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Letter

First evidence of new physics in $b \leftrightarrow s$ transitions

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Abstract

We combine all the available experimental information on B_s mixing, including the very recent tagged analyses of $B_s \rightarrow J/\Psi\varphi$ by the CDF and DØ collaborations. We find that the phase of the B_s mixing amplitude deviates more than 3σ from the Standard Model prediction. While no single measurement has a 3σ significance yet, all the constraints show a remarkable agreement with the combined result. This is a first evidence of physics beyond the Standard Model. This result disfavours New Physics models with Minimal Flavour Violation with the same significance.

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1. Letter

In the Standard Model (SM), all flavour and CP violating phenomena in weak decays are described in terms of quark masses and the four independent parameters in the Cabibbo-Kobayashi-Maskawa (CKM) matrix [1,2]. In particular, there is only one source of CP violation, which is connected to the area of the Unitarity Triangle (UT). A peculiar prediction of the SM, due to the hierarchy among CKM matrix elements, is that CP violation in B_s mixing should be tiny. This

property is also valid in models of Minimal Flavour Violation (MFV) [3-8], where flavour and CP violation are still governed by the CKM matrix. Therefore, the experimental observation of sizable CP violation in B_s mixing is a clear (and clean) signal of New Physics (NP) and a violation of the MFV paradigm. In the past decade, *B* factories have collected an impressive amount of data on B_d flavour- and CP-violating processes. The CKM paradigm has passed unscathed all the tests performed at the *B* factories down to an accuracy just below 10% [9-11]. This has been often considered as an indication pointing to the MFV hypothesis, which has received considerable attention in recent years. The only possible hint of non-MFV NP is found in the penguin-dominated $b \rightarrow s$ non-leptonic decays. Indeed, in the SM, the $S_{q\bar{q}s}$ coefficient of the time-dependent CP asymmetry in these channels is equal to the $S_{c\bar{c}s}$ measured with $b \rightarrow c\bar{c}s$ decays, up to hadronic uncertainties related to subleading terms in the decay amplitudes. Present data show a systematic, although not statistically significant, downward shift of $S_{q\bar{q}s}$ with respect to $S_{c\bar{c}s}$ [12-21], while hadronic models predict a shift in the opposite direction in many cases [22-29].

From the theoretical point of view, the hierarchical structure of quark masses and mixing angles of the SM calls for an explanation in terms of flavour symmetries or of other dynamical mechanisms, such as, for example, fermion localization in models with extra dimensions. All such explanations depart from the MFV paradigm, and generically cause deviations from the SM in flavour violating processes. Models with localized fermions [30-32], and more generally models of Next-to-Minimal Flavour Violation [33], tend to produce too large effects in ε_K [34,35]. On the contrary, flavour models based on nonabelian flavour symmetries, such as $U(2)$ or $SU(3)$, typically suppress NP contributions to $s \leftrightarrow d$ and possibly also to $b \leftrightarrow d$ transitions, but easily produce large NP contributions to $b \leftrightarrow s$ processes. This is due to the large flavour symmetry breaking caused by the top quark Yukawa coupling. Thus, if (nonabelian) flavour symmetry models are relevant for the solution of the SM flavour problem, one expects on general grounds NP contributions to $b \leftrightarrow s$ transitions. On the other hand, in the context of Grand Unified Theories (GUTs), there is a connection between leptonic and hadronic flavour violation. In particular, in a broad class of GUTs, the large mixing angle observed in neutrino oscillations corresponds to large NP contributions to $b \leftrightarrow s$ transitions [36-39].

In this Letter, we show that present data give evidence of a B_s mixing phase much larger than expected in the SM, with a significance of more than 3σ. This result is obtained by combining all available experimental information with the method used by our collaboration for UT analyses and described in Ref. [40].

We perform a model-independent analysis of NP contributions to B_s mixing using the following parametrization [41-46]:

Table 1: Input parameters used in the analysis.

