Doubly-charged Higgs production at lepton colliders within type-II seesaw model

Higgs Potential - Hefei

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Outline

1. Type-II seesaw model
2. Parameter space and production cross section
3. Background analysis
4. Summary

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1. **Type-II seesaw model**
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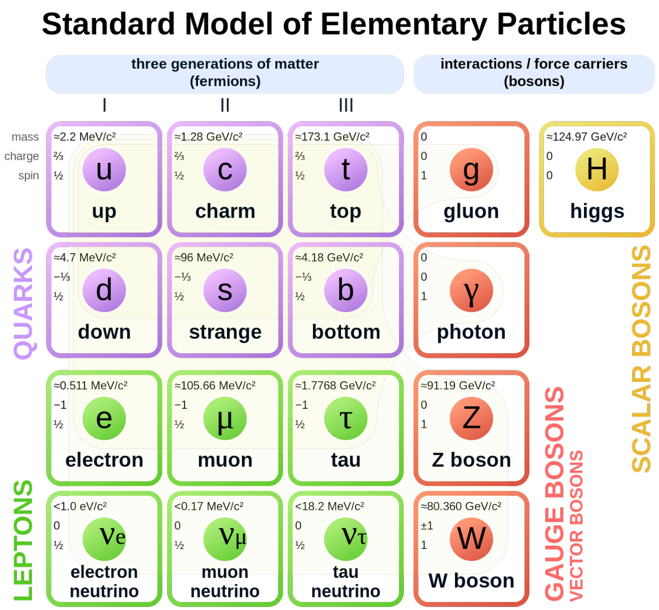
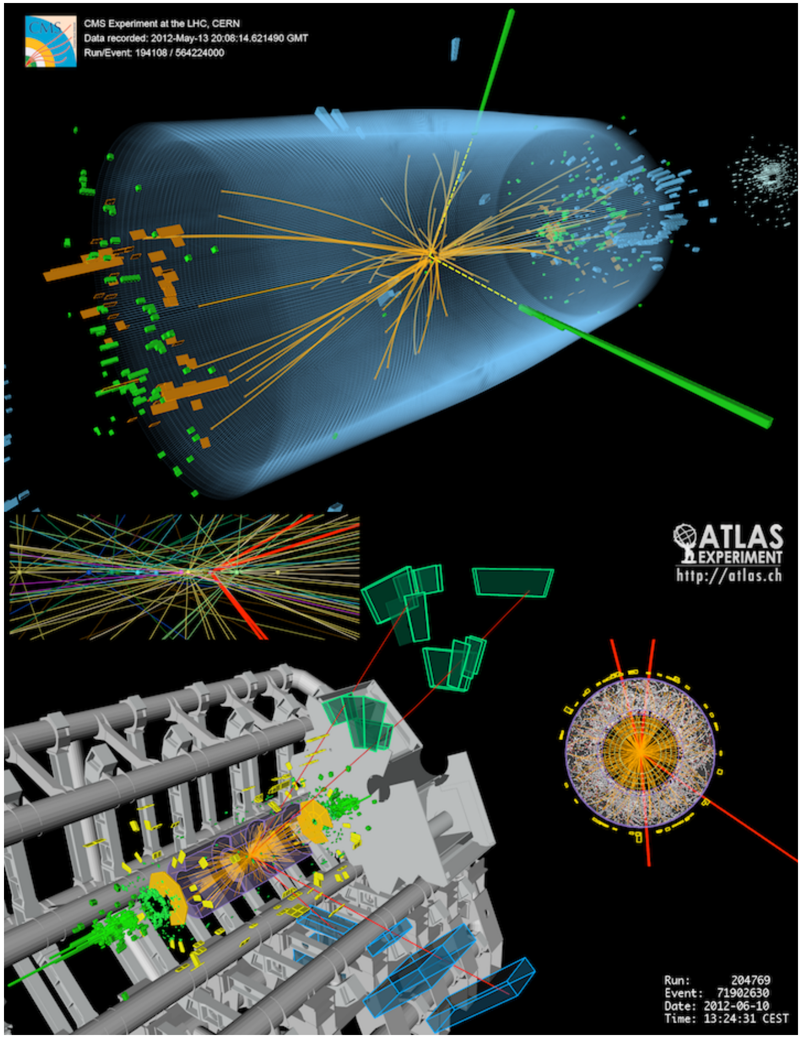
1.1 Beyond the SM

- The Standard Model (SM) is successful



- The SM needs to be extended:
  - neutrino oscillation
  - dark matter
  - CP violation
  - ...



