PRECISION FLAVOUR PHYSICS WITH B DECAYS INTO LIGHT VECTOR MESONS

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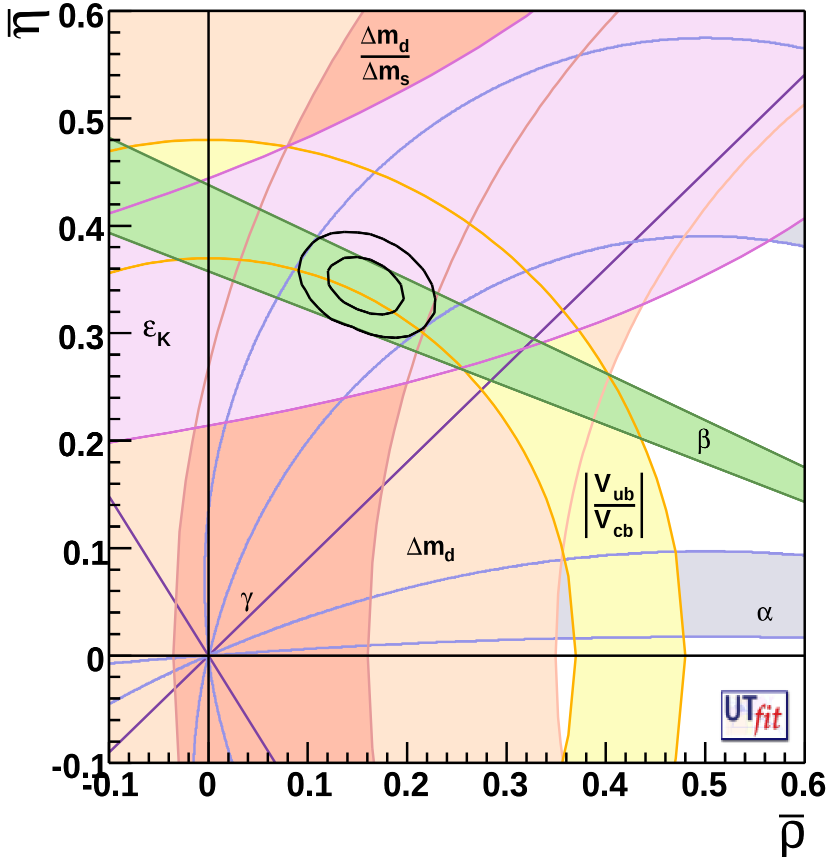
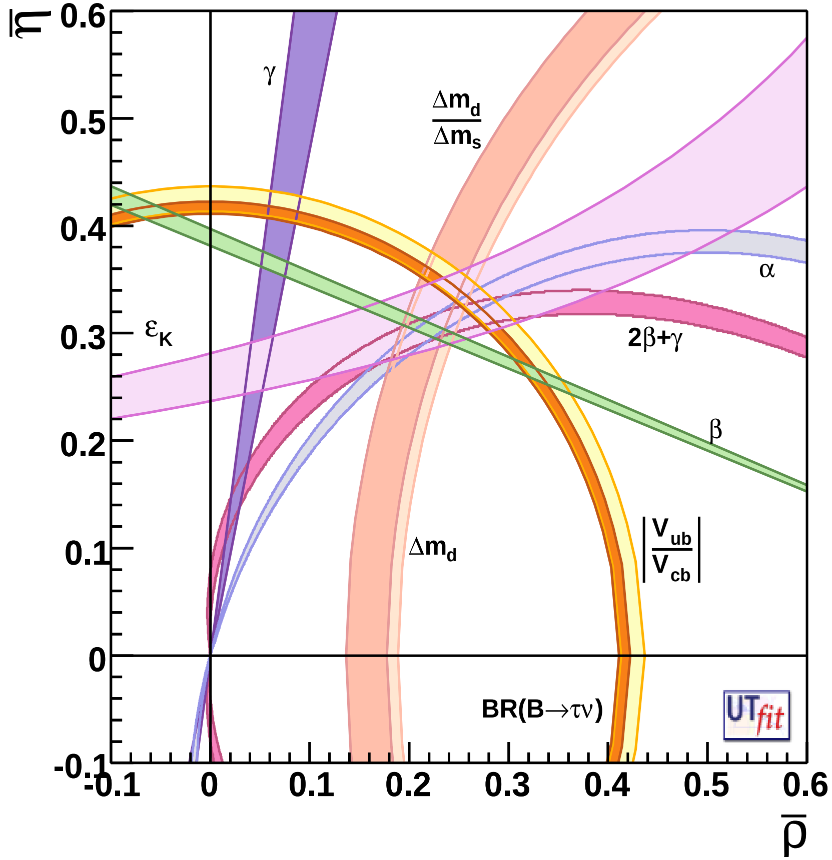
- Introduction
- Theory of $B \to M_1 M_2$
- $B \to V_L V_L$ Branching Fractions
- CP Violation and Flavour Physics

