Probing the charged Higgs boson at the LHC in the CP-violating type-II 2HDM

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Outline

- Motivation
  - Standard Model: a solid start
  - Bottom-up approach: why a Higgs doublet only?
- Introduction
  - The 2HDM potential
  - The 2HDM Yukawa sector
- Type-II and implications at the LHC
  - The CP-violating parameter space
  - Profiling the charged Higgs
  - $pp \to H^{\pm}W^{\mp}$: significance analysis at 14 TeV
- Conclusion

Standard Model: a solid start

LHC (ATLAS&CMS combined) discovered a scalar resonance at ~ 125 GeV: a triumph for Particle Physics and QFT!

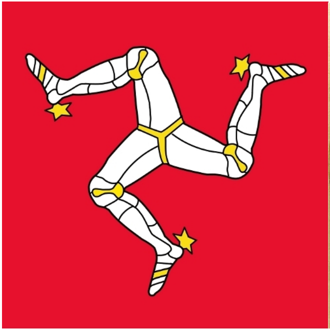
Many unsolved problems are left to the community:

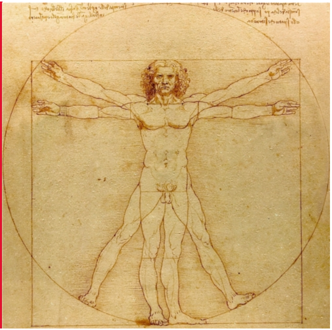
- T fine tuning, hierarchy problem, GUT hypothesis, et cetera;
- E neutrino masses, dark matter and dark energy observations, various tensions in b-physics, discrepancies in proton radius estimations, et cetera.

The LHC represents the most important chance to deeply test the minimality of the SM, hopefully probing the existence of new objects that could address the mentioned issues.

Bottom-up approach: why a Higgs doublet only?

In fact, Nature doesn't always prefer minimality!





So... why should we prefer a minimal Higgs sector?!
Extended scenarios deserve investigation!

The 2HDM potential

The general Higgs potential is:

$$
\begin{aligned}
V &= m_{11}^2\phi_1^\dagger\phi_1 + m_{22}^2\phi_2^\dagger\phi_2 + (m_{12}^2\phi_1^\dagger\phi_2 + \text{h.c.}) + \\
&+ \frac{1}{2}\lambda_1(\phi_1^\dagger\phi_1)^2 + \frac{1}{2}\lambda_2(\phi_2^\dagger\phi_2)^2 + \lambda_3(\phi_1^\dagger\phi_1)(\phi_2^\dagger\phi_2) + \\
&+ \lambda_4(\phi_1^\dagger\phi_2)(\phi_2^\dagger\phi_1) + \frac{1}{2}[\lambda_5(\phi_1^\dagger\phi_2)^2 + \text{h.c.}] + \\
&+ [(\lambda_6\phi_1^\dagger\phi_1 + \lambda_7\phi_2^\dagger\phi_2)(\phi_1^\dagger\phi_2) + \text{h.c.}],
\end{aligned}
$$

where m_{12}^2, λ_5, λ_6 and λ_7 are complex parameters.

Setting $\lambda_6 = \lambda_7 = 0$ will suppress any FCNC.

The 2HDM Yukawa sector

Several assumptions are possible: each corresponds to a different “typology” of 2HDM.

Type-I? Type-II? Type-III? Type-X? Type-Y? (Or variants?)

$FCNC$s are naturally avoided if only one of the two Φ_i is coupled to each family.

In this presentation we focus on:

- Type-I: only ϕ_2 coupled to the matter;
- Type-II: ϕ_1 coupled to d-type quarks and leptons
  ϕ_2 coupled to u-type quarks.

Yukawa reprise

The Yukawa Lagrangian for a Type-II(I) 2HDM is:

$$\Delta\mathcal{L} = \sum_{i=1}^{2}(D^\mu\Phi_i)^\dagger(D_\mu\Phi_i) - \overline{Q}_L Y_u \widetilde{\Phi}_{2(2)} u_R - \overline{Q}_L Y_d \Phi_{1(2)} d_R - \overline{L}_L Y_l \Phi_{1(2)} l_R + \text{h.c.},$$

where $\widetilde{\Phi}_2 = i\sigma_2\Phi_2^*$.

The Feynman vertex for the $H_i b\bar{b}$ and $H_i t\bar{t}$ interactions in the type-I and the type-II version of the 2HDM are:

	$H_i b\bar{b}$	$H_i t\bar{t}$
type-I	$m_b(R_{i2} + i\gamma^5 R_{i3}\cos\beta)/v_2$	$m_t(R_{i2} - i\gamma^5 R_{i3}\cos\beta)/v_2$
type-II	$m_b(R_{i1} - i\gamma^5 R_{i3}\sin\beta)/v_1$	$m_t(R_{i2} - i\gamma^5 R_{i3}\cos\beta)/v_2$

Probing the charged Higgs boson at the LHC

Why CP-violating 2HDM type-II?