Candidate Higgs events in ATLAS and CMS

1.2 Seesaw mechanism

Seesaw mechanism is introduced to explain the small masses of neutrinos.

✦ Type-I seesaw:

$$-\mathcal{L}_\nu = Y_D \overline{L_L} \tilde{\Phi} N_R + \frac{1}{2} M_R \overline{N_R^c} N_R + h.c.$$

N_R is a right-handed fermion singlet.
Neutrino mass (with $M_R \gg m_D$):

$$m_\nu = -m_D^T M_R^{-1} m_D$$

✦ Type-III seesaw:
Introduce a fermion triplet...

✦ **Type-II seesaw**:

$$-\mathcal{L}_\nu = Y_L \overline{L_L^c} i\sigma_2 \Delta L_L + h.c.$$

Δ is a left-handed scalar triplet with vev v_Δ. Neutrino mass:

$$m_\nu = \sqrt{2} Y_L v_\Delta$$

1.3 Type II seesaw model

The simplest implementation of the type-II seesaw mechanism.

Adding a SU(2) triplet scalar with hypercharge $Y = 2$ to the SM

$$\Delta = \begin{pmatrix} \frac{\delta^+}{\sqrt{2}} & \delta^{++} \\ \frac{1}{\sqrt{2}}(\delta^0 + i\xi_\Delta + v_\Delta) & -\frac{\delta^+}{\sqrt{2}} \end{pmatrix}$$

The full Lagrangian of the type-II seesaw model:

$$\mathcal{L}_{\text{Type-II}} = \mathcal{L}_{\text{SM}} + \mathcal{L}_\nu + \text{Tr}\left[\left(D_\mu \Delta\right)^2\right] - V_{\Delta,\Phi}$$

The complete **Higgs potential**:

$$\begin{aligned} V_\Phi + V_{\Delta,\Phi} = & -\mu_\Phi^2\left(\Phi^\dagger\Phi\right) + \frac{\lambda}{4}\left(\Phi^\dagger\Phi\right)^2 - \mu_\Delta^2 \,\text{Tr}\left(\Delta^\dagger\Delta\right) + \lambda_1\left(\Phi^\dagger\Phi\right)\text{Tr}\left(\Delta^\dagger\Delta\right) \\ & + \lambda_2\left[\text{Tr}\left(\Delta^\dagger\Delta\right)\right]^2 + \lambda_3 \,\text{Tr}\left[\left(\Delta^\dagger\Delta\right)^2\right] + \lambda_4 \Phi^\dagger\Delta\Delta^\dagger\Phi \\ & + \left[\mu\Phi^T i\sigma_2\Delta^\dagger\Phi + \text{h.c.}\right] \end{aligned}$$

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1.3 Type II seesaw model

Mass spectrum of the scalar sector (in the limit $v_\Delta \ll v_\Phi$, see later slide)

$$M_{H^{\pm\pm}} = M_\Delta^2 - \frac{1}{2}\lambda_4 v_\Phi^2, \qquad M_{H^\pm} = M_\Delta^2 - \frac{1}{4}\lambda_4 v_\Phi^2,$$

$$M_{A^0}^2 = M_{H^0}^2 = \underbrace{\boxed{M_\Delta^2}}_{\frac{\mu v_\Phi^2}{\sqrt{2} v_\Delta}}, \qquad \underbrace{\boxed{M_{h^0}^2}}_{(125\ \mathrm{GeV})^2} = \frac{\lambda v_\Phi^2}{2}$$

$v_\Delta, M_{H^{\pm\pm}}, \lambda_{1-4}, Y_L$ as model inputs.

