
Summer student report

11 September 2015

Feasibility study of the event-mixing technique in the context of a SUSY search in the same-flavour opposite-sign di-lepton channel

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Abstract

The $t\bar{t}$ production is one of the main backgrounds for many BSM searches looking for new structures in the invariant mass distribution of di-leptons produced in LHC collisions. This report studies the feasibility of applying the data-driven estimation method, the event-mixing technique, to determine that distribution. The event assumes a complete decorrelation between the two leptons, which has seen to be false in most of the control regions. For that reason, we conclude that the method is not robust enough to be applied as a background estimation in BSM searches.

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1 Introduction

This report aims to consider the $t\bar{t}$ prediction potential of the event-mixing technique for di-lepton SUSY searches. Section 2 comprises a short description of these searches and the main background sources. Section 3 introduces the event-mixing technique and establishes the hypothesis under which it should successfully predict the $t\bar{t}$ background. Sections 4, 5 and 6 discuss several limitations of the method: the former evaluates the impact of the dependency of mixed events, section 5 discuss the effect of the event selection on the prediction potential, and the latter examines the effect of the physical particularities of the $t\bar{t}$ production and decay processes. In section 7, the conclusions of the report are presented.

2 SUSY searches in the di-lepton channel: a search for a kinematic edge

In this report, we study a search for new physics in the same-flavour opposite-sign di-lepton channel. This searches are justified by the prediction of events with such topology by several SUSY models. This kind of searches have already been performed during the Run I of the LHC by the CMS Collaboration, yielding to a 2.6σ deviation from the Standard Model (SM) predictions [1].

Figure 1 shows different decay cascade decays that justify this searches. In those cascades, a pair of same-flavour opposite-sign leptons is produced through the decay of a Z boson or an slepton. In all cases, the presence of an LSP in the final state, which escapes undetected, will yield to a non-negligible amount of missing transverse momentum ($\cancel{E}_T$). Leptons can be measured very precisely in the CMS detector, so the di-lepton invariant mass distribution can be used as a discovery variable. This three processes yield to an excess in the di-lepton mass distribution. In the case in which the leptons are produced in a decay of an on-shell Z boson, the excess will appear in the Z peak region, while if they are produced in the decay in an off-shell Z boson or a slepton, a characteristic triangular shape will appear in the mass spectrum.

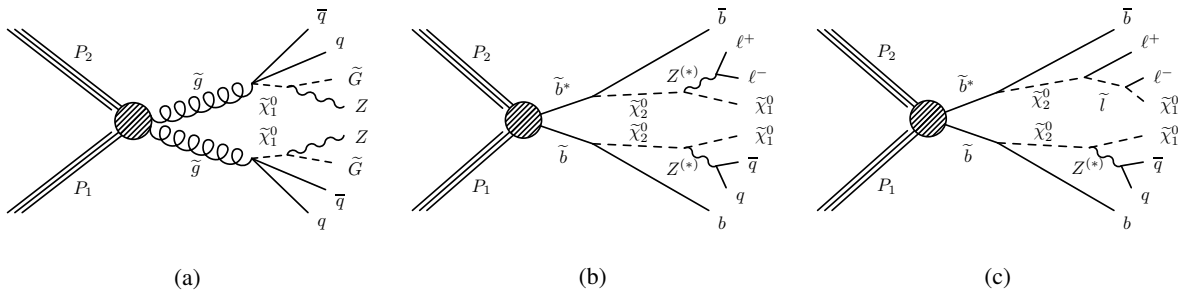


Figure 1: Several SUSY processes which may involve the presence of an opposite-sign same-flavour dilepton pair in the final state. Models (b) and (c) may present an off- Z resonance, while the signature of model (a) would be an excess within the Z peak.

The background processes contributing to this searches can be classified into two groups: flavour symmetric and non-flavour symmetric. The former group is mostly composed by $t\bar{t}$ events, although WW , single top (tW) and $Z \rightarrow \tau\tau$ production can have non-negligible contributions. Non-flavour symmetric events are mainly produced by Drell-Yan processes, together with diboson production (WZ , ZZ) processes. $\cancel{E}_T$ in Drell-Yan processes is due to an instrumental effect, while in diboson production, it can be genuine.

The report will focus in estimating the shape of the invariant mass of the di-lepton system produced in the $t\bar{t}$ decays.

3 Event-mixing technique

The event-mixing technique [2] can be used to predict the $t\bar{t}$ contribution to the signal region in a purely data-driven fashion. The method exploits the fact that, while leptons produced in signal events come from the decay of a single particle and are therefore strongly correlated, leptons from $t\bar{t}$ processes are the product of longer decay chains, with additional decay products. Although some correlations between the two leptons must arise due to the fact that the two top quarks are produced in the same process, this correlations may be diminished as an effect of the longer decay cascades: the presence of many decay products (two b quarks, two neutrinos and two leptons), altogether with the high mass difference between the top and bottom quarks, inserts an additional random component that may hide the correlations.

