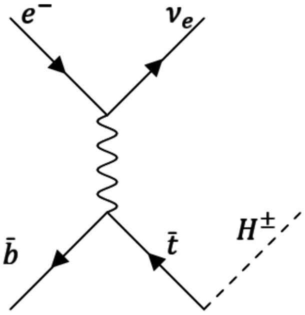
Probing the charged Higgs in single anti-top production at the e^-p

The $Y = 0$ real Higgs triplet model (ΔSM)



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Motivation: why extend the Standard Model?

The Standard Model is remarkably successful, yet **some blanks need to be filled**:

- **Dark matter** -∼27% of the Universe has no SM candidate; extended scalar sectors can host stable neutral states.
- **Electroweak symmetry breaking** -the SM assumes a *single* Higgs doublet by minimality; nothing forbids a richer scalar sector.
- **Baryon asymmetry** - a first-order electroweak phase transition (and extra CP violation) requires new scalars.
- **Naturalness** -the stability of the EW scale hints at new physics nearby.

The **scalar sector** is the least constrained and most likely place for new physics to appear.

Why the charged Higgs $H^{\pm}$?

- The SM has one Higgs doublet $\Rightarrow$ *no* charged scalar.

  $H^{\pm}$ **cannot exist in the SM**- observing one is an unambiguous signal of an extended scalar sector.

- Extended sectors (2HDM, triplets) generically predict $H^{\pm}$.
- In the $Y = 0$ **real Higgs triplet (ΔSM)**, the charged triplet components mix to give a physical $H^{\pm}$.

- Its couplings are fixed by a *single* parameter (the triplet VEV v_{Δ}), making it a sharply predictive target.

The handle

$H^{\pm}$ is a **clean, unambiguous** BSM signature - impossible in the SM, and a **direct prediction** of the ΔSM.

Finding it directly probes the triplet sector.

Why the LHeC, and not *pp*?

The **Large Hadron electron Collider**: $E_e = 60$ GeV $\times$ $E_p = 7$ TeV, $\sqrt{s} \approx 1.3$ TeV, polarised electron beam.

Advantages over *pp*:

- **Clean $e^- p$ environment** - no pile-up, vastly reduced QCD multijet background.
- **Electroweak production** with a well-defined initial state.
- **Polarised e^- (-80%)**: a handle to enhance signal and suppress background.
- **Forward topologies** aid tagging.

Why it matters here

A light, near-fermiophobic $H^\pm$ decaying to **jets** ($s\bar{c}$) is overwhelmed by QCD at the LHC.

The low-background $e^- p$ environment is what makes this search **feasible** - complementary to, not a duplicate of, *pp*.

The ΔSM: scalar potential and fields

Extend the SM by a real $SU(2)_L$ triplet Δ with $Y = 0$:

$$\Phi = \begin{pmatrix} h_\Phi^+ \\ \frac{1}{\sqrt{2}}\left(v_\Phi + h_\Phi^0 + iG^0\right) \end{pmatrix},$$

$$\Delta = \frac{1}{2}\begin{pmatrix} v_\Delta + h_\Delta^0 & \sqrt{2}\,h_\Delta^+ \\ \sqrt{2}\,h_\Delta^- & -(v_\Delta + h_\Delta^0) \end{pmatrix}.$$

Renormalisable scalar potential:

$$\begin{aligned} V(\Phi,\Delta) = &-\mu_\Phi^2\,\Phi^\dagger\Phi + \frac{\lambda_\Phi}{4}(\Phi^\dagger\Phi)^2 - \mu_\Delta^2\,\mathrm{Tr}(\Delta^\dagger\Delta) + \frac{\lambda_\Delta}{4}\left[\mathrm{Tr}(\Delta^\dagger\Delta)\right]^2 \\ &+ A\,\Phi^\dagger\Delta\,\Phi + \lambda_{\Phi\Delta}\,\Phi^\dagger\Phi\,\mathrm{Tr}(\Delta^\dagger\Delta). \end{aligned}$$

All parameters real.

