Fat Jets for a Light Higgs

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At the LHC associated top quark and Higgs boson production with a Higgs decay to bottom quarks has long been a heavily disputed search channel. Recently, it has been found to not be viable. We show how it can be observed by tagging massive Higgs and top jets. For this purpose we construct boosted top and Higgs taggers for Standard Model processes in a complex QCD environment.

The main task of the LHC is to understand electroweak symmetry breaking, e.g. by confirming or modifying the minimal Higgs mechanism of the Standard Model [1, 2]. In the Standard Model as well as its typical perturbative extensions, electroweak precision data clearly prefer a light Higgs boson [3], most likely well below the threshold of Higgs decays to W bosons. If only because 68% of light Higgs bosons (m_H = 120 GeV) decay to bottom quarks [4], we should look for this Higgs signature.

Over the past years, Higgs search strategies based on different production mechanisms have been developed.

The dominant gluon-fusion production process is the only way to reliably measure the top Yukawa. All of these arguments point to a measurement based on a direct (tree level) Higgs production process is the only way to reliably measure the top Yukawa. All of these arguments point to a (too) low signal-to-background ratio S/B ∼ 1/9 this channel might not reach a 5σ significance for any luminosity. The main problems are the combinatorial background of bottom jets and the lack of a truly distinctive kinematic feature of the Higgs decay jets.

Any meaningful analysis of the Higgs sector has to test the Yukawa nature of the Higgs fermion couplings. In addition to the bottom Yukawa coupling discussed above we expect to extract the top Yukawa coupling from one-loop contribution to the higher-dimensional ggH and γγH couplings. However, any kind of new heavy particle will also contribute to both of them, which makes it hard to perform a model independent top coupling measurement. A measurement based on a direct (i.e. tree level) process production is the only way to reliably measure the top Yukawa. All of these arguments point to

\[ pp \rightarrow t\bar{t}H \rightarrow t\bar{t} b\bar{b} \]  \hspace{1cm} (1)

as a prime ingredient for understanding the Higgs sector at the LHC [5].

In this paper we show how, using fat jets, this Standard Model search channel can indeed be extracted with reasonable statistical significance and most importantly a much reduced sensitivity on systematics. The combinatorial problem in the signal we solve by the construction of two fat jets; based on those we find plenty of kinematic distributions which separate signal and background.

Fat jets have been studied in the framework of searches for strongly interacting W bosons [13], supersymmetric particles [16], heavy resonances decaying to strongly boosted top quarks [17], as well as the WH/ZH search mentioned above [8, 10]. For leptonic top quarks they are similar to complex mass and momentum reconstruction tools [18]. Top taggers [19, 20] have been studied in high-p_T contexts, but differ in their applicability once the top quarks are only slightly boosted, E/m_t ≥ 1. Therefore, we construct Standard-Model Higgs and top taggers for tagging in busy environments at moderately high p_T and show how fat Higgs as well as top jets can be used to identify a Standard Model Higgs signature.

The main task of the LHC is to understand electroweak symmetry breaking, e.g. by confirming or modifying the minimal Higgs mechanism of the Standard Model [1, 2]. In the Standard Model as well as its typical perturbative extensions, electroweak precision data clearly prefer a light Higgs boson [3], most likely well below the threshold of Higgs decays to W bosons. If only because 68% of light Higgs bosons (m_H = 120 GeV) decay to bottom quarks [4], we should look for this Higgs signature.

Over the past years, Higgs search strategies based on different production mechanisms have been developed.

The dominant gluon-fusion production process cannot be combined with a decay to bottom quarks, because of its overwhelming QCD background. For this production process all hopes rest on the Higgs decay to photons [6] with its challenging signal-to-background ratio.

Higgs production in weak boson fusion with a decay to bottoms challenges the Atlas and CMS triggers [7]. Combined with a decay to taus instead, it is one of the discovery channels [8] — provided analysis techniques like a central jet veto and collinear ττ mass reconstruction work in the QCD environment of the LHC.

