Gudrun Hiller
Dortmund U.

DPG-Tagung, Dortmund, March 31, 2006

- (quark)-flavor within SM and beyond: CKM and more
- rare processes: b-decays and mixing

CKM and CP $\longrightarrow$ Klaus Schubert
rare decays $\longrightarrow$ Manfred Paulini
B_s-mixing $\longrightarrow$ Stephanie Menzemer
and many more in BSM, heavy quarks, rare decays sessions !

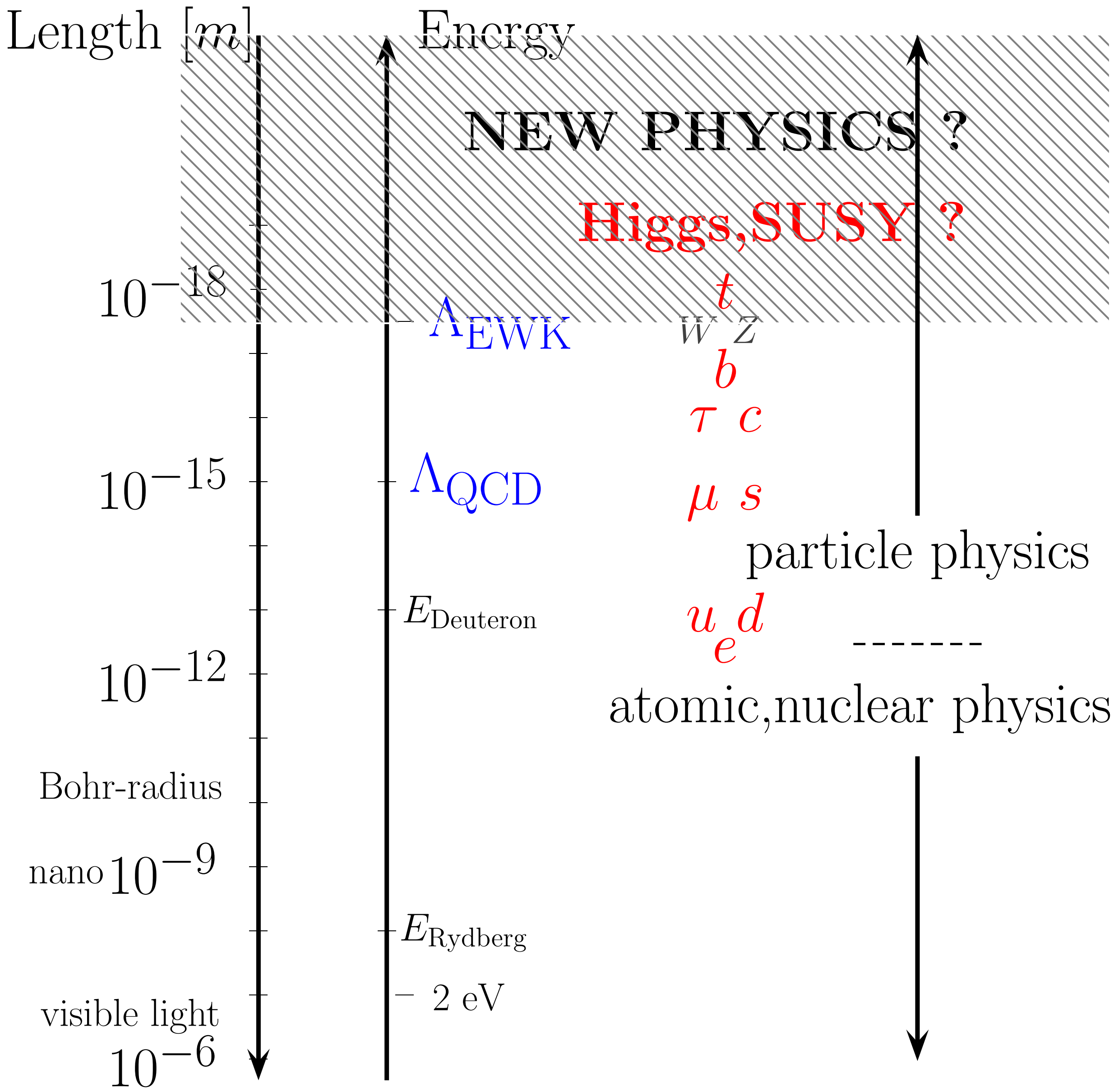
Core questions of flavor physics

- CP violation needed for baryogenesis $(n - \bar{n})/s \simeq 10^{-10}$
  SM not sufficient
- strong CP problem: Why is $\bar{\Theta} \lesssim 10^{-10}$ and $\delta_{CKM} = \mathcal{O}(1)$?
- origin of flavor; explanation of peculiar masses and mixings
- neutrino masses

... are core questions of the SM, plus: unification, Higgs mass, dark matter, dark energy, gravity

despite its impressive experimental support the SM is rather viewed as an effective theory valid up to $\Lambda \sim \mathcal{O}(m_W)$

The high energy frontier



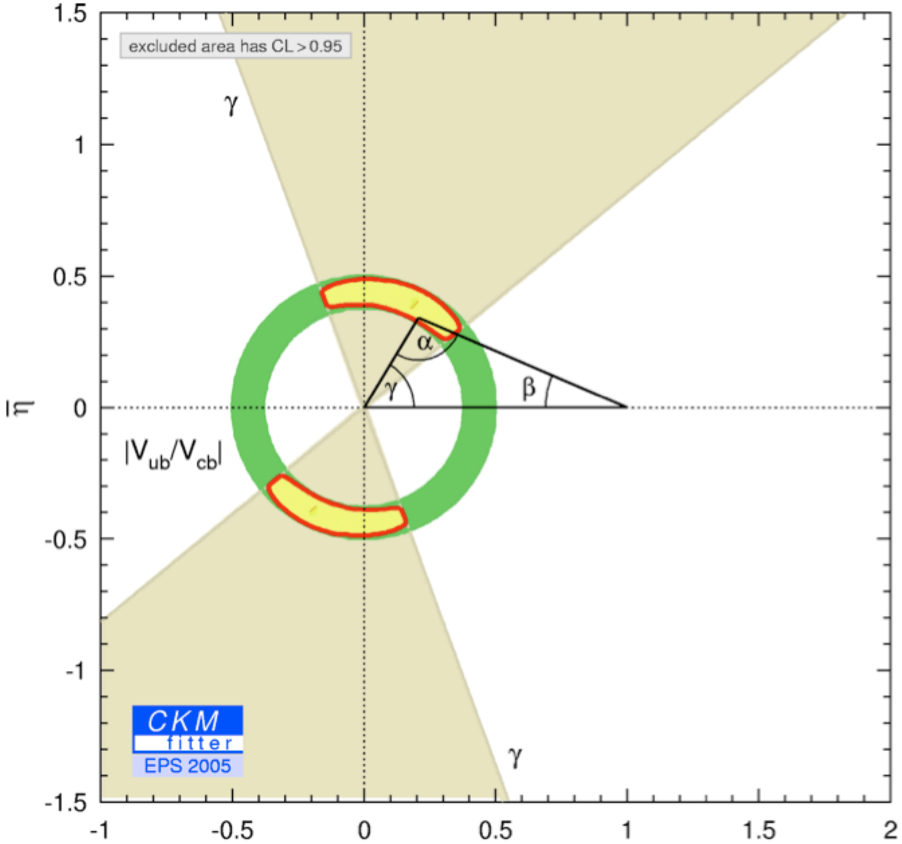
flavor and CP in SM: $-\mathcal{L}_Y = \bar{Q} Y_u h^C U + \bar{Q} Y_d h D + \bar{L} Y_e h E + h.c.$

