Exploring New Physics in $B \to \pi K$ Decays

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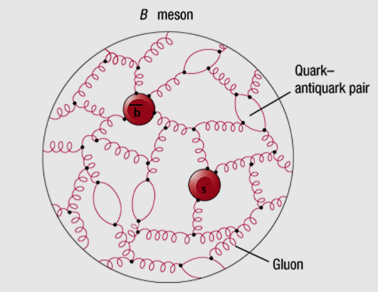
Based on:
arXiv:1712.02323 [hep-ph]
arXiv:1806.08783 [hep-ph]

Introduction

B-mesons

- Important system to test the flavour and CP-violating sector of the SM
- After BaBar, Belle, Tevatron, LHCb governs the experimental stage
- In the future: Belle II will offer new opportunities along with the LHCb upgrade



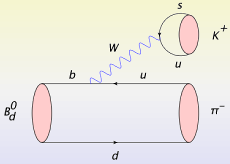
$B \to \pi K$ channels play a key role in these studies

Non-leptonic $B \to \pi K$ decays

$B \to \pi K$ Decays

- Naively, we would assume tree contributions playing the leading role **but** they are strongly suppressed by the CKM matrix element $|V_{ub}|$

color allowed tree

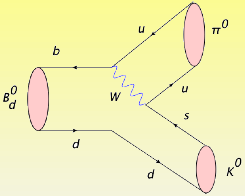


- Dominated by QCD penguin

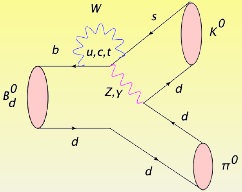
- In the case of $B^+ \to \pi^0 K^+$ and $B_d^0 \to \pi^0 K^0$
colour allowed electro-weak penguins (EWP) enter at the same level as colour allowed trees, contributing $\mathcal{O}(10\%)$ to decay amplitudes

Illustrating contributions to $B_d^0 \to \pi^0 K_S$ as an example

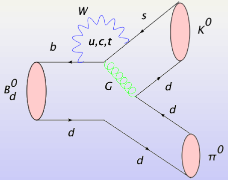
colour suppressed tree



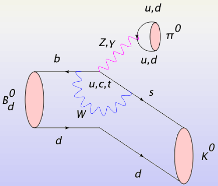
colour suppressed EWP



QCD penguin



colour allowed EWP



The decay is:

- dominated by gluonic (QCD) penguins **<u>BUT</u>**
- electroweak penguins: also important

$B_d^0 \to \pi^0 K_S$ Decays

- New Physics (NP) may enter through EW penguins:
  thus, very promising decay

- NP contributions: related to new CP violation sources
  (probed through CP violating observables)

- significance of $B_d^0 \to \pi^0 K_S$:
  the only $B \to \pi K$ mode exhibiting mixing-induced CP violation
  outstanding role for testing SM with $B \to \pi K$ system

Amplitudes

- Non-leptonic decays: challenging due to hadronic matrix elements
- Flavour symmetries of strong interactions show connection between amplitudes of $B \to \pi K$ and $B \to \pi\pi$, $B \to KK$, from which
  - either hadronic amplitudes are eliminated or
  - determined from experimental data of the latter

In our analysis:

- strong interactions theoretical assumptions: as minimal as possible
- use results of QCDF to include SU(3)-breaking corrections

Hadronic Parameters

$$\lambda = |V_{us}|$$

$$R_b = \left(1 - \frac{\lambda^2}{2}\right) \frac{1}{\lambda} \left|\frac{V_{ub}}{V_{cb}}\right|$$

$$re^{i\delta} = \left(\frac{\lambda^2 R_b}{1-\lambda^2}\right)\left[\frac{T-(P_t-P_u)}{P_t-P_c}\right]$$

$$r_c e^{i\delta_c} = \left(\frac{\lambda^2 R_b}{1-\lambda^2}\right)\left[\frac{T+C}{P_t-P_c}\right]$$

$$\rho_c e^{i\theta_c} = \left(\frac{\lambda^2 R_b}{1-\lambda^2}\right)\left[\frac{P_t-P_u}{P_t-P_c}\right] \approx 0$$

$$\rho_n e^{i\theta_n} = \left(\frac{\lambda^2 R_b}{1-\lambda^2}\right)\left[\frac{C+(P_t-P_c)}{P_t-P_c}\right] = r_c e^{i\delta_c} - re^{i\delta}$$

