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HEAVY QUARK PRODUCTION IN HADRONIC COLLISIONS [1]

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Abstract

We review the physics of heavy quark and quarkonium production in high energy hadronic collisions. We discuss the status of the theoretical calculations and compare the current results with the most recent measurements from the Tevatron collider experiments.

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1 Introduction

Heavy quark production in high energy hadronic collisions constitutes a benchmark process for the study of perturbative QCD and an important tool to explore flavour physics.

- b quarks are produced in abundance in hadronic collisions, and will eventually allow ultimate tests of CP violation in the b system, as well as studies of rare b decays with branching ratio levels of the order of 10^{-10}. A detailed understanding of the production properties at future machines (such as the LHC) is therefore of the utmost importance.

- The comparison of the current experimental data with the predictions of QCD provides a necessary check that the ingredients entering the evaluation of hadronic processes (partonic distribution functions and higher order corrections) are under control and can be used to evaluate the rates for more exotic phenomena or to extrapolate the calculations to even higher energies.

- Accurate studies of the production properties of the *top* quark rely on a solid understanding of the QCD dynamics, in order to isolate possible contributions from new phenomena.

- Measurements of heavy quark production in fixed target experiments are dominated by data at low p_{T}, a region where non-perturbative effects are not negligible. The comparison of data with the expectations of perturbative QCD offers the possibility to explore some interesting features of non-perturbative hadronic dynamics [1].

- At HERA, c and b quarks are largely produced via photon-gluon fusion, therefore providing a direct probe on the gluon density of the proton, complementary to the information extracted from the measurement of structure functions. First data have already become available, and have been shown at this Conference.

- Production of quarkonium states, in addition to providing yet another interesting framework for the study of the boundary between perturbative and non-perturbative QCD, is important in view of the use of exclusive charmonium decays of b hadrons for the detection of CP violation phenomena.

In this presentation we review the current status of theoretical calculations, and discuss the implications of the most recent experimental measurements of b quarks and charmonium states performed at the Tevatron $p\bar{p}$ collider.

2 Open Flavour Production: Theory Overview

To start with, we briefly report on the current status of the theoretical calculations. A distinction must be made between calculations performed at a complete but fixed order in perturbation theory (PT), and those performed by resumming classes of potentially large logarithmic contributions that arise at any order in PT. The exact matrix elements squared for heavy quark production in hadronic collisions are fully known up to the $\mathcal{O}({\alpha_s}^3)$, for both real and virtual processes. These matrix elements have been used to evaluate at the next-to-leading order (NLO) the total production cross section [2], single-particle inclusive distributions [3] and two-particle inclusive distributions (a.k.a. correlations) [4].

Three classes of large logarithms can appear in the perturbative expansion for heavy quark production:

1. $[\alpha_s \log(S/m_Q^2)]^n \sim [\alpha_s \log(1/x_{\rm Bj})]^n$ terms, where S is the hadronic CM energy squared. These small-x effects are possibly relevant for the production of charm or bottom quarks at the current energies, while they should have no effect on the determination of the top quark cross section, given the large t mass. Several theoretical studies have been performed [5], and the indications are that b production cross sections should not increase by more than 30–50% at the Tevatron energy because of these effects.

2. $[\alpha_s \log(m_Q/p^T_{QQ})]^n$ terms, where p^T_{QQ} is the transverse momentum of the heavy quark pair. These contributions come from the multiple emission of initial-state soft gluons, similarly to standard Drell Yan corrections. These corrections have been studied in detail in the case of top production, where the effect is potentially large due to the heavy top mass [6]. They are not relevant to the total cross section of b quarks, but affect the kinematical distributions of pairs produced just above threshold [7], or in regions at the edge of phase space, such as $\Delta\phi = \pi$.

3. $[\alpha_s \log(p_T/m_Q)]^n$ terms, where p_T is the transverse momentum of the heavy quark. These terms arise from multiple collinear gluons emitted by a heavy quark produced at large transverse momentum, or from the branching of gluons into heavy quark pairs. Again these corrections are not expected to affect the total production rates, but will contribute to the large-$p_{\rm T}$ distributions of c and b quarks. No effect is expected for the top at current energies. These logarithms can be resummed using a fragmentation function formalism [8], with a significant improvement in the stability w.r.t. scale changes for $p_{\rm T} > 50$ GeV.

