Measurement of angular coefficients in $Z \to e^- e^+$ process in the high mass region

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SUMMER STUDENT PROJECT
2018 June-September

Abstract

Measurements on LHC allow tests of electroweak corrections and can be used to improve the precision of them. Different Monte Carlo generators implement higher order electroweak corrections with different precision and assumptions. With analyzing the angular distributions of the Drell-Yan e^+e^- *pairs we can test the accuracy of these corrections. Electroweak corrections have a large effect on the Z-boson invariant mass distribution in particular above twice the W-mass where multi-gauge boson production becomes large. The goal of the project is to validate of these tools to be able to achieve higher precision at the LHC. This note presents a measurement of the complete set of angular coefficients describing these distributions in the Z-boson rest frame.*

1 Introduction

This paper presents a measurement of the angular distributions of $\ell^+\ell^-$ pairs from Z-boson decays in the centre-of-mass of the Z-boson, based on MC simulations from pp collisions at $\sqrt{s} = 13$ TeV at the Large Hadron Collider with the ATLAS experiment.

The measurement of the angular distribution of leptons from the decay of a gauge boson $Z \to \ell\ell$ produced in hadronic collisions via the Drell-Yan process, provides a detailed test of the production mechanism of the Z boson. From the fact that the gauge boson is produced with significant transverse momentum, one can define an event plane spanned by the beam and the gauge-boson momentum direction as a reference plane for a detailed study of lepton-hadron correlation effects using the decay leptons from the decay of the gauge bosons.

By providing the possibility to measure the angular distributions of the leptons in the rest frame of the lepton pair, the Drell-Yan process is a unique one to study.

At all orders in QCD, the differential cross-section has a general form eg. as described below in equation (1), where p_T and y denote the transverse momentum and rapidity of the Z-boson in the laboratory frame and the angles θ and ϕ are the polar and azimuthal decay angles of the leptons in the Z boson rest frame, as measured with respect to axes defined in the Collins-Soper frame.

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

where $d\sigma^{U+L}$ is the unpolarised differential cross-section.

The Collins-Soper reference frame is defined as a rest-frame of the Z-boson, with the polar and azimuthal angles defined using the proton directions in that frame. Since the Z-boson has a transverse momentum, the directions of initial protons are not collinear in the Z-boson rest frame. The polar axis (z-axis) is defined in the Z-boson rest frame such that it is bisecting the angle between the momentum of one of the proton and inverse of the momentum of the second one. The sign of the z-axis is defined by the sign of the Z-boson momentum with respect to z-axis in the laboratory frame. To complete the coordinate system the y-axis is defined as the normal vector to the plane spanned by the two incoming proton momenta and the x-axis is chosen to set a right-handed Cartesian coordinate system with the other two axes. Polar and azimuthal angles are calculated with respect to the outgoing lepton and are labeled θ^{CS} and ϕ^{CS} respectively (Fig. 1).

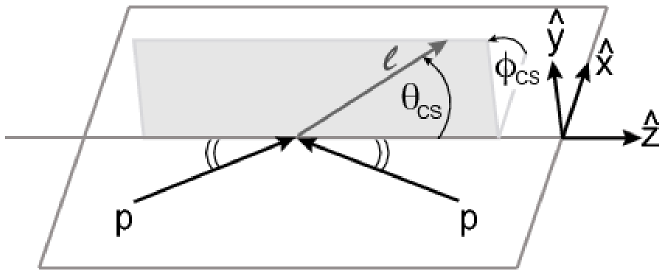

Figure 1: *The Collin-Soper frame*

Angular measurements of the Z-boson decay are usually presented in the Collins-Soper frame.

The A_0-A_7 coefficients are the ratios of the helicity cross-sections for boson production relative to unpolarised production, and are functions of kinematic variables of the Z-boson. They vanish when the Z-boson transverse momentum is zero, except for A_4 which is present at lowest order in QCD and generates the forward-backward asymmetry.

