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Heavy Flavours in DIS and Hadron Colliders: Working Group Summary

Katerina Lipka
DESY
Notkestrasse 85, D-22607, Hamburg, Germany
E-mail: katerina.lipka@desy.de

Gennaro Corcella
Museo Storico della Fisica, Centro Studi e Ricerche E. Fermi,
Piazza del Viminale 1, I-00184 Roma, Italy,
Scuola Normale Superiore, Piazza dei Cavalieri 7, I-56123 Pisa, Italy,
INFN, Sezione di Pisa, Largo Fibonacci 3, I-56127, Pisa, Italy
E-mail: gennaro.corcella@sns.it

The recent theory developments and latest experimental results on heavy-flavour production in Deep Inelastic Scattering and at hadron colliders are summarized. Models of heavy quarkonia production, non-perturbative corrections to fragmentation, theory of heavy-hadron production in heavy-ion collisions, and interpretation of new exotic hadrons are discussed. Progress in event generators development is reported. Most recent experimental results from HERA and e^+e^- colliders as well as from proton-(anti)proton and heavy ion experiments are presented and the role of charm and beauty quarks in the analyses of the proton structure is stressed.

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1. Introduction

Heavy flavours (charm, bottom and top quarks) play a particularly important role in particle physics and their production in different environments is interesting from both theoretical and experimental points of view. The large masses of charm, beauty and top quarks with respect to the hadronisation scale, say $\Lambda^{\overline{\rm MS}}_{\rm QCD} \approx$ 200-300 MeV, makes perturbative QCD (pQCD) applicable.

Fixed-order QCD calculations are reliable to calculate total heavy-quark production cross sections. However, resummations are necessary in order to improve differential distributions, since those typically exhibit contributions which are enhanced for soft- or collinear-parton radiation and need to be summed to all orders. Also, perturbative QCD is unable to describe the transition of a heavy quark into a heavy hadron, but a reliable hadronisation model is needed.

Studying heavy-flavour production and decay provides precision tests of QCD and of the Standard Model of the electroweak interactions. Such, in lepton-nucleon scattering, the charm- and beauty-production mechanism is directly sensitive to parton distributions in the nucleon. Production of heavy quarks is a tool to test the Standard Model in electron-positron collisions and a unique probe of the properties of the hot and dense medium created in heavy-ion experiments. Being the heaviest fundamental particle, the top quark continues to be an exciting topic for both experiment and phenomenology. The determination of the top quark properties provides a perfect testing ground of the Standard Model: in fact, the top quark plays a crucial role in the electroweak precision tests and its mass constrains the Higgs mass.

Modern heavy-flavour physics represents an enterprise of precise experimental measurements and theory developments connected in a common effort. The most recent results achieved by experiments and theory groups since last DIS workshop in 2009 were lively discussed in the working group. In the following, the main issues are summarised. Special attention is given to the treatment of heavy quarks in the QCD analyses of the proton structure functions, discussed in a joined session between heavy-flavour and PDF working groups.

2. Theory Issues

The presentations on the theory and phenomenology of heavy flavours dealt with heavy-quark and heavy-flavoured hadron production in DIS, pp, $p\bar{p}$, e^+e^- and heavy-ion collisions, top quark phenomenology and the observation of exotic hadrons at the Tevatron.

2.1 J/ψ photo- and electroproduction

New results were presented for the photoproduction of J/ψ at next-to-leading order (NLO) in the framework of Non Relativistic Quantum Chromodynamics (NRQCD) [1], which provides a rigorous factorisation theorem for heavy-quarkonium production and decay. The production of $c\bar{c}$ pairs can be calculated in pQCD, whereas the transition to the J/ψ involves non-perturbative matrix elements, containing parameters which must be fitted to experimental data. In NRQCD, the amplitudes can be written as a double expansion with respect to the relative quark-antiquark velocity v and the strong coupling constant α_S. The LO term in v, i.e. $\mathscr{O}(v^2)$, corresponds to the state ${}^3S_1^{[1]}$, which is colour-singlet. At NLO, i.e. $\mathscr{O}(v^2)$, also the colour-octet states, namely ${}^3S_1^{[1]}$, ${}^3S_1^{[8]}$ and ${}^3P^{[8]}_{0/1/2}$, should be accounted for, as discussed in [1] for J/ψ photoproduction. After the inclusion of NLO colour-octet contributions, the calculations describe the HERA measurements of the photon-proton invariant mass or J/ψ transverse momentum within the theoretical uncertainties. However, discrepancies with data are observed in the J/ψ elasticity z distribution, at small values of z.

J/ψ photo- and electroproduction was also discussed in the framework of a dual model [2]. In fact, the idea of duality is that, in a scattering process, the sum over intermediate resonances in the s-channel is equivalent to Regge exchanges in the t-channel. The model [2] consists in Pomeron (P) exchange and smooth non-resonant background close to the J/ψ threshold, i.e. $M_P + M_{J/\psi}$. It presents two trajectories and a few parameters, namely 8 for photoproduction and 3 more for electroproduction, which must be tuned to data. The predictions of the model on differential and elastic cross sections at HERA were compared with the data and exhibited an overall good agreement for both J/ψ photo- and electroproduction.