- Strong connection with a tree-level MSSM Higgs sector;
- CP-violation could be induced by loop corrections to the Higgs potential;

It is possible that the Higgs sector lies in a lower mass range than the super-partners of the SM contents and can be accessible by the LHC. In this regard, a type-II 2HDM should be explored as an effective low-energy MSSM-like Higgs sector.

If this is true, we have a charged Higgs somewhere. . .

Three steps towards the Charged Higgs

The phenomenological analysis focuses on:

1. the CP-violating parameter space in the light of theoretical arguments and experimental data (up to the newest LHC results);
2. the profiling of the Charged Higgs in surviving portions of the parameter space;
3. a strategy to discover a charged Higgs associated with a W and decaying in a Wbb final state at $\tan\beta \sim \mathcal{O}(1)$.

Theory and Experiment conspire together

Constraints from theory:

- positivity;
- tree-level unitarity;
- perturbativity.

Constraints from Experiment:

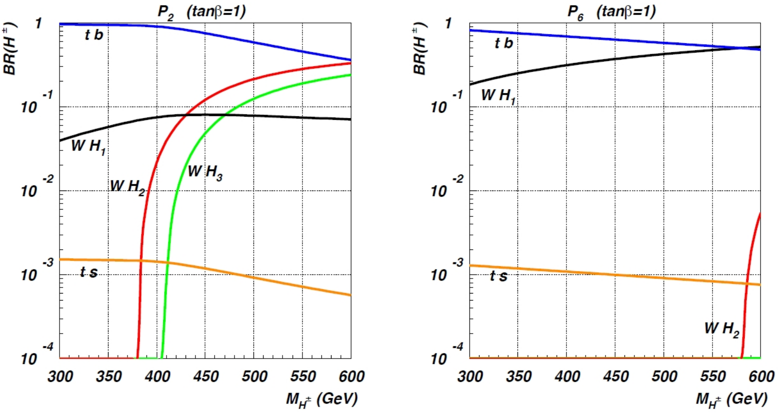
- $B \to X_s\gamma$ (!!!);
- $B_u \to \tau\nu_\tau$;
- $B \to D\tau\nu_\tau$ (!!!);
- $D \to \tau\nu_\tau$;
- $B_{d,s} \to \mu^+\mu^-$;
- $B^0 - \bar{B}^0$ mixing;
- $R_b = \Gamma_{Z\to b\bar{b}}/\Gamma_{Z\to had}$;
- $pp \to H_i X$;
- T and S from the EWPT;
- neutron EDM.

Benchmark points

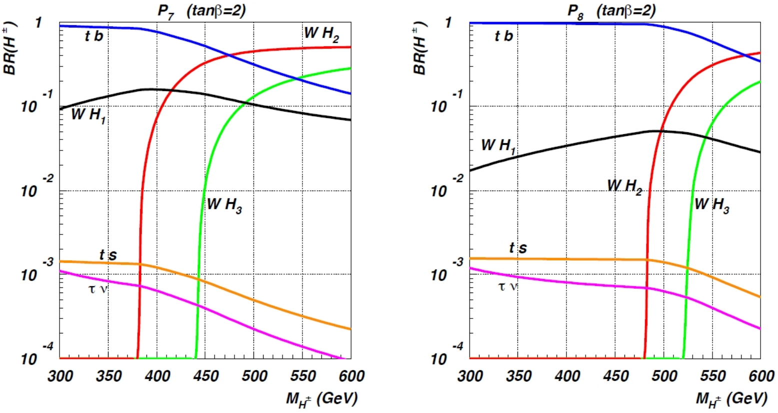
	α_1/π	α_2/π	α_3/π	$\tan\beta$	M_2	$M_{H^\pm}^{\text{min}}, M_{H^\pm}^{\text{max}}$
P_1	0.23	0.06	0.005	1	300	300,325
P_2	0.35	−0.014	0.48	1	300	300,415
P_3	0.35	−0.015	0.496	1	350	300,450
P_4	0.35	−0.056	0.43	1	400	300,455
P_5	0.33	−0.21	0.23	1	450	300,470
P_6	0.27	−0.26	0.25	1	500	300,340
P_7	0.39	−0.07	0.33	2	300	300,405
P_8	0.34	−0.03	0.11	2	400	300,315
P_9	0.47	−0.006	0.05	10	400	400,440
P_{10}	0.49	−0.002	0.06	10	600	600,700

Masses M_2 and allowed range of $M_{H^\pm}$ are in GeV. For P_1–P_8, $\mu = 200$ GeV, whereas for P_9 and P_{10}, $\mu = M_2$.

