Charged Higgs boson production via cb-fusion at the Large Hadron Collider.

Sebastián Rosado Navarro (Speaker) †
Jaime Hernández Sánchez †
Carlos Gerardo Honorato Méndez †
Stefano Moretti ‡

† Benemérita Universidad Autónoma de Puebla, ‡ University of Southampton

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Motivations for the model:

- 2HDM-III agrees with the most important low and high energy processes.
- 2HDM-III can be an effective theory of other more complex theories.
- The phenomenology of the neutral and charged Higgs bosons could be different to the usual 2HDM.
- Our model has scenarios with $BR(H^{\pm} \to cb) \sim 0.1 - 0.2$ and $BR(H^{\pm} \to \tau\nu_{\tau}) \sim 0.7 - 0.9$, keeping the h boson decays compatibles with the SM.

Our Yukawa Lagrangian is build as [1]:

$$\begin{aligned} \mathcal{L}_Y &= -(Y_1^u \bar{Q}_L \tilde{\Phi}_1 u_R + Y_2^u \bar{Q}_L \tilde{\Phi}_2 u_R + Y_1^d \bar{Q}_L \Phi_1 d_R \\ &+ Y_2^d \bar{Q}_L \Phi_2 d_R + Y_1^l \bar{L}_L \tilde{\Phi}_1 l_R + Y_2^l \bar{L}_L \tilde{\Phi}_2 l_R), \end{aligned} \tag{1}$$

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

$$M_f = \begin{pmatrix} 0 & C_f & 0 \\ C_f^* & \tilde{B}_f & B_f \\ 0 & B_f^* & A_f \end{pmatrix} \tag{2}$$

Following [1], we have a generic expression for the couplings between the charged Higgs bosons and the fermions

$$\mathcal{L}^{\bar{f}_i f_j \phi^{\pm}} = - \left\{ \frac{\sqrt{2}}{v} \bar{u}_i \left(m_{d_j} X_{ij} P_R + m_{u_i} Y_{ij} P_L \right) d_j H^+ + \frac{\sqrt{2} m_{l_j}}{v} Z_{ij} \bar{\nu}_L l_R H^+ + h.c. \right\}. \tag{3}$$

The Charged Higgs couplings with two fermions ($\phi^{\pm} f_u f_d$) are:

$$g^{\phi^{\pm} f_u f_d}_{2HDM-III} = g^{\phi^{\pm} f_u f_d}_{2HDM-any} + \Delta g \tag{4}$$

[1] J. Hernandez-Sanchez, S. Moretti, R. Noriega-Papaqui and A. Rosado, JHEP 1307, 044 (2013)

Experimental constraints from colliders:

- LEP limits: $M_{H^{\pm}} \geq 78.6$ GeV.
- LHC limits: CMS: $BR(t \to H^+ b) = 2 - 3\%$ for $BR(H^+ \to \tau^+ \nu) = 1$, $M_{H^{\pm}} = 80 - 160$ GeV.
  ATLAS and CMS: For $BR(H^+ \to c\bar{s}) = 1$, $BR(t \to H^+ b) \approx 20\%$, $M_{H^{\pm}} = 90 - 160$ GeV.
  CMS: $BR(t \to H^+ b) = 0.5 - 0.8\%$ for $BR(H^+ \to c\bar{b}) = 1$, $M_{H^{\pm}} = 90 - 150$ GeV.
  CMS: Extensive study for $H^{\pm} \to \tau \nu_{\tau}$ for $M_{H^{\pm}} = 80 - 3000$ GeV.

Flavour physics constraints (low energy processes):

- $\mu - e$ universality in the τ decays.
- The leptonic decay of a charged meson, $M \to l \nu_l$, is sensitive to $H^{\pm}$.
- $B \to X_s \gamma$ decays.
- The $B^0 - \bar{B}^0$ and $K^0 - \bar{K}^0$ mixing.

Theoretical constraints:

- EW precission observables
- Perturbativity
- Vacuum stability and unitarity

Quark fusion $q_1 q_2 \to H^{\pm} \to \tau\nu_\tau$

$H^{\pm}$ production:

- Quark-fusion: $cb \to H^{\pm} \to \tau\nu_\tau$ decay.
- All experimental bounds and theoretical constraints are considered.
- Scenarios $I - like$, $II - like$ and $Y - like$ are discarded
- 2HDM-III $X - like$ (lepton specific) scenario is considered, with $BR(H^{\pm} \to cb) \sim 0.1 - 0.2$ and $BR(H^{\pm} \to \tau\nu_\tau) \sim 0.7 - 0.9$. (These are enhanced by the Yukawa textures. [2])

Backgrounds in the analysis:

- Irreducible background: $q_1 q_2 \to W^{\pm} \to l\nu_l$.
- The reducible backgrounds: $gq' \to W^{\pm}q$ and $q\bar{q} \to W^{+}W^{-} \to l^{+}l^{-}\nu\nu$.

