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$B_s^0 \to D_s^\pm K^\mp$ decays: Can they reveal New Physics?

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The non-leptonic $B_s^0 \to D_s^\pm K^\mp$ decays, which occur via pure tree diagrams, allow a theoretically clean determination of the CKM angle γ. Considering recent LHCb results, and combining them with data for $B_s \to D^\mp \pi^\pm$ modes, our goal is to shed more light on the resolution of the ambiguities in the extraction of gamma of the unitarity triangle as well as to explore possible New Physics effects.

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1. Introduction

The violation of the charge conjugation-parity (CP) symmetry is one of the most important topics in particle physics, and an essential point to explain matter and anti-matter asymmetry in the universe. Within the Standard Model (SM), CP violation is described by the Cabibbo-Kobayashi-Maskawa (CKM) matrix [1, 2]. In our analysis, we focus on the unitarity triangle of the CKM matrix and its angles α, β and γ [3]. Our aim is to test the SM, to precisely determine CKM parameters in SM and to search for possible indirect signals of New Physics (NP).

B meson decays are significant for these studies and one of the things that play a key role is the extraction of the CKM angle γ. The angle γ, which is defined as $\gamma = \arg\left[-V_{ud}V_{ub}^*/V_{cd}V_{cb}^*\right]$, is the least precisely known angle of the unitarity triangle (UT): $V_{ud}V_{ub}^* + V_{cd}V_{cb}^* + V_{td}V_{tb}^* = 0$. In Fig. 1, both the UT triangle and the angle γ with its error bands are shown [4]. We can also see all the different circles coming from semi-leptonic B decays, the ε_k hyperbola arising from the neutral kaon decays and describing indirect CP violation as well as the straight lines corresponding to the $\sin 2\beta$ direct measurements (with the help of the $B_d^0 \to J/\psi K_S$ decay). Even though the global consistency is very good, there is still a lot of space to detect possible inconsistencies that could give hints about physics beyond the SM.

For precision measurements of γ, one of the most interesting decays that we can use is the $B_s^0 \to D_s^{\pm} K^{\mp}$, which is a non-leptonic decay [5, 6]. Non-leptonic decays are not clean decays, because of the hadronic matrix elements. However, the $B_s^0 \to D_s^{\pm} K^{\mp}$ decays receive only tree diagram contributions (Fig. 2). In addition, due to the neutral B meson, there are $B^0 - \bar{B}^0$ oscillations. The important feature is that both B_s^0 and $\bar{B}_s^0$ may decay into the same final state. Thus, interference effects between $B_s^0 - \bar{B}_s^0$ mixing and decay processes arise, allowing a clean determination of $\gamma + \phi_s$, with ϕ_s being determined with the help of $B_s^0 \to J/\psi\phi$.

Our motivation for these studies was the intriguing value of the angle γ which was announced by LHCb in [7]: $\gamma = (128^{+17}_{-22})^{\circ}$. The central value is surprisingly large but due to the significant uncertainties we cannot draw yet a conclusion. Thus, it is important to shed more light on the $B_s^0 \to D_s^{\pm} K^{\mp}$ decay. Here, we analyse this decay, focusing on the amplitude analysis, we propose a strategy that allows a clean extraction of the angle γ and we comment on possible NP effects.

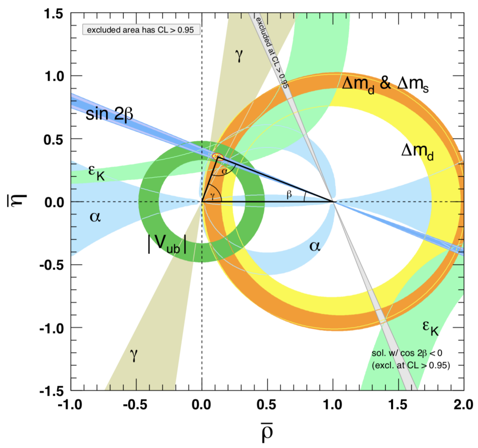
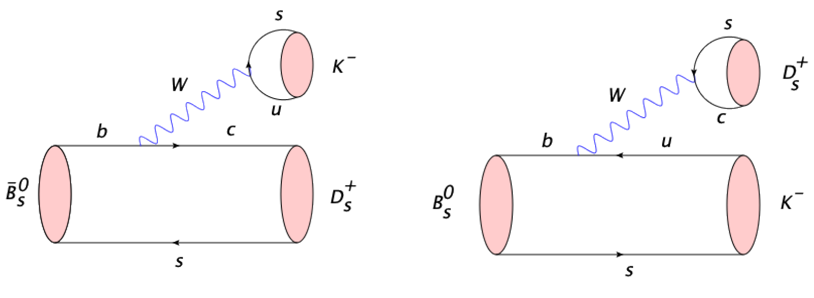


