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Matter-Antimatter Split Hints at Physics Breakdown

What's the matter with antimatter? New data may hold the answer.

By JR Minkel

Nature may have handed scientists a new clue in a longstanding mystery: how matter beat out antimatter for dominance of the universe. Early data from twin experiments at the Tevatron, the world's reigning particle accelerator at Fermi National Accelerator Laboratory (Fermilab) in Batavia, Ill., suggest an unexpected chink in the hugely successful standard model of particle physics.

The twist comes from odd behavior in a particle called the B_S (pronounced "B-sub-S"), which flips back and forth between its matter and antimatter forms three trillions times per second. Researchers believe that such a breakdown, known as CP violation, is required to explain why matter is so abundant.

Researchers say the finding is well worth following up to make sure it is not a random clump in the data, as frequently happens in particle physics experiments. "This is exciting, definitely," says physicist Jacobo Konigsberg of the University of Florida in Gainesville, cospokesperson for CDF, one of two detectors that may have glimpsed the effect.

Antimatter is well-known to science fiction fans as the stuff that explodes on contact with regular particles such as protons and electrons, which have the same mass as their antiparticles but the opposite charge. The hot, early universe contained equal parts matter and antimatter. Yet somehow, as the cosmos cooled, matter was not completely annihilated.

Researchers strongly suspect that the key to this riddle lies in the weak nuclear force, which governs radioactive decay, along with more exotic reactions created in particle accelerators. In nearly all cases, matter obeys something called CP symmetry, which states that a particle ought to behave identically to the mirror image of its antiparticle. Not so when acted on by the weak nuclear force.

The amount of CP violation observed in experiments (and enshrined in the standard model), however, is far too little to explain why matter should have prevailed in its ancient war with antimatter. To get a clean look at CP symmetry, DZero and its sibling detector, CDF, focus on the B_S, which consists of a bottom quark and a strange antiquark. (Quarks are components of protons and neutrons.) Working independently, the two detectors both found an extra dose of CP violation beyond what the standard model predicts.

Neither result on its own was very convincing, so a team of European researchers combined the data, similar to the way medical researchers cull information from independent clinical trials, to look for rare side effects. Together, the data make it 99.7 percent likely that the discrepancy is real, not due to chance, says physicist Luca Silvestrini of the National Institute for Nuclear Physics in Rome, who took part in the study submitted to *Physical Review Letters*.

Such analyses require making judgment calls, but Silvestrini says he is confident in the finding. "Everything points in the same direction, and so I think it's rather unlikely this is a statistical fluke," he says. Konigsberg says that if it is a fluke, that should become clear by the end of the summer as the Fermilab teams analyze more data.

Whether the hypothetical CP violation would fully explain matter's dominance over antimatter depends on the new physics that gave rise to it. According to theoretical physicist Robert Fleischer of CERN, the European Organization for Nuclear Research in Geneva, Switzerland, the simplest explanation would be a massive, photonlike particle similar to known members of the standard model and capable of interacting directly with bottom quarks and strange antiquarks.

Another possibility is supersymmetry, a proposed standard model extension that gives each known particle a heavier doppelganger, or super-partner. In that case, the B_S oscillations could feel indirect effects from different combinations of super-partners, Fleischer says.

He notes that if the effect is real, the Large Hadron Collider, set to become the world's top dog in particle smashers after it goes on line later this year near Geneva, should be able to quickly confirm it and then probe for the underlying particles. "By 2010," he says, "I'm sure we will know the final answer."

FIRST EVIDENCE OF NEW PHYSICS IN b $\leftrightarrow$ s TRANSITIONS

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We combine all the available experimental information on B_s mixing, including the very recent tagged analyses of $B_s \to J/\Psi\phi$ 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.

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]. 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) [2], 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% [3, 4]. 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 $b \to s$ 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 $b \to c\bar{c}s$ 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 $S_{c\bar{c}s}$ [5], while hadronic models predict a shift in the opposite direction in many cases [6, 7].

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 [8], and more generally models of Next-to-Minimal Flavour Violation [9], tend to produce too large effects in ε_K [10, 11]. 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 [12].

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. [13].

We perform a model-independent analysis of NP contributions to B_s mixing using the following parametrization [14]:

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

where $H_{\rm eff}^{\rm full}$ is the effective Hamiltonian generated by both SM and NP, while $H_{\rm eff}^{\rm SM}$ 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.[1]

Δm_s [ps^{-1}]	17.77 ± 0.12	[15]
$A_{\rm SL}^s \times 10^2$	2.45 ± 1.96	[16]
$A_{\rm SL}^{\mu\mu} \times 10^3$	-4.3 ± 3.0	[17, 18]
$\tau_{B_s}^{\rm FS}$ [ps]	1.461 ± 0.032	[19]
ϕ_s	`http://tinyurl.com/2f9rtl`	[20]
$\Delta\Gamma_s$	`http://tinyurl.com/2f9rtl`	[20]
ϕ_s [rad]	0.60 ± 0.27	[21]
$\Delta\Gamma_s$ [ps^{-1}]	0.19 ± 0.07	[21]
τ_{B_s} [ps]	1.52 ± 0.06	[21]
$C_{\phi_s,\Delta\Gamma_s} = -0.042$	$C_{\phi_s,\tau_{B_s}} = -0.571$	$C_{\tau_{B_s},\Delta\Gamma_s} = 0.23$

TABLE I: Input parameters used in the analysis. We also show the correlation coefficients Cs of the measurements of ϕ_s, $\Delta\Gamma_s$ and τ_{B_s} from ref. [21].

