

Flavour
change
proofs in
the Higgs
bosons
production
at the
LHeC.

S. Rosado
Navarro

2HDM

2HDM La-
grangian

Benchmark
Points
scenarios

Charged
Higgs
boson:
Bench-
mark
points
scenarios

Flavour change proofs in the Higgs bosons production at the LHeC.

Sebastián Rosado Navarro
Dr. Jaime Hernández Sánchez
Prof. Stefano Moretti

Southampton High Energy Physics (SHEP)

June 2017

Index

Flavour
change
proofs in
the Higgs
bosons
production
at the
LHeC.

S. Rosado
Navarro

2HDM

2HDM La-
grangian

Benchmark
Points
scenarios

Charged
Higgs
boson:
Bench-
mark
points
scenarios

1 2HDM

2 2HDM Lagrangian

3 Benchmark Points scenarios

4 Charged Higgs boson: Benchmark points scenarios

Motivations for the model:

- 2HDM-III agrees with the most important low energy processes.
- The phenomenology of the neutral and charged Higgs bosons could be different to the usual 2HDM.
- Interesting tree-level decay channels: $H, h, A \rightarrow bs, \tau\mu, H+ \rightarrow cb, ts$. The decays are sensitive towards Yukawa texture patterns.
- Scenarios might have a $BR(H^\pm \rightarrow cb) \sim 0.7 - 1$, keeping the h boson decays compatibles with the SM.

In the 2HDM, the two Higgs scalar doublets, $\Phi_1^\dagger = (\phi_1^-, \phi_1^{0*})$ y $\Phi_2^\dagger = (\phi_2^-, \phi_2^{0*})$ have a +1 hyper-charge, so that both couple to the same quark flavour. Since we implement a four-zero texture as one flavour symmetry in the Yukawa sector, the FCNC is controlled, therefore it is not necessary a discrete symmetry in the Higgs potential¹.

The most general invariant scalar potential $SU(2) \times U(1)_Y$ can be written as:

$$\begin{aligned} V(\Phi_1, \Phi_2) = & \mu_1^2(\Phi_1^\dagger \Phi_1) + \mu_2^2(\Phi_2^\dagger \Phi_2) - \left(\mu_{12}^2(\Phi_1^\dagger \Phi_2 + h.c.) \right) \\ & + \frac{1}{2}\lambda_1(\Phi_1^\dagger \Phi_1)^2 + \frac{1}{2}\lambda_2(\Phi_2^\dagger \Phi_2)^2 + \lambda_3(\Phi_1^\dagger \Phi_1)(\Phi_2^\dagger \Phi_2) \\ & + \lambda_4(\Phi_1^\dagger \Phi_2)(\Phi_2^\dagger \Phi_1) \\ & + [\frac{1}{2}\lambda_5(\Phi_1^\dagger \Phi_2)^2 + \lambda_6(\Phi_1^\dagger \Phi_1)(\Phi_1^\dagger \Phi_2)] \\ & + \lambda_7(\Phi_2^\dagger \Phi_2)(\Phi_1^\dagger \Phi_2) + h.c.], \end{aligned} \quad (1)$$

¹A. Cordero-Cid, J. Hernandez-Sanchez, C. G. Honorato, S. Moretti, M. A. Perez and A. Rosado, JHEP 1407, 057 (2014)

It has been proposed that there are four possibilities to satisfy the Paschos-Glashow-Weinberg theorem ² in the 2HDMs ³. They are defined as:

- Type-I (one Higgs doublet couples to all fermions).
- Type-II (one Higgs doublet couples to quarks type up and the other with quarks type down).
- Type-X (also called "Lepton-specific", where the quark couplings are Type-I and the lepton couplings are Type-II).
- Type-Y (also called "flipped" model, where the quark couplings are Type-II and the lepton couplings are Type-I).

²A. Crivellin, A. Kokulu and C. Greub, Phys. Rev. D 87, no. 9, 094031 (2013).