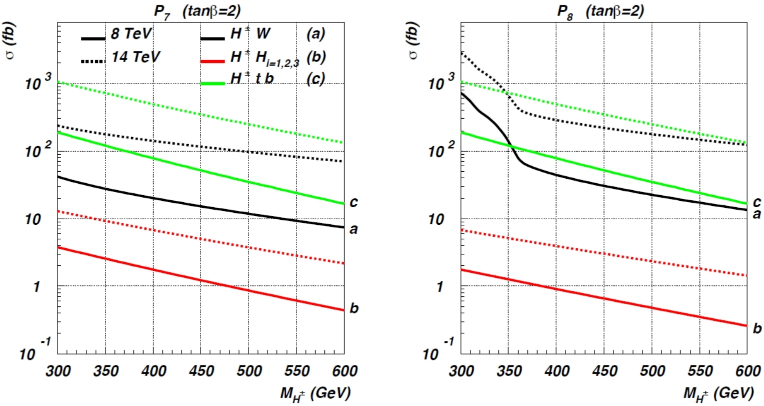
Charged Higgs Branching Ratios (1)



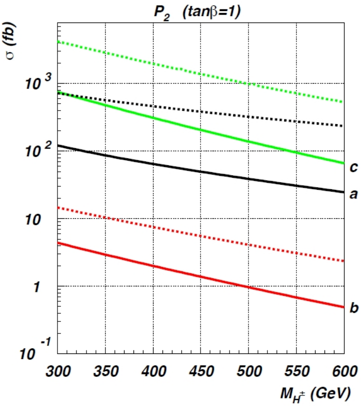
Charged Higgs Branching Ratios (2)



Charged Higgs production mechanisms (1)



Charged Higgs production mechanisms (2)



$pp \to H^{\pm}W^{\mp}$: significance analysis

The idea is to use the light Neutral Higgs as a portal for the Charged Higgs discovery in order to avoid the enormous $t\bar{t}$ background.

For this we consider the final state:
$W^{\mp}H^{\pm} \to W^{\mp}W^{\pm}H_1 \to W^{\mp}W^{\pm}b\bar{b} \to 2j + 2b + 1\ell +$ MET
produced at 14 TeV, with a luminosity of $L = 100$ fb^{-1}.

Among the possible decay patterns of the two W bosons, the semi-leptonic one was chosen, allowing the full reconstruction of the events.

Selection cuts (1)

1) **Kinematics:** standard detector cuts

$$p_\ell^T > 15 \text{ GeV}, \qquad |\eta_\ell| < 2.5,$$
$$p_j^T > 20 \text{ GeV}, \qquad |\eta_j| < 3,$$
$$|\Delta R_{jj}| > 0.5, \qquad |\Delta R_{\ell j}| > 0.5;$$

with η the pseudo-rapidity and $\Delta R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2}$.

2) **Light Higgs reconstruction:**

$$\left| M(b\bar{b}) - 125 \text{ GeV} \right| < 20 \text{ GeV};$$

3) **hadronic W reconstruction ($W_h \to jj$):**

$$|M(jj) - 80 \text{ GeV}| < 20 \text{ GeV}.$$

Selection cuts (2)

4) **Top veto**: if $\Delta R(b_1, W_h) < \Delta R(b_2, W_h)$, then

$$M(b_1 jj) > 200 \text{ GeV}\,, \qquad M_T(b_2 \ell \nu) > 200 \text{ GeV}\,,$$

otherwise $1 \leftrightarrow 2$;

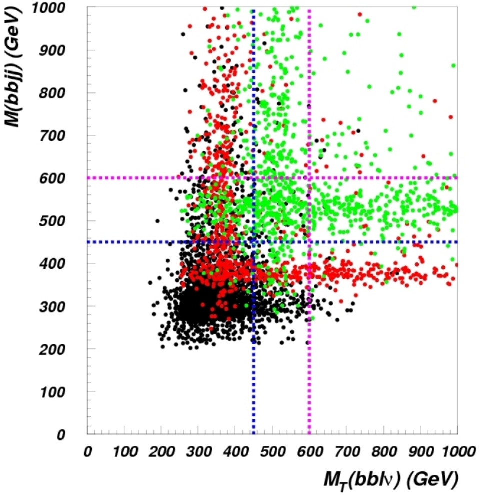
5) **same-hemisphere b quarks:**

$$\frac{\mathbf{p}_{b_1}}{|\mathbf{p}_{b_1}|} \cdot \frac{\mathbf{p}_{b_2}}{|\mathbf{p}_{b_2}|} > 0\,.$$

After this set of cuts, the significance timidly grows (~ 2).

It is not enough: we need a strategic cut.

