Family Non-universal $U(1)'$ Gauge Symmetries and $b \longrightarrow s$ Transitions

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- V. Barger, L. Everett, J. Jiang, P. Langacker, T.L. and C. Wagner, "Family Non-universal $U(1)'$ Gauge Symmetries and $b \longrightarrow s$ Transitions," arXiv:0902.4507 [hep-ph].
- V. Barger, L. Everett, J. Jiang, P. Langacker, T.L. and C. Wagner, "$b \longrightarrow s$ Transitions in Family-dependent $U(1)'$ Models," arXiv:0905.xxxx [hep-ph].

Outlines

- Recent Experimental Progresses on $b \longrightarrow s$ FCNC Effects
- Family Non-universal $U(1)'$ Models and $b \longrightarrow s$ Transitions
- Correlated Analysis of $B_s - \bar{B}_s$ Mixing and B_d Decays
- Discussions and Conclusions

Recent Experimental Progresses on $b \longrightarrow s$ FCNC Effects

- Three classes of FCNC processes:
  - $d \longrightarrow s$ transitions: e.g., $K - \bar{K}$ mixing
  - $b \longrightarrow d$ transitions: e.g., $B_d - \bar{B}_d$ mixing
  - $b \longrightarrow s$ transitions: e.g., $B_s - \bar{B}_s$ mixing
- Absent at tree level in the SM and sensitive to UV physics.

  $\Rightarrow$ A useful tool to probe or constrain NP models.

A. $\Delta B = 2$ processes via $b \to s$: $B_s - \bar{B}_s$ mixing

Key observables: off-diagonal element of the mixing matrix

$$M_{12}^{B_s} = (M_{12}^{B_s})_{\rm SM} C_{B_s} e^{2i\phi_{B_s}^{\rm NP}}$$

SM predictions: $C_{B_s} = 1$ and $\phi_{B_s}^{\rm NP} = 0$

Table: The fit results for the $B_s - \bar{B}_s$ mixing parameters (UTfit Collaboration' 08), obtained by combining the analyses of $B_s \to \psi\phi$ by (CDF Collaboration' 08) and (D0 Collaboration' 08)

Observable	1σ C.L.	2σ C.L.
$\phi_{B_s}^{\rm NP}[^\circ]$ (S1)	-19.9 $\pm$ 5.6	[-30.45,-9.29]
$\phi_{B_s}^{\rm NP}[^\circ]$ (S2)	-68.2 $\pm$ 4.9	[-78.45,-58.2]
C_{B_s}	1.07 $\pm$ 0.29	[0.62,1.93]

- C_{B_s} is consistent with its SM prediction, for given significance.
- $\phi_{B_s}^{\rm NP}$ has two solutions, denoted as “S1” and “S2”.
- Both of them deviate from its SM prediction by more than 3σ.

B. $\Delta B = 1$ **processes via** $b \to s$**:** $B_d \to (\phi, \eta', \pi, \rho, \omega, f_0) K_S$
Key observables: time-dependent CP asymmetries

$$\mathcal{C}_{f_{CP}} = \frac{1 - |\lambda_{f_{CP}}|^2}{1 + |\lambda_{f_{CP}}|^2}\,, \qquad \mathcal{S}_{f_{CP}} = \frac{2\mathrm{Im}\left[\lambda_{f_{CP}}\right]}{1 + |\lambda_{f_{CP}}|^2}. \qquad (1)$$

The $\lambda_{f_{CP}}$ parameter ($A_{f_{CP}}$ is decay amplitude of $B_d \to f_{CP}$.):

$$\lambda_{f_{CP}} \equiv \eta_{f_{CP}} e^{-2i\phi_{B_d}} \frac{\bar{A}_{f_{CP}}}{A_{f_{CP}}} \qquad (2)$$