³G. C. Branco, P. M. Ferreira, L. Lavoura, M. N. Rebelo, M. Sher and J. P. Silva, Phys. Rept. 516, 1 (2012)



Our Yukawa Lagrangian is build as ⁴:

$$\begin{aligned}\mathcal{L}_Y = & -(Y_1^u \bar{Q}_L \tilde{\Phi}_1 u_R + Y_2^u \bar{Q}_L \tilde{\Phi}_2 u_R + Y_1^d \bar{Q}_L \Phi_1 d_R \\ & + Y_2^d \bar{Q}_L \Phi_2 d_R + Y_1^l \bar{L}_L \tilde{\Phi}_1 l_R + Y_2^l \bar{L}_L \tilde{\Phi}_2 l_R),\end{aligned}\quad (2)$$

where $\Phi_{1,2} = (\phi_{1,2}^+, \phi_{1,2}^0)^T$ refer to the two Higgs doublets, $\tilde{\Phi}_{1,2} = i\sigma_2 \Phi_{1,2}^*$.

$$M_f = \frac{1}{\sqrt{2}} (v_1 Y_1^f + v_2 Y_2^f), \quad f = u, d, l,$$

$$M_f = \begin{pmatrix} 0 & C_f & 0 \\ C_f^* & \tilde{B}_f & B_f \\ 0 & B_f^* & A_f \end{pmatrix} \quad (3)$$

After the diagonalization, $\bar{M}_f = V_{fL}^\dagger M_f V_{fR}$, one has $\bar{M}_f = \frac{1}{\sqrt{2}} (v_1 \tilde{Y}_1^f + v_2 \tilde{Y}_2^f)$, where $\tilde{Y}_i^f = V_{fL}^\dagger Y_i^f V_{fR}$. One can obtain a good approximation for the $V_f Y_n^f V_f^\dagger$ product, by expressing the rotated matrix \tilde{Y}_n^f as

$$\left[\tilde{Y}_n^f \right]_{ij} = \frac{\sqrt{m_i^f m_j^f}}{v} \left[\tilde{\chi}_n^f \right]_{ij} = \frac{\sqrt{m_i^f m_j^f}}{v} \left[\chi_n^f \right]_{ij} e^{i\vartheta_{ij}^f}, \quad (4)$$

where the χ 's are free parameters that get adjusted to the CKM matrix and flavour physics constraints.

⁴A. Cordero-Cid, J. Hernandez-Sanchez, C. G. Honorato, S. Moretti, M. A. Perez and A. Rosado, JHEP 1407, 057 (2014)

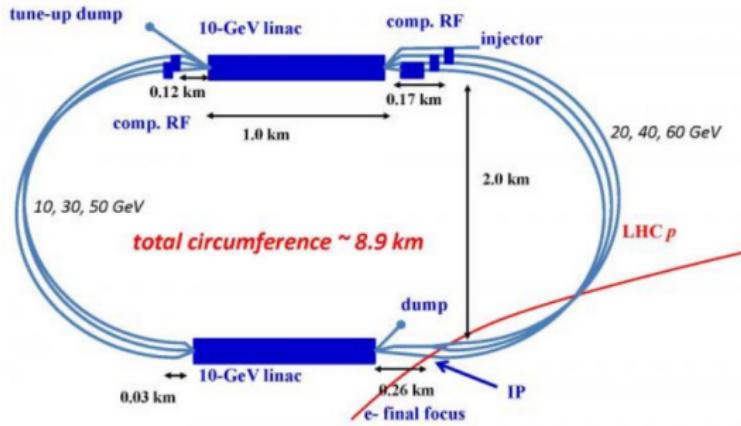
where $f(X) = \sqrt{1 + x^2}$, ξ_ϕ^f are related to the trigonometrical ratios (i.e., $\cos\alpha/\sin\beta$, $\sin\alpha/\sin\beta$, $\cos\alpha/\cos\beta$, $\sin\alpha/\cos\beta$) and the X , Y and Z can be related to $\tan\beta$ or $\cot\beta$, according to the many 2HDM forms ⁵.

