“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” by The CMS Collaboration

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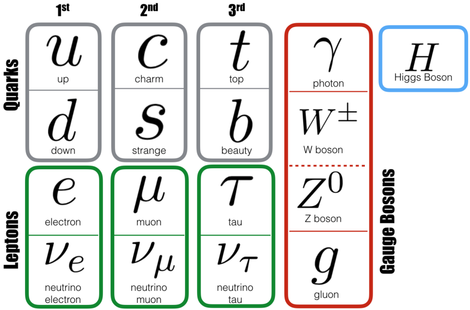
Standard Model

The Standard Model is a $SU(3) \times SU(2) \times U(1)$ gauge theory, which describes all the fundamental particles observed until now;



Scalar sector

The scalar sector of the SM contains one scalar doublet,

$$\Phi = \begin{pmatrix} \varphi^{+} \\ \varphi^{0} \end{pmatrix}. \tag{1}$$

The neutral field of the doublet acquires a Vacuum Expectation Value (VEV), $\langle 0|\, \varphi^0 \,|0\rangle = v$, which breaks the gauge group $SU(2) \times U(1)$ into $U(1)$.
The scalar doublet can be written as

$$\Phi = \begin{pmatrix} \xi^{+} \\ v + \frac{1}{\sqrt{2}}\left(H + i\xi^{0}\right) \end{pmatrix}. \tag{2}$$

Georgi-Machacek Model

There are some models that propose an extended Higgs sector.
One of them is the Georgi-Machacek (GM) model.
This model contains:

- one SM-like scalar doublet, $\begin{pmatrix} \varphi^+ \\ \varphi^0 \end{pmatrix}$;
- one scalar triplet, $\begin{pmatrix} \lambda^+ \\ \lambda^0 \\ -\lambda^- \end{pmatrix}$;
- one scalar triplet, $\begin{pmatrix} \xi^{++} \\ \xi^+ \\ \xi^0 \end{pmatrix}$.

The neutral fields acquire VEVs $\langle 0| \varphi^0 |0\rangle = a$,
$\langle 0| \lambda^0 |0\rangle = \langle 0| \xi^0 |0\rangle = b$.

Georgi-Machacek Model

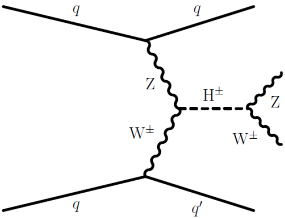
These scalars mix to form physical scalars. The physical scalars can be put in multiplets of a custodial $SU(2)$ symmetry

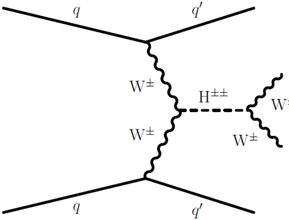
$$H_5 = \begin{pmatrix} H_5^{++} \\ H_5^{+} \\ H_5^{0} \\ H_5^{-} \\ H_5^{--} \end{pmatrix}, \quad H_3 = \begin{pmatrix} H_3^{+} \\ H_3^{0} \\ H_3^{-} \end{pmatrix}, \quad H_1, \quad H_1'.$$

Scalars in the same multiplet have the same mass.
The charged scalars $H_3^{\pm}$ have only fermionic couplings and are not considered in the paper.
The H_5 states are fermiophobic and are assumed to decay to vector boson pairs with branching fraction of 100%. Production and decays of these states depend on the mass of these scalars and on the parameter $s_H \equiv \frac{2b}{\sqrt{a^2+4b^2}}$.

Search for charged Higgs bosons

In the paper that I am presenting about, they report a search for charged Higgs bosons produced in vector boson fusion (VBF) processes and decaying into vector bosons, using proton-proton collisions at $\sqrt{s} = 13$ TeV at the CMS detector at the LHC.

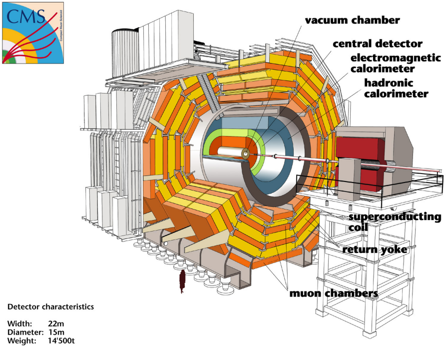




The searches for $H^\pm$ and $H^{\pm\pm}$ are performed in the leptonic decay modes $W^\pm Z \rightarrow \ell^\pm \nu \ell'^\pm \ell'^\mp$ and $W^\pm W^\pm \rightarrow \ell^\pm \nu \ell'^\pm \nu$, where $\ell, \ell' = e, \mu$.