SM prediction: $\phi_{B_d} = \beta \equiv \arg\left[-(V_{cd}V_{cb}^*)/(V_{td}V_{tb}^*)\right]$ and $\bar{A}_{f_{CP}} \simeq A_{f_{CP}} \Rightarrow$

$$\mathcal{C}_{f_{CP}} \simeq 0, \qquad -\eta_{f_{CP}}\mathcal{S}_{f_{CP}} \simeq \sin 2\beta. \qquad (3)$$

Table: World averages of the experimental results (HFAG'08).

f_{CP}	$-\eta_{CP}\mathcal{S}_{f_{CP}}$ (1σ C.L.)	$\mathcal{C}_{f_{CP}}$(1σ C.L.)
ψK_S	$+0.672 \pm 0.024$	$+0.005 \pm 0.019$
ϕK_S	$+0.44^{+0.17}_{-0.18}$	-0.23 ± 0.15
$\eta' K_S$	$+0.59 \pm 0.07$	-0.05 ± 0.05
πK_S	$+0.57 \pm 0.17$	$+0.01 \pm 0.10$
ρK_S	$+0.63^{+0.17}_{-0.21}$	-0.01 ± 0.20
ωK_S	$+0.45 \pm 0.24$	-0.32 ± 0.17
$f_0 K_S$	$+0.62^{+0.11}_{-0.13}$	0.10 ± 0.13

- $\sin 2\beta$ obtained from the penguin-dominated modes are systematically below that obtained from $B_d \to \psi K_S$.
- $|\mathcal{C}_{(\phi,\omega)K_S}| \gg |\mathcal{C}_{\psi K_S}|$
- $B_d \to \psi K_S$ is dominated by the SM tree-level amplitude, $-\eta_{f_{CP}}\mathcal{S}_{f_{CP}} \neq -\eta_{\psi K_S}\mathcal{S}_{\psi K_S}$ or $\mathcal{C}_{f_{CP}} \neq \mathcal{C}_{\psi K_S}$ may imply interesting NP.

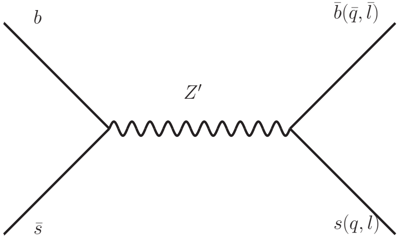
Non-universal $U(1)'$ Models and $b \to s$ Transitions

Non-universal $U(1)'$: (1) quarks, leptons charged in a family dependent way; (2) their couplings to Z' are phenomenologically characterized by the following structure:

$$\begin{aligned} B^{\psi_{L,R}} &\equiv \frac{g_2 M_Z}{g_1 M_{Z'}} V_{\psi_{L,R}} \tilde{\epsilon}^{\psi_{L,R}} V^{\dagger}_{\psi_{L,R}} \\ &= \begin{pmatrix} B_{11}^{\psi_{L,R}} & 0 & B_{13}^{\psi_{L,R}} \\ 0 & B_{11}^{\psi_{L,R}} & B_{23}^{\psi_{L,R}} \\ B_{13}^{\psi_{L,R}*} & B_{23}^{\psi_{L,R}*} & B_{33}^{\psi_{L,R}} \end{pmatrix} \end{aligned} \tag{4}$$

- $\psi_{L,R}$ – weak eigenstates of the SM fermions
  $\tilde{\epsilon}^{\psi_{L,R}}$ – $U(1)'$ gauge charge matrix of $\psi_{L,R}$, which is diagonal
  $V_{\psi_{L,R}}$ – the unitary matrices diagonalizing fermion mass matrices
- Such a structure can be generated in the case with $\tilde{\epsilon}_1^{\psi_{L,R}} = \tilde{\epsilon}_2^{\psi_{L,R}} \neq \tilde{\epsilon}_3^{\psi_{L,R}}$ and small fermion mixing angles in $V_{\psi_{L,R}}$.
- Non-trivial $B_{12}^{\psi_{L,R}}$ is excluded by $K - \bar{K}$ and $\mu - e$ constraints for down-type fermions; $B_{23}^{\psi_{L,R}}$ can lead to sizable FCNC effects in $b \to s$.

