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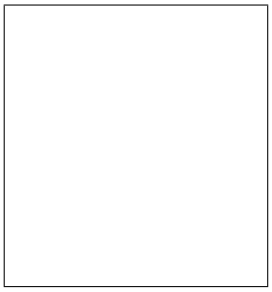
B Physics at CDF

Jonas Rademacker
on behalf of the CDF Collaboration
Department of Physics, 1 Keble Road, Oxford OX1 3RH, UK



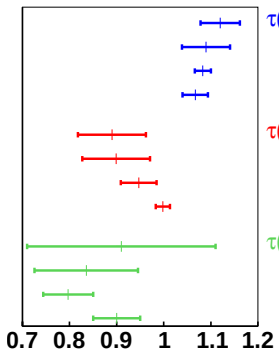
Due to the large $b\bar{b}$ cross section at 1.96 TeV $\mathrm{p}-\bar{\mathrm{p}}$ collisions, the Tevatron is currently the most copious source of B hadrons. Recent detector upgrades for Run II have made these more accessible, allowing for a wide range of B and $\not{C}\not{P}$ physics with B hadrons of all flavours. In this paper we present B-physics results, and, using the versatile hadronic Two Track Trigger, a search for $\Xi(1860)$, from up to $240\,\mathrm{pb}^{-1}$ of data.

1 Introduction

CDF has been taking data at Tevatron Run IIa for about two years. For $\mathrm{p\bar{p}}$ collisions at 1.96 TeV, the $b\bar{b}$ production cross section is $\sigma_{b\bar{b}} \sim 0.1\,\mathrm{mb}$. CDF has undergone major upgrades for Run II, optimising its B physics potential. The upgrades most relevant for CDF's B physics program include a new tracking system with a new, faster drift chamber, and new Silicon vertex trackers providing excellent proper time resolution, sufficient to resolve the expected fast oscillations in the $\mathrm{B_s^0}$ system. The excellent impact parameter resolution is used for triggering on B-events. The muon coverage has been increased. A di-muon trigger efficiently finds $\mathrm{B} \to \mathrm{J}/\psi\mathrm{X}$ decays.

Here we present some of the wide range of analyses of the current CDF B physics program, which includes a wide range of studies, involving all types of B-hadrons, including leptonic as well as fully hadronic decays of $\mathrm{B_d}, \mathrm{B^+}, \mathrm{B_s}, \mathrm{B_c}, \Lambda_\mathrm{b}$. The impact-parameter based trigger also provides a very large sample of long-lived Ξ^-. This has been used for a sensitive search for $\Xi^0(1860) \to \Xi^-\pi^+$ and $\Xi^{--} \to \Xi^-\pi^-$, which have been observed at NA49 [1] and are often interpreted as pentaquark states.

Table 1: Lifetimes and lifetime ratios in Run II from $B_u^+ \to J/\psi(\mu^+\mu^-)K^+$ ($240\,pb^{-1}$), $B_d^0 \to J/\psi(\mu^+\mu^-)K^{(*)0}$ ($240\,pb^{-1}$), $B_s^0 \to J/\psi(\mu^+\mu^-)\phi$ ($240\,pb^{-1}$), $\Lambda_b \to J/\psi(\mu^+\mu^-)\Lambda$ ($65\,pb^{-1}$) compared with world average (HFAG [4], results for PDG 04, and, for Λ_b, results for PDG 02), Run I results [5] and HQE predictions [6]. Run I results are from all channels combined, Run II results from fully reconstructed $J/\psi(\mu\mu)X$ only.



Channel	Result (ps)
$B_u^+ \to J/\psi(\mu^+\mu^-)K^+$	$1.662 \pm 0.022 \pm 0.008$
$B_d^0 \to J/\psi(\mu^+\mu^-)K^{(*)0}$	$1.539 \pm 0.051 \pm 0.008$
$B_s^0 \to J/\psi(\mu^+\mu^-)\phi$	$1.369 \pm 0.100^{+0.008}_{-0.010}$
$\Lambda_b^0 \to J/\psi(\mu^+\mu^-)\Lambda$	$1.25 \pm 0.25 \pm 0.10$

Note that the Run II result for $B_s \to J/\psi\phi$ is dominated by the (shorter) lifetime of the CP-even component.