- B factories: CKM confirmed
- LHC, LHCb, SFF: precision flavour studies
- flavour physics complements direct collider searches for NP

B physics highlights

- precision CKM: CPV in $B \to M_1 M_2$, α, β, γ
- rare decays: $B \to K^{(*)} l^+ l^-$, $K^{(*)} \nu\bar{\nu}$, $\rho\gamma$, $\rho l \nu$, $\tau\nu$, $D\tau\nu$
- inclusive modes: $B \to X_s \gamma$, $X_s l^+ l^-$ (SFF)





UTfit collaboration

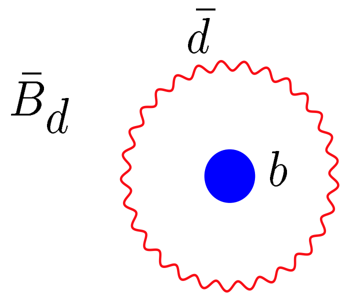
Hamiltonian (e.g. for $B \to \pi\pi$, $\rho\rho$)

$$\mathcal{H}_{eff} = \frac{G_F}{\sqrt{2}} V_{ud}^* V_{ub} \left(\overset{(\bar{u}b)(\bar{d}u)\downarrow}{C_1 Q_1^u + C_2 Q_2^u} + \overset{(\bar{d}b)(\bar{q}q)\downarrow}{\sum_{penguins} C_p Q_p} \right)$$

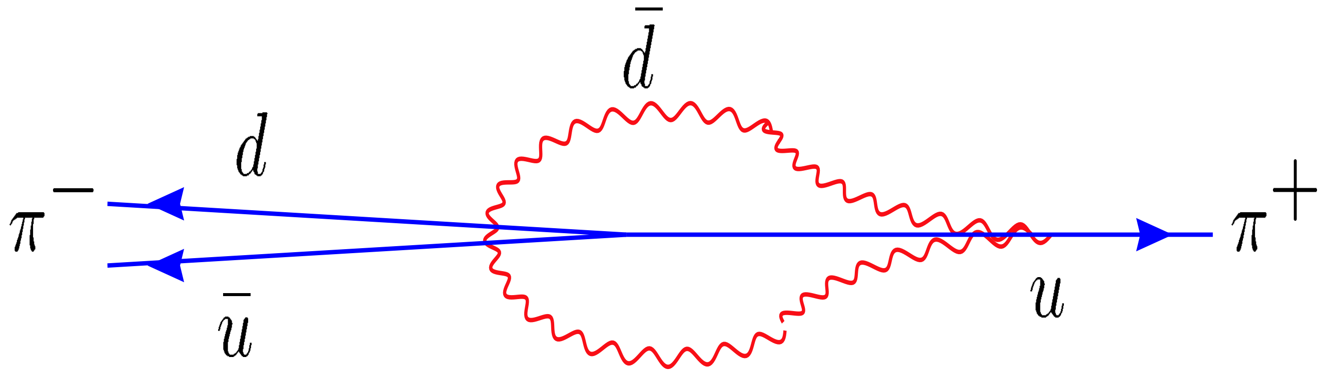
$$+ \frac{G_F}{\sqrt{2}} V_{cd}^* V_{cb} \left(C_1 Q_1^c + C_2 Q_2^c + \sum_{penguins} C_p Q_p \right)$$