Through current-current interactions, three classes of processes via $b \to s$ can be affected at tree-level by Z'-induced FCNC effects: (1) $B_s - \bar{B}_s$ mixing; (2)$b \to s\bar{q}q$, involved in B_d meson decays; (3) $b \to s\bar{l}l$



Strategy to study $B_s - \bar{B}_s$ mixing $+$ Penguin-dominated B_d decays:

- Work in two representative limits (1) LR limit: $B^L_{bs} = B^R_{bs}$; (2) LL limit: $B^R_{bs} = 0$
- Assume that NP enters only through EW penguins (A. Buras et. al.' 04) $\Rightarrow$ three relevant parameters: $|B^L_{bs}|$, ϕ^L_{bs} and B^R_{dd}

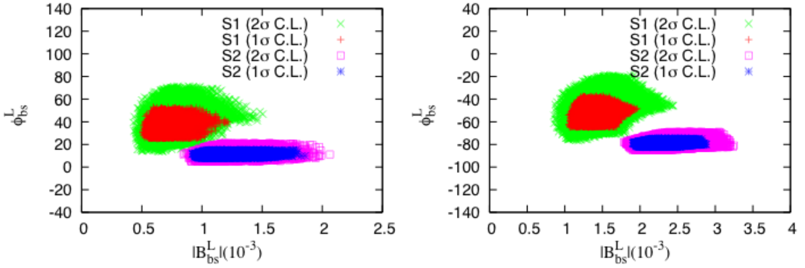
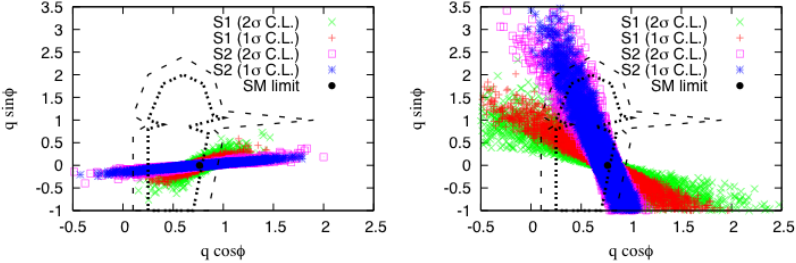


Figure: $B_s - \bar{B}_s$ mixing, in the LR and LL limits.

$$C_{B_s} e^{2i\phi^{NP}_{B_s}} = 1 - 3.59 \times 10^5 (\Delta C_1^{B_s} + \Delta \tilde{C}_1^{B_s}) + 2.04 \times 10^6 \Delta \tilde{C}_3^{B_s} \qquad (5)$$

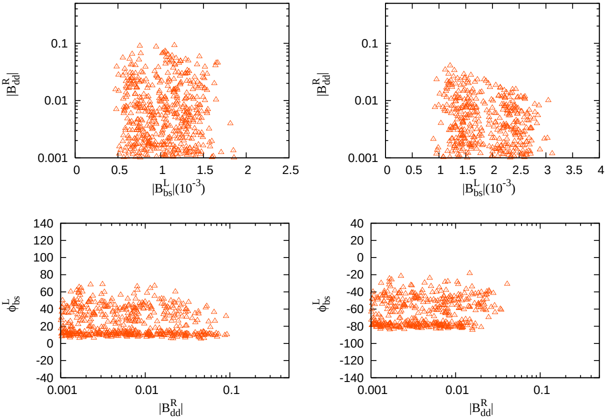
- LR limit: $\Delta C_1^{B_s} = \Delta \tilde{C}_1^{B_s} = \Delta \tilde{C}_3^{B_s} = -(B^L_{bs})^2$
- LL limit: $\Delta C_1^{B_s} = -(B^L_{bs})^2, \Delta \tilde{C}_1^{B_s} = \Delta \tilde{C}_3^{B_s} = 0$
- Two parameters involved: $|B^L_{bs}|$ and ϕ^L_{bs}; $|B^L_{bs}| \sim 10^{-3}$.

