Physics Letters B 715 (2012) 66–87

Contents lists available at SciVerse ScienceDirect

Physics Letters B

www.elsevier.com/locate/physletb

# Study of W boson production in PbPb and pp collisions at $\sqrt{s_{NN}} = 2.76$ TeV ☆

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ARTICLE INFO

*Article history:*
Received 29 May 2012
Received in revised form 3 July 2012
Accepted 11 July 2012
Available online 17 July 2012
Editor: M. Doser

*Keywords:*
CMS
Physics
Heavy-ions
W bosons

ABSTRACT

A measurement is presented of W-boson production in PbPb collisions carried out at a nucleon–nucleon (NN) centre-of-mass energy $\sqrt{s_{NN}}$ of 2.76 TeV at the LHC using the CMS detector. In data corresponding to an integrated luminosity of 7.3 $\mu b^{-1}$, the number of $W \to \mu\nu_\mu$ decays is extracted in the region of muon pseudorapidity $|\eta^\mu| < 2.1$ and transverse momentum $p_T^\mu > 25$ GeV/$c$. Yields of muons found per unit of pseudorapidity correspond to $(159 \pm 10(\text{stat.}) \pm 12(\text{syst.})) \times 10^{-8}$ $W^+$ and $(154 \pm 10(\text{stat.}) \pm 12(\text{syst.})) \times 10^{-8}$ $W^-$ bosons per minimum-bias PbPb collision. The dependence of W production on the centrality of PbPb collisions is consistent with a scaling of the yield by the number of incoherent NN collisions. The yield of W bosons is also studied in a sample of pp interactions at $\sqrt{s} = 2.76$ TeV corresponding to an integrated luminosity of 231 $nb^{-1}$. The individual $W^+$ and $W^-$ yields in PbPb and pp collisions are found to agree, once the neutron and proton content in Pb nuclei is taken into account. Likewise, the difference observed in the dependence of the positive and negative muon production on pseudorapidity is consistent with next-to-leading-order perturbative QCD calculations.



## 1. Introduction

The hot and dense matter produced in heavy-ion (AA) collisions can be studied in a variety of ways. One approach is to compare AA to proton–proton (pp) collisions as well as to collisions of protons or deuterons with nuclei. Another way is to compare yields of particles whose properties are modified by the produced medium to those of unmodified reference particles in the same AA collisions. Direct photons play the reference role at the Relativistic Heavy Ion Collider (RHIC) [1] and, more recently, also at the Large Hadron Collider (LHC) [2,3]. However, their measurement is complicated by copious background from $\pi^0$ and $\eta$ meson decays, and by the presence of photons produced in fragmentation processes of final-state partons that can be affected by the medium [4]. At LHC energies, new and cleaner references such as weak bosons in their leptonic decay modes become available [5–7]. The ATLAS and CMS collaborations recently reported first observations of Z bosons in heavy-ion interactions, showing that their yields per nucleon–nucleon (NN) collision are essentially unmodified by the medium [8,9].

Weak-boson production is recognised as an important benchmark process at hadron colliders. Measurements at 7 TeV centre-of-mass (CM) energy in pp collisions at the LHC [10–17] and previously, at other hadron colliders (Tevatron [18,19], RHIC [20,21] and Sp$\bar{p}$S [22,23]) with various collision energies, are well described by calculations based on higher-order perturbative quantum chromodynamics (QCD) using recent parton distribution functions (PDF). In PbPb collisions, W-boson production can be affected by initial-state conditions [5,24–26], such as the mix of protons and neutrons. Since the leading-order W-production processes $u\bar{d} \to W^+$ and $d\bar{u} \to W^-$ reflect mainly interactions that take place between valence quarks and sea antiquarks, the individual $W^+$ and $W^-$ rates are expected to be modified relative to pp collisions, but not their sum. This is often referred to as the isospin effect, as it stems from a different content of u and d quarks in the proton relative to lead nuclei. The PDF can also be modified in nuclei, as parton depletion (or shadowing) could change the yield of W bosons at the LHC by as much as 15% in certain regions of kinematics [26]. Precise measurements of W production in heavy-ion collisions can therefore constrain the nuclear PDF and, moreover, provide insight into the PDF for neutrons.

