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CP Violation in $B_s^0 \to J/\psi\phi$ at the Tevatron

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I review the history and present status of *CP* violation measurments made during Run II of the Fermilab Tevatron. Both flavor-tagged and untagged measurements of the *CP*-violating phase $\beta_s^{J/\psi}$ are discussed, as well as measurments of the width difference $\Delta\Gamma_s$ between heavy and light B_s^0 mass eigenstates made in the $B_s^0 \to J/\psi\phi$ system.

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1. History of $B_s^0 \to J/\psi\phi$ measurements

The first measurement made in the $B_s^0 \to J/\psi\phi$ system during Run II of the Fermilab Tevatron immediately drew attention with an unexpectedly large measurement of the width difference $\Delta\Gamma_s$ between heavy and light B_s^0 mass eigenstates: $\Delta\Gamma_s \equiv \Gamma_L - \Gamma_H$. This measurement, made with 203 ± 15 $B_s^0 \to J/\psi\phi$ candidate events that were observed in the first 270 pb^{-1} of integrated luminosity collected with the CDF II detector, found an approximately two sigma discrepancy with the standard model expectation of $\Delta\Gamma_s/\Gamma_s \approx 0.1$, obtaining $\Delta\Gamma_s/\Gamma_s = 0.65^{+0.25}_{-0.33}$ ps^{-1} [1]. Such a large values of $\Delta\Gamma_s$, if true, would have implied a $B_s^0 - \bar{B}_s^0$ oscillation frequency of $\Delta m_s \equiv m_H - m_L \sim 125$ ps^{-1}, a matter of some interest before the observation of B_s^0 mixing in 2006 [2]. As the value of the B_s^0 mixing frequency was unknown, a comparatively simple parameterization that made use of the standard model assumption that the CP-violating phase $\beta_s^{J/\psi} \approx 0$ is negligible [3], was used to determine the width difference in an unbinned maximum likelihood fit:

$$\frac{d^4\mathscr{P}(\vec{\rho},t)}{dtd\vec{\rho}} \propto |A_0|^2 e^{-\Gamma_L t} f_1(\vec{\rho}) + |A_\parallel|^2 e^{-\Gamma_L t} f_2(\vec{\rho}) + |A_\perp|^2 e^{-\Gamma_H t} f_3(\vec{\rho}) + \Re(A_0^* A_\parallel) e^{-\Gamma_L t} f_5(\vec{\rho})$$

where the amplitudes $|A_0|^2$, $|A_\parallel|^2$, and $|A_\perp|^2$ and angles $\vec{\rho} = \cos\theta, \phi, cos\psi$ are defined in the transversity basis [4]. Six functions of transversity angles $f_1(\vec{\rho})...f_6(\vec{\rho})$ that describe the decay of a pseudo-scalar meson to a two vector meson final state are also defined [4], although only four survive in the $B_s^0 \to J/\psi\phi$ system without the inclusion of the mixing frequency and CP-violating phase $\beta_s^{J/\psi}$. However, in the $B^0 \to J/\psi K^{*0}$ system, all six functions of transversity angles are present. The higher candidate yield available in the $B^0 \to J/\psi K^{*0}$ decay, as well as independent measurements by the B factories, provided a valuable cross-check of the fit to the transversity angles. Good agreement between the $B_s^0 \to J/\psi\phi$ and $B^0 \to J/\psi K^{*0}$ transversity angle fit projections and transversity amplitudes was observed, although statistical precision was limited. Thus the "mystery" of the large observed width difference remained.

The D0 collaboration soon made an independent measurement of $\Delta\Gamma_s/\Gamma_s$ using 470 pb^{-1} of integrated luminosity and found agreement both with the standard model and the previous CDF result: $\Delta\Gamma_s/\Gamma_s = 0.24^{+0.28}_{-0.38}$ ps^{-1} [5]. Shortly after this measurement, D0 included the $\beta_s^{J/\psi}$ phase in an untagged likelihood fit that did not depend on the value of Δm_s to a dataset encompassing 1 fb^{-1} of integrated luminosity. The likelihood was now expanded to include all six functions of transversity angles:

