Low-mass doubly charged Higgs bosons at the LHC

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Neutrino Mass Mechanism: Going beyond the Standard Model

The usual Higgs mechanism:

- Introduce a right-handed neutrino ν_R

$$-\mathcal{L}_\nu = Y_\nu \bar{L} H \nu_R$$

- Dirac mass

$$m_\nu = Y_\nu v/\sqrt{2}$$

ad-hoc LNC, gague singlet, and tiny Yukawa coupling: "philosophically displeasing"

The seesaw mechanism:

- Invoke Lepton number violating *New Physics* Weinberg 79

$$\mathcal{L}_{d=5} \propto \frac{1}{\Lambda} LLHH$$

- Majorana neutrino mass

$$m_\nu \propto \frac{v^2}{\Lambda}$$

"Majorana seesaw formula"

- Three tree level realisations of $\mathcal{L}_{d=5}$ Ma 98
  Type-I Minkowski 77, Yanagida 79, Glashow 80, Mohapatra & Senjanovic 80
  Type-II Konetschny & Kummer 77, Cheng & Li 80, Schechter & Valle 80, Lazarides, Shafi & Wetterich 81, Magg & Wetterich 80, Mohapatra & Senjanovic 81
  Type-III Foot, Lew, He & Joshi 89

Type-II Seesaw

- SM + $SU(2)_L$ triplet scalar field

$$\Delta = \begin{pmatrix} \Delta^+/\sqrt{2} & \Delta^{++} \\ \Delta^0 & -\Delta^+/\sqrt{2} \end{pmatrix}, \quad \langle \Delta^0 \rangle = v_t/\sqrt{2}, \quad \langle \Phi^0 \rangle = v_d/\sqrt{2}$$

- Scalar potential   Phys.Rev.D 84 (2011) 095005

$$V(\Phi,\Delta) = -m_\Phi^2 \Phi^\dagger\Phi + \frac{\lambda}{4}(\Phi^\dagger\Phi)^2 + m_\Delta^2 \mathrm{Tr}(\Delta^\dagger\Delta) + \left[\mu(\Phi^T i\sigma^2 \Delta^\dagger \Phi) + \mathrm{h.c.}\right] + \lambda_1(\Phi^\dagger\Phi)\mathrm{Tr}(\Delta^\dagger\Delta) + \lambda_2\left[\mathrm{Tr}(\Delta^\dagger\Delta)\right]^2 + \lambda_3\left[\mathrm{Tr}(\Delta^\dagger\Delta)^2\right] + \lambda_4 \Phi^\dagger\Delta\Delta^\dagger\Phi .$$

- Yukawa interaction & neutrino mass

$$-\mathcal{L}_\nu = Y_{ij}^\nu L_i^T C i\sigma^2 \Delta L_j + \mathrm{h.c.} \quad \xRightarrow{EWSB} \quad m_\nu = \sqrt{2} Y^\nu v_t$$

- For $v_d^2 \gg v_t^2$, minimisation of $V(\Phi,\Delta) \Rightarrow$ $v_t \approx \mu v_d^2/\sqrt{2} m_\Delta^2$ **"Seesaw spirit"**
- After EWSB mixing, massive triplet-like physical states: $H^{\pm\pm}$, $H^\pm$, H^0 and A^0

$$m_{H^{\pm\pm}}^2 - m_{H^\pm}^2 \approx m_{H^\pm}^2 - m_{H^0/A^0}^2 \approx -\frac{\lambda_4}{4} v_d^2$$

- Broadly, phenomenology is governed by three parameters only — $m_{H^{\pm\pm}}$, Δm and v_t.

Outset

- ATLAS has excluded $H^{\pm\pm}$ decaying into $W^{\pm}W^{\pm}$ within the mass range 200–350 GeV
- Our reinterpretation JHEP 03 (2022) 195 results in an improved exclusion range of 200–400 GeV
- Kanemura et al. (PTEP 2015, 051B02) has derived an exclusion limit of 84 GeV

Nutshell: $H^{\pm\pm}$ decaying into $W^{\pm}W^{\pm}$ are still allowed in the 84–200 GeV mass window.

The CDF m_W measurement can be explained within this model predicting such low-mass $H^{\pm\pm}$ and slightly heavier singly-charged and neutral scalars.

PLB 831 (2022) 137217, PRD 106 (2022) 015004, EPJC 82 (2022) 944, arXiv:2208.06760

Paramount to look for low-mass $H^{\pm\pm}$ at the LHC.

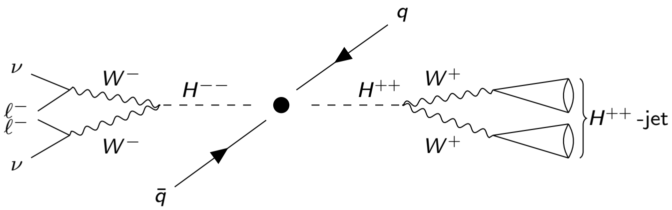
- At 13 TeV LHC, $\sigma(pp \to H^{++}H^{--})$: 65–1500 fb
- Sizeable cross-section, yet overlooked by the CMS and ATLAS collaborations

> Challenging to search using the conventional LHC searches:
>
> 1. Eventual decay products tend to be not so hard and are likely to be drowned in the towering EW and QCD backgrounds.
> 2. Ineludible contamination from the SM resonances

Aim: to delineate a novel search strategy for low-mass $H^{\pm\pm}$ at the LHC.

