CP **Violation in** B_s^0 **Mesons**

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The B_s^0 meson is a bound state of b and s type quark. A CP violation parameter, β_s, of that system is the analogue of the parameter β measured precisely at the B factories in B^0 decays. The standard model predicts, robustly and precisely, a value of β_s which is very close to zero. The CDF and D0 experiments now have about 2000 fully reconstructed and flavor-tagged $B_s^0 \to J/\psi\phi$ decays each, with which they set new experimental bounds on β_s. A combination of results from CDF and D0 is consistent with the standard model at only the 2.2 σ level. If the discrepancy is not a statistical fluctuation, it would indicate new sources of CP violation.

1. Introduction

For many years, the neutral kaon system was the only place in which the violation of CP symmetry was observed[1]. The last decade has witnessed an intensive effort to record and interpret as many cases of CP violation in neutral and charged b mesons as possible. The CDF and D0 experiments now, for the first time, are able to extend the search for CP violation to the neutral B_s^0 meson. This system combines observable fast particle-antiparticle oscillations familiar from the B^0 system, with an observable separation into distinct lifetime states best known from the neutral kaon system. CP violation in the B_s^0 system, the subject of this paper, contains some elements resembling CP violation in the kaon system, and others that resemble CP violation in the B^0 system.

One of the manifestations of the large CP violation in the neutral B^0 is the CP asymmetry in certain decays such as $B^0 \to J/\psi K_s^0$. This CP asymmetry is characterized by the angle

$$\beta = \arg\left(-\frac{V_{cd}V_{cb}^*}{V_{td}V_{tb}^*}\right) \qquad (1)$$

of the unitarity triangle, shown in Fig. 1. The groundbreaking measurements[2, 3] of the angle β stand out from the other dozen or so other measurements of CP violation[4], because the measurement is experimentally clean and the prediction is largely free from theoretical uncertainties. In the neutral B_s^0 system, the same comments apply to the decay $B_s^0 \to J/\psi\phi$, where one can measure the quantity

$$\beta_s = \arg\left(-\frac{V_{ts}V_{tb}^*}{V_{cs}V_{cb}^*}\right), \qquad (2)$$

an angle of the "squashed" (bs) unitarity triangle (Fig. 2), whose standard model value is $\lambda^2\eta = 0.019 \pm 0.001$, where λ=0.2257$^{+0.0009}_{-0.0010}$ and η =0.349$^{+0.015}_{-0.017}$ are parameters of the CKM matrix[5]. It is measurable[6] in the decay $B_s^0 \to J/\psi\phi$, through the interference of mixing and decay. The measurement is sensitive to new physics, particularly if it affects the $t \to s$ transition. One such scenario is discussed in reference [7].

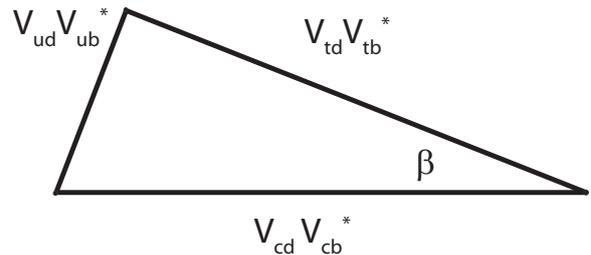Figure 1: The usual (bd) unitarity triangle, showing the angle β, measured precisely in decays like $B^0 \to J/\psi K_s^0$ at the B-Factories. All sides of this triangle are $\mathcal{O}(\lambda^3)$

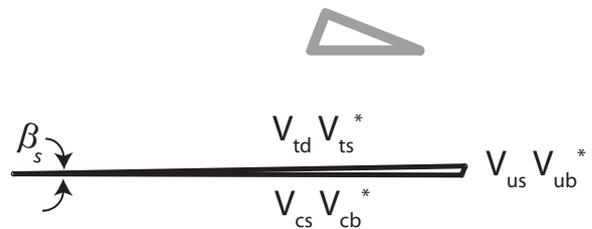Figure 2: The "squashed" (bs) unitarity triangle showing β_s, the angle at the most acute vertex of the triangle. This triangle has two sides of length O(λ^2) and a third side of length O(λ^4). For comparison the (bd) unitarity triangle is drawn, to scale, in light gray.

