MLRSM Higgs bosons at the LHC and beyond

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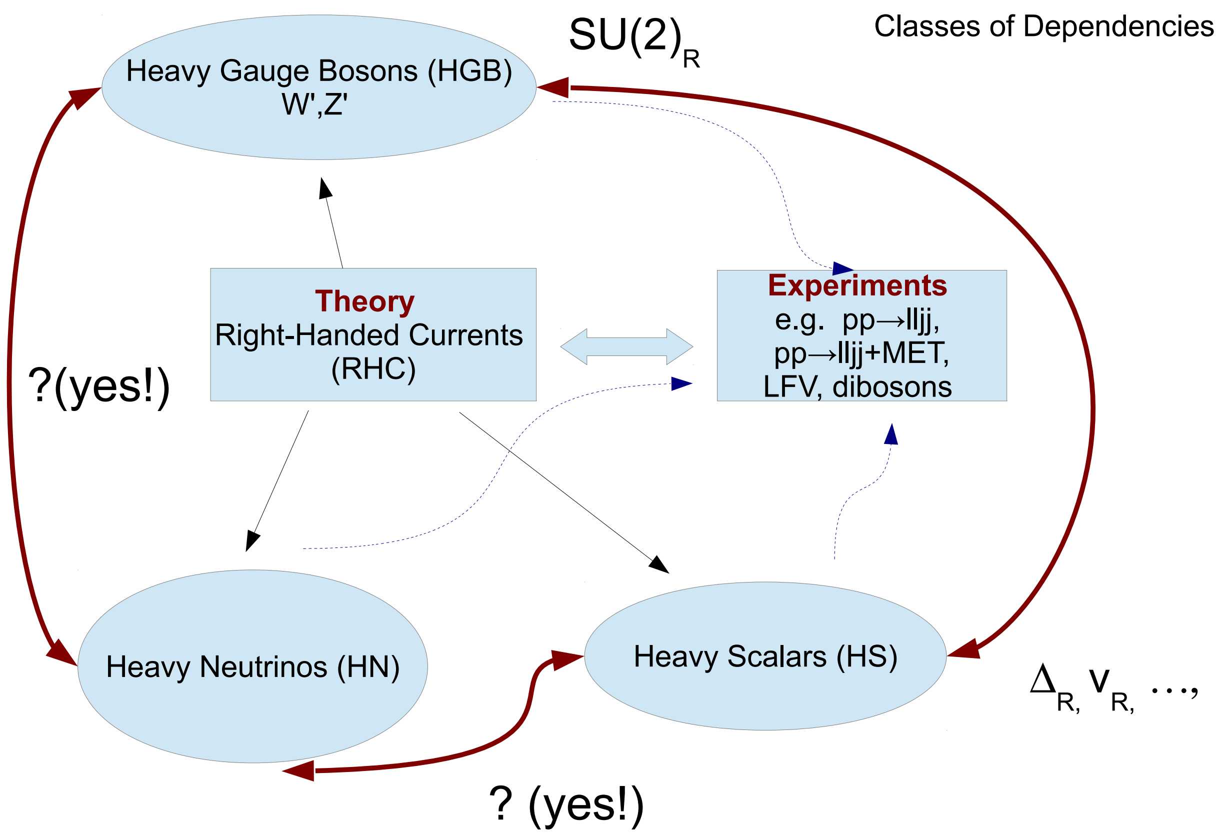
RHC includes plenty of connected issues



Right-handed currents

$$\mathcal{L} \supset \frac{g_L}{\sqrt{2}} \overline{N}_a \gamma^\mu P_R (K_R)_{aj} l_j W^+_{2\mu} + \text{h.c.}$$

$$M_\nu = \begin{pmatrix} 0 & M_D \\ M_D^T & M_R \end{pmatrix}, \qquad U \approx \begin{pmatrix} 1 & 0 \\ 0 & K_R^\dagger \end{pmatrix}$$

