# Low scale type II seesaw: present constraints and prospect for displaced vertex signature

based on S. Antusch, O. Fischer, A. Hammad, and C. Scherb, arxiv: 1811.03476

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# Outline

# Type II Seesaw

# Model

Scalar sector:

$$\Phi = \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix}, \ \Delta = \begin{pmatrix} \frac{\Delta^+}{\sqrt{2}} & \Delta^{++} \\ \Delta^0 & -\frac{\Delta^+}{\sqrt{2}} \end{pmatrix}$$

$$\mathcal{L} \supset (D_\mu \Phi)^\dagger (D^\mu \Phi) + Tr((D_\mu \Delta)^\dagger (D^\mu \Delta)) - V(\Phi, \Delta) - \mathcal{L}_{Yukawa}$$

$$\begin{aligned} V(\Phi, \Delta) = & -\mu^2 \Phi^\dagger \Phi + M_T^2 Tr(\Delta^\dagger \Delta) + \frac{\lambda}{4} |\Phi^\dagger \Phi|^2 + \lambda_{HT} \Phi^\dagger \Phi Tr(\Delta^\dagger \Delta) \\ & + \lambda_T (Tr(\Delta^\dagger \Delta))^2 + \lambda'_T Tr((\Delta^\dagger \Delta)^2) \\ & + \lambda'_{HT} \Phi^\dagger \Delta \Delta^\dagger \Phi + (\kappa \Phi^\top i \sigma^2 \Delta^\dagger \Phi + h.c.) \end{aligned} \tag{1}$$

$$\mathcal{L}_{Yukawa} = Y_\Delta i \sigma^2 \bar{l}^c \Delta l + h.c. \tag{2}$$

# Masses for the Neutrinos

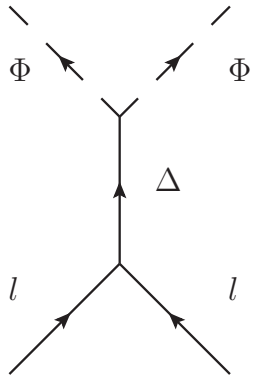
SSB:

$$\langle \Phi \rangle = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v \end{pmatrix}, \langle \Delta \rangle = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 & 0 \\ v_T & 0 \end{pmatrix}$$

$$\mathcal{L}_{Yukawa} = Y_\Delta \frac{v_T}{\sqrt{2}} \bar{\nu^c} \nu + h.c.$$

Seesaw Relation:

$$v_T = \frac{\kappa v^2}{\sqrt{2} M_T^2}$$




Neutrino Masses:

$$m_\nu = Y_\Delta \sqrt{2} v_T = Y_\Delta \frac{\kappa v^2}{M_T^2}$$

$$(Y_\Delta)_{ij} = \frac{1}{\sqrt{2} v_T} U_{PMNS}^\dagger m_\nu^{diag} U_{PMNS}$$

Normal hierarchy, $\delta_{CP} = 0$

# Masses for the Scalars

- seven physical scalar bosons: $H^{\pm\pm}$, $H^{\pm}$, $h$, $H$ and $A^0$

$$m^2_{H^{\pm\pm}} = \frac{\kappa v^2}{\sqrt{2} v_T} + \frac{\lambda'_{HT} v^2}{2} + \lambda'_T v_T^2$$

$$m^2_{H^{\pm}} = \frac{\kappa v^2}{\sqrt{2} v_T} - \frac{\lambda'_{HT} v^2}{4} - \frac{\lambda'_{HT} v_T^2}{2} + \sqrt{2}\kappa v_T$$

$$m^2_h = \frac{1}{2}(A + C - \sqrt{(A-C)^2 + 4B^2})$$

$$m^2_H = \frac{1}{2}(A + C + \sqrt{(A-C)^2 + 4B^2})$$

$$m^2_{A^0} = \frac{\kappa v^2}{\sqrt{2} v_T} + 2\sqrt{2}\kappa v_T$$

with $A = -\frac{\lambda}{2} v^2$, $B = -(\lambda_{HT} + \lambda'_{HT}) v_T v - \sqrt{2}\kappa v$ and $C = \frac{\kappa v^2}{\sqrt{2} v_T} - 2(\lambda_T + \lambda'_T) v_T^2$

# Non-Collider Constraints

# Electroweak Parameters

$$\rho = \frac{m_W^2}{\cos\theta_W m_Z^2}$$

$$\rho = \frac{1 + \frac{2v_T^2}{v^2}}{1 + \frac{4v_T^2}{v^2}} = 1 + \delta\rho$$