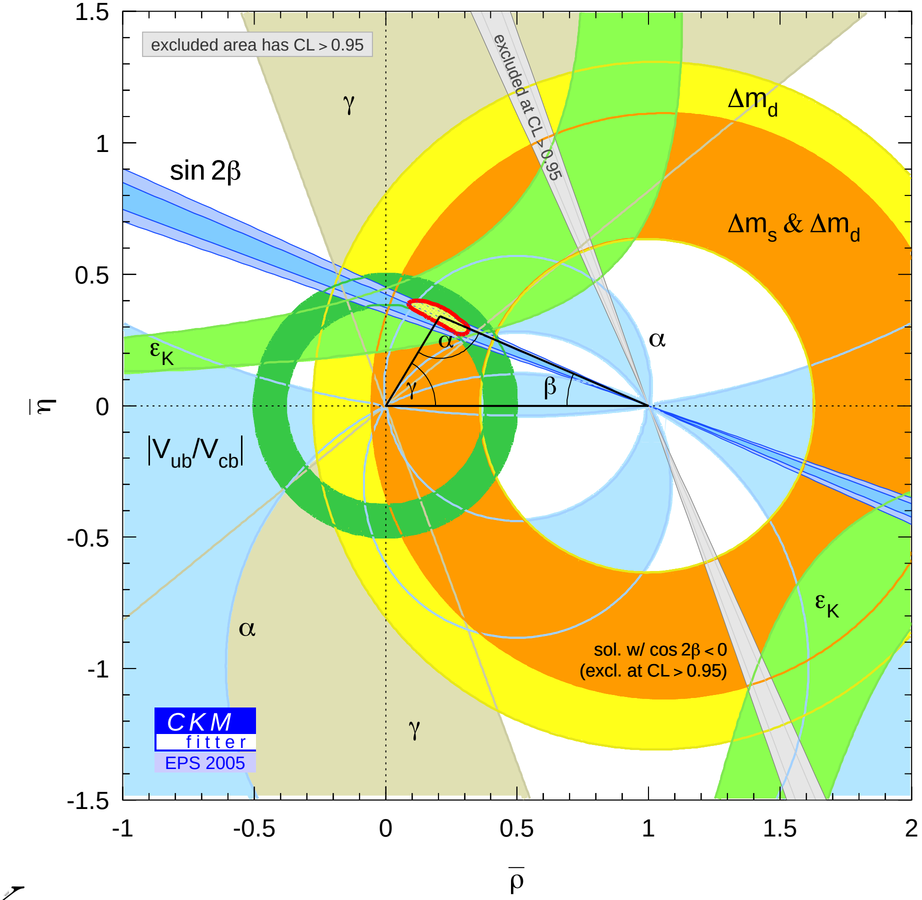
flavor symmetry: $U(3)^5 \stackrel{Y}{\rightarrow} U(1)_B \times U(1)_L \times U(1)_Y$

quarks: $Y_{u,d}$ 36 real numbers $\rightarrow$ 10 physical parameters: 6 quark masses plus CKM (3 angles, 1 phase)

- determine 10 parameters
- how do the Yukawas look like ? top-down, GUT's, textures, ED's, Froggatt-Nielsen, horizontal symmetries, anarchy, ..
- test the CKM-picture of flavor/CP violation, that is, MFV minimal flavor violation = no further breaking of flavor than through Yukawas
- are there deviations from the SM in rare processes ?

