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The HLT2 Topological Lines

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Abstract

The HLT2 topological lines have been redesigned to trigger inclusively on n-body B decays. They are able to maintain high signal selection efficiencies, while simultaneously providing a large background rejection factor (even at large μ). The timing performance of these lines is also impressive. This note discusses the current status and performance of the HLT2 topological lines, along with plans for future improvements.

Contents

1 Introduction

The LHC*b* trigger is divided into three stages: a hardware, or level-0 (L0) stage, and two software, or high-level, stages (HLTs) [1]. The L0 trigger estimates the transverse energy (E_T) and momentum (P_T) of individual tracks using information from the calorimeters and muon stations. This information is then used to reduce the visible *pp* interaction rate delivered by the LHC down to 1 MHz (the maximum rate at which all of LHC*b*'s subdetectors can be read out) by requiring the presence of at least one high E_T hadron, electron or photon, or a high P_T muon in order to retain the event for further processing. The value of the cuts on E_T and P_T vary depending on the running conditions of the LHC; however, they are typically around $\mathcal{O}$(3 GeV) for hadrons and photons, $\mathcal{O}$(2 GeV) for electrons and $\mathcal{O}$(1 GeV) for muons.

The HLT utilizes a computing farm (that will be comprised of around 20,000 cores in 2011) to process events and reduce the rate at which events are kept for offline processing down to around 2 kHz. The first stage of the HLT, called HLT1, is based around a single track trigger [2] and reduces the input rate obtained from L0 by a factor of ~ 20 by searching for a single track with high momentum, a large impact parameter with respect to all primary vertices (PVs) in the event, and good track quality. In addition to this, lifetime unbiased muon [3] and electron triggers are used for analyses such as the β_s measurement from $B_s \to J/\psi\phi$; such measurements are sensitive to the presence of lifetime biases. These triggers are based around confirming the L0 trigger decision by matching tracks reconstructed in the HLT to the objects (muon segments or calorimater clusters) used in the L0 trigger decision. The design of HLT1 minimizes the impact of varying running conditions on its performance. HLT1 takes $\sim$ 15 ms to process a L0 accepted minimum bias event and has a retention of $\sim 5\%$ on these events. It is more than 80% efficient on signal events for the majority of LHCb's benchmark B decay modes. More details of the performance of HLT1 can be found in Refs. [2, 3].

The second stage of the HLT (HLT2) processes few enough events that it is possible to perform reconstruction that is very similar to what is done offline (see Section 2 for details on the differences). This allows the HLT2 to use event-selection criteria that are more in line with those used in offline analyses. There are many HLT2 lines dedicated to triggering on various types of events. This note provides a detailed description of the HLT2 *topological* lines. Most n-body hadronic B decays ($n \geq 3$) are only triggered on efficiently in LHCb by these lines; thus, it is extremely important that they perform well under the envisioned LHC running conditions for 2011. The current plan is to run with 900 colliding bunches at $\mu = 2.5$ (a visible interaction rate of about 12 MHz). This is not an easy environment in which to run a hadronic trigger.

Previous HLT2 versions used large numbers of exclusive lines to obtain high efficiencies on a number of hadronic B decays. These previous HLT2 versions also employed topological lines that were inclusive in the sense that the cuts on quantities like the mass of the B candidate were loose. The following unavoidable problems arise when using this approach:

- the background retention rate increases with the number of trigger lines;
- the time required to process an event increases with the number of trigger lines;
- the background retention rate increases when cuts are made looser (while this may seem blatantly obvious, it is worth pointing out that this fact makes exclusive selections more vulnerable to altering cut values than inclusive ones);
- the efficiency on channels that do not have an exclusive line is much lower than on those that do.

The result was a trigger that was not fit for purpose; *i.e.*, this approach to the HLT2 was too slow and had a background retention rate that was way too high to be used during the 2011 LHC running conditions. It also had poor data-mining properties due to the fourth bullet point above.

The new HLT2 topological trigger takes a very different approach: it uses three lines, designed to be inclusive (details on this can be found in Section 2), to obtain high efficiency on almost all n-body B decays while simultaneously providing a large background rejection factor and good timing performance. The advantages of this approach are as follows:

- high efficiency for any B decay with at least 2 charged daughters due to the inclusive nature of the trigger lines;
- excellent timing performance due to the small number of trigger lines;

- excellent background rejection due to the small number of lines and because cuts do not need to be loosened to make the trigger inclusive;

- robustness against changes made *upstream* of the HLT2 topological lines (*e.g.*, higher $P_T^{\min}$ cuts in the HLT2 reconstruction);

- excellent data-mining properties;

- trigger redundancy for *golden modes* that do have exclusive (or, at least, specific) HLT2 lines.

These properties will allow LHC*b* to trigger efficiently on hadronic B decays under the 2011 LHC running conditions.

The methodology and architecture of the HLT2 topological lines are described in Section 2. The performance of the lines (signal efficiencies, background rejection, *etc.*) is discussed in Section 3, while the timing aspects are discussed in Section 4. Future improvements are outlined in Section 5 and the conclusions are presented in Section 6.

2 Methodology & Architecture

The HLT2 topological lines are designed to trigger efficiently on any B decay with at least 2 charged daughters. This is achieved by employing an inclusive strategy. To obtain manifestly inclusive trigger lines, quantities like the mass of the B candidate, how well the direction of its momentum agrees with the direction defined by the primary and secondary vertex (its *pointing*), *etc.* cannot be cut on. To trigger efficiently on B decays with long-lived resonances (*e.g.*, D mesons), tight cuts on the quality of the verticies must also be avoided. Instead, quantities that preserve the inclusiveness of the trigger while also providing large background rejection factors must be used.

First, we will discuss the cuts made on the input particles. We can afford to make fairly tight cuts on the input particles because the trigger is designed to handle the possible omission of a daughter or daughters. To save time in the HLT2 reconstruction, only tracks with $P_T > 500$ MeV and $P > 5$ GeV are reconstructed; thus, these cuts are also made in the HLT2 topological lines. To reduce the background rate due to ghosts, all tracks are required to have a track χ^2 value less than 5. To reduce the background rate due to prompt particles, all tracks are required to have an impact parameter χ^2 value greater than 16. Due to the inclusive nature of the HLT2 topological lines, this does not mean that all of the B daughters need to satisfy these criteria. The trigger is designed to allow for the omission of one or more daughters when forming the trigger candidate.

