B, Λ_b and Charm Results from the Tevatron

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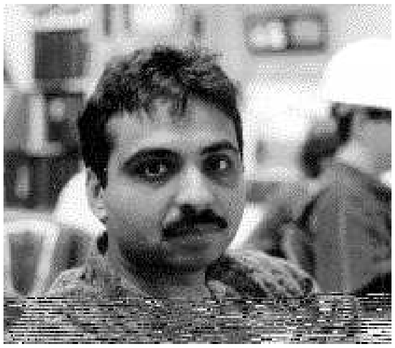

ABSTRACT

Recent results on B_d, $B_u^{\pm}$, B_s, Λ_b and Charm hadrons are reported from $\approx 75 \mathrm{pb}^{-1}$ and ≈ 40 pb^{-1} of data accumulated at the upgraded CDF and D0 experiments at the Fermilab Tevatron $\bar{p}-p$ collider, during Run-II. These include lifetime and mass measurements of B and Charm hadrons, searches for rare decays in charm and B hadrons and CP-violation in Charm decays. Results relevant to CP-violation in B-decays are also reported.

1 Tevatron $p-\bar{p}$ collider and performance during Run-II

The Tevatron $p-\bar{p}$ collider is being used for extended data-taking for the second time in 10 years. During the period between 1992 and 1996 (Run-I) an integrated luminosity of 110pb^{-1} was delivered; the goals for the current period starting May 2001 (Run-II) are 2 fb^{-1}, which is a × 20 increase over Run-I. The upgrades for Run-II consist of a new injection stage delivering more protons, an increased $\bar{p}$ transfer efficiency and a $\bar{p}$ recycler (undergoing commisioning) that uses remaining $\bar{p}$ from the previous store. A table of Run-I and Run-II operating parameters is given in table 1. The peak luminosity, though improving, is still × 4 below target.

Table 1: *Tevatron Performance Improvement Run-I vs. Run-II.*

	Collision Rate	Bunches	Center of Mass Energy	Peak Luminosity
Run-I:	3.5μs (Run-I)	6x6	1.8 TeV/c^2	2.4x10^{31}
Run-II:	396 ns	36x36	1.96 Tev/c^2	4.4x10^{31}

2 B Physics at Hadron Colliders: The CDF and D0 Detectors

The $b\bar{b}$ production cross section $\sigma(b\bar{b})$ is $\approx 150\mu$b at $p-\bar{p}$ at the Tevatron, 1 nb at the $\Upsilon(4s)$ and 7 nb at the Z_0. All B-hadrons are produced at the Tevatron (unlike the B factories), the drawback being the inelastic cross section which is $1000\times\sigma(b\bar{b})$ making online data selection crucial.

The CDF [1] and D0 detectors [2] have been described elsewhere. In order to utilize the high $b\bar{b}$ production cross section clean signatures of B hadron decays must be used when selecting data online. During Run-I CDF used the clean signatures of $B \to J/\psi \to \mu^+\mu^-$ and the decays of B hadrons to high transverse momentum (P_T) leptons. Now the long lifetime of B hadrons is being utilized at CDF, events containing ≥2 tracks with high impact parameters (d_0) consistent with being daughters of B hadrons are selected using the Silicon Vertex Trigger, events selected in this way are categorized as “hadronic B trigger” or “displaced track trigger” events. Another trigger used for B selection selects events requires the presence of a single high P_T lepton and a high d_0 track, this is called the “lepton+SVT trigger ” or “lepton+displaced track trigger”. The high d_0 triggers have allowed CDF to significantly advance its B and charm physics capability, now CDF can reconstruct B decays to fully hadronic final states as well as use the conventional J/ψ and high P_T lepton triggers.

The D0 experiment utilizes the $\mu^+\mu^-$ signature to select J/ψs (which may be prompt or long-lived—coming from B hadrons). D0 triggers also use B decays to high P_T leptons. With the advent of a magnetic field and a completely new tracking system D0 has acquired a whole new capability in B physics and several $B \to J/\psi X$ decay modes have been observed during Run-II. The D0 experiment is on its way to introducing a hadronic B trigger that uses online silicon pattern recognition to select tracks with high d_0, this will be a welcome addition to D0's already enhanced capability in B physics.