2. The decay $B_s^0 \to J/\psi\phi$

It is useful to think of the CP-mixed $J/\psi\phi$ as three distinct final states, characterized either by the orbital angular momentum of the two vector mesons J/ψ and ϕ, or by their relative polarization $\{0, \parallel, \perp,$

where the first symbol indicates longitudinal polarization vectors, the second indicates transverse polarization vectors which are mutually parallel, and the third indicates transverse polarization vectors which are mutually perpendicular. We designate the three states as $\mathcal{P}_0$, $\mathcal{P}_\parallel$ and $\mathcal{P}_\perp$ the first two being CP-even and the third CP-odd. It is also useful to think of the B_s^0 as two distinct initial states, the longlived "heavy" and shortlived "light" mesons:

$$|B_s^H\rangle = p\,|B_s^0\rangle - q\,|\bar{B}_s^0\rangle, \qquad |B_s^L\rangle = p\,|B_s^0\rangle + q\,|\bar{B}_s^0\rangle.$$

CP violation in this system presents itself in two ways. If $[H, CP] \neq 0$ then the long-and-shortlived mass eigenstates are *not* CP eigenstates and may decay to both CP even or CP odd final states. This is reminiscent of the neutral kaon system. Additionally, the expectation value $\langle CP \rangle$ from an initially pure B_s^0 or $\bar{B}_s^0$ evolves with time: $d\langle CP\rangle/dt \neq 0$. The time evolution is an oscillation with B_s^0 mixing frequency of Δm_s=17.77 $\pm$ 0.10 $\pm$ 0.07 ps^{-1}[8]. The time-dependent CP expectation reflects itself in a time-dependent polarization of the two vector mesons, and finally in a time variation of the angular distributions of their decay products. This is similar to the situation in the B^0 system, particularly in the $B \to VV$ decay $B^0 \to J/\psi K^{0*}$. The CDF and D0 analyses, which fit the differential rate of $B_s^0 \to J/\psi\phi \to \mu^+\mu^- K^+K^-$, have simultaneous sensitivity to both effects.

The time-dependent rates for initially pure B_s^0 and $\bar{B}_s^0$ are

$$P_B(\hat{n}, \psi, t) = \frac{9}{16\pi}|\mathbf{A}(\psi, t) \times \hat{n}|^2$$

$$P_{\bar{B}}(\hat{n}, \psi, t) = \frac{9}{16\pi}|\bar{\mathbf{A}}(\psi, t) \times \hat{n}|^2 \qquad (3)$$

[9] where $\hat{n}$ is the direction of the μ^+ in the rest frame of the J/ψ, ψ is the helicity angle in the ϕ decay, and $\mathbf{A}(\psi, t)$ and $\bar{\mathbf{A}}(\psi, t)$ are complex vectors[1], described below, reflecting the time-dependent polarization. A coordinate system is needed to express the vectors $\hat{n}$, $\mathbf{A}$, and $\bar{\mathbf{A}}$: two common choices are the *transversity basis*, and the *helicity basis*. The transversity basis has the x-axis along the ϕ direction in the rest frame of the B, the y-axis lying in the decay plane of the ϕ such that $P_y(K^+) > 0$, and $\hat{z} = \hat{x} \times \hat{y}$. The helicity basis is a cyclic permutation of the axes in the transversity basis: $\hat{x}_T = \hat{z}_H$, etc. CDF and D0 employ the transversity basis, in which $\hat{n} = (\sin\theta_T\cos\phi_T, \sin\theta_T\sin\phi_T, \cos\theta_T)$ and

$$\mathbf{A}(\psi, t) = (\mathcal{A}_0(t)\cos\psi, -\frac{\mathcal{A}_\parallel(t)\sin\psi}{\sqrt{2}}, i\frac{\mathcal{A}_\perp(t)\sin\psi}{\sqrt{2}})$$

$$\bar{\mathbf{A}}(\psi, t) = (\bar{\mathcal{A}}_0(t)\cos\psi, -\frac{\bar{\mathcal{A}}_\parallel(t)\sin\psi}{\sqrt{2}}, i\frac{\bar{\mathcal{A}}_\perp(t)\sin\psi}{\sqrt{2}})$$