While at the Tevatron the associated ZH and WH production serves as a discovery channel, at the LHC it is plagued by QCD backgrounds. Nevertheless, a recent study has shown that using a fat Higgs jet — i.e. a jet from a massive particle decay with subjet structure — we can extract WH/ZH production with H → bb for a Higgs mass of 120 GeV at the ∼ 4σ level using 30 fb^{-1} of data [8, 10].

Additional search channels like weak-boson-fusion production of γH [11] or WH [12] final states combined with a decay H → bb might be visible, but lack a final experimental word. It is clear, though, that none of them will lead to a discovery in the first years of LHC running.

Last but not least, the associated production of a top quark with a Higgs boson at the LHC has a long history, usually in combination with a Higgs decay to bottoms. At some point it was expected to be the leading discovery channel for a light Higgs boson [13], but recently it has been removed from the Higgs discovery plots by Atlas and CMS [14]. Without systematic uncertainties, Atlas quotes a significance of 1.8 to 2.2σ for 30 fb^{-1}. Due to a (too) low signal-to-background ratio S/B ∼ 1/9 this channel might not reach a 5σ significance for any luminosity. The main problems are the combinatorial background of bottom jets and the lack of a truly distinctive kinematic feature of the Higgs decay jets.
Signal and backgrounds — We consider associated top and Higgs production with one hadronic and one leptonically decaying top. The latter allows the events to pass the Atlas and CMS triggers. The main backgrounds are

\begin{align*}
pp &\rightarrow \bar{t}\bar{t}bb & \text{irreducible QCD background} \\
pp &\rightarrow t\bar{t}Z & \text{irreducible Z-peak background} \\
pp &\rightarrow t\bar{t} + \text{jets} & \text{include fake bottoms} \tag{2}
\end{align*}

To account for higher-order effects we normalize our total signal rate to the next-to-leading order prediction of 702 fb for \(m_H = 120\) GeV \[21\]. The \(\bar{t}\bar{t}b\bar{b}\) continuum background we normalize to 2.6 pb after the acceptance cuts \(|y_b| < 2.5, p_{T,b} > 20\) GeV and \(R_{bb} > 0.8\) of Ref. \[22\]. This conservative rate estimate for very hard events implies a \(K\) factor of \(\sigma_{\text{NLO}}/\sigma_{\text{LO}} = 2.3\) which we need to attach to our leading-order background simulation — compared to \(K = 1.57\) for the signal. Finally, the \(t\bar{t}Z\) background at NLO is normalized to 1.1 pb \[23\]. For \(t\bar{t}\) plus jets production we do not apply a higher-order correction because the background rejection cuts drives it into kinematic configuration in which a constant \(K\) factor cannot be used. Throughout this analysis we use an on-shell top mass of 172.3 GeV. All hard processes we generate using MadEvent \[24\], shower and hadronize via Herwig++ \[25\] (without \(g \rightarrow bb\) splitting) and analyze with FastJet \[26\]. We have verified that we obtain consistent results for signal and background using Alpgen \[27\] and Herwig 6.5 \[28\].

An additional background is \(W + \text{jets}\) production. The \(Wjj\) rate starts from roughly 15 fb with \(p_{T,j} > 20\) GeV. Asking for two very hard jets, mimicking the boosted Higgs and top jets, and a leptonically decaying \(W\) reduces this rate by roughly three orders of magnitude. Our top tagger described below gives a mis-tagging probability around 5% including underlying event, the Higgs mass window another reduction by a factor 1/10, i.e. the final \(Wjj\) rate without flavor tags ranges around 100 fb.

Adding two bottom tags we expect a purely fake-bottom contribution around 0.01 fb. To test the general reliability of bottom tags in QCD background rejection we also simulate the \(Wjj\) background including bottom quarks from the parton shower and find a remaining background of \(\mathcal{O}(0.1)\) fb, well below 10% of the \(tt\) + jets background already for two bottom tags. For three bottom tags it is essentially zero, so we neglect it in the following.

