Theory determination of γ and ϕ_s from $B_{(s)} \to hh$ decays

K. Keri Vos

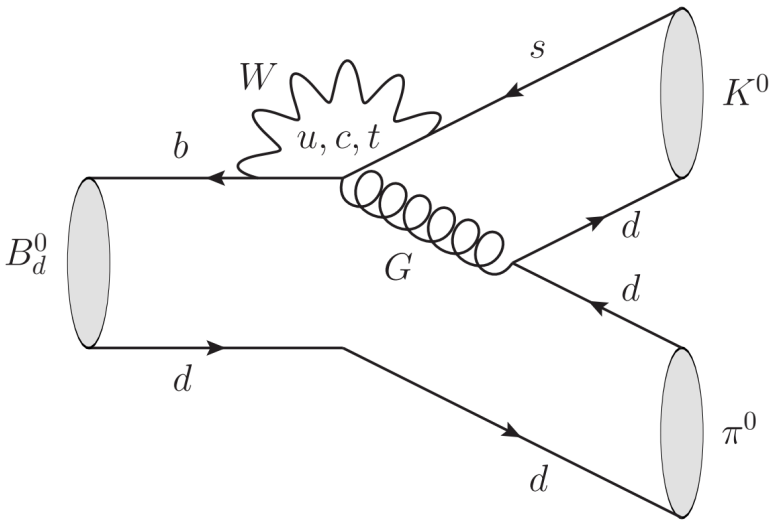
Maastricht University & Nikhef

in collaboration with Ruben Jaarsma and Robert Fleischer, JHEP02 (2023) 081

[2211.08346]

The challenge of nonleptonic B decays

- Nonleptonic decays are important probes of CP violation
  - Direct CP violation due to different strong and weak phases
  - Mixing-induced CP violation in neutral decays probe mixing phase $\phi_{d,s}$
  - Sensitivity to NP in loops (penguins)
- CP violation in the SM is too small and peculiar!
  - CKM CP violating effects only from flavour changing currents
  - Flavour diagonal CP violation tiny in SM (EDMs)
  - Large CP asymmetries with processes with tiny BRs and vice versa



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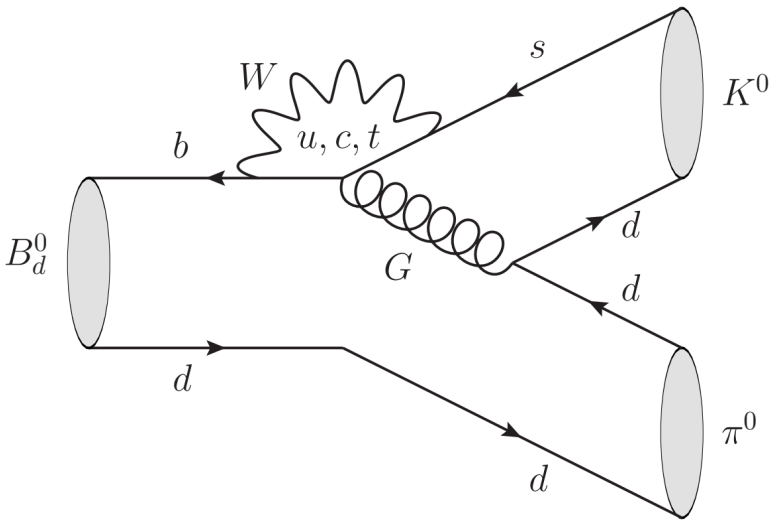
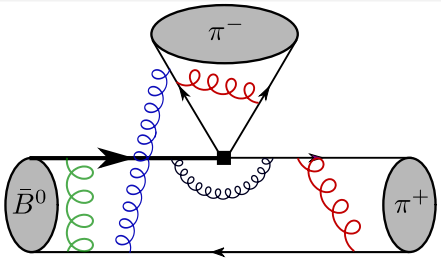


Challenge: Calculation of Hadronic matrix elements

How to handle nonleptonic B decays?



QCD Factorization Beneke, Buchalla, Neubert, Sachrajda: Talk by T. Huber@CKM

- Disentangle perturbative (calculable) and non-perturbative dynamics using HQE

Flavour symmetries (Isospin or $SU(3)$)

