

Recent Results from DØ and CDF

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Abstract A summary of the Tevatron's measurements and searches for pentaquarks and X(3872) are presented. No evidence for pentaquarks has been observed, while the X(3872) has been confirmed and some characterization has been performed. While the initial measurements are of a simple nature, the X(3872) behaves similarly to the $\psi(2S)$, suggesting the X(3872) may be a form of unanticipated charmonium rather than a more exotic bound state of D mesons. In addition, a selected number of lifetime measurements of b-quark carrying hadrons are presented. While preliminary, these measurements are becoming competitive in precision with the B factories. These Proceedings end with some interesting measurements of the inclusive Pt and dijet mass cross-sections of b-quark containing jets.

Fermilab's Run II, which began in February of 2001, is producing many results that are now becoming available. While much of the two collider experiment's efforts are aimed at the energy frontier, there are a considerable number of physicists working on the interesting field of research of interest to this Conference: lower energy behavior which does not lend itself to easy perturbative QCD calculations. While the two experiments have presented many preliminary results regarding b-quark carrying hadron spectroscopy, time and space considerations only allow a few to be described here. In addition, much recent effort has been put into the study of an entirely new type of hadron, the so-called pentaquark, containing four quarks and an anti-quark. While the traditional high-Pt jet measurements are not the focus of this Conference, a newer series of measurements of the exclusive state of b-quark containing jets are becoming available.

In the summer of 2003, the several experiments reported evidence of a new hadron, since named the Θ^+ pentaquark, interpreted as containing the quark structure uudds. A review of the experimental signature is given in [1]. The pentaquark was not entirely unprecedented, being predicted soon after the proposal of the quark model [2], but had not been observed previously. Since the initial observation, several groups have tried to confirm the observation, with ten reporting supporting evidence and three finding no corroborating signal. The Θ^+ pentaquark has been observed decaying into two modes ($p^+ K_s^0$ and $n K^+$) although generally not both modes by one experiment. (For the all of the following discussion, the study also includes the charge conjugate state.)

The CDF collaboration, with its superb particle identification, has looked carefully for the Θ^+ . Figure 1a shows the clear distinction between protons, kaons and pions, using standard time of flight (TOF) methods. Not shown, but also present is a complementary particle identification system using dE/dx .

Both are combined to extract a fairly-pure proton signal. Figure 1b clearly shows the K_s^0 peak, containing nearly 700k K_s^0 's. In this study, the $K_s^0 \rightarrow \pi^+\pi^-$ decay mode was used.

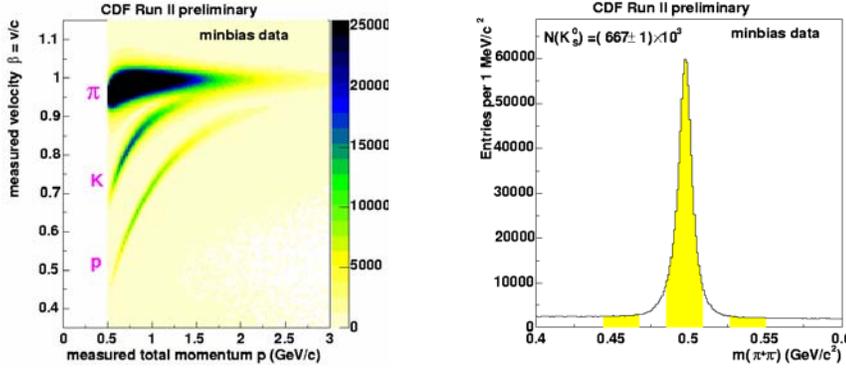


Figure 1 (a) π , K, p separation using the CDF's TOF system. (b) a clear K_s^0 peak.

Before tackling the pentaquark signal, CDF verified that they were sensitive to hadrons of similar mass. $\phi \rightarrow K^+ K^-$, $K^{*0} \rightarrow K^+ \pi^-$, $\Lambda(1520) \rightarrow p^+ K^-$ and $K^{*+} \rightarrow K_s^0 \pi^+$ are the four channels used to verify sensitivity to well-established hadrons in the mass region occupied by the Θ^+ . Figure 2 illustrates the sensitivity to the ϕ and the $\Lambda(1520)$. The other signals are similar.