With moments method we can extract the coefficients from generated Monte Carlo events by taking moments of the distributions with respect to an appropriate product of trigonometric polynomials. With this very simple method, it is possible to disentangle the coefficients which remain functions of p_T, y and mass of the Z boson. A definition for the moments is:

$$< m >= \frac{\int d\sigma(p_T, y, \theta, \phi) m d\cos\theta d\phi}{\int d\sigma(p_T, y, \theta, \phi) d\cos\theta d\phi} \tag{2}$$

which leads to the following results

$$\begin{aligned}
< \frac{1}{2}(1 - 3\cos^2\theta) > &= \frac{3}{20}(A_0 - \frac{2}{3}) \\
< \sin 2\theta \cos\phi > &= \frac{1}{5} A_1 \\
< \sin^2\theta \cos 2\phi > &= \frac{1}{10} A_2 \\
< \sin\theta \cos\phi > &= \frac{1}{4} A_3 \\
< \cos\theta > &= \frac{1}{4} A_4 \\
< \sin^2 \sin 2\phi > &= \frac{1}{5} A_5 \\
< \sin 2\theta \sin\phi > &= \frac{1}{5} A_6 \\
< \sin\theta \sin\phi > &= \frac{1}{4} A_7
\end{aligned} \tag{3}$$

2 Results

Using moments method described above, two different samples were studied. The first sample generated without any EW corrections, but as a result of theoretical predictions, different electroweak corrections can be added separately. The second sample generated with the electroweak corrections with the generator `Powheg`. The following samples, with the weighting described below were compared:

- 13TeV Zee nominal-no EW correction applied
- 13TeV Zee with EBA- EW couplings and form factors added
- 13TeV Zee with EW loop corrections
- 13TeV Zee with EW loop corrections without box diagrams
- 13TeV Zee PhowegEW

All the angular coefficients were calculated in a high $m_{\ell\ell}$ binning. As it mentioned, EW corrections have a large effect on the Z-boson invariant mass distribution, in particular above twice the W-mass where multi-gauge boson production becomes large. So the binning contains 6 unequal bins from 100 to 240 GeV:

$$m_{\ell\ell} = [100, 120, 140, 160, 180, 185, 210, 240] \tag{4}$$

The plots below show all the angular coefficients in the binning mentioned above. Comparing all the angular coefficients A_4 shows the best correlation between the samples (Fig. 2). As it mentioned, A_4 presents the lowest order in QCD, and generates the forward-backward asymmetry. In the last binning the `PhowegEW` sample doesn't show a good match, but since the errors was not applied correctly, it can be only fluctuation, due the low number of events in the sample.

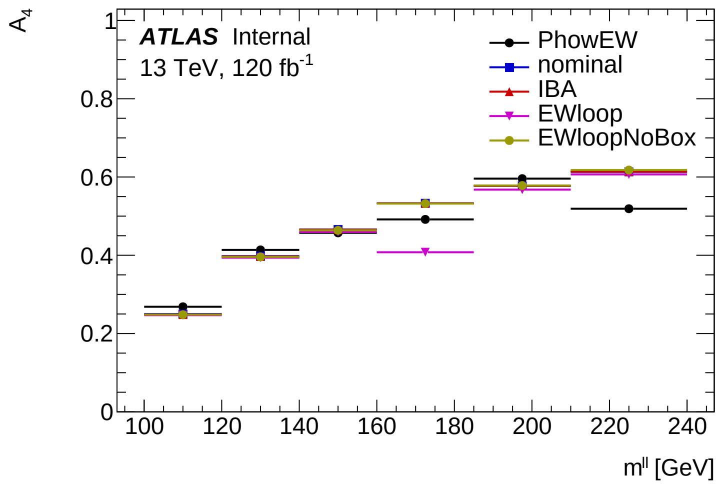

Figure 2: *The angular coefficient A_4 in high mass $m_{\ell\ell}$ binning. In this plot two samples were compared with different types of EW corrections. Between all the angular coefficients, A_4 shows the best correlation.*

The PhowegEW sample has much lower statistic (only 100000 events in the hight $m_{\ell\ell}$ binning) so the error bars showed on the plots are suppose to be bigger due the statistical fluctuations. This can be seen om the plots of A_1 to A_3 where is the PhowegEW sample have bigger fluctuation than the Nominal sample applied with the different weights. Considering these fluctuations, the angular coefficients of A_1 to A_3, shows satisfying match between the samples.

