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HEAVY FLAVOR PRODUCTION IN HADRONIC COLLISIONS

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We discuss current issues in the study of heavy flavor quarks and "onia" state production. In particular recent results from the Tevatron and Hera experiments are summarized. Expectations for the future high luminosity Tevatron run are also presented.

1 Introduction

The study of processes involving heavy flavored quarks is part of the physics program of almost any major high-energy physics experiment. Indeed, they provide unique opportunities to test the higher order predictions of the Standard Model, which could be affected by the presence of new physics. Furthermore, heavy flavored quarks couple quite naturally with the Electroweak symmetry-breaking sector of the Standard Model and its extensions, thus providing important experimental signatures. The understanding of heavy flavor quark production rates and features is then of great importance to estimate and optimize their detection and, also, to evaluate the backgrounds in searches for processes with characteristic heavy flavor final states.

The calculation of heavy flavor production is an excellent test of QCD since the various quark masses provide a wide range of natural scales (from 1.5 GeV/c^2 of the charm to 175 GeV/c^2 of the top quark). Furthermore the non-zero mass protects the perturbative calculation from infrared and collinear divergences, that are in other cases reabsorbed in the non-perturbative contributions. Nonetheless the calculations are quite complex, because the Next to Leading Order contributions (NLO) have typically a size similar to that of the Born level (LO). Since a full Next to Next to Leading Order calculation is nearly impossible, theorists have tried to deal partially with the problem by taking into account some particular classes of diagrams to all orders in perturbation theory (resummation), in particular the ones giving the largest contributions at NLO, also known as "large logs".

In the first section that follows we shall describe recent experimental results in open production of top, bottom and charm quark and compare them to expectations from QCD.

Charm or bottom quark-antiquark pairs can also form bound states like ψ's or Υ's, also called charmonium or bottomonium respectively, or more generally "onia". The process of "onia" formation is completely non-perturbative, nonetheless some QCD-based models have been proposed to describe it and have received considerable attention in recent years.

In the second section that follows we shall describe recent experimental results on "onia" production and compare them to current theoretical expectations.

2 Open heavy flavor production

A full NLO calculation of the heavy flavor production cross section has been available since the late 1980's [1]. Correlations between the kinematical variables of the two final state heavy flavored quarks have been included shortly afterwards [2] at the same order in the perturbative expansion. Much work has gone during the 1990's into the resummation of several classes of "large logs"; for instance those related to soft t-channel gluon exchanges [3], to hard collinear gluon radiation [4] and to soft gluon radiation in the production near threshold [5]. We shall see that in spite of all of these efforts, these calculations provide a good description of the current experimental data only in the case of the top quark. These calculations provide a good description of many features of the experimental data, however, with the exception of the top quark case, they still suffer from a significant dependence of the overall normalization on the choice of some parameters, such as, for instance, the renormalization scale or the quark mass. When the most natural assumption for these parameters is made the predicted cross sections for charm and beauty quarks are significantly smaller than the ones observed.

2.1 Top quark production

The top quark is by far the most massive, so massive that it can be produced only at the Fermilab Tevatron Collider at this particular time. The present combined CDF and D0 measurement of its mass is 174.3±5.1 GeV/c^2 [6]. It is to be expected that QCD would perform well at such large scales. Indeed both the D0 measurement, $\sigma_{t\bar{t}} = 5.9 \pm 1.7$ pb [7], and the recently updated CDF measurement, $\sigma_{t\bar{t}} = 6.5^{+1.7}_{-1.4}$ pb [8], are consistent to within one standard deviation with the most recent calculations [5].

Other features of top quark production, like the top p_t and the invariant mass of the two top quarks, have been investigated by the Tevatron experiments [9,11], but no significant deviation from the QCD predictions have been observed with the limited statistics available.

