CP-Violation and Rare B-Decays in the SM & SUSY

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Plan of Talk

- Flavour Mixing in the SM & SUSY
- CP-Violation in B-decays & possible SUSY effects
- Rare B-decays in the SM & SUSY
- Summary

The Cabibbo-Kobayashi-Maskawa Matrix

$$V_{\rm CKM} \equiv \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$

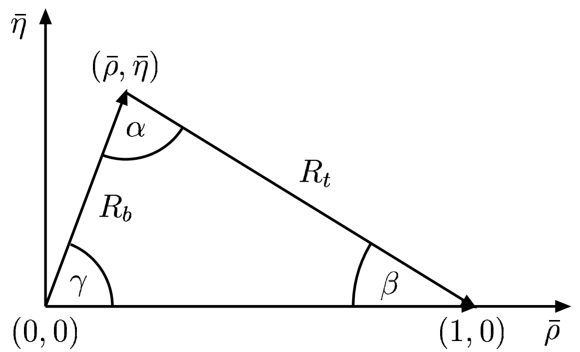
- Customary to use the handy Wolfenstein parametrization

$$V_{\rm CKM} \simeq \begin{pmatrix} 1-\frac{1}{2}\lambda^2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda(1+iA^2\lambda^4\eta) & 1-\frac{1}{2}\lambda^2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2(1+i\lambda^2\eta) & 1 \end{pmatrix}$$

- Four parameters: $A, \ \lambda, \ \ \rho, \ \ \eta$
- Perturbatively improved version of this parametrization

$$\bar{\rho} = \rho(1-\lambda^2/2), \ \ \bar{\eta} = \eta(1-\lambda^2/2)$$

- The CKM-Unitarity triangle $[\phi_1 = \beta; \ \ \phi_2 = \alpha; \ \ \phi_3 = \gamma]$



Superfield Classification in the MSSM

- Superfields classified according to their $SU(3)_C \otimes SU(2)_I \otimes U(1)_Y$ Quantum Numbers; $i = 1, 2, 3$ a generation index
- Chiral Superfields for Quarks $(\hat{Q}_i, \hat{U}_i^c, \hat{D}_i^c)$

$$\hat{Q}_i(3, 2, 1/6); \quad \hat{U}_i^c(\bar{3}, 1, -2/3); \quad \hat{D}_i^c(\bar{3}, 1, 1/3)$$

$$\hat{Q}_i = (\tilde{Q}_{L_i}, Q_{L_i}); \quad \hat{U}_i^c = (\tilde{U}_{L_i}^c, U_{L_i}^c); \quad \hat{D}_i^c = (\tilde{D}_{L_i}^c, D_{L_i}^c)$$

- Chiral Superfields for Leptons $(\hat{L}_i, \hat{E}_i^c)$

$$\hat{L}_i(1, 2, -1/2); \quad \hat{E}_i^c(1, 1, 1)$$

$$\hat{L}_i = (\tilde{E}_{L_i}, E_{L_i}); \quad \hat{E}_i^c = (\tilde{E}_{L_i}^c, E_{L_i}^c)$$

- Chiral Superfields for Two Higgs Doublets (also denoted as $\hat{H}_1$ & $\hat{H}_2$)

$$\hat{H}_u(1, 2, -1/2); \quad \hat{H}_d(1, 2, 1/2)$$

$$\hat{H}_u = (H_u, \tilde{H}_u); \quad \hat{H}_d = (H_d, \tilde{H}_d)$$

- Vector Superfields $(\hat{G}, \hat{W}, \hat{B})$ (α is an SU(2) index)

$$\hat{G}(8, 1, 1); \quad \hat{W}^\alpha(1, 3, 1); \quad \hat{B}(1, 1, 1)$$

$$\hat{G} = (g, \tilde{g}); \quad \hat{W} = (W^\alpha, \tilde{W}^\alpha); \quad \hat{B} = (B, \tilde{B})$$

Flavour Mixing in the MSSM

- Flavour mixings in the MSSM reside in the Superpotential $W_{\rm MSSM}$ and in the soft supersymmetry-breaking Lagrangian $\mathcal{L}_{\rm soft}$
- Assume R-parity: $R = (-1)^{3(B-L)+2S}$; where $B(L)$ is Baryon (Lepton) quantum number and S is the spin: SM particles are R-even, supersymmetric particles are R-odd
- $W_{\rm MSSM}$

$$W_{\rm MSSM} = \epsilon_{\alpha\beta}[-\hat{H}_u^\alpha \hat{Q}_i^\beta Y_u^{ij} \hat{U}_j^c + \hat{H}_d^\alpha \hat{Q}_i^\beta Y_d^{ij} \hat{D}_j^c + \hat{H}_d^\alpha \hat{L}_i^\beta Y_e^{ij} \hat{E}_j^c - \mu \hat{H}_d^\alpha \hat{H}_u^\beta]$$

$$\epsilon_{\alpha\beta} = -\epsilon_{\beta\alpha}; \quad \epsilon_{12} = 1$$

- $\mathcal{L}_{\rm soft}$

$$\mathcal{L}_{\rm soft} = \frac{1}{2}[M_3 \tilde{g}\tilde{g} + M_2 \tilde{W}^\alpha \tilde{W}^\alpha + M_1 \tilde{B}\tilde{B} + h.c.]$$
$$+\epsilon_{\alpha\beta}[-bH_d^\alpha H_u^\beta - H_u^\alpha \tilde{Q}_i^\beta \tilde{A}_{u_{ij}} \tilde{U}_j^c + H_d^\alpha \tilde{Q}_i^\beta \tilde{A}_{d_{ij}} \tilde{D}_j^c + H_d^\alpha \tilde{L}_i^\beta \tilde{A}_{e_{ij}} \tilde{E}_j^c + h.c.]$$
$$+m_{H_d}^2 |H_d|^2 + m_{H_u}^2 |H_u|^2 + \tilde{Q}_i^\alpha m_{Q_{ij}}^2 \tilde{Q}_j^{\alpha *}$$
$$+\tilde{L}_i^\alpha m_{L_{ij}}^2 \tilde{L}_j^{\alpha *} + \tilde{U}_i^{c*} m_{U_{ij}}^2 \tilde{U}_j^c + \tilde{D}_i^{c*} m_{D_{ij}}^2 \tilde{D}_j^c + \tilde{E}_i^{c*} m_{E_{ij}}^2 \tilde{E}_j^c$$

- MSSM contains 124 parameters residing in the Superpotential $W_{\rm MSSM}$ (Yukawa couplings) and Soft-SUSY-breaking $\mathcal{L}_{\rm soft}$ (Scalar) terms
- Various realizations of the MSSM differ from each other in the details of $\mathcal{L}_{\rm soft}$

SUGRA and mSUGRA models

- CKM matrix is the only source of Flavour transitions
- In SUGRA models, this is achieved by assuming that the SUSY-breaking parameters have a simple structure at the GUT scale (m_X)

$$(m_Q^2)_j^i = (m_E^2)_j^i = (m_D^2)_j^i = (m_U^2)_j^i = (m_L^2)_j^i = M_0^2 \delta_j^i$$

$$m_{H_d}^2 = m_{H_u}^2 = \Delta_0^2$$

$$M_1 = M_2 = M_3 = M_{1/2}$$

$$A_{d_{ij}} = A_0 (Y_d)_{ij}; \quad Au_{ij} = A_0 (Y_u)_{ij}; \quad Ae_{ij} = A_0 (Y_e)_{ij}$$

- In MSUGRA model, in addition $\Delta_0^2 = M_0^2$
- RG running ($m_X \to m_W$) induces flavour non-diagonal terms, but they are small
- This reduces the number of parameters enormously, leaving the parameters: M_0, $M_{1/2}$, $|A_0|$, $\tan\beta$, ϕ_μ, ϕ_A, where the phases are constrained by the EDMs
- Minimal flavour violation (MFV) models are highly predictive, and hence highly constrained

General Flavour Violating SUSY & The MIA Technique

- In a general SUSY Model, many more sources of Flavour Violation
- A technique to carry out an analysis in a general SUSY framework is the Mass Insertion Approximation (MIA) [Hall, Kostelecky, Raby 1986]
- In the MIA approach, one choses a basis in which the couplings of $\tilde{f}_i \tilde{g} f_j$ are flavour-diagonal $(\propto \ \delta_{ij})$; FC take place on the sfermion propagators by mass insertions: Δ^u_{ij}, Δ^d_{ij} etc.

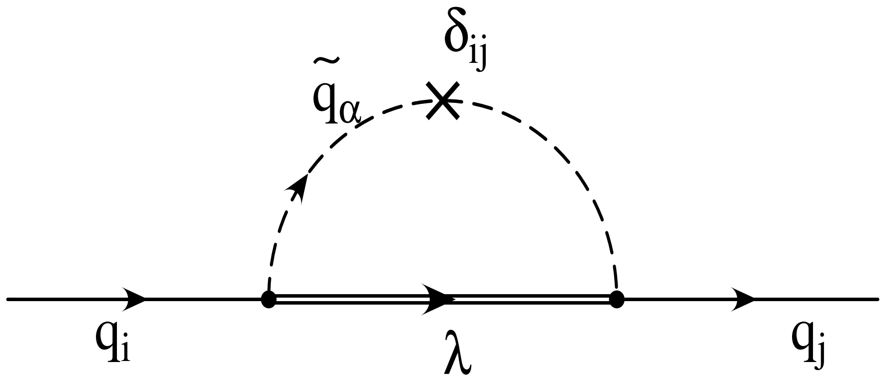
$$(m_0^2)_i \delta_{ij} + \Delta_{ij}$$

- Need not know the full diagonalization of the sfermion $(\tilde{f})$ mass matrices; sufficient to compute the ratios ($\langle m_0^2 \rangle$ is an average sfermion mass squared):

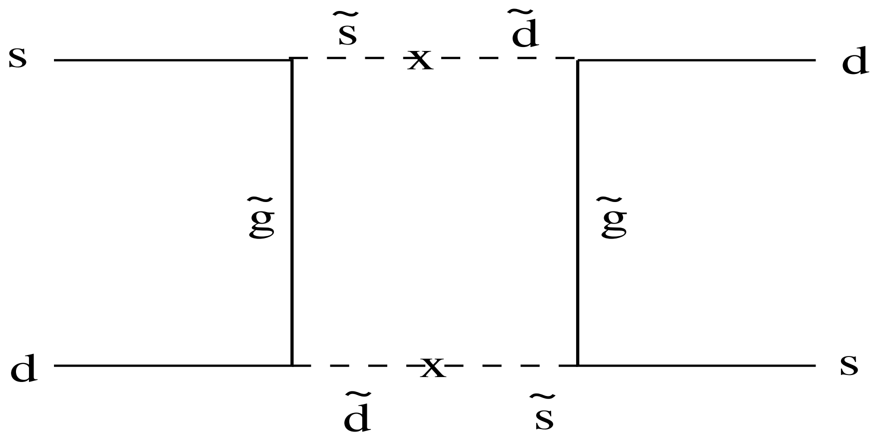
$$\delta_{ij} = \frac{\Delta_{ij}}{\langle m_0^2 \rangle}$$

- All FC effects can be parametrized in terms of a limited number of complex MIA parameters: $(\delta^u_{ij})_{AB}$ & $(\delta^u_{ij})_{AB}$, $(A, B = L, R)$
- Typically, one expects $(\delta^f_{ij})_{AB} \leq 1$
- Analysis for FV processes can then be carried out in terms of the SUSY-MFV contributions and the MIA parameters [Masiero et al.,...]

Typical Mass Insertion Diagrams



A SUSY contribution for K^0 - $\overline{K^0}$ Mixing

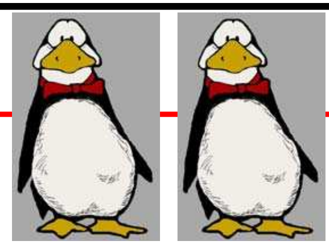


- For B_d^0 - $\overline{B_d^0}$ Mixings: $s \longrightarrow b$; $\tilde{s} \longrightarrow \tilde{b}$
- For B_s^0 - $\overline{B_s^0}$ Mixings: $d \longrightarrow b$; $\tilde{d} \longrightarrow \tilde{b}$

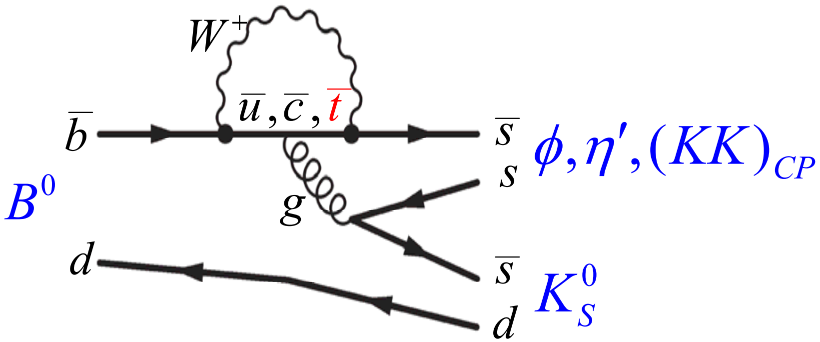
A list of flavour-violating observables

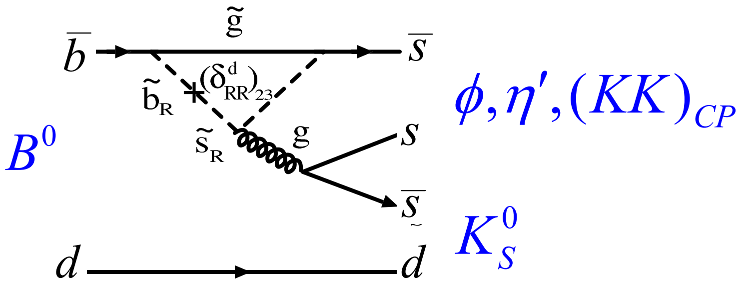
Observable	SM Prediction	MSSM-MIA (AB=LL, LR, RL, RR)
Δm_K	$\sim (V_{cs}^* V_{cd})^2$	$(\delta_{AB})_{12}$
ϵ	$\sim \text{Im}(V_{ts}^* V_{td}) \text{Re}(V_{cs}^* V_{cd})$	$(\delta_{AB})_{12}$
$\epsilon^{'}/\epsilon$	$\sim \text{Im}(V_{ts}^* V_{td})$	$(\delta_{AB})_{12}$
$b \to s\gamma$	$\sim V_{tb} V_{ts}^*$	$(\delta_{AB})_{23}$
$A_{CP}(b \to s\gamma)$	$\sim \alpha_s(m_b) \frac{V_{ub}}{V_{cb}} \frac{m_c^2}{m_b^2}$	$(\delta_{AB})_{23}$
Δm_{B_d}	$\sim (V_{td}^* V_{tb})^2$	$(\delta_{AB})_{13}$
Δm_{B_s}	$\sim (V_{ts}^* V_{tb})^2$	$(\delta_{AB})_{23}$
$A_{CP}(B \to \psi K_S)$	$= \sin 2\beta$	$(\delta_{AB})_{13}$
$A_{CP}(B \to \phi K_S)$	$= \sin 2\beta$	$(\delta_{AB})_{23}$

Feynman Diagrams for $\sin 2\beta$ from Penguins

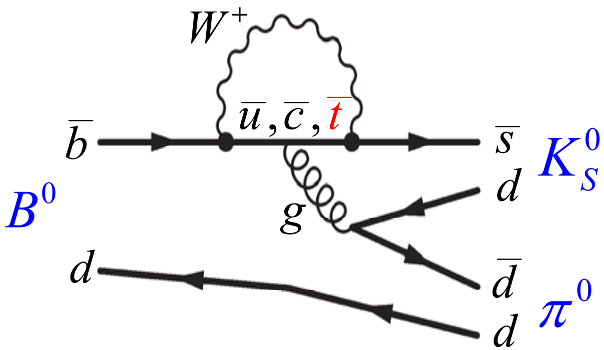
$\sin 2\beta$ and...  and.... 

