NNV Subatomic Physics Meeting

$B_s \to D_s^{\pm} K^{\mp}$ decays
Can they reveal New Physics?

Eleftheria Malami

Nikhef, Theory Group

National Institute for Subatomic Physics

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Based on:

1. arXiv:hep-ph/0304027
2. arXiv:1208.6463 [hep-ph]
3. arXiv:1712.07428

Introduction

CP Violation and Flavour Physics

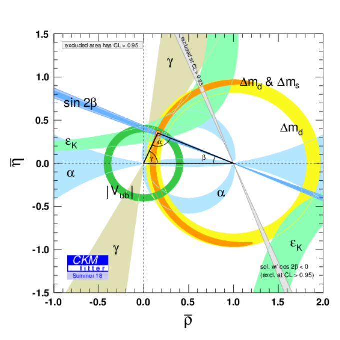
- Within the SM, CP violation is described by the Cabibbo-Kobayashi-Maskawa (CKM) matrix
  - the complex phase $\Rightarrow$ source of CP violation in SM
- **Goal**: test the SM
  precisely determine CKM parameters in SM
  search for possible indirect signals of New Physics (NP)
- B meson decays are significant for these studies
- A key parameter is the extraction of the CKM angle γ
  - for precision measurements of γ
    $\Rightarrow$ we can use $B_s \to D_s^{\pm} K^{\mp}$ decays

Angle γ and the Unitarity Triangle

$$\gamma = \arg\left[-\frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*}\right]$$

Unitarity Triangle

$$V_{ud}V_{ub}^* + V_{cd}V_{cb}^* + V_{td}V_{tb}^* = 0$$



- The important question is whether:
  - the curves (from different decays and transitions- using SM formulae) intersect in a single point and
  - the triangle angles agree with the angles from CP asymmetries in B systems and CP conserving B decays
- Any inconsistency will give hints about physics beyond the SM

Motivation

- **Intriguing value of the angle γ by LHCb$_{[3]}$**

$$\gamma = \left(128^{+17}_{-22}\right)^{\circ}$$

- **Shed more light on the $B_s^0 \to D_s^{\pm} K^{\mp}$ decay**

arXiv:1712.07428v3 [hep-ex] 20 Mar 2018

Measurement of CP asymmetry in $B_s^0 \to D_s^{\mp} K^{\pm}$ decays

LHCb collaboration[†]

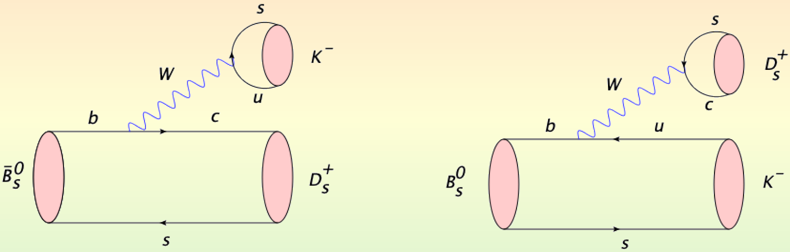
Abstract

We report the measurements of the CP-violating parameters in $B_s^0 \to D_s^{\mp} K^{\pm}$ decays observed in pp collisions, using a data set corresponding to an integrated luminosity of $3.0\,\text{fb}^{-1}$ recorded with the LHCb detector. We measure $C_f = 0.73 \pm 0.14 \pm 0.05$, $A_f^{\Delta\Gamma} = 0.39 \pm 0.28 \pm 0.15$, $A_{\bar{f}}^{\Delta\Gamma} = 0.31 \pm 0.28 \pm 0.15$, $S_f = -0.52 \pm 0.20 \pm 0.07$, $S_{\bar{f}} = -0.49 \pm 0.20 \pm 0.07$, where the uncertainties are statistical and systematic, respectively. These parameters are used together with the world-average value of the B_s^0 mixing phase, $-2\beta_s$, to obtain a measurement of the CKM angle γ from $B_s^0 \to D_s^{\mp} K^{\pm}$ decays, yielding $\gamma = (128\,^{+17}_{-22})^{\circ}$ modulo 180°, where the uncertainty contains both statistical and systematic contributions. This corresponds to $3.8\,\sigma$ evidence for CP violation in the interference between decay and decay after mixing.

