Status and Prospects of Nonleptonic B Decays

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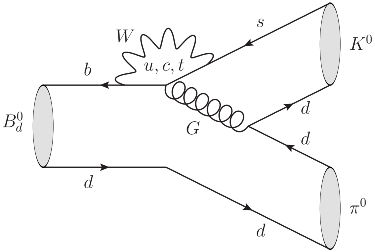
Puzzles in nonleptonic decays

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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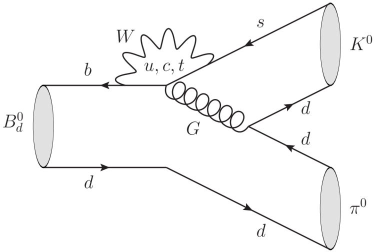
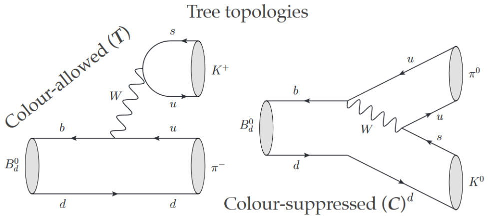
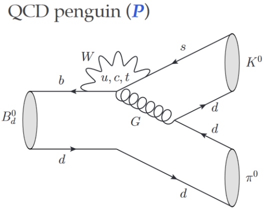
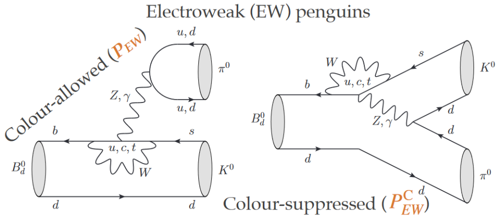


Challenge: Calculation of Hadronic matrix elements

Why $B \to \pi K$ decays?







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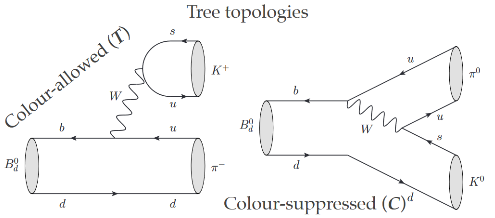
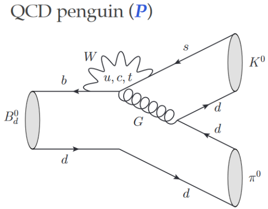
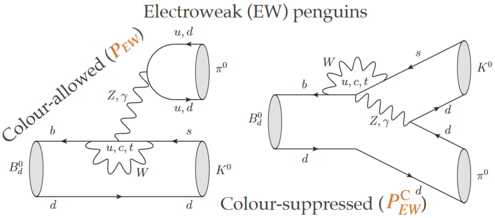
- QCD penguins dominant
- EW penguins at same level as tree







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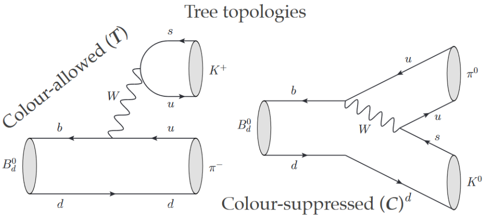

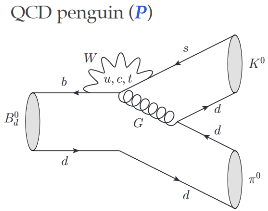

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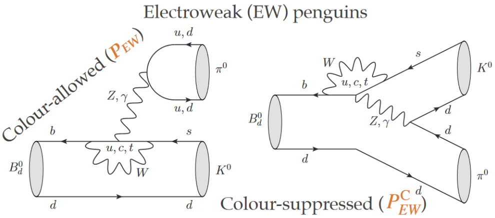
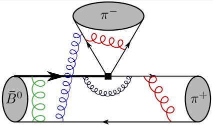
- Interesting probes of New Physics
  - Search for tiny deviations of SM predictions



How to handle nonleptonic B decays?