On Fig. 3 the coefficients A_5 to A_7 also represented. These coefficients are expected to be close to 0, what is agree with our results showed in Fig. 3. As it can be seen, the fluctuation of the PhowegEW sample is bigger, what is again happen because of the lower statistic of the sample.

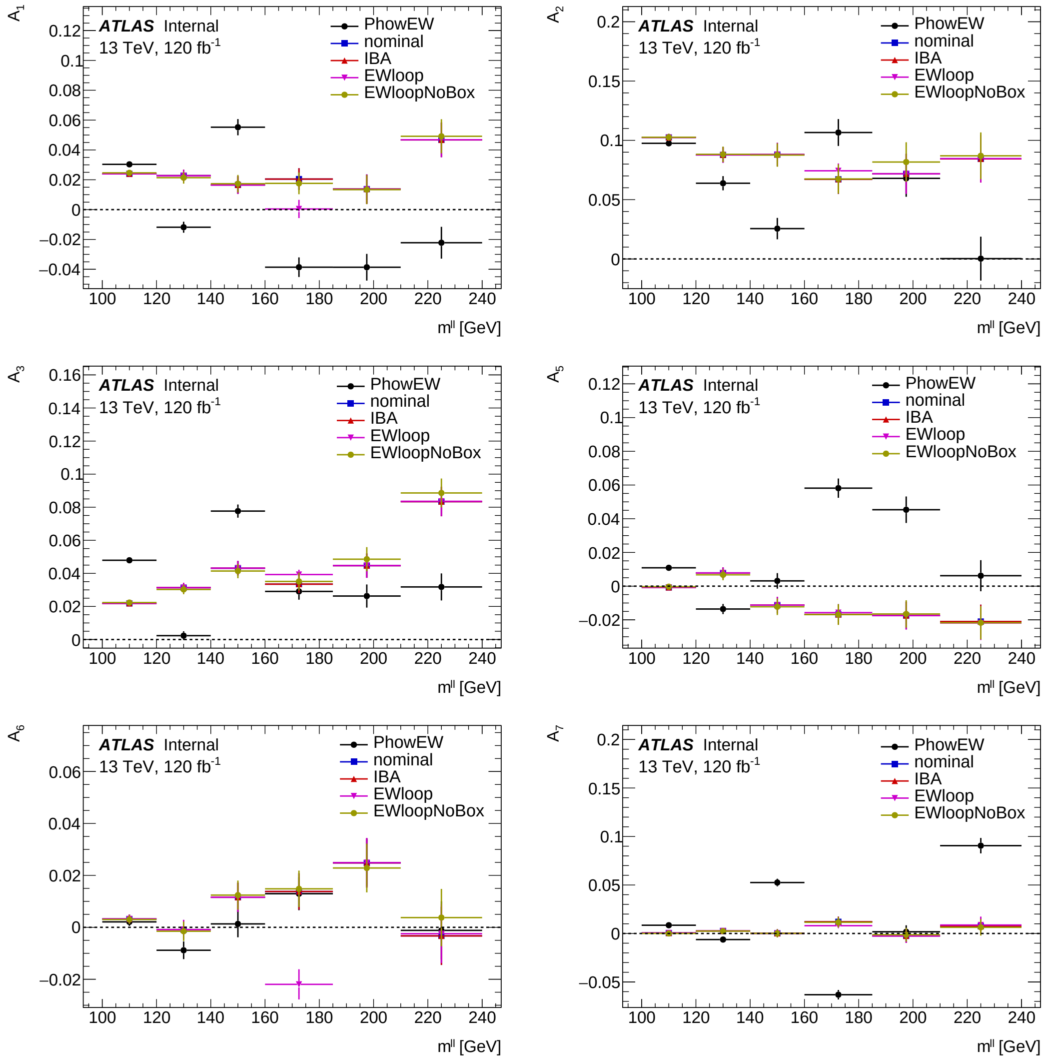

Figure 3: *The angular coefficients of A_1 to A_7 except A_4. Considering the fluctuation and the incorrect error bars of the* PhowegEW*, the plots show nice correlation between the different samples. The coefficients A_5 to A_7 are expected to be close to 0, what is agree with the results showed above.*

In addition, on the plot below, the angular coefficient A_0 is showed. As it can be seen, there is also some fluctuations in the `PhowegEW` sample, but there is a bigger difference in the applied EWloop correction. When the correction applied, the results represent a minus value in between 160 and 180 GeV, what is against our expectations (Fig. 4). The problem is most apparent in the angular coefficient A_0, but also visible in other angular coefficient distributions, also in the case of A_1 or A_6 (Fig. 3). To see why is the problem occurs, we need extra validation of the sample and the weighting applied.

