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# Data driven trigger efficiency determination at LHCb

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**Abstract**

We demonstrate in detail the trigger efficiency evaluation of the LHCb trigger system purely on data with the so-called `TISTOS` method. The discussion includes an explicit overview of the uncertainty propagation. Additionally, we present a way to reduce the systematic uncertainty of the `TISTOS` method by binning the phase space. As an example, the binning is performed in the $B$ meson phase space for $B^+ \to J/\psi K^+$ decays.

A large sample of simulated events is used to determine the systematic uncertainties. Following the procedure discussed in this note, the trigger efficiency can be correctly determined for any dataset of sufficient size, including a realistic determination of systematic uncertainties.

The developed method is used to measure the trigger efficiency of $B^+ \to J/\psi K^+$ events in a dataset corresponding to an integrated luminosity of $3\,\text{fb}^{-1}$, collected in 2011 and 2012. The numerical values determined here have been used for the $3\,\text{fb}^{-1}$ measurement of the branching fraction of the rare decay $B_s^0 \to \mu^+\mu^-$ .

# Contents

# 1 Introduction

This paper describes in detail the determination of the trigger efficiency using the data driven TISTOS method.

We provide a complete overview of how the TISTOS method can be used to determine the trigger efficiencies on data, highlight the underlying assumptions, and explicitly show how to treat the uncertainties. Thereafter, we validate the performance of the TISTOS method on the simulated $B^+ \to J/\psi K^+$ samples, and demonstrate how the uncertainties can be reduced by the procedure of binning.

Finally, we determine the trigger efficiencies for $B^+ \to J/\psi K^+$ candidates on LHCb data, collected in years 2011 and 2012. The LHCb detector is a forward single-arm spectrometer at LHC, aimed at studies of CP-symmetry violation and rare decays in the LHC collider environment. It is discussed in more detail elsewhere [1].

The method presented here was developed in the work for the $B^0_{s,d} \to \mu^+\mu^-$ analysis and the numbers obtained for the $B^+ \to J/\psi K^+$ channel are used in the $3\,\mathrm{fb}^{-1}$ measurement of $B^0_{s,d} \to \mu^+\mu^-$ [2]. The TISTOS method, however, is applicable for any other decay channel.

# 2 Estimating the trigger efficiency

Various effects contribute to the efficiency with which a given decay channel can be detected: acceptance, trigger, reconstruction, and selection efficiencies. The particles in the candidate events must first lie within the detector acceptance, then be triggered, reconstructed, and finally pass the offline selection requirements. Each consecutive step reduces the sample further, leaving us with a subset of all the events determined by the total decay rate. The overall efficiency can thus be written as a product:

$$\epsilon_{Tot} = \epsilon_{Acc} \cdot \epsilon_{Trig|Acc} \cdot \epsilon_{Rec|Trig} \cdot \epsilon_{Sel|Rec} \tag{1}$$

The (conditional) trigger efficiency $\epsilon_{Trig|Acc}$ for a given decay channel is defined as the fraction of trigger accepted events, that contain a signal candidate within the acceptance:

$$\epsilon_{Trig|Acc} \equiv \frac{N_{Trig|Acc}}{N_{Acc}}. \tag{2}$$

As the detector records only events passing the trigger the number of events that the trigger processes ($N_{Acc}$) is not directly observable. A possible solution to the problem of determining $\epsilon_{Trig|Acc}$ is based on a complete simulation of the trigger decision process. In this note, an alternative procedure is described that makes use of measured data sets.

In LHCb, conventionally we write the efficiencies as product of terms:

$$\epsilon_{Tot} = \epsilon_{Trig|Sel} \cdot \epsilon_{Sel|Rec} \cdot \epsilon_{Rec|Acc} \cdot \epsilon_{Acc}, \tag{3}$$

which are different than the terms in Eq. (1), as the trigger efficiency is defined on the final sample of selected events:

$$\epsilon_{Trig} \equiv \epsilon_{Trig|Sel} \equiv \frac{N_{Trig|Sel}}{N_{Sel}}. \tag{4}$$

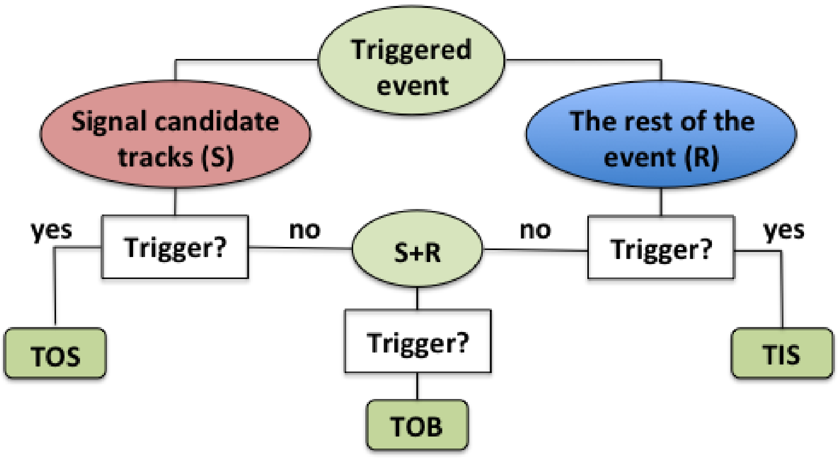


Figure 1: Diagram explaining the logic behind categorizing events into Trigger On Signal (TOS), Trigger Independent of Signal (TIS) and Trigger On Both (TOB) trigger categories. Note that an event can be both TIS and TOS simultaneously.

