Large transverse momentum leptons
in
(very) high proton-(anti)proton collisions

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Abstract

We have extended an earlier study on open heavy flavour production in hadron-hadron collisions by including $O(\alpha_s^4)$ QCD tree level calculations. The effect on the inclusive muon and inclusive dimuon transverse momentum distributions and opening angle between the muons from the UA1 so-called non-isolated dimuon sample is estimated.

Using the CERN collider data as a reference, we have extrapolated open heavy flavour production cross-sections for future accelerators and we discuss the semileptonic decay of heavy flavours as a possible important background signal for neutral Higgs searches at LHC energies.

In addition, we have studied large transverse momentum J/ψ and Υ production at presently available collider energies and have compared our results with data recently obtained by the UA1 collaboration. Provided we include a K-factor of $\sim 1.5 - 2$ for direct production mechanisms, we find good agreement with theoretical predictions on both shape of the transverse momentum and rapidity distributions and absolute cross-section times branching ratio as measured by UA1: $\sigma \cdot BR(J/\psi \rightarrow \mu^+ \mu^-) = 7.5 \pm 0.7 \pm 1.2$ nb. We estimate $\sigma(p\bar{p} \rightarrow \Upsilon X) = 0.8 - 2$ nb, which compares well with the UA1 result $\sigma(p\bar{p} \rightarrow \Upsilon X) = 0.98 \pm 0.21 \pm 0.19$ nb.

Since the bound states are mainly produced via gluon interactions we discuss the sensitivity of the production cross-sections on the parametrization of the gluon structure function in the colliding hadrons. Finally we investigate cross-section extrapolations for future colliders at various centre-of-mass energies.

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1. Introduction

The analysis of 'prompt' muons signaled by the UA1 detector at the CERN Sp $\bar{p}$ S collider has considerably added to our understanding of heavy flavour production mechanisms in hadron-hadron interactions. Despite the large background from decays in flight of pions and kaons, a rather 'clean' sample of prompt muon events was obtained. Especially the dimuon sample or, more general, a sample of events with more than one muon can be made relatively background free by applying reasonably large transverse momentum (with respect to the colliding beams) cuts on the muons. In addition to the continuum creation of heavy flavour pairs via strong interactions [1 - 4], convincing evidence has been found for sizable heavy flavour bound state production. The UA1 collaboration has reported clean J/ψ and Υ resonances via the observation of their muonic decay channels [1], [5].

The outline of this paper is as follows. In the next section we briefly review open heavy flavour production mechanisms at hadron colliders and describe the model and computer program we have used to calculate theoretical distributions. In section 3 we make a comparison of our theoretical model with data obtained by the UA1 collaboration. New results on $O(\alpha_s^4)$ QCD heavy flavour calculations are presented as well as cross-section extrapolations to FNAL-collider, LHC and SSC energies. Heavy flavour bound states are the subject of section 4, while comparisons with Sp $\bar{p}$ S collider J/ψ and Υ data are presented in section 5. In the same section we show that provided sufficient statistics and good detector acceptance, onium signals carry information on the behaviour of the gluon structure function in the colliding (anti)proton at small values of x and may serve as calibration signals at future accelerators.

2. Open heavy flavour production

Because of the low centre-of-mass energies and the relatively small charm quark mass, early comparisons between FNAL-ISR data and QCD calculations have failed to give agreement. With about an order of magnitude more energy at hand at the Sp $\bar{p}$ S collider, it is interesting to study heavy flavour production in detail in this new energy domain.

Fig. 1: Schematic description of inelastic hadron-hadron interactions.

It is particularly interesting to see whether we are able to use data taken at $\sqrt{s} = 630$ GeV to make reasonably reliable predictions for future collider projects as aimed at, at this workshop.

In order to obtain numerical results on theoretical cross-sections, the conventional parton picture is used. That is to convolute the amplitudes squared of the matrix elements with the appropriate parton structure functions in the colliding hadrons. Since we are mainly interested in the properties of (prompt) leptons, the fragmentation of the bare partons and subsequent decay of (heavy) particles has to be treated in detail. They are the basic ingredients for either a analytical or Monte Carlo calculation of differential cross-section distributions. The procedure is schematized in figure 1. All theoretical distributions presented in this paper were obtained with the EUROJET Monte Carlo program for hard hadronic interactions [6]. At present, the EUROJET program contains five different sets of structure functions [7 - 9], which enables the user to compare different Q^2 evolutions for various choices of the QCD scale parameter Λ . We recall that Λ and the definition of Q^2 strongly effect the value of the strong coupling constant entering in the amplitude of the hard scattering process:

$$\alpha_s \sim \frac{1}{\log \frac{Q^2}{\Lambda^2}} \quad (1)$$

Fig. 2: Heavy flavour pair production mechanisms up to $O(\alpha_s^4)$. The $gg \rightarrow Q\bar{Q} X$ diagrams dominate at all orders of α_s . The heavy flavour contents of the interacting hadrons is assumed to be zero, avoiding double counting.

