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 (Review)

Course on Physics at the LHC

17/06/2022

Nuno dos Santos Fernandes

TÉCNICO LISBOA

LABORATÓRIO DE INSTRUMENTAÇÃO E FÍSICA EXPERIMENTAL DE PARTÍCULAS

ATLAS EXPERIMENT

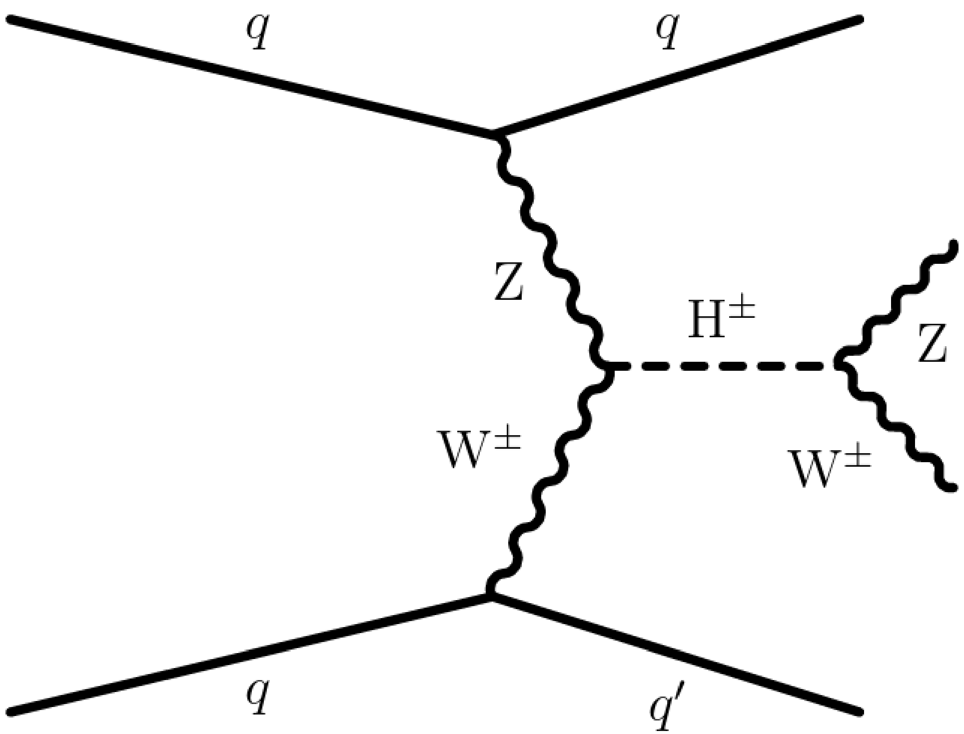
Purpose of the Study

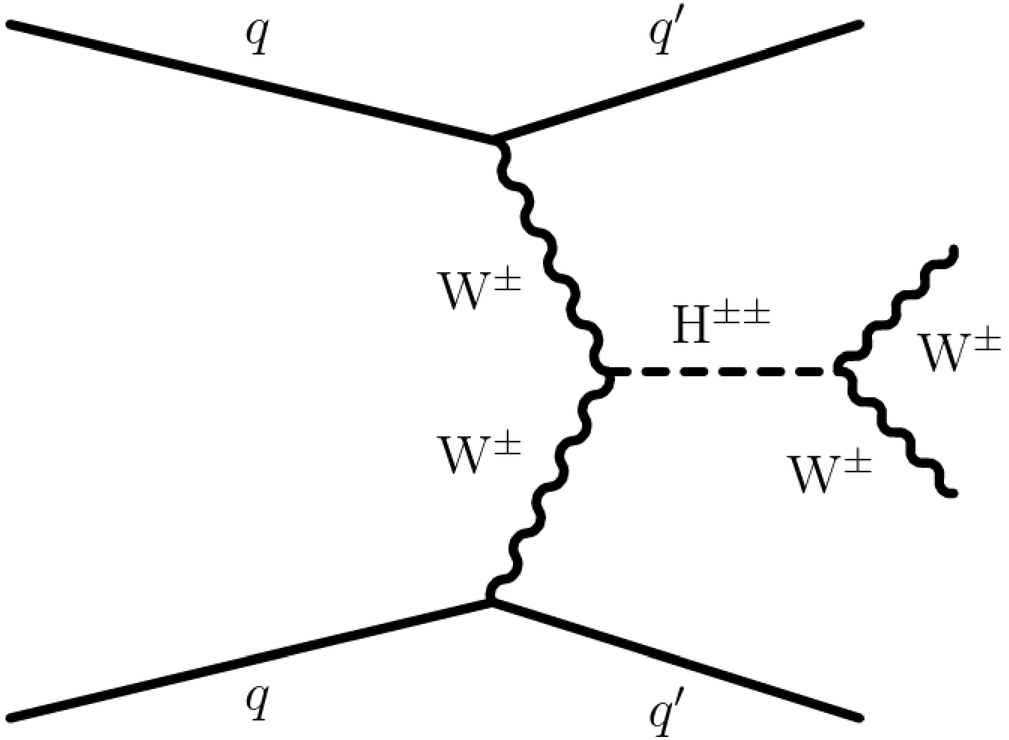
- Vector boson scattering can reveal possible physics beyond the Standard Model
- Extended Higgs sectors with additional SU(2) doublets or triplets have coupling of gauge bosons to Higgs(es)
- This can allow decays to vector boson pairs
- Finding an excess of vector boson scattering events in regards to the Standard Model can mean new resonances
- Lack of such events can constrain the parameters of the models
- This study focuses on the single and doubly charged Higgs of the Georgi-Machacek model