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[1]Complex conjugation is implied in the square magnitude.

where the time dependence is contained in the term

$$\mathcal{A}_i(t) = A_i(0)\left[E_+(t) \pm e^{2i\beta_s}E_-(t)\right],$$
$$\bar{\mathcal{A}}_i(t) = A_i(0)\left[\pm E_+(t) + e^{-2i\beta_s}E_-(t),\right] \qquad (4)$$

where:

$$E_\pm(t) \equiv \frac{1}{2}\left[e^{+\left(\frac{-\Delta\Gamma_s}{4} + i\frac{\Delta m}{2}\right)t} \pm e^{-\left(\frac{-\Delta\Gamma_s}{4} + i\frac{\Delta m}{2}\right)t}\right].$$

Two strategies can be pursued. One can measure the differential rates given in Eq. 3, without attempting to distinguish B_s^0 from $\bar{B}_s^0$, effectively summing the rates over both species. Or, one can try to measure the differential rates for B_s^0 and $\bar{B}_s^0$ separately, using a technique called flavor tagging.

Eq. 3 contains a lot of hidden richness, including a measurable width difference between two mass eigenstates, CP asymmetries that are measurable in a flavor-tagged analysis, with simultaneous sensitivity to *both* $\sin 2\beta_s$ and $\cos 2\beta_s$. Even without flavor tagging, a residual sensitivity to CP violation is present. This arises partly due to the ability to detect the decay of the shortlived, nominally CP-even mass eigenstate to the CP-odd polarization states (and vice-versa), which was historically the basis of the first observation of CP violation. And partly it arises from the interference between the even and odd polarization states of the vector mesons, which are, in fact "intermediate", not "final" states. Even in case $[H, CP] = 0$, the differential rates in Eq. 3 have a sensitivity to B_s^0-$\bar{B}_s^0$ oscillations, though neither experiment can exploit it with present statistics.

3. Detector Effects and their Impact

In each event one measures, in addition to the proper decay time t, the kinematic quantities $\cos\psi$, $\cos\theta_T$, and ϕ_T. Three significant detector effects alter the theoretical model (Eq. 3). First, measurement uncertainty smears significantly the oscillatory time dependence of the rates. Second, the flavor tagging algorithms in use at the Tevatron give very limited discrimination between B_s^0 and $\bar{B}_s^0$ mesons. Third, the detector acceptance alters the angular distributions in Eq. 3. The first two effects limit the measurements, while the second does not have a significant impact if properly accounted for.