Since we will only consider tree level contributions in our Monte Carlo approach, diminution of Q will lead to an increase of the cross-section.

The $O(\alpha_s^2)$, $O(\alpha_s^3)$ and $O(\alpha_s^4)$ contributions to heavy flavour pair production are shown in fig. 2.

The heavy flavour content of the colliding hadrons, as calculated in ref. [7] is neglected in order to avoid double counting via the gluon splitting diagrams.

The overall uncertainty in our calculations due to the variation of scale parameters is discussed in detail in ref. [3] and [6]. All distributions have been calculated with the structure functions of Eichten et al. [7] which were derived for $\Lambda = 200$ MeV. For the heavy flavour production processes depicted in fig. 2, the scale was fixed at $Q^2 = p_t^2 + M_Q^2$, motivated by the UA1 inclusive jet analysis [10], with M_Q the mass of the heavy quark. For the $O(\alpha_s^2)$ [11] and $O(\alpha_s^3)$ [12] matrix elements, the mass of the heavy quark was explicitly taken into account. As the lowest order cross-sections are finite, we only have to worry about the divergencies occurring at higher orders. To regulate the soft and collinear divergencies in the $O(\alpha_s^3)$ processes, we have introduced a cut-off on the transverse momentum of the additional jet to the heavy flavour pair. The cut-off value was fixed at $p_t^{\text{jet}} > 5$ GeV/c, giving a K-factor in agreement with leading logarithm calculations [13]. A comparison of these calculations with the UA1 measurement [14] of the number of D^* inside jets is shown in fig. 3.

Fig. 3: The UA1 inclusive D^* measurement inside jets [14], is consistent with gluon splitting calculations for $g \rightarrow c\bar{c}$ [13].

The $O(\alpha_s^4)$ expressions are only available in the massless limit [15]. However, we assume that for large enough heavy flavour transverse momenta, mass terms in the expressions for the matrix elements only affect the overall K-factor and do not significantly distort kinematical distributions. Note that we do simulate the correct phase-space properties of the event. The regularization of the divergencies at this order becomes rather complicated. We divert the discussion of this issue to a separate paper [16]. 'Reasonable' cuts are a cut-off on the transverse momentum of the (massless)

outgoing parton and a minimum separation in rapidity-phi space of all incoming and outgoing partons:

$$p_t^{\text{jet}} > 7 \text{ GeV}/c, \\ \Delta R = \sqrt{\Delta\eta^2 + \Delta\phi^2} > 0.5 \quad (2)$$

Quark fragmentation and particle decay properties have been carefully modeled. For details and comparisons with e^+e^- data we refer the reader to ref. [3] and [6].

3. Comparison with UA1 collider data and extrapolations to higher energies

In order to enhance the contribution from semileptonic heavy flavour decays to the dimuon sample, a minimum amount of hadronic activity around the muons is demanded. Motivated by the isolation studies of muons from the decay of weak charged bosons and the observation that fragmentation and decay of heavy flavours introduce additional hadronic activity, a highly efficient isolation variable has been defined to discriminate against W, Z decays and muons from genuine Drell-Yan pair production [1]:

$$S = \left(\sum_{\Delta R < 7} E_t \right)_{\mu_1}^2 + \left(\sum_{\Delta R < 7} E_t \right)_{\mu_2}^2 \quad (3)$$

The hadronic isolation of a single muon is visualized in fig. 4.

Fig. 4: Hadronic activity in a cone around the μ -vector determines the isolation of the muon.

All dimuon events from the non-isolated dimuon sample satisfy $S > 9 \text{ GeV}^2$. We have studied two classes of events namely, one set of non-isolated dimuons with [1]:

$$\begin{aligned} p_t^{\mu_1}, p_t^{\mu_2} &> 3 \text{ GeV}/c, \\ M^{\mu\mu} &> 6 \text{ GeV}/c^2 \end{aligned} \quad (4)$$

and a second set with [2]:

$$\begin{aligned} p_t^{\mu_1} &> 7 \text{ GeV}/c, p_t^{\mu_2} > 3 \text{ GeV}/c, \\ \text{at least one jet with } E_t^{\text{jet}} &> 12 \text{ GeV} \end{aligned} \quad (5)$$

One of the distributions, that is highly sensitive to higher order contributions in α_s , is the opening angle between the muons, measured in the transverse plane with respect to the beams. In figure 5 a comparison is shown of our theoretical distributions with UA1 data. The muons satisfy the requirements of (4). In fig. 6a and 6b typical subsets of contributions from same sign and opposite sign dimuons are shown separately. The analysis is repeated for the cuts of (5) and is presented in figures 7 and 8. The comparison of our theoretical distributions with UA1 data shows for both dimuon samples a remarkably good agreement.