Figure: $B_d \to \pi K_S$, in the LR and LL limits.



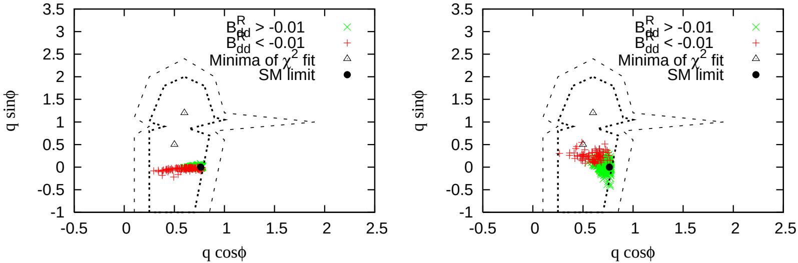
- A deviation of $\mathcal{S}_{\pi K_S}$ from its SM prediction can be understood as a modification of $qe^{i\phi} = \frac{P}{T+C}$ (A. Buras et. al.' 04). The experimental constraints on $qe^{i\phi}$ have been obtained from χ^2 fit of the $B \to \pi K$ + $B \to \pi\pi$ data (R. Fleischer et. al.' 08)
- In our models: $qe^{i\phi} = 0.76(1 + 158.1\Delta C_7 - 102.4\Delta \tilde{C}_9)$
- LR (LL) limit: $\Delta C_7 = \Delta \tilde{C}_9 = \frac{4}{V_{tb}V_{ts}^*} B_{bs}^L B_{dd}^R$ ($\Delta C_7 = \frac{4}{V_{tb}V_{ts}^*} B_{bs}^L B_{dd}^R$)

Figure: $B_s - \bar{B}_s$ mixing (2σ C.L.) + χ^2 fit of ($B \to \pi K_S + B \to \pi\pi$) ($1\sigma$ C.L.) + $\mathcal{C}_{(\phi,\eta',\rho,\omega,f_0)K_S}$, $\mathcal{S}_{(\phi,\eta',\rho,\omega,f_0)K_S}$ (1.7σ C.L.), in the LR and LL limit.



- Both solutions “S1” and “S2” in $B_s - \bar{B}_s$ mixing can be explained.
- $|B^R_{dd}| \lesssim 10^{-1}$. But, to get better fit, ...

Figure: $B_d \to \pi K_S$ (correlated analysis), in the LR and LL limits



Obviously, to get a relatively small χ^2 value, we need $|B^R_{dd}| \gtrsim 10^{-2}$.

Discussions and Conclusions

- $|B^L_{bs}| \sim 10^{-3}$, consistent with the assumption of small fermion mixing angles, since $B^L_{bs} \propto \frac{g_2 m_Z}{g_1 m_{Z'}} \times \text{fermion mixing angle}$.
- $|B^R_{dd}| \gtrsim 10^{-2}$ is typically required for a good fit. $\Rightarrow$ $\frac{g_2 m_Z}{g_1 m_{Z'}} \sim 10 - 100$ or TeV scale Z' for $g_1 \gtrsim g_2$, given $(V_{d_R} \tilde{\epsilon}^{d_R} V_{d_R})_{11} \sim \mathcal{O}(1)$.
- The assumption of small QCD penguin corrections by the NP implicitly requires $|B^L_{bs}| < |B^L_{dd}| \ll |B^R_{dd}|$. This relation can be easily accommodated.

Conclusion: Within this class of family non-universal $U(1)'$ models, the anomalies in $B_s - \bar{B}_s$ mixing and the time-dependent CP asymmetries of the penguin-dominated $B_d \to (\pi, \phi, \eta', \rho, \omega, f_0)K_S$ can be consistently accommodated!