QCD Factorization
Beneke, Buchalla, Neubert, Sachrajda

- Disentangle perturbative (calculable) and non-perturbative dynamics using HQE
- Systematic expansion in α_s and $1/m_b$ (studied up to α_s^2) Bell, Beneke, Huber, Li

$$\langle \pi^+\pi^- | \mathcal{Q}_i | B \rangle = T_i^I \otimes F^{B\to\pi^+} \otimes \Phi_{\pi^-} + T_i^{II} \otimes \Phi_{\pi^-} \otimes \Phi_{\pi^+} \otimes \Phi_B$$

- Non-perturbative form factors and LCDAs
  - from data, lattice or Light-Cone Sum Rules
- No systematic framework to compute power corrections (yet?)
- Strong phases suffer from large uncertainties
- Theoretical challenge: reliable computations of observables
- Recent progress: include QED corrections Talks by Martin and Gael Beneke, Boer, Toelstede, KKV [2020]

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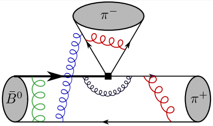

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Flavour symmetries (Isospin or $SU(3)$)

- Many studies e.g. Fleischer, Jaarsma, KKV, Malami [2017,2018]
- Recent progress: Global $SU(3)$ fit to $B \to PP$ decays Huber, Tetlalmatzi-Xolocotzi [2111.06418]

Light-cone sumrules

- Work in progress by Jung, Melic, Khodjamirian

SM predicitions for non-leptonic B decays

$$A_{M_1 M_2} \equiv i \frac{G_F}{\sqrt{2}} m_B^2 F_0^{BM_1} f_{M_2}$$

Amplitude parametrization a la QCDF [Beneke, Neubert [2003]]

$$\begin{aligned}
\mathcal{A}_{B^-\to\pi^-\bar{K}^0} &= A_{\pi K}\hat{\alpha}_4^p \ , \\
\sqrt{2}\mathcal{A}_{B^-\to\pi^0 K^-} &= A_{\pi K}\left[\delta_{pu}\alpha_1 + \hat{\alpha}_4^p\right] + A_{K\pi}\left[\delta_{pu}\alpha_2 + \delta_{pc}\frac{3}{2}\alpha_{3,\mathrm{EW}}^c\right] \ , \\
\mathcal{A}_{\bar{B}^0\to\pi^+ K^-} &= A_{\pi K}\left[\delta_{pu}\alpha_1 + \hat{\alpha}_4^p\right] \ , \\
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\end{aligned}$$

- α_1 and α_2 color-allowed and color-suppressed tree coefficients
- α_4 and $\alpha_{3,\mathrm{EW}}$ penguin and electromagnetic penguin coefficients
- contain all perturbative effects up to NNLO (α_s^2) e.g. [Bell, Beneke, Huber, Li]

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- QED can be included! Beneke, Boer, Toelstede, KKV, JHEP 11 (2020) 081 [2008.10615]

Different QED effects

$$\mathcal{A}(M_1 M_2) \equiv i \frac{G_F}{\sqrt{2}} m_B^2 \mathcal{F}_{Q_2}^{BM_1}(0) F_{M_2}$$

$$\langle M_1 M_2 | Q_i | B \rangle = \mathcal{A}(M_1 M_2) \alpha_i(M_1 M_2) = A_{M_1 M_2} \left(\alpha_i^{\rm QCD}(M_1 M_2) + \delta\alpha_i(M_1 M_2) \right)$$

- Electroweak scale to m_B: QED corrections to the Wilson coefficients
- m_B to μ_c: QED corrections to the hard-scattering kernels, form factors and decay constants
- below $\Lambda_{\rm QCD}$: Ultrasoft QED effects (for the rate!)

$$\delta\alpha_i(M_1 M_2) \equiv \delta\alpha_i^{\rm WC}(M_1 M_2) + \delta\alpha_i^{\rm K}(M_1 M_2) + \delta\alpha_i^{\rm F,V}(M_1 M_2) + \delta\alpha_i^{\rm F,sp}(M_1 M_2)\,.$$

$\rightarrow$ $\delta\alpha_i^{\rm WC} = \mathcal{O}(10^{-3})$ [Huber, Lunghi, Misiak, Wyler [2006]]

$\rightarrow$ $\delta\alpha_i^{\rm K} = \mathcal{O}(10^{-3})$

$\rightarrow$ $\delta\alpha_i^{\rm F,V} =$?? [Beneke, Boer, Toelstede, KKV [2021]]

$\rightarrow$ $\delta\alpha_i^{\rm F,sp} =$?? but $\mathcal{O}(\alpha_{\rm em}\alpha_s)$

Ultrasoft Contribution

- Ultrasoft effects dress braching ratio
- Key point: scale dependence cancels!!

$$U(M_1M_2) = \left(\frac{2\Delta E}{m_B}\right)^{-\frac{\alpha_{\rm em}}{\pi}\left(Q_B^2+Q_{M_1}^2\left[1+\ln\frac{m_{M_1}^2}{m_{B_q}^2}\right]+Q_{M_2}^2\left[1+\ln\frac{m_{M_2}^2}{m_B^2}\right]\right)}$$

- Recover the standard QED factor
- ΔE is the window of the πK invariant mass around m_B
- Theory requires $\Delta E \ll \Lambda_{\rm QCD} = 60\,\text{MeV}$

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- Experimentally usoft effects included using PHOTOS
- Challenging to compare theory with experiment! Work in progress!

