

Summary of the Heavy Flavour Working Group

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We review theoretical and phenomenological aspects of heavy flavour production as discussed in the heavy flavour working group of the DIS 2012. Recent theoretical progress includes approximate NNLO calculations for heavy quark structure functions in deep inelastic scattering, the extension of the ACOT heavy flavour scheme to jet production, and advances in top physics where the highlight is clearly the first complete NNLO QCD prediction for top pair production in the $q\bar{q}$ annihilation channel. Furthermore, state of the art phenomenological predictions for open charm and bottom, charmonium, and single top and top pair production are discussed in addition to other topics such as the effect of double parton scattering on heavy quark production. New measurements on charm and beauty production presented in the heavy flavor working group are summarized and discussed in comparison with QCD predictions. Top quark strong and weak couplings as well as top quark properties are being measured with precision at the LHC and the Tevatron. We summarize also recent results on spectroscopy of charmonia, bottomonia and b -hadrons, along with studies of their decays and properties. Searches for physics beyond Standard Model through precise measurements of rare decays of heavy flavours are discussed as well.

1 Introduction

The measurement of heavy quark production provides a test of many aspect of QCD. A considerable progress in the QCD calculations for heavy-quark production has been done in the recent years. The theoretical results presented at this workshop are reviewed in Section 2. Many new results have been presented on the production of heavy quarks from different types of collisions: deep inelastic scattering, photoproduction, pp and $p\bar{p}$, and nuclear collisions (PbPb, AuAu, CuCu, dAu). Results on charm and beauty production are summarized in Section 3. Due to space constraints the results from heavy-ion collisions, which would deserve a dedicated summary, are not discussed. The measurements of top quark production are discussed in Section 4 with the new results on top properties. Finally Section 5 summarizes the updates in heavy hadron spectroscopy and on searches beyond the Standard Model exploiting B-hadron decays.

2 Theory

2.1 Deep inelastic scattering

Deep inelastic scattering (DIS) data form the backbone of global analyses of parton distribution functions (PDFs). Precise determinations of PDFs require the inclusion of heavy (charm,

bottom) quark mass terms in the calculation of DIS structure functions at higher orders in perturbation theory. In fixed order perturbation theory the charm contribution F_a^c to the inclusive DIS structure function F_a ($a = 2, L$) is given as a convolution of PDFs f_j with heavy quark Wilson coefficients H_j ($j = g, u, d, s$):

$$F_a^c(x, Q^2) = H_{a,j}(x, \frac{Q^2}{\mu^2}, \frac{m^2}{\mu^2}) \otimes f_j(x, \mu^2), \quad (1)$$

where m is the charm quark mass and μ the factorization scale (which has been identified with the renormalization scale). For neutral current DIS, the coefficients $H_{a,j}$ are currently known to order $\mathcal{O}(\alpha_s^2)$. At this conference, progress has been reported to construct approximate heavy quark Wilson coefficients at order $\mathcal{O}(\alpha_s^3)$ using the information from different kinematic limits.

Due to mass factorization, in the limit $Q^2 \gg m^2$ the $H_{a,j}$ can be written as a convolution of light flavor Wilson coefficients $C_{a,i}$ with universal operator matrix elements (OMEs) A_{ij} :

$$H_{a,j} \simeq C_{a,i}(x, \frac{Q^2}{\mu^2}) \otimes A_{ij}(x, \frac{m^2}{\mu^2}). \quad (2)$$

Indicating the loop order as upper index one can write generically

$$H^{(3)} \simeq C^{(0)} \otimes A^{(3)} + C^{(1)} \otimes A^{(2)} + C^{(2)} \otimes A^{(1)}, \quad (3)$$

where the light flavor Wilson coefficients are available up to order $\mathcal{O}(\alpha_s^3)$ [1]. In order to construct the heavy quark Wilson coefficient functions $H_{a,j}^{(3)}$ in the asymptotic limit, the OMEs are needed up to the same order $\mathcal{O}(\alpha_s^3)$ and partial results for certain color factors have been obtained very recently [2]. As an important application, the OMEs are needed for the definition of variable flavor number schemes since they enter the matching conditions for the PDFs with n_f and $n_f + 1$ active flavours.

In addition to the asymptotic limit $Q^2 \gg m^2$, it is possible to exploit universal features in the threshold region $\beta = \sqrt{1 - 4m^2/s} \simeq 0$ where Sudakov logarithms $\ln \beta$ can be resummed and in the high energy limit where information on leading and next-to-leading small- x logarithms is available in order to construct improved heavy quark coefficient functions at order $\mathcal{O}(\alpha_s^3)$ [3, 4].

As is well-known, the heavy quark coefficient functions H_i are not IR-safe: $H_i \rightarrow \infty$ for $\frac{Q^2}{m^2} \rightarrow \infty$. Therefore, most of the modern global analyses of PDFs use so called general mass variable flavor number schemes (GM-VFNS) where the large logarithms $\ln \frac{Q^2}{m^2}$ are removed from the coefficients H_i and resummed by heavy quark initiated subprocesses with evolved heavy quark parton distributions. At the same time, finite mass terms $\frac{m^2}{Q^2}$ are retained in the subtracted IR-safe Wilson coefficients $\hat{H}_i$. For use in precision determinations of PDFs, these GM-VFNS have to be formulated at NNLO and F. Olness presented approximate results for the neutral current structure functions F_2 and F_L in the ACOT GM-VFNS [5] up to order $\mathcal{O}(\alpha_s^3)$ [6].

2.2 Open charm and beauty

Most of the heavy flavour schemes have been formulated for inclusive DIS processes and are used in global analyses of PDFs. On the other hand, less inclusive processes provide many additional tests of pQCD in various kinematic regions and are closer to the experimental measurements.