In the remainder of this note, we will describe how this definition allows the evaluation of the trigger efficiency using only quantities measurable from the data samples.

### 2.1 Trigger categories

To estimate the trigger efficiency as given in Eq. (4) from the data itself, we split events accepted by the trigger into three categories:

1. Triggered On Signal (TOS): events for which the presence of the signal is sufficient to generate a positive trigger decision[1].

2. Triggered Independent of Signal (TIS): the "rest" of the event is sufficient to generate a positive trigger decision, where the rest of the event is defined through an operational procedure consisting in removing the signal and all detector hits belonging to it.

3. Triggered On Both (TOB): these are events that are neither TIS nor TOS; neither the presence of the signal alone nor the rest of the event alone are sufficient to generate a positive trigger decision, but rather both are necessary.

The logic behind the categorization is illustrated in Fig. 1. Note that a single event can be simultaneously TIS and TOS (TISTOS) if both the presence of the signal alone as well as the rest of the event alone are sufficient to generate a positive trigger decision[2]. Using

[1] For a simple trigger candidate (e.g. Track), more than around 70% (depending on the subdetector) of the *online* reconstructed trigger candidate hits need to be contained within the set of all the hits from all offline reconstructed signal parts. For a composite candidate, the combination of all individual trigger candidates is compared to the set of offline candidates.

[2] TOB events on the other hand can be neither TIS nor TOS. As the TOB category, for the trigger decisions under consideration, only pertains to 0.5% of the events, and these are not relevant for the described `TISTOS` method, we do not examine them any further.

these event categories, we define the partial efficiencies:

$$\epsilon_{TOS} \equiv \frac{N_{TOS|Sel}}{N_{Sel}}, \qquad \epsilon_{TIS} \equiv \frac{N_{TIS|Sel}}{N_{Sel}}, \qquad \epsilon_{TISTOS} \equiv \frac{N_{TISTOS|Sel}}{N_{Sel}}. \tag{5}$$

In practice, an event is either TIS, TOS, or TOB always with respect to a specified selection of trigger decisions, applicable for a signal decay under consideration.

## 2.2 Estimating the trigger efficiency

The trigger efficiency defined in Eq. (4) can be expressed using the trigger categories defined in Sec.2.1:

$$\epsilon_{Trig} = \frac{N_{Trig|Sel}}{N_{Sel}} = \frac{N_{Trig|Sel}}{N_{TIS|Sel}} \times \frac{N_{TIS|Sel}}{N_{Sel}} = \frac{N_{Trig|Sel}}{N_{TIS|Sel}} \times \epsilon_{TIS}\,. \tag{6}$$

Henceforth, we will omit the "$|Sel$" subscript with the understanding that all efficiencies are defined on a sample of selected events. Eq. (6) is formally correct, but like Eq. (2), requires the knowledge of a quantity that is not directly measurable from data, the $\epsilon_{TIS}$.

On the other hand, we can determine from data the TIS efficiency within the TOS subsample. It can be evaluated from the overlap between TIS and TOS events:

$$\epsilon_{TIS|TOS} = \frac{N_{TISTOS}}{N_{TOS}}\,. \tag{7}$$

Provided that the TIS efficiency of any subsample of the triggered events is the same as that of the whole sample of selected events, it can thus be measured on the TOS sample:

$$\epsilon_{TIS} \equiv \epsilon_{TIS|TOS}\,. \tag{8}$$

The trigger efficiency can now be determined as

$$\epsilon_{Trig} = \frac{N_{Trig|Sel}}{N_{TIS|Sel}} \times \frac{N_{TISTOS}}{N_{TOS}}\,, \tag{9}$$

where all four quantities can directly be measured from data.

The assumption that $\epsilon_{TIS}$ is independent of the chosen subsample is the main assumption of this approach. Studying the validity of this assumption and its consequences is the main objective of this note.

Note, that the overall true TIS efficiency ($\epsilon_{TIS}$) has to be independent of the signal sample. If the signal candidates were completely uncorrelated with the rest of the event, also $\epsilon_{TIS|TOS}$ would also be independent of the chosen signal sample (and Eq. (8) satisfied). This correlation, however, exists and is not negligible.