3 Physics Results: Testing Heavy Quark Expansion: Lifetimes of B Hadrons at CDF and D0

Precise measurements of lifetimes of B hadrons allow tests of the Heavy Quark Expansion (HQE) which predicts the following hierarchy for B hadron lifetimes: $\tau_{B_c^\pm} < \tau_{\Lambda_b} < \tau_{B_d} \approx \tau_{B_s} < \tau_{B_u^\pm}$. Both CDF and D0 are working toward precision tests of this theory.

3.1 Charged to Neutral Lifetime Ratio of B Hadrons, and B_s Lifetime from fully reconstructed decays

The ratio of the lifetimes of $B_u^\pm$ to B_d has been measured at CDF, and the $B_u^\pm$ lifetime has been measured at D0 using fully reconstructed $B_d \to J/\psi K^*$ and $B_u^\pm \to J/\psi K^\pm$ decays. The decays are fully reconstructed, the invariant mass and proper decay length ($c\tau$) distributions of the Bs are calculated from an un-binned log-likelihood function determining both mass and lifetime in a single fit. The result is 1.11 ± 0.09 at CDF using 70 pb^{-1} of data, whereas the $B_u^\pm$ lifetime has been measured to be 1.76 ± 0.24 ps at D0. Both these measurements test HQE and are consistent with the more accurate measurements at BaBar and Belle.

3.2 B_s Lifetime from the fully reconstructed decay $B_s \to J/\psi\phi$, $J/\psi \to \mu^+\mu^-$ and $\phi \to K^+K^-$

The world's largest number of fully reconstructed B_s decays has been at the Tevatron since Run-I. CDF and D0 has successfully reconstructed this decay using data from their $J/\psi \to \mu^+\mu^-$ trigger during Run-II, the reconstructed signals are shown in Fig. 1. A measurement of the lifetime is underway at D0, CDF has measured a ratio of $\frac{\tau B_s}{\tau B_d} = 0.89 \pm 0.15$ based on 70pb^{-1} collected during Run-II.

Strictly speaking this ratio isn't what should be tested, since the CP composition of the final state is not known. The final state is a mixture of CP eigenstates,

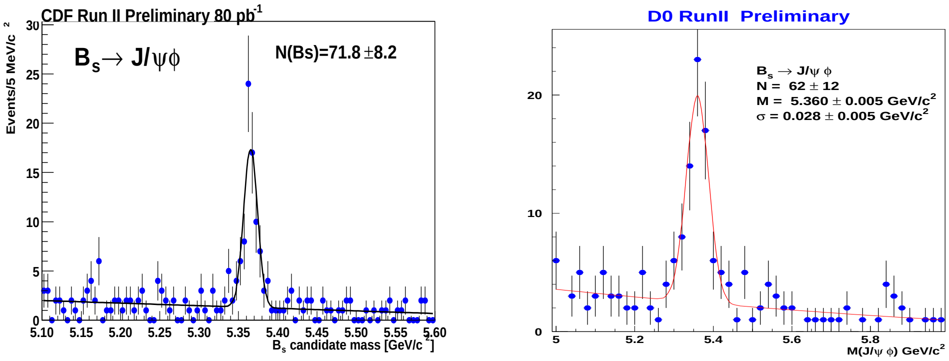

Figure 1: *$B_s \to J/\psi\phi$ with $J/\psi \to \mu^+\mu^-$ and $\phi \to K^+K^-$ at CDF (72 events) and D0 (61 events)*

and the B_s CP even and odd eigenstates can have a difference in lifetime of upto 10 % as predicted by theory, by fitting a single lifetime in this mode an "average" lifetime has been determined. The relationship between splitting in width (lifetime) of the B_s CP eigenstates and the B_s mixing parameter is known in the Standard Model, therefore a measurement of the width (lifetime) difference and mixing parameter provides a test of new Physics. It is planned to measure the lifetime difference of the B_s CP eigenstates by utilizing angular variables to disentangle the two CP eigenstates and fitting two lifetimes, this approach will become viable with higher statistics. An accuracy of 5 % in determining the lifetime splitting is expected at CDF using 4000 $B_s \to J/\psi\phi$ decays.

