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Measurement of the $W$ charge asymmetry in the $W \rightarrow \mu \nu$ decay mode in $pp$ collisions at $\sqrt{s} = 7$ TeV with the ATLAS detector

ATLAS Collaboration

1. Introduction

The measurement of the charge asymmetry of leptons originating from the decay of singly produced $W$ bosons at $pp$, $p\bar{p}$ and $e^+e^-$ colliders provides important information about the proton structure as described by parton distribution functions (PDFs). The $W$ boson charge asymmetry is mainly sensitive to valence quark distributions [1] via the dominant production process $u\bar{d}(ud) \rightarrow W^{+}(\rightarrow \mu^+\nu)$ and provides complementary information to that obtained from measurements of inclusive deep inelastic scattering cross-sections at the HERA electron–proton collider [2–5]. The HERA data do not strongly constrain the ratio between $u$ and $d$ quarks in the kinematic regime of low $x$, where $x$ is the proton momentum fraction carried by the parton [6]. A precise measurement of the $W$ asymmetry at the Large Hadron Collider (LHC) [7] on the other hand, can contribute significantly to the understanding of PDFs and quantum chromodynamics (QCD) in the parton momentum fraction range $10^{-3} \lesssim x \lesssim 10^{-1}$ [8].

In $pp$ collisions the overall production rate of $W^+$ bosons is significantly larger than the corresponding $W^-$ rate, since the proton contains two $u$ and one $d$ valence quarks. The first measurements of the inclusive $W^\pm$ cross-sections at the LHC by the ATLAS [9] and the CMS [10] Collaborations confirmed the difference predicted by the Standard Model. The asymmetry in $pp$ collisions is symmetric with respect to the $W^+$ rapidity, whereas in $p\bar{p}$ collisions it is antisymmetric; the small sensitivity to sea-quark contributions is strongly suppressed in $p\bar{p}$ compared to $pp$ collisions [11]. Measurements in $p\bar{p}$ collisions have been performed at the Tevatron by both the CDF [12,13] and DØ [14,15] Collaborations, also using an iterative procedure extracting the $W$ asymmetry as a function of $y_W$ [16]. The data have been included in global fits of parton distributions [17,18].

This Letter presents a differential measurement of the muon charge asymmetry from the decay of $W^\pm$ bosons in $pp$ collisions at a centre-of-mass energy of $\sqrt{s} = 7$ TeV at the LHC. The asymmetry varies significantly as a function of the pseudorapidity $\eta_\mu$ of the charged decay lepton owing to its strong correlation with the momentum fraction $x$ of the partons producing the $W$ boson. It is defined from the cross sections for $W \rightarrow \mu \nu$ production $d\sigma_{W\mu}/d\eta_\mu$ as:

$$A_\mu = \frac{d\sigma_{W\mu^+}/d\eta_\mu - d\sigma_{W\mu^-}/d\eta_\mu}{d\sigma_{W\mu^+}/d\eta_\mu + d\sigma_{W\mu^-}/d\eta_\mu}$$

where the cross sections include the event kinematical cuts used to select $W \rightarrow \mu \nu$ events. No extrapolation to the full phase space is attempted in order to reduce the dependence on theoretical predictions.

Systematic effects on the $W$-production cross-section measurements are typically the same for positive and negative muons, mostly canceling in the asymmetry. The ATLAS detector measures

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1 The nominal $pp$ interaction point at the centre of the detector is defined as the origin of a right-handed coordinate system. The positive $x$-axis is defined by the direction from the interaction point to the centre of the LHC ring, with the positive $y$-axis pointing upwards. The azimuthal angle $\phi$ is measured around the beam axis and the polar angle $\theta$ is the angle from the $z$-axis. The pseudorapidity is defined as $\eta = -\ln\tan(\theta/2)$. 

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muons with two independent detector systems. These two indepen-
dent measurements allow systematic uncertainties to be con-
trolled. The results presented are based on data collected in 2010
with an integrated luminosity of 31 pb$^{-1}$. These results signifi-
cantly improve on the previous measurement by the ATLAS Collab-
oration [9], which is based on a data set approximately 100 times
smaller.

