PROSPECTS OF MEASURING ZZ AND WZ POLARIZATION WITH ATLAS

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Abstract

The measurement of angular distributions of the decay leptons in di-boson final states allows the reconstruction of the spin density matrix element ρ_{00} in processes where ZZ and WZ final states are produced via quark anti-quark annihilation in proton-proton collisions at the LHC. This note presents the expected sensitivity of such measurements with the ATLAS experiment, using electrons and muons as final state leptons, based on an integrated luminosity of 100 fb^{-1}. Besides the statistical accuracy on the fractions of longitudinally polarized Z or W bosons, various contributions to the systematic uncertainty have been studied.

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The W gauge boson is mainly produced singly in $q\bar{q}$ annihilation at hadron-hadron colliders. The same is true for the Z gauge boson, which has also been produced in electron-positron annihilations at LEP. In these processes, the gauge boson has always transverse polarization due to the helicity conservation in the annihilation process. However, some fraction of longitudinal polarization is allowed and expected in the Standard Model (SM) when the annihilation process yields two gauge bosons. Longitudinally polarized W bosons have been observed for the first time at LEP [1], in W^+W^- production, and later also at the Tevatron [2] in top-quark decays. The longitudinal polarization degree of freedom for the W and the Z bosons is a direct result of the Higgs mechanism, and it would be a valuable test of the SM to measure the fraction of longitudinally produced bosons in di-boson events at hadron colliders and compare with theory. Any deviation from the SM predictions would be evidence for new physics. Furthermore, di-boson events can be produced as decay products of the Higgs boson, and their polarization state might be of help in the determination of the Higgs spin [3] and its separation from the di-boson continuum.

This note describes feasibility studies using Monte Carlo (MC) events of the ZZ [4] and WZ [5] production channels at LHC, to be measured by the ATLAS detector [6]. LHC is a proton-proton collider at CERN which is expected to start operation at the end of 2009, and eventually will reach a center-of-mass (c.m.s) energy of 14 TeV. This energy value was assumed in our study with an integrated luminosity of 100 fb^{-1}, which is the expected luminosity value, before a possible upgrade of the machine into Super LHC (SLHC), expected to achieve a luminosity increase by an order of magnitude. Background considerations lead us to use only the leptonic decays, $W \to \ell\nu$ and $Z \to \ell^+\ell^-$, where $\ell = e, \mu$.

Electron energy is measured at ATLAS by the liquid argon electromagnetic calorimeter with a resolution of 1.2% for electron energy around 100 GeV [7]. The electron direction is obtained from the inner detector consisting of pixel detectors, silicon strip layers and a straw-tube transition radiation detector which also assists electron identification. The electromagnetic calorimeter is inside the hadron calorimeter, which is surrounded by the muon spectrometer measuring the muon momenta with a resolution of (4 - 5)% for muons with transverse momentum, p_T, below 150 GeV [7]. The pseudo-rapidity range for triggering and measuring electrons and muons is $|\eta| < 2.5$. The calorimeters cover a larger range, up to $|\eta| = 5$. This hermetic coverage allows a precise measurement of the missing transverse energy, E_T, which is used to identify the neutrino from the W decay and obtain its transverse momentum.

Monte Carlo event samples have been generated using Pythia [9] for the ZZ and MC@NLO [9] for the WZ channel. These events have been passed through the full ATLAS detector simulation and then through the ATLAS reconstruction program to be used also for real data events. Similar event samples have been used also for the expected background processes (see below).

ZZ candidates are required to have two lepton anti-lepton pairs, each pair with invariant mass within 12 GeV of the Z mass. All leptons are required to have $|\eta| < 2.5$. Two of the leptons must satisfy $p_T > 20$ GeV and the other two must have $p_T > 7$ GeV. Following these cuts, 2194 events are left in our 100 fb^{-1} pseudo-data sample. Background sources considered were $\mathrm{t\bar{t}}$ and $\mathrm{Zb\bar{b}}$ events, and the total background level was found to be less than 1% and was neglected.