A clean measurement of the width difference $(\frac{\Delta\Gamma}{\Gamma})_{Bs}$, can be made by measuring a single lifetime in a decay of the B_s to a CP eigenstate *e.g.* $B_s \to D_s^+ D_s^-$ and $B_s \to K^+K^-$. This approach is planned as well.

3.3 Measurement of the Λ_b Lifetime

The Λ_b has been reconstructed at both CDF and D0 in various modes, Fig. 2 shows the reconstruction in the fully hadronic mode at CDF and in $\Lambda_b \to J/\psi\Lambda$ at D0.

CDF has also reconstructed Λ_b in the decays $\Lambda_b \to J/\psi\Lambda$ (53 events) and $\Lambda_b \to \Lambda\ell\nu_\ell$ (640 events) and in the purely hadronic decay mode $\Lambda_b \to \Lambda_c^\mp\pi^\pm$ with $\Lambda_c \to pK\pi$. A lifetime measurement has just been completed at CDF using the fully reconstructed decay $\Lambda_b \to J/\psi\Lambda$ with a result $\tau_{\Lambda_b} = 1.25 \pm 0.26(stat) \pm 0.1(syst)$ ps shown in Fig. 3. Work on D0's Λ_b lifetime currently underway.

The decays $\Lambda_b \to \Lambda_c^\pm\ell\nu_\ell$ and $\Lambda_b \to \Lambda_c^\pm\pi^\mp$ are selected using a trigger with d_0 cut, the resulting biases in the $c\tau$ distribution have to be understood before a

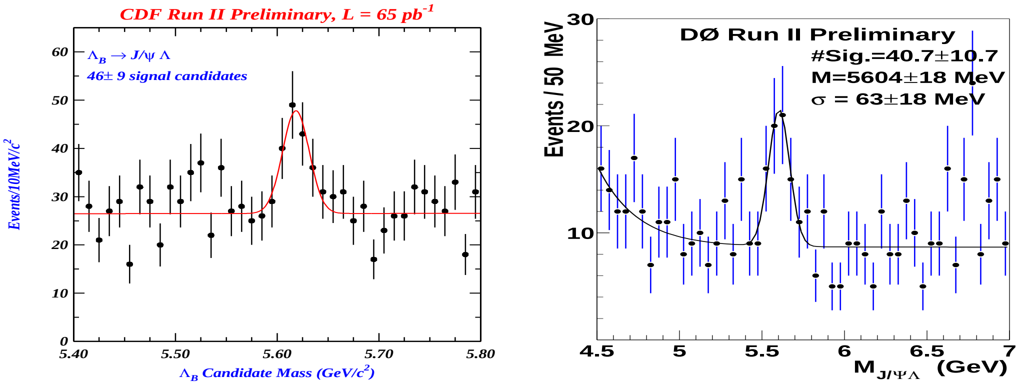

Figure 2: *CDF (left) and D0 (right) reconstruction of* $\Lambda_b \to J/\psi\Lambda$*.*

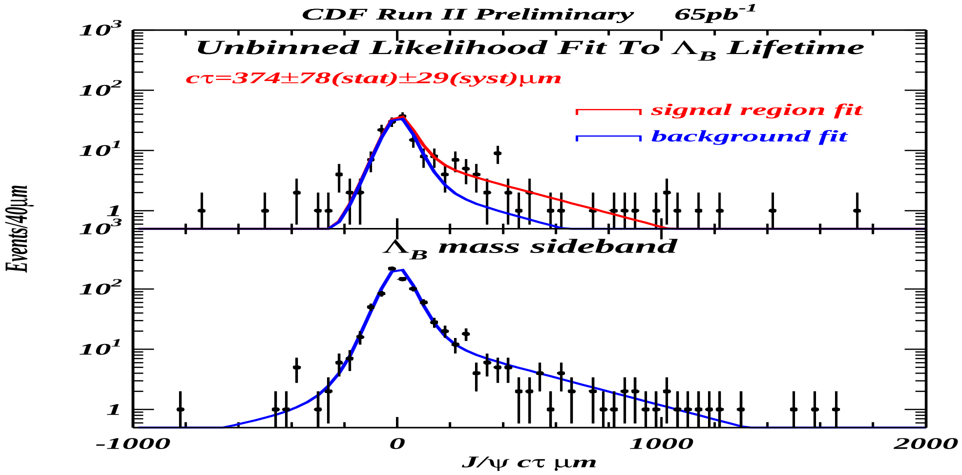

Figure 3: *Lifetime distribution of* $\Lambda_b \to J/\psi\Lambda$ *decays at CDF in micro-meters.*

lifetime measurement from these modes can be completed and CDF expects this will be done soon.