2HDM-III	X	Y	Z	ξ_h^u	ξ_h^d	ξ_H^l	ξ_H^u	ξ_H^d	ξ_H^l
2HDM-I-Like	$-ct_\beta$	ct_β	$-ct_\beta$	c_α/s_β	c_α/s_β	c_α/s_β	s_α/s_β	s_α/s_β	s_α/s_β
2HDM-II-Like	t_β	ct_β	t_β	c_α/s_β	$-s_\alpha/c_\beta$	$-s_\alpha/c_\beta$	s_α/s_β	c_α/c_β	c_α/c_β
2HDM-X-Like	$-ct_\beta$	ct_β	t_β	c_α/s_β	c_α/s_β	$-s_\alpha/c_\beta$	s_α/s_β	s_α/s_β	c_α/c_β
2HDM-Y-Like	t_β	ct_β	$-ct_\beta$	c_α/s_β	$-s_\alpha/c_\beta$	c_α/s_β	s_α/s_β	c_α/c_β	s_α/s_β

Taking into account that the Higgs coupling to two fermions (ϕff) in the 2HDM-III is written as $g_{2HDM-III}^{\phi ff} = g_{rm22HDM-any}^{\phi ff} + \Delta g$ where $g_{rm22HDM-any}^{\phi ff}$ is the ϕff coupling in some 2HDM with discrete symmetry and Δg is the four-zero texture contribution.

⁵A. Cordero-Cid, J. Hernandez-Sanchez, C. G. Honorato, S. Moretti, M. A. Perez and A. Rosado, JHEP 1407, 057 (2014)

The kinematic accessible range in the LHeC will be 20 times greater than HERA.



$$\sqrt{s} = \sqrt{E_e E_p} = 1.296 \text{ TeV}, (e^- = 60 \text{ GeV}, p = 7000 \text{ GeV}), 100/fb$$

To estimate the LHeC cross-section ⁶, we consider an electron beam Energy of $E_{e^-} = 60$ GeV and one proton beam of $E_p = 7000$ GeV, corresponding to an approximate center of mass energy of $\sqrt{s} = 1.296$ TeV. The integrated luminosity is 100 fb^{-1} . To estimate the event ratio at partonic level we apply the next basic pre-selections:

- $p_T^q > 15 \text{ GeV}$,
- $\Delta R(q, q) > 0.4$, with $\Delta R = \Delta\eta^2 + \Delta\phi^2$, where η and ϕ are the pseudorapidity and azimuthal angle.
- $m_t = 173.3 \text{ GeV}$ as the top quark mass.
- We adopt the CTEQ6L ⁷ as partonic distribution functions, with α_s (strong coupling constant) evaluated consistently in each stage.

⁶<https://lhec.web.cern.ch>

⁷J. Pumplin, D. R. Stump, J. Huston, H. L. Lai, P. M. Nadolsky and W. K. Tung, JHEP **0207**, 012 (2002)