similar for $B \to K^* \rho$, $B \to J/\Psi K_S$ $(d \leftrightarrow s)$

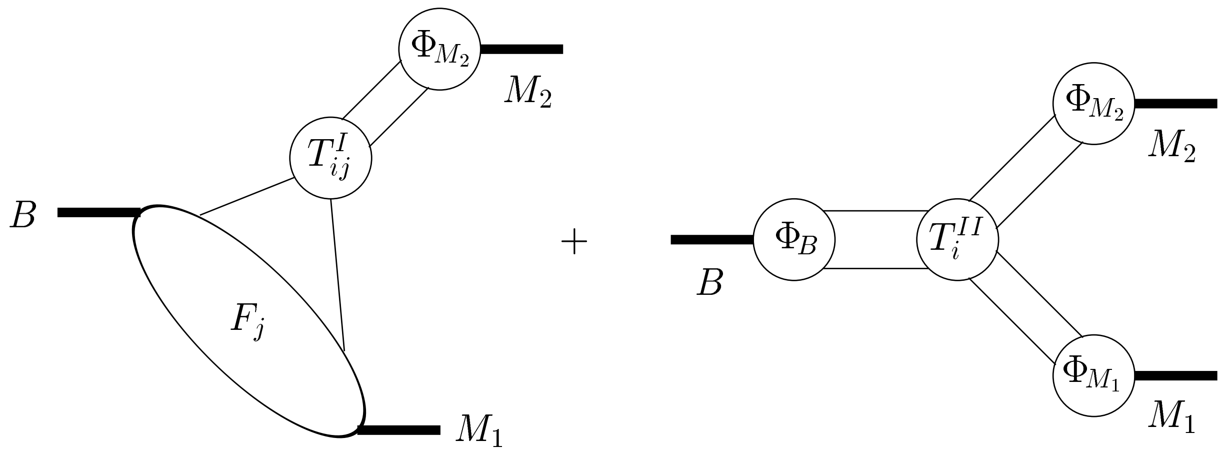
tree dominated	$\bar{B}_d \to \pi^+\pi^-$, $\rho^+\rho^-$	$b(\bar{d}) \to d\bar{u}u(\bar{d})$
pure penguin	$B^- \to \bar{K}^0 \pi^-$	$b(\bar{u}) \to s\bar{d}d(\bar{u})$
pure annihilation	$\bar{B}_d \to K^+ K^-$	$b(\bar{d}) \to u\bar{s}s\bar{u}$



$m_B \gg \Lambda_{\rm QCD}$

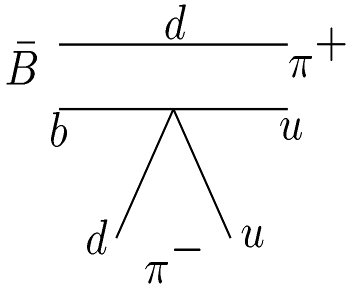


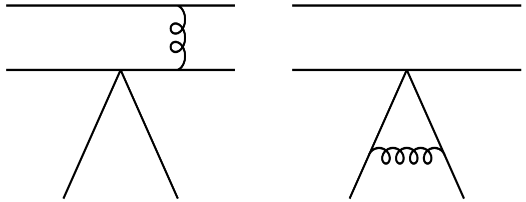
$B \to M_1 M_2$ simplifies in the heavy-quark limit