Flavor tagging is an essential ingredient for many studies of B mixing and CP violation. Flavor tagging endeavors to determine, from the tracks lying near to, or opposite from, a reconstructed meson, the flavor of that meson (B^0 or $\bar{B}^0$, B_s^0 or $\bar{B}_s^0$) at production. In a decay of a neutral b-meson to a flavor-specific final state, the flavor at production could be different from the flavor at decay, while, in a decay to a CP eigenstate like $J/\psi\phi$, the flavor at decay is undetermined.
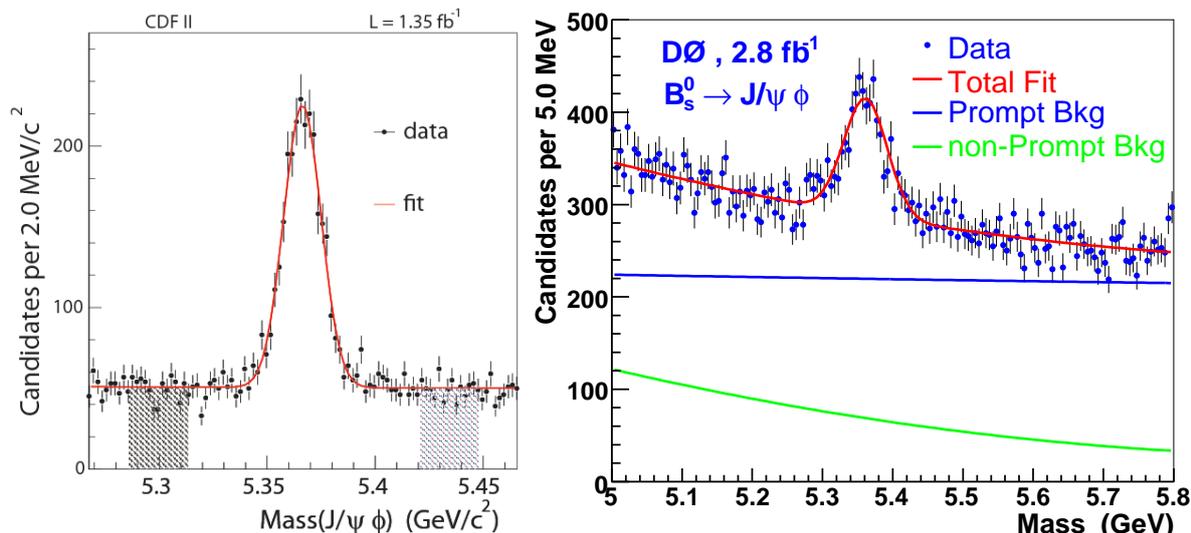
Figure 3: Data samples for the CDF tagged analysis of $B_s^0 \to J/\psi\phi$. The CDF experiment reports 2019±73 events while the D0 experiment reports 1967 ± 65 events.

Three independent flavor-tagging algorithms are currently in use at CDF and D0; these are categorized as *same-side* tagging or *opposite-side* tagging algorithms. Same-side tagging establishes[10], on a statistical basis, the b-hadron flavor through its correlation with the charge of nearby fragmentation tracks. Two varieties of opposite side tagging establish the flavor of the b-hadron on the away side, from which one infers the flavor of the near side b-meson. Opposite side lepton tagging uses a soft lepton on the away side, while opposite side jet charge tagging uses the charge of a jet on the away side. The efficiency ϵ of any tagging algorithm is the fraction of the events to which it can be applied.

The tagging algorithm also estimates its uncertainty. The tag decision being a discrete variable, the uncertainty is quantified by the dilution $D = (R - W)/(R + W)$ where R is the frequency of a right decision and W is the frequency of a wrong decision. The effective tagging efficiency, ϵD^2, is the figure-of-merit for a tagging algorithm and can be related directly[11] to the expected uncertainty in mixing and CP asymmetry measurements[2]. Despite rather different tracking and particle identification technologies, CDF and D0 both report very similar effective tagging efficiencies, $\epsilon D^2 \approx 4.7\%$ in D0 and $\epsilon D^2 \approx 4.8\%$ in CDF.

Another important feature of the detector systems used in the analysis is their proper time resolution. In a mixing or CP measurement, proper time resolution

further degrades the uncertainty on CP asymmetries by the factor[3] $\exp\left(-(\Delta m_s \sigma_t)^2/2\right)$. Both CDF and D0 now employ low-mass, small-radius silicon detectors called "Layer 00", mounted directly on the beampipe, to achieve the best possible resolution, under 25 μm in both experiments. This is discussed more fully in reference[12].

The differential rates in Eq. 3 are sensitive to the CP phase β_s, the decay width difference $\Delta\Gamma_s$, the mean lifetime $\bar{\tau}_s = 2/(\Gamma_H + \Gamma_L)$, and the amplitudes $A_\perp(0)$, $A_\parallel(0)$, and $A_0(0)$, with phases $\delta_\perp$, $\delta_\parallel$, and zero, normalized such that $|A_0(0)|^2 + |A_\parallel(0)|^2 + |A_\perp(0)|^2 = 1$. An expansion of Eq. 3 is convolved with event-by-event proper time resolution, adjusted for detector acceptance and re-normalized according to one of several schemes. In the tagged analyses, event-per-event dilutions are also incorporated into the probability densities.