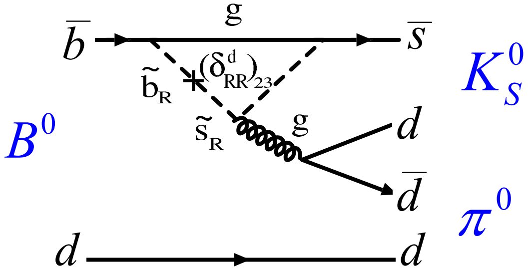
In SM interference between B mixing, K mixing and Penguin $b \to s\bar{s}s$ or $b \to s\bar{d}d$ gives the same $e^{-2i\beta}$ as in tree process $b \to c\bar{c}s$. However loops can also be sensitive to New Physics!





New phases from SUSY?





ICHEP04-北京
August 20, 2004

Marcello A. Giorgi

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Introduction to CP Violation in B Decays & Mixings -1

- CKM Violation in the SM is due to the phase η in the CKM matrix
- All CP violations in the SM are due to the interference of two *different* amplitudes

Three Classes of CP Violation in B Decays

1. Direct CP Violation: e.g., in $B^\pm \to K_s \pi^\pm$ decays

$$\mathcal{A}_{\rm CP} = \frac{2|A_1||A_2| \sin(\delta_1 - \delta_2) \sin(\phi_1 - \phi_2)}{|A_1|^2 + 2|A_1||A_2| \cos(\delta_1 - \delta_2) \cos(\phi_1 - \phi_2) + |A_2|^2}$$

   • Requires Strong phase difference $(\delta_1 - \delta_2) \neq 0$ & Weak phase difference $(\phi_1 - \phi_2) \neq 0$; Difficult to calculate

2. Indirect CP Violation:

$$\mathcal{A}_{\rm SL} = \frac{\Gamma(\overline{B^0} \to \ell^+ X) - \Gamma(B^0 \to \ell^- X)}{\Gamma(\overline{B^0} \to \ell^+ X) + \Gamma(B^0 \to \ell^- X)}$$

   • Involves the relative phase in the absorptive & dispersive parts of the B^0 - $\overline{B^0}$ Mixing Amplitude: $\mathcal{A}_{\rm SL} = {\rm Im}(\frac{\Gamma_{12}}{M_{12}})$

   • Writing $(\frac{\Gamma_{12}}{M_{12}})_q = r_q e^{i\zeta_q}$: $\mathcal{A}_{\rm SL}(B_d) = r_d \sin \zeta_d$

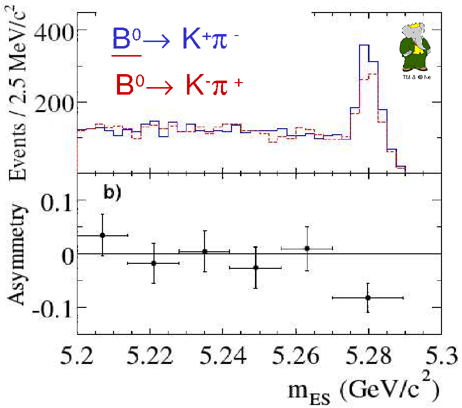
   • SM (NLO): $\mathcal{A}_{\rm SL}(B_d) = -(5.5 \pm 1.3)(10^{-4})$ [Beneke et al.; Ciuchini et al.]

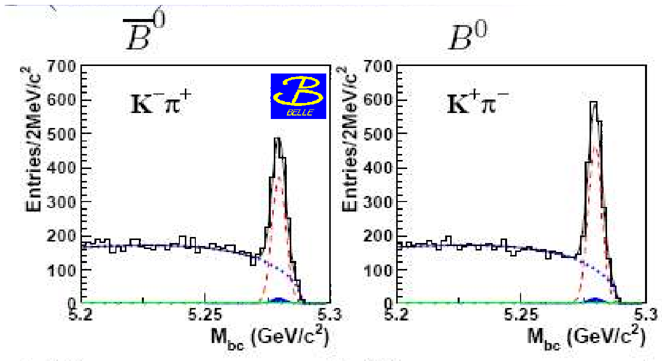
   • Present Experimental Constraint: $\mathcal{A}_{\rm SL}(B_d) = (-0.05 \pm 0.71) \times 10^{-2}$

Direct CP-asymmetry in $B \to K\pi$ [EPS 2005]

Direct CP violation

For two-body decays : only seen clearly (> 4σ) in one single channel





Experiment	$A_{K\pi}$	# σ
BaBar (227 x 10⁶ BB)	$-0.133 \pm 0.030_{stat} \pm 0.009_{syst}$	4.2
BELLE (386 x 10⁶ BB)	$-0.113 \pm 0.022_{stat} \pm 0.008_{syst}$	~5

For three-body decays : first sign of direct CPV

Full Dalitz Kππ fit

$A_{CP}(\rho^0 K^\pm) = (30 \pm 11_{stat} {}^{+11}_{-4}{}_{syst+model})\%$ BELLE (386 x 10⁶ BB)

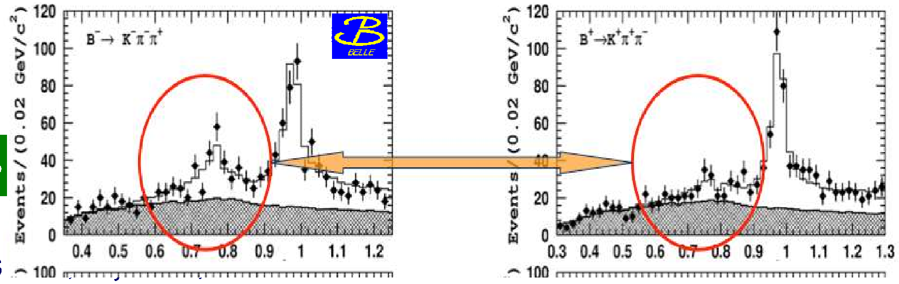
Fit projections in the ρ region

Direct CP violation at 3.9

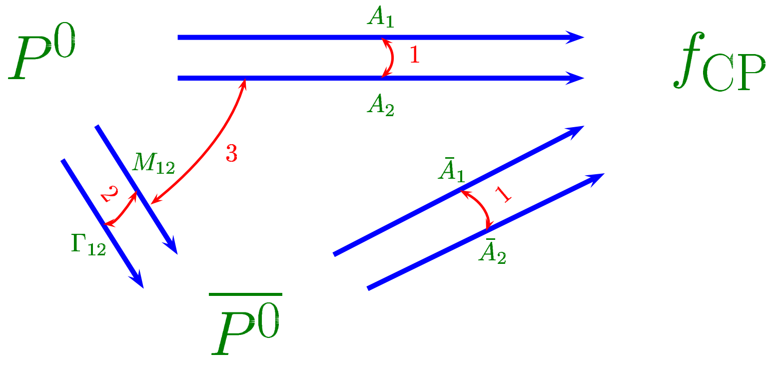
$A_{CP}(\rho^0 K^\pm) = (34 \pm 13_{stat} \pm 6_{syst} {}^{+15}_{-20}{}_{model})\%$

BABAR 227 10⁶ BB

HEP-EPS



CP violation in neutral meson decay into a CP eigenstate



1. In decay: $\bar{A}/A \neq 1$ $\quad \left(\frac{\bar{A}}{A} = \frac{\bar{A}_1+\bar{A}_2}{A_1+A_2}\right)$
   (For example, A_1 is a Tree amplitude & A_2 is Penguin)
2. In mixing: $|q/p| \neq 1$ $\quad \left(\frac{q}{p} = \frac{2M_{12}^* - i\Gamma_{12}^*}{\Delta m - (i/2)\Delta\Gamma}\right)$
3. In interference: $\mathcal{I}m\lambda \neq 1$ $\quad \left(\lambda = \frac{q}{p}\frac{\bar{A}}{A}\right)$

- The case theorists love!
  - Decay dominated by a single CPV phase: $|\frac{\bar{A}}{A}| = 1$;
  - CPV in mixing negligible $|\frac{q}{p}| = 1$;
  - The remaining eefect is: $S_f \sim \sin[\arg(M_{12}) - 2\arg(A)] = 1$

Interplay of Mixing & Decays of B^0 and $\overline{B^0}$ to CP Eigenstate

- Involving tree-dominated B-decays ($b \to c\bar{c}s$), such as $B^0/\overline{B^0} \to J/\psi K_s;\ J/\psi K_L$

$$\mathcal{A}_f(t) = \frac{\Gamma(\overline{B^0}(t) \to f) - \Gamma(B^0(t) \to f)}{\Gamma(\overline{B^0}(t) \to f) + \Gamma(B^0(t) \to f)}$$

$$= C_f \cos(\Delta M_B t) + S_f \sin(\Delta M_B t)$$

$$C_f = \frac{(|\lambda_f|^2) - 1}{(|\lambda_f|^2 + 1)}; \quad S_f = \frac{2\ \mathrm{Im}\lambda_f}{(|\lambda_f|^2 + 1)}$$

- Definitions:

$$\lambda_f \equiv (q/p)\ \rho(f); \quad \rho(f) = \frac{\bar{A}(f)}{A(f)}$$

$$A(f) = \langle f|H|B^0\rangle; \quad \bar{A}(f) = \langle f|H|\overline{B^0}\rangle$$

$$q/p = \frac{V_{tb}^* V_{td}}{V_{tb} V_{td}^*} = \mathrm{e}^{-2i\phi_{\mathrm{mixing}}} = \mathrm{e}^{-2i\beta}$$

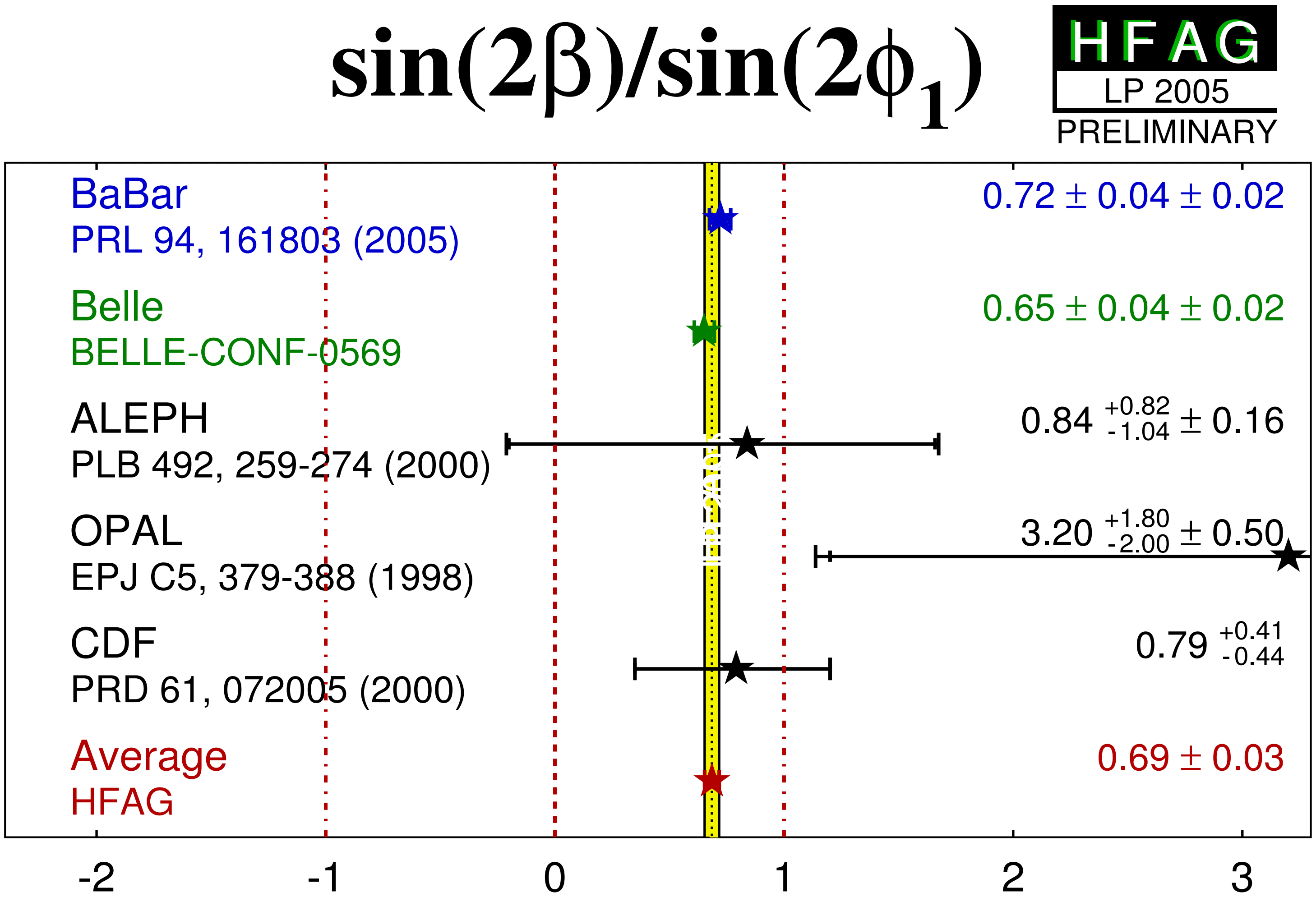
- If only a Single Amplitude dominant, then one can write:

$$\rho(f) = \eta_f \mathrm{e}^{-2i\phi_{\mathrm{decay}}}$$

where $\eta_f = \pm 1$ is the intrinsic CP-Parity of the state $f \Rightarrow |\rho(f)| = 1$

$$\mathcal{A}_f(t) = S_f \sin(\Delta M_B t);\ S_f = -\eta_f \sin 2(\phi_{\mathrm{mixing}} + \phi_{\mathrm{decay}});\ C_f = 0$$

Current World Average [EPS 2005]



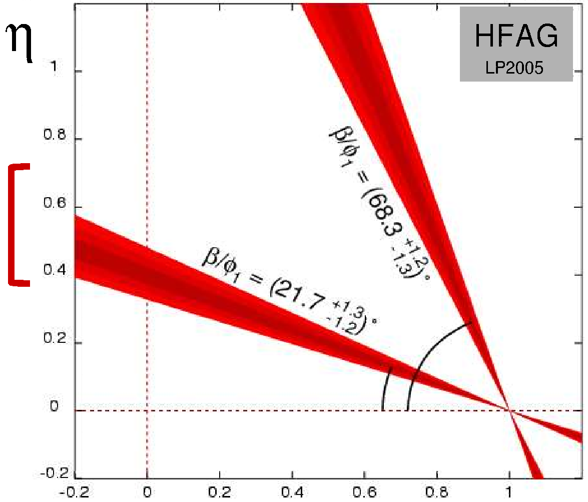
Current World Average [EPS 2005]

Determination of β/φ$_1$

Experiment	BaBar (227 x 10^6 BB)	Belle (386 x 10^6 BB)
sin2β from (cc) K_S	$0.75 \pm 0.04_{stat}$	$0.668 \pm 0.047_{stat}$
(cc) K_L	$0.57 \pm 0.09_{stat}$	$0.619 \pm 0.069_{stat}$
All charmonium	$0.722 \pm 0.040_{stat} \pm 0.023_{syst}$	$0.652 \pm 0.039_{stat} \pm 0.020_{syst}$

HFAG Average : 0.685 ± 0.032 ~5% precision

Constraint from sides only: 0.720±0.024 (CKMFitter) → **Coherent description of CPV within the SM**
SM is the dominant source of CPV



Preferred solution:

Use of the $B^0 \to J/\psi K^*(\to K_s\pi^0)$ (VV decay) information on cos(2β) (after strong phase ambiguity resolution) BABAR PRD 71, 032005 (2005): cos(2β)>0 at 86%CL

HEP-EPS 2005, July 21-27, Lisboa

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Specific realizations of MFV Models

[Ciuchini et al.; Degrassi et al.; Carena et al.; London, AA; Buras et al.; Bartl et al.; Bobeth et al.;...]

