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CDF RESULTS ON *B* PHYSICS

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Selected recent B physics results from CDF are reviewed. In particular, CDF's measurements of B_c mass and lifetime, the CP asymmetry in $B^0 \to K\pi$, the lifetime of B_s in the CP even decay mode $B_s \to K^+K^-$ and subsequent determination of $\Delta\Gamma_s/\Gamma_s$ are covered. Finally, the development of the new flavor tagging algorithm called Same Side Kaon Tagging (SSKT), optimized for the search B_s^0 oscillations, is discussed in detail.

1 Introduction

The B physics program at the Tevatron is based upon the large inclusive b quark cross-section: $\sigma_b \sim 100\ \mu$b for a single b-quark above 6 GeV$/c$ in the central region ($|\eta| < 1$). In addition, the two b-quark hadronize independently from each other, and thus all species of b-hadrons are produced in $p\bar{p}$ collisions. Unfortunately, the cross-section for the soft QCD processes is ~ 1000 times bigger, so the B physics at the Tevatron crucially depends on the fast DAQ system and clever trigger strategies. In particular, the CDF II detector[1] uses the 'dead-time-less' readout of the silicon detector[2]. The silicon hits are passed to the Silicon Vertex Trigger (SVT)[3] which uses fast pattern recognition to identify displaced tracks, allowing CDF to collect large samples of fully hadronic D and B meson decays.

2 Measurements of the lifetime and the mass of B_c

The weak decay of a $B_c(\bar{b}c)$ meson can, at the tree level, proceed via the weak decay of either the $\bar{b}$ or the c quark, or the annihilation through a virtual W, with partial widths of 0.6 ps^{-1}, 1.2 ps^{-1}, and 0.1 ps^{-1}, respectively. To check this picture, we measure the lifetime of B_c in the $J/\psi e^+\nu_e$ decay channel in 360 pb^{-1} of $J/psi \to \mu^+\mu^-$ triggered data. The B_c^+ candidates are reconstructed from $J/\psi + e$ pairs with a displaced vertex and an invariant mass in the kinematically allowed range $4 < m(J/\psi e) < 6$ GeV$/c^2$

(Fig. 1, left). Background contributions from fake electrons, photon conversions and $b\bar{b}$ contamination are estimated using hadron tracks and electron tracks tagged as conversions in the data and from Monte Carlo simulations. The B_c^+ lifetime is measured from the distribution of the proper-times of the B_c decays. The decay distance in the transverse plane, L_{xy}, is reconstructed by the silicon detector and converted into the proper time by the Lorentz boost $m(J/\psi e)/p_T(J/\psi e)$ corrected by a factor accounting for a missing neutrino: $K \equiv (m_B/p_T(B))/(m(J/\psi e)/p_T(J/\psi e))$, and thus $ct = L_{xy}Km(J/\psi e)/p_T(J/\psi e) = K \cdot ct^*$ where t is the proper time and ct^* is pseudo-proper decay length. The fit to the ct^* distribution is shown in Fig. 1 (right), and yields $\tau(B_c^+) = 0.474^{+0.073}_{-0.066}(stat.) \pm 0.033(syst.)$ ps. This result confirms that all three diagrams contribute to the B_c decay width.

