Phenomenology of New Physics

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- *NP in low energy processes; phenomenology of flavor and CP violation*
- *pattern of NP from* $b \to s\bar{s}s$ *and* $b \to s\gamma$, $b \to s\ell^+\ell^-$, Δm_s
- *model independent analysis, status, highlights*
- $B_{d,s} \to \mu^+\mu^-$*: large signals without BSM flavor violation*
- *minimal flavor violation (MFV) as a paradigm: EFT construction*
- *summary*

enomena not part of the SM:

utrino masses $m_\nu \neq 0$, dark energy $\Omega_{DE} \lesssim 0.7$, gravity, matter
ti-matter asymmetry

estions that cannot be answered within the SM:

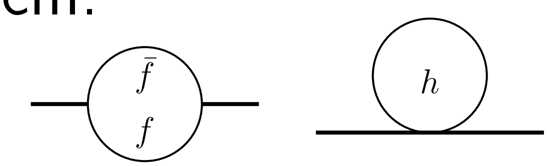
fication, origin of flavor and CP, CKM and fermion masses =
rameters of the SM (also leptonic sector)

I has problems:

strong CP, $\delta_{CKM} = \mathcal{O}(1)$ but $\bar{\Theta} \leq 10^{-10}$

gauge hierarchy problem:

$\delta m_h^2 \sim$



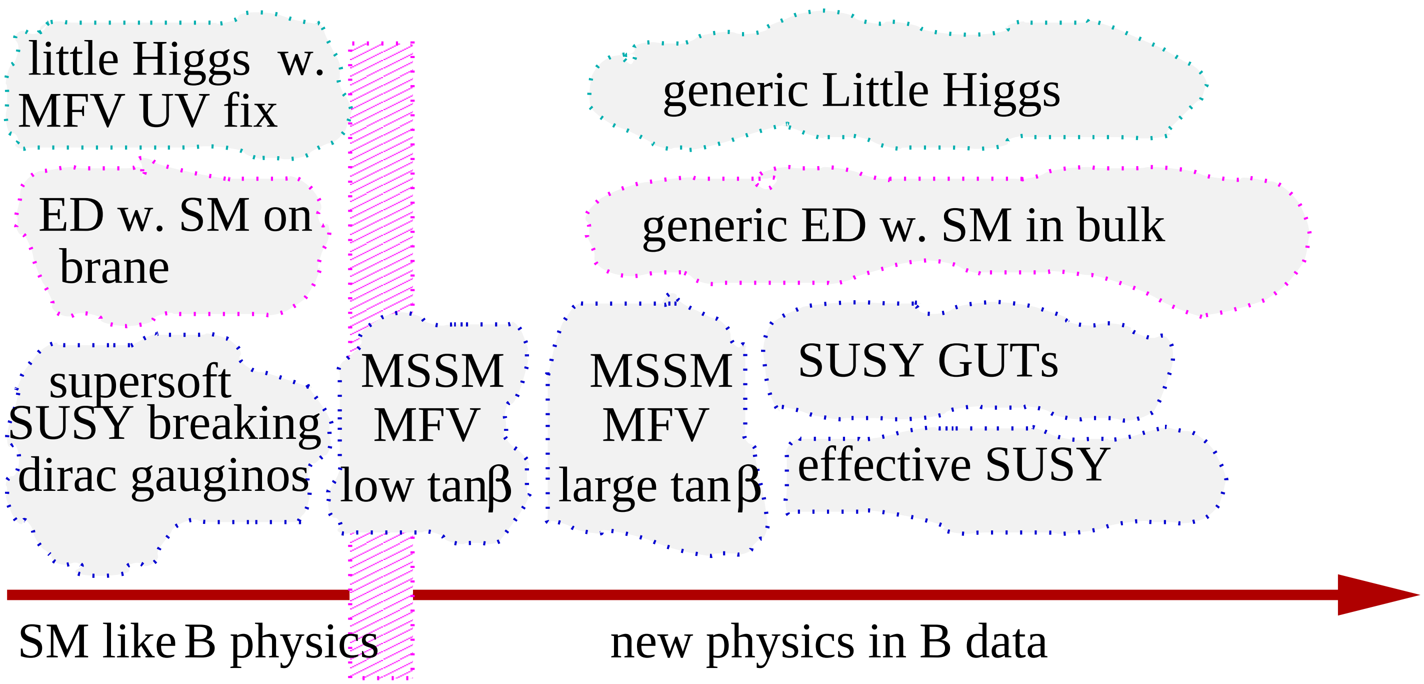
$+ \text{gauge} \quad \sim \frac{1}{16\pi^2}\Lambda^2$

SM only natural up to ~ 1 TeV; we probe higher in near future (LHC)

flavor violation in models of EWKSB

cure fine tuning problems related to m_h extend SM: SUSY, extra
nensions (ED), strong dynamics (technicolor, little Higgs) + hybrids

all of them we expect NP @ TeV, to be seen at LHC, (Tevatron) or LC



ch in indirect signals (rare b, c, K, τ-decays, mixing, EDMs, g-2)
pends on beyond-SM flavor and/or CP violation Fig from hep-ph/0207121

MFV vs non MFV

ssify NP into minimal vs non minimal flavor violation (MFV)

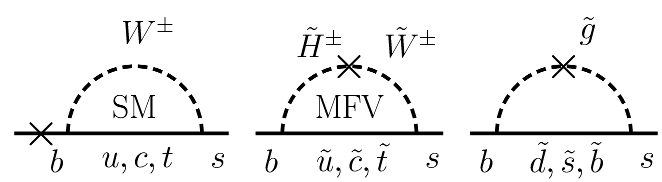
FV = no more flavor/CP violation than in SM, i.e. in Yukawas (CKM)