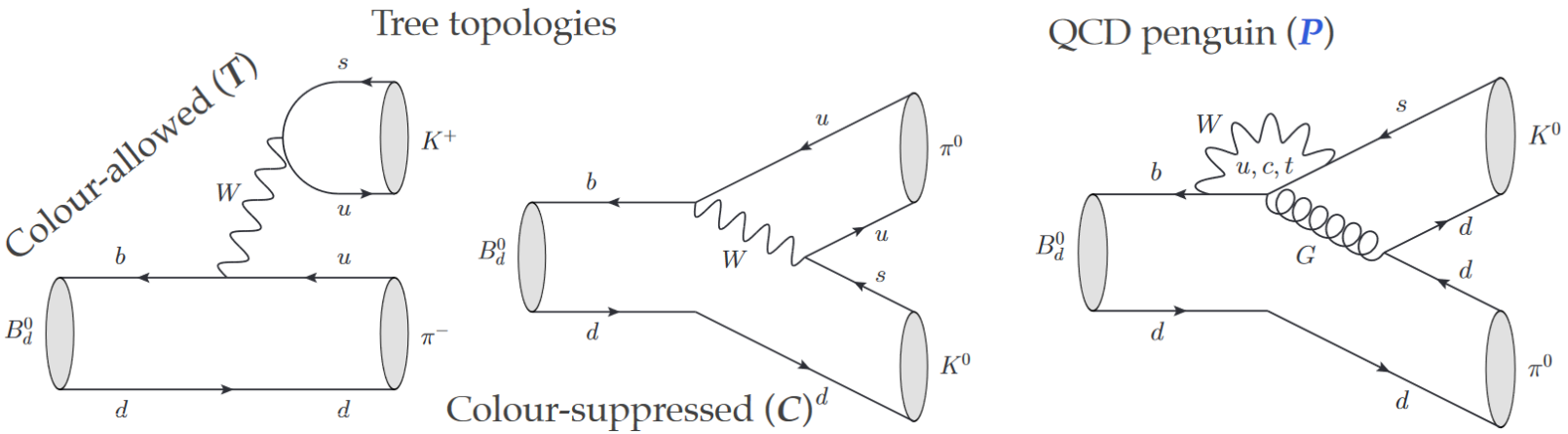
- Puzzles in $B \to \pi K$ e.g. Fleischer, Jaarsma, KKV, Malami [2017,2018] and $B \to DK$ Talk by E. Malami@CKM
- Global $SU(3)$ fit to $B \to PP$ decays Huber, Tetlalmatzi-Xolocotzi [2111.06418]

Light-cone sumrules

- Work in progress Jung, Melic, Khodjamirian

Topologies for $B \to hh$ decays

- Main contributions to $B \to hh$
- Tree and penguin contributions



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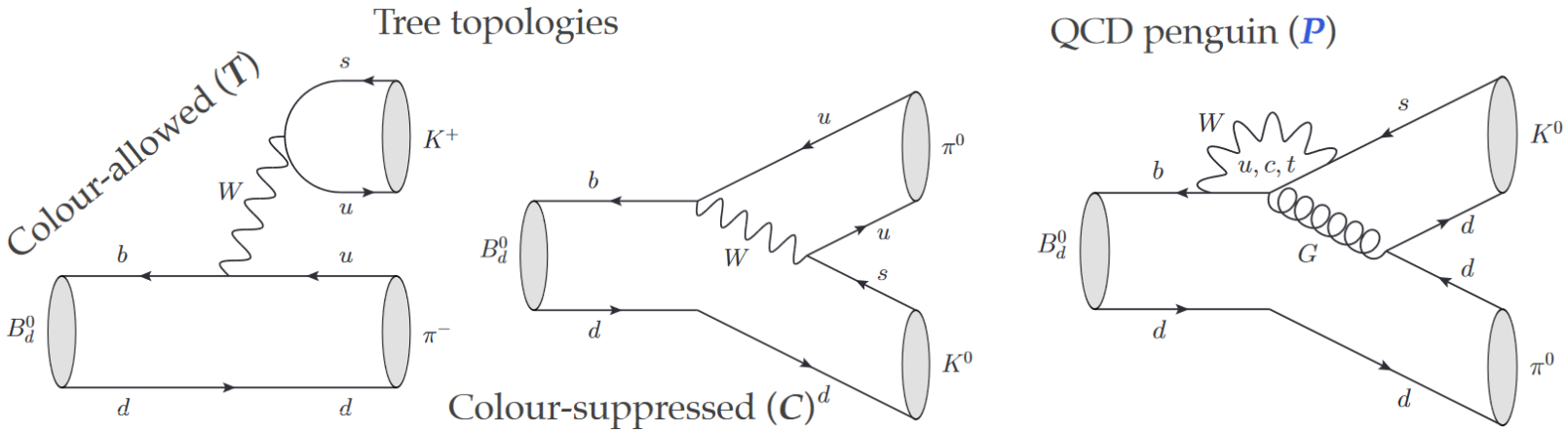