2.2 Heavy quark production and Regge theory

The study [3] discusses inclusive hadroproduction of single b-jets, $b\bar{b}$ dijets and $b\gamma$ dijets at the Tevatron in the Regge limit at leading order. The calculation is based on an effective field theory, with a non-Abelian gauge-invariant action, and is characterised by Reggeized quarks and gluons. Within suitable ranges of possibly ordered rapidities, b, $b\bar{b}$ and $b\gamma$ production can be described by means of a t-channel scattering mediated by Reggeized quarks and gluons. In spite of the simplicity of its formulae and assumptions, this model describes the Tevatron data in the relevant kinematics regimes. In detail, its predictions fare rather well with respect to the CDF data on transverse momentum (b jets), transverse energy, invariant mass, pseudorapidity, azimuthal distributions ($b\bar{b}$ dijets) and photon transverse momentum ($b\gamma$ dijets).

2.3 Higher-order QCD calculations for heavy quarks and extraction of the the gluon polarisation

Progresses towards the computation of the heavy-quark contributions to the structure function F_2, to three-loop accuracy, were reported in [4]. The calculation of the massive Wilson coefficients was carried out in Mellin moment space for generic N and is based on hypergeometric functions and advanced summation techniques. The large logarithms of the ratio of the factorisation scale and heavy-quark mass, i.e. terms $\sim \alpha_S^k \ln^m(\mu_F^2/m^2)$, have already been calculated for $k = 3$ and $m \leq 3$ in N-space and should be soon available even in x-space. The status of the calculation of the contribution $\sim T_F^2 n_f C_{A,F}$ to the structure function $F_2(x,Q^2)$ was also presented.

New results on threshold resummation, i.e. large-x contributions, for charm production in Neutral Current DIS were presented. In particular, as discussed in [5], the coefficient function C_2 contains in Mellin space enhanced logarithms $\alpha_S^n \ln^k N$, with $k \leq 2n$, and logarithms of the heavy-quark velocity, i.e. $\ln^m \beta$, enhanced for $\beta \to 0$. The charm structure function $F_2^c(x,Q^2)$ was then computed at fixed order, i.e. NLO and NNLO, and including NLL threshold resummation, employing the ABKM(09) parton distributions. In particular, Ref. [5] shows $F_2^c(x,Q^2)$ at fixed order, with the inclusion terms $\sim \ln\beta$ and $\sim \ln^2\beta$, and accounting for Coulomb corrections as well. Furthermore, the differential distribution dF_2^c/dp_T^2, obtained for fixed Q^2 and x, exhibits milder dependence on the factorisation scale once NLL resummation is included.

As far as higher-order calculations are concerned, a progress report on the status of the NLO corrections to 4 b-quark production at the LHC was presented in [6]. In fact, the production of four beauty quarks in pp collisions is particularly relevant since it is a background for Higgs decays $H \to b\bar{b}b\bar{b}$ in the MSSM. The calculation of real and virtual diagrams was undertaken by using the subtraction method for soft and collinear singularities: the $q\bar{q} \to 4b$ computation is available, while the full $pp \to 4b$ has not been completed yet. Preliminary results exhibit a strong impact of the NLO calculation: the dependence on the renormalisation scale is much milder and the prediction of the invariant-mass distribution of a final-state b-quark is more stable after the inclusion of the higher-order terms. It was also pointed out that, although the uncertainty on the prediction gets much lower, the shapes of invariant-mass and b transverse-momentum spectra is roughly the same, regardless of the NLO contributions.

The extraction of the gluon polarisation from open D^0 production at COMPASS was investigated in [7]. The asymmetries measured by the COMPASS experiment are compared to the predictions of the AROMA event generator, which includes LO/NLO hard-scattering cross section and parton showers. In this way, one can extract the gluon polarisation and distinguish the two cases $\Delta g > 0$ and $\Delta g < 0$.

2.4 An effective-coupling model for heavy-quark fragmentation

A novel model to include non-perturbative corrections to heavy-quark production was discussed in [8] and applied to B and D production in e^+e^- annihilation at LEP and B-factories. Unlike the conventional approach, which uses hadronisation models depending on a few tunable parameters, one can construct an effective strong coupling constant in such a way that a power-suppressed term subtracts the Landau pole off. Such an effective coupling is thus finite at small scales. Following [8], heavy-quark production is described in the framework of perturbative fragmentation functions, which factorises the heavy-quark spectrum as a convolution of a massless process-dependent coefficient function and a process-independent perturbative fragmentation function, expressing the transition of a light parton into the heavy quark. The coefficient function is thus calculated at NLO, the perturbative fragmentation function evolves to NLL accuracy, and NNLL threshold resummation is implemented in both coefficient function and initial condition of the perturbative fragmentation function. The effective-coupling model is able to describe, within the theoretical error, the B- and D-hadron energy spectra measured at LEP in x-space, whereas significant discrepancies are present when comparing with D-hadron data from B-factories. All considered data, however, can be reproduced in N-space. The inclusion of further NNLO terms in the coefficient function and in the Altarelli–Parisi splitting functions should decrease the theoretical uncertainties and, at the same time, shed light on the comparison with B-factory data on charmed hadrons, which, for the time being, cannot be reproduced in x-space.