Ratios and isospin sumrules

Beneke, Boer, Toelstede, KKV, JHEP 11 (2020) 081 [2008.10615]

- QED gives sub-percent corrections to Branching ratios [Talk by Gael F.]

Ratios and isospin sumrules

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- Beneficial to consider ratios in which QCD is suppressed

$$R_L = \frac{2\mathrm{Br}(\pi^0 K^0) + 2\mathrm{Br}(\pi^0 K^-)}{\mathrm{Br}(\pi^- K^0) + \mathrm{Br}(\pi^+ K^-)} = R_L^{\mathrm{QCD}} + \cos\gamma \mathrm{Re}\, \delta_{\mathrm{E}} + \delta_U$$

- new structure dependent QED corrections enter linearly, QCD only quadratically

$$\delta_E = (-1.12 + 0.16i) \cdot 10^{-3}$$

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- Combined QED effect larger than QCD uncertainty!

$B \to \pi K$ puzzle

The $B \to K\pi$ Puzzle

e.g. Buras, Fleischer, Recksiegel, Schwab [2004, 2007];Fleischer, Jaeger, Pirjol, Zupan [2008]
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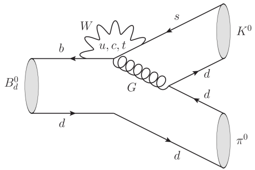
(Longstanding) Puzzling patterns in $B \to \pi K$ data

- First Example:

$$\delta(\pi K) \equiv A_{\rm CP}(\pi^0 K^-) - A_{\rm CP}(\pi^+ K^-)$$

- Recent LHCb measurement for $A_{\rm CP}(K^-\pi^0)$
  LHCb Collaboration, PRL 126, 091802 [2021]
- Confirms and enhances the observed difference
  - $\delta(\pi K)^{\rm exp} = (11.5 \pm 1.4)\%$
  - 8σ from 0



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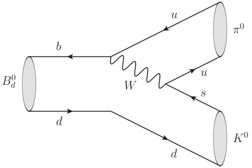

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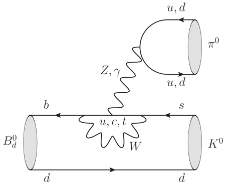
- Hint for NP in the EWP sector?



Light-cone sumrules predictions

Work in progress Jung, Melic, Khodjamirian (see MITP workshop 2019)

Preliminary!

Decay mode	BR-exp (in 10^{-6})	$A_{CP} = -C_{CP}$	BR-th	A_{CP}-th
$\Delta S = -1$				
$B^- \to \pi^0 K^-$	12.7 ± 0.6	0.040 ± 0.021	13.74	0.050
$B^- \to \pi^- \bar{K}^0$	23.3 ± 0.8	-0.017 ± 0.016	24.56	-0.012
$\bar{B}^0 \to \pi^+ K^-$	20.0 ± 0.6	-0.082 ± 0.006	20.10	0.057
$\bar{B}^0 \to \pi^0 \bar{K}^0$	10.1 ± 0.5	-0.01 ± 0.10	8.87	-0.021

- LCSR calculations (+some QCDF input)
- More reliable than for $B \to \pi\pi$
- Different sign for $B \to K^+\pi^-$ (as in QCDF)

Isospin sumrule

e.g. Gronau [2005]; Gronau, Rosner [2006]

$$\Delta(\pi K) \equiv A_{\rm CP}(\pi^+ K^-) + \frac{\Gamma(\pi^- \bar{K}^0)}{\Gamma(\pi^+ K^-)} A_{\rm CP}(\pi^- \bar{K}^0) - \frac{2\Gamma(\pi^0 K^-)}{\Gamma(\pi^+ K^-)} A_{\rm CP}(\pi^0 K^-) - \frac{2\Gamma(\pi^0 \bar{K}^0)}{\Gamma(\pi^+ K^-)} A_{\rm CP}(\pi^0 \bar{K}^0) \equiv \Delta(\pi K)^{\rm QCD} + \delta\Delta(\pi K)$$