Thank you!

A. Effective Halmiltonian of Family Non-universal $U(1)'$ Models

$$\begin{aligned}
\mathcal{H}_{eff}^{Z'}(B_s-\bar{B}_s) &= -\frac{G_F}{\sqrt{2}}(\Delta C_1^{B_s}Q_1^{B_s}+2\Delta\tilde{C}_3^{B_s}\tilde{Q}_3^{B_s}+\Delta\tilde{C}_1^{B_s}\tilde{Q}_1^{B_s})+h.c.\\
\mathcal{H}_{\rm eff}^{Z'}(b\to s\bar{q}q) &= -\frac{G_F}{\sqrt{2}}V_{tb}V_{ts}^{*}(\Delta C_3Q_3+\Delta C_5Q_5+\Delta C_7Q_7+\Delta C_9Q_9\\
&+\Delta\tilde{C}_3\tilde{Q}_3+\Delta\tilde{C}_5\tilde{Q}_5+\Delta\tilde{C}_7\tilde{Q}_7+\Delta\tilde{C}_9\tilde{Q}_9)+\text{h.c.}\\
\mathcal{H}_{eff}^{Z'}(b\to s\bar{l}l) &= -\frac{G_F}{\sqrt{2}}V_{tb}V_{ts}^{*}\Big(\Delta C_{9V}Q_{9V}+\Delta C_{10A}Q_{10A}\\
&+\Delta\tilde{C}_{9V}\tilde{Q}_{9V}+\Delta\tilde{C}_{10A}\tilde{Q}_{10A}\Big)+\text{h. c.} \qquad (6)
\end{aligned}$$

- Qs: SM operators in OPE; $\tilde{Q}$s: new operators introduced by NP
- Q_is and $\tilde{Q}_i$s: QCD penguin for $i=3,...6$ and EW penguin for $i=7,...10$
- The relevant Wilson coefficients are bilinear in terms of Z' couplings, i.e., the elements in the $B^{\psi_{L,R}}$ matrix

B. Operators of Effective Hamiltonian

QCD-Penguins Operators:

$$Q_3 = (\bar{s}b)_{\mathrm{V-A}} \sum_q (\bar{q}q)_{\mathrm{V-A}} \qquad Q_4 = (\bar{s}_\alpha b_\beta)_{\mathrm{V-A}} \sum_q (\bar{q}_\beta q_\alpha)_{\mathrm{V-A}}$$

$$Q_5 = (\bar{s}b)_{\mathrm{V-A}} \sum_q (\bar{q}q)_{\mathrm{V+A}} \qquad Q_6 = (\bar{s}_\alpha b_\beta)_{\mathrm{V-A}} \sum_q (\bar{q}_\beta q_\alpha)_{\mathrm{V+A}}$$

$$\tilde{Q}_3 = (\bar{s}b)_{\mathrm{V+A}} \sum_q (\bar{q}q)_{\mathrm{V+A}} \qquad \tilde{Q}_4 = (\bar{s}_\alpha b_\beta)_{\mathrm{V+A}} \sum_q (\bar{q}_\beta q_\alpha)_{\mathrm{V+A}}$$

$$\tilde{Q}_5 = (\bar{s}b)_{\mathrm{V+A}} \sum_q (\bar{q}q)_{\mathrm{V-A}} \qquad \tilde{Q}_6 = (\bar{s}_\alpha b_\beta)_{\mathrm{V+A}} \sum_q (\bar{q}_\beta q_\alpha)_{\mathrm{V-A}}$$

