New Physics Searches in b-Physics

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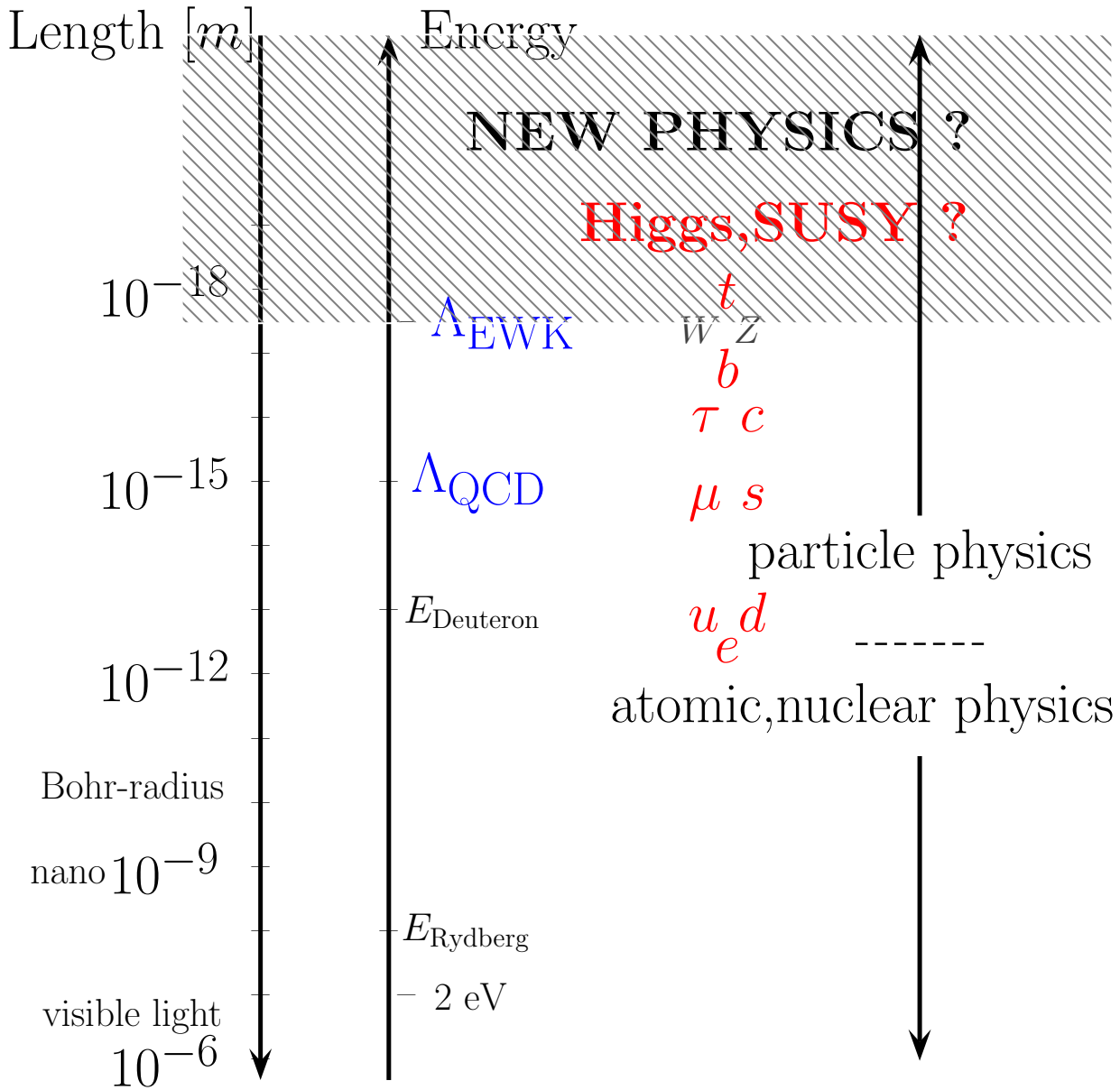
"Where are we in penguin physics and what's next ?
Implications for beyond-the-SM Physics"

SM=Standard Model, NP=New Physics, EWKSB=electroweak symmetry breaking, FCNC=Flavor changing neutral currents

High energy physics



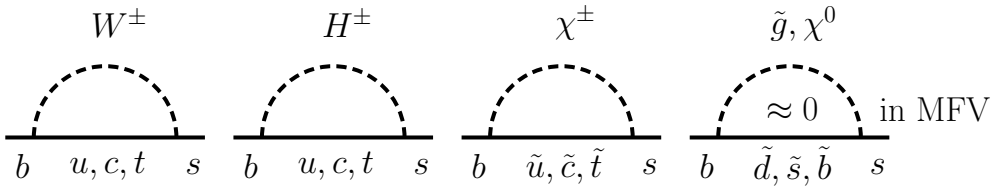
SM tests with indirect processes

indirect loop processes: $\Lambda \gtrsim m_W$ scale of New Physics

$$\mathcal{L}_{eff} = \sum_i c_i^{(n)} \frac{O_i^{(n)}}{\Lambda^n} \qquad c_i^{(n)} \leftrightarrow f(\underbrace{m_j, g_l, \ldots}_{colliders}; \underbrace{\varphi_{\rm CKM}, \varphi_m, \delta_n}_{flavorphysics})$$

no competition from large SM tree contributions

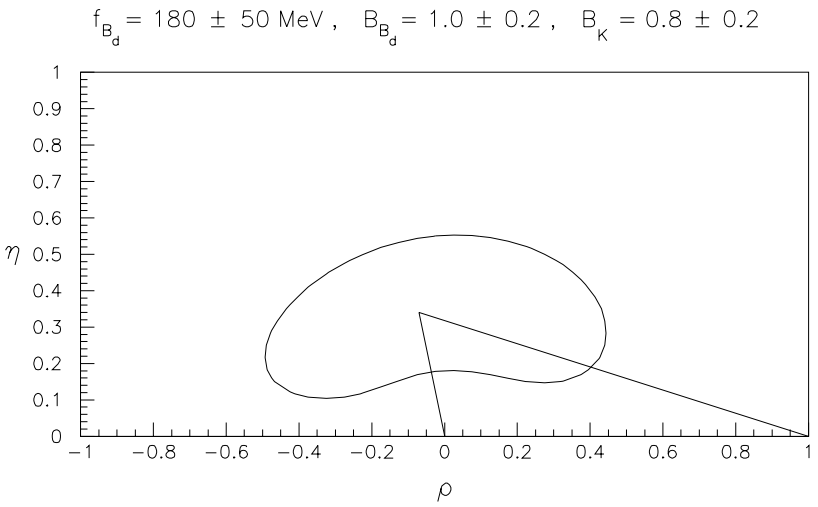
FCNC: sensitivity to SM, NP phases φ, flavor-breaking couplings δ

