ATLAS Note

18th August 2017

Sensitivity study for the measurement of the W-boson charge and forward-backward asymmetries at 13 TeV with the ATLAS detector

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This report describes a sensitivity study of the measurement of W-boson charge and forward-backward asymmetries in p-p collision events produced at a center-of-mass energy of 13 TeV. The statistical uncertainties for the measurement of both observables as a function of $y_{\ell\ell}$, as expected from the analysis of data collected in 2015 at $\sqrt{13}$ TeVwith the ATLAS detector, are presented.

1 Introduction

The angular distributions of lepton pairs produced in Drell–Yan processes provide insight into perturbative and non perturbative QCD dynamics. The large amount of data collected at the LHC enables performing measurements of these processes at an unprecedented level of precision. This report describes a sensitivity study for the measurement of W-boson charge and forward-backward asymmetries in events produced at a center-of-mass energy of 13 TeV.

At leading order, the partonic Drell-Yan cross section for the $u\bar{d} \to W^+ \to e^+\nu$ process can be written as

$$\frac{d\sigma}{dm_{\ell\ell} d\cos\theta} \propto |V_{ud}|^2 G_f^2 m_W^4 \frac{m_{\ell\ell}^2}{(m_{\ell\ell}^2 - m_W^2)^2 + \Gamma_w^2 m_W^2} \left[\left(1 + \cos^2\theta\right) + A_4 \cos\theta \right], \quad A_4 = 2$$

where $m_{\ell\ell}$ is the invariant mass of the dilepton system, θ is the angle between the lepton and the quark, m_W and Γ_W are the mass and width of the W boson, V_{ud} is the CKM matrix element and G_f is the Fermi coupling constant. The linear term in $\cos\theta$, with coefficient A_4, determines a forward-backward asymmetry.

It is possible to define a W-boson rest frame, so called Collins-Soper (CS) reference frame [1] (Figure 1), in which the polar (θ) and azimuthal (ϕ) angles are defined as follows:

$$\cos\theta = 2\frac{(l^+\bar{l}^- - l^-\bar{l}^+) \cdot \mathrm{sign}(y_{\ell\ell})}{m_{\ell\ell}\sqrt{m_{\ell\ell}^2 + \vec{p}_T^{\,2}}}, \tag{1}$$

$$\phi = \arctan 2\left(\frac{m_{\ell\ell}(\Delta_T \cdot \widehat{p}_T)}{\sqrt{m_{\ell\ell}^2 + \vec{p}_T^{\,2}}}, \vec{\Delta}_T \cdot \widehat{R}_T \cdot \mathrm{sign}(y_{\ell\ell}) \right) \tag{2}$$

Where p_T is the dilepton transverse momentum, $m_{\ell\ell}$ is the dilepton mass, $y_{\ell\ell}$ is the dilepton rapidity, $l^\pm = E \pm p_z$for the lepton and $\bar{l}^\pm = E \pm p_z$for the antilepton, $\Delta^j = l^j - \bar{l}^j$ and $\widehat{R_T}$ is a transverse unit vector in the direction of $\vec{p}_{\text{beam}} \times \vec{p}_{\ell\ell}$.

In W-boson production we have the disadvantage that the decay kinematics cannot be completely reconstructed due to the unobservability of the neutrino longitudinal momentum. The transverse momentum of the neutrino can be inferred from momentum balance.

By imposing the invariant mass of the dilepton system to be equal to the W-boson pole mass, m_W, the longitudinal momentum of the neutrino can be recovered up to a towfold ambiguity, by solving the second order equation:

$$(p^\mu + q^\mu)^2 = m_W^2 \quad \Rightarrow \quad q_z(1,2) = \frac{-b \pm \sqrt{b^2 - 4ac}}{2a} \tag{3}$$

$$\tag{4}$$

where p^μ and q^μ are the four-momenta of the charged lepton and neutrino, respectively, and

$$a = (p_x^2 + p_y^2), \quad b = p_z[2(p_x q_x + p_y q_y) + m_W^2], \tag{5}$$

$$c = |p|^2(q_x^2 + q_y^2) - \left[2(p_x q_x + p_y q_y) + \frac{m_W^2}{2}\right] \tag{6}$$