FV: 2HDMI, 2HDMII, MSSM w. flavor blind SUSY breaking such as
ISB (modulo small RGE effects) $A-$terms $\propto Y$, squark masses $\propto 1$

n-MFV: 2HDM III (tree level FCNC), 4th generation, VLdQ (tree level
NC to the Z), generic MSSM w/o R-parity

y different phenomenology and model building (feedback important)

ample: $b \to s\gamma, g, h^0$ in MSSM



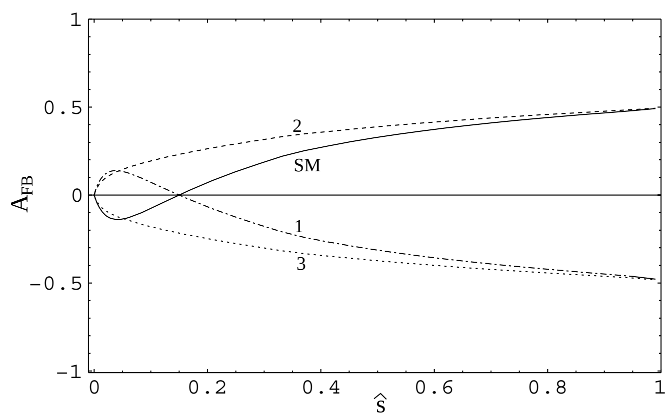
l: $A \sim V_{tb}V_{ts}^* \alpha_w m_b f(m_t/m_w)$

FV MSSM: $A \sim V_{tb}V_{ts}^* \alpha_w m_b \tan\beta g(m_{\tilde{q}}/m_{\tilde{\chi}})$ $\tan\beta$ enhanced

n-MFV MSSM: $A \sim (\delta_{23}^D)_{LR} \alpha_s m_{\tilde{g}} h(m_{\tilde{q}}/m_{\tilde{g}})$ evade CKM suppression,
$/\alpha_w$, $m_{\tilde{g}}/m_b$ enhanced + new source of CPX

smoking guns for non-MFV

- non standard CP violation, e.g. $\sin 2\beta(\Phi K_S) \neq \sin 2\beta((c\bar{c})K_S)$
- right handed currents: $C'_i \sim m_s/m_b C_i$ in MFV
- shape of Forward -Backward asymmetry $A_{FB}(B \to (X_s, K^*)\ell^+\ell^-$



curve 1,3 or flat $A_{FB}(\hat{s}) \sim 0$ possible in non MFV

curve 2 (MFV): flip sign of $C_{7\gamma}$, no zero

- no "CKM-link" among $b \to s, b \to d, s \to d$ transitions

sting 2.7σ hint for NP is non-MFV: beyond the SM CPX in $B \to \Phi K_S$

CP asymmetries in $B \to \Phi K_S$ and SM BGD

	BaBar	Belle	average	SM+MFV
ΦK_S	$-0.18 \pm 0.51 \pm 0.07$	$-0.73 \pm 0.64 \pm 0.22$	-0.38 ± 0.41	$\sin 2\beta + \mathcal{O}(\lambda^2)$
ΦK_S	$-0.80 \pm 0.38 \pm 0.12$	$+0.56 \pm 0.41 \pm 0.16$	-0.19 ± 0.30	$\mathcal{O}(\lambda^2)$

$2\beta_{worldave} = +0.734 \pm 0.054$ $\quad \sin 2\beta_{UTfit} = +0.74 \pm 0.10$ @95%C.L.

$_{P}(B^\pm \to \Phi K^\pm) = 0.039 \pm 0.086 \pm 0.011$ BaBar hep-ph/0303029

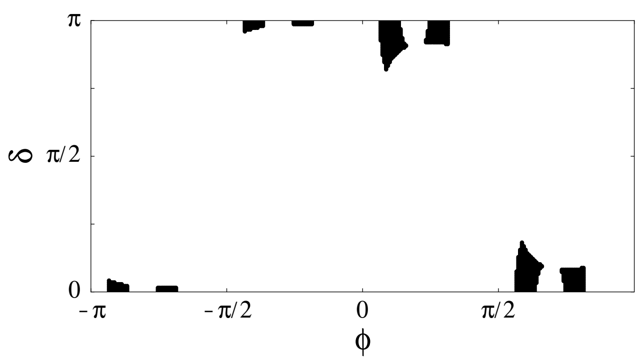
loop maybe enhanced ? $\quad |\sin 2\beta(\Phi K_S) - \sin 2\beta| \leq 2 \cos 2\beta |\xi_{\Phi K^0}|$

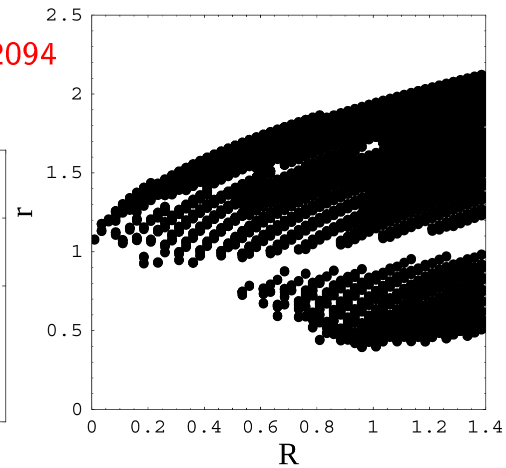
(3) analysis + data: $|\xi_{\Phi K^0}| \leq 0.25$ assuming $|\xi_{\Phi K^0}| \leq |\xi_{\Phi K^+}|$ hep-ph/0303171

und can be experimentally improved and be made independent of the n-cancellation assumption of large amplitudes (branching ratios of $\to \Phi \pi^+$,$B^+ \to \bar{K}^{*0} K^+$ for $|\xi_{\Phi K^+}|$ and 11 Br's for $|\xi_{\Phi K^0}|$)

NP explanations of $\sin 2\beta(\Phi K_S)$

$= Br(B \to \Phi K^0)/Br(B \to \Phi K^0)^{SM}$ $r = A_{NP}/A_{SM}$; δ, Φ, rel. strong,
ak phase left fig: $R = 1$ Figs from hep-ph/0302094





rrent central value $S_{\Phi K_S}$ needs $O(1)$ NP amplitude with $O(1)$ CP phase