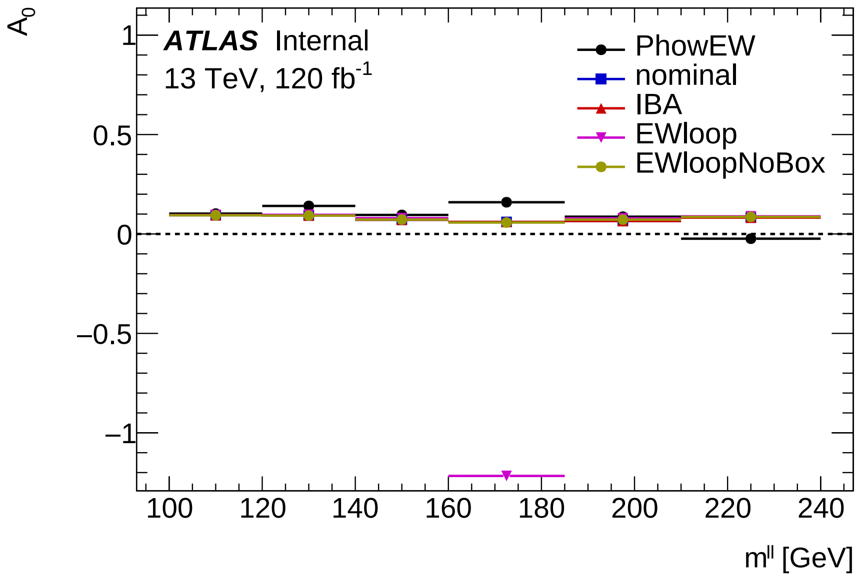

Figure 4: *Distribution od angular coefficient A_0 in the high $m_{\ell\ell}$ binning. When the EWloop correction applied, the results represent a minus value in between 160 and 180 GeV, what is against our expectations. To see why is the problem occurs, we need extra validation of the samples.*

2.1 Validation of the samples

Considering the plots above, the distribution of A_0 (Fig. 4) seems incorrect between 160 and 185 GeV. The unexpected value only shows up in one kind of weighting, the EWloop correction. An additional validation applied on the samples, to check the reason behind the unexpected distribution.

The given samples were validated with a different code, not with the main A_i code. In the process of validation smaller binning were used between 156 and 180, so in the region where is the problem occurred. In the validation were only checked the samples without weight (Nominal) and with the EWloop weighting. The input samples are divided into four groups because of a memory leaking within the code. From total 74 samples the first group is the sample number $0 - 19$, the second is from $20 - 37$, the third is from 38 to 56, and the last group is the sample number $57 - 73$. The angular coefficients, the $m_{\ell\ell}$ and $\cos\theta$ distributions were also checked between the given binning.

In the Figure 5 the distribution of the invariant mass ($m_{\ell\ell}$) showed in the different groups. The Nominal values showed with the full blue line, and the weighting is with the blue crosses. The first group of samples showed in the top left plot, then the second group of the samples in the right top plot, and so on. In the plots there is an unexpected value for the weighting between 160 and 164 GeV. That anomaly is the reason behind the unexpected value in the angular coefficient distribution.

