# Topics in Particle Physics: Charged Higgs bosons in the Georgi-Machacek model

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TÉCNICO LISBOA

# Objective

**Objective:** present and discuss [2104.04762].

Search for charged Higgs bosons produced in vector boson fusion processes and decaying into vector boson pairs in proton-proton collisions at $\sqrt{s} = 13$ TeV

The CMS Collaboration*

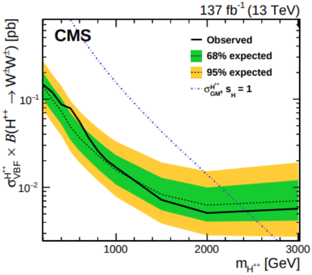
**Abstract**

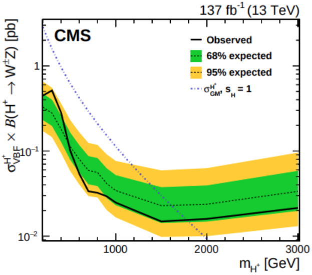
A search for charged Higgs bosons produced in vector boson fusion processes and decaying into vector bosons, using proton-proton collisions at $\sqrt{s} = 13$ TeV at the LHC, is reported. The data sample corresponds to an integrated luminosity of 137 $fb^{-1}$ collected with the CMS detector. Events are selected by requiring two or three electrons or muons, moderate missing transverse momentum, and two jets with a large rapidity separation and a large dijet mass. No excess of events with respect to the standard model background predictions is observed. Model independent upper limits at 95% confidence level are reported on the product of the cross section and branching fraction for vector boson fusion production of charged Higgs bosons as a function of mass, from 200 to 3000 GeV. The results are interpreted in the context of the Georgi–Machacek model.

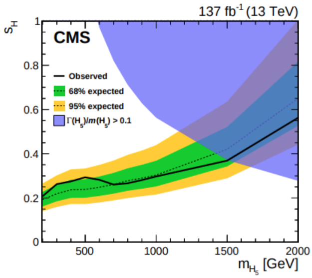
# Outline

- Georgi-Machacek model:
  - physical spectrum;
  - interactions;
- Model analysis;
- Discussion of CMS searches for charged scalars;

# Main results

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Variables: $m_{H^{\pm\pm}} = m_{H^{\pm}} = m_{H_5} = m_5$ and $\mathrm{s_H} = \mathrm{s}_\beta$.

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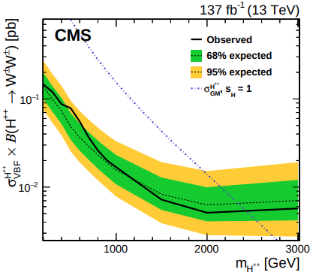


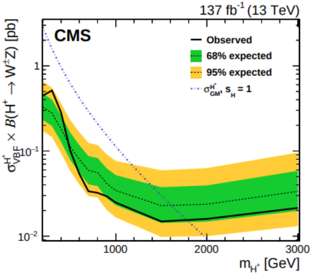


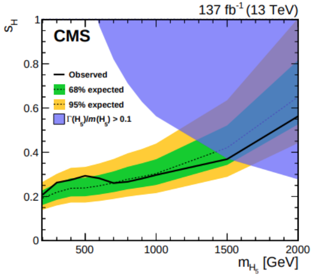


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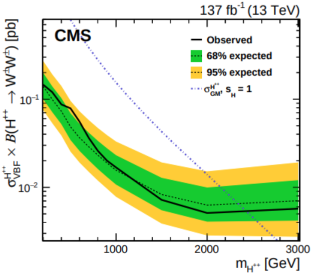


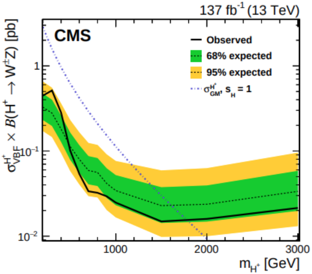


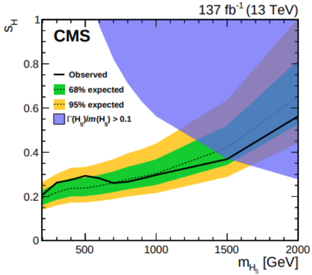


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# Georgi-Machacek model: generalities

Gauge eigenstates:

SM-like $\phi$ ($Y = 1$), real triplet $\xi$ ($Y = 0$), complex triplet $\chi$ ($Y = 2$),

$$\phi = \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix}, \quad \xi = \begin{pmatrix} \xi^+ \\ \xi^0 \\ \xi^- \end{pmatrix}, \quad \chi = \begin{pmatrix} \chi^{++} \\ \chi^+ \\ \chi^0 \end{pmatrix}.$$

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The $\mathrm{SU(2)_L} \otimes \mathrm{SU(2)_R}$ covariant forms ($\Psi \to U_{nL}\, \Psi\, U_{nR}^\dagger$):

$$\Phi = \left[ \begin{pmatrix} 0 & 1 \\ -1 & 0 \end{pmatrix} \phi^*, \, \phi \right] = \begin{pmatrix} (\phi^0)^* & \phi^+ \\ -(\phi^+)^* & \phi^0 \end{pmatrix},$$

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Phase convention:

$$\chi^{--} = \left(\chi^{++}\right)^*,$$
$$\phi^- = -\left(\phi^+\right)^*, \quad \chi^- = -\left(\chi^+\right)^*, \quad \xi^- = -\left(\xi^+\right)^*.$$

# Georgi-Machacek model: physical spectrum

The most general gauge-invariant scalar potential involving these fields that conserves custodial SU(2) is given by

$$\begin{aligned} V = & \frac{\mu_2^2}{2} \operatorname{Tr}\left(\Phi^\dagger \Phi\right) + \frac{\mu_3^2}{2} \operatorname{Tr}\left(X^\dagger X\right) + \lambda_1 \left[\operatorname{Tr}\left(\Phi^\dagger \Phi\right)\right]^2 + \lambda_2 \operatorname{Tr}\left(\Phi^\dagger \Phi\right) \operatorname{Tr}\left(X^\dagger X\right) \\ & + \lambda_3 \operatorname{Tr}\left(X^\dagger X X^\dagger X\right) + \lambda_4 \left[\operatorname{Tr}\left(X^\dagger X\right)\right]^2 - \lambda_5 \operatorname{Tr}\left(\Phi^\dagger \tau^a \Phi \tau^b\right) \operatorname{Tr}\left(X^\dagger t^a X t^b\right) \\ & - M_1 \operatorname{Tr}\left(\Phi^\dagger \tau^a \Phi \tau^b\right) \left(U X U^\dagger\right)_{ab} - M_2 \operatorname{Tr}\left(X^\dagger t^a X t^b\right) \left(U X U^\dagger\right)_{ab} . \end{aligned}$$

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The five-plet states are fermio-phobic and $H_3^\pm$ is gauge-phobic.

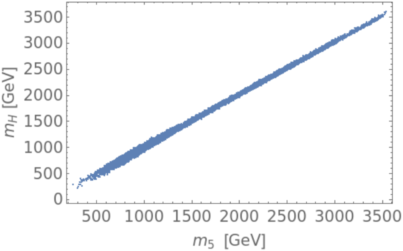
# Model analysis

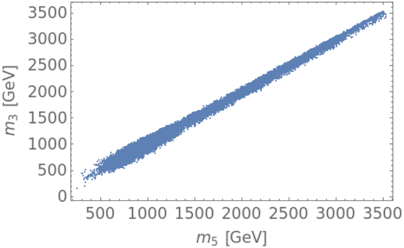
Model input: $\{\mu_3^2,\ \lambda_2,\ \lambda_3,\ \lambda_4,\ \lambda_5,\ M_1,\ M_2\}$ + $m_h$ fixed.

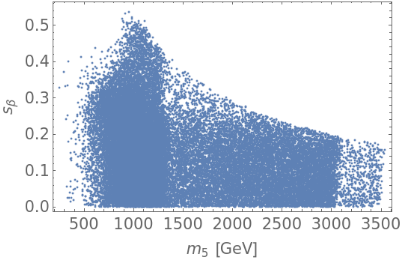
Cuts:

- Theoretical constraints (quartic couplings, potential stability, absence of deeper minima, perturbative unitarity);
- SM-like limit ($\Gamma_h$, $VVh$ and $ffh$);
- GMCALC 1.5.0 [1412.7387]:
  - Indirect experimental constraints (Peskin-Takeuchi parameters, $b \to s\gamma$, $B_s^0 \to \mu^+\mu^-$);
  - Direct experimental constraints ($H_5^{\pm\pm} \to W^\pm W^\pm \to$ like-sign dileptons, Drell-Yan production of $H_5^{++}H_5^{--}$ and $H_5^{\pm\pm}H_5^{\mp}$ with $H_5^{\pm\pm} \to W^\pm W^\pm$, Drell-Yan production of $H_5^0 H_5^\pm$ with $H_5^0 \to \gamma\gamma$);