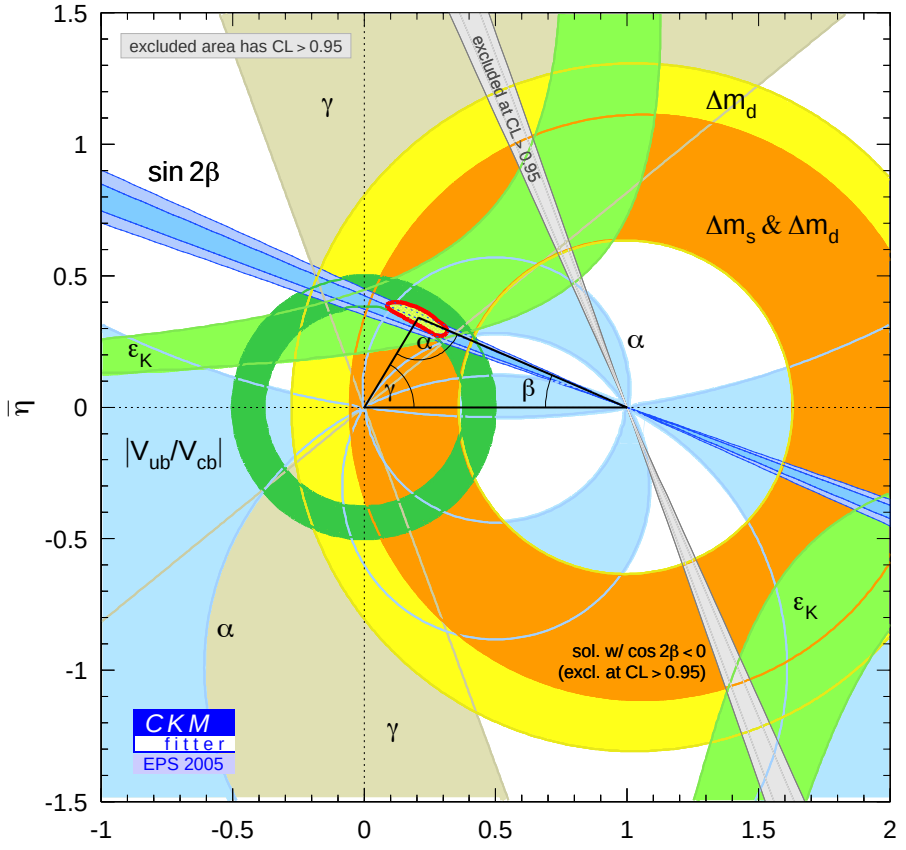


MFV $=$ no more flavor/CP violation than in SM, i.e. in Yukawas

(CKM) $U(3)^5$ symmetry only broken by "Y" spurions; RG-invariant

CKM 1995: ϵ_K, Δm_d, $|V_{ub}/V_{cb}|$, $|V_{cb}|$, λ hep-ph/9508272



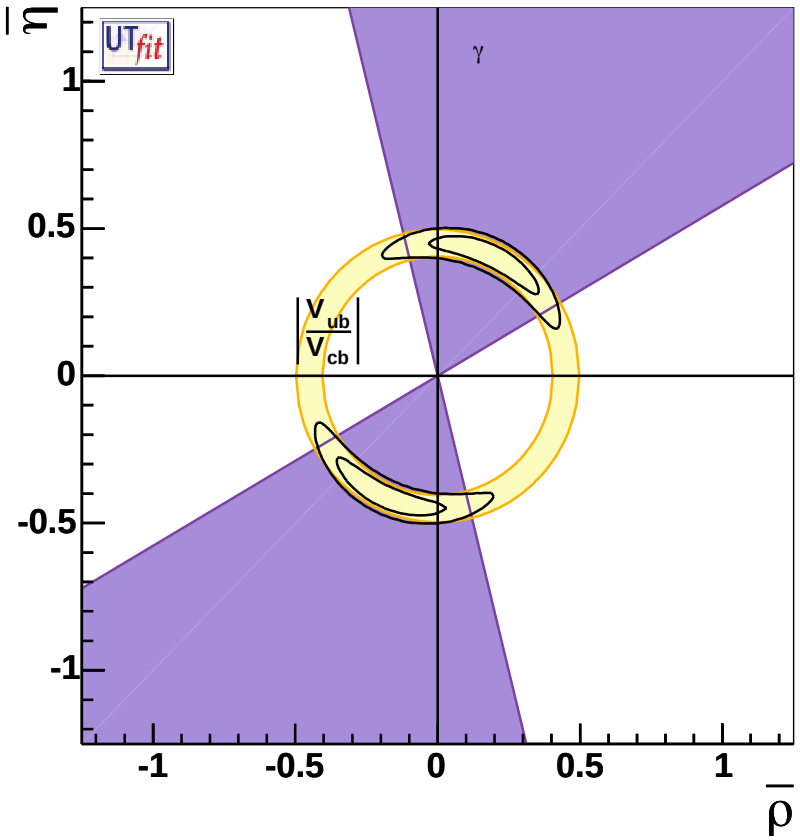


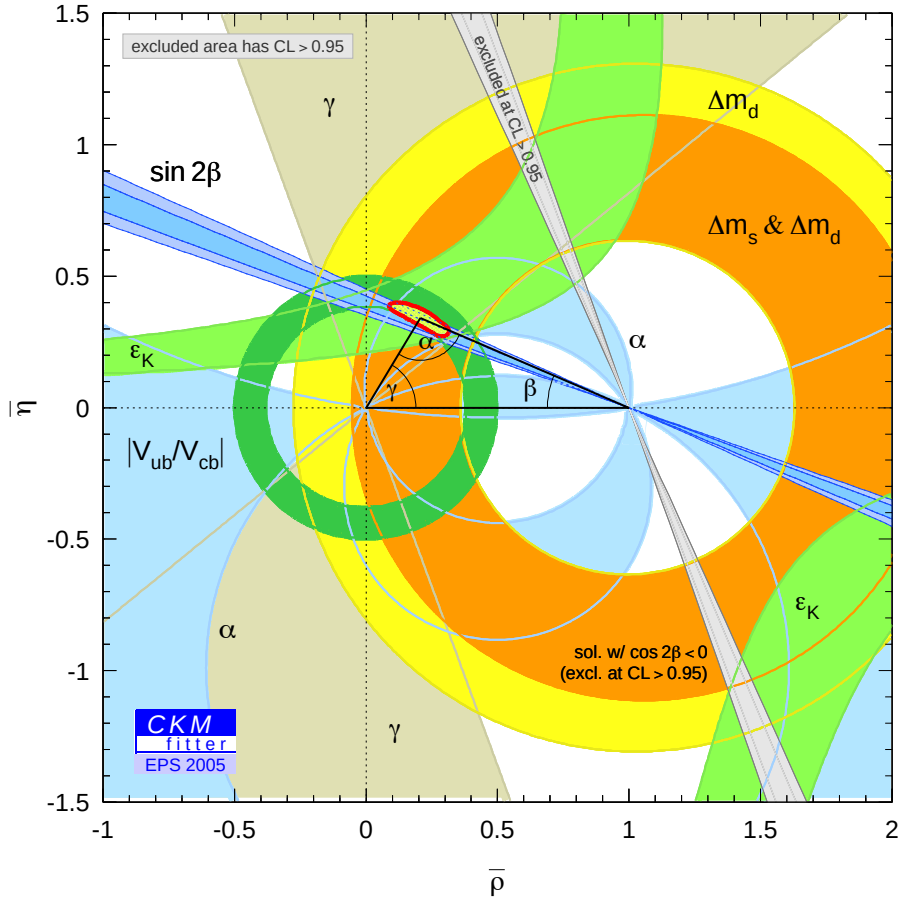
2005: SM (MFV)-like picture

at least for $b \to \bar{c}cs$, K-,B_d-mixing

CKM=precision input within MFV $\epsilon(\alpha) = 6\%, \epsilon(\beta) = 4\%, \epsilon(\gamma) = 10\%$

