BSM Phenomenology of the Higgs sector

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Mini workshop on HHH and other extended scalar sector signatures

29-31 July 2024, Institut Ruđer Bošković, Zagreb, Croatia.

Overview

Experimental studies of the Higgs boson at the LHC

- Higgs production rate (cross section, differential cross section)
- Higgs mass, width, spin, parity
- Higgs couplings
- Higgs decay modes
- Search for more Higgs bosons
- Higgs as a new tool for discovery
- It is about 11 years since the Higgs discovery in July, 2012.
- LHC Run 1 collected about 25 fb^{-1} @ 7 and 8 TeV (2010 – 2012)
- LHC Run 2 collected about 130 fb^{-1} @ 13 TeV (2015 – 2018)
- The future LHC Run 3 with an energy of 13.6 and 14 TeV (2021 – 2024).

Overview

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The future LHC Run 3 with an energy of 13.6 and 14 TeV (2021 – 2024).

Several reasons justify expanding the Standard Model by introducing a second Higgs doublet, Singlet and triplet.

- Supersymmetric models and fermion masses.
- Electroweak baryogenesis (2HDM).
- TeV-scale dark matter.
- Vacuum stability can be maintained up to the Planck scale (2HDM).
- The small masses of neutrinos (HTM)
- Left-right symmetric models, axion models, and grand unified theories.
- In addition to the observed Higgs boson with a mass of approximately 125.09 GeV, they were able to predict a rich phenomenology compared to that of the Standard Model.

GENERAL 2-HIGGS-DOUBLET MODEL

The most general scalar potential of the 2HDM :

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

Where,

$$\Phi_i = \begin{pmatrix} \Phi_i^+ \\ \Phi_i^0 \end{pmatrix}, < 0|\Phi_i|0 >= \begin{pmatrix} 0 \\ \frac{v_i}{\sqrt{2}} \end{pmatrix}, i = 1,2 \qquad (2)$$

- $\Longrightarrow$ 8 degrees of freedom
- 5 physical Higgses : 2 CP-even h and H, 1 CP-odd A and 2 Charged Higgs $H^\pm$
- Avoid FCNC $\Longrightarrow$, $\mathcal{Z}_2$ symmetry($\lambda_6 = \lambda_7 = 0$)
- The CP-conserving of the potential $\Longrightarrow$ all parameter are real.
- 2 minimization conditions and the combination $v_1^2 + v_2^2 \Longrightarrow$ 7 free parameters : $m_h < m_H, m_H^\pm, m_A, \sin(\beta-\alpha), \tan\beta = \frac{v_2}{v_1}$ and m_{12}^2.

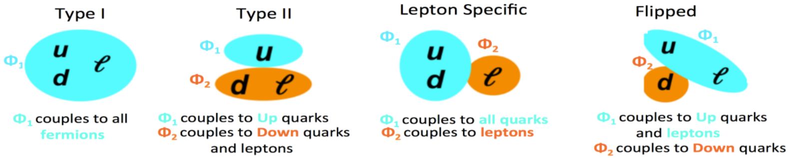
GENERAL 2-HIGGS-DOUBLET MODEL

YUKAWA COUPLINGS

The Yukawa Lagrangian, which describes the interactions between the Higgs sector and the fermion sector, is given as follows

$$\mathcal{L}_Y = \bar{Q}'_L(Y_1^u\tilde{\Phi}_1 + Y_2^u\tilde{\Phi}_2)U'_R + \tilde{Q}'_L(Y_1^d\Phi_1 + Y_2^d\Phi_2)d'_R + \bar{L}'_L(Y_1^l Q_1 + Y_2^l\Phi_2)l'_R + h.c \qquad (3)$$

- $\mathcal{Z}_2$ Symmetry



Type I

Φ_1 couples to all fermions

Type II

Φ_1 couples to Up quarks
Φ_2 couples to Down quarks and leptons

Lepton Specific

Φ_1 couples to all quarks
Φ_2 couples to leptons

Flipped

Φ_1 couples to Up quarks and leptons
Φ_2 couples to Down quarks

Type	ξ_u^h	ξ_d^h	ξ_l^h	ξ_u^H	ξ_d^H	ξ_l^H	ξ_u^A	ξ_d^A	ξ_l^A
I	c_α/s_β	c_α/s_β	c_α/s_β	s_α/s_β	s_α/s_β	s_α/s_β	ct_β	$-ct_\beta$	$-ct_\beta$
II	c_α/s_β	$-s_\alpha/c_\beta$	$-s_\alpha/c_\beta$	s_α/s_β	c_α/c_β	c_α/c_β	ct_β	t_β	t_β
X	c_α/s_β	c_α/s_β	$-s_\alpha/c_\beta$	s_α/s_β	s_α/s_β	c_α/c_β	ct_β	$-ct_\beta$	t_β
Y	c_α/s_β	$-s_\alpha/c_\beta$	c_α/s_β	s_α/s_β	c_α/c_β	s_α/s_β	ct_β	t_β	$-ct_\beta$

INERT DOUBLET MODE (IDM)

- The 'Inert-Doublet Model' (IDM) is a version of the Two-Higgs Doublet Model (2HDM) with an exact and unbroken Z_2 symmetry.
- The potential of the IDM is defined from that of the 2HDM, with $\lambda_6 = \lambda_7 = 0$ and, $m_{12}^2 = 0$.
- The Z_2 symmetry $\Longrightarrow$ only the doublet Φ_1 is allowed to develop a non-zero vacuum expectation value : $v_1 = v_{ms}, v_2 = 0$.

$$\Phi_1 = \left(\begin{array}{c} G^{\pm} \\ \frac{1}{\sqrt{2}}(v + h + iG^0) \end{array} \right), \qquad \Phi_2 = \left(\begin{array}{c} H^{\pm} \\ \frac{1}{\sqrt{2}}(H^0 + iA^0) \end{array} \right) \tag{4}$$

$\Longrightarrow$ Following the standard procedure, we minimize the potential and determine the number of free independent parameters.