- heavy gauge boson $W_2^\pm$, $M_{W_2} \sim 2$ TeV
- heavy neutrinos N_a, $M_D \ll M_R$
- K_R is heavy neutrino mixing matrix defined by $M_R = K_R^T \text{diag}(M_{N_1}, M_{N_2}, M_{N_3}) K_R$

LHC-1 excess data

A few deviations from the SM reported by the ATLAS and CMS in invariant mass distributions near 2 TeV:

(i) 3.4σ excess at ∼2 TeV in the ATLAS search interpreted as a W' boson decaying into $WZ \to jj$

(ii) 1.4σ excess at ∼1.9 TeV in the CMS search for jj resonances without distinguishing between the W- and Z-tagged jets

(iii) 2.8σ excess in the 1.8 – 2.2 TeV bin in the CMS search for a W' and a heavy "right-handed" neutrino, N_R, through the $W' \to N_R\, e \to eejj$ process

(iv) 2.2σ excess in the 1.8 – 1.9 TeV bin in the CMS search for $W' \to Wh^0$, where the SM Higgs boson, h^0, is highly boosted and decays into $b\bar{b}$, while $W \to \ell\nu$

(v) 2σ excess at ~ 1.8 TeV in the CMS dijet resonance search The ATLAS search in the same channel has yielded only a 1σ excess at 1.8 TeV

Higgs sector consists of two triplets $\Delta_{L,R}$ and one bidoublet ϕ

$$\Delta_{L,R} = \begin{pmatrix} \delta^+_{L,R}/\sqrt{2} & \delta^{++}_{L,R} \\ \delta^0_{L,R} & -\delta^+_{L,R}/\sqrt{2} \end{pmatrix}, \qquad \Phi = \begin{pmatrix} \phi^0_1 & \phi^+_1 \\ \phi^-_2 & \phi^0_2 \end{pmatrix}.$$

with vacuum expectation values for the neutral scalars

$$\frac{v_L}{\sqrt{2}} = \langle \delta^0_L \rangle, \quad \frac{v_R}{\sqrt{2}} = \langle \delta^0_R \rangle, \qquad SU(2)_R \text{ breaking scale: } v_R \sim \mathcal{O}(10)\,\text{TeV}$$

$$\frac{\kappa_1}{\sqrt{2}} = \langle \phi^0_1 \rangle, \quad \frac{\kappa_2}{\sqrt{2}} = \langle \phi^0_2 \rangle, \qquad \text{SM scale: } \sqrt{\kappa_1^2 + \kappa_2^2}$$

Physical scalars

- 4 neutral scalars: $H_0^0,\ H_1^0, H_2^0, H_3^0,$
  (the first can be considered to be the light Higgs of the SM),

- 2 neutral pseudo-scalars: A_1^0, A_2^0,

- 2 charged scalars: $H_1^{\pm}, H_2^{\pm},$

- 2 doubly charged scalars: $H_1^{\pm\pm}, H_2^{\pm\pm}$.

