Boosted Hadronically Decaying Tops in New Physics Searches

Michihisa Takeuchi

Universität Heidelberg, Heidelberg, Germany

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Top momentum reconstruction often plays an important role for new physics signal reconstruction at the LHC. In principle, it is possible to reconstruct hadronically decaying top momentum fully but suffering from large QCD and combinatorics background. Starting from geometrically large size of jets and looking into their substructure, we can efficiently reduce these background. We develop HEPTopTagger by adopting combination of Cambridge/Aachen algorithm and mass drop criterion. For physics applications, we illustrate scalar top reconstruction and top forward-backward asymmetry at the LHC.

1 Moderately Boosted Tops at the LHC

For the fine tuning problem of the Higgs sector, top quark plays a important role due to large top yukawa coupling and a top partner particle plausibly exists for the solution. Thus, analyzing top sector is strongly related with revealing the origin of electro-weak symmetry breaking. Additionally, several anomalies related with tops are reported by Tevatron, for example, A^t_{FB} [1, 2, 3], single top cross sections etc. These facts motivate us to study top sector.

At the LHC we expect top pairs copiously generated via the strong interactions and it is time to start the precision physics. For hadronic tops, we can reconstruct the top momentum in principle unlike leptonic decays, where we need to infer at least neutrino momentum from missing momentum. The disadvantage for using hadronic decaying tops is that we need to address tremendous QCD combinatorial background. For this purpose, focusing on boosted top is one of the effective strategies. Many works have been done in this direction using substructures of geometrically large jets, and several top taggers have been developed. However, most of the taggers mainly focus on highly boosted tops, typically tops with $p_T > 500$ GeV.

We developed top tagger focusing on more specific regime, so-called *moderately boosted tops*, which are tops with 200 GeV $< p_T <$ 500 GeV. In the region we have larger number of tops in the Standard Model, which makes our top tagger testable by data. Moreover, the momentum range is also the same as tops expected from light scalar top decays. In the following we shortly explain our top tagging algorithm HEPTopTagger and its applications [4, 5, 6, 7, 8].

2 HEPTopTagger

Since we focus on lower p_T tops we need to enlarge the effective jet size to capture three decay products from a top. We show ΔR_{bjj} vs. p_T distribution, where ΔR_{bjj} is geometrical separation of them, for a $t\bar{t}$ sample in the left panel of Figure 1. As seen in the plot we need to start with $R = 1.5$ to capture a top with $p_T \sim 200$ GeV. The following steps show the HEPTopTagger algorithm [4, 5, 6]:

1. **fat jets** define a fat jet using the Cambridge/Aachen algorithm with $R = 1.5$.

2. **find all subjets using a mass drop criterion**

   During unclustering a jet j into two subjets j_1, j_2 ($m_{j_2} < m_{j_1}$), keep both j_1 and j_2 only if $m_{j_1} < 0.8\ m_j$, otherwise keep only j_1. Each subjet j_i we either further decompose if $m_{j_i} > 50$ GeV or add to the list of relevant subjets.

3. **choose three subjets with best filtered mass**

   choose three subjets with best filtered mass m_{jjj}^{filt} in all pairings: the filtering parameters we choose $R_{\text{filter}} = \min(0.3, \Delta R_{jk}/2), n_{\text{filter}} = 5$. We regard it as a top candidate when $|m_{jjj}^{\text{filt}} - m_t| < 25$ GeV.

4. **check mass ratios**

   construct exactly three subjets j_1, j_2, j_3 from the five filtered constituents, ordered by p_T. If the masses (m_{12}, m_{13}, m_{23}) satisfy one of the following three criteria, accept them as a tagged top:

$$0.2 < \arctan\frac{m_{13}}{m_{12}} < 1.3 \text{ and } \quad R_{\min} < \frac{m_{23}}{m_{123}} < R_{\max}$$
$$R_{\min}^2\left(1 + \left(\frac{m_{13}}{m_{12}}\right)^2\right) < 1 - \left(\frac{m_{23}}{m_{123}}\right)^2 < R_{\max}^2\left(1 + \left(\frac{m_{13}}{m_{12}}\right)^2\right) \text{ and } \quad \frac{m_{23}}{m_{123}} > 0.35$$
$$R_{\min}^2\left(1 + \left(\frac{m_{12}}{m_{13}}\right)^2\right) < 1 - \left(\frac{m_{23}}{m_{123}}\right)^2 < R_{\max}^2\left(1 + \left(\frac{m_{12}}{m_{13}}\right)^2\right) \text{ and } \quad \frac{m_{23}}{m_{123}} > 0.35$$

   with $R_{\min} = 85\% \times m_W/m_t$ and $R_{\max} = 115\% \times m_W/m_t$. The numerical soft cutoff at 0.35 is independent of the masses involved and only removes QCD events.

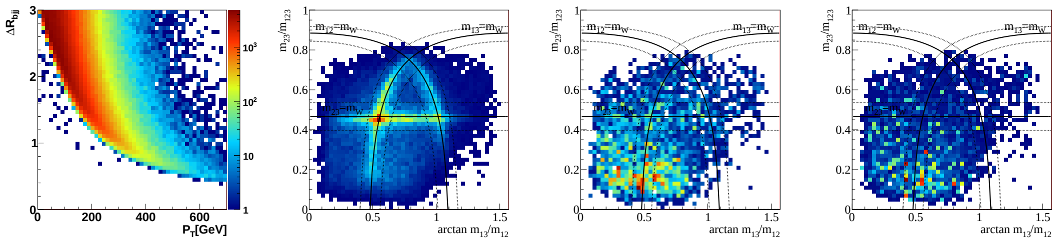

Figure 1: Left: ΔR_{bjj} vs p_T distribution for a $t\bar{t}$ sample. Distributions in the $\arctan m_{13}/m_{12}$ vs m_{23}/m_{123} plane for $t\bar{t}$, W+jets and pure QCD jets samples from second left to right.

As a result, tagging efficiency relative to all hadronic tops is 20% to 40% and mis-tagging rates for QCD and W+jets relative to all fat jets are 2% to 4% depending on p_T. We also check the tagged top momentum is well reconstructed.

3 Application for scalar top partner searches

For illustrating a benefit of the top tagger we show searches for stop pairs in purely hadronic top decays at the LHC. With the top tagging we can use reconstructed top momentum and analyze the angular correlations directly. We consider the following process with assuming $m_{\tilde{\chi}_1^0} = 98$ GeV and 100% branching ratio for $\tilde{t}_1 \to t\tilde{\chi}_1^0$:

$$pp \to \tilde{t}_1\tilde{t}_1^* \to (t\tilde{\chi}_1^0)\,(\bar{t}\tilde{\chi}_1^0) \to (bjj\tilde{\chi}_1^0)\,(\bar{b}jj\tilde{\chi}_1^0)\ .$$

Main Standard Model backgrounds are $t\bar{t}$+jets, W+jets and QCD after usual supersymmetric particle search cuts. A set of cuts used for selecting scalar top pair signal is listed in the following table.

no lepton, $\not{E}_T > 150$ GeV	
two fat jets	
two tagged tops	W+jets, Z+jets negligible
b-tag for 1st tagged top	QCD negligible
$m_{T2} > 250$GeV	$t\bar{t}$+jets controllable

After requiring two tagged tops in a event we efficiently drop the background contributions from W+jets and Z+jets. For reducing QCD contribution we require b-tagged jet inside a first tagged top, which doesn't work for reducing $t\bar{t}$ background. For reducing $t\bar{t}$ background we require m_{T2} variable should exceed a certain threshold. For the detailed numbers see Ref. [4]. As a result, for stop mass $m_{\tilde{t}} = 340$ GeV we achieve $S/B \sim 1$ and $S/\sqrt{B} > 5$ for 10 fb^{-1} at 14 TeV run of the LHC. Scalar top mass measurement using m_{T2} endpoint is also possible due to good momentum reconstruction for two tagged tops. We also achieved $S/B \sim 2$ with $S/\sqrt{B} > 5$ for the semi-leptonic mode by requiring one top tag and one isolated lepton [5].