Figure 1: Unitarity triangle and the angle γ [4].



(a) (b)

Figure 2: Feynman diagrams.

2. Theoretical Framework

2.1 Decay Amplitude Analysis

As we have already mentioned, the $B_s^0 \to D_s^\pm K^\mp$ decay involves only tree level processes and both B_s^0 and $\bar{B}_s^0$ mesons decay to the same final state, which can be either $D_s^+ K^-$ or $D_s^- K^+$. In general, the amplitude of the B_s^0 meson decaying into the final state $D_s^+ K^-$ can be written as:

$$A(B_s^0 \to D_s^+ K^-) = < K^- D_s^+ | H_{\text{eff}}(B_s^0 \to D_s^+ K^-) | B_s^0 > . \tag{2.1}$$

where H_{eff} is the low-energy effective Hamiltonian of the system. A similar relation can also be written for the CP conjugate case.

Introducing the CKM factors υ_s, $\bar{\upsilon}_s$, υ_s^*, $\bar{\upsilon}_s^*$ and the hadronic matrix elements M_s, $\bar{M}_s$, we can rewrite the amplitudes of the decays to the final state $D_s^+ K^-$ as [5]:

$$A(\bar{B}_s^0 \to D_s^+ K^-) = \frac{G_F}{\sqrt{2}} \bar{\upsilon}_s \bar{M}_s, \tag{2.2}$$

$$A(B_s^0 \to D_s^+ K^-) = (-1)^L e^{i\phi_{CP}} \frac{G_F}{\sqrt{2}} \upsilon_s^* M_s, \tag{2.3}$$

where L denotes the angular momentum of the final state $D_s^+ K^-$ (and it is equal to 0 in this case) and the phase ϕ_{CP} is a convention dependent CP phase.

We define the parameter ξ_s, which is a physical observable that gives a measure of the strength of the interference effects that arise between $B_s^0 - \bar{B}_s^0$ mixing and decay processes, with the help of the amplitudes as follows [5]:

$$\xi_s = -e^{-i\phi_s} \left[e^{i\phi_{CP}} \frac{A(\overline{B}_s^0 \to D^+ K^-)}{A(B_s^0 \to D^+ K^-)} \right], \tag{2.4}$$

where ϕ_s is the weak CP violating phase involved in the $B_s^0 - \bar{B}_s^0$ mixing. Inserting the amplitude formulas (Eqs. 2.3) in the previous relation (Eq. 2.4), the phase ϕ_{CP} gets cancelled and we get the simpler form:

$$\xi_s = -(-1)^L e^{-i(\phi_s + \gamma)} \left[\frac{1}{x_s e^{i\delta_s}} \right]. \tag{2.5}$$

The term x_s in Eq. 2.5 is defined as: $x_s = R_b a_s$, where R_b denotes the one side of the UT:

$$R_b = \left(1 - \frac{\lambda^2}{2}\frac{1}{\lambda}\left|\frac{V_{ub}}{V_{cb}}\right|\right), \tag{2.6}$$

where V_{ub}, V_{cb} are the CKM elements and λ the Wolfenstein parameter (numerical values in [4]), and regarding a_s we get the physical observable:

$$a_s e^{i\delta_s} = e^{-i[\phi_{CP}(D)-\phi_{CP}(K)]}\frac{M_s}{\bar{M}_s}, \tag{2.7}$$

where the ϕ_{CP} phases get cancelled in the ratio of the hadronic matrix elements.