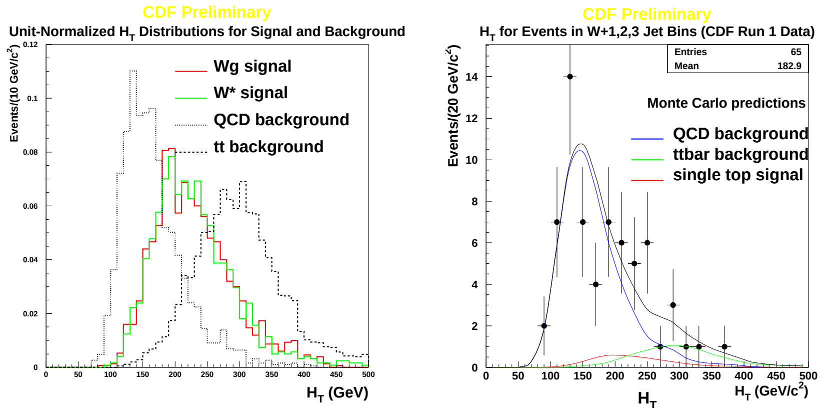

Figure 1. Left: H_t distribution expected for single top and the most relevant backgrounds. Right: CDF fit to H_t distribution.

The search for the predicted production of single top has received considerable interest lately by both the CDF and D0 collaborations. This search is hard since the expected cross section is in the order of a couple of pb [10] and the background from W plus heavy flavors as well as top quark pair production is substantial. CDF has shown this year an updated result using the variable H_t to improve the separation between signal and background [11]. H_t is defined as the scalar sum of the E_T of all objects in the event: hard leptons, missing transverse energy and all jets. On the left side of fig. 1 we show the expected shapes for the signal as well as the QCD and $t\bar{t}$ backgrounds. On the right side of the figure we show the result of a three-component fit to the data, which allows the extraction of the upper limit on the total single top cross-section: $\sigma(s\ and\ t - channel) < 13.5$ pb at 95 % confidence level. This is an improvement both over other CDF analyses [11] and published D0 results [12].

The Tevatron is the only accelerator where improvements in the measurement of top properties can be made in the near future. In the order of 2 fb^{-1} are expected to be collected by each experiment by the end of 2003 (Run IIa), and more than 15 fb^{-1} could be integrated in the following years (Run IIb). Assuming the Run IIa luminosity, the expectation is that the single top cross-section will be eventually measured with a ~25% error, and that the error on the top mass and cross-section will drop respectively to about

1.5% and 9%. These and other measurements will provide a severe test of the Standard Model in this high Q^2 region, where it is expected to have a very good predictive power.

2.2 Bottom quark production

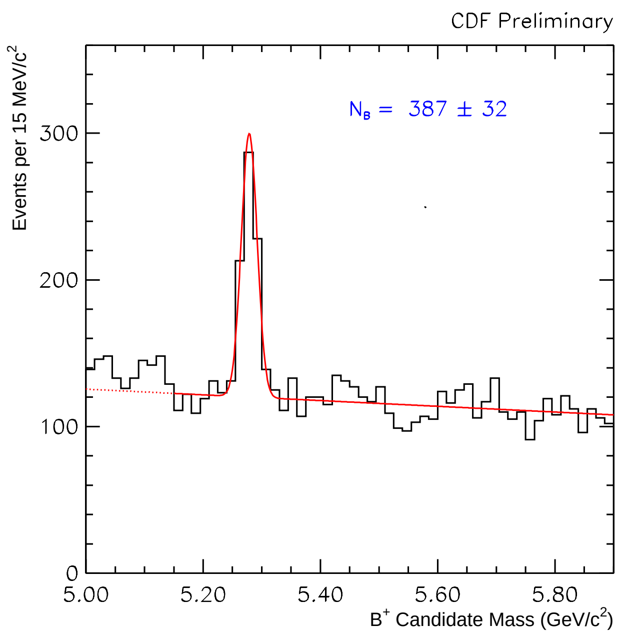

Figure 2. CDF B^+ signal for B^+ with $p_T > 6$ GeV/c.

Hadronic production of bottom quarks has been studied in a number of different experimental situations: several Fermilab and CERN fixed target experiments, the CDF and D0 experiments at the Tevatron Collider, and at HERA in photon-proton interactions. Recently some low statistics results in $\gamma - \gamma$ production at LEP have been also reported [13].

Bottom production has been very difficult to measure at fixed target experiments due to low cross-sections and very high backgrounds; typical S/N is in the order of 10^{-6}. Currently published results [14,15] are based on small number of events, but the theoretical uncertainties of the NLO calculations are also very large at this energies.