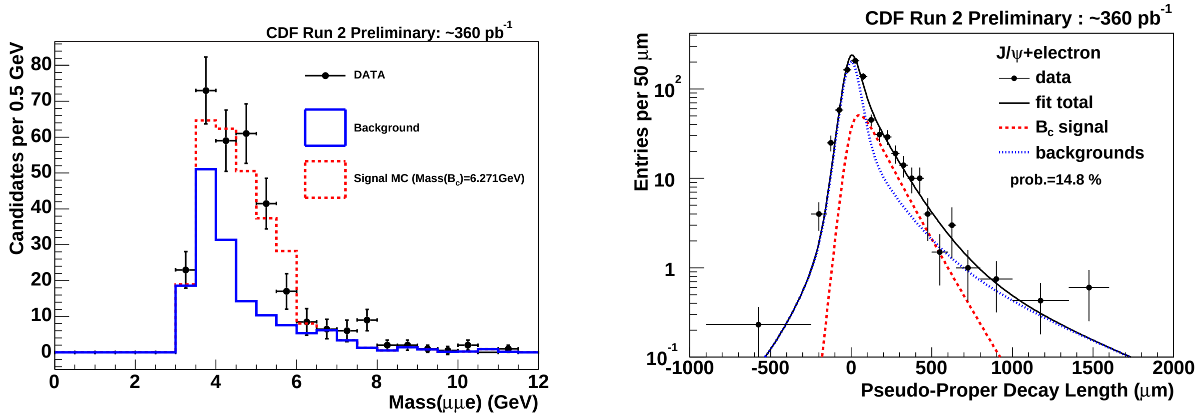

Figure 1: Left: the invariant mass of $B_c \to J/\psi \nu e$ candidates. Right: the pseudo-proper-time distribution with the unbinned likelihood fit for the lifetime of $\tau(B_c)$ overlaid.

In order to measure the mass of B_c, a fully reconstructed decay is needed. We reconstruct $B_c \to J/\psi\pi$, and observe an excess of events attributed to the B_c meson with a significance greater than 6σ. We measure the mass of the B_c meson to be: $m(B_c) = 6275.2 \pm 4.3(stat.) \pm 2.3(syst.)$ MeV$/c^2$. This compares favorably to the recent lattice QCD calculations [4] which predict $m(B_c) = 6304 \pm 12^{+18}_{-0}$ MeV$/c^2$.

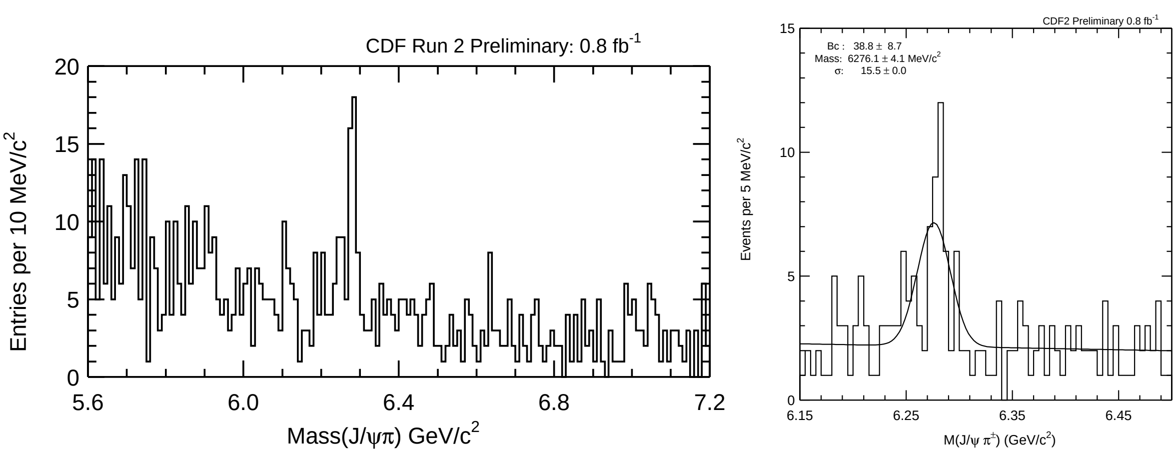

Figure 2: Left: the invariant mass of $B_c \to J/\psi\pi$ candidates, including the whole search window. Right: the invariant mass of $B_c \to J/\psi\pi$ (narrow window) with the binned fit overlaid.