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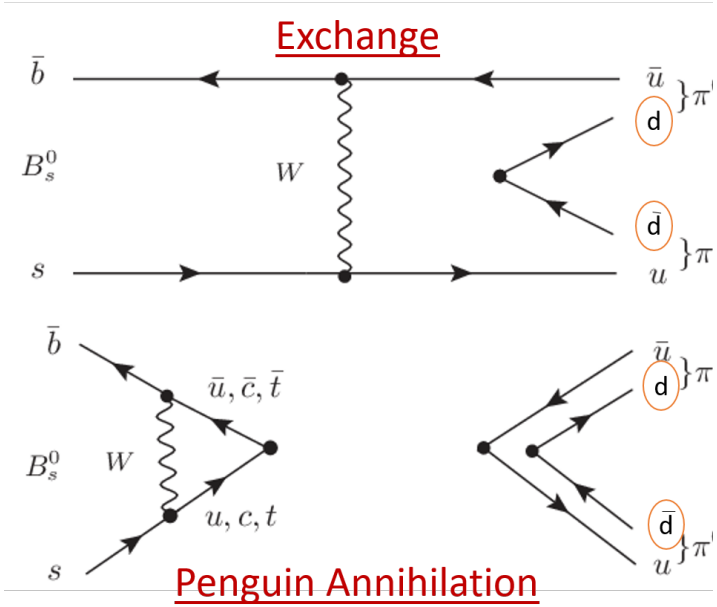
Topologies for $B \to hh$ decays

- Suppressed (?) contributions to $B \to hh$
- Exchange and Penguin Annihilation usually neglected



Motivation: New puzzles?

LHCb [2012.05319], Fleischer, Jaarsma, KKV, JHEP 02 (2023) 081 [2211.08346]

- New! First observation of CP violation in penguin dominated $B_s \to K^- K^+$ [LHCb]
  - Allows determination of γ and ϕ_s
  - Interesting to compare loops with tree!
- Updated measurements of CP asymmetries for other $B \to hh$ modes [LHCb]

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New Puzzle?

$$\mathcal{A}_{\rm CP}^{\rm dir}(B_s^0 \to K^- K^+) - \mathcal{A}_{\rm CP}^{\rm dir}(B_d^0 \to \pi^- K^+) = 0.089 \pm 0.031$$
$$\mathcal{A}_{\rm CP}^{\rm dir}(B_d^0 \to \pi^- \pi^+) - \mathcal{A}_{\rm CP}^{\rm dir}(B_s^0 \to K^- \pi^+) = -0.095 \pm 0.040$$

- Modes only differ by their spectator quark!
- Can exchange and penguin annihilation contributions cause this?

Today: New determinations of γ, ϕ_s and of exchange and penguin annihilation effects!

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Extracting γ from QCD penguin decays

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

Fleischer [1999, 2007]; Fleischer, Knegjens [2011]

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

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

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

- d and θ penguin parameters [$\epsilon \sim 0.04$]
- Extract hadronic parameters from direct and mixing-induced CP asymmetries

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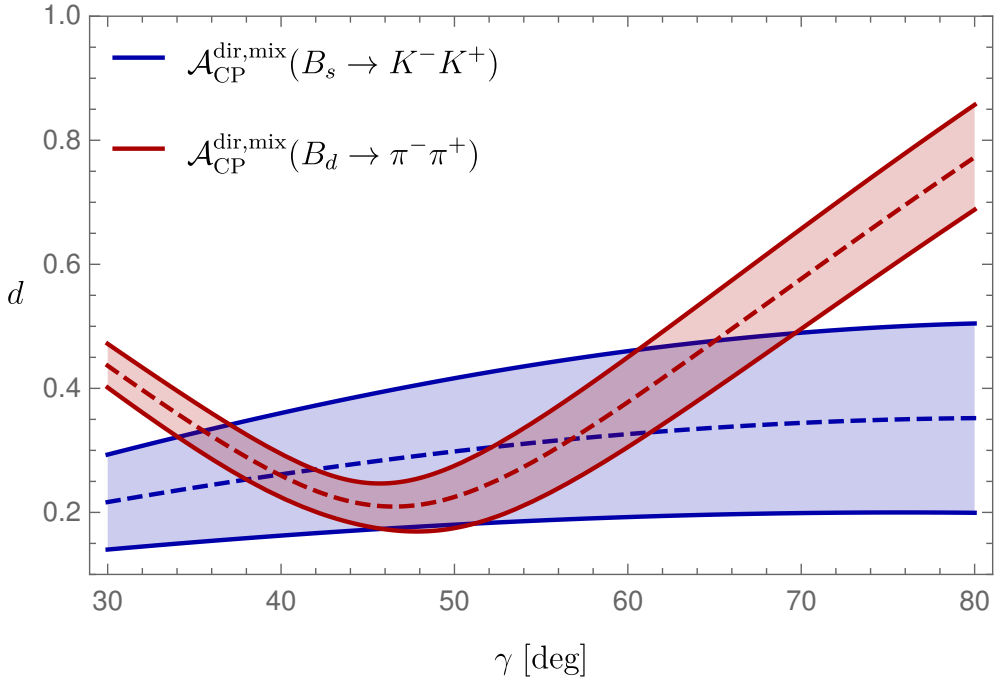
U-spin symmetry