- CKM matrix is the only source of Flavour transitions
- Effective Lagrangian in MFV models consists of the same operator basis as in the SM (except for Higgs-induced operators in large-$\tan\beta$-regime)

$$\mathcal{H}_{\rm eff}(\Delta F=2) = -\frac{G_F^2 m_W^2}{(2\pi)^2}(V_{tq}^* V_{tq})^2[C_1(Q)\mathcal{O}_1 + C_2(Q)\mathcal{O}_2 + C_3(Q)\mathcal{O}_3]$$

$$\mathcal{O}_1(|\Delta B|=2) = \mathcal{O}_1^{\rm SM} = \bar{d}_L^\alpha \gamma_\mu b_L^\alpha \cdot \bar{d}_L^\beta \gamma^\mu b_L^\beta$$

$$\mathcal{O}_2(|\Delta B|=2) = \bar{d}_L^\alpha b_R^\alpha \bar{d}_L^\beta b_R^\beta$$

$$\mathcal{O}_3(|\Delta B|=2) = \bar{d}_L^\alpha b_R^\beta \bar{d}_L^\beta b_R^\alpha$$

- SUSY effects are encoded in Wilson coefficients or, equivalently, in terms of a limited set of Inami-Lim functions which depend on the SUSY parameters

$$C_1(m_W) = C_1^W(m_W) + C_1^\chi(m_W, m_\chi) + C_1^H(m_W, m_H)$$

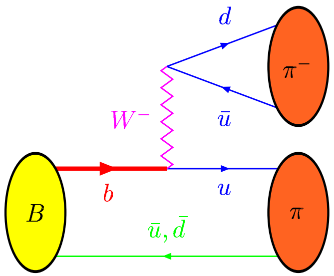
$$C_2(m_W) \propto m_b^2/m_W^2; \quad C_3(m_W) \propto m_b^2/(m_W^2 \cos^2\beta)$$

- Typically, $C_2(m_W)/C_1(m_W), C_3(m_W)/C_1(m_W) \ll 1$
- In constrained MSSM models, $C_1(m_W)^{\rm SUSY}/C_1(m_W)^{\rm SM} = 1+\delta$, with $\delta \ll 1 \Longrightarrow$ UT(MFV) similar to UT(SM)

$B \to \pi\pi$ *Topologies*

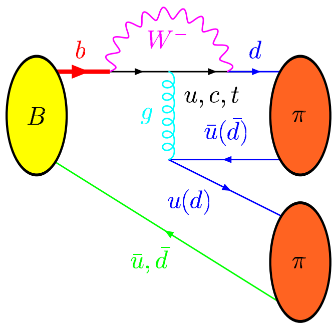
Dominant topologies contributed within the Standard Model

Tree ($\mathcal{T}$)



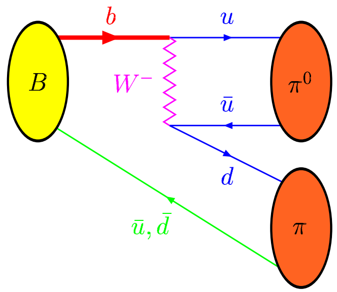
$B^- \to \pi^-\pi^0$
$\bar{B}^0 \to \pi^+\pi^-$

Penguin ($\mathcal{P}$)



$\bar{B}^0 \to \pi^+\pi^-$
$\bar{B}^0 \to \pi^0\pi^0$

Color-suppressed ($\mathcal{C}$)



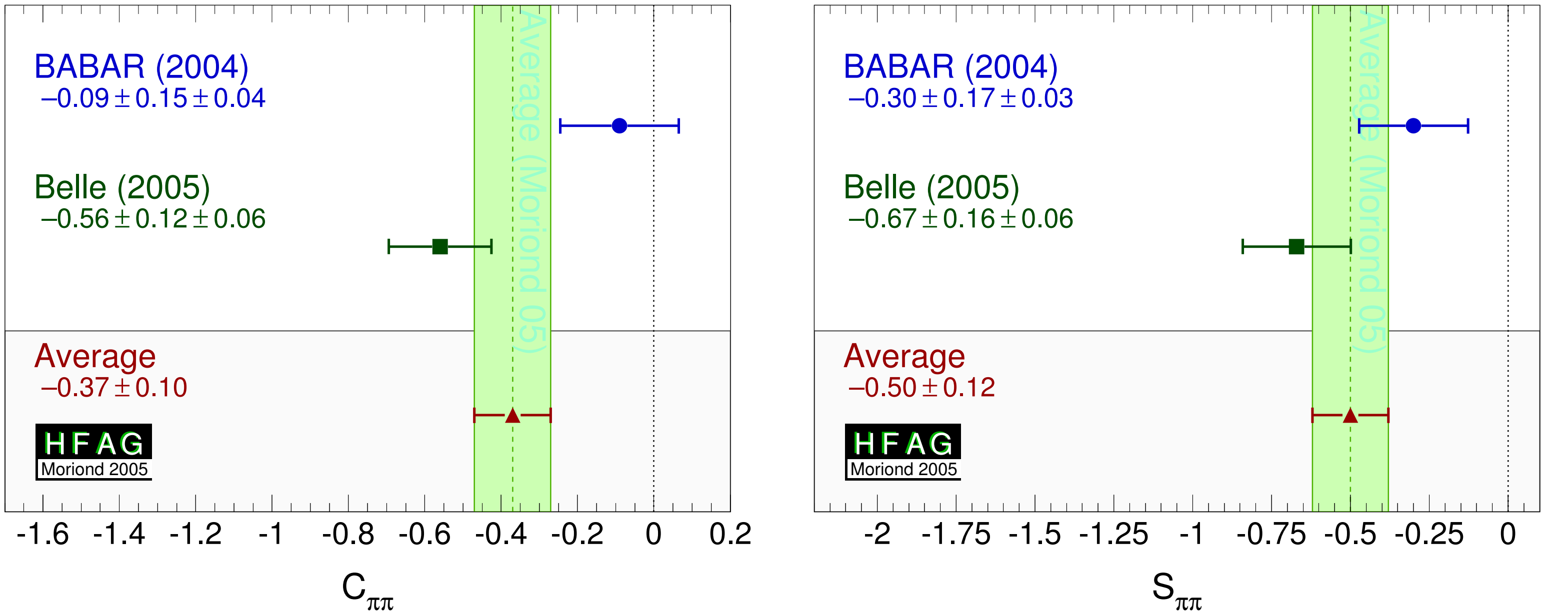
$B^- \to \pi^-\pi^0$
$\bar{B}^0 \to \pi^0\pi^0$

Subdominant topologies:

- exchange ($\mathcal{E}$) $\Longrightarrow$ $\bar{B}^0 \to \pi^+\pi^-,\ \pi^0\pi^0$
- annihilation ($\mathcal{A}$) $\Longrightarrow$ $B^- \to \pi^-\pi^0$
- penguin-annihilation ($\mathcal{PA}$) $\Longrightarrow$ $\bar{B}^0 \to \pi^+\pi^-,\ \pi^0\pi^0$
- electroweak-penguin ($\mathcal{P}_{\rm EW}$) $\Longrightarrow$ $B^- \to \pi^-\pi^0,\ \bar{B}^0 \to \pi^0\pi^0$
- color-suppressed electroweak-penguin ($\mathcal{P}^C_{\rm EW}$) $\Longrightarrow$ $\bar{B}^0 \to \pi^+\pi^-,\ \pi^0\pi^0$

Time-dependent CP-asymmetry in $B^0/\overline{B^0} \to \pi^+\pi^-$

$$
\begin{aligned}
a_{\pi\pi}^{+-}(t) &\equiv \frac{\Gamma[\bar{B}^0(t) \to \pi^+\pi^-] - \Gamma[B^0(t) \to \pi^+\pi^-]}{\Gamma[\bar{B}^0(t) \to \pi^+\pi^-] + \Gamma[B^0(t) \to \pi^+\pi^-]} \\
&= S_{\pi\pi}^{+-}(t)\sin(\Delta M_B t) - C_{\pi\pi}^{+-}(t)\cos(\Delta M_B t)
\end{aligned}
$$



- BELLE and BABAR are in better agreement now (2.3σ)

$C_{\pi\pi} - S_{\pi\pi}$ Data vs. QCDF & PQCD

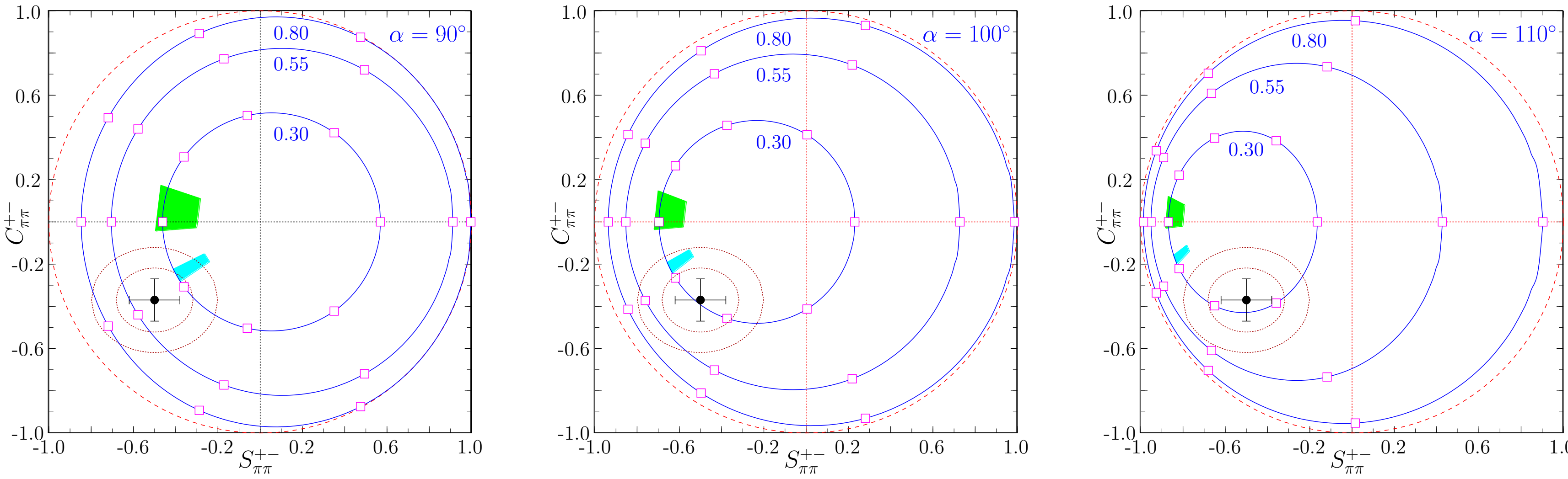
- Isospin-based analysis of data (68% C.L.)

[Lunghi, Parkhomenko, AA; Parkhomenko '05]

$$|P/T| = 0.48^{+0.09}_{-0.08} \qquad \delta = (-38^{+9.3}_{-9.0})^\circ$$

- Similar analyses by Buras et al.; Bauer et al.; Gronau et al.; ...
- Theoretical predictions based on Factorization

$$|P/T| = 0.29 \pm 0.09 \qquad \delta = (9 \pm 15)^\circ \qquad \text{QCDF}$$
$$|P/T| = 0.23^{+0.07}_{-0.05} \qquad \delta = (-37 \pm 5)^\circ \qquad \text{PQCD}$$



- Data supports large penguin contribution and strong phase difference

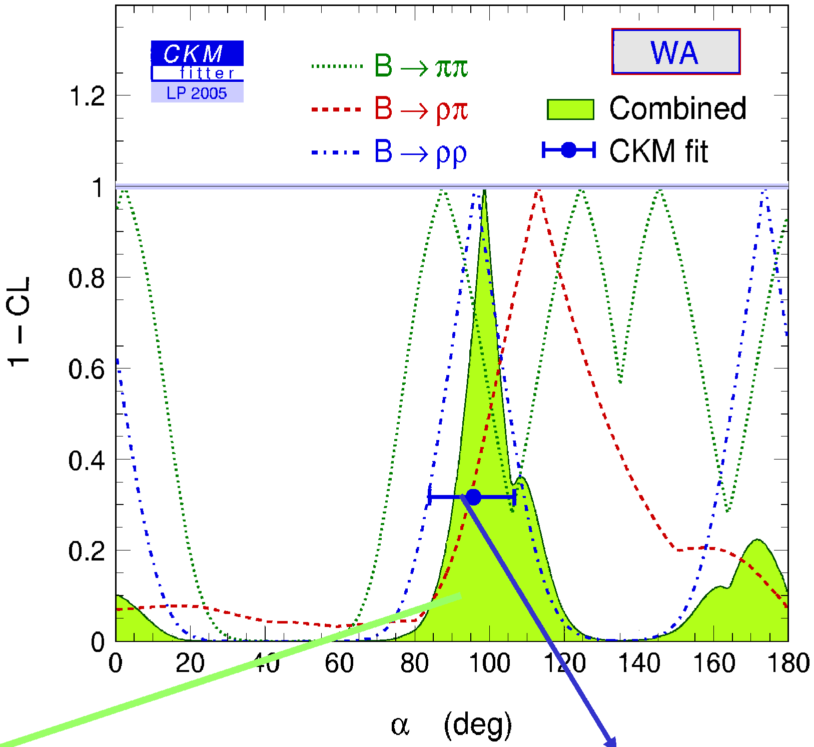
Overall constraint on α

Additional constraints on α from time dependent CP violation analysis of $B \to \rho\pi$

ππ determination very weak

ρρ best individual measurement

Mirror solution are disfavored by ρπ



$\alpha = (99^{+12}_{-9})^\circ$

Same precision as global CKM fit :

$\alpha_{CKM} = (94.9^{+9.6}_{-13.3})^\circ$

HEP-EPS 2005, July 21-27, Lisboa

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Current World Average of γ [EPS 2005]

Overall information on r_B and ϕ_3/γ from GLW, ADS, Dalitz

$r_{DK} = 0.081 \pm 0.029$ [0.021,0.138] @95% CL

$r_{D^*K} = 0.088 \pm 0.042$ [0.010,0.170] @95% CL

$r_{DK^*} = 0.15 \pm 0.09$ [0.01,0.31] @95% CL

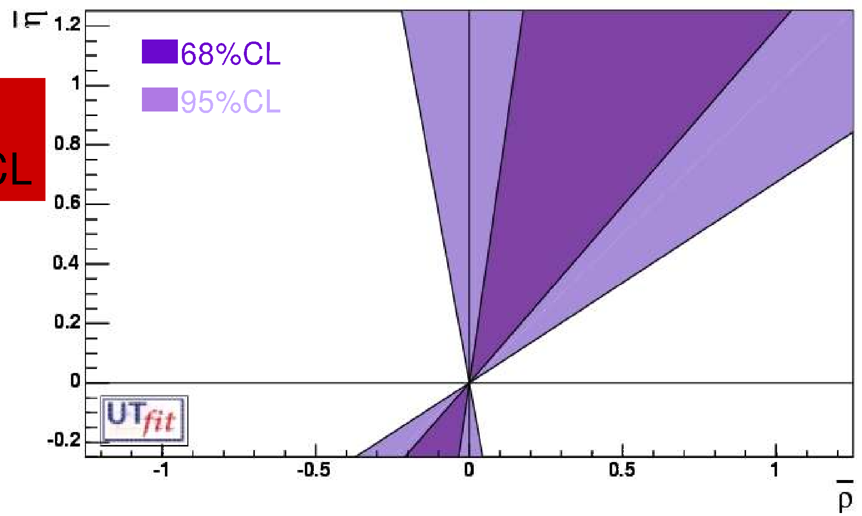
UTFit

$\Rightarrow r_B$ is small

$\Rightarrow \gamma$ is not easy to measure….