Fig. 5: $\Delta\Phi^{\mu\mu}$ (opening angle in the azimuthal plane between the muons from the UA1 non-isolated dimuon sample) compared with fixed order QCD calculations.

Fig. 6: $O(\alpha_s^3)$ and $O(\alpha_s^4)$ contributions to $d\sigma/d\Phi^{\mu\mu}$ in fig. 5 for opposite sign dimuons (a) and same sign dimuons (b).

Fig. 7: The $\Delta\Phi^{\mu\mu}$ distribution for non-isolated dimuons, demanding $p_t^{\mu_1} > 3$ GeV/c, $p_t^{\mu_2} > 7$ GeV/c and at least one jet with $E_t > 12$ GeV, compared with tree level $O(\alpha_s^2)$, $O(\alpha_s^3)$ and $O(\alpha_s^4)$ QCD calculations.

Fig. 8: $O(\alpha_s^3)$ and $O(\alpha_s^4)$ contributions to $d\sigma/d\Phi^{\mu\mu}$ for opposite sign dimuons (a) and same sign dimuons (b). The curves satisfy the selection criteria applied to the data of fig. 7.

Fig. 9: Inclusive muon and inclusive (non-isolated) dimuon transverse momentum distributions [11] compared with QCD predictions from open charm and bottom production [10].

The $O(\alpha_s^4)$ contributions to the inclusive muon and inclusive dimuon signals are typically an order of magnitude smaller than the leading order contributions (fig. 9). A detailed topological event analysis and a detailed Monte Carlo event simulation for events with more than two well defined jets may give some more information on the absolute contribution of the $O(\alpha_s^4)$ processes to the heavy flavour cross-section at the CERN collider.

In fig. 10, the $O(\alpha_s^2)$ cross-sections for heavy flavour production at the FNAL-collider are shown.

The cross-sections are based on extrapolations from collider data taken at $\sqrt{s} = 630$ GeV. In fig. 10a the inclusive heavy quark transverse momentum distributions are presented after demanding $|\eta^Q| < 5$. The inclusive rapidity distributions are given in fig. 10b, where each heavy quark satisfies a cut on the transverse momentum, $p_t^Q > 5$ GeV/c.

The search for (very) massive particles is one of the major motivations to increase beam energies and luminosity at future colliders. The accessible mass range will be determined by the type of colliding beams as well as both centre-of-mass energy and luminosity. In many searches for exotic particles, heavy flavours may play an important role. Their semileptonic decays for instance, can fake a direct or indirect leptonic decay of a 'new' particle when this particle is created in a complicated hadronic environment. In fig. 11a and 11b we present similar heavy flavour cross-section extrapolations as for the Fermilab collider, but at $\sqrt{s} = 16$ TeV. An increase of one order of magnitude in $\sqrt{s}$, leads to roughly a two orders of magnitude increase in cross-section for top quarks.

Fig. 10a: Inclusive transverse momentum distribution $d\sigma(p\bar{p} \rightarrow Q X)/dp_t^Q$ ($|\eta| < 5$), for

$Q = c, b, t$ and a heavy fourth generation 'down-like' quark at $\sqrt{s} = 2$ TeV.

Fig. 10b: Inclusive rapidity distribution $d\sigma(p\bar{p} \rightarrow Q X)/dy^Q$ ($dp_t^Q > 5$), for $Q = c, b, t$ and a

heavy fourth generation 'down-like' quark at $\sqrt{s} = 2$ TeV.

Fig. 11a: Inclusive transverse momentum distribution $d\sigma(p\bar{p} \rightarrow Q X)/dp_t^Q$ ($|y| < 5$), for

$Q = c, b, t$ and a heavy fourth generation 'low' quark at $\sqrt{s} = 16$ TeV.

Fig. 11b: Inclusive rapidity distribution $d\sigma(p\bar{p} \rightarrow Q X)/dy^Q$ ($dp_t^Q > 5$), for $Q = c, b, t$ and

a low quark at $\sqrt{s} = 16$ TeV.

Fig. 12: $O(\alpha_s^2)$ integrated inclusive heavy flavour cross-sections as a function of the centre-of-mass energy ($E^Q > 10$ GeV, $|y^Q| < 5$).

Integrated $O(\alpha_s^2)$ inclusive heavy flavour cross-sections in $p\bar{p}$ interactions are presented in figure 12, where $E^Q > 10$ GeV and $|\eta^Q| < 5$. The charm and bottom quark cross-sections dominate over the full range of centre-of-mass energies. Included are a cross-section prediction for a heavy low quark of 500 GeV/c² and top quark cross-sections for different masses of the top quark.