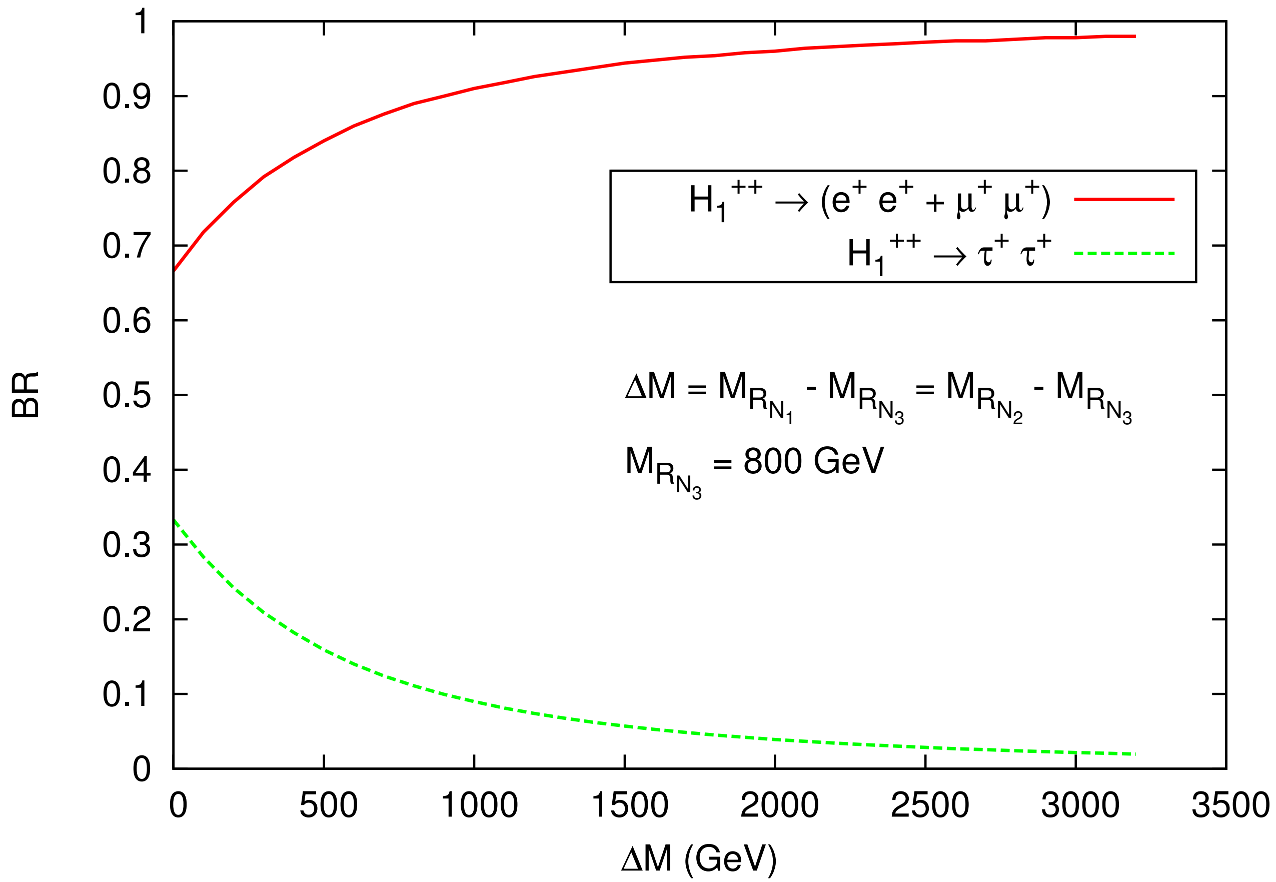
Primary production	Secondary production	Signal
I. $H_1^+ H_1^-$	$\ell^+ \ell^- \nu_L \nu_L$	$\ell^+ \ell^- \oplus MET$
–	$\ell^+ \ell^- \nu_R \nu_R$	depends on ν_R decay modes
–	$\ell^+ \ell^- \nu_L \nu_R$	depends on ν_R decay modes
II. $H_2^+ H_2^-$	$\ell^+ \ell^- \nu_L \nu_L$	$\ell^+ \ell^- \oplus MET$
–	$\ell^+ \ell^- \nu_R \nu_R$	depends on ν_R decay modes
–	$\ell^+ \ell^- \nu_L \nu_R$	depends on ν_R decay modes
III. $H_1^{++} H_1^{--}$	–	$\ell^+ \ell^+ \ell^- \ell^-$
–	$H_1^+ H_1^+ H_1^- H_1^-$	See I
–	$H_1^\pm H_1^\pm H_2^\mp H_2^\mp$	See I & II
–	$H_2^+ H_2^+ H_2^- H_2^-$	See II
–	$W_i^+ W_i^+ W_j^- W_j^-$	depends on W's decay modes
IV. $H_2^{++} H_2^{--}$	–	$\ell^+ \ell^+ \ell^- \ell^-$
–	$H_2^+ H_2^+ H_2^- H_2^-$	See II
–	$H_1^\pm H_1^\pm H_2^\mp H_2^\mp$	See I & II
–	$H_1^+ H_1^+ H_1^- H_1^-$	See I
–	$W_i^+ W_i^+ W_j^- W_j^-$	depends on W's decay modes
V. $H_1^{\pm\pm} H_1^\mp$	–	$l^\pm l^\pm l^\mp \nu_L$
VI. $H_2^{\pm\pm} H_2^\mp$	–	$l^\pm l^\pm l^\mp \nu_L$
VII. $H_1^\pm Z_i, H_1^\pm W_i$	–	See I & Z_i, W_i decay modes
VIII. $H_2^\pm Z_i, H_1^\pm W_i$	–	See II & Z_i, W_i decay modes
IX. $H_1^\pm A$	–	See I
X. $H_2^\pm A$	–	See II