2. The ATLAS detector

The ATLAS detector [19,20] consists of an inner tracking system
(inner detector, or ID) surrounded by a superconducting solenoid
providing a 2 T magnetic field, electromagnetic and hadronic
calorimeters and a muon spectrometer (MS). The ID consists of
pixel and silicon microstrip (SCT) detectors, surrounded by a tran-
sition radiation tracker (TRT). The electromagnetic calorimeter is
a lead liquid-argon (LAr) detector in the barrel and the endcap,
and in the forward region copper LAr technology is used. Hadron
calorimetry is based on two different detector technologies, with
scintillator tiles or LAr as the active media, and with either steel,
copper, or tungsten as the absorber material. There is a poorly
instrumented transition region between the barrel and endcap
calorimeter, 1.37 < $|\eta|$ < 1.52, where electrons cannot be precisely
measured. In view of a later combination, this motivates the bining
in that region for the present muon analysis. The MS is based
on three large superconducting toroids, and a system of three sta-
tions of chambers for trigger and precise tracking measurements.
There is a transition between the barrel and endcap muon detect-
ors around $|\eta| = 1.05$.

3. Data and simulated event samples

The data used in this analysis were collected from the end
of September to the end of October 2010. Basic requirements on
beam, detector, stable trigger conditions and data-quality were
used in the event selection, resulting in a total integrated luminos-
ity of 31 pb$^{-1}$. Events in this analysis are selected using a single-
muon trigger with a requirement on the momentum transverse to
the beam ($p_T$) of at least 13 GeV. The trigger includes three lev-
els of event selection: a first level hardware-based selection using
hit patterns in the MS and two higher levels of software-based re-
quirements.

Simulated event samples are used for the background estima-
tion, the acceptance calculation and for comparison of data with
theoretical expectations. The processes considered are the $W \rightarrow \mu \nu$ signal, and backgrounds from $W \rightarrow \tau \nu$, $Z \rightarrow \mu\mu$, $Z \rightarrow \tau\tau$, $t\bar{t}$
and jet production via QCD processes (referred to as “QCD back-
ground” in the text). The simulated signal and background samples
(except $t\bar{t}$) were generated with PYTHIA 6.421 [21] using MRST
2007 LO [22] PDFs. The $t\bar{t}$ sample was generated with POWHEG-
HQV v1.01 patch 4 [23]; the PDF set was CTEQ 6.6M [24] for the
NLO matrix element calculations, while CTEQ 6L1 was used for
the parton showering and underlying event via the POWHEG in-
terface to PYTHIA. The radiation of photons from charged leptons
was treated using PHOTOS v2.15.4 [25] and TAUOLA v1.0.2 [26]
was used for tau decays. The underlying and pile-up events were
simulated according to the ATLAS MC09 tune [27]. The gener-
ated samples were passed through the GEANT4 [28] simulation
of the ATLAS detector [29], reconstructed and analysed with the
same analysis chain as the data. The cross-section predictions for
$W$ and $Z$ were calculated to next-to-next-to-leading-order (NNLO)
using FEWZ [30] with the MSTW 2008 [31] PDFs. The $t\bar{t}$ cross-
section was obtained at next-to-leading-order (plus next-to-
next-to-leading-log, NNLL) using POWHEG [32]. The Monte Carlo (MC)
were generated with, on average, two soft inelastic collisions over-

4. Event selection

The criteria for the event selection and muon identification fol-
low closely those used for the $W$ boson inclusive cross-section
measurement [9], with an improved muon quality selection [33].
Events from $pp$ collisions are selected by requiring a collision ver-
tex with at least three tracks each with transverse momentum
greater than 150 MeV. A beam-spot constraint has been applied in
the collision vertex reconstruction stage significantly improving the
resolution on the collision vertex position in the transverse plane.

Events with a high transverse momentum muon are selected by
imposing stringent requirements to ensure good discrimination of
$W \rightarrow \mu \nu$ events from background. The muon parameters
are first reconstructed separately in the MS and ID. Subsequently,
the tracks from the ID and MS are matched. Their parameters are then
combined, weighted by their respective errors, to form a combined
muon. The $W$ candidate events are required to have at least one
combined muon track with $p_T > 20$ GeV and $p_T$ measured by the
MS alone greater than $p_T^{MS} > 10$ GeV, within the range $|\eta| < 2.4$.
The difference between the ID and MS $p_T$, corrected for the mean
energy loss in the material traversed between the ID and MS, is
required to be less than 0.5 times the ID $p_T$, $p_T^{MS}$ (energy loss corrected) $- p_T^{ID} < 0.5p_T^{ID}$.