Georgi-Machacek Model

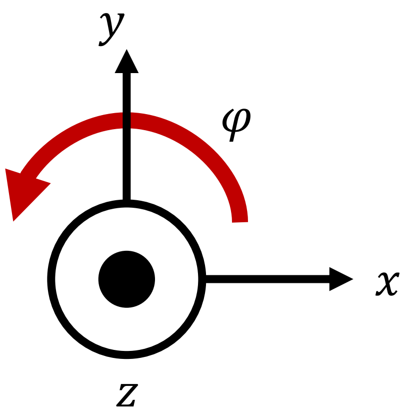
- Additional complex and real $SU(2)$ Higgs triplet (besides the SM doublet)
- Lagrangian invariant under $SU(2)_L \times SU(2)_R$
- Symmetry breaking due to the vacuum expectation values of the scalar fields
- Custodial symmetry under $SU(2)_V$ protects the W and Z mass ratio at tree level from radiative corrections
- Mass degenerate quintuplet (m_{H_5}) with singly and doubly charged Higgs ($H^{\pm}$ and $H^{\pm\pm}$)
- Production and decay depend on m_{H_5} and s_H (contribution of the additional triplets' vacuum expectation value to the Standard Model one)
- Quintuplet decays to vector boson pair with a branching ratio of 100% (singly charged to $W^{\pm}Z$, doubly charged to $W^{\pm}W^{\pm}$)
- There is also a triplet of singly charged Higgs, coupled to fermions, which will not be relevant for the study