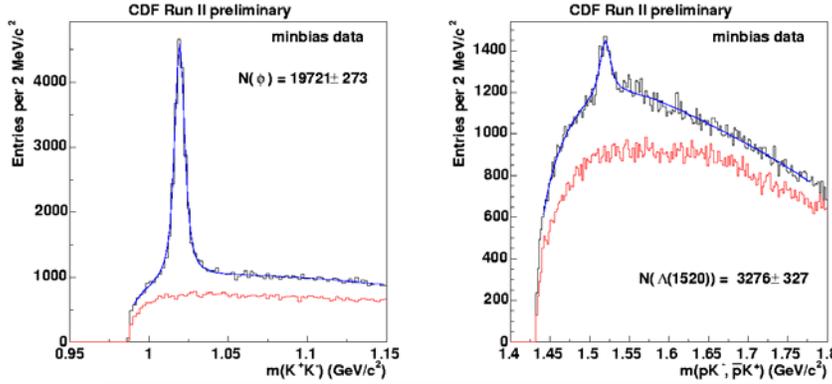


Figure 2 (left) ϕ signal (right) $\Lambda(1520)$ signal. In both cases the blue (signal containing) curves are opposite sign decay product combinations, while the red (no signal) curves are same-sign.

With experimental sensitivity established, CDF presents their results by simply showing the mass distribution in the mass-region suggested by earlier experiments (1540 GeV). In figure 3, the mass distributions with and without a polynomial background subtraction are given. No evidence for an excess is observed.

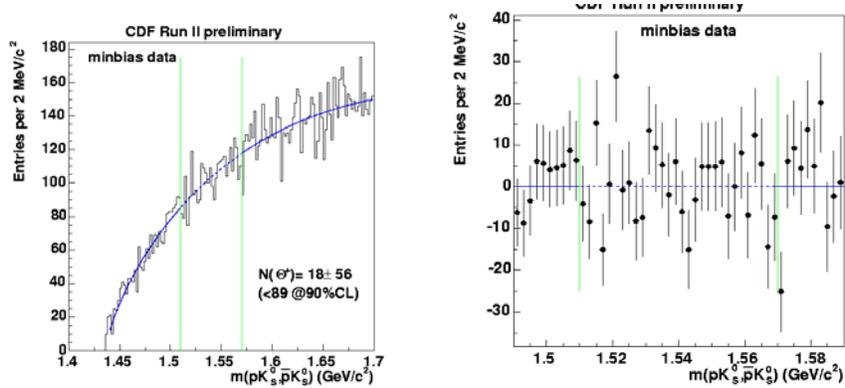


Figure 3 Results of a mass search of hypothetical particle with mass near 1540 GeV decaying into a proton and a K_s^0 . No excess is observed.

While the Θ^+ pentaquark was the first observed, it is not the only one. The H1 experiment has reported evidence for another pentaquark candidate [3], this one with a mass of 3099 GeV. This new pentaquark candidate was found by looking for particles decaying into $D^{*+} p$ and then $D^{*+} \rightarrow D^0 \pi^+$ and $D^0 \rightarrow K^- \pi^+$. CDF looked for the same mode. To establish sensitivity, they first looked for $D_1(2420)$ and $D_2^*(2460)$ which both decay via $D^{*+} \pi^-$, with the subsequent decay chain identical. CDF observed approximately 3M D^0 's, 0.5M D^{*+} 's and about 15k $D_1(2420)$ and $D_2^*(2460)$'s (combined).