2.5 Monte Carlo generators for heavy flavour physics

Progress in the implementation of heavy-quark production and decay in Monte Carlo event generators was presented. In POWHEG [9], NLO calculations are matched with parton cascades without yielding negative weights and in a manner which is independent of the particular shower model. Thanks to the fact that the first emission is generated at the largest transverse momentum, this method can be implemented straightforwardly in the framework of showers ordered in transverse momentum, e.g. the latest PYTHIA version. However, it would be necessary to include the so-called truncated showers to recover colour coherence, when running angular-ordered parton cascades, such as HERWIG. Top-pair production has been implemented in POWHEG since a while ago and lately even single-top production in both s- and t-channels has been included. The implementation of the Wt channel, i.e. scatterings like $gb \to Wt$, which are negligible at the Tevatron, but relevant at the LHC, is still in progress. Several results were shown in [9] for single-top production at the Tevatron, including transverse-momentum, rapidity and angular distributions. POWHEG predictions are in reasonable agreement with MC@NLO, the other Monte Carlo program available to match NLO computations with HERWIG parton showers. Moreover, it exhibits remarkable improvement with respect to PYTHIA, which includes extra-parton radiation in single-top processes only in the soft/collinear approximation, as matrix-element corrections are presently missing. For example, unlike POWHEG, PYTHIA does not generate B-hadrons at large transverse momentum. In addition, POWHEG includes angular correlations between the top-decay products a posteriori, providing the user with angular distributions, which are not available in PYTHIA.

The CASCADE event generator was also reviewed in [10]: initial-state multiple radiation is implemented according to the CCFM equation, whereas final-state parton showers satisfy the angular-ordering prescription and DGLAP evolution. Also, it is important to point out that in CASCADE gluons are the only available partons in the proton. As for the initial state, CASCADE uses unintegrated parton distributions, obtained from a fit based on the CCFM equations, using H1 data for $x < 0.005$ and $Q^2 > 5$ GeV^2: in this way, also non-collinear evolution is included. Hadronisation is finally simulated by means of the Lund string model. Ref [10] presents studies on the transverse momentum of D^+ and B^+ hadrons at the Tevatron and CASCADE is able to reproduce the CDF data. Comparisons with data on jet-jet (hadron-hadron) azimuthal separations were also discussed: as pointed out in [10], in order to reproduce the CDF data, it was necessary to vary the upper limit of the evolution variable from $Q^2 = m^2$, m being the heavy-quark mass, to $Q^2 = m_T^2$, where m_T is the transverse mass. Good agreement with the measurements of $\Delta\Phi_{jj}$ and $\Delta\Phi_{D^0D^+}$ was thus obtained. CASCADE was also compared to D^* and jet photoproduction at H1 [11], but it turned out to be unable to describe the shapes of the double-differential distributions.

2.6 Open heavy quarks in heavy-ion collisions

Several issues related to open heavy-flavour production in heavy-ions collisions were discussed [12]. The FONLL calculation, based on a NLL soft/collinear resummation, matched to the NLO cross section, works well for b production at the Tevatron, but lies systematically below the heavy-hadron production measurements of STAR and PHENIX experiments at RHIC. Nevertheless, the RHIC measurements of observables relying on semi-leptonic decays of heavy hadrons are described well for $p_T > 2.5$ GeV, within the errors. Progress on the determination of nuclear parton densities was also reported: the current nuclear PDF sets are available to NLO and are obtained using data from Drell–Yan interactions, π^0 decays, and Neutral Current DIS, whereas the inclusion of neutrino data is under discussion.

The main mechanisms for heavy-quark energy loss in a dense medium were then reviewed: radiative and collisional energy loss, which do not account for hadronisation, and meson dissociation, which is instead driven by hadronisation. When comparing with RHIC data, radiative energy loss tends to overestimate the data, except for charm-quark production. Collisional dissociation, including radiative contributions, is instead able to describe the data, as long as one assumes that hadronisation is almost instantaneous. Predictions for the LHC were shown [12]: remarkably, both collisional and radiative scenarios lead to different transverse-momentum spectra for charm and beauty quarks, whereas the meson-dissociation model predicts similar suppression for D and B hadrons. These results imply that at the LHC the separation of charm and beauty production should be possible.

2.7 Loosely bound molecules at hadron colliders

Production of loosely-bound molecules at hadron colliders was addressed in [13], taking particular care about the discovery of the $X(3827)$ particle by the CDF collaboration at the Tevatron. As it is a $J^{PC} = 1^{++}$ state, it could not be interpreted as standard charmonium, and therefore it was first described as a $D^0\bar{D}^{0*}$ molecule with a radius $r = 8$ fm. However, using the hadronisation models contained in HERWIG or PYTHIA to estimate the transition probability of $p\bar{p}$ into a DD^* molecule, one obtains a much lower cross section for $X(3827)$ production than the measured one. In principle, one may invoke final-state interactions and the Watson theorem to reconcile theory and experiment, but nonetheless this theorem can be applied only for two-particle final states, which is not the case in the Tevatron environment. Also, if the $X(3827)$ were indeed a molecule, CDF should have even observed a $D_sD_s^*$ molecule, but such an observation was never reported so far. The conclusion of [13] is therefore that the hypothesis of tetraquarks should possibly be reconsidered. In this case, it will be particularly interesting searching for a X^{++}, i.e. a $[cu][\bar{d}\bar{s}]$ state, at the LHC in the next few years.