2005: first unitarity triangle from tree level





tree fit V_{ub}, $\gamma(DK)$: $\sin 2\beta_{tree-fit} = 0.782 \pm 0.065$ hep-ph/0509219

loop input to full fit: meson mixing, $\sin 2\beta(\bar{c}c)_{data-ave} = 0.687 \pm 0.032$

$|V_{ub}|$ too big for $\sin 2\beta(\bar{c}c)$; iff persists: NP in mixing or $b \to \bar{c}cs$ decays

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

$$A(b \to \bar{c}cs) = V_{cb}V_{cs}^*(T - P) + V_{ub}V_{us}^*(T_u - P)$$

SM: perturbative ($\bar{u}u$-loop) phase: $\sim \frac{\alpha_s}{4\pi}\frac{V_{ub}V_{us}^*}{V_{cb}V_{cs}^*} \sim 10^{-3}$ hep-ph/0403085

$J/\Psi\pi^0$ data, $SU(3)^*$: $\sin 2\beta(J/\Psi K^0) - \sin 2\beta_{\rm mix} = 0 \pm 0.017$ hep-ph/0507290

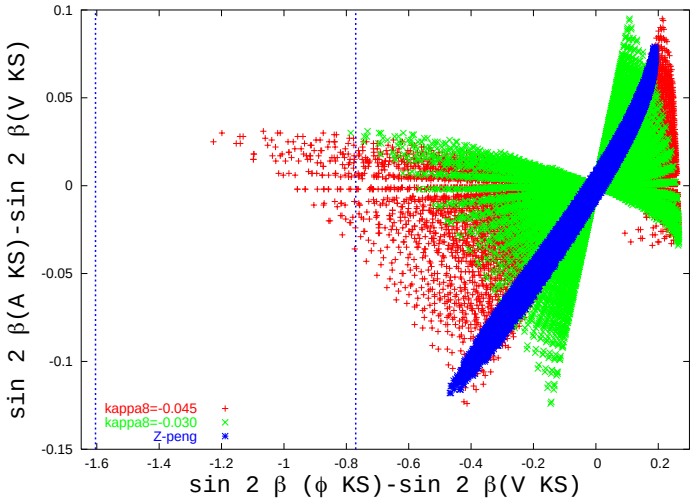
BSM: NP in P (as in $b \to s\bar{s}s$): hep-ph/0307251

$|\sin 2\beta(c\bar{c}K) - \sin 2\beta_{\rm mix}| \lesssim \arg(P/T)|P/T| \sim \varphi_{NP} \times 0.1$

NP distinguishes between final $(\bar{c}c)$ CP $V = J/\Psi, \Psi', A = \chi_1, \eta_c$

$\sin 2\beta(AK_S) - \sin 2\beta(VK_S) = -0.12 \pm 0.22$ from BaBar 0408127,no breakdown from Belle

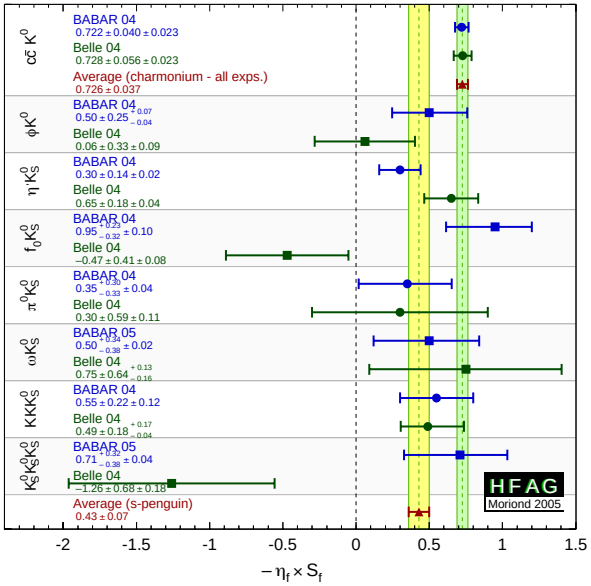
dipole vs 4-Fermi

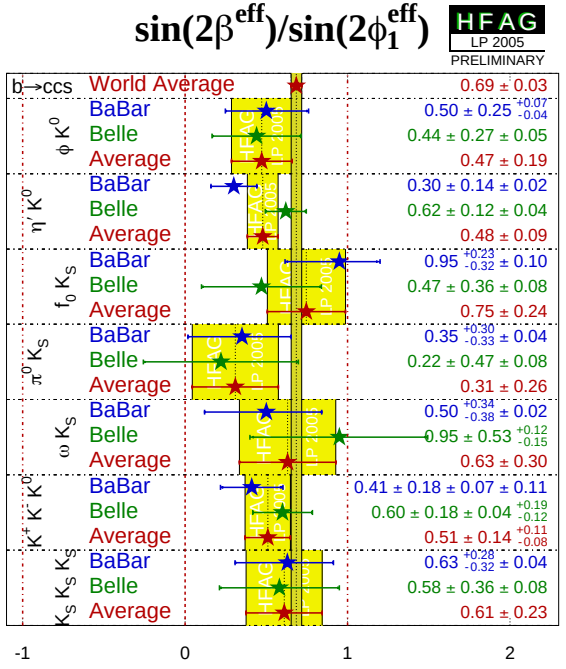


Time-dependent CP asymmetries in $b \to s\bar{q}q$ decays

SM+MFV: $-\eta_{CP} \sin 2\beta(\underbrace{(\bar{s}s)K_S}_{FCNC}) = \sin 2\beta(\underbrace{(\bar{c}c)K_S}_{tree}) + |\underbrace{\frac{V_{ub}V_{us}^*}{V_{tb}V_{ts}^*}}_{\mathcal{O}(\lambda^2)}| \cdot \#$

SM background $\mathcal{O}(\lambda^2) \sim 0.04$, $\#$ non-universal, hadronic physics





since Moriond05:$\sim 1\sigma$ in $\bar{c}c$, Φ, larger shifts in K_S^3, f_0; η' off by 2.3σ

better agreement between Belle and BaBar

SM background to ΔS

$$\Delta S = -\eta_f S_f - \sin 2\beta_{\rm mix}$$

hep-ph/0505075, 0503151 hep-ph/9708305, 0310020, 0303171, 0403287

f	$\Delta S_{SM}^{QCDF@NLO}$	$\Delta S_{SM}^{QCDF@LO}$	$\lvert\Delta S_{SM}^{SU(3)+}\rvert$	S_f LP'05	C_f LP'05
ΦK_S	$0.01 \ldots 0.03$	0.02	$\lesssim 0.3$	0.47 ± 0.19	-0.09 ± 0.14
$\eta' K_S$	$0 \ldots 0.02$	$-0.01 \ldots 0.02$	$\lesssim 0.15$	0.48 ± 0.09	-0.08 ± 0.07
$\pi^0 K_S$	$0.03 \ldots 0.12$	$0.03 \ldots 0.10$	$\lesssim 0.2$	0.31 ± 0.26	-0.02 ± 0.13
ωK_S	$0.05 \ldots 0.22$	$0.05 \ldots 0.25$	–	0.63 ± 0.30	-0.44 ± 0.23