- M_h and v fixed $\Longrightarrow$ there remain 5 independent real free parameters :

$$\{\mu_2^2(\lambda_L),\ \lambda_2,\ m_h = 125.09 \text{ GeV},\ \mathrm{m_H},\ \mathrm{m_A},\ \mathrm{m_{H^\pm}}\} \tag{5}$$

- Due to the Z_2 symmetry, the additional scalars H, A, and $H^{\pm}$ do not couple to fermions in the IDM.
- The lightest neutral scalar, H or A, could be a candidate for dark matter.

Higgs Triplet Model:HTM

Instead of another doublet, as has been seen previously, an additional $SU(2)_L$ real triplet, Δ with hypercharge $Y_\Delta = 2$ is introduced to the SM Higgs sector. The Higgs potential is given by

$$\begin{aligned} V(H,\Delta) &= -m_H^2 H^\dagger H + \frac{\lambda}{4}(H^\dagger H)^2 + M_\Delta^2 \mathrm{Tr}(\Delta^\dagger \Delta) + [\mu(H^T i\sigma^2 \Delta^\dagger H) + \mathrm{h.c.}] \\ &+ \lambda_1 (H^\dagger H)\mathrm{Tr}(\Delta^\dagger \Delta) + \lambda_2 (\mathrm{Tr}\Delta^\dagger \Delta)^2 + \lambda_3 \mathrm{Tr}(\Delta^\dagger \Delta)^2 + \lambda_4 H^\dagger \Delta \Delta^\dagger H \end{aligned}$$

in which the two Higgs multiplets are parameterized by,

$$\Delta = \begin{bmatrix} \frac{\delta^+}{\sqrt{2}} & \delta^{++} \\ \delta^0 & -\frac{\delta^+}{\sqrt{2}} \end{bmatrix} \quad \text{and} \quad H = \begin{bmatrix} \phi^+ \\ \phi^0 \end{bmatrix}. \tag{6}$$

HTM Parameters :

$$\mu,\ m,\ M, \lambda_i, i = 1, \ldots, 5. \Longrightarrow v, v_\Delta, m_{H^{++}}, m_{H^+}, m_A, m_h, m_H, \alpha \tag{7}$$

- Motivations:
  - The Higgs Triplet Model provides Majorana neutrinos masses via the product of a triplet Yukawa couplings h_{ij} and a triplet vev v_Δ.
  - Rich phenomenology for new physics, charged and doubley charged Higgs boson

123-Model

- In addition to the usual SM scalar doublet, namely ϕ , a singlet σ , and a triplet Δ have been added together to fundamentally build blocks for the 123-model.

$$\begin{aligned} \sigma &= \frac{1}{\sqrt{2}}(v_\sigma + R_\sigma + iI_\sigma), \\ \phi &= \begin{pmatrix} \frac{1}{\sqrt{2}}(v_\phi + R_\phi + iI_\phi) \\ \phi^- \end{pmatrix}, \\ \Delta &= \begin{pmatrix} \frac{1}{\sqrt{2}}(v_\Delta + R_\Delta + iI_\Delta) & \Delta^+/\sqrt{2} \\ \Delta^+/\sqrt{2} & \Delta^{++} \end{pmatrix}, \end{aligned} \tag{8}$$

- The scalar potential

$$\begin{aligned} V(\sigma,\phi,\Delta) = {} & \mu_\sigma^2 \sigma^\dagger \sigma + \mu_\phi^2 \phi^\dagger \phi + \mu_\Delta^2 \mathrm{Tr}(\Delta^\dagger \Delta) + \lambda_1 (\phi^\dagger \phi)^2 \\ & + \lambda_2 \left[\mathrm{Tr}(\Delta^\dagger \Delta)\right]^2 + \lambda_3 (\phi^\dagger \phi)\mathrm{Tr}(\Delta^\dagger \Delta) \\ & + \lambda_4 \mathrm{Tr}(\Delta^\dagger \Delta \Delta^\dagger \Delta) + \lambda_5 (\phi^\dagger \Delta^\dagger \Delta \phi) + \beta_1 (\sigma^\dagger \sigma)^2 \\ & + \beta_2 (\phi^\dagger \phi)(\sigma^\dagger \sigma) + \beta_3 \mathrm{Tr}(\Delta^\dagger \Delta)(\sigma^\dagger \sigma) \\ & - \kappa(\phi^T \Delta \phi \sigma + \mathrm{h.c.}), \end{aligned} \tag{9}$$

- The Model parameters : m_{h_1} , m_A , $\lambda_j\,(i = 2,4,5)$, $m_{H\pm}$, β_3 , $\alpha_{i\,(i=1,2,3)}$, v_σ , v_Δ.

Constraints

- Unitarity constraint,
- Perturbativity,
- Vacuum Stability,
- Oblique parameters: S, T, et U

  2HDMC Code (D. Eriksson, J. Rathsman and O. Stål)
- Constraints of flavour physics observables, namely, $B \to X_s\gamma$, $B_{s,d} \to \mu^+\mu^-$ and Δ^0.

  SuperIso (F. Mahmoudi)
- Exclusion limits at 95% Confidence Level (CL) from Higgs searches at colliders (LEP, Tevatron and LHC).
- Constraints from the Higgs boson signal strength measurements.

  HiggsBounds (P. Bechtle et al), and HiggsSignal (P. Bechtle et al)

Constraints

In addition to the constraints above, we consider the following constraint in the IDM model.

- Condition to be in the inert vacuum $\frac{m_{11}^2}{\sqrt{\lambda_1}} > \frac{m_{22}^2}{\sqrt{\lambda_2}}$,
- Constraint from electroweak gauge boson decay :

$$W^{\pm} \to HH^{\pm} \text{ and } W^{\pm} \to AH^{\pm}, \tag{10}$$

$$Z \to H^{\pm}H^{\mp} \text{ and } Z \to HA. \tag{11}$$

- unstable charged Higgs boson $\Longrightarrow \Gamma(H^{\pm}) \geq 6.58 \times 10^{-19}$.
- Dark matter relic density (upper bound) $\Omega_{DM}h^2 \leq \Omega_c h^3 = 0.1197 \pm 0.002$.
- Direct detection of dark matter by LUX and XENON1T : $\hat{\sigma_{SI}} = R_\Omega \times \sigma_{SI}$ where, $R_\Omega = \frac{\Omega^{DM}}{\Omega^{Plank}}$.
  micrOMEGAs (G. Bélanger, A. Mjallal, A. Pukhov)
- Invisible Higgs boson decays: $BR(h \to invisible) \leq 11\%$

Excesses of γZ vs charged Higgs BSM.

