Right-handed currents and doubly charged Higgs bosons

Proposal for the Report on Physics at 100 TeV

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CERN, 28.10.2015, Vidyo transmission

FCC-hh BSM group informal meeting, indico

Studies including FCC-hh:

- G. Bambhaniya, J. Chakrabortty, J. Gluza, T. Jeliński and R. Szafron,
  "Search for doubly charged Higgs bosons through VBF at the LHC and beyond ,"
  e-Print: arXiv:1504.03999, to appear in PRD.
- G. Bambhaniya, J. Chakrabortty, J. Gluza, T. Jeliński and M. Kordiaczyńska,
  "Lowest limits on the doubly charged Higgs boson masses in the minimal left-right symmetric model,"
  e-Print: arXiv:1408.0774, Phys. Rev. D **90** (2014) 9, 095003

Related studies:

- G. Bambhaniya, J. Chakrabortty, J. Gluza, M. Kordiaczyńska and R. Szafron,
  "Left-Right Symmetry and the Charged Higgs Bosons at the LHC,"
  e-Print: arXiv:1311.4144, JHEP **1405** (2014) 033
- J. Chakrabortty, J. Gluza, R. Sevillano, R. Szafron,
  "Left-Right Symmetry at LHC and Precise 1-Loop Low Energy Data"
  e-Print: arXiv:1204.0736, JHEP **1207** (2012) 038.
- J. Chakrabortty, P. Konar, T. Mondal, "Constraining a class of B-L extended models from vacuum stability and perturbativity"
  e-Print: arXiv:1308.1291, Phys.Rev. D89 (2014) 056014.

Higgs sector consists of two triplets and one bidoublet

$$\Delta_{L,R} = \begin{pmatrix} \delta^{+}_{L,R}/\sqrt{2} & \delta^{++}_{L,R} \\ \delta^{0}_{L,R} & -\delta^{+}_{L,R}/\sqrt{2} \end{pmatrix},$$

$$\Phi = \begin{pmatrix} \phi^{0}_{1} & \phi^{+}_{1} \\ \phi^{-}_{2} & \phi^{0}_{2} \end{pmatrix}.$$

with vacuum expectation values allowed for the neutral particles

$$\frac{v_L}{\sqrt{2}} = \langle \delta^0_L \rangle,$$

$$\text{new HE scale :}\frac{v_R}{\sqrt{2}} = \langle \delta^0_R \rangle,$$

$$\text{SM VEV scale :}\sqrt{\kappa_1^2 + \kappa_2^2}$$

$$\frac{\kappa_1}{\sqrt{2}} = \langle \phi^0_1 \rangle,$$

$$\frac{\kappa_2}{\sqrt{2}} = \langle \phi^0_2 \rangle.$$

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: $H_1^{\pm\pm}, H_2^{\pm\pm}$.