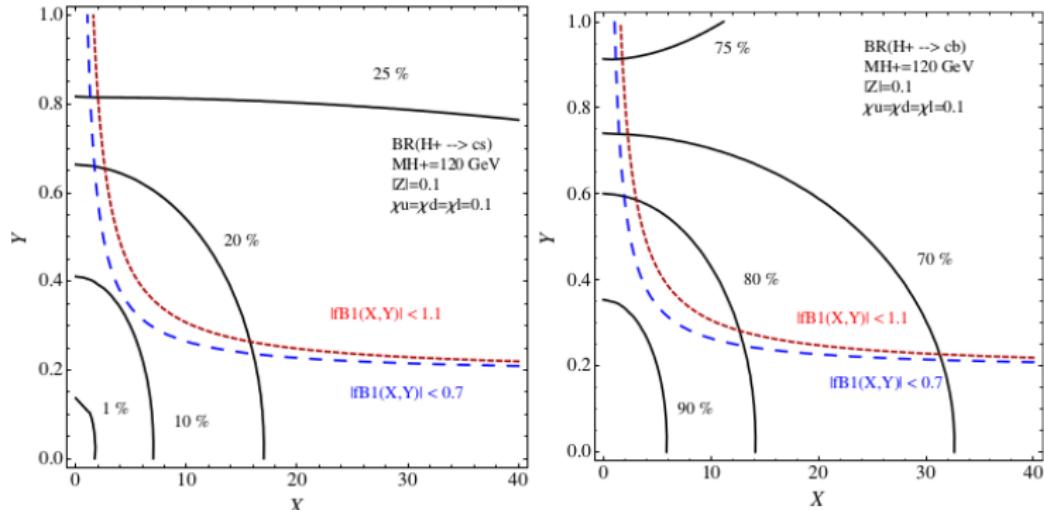


Figure : Contours of the $BR(H^\pm \rightarrow cs)$ to the left, and $BR(H^\pm \rightarrow cb)$ to the right in the plane $[X, Y]$ with $Z = 0.1$, $m_A = 100$ GeV, $m_{H^\pm} = 120$ GeV and $\chi_{ij}^f = 0.1$.

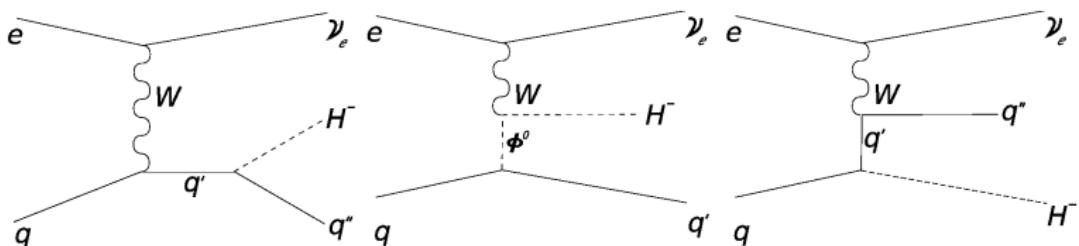


Figure : Charged Higgs generation Feynman diagrams.

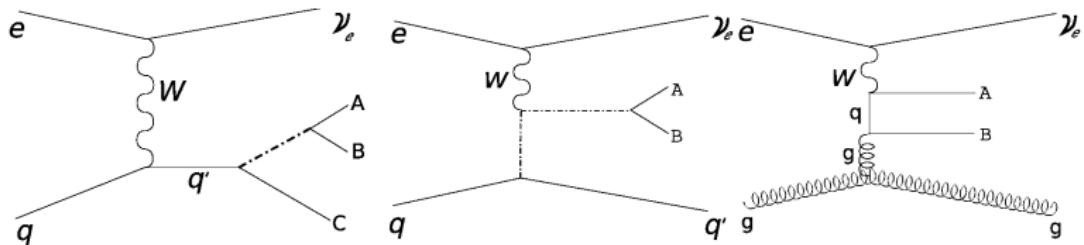


Figure : Background Feynman diagrams. A and B represent b , c quarks or jets.