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- Isospin sumrule also robust against QED effects!
- Updates of modes with neutral pions necessary $\rightarrow$ Belle II
- Or can be used to predict the direct CP in $B \rightarrow \pi^0 K^0$
- Mixing-induced CP asymmetry in $B \rightarrow \pi^0 K^0$ provides additional test Fleischer, Jaarsma, Malami, KKV [2016,2018]

Isospin Amplitude Triangles

Nir, Quin [1991]; Gronau, Hernandez, London, Rosner [1995]

Fleischer, Jaeger, Pirjol, Zupan [2008]; Fleischer, Jaarsma, KKV [2018]

$$\sqrt{2}A(B^0 \to \pi^0 K^0) + A(B^0 \to \pi^- K^+)$$
$$= \sqrt{2}A(B^+ \to \pi^0 K^+) + A(B^+ \to \pi^+ K^0)$$
$$= -(\hat{T} + \hat{C})\left(e^{i\gamma} - q e^{i\phi} e^{i\omega}\right) \equiv 3A_{3/2} = 3|A_{3/2}|e^{i\phi_{3/2}} \,,$$

- QCD penguin and colour-suppressed EWPs cancel
- Minimal $SU(3)$ input

$$|\hat{T} + \hat{C}| = R_{T+C}\, |V_{us}/V_{ud}|\, \sqrt{2}|A(B^+ \to \pi^+ \pi^0)|$$

$$R_{T+C}|_{\text{fact}} = f_K/f_\pi = 1.2 \pm 0.2$$

Uncertainty accounts for non-factorizable $SU(3)$ breaking

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- QCD penguin and colour-suppressed EWPs cancel
- EWPs described by ($\phi(\omega)$) CP-violating (conserving) phases)

$$q e^{i\phi} e^{i\omega} \equiv -\left(\frac{\hat{P}_{EW} + \hat{P}^{\rm C}_{EW}}{\hat{T} + \hat{C}}\right) \stackrel{\rm SM}{=} \frac{-3}{2\lambda^2 R_b} R_q \frac{C_9 + C_{10}}{C_1 + C_2} = 0.68 R_q$$

Isospin Amplitude Triangles

Nir, Quin [1991]; Gronau, Hernandez, London, Rosner [1995]
Fleischer, Jaeger, Pirjol, Zupan [2008]; Fleischer, Jaarsma, KKV [2018]

$$\begin{aligned}&\sqrt{2}A(B^0 \to \pi^0 K^0) + A(B^0 \to \pi^- K^+)\\ &\quad = \sqrt{2}A(B^+ \to \pi^0 K^+) + A(B^+ \to \pi^+ K^0)\\ &\quad\quad = -(\hat{T} + \hat{C})\left(e^{i\gamma} - q e^{i\phi} e^{i\omega}\right) \equiv 3A_{3/2} = 3|A_{3/2}|e^{i\phi_{3/2}} ,\end{aligned}$$

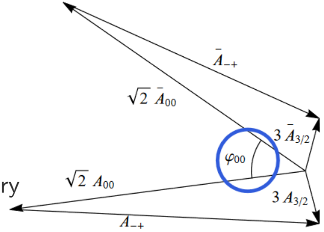
- QCD penguin and colour-suppressed EWPs cancel

$$q e^{i\phi} e^{i\omega} \equiv -\left(\frac{\hat{P}_{EW} + \hat{P}_{EW}^{\mathrm{C}}}{\hat{T} + \hat{C}}\right) \overset{\mathrm{SM}}{=} \frac{-3}{2\lambda^2 R_b} R_q \frac{C_9 + C_{10}}{C_1 + C_2} = 0.68 R_q$$

- New CP violating physics might enter with a large phase ϕ

Isospin Amplitude Triangles

Fleischer, Jaeger, Pirjol, Zupan [2008]; Fleischer, Jaarsma, KKV [2018]



$$A_{\text{mix}}^{\pi^0 K_S} = \sin(\phi_d - \phi_{00})\sqrt{1-(A_{\text{dir}}^{\pi^0 K_S})^2}$$

- Only πK mode with mixing-induced CP asymmetry
- ϕ_d B_d mixing phase
- Amplitude triangles give ϕ_{00}
- Gives a clean correlation between the CP asymmetries in $B_d \to \pi^0 K_S$