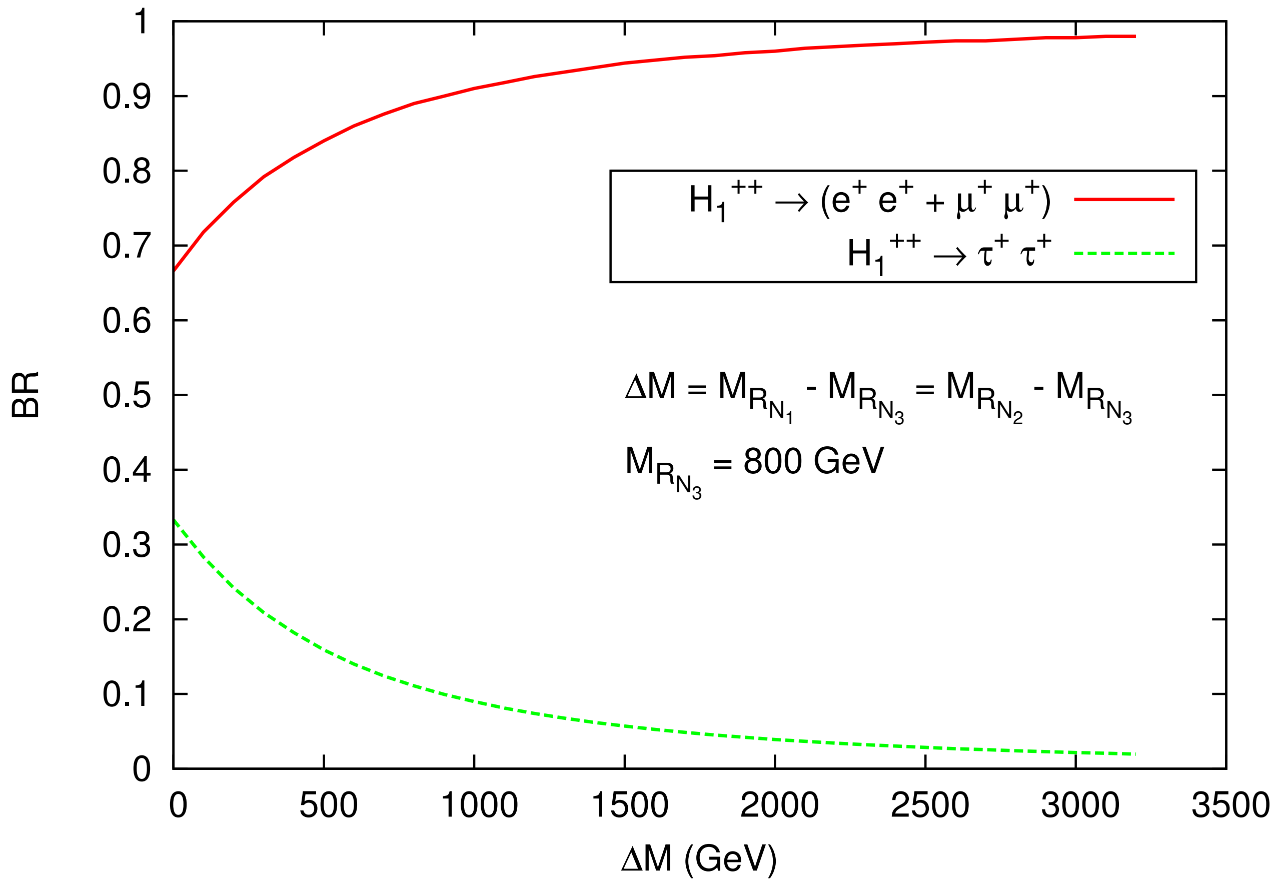
Primary production	Secondary production	Signal
I. $H_1^+ H_1^-$	$\ell^+ \ell^- \nu_L \nu_L$	$\ell^+ \ell^- \oplus MET$
–	$\ell^+ \ell^- \nu_R \nu_R$	depends on ν_R decay modes
–	$\ell^+ \ell^- \nu_L \nu_R$	depends on ν_R decay modes
II. $H_2^+ H_2^-$	$\ell^+ \ell^- \nu_L \nu_L$	$\ell^+ \ell^- \oplus MET$
–	$\ell^+ \ell^- \nu_R \nu_R$	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,