3 Single Inclusive Bottom Production

The status of b production at hadron colliders has been quite puzzling for some time. Data collected by UA1 [9] at the CERN S$p\bar{p}$S collider ($\sqrt{S} = 630$ GeV) were in good agreement with theoretical expectations based on the NLO QCD calculations [3]. On the contrary, the first measurements performed at 1.8 TeV by the CDF [10] experiment at the Fermilab collider showed a significant discrepancy with the same calculation. The new data presented at this Conference [11] by the two Fermilab experiments, CDF and D0, allow us to draw a more complete picture of the situation.

We present all three sets of data from UA1, CDF and D0 in a single plot, containing the ratio of the measurements to the theory, for a uniform choice of parameters entering the theoretical calculation. In fig. 1, we choose the same theoretical prediction as was available at the time of the UA1 measurements, namely the central set of the DFLM [12] parton distributions ($\Lambda_5^{\overline{\rm MS}} = 173$ MeV), $m_b = 4.75$ GeV and renormalization/factorization scales

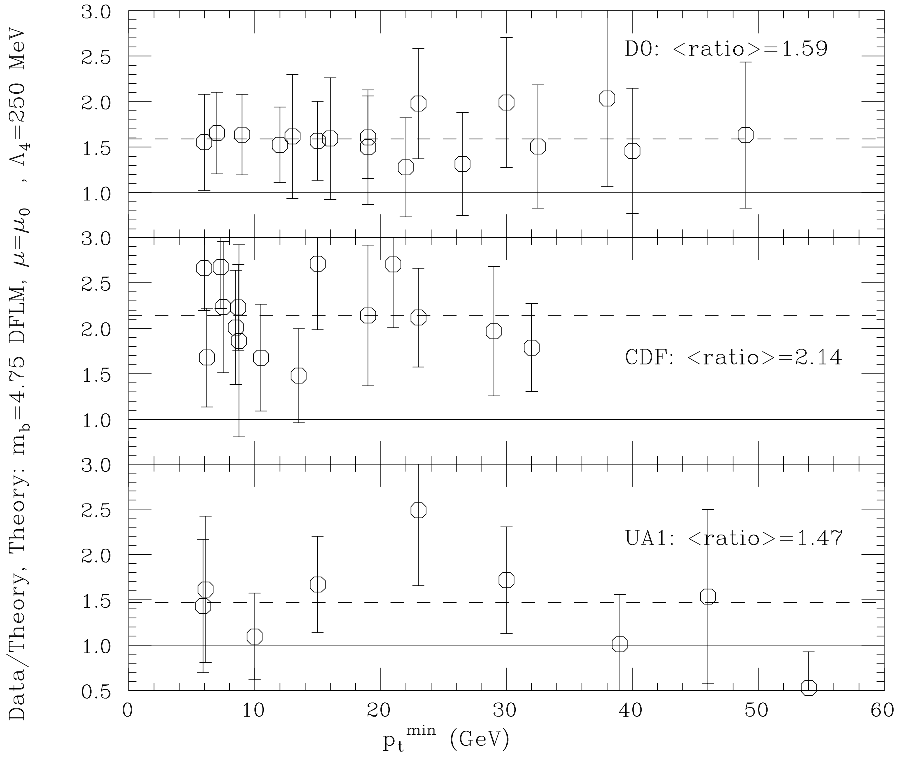

Figure 1: Ratio of data and theory for the integrated b p_{T} distribution at UA1, CDF and D0. Theory evaluated at NLO [3] using DFLM parton densities [12] ($\Lambda_5^{\overline{\mathrm{MS}}} = 173$ MeV), $m_b = 4.75$ GeV, $\mu_F = \mu_R = \sqrt{m^2 + p_T^2}$.