$$\delta\rho = -\frac{|\kappa|^2\sqrt{2}}{M_T^4 G_F}$$

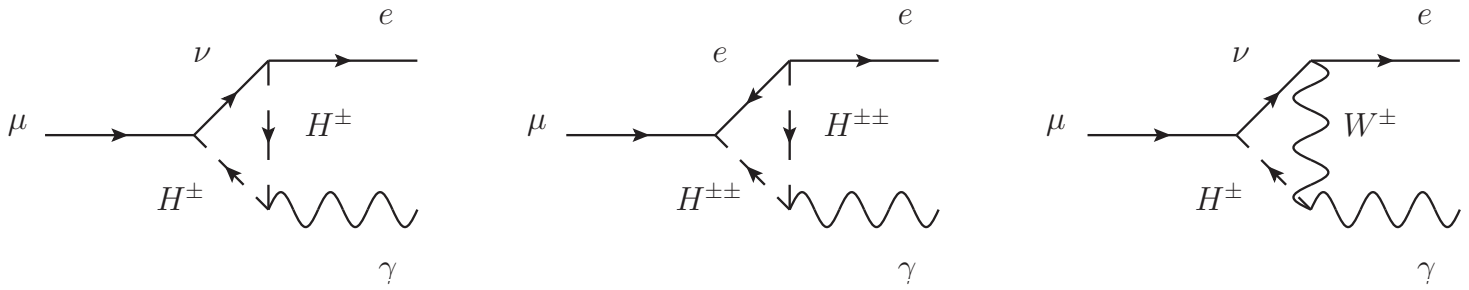
$\Rightarrow v_T < 2.1$ GeV

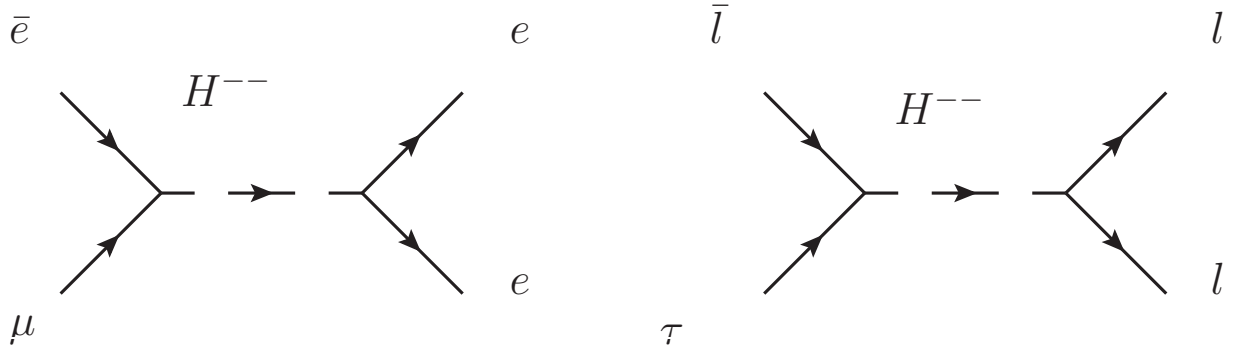
$$\Gamma_Z < 2\text{MeV at 95 \% CL}$$

$\Rightarrow m_{H^{\pm\pm}} > 42.9$ GeV

# LFV

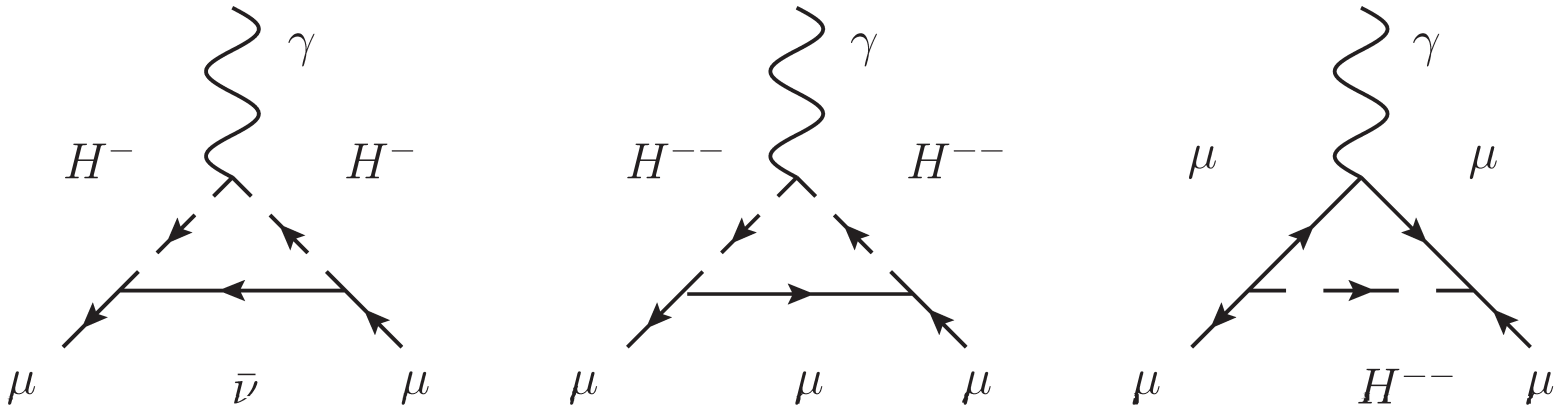
- can mediate LFV processes like $l_i \to l_j \gamma$ and $l_i \to \bar{l}_k l_m l_n$:



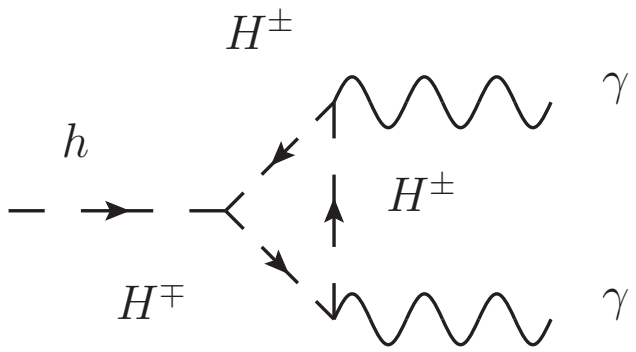

- $l_i \to \bar{l}_k l_m l_n$ proportional to $|(Y_\Delta)_{mn}(Y_\Delta)_{ki}|^2/m^2_{H^{\pm\pm}}$
- strongest bound from $Br(\mu \to \bar{e}ee) < 10^{-12}$ (SINDRUM, 1988)

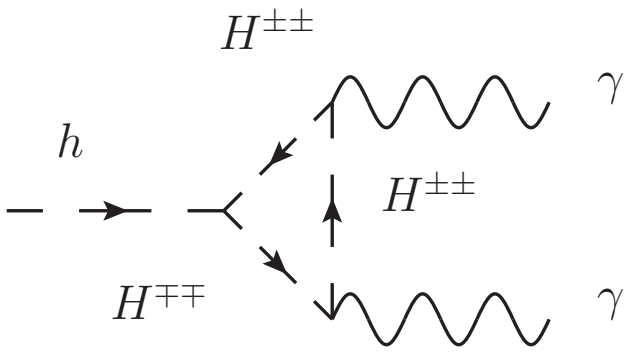
- measured and predicted value vary about $3\sigma$
- charged scalars contribute to anomalous magnetic moment of muon




- proportional to $|(Y_\Delta)_{ij}(Y_\Delta)_{ij}|^2/m^2_{H^{\pm\pm}}$

# Higgs-to-diphoton rate



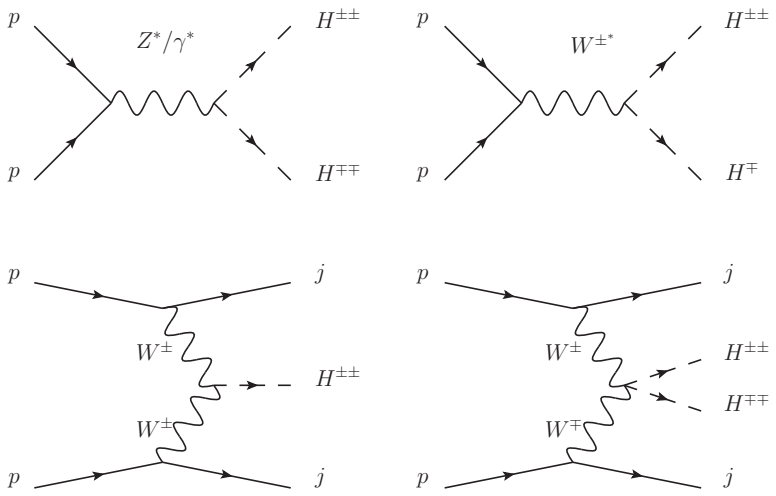



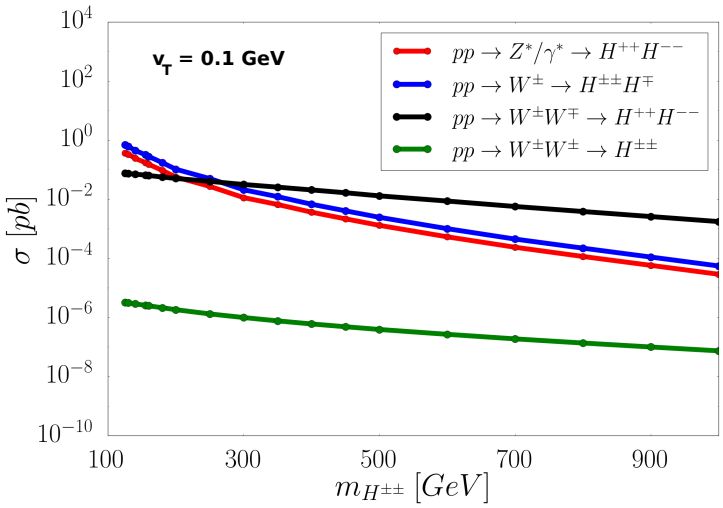

- contribution from $H^{\pm}$: $g_{hH^{\pm}H^{\mp}} \approx \frac{v^2}{m^2_{H^{\pm}}}\left(\lambda_{HT} + \frac{1}{2}\lambda'_{HT}\right)$
- contribution from $H^{\pm\pm}$: $g_{hH^{\pm\pm}H^{\mp\mp}} \approx \frac{v^2}{m^2_{H^{\pm\pm}}}\lambda_{HT}$

