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

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Outline

1 2HDM — Why do we care?
   - The extended Higgs sector
   - Experimental signatures

2 What do we need to see $H^\pm$ at the TeV scale?
   - A better $b$-tag ... $\mu_x$

3 What could we see with the $\mu_x$ tag?
   - 14 TeV
   - 100 TeV
Two Higgs-doublet models (2HDM)

What questions precipitate two Higgs doublet models (2HDM)?

- How can we avoid fine tuning? Supersymmetry
- Why doesn’t the strong force violate CP? Axions
- Where’s all the antimatter? CP-violating Higgs sector

2HDM: $\Phi_1$ and $\Phi_2$

- 3 scalars ($h$, $H$, and $H^\pm$) and a pseudo-scalar ($A$)
- $\tan \beta \equiv \frac{v_2}{v_1}$

Strongly couple to top and bottom quarks; lots of $b$ jets ($b$ tags)!

$H^\pm \to tb$ 95% exclusion estimates

<table>
<thead>
<tr>
<th>$m_{H^\pm}$ (GeV)</th>
<th>$\tan \beta$</th>
</tr>
</thead>
<tbody>
<tr>
<td>500 600 700 800 900 1000</td>
<td>0.5 1 2 3 10 20 30 100</td>
</tr>
<tr>
<td>CL exclusion $\sigma^2 L dt = 300$ fb$^{-1}$</td>
<td></td>
</tr>
<tr>
<td>$\int$ 14 TeV LHC,</td>
<td></td>
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<tr>
<td>$\int$ 14 TeV LHC,</td>
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</tbody>
</table>

JHEP1506(15)137
300 and 3000 fb$^{-1}$
14 TeV

JHEP1511(15)124
300 and 3000 fb$^{-1}$
14 TeV
(checkered/hatched)

3 and 30 ab$^{-1}$
100 TeV
(dark/light salmon)
The dominant channels

2HDM are strongly constrained by precision electroweak measurements

- No flavor-changing neutral current at tree-level
- **Type-I**: All quarks couple to only one of the doublets
- **Type-II**: $u^i_R$ and $d^i_R$ couple to opposite doublets (SUSY, axions, ...)
- The 125 GeV scalar *really* looks like a Standard Model Higgs.

$$H_{SM}^0 = -R (\alpha - \beta) \begin{pmatrix} H \\ h \end{pmatrix}$$

- We live near **alignment** ($H_{SM}^0 = h$) ... no HEAVY $\rightarrow$ light Higgs decays.

We assume that heavy Higgs mass spectrum is mostly degenerate

- A natural outcome of the MSSM 2HDM, in the alignment limit
- Suppresses decays *between* heavy Higgs

$$B(H/A \rightarrow t\bar{t}) \approx 1 \quad \tan(\beta) \gg 6$$
$$B(H/A \rightarrow b\bar{b}) \approx 1 \quad \tan(\beta) \ll 6$$
$$B(H^{\pm} \rightarrow tb) \approx 1 \quad \forall \tan(\beta)$$
$$B(H^{\pm} \rightarrow \tau\nu) = \mathcal{O}(1\%) \quad \tan(\beta) \gg 6$$
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Light jets dominate channels with boosted $b$ jets

- Probability to tag light flavors *rises dramatically* for boosted jets!
  - Light jet = no $b$ or $c$ hadrons; experiments can’t differentiate $b$-initiated jets and $g \to b\bar{b}$ jets.
- Huge (40%) systematic uncertainties in tagging efficiency can dominate experimental results/exclusions.
- Many exotic searches rely on seeing final states with $b$ jets!

[CMS PAS BTV-09-001] Fig. 12

Maintaining 50% $b$ jet efficiency

[ATL-PHYS-PUB-2014-014] Fig. 14b
The $\mu_x$ boosted-$b$ tag


- **CM**: The muon is emitted with speed $\beta_{\mu,\text{cm}}$ at angle $\theta_{\text{cm}}$.
- **Lab**: Muon is detected at angle $\theta_{\text{lab}}$ w.r.t. the centroid of the decay subjet (boosted by $\gamma_B$).

\[ p_{\text{subjet}} = p_\mu + p_\nu + p_{\text{core}} \]

\[ x \equiv \gamma_B \tan(\theta_{\text{lab}}) = \frac{\sin(\theta_{\text{cm}})}{\kappa + \cos(\theta_{\text{cm}})} \]

\[ \kappa \equiv \beta_B / \beta_{\mu,\text{cm}} \]

\[ x = \tan(\theta_{\text{cm}}/2) \quad \text{(when } \kappa \rightarrow 1) \]
The $\mu_x$ boosted-$b$ tag