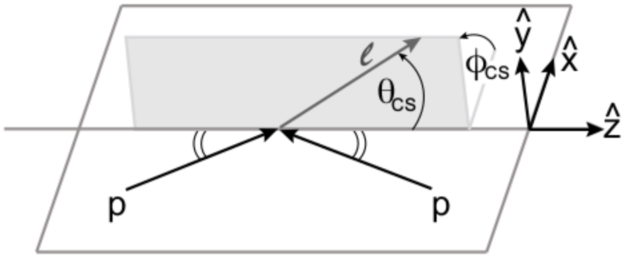


Figure 1: Collins-Soper Reference Frame

The two solutions have the same ϕ and p_T, they differ by a sign in $\cos\theta$ and correspond to two solutions of rapidity, $y_{\ell\ell;1,2}$. The ambiguity in the sign of $\cos\theta$ is partially solved because for some events the two solutions $y_{\ell\ell;1}$ and $y_{\ell\ell;2}$ have opposite sign, and the term $\mathrm{sign}(y_{\ell\ell})$ in Eq. 2 cancels the sign flip between the two $\cos\theta$ solutions.

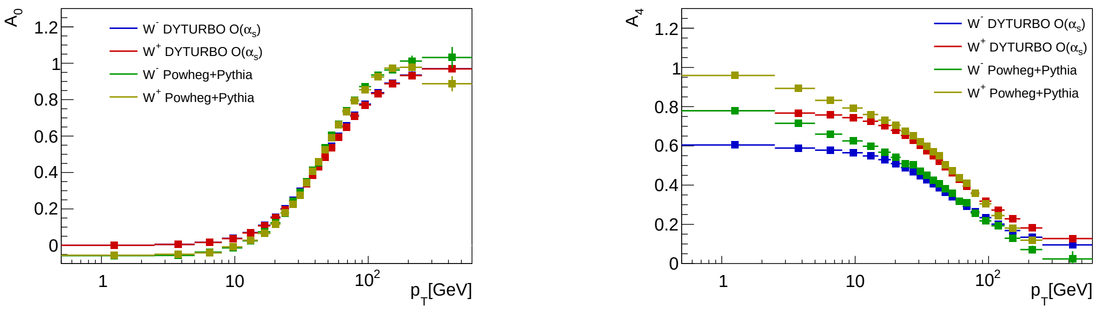
In the CS reference frame, the differential cross section describing the kinematics of the two leptons from the W-boson decay can be decomposed as a sum of nine harmonic polinomials, wich depend on $\cos\theta$ and ϕ, multiplied by corresponding helicity cross-sections that depend on the W-boson transverse momentum (p_T), rapidity ($y_{\ell\ell}$), and invariant mass ($m_{\ell\ell}$). It is a standard convention to factorise out the unpolarised cross-section, denoted in the literature by σ^{U+L}, and to present the five-dimensional differential cross-section as an expansion into nine harmonic polynomials $P_i(\cos\theta, \phi)$ and dimensionless angular coefficients $A_{0-7}(p_T, y_{\ell\ell}, m_{\ell\ell})$ [2]

$$\begin{aligned}\frac{d\sigma}{dp_T dy_{\ell\ell} dm_{\ell\ell} d\cos\theta d\phi} &= \frac{3}{16\pi}\frac{d\sigma^{U+L}}{dp_T dy_{\ell\ell} dm_{\ell\ell}} \times \{(1+\cos^2\theta) + \frac{1}{2}A_0(1-3\cos^2\theta) + A_1 \sin 2\theta \cos\phi \\ &+ \frac{1}{2}A_2 \sin^2\theta \cos 2\phi + A_3 \sin\theta\cos\phi + A_4\cos\theta + A_5 \sin^2\theta \sin 2\phi + A_6 \sin 2\theta \sin\phi + +A_7 \sin\theta \sin\phi\}\end{aligned} \tag{7}$$

2 Predictions

Predictions of the angular coefficients were computed at leading order and at next-to-leading order (NLO) using DYTURBO and at NLO + parton shower using the Powheg+Pythia MC event generator. Figure 2 shows predictions of A_0 and A_4 as a function of p_T. The two predictions are in good agreement for A_0 whereas some differences are observed for A_4 at low p_T.