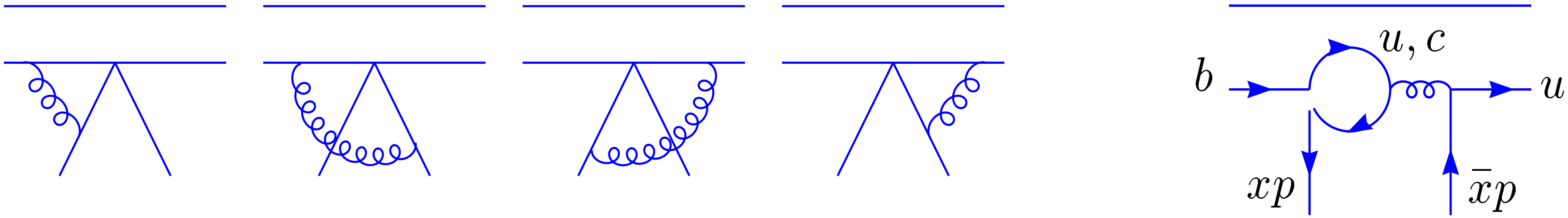


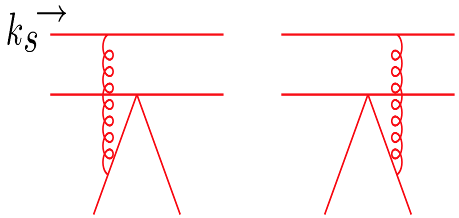
- successful phenomenology
  (penguin/tree; $V_L V_L$ vs. PP penguins; annihilation modes small; moderate direct CPV)
- form factors: reduced dependence in amplitude ratios
- computation of SU(3) breaking
- limitation: power corrections (weak annihilation)

Beneke, G.B., Neubert, Sachrajda









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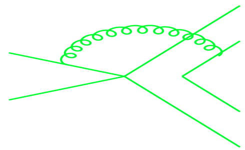
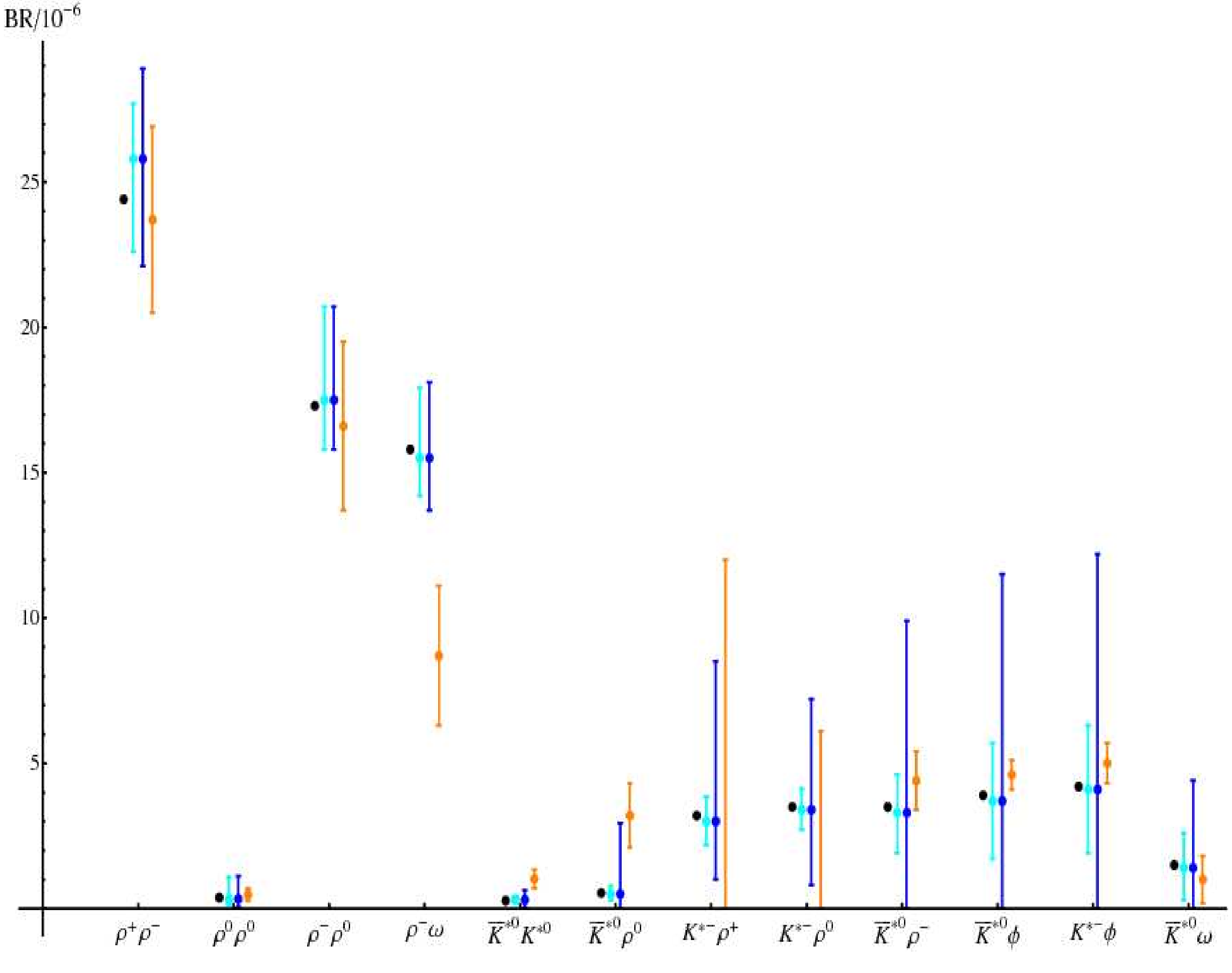