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

- Or assume $d = d'$ and extract γ
- Limited by *U*-spin breaking corrections

CKM-angle γ from non-tree decays

Fleischer [1999,2007]; Fleischer, Knegjens [2011]; Fleischer, Malami, Jaarsma, KKV [2016]
Cuichini, Franco, Mishima, Silvestrini [2012], Data from LHCb [2022]Fleischer, Jaarsma, KKV [2211.08346]



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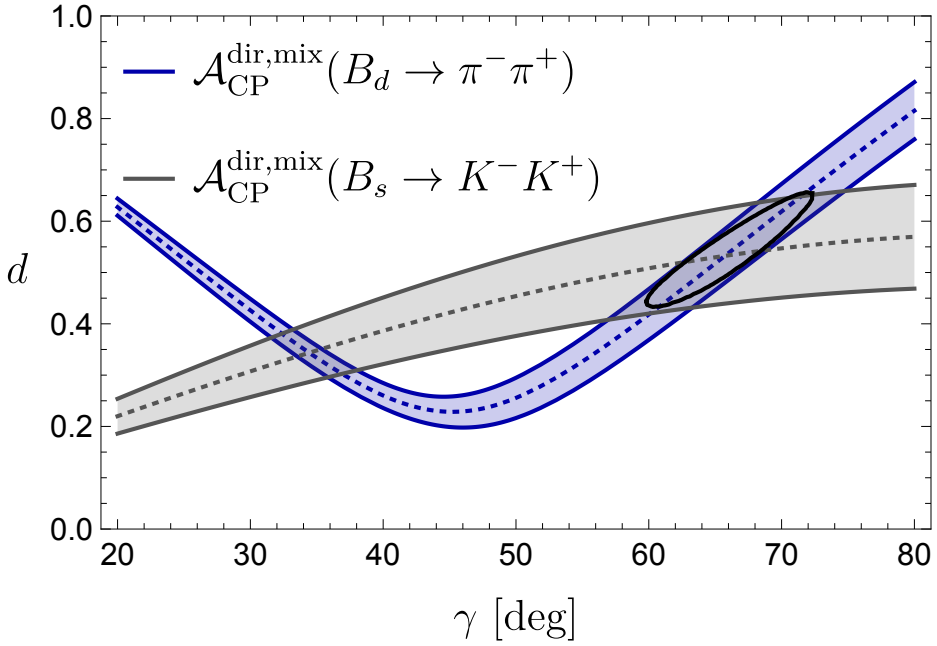

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- New! First determination of γ with only CP asymmetries
- $\gamma = (65^{+7}_{-5})^\circ$ Fleischer, Jaarsma, KKV [2111.08346]
- Agrees with tree determinations: $\gamma = (64.9 \pm 4.5)^\circ$ LHCb [2021] without B_s modes

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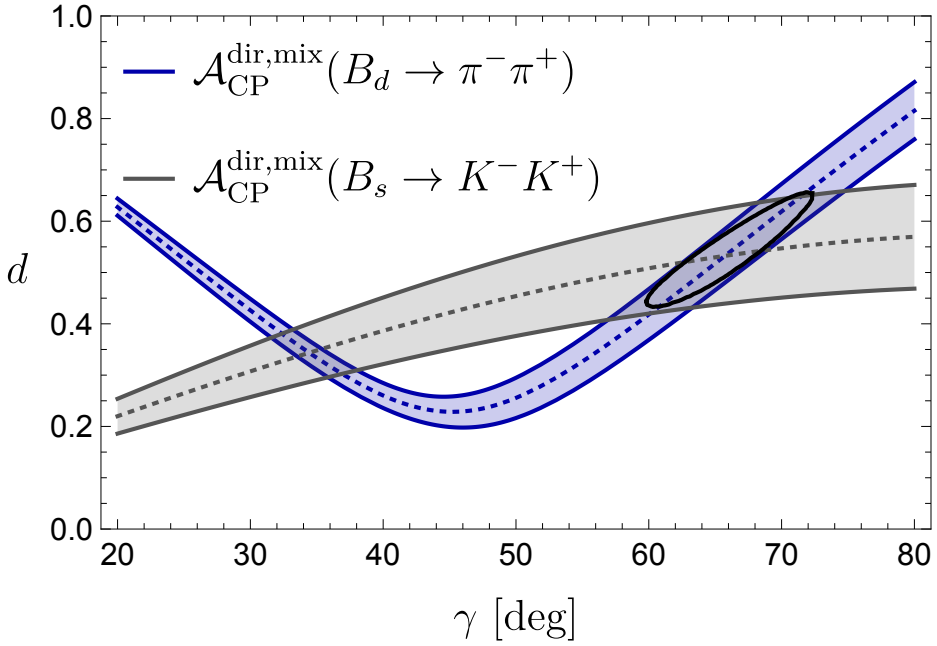

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- Can exchange and penguin annihilation contributions cause this?
- Challenging to compute $\rightarrow$ data-driven approach

How to determine E and PA amplitudes?