3. Experimental Issues

Recent results on charm and beauty production in lepton-nucleon collisions were presented by the H1, ZEUS, NOMAD and COMPASS experiments. BaBar and Belle reported on Standard Model tests using heavy quarks in electron-positron collisions. STAR and PHENIX experiments discussed heavy quarks as probes of quark-gluon plasma; CDF and D0 showed precision measurements of the top quark properties. First physics using the LHC data was presented by ALICE, ATLAS, CMS and LHCb experiments.

3.1 QCD tests using heavy-quarkonium production

Heavy-quarkonium production in ep and $p\bar{p}$ collisions serves for precision tests of perturbative QCD calculations as well as for the modelling of hadronisation corrections. At HERA inelastic J/ψ photoproduction cross sections and polarisation are measured [14, 15] and compared to the calculations of Colour-Singlet (CS) and Colour-Octet (CO) models in Non-Relativistic QCD (NRQCD), and in the framework of k_T-factorisation in Fig. 1. The CS model at NLO describes the shape of the p_T distribution quite well, while it is unable to predict the overall normalization. After including the CO contribution, the NLO NRQCD prediction is able to reproduce the normalization of the H1 data within large theoretical uncertainty, although fails to describe the shape of the elasticity distribution. At HERA the J/ψ polarisation parameters, extracted using the angular measurements, might indicate a need for CO terms in the QCD calculations. Various predictions

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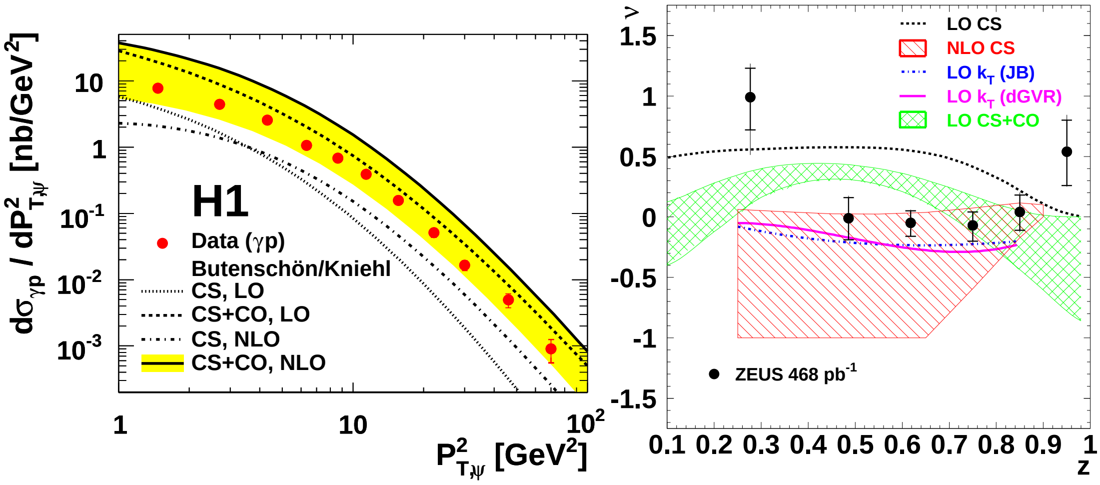

Figure 1: Left: Cross section of J/ψ photoproduction as a function of the meson transverse momentum p_T. Right: Polarisation parameter ν as a function of the fractional photon energy z carried by the meson.

show different deficits to describe the precise HERA data, and apparently higher order calculations would be necessary to draw a final conclusion.

Disagreement of J/ψ polarisation measurement in $p\bar{p}$ collisions with NRQCD prediction was observed earlier at Tevatron [16]. The CDF experiment presented a measurement of the $\Upsilon(1S)$ polarisation [17] as shown in Fig. 2. The preliminary data indicate a trend towards longitudinal polarisation and disagree with the NRQCD prediction. Also, a disagreement between CDF and D0 measurements was pointed out.

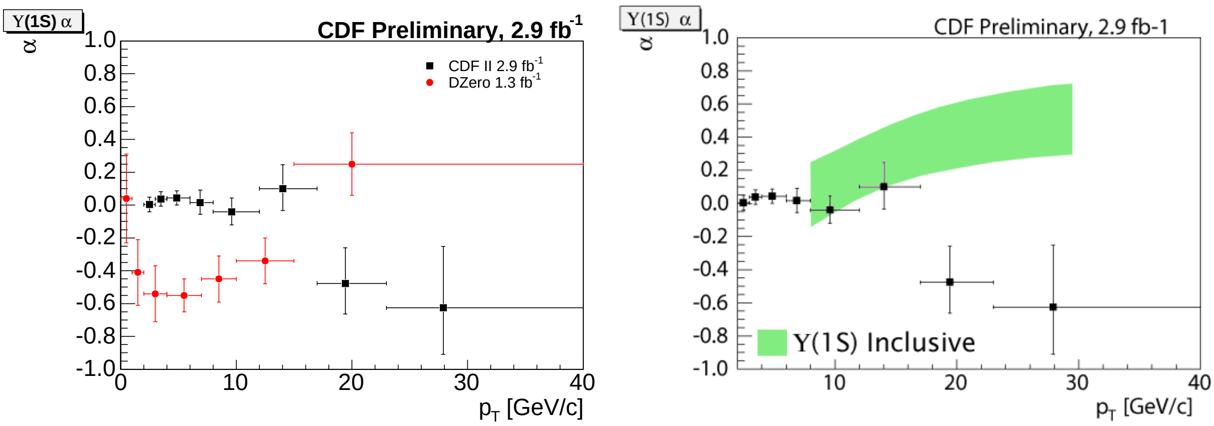

Figure 2: Left: Polarisation parameter for the $\Upsilon(1S)$ as a function of transverse momentum as measured by CDF and D0. Right: CDF data compared to the NRQCD prediction (shaded band).