We use the following experimental input: the CDF measurement of Δm_s [15], the semileptonic asymmetry in B_s decays $A_{\rm SL}^s$ [16], the dimuon charge asymmetry $A_{\rm SL}^{\mu\mu}$ from DØ [17] and CDF [18], the measurement of the B_s lifetime from flavour-specific final states [19], the two-dimensional likelihood ratio for $\Delta\Gamma_s$ and $\phi_s = 2(\beta_s - \phi_{B_s})$ from the time-dependent tagged angular analysis of $B_s \to J/\psi\phi$ decays by CDF [20] and the correlated constraints on Γ_s, $\Delta\Gamma_s$ and ϕ_s from the same analysis performed by DØ [21]. 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 I of ref. [21]. 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 ($\phi_s \to \pi - \phi_s$, $\Delta\Gamma_s \to -\Delta\Gamma_s$, $\cos\delta_{1,2} \to -\cos\delta_{1,2}$) for arbitrary strong phases was removed using a value for $\cos\delta_{1,2}$ derived from the BaBar analysis of $B_d \to J/\Psi K^*$ using SU(3). However, the strong phases in $B_d \to J/\Psi K^*$ and $B_s \to J/\Psi\phi$ 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. [21], 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. [10], obtaining $\bar\rho = 0.140 \pm 0.046$, $\bar\eta = 0.384 \pm 0.035$ and $\sin 2\beta_s = 0.0409 \pm 0.0038$. The new input parameters used in our analysis are summarized in Table I, all the others are given in Ref. [10]. The relevant NLO formulae for $\Delta\Gamma_s$ and for the semileptonic asymmetries in the presence of NP have been already discussed in refs. [10, 22, 23].

[1] We are using the usual CKM phase convention in which $V_{cs}V_{cb}^*$ is real to a very good approximation.

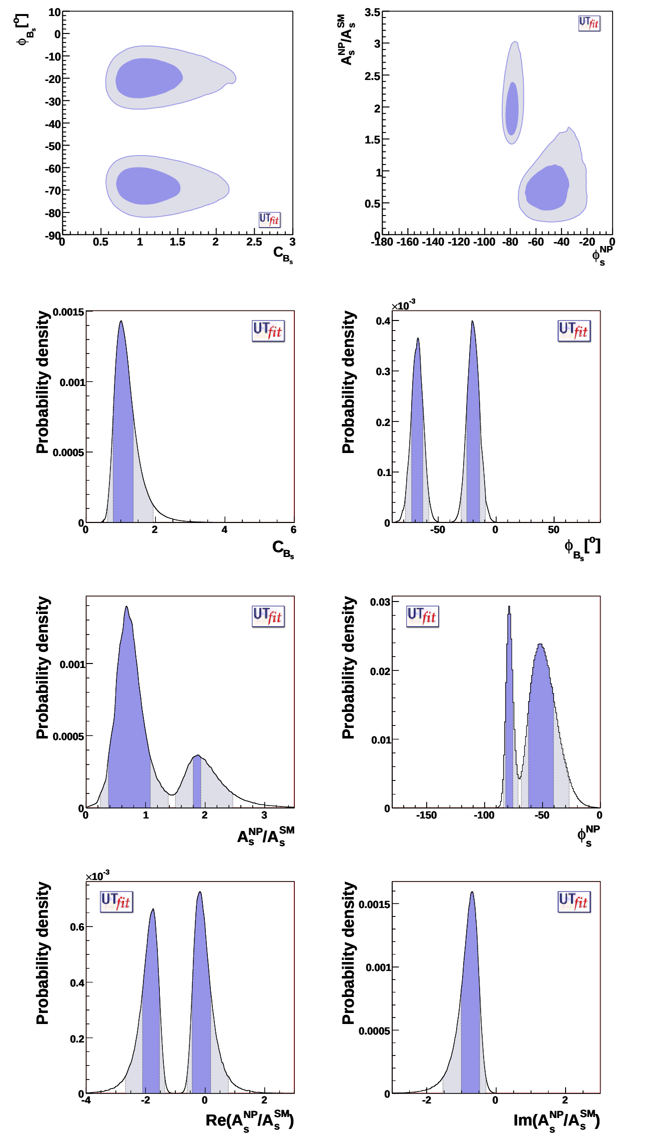

FIG. 1: From left to right and from top to bottom, 68% (dark) and 95% (light) probability regions in the $\phi_{B_s} - C_{B_s}$, $A_s^{\rm NP}/A_s^{\rm SM} - \phi_s^{\rm NP}$ planes and p.d.f for C_{B_s}, ϕ_{B_s}, $A_s^{\rm NP}/A_s^{\rm SM}$, $\phi_s^{\rm NP}$, Re $A_s^{\rm NP}/A_s^{\rm SM}$, Im $A_s^{\rm NP}/A_s^{\rm SM}$.