Δm_s [ps^{-1}]	17.77 ± 0.12	[47]
$A_{SL}^s \times 10^2$	2.45 ± 1.96	[48]
$A_{SL}^{\mu\mu} \times 10^3$	-4.3 ± 3.0	[49,50]
$\tau_{B_s}^{FS}$ [ps]	1.461 ± 0.032	[51-59]
φ_s	see ref. [60]	[60]
$\Delta\Gamma_s$	see ref. [60]	[60]
φ_s [rad]	0.60 ± 0.27	[61]
$\Delta\Gamma_s$ [ps^{-1}]	0.19 ± 0.07	[61]
τ_{B_s} [ps]	1.52 ± 0.06	[61]

$$C_{\phi_s,\Delta\Gamma_s} = -0.042 \quad C_{\phi_s,\tau_{B_s}} = -0.571 \quad C_{\tau_{B_s},\Delta\Gamma_s} = 0.23$$

We also show the correlation coefficients Cs of the measurements of φ_s, $\Delta\Gamma_s$ and τ_{B_s} from ref. [61].

$$C_{B_s}e^{2i\phi_{B_s}} = \frac{A_s^{SM}e^{-2i\beta_s} + A_s^{NP}e^{2i(\phi_s^{NP} - \beta_s)}}{A_s^{SM}e^{-2i\beta_s}} = \frac{\langle B_s|H_{eff}^{full}|\bar{B}_s\rangle}{\langle B_s|H_{eff}^{SM}|\bar{B}_s\rangle}, \qquad (1)$$

where H_{eff}^{full} is the effective Hamiltonian generated by both SM and NP, while H_{eff}^{SM} only contains SM contributions. The angle β_s is defined as $\beta_s = \arg(-(V_{ts}V_{tb}^*)/(V_{cs}V_{cb}^*))$ and it equals 0.018 ± 0.001 in the SM (we are using the usual CKM phase convention in which $V_{cs}V_{cb}^*$ is real to a very good approximation).

We use the following experimental input: the CDF measurement of Δm_s [47], the semileptonic asymmetry in B_s decays A_{SL}^s [48], the dimuon charge asymmetry $A_{SL}^{\mu\mu}$ from DØ [49] and CDF [50], the measurement of the B_s lifetime from flavour-specific final states [51-59], the two-dimensional likelihood ratio for $\Delta\Gamma_s$ and $\varphi_s = 2(\beta_s - \phi_{B_s})$ from the time-dependent tagged angular analysis of $B_s \to J/\psi\varphi$ decays by CDF [60] and the correlated constraints on Γ_s, $\Delta\Gamma_s$ and φ_s from the same analysis performed by DØ [61]. For the latter, since the complete likelihood is not available yet, we start from the results of the 7-variable fit in the free-φ_s case from Table one of ref. [61]. We implement the 7×7 correlation matrix and integrate over the strong phases and decay amplitudes to obtain the reduced 3×3 correlation matrix used in our analysis. In the DØ analysis, the twofold ambiguity inherent in the measurement ($\varphi_s \to \pi - \varphi_s$, $\Delta\Gamma_s \to -\Delta\Gamma_s$, $\cos\delta_{1,2} \to -\cos\delta_{1,2}$)

for arbitrary strong phases was removed using a value for cos $\delta_{1,2}$ derived from the BaBar analysis of $B_d \rightarrow J/\Psi K^*$ using SU(3). However, the strong phases in $B_d \rightarrow J/\Psi K^*$ and $B_s \rightarrow J/\Psi \varphi$ cannot be exactly related in the SU(3) limit due to the singlet component of φ. Although the sign of cos $\delta_{1,2}$ obtained using SU(3) is consistent with the factorization estimate, to be conservative we reintroduce the ambiguity in the DØ measurement. To this end, we take the errors quoted by DØ as Gaussian and duplicate the likelihood at the point obtained by applying the discrete ambiguity. Indeed, looking at Fig. 2 of ref. [61], this seems a reasonable procedure. Hopefully DØ will present results without assumptions on the strong phases in the future, allowing for a more straightforward combination. Finally, for the CKM parameters we perform the UT analysis in the presence of arbitrary NP as described in ref. [34], obtaining $\bar{\rho}$ = 0.140 ± 0.046, $\bar{\eta}$ = 0.384 ± 0.035 and sin $2\beta_s$ = 0.0409 ± 0.0038. The new input parameters used in our analysis are summarized in Table 1, all the others are given in Ref. [34]. The relevant NLO formulae for $\Delta\Gamma_s$ and for the semileptonic asymmetries in the presence of NP have been already discussed in refs. [34,62,63].