2 Results from the Di-Muon Trigger

2.1 b Production Cross Section

The inclusive b-hadron production cross-section is measured from the b-fraction in the reconstructed J/ψ sample up to February 2002 ($37\,pb^{-1}$). Combining this number with the inclusive $J/\psi X$ cross section, and the appropriate branching fractions, allows to calculate the absolute b production cross section. The long lifetime of B-hadrons is used to discriminate between prompt J/ψ and J/ψ from B-hadron decays. The total single b-quark cross-section integrated over one unit of rapidity is

$$\sigma(p\bar{p} \to \bar{b}X : \ |y| < 1.0) = 29.4 \pm 0.6(stat) \pm 6.2(sys)\,\mu b$$

where the largest contributions to the systematic error come from uncertainties in the acceptance and the inclusive B-hadron to J/ψ branching ratio.

2.2 Lifetimes

Life time measurements in the heavy quark sector gain specific significance due to the precise predictions of Heavy Quark Expansion [2 3] thus providing a testing ground for this theoretical tool that is frequently used, for example to relate experimental measurements to CKM parameters like Γ_d to $|V_{cb}|$ or $\Delta m_s/\Delta m_d$ to $|V_{ts}/V_{td}|$.

Fully reconstructed hadronic $B \to J/\psi X$ decays, found with CDF's di-muon trigger, provide a clean method for measuring B lifetimes, free from the systematic uncertainties associated with semileptonic decays due to the missing momentum of the ν, and free from the lifetime bias in impact parameter-based trigger samples. Of specific interest at CDF are the lifetimes of the B_s and Λ_b, which are currently produced in large quantities only at the Tevatron. Lifetime results, and lifetime ratios, compared to theory predictions, Run I results, and world averages, are summarised in Table 1.

2.3 CP content of $B_s \to J/\psi\phi$

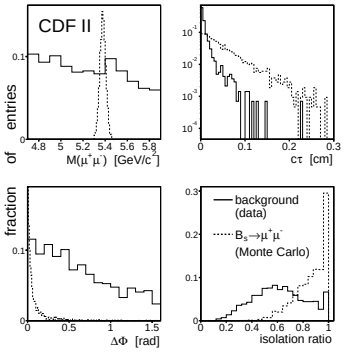
The measurement of the average lifetime in $B_s \to J/\psi\phi$ constitutes a first step towards a measurement of $\Delta\Gamma_s$, the width difference between the long and short lived CP eigenstates, which has some sensitivity to new physics, especially when compared to the mass difference, Δm_s, which is also going to be measured at the Tevatron. The CP-even and odd contribution in $B_s \to J/\psi\phi$ can be disentangled by analysing the decay in terms of transversity angles, leading

Table 2: Transversity-angle analysis in $B_s \to J/\psi\phi$ and $B_d \to J/\psi K^{*0}$. A_0 and $A_\parallel$ are CP even decay amplitudes, $A_\perp$ is CP-odd, normalised such that $|A_0|^2 + |A_\parallel|^2 + |A_\perp|^2 \equiv 1$.

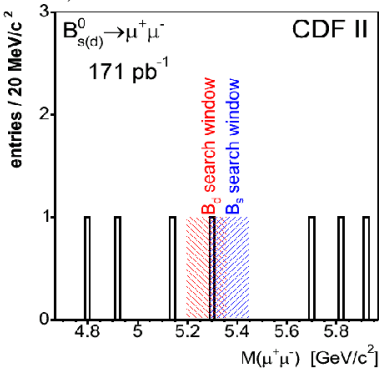
$B_s \to J/\psi\phi$	$B_d \to J/\psi K^{*0}$
$A_0 = 0.762 \pm 0.044 \pm 0.07$	$A_0 = 0.796 \pm 0.022 \pm 0.012$
$A_\parallel = (0.433 \pm 0.199 \pm 0.011)\ e^{i(2.08 \pm 0.51 \pm 0.06)}$	$A_\parallel = (0.433 \pm 0.037 \pm 0.014)\ e^{i(3.10 \pm 0.50 \pm 0.06)}$
$\lvert A_\perp \rvert = 0.481 \pm 0.104 \pm 0.025$	$A_\perp = (0.422 \pm 0.050 \pm 0.027)\ e^{i(0.18 \pm 0.26 \pm 0.02)}$

Figure 1: Search for $B_{d,s} \to \mu^+\mu^-$

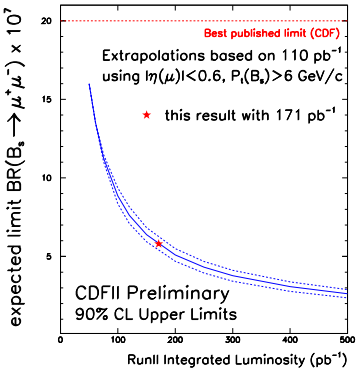
(a) Discriminating Variables: Mass, lifetime, $\Delta\phi$ and isolation ($p_t(\mu)$ divided by all p_t in a cone around the μ).