3 Measurement of $A_{CP}(B^0 \to K\pi)$

Several important measurements are possible with a sample of two-track B decays selected by the SVT. The invariant mass of the $B \to h^+ h'^-$ candidates, where h and h' are charged hadrons (K or π), corresponding to $\sim 355\ \text{pb}^{-1}$, is shown in Fig. 3. A pion mass is assigned to both tracks, and the mass peak is a mixture of $B^0 \to K\pi$, $B^0 \to \pi\pi$, $B_s \to KK$ and $B_s \to K\pi$. (The decays $\Lambda_b \to p\pi$ and $\Lambda_b \to pK$ would appear $\sim 5.45\ \text{GeV}/c^2$, but there are no sight of them yet.[5]) A combination of the kinematics and the particle identification information (from dE/dx) can be used to separate the four components on the statistical basis. The result of the combined unbinned likelihood fit is shown on Figs. 3(right) and 4. The fit can clearly distinguish all four components, even though the $K-\pi$ separation based on dE/dx is only $\sim 1.4\sigma$.

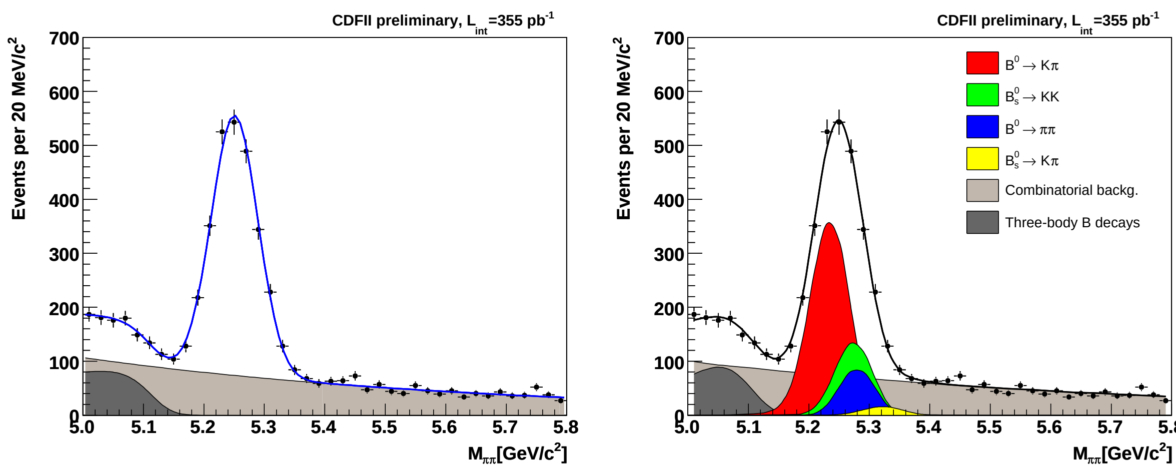

Figure 3: Left: the invariant mass of $B \to hh'$ candidates, assuming the pion mass hypothesis for both tracks. Right: the projections of the total PDF of the unbinned likelihood fit to the $B \to hh'$ sample on $m(\pi,\pi)$.

We search for the direct CP violation in $B^0 \to K\pi$ decays and measure

$$A_{CP}(B^0 \to K\pi) \equiv \frac{N(\overline{B}_d^0 \to K^-\pi^+) - N(B_d^0 \to K^+\pi^-)}{N(\overline{B}_d^0 \to K^-\pi^+) + N(B_d^0 \to K^+\pi^-)} = -0.058 \pm 0.039(stat.) \pm 0.007(syst.)$$

This result is compatible with both zero and the world average[8] $A_{CP}(B^0 \to K^+\pi^-) = -0.115 \pm 0.018$. Although the statistical resolution of current CDF result is not yet competitive with the B-factories,[6,7] CDF has a smaller systematics uncertainty, which is encouraging since the data used are only 1/3 of the sample now available.

4 B_s lifetime in $B_s \to K^+K^-$ decays and the measurement of $\Delta\Gamma_s/\Gamma_s$

The CDF also performed the first measurement of the lifetimes of the B_s and B^0 mesons in two-body charmless decays in the $B \to hh'$ sample. The lifetime measurement proceeds identically to the A_{CP} measurement except that it also includes the measurement of the proper time obtained from $t = L_{xy}m/(cp_T)$. We measure $\tau(B^0) = 1.51 \pm 0.08(stat) \pm 0.02(syst)$ ps and $\tau(B_s \to K^+K^-) = 1.53 \pm 0.18(stat) \pm 0.02(syst)$ ps. The decay $B_s \to KK$ is CP even and thus measures the lifetime of the "B_s light", $\tau(B_{sL})$, which is related to the flavor specific lifetime $\tau(B_{sFS})$ via

$$\tau(B_{sFS}) = \frac{\tau(B_{sL})^2 + \tau(B_{sH})^2}{\tau(B_{sL}) + \tau(B_{sH})} \tag{1}$$

