Δϕ distributions between final state particles as a criterion of the pile-up background mismodeling and its impact on $Z(\nu\nu)\gamma$ process

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Abstract. In the case of the pile-up background (background from the neighboring interactions inside the bunch crossing) for $Z(\nu\nu)\gamma$ process at the Large Hadron Collider (LHC) experiments, its accurate calculation is very challenging. If the impact of the pile-up background is negligible, as it is expected in the case of $Z(\nu\nu)\gamma$ process selection, some global uncertainty from this source can be used. This report studies the pile-up background and shows that it is expected to have a completely different shape for Δϕ distributions between final state particles in comparison to the signal and other background processes. Thus, the absence of Δϕ-mismodeling in the analysis proves that the pile-up background is indeed negligible.

1. Introduction
An increase in the number of collisions per LHC bunch crossing can lead to an overlay of associated final state particles from different pp-collisions in the same bunch crossing. A non-negligible possibility of such combination corresponds to the pile-up background presence in multiboson studies. Since the probability of producing a Z boson and a photon is higher than to produce two massive vector bosons, $Z\gamma$ process is preferable for considering this background. An example of such a layout is the ATLAS $Z(ll)\gamma$ analysis [1], where a lepton-pair event combines with a photon from different collisions since there is no explicit requirement on the point of the photon origin. Such a background reaches a sizeable level of 5% in this analysis. Over time, with a further increase in luminosity, the pile-up background can become significant for other processes as well.

Even if an estimate of the pile-up background shows its negligible contribution, in the case of the small statistics it may be wrong and should be confirmed independently. If the shape of the pile-up background differs from the processes from a single pp-interaction, a shape normalization can be distorted. To check this possibility, the distributions of the azimuthal angle difference Δϕ between final state particles can be used as a criterion of the pile-up background mismodeling.

Section 2 describes the basic method for estimating the pile-up background fraction. Section 3 contains information about the main idea of checking deviations in the shape of the pile-up background and such technical details as used Monte Carlo (MC) samples and applied selections. The results are presented in Section 4. Conclusions are outlined in Section 5.
2. Pile-up background fraction estimation

The technique for estimating the pile-up background is based on different shapes of distributions of the longitudinal separation \( \Delta z = z_{\gamma} - z_{\text{vtx}} \) between the identified primary vertex position \( z_{\text{vtx}} \) and the position \( z_{\gamma} \) of the photon candidate. \( \Delta z \) distribution for pile-up events arising from separate pp-interactions is expected to be broader than for events associated with a single pp-interaction. This fact makes \( \Delta z \) variable a good candidate for the pile-up background detection, as background events are concentrated in the tails of the distribution at high \( \Delta z \) values [1].

With this in mind, the fraction of pile-up background \( f_{PU} \) can be estimated in a data-driven way as follows:

\[
 f_{PU} = \frac{N_{\Delta z|x>\text{data}} - SF_1 \times SF_2 \times N_{\Delta z|x>\text{MC}}}{C \times N_{\text{data}}},
\]

where \( N_{\Delta z|x>\text{data}} \) and \( N_{\Delta z|x>\text{MC}} \) are the numbers of data and MC events respectively in the selected region \( |\Delta z| > x \), where the pile-up background is concentrated (usually, \( x \) equals to the width of the Gaussian distribution \( \sigma \)). \( N_{\text{data}} \) is a number of data events without any cuts on \( \Delta z \). The first scale-factor \( SF_1 \) is equal to the ratio of the number of events in data to the number of events in MC sample near the peak \( \Delta z = 0 \). Due to the mismodeling of \( \Delta z \) in the tails, an additional normalization factor \( SF_2 \) is needed to correct the distribution in the region of \( |\Delta z| > x \). \( C \) corresponds to the fraction of the number of events in the range of \( |\Delta z| < x \) based on the relation between \( x \) and \( \sigma \) of \( \Delta z \) distribution.

Nevertheless, in some cases, this method gives a statistically poor result.

3. MC samples and event selection criteria

The absence of mismodeling of \( \Delta \phi \) distributions between final state particles can prove that there is no significant pile-up contribution and some global systematics can be used. For this, the fact is used that the distributions between particles from two vertices are flat, while there is a correlation for particles from one vertex.

This study is done with \( Z(\nu\nu)\gamma \) [2] (signal), \( Z \rightarrow \nu\nu \) and \( \gamma + j \) (background) processes simulation using Monte Carlo methods by checking angular distributions between particles from one and two vertices. Signal and background processes production in pp-collisions at centre-of-mass energy of 13 TeV is generated using MadGraph5 framework [3]. Events showering and hadronization are done with Pythia8 tool [4]. ATLAS detector response is simulated using Delphes program [5].