Published in JHEP 03 (2018) 059

$B_s \to D_s^{\pm} K^{\mp}$

- non-leptonic decay $\Rightarrow$ not clean decays (due to the hadronic matrix elements)
- only tree diagram contributions
- both B_s^0 and $\bar{B}_s^0$ may decay into the same final state



- neutral B meson $\longrightarrow B_s^0 - \bar{B}_s^0$ mixing
- interference effects between $B_s^0 - \bar{B}_s^0$ mixing and decay processes
- **clean determination of $\gamma + \phi_s$** (ϕ_s: determined with $B_s^0 \to J/\psi\phi$)

Theoretical Background

Amplitudes and the parameter ξ_s

We can write the amplitude in the general form:

$$A(\overline{B}_s^0 \to D_s^+ K^-) =< K^- D_s^+ | H_{eff}(\overline{B}_s^0 \to D_s^+ K^-) | \overline{B_s^0} >$$

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Introducing the:

- $\boldsymbol{\upsilon_s}, \overline{\boldsymbol{\upsilon}}_{\boldsymbol{s}}, \boldsymbol{\upsilon}_{\boldsymbol{s}}^*$: CKM factors and
- M_s, $\overline{M}_s$: hadronic matrix elements

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$$A(\overline{B}_s^0 \rightarrow D_s^+ K^-) = \frac{G_F}{\sqrt{2}} \bar{\boldsymbol{\upsilon}}_{\boldsymbol{s}} \bar{M}_s$$

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- We define the parameter $\boldsymbol{\xi_s}$ as:

$$\boldsymbol{\xi_s} = -e^{-i\phi_s} \left[e^{i\phi_{CP}} \frac{A(\overline{B}_s^0 \to D_s^+ K^-)}{A(B_s^0 \to D_s^+ K^-)} \right]$$

Amplitudes and the parameter $\overline{\xi}_s$

Similarly, for the final state $D_s^- K^+$ and again with the help of:

- $\boldsymbol{\upsilon_s}$,$\boldsymbol{\overline{\upsilon}_s}$,$\boldsymbol{\upsilon_s^*}$: CKM factors and
- M_s, $\overline{M}_s$: hadronic matrix elements

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Rewriting the Parameters ξ_s and $\overline{\xi}_s$

- Inserting the amplitude formulas in the previous relation, the convention dependent phase ϕ_{CP} gets cancelled:

$$\xi_s = -(-1)^L e^{-i(\phi_s+\gamma)} \left[\frac{1}{x_s e^{i\delta_s}}\right]$$

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$$a_s e^{i\delta_s} = e^{-i[\phi_{CP}(D)-\phi_{CP}(K)]} \frac{M_s}{\overline{M}_s}$$

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- Similarly, for the CP conjugate case, we get:

$$\overline{\xi}_s = -(-1)^L e^{-i(\phi_s+\gamma)} \left[x_s e^{i\delta_s}\right]$$

Combining ξ_s and $\bar{\xi}_s$

Important relation

$$\xi_s \times \bar{\xi}_s = e^{-i2(\phi_s+\gamma)}$$

where the hadronic parameters $x_s e^{i\delta_s}$ cancels.

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- Otherwise: factorization $\Rightarrow$ to handle hadronic matrix elements
- Plugging form factor F_0 and decay constants f_K into the factorised matrix element, the decay amplitude takes the form:

$$< D_s^+ K^- | H_{eff} | \bar{B}_s^0 > = i \frac{G_F}{\sqrt{2}} V_{CKM}\, a(\mu)\, f_K\, F^0_{\bar{B}_s^0 \to D_s}(M_K^2)\, (M_{B_s}^2 - M_{D_s}^2)$$

Observables

final state f is $\mathrm{D}_s^+ K^-$

- Time-dependent CP Asymmetry

$$\frac{\Gamma(B_s^0(t) \to f) - \Gamma(\overline{B}_s^0(t) \to f)}{\Gamma(B_s^0(t) \to f) + \Gamma(\overline{B}_s^0(t) \to f)} = \left[\frac{C \cos(\Delta M_s\, t) + S \sin(\Delta M_s\, t)}{\cosh(\Delta\Gamma_s\, t/2) + \mathcal{A}_{\Delta\Gamma} \sinh(\Delta\Gamma_s\, t/2)}\right]$$

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  * where we have the asymmetries:

$$C = \frac{1-|\xi_s|^2}{1+|\xi_s|^2} = \frac{|A(B_s^0 \to f)|^2 - |A(\bar{B}_s^0 \to f)|^2}{|A(B_s^0 \to f)|^2 + |A(\bar{B}_s^0 \to f)|^2}$$

$$S = \frac{2\,\mathrm{Im}\xi_s}{1+|\xi_s|^2} \longrightarrow \text{mixing induced CP asymmetry}$$