The results of our analysis are summarized in Table 2. We see that the phase ϕ_{B_s} deviates from zero at 3.7σ. We comment below on the stability of this significance. In Fig. 1 we present the two-dimensional 68% and 95% probability regions for the NP parameters C_{B_s} and ϕ_{B_s}, the corresponding regions for the parameters A_s^{NP}/A_s^{SM} and ϕ_s^{NP}, and the one-dimensional distributions for NP parameters. Notice that the ambiguity of the tagged analysis of $B_s \rightarrow J/\Psi \varphi$ is slightly broken by the presence of the CKM-subleading terms in the expression of Γ_{12}/M_{12} (see for example eq. (5) of ref. [63]). The solution around $\phi_{B_s} \sim$ -20° corresponds to $\phi_s^{NP} \sim$ -50° and $A_s^{NP}/A_s^{SM} \sim 75\%$. The second solution is much more distant from the SM and it requires a dominant NP contribution ($A_s^{NP}/A_s^{SM} \sim 190\%$). In this case the NP phase is thus very well determined. The strong phase ambiguity affects the sign of cos φ_s and thus Re A_s^{NP}/A_s^{SM}, while Im $A_s^{NP}/A_s^{SM} \sim$ - 0.74 in any case.

Before concluding, we comment on our treatment of the DØ result for the tagged analysis and on the stability of the NP fit. Clearly, the procedure to reintroduce the strong phase ambiguity in the DØ result and to combine it with CDF is not unique given the available information. In particular, the Gaussian assumption can be questioned, given the likelihood profiles shown in Ref. [61]. Thus, we have tested the significance of the NP signal against different modeling of the probability density function (p.d.f.). First, we have used the 90% C.L. range for φ_s = [-0.06, 1.20]°
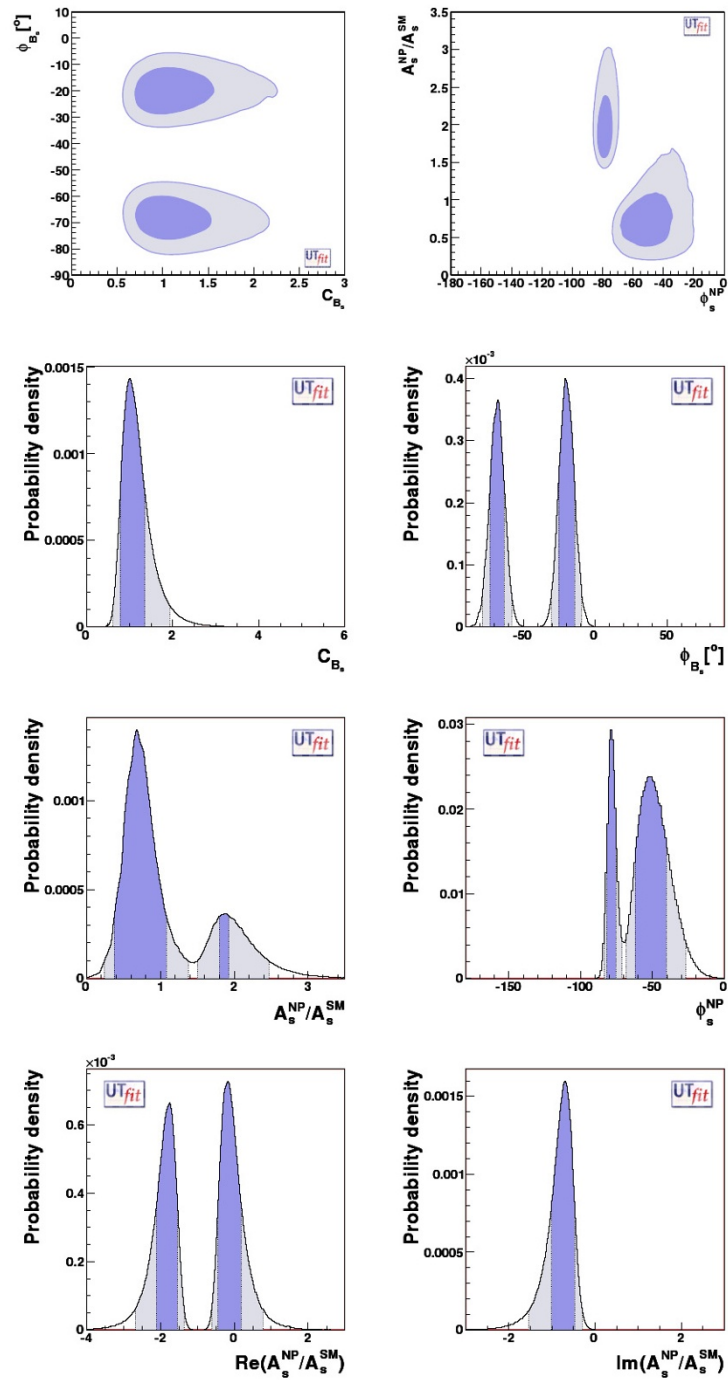
Figure 1

