QCD MEASUREMENTS AND (DOUBLE) CHARM PRODUCTION*

LUCIO ANDERLINI

for the LHCb Collaboration

Istituto di Fisica Nucleare, Sezione di Firenze
e Dipartimento di Fisica, Università di Firenze
via G. Sansone, 1, Sesto Fiorentino 50019, Firenze, Italy

Due to its unique pseudorapidity coverage and to the possibility of extending the measurement to low transverse momenta, LHCb is able to provide important input to the understanding of particle production and energy flow in a kinematical range where QCD models have large uncertainties. The measurements are performed in a pseudorapidity range $2 < \eta < 5$ which corresponds to the main detector acceptance of the LHCb spectrometer. The measurement of energy flow is compared to predictions given by several Monte Carlo event generators, which model the underlying event activity in different ways. Associative J/ψ and open charm cross-sections has been investigated in the context of multiple parton interactions at gluon densities achievable at LHC.

1. Introduction

The Large Hadron Collider (LHC) provides new opportunities to study pp interactions at energy in the centre of mass $\sqrt{s} = 7$ TeV and above. While hard interactions at LHC result from parton scattering, mainly due to gg fusion, it is not obvious that soft interactions can be described with such a paradigm. Due to the large parton densities reached at the LHC energies, it is possible to test multi-parton interaction models. The unique pseudorapidity coverage of the LHCb experiment, together with its excellent performance, allows to exploit the large dataset collected in 2010 and 2011 to test such models.

The LHCb detector [1] is a single-arm forward spectrometer covering the pseudorapidity range $2 < \eta < 5$. It ran at an instantaneous luminosity of $1.6 \times 10^{32}\,\mathrm{cm}^{-1}\mathrm{s}^{-1}$ in 2010, $3.5 \times 10^{32}\,\mathrm{cm}^{-1}\mathrm{s}^{-1}$ in 2011, and $4.5 \times 10^{32}\,\mathrm{cm}^{-1}\mathrm{s}^{-1}$ in 2012. This is significantly lower than ATLAS and CMS and means the experiment is not affected by large pile-up.

In this contribution, I report about a measurement of the forward energy flow and the double charm production cross section at $\sqrt{s} = 7\,\mathrm{TeV}$.

2. Forward energy flow at $\sqrt{s} = 7$ TeV

In order to probe various aspects of multi-particle production in high-energy hadron–hadron collisions, measurements are performed for four classes of events: inclusive minimum-bias, hard scattering, diffractive and non-diffractive enriched interactions.

The energy flow is defined as $\mathrm{EF} = \frac{1}{N_{\mathrm{int}}}\frac{dE_{\mathrm{tot}}}{d\eta}$, where E_{tot} is the total energy of stable particles measured in bins of pseudorapidity η and N_{int} is the number of inelastic pp interactions.

The analysis [2] is performed using a $0.1\,\mathrm{nb}^{-1}$ sample of minimum-bias data collected by the LHCb experiment in pp collisions at $7\,\mathrm{TeV}$ during a low luminosity running period of the LHC in May 2010. The events were recorded using a trigger requiring at least one reconstructed track segment in the detector. The fraction of bunch crossings with two or more collisions ("pile-up" events) is estimated to be approximately 5%. When more than one proton–proton interaction is reconstructed, the event is discarded from the analysis.

Monte Carlo samples with simulated minimum-bias pp interactions at $\sqrt{s} = 7\,\mathrm{TeV}$ have been generated using the LHCb [3], Perugia 0 and Perugia NOCR [4] tunes of Pythia 6.4, differing in the choice of parameters to describe multiparticle interactions. In both Perugia samples, diffractive events are suppressed at generator level, whereas the samples generated with the LHCb tune contain the contributions from both single and double diffractive dissociation. A sample of diffractive events generated with Pythia 8 [5] is used in addition. Pythia 8 introduces the description of hard diffractive processes achieving a more accurate description of pp diffractive interactions. To allow comparison, the results obtained with cosmic-ray interaction models QGSJET01, QGSJETII-03 [6], SIBYLL 2.1 [7] and EPOS 1.99 [8], implemented into the Monte Carlo event generator, are reported.