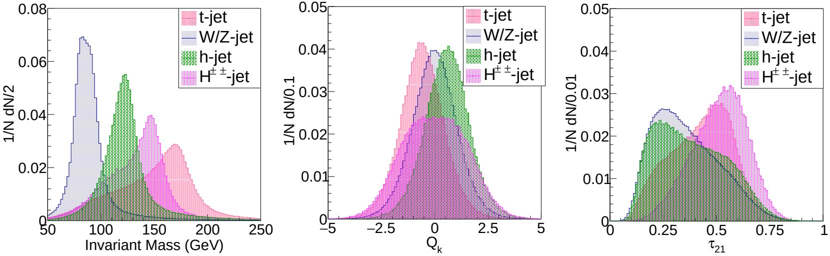
Search Strategy for low-mass $H^{\pm\pm}$

- $H^{\pm\pm}$ pair production in a **highly Lorentz-boosted** regime
- **back-to-back** production of $H^{++} - H^{--}$ pair with large p_T
- manifests as a **single fat jet** or a **pair of adjacent same-sign leptons plus** p_T^{miss}



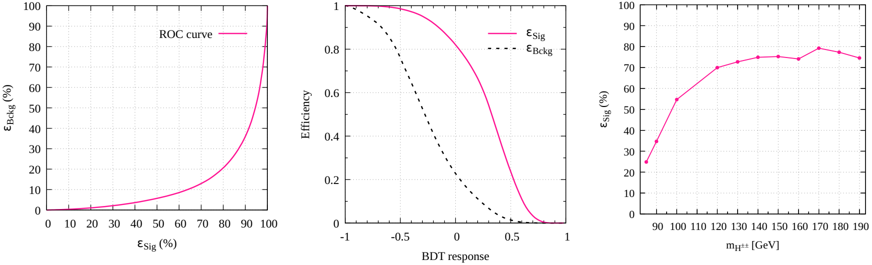
- **Final state:** an $H^{\pm\pm}$-jet and SSD plus p_T^{miss}
- **Disadvantage:** the large p_T requirement significantly reduces the signal cross-section.
- **Advantage:** this final reduces the SM background more aggressively, *proviso* we **discern the $H^{\pm\pm}$-jets from the SM jets**.

- (skipping) object reconstruction and selection
- Multivariate analysis with the BDT classifier (skipping the details)
- Inputs to BDT:
  1. invariant mass m
  2. b-tag
  3. jet charge $Q_k = \frac{\sum_i q_i (p_{T,i})^k}{\sum_i p_{T,i}}$ (we take $k = 0.2$)
  4. N-subjettiness variables $\tau_1, \tau_{21}, \tau_{32}$ and τ_{43}.



These variables constitute a minimal set with (a) good discrimination power and (b) low correlations. ([skipping] measures: method-unspecific separation, correlations and method-specific ranking)

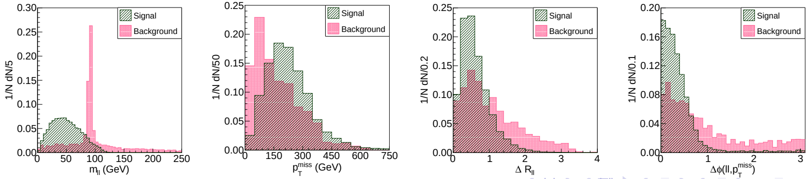
BDT Performance: ROC Curve and Efficiency Plots



- Area below the ROC curve $\sim 0.13 \Rightarrow$ well separation between the signal and background.
- (Middle panel) We choose an optimum value of 0.1 for the BDT response ($\epsilon_{\rm bckg}$: 13-20%)

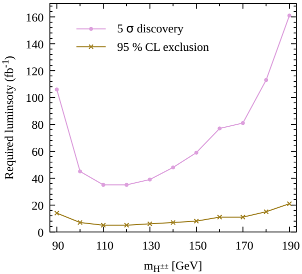
Event Selection and Analysis

- SM backgrounds:
  1. prompt
  2. non-prompt (**jet misidentified as lepton** and **electron charge misidentification** considered)
- PreSelection (S0)
  1. one fat jet with $p_T > 300$ GeV
  2. two same-sign leptons
  3. $\Delta R_{\ell\ell} > 0.05$
  4. $m_{\ell\ell} > 1$ GeV as well as $m_{\ell\ell} \notin [3, 3.2]$ GeV
- Selection
  1. S1: BDT response > 0.1.
  2. S2:$m_{\ell\ell} < 80$ GeV.
  3. S3: $\Delta R_{\ell\ell} < 1.2,\ p_T^{\text{miss}} > 80$ GeV$,\ \Delta\phi(\ell\ell, p_T^{\text{miss}}) < 0.8$



Results and Outlook

- (skipping) Cut-flow
- (Conservative approach) Assume an overall 20% total background uncertainty



$H^{\pm\pm}$ in the [84,200] GeV mass range could be probed with the already collected LHC data.

Similar search strategy is applicable to any low-mass BSM Higgses (charged as well as neutral) decaying into a pair of SM gauge bosons.

Thank You **Any Question?**