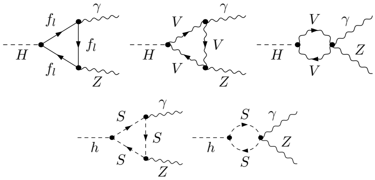


Figure: The generic Feynman diagrams for $H \to \gamma Z$ in the SM (upper) and BSM (lower)

- ATLAS
  $\mu_{\gamma\gamma} = 0.99^{+0.15}_{-0.14}, \mu_{\gamma Z} = 2.0^{+1.0}_{-0.9}$
- CMS
  $\mu_{\gamma\gamma} = 1.18^{+0.17}_{-014}, \mu_{\gamma Z} = 2.4^{+0.9}_{-0.9}$
- HL-LHC
  $\mu_{\gamma\gamma} = 1.0^{+0.04}_{-0.04}, \mu_{\gamma Z} = 1.0^{+0.23}_{-0.23}$

$m_{H^\pm} \sim v$, $m_{H^\pm} >> v$, but $m_{H^\pm}$ very large

$$\kappa_{hH^+H^-} = \frac{1}{v} \times \left[(m_h^2 - 2m_{H^\pm}^2) s_{\beta-\alpha} - \frac{2c_{\beta+\alpha}}{s_{2\beta}^2} (m_h^2 s_{2\beta} - 2m_{12}^2) \right] \tag{12}$$

$$\mu_{\gamma Z}^{NP} = \frac{\sigma(pp \to h \to \gamma Z)^{\mathrm{NP}}}{\sigma(pp \to h_{\mathrm{SM}} \to \gamma Z)} = \frac{Br(h \to \gamma Z)^{\mathrm{NP}}}{Br(h_{\mathrm{SM}} \to \gamma Z)} \times \begin{cases} 1 & \text{(Inert)} \\ \frac{\sigma(gg \to h)^{\mathrm{NP}}}{\sigma(gg \to h)^{\mathrm{SM}}} & \text{(others)} \end{cases} \tag{13}$$

Sc&P	M_h [GeV]	M_H [GeV]	M_A [GeV]	$M_{H^\pm}$ [GeV]	$\sin(\beta-\alpha)$	$\tan\beta$	m_{12}^2 [GeV^2]
I&X	125.09	[126; 1000]	[60; 1000]	[80; 1000]	[0.95; 1]	[2; 20]	$m_H^2 \cos\beta \sin\beta$
II&Y	125.09	[500; 1000]	[500; 1000]	[580; 1000]	[0.95; 1]	[2; 20]	$m_H^2 \cos\beta \sin\beta$

Table: 2HDMs type-I,II,X and type-Y input parameters.

Excesses of γZ vs charged Higgs BSM:2HDM.

- Signal strength

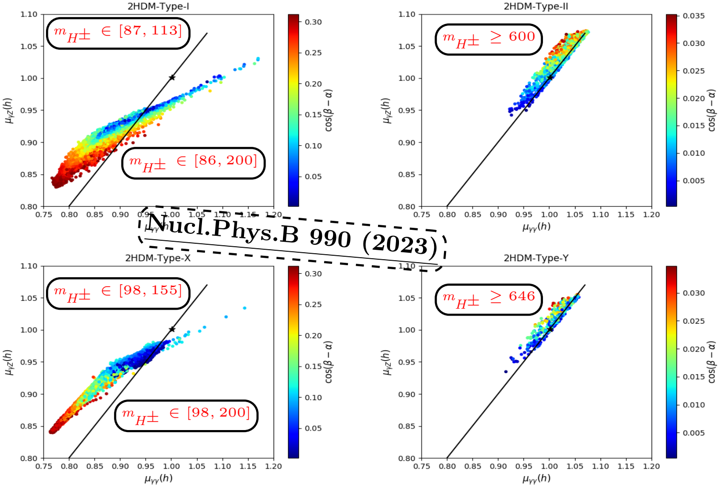


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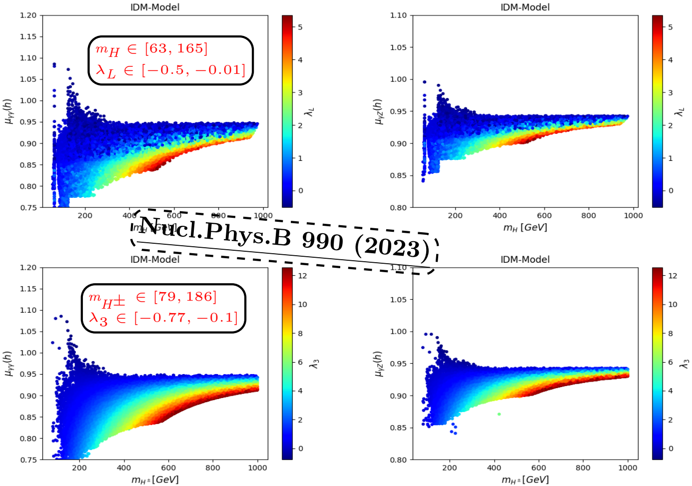
Figure: Correlation between $\mu_{\gamma\gamma}(h)$ and $\mu_{\gamma Z}(h)$ as a function of $\cos(\beta-\alpha)$ at NNLO in 2HDMs Types I (top left), II (top right), X (bottom left), and Y (bottom right).