Electroweak-Penguins Operators:

$$Q_7 = \frac{3}{2}(\bar{s}b)_{\mathrm{V-A}} \sum_q e_q (\bar{q}q)_{\mathrm{V+A}} \qquad Q_8 = \frac{3}{2}(\bar{s}_\alpha b_\beta)_{\mathrm{V-A}} \sum_q e_q (\bar{q}_\beta q_\alpha)_{\mathrm{V+A}}$$

$$Q_9 = \frac{3}{2}(\bar{s}b)_{\mathrm{V-A}} \sum_q e_q (\bar{q}q)_{\mathrm{V-A}} \qquad Q_{10} = \frac{3}{2}(\bar{s}_\alpha b_\beta)_{\mathrm{V-A}} \sum_q e_q (\bar{q}_\beta q_\alpha)_{\mathrm{V-A}}$$

$$\tilde{Q}_7 = \frac{3}{2}(\bar{s}b)_{\mathrm{V+A}} \sum_q e_q (\bar{q}q)_{\mathrm{V-A}} \qquad \tilde{Q}_8 = \frac{3}{2}(\bar{s}_\alpha b_\beta)_{\mathrm{V+A}} \sum_q e_q (\bar{q}_\beta q_\alpha)_{\mathrm{V-A}}$$

$$\tilde{Q}_9 = \frac{3}{2}(\bar{s}b)_{\mathrm{V+A}} \sum_q e_q (\bar{q}q)_{\mathrm{V+A}} \qquad \tilde{Q}_{10} = \frac{3}{2}(\bar{s}_\alpha b_\beta)_{\mathrm{V+A}} \sum_q e_q (\bar{q}_\beta q_\alpha)_{\mathrm{V+A}}$$

$B_s - \bar{B}_s$ Mixing Operators:

$$Q_1^{B_s} = (\bar{s}b)_{V-A}(\bar{s}b)_{V-A} \qquad Q_2^{B_s} = (\bar{s}_\alpha b_\beta)_{V-A}(\bar{s}_\beta b_\alpha)_{V-A}$$

$$\tilde{Q}_1^{B_s} = (\bar{s}b)_{V+A}(\bar{s}b)_{V+A} \qquad \tilde{Q}_2^{B_s} = (\bar{s}_\alpha b_\beta)_{V+A}(\bar{s}_\beta b_\alpha)_{V+A}$$

$$Q_3^{B_s} = \tilde{Q}_3^{B_s} = (\bar{s}b)_{V+A}(\bar{s}b)_{V-A} \qquad Q_4^{B_s} = \tilde{Q}_4^{B_s} = (\bar{s}_\alpha b_\beta)_{V+A}(\bar{s}_\beta b_\alpha)_{V-A}$$

C. Corrections of Family Non-universal Z' to Wilson Coefficients

(1) LR limit: $B^L_{bs} = B^R_{bs}$

$$\begin{aligned}
\Delta C_1^{B_s} &= \Delta \tilde{C}_1^{B_s} = \Delta \tilde{C}_3^{B_s} = -(B^L_{bs})^2, \\
\Delta C_3 &= \Delta \tilde{C}_5 = -\frac{2}{V_{tb}V^*_{ts}} B^L_{bs} B^L_{dd}, \\
\Delta \tilde{C}_3 &= \Delta C_5 = -\frac{2}{3V_{tb}V^*_{ts}} B^L_{bs} \left(B^R_{uu} + 2B^R_{dd} \right), \\
\Delta C_7 &= \Delta \tilde{C}_9 = -\frac{4}{3V_{tb}V^*_{ts}} B^L_{bs} \left(B^R_{uu} - B^R_{dd} \right), \\
\Delta C_{9V} &= \Delta \tilde{C}_{9V} = -\frac{2}{V_{tb}V^*_{ts}} B^L_{bs} (B^L_{ll} + B^R_{ll}), \\
\Delta C_{10A} &= \Delta \tilde{C}_{10A} = -\frac{2}{V_{tb}V^*_{ts}} B^L_{bs} (-B^L_{ll} + B^R_{ll}).
\end{aligned}$$