The $W \to l\nu_l$ decays are of particular interest, since the charged leptons ($l$) lose negligible energy in the produced medium, regardless of its nature (partonic or hadronic) or specific properties [6,7]. Since they are dominantly created from a left-handed valence quark and a right-handed sea antiquark, W bosons are mostly left-handed and emitted in the valence quark direction, thus towards non-zero rapidity. The $W^+$ decays to a left-handed neutrino and a right-handed positive lepton, which is thus boosted back towards midrapidity, while the $W^-$ decays to a left-handed negative lepton which is boosted towards higher rapidity. This fact creates a difference in $l^+$ and $l^-$ yields as a function of lepton


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http://dx.doi.org/10.1016/j.physletb.2012.07.025

pseudorapidity, $\eta$, defined as $\eta = -\ln[\tan(\theta/2)]$, $\theta$ being the polar angle of a particle trajectory with respect to the direction of the anticlockwise-circulating heavy-ion beam. This angular difference and the relative abundances of $W^+$ and $W^-$ bosons produced in PbPb compared to pp collisions (isospin effect) manifests itself in a lepton charge asymmetry, defined as a difference in $l^+$ and $l^-$ contributions divided by their sum. The measurement of this asymmetry as a function of muon pseudorapidity is quite robust, as it is insensitive to many systematic uncertainties. The W bosons appear therefore to be well suited to probe the characteristics of the initial state of PbPb collisions at LHC energies.

This Letter reports the observation of W-boson production in a minimum bias (MB) sample of $N_{MB} = 55.7 \times 10^6$ events from PbPb collisions collected with the Compact Muon Solenoid (CMS) detector at the CM energy for colliding nucleon pairs of $\sqrt{s_{NN}} = 2.76$ TeV. This sample corresponds to an integrated luminosity of $(7.3 \pm 0.3)\ \mu b^{-1}$. These data were recorded during the first PbPb LHC data taking period at the end of 2010. In addition, we present results of a comparison analysis of W production in pp interactions in data obtained at the same $\sqrt{s_{NN}}$ for an integrated luminosity of $(231 \pm 14)\ nb^{-1}$, which is of a similar size to the nucleon–nucleon equivalent luminosity of the PbPb data.

The Letter is organised as follows: the CMS detector is briefly described in Section 2, followed by the description of the experimental methods used for online and offline data selection in the PbPb and pp collected samples of events. The Monte Carlo (MC) simulations and the acceptance and efficiency correction factors derived from them are described there as well. The results and their discussion, together with comparison with theoretical predictions, are presented in Section 3. Finally the conclusions of this study are summarised in Section 4.

## 2. Experimental methods

A detailed description of the CMS detector can be found in Ref. [27]. In brief, a silicon pixel and strip tracker is located within a superconducting solenoid of 6 m internal diameter that provides a magnetic field of 3.8 T. The tracker consists of 66 million pixel and 10 million strip-detector channels, used to measure charged-particle trajectories for $|\eta| < 2.5$. It provides a vertex resolution of $\approx 15\ \mu m$ in the transverse plane. Located within the solenoid, but outside of the tracker, are a crystal electromagnetic calorimeter and a brass/scintillator hadron calorimeter. Muons are measured within $|\eta| < 2.4$ in gaseous detector planes embedded in the steel return yoke of the magnet. A matching of outer muon trajectories to the tracks measured in the silicon tracker provides a transverse momentum ($p_T$) resolution between 1 and 2%, for $p_T$ values up to 100 GeV/$c$. In addition, CMS has extensive forward calorimetry, in particular, two steel/quartz-fibre Cherenkov, forward hadron calorimeters (HF), on each side of the collision point, covering $2.9 < |\eta| < 5.2$.

The centrality of PbPb collisions reflects the geometric overlap (impact parameter) of the incoming nuclei, and is related to the energy released in these collisions and the effective number of NN interactions. CMS defines the centrality of a PbPb collision through bins that correspond to fractions of the total hadronic inelastic cross section, as observed in the distribution of the sum of the energy deposited in the HF [28,29]. The five bins in centrality used in this analysis, ordered from the smallest to the largest energy deposited in the HF, range from the most peripheral, 50–100%, 30–50%, 20–30%, 10–20%, to the most central, 0–10%, collisions. These bins can be related through a Glauber model [30] to the number of nucleon–nucleon collisions per event.

