New Strategy to Explore CP Violation with $B_s \to K^- K^+$

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Motivation

- B meson decays offer an interesting laboratory to search for new physics
  - New sources of CP violation
- Unprecedented precision required for LHCb upgrade and Belle II
- Theoretical precision limited by strong interactions

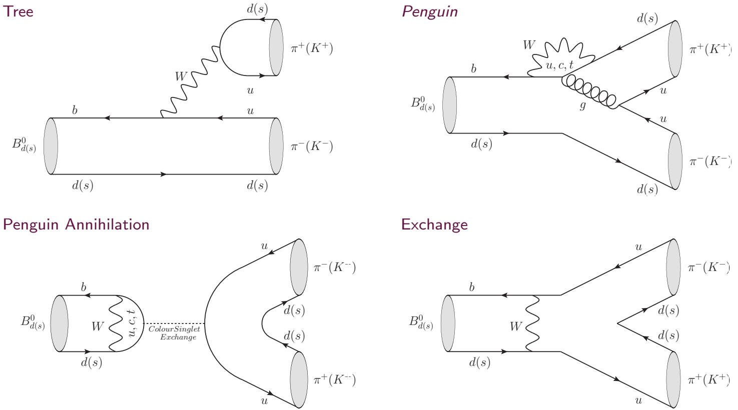
U-spin symmetry

Flavor symmetries provide valuable insights into hadronic non-perturbative parameters

- Precision limited by symmetry-breaking corrections
- *New strategy*

$B_s^0 \to K^- K^+$ decay topologies

R. Fleischer [1999]



- Penguin topologies dominate
  - Sensitive to physics beyond the Standard Model
- Related to $B_d^0 \to \pi^- \pi^+$ via U-spin symmetry (s-quark $\leftrightarrow$ d-quark)

$B_s^0 \to K^-K^+$ and $B_d^0 \to \pi^-\pi^+$

R. Fleischer [1999]

$$A(B_s^0 \to K^-K^+) = \sqrt{\epsilon} e^{i\gamma} \mathcal{C}' \left[1 + \tfrac{1}{\epsilon} d' e^{i\theta'} e^{-i\gamma}\right]$$
$$A(B_d^0 \to \pi^-\pi^+) = e^{i\gamma} \mathcal{C} \left[1 - d e^{i\theta} e^{-i\gamma}\right]$$

$$\mathcal{C}' \propto T' + P^{(ut)\prime} + E' + PA^{(ut)\prime} \qquad d' e^{i\theta'} \propto \frac{P^{(ct)\prime} + PA^{(ct)\prime}}{T' + P^{(ut)\prime} + E' + PA^{(ut)\prime}}$$

- Penguin dominated $\epsilon \simeq 0.05$
- Weak phase γ of Unitarity Triangle
- $\mathcal{C}$ and d analogous to $\mathcal{C}'$ and d'

U-spin symmetry

$$d e^{i\theta} = d' e^{i\theta'} \text{ and } \mathcal{C} = \mathcal{C}'$$

R. Fleischer [1999]

- Direct and Mixing induced CP violation

$$\mathcal{A}_{\rm CP}(t) \equiv \frac{\Gamma(B_q^0(t) \to f) - \Gamma(\bar{B}_q^0(t) \to \bar{f})}{\Gamma(B_q^0(t) \to f) + \Gamma(\bar{B}_q^0(t) \to \bar{f})}$$
$$\propto \mathcal{A}_{\rm CP}^{\rm dir}(B_q \to f)\cos(\Delta M_q t) + \mathcal{A}_{\rm CP}^{\rm mix}(B_q \to f)\sin(\Delta M_q t)$$

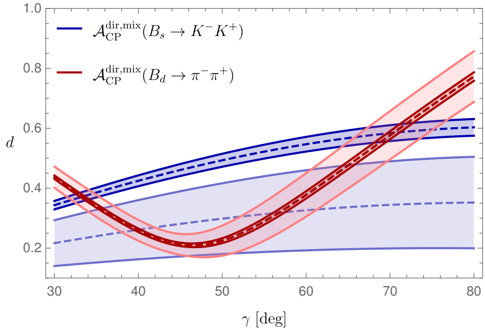
  - Depend on γ and hadronic parameters d and θ
  - $\mathcal{A}_{\rm CP}^{\rm mix}$ depends also on B_q^0-$\bar{B}_q^0$ mixing angle ϕ_q

