I present a new scheme for tagging boosted heavy flavor jets called “μx tagging” and its application to TeV-scale physics beyond the Standard Model. Using muons from B hadron decay to define a particular combination “x” of angular information, and jet substructure variables, we identify a clean (ϵ_{fake}/ϵ_b ≈ 1/100) good efficiency (ϵ_b = 14%) tag. I demonstrate the usefulness of this new scheme by showing the reach for discovery of leptophobic $Z' \rightarrow b\bar{b}$ and $tH^\pm \rightarrow ttb$. 

1 Introduction

As searches for new particles at the CERN Large Hadron Collider (LHC) shift to TeV-scale energies, observation of their decays into jets becomes challenging. Dijet resonances are typically smaller than the QCD background unless top or bottom tags are applied. Unfortunately, current b-tagging efficiencies degrade (28–15%) around 1–2 TeV for light-jet fake rates of 1–2% (producing low purity $ϵ_{fake}/ϵ_b \sim 1/10$). At this conference, I presented a new method for flavor tagging at TeV-scale energies called “μx boosted-bottom-jet tagging.” This method is derived from kinematic first principles, and provides a 14% efficiency for b-tagging, with a factor of 10 improvement in fake rejection over existing tags ($ϵ_{fake}/ϵ_b \sim 1/100$). In Sec. 2 I summarize the μx definition and cuts, and plot its transverse momentum- and pseudorapidity-dependent efficiencies. In Sec. 3 I briefly describe the reach provided by μx boosted-b tagging in an analysis for discovery of a leptophobic $Z' \rightarrow b\bar{b}$. Following the recent provocative proposals to measure $H^\pm \rightarrow tb$ in $tbH^\pm$-associated production at the LHC, I use the μx tag in Sec. 4 to provide a realistic estimate of the reach at a 14 TeV machine. I summarize our results in Sec. 5.

2 μx boosted-b tag

In Ref. 2 we introduced the μx boosted-b tag, a high purity b tag for use with boosted jets ($p_T > 500$ GeV) based on the kinematics of semi-muonic B hadron decay and jet substructure. At large momentum, the boost $γ_B$ of the B hadron compresses its decay products into a narrow
subjet at high energy. We define a “smart” angular lab frame observable

$$x \equiv \gamma_B \tan \theta_{\text{lab}},$$  \hspace{1cm} (1)

where $\theta_{\text{lab}}$ is the angle between the muon and the direction of the $B$ hadron in the jet. For sufficiently boosted $B$ hadrons ($\gamma_B \geq 3$) the lab frame distribution of the muon count $N$ vs. $x$ follows a universal shape. We define the $\mu_x$ boosted-$b$ tag by first demanding $x < 3$ to capture 90% of muons from the $B$ decays. Then we demand

$$f_{\text{subj}} \equiv \frac{p_T_{\text{subj}}}{p_T_{\text{jet}}} \geq 0.5,$$  \hspace{1cm} (2)

to account for the observation that the hard fragmentation function for $b$ quarks leads to the $B$ hadron subjet carrying a large fraction $f_{\text{subj}}$ of the total jet momentum.

Both cuts in the $\mu_x$ tag depend on identification of the subjet containing the $B$ hadron. While exact identification of the $B$ is not possible, an effective proxy can be found by taking standard anti-$k_T$ clustered jets with $R = 0.4$, and reclustering the muon and calorimeter towers using a smaller $R = 0.04$. Following the detailed reconstruction algorithm of Ref. 2, we combine an identified probable charm subjet remnant, with double the muon momentum (as a boosted neutrino proxy) to provide the input to $\gamma_B$ and $p_T_{\text{subj}}$. A custom $\mu_x$ tagging module $\text{MuXboostedBTagging}$ for DELPHES$^1$ is available on GitHub.$^3$

In Fig. 1 we see $\mu_x$ tagging 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 nearly flat $p_T$ efficiencies when $p_T > 500$ GeV. The $\eta$ distribution is also flat except for $B$ hadrons from gluon splitting. This leads to the intriguing possibility that the $g \rightarrow b\bar{b}$ contribution to jets in the Monte Carlo could be calibrated using the rapidity dependence of these highly-boosted jets.

![Image of tagging efficiencies vs. jet $p_T$ and $\eta$](image)

Figure 1 – $\mu_x$ tagging efficiency vs. (left) jet $p_T$ and (right) $\eta_{\text{jet}}$. Solid (dashed) lines include $\mu = 0$ (40) pileup events.