From left to right and from top to bottom, 68% (dark) and 95% (light) probability regions in the ϕ_{B_s}

- A_{SL}^s, A_s^{NP}/A_s^{SM} - ϕ_s^{NP} planes and p.d.f for C_{B_s}, ϕ_{B_s}, A_s^{NP}/A_s^{SM}, ϕ_s^{NP}, Re A_s^{NP}/A_s^{SM}, Im

A_s^{NP}/A_s^{SM}.

Table 2: Fit results for NP parameters, semileptonic asymmetries and width differences.

Observable	68% Prob.	95% Prob.
ϕ_{B_s} [°]	-19.9 ± 5.6	[-30.45,-9.29]
C_{B_s}	-68.2 ± 4.9	[-78.45,-58.2]
	1.07 ± 0.29	[0.62,1.93]
ϕ_s^{NP} [°]	-51 ± 11	[-69,-27]
A_s^{NP} / A_s^{SM}	-79 ± 3	[-84,-71]
	0.73 ± 0.35	[0.24,1.38]
	1.87 ± 0.06	[1.50,2.47]
Im A_s^{NP} / A_s^{SM}	-0.74 ± 0.26	[-1.54,-0.30]
Re A_s^{NP} / A_s^{SM}	-0.13 ± 0.31	[-0.61,0.78]
	-1.82 ± 0.28	[-2.68,-1.36]
$A_{SL}^s \times 10^2$	-0.34 ± 0.21	[-0.75,0.03]
$A_{SL}^{\mu\mu} \times 10^3$	-2.1 ± 1.0	[-4.7,-0.3]
$\Delta\Gamma_s/\Gamma_s$	0.105 ± 0.049	[0.02,0.20]
	-0.098 ± 0.044	[-0.19,-0.02]

Whenever present, we list the two solutions due to the ambiguity of the measurements. The first line corresponds to the one closer to the SM.

given by DØ to estimate the standard deviation, obtaining $\varphi_s = (0.57 \pm 0.38)$° as input for our Gaussian analysis. This is conservative since the likelihood has a visibly larger half-width on the side opposite to the SM expectation (see Fig. 2 of Ref. [61]). Second, we have implemented the likelihood profiles for φ_s and $\Delta\Gamma_s$ given by DØ, discarding the correlations but restoring the strong phase ambiguity. The likelihood profiles include the second minimum corresponding to $\varphi_s \to \varphi_s + \pi$, $\Delta\Gamma \to -\Delta\Gamma$, which is disfavoured by the oscillating terms present in the tagged analysis and is discarded in our Gaussian analysis. Also this approach is conservative since each one-dimensional profile likelihood is minimized with respect to the other variables relevant for our analysis. It is remarkable that both methods give a deviation of ϕ_{B_s} from zero of 3 σ (the 3 σ ranges for ϕ_{B_s} are [-88, -48]° $\cup$ [-41, 0]° and [-88, 0]° for the two methods respectively). We conclude that the combined analysis gives a stable evidence for NP, although the precise number of standard deviations depends on the procedure followed to combine presently available data.