Predictions of A_4 as a function of rapidity are shown in Figure 3.



(a) (b)

Figure 2: Angular coefficients A_0 (a) and A_4 (b) as a function of p_T for W^+ and W^- as predicted with DYTURBO and Powheg+Pythia.

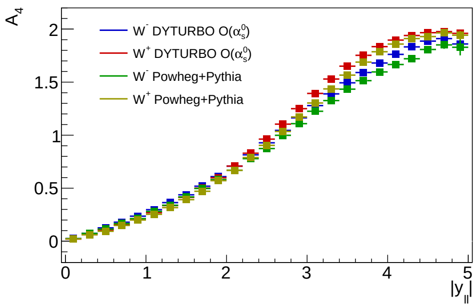


Figure 3: Angular coefficient A_4 as a function of $|y|$ for W^+ and W^- as predicted with DYTURBO and Powheg+Pythia.

3 Sensitivity study

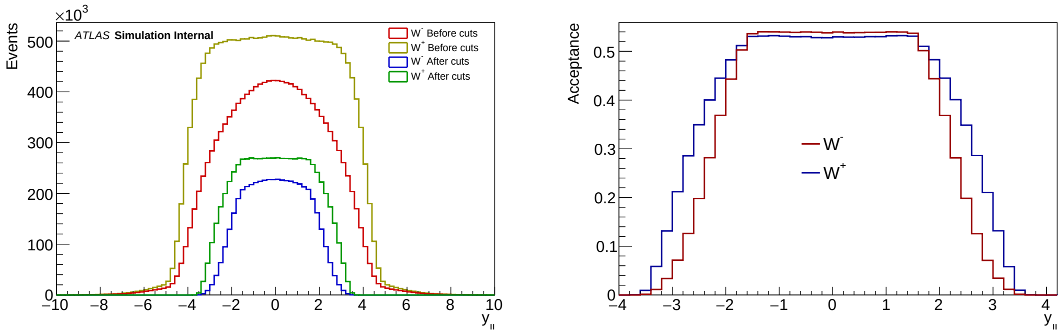
A sensitivity study was perfomed, aimed at evaluating the statistical uncertainty expected for the analysis of 3.2 fb^{-1} of integrated luminosity collected with the ATLAS detector in 2015 at $\sqrt{s} = 13$ TeV. Two observables were considered, A_4 and the W-boson charge asymmetry, defined as

$$A_W = \frac{N_{W^+} - N_{W^-}}{N_{W^+} + N_{W^-}} \tag{8}$$

where N_{W^+} and N_{W^-} are the number of W^+ and W^- events, respectively. Both observables are considered as functions of $y_{\ell\ell}$, in the range $|y_{\ell\ell}| < 2.4$ and using equally spaced bins of 0.2.

The analysis closely follows the methodology used in Ref. [3] for Z-boson events. Events were required to have transverse momentum of the charged lepton $p_T^\ell > 25$ GeV, absolute pseudorapidity of the charged lepton $|\eta_\ell| < 2.5$, transverse momentum of the neutrino $p_T^\nu > 25$ GeV and transverse mass $m_T = \sqrt{2p_T^\nu p_T^\ell[1 - \cos\Delta\phi(\ell,\nu)]} > 50$ GeV.