The true mass (or PID) of the daughters is not very important because of the fact that the mass difference between electrons, muons, pions, Kaons and protons is small compared to the mass of the B; thus, processing time is saved in the HLT2 topological lines by simply assigning each input particle a Kaon mass. There is virtually zero loss in efficiency due to this choice.

The n-body candidates are built as follows: two input particles are combined to form a 2-body object; another input particle is added to the 2-body object (that, at this point, is treated like a single particle; more on this below) to form a three-body object; a fourth input particle is added to the three-body object (that is now treated like a single particle) to form a 4-body candidate. Thus, an n-body candidate is formed by combining an $(n-1)$-body candidate and a particle, not by combining n particles.

The importance of this distinction is in how the DOCA cuts are made. When a 2-body object is built, a DOCA < 0.15 mm cut is imposed for the object to either become a 2-body candidate or input (when combined with another particle) to a 3-body candidate. When a 3-body object is made by combining a 2-body object and another particle, another DOCA < 0.15 mm cut is imposed for the object to either become a 3-body candidate or input to a 4-body candidate. This DOCA is of the 2-body object and the additional particle, not the maximum DOCA of the three particles. This is a very important difference; it greatly enhances the efficiency of the HLT2 topological lines on $B \to DX$ decays. A similar procedure is followed when making 4-body candidates from 3-body objects and an additional particle. All n-body candidates that pass these DOCA cuts are then filtered using a number of other selection criteria.

If a trigger candidate only contains a subset of the daughter particles, then the mass of the candidate will be less than the mass of the B. Thus, any cuts on the mass would need to be very loose if the trigger is to be inclusive. A better approach is to not cut on the mass but to instead correct the mass of the trigger candidate to account for the missing daughters. Of course, it is not possible to do this exactly because one can never know how many daughters are missing or what type of particles they are; however, it is possible to obtain a very good approximation to the correction using the following equation [4]:

$$m_{\text{corrected}} = \sqrt{m^2 + |p'_{T\text{missing}}|^2} + |p'_{T\text{missing}}|, \tag{1}$$

where $p'_{T\text{missing}}$ is the missing momentum transverse to the direction of flight of the trigger candidate (obtained from the primary and secondary verticies). The quantity $m_{\text{corrected}}$ would be the mass of the parent if a massless particle was omitted from the trigger candidate, *i.e.*, it is the minimum correction to the trigger-candidate mass if any daughters are missing.

Figures 1 and 2 demonstrate the performance of $m_{\text{corrected}}$. For cases where there are missing daughters, the $m_{\text{corrected}}$ distributions are fairly narrow and peak near the B mass. When the trigger candidate is formed from all of the daughters, the $m_{\text{corrected}}$ distributions, as expected, are slightly wider and shifted upwards by a small amount as compared with the mass distributions. Thus, the performance of $m_{\text{corrected}}$ is ideal for an inclusive trigger line. The HLT2 topological lines require 4 GeV $< m_{\text{corrected}} <$ 7 GeV.

Because B's are heavy high-momentum particles, their daughters tend to have large P_T values. The HLT2 topological lines use this fact to reduce the background retention rate by requiring the P_T of the hardest daughter be greater than 1.5 GeV and also that the sum of the daughter P_T values be greater than 4 GeV, 4.25 GeV and 4.5 GeV for the 2-body, 3-body and 4-body lines, respectively. To further reduce the background rate

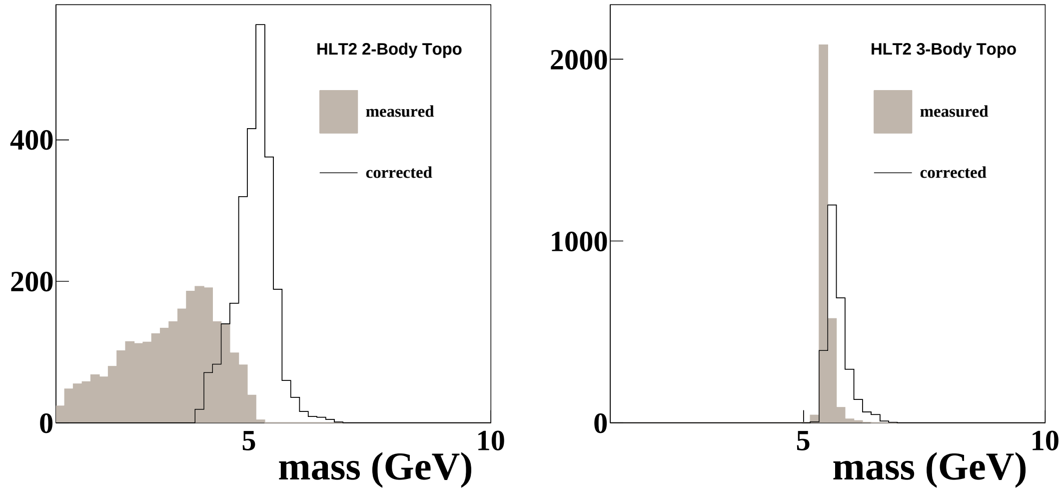

Figure 1: B-candidate masses from $B \to K\pi\pi$ decays: (left) HLT2 2-body topological trigger candidates; (right) HLT2 3-body topological trigger candidates. In each plot, both the measured mass of the $n = 2, 3$ particles used in the trigger candidate (shaded) and the corrected mass obtained using Eq. 1 (unshaded) are shown. See Section 2 for discussion.

from candidates with ghost tracks and to keep the HLT2 topological lines in line with HLT1, the HLT2 topological lines require that at least one daughter particle has a track χ^2 value less than 3.

B mesons are long-lived particles; their mean flight distance in the LHCb detector is $\mathcal{O}(1\text{ cm})$. The HLT2 topological lines exploit this fact by requiring that the trigger candidate's flight-distance χ^2 value be greater than 64. The direction of flight is also required to be downstream, *i.e.*, the secondary vertex must be downstream of the primary vertex. A large flight distance combined with a high parent mass results (on average) in daughters with large impact parameters. The HLT2 topological lines require that the sum of the daughter IPχ^2 values be greater than 100, 150 and 200 for the 2-body, 3-body and 4-body lines, respectively.

