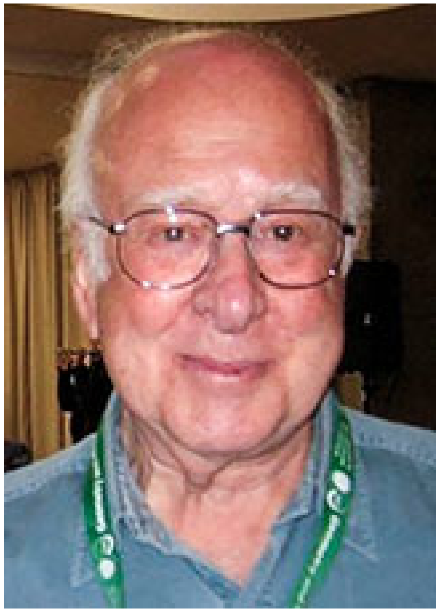
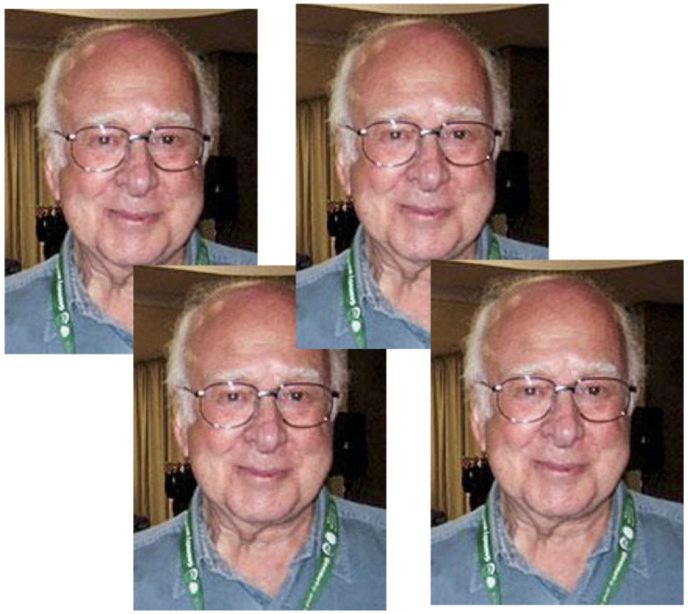
One or more Higgses?

Janusz Gluza

Institute of Physics, University of Silesia





NA61/SHINE meeting, Katowice, 28 January 2015

2012, Polish popular journal

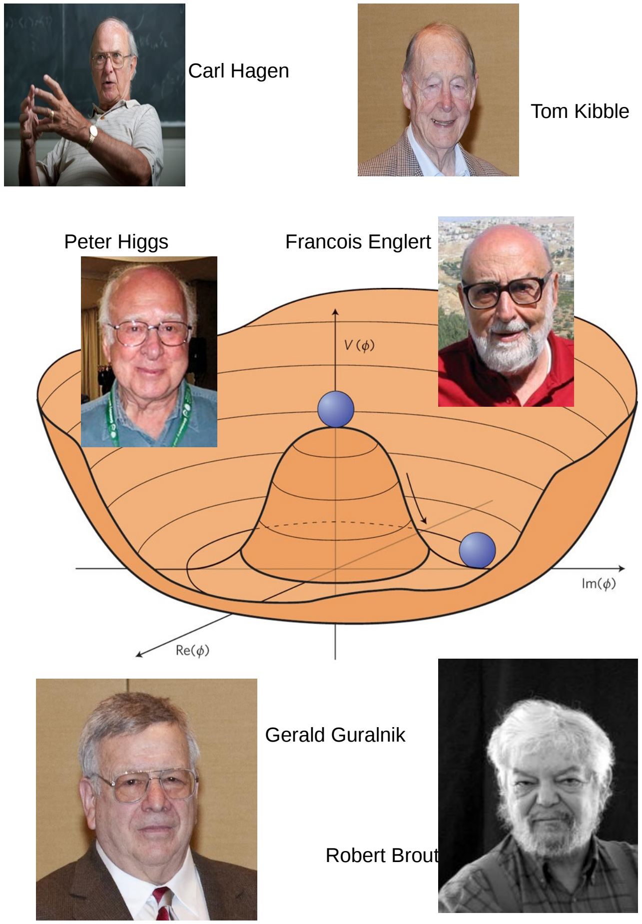
Marek Raczkowski w Gazeta.pl [WSZYSTKIE RYSUNKI]

Gazeta.pl | 01.10.2013 17:33 , aktualizacja 18.11.2013 08:14

rys. Marek Raczkowski

"Father, and what is it, this Higgs boson?"

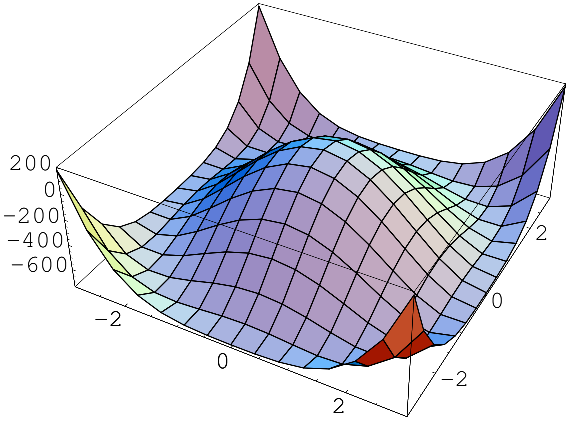
In 2012 SM has been crowned and, finally, SSB mechanism appreciated



Englert-Brout-Higgs-Guralnik-Hagen-Kibble mechanism

Is Particle Physics scalar landscape so simple? Mount Mayon

(Renowned as the "perfect cone" because of its almost symmetric conical shape)

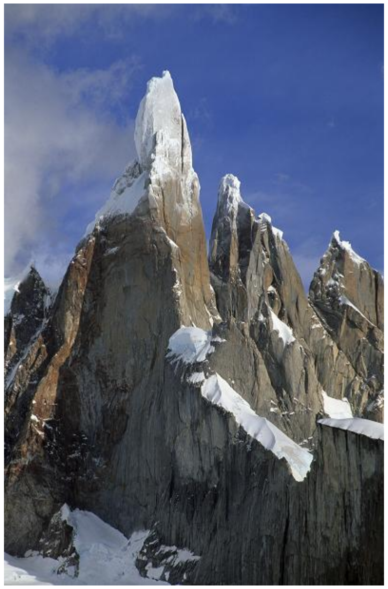


$$\begin{aligned} \Phi \equiv \Phi_{SM} &= \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix} \\ V &= -\mu^2 \Phi^\dagger \Phi + \lambda (\Phi^\dagger \Phi)^2 \\ V_{min} &= v/\sqrt{2}, v = \sqrt{\mu^2/\lambda} \simeq 250 \text{ GeV} \end{aligned}$$

What if not?

e.g.

$$\begin{aligned} V \quad = \quad & m_{11}^2\,\Phi_1^\dagger\Phi_1 + m_{22}^2\,\Phi_2^\dagger\Phi_2 - m_{12}^2\,\left(\Phi_1^\dagger\Phi_2 + \Phi_2^\dagger\Phi_1\right) + \frac{\lambda_1}{2}\left(\Phi_1^\dagger\Phi_1\right)^2 + \frac{\lambda_2}{2}\left(\Phi_2^\dagger\Phi_2\right)^2 \\ & +\lambda_3\,\Phi_1^\dagger\Phi_1\,\Phi_2^\dagger\Phi_2 + \lambda_4\,\Phi_1^\dagger\Phi_2\,\Phi_2^\dagger\Phi_1 + \frac{\lambda_5}{2}\left[\left(\Phi_1^\dagger\Phi_2\right)^2 + \left(\Phi_2^\dagger\Phi_1\right)^2\right], \end{aligned}$$



$$\Phi_a = \left(\begin{array}{c} \phi_a^+ \\ \left(v_a + \rho_a + i\eta_a\right)\Big/\sqrt{2} \end{array}\right), \quad a = 1, 2.$$

One fact and two important questions

- **There is a scalar, fundamental particle!**
- Do we need more of them?
- What kind of?