equal to the transverse mass of the b quark, $\mu_F = \mu_R = \sqrt{m^2 + p_T^2} \equiv \mu_0$. Depending on whether we use the D0 or the CDF data as representative of the b cross section at 1.8 TeV, we can draw two different conclusions. The plot shows clearly that the ratio *data/theory* is the same, at UA1 and at D0, to within less than 10%. While larger than 1, this ratio can be reduced by selecting different input parameters, still in the range of acceptable values. For example, fig. 2 shows the same distributions with the theory evaluated using the more recent set of parton densities MRSA [13], $m_b = 4.5$ GeV, $\mu_F = \mu_R = \mu_0/2$ and $\Lambda_5^{\overline{\mathrm{MS}}} = 300$ MeV, a value close to the LEP measurement of α_s. With this choice of parameters the agreement between NLO QCD and data is perfect, both at 630 and at 1800 GeV. The data from CDF are in good agreement with the theory shape, but are about 30–40% higher in normalization relative to the D0 ones. If one were to choose CDF data as representative of the Tevatron rate, the conclusion would be that the b production cross section grows between 630 and 1800 GeV by a factor of 40% more than NLO QCD predicts. An effect of such a size would be in agreement with the evaluation of the small-x effects mentioned earlier. The only conclusions we can therefore draw from the current data are that:

1. the comparison of data and NLO predictions for the b production at 630 and 1800 GeV favours small values of the b mass and values of α_s consistent with the LEP

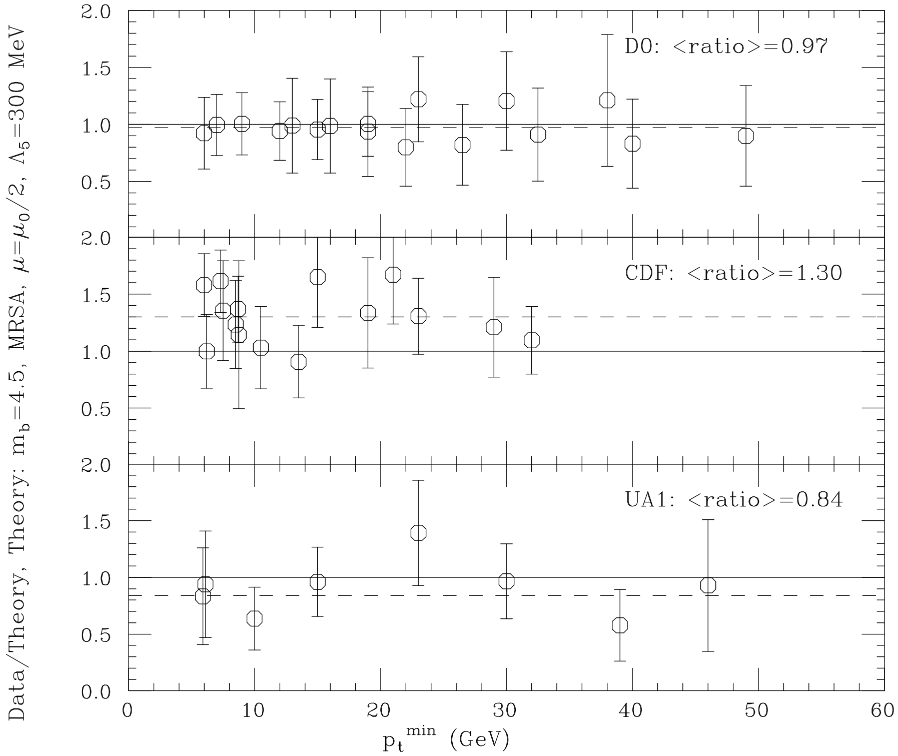

Figure 2: Ratio of data and theory for the integrated b p_T distribution at UA1, CDF and D0. Theory evaluated at NLO [3] using MRSA parton densities [13], $\Lambda_5^{\overline{\rm MS}} = 300$ MeV, $m_b = 4.5$ GeV, $\mu_F = \mu_R = \sqrt{m^2+p_T^2}/2$.

measurement;

2. the relative difference in the data/theory ratio at 630 and 1800 GeV is at most 40%, value obtained using the CDF data. This is consistent with the estimated effect of small-x higher order corrections;

3. there is a residual 30–40% discrepancy in absolute normalization between the CDF and the D0 results, that will need to be resolved before additional progress can be made in interpreting the data.