CKM 2005: unitarity triangle from tree level, precision





tree fit with V_{ub}, γ from $B \to DK$

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

SM/MFV-like picture at least for $b \to \bar{c}cs$, K-,B_d-mixing

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

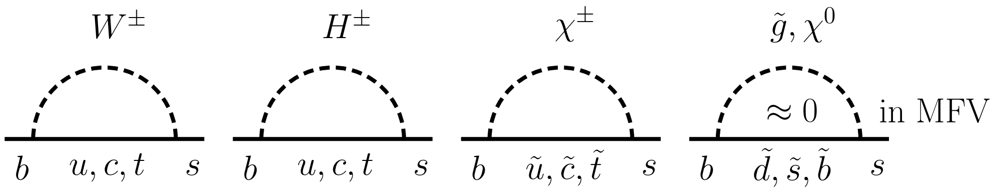
SM tests with indirect processes

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

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

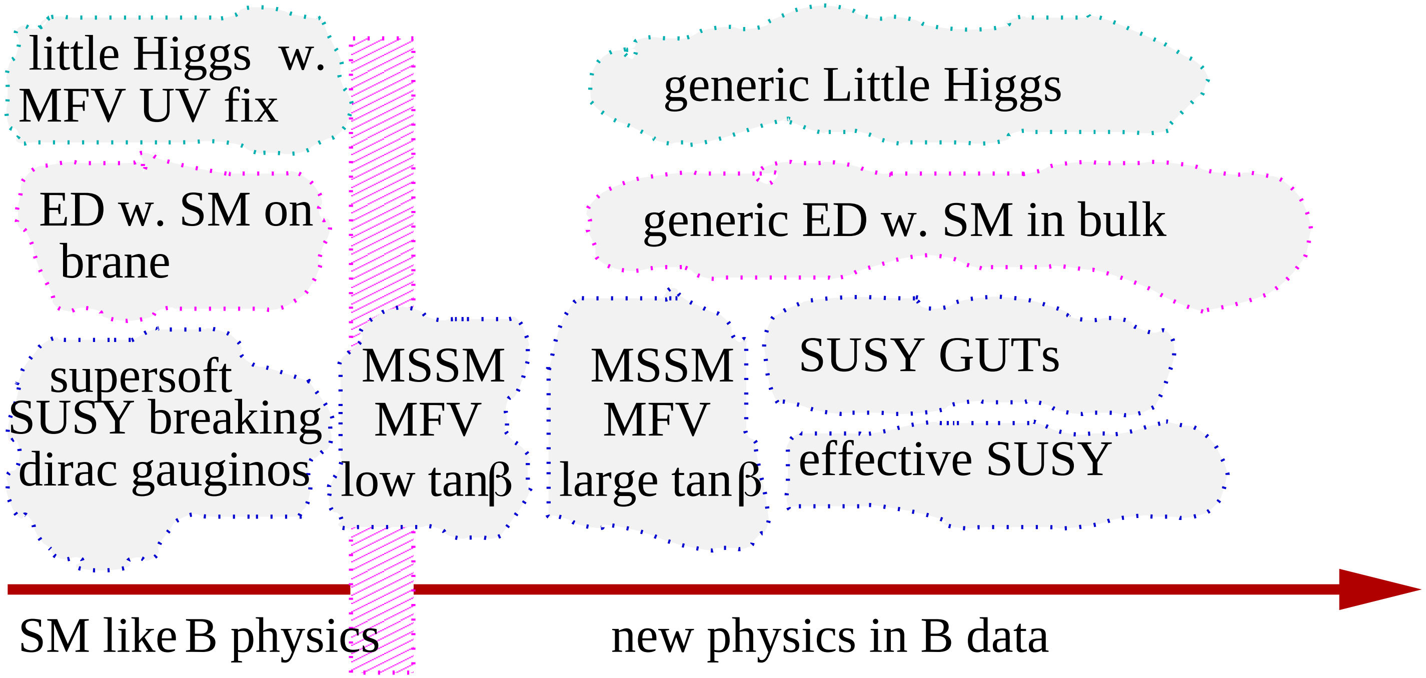
no competition from large SM tree contributions

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



BSM contributions to FCNC can offset rates, distort spectra, induce CP-asymmetries, V+A currents models of EWKSB with NP @ TeV

Fig from hep-ph/0207121



reach in indirect signals rare b, c, K, τ-decays, mixing, EDMs, g-2

depends on beyond the SM flavor/CP violation (minimal=CKM ?),

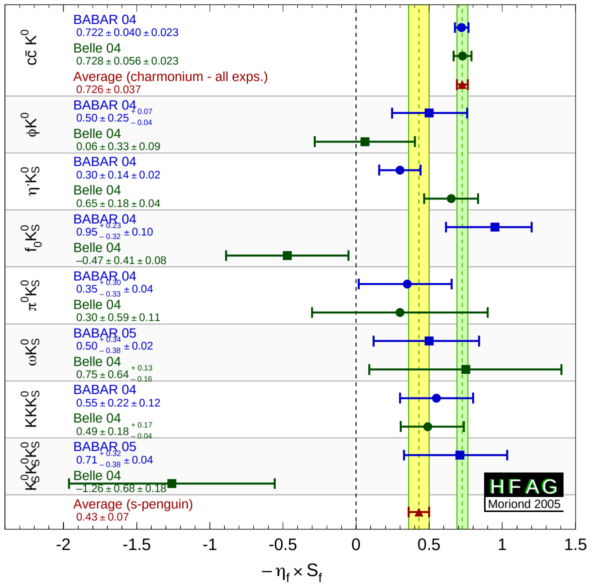
large parameters e.g. $\tan\beta$ and theor. and exp. uncertainties

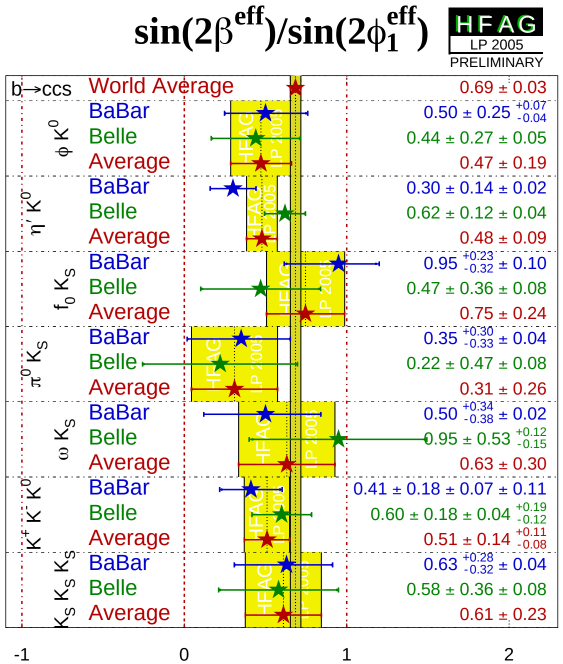
- searching for BSM CP-violation in $b \to s$ penguins
- todays and future impact of $b \to s\ell\ell$ modes
- $B_s - \bar{B}_s$ mixing

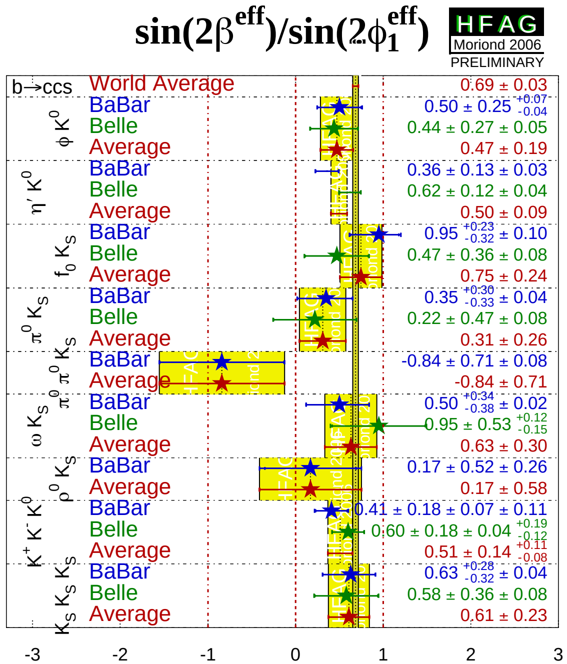
Time-dependent CP asymmetries in $b \to s\bar{q}q$ decays

