$B \to K\pi$ and new physics in electroweak penguins

Lars Hofer
Universität Würzburg

in collaboration with Dominik Scherer, Leonardo Vernazza

Valencia, February 2013

Motivation

- tension at 2.2σ level in $B \to \pi K$ CP asymmetries:

$$\Delta A_{\rm CP} \equiv A_{\rm CP}(B^- \to \pi^0 K^-) - A_{\rm CP}(\bar{B}^0 \to \pi^+ K^-)$$
$$= 1.9^{+5.8}_{-4.8}\%\Big|_{\rm theo}\,, \qquad 12.6^{+2.2}_{-2.2}\%\Big|_{\rm exp}$$

Motivation

- tension at 2.2σ level in $B \to \pi K$ CP asymmetries:

$$\begin{aligned}\Delta A_{\rm CP} &\equiv A_{\rm CP}(B^- \to \pi^0 K^-) - A_{\rm CP}(\bar{B}^0 \to \pi^+ K^-) \\ &= 1.9^{+5.8}_{-4.8}\%\Big|_{\rm theo}\,, \qquad 12.6^{+2.2}_{-2.2}\%\Big|_{\rm exp}\end{aligned}$$

- possible explanations:
  - new physics in the electroweak penguin sector [Buras, Fleischer, Recksiegel, Schwab; ...]
  - large uncertainties in theory predictions due to low-energy QCD effects
  - statistical fluctuation

Motivation

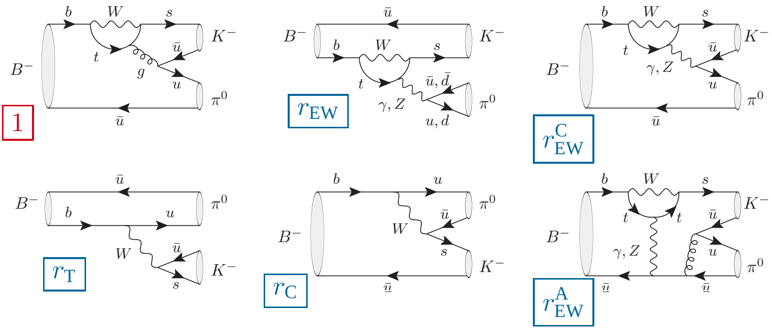
- tension at 2.2σ level in $B \to \pi K$ CP asymmetries:

$$\begin{aligned} \Delta A_{\rm CP} &\equiv A_{\rm CP}(B^- \to \pi^0 K^-) - A_{\rm CP}(\bar{B}^0 \to \pi^+ K^-) \\ &= 1.9^{+5.8}_{-4.8}\%\Big|_{\rm theo}, \qquad 12.6^{+2.2}_{-2.2}\%\Big|_{\rm exp} \end{aligned}$$

- possible explanations:
  - new physics in the electroweak penguin sector
    [Buras, Fleischer, Recksiegel, Schwab; ...]
  - large uncertainties in theory predictions due to low-energy QCD effects
  - statistical fluctuation

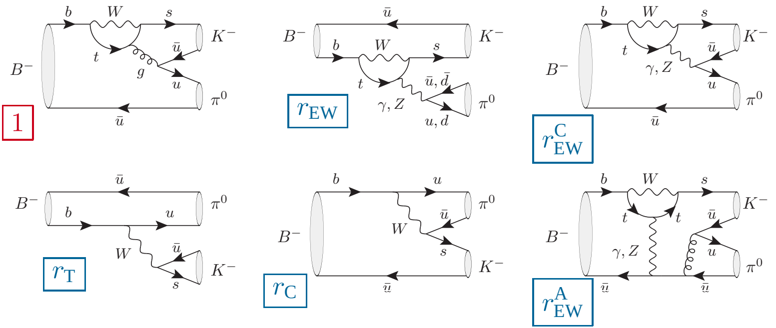
- situation not clear $\Rightarrow$ study other decay modes

$B \longrightarrow \pi K$: Topologies



- normalized to dominant QCD penguin $\longrightarrow$ $|r_i| \sim \mathcal{O}(0.1)$