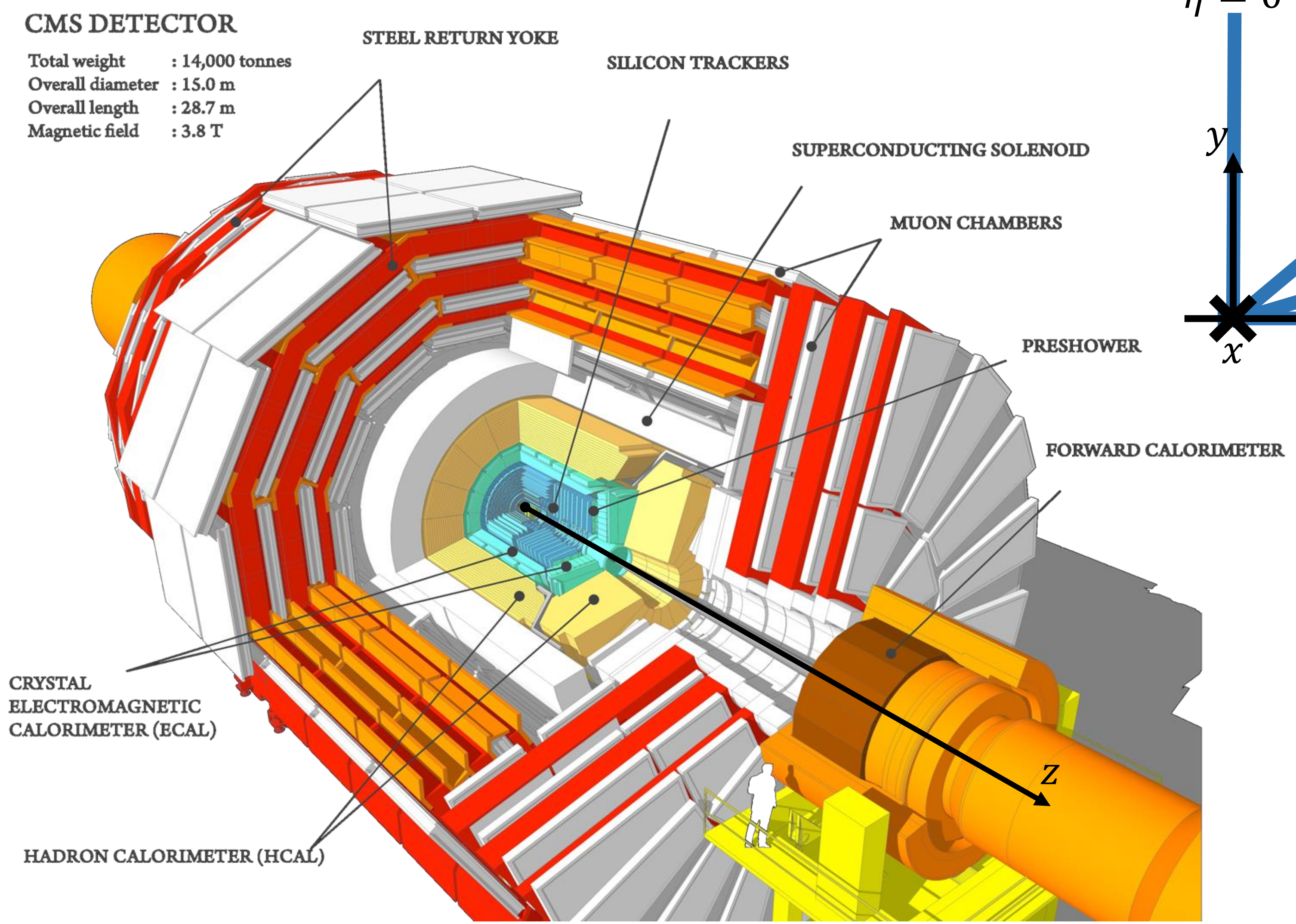
Georgi-Machacek Model

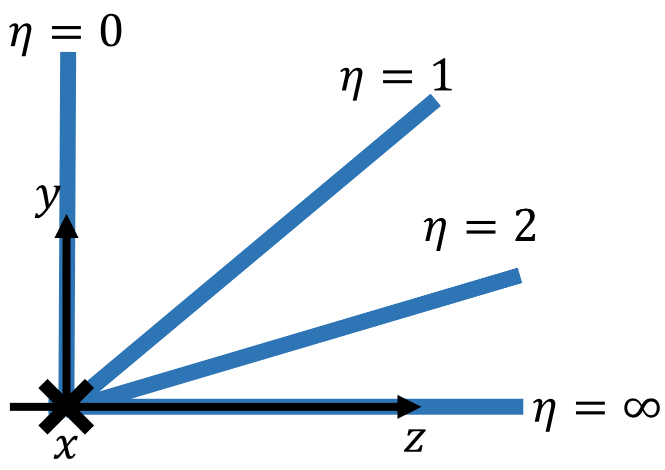




The CMS Detector







Source: Tai Sakuma and Thomas McCauley, “Detector and Event Visualization with SketchUp at the CMS Experiment”

The Data

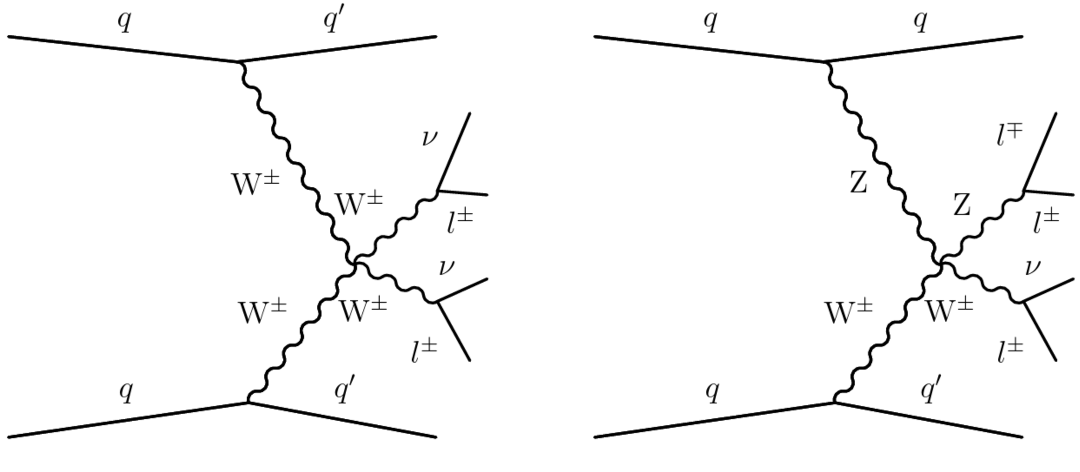
- Proton-proton collisions with $\sqrt{s} = 13$ TeV
- Three data sets from CMS, collected in 2016, 2017, 2018
- Data sets analysed independently, with separate calibrations and corrections
- Total integrated luminosity: $\mathcal{L} = 137 \pm 2\ \mathrm{fb}^{-1}$