I will focus on non-supersymmetric theories with Left-Right gauge symmetry.

Parity restoration, a lot of theoretical and experimental activity (triggered by LHC)

Start: 1973-1974,

Pati, Salam, Senjanovic, Mohapatra

gauge group $SU(2)_L \otimes SU(2)_R \otimes U(1)_{B-L}$
(i) restores left-right symmetry to e-w interactions

$$\begin{pmatrix} \nu_L \\ e_L \end{pmatrix}, \quad \begin{pmatrix} \nu_R \\ e_R \end{pmatrix}, \qquad \begin{pmatrix} u_L \\ d_L \end{pmatrix}, \quad \begin{pmatrix} u_R \\ d_R \end{pmatrix}$$

(ii) hypercharge interpreted as a difference of baryon and lepton numbers

$$Q = T_{3L} + T_{3R} + \frac{B-L}{2}$$

$$\begin{array}{ccc} W_L^{\pm}, W_L^0 & & W_1^{\pm}, W_2^{\pm} \\ W_R^{\pm}, W_R^0 & \rightarrow [SSB] & Z_1, Z_2 \\ B^0 & & \gamma \end{array}$$

The minimal Higgs sector consists of two triplets and one bidoublet

$$\begin{aligned} \Delta_{L,R} &= \begin{pmatrix} \delta^{+}_{L,R}/\sqrt{2} & \delta^{++}_{L,R} \\ \delta^{0}_{L,R} & -\delta^{+}_{L,R}/\sqrt{2} \end{pmatrix}, \\ \Phi &= \begin{pmatrix} \phi^{0}_{1} & \phi^{+}_{1} \\ \phi^{-}_{2} & \phi^{0}_{2} \end{pmatrix}. \end{aligned}$$

with vacuum expectation values allowed for the neutral particles

$$\begin{aligned} \frac{v_L}{\sqrt{2}} &= \langle \delta^0_L \rangle, \\ \text{new HE scale}: \frac{v_R}{\sqrt{2}} &= \langle \delta^0_R \rangle, \\ & \qquad \text{SM VEV scale}: \sqrt{\kappa_1^2 + \kappa_2^2} \\ \frac{\kappa_1}{\sqrt{2}} &= \langle \phi^0_1 \rangle, \\ \frac{\kappa_2}{\sqrt{2}} &= \langle \phi^0_2 \rangle. \end{aligned}$$

Mohapatra, Senjanovic (1980); Deshpande, Gunion, Kayser, Olness, 1991

$$
\begin{aligned}
&\mathcal{L}_{Higgs} = \\
&-\mu_1^2 Tr[\Phi^\dagger \Phi] - \mu_2^2 (Tr[\tilde{\Phi}\Phi^\dagger] + Tr[\tilde{\Phi}^\dagger \Phi]) - \mu_3^2 (Tr[\Delta_L \Delta_L^\dagger] + Tr[\Delta_R \Delta_R^\dagger]) \\
&+\lambda_1 Tr[\Phi\Phi^\dagger]^2 + \lambda_3 (Tr[\tilde{\Phi}\Phi^\dagger] Tr[\tilde{\Phi}^\dagger \Phi]) \\
&+\rho_1 (Tr[\Delta_L \Delta_L^\dagger]^2 + Tr[\Delta_R \Delta_R^\dagger]^2) \\
&+\rho_2 (Tr[\Delta_L \Delta_L] Tr[\Delta_L^\dagger \Delta_L^\dagger] + Tr[\Delta_R \Delta_R] Tr[\Delta_R^\dagger \Delta_R^\dagger]) \\
&+\rho_3 (Tr[\Delta_L \Delta_L^\dagger] Tr[\Delta_R \Delta_R^\dagger]) \\
&+\alpha_3 (Tr[\Phi\Phi^\dagger \Delta_L \Delta_L^\dagger] + Tr[\Phi^\dagger \Phi \Delta_R \Delta_R^\dagger]) + \ldots
\end{aligned}
$$

invariant under the symmetry $\Delta_L \leftrightarrow \Delta_R, \quad \Phi \leftrightarrow \Phi^\dagger, \quad .$

Physical scalars

- 4 neutral scalars: H_0^0, H_1^0, H_2^0, H_3^0,
  the light Higgs of the SM at tree level),

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

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

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

- see-saw mechanism for the generation of light neutrino masses, with specific SB sectors. The neutrino mass matrix

$$M_\nu = \begin{pmatrix} M_L(v_L) & M_D(\kappa_{1,2}) \\ M_D^T & M_R(v_R) \end{pmatrix}, \qquad \text{with } M_L \ll M_D \ll M_R.$$

This is a complicated model, we consider the simplest, Minimal Left-Right Symmetric model (MLRSM)

AIM of investigations:

- apply low-energy as well as high energy experimental limits on model parameters, plus theoretical consistency
- with these restrictions at hand:
  What kind of signals can we expect at LHC/FCC for charged Higgs particles productions and decays?

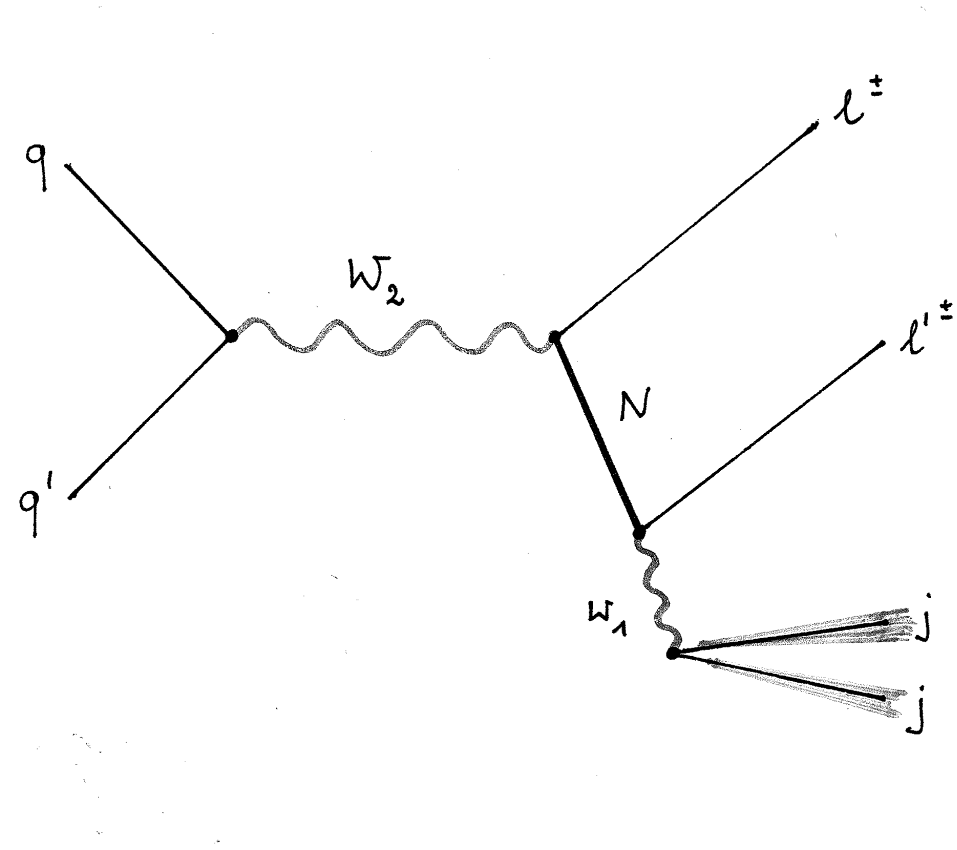
- G. Bambhaniya, J. Chakrabortty, J. Gluza, M. Kordiaczyńska and R. Szafron,
  "Left-Right Symmetry and the Charged Higgs Bosons at the LHC,"
  JHEP **1405** (2014) 033 [arXiv:1311.4144 [hep-ph]]