(b) 1 event found in overlap of search windows - consistent with bgk estimate of 1.05 ± 0.30 (B_d), 1.07 ± 0.31 (B_s), 1.75 ± 0.34 (combined).



(c) Projected and current sensitivity to $B_s \to \mu\mu$ at CDF, not including expected improvements due to increased μ coverage.



to the measurement of two CP even amplitudes A_0 and $A_\parallel$, and one CP-odd amplitude, $A_\perp$ [7]. The CDF Run II results for $192\,\mathrm{pb}^{-1}$ are shown in Table 2, for both $B_s \to J/\psi\phi$ and, as a cross check, $B_d \to J/\psi K^{*0}$. The B_d results are consistent with those from BaBar [8] and CLEO [9]. The phases of the amplitudes provide an interesting test of factorisation, which predicts the relative phases to be either 0 or π [10]. The amplitude measurements imply a CP-even content in $B_s \to J/\psi\phi$ of $77\% \pm 10\%$. Work is in progress to combine this technique with the lifetime analysis for a $\Delta\Gamma_s$ measurement.

2.4 Search for New Physics with $B_{d,s} \to \mu^+\mu^-$

While in the Standard Model, the branching ratio of $B_{d,s} \to \mu^+\mu^-$ is $\mathcal{O}(10^{-9})$, which is below the sensitivity of the Tevatron, many New Physics models predict enhancements of this mode by several orders of magnitude, for example mSUGRA [11] and SO(10) Symmetry Breaking models [12]. In mSUGRA, the $B_{d,s} \to \mu^+\mu^-$ branching ratio is approximately [11]

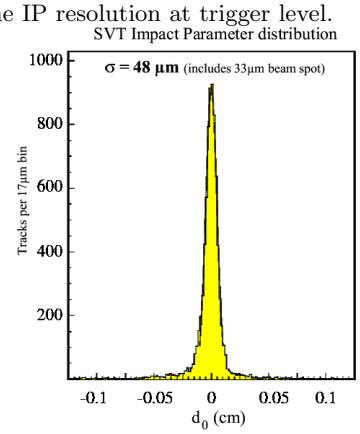
$$\mathrm{BR}_{\mathrm{mSUGRA}}\,(B_s \to \mu\mu) \approx 10^{-6} \cdot \tan^6\beta \frac{M_{1/2}^2 \mathrm{GeV}^4}{(M_{1/2}^2 + M_0^2)^3}$$

which increases rapidly with large $\tan\beta$.

The search for $B_{d,s} \to \mu^+\mu^-$ was performed as a blind analysis. The cuts were optimised using Monte-Carlo generated signal events and background events from real data. Signal and background distributions for the most important cuts are shown in Figure 1 (a). After all cuts are applied, 1.05 ± 0.30 background events are expected in the B_d mass window and 1.07 ± 0.31

Figure 2: The CDF hadronic 2-Track-Trigger. $\Delta\phi$ is the angle between the tracks in the transverse plane. IP is the 2-D impact parameter of each of the two tracks. L_{xy} is the decay length in the transverse plane. The table on the left lists the trigger requirements. The figure on the right shows the IP resolution at trigger level.

L1: 2 XFT tracks, $p_t > 2\,\text{GeV}$, $\Delta\phi < 135°$, $p_{t1}+p_{t2} > 5.5\,\text{GeV}$.	
L2:	
2-body: e.g. $B^0_d \to \pi\pi$	Multi-body: e.g. $B^0_s \to D_s\pi$
$100\,\mu\text{m} < IP < 1\,\text{mm}$	$120\,\mu\text{m} < IP < 1\,\text{mm}$
$20° < \Delta\phi < 135°$	$2° < \Delta\phi < 90°$
$L_{xy} > 200\,\mu\text{m}$	$L_{xy} > 200\,\mu\text{m}$
IP of B $< 140\,\mu\text{m}$	–
L3: Same with refined tracks & mass cuts.	