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

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

- Step 0: Use γ as input, use only direct CP asymmetry (no ϕ input)
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- Mismatch parametrized by

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- Cannot fully determine parameters yet!

Additional information!

Fleischer, Jaarsma, KKV [2211.08346]

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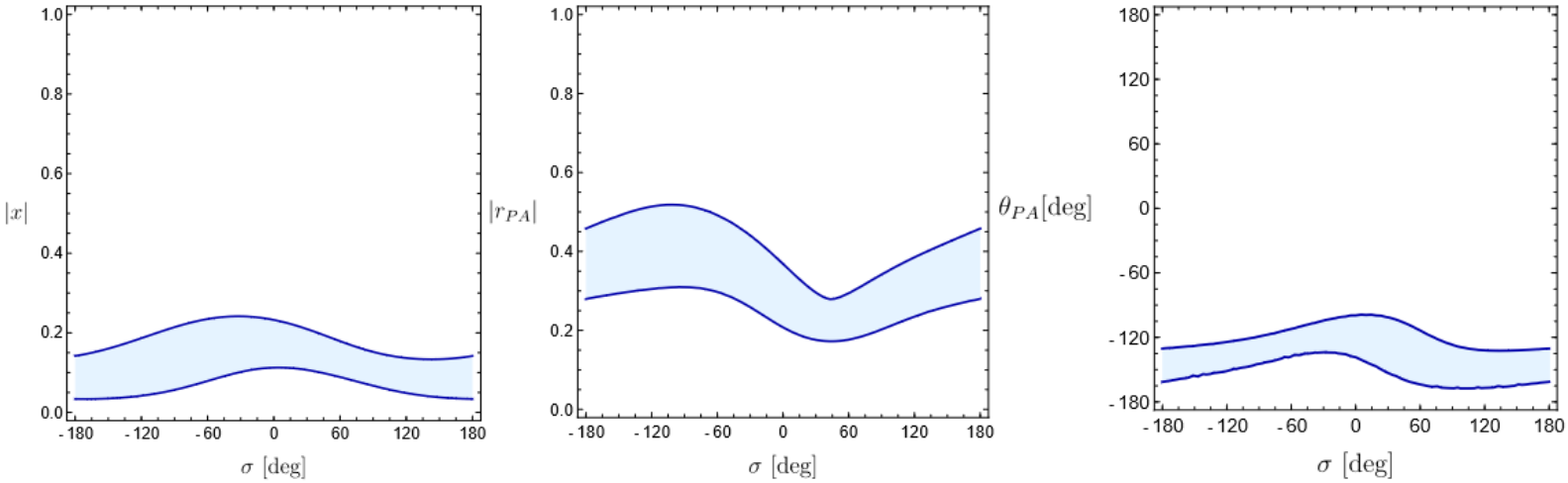
- Only branching ratios available

Current constraints

Fleischer, Jaarsma, KKV [2211.08346]



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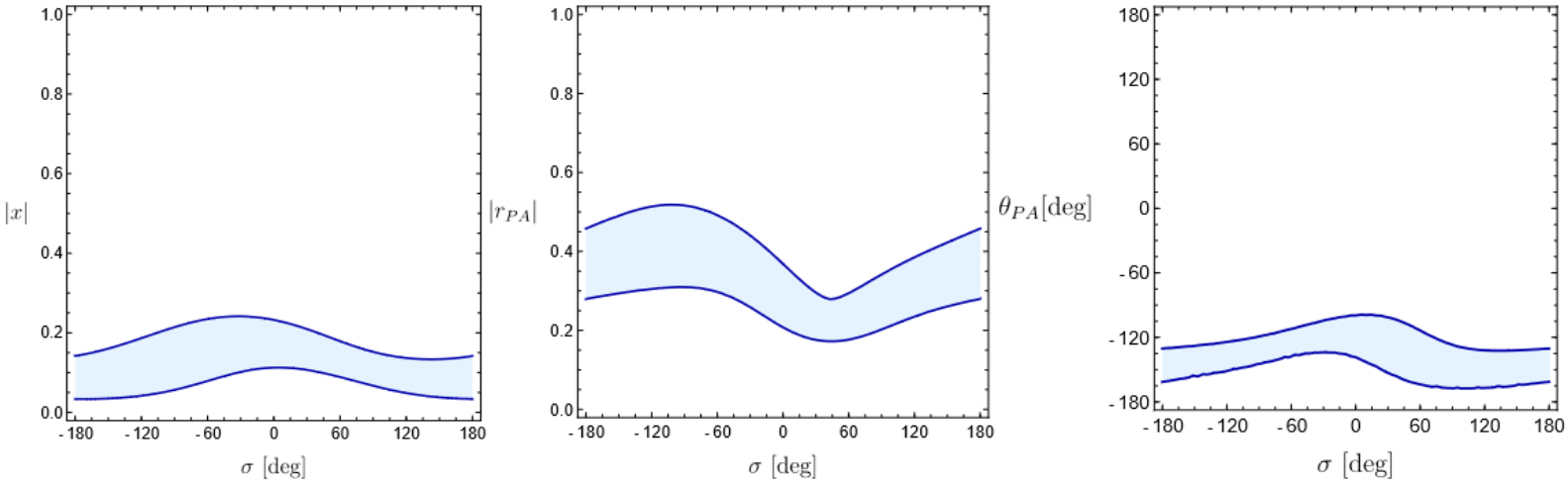