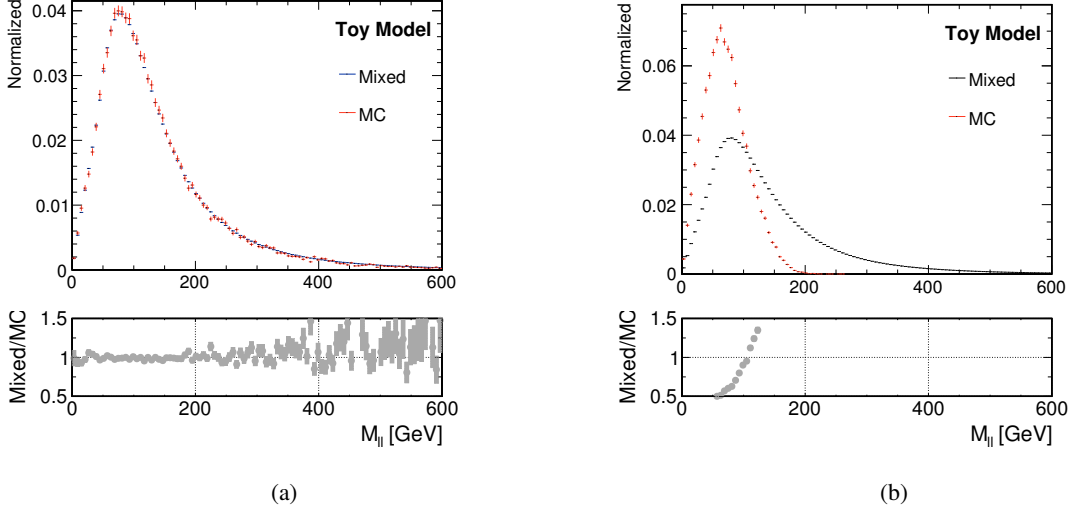


Figure 2: Event-mixing technique performed over toy simulations. Figure (a) shows the technique in events in which the top quarks are uncorrelated, while in the fig. (b) the momenta of the top quarks is modelled with a slight correlation. The former shows a good agreement between the method prediction and the MonteCarlo, while in the latter both distributions clearly disagree.

Given the assumption that leptons produced in $t\bar{t}$ decays are totally uncorrelated, the event-mixing technique can be used to estimate the shape of the mass distribution of the two leptons produced in the $t\bar{t}$ decays using events in a given signal region. For this method, one can study all the combinations of di-lepton pairs in the selected events, choosing at random leptons from different events. We denote this combinations as “mixed events” and, given a sample of n selected events, $n(n-1)$ mixed events can be obtained, substantially decreasing the statistical uncertainty of the distribution. Events with two μ and two electrons are mixed separately to avoid differences in the energy scale resolution.

We have developed a MonteCarlo toy model of the $t\bar{t}$ topology, in which the decay of the top quarks have been implemented, while their initial state and correlations can be set by the user. In absence of correlations, the mass distribution of the mixed events should completely reproduce the mass distribution of the observed events. This has been seen with a toy model of the $t\bar{t}$ decay. In fig. 2a the momenta distributions of both the t quarks are assumed to be random and totally independent, while in fig. 2b, the momenta of both top quarks are slightly correlated. While in the former the distributions agree, the latter shows discrepancies due to the correlation that propagate from the $t\bar{t}$ system to the di-lepton system.

We have tested the event-mixing technique in $t\bar{t}$ MonteCarlo simulations, using the generator MADGRAPHMC@NLO, modelling the decay with MADSPIN, and the showering and hadronization with PYTHIA8. For that purpose, events with a same-flavour opposite-sign di-lepton pair are selected. The p_T of the leading (trailing) lepton is required to be higher than 25 (20) GeV, both leptons are also required to fall within the detector acceptance ($|\eta| < 2.4$) and, to avoid the ECAL crack leptons with $1.4 < |\eta| < 1.6$ are rejected. We have chosen this minimum bias selection in order to avoid introducing extra correlations into the leptons.

Since MADGRAPHMC@NLO is a NLO generator, some of the MonteCarlo events have negative weights. In order to apply the mixing method to the MonteCarlo sample, events with positive and negative weights are mixed separately. The resulting distributions are then added weighted, in order to preserve the proportion of negative events in the sample.

The comparison between the mixing distribution and the MonteCarlo prediction is shown in fig. 3a, showing a reasonably good agreement between both distributions. Since the invariant mass distribution is particularly sensitive to the opening angle between the two leptons, we also show in fig. 3ab its distribution. This magnitude is also sensitive to angle correlations in the $t\bar{t}$ that may propagate to the ll system. However, its distribution reflects a good agreement between MonteCarlo and mixed events. This results have also been crosschecked using POWHEG as an event generator.

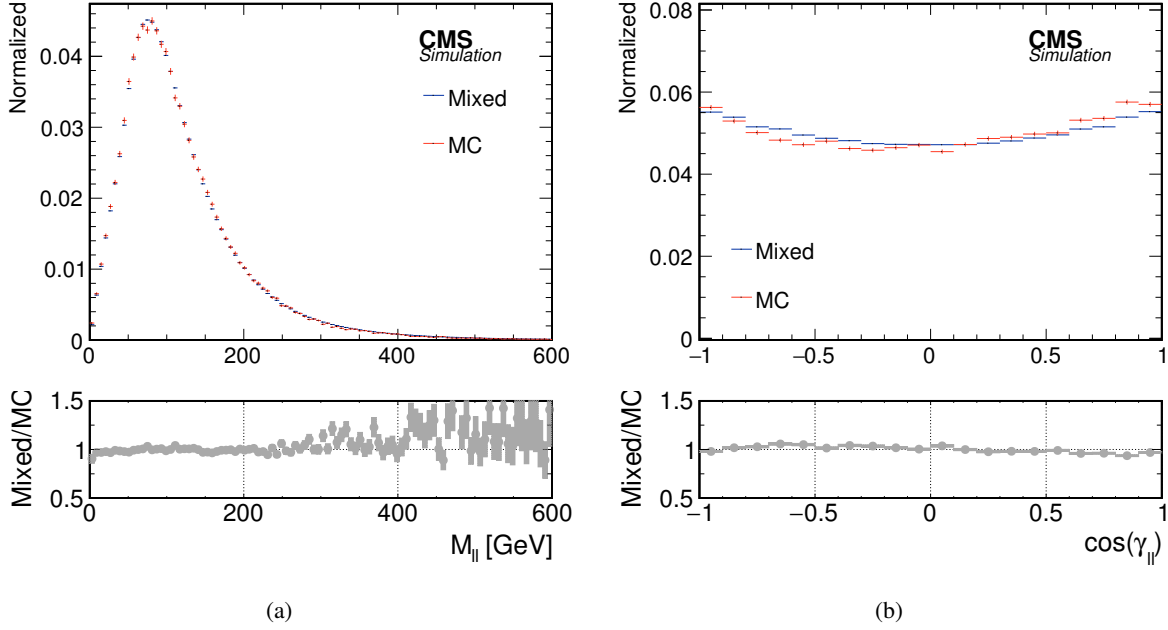


Figure 3: Figure (a) shows the di-lepton invariant mass distribution for MonteCarlo and mixed events, showing a good agreement below 400 GeV. Figure (b) shows the opening angle of the two selected leptons in both distributions, also showing a good agreement.