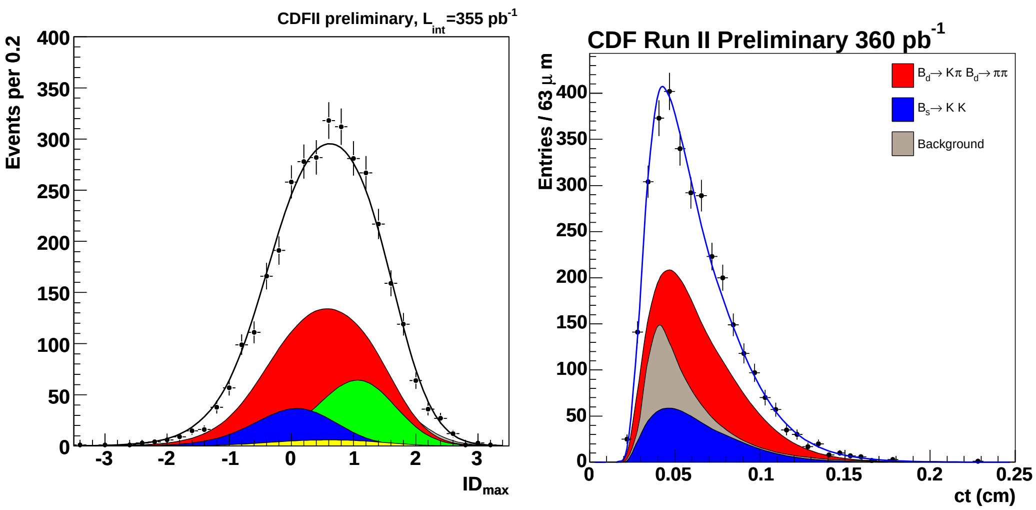

Figure 4: The projections of the total PDF of the unbinned likelihood fit to the $B \to hh'$ sample. Left: the projection on the particle identification variable (based on dE/dx) of the higher momentum track. Right: the projection of the unbinned likelihood fit to the $B \to hh'$ on the ct axis, where c is the speed of light and t is the proper time of the B_s decay.

where $\tau(B_{sH})$ is the lifetime of "B_s heavy". The knowledge of $\tau(B_{sL})$ and $\tau(B_{sFS})$ thus allows the extraction of $\Delta\Gamma_{CP} \equiv \Gamma(B_{sL}) - \Gamma(B_{sH})$. We allow for a $\sim 5\%$ pollution from the CP odd B_s heavy which, at a very low level, could also decay to K^+K^- final state;[9] this effect is included into the systematic uncertainties.

Combining the latest HFAG average of the B_s lifetime in flavor specific decays, $\tau(B_{sFS}) = 1.454 \pm 0.040$ ps [8] and our measurement of the $B_s \to KK$ lifetime, we obtain $\Delta\Gamma_{CP}/\Gamma_{CP}(B_s \to K^+K^-) = -0.08 \pm 0.23 \pm 0.03$.

5 Same Side Kaon Tagging

$B^0_s - \bar{B}^0_s$ mixing is one of the rare remaining measurements which could impact the determination of the Unitarity Triangle, and thus indirectly limit the New Physics contributions to the mixing box diagram. The B_s meson decays as either mixed (it changed flavor) or "unmixed" (it did not), and the probabilities for the two components are $P(t) = (e^{-t/\tau}/2\tau)(1 \pm D cos \Delta m_s t)$. The dilution, D, is a measure of the purity of the flavor tagging ($D \equiv 1$ for the perfect tagging; $1-2D$ is the mistag rate). The statistical power of flavor tagging is characterized by $N\varepsilon D^2$, where N is the number of events prior to tagging, ε is the tagging efficiency.