Isospin Amplitude Triangles

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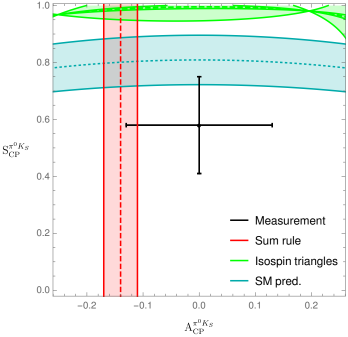
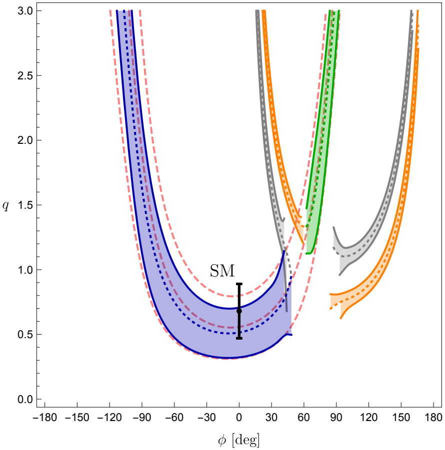


Hints at New Physics in the EWP sector?

New Physics in the EWP sector

Current constraints on new physics in EWP sector

Fleischer, Jaarsma, KKV [2018]; Fleischer, Jaarsma, Malami, KKV [2018]



- Allow for New Physics in EWPs $qe^{i\phi}e^{i\omega} \equiv -\left(\frac{\hat{P}_{EW}+\hat{P}^{C}_{EW}}{\hat{T}+\hat{C}}\right)$
- Isospin relation holds for neutral and charged decays
- Current uncertainties in neutral decays still large → charged decays
- Only minimal $SU(3)$

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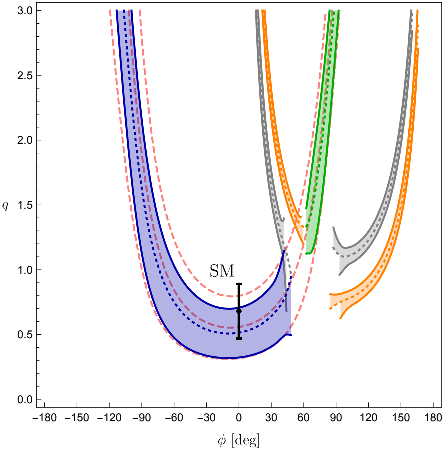

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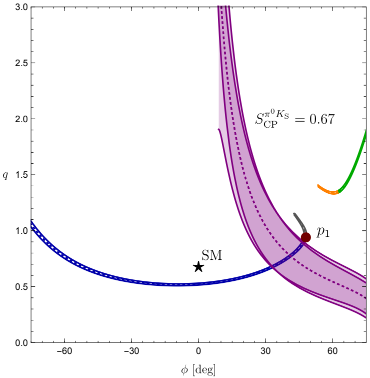
  $q e^{i\phi} e^{i\omega} \equiv -\left(\frac{\hat{P}_{EW}+\hat{P}^{C}_{EW}}{\hat{T}+\hat{C}}\right)$
- Isospin relation holds for neutral and charged decays
- Current uncertainties in neutral decays still large $\rightarrow$ charged decays
- Only minimal $SU(3)$
- Further input necessary

Pinning down NP - Future Scenario

Fleischer, Jaarsma, KKV [2018]

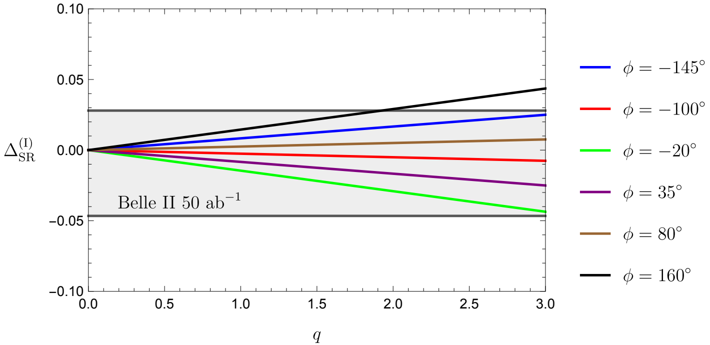


Perpendicular constraint from mixing-induced CP asymmetry $B_d \to \pi^0 K_S$

- Theory uncertainties (wide band) match experimental (smaller band)
- Include hadronic uncertainties in data-driven way