4 Charmonium production

The production of heavy quarkonium states in high energy processes has recently attracted a lot of theoretical and experimental interest. Detailed measurements of differential cross sections for production of ψ, ψ' and χ states have recently become available [14–18], and have been reviewed at this Conference [19]. Theoretical models for production have existed for several years (see ref. [20] for a comprehensive review and references). The comparison of these models with the most recent data has shown dramatic discrepancies,

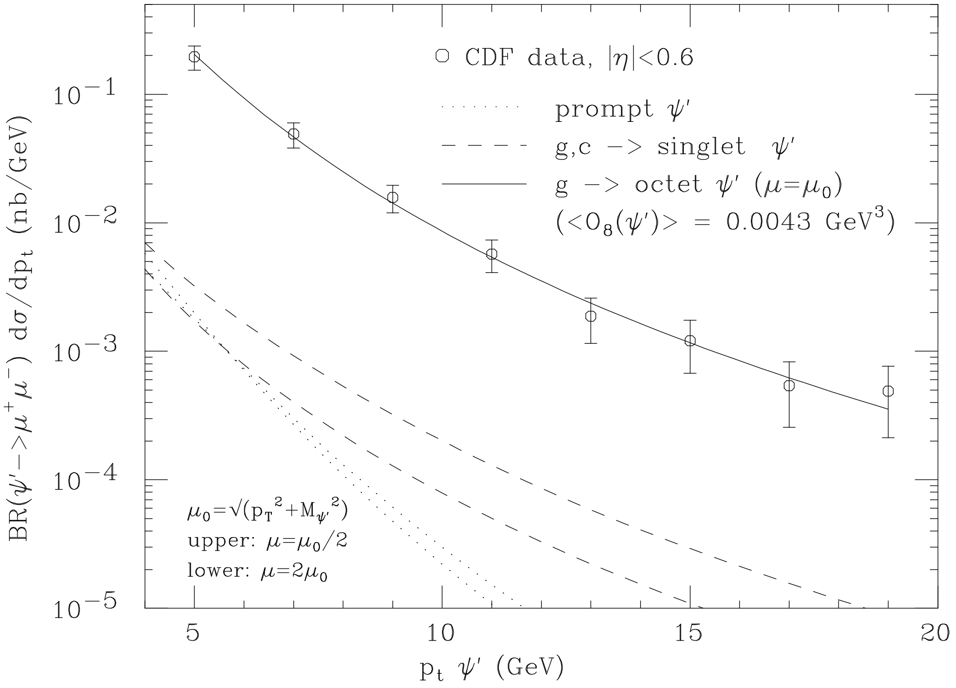

Figure 3: Inclusive prompt ψ' p_T distribution. CDF data versus theory. We show the contribution of the different sources. Dotted lines: LO production in the CSM; dashed lines: gluon and charm fragmentation in the CSM; solid line: gluon fragmentation in the colour octet mechanism.

the most striking one (theory predicting a factor of 50 fewer prompt ψ' than measured by CDF [16]) having become known as the "CDF anomaly". Attempts to explain the features of these data have recently led to a deeper theoretical understanding of the mechanisms of quarkonium production. I will briefly summarize here this progress (for a more complete review, see ref. [21]).

The production of quarkonium at large p_{T} is a phenomenon with two different time scales: the shorter time scale corresponds to the generation of the heavy quark pair, the longer one to the binding of the pair. In all models, it is assumed that the details of the bound state formation can be absorbed into some non-perturbative parameter, directly related to the value of the non-relativistic wave function at the origin. Where the models differ is in specifying how the heavy quark pair, produced by the hard scattering in a generic colour and angular momentum state, evolves into a state with the right quantum numbers to form the desired hadron. In the first QCD-based model, the so-called colour singlet model (CSM, [22]), it was assumed that the quark pair is produced in a colour singlet state with the right angular momentum already during the hard collision. It is easy to show that the production of quarkonium in the CSM is heavily suppressed at large p_{T}, mainly because it is difficult to hold the bound state together when this is probed at the

