Forward physics with the LHCb experiment

Dmytro Volyanskyy (on behalf of the LHCb collaboration)

Max-Planck-Institut für Kernphysik, PO Box 103980, 69029 Heidelberg, Germany

Abstract. Due to its unique pseudorapidity coverage and the ability to perform measurements at low transverse momenta \( p_T \), the LHCb detector allows a unique insight into particle production in the forward region at the LHC. Using large samples of proton-proton collision data accumulated at \( \sqrt{s} = 7 \) TeV, the LHCb collaboration has performed a series of dedicated analyses providing important input to the knowledge of the parton density functions, underlying event activity, low Bjorken-\( x \) QCD dynamics and exclusive processes. Some of these are briefly summarised here.

Keywords: forward physics, QCD, minimum bias, exclusive production, electroweak processes

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FORWARD ENERGY FLOW

The energy flow \( dE_{\text{total}}/d\eta \) created in high-energy hadron-hadron collisions at large values of pseudorapidity \( \eta \) is expected to be directly sensitive to the amount of parton radiation and multi-parton interactions [1]. The latter represent a predominant contribution to the soft component of a hadron-hadron collision, called the underlying event. Its precise theoretical description still remains a challenge. To constrain the underlying event models, the energy flow is measured in \( pp \) collisions at \( \sqrt{s} = 7 \) TeV within the pseudo-...

FIGURE 1. Total energy flow for inclusive minimum-bias interactions along with predictions given by PYTHIA-based (left) and cosmic-ray interaction models (right). The data are indicated by points with error bars representing the systematic uncertainties, while MC predictions are shown as histograms. The statistical uncertainties are negligible. The results for other event classes can be found in Ref. [3].

\(^1\) presented at DIFFRACTION 2012, Puerto del Carmen, Lanzarote, Spain, September 10-15th, 2012.
rapidity range $1.9 < \eta < 4.9$ with data recorded by the LHCb detector [2]. As described in Ref. [3], the primary measurement is the energy flow carried by charged particles, while a data-constrained Monte Carlo (MC) estimate of the neutral component is used for the measurement of the total energy flow. To probe various aspects of multi-particle production in hadron-hadron collisions, the measurements are performed for inclusive minimum-bias (containing at least one track with $p > 2$ GeV/c in $1.9 < \eta < 4.9$), hard scattering (having at least one track with $p_T > 3$ GeV/c in $1.9 < \eta < 4.9$), diffractive, and non-diffractive enriched interactions. The last two event types were selected among the inclusive minimum-bias interactions requiring the absence or presence of at least one backward track reconstructed by the LHCb Vertex Locator in $-3.5 < \eta < -1.5$, respectively. Experimental results are compared to predictions given by the PYTHIA-based [4, 5, 6] and cosmic-ray MC event generators [7], which model the underlying event activity in different ways. Though the evolution of the energy flow as a function of $\eta$ is reasonably well reproduced by the MC generators, none of the models used in this analysis are able to describe the energy flow measurements for all event classes that have been studied. The majority of the PYTHIA tunes underestimate the measurements at large $\eta$, while most of the cosmic-ray interaction models overestimate them as can be seen in Fig. 1. The energy flow is found to increase with the momentum transfer in an underlying $pp$ inelastic interaction.

**EXCLUSIVE DIMUON PRODUCTION**

In $pp$ collisions exclusive processes are elastic reactions of the type $pp \rightarrow ppX$, where the protons remain intact and $X$ can either be a resonance or a continuum state created through photon and/or gluon propagators. If the latter is involved, exclusive processes allow investigation of pomeron and odderon states. These studies can be performed in a clean experimental environment when $X$ represents a dimuon final state which can be produced via the diphoton process leading to a continuous dimuon invariant mass spectrum, or via the photon-pomeron process which can produce $\phi$, $J/\psi$, $\psi(2S)$ and $\Upsilon$ family resonances which decay into two muons. These processes were studied at LHCb by selecting $pp$ collision events with no backwards tracks reconstructed by the Vertex Locator and exactly two forward tracks. By adding a photon in the final state, exclusive production of $\chi_c$ states, occurring via pomeron-pomeron fusion, has also been explored.