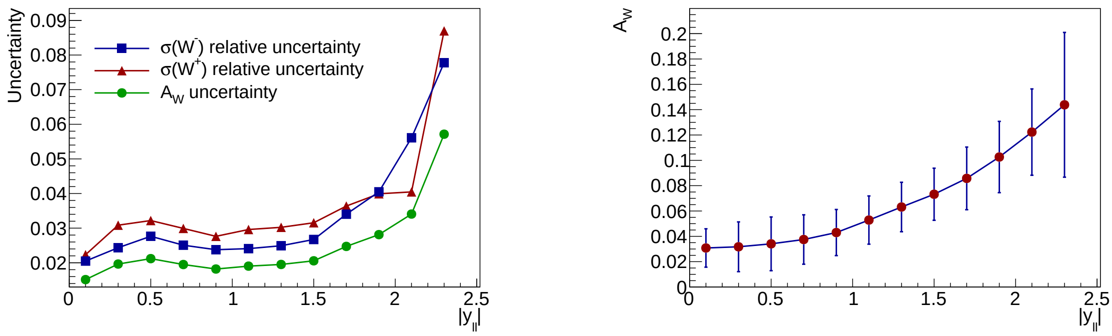
Figure 4 (a) shows the number of expected W^+ and W^- events as a function of $y_{\ell\ell}$ before and after applying the event requirements. Figure 4 (b) shows the corresponding acceptance.



(a) (b)

Figure 4: Number of expected events as a function of $y_{\ell\ell}$ (a) and acceptance of the event requirements (b).

The unpolarized cross sections and the A_{0-7} coefficients as functions of $y_{\ell\ell}$ are extracted simultaneously through a maximum log-likelyhood fit, and statistical uncertainties are determined with the Minos algorithm. The MC prediction is used as pseudodata in the fit. Figure 5 (a) shows the expected relative statistical uncertainties for the W^+ and W^- cross sections, and the absolute uncertainty for A_W. Figure 5 (b) shows A_W as extracted from the fit to the pseudodata.



(a) (b)

Figure 5: Expected uncertainties for the W^+ and W^- cross sections and for A_W as a function of $|y_{\ell\ell}|$(a). A_W as a function of $|y_{\ell\ell}|$ as extracted from the fit to the pseudodata.

Figure 6 shows the expected statistical uncertainties for the W^+ and W^- A_4 coefficient.

4 Conclusion

The statistical uncertainties for the measurement of A_4 and the W-boson charge asymmetry as a function of $y_{\ell\ell}$, as expected from the analysis of data collected in 2015 at $\sqrt{13}$ TeVwith the ATLAS detector, were evaluated. The sensitivity study showed that A_W can be measured with a statistical uncertainty of approximately 2% in the range $|y_{\ell\ell}| < 1.5$ and smaller than 5% for $|y_{\ell\ell}| < 2.4$. The statistical uncertainties on A_4 is expected to be 0.07 for $|y_{\ell\ell}| < 1.5$ and smaller than 0.1 in the range $|y_{\ell\ell}| < 2$.

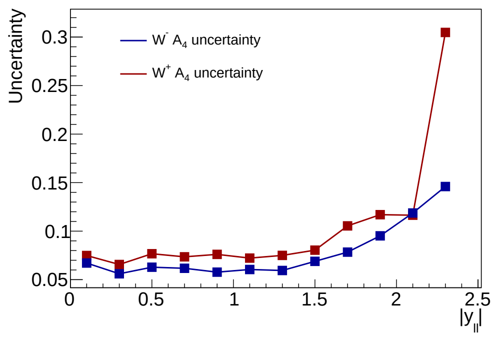


Figure 6: Expected uncertainties for the W^+ and W^- A_4 coefficient as a function of $|y_{\ell\ell}|$

References

[1] J. C. Collins and D. E. Soper,
Angular Distribution of Dileptons in High-Energy Hadron Collisions, Phys. Rev. **D16** (1977) 2219.

[2] E. Mirkes, *Angular decay distribution of leptons from W-bosons at NLO in hadronic collisions*, Nuclear Physics B **387** (1992) 3, ISSN: 0550-3213,
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[3] G. Aad et al., *Measurement of the angular coefficients in Z-boson events using electron and muon pairs from data taken at* $\sqrt{s} = 8$ *TeV with the ATLAS detector*, JHEP **08** (2016) 159,
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