4 Charm Physics: $D_s^\pm - D^\pm$ mass difference

The first CDF Run-II publication [3] was a measurement of the mass difference $\Delta M = M_{D_s^\pm} - M_{D^\pm}$. Both the $D_s^\pm$ and $D^\pm$ decay to $\phi\pi^\pm$ with $\phi \to K^+K^-$ with almost identical kinematics. Using data selected by the displaced-track hadronic trigger 2400 $D_s^\pm$ and 1600 $D^\pm$ were reconstructed using only 11.6 pb^{-1} of data. The measurement of $\Delta M = 99.28 \pm 0.43(stat) \pm 0.27(syst)$ MeV/c^2 is consistent with the current world average [16] of 99.2 ± 0.5 MeV/c^2.

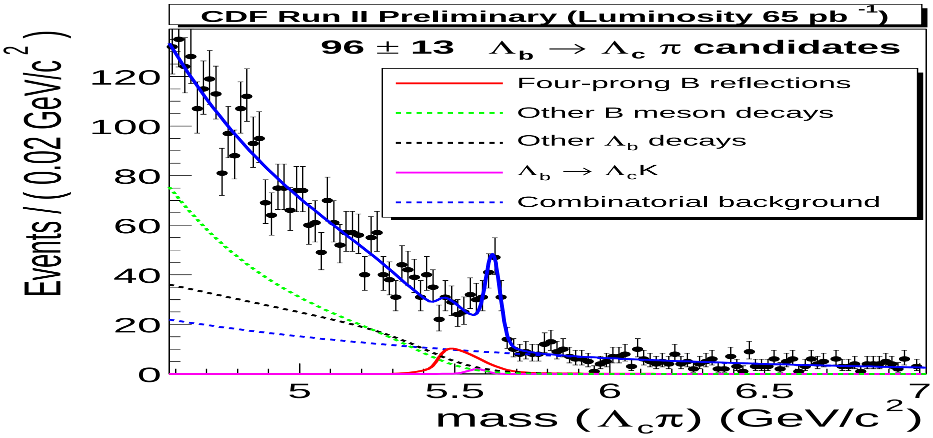

Figure 4: *Invariant Mass distribution of the purely hadronic* Λ_b *decay mode* $\Lambda_b \to \Lambda_c^{\pm}\pi^{\mp}$ *at CDF.*

5 Rare Decays: The Search for the Flavour Changing Neutral Current Decay $D \to \mu^+\mu^-$ and $B_s^0 \to \mu^+\mu^-$

The standard model predicts a branching ratio of $O(10^{-13})$ for the decay $D^0 \to \mu^+\mu^-$ via second order weak interactions. Some R-parity violating SUSY models predict branching ratios $\leq O(10^{-6})$ [10]. CDF has searched for $D^0 \to \mu^+\mu^-$ decays using hadronic trigger data and $D^0 \to \pi^+\pi^-$ decays which have almost identical acceptance and kinematics to $D^0 \to \mu^+\mu^-$. The probability of a $\pi^{\pm}$ faking a $\mu^{\pm}$ must be calculated, unambiguously identified pions are obtained using the decay chain $D^{*\pm} \to D^0\pi^{\pm}$, $D^0 \to K^{\mp}\pi^{\pm}$, the charge of the $\pi^{\pm}$ from the $D^{*\pm}$ determines the flavour of the D^0 and distinguishes the $K^{\pm}$ from the $\pi^{\pm}$. The number of times a $\pi^{\pm}$ is reconstructed as a $\mu^{\pm}$ is determined after which $D^0 \to \mu^+\mu^-$ are reconstructed and expected number of $D^0 \to \pi^+\pi^-$ decays faking $D^0 \to \mu^+\mu^-$ is subracted, 0 events are found in a 2σ search window. A limit for this branching ratio $\leq 2.4 \times 10^{-6}$ is calculated at 90 % confidence level, better than the best published limit of 4.1×10^{-6} [11] [16].