However, theoretical calculations are much more challenging and even more so if heavy quark mass effects have to be taken into account. Nevertheless, any heavy flavour scheme should also be applicable to less inclusive observables in order to be considered a general formalism of perturbative QCD (pQCD) including heavy quark masses [7]. Relying on a factorization theorem with heavy quarks [8], ACOT-like variants of the GM-VFNS have been applied to inclusive heavy meson production in DIS [9], photoproduction [10], hadroproduction [11, 12], and electron-positron annihilation [13]. At this conference updated numerical results for inclusive D and B meson production in the GM-VFNS at the LHC have been presented [14]. Furthermore, a new method for calculating DIS jet production in the ACOT scheme has been reported extending the dipole subtraction formalism to all possible QCD splitting processes with heavy quarks including splittings of coloured, massive particles in the initial state [15].

An interesting feature of exclusive processes with a heavy quark in the final state is that they are useful to probe heavy flavour PDFs. In most global analyses of PDFs the charm and bottom distributions are generated “radiatively” using perturbatively calculated boundary conditions. With other words, no new fit parameters are associated to the charm and bottom PDFs. However, a purely perturbative treatment might not be adequate, in particular for the charm quark with mass $m_c \simeq 1.5$ GeV, and in fact non-perturbative models exist that predict an intrinsic charm (IC) component in the nucleon [16]. Clearly, the heavy quark PDFs should be tested since they play an important role in some key processes at the LHC [17]. A promising way to constrain models on IC is the measurement of inclusive D meson production at RHIC or with the LHCb detector at the LHC where at forward rapidities the differential cross section can be enhanced by a factor of up to 5 compared to the prediction with a radiatively generated charm PDF [14]. Another process which is very sensitive to the heavy quark PDF is direct photon production in association with a heavy quark jet [18]. Data from the D0 experiment at the Tevatron [19, 20] overshoot the standard NLO QCD predictions [21] at large transverse photon momenta and the inclusion of an intrinsic heavy quark component in the nucleon can reduce the difference between data and theory but not fully resolve it. Measurements of this process at RHIC and the LHC probe the heavy quark PDFs in different regions of the momentum fraction x and would be useful to shed more light on the current situation. In addition, the measurements at the LHC would provide a baseline for $\gamma + Q$ production in pA [22] and AA collisions [23].

Finally, work has been presented on $c\bar{c}$ production in the k_T -factorization formalism. The predictions for D meson production at the LHC somehow undershoot the data of ALICE and LHCb (preliminary). Furthermore, the production of two $c\bar{c}$ pairs in a formalism with double-parton scattering has been discussed. The predicted cross sections for $c\bar{c}c\bar{c}$ at the LHC receive similar contributions from single-parton and from double-parton scattering [24].

2.3 Charmonium production

The charmonium J/ψ has been extensively studied experimentally ever since its discovery in 1973. However, theoretically, heavy quarkonium production and decay are still not well understood. A rigorous framework for theoretical studies is provided by the factorization theorem of nonrelativistic QCD (NRQCD) [25] where the charmonium production cross section factorizes into calculable short distance cross sections for the production of a heavy quark pair $c\bar{c}[n]$ in a Fock state n and nonperturbative long distance matrix elements (LDMEs) $\langle \mathcal{O}^{J/\psi}[n] \rangle$ which have to be extracted from experiment. The Fock states are described by quantum numbers for spin, orbital and total angular momentum and color, $n = {}^{2s+1}L_J^{[c]}$. For J/ψ production

the following states are considered: $n = {}^3S_1^{[1]}, {}^1S_0^{[8]}, {}^3S_1^{[8]}, {}^3P_J^{[1]}$ including color-octet (CO) states $[c] = [8]$ in addition to color singlet (CS) states $[c] = 1$.

A NLO NRQCD analysis of the J/ψ yield and polarization based on the results in [26] can be summarized as follows [27, 28]: (i) A global analysis of unpolarized world J/ψ data from hadroproduction, photoproduction, two-photon scattering and electron-positron annihilation experiments allows to determine the three CO LDMEs $\langle \mathcal{O}^{\mathcal{T}/\psi}({}^3S_1^{[1]}) \rangle, \langle \mathcal{O}^{\mathcal{T}/\psi}({}^1S_0^{[8]}) \rangle, \langle \mathcal{O}^{\mathcal{T}/\psi}({}^3S_1^{[8]}) \rangle$ and the data are well described. Here it is important to note that hadroproduction data alone can not constrain all three matrix elements even including polarization data. (ii) The predictions from the NLO NRQCD global analysis of unpolarized world data do not agree with J/ψ polarization data from CDF I and the new measurements from CDF II. With other words it is not possible to describe the unpolarized hadro- and photoproduction data and the CDF polarization measurements with one set of CO LDMEs. Conversely, the new measurements from ALICE agree with NLO NRQCD within errors. Future precise polarization measurements at the LHC will have the potential to confirm or dismiss the universality of the LDMEs.