To illustrate the impact of the experimental constraints, we show in Fig. 2 the p.d.f. for ϕ_{B_s} obtained without the tagged analysis of $B_s \to J/\Psi\varphi$ or including only CDF or DØ results. Including only the CDF tagged analysis, we obtain $\phi_{B_s} < 0$ at 97.7% probability (2.3σ). For DØ, we show results obtained with the Gaussian and likelihood profile treatment of the errors. In the
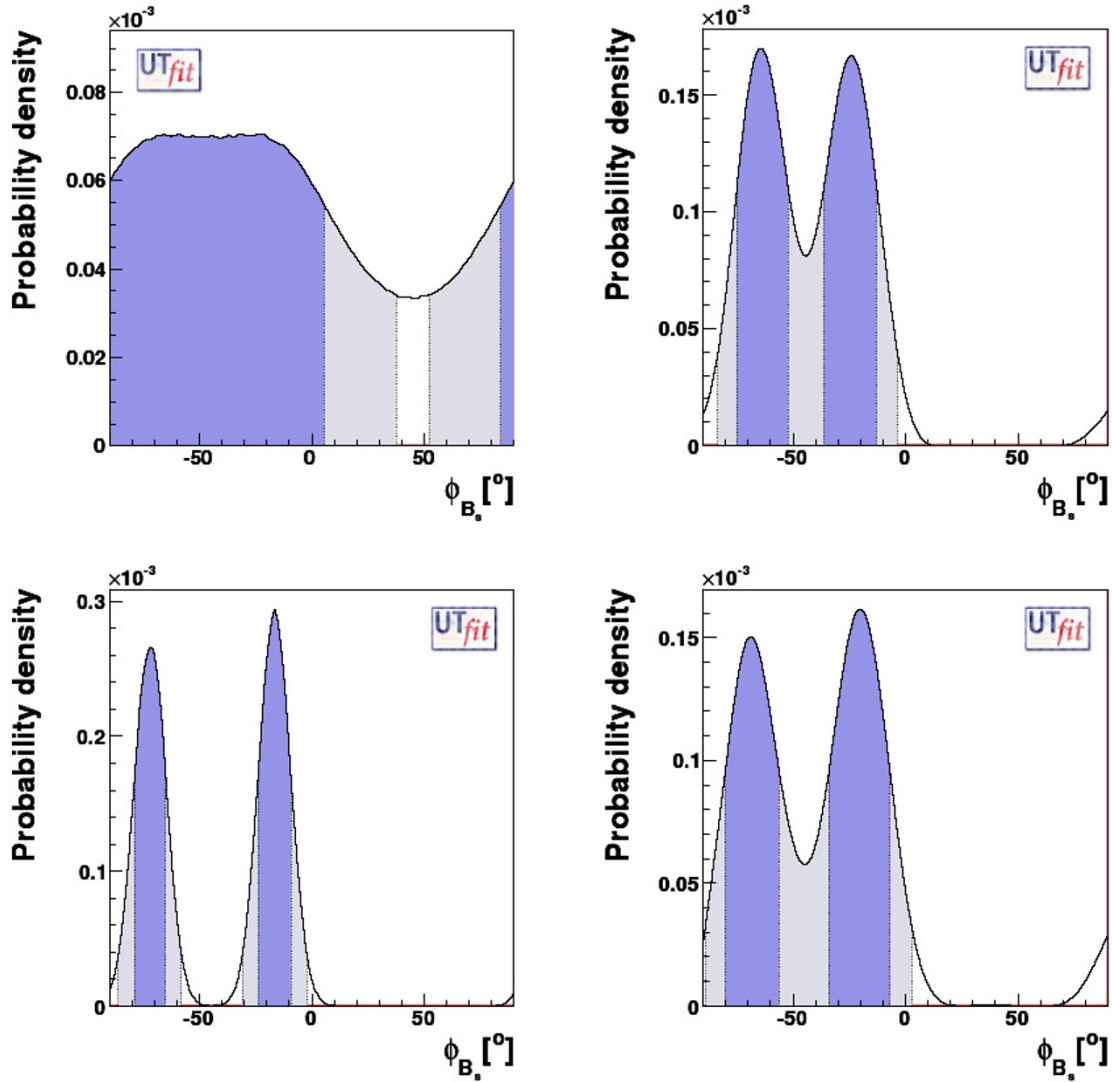
Figure 2
From left to right: P.d.f. for ϕ_{B_s} without the tagged analysis of $B_s \rightarrow J/\Psi\varphi$, including only the CDF analysis, including only the DØ Gaussian analysis, including only the DØ likelihood profiles. We show 68% (dark) and 95% (light) probability regions.

