PROCEEDINGS OF SCIENCE

Mixing and CP Violation of the B_s at the Tevatron

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Recent results on B_s oscillations and CP violation parameters as performed by the CDF and D0 collaborations are presented.

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1. Introduction

The Tevatron is a heavy flavour factory that has produced large samples of B_s mesons allowing for in-depth study and measurement of the mixing and CP parameters Δm_s, Γ_s, a^s_{sl}. This paper presents measurements of B_s mixing, a^s_{sl} using same-sign dimuon events and an analysis of $B_s \to D_s^- \mu^+ X$ decays, and $\Delta\Gamma_s$ in $B_s \to D_s^* D_s^*$. Combinations of these results are also presented.

2. B_s Mixing

Since neutral B meson mass eigentstates can be described as a linear combination of the weak eigenstates they can mix. For the B_s meson we can write:

$$|B_{L,H} >= p|B_s^0 > \pm q|\overline{B}_s^0 > \tag{2.1}$$

where the mass difference between the eigenstates is given by $\Delta m_s = M_H - M_L$ and the lifetime difference is $\Delta\Gamma_s = \Gamma_L - \Gamma_H = 2|\Gamma|\cos\phi_s$ where $\phi_s = \arg(-M_{12}/\Gamma_{12})$.

D0 and CDF reconstruct the decays $B_s \to D_s X$ where X can be leptons, one pion, or three pions. Decays including leptons (typically muons) are easier to trigger on but cannot be fully reconstructed because of the neutrino in the final state. Decays to pions can be fully reconstructed and hence have much better lifetime resolution but require a trigger on the displaced vertex of the decay.

To fit the mixing parameters the flavour of the B meson at production is required. This is identified using same side and opposite side tagging. The accuracy and precision of the tagging is confirmed using B_d oscillations [1]. The probability that any given event originated from a given B_s flavour is determined and combined in an unbinned maximum likelihood fit. An example of the resulting amplitude scan is shown for the CDF experiment in Fig. 1. CDF's inclusion of the hadronic decay channels allow them to observe B_s oscillations [2] and they measure $\Delta m_s = 17.77 \pm 0.10(\text{stat}) \pm 0.07(\text{syst})\,\text{ps}^{-1}$ with a significance larger than 5σ using 1.0 pb^{-1} of data. D0's measurement [3] is dominated by the semileptonic decay channels and has a significance of 3σ and they find $\Delta m_s = 18.53 \pm 0.93(\text{stat}) \pm 0.30(\text{syst})\,\text{ps}^{-1}$ using 2.4 pb^{-1} of data.

3. CP Violation in Mixing: a^s_{sl}

3.1 Same Sign Dimuon Asymmetry

CP violation in the mixing of neutral B mesons can be searched for by measuring the asymmetry in same sign dimuon events:

$$A^{\mu\mu}_{sl} = \frac{N(\mu^+\mu^+) - N(\mu^-\mu^-)}{N(\mu^+\mu^+) + N(\mu^-\mu^-)}. \tag{3.1}$$

CDF [4] uses the two dimensional $(\mu\mu)$ impact parameter to identify the contributions from different sources (which include b, c, decays and fakes) to extract an asymmetry value of $A^{\mu\mu}_{sl} = -0.0080 \pm 0.0090(\text{stat}) \pm 0.0068(\text{syst})$ using 1.6 pb^{-1} of data.