$$\begin{aligned}\frac{d^4\mathscr{P}(\vec{\rho},t)}{dtd\vec{\rho}} \propto\ & |A_0|^2 \mathscr{T}_+ f_1(\vec{\rho}) + |A_\parallel|^2 \mathscr{T}_+ f_2(\vec{\rho}) + |A_\perp|^2 \mathscr{T}_- f_3(\vec{\rho}) + |A_0||A_\parallel| \mathscr{T}_+ \cos(\delta_\parallel) f_5(\vec{\rho}) \\ & + |A_\parallel||A_\perp| \sin(2\beta_s^{J/\psi})(e^{-\Gamma_H t} - e^{-\Gamma_L t})/2 \cos(\delta_\perp - \delta_\parallel) f_4(\vec{\rho}) \\ & + |A_0||A_\perp| \sin(2\beta_s^{J/\psi})(e^{-\Gamma_H t} - e^{-\Gamma_L t})/2 \cos(\delta_\perp) f_6(\vec{\rho}),\end{aligned}$$

where $\mathscr{T}_\pm = [(1 \pm \cos(2\beta_s^{J/\psi}))e^{-\Gamma_L t} + (1 \mp \cos(2\beta_s^{J/\psi}))e^{-\Gamma_H t}]/2$. Without flavor tagging, a fourfold ambiguity in the determination of the phase $\beta_s^{J/\psi}$ exists. Allowing for the known transformations between the four solutions, the D0 collaboration quoted a point estimate of $\phi_s = -0.79 \pm 0.56$, where $\phi_s \equiv -2\beta_s^{J/\psi}$ [6], as well as point estimates for the B_s^0 lifetime $\tau(B_s^0) = 1.52 \pm$

0.08 (stat)$^{+0.01}_{-0.03}$ (syst) ps and width difference $\Delta\Gamma_s = 0.17 \pm 0.09$ (stat) ± 0.02 (syst) ps^{-1} [7]. Although the value of the *CP* phase observed was large, the value of the width difference was in good agreement with the standard model expectation of $\Delta\Gamma_s = 0.096$ ps^{-1} [3], while agreement with the CDF collaboration's high central value was not as good.

However, further study by the CDF collaboration soon indicated that the situation was not so straight-forward and did not permit point estimates to be readily quoted when $\beta_s^{J/\psi}$ was included in the likelihood fit as a freely floating parameter. In particular, point estimates appeared to be possible in a limited statistics regime when $\beta_s^{J/\psi}$ was fixed to zero, but significant biases in the fitted results for $\beta_s^{J/\psi}$ and $\Delta\Gamma_s$ were observed in pseudo-experiments when $\beta_s^{J/\psi}$ was allowed to float. Consequently, the CDF collaboration chose to quote confidence regions in the $\beta_s^{J/\psi} - \Delta\Gamma_s$ plane in the general case where $\beta_s^{J/\psi}$ floated freely and point estimates for the B_s^0 lifetime, width difference, and transversity amplitudes when $\beta_s^{J/\psi}$ was fixed to zero in the likelihood fit [8]. The B_s^0 lifetime obtained in 1.7 fb^{-1} of integrated luminosity was $\tau(B_s^0) = 1.52 \pm 0.04$ (stat) ± 0.02 (syst) ps and the width difference obtained, $\Delta\Gamma_s = 0.076^{+0.059}_{-0.063}$ (stat) ± 0.006 (syst) ps^{-1}, came into good agreement with both the D0 collaboration's result and the standard model.

While untagged *CP*-phase measurements were being developed and understood, a major breakthrough occurred to facilitate *CP*-violation measurements in the B_s^0 system. In the summer of 2006, the CDF collaboration observed $B_s^0 - \bar{B}_s^0$ oscillations and precisely determined the mixing frequency, $\Delta m_s = 17.77 \pm 0.12$ ps^{-1} [2], while also validating the same side kaon tagging (SSKT). This development permitted the inclusion of flavor tagging in the likelihood fit for $\beta_s^{J/\psi}$:

$$
\begin{aligned}
\frac{d^4P(t,\vec{\rho})}{dtd\vec{\rho}} \propto\; & |A_0|^2\mathscr{T}_+ f_1(\vec{\rho}) + |A_\parallel|^2\mathscr{T}_+ f_2(\vec{\rho}) \\
+\; & |A_\perp|^2\mathscr{T}_- f_3(\vec{\rho}) + |A_\parallel||A_\perp|\mathscr{U}_+ f_4(\vec{\rho}) \\
+\; & |A_0||A_\parallel|\cos(\delta_\parallel)\mathscr{T}_+ f_5(\vec{\rho}) \\
+\; & |A_0||A_\perp|\mathscr{V}_+ f_6(\vec{\rho}).
\end{aligned}
$$