$+ \ldots$

$$\langle \pi\pi | Q | B \rangle = F(B \to \pi) \cdot \int_0^1 dx\; T^I(x)\; \Phi_\pi(x) + \int_0^1 d\xi\, dx\, dy\; T^{II}(\xi, x, y)\; \Phi_B(\xi)\, \Phi_\pi(x)\, \Phi_\pi(y)$$

Branching Fractions $B \to V_L V_L$

Beneke, Rohrer, Yang; H.Y. Cheng, K.C. Yang; Bartsch, G.B., Kraus



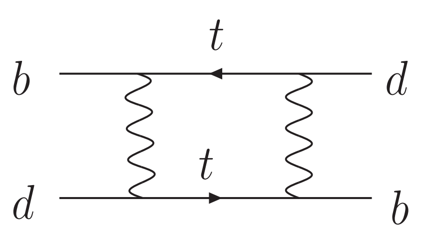
BaBar, Belle, HFAG

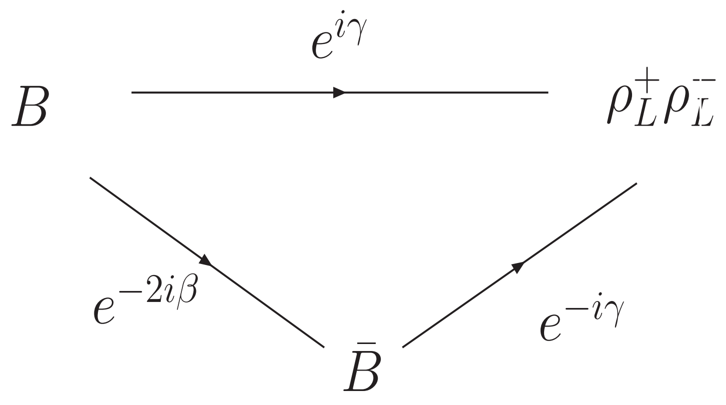
VV	$B(\bar{B} \to VV)/10^{-6}$	f_L	$B(\bar{B} \to V_L V_L)/10^{-6}$	A_{CP}
$\rho^+\rho^-$	$24.2^{+3.1}_{-3.2}$	$0.978^{+0.025}_{-0.022}$	23.7 ± 3.2	0.06 ± 0.13 (L)
$\rho^0\rho^0$	0.68 ± 0.27	0.70 ± 0.15	0.48 ± 0.21	-0.4 ± 0.9 (L)
$\rho^-\rho^0$	18.2 ± 3.0	$0.912^{+0.044}_{-0.045}$	16.6 ± 2.9	-0.08 ± 0.13
$\rho^-\omega$	$10.6^{+2.6}_{-2.3}$	0.82 ± 0.11	8.7 ± 2.4	0.04 ± 0.18
$\bar{K}^{*0}K^{*0}$	$1.28^{+0.37}_{-0.32}$	$0.80^{+0.12}_{-0.13}$	1.02 ± 0.32	—
$\bar{K}^{*0}\rho^0$	5.6 ± 1.6	0.57 ± 0.12	3.2 ± 1.1	0.09 ± 0.19
$K^{*-}\rho^+$	< 12	—	< 12	—
$K^{*-}\rho^0$	< 6.1	$0.96^{+0.06}_{-0.16}$	< 6.1	$0.20^{+0.32}_{-0.29}$
$\bar{K}^{*0}\rho^-$	9.2 ± 1.5	0.48 ± 0.08	4.4 ± 1.0	-0.01 ± 0.16
$\bar{K}^{*0}\varphi$	9.5 ± 0.8	0.484 ± 0.034	4.6 ± 0.5	-0.01 ± 0.06
$K^{*-}\varphi$	10.0 ± 1.1	0.50 ± 0.05	5.0 ± 0.7	-0.01 ± 0.08
$\bar{K}^{*0}\omega$	$1.8^{+0.8}_{-0.7}$	$0.56^{+0.34}_{-0.30}$	1.0 ± 0.7	—