Features of the Type-II seesaw model

- neutrino masses
- doubly-charged Higgs
- lepton number violation

1.3 Type II seesaw model

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2.1 Experimental constraints

- ρ-parameter: [PDG, 2024]

$$\rho \equiv \frac{m_W^2}{m_Z^2 \cos^2\theta_W} = \frac{1 + 2v_\Delta^2/v_\Phi^2}{1 + 4v_\Delta^2/v_\Phi^2} = 1.0001 \pm 0.0009$$

$$\downarrow \sqrt{v_\Phi^2 + v_\Delta^2} = 246 \text{ GeV}$$

$$v_\Delta < 4.9 \text{ GeV} \ll v_\Phi$$

- Direct search

$M_{H^{\pm\pm}}$ [ATLAS, 2023] [ATLAS, 2021]

$$M_{H^{\pm\pm}} > 1065 \text{ GeV}, \qquad \text{assuming Br}(H^{\pm\pm} \to l^\pm l^\pm) = 100\%$$

$$M_{H^{\pm\pm}} > 350 \text{ GeV}, \qquad \text{assuming Br}(H^{\pm\pm} \to W^\pm W^\pm) = 100\%$$

m_ν [Planck, 2018]

$$\sum_i m_{\nu_i} < 0.12 \text{ eV}$$

2.1 Experimental constraints

- Constraints on Y_L ($M_{H^{\pm\pm}} = 1$ TeV) [Bhupal, 2018]

$e^+e^- \to l^+l^-$

$$|Y_{ee}|^2 < 0.12, \qquad |Y_{e\mu}|^2 < 0.064, \qquad |Y_{e\tau}|^2 < 0.054$$

muonium oscillation

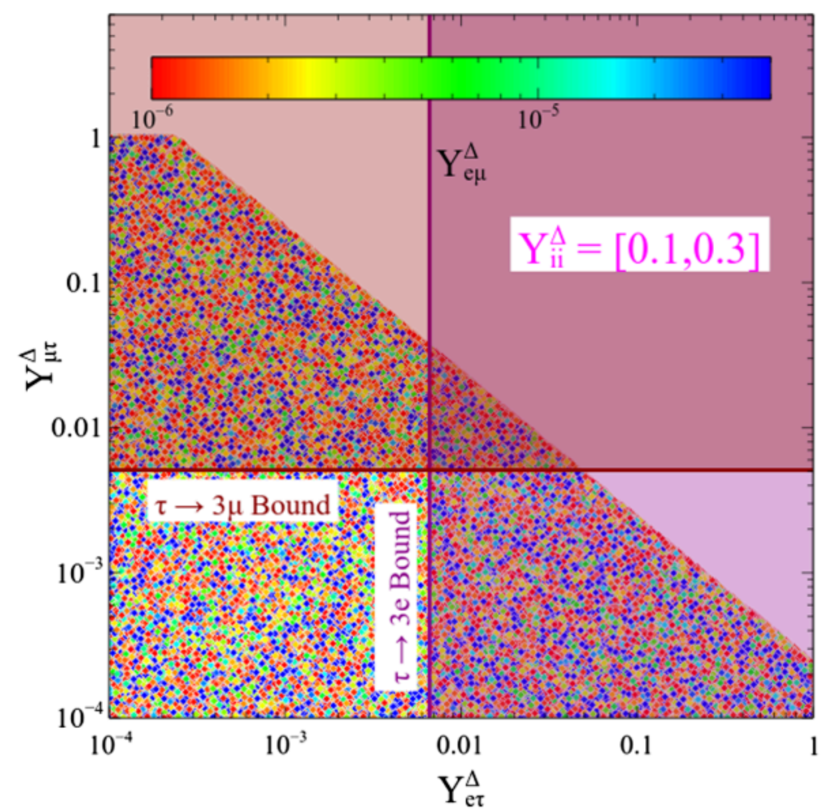
$$\left|Y_{ee}^{\dagger} Y_{\mu\mu}\right| < 0.12$$

lepton flavor violation (LFV)

