Flavor tagging TeV jets for physics beyond the Standard Model

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\begin{abstract}

We present a new scheme for tagging boosted heavy flavor jets called “\( \mu_x \) tagging.” At the LHC, the primary method to tag \( b \)-jets relies on tracking their charged constituents. However, when highly boosted, track-based \( b \)-tags lose efficiency, and the probability to mistag light jets rises dramatically. Using muons from \( B \) hadron decay and defining a particular combination “\( x \)” of angular information and boost estimation, we find fairly flat efficiencies to tag \( b \)-jets, \( c \)-jets, light-quark jets, and light-heavy jets (containing \( B \) hadrons from gluon splitting) of \( \epsilon_b = 14\% \), \( \epsilon_c = 6.5\% \), \( \epsilon_{\text{light-light}} = 0.1\% \), and \( \epsilon_{\text{light-heavy}} = 0.5\% \), respectively. We demonstrate the usefulness of this new scheme by showing the reach for discovery of a leptophobic \( Z' \rightarrow bb \) in the dijet channel.

\end{abstract}

\section{Introduction}

As searches for \( W' \) and \( Z' \) bosons at the CERN Large Hadron Collider (LHC) shift to TeV-scale energies, observation of their decay products becomes challenging. Observation of dijet resonances above QCD background is hampered by falling \( b \)-tagging efficiencies (28–15\% around 1–2 TeV) and large light-jet fake rates of 1–2\% \cite{1}. In addition to the low purity (\( \epsilon_{\text{fake}}/\epsilon_b \sim 1/10 \)), large uncertainties in the tagging efficiencies affect the mass limits; e.g., the ATLAS \( b \)-tag uncertainty is 35\% for \( p_T \) \( > \) 500 GeV \cite{2}. In order to discover multi-TeV physics beyond the Standard Model (BSM), we need a better \( b \) tag with good efficiency and purity.

At this conference, we presented a new method for flavor tagging at TeV-scale energies called “\( \mu_x \) boosted-bottom-jet tagging” \cite{3}. This method is derived from kinematic first principles, and provides both a well-determined 14\% efficiency for \( b \)-tagging, and a factor of 10 improvement in fake rejection over existing tags (\( \epsilon_{\text{fake}}/\epsilon_b \sim 1/100 \)). In Sec. 2 we summarize the algorithm and cuts for the \( \mu_x \) tag, show why it works, and plot its transverse momentum \( p_T \)- and pseudorapidity \( \eta \)-dependent efficiencies. In Sec. 3 we briefly describe the application of \( \mu_x \) boosted-\( b \) tagging to an analysis for discovery of a leptophobic \( Z' \rightarrow bb \). We summarize our results in Sec. 4.

\section{\( \mu_x \) boosted-\( b \) tag}

Consider a jet containing a semi-muonic decay of a \( B \) hadron. In the center-of-momentum (CM) frame, the muon is emitted with a speed \( \beta_{\mu,\text{cm}} \) and at an angle \( \theta_{\text{cm}} \) with respect to the beam axis (see

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In the lab frame, the boost $\gamma_B$ of the $B$ hadron compresses its decay products into a narrow subjet at high energy. We define a lab frame observable

$$ x \equiv \gamma_B \tan \theta_{lab}= \frac{\sin \theta_{cm}}{\kappa + \cos \theta_{cm}}. \quad (1) $$

where $\kappa \equiv \beta_B/\beta_{\mu,cm}$.

![Diagram](https://via.placeholder.com/150)

**Figure 1.** Nomenclature for the center-of-momentum frame and boosted lab frame.

While $\kappa$ is unobservable, for sufficiently boosted $B$ hadrons ($\gamma_B \gg \gamma_{\mu,cm} \geq 3$) the lab frame distribution of the muon count $N$ vs. $x$ is effectively independent of $\kappa$,

$$ \frac{dN}{dx} \approx \frac{2x}{(x^2 + 1)^2}. \quad (2) $$

This leads to a universal shape in $x$ for highly boosted jets containing $B$ hadrons. Using this shape we define the $\mu_x$ boosted-$b$ tag as a cut on two variables: We capture 90% of muons from $B$ decay by demanding $x < 3$. To further isolate $b$ decays, we note the hard fragmentation function for $b$ quarks leads to the $B$ hadron subjet carrying a large fraction $f_{subjet}$ of the total jet momentum. Hence, we demand

