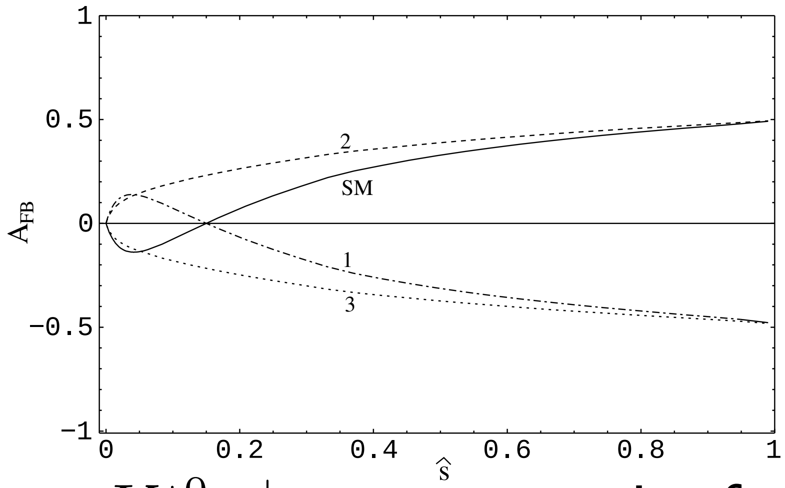
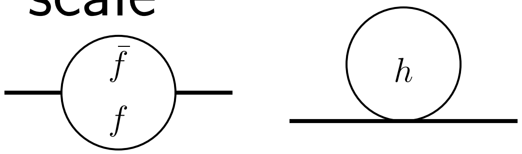
asymmetry between N(forward) and N(backward) scattered ℓ^- in dilepton CMS w.r.t. B-meson $A_{FB}(\hat{s}) \sim C_{10}\,[C_7 + \beta(\hat{s}) Re(C_9)]$

- SM or $C_7 < 0$:A_{FB} has zero in low inv mass
- $C_7 > 0$ NO zero (curve 2) e.g. MFV MSSM
- C_{10} non-SM curve 3 or 1 or flat $A_{FB}(\hat{s}) \sim 0$ possible !!



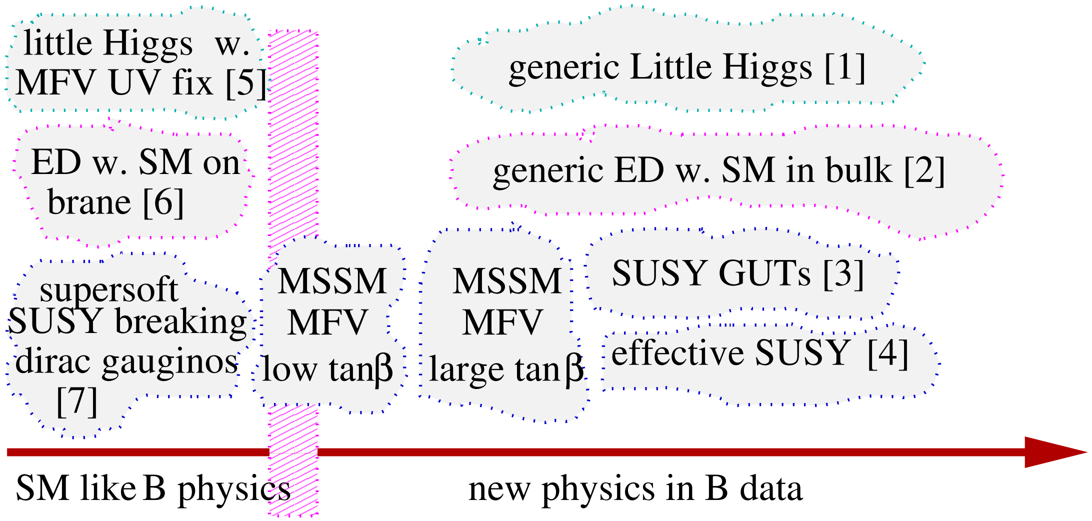
$A_{FB}(\hat{s})$ in exclusive $B \to K^{*0}\mu^+\mu^-$ opportunity for hadron colliders
yield for $2fb^{-1}$ CDF,BTeV,ATLAS, CMS, LHCb 59, 2240, 665,4200, 4500

with NP at/below the TeV scale

$\delta m_h^2 \sim$  $+ \text{gauge} \sim \frac{1}{16\pi^2}\Lambda^2$

3 major scenarios: SUSY, little Higgs (theory space), extra dimensions (ED) plus hybrids

why do we believe to see new physics in low energy signals ? minimal vs non minimal flavor violation; survey 2002



flavor/CP in models of EWK symmetry breaking

[1]Chivukula etal hep-ph/0204193 for flavor physics and fine tuning, "minimal moose for little higgs" by Arkani-Hamed etal hep-ph/0206020

[2] Delgado etal hep-ph/9911252, ED general e.g. Arkani-Hamed etal hep-ph/9803315

[3] Barbieri etal hep-ph/9504373 , Chang etal hep-ph/0205111,

[4] Cohen etal "more minimal SSM" hep-ph/9610252,Hisano etal hep-ph/0002286 , 1st+2nd generation superpartners heavy, 3rd < 1 TeV