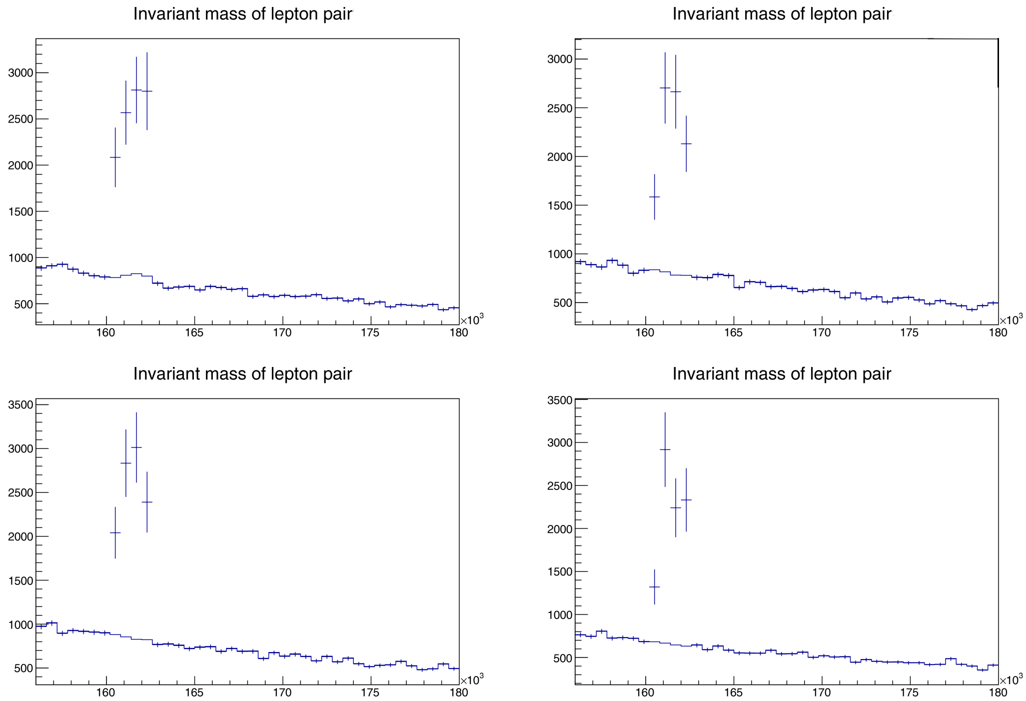

Figure 5: *Invariant mass of the lepton pair in a finer binning between 156 and 180 GeV within all four groups. With the blue full line the Nominal value, and with the blue cross the applied EWloop weighting showed.*

Since the angular coefficient A_0 is strongly dependent from the $\cos^2\theta$ (Equation (3)), the $\cos\theta$ distribution were also checked in the sample validation process. The results are showed on the Figure 6. In all the four groups an anomaly can be seen in the weighting above the value of 0.9. This is also the reason behind the unexpected value in the angular coefficients.

In Figure 7 the distribution of the EWloop event weight showed within all the four samples group. As it can be seen some of the events have an unexpected high value of event weight, what is the main reason behind the anomaly in the angular coefficient distribution.