With the experimental sensitivity established to hadrons of similar mass and decay chain, the search was expanded to include four separate channels ($\Theta_c^0 \rightarrow D^{*+} p$), ($\Theta_c^0 \rightarrow D^+ p$), ($\Theta_c^- \rightarrow D^0 p$) and ($\Theta_c^- \rightarrow D^0 p$). To fully exploit CDF's powerful particle identification, both TOF, and dE/dx methods were used. First a χ^2 was formed for each particle ID technique, testing the hypothesis that a particular track was a (p, e, K, μ or π). Then a combined $\chi^2 = \chi^2(\text{TOF}) + \chi^2(dE/dx)$ was calculated and used to determine a likelihood function [$lh = \exp(-\chi^2/2)$]. Finally a likelihood ratio $LH_{\text{desired particle}}$ is formed.

$$lh(i) = \exp(-\chi_i^2/2), \quad i \in \{p, e, K, \mu, \pi\}$$

$$LH_i = \frac{lh(i)}{lh(p) + lh(e) + lh(K) + lh(\mu) + lh(\pi)}$$

From the likelihood ratio, cuts were made (LH_p) were made to ensure that a(n) (anti)proton was present in the initial decay. As in earlier cases, the charge conjugate case is implied. Figure 4 shows examples of the mass distributions for the $D^0 p$ and $D^\pm p^\mp$ channels. No such pentaquark excess has been observed.

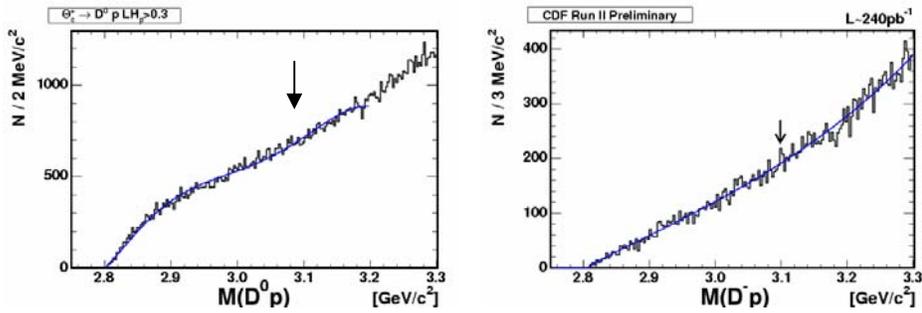


Figure 4 Mass distributions for (left) $D^0 p$ and (right) $D^\pm p^\mp$. For both distributions, the observed position for the Θ_c is indicated by arrows. No excess is observed. The results for the other decay channels mentioned in the text give comparable results

A third pentaquark candidate has been reported by the NA49 collaboration [4]. This pentaquark candidate is consistent for having two units of strangeness, hence the early name “ Ξ ”. Recently the commonly used name for this state is Φ . Two states have been observed, both with spin 3/2, one electrically neutral, while the other is doubly-negative. The so-called $\Phi_{3/2}^{--}$ decays into $\Xi^- \pi^-$ with $\Xi^- \rightarrow \Lambda \pi^-$, and $\Lambda \rightarrow \pi^- p$. The pentaquark candidate $\Phi_{3/2}^0$ decays into $\Xi^- \pi^+$ with the identical ensuing decay chain. This candidate was observed to have a mass of 1860 GeV.

As in the earlier pentaquark searches, CDF first established sensitivity to known hadrons of similar mass and decay chain. The hadron in this case is the $\Lambda(1530)$, which has a decay chain identical to the $\Phi_{3/2}^0$. Starting with a well-resolved Ξ^- peak, consisting of 36k events, CDF applied the standard particle identification techniques and present their observed mass distributions. These are seen in figure 5. The left-most plot contains their opposite-sign distribution, with the $\Lambda(1530)$ clearly seen. As expected, no such peak is observed in same-sign distribution. The position of the observed resonance at 1860 GeV is indicated and no excess is observed.

