Towards New Frontiers in the Exploration of Charmless Non-Leptonic B Decays

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in collaboration with

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Theor. Physik 1

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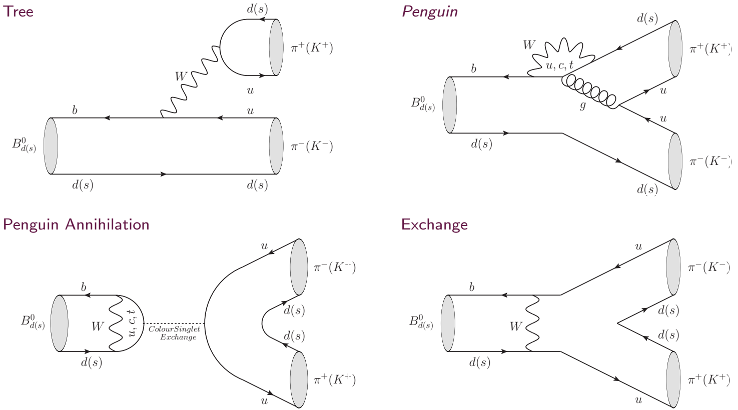
Motivation

- Non-leptonic B meson decays offer an interesting laboratory to search for new physics
  - New sources of CP violation
- Theoretical precision limited by strong interactions
- Unprecedented precision required for LHCb upgrade and Belle II
- Two-body decays well established
  - QCD Factorization, Flavor symmetries and semileptonic ratios
- New strategy for upgrade era Fleischer, Jaarsma, KKV [2016]

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

R. Fleischer [1999]



- Dominated by QCD Penguin topologies
- Related to $B_d^0 \to \pi^- \pi^+$ via *U*-spin symmetry (s-quark $\leftrightarrow$ d-quark)

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

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

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

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

- Penguin dominated $\epsilon \simeq 0.05$, weak phase γ of Unitarity Triangle

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

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

- Depend on γ, penguin parameters d, θ and $B_q^0 - \bar{B}_q^0$ mixing angle ϕ_q

Flavor symmetries

- Flavor symmetries provide valuable insights into hadronic non-perturbative parameters

Original Strategy

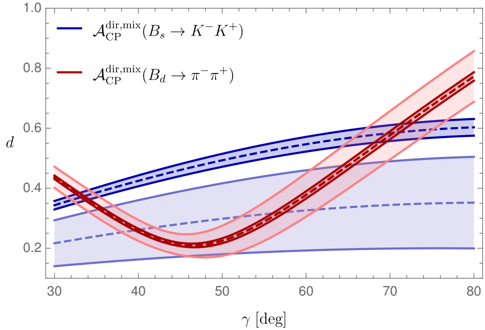
Hadronic parameters are related to those in $B_d^0 \to \pi^-\pi^+$ by U-spin

$$d e^{i\theta} = d' e^{i\theta'}$$

- Extract γ and ϕ_s from CP asymmetries
- Limited by U-spin breaking corrections

Original Strategy

R. Fleischer and R. Knegjens [2011]
R. Fleischer [1999,2007]



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

- U-spin-breaking effects increase uncertainty

$$\xi \equiv \frac{d'}{d} = 1 \pm 0.2 \ \text{ and } \ \Delta \equiv \theta' - \theta = (0 \pm 20)^\circ$$

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

Original Strategy

- CP asymmetries determine the "effective" mixing angle

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

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- U-spin symmetry $\to \Delta\phi_{KK}$
  - LHCb upgrade ϕ_s^{eff} of $\mathcal{O}(0.5^\circ)$ similar to future $B_s^0 \to J/\psi\phi$ precision
  - U-spin breaking of 20% gives $\Delta\phi_{KK} = -(9.0 \pm 2.6)^\circ$