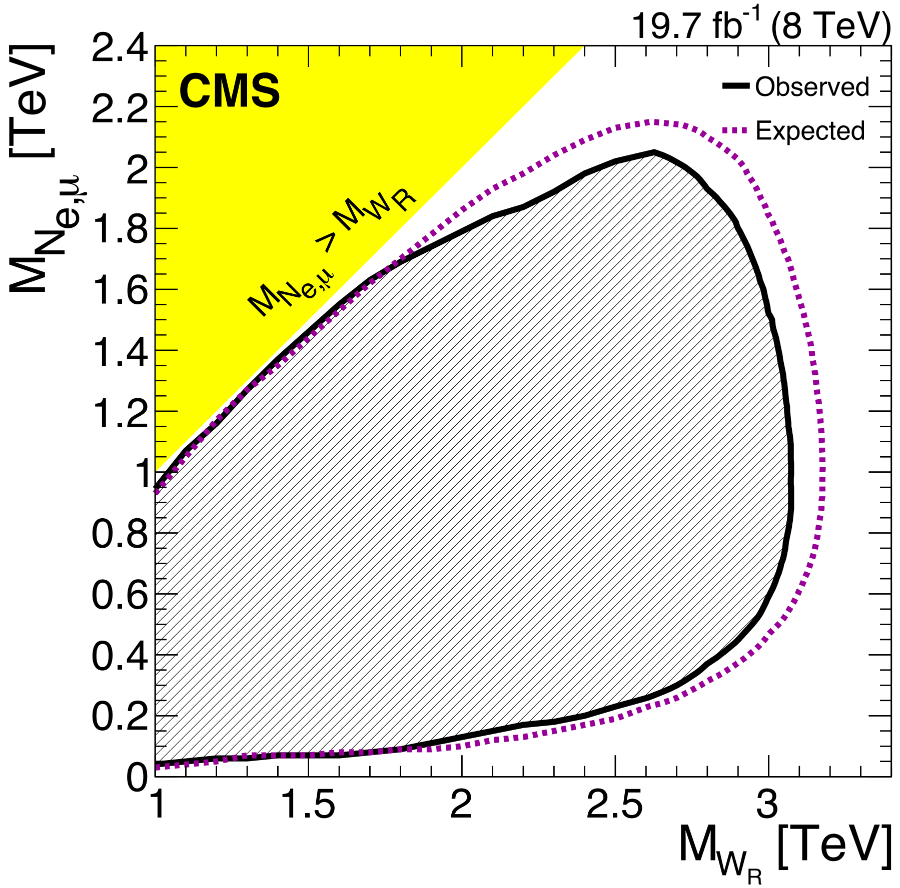
- G. Bambhaniya, J. Chakrabortty, J. Gluza, T. Jeliński and M. Kordiaczyńska,
  "Lowest limits on the doubly charged Higgs boson masses in the minimal left-right symmetric model,"
  Phys. Rev. D **90** (2014) 9, 095003

- G. Bambhaniya, J. Chakrabortty, J. Gluza, T. Jeliński and R. Szafron,
  "Doubly charged Higgs bosons through a vector boson fusion at the LHC and beyond,"
  work in progress

Gulab Bambhaniya - Physical Research Laboratory, Ahmedabad, India
Joydeep Chakrabortty - Indian Institute of Technology, Kanpur, India
Robert Szafron - U. Alberta, Canada
Tomasz Jeliński, Magdalena Kordiaczyńska, US, Katowice

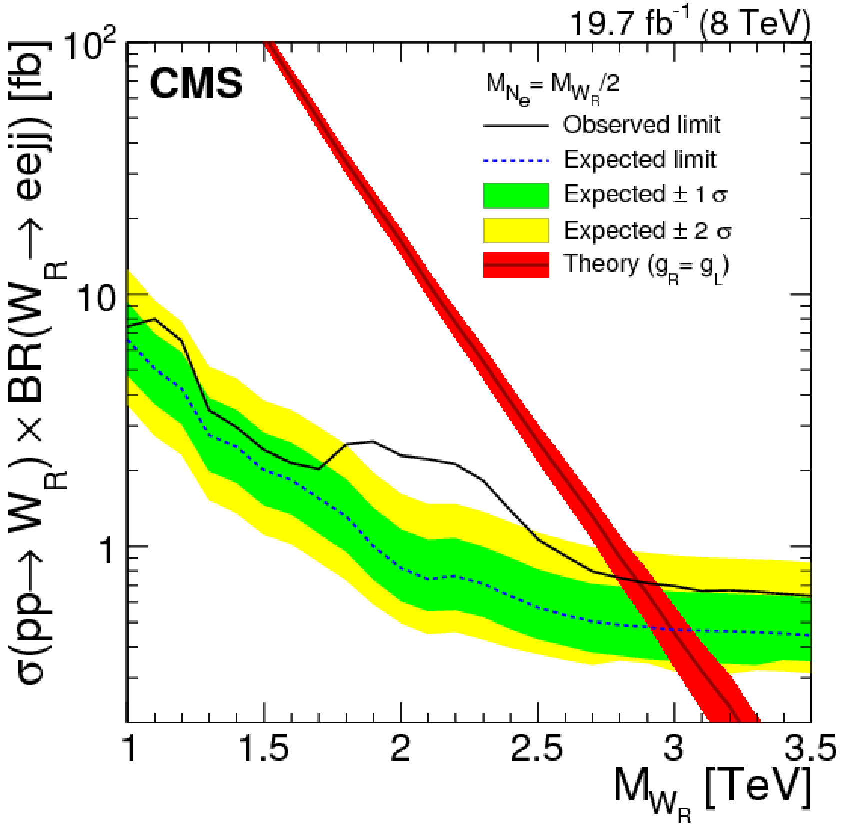
Experimental status for heavy particles searches: M_{W_R} and M_N



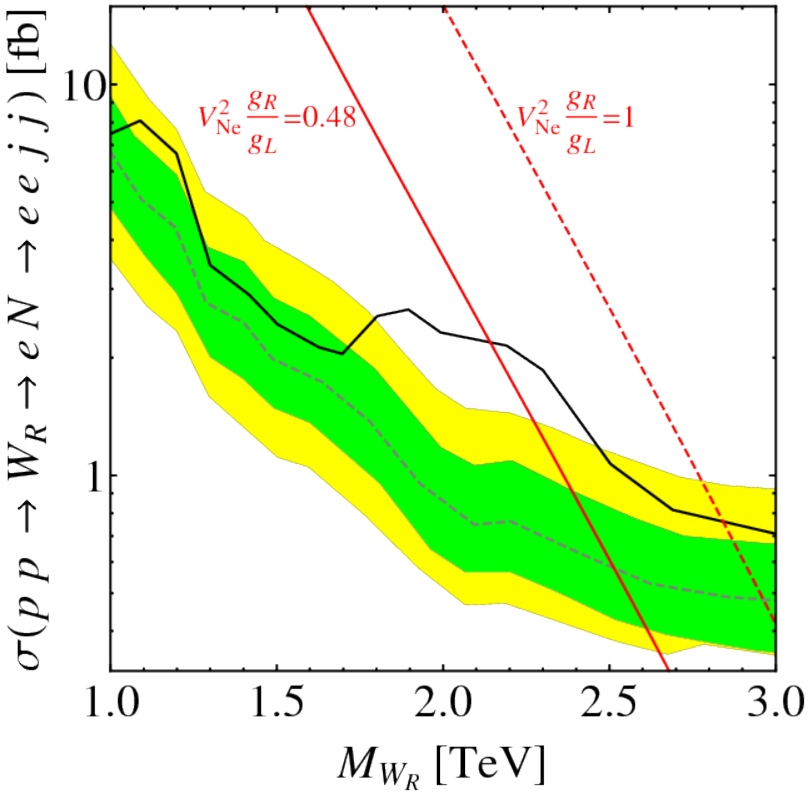


'golden' channel, (W_R, N are on-shell)