The charm-flavored \(Wc_j\) rate starts off with 1/6 of the purely mis-tagged \(Wjj\) rate. A tenfold mis-tagging probability still leaves this background well below the effect of bottoms from the parton shower. Finally, a lower limit \(m_{bc}^{\text{rec}} > 110\) GeV keeps us safely away from CKM-suppressed \(W \rightarrow bc\) decays where the charm is mis-identified as a bottom jet.

Search strategy — The motivation for a \(t\bar{t}H\) search with boosted heavy states can be seen in Fig. \[1\] the leading top quark and the Higgs boson both carry sizable transverse momentum. We therefore first cluster

\begin{align*}
\text{FIG. 1: Normalized top and Higgs transverse momentum spectra in } t\bar{t}H \text{ production (solid). We also show } p_{T,H} \text{ in } W^+H \text{ production (dashed) and the } p_{T} \text{ of the harder jet in } W^{-}jj \text{ production with } p_{T,j} > 20 \text{ GeV (dotted).}
\end{align*}

The maximum Higgs jet rapidity \(y_j^{(H)}\) is limited by the requirement that it be possible to tag its b-content. For lepton identification and isolation we assume an 80% efficiency, in agreement with what we expect from a fast Atlas detector simulation. The outline of our analysis is then as follows (cross sections at various stages are summarized in Tab. \[1\]):

\begin{align*}
(1) \text{ one of the two jets should pass the top tagger (described below). If two jets pass we choose the one whose top candidate is closer to the top mass.} \\
(2) \text{ the Higgs tagger (also described below) runs over all remaining jets with } |y_j| < 2.5. \text{ It includes a double bottom tag.} \\
(2') \text{ a third } b \text{ tag can be applied in a separate jet analysis after removing the constituents associated with the top and Higgs.} \\
(3) \text{ to compute the statistical significance we require } m_{bc}^{\text{rec}} = m_H \pm 10 \text{ GeV.}
\end{align*}

In this analysis, QCD \(t\bar{t}\) plus jets production can fake the signal assuming three distinct topologies: first, the Higgs candidate jet can arise from two mis-tagged QCD jets. The total rate without flavored jets exceeds \(t\bar{t}bb\) production by a factor of 200. This ratio can be balanced by the two \(b\) tags inside the Higgs resonance. Secondly, there is an \(\mathcal{O}(10\%)\) probability for the bottom from the leptonic top decay to leak into the Higgs jet and combine with a QCD jet, to fake a Higgs candidate. This topology is the most dangerous and can be essentially removed by a third \(b\) tag outside the Higgs and top substructures. Finally, the bottom from the hadronic top can also leak
into the Higgs jet after being replaced by a QCD jet with the appropriate kinematics in the top reconstruction.

These three distinct topologies appear in the $t\bar{t}$ background because of the unusually large QCD jet activity which we corresponds to the huge QCD correction to the total rate. The impact of these background configurations on our analysis critically depends on the detailed simulation of QCD jet radiation in $t\bar{t}$ events. We therefore perform our entire analysis for the minimal two $b$ tags as well as for a safe scenario with three $b$ tags, to achieve a maximal reduction of this background.

**Top and Higgs taggers** — In contrast to other Higgs physics [13] or new physics [15, 16] applications our Higgs and top taggers cannot rely on a clean QCD environment: on the one hand their initial cone size has to be large enough to accommodate only mildly boosted top and Higgs states, so additional QCD jets will contaminate our fat jets [20]. On the other hand, the small number of signal events does not allow any sharp rejection cuts for dirty QCD events. Therefore, the taggers need to be built to survive busy LHC events.

Our starting point is the C/A jet algorithm with $R = 1.5$. For a top candidate, which typically has a jet mass above 200 GeV, we assume that there could be a complex hard substructure inside the fat jet. To reduce this fat jet to the relevant substructures we apply the following recursive procedure. The last clustering of the jet $j$ is undone, giving two subjets $j_1, j_2$, ordered such that $m_{j_1} > m_{j_2}$. If $m_{j_2} > 0.8 m_j$ (i.e. $j_2$ comes from the underlying event or soft QCD emission) we discard $j_2$ and keep $j_1$, otherwise both $j_1$ and $j_2$ are kept; for each subjet $j_i$ that is kept, we either add it to the list of relevant substructures (if $m_{j_i} < 30$ GeV) or further decompose it recursively.