4 Statistical discussion of the event-mixing technique

In most high energy physics experiments, it is assumed that all the observed events are independent. This assumption is justified by the fact that the experiments performed should be reproducible and yields to the conclusion that each bin in a distribution of a given quantity follows a Poisson distribution. However, this principle does not stand for the mixed events obtained in the previous section: two given mixed events can be dependent because they may include the same lepton. Under this conditions, the number of events in a given bin of a distribution may not follow a Poisson distribution and can, therefore, bias the estimation of the statistical uncertainty. In order to provide a meaningful and useful background prediction the statistical uncertainties of the method must be understood since this will play an important role in the posterior significance calculation. In this section, we therefore evaluate deviations of this distributions from the Poisson statistics for the M_{ll} distribution.

For this purpose, we select events that contain a pair ee or $\mu\mu$ from a simulated $t\bar{t}$ sample and divide it in 1200 subsamples with 5000 events, to which we apply the event-mixing method. Given a bin of the mass distribution, we build the empirical distribution of the number of events that populate that bin. Under the hypothesis of independent events, this distribution should be Poissonian. We test this hypothesis in a χ^2 test. In fig. 4a, the p -value obtained in the test for each bin. In figs. 4b and c, we show two examples of the fit of the empirical distribution of two of those bins to a Poisson distribution, showing significant deviations.

The mentioned p -values are below 10^{-2} and can be even lower in some cases, which show that the distributions of the number of events differs significantly from a Poissonian distribution. That can be seen in figs. 4 (b) and (c), where the distribution of the number of events has a larger dispersion, which yields to slightly displaced fitted distributions.

In conclusion, as it was expected, we have shown that the number of events in each bin does not follow the Poisson statistics. The actual distribution is seen to have a higher dispersion, which would moderately increase the statistical uncertainty for the distribution. The fact that statistical uncertainties in this method do not follow poisson statistics adds an extra layer of complication for the effective application of mixing in real data.

5 Physical discussion of the event-mixing technique

In this section, we describe how the correlations present in the $t\bar{t}$ system can propagate to the di-lepton system and spoil the predictions obtained with the mixing method. These effects can play an important role when applying the method to real data or applying additional cuts: additional correlations might arise due to a mis-modeling of the

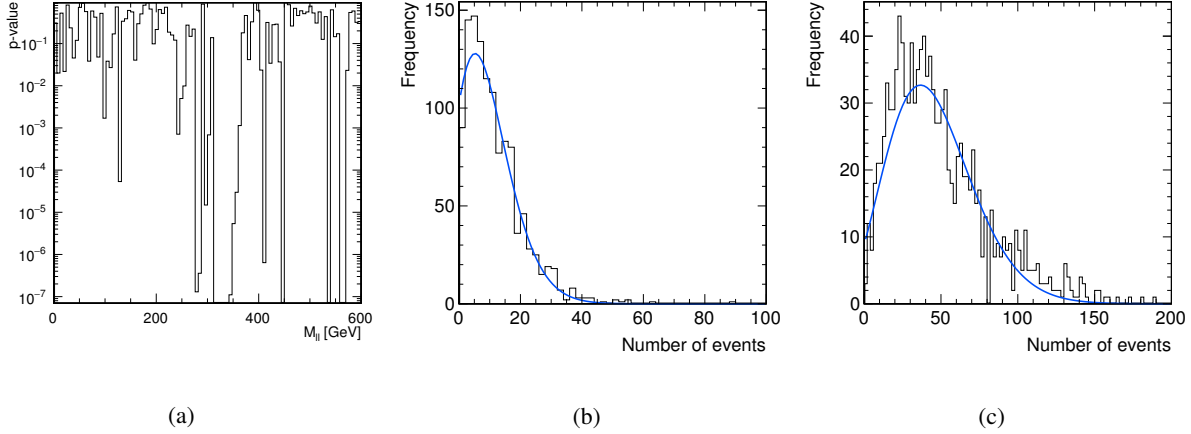


Figure 4: (a) p-value of the fit of the number of events on each bin to a Poisson distribution. Figures (b) and (c) show examples of two of those fits showing significant differences.

process in the MonteCarlo simulations or to the additional cuts. It is known that there exist three kinematic features that can yield to correlations in the $t\bar{t}$ system: the invariant mass of the $t\bar{t}$ system; the transverse component of the $t\bar{t}$ momentum, which is due to the initial state radiation (ISR), and the z -component of the $t\bar{t}$ momentum, which is due primarily to energy difference between the colliding particles, driven by the $pdfs$, and secondarily to the ISR.

As we will show, these effects introduce angular correlations between the top quarks produced in the collisions. In this report, we will use the $\cos \gamma_{ll}$, the cosine of the opening angle between the leptons, as the figure-of-merit for the angular correlation. This decision is also justified by the fact that the M_{ll} can be calculated as

$$M_{ll} = \sqrt{2E_1 E_2 (1 - \cos \gamma_{ll})}. \quad (1)$$

This variable can be indeed misleading in some occasions: although in the γ_{ll} distribution, the region with $\gamma_{ll} 0, \pi$ is not very populated, the $\cos \gamma_{ll}$ highlights this region, due to the convolution of the γ_{ll} distribution with the sine of the angle.

In fig. 5a it can be seen that in the events selected in section 3, the $t\bar{t}$ system has a preference for a back-to-back topology, which is not observed in the di-lepton system (fig. 3b). However, in fig. 5b, it can be seen how a initial opening angle between the two top quarks propagates to the leptons produced in the decays: $\cos \gamma_{t\bar{t}}$ and $\cos \gamma_{ll}$ are positively correlated, with a correlation factor of $\rho = 0.56$. This shows that, although the long decay chains slightly randomize the opening angle, correlations might still be present in the di-lepton system; and, in different regions in which the two top quarks are even more correlated, this correlations can arise in the di-lepton system. In fact, we will show that the effect of the $M_{t\bar{t}}$ and the $t\bar{t}$ boost can be studied through the kinematic variables of the di-lepton system.