Scalar top search at 8 TeV run of the LHC [7] would be more interesting. We need to improve the search strategy due to small scalar top production cross section compared with 14 TeV run. Since two tops from two scalar top decays are not produced in back-to-back they have no correlation in p_T unlike $t\bar{t}$ production, thus both tops hardly have $p_T > 200$ GeV. Hence, we should aim the events with one top boosted and the other top not boosted.

We mainly work on three modes: one boosted tops with one bottom jet, one boosted tops with one isolated lepton, and two isolated leptons. By requiring selection cuts on $m_T^{(b)}$, m_T^{ℓ}, and $m_{T2}^{\ell\ell}$ respectively for the three modes we can reduce effectively $t\bar{t}$ background, which is the dominant background at the end. The detailed descriptions of the cuts and resulting numbers are seen in Ref. [7]. As a result, we achieve $S/B \sim 1$ and $S/\sqrt{B} = 3$ in hadronic mode with one top tag for $m_{\tilde{t}} = 400$ GeV. In the semi-leptonic mode we achieve $S/B \sim 2$ and $S/\sqrt{B} = 5.4$ with one top tag. In the di-lepton mode, we achieve $S/B = 5.8$ and $S/\sqrt{B} = 15.8$ although it would not be a direct discovery for scalar tops. All $S/\sqrt{B}$ values quoted is for 10 fb^{-1}. We can also exclude scalar top existence up to ~ 600 GeV at 95% C.L.

4 Application for top forward backward asymmetry A_{FB}^t

We also utilize our top tagger for measuring top forward-backward asymmetry A_{FB}^t, where some discrepancy with Standard Model expectations seen according to the recent Tevatron measurement, in particular in large $m_{t\bar{t}}$ regime [1, 2, 3]. Thus, more investigation of A_{FB}^t in large $m_{t\bar{t}}$ regime, in other word, boosted top regime is desirable. For this purpose it is suit to use our top tagging algorithm [8].

Our event selection is basically one top tag and one isolated lepton. We can determine the corresponding top charge from the isolated lepton charge. Once top and lepton momenta are given we reconstruct the observable

$$\mathcal{A}_C(y_0) = \frac{N_t(|y| < y_0) - N_{\bar{t}}(|y| < y_0)}{N_t(|y| < y_0) + N_{\bar{t}}(|y| < y_0)},$$

where $N_{t/\bar{t}}(|y| < y_0)$ is the number of (anti-)tops with absolute value of its rapidity y satisfying $|y| < y_0$. In the Standard Model, due to the difference of parton distribution functions between quarks and anti-quarks anti-top rapidity distribution is expected more central than top, leading $\mathcal{A}_C < 0$. According to the efficiency of the tagger we can estimate how much integrated luminosity is needed to see non-zero NLO effect predicted by the Standard Model QCD. As a result we see it at 5σ level with 60 fb^{-1} at 14 TeV run of the LHC.

Adding the four-fermi quark interactions to the Standard Model Lagrangian for reproducing the Tevatron results predicts more significant effect at the LHC. We can see the effect at 5σ level only with 2 fb^{-1} at 14 TeV run and at 2.8σ level with 10 fb^{-1} at 7 TeV run.

5 Summary

We focus on top tagging for moderately boosted tops down to $p_T \sim 200$ GeV, which makes the tagger testable using Standard Model top data. One of the general idea behind our work is to treat tops at the LHC just like bottoms. By using jet substructure, which is information previously thrown away, we can enhance S/B ratio against QCD combinatorial backgrounds even in fully hadronic mode. To utilize data at the LHC maximally we should make an effort to use more information available.

We have shown the possible applications using HEPTopTagger for scalar top pair searches and for top forward-backward asymmetry measurement. The results for light scalar top searches with moderately boosted tops show enough chance to discover it at the LHC even at a center-of-mass energy of 8 TeV.

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