# Collider Signatures

# Production Modes

- focus on $H^{\pm\pm}$
- searches for $H^{\pm}$ also exist, but are weaker

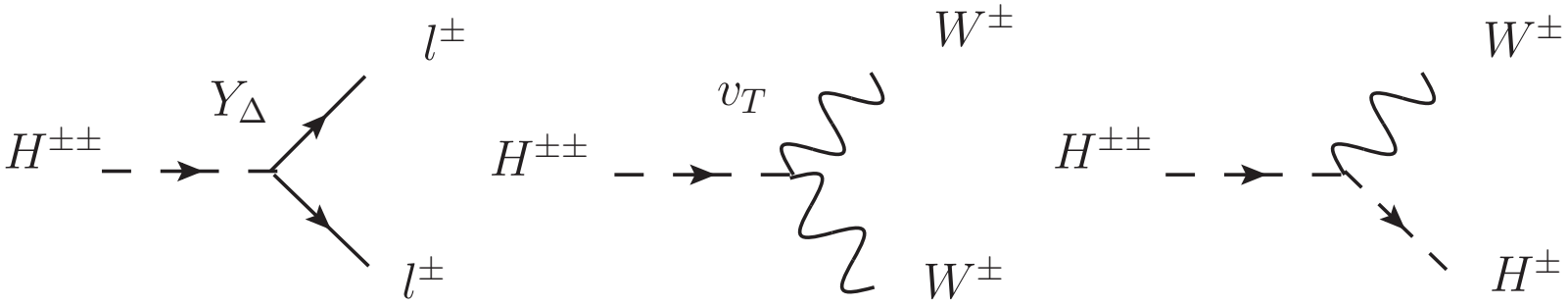



- cross sections for $v_T = 0.1$ GeV, $\lambda'_{HT} = 0$

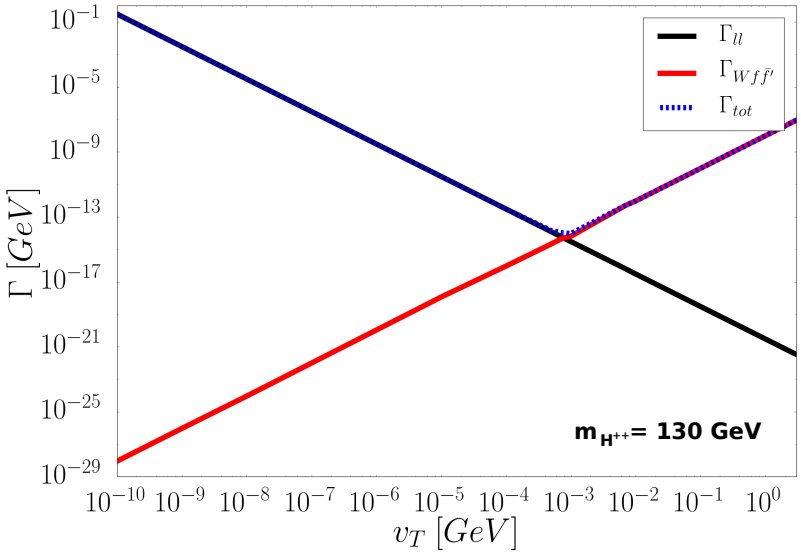
# Decay Channels

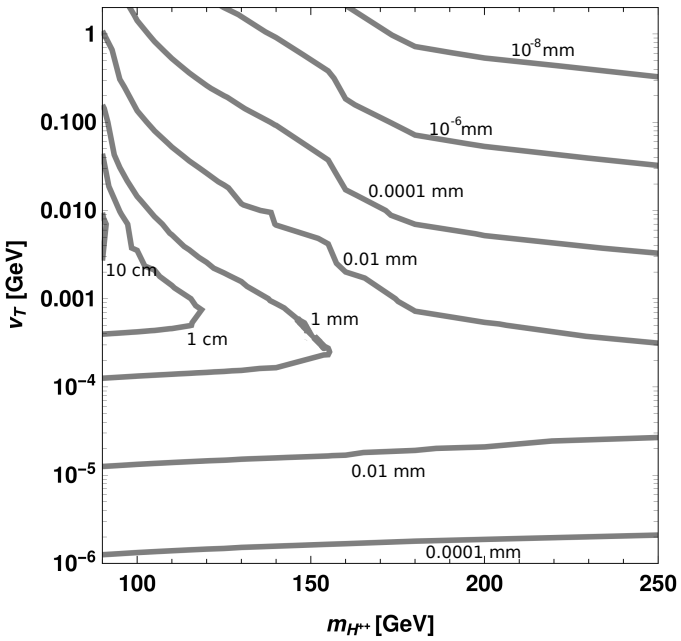
- possible decay channels: $H^{\pm\pm} \to l^{\pm} l^{\pm}$, $H^{\pm\pm} \to W^{\pm} W^{\pm}$ and $H^{\pm\pm} \to H^{\pm} W^{\pm}$




- for $\lambda'_{HT} \sim 0$: $H^{\pm\pm} \to H^{\pm} W^{\pm}$ kinematically forbidden
- for $v_T \gtrsim 10^{-4}$ GeV $H^{\pm\pm} \to W^{\pm} W^{\pm}$ dominant
- for $v_T \lesssim 10^{-4}$ GeV and $m_{H^{\pm\pm}} < 160$ GeV: all decay modes small $\Rightarrow$ small decay width $\Rightarrow$ large lifetimes