CPV in $B \to \rho^+ \rho^-$

$$\mathcal{A}_{CP}(t) = \frac{\Gamma(\bar{B}(t)\to\rho_L^+\rho_L^-)-\Gamma(B(t)\to\rho_L^+\rho_L^-)}{+} = S_\rho \sin(\Delta M_d t) - C_\rho \cos(\Delta M_d t)$$

without penguins $\to$ $S = \sin 2\alpha$, $C = 0$





$$\exp(-2i(\beta+\gamma+\alpha-\alpha))$$
$$= \exp(2i\alpha)$$

$$A(\bar{B} \to \rho^+\rho^-) \sim \sqrt{\bar{\rho}^2+\bar{\eta}^2}\, e^{-i\gamma} + r e^{i\varphi}$$
$$\sim \quad \lambda_u\, a_u \quad + \; \lambda_c\, a_c$$

$\tau \equiv \cot\beta = 2.54 \pm 0.13$

$B \to \rho_L^+ \rho_L^-$: $S = -0.05 \pm 0.17$ $r \approx r\cos\varphi = 0.04 \pm 0.02$

$$\bar\eta \doteq \frac{1 + \tau S - \sqrt{1 - S^2}}{(1+\tau^2) S}(1 + r\cos\varphi) \qquad \bar\rho = 1 - \tau\,\bar\eta$$

$$\gamma \doteq \frac{\pi}{2} - \beta + \frac{S}{2} + \tau\, r\cos\varphi$$

$$\Rightarrow \qquad \gamma = 72.4^\circ \pm 1.3^\circ(\beta) \pm 5.1^\circ(S) \pm 3.2(r\cos\varphi)$$

$$R_b \equiv \sqrt{\bar\rho^2+\bar\eta^2} = \sin\beta\left[1+\frac{1}{2}\left(\frac{S}{2}+\tau r\cos\varphi\right)^2\right] = 0.367\pm 0.016^{+0.005}_{-0.002}$$

$$\Rightarrow$$

$$|V_{ub}|/10^{-3} = 3.54\pm 0.15(\beta)^{+0.05}_{-0.02}(S,r)\pm 0.05(V_{cb})\pm 0.03(V_{us}) = 3.54\pm 0.17$$

then $|V_{ub}|_{\text{excl.semilept.}}/10^{-3} = 3.54\pm 0.40$ implies $|\Delta\beta_{\text{NP}}| < 2.7^\circ$

