Measurement of the $Z/\gamma^*$ forward-backward asymmetry in muon pairs with the ATLAS experiment at the LHC

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Abstract. A study on muon pairs produced through an intermediate $Z/\gamma^*$, in $pp$ collisions at the LHC, at a center-of-mass energy of 7 TeV, is presented. After a selection aimed at enhancing the contribution from $Z$ boson decay, the topology of the events is analyzed, and the forward-backward asymmetry is measured. The result is then used to test a method to measure the effective weak mixing angle $\sin^2 \theta_W^{\text{eff}}$. This note summarizes the results obtained with 2011 data collected by the ATLAS experiment at the LHC, corresponding to an integrated luminosity of 4.8 fb$^{-1}$.

1. Introduction
The electroweak theory represents a fundamental component of what is believed to be the theory that describes all the particles and their interactions, the Standard Model (SM). Despite the great success of the Standard Model, it is not believed to be the final theory that describes particle interactions. Many open questions remain, i.e. the verification of mass generation by spontaneous symmetry breaking and the origin of the so called dark matter, which is a major component of the universe and cannot be explained in terms of known particles.

The Large Hadron Collider (LHC) at CERN, as the largest proton-proton collider in the history of particle physics, is designed to answer these questions. Since its first physics run on 20 November 2009 at 900 KeV, it has reached a center of mass energy of 7 TeV in 2010 and by November 2011 an integrated luminosity of about 5 fb$^{-1}$ has been recorded by the ATLAS experiment. The integrated luminosity recorded at LHC has already allowed to perform several tests of the Standard Model.

In ATLAS, the process $pp \rightarrow l^+l^- + X$, with two leptons in the final state, is currently produced with an high rate. This process is mediated primarily by virtual photons at low values of di-lepton invariant mass ($m_{ll}$) [1], primarily by the $Z$ at $m_{ll} \sim m_Z$, and by a combination of photons and $Z$ bosons outside these regions. The presence of both vector and axial-vector couplings of electroweak bosons to fermions in the process $q\bar{q} \rightarrow Z/\gamma^* \rightarrow l^+l^-$ gives rise to a forward-backward asymmetry ($A_{fb}$) in the polar angle of the lepton momentum relative to the incoming quark momentum in the rest frame of the dilepton pair.

In this note a measurement of the forward-backward asymmetry with the ATLAS experiment, using $pp \rightarrow Z/\gamma^* \rightarrow \mu^+\mu^-$ events at $\sqrt{s} = 7$ TeV, is presented. The analysis focuses on the decay of the $Z$ boson into two muons, since this provides a relative clean signature which can be clearly
discriminated from other processes. Section 2 focuses on the definition of the forward-backward asymmetry and the Collins-Soper reference frame. In Section 3 I present the analysis to select the Z/γ* candidates and the measurement of A_{fb} as a function of the di-muon invariant mass. In Section 4, a method based on a fit on the asymmetry distribution is proposed, in order to extract the weak mixing angle sin^2 θ_W. A Monte Carlo closure test is preformed, and a quite good agreement with the Monte Carlo default value is observed.

2. The Forward-Backward charge asymmetry

At LHC, the Drell-Yan process is q̅q → Z/γ* → μ⁺μ⁻; the lowest order proceeds via photon and Z boson exchange. The neutral current couplings of a fermion f to the Z boson has vector and axial-vector components: J_{Zf} = f(g^V_{1f} + g^A_{1f}γ_5)f, where g^V_{1f} and g^A_{1f} are vector and axial-vector couplings of the fermion to the Z respectively.

The differential cross section for fermion pair production around the Z-pole can be written as:

\[
\frac{dσ(q̅q → μ^+μ^-)}{d cos θ} = C \pi α^2 \frac{Q^2 μ Q^2 q(1 + cos^2 θ) + QμQq Re(χ(s))(2g^V_{1f}g^A_{1f}(1 + cos^2 θ) + 4g^A_{2f}g^V_{2f}) + |χ(s)|^2((g^V_{1f}g^A_{1f})^2 + g^A_{2f}g^A_{2f})(1 + cos^2 θ) + 8g^V_{1f}g^V_{2f}g^A_{1f}g^A_{2f}cos θ)}{2s}
\]

where C is the color factor, θ is the emission angle of the muon (anti-muon) relative to the quark(anti-quark) in the rest frame of the muon pair, and

\[
χ(s) = \frac{1}{cos^2 θ_W sin^2 θ_W s - M_Z^2 + iΓ_Z M_Z}
\]

The first and the third terms in Equation 2 correspond to the pure γ* and Z exchange respectively while the second term corresponds to the Z/γ* interference. The angular dependence of the various term is either cos θ or (1 + cos^2 θ). The cos θ terms integrate to zero in the total cross section but induce the forward-backward asymmetry.