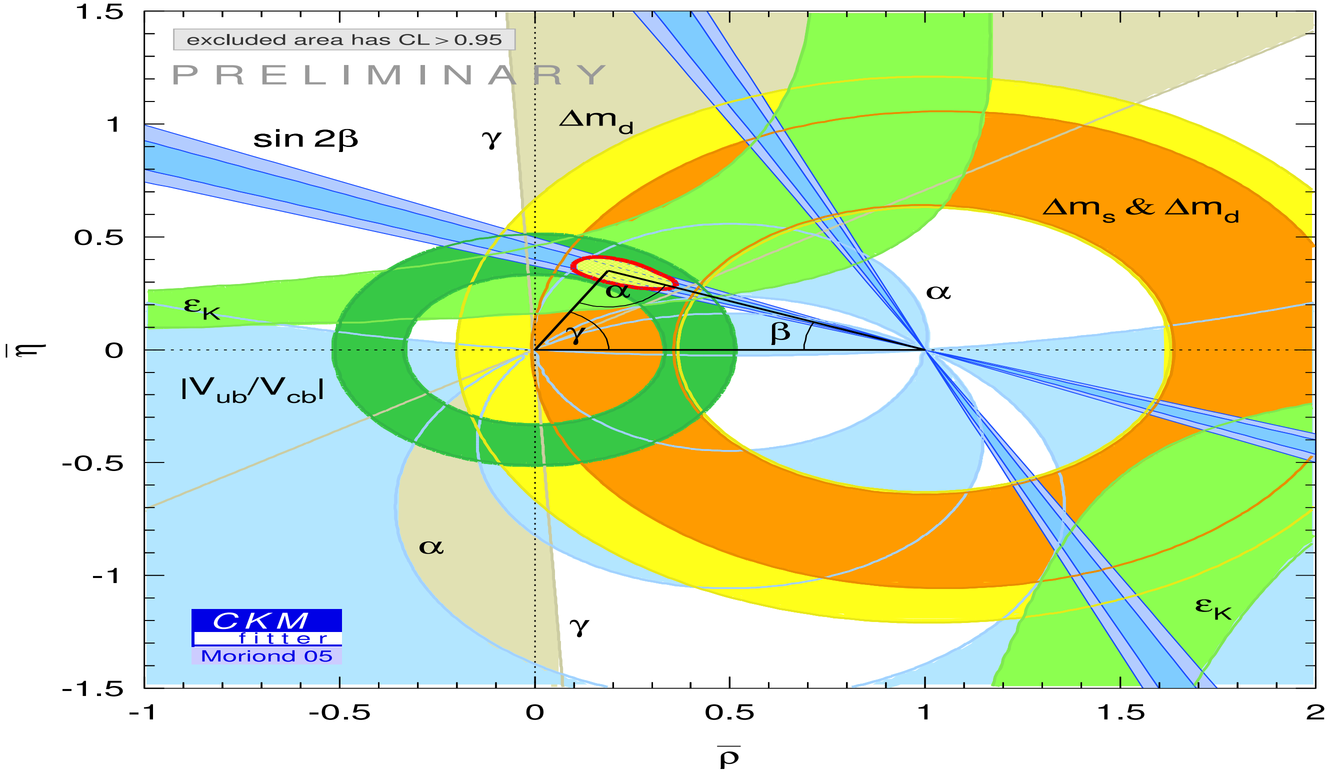
$\gamma = 66 \pm 17$ [32,102] at 95% CL

$\gamma = -114 \pm 17$ [-148,-78] at 95% CL



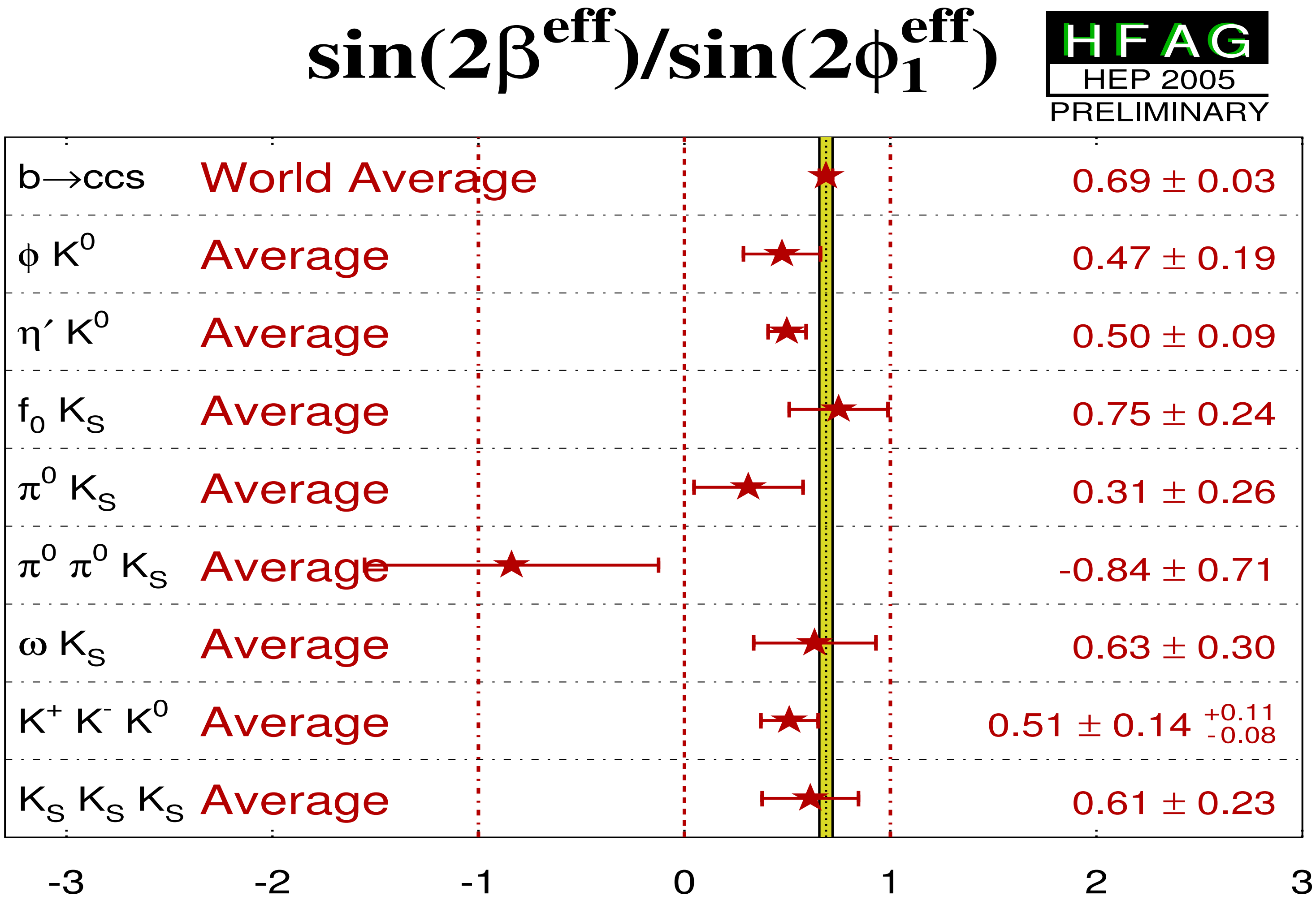
HEP-EPS 2(

SM confronts measurements of $\sin 2\beta, \quad \alpha, \quad \gamma$

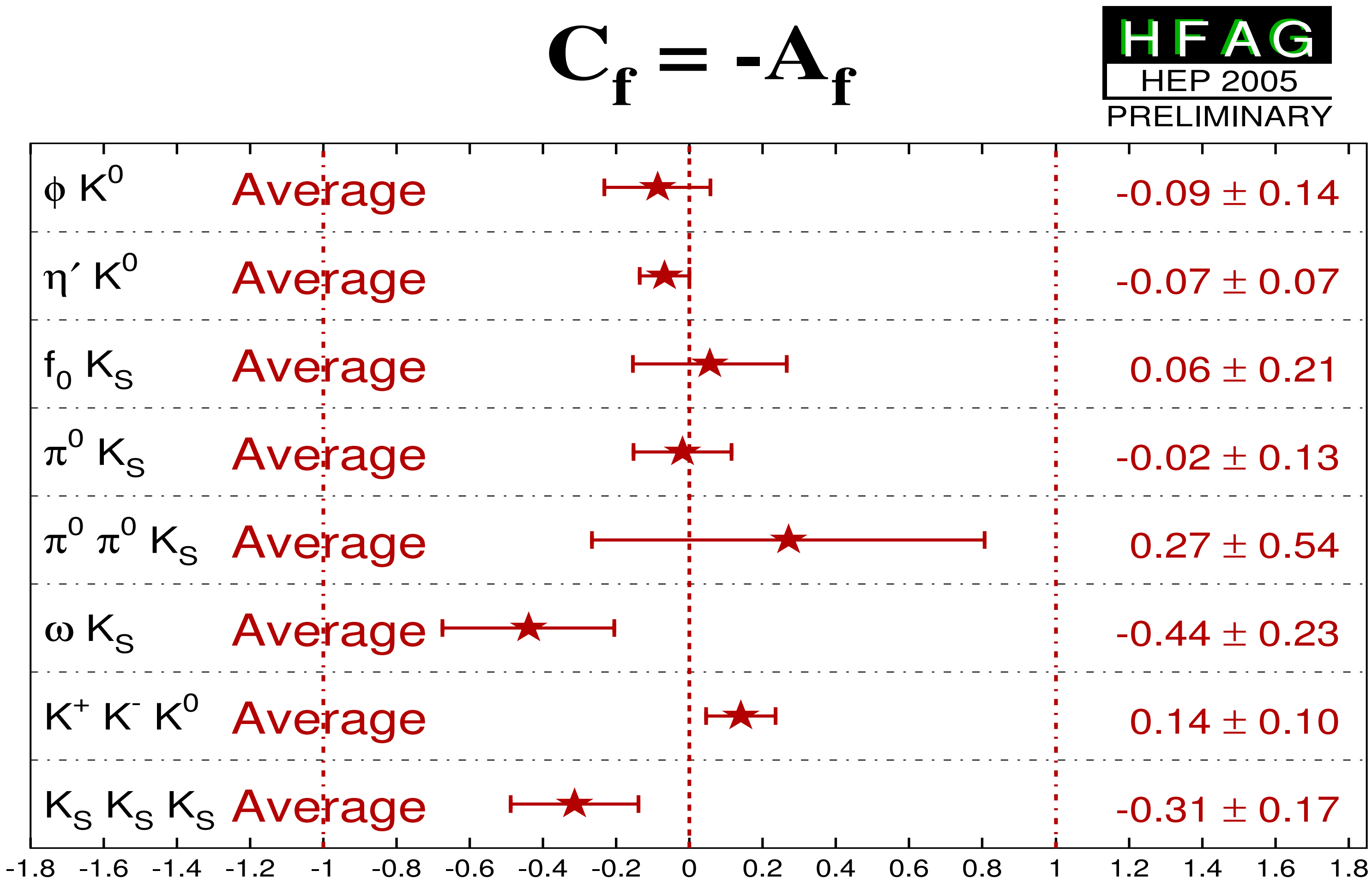


- $\sin 2\beta = 0.685 \pm 0.032 (\beta = [21.7 \pm 1.3]^\circ)$
- $\alpha = [99^{+12}_{-9}]^\circ$
- $\gamma = [66 \pm 17]^\circ$
- Direct and indirect measurements of angles agree very well
- Unconstrained sum of angles $= (187 \pm 21)^\circ$, consistent with unitarity sum within errors

$S_{b\to q\bar{q}s}$ and $C_{b\to q\bar{q}s}$ [HFAG 2005; hep-ex/0505100]



$S_{b\to q\bar{q}s}$ and $C_{b\to q\bar{q}s}$ [HFAG 2005; hep-ex/0505100]



The effective Lagrangian:

$$\mathcal{L} = \mathcal{L}_{QCD\times QED}(q,l) + \frac{4G_F}{\sqrt{2}} V_{ts}^* V_{tb} \sum_{i=1}^{10} C_i(\mu) O_i$$

$(q = u, d, s, c, b, \; l = e, \mu)$

$$O_i = \begin{cases} (\bar{s}\Gamma_i c)(\bar{c}\Gamma_i' b), & i = 1,2, \quad |C_i(m_b)| \sim 1 \\ (\bar{s}\Gamma_i b)\mathbf{\Sigma}_q(\bar{q}\Gamma_i' q), & i = 3,4,5,6, \quad |C_i(m_b)| < 0.07 \\ \frac{em_b}{16\pi^2}\bar{s}_L\sigma^{\mu\nu}b_R F_{\mu\nu}, & i = 7, \quad C_7(m_b) \sim -0.3 \\ \frac{gm_b}{16\pi^2}\bar{s}_L\sigma^{\mu\nu}T^a b_R G^a_{\mu\nu}, & i = 8, \quad C_8(m_b) \sim -0.15 \\ \frac{e^2}{16\pi^2}(\bar{s}_L\gamma_\mu b_L)(\bar{l}\gamma^\mu \gamma_5 l), & i = 9, \mathbf{10} \quad |C_i(m_b)| \sim 4 \end{cases}$$

Three steps of the calculation:

Matching: Evaluating $C_i(\mu_0)$ at $\mu_0 \sim M_W$ by requiring equality of the SM and the effective theory Green functions

Mixing: Deriving the effective theory RGE and evolving $C_i(\mu)$ from μ_0 to $\mu_b \sim m_b$

Matrix elements: Evaluating the on-shell amplitudes at $\mu_b \sim m_b$

$\bar{B} \to X_s l^+ l^-$

- The NNLO calculation of $\bar{B} \to X_s l^+ l^-$ corresponds to the NLO calculation of $\bar{B} \to X_s \gamma$, as far as the number of loops in the diagrams is concerned.

- Coefficients of the two additional operators

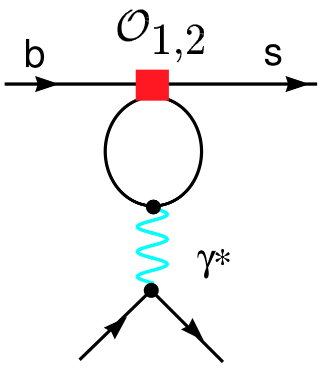
$$O_i = \frac{e^2}{16\pi^2} (\bar{s}_L \gamma_\mu b_L)(\bar{l}\gamma^\mu \gamma_5 l), \qquad i = 9, 10$$

have the following perturbative expansion:

$$\begin{aligned} C_9(\mu) &= \frac{4\pi}{\alpha_s(\mu)} C_9^{(-1)}(\mu) + C_9^{(0)}(\mu) + \frac{\alpha_s(\mu)}{4\pi} C_9^{(1)}(\mu) + \ldots \\ C_{10} &= C_{10}^{(0)} + \frac{\alpha_s(M_W)}{4\pi} C_{10}^{(1)} + \ldots \end{aligned}$$

- After an expansion in α_s, the term $C_9^{(-1)}(\mu)$ reproduces (the dominant part of) the electro-weak logarithm that originates from photonic penguins with charm quark loops:

$$\frac{4\pi}{\alpha_s(m_b)} C_9^{(-1)}(m_b) = \frac{4}{9} \ln \frac{M_W^2}{m_b^2} + \mathcal{O}(\alpha_s)$$



$C_9^{(-1)}(m_b) \simeq 0.033 \ll 1 \quad \Longrightarrow \quad \frac{4\pi}{\alpha_s(m_b)} C_9^{(-1)}(m_b) \simeq 2$

On the other hand: $\quad C_9^{(0)}(m_b) \simeq 2.2$

NNLO Calculations of BR($\bar{B} \to X_s \ell^+ \ell^-$)

- Two-loop matching, three-loop mixing and two-loop matrix elements have been completed
  - Matching: [Bobeth, Misiak, Urban]
  - Mixing: [Gambino, Gorbahn, Haisch]
  - Matrix elements:
    [Asatryan, Asatrian, Greub, Walker;
    Asatrian, Bieri, Greub, Hovhannissyan;
    Ghinculov, Hurth, Isidori, Yao;
    Bobeth, Gambino, Gorbahn, Haisch]
- Power corrections in $B \to X_s \ell^+ \ell^-$ decays
  - $1/m_b$ corrections [A. Falk et al.; AA, Handoko, Morozumi,Hiller;
    Buchalla, Isidori]
  - $1/m_c$ corrections [Buchalla, Isidori, Rey]
- NNLO Phenomenological analysis of $B \to X_s \ell^+ \ell^-$ decays
  [AA, Greub, Hiller, Lunghi]
  - $\mathrm{BR}(\bar{B} \to X_s \mu^+ \mu^-); \quad q^2 > 4m_\mu^2 = (4.2 \pm 1.0) \times 10^{-6}$
  - $\mathrm{BR}(\bar{B} \to X_s e^+ e^-) = (6.9 \pm 0.7) \times 10^{-6}$

Electroweak Penguins $b \to s\ell^+\ell^-$

- $B \to X_s\ell^+\ell^-$ decay rate

$$\mathcal{B}(B \to X_s\ell^+\ell^-) = (4.46^{+0.98}_{-0.96}) \times 10^{-6} \;\; [\mathrm{HFAG'05}]$$

$$SM: (4.2 \pm 0.7) \times 10^{-6} \;\; [\mathrm{AGHL'01}]; \;\; (4.6 \pm 0.8) \times 10^{-6} \;\; [\mathrm{GHIY'04}]$$