2.4 Top quark physics

In the past few years, there has been impressive theoretical progress in the calculation of top quark pair production beyond NLO. A highlight has certainly been the completion of the exact NNLO QCD corrections to $q\bar{q} \rightarrow t\bar{t} + X$ which represents a theoretical breakthrough because it is the first ever NNLO calculation involving more than two coloured particles and/or massive fermions [29, 30]. As a last missing piece for this calculation, suitable counter terms needed to regulate infrared divergences in the interference terms of tree-level and one-loop amplitudes with three particles in the final state (of which two are massive) have been derived in [31, 32]. For $\mu_R = \mu_F =: \mu$ the partonic cross section reads in NNLO ($k \leq 2$):

$$\hat{\sigma}_{q\bar{q}}(\beta, m^2, \mu^2) = \frac{\alpha_s^2}{m^2} \sum_{k=0}^2 \sum_{l=0}^k \alpha_s^k \sigma_{q\bar{q}}^{(k,l)}(\beta) L^l, \quad (4)$$

where $L = \ln(\mu^2/m^2)$. The scale-dependent terms $\sigma_{q\bar{q}}^{(k,l)} L^l$ with $l \geq 1$ can be generally computed from the lower order functions $\sigma_{q\bar{q}}^{(k' < k, l=0)}$ by renormalization group methods [33] so the new information resides in the function $\sigma_{q\bar{q}}^{(2,0)}(\beta)$. Furthermore, it is possible to perform an all order resummation of universal Sudakov logarithms $\ln \beta$, which become dominant close to the production threshold ($\beta \rightarrow 0$), at next-to-next-to-leading logarithmic (NNLL) accuracy. The NNLO+NNLL result allows one to predict the $t\bar{t}$ production cross section at the Tevatron with significantly improved precision at the level of 3% [30]. A C++ program for the calculation of the $t\bar{t}$ total cross section including the full NNLO corrections is publicly available [34].

In addition to the production threshold ($\beta = \sqrt{1 - 4m_t^2/\hat{s}} \rightarrow 0$) all order resummations can also be performed for the pair invariant mass (PIM) threshold $z = M_{t\bar{t}}^2/\hat{s} \rightarrow 1$ treating the $t\bar{t}$ system as a pair and the one particle inclusive (1PI) threshold $s_4 = \hat{s} + \hat{t}_1 + \hat{u}_1 \rightarrow 0$ where one integrates over the phase space of one of the heavy quarks. The latter two thresholds are relevant for differential distributions in the pair invariant mass and for the transverse momentum or rapidity of the observed heavy quark, respectively, in addition to the total cross section and different approaches to resum them exist in the literature [35, 36, 37]. The differences between the methods concern formally subleading terms which, however, can be numerically important. Alternatively, approximate NNLO theories can be constructed by combining the

information from the exact NLO calculation with all universal (soft and collinear) logarithmic terms appearing at NNLO, see also Sec. 2.1.

Within the approach based on soft-collinear-effective theory (SCET), phenomenological predictions for the total cross section [38] and various differential distributions [39] at the Tevatron and the LHC have been discussed [35]. Furthermore, using standard momentum-space resummation in pQCD, a large number of numerical results for the differential and total cross sections for both, top pair [40] and single top production [41], have been presented by N. Kidonakis [36]. One observable which has received a lot of attention recently is the top quark charge asymmetry. It was shown, that the higher order predictions are consistent with NLO and hence do not resolve the discrepancy with the Tevatron data at high invariant mass and rapidity [42].

More exclusive top observables are important because they can have sizable production cross sections or constitute important backgrounds for Higgs searches. Here theoretical progress has been achieved by merging exact NLO calculations with parton showers. At this conference, results have been presented for the production of top quark pairs with one jet ($t\bar{t} + j$) [43, 44]. In addition, several processes ($t\bar{t} + j$ [45], $t\bar{t} + Z$ [46], $t\bar{t} + H/A$ [47] and $W^+W^-b\bar{b}$) have been implemented into the PowHel framework as has been discussed in a talk by A. Kardos [48].

3 Charm and beauty production

3.1 Heavy quarkonium production

Measurements of the production cross sections of prompt J/ψ have been performed by the four LHC collaborations. In addition CMS [49] and LHCb [50] also presented measurements of $\psi(2S)$ production which is less influenced by feed-down from the decays of heavier states. These results are reasonably well described by the NRQCD predictions including CS+CO contributions at NLO as discussed in the theory section 2. Calculations based on the k_T factorization approach including only CS diagrams are also able to describe the data.

The situation is less clear when the polarization of the produced state is considered. The new measurements of the J/ψ and $\Upsilon(nS)$ helicity, presented respectively by the ALICE [51] and CDF [52, 53] collaborations, agree marginally with the NRQCD NLO prediction. The CDF Υ result, obtained with a integrated luminosity of 5.7 fb^{-1} , is in good agreement with previous CDF data obtained with lower luminosity while the disagreement with the measurement by the D0 collaboration persists.

3.2 Charm production in DIS and $F_2^{c\bar{c}}$

The H1 and ZEUS collaborations are finalizing their effort to measure charm and beauty production in DIS and to provide the best possible measurement of $F_2^{c\bar{c}}$, the component of the inclusive structure function F_2 with charm in the final state. The H1 collaboration published their final measurement of D^{*+} production in DIS [54], while ZEUS presented preliminary results on D^{*+} production and on charmed jets tagged using secondary vertices [55, 56]. These results are reasonably well described by NLO QCD calculations as shown in Fig. 1 (left) for the D^{*+} case. Charm cross section measurements obtained with different techniques are used to extract $F_2^{c\bar{c}}$. Figure 1 (right) shows the ZEUS preliminary measurements compared to a preliminary combination including H1 data and ZEUS measurements from older data sets. Once combined, these data will improve the knowledge of $F_2^{c\bar{c}}$, reaching a precision of about 5% over a wide range of x and Q^2 .