# Lifetime


$\Gamma_{ll}$
$\Gamma_{Wff'}$
$\Gamma_{tot}$
$m_{H^{++}}$= 130 GeV
$\Gamma\ [GeV]$
$v_T\ [GeV]$


$10^{-8}$mm
$10^{-6}$mm
0.0001 mm
0.01 mm
1 mm
1 cm
10 cm
0.01 mm
0.0001 mm
$v_T$ [GeV]
$m_{H^{++}}$ [GeV]

# Prompt $H^{\pm\pm}$ Decays

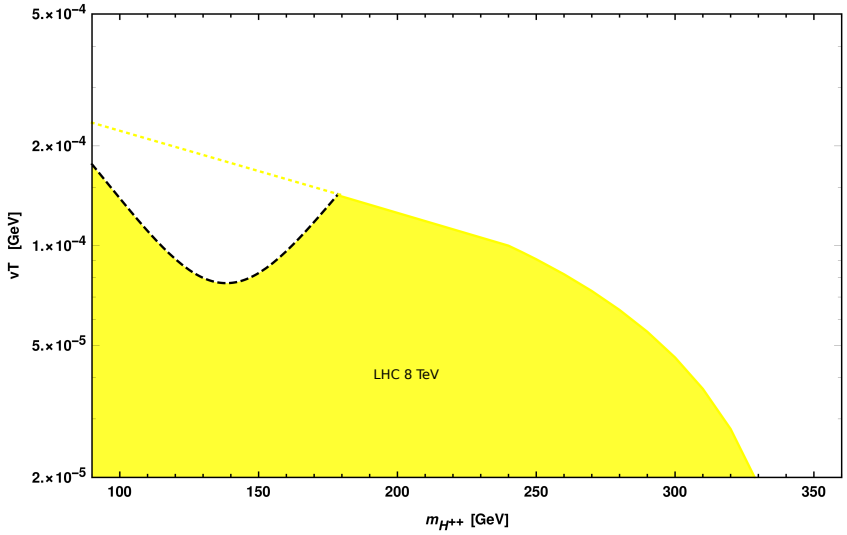
- searches for $H^{\pm\pm} \to l_i^{\pm} l_j^{\pm}$ have been done at LHC, LEP and Tevatron
- stringenst bounds arise from LHC measurements, excluding $m_{H^{\pm\pm}} \lesssim 600$ GeV (arxiv:1710.09748, CMS-PAS-HIG-16-036)
- prompt is defined as (arxiv: 1412.0237)

$$|z_0 \times \sin\theta| < 1 \text{ mm}$$
$$|d_0| < 0.2 \text{ mm}$$

- searches for $H^{\pm\pm} \to W^{\pm} W^{\pm}$ have been done at LHC, excluding the region $200 \leq m_{H^{\pm\pm}} \leq 220$ GeV and $v_T \gtrsim 3 \times 10^{-4}$ GeV (arxiv: 1808.01899)

# Prompt Constraints Recasted to Long-lived $H^{\pm\pm}$

- in the from prompt searches excluded region non-prompt decays happen
- only events fulfilling the promptness criteria