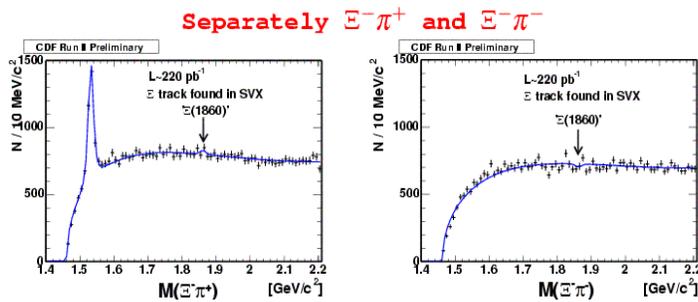


Figure 5 (left) mass distribution for $\Xi^- \pi^+$. (right) mass distribution for $\Xi^- \pi^-$. In both cases, no pentaquark candidate signal is observed.

CDF’s final pentaquark search is unique in that it is for a state that has not been observed in prior experiments. This state is a hypothetical long-lived state containing b-quarks [5]. These long-lived states have negative parity and the proposed quark content $b(ud)(su)$ and are predicted to decay into $J/\psi p^+$. The J/ψ is observed via standard di-lepton decay. This proposed pentaquark is named R_s^+ . The similar, well-established hadron used to establish detector sensitivity is $B^\pm \rightarrow J/\psi K^\pm$. CDF’s

ability to observe B mesons is well established, the results of which are mentioned later in this proceedings.

Because the R_s^+ is wholly theoretical, the search spans a greater phase space. The mass range that would yield a long-lived state is expected to be 5725 – 6380 MeV. Above a mass of 6215 GeV, the R_s^+ could decay strongly. In the event that the prediction of the longevity of the proposed pentaquark is in error, two distributions were made, the first requiring that the two-dimensional decay length exceeded 100 μm , while the other distribution required a smaller two-dimensional decay length (L_{xy}).

Figure 6 gives the mass distributions for $J/\psi p^+$ for both restrictions on the L_{xy} . Both plots present an additional curve, for which the particle identification for the proton is not imposed. In none of the plots is any statistically-significant excess observed.

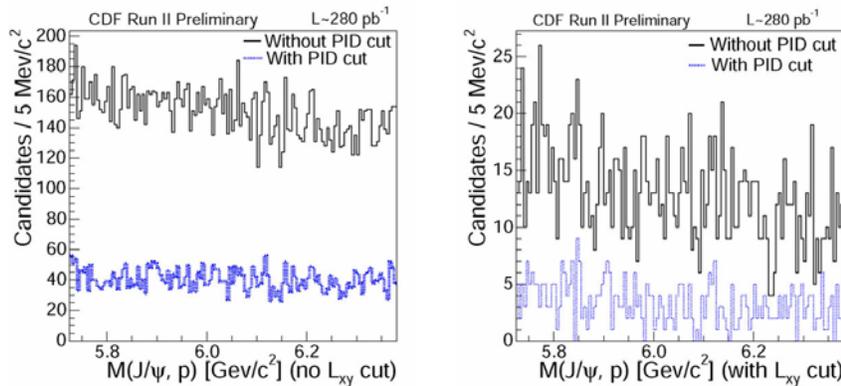


Figure 6 The mass distribution of $J/\psi p^+$ for $L_{xy} < 100 \mu\text{m}$ (left) and for $L_{xy} > 100 \mu\text{m}$ (right). The higher statistics curve is for no particle ID imposed on the proton candidate track, while the lower statistics curve has proton particle identification imposed. No excess is observed in the explored mass range.

In summary, no evidence is observed at the Tevatron for pentaquarks, previously observed or postulated. Given the broad number of experiments that have observed pentaquark evidence, one must wonder why CDF has not observed them. Since most experiments that have reported evidence for pentaquarks are generally of lower energy, it is possible that there is a suppression in the production mechanism at the Tevatron's higher energy. Clearly additional study is warranted.

While pentaquarks are a new and exciting opportunity to explore QCD dynamics, there exists another new particle, recently observed by the Belle experiment [6], that has its own mystery. The X(3872) was first observed in the decay chain of the B^+ meson ($B^+ \rightarrow K^+ X(3872)$, with $X(3872) \rightarrow J/\psi \pi^+ \pi^-$.) The mass of the X(3872) as reported by Belle is $3872.0 \pm 0.6 \pm 0.5 \text{ MeV}$. While Belle was the first experiment to claim discovery of this hadron, earlier experiments (E705 [7] and E672/E706 [8]) reported statistically suggestive, but not significant, signals.