- Differential distributions in $B \to X_s\ell^+\ell^-$

• $M(X_s)$-distribution: tests $s \to X_s$ fragmentation model; current FMs provide reasonable fit to data

• $q^2 = M^2_{\ell^+\ell^-}$-distribution away from the $J/\psi, \psi', \ldots$ resonances is sensitive to short-distance physics; current data in agreement with the SM estimates but the precision is not better than 25%

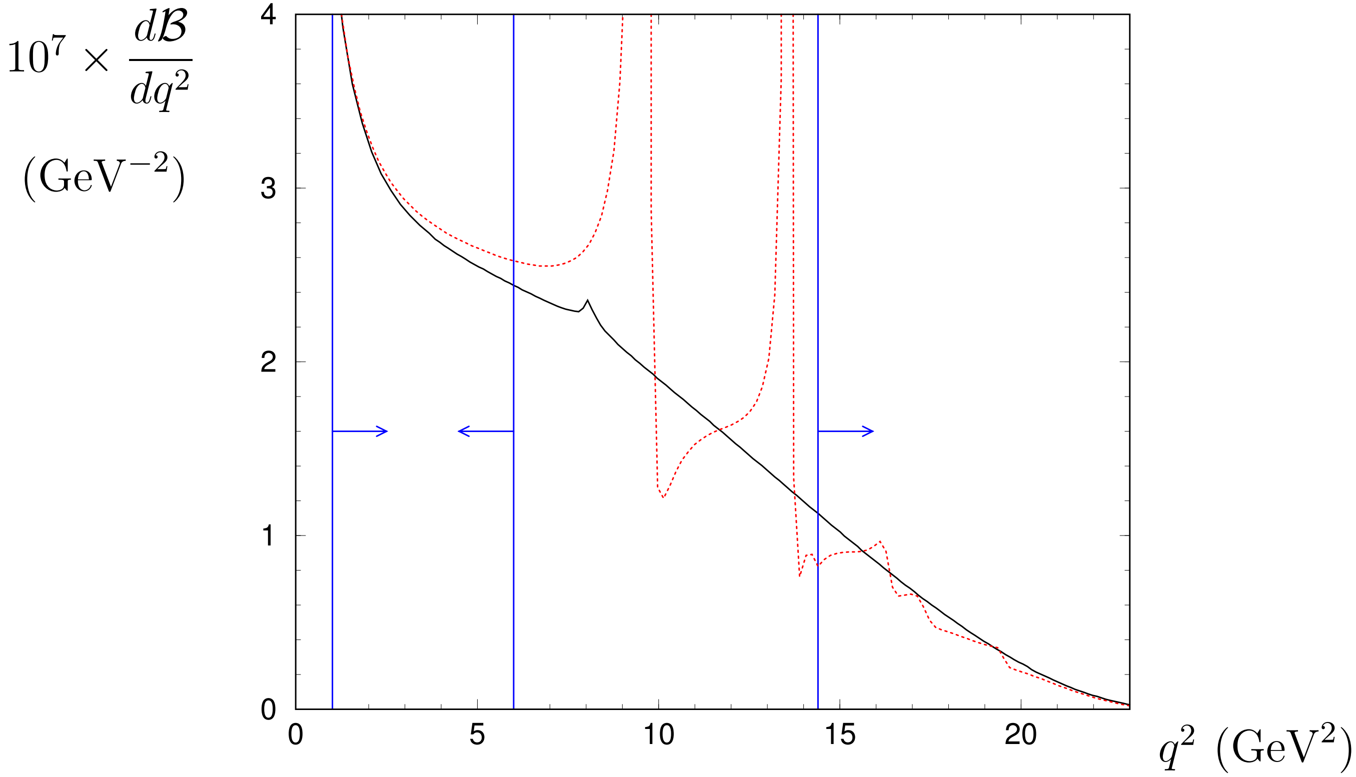
• Forward-Backward Asymmetry (FBA) is likewise sensitive to the SM and BSM effects, in particular encoded in the Wilson coefficients C_7, C_9 and C_{10}

$$A_{\mathrm{FB}}(\hat{s} \sim C_{10}(2C_7 + C_9(\hat{s})\hat{s}); \quad \hat{s} = q^2/M_B^2$$

- $A_{\mathrm{FB}}(\hat{s})$ not yet measured; possible only in experiments at B factories

Dilepton invariant mass distribution in $\bar{B} \to X_s \ell^+ \ell^-$:

[Ghinculov, Hurth, Isidori, Yao 2004]

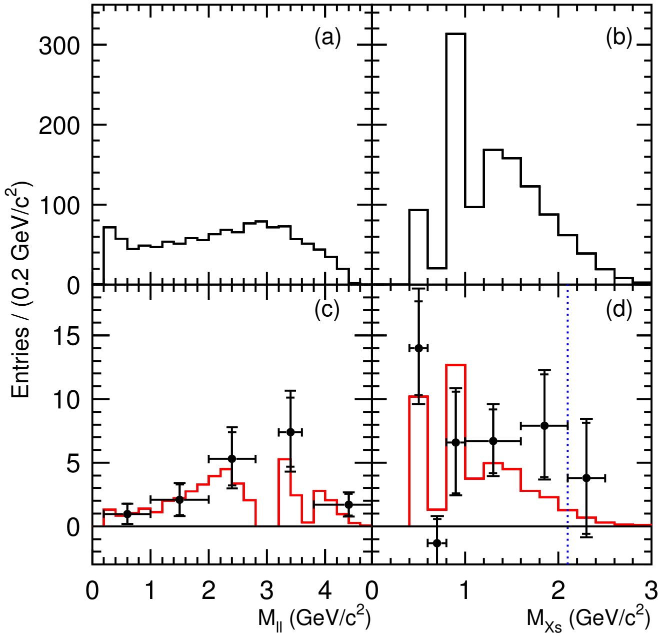


- $\mathbf{BR}(\bar{B} \to X_s \ell^+ \ell^-)$; $\quad q^2 \in [1, 6]\ \mathrm{GeV}^2 = (1.63 \pm 0.20) \times 10^{-6}$
- $\mathbf{BR}(\bar{B} \to X_s \ell^+ \ell^-)$; $\quad q^2 > 14\ \mathrm{GeV}^2 = (4.04 \pm 0.78) \times 10^{-7}$
- $\mathbf{BR}(\bar{B} \to X_s \mu^+ \mu^-)$; $\quad q^2 > 4 m_\mu^2 = (4.6 \pm 0.8) \times 10^{-6}$,
  in agreement with the earlier NNLO analysis
  [AA, Greub, Hiller, Lunghi 2001; Bobeth, Gambino, Gorbahn, Haisch, 2003]

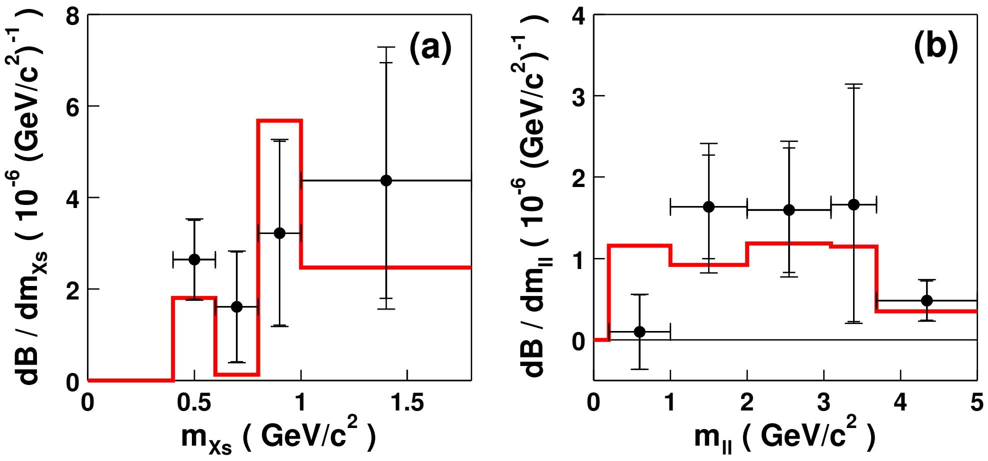
Decay distributions in $\bar{B} \to X_s \ell^+ \ell^-$

$M_{\ell\ell}$ and M_{X_s} Spectra

[BELLE]



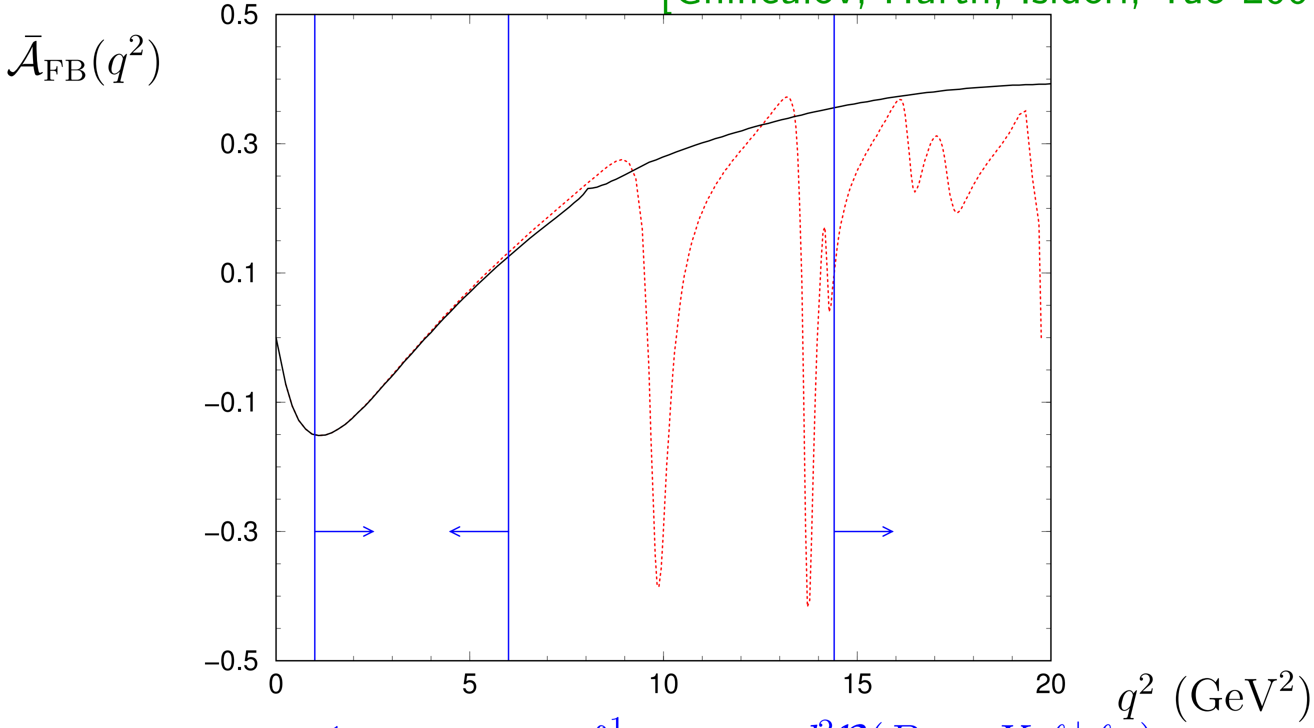
[BABAR]



- In agreement with the NNLO SM calculations

Normalized FB-Asymmetry in $\bar{B} \to X_s \ell^+ \ell^-$:

[Ghinculov, Hurth, Isidori, Yao 2004]



$$\bar{\mathcal{A}}_{\rm FB}(q^2) = \frac{1}{d\mathcal{B}(B \to X_s \ell^+ \ell^-)/dq^2} \int_{-1}^{1} d\cos\theta_\ell \, \frac{d^2\mathcal{B}(B \to X_s \ell^+ \ell^-)}{dq^2 \; d\cos\theta_\ell} \mathrm{sgn}(\cos\theta_\ell)$$

- Zero of the FB-Asymmetry is a precision test of the SM

$q_0^2 = (3.90 \pm 0.25)$ GeV^2 [Ghinculov, Hurth, Isidori, Yao 2004]

$q_0^2 = (3.76 \pm 0.22_{\rm theory} \pm 0.24_{m_b})$ GeV^2 [Bobeth, Gambino, Gorbahn, Haisch 2003]

Electroweak Penguins $b \to s\ell^+\ell^-$

- $B \to (K, K^*)\ell^+\ell^-$ decay rates

  • Decay rates and distributions depend on the form factors; estimates given below based on Light-cone QCD Sum Rules [Ball, Hiller, Handoko,AA]; Several competing estimates available in the literature [Zhong et al; Melnikov et al.;...]

  $\mathcal{B}(B \to K\ell^+\ell^-) = (0.45 \pm 0.05) \times 10^{-6}$ [HFAG'05]; $(0.35 \pm 0.12) \times 10^{-6}$ [SM]

  $\mathcal{B}(B \to K^* e^+e^-) = (1.26 \pm 0.28) \times 10^{-6}$ [HFAG'05]; $(1.6 \pm 0.5) \times 10^{-6}$ [SM]

  $\mathcal{B}(B \to K^* \mu^+\mu^-) = (1.45 \pm 0.23) \times 10^{-6}$ [HFAG'05]; $(1.2 \pm 0.5) \times 10^{-6}$[SM]

- Differential distributions in $B \to (K, K^*)\ell^+\ell^-$

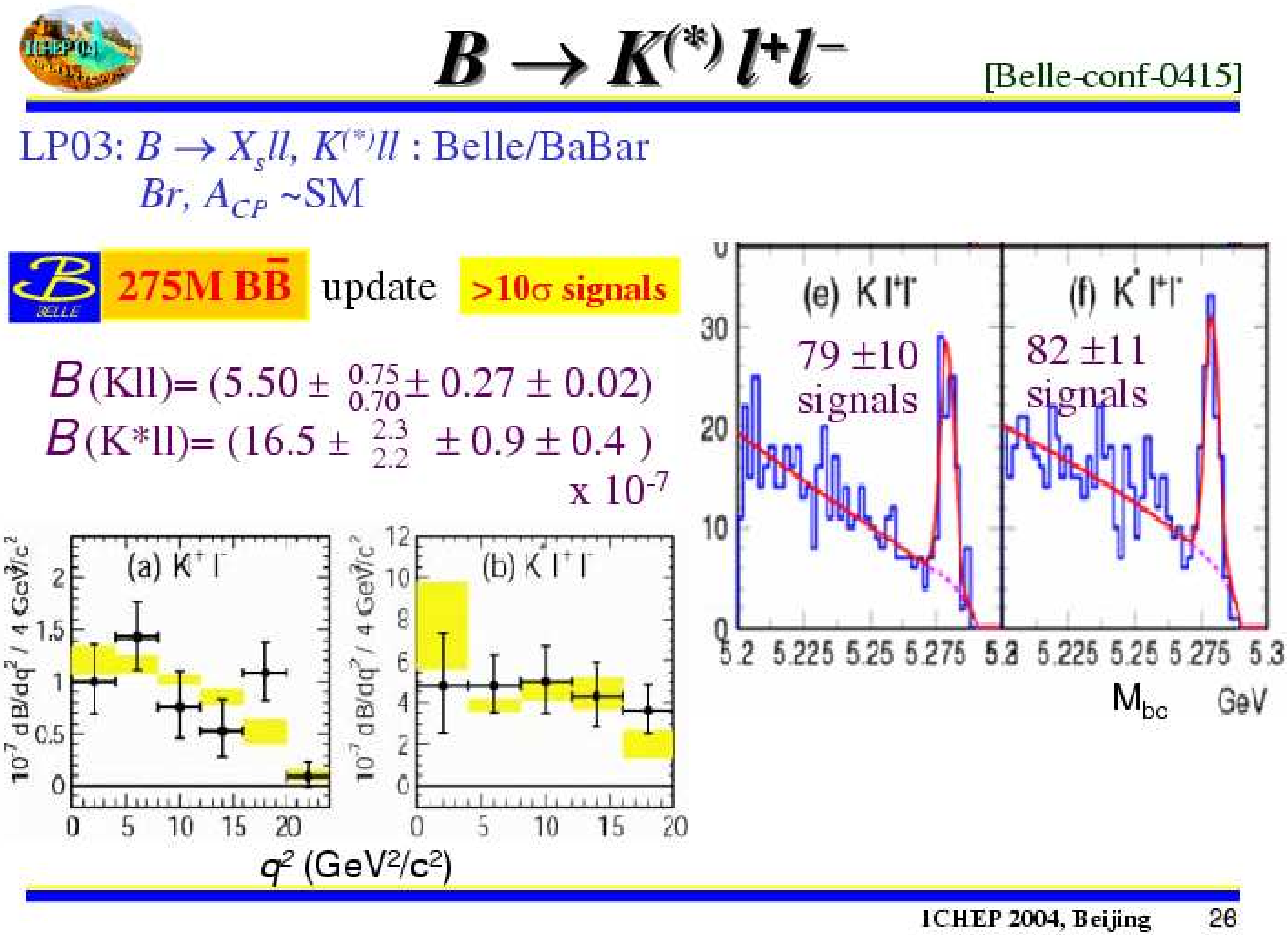
  • $q^2 = M^2_{\ell^+\ell^-}$-distribution away from the $J/\psi, \psi', \ldots$ resonances is sensitive to short-distance physics; current data in agreement with the SM estimates but theoretical precision is not better than 35% due to FF dependence