[2] J. Hernández-Sánchez, C. G. Honorato, S. Moretti, and S. Rosado-Navarro Phys. Rev. D 102, 055008

To generate the partonic events we used the CalcHEP package. We consider

- Proton beams of E_p= 7 TeV, i.e., $\sqrt{s} = 14$ TeV, $L = 36.1$ fb^{-1}.
- $p_T^q > 15$ 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 GeV as the top quark mass.
- CTEQ6L [3] as partonic distribution functions, with α_s (strong coupling constant) evaluated consistently in each stage.
- We configure the Scenario $X - like$ as: $\cos(\beta - \alpha) = 0.1$, $M_h = 125$ GeV, $M_A = 100$ GeV, $M_H = 150$ GeV and Yukawa textures parameters ~ 0.1.

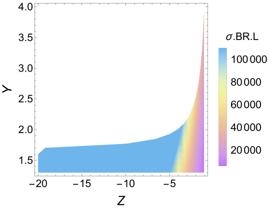


Figure: Event rates for $m_{H^{\pm}} = 120$ GeV. The best point has $\approx 2.276 \times 10^6$ events.

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

MadAnalysis 5 setup:

- A veto on the jets.
- At least one lepton was detected.

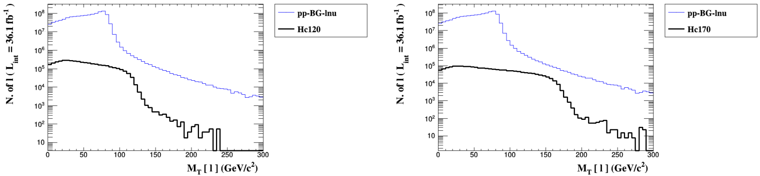


Figure: Comparison plot of the transverse mass for the quark fusion process with setup cuts for $m_{H^{\pm}} = 120$, GeV (left) and $m_{H^{\pm}} = 170$, GeV (right).

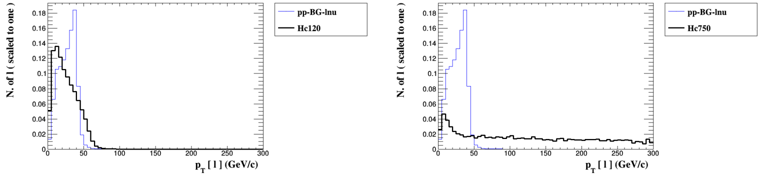


Figure: Leptonic transverse momentum plots for the quark fusion process. In this case, it can be defined that the cut for all the charged Higgs boson masses is $P_{T(l)} \geq 45$ GeV.

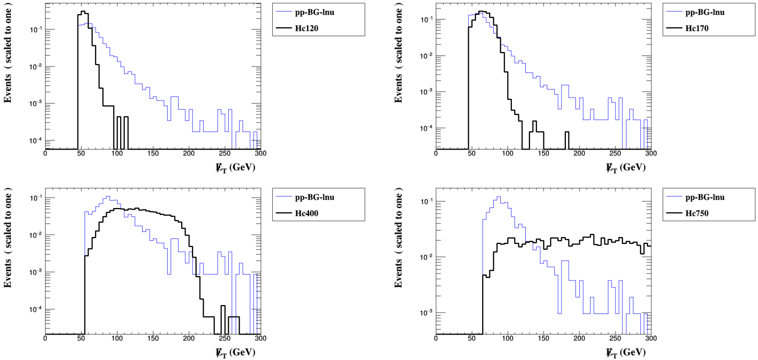
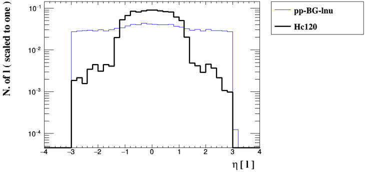


Figure: Missing energy plots for the quark fusion process, the cuts defined by these are as follows: $M_{H^\pm} = 120$ GeV, 40 GeV $\leq \not{E}_T \leq$ 70 GeV; $M_{H^\pm} = 170$ GeV, 60 GeV $\leq \not{E}_T \leq$ 90 GeV; $M_{H^\pm} = 200$ GeV, 70 GeV $\leq \not{E}_T \leq$ 105 GeV; $M_{H^\pm} = 400$ GeV, 100 GeV $\leq \not{E}_T \leq$ 225 GeV; $M_{H^\pm} = 500$ GeV, 90 GeV $\leq \not{E}_T \leq$ 270 GeV; $M_{H^\pm} = 750$ GeV, 105 GeV $\leq \not{E}_T$.



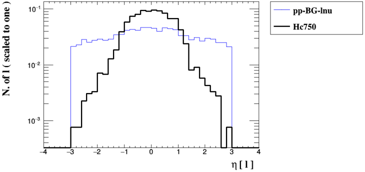


Figure: Pseudorapidity plots for the quark fusion process. In this case, the cuts can be defined for all charged Higgs masses as $|\eta_{(l)}| \leq 1.2$ GeV.