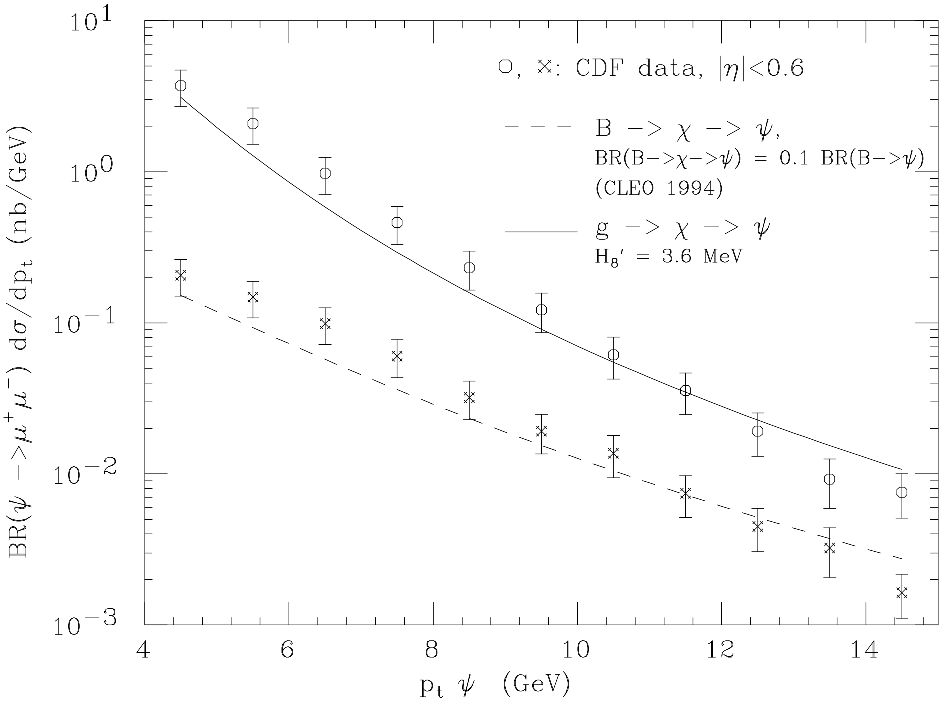

Figure 4: Inclusive p_T distribution of ψ's from χ_c production and decay.

large virtualities typical of a high-p_{T} phenomenon [21]. In other words, in the naive CSM, production of quarkonium is a higher-twist effect, highly suppressed by a form-factor-like damping as soon as p_{T} becomes larger than the mass of the state.

This prediction has been recently disproved by the data. The dotted line in fig. 3, for example, shows the prediction of the CSM model for ψ' production at the Tevatron, compared to the CDF data [16]. Not only is the overall normalization of the theory curve significantly lower than the data, but also the shape is much steeper than observed.

It has been pointed out recently [23] that higher order contributions in α_s can dominate production at large p_{T}. The process responsible for these contributions is the splitting of a large-p_{T} gluon into a $Q\bar{Q}$ pair, which then evolves into a colour singlet state by emission of one or more perturbative gluons. The additional powers of α_s required for this process are largely compensated by the absence of a form factor suppression. It turns out, in fact, that these terms are of order $[\alpha_s \times (p_{\mathrm{T}}/m)^2]^n$ relative to the LO diagrams ($n = 1$ in the case of χ production, and $n = 2$ in the case of ψ or ψ'), and become dominant as soon as p_{T} is slightly larger than m, the quarkonium mass.

The effect of these *fragmentation* contributions is shown by the dashed line in fig. 3: the p_{T} shape is now correct, although the total rate is still low by more than an order of magnitude. A similar behaviour is observed in the production of ψ's. On the contrary, the predictions for χ production, as shown in fig. 4, agree with the data both in shape and in rate [24].