$\sim C_3 + C_4 + C_5 + \frac{C_3+C_4+C_6}{N_C} - \frac{1}{2}(C_7 + C_9 + C_{10} + \frac{C_8+C_9+C_{10}}{N_C}) + \kappa_2 C_2 + \kappa_8 C_{8g} + C_i'$

non factorizable corrections

? in QCD $C_{3,\ldots 6}$ EWK penguins $C_{7,\ldots 10}$ and/or gluon dipole C_{8g}

planations: RPV, LR-Symm, gluino-down squark loops, Z-penguins

ep-ph/0207356,0208016, 0208226,0208091, 0212092, 0212180, 0212397; not possible with 2HDMIII

non standard FCNC Z-couplings

n SM sZb couplings arise in models with vector like down quarks, 4th neration, non-MFV SUSY, anomalous couplings, Z',..

$$= \frac{g^2}{4\pi^2} \frac{g}{2\cos\Theta_W} (\bar{b}_L \gamma_\mu s_L Z_{sb} + \bar{b}_R \gamma_\mu s_R Z'_{sb}) Z^\mu + h.c.$$

odify $C^{(*)}_{3,7,9}$ 4-Fermi operators in $b \to s\bar{s}s$ decays

m $B \to X_s e^+ e^-$, $b \to s\gamma$ data @ 90% C.L. and NNLO theory

$$\overline{Z_{sb} + Z^{SM}_{sb}|^2 + |Z'_{sb}|^2} \leq 0.08 \qquad Z^{SM*}_{sb} = -V_{tb}V^*_{ts} \sin^2\Theta_w C^{SM}_{10\ell} \simeq -0.04$$

$^{)}_{b}$ large and complex can explain anomaly in $B \to \Phi K_S$ hep-ph/0207356

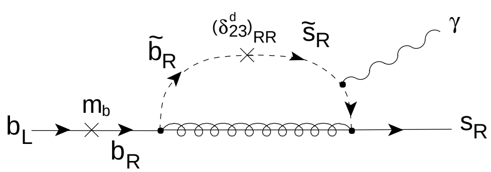
plications:

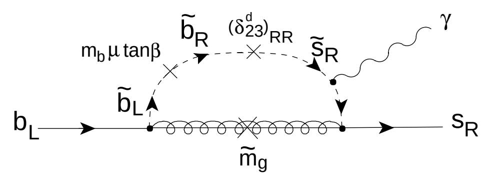
lepton sprectra, A_{FB} shape in $b \to s\ell^+\ell^-$, $b \to s\nu\bar{\nu}$ branching ratio

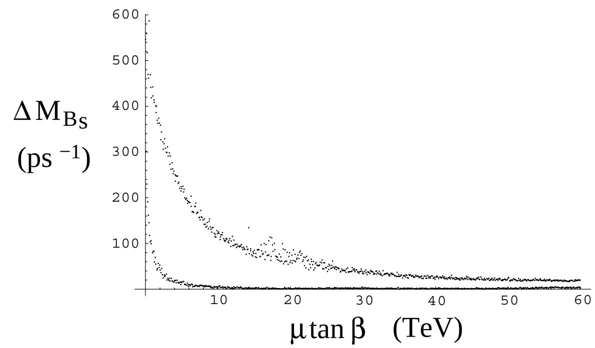
duce non-zero Forward-Back-CP asymmetry $A^{CP}_{FB} \equiv \frac{A_{FB}+\bar{A}_{FB}}{A_{FB}-\bar{A}_{FB}} \sim \frac{Im(C_{10\ell})}{Re(C_{10\ell})}$

obes phase in sZb vertex; in SM $A^{CP}_{FB} < 10^{-3}$ hep-ph/0006136

ge $\nu_\mu - \nu_\tau$ mixing in $SO(10)$ GUT models implies large mixing between
ht handed $\tilde{s} - \tilde{b}$: $(\delta^D_{23})_{RR}$ large and complex Figs from hep-ph/0212180







odifies (flipped) $C'_{3\ldots6}$ and C'_{8g}

oid $\mathcal{B}(b \to s\gamma)$ enhancement by $m_{\tilde{g}} \ll m_{\tilde{q}}$

plications:

Δm_s can be huge $\sim 100\, ps^{-1}$ (range in right fig)

rge RH currents: wrong helicity contributions to $b \to s\gamma$, i.e. in $C'_{7\gamma}$

$C'_{7\gamma}(\mu_b)| \lesssim 0.4|C_{7\gamma}(\mu_b)|$

nly flipped $C'_{7\gamma,8g,\ldots}$ have NP phase, direct CPX in $b \to s\gamma$ SM like

model correlations

	Z-penguins	MSSM with $(\delta_{23}^D)_{RR}$
, $A_{FB}(b \to s\ell^+\ell^-)$	$\mathcal{O}(1)$	SM like
$\mathcal{B}(B_s \to \mu^+\mu^-)$	$\mathcal{O}(10) \cdot \mathcal{B}_{SM}$	$\mathcal{B}_{exp.\ bound} \sim \mathcal{O}(10^3) \cdot \mathcal{B}_{SM}$*
Δm_s	up to $0.5 \cdot \Delta m_{s\ SM}$	$\approx \Delta m_{s\ SM} \ldots$ few $100\ ps^{-1}$
$\to s\gamma$ helicity flip	SM like $\lvert C'_{7\gamma}/C_{7\gamma}\rvert \simeq m_s/m_b$	$\lvert C'_{7\gamma}/C_{7\gamma}\rvert \leq 0.4$
$a_{CP}(b \to s\gamma)$	SM like	SM like

r large $\tan\beta$ constraints on $(\delta_{23}^D)_{RR}$ by $\mathcal{B}(B_s \to \mu^+\mu^-)$ hep-ph/0208159

o correlations with

$B \to (c\bar{c})K$ decays; $C_{8g}^{(\prime)}$ is color octet suppressed

$B_s \to (c\bar{c})\Phi$, $B_s \to \Phi\Phi$ decays

NP in the golden $b \to c\bar{c}s$ modes

1) NP in $b \to s\bar{s}s$ implies $\sim 10\%$ in $b \to c\bar{c}s$; within errors of UT fit