Original Strategy

- Hadronic parameters are related to those in $B_d^0 \to \pi^-\pi^+$ by U-spin
  - Extract γ and ϕ_s from CP asymmetries

Original Strategy

R. Fleischer and R. Knegjens [2011]
R. Fleischer [1999,2007]
T. Abe et al. (Belle-II)[2010]
R. Aaij et al. (LHCb)[2013]



- LHCb[2015] $\gamma = (63.5^{+7.2}_{-6.7})^\circ$
- Future γ of $\mathcal{O}(1^\circ)$
  - Same uncertainty as future tree determination

- <u>U-spin breaking</u> $\xi \equiv \frac{d'}{d} = 1 \pm 0.2$ and $\Delta \equiv \theta' - \theta = (0 \pm 20)^\circ$
- Uncertainty on γ of $\mathcal{O}(5^\circ)$

Original Strategy

- CP asymmetries determine the "effective" mixing angle

$$\sin\phi_s^{\text{eff}} = \frac{\mathcal{A}_{\text{CP}}^{\text{mix}}(B_s \to K^- K^+)}{\sqrt{1 - \mathcal{A}_{\text{CP}}^{\text{dir}}(B_s \to K^- K^+)^2}}$$

- B_s^0-$\bar{B}_s^0$ mixing angle determined via $\sin\phi_s^{\text{eff}} \equiv \sin(\phi_s + \Delta\phi_{KK})$
- Hadronic non-perturbative correction $\Delta\phi_{KK}$

$$\tan\Delta\phi_{KK} = \frac{2\epsilon d' \cos\theta' \sin\gamma + \epsilon^2 \sin(2\gamma)}{d'^2 + 2\epsilon d' \cos\theta' \cos\gamma + \epsilon^2 \cos(2\gamma)},$$

- U-spin symmetry $\to \Delta\phi_{KK}$
  - LHCb[2015] $\phi_s = -(6.9^{+9.2}_{-8.0})^\circ$
  - Current PDG average $\phi_s = -(0.68 \pm 2.2)^\circ$

Original Strategy

$\sin \phi_s^{\text{eff}} \equiv \sin(\phi_s + \Delta\phi_{KK})$

- LHCb upgrade $\phi_s^{\text{eff}} \sim \mathcal{O}(0.5^\circ)$

- Hadronic non-perturbative correction
  - U-spin symmetry $\rightarrow \Delta\phi_{KK} \sim \mathcal{O}(0.3^\circ)$
  - U-spin breaking of 20% gives $\Delta\phi_{KK} = -(9.0 \pm 2.6)^\circ$

- Future $B_s^0 \rightarrow J/\psi\phi$ of $\mathcal{O}(0.5^\circ)$

- To match future experimental precision U-spin breaking corrections have to be known at the few percent level

New Strategy

- Minimize use of U-spin symmetry
- Use γ and ϕ_d as input
- Non-factorizable effects probed by semileptonic ratios

New Strategy

Non-factorizable effects probed by semileptonic ratios

$$R_\pi \equiv \frac{\Gamma(B_d \to \pi^-\pi^+)}{|d\Gamma(B_d \to \pi^-\ell^+\nu_\ell)/dq^2|_{q^2=m_\pi^2}} = 6\pi^2 X_\pi |V_{ud}|^2 f_\pi^2 |a_{\rm NF}|^2 r_\pi$$

$$R_K \equiv \frac{\Gamma(B_s \to K^-K^+)}{|d\Gamma(B_s \to K^-\ell^+\nu_\ell)/dq^2|_{q^2=m_K^2}} = 6\pi^2 X_K |V_{us}|^2 f_K^2 |a'_{\rm NF}|^2 r_K$$

- $r_\pi = 1 - 2d\cos\theta\cos\gamma + d^2 \to$ from CP asymmetries in $B_d^0 \to \pi^-\pi^+$
- $r_K = 1 - 2d'/\epsilon\cos\theta'\cos\gamma + d'^2/\epsilon^2$
- $a_{\rm NF} \equiv (1 + r_P)(1 + x)a_{\rm NF}^T$
  - $r_P \equiv P^{(ut)}/T$
  - $x \equiv \frac{E+PA^{(ut)}}{T+P^{(ut)}}$

New Strategy

- Determine d' and θ' using $r_K = r_\pi \frac{R_K}{R_\pi} \left|\frac{V_{ud}}{V_{us}}\right|^2 \left(\frac{f_\pi}{f_K}\right)^2 \frac{X_\pi}{X_K} (\xi^a_{\mathrm{NF}})^2$
  - $\Delta\phi_{KK}$ and ϕ_s