Similarly, the amplitudes for the final state $D_s^- K^+$ can be expressed as [5]:

$$A(\bar{B}_s^0 \to D_s^- K^+) = \frac{G_F}{\sqrt{2}} \upsilon_s M_s, \tag{2.8}$$

$$A(B_s^0 \to D_s^- K^+) = (-1)^L e^{i\phi_{CP}} \frac{G_F}{\sqrt{2}} \bar{\upsilon}_s^* \bar{M}_s, \tag{2.9}$$

and inserting Eqs. 2.9 in the definition of the parameter $\bar{\xi}_s$:

$$\bar{\xi}_s = -e^{-i\phi_s}\left[e^{i\phi_{CP}}\frac{A(\bar{B}_s^0 \to D^- K^+)}{A(B_s^0 \to D^- K^+)}\right], \tag{2.10}$$

we obtain the much simpler relation which follows:

$$\bar{\xi}_s = -(-1)^L e^{-i(\phi_s+\gamma)}\left[x_s e^{i\delta_s}\right], \tag{2.11}$$

where the convention dependent phase ϕ_{CP} again get cancelled.

The form of the Eq. 2.5 and the Eq. 2.11 leads to the very important relation:

$$\xi_s \times \bar{\xi}_s = e^{-i2(\phi_s+\gamma)}, \tag{2.12}$$

where the troublesome hadronic parameters $x_s e^{i\delta_s}$ cancel. Thus, we have a very clean relation that depends only on ϕ_s and γ. This relation is the main point of our strategy. So, with Eq. 2.12, we may extract $\phi_s + \gamma$ in a theoretically clean way using only the observables, as we will see later on.

2.2 Asymmetries

The parameters ξ_s and $\bar{\xi}_s$ govern the asymmetries, thus they help us to get access to interesting observables. Having the neutral B_s^0 and $\bar{B}_s^0$ mesons both decaying into the same final state, we can write the time-dependent decay rate asymmetry [5]:

$$\frac{\Gamma(B_s^0(t) \to D_s^+ K^-) - \Gamma(\bar{B}_s^0(t) \to D_s^+ K^-)}{\Gamma(B_s^0(t) \to D_s^+ K^-) + \Gamma(\bar{B}_s^0(t) \to D_s^+ K^-)} = \left[\frac{C\cos(\Delta M_s\, t) + S\sin(\Delta M_s\, t)}{\cosh(\Delta\Gamma_s\, t/2) + \mathscr{A}_{\Delta\Gamma}\sinh(\Delta\Gamma_s\, t/2)}\right], \tag{2.13}$$

where ΔM_s denotes the mass difference between heavy and light mass eigenstates and $\Delta\Gamma_s$ is the decay width difference. The coefficients of the oscillatory terms $\cos(\Delta M_s t)$ and $\sin(\Delta M_s t)$ are the following asymmetries:

$$C_s = \frac{1-|\xi_s|^2}{1+|\xi_s|^2} = \frac{|A(B_s^0 \to D_s^+ K^-)|^2 - |A(\bar{B}_s^0 \to D_s^+ K^-)|^2}{|A(B_s^0 \to D_s^+ K^-)|^2 + |A(\bar{B}_s^0 \to D_s^+ K^-)|^2}, \tag{2.14}$$

$$S_s = \frac{2\,\mathrm{Im}\xi_s}{1+|\xi_s|^2}, \tag{2.15}$$

with S_s indicating the mixing induced CP violation. Last but not least, the observable $\mathscr{A}_{\Delta\Gamma}$, coming with the $\Delta\Gamma_s$ term, is defined as:

$$\mathscr{A}_{\Delta\Gamma_s} = \frac{2\,\mathrm{Re}\xi_s}{1+|\xi_s|^2}. \tag{2.16}$$

We point out that we get access to this observable because of the fact that the term $\Delta\Gamma_s$ is sizeable ($\Delta\Gamma_s/\Gamma_s = 0.135 \pm 0.008$ [4]). The observable $\mathscr{A}_{\Delta\Gamma_s}$ depends on C and S, according to the relation $\mathscr{A}^2_{\Delta\Gamma_s} + C_s^2 + S_s^2 = 1$.

The time-dependent decay rate asymmetry into the $D_s^- K^+$ final state is defined in analogy to Eq. 2.13 and analogous relations hold for the observables $\bar{C}_s$, $\bar{S}_s$ and $\bar{\mathscr{A}}_{\Delta\Gamma_s}$.