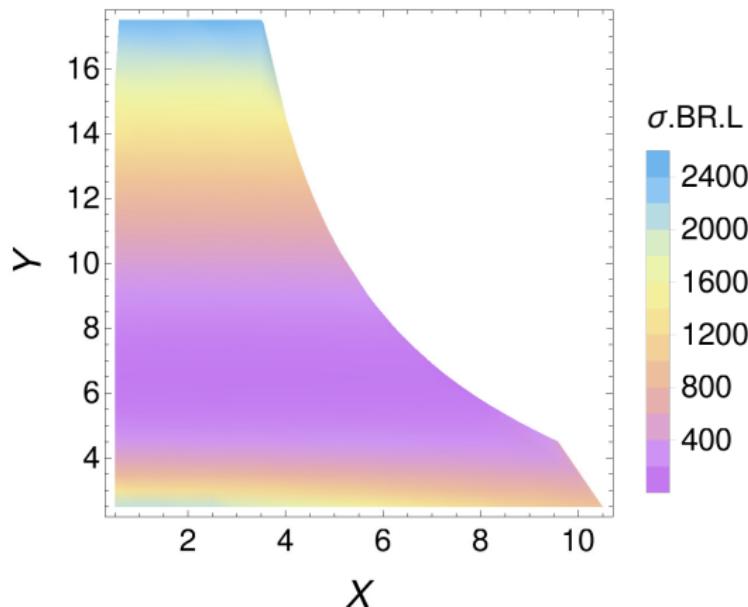


Figure : Scenario-Ia: $\cos(\beta - \alpha) = 0.1$, $\chi_{22}^u = 1$, $\chi_{33}^u = 1.4$, $\chi_{22}^d = 1.8$, $\chi_{33}^d = 1.2$, $\chi_{23}^{u,d} = 0.1$, $\chi_{22}^\ell = -0.4$, $\chi_{33}^\ell = 1$, $\chi_{23}^\ell = 0.1$, $m_A = 100$ GeV and $m_{H^\pm} = 110$ GeV. The plot shows the number of events in the given scenario.

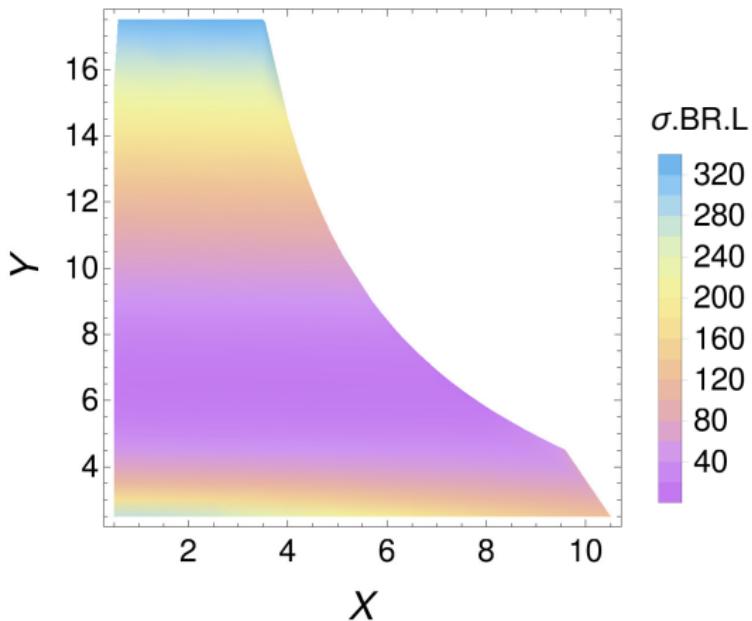


Figure : Scenario-Ia: $\cos(\beta - \alpha) = 0.1$, $\chi_{22}^u = 1$, $\chi_{33}^u = 1.4$, $\chi_{22}^d = 1.8$, $\chi_{33}^d = 1.2$, $\chi_{23}^{u,d} = 0.1$, $\chi_{22}^\ell = -0.4$, $\chi_{33}^\ell = 1$, $\chi_{23}^\ell = 0.1$, $m_A = 100$ GeV and $m_{H^\pm} = 150$ GeV. The plot shows the number of events in the given scenario.

