B Physics @ the Tevatron

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1 Introduction

The Tevatron collider at Fermilab, operating at a center-of-mass energy of $\sqrt{s} = 1.96$ TeV has a huge $b\bar{b}$ production cross section (≈ 1 nb), which is about five orders of magnitude larger than the $b\bar{b}$ production rate at the B factories PEP and KEK, e^+e^- colliders running on the $Y(4S)$ resonance. In addition, only B^+ and B_d mesons are produced at $Y(4S)$, while higher mass b hadrons such as B_s, B_c, b baryons, B^* and p-wave B mesons are currently produced only at the Tevatron. In order to exploit the possibility to study those variety of heavy b hadrons in a busy hadronic environment, dedicated detector systems, triggers and reconstruction are crucial.
Both D0 and CDF are multipurpose detectors featuring high resolution tracking in a magnetic field and lepton identification. These detectors are symmetrical in polar and azimuthal angles around the interaction point, with approximate 4π coverage [1, 2]. The CDF and D0 experiments are able to trigger at hardware level on large track impact parameters. CDF exploits this trigger to collect a sample of fully reconstructed B mesons, substantially enhancing the potential of its B physics program. At D0 the displaced track trigger is for the time being only used at lower bandwidth, e.g. for b tagging of potential Higgs candidates. CDF has a dedicated particle identification system composed of a time-of-flight detector and dE/dx measurements in the drift-chamber, which allows kaon-pion separation of at least 1.5 σ throughout the whole momentum range. D0 has an excellent muon system and a tracking coverage in the forward region up to a pseudo-rapidity of $\eta = 2.5$.
About 3 fb^{-1} of data has been collected in the meantime by each of the both experiments. About 6-8 fb^{-1} are expected till the shutdown of the Tevatron end of 2009.

2 B Physics @ the Tevatron

The Tevatron has a rich B physics program, including several observations of heavy B hadrons and measurements of their branching ratios and lifetimes, such as Σ_b, B_s^{**}, Ξ_b, B_c and λ_b. Measurement of CP asymmetries in various decay channels, precision mass measurements and searches for rare decays such as $B_s \to \mu^+\mu^-$ and $B_s \to \phi\phi$ have been performed. Many analysis are for the moment still statistically

limited. However for most of them about a factor 4-6 more data is expected. Thus many more exciting results are to come soon.
At the Argus Symposium only a small selection of these results was presented. Within the context of the 20th anniversary of the discovery of B_d mixing, the focus was put on the mixing in the B_s system.

3 Observation of B_s Mixing

The probability $\mathcal{P}$ for a B_s meson produced at time $t = 0$ to decay as a B_s ($\overline{B_s}$) at proper time t > 0 is, neglecting effects from CP violation as well as possible lifetime difference between the heavy and light B_s^0 mass eigenstates, given by

$$\mathcal{P}_{\pm}(t) = \frac{\Gamma_s}{2} e^{-\Gamma_s t}[1 \pm \cos \Delta m_s t)], \tag{1}$$

where the subscript "+" ("-") indicates that the meson decays as B_s ($\overline{B_s}$). Γ_s is the average B_s decay width and Δm_s the mass difference of the heavy and light B_s mass eigenstates.
Oscillation has been observed and well established in the B_d system. The mass difference Δm_d is measured to be [3]

$$\Delta m_d = 0.505 \ \pm \ 0.005 \text{ ps}^{-1}. \tag{2}$$

In the B_s system oscillation has been observed, too. However till winter 2006 all attempts to measure Δm_s have only yielded a combined lower limit on the mixing frequency of $\Delta m_s > 14.5$ ps^{-1} @ 95 % confidence level (C.L.). Indirect fits constraint Δm_s to be below 24 ps^{-1} @ 95 % C.L. within the Standard Model (SM). In March 2006 the D0 collaboration presented the first double sided 90 % C.L. limit [4] and CDF shortly afterwards presented the first precision measurement of Δm_s, with a significance of the signal of about 3 σ at that time [5]. Just a few months later the CDF collaboration updated their result using the very same data, but improved analysis technics and announced the observation of the $B_s - \overline{B_s}$ mixing frequency [6]. In this chapter we will focus on this analysis, which is based on 1 fb^{-1} of data.