- $re^{i\delta}$ and $r_c e^{i\delta_c}$: non-perturbative (difficult to calculate)
- we calculate them using $B \to \pi\pi$ and SU(3) flavour symmetry:

$$r_c e^{i\delta_c} = (0.17 \pm 0.06) e^{i(1.9\pm23.9)^o}$$

$$re^{i\delta} = (0.09 \pm 0.03) e^{i(28.6\pm21.4)^o}$$

[A. J. Buras, R. Fleischer, S. Recksiegel, F. Schwab (2004)]

Electroweak Penguin Parameters q, ϕ

[R. Fleischer (1995); A. J. Buras, R. Fleischer (1998); M. Neubert, J. L. Rosner (1998)]

$\Longrightarrow$ Parametrization of EW penguin effects by:

$$qe^{i\phi}e^{i\omega} = \frac{\hat{P}_{EW} + \hat{P}^{C}_{EW}}{\hat{T} + \hat{C}}$$

ω: strong phase (quite small)
$\hat{T}$: color-allowed tree contributions,
$\hat{P}_{EW}$: color-allowed EWP,

ϕ: CP- violating phase
$\hat{C}$: colour-suppressed tree,
$\hat{P}^{C}_{EW}$: color-suppressed EWP

$$qe^{i\phi}e^{i\omega} = -\frac{-3}{2\lambda^2 R_b}\left[\frac{C_9(\mu) + C_{10}(\mu)}{C_1(\mu) + C_2(\mu)}\right] R_q = (0.68 \pm 0.05) R_q$$

$C_i(\mu)$: Wilson coefficients

- The ratio has been calculated for the SM values of $\phi = 0$
- Are there any deviations from the SM values?
- **Do the deviations indicate New Physics?**

CP Asymmetries in $B_d^0 \to \pi^0 K_S$

- The time-dependent CP asymmetry:

$$A_{CP}(t) = \frac{\Gamma(\bar{B}^0(t) \to \pi^0 K_S) - \Gamma(B^0(t) \to \pi^0 K_S)}{\Gamma(\bar{B}^0(t) \to \pi^0 K_S) + \Gamma(B^0(t) \to \pi^0 K_S)}$$
$$= A_{\pi^0 K_S} \cos(\Delta M t) + S_{\pi^0 K_S} \sin(\Delta M t),$$

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- The mixing-induced CP asymmetry:
(from interference between $B^0 - \bar{B}^0$ mixing and decay processes of B_d^0, $\bar{B}_d^0$ mesons into $\pi^0 K_s$ final state):

$$S_{\pi^0 K_S} = \frac{2|A_{00}\bar{A}_{00}|}{|\bar{A}_{00}|^2 + |A_{00}|^2} \sin(2\beta - 2\phi_{\pi^0 K_S})$$

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State-of-the-art analysis

- How do we find the angles $2\phi_{\pi^0 K_S} = \arg[\bar{A}_{00} A_{00}^*]$?
  - With the help of isospin relation

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

we construct triangles in the complex plane

[Y. Nir, H. R. Quinn (1991); M. Gronau, O. F. Hernndez, D. London, J. L. Rosner (1995)]

- We get 4 possible combinations between A_{00} and $\bar{A}_{00}$, thus 4 angles
- So, 4 cases for $S_{\pi^0 K_S}$ $\to$ 4 branches in the $S_{\pi^0 K_S} - A_{\pi^0 K_S}$ plot

Isospin Triangles in the complex plane

$$3A_{3/2} = A\left(B^0 \to \pi^- K^+\right) + \sqrt{2}A\left(B^0 \to \pi^0 K^0\right)$$

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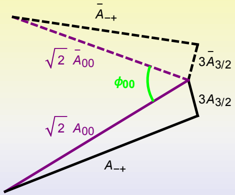

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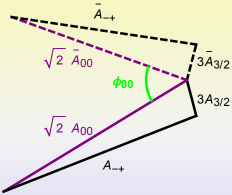

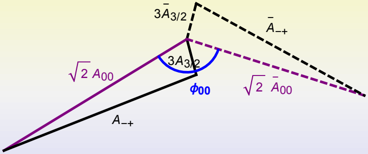

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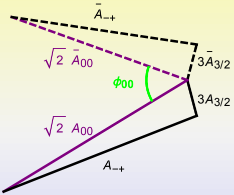