The $\gamma p \to b\bar{b}X$ cross-section has been measured at HERA by both the H1 [16] and, more recently, the ZEUS [17] experiments by studying inclusive muon production. Both measurements are higher than the QCD NLO prediction, but the experimental errors are still quite large.

The Tevatron Collider is by far the best place where to study bottom production since the cross-sections are in the order of tens of microbarns, the $S/N \sim 10^{-3}$ and the QCD predictions are more reliable given the higher typical Q^2.

Both the CDF and D0 experiments make extensive use of muons to signal the production of b-quarks. The bottom content of hadronic jets containing a muon can be determined by studying the shape of the distribution of the momentum of the muon relative to the jet axis. Opposite sign muon pairs with invariant mass consistent with the J/ψ mass are significantly enriched in b-hadrons. At CDF this sample can be made almost 100% pure by requiring a J/ψ vertex well separated from the primary event vertex. Additional techniques are used at CDF to extract samples rich in b-quarks: reconstruction of exclusive charmed meson decays in association with electrons or muons signal semileptonic b-meson decays; full reconstruction of exclusive b-meson decays containing J/ψ's, as shown for instance in fig. 2.

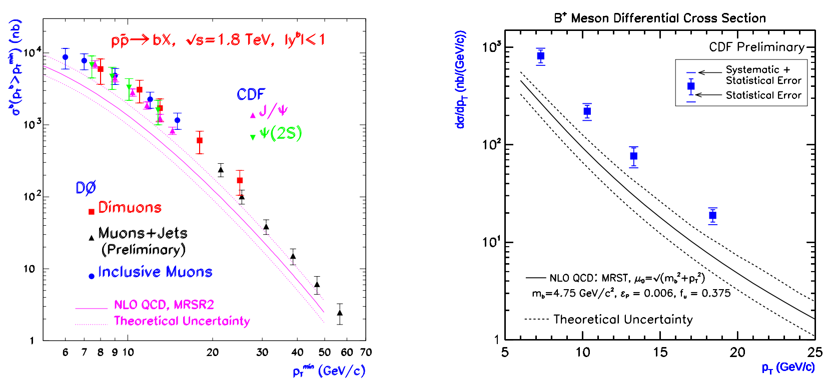

Figure 3. Left: Comparison of CDF and D0 measured b-quark cross sections as a function of the minimum b-quark p_T. Right: CDF B meson cross section measurement using exclusive B meson decays.

The bottom quark cross-sections measured by CDF and D0 in the central rapidity region ($|y^b| < 1$) are consistent with each other [18,19], their shape is consistent with QCD calculations, but are a factor 2.5 higher than the central prediction from fixed order NLO QCD [1,2], as shown in fig. 3-left. Additional D0 measurements [20] suggest that this factor is even higher at high rapidity, fig. 4-left. Much experimental and theoretical work has gone in trying to understand the reason of these discrepancies. We summarize in the following the major parts of these studies.

Both Tevatron experiments have taken data at center of mass energy of 630 GeV. This allows a comparison with previous measurements made by the UA1 experiment [21]. Current results [22,23] show consistency with older CERN data and rule out an overall normalization problem with the Tevatron data. Interestingly enough the ratio between the b-quark cross-section at 630 Gev and that at 1800 GeV is quite consistent with QCD predictions [22]. CDF has recently completed a measurement of the B cross section using fully

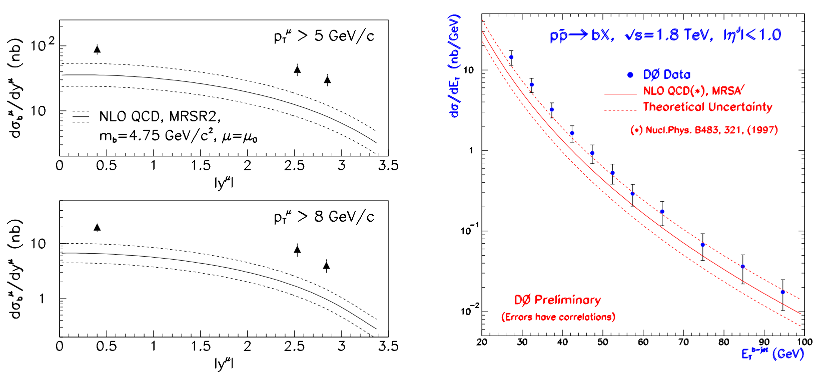

Figure 4. Left: D0 b-quark cross section as a function of rapidity for two choices of minimum muon p_T. Right: D0 b-jet cross section compared to theoretical estimates [26].

reconstructed B_0 and $B^{\pm}$ mesons [24]. The results are about a factor of 3 higher than QCD predictions and are roughly consistent with previous measurements. Given the high level of purity of the signal in this case (see for instance fig. 2), this is reassuring that no significant background subtraction problems were present in other previous b-quark cross section analyses.