$B \to \pi K$: Topologies



- normalized to dominant QCD penguin $\quad \longrightarrow \quad |r_i| \sim \mathcal{O}(0.1)$
- approximate isospin symmetry

$$\mathcal{H}_{\rm eff} = \mathcal{H}_{\rm eff}^{\Delta I=0} + \mathcal{H}_{\rm eff}^{\Delta I=1}$$

$$1,\ (r_{\rm T},\ r_{\rm C},\ r_{\rm EW}^{\rm (C,A)}) \qquad\qquad r_{\rm T},\ r_{\rm C},\ r_{\rm EW}^{\rm (C,A)}$$

$B \to \pi K$: branching ratios

- ratios of BR's sensitive to isospin violation:
  e.g.
  $$R_c^B \equiv 2\,\frac{\mathrm{Br}(B^-\to\pi^0K^-)+\mathrm{Br}(B^+\to\pi^0K^+)}{\mathrm{Br}(B^-\to\pi^-\bar{K}^0)+\mathrm{Br}(B^+\to\pi^+K^0)} = 1 + \mathcal{O}(r_T, r_{EW}, r_C)$$
- tensions with data in the past led to speculations on a "$B \to \pi K$ puzzle" [Buras, Fleischer, Recksiegel, Schwab 2003; ...]

$B \to \pi K$: branching ratios

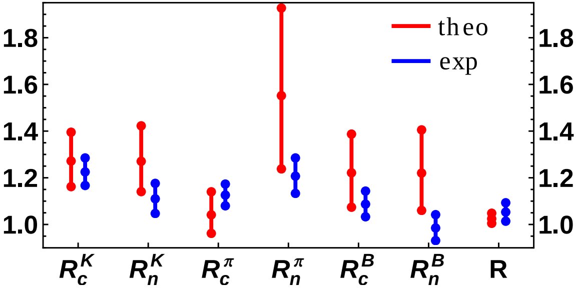
- ratios of BR's sensitive to isospin violation:

  e.g.

$$R_c^B \equiv 2\,\frac{\mathrm{Br}(B^-\to\pi^0K^-)+\mathrm{Br}(B^+\to\pi^0K^+)}{\mathrm{Br}(B^-\to\pi^-\bar{K}^0)+\mathrm{Br}(B^+\to\pi^+K^0)} = 1 + \mathcal{O}(r_T, r_{EW}, r_C)$$

- tensions with data in the past led to speculations on a "$B \to \pi K$ puzzle" [Buras, Fleischer, Recksiegel, Schwab 2003; ...]

- today: good agreement between theory and experiment:

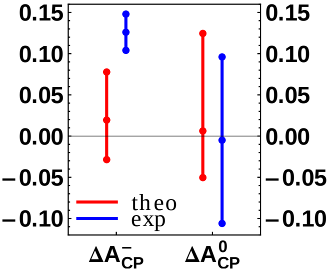


$B \longrightarrow \pi K$: CP asymmetries

- $A_{\rm CP}(B^- \to \pi^0 K^-)$ and $A_{\rm CP}(\bar{B}^0 \to \pi^+ K^-)$ dominated by P/T interference.
- consider their difference:
$\Delta A_{\rm CP} \equiv \Delta A_{\rm CP}^- \simeq -2\,[{\rm Im}(r_C) - {\rm Im}(r_T\, r_{EW})]\,\sin\gamma$
- analogously:
$\Delta A_{\rm CP}^0 = A_{\rm CP}(B^- \to \pi^- \bar{K}^0) - A_{\rm CP}(\bar{B}^0 \to \pi^0 \bar{K}^0)$

$B \to \pi K$: CP asymmetries

- $A_{\rm CP}(B^- \to \pi^0 K^-)$ and $A_{\rm CP}(\bar{B}^0 \to \pi^+ K^-)$ dominated by P/T interference.
- consider their difference:
  $\Delta A_{\rm CP} \equiv \Delta A^-_{\rm CP} \simeq -2\,[{\rm Im}(r_C) - {\rm Im}(r_T\, r_{EW})]\sin\gamma$
- analogously:
  $\Delta A^0_{\rm CP} = A_{\rm CP}(B^- \to \pi^- \bar{K}^0) - A_{\rm CP}(\bar{B}^0 \to \pi^0 \bar{K}^0)$
- 2.2σ tension in $\Delta A_{\rm CP}$:



NP in EW penguins and ΔA_{CP}

- $\Delta A_{CP} \simeq -2\,\mathrm{Im}(r_C)\sin\gamma$

NP in EW penguins and ΔA_{CP}

- $\Delta A_{CP} \simeq -2\,\mathrm{Im}(r_C)\sin\gamma + 2\,\mathrm{Im}(\tilde{r}_{\mathrm{EW}} + \tilde{r}^{\mathrm{A}}_{\mathrm{EW}})\sin\delta$
- new EW penguin contribution with new CP phase:

$$r^{(\mathrm{C,A})}_{\mathrm{EW}} \to r^{(\mathrm{C,A})}_{\mathrm{EW}} + \tilde{r}^{(\mathrm{C,A})}_{\mathrm{EW}}\, e^{-i\delta}$$

NP in EW penguins and $\Delta A_{\rm CP}$

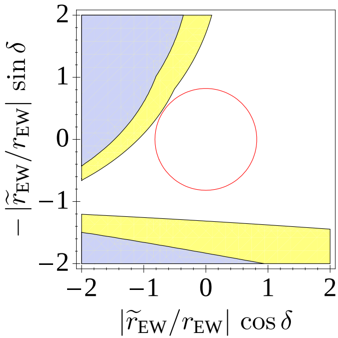
- $\Delta A_{CP} \simeq -2\,{\rm Im}(r_C)\sin\gamma + 2\,{\rm Im}(\tilde r_{\rm EW} + \tilde r_{\rm EW}^{\rm A})\sin\delta$

- new EW penguin contribution with new CP phase:

$$r_{\rm EW}^{\rm (C,A)} \longrightarrow r_{\rm EW}^{\rm (C,A)} + \tilde r_{\rm EW}^{\rm (C,A)}\, e^{-i\delta}$$

- $\Delta A_{\rm CP}$ - tension can be alleviated for $|\tilde r_{\rm EW}^{\rm (A)}| \sim |r_{\rm EW}|$

- example:
  NP in Wilson coefficient C_9
  yellow region:
  tension in $\Delta A_{\rm CP}$ below $1\,\sigma$



Is there NP in EW penguins?

- $\Delta A_{CP} \simeq -2\,\mathrm{Im}(r_C)\sin\gamma + 2\,\mathrm{Im}(\tilde{r}_{\mathrm{EW}} + \tilde{r}^{\mathrm{A}}_{\mathrm{EW}})\sin\delta$
- QCDF: $\mathrm{Im}(r_C)$ either $\mathcal{O}(\alpha_s)$ or $\mathcal{O}(\Lambda_{\mathrm{QCD}}/m_B)$
  - small strong phases disfavour ΔA_{CP} explanation via r_C
  - r_C suffers from large hadronic uncertainties
- possible explanations:
  1. NP in EW penguins
  2. hadronic uncertainties in r_C

Is there NP in EW penguins?

- $\Delta A_{CP} \simeq -2\,\mathrm{Im}(r_C)\sin\gamma + 2\,\mathrm{Im}(\tilde{r}_{\mathrm{EW}} + \tilde{r}^{\mathrm{A}}_{\mathrm{EW}})\sin\delta$
- QCDF: $\mathrm{Im}(r_C)$ either $\mathcal{O}(\alpha_s)$ or $\mathcal{O}(\Lambda_{\mathrm{QCD}}/m_B)$
  - small strong phases disfavour ΔA_{CP} explanation via r_C
  - r_C suffers from large hadronic uncertainties
- possible explanations:
  1. NP in EW penguins
  2. hadronic uncertainties in r_C
- topological parametrisation redundant:
  $\tilde{r}_{\mathrm{EW}}$ and r_C always in combination $\tilde{r}_{\mathrm{EW}} e^{-i\delta} - r_C e^{-i\gamma}$
  - BR's $\sim$ $\mathrm{Re}(\tilde{r}_{\mathrm{EW}})\cos\delta - \mathrm{Re}(r_C)\cos\gamma$
  - CP asymmetries $\sim$ $\mathrm{Im}(\tilde{r}_{\mathrm{EW}})\sin\delta - \mathrm{Im}(r_C)\sin\gamma$

Is there NP in EW penguins?