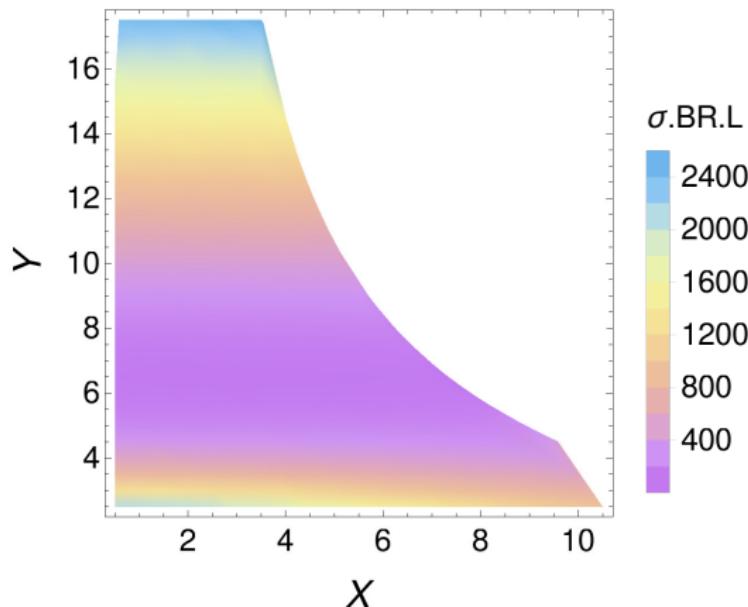


Figure : Scenario-Ib: $\cos(\beta - \alpha) = 0.5$, $\chi_{22}^u = 1$, $\chi_{33}^u = 1.4$, $\chi_{22}^d = 1.8$, $\chi_{33}^d = 1.2$, $\chi_{23}^{u,d} = 0.1$, $\chi_{22}^\ell = -0.4$, $\chi_{33}^\ell = 1.2$, $\chi_{23}^\ell = 0.1$, $m_A = 100$ GeV and $m_{H^\pm} = 110$ GeV. The plot shows the number of events in the given scenario.

Flavour
change
proofs in
the Higgs
bosons
production
at the
LHeC.

S. Rosado
Navarro

2HDM

2HDM La-
grangian

Benchmark
Points
scenarios

Charged
Higgs
boson:
Bench-
mark
points
scenarios

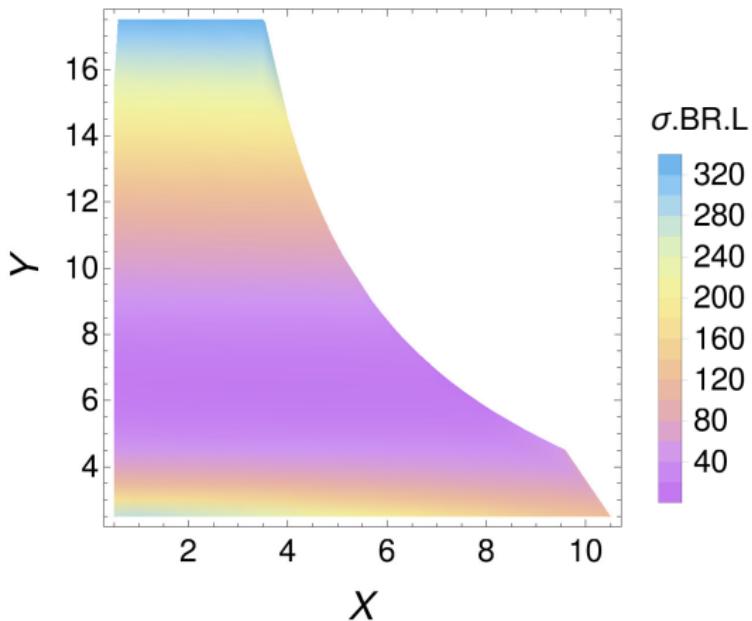


Figure : Scenario-Ib: $\cos(\beta - \alpha) = 0.5$, $\chi_{22}^u = 1$, $\chi_{33}^u = 1.4$, $\chi_{22}^d = 1.8$, $\chi_{33}^d = 1.2$, $\chi_{23}^{u,d} = 0.1$, $\chi_{22}^\ell = -0.4$, $\chi_{33}^\ell = 1.2$, $\chi_{23}^\ell = 0.1$, $m_A = 100$ GeV and $m_{H^\pm} = 150$ GeV. The plot shows the number of events in the given scenario.