This requirement increases the robustness against track recon-
struction mismatches, including decays-in-flight of hadrons. In ad-
dition, a minimum number of hits in the ID is required to ensure
high quality tracks [33]. In order to further reduce non-collision
backgrounds, the difference between the $z$ position of the muon
track extrapolated to the beam line and the $z$ coordinate of the
collision vertex is required to be less than 1 cm. A track-based iso-
lation for the muon is defined as $\sum_{i} p_T^{i}/p_T < 0.2$, where $\sum p_T^{i}$
is the scalar sum of transverse momenta of all other tracks mea-
sured in the ID belonging to the same collision vertex within a cone
$\Delta R < 0.4$ around the muon direction excluding the ID track
associated with the muon, and $p_T$ is the transverse momentum of
the muon combined track.

The reconstruction of the missing transverse energy ($E_T^{miss}$
and the transverse mass ($m_T$) follows the prescription in [9].
The $E_T^{miss}$ is determined from the energy deposits of calibrated
calorimeter cells in three-dimensional clusters and is corrected for
the momentum of all muons reconstructed in the event. Jet-quality
requirements are applied to remove a small fraction of events
where sporadic calorimeter noise and non-collision backgrounds
can affect the $E_T^{miss}$ reconstruction [34]. The transverse mass is de-

$$m_T = \sqrt{2p_T^{\mu}p_T^{\nu}(1 - \cos(\phi^{\mu} - \phi^{\nu}))},$$

(2)

where the highest $p_T$ muon is used and the $(x, y)$ components
of the neutrino momentum are inferred from the corresponding
$E_T^{miss}$ components. Events are required to have $E_T^{miss} > 25$ GeV
and $m_T > 40$ GeV, yielding 129157 W candidates.

\footnote{\Delta R is defined as $\Delta R = \sqrt{\Delta \eta^2 + \Delta \phi^2}$.}
5. $W^\pm$ signal yield and background estimation

Many components in the $W$ cross-section measurement, such as the luminosity or detector efficiencies, are in principle the same for positive and negative muons and therefore mostly cancel in the asymmetry calculation. The main experimental biases on the asymmetry measurement come from possible differences in the reconstruction of positive and negative muons. Each effect (trigger and reconstruction efficiency and momentum scale) is examined to check that the two charges behave in the same way within the systematic uncertainties. These studies are performed in absolute pseudorapidity in order to reduce the uncertainty associated with the limited size of the data samples used.

As in past $W$ analyses, trigger [33] and muon reconstruction [9, 33] efficiencies as a function of muon $\eta_{\mu}$ have been measured in data using a sample of unbiased muons from $Z \rightarrow \mu\mu$ decays, which provides a source of muons with small background. The trigger efficiency is determined relative to a reconstructed muon satisfying the selection criteria of the analysis. The average trigger efficiencies after the full $W$ selection are $(81 \pm 2)%$ in the central detector region or low-$\eta$ region, $|\eta_{\mu}| < 1.05$, and $(94 \pm 1)%$ in the forward detector region or high-$\eta$ region, $1.05 < |\eta_{\mu}| < 2.4$, where the differences are due to the geometrical acceptance of the muon trigger chambers. In the same sample, the muon reconstruction efficiency relative to an ID track is measured to be $(93 \pm 1)%$ overall. The efficiency for reconstructing an ID track is $(99 \pm 1)%$ [9]. The quoted uncertainties on these efficiencies are statistical.

Corrections have been applied to the simulated samples to account for differences in the trigger and reconstruction efficiencies between data and simulation. These are based on the ratio of the efficiency in data and in simulation, and are computed as a function of the muon $\eta_{\mu}$ and charge. The corrections for each charge agree within the statistical uncertainties, so the charge-averaged result is applied. For the trigger, the corrections are 0.98 and 1.03 in the central and forward MS regions, respectively. For the reconstruction efficiency, the correction factors are about 0.99 per $\eta_{\mu}$ bin except for the central-forward MS transition region ($|\eta_{\mu}| < 1.05$) where the correction factor is 0.94.