In particular $B$ mesons are usually produced correlated with another $b$-hadron (as the $b\bar{b}$ quark pair is produced), therefore the "rest of the event" is very likely not to be independent as far as momentum spectra are concerned. The trigger selection is mainly

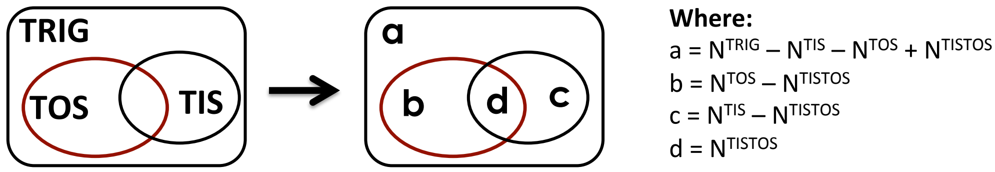


Figure 2: Redefining yields with independent terms in uncertainty calculation for selected number of events.

based on transverse momentum ($p_T$) and impact parameter ($IP$) cuts, and thus introduces a correlation between the signal and the remainder of the event.

However, signal and underlying event properties can be assumed to be largely uncorrelated in small enough regions of the signal $B$ meson phase space. In other words, for an infinitesimally small volume of signal phase space, Eq. (8) can be used to express the total TIS efficiency completely in terms of quantities measurable from data

$$\epsilon_{Trig} = \frac{N_{Trig|Sel}}{\sum_i N^i_{Sel}} = \frac{N_{Trig|Sel}}{\sum_i \frac{N^i_{TIS|Sel}}{\epsilon^i_{TIS}}} = \frac{N_{Trig|Sel}}{\sum_i \frac{N^i_{TIS|Sel} N^i_{TOS|Sel}}{N^i_{TISTOS|Sel}}}. \tag{10}$$

Here the summation is performed over all the bins in the phase space of the signal $B$ meson.

## 2.3 Estimating the trigger efficiency uncertainty

Calculation of the trigger efficiency from Eq. (10) is straightforward once individual trigger yields (TRIG, TIS, TOS, and TISTOS) are known. Since the TRIG, TIS, TOS, and TISTOS yields partly contain the same events, the propagation of their uncertainties to the efficiency needs care. To make this explicit, let us rewrite Eq. (10) as

$$\epsilon_{Trig} = \frac{N_{Trig|Sel}}{\sum_i \frac{N^i_{TIS|Sel} N^i_{TOS|Sel}}{N^i_{TISTOS|Sel}}} = \frac{N_{Trig|Sel}}{\sum_i \frac{(b_i+d_i)(c_i+d_i)}{d_i}}, \tag{11}$$

where we have denoted $N^i_{TISTOS|Sel}$ by $d_i$ and the non-overlapping part of $N^i_{TIS|Sel}$ and $N^i_{TOS|Sel}$ by $b_i$ and $c_i$, respectively.

The denominator of Eq. (11) is now written in terms of independent quantities (see

Fig. 2) and therefore its uncertainty can be calculated as follows[3]

$$
\begin{aligned}
\sigma^2_{N_{Sel}} &= \sum_i \sigma^2_{N^i_{Sel}} \\
&= \sum_i \left(\frac{\partial N^i_{Sel}}{\partial b_i}\right)^2 \sigma^2_{b,i} + \left(\frac{\partial N^i_{Sel}}{\partial c}\right)^2 \sigma^2_{c,i} + \left(\frac{\partial N^i_{Sel}}{\partial d}\right)^2 \sigma^2_{d,i}, \\
&= \sum_i \left(\frac{c_i + d_i}{d_i}\right)^2 b_i + \left(\frac{b_i + d_i}{d_i}\right)^2 c_i + \left(1 - \frac{b_i c_i}{d_i^2}\right)^2 d_i.
\end{aligned}
\tag{12}
$$

Analogously, the trigger efficiency can be written indicating explicitly the contribution of disjointed sets, $N_{Trig|sel} = n$ and $N_{sel} = n + m$:

$$
\epsilon_{Trig} = \frac{n}{n+m}, \tag{13}
$$

which leads to

$$
\begin{aligned}
\sigma^2_{\epsilon_{Trig}} &= \left(\frac{m}{(n+m)^2}\right)^2 \cdot \sigma^2_n + \left(\frac{-n}{(n+m)^2}\right)^2 \cdot \sigma^2_m \\
\sigma^2_{\epsilon_{Trig}} &= \left(\frac{m}{(n+m)^2}\right)^2 \cdot N_{Trig|Sel} + \left(\frac{-n}{(n+m)^2}\right)^2 \cdot (\sigma^2_{N_{Sel}} - N_{Trig|Sel})
\end{aligned}
\tag{14}
$$

where in the last step we have used the fact that $\sigma^2_{N_{sel}} = \sigma^2_n + \sigma^2_m$.

## 2.4 Binning the phase space

The phase space of the $B$ meson can be parameterized by the transverse and longitudinal momenta.

At first we calculate the binning boundaries for both variables independently, such that about the same number of TISTOS events fall into each bin [4].

For both dimensions independently, the number of events in the bins with the optimized boundaries agrees within a few percent. After applying the independently optimized bin boundaries on the 2 dimensional phase space, the number of events that fall in each bin show a greater variance. This is due to the fact that transverse and longitudinal momentum are not independent variables.

The slight correlation between the chosen variables does not jeopardise the performace of the `TISTOS` method, where the underlying assumption is that TIS and TOS decisions are uncorrelated for the events within the same small region of phase space.