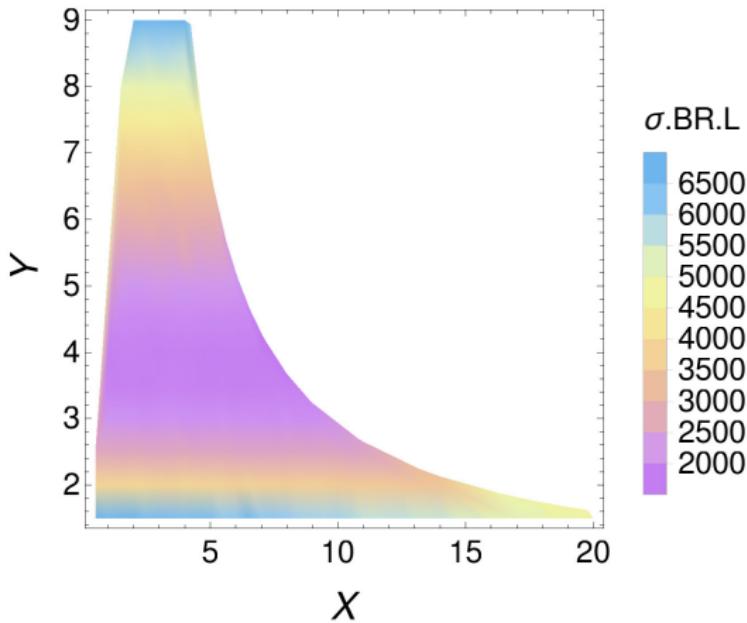


Figure : Scenario-IIa: $\cos(\beta - \alpha) = 0.1$, $\chi_{22}^u = 0.5$, $\chi_{33}^u = 1.4$, $\chi_{22}^d = 2$, $\chi_{33}^d = 1.3$, $\chi_{23}^u = -0.53$, $\chi_{23}^d = 0.2$, $\chi_{22}^\ell = 0.4$, $\chi_{33}^\ell = 1.2$, $\chi_{23}^\ell = 0.1$, $m_A = 100$ GeV and $m_{H^\pm} = 110$ GeV. The plot shows the number of events in the given scenario.

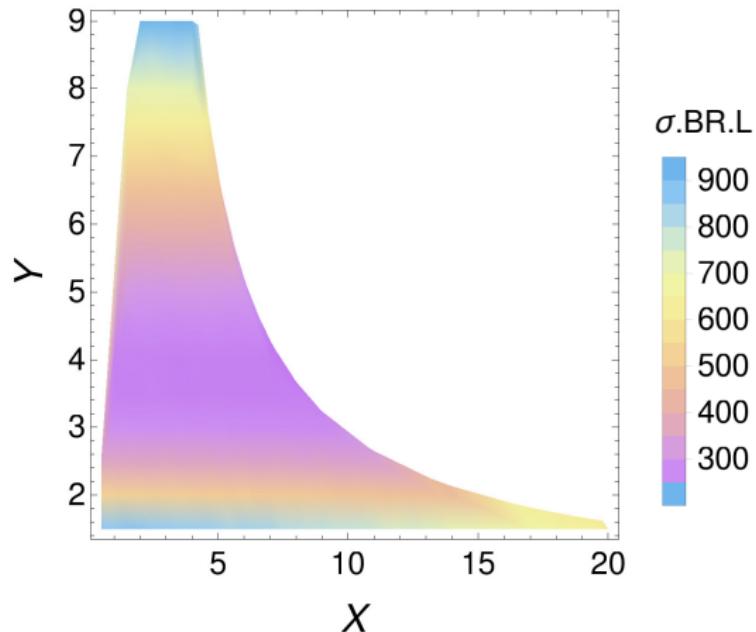


Figure : Scenario-IIa: $\cos(\beta - \alpha) = 0.1$, $\chi_{22}^u = 0.5$, $\chi_{33}^u = 1.4$, $\chi_{22}^d = 2$, $\chi_{33}^d = 1.3$, $\chi_{23}^u = -0.53$, $\chi_{23}^d = 0.2$, $\chi_{22}^\ell = 0.4$, $\chi_{33}^\ell = 1.2$, $\chi_{23}^\ell = 0.1$, $m_A = 100$ GeV and $m_{H^\pm} = 150$ GeV.
The plot shows the number of events in the given scenario.