Branching ratios

$$
\begin{array}{ll}
\text{(i)} & H_1^{\pm\pm} \to l^\pm l^\pm, \text{ where } l = e, \mu, \tau; \\
\text{(ii)} & H_1^{\pm\pm} \to H_1^\pm W_1^\pm; \\
\text{(iii)} & H_2^{\pm\pm} \to l^\pm l^\pm, \text{ where } l = e, \mu, \tau; \\
\text{(iv)} & H_2^{\pm\pm} \to H_2^\pm W_2^\pm; \\
\text{(v)} & H_2^{\pm\pm} \to W_2^\pm W_2^\pm; \\
\text{(vi)} & H_2^{\pm\pm} \to H_2^\pm W_1^\pm;
\end{array}
$$

In principle we can have both LNV and LFV,

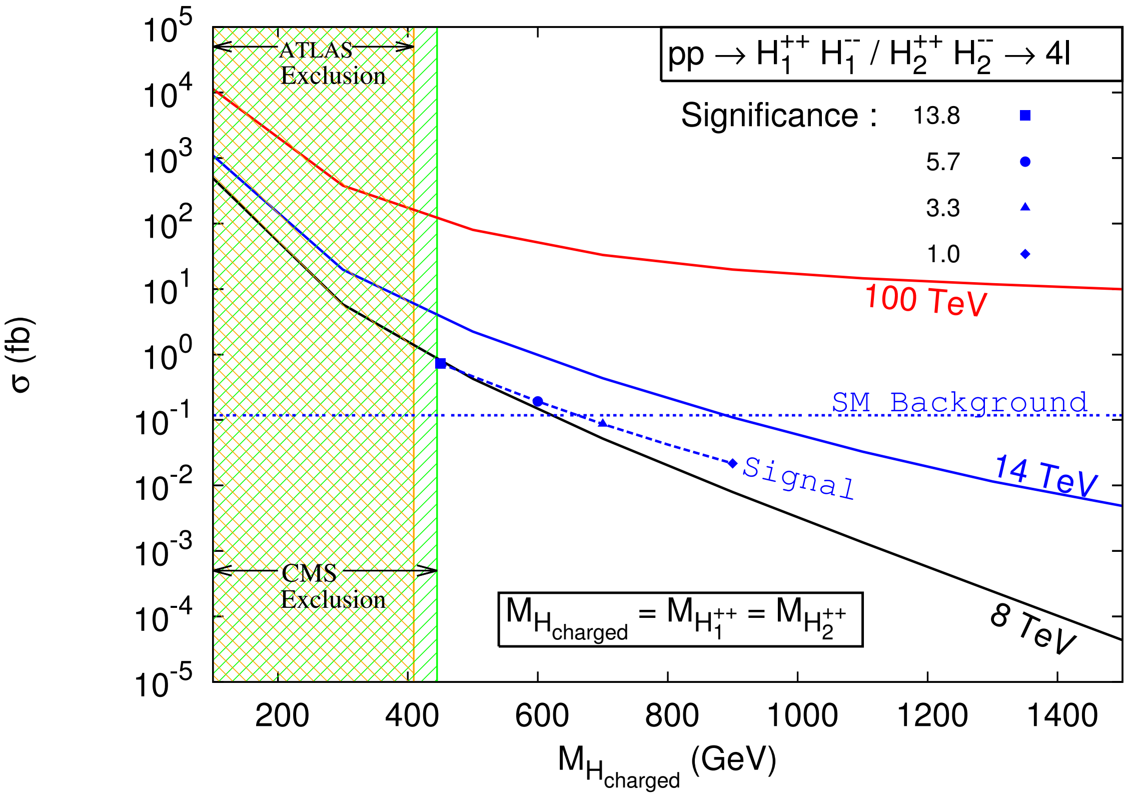
$$
\begin{array}{c}
BR(H_{1/2}^{\pm\pm} \to e^\pm e^\pm) = 37.9\% \\
BR(H_{1/2}^{\pm\pm} \to \mu^\pm \mu^\pm) = 37.9\% \\
BR(H_{1/2}^{\pm\pm} \to \tau^\pm \tau^\pm) = 24.2\%.
\end{array}
$$