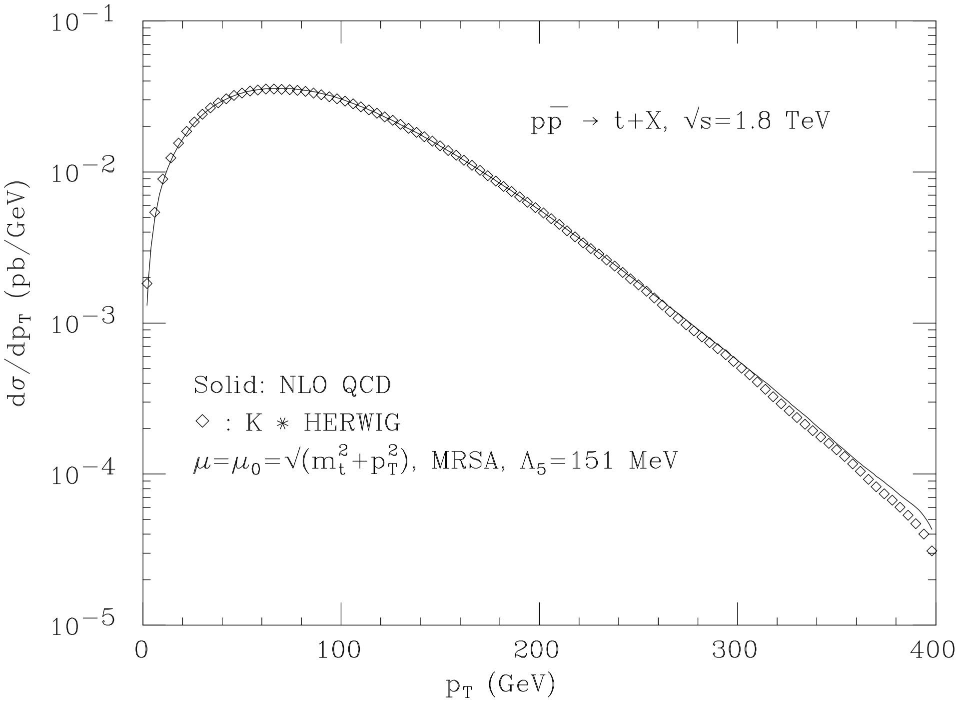

Figure 5: Inclusive p_{T} distribution of the top quark.

A possible solution to this remaining discrepancy in the ψ and ψ' sector was recently suggested by Braaten and Fleming [25]. Their proposal is based on the observation that, contrary to the case of the gluon fragmentation into ψ states, where the emitted gluons are both hard, the fragmentation process into χ states is dominated by emission of a soft gluon. A large infrared logarithm enhances the fragmentation rate of a gluon into χ's relative to that into ψ's. This logarithm signals the presence in the χ state of a large component made by a $c\bar{c}$ pair in a colour octet $^3S_1$ state, accompanied by an on-shell gluon [26]. This component has a non-zero overlap with the $c\bar{c}$ state produced by the splitting of the large-p_{T} gluon. Braaten and Fleming suggested that a similar colour octet $^3S_1$ component might be present in the relativistic expansion of the ψ and ψ' wave function. The work of ref. [26] indicates that such a component should have an amplitude of order v^2 relative to the leading order, colour singlet component. Therefore, the transition of a hard gluon into a ψ, via coupling to the $^3S_1$ colour octet component of the ψ wave function, would be of order $v^4/{\alpha_s}^2$ relative to the standard fragmentation function of the CSM. A detailed evaluation of the transition amplitudes, [25], shows that the ratio of the two contributions is actually $\sim 25\pi^2\mathcal{O}(v^4)/{\alpha_s}^2$, a number large enough to explain the factor of 50 discrepancy between the data and the predictions of the CSM model.

The contribution of this colour octet production to the ψ' distribution is shown as a solid line in fig. 3. Here the new non-perturbative parameter $\langle\mathcal{O}_8^{\psi'}(^3S_1)\rangle$, *i.e.* the value of the overlap squared between the $c\bar{c}$ colour octet state from gluon splitting and the ψ' wave function, was derived from a fit to the data. Its numerical value has the right order of magnitude expected from the v^2 suppression, consistently with what was suggested