As we can see, having the absolute value of ξ_s (and $\bar{\xi}_s$) as well as its real and imaginary part included in the observables expressions, we are able to pin down its value in a nice, unambiguous way, as we will describe in the following sections.

3. Analysis

3.1 SM expressions for the CP Asymmetries

We may express all of the CP asymmetries, with the help of the ratio x_s:

$$x_s = \left| \frac{A(\bar{B}_s^0 \to D_s^+ K^-)}{A(B_s^0 \to D_s^+ K^-)} \right|, \tag{3.1}$$

introducing the strong phase δ_s and with the proper signs, as follows [5]:

$$C_s = -\left[\frac{1-x_s^2}{1+x_s^2}\right], \qquad \bar{C}_s = +\left[\frac{1-x_s^2}{1+x_s^2}\right], \tag{3.2}$$

$$S_s = \frac{2\,x_s \sin(\phi_s+\gamma+\delta_s)}{1+x_s^2}, \qquad \bar{S}_s = \frac{2\,x_s \sin(\phi_s+\gamma-\delta_s)}{1+x_s^2}, \tag{3.3}$$

$$\mathscr{A}_{\Delta\Gamma_s} = -\frac{2\,x_s \cos(\phi_s+\gamma+\delta_s)}{1+x_s^2}, \qquad \bar{\mathscr{A}}_{\Delta\Gamma_s} = -\frac{2\,x_s \cos(\phi_s+\gamma-\delta_s)}{1+x_s^2}. \tag{3.4}$$

It is important to mention, that in the SM the following relation holds: $C_s = \bar{C}_s$. We use this relation as an assumption [7] for the rest of the analysis, thus for the NP studies.

For our numerical analysis, we use the values of the CP asymmetries, which have been measured by the LHCb collaboration [7]. These values are presented on Table 3.1, where we have fixed the signs in order to agree with our notation. We also use ϕ_s as input parameter, taking the average determined by HFLAV [8]:

$$\phi_s = -(1.2 \pm 1.8)^{\mathrm{o}}. \tag{3.5}$$

Last but not least, regarding the branching ratio, we use the following ratio [9]:

$$\frac{\mathscr{B}(B_s^0 \to D_s^{\mp} K^{\pm})}{\mathscr{B}(B_s^0 \to D_s^- \pi^+)} = 0.0752 \pm 0.0015\ (\mathrm{stat}) \pm 0.0019\ (\mathrm{syst}). \tag{3.6}$$

Asymmetries	Values	Asymmetries	Values
C_s	0.73 ± 0.15	$\bar{C}_s$	0.73 ± 0.15
S_s	0.49 ± 0.21	$\bar{S}_s$	0.52 ± 0.21
$\mathcal{A}_{\Delta\Gamma_s}$	0.31 ± 0.32	$\bar{\mathcal{A}}_{\Delta\Gamma_s}$	0.39 ± 0.32

Table 1: Central values and errors of the CP Asymmetries of the $(B_s^0 \to D_s^{\mp} K^{\pm})$ decay [7].

3.2 Determining γ and Resolving the Ambiguities

Here, we present the steps that we follow in order to extract the angle γ. For this purpose, we use the values that we showed before. Thus, we will be able to confirm whether our strategy works, by checking if the value of the γ that we obtain is the same with the one that [7] provides, since we use the same input parameters. We point out, that for the SM analysis, we don't make use of the branching ratio information.

From the asymmetry $\bar{C}_s$ we may determine the parameter x_s yielding:

$$x_s = \sqrt{\frac{1-\bar{C}_s}{1+\bar{C}_s}} = 0.4 \pm 0.13. \tag{3.7}$$

Having the value of x_s, we may plug it into the formulas of S_s, $\bar{S}_s$, $\mathcal{A}_{\Delta\Gamma_s}$ and $\bar{\mathcal{A}}_{\Delta\Gamma_s}$. Thus, we will be able to obtain contours in the (δ_s, γ) plane.

