Probing the $H^\pm$ with the $\mu_\chi$ boosted-bottom-jet tag

ILLINOIS INSTITUTE OF TECHNOLOGY

Keith Pedersen  Zack Sullivan

Two-Higgs doublet models (2HDM)

Two-Higgs doublet models (2HDM) are common features in extensions to the SM, especially in SUSY (which needs at least two Higgs doublets). Symmetry breaking produces three scalar Higgs ($h$, $H$, $H^\pm$) and a pseudo-scalar ($A$).

$$\tan(\beta): \text{the ratio of the two VEVs} \quad \beta - \alpha: \text{the doublet mixing angle}$$

Realistic 2HDM

- FCNC are absent at tree level in type-II 2HDM; these also respect SUSY’s requirement that $m_h$ and $m_A$ couple to opposite doublets.
- There’s a $126\,\text{GeV}$ boson that couples like a Standard Model Higgs! 2HDM must exist close to the “alignment” limit ($\tan(\beta) \sim 0$), so that $h$ is the SM Higgs.

Phenomenological considerations

- If $H$, $A$ and $H^\pm$ have similar masses (a consequence of SUSY in the alignment limit), they won’t decay to each other, but to the SM particles with the largest Yukawa coupling to $H^\pm$.
- Interference with SM background makes $H$ difficult to detect and model. Associated $H^\pm$ production avoids this, and adds more heavy-flavored jets to tag.

### Experimental challenges

1. The wedge: A “natural” 2HDM should have $\tan(\beta) \sim 0$. This range covers a “wedge” of low production cross section, where the Yukawa coupling to $H^\pm$ transitions from top-dominated ($\tan(\beta) < 1$) to bottom-dominated ($\tan(\beta) > 1$).

2. The boosted $b$: As $H^\pm$ searches push towards TeV masses, the $H^\pm$ bottom jet becomes increasingly boosted. Unfortunately, standard track-vertex bottom jet tags (which use charged tracks to find evidence of a decay vertex slightly displaced from the beam) degrade for boosted $b$ jets. As jet $p_T$ increases, the probability to tag a $b$ jet decreases, while the probability to mis-tag a light jet increases.

Several groups have made predictions for excluding an $H^\pm$ heavier than 500 GeV. These predictions rely on simulating track-vertex $b$ tags inside very boosted jets. What happens when we use a more robust $b$ tag?

The $\mu_\chi$, boosted-bottom-jet tag

Consider a jet containing a B meson decaying semi-leptonically. In the center-of-momentum (CM) frame, a muon is emitted at some angle $\phi_{\mu}$ w.r.t. the boost axis. In the lab frame, the boost $\gamma$ compresses the B meson products into a subject. Reconstructing this subject allows the measurement of a lab frame observable.

$$x \equiv y_{\mu} \tan(\theta_{\mu}) \approx \sin(\theta_{\mu}) / 1 + \cos(\theta_{\mu})$$

At least 90% of muons arrive in a cone defined by $x \lesssim 2$. In addition, the boosted subject should carry a large fraction of its jet’s momentum $p_{T,\mu} / p_{T,j} > 0.5$.

### Exclusion predictions at 14 and 100 TeV

We analyzed $H^\pm$ at LO using MadGraph5, Pythia8, and Delphes3. For the inclusive final state, the $H^\pm$ is reconstructed from (i) a “narrow” jet (anti-kt, $R=0.4$) tagged with $\mu$, and (ii) a “fat” jet (CA, $R=0.3$) tagged by a boosted hadronic top tag. The associated top is reconstructed as a resolved, leptonic top. The dominant background is $tt\eta X$, with $ttbb/\eta c$ about five times smaller. Since the $3b$ final state accounts for at least 60% of the cross section, we determine that exclusive cuts (requiring an associated $b$) do not improve the reach of a search.

We find that at $14\,\text{TeV}$, the search is entirely limited by the $H^\pm$ cross section, due to the $O(10\%)$ branching ratio of the semi-leptonic $t$ channel and the $O(1\%)$ acceptance of the inclusive cuts. However, the signal is quite pure, with signal-over-background ranging from 1/3 to above 1.

At $100\,\text{TeV}$, the search is background limited, with $S/B$ ranging from 1% to 5%.

We conclude that our $14\,\text{TeV}$ results are comparable to Craig et al., and that the search for $H^\pm$ in the TeV regime is a strong motivation for a 100 TeV collider.

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Craig et al. JHEP06(15)037[1504.04630]

Hajer et al. JHEP11(15)124[1504.07617]

Chekered: 95% @ 14 TeV [300 to 3000 fb$^{-1}$] Tan/orange: 95% @ 100 TeV (330 ab$^{-1}$)