[5] with a clever UV completion the bounds in [1] might be evaded; see ref [18] in "minimal moose for little higgs"

[6] Randall Sundrum hep-ph/9905221

[7] Fox et al hep-ph/0206096 highly degenerate susy breaking and heavy superpartners

top 10 observables beyond $\mathcal{B}(b \to s\gamma)$

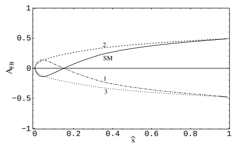
1. CP asymmetry $a_{CP}(b \to s\gamma)$; in SM direct CP violation in $b \to s$ is small: $a_{CP} = \frac{|A|^2-|\bar{A}|^2}{|A|^2+|\bar{A}|^2} \propto \alpha_s(m_b) Im \frac{V_{ub}V_{us}^*}{V_{tb}V_{ts}^*} \sim \alpha_s(m_b)\lambda^2 \lesssim \mathcal{O}(1\%)$
$a_{CP} = (-0.079 \pm 0.108 \pm 0.022)(1 \pm 0.03)$ CLEO hep-ex/0010075

2. search for wrong helicity $\bar{s}_R \sigma_{\mu\nu} b_L$ in $b \to s\gamma$; in SM small $C_7' = m_s/m_b C_7$ e.g. with polarization studies in $\Lambda_b \to \Lambda\gamma$ at Tevatron, LHC, GigaZ hep-ph/0108074

3. $|\sin 2\beta_{(J/\Psi K)} - \sin 2\beta_{(\Phi K)}|$ is $\lesssim \mathcal{O}(\lambda^2)$ in SM; direct CPX in $b \to s\bar{s}s$
$\mathcal{B}(B \to \Phi K_0)_{ave} = 8.8^{+2.7}_{-2.3} \cdot 10^{-6}$ Belle, Babar preliminary
$\sigma_{\Phi K_s}(stat) = 0.56, 0.18$ with $0.1, 1ab^{-1}$ hep-ph/0112312

4. precision study in inclusive $b \to s\ell^+\ell^-$ branching ratio at NNLO for low dilepton inv mass below $c\bar{c}$ threshold hep-ph/0112300

top 10 observables beyond $\mathcal{B}(b \to s\gamma)$



5. For-Back-asymmetry $A_{FB}(B \to (X_s, K^*)\ell^+\ell^-)$ sign/shape

6. if it exists, what is the position of the A_{FB} zero in low q^2

7. Forward-Back-CP asymmetry $A_{FB}^{CP} \equiv \frac{A_{FB}+\bar{A}_{FB}}{A_{FB}-\bar{A}_{FB}} \sim \frac{Im(C_{10})}{Re(C_{10})}$ probes non-SM CP phase in sZb vertex; in SM $A_{FB}^{CP} < 10^{-3}$ hep-ph/0006136

8. $B_s - \bar{B}_s$ mixing, Z-penguins

9. $\mathcal{B}(B_{d,s} \to \mu^+\mu^-)$, sensitive to neutral higgs exchange

10. nEDMs, strong CP problem $\bar{\Theta} < 10^{-10}, \delta_{CKM} \sim O(1)$? sensitive to flavor blind CP violation if PQ-axion solution, if spontaneously broken CP tight constraints on flavor structure hep-ph/0201251

top 100: $b \to s\nu\bar{\nu}$, $K \to \pi\nu\bar{\nu}$, $D_0 - \bar{D}_0$, leptons, neutrinos

illustration: extend SM by adding
a) symmetry b) Higgs c) matter d) gauge interactions
! drastic non-SM effect possible – in allowed parameter space

example	flip C_7	$a_{CP}^{b\to s\gamma}$	$\arg(\frac{\bar{A}}{A})_{\Phi K_S}$	C_7'	sZb	$B \to \mu^+\mu^-$
a) MSSM+MFV	!	$\lesssim 1\%$	-	$\sim \frac{m_s}{m_b}$	$\lesssim 10\%$	! large $\tan\beta$
b) 2HDM III	-	$\lesssim 1\%$	! $\lesssim 0.2(C_8)$	$\sim \frac{m_s}{m_b}$	-	-
c) VLdQ	-	$\lesssim 1\%$	! $\lesssim 0.7(U_{bs})$	$\sim \frac{m_s}{m_b}$	!	-
d) anomal. coupl.	!	!	!	!	!	!

also in last row: MSSM without R parity, MSSM with generic soft terms: "can do everything except making coffee" (Babar book)

sZb effects include C_{10}, flipping A_{FB}, $B_s - \bar{B}_s$ mixing

c) extra colored fermions $\to$ non unitarity of CKM: measure V_{ts} important

- branching ratio in $b \to s\gamma$ decays hit limit $\sigma_{exp} \lesssim \sigma_{theory}$
- next precision observable in $b \to s\ell^+\ell^-$ decays: additional and complementary information to radiative mode and collider searches
  - branching ratio at NNLO for low dilepton invariant mass
  - Forward -backward asymmetry in inclusive and exclusive $B \to K^*\ell^+\ell^-$ decays (Tevatron, LHC)
- this is just the beginning: study flavor/CP sensitive observables and do global analysis "Wilson fitter"
- with new physics at the TeV scale there is a good chance that there are plenty of indirect signals to establish this @5GeV
- potential to distinguish between models