Both the $D\bar{D}$ and CDF experiments have confirmed the existence of X(3872) [9], both reporting masses consistent with Belle's earlier measurement. Like Belle, both experiments have shown that the signal for X(3872) is only observed if a minimum mass is required of the $\pi^+ \pi^-$ pair, suggesting that perhaps the pion pair is not prompt from the X(3872) decay, but rather a subsequent decay from an intermediate state. At this Conference, both experiments promised to soon make available the mass distribution of the hypothesized intermediate state, but as of this writing, this is not available.

In figure 7, the CDF's mass distribution for $J/\psi \pi^+ \pi^-$ is shown with a maximum and minimum di-pion mass of 0.5 GeV. In both cases, the $\psi(2S)$ is clearly observed, while the X(3872) is only observed for higher di-pion masses. Similarly, the $D\phi$ experiment imposes a minimum di-pion mass of 0.6 GeV. Further, while CDF restricts their analysis to $|\eta| < 1.0$, $D\phi$ presents two separate angular regions ($|\eta| < 1.0$ and $1.0 < |\eta| < 2.0$). Both of these results are also presented in figure 7.

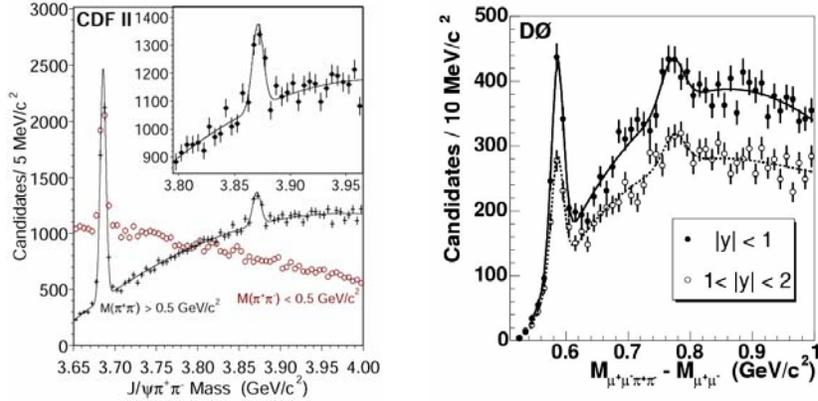


Figure 7 (left) CDF's X(3872) signal. (right) $D\phi$'s signal. Both experiments clearly confirm Belle's earlier observation. CDF's result clearly indicates the probability that the di-pions are the decay products of an intermediate state of moderate mass. In both plots, the $\psi(2S)$ is clearly evident.

While the observation and confirmation of the existence of the X(3872) is important, naturally the nature of the X(3872) is of interest. Various theories have been put forth, including an unexpected form of charmonium, a $D-D^*$ molecule and a ccg hybrid are but a few. Given the similarity in mass and overall charm content to the $\psi(2S)$, it is natural to compare gross features of the two hadrons. Towards this end, $D\phi$ has investigated several variables which explore various production characteristics. These variables are:

- The fraction of X(3872) or $\psi(2S)$ with a Pt > 15 GeV.
- The fraction produced with $|\eta| < 1$.
- The fraction of events in which θ_π (i.e. the helicity angle when boosted into the di-pion system) follows $[\cos(\theta_\pi) < 0.4]$.
- The fraction of events in which the hadron decays with 2D decay length less than 0.1 mm.
- The fraction of events in which the hadron of interest is isolated within a cone of radius 0.5.
- As (c) except in this case the reference frame is the di-muon frame.

Figure 8 shows a comparison between X(3872) and $\psi(2S)$ for the six variables. In all cases, the fractions are statistically identical.