- $\Delta A_{CP} \simeq -2\,\mathrm{Im}(r_C)\sin\gamma + 2\,\mathrm{Im}(\tilde{r}_{\mathrm{EW}} + \tilde{r}^{\mathrm{A}}_{\mathrm{EW}})\sin\delta$
- QCDF: $\mathrm{Im}(r_C)$ either $\mathcal{O}(\alpha_s)$ or $\mathcal{O}(\Lambda_{\mathrm{QCD}}/m_B)$
  - small strong phases disfavour ΔA_{CP} explanation via r_C
  - r_C suffers from large hadronic uncertainties
- possible explanations:
  1. NP in EW penguins
  2. hadronic uncertainties in r_C
- topological parametrisation redundant:
  $\tilde{r}_{\mathrm{EW}}$ and r_C always in combination $\quad \tilde{r}_{\mathrm{EW}} e^{-i\delta} - r_C e^{-i\gamma}$
  - BR's $\sim$ $\mathrm{Re}(\tilde{r}_{\mathrm{EW}})\cos\delta - \mathrm{Re}(r_C)\cos\gamma$
  - CP asymmetries $\sim$ $\mathrm{Im}(\tilde{r}_{\mathrm{EW}})\sin\delta - \mathrm{Im}(r_C)\sin\gamma$

$\Rightarrow$ test new EW penguin hypothesis in other decays

Probing EW penguins

- EW penguins are most easily probed through (semi-)leptonic B decays

  however: typically uncorrelated to $B \to \pi K$

Probing EW penguins

- EW penguins are most easily probed through (semi-)leptonic B decays

  however: typically uncorrelated to $B \to \pi K$

- EW penguins in hadronic B, B_s decays are usually overshadowed by QCD penguins

  $\Rightarrow$ isolate isospin-violating $\Delta I = 1$ -component

Probing EW penguins

- EW penguins are most easily probed through (semi-)leptonic B decays

  however: typically uncorrelated to $B \to \pi K$

- EW penguins in hadronic B, B_s decays are usually overshadowed by QCD penguins

  $\Rightarrow$ isolate isospin-violating $\Delta I = 1$ -component

- $B \to \pi K, \rho K, \pi K^*, \rho K^*$:
  construct observables which project out the $\Delta I = 1$ - component (like ΔA_{CP})

Probing EW penguins

- EW penguins are most easily probed through (semi-)leptonic B decays

  however: typically uncorrelated to $B \to \pi K$

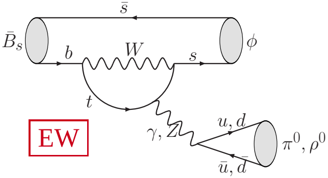
- EW penguins in hadronic B, B_s decays are usually overshadowed by QCD penguins

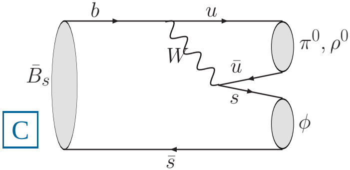
  $\Rightarrow$ isolate isospin-violating $\Delta I = 1$-component

- $B \to \pi K, \rho K, \pi K^*, \rho K^*$:
  construct observables which project out the $\Delta I = 1$-component (like ΔA_{CP})

- $B_s \to \phi\pi, \phi\rho$:
  - pure $\Delta I = 1$ decays $\Rightarrow$ no QCD penguins
  - no other hadronic $b \to s$ decays with this property

The decays $B_s \to \phi\pi, \phi\rho$





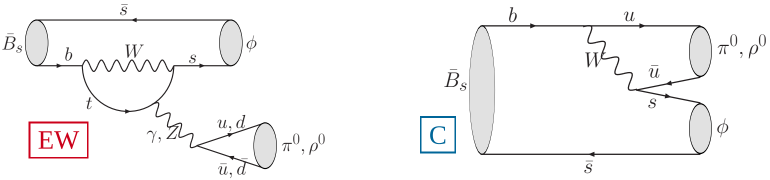
- dominated by EW penguin contribution [Fleischer]:

$$\sqrt{2}\, A(\bar{B}_s \to \phi\pi, \phi\rho) \;=\; P_{\rm EW}^{\pi,\rho} \left(1 \;-\; r_{\rm C}^{\pi,\rho}\, e^{-i\gamma}\right)$$

- SM branching fractions:

$$\mathrm{Br}(\bar{B}_s \to \phi\pi^0) = 1.6^{+1.0}_{-0.3} \cdot 10^{-7}, \qquad \mathrm{Br}(\bar{B}_s \to \phi\rho^0) = 4.4^{+2.4}_{-0.7} \cdot 10^{-7}$$