3.2 Open charm and beauty production in QCD analysis of the nucleon structure

At HERA open charm and beauty quarks are produced dominantly in boson-gluon fusion, a process particularly well suited to study QCD. Production of charm and beauty (jets) in DIS and photoproduction provides a powerful testing ground for pQCD calculations. Experimentally-determined charm and beauty structure functions set constraints on different phenomenological prescriptions for the treatment of heavy flavours in the QCD analyses of the proton structure. Furthermore, such measurements provide a direct cross check of the gluon distribution function obtained from scaling violations. At HERA charm and beauty events are tagged either in full reconstruction of heavy-flavoured mesons, or using the vertex-detector information, sensitive to the long lifetime of such hadrons. Results obtained by different methods can be combined.

3.2.1 QCD tests using open charm and beauty production at HERA

Recent HERA results on beauty production in DIS [18, 19] and in photoproduction [20] were discussed. In Fig. 3 HERA results on beauty production are shown in comparison with pQCD predictions at NLO in the fixed-flavour number scheme (FFNS), taking into account the *b*-quark mass. Different methods to tag beauty in photoproduction at HERA were used: the results agree very well and are described well by the NLO calculation. The cross-section of beauty jet production in DIS is measured as a function of the transverse jet energy and is described well by the massive NLO calculation even when using two different choices of the renormalisation and factorisation scales $\mu_r = \mu_f = \mu$. In contrary, charm-jet production in DIS is sensitive to the choice of the scales in the QCD calculation [19].

New analyses of open charm production in DIS [19, 21, 22] and in photoproduction [11] were presented. The cross sections of D^+-meson production are shown as a function of the meson transverse momentum in Fig. 4 and compared with the QCD calculation at NLO. Above the charm-production threshold (large $p_T(D^+)$) the calculation describes data well, while at threshold and below ($p_T(D^+) < 1.5$ GeV) it underestimates the data.

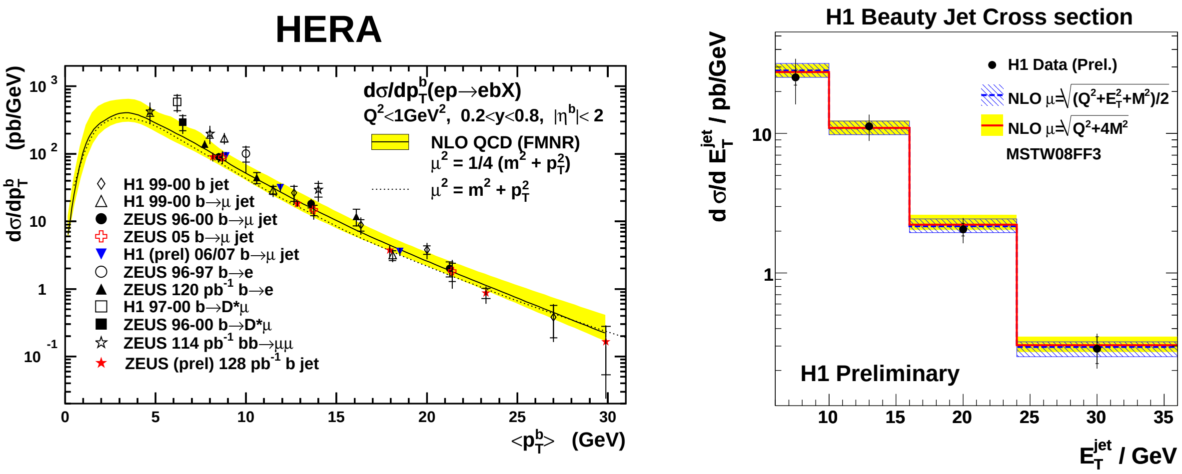

Figure 3: Left: HERA results on beauty photoproduction cross-section as a function of transverse momentum of the b-quark. Different symbols correspond to various beauty tagging methods. Measurements are compared to the NLO QCD (shaded band). Right: Beauty jet production cross-section in DIS as a function of transverse jet energy compared to the NLO QCD calculation for different scale choice (shaded bands).