U-spin parametrization

$$\xi^a_{\mathrm{NF}} \equiv \left|\frac{a_{\mathrm{NF}}}{a'_{\mathrm{NF}}}\right| = \left|\frac{a^T_{\mathrm{NF}}}{a^{T\prime}_{\mathrm{NF}}}\right| \left|\frac{1+r_P}{1+r'_P}\right| \left|\frac{1+x}{1+x'}\right|$$

- Very favorable structure in terms of U-spin-breaking parameters
  - Robust structure
  - Minimal use of U-spin symmetry

New Strategy

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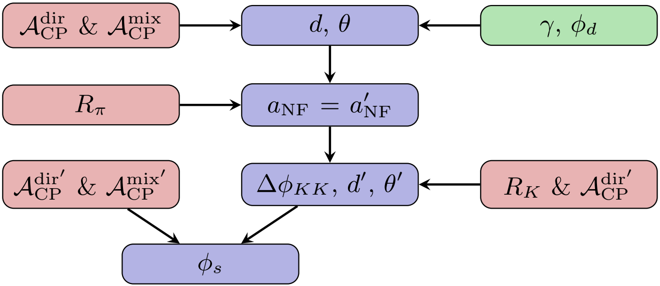

U-spin-breaking corrections

$$\xi^a_{\rm NF} \equiv \left|\frac{a^T_{\rm NF}}{a^{T\prime}_{\rm NF}}\right| \left|\frac{1+r_P}{1+r'_P}\right| \left|\frac{1+x}{1+x'}\right|$$

Beneke, Huber, Li [2010] Gronau *et al.* [1995]
Fleischer, Jaarsma, and KKV[2016]

- Use data to quantify U-spin-breaking corrections

- QCD factorization $a^T_{\rm NF} = 1.000^{+0.029}_{-0.069} + (0.011^{+0.023}_{-0.050})i$
- $a^T_{\rm NF}/a^{T\prime}_{\rm NF} \simeq 1 + \Delta^T_{\rm NF}\xi^T_{NF} + \mathcal{O}((\Delta^T_{\rm NF})^2)$

- U-spin breaking of 20% gives a correction of $\mathcal{O}(1\%)$

U-spin-breaking corrections

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- $r_P = P^{(ut)}/T \simeq 0.2$ from pure Penguin decays
- $\frac{1+r_P}{1+r'_P} \simeq 1 + (1-\xi_P)r_P + \mathcal{O}(r_P^2)$
- U-spin breaking of $\xi_P \sim 0.2$ gives a correction of $\mathcal{O}(4\%)$.

Exchange and Penguin Annihilation contributions

Gronau *et al.* [1995]
Fleischer, Jaarsma, and KKV[2016]

- $x = \frac{E+PA^{(ut)}}{T+P^{(ut)}}$ expected to be small
  - Constrained by pure exchange and penguin annihilation topologies $B_d^0 \to K^+K^-$ and $B_s^0 \to \pi^+\pi^-$
  - New ICHEP data $x \sim 0.15$
- $\frac{1+x}{1+x'} = 1 + (1 - \xi_x)x + \mathcal{O}(x^2)$
- U-spin breaking of 20% gives a correction of $\mathcal{O}(3\%)$
  - Future data will narrow this down further