D0 has recently measured the b-quark jet cross section [25] following a theoretical suggestion [26] that non-perturbative fragmentation effects would contribute less to the calculation of this quantity than to a generic b-quark cross section. Indeed the agreement with theory (fig. 4-right) appears to be better, but it is also consistent with previous measurements within the current errors.

Except for this overall normalization issue, the agreement with theory is generally quite good, even in the case of quantities related to the correlation between the two pair produced b-quarks, which are very sensitive to the higher order corrections [27,18,19].

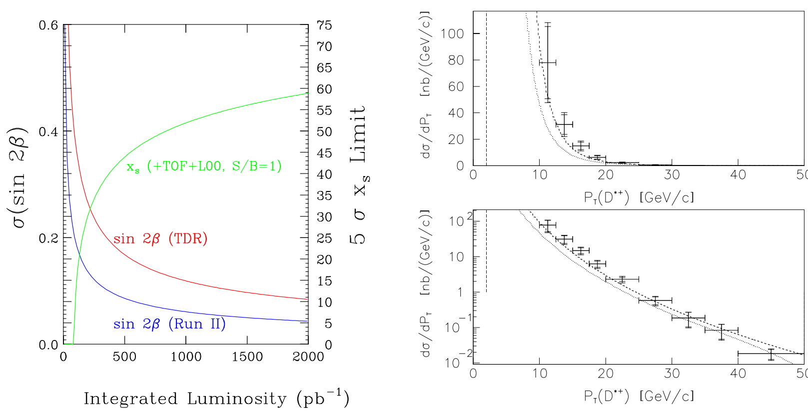

Figure 5. Left: CDF expectations for the resolution on $sin(2\beta)$ and the 5σ reach on x_s as a function of the integrated luminosity. Right: D^* production cross section as a function of the minimum meson p_T.

It is worth mentioning that the bottom physics output of the Tevatron has gone much further than production studies. In particular detailed measurements of b-hadron lifetimes, masses and mixing have been made [28]. Based on this experience we foresee many opportunities of important measurements with the data of the new Tevatron run. In fig. 5-left we use the resolution on the CP violation parameter, $sin(2\beta)$, and the maximum measurable B_s mixing parameter (at the 5σ level), x_s, to benchmark the capabilities of the CDF experiment as a function of the accumulated luminosity. A very good measurement of each of these parameters is expected after only 500 pb^{-1} corresponding approximately to the first year of data taking: $\sigma(sin(2\beta)) \sim 0.1$ and sensitivity to x_s up to ~ 40. It is to be expected that the Tevatron will play a major role in b-quark physics, in combination with the B-factories, in the near future.

2.3 Charm quark production

Results on charm-quark production come mainly from fixed target experiments at CERN and Fermilab, HERA experiments and CDF at the Tevatron. Theoretical uncertainties, especially on the overall normalization, are much larger for the production of charm than beauty. This is even more relevant at low energy. For this reason results at the highest energy are particularly interesting.

There are no significant recent results from the fixed target experiment on charm production from the 91/92 data from CERN and FNAL, and most of the effort on the 96/97 Fermilab data is now concentrated mostly on the charm decay properties [29]. The main conclusions drawn from this large body of charm data (see for instance [30,31]) is again an overall consistency with the general features of NLO QCD within the quoted large uncertainties of the predictions. Interesting non-perturbative "beam drag" effects, related to the contribution of spectator quarks from the incoming particles kinematically close to the final state quarks, have also been observed.