Top quarks produced in events with high $M_{t\bar{t}}$ will be emitted more energetically and will therefore have a preference for being produced back-to-back. This correlation may be preserved in the decay, yielding to a preference of the leptons to be emitted back-to-back, contradicting the mixing method hypothesis. However, a boost of the components of the $t\bar{t}$ system momentum produce a different effect on the di-lepton system: top quarks in events with high momentum are emitted in collinear directions. If this effect propagates to the di-lepton system, it inserts a correlation between the leptons.

The fact that in fig. 3a no correlations are observed is due to the partial compensation of both effects. This, together with the slight randomization introduced in the $t\bar{t}$ decays, yields to a almost flat opening angle distribution. The question is to determine under which circumstances this compensation stands and how any extra criteria in the event selection can affect it. For that purpose, we will first study variations in the $t\bar{t}$ mass and boost distributions. Secondly, in section 6, we will study the effect of cuts in the kinematic variables.

For this purpose, we study the kinematic variables for events in different $t\bar{t}$ regions mass. The $t\bar{t}$ boost can be produced by the difference on the initial energy of the colliding partons and by the ISR. The former effect only affects the z component of the momentum and is expected to be the bigger effect, while the latter can affect all the directions of the momentum. For that reason, we choose $p_z^{t\bar{t}}$ as the figure-of-merit for evaluating the former effect, while we choose $p_T^{t\bar{t}}$ for evaluating the latter effect.

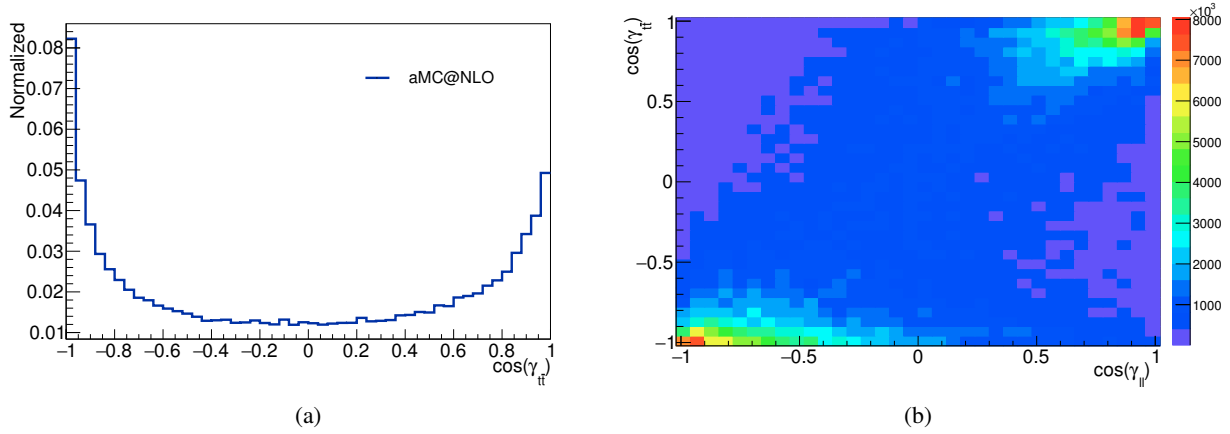


Figure 5: Figure (a) shows the opening angle of the $t\bar{t}$ pair, showing a preference for a back-to-back configuration over the colinear configuration. Figure (b) shows the correlation between the opening angle of the top-anti top pair and the opening angle of the di-lepton pair. Both magnitudes are positively correlated, with a correlation factor of $\rho = 0.56$.

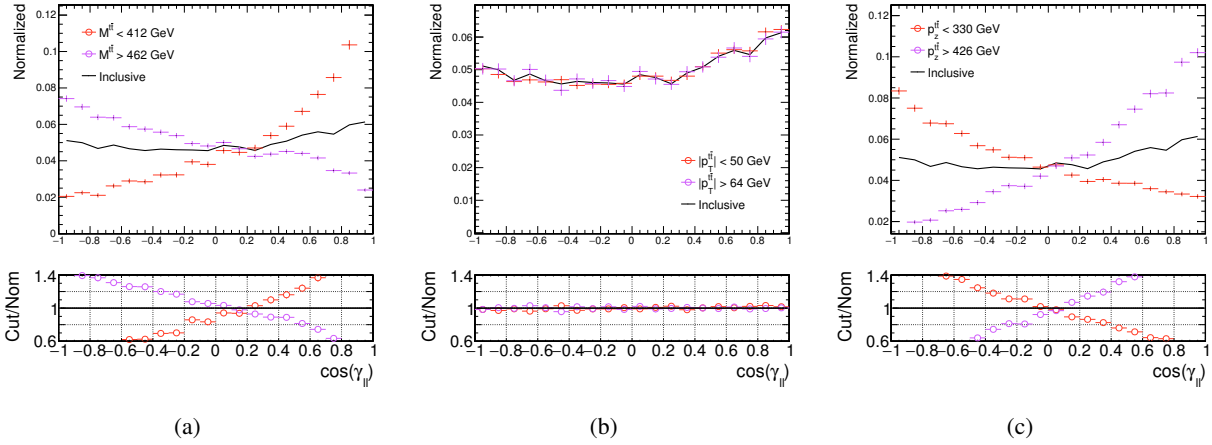


Figure 6: Effect of the $M_{t\bar{t}}$, $p_T^{t\bar{t}}$ and $p_z^{t\bar{t}}$ on the opening angle of the two leptons. Higher $M_{t\bar{t}}$ values yield to back-to-back topologies, while higher $p_z^{t\bar{t}}$ values yield to leptons emitted in collinear directions. On the other hand, $p_T^{t\bar{t}}$ cuts do not produce significant differences, which implies that ISR does not play a important role in the correlations.

Figure 6 shows the effect of the $t\bar{t}$ kinematic variables on the di-lepton system. As it was mentioned, events with higher $t\bar{t}$ mass have larger opening angles, while events with higher $p_z^{t\bar{t}}$ have lower. The figure also shows that the ISR does not modify significantly the $\cos \gamma_{ll}$ distribution. This shows that the effect of the ISR does not introduce relevant angular correlations and therefore, will not spoil the predictions of the event-mixing technique.