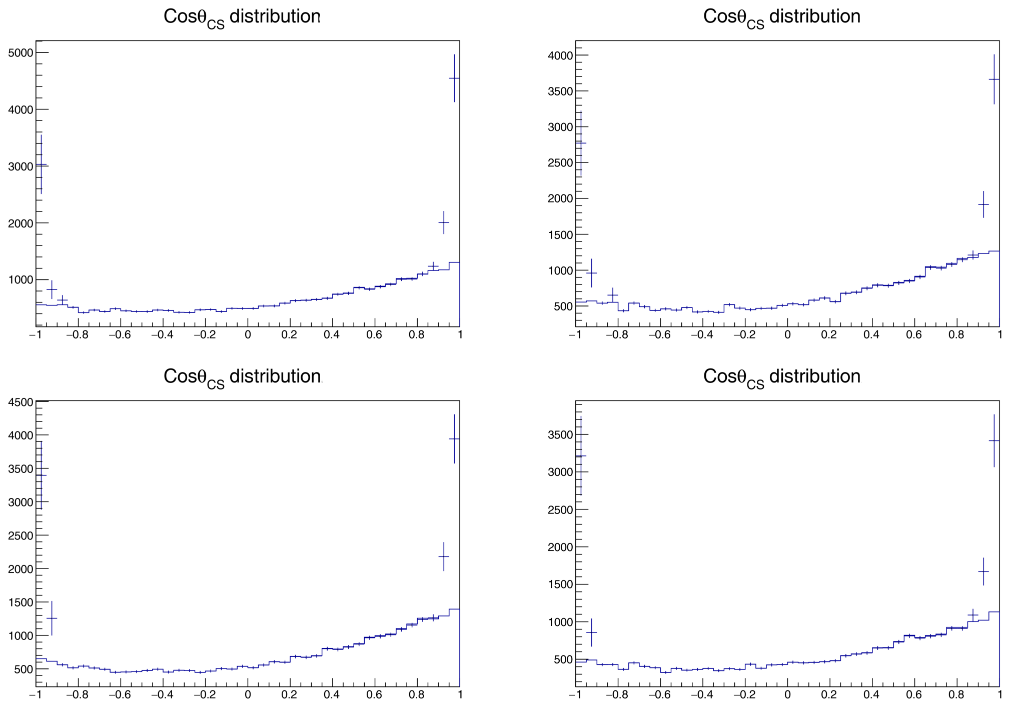

Figure 6: $\cos\theta$ *distribution within all four groups. With the blue full line the Nominal value, and with the blue cross the applied EWloop weighting showed.*

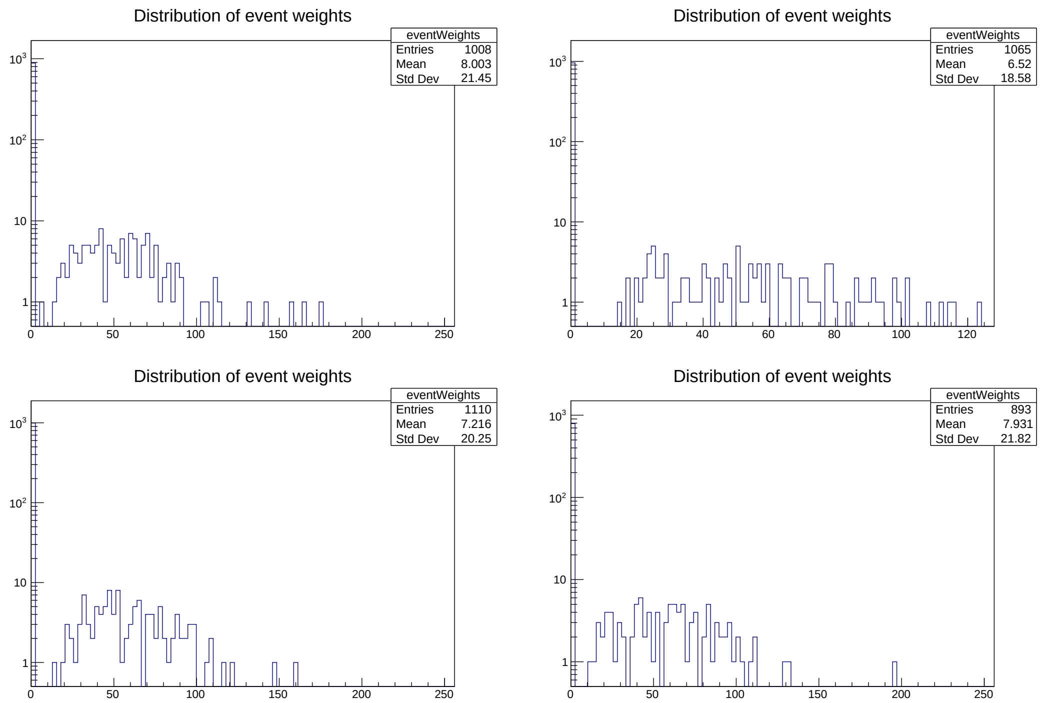

Figure 7: *Distribution of EWloop event weights within all four groups.Some of the events have a high value weighting, what is the cause of the anomaly in the angular coefficient values.*

3 Discussion

In this paper the the angular distributions of the Drell-Yan e^+e^- pairs were analyzed in two different samples and 3 different weighting applied. The goal of the project were to validate of these weighting and samples in particular above twice the W-mass where multi-gauge boson production becomes large. This note presented a measurement of the complete set of angular coefficients describing these distributions in the Z-boson rest frame.

As it already mentioned, some of the weighting needs additional validation, or a more precise measurement, and also samples needed with more generated events, in order to decrease the fluctuations in the samples. But beside the problems showed, the weighting matches correctly, most likely within the calculated errors, and sample fluctuations.

References

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[3] J. C. Collins and D. E. Soper, *Angular Distribution of Dileptons in High-Energy Hadron Collisions* Phys. Rev. D 16 (1977) 2219.