Constraints on new physics from the sum rule

Fleischer, Jaarsma, KKV [2018]

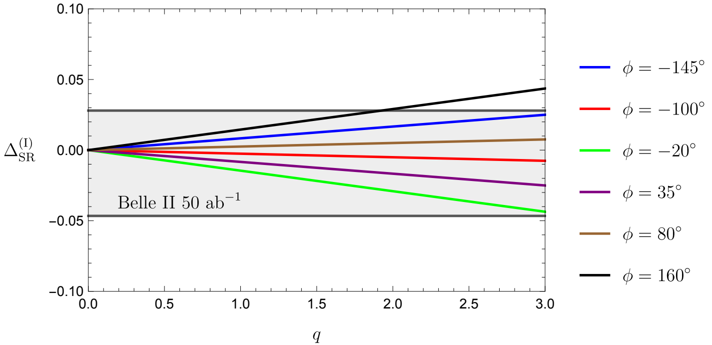


- Projected sensitivity at Belle II for $\pi^0 K_S$
- Limited sensitivity to q and ϕ for $q < 3$

$$\Delta(\pi K) \equiv A_{\rm CP}(\pi^+ K^-) + \frac{\Gamma(\pi^- \bar{K}^0)}{\Gamma(\pi^+ K^-)} A_{\rm CP}(\pi^- \bar{K}^0) - \frac{2\Gamma(\pi^0 K^-)}{\Gamma(\pi^+ K^-)} A_{\rm CP}(\pi^0 K^-)$$
$$- \frac{2\Gamma(\pi^0 \bar{K}^0)}{\Gamma(\pi^+ K^-)} A_{\rm CP}(\pi^0 \bar{K}^0) \equiv \Delta(\pi K)^{\rm QCD} + \delta\Delta(\pi K)$$

Constraints on new physics from the sum rule

Fleischer, Jaarsma, KKV [2018]



- Projected sensitivity at Belle II for $\pi^0 K_S$
- Limited sensitivity to q and ϕ for $q < 3$
- Use mixing-induced CP asymmetry to pin down NP

$$\Delta(\pi K) \equiv A_{\rm CP}(\pi^+ K^-) + \frac{\Gamma(\pi^- \bar{K}^0)}{\Gamma(\pi^+ K^-)} A_{\rm CP}(\pi^- \bar{K}^0) - \frac{2\Gamma(\pi^0 K^-)}{\Gamma(\pi^+ K^-)} A_{\rm CP}(\pi^0 K^-)$$
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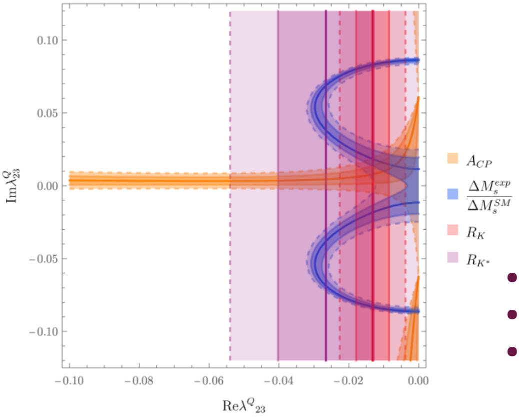
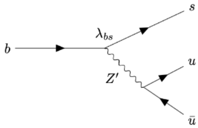
New Physics in EWPs - Z'

Lenz, Kirk, Di Luzio [2017]; Kirk, Di Luzio, Lenz, Rauh [2019], KKV, M. Burgos [in progress]





- Modified EWPs by Z'
- Would also influence $B_s - \bar{B}_s$ mixing
- In progress

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]

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

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

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

U-spin symmetry

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

- Extract hadronic parameters from direct and mixing-induced CP asymmetries

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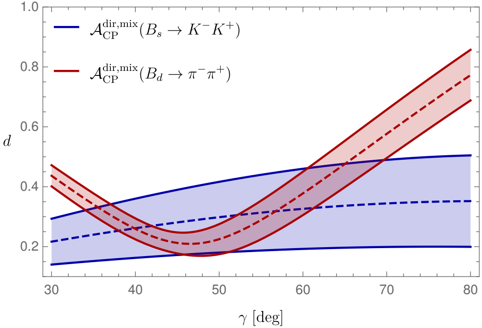
U-spin symmetry