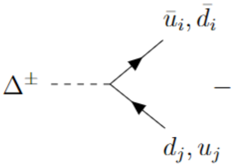
[Anatomy, arXiv:2411.18618; Maharathy *et al.*, arXiv:2509.14378]

Charged-Higgs Feynman rules ($\propto \sin\beta$)

From Appendix A of the Anatomy paper
[arXiv:2411.18618] ($s_\beta \equiv \sin\beta$):

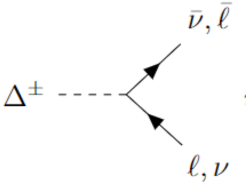
- **Quark** $\bar{t}\, b\, \Delta^-$ (production & $\Delta^- \to s\bar{c}$):

$$-\,i\frac{\sqrt{2}}{v_\Phi}\, s_\beta\, V_{tb}\big(m_t P_L - m_b P_R\big)$$



- **Lepton** $\ell\, \nu\, \Delta^-$ (the $\tau\nu$ channel):

$$\frac{\sqrt{2}}{v_\Phi}\, s_\beta\, m_\ell\, P_{R,L}$$



The triplet does *not* couple to fermions at Lagrangian level
— the coupling arises *only* through mixing $\Rightarrow \propto s_\beta$.

Every $\Delta^\pm$ coupling carries $s_\beta = -2v_\Delta/\sqrt{v_\Phi^2 + 4v_\Delta^2} \;\Rightarrow$ single knob v_Δ, and $\sigma \propto \sin^4\beta$.

Analysis setup

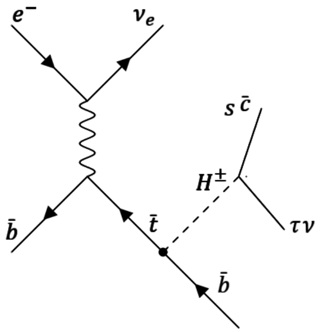
Process:

$$e^- \bar{b} \to \nu_e \, \bar{t}, \bar{t} \to \bar{b} \, H^-, H^- \to s\bar{c}/\tau\nu$$

(charged-Higgs production via top decay, $m_{H^\pm} < m_t$). **LHeC parameters:**

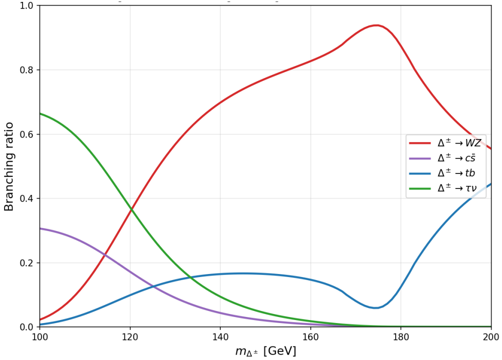
- $E_e = 60$ GeV, $E_p = 7$ TeV, $\sqrt{s} \approx 1.3$ TeV
- -80% electron polarisation

Tools: MadGraph5_aMC@NLO + MadAnalysis5, UFO model was created fit specifically for this Triplet model with the studied $\bar{t}bH^-$ coupling



H^- decay: widths, branching ratios, and the Lagrangian

$$\mathcal{L}_{H^\pm ff'} \supset -i\frac{\sqrt{2}}{v_\Phi} s_\beta V_{u_i d_j} \bar{u}_i \left(m_{u_i} P_L - m_{d_j} P_R\right) d_j H^- + \frac{\sqrt{2}}{v_\Phi} s_\beta m_\ell \bar{\nu}_\ell P_R \ell H^- + \text{h.c.}$$



Dominant $\Delta^\pm$ branching ratios vs. $m_{H^\pm}$ ($\alpha \approx 0$). Reproduces Fig. 3 of arXiv:2509.14378.