The observed correlation can affect the predictions provided by the mixing methods in several scenarios. In fig. 7, the mixing technique is performed over distributions with cuts in $M_{t\bar{t}}$ and $p_z^{t\bar{t}}$. These cuts introduce modify the correlations present in the angular distributions of the di-lepton pair, so the $M_{t\bar{t}}$ and $p_z^{t\bar{t}}$ effect do not compensate each other anymore. This will introduce correlations in the di-lepton system, which contradict the hypothesis of the mixing method. The effect of these correlations are clear: $M_{t\bar{t}}$ cuts choose events with collinear top quarks, which displaces the MC M_{ll} distribution to lower values. In the other hand, $p_z^{t\bar{t}}$ cuts select events in which the top quarks are emitted back-to-back, which displaces the MC M_{ll} distribution to higher values. These additional correlations eliminate the compensation observed in. 3a: when applying cuts in $M_{t\bar{t}}$ or $p_z^{t\bar{t}}$, the effects of the other variable dominate, showing deviations.

The cuts applied in fig. 7 are rather soft, which yields to the conclusion that the mixing method is not robust to variations of the $M_{t\bar{t}}$ and $p_z^{t\bar{t}}$ distributions.

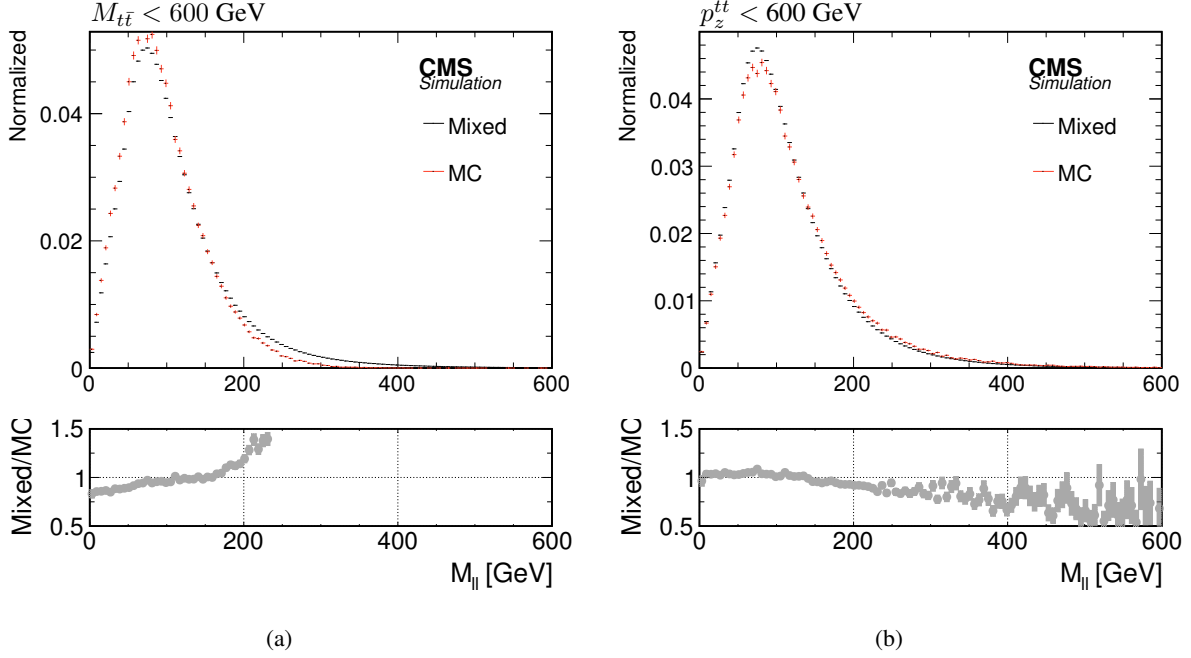


Figure 7: Results of the mixing method performed over samples with biased $M_{t\bar{t}}$ and $p_z^{t\bar{t}}$ distributions. In fig. (a), only events with $M_{t\bar{t}} < 600$ GeV are taken into account, while in fig. (b), only events with $p_z^{t\bar{t}} < 600$ GeV. In both cases, the mixed method does not reproduce the $M_{t\bar{t}}$ distribution precisely.

6 Operational drawbacks of the event-mixing technique

In this section, we describe how the cuts performed in a SUSY analysis in the di-lepton channel, such as [1], can spoil the predictions of the mixing technique. Typically, these cuts affect the $M_{t\bar{t}}$ and $p_z^{t\bar{t}}$ distributions, introducing correlations in the $t\bar{t}$ system, which can propagate to the di-lepton system, as shown in the previous section.

ΔR cut In some analyses, in order to avoid overlap in the isolation cones of the selected leptons, events in which the first and second lepton have $\Delta R < 0.3$ are rejected. This automatically introduces a correlation in the angular distribution of those leptons. In order to try to correct this, we also require mixed event to fulfil this ΔR criterion. However, as it is shown in fig. 8, this does not solve the discrepancies that appear in the lower di-lepton mass region. This differences are directly related to the ΔR cut, because at it is seen in fig. 8, the $\cos \gamma_{ll}$ distribution shows discrepancies in the collinear region, when ΔR is also small.

Central cut Some SUSY searches, such as [1], divide the signal region in two regions according to the η of the measured leptons: central ($|\eta| < 1.4$) and forward ($|\eta| > 1.4$). This is justified for two reasons: heavy particles are expected to have a low boost in the z direction and, therefore the central region should be more sensitive. Moreover, resolutions in barrel and endcap are very different, so it is not trivial to mix both regions.

For simplicity, we will only study the central region. Figure 9 shows the $p_z^{t\bar{t}}$ and $M_{t\bar{t}}$ distributions for events with both leptons at $|\eta| < 1.4$ and leptons with $|\eta| < 2.4$. While the $M_{t\bar{t}}$ distributions are similar for both subsamples, events in the central region present a softer $p_z^{t\bar{t}}$ distribution. For that reason, in events in the central region, the $M_{t\bar{t}}$ dominates over the $t\bar{t}$ boost in the way that both effects do not compensate each other. In those cases, the leptons produced in the $t\bar{t}$ decays tend to be emitted back-to-back, contradicting the hypothesis of the mixing method. Figure 10 shows the comparison between the $M_{t\bar{t}}$ provided by MonteCarlo simulations and the mixing method, showing clear discrepancies. Figure 10b shows the angular correlation of the events, which account for the discrepancies in fig. 10a.