One of the larger background contributions to the HLT2 topological lines comes from prompt D mesons. To reduce this background, the HLT2 topological lines require that all $(n-1)$-body objects used by an n-body line either have a mass greater than 2.5 GeV (the object is too heavy to be a D) or that they have an IP$\chi^2 > 16$ (the object does not point at the primary vertex). An exhaustive list of the cuts used in all three of the HLT2 topological lines is given in Table 1.

3 Performance

Table 2 gives the efficiency of the HLT2 topological lines on events that pass the L0 and HLT1 one-track triggers for various offline-selected B-decay Monte Carlo samples.

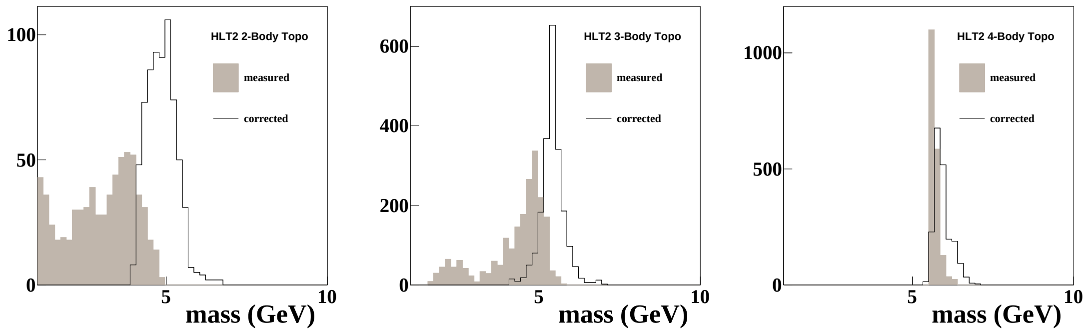

Figure 2: B-candidate masses from $B \to K^* \mu\mu$ decays: (left) HLT2 2-body topological trigger candidates; (center) HLT2 3-body topological trigger candidates; (right) HLT2 4-body topological trigger candidates. In each plot, both the measured mass of the $n = 2, 3, 4$ particles used in the trigger candidate (shaded) and the corrected mass obtained using Eq. 1 (unshaded) are shown. See Section 2 for discussion.

Table 1: All of the selection criteria used in the HLT2 topological lines.

Quantity	Selection Criteria
all input particle transverse momenta	$P_T^{\text{min}} > 500$ MeV
all input particle momenta	$P^{\text{min}} > 5$ GeV
all input particle track χ^2 values	track $\chi^2_{\text{max}} < 5$
all input particle IPχ^2 values	IP$\chi^2_{\text{min}} > 16$
B candidate corrected mass	4 GeV $< M_{\text{corrected}} <$ 7 GeV
hardest daughter momentum	$P_T^{\text{max}} > 1.5$ GeV
best daughter track χ^2	track $\chi^2_{\text{min}} < 3$
sum of daughter transverse momenta	$\sum P_T >$ 4,4.25,4.5 GeV (2,3,4-body)
sum of daughter IPχ^2	$\sum$ IP$\chi^2 >$ 100,150,200 (2,3,4-body)
particle/particle & particle/n-body DOCA	DOCA $<$ 0.15 mm
B candidate flight distance χ^2	FD$\chi^2 > 64$
B candidate signed flight distance	FD > 0
prompt D veto	$M >$ 2.5 GeV OR 2,3-body IP$\chi^2 > 16$

The results are impressive; the HLT2 topological lines are typically 85%-90% efficient for B decays that do not have any K_S, π^0 or ν daughters. The retention fraction of the HLT2 topological lines on minimum-bias events is shown in Figure 3. The statistical uncertainties are fairly large, but the performance under the 2010 running conditions is acceptable for $\mu \leq 2.5$.

For many analyses, the most important quality of a trigger is not the global efficiency but rather the lack of any biasing of kinematic distributions. Figure 4 shows the effect of the HLT2 topological lines on the Dalitz-plot distribution of the decay $B \to K\pi\pi$. The inclusive nature of the HLT2 topological lines leads to a trigger which does not bias the

Table 2: Signal efficiency of the HLT2 topological trigger lines on events that pass the L0 and HLT1 one-track triggers.

channel	efficiency	channel	efficiency
$B \to D(K\pi)K$	92%	$B \to K\pi\pi$	90%
$B \to D(K\pi)K\pi$	87%	$B \to D(4h)K$	89%
$B \to K^*\mu\mu$	87%	$B \to K^*ee$	83%
$B \to D(K_S^{\rm LL}\pi\pi)K$	73%	$B \to D(K_S^{\rm DD}\pi\pi)K$	70%
$B \to D_s(KK\pi)K\pi\pi$	84%		

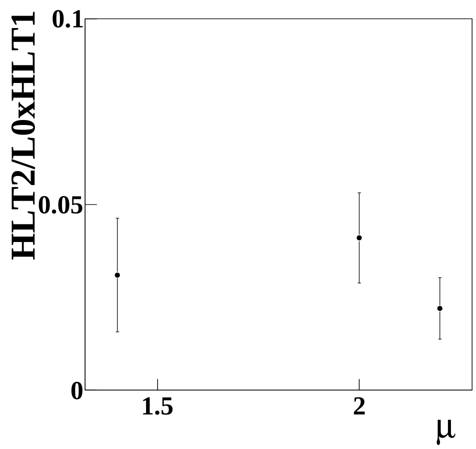

Figure 3: Fraction of events that pass L0xHLT1 that also pass the HLT2 topological trigger lines *vs.* μ.

Dalitz plot. If the HLT2 topological lines were not designed to trigger inclusively, *i.e.*, if they required all three tracks to form a trigger candidate that passes, then the $P_T^{\rm min} >$ 500 MeV cut applied in the HLT2 reconstruction would strongly bias the edges of the Dalitz plot. Figure 5 shows the efficiency of HLT2 lines on $B \to K^*\mu\mu$ events that pass the L0 and HLT1 one-track triggers. Again, the HLT2 topological lines do not bias the angular distributions. Thus, the inclusive nature of the HLT2 topological lines is vitally important to decays such as $B \to K^*\ell\ell$, $B \to hhh$, $B \to D(hh)K\pi$, $B \to D(hhh)K$, *etc.* The HLT2 topological lines are highly efficient and non-biasing on n-body B decays and provide a large background rejection factor.