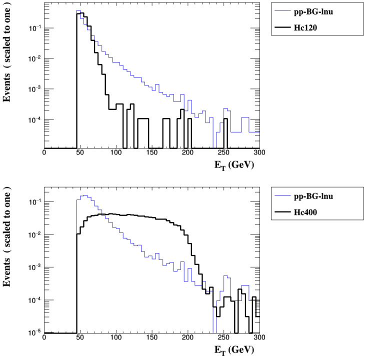


Figure: Transverse energy plots for the quark fusion process. From these plots the cuts can be defined as: $M_{H^{\pm}} = 120,\ 170$ GeV, $E_{(total)} \geq 55$ GeV; $M_{H^{\pm}} = 200$ GeV, $E_{(total)} \geq 60$ GeV; $M_{H^{\pm}} = 400$ GeV, $E_{(total)} \geq 80$ GeV; $M_{H^{\pm}} = 500$ GeV, $E_{(total)} \geq 75$ GeV; $M_{H^{\pm}} = 750$ GeV, $E_{(total)} \geq 80$ GeV.

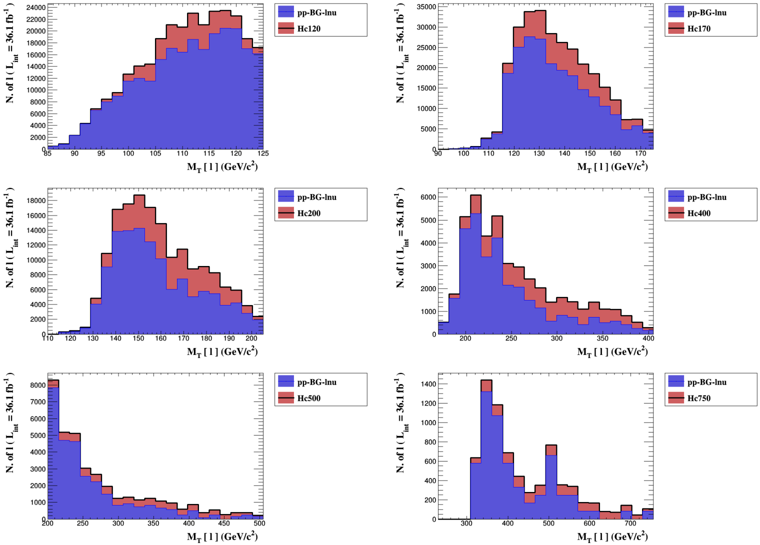


Figure: Transverse mass plots for the quark fusion process with all the cuts applied.

After doing the analysis for these cases, we proceeded to do the same for other charged Higgs boson masses.

$H^{\pm}$ mass (GeV)	Signal	Background	$S/\sqrt{S+B}$
120	82147	795470	87.688
130	111026	745095	119.994
140	138553	852330	139.189
150	133205	719156	144.282
155	123148	633444	141.578
160	131734	673010	146.849
165	133767	683161	147.999
170	113758	536547	141.067
175	117716	544818	144.621
180	121355	566716	146.299
200	80453	290406	132.111
220	79475	292568	130.297
250	73119	314654	117.420
300	38855	112403	99.906
400	20578	74904	66.597
500	12021	71238	41.66
750	2279.4	10714	19.997
800	1643.8	9586.2	15.511
1000	637.5	5263	8.299

Table: Significances after the complete sequence of cuts described in the text with $L = 36.1\ \text{fb}^{-1}$.

Conclusions

- Significant chances to extract a charged Higgs boson signal 2HDM-III scenario in its like-X incarnation, through $b\bar{c} \to H^- \to \tau\bar{\nu}_\tau$.
- This can be achieved by the end of Run 3 over a $H^\pm$ mass interval ranging from 100 GeV or so up to the TeV scale.
- We have proven this to be very effective against the (dominant) background given by $q_1 q_2 \to W^\pm \to l\nu_l$ as well as the (subdominant) noise produced via $gq' \to W^\pm q$ and $q\bar{q}' \to W^+W^- \to l^+l^-\nu\nu$.
- We are confident that our results are realistic, as we have obtained these through a sophisticated MC analysis exploiting advanced computational tools. We are therefore looking forward to ATLAS and CMS adopting our recommended approach, so as to confirm or disprove the 2HDM-III hypothesis.

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There are four possibilities of 2HDMs with the Z_2 symmetry [4]. 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).

We use the 2HDM-III, the most general model, with a four zero Yukawa textures. By using the textured 2HDM-III we can take limits of it corresponding to the standard four types above.

[4] G. C. Branco, P. M. Ferreira, L. Lavoura, M. N. Rebelo, M. S her and J. P. Silva, Phys. Rept. 516, 1 (2012)

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