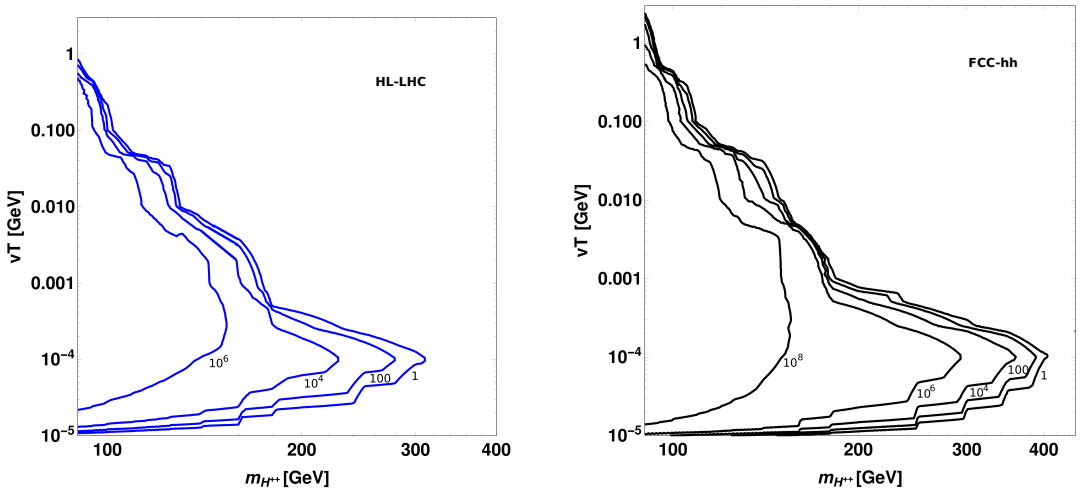


# Search for Long-lived $H^{\pm\pm}$

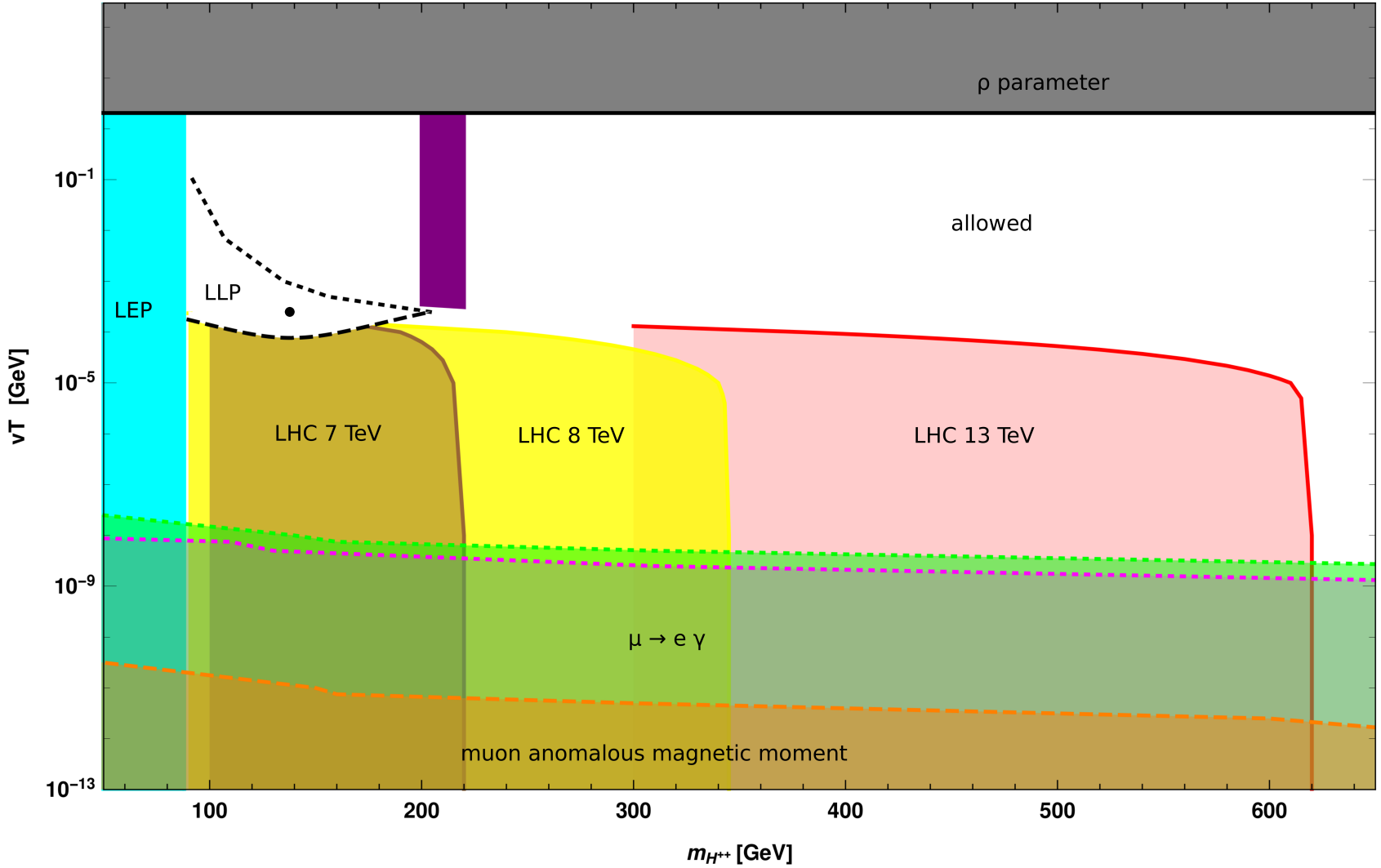
- searches for HSCPs have been done at LHC, Tevatron and LEP
- in most analyses particles are assumed to decay outside the detector
- probability for decays in a certain range

$$P(x_1, x_2) = e^{-\frac{x_1}{x_{\mathrm{lab}}}} - e^{-\frac{x_2}{x_{\mathrm{lab}}}}$$

- tracker-only analysis for doubly charged fermion-like particles (arxiv:1609.08382)
- significant number of events inside the tracker




- tracker-only analysis of charged scalars would be desirable


ρ parameter
allowed
LEP
LLP
LHC 7 TeV
LHC 8 TeV
LHC 13 TeV
μ → e γ
muon anomalous magnetic moment
vT [GeV]
$10^{-1}$
$10^{-5}$
$10^{-9}$
$10^{-13}$
100
200
300
400
500
600
$m_{H^{++}}$ [GeV]

# Analysis for a Benchmark Point

# Benchmark Point

- benchmark point: $v_T = 5 \times 10^{-4}$ GeV, $m_{H^{\pm\pm}} = 130$ GeV, $\lambda'_{HT} = 0$, $c\tau \approx 1$ cm
- LHC with 13 TeV, 100 fb$^{-1}$
- HL-LHC with 14 TeV, 3000 fb$^{-1}$
- FCC-hh with 100 TeV, 20 ab$^{-1}$