At HERA a significant data sample of D mesons has been collected by both ZEUS and H1. Typically this data is distinguished as photoproduction for $Q^2 < 1$ GeV^2 and deep inelastic (DIS) for $Q^2 > 1$ GeV^2. All of the analyses in the last years have been based on D^* [32], but recently ZEUS has also added a sample of D_s from photoproduction [32]. For DIS processes the distribution of many kinematical quantities is consistent with fixed order NLO QCD [33], except for the observation of possible "beam drag" effects, similar to those seen by fixed target experiments, in the D^* rapidity distribution. Photoproduction data, including the recent D_s signal, are in general harder to interpret and require higher order resummations [34,35] to improve the agreement with data.

The Tevatron Collider experiments are not optimized to detect charm. A reasonable signal of $\sim$ 8,000 D^* events with a S/N $\sim$ 1 has been recently obtained by CDF selecting $D^{*+} \to D^0 \pi_s^+$ followed by $D^0 \to K^- \mu^+ + X$. In this reaction the trigger efficiency is guaranteed by the presence of the muon, and the requirement of same sign between the μ and the π_s reduces the combinatorics. In addition wrong sign combinations can be used to estimate the background features. In fig. 5-right we show the measured D^* cross section as a function of their minimum p_T. Overlaid are the prediction for fixed order NLO QCD [2](lower curve) and one including resummation of higher orders [4](upper curve). Both predictions use: $M_{charm} = 1.5$ GeV/c^2, μ (renormalization/factorization scale) $= \sqrt{M_c^2 + p_t^2}$ and the CTEQ3M structure functions. The latter gives clearly a better description of the data, especially at the lower p_t, but is still lower than the data.

3 Hidden heavy flavor production

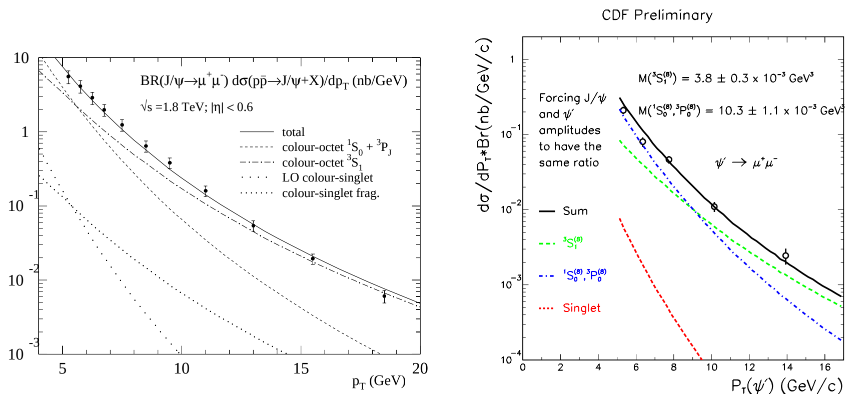

Figure 6. Left: CDF J/ψ cross section as a function of p_T with NRQCD predictions overlaid. Right: CDF ψ' cross section as a function of p_T compared to NRQCD predictions.

The production of bound states of two heavy quarks with the same flavor (onia) has received much attention in recent years; especially since CDF measured the p_t dependence of the J/ψ and ψ' cross section [36] to be much larger than expected [37] at the time. Those calculations assumed that onia production was dominated by t-channel gluon fusion generating two heavy quarks and a gluon in the final state; the probability for the two quarks to form a bound state was then derived from potential models. Several improvements have been proposed to this basic model during the last years: in particular higher order diagrams have been added and, also, diagrams where the bound state is formed in a color octet state rather than a color singlet. The octet state is assumed to go back to a final color singlet via soft gluon emission. The perturbative expansion including all these contribution has been put on solid theoretical ground and is usually referred to as NRQCD [38]. NRQCD has been quite successful in predicting the behaviour of J/ψ and ψ' cross-sections at CDF as shown in fig. 6. It should be reminded, however, that this model requires two matrix elements that are not predicted from the theory and are fit to agree with the data, so cross checks with other measurements are very important to verify this approach.