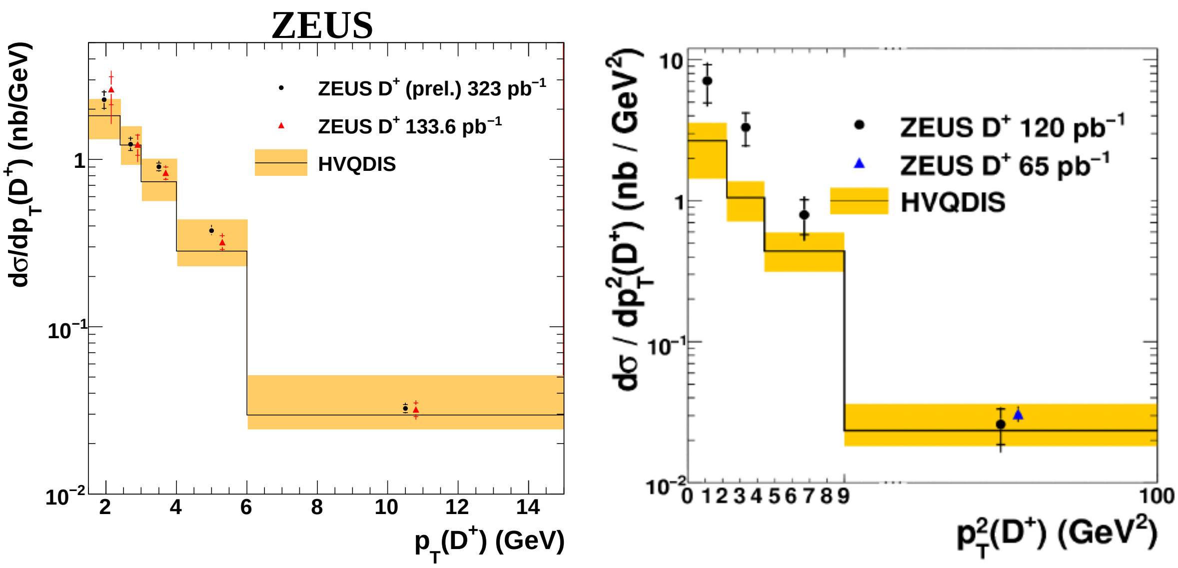

Figure 4: Left: Cross section of D^+ production in DIS as a function of the meson transverse momentum. Data (filled symbols) are compared to the NLO QCD (shaded band). Right: Measurement of D^+ production cross section at low transverse momenta as compared to the NLO QCD (shaded band).

3.2.2 Heavy quark structure functions at HERA

New measurements of the charm and beauty contributions, F_2^c and F_2^b, to the inclusive proton structure function F_2 were presented [18, 19, 21, 22] and discussed in the context of QCD analyses of the proton structure.

A topic of special interest was the HERA combined F_2^c measurement [23], where various methods of charm tagging at both H1 and ZEUS experiments were combined, taking into account systematic correlations. Due to partially orthogonal uncertainty sources in the different tagging methods, a significant improvement in the overall precision of F_2^c is observed. The data were compared to a variety of QCD predictions based on different prescriptions of the heavy-quark treatment in the PDF fits. The average precision of the data is about 10% and is significant to distinguish between different models. In Fig. 5 the HERA F_2^c structure function is compared with the QCD prediction using the HERAPDF1.0 set [24]. The prediction of F_2^c based on HERAPDF1.0 (which does not include charm data) describes the data very well except for low photon virtualities of $Q^2 = 2$ GeV^2. The variation of the charm mass m_c, 1.35 GeV$< m_c <$ 1.65 GeV, in the PDF fit is investigated and accounted for as an additional model uncertainty in HERAPDF1.0. The choice of a larger m_c was motivated by a recent determination of the charm pole mass. The F_2^c measurements appear to be very sensitive to the choice of m_c and exhibit a clear preference for the larger values of m_c. Choice of large m_c in the QCD analysis of inclusive data results in a steeper gluon distribution. A sizable effect on the light quark distributions is also observed. These effects are not only very important for the QCD tests at HERA. Such, the NLO predictions for the cross-sections of W- and Z-boson production at the LHC using the PDFs determined with $m_c = 1.65$ GeV rise by 3% compared to those using PDFs with $m_c = 1.4$ GeV. A new PDF fit [25] using the preliminary charm data was performed at HERA for $Q^2 > 3.5$ GeV^2, using the same formalism as for HERAPDF1.0.

