Revised Exclusion Limits on Doubly Charged Higgs Bosons

From a Reanalysis of the ATLAS Multi-Lepton Search at $\sqrt{s} = 13$ TeV

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Outline

Motivation

A Theoretical Bound on the Four-Lepton Efficiency

Independent Signal Simulation

Results

Conclusions

Why Doubly Charged Higgs Bosons?

Doubly charged scalars $H^{\pm\pm}$ appear in several well-motivated SM extensions:

- **Type-II seesaw / LRSM:** $SU(2)_L$ triplet with $Y = 2$ generates Majorana neutrino masses; $H_L^{\pm\pm}$ (and $H_R^{\pm\pm}$ in LR-symmetric models) couples directly to same-sign lepton pairs.
- **Zee–Babu model:** $SU(2)_L$ singlet $k^{\pm\pm}$ generates neutrino masses radiatively.

Collider signature

For small triplet VEV v_Δ: $H^{\pm\pm} \to \ell^\pm \ell'^\pm$ dominates $\Rightarrow$ striking **same-sign dilepton resonance**. Pair production $pp \to \gamma^*/Z^* \to H^{++}H^{--}$ is purely electroweak, depending only on $m(H^{\pm\pm})$.

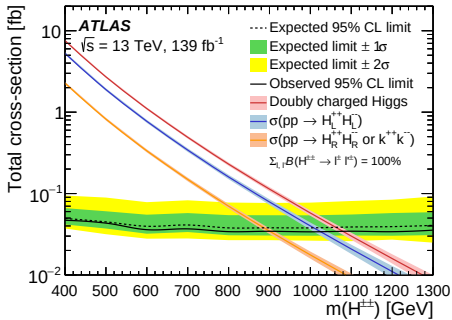
The ATLAS Search

ATLAS Run-2, 139 fb^{-1} at $\sqrt{s} = 13$ TeV [Eur. Phys. J. C 83 (2023) 605]:

Signal regions & current limits

- Three signal regions: **SR2L**, **SR3L**, **SR4L**
- SR4L: essentially background-free, drives combined sensitivity
- Current 95% CL expected mass limits:

Model	ATLAS limit
Type-II seesaw / LRSM ($H_L^{\pm\pm}$)	1065 GeV
Zee–Babu ($k^{\pm\pm} \sim H_R^{\pm\pm}$)	880 GeV



Setting Up the Bound

Equal-branching-ratio benchmark:

$$\mathcal{B}(H^{\pm\pm} \to \ell^{\pm}\ell'^{\pm}) = \frac{1}{6}, \qquad \ell, \ell' \in \{e, \mu, \tau\},$$

Treat each $H^{\pm\pm}$ as an independent decay "arm." Per-arm probability of a reconstructed same-sign light-lepton pair (e, μ only, including leptonic τ decays):

$$\Sigma f_2 = f(ee) + f(e\mu) + f(\mu\mu) = \tfrac{1}{6}\left(3 + 2b_\ell + b_\ell^2\right) = 0.64,$$

with $b_\ell = B(\tau \to e\nu\bar{\nu}) + B(\tau \to \mu\nu\bar{\nu}) = 0.35$.

The Bound

Truth-level four-lepton fraction:

$$P_4^{\text{truth}} = (\Sigma f_2)^2 = 0.41$$

Folding in ATLAS reconstruction efficiencies ($\epsilon_e = 0.88$, $\epsilon_\mu = 0.95$):

$$P_4^{\text{reco}} = 0.29$$

Strict hierarchy

$$P_4^{\text{obs}} \;\leq\; P_4^{\text{reco}} = 0.29 \;\leq\; P_4^{\text{truth}} = 0.41$$

ATLAS's own auxiliary cutflow retains 0.43–0.46 of events at the four-tight-lepton stage — above *both* bounds, even above P_4^{truth} itself.

Could Fakes Explain the Excess?

Matching the observed ATLAS tight-lepton fraction (≈ 0.45) via hadronic-τ or jet $\to e$ misidentification would require

$$\epsilon^{\text{tight}}_{\tau_h \to e} \approx 0.55$$

Not physical

Realistic ATLAS electron fake rates are $\lesssim$ a few percent — roughly an **order of magnitude** too low. No combination of per-jet fake rates reproduces the excess once more than one fake-capable object is required.

$\Rightarrow$ points to an issue in the **signal efficiency itself**, not the background estimate.

Simulation Pipeline

We regenerate the $H^{\pm\pm}$ signal from first principles:

MadGraph5_aMC@NLO (type-II seesaw) $\longrightarrow$ **Pythia 8** (shower/hadronisation) $\longrightarrow$ **Delphes 3** (detector sim)

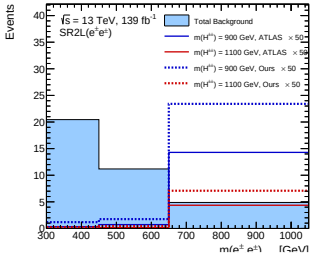
- Tuned to ATLAS lepton efficiencies, isolation, acceptance
- Reproduces the ATLAS object and event selection exactly (SR2L, SR3L, SR4L)