The WZ channel is more difficult to separate from background and more stringent cuts are needed. WZ candidates are required to have three leptons with $p_T > 25$ GeV and $|\eta| < 2.5$. Out of these three leptons, there must be one lepton anti-lepton pair with invariant mass within 12 GeV of the Z mass. In addition the event must have missing E_T above 25 GeV, and the transverse mass constructed from the missing E_T and the third lepton must be between 50 and 90 GeV. The angle in the transverse plane between the missing E_T vector and the third lepton must exceed 40^o. Finally, to further suppress background from $\mathrm{t\bar{t}}$ events, no more than one jet is allowed in the event, and its transverse momentum should not exceed 30 GeV. In our 100 fb^{-1} pseudo-data sample, 2873 WZ candidates are left after these cuts with a background level of 1%, where the background sources considered were $\mathrm{t\bar{t}}$, $\mathrm{W^+W^-}$, ZZ, Z+jet and $\mathrm{Z}\gamma$ events. This background was neglected in the further analysis.

The kinematic observable which is sensitive to the gauge boson polarization is the boson decay angle, θ^*_ℓ, which is the angle between the lepton (anti-lepton) produced in the $\mathrm{W^-}$, Z ($\mathrm{W^+}$) decay in the rest-frame of the boson with respect to the boson momentum in the di-boson rest-frame. Its distribution is given by,

$$\frac{1}{\sigma}\frac{\mathrm{d}\sigma}{\mathrm{d}\cos\theta^*_\ell} = \rho_{--}\frac{3}{8}(1+\cos\theta^*_\ell)^2 + \rho_{++}\frac{3}{8}(1-\cos\theta^*_\ell)^2 + \rho_{00}\frac{3}{4}\sin^2\theta^*_\ell,$$

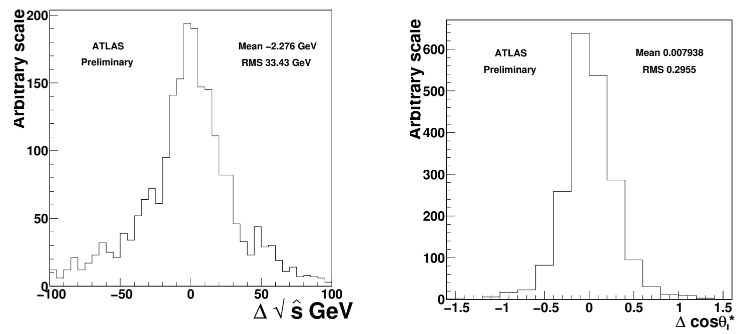
for the W boson, and by,

$$\frac{1}{\sigma}\frac{\mathrm{d}\sigma}{\mathrm{d}\cos\theta^*_\ell} = \rho_{--}\frac{3}{8}(1+2A\cos\theta^*_\ell+\cos^2\theta^*_\ell) + \rho_{++}\frac{3}{8}(1-2A\cos\theta^*_\ell+\cos^2\theta^*_\ell) + \rho_{00}\frac{3}{4}\sin^2\theta^*_\ell,$$

for the Z boson. Here, $A = 2v_\ell a_\ell/(v_\ell^2 + a_\ell^2)$, where v_ℓ (a_ℓ) is the vector (axial-vector) coupling of the Z boson to leptons. The spin density matrix elements, ρ_{--}, ρ_{++} and

ρ_{00} correspond to transverse left-handed, transverse right-handed and longitudinal polarization of the boson. They satisfy $\rho_{--} + \rho_{++} + \rho_{00} = 1$ and each one of them can be interpreted as the fraction of bosons produced in the corresponding polarization state.

For ZZ events, it is rather straightforward to obtain θ_ℓ^* from the measured kinematic observables of the four leptons. For the WZ events, the longitudinal momentum of the neutrino, p_ℓ^ν, is not measured, but it can be calculated if the neutrino and the the corresponding lepton are constrained to the W mass. A quadratic equation is obtained yielding two solutions for p_ℓ^ν. The value taken for p_ℓ^ν is a weighted average of the two solutions, where the weights are the corresponding SM cross-section values [8]. The resulting resolutions in the di-boson invariant mass, $\sqrt{\hat{s}}$, and in $\cos\theta_\ell^*$ are shown in Fig. 1.