$$ f_{subjet} \equiv \frac{p_{Tsubjet}}{p_{Tjet}} \geq 0.5. \quad (3) $$

There are two challenges in applying the $\mu_x$ tag to real events: we must identify the correct decay remnant of the $B$ hadron to reconstruct its four-vector $p_{subjet}$, and we must deal with the missing muon neutrino. Most of the neutrino energy in the lab frame comes from the boost, so we use the measured four-vector of the muon as a proxy $p_{\nu} = p_{\mu} > 10$ GeV. In order to find the non-leptonic remnant “core” of the subjet, we need a more sophisticated algorithm.

In order to reconstruct the boosted subjet we first cluster the jet using the anti-$k_T$ algorithm with a $R = 0.4$. We then search for the core (generally the charm hadron remnant) by reclustering the muon and calorimeter towers with total jet energy fraction $f_{min}^{tower} > 0.05$ using a smaller $R_{core} = 0.04$. We assume $m_{core} = 2$ GeV (a typical charm hadron mass), and identify the “correct” core as the one which comes closest to $\sqrt{p_{subjet}^2} = 5.3$ GeV. Since mismeasurements smear out the reconstructed energy of the subjet, if $m_{subjet} > 12$ GeV we constrain the subjet mass to be 12 GeV. The parameters of the $\mu_x$ tag are summarized in Table 1.

**Table 1.** A summary of parameters chosen for $\mu_x$ boosted bottom jet tagging.

| $R$     | 0.4 | $m_{core}$      | 2 GeV | $p_{T\mu}^{min}$ | 10 GeV | $R_{core}$ | 0.04 | $m_B$ | 5.3 GeV | $x_{max}$ | 3 (x90%) | $f_{min}^{tower}$ | 0.05 | $m_{max}^{subjet}$ | 12 GeV | $f_{min}^{subjet}$ | 0.5 |
|---------|-----|-----------------|-------|-----------------|--------|------------|------|-------|---------|-----------|----------|-----------------|------|----------------------|-------|-----------------|------|

In spite of its non-trivial reconstruction, $x$ is effectively a dynamic angular cut on the muon. Defining $\xi$, the lab frame angle between the muon and the core, it is possible to calculate $\xi_{max}$, the
maximum $\mu$-to-core angle which produces $x \leq 3$. For “soft” muons ($E_\mu \ll E_{\text{core}}/18$), this angular cut is relatively tight

$$\xi_{\text{max}}^{\text{soft}} \approx 3 \frac{m_{\text{core}}}{E_{\text{core}}}.$$  \hspace{1cm} (4)

Once the muons become “hard” ($E_\mu \geq E_{\text{core}}/18$), the cut loosens significantly

$$\xi_{\text{max}}^{\text{hard}} \approx 3 \frac{m_{\text{subjet}}}{E_{\text{core}}}.$$  \hspace{1cm} (5)

While the transition between these limits depends explicitly on the muon’s $p_T$, this dependence is small until just below the hard threshold. Thus, not only is $x$ a smart angular cut — scaling with the energy of the core — it is a dual angular cut; tight for soft muons, looser for hard muons, and sensitive to the $p_T$ resolution of the muon system only within the narrow transition region.

The separation of reconstructed $b$ jets from light-quark-initiated jets can be seen in Fig. 2. Bottom jets ($b$-quarks hadronized as $B$ hadrons) above 500 GeV produce large $f_{\text{subjet}}$ and $x \approx 0.8$. Light jets (mostly $\pi$ and $K$) produce either incompatible values of $x > 3$, or random subjet recombinations that lead to small $f_{\text{subjet}}$. A small fraction of $b$ jets is not well-reconstructed (represented by the low-$f_{\text{subjet}}$ tail), but it has little effect on the total efficiency.