Excesses of γZ vs scalar sector BSM:IDM



$m_H \in [63, 165]$
$\lambda_L \in [-0.5, -0.01]$

$m_{H\pm} \in [79, 186]$
$\lambda_3 \in [-0.77, -0.1]$

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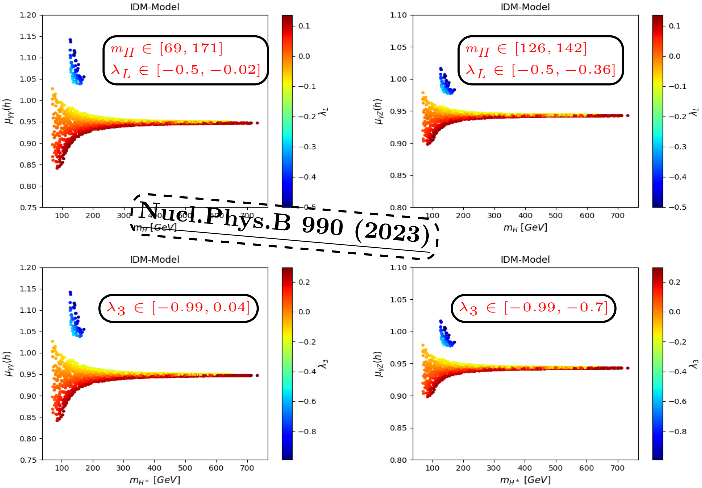
Figure: signal strengths $\mu_{\gamma\gamma}(h)$(left panel) and $\mu_{\gamma Z}(h)$(right panel) in IDM(General case) as a function of m_H overlaid on λ_L (upper panel), and $m_{H\pm}$ overlaid on λ_3 (lower panel).

Excesses of γZ vs scalar sector BSM: IDM



$m_H \in [69, 171]$
$\lambda_L \in [-0.5, -0.02]$

$m_H \in [126, 142]$
$\lambda_L \in [-0.5, -0.36]$

$\lambda_3 \in [-0.99, 0.04]$

$\lambda_3 \in [-0.99, -0.7]$

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Figure: signal strengths $\mu_{\gamma\gamma}(h)$(left) and $\mu_{\gamma Z}(h)$(right) in IDM (approximately degenerate case) as a function of m_H overlaid on λ_L (upper panel), and $m_{H\pm}$ overlaid on λ_3 (lower panel).

Excesses of γZ vs scalar sector BSM: HTM

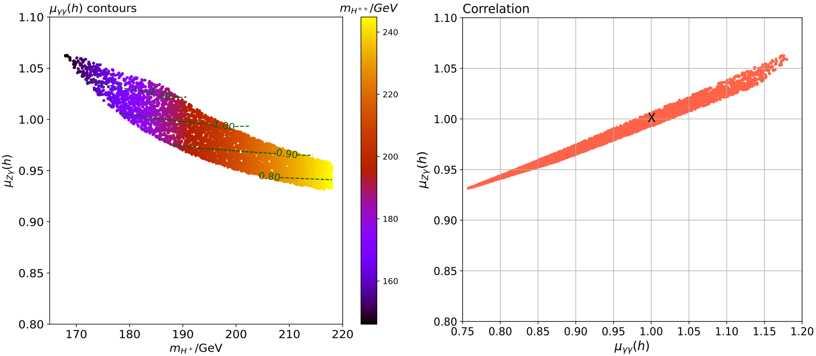

Figure: $\mu_{\gamma\gamma}(h)$ and $\mu_{\gamma Z}(h)$ correlation in the HTM.

CHARED HIGGS PRODUCTIONS AT LHC.

At hadron colliders, a charged Higgs boson can be produced through several channels:

- the $pp \to t\bar{t} \to b\bar{b}H^- H^+ + c.c$;process via the top decay $t \to bH^+$ (or the equivalent antitop mode).
- $pp \to H^\pm tb$: $g\bar{b} \to \bar{t}H^\pm + C.C$ and $gg \to tbH^+$
- Associated production with a $W^\pm$ gauge boson: $gg \to W^\pm H^\mp$ and $b\bar{b} \to W^\pm H^\mp$.
- Production in association with a bottom quark and a light-jet: $pp \to H^\pm bj$.
- Resonant production via $c\bar{s}, c\bar{b} \to H^+$
- Associate production with a neutral Higgs: $q\bar{q}^{'} \to H^\pm \Phi_i$ where Φ_i denotes one of the three neutral Higgs bosons, $\Phi = h, H\ or\ A$
- Pair production: $gg \to H^+ H^-$ and $q\bar{q} \to H^+ H^-$.

Charged Higgs Boson on the 2HDM

- Gauge couplings

$$H^{\pm}W^{\mp}h \propto \cos(\beta-\alpha),\;\; H^{\pm}W^{\mp}H \propto \sin(\beta-\alpha),\;\; H^{\pm}W^{\mp}A \propto \frac{g}{2}. \tag{14}$$

$$VVh \propto \sin(\beta-\alpha),\;\; VVH \propto cos(\beta-\alpha),\;\; VVA = 0 \tag{15}$$

- Yaukawa coupling We can write the charged-Higgs Lagrangian for one generation in the simplified form (neglecting elements of the CKM matrix):

$$\mathcal{L}_{ch} = \frac{g}{\sqrt{2}m_W}\left\{\left[\bar{u}(m_d P_R \mathcal{F}^D + m_u P_L \mathcal{F}^u)d + \bar{\nu} m_l P_R \mathcal{F}^l l\right] H^+\right\} \tag{16}$$

2HDMs Type	$\mathcal{F}^D$	$\mathcal{F}^U$	$\mathcal{F}^l$
I	$-\cot\beta$	$\cot\beta$	$-\cot\beta$
II	$\tan\beta$	$\cot\beta$	$\tan\beta$
X(lepton-specific)	$-\cot\beta$	$\cot\beta$	$\tan\beta$
Y(Flipped)	$\tan\beta$	$\cot\beta$	$-\cot\beta$

- Decays

$$H^{\pm} \to c\bar{s},\;\; c\bar{b},\;\; \tau^{+}\nu_{\tau},\;\; t\bar{b}, \tag{17}$$

$$H^{\pm} \to W^{\pm}\gamma,\;\; W^{\pm}Z,\;\; W^{\pm}\Phi(\Phi \equiv h, H, A) \tag{18}$$

Production through $pp \to H^{\pm}W^{\mp}$ & $pp \to H^{\pm}bj$

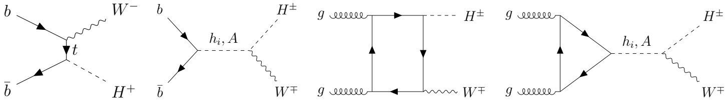

Figure: Feynman diagrams contributing to the $H^{\pm}W^{\mp}$ production.