LO captures central value and uncertainty of full NLO calc. of ΔS_f

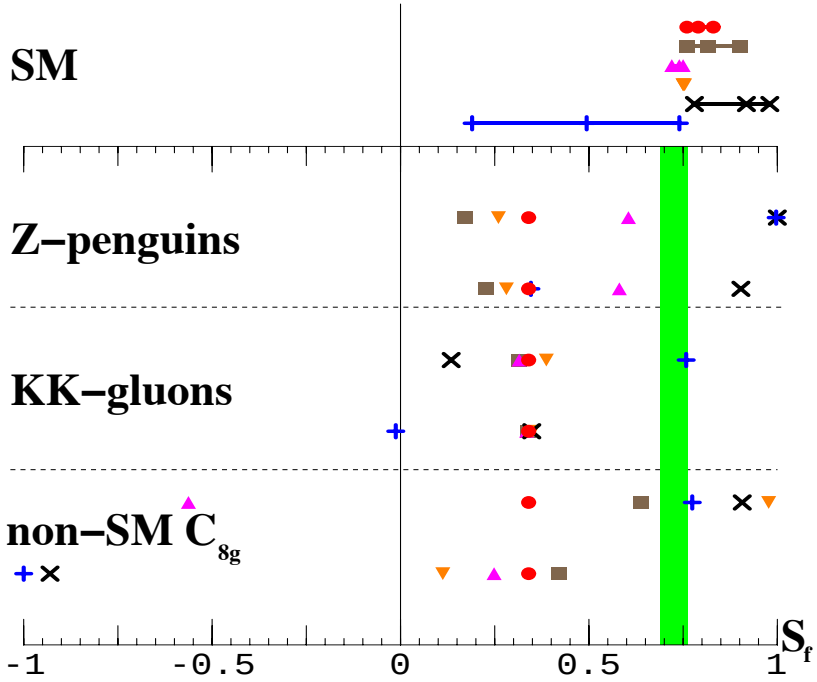
for all above modes: QCD factorization predicts $\Delta S_f > 0$, experimental shifts < 0; no significant $C_f \neq 0$

ultimately more precision needed; all exp. errors $\lesssim 0.1$ only by time of super-b-factory hep-ph/0503261

Pattern of NP in $b \to s$ Penguin modes

generic NP scenarios with one additional phase, use QCDF @ LO

hep-ph/0503151



input: $S_{\pi^0 K_S} = 0.34$ ● and maximal NP amplitude ok with other data

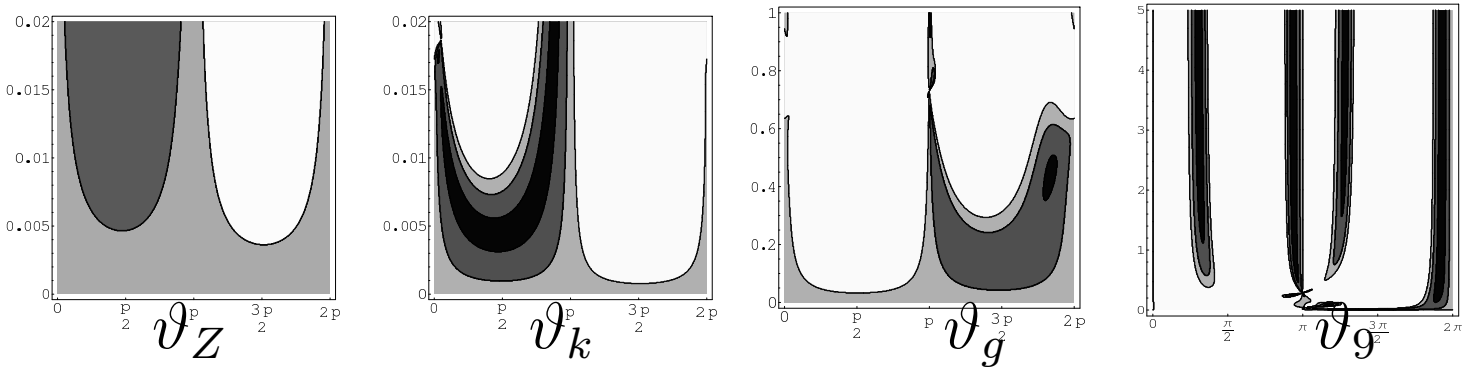
predict S_f for: ▼ $= \Phi$, ▲ $= \eta'$, ■ $= \eta$, × $= \omega$, + $= \rho$

goal: identify type of NP from characteristic SM departure

Fit generic NP scenarios to current data

$A = A_{SM} + A_{NP}$; $A_{NP} \propto \epsilon_i e^{i\vartheta_i}$; 3 NP scenarios sZb, KK, sbg hep-ph/0503151

χ^2-fit to $b \to s$ penguin data, LP'05 update



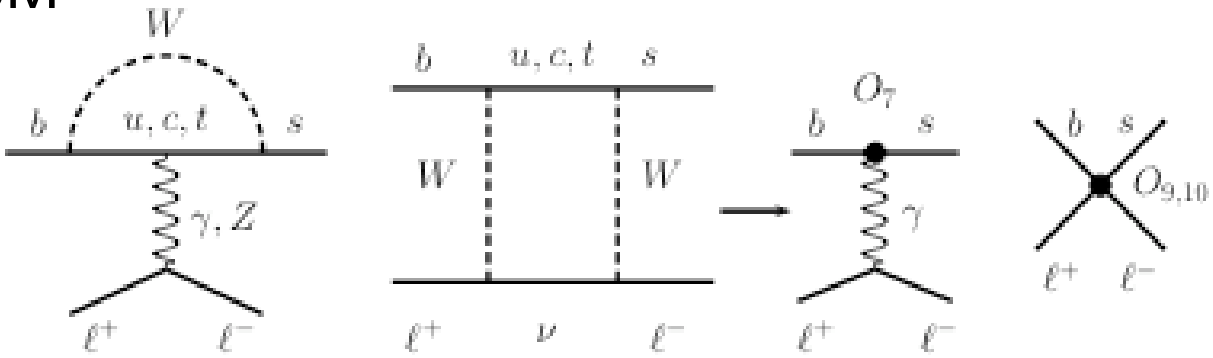
black, dark grey, light grey regions: probability $>$ 0.32, 0.046, 0.0027

$A_{NP} >> A_{SM}$: 4-fold solution $\sin 2(\beta + \vartheta) \simeq 0.4$ (with $\cos 2\beta > 0$)

NP amplitudes can be larger if no phase $\vartheta = 0, \pi$

all 3 scenarios have solution, which is more favored than SM $(\epsilon_i = 0)$

diagrams in SM



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

dipole operators $O_7 \propto \bar{s}_L \sigma_{\mu\nu} b_R F^{\mu\nu}$ $O_8 \propto \bar{s}_L \sigma_{\mu\nu} b_R G^{\mu\nu}$