(a) (b)

Figure 1: Resolution for WZ events in **(a)** $\sqrt{\hat{s}}$, **(b)** $\cos\theta_\ell^*$

Since the gauge boson polarization is expected to depend on $\sqrt{\hat{s}}$, the analysis is done separately for 4 (3) bins in $\sqrt{\hat{s}}$, for the ZZ (WZ) channels. In addition, there is a separation between the W^+Z and W^-Z channels. To correct for detector and analysis effects, the MC events are further divided into 10 bins in $\cos\theta_\ell^*$. For each bin i, the ratio between the number of events at the generator level and the number after the detector and selection is the correction factor, C_i, which accounts for both overall efficiency and resolution effects.

For the ZZ channel, we extract ρ_{00} using the event-by-event "projection operator" method,

$$\rho_{00} = \frac{1}{N_{\text{events}}} \sum_{\text{events}} C_i \cdot \Lambda_{00}(\cos\theta_\ell^*)$$

where C_i corresponds to the $(\sqrt{\hat{s}}, \cos\theta_\ell^*)$ bin containing the event and Λ_{00} is the projection operator for the longitudinal polarization state, given by, $\Lambda_{00} = 2 - 5\cos^2\theta_\ell^*$, and calculated for the measured $\cos\theta_\ell^*$ of that particular event.

This projection operator method could not be used for the WZ channels, since some of the bins in the MC distribution after the detector were sparse, yielding very large, uncertain and sometimes even infinite correction factors. Therefore, an event-by-event maximum likelihood method was adopted, where the inverse correction factors are used, and they multiply the theoretical $\cos\theta_\ell^*$ distribution for each event.

The systematic effect from the uncertainty in the Parton Distribution Functions (PDF) was studied in the ZZ channel by using different sets of PDFs (CTEQ, MRST, EHLQ2), and in the WZ channels by using the 40 CTEQ6M [9] error sets. Another source of systematic errors considered is MC statistics. For the WZ channels, the dominating systematic effect comes from the replacement of the SM cross-section values used for the weighted average of the two solutions for p_ℓ^ν by theoretical cross-section values [8] calculated with anomalous couplings within the Tevatron limits. The overall systematic errors are typically (20 - 50)% of the statistical ones.

Fig. 2 shows the results of the longitudinal polarization fraction, ρ_{00}, for the different channels as function of $\sqrt{\hat{s}}$. The curves correspond to the theoretically expected $\rho_{00}(\sqrt{\hat{s}})$, as obtained from large statistics, generator level MC samples.

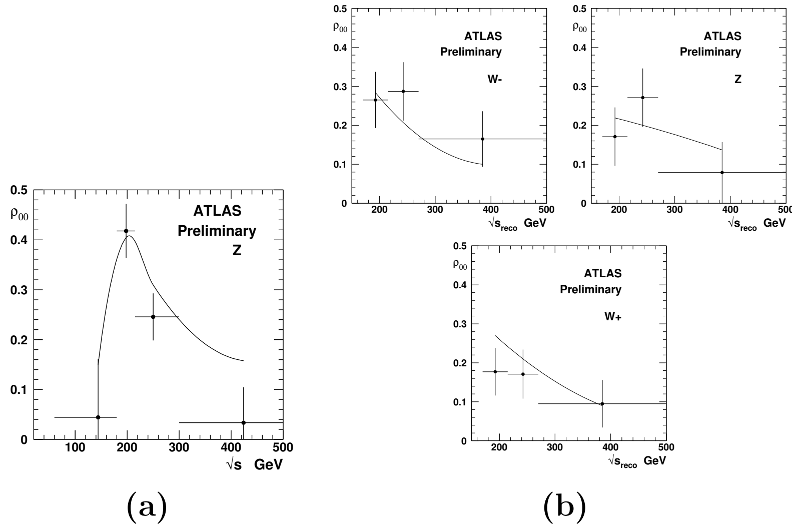


Figure 2: Longitudinal polarization fraction, ρ_{00}, as function of the di-boson mass, $\sqrt{\hat{s}}$, obtained from our 100 fb^{-1} pseudo-data samples, for **(a)** Z in ZZ events, **(b)** W^- (left), Z (right), W^+ (bottom)

In summary, it has been shown in this note that the measurement of the Z and W polarizations in ZZ and WZ events is feasible with an integrated luminosity of 100 fb^{-1}, which will be available only after several years of successful LHC running. The errors are dominated by statistics, and more accurate results are expected with the higher luminosities expected in SLHC.

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