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* Due to the $\Delta\Gamma_s$, we get access to another observable, the $\mathcal{A}_{\Delta\Gamma}$, which depends on C and S:

$$\mathcal{A}_{\Delta\Gamma} = \frac{2\,\mathrm{Re}\xi_s}{1+|\xi_s|^2}$$

Analysis

SM expressions for the CP Asymmetries

- With the help of

$$x_s = \left| \frac{A(\bar{B}_s^0 \to D_s^+ K^-)}{A(B_s^0 \to D_s^+ K^-)} \right|$$

we rewrite the asymmetries as follows:

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$$S = \frac{2\, x_s \sin(\phi_s + \gamma + \delta_s)}{1 + x_s^2}, \qquad \overline{S} = \frac{2\, x_s \sin(\phi_s + \gamma - \delta_s)}{1 + x_s^2}$$

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$$\mathcal{A}_{\Delta\Gamma} = -\frac{2\, x_s \cos(\phi_s + \gamma + \delta_s)}{1 + x_s^2}, \qquad \overline{\mathcal{A}}_{\Delta\Gamma} = -\frac{2\, x_s \cos(\phi_s + \gamma - \delta_s)}{1 + x_s^2}$$

LHCb Collaboration Measurements

$$\bar{C}_s = 0.73 \pm 0.15$$

$$S_s = 0.49 \pm 0.21 \qquad \overline{S}_s = 0.52 \pm 0.21$$

$$\mathcal{A}_{\Delta\Gamma s} = 0.31 \pm 0.32 \qquad \overline{\mathcal{A}}_{\Delta\Gamma s} = 0.39 \pm 0.32$$

We use ϕ_s, taking the average determined by HFLAV:

$$\phi_s = (-1.2 \pm 1.8)^\circ$$

Measurements of the $B_s^0 \to D_s^\pm K^\mp$ branching ratios from LHCb:

$$\frac{BR(B_s^0 \to D_s^\pm K^\mp)_{\text{exp}}}{BR(B_s^0 \to D_s^\pm \pi^\mp)_{\text{exp}}} = 0.0646 \pm 0.0043 \pm 0.0025$$

Using data from $B_d^0 \to D^\pm \pi^\mp$ decay

- We can combine information from the two systems linked by U-spin symmetry
- With U-spin flavour symmetry of strong interactions:
  - hadronic parameters x_s and δ_s of $B_s^0 \to D_s^\pm K^\mp$ are related to x_d and δ_d of the $B_d^0 \to D^\pm \pi^\mp$

$$x_s = -\frac{x_d}{\epsilon} = 0.31^{+0.046}_{-0.053}\big|_{\text{input}} \pm 0.06\big|_{\text{SU(3)}}$$

$$\delta_s = \delta_d = \left[-35^{+69}_{-40}\big|_{\text{input}} \pm 20\big|_{\text{SU(3)}}\right]^\circ$$

$\epsilon = \frac{\lambda^2}{1-\lambda^2}$,
$\lambda = |V_{us}|$

- With the help of hadronic parameters, we may calculate $B_s^0 \to D_s^\pm K^\mp$ observables

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- With the help of hadronic parameters, we may calculate $B_s^0 \to D_s^\pm K^\mp$ observables

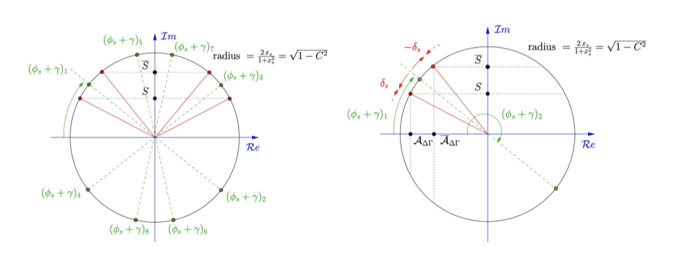
However, we have enough info to analyse each one of the systems separately [and to avoid the hadronic parameters]
$\Rightarrow$ we don't have to make any U-spin assumptions and
$\Rightarrow$ we may use these decays to test the U-spin symmetry.

