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QCD RESULTS IN THE FORWARD REGION (LHCb)*

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LHCb, while conceived initially for b-physics, also functions as a general purpose forward detector, covering the pseudo-rapidity range from 2.0 to 5.0. A wide variety of forward QCD measurements have been performed, including jet production measurements, soft inclusive particle distributions and correlations, and central exclusive production. A selection of these results will be presented, highlighting the scope of the LHCb physics programme.

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1. Introduction

LHCb is one of the four primary detectors of the Large Hadron Collider (LHC) project at CERN (Geneva, Switzerland). LHCb is a single-arm forward spectrometer with a unique coverage in terms of pseudo-rapidity, η, with a fully instrumented detector. While originally designed to study the production and decay of b- and c-hadrons, LHCb has extended its physics programme to include also other areas such as QCD measurements at electroweak (EW) scales, the study of central exclusive production or heavy-ions physics. Notable features of LHCb include excellent particle identification (including K/π separation), secondary vertex reconstruction, lifetime and momentum resolution [1].

During Run 1 of LHC, LHCb recorded proton–proton collision data at centre-of-mass energies of $\sqrt{s} = 7$ TeV (2010 and 2011) and 8 TeV (2012). To optimise the performances for b-physics, LHCb runs with lower instantaneous luminosity than ATLAS and CMS, with the advantage of having stable

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conditions in terms of the instantaneous luminosity during a fill (thanks to the luminosity levelling) and low pile-up. LHCb recorded 1 fb^{-1} in 2011 and 2 fb^{-1} in 2012, respectively. Apart from this, LHCb took also smaller amounts of data involving nuclei at different centre-of-mass energies. Apart from a sample of Pb–Pb data, taken at the end of 2015, LHCb has also recorded collisions involving Pb–p, p–Pb, p–SMOG[1] and Pb–SMOG. The SMOG is a system designed originally to measure the integrated luminosity more accurately [2] and that allows injecting noble gases (He, Ne or Ar) into the interaction region. When such gases are injected, LHCb records collisions between their atoms (fixed target) and either protons or Pb ions accelerated by the LHC. The physics associated to these collisions is very interesting. Examples of this are the study of open heavy flavour and quarkonia production, quark–gluon plasma physics, the measurement of antiproton production in p–He collisions or the study of cold nuclear matter effects.

2. Selection of QCD results at LHCb

The LHCb η coverage makes it unique within the LHC for several relevant QCD related measurements, even for those not directly related to the production of particles with the b or c quark. The following subsections address different categories of these measurements. A selection of LHCb results will be included for each of these categories.

2.1. EW production measurements

LHCb produces W/Z in p–p collisions between low-x and high-x partons[2], which allows exploring two different Björken x regions (at $x \sim 10^{-3}$ and $x \sim 1$). In particular, the low-x region had not been previously explored by other experiments. In this regard, the LHCb measurements are useful to help constraining the proton parton distribution functions (PDFs).

An example of this is the measurement of the Z and W boson cross sections in the muon final states at an energy of $\sqrt{s} = 8$ TeV [3]. LHCb has performed measurements of the total and differential cross sections, as well as different ratios between these. The absolute integrated cross-sections measurements are the most precise among those performed at the LHC, thanks to the small error on the integrated luminosity measurement, at the level of 1%. Figure 1 shows two-dimensional plots of the cross sections compared to NNLO predictions for various parameterisation of the PDFs. Other interesting related results, not covered in these proceedings, include measurements with jets. Examples of these are the measurements of $W + b$

[1] System for Measuring the Overlap with Gas.

[2] With Björken x being the parton longitudinal momentum fraction.

and $W + c$ cross sections at 7 and 8 TeV [4], and the first observation of the top quark in the forward direction [5]. For both of this, the development of a performing b and c jet tagger [6] has been crucial.