further improvement? r in $B\to\rho^+\rho^-$ from $B\to\bar K^{*0}K^{*0}$ with SU(3)

$$B(\bar{B}_d \to \bar{K}^{*0}_L K^{*0}_L) =$$

$$\frac{\tau_{B_d} G_F^2 \, |\lambda_c|^2}{32\pi m_B} \left[f_0 |a_c(K^*)|^2 + 2 f_1 \, \mathrm{Re}\, a_c^*(K^*) \, \Delta(K^*) + f_2 |\Delta(K^*)|^2 \right]$$

$$|\Delta(K^*)| = |a_c(K^*) - a_u(K^*)| = \left(0.25^{+0.12}_{-0.10}\right) \cdot |a_c(K^*)|$$

$$\begin{aligned} f_0 &= |\lambda_t|^2/|\lambda_c|^2 \approx 0.84 \\ f_1/f_0 &= \mathrm{Re}\, \lambda_t^* \lambda_u / |\lambda_t|^2 = 0.018 \pm 0.086 \\ f_2/f_0 &= |\lambda_u|^2/|\lambda_t|^2 \approx 0.16 \end{aligned}$$

	central	τ	S_ρ	C_ρ	b	$\lvert\xi\rvert$
$\bar{\eta}$	0.359	$\begin{matrix}-0.014\\+0.015\end{matrix}$	$\begin{matrix}+0.011\\-0.011\end{matrix}$	$\begin{matrix}+0.000\\-0.004\end{matrix}$	$\begin{matrix}+0.004\\-0.004\end{matrix}$	$\begin{matrix}-0.002\\+0.003\end{matrix}$
γ[deg]	76.2	$\begin{matrix}+1.0\\-1.0\end{matrix}$	$\begin{matrix}+4.7\\-4.9\end{matrix}$	$\begin{matrix}+0.0\\-1.6\end{matrix}$	$\begin{matrix}+1.5\\-1.8\end{matrix}$	$\begin{matrix}-0.9\\+1.1\end{matrix}$
r_ρ	0.064	$\begin{matrix}-0.003\\+0.004\end{matrix}$	$\begin{matrix}-0.002\\+0.003\end{matrix}$	$\begin{matrix}+0.000\\-0.000\end{matrix}$	$\begin{matrix}+0.010\\-0.012\end{matrix}$	$\begin{matrix}-0.006\\+0.008\end{matrix}$
φ_ρ	-0.20	$\begin{matrix}+0.00\\-0.00\end{matrix}$	$\begin{matrix}+0.00\\-0.00\end{matrix}$	$\begin{matrix}+0.43\\-0.47\end{matrix}$	$\begin{matrix}+0.03\\-0.05\end{matrix}$	$\begin{matrix}-0.02\\+0.02\end{matrix}$

$\tau = \cot\beta = 2.54 \pm 0.13$, $S_\rho = -0.05 \pm 0.17$, $C_\rho = -0.06 \pm 0.13$

$b = B(\bar{B}_d \to \bar{K}_L^{*0} K_L^{*0})/B(\bar{B} \to \rho_L^+ \rho_L^-) = 0.043 \pm 0.015$

$SU(3)$ factor $|\xi| = 1.28 \pm 0.14$

Conclusions

- $B(B \to V_L V_L)$: good agreement with available data

- Unitarity triangle from $S_{\rho^+\rho^-}$ and $\sin 2\beta$:
- $\gamma = (72.4 \pm 6.2)^\circ$ [theory $\pm 3^\circ$]
- $|V_{ub}| = (3.54 \pm 0.17) \cdot 10^{-3}$

- $\rho_L^+ \rho_L^-$ penguin from $\bar{B} \to \bar{K}^{*0} K^{*0}$
  through $SU(3)$ flavour symmetry $(u \leftrightarrow s)$: theory error $\lesssim 1^\circ$

- $\to$ rich and promising phenomenology of $B \to V_L V_L$ decays