- $b\bar{b}$-resonant channel is negligible since the Yukawa couplings are small.
- gg-resonant is only relevant when $M_H > M_{H^{\pm}} + M_W$ or $M_A > M_{H^{\pm}} + M_W$

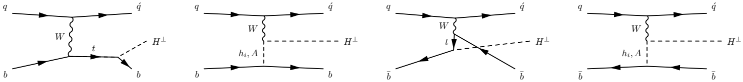

Figure: Feynman diagrams contributing to the $H^{\pm}bj$ production.

- $qb \to q^{'}bH^{\pm}$ (s and t-channel) and $q\bar{b} \to q^{'}bH^{\pm}$(u and t-channel)
- $M_{H^{\pm}} < m_t - m_b$, s-channel dominate, Other diagram contribute for $M_{H^{\pm}} > m_t - m_b$

RESULTS AND DISCUSSION

- We randomly scan the space parameter as set in bellow:

Sc&P	M_h [GeV]	M_H [GeV]	M_A [GeV]	$M_{H^\pm}$ [GeV]	$\sin(\beta-\alpha)$	$\tan\beta$	m_{12}^2 [GeV^2]
NS	125.09	[126; 700]	[15; 700]	[80; 700]	[0.95; 1]	[2; 25]	[0; $m_H^2\cos\beta\sin\beta$]
IS	[15; 120]	125.09	[15; 700]	[80; 700]	[−0.5; 0.5]	[2; 25]	[0; $m_h^2\cos\beta\sin\beta$]

Table: 2HDM type-I and type-X input parameters.

- we concentrate on the following signatures:

$$\sigma^S(pp \to xWW) = \sigma(pp \to H^\pm W^\mp \to W^\pm S W^\mp \to xW^\pm W^\mp), \quad (19)$$

$$\sigma^S(pp \to xWbj) = \sigma(pp \to H^\pm bj \to W^\pm Sbj \to xW^\pm bj), \quad (20)$$

where S can be either h or A, and x stands for bb, $\tau\tau$ or $\gamma\gamma$.

- In both Scenario, we could expect the following signatures: $bbWW, \tau\tau WW, \gamma\gamma WW, bbWbj, \tau\tau Wbj$ and $\gamma\gamma Wbj$

$pp \to H^\pm W^\mp \to W^\pm W^\mp A \to W^\pm W^\mp bb$ and $W^\pm W^\mp \tau\tau$

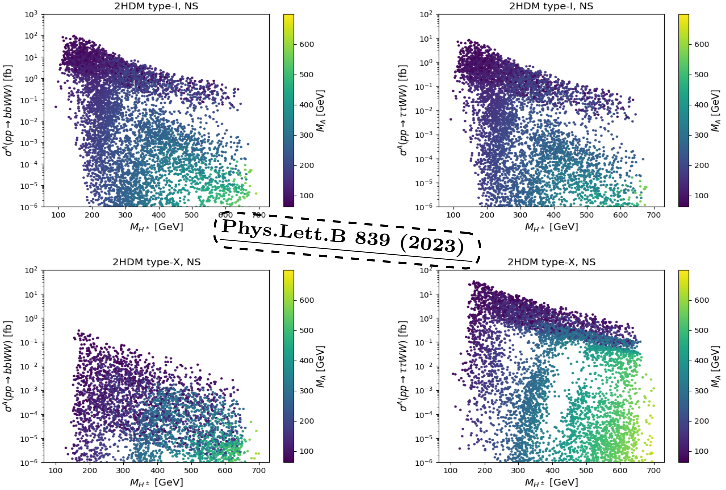

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Figure: The final states, $\sigma^H(pp \to bbWW)$ (left) and $\sigma^H(pp \to \tau\tau WW)$ (right) as a function of $M_{H\pm}$ and M_A. The upper (lower) panels show Type I (Type X) results.

$pp \to H^\pm bj \to W^\pm A bj \to b\bar{b} W^\mp bj$ and $\tau\tau W^\mp bj$

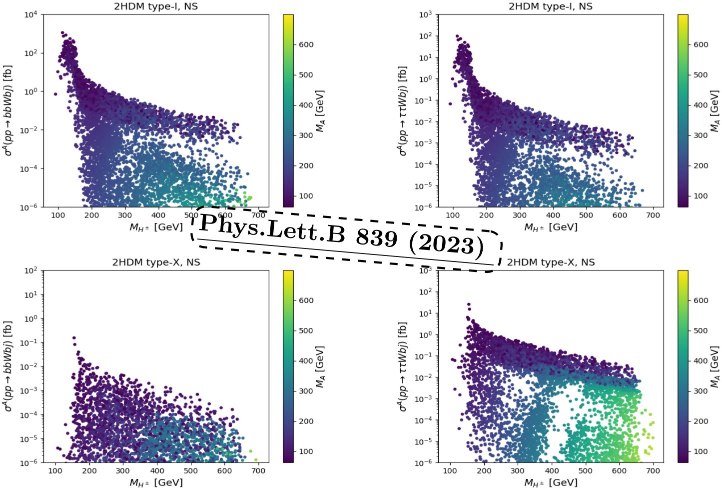

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Figure: $\sigma^A(pp \to bb\,Wbj)$ (left panel), $\sigma^A(pp \to \tau\tau\,Wbj)$ (right panel) as a function of $M_{H\pm}$, with the color code showing M_A. Upper (lower) panels present the type-I (type-X) results.

$pp \to H^\pm W^\mp \to W^\pm W^\mp h \to WWb\bar{b}$ and $WW\tau\tau$

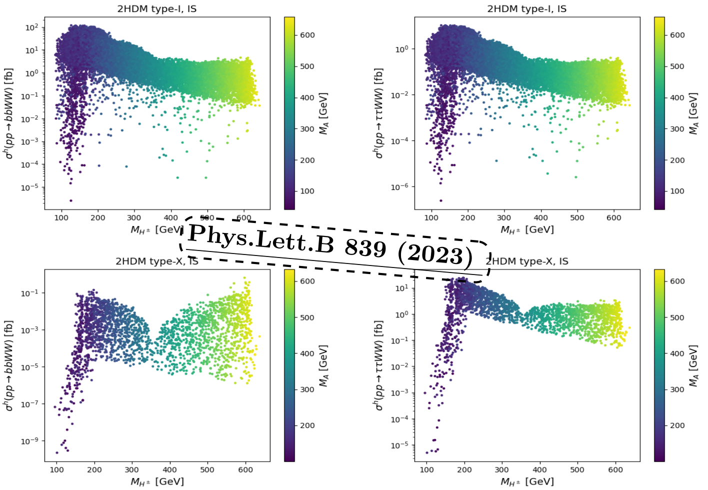

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Figure: $\sigma^h(pp \to bbWW)$ (left panel) and $\sigma^h(pp \to \tau\tau WW)$ (right panel) as a function of $M_{H^\pm}$, with the color code showing M_A. Upper (lower) panels present the type-I (type-X) results.