The canonical B mixing analysis proceeds as follows. The flavor of the B_s meson at decay time is determined from the charges of the reconstructed decay products in the final state. The proper is determined from the displacement of the B_s decay vertex with respect to the primary vertex, and the B_s transverse momentum. The transverse plane is here defined with respect to the proton beam. Finally, the so-called tagging algorithms deduce the B_s production flavor, in order to classify the meson as mixed or unmixed. Then the asymmetry can be measured:

$$\mathcal{A}(t) \equiv \frac{N(t)_{unmixed} - N(t)_{mixed}}{N(t)_{unmixed} + N(t)_{mixed}} = \mathcal{D} \cos(\Delta m_s t), \tag{3}$$

where $N(t)$ are the time-dependent rates for mixed and unmixed B_s decays. $\mathcal{D}$ is the so-called dilution, a damping term which is related to imperfect tagging. It is

defined as $\mathcal{D} = 1 - P_w$, where P_w is the probability for a wrong tag.
The significance $\mathcal{S}$ of a mixing signal is given by:

$$\mathcal{S} = \sqrt{\frac{\epsilon \mathcal{D}^2}{2}} \sqrt{\frac{S}{S+B}} e^{-\frac{(\Delta m_s \sigma_{ct})^2}{2}} \tag{4}$$

S and B are the rates of signal and background events respectively. $\epsilon \mathcal{D}^2$ is the figure of merit for the flavor tagging, where ϵ is the efficiency to actually apply a tag to a given B_s candidate. σ_{ct} is the proper decay time resolution. Especially at large Δm_s values a high proper time resolution is crucial for this analysis.

3.1 Signal Yields

CDF studied fully and partial reconstructed hadronic and semileptonic B_s candidates in events collected by the displaced track trigger. About 2000 candidates are fully reconstructed in the cleanest, so-called golden mode $B_s \to D_s(\phi\pi)\pi$. About 3200 partially reconstructed B_s candidates coming from $B_s \to D_s^*(\phi\pi)\pi$ and $B_s \to D_s(\phi\pi)\rho$ are reconstructed with the same signal signature. Those events have slightly worse proper decay time resolution, due to γ or π^0, which escaped reconstruction. 3600 B_s candidates are fully reconstructed in additional modes. Neural network technics have been used to enhance signal yield and to improve signal/background ratio.
A large sample of 61.500 semileptonic $B_s \to \ell D_s X$ candidates has been studied. Due to missing momentum of the non reconstructed particles in this decay a correction factor derived in Monte Carlo, has been applied to scale the ℓD_s momentum:

$$ct = \frac{L_{xy} M(B_s)}{p_T(B_s)} = \frac{L_{xy} M(B)}{p_T(\ell D_s)} * k. \tag{5}$$

The spread of the k factor distribution limits the proper time resolution. The invariant ℓD_s mass is a good variable, to split the data set in samples of different k factor distributions and thus to enhance the significance of the analysis. (Fig. 1).

3.2 Decay Length Resolution

One of the critical input to the analysis is the proper decay time resolution. It is the limiting factor of the sensitivity at large Δm_s values. σ_{ct} has been measured directly on data. CDF exploits prompt D decays plus tracks from the primary vertex to mimic all B decay topologies studied in this analysis. On an event-by-event basis, the decay time resolution is predicted, taking into account dependences on several variables, such as isolation, vertex χ^2 etc. The mean σ_{ct} for hadronic events is 26 μm and for semileptonic events about 45 μm.

3.3 Flavor Tagging

Two type of flavor tags can be applied: opposite-side and same-side tags. Opposite-side tags infer the production flavor of the B_s from the decay products of the B

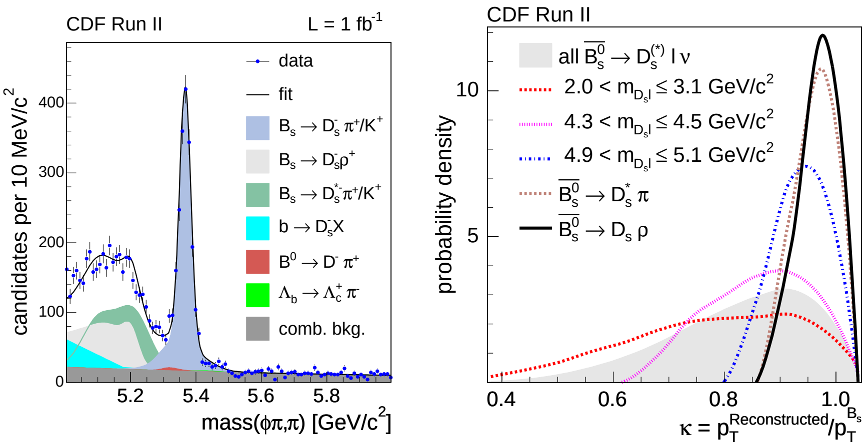


Figure 1: Left: Invariant mass of $B_s \to D_s(\phi\pi)\pi$ candidates. Right: k factor distribution for several ℓD_s mass values for semileptonic and partially reconstructed hadronic decays.