BR
ΔM (GeV)
$H_1^{++} \to (e^+ e^+ + \mu^+ \mu^+)$
$H_1^{++} \to \tau^+ \tau^+$
$\Delta M = M_{R_{N_1}} - M_{R_{N_3}} = M_{R_{N_2}} - M_{R_{N_3}}$
$M_{R_{N_3}}$ = 800 GeV
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
0
500
1000
1500
2000
2500
3000
3500

Doubly charged Higgses production (Drell-Yan)

$$m_{H^{\pm\pm}_{1,2}} = 600 \text{ GeV} :$$

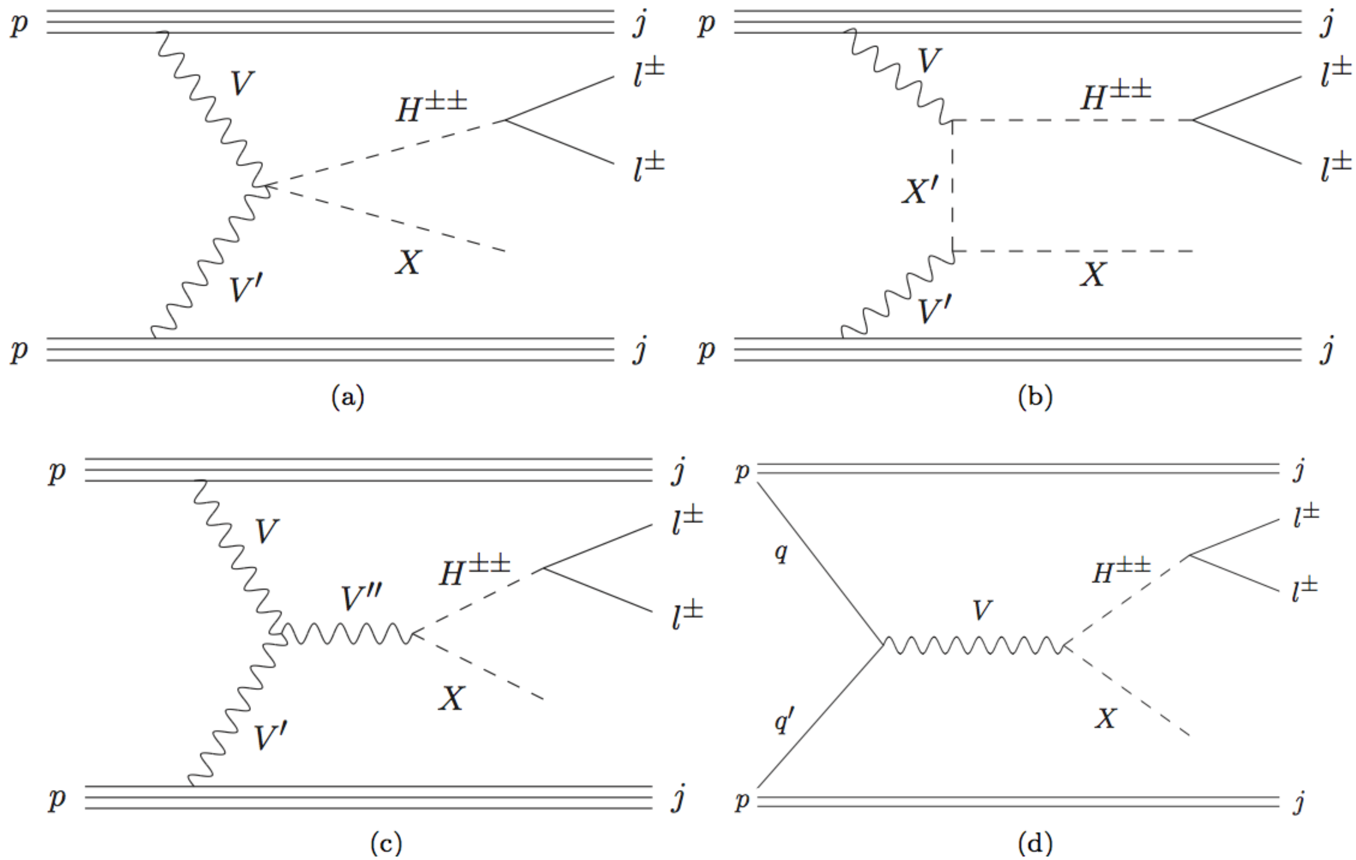
$$\sigma(pp \to H^{++}_{1,2} H^{--}_{1,2} \to l_i{}^+ l_i{}^+ l_j{}^- l_j{}^-) \quad = \quad 0.144(0.9498) \text{ fb for } \sqrt{s} = 8(14) \text{ TeV}.$$