The simultaneous transformation $\beta_s \to \pi/2 - \beta_s$, $\Delta\Gamma_s \to -\Delta\Gamma_s$, $\delta_\parallel \to 2\pi - \delta_\parallel$, and $\delta_\perp \to \pi - \delta_\perp$, is an exact symmetry of the differential rates, so, decays of $B_s^0 \to J/\psi\phi$ alone cannot resolve the corresponding ambiguity. This symmetry is an experimental headache, and has a significant impact on results from the experiments, particularly since, with presently available statistics, the two solutions are not well separated. Untagged analyses possess an even a higher degree of symmetry, since the simultaneous transformation $\delta_\perp \to \pi + \delta_\perp$, $\beta_s \to -\beta_s$ is also an exact symmetry.

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[2]However, since the analyses we describe are not purely measurements of a CP asymmetry, one cannot use the formula $\delta(A_{cp}) = \sqrt{2/\epsilon D^2 N}$, developed for that purpose.

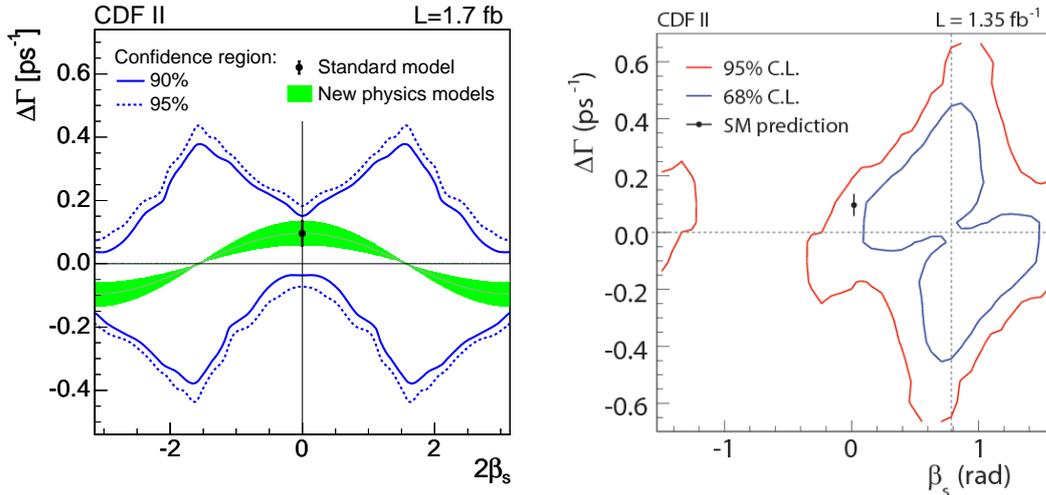[3]As before, the formula is not directly applicable in these analyses.

Figure 4: Confidence regions in the space of parameters $\Delta\Gamma_s$ and β_s, from 1.7 fb^{-1} of untagged data (left) and 1.35 fb^{-1} of flavor tagged data (right). The green band corresponds to new physics models, as described in the text.

4. Results

CDF performs an analysis without flavor tagging on a 1.7 fb^{-1} sample of data[13], and with flavor tagging[14] on a 1.35 fb^{-1} sample. The former is used for SM fits ($\beta_s = 0$) and CP fits ($\beta_s \neq 0$), while the latter is used only for CP fits. D0 performs both SM and CP fits to a 2.8 fb^{-1} sample of tagged data[15]. Mass distributions of the signals from the two experiments are shown in Fig. 3. In the CDF untagged analysis, the SM fit obtains the results shown in Table I. This set includes an important measurement of $\Delta\Gamma_s$, as well as an interesting measurement $\bar{\tau}_s$, consistent with the HQET expectation[16] that $\bar{\tau}_s = (1.00\pm0.01)\cdot\tau_0$ where $\tau_0 = 1.530\pm 0.009$ ps is the world average B^0 lifetime. The amplitudes are consistent with those measured[17, 18] in the related decay $B^0 \to J/\psi K^{0*}$. Point estimates are not obtained for the strong phases, since the measurement is insensitive to $\delta_\perp$ for $\beta_s = 0$ while for $\delta_\parallel$ the likelihood is nonparabolic (a result of the symmetries referred to in section 3). CP fits in the untagged analysis, do not yield point estimates for any of the physics parameters. They do give, however, a Feldman-Cousins confidence region[19] shown in Fig. 4 (left). One can see that the bounds agree with the standard model (the p-value is 22%, or 1.2 Gaussian standard deviations). Also shown in Fig. 4 (left) is the "new physics" expectation, based on the theoretical value of the decay matrix element $2|\Gamma_{12}^s| = 0.096\pm 0.039$ ps^{-1}[20], plus the assumption of mixing-induced CP violation. The confidence region is in good agreement with this assumption, and cannot rule out any value of the CP phase. The fourfold symmetry of the confidence region is apparent. In the CDF tagged analysis, shown in Fig. 4 (right), this symmetry is broken quite strongly, and