Gaussian case, the DØ tagged analysis gives $\phi_{B_s} < 0$ at 98.0% probability (2.3σ), while using the likelihood profiles $\phi_{B_s} < 0$ at 92.8% probability (1.8σ). Finally, it is remarkable that the different constraints in Fig. 2 are all consistent among themselves and with the combined result. We notice, however, that the top-left plot is dominated by the measurement of $A_{SL}^{\mu\mu}$ while A_{SL}^s

favours positive ϕ_{B_s}, although with a very low significance. For completeness, in Table 2 we also quote the fit results for A_{SL}^s, $A_{SL}^{\mu\mu}$ and for $\Delta\Gamma_s/\Gamma_s$.

In this Letter we have presented the combination of all available constraints on the B_s mixing amplitude leading to a first evidence of NP contributions to the CP-violating phase. With the procedure we followed to combine the available data, we obtain an evidence for NP at more than 3σ. To put this conclusion on firmer grounds, it would be advisable to combine the likelihoods of the tagged $B_s \to J/\Psi\varphi$ angular analyses obtained without theoretical assumptions. This should be feasible in the near future. We are eager to see updated measurements using larger data sets from both the Tevatron experiments in order to strengthen the present evidence, waiting for the advent of LHCb for a high-precision measurement of the NP phase.

It is remarkable that to explain the result obtained for φ_s, new sources of CP violation beyond the CKM phase are required, strongly disfavouring the MFV hypothesis. These new phases will in general produce correlated effects in $\Delta B = 2$ processes and in $b \to s$ decays. These correlations cannot be studied in a model-independent way, but it will be interesting to analyse them in specific extensions of the SM. In this respect, improving the results on CP violation in $b \to s$ penguins at present and future experimental facilities is of the utmost importance.

2. Note added

During the review procedure of this Letter, results based on new data were presented by the Tevatron experiments, as well as a combination of Tevatron results on the tagged angular analysis of $B_s \to J/\psi\varphi$. However these updates are all unpublished. Furthermore, the likelihoods required by our analysis are not publicly available except for the new DØ analysis with no assumption on strong phases [64]. For the sake of completeness, we quote ϕ_{B_s} = (-19 ± 8)° ∪ (-69 ± 7)° ([-36, -5]° ∪ [-83, -54]° at 95% probability), obtained using this new likelihood for the DØ tagged angular analysis of $B_s \to J/\psi\varphi$. Clearly, we no longer need to manipulate the DØ likelihood to remove the strong phase assumption and to account for the non-Gaussian shape as described above. Remarkably, this updated result is well compatible with the results of this Letter, confirming a deviation from the SM at the level of ~3σ (99.6% probability). More recent experimental results seem to confirm the effect discussed in this Letter. We will include them in future analyses as soon as they become available.

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