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

better agreement between Belle and BaBar; new 2006: ρK_S (BaBar)

$\Delta S = -\eta_f S_f - \sin 2\beta$ 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^0	$0.01 \ldots 0.03$	0.02	$\lesssim 0.3$	0.47 ± 0.19	-0.09 ± 0.14
$\eta' K^0$	$0 \ldots 0.02$	$-0.01 \ldots 0.02$	$\lesssim 0.15$	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

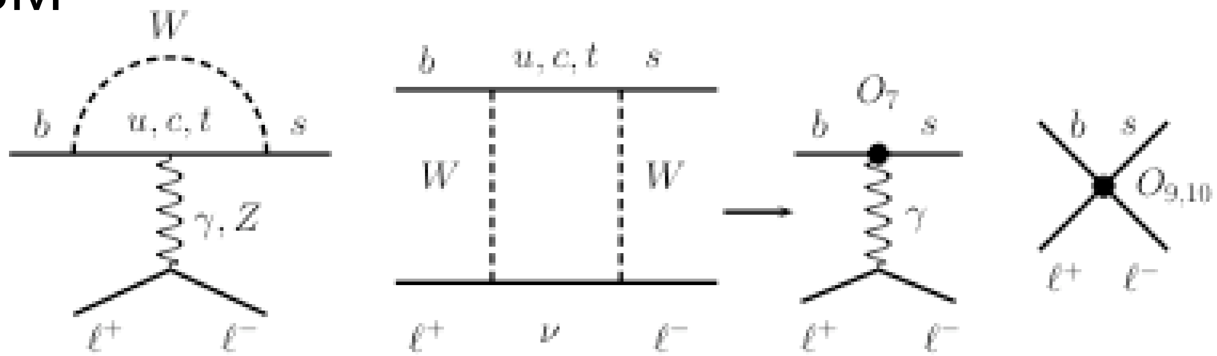
LO captures central value and uncertainty of full NLO calc. of ΔS_f

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; ηK_S data missing

SM tests with $b \to s\gamma, b \to s\ell^+\ell^-$ decays

diagrams in SM



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

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

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

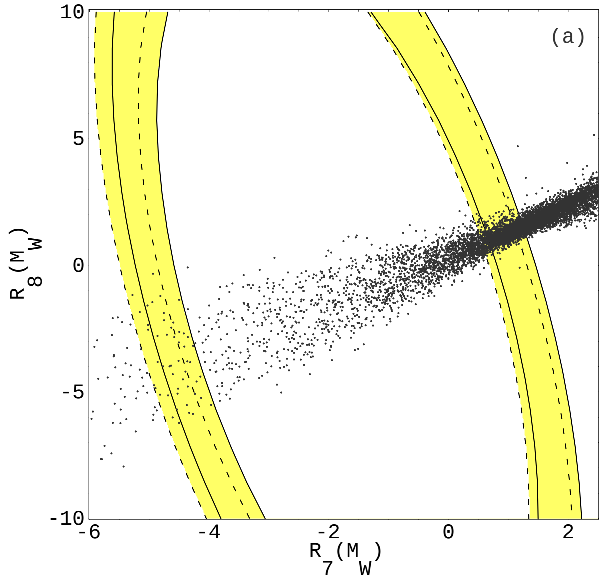
NP in Wilson coefficients $C_i = C_i^{SM} + C_i^{NP}$ or new operators

model-independent analysis: Br's, $A_{CP}, A_{FB} = f(C_i) \to$ fit! hep-ph/9408213

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

$R_8 - R_7$:



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

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

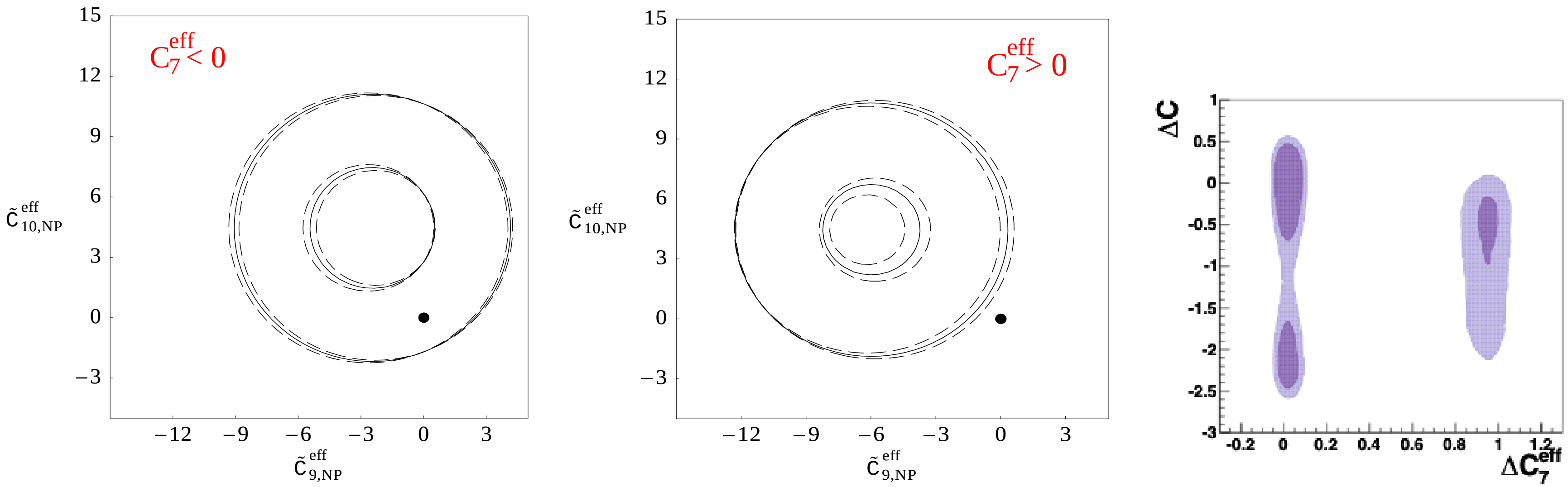
$C_7^{\chi^\pm} \propto \mu A_t \tan\beta f(m_{\tilde{t}_i}, m_{\tilde{\chi}_j}) m_b/(v(1+\epsilon\tan\beta))$; $\epsilon \propto (\alpha_s/\pi)\mu m_{\tilde{g}} \tan\beta$