CDF has done a similar analysis of the decay $B_s \to \mu^+\mu^-$ using 113 pb^{-1} of Run-II data. Standard Model prediction for the branching ratio is $3.8 \pm 1 \times 10^{-9}$. Various SUSY models [13] allow for an enhancement by a factor of upto $\times 10^3$, areas of m-SUGRA space that overlap those predicting deviations of the g_μ from 2 are roughly consistent [14] with recent experimental measurements [15]. CDF's measurement yields limits $BR(B_s \to \mu^+\mu^-) < 9.5 \times 10^{-7}$ and 1.2×10^{-6} at the 90 % and 95 % confidence intervals respectively—a factor of 2 better than the best previous measurement [16].

6 CP Violation in Charm Decays

The Standard model prediction for CP violation in charm decays is of order 0.1-1 %. Since c and u quarks do not couple to t quarks, box diagram contributions to mixing in charm are tiny, and so CP violation in Charm decays is almost entirely due to interference in decay (direct CP violation). A search for CP violation in charm decays has been done at CDF. Rates of decays of D^0 and $\bar{D^0}$ decaying to the CP eigenstates $f = K^+K^-$ and $f = \pi^+\pi^-$ are measured. The flavour of the D^0 is tagged as described in section 5, and $D^0 \rightarrow \pi^+\pi^-$ and $\rightarrow K^+K^-$ decays are reconstructed and counted and the asymmetry

$$A_{CP} = \frac{\Gamma(D^0 \rightarrow f) - \Gamma(\bar{D^0} \rightarrow f)}{\Gamma(D^0 \rightarrow f) + \Gamma(\bar{D^0} \rightarrow f)} \tag{1}$$

for each mode is calculated. The results are $A_{CP}(D^0 \rightarrow \pi^+\pi^-) = 2.0 \pm 1.7(stat) \pm 0.6(syst)$ % and $A_{CP}(D^0 \rightarrow K^+K^-) = 3.0 \pm 1.9(stat) \pm 0.6(syst)$ %, consistent with both the world averages of 0.5 ± 1.6 % and 2.1 ± 2.6 % [16] and better than the most recent (2001) CLEO results of $0.0 \pm 2.2 \pm 0.8$ % and $1.9 \pm 3.2(stat) \pm 0.8(syst)\%$ respectively [4].

As a check of possible biases in counting, the ratios of branching ratios: $\frac{\Gamma(D^0 \rightarrow K^+K^-)}{\Gamma(D^0 \rightarrow K^\pm\pi^\mp)}$ and $\frac{\Gamma(D^0 \rightarrow \pi^+\pi^-)}{\Gamma(D^0 \rightarrow K^\pm\pi^\mp)}$ were also calculated and found to be $9.38 \pm 0.18(stat) \pm 0.10(syst)\%$ and $3.686 \pm 0.076(stat) \pm 0.036(syst)\%$ respectively. These compare well with the measurements at FOCUS [6] $9.93 \pm 0.14(stat) \pm 0.14(syst)\%$ and $3.53 \pm 0.12(stat) \pm 0.06(syst)\%$.

7 Towards CP violation in B-hadron decays and B_s mixing

In Run-I the CDF was able to competetively measure the B_d mixing parameter $(\frac{\Delta M}{\Gamma})_{B_d} = x_d$ and also perform a 2σ measurement of the CP asymmetry in the decay $B_d \rightarrow J/\psi K_S$ ($\sin 2\beta$) [9]. The Run-I measurement was $\sin 2\beta = 0.79 \pm 0.39(stat) \pm 0.16(syst)$, BaBar and Belle already have measurements of $0.76 \pm 0.067(stat) \pm 0.034(syst)$ and $0.733 \pm 0.057(stat) \pm 0.028(syst)$ respectively [7] [8]. With ×40-50 more decays expected when 2 fb^{-1} have been accumulated, CDF's precision should be $\delta(\sin 2\beta) \approx 0.05$, D0 should have similar statistics. Clearly D0 and CDF cannot compete with the B-factories $\sin 2\beta$ measurement, but $\sin 2\beta$ will be measured as a benchmark, and a test of various flavour tagging schemes.