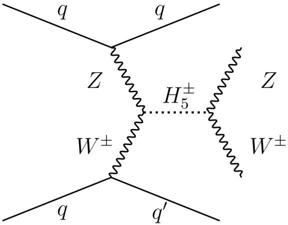
# Model analysis

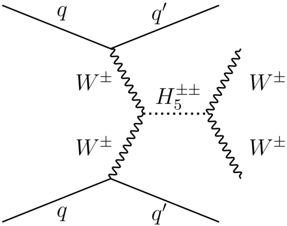


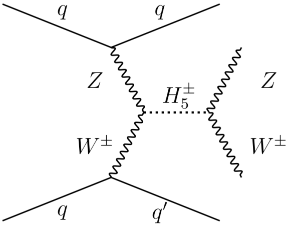



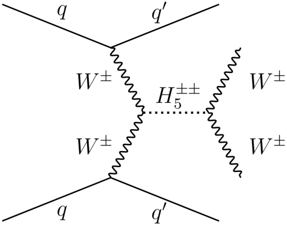



# CMS paper analysis: introduction



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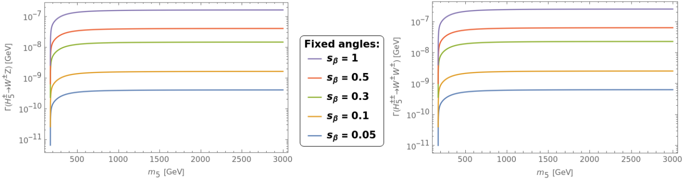
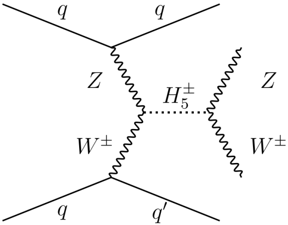
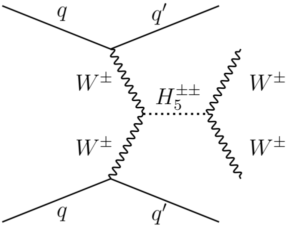


# CMS paper analysis: introduction

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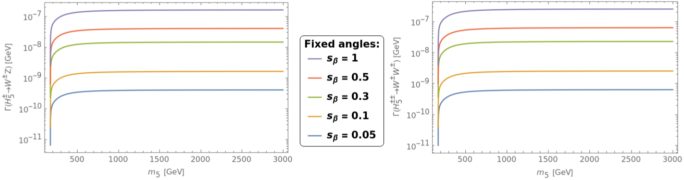


It is assumed that Br $\left(H_5^{\pm} \to W^{\pm} Z\right) = 1$ and Br $\left(H_5^{\pm\pm} \to W^{\pm} W^{\pm}\right) = 1$.
Analysis performed for $m_5 \in [200; 3000]$ GeV.

# CMS paper analysis: signal and background simulation

Signal samples simulated at LO MADGRAPH5_aMC@NLO2.4.2. Predicted signal cross-sections are taken at NNLO from [LHCHXSWG-2015-001]:

| | LO | NLO | NNLO |
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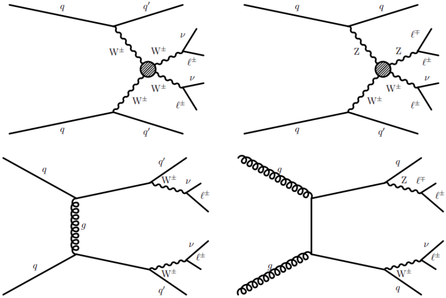


[2005.01173]

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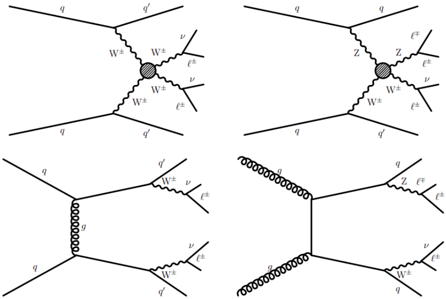


[2005.01173]

Background contribution: $tZq$, $t\bar{t}$, $tW$, $t\bar{t}W$, $t\bar{t}Z$, $t\bar{t}\gamma$, $VVV$, $p-p$.