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

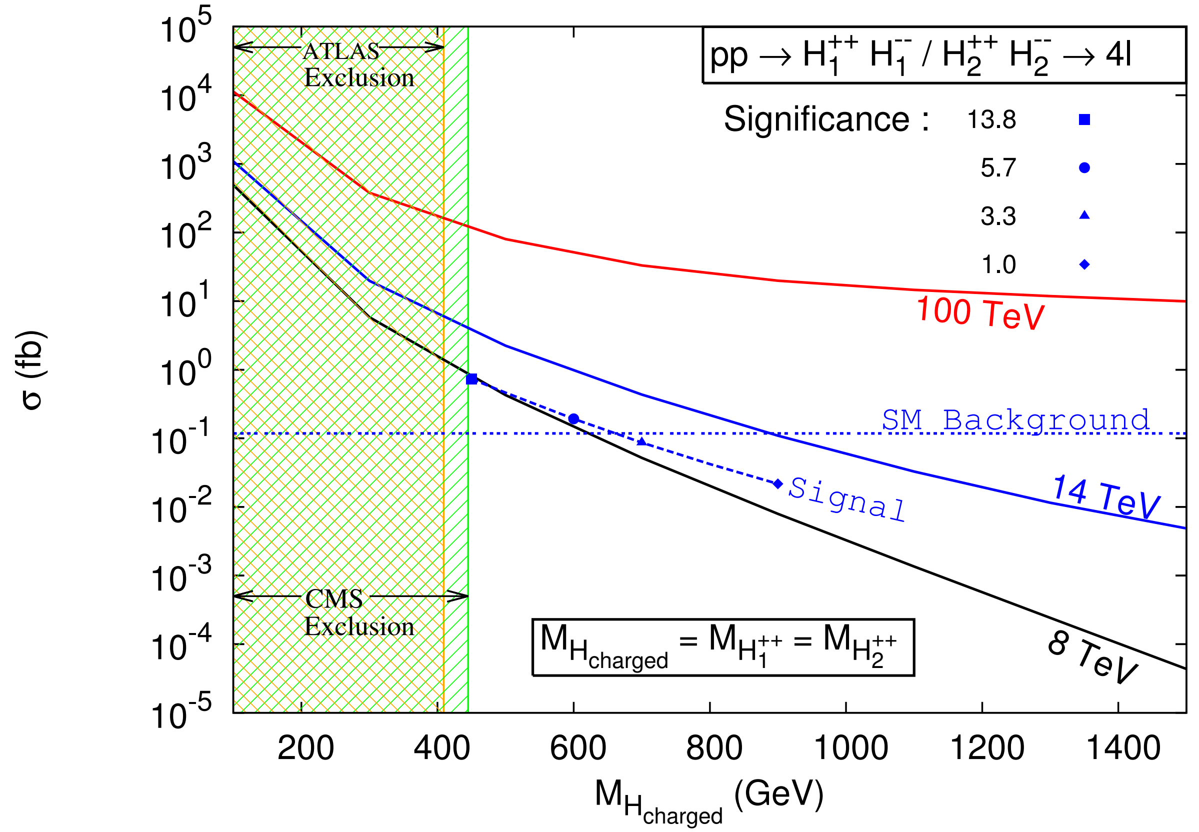


Should be updated!

Doubly charged Higgses production (Drell-Yan)

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

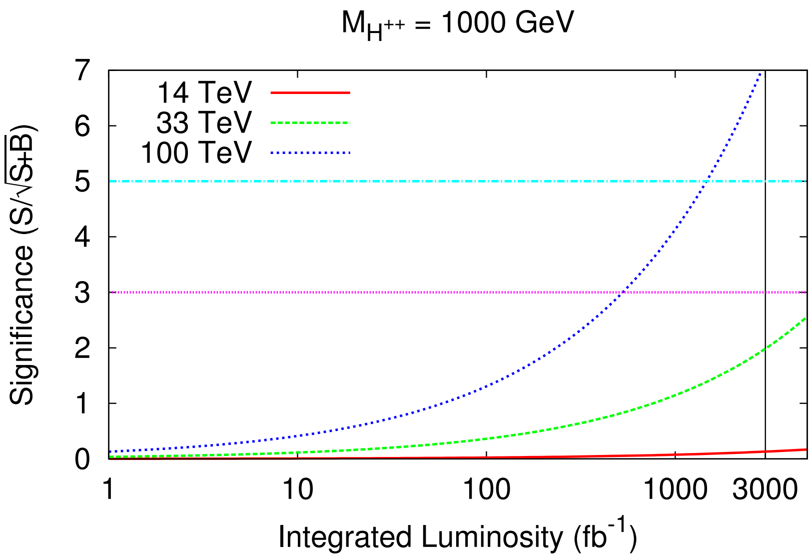
$$\sigma(pp \to H^{++}_{1,2} H^{--}_{1,2} \to l_i{}^+ l_i{}^+ l_j{}^- l_j{}^-) \quad = \quad 0.144(0.9498)\ fb \text{ for } \sqrt{s} = 8(14) \text{ TeV}.$$

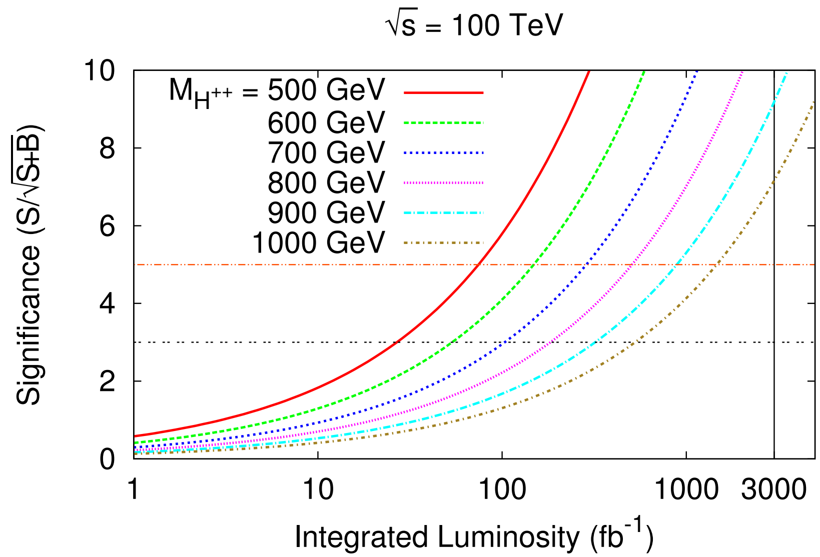


Kinematic cuts for H^{++} studies [used for LHC!]