The decays $B_s \to \phi\pi, \phi\rho$



- dominated by EW penguin contribution [Fleischer]:

$$\sqrt{2}\, A(\bar{B}_s \to \phi\pi, \phi\rho) \;=\; P_{\rm EW}^{\pi,\rho} \left(1 \,-\, r_{\rm C}^{\pi,\rho}\, e^{-i\gamma} \,+\, \widetilde{r}_{\rm EW}^{\pi,\rho}\, e^{-i\delta}\right)$$

- SM branching fractions:

$$\mathrm{Br}(\bar{B}_s \to \phi\pi^0) = 1.6^{+1.0}_{-0.3} \cdot 10^{-7}, \qquad \mathrm{Br}(\bar{B}_s \to \phi\rho^0) = 4.4^{+2.4}_{-0.7} \cdot 10^{-7}$$

- A new EW penguin contribution $\widetilde{r}_{\rm EW}^{\pi,\rho}\, e^{-i\delta}$ with $\left|\widetilde{r}_{\rm EW}^{\pi,\rho}\right| \sim 1$ can lead to significant enhancement of the BRs

  $\Rightarrow$ can be studied at LHCb and SuperB

The decays $B_s \to \phi\pi, \phi\rho$

- $r_{\mathrm{C}}^{\pi,\rho}$, $\tilde{r}_{\mathrm{EW}}^{\pi,\rho}$ again in combination $r_{\mathrm{C}}^{\pi,\rho}\, e^{-i\gamma} + \tilde{r}_{\mathrm{EW}}^{\pi,\rho}\, e^{-i\delta}$

  However:

  - BR's $\sim$ $\mathrm{Re}(r_{\mathrm{C}}^{\pi,\rho}) \cos\gamma$

    $\longrightarrow$ smaller hadronic uncertainties in QCDF
  - BR's $\sim$ $\mathrm{Re}(r_{\mathrm{EW}}^{\pi,\rho}) \cos\delta$, $|r_{\mathrm{EW}}^{\pi,\rho}|^2$ for $|r_{\mathrm{EW}}^{\pi,\rho}| \sim 1$

    $\longrightarrow$ sensitive to $r_{\mathrm{EW}}^{\pi,\rho}$ irrespective of NP phase
  - no uncertainties from QCD penguin dominance

The decays $B_s \to \phi\pi, \phi\rho$

- $r_C^{\pi,\rho}$, $\tilde{r}_{EW}^{\pi,\rho}$ again in combination $r_C^{\pi,\rho}\, e^{-i\gamma} + \tilde{r}_{EW}^{\pi,\rho}\, e^{-i\delta}$

  However:

  - BR's $\sim$ $\mathrm{Re}(r_C^{\pi,\rho}) \cos\gamma$

    $\to$ smaller hadronic uncertainties in QCDF
  - BR's $\sim$ $\mathrm{Re}(r_{EW}^{\pi,\rho}) \cos\delta$, $|r_{EW}^{\pi,\rho}|^2$ for $|r_{EW}^{\pi,\rho}| \sim 1$

    $\to$ sensitive to $r_{EW}^{\pi,\rho}$ irrespective of NP phase
  - no uncertainties from QCD penguin dominance

- $B_s \to \phi\pi$ probes different chirality structure than $B \to \pi K$:

  $B \to \pi K \sim C_{7,9} - C'_{7,9}$, $\qquad B_s \to \phi\pi \sim C_{7,9} + C'_{7,9}$

- hadronic parameters non-universal in different hadronic channels

  $\to$ different combinations of Wilson coefficients probed

Strategy of our analysis

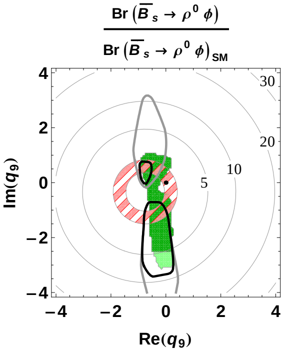
- parametrize NP in Wilson coefficients in a model-independent/model-inspired way
- perform a frequentist χ^2-fit to the $B \to \pi K$ observables using the Rfit method [Hoecker,Lacker,Laplace,Le Diberder]
- include constraints from other processes at the 2σ-level
- study enhancement $\mathrm{Br}^{\mathrm{SM+NP}}/\mathrm{Br}^{\mathrm{SM}}$ of the $B_s \to \phi\pi,\ \phi\rho$ branching ratio with simultaneous consideration of the $B \to \pi K$ - fit
- use QCD factorization for calculation of hadronic matrix elements [Beneke,Buchalla,Neubert,Sachrajda; Beneke,Rohrer,Yang]