about half of the parameter space for β_s is ruled out. The p-value for the standard model is 15%. Statistical uncertainty dominates the measurement. A frequentist incorporation of systematic uncertainties[21] is included in the contour.

Table I Standard model fits in the CDF untagged analysis.

Parameter	CDF Measurement (untagged)
$\bar{\tau}_s = 2/(\Gamma_H + \Gamma_L)$	$1.52 \pm 0.04\pm0.02$ ps
$\Delta\Gamma_s = \Gamma_H - \Gamma_L$	$0.076 \, ^{+0.059}_{-0.063}\pm0.006$ ps^{-1}
$|A_0|^2$	$0.531 \pm0.020 \pm0.007$
$|A_\perp(0)|^2$	$0.239 \pm0.029 \pm0.011$
$|A_\parallel(0)|^2$	$0.230 \pm0.026 \pm0.009$

The D0 experiment employs a different strategy for dealing with the twofold ambiguity in the tagged analysis. They constrain the strong phases $\delta_\parallel$ and $\delta_\perp$ to the world average values[22] in the related decay $B^0 \to J/\psi K^{*0}$, within a Gaussian uncertainty of $\pm\pi/5$. Some recent theoretical work provides justification for this approach: in reference [23] the phases in the two systems are estimated to be equal within ten degrees. Results of the constrained fits are shown in Table II. Three types of fit are performed: a standard model fit, a CP fit, and the new physics (NP) fit, using the previously discussed NP constraint. The quantities $\bar{\tau}_s$, and the decay amplitudes are consistent with expectations and with CDF's measurement. D0 uses $\phi_s^{J/\psi\phi}$, the equivalent to $-2\beta_s$ in Eq. 4 as their CP violation parameter[4]. Likelihood profiles in the space

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[4]The nomenclature $\phi_s^{J/\psi\phi}$ has recently been invented to des-

of $(\phi_s^{J/\psi\phi}, \Delta\Gamma_s)$, as well as in $\phi_s^{J/\psi\phi}$ and $\Delta\Gamma_s$ separately, are shown in Fig. 5. D0 gives point estimates $\phi_s^{J/\psi\phi} = $ -0.57 $^{+0.24}_{-0.30}$ (stat) $^{+0.07}_{-0.02}$ (syst) and $\Delta\Gamma_s$=0.19 $\pm$ 0.07 (stat) $^{+0.02}_{-0.01}$ (syst) ps^{-1}, based upon their CP-fit. Using simulation, D0 finds for the standard model a p-value of 6.6%. The apparent discrepancy (or fluctuation) goes in the same direction as CDF.
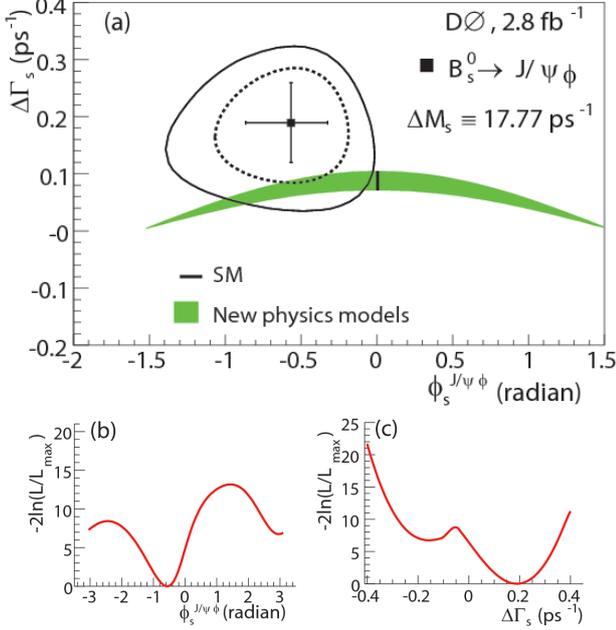