Strategic cut (1)



Single cut

or

Square cut?

Strategic cut (2)

We define a single cut and a square cut:

$$\mathrm{C_{squ}} = \max\left(M(b\bar{b}jj), M_T(b\bar{b}\ell\nu)\right) > M_{\mathrm{lim}}$$
$$\mathrm{C_{sng}} = M_T(b\bar{b}\ell\nu) > M_{\mathrm{lim}}\,.$$

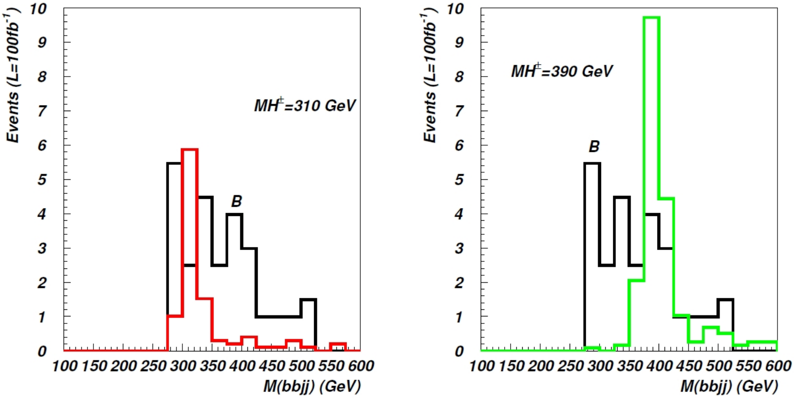
When $M_{\mathrm{lim}} = 600$ GeV the significance reaches the best value.

Finally, if we define a further cut on the peak:

$$|M - M_{H^\pm}| < 50\ \mathrm{GeV}\,,$$

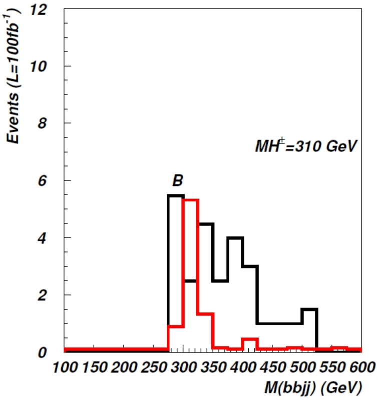
we find that $\mathrm{C_{sng}}$ is always better than $\mathrm{C_{squ}}$.

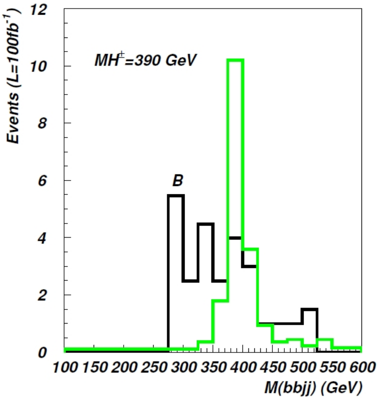
Results: P_3



$$\sqrt{s} = 14 \text{ TeV}$$

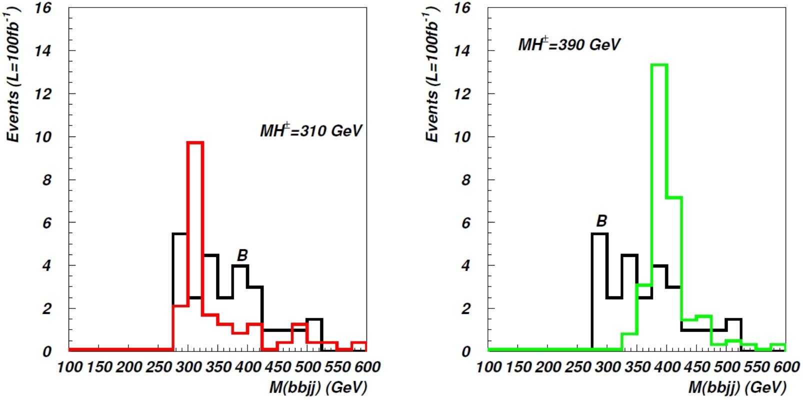
Results: P_4





$$\sqrt{s} = 14 \text{ TeV}$$

Results: P_5



$$\sqrt{s} = 14\ \text{TeV}$$

Conclusion

We have studied the phenomenology of the Charged Higgs in a CP-violating 2HDM type II.

- √ We have analysed the surviving parameter space (in the light of the latest LHC data);
- √ we have profiled the Charged Higgs in several benchmark points;
- √ we have proposed a strategy to discover this particle at the LHC at 14 TeV and 100 fb^{-1} in the process: $pp \to H^{\pm}W^{\mp} \to W^{\pm}W^{\mp}H_1 \to W^{\pm}W^{\mp}b\bar{b}$.

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