The muon momentum resolution is affected by the amount of material traversed by the muon, the spatial resolution of the individual track points and the degree of internal alignment of the ID and MS [35]. This resolution has been measured as a function of $\eta_{\mu}$ for the main detector regions (in $\eta_{\mu}$ ranges delimited by 1.05, 1.7, 2.0 and 2.4) from the width of the di-muon invariant mass distribution in $Z \rightarrow \mu\mu$ decays and from the comparison of the momentum measurements in the ID and MS in $Z \rightarrow \mu\mu$ and $W \rightarrow \mu\nu$ decays. The measured resolution is worse than expected from simulation by 1–5%, with the maximum discrepancy reached in the high-$\eta_{\mu}$ region of the detector [36]. The discrepancy is due to residual mis-alignments in the ID and MS, imperfections in the description of the inert material in simulation and an imperfect mapping of the magnetic field in the MS transition region where the field is highly non-uniform. Smearing corrections are therefore applied to the simulation in order to improve the agreement with data.

If the accuracy of the muon momentum measurement is different for positive and negative muons, this difference can produce a bias in the acceptance of $\mu^+$ with respect to $\mu^-$. Differences in the muon $p_T$ measurement between data and simulation have been evaluated comparing the curvature of muons from $W$ candidates in data and in templates derived from simulation. A binned likelihood fit for a momentum-scale correction that yields the best agreement between data and simulation is performed as a function of $\eta_{\mu}$ separately for positive and negative charges. The measured biases in the $p_T$ scale between the two charges are < 1%, but they increase to about 3% in the transition and high-$\eta_{\mu}$ regions due to residual mis-alignments in the ID and MS. These corrections are applied to the muon momenta in the simulated samples.

Fig. 1 shows the pseudorapidity distribution of the selected positive and negative muons. Data distributions are compared to the PYTHIA MC simulation, normalised to the total number of events in data. The shape of the simulation agrees well with the shape of the data after the corrections for the reconstruction and trigger efficiencies, and the muon-momentum scale and resolution.

The main backgrounds to $W \rightarrow \mu\nu$ arise from heavy flavour decays in multijet events and from the electro-weak background from $W \rightarrow \tau\nu$ where the tau decays to a muon, $Z \rightarrow \mu\mu$ where one muon is not reconstructed and produces fake $E_T^{miss}$, and $Z \rightarrow \tau\nu$ where one tau decays to a muon, as well as semileptonic $t\bar{t}$ decays in the muon channel. Backgrounds from the production of di-bosons ($WW, WZ$ and $ZZ$) and single top quarks are found to be negligible. The $W \rightarrow \tau\nu$ contribution is treated as a background. While this contribution presents the same asymmetry as the $W \rightarrow \mu\nu$ signal, it is difficult to include in PDF fits, which assume that the asymmetry is a function of $\eta_{\mu}$ for $W \rightarrow l\nu$. No explicit veto on events with a second muon is applied.

The background estimates of the electro-weak and $t\bar{t}$ backgrounds and the QCD background closely follow the methods used in the $W$ inclusive cross-section measurement [9]. They are determined separately for positive and negative muons as a function of $\eta_{\mu}$. The electro-weak and $t\bar{t}$ backgrounds are estimated using MC simulation. The QCD background comes primarily from $b$ and $c$ quark decays, with a smaller contribution from pion and kaon decays in flight. This background is estimated using a data-driven method similar to the one described in [9]. The sample of events fulfilling the full $W$ selection criteria with the exception of the muon isolation requirement is compared before and after the isolation requirement. The isolation efficiency for non-QCD events is measured in data with the $Z \rightarrow \mu\mu$ sample. The efficiency for QCD events is estimated in a control sample of low-$p_T$ muons extrapolated to the high-$p_T$ and high-$E_T^{miss}$ signal region using the simulated jet sample. Since the samples before and after isolation can be defined in terms of a QCD and non-QCD component, the expected number of QCD events can thus be determined.