LFV process	Constraint
$\mu^- \to e^- e^+ e^-$	$\left\|Y_{ee}^{\dagger} Y_{e\mu}\right\| < 2.3 \times 10^{-5}$
$\tau^- \to e^- e^+ e^-$	$\left\|Y_{ee}^{\dagger} Y_{e\tau}\right\| < 6.5 \times 10^{-3}$
$\tau^- \to \mu^- \mu^+ \mu^-$	$\left\|Y_{\mu\mu}^{\dagger} Y_{\mu\tau}\right\| < 6.1 \times 10^{-3}$
...	...

Digonal Y_L are expected to be larger,
off-diagonal Y_L are highly suppressed.

Allowed off diagonal Yukawa couplings Dev, 2019



2.2 Parameter setting and benchmark points

$$\lambda_1 = 1, \lambda_2 = \lambda_3 = 0, \lambda_4 = 0.2, Y_{ij} = Y_{ee}\delta_{ie}\delta_{je}$$

Two benchmark points feature a stronger Yukawa coupling and a stronger gauge coupling, respectively.

$$\text{BP1}: \quad M_{H^{\pm\pm}} = 1.1 \text{ TeV}, \quad v_\Delta = 2 \times 10^{-10} \text{ GeV}, \quad Y_{ee} = 0.35$$

$$\text{BP2}: \quad M_{H^{\pm\pm}} = 0.4 \text{ TeV}, \quad v_\Delta = 4.5 \text{ GeV}, \quad Y_{ee} = 1.5 \times 10^{-11}$$

$$m_{\nu_e} \approx 0.1 \text{ eV}$$

The branching ratios at different BPs

$$\text{BP1}: \quad \text{Br}(H^{\pm\pm} \to e^\pm e^\pm) = 100\%$$

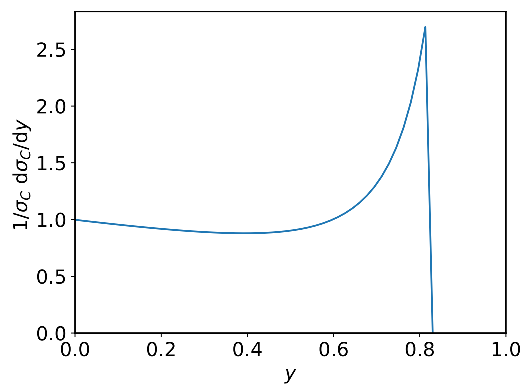
$$\text{BP2}: \quad \text{Br}(H^{\pm\pm} \to W^\pm W^\pm) = 100\%$$

2.3 Production at lepton colliders

Lepton colliders with energy above our benchmark $M_{H^{\pm\pm}}$

	ILC	CLIC phase II	CLIC phase III
$\sqrt{s}$ (TeV)	1.0	1.5	3.0
$\mathscr{L}$ $(\text{ab})^{-1}$	2.0	2.5	5.0

Photon energy spectrum at $x = 4.5$



Consider 4 collision modes:

$$e^+e^- \qquad e^-e^- \qquad e^-\gamma \qquad \gamma\gamma$$

Photon beam from Compton scattering

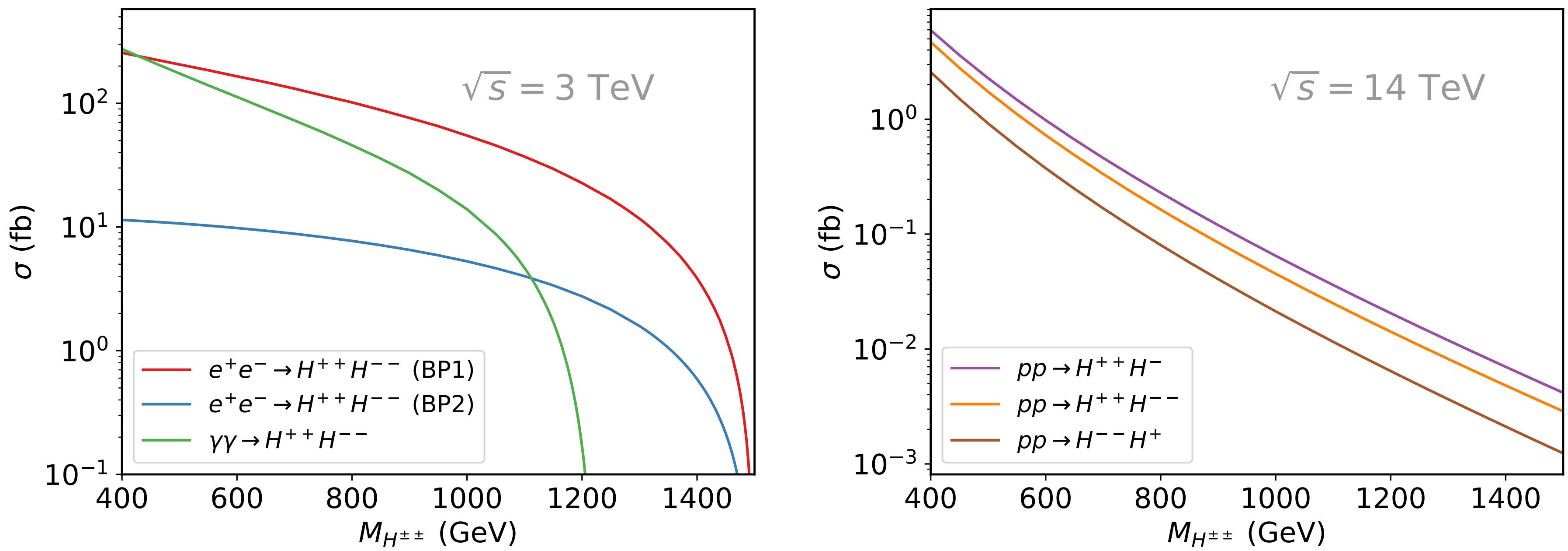
$y_{\max} = 0.83$

$$\frac{1}{\sigma_C}\frac{d\sigma_C}{dy} = \left[1 - y + \frac{1}{1-y} - \frac{4y}{x\,(1-y)} + \frac{4y^2}{x^2(1-y)^2}\right] / (\ln x + 1/2)$$