![Figure 2. Density of reconstructed candidate tags with $\mu = 40$ pileup events as a function of $f_{\text{subjet}}$ vs. $x$ for (left) bottom and (right) light-quark-initiated jets.](image)

We extract the standalone $\mu_x$ tagging efficiencies using PYTHIA 8.210 [4, 5] fed into an ATLAS-like version of DELPHES 3.2 [1], and a custom $\mu_x$ tagging module MuXboostedBTagging (available on GitHub [6]). In Fig. 3 we show separate efficiencies as a function of $p_T$ and $\eta$ for bottom jets, charm jets, light-light jets (where the muon came from a light-flavor hadron), and light-heavy jets (where a gluon split to $b\bar{b}/c\bar{c}$ — producing heavy-flavor hadrons in the final state). The kinematic nature of the tagging variables leads to fairly flat efficiencies in pseudorapidity, and when $p_T > 500$ GeV. The exception is the $\eta$ distribution for $B$ hadrons from gluon splitting. This leads to the intriguing possibility that the $g \to b\bar{b}$ contribution to jets in the Monte Carlo could be calibrated using the rapidity dependence of these highly-boosted jets.

3 A search for leptophobic $Z' \to b\bar{b}$

Very massive $Z'$ bosons are expected to exist in many BSM models. We test the $\mu_x$ boosted-bottom tag by examining the reach at a 13 TeV LHC for a leptophobic $Z'$ decaying to $b\bar{b}$ or $c\bar{c}$. For this study
we choose a $U(1)'_B$ Lagrange density

$$\mathcal{L} = \frac{g_B}{6} Z'_B \bar{q} \gamma^\mu q,$$

with a flavor-independent coupling to quarks [7, 8].

We simulate the signal and backgrounds using a MLM-matched MadEvent sample [9] and CT14lo PDFs [10] fed through PYTHIA into DELPHES. In addition to demanding one or two $\mu_x$ tags (as defined in Sec. 2), we require $|\eta_j| < 2.7$, and $\Delta \eta_{jj} < 1.5$. We reconstruct a dijet mass out of the two leading-$p_T$ jets, and look for a resonance in the mass window $[0.85, 1.25] \times M_{Z'}$.

The results for 5$\sigma$ discovery of this leptophobic $Z'$ are shown in Fig. 4 for a two-tag, and one-tag inclusive sample, compared to current exclusion limits from Ref. [7]. In 100 fb$^{-1}$ of integrated luminosity at 13 TeV, a two $b$-tag analysis could discover a $Z'$ of 3 TeV if the universal coupling $g_B \sim 2.5$. For this particular model, the single-tag inclusive search would be more effective — allowing for discovery up to nearly 1 TeV above current mass limits. Should a discovery not be made, the two-tag search (not shown) would set a 95% C.L. exclusion comparable to the one-tag discovery reach; while the one-tag search would set a 95% C.L. exclusion that can access $g_B$ couplings a factor of 2 smaller than current limits, and masses up to 2 TeV higher.

### 4 Conclusions

In this paper we discuss the new $\mu_x$ boosted-bottom-jet tag. Combining angular information $x$ from $B$ hadron decay with jet substructure $f_{\text{subjet}}$ in TeV-scale jets allows for tagging efficiencies of $\epsilon_b = 14\%$, $\epsilon_c = 6.5\%$, $\epsilon_{\text{light-light}} = 0.1\%$, and $\epsilon_{\text{light-heavy}} = 0.5\%$, respectively. The results here focused on ATLAS because their standalone non-isolated muon tagging efficiency is publicly available. We expect that if CMS has similar non-isolated muon tagging capability this tag will be just as effective, since it is kinematically driven and not sensitive to fine details of the detector.

When applying the $\mu_x$ tag to a search for leptophobic $Z'$ bosons, we find that the reach for discovery at a 13 TeV LHC is about 1 TeV higher than current limits. If a $Z'$ is not found, 95% C.L.

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**Figure 3.** $\mu_x$ tagging efficiency vs. (left) jet $p_T$ and (right) $\eta_{\text{jet}}$. Solid (dashed) lines include $\mu = 0$ (40) pileup events.
Figure 4. 5σ discovery reach for a leptophobic $Z'$ with universal coupling in the with one or two boosted-$b$ tags at a 13 TeV LHC compared to exclusion limits from Ref. [7]. Also shown is the 95% C.L. exclusion reach of the one-tag analysis.

exclusion limits can be set up to 2 TeV higher, or for $g_B$ couplings a factor of 2 smaller, than the current limits. In addition to $Z' \rightarrow b \bar{b}$, the $\mu_x$ tag should be of immediate use in the search for $W' \rightarrow t \bar{b}$ in the boosted-top and boosted-bottom channel [11] conducted by the ATLAS Collaboration [2].

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