- The ratio $\mathcal{B}(B \to K^*\mu^+\mu^-)/\mathcal{B}(B \to K^*e^+e^-)$ sensitive to SUSY effects in the large-$\tan\beta$ region due to Higgs effects

  • $A_{\rm FB}(\hat{s})[B \to K\ell^+\ell^-] \simeq 0$ in the SM and most BSM extensions; in agreement with data which is used as a control sample to measure $A_{\rm FB}(\hat{s})[B \to K^*\ell^+\ell^-]$

  • $A_{\rm FB}(\hat{s})$ in $B \to K^*\ell^+\ell^-$ qualitatively similar to $A_{\rm FB}(\hat{s})$ in $B \to X_s\ell^+\ell^-$, except for FF complication; First measurements from BELLE at hand, appear SM-like; Super-B and LHC-B will measure $A_{\rm FB}(\hat{s})$ precisely

Sakai (FPCP 2004)



Comparison of $\mathcal{B}(B \to (K, K^*)\ell^+\ell^-$ with SM-1

$B \to K\ell^+\ell^-$ and $B \to K^*\ell^+\ell^-$

Belle branching fractions (253 fb^{-1})

– $K\ell^+\ell^-$: $(5.50^{+0.75}_{-0.70} \pm 0.27 \pm 0.02) \times 10^{-7}$

– $K^*\ell^+\ell^-$: $(16.5^{+2.3}_{-2.2} \pm 0.9 \pm 0.4) \times 10^{-7}$

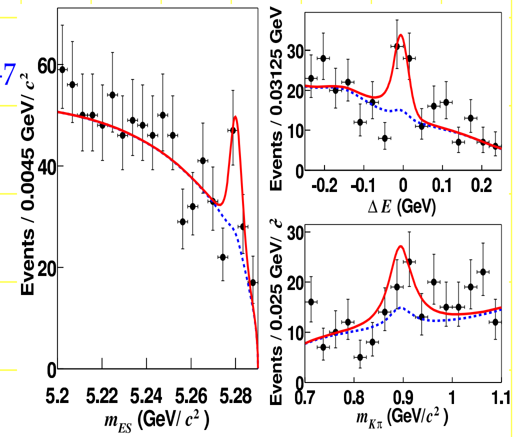
New BaBar results (208 fb^{-1})

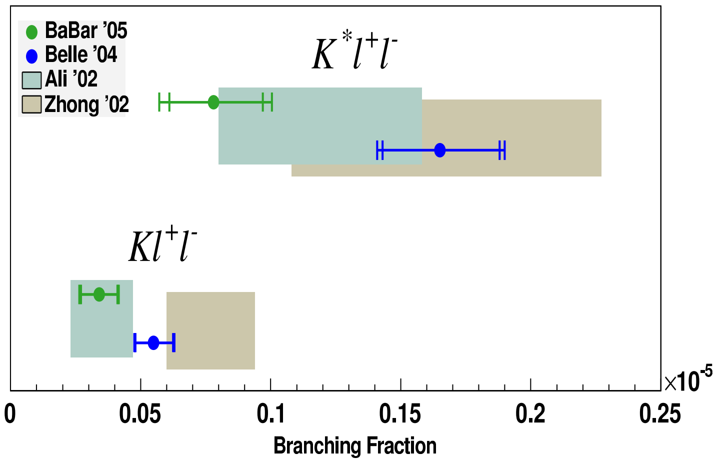
– $K\ell^+\ell^-$: $(3.4 \pm 0.7 \pm 0.3) \times 10^{-7}$

– $K^*\ell^+\ell^-$: $(7.8^{+1.9}_{-1.7} \pm 1.2) \times 10^{-7}$

$A_{CP}(B^+ \to K^+\ell^+\ell^-) = -0.08 \pm 0.22 \pm 0.11$

$A_{CP}(B \to K^*\ell^+\ell^-) = +0.03 \pm 0.23 \pm 0.12$

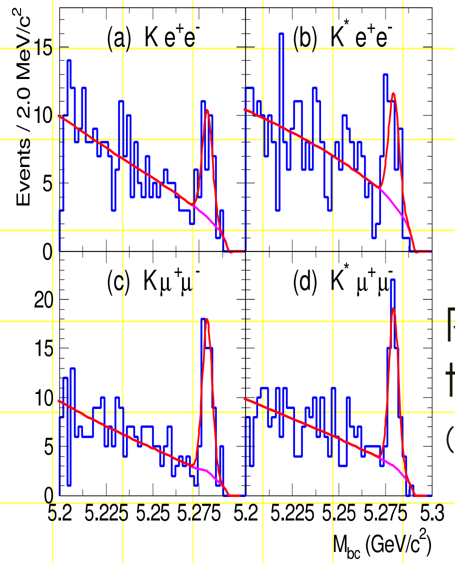


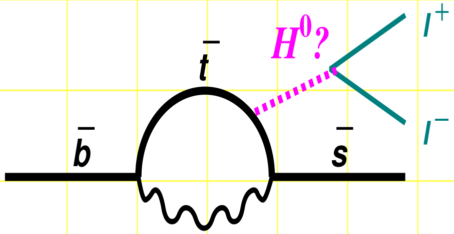


Radiative Pengiuns — Mikihiko Nakao — p.25

Comparison of $\mathcal{B}(B \to (K, K^*)\ell^+\ell^-$ with SM-2

$B \to K^{(*)}e^+e^-$ vs $B \to K^{(*)}\mu^+\mu^-$





Ratio of $K^{(*)}\mu^+\mu^-$ to $K^{(*)}e^+e^-$ is sensitive to neutral SUSY Higgs if $\tan\beta$ is large

($O(1)$ enhancement if $\tan\beta \sim 30$)

Belle ratios:

$\mathcal{B}(B \to K\mu^+\mu^-)/\mathcal{B}(B \to Ke^+e^-) = 1.38\,^{+0.39}_{-0.41}\,^{+0.06}_{-0.07}$ (1.00 in SM)

$\mathcal{B}(B \to K^*\mu^+\mu^-)/\mathcal{B}(B \to K^*e^+e^-) = 0.98\,^{+0.30}_{-0.31} \pm 0.08$ ($\sim$ 0.75 in SM)

Babar ratios:

$\mathcal{B}(B \to K\mu^+\mu^-)/\mathcal{B}(B \to Ke^+e^-) = 1.06 \pm 0.48 \pm 0.05$ (1.00 in SM)

$\mathcal{B}(B \to K^*\mu^+\mu^-)/\mathcal{B}(B \to K^*e^+e^-) = 0.93 \pm 0.46 \pm 0.06$ ($\sim$ 0.75 in SM)

Radiative Pengiuns — Mikihiko Nakao — p.26

Forward-Backward Asymmetry in $B \to K^* \ell^+ \ell^-$

$$\frac{dA_{FB}}{d\hat{s}} = -\int_0^{\hat{u}(\hat{s})} d\hat{u} \frac{d\Gamma}{d\hat{u}d\hat{s}} + \int_{-\hat{u}(\hat{s})}^{0} d\hat{u} \frac{d\Gamma}{d\hat{u}d\hat{s}}$$

$$\sim C_{10}[\mathrm{Re}(C_9^{eff}) V A_1 + \frac{\hat{m}_b}{\hat{s}} C_7^{eff} (V T_2 (1 - \hat{m}_V) + A_1 T_1 (1 + \hat{m}_V))]$$

- $\boldsymbol{T_1, T_2, V, A_1}$ form factors
  - Probes different combinations of WC's than dilepton mass spectrum; has a characteristic zero in the SM $(\hat{s}_0)$ below $m^2_{J/\psi}$

Position of the $A_{FB}(\hat{s})$ zero $(\hat{s}_0)$ in $B \to K^* \ell^+ \ell^-$

$$\mathrm{Re}(\mathrm{C_9^{eff}}(\hat{\mathrm{s}}_0)) = -\frac{\hat{\mathrm{m}}_\mathrm{b}}{\hat{\mathrm{s}}_0} \mathrm{C_7^{eff}} (\frac{\mathrm{T_2}(\hat{\mathrm{s}}_0)}{\mathrm{A_1}(\hat{\mathrm{s}}_0)}(1 - \hat{\mathrm{m}}_\mathrm{V}) + \frac{\mathrm{T_1}(\hat{\mathrm{s}}_0)}{\mathrm{V}(\hat{\mathrm{s}}_0)}(1 + \hat{\mathrm{m}}_\mathrm{V}))$$

- Model-dependent studies $\Longrightarrow$ small FF-related uncertainties in $\hat{s}_0$ [Burdman '98]
- HQET provides a symmetry argument why the uncertainty in $\hat{s}_0$ is small. In leading order in $1/m_B$, $1/E$ ($E = \frac{m_B^2 + m_{K^*}^2 - q^2}{2m_B}$) and $O(\alpha_s)$:

$$\frac{T_2}{A_1} = \frac{1 + \hat{m}_V}{1 + \hat{m}_V^2 - \hat{s}}(1 - \frac{\hat{s}}{1 - \hat{m}_V^2}); \quad \frac{T_1}{V} = \frac{1}{1 + \hat{m}_V}$$

- No hadronic uncertainty in $\hat{s}_0$ [AA, Ball, Handoko, Hiller '99]:
  $C_9^{eff}(\hat{s}_0) = -\frac{2m_b M_B}{s_0} C_7^{eff}$

$O(\alpha_s)$ corrections to FB-Asymmetry in $B \to K^* \ell^+ \ell^-$

- $O(\alpha_s)$ corrections to the LEET-symmetry relations lead to substantial perturbative shift in $\hat{s}_0$ [Beneke, Feldmann, Seidel '01]

$$C_9^{eff}(\hat{s}_0) = -\frac{2m_b M_B}{s_0} C_7^{eff}(1 + \frac{\alpha_s C_F}{4\pi}[\ln \frac{m_b^2}{\mu^2} - L] + \frac{\alpha_s C_F}{4\pi} \frac{\Delta F_\perp}{\xi_\perp(s_0)})$$

[AA, A.S. Safir (hep-ph/02054)]

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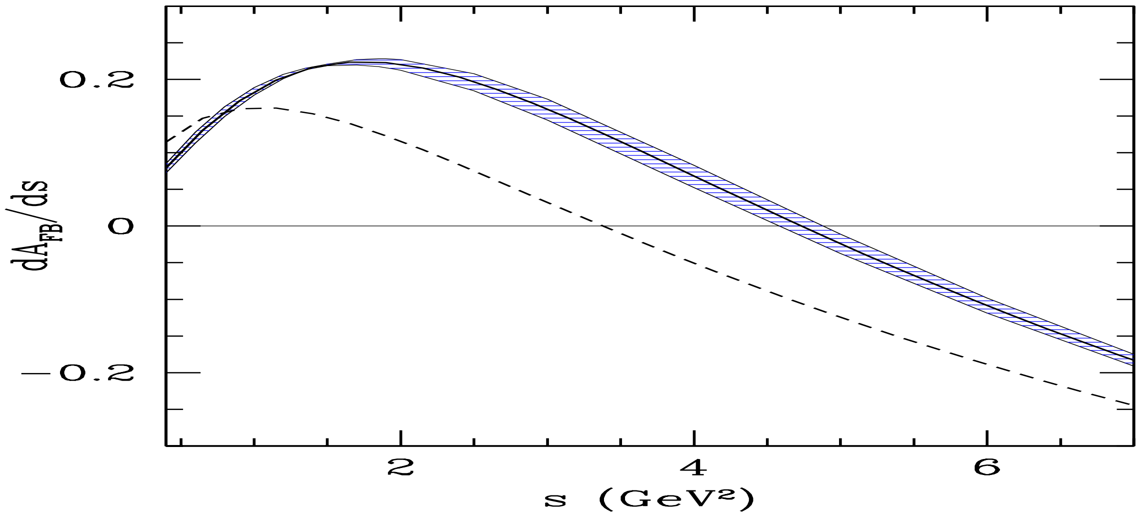


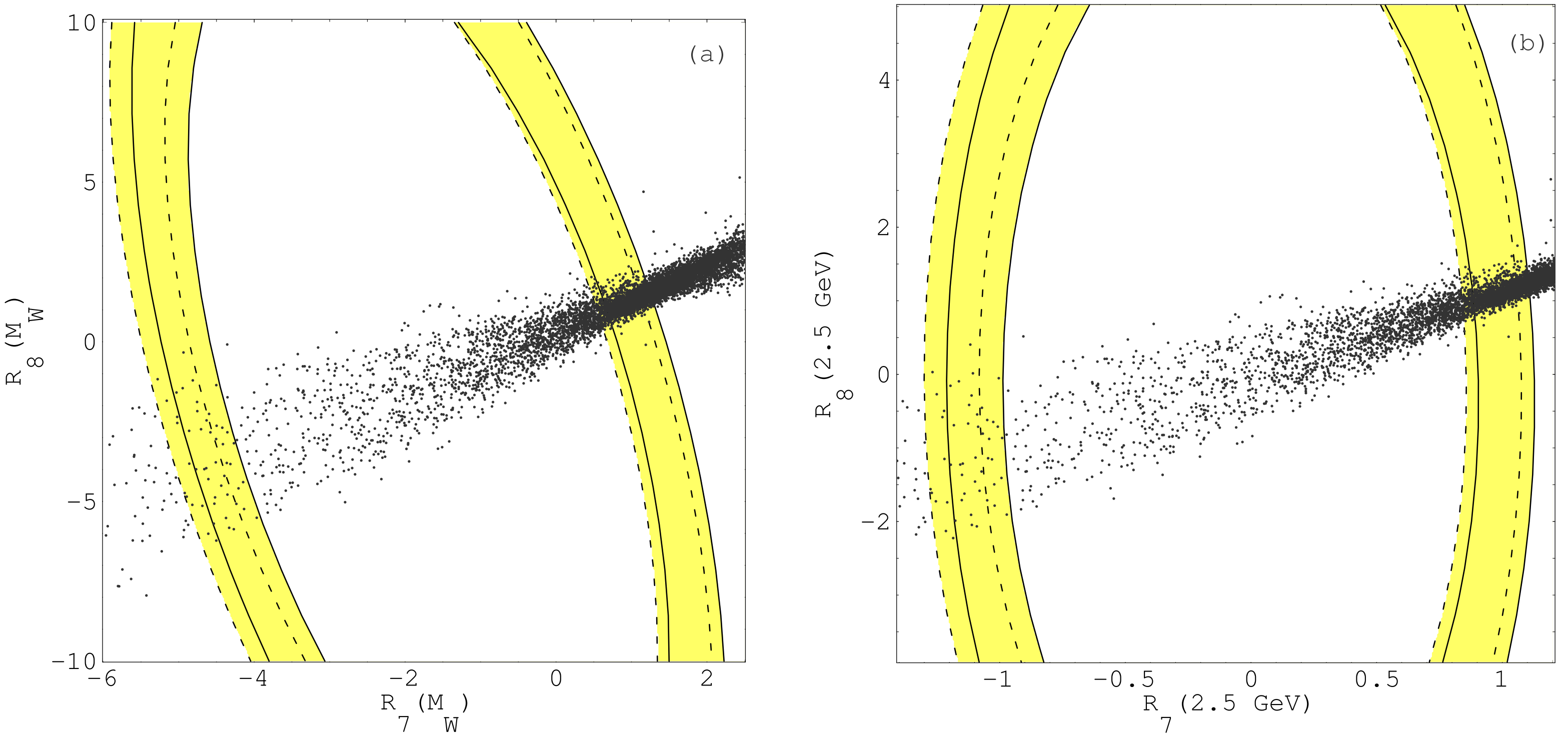
Forward-backward asymmetry $dA_{FB}(B \to K^* l^+ l^-)/ds$ at next-to-leading order (solid center line) and leading order (dashed)