High energy, high luminosity hadron-hadron interactions will cause huge experimental problems since the number of inelastic parton-parton interactions per beam crossing rapidly increases as a function of these parameters. At LHC ($\sqrt{s} = 16$ TeV) for instance, one could expect of order 15 inelastic interactions per bunch crossing at a design luminosity of $5 \cdot 10^{34}$ cm⁻²s⁻¹. It will become a complicated enterprise to trigger on very rare physics channels. However, a beam dump type of experiment, where muons emerging from the interaction vertex could be reliably separated from decay background, may still provide an important method to investigate new physics. As an example we discuss the search for a very massive neutral Higgs particle with its (in the Glashow-Weinberg-Salam scenario) dominant decay mode into a pair of neutral weak gauge bosons:

$$pp \rightarrow H^0 \rightarrow Z^0 Z^0 \rightarrow \mu\mu X \quad (6)$$

We assume that we can discriminate against decay backgrounds by imposing a relatively large transverse momentum cut on the muons. The process of (6) receives considerable background from large transverse momentum boson pair production [18],

$$pp \rightarrow Z^0 Z^0 \rightarrow \mu\mu X \quad (7)$$

and the 'standard' channel, where the Z^0 is recoiling against an energetic jet,

$$pp \rightarrow Z^0 X \rightarrow \mu\mu X' \quad (8)$$

Altarelli et al. [19] predict that 1.1 % of the Z^0 bosons will be produced with a transverse momentum larger than 140 GeV/c at $\sqrt{s} = 10$ TeV. For all processes (6) - (8) the invariant dimuon mass will have to match within the detector resolution with the Z^0 mass. Open heavy flavour production forms the third important background from 'known' physics. It is dominated by the $O(\alpha_s^3)$ contributions

$$pp \rightarrow b\bar{b}g \rightarrow \mu\mu X \quad (9)$$

Since we require muons at large p_t , the $b\bar{b}$ pair has to recoil against an energetic gluon jet. Therefore, we expect that tree level calculations are highly insensitive to the arbitrary soft gluon cut-off that we had to impose in our analysis of the muon data at the SppS collider. In figure 13a we have summarized the results for $m_H = 800$ GeV/c². We have assumed a dimuon invariant mass resolution to reconstruct the Z^0 mass of $M_Z \pm 5$ GeV/c². The total number of events is calculated assuming an integrated luminosity of $5 \cdot 10^{41}$ cm⁻². The background from semileptonic bottom decays (9) drops rapidly as the transverse momentum of the dimuon pair increases. However, since the top quark

mass is still a free, although restricted parameter, an even more important background may come from

$$pp \rightarrow t\bar{t} g \rightarrow \mu\mu X \quad (10)$$

in the rather peculiar situation that the invariant mass of the $t\bar{t}$ pair is close to or above the Z^0 mass, where the top quark decays into a hard muon and (soft) bottom jet. The background from this channel (for $m_t = 50 \text{ GeV}/c^2$) is compared with the heavy flavour background from (9) and is shown in fig. 13b.

Fig. 13: The background to $pp \rightarrow H^0 \rightarrow Z^0 Z^0 \rightarrow \mu\mu X$ ($m_H = 800 \text{ GeV}/c^2$) from semileptonic decays of bottom quarks (a). The background from open top production exceeds the background from decaying bottom quarks considerably when the mass of the top quark is close to half the Z^0 mass (b) [20].

Although the integrated inclusive top quark cross-section is much lower than the inclusive bottom quark cross-section (fig. 12), the window on the invariant dimuon mass enhances the background from (10) considerably. Details on the calculation can be found in ref. [20].

4. Heavy flavour bound state sources in hadron-hadron interactions

At the CERN $p\bar{p}$ collider, the UA1 collaboration has measured significant heavy flavour bound state cross-sections [1], [5]. The bound states are triggered via their muonic decay channels. The hardware of the UA1 muon trigger and additional software cuts impose a cut-off on the transverse momentum of the muons with respect to the colliding proton and antiproton beams. This leads to an effective transverse momentum cut-off on the charmonium state ($p_t^{J/\psi} > 4 \text{ GeV}/c$). A close analysis of the dimuon invariant mass spectrum (where both muons are selected such that they appear to be relatively isolated) shows a distinct mass peak in agreement with expectations for 1S_1 bottom quark ($\Upsilon, \Upsilon', \Upsilon''$) bound states [1]. Although the production of large transverse momentum vector bottomonium states is completely dominated by the so-called direct production mechanisms [21], [22],

$$\begin{aligned}
 q\bar{q} &\rightarrow {}^3P_j g \\
 gq &\rightarrow {}^3P_j q \\
 g\bar{q} &\rightarrow {}^3P_j \bar{q} \\
 gg &\rightarrow {}^3P_j, {}^1S_1 g
 \end{aligned} \tag{11}$$