Partial widths (fermionic modes $\propto s_\beta^2$):

$$\Gamma(\Delta^\pm \to ff') = \frac{N_c\, m_{\Delta^\pm}^3 s_\beta^2}{8\pi v_\Phi^2} \beta_{ff'}\left(\frac{m_f^2}{m_{\Delta^\pm}^2}, \frac{m_{f'}^2}{m_{\Delta^\pm}^2}\right)$$

$$\Gamma(\Delta^\pm \to W^\pm Z^*) = \frac{9g^2 \lambda_{\Delta^\pm W^\mp Z}^2}{128\pi^3 \cos^2\theta_w\, m_{\Delta^\pm}} \left(\frac{7}{12} - \frac{10}{9} s_w^2 + \frac{40}{27} s_w^4\right) H$$

$$\Gamma(\Delta^\pm \to t^* \bar{b}) = \frac{3m_t^4 m_{\Delta^\pm} s_\beta^2}{128\pi^3 v_\Phi^4} \beta_t\left(\frac{m_t^2}{m_{\Delta^\pm}^2}, \frac{m_W^2}{m_{\Delta^\pm}^2}\right)$$

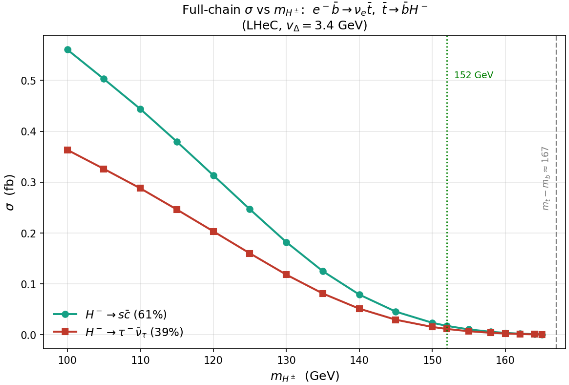
$$\lambda_{\Delta^\pm W^\mp Z} = -\frac{g^2}{2\cos\theta_w}\left(2v_\Delta \cos^2\theta_w\, c_\beta - v_\Phi \sin^2\theta_w\, s_\beta\right)$$

H^- decay: a conventional light charged Higgs

Branching ratios at $m_{H^\pm} = 152$ GeV (computed from the model):

- $H^- \to s\bar{c}$: **61%**
- $H^- \to \tau^-\nu$: **39%**
- $H^- \to W^-Z$: off-shell (< 171 GeV), negligible

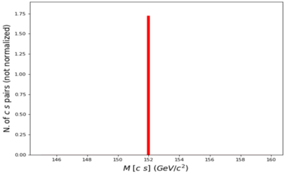
Matches standard 2HDM light-$H^\pm$ phenomenology [Li, Song, Su 2024]. Extremely narrow: $\Gamma_H \sim 10^{-6}$ GeV.



Full-chain σ for both channels; $\tau\nu$ is $0.65\times$ the $s\bar{c}$ rate (BR ratio).

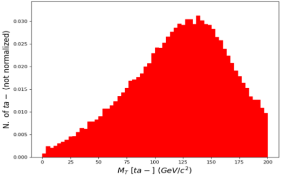
Reconstruction: sharp resonances and top consistency

$s\bar{c}$ channel

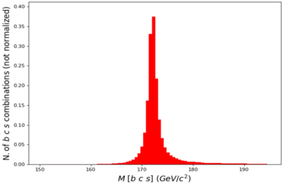


$M(s\bar{c})$: razor-sharp H^- peak at 152 GeV (RMS ∼37 MeV).

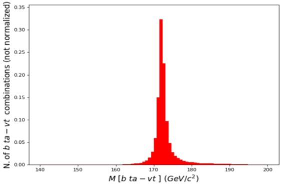
$\tau\nu$ channel



$M_T(\tau, \text{MET})$: Jacobian edge at 152 GeV (neutrino escapes).



$M(\bar{b}s\bar{c})$: top check at 172.7 GeV.