# Results

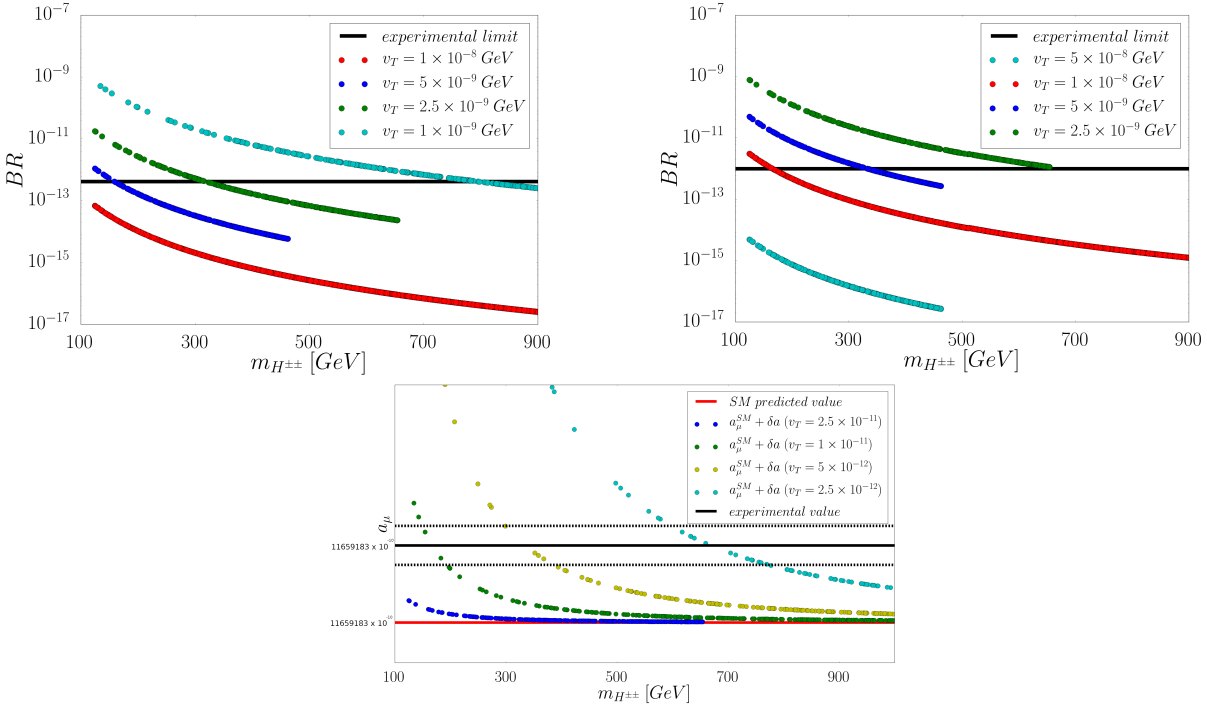
| Cuts | LHC | HL-LHC | FCC-hh |
|---|---|---|---|
| Expected events (detector level) | 280 | 10640 | 345323 |
| Two same sign muons | 220 | 8135 | 244050 |
| $P_T(\mu) > 25$ GeV&$\lvert\eta(\mu)\rvert < 2.5$&$\Delta R(\mu,\mu) > 0.2$ | 180 | 6508 | 209883 |
| 110 GeV$< m_{H^{\pm\pm}} <$ 150 GeV | 175 | 6332 | 203586 |
| $L_{xy} > 8$ mm | 76 | 2749 | 105864 |
| $d_0 > 4$ mm | 13.6 | 467 | 31759 |

# Summary

- minimal model for neutrino masses with interesting phenomenology
- wide part of well motivated parameter space is unconstrained
- no searches for the displaced same-sign dilepton signature
- already in the current data $\sim 13$ events could be found
- collider searches would be desirable