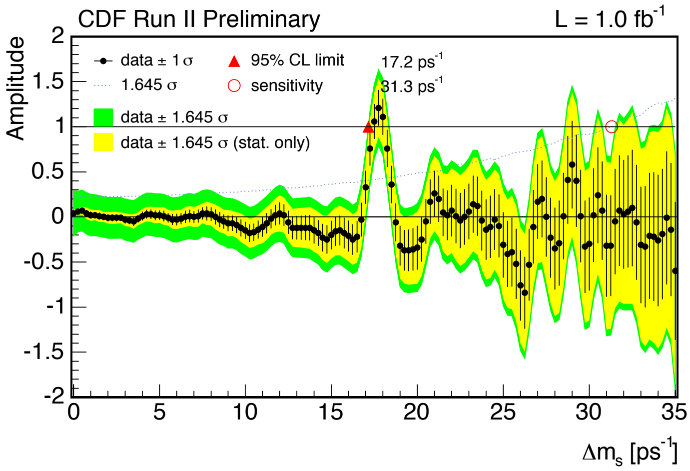

Figure 1: Combined (semileptonic+hadronic) amplitude as a function of Δm_s with statistical and systematic uncertainties for CDF [2].

D0 [5] makes use of the ability to reverse its magnetic field to reduce the background asymmetry. The resulting asymmetry is found to be $A_{sl}^{\mu\mu} = -0.0053 \pm 0.0025(\text{stat}) \pm 0.0018(\text{syst})$ using 1.0 pb^{-1} of data.

Both experiments then have to extract the value of a_{sl}^s by determining the fraction of the sample from B_s decays and the probability of oscillations. The final asymmetry is corrected to take into account the asymmetry of B_d decays (a_{sl}^d) as determined by the B factories. The results are:

- CDF: $a_{sl}^s = 0.020 \pm 0.021(\text{stat}) \pm 0.0016(\text{syst}) \pm 0.0009(\text{inputs})$;
- D0: $a_{sl}^s = -0.0064 \pm 0.0101(\text{combined})$.

3.2 $B_s \to D_s^- \mu^+ X$ Lifetime Analysis

a_{sl}^s can also be measured via a tagged lifetime analysis of the decays $B_s \to D_s^- \mu^+ X$. D0 [6] analyse the two decay channels where $D_s^- \to \phi\pi^-$; $\phi \to K^+K^-$, and $D_s^- \to K^{0*}K^-$; $K^{0*}K^- \to K^+\pi^-$ (see Fig.2) using 5.0 pb^{-1} of data. . Here

$$a_{fs}^s = \frac{\Gamma_{\overline{B}_s(t)} - \Gamma_{B_s(t)}}{\Gamma_{\overline{B}_s(t)} + \Gamma_{B_s(t)}} = \frac{\Delta\Gamma_s}{\Delta m_s} \tan\phi_s \tag{3.2}$$

The asymmetry values are extracted via an unbinned likelihood fit of the visible proper decay length taking into account of tagging probabilities, decay length resolution and the contributions from backgrounds such as B_d and B^+ decays. The likelihood function used is

$$\Gamma_{B_s(t)\to\bar{f}} = N_f |\bar{A}_{\bar{f}}|^2 \left(1 - a_{fs}^s\right) \exp\left(-\Gamma_s t\right) \left[\frac{\cosh(\Delta\Gamma_s t/2) - \cos(\Delta m_s t)}{2}\right] \tag{3.3}$$

The number of signal events for oscillated B_s decays are extracted for the various different magnet polarities and used to determine a_{fs}^s:

$$a_{fs}^s = \left[-1.7 \pm 9.1(\text{stat})\,{}^{+1.2}_{-2.3}(\text{syst.})\right] \times 10^{-3} \tag{3.4}$$

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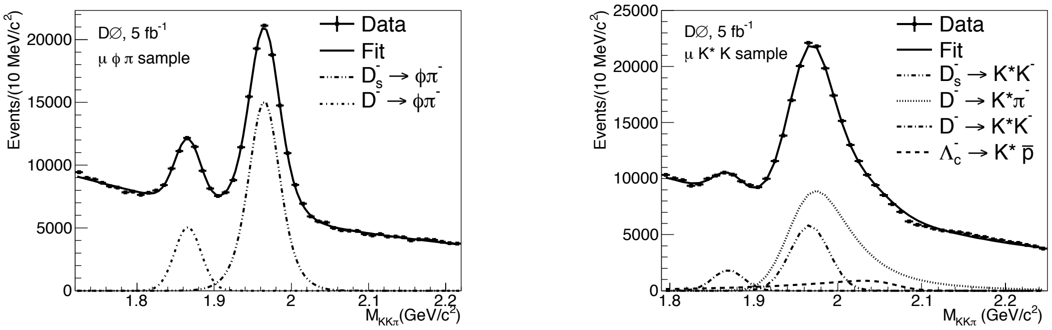