In other words, knowing x_s and the values of the mixing induced CP asymmetries, we may firstly use the relations of S_s and $\bar{S}_s$ to determine δ_s and γ. In this way, making use only of $C_s = \bar{C}_s$, S_s and $\bar{S}_s$ we get 8 solutions. However, the observables $\mathcal{A}_{\Delta\Gamma_s}$ and $\bar{\mathcal{A}}_{\Delta\Gamma_s}$ also allow us to extract δ_s and γ. So, using only C_s, $\mathcal{A}_{\Delta\Gamma_s}$ and $\bar{\mathcal{A}}_{\Delta\Gamma_s}$, we get again an 8-fold solution. Therefore, it's necessary to resolve this 8-fold ambiguity.

The number of discrete ambiguities can be reduced by combining the information obtained from S_s, $\bar{S}_s$, $\mathcal{A}_{\Delta\Gamma_s}$ and $\bar{\mathcal{A}}_{\Delta\Gamma_s}$. In this case, we are left with a twofold ambiguity, which can further be resolved. Thus, we realise the important role of the $\mathcal{A}_{\Delta\Gamma_s}$ and $\bar{\mathcal{A}}_{\Delta\Gamma_s}$ observable in the reduction of the number of the ambiguities.

Fig. 3 illustrates the contours coming from the above mentioned observables in the (δ_s, γ) plane, indicating the solutions that we get for γ. The blue and the red contours arise from the S_s and $\bar{S}_s$ asymmetries while the green and the purple contours come from the $\mathcal{A}_{\Delta\Gamma_s}$ and $\bar{\mathcal{A}}_{\Delta\Gamma_s}$ observable. There are only two points, where all four contours intersect. These two points indicate the two solutions. So, we have:

$$(\delta_s, \gamma) = \left(-181^{+17}_{-18}, -52^{+16}_{-19}\right)^{\mathrm{o}} \quad \vee \quad (\delta_s, \gamma) = \left(-0.8 \pm 17, 128^{+16}_{-19}\right)^{\mathrm{o}}, \tag{3.8}$$

the solutions of δ_s and γ for the current data. In Fig. 3, we also show the 1σ regions which we get by performing a χ^2 fit to all CP asymmetries.

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

Another interesting decay, which can provide us with useful information, is the $B_d^0 \to D^{\pm}\pi^{\mp}$ decay. The systems $B_s^0 \to D_s^{\pm} K^{\mp}$ and $B_d^0 \to D^{\pm}\pi^{\mp}$ are linked by U-spin symmetry (which interchanges the d and the s quark). Therefore, making use of the $B_d^0 \to D^{\pm}\pi^{\mp}$ data, one is able to combine information arising from both systems.

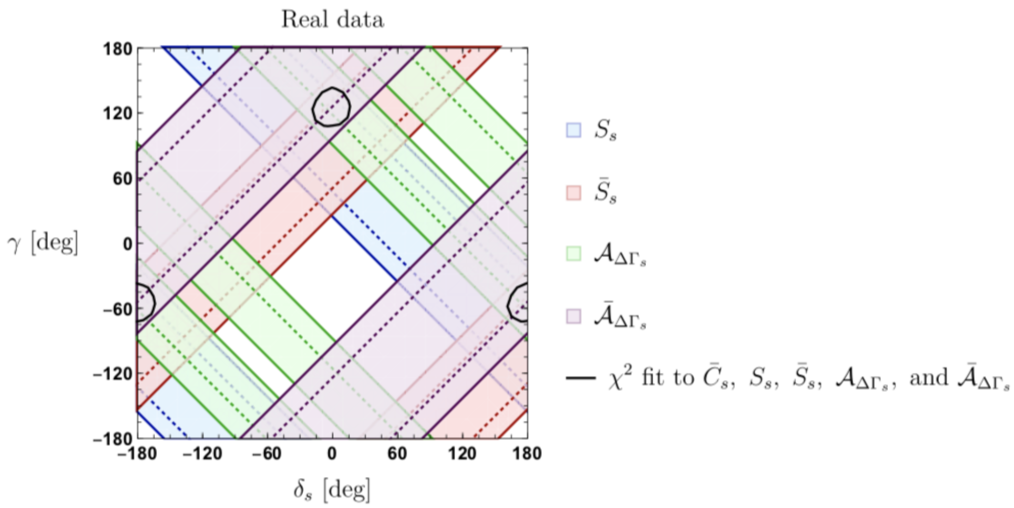


Figure 3: Constraints in the (δ_s, γ) plane from LHCb measurements of S_s, $\bar{S}_s$, $\mathscr{A}_{\Delta\Gamma_s}$ and $\bar{\mathscr{A}}_{\Delta\Gamma_s}$ [7]. Performing a χ^2 fit to all CP asymmetries, we obtain the 1σ regions.