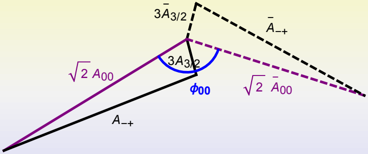

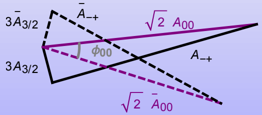

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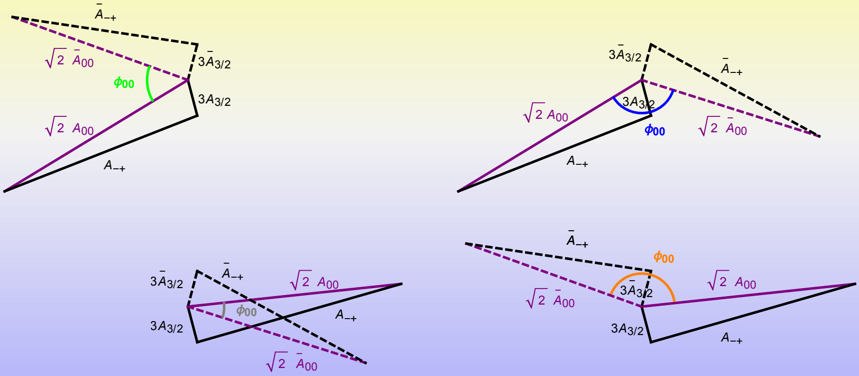
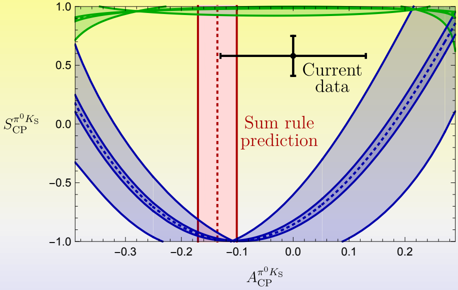
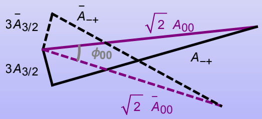
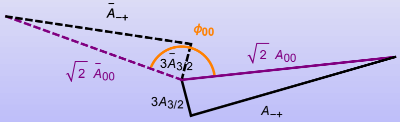


$S_{\pi^0 K_S} - A_{\pi^0 K_S}$ plot







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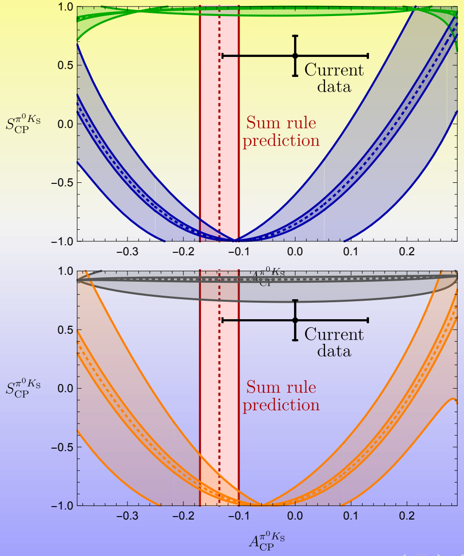

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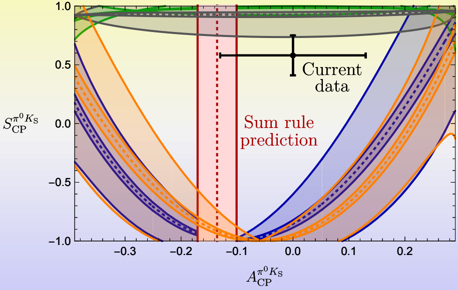

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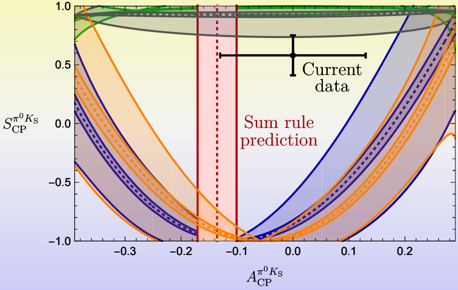
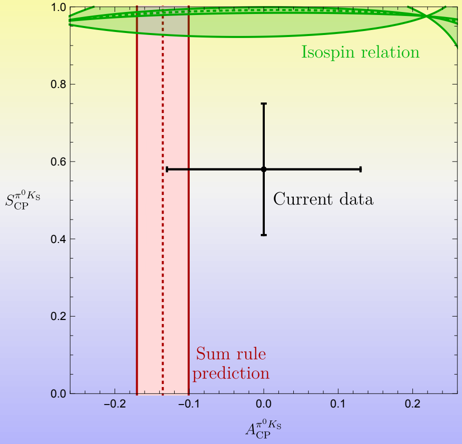