with ${}^3P_j \rightarrow {}^1S_1$, the charmonium cross-section receives a significant contribution from the decay of B hadrons,

$$B \rightarrow {}^1S_1 X \tag{12}$$

As we have seen in the previous sections, open heavy flavour cross-sections may be determined by correcting the inclusive single muon and inclusive dimuon cross-section by the appropriate charm hadron and bottom hadron semileptonic branching ratios, heavy quark fragmentation functions and experimental acceptance. The UA1 Υ trigger forms a subset of the inclusive dimuon trigger. Therefore, one expects many systematical errors for the heavy flavour sample to be similar to the ones for the Υ sample. In other words, taking cross-section ratios leads to cancellations of number of systematical uncertainties. In order to obtain a significant 1S_1 ($J/\psi, \psi'$) signal the cut on the transverse momentum of one of the muons was largely reduced ($p_t^{\mu_1} > 3 \text{ GeV}/c$, $p_t^{\mu_2} > 0.75 \text{ GeV}/c$) whereas the mass window lies in the J/ψ mass range ($2 - 4 \text{ GeV}/c^2$), consequently introducing different acceptance and trigger corrections. The obtained J/ψ sample turns out to be surprisingly clean and the invariant dimuon mass distribution may even indicate the presence of a ψ' signal [5]. Since the mass of the charmonium bound states are small compared to the total centre of mass energy at the collider, the interacting partons carry only a small fraction of the beam energy. The Υ and J/ψ signals may serve as a good probe for the (gluon) structure function behaviour at small values of x ($< O(10^{-2})$) [21], [22]. Detection of these signals at present (Sp $\bar{p}$ S, Fermilab) and future (LHC, SSC) colliders may pin down the gluon structure function at these very small values of x [22].

The relevant Feynman diagrams contributing to the direct production of large transverse momentum bound states of eq. (11) are shown in figure 14. Note that unlike in e^+e^- annihilation, in $p\bar{p}$ collisions all possible quantum numbers of heavy quark bound states can be produced.

Fig. 14: Feynman diagrams for large transverse momentum quarkonium production in hadronic interactions: (a) $q\bar{q}$ and $q\bar{q}$ scattering and (b) $gg \rightarrow 2S+1L_j g$, with $L = S$ or P .

The matrix elements squared have been calculated by several authors [23 - 24]. For the three gluon processes very compact formulas have been derived by Gastmans, Troost and Wu [24]. The differential cross-section for the various processes can be expressed in terms of a summation and integration over all parton species:

$$\frac{d\sigma}{dp_t^2 dy} = \sum_{ij} \int dx_1 dx_2 F_i(x_1, Q^2) F_j(x_2, Q^2) \frac{d\sigma_{ij}}{dt} \quad (12)$$

Using the wave function formalism to calculate the absolute cross-section, $d\sigma_{ij}$ may be written as [26]:

$$\frac{d\sigma_{ij}}{dt} = |R(0)|^2 \alpha_s^3(\Lambda^2, Q^2) |A|^2 \quad (13)$$

where $R(0)$ is either the quarkonium wave function at the origin (S waves) or its derivative (P waves), α_s the strong running coupling constant and $|A|^2$ the sub-process matrix element squared. We have adopted the wave function values of ref. [26], [23], which were obtained from a QCD potential model analysis:

$$\begin{aligned}
|R_s(0)|^2 &= \frac{\Gamma_{ee}}{4\alpha^2 e_Q^2} M_{\alpha\bar{Q}}^2 \\
|R_p(0)|^2 &= 9.1 \cdot 10^{-3} M_{\chi_c}^2 \\
|R_p(0)|^2 &= 1.5 \cdot 10^{-2} M_{\chi_b}^2
\end{aligned} \tag{14}$$

The $O(\alpha_s^3)$ cross-sections are divergent in the forward direction, $t \rightarrow 0$, and contain an infrared divergence when the recoil jet to the onium becomes soft ($E^{\text{jet}} \rightarrow 0$). Although $O(\alpha_s^2)$ diagrams dominate the total integrated cross-section, their contribution to large p_t bound state production can safely be neglected [22]. All hadronic and leptonic decay branching ratios are summarized in ref. [22] and were mainly taken from [27].

The dominant open heavy flavour production mechanisms $gg \rightarrow Q\bar{Q}$ and $gg \rightarrow Q\bar{Q}g$ have been discussed in detail in the previous section. However, we would like to stress that since the bottom hadrons are produced at large transverse momentum at $O(\alpha_s^2)$ as well as at $O(\alpha_s^3)$, we expect that both will contribute roughly equally to the 'indirect' J/ψ (and ψ') signals. The $O(\alpha_s^4)$ contributions are again suppressed [16] and we will neglect them in further discussions. The spectator description of the weak decay of a bottom meson is depicted in figure 15.