Various tagging schemes are under examination at CDF; including jet-charge, opposite and same-side tagging and using time of flight to identify Ks. A final number for the statistical power *i.e.* ϵD^2 has not yet been calculated using data.

7.1 Measurement of $\sin 2\gamma$ using $B_d \rightarrow \pi^+\pi^-$ and $B_s \rightarrow K^+K^-$

Both tree and penguin graphs contribute to $B_d \rightarrow \pi^+\pi^-$ and $B_s \rightarrow K^+K^-$ with the tree dominating in the former and the penguin in the latter. Without the penguin contributions the CP asymmetry (A_{CP}) in $B_d \rightarrow \pi^+\pi^-$ is proportional to the CKM quantity $\sin 2(\gamma + \beta)$ and A_{CP} in $B_s \rightarrow K^+K^-$ is proportional to $\sin 2\gamma$. Assuming **SU(3)** symmetry and interchanging s and d, the hadronic matrix element penguin to tree ratios are the same, the mixing and decay induced $A_{CP}(t)$ are functions of $\sin 2\gamma$, $\sin 2\alpha$, $\sin 2\beta$, the ratio of the hadronic matrix element amplitudes and the phase of this ratio. A measurement of the A_{CP} thus determines $\sin 2\gamma$ and $\sin 2\alpha$. Before measuring this asymmetry the various $B_d \rightarrow h^+h^-$ and $B_s \rightarrow h^+h^-$ decays must be separated. Reconstructing $B_d \rightarrow \pi^+\pi^-$ without clear hadron identification leads to a very broad peak in which the individual modes $B_d \rightarrow K^\pm\pi^\mp$, $B_s \rightarrow K^\pm\pi^\mp$, $B_d \rightarrow \pi^+\pi^-$ and $B_s \rightarrow K^+K^-$ are indistinguishable. These can be separated at CDF utilizing $\frac{dE}{dx}$ using drift chamber charge deposition and kinematical variable separation. CDF has reconstructed 39 ± 14 $B_d \rightarrow \pi^+\pi^-$ and 90 ± 17 $B_s \rightarrow K^+K^-$ decays, the latter is a first observation. The invariant mass distribution of all B hadrons decaying to h^+h^- is shown in figure 5.

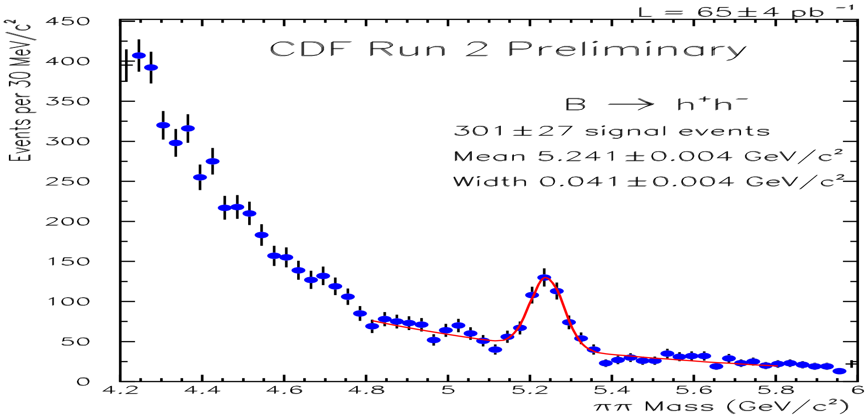

Figure 5: *Invariant Mass distribution of all* $B \rightarrow h^+h^-$, *decays at CDF. Both tracks are assigned the mass of a* π.