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

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

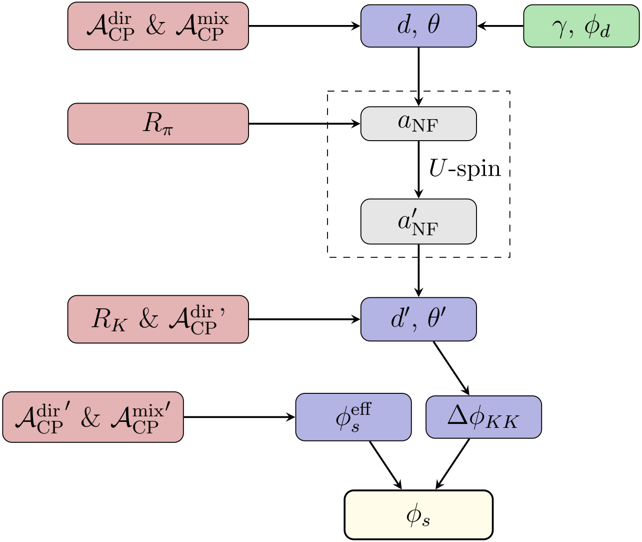
$$R_K \equiv \frac{\Gamma(B_s \to K^- K^+)}{|d\Gamma(B_s \to K^- \ell^+ \nu_\ell)/dq^2|_{q^2=m_K^2}} = 6\pi^2 X_K |V_{us}|^2 f_K^2 |a'_{\rm NF}|^2 r_K$$

- $r_\pi (r_K)$ depend on penguin parameters $d, \theta (d', \theta')$
- X_π, X_K contain form-factor ratios

$$a_{\rm NF} \equiv (1 + r_P)(1 + x) a_{\rm NF}^T$$

$$r_P \equiv \frac{P^{(ut)}}{T} \;\; \text{and} \;\; x \equiv \frac{E + PA^{(ut)}}{T + P^{(ut)}}$$

New Strategy



New Strategy

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
  - Use data to quantify *U*-spin breaking corrections

U-spin-breaking corrections - factorization

Fleischer, Jaarsma, and KKV[2016]

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

with

$$\frac{a^T_{\rm NF}}{a^{T\prime}_{\rm NF}} \simeq 1 + \Delta^T_{\rm NF}\xi^T_{NF} + \mathcal{O}((\Delta^T_{\rm NF})^2)$$

- QCD factorization $a^T_{\rm NF} = 1.000^{+0.029}_{-0.069} + (0.011^{+0.023}_{-0.050})i$ Beneke, Huber, Li [2010]
- U-spin breaking of 20% gives a correction of $\mathcal{O}(1\%)$

U-spin-breaking corrections - penguins

Fleischer, Jaarsma, and KKV[2016]

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

with

$$\frac{1+r_P}{1+r'_P} \simeq 1 + (1-\xi_P)r_P + \mathcal{O}(r_P^2)$$

- $r_P = P^{(ut)}/T = 0.22$ from pure penguin decays $B^+ \to \pi^+ K^0$ and $B^+ \to K^+ \bar{K}^0$
- U-spin breaking of $\xi_P \sim 0.2$ gives a correction of $\mathcal{O}(4\%)$

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- $r_P = P^{(ut)}/T = 0.22$ from pure penguin decays $B^+ \to \pi^+ K^0$ and $B^+ \to K^+ \bar{K}^0$
- U-spin breaking of $\xi_P \sim 0.2$ gives a correction of $\mathcal{O}(4\%)$
- Future measurements of CP violation in $B^0_d \to K^0 \bar{K}^0, B^0_s \to K^0 \bar{K}^0$

Exchange and Penguin Annihilation contributions

Fleischer, Jaarsma, and KKV[2016]