- x and r_{PA} constrained at 20% and 30% level
- The difference in the direct CP asymmetries can be accommodated by exchange and penguin annihilation effects at the level of (20–30)%.
- No anomalously enhanced rescattering effects

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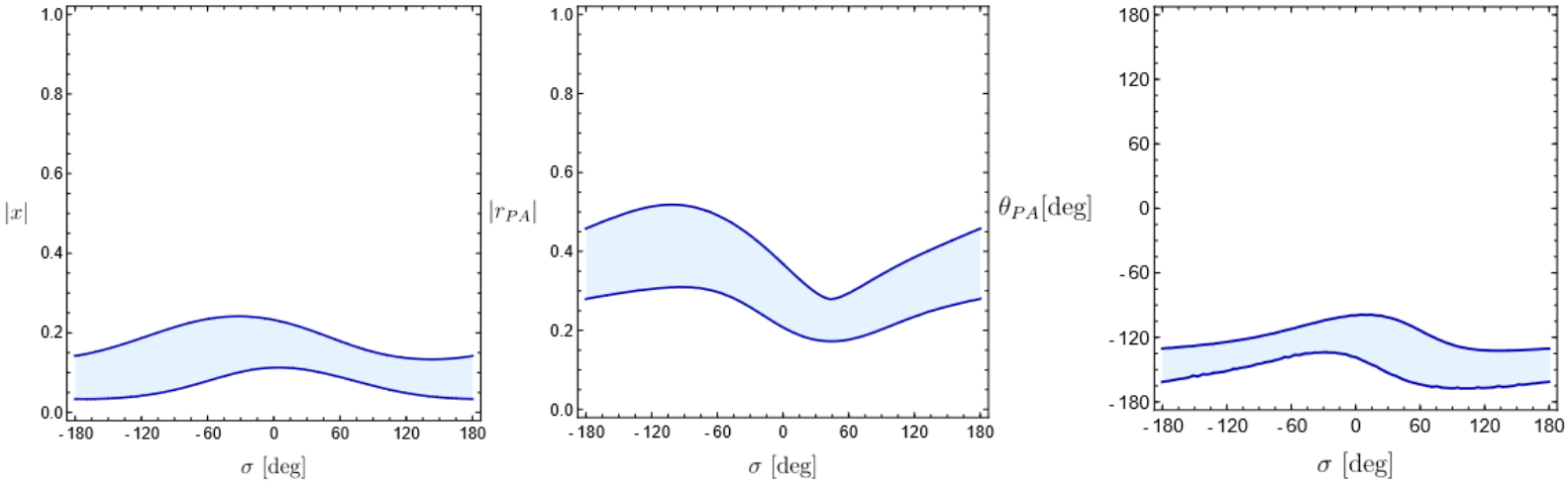

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- CP asymmetries in the $B_s^0 \to \pi^-\pi^+, B_d^0 \to K^-K^+$ system would provide even more info!

Determination of ϕ_s

Fleischer, Jaarsma, KKV, JHEP 02 (2023) 081 [2211.08346]

- CP violation in $B_s \to K^+K^-$ also gives access to ϕ_s

$$\phi_s^{\text{eff}} = \frac{\mathcal{A}_{\text{CP}}^{\text{mix}}(B_s^0 \to K^-K^+)}{\sqrt{1-(\mathcal{A}_{\text{CP}}^{\text{mix}}(B_s^0 \to K^-K^+))^2}}$$

- $\phi_s^{\text{eff}} \equiv \phi_s + \Delta\phi_{KK}$
- LHCb measurement: $\phi_s^{\text{eff}} = -(8.1 \pm 1.9)^\circ$ LHCb 2022

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- $\Delta\phi_{KK}$ hadronic phase shift

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How to determine the penguin parameters?