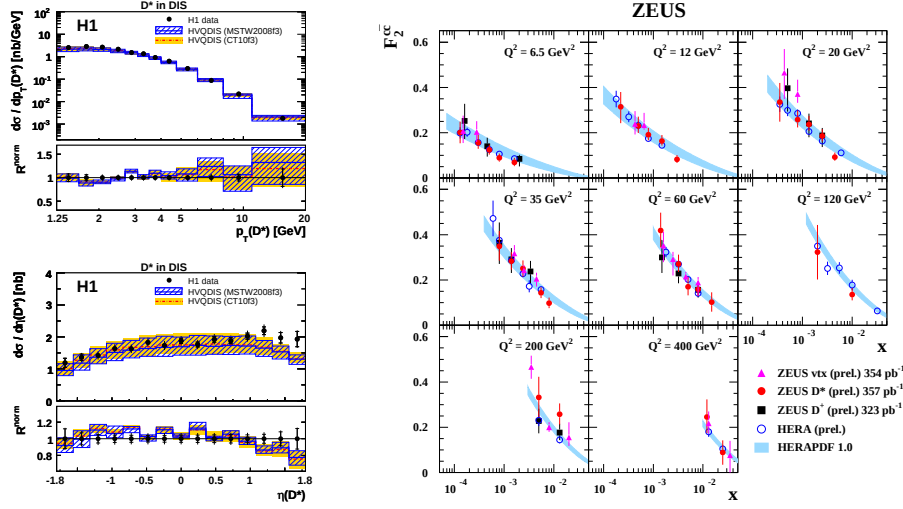


Figure 1: Left: H1 measurement of the D^{*+} meson production in DIS for $Q^2 > 5 \text{ GeV}^2$, $p_T > 1.25 \text{ GeV}$ and $|\eta| < 1.8$ as a function of p_T and η , compared to NLO QCD calculations. Right: the charm structure function $F_2^{c\bar{c}}$. Recent preliminary ZEUS results based on secondary vertex tagging, on D^{*+} and D^+ mesons are compared to the preliminary combination of H1 and previous ZEUS data and to a GM-VFNS prediction based on the HERAPDF1.0 PDFs.

3.3 Charm photo- and hadro-production

The H1 collaboration presented a new measurement of the D^{*+} photoproduction cross sections [57] that has been compared to various QCD calculations: fixed-order NLO, the NLO Monte-Carlo matched to parton-shower (MC@NLO) [58] and GM-VFNS. They all describe well the data within their theoretical uncertainties. The ZEUS collaboration presented a precise measurement of the charm fragmentation fractions into different charmed hadrons, based on photoproduction data [59]. The good agreement with e^+e^- results supports the universality of charm fragmentation.

The ATLAS and ALICE collaborations presented differential cross sections for the production of D mesons [60, 61]. The results are in agreement with QCD predictions at NLO matched to next-to-leading-log resummation (FONLL) [62] and, at transverse momenta larger than the charm mass, also to GM-VFNS calculations [14]. Compared to FONLL, data are in general on the upper edge of the theoretical uncertainty, which is particularly large at low transverse momenta, as shown e.g. in Fig. 2 (left). Less inclusive observables do not match completely the standard expectations. This is the case of the measurement of D^* jets by ATLAS [63], in which the fraction of the jet momentum carried by the associated D^* is on average lower than the predictions based on standard QCD programs and on the charm fragmentation functions measured in e^+e^- experiments. The measurement of double charm (CC) and charmonium-charm ($J/\psi C$) production made by the LHCb collaboration [64] is also challenging our understanding of heavy-flavour production. The rate of CC meson pairs is $\approx 10\%$ of the $C\bar{C}$ rate, as shown in Fig. 2 (right). Considering that cc production occurs at $O(\alpha_s^4)$, while $c\bar{c}$ pairs are produced at

$O(\alpha_s^2)$, this result appears unexpected at a first sight. Anyway a comparison with detailed QCD calculations is needed to understand the origin of this large CC fraction. Proposed explanations are multiparton interactions or the excitation of intrinsic charm in the proton.

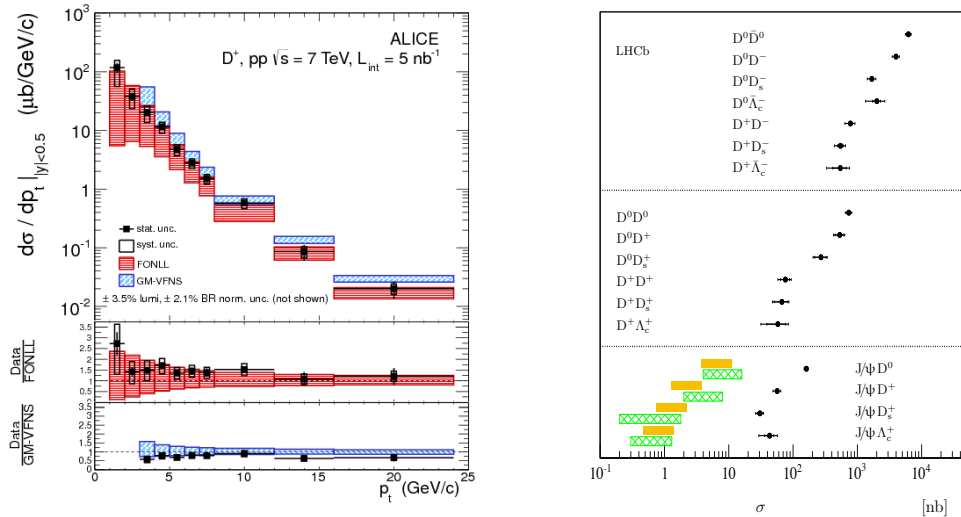


Figure 2: Left: D^+ meson production cross section differential in p_T as measured by ALICE in pp collisions compared to FONLL and GM-VFNS predictions. Right: cross section for the production of two hadrons containing charm quarks as measured by LHCb for $2 < y < 4$ and $3 < p_T < 12 \text{ GeV}$: $C\bar{C}$ (up), CC (middle), $J/\psi C$ (bottom). Filled areas correspond to theoretical calculations for gluon-gluon processes.