In the resulting set of relevant substructures, we examine all two-subjet configurations to see if they could correspond to a $W$ boson: after filtering as in Ref.9 to reduce contamination from the underlying event, the mass of the substructure pair should be in the range $m_W^{rec} = 65 - 95$ GeV (shown in Fig. 2). To tag the top quark, we then add a third subjet and, again after filtering $t\bar{t}$, require $m_{t\bar{t}}^{rec} = 150 - 200$ GeV. We additionally require that the $W$ helicity angle $\theta$ with respect to the top candidate satisfies $\cos \theta < 0.7$, as in Ref.[19]. For more than one top tag in the event we choose the one with the smaller $|m_{t\bar{t}}^{rec} - m_{t\bar{t}}^{pole}| + |m_{WW}^{pole} - m_{WW}^{pole}|$. The resulting top tagging efficiency in the signal, including underlying event, is 43%, with a 5% mis-tagging probability in $W+\text{jets}$ events. Note that these values hold for only slightly boosted tops and in a particularly complex QCD environment.

In contrast to the top tagger which identifies a top quark using its known mass and properties, our Higgs tagger $t\bar{t}$ has to search for a Higgs peak in the reconstructed $m_{t\bar{t}}^{rec}$ without any knowledge of the Higgs mass. We use the same decomposition procedure described above (but now with a mass cutoff at 40 GeV and a mass drop threshold of 0.9). We then order all possible pairs of subjets by the modified Jade distance [10]

$$J = p_T,1p_T,2(\Delta R_{12})^4,$$

similar to the mass of the hard splitting, but shifted towards larger jet separation. The three leading pairings we filter and keep for the Higgs mass reconstruction. For these events we explicitly confirm that indeed we are dominated by $p_T,H \sim 200$ GeV.

Double vs triple bottom tag — At this stage we have not yet included any flavor tags to control the $t\bar{t}$+jets and $W$+jets backgrounds. To reduce the leading $t\bar{t}$+$jj$ topology we first require two bottom tags for the substructure pairings reconstructing the Higgs. Based on the detector-level study [10] we assume a 70% efficiency with a 1% mis-tagging probability for $b$ tags of filtered Higgs subjets.

We then apply a $\pm 10$ GeV mass window, after checking that the tails of the signal distribution drop sharply in particular towards larger mass values. In the double $b$-tag analysis we find for an integrated luminosity of 100 fb$^{-1}$:

| $m_{bb}^{rec}$ | $m_{WW}^{rec}$ |
|----------------|----------------|
| 120 GeV        | 130 GeV        |

**TABLE I:** Number of events or $m_{bb}^{rec}$ histrogram entries per 1 fb$^{-1}$ including underlying event, assuming $m_H = 120$ GeV. The third row gives the number of events with at least one subjet pairing in the Higgs mass window while the fourth row (and below) gives the number of entries according to our algorithm based on the three leading modified Jade distances.

**FIG. 2:** Individually normalized $m_{WW}^{rec}$ and $m_{t\bar{t}}^{rec}$ distributions for signal and background (with underlying event).
This result shows that we can extract the $t\bar{t}H$ signal with high significance. On the other hand, similar to the original Atlas and CMS analyses it suffers from low $S/B$, the impact of the poorly understood $t\bar{t}$ + jets background with its different kinematic topologies, its large theory uncertainty and potentially large next-to-leading order corrections, and the missing underlying event.

To improve the signal-to-background ratio $S/B$ and remove the impact of the $t\bar{t}$ + jets background (at the expense of the final significance) we can apply a third $b$ tag. Targeting the second $t\bar{t}$ + jets topology we remove the Higgs and top constituents from the event and cluster the remaining particles into jets using the C/A algorithm with $R = 0.6$, considering all jets with $p_T > 30$ GeV. Amongst these jets we require one $b$ tag with $\eta < 2.5$ and a distance $\Delta R_{b,j} > 0.4$ to the Higgs and top sub-jets, assuming $60\%$ efficiency and $2\%$ purity. The last row of Table I confirms that requiring three bottom tags leaves the continuum $t\bar{t}b\bar{b}$ production as the only relevant background.