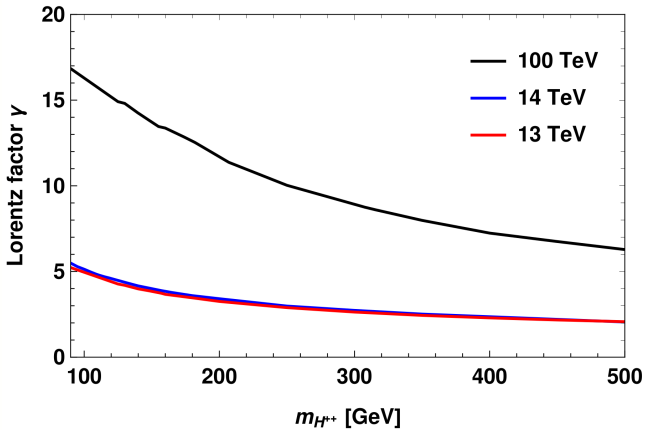
# Backup Slides

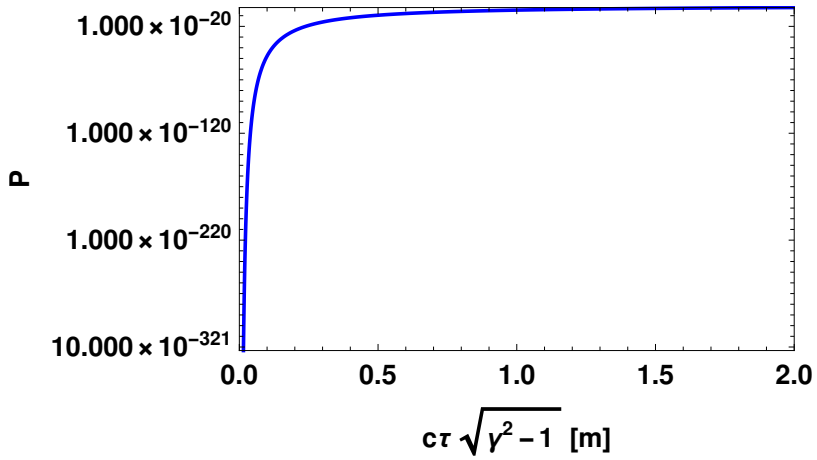
# LFV Plots




- bounds from $\mu \to e\gamma$, $\mu \to \bar{e}ee$ and muon anomalous magnetic moment

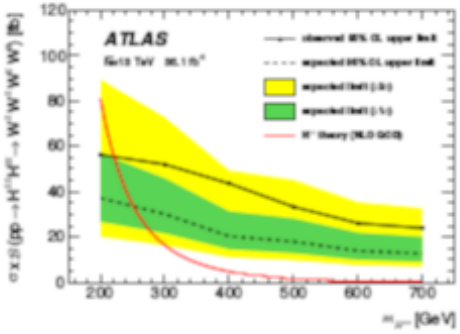
# $\gamma$ and Probability

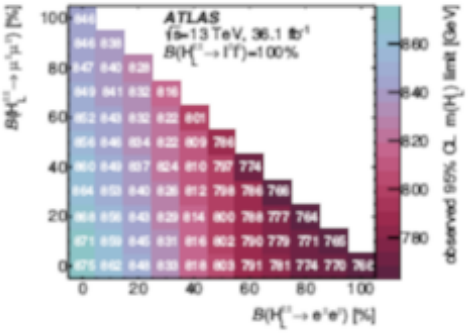


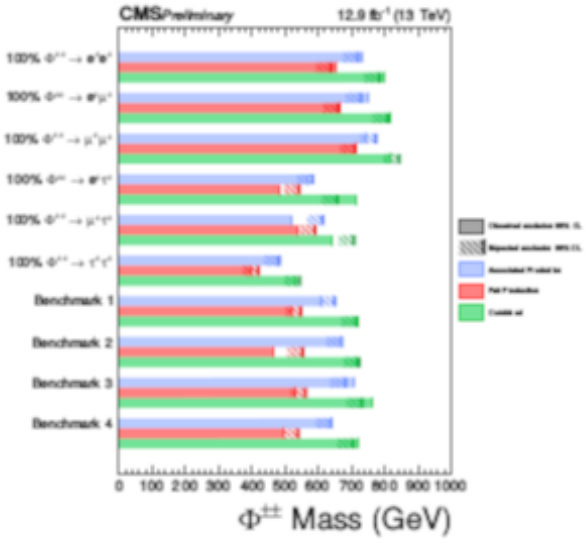




- mean Lorentz factor from simulations and probability for decays outside the detector (after $\sim$ 11 m)

# Collider Constraints



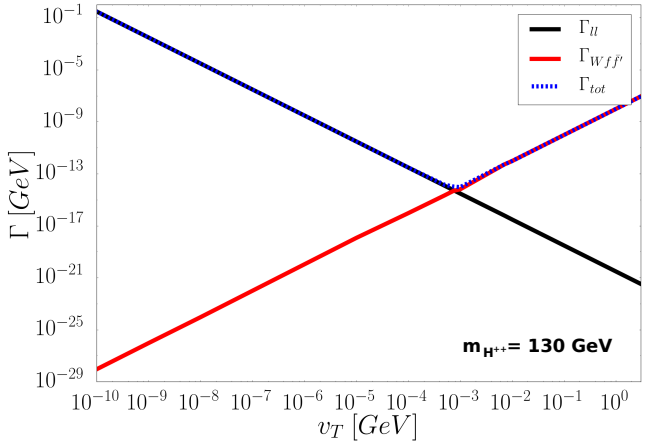

taken from arxiv: 1901.05269

# Decay Width

$$\Gamma(H^{\pm\pm} \to W^{\pm} W^{\pm *} \to W^{\pm} f \bar{f}') = \frac{g^6 v_T^2 m_{H_{\pm\pm}}}{6144\pi^3 m_{W^{\pm}}^2} \left(3 + N_C \sum_{q,q'} |V_{q,q'}|^2\right) F\left(\frac{m_{W^{\pm}}^2}{m_{H^{\pm\pm}}^2}\right)$$

$$\Gamma(H^{\pm\pm} \to l_i^{\pm} l_j^{\pm}) = \frac{|Y_{\Delta_{ij}}|^2}{4\pi(1+\delta_{ij})} m_{H^{\pm\pm}}$$

$$F(x) = 47x^2 - 60x + 15 - \frac{2}{x} - 3(4x^2 - 6x + 1)\log x + \frac{6(20x^2 - 8x + 1)}{\sqrt{4x-1}} \arccos\left(\frac{3x-1}{2x^{3/2}}\right)$$



# Plots before Cuts