4 Timing

To study the timing of the HLT2 topological trigger lines, we ran over several large samples of minimum bias data, each with a different average value of μ. The tests were performed on a machine that is similar to those used in the HLT farm in order to approximate the

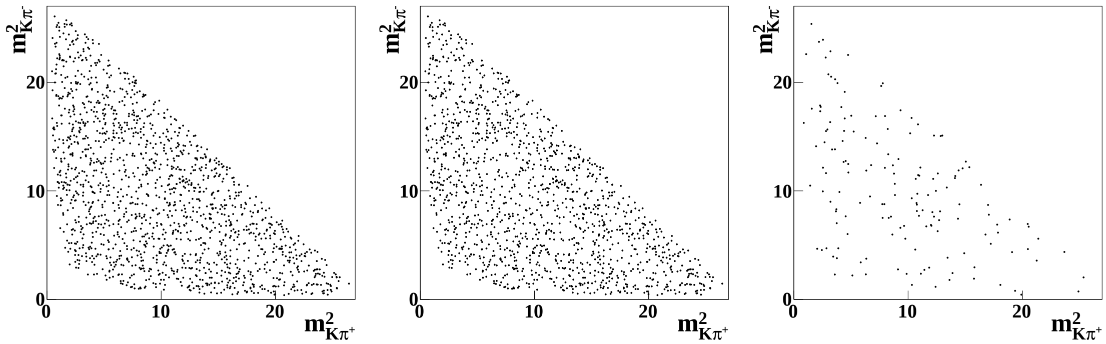

Figure 4: Dalitz-plot distributions from $B \to K\pi\pi$ decays: (left) events that pass the L0 and HLT1 one-track triggers; (center) events from (left) that also pass the HLT2 topological trigger; (right) events from (left) that fail the HLT2 topological trigger.

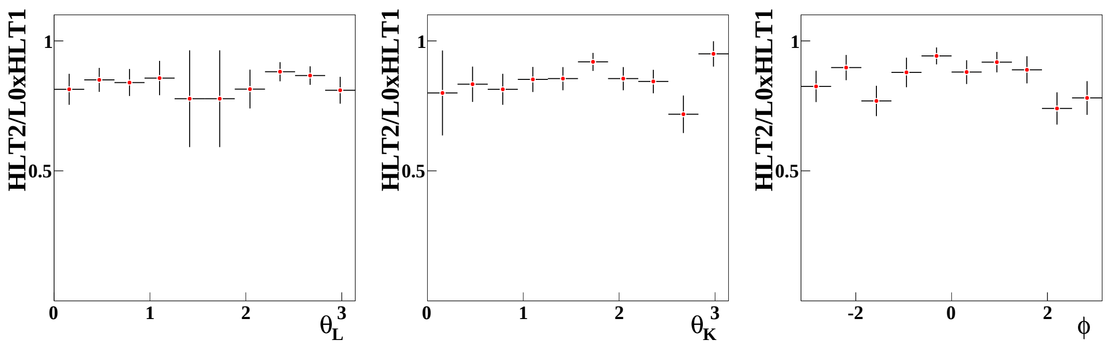

Figure 5: HLT2 efficiency for $B \to K^*\mu\mu$ events that pass L0 and the HLT1 one-track lines *vs* (left) θ_L; (center) θ_K; (right) ϕ. The uncertainties are binomial.

online trigger performance as closely as possible. Moore v10r2 was run with standardised threshold settings (Physics_3000Vis_200L0_20Hlt1_CoreHlt2_Oct10) and with L0TCK set to 0x002a. The timing for each algorithm was obtained from the log file produced at the end of each Moore job. Tables 3–6 show the results for each algorithm for $\mu = 0.234$, 0.840, 1.405 and 1.896.

The most time-expensive sub-algorithms are the multibody combinatoric algorithms (Hlt2TopoOSTF[2,3,4]BodyCombine) and the filters applied to the combined objects (Hlt2OSTFTopo[2,3,4]BodyFilter). The input particle filter applied before the two-body stage (Hlt2TopoOSTFInputKaonsFilter) also takes up a non-negligible (but small) amount of time. The time per event of the 2, 3 and 4-body lines increases steadily with increasing μ. This is expected because a higher μ results in a higher track multiplicity per event and hence more combinatorics. There is one exception to this trend: the time per event of the 4-body lines decreases from 0.170ms to 0.112ms between $\mu = 1.405$ and $\mu = 1.896$. This is due to some exceptionally noisy events in the $\mu = 1.405$ sample; however, the overall trend is clear.

In order to study the timing of the topological algorithms further, we ran the HLT2

Table 3: Topological timing, default setup, $\mu = 0.234$

Algorithm	Time per event (ms)	Number of events	Total time (s)
Hlt2TopoOSTF2Body	0.080	9971	0.795
Hlt2TopoOSTF2BodyPreScale	0.002	9971	0.018
Hlt2TopoOSTF2BodyHltFilter	0.010	9971	0.102
Hlt2TopoOSTF2BodyVoidFilter	0.009	2368	0.022
Hlt2TopoOSTF2BodyFilterSequence	0.173	2368	0.410
Hlt2TopoKillTooManyInTrkAlg	0.011	2368	0.026
Hlt2TopoOSTFInputKaonsFilter	0.093	1998	0.186
Hlt2TopoOSTF2BodyCombine	0.145	729	0.106
Hlt2OSTFTopo2BodyFilter	0.049	89	0.004
Hlt2TopoOSTF2BodyDecision	0.003	2	0.000
Hlt2TopoOSTF2BodyPostScale	0.002	2	0.000
Hlt2TopoOSTF3Body	0.042	9971	0.421
Hlt2TopoOSTF3BodyPreScale	0.002	9971	0.018
Hlt2TopoOSTF3BodyHltFilter	0.010	9971	0.104
Hlt2TopoOSTF3BodyVoidFilter	0.010	2368	0.023
Hlt2TopoOSTF3BodyFilterSequence	0.016	2368	0.039
Hlt2TopoOSTF3BodyCombine	0.278	89	0.025
Hlt2OSTFTopo3BodyFilter	0.144	26	0.004
Hlt2TopoOSTF3BodyDecision	0.003	6	0.000
Hlt2TopoOSTF3BodyPostScale	0.002	6	0.000
Hlt2TopoOSTF4Body	0.041	9971	0.405
Hlt2TopoOSTF4BodyPreScale	0.002	9971	0.019
Hlt2TopoOSTF4BodyHltFilter	0.010	9971	0.099
Hlt2TopoOSTF4BodyVoidFilter	0.009	2368	0.021
Hlt2TopoOSTF4BodyFilterSequence	0.012	2368	0.029
Hlt2TopoOSTF4BodyCombine	0.669	26	0.017
Hlt2OSTFTopo4BodyFilter	0.455	10	0.005
Hlt2TopoOSTF4BodyDecision	0.003	3	0.000
Hlt2TopoOSTF4BodyPostScale	0.002	3	0.000
Total topological	0.163	9971	1.621
Total HLT2	8.891	9971	88.652
Topological/HLT (%)	1.83		1.83