Fig. 15: Weak decay of the B meson: $B \rightarrow J/\psi X$.

In our calculations we have used the decay branching ratio $B \rightarrow J/\psi \sim 1\%$ and leptonic decay ratio $J/\psi \rightarrow \mu^+\mu^- \sim 7.4\%$ as measured by e^+e^- experiments [27], [28]. Comparison of the J/ψ momentum spectrum (measured in the rest-frame of the B meson) with data obtained by the CLEO [29] and ARGUS [30] experiments (fig. 16) shows that our model describes the data rather well. QCD corrections to the spectator decay model hardly modify the momentum spectrum and are omitted.

Fig. 16: J/ψ momentum spectrum in the decay $B \rightarrow J/\psi X$ compared with CLEO [29] and ARGUS [30] data. The theoretical prediction is corrected for the Lorentz boost of the B meson produced at the $\Upsilon(4s)$ ($p \sim 500$ MeV/c).

5. Comparison with data and extrapolations to higher beam energies

In comparing the absolute magnitude of theoretical cross-sections with the event rates observed by the UA1 collaboration, we are actually limited to a global shape analysis of various distributions. This is due to the large theoretical uncertainties in our calculations. Although the total cross-section for 'indirect' J/ψ is more or less determined by scaling the observed non-isolated dimuon rate, a number of uncertainties enter into the calculation of the 'direct' production processes. First, we have to regulate the divergencies for different kinematical regions which appear in the expressions for the matrix elements. Since we are still lacking the calculations of virtual corrections we impose a transverse momentum cut-off of 5 GeV/c on the bound state (hence, this is similar to the regularization of the open heavy flavour divergencies). By applying this cut we are satisfying both the experimental cuts and the requirement that we are well away from the divergencies. Secondly, although one expects that potential model analysis of bound states of two heavy quarks should be more reliable than similar analysis of single heavy quark mesons, the determination of the derivative of the wave function at the origin (and the wave function itself) is largely model dependent. Finally, the most important uncertainty is introduced by the unknown K-factor, Q^2 scale and QCD scale parameter Λ . For all presented calculations we have chosen the structure function parametrizations of Eichten et al. [7] with $\Lambda = 200$ MeV, whereas the scale was

fixed at $Q^2 = p_t^2 + M_{Q\bar{Q}}^2$ for direct onium production and $Q^2 = p_t^2 + m_Q^2$ for the calculation of the open heavy flavour tree level amplitudes, unless stated otherwise. Although a K-factor of order $1.5 \sim 2$ is by no means an unreasonable assumption, we have set $K = 1$, obtaining a conservative cross-section estimate for the direct processes.

Tables 1a and 1b illustrate the contributions from the individual $O(\alpha_s^3)$ subprocesses to the charmonium and bottomonium cross-section, respectively, calculated at $\sqrt{s} = 630$ GeV. Due to the large gluon flux at small x , the production of χ states is strongly dominated by the three gluon processes, whereas the $q\bar{q}$ contribution is negligible. The radiative χ_c decays form the main contribution to the J/ψ signal, whereas direct Υ production is typically of the same order of magnitude as Υ production via radiative χ_b decays. Because of their extremely small leptonic widths, η states do not contribute to the dimuon signal and are omitted.

	gg	gq	$q\bar{q}$
ψ	1.78	-	-
ψ'	0.91	-	-
ψ''	0.48	-	-
χ_0	29.6	6.81	0.002
χ_1	72.1	17.8	0.02
χ_2	43.2	11.7	0.007

Table 1a: The individual contributions from the subprocesses gg , gq and $q\bar{q}$ to $\sigma(p\bar{p} \rightarrow \psi, \chi_c X)$ [nb] at $\sqrt{s} = 630$ GeV with $p_t^{\text{onium}} > 5$ GeV/c.

	gg	gq	$q\bar{q}$
Υ	1.29	-	-
Υ'	0.55	-	-
Υ''	0.34	-	-
χ_0	2.47	0.77	$4.0 \cdot 10^{-5}$
χ_1	1.41	0.52	$2.0 \cdot 10^{-3}$
χ_2	3.15	1.14	$1.0 \cdot 10^{-3}$

Table 1b: The individual contributions from the subprocesses gg , gq and $q\bar{q}$ to $\sigma(p\bar{p} \rightarrow \Upsilon, \chi_b X)$ [nb] at $\sqrt{s} = 630$ GeV with $p_t^{\text{onium}} > 5$ GeV/c.

In fig. 17a we show the p_t distributions of directly formed J/ψ , J/ψ from radiative ψ' and χ_c decays and from B meson decays at $\sqrt{s} = 630$ GeV. The transverse momentum distribution for J/ψ from B meson decays is seen to fall off less steep than the other distributions. The rapidity distributions for

the same processes are shown in fig. 17b.