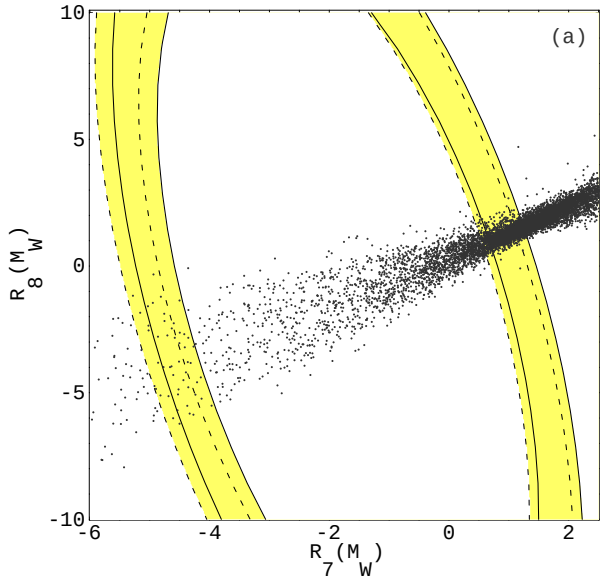
4-Fermi operators $O_9 \propto (\bar{s}_L \gamma_\mu b_L)(\bar{\ell}\gamma^\mu \ell)$ $O_{10} \propto (\bar{s}_L \gamma_\mu b_L)(\bar{\ell}\gamma^\mu \gamma_5 \ell)$

NP in Wilson coefficients $C_i = C_i^{SM} + C_i^{NP}$ or new operators

model-independent analysis: Br's, $A_{CP}, A_{FB} = f(C_i) \to$ fit !

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

$\mathcal{B}(b \to s\gamma)_{LO} \sim |C_7(m_b)|^2$ at NLO $R \equiv \frac{C^{SM}+C^{NP}}{C^{SM}}$ hep-ph/0112300



theory errors renorm. scale and charm mass solid:pole, dashed:$\overline{\text{MS}}$

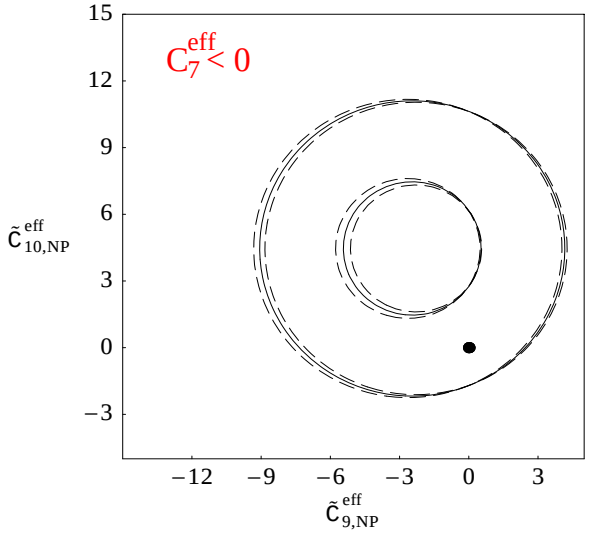
scatter points: MSSM with MFV: $C_7 = \underbrace{C_7^{SM} + C_7^{H^\pm}}_{<0} + C_7^{\chi^\pm}$

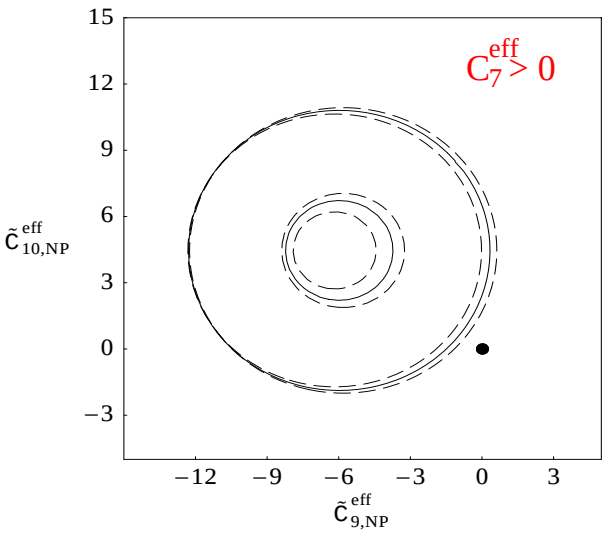
$C_7^{\chi^\pm} \propto \mu A_t \tan\beta f(m_{\tilde{t}_i}, m_{\tilde{\chi}_j}) m_b/(v(1+\epsilon\tan\beta))$; $\epsilon \propto (\alpha_s/\pi)\mu m_{\tilde{g}} \tan\beta$

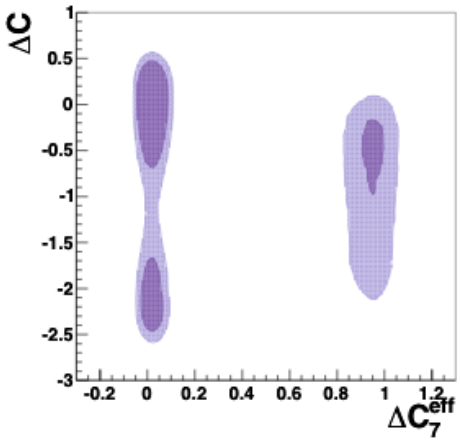
beyond MFV: gluino loops with down squark-mixing δ^D_{23} e.g. hep-ph/0212397

Combined $b \to s\ell^+\ell^-$ and $b \to s\gamma$ data

$$\frac{d\Gamma(B \to X_s\ell^+\ell^-)}{d\hat{s}} = \left(\frac{\alpha}{4\pi}\right)^2 \frac{G_F^2 m_b^5 \left|V_{ts}^* V_{tb}\right|^2}{48\pi^3}(1-\hat{s})^2 \left[(1+2\hat{s})\left(\left|C_9^{\rm eff}\right|^2 + \left|C_{10}^{\rm eff}\right|^2\right) f_1 \right.$$
$$\left. + \; 4\,(1+2/\hat{s})\left|C_7^{\rm eff}\right|^2 f_2 + 12{\rm Re}\left(C_7^{\rm eff} C_9^{\rm eff\,*}\right) f_3 + f_c\right] \qquad f_i\text{: } 1/m_{c,b}^2 \text{ corr.}$$







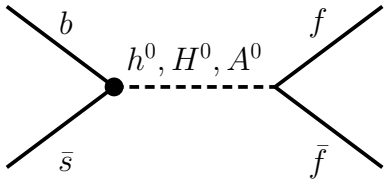
non-SM sign $C_7^{\rm eff} > 0$ disfavored iff no BSM ops hep-ph/0410155, 0505110(C10-C7study)