Figure 2: Reconstruction of B_s decays in D0. Left: $K^+K^-\pi^-$ invariant mass distribution for the $\mu^+\phi\pi^-$ sample with the solid line representing the mass fit result. Right: $K^+K^-\pi^-$ invariant mass distribution for the $\mu^+K^{*0}K^-$ sample with the solid line representing the mass fit result.

All of the a^s_{sl} results presented here have been combined by HFAG [7] resulting in $a^s_{sl} = -0.0027 \pm 0.0066$ which is consistent with the predictions of the Standard Model.

3.3 Aside: CP Violation of $B^+ \to J/\Psi K^+$

D0 has also measured the CP violating asymmetry between B^+ and B^- [8] by making use of the ability to reverse the magnetic field using 2.8 pb^{-1} of data. . The resulting measurement of the asymmetry is the most precise in this channel, out-performing the performance of the B factories:

$$A_{CP} = (B^+ \to J/\Psi K^+) = -0.0075 \pm 0.0061(\text{stat}) \pm 0.027(\text{syst.}) \tag{3.5}$$

3.4 $\Delta\Gamma_s$ from $D_s^{(*)}D_s^{(*)}$

The final state in the decay $B_s \to D_s^{(*)}D_s^{(*)}$ should be CP-even (however, the theoretical uncertainties are not fully understood). This means that the measurement of the branching ratio $\mathscr{B}(B_s \to D_s^{(*)}D_s^{(*)})$ can be used to calculate the decay width difference using the relation:

$$\frac{\Delta\Gamma_s^{CP}}{\Gamma_s} \simeq \frac{2\mathscr{B}(B_s \to D_s^{(*)}D_s^{(*)})}{1 - \mathscr{B}(B_s \to D_s^{(*)}D_s^{(*)})}. \tag{3.6}$$

D0 [9] reconstructs the semi-leptonic decay $B_s \to \mu\nu D_s^{(*)}$ in two channels, the hadronic $D_s \to \phi\pi$ and the semi-leptonic $D_s \to \phi\mu\nu$ where $\phi \to KK$. The signal for $B_s \to D_s^{(*)}D_s^{(*)}$ is extracted using an unbinned likelihood fit using a comparison between the two reconstructed signal channels. D0 sees evidence for $B_s \to D_s^{(*)}D_s^{(*)}$ decays observing 26.6 ± 8.4 signal events using 2.8 pb^{-1} of data. . This signal is then used to extract the branching ratio:

$$\mathscr{B}(B_s \to D_s^{(*)}D_s^{(*)}) = 0.035 \pm 0.010(\text{stat.}) \pm 0.008(\text{exp syst.}) \pm 0.007(\text{ext syst.}) \tag{3.7}$$

where the systematic uncertainties are separated into contributions from the measurement technique (exp syst.) and other measurements and theoretical uncertainties (ext syst.). The result is then used to extract

$$\frac{\Delta\Gamma_s^{CP}}{\Gamma_s} \simeq \frac{2\mathscr{B}(B_s \to D_s^{(*)}D_s^{(*)})}{1 - \mathscr{B}(B_s \to D_s^{(*)}D_s^{(*)})} = 0.072 \pm 0.021(\text{stat}) \pm 0.022(\text{syst.}). \tag{3.8}$$

4. Conclusion

The Tevatron experiments have made several interesting measurements of the B_s oscillation and CP violation parameters. These measurements are sensitive to physics beyond the Standard Model and further improvement in uncertainties with increased data samples over the next couple of years will improve the sensitivity of these measurements.

References

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