3.4 Beauty production

New measurements of open beauty production at the LHC have been presented, using different techniques in different kinematic ranges. All the four LHC experiments measured beauty production by tagging non-prompt J/ψ or $\psi(2S)$ from B-hadron decays, covering a large range in p_T (from zero to tens of GeV) and in rapidity ($0 < y < 4.5$). The results are in good agreement with the FONLL theory within relatively large theoretical uncertainties, as shown in Fig. 3 (left) for the CMS case. The CMS collaboration also presented a measurement of the cross section for di-muons originating from the decays of $b\bar{b}$ pairs [65] which provides precise data in the low- p_T regime. The measured cross section is in agreement with the MC@NLO prediction within the $\approx 30\%$ theoretical uncertainty.

At high p_T , the measurement of beauty production has been extended by the ATLAS and CMS collaborations using b-jet tagging algorithms [66, 67]. Figure 3 (right) shows, as an example, the ATLAS inclusive b-jet cross section in bins of p_T and rapidity, measured using 2010 data and compared to the predictions from the MC@NLO and the POWEG+Pythia [68] NLO Monte Carlos. The agreement is good, especially with POWEG+Pythia which features a better treatment of beauty fragmentation and decays. The uncertainty is dominated by the experimental systematics on b-tagging efficiency and on b-jet energy scale that sum up to $\approx 16\%$ at $p_T = 100 \text{ GeV}$ and central rapidity.

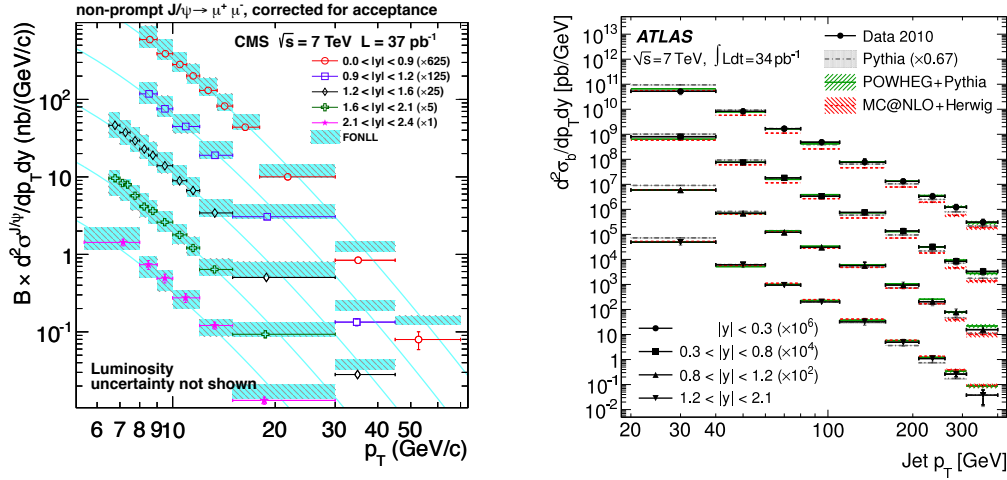


Figure 3: Left: non-prompt J/ψ production from b-hadron decays measured by CMS compared to FONLL predictions. Right: comparison of the inclusive b-jet cross section measured by ATLAS to various QCD predictions.

4 Top quark physics

Many top quark measurements have been made at the Tevatron and the LHC, both in top quark pair and single top production. At the Tevatron, results using half or all of the final data set have been released, and results from the LHC with 2011 data collected at 7 TeV are available.

4.1 Top quark pair production

The top quark pair production cross section has been measured in different final states. Cross section measurements from the CDF and D0 collaborations with up to 5 fb^{-1} of 1.96 TeV proton-antiproton data utilize electrons, muons, taus and all-hadronic final states. Each experiment has measured the cross section with an uncertainty of better than 8% [69, 70].

The LHC collaborations ATLAS [71, 72] and CMS [73, 74] have measured the top quark pair production cross section in several different final state configurations, summarized in Fig. 4. This includes tau lepton final states, and for ATLAS even the tau+jets and all-hadronic final states. All measurements show good agreement with the SM expectation.

CMS additionally has a preliminary measurement of the differential cross section as a function of p_T and rapidity of the $t\bar{t}$ system [75]. ATLAS has preliminary measurements of the $t\bar{t}$ cross section with a veto on forward jets [76] and of the cross section for $t\bar{t}$ production in association with a photon [77].

4.2 Single top quark production

Single top quark production has been observed both at the Tevatron and the LHC. D0 has measured the cross section for the t -channel production mode [78] as well as the total single