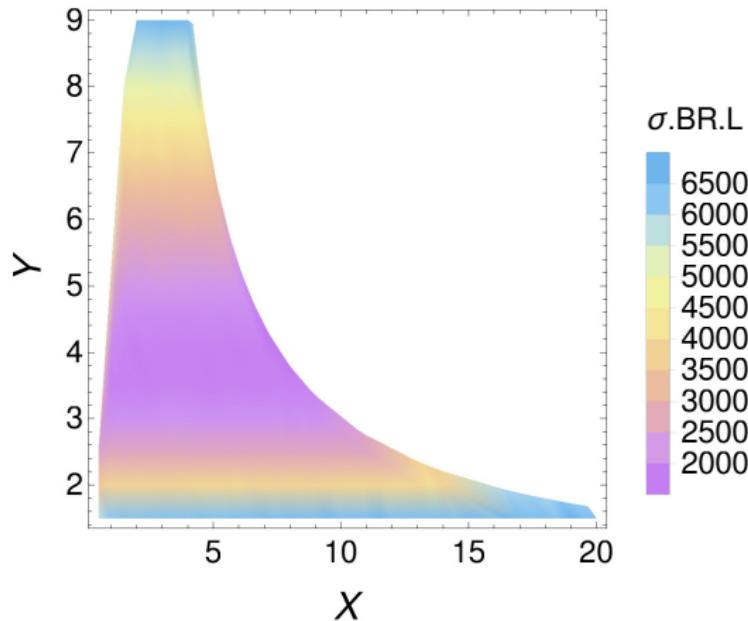


Figure : Scenario-Y: $\cos(\beta - \alpha) = 0.1$, $\chi_{22}^u = 0.5$, $\chi_{33}^u = 1.4$, $\chi_{22}^d = 2$, $\chi_{33}^d = 1.3$, $\chi_{23}^u = -0.53$, $\chi_{23}^d = 0.2$, $\chi_{22}^\ell = 0.4$, $\chi_{33}^\ell = 1.2$, $\chi_{23}^\ell = 0.1$, $m_A = 100$ GeV and $m_{H^\pm} = 110$ GeV. The plot shows the number of events in the given scenario.

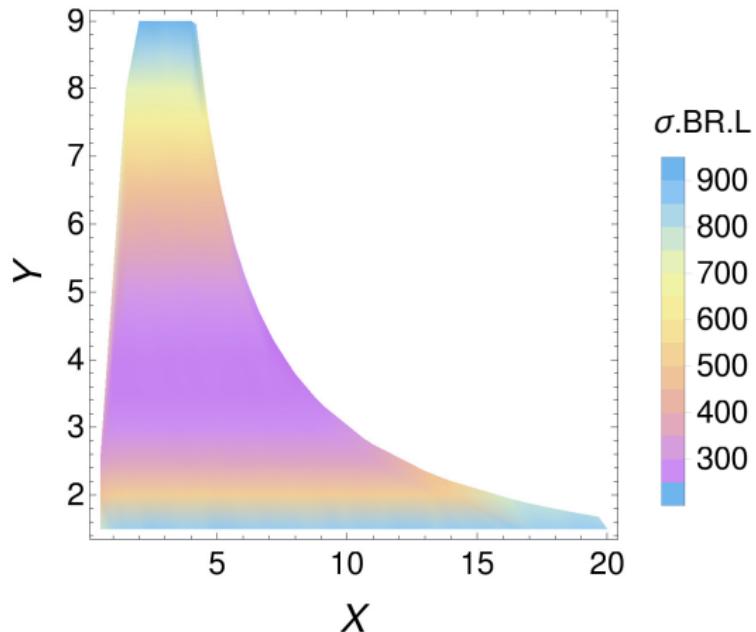


Figure : Scenario-Y: $\cos(\beta - \alpha) = 0.1$, $\chi_{22}^u = 0.5$, $\chi_{33}^u = 1.4$, $\chi_{22}^d = 2$, $\chi_{33}^d = 1.3$, $\chi_{23}^u = -0.53$, $\chi_{23}^d = 0.2$, $\chi_{22}^\ell = 0.4$, $\chi_{33}^\ell = 1.2$, $\chi_{23}^\ell = 0.1$, $m_A = 100$ GeV and $m_{H^\pm} = 150$ GeV. The plot shows the number of events in the given scenario.

We managed to constrain the model and found cross sections that generate events in the order of 10^3 . We still need to study the background, a work being done at this time.