[3]Here we assume the yield uncertanties follow a Gaussian distribution and use the first-order Taylor series approximation for the uncertainty propagation. For the Gaussian assumption to be valid, the yields in each bin need be large enough ( $\mathcal{O}(10)$).

[4]TISTOS is the category with the smallest statistics and therefore influences the method performance the most. Dividing events equally between the bins minimizes the chances of encountering a bin with too few or no statistics.

# 3 Performance on simulation

In this section, we will demonstrate how the previously described TISTOS method (see Sec.2) performs on the simulated events. The TISTOS result are compared to the true efficiency of the simulated sample.

## 3.1 The Monte Carlo sample

The $pp$ interactions are simulated using the Monte Carlo (MC) technique. Only those $pp$ interactions are accepted where one or more[5] signal events (i.e. $B^+ \to J/\psi K^+$ ) lie within the LHCb detector acceptance. The accepted MC events are next processed by the LHCb trigger, reconstruction, and selection algorithms just as the events from real $pp$ collisions.

Note that accepted MC events contain also accompanying decays besides the signal. Thus, it may well happen that some of those mimic the signal well enough to pass all the following signal selection criteria.

We have produced two MC samples for $B^+ \to J/\psi K^+$ decay channel with slightly different detector configurations and sample sizes. The smaller sample contains $127 \times 10^3$ generated events in the detector acceptance (MC127k in the following) and it is generated with the same detector configuration as used during the data taking in May and June, 2012. The larger MC sample of $1000 \times 10^3$ events (MC1000k) uses the detector configuration from July, August and September, 2012.

For both samples, the $pp$ interactions have been simulated assuming a beam energy of 4 TeV, an average number of interactions per crossing $\nu = 2.5$, which corresponds to an average number of visible interactions per crossing $\mu = 1.75$.

## 3.2 True trigger efficiency and signal separation

The true trigger efficiency from the MC is an important benchmark in our study. It provides a reference point and allows us to test how well the TISTOS method performs. Eventually, it makes it possible to evaluate the bias of the TISTOS method and use it as a systematic uncertainty assigned to the approach.

On MC, the trigger can be emulated in a way that also the selected events which do not pass the trigger requirements are kept. Thus, the trigger efficiency defined in Eq. (4) can be evaluated directly from $N^{TRIG}/N^{SEL}$. We will refer to this quantity as *true trigger efficiency*.

Calculation of any trigger efficiency relies on the methods of separating the signal candidates from the rest. In this note we consider two different methods to determine the signal yield in the samples: Sideband Subtraction (SB) and a Maximum Likelihood (ML) fit. In the following, we will demonstrate the performance of the methods with respect to each other, and also with respect to the truth information available in the simulated events.

[5] The fraction of events with more than one entry is at 0.1% level.

SB serves as the main signal yield determination method in our study. This is mainly because of its robustness when dealing with bins containing fewer events, but also because of the possibility to perform SB on the whole phase space (i.e. all the bins) at once.

SB is performed on the $B$ meson invariant mass distribution, where the $B$ meson invariant mass is calculated after using a constraint on the $J/\psi$ mass. We look at a mass window of $\pm$ 100 MeV/$c^2$ around the PDG mass, where the events that lie away more that 55 MeV/$c^2$ from the mean mass value form the sidebands. The yield in the sidebands is extrapolated over the whole mass window, and thereafter subtracted from the total yield in the mass window.

For the ML fit, we build first a probability density function (*p.d.f.*) describing the $B$ meson invariant mass distribution. The `RooFit` package [3] performs the evaluation of the total likelihoods for all the events in the data sample. `MINUIT` minimizer [4] is used to find the set of parameter values that maximise the total likelihood calculated by `RooFit`.

The invariant mass model *p.d.f.* for $B^+ \to J/\psi K^+$ decay consists of two Gaussians with a shared mean, but different (independent) widths. The background model has two parts, first an exponential to describe the combinatorial background, and secondly a Crystal Ball function to describe the events where a pion has been mis-identified as a kaon. This mis-identified component has a fixed mean with respect to the signal mean mass value.

As the third option, in the simulated sample we can use the MC matching procedure to select the true signal events. The matching procedure relies on the MC truth information for every particle in the simulated event. In particular, for $B^+ \to J/\psi K^+$ to be matched as a signal event, the particles must first not be misidentified, and secondly, they need to be properly linked in the decay chain (e.g. the $J/\psi$ needs to originate from the $B^+$ decay, etc.).

The events that pass the MC matching criteria (i.e matched events), will form the matched sample. Note that even the MC truth matching process that provides MC truth information for the particles is not 100% efficient[6]. This means that not all the signal candidates reside in the matched sample.

For the comparison of the methods, we apply both SB and ML and calculate the true trigger efficiency on (i) the matched sub-sample, (ii) the un-matched sub-sample, and (iii) the total simulated sample.

The results are shown in Table 1, whereas the result from the matched sample is assumed to be the closest to the true value.