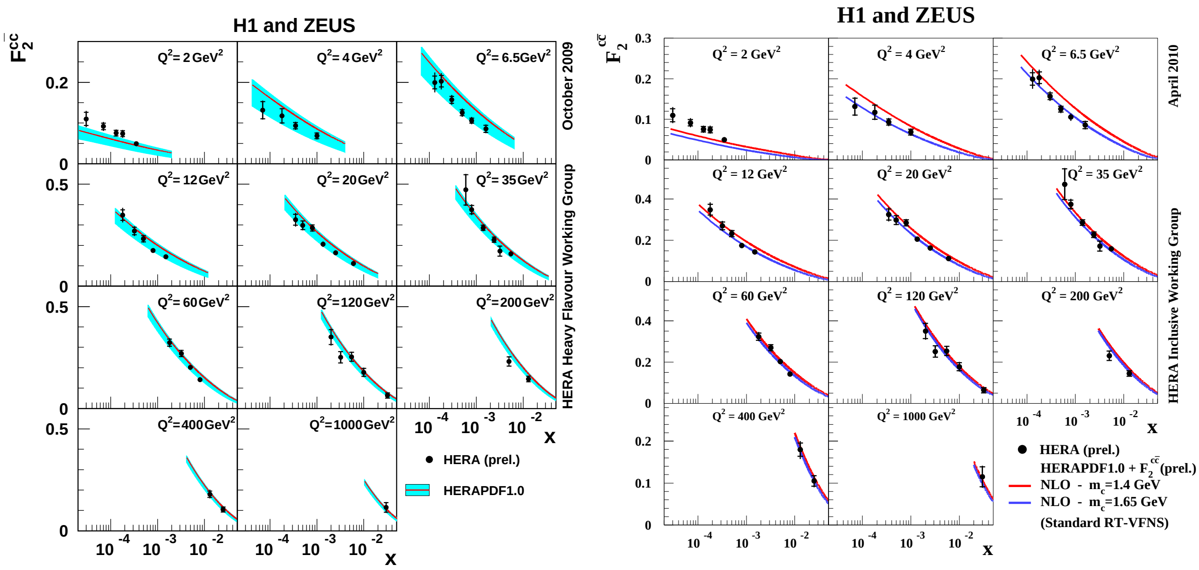

Figure 5: Left: HERA combined F_2^c as a function of Bjorken scaling variable x in bins of photon virtuality Q2. The data (filled symbols) are compared to QCD prediction at NLO using HERAPDF1.0. Right:. The shaded band represent the uncertainty due to variation of charm mass in the PDF fit $1.35 < m_c < 1.65$ GeV. HERA F_2^c as compared to QCD prediction using HERA PDF fit using F_2^c data for $m_c = 1.4$ GeV (red line) and m_c=1.65 GeV (blue line).

Two values of m_c were studied, resulting in a best fit for $m_c = 1.65$ GeV and a steeper gluon distribution. Different prescriptions of the heavy-quark treatment in the PDF analyses were tested using HERA charm data. High sensitivity of the charm measurements to the heavy-flavour schemes in the PDFs in demonstrated. However, the effects due to the heavy-flavour scheme and the choice of the heavy-quark mass in the QCD analyses are difficult to disentangle, and it is indeed impossible with inclusive DIS data alone. Therefore, heavy-flavour measurements at HERA provide a unique opportunity to test the heavy-flavour treatment schemes, however using an externally determined value of charm quark mass.

3.2.3 Charm structure function in neutrino-nucleon scattering

In neutrino-nucleon scattering the charm contribution F_2^c to the inclusive structure function F_2 is sensitive to the strangeness distribution in the nucleon. The NOMAD collaboration presented impressive measurements of the ratio of di-muon to charm cross-sections close to the charm threshold [26]. In Fig. 6 the cross-section ratio is shown as a function of Bjorken variable x. The data have a significant impact on the QCD analyses of the proton structure. Using NOMAD measurements in PDF fits results in improvement of the precision on the strange sea distribution by a factor of 2.

3.3 Standard Model tests using heavy-quark production in e^+e^- annihilation

Measurements of charm and beauty production in e^+e^- collisions play a crucial role in the understanding of the heavy-flavour sector of the Standard Model of electroweak interactions. Re-

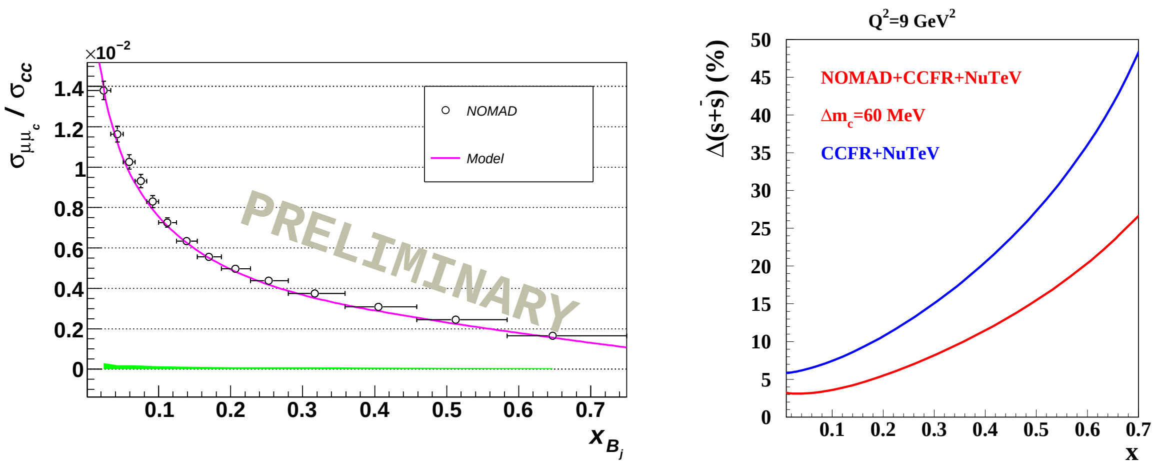

Figure 6: Left: Cross section ratio of charm production in dimuon-channel to the total charm cross section as a function of the Bjorken scaling variable x. The data (open symbols) are compared to the QCD prediction (line). Right: Uncertainty on the strangeness distribution resulting from the PDF Fit before (blue) and after (red) including the NOMAD data.

cent results on charm physics from Belle and BaBar were presented [27, 28], including studies of charm mixing, CP violation in the charm sector and properties of charmed meson decay. Measurements of the D_s pseudoscalar purely leptonic decay branching fractions are also reported and a comparison with the lattice calculation of the f_{D_s} decay constant is shown. The discrepancy of the current f_{D_s} world average with the theoretical value is reduced. Recent results on charm mixing and CP-violation in D^0 and $\bar{D}^0$ are presented: the mixing parameters are in a good agreement with the Standard Model expectations, whereas no evidence for T-violation in D^0 multi-body decays is found. BaBar and Belle report disagreement between their measurements of polarization in B-meson decays to vector final states. Moreover, for the first time an observation of 4-body charmless baryonic B decays was presented.