In Fig. we show the signal from the three leading (by modified Jade distance) $m_{bb}^{\text{rec}}$ entries of double-$b$-tagged combinations; our Higgs tagger returns a sharp mass peak. The bigger tail towards small $m_{bb}^{\text{rec}}$ we can reduce by only including the two leading jet combinations. This does not change the significance but sculpts the background more. Assuming that at this stage we will know the Higgs mass, we estimate the background from a clean right and a reasonably clean left side bin combined with a next-to-leading order prediction. The result of the triple $b$-tag analysis is then (again assuming $100$ fb$^{-1}$):

\[
\begin{array}{cccc}
  m_H & S/B & S/\sqrt{B} \\
  115 \text{ GeV} & 57 & 118 & 1/2.1 & 5.2 (5.7) \\
  120 \text{ GeV} & 48 & 115 & 1/2.4 & 4.5 (5.1) \\
  130 \text{ GeV} & 29 & 103 & 1/3.6 & 2.9 (3.0) \\
\end{array}
\]

The numbers in parentheses are without underlying event. While removing the highly uncertain $t\bar{t}$ + jets background has indeed lowered the final significance, the background of the three $b$-tag analysis is completely dominated by the well-behaved $t\bar{t}b\bar{b}$ continuum production.

Further improvements — One of the problems in this analysis is that higher-order QCD effects harm its reach. Turning this argument around, we can use the additional QCD activity in the signal and continuum $t\bar{t}b\bar{b}$ background to improve our search. Before starting with the fat-jet analysis we can for example analyze the four leading jets with a radius $R = 0.6$ and $p_T < 40$ GeV and require a set of jet-jet and jet-lepton separation criteria [32]: we reject any event for which one of the three

\[
\begin{align*}
\cos \theta^*_{p_1} & < -0.4 \quad \text{and} \quad \Delta k_{T,j} \epsilon \in [70, 160] \text{ GeV} \\
\cos \theta^*_{p_2} & > 0.4 \quad \text{and} \quad \Delta R_{j,j} > 2.5 \\
\Delta R_{j,j} & > 3.5 \quad \text{for any of the four leading jets.}
\end{align*}
\]

conditions holds

$\theta^*_{p_1}$ is the angle between $\vec{p}_1$ in the center-of-mass frame of $P_1 + P_2$ and the center of mass direction ($\vec{p}_1 + \vec{p}_2$) in the lab frame. It is not symmetric in its arguments; if the two particles are back to back and $|\vec{p}_1| > |\vec{p}_2|$ it approaches $\cos \theta^* = 1$, whereas for $|\vec{p}_1| < |\vec{p}_2|$ it becomes $-1$ [32]. The $k_T$ distance between two particles is $(\Delta k_{T,j})^2 = \min(\vec{p}_{1,j}^2, \vec{p}_{2,j}^2) \Delta R_{j,j}^2$. At this stage and with our limited means of detector simulation this QCD pre-selection at least shows that there are handles to further improve $S/B$ from 1/2.4 to roughly 1/2 (for $m_H = 120$ GeV) with hardly any change to the final significance.

In addition, we can envisage improving the analysis in several ways in the context of a full experimental study, including data to help constrain the simulations:

1. Replace the $m_{bb}^{\text{rec}}$ side bins by a likelihood analysis of the well-defined alternative of either $t\bar{t}H$ signal or $t\bar{t}b\bar{b}$ continuum background after three $b$ tags. This increases the final number of events, our most severe limitation.
2. Provided the events can be triggered/tagged, include two hadronic or two leptonic top decays. This more than triples the available rate and includes a combinatorial advantage of requiring one of two tops to be boosted.
3. Without cutting on missing energy as part of the acceptance cuts use its measurement within errors to assign the correct jet to the leptonic top and become less dependent on the third $b$ tag.