topological trigger lines in isolation on the same sample of $\mu = 1.896$ data; all other HLT lines were turned off. This is a hypothetical situation that shows how the topological trigger would perform if all of its external dependencies were called during its operation. The results are shown in Table 7. The timing performance of the 3 and 4-body lines was not affected by this change (as expected); thus, the results for these lines are not included in the table. The HLT2 topological trigger lines rely on some relatively time-expensive algorithms, in particular Hlt2RecoVeloGeneral (1.246 ms/event), Hlt2RecoForward (14.864 ms/event) and Hlt2BiKalmanFittedForward (13.624 ms/event); however, these algorithms are used by almost all of the other HLT2 lines as well.

The HLT2 topological trigger takes a very short amount of time when compared to the overall HLT2; about $1.5-2\%$ of the total time per event. This has been verified on several data samples.However, in the future improvements to the timing may be required;

Table 4: Topological timing, default setup, $\mu = 0.840$

Algorithm	Time per event (ms)	Number of events	Total time (s)
Hlt2TopoOSTF2Body	0.112	4631	0.518
Hlt2TopoOSTF2BodyPreScale	0.002	4631	0.009
Hlt2TopoOSTF2BodyHltFilter	0.010	4631	0.047
Hlt2TopoOSTF2BodyVoidFilter	0.009	1358	0.013
Hlt2TopoOSTF2BodyFilterSequence	0.245	1358	0.333
Hlt2TopoKillTooManyInTrkAlg	0.010	1358	0.014
Hlt2TopoOSTFInputKaonsFilter	0.136	1184	0.161
Hlt2TopoOSTF2BodyCombine	0.176	550	0.097
Hlt2OSTFTopo2BodyFilter	0.061	71	0.004
Hlt2TopoOSTF2BodyDecision	0.003	3	0.000
Hlt2TopoOSTF2BodyPostScale	0.002	3	0.000
Hlt2TopoOSTF3Body	0.050	4631	0.231
Hlt2TopoOSTF3BodyPreScale	0.002	4631	0.008
Hlt2TopoOSTF3BodyHltFilter	0.010	4631	0.047
Hlt2TopoOSTF3BodyVoidFilter	0.009	1358	0.012
Hlt2TopoOSTF3BodyFilterSequence	0.038	1358	0.051
Hlt2TopoOSTF3BodyCombine	0.557	71	0.040
Hlt2OSTFTopo3BodyFilter	0.171	26	0.004
Hlt2TopoOSTF3BodyDecision	0.003	5	0.000
Hlt2TopoOSTF3BodyPostScale	0.001	5	0.000
Hlt2TopoOSTF4Body	0.057	4631	0.264
Hlt2TopoOSTF4BodyPreScale	0.002	4631	0.009
Hlt2TopoOSTF4BodyHltFilter	0.010	4631	0.046
Hlt2TopoOSTF4BodyVoidFilter	0.009	1358	0.012
Hlt2TopoOSTF4BodyFilterSequence	0.065	1358	0.088
Hlt2TopoOSTF4BodyCombine	2.754	26	0.072
Hlt2OSTFTopo4BodyFilter	0.909	13	0.012
Hlt2TopoOSTF4BodyDecision	0.003	2	0.000
Hlt2TopoOSTF4BodyPostScale	0.002	2	0.000
Total topological	0.219	4631	1.013
Total HLT2	13.177	4631	61.023
Topological/HLT (%)	1.66		1.66

some possibilities are discussed in Section 5.

5 Future Improvements

The HLT2 topological trigger already delivers a very impressive performance, both in terms of rejecting backgrounds and retaining signal; however, the running conditions in 2011 are expected to be much harsher than those used in 2010, so it is likely that the performance of the HLT2 topological lines will need to be improved even further. *E.g.* the number of colliding bunches in the LHC is expected to be (at least) twice what it was in 2010 in 2011. Thus, to keep the output rate near 2 kHz the HLT2 topological background rejection factor will need to be increased by (at least) a factor of two. Other changes