Sum Rule

Using the information encoded in the CP-averaged branching ratios:

$$\begin{aligned}\Delta_{\mathrm{SR}}^{(\mathrm{I})} &= A_{\mathrm{CP}}^{\pi^\pm K^\mp} + A_{\mathrm{CP}}^{\pi^\pm K^0}\frac{\mathcal{B}(B^+\to\pi^+K^0)}{\mathcal{B}(B_d^0\to\pi^-K^+)}\frac{\tau_{B^0}}{\tau_{B^+}} \\ &\quad - A_{\mathrm{CP}}^{\pi^0 K^\pm}\frac{2\mathcal{B}(B^+\to\pi^0K^+)}{\mathcal{B}(B_d^0\to\pi^-K^+)}\frac{\tau_{B^0}}{\tau_{B^+}} - A_{\mathrm{CP}}^{\pi^0 K^0}\frac{2\mathcal{B}(B_d^0\to\pi^0K^0)}{\mathcal{B}(B_d^0\to\pi^-K^+)} \\ &= 0+\mathcal{O}(r_{(\mathrm{c})}^2,\rho_{\mathrm{c}}^2)\ ,\end{aligned}$$

which offers an interesting test of the SM.

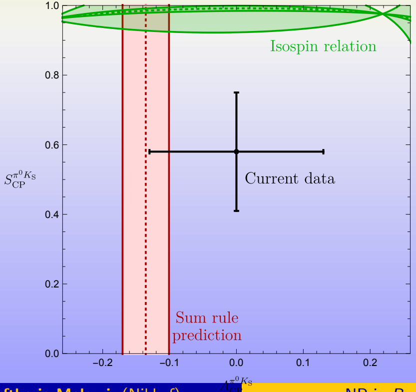
$$\Delta_{\mathrm{SR}}^{(\mathrm{I})}|_{SM} = -0.009\pm0.013$$

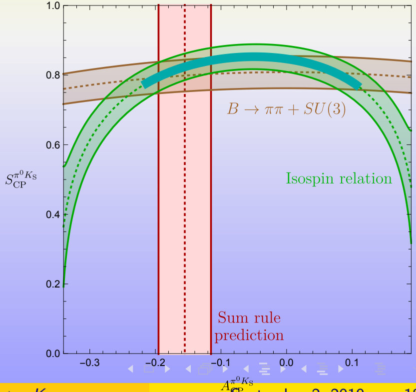
$$\Delta_{\mathrm{SR}}^{(\mathrm{I})}|_{exp} = -0.15\pm0.14$$

Can we resolve $B \to \pi K$ puzzle?

1 **change of data?**

- prime candidate: branching ratio (due to large experimental uncertainty on $B^0 \to \pi^0 K^0$)
- lowering branching ratio's central value (2.5 σ) gives consistent picture with SM





Can we resolve $B \to \pi K$ puzzle?

2 **effects of NP?**

- very promising sector for NP signals: EW penguin sector
- affecting values of q, ϕ
- sensitivity to new CP violation sources

$\star$ NP scenarios with extra Z'boson
  - links to anomalies in rare B-decays

Using charged $B \to \pi K$ decays

To determine q and ϕ, we make use of the **charged** $B \to \pi K$ decays

- only direct CP asymmetry (not mixing induced)
- following similar isospin analysis for the charged case

$$\begin{aligned} 3A_{3/2} &= A(B^+ \to \pi^+ K^0) + \sqrt{2}A(B^+ \to \pi^0 K^+) \\ &= (\hat{T} + \hat{C})(e^{i\gamma} - qe^{i\phi}e^{i\omega}) \end{aligned}$$

Important ratio of branching ratio:

$$R_c = 2\left[\frac{\mathcal{B}r(B \to \pi^0 K)}{\mathcal{B}r(B \to \pi K^0)}\right] = 1.09 \pm 0.06$$