Determination of ϕ_s (I)

Strategy I:

Fleischer, Jaarsma, KKV, JHEP 02 (2023) 081 [2211.08346] (and [1612.07342])

- Use semileptonic decays

$$R_\pi \equiv \frac{\Gamma(B_d^0 \to \pi^-\pi^+)}{|d\Gamma(B_d^0 \to \pi^-\ell^+\nu_\ell)/dq^2|_{q^2=m_\pi^2}} \qquad R_K \equiv \frac{\Gamma(B_s^0 \to K^-K^+)_{\rm theo}}{|d\Gamma(B_s^0 \to K^-\ell\nu_\ell/dq^2|_{q^2=m_K^2}}$$

- Gives access to hadronic parameters $r_K = (1 + \left(\frac{d'}{\epsilon}\right)^2 + 2d'/\epsilon \cos\theta' \cos\gamma)$
- Use ratios to get favorable structure!

$$r_K = \frac{R_K}{R_\pi}\left(\frac{|V_{ud}|f_\pi}{|V_{us}|f_K}\right)^2 \frac{X_\pi}{X_K}\left(\xi^a_{\rm NF}\right)^2 r_\pi$$

- $X_{\pi,K}$ ratio of form factor $\to$ input

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- Non-factorisable U-spin-breaking contributions:

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

- $a^T_{\rm NF}$ tree-level contribution from QCDF

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- $a^T_{\rm NF}$ tree-level contribution from QCDF
- $\xi^a_{\rm NF} = 1.00 \pm 0.07 \to 0.8^\circ$ theoretical uncertainty on $\Delta\phi_{KK}$

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Strategy I:

- Use semileptonic decays

$$R_\pi \equiv \frac{\Gamma(B_d^0 \to \pi^-\pi^+)}{|d\Gamma(B_d^0 \to \pi^-\ell^+\nu_\ell)/dq^2|_{q^2=m_\pi^2}} \qquad R_K \equiv \frac{\Gamma(B_s^0 \to K^-K^+)_{\rm theo}}{|d\Gamma(B_s^0 \to K^-\ell\nu_\ell/dq^2|_{q^2=m_K^2}}$$

- Experimental input not available!
- Theoretical control over penguin effects excellent!
- $\xi^a_{\rm NF} = 1.00 \pm 0.07 \to 0.8^\circ$ theoretical uncertainty on $\Delta\phi_{KK}$

Determination of ϕ_s (II)

Fleischer, Jaarsma, KKV, JHEP 02 (2023) 081 [2211.08346]

Strategy II:

- Use ratio of branching ratios of $B_d \to \pi\pi$ and $B_s \to KK$ decays

$$K \equiv \frac{1}{\epsilon}\left[\frac{m_{B_s}}{m_{B_d}}\frac{\Phi(m_\pi/m_{B_d}, m_\pi/m_{B_d})}{\Phi(m_K/m_{B_s}, m_K/m_{B_s})}\frac{\tau_{B_d}}{\tau_{B_s}}\right]\frac{\mathcal{B}(B_s^0 \to K^-K^+)_{\rm theo}}{\mathcal{B}(B_d^0 \to \pi^-\pi^+)} = 105.3 \pm 9.6$$

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- Gives access to hadronic parameters

$$r_K = \left|\frac{\mathcal{C}}{\mathcal{C}'}\right|^2 K r_\pi = (1 + \left(\frac{d'}{\epsilon}\right)^2 + 2d'/\epsilon \cos\theta' \cos\gamma)$$

$$\left|\frac{\mathcal{C}}{\mathcal{C}'}\right| = \frac{f_\pi}{f_K}\left[\frac{m_{B_d}^2 - m_\pi^2}{m_{B_s}^2 - m_K^2}\right]\left[\frac{F_0^{B_d\pi}(m_\pi^2)}{F_0^{B_sK}(m_K^2)}\right]\xi_{\rm NF}^a$$

- Non-factorisable U-spin-breaking contributions:

$$\xi_{\rm NF}^a \equiv \left|\frac{1+r_P}{1+r_P'}\right|\left|\frac{1+x}{1+x'}\right|\left|\frac{a_{\rm NF}^T}{a_{\rm NF}^{T'}}\right| = 1.00 \pm 0.07,$$

- $a_{\rm NF}^T$ tree-level contribution from QCDF

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- Use form factor information: 10% uncertainty
- $\Delta\phi_{KK} = -(4.5 \pm 5.3)^\circ$
- With $\phi_s^{\rm eff} = -(8.1 \pm 1.9)^\circ \to \phi_s = -(3.6 \pm 5.7)^\circ$

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Remarkable agreement with $B^0_s \to J/\psi\phi$ determination: $\phi_s = -(4.2 \pm 1.4)^\circ$

Challenges in (nonleptonic) B decays

Summary & Outlook

We are in the High-precision Era in Flavour Physics!