Model-independent analysis

$$C_{7,9}^{(\prime),\mathrm{NP}}(M_W) = C_9^{\mathrm{SM}}(M_W)\, q_{7,9}^{(\prime)} \quad \text{with} \quad q_{7,9}^{(\prime)} = |q_{7,9}^{(\prime)}|\, e^{i\varphi_{7,9}^{(\prime)}}$$

Model-independent analysis

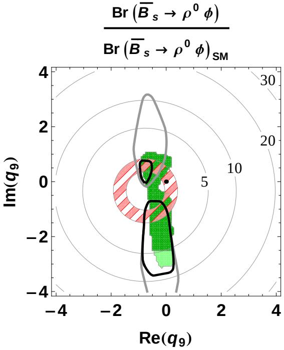
$$C_{7,9}^{(\prime),\mathrm{NP}}(M_W) = C_9^{\mathrm{SM}}(M_W)\, q_{7,9}^{(\prime)} \quad \text{with} \quad q_{7,9}^{(\prime)} = |q_{7,9}^{(\prime)}|\, e^{i\varphi_{7,9}^{(\prime)}}$$

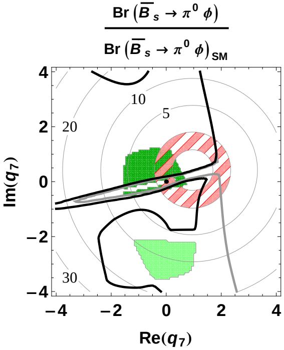


- black line: 1σ - region of $B \to \pi K$ - fit
  green region: Allowed at 2σ from $B \to \pi K^{(*)},\ \rho K^{(*)},\ \phi K^{(*)}$
  and $B_s \to \phi\phi,\ KK$
- Light colors: isospin-violating observables only

Model-independent analysis

$$C_{7,9}^{(\prime),\mathrm{NP}}(M_W) = C_9^{\mathrm{SM}}(M_W)\, q_{7,9}^{(\prime)} \quad \text{with} \quad q_{7,9}^{(\prime)} = |q_{7,9}^{(\prime)}|\, e^{i\varphi_{7,9}^{(\prime)}}$$



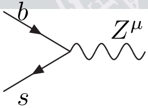


- black line: 1σ - region of $B \to \pi K$ - fit
  green region: Allowed at 2σ from $B \to \pi K^{(*)},\ \rho K^{(*)},\ \phi K^{(*)}$
  and $B_s \to \phi\phi,\ KK$
- Light colors: isospin-violating observables only

Model-independent analysis

- data from hadronic B decays constrain NP in EW penguins to $|q_i^{(\prime)}| \lesssim 2$
- $B \to \pi K$ - fit works well for $q_9^{(\prime)} \neq 0$:
  best fit point: $|q_9^{(\prime)}| = 1.9, \quad \varphi_9^{(\prime)} = -100°(+180°)$
- $q_7^{(\prime)}$ not much constrained from $B \to \pi K$
  $\to$ complementary constraints from $B \to \rho K, \pi K^*, \rho K^*$
- large enhancement (up to factor of 5) of $B_s \to \phi\pi, \phi\rho$ possible in many scenarios
- $B \to \pi K$ cannot distinguish $q_{7,9} \leftrightarrow -q'_{7,9}$ and is not affected by parity-symmetric NP with $q_{7,9} = q'_{7,9}$
  $\to$ complementary information from $B \to \pi K^*, \rho K,$
  $B_s \to \phi\pi$

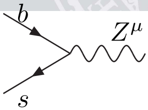
Modified Z coupling



$$-i\frac{g}{\cos\theta_W}\gamma^\mu\left(\kappa_L^{sb}P_L+\kappa_R^{sb}P_R\right)$$

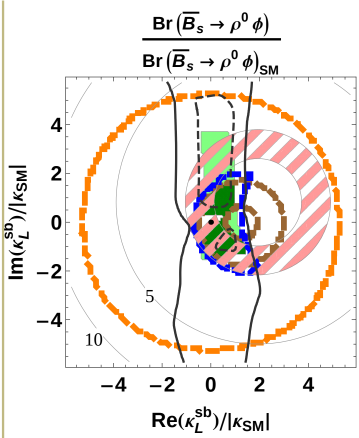
- additional constraints from $B_s-\bar{B}_s$ mixing, semileptonic B decays , $B_s\to\mu^+\mu^-$