The probability $\bar{P}$ for $\bar{B}_s^0$ is obtained by substituting $\mathscr{U}_+ \to \mathscr{U}_-$ and $\mathscr{V}_+ \to \mathscr{V}_-$. The time-dependent term $\mathscr{T}_\pm$ is defined as

$$
\begin{aligned}
\mathscr{T}_\pm = e^{-\Gamma t} \;\times\; & [\cosh(\Delta\Gamma t/2) \mp \cos(2\beta_s)\sinh(\Delta\Gamma t/2) \\
& \mp \eta \sin(2\beta_s)\sin(\Delta m_s t)],
\end{aligned}
$$

where $\eta = +1$ for P and -1 for $\bar{P}$. The other time-dependent terms are defined as

$$
\begin{aligned}
\mathscr{U}_\pm = \pm e^{-\Gamma t} \;\times\; & \left[\sin(\delta_\perp - \delta_\parallel)\cos(\Delta m_s t)\right. \\
& - \cos(\delta_\perp - \delta_\parallel)\cos(2\beta_s)\sin(\Delta m_s t) \\
& \pm \left.\cos(\delta_\perp - \delta_\parallel)\sin(2\beta_s)\sinh(\Delta\Gamma t/2)\right], \\
\mathscr{V}_\pm = \pm e^{-\Gamma t} \;\times\; & [\sin(\delta_\perp)\cos(\Delta m_s t) \\
& - \cos(\delta_\perp)\cos(2\beta_s)\sin(\Delta m_s t) \\
& \pm \cos(\delta_\perp)\sin(2\beta_s)\sinh(\Delta\Gamma t/2)].
\end{aligned}
$$

The additional terms in the time-dependence removed one of the exact symmetries present in the untagged fit, leaving only one symmetric solution in the determination of $\beta_s^{J/\psi}$ and $\Delta\Gamma_s$:

$$2\beta_s^{J/\psi} \to \pi - 2\beta_s^{J/\psi}$$

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$$\Delta\Gamma_s \to -\Delta\Gamma_s$$
$$\delta_\parallel \to 2\pi - \delta_\parallel$$
$$\delta_\perp \to \pi - \delta_\perp.$$

The CDF collaboration again quoted a confidence region in the $\beta_s^{J/\psi} - \Delta\Gamma_s$ plane and found a 1.5σ discrepancy with the standard model prediction [9] that agreed closely with the trend observed in the untagged results from the CDF and D0 collaborations. Although the true symmetry is known and could, in principle, be removed by restricting one of the strong phases such that only one solution is possible, CDF found that for "low" statistics (*i.e.* less than $\approx 10,000$ $B_s^0 \to J/\psi\phi$ signal events), an approximate symmetry remains that cannot be readily removed without severe restriction on the strong phases.

The D0 collaboration soon followed the CDF collaboration and released their own flavor-tagged measurement. In this measurement D0 attempted to remove the approximate symmetry by tightly restricting the strong phases $\delta_\parallel$ and $\delta_\perp$ to lie within $\pi/5$ of the values measured in the $B^0 \to J/\psi K^{*0}$ system [10]. Although this is clearly a choice that can be made, the similarity or difference of the strong phases between the $B^0 \to J/\psi K^{*0}$ and $B_s^0 \to J/\psi\phi$ system is presently a matter of debate.

2. Present $B_s^0 \to J/\psi\phi$ results

In the summer of 2008, the CDF collaboration released a flavor-tagged measurement in which the dataset analyzed was increased from 1.3 fb^{-1} to 2.8 fb^{-1}. As the particle identification was not able to be calibrated for the full dataset at that time, the increase in $B_s^0 \to J/\psi\phi$ yield was somewhat less than double that of the previous result, with roughly 3200 $B_s^0 \to J/\psi\phi$ candidate events compared with about 2000 events in the previous iteration of the analysis. The SSKT was also not included in the second half of the data, as it depends heavily on particle ID. The point estimates for the B_s^0 lifetime and width difference obtained without flavor tagging and assuming $\beta_s^{J/\psi} = 0$ show good agreement with the previous results: $\tau(B_s^0) = 1.53 \pm 0.04$ (stat) ± 0.01 (syst) ps and $\Delta\Gamma_s = 0.02 \pm 0.05$ (stat) ± 0.01 (syst) ps^{-1} [11]. Additionally, a 1.8σ deviation from the standard model, shown in Fig. 1, is observed.