The case of one vertex corresponds to \( Z(\nu\nu)\gamma \) process (figure 1(a)). To work with two vertices a pair of neutrinos from \( Z \rightarrow \nu\nu \) process (figure 1(b)) and a photon from \( \gamma + j \) production (figure 1(c)) are combined.

![Figure 1](https://via.placeholder.com/150)

**Figure 1.** Feynman diagrams of (a) \( Z(\nu\nu)\gamma \), (b) \( Z \rightarrow \nu\nu \) and (c) \( \gamma + j \) production.

Table 1 presents the event selection criteria used in this study for \( Z(\nu\nu)\gamma \) candidate events.
Table 1. Event selection criteria for $Z(\nu\nu)\gamma$ candidate events.

| Selections                  | Cut Value                                             |
|-----------------------------|-------------------------------------------------------|
| Missing transverse energy   | $E_{T}^{miss} > 120$ GeV                             |
| Photon transverse energy    | $E_{T}^{\gamma} > 150$ GeV                           |
| Number of isolated photons  | $N_\gamma = 1$                                      |
| Lepton veto                 | $N_e = 0, N_\mu = 0$                                 |
| Jets                        | $N_{jets} \geq 2 (p_T^j > 20$ GeV, $|\eta_j| < 4.5$) |

In the case of summing $Z \rightarrow \nu\nu$ and $\gamma + j$ processes, cuts on variables are applied only to the corresponding process.

4. Azimuthal angle difference distributions
To estimate the pile-up background contribution, a method based on the shape of the azimuthal angle difference distributions between final state particles was developed. The azimuthal angle difference distributions can be found in figure 2.

![Figure 2](image-url)

**Figure 2.** Distributions of the azimuthal angle difference between (a) photon and missing transverse energy $\Delta \phi(\gamma, E_{T}^{miss})$, (b) jet and missing transverse energy $\Delta \phi(j, E_{T}^{miss})$, (c) photon and jet $\Delta \phi(\gamma, j)$, and (d) two jets $\Delta \phi(j_1, j_2)$ for $Z(\nu\nu)\gamma$ process (blue) and summing $Z \rightarrow \nu\nu$ and $\gamma + j$ processes (red).
In the case of two vertices for $\Delta \phi(\gamma, E_{\text{miss}}^T)$ and $\Delta \phi(j, E_{\text{miss}}^T)$ distributions, $E_{\text{miss}}^T$ is selected from $Z \rightarrow \nu \nu$ sample, while a photon and a jet correspond to $\gamma + j$ process. For $\Delta \phi(\gamma, j)$ distribution, a jet from $Z \rightarrow \nu \nu$ process and a photon from $\gamma + j$ process are used. For the distribution of the azimuthal angle difference between two jets, one jet is selected from $Z \rightarrow \nu \nu$ sample and the other from $\gamma + j$ process.

The distributions for particles from two vertices are flat, while for particles from one vertex there is a dependence on the azimuthal angle difference in distributions.

5. Conclusions

This article presents a method for estimating the pile-up background and its independent confirmation in the case of limited statistics. Even if the pile-up background fraction shows that this source of the background looks negligible (as for $Z(\nu \nu)\gamma$ production), there is a method to confirm this independently despite the statistically poor result.

The pile-up background does not have the same shape as the signal and background processes, thus it leads to the clear mismodeling of the control distributions. To make sure that this is not the case, it should be checked that $\Delta \phi$ distributions between the objects from different vertices are flat.

For $Z(\nu \nu)\gamma$ production there are azimuthal angle differences between a photon and missing transverse energy, a jet and missing transverse energy, a photon and a jet, two jets. The absence of $\Delta \phi$-mismodeling in the following combinations proves that the pile-up background has a negligible impact on the shapes and additional uncertainty for signal and all background processes can be used to take into account the pile-up background.

This method of the pile-up background estimation is valid not only for $Z\gamma$ process but also for other associated productions.

Acknowledgments

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References

[1] Aad G et al. 2020 J. High Energy Phys. JHEP03(2020)054
[2] Aad G et al. 2018 J. High Energy Phys. JHEP12(2018)010
[3] Alwall J et al. 2014 J. High Energy Phys. JHEP07(2014)079
[4] Sjostrand T et al. 2015 Comput. Phys. Commun. 191 159
[5] Favereau J et al. 2014 J. High Energy Phys. JHEP02(2014)057