Modified Z coupling



$$-i\frac{g}{\cos\theta_W}\gamma^\mu\left(\kappa_L^{sb}P_L + \kappa_R^{sb}P_R\right)$$

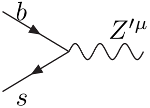
- additional constraints from $B_s - \bar{B}_s$ mixing, semileptonic B decays , $B_s \to \mu^+\mu^-$



Modified Z coupling

- constraints from semileptonic B decays
  - inclusive branching ratio $B \to X_s e^+ e^-$
  - forward-backward asymmetry of $B \to K^* \ell^+ \ell^-$
- with these constraints:
  - practically no enhancement of $B_s \to \phi\pi, \phi\rho$ compared to SM expectation
  - solution of ΔA_{CP} tension still possible
- more complete analysis of exclusive semileptonic constraints
  $\to$ exclusion of ΔA_{CP} - solution via new EW penguin?

Model with Z' boson

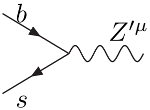


$$-i\frac{g_{U(1)'}}{\sqrt{2}\,\xi}\,\gamma^\mu\left(\tilde{\zeta}_L^{\,sb}\,P_L + \tilde{\zeta}_R^{sb}\,P_R\right), \qquad \xi = \frac{g^2_{U(1)'}}{g^2}\frac{M_W^2}{M_{Z'}^2}$$

- leptophobic Z' avoids constraints from semileptonic B decays
- interesting correlation with $B_s - \bar{B}_s$ mixing:

$$C_7 \propto \tilde{\zeta}_L^{sb},\; C_9' \propto \tilde{\zeta}_R^{sb} \qquad \leftrightarrow \qquad C_i^{\Delta B=2} \propto \left(\tilde{\zeta}_{L,R}^{sb}\right)^2 \cdot \frac{1}{\xi}$$

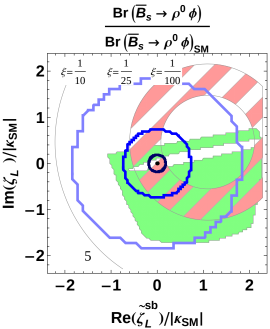
Model with Z' boson

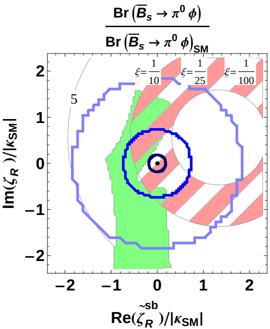


$$-i\frac{g_{U(1)'}}{\sqrt{2}\,\xi}\,\gamma^{\mu}\left(\tilde{\zeta}_L^{\,sb}\,P_L + \tilde{\zeta}_R^{sb}\,P_R\right), \qquad \xi = \frac{g^2_{U(1)'}}{g^2}\,\frac{M_W^2}{M_{Z'}^2}$$

- leptophobic Z' avoids constraints from semileptonic B decays
- interesting correlation with $B_s - \bar{B}_s$ mixing:

$$C_7 \propto \tilde{\zeta}_L^{sb},\; C_9' \propto \tilde{\zeta}_R^{sb} \qquad \leftrightarrow \qquad C_i^{\Delta B=2} \propto \left(\tilde{\zeta}_{L,R}^{sb}\right)^2 \cdot \frac{1}{\xi}$$





Conclusions

- NP in EW penguins can alleviate the $2.2\,\sigma$ tension in ΔA_{CP}
- NP hypothesis should be tested in other decay modes:
  $B_s \to \phi\pi, \phi\rho$ are pure $\Delta I = 1$ - decays
  $\Rightarrow$ very sensitive to NP in EW penguins
- Current data on $B \to \pi K$ and other hadronic B decays allow for an enhancement of $\mathrm{Br}(B_s \to \phi\pi, \phi\rho)$ of up to a factor of 5 (in generic NP models)
- in Z' models: interesting correlation with $B_s - \bar{B}_s$ mixing

$\Rightarrow$ study $B_s \to \phi\pi, \phi\rho$ at LHCb and SuperB!!!