The expected background amounts to 7% of the selected events; 6% is the electro-weak and $t\bar{t}$ contribution (3% $Z \rightarrow \mu\mu$, 2% $W \rightarrow \tau\nu$, and 1% for the sum of $t\bar{t}$ and $Z \rightarrow \tau\nu$) and the remainder is the QCD background. The cosmic ray background contamination is estimated to be smaller by a factor of $10^5$ compared to the signal and thus negligible. The $W^\pm$ candidate events and expected background contributions are summarised in Table 1.

Fig. 2 shows the transverse momentum distribution for positive and negative muons after the full event selection. They are compared with the distributions predicted by the corrected PYTHIA MC simulation normalised to the total number of events in data. The correction factors, $C_{Wl\pm}$, corresponding to the ratio of reconstructed over generated events in the simulated $W$ sample, satisfying all kinematic requirements of the event selection, $p_T > 20$ GeV, $p_T > 25$ GeV, $m_T > 40$ GeV, are also listed in Table 1. No correction is made to the full acceptance. The discrepancies between data and MC are taken into account by the systematic uncertainty assigned to the measurement of muon momenta explained in Section 6. The $C_{Wl\pm}$ factors include trigger and muon reconstruction scale factors to correct for observed deviations between data and MC efficiencies. Due to a reduced geometric acceptance in the trigger, the $C_{Wl\pm}$ factors for the lowest $|\eta_{\mu}|$ bins are significantly smaller than those for the higher $|\eta_{\mu}|$ regions.
6. Systematic uncertainties

All systematic uncertainties on the asymmetry measurement are determined in each $|\eta_{\mu}|$ bin accounting for correlations between the charges and are summarised in Table 2. The dominant sources of systematic uncertainty on the asymmetry come from the trigger and reconstruction efficiencies. The determination of these efficiencies is affected by the statistical uncertainty due to the small available sample of $Z \rightarrow \mu\mu$ events. Systematic uncertainties on the efficiencies are determined from studies of the impact of the selection criteria and backgrounds, and no significant charge biases are found. There is a loss of trigger efficiency in the low pseudorapidity region due to reduced geometric acceptance, resulting in a larger statistical error. As a result,
the trigger systematic uncertainty on the asymmetry is largest in
the low pseudorapidity bins (6–7% for central $|\eta_{\mu}|$ and 2–3% for
forward $|\eta_{\mu}|$). Similarly, the uncertainties associated with the re-
construction efficiency are larger in the lowest pseudorapidity bin
(about 7%), and in the MS central-forward transition region (about
3%), due to geometrical acceptance effects associated with reduced
chamber coverage. In the remaining regions, the uncertainty is
about 1–2%.

The muon momentum scale and resolution corrections con-
tribute to the uncertainty primarily due to the limited statistics
for the fitting procedures used to measure the differences between
the data and simulation. An additional source of uncertainty arises
from potential biases in the template shapes. The size of this effect
is determined by using different templates created by shifting the
resolution parameters in opposite directions to account for possible
charge biases. Uncertainties associated with the modelling of the
background contributions to the templates, particularly the QCD
background, are also included. The resulting uncertainty on the
asymmetry is in the 1–2% range, with little dependence on $\eta_{\mu}$.

The redundant ID and MS momentum measurements result in a
rate of charge mis-identification smaller than $10^{-4}$ in the $p_T$ range
considered, resulting in a negligible impact on the asymmetry.

The momentum-scale correction procedure is further tested by
exploiting the redundant muon-momentum measurements offered
by the ATLAS detector. The full asymmetry measurement is per-
formed with the ID and MS components of the combined muon
separately, including the scale corrections. Fig. 3 compares the two
independently corrected charge-asymmetry distributions, showing
good agreement within the systematic uncertainty associated with
the momentum-scale correction.

The systematic uncertainties on the QCD background arise pri-
marily from the uncertainty on the isolation efficiency for muons
in QCD events due to possible mis-modellings of the extrapolation
of the isolation efficiency to the large $p_T$ and $E_{\text{T,miss}}$ region
in the QCD simulation (40%). This has been derived from differ-
ences in the efficiency predictions between data and simulation in
the low muon $p_T$ control region and in sideband regions where
the muon $p_T$ or $E_{\text{T,miss}}$ cuts are reversed. The electro-weak and $t\bar{t}$
background and signal contributions are subtracted from data in
these comparisons. Additional uncertainties due to the non-QCD
isolation efficiency and the statistical uncertainty are included in
the total uncertainty on the QCD background estimate. The corre-
sponding systematic uncertainty on the asymmetry is 1–2%, with
little dependence on $\eta_{\mu}$.