The results of our analysis are summarized in Table II. We see that the phase ϕ_{B_s} deviates from zero at

Observable	68% Prob.	95% Prob.
$\phi_{B_s}[^\circ]$	-19.9 ± 5.6	[-30.45,-9.29]
	-68.2 ± 4.9	[-78.45,-58.2]
C_{B_s}	1.07 ± 0.29	[0.62,1.93]
$\phi_s^{\mathrm{NP}}[^\circ]$	-51 ± 11	[-69,-27]
	-79 ± 3	[-84,-71]
$A_s^{\mathrm{NP}}/A_s^{\mathrm{SM}}$	0.73 ± 0.35	[0.24,1.38]
	1.87 ± 0.06	[1.50,2.47]
Im $A_s^{\mathrm{NP}}/A_s^{\mathrm{SM}}$	-0.74 ± 0.26	[-1.54,-0.30]
Re $A_s^{\mathrm{NP}}/A_s^{\mathrm{SM}}$	-0.13 ± 0.31	[-0.61,0.78]
	-1.82 ± 0.28	[-2.68,-1.36]
$A_{\mathrm{SL}}^s \times 10^2$	-0.34 ± 0.21	[-0.75,0.03]
$A_{\mathrm{SL}}^{\mu\mu} \times 10^3$	-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]

TABLE II: Fit results for NP parameters, semileptonic asymmetries and width differences. 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.

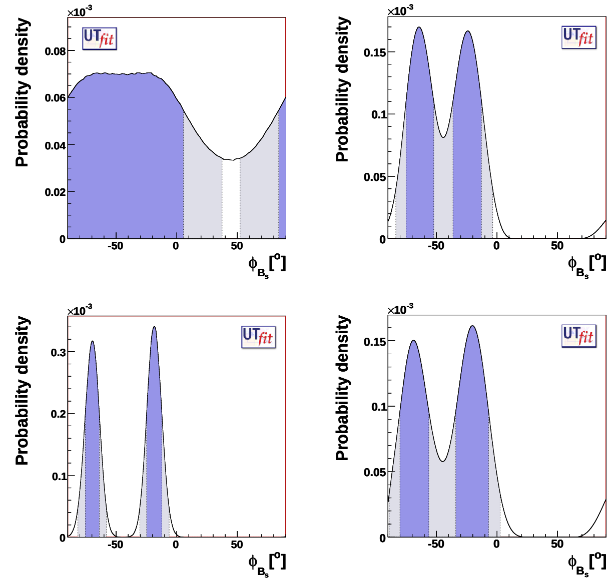

FIG. 2: P.d.f. for ϕ_{B_s} without the tagged analysis of $B_s \to J/\Psi\phi$ (top left), including only the CDF analysis (top right), including only the DØ Gaussian analysis (bottom left), including only the DØ likelihood profiles (bottom right). We show 68% (dark) and 95% (light) probability regions.

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 $A_s^{\mathrm{NP}}/A_s^{\mathrm{SM}}$ and ϕ_s^{NP}, and the one-dimensional distributions for NP parameters. Notice that the ambiguity of the tagged analysis of $B_s \to J/\Psi\phi$ 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. [23]). The solution around $\phi_{B_s} \sim -20^\circ$ corresponds to $\phi_s^{\mathrm{NP}} \sim -50^\circ$ and $A_s^{\mathrm{NP}}/A_s^{\mathrm{SM}} \sim 75\%$. The second solution is much more distant from the SM and it requires a dominant NP contribution ($A_s^{\mathrm{NP}}/A_s^{\mathrm{SM}} \sim 190\%$). In this case the NP phase is thus very well determined. The strong phase ambiguity affects the sign of $\cos\phi_s$ and thus Re $A_s^{\mathrm{NP}}/A_s^{\mathrm{SM}}$, while Im $A_s^{\mathrm{NP}}/A_s^{\mathrm{SM}} \sim -0.74$ 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. [21]. 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 $\phi_s = [-0.06, 1.20]^\circ$ given by DØ to estimate the standard deviation, obtaining $\phi_s = (0.57 \pm 0.38)^\circ$ 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. [21]). 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 $\phi_s \to \phi_s + \pi$, $\Delta\Gamma \to -\Delta\Gamma$, 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 $3\,\sigma$ (the $3\,\sigma$ ranges for ϕ_{B_s} are $[-88, -48]^\circ \cup [-41, 0]^\circ$ and $[-88, 0]^\circ$ 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 $B_s \to J/\Psi\phi$ or including only CDF or DØ results. In particular, we show the DØ result with the Gaussian and likelihood profile treatment of the errors. In the Gaussian case, the DØ tagged analysis gives the strongest bounds, while using the likelihood profiles CDF and DØ give similar constraints. It is remarkable that the different measurements are all consistent among themselves and with the combined result.

For completeness, in Table II we also quote the fit results for A_{SL}^s, $A_{\mathrm{SL}}^{\mu\mu}$ 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 $B_s \to J/\Psi\phi$ 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.

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