B_s mass window, both are 200 MeV wide, and overlap. The number of background events predicted for the combined mass window is 1.75 ± 0.34. Several cross checks in real data have been performed before unblinding, for example using wrong-sign di-muon events ($\mu^+\mu^+$ and $\mu^-\mu^-$), which yielded consistent results. The total number of events found after unblinding is 1 event in the overlap region of the two mass windows, as shown in Figure 1 (b), resulting in the following 90% confidence limits:

$$\text{BR}(B_d \to \mu^+\mu^-) < 1.5 \cdot 10^{-7}\ (90\%\text{CL}) \qquad \text{BR}(B_s \to \mu^+\mu^-) < 5.8 \cdot 10^{-7}\ (90\%\text{CL})$$

which is, for the B_d, similar to the results from BaBar and BELLE, and more than a factor of 3 better than the previous best limit for $B_s \to \mu\mu$, which was provided by CDF Run I. The projected performance as a function of integrated luminosity, ignoring future improvements due to the expected increase in muon coverage, is shown in Figure 1 (c).

3 Results from the Impact Parameter-Based Hadronic B Trigger

3.1 CDF's Two Track Trigger

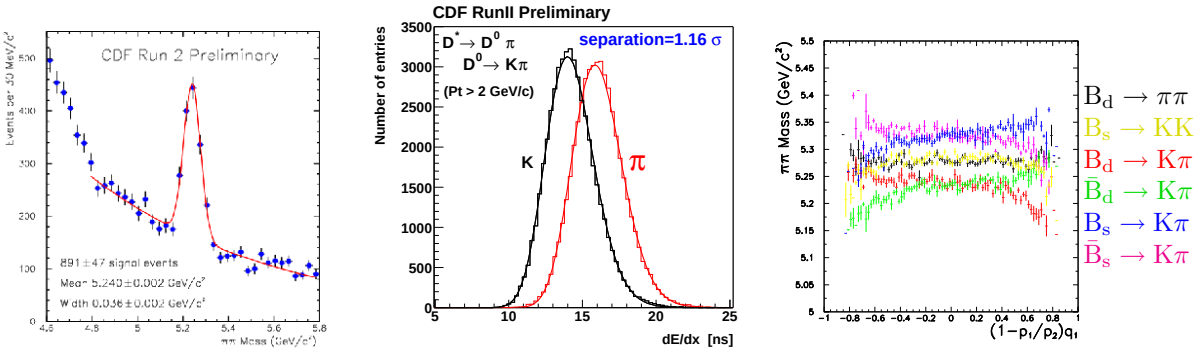
One of the most innovative improvements for B physics at CDF is the large-bandwidth hadron trigger, which triggers on the impact parameters of tracks at Level 2. The trigger requirements for the two scenarios, 2-body and multi-body B decays, are given in Figure 2. CDF's Two Track Trigger provides a unique sample of hadronic bottom and charm decays, that would otherwise be inaccessible, for example $B^0 \to \pi\pi$ and $B_s \to D_s\pi$.

3.2 $B \to hh$

Figure 3 (a) shows the invariant mass of reconstructed B to two-hadron events (assuming the hadrons are pions). About 900 events are found. In order to discriminate the different decay modes, pions and kaons are separated using their specific energy loss, $\frac{dE}{dx}$. The π/K discrimination using $\frac{dE}{dx}$ has been measured using D^* decays and has been found to be 1.16σ, as shown in figure 3 (b). Further discrimination between the different $B \to hh$ decay modes is achieved using decay kinematics, as shown in 3 (c). The plot shows the reconstructed B mass in Monte Carlo simulated $B \to hh$ events vs $(1 - p_1/p_2) \cdot q_1$ for different decay modes. Here, p_1 is the smaller of the two momenta, q_1 is the charge of the particle with momentum p_1, and the mass is calculated assuming the decay products are pions. This led to the first observation of the decay

Figure 3: B → hh

(a) 891 B → hh in 190 pb^{-1} (b) K/π sep. from $\frac{dE}{dx}$ (c) Kinematic variables (MC)



$B_s \to K^+K^-$. A summary of the results from analysing B → hh events in 65 pb^{-1} of data are given below:

- First observation of $B_s \to KK$: 90 ± 24 out of 300 B → hh events.
- Search for $\not{CP}$ in time-integrated rates
  $A_{CP} = \frac{\Gamma(\bar{B}^0_d \to K^-\pi^+) - \Gamma(B^0_d \to K^+\pi^-)}{\Gamma(\bar{B}^0_d \to K^-\pi^+) + \Gamma(B^0_d \to K^+\pi^-)} = 0.02 \pm 0.15 \pm 0.017$
- Ratios of B.R.:
  $\frac{\Gamma(B^0_d \to \pi^+\pi^-)}{\Gamma(B^0_d \to K^\pm\pi^\mp)} = 0.26 \pm 0.11 \pm 0.06$, $\frac{\Gamma(B^0_s \to K^+K^-)}{\Gamma(B^0_s \to K^\pm\pi^\mp)} = 2.71 \pm 0.73 \pm 0.35(f_s/f_d) \pm 0.81$,
  where (f_s/f_d) refers to the uncertainty due to the B_s/B_d production ratio.

Results for 195 pb^{-1} should follow, soon. In the long term, these methods can be used to extract the CP-violating phase γ from a combined analysis of time-dependent decay rate asymmetries in $B_d \to \pi\pi$ and $B_s \to KK$ [13].

3.3 $D^0 \to hh$

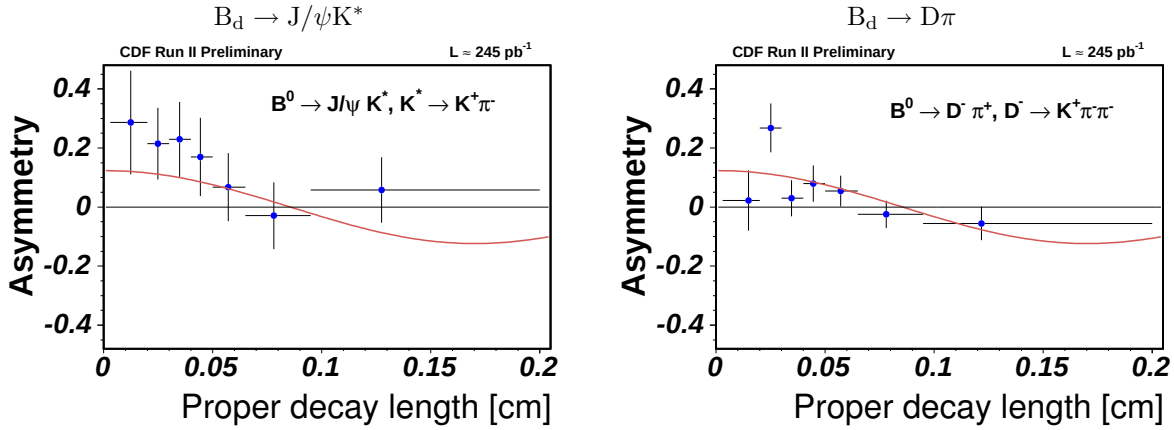
The Two Track Trigger also provides a huge charm signal, where the same methods can be applied. In the analysis presented here, only D^0 mesons from D^* decays are used, which has two advantages: a very clean signal due to the highly effective cut on the difference between the reconstructed D^* and D^0 mass, and the flavour of the D^0 is known from the charge of the D^*. This allows a precise measurement of time-integrated CP asymmetries, which are expected to vanish in the Standard Model:

- $A_{CP\,KK} = \frac{\Gamma(\bar{D}^0 \to K^+K-) - \Gamma(D^0 \to K^+K^-)}{\Gamma(\bar{D}^0 \to K^-K^+) + \Gamma(D^0 \to K^+K^-)} = 2.0\% \pm 1.2\% \pm 0.6\%$
- $A_{CP\,\pi\pi} = \frac{\Gamma(\bar{D}^0 \to \pi^+\pi-) - \Gamma(D^0 \to \pi^+\pi^-)}{\Gamma(\bar{D}^0 \to \pi^-\pi^+) + \Gamma(D^0 \to \pi^+\pi^-)} = 1.0\% \pm 1.2\% \pm 0.6\%$

Branching ratios of D^0 mesons are also of some interest, for example $\frac{\Gamma(D^0 \to K^+K^-)}{\Gamma(D^0 \to \pi^+\pi^-)}$, which is consistently larger experimentally, than theoretically predicted. The following summarises the ratios of B.R. results:

- $\frac{\Gamma(D^0 \to K^+K^-)}{\Gamma(D^0 \to K^\pm\pi^\mp)} = 9.96\% \pm 0.11\% \pm 0.12\%$
- $\frac{\Gamma(D^0 \to \pi^+\pi^-)}{\Gamma(D^0 \to K^\pm\pi^\mp)} = 3.608\% \pm 0.054\% \pm 0.12\%$
- $\frac{\Gamma(D^0 \to K^+K^-)}{\Gamma(D^0 \to \pi^+\pi^-)} = 2.762\% \pm 0.040\% \pm 0.034\%$

Figure 4: Time-dependent decay rate asymmetries for B_d mixing measurement, fitted simultaneously.