New strategy to determine q and ϕ

- Defining the angle $\Delta\phi_{3/2}$ and converting $A_{3/2}$ to the quantity N

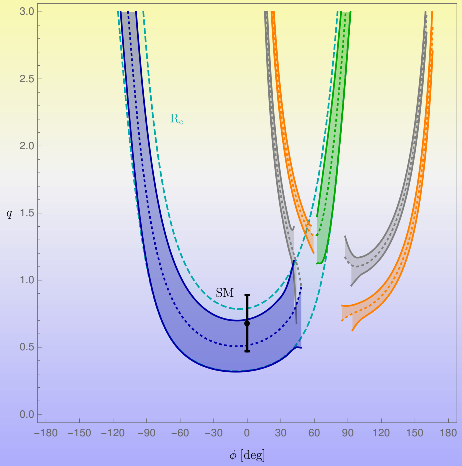
$$\Delta\phi_{3/2} = \phi_{3/2} - \bar{\phi}_{3/2}, \qquad \sqrt{N} = 3\left|\frac{A_{3/2}}{\hat{T}+\hat{C}}\right|$$

$$c = \pm\sqrt{N}\cos\left(\frac{\Delta\phi_{3/2}}{2}\right), \qquad s = \pm\sqrt{N}\sin\left(\frac{\Delta\phi_{3/2}}{2}\right)$$

$$q = \pm\sqrt{N + 1 - 2c\cos\gamma - 2s\sin\gamma}$$

$$\tan\phi = \frac{\sin\gamma - s}{\cos\gamma - c}$$

The picture we get for the current data



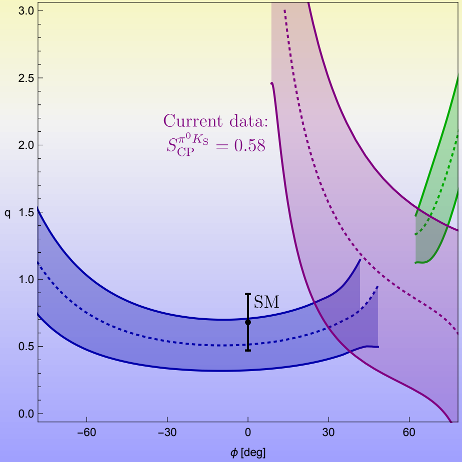
four contours come from isospin analysis

cyan dotted line: complement analysis with R_c

$$R_c = 1 - 2r_c \cos\delta_c(\cos\gamma - q\cos\phi) + \mathcal{O}(r_c^2)$$

Utilizing the mixing induced CP violation in $B^0 \to \pi^0 K_s$

How can we get further info for the q, ϕ determination?
Using $S_{CP}^{\pi^0 K_S} \Rightarrow$ extraction of ϕ_{00} phase



$$\phi_{00} = (7.7 \pm 12.1)^o$$

with hadronic par. values:

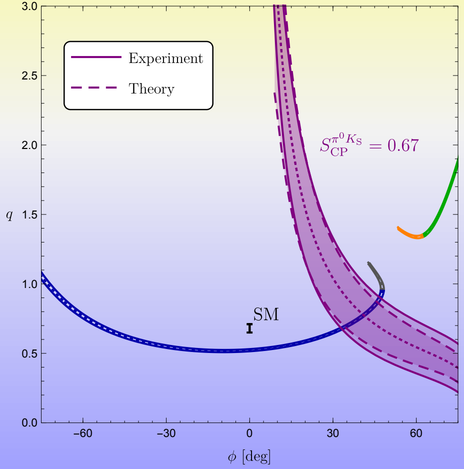
contributions from CS EW penguins

$S_{CP}^{\pi^0 K_S}$ converts to purple contour

isospin analysis contours agree with R_c

Illustrating a future scenario

Demonstrating a future application of our strategy considering a scenario for $S_{CP}^{\pi^0 K_S}$ measurements



Constraints from $S_{CP}^{\pi^0 K_S}$ and isospin determination

Experimental precision and theory can be matched

Conclusions

To Sum Up...

Final Remarks

- B $\rightarrow \pi K$ decays: important to test SM and search for NP
- There is tension in the data $\Rightarrow$ Something has to happen
  - either data should move to confirm the SM
  - or maybe there is NP
- We proposed a new strategy to determine q and ϕ
- Data from Belle II and LHCb upgrade will allow exciting new opportunities

Thank you!