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

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

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

f_i: $1/m_{c,b}^2$ 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

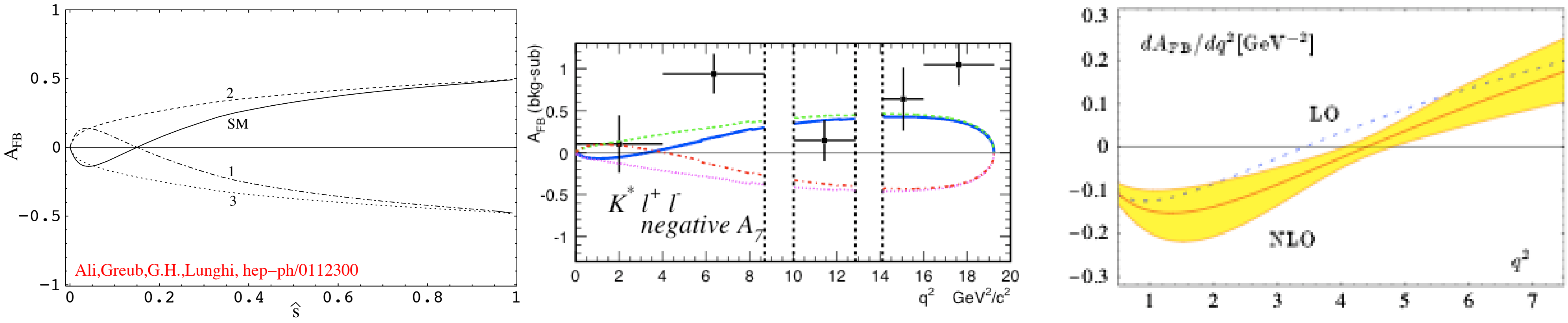
neutral Higgs effects $O^f_{S(P)} \sim \bar{s}_L b_R \bar{f}(\gamma_5) f$, $\tan\beta$ enhanced

check for BSM operators *i* (pseudo)scalar *ii* $L \leftrightarrow R$ flipped O_i' *iii* ..

NP sensitivity of $b \to s\ell^+\ell^-$ spectra, perspectives

A_{FB}: # forward - # backward ℓ^+ in dilepton CMS w.r.t. $\bar{B}$ (CP-odd)

$A_{FB}(\hat{s}) \sim \mathrm{Re}\left[C_{10}^*(C_7^{\mathrm{eff}} + \beta(\hat{s})C_9^{\mathrm{eff}})\right]$ also $B \to K^*\ell^+\ell^-$ Belle 0508009,0603018



<u>shape</u> sensitive to sign C_7; $A_{FB} \propto C_{10}$; flat possible

<u>zero</u> X_S: $\hat{s}_{SM}^{NNLL} = 0.162 \pm 0.002(8)$ hep-ph/0208088,0209006

K^*: $s_{SM}^{NLO} = 4.4 \pm 0.4$ GeV^2 hep-ph/0106067

<u>CP</u> $A_{FB}^{CP} \equiv \frac{A_{FB}+\bar{A}_{FB}}{A_{FB}-\bar{A}_{FB}} \sim \arg C_{10} \arg C_9^{\mathrm{eff}}$; $A_{FB}^{CP}|_{SM} \lesssim 10^{-3}$ hep-ph/0006136

full angular analysis $B \to K^*(\to K\pi)\ell^+\ell^-$ hep-ph/9907386

$$d\Gamma^4 \sim I(s, \Theta_l, \Theta_{K^*}, \Phi) ds\, d\cos\Theta_l\, d\cos\Theta_{K^*}\, d\Phi$$

More model-independent studies, neutral Higgses

Higgses split between $\mu^+\mu^-$ and e^+e^- in $b \to s\ell^+\ell^-$

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

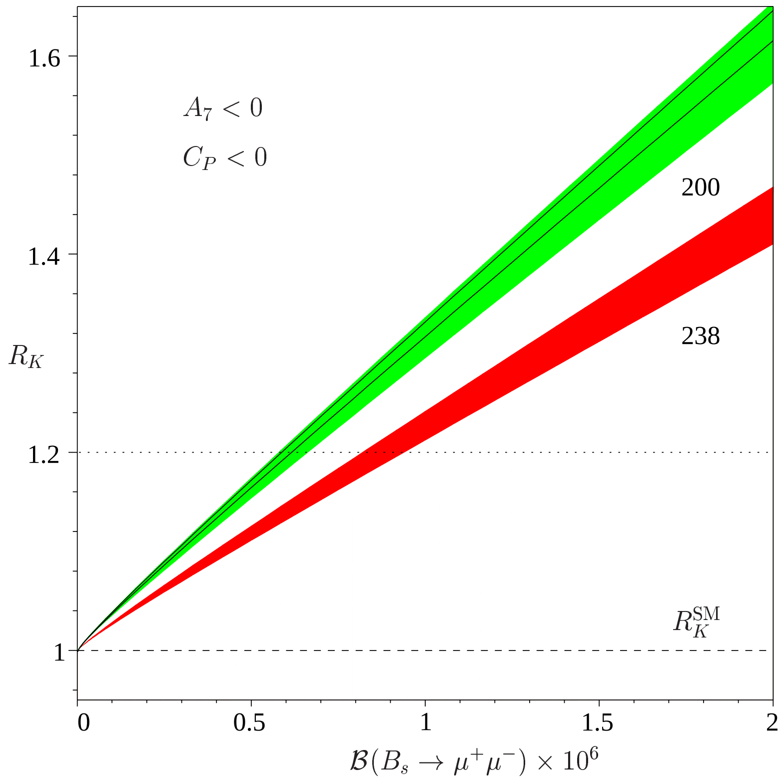
$$R_H \equiv \frac{\int_{4m_\mu^2}^{q^2_{\max}} dq^2 \frac{d\Gamma(B\to H\mu^+\mu^-)}{dq^2}}{\int_{4m_\mu^2}^{q^2_{\max}} dq^2 \frac{d\Gamma(B\to He^+e^-)}{dq^2}} \qquad H = X_s, K^{(*)}$$