3.4 $B_s \to D_s\pi$

The decay of B_s to the flavour-eigenstate $D_s\pi$ is the "flagship mode" for B_s mixing at CDF. Being fully reconstructible (no missing ν), it provides for excellent time resolution - in topologically similar decays, CDF currently achieves ~ 67 fs, and hopes to improve once the innermost Si layer has been fully commissioned and aligned. In $119\,\mathrm{pb}^{-1}$, 84 ± 11 $B_s \to D_s\pi$ have been reconstructed with a signal to background ratio of ~ 2. The reconstruction efficiency has been increased since data taking has started and is now at ~ 1.6 events per pb^{-1}. These data can be used to calculate the relative production×B.R. in $B_s \to D_s\pi$ and $B_d \to D\pi$:

$$\frac{f_s \cdot BR(B_s^0 \to D_s^- \pi^+)}{f_d \cdot BR(B_d^0 \to D^- \pi^+)} = 0.35 \pm 0.05 \pm 0.04 \pm 0.09(BR)$$

where the last error is due to the uncertainty in the B.R. of the charm mesons.

3.5 B_d mixing

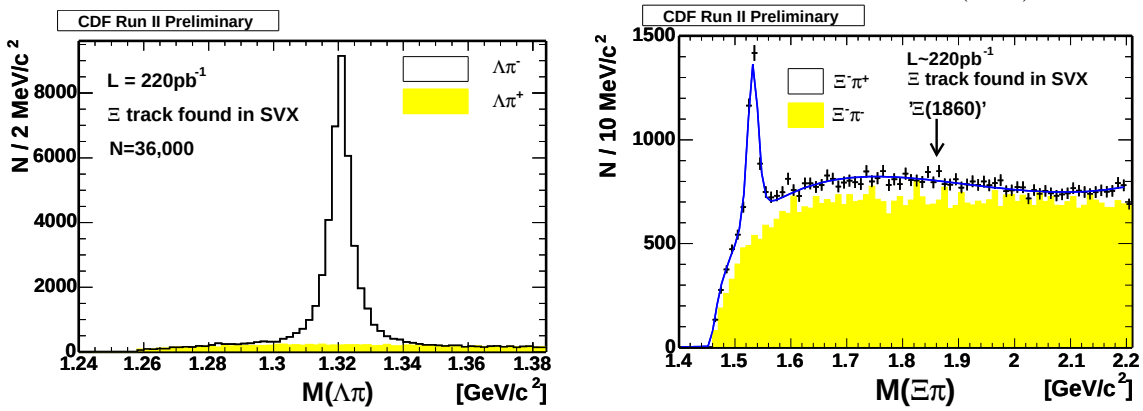
A further step towards measuring B_s mixing is to make the somewhat easier measurement in the B_d system and check for consistency with the well-established results from the B factories, and Run 1. About $1k$ $B_d \to J/\psi K^*$ and $5k$ $B_d \to D\pi$ events from $270\,\mathrm{pb}^{-1}$ were used for this measurement. The mass difference is extracted by measuring the oscillation frequency in time-dependent decay rate asymmetries. The asymmetries are between B decays that did not change flavour (e.g. $B^0 \to \bar{D}^0\pi^-$, neglecting Cabbibo suppressed decays)), and those that did (e.g. $B^0 \to D^0\pi^+$). In the measurement presented here, the flavour of the B^0 at birth was determined using same-side tagging only, which is based on the correlation of the B_d^0 or $\bar{B}_d^0$ flavour at birth, and the charge of the pion produced alongside, picking up the "left over" $\bar{d}$ or d quark. (The same principle can be applied to B_s mesons, using Kaon tags.) The tagging efficiency and dilution are measured using charged B decays. The tagging power for same-side pion tagging is