y: ω_γ / E_e

x: $4E_e\omega_0/m_e^2 = 4.5$

2.4 Pair production cross section

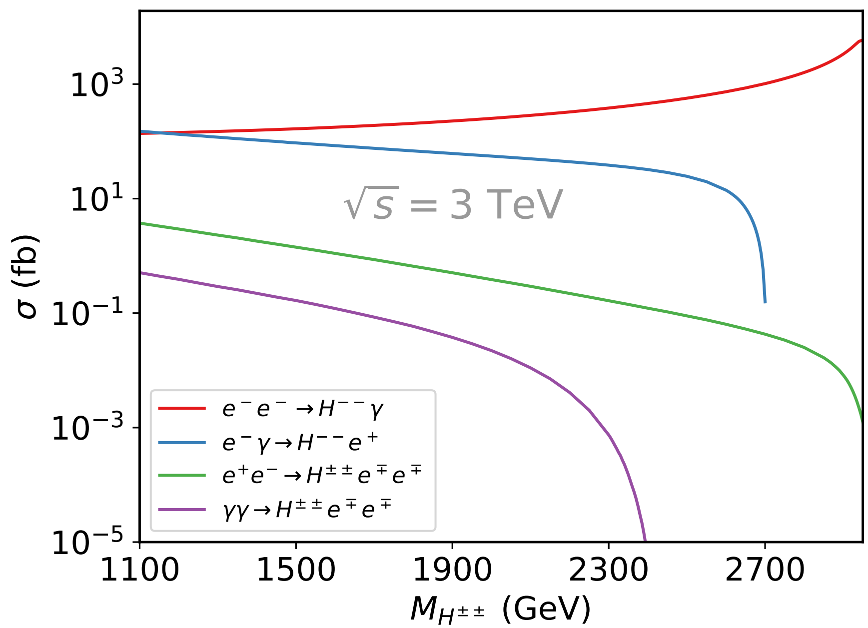


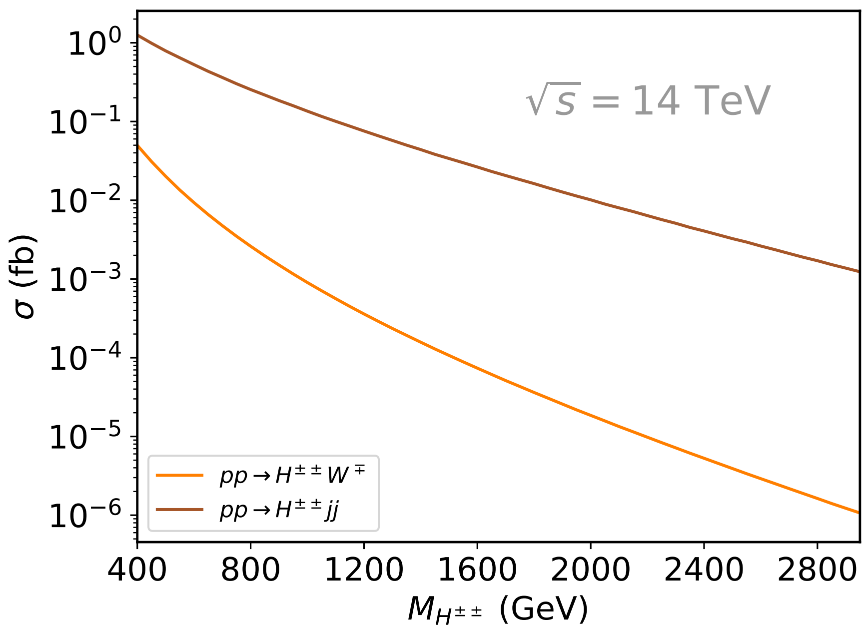
Pair production at lepton and *pp* colliers.

- e^+e^- **mode** The t-channel exchange of $H^{\pm\pm}$ contributes significantly at large Yukawa coupling (BP1).
- $\gamma\gamma$ **mode** threshold effect: $y_{\max} \times \sqrt{s}/2 \approx 1200$ GeV.
- ***pp* collider** smaller compared lepton colliders.

2.5 Single production cross section

The dominant single production processes at BP1 (left) and BP2 (right)





- **lepton collider** dominates with larger Yukawa coupling
- ***pp* collider** benefits from stronger gauge coupling
- **e^-e^- mode** largest cross section, increase due to $\frac{1}{s-M^2_{H^{\pm\pm}}}$

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3.1 Pair production background - *pp*

Take pair production at *pp* collider as a demonstration of our background analysis.

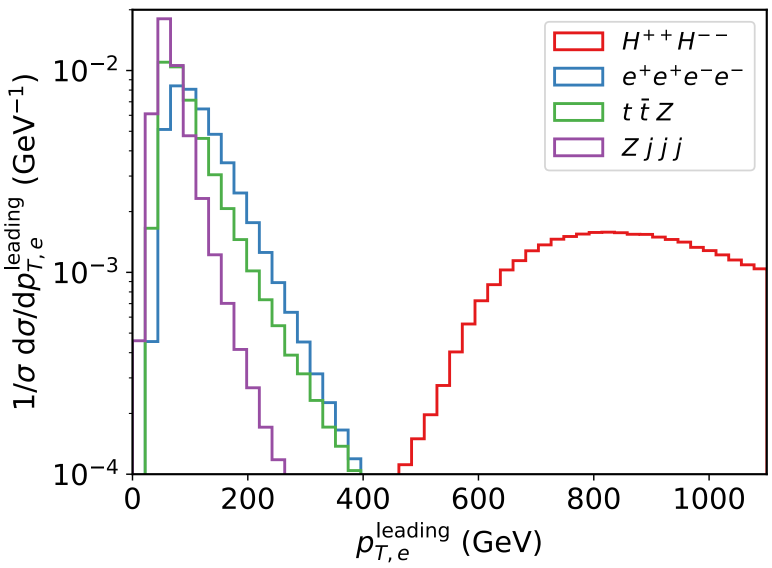
Cross sections of $H^{++}H^{--}$ and dominant background processes ($\sqrt{s} = 14$ TeV).