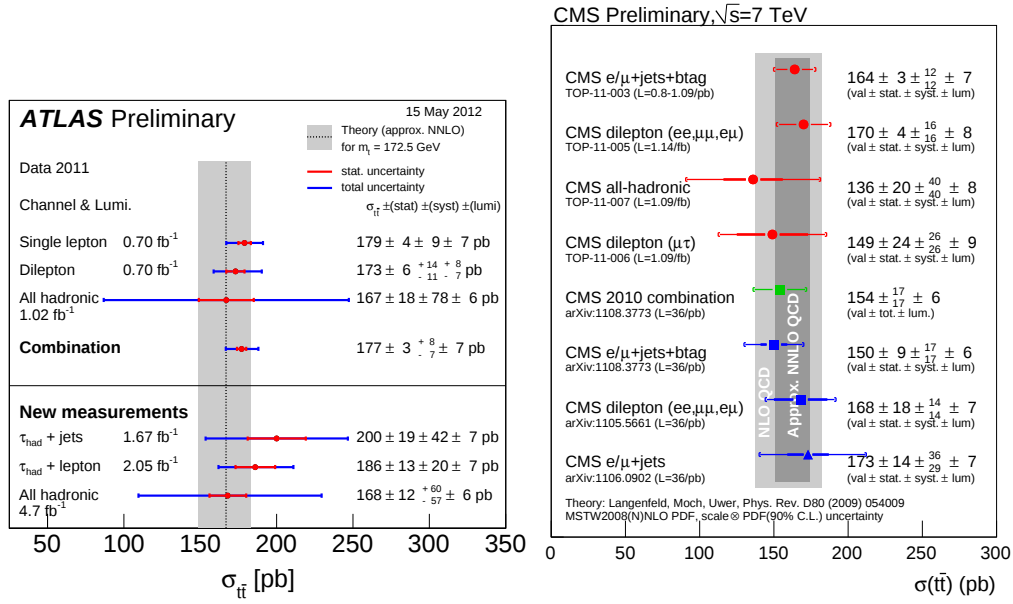


Figure 4: Summary of top quark pair production cross section measurements (left) by ATLAS and (right) by CMS.

top production cross section [79]. CDF has a preliminary measurement of single top quark production based on 7.5 fb⁻¹ of data [80]. Figure 5 (left) shows the 2d contour of t -channel vs s -channel cross sections measured by CDF and compares them to the SM.

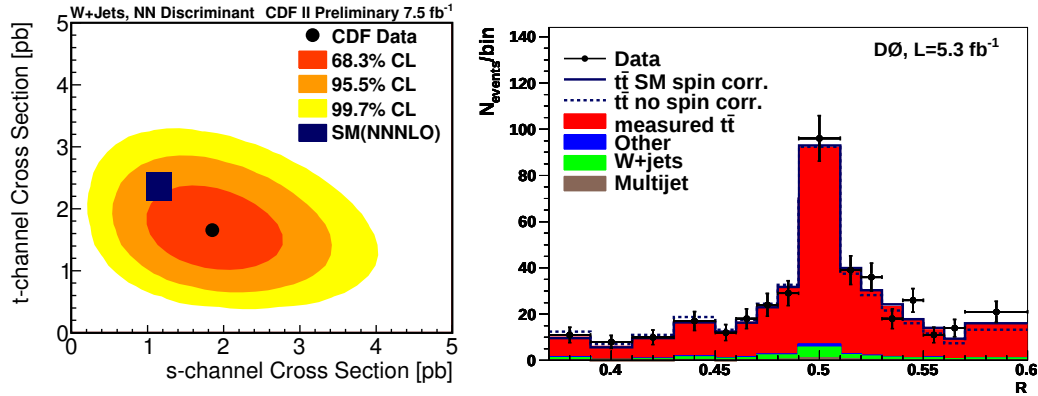


Figure 5: (left) Single top quark production cross section for s -channel and t -channel from CDF and (right) top quark spin correlation measurement by D0.

ATLAS has measured the t -channel cross section to be 83 ± 20 pb using 1 fb⁻¹ of 7 TeV data using a neural network approach [81]. A cut-based measurement also provides separate

top and antitop quark t -channel cross sections [81]. CMS has measured a t -channel cross section of 70.3 ± 11.5 pb [82]. ATLAS and CMS also have first searches for Wt associated production [83, 84], but have not yet measured the cross section. ATLAS also has searched for s -channel single top quark production [85].

The single top quark cross section is proportional to the CKM matrix element $|V_{tb}|^2$, and all collaborations have derived lower limits on $|V_{tb}|$. D0 has also extracted a measurement of the top quark width from the t -channel cross section through a combination with the flavour composition measurement in top quark decays [86].

The single top quark final state is sensitive to many models of new physics. Recent searches for flavor-changing neutral currents [87] and new heavy bosons by ATLAS [88], and for anomalous couplings by D0 [89, 90] have not found any evidence for new physics and set stringent limits.

4.3 Top quark mass

The mass of the top quark has been measured with high precision at both the Tevatron and the LHC. D0 has a new top quark mass measurement in the dilepton channel [91] and CDF has a new measurement in the lepton+jets channel [92] with an uncertainty of 1.3 GeV. The Tevatron average of 173.2 GeV has an uncertainty of only 1.0 GeV [93].

ATLAS and CMS have not yet reached that level of precision but have also produced first results. The ATLAS top quark mass measurement has an uncertainty of 2.4 GeV and the CMS measurement has an uncertainty of 1.3 GeV. CMS also measures the mass difference between top and antitop quarks [94].

4.4 Top quark properties

Abundant top quark samples are now available making measurements such as spin correlation in top quark pair production possible. D0 has reported evidence for spin correlation [95], shown in Fig. 5 (right). A preliminary CDF study finds a value consistent with no spin correlation in a similar size data set [96]. ATLAS also observes spin correlation [97].

Since the Tevatron is a proton-antiproton collider, a forward/backward asymmetry in top quark pair production can be measured in the rapidity difference between the top and antitop quark. CDF has a preliminary result for the full Tevatron data set [98], finding a significant deviation from the SM. D0 also sees a deviation from the SM expectation [99].

At the LHC proton-proton collider, a possible asymmetry is reflected as a charge asymmetry which is more difficult to measure. The ATLAS measurement of the charge asymmetry is consistent with the SM expectation [100]. The CMS measurement is also consistent with the SM [101].

5 Spectroscopy and rare decays

5.1 Spectroscopy of heavy quarkonia and b-hadrons

Comprehensive study of heavy quarkonia is an important test of the QCD. The goal is to complete the predicted $c\bar{c}$ and $b\bar{b}$ spectra, measure their properties and transitions. Such an experimental information allows validating the QCD predictions obtained either in the theoretical approach, where the $Q\bar{Q}$ multiplets are calculated on the lattice, or in the phenomenological

one i.e. from the potential models which attempt to model QCD features by describing the interquark potential.