$$x = \frac{E + PA^{(ut)}}{T + P^{(ut)}}$$

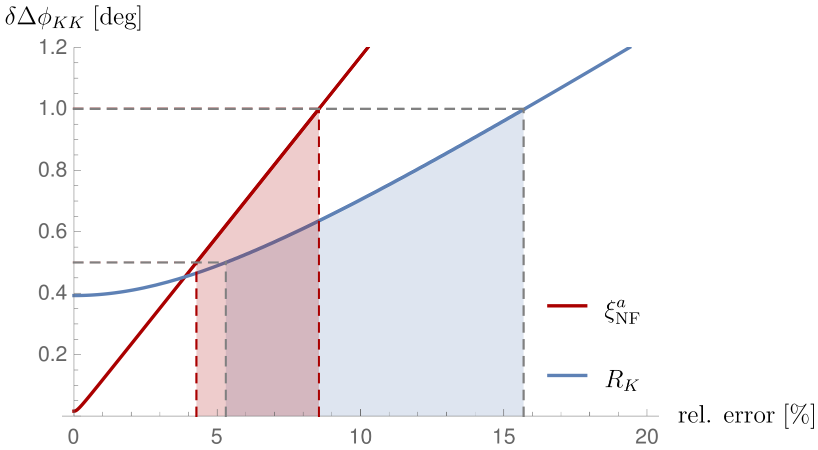
- Constrained by pure exchange and penguin annihilation topologies
  $B_d^0 \to K^+K^-$ and $B_s^0 \to \pi^+\pi^-$
- Recent LHCb data $x \sim 0.15$

$$\frac{1+x}{1+x'} = 1 + (1-\xi_x)x + \mathcal{O}(x^2)$$

- U-spin breaking of 20% gives a correction of $\mathcal{O}(3\%)$
- Future data will narrow this down further (CP asymmetries)

Expected combined correction $\xi^a_{\mathrm{NF}} \sim \mathcal{O}(5\%)$

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

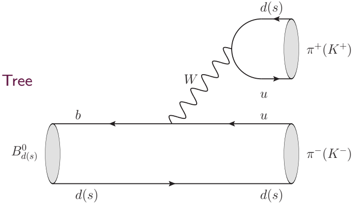


- 0.5° precision on $\Delta\phi_{KK}$ requires $\mathcal{O}(5\%)$ precision on R_K and $\xi^a_{\rm NF}$

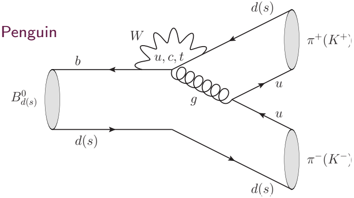
Picture from Current Data

- $B_s^0 \to K^- \ell^+ \nu_\ell$ not yet measured
- Demonstration: $B_d^0 \to \pi^- K^+$
  - 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 $\tilde{d}' = d' \to \Delta\phi_{KK} = -(10.7 \pm 0.6)^\circ$
- CP asymmetries in $B_s^0 \to K^- K^+$ 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 $\phi_s = -(6.9^{+9.2}_{-8.0})^\circ$

Picture from Current Data

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

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

- First U-spin symmetry test with current data

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

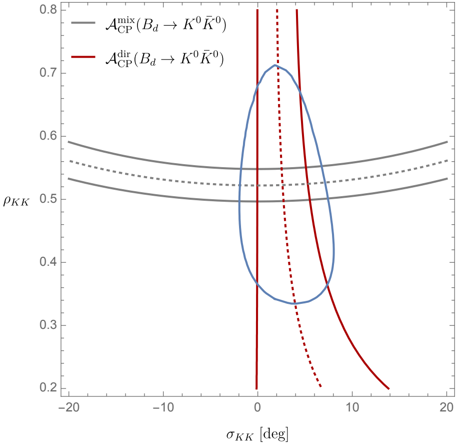
- Upgrade era if ξ^a_{NF} and R_K, R_π known with 5% precision

ξ at 0.07 level

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
  - U-spin breaking corrections can be pinned down with data
- Theoretical precision of $\mathcal{O}(0.5^\circ)$ attainable
- Current data show promising picture
- Extensive study of Exchange and Penguin Annihilation topologies
  - Interesting prospects for future data
- Analyses of $B_s^0 \to K^- \ell^+ \nu_\ell$ strongly advocated

Backup: U-spin-breaking corrections - penguins

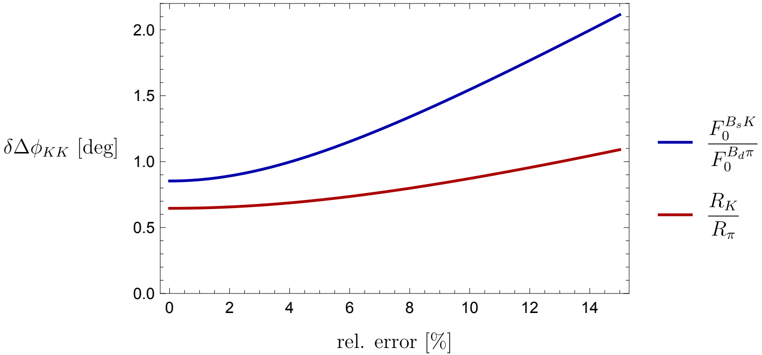


Fleischer, Jaarsma, and KKV[2016]