**TABLE 1.** Cross-section measured in $pp$ collisions at $\sqrt{s} = 7$ TeV for different exclusive processes. The final state particles are required to have pseudorapity in the range $2.0 < \eta < 4.5$. The first uncertainty is statistical, the second is systematic, and the third is due to the luminosity. See Ref. [8] for details.

| Process                                           | Cross-section ( pb ) |
|---------------------------------------------------|----------------------|
| $pp \rightarrow pp J/\psi(\mu^+\mu^-)$           | $474 \pm 12 \pm 51 \pm 92$ |
| $pp \rightarrow pp \psi(2S)(\mu^+\mu^-)$         | $12.2 \pm 1.8 \pm 1.3 \pm 2.4$ |
| $pp \rightarrow pp \chi_{c0}(J/\psi(\mu^+\mu^-))$ | $9.3 \pm 2.2 \pm 3.5 \pm 1.8$ |
| $pp \rightarrow pp \chi_{c1}(J/\psi(\mu^+\mu^-))$ | $16.4 \pm 5.3 \pm 5.8 \pm 3.2$ |
| $pp \rightarrow pp \chi_{c2}(J/\psi(\mu^+\mu^-))$ | $28.0 \pm 5.4 \pm 9.7 \pm 5.4$ |
| $pp \rightarrow pp \mu^+\mu^-; M_{\mu\mu} > 2.5$ GeV/c$^2$ | $67 \pm 10 \pm 7 \pm 15$ |
First cross-section measurements for exclusive $J/\psi$, $\psi(2S)$, $\chi_c$, and for non-resonant production $pp \rightarrow pp\mu^+\mu^-$ are carried out with 3 pb$^{-1}$ of low pile-up data recorded by the LHCb detector at $\sqrt{s} = 7$ TeV and are summarised in Table 1. The measured cross-sections are found to be in agreement with the corresponding theoretical predictions which have large uncertainties [8].

**ELECTROWEAK BOSON PRODUCTION**

Measurements of the $W$, $Z$ and low mass Drell-Yan production cross-sections in the forward region at LHC energies constitute an important test of the Standard Model and provide valuable input to the knowledge of the parton density functions of the proton. These measurements are carried out for the first time within the LHCb acceptance using 37 pb$^{-1}$ of $pp$ collision data recorded at $\sqrt{s} = 7$ TeV [9, 10]. The $W$ and $Z$ bosons are reconstructed from muons with $p_T > 20$ GeV/c and $2.0 < \eta < 4.5$, and, in the case of $Z$, a dimuon invariant mass $M_{\mu\mu}$ between 60 and 120 GeV/$c^2$. The cross-sections are measured to be $831 \pm 9 \pm 27 \pm 29$ pb for $W^+$, $656 \pm 8 \pm 19 \pm 23$ pb for $W^-$, $76.7 \pm 1.7 \pm 3.3 \pm 2.7$ pb for $Z$, where the first uncertainty is statistical, the second is systematic and the third is due to the luminosity. The $W$ and $Z$ cross-section ratios and the lepton charge asymmetry are also measured in the same kinematic region. Figure 2 (left) shows the cross-sections and their ratios along with NNLO QCD predictions with 6 different sets for the parton density functions. The lepton charge asymmetry, which has a strong $\eta$ dependence in the forward region, is shown in Fig. 2 (right). All $W$ and $Z$ measurements are found to be in general agreement with the NNLO predictions. Further cross-section measurements are performed with $Z \rightarrow \tau\tau$ and $Z \rightarrow e^+e^-$ channels [11, 12].

Low mass Drell-Yan dimuon production is studied in the mass range $5 < M_{\mu\mu} < 20$ GeV/c.
Dimuon invariant mass [GeV/c²]

Data

LO PYTHIA (CTEQ5L)

NLO FEWZ (MSTW08)

NLO DYNNLO (MSTW08)

2.0 < \eta^\gamma < 4.5
p_T^\gamma > 10 GeV/c
p_T^\mu > 3 (15) GeV/c

FIGURE 3. Differential cross-section for \( \gamma^* \to \mu\mu \) as a function of \( M_{\mu\mu} \). The dark shaded (orange) bands indicate the statistical uncertainties, while the light shaded (yellow) bands show the total uncertainties. The shaded vertical band corresponds to the excluded mass region of the Y meson. Superimposed are the PYTHIA and NLO predictions as described in Ref. [10].

120 GeV/c². Figure 3 illustrates its differential cross-section as a function of \( M_{\mu\mu} \) for muons with \( 2.0 < \eta < 4.5 \), \( p > 10 \text{ GeV/c} \) and \( p_T > 3 \text{ GeV/c} \) (\( p_T > 15 \text{ GeV/c} \) for \( M_{\mu\mu} > 40 \text{ GeV/c}^2 \)). The data are found to be in reasonable agreement with two different NLO predictions, while the LO PYTHIA underestimates the measurements for low \( M_{\mu\mu} \).

SUMMARY

In addition to a rich heavy flavour physics programme, the LHCb experiment performs important studies of QCD and electroweak processes in a unique kinematic range. These measurements provide a sensitive test of the Standard Model delivering valuable input for theoretical models.

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