$pp \to H^\pm bj \to W^\pm hbj \to bbWbj$ and $\tau\tau Wbj$

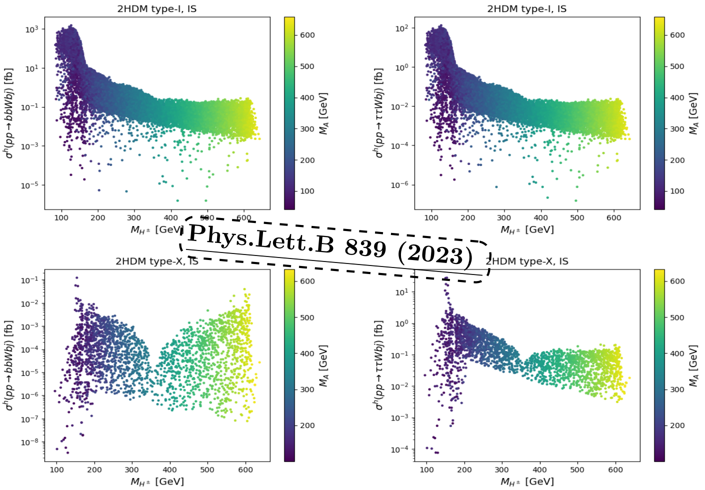

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Figure: $\sigma^h(pp \to bb\,Wbj)$ (left panel) and $\sigma^h(pp \to \tau\tau\,Wbj)$ (right panel) as a function of $M_{H^\pm}$, with the color code showing M_A. Upper (lower) panels present the type-I (type-X) results.

Benchmarks Points type-I

Parameters	BP1	BP2	BP3	BP4	BP5	BP6
M_h (GeV)	125.09	125.09	125.09	125.09	125.09	125.09
M_H (GeV)	135.07	144.62	132.07	130.26	135.12	134.75
M_A (GeV)	200.95	219.65	67.01	74.07	62.97	66.54
$M_{H^\pm}$ (GeV)	226.20	259.66	146.88	144.66	113.18	123.09
$\sin(\beta-\alpha)$	0.994	0.985	0.989	0.985	0.991	0.968
$\tan\beta$	3.97	2.77	3.53	3.55	4.26	4.37
m_{12}^2 (GeV^2)	4322.16	6675.8	4565.08	4417.98	4055.61	3949.10
BR($H^\pm \to XY$) in %						
BR($H^\pm \to W^\pm H$)	35.41	46.78	–	–	–	–
BR($H^\pm \to W^\pm A$)	–	–	98.12	95.37	92.47	95.19
BR($h \to XY$) in %						
BR($H \to b\bar{b}$)	53.68	29.76	11.01	11.20	1.68	0.16
BR($H \to \tau\tau$)	5.26	2.95	1.07	1.09	0.16	0.01
BR($H \to \gamma\gamma$)	0.34	0.33	0.11	0.24	0.03	0.07
BR($A \to XY$) in %						
BR($A \to b\bar{b}$)	22.54	17.96	79.98	78.51	80.80	80.08
BR($A \to \tau\tau$)	2.43	1.97	6.96	6.97	6.94	6.95
BR($A \to \gamma\gamma$)	0.05	0.05	0.01	0.01	0.01	0.01
σ in fb						
$\sigma^H(pp \to bbWW)$	9.23	8.95	–	–	–	–
$\sigma^H(pp \to \tau\tau WW)$	0.90	0.88	–	–	–	–
$\sigma^H(pp \to \gamma\gamma WW)$	0.05	0.09	–	–	–	–
$\sigma^A(pp \to bbWW)$	–	–	93.43	88.32	81.14	72.36
$\sigma^A(pp \to \tau\tau WW)$	–	–	8.13	7.84	6.97	6.28
$\sigma^A(pp \to \gamma\gamma WW)$	–	–	0.02	0.02	0.01	0.01
$\sigma^H(pp \to bbWbj)$	0.55	0.53	–	–	–	–
$\sigma^H(pp \to \tau\tau Wbj)$	0.05	0.05	–	–	–	–
$\sigma^H(pp \to \gamma\gamma Wbj)$	< 0.01	0.01	–	–	–	–
$\sigma^A(pp \to bbWbj)$	–	–	349.75	410.27	1088.35	815.06
$\sigma^A(pp \to \tau\tau Wbj)$	–	–	30.43	36.43	93.51	70.82
$\sigma^A(pp \to \gamma\gamma Wbj)$	–	–	0.056	0.08	0.15	0.12

Table: 2HDM type-I selected BPs in the NS.