Illustrating the Discrete Ambiguities

$$C^2 + S^2 + \mathcal{A}_{\Delta\Gamma}^2 = 1 = \bar{C}^2 + \bar{S}^2 + \bar{\mathcal{A}}_{\Delta\Gamma}^2$$

$$\mathcal{A}_{\Delta\Gamma} + iS = -(-1)^L \sqrt{1 - C^2}\, e^{-i(\phi_s + \gamma + \delta_s)}$$

$$\bar{\mathcal{A}}_{\Delta\Gamma} + i\bar{S} = -(-1)^L \sqrt{1 - \bar{C}^2}\, e^{-i(\phi_s + \gamma - \delta_s)}$$



Assumption: $C = -\bar{C}$

The picture we get for the Current data

From $\overline{C}_s$ we may determine x_s yielding: $x_s = \sqrt{\frac{1-\overline{C}_s}{1+\overline{C}_s}} = 0.4 \pm 0.13$

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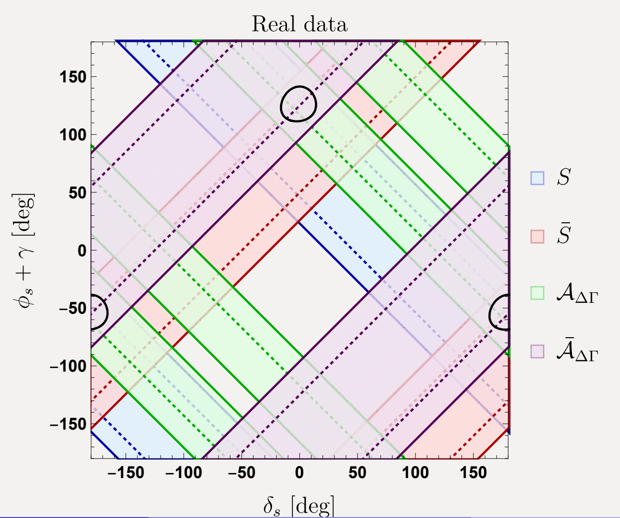

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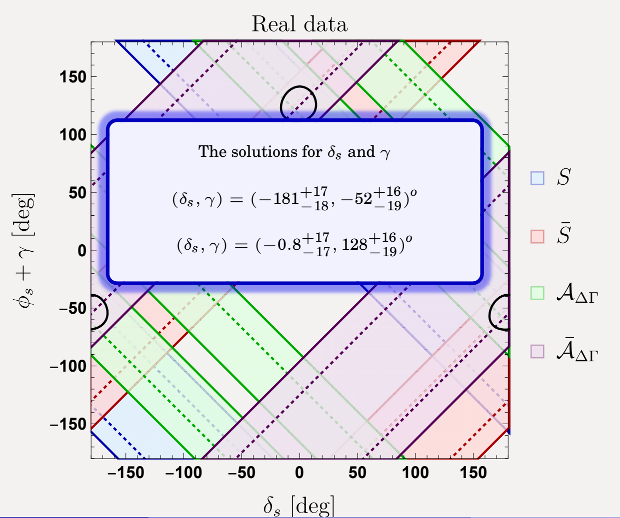

Moving to New Physics...

- Could it be New Physics?
- How would it enter?
  - Might NP appear at the amplitude level?
- How would it affect the observables?
- Interplay with other New Physics constraints?

This is still work in progress
Stay tuned!

Conclusions

Final Remarks

- **Our Strategy**:

  $\xi_s \times \bar{\xi}_s$ can be calculated from the corresponding observables and leads to the determination of $\phi_s + \gamma$

- Even though $B_s \to D_s^{\pm} K^{\mp}$ is not a clean decay (non-leptonic), it allows a clean extraction of $\phi_s + \gamma$ (ϕ_s is determined)

- The value of $\left(\gamma = 128^{+17}_{-22}\right)^{\circ}$ by LHCb is intriguing

- The observable $\mathcal{A}_{\Delta\Gamma}$ (and $\overline{\mathcal{A}}_{\Delta\Gamma}$) is crucial to resolve ambiguities

- Room to explore NP [work in progress]

Thank you!

Backup Slides

Branching Ratios

- Experimental branching ratio:

$$BR(B_s \to f)_{exp} = \frac{1}{2} \int < \Gamma(B_s(t) \to f) > dt$$

- Theoretical branching ratio:

$$BR(B_s \to f)_{theo} = \frac{\tau_{B_s}}{2} < \Gamma(B_s^0(t) \to f) > |t = 0$$

- Connecting the experimental to the theoretical branching ratio

$$BR(B_s \to f)_{theo} = \frac{1 - y_s^2}{1 + \mathcal{A}_{\Delta\Gamma} y_s} BR(B_s \to f)_{exp}$$

- Importance of $\Delta\Gamma_s$

$$y_s = \frac{\Delta\Gamma_s}{2\Gamma_s} \approx 0.1$$