The differential cross section in Equation 2 simplified into:

\[
\frac{dσ}{d cos θ} = A(1 + cos^2 θ) + B cos θ
\]

where A and B are functions that take into account the weak isospin and charge of the incoming quarks and the transferred momentum Q^2 of the interaction. Events with cos θ > 0 are called forward events, and events with cos θ < 0 are called backward events. The integrated cross section for forward events is thus \(σ_F = \int_0^1 \frac{dσ}{d cos θ} d cos θ\) and the integrated cross section for backward events is \(σ_B = \int_{-1}^0 \frac{dσ}{d cos θ} d cos θ\). The forward-backward charge asymmetry \(A_{FB}\) is defined as

\[
A_{FB} = \frac{σ_F - σ_B}{σ_F + σ_B} = \frac{\int_0^1 \frac{dσ}{d cos θ} d cos θ - \int_{-1}^0 \frac{dσ}{d cos θ} d cos θ}{\int_0^1 \frac{dσ}{d cos θ} d cos θ + \int_{-1}^0 \frac{dσ}{d cos θ} d cos θ} = \frac{N_F - N_B}{N_F + N_B} = \frac{3B}{8A}
\]

where \(N_F\) and \(N_B\) are numbers of forward and backward events.

When the incoming quarks participating in the Drell-Yan process have no transverse momentum relative to their parent baryons, θ is determined unambiguously from the four-momenta of the muons by calculating the angle that the muon makes with the proton beam in the center-of-mass frame of the muon pair. When either of the incoming quarks has significant transverse momentum, however, there exists an ambiguity in the four-momenta of the incoming quarks in the frame of the di-muon pair, since one can not determine the four-momenta of the
quark and antiquark individually. The Collins-Soper formalism\[3\] is adopted to minimize the effects of the transverse momentum of the incoming quarks. In this formalism, the polar axis is defined as the bisector of the proton beam momentum and the negative of the anti-proton beam momentum when they are boosted into the center-of-mass frame of the di-muon pair, which is shown in Figure 1. The variable $\theta^*$ is defined as the angle between the muon and the polar axis. Let $Q(Q_T)$ be the four momentum (transverse momentum) of the dimuon pair, $P_1$ and $P_2$

![Figure 1. The Collins-Soper reference frame](image)

be the four-momentum of the muon and anti-muon respectively, all measured in the lab frame. Then $\cos \theta^*$ is given by

$$
\cos \theta^* = \frac{2}{Q \sqrt{Q^2 + Q_T^2}} (P_1^+ P_2^- - P_1^- P_2^+ )
$$

(5)

where $P_i^\pm = \frac{1}{\sqrt{2}} (P_i^0 \pm P_i^3)$, and $P^0$ and $P^3$ represent energy and longitudinal component of the momentum.

3. Measurement and unfolding of the $A_{fb}$

The event topology of $pp \to Z/\gamma^* \to \mu^+ \mu^+$ has a very characteristic signature: two high energetic and isolated muons in the final state are produced. The data sample used in this analysis was collected using the ATLAS detector between March 21 and October 30. The number of events in the data correspond to an integrated luminosity of 4.8 fb$^{-1}$. The way to select only interesting events is to use the characteristic signature of the signal process. Some constraints on the kinematic quantities of muons in data sample are applied and, at the end, an almost pure $Z/\gamma^* \to \mu^+ \mu^+$ sample is obtained. After the application of the selection requirements we found 1.3M $Z/\gamma^*$ candidates in data sample. The final sample is still contaminated by some background events surviving the selection but this contamination is expected to be very low because, as already mentioned, the signal process is characterized by a very clear signature. The same selection cuts are also applied to Monte Carlo signal and to the background samples.

The selection of $Z/\gamma^*$ candidates allows to measure some direct observables related to the process $Z/\gamma^* \to \mu^+ \mu^+$. The forward-backward asymmetry $A_{fb}$ of the muons pair is one of the observables that can be used to test the validity of the electroweak theory and, at the same time, to search for new physics signatures. A measurement of the forward-backward asymmetry can be performed following the steps below:

- Divide the mass spectrum in a certain number of bins.
- In each bin count the number of forward and backward events.
- Subtract the number of forward and backward events due to the background.
Figure 2. Spectrum of measured $A_{fb}$. Squares refer to raw $A_{fb}$ spectrum. Circles refer to unfolded $A_{fb}$ spectrum.

- Compute the $A_{fb}$ value using the relation:

$$A_{fb} = \frac{N^F - N^B}{N^F + N^B}$$

We divide an invariant-mass range, from 60 to 1000 GeV, in 21 bins. We apply the measurement procedure to the $Z/\gamma^*$ candidates found in data sample and obtain a distribution of raw $A_{fb}$ vs. $m_{\mu\mu}$.