Table 5: Topological timing, default setup, $\mu = 1.405$

Algorithm	Time per event (ms)	Number of events	Total time (s)
Hlt2TopoOSTF2Body	0.156	4458	0.696
Hlt2TopoOSTF2BodyPreScale	0.002	4458	0.009
Hlt2TopoOSTF2BodyHltFilter	0.010	4458	0.045
Hlt2TopoOSTF2BodyVoidFilter	0.009	1482	0.014
Hlt2TopoOSTF2BodyFilterSequence	0.347	1481	0.513
Hlt2TopoKillTooManyInTrkAlg	0.010	1481	0.015
Hlt2TopoOSTFInputKaonsFilter	0.201	1346	0.271
Hlt2TopoOSTF2BodyCombine	0.199	735	0.146
Hlt2OSTFTopo2BodyFilter	0.054	110	0.006
Hlt2TopoOSTF2BodyDecision	0.003	7	0.000
Hlt2TopoOSTF2BodyPostScale	0.002	7	0.000
Hlt2TopoOSTF3Body	0.073	4458	0.326
Hlt2TopoOSTF3BodyPreScale	0.002	4458	0.008
Hlt2TopoOSTF3BodyHltFilter	0.010	4458	0.046
Hlt2TopoOSTF3BodyVoidFilter	0.009	1482	0.013
Hlt2TopoOSTF3BodyFilterSequence	0.098	1481	0.146
Hlt2TopoOSTF3BodyCombine	1.163	110	0.128
Hlt2OSTFTopo3BodyFilter	0.229	38	0.009
Hlt2TopoOSTF3BodyDecision	0.003	7	0.000
Hlt2TopoOSTF3BodyPostScale	0.001	7	0.000
Hlt2TopoOSTF4Body	0.170	4458	0.756
Hlt2TopoOSTF4BodyPreScale	0.002	4458	0.008
Hlt2TopoOSTF4BodyHltFilter	0.010	4458	0.044
Hlt2TopoOSTF4BodyVoidFilter	0.009	1482	0.013
Hlt2TopoOSTF4BodyFilterSequence	0.392	1481	0.580
Hlt2TopoOSTF4BodyCombine	13.771	38	0.523
Hlt2OSTFTopo4BodyFilter	5.534	9	0.050
Hlt2TopoOSTF4BodyDecision	0.004	2	0.000
Hlt2TopoOSTF4BodyPostScale	0.002	2	0.000
Total topological	0.399	4458	1.778
HLT2	19.142	4458	85.335
Topological/HLT (%)	2.08		2.08

in the running conditions currently being considered could force the HLT2 topological background rejection factor to be increased by as much as a factor of 5. This section describes two possible approaches to make the HLT2 topological trigger more robust against possible future (extreme) running conditions.

5.1 Multivariate Cuts

The current HLT2 topological trigger lines are implemented using a simple cut-based scheme. Each of the cuts made on the variables used in these lines has already been tightened as much as possible without losing significant fractions of signal events; thus, any further increase in the background rejection factor will also result in a noticable loss of signal. This is a problem since we know that a large increase in the background rejection

Table 6: Topological timing, default setup, $\mu = 1.896$

Algorithm	Time per event (ms)	Number of events	Total time (s)
Hlt2TopoOSTF2Body	0.206	7807	1.612
Hlt2TopoOSTF2BodyPreScale	0.002	7807	0.014
Hlt2TopoOSTF2BodyHltFilter	0.010	7807	0.079
Hlt2TopoOSTF2BodyVoidFilter	0.009	2730	0.025
Hlt2TopoOSTF2BodyFilterSequence	0.474	2725	1.291
Hlt2TopoKillTooManyInTrkAlg	0.010	2725	0.028
Hlt2TopoOSTFInputKaonsFilter	0.286	2548	0.729
Hlt2TopoOSTF2BodyCombine	0.236	1517	0.357
Hlt2OSTFTopo2BodyFilter	0.045	288	0.013
Hlt2TopoOSTF2BodyDecision	0.004	8	0.000
Hlt2TopoOSTF2BodyPostScale	0.002	8	0.000
Hlt2TopoOSTF3Body	0.065	7807	0.504
Hlt2TopoOSTF3BodyPreScale	0.002	7807	0.015
Hlt2TopoOSTF3BodyHltFilter	0.010	7807	0.081
Hlt2TopoOSTF3BodyVoidFilter	0.009	2730	0.025
Hlt2TopoOSTF3BodyFilterSequence	0.068	2725	0.185
Hlt2TopoOSTF3BodyCombine	0.548	288	0.158
Hlt2OSTFTopo3BodyFilter	0.100	76	0.008
Hlt2TopoOSTF3BodyDecision	0.003	7	0.000
Hlt2TopoOSTF3BodyPostScale	0.002	7	0.000
Hlt2TopoOSTF4Body	0.112	7807	0.871
Hlt2TopoOSTF4BodyPreScale	0.002	7807	0.014
Hlt2TopoOSTF4BodyHltFilter	0.010	7807	0.077
Hlt2TopoOSTF4BodyVoidFilter	0.009	2730	0.024
Hlt2TopoOSTF4BodyFilterSequence	0.207	2725	0.564
Hlt2TopoOSTF4BodyCombine	6.882	76	0.523
Hlt2OSTFTopo4BodyFilter	1.454	20	0.029
Hlt2TopoOSTF4BodyDecision	0.004	3	0.000
Hlt2TopoOSTF4BodyPostScale	0.004	3	0.000
Total topological	0.383	7807	2.987
Total HLT2	25.104	7807	195.983
Topological/HLT (%)	1.53		1.52

factor will be needed in 2011.

The most efficient way to separate signal and background in a multivariate analysis is to use a multivariate classifier (*e.g.*, an artifical neural network, a boosted decision tree, *etc.*). One problem with using these types of methods in the trigger is that the available signal samples are all from Monte Carlo data that has known discrepancies with real LHC*b* data. One could then ask: can we trust that the multivariate classifier has been trained in a way that these discrepancies won't affect its performance on the real data? Another possible problem is that multivariate classifiers often select small and disjoint regions of phase space. If these regions of phase space are small relative to the resolution and stability of the detector, then the trigger performance could vary wildly during actual data-taking conditions. A solution to these problems has been found and is currently being optimized for the 2011 running conditions. Preliminary tests show that

Table 7: Topological timing, topological in isolation, $\mu = 1.896$

Algorithm	Time per event (ms)	Number of events	Total time (s)
Hlt2TopoOSTF2Body	11.250	7775	87.468
Hlt2TopoOSTF2BodyPreScale	0.002	7775	0.014
Hlt2TopoOSTF2BodyHltFilter	0.010	7775	0.077
Hlt2TopoOSTF2BodyVoidFilter	0.013	2688	0.035
Hlt2TopoOSTF2BodyFilterSequence	32.411	2688	87.120
Hlt2RecoVeloGeneral	1.246	2688	3.350
Hlt2RecoForward	14.864	2688	39.955
Hlt2UnfittedForwardInser	0.042	2688	0.114
Hlt2UnfittedForwardTrack	0.106	2688	0.284
Hlt2TopoKillTooManyInTrkAlg	0.016	2688	0.042
Hlt2BiKalmanFittedForwar	13.624	2606	35.504
Hlt2BiKalmanFittedKaons	0.137	2606	0.358
Hlt2TopoOSTFInputKaonsFilter	0.337	2508	0.845
Hlt2TopoOSTF2BodyCombine	0.286	1493	0.427
Hlt2OSTFTopo2BodyFilter	0.044	284	0.013
Hlt2TopoOSTF2BodyDecision	0.004	10	0.000
Hlt2TopoOSTF2BodyPostScale	0.002	10	0.000

this solution may be able to obtain a large reduction in the background retention rate while maintaining (or even increasing) the signal efficiency.