In this analysis, W bosons are measured through their $W \to \mu\nu_\mu$ decays. Muons can be cleanly identified and reconstructed, despite the high-multiplicity environment of heavy-ion collisions, a fact that makes this channel particularly suitable for measuring W production. The muon charge and transverse momentum vector are evaluated from the curvature of the track in the silicon tracker. The neutrino is not detected, but a large imbalance in the vector sum of the transverse momenta of all charged particles measured in the tracker is used to signal its presence.

A sample of MB events is selected that have a reconstructed primary vertex based on at least two tracks, and an offline-determined coincidence of energy depositions in both HF calorimeters, with at least three towers, each above 3 GeV. These criteria reduce contributions from single-beam interactions with the environment (e.g. beam–gas and beam–halo collisions within the beam pipe), ultra-peripheral electromagnetic collisions and cosmic-ray muons. The acceptance of this selection corresponds to $(97 \pm 3)\%$ of the hadronic PbPb inelastic cross section [28].

Events for this analysis are selected using the two-level trigger of CMS. At the first (hardware) level, one muon candidate with a $p_T$ of at least 3 GeV/$c$ is required in the muon detectors. At the software-based higher level, one reconstructed track with a more precisely determined $p_T > 3$ GeV/$c$ is again required in the muon detectors. For muons from W-boson decays, the single-muon trigger efficiency is estimated as $(97.0 \pm 2.3)\%$.

Muon offline reconstruction has $\approx$99% efficiency to find tracks when hits in the muon detectors are taken as seeds. These tracks (called stand-alone muons) are matched to tracks reconstructed in the silicon tracker by means of an algorithm optimised for the heavy-ion environment [29,31]. For a muon from W decays, the silicon-tracking efficiency is $\approx$85%, which is less than for pp collisions, as track reconstruction in the PbPb environment requires more pixel hits to reduce the number of possible combinations resulting from large particle multiplicities. Combined fits of the stand-alone muon and tracker trajectories (called global muons) are used in extracting the results of this analysis. Muon pseudorapidities are restricted to $|\eta^\mu| < 2.1$, which provides uniform and good resolution both at the trigger stage and in offline reconstruction.

A Z-boson veto is applied to reject events that contain a second muon of opposite charge with $p_T > 10$ GeV/$c$ that forms a dimuon invariant mass of $60 < m_{\mu\mu} < 120$ GeV/$c^2$. Background muons from cosmic rays and heavy-quark semileptonic decays are rejected by requiring a transverse impact parameter of less than 0.3 mm relative to the measured vertex. No muon isolation criteria are required. The single-muon $p_T$ spectrum following this selection is shown in Fig. 1(a) with red-filled circles. The enhancement in the number of muons with $p_T > 25$ GeV/$c$, expected from the decay of W bosons (green-hatched histogram), is evident. Details on the fit to the data are given below.

To further characterise events with muons arising from W decays, the imbalance ($\not{p}_T$) in the sum of the charged-particle transverse momenta with $p_T > 3$ GeV/$c$ is computed for each event. The mean value of this transverse-momentum imbalance as a function of centrality of the PbPb collision is presented in Fig. 1(b) for data (black-filled squares) selected with the two-level muon trigger described above. The presence of significant $\not{p}_T$ in central events is expected as these events contain many particles that are not included in the sum, such as neutrals or charged particles produced at low transverse momentum or at large pseudorapidity. For peripheral collisions, the net $\not{p}_T$ tends to be quite small. Once a high-$p_T$ muon is required in the data (red-filled circles), the $\langle\not{p}_T\rangle$ shifts to higher values of $\approx$40 GeV/$c$, and is far less dependent on the centrality of the collision. This agrees with expectations (green triangles) for $\not{p}_T$ values of undetected neutrinos originating from W decay. To enhance the contribution from the W signal, events are therefore required to have $p_T^\mu > 25$ GeV/$c$ and $\not{p}_T > 20$ GeV/$c$.