MSSM+MFV: C_9, C_{10} near SM, not $\tan\beta$ enhanced hep-ph/0112300

neutral Higgs effects in SUSY, $\tan\beta$ enhanced? *i* ok for low $\tan\beta$ *ii* discard $C_7^{\rm eff} > 0$ careful *iii* or use A_{FB}-data/fit to $B \to X_s e^+ e^-$ only

ii More model-independent studies, neutral Higgses

$O^f_{S(P)} \sim \bar{s}_L b_R \bar{f}(\gamma_5) f$

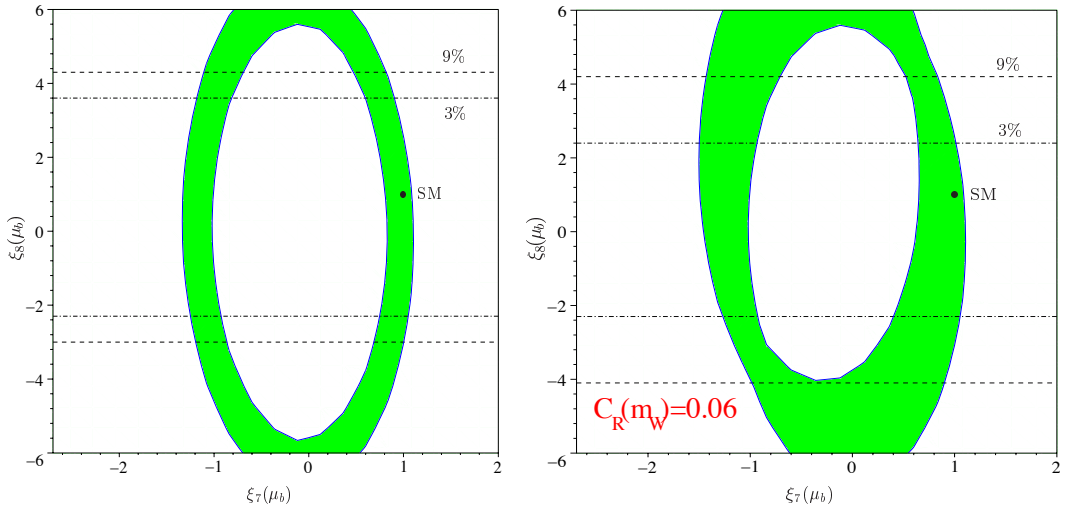


$C^f_{S,P} \propto m_f$ big effects in (pseudo)-scalar operators with b-quarks

$\mathcal{O}^f_{L(R)} = (\bar{s}Rb)(\bar{f}L(R)f)$ non-trivial mixing onto dipoles hep-ph/9911245, 0310219

$\delta C_7(m_b) \simeq 0.71 C^b_R(m_W)$ $\rightarrow O(10\%)$ NP effect

$\delta C_8(m_b) \simeq -2.95 C^b_R(m_W)$ $\rightarrow O(100\%)$ NP effect



MSSM+MFV: $|C^b_R(m_W)| < 10^{-3}$ imprint of Higgs sector hep-ph/0404220

iii More model-independent studies, neutral Higgses

Higgs effect splits between $\mu^+\mu^-$ and e^+e^- in $b \to s\ell^+\ell^-$ processes

define ratios with the SAME cut on the dilepton mass hep-ph/0310219

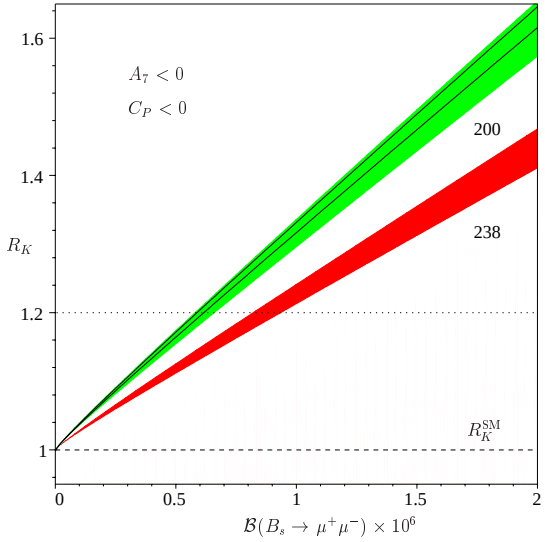
$$R_H \equiv \frac{\int_{4m_\mu^2}^{q^2_{\rm max}} dq^2 \, \frac{d\Gamma(B\to H\mu^+\mu^-)}{dq^2}}{\int_{4m_\mu^2}^{q^2_{\rm max}} dq^2 \, \frac{d\Gamma(B\to He^+e^-)}{dq^2}} \qquad H = X_s, K^{(*)}$$

$$R_H^{SM} = 1 + \mathcal{O}(m_\mu^2/m_b^2) \qquad \text{very clean}$$

measurement: $R_K = 1.06 \pm 0.48 \pm 0.05$ BaBar 0507005

$R_K = 1.38^{+0.39+0.06}_{-0.41-0.07}$ Belle 0410006

constraints on (pseudo)-scalar couplings



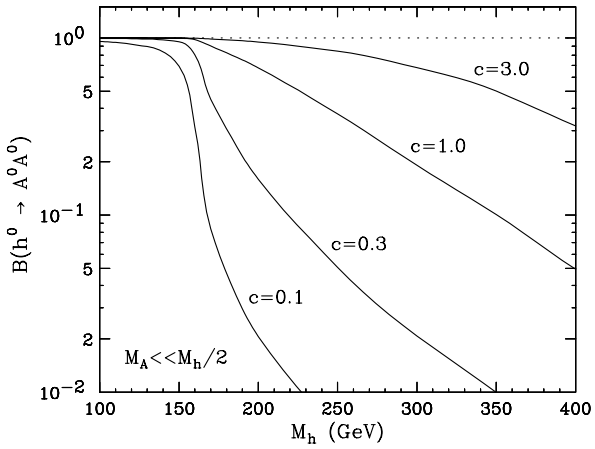
complementarity: with right-handed currents $O^{f\prime}_{S(P)} \sim \bar{s}_R b_L \bar{f}(\gamma_5) f$

R_K constrains $C_{S,P} + C'_{S,P}$, $\mathcal{B}(B_s \to \mu^+\mu^-)$ constrains $C_{S,P} - C'_{S,P}$

Light CP-odd A^0: implications for hadron colliders

direct searches: $h^0 \to A^0 A^0$ open if $2m_{A^0} < m_{h^0}$

can be VERY important for $\mathcal{O}(1)$ $h^0 A^0 A^0$-coupling c hep-ph/0005308



decay modes: $A^0 \to b\bar{b}, \tau\tau$, 3π or higher hadronic, $\mu\mu, ee, \gamma\gamma$

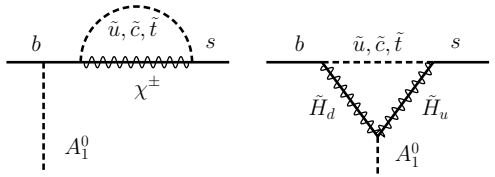
if A^0 very light and weakly coupled, it becomes missing energy

Υ-decays, beam dump, astro physics $m_{A^0} \gtrsim \mathcal{O}(100\text{MeV})$ ok

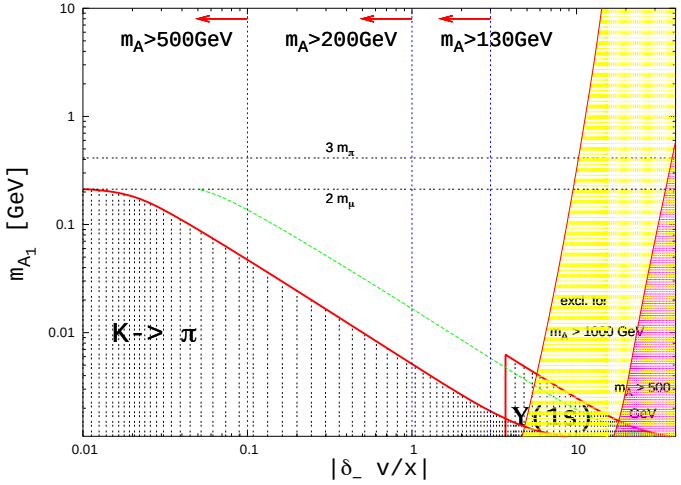
NMSSM constraints from indirect signals

$W = QY_u H_u U + QY_d H_d D + LY_e H_d E + \lambda H_d H_u N - \frac{1}{3} k N^3$ N:singlet

at large $\tan\beta$: naturally light A_1^0, rad. stable $b \to s A_1^0$ transitions