It is possible to make sizeable gains in signal efficiency by loosening the cut on the impact parameter χ^2 value made at the input particle filtering stage. The problem with this is that loosening this cut greatly increases the amount of time it takes to run the HLT2 topological lines (since many more prompt particles are considered in the combinatorics). Thus, to make these gains in signal efficiency online we need to reduce the timing in other ways. One possibility is to simply cut harder on the track χ^2 values at the input particle filtering stage. Another method is discussed in the next section. The next version of the HLT2 topological lines will most likely include some combination of both of these methods for increasing the timing performance.

5.2 TOS filter

Studies on Monte Carlo data show that trigger decisions of the HLT1 1-track and HLT2 topological triggers are highly correlated for hadronic B-decays. Futhermore, offline analyses are typically only interested in events that are TOS with respect to both of these trigger lines. Table 8 shows the relative efficiency between the topological and 1-track lines in terms of both decisions and TOS classification. Only events that passed both the 1-track and topological lines were considered. The events used to evaluate the TOS efficiency were required to be TOS at both stages. Unsuprisingly, most events that pass the 1-track trigger are TOS with respect to this trigger. In this context, a track is TOS if the set of LHCbIDs associated with the 1-track trigger decision is predominantly contained in the set of LHCbIDs of the track itself.

Table 8: Efficiency of the topological lines with respect to the 1-track lines for different decay channels. The Decision column shows the fraction of events passing the topological lines that also pass the 1-track; the TOS column shows the fraction of events that are TOS with respect to the topological lines that are also TOS with respect to the 1-track lines.

Decay mode	Decision (%)	TOS (%)
$B^\pm \to hhh$	91.6 ± 0.9	93.0 ± 0.8
$B^\pm \to (K^\pm\pi^\mp)_D K^\pm$	93.7 ± 1.2	94.8 ± 1.1
$B^\pm \to (K^\pm\pi^\mp\pi^0)_D K^\pm$	78.1 ± 1.9	80.1 ± 1.9
$B^\pm \to (K_S^{0\,DD}\pi^\pm\pi^\mp)_D K^\pm$	76.3 ± 1.7	77.1 ± 1.7

Requiring that a HLT2 topological trigger candidate is TOS with respect to the 1-track trigger should retain nearly all of the signal candidates, while reducing the minimum bias retention rate. One would also expect such a requirement to significantly reduce the time it takes to run the HLT2 topological lines due to the large reduction in the combinatorics. This will be especially useful during the high pileup running conditions expected in 2011. Two methods of incorporating this requirement into the HLT2 topological trigger lines are investigated in this section. Both methods use the TisTosParticleTagger [5], a DVAlgorithm that is able to perform TISTOS decisions on the fly in the HLT and filter particles according to user-specified criteria.

5.2.1 Two-body TOS filter

The current (or default) HLT2 topological lines proceed as shown in Figure 6. In Section 4 we showed that the 3 and 4-body lines take up most of the HLT2 topological running time. Therefore, it is desirable to enforce the 1-track-TOS requirement before these lines are run. We will first explore inserting the TOS filter in the 2-body combinatoric stage, after the 2-body combinatoric container has been created. We found that the precise location of the TOS filter in the 2-body stage does not make a significant difference to the timing.

A 2-body object is passed by the TOS filter if at least one of the constituent tracks is TOS with respect to the 1-track trigger. For the majority of cases, the constituent track that passes this criteria is, in fact, the same track used by the 1-track trigger.

The selection efficiency of the topological trigger both with and without the 2-body TOS filter on several hadronic B decays is shown in Table 9. Both the ratio of positive decisions and the ratio of positive TOS classifications (using the offline B-candidate as signal) between each stage are shown. An event must have passed the 1-track stage before it is used to evaluate the topological selection efficiency. Both types of efficiency decrease by $3-5\%$ when the 2-body TOS filter is used. In particular, some events that are TOS with respect to both the 1-track and topological lines are lost; this is undesirable. The reason for this loss is that the cuts made at the 2-body and 3-body stages are not symmetric; *i.e.*, it does matter at which stage a track is added. *E.g.*, for $B \to DX$ decays the bachelor is the track that is most likely to have passed the 1-track trigger; however,

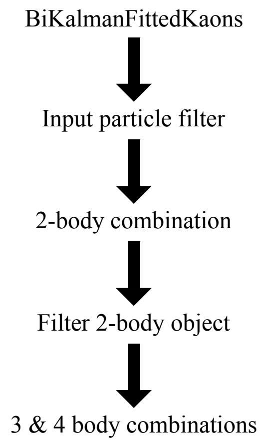

Figure 6: Topological default progression.

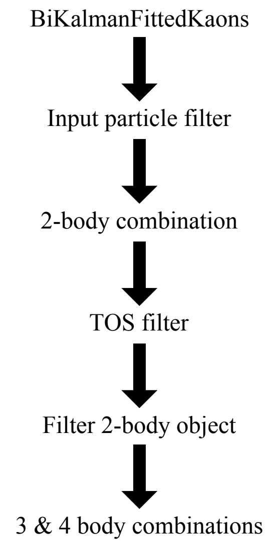

Figure 7: Topological TOS filter progression.

some events will only pass the HLT2 topological trigger by using the bachelor at the 3-body stage (not the 2-body stage). Such events will fail the TOS filter used in this section.

Table 9: Efficiency of the topological lines with respect to the 1-track lines for different decay channels, both with and without the 2-body TOS filter. The Decision column shows the fraction of events passing the topological lines that also pass the 1-track; the TOS column shows the fraction of events that are TOS with respect to the topological lines that are also TOS with respect to the 1-track lines.