Figure 5: D0's confidence regions in the $\Delta\Gamma_s - \phi_s^{J/\psi\phi}$ plane. Shown are the 68.3% C.L. (dashed) and 90% C.L. contours, and the expectation from the standard model (black vertical line) and mixing-induced CP violation from new physics sources (green band). Below are one-dimensional likelihood profiles for $\phi_s^{J/\psi\phi}$ and $\Delta\Gamma_s$.

Table II Results of fits to the $B_s^0 \to J/\psi\phi$ from the D0 collaboration. In the first column is the CP fit; in the second column is the SM fit, and in the third column is the NP fit. See the text for further explanation.

Parameter	D0 CP	D0 SM	D0 NP
$\bar{\tau}_s$ (ps)	1.52 ± 0.06	1.53 ± 0.06	1.49 ± 0.05
$\Delta\Gamma_s$ (ps)$^{-1}$	0.19 ± 0.07	0.14 ± 0.07	0.083 ± 0.018
$A_\perp(0)$	0.41 ± 0.04	0.44 ± 0.04	0.45 ± 0.03
$|A_0(0)|^2 - |A_\parallel(0)|^2$	0.34 ± 0.05	0.35 ± 0.04	0.33 ± 0.04
$\delta_1 = \delta_\perp - \delta_\parallel$	-0.52 ± 0.42	-0.48 ± 0.45	-0.47 ± 0.42
$\delta_2 = \delta_\perp - \delta_0$	3.17 ± 0.39	3.19 ± 0.43	3.21 ± 0.40
$\phi_s^{J/\psi\phi}$	-0.57$^{+0.24}_{-0.30}$	≡ -0.04	-0.46 ± 0.28

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ignate this quantity, in order to distinguish it from the ϕ_s that we soon define, and from $-2\beta_s$ which by definition does not include new physics sources of mixing-induced CP violation.

5. Semileptonic Asymmetry

Models with extra sources of mixing-induced CP violation can have small amounts of CP violation in the mixing (defined as $|q/p| \neq 1$). An observable quantity called the semileptonic asymmetry

$$A_{SL}^s = \frac{d\Gamma/dt\left[\bar{B}_s^0 \to l^+X\right] - d\Gamma/dt\left[B_s^0 \to l^-X\right]}{d\Gamma/dt\left[\bar{B}_s^0 \to l^+X\right] + d\Gamma/dt\left[B_s^0 \to l^-X\right]}$$

related to $|q/p|$ through the definition

$$A_{SL}^s = \frac{1 - |q/p|^4}{1 + |q/p|^4}$$

can be measured using semileptonic decays. In B_s^0 mesons a phase $\phi_s = \arg(M_{12}/\Gamma_{12})$, where M_{12} is a mass-matrix element and Γ_{12} is a width matrix element, governs the size of the asymmetry through the approximate relation (see Ref. [20])

$$A_{SL}^s = \left|\frac{\Gamma_{12}^s}{M_{12}}\right| \sin\phi_s.$$

The phase ϕ_s differs from $\phi_s^{J/\psi\phi}$ by a small shift, negligible compared to experimental resolution. Since

$$\left|\frac{\Gamma_{12}^s}{M_{12}^s}\right| = (49.7 \pm 9.4) \times 10^{-4},$$

this asymmetry can hardly be more than about half a percent. Disregarding any theoretical input to $|\Gamma_{12}^s|$ while applying the relation $\Delta m_s = 2|M_{12}^s|$ and the NP constraint that $\Delta\Gamma_s = 2|\Gamma_{12}^s| \times \cos\phi_s$ one obtains