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

- Extract hadronic parameters from direct and mixing-induced CP asymmetries
- 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,in progress]
Cuichini, Franco, Mishima, Silvestrini [2012], Data from LHCb [2022]



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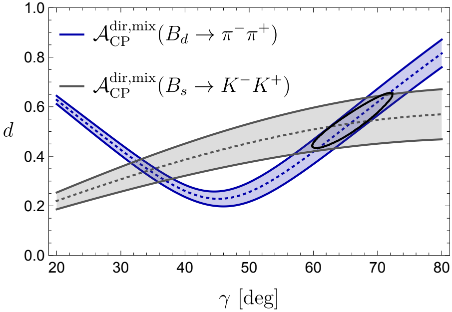

- $\gamma = (65^{+7}_{-5})^\circ$ Jaarsma, Fleischer, KKV [in progress]
- Agrees with tree determinations
- $\gamma = (64.9 \pm 4.5)^\circ$ LHCb [2021] without B_s modes

Challenges in (nonleptonic) B decays

Summary & Outlook

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

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- QED is important!

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Close collaboration between theory and experiment necessary!

Summary & Outlook

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

- QED is important!
- Rethink our previous assumptions
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Next time in Maastricht?

Backup

The Challenge of QED Corrections

Electromagnetic Effects

Beneke, Boer, Toelstede, KKV, JHEP 11 (2020) 081 [2008.10615]

$$\Gamma[\bar{B} \to M_1 M_2](\Delta E) \equiv \Gamma[\bar{B} \to M_1 M_2 + X_s]\Big|_{E_{X_s} \leq \Delta E},$$

- IR finite observable (width) must include ultra-soft photon radiation
- X_s are soft photons with total energy less than ultrasoft scale ΔE
- Factorizes in non-radiative amplitude and ultrasoft function

$$\Gamma[\bar{B} \to M_1 M_2](\Delta E) = |\mathcal{A}(\bar{B} \to M_1 M_2)|^2 \sum_{X_s} |\langle X_s|(\bar{S}_v^{(Q_B)} S_{v_1}^{\dagger(Q_{M_1})} S_{v_2}^{\dagger(Q_{M_2})})|0\rangle|^2 \, \theta(\Delta E - E_{X_s})$$

Simple classification:

- Ultra-soft photons: eikonal approximation, well understood

$$\Delta E \ll \Lambda_{\mathrm{QCD}}$$

- NEW: Non-universal, structure dependent corrections Beneke, Boer, Toelstede, KKV [2020]
- Both effects important: virtual photons can resolve the structure of the meson!

Electromagnetic Effects

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Simple classification:

- Ultra-soft photons: eikonal approximation, well understood

$$\Delta E \ll \Lambda_{\rm QCD}$$

- Often done: Assume pointlike approximation up to the scale m_B [Baracchini, Isidori]
  - $\rightarrow$ fails to account for all large logarithms (and scales)!
  - $\rightarrow$ photons with energy $\gtrsim \Lambda_{\rm QCD}$ probe the partonic structure of the mesons

Ultrasoft Contribution

- Ultrasoft effects dress braching ratio

$$U(M_1 M_2) = \left(\frac{2\Delta E}{m_B}\right)^{-\frac{\alpha_{\rm em}}{\pi}\left(Q_B^2 + Q_{M_1}^2\left[1+\ln\frac{m_{M_1}^2}{m_{B_q}^2}\right] + Q_{M_2}^2\left[1+\ln\frac{m_{M_2}^2}{m_B^2}\right]\right)}$$

- Recover the standard eikonal/QED factor Beneke, Boer, Toelstede, KKV [2020]
- ΔE is the window of the πK invariant mass around m_B
- Theory requires $\Delta E \ll \Lambda_{\rm QCD} = 60\,\text{MeV}$

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  $\rightarrow$ $U(\pi^+ K^-) = 0.914$, $U(\pi^0 K^-) = U(K^- \pi^0) = 0.976$ and $U(\pi^- \bar{K}^0) = 0.954$

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- Experimentally usoft effects included using PHOTOS
- Challenging to compare theory with experiment! In progress... See e.g. Isidori, Zwicky, Nabeebaccus, Bordone, Pattori