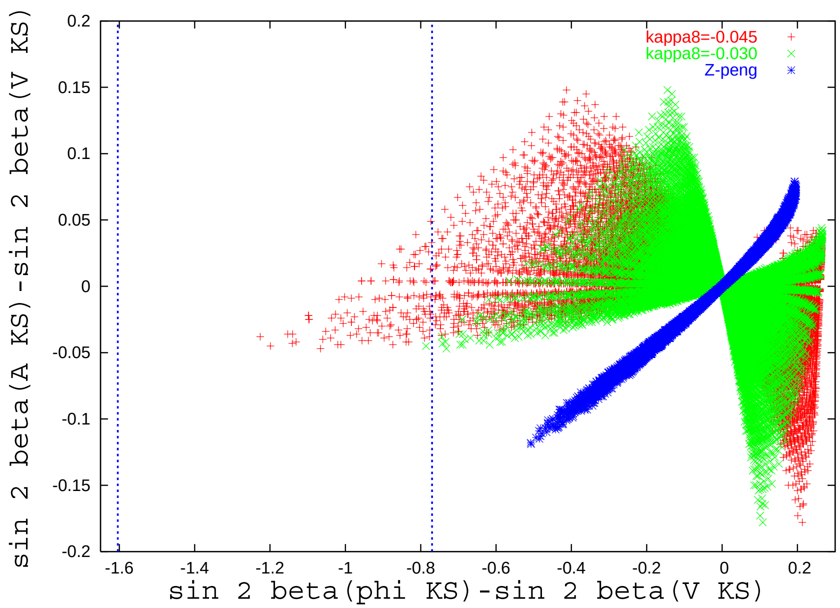
$$n\,2\beta(c\bar{c}K) - \sin 2\beta| \lesssim \arg(P/T)|P/T|$$

' effect is split among final states with same flavor content but different

quantum numbers $\sin 2\beta(AK_S) - \sin 2\beta(VK_S) = -0.05 \pm 0.26$ BaBar'02

$= J/\Psi, \Psi'$

$= \chi_1, \eta_c$



tinguish NP in dipole from 4-Fermi; independent of improvement in UT

$\epsilon(\sin 2\beta)_{worldave} = 7\%$ $\epsilon(\sin 2\beta)_{UTfit} = 14\%$ LMU 09/03 D.Atwood,G.H.

model independent analysis/points of interest

operator	magnitude	phase	$L \leftrightarrow R$ in $\bar{s}\Gamma b$
$O_{7\gamma} \sim \bar{s}_L \sigma_{\mu\nu} b_R F^{\mu\nu}$	$b \to s\gamma$	$a_{CP}(b \to s\gamma)$	$\Lambda_b \to \Lambda\gamma$ $B \to (K^* \to K\pi)\ell^+\ell^-$ $B \to (K^{**} \to K\pi\pi)\gamma$
$O_{8g} \sim \bar{s}_L \sigma_{\mu\nu} b_R G^{\mu\nu}$	$b \to s\gamma$ $B \to \not{X}_c +$ theory	$a_{CP}(b \to s\gamma)$ $B \to K\Phi$	$\Lambda_b \to \Lambda\Phi$ $B \to K^*\Phi$
$O_{9,10\ell} \sim \bar{s}_L \gamma_\mu b_L \bar{\ell} \gamma^\mu (\gamma_5) \ell$	$b \to s e^+ e^-$	$A_{FB}(b \to s\ell^+\ell^-)$	$B \to (K^* \to K\pi)\ell^+\ell^-$
$O_{S,P} \sim \bar{s}_L b_R \bar{\ell}(\gamma_5)\ell$	$B_{d,s} \to \mu^+\mu^-$	$B_{d,s} \to \tau^+\tau^-$	$b \to s\tau^+\tau^-$

- test 4-quark operators in hadronic decays, CP-asymmetries cleaner than rates; isospin asymmetry in $B \to K^*\gamma$ hep-ph/0110078

  $\Delta_{0-\ SM}^{QCDfac} = 8.0^{+2.1}_{-3.2}\% \times 0.3/F_{K^*}$ $\mathrm{sign}\Delta_{0-} = \mathrm{sign}(\mathrm{ReC}_6/\mathrm{C}_{7\gamma})$

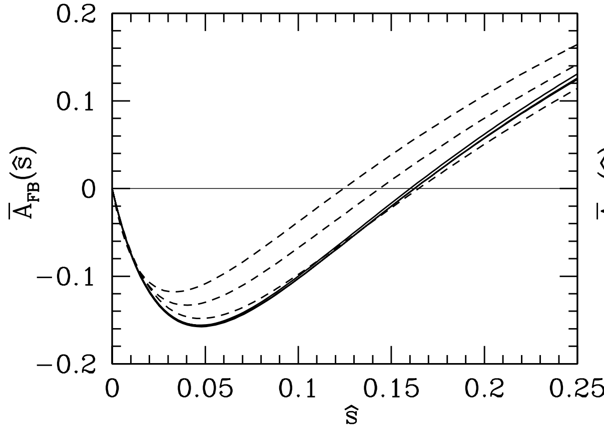
  $\Delta_{0-}^{data} = 0.005 \pm 0.05$

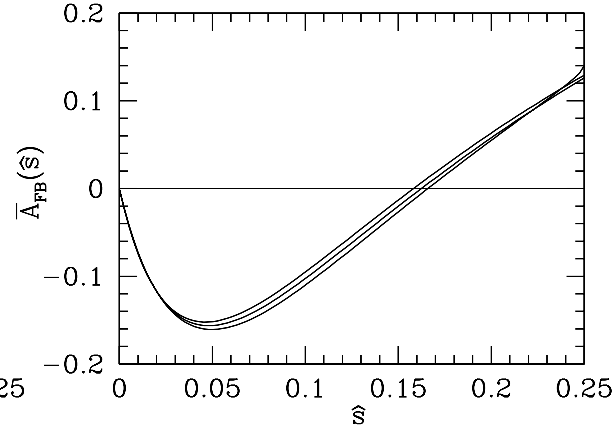
- RH currents, angular analysis in $B \to (K^* \to K\pi)\ell^+\ell^-$ hep-ph/9907386

model independent analysis/points of interest

- $b \to s\ell^+\ell^-$ @ NNLO $\qquad A_{FB}(\hat{s}) \sim \mathrm{Re}\,(C^*_{10\ell}\,[C_{7\gamma} + \beta(\hat{s})C_{9\ell}])$