Until now, CDF relied solely on the "opposite side" flavor taggers (OST) – *i.e.*, the algorithms which use the event information on the hemisphere opposite with respect of the B meson which is being tagged. These methods rely on identifying at least some decay products of the "other b-hadron" on the opposite side – a soft lepton (e or μ), or a "jet". The charge of the soft lepton or a weighted average of the charges of the tracks in the "jet" identify the decay flavor of the opp.side b-hadron, and the production flavor of the B meson being tagged is inferred from it. All opposite side taggers achieve an average $\varepsilon D^2 \sim 1.5\%$. The two b-quarks produced in $p\bar{p}$ collision hadronize independently from each other, and thus the dilution of an OST algorithm does not depend on the species of the b-hadron that is being tagged. This allows for a calibration of the dilution of the OS taggers used in the search for B_s – D_{OST} is measured in the decays of B^+ and B^0 mesons, and is simply transfered to the B_s sample. Until the B_s oscillations are seen, the dilution cannot be measured in B_s sample itself, and thus knowing D is requisite for setting a limit on Δm_s.

The 'problem' with OST is that at least some decay products of the other b-hadron need to be identified, since once one B meson is in the central region of a detector such as CDF, the other b-hadron is also in the central region only $20-40\%$ of the time, and thus it often cannot be reconstructed. In 1992, Gronau, Nippe and Rosner [10] proposed that the particles produced along with a B meson be used for flavor tagging. For example, a hadronization of a $\bar{b}$ quark would produce a B_s^0 followed by K^+ as the next particle in the hadronization chain. A $\bar{K}^{*0}$ could also be produced, yielding a K^+ as one of its decay products. In both cases the charge of the "first hadronization kaon" uniquely identifies the production flavor of the B_s meson. Analogously, the B^+ is produced with a π^-, whereas B^0 is produced with a π^+. In addition, in the case of B^+ and B^0 (but not B_s!) the correlated pions could also arise from B^{**0} and B^{**+} states. The method of identifying the production flavor using the charged particles on the "same side" (*i.e.*, around the B meson) is called Same Side Tagging (SST). A version dedicated to identifying production kaons – and which is thus particularly suited for the search for B_s oscillations – is called Same Side Kaon Tagging (SSKT). The $B-\pi$ charge-flavor correlations were confirmed and further studied in B^0 and B^+ mesons by CDF using Run 1 data. [11]

However, by the very nature of how the charged particles around B mesons are produced, their composition, number and kinematics are different between the B meson species. The SS(K)T dilutions for B_s mesons are different from dilutions for B^+ and B^0, and thus it is not possible to directly calibrate the B_s dilutions in the high-statistics B^+ and B^0 samples.

We use the Pythia Monte Carlo generator to perform an 'indirect' calibration of D_{SSKT} for B_s. We first ensure that Pythia matches data in all respects, both at the level of tracks around B mesons, and also that the SST dilutions for B^0 and B^+ samples measured in data agree with the Pythia predictions. In this process, we also ensure that the systematic variations in the Pythia set-up cover any minor discrepancies. Finally, we obtain the D_{SSKT} for B_s from Pythia, and use the variations in the Pythia set-up to evaluate the systematic uncertainties.

We select the same-side tagging kaon track in the cone of $\sqrt{\Delta\phi^2+\Delta\eta^2}<1.0$ around the B meson. If there is only one track, it is used as the tag. If there are two or more, we select the one with the largest value of

$$CLL \equiv log\left(\frac{P_{tof}(K)\cdot P_{dEdx}(K)}{0.9\cdot P_{tof}(\pi)\cdot P_{dEdx}(\pi)+0.1\cdot P_{tof}(p)\cdot P_{dEdx}(p)}\right) \quad (2)$$

where $P_{tof}(i)$ and $P_{dEdx}(i)$ are likelihoods that the particle of species i will leave the observed signal in the Time-of-Flight detector and dE/dx in the drift chamber, respectively.