The SB and ML results are in all the cases almost indistinguishable. However, the trigger efficiency between the matched and the un-matched sample, that has much more background events compared to signal events, differs significantly. The results from the total sample are in good agreement with the true efficiency in the matched sample.

From this we conclude that SB and ML are capable of separating the signal yield on the total sample and it is sufficient to apply SB/ML directly on the total MC sample

[6]The mistakes can happen because of possible wrong links between the true simulated and reconstructed detector hits.

without requiring truth matching. Thus, $\epsilon_{true}$ is chosen as the benchmark in the following MC studies.

### 3.3 Results with different phase space binnings

It has become a common practice in the LHCb collaboration to use `TISTOS` method in the trigger efficiency determination directly from the data. Even so, binning Eq. (9) (or Eq. (5) for TOS efficiencies) in the phase space is not always implemented.

This results in a considerable, and furthermore, unnecessary increase in the assigned systematic uncertainty to the trigger efficiency estimation. On MC127k sample, the `TISTOS` method without binning gives more than 5% higher result when compared to the true efficiency in the same sample (Tab. 2).

The relative bias of the `TISTOS` method (and thus the systematic uncertainty) can be significantly reduced by treating different regions of phase space independently and combining the results into an overall efficiency of the sample.

The `TISTOS` method was applied with increasing number of bins on both MC samples. Comparing the efficiencies with different binning schemes with respect to the true efficiency of the sample, one clearly sees the `TISTOS` result converging to the true efficiency value when the number of bins in the $B$ meson phase space increases (Fig. 3 and 4, for MC127k and MC1000k, respectively).

As a cross check, we performed an identical study using the ML method instead of SB. The comparison between the SB and MLL on MC127k sample is shown in .

For a lower number of bins, the results are in good agreement. As the number of bins increases, the individual bins contain less and less statistics. Eventually, the ML fit will not have enough statistics to separate the signal and becomes unreliable (Fig. 5). In the rest of the note we will use SB, yet it is important to note that ML perform equally well given sufficient statistics[7].

### 3.4 Results with the best phase space binning

We define the best binnning scheme to be a compromise between the smallest relative bias and the statistical uncertainty of the efficiency. Hence the optimal binning scheme

[7]Moreover, for a number of signal channels the Sideband Subtraction might not be an option (e.g. because of additional peaking components in the background distribution).

Table 1: True unbinned trigger efficiency on matched ($\epsilon_{match}$), not-matched ($\epsilon_{notmatch}$), and on the whole MC127k sample ($\epsilon_{true}$).

| Signal separation | $\epsilon_{match}$ | $\epsilon_{notmatch}$ | $\epsilon_{true}$ |
|---|---|---|---|
| Sideband subtraction | $87.39 \pm 0.22\%$ | $84.44 \pm 1.61\%$ | $87.32 \pm 0.22\%$ |
| MLL fit | $87.37 \pm 0.22\%$ | $85.56 \pm 1.54\%$ | $87.32 \pm 0.22\%$ |