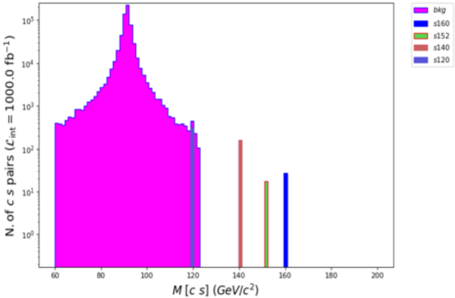


$M(\bar{b}\tau\nu)$: top check at 172.7 GeV.

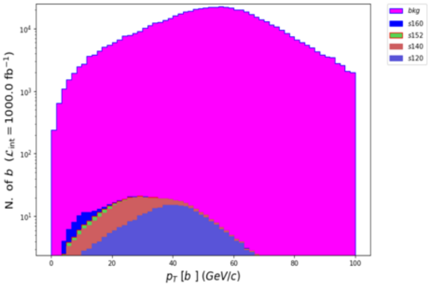
Both channels rebuild the top ($\bar{b} + H^-$ products →∼172 GeV): the decay chain is consistent.

Discriminating observables ($s\bar{c}$ channel)

Signal ($m_{H^\pm} = 120$–160 GeV) vs. the SM $\bar{t} \to \bar{b}W^-$ background:



$M(s\bar{c})$: **signal peaks at** $m_{H^\pm}$, background at $m_W \approx 91$ GeV.



$p_T(\bar{b})$: spectator b is **soft** for signal, **hard** for background.

Three handles $\Rightarrow$ mass window on $M(s\bar{c})$, plus $p_T(\bar{b})$ and $\Delta\phi$ cuts. The $M(s\bar{c})$ peak alone makes the signal region essentially background-free.

Backgrounds and event selection

Signal: $e^- \bar{b} \to \nu_e \, \bar{t}, \quad \bar{t} \to \bar{b} H^-, \quad H^- \to s\bar{c}$

Background processes (same visible final state, SM top decay):

- $e^- \bar{b} \to \nu_e \, \bar{t}, \quad \bar{t} \to \bar{b} W^-, \quad W^- \to s\bar{c}, \quad \sigma = 0.627$ pb
- ($\tau\nu$ channel: $W^- \to \tau^- \bar{\nu}_\tau, \quad \sigma = 0.209$ pb)

This SM top decay is the irreducible background (identical topology). Non-top backgrounds (W+jets, DIS+jets) are suppressed by the b-tag and top-mass reconstruction requirements.

Discriminating observables:

- $M(s\bar{c})$: signal at $m_{H^\pm}$, bkg at $m_W \approx 91$ GeV
- $p_T(\bar{b})$: soft spectator (signal) vs. hard (bkg)

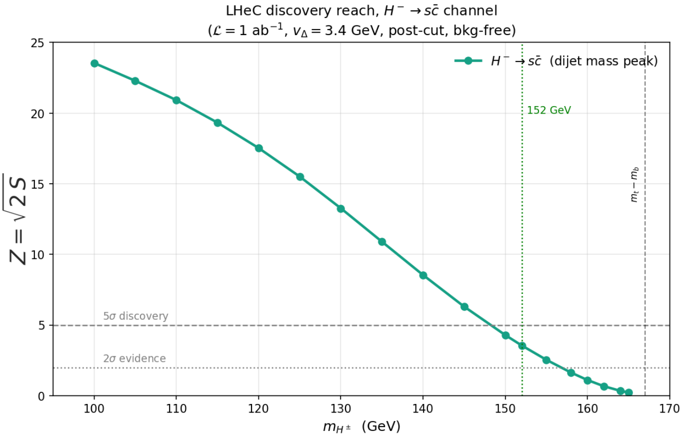
The dijet mass peaks at m_W for background but at $m_{H^\pm}$ for signal $\Rightarrow$ a mass window makes the signal region essentially background-free.