A Model-independent Analysis of $B \to X_s\gamma$ & $B \to X_s\ell^+\ell^-$

- Assume $\mathcal{H}_{eff}^{\rm SM}$ a sufficient operator basis also for Beyond-the-SM physics
- Shifts due to Beyond-the-SM [BSM] physics only in $C_7(\mu_W)$,$C_8(\mu_W)$, $C_9(\mu_W)$, and $C_{10}(\mu_W)$
- BSM Coefficients: $R_7 - 1$, $R_8 - 1$, $C_9^{\rm NP}$, & $C_{10}^{\rm NP}$
- Define: $R_{7,8}(\mu_W) \equiv \frac{C_{7,8}^{\rm tot}(\mu_W)}{C_{7,8}^{\rm SM}(\mu_W)}$
  with $C_{7,8}^{\rm tot}(\mu_W) = C_{7,8}^{\rm SM}(\mu_W) + C_{7,8}^{\rm NP}(\mu_W)$
- Set the scale $\mu_W = M_W$, and use RGE to evolve
  $$R_{7,8}(\mu_W) \to R_{7,8}(\mu_b) = \frac{A_{7,8}^{\rm tot}(\mu_b)}{A_{7,8}^{\rm SM}(\mu_b)}$$
- Impose constraints from $R_7(\mu_b)$ and $R_8(\mu_b)$ from $B \to X_s\gamma$ Data
- Use Data on $B \to (X_s, K^*, K)\ell^+\ell^-$ BRs to constrain $C_9^{\rm NP}$ and $C_{10}^{\rm NP}$
- Two-fold ambiguity due to the sign of C_7^{eff} can be resolved by data on $\boldsymbol{B \to (X_s, K, K^*)\ell^+\ell^-}$

Simulation of $B \to X_s\gamma$ in SUSY-MFV Models

- 90% C.L. bounds in the $[R_7(\mu), R_8(\mu)]$ plane from the $\mathcal{B}(B \to X_s\gamma)$
  $\mu = m_W$ (left-hand plot); $\mu = 2.5$ GeV (right-hand plot)



$$A_7^{\rm tot} - \text{negative} : -0.37 \leq A_7^{{\rm tot},<0}(2.5\ \text{GeV}) \leq -0.17$$

$$A_7^{\rm tot} - \text{positive} : 0.21 \leq A_7^{{\rm tot},>0}(2.5\ \text{GeV}) \leq 0.43$$

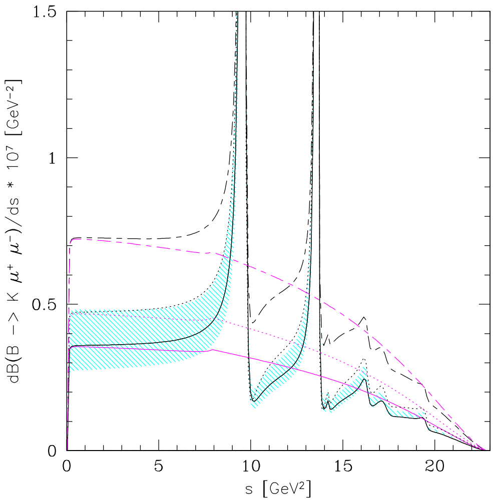
Dilepton mass-Spectrum in $\bar{B} \to (K, K^*)\ell^+\ell^-$ in SM and SUSY

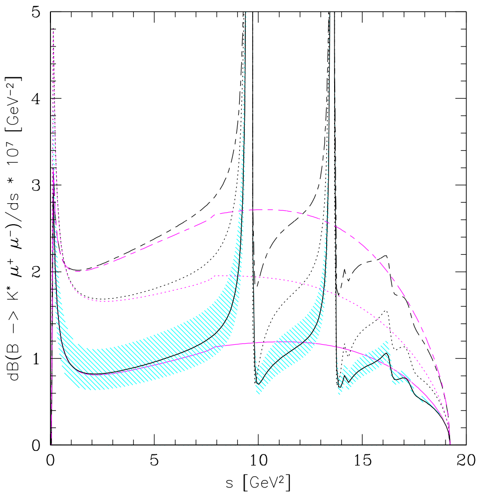
AA, Ball, Handoko, Hiller; hep-ph/9910221

- NP contributions coded in $R_i(\mu)$; $i = 7,\ 9,\ 10$

$$R_i(\mu) \equiv \frac{C_i^{\mathrm{NP}} + C_i^{\mathrm{SM}}}{C_i^{\mathrm{SM}}}$$

  - SM (solid); SUGRA $[R_7 = -1.2]$ (dots);
  - MIA $[R_7 = -0.83,\ R_9 = 0.92,\ R_{10} = 1.6]$ (dashed)

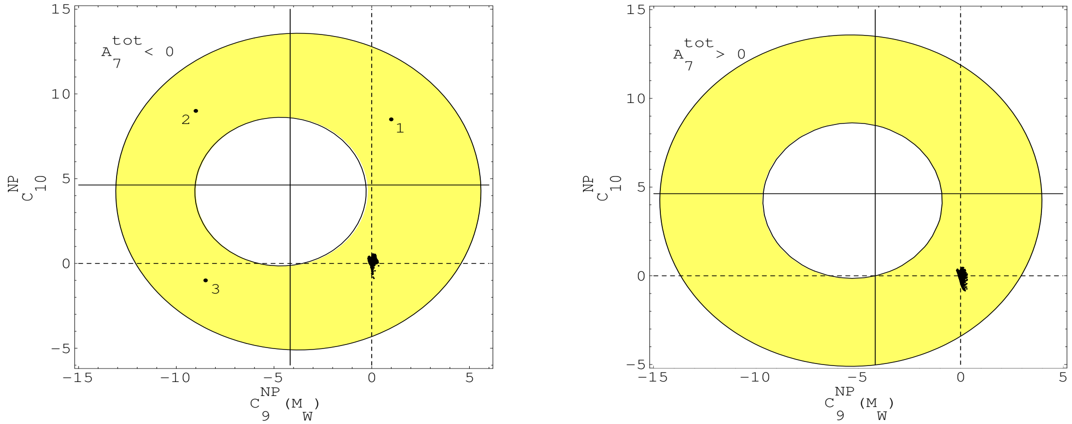




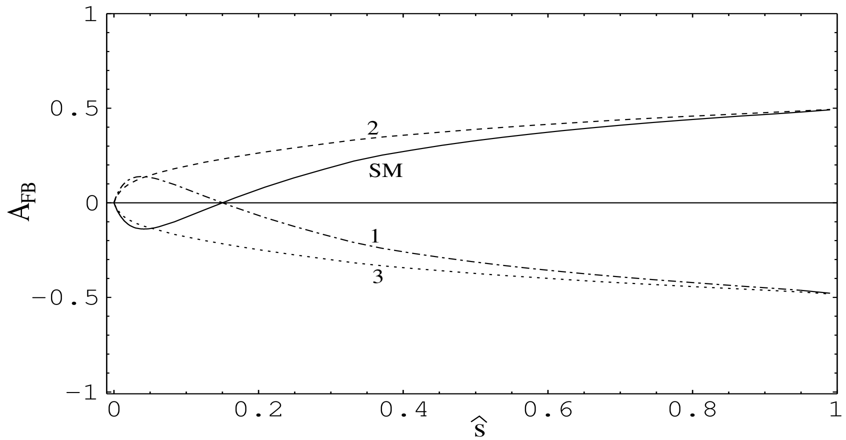
Combined analysis of $B \to X_s\gamma$ & $B \to (X_s, K, K^*)\ell^+\ell^-$

[A.A., Lunghi, Greub, Hiller; DESY 01-217; hep-ph/0112300]

- Constraints from radiative and semileptonic rare decays (Points: SUSY-MFV Model)



- FB asymmetry for $\bar{B} \to X_s\ell^+\ell^-$, corresponding to the points indicated above

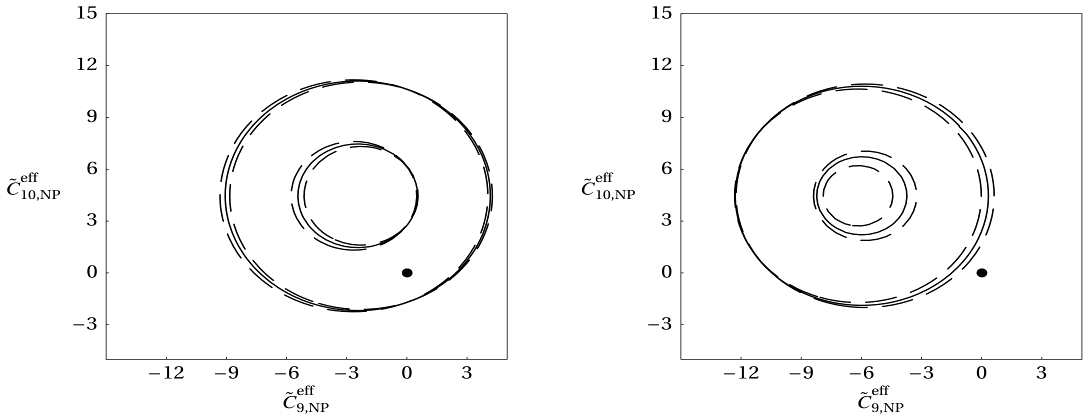


First hints on the sign of the $B \to X_s \gamma$ amplitude

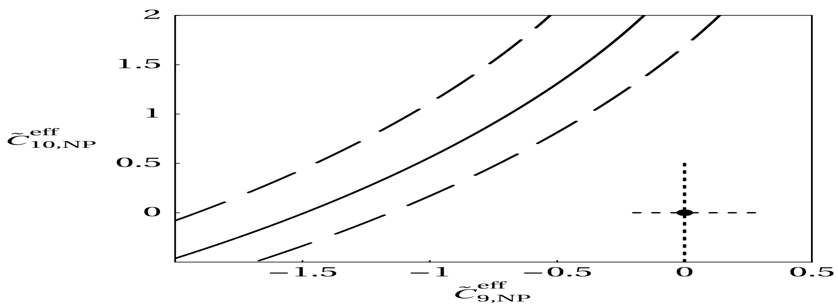
[Gambino, Haisch, Misiak; hep-ph/0410155]

90% C.L. constraints from $\boldsymbol{B \to X_s \gamma}$ and $\boldsymbol{B \to X_s \ell^+ \ell^-}$

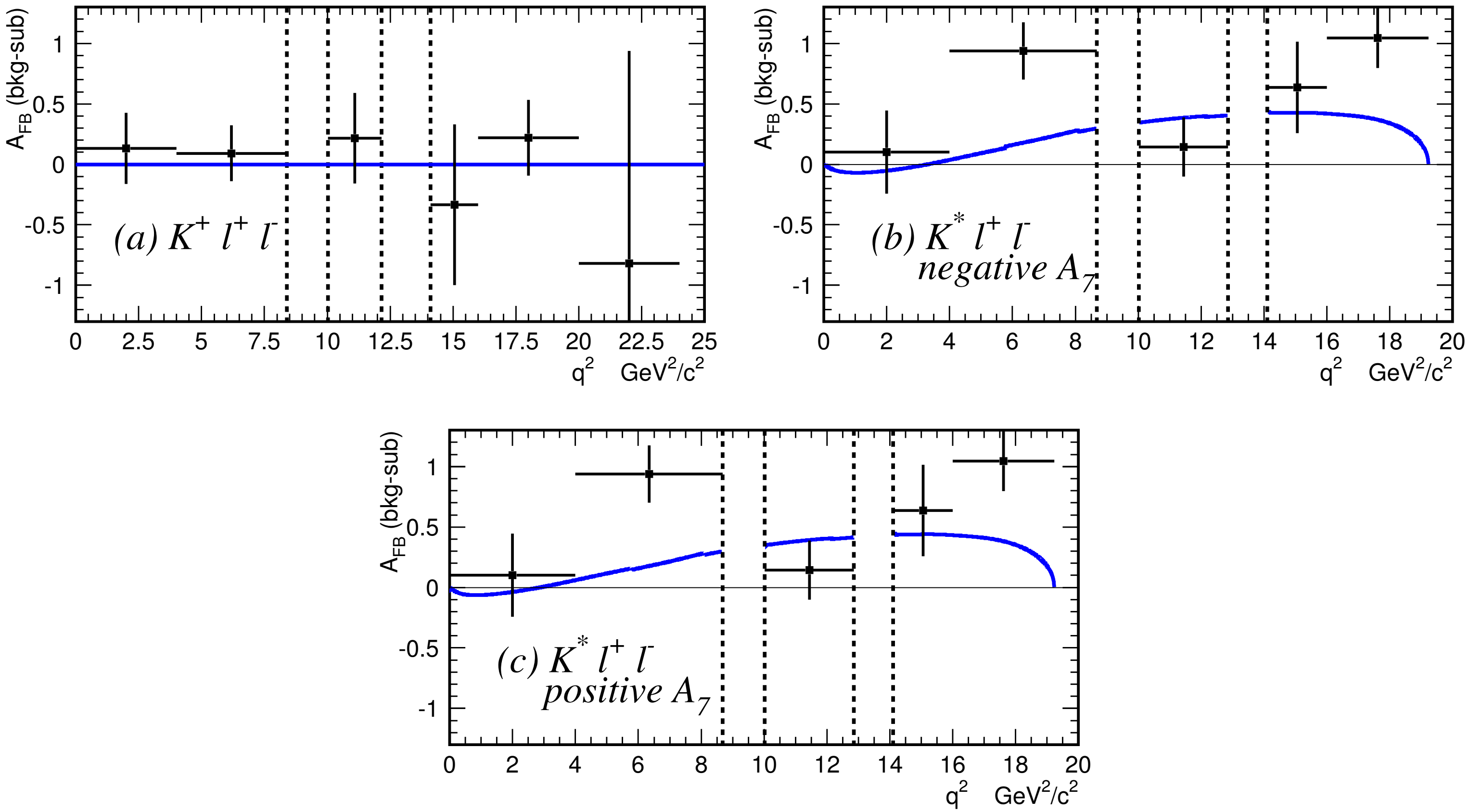
C_7 SM-like (left frame) $\qquad$ C_7 opposite sign (right frame)



Surroundings of the origin in the right frame above; dashed lines: MFV-MSSM



Belle FB Asymmetry Distributions (EPS 2005)



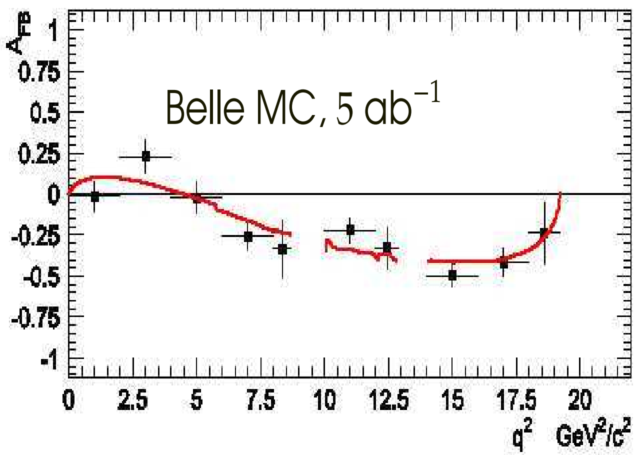
Best Fits

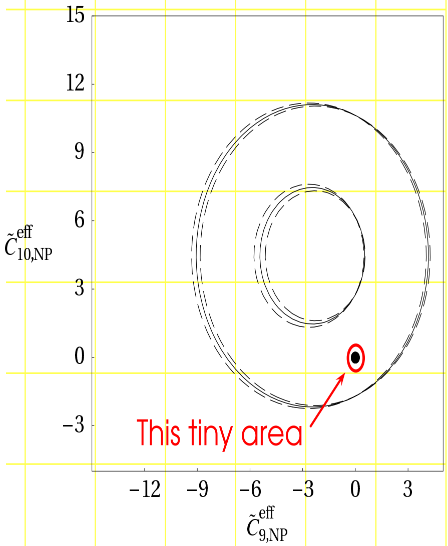
- $A_7 = -0.33$: $A_9/A_7 = -15.3^{+3.4}_{-4.8}$; $A_{10}/A_7 = 10.3^{+5.2}_{-3.5}$
- $A_7 = +0.33$: $A_9/A_7 = -16.3^{+3.7}_{-5.7}$; $A_{10}/A_7 = 11.1^{+6.0}_{-3.9}$
- SM: $A_7 = -0.33$; $A_9/A_7 = -12.3$; $A_{10}/A_7 = 12.8$