$\cancel{E}_T$ cuts Most SUSY searches study only events with a non-negligible amount of $\cancel{E}_T$, driven by the fact that the stable LSP escapes undetected. Applying criteria for this variable can also affect the mixing method. Figure 11 shows the $p_z^{t\bar{t}}$ and $M_{t\bar{t}}$ distributions, together with the opening angle of the leptons in all the selected events and in events with $\cancel{E}_T > 100$ GeV. These distributions show that events with higher $\cancel{E}_T$ tend to have a higher $t\bar{t}$ mass.

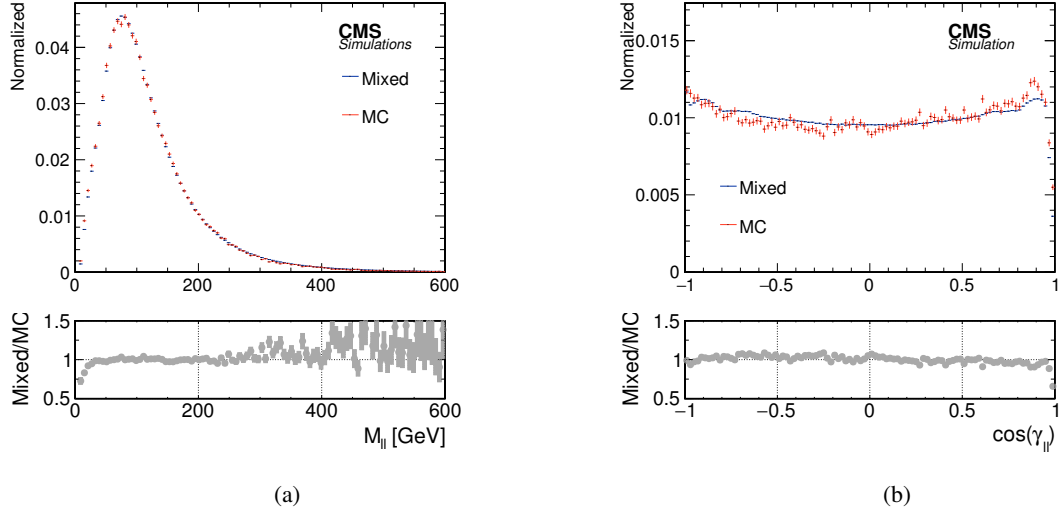


Figure 8: Mixing distribution using events with $\Delta R^{ll} > 0.3$. The mixing and MonteCarlo distributions show disagreement at the low mass region. This discrepancies are due to the ones seen in the $\cos \gamma_{ll}$ distribution, in the collinear region ($\cos(\gamma_{ll}) \sim 1$).

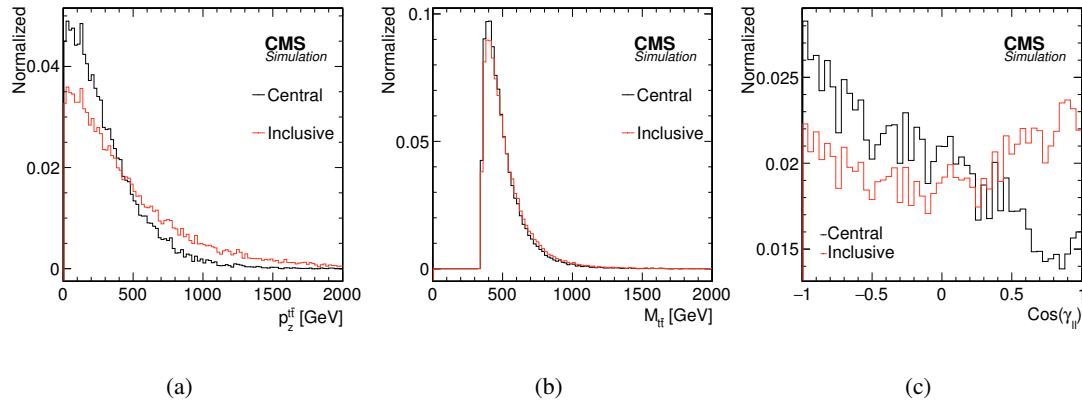


Figure 9: Figure (a) shows the $p_z^{t\bar{t}}$ distribution of events all the selected events (Inclusive) and events with both leptons in the central region ($|\eta| < 1.4$), showing that the latter events follow a softer distribution. In the other hand, fig. (b) shows the $M_{t\bar{t}}$ distribution for the same subsamples, both in good agreement. For that reason, leptons of the central subsample tend to be emitted back-to-back, as it can be seen in the $\cos \gamma_{ll}$ distribution displayed in fig. (c).