- The Parton Distribution Function (PDF) CTEQ6L1
- Initially to select a lepton, CALCHEP, 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)





- Left: 1 TeV doubly charged scalar can be probed with a significance of 5 only with 100 the 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}.

Summary

- Discovery of doubly charged Higgs particles would be something incredibly new and would define new directions in physics (e.g. issue of supersymmetry)
- FCC-hh opens up a very wide range of Higgs boson masses which can be explored.

Plans for a report:

$\rightarrow$ Completing significance studies for $\sigma(pp \rightarrow H_{1,2}^{++} H_{1,2}^{--} \rightarrow {l_i}^+ {l_i}^+ {l_j}^- {l_j}^-)$ at 100 TeV, taking into account MODEL's CONSISTENCY (RGE, stability, unitarity, FCNC,...)

$\rightarrow$ Delivering mass spectrum benchmarks

BACKUP SLIDES

Phenomenology: approximations, estimations, simplifications,...

For obvious reasons, usually we are forced to simplify our approaches theory $\rightarrow$ phenomenology (supersymmetry,...)

This seems to be fine, especially when considering very heavy NP particles

$$m_i(H, N, W', Z', ...) >> E_{\rm process}$$

For FCC, situation much realeased! Still, there are strong relations among scalar masses which should be taken into account.

New Physics and radiative corrections

Not always - depending on renormalization strategy - radiative corrections connected with the SM particles inside complete NP model are the same as in the SM itself.

E.g. $\Delta\rho$ correction in muon decay decay width, and top quark (also scalars!):

$$(\Delta\rho)_{SM} \simeq \frac{m_t^2}{M_W^2}$$

$$(\Delta\rho)_{LRM} \simeq \frac{m_t^2}{M_{W_2}^2 - M_{W_1}^2}$$

M. Czakon, JG, F. Jegerlehner, M. Zralek, hep-ph/9909242

Present example - scalar physics.

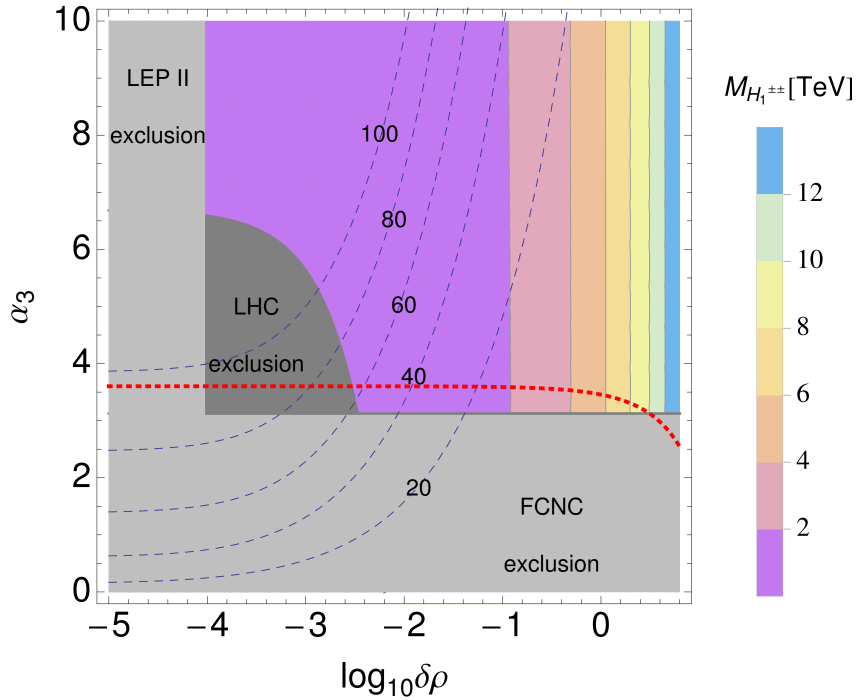
We try to care on MODELS CONSISTENCY - important for FCC predictions

Constraints, dependences: theory and experiment

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

- 124.7 GeV $< M_{H_0^0} <$ 126.2 GeV

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



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 <u>below</u> 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 $W_1^\pm$