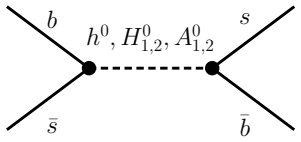
bounds from $B \to K A_1^0, K \to \pi A_1^0, \Upsilon(1s) \to \gamma A_1^0$ decays



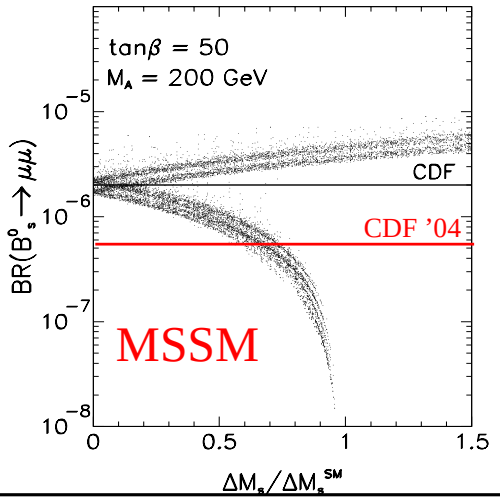
A_1^0 masses as low as $\mathcal{O}(10\text{MeV})$ viable hep-ph/0404220

Light CP-odd A^0: further tests from b-physics

- improve bounds from radiative Υ-decays or $B \to K+$ missing E
- for $m_{\psi'} < m_{A_1^0} \lesssim m_B$: search for A_1^0 in $b \to s\tau^+\tau^-$ processes
  sensitivity e.g. $\mathcal{B}(B \to X_s\tau^+\tau^-) \sim 10^{-3}$



- $B_s - \bar{B}_s$ mixing and CDF/D0: $\mathcal{B}(B_s \to \mu^+\mu^-) < 1.2 \cdot 10^{-7}$
  in MSSM correlated Fig adopted from hep-ph/0207241
  in NMSSM: SM-like Δm_s (A_1^0 contribution constrained by Δm_d),
  but not correlated with $\mathcal{B}(B_s \to \mu^+\mu^-)$ hep-ph/0404220



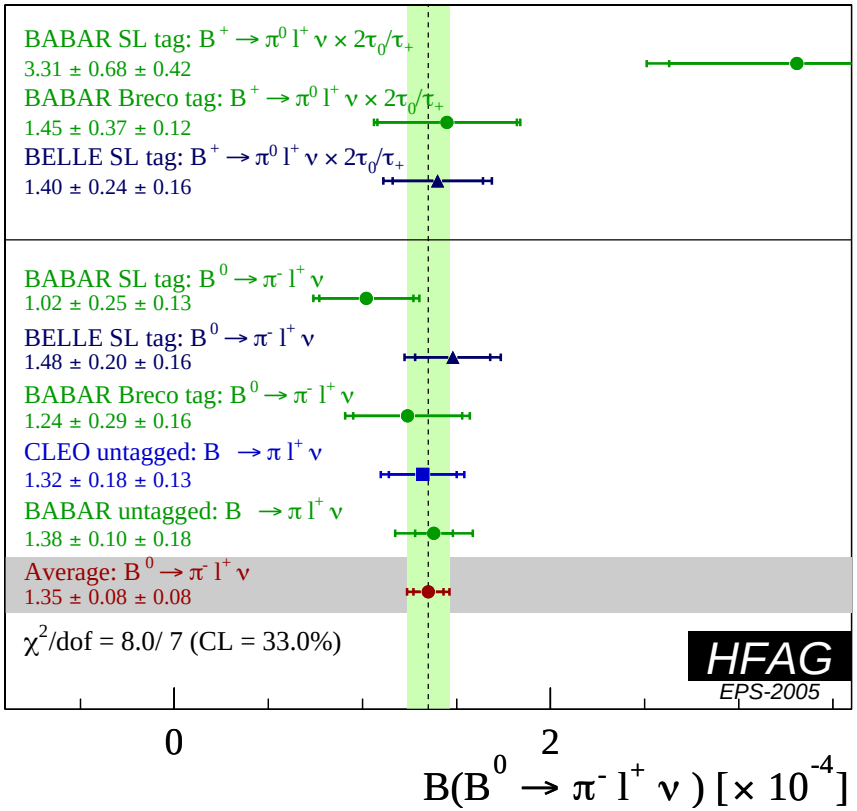
Bottomline

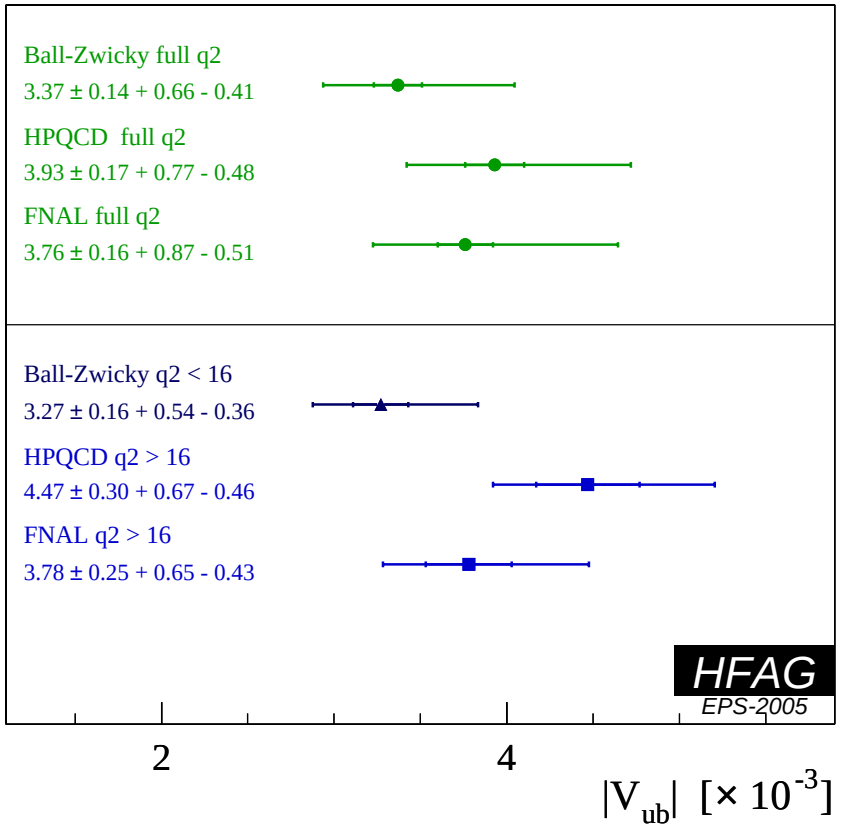
- CKM@tree: input (SM tests, flavor model building..)
- in 2005 $\sin 2\beta_{\rm penguin}$ moved closer to MFV, some hints $\eta' K^0$ $\beta_{\rm tree}$ vs. $\beta_{(\bar{c}c)K} \rightarrow$ compare $\sin 2\beta (\bar{c}c)_i K_S$
- $b \rightarrow s\ell\ell$ modes under th and exp investigation; model independent analysis (w. $b \rightarrow s\gamma$) $\rightarrow$ do e and μ separately
- $b \rightarrow d$ FCNCs beginning to be probed
- B_s, B_c, Λ_b-physics coming up CDF&D0; much more from LHC(b)
- study correlations & pattern between observables –also w. direct searches (Higgs, top FCNC,..) and LFV
- indirect (loop) processes are unique probes of CP/flavor sector
- many FCNCs only weakly or just un-constrained ..Δm_s,$\tau^{\pm}$,..