Kinematic cuts for H^{++} production at the LHC

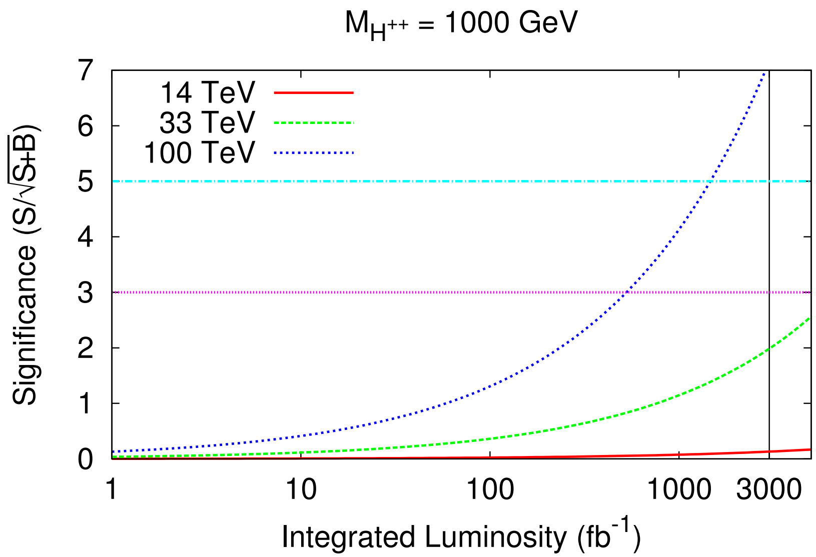
- The Parton Distribution Function (PDF) CTEQ6L1
- Initially to select a lepton, MadGraph, PYTHIA, $|\eta| < 2.5$ and $p_T > 10$ GeV
- Detector efficiency cut for leptons is as follows:
  - For electron (either e^- or e^+) detector efficiency is 0.7 (70%);
  - For muon (either μ^- or μ^+) detector efficiency is 0.9 (90%).
- Smearing of electron energy and muon p_T are done
- Lepton-lepton separation. $\Delta R_{ll} \geq 0.2$
- Lepton-photon separation cut is also applied: $\Delta R_{l\gamma} \geq 0.2$ with all the photons having $p_{T\gamma} > 10$ GeV;
- Lepton-jet separation: The separation of a lepton with all the jets should be $R_{lj} \geq 0.4$, otherwise that lepton is not counted as lepton. Jets are constructed from hadrons using PYCELL within the PYTHIA.
- Hadronic activity cut. This cut is applied to take only pure kind of leptons that have very less hadronic activity around them. Each lepton should have hadronic activity, $\frac{\sum p_{T_{hadron}}}{p_{T_l}} \leq 0.2$ within the cone of radius 0.2 around the lepton.
- Hard p_T cuts: $p_{Tl_1} > 30$ GeV, $p_{Tl_2} > 30$ GeV, $p_{Tl_3} > 20$ GeV, $p_{Tl_4} > 20$ GeV.
- Missing p_T cut. Since 4-lepton final state is without missing p_T, missing p_T cut is not applied while for 3-lepton final state there is a missing neutrino, so missing p_T cut $(p_T > 30$ GeV) is applied.
- Z-veto is also applied to suppress the SM background. This has larger impact while reducing the background for four-lepton without missing energy.