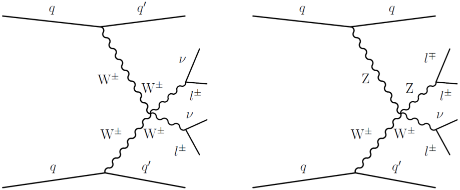
CMS Detector

The CMS detector has a superconducting solenoid of 6 m internal diameter, providing a magnetic field of 3.8 T. Within the solenoid volume are a silicon pixel and strip tracker, an electromagnetic calorimeter and a hadron calorimeter. Muons are detected in gas-ionization chambers embedded in the steel magnetic flux-return yoke outside the solenoid.

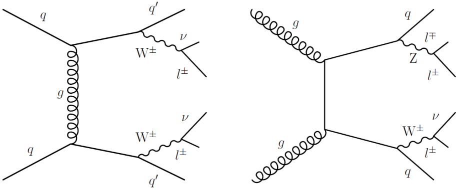


Background

Some of the processes that contibute to background are shown here



Processes of order $\mathcal{O}(\alpha^4)$



Processes of order $\mathcal{O}(\alpha^2 \alpha_S^2)$

Signal Regions

In this table are the selection requirements used to define the $W^{\pm}W^{\pm}$ and WZ signal regions (SRs).

Variable	$W^{\pm}W^{\pm}$	WZ
Leptons	2 leptons, $p_T > 25/20$ GeV	3 leptons, $p_T > 25/10/20$ GeV
p_T^j	$>50/30$ GeV	$>50/30$ GeV
$\lvert m_{\ell\ell} - m_Z \rvert$	>15 GeV (ee)	<15 GeV
$m_{\ell\ell}$	>20 GeV	—
$m_{\ell\ell\ell}$	—	>100 GeV
p_T^{miss}	>30 GeV	>30 GeV
b jet veto	Required	Required
τ_h veto	Required	Required
$\max(z_\ell^*)$	<0.75	<1.0
m_{jj}	>500 GeV	>500 GeV
$\lvert \Delta\eta_{jj} \rvert$	>2.5	>2.5

Control Regions

A combination of methods based on simulation and on control regions (CRs) in data was used to estimate background contributions.
Three control regions were used:

- **Nonprompt letpon CR:** same selection as for the $W^{\pm}W^{\pm}$ SR, but with the b jet veto requirement inverted.
- ***tZq* CR:** same selection as for the WZ SR, but with the b jet veto requirement inverted.
- ***ZZ* CR:** events with two opposite-sign same-flavor lepton pairs with the same VBS-like requirements.

Signal Extraction

A binned maximum-likelihood fit is performed using the $W^{\pm}W^{\pm}$ and WZ SRs, and the nonprompt lepton, tZq, and ZZ CRs to discriminate between the signal and the remaining backgrounds.

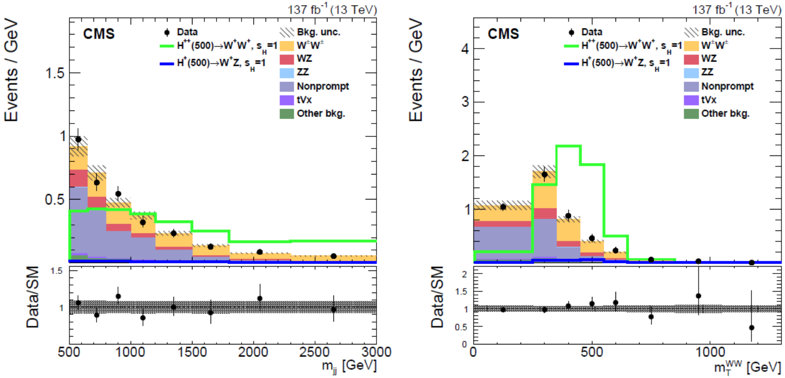
The diboson transverse mass is defined as

$$m_T^{VV} = \sqrt{\left(\sum_i E_i\right)^2 - \left(\sum_i p_{z,i}\right)^2}, \quad (3)$$

where E_i and $p_{z,i}$ are the energies and longitudinal components of the momenta of the leptons and neutrino system from the decay of the gauge bosons in the event.