hadron produced from the other b quark in the event. A tagging performance of $\epsilon\mathcal{D}^2 = 1.8\%$ has been calibrated on kinematically similar B^+ and B_d decays. This value has to be compared to $\epsilon\mathcal{D}^2$ of about 30% at the B factories.
Same-side flavor tags are based on the charge of kaons produced in the fragmentation of the signal B_s meson. Contrary to the opposite-side tagging algorithms, its performance can not be calibrated on data. One has to rely on Monte Carlo samples till a significant B_s mixing signal has been established. Exploiting the particle identification system of the CDF detector, the same-side tagging algorithm yields a performance of $\epsilon\mathcal{D}^2 = 3.7/\ 4.8$ % for hadronic and semileptonic modes respectively. Thus the same-side tags enlarge the tagging power by a factor of 3-4!

3.4 Fit and Results

An unbinned maximum likelihood fit is utilized to search for $B_s - \overline{B_s}$ oscillations. The likelihood combines mass, proper decay time, proper decay time resolution and flavor tagging information for each candidate. Separate probability density functions are used to describe signal and each type of background. The amplitude scan method [7] was used to search for oscillations. This procedure corresponds to a Fourier transformation of the proper time space into the frequency space. In the case of infinite statistics and perfect resolution, it is expected to find an amplitude $\mathcal{A} = 1$ for the true value of Δm and $\mathcal{A} = 0$ otherwise.
The amplitude scan of the CDF data is consistent with unity around $\Delta m_s = 17.75$ ps^{-1} (Fig. 2). For all other Δm_s values, it is consistent with zero. Toy experiments evaluated the probability of tagged data to produce a maximum likelihood value higher than the one in data at any value of Δm_s. It was found to be smaller than 8 $\times$

10^{-8}, which corresponds to a 5.4 σ signal. The fit for Δm_s results in

$$\Delta m_s = 17.77 \ \pm \ 0.10 \text{ (stat.)} \ \pm \ 0.07 \text{ (syst) ps}^{-1}. \tag{6}$$

The dominant contributions to the systematic uncertainties come from uncertainties on the absolute scale of the decay time measurement.
The $B_s - \overline{B_s}$ oscillations are displayed in Fig. 2. Candidates in the hadronic sample are collected in five bins of proper decay time modulo $2\pi/\Delta m_s$. The curve corresponds to a cosine wave with amplitude equal to 1.28, which is the fitted value in the hadronic sample.

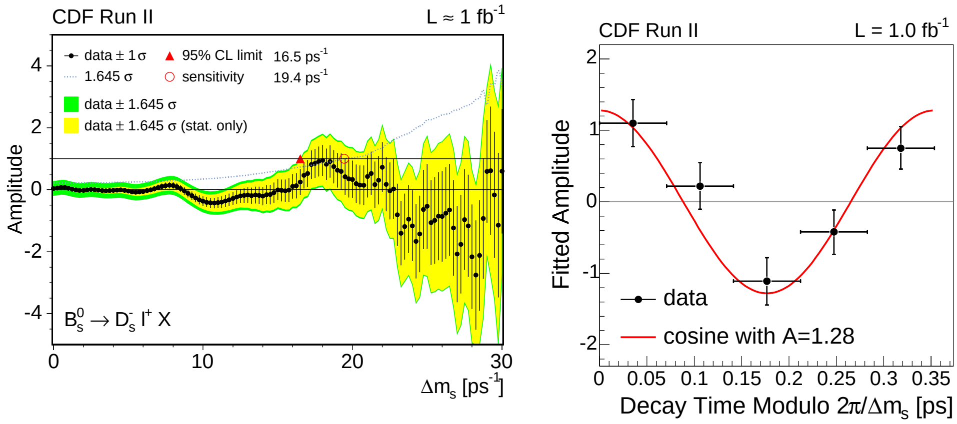


Figure 2: Left: Combined amplitude scan of hadronic and semileptonic modes. Right: The $B_s - \overline{B_s}$ oscillation signal (only hadronic modes) measured in five bins of proper decay time modulo the measured oscillation period $2\pi/\Delta m_s$. This plot does not contain the full statistic of this analysis.