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

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

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

constrain (pseudo)-scalar couplings



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

correlation breaks down if $C_{S,P} \not\propto m_\ell$

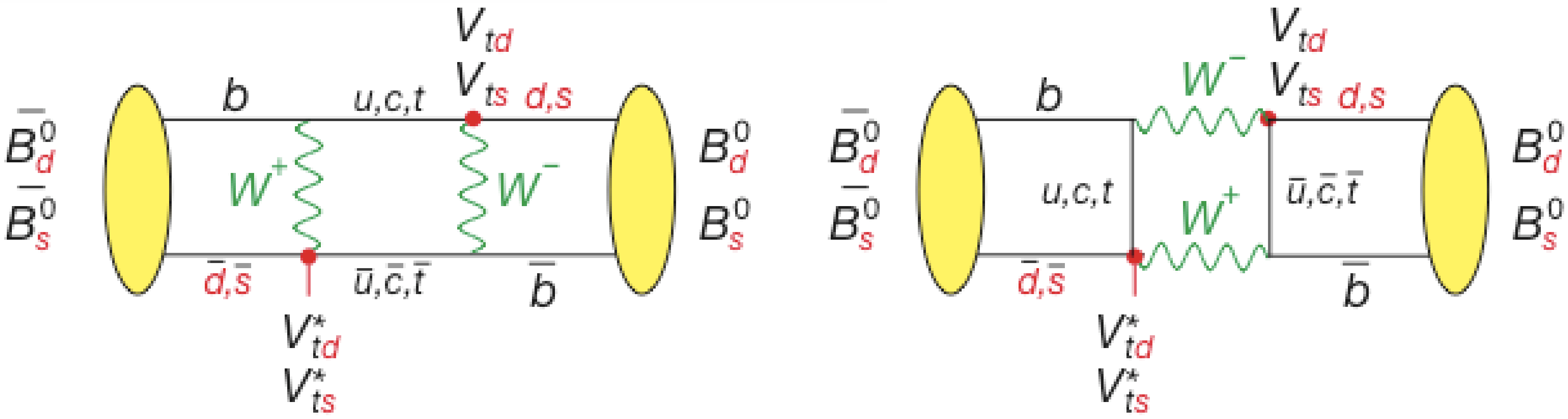
What if Δm_s is around its SM value?*

a theoretical exercise

*D∅: $17 < \Delta m_s < 21$ ps^{-1} at 90% C.L. hep-ex/0603029

SM: $W-(u,c,t)$-box $\qquad \Delta m_s^{\rm SM} \sim (V_{tb}^* V_{ts})^2 \frac{g^4}{16\pi^2} \frac{(\bar b \Gamma s)(\bar b \Gamma' s)}{m_W^2}$

top dominated; $V_{tb} \simeq 1$, $V_{ts} = -A\lambda^2$ independent of CKM-triangle-fit



$\Delta m_d^{world\,ave} = 0.570 \pm 0.004\, ps^{-1}$ (HFAG '05)

$\Delta m_s^{\rm SM} = 18.3^{+6.5}_{-1.5}\, ps^{-1}$ (CKMfitter/EPS'05) $\Delta m_s^{\rm SM} = 20.0 \pm 1.8\, ps^{-1}$ (UTfit hep-ph/0501199)

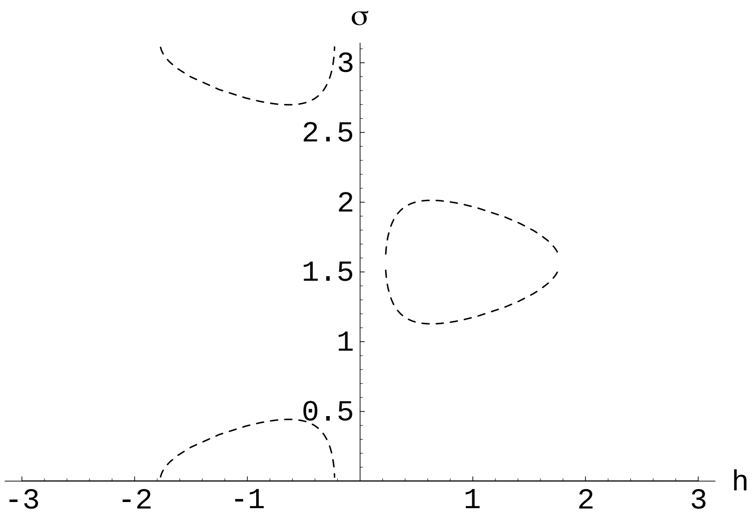
assume in plots: $\Delta m_s^{\rm SM} = \Delta m_s^{data} = 19.0 \pm 2\, ps^{-1}$ @ 90 % C.L.

generic NP constraints from lower bound

mixing with NP: $\Delta m_s = \Delta m_s^{\rm SM} \cdot \left|1 + h e^{2 i \sigma}\right|$ see also hep-ph/0509117 for nicer plots

only lower bound near SM $\Delta m_s > 16.6\, ps^{-1}$ @ 95 % C.L. (HFAG '05)

$\Delta m_s > \Delta m_s^{\rm SM}(1-\epsilon)$:



dotted: $\epsilon = 0.23$

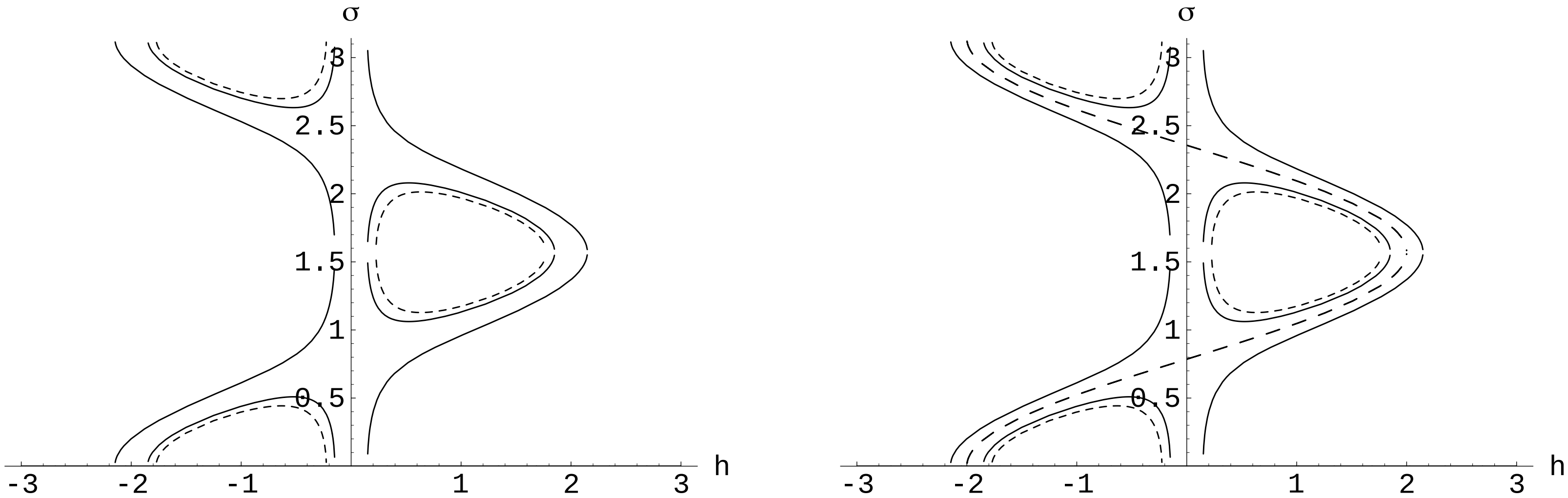
gaps excluded around $h \simeq +1$, $\sigma \simeq \pi/2$ and $h \simeq -1$ with $\sigma \simeq 0, \pi$