Prospects of precise determination of C_9, C_{10} at Super-B Factory

Extracting C_9 and C_{10} from $B \to K^* \ell^+ \ell^-$

- Precise determination of C_9 and C_{10} is possible
- $\Delta C_9/C_9 \sim 11\%$, $\Delta C_{10}/C_{10} \sim 13\%$ at 5 ab^{-1}, C_7 fixed from $b \to s\gamma$
  - Current branching fraction / background extrapolated
  - Fit to 2-dim q^2 vs angular distribution, not simple A_{FB}
  - Systematic error is neglected





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LHC-B MC Studies

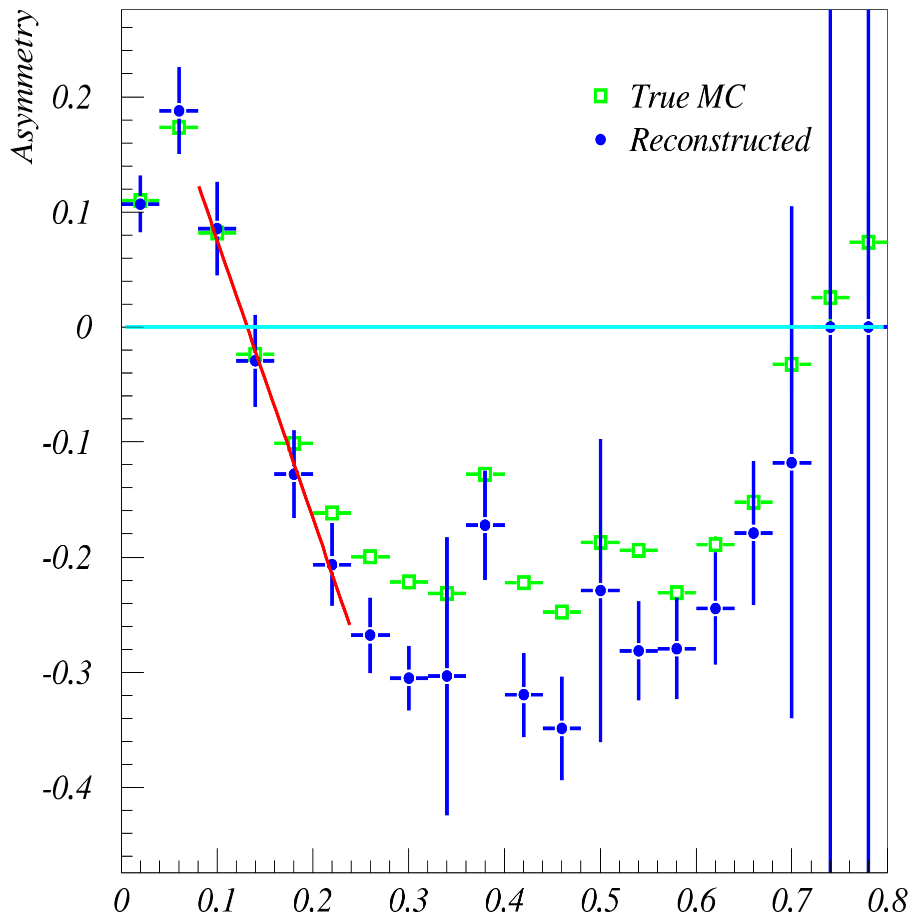


Figure 4: FB Asymmetry versus $\hat{s}$ for $B \xrightarrow{\hat{s}} \mu^+\mu^- K^*$ (from Koppenburg)

$B_s \to \mu^+\mu^-$ in SM

- Effective Hamiltonian

$$\mathcal{H}_{eff} = -\frac{G_F\alpha}{\sqrt{2}\pi} V_{ts}{}^* V_{tb} \sum_i \left[C_i(\mu)\mathcal{O}_i(\mu) + C'_i(\mu)\mathcal{O}'_i(\mu)\right]$$

$$\mathcal{O}_{10} = (\bar{s}_\alpha \gamma^\mu P_L b_\alpha)\,(\bar{l}\gamma_\mu\gamma_5 l)\,, \qquad \mathcal{O}'_{10} = (\bar{s}_\alpha \gamma^\mu P_R b_\alpha)\,(\bar{l}\gamma_\mu\gamma_5 l)$$

$$\mathcal{O}_S = m_b\,(\bar{s}_\alpha P_R b_\alpha)\,(\bar{l}l)\,, \qquad \mathcal{O}'_S = m_s\,(\bar{s}_\alpha P_L b_\alpha)\,(\bar{l}l)$$

$$\mathcal{O}_P = m_b\,(\bar{s}_\alpha P_R b_\alpha)\,(\bar{l}\gamma_5 l)\,, \qquad \mathcal{O}'_P = m_s\,(\bar{s}_\alpha P_L b_\alpha)\,(\bar{l}\gamma_5 l)$$

$$\mathrm{BR}\left(\bar{B}_s \to \mu^+\mu^-\right) = \frac{G_F^2\alpha^2 m_{B_s}^2 f_{B_s}^2 \tau_{B_s}}{64\pi^3} |V_{ts}{}^* V_{tb}|^2 \sqrt{1 - 4\hat{m}_\mu^2} \times \left[\left(1 - 4\hat{m}_\mu^2\right)|F_S|^2 + |F_P + 2\hat{m}_\mu^2 F_{10}|^2\right]$$

where $\hat{m}_\mu = m_\mu / m_{B_s}$ and

$$F_{S,P} = m_{B_s}\left[\frac{C_{S,P}m_b - C'_{S,P}m_s}{m_b + m_s}\right], \qquad F_{10} = C_{10} - C'_{10}$$

$$\mathrm{BR}\left(\bar{B}_s \to \mu^+\mu^-\right)_{\mathrm{SM}} = (3.46 \pm 1.5) \times 10^{-9} \quad [\mathrm{Buchalla, Buras}]$$

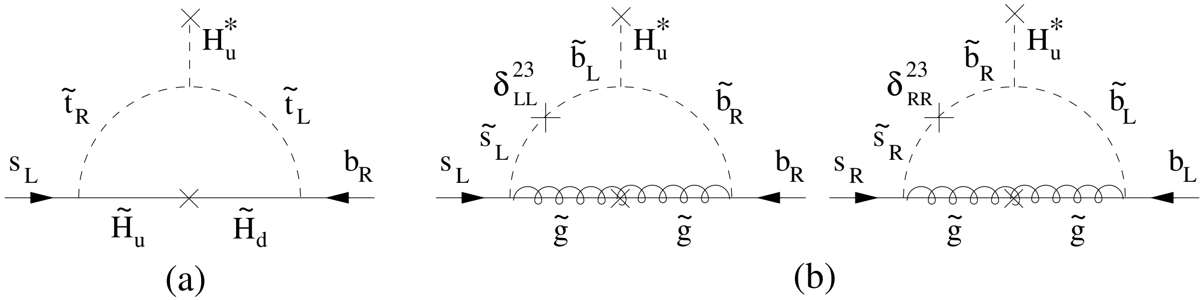
$$f_{B_s} = (230 \pm 30)\ \mathrm{MeV}$$

$B_s \to \mu^+\mu^-$ in Supersymmetric Models

- The decay $B_s \to \mu^+\mu^-$ probes essentially the Higgs sector of Supersymmetry, a type-II two-Higgs doublet model; One Higgs field (H_u) couples to the up-type quarks, the other (H_d) couples to the down-type quarks

$$\mathcal{L} = \overline{Q} Y_U U_R H_u + \overline{Q}_L Y_D D_R H_d$$

- Supersymmetry does not have discrete symmetries to protect the alignment of the Higgs boson interaction eigenbasis with the fermion mass eigenbasis; Higgs-induced FCNC interactions are generated through loops



- As H_u gets a VEV (v_u), it contributes an off-diagonal piece to the down-type fermion mass matrix, mixing s_L and b_L by an angle θ

$$\sin\theta = y_b \epsilon v_u / m_b; \quad \text{as } m_b = y_b v_d, \ \sin\theta = \epsilon \tan\beta$$

- $\mathcal{A}(b\bar{s} \to \mu^+\mu^-) \simeq \sin\theta \mathcal{A}(b\bar{b} \to \mu^+\mu^-) \ \propto \tan\beta / \cos^2\beta \Longrightarrow \tan^3\beta$ for large-$\tan\beta$

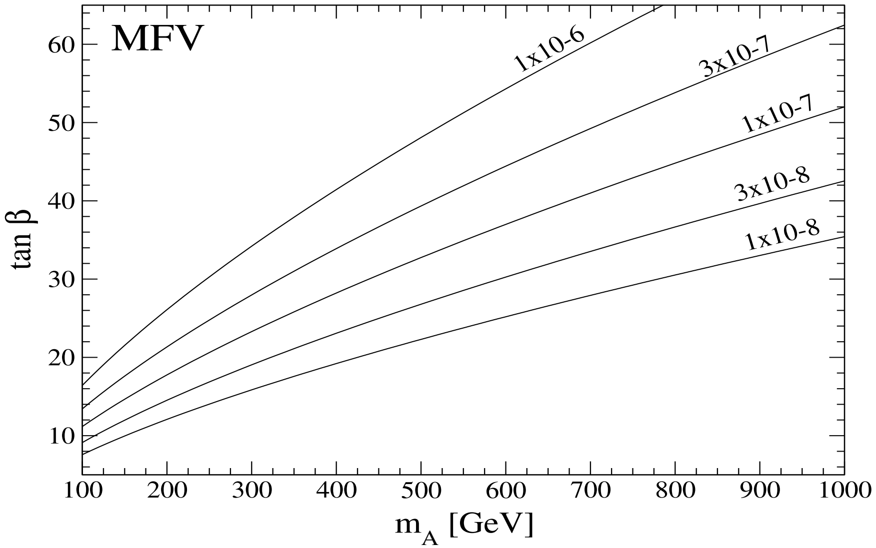
$B_s \to \mu^+\mu^-$ in Minimal Flavor Violation SUSY Models

- Higgsino contribution to $\mathcal{B}(B_s \to \mu^+\mu^-)$ [Babu, Kolda;...]

$$\mathcal{B}(B_s \to \mu\mu) \simeq \frac{G_F^2}{8\pi}\,\eta_{\rm QCD}^2 m_{B_s}^3 f_{B_s}^2 \tau_{B_s} m_b^2\, m_\mu^2 \left(\frac{\tan^2\beta}{\cos^4\beta}\right)\left(\frac{\kappa_{\widetilde{H}}^2}{m_A^4}\right).$$

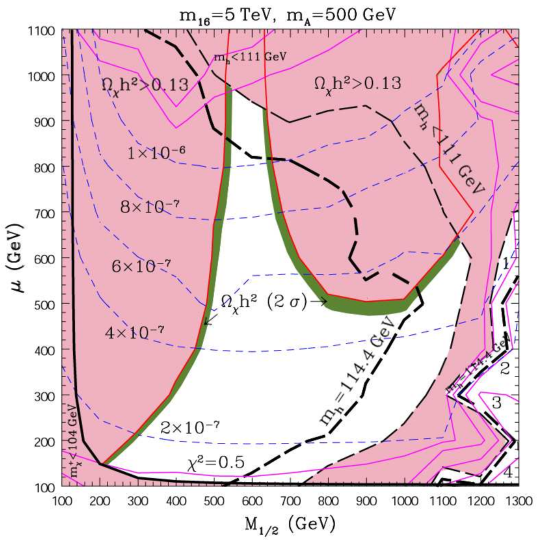
- $\eta_{\rm QCD} \simeq 1.5$ is the QCD correction due to the RG between the SUSY and B_s scales

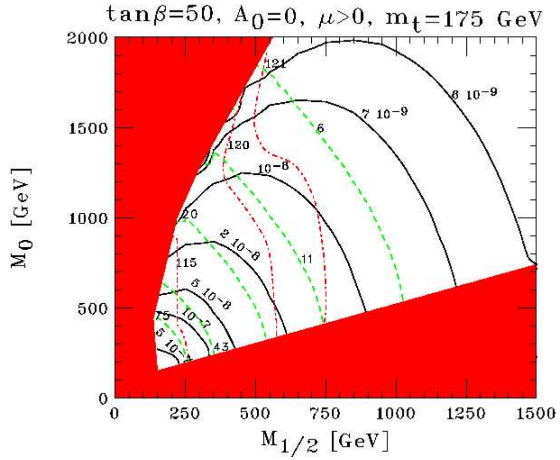
$$\kappa_{\widetilde{H}} = -\frac{G_F\, m_t^2\, V_{ts} V_{tb}}{4\sqrt{2}\pi^2 \sin^2\beta}\,\mu A_t\, f(\mu^2, m_{\tilde{t}_L}^2, m_{\tilde{t}_R}^2)$$



Constraints from $\mathcal{B}(B_s \to \mu^+\mu^-)$ on SUSY Models

- **CDF $B_s^0/B_d^0 \to \mu^+\mu^-$ Limits [hep-ex/0508036]:**
  $\mathcal{B}(B_s \to \mu^+\mu^-) < 1.5 \times 10^{-7}(2.0 \times 10^{-7})$ at 90%(95%) CL
  $\mathcal{B}(B_d \to \mu^+\mu^-) < 3.9 \times 10^{-8}(5.1 \times 10^{-8})$ at 90%(95%) CL
- **D0 $B_s^0 \to \mu^+\mu^-$ Limits [D0note 4733-Conf (2005)]:**
  $\mathcal{B}(B_s \to \mu^+\mu^-) < 3.2 \times 10^{-7}(4.0 \times 10^{-7})$ at 90%(95%) CL
  $\Longrightarrow$ **complementary limits on models of BSM physics, such as MSUGRA [Dedes et al., hep-ph/0108037], SO(10) [Dermisek et al., hep-ph/0304101; Foster et al., hep-ph/0506146] and MFV models [Bobeth et al., hep-ph/0505110]**





Summary

- All current measurements involving CP violation and FCNC processes (decay rates and distributions) are in agreement with the SM expectations
- A non-trivial test of the CKM paradigm for CP violation in the K- and B-meson sectors has been carried out at the current B-factories by overconstraining the CKM unitarity triangle
- B-factories have measured all three inner angles of the UT triangle:
  $\boldsymbol{\alpha = (99^{+12}_{-9})^\circ}$; $\boldsymbol{\beta = (21.7 \pm 1.3)^\circ}$; $\boldsymbol{\gamma = (66 \pm 17)^\circ}$
- Largest current discrepancy from SM is in CPV $\boldsymbol{b \longrightarrow s\bar{s}s}$ penguins; $\boldsymbol{3\ \sigma}$ effect
- Rare B-decays and B^0 - $\overline{B^0}$ mixings have made a great impact on the determination of the CKM matrix elements in the third row of $V_{\rm CKM}$; In particular
  $B \to X_s\gamma \quad \Longrightarrow \quad V_{ts} = -(46.0 \pm 8.0) \times 10^{-3}$
  $B \to (\rho, \omega, K^*)\gamma \quad \Longrightarrow \quad |\frac{V_{td}}{V_{ts}}| = 0.200^{+0.026}_{-0.025}{}^{+0.038}_{-0.029}$
- A number of benchmark measurements remain to be done. These include, among others, $\mathcal{B}(B_s \to \mu^+\mu^-)$ and ΔM_{B_s}, which will be carried out at Fermilab and LHC; Correlations between these and other Rare B/K-decays crucial to disentangle BSM physics in the flavour sector
- Hope that the synergy of high energy frontier and low energy precision physics, which worked so well in piecing together the SM, will continue to hold sway in the LHC-era, providing valuable information about the flavour aspects of the BSM physics