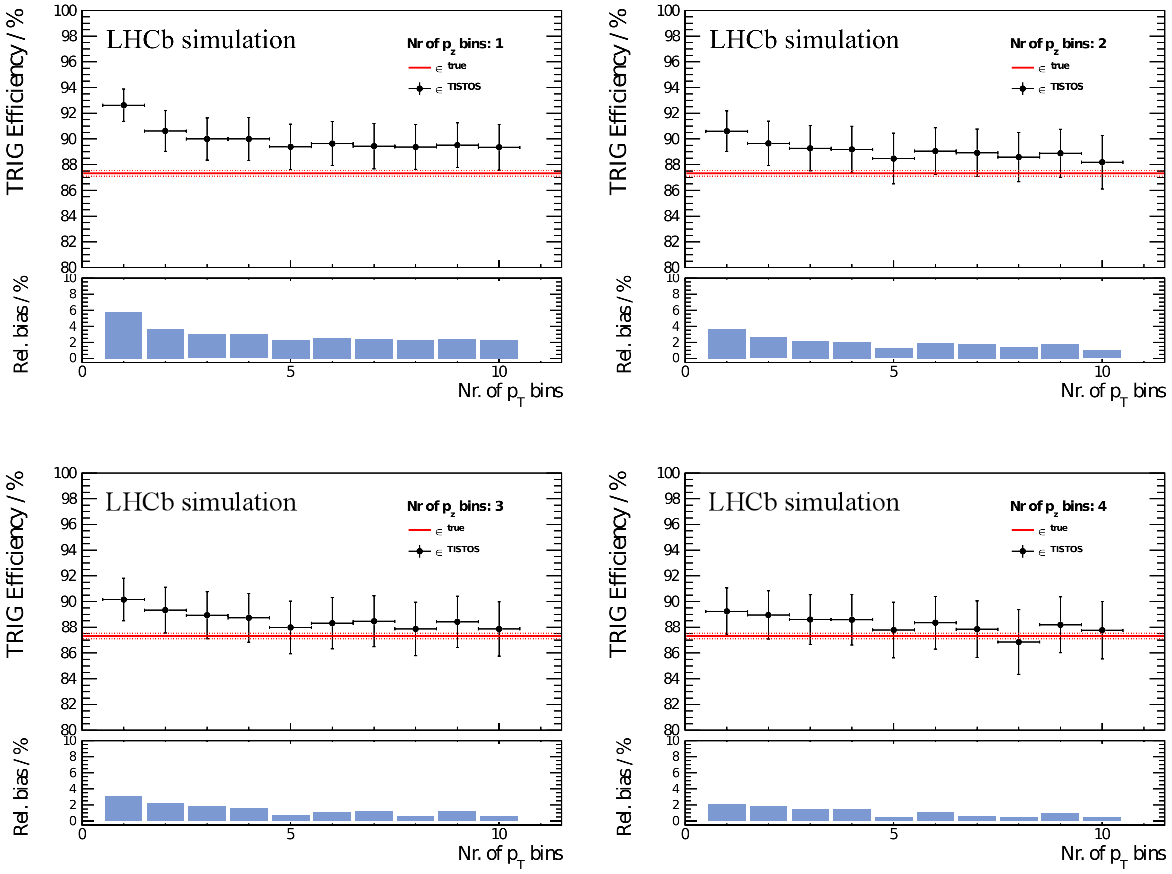


Figure 3: The true trigger efficiency (red line), efficiency calculated with the `TISTOS` method, and the relative bias of the TISTOS efficiency in the MC127k sample depending on the number of B meson $p_Z$ and $p_T$ bins.

depends slightly on the sample size. The dependence is studied on using two MC samples with similar configurations yet different sizes, MC127k and MC1000k.

For the smaller sample, MC127k, the best results are obtained with 4 bins in $p_z$ and 5 in $p_T$. The relative bias could be reduced considerably, from $(5.5 \pm 1.5)\%$ down to $(0.5 \pm 0.4)\%$.

The best binning on the larger sample, MC1000k, has 4 bins in $p_z$ and 9 in $p_T$. On MC1000k the relative bias can be reduced from $(3.9 \pm 0.1)\%$ down to $(0.25 \pm 0.1)\%$ (Tab. 3).

From comparing the best binning schemes on the smaller and larger MC sample, (4

Table 2: Efficiency evaluated with the `TISTOS` method ($\epsilon_{TisTos}$) and its relative bias with respect to the $\epsilon_{true}$ ($Bias(\epsilon)$).

| Signal separation method | $\epsilon_{true}$ | $\epsilon_{TisTos}$ | $Bias(\epsilon)$ |
|---|---|---|---|
| Sideband subtraction | $87.322 \pm 0.22\%$ | $92.622 \pm 1.523\%$ | $5.723 \pm 3.26\%$ |
| MLL fit | $87.324 \pm 0.22\%$ | $92.337 \pm 1.532\%$ | $5.429 \pm 3.27\%$ |