CMS Collaboration, arXiv:1407.3683v2

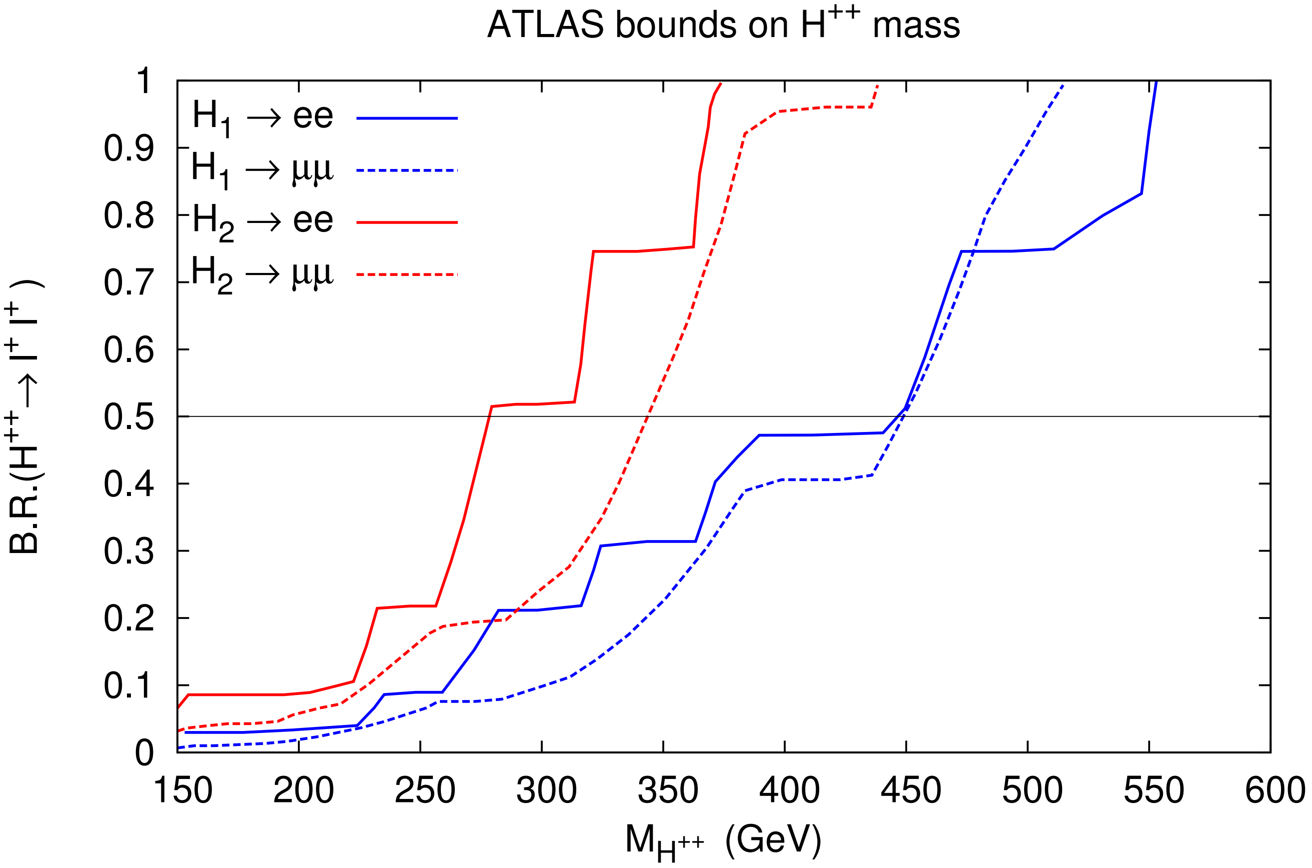


CMS Collaboration, arXiv:1407.3683v2



F. F. Deppisch et al., arXiv:1407.5384

Recent ATLAS limits on BR of $H^{\pm\pm}$ in MLRSM



ATLAS Collaboration, arXiv: 1412.0237

Summary

Typically, present direct limits on singly and doubly charged Higgs particle masses at LHC are at the level of $400 \div 450$ GeV.

But, are such relatively light masses allowed by MLRSM theory, if parity breaking scale v_R is much higher?

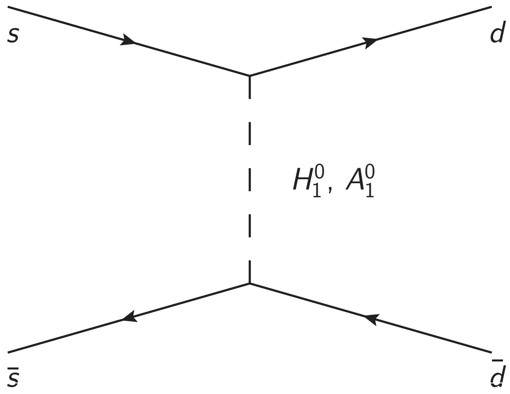
Yet another problem ...

FCNC in MLRSM

$$\begin{aligned} L_{quark-Higgs}(u,d) = \quad & - \quad \bar{U}\Big[P_L\Big(M^u_{diag}B_0^* + U^{CKM}M^d_{diag}U^{CKM\dagger}A_0\Big) \\ & + \quad P_R\Big(M^u_{diag}B_0 + U^{CKM}M^d_{diag}U^{CKM\dagger}{A_0}^*\Big)\Big]U \end{aligned}$$

The A_0, B_0, $A^{\pm}$ and $B^{\pm}$ are combinations of physical Higgs fields and Goldstone bosons:

$$A_0 \quad = \quad \frac{\sqrt{2}}{\kappa_-^2}\left(\kappa_1\phi_2^0 - \kappa_2\phi_1^{0*}\right) = \frac{\kappa_+}{\kappa_-^2}\left(H_1^0 - iA_1^0\right),$$



Strategy

We choose conservatively:

- $v_R = 8$ TeV ($M_{W_2} \geq 3.7$ TeV, expected limit in the next LHC run);
- masses of neutral Higgs particles $\simeq 10$ TeV (demanded also by problems with FCNC)
- charged Higgs particles with masses testable by LHC

In such a scenario there is a chance to pin down charged Higgs boson signals

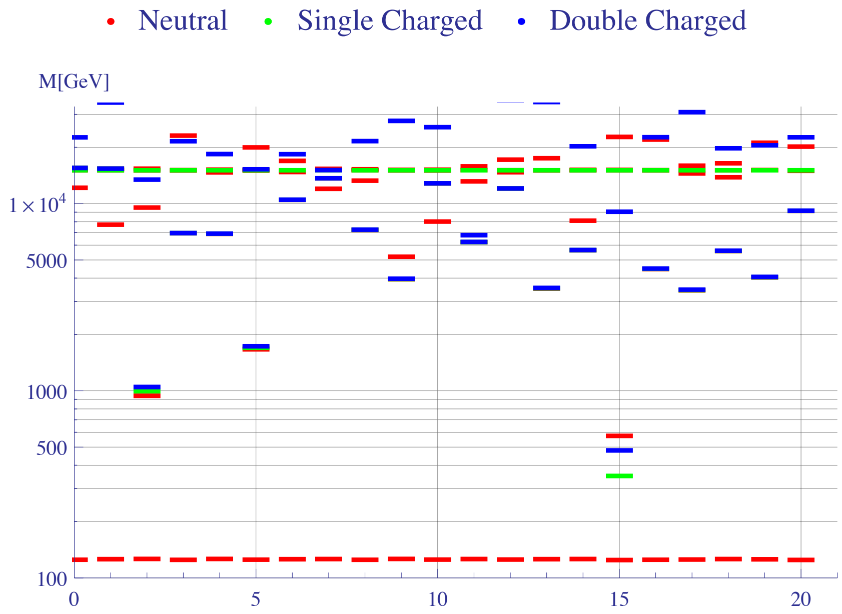
Theory: stability of the scalar potential - looking for global minimum