Hadronic parameters

- Isospin parametrization Buras, Fleischer, Recksiege, Schwab [2004]

$$
\begin{aligned}
A(B^+ \to \pi^+ K^0) &= -P' \left[1 + \rho_c e^{i\theta_c} e^{i\gamma}\right] \\
\sqrt{2} A(B^+ \to \pi^0 K^+) &= P' \left[1 + \rho_c e^{i\theta_c} e^{i\gamma} - \left(e^{i\gamma} - q e^{i\phi} e^{i\omega}\right) r_c e^{i\delta_c}\right] \\
A(B_d^0 \to \pi^- K^+) &= P' \left[1 - r e^{i\delta} e^{i\gamma}\right] \\
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\end{aligned}
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\end{aligned}
$$

- Hadronic parameters determined from $B \to \pi\pi$

$$
\begin{aligned}
r_c e^{i\delta_c} &\equiv (\hat{T} + \hat{C})/P' = (0.17 \pm 0.06) e^{i(1.9 \pm 23.9)^\circ} \ , \\
r e^{i\delta} &\equiv (\hat{T} - \hat{P}_u + \hat{P}_t)/P' = (0.09 \pm 0.03) e^{i(28.6 \pm 21.4)^\circ} \ , \\
\rho_c e^{i\theta_c} &\equiv (\hat{P}_t - \hat{P}_u)/(\hat{P}_t - \hat{P}_c) \sim 0
\end{aligned}
$$

- Hadronic parameters of $\mathcal{O}(\lambda)$ and include 20% $SU(3)$ corrections
- Can be compared to the QCDF calculations

Pinning down New Physics in EWP sector

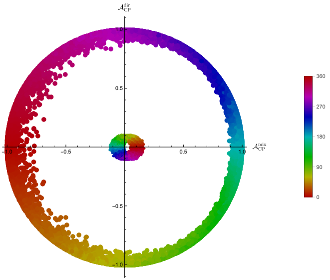
- Complement the isospin analysis with $S_{\rm CP}^{\pi^0 K_S}$

$$\tan\phi_{00} = 2(r\cos\delta - r_c\cos\delta_c)\sin\gamma + 2r_c(\cos\delta_c - 2\tilde{a}_{\rm C}/3)q\sin\phi + \mathcal{O}(\lambda^2)$$

- r, δ, r_c and δ_c hadronic parameters determined from $B \to \pi\pi$
- Only cosines of small phases, low sensitivity to variations
- Includes color-suppressed EWPs $\tilde{a}_{\rm C} = a_{\rm C}\cos(\Delta_{\rm C} + \delta_c)$
- Effects included in a data-driven way

$$R \equiv \frac{{\rm Br}(\pi^- K^+)}{{\rm Br}(\pi^+ K^0)} = 0.89 \pm 0.04 = 1 - 2r\cos\delta\cos\gamma + 2r_c\tilde{a}_C q\cos\phi + \mathcal{O}(\lambda^2)$$

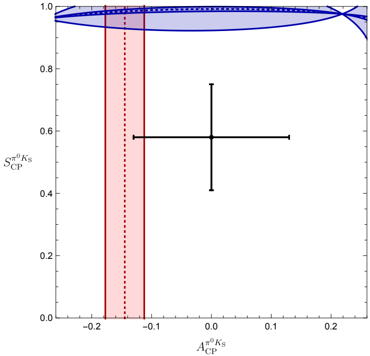
CP asymmetries in $B_s \to \pi\pi$ and $B_d \to KK$

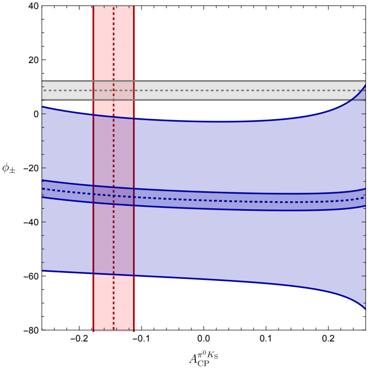


- Correlation between CP asymmetries in $B_s \to \pi\pi$ (small circle) and $B_d \to KK$ (wide) for different strong phases
- Important also to improve QCDF

Correlation between CP asymmetries in $B_d^0 \to \pi^0 K^0$

Fleischer, Jaeger, Pirjol, Zupan [2008]; Fleischer, Jaarsma, KKV [2018]





New element: constraint on angle $\phi_\pm = \arg(\bar{A}_\pm A_\pm^*)$

$$\phi_\pm|_{\rm SM,\phi=0} = 2r\cos\delta\sin\gamma + \mathcal{O}(\lambda^2) = (8.7 \pm 3.5)^\circ$$