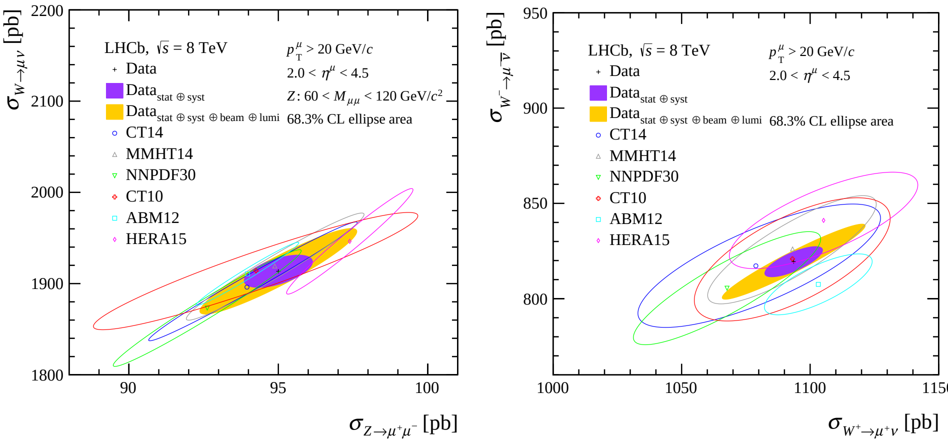

Fig. 1. Two-dimensional plots of electroweak boson cross sections compared to NNLO predictions for various parameterisation of the PDFs. All ellipses correspond to uncertainties at 68.3% C.L. Figures taken from [3]. Theoretical references can be found in [7–12].

2.2. Central Exclusive Production (CEP)

CEP events are produced in collisions in which both protons remain intact, and they are interesting to study different QCD related phenomena, such as pomeron flux, odderon, or glueball searches. Experimentally, these are low-multiplicity events with soft transverse momentum (p_{T}) particles, which are challenging to trigger on. The main background for CEP are inelastic events in which one of the protons is dissociated, which tend to have additional particles in the very forward region. Because of this, LHCb has installed a new sub-detector, Herschel [13], composed of a series of forward scintillators for selecting rapidity gaps and thanks to which the η range under scrutiny goes now from 2.0 to 8.0. Herschel has been fully operational since 2015 and contributing in all data registered by LHCb during Run 2.

The Υ cross section in CEP events has been measured by LHCb [14] with the Run 1 dataset, at energies of $\sqrt{s} = 7$ and 8 TeV. In this case, the Υ is produced via photoproduction, and a relatively clean sample can be obtained in the $\mu\mu$ final state. Furthermore, the inelastic component is subtracted with a fit to the p_{T}^2 distribution. This fit becomes the source of the dominant systematic uncertainty, which is expected to decrease significantly once Herschel information is included, in Run 2 measurements. Figure 2 shows the results of the Υ central production cross-section measurements.

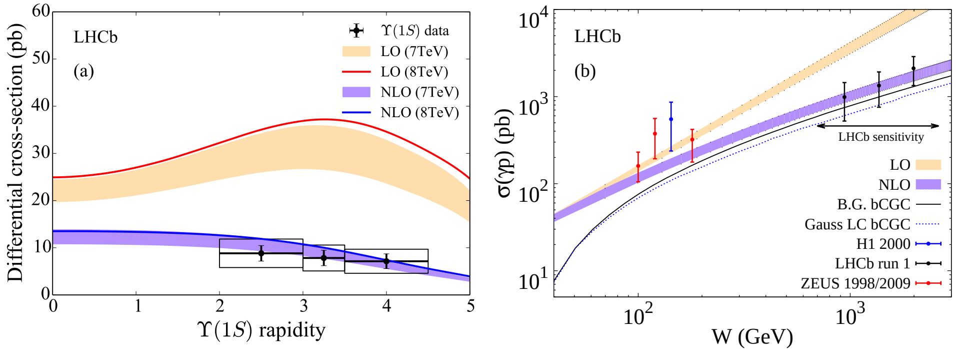

Fig. 2. Υ (left) and photoproduction (right) differential cross sections as a function of the Υ rapidity and γp centre of mass (W). Figures taken from [14]. Experimental and theoretical references can be found in [15–17] and [18–20], respectively.

2.3. Study of different hadron collisions

LHCb is currently analysing the Pb–Pb, p–Pb, Pb–p, p–SMOG and Pb–SMOG data, which allows accessing different interesting QCD phenomenology, such as the examples mentioned above. In particular, it should be remarked that the forward coverage makes it particularly interesting to study asymmetric configurations, such as p–Pb *vs.* Pb–p, in which the features of the collision are very different depending on the side of the detector