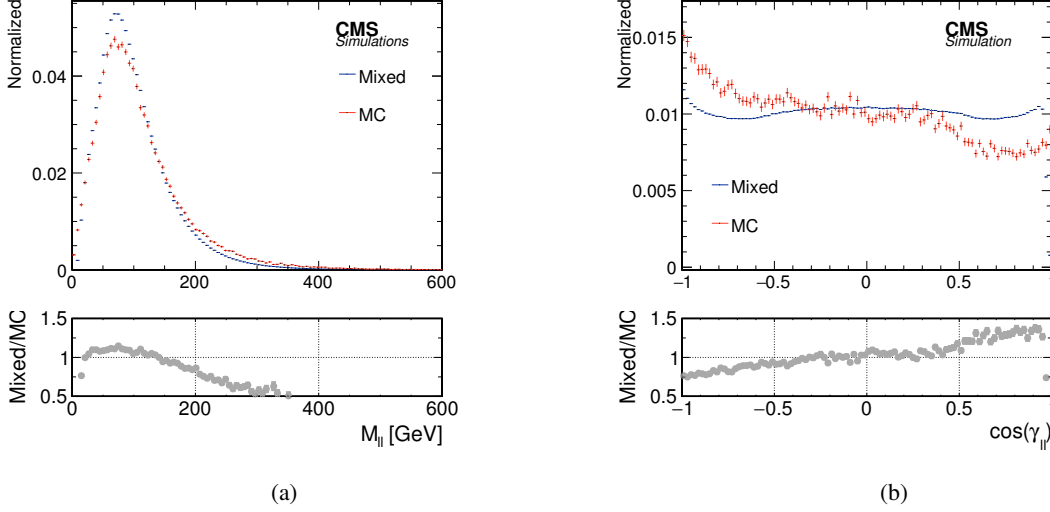


Figure 10: Relevant distributions for the mixing technique in the central region. Figure (a) shows the mixed and MonteCarlo distributions of M_{ll} , high big discrepancies. Figure (b) shows the opening angle between the two leptons, showing a trend for back-to-back topologies for the MonteCarlo distribution.

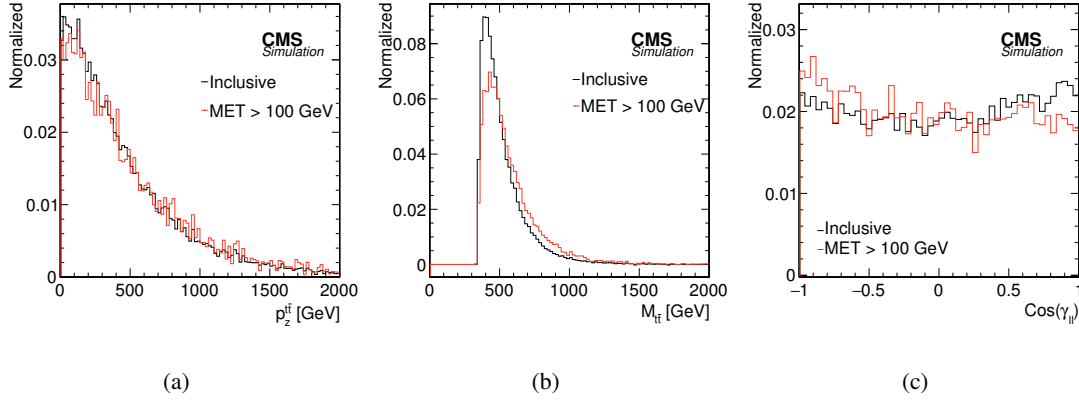


Figure 11: Relevant $t\bar{t}$ kinematic variables in a inclusive region and in events with $\cancel{E}_T > 100$ GeV. Figure 11a shows $p_z^{t\bar{t}}$, b shows $M_{t\bar{t}}$ and c, the opening angle between the leptons.

This is due to the fact that events with low $M_{t\bar{t}}$ yield to low energetic neutrinos and therefore populate the low $\cancel{E}_T$ region.

This effect also distorts the mixing method. Events with $\cancel{E}_T$ also have a higher $t\bar{t}$ mass and the leptons produced are therefore emitted slightly more back-to-back. In fig. 12, the relevant plots related to the mixing are shown. Figure 12a shows clear discrepancies between the mixing and the MonteCarlo prediction, which is due to the fact that in MonteCarlo events, leptons are emitted rather in the back-to-back direction, introducing again an angular correlation.

As a conclusion, it is clear that every cut applied on the event kinematic variables can induce additional correlations on the $t\bar{t}$ system, that will propagate to the di-lepton system, distorting the compensation that was observed in the event selection of section 3. This occurs even when the cuts applied are not particularly tight: the cuts studied in this section are comparable to the ones applied in [1].

7 Event mixing in Run II data

In this section, we try to apply the mixing technique to events recorded in CMS in collisions at $\sqrt{s} = 13$ TeV during the first weeks of the Run II of the LHC. The total integrated luminosity recorded in this period is $\mathcal{L} = 40 \text{ pb}^{-1}$. In order to be able to study the mixing technique in data, we define a control region enriched in $t\bar{t}$ events. Instead of studying events with a same-flavour lepton pair, we select events with a opposite-flavour lepton pair, in order

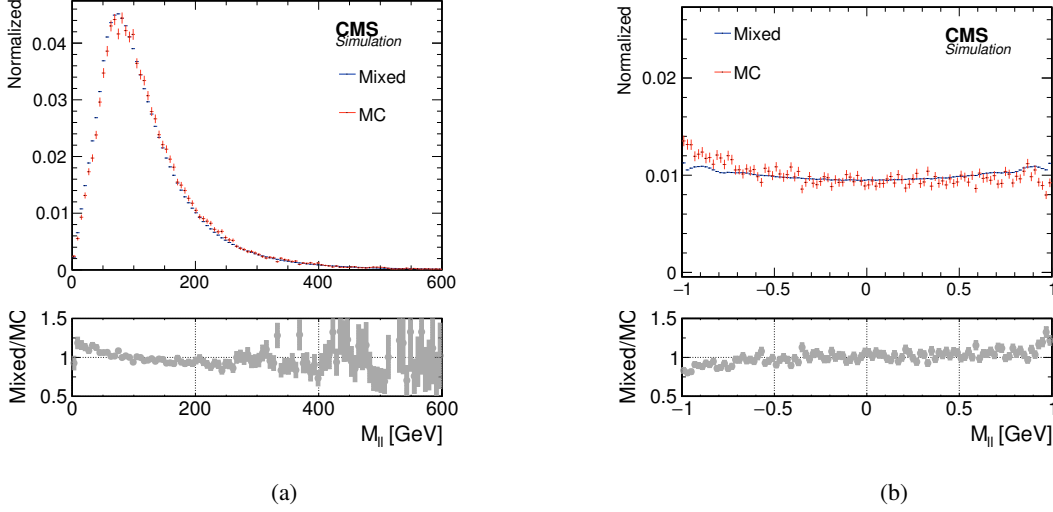


Figure 12: Relevant mixing variables, performing the mixing technique in a sample with $\cancel{E}_T > 100$ GeV, showing discrepancies between the MonteCarlo and the mixing-technique predictions.

to decrease the contribution of the Drell-Yan process. In this control region, we apply a modified version of the mixing technique: instead of mixing leptons at random, we produce mixed events with a $e\mu$ pair. Note that the control region chosen is kinetically equivalent to the one in 3.