- Nonleptonic decays are challenging but important!
- $B_s \to KK$ gives consistent γ and ϕ_s determinations
- Exchange and Penguin Annihilation not anomalously large
- CP asymmetries in $B_d \to KK$ and $B_s \to \pi\pi$ would provide more input
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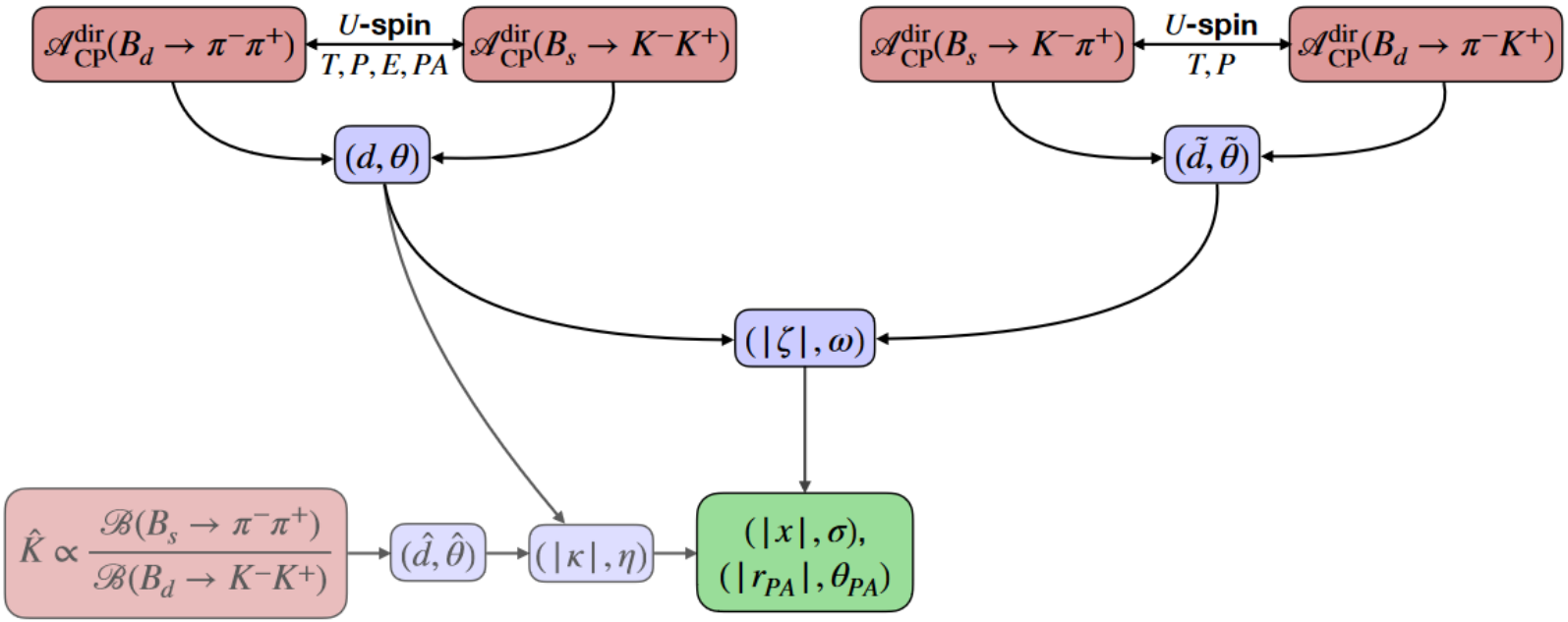
Close collaboration between theory and experiment necessary!

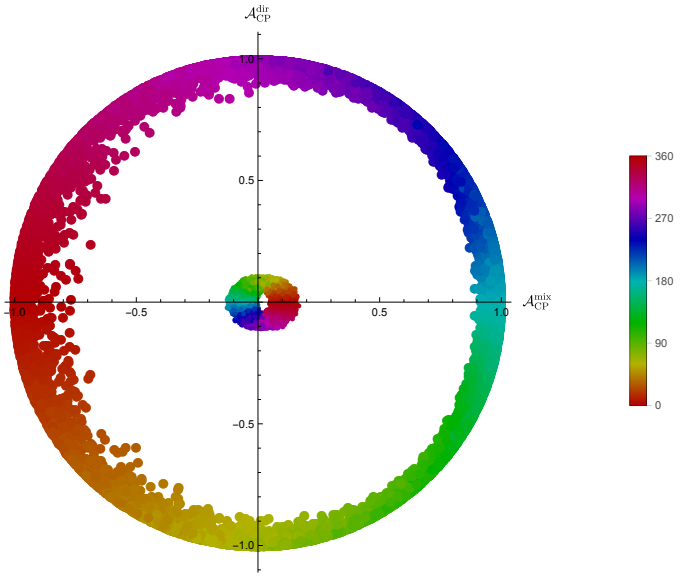
Backup

Strategy to extract E and PA

Fleischer, Jaarsma, KKV [2211.08346]



CP asymmetries in $B_s \to \pi\pi$ and $B_d \to KK$



- Correlation between CP asymmetries in $B_s \to \pi\pi$ (small circle) and $B_d \to KK$ (wide) for different strong phases
- Important also to improve QCDF