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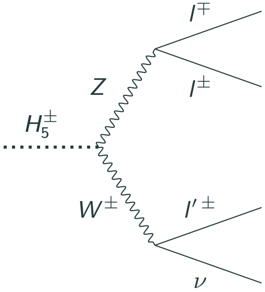

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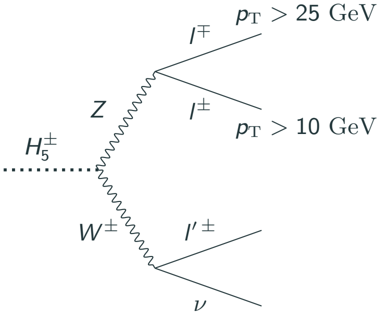

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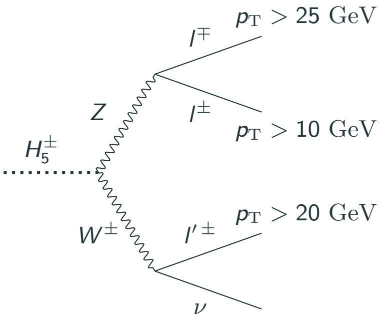

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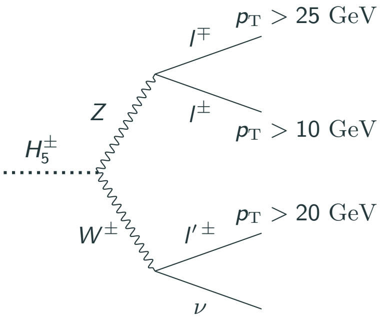


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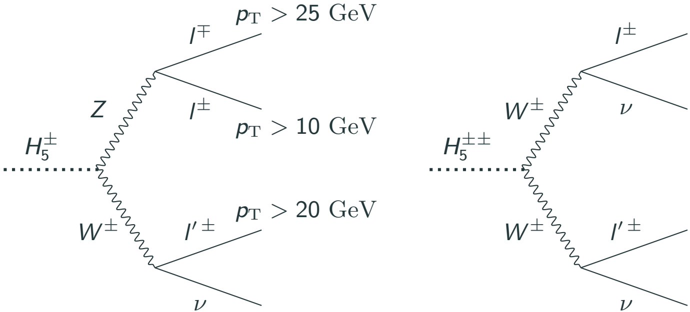


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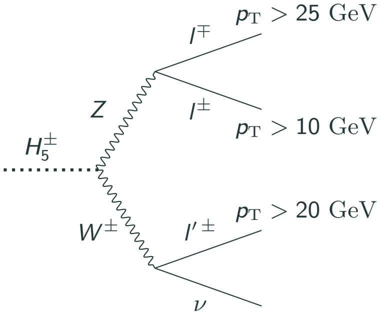


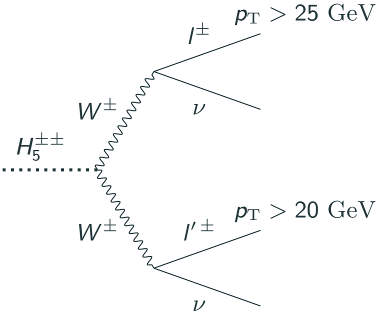


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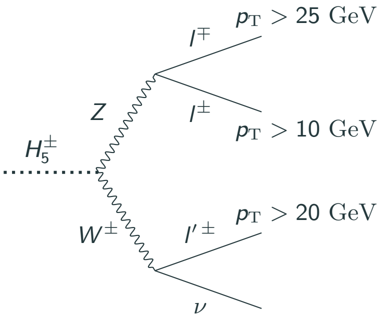


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# CMS paper analysis: signal extraction

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VBF and VBS topologies typically exhibit large values for the dijet mass.