In the charmonium landscape, all the states lying below the threshold for decays to open charm were discovered. Agreement with predictions of the potential models is quite good, whereas the lattice usually underestimates some of the splittings, for instance the $J/\psi - \eta_c(1S)$ hyperfine one [102]. The era of precise lattice QCD calculations for charmonia above the $D\bar{D}$ threshold has only begun. There are only a few such charmonia observed, whereas most of the missing states (except for ground D -wave states) are expected to decay dominantly into $D^{(*)}\bar{D}^{(*)}$ -like final states and to have quite large widths. Over the last decade many $c\bar{c}$ -like states, called the X , Y , Z , were observed by experiments at e^+e^- as well as hadron colliders [102]. Their properties are either unusual for conventional charmonia (large widths for hadronic transitions, non-zero electric charge) or simply don't match any empty slots in the $c\bar{c}$ spectrum. Therefore they are considered as candidates for exotic hadrons, like molecules, tetraquarks or hybrids, which are also predicted within the QCD framework. The experiments continue their efforts to confirm and/or further study properties of these resonances. Belle have investigated the properties of the most famous $c\bar{c}$ -like state, the $X(3872)$ in its discovery decay mode $J/\psi\pi^+\pi^-$. The world best upper limit on its width was set at $1.2 \text{ MeV}/c^2$ [103]. Neither the charged partner $X^\pm \rightarrow J/\psi\pi^\pm\pi^0$ nor the C -odd partner searched for in $J/\psi\eta$ and $\chi_{c1}\gamma$ final states have been observed. Instead, Belle found the first evidence of the narrow $\psi_2(1D)$ charmonium decaying to the $\chi_{c1}\gamma$ at the mass of $3823 \pm 3 \text{ MeV}/c^2$ [104]. Babar have reported study of the $\eta_c\pi^+\pi^-$ produced in two-photon annihilation. Such a study is important to test an interpretation of the $X(3872)$ as the $\eta_{c2}(1D)$ or to search for the $\eta_{c2}(1D)$ itself, but no significant signal for neither of them has been found. Charged $c\bar{c}$ -like states play a special role, as they must consist of at least four quarks. Belle observed three such resonances, the $Z(4430)^\pm \rightarrow \psi'\pi^\pm$ and $Z(4050)^\pm, Z(4250)^\pm \rightarrow \chi_{c1}\pi^\pm$ produced in $B \rightarrow Z^\pm K$ decays [105], however Babar have not confirmed any of them [106]. Since the upper limits set by Babar on the product branching fractions do not contradict the Belle measurements, the conclusive results are expected to come from the LHC experiments. Both LHCb and CMS have demonstrated that they will play an important role in studies of $c\bar{c}$ spectroscopy. Using only a small fraction of their data, they measured precisely mass and pp production of the $X(3872)$ [107, 108]. The $X(3872) \rightarrow J/\psi\pi^+\pi^-$ yield expected with the 2011 Run data will hopefully allow them to discriminate between the two possible spin-parities of the $X(3872)$, 1^{++} and 2^{-+} .

Experimental data on the bottomonium spectrum remain even more incomplete. The field has become lively once B -factories took data at $\Upsilon(nS)$'s other than $\Upsilon(4S)$, which allowed Babar to discover the ground bottomonium $\eta_b(1S)$ in the $\Upsilon(2,3S) \rightarrow \eta_b(1S)\gamma$ transitions [109]. Belle studies of the data collected at the $\Upsilon(5S)$ have revealed that its properties differ from other $\Upsilon(nS)$'s. A reason for abnormally large transitions $\Upsilon(5S) \rightarrow \Upsilon(1,2,3S)\pi^+\pi^-$ [110] are two charged $b\bar{b}$ -like states $Z_b(10610)^\pm, Z_b(10650)^\pm \rightarrow \Upsilon(1,2,3S)\pi^\pm$ that mediate these transitions [111]. The $\Upsilon(5S) \rightarrow h_b(1,2P)\pi^+\pi^-$ transitions have been found to be as large and also saturated with the $Z_b(10610)^\pm, Z_b(10650)^\pm \rightarrow h_b(1,2P)\pi^\pm$ amplitudes. Interpretation of the $Z_b^\pm$ states as $B^{(*)}\bar{B}^*$ molecules seems to be supported by their masses and decay amplitude pattern [112]. The $\Upsilon(5S) \rightarrow h_b(1,2P)\pi^+\pi^-$ transitions allowed the first observation of the spin-singlet $h_b(1P)$ and $h_b(2P)$ bottomonia [113]. Belle have also reported a measurement of the mass and the first measurement of the width of the $\eta_b(1S)$ produced in $h_b(1P) \rightarrow \eta_b(1S)\gamma$. Measured $\eta_b(1S) - \Upsilon(1S)$ hyperfine splitting improved agreement with the theoretical predictions [102]. The $b\bar{b}$ spectroscopy is also studied at the hadron colliders. The first particle observed at the LHC has been a candidate for $\chi_b(3P)$ found at $10530 \pm 51 \text{ MeV}/c^2$ by Atlas in

$\chi_b(3P) \rightarrow \Upsilon(1, 2S)\gamma$ transitions [115]; it has been soon confirmed by DØ [116].

LHCb has taken over a leading role in studies of b -hadrons being out of reach of the B -Factories. The presented results on B_c mesons, such as a mass measurement using the $B_c^+ \rightarrow J/\psi\pi^+$ decays, their production relative to topologically similar $B^+ \rightarrow J/\psi K^+$ reference decays, as well as the first observation of the $B_c^+ \rightarrow J/\psi\pi^+\pi^-\pi^+$ decays, comprise an important experimental input on this heaviest b -meson observed so far [117]. The world best mass measurements of b -baryons: Λ_b^0 , Ξ_b^- and Ω_b^- and study of the Λ_b production allowing extraction of the $\frac{f_{\Lambda_b}}{f_d+f_u}$ production fraction, nicely improve previous Tevatron measurements.