  A_{FB} has zero in SM $\quad \hat{s}_{SM}^{NNLL} = 0.162 \pm 0.002(8)$ hep-ph/0208088,0209006





left fig NNLO (solid) vs NLO (dashed) for $\mu = m_b/2, m_b, 2m_b$, $m_c/m_b = 0.29$ right fig NNLO $\mu = m_b$, $m_c/m_b = 0.29 \pm 0.04$

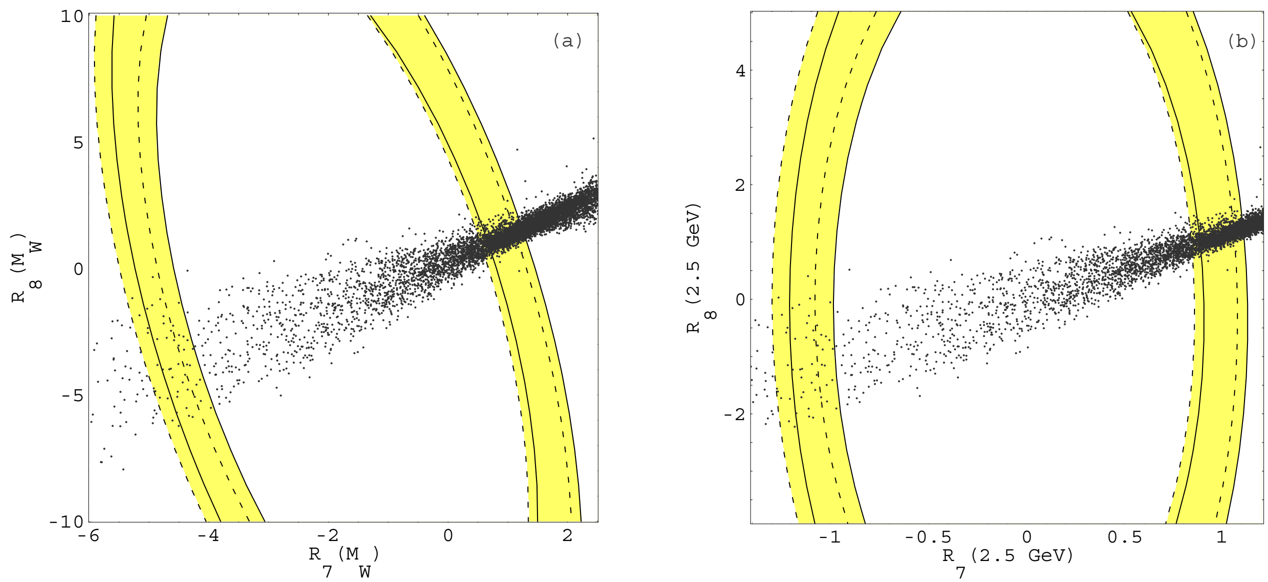
Figs from hep-ph/0209006

- $B \to X_s \nu\bar{\nu}$ very clean, biggest uncertainty $\delta\Gamma_{SM} = 6\%$ from m_t
- $C_{S,P}^{SM} \sim m_\ell m_b/m_W^2$ very small even for τ, large in MFV MSSM

constraints from $b \to s\gamma$ branching ratio

$_\gamma \propto \bar{s}_L \sigma_{\mu\nu} b_R F^{\mu\nu}$ $O_{8g} \propto \bar{s}_L \sigma_{\mu\nu} b_R G^{\mu\nu}$ $\mathcal{B}(b \to s\gamma)_{LO} \sim |C_{7\gamma}(m_b)|^2$

$\mu) \equiv \frac{C^{SM}(\mu)+C^{NP}(\mu)}{C^{SM}(\mu)}$ NLO @90%C.L. $|R_{8g}(m_W)| \leq 10$ Figs from hep-ph/0112300



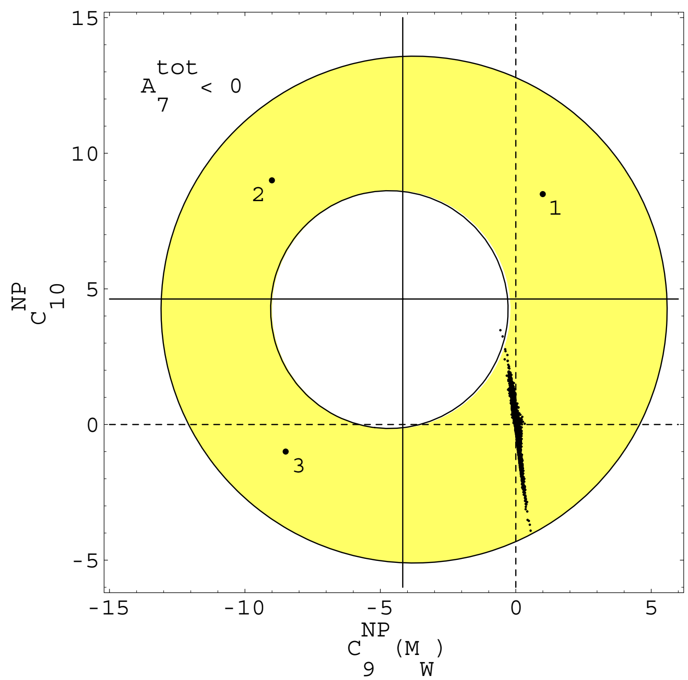
tter plot: MFV MSSM reach, both signs of $C_{7\gamma}$ allowed