Outlook — In this paper we have presented a new strategy to extract the Higgs production process $t\bar{t}H$ with the decay $H \to b\bar{b}$ at the LHC. After long debates this
signature has recently been abandoned by both LHC experiments, even though it would be an especially useful ingredient to a complete Higgs sector analysis at the LHC [3]. We propose two analysis strategies based on a boosted Higgs boson [7] and a boosted top quark; one with a double and one with a triple $b$ tag. The latter compensates its reduced statistical significance with a strongly reduced dependence on systematic uncertainties. The only remaining background after three $b$ tags is continuum $t\bar{t}bb$ production with accessible side bins.

For an integrated luminosity of 100 fb$^{-1}$ and a Higgs mass of 120 GeV our three $b$-tag analysis gives a statistical significance of at least 4.5$\sigma$ and a signal-to-background ratio of at least $S/B = 1/2.4$. The signal-to-background ratio can be further improved using the structure of the QCD radiation for signal and background. Combinatorial backgrounds are not a problem, and we find a multitude of distributions distinguishing between signal and continuum background.

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[1] P. W. Higgs, Phys. Lett. 12, 132 (1964) and Phys. Rev. Lett. 13, 508 (1964); F. Englert and R. Brout, Phys. Rev. Lett. 13, 321 (1964).
[2] A. Djouadi, Phys. Rept. 457, 1 (2008); V. Bösch and K. Jakobs, Int. J. Mod. Phys. A 20, 2523 (2005); D. Rainwater, ATL-PHYS-PUB-2009-088.
[3] M. W. Grunewald, J. Phys. Conf. Ser. 110, 042006 (2008).
[4] A. Djouadi, J. Kalinowski and M. Spira, Comput. Phys. Commun. 108, 56 (1998).
[5] D. Zeppenfeld, R. Kinnunen, A. Nikitenko and E. Richter-Was, Phys. Rev. D 62, 013009 (2000); M. Dührssen et al., Phys. Rev. D 70, 113009 (2004); R. Lafaye, T. Plehn, M. Rauch, D. Zerwas and M. Dührssen, arXiv:0904.3866 [hep-ph].
[6] S. Abdullin, M. Dubinin, V. Ilyin, D. Kovalenko, V. Savrin and N. Stepanov, Phys. Lett. B 431, 410 (1998); F. Stöckli, A. G. Holzner and G. Dissertori, JHEP 0509, 070 (2005).
[7] M. L. Mangano, M. Moretti, F. Piccinini, R. Pittau and A. D. Polosa, Phys. Lett. B 556, 50 (2003).
[8] D. L. Rainwater, D. Zeppenfeld and K. Hagiwara, Phys. Rev. D 59, 014037 (1999); T. Plehn, D. L. Rainwater and D. Zeppenfeld, Phys. Rev. D 61, 093005 (2000); S. Asai et al., Eur. Phys. J. C 3252, 19 (2004).
[9] J. M. Butterworth, A. R. Davison, M. Rubin and G. P. Salam, Phys. Rev. Lett. 100, 242001 (2008).
[10] ATLAS note, ATL-PHYS-PUB-2009-088.
[11] E. Gabrielli et al., Nucl. Phys. B 781, 64 (2007).
[12] D. Rainwater, Phys. Lett. B 503, 320 (2001); A. Ballestrero, G. Bevilacqua and E. Maina, JHEP 0808, 059 (2008).