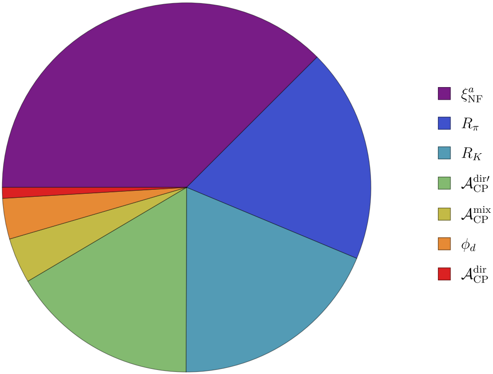
$$1 + r_P = \frac{1}{1 - d e^{i\theta} \rho_P}, \text{ where } \rho_P = \rho_{KK} e^{i\sigma_{KK}} \propto \frac{P^{(ut)}}{P^{(ct)}}$$

Backup: Form factors

Fleischer, Jaarsma, and KKV[2016]

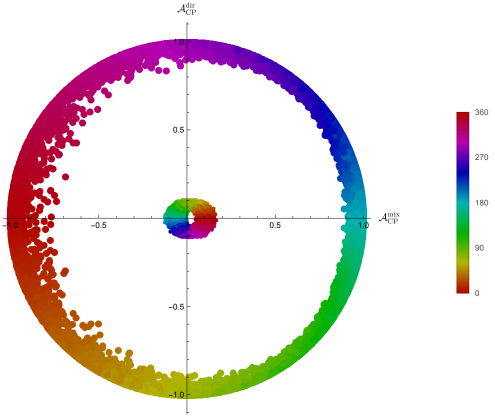


Backup: Illustration of the Error on $\Delta\phi_{KK}$



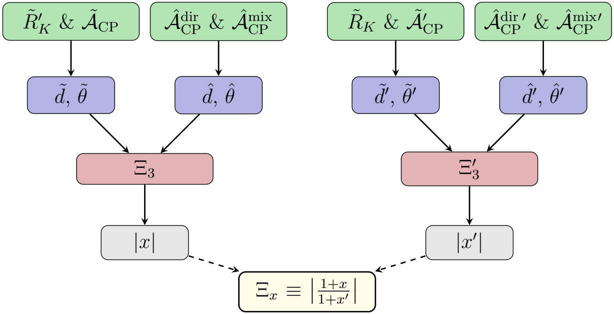
- Error budget for $\mathcal{O}(5\%)$ precision on R_K, R_π and $\xi^a_{\rm NF}$

Backup: CP asymmetries

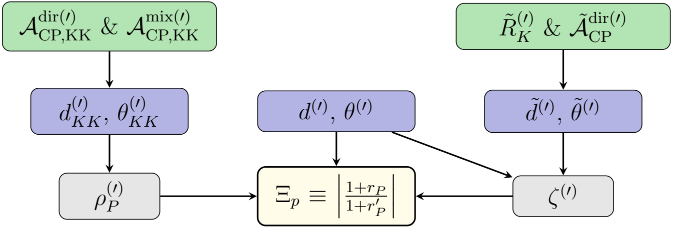


- Correlation between the $B_d^0 \to K^+K^-$ and $B_s^0 \to \pi^+\pi^-$

Backup: Flowchart



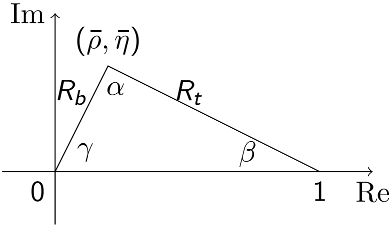
Backup: Flowchart



Backup: CKM Matrix

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

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



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