The analysis is performed for four event classes: Minimum bias events are required to contain at least one well reconstructed track traversing the whole detector, with a momentum of at least $2\,\mathrm{GeV}/c$. If such a track has also a transverse momentum larger than $3\,\mathrm{GeV}/c$, the event is classified as a hard scattering event. To study diffractive events, a diffractive enriched event

class is defined by requiring the absence of backward tracks in the pseudo-rapidity range $-3.5 < \eta < -1.5$. The Vertex Locator, a silicon-strip vertex detector surrounding the pp, is used to measure these tracks. The charged energy flow, defined as the energy carried by charged particles traversing the detector, is evaluated from track momentum measurement. The total energy flow is obtained using a data-constrained Monte Carlo estimate of the neutral fraction of the total energy flow. A bin-by-bin Monte Carlo driven correction is finally applied to compare the measured energy flow to the generator-level distributions. Such a correction is based on a Monte Carlo simulation describing decays of hadronic particles by EVTGEN [9] in which final state radiation is generated using PHOTOS [10]. The interaction of the generated particles with the detector and its response are implemented using the GEANT4 toolkit [11, 12] as described in Ref. [13].

Due to the use of Monte Carlo simulations of the detector, the systematic uncertainties dominate with respect to statistical ones. The main sources of uncertainty are the simulation of the tracking system, accounting for 3%, and the pile-up contamination, due to events with more than one interaction per bunch crossing, accounting for 1.7%. The uncertainty due to the bin-by-bin correction depends on the event class and has been estimated from the spread of corrections obtained with different Monte Carlo models. The accounted uncertainty varies from 15% for the diffractive enriched event class, to 1–2% for the other classes.

The charged energy flow classified in the four event classes described above for data and PYTHIA-based Monte Carlo, is shown in figure 1. The plots for the total energy flow (see [2]) are similar. PYTHIA based generators tend to underestimate the energy flow at high η. As expected, PYTHIA 8 describes diffractive events better than PYTHIA 6.

Cosmic ray interaction models are found to overestimate the energy flow, apart from diffractive events, for which the energy flow is underestimated. SYBILL and EPOS describe better the inclusive minimum-bias events. QGSJETII-03 gives a reasonable description of the hard-scattering events.

Comparison between measured and simulated energy flow distributions shows that the absence of hard diffractive processes results in a underestimation of the forward energy flow. It is thus important to include such interactions to achieve a precise description of partonic interaction. Higher-order QCD effects as contained in the diffractive event phenomenology are also found to be important in the forward region. The measured energy flow distribution in the forward region can be used to improve Monte Carlo generators.
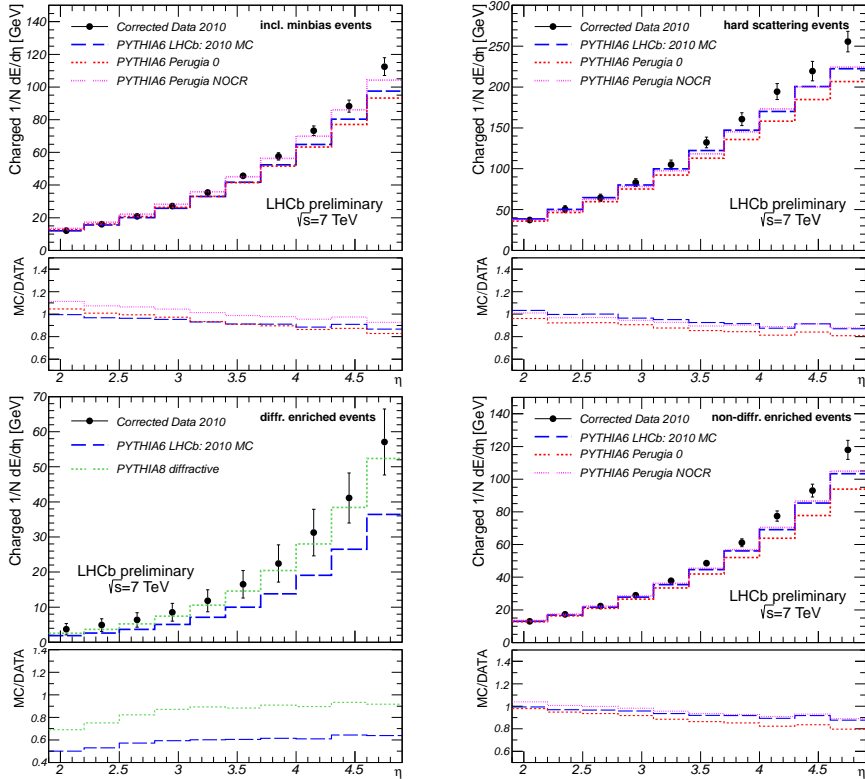
Fig. 1. Corrected charged energy flow obtained for all event classes under consideration. The measurements are indicated by points with error bars representing the systematic uncertainties, while the generator level predictions given by the PYTHIA-based models are shown as histograms. The ratios between the model predictions and corrected data are shown.