### 3 Leptophobic $Z' \rightarrow b\bar{b}$ at the LHC

New neutral vectors, generically called $Z'$ bosons, appear in many BSM models. In cases where the decay to leptons is suppressed, we look to tag heavy flavors to overcome the QCD dijet background. We examine the reach$^2$ at a 13 TeV LHC for a leptophobic $Z'$ decaying to $b\bar{b}$ or $c\bar{c}$ using a $U(1)'_B$ Lagrange density$^4$

$$\mathcal{L} = \frac{g_B}{6} Z_B' \bar{q} \gamma^\mu q,$$  \hspace{1cm} (3)
with flavor-independent coupling to quarks.

The signal and backgrounds are simulated using a MLM-matched MadEvent sample\(^5\) and CT14lo PDFs\(^6\) fed through PYTHIA 8\(^7\) into DELPHES. We demand one or two \(\mu_x\) tags, \(|\eta_j| < 2.7\), 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 \([0.85, 1.25] \times M_{Z'\beta}\).

We see the reach for 5\(\sigma\) discovery of this leptophobic \(Z'\) in Fig. 2 for a two-tag, and one-tag inclusive sample,\(^8\) compared to current exclusion limits from Ref. 4. 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 \(g_B \sim 2.5\). The single-tag inclusive search is even more effective — allowing for discovery up to 1 TeV above mass limits from Run I. In the absence of a discovery, 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 Associated top–charged Higgs production \(tH^\pm \rightarrow ttb\)

In the MSSM, associated production of charged Higgs with a top quark produces a final state rich in \(b\) jets. Recent excitement was generated by a claim\(^9\) that the “wedge region” in \(\tan \beta\) (\(\tan \beta \sim 6\) where the \(h^0\) shares equal coupling to top and bottom) could be explored up to 2 TeV in \(H^\pm\) mass at a 14 TeV LHC through the channel \(tbH^\pm \rightarrow t(\bar{t}b)\). In contrast, others\(^10\) found that even 500 GeV could not be probed. We explore\(^11\) whether the \(\sim 2\) TeV limit can be reached in the wedge region, and how \(\mu_x\) tagging performs in this final state.

Using MLM-matched samples for \(tH^\pm \rightarrow ttb\) generated in MadEvent, showered in PYTHIA, and reconstructed in DELPHES, we look for final states involving one boosted-top tag, one \(\mu_x\) boosted-\(b\) tag, and a fully reconstructed \(t \rightarrow bl\nu\) decay (with a normal low-energy \(b\) tag). The background is dominated by fake tags from \(t\bar{t}j\) and \(tjj\) that we take as measured from CMS data. After cuts on the relative \(p_T\) and angle of the two leading jets, we find \(S/B \sim 1/10\). A preliminary estimate of the reach in \(H^\pm tb\) Yukawa coupling \(y_{tb}\) and \(\tan \beta\) are shown vs. \(H^\pm\) mass in Fig. 3. Our analysis appears to extend the results of Ref. 10 up to 2 TeV — meaning the wedge remains. It appears the wedge region will need to wait until a 100 TeV machine.
Figure 3 – 95% C.L. exclusion limits that can be reached as a function of $H^\pm$ mass at a 14 TeV LHC for (left) $H^\pm tb$ Yukawa coupling $y_{tb}$ and (right) $\tan \beta$.

5 Conclusions

At Moriond 2016 I presented the new $\mu_x$ boosted-bottom jet tag and its applications to some important searches for new physics at the LHC. Combining angular information $x$ from $B$ hadron decay with jet substructure $f_{subjet}$ in TeV-scale jets allows for clean extraction of signals for $Z'$ and MSSM charged Higgs above backgrounds. We find that the reach for leptophobic $Z'$ discovery at a 13 TeV LHC is about 1 TeV higher than current limits. If a $Z'$ is not found, 95% C.L. exclusion limits can be set up to 2 TeV higher, or $g_B$ couplings a factor of 2 smaller, than the current limits.

Despite recent excitement, the search for MSSM charged Higgs in the mid-$\tan \beta$ “wedge” region in $tH^\pm \rightarrow t(tb)$ will remain elusive. The signal appears to be too small when realistic tagging efficiencies are applied. A 100 TeV collider is likely needed to fill this region. On the other hand, the $\mu_x$ tag could be used to immediately improve the existing searches for $W' \rightarrow t\bar{b}$ in the boosted-top and boosted-bottom channel. 12 The $\mu_x$ boosted-bottom jet tag is a powerful new tool in the exploration for physics beyond the Standard Model.

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