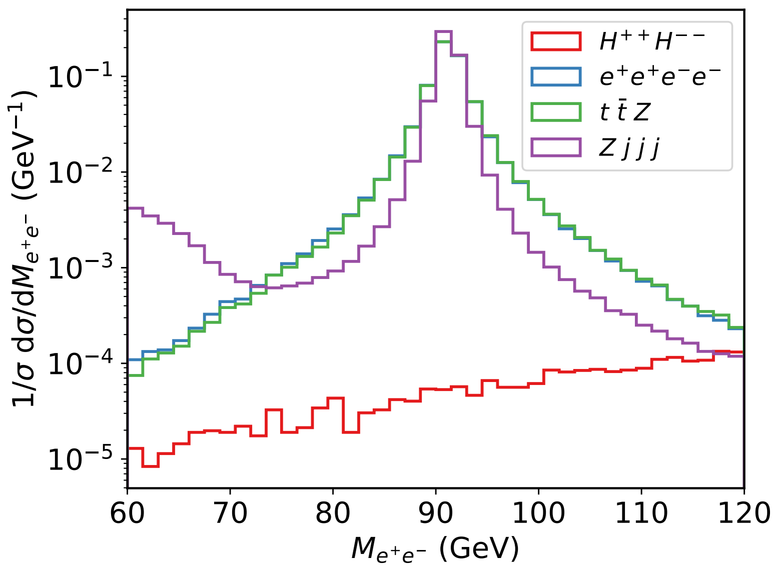
Process	σ **(pb)**	**Decay channel**	σ' **(fb)**
$H^{++}H^{--}$	2.50×10^{-5}	$e^+e^+ + e^-e^-$	0.0219
$e^+e^+e^-e^-$	0.00648		6.48
$t\bar{t}Z$	0.693	$e^+\nu_e b + e^-\bar{\nu}_e\bar{b} + e^+e^-$	0.181
$Zjjj$	2.33×10^3	e^+e^-	0.167

σ' is obtained by multipling the branching ratio and applying the baseline cut (selection):

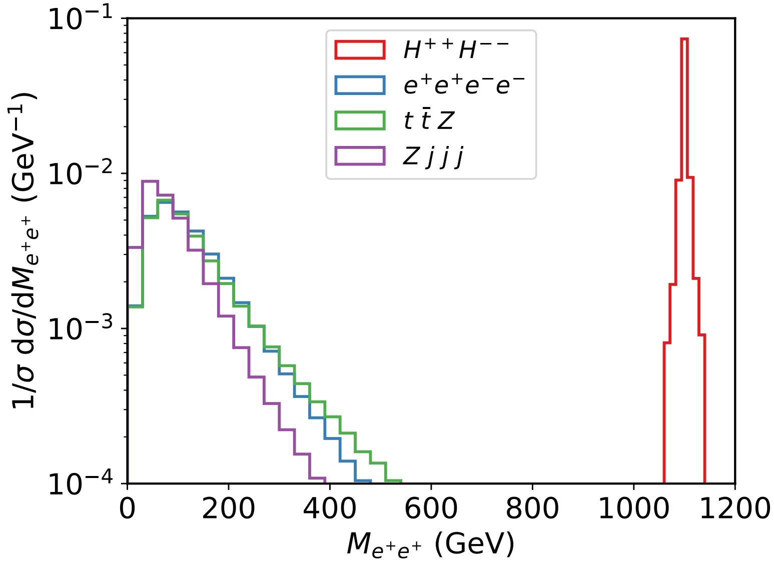
$$p_T(e) > 10 \text{ GeV}, \quad |\eta(e)| < 2.5, \quad \Delta R(e,e) > 0.4$$