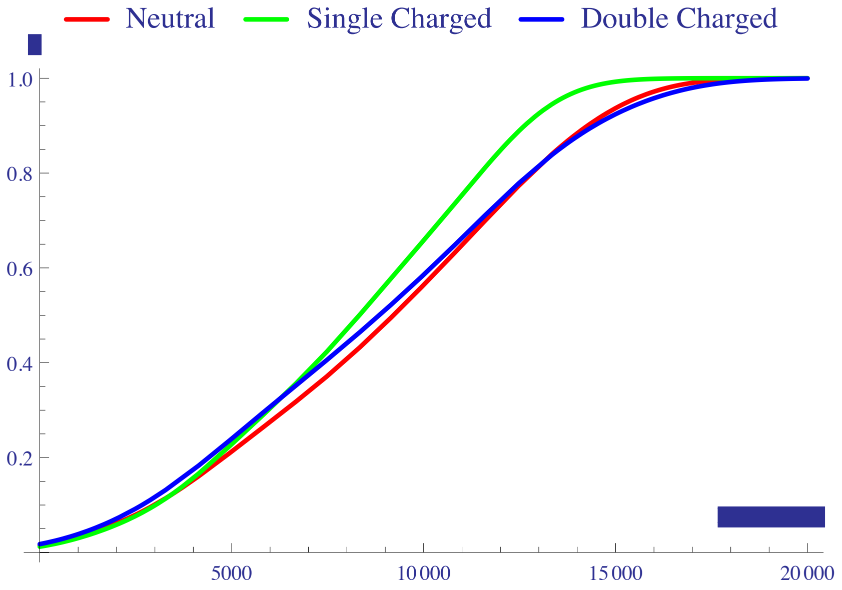
Naturally, $m_H^{\pm,0} \propto v_R$.

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

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

For $v_R = 8$ TeV a fraction of the parameter space that gives lightest scalar masses below 1 TeV is not more than 4%



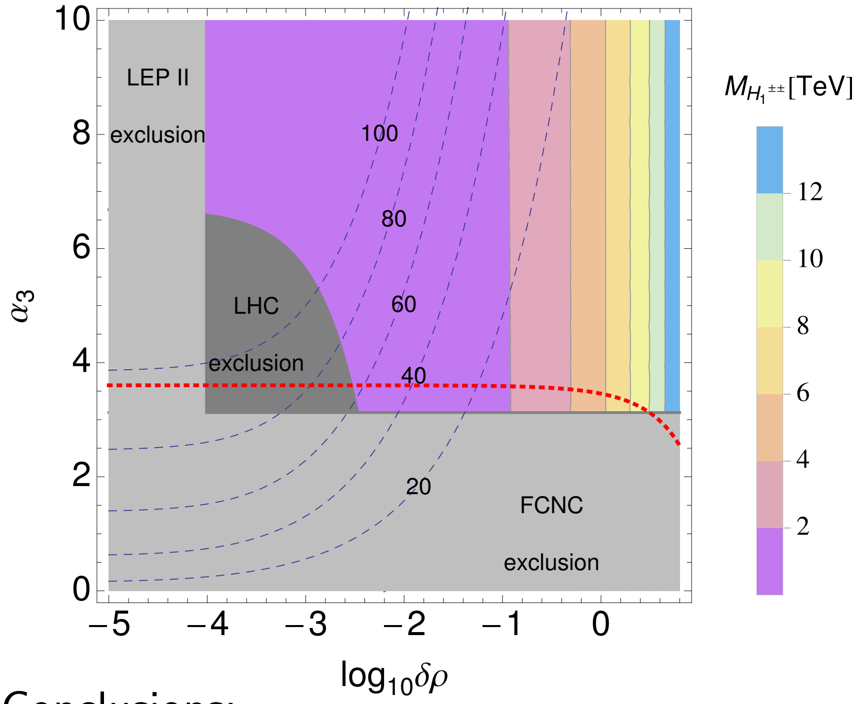


On left: an example of 20 Higgs mass spectra obtained by randomly chosen Higgs potential parameters. On right: cummulative distribution function P of the lowest mass of singly and doubly charged and next to lightest neutral scalars.

Consistency of the model: only 3 out of 4 charged scalars of the model can be light!

Necessary condition for the boundness of the scalar potential V (J. Chakrabortty et al):

$$\alpha_3 \leq \sqrt{8\lambda_1(4\pi - \delta\rho)}$$



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

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

$\alpha_3 = 3.4$

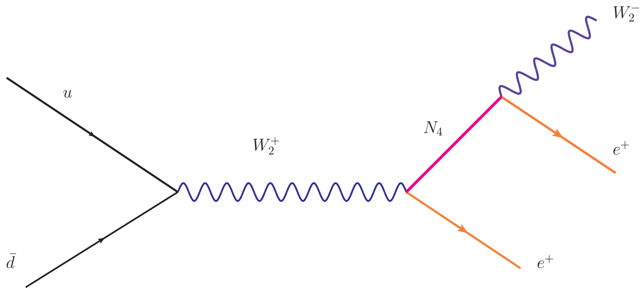
$\rho_1 = 5.7, \quad \rho_2 = 1.15 \times 10^{-3}, \quad \rho_3 = 11.40$

Conclusions:

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

Importance of precise low energy calculations

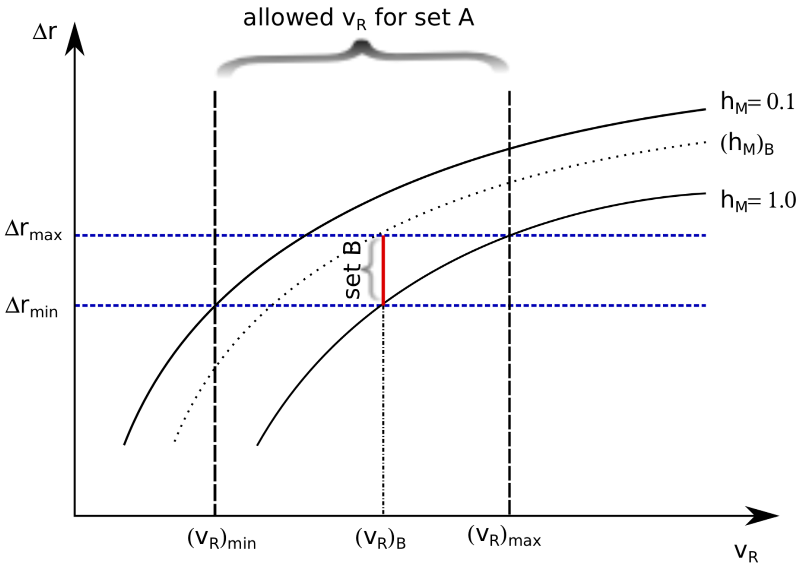
"Left-Right Symmetry at LHC and Precise 1-Loop Low Energy Data", J. Chakrabortty et al, JHEP 1207 (2012) 038