The CP asymmetries of $B_d^0 \to D^{\pm}\pi^{\mp}$ have been measured by BaBar [10] and Belle [11], as well as recently by LHCb [12]. With U-spin flavour symmetry of strong interactions, the hadronic parameters x_s and δ_s of $B_s^0 \to D_s^{\pm} K^{\mp}$ are related to the parameters x_d (doubly Cabibbo suppressed) and δ_d of the $B_d^0 \to D^{\pm}\pi^{\mp}$ decay as follows :

$$x_s = -\frac{x_d}{\varepsilon} = 0.31^{+0.046}_{-0.053}|_{\text{input}} \pm 0.06|_{\text{SU(3)}}, \quad [13] \tag{3.9}$$

$$\delta_s = \delta_d = \left[-35^{+69}_{-40}|_{\text{input}} \pm 20|_{\text{SU(3)}}\right]^{\text{o}}, \quad [13] \tag{3.10}$$

where $\varepsilon = \lambda^2/(1-\lambda^2)$ and $\lambda = |V_{us}|$ [4]. These values can be compared with our calculations in Eq. 3.7 and Eq. 3.8. With the help of these hadronic parameters, one may then calculate the $B_s^0 \to D_s^{\pm} K^{\mp}$ observables.

However, we have enough information in order to analyse each one of the systems separately. In this way, we avoid working with the hadronic parameters and making use of the factorisation method. Thus, there is no need to make any U-spin assumptions. We perform our analysis using only the available $B_s^0 \to D_s^{\pm} K^{\mp}$ data. The $B_d^0 \to D^{\pm}\pi^{\mp}$ decay decays though are still useful, as they can be used in order to test the U-spin symmetry.

3.4 Could there be New Physics?

It is very interesting to continue our studies and search for New Physics. The surprisingly large value of γ that LHCb presented [7], raises questions whether there could be physics beyond SM and how much room there is for NP. If there is indeed NP, we should test how this would enter and how it would affect our observables. In this case, it is also important to see whether we could have interplay with other NP constraints.

All these are questions that naturally follow from our analysis. However, this is still work in progress and we will not make any further comments before the corresponding paper is published.

4. Conclusions

The decay $B_s \to D_s^{\pm} K^{\mp}$ is a very interesting decay in the analysis and determination of the angle γ of the unitarity triangle. We highlight that, even though $B_s \to D_s^{\pm} K^{\mp}$ is not a theoretically clean system, as it is a non-leptonic decay, suffering from hadronic matrix elements which are not easy to handle, it still allows a clean extraction of the γ angle.

Here, we presented our strategy according to which, the product $\xi_s \times \bar{\xi}_s$ can be calculated from the corresponding observables, which are experimentally measured. Knowing this product leads to the determination of the quantity $\phi_s + \gamma$ (Eq. 2.12) and, since ϕ_s is already known from the decay $B_s^0 \to J/\psi\phi$, to the determination of the angle γ.

We applied our strategy in the current data, using as input parameters, the values of the observables, which were measured by LHCb [7]. Finding solutions consistent with [7], we confirmed our numerical analysis. An essential point in our studies is the observable $\mathscr{A}_{\Delta\Gamma_s}$ (and $\bar{\mathscr{A}}_{\Delta\Gamma_s}$), which is crucial to resolve the ambiguities. Having access to the real part of the parameter ξ_s from the definition of $\mathscr{A}_{\Delta\Gamma_s}$ and to its imaginary part from the S_s observable (and similarly for the CP conjugate case), we are able to unambiguously determine γ.

The value of $\left(\gamma = 128^{+16}_{-19}\right)^{\circ}$ that we calculated, and which agrees with the value which was reported by LHCb [7], is really intriguing. The central value is surprisingly large. However, the fact that there are significant uncertainties does not allow us to draw yet a conclusion. Therefore, it is important to understand why we get this value. Could this imply NP? Further studies should be performed in order to shed more light on the situation.

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