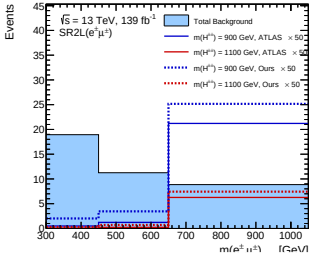
SR4L Cutflow: Ours vs. ATLAS

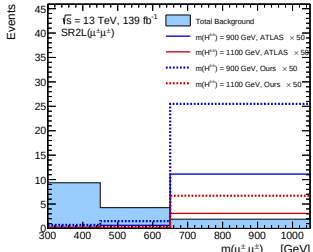
$m(H^{\pm\pm})$	ATLAS (4-tight)	Ours	Ratio
700 GeV	31	11.4	0.36
900 GeV	7.2	2.6	0.36
1100 GeV	1.9	0.72	0.38
1300 GeV	0.52	0.20	0.38

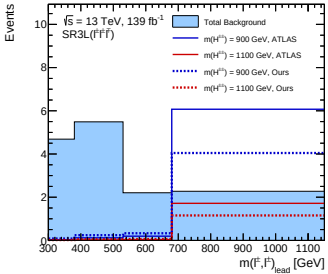
Ours/ATLAS ratio is essentially **mass-independent** (0.36–0.40), sitting just below $P_4^{\mathrm{truth}} = 0.41 \Rightarrow$ points to a normalisation offset in the ATLAS signal samples.

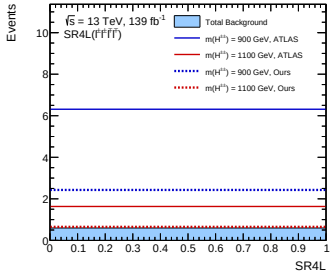
Signal vs Background Distributions









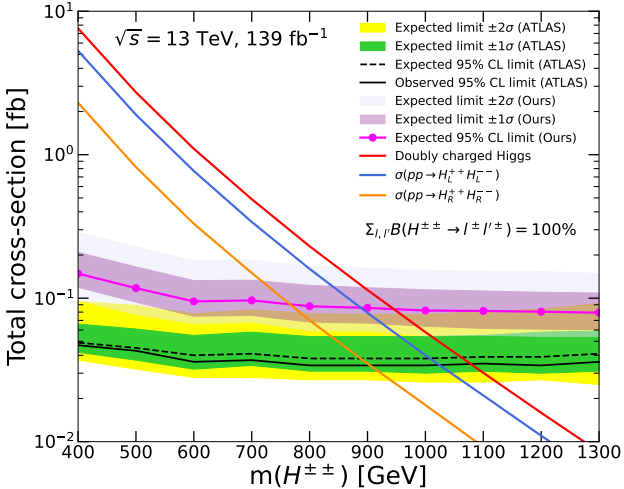


Statistical Reanalysis

Combine corrected signal yields with ATLAS's published post-fit background predictions and uncertainties:

- Reproduce the ATLAS CL_s procedure exactly with `pyhf`
- Binned likelihood fit, SR2L/SR3L/SR4L combined

Revised Cross-Section Limits



Revised Mass Limits

Model	ATLAS	This work
Type-II seesaw / LRSM ($H_L^{\pm\pm}$)	1065 GeV	$\sim$ 950 **GeV**
Zee–Babu ($k^{\pm\pm} \sim H_R^{\pm\pm}$)	880 GeV	$\sim$ 770 **GeV**

Both expected mass bounds shift down by $\approx$ 100–115 **GeV** once the four-lepton signal efficiency is corrected to respect the theoretical bound.

Conclusions & Outlook

- ATLAS's SR4L signal efficiency exceeds a strict, model-independent theoretical ceiling, not explainable by realistic fake rates
- Independent MG5+Pythia8+Delphes3 simulation: flat Ours/ATLAS ratio of 0.36–0.40 $\Rightarrow$ points to a normalisation issue
- Corrected exclusion weaker by $\gtrsim 2\times$ in cross section $\Rightarrow$ mass limits lower by ~ 100 GeV
- Widely used $H^{\pm\pm}$ bounds on BSM scenarios derived from this search may need revision

Thank you!

Backup: $H^{\pm\pm}$ Decay Width to Leptons

Partial decay width

For a doubly charged scalar coupling to leptons via the Yukawa term $\mathcal{L} \supset h_{ij}\,\overline{\ell_i^c}\,\ell_j\,H^{++} + \text{h.c.}$, the tree-level partial width is

$$\Gamma\left(H^{\pm\pm} \to \ell_i^{\pm}\ell_j^{\pm}\right) = \frac{|h_{ij}|^2}{8\pi\,(1+\delta_{ij})}\,M_{H^{\pm\pm}}$$

- h_{ij} : leptonic Yukawa coupling matrix (flavour-dependent, sets the branching ratios)
- $M_{H^{\pm\pm}}$: doubly charged Higgs mass
- δ_{ij} : Kronecker delta – symmetry factor for identical final-state leptons ($i = j$)

References

- G. Aad et al. (ATLAS), *Eur. Phys. J. C* 83, 605 (2023), arXiv:2211.07505
- J. Alwall et al., *JHEP* 07, 079 (2014), arXiv:1405.0301
- L. Heinrich et al., *JOSS* 6, 2823 (2021) [`pyhf`]
- K. Ghosh, A. K. Nayak, D. Sahoo, arXiv:2608.03988 [hep-ph] (2026)