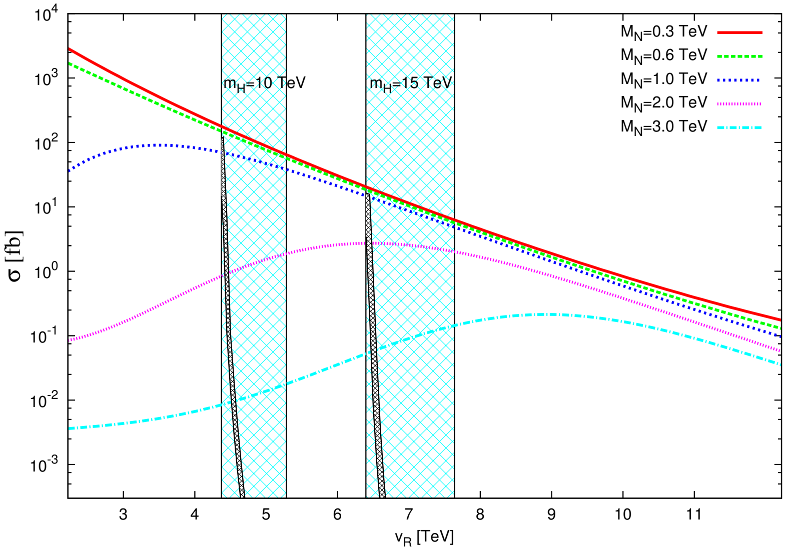


Muon decay constrain parameter space of a model

$$\frac{G_F}{\sqrt{2}} = \frac{e^2}{8(1 - M_W^2/M_Z^2)M_W^2}(1 + \Delta r). \tag{1}$$

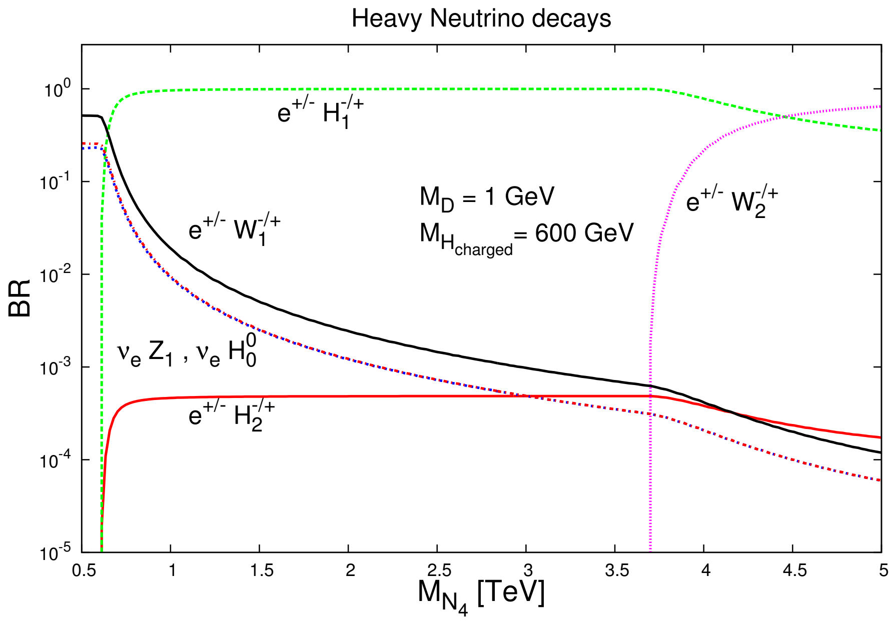
⇒ calculate Δr in LR
⇒ do the matching with SM
⇒ compare with data
M. Czakon, J. Gluza,M. Zrałek, Nucl. Phys. **B573** (2000) 57 and
M. Czakon, J. Gluza, J. Hejczyk, Nucl. Phys. **B642** (2002) 157-172.

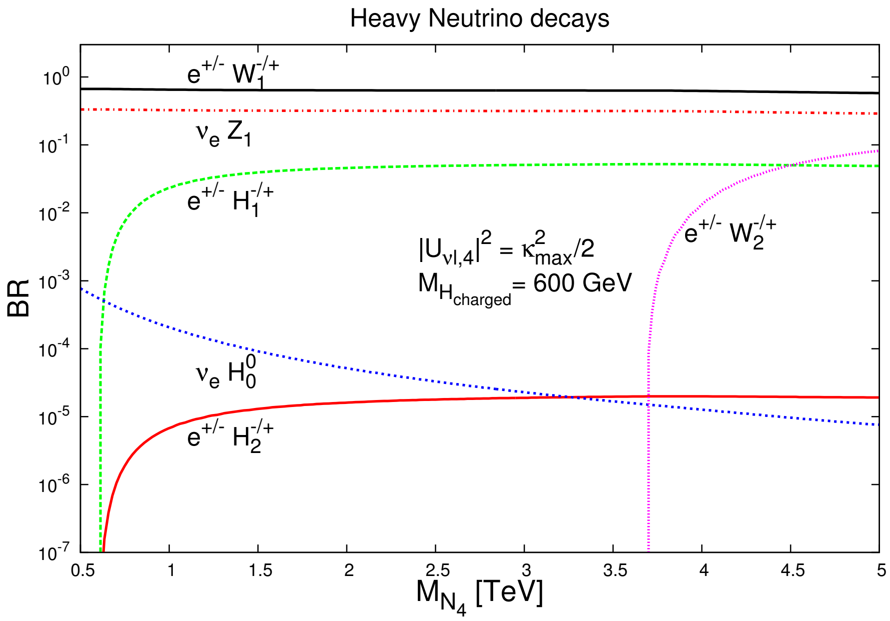

allowed v_R for set A
Δr
$h_M = 0.1$
$(h_M)_B$
$h_M = 1.0$
Δr_{max}
Δr_{min}
set B
$(v_R)_{min}$
$(v_R)_B$
$(v_R)_{max}$
v_R


10^4
10^3
10^2
10^1
10^0
10^{-1}
10^{-2}
10^{-3}
σ [fb]
m_H=10 TeV
m_H=15 TeV
M_N=0.3 TeV
M_N=0.6 TeV
M_N=1.0 TeV
M_N=2.0 TeV
M_N=3.0 TeV
3
4
5
6
7
8
9
10
11
v_R [TeV]

Decays scenarios

Lowering Higgs mass spectrum below 1 TeV influences decay channels.