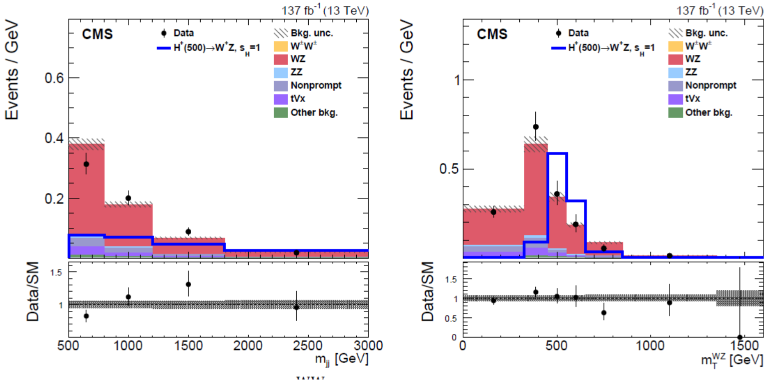
A two-dimensional distribution is used in the fit for the $W^{\pm}W^{\pm}$ SR with 8 bins in m_T^{VV} and 4 bins in m_{jj}. Similarly, a two-dimensional distribution is used in the fit for the WZ SR with 7 bins in m_T^{VV} and 2 bins in m_{jj}. The m_{jj} distribution is used for the CRs in the fit with 4 bins.

Results



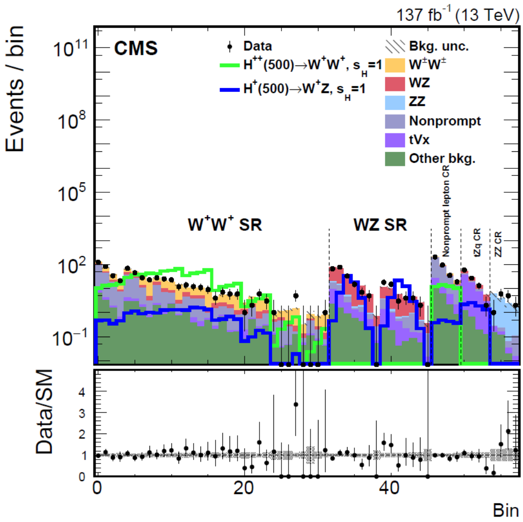
The m_{jj} (left) and m_T^{WW} (right) distributions in the WW SR for signal, backgrounds, and data.

Results



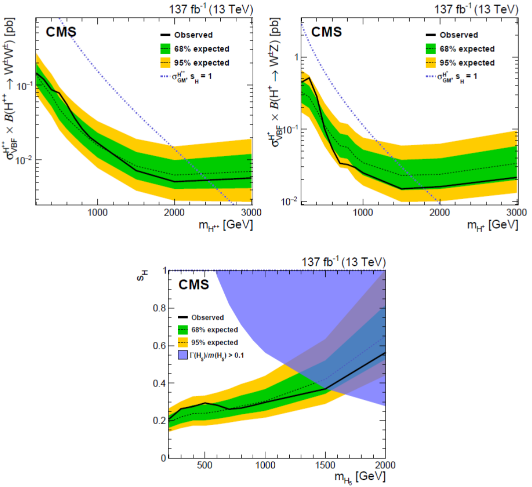
The m_{jj} (left) and m_T^{WZ} (right) distributions in the WZ SR for signal, backgrounds, and data.

Results



Distributions for signal, backgrounds, and data for the bins used in the simultaneous fit.

Results



Expected and observed exclusion limits at 95% CL for $\sigma_{VBF}(H^{\pm\pm})\mathcal{B}(H^{\pm\pm} \to W^{\pm}W^{\pm})$ as functions of $m_{H^{\pm\pm}}$ (upper left), for $\sigma_{VBF}(H^{\pm})\mathcal{B}(H^{\pm} \to WZ)$ as functions of $m_{H^{\pm}}$ (upper right), and for s_H as functions of m_{H_5} in the GM model (lower).