3. Double charm production

The large cross-sections of single charmonium production at the LHC allow studies of multiple production, probing the quarkonium production mechanism in a complementary way. Due to the large parton density, production mechanisms as Double Parton Scattering (DPS) [14, 15] are possible. The contribution from Double Parton Scattering can be estimated using the individual measured cross-sections for the single charm processes [16, 17] and a parameter, the effective cross-section, determined at the Tevatron [18]. The LHCb experiment has performed first studies of both double hidden charm [19] and associated hidden and open charm production in *pp* collisions [20].

Using a data sample of $355\,\mathrm{pb}^{-1}$ collected in 2011, LHCb has made the first observation of associated production of an open charm with a J/ψ or another open-charm. The open-charm hadrons D^0, D^+, D_s^+ and Λ_c^+, used for these studies, will be denoted as C in the following.

The cross-sections for $J/\psi\,C$ events have been measured in the fiducial range $2 < y_{J/\psi},\ y_C < 4$, $p_{J/\psi}^{\mathrm{T}} < 12$ GeV/c, $3 < p_C^{\mathrm{T}} < 12$ GeV/c. The measured cross-sections are significantly higher than LO QCD calculations [21–23] suggesting that DPS may play a role.

The ratio between the product of two single charm production cross-sections and their associative production cross-section, assessment of the effective cross-section, is calculated for each observed mode in order to probe the DPS model. The results of studied modes, summarized in Fig. 2, are in agreement with each other and consistent with the effective cross-section measured by Tevatron. The properties of the decays have been studied in detail. In particular, no significant azimuthal or rapidity correlation has
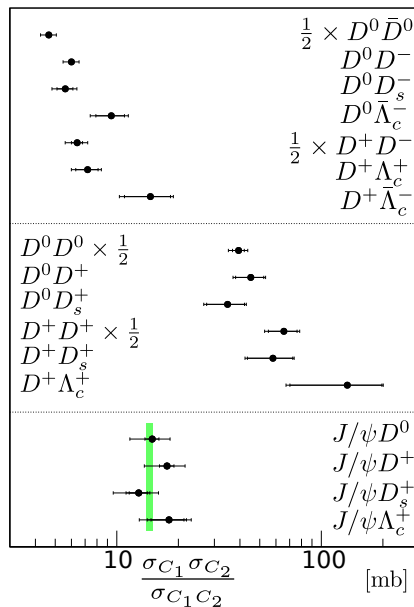

Fig. 2. Measured ratios $\sigma_{C_1}\sigma_{C_2}/\sigma_{C_1C_2}$ (points with error bars) in comparison with the expectations from DPS using the cross-section measured at Tevatron for multijet events (light green/grey shaded area). The inner error bars indicate the statistical uncertainty, whilst the outer error bars indicate the sum of the statistical an systematic uncertainty in quadrature. For the $J/\psi\,C$ case, the outermost error bars correspond to the total uncertainties including the uncertainties due to the unknown polarization of the prompt J/ψ mesons.

been observed for $J/\psi\,C$ and CC events, whilst it is present in $C\bar{C}$ events. Such an observation supports DPS model for which no correlation in the production of the charmed hadrons is expected. Correlations in $C\bar{C}$ events suggest contribution from the gluon splitting production mechanism.