Heavy Neutrino decays


Heavy Neutrino decays

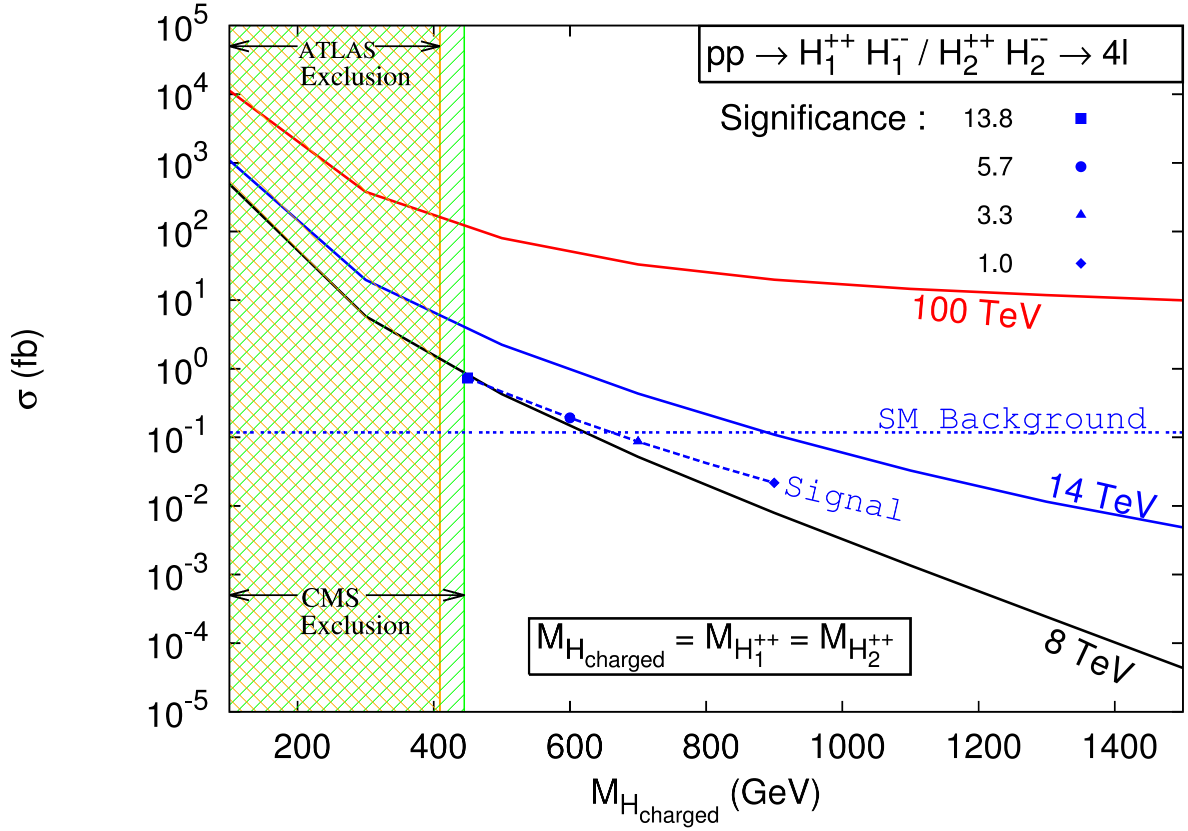
Kinematic cuts

- 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 Higgses production (Drell-Yan)

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

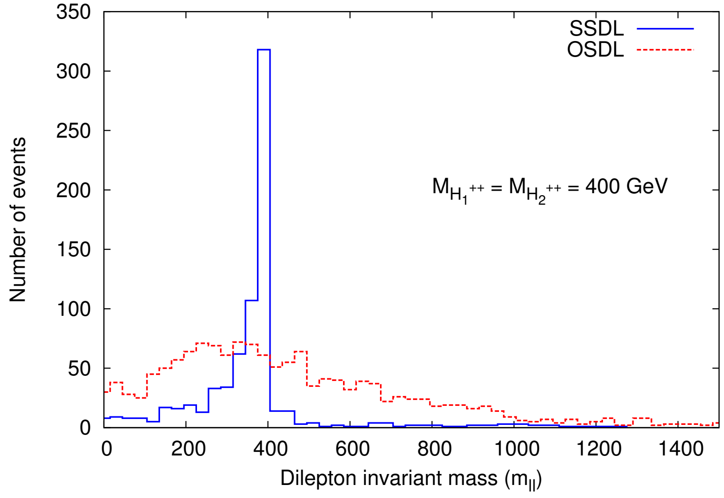
$$\sigma(pp \to H_{1,2}^{++} H_{1,2}^{--} \to l_i{}^+ l_i{}^+ l_j{}^- l_j{}^-) \quad = \quad 0.144(0.9498)\ fb \text{ for } \sqrt{s} = 8(14) \text{ TeV}.$$



Signal events for doubly charged Higgs particles in MLRSM: 4l signals

All analysis for: $\sqrt{s} = 14$ TeV and $L = 300\ fb^{-1}$

- no missing energy or jet involved
- reconstructed invariant masses for same sign dileptons (SSDL) and opposite sign dileptons (OSDL). *A*s the doubly charged scalars are the parents of the dilepton pair, invariant mass of the SSDL is expected to give a clean peak around the mass of the doubly charged scalar: a smoking gun feature indicating the presence of doubly charged scalars



Background estimation

The cuts are optimised in a way such that we can reduce the SM background and enhance the signal events.

Standard Model background cross-sections for tri- and four-lepton signals are as follow:

processes	$\mathbf{3\ell}$ (fb)	$\mathbf{4\ell}$ (fb)
$t\bar{t}$	18.245	–
$t\bar{t}(Z/\gamma^\star)$	1.121	0.069
$t\bar{t}W^\pm$	0.656	–
$W^\pm(Z/\gamma^\star)$	10.590	–
$(Z/\gamma^\star)(Z/\gamma^\star)$	1.287	0.047
TOTAL	**31.899**	**0.116**

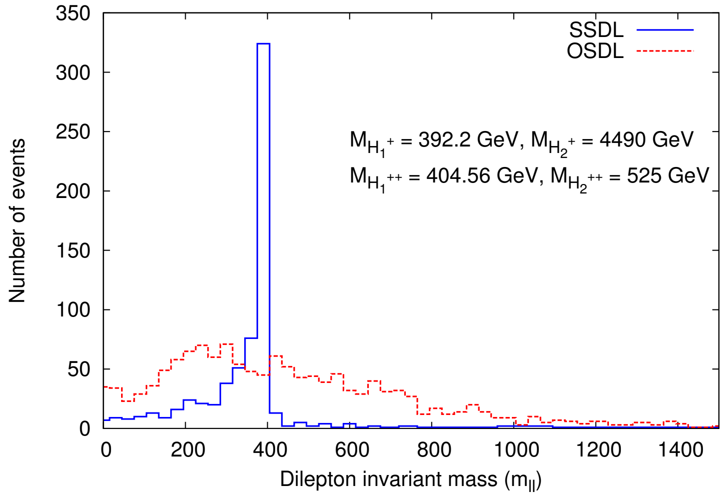
Luminosity	Background 3ℓ events	Signal 3ℓ events	Background 4ℓ events	Signal 4ℓ events scenario I	Signal 4ℓ events scenario II
25 fb^{-1}	797.5	55.9	2.9	(i) 30 (ii) 4.4	24.8
300 fb^{-1}	9569.7	671	34.8	(i) 360 (ii) 53	298

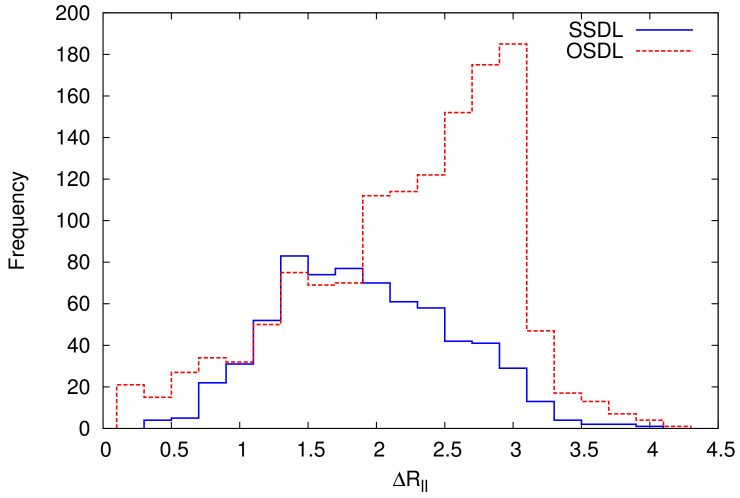
$\sqrt{s} = 8$ TeV Degeneracy: I, (i) $m_H = 400$ GeV, I, (ii) $m_H = 600$ GeV; Scenario II realizes $m_H = 400$ and $m_H = 500$.

Significance	3ℓ events	4ℓ events scenario I	4ℓ events scenario II
S/$\sqrt{B}$	6.86	(i) NA (ii) NA	NA
S/$\sqrt{(S+B)}$	6.63	(i) 18.11 (ii) 5.65	16.34

Assuming the significance at the level of 5 as a comfortable discovery limit, LHC2 will be sensitive to masses of MLRSM doubly charged Higgs bosons up to approximately 600 GeV.