$$\varepsilon D^2 = (1.0 \pm 0.5 \pm 0.1)\,\%.$$

where $\varepsilon = (63 \pm 0.6)\%$ is the tagging efficiency (fraction of tagged events) and $D = (12.4 \pm 3.3)\%$ the "dilution" defined as $D \equiv (1 - 2\omega)$, where ω is the mis-tag fraction. Note that a large "dilution", according to this definition, is a good thing. The tagging power εD^2 describes the statistical power of the tag: N events before tagging are statistically equivalent $\varepsilon D^2 \times N$ perfectly tagged events. A simultaneous fit to the time-dependent decay rate asymmetries in $B_d \to J/\psi K$ and $B_d \to D\pi$, shown in Figure 4 yields for the mass difference in the B_d system:

$$\Delta m_d = (0.55 \pm 0.10 \pm 0.01)\ \mathrm{ps}^{-1}$$

Figure 5: Searching for Ξ(1860).
(a) $\Xi^- \to \Lambda(p\pi)\pi^-$ reconstruction. (b) Invariant mass $M(\Xi^-, \pi^\pm)$. The peak at 1530 MeV is the well-known $\Xi^0(1530)$.



Opposite side tagging In independent studies, other tagging methods have been investigated. Opposite side muon tagging yields a tagging power of $\varepsilon D^2 = (0.660 \pm 0.093)\,\%$, jet charge tagging $\varepsilon D^2 = (0.419 \pm 0.024(stat))\,\%$. Further taggers are under investigation.

3.6 Pentaquarks

The impact-parameter based trigger does not only provide large numbers of bottom and charm mesons, but of all long lived particles, including the Ξ^-. Combining this with a pion allows to search for the $\Xi^0(1860)$ and Ξ^{--} observed at NA49[1], which is often interpreted as a pentaquark.

CDF searches for the $\Xi^0(1860)$ and Ξ^{--} in the decay modes $\Xi^0(1860) \to \Xi^-\pi^+$ and $\Xi^{--} \to \Xi^-\pi^-$ with $\Xi^- \to \Lambda(p\pi)\pi^-$. The Ξ^- lives long enough to leave hits in the Si detector before decaying. Requiring hits from the Ξ^- in the Si provides a very efficient cut. Figure 5 (a) shows the mass distribution a sample of $36,000$ Ξ^-. The tiny background contribution, estimated from wrong-charge combinations, is superimposed as the shaded histogram.

In a second step, the Ξ^- is combined with a $\pi^\pm$. Figure 5 (b) shows the invariant mass distribution for same charge (shaded histogram) and opposite charge (black crosses) combinations of Ξ^- and pions. The line represents a fit to the opposite charge mass distribution. There is a clear peak at the well-known $\Xi^0(1530)$ resonance, that is used as a reference in this analysis. However, neither the same sign nor the opposite sign combination show any evidence of a resonance at 1860 MeV. As a cross check, the analysis was repeated using the Jet20 trigger sample, that is not affected by an impact parameter cut. For $4k$ Ξ^- in the Jet20 sample, no evidence of a Ξ(1860) was found. The 95% upper confidence limits for the *ratio* of Ξ(1860) to the known $\Xi^0(1530)$ are:

$\Xi^-\pi^+$ (search) / Ξ(1530)(control)	0.07
$\Xi^-\pi^-$ (search) / Ξ(1530)(control)	0.04

4 Conclusion

Large numbers of B hadrons of all flavours are produced at the Tevatron. CDF has measured the b production cross section in $b \to J/\psi X$ events. Fully reconstructed $B \to J/\psi X$ events have been used for precise lifetime measurements of B_d, B_s and Λ_b hadrons, which will provide a test of Heavy Quark Expansion. The CP content of $B_s \to J/\psi\phi$ has been measured using a transversity angle analysis, which will be combined with the lifetime measurment to extract $\Delta\Gamma_s$. Data from

the leptonic B trigger were also used to obtain the best current limit on the B.R. of $B_s \to \mu\mu$, one of the most sensitive probes of new physics at the Tevatron.

CDF's high bandwidth Two Track Trigger provides a unique sample of hadronic B and Charm decays, including $B \to hh$, which led to the first observation of $B_s \to KK$, and will be used for CP violation studies as more data become available. First steps towards a B_s mixing measurement have been taken with the reconstruction of $B_s \to D_s\pi$ events, and mixing measurements in the B_d system.

The huge sample of Ξ^- found in the Two Track Trigger has been used for a sensitive search for $\Xi(1860)$, which was not found. The B triggers will be used for many more pentaquark searches, especially those decaying to J/ψ or D and baryons.

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