The current D0 collaboration result also uses 2.8 fb^{-1} of integrated luminosity and finds a similar discrepancy with the standard model [12]. D0 recently included systematic uncertainties on Δm_s in their analysis, which leads to an increase in the area of their contours, shown in Fig. 2. The D0 collaboration also quotes point estimates in an untagged fit for the fit parameters with $\beta_s^{J/\psi}$ fixed to zero and finds good agreement between the $B_s^0 \to J/\psi\phi$ and $B^0 \to J/\psi K^{*0}$ systems [13].

A recent combination of the CDF and D0 results indicates a discrepancy with the standard model of 2.1σ [14], shown in the left plot of Fig. 3. This result is intriguing, both because its presence would be a clear indication of new physics [3] and because of the similarity between the two experimental results. The deviation from Gaussian errors is still present in both experiments, as can be seen in the right plot of Fig. 3, but is expected to lessen considerably as data is added to the measurements. Once a Gaussian error regime is established, perhaps with roughly 6,000 or 7,000 $B_s^0 \to J/\psi\phi$ events per experiment, less rigorous adjustments to the contours to properly cover the quoted confidence region will be necessary.

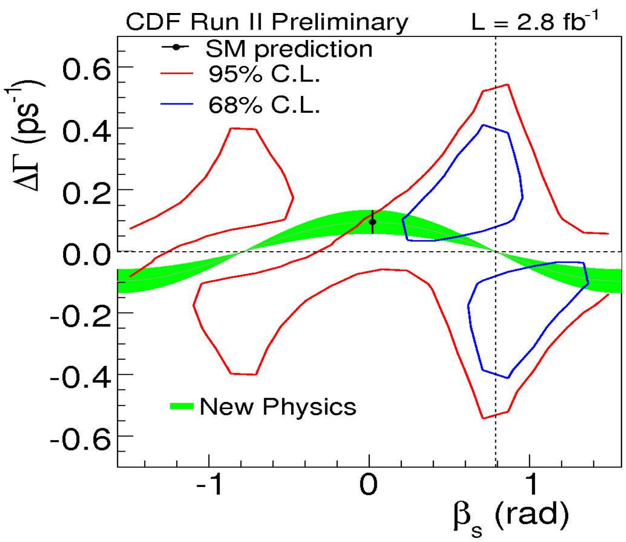

Figure 1: Feldman-Cousins confidence region in the $\beta_s^{J/\psi} - \Delta\Gamma_s$ plane, where the standard model-favored point is shown with error bars [3]. The intersection of the horizontal and vertical dotted lines indicates the reflection symmetry in the $\beta_s^{J/\psi} - \Delta\Gamma_s$ plane, while the green band indicates the region allowed by new physics models.