size of NP-amplitude h unconstrained

generic NP constraints: measurement

$\Delta m_s = \Delta m_s^{\rm SM} \cdot \left|1 + h e^{2i\sigma}\right|$; with $\Delta m_s \simeq \Delta m_s^{\rm SM}(1 \pm \epsilon)$

$\Delta m_s^{data} = 19.0 \pm 2\, ps^{-1}$ @ 90 % C.L.



dotted: lower bound only, solid: $\epsilon = 0.15$, dashed (and $h = 0$): $\epsilon = 0$

size of NP-amplitude $|h| < 2 + \epsilon$ limited

$\mathcal{O}(1)$ NP-amplitude possible if NP-phase σ cooperates

large $|h|$ is fine-tuned to some degree for small errors $\epsilon \to 0$

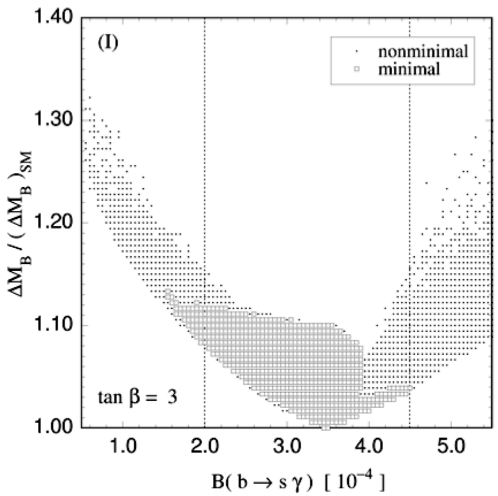
I. low $\tan\beta$: CKM-ology: hep-ph/9903535, SUGRA: hep-ph/9908499

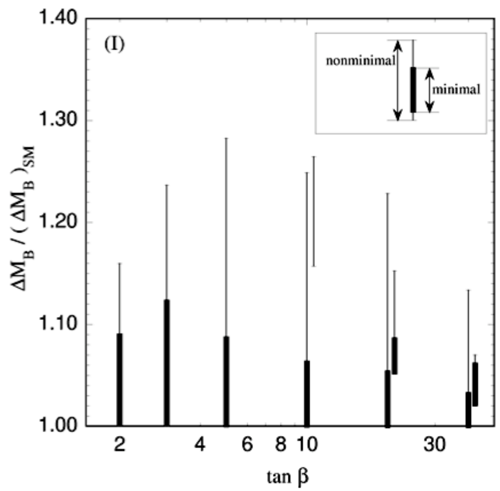
$h = h_{H^\pm} + h_{\chi^\pm}$; $\sigma = 0$ (no BSM CP-violation)

$h > 0$ in whole parameter space $\quad$ h equal for B_d and B_s

ok with $b \to s\gamma$, $m_\chi > 91$ GeV, all other charged SUSY-partners above 80 GeV: $0 < h \lesssim 0.75$; h decreases for heavy $m_{\tilde{t}}$,$m_{\tilde{\chi}}$,$m_{H^\pm}$

SUGRA: $h \lesssim 0.4$; calc. only valid up to moderate $\tan\beta$ (see next slide)



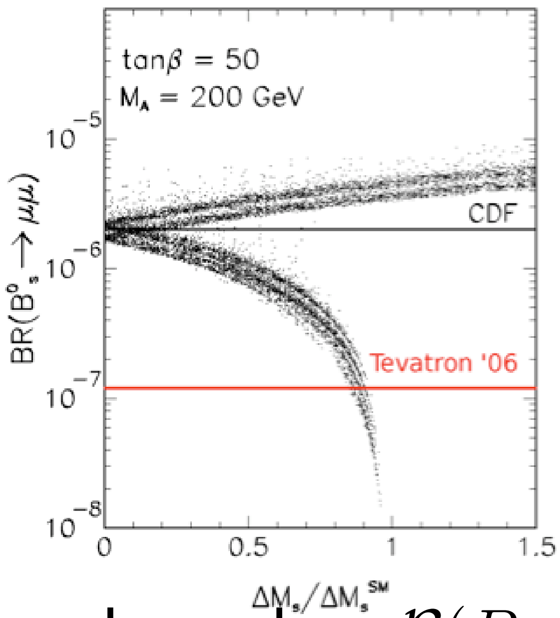


II. large $\tan\beta$: hep-ph/0210145 $h = \underbrace{h_{H^\pm}}_{<0} + \underbrace{h_{\chi^\pm}}_{>0} + \underbrace{h_{DP}}_{<0}$, $\sigma = 0$

$h < 0$ in most of the parameter space; $h(B_d) \neq h(B_s)$ due to DP

DP: double penguin from neutral Higgses: DP$(B_s) \propto m_s \tan\beta^4$ big!