For the electro-weak and $t\bar{t}$ backgrounds, the uncertainties in
the cross-sections include the PDF uncertainties (3%), and the un-
certainties estimated from varying the renormalization and factor-
ization scales: 5% for $W$ and $Z$, and 6% for $t\bar{t}$ [37,38,9]. These
uncertainties are taken as overall uncertainties, no $\eta$ dependence
is accounted for. An additional uncertainty from the luminosity of
11% is included, since the backgrounds are scaled to the luminos-
ity measured in data. The combination of all these contributions
results in an uncertainty on the asymmetry of less than 1%.

The impact of using an NLO MC using the CTEQ 6.6 PDF rather
than PYTHIA with MRST LO $^*$ PDF in the $c_{\text{W},\mu}$ factor calculation
has been evaluated and an additional systematic uncertainty of
about 3% is included to account for the small variations observed,
as listed in Table 2 as the uncertainty due to theoretical mod-
elling. PYTHIA uses a leading-log calculation for $W$ production
and is expected to give a reasonably accurate prediction for the
low $W$ transverse momentum $p_T^W$ region whereas MC@NLO [39]
uses higher-order matrix elements and is therefore expected to be
more reliable in the high $p_T^W$ region. Therefore the differences
in the scale factors associated with these two MC calculations gives
a reasonable estimate of the associated systematic error.

7. Results and conclusions

The measured differential muon charge asymmetry in eleven
bins of muon absolute pseudorapidity is shown in Table 3 and
Fig. 4. The statistical and systematic uncertainties per $|\eta_{\mu}|$ bin
are included and contribute comparably to the total uncertainty.
Table 3 and Fig. 4 also show expectations for the muon asym-
metry from $W$ predictions at NLO with different PDF sets: CTEQ
6.6 [18], HERA 1.0 [5] and MSTW 2008 [17]; all predictions are
presented with 90% confidence-level error bands. All MC predic-
tions are calculated using MC@NLO, with all kinematic selection
criteria applied to the truth particles. The PDF uncertainty bands
are obtained by summing in quadrature the deviations of each of
the PDF error sets [40] from the respective nominal predictions,
according to the specifications of the corresponding PDF Collab-
orations to get 90% C.L. bands. These uncertainties for all pre-
dictions include experimental uncertainties as well as model and
parametrisation uncertainties. The HERA 1.0 [5] set also includes
the uncertainty in $x_{\mu}$, which, however, is not the dominant source
of uncertainty.

While the predictions with different PDF sets differ within their
respective uncertainty bands [41,42], they follow the same global
trend, rising with $\eta_{\mu}$. The measured asymmetry agrees with
this expectation. As demonstrated graphically in Fig. 4, the data are
roughly compatible with all the predictions with different PDF sets,
though some are slightly preferred to others. A $\chi^2$-comparison
using the measurement uncertainty and the central value of the
PDF predictions yields values per number of degrees of freedom of
9.16/11 for the CTEQ 6.6 PDF sets, 35.81/11 for the HERA 1.0 PDF
sets and 27.31/11 for the MSTW 2008 PDF sets.

In summary, this Letter reports a measurement of the $W$ charge
asymmetry in $pp$ collisions at $\sqrt{s} = 7$ TeV performed in the $W \rightarrow
\mu\nu$ decay mode using 31 pb$^{-1}$ of data recorded with the ATLAS
detector at the LHC. Until the start of the LHC, it has not been kine-
nically possible to precisely measure the valence quark distribu-
tions and in particular to constrain the ratio of $u/d$ quarks below
$x \leq 0.05$ as assessed by [17]. Whereas none of the predictions with
different PDF sets is inconsistent with these data, the predictions
are not fully consistent with each other since they are all phe-
nomenological extrapolations in $x$. The input of the data presented
here is therefore expected to contribute to the determination of
the next generation of PDF sets, helping reduce PDF uncertainties, particularly the shapes of the valence quark distributions in the low-x region.

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