[13] Z. Kunst, Nucl. Phys. B 247, 339 (1984); W. J. Marciano and F. E. Paige, Phys. Rev. Lett. 66, 2433 (1991); J. F. Gunion, Phys. Lett. B 261, 510 (1991); E. Richter-Was and M. Sapinski, Acta Phys. Polon. B 30, 1001 (1999); V. Droullinger, T. Müller and D. Denegri, arXiv:hep-ph/0111312.
[14] G. L. Bayatian et al. [CMS Collaboration], J. Phys. G 34, 995 (2007); G. Aad et al. [The ATLAS Collaboration], arXiv:0901.0512 [hep-ex].
[15] M. H. Seymour, Z. Phys. C 62, 127 (1994); J. M. Butterworth, B. E. Cox and J. R. Forshaw, Phys. Rev. D 65, 096014 (2002); W. Skiba and D. Tucker-Smith, Phys. Rev. D 75, 115010 (2007); B. Holdom, JHEP 0703, 063 (2007).
[16] J. M. Butterworth, J. R. Ellis and A. R. Raklev, JHEP 0705, 033 (2007); J. M. Butterworth, J. R. Ellis, A. R. Raklev and G. P. Salam, arXiv:0906.0728 [hep-ph]; C. S. Cowden, S. T. French, J. A. Frost and C. G. Lester, ATLAS-PHYS-PUB-2009-076, June 2009.
[17] see e.g. U. Baur and L. H. Orr, Phys. Rev. D 77, 114001 (2008); P. Fileviez Perez, R. Gavin, T. McElmurry and F. Petriello, Phys. Rev. D 78, 115017 (2008); Y. Bai and Z. Han, JHEP 0904, 056 (2009).
[18] see e.g. V. Barger, T. Han and D. G. E. Walker, Phys. Rev. Lett. 100, 031801 (2008); U. Baur and L. H. Orr, Phys. Rev. D 76, 094012 (2007); T. Han, R. Mahbubani, D. G. E. Walker and L. T. E. Wang, JHEP 0905, 117 (2009).
[19] D. E. Kaplan, K. Rehermann, M. D. Schwartz and B. Tweedie, Phys. Rev. Lett. 101, 142001 (2008).
[20] K. Agashe et al. Phys. Rev. D 77, 015003 (2008); G. Brooijmans, ATL-PHYS-CONF-2008-008 and ATL-COM-PHYS-CONF-2008-001, Feb. 2008 J. Thaler and L. T. Wang, JHEP 0807, 092 (2008); L. G. Almeida et al., Phys. Rev. D 79, 074017 (2009); L. G. Almeida et al., Phys. Rev. D 79, 074012 (2009); D. Krohn, J. Thaler and L. T. Wang, arXiv:0903.0392 [hep-ph].
[21] W. Beenakker et al., Phys. Rev. Lett. 87, 201805 (2001); S. Dawson et al., Phys. Rev. D 68, 034022 (2003).
[22] A. Bredenstein, A. Denner, S. Dittmaier and S. Pozzorini, arXiv:0905.0110 [hep-ph]; G. Bevilacqua et al., arXiv:0907.4723 [hep-ph].
[23] A. Lazopoulos, T. McElmurry, K. Melnikov and F. Petriello, Phys. Lett. B 666, 62 (2008).
[24] J. Alwall et al., JHEP 0709, 028 (2007).
[25] M. Bahr et al., arXiv:0812.0529 [hep-ph].
[26] M. Cacciari and G. P. Salam, Phys. Lett. B 641, 57 (2006); M. Cacciari, G. P. Salam and G. Soyez, http://fastjet.fr.
[27] M. L. Mangano, M. Moretti, F. Piccinini, R. Pittau and A. D. Polosa, JHEP 0307, 001 (2003).
[28] G. Corcella et al. [arXiv:hep-ph/0210213]
[29] Y. L. Dokshitzer, G. D. Leder, S. Moretti and B. R. Webber, JHEP 9708, 001 (1997); M. Wobisch and T. Wengler, [arXiv:hep-ph/9907280]
[30] S. D. Ellis, C. K. Vermilion and J. R. Walsh, [arXiv:0903.5081 [hep-ph]].
[31] G. L. Bayatian et al. [CMS Collaboration], J. Phys. G 34, 995 (2007).
[32] for a similar case see e.g. D. O. Carlson and C. P. Yuan, Phys. Lett. B 306, 386 (1993); T. Plehn, M. Rauch and M. Spannowsky, [arXiv:0906.1803 [hep-ph]].