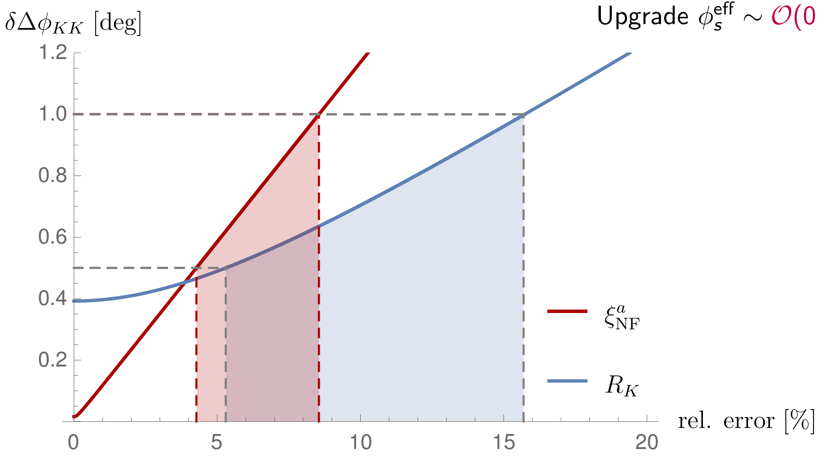
U-spin-breaking corrections

Expected combined correction $\xi_{\rm NF}^a \sim \mathcal{O}(5\%)$

Illustration of the Error on $\Delta\phi_{KK}$

$\phi_s = \phi_s^{\text{eff}} - \Delta\phi_{KK}$

Upgrade $\phi_s^{\text{eff}} \sim \mathcal{O}(0.5^\circ)$

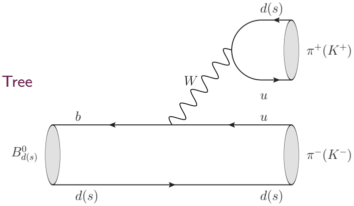


- 0.5° precision on $\Delta\phi_{KK}$ requires $\mathcal{O}(5\%)$ precision on R_K and ξ^a_{NF}

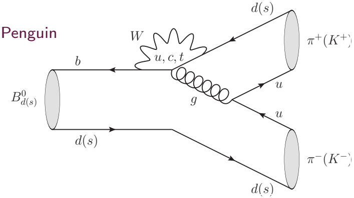
Picture from Current Data

- $B_s^0 \to K^- \ell^+ \nu_\ell$ not yet measured
- $B_d^0 \to \pi^- K^+$ has only Tree and Penguin topologies
  - Similar to $B_s^0 \to K^- K^+$
  - Ignoring E and PA topologies, only spectator quark difference
  - $\tilde{R}_K \equiv \frac{\Gamma(B_d \to \pi^- K^+)}{|d\Gamma(B_d \to \pi^- \ell^+ \nu_\ell)/dq^2|_{q^2=m_K^2}}$
  - Semileptonic rate cancels largely in the ratio $R_\pi / \tilde{R}_K$

Tree



Penguin



Picture from Current Data

- Using $\gamma = (70 \pm 7)^\circ$

$$d = 0.58 \pm 0.16, \quad \theta = (151.4 \pm 7.6)^\circ,$$
$$\tilde{d}' = 0.50 \pm 0.03, \quad \tilde{\theta}' = (157.2 \pm 2.2)^\circ.$$

- Assuming U-spin symmetry $\tilde{d}' = d' \rightarrow \Delta\phi_{KK} = -(10.7 \pm 0.6)^\circ$
- CP asymmetries in $B_s^0 \rightarrow K^- K^+$ give $\phi_s^{\text{eff}} = -(17.6 \pm 7.9)^\circ$

$$\phi_s = \phi_s^{\text{eff}} - \Delta\phi_{KK} = -(6.9 \pm 7.9)^\circ.$$

- Very consistent with LHCb determination $\phi_s = -(6.9^{+9.2}_{-8.0})^\circ$

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First U-spin test

$$\xi = \tilde{d}'/d = 0.87 \pm 0.20 \quad \Delta = \tilde{\theta}' - \theta = (5.8 \pm 8.3)^\circ$$

Conclusion

- New strategy to extract mixing angle ϕ_s
  - Semileptonic $B_d^0 \to \pi^- \ell^+ \nu_\ell$, $B_s^0 \to K^- \ell^+ \nu_\ell$ decays
  - Apply U-spin symmetry to robust quantities
- Theoretical precision of $\mathcal{O}(0.5^\circ)$ attainable
- Current data show promising picture

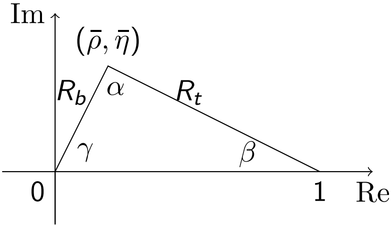
Outlook

- Extensive study of Exchange and Penguin Annihilation topologies
- Analyses of $B_s^0 \to K^- \ell^+ \nu_\ell$ strongly advocated
- New sources of CP violation may be revealed

CKM Matrix

Wolfenstein [1983]
Buras *et. al* [1994]

$$\begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} = \begin{pmatrix} 1-\frac{1}{2}\lambda^2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\frac{1}{2}\lambda^2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix} + \mathcal{O}(\lambda^4)$$



$$\bar{\rho} \equiv \rho \left(1 - \frac{1}{2}\lambda^2\right)$$
$$\bar{\eta} \equiv \eta \left(1 - \frac{1}{2}\lambda^2\right)$$