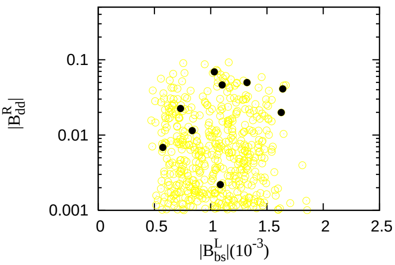
(2) LL limit: $\epsilon^{\psi_R} \propto I$

$$
\begin{aligned}
\Delta C_1^{B_s} &= -(B_{bs}^L)^2, \\
\Delta C_3 &= -\frac{2}{V_{tb}V_{ts}^*} B_{bs}^L B_{dd}^L, \\
\Delta C_5 &= -\frac{2}{3V_{tb}V_{ts}^*} B_{bs}^L \left(B_{uu}^R + 2B_{dd}^R\right), \\
\Delta C_7 &= -\frac{4}{3V_{tb}V_{ts}^*} B_{bs}^L \left(B_{uu}^R - B_{dd}^R\right), \\
\Delta C_{9V} &= -\frac{2}{V_{tb}V_{ts}^*} B_{bs}^L (B_{ll}^L + B_{ll}^R), \\
\Delta C_{10A} &= -\frac{2}{V_{tb}V_{ts}^*} B_{bs}^L (-B_{ll}^L + B_{ll}^R).
\end{aligned}
$$

(3) RR limit: $\epsilon^{\psi_L} \propto I$

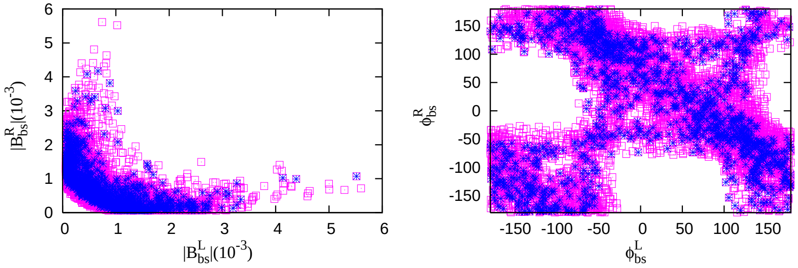
$$
\begin{aligned}
\Delta \tilde{C}_1^{B_s} &= -(B_{bs}^R)^2, \\
\Delta \tilde{C}_3 &= -\frac{2}{3 V_{tb} V_{ts}^*} B_{bs}^R \left(B_{uu}^R + 2 B_{dd}^R \right), \\
\Delta \tilde{C}_5 &= -\frac{2}{V_{tb} V_{ts}^*} B_{bs}^R B_{dd}^L, \\
\Delta \tilde{C}_9 &= -\frac{4}{3 V_{tb} V_{ts}^*} B_{bs}^R \left(B_{uu}^R - B_{dd}^R \right), \\
\Delta \tilde{C}_{9V} &= -\frac{2}{V_{tb} V_{ts}^*} B_{bs}^R (B_{ll}^L + B_{ll}^R), \\
\Delta \tilde{C}_{10A} &= -\frac{2}{V_{tb} V_{ts}^*} B_{bs}^R (-B_{ll}^L + B_{ll}^R).
\end{aligned}
$$

D. Correlated Analyses in LR limit



E. $B_s - \bar{B}_s$ Mixing in General Case

Figure: Distributions of $|B_{bs}^{L,R}|$ and $\phi_{bs}^{L,R}$, in the general case.



Three representative limits:

- Diagonal lines (from left-bottom to right-up): $B_{bs}^L = B_{bs}^R$ (LR limit)
- Bottom lines: $\tilde{\epsilon}^{\psi_R} \propto I \Rightarrow B_{bs}^R = 0$ (LL limit)
- Left vertical lines: $\tilde{\epsilon}^{\psi_L} \propto I \Rightarrow B_{bs}^L = 0$ (RR limit)
- Three parameters. LR (LL): $|B_{bs}^L|$, ϕ_{bs}^L, B_{dd}^R; RR: $|B_{bs}^R|$, ϕ_{bs}^R, B_{dd}^R.