4 B_s Lifetime Difference & Mixing Phase

Beside the mass difference Δm_s, there are two more parameters which determine the B_s system. Those are the decay width difference of the heavy and light B_s mass eigenstates $\Delta\Gamma_s = \Gamma_L - \Gamma_H$ and the mixing phase ϕ_s. While the first one is expected to be sizeable with in the SM ($\Delta\Gamma_s/\Gamma_s \approx 15\%$) the phase ϕ_s^{SM} is predicted to be small [8]. Thus to a good approximation the two mass eigenstates are CP eigenstates. New phenomena may introduce a non-vanishing mixing phase ϕ_s^{NP}, leading to a reduction of the observed $\Delta\Gamma_s$ compared to the SM prediction: $\Delta\Gamma_s = \Delta\Gamma_s^{SM} \times |\cos(\phi_s^{SM} + \phi_s^{NP})|$.
Several analysis have been performed at the Tevatron, to access $\Delta\Gamma_s$ and/or ϕ_s:
$B_s \to K^+K^-$ is a pure CP even state. Assuming a small CP violating phase, the measurement of the lifetime in this final state directly corresponds to the measurement of the lifetime of the B_s(light), which can then be compared to measurements of lifetimes in flavor specific eigenstates [3].
The untagged decay rate asymmetry in semileptonic B_s decays (A_{SL}^s) is another handle on the mixing parameters of the B_s system [9]:

$$A_{SL}^s = \frac{\Delta\Gamma_s}{\Delta m_s}\tan(\phi_s) \tag{7}$$

A third approach is the measurement of the branching ration of $B_s \to D_s^{(*)}D_s^{(*)}$. This decay is predominantly CP even [10] and gives the largest contribution in the lifetime difference between the B_s(heavy) and B_s(light). The following relation can be obtained [8]:

$$2 * BR(B_s \to D_s^{(*)}D_S^{(*)}) \approx \frac{\Delta\Gamma_s}{\cos(\phi_s)\Gamma_s}[1 + O(\frac{\Delta\Gamma}{\Gamma_s})]. \tag{8}$$

The decay $B_s \to J/\Psi\phi$, through the quark process $b \to c\bar{c}s$, gives rise to both CP even and CP odd final states. It is possible to separate the two CP components of this decay, and thus to measure the lifetime difference, through a simultaneous study of the time evolution and the angular distributions of the decay products of the J/Ψ and the ϕ meson. Moreover, with a sizeable lifetime difference, there is a sensitivity to the mixing phase through the interference terms between the CP even and CP odd waves. This later analysis is rather complex, however it is a very promising approach. The relatively high branching ratio of the decay $B_s \to J/\Psi\phi$ will allow a significant simultaneous measurement of $\Delta\Gamma_s$ and ϕ_s.

Both the CDF and D0 collaboration presented preliminary results of this analysis.
Figure 3 shows the projection of the fit result onto the proper decay time distribution and onto $\cos\theta$, one of the transversity angles[1] for the D0 analysis.
Both experiments demonstrated the capability to perform this analysis, however

[1]For a detailed definition of the transversity angles see [11]

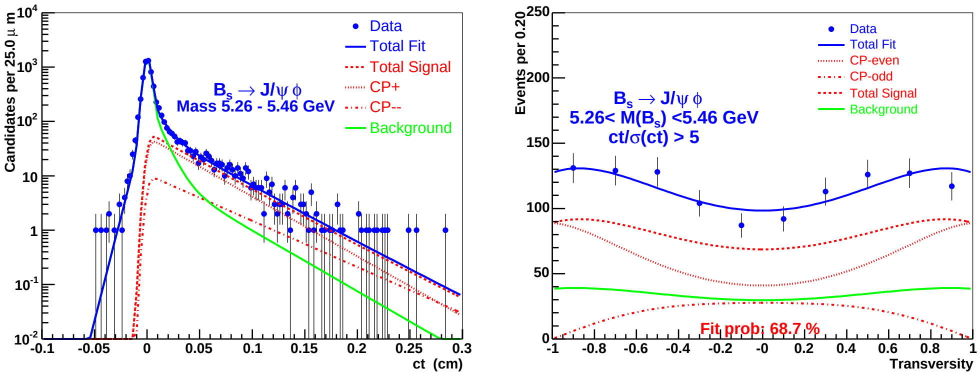


Figure 3: Lifetime and transversity angle distribution for CP even and CP odd $B_s \rightarrow J/\Psi\ \Phi$ decays of the D0 analysis.