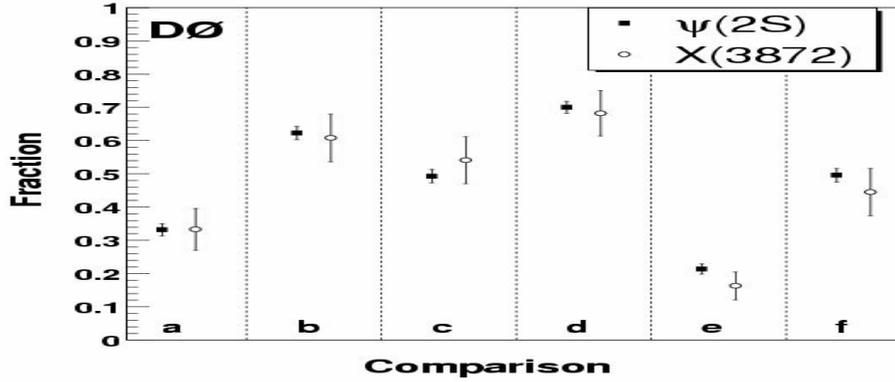


Figure 8 A comparison between X(3872) and $\psi(2S)$ for six variables, sensitive to various aspects of the production mechanisms. In all cases, the two hadrons decay in statistically-indistinguishable ways.

In addition, CDF performed an analysis similar to that defined by category (d) above. Specifically, an estimate of the “proper 2D decay length” was made.

$$L_{xy} = \frac{(\bar{x}_{decay} - \bar{x}_{primary}) \cdot \vec{p}_t}{|\vec{p}_t|}$$

$$ct = \frac{M(J/\psi \pi^+ \pi^-)}{p_t(J/\psi \pi^+ \pi^-)} L_{xy}$$

As DØ, CDF compared the behavior of X(3872) with that of $\psi(2S)$, in this case by finding the fraction of hadrons produced promptly as opposed to those produced through the longer-lived decay of other hadrons (e.g. Belle’s decay of the B^+). CDF quotes the fraction of $\psi(2S)$ ’s exhibiting long-lived behavior as $28.3 \pm 1.0(stat) \pm 0.7(sys)\%$. The identical fraction for X(3872) is $16.1 \pm 4.9(stat) \pm 2.0(sys)\%$. The approximately two standard deviation difference is insufficient to claim that the two hadrons are produced differently.

While the discussion thus far has focused on exotic hadrons, both DØ and CDF have also expended considerable effort towards characterizing the lifetime and lifetime ratios of a number of b-quark carrying hadrons. The results presented here achieved from a sample of 3390 (B^+), 1160 (B^0) and 260 (B_s) events [CDF], and (61) (Λ_b), 337 (B_s) and 1370 (B^0) events [DØ]. While the precision of the results presented here are preliminary, their precision begins to approach that of the single best measurement in many of the channels. When a full 2 fb^{-1} of luminosity is recorded, it is expected that the lifetime errors will be on the order of 1%.

	CDF	DØ
B^+	$1.662 \pm 0.033 \pm 0.008$ ps	$1.65 \pm 0.08 \pm 0.12$ ps (2003)
B^0_d	$1.539 \pm 0.051 \pm 0.008$ ps	$1.473 (+0.052 - 0.050, stat) \pm 0.023$ ps
B^0_s	$1.369 (+0.100 - 0.008) \pm 0.01$ ps	$1.444 (+0.098 - 0.090, stat) \pm 0.020$ ps
B_c	$0.46 (+0.18 - 0.16) \pm 0.03$ ps	$0.448 (+0.123 - 0.096, stat) \pm 0.121$ ps
Λ_b	$1.25 \pm 0.26 \pm 0.10$ ps (2003)	$1.221 (+0.217 - 0.179, stat) \pm 0.043$ ps
$\tau(\Lambda_b)/\tau(B^0)$	0.91 ± 0.20 (tot) (2003)	$0.874 (+0.169 - 0.142, stat) \pm 0.028$
$\tau(B^+)/\tau(B^0)$	1.08 ± 0.042 (tot.)	$1.080 \pm 0.016 \pm 0.014$
$\tau(B_s)/\tau(B^0)$	0.890 ± 0.072 (tot.)	$0.980 (+0.075 - 0.070, stat) \pm 0.003$

Table 1 Summary of lifetimes and lifetime ratios for various b-quark carrying hadrons. The reported errors are beginning to approach the world averages. With full luminosity, each experiment will approach 1% statistical error.