3.1 Pair production background - pp





Normalized distribution for $p_{T,e}^{\text{leading}}$, $M_{e^+e^-}$ and $M_{e^+e^+}$



3.1 Pair production background - pp

Number of events after cut ($\mathscr{L} = 300\ \mathrm{fb}^{-1}$)

Process	Baseline cut	$p_{T,e}^{\text{leading}}$	$M_{e^+e^-}$	$M_{e^\pm e^\pm}$
$H^{++}H^{--}$	6.58	6.44	6.42	6.42
$e^-e^-e^+e^-$	1.94×10^3	0.27	0.0311	0
$t\bar{t}Z$	54.4	0.0673	7.05×10^{-4}	0
$Zjjj$	50.2	0.109	0.00115	0

Cuts flow:

1. $p_{T,e}^{\text{leading}}$

$$p_{T,e}^{\text{leading}} > M_{H^{\pm\pm}}/2$$

2. $M_{e^+e^-}$

$$\forall (e^+, e^-) \qquad |M_{e^+e^-} - M_Z| > 10\ \text{GeV}$$

3. $M_{e^\pm e^\pm}$

$$|M_{e^\pm e^\pm} - M_{H^{\pm\pm}}| < 0.1 \times M_{H^{\pm\pm}}$$

Signal significance:

$$\mathcal{S} = 2.54$$

3.2 Single production background - $e^- e^-$

Cross sections of $H^{--}\gamma$ and dominant background processes ($\sqrt{s} = 3.0$ TeV).

Process	σ (fb)	Decay channel	σ' (fb)
$H^{--}\gamma$	138	$e^- e^-$	138
$e^- e^- \gamma$	199		199
$e^- \nu_e W^- \gamma$	89.9	$e^- \bar{\nu}_e$	9.63
$e^- e^- \gamma\gamma$	5.25		0.525
$\nu_e \nu_e W^- W^- \gamma$	5.66	$e^- \bar{\nu}_e + e^- \bar{\nu}_e$	0.0649

Number of events after cut ($\mathscr{L} = 300$ fb^{-1}). $\mathcal{S} = 173.7$

Process	Baseline cut	$p_{T,e}^{\text{leading}}$	$M_{e^-e^-}$
$H^{--}\gamma$	3.88×10^4	3.02×10^4	3.02×10^4
$e^- e^- \gamma$	5.96×10^3	2.42×10^3	38.7
$e^- \nu_e W^- \gamma$	224	40.3	4.68
$e^- e^- \gamma\gamma$	15.7	8.64	0.304
$\nu_e \nu_e W^- W^- \gamma$	1.67	0.0672	0.00759

3.3 Significance

Signal significance for pair production in different modes at BP1

$M_{H^{\pm\pm}}$	1100	1250	1400
e^+e^-	97	64	29
$\gamma\gamma$	31	/	/

The 5σ sensitivity reach of Y_{ee} for single production at BP1.

$M_{H^{\pm\pm}}$	1100	1500	1900	2300	2700
e^-e^-	0.022	0.022	0.021	0.020	0.020
$e^-\gamma$	0.019	0.023	0.029	0.040	1.5
e^+e^-	0.068	0.12	0.22	0.43	1.1
$\gamma\gamma$	0.21	0.43	1.1	12	/

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4.1 Summary

- Consider four collision modes at 3 TeV CLIC
- Compare the pair and single production $H^{\pm\pm}$ with 14 TeV LHC
- Pair production signals are much more significant at CLIC
- Yukawa coupling at two hundredths level $\Rightarrow$ doubly charged Higgs discovery

4.1 Summary

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Thanks!