$m_{H^\pm}$	S (post-cut)	Z
120	156	17.7
140	54	10.4
152	**13.4**	**5.2**
160	2.7	2.3

$s\bar{c}$ channel, 1 ab^{-1}; background $\to$ 0 after the mass window.

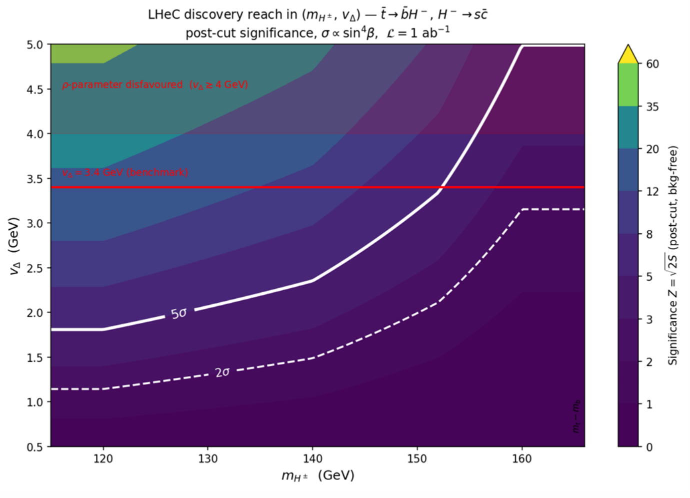
$s\bar{c}$ is the discovery channel; $\tau\nu$ is swamped by the M_T background tail.

Significance: $s\bar{c}$ vs. $\tau\nu$



- **$s\bar{c}$:** 5σ to $m_{H^\pm} \approx 152$ GeV; background-free.
- **$\tau\nu$:** $Z < 1$ everywhere the $W \to \tau\nu$ transverse-mass tail dominates. Hence, at parton level we are not displaying $W \to \tau\nu$ as we need to further make use of detector simulation later on and see how the channel improves
- Counter to naive expectation, the *fully-reconstructable* dijet wins at e^-p.

Discovery reach in $(m_{H^\pm},\, v_\Delta)$



- $\sigma \propto \sin^4\beta$; reach scales steeply with v_Δ.
- At benchmark $v_\Delta = 3.4$ GeV: 5σ to $m_{H^\pm} \approx 152$ GeV.
- Bounded above by the ρ-parameter ($v_\Delta \lesssim 4$ GeV).
- The ΔSM analogue of the 2HDM $(m_{H^\pm}, \tan\beta)$ plots.

Main result: a bounded discovery region in the model parameter space.

Summary

- Studied $H^{\pm}$ via $e^- \bar{b} \to \nu_e \bar{t}$, $\bar{t} \to \bar{b} H^-$ at the LHeC in the ΔSM.
- Production is flat in $m_{H^\pm}$; the **top-decay** channel carries the mass dependence.
- $H^- \to s\bar{c}$ (61%) and $\tau\nu$ (39%), conventional light-$H^{\pm}$ decays.
- The coupling is set by a **single parameter** v_Δ ($\sin\beta = -2v_\Delta/\sqrt{v_\Phi^2 + 4v_\Delta^2}$), giving $\sigma \propto \sin^4\beta$.
- $s\bar{c}$ **is the discovery channel:** 5σ to $m_{H^\pm} \approx 152$ GeV at 1 ab^{-1}, background-free; $\tau\nu$ not competitive.
- Reach mapped in $(m_{H^\pm}, v_\Delta)$, bounded by the ρ-parameter.

Outlook

Next steps:

- Detector-level study (Delphes): jet resolution, τ-tagging.
- Other production modes / off-shell region above threshold.
- Low masses below 100 GeV would be ideal to see how the sensitivity of the coupling behaves

Thank you!

Questions?

Model: HTM0 (FeynRules/UFO). Refs: arXiv:2503.16245, arXiv:2412.04572.