3.4 Charm and beauty in heavy ion collisions

At RHIC heavy quarks are used as a probe of quark-gluon plasma. STAR and PHENIX reported on recent results on charm and beauty production [29, 30]. Heavy-quark production is tagged in semi-leptonic decays into electrons. After the new analysis of the STAR data, the electron cross-section measurements by the RHIC experiments exhibit very good agreement and are well described by the FONLL prediction. Future plans for heavy-quark physics for RHIC-II and first steps towards physics analysis at the ALICE were also presented [31].

3.5 Top-quark production and properties

Due to its very large mass, the top quark does not hadronize, but decays into a W and a b quark, with a branching ratio of almost 100%. Such, an insight to the ‘bare’ quark properties is possible. Precision measurements of the top-quark properties provide precision tests of the Standard Model. Fig. 7 shows the cross section measurements of top-pair production at the Tevatron [32, 33], compared with theoretical predictions at NLO, with the possible inclusion of NLL soft/collinear resummation and some NNLO contributions. Several analysis methods are explored and all the top decay channels are considered, in order to better constrain the properties of the top quark and to search for possible sources of new physics affecting the $t\bar{t}$-production mechanism.

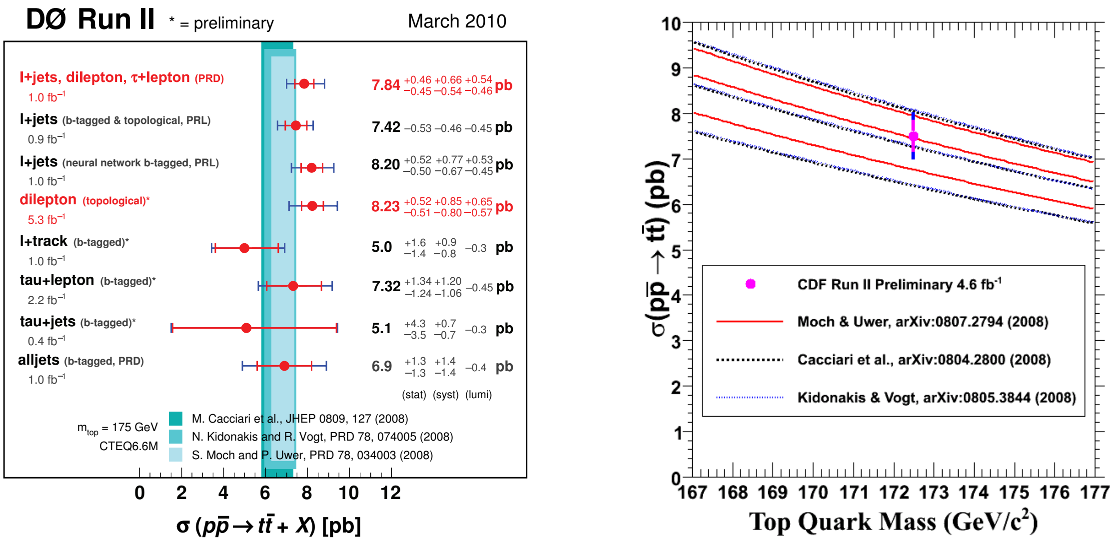

Figure 7: Left: Cross section of top-pair production as measured by D0 experiment in different channels of W decay. The data (filled symbols) are compared with a few calculations, as discussed in the text. Right: The cross-section of top-pair production as a function of a top quark mass compared to the theoretical predictions.

Precision measurements of the cross section can also be used for the extraction of the pole top quark mass using higher-order calculations. However, the theoretical uncertainties on the top cross section predictions are quite large. Direct measurement of the top quark mass using various methods by CDF and D0 collaborations also discussed [34, 35]. These measurements can reach very high precision, but are limited by systematic uncertainty. However, since such analyses are mostly driven by Monte Carlo event generators, the physical interpretation of the measured top mass in terms of a well-defined theoretical definition is not straightforward. Other top quark properties, such as charge, helicity, width and lifetime have been measured at the Tevatron [36] and have been shown to be consistent with the Standard Model expectations. Ref. [37] presents the plans and strategies of ATLAS and CMS to measure the $t\bar{t}$ cross section using early LHC data and a centre-of-mass energy of 10 TeV. According to [37], it will be possible to measure this cross section with a precision of 20-30% even with a luminosity of a few tens inverse picobarns.

4. Conclusions

The session on heavy flavours in DIS and hadron colliders at the DIS2010 workshop had a number of impressing presentations, discussing recent theoretical improvements as well as experimental results and prospectives for heavy-quark and heavy-hadron production in several different experimental environments. Especially worth to mention are the latest calculations in perturbative QCD, NRQCD, Regge and non-perturbative models, as well as presentations of heavy-ion collisions, developments of Monte Carlo generators and interpretation of exotic hadrons observed at the Tevatron. Latest experimental results from major experiments as HERA, Tevatron, RHIC and B-factories, as well as the prospects for heavy-flavour measurements at the LHC were presented. In general, the experimental data are in reasonable agreement with the theoretical predictions, however, as discussed throughout this paper, there are still several open issues calling for more refined computations, along with more precise data. With the increasing precision of the measurements, close collaboration between experimentalists and theorists will be inevitable for probing and understanding the mechanisms of heavy-flavour production and its particular role in the structure of matter.

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