One important prediction of NRQCD is that the onia polarization should increase with p_t. So far CDF data do not appear to support this [39], as shown fig. 7. The polarization p_t dependence of J/ψ and ψ' originating from B

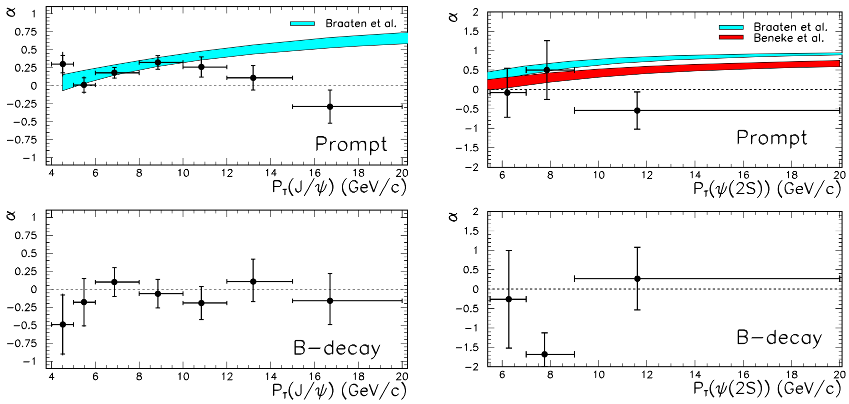

Figure 7. Left: CDF J/ψ polarization measurements as a function of p_T compared to predictions from ref. [40]. Right: CDF ψ' polarization measurements as a function of p_T compared to prediction from ref. [40,41].

meson decays is shown as a cross check of the analysis. A similar measurement from the E866 experiment at Fermilab is also measuring a J/ψ polarization smaller than NRQCD predictions [42]. CDF has also studied the Υ and its radial excitations, but no complete theoretical calculations are yet available to compare with the data. In fig. 8-right we show a study of the Υ polarization for a p_t range between 8 and 20 GeV/c indicating consistency with being unpolarized. At these low p_t however only a small polarization would be expected.

The experiments at HERA have collected substantial samples of J/ψ and compared production features with the predictions of several models [43]. Large k factors are in general needed to attain agreement with the data. In addition, NLO corrections are necessary to properly describe the shapes of the p_t and z distributions (z is the fraction of the photon momentum carried by the ψ). Differences between models including color octet contributions and those including only color singlet can be observed only at small z. Recent H1 results suggest consistency with color octet models as shown in fig. 8.

4 Conclusions

The study of heavy flavor production has proven so far a very interesting and challenging ground for QCD and QCD-inspired models. Several new analyses of Fermilab and DESY data have become available during the last

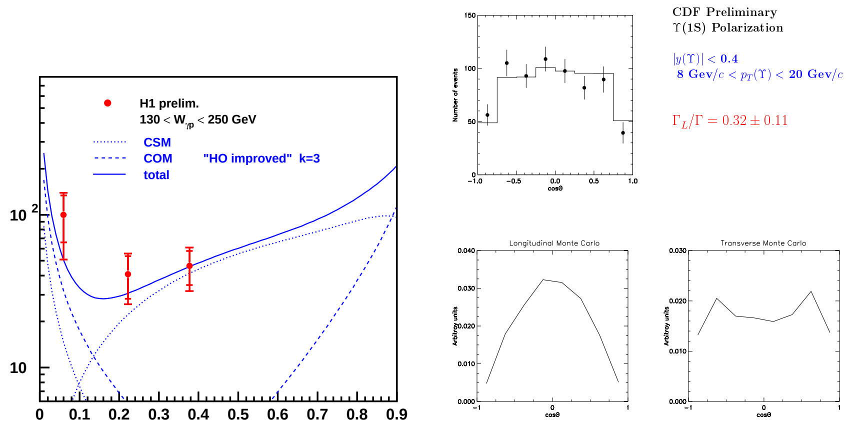

Figure 8. Left: H1 J/ψ production cross section at low z. Right: CDF Υ polarization measurement for 8 GeV/c $< p_T^{\Upsilon} <$ 20 GeV/c.

year. The theory so far has been able to describe many features of heavy flavor production, but some problems still remain. With substantially more data in the coming years, both the Tevatron and the HERA experiments will be able to improve the accuracy and the range of their measurements. Hopefully more detailed calculations will become available on the same time scale and a better understanding of higher order corrections will allow to address current and future problems.

I wish to thank all the people who helped in collecting and organizing the information on this rather broad subject. A special thank to the conference organizers who have made this meeting a unique and very pleasant experience.

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