Some further searches with b-physics

	experiment	SM	comments
$a_{CP}(b \to s\gamma)$	$0.4 \pm 3.6\,\%$	$0.42 \pm 0.17\,\%$ hep-ph/0312260	CPX in $bs\gamma, g$
$a_{CP}(b \to d/s\gamma)$	-0.110 ± 0.116 BaBar'05	10^{-9} hep-ph/0312260	test MFV
$S_{K_S\pi^0\gamma}$	0.00 ± 0.28 Belle/BaBar'05	$-2m_s/m_b$	V+A FCNCs
$\mathcal{B}(B \to X_s g)$	$< 9\%$ CLEO'97	$5.0 \pm 1.0 \cdot 10^{-3}$	NP in bsg
$\mathcal{B}(B \to X_s \bar{\mu}\mu)$	$4.3 \pm 1.2 \cdot 10^{-6}$	$4.3 \pm 0.7 \cdot 10^{-6}$	q^2-spectra
$a_{CP}(B \to X_s \bar{\ell}\ell)$	-0.22 ± 0.26	-0.2 ± 0.2 % hep-ph/9812267	CPX
$A_{FB}^{CP}(B \to K^* \bar{\ell}\ell)$	–	$\lesssim 10^{-3}$ hep-ph/0006136	CPX in bsZ
R_K $\mu\mu$ vs. ee	1.06 ± 0.48 BaBar'05	$1 + \mathcal{O}(m_\mu^2/m_b^2)$ hep-ph/0310219	non-SM Higgs
$\mathcal{B}(B \to K\nu\bar{\nu})$	$< 3.6 \cdot 10^{-5}$ Belle'05	$3.8^{+1.2}_{-0.6} \cdot 10^{-6}$	$O(10)$ from SM
$\mathcal{B}(B_s \to \mu^+\mu^-)$	$< 1.2 \cdot 10^{-7}$ hep-ex/0508058	$3.2 \pm 1.5 \cdot 10^{-9}$	$O(50)$ from SM
$\mathcal{B}(B_s \to \tau^+\tau^-)$	$< \mathcal{O}(5\%)$	$7.2 \pm 1.1 \cdot 10^{-7}$	$O(10^5)$ from SM
Δm_s	$> 15/\mathrm{ps}$	$(15-22)/\mathrm{ps}$	hadron colliders

back up slides





CKMfitter,incl-excl-ave: $|V_{ub}| = (4.22 \pm 0.11 \pm 0.24) \cdot 10^{-3}$ hep-ph/0406184

HPQCD $q^2 > 16\text{GeV}^2$: $|V_{ub}| = (4.22 \pm \underbrace{0.30}_{exp} \pm \underbrace{0.51}_{lattice}) \cdot 10^{-3}$ hep-lat/0601021

inclusive HFAG EPS05: $|V_{ub}| = (4.39 \pm 0.19 \pm 0.27) \cdot 10^{-3}$

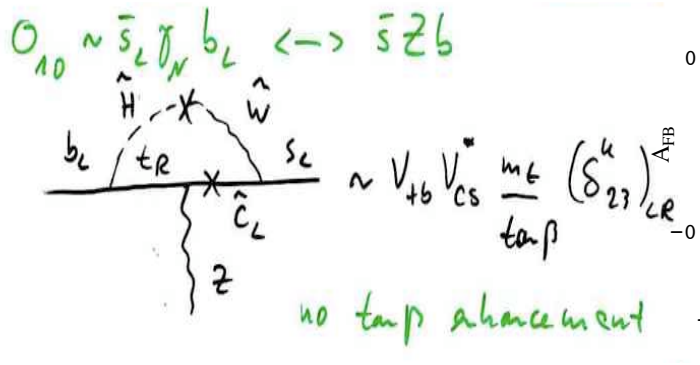
Impact of $b \to s\ell^+\ell^-$ beyond MFV, perspectives

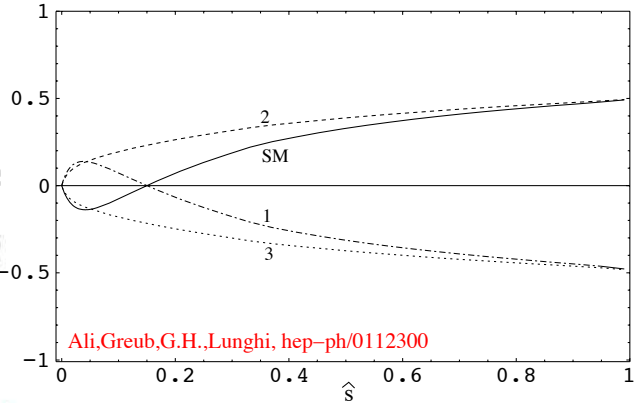
$\mathcal{B}(b \to s\ell^+\ell^-)$: best bound on $\bar{s}Zb$-penguin $\sim C_{10} \lesssim 2C_{10}^{\rm SM}$

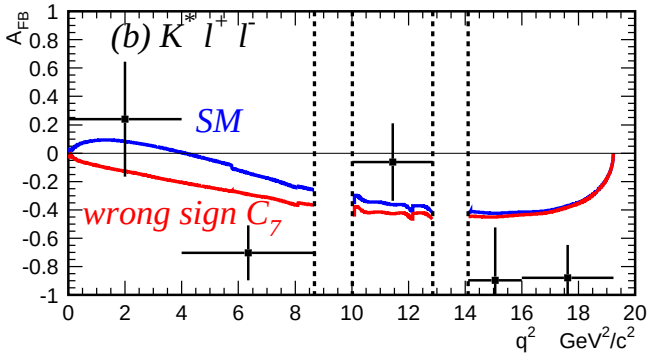
SUSY O(1) effects in C_{10} from δ^U_{23} possible (LR and LL) hep-ph/9906286,0006136

great NP sensitivity in q^2-spectra in $b \to s\ell^+\ell^-$; asy # forward - # backward ℓ^+ in dilepton CMS w.r.t. $\bar{B}$ needs tagging $A_{FB}^{SM} + \bar{A}_{FB}^{SM} \simeq 0$

$A_{FB}(\hat{s}) \sim \mathrm{Re}\left[C_{10}^*(C_7^{eff} + \beta(\hat{s})C_9^{eff})\right]$ also $B \to K^*\ell^+\ell^- \to$ Belle'04







shape sensitive to signC_7; $A_{FB} \propto C_{10}$; flat possible

zero allows precision test $\hat{s}_{SM}^{NNLL} = 0.162 \pm 0.002(8)$ hep-ph/0208088,0209006