$$A_{SL}^s = \frac{\Delta\Gamma_s}{\Delta m_s} \tan\phi_s.$$

In constraining such models, then, one can choose as input either $|\Gamma_{12}^s|$, or a measured value of A_{SL}^s, or both. CDF, using dimuon pairs in 1.6 fb^{-1} of data, measures $A_{sl}^s = 0.020 \pm 0.028$[24] while D0, using both dimuon pairs and decays $B_s^0 \to \mu\nu D_s$ with $D_s \to \phi\pi$ from 1.1 fb^{-1} of data, measures $A_{SL}^s = 0.0001 \pm 0.0090$[25]. At this level of precision, the theory value of $|\Gamma_{12}^s|$ is a more powerful constraint than the experimental value of A_{SL}^s, on new physics models.

6. Combined results

The analyses of $B_s^0 \to J/\psi\phi$ from CDF and D0 are compatible with each other, and with the the standard model at only the 15% C.L. (CDF) and the 6.6% C.L.(D0). Following a new analysis of the D0 data, in which the strong phase constraints were dropped, the HFAG group has combined the two analyses. Details of the procedure can be found in Ref. [26]. The combined contours are shown in Fig. 6. The p-value for the combined result is 3.1%, corresponding to 2.2 Gaussian standard deviations.
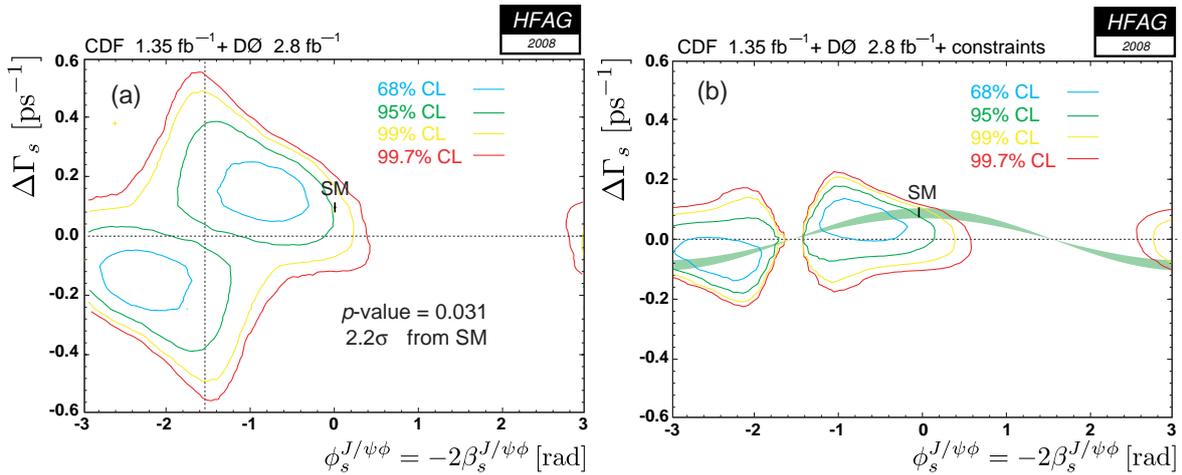
Figure 6: HFAG Combinations of the D0 tagged analysis and the CDF tagged analysis. The standard model is consistent with this data at the 2.2 σ confidence level. The plot on the right makes use of the semileptonic asymmetry A_{SL}^s

7. Conclusion

Discrepancy? Or fluctuation? Today, the only known source of CP violation in the physics of elementary particles is the CKM mechanism, arising from the Higgs-Yukawa sector of the three-generation standard model. A firmly established discrepancy between the predicted value of β_s and the standard model value would imply new sources of CP violation, possibly from heavier particles out of the reach of today's accelerators. It could have a broader impact as well, and shed light on the baryon asymmetry of the universe. Unfortunately, with the present uncertainty (statistical, mostly) and at the present significance (2.2 σ) the question is not yet settled.

Acknowledgments

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