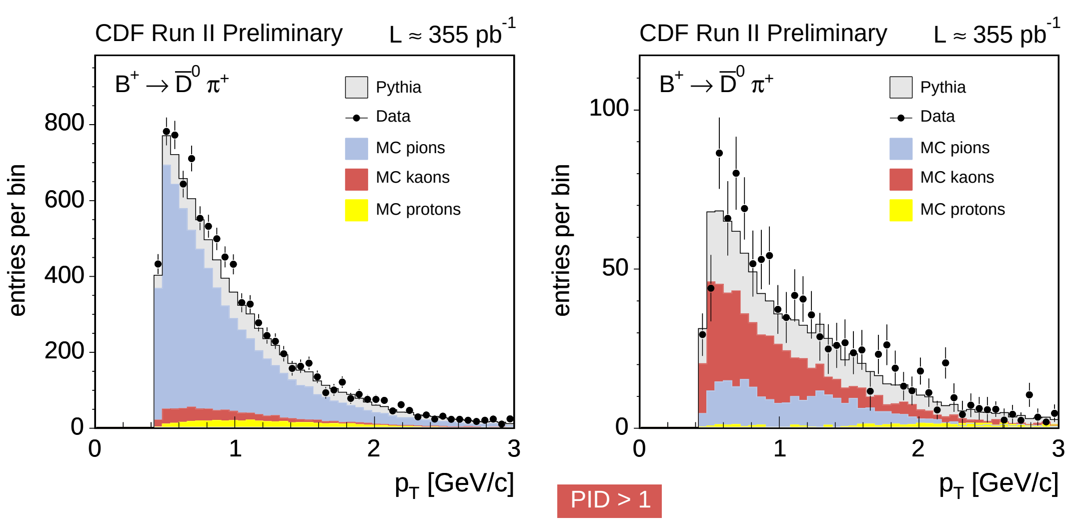

Figure 5: The distribution of the p_L^{rel} for the track selected as the tag, in $B^+ \to \bar{D}^0\pi^+$ sample. Solid points are data, and the histogram is Pythia Monte Carlo. Left: no cut on CLL. Right: after the cut CLL>1.

This version of Pythia has undergone extensive tuning of the underlying event.[12] By fitting $\Delta\phi$ between a B meson and an opposite side b-hadron, we measure the gluon splitting fraction in data and

Pythia MC samples and confirm that they agree within statistics. We observe the narrow B^{**} states and verify that the track densities in Pythia with the B^{**} states included match the data. We find that the data/Pythia agreement is only sensitive to the location of the 'peak' of the fragmentation function. We measure the particle content around the B^+, B^0 and B_s mesons, and find that all particle fractions (pions, kaons, protons) agree well in B^+ and B^0; Pythia predicts $\sim 3\%$ more kaons than data, and we take that into account in predicting the dilutions by randomizing the charge of the excess kaons. Next we compare various distributions of kinematic and particle identification quantities for the track around B mesons. A typical comparison of track-level quantities related to SSKT algorithm is shown in Fig. 5. We also ensure that the systematic variations used in Pythia cover small discrepancies between data and Pythia (an illustration is given in Fig. 6).