$pp \to H_1^{\pm\pm} H_1^{\mp}$ and $pp \to H_2^{\pm\pm} H_2^{\mp}$: tri-lepton events with missing p_T



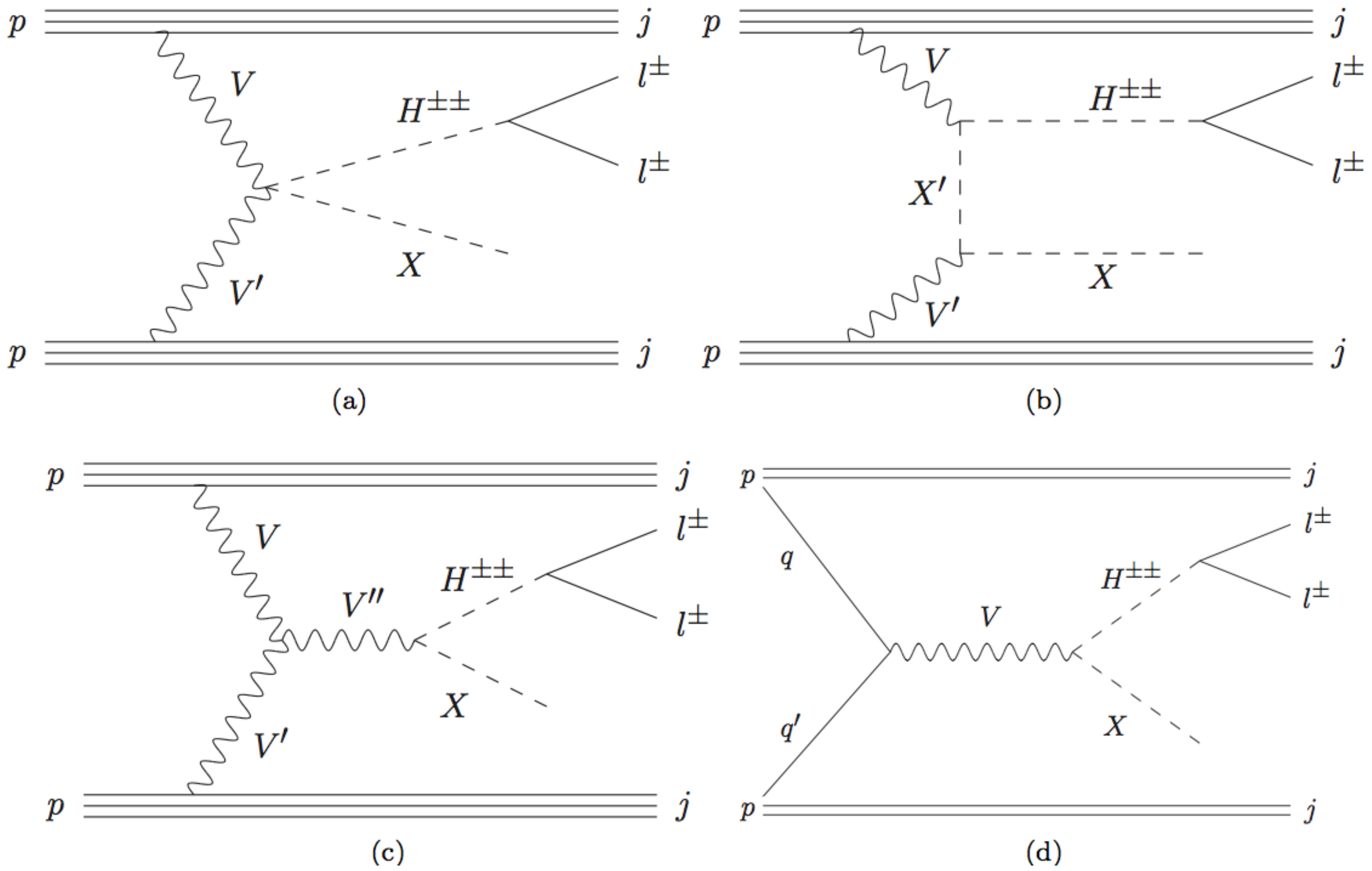


in the opposite sign lepton pairs two leptons have different origin thus their invariant mass distribution is continuous while the same sign dilepton invariant mass distributions always peak around mass of the doubly charged scalars

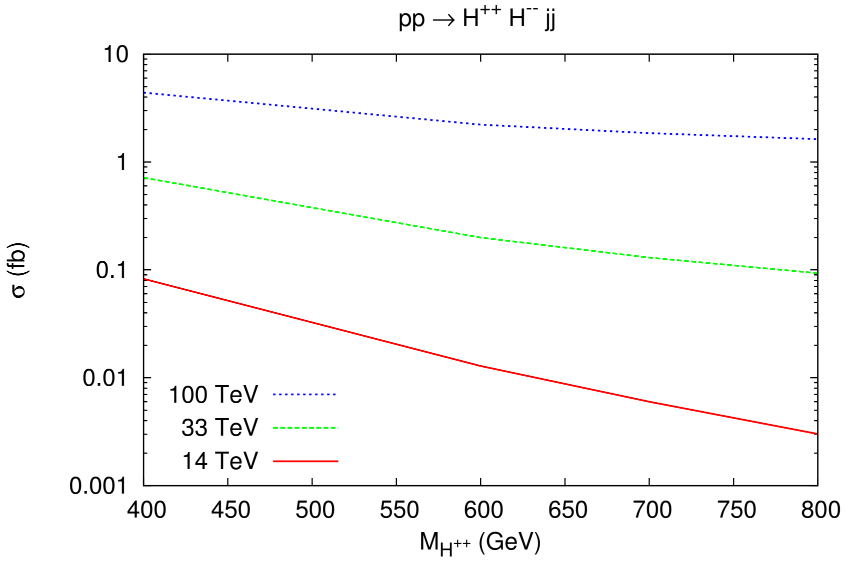
We estimate for $\sqrt{s} = 14$ TeV and integrated luminosity 300 fb^{-1} 671 tri-lepton signal events after all the cuts

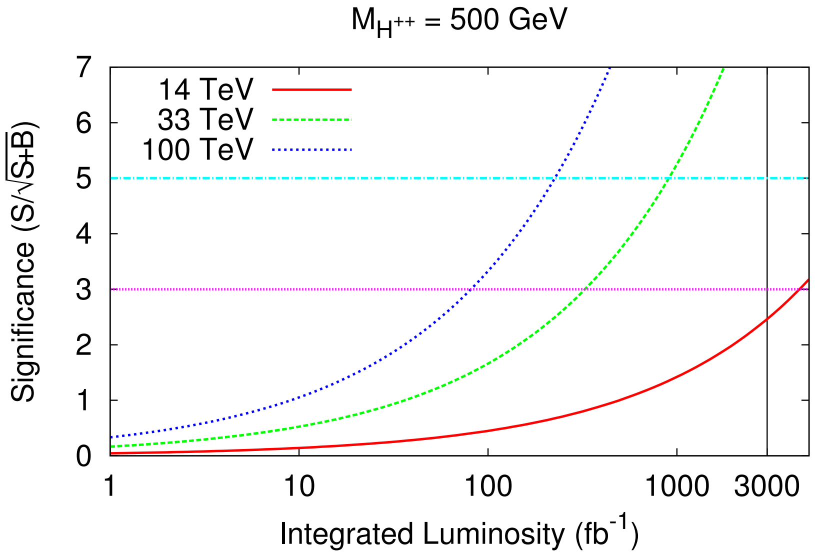
$$\begin{aligned} R^+_- &= \frac{\#\text{ of events for } \ell^+\ell^+\ell^-}{\#\text{ of events for } \ell^-\ell^-\ell^+} = \frac{464}{207} \simeq 2.24; \\ (R^+_-)_{SM} &= \frac{17.751}{14.962} = 1.186 \end{aligned}$$

Vector Boson Fusion with 2 jets



Doubly charged Higgses production (Vector Boson Fusion with 2 jets)





Assuming Significance=5, LHC can explore 500 GeV $H^{\pm\pm}$ with:

- 100 TeV collision and with 300 inv-fb luminosity;
- 33 TeV collision with 1000 inv-fb luminosity;
- no signal reached with 14 TeV collision, even with 3000 inv-fb luminosity

Summary

- We are in an exciting moment, there is still a lot of place at LHC on many potential discoveries, including GUT models, and additional scalar particles
- Discovery of doubly charged Higgs particles would be something incredibly new and would define new directions in physics (e.g. issue of supersymmetry)