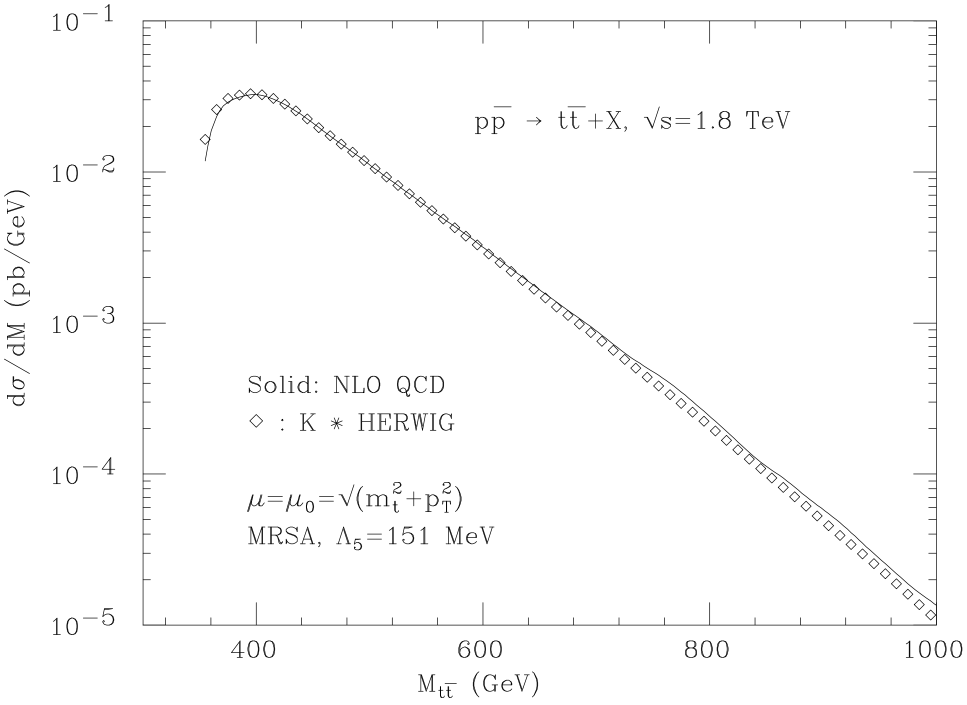

Figure 6: Invariant mass distribution of the $t\bar{t}$ pair.

earlier. Similar results can be obtained for the production of ψ's [27].

The model of quarkonium production via the colour octet mechanisms is now the subject of intense work, and we will soon have available a more complete picture of its implications, including the phenomenology of Υ and charmonium in fixed target experiments.

5 Top quark production

Now that the existence of the *top* quark has been firmly established via its detection in hadronic collisions [28], experimental studies will focus on the determination of its properties. In particular, the measurement of its mass and of the production cross section and distributions will certainly be among the first studies of interest. The production properties, should they display anomalies, could point to the existence of exotic phenomena [30]. We present here some kinematical distributions [29] that are of potential interest for these comparisons.

The inclusive $p_{\rm T}$ distribution is sensitive to channels such as $Wg \rightarrow t\bar{b}$ [31], which are found to contribute with a small cross section, predominantly at low $p_{\rm T}$. The invariant mass of the pair is an obvious probe of the possible existence of strongly coupled exotic resonances, such as technimesons [30]. The transverse momentum of the pair is an indication of the emission of hard hadronic jets in addition to those coming from the top decays. The presence of these additional jets generates potentially large combinatorial