Decay mode	Default topo		Topo with 2-body TOS filter	
	Decision (%)	TOS (%)	Decision (%)	TOS (%)
$B^{\pm} \to hhh$	91.6 ± 0.9	93.0 ± 0.8	88.8 ± 1.0	89.9 ± 0.9
$B^{\pm} \to (K^{\pm}\pi^{\mp})_D K^{\pm}$	93.7 ± 1.2	94.8 ± 1.1	90.6 ± 1.4	91.6 ± 1.4
$B^{\pm} \to (K^{\pm}\pi^{\mp}\pi^0)_D K^{\pm}$	78.1 ± 1.9	80.1 ± 1.9	74.3 ± 2.0	75.8 ± 2.0
$B^{\pm} \to (K_S^{0\,DD}\pi^{\pm}\pi^{\mp})_D K^{\pm}$	76.3 ± 1.7	77.1 ± 1.7	71.8 ± 1.8	72.4 ± 1.8

5.2.2 Parallel TOS filter

Another way to implement a TOS filter is to check for the presence of the TOS particle in the input Kaon container. To do this, all of the input Kaons are passed through the TOS filter; if the resulting container contains at least one Kaon the TOS particle is assumed to be present and the HLT2 topological lines executes as normal. Conversely, if the container is empty the event is skipped without proceeding with the combinatorics. In contrast to the two-body TOS filter, the TOS-filtered particles are not used in the topological any further. A `LoKi::VoidFilter` is used to check the size of the TOS-filtered container. This progression is shown in Figure 8. Hadronic B decays that pass the 1-track line should not be affected by this filter, but it should still have good rejection power on minimum bias events, especially those with high pileup. The effects on selection efficiencies are shown in Table 10. The parallel TOS filter has only a small decrease in efficiency when compared to the default setup. In addition it does not remove any events that are TOS with respect to both the 1-track and topological lines, which is an improvement over the two-body TOS filter (note that some events that are TOS with respect to only one stage are removed).

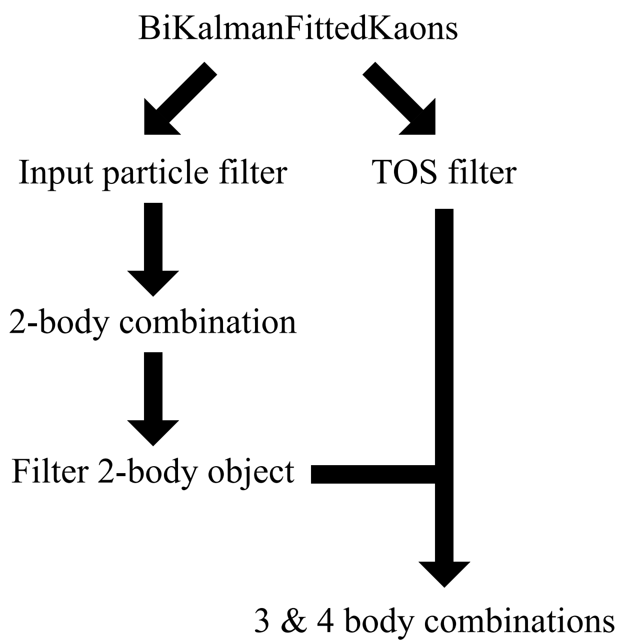

Figure 8: Progression of the parallel TOS filter

Table 10: 1-track/topological efficiencies for various channels and TOS filters.

Decay mode	Default topo		Topo with 2-body TOS filter		Topo with parallel TOS filter	
	Decision (%)	TOS (%)	Decision (%)	TOS (%)	Decision (%)	TOS (%)
$B^{\pm} \to hhh$	91.6 ± 0.9	93.0 ± 0.8	88.8 ± 1.0	89.9 ± 0.9	91.1 ± 0.9	92.5 ± 0.8
$B^{\pm} \to (K^{\pm}\pi^{\mp})_D K^{\pm}$	93.7 ± 1.2	94.8 ± 1.1	90.6 ± 1.4	91.6 ± 1.4	93.5 ± 1.2	94.6 ± 1.1
$B^{\pm} \to (K^{\pm}\pi^{\mp}\pi^0)_D K^{\pm}$	78.1 ± 1.9	80.1 ± 1.9	74.3 ± 2.0	75.8 ± 2.0	77.9 ± 1.9	79.9 ± 1.9
$B^{\pm} \to (K_S^{0\,DD}\pi^{\pm}\pi^{\mp})_D K^{\pm}$	76.3 ± 1.7	77.1 ± 1.7	71.8 ± 1.8	72.4 ± 1.8	75.7 ± 1.7	76.4 ± 1.8

5.2.3 Timing results

The effects of both the 2-body and parallel TOS filters on the HLT2 topological timing were determined by running over the same high-statistics sample of $\mu = 1.896$ data used in Section 4. The results are shown in Table 11. Both TOS filter implementations reduce the timing significantly, especially for the multibody combinatorics, but there is some extra overhead introduced by loading the TisTosParticleTagger.

Table 11: Timing results for various TOS filtering schemes.

Topological type	Time per event (ms)				Total time (s)			
	Two-body	Three body	Four body	Total	Two-body	Three body	Four body	Total
Default	0.202	0.066	0.096	0.364	1.573	0.516	0.749	2.838
Two-body TOS filter	0.206	0.045	0.041	0.292	1.600	0.346	0.321	2.267
Parallel TOS filter	0.182	0.046	0.043	0.271	1.410	0.358	0.332	2.100

5.2.4 Conclusions

Two types of TOS filter have been investigated, both of which exploit the fact that most events that pass the topological are TOS with respect to the 1-track lines. Both filters improve the background rejection and timing performance of the HLT2 topological trigger lines. The parallel TOS filter yields a very small decrease in signal efficiency and retains all of the events that are TOS at both HLT stages; therefore, it would seem that this is the more promising approach.

6 Conclusions

The HLT2 topological lines are highly efficient on almost all hadronic B decays and provide a large background rejection factor. Due to the inclusive nature of their design, they induce a minimum amount of biasing in Dalitz-plot and other kinematic distributions. Further improvements will need to be made to handle the 2011 running conditions at the LHC. Work has begun on these improvements and we expect the performance of the HLT2 topological lines to continue to be excellent in the future under any running conditions.

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