# CMS paper analysis: systematic uncertainties

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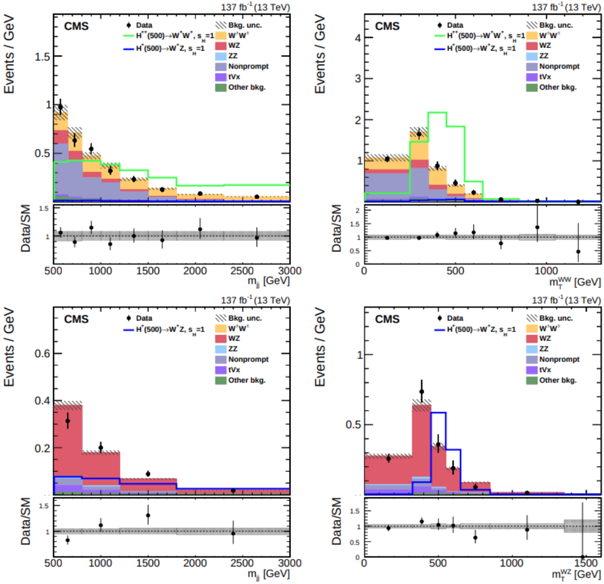
| Source of uncertainty | $\Delta\mu$ background-only | $\Delta\mu$ $s_H = 1.0$ and $m_{H_5} = 500\,\text{GeV}$ |
|---|---|---|
| Integrated luminosity | 0.002 | 0.019 |
| Pileup | 0.001 | 0.001 |
| Lepton measurement | 0.003 | 0.033 |
| Trigger | 0.001 | 0.007 |
| JES and JER | 0.003 | 0.006 |
| b tagging | 0.001 | 0.006 |
| Nonprompt rate | 0.002 | 0.002 |
| $W^{\pm}W^{\pm}/WZ$ rate | 0.014 | 0.015 |
| Other prompt background rate | 0.002 | 0.015 |
| Signal rate | — | 0.064 |
| Simulated sample size | 0.005 | 0.005 |
| Total systematic uncertainty | 0.016 | 0.078 |
| Statistical uncertainty | 0.021 | 0.044 |
| Total uncertainty | 0.027 | 0.090 |

[2104.04762]

# CMS paper analysis: results




[2104.04762]

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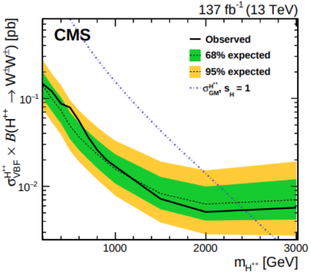
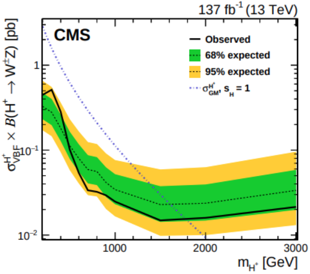
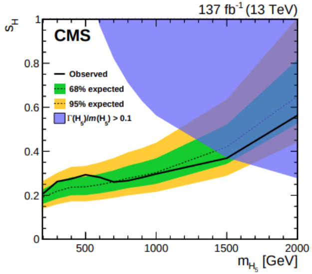
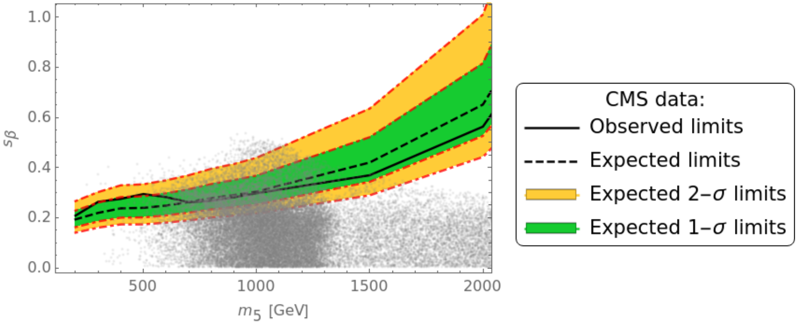



[2104.04762]


1.0
0.8
0.6
0.4
0.2
0.0
$s_\beta$
500
1000
1500
2000
$m_5$ [GeV]
CMS data:
Observed limits
Expected limits
Expected 2–σ limits
Expected 1–σ limits

# Summary

[2104.04762]:

A search for charged Higgs bosons produced in vector boson fusion processes and decaying into vector bosons, and further into leptonic decay modes was reported based on the 2016 - 2018 CMS data.

The $W^{\pm}W^{\pm}$ and $WZ$ channels were simultaneously studied by performing a binned maximum-likelihood fit using the transverse mass and dijet invariant mass distributions.

No excess of events with respect to the standard model background predictions was observed.

The observed 95% confidence level limits exclude GM $\mathrm{s_H}$ parameter values greater than 0.20–0.35 for the mass range $m_{H_5}$ from 200 to 1500 GeV.