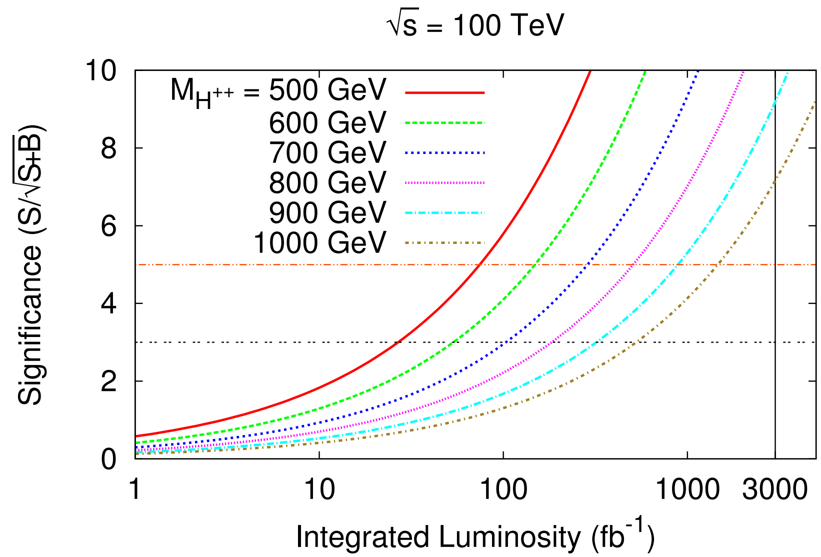
Doubly charged Higgs bosons production (Vector Boson Fusion with 2 jets)



LHC has dedicated search channels for tagged forward jets.

Doubly charged Higgs bosons production (Vector Boson Fusion with 2 jets)





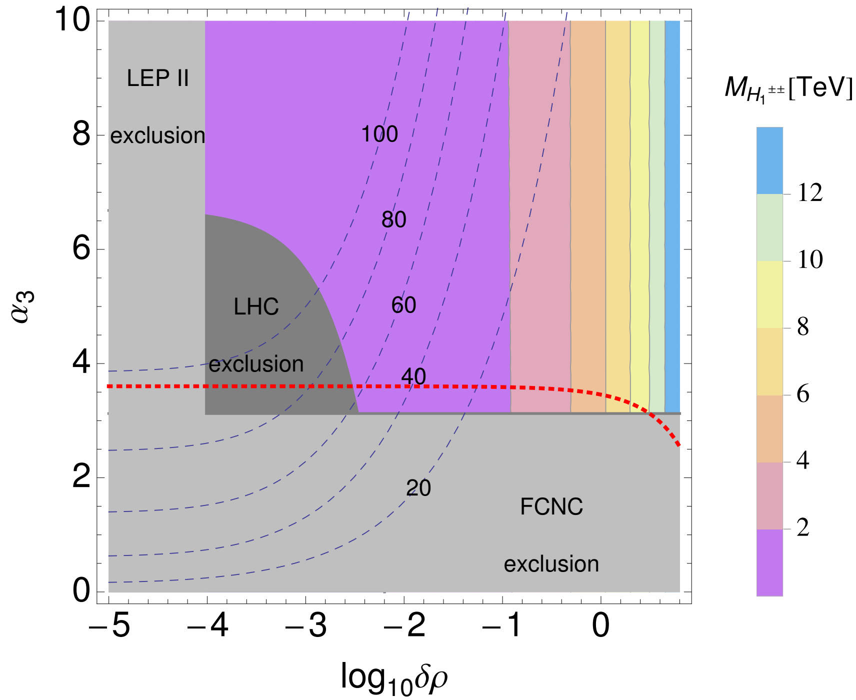
- Left: 1 TeV doubly charged scalar can be probed with a significance of 5 only with 100 TeV collider with luminosity at least 1000 fb^{-1}
- Right: significance at the level of 7 can be reached for $M_{H^{\pm\pm}} = 1\,\mathrm{TeV}$ and $\sqrt{s} = 100$ TeV with integrated luminosities around 3000 fb^{-1}.