We want a boosted $b$ hadron

$$\gamma_B \gtrsim 60 \gg \gamma_{\mu,\text{cm}}$$

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

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

$$x = \tan(\theta_{\text{cm}}/2) \quad \text{(when } \kappa \to 1 \text{)}$$
$x$ is mostly an angular cut

The $\mu_x$ tag is two major cuts to identify $b$-like decays

\[ x \leq 3 \]

\[ p_{\text{subj}} = p_\mu + p_\nu + p_{\text{core}} \]

\[ \frac{p_{\text{subj}}}{p_{\text{jet}}} > 0.5 \]

For detailed explanation, see 1511.05990:

- $p_\nu$ is estimated from muon
- $x$ is robust to measurement error in muon $p_T$
- $x \leq 3$ is a cut on the angle between the $\mu$ and the $D$ remnants (core)

The maximum angle $\xi_{\text{max}}$ scales linearly with $E_{\text{core}}$ ($m_D = 1.9$ GeV)

- "Soft" muons must fall in a tight cone:
  \[ \xi_{\text{max}}^{\text{soft}} = 3 \frac{m_D}{E_{\text{core}}} \]

- "Hard" muons have more breathing room:
  \[ \xi_{\text{max}}^{\text{hard}} = 18 \frac{m_D}{E_{\text{core}}} \]
Boosted kinematics turn on at 300 GeV.

**Light jets** classified by hadronic origin of tagging muon (light-heavy are \(b\) jets from gluon splitting — rapidity handle?)

**Signal efficiencies**
- \(~14\%\) of \(b\)-jets
- \(~6.5\%\) of \(c\)-jets

**Light jet **fake rate**
- Light-light \(\mathcal{O}(0.1\%)\)
- All light \(\mathcal{O}(0.6\%)\)

Pileup helps (a bit)
- **Solid**: no pileup
- **Dotted**: \(\mu = 40\)
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$H^\pm \to tb$ with the $\mu_x$ tag

$\mu_x$ is well-suited for detecting TeV-scale $H^\pm$ in a semi-leptonic channel:

$$pp \to t_{l^\pm}(b)H^\pm \to t_{l^\pm}(b)t_{\text{had}}b_{\mu_x}$$

- Boosted-$b$ via $\mu_x$ tag ($R_{kt^{-1}} = 0.4$) — high purity across TeV range
- Boosted hadronic top using existing substructure tags ($R_{CA} = 0.8$) (CMS PAS JME-09-001 / CERN-EP-2016-010)
- Leptonic top via isolated lepton and normal track-based $b$-tag (much lower $p_T$ than boosted $b$, tag is more stable).
- **caveat:** $E_T$ is heavily smeared by neutrino intrinsic to the $\mu_x$ tag, minimally useful for top reconstruction.
- $H^\pm$ is very heavy, minimal transverse boost; require $\Delta Z < 0.4$:

$$\Delta Z = \sqrt{\left(\frac{p^b_T - p^t_T}{p^b_T + p^t_T}\right)^2 + \cos(\Delta \phi)^2}$$
Extending the mass reach at 14 TeV

FeynRules → MadGraph5 → PYTHIA 8 → Delphes 3 (w/ FastJet 3)

- $bg \rightarrow H^\pm t$ is a significant contribution to $\sigma$
- $ttj(j)$ is dominant BG, followed by $ttbb/ttcc$ and $ttb(j)/ttc(j)$
- Our results look like an extension of Craig et al. above a TeV

14 TeV cross section is too small to plug “the wedge” ... 100 TeV?
A case for 100 TeV

- In 100 TeV pp collisions, $H^\pm$ gets a strong kick from the beam. Discard "back-to-back" $\Delta Z$ cut.
- Background is still dominated by same QCD processes as 14 TeV, use $\Delta \eta$ cuts to suppress $t$-channel.

\[ \tan \beta \]

\[ M_{H^+} \text{ (TeV)} \]

\[ 300 \text{ fb}^{-1} \]

\[ 3000 \text{ fb}^{-1} \]

\[ 95\% \text{ C.L. exclusion} \]

preliminary

\[ \sqrt{s} = 100 \text{ TeV} \] provides access to useful 2HDM parameter space.

- It’s important to use realistic $b$-tagging fake rates (even at 14 TeV)!

14 TeV

100 TeV
Thank you for your attention!
$\mu_x$ tags applied to $b$, $c$, and light initiated jets

Keith Pedersen (IIT)  $H^\pm$ with $\mu_x$ boosted-bottom-jet tagging  Pheno 2016