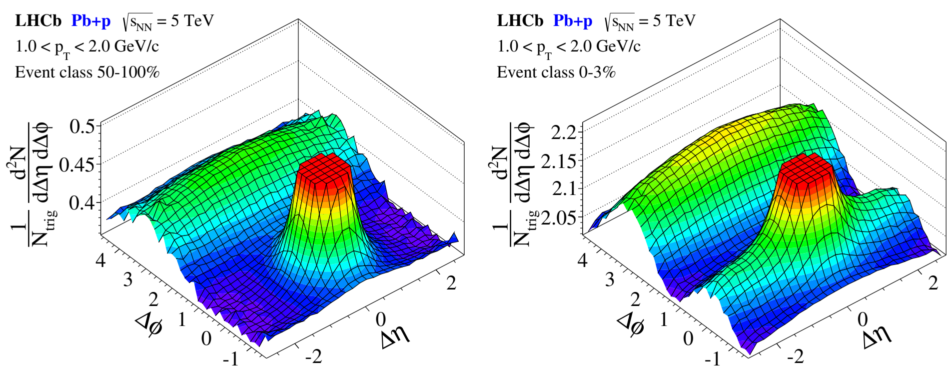

Fig. 3. Angular correlation distributions for low- (left) and high- (right) multiplicity events in Pb–p collisions for particles in a p_{T} range of 1–2 GeV$/c$. The structure of interest is the near-side (small $\Delta\phi$) long-range (large $\Delta\eta$) ridge. Additionally, the away-side structure is a consequence of the momentum conservation and the near-side near-range structure corresponds to jets. The jet structure is truncated for visibility. Figures taken from [21].

from which the colliding particles come. In this regard, the nucleon–nucleon centre-of-mass boost in rapidity changes significantly for each configuration, with the coverage becoming $-5.4 < \eta_{\mathrm{CM}} < -2.5$ in Pb–p collisions and $1.5 < \eta_{\mathrm{CM}} < 4.4$ in p–Pb collisions. This type of collisions is very important for a better understanding of the Pb–Pb physics in the forward region.

One of the main results performed by LHCb so far in this category is that of the two-particle angular correlations using $\sim 0.46\ \mathrm{nb}^{-1}$ of p–Pb and $\sim 0.30\ \mathrm{nb}^{-1}$ of Pb–p data [21]. In this case, the measurement is performed in different event activity and particle p_{T} classes. LHCb was able to confirm the near-side (small $\Delta\phi$) long-range (large $\Delta\eta$) ridge in high multiplicity events seen by other experiments [22–24]. Figure 3 shows these distributions for low- and high-multiplicity events in Pb–p collisions in a p_{T} range of 1–2 GeV/c.

2.4. Soft QCD studies

LHCb has also been used to test different MC models and to perform different cross-section measurements, such as the p–p inelastic cross section.

LHCb has measured the p–p inelastic cross section at an energy of $\sqrt{s} =$ 7 TeV [25] for events with at least one particle in the LHCb acceptance. The result, $\sigma_{\mathrm{inel}}^{\mathrm{acc}} = 55.0 \pm 2.4$ mb, is systematically limited, primarily by the uncertainty on the integrated luminosity. This measurement has also been extrapolated to the full phase space using PYTHIA 6 [26]. Figure 4 shows the LHCb result in comparison with the theory prediction and measurements from other experiments.

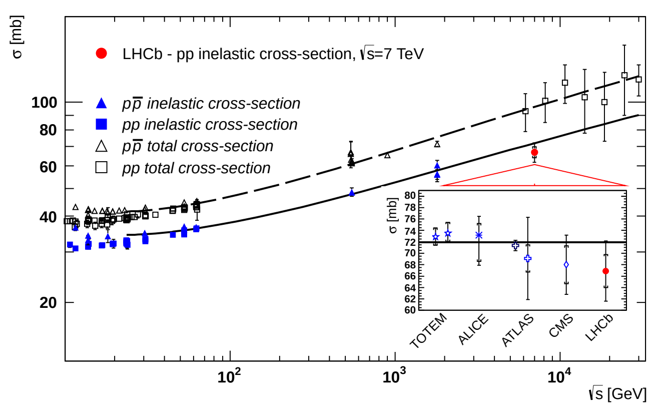

Fig. 4. Inelastic p–p cross section as a function of the centre-of-mass energy, as measured by LHCb and other experiments. A comparison to theoretical predictions is also shown. Figure taken from [25]. Experimental and theoretical references can be found in [27–32] and [33–35], respectively.

3. Conclusions

LHCb is currently performing a wide program on QCD physics, exploiting its unique geometrical acceptance to complement other experiments. A small subset of results has been presented, including analyses related to EW bosons, CEP and heavy-ion physics. The study of the remaining Run 1 and 2015 data and the Run 2 data yet to be taken are expected to continue producing interesting QCD related results.

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