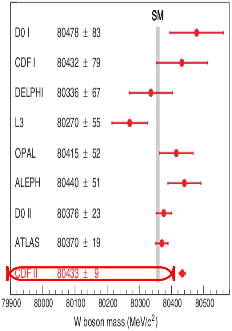
Parameters	BP1	BP2	BP3	BP4	BP5	BP6
M_h (GeV)	64.68	68.22	69.29	112.45	115.42	71.68
M_H (GeV)	125.09	125.09	125.09	125.09	125.09	125.09
M_A (GeV)	130.84	147.98	132.88	53.72	51.90	135.54
$M_{H^\pm}$ (GeV)	126.68	139.15	163.20	101.36	119.45	115.38
$\sin(\beta-\alpha)$	0.127	0.140	-0.062	0.175	0.134	-0.144
$\tan\beta$	3.46	3.35	3.13	4.02	3.80	6.94
m_{12}^2 (GeV^2)	1053.71	511.93	850.14	2757.59	2782.55	177.81
BR($H^\pm \to XY$) in %						
BR($H^\pm \to W^\pm h$)	94.72	95.95	99.54	–	–	94.11
BR($H^\pm \to W^\pm A$)	–	–	0.03	90.00	97.52	–
BR($h \to XY$) in %						
BR($h \to b\bar{b}$)	85.76	85.49	85.39	5.38	1.08	9.71
BR($h \to \tau\tau$)	7.37	7.41	7.43	0.51	0.10	0.85
BR($h \to \gamma\gamma$)	< 0.01	< 0.01	0.02	< 0.01	< 0.01	51.14
BR($A \to XY$) in %						
BR($A \to b\bar{b}$)	30.88	16.29	36.79	82.60	82.94	13.45
BR($A \to \tau\tau$)	3.07	1.66	3.67	6.87	6.85	1.35
BR($A \to \gamma\gamma$)	0.02	0.02	0.03	0.01	0.01	0.01
σ in fb						
$\sigma^h(pp \to bbWW)$	118.15	115.14	115.07	–	–	3.65
$\sigma^h(pp \to \tau\tau WW)$	10.16	9.99	10.01	–	–	0.32
$\sigma^h(pp \to \gamma\gamma WW)$	< 0.01	< 0.01	0.03	–	–	19.24
$\sigma^A(pp \to bbWW)$	–	–	0.02	100.57	103.02	–
$\sigma^A(pp \to \tau\tau WW)$	–	–	< 0.01	8.37	8.51	–
$\sigma^A(pp \to \gamma\gamma WW)$	–	–	< 0.01	0.01	0.01	–
$\sigma^h(pp \to bbWbj)$	1524.43	838.06	22.80	–	–	63.37
$\sigma^h(pp \to \tau\tau Wbj)$	131.05	72.70	1.98	–	–	5.55
$\sigma^h(pp \to \gamma\gamma Wbj)$	0.01	0.01	0.01	–	–	333.74
$\sigma^A(pp \to bbWbj)$	–	–	< 0.01	2179.63	1618.58	–
$\sigma^A(pp \to \tau\tau Wbj)$	–	–	< 0.01	181.28	133.67	–
$\sigma^A(pp \to \gamma\gamma Wbj)$	–	–	< 0.01	0.22	0.15	–

Table: 2HDM type-I selected BPs in the IS.

- 2HDM type-I paramters, branching ratios and signal cross sections corresponding to the selected BPs.
- We point out that the $bbWW$ and $bbWbj$ signals are plagued by the huge QCD background, especially the $t\bar{t}$ one, yielding poor significance.
- The signatures $\tau\tau WW$ and $\tau\tau Wbj$ can give the best reach since they would suppress the $t\bar{t}$ background, especially if we require at least one leptonic decay of tau leptons.
- We also suggest $\gamma\gamma WW$ and $\gamma\gamma Wbj$ as clean signatures in the inverted scenario.
- Such signals could provide a complementary search for a charged Higgs boson at the LHC.

CDF-II W boson mass with 2HDMs and 123-Model

Fig. 5. Comparison of this CDF II measurement and past M_W measurements with the SM expectation. The latter includes the published estimates of the uncertainty (4 MeV) due to missing higher-order quantum corrections, as well as the uncertainty (4 MeV) from other global measurements used as input to the calculation, such as m_t. c, speed of light in a vacuum.



- CDF-II: $M_W = 80433,5 \pm 6,4_{stat} \pm 6,9_{sys} = 80433,5 \pm 9.4 \mathrm{MeV/c}^2$.
- This measurement is in significant tension with the standard model expectation by 7σ.

RESEARCH

PARTICLE PHYSICS

High-precision measurement of the *W* boson mass with the CDF II detector

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Catastini[46], D. Cauz[45,47,48], V. Cavaliere[42], A. Cerri[22], L. Cerrito[41], Y. C. Chen[49], M. Chertok[50], G. Chiarelli[25], G. Chlachidze[6], K. Cho[15,16,17,18,19,20,21], D. Chokheli[11], A. Clark[51], C. Clarke[52], M. E. Convery[6], J. Conway[50], M. Corbo[6], M. Cordelli[7], C. A. Cox[50], D. J. Cox[50], M. Cremonesi[25], D. Cruz[12], J. Cuevas[44], R. Culbertson[6], N. d'Ascenzo[6], M. Datta[6], P. de Barbaro[32], L. Demortier[30], M. Deninno[35]§, M. D'Errico[3,4], F. Devoto[1,2], A. Di Canto[25,27], B. Di Ruzza[6], J. R. Dittmann[31], S. Donati[25,27], M. D'Onofrio[53], M. Dorigo[45,54], A. Driutti[45,47,48], K. Ebina[10], R. Edgar[5], A. Elagin[34], R. Erbacher[50], S. Errede[42], B. Esham[42], S. Farrington[14], J. P. Fernández Ramos[55], R. Field[43], G. Flanagan[6], R. Forrest[50], M. Franklin[46], J. C. Freeman[6], H. Frisch[34], Y. Funakoshi[10], C. Galloni[25,27], A. F. Garfinkel[23], P. Garosi[25,26], H. Gerberich[42], E. Gerchtein[6], S. Giagu[56], V. 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Corrections to the m_W^2 and $\sin^2\theta_{eff}$: Implications

- The corrections of BSM to the mass of the W boson and the effective weak mixing angle, $\sin^2\theta_{\rm eff}$, can be parameterized by the formalism S, T, and U:

$$\Delta m_W^2 = \left(m_W^{\rm BSM}\right)^2 - \left(m_W^{\rm SM}\right)^2 = \frac{\alpha_0\, c_W^2 m_Z^2}{c_W^2 - s_W^2}\left[-\frac{1}{2}S + c_W^2 T + \frac{c_w^2 - s_w^2}{4 s_W^2}U\right], \quad (21)$$

$$\Delta \sin^2\theta_{\rm eff} = \sin^2\theta_{\rm eff}\Big|_{\rm BSM} - \sin^2\theta\Big|_{\rm SM} = \frac{\alpha_0}{c_W^2 - s_W^2}\left[\frac{1}{4}S - s_W^2 c_W^2 T\right]. \quad (22)$$

- Parameters space

Parameters	SN	SI
m_h(GeV)	125.09	[15; 120]
m_H(GeV)	[126; 1000]	125.09
m_A(GeV)	[15; 1000]	[15; 1000]
$m_{H^\pm}$(GeV)	[80; 1000]	[80; 1000]
$\tan\beta$	[2; 25]	[2; 25]
$\sin(\beta-\alpha)$	[−0.5; 0.5]	[0.95; 1]
m_{12}^2(GeV^2)	$[0; m_H^2 s_\beta c_\beta]$	$[0; m_h^2 s_\beta c_\beta]$

Table: The independent parameters of Type I and X 2HDMs for testing their consistency with the new measurement of the W boson mass at CDF.