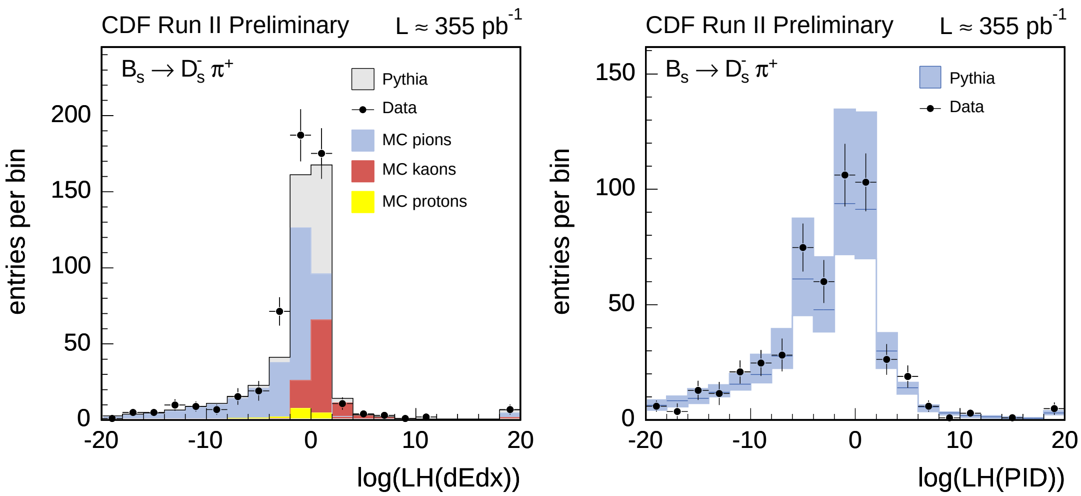

Figure 6: The distribution of the value of the combined PID likelihood ratio (CLL) in data (solid circles) and Pythia Monte Carlo simulation (histogram). Left: the comparison of CLL between data and Pythia, with all the components shown separately. Right: the same plot but with the addition of the systematic errors on the prediction from Pythia (light blue boxes). Even though the Pythia MC prediction appears to disagree from data points, the differences are well within the systematic errors assigned to the Pythia MC sample.

The SSKT dilutions using the CLL algorithm from Eq. 2 are shown in Fig.7. The Pythia predictions agrees well with the values obtained from data. The agreement furthermore persists when the B^{**} signal region is excluded, indicating that SST effects from B^{**} and hadronization are both correctly modeled by Monte Carlo simulation.

Finally, the SSKT dilution is $D = 28.3^{+3.2}_{-4.2}\%$ and resulting in $\varepsilon D^2 = 4.0^{+0.9}_{-1.2}\%$, which increases CDF's power of flavor tagging by a factor of ~ 2.5.

6 Conclusion and Post-scriptum

The measurements of B_c mass and lifetime, the CP asymmetry in $B^0 \to K\pi$, the lifetime of B_s in the CP even decay mode $B_s \to K^+K^-$ and subsequent determination of $\Delta\Gamma_s/\Gamma_s$ were highlighted. In addition, the Same Side Kaon Tagging has improved the tagging capabilities of CDF B_s mixing analysis by more than a factor of 2.5. At the time of the Moriond conference, we still did not analyze all the available data, and the B_s mixing results were not ready. However, in subsequent weeks all the flavor taggers – including the SSKT – were applied to all available B_s decays (both fully reconstructed and semileptonic). The observed minimum in the likelihood function is consistent with $B_s^0\bar{B}_s^0$ oscillations (at a $\sim 3.5\sigma$ level), with the probability of background mimicking such a signal of 0.5%. Under the assumption that this signal is due to $B_s^0\bar{B}_s^0$, we measure $\Delta m_s = 17.33^{+0.42}_{-0.21}(stat.) \pm 0.07(syst.)\ \mathrm{ps}^{-1}$.

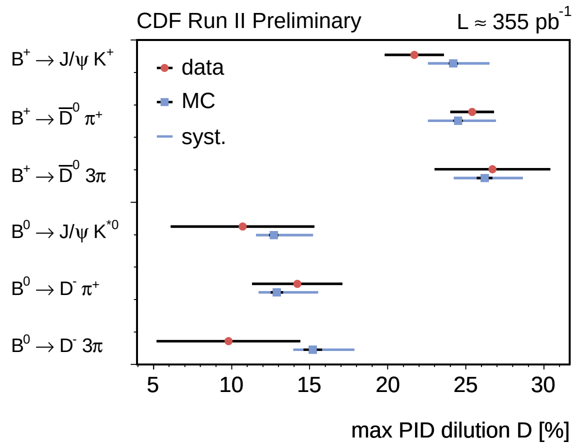

Figure 7: Comparison of the dilution of the "max CLL" algorithm between data (red circles) and Pythia Monte Carlo simulation (light blue squares). All dilutions agree within the errors.

Acknowledgments

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