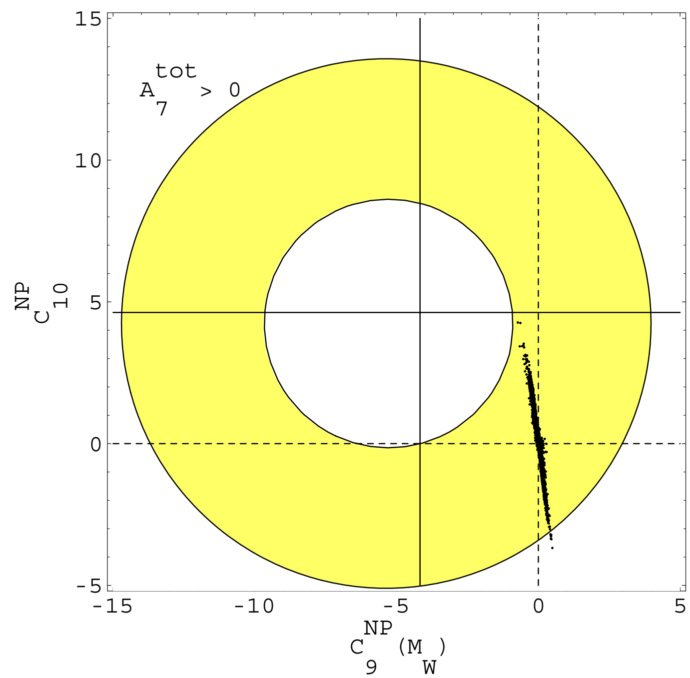
eory errors μ and charm mass solid:pole, dashed:$\overline{\text{MS}}$ prospects: 2005

factories have $500 fb^{-1}$, $\sigma(stat, sys)_{b \to s\gamma} = 1.8\%, 3\%$ hep-ex/0112041

$_\ell \propto \bar{s}_L\gamma_\mu b_L\bar{\ell}\gamma^\mu\ell$ $\quad O_{10\ell} \propto \bar{s}_L\gamma_\mu b_L\bar{\ell}\gamma^\mu\gamma_5\ell$ NNLO @ 90% C.L.

l data on $B \to K\mu^+\mu^-$, $B \to X_s e^+e^-$, $b \to s\gamma$ Figs from hep-ph/0112300





und on sZb-penguins $\sim C_{10\ell}$, impact on $b \to s\bar{q}q, b \to s\bar{\nu}\nu$

SSM MFV: effects on $C_{9\ell}, C_{10\ell}$ small, $R_{9,10\ell}(m_W) \lesssim 20\%$

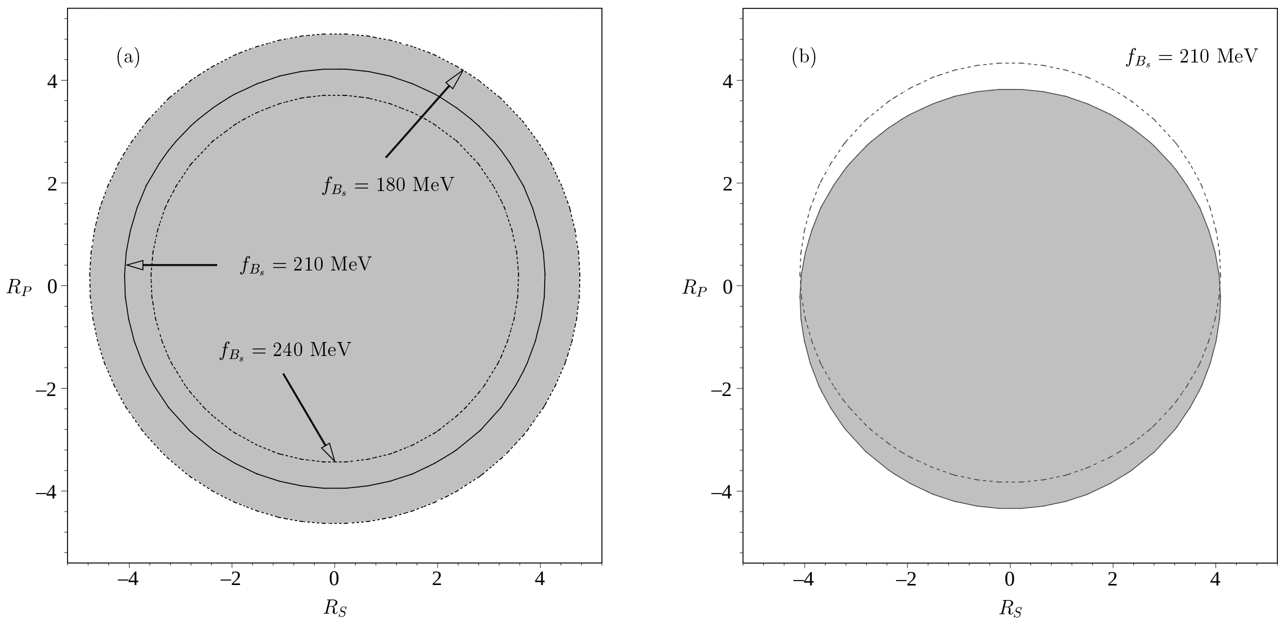
tter plot: non MFV scenario with up-squark mixing $(\delta^U_{23})_{LL}, (\delta^U_{23})_{LR}$

icity suppressed in SM

$B_s \to \ell^+\ell^-) \sim |V_{tb}V_{ts}^*|^2 f_{Bs}^2(|m_\ell/m_{B_s}C_{10\ell} + C_P/2|^2 + |C_S/2|^2)$

$\propto \bar{s}_L b_R \bar{\ell}\ell \qquad O_P \propto \bar{s}_L b_R \bar{\ell}\gamma_5\ell$