The transverse momentum spectra for these events have also been studied. For J/ψ from $J/\psi\,C$ events are significantly harder than those observed in prompt J/ψ production. The spectra for open charm mesons in $J/\psi\,C$ events are similar to those observed for prompt charm hadrons. Similar transverse momentum spectra for CC and $C\bar{C}$ events are observed. Finally, spectra for $C\bar{C}$ events and prompt charm appear to be different, in contrast with what expected.

Further measurements will be devoted to a clarification of the picture by disentangling the contributions from single and double parton scattering.

REFERENCES

[1] LHCb Collaboration, A.A. Alves Jr. *et al.*, *JINST* **3**, S08005 (2008).

[2] LHCb Collaboration, Conference Note LHCb-CONF-2012-012, (2012).

[3] I. Belyaev *et al.*, *Nuclear Science Symposium Conference Record IEEE NSS/MIC*, 1155 (2010).

[4] P.Z. Skands, *Phys. Rev.* **D82**, 074018 (2010) [arXiv:1005.3457 [hep-ph]].

[5] T. Sjostrand, S. Mrenna, P.Z. Skands, *Comput. Phys. Commun.* **178**, 852 (2008) [arXiv:0710.3820 [hep-ph]].

[6] S. Ostapchenko, *AIP Conf. Proc.* **928**, 118 (2007) [arXiv:0706.3784 [hep-ph]].

[7] E.J. Ahn *et al.*, *Phys. Rev.* **D80**, 094003 (2009) [arXiv:0906.4113 [hep-ph]].

[8] T. Pierog, K. Werner, *Nucl. Phys. Proc. Suppl.* **196**, 102 (2009) [arXiv:0905.1198 [hep-ph]].

[9] D.J. Lange, *Nucl. Instrum. Methods* **A462**, 152 (2001).

[10] P. Golonka, Z. Was, *Eur. Phys. J.* **C45**, 97 (2006) [arXiv:hep-ph/0506026].

[11] GEANT4 Collaboration, J. Allison *et al.*, *IEEE Trans. Nucl. Sci.* **53**, 270 (2006).

[12] GEANT4 Collaboration, S. Agostinelli *et al.*, *Nucl. Instrum. Methods* **A506**, 250 (2003).

[13] M. Clemencic *et al.*, *J. Phys.: Conf. Ser.* **331**, 032023 (2011).

[14] C. Kom, A. Kulesza, W. Stirling, *Phys. Rev. Lett.* **107**, 082002 (2011) [arXiv:1105.4186 [hep-ph]].

[15] S. Baranov, A. Snigirev, N. Zotov, *Phys. Lett.* **B705**, 116 (2011) [arXiv:1105.6276 [hep-ph]].

[16] LHCb Collaboration, Conference Note LHCb-CONF-2010-013 (2010).

[17] LHCb Collaboration, R. Aaij *et al.*, *Eur. Phys. J.* **C71**, 1645 (2011) [arXiv:1103.0423 [hep-ex]].

[18] CDF Collaboration, F. Abe *et al.*, *Phys. Rev.* **D56**, 3811 (1997).

[19] LHCb Collaboration, R. Aaij *et al.*, *Phys. Lett.* **B707**, 52 (2012) [arXiv:1109.0963 [hep-ex]].

[20] LHCb Collaboration, R. Aaij *et al.*, *J. High Energy Phys.* **1206**, 141 (2012) [arXiv:1205.0975 [hep-ex]].

[21] S. Baranov, *Phys. Rev.* **D73**, 074021 (2006).

[22] A. Berezhnoy *et al.*, *Phys. Rev.* **D57**, 4385 (1998) [arXiv:hep-ph/9710339].

[23] J. Lansberg, *Eur. Phys. J.* **C61**, 693 (2009) [arXiv:0811.4005 [hep-ph]].