Constraints, dependences: theory and experiment

Naturally, $m_H^{\pm,0} \propto v_R$.

❖ 124.7 GeV $< M_{H_0^0} <$ 126.2 GeV

$$\begin{aligned}
M^2_{H_0^0} &\simeq 2\kappa_+^2\lambda_1 - \frac{\alpha_1^2}{2\rho_1}, \\
M^2_{H_1^0}(FCNC) &\simeq \frac{1}{2}\alpha_3 v_R^2 && FCNC > 10 \text{ TeV}, \\
M^2_{H_2^0} &\simeq 2\rho_1 v_R^2 \\
M^2_{H_1^\pm}(LHC) &= \frac{1}{2}v_R^2\delta\rho + \frac{1}{4}\alpha_3\kappa_+^2, && (\delta\rho = \rho_3 - 2\rho_1) \\
M^2_{H_1^{\pm\pm}}(LHC) &= \frac{1}{2}\left[v_R^2\delta\rho + \alpha_3\kappa_+^2\right], \\
M^2_{H_2^{\pm\pm}}(LHC) &= 2\rho_2 v_R^2 + \frac{1}{2}\alpha_3\kappa_+^2. && LHC < 1 \text{ TeV}
\end{aligned}$$



masses (in GeV)

$M_{H_0^0} = 125,$

$M_{H_1^0} = 10431, \quad M_{H_2^0} = 27011, \quad M_{H_3^0} = 384$

$M_{A_1^0} = 10437, \quad M_{A_2^0} = 384$

$M_{H_1^\pm} = 446, \quad M_{H_2^\pm} = 10433$

$M_{H_1^{\pm\pm}} = 500, \quad M_{H_2^{\pm\pm}} = 500$

parameters

$\lambda_1 = 0.13, \quad \lambda_3 = 1$

$\alpha_3 = 3.4$

$\rho_1 = 5.7, \quad \rho_2 = 1.15 \times 10^{-3}, \quad \rho_3 = 11.40$

Conclusions:

- only region below the red dotted line is allowed. That line corresponds to the the stability condition.
- $M_{H_1^{\pm\pm}} - M_{H_1^\pm} < M_{W_1^\pm}$, hence on-shell $H_1^{\pm\pm}$ cannot decay to $H_1^\pm$ and $W_1^\pm$

Summary

- some details of Higgs sector are important for interpreting experimental data
- discovery of doubly charged Higgs particles would be something incredibly new and would define new directions in physics
- 100 TeV collider would open up a very wide range of Higgs boson masses which can be explored
- $\rightarrow$ complete significance studies $\sigma(pp \rightarrow H^{++}_{1,2} H^{--}_{1,2} \rightarrow {l_i}^+ {l_i}^+ {l_j}^- {l_j}^-)$ at 100 TeV and estimate SM background, take into account also RGE and unitarity constraints