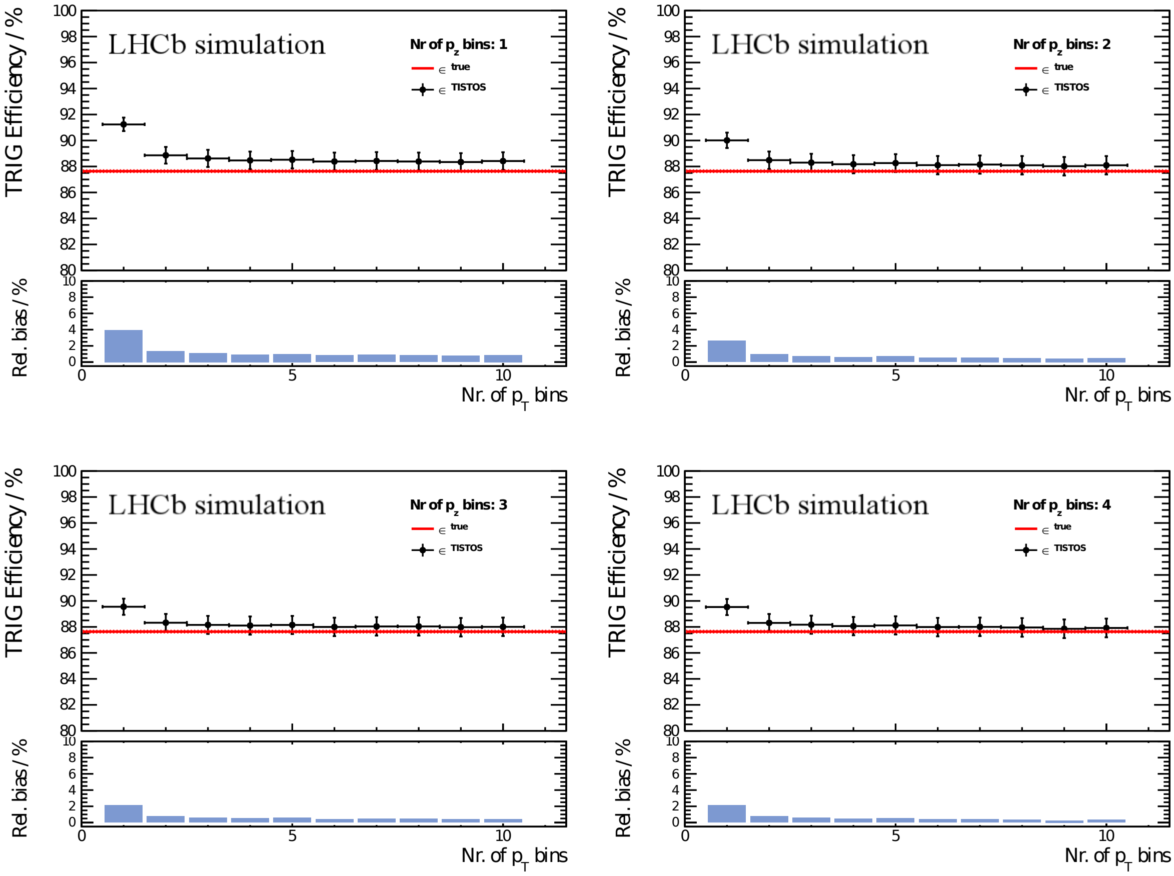


Figure 4: The true trigger efficiency (red line), efficiency calculated with the `TISTOS` method, and the relative bias of the TISTOS efficiency in the MC1000k sample depending on the number of B meson $p_Z$ and $p_T$ bins.

bins in $p_z$ and 9 in $p_T$ on MC1000k, instead of 4 and 5 on MC127k) we conclude that the effect of the sample size on choosing the best binning is not significant.

In other words, we can use the best binning scheme taken from a respective MC sample directly on the data sample with a different size Also, the study shows that the change in the number of bins has a relatively small effect on the bias when the number of bins exceeds 3 in both dimensions.

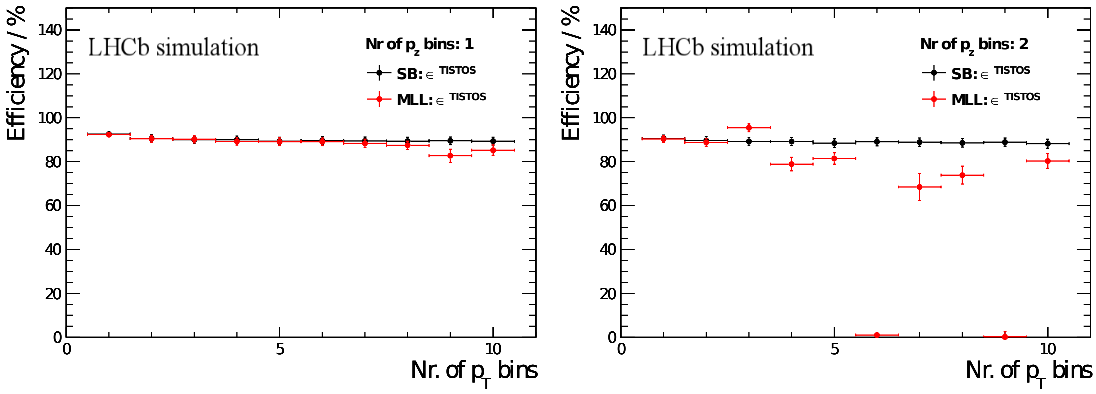


Figure 5: The TISTOS trigger efficiency calculated on MC127k depending on the number of $B$ meson $p_Z$ and $p_T$ bins. The black points represent results with sideband subtracted (SB) signal yields, the red points from the signal yields from maximum likelihood (MLL) fit.

Table 3: Efficiency evaluated with the `TISTOS` method ($\epsilon_{TisTos}$) and its relative bias with respect to the $\epsilon_{true}$ ($Bias(\epsilon)$) with no binning and the best chosen binning schemes.

| Sample / Binning ($p_Z, p_T$) | $\epsilon_{true}$ | $\epsilon_{TisTos}$ | $Bias(\epsilon)$ |
|---|---|---|---|
| MC127k/ No binning | $87.3 \pm 0.2\%$ | $92.6 \pm 1.3\%$ | $5.7 \pm 0.3\%$ |
| MC127k/ 4x5 | $87.3 \pm 0.2\%$ | $87.8 \pm 2.2\%$ | $0.5 \pm 0.4\%$ |
| | | | |
| MC1000k/ No binning | $87.6 \pm 0.1\%$ | $91.2 \pm 0.5\%$ | $3.9 \pm 0.1\%$ |
| MC1000k/ 4x9 | $87.6 \pm 0.1\%$ | $87.9 \pm 0.7\%$ | $0.25 \pm 0.1\%$ |

# 4 Performance on data

The TISTOS based procedure and the binning developed in the previous sections is applied on the $B^+ \to J/\psi K^+$ candidates in the full LHCb data set from years 2011 and 2012. The trigger efficiencies determined here are also used for the analysis of the rare decays $B^0_{s,d} \to \mu^+\mu^-$.