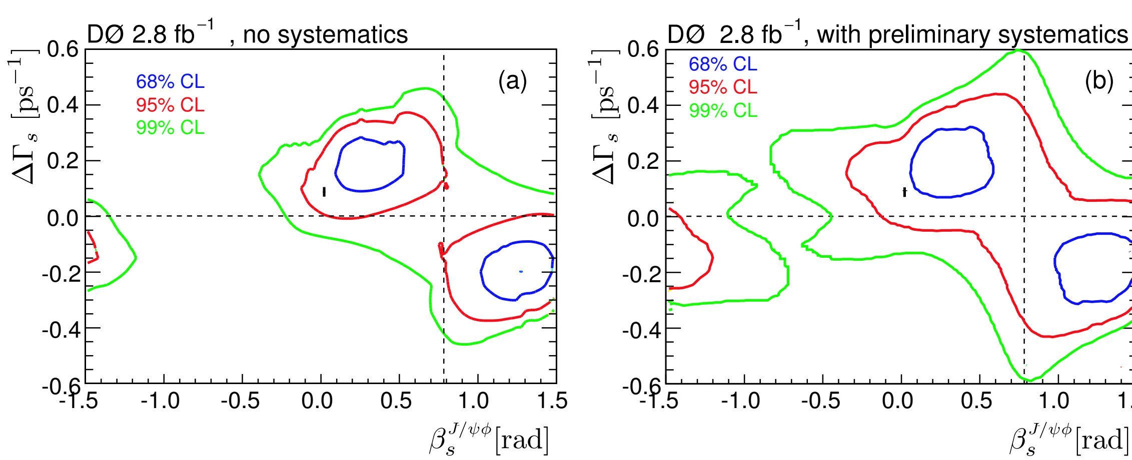

Figure 2: Confidence region in the $\beta_s^{J/\psi} - \Delta\Gamma_s$ plane, where the standard model-favored point is shown with error bars. The left plot indicates the result without systematic errors included, while the right plot shows the effect of including systematic errors on Δm_s. The intersection of the horizontal and vertical dotted lines indicates the reflection symmetry in the $\beta_s^{J/\psi} - \Delta\Gamma_s$ plane, while the green band indicates the region allowed by new physics models.

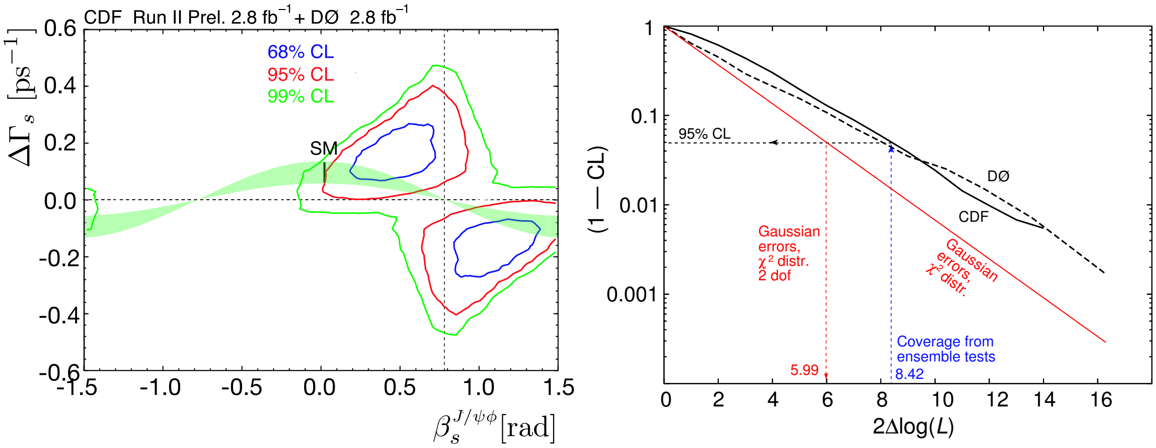

Figure 3: Combined CDF and D0 confidence region in the $\beta_s^{J/\psi} - \Delta\Gamma_s$ plane (left), where the standard model-favored point is shown with error bars. The right plot indicated the deviation of the individual experiments from a Gaussian error regime.

3. The future

What can be said of the future? Optimism is an intrinsic feature of human nature and there is no lack of it in the CDF and D0 experiments, likely with good reason. The $B_s^0 \to J/\psi\,\phi$ results that will come from the two experiments in the last years of the Tevatron should provide significant contributions to the field even as we enter the LHC era and may possibly provide a glimpse of new physics that is waiting to be discovered at LHC. Presently, each experiment has collected over 6 fb^{-1} of luminosity, with more than 5 fb^{-1} of that good for B physics. Both experiments intend to use the full datasets available to their best advantage (*i.e.* including complete particle ID and flavor tagging for all updated results). They also plan to address the question of the non-resonant K^+K^- S-wave contribution to the ϕ mass. Finally, efforts are afoot to combine the two experimental results in a simultaneous likelihood fit, which would provide the most powerful combination and allow different statistical interpretations (*e.g.* Bayesian vs. frequentist) to be presented. Particle physicists the world over hope that the time for new physics discovery is nigh. Perhaps that time will arrive shortly within the $B_s^0 \to J/\psi\,\phi$ system.

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without mixing, $\beta_s^{J/\psi} = \arg\left(-\frac{V_{ts}V_{tb}^*}{V_{cs}V_{cb}^*}\right)$. These two phases can be treated as equivalent only in the presence of a large new physics phase that is expected to be significantly larger than either ϕ_s or $\beta_s^{J/\psi}$, both of which are approximately zero in the standard model.

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