Δm_s correlated with $\mathcal{B}(B_s \to \mu^+\mu^-) < 1.2 \cdot 10^{-7}$ hep-ph/0207241



lower bound on Δm_s predicts upper bound on $\mathcal{B}(B_s \to \mu^+\mu^-)$

$B_s - \bar{B}_s$ in MVF NMSSM @ large $\tan\beta$

$W = QY_uH_uU + QY_dH_dD + LY_eH_dE + \lambda H_dH_uN - \frac{1}{3}kN^3$ N:singlet

at large $\tan\beta$: naturally light pseudoscalar A_1^0, radiatively stable

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

iff very light and weakly coupled, A_1^0 becomes missing E

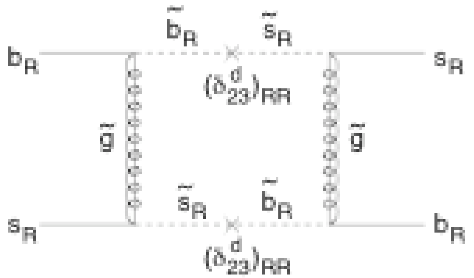
$h^0 \to A^0A^0$ very important for Higgs searches hep-ph/0005308

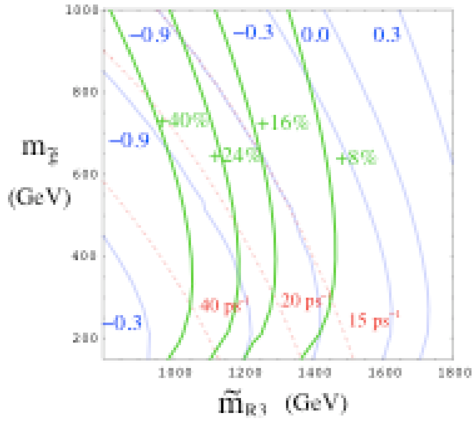
NMSSM at large $\tan\beta$: $h = h_{MSSM}^{large\ \tan\beta} + h_{A_1^0}$; $h_{A_1^0} \propto \tan\beta^2/m_{A_1^0}^2$

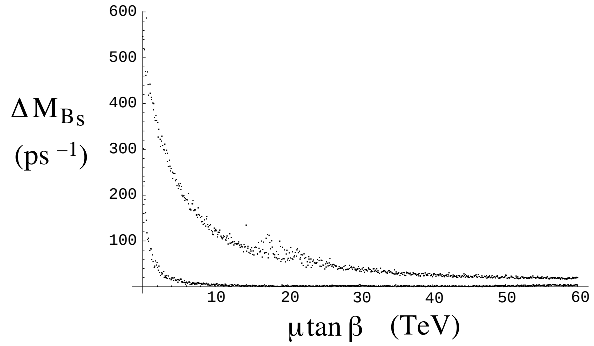
$h_{A_1^0}(B_d) = h_{A_1^0}(B_s)$

from Δm_d-measurement: $|h| \lesssim 0.4$

unlike MSSM, no correlation with $\mathcal{B}(B_s \to \mu^+\mu^-)$ hep-ph/0404220 large $\nu_\mu - \nu_\tau$ mixing in $SO(10)$ GUT models implies large mixing between right handed $\tilde{s} - \tilde{b}$: $(\delta^D_{23})_{RR}$ large and complex Figs from hep-ph/0212180







implications: Δm_s can be huge $\sim 100\ ps^{-1}$ (range in right fig)
but can be also SM-like (middle fig):

needs heavy superpartners $m_{Q2,Q3,D2} \sim$ 2TeV
or small couplings $(\delta^D_{23})_{RR}$

(green: percent increase in $B(b \to s\gamma)$, blue: $S_{\Phi K_S}$)

Summary

- CKM@tree: input for SM tests and flavor model building thanks to tremendeous exp and th (loops, HQET, lattice, ..) efforts
- in 2005 $\sin 2\beta_{\text{penguin}}$ moved closer to MFV, some hints $\eta' K^0$
- $b \to s\ell\ell$ modes under th and exp investigation; model independent analysis (w. $b \to s\gamma$) $\to$ do e and μ separately long term goal: angular analysis in $B \to K^*(\to K\pi)\ell\ell$
- tool in peguin-physics: multi-observable analyses and fits
- $b \to d$ FCNCs beginning to be probed
- B_s, B_c, Λ_b-physics coming up CDF&D0; much more from LHC(b)

Summary

- an upper bound on $B_s - \bar{B}_s$ mixing touches unknown territory

  IFF $\Delta m_s \simeq \Delta m_s^{\rm SM}$

- generically, $O(1)$ NP allowed with some amount of fine-tuning and CP-phase; further constrains from $\Delta\Gamma$ and CP-asymmetries
- models with MFV, such as CMSSM can accommodate SM-like $B_s - \bar{B}_s$-mixing within errors $|h| < \epsilon$
- models beyond MFV are constrained by this significantly
- $|V_{td}/V_{ts}|_{treeUT}$ vs $|V_{td}/V_{ts}|$ from $\frac{\Delta m_d}{\Delta m_s} = \left|\frac{V_{td}}{V_{ts}}\right|^2 \xi^{-2} \frac{m_{B_d}}{m_{B_s}}$: SM test !
- so far no significant conflict with SM/MFV; many FCNCs only weakly or just un-constrained$V+A$, $\tau^\pm$, $\nu\bar{\nu}$, $b \to d$, B_s-physics

Some (further) SM tests 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
spin $\Lambda_b \to \Lambda\gamma$	–	$\sim m_s/m_b$	V+A FCNCs
$\mathcal{B}(B \to X_s g)$	$< 9\%$ CLEO'97	$5.0 \pm 1.0 \cdot 10^{-3}$	NP in bsg
TDCPA $b \to s\bar{s}s$	$S_{ave} = 0.50 \pm 0.06$	$\sin 2\beta + \Delta S$	CPX
$\mathcal{B}(B \to X_s \bar{\mu}\mu)$	$4.3 \pm 1.2 \cdot 10^{-6}$	$4.3 \pm 0.7 \cdot 10^{-6}$	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
$\mathcal{B}(B_s \to \mu^+\mu^-)$	$< 1.2 \cdot 10^{-7}$	$3.2 \pm 1.5 \cdot 10^{-9}$	$O(50)$ 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
$\mathcal{B}(B_d \to \tau^+\tau^-)$	$< 3.4 \cdot 10^{-3}$ BaBar'05	$2.1 \pm 0.3 \cdot 10^{-8}$	$O(10^5)$ from SM

order 1 NP on $\Delta m_s^{\rm SM} \sim (V_{tb}^* V_{ts})^2 \frac{g^4}{16\pi^2} \frac{(\bar{b}\Gamma s)(\bar{b}\Gamma' s)}{m_W^2}$ implies

	NP from loops	tree level NP
MFV	$\Lambda \gtrsim m_W \sim O(100)$ GeV	$\Lambda \gtrsim 4\pi m_W \sim O(1)$ TeV
non MFV	$\Lambda \gtrsim m_W/\|V_{ts}\| \sim O(2-3)$ TeV	$\Lambda \gtrsim 4\pi m_W/\|V_{ts}\| \sim O(30)$ TeV

origin of flavor is still a mystery

whether it is connected to the NP scale Λ we are probing now