- Parameters S and T.

$$\text{PDG}: S = 0.05 \pm 0.08,\quad T = 0.09 \pm 0.07,\quad \rho_{ST} = 0.92 \quad (23)$$

$$\text{CDF}: S = 0.15 \pm 0.08,\quad T = 0.27 \pm 0.06,\quad \rho_{ST} = 0.93, \quad (24)$$

Corrections to the m_W^2 and $\sin^2\theta_{eff}$: Implications

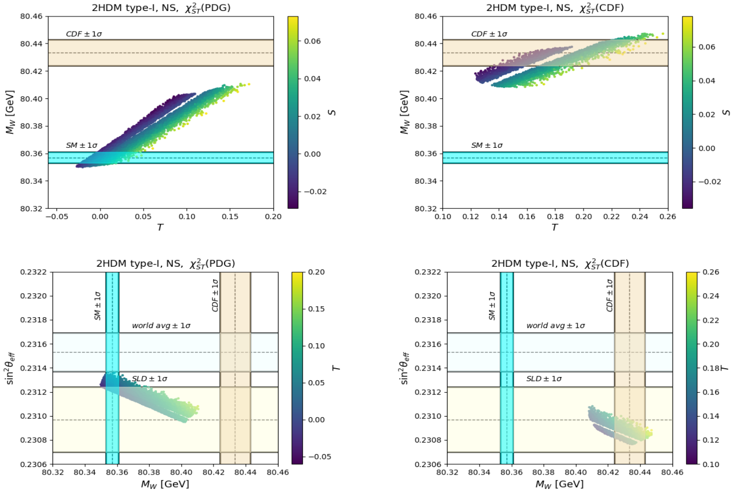
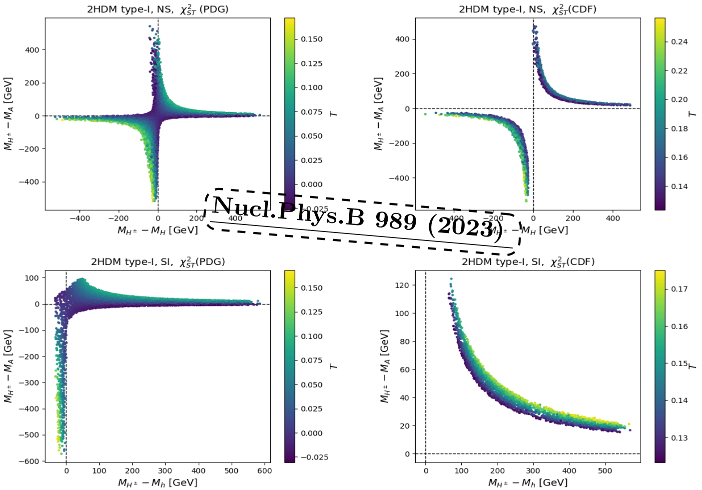


Figure: The prediction of 2HDMs for the mass of the W boson as a function of the T and S parameters with measurements from PGD (left) and those from CDF (right)

CDF-II W boson mass with Vs 2HDMs.

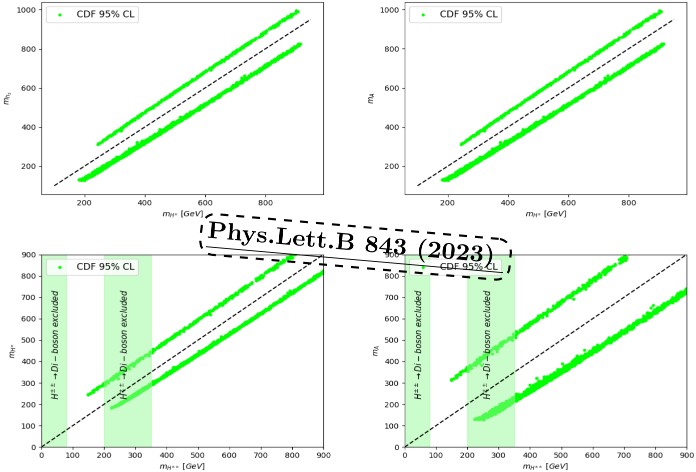
- For the 2HDMs.



Nucl.Phys.B 989 (2023)

Figure: Mass splitting within PDG (left) and CDF (right).

CDF-II W boson mass with Vs 123-Model



Phys.Lett.B 843 (2023)

Figure: Dependence of the Higgs bosons masses on each other on the light of the recent CDF (green points) measurement. The black line indicates the region of the full degenerate masses. The green bands indicate the region excluded by the $H^{\pm\pm} \to W^\pm W^\pm$.

Conclusion

- In particle physics, it has become inevitable to consider theories beyond the Standard Model in order to advance research.
- Two Higgs doublet models, 2HDM and IDM, are among the simplest extensions proposed to expand the Standard Model.
- The deviations observed in the signal strengths $\mu_{\gamma\gamma}$ and $\mu_{\gamma Z}$ can be explained within the framework of the 2HDM and IDM models.
- The search for the charged Higgs boson in particle collisions can provide direct indications of new physics beyond the Standard Model.
- The study of the production processes of the charged Higgs boson: $pp \to H^{\pm} W^{\mp}$ and $pp \to H^{\pm} bj$, has allowed us to propose complementary signatures for the search for the charged Higgs boson at the LHC.
- The types I and X of the 2HDMs are consistent with the new measurement of the W boson mass (MW) conducted by CDFII at Fermilab.

Thank you for your attention.