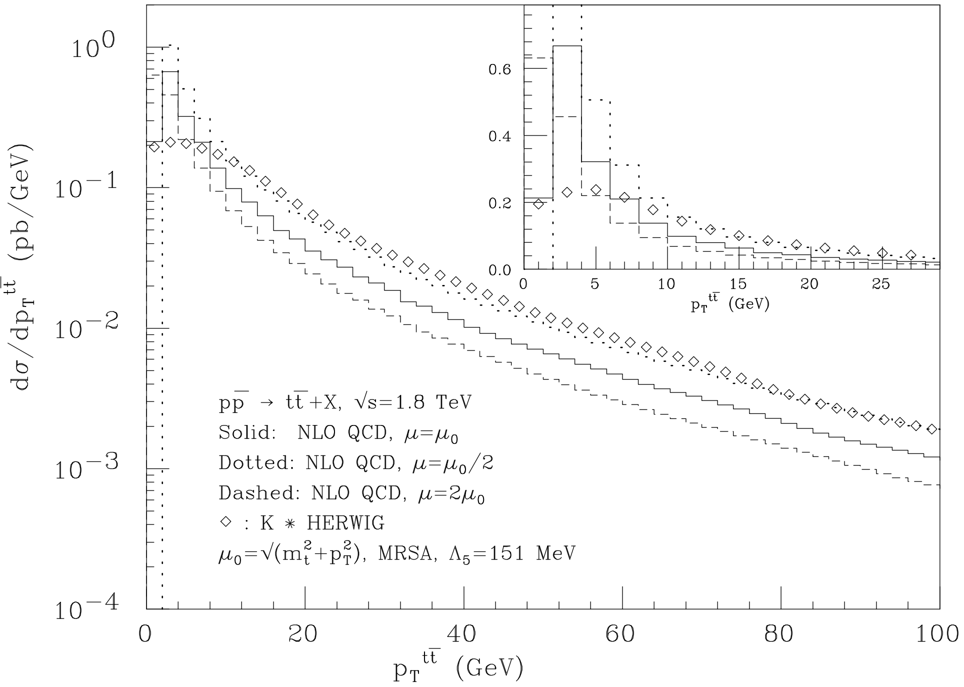

Figure 7: Transverse momentum distribution of the $t\bar{t}$ pair.

backgrounds to the reconstruction of the top mass peak from the decay products [32]. An accurate understanding of these backgrounds is very important for a precise measurement of the top mass.

All the results we show were obtained using the NLO QCD matrix elements [3, 4], MRSA parton densities [13], $m_{top} = 176$ GeV. Since most experimental studies are performed using shower Monte Carlo event generators to simulate the behaviour of the events in the detectors, we will compare our NLO results with those we obtained with HERWIG [33]. This is important in order to assess the reliability of the theoretical inputs used by the experiments. Throughout our plots, we rescale the HERWIG calculations by the perturbative K factor given by the ratio of the NLO to LO results. The K factor is of the order of 1.3 for all choices of parameters.

As an example of a single inclusive quantity, we show the top $p_{\rm T}$ distribution in fig. 5. The solid line corresponds to the NLO result obtained using $\mu_R = \mu_F = \mu_0$. The square points correspond to the HERWIG prediction, rescaled by a K factor equal to 1.34. The curves obtained by changing μ_R and μ_F by a factor 0.5 to 2 show an overall normalization change by approximately ±10%. No change in the shape is observed. The agreement between the NLO and HERWIG results, and the stability under scale changes, indicate that the prediction for the $p_{\rm T}$ distribution of top quarks is solid. Aside from an overall small change in normalization, this result is not affected by the inclusion of higher order soft gluon emission, [34].

Similar conclusions [29] can be drawn for the rapidity distribution, and for the distribution in invariant mass of the top pair, shown in fig. 6.

Those distributions which are trivial at leading order, $\Delta\phi$ and $p_T^{t\bar{t}}$, are on the contrary most sensitive to multiple gluon emission from the initial state. This is because even small perturbations can smear a distribution that at leading order is represented by a delta function, as is the case for the $p_T^{t\bar{t}}$ and $\Delta\phi$ ones. The largest effect is observed in $p_T^{t\bar{t}}$, fig. 7, where we include the NLO curves relative to the three choices of scales, $\mu_R = \mu_F = \mu_0$ (solid), $\mu_0/2$ (dots) and $2\mu_0$(dashes). Contrary to the previous cases, significant differences in shape arise here among the three choices in the small-$p_{\rm T}$ region. The HERWIG result (normalized to the area of the solid curve) is also shown. The NLO and the HERWIG distributions assume the same shape only for $p_T^{t\bar{t}}$ larger than approximately 20 GeV. We conclude that an accurate description of the region $p_T^{t\bar{t}} < 20$ GeV requires the resummation of leading soft and collinear logarithms, as implemented in appropriate shower Monte Carlo programs.

Studies of the angular correlations between bremstrahlung gluon jets and the b-jets from the decay of the top quarks have been performed in ref. [35]. These authors found some important discrepancies between the results obtained from a fixed order perturbative calculation and from HERWIG. A full understanding of the origin of these discrepancies and a detailed study of their possible impact on the combinatorial background to the reconstruction of the top mass are in progress.

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