$_{,P}$ Wilson coefficients at $\mu = m_b$ Figs from hep-ph/0104284

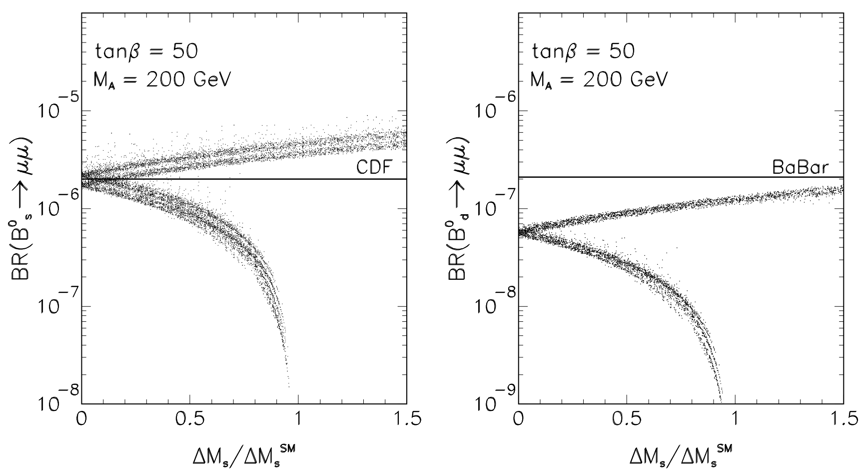


t fig theory error f_{Bs} right fig for $R_{10\ell} = -2$ (solid), $+2$ (dashed)

impact of $B_{d,s} \to \mu^+\mu^-$

mode	90%C.L. bounds	SM branching ratio	upper bound MSSM MFV*
$_s \to \mu^+\mu^-$	$2.0 \cdot 10^{-6}$ CDF	$(3.2 \pm 1.5) \cdot 10^{-9}$	$8 \cdot 10^{-7}$
$_d \to \mu^+\mu^-$	$2.0 \cdot 10^{-7}$ BaBar	$\mathcal{O}(10^{-10})$	$2 \cdot 10^{-8}$

β^3 enhanced in MSSM, can saturate exp. bounds; correlation with
$- \bar{B}_s$ mixing in MFV MSSM   *for $\Delta m_s^{SM} \leq 21.0 ps^{-1}$ Figs from hep-ph/0207241



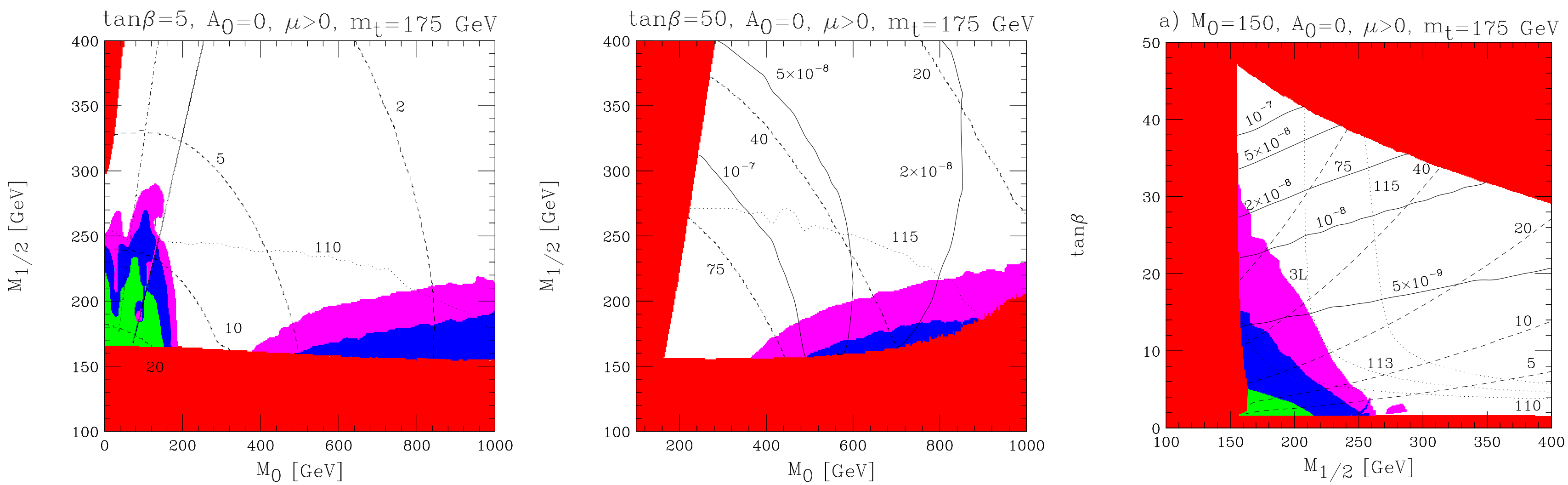
$B_{d,s} \to \mu^+\mu^-$) and Δm_s cannot be both enhanced in MSSM MFV

$B_d \to \mu^+\mu^-)/\mathcal{B}(B_s \to \mu^+\mu^-) = |V_{td}/V_{ts}|^2$ in MFV

M relation broken in non-MFV $O(1)$ possible

$B_s \to \mu^+\mu^-$ complements direct mSUGRA searches

from hep-ph/0207026



vatron 5σ trilepton reach $30 fb^{-1}$ $10 fb^{-1}$ $2 fb^{-1}$

id: $\mathcal{B}(B_s \to \mu^+\mu^-)$ dotted: δa_μ in 10^{-10} dashed: m_h

F can discover $B_s \to \mu^+\mu^-$ with $15 fb^{-1}$ if $\mathcal{B}(B_s \to \mu^+\mu^-) \geq 1.2 \cdot 10^{-8}$

$M_{1/2} \lesssim 250\text{GeV} - 70\text{GeV} \tan\beta/23$

e decay: $M_{1/2} \lesssim 19\text{GeV} \tan\beta - 260\text{GeV}$ for $\tan\beta > 32$

MFV effective field theories

l is EFT valid up to cut-off $\Lambda =$ scale of NP $\mathcal{L} = \mathcal{L}_{SM} + \sum_i \mathcal{O}_i^{(n)}/\Lambda^n$

$Y_u = Y_d = Y_\ell = 0$ the SM i.e. $\mathcal{L}_{SM}^{gauge}$ has $G_F = U(3)^5$ symmetry

ume G_F is exact and only broken by Yukawas $Y \simeq <\varphi>$

T is MFV if all $\mathcal{O}_i^{(n)}$ from SM and "Y" fields are invariant under G_F