## 4.1 Data sample

The results described in this section are obtained using the *pp* collision data collected by LHCb in years 2011 and 2012 at a centre-of-mass energy of $\sqrt{s} = 7\,\text{TeV}$ ( $1\,\text{fb}^{-1}$ of integrated luminosity) and $8\,\text{TeV}$ ( $2\,\text{fb}^{-1}$), respectively.

In 2011 the LHC machine started the operations from a a peak luminosity L $\sim 1.6 \times 10^{32}$ $\text{cm}^{-2}$ $\text{s}^{-1}$ with 228 bunches (180 bunches colliding in LHCb) and an average number of *pp* visible interactions per crossing of $\mu \sim 2.5$. After the first 10 $\text{pb}^{-1}$ collected by LHCb, the machine moved to the 50 ns bunch scheme and kept increasing the number of bunches by 144 every three fills, by reaching 1380 circulating bunches (1296 colliding bunches in LHCb). Since then the peak luminosity in LHCb was continuously levelled in order not to exceed $3 - 3.5 \times 10^{32}$ $\text{cm}^{-2}$ $\text{s}^{-1}$ corresponding to an average $< \mu > \sim 1.5$.

During 2012, the data taking conditions were very stable. The first $100\,\text{pb}^{-1}$ were collected while the machine was ramping up the luminosity to $4 \times 10^{32}\,\text{cm}^{-2}$ $\text{s}^{-1}$, at which the remaining $2\,\text{fb}^{-1}$ were taken. The average number of *pp* visible interactions per crossing was very stable at $\mu \sim 1.6$. All data were recorded with a LHC bunch spacing of 50 ns.

## 4.2 Results on the data

The trigger efficiencies measured in this section are obtained for the combined physics decision of each trigger level. Physics decision will be positive, if the event was triggered by any of the physics lines in the trigger level. The combined trigger decision is positive only if the events has a positive physics decision from all the three trigger levels.

Whereas the trigger configurations are slightly different between the years 2011 and 2012, and also between the simulated samples and the recorded ones[8], the bias and systematic uncertainty determined in Sec. 3 is assumed to be independent of these small changes.

Different binning schemes have been studied on a large MC sample with similar conditions to the 2012 data taking period. The results and the choice for the best performing binning are described in Sec. 3.3, where we have also evaluated the relative bias of the TISTOS method for the best binning (4 bins in $p_Z$, 9 in $p_T$) to be 0.25%.

The binning scheme obtained on the MC is applied on both 2011 and 2012 data samples, whereas the estimated relative bias is used as a systematic uncertainty on the final result.

[8]For practical reasons, the trigger configuration in data is adjusted over the year to adjust to the boundary conditions like available delivered luminosity, farm size or physics focus. In MC, only the dominant configuration is simulated.

The trigger efficiencies from the binned TISTOS method compared to the unbinned TISTOS method are in general by $4-5\%$ lower on data (Tab. 4). The same pattern was observed on the simulated samples (Tab. 3).

We can reduce the total uncertainty of the TISTOS method on the 2011 and 2012 data samples from 4% down to 0.3% by binning the $B$ meson phase space.

Table 4: Trigger efficiencies in the data with and without binning the $B$ meson phase space.

| Binning | $\epsilon_{TisTos}$ | $\pm Abs.Stat.Unc.$ | $\pm Abs.Syst.Unc.$ | $Rel.Syst.Unc.$ |
|---|---|---|---|---|
| Data: 2011 S20r1 | | | | |
| No binning | 92.9% | 0.5% | 3.6% | 3.9% |
| 4x9 | 87.8% | 0.6% | 0.2% | 0.25% |
| Data: 2012 S20 | | | | |
| No binning | 92.0% | 0.3% | 3.6% | 3.9% |
| 4x9 | 87.8% | 0.4% | 0.2% | 0.25% |

## 5 Summary

Trigger efficiencies can be determined from the measured data with the TISTOS method, provided the trigger performs the necessary classification of the events. Furthermore, there is a way to reduce the systematic uncertainty of the method that mainly arises from the correlations between the trigger classifications.

As has been demonstrated on the simulated $B^+ \to J/\psi K^+$ data samples, binning the phase space of the $B$ meson in the transverse and longitudinal momentum plane reduces the systematic bias of the TISTOS method considerably: from a relative 4% to 0.3% on the 2012 MC sample.

The residual relative bias determined is recommended to be added as relative systematic uncertainty to the trigger efficiency determined with the binned TISTOS method, when using the best determined binning scheme.

The TISTOS method with the chosen best binning scheme of 9 $B$ meson $p_T$ bins and 4 $B$ meson $p_Z$ bins has been applied on the full 2011 and 2012 data sets from LHCb. The physics decision trigger efficiency for $B^+ \to J/\psi K^+$ candidates in 2011 is

$$\epsilon_{2011}^{TRIG} = 87.8\% \pm 0.6\%(stat) \pm 0.2\%(syst),$$

and in 2012

$$\epsilon_{2012}^{TRIG} = 87.8\% \pm 0.4\%(stat) \pm 0.2\%(syst).$$

The results agree well to each other, and are dominated by the statistical uncertainty when using the phase space binning for the TISTOS method.

## References


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