5.2 Rare decays of heavy flavours

Search for physics beyond the Standard Model (SM) is nowadays one of the main goals of particle physics. Precision studies of the $B_{(s)}$, $D_{(s)}$ and τ decays which in the SM are either suppressed or forbidden, allow one to search for New Physics (NP) effects. Virtual contributions of NP particles can enter the diagrams underlying the studied processes and modify the SM predictions for various observables, like decay rate, CP violation or polarization. The deviation of a given observable from the SM will be a sign of NP, whereas the study of correlations between observables will allow one to identify the nature of NP. Such indirect searches are complementary to the direct ones performed at the LHC. All the measurements performed so far to overconstrain the unitarity triangle (UT) describing B meson system seem to be consistent with each other within their uncertainties [118] and thus constrain NP corrections to be at most at the 10% level. Numerous tensions between the measurements and the SM predictions reported over the last few years encourage to investigate them further with increased precision.

The asymmetry of same-sign muon pairs from semileptonic $B_{(s)}$ decays was found by D to be larger than the SM prediction by 3.9σ [119]. This asymmetry is related to CP violation in $B^0-\bar{B}^0$ and $B_s^0-\bar{B}_s^0$ mixing. A phase entering the latter, the ϕ_s , can be independently measured via a time dependent analysis of $B_s^0 \rightarrow J/\psi\phi$, where CP violation occurs via interference between the decay proceeding with and without B_s mixing. Updated measurements of the ϕ_s and $\Delta\Gamma_s$ by CDF [120] and LHCb [121] show that the overall agreement with the SM is good. This might suggest the NP contribution in the $B^0-\bar{B}^0$ mixing, and such a picture seems to be supported by a 2.5σ discrepancy between the $\sin 2\beta$ UT parameter measured directly from the $B^0 \rightarrow c\bar{c}K^0$ decays and indirectly determined from the global fit to all the remaining UT measurements [118].

The golden mode for NP searches, the $B_s^0 \rightarrow \mu^+\mu^-$, is very clean from the theoretical as well as the experimental point of view. The SM prediction for its branching ratio is only $(3.2 \pm 0.2) \times 10^{-9}$, while a broad class of NP models can enhance it up to 10^{-7} . A global effort has been made to find the $B_s^0 \rightarrow \mu^+\mu^-$ signal and the strongest constraint of $\mathcal{BR}(B_s^0 \rightarrow \mu^+\mu^-) < 3.8 \times 10^{-9}$ comes from LHCb [122]. CDF measurement updated with their full data sample [123] has not reinforced previously found signal increase.

Contrary to the $D^0-\bar{D}^0$ mixing, where any NP effects would be obscured by long distance contributions, CP violation in D meson decays has been over last the years suggested to be a good place for NP searches. In the SM it is expected to be very small, at the level of 10^{-3} at most, and experimental measurements have reached that precision only recently. First evidence of CP violation in charm decays has been found by LHCb in the measurement of $\Delta A_{CP} = A_{CP}(D^0 \rightarrow K^+K^-) - A_{CP}(D^0 \rightarrow \pi^+\pi^-) = (-0.82 \pm 0.21 \pm 0.11)\%$ [124], which in a first approximation corresponds to the difference of direct CP violation. Together with the result reported by CDF [125], no CP violation scenario is excluded at the 4σ level. However,

according to the revised theoretical calculations such an increased CP violation can be still accommodated within the SM [126].

Indirect searches for NP in the heavy flavour sector have been very lively. Many rare processes only come within reach thanks to increasing sensitivity obtained with data from LHC and full data samples from B -Factories and Tevatron experiments being analyzed. Some of the important studies, like precision $\mathcal{BR}(B \rightarrow \tau\nu)$, polarization measurements in $B \rightarrow \bar{D}^{(*)}\tau\nu$, lepton flavour violation in τ decays will be feasible only with Super B -Factories being under construction.

6 Conclusions

There has been theoretical progress concerning approximate NNLO calculations for heavy quark structure functions in deep inelastic scattering, the extension of the ACOT heavy flavour scheme to jet production, and advances in top physics (soft gluon resummations, merging with parton showers) where the highlight is clearly the first complete NNLO QCD prediction for top pair production in the $q\bar{q}$ annihilation channel. Furthermore, state of the art phenomenological predictions for open charm and bottom, charmonium, and single top and top pair production have been discussed in addition to other topics such as the effect of double parton scattering on heavy quark production.

A huge amount of measurements of heavy-quarkonium and of open charm and beauty production has been produced from HERA, LHC, Tevatron, and RHIC. These measurements challenge the QCD predictions that are typically less precise than experimental data. The agreement between data and theory is in general good. Some measurements, for which the agreement is marginal, deserve further studies: the polarization of heavy quarkonium, the measurement of jets associated to a D^{*+} presented by ATLAS, and the measurement of double charm production performed by LHCb.

The top quark is being scrutinized with unparalleled precision at both the Tevatron and the LHC. The D0 and CDF experiments are measuring the strong and electroweak production cross section as well as the top quark mass very precisely.

New $c\bar{c}$ and $b\bar{b}$ states have been observed and exotic quarkonia extensively studied by B -Factories as well as LHC and Tevatron experiments. LHCb have performed the world best measurements of properties of B_c and b -baryons.

Rare decays of $D_{(s)}$, $B_{(s)}$ and τ have been measured with increased sensitivity. Some of them show tensions with Standard Model predictions and thus give hints of New Physics.

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