Fig. 17a: Transverse momentum distributions of the J/ψ for the so-called direct and indirect production mechanisms at $\sqrt{s} = 630$ GeV. Except for the p_T cut on the recoil jet ($p_T^{\text{jet}} > 5$ GeV/c) no additional cuts have been applied.

Fig. 17b: Rapidity distributions of the J/ψ for the various processes at $\sqrt{s} = 630$ GeV.

The J/ψ rapidity distribution from B decays tends to be slightly more peaked at small $|y|$ values. Figure 18 illustrates the effect of the harder p_t spectrum of J/ψ from B hadron decays on the inclusive muon spectrum. The muon transverse momentum spectrum from direct processes becomes considerably softer. And indeed, a relaxed cut on the p_t of one of the muons in the UA1 J/ψ analysis considerably enhances the acceptance for the J/ψ signal.

Fig. 18: Inclusive differential muon cross-sections $d\sigma(p\bar{p} \rightarrow {}^{2S+1}L_J X \rightarrow \mu^+ \mu^- X')/dp_t^\mu$ ($L = S, P$) and $d\sigma(p\bar{p} \rightarrow b\bar{b} X \rightarrow J/\psi X' \rightarrow \mu^+ \mu^- X'')/dp_t^\mu$ at $\sqrt{s} = 630$ GeV.

Contributions from $\psi' \rightarrow \mu^+ \mu^-$ etc. are also included. The contributions from $O(\alpha_s^2)$ and $O(\alpha_s^3)$ open bottom production are shown separately.

We expect that at relatively high p_t^μ (typically $p_t^\mu > 7$ GeV/c), a large fraction of the muons from the J/ψ decay originate from J/ψ mesons produced in B decays. As long as the relative normalizations of the cross-sections for direct and indirect production stay within 'reasonable' limits, this may serve as a tool to separate the direct production mechanisms from the open $b\bar{b}$ channel.

To compare our predictions with the experimental results we have applied the same cuts on our simulated events as UA1 [5] has introduced in the search for the J/ψ and Υ signals via their muonic decay channels. The limited muon chamber geometry implies that only muons with $|y| < 2$ can be detected whereas at least one muon has to satisfy $|y| < 1.3$ in order to trigger the apparatus. Furthermore, a transverse momentum cut of 3 GeV/c on the muons is required. (recall that for the analysis presented in ref. [5], this cut was relaxed to allow one of the muons to have $p_t > 0.75$ GeV/c. In addition a cut $p_t > 5$ GeV/c is applied to the transverse momentum of the muon pair. Muon pairs in

the invariant dimuon mass range 2 - 4 GeV/c² are considered as candidates for the J/ψ resonance, while the mass range for Υ, Υ' and Υ'' candidates is limited to 8.7 - 10.5 GeV/c².

Fig. 19a: Comparison of UA1 data with our theoretical predictions for $d\sigma(p\bar{p} \rightarrow J/\psi + X)/dp_T$. The band illustrates the uncertainties in the calculation of the direct processes due to different choices of scale and structure functions ($K = 1$). The drawn curve shows the $O(\alpha_s^2) + O(\alpha_s^3)$ contribution from B-meson decays for a fixed set of parameters (see text).

Fig. 19b: Comparison of UA1 data and our theoretical predictions for $d\sigma(p\bar{p} \rightarrow J/\psi + X)/dy$. Note that $p_T^{J/\psi} > 5$ GeV/c and we have assumed $K = 1$.

The comparisons of the theoretical J/ψ transverse momentum and rapidity distributions with the UA1 data are presented in fig. 19.

The uncertainties due to the different choices of structure functions, scale etc. are indicated by a band between the two dashed lines. The borders of the band were obtained by using the structure function parametrizations of refs. [7], [8] and [9]. Two different scale definitions have been studied: $Q^2 = M_{Q\bar{Q}}^2$ and $Q^2 = p_t^2 + M_{Q\bar{Q}}^2$. The contributions from B-meson decays are calculated using our standard set of parameters. The sum of the $O(\alpha_s^2)$ and $O(\alpha_s^3)$ indirect processes is illustrated by the drawn curve. The borders of the bands show the typical form of the distributions if we sum over all subprocesses and hence the shape of both transverse momentum and rapidity distributions is in rather good agreement with the data. Using the above defined cuts we obtain a total cross-section of 25 - 65 nb for the production of J/ψ 's at $\sqrt{s} = 630$ GeV. The B-meson decays add about 20 - 30 nb, which is of the same order of magnitude as the contribution from direct production channels. The experimental cross-section times branching ratio: $\sigma \cdot \text{BR}(\psi \rightarrow \mu^+ \mu^-) = 7.5 \pm 0.7 \pm 1.2$ nb, quoted in ref. [5], leads to a cross-section of ~ 100 nb, which is a factor 1.5 - 2 larger than our predictions. A K-factor may account for the difference.