sensitivity is still statistical limited by. While D0 performed a simultaneous fit of $\Delta\Gamma_s$ and ϕ_s, CDF quote only $\Delta\Gamma_s$ results with ϕ_s fixed to SM expectations:

$$\Delta\Gamma_s = 0.17 \pm 0.09\ (\text{stat.}) \pm 0.02\ (\text{syst.})\ \text{ps}^{-1}\ \ (\text{D0}) \tag{9}$$

$$\phi_s = -0.79 \pm 0.56\ (\text{stat.})^{+0.14}_{-0.01}\ (\text{syst.})\ \ (\text{D0}) \tag{10}$$

$$\Delta\Gamma_s = 0.076^{+0.059}_{-0.063}\ (\text{stat.}) \pm 0.006\ (\text{syst.})\ \text{ps}^{-1}\ \ (\text{CDF}) \tag{11}$$

The analysis are based on 1.7 and 1.0 fb^{-1} of data respectively. Figure 4 shows the allowed ranges in $\Delta\Gamma_s/\phi_s$ space. Improvement in this analysis will come from additional data and the use of flavour tagging. Performing the analysis separately for B_s and $\overline{B_s}$ candidates with the given flavour tagging performance will reduce the statistical uncertainties of the analysis by an additional factor of 1.5. If $\Delta\Gamma_s/\Gamma_s$ is around the expected value of 15%, the Tevatron experiments have a good chance to establish a significant non-zero $\Delta\Gamma_s$ before the LHCb will take over. However the first significant measurement of ϕ_s is most likely to be performed at LHCb.

5 Summary

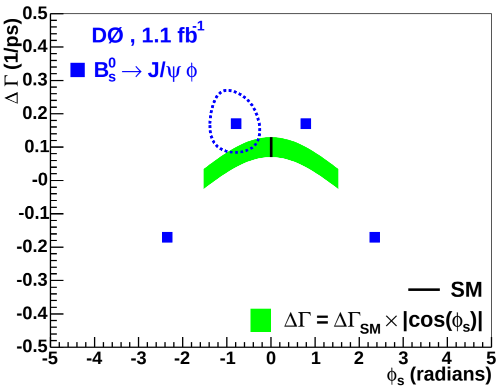
The Tevatron has a rich and exciting B physics program. The key to select interesting events out of the huge background in an hadronic environment is the trigger system.

CDF and D0 have proven the capability to perform high precision measurements at a hadron collider. Among those are the observation of the B_s mixing frequency:

$$\Delta m_s = 17.77 \pm 0.10\ (\text{stat.}) \pm 0.07\ (\text{syst})\ \text{ps}^{-1} \tag{12}$$

and the discovery of several B hadrons, such as Σ_b, Ξ_b and B_s^{**}.

Only a fifth of the data expected from the Tevatron has been analyzed sofar. Thus



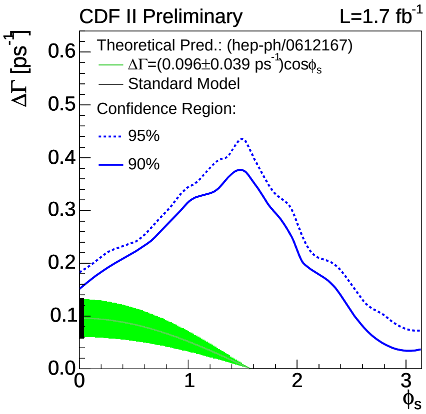


Figure 4: Allowed region for $\Delta\Gamma_s/\phi_s$ for the D0 (left) and CDF (right) analysis. In the left plot the contour corresponds to a 68% confidence region. The right plot shows only one solution of the four-folded ambiguity.

significant improvement in many statistical limited analysis, such as the measurement of $\Delta\Gamma_s$ are expected to come. For others such as the measurement of ϕ_s the Tevatron has proven their feasibility, however will pass over the field to the next generation of B physics experiments.

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