A final analysis presented here involves CDF's preliminary results looking at jet cross-sections for exclusively b-jets. DØ's results are under internal review and were not quite ready for this Conference. For CDF, the transverse momentum (b-jet only) cross-section is available. For this analysis, only 150 pb^{-1} of data is used and is restricted to the Pt range 30-210 GeV. A jet cone radius (η, ϕ) of 0.7 is used and the jets are restricted to the usual angular range of $0.1 < |\eta_{\text{jet}}| < 0.7$. Jets are tagged by means of the presence of a secondary vertex. In this analysis, which is very preliminary, only a shape analysis is presented, with no unsmearing. The data is compared to fully-simulated Pythia. Figure 9 illustrates this result. While this analysis will require additional work, it shows that the analysis is far along.

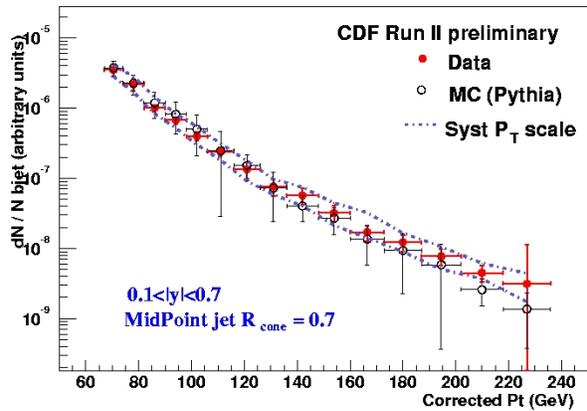


Figure 9 Transverse momentum cross-section for inclusive b-jets. Data and Monte Carlo are normalized to equal area.

A final b-quark analysis is the bb dijet mass. As in the previous analysis, full unsmearing and luminosity normalization is not yet available, but even so, considerable work has been done. In this analysis, both jets are tagged by the secondary vertex. While not required for the analysis, if the jet is also tagged by the presence of a soft electron, the transverse momentum of the electron with respect to the direction of the jet and electron (combined) can be used to establish b-quark content.

For this analysis, the two jets are both central, with the higher Pt jet being required to have a transverse momentum exceeding 30 GeV, while the second jet had a minimum transverse momentum of 10 GeV. Figure 10 shows a comparison between a Pythia calculation and the data. In this preliminary result, it appears that there is an excess of events at high dijet mass. However, further analysis is required to understand if the effect persists.

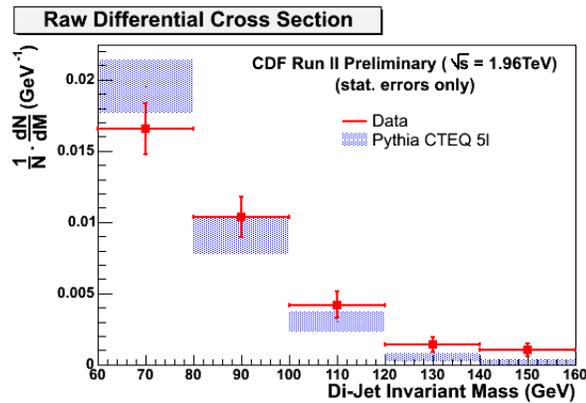


Figure 10 Dijet mass cross-section for both jets tagged as b-jets. Presented distribution is merely a shape comparison. While the data distribution is harder than Pythia, the difference is not statistically significant.

The Tevatron will run through the startup of the LHC. In the meantime, there will be many additional results, as well improved versions of the measurements presented in these Proceedings. The reader is invited to peruse both DØ's and CDF's web site for the most up-to-date results.

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