The decays are characterized by either the associated production of a strange particle ($B \rightarrow J/\psi$ 'S') or an associated photon ($\chi, \psi' \rightarrow J/\psi \gamma$). Therefore, correlations between the muons (J/ψ) and kaons may be an additional tool to separate direct and indirect mechanisms, although the associated kaons may be hard to disentangle from the strange particles originating from underlying beam fragments. A detailed discussions on hadronic isolation of the muons as well as whether a photon may be associated to the radiative decay of a bound state can be found in ref. [22].

A similar study was performed to obtain the contributions to the 3S_1 bottom quark bound states. The UA1 measurement: $\sigma(p\bar{p} \rightarrow \Upsilon X) = 0.98 \pm 0.21 \pm 0.19$ nb [1] is, if we take into account all above discussed uncertainties, well in agreement with our theoretical calculations. We find $\sigma(p\bar{p} \rightarrow \Upsilon X) = 0.8 - 2$ nb.

Based on the comparisons with the collider data we are able to make predictions for onium production at (future) colliders. In table 2 we have summarized the dominant direct production contributions to the J/ψ and Υ cross-sections as a function of the centre-of-mass energy. The cross-sections are obtained by integration over the transverse momentum of the resonance for $p_t > 5$ GeV/c. We have studied uncertainties in the cross-section determination by choosing different structure functions and scale parameters. We find that the uncertainty grows significantly with increasing beam energy. In figures 20a and 20b we show extremes for the 3S_1 $c\bar{c}$ and $b\bar{b}$ bound state cross-sections as a function of $\sqrt{s}$. The solid curves are obtained with the Glück et al. parametrizations [8] at $Q^2 = M_{Q\bar{Q}}^2$, while the dashed curves are a result of the Duke and Owens parametrizations with $Q^2 = p_t^2 + M_{Q\bar{Q}}^2$. Although we are aware of the momentum sum-rule violation by the D & O structure functions for $Q > 10^3$, we find that the Eichten et al. parametrizations lead to very similar results.

	630 GeV.	2 TeV.	16 TeV.	40 TeV.
ψ	1.78	6.02	33.6	66.2
χ_c^0	36.4	146.	908.	$1.68 \cdot 10^3$
χ_c^1	90.0	354.	$2.62 \cdot 10^3$	$7.78 \cdot 10^3$
χ_c^2	54.9	226.	$1.55 \cdot 10^3$	$4.00 \cdot 10^3$
Υ	1.29	5.69	45.1	96.7
χ_b^0	3.24	18.4	186.	419.
χ_b^1	1.93	11.2	122.	278.
χ_b^2	4.29	23.7	270.	682.

Table 2: $O(\alpha_s^3)$ contributions to the total cross-section $\sigma(p\bar{p} \rightarrow \text{charmonium, bottomonium} + X)$ [nb] at different centre-of-mass energies, with $p_t^{\text{onium}} > 5 \text{ GeV}/c$.

Fig. 20a: ψ cross-sections as a function of $\sqrt{s}$. The drawn curves correspond to the Glück et al. [9] structure functions with scale $Q^2 = M_{Q\bar{Q}}^2$. The dashed curves are calculated using the Duke and Owens parametrization [8] ($Q^2 = p_t^2 + M_{Q\bar{Q}}^2$).

Fig. 20b: Υ cross-sections as a function of $\sqrt{s}$. The drawn curves correspond to the Glück et al. [9] structure functions with $Q^2 = M_{Q\bar{Q}}^2$. The dashed curves are calculated using the Duke and Owens parametrization [8] with $Q^2 = p_t^2 + M_{Q\bar{Q}}^2$.

Fig. 21: Transverse momentum distribution of the J/ψ for both direct and indirect production mechanisms at $\sqrt{s} = 40$ TeV. The various parameters entering into the calculation are defined in the text.

At SSC energies there is almost an order of magnitude difference between the two extremes,

reflecting the uncertainty on the poorly known gluon structure function at small values of x . Finally, we present in fig. 21 the J/ψ transverse momentum distribution extrapolated to SSC energies ($\sqrt{s} = 40$ TeV). Our standard choice of parameters, with $K = 1$, may be considered as very conservative. The p_t distributions are considerably flatter whereas the width of the rapidity distributions increase by about a factor two compared to the width of the distributions obtained at $\sqrt{s} = 630$ GeV. For the time being it remains an open question up to which centre-of-mass energies one will be able to disentangle bound state signals experimentally. However, at LHC and SSC energies, muons are believed to provide the most clean signals for existing and new physics phenomena. Therefore, known physics may provide important calibration signals.

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