In fig. 13, we show the prediction potential of the mixing technique in this control region. In fig. 13 (a), the $t\bar{t}$ prediction is performed using the mixing technique, normalizing the given distribution to the number of expected events given by the MonteCarlo simulation. The Drell-Yan estimation is fully MonteCarlo-driven. For comparison, we show in fig. 13 (b) another data-MonteCarlo comparison plot with a fully MonteCarlo-driven estimation of the backgrounds. The discrepancies at low invariant mass in both plots are due to the fact that there is no Drell-Yan MonteCarlo sample with $m_Z < 10$ GeV.

The event mixing technique is able to reproduce the M_{ll} distribution in this control region: the discrepancies are comparable to the statistical uncertainty, which is rather high. However, it is also clear that the $t\bar{t}$ distribution obtained from the mixed is slightly displaced to lower values compared to the one obtained from MonteCarlo simulations. This is due to the difference of energy spectrum of the leptons produced in Drell-Yan processes compared to the ones produced in $t\bar{t}$ decays. This leptons also take part in the mixing, leading to lower values of the invariant mass.

8 Conclusions

In this report, we have studied the feasibility of the application of the event-mixing technique to the estimation of the invariant mass distribution of di-lepton pairs produced in $t\bar{t}$ decays.

In the first part of this report, we have studied the effect of the dependency of the mixed events on the distribution of the number of events in a given bin of the distribution. We have shown that this distribution differs significantly from a Poisson distribution. However, the differences are not dramatical and could be corrected.

We have also studied using MonteCarlo simulations the effect of the $t\bar{t}$ kinematic variables on the angular variables of the di-lepton system. We have discovered that they introduce correlations, contradicting the hypothesis assumed for applying the mixed technique. However, in the particular region chosen for the study, these effects compensate each other, leading the mixing technique to a good estimation of the M_{ll} distribution.

In the following section, we have studied, also with MonteCarlo simulations, the effect of the cuts applied on a standard SUSY search to the correlations in the di-lepton system. This cuts arise strong angular correlations between the two leptons, which heavily distort the event-mixing method. The method has been seen not to be robust enough to the effect of this correlations, leading to great discrepancies from the simulations.

In the last part of the report, we present the results of the mixing technique applied in the control region in which the correlations are compensated. The data and mixing distribution do not show significant discrepancies. However, the distribution estimated with the mixing technique is displaced to the right with respect of the one given by

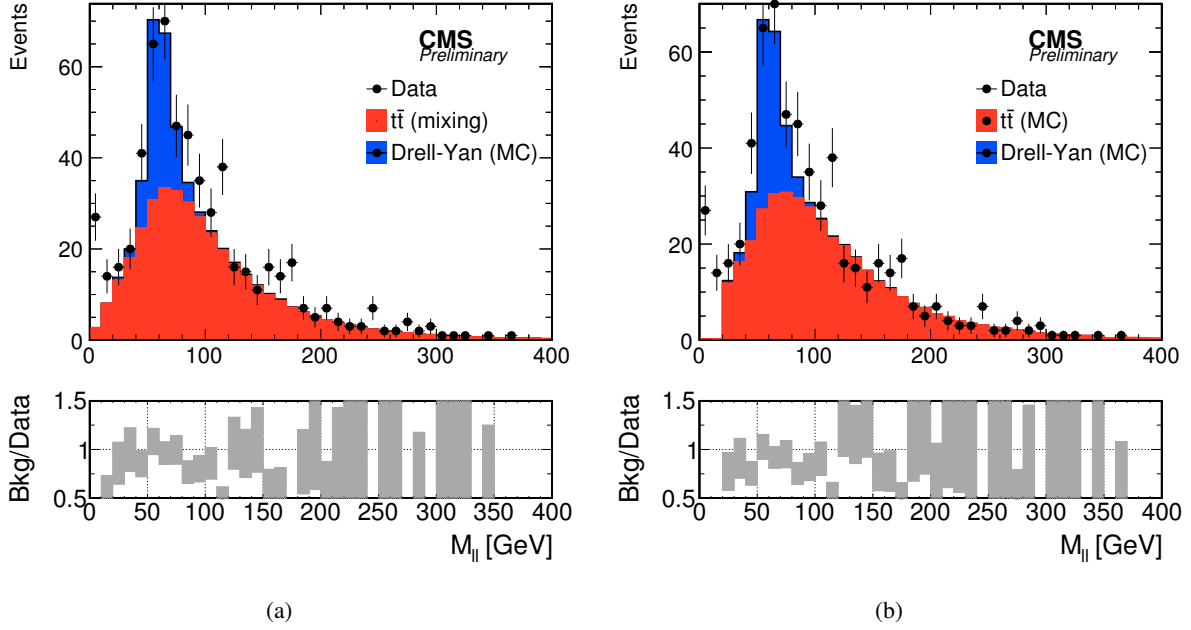


Figure 13: Event mixing technique applied on $\sqrt{s} = 13$ TeV data. Figure (a) shows the estimation of the $t\bar{t}$ using the event-mixing technique. Figure (b) shows a fully MonteCarlo-driven estimation of the background for comparison.

MonteCarlo simulations due to the presence of Drell-Yan events in the mixing.

From all the reasons stated above, we conclude that the mixing technique is able to reproduce the M_{ll} of leptons produced in $t\bar{t}$ events in some particular circumstances in which the correlations present in the $t\bar{t}$ system are, at least, partially compensated. However, the method was seen not to be robust enough to variations in common kinematic variables to provide a precise way of estimating the $t\bar{t}$ background in most searches.

References

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- [2] Schettler, H., “The Event-Mixing Technique for Modeling the $t\bar{t}$ Background in a Search for Supersymmetry in the Di-Lepton Channel”. <https://cms.desy.de/e128524/e223471/DESY-2013-01131.pdf>