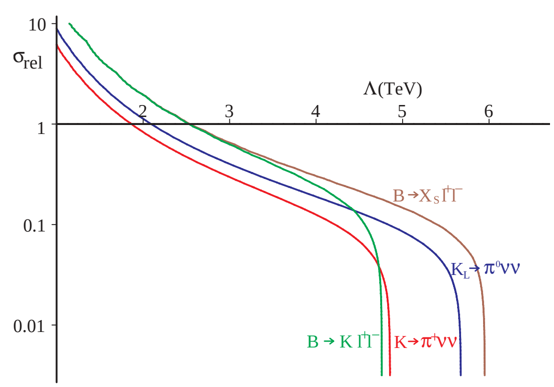
l if theory gets strongly coupled at Λ

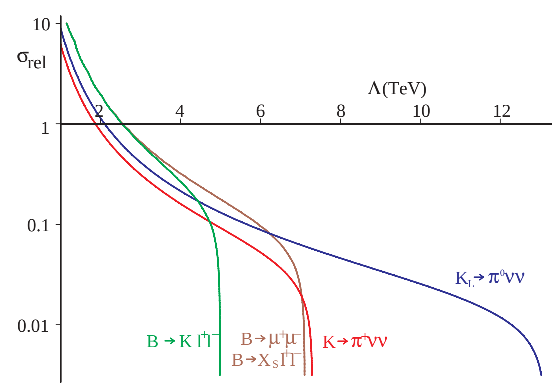
unds from meson mixing: $\Lambda \gtrsim \mathcal{O}(100)$ TeV in general non MFV case

$\gtrsim$ few TeV in MFV (with 1 Higgs); similar to EWK precision data

ch with 10% (left) 1% (right) CKM factor uncertainty for data w. σ_{rel}

hep-ph/0207036





summary

- because of unstable Higgs mass in the SM we expect to see NP @ TeV
- impact on low energy observables depends on amount of flavor/CP violation, presence of large parameters, particle spectrum and errors
- drastic $\mathcal{O}(1)$ signals in non-MFV possible: time dependent CP asymmetries, $A_{FB}(B \to (X_s, K^*)\ell^+\ell^-)$, $a_{CP}(b \to s\gamma)$...

  this is very complementary to direct collider searches which are flavor diagonal; search for surprises in "SM-zero" observables: $C'_{7\gamma}$ large (e.g. baryon polarization $\Lambda_b \to \Lambda\gamma$), $\sin 2\beta(c\bar{c}_A K) - \sin 2\beta(c\bar{c}_V K)$
- MFV large effects in helicity flip operators $\bar{f}'_{L(R)}\Gamma f_{R(L)}$ at large $\tan\beta$, e.g. $\mathcal{B}(B_{d,s} \to \mu^+\mu^-)$, $C_{7\gamma}$ flips sign (A_{FB}); many correlations among different processes; precision long term study in $b \to s\ell^+\ell^-, \nu\bar{\nu}$, $s \to d\ell^+\ell^-, \nu\bar{\nu}$ promising

summary

- NP with MFV or not has very different model building; experiments with rare processes can distinguish them – pre LHC

ack up slides

$\sin 2\beta(\eta' K_S)$ and $\sin 2\beta((K^+K^-)_{CP+} K_S)$

	BaBar	Belle	average
$S_{\eta' K_S}$	$+0.02 \pm 0.34 \pm 0.03$	$+0.71 \pm 0.37^{+0.05}_{-0.06}$	$+0.33 \pm 0.25$
$C_{\eta' K_S}$	$+0.10 \pm 0.22 \pm 0.03$	$-0.26 \pm 0.22 \pm 0.03$	-0.08 ± 0.16
$S_{(K^+K^-)_+ K_S}$		$+0.49 \pm 0.43 \pm 0.11^{+0.33}_{-0.00}$	
$C_{(K^+K^-)_+ K_S}$		$+0.40 \pm 0.33 \pm 0.10^{+0.00}_{-0.26}$	

$_P(B^\pm \to \eta' K^\pm) = 0.037 \pm 0.045 \pm 0.011$ BaBar hep-ph/0303029

K^+K^- have 2nd weak amplitude from $u\bar{u}$ at tree level –unlike Φ

(3)+data: $|\xi_{\eta' K^0}| \leq 0.36$ (≤ 0.09 if $|\xi_{\eta' K^0}| \leq |\xi_{\eta' K^+}|$ leading color)

$_{+K^- K^0}| \sim 0.13$ hep-ph/0303171 $0.2 \leq -S_{(K^+K^-)_+ K_S} \leq 1$ hep-ph/0304178 (I,U-spin)

$b \to s\ell^+\ell^-$ status

⋆ 2001 first observation of exclusive decay ⋆⋆⋆

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

$B \to K\ell^+\ell^-) = 0.58^{+0.17}_{-0.15} \pm 0.06 \cdot 10^{-6}$ Belle prelim. ICHEP 2002

$B \to K\ell^+\ell^-) = 0.78^{+0.24+0.11}_{-0.20-0.18} \cdot 10^{-6}$ BaBar prelim. ICHEP 2002

$B \to K^*\mu^+\mu^-)_{SM} = 1.19 \pm 0.39 \cdot 10^{-6}$ NNLO hep-ph/0112300

$B \to K^*e^+e^-)_{SM} = 1.58 \pm 0.49 \cdot 10^{-6}$ NNLO hep-ph/0112300

$B \to K^*\ell^+\ell^-) < 1.4 \cdot 10^{-6}$ @ 90%C.L. Belle prelim. ICHEP 2002

$B \to K^*\ell^+\ell^-) < 3.0 \cdot 10^{-6}$ @ 90%C.L. BaBar prelim. ICHEP 2002

inclusive mode	Br_{exp} Belle prelim'02	signif.	Br_{SM} hep-ph/0112300
$B \to X_s\mu^+\mu^-$	$7.9 \pm 2.1^{+2.0}_{-1.5} \cdot 10^{-6}$	4.7σ	$4.15 \pm 0.70 \cdot 10^{-6}$
$B \to X_s e^+e^-$	$5.0 \pm 2.3^{+1.2}_{-1.1} \cdot 10^{-6}$	3.4σ	$6.89 \pm 1.01 \cdot 10^{-6}$
$B \to X_s\ell^+\ell^-$	$6.1 \pm 1.4^{+1.3}_{-1.1} \cdot 10^{-6}$	5.4σ	