The measured spectrum of the asymmetry needs to be corrected for three main effects: radiative corrections, detector resolution and dilution. The effect of radiative corrections and detector resolution \cite{4} is mainly to deform the shape of the $Z/\gamma^*$ mass spectrum; this effect is called mass migration. Photon radiation of the muons lowers the di-muon invariant mass. Events from the $Z$ peak region are therefore shifted towards smaller values of $m_{\mu\mu}$, thus reducing the cross section in and above the peak region, and increasing the rate below the $Z$ pole. Since events from the $Z$ peak, where $A_{fb}$ is positive and small, are shifted towards smaller values of $m_{\mu\mu}$ by photon radiation, the forward-backward asymmetry is significantly reduced in magnitude by radiative corrections. The other important correction is called dilution, an effect directly related to the direction of the incoming quark. In $pp$ collisions, there is in principle no way of knowing which one of the beams contributed a quark to the collision. This effect gives rise to a sensible reduction of the $A_{fb}$.

The measurement of $A_{fb}$ is corrected for this effect by means of a response-matrix based unfolding. Using the available Monte Carlo $Z/\gamma^* \rightarrow \mu\mu$ samples, we can calculate the probability that an event with a given true $m_{\mu\mu}$ will be reconstructed with a different value of $m_{\mu\mu}$. This matrix is then applied to the observed spectrum (and $A_{fb}$) to the one at Born level.

Also dilution correction is based on response matrices. The unfolding procedure is the same as the mass-migration correction. By the fact that dilution deforms the $\cos \theta^*$ distribution, we can consider the true $\cos \theta^*$ of a given event and calculate the probability that true $\cos \theta^*$ will be reconstructed with a different value. The resulting spectrum of $A_{fb}$ is showed in figure 2. No particular deviation from the SM prediction is observed.
4. Extraction of $\sin^2 \theta_W^{eff}$

The measurement of the asymmetry presented in the Section 3 can be interpreted as a measurement of $\sin^2 \theta_W^{eff}$. In fact the axial and axial-vector couplings that appear in the expression of $A_{fb}$ are directly related with the value of $\sin^2 \theta_W^{eff}$ by the relations

$$g_V^f = I_3^f - 2Q_f \sin^2 \theta_W^{eff} \quad (7)$$

$$g_A^f = I_3^f \quad (8)$$

In order to extract a measurement of $\sin^2 \theta_W^{eff}$ from the unfolded $A_{fb}$ spectrum we use an expansion of $A_{fb}$ in terms of the center of mass energy, around the Z pole\cite{5}

$$A_{fb}(s) \simeq A_{fb}\left(m_Z^2\right) + \frac{(s - m_Z^2)}{s} \left[ \frac{3s}{128\pi^2} \left( \frac{m_Z^4}{s} - \sin^2 \theta_W^{eff} \right) \right] \quad (9)$$

This expansion can be used to determine the value of $\sin^2 \theta_W^{eff}$ by fitting the $A_{fb}$ vs. $m_{\mu\mu}$ distribution in the vicinity of the Z pole. In order to test the validity of the fitting procedure, a closure test on the true Monte Carlo sample has been performed. The Monte Carlo default value of the weak mixing angle is $\sin^2 \theta_W^{eff} = 0.232$. The result of the fitting procedure applied to the true $A_{fb}$ distribution should be in agreement with this default value of the weak mixing angle. The value of $\sin^2 \theta_W^{eff}$ extracted from the true $A_{fb}$ distribution around the Z pole is

$$\sin^2 \theta_W^{eff} = 0.23202 \pm 0.00043 \quad (10)$$

5. Conclusions

The study of $pp \to Z/\gamma^* \to \mu^+\mu^-$ process played an important role in this two years of data taking at LHC. The clear signature, given by the two isolated muons in the final state, allows to easily discriminate the signal from the background and the cross section of about 1 nb provides a large yield of $Z$ bosons relative to the luminosity reached by LHC.

In this work, a sample of about 4.8 fb$^{-1}$ was analyzed. After the application of kinematic cuts, about 1.3M $Z/\gamma^*$ candidates were found. The candidates have been used to obtain a measurement of $A_{fb}$. The $A_{fb}$ spectrum has been corrected for the effects of radiative corrections and dilution. No particular deviation from the SM prediction is seen. A method to extract the weak mixing angle $\sin^2 \theta_W^{eff}$, based on a fit on the unfolded $A_{fb}$ distribution, has been tested with a Monte Carlo closure test. The extracted value of $\sin^2 \theta_W^{eff}$ is in agreement with the default value of the Monte Carlo sample.

6. References

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