As a check the ratio of branching ratios $\frac{\Gamma(B_d \rightarrow \pi^+\pi^-)}{\Gamma(B_d \rightarrow K^\pm\pi^\mp)}$ has been measured, the result $0.26 \pm 0.11(stat) \pm 0.055(syst)$ is consistent with the world-average 0.253 ± 0.064 [16]. The CDF experiment expects to be able to measure γ to an accuracy of $\sigma(\gamma) \approx 10$ degrees.

7.2 Measurement of the B_s Mixing parameter $x_s = \frac{\Delta M_{B_s}}{\Gamma_{B_s}}$

The measurement of the B_s mixing parameter $x_s = \frac{\Delta M_{B_s}}{\Gamma_{B_s}}$ is one of the major goals of the Tevatron during Run-II. An observation of the flagship mode for measuring x_s, $B_s \rightarrow D_s^{\pm}\pi^{\mp}$ has been made at CDF. In addition to this mode B_s mixing can also be measured using modes such as $B_s \rightarrow \mu^{\pm}\nu_{\mu}D_s^{\mp}$ and $B_s \rightarrow e^{\pm}\nu_e D_s^{\mp}$, however the vertex resolution in these decays is worse due to the missed neutrino. If a single B_s lifetime is fit in any of these or any flavour specific mode the relation between the fit lifetime τ_{fit} and the CP odd and even lifetimes τ_{CP+}, τ_{CP-} is $\tau_{fit} = \frac{(\tau_{CP+}^2 + \tau_{CP-}^2)}{(\tau_{CP+} + \tau_{CP-})}$, which can be used for a measurement of $\Delta\Gamma_{B_s}$ and to provide a useful constraint for the two-lifetime fit with $B_s \rightarrow J/\psi\phi$ described earlier. The first observation of 40 $B_s \rightarrow D_s^{\pm}\pi^{\mp}$ decays has been made using hadronic trigger data at CDF, shown in Fig. 6. Also 309 $B_s \rightarrow \mu^{\pm}\nu_{\mu}D_s^{\mp}$ and 245 $B_s \rightarrow e^{\pm}\nu_e D_s^{\mp}$ have been observed using lepton+displaced track trigger data.

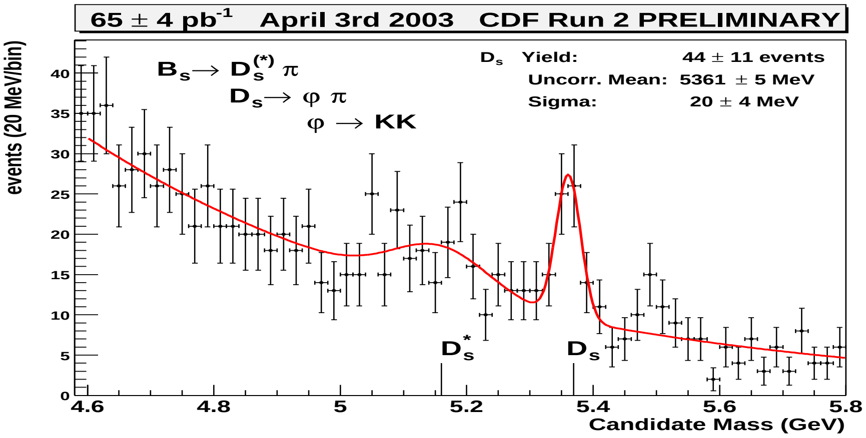

Figure 6: *First observation of $B_s \rightarrow D_s^{\pm}\pi^{\mp}$, made at CDF.*

8 Conclusions

Both CDF and D0 are in the first phase of data taking ($\int Ldt < 200\text{pb}^{-1}$) which will test HQE with Λ_B and B_s lifetimes, and yield limits for CP violation and rare decays in B and charm decays. Tagging and lifetime measurement techniques (for hadronic trigger data) will also be tested. In the next phase ($200 < \int Ldt < 500\text{pb}^{-1}$) limits on B_s mixing will be set and CP violation searches in the B system will be done. In the final phase ($500 < \int Ldt < 2000\mathrm{pb}^{-1}$) $\Delta\Gamma_{B_s}$, x_s, and the CKM angle γ will be measured and finally a search for unexpectedly large CP violation in $B_s \rightarrow J/\psi\phi$ will be pursued.

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