The Background

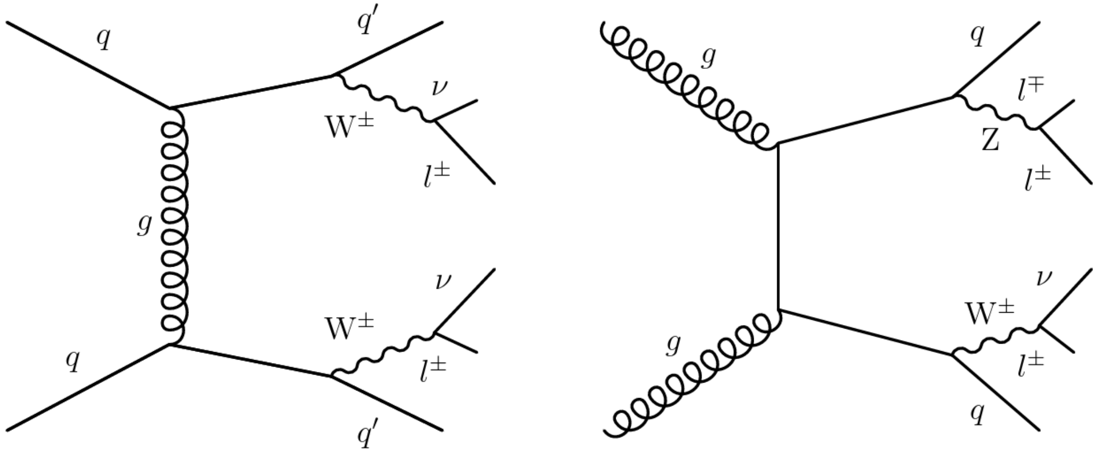
- Vector boson scattering has two gauge bosons, two jets with large η separation and large di-jet invariant mass

- Two main backgrounds:

Electro-weak di-boson production (tree-level $\mathcal{O}(\alpha^4)$)



QCD di-boson production (tree-level $\mathcal{O}(\alpha^2\alpha_s^2)$)



- Other processes: tZq, tW, $t\bar{t}$, $t\bar{t}Z$, $t\bar{t}\gamma$, triple vector boson (VVV), double parton scattering

Background Simulation

- Monte-Carlo with on-shell particles (separate simulations for each year)
- Charged Higgs from MADGRAPH at leading-order, cross sections at next-to-next-to-leading-order
- Backgrounds from MADGRAPH, POWHEG and PYTHIA
- Jet multiplicities are merged through the MLM algorithm
- Events are processed in a GEANT4 simulation of the CMS detector, including pile-up
- Events are then reconstructed with the same algorithms that will be used for data

Event Reconstruction

- Particle Flow algorithm combines tracker, calorimeter and muon information to reconstruct hadrons, photons, muons and electrons
- Jets are reconstructed through the anti-k_T algorithm, with corrections for pile-up and detector response
- Jet cuts at $p_T > 30$ GeV and $|\eta| < 4.7$
- Electons and muons are reconstructed through a combination of tracking and calorimeter clustering or muon.
- Lepton cuts at $p_T > 10$ GeV, $|\eta_e| < 2.5$ and $|\eta_\mu| < 2.4$
- Stricter criteria depending on the impact parameter in relation to primary vertex and isolation
- Electron charges are reconstructed through three different methods, whose results must agree, to prevent misidentification
- The DEEPCSV b-tagger is used to reject events with one jet consistent with a b quark fragmentation (and $p_T > 20$ GeV and $|\eta| < 2.4$)
- The Hadrons-Plus-Strips algorithm is used to reject events with at least one τ decaying (and $p_T > 18$ GeV and $|\eta| < 2.3$)

Event Selection

- Single electron trigger with $p_T > 27$ GeV, single muon $p_T > 24$ GeV. Di-lepton triggers with lower p_T.
- $W^{\pm}W^{\pm}$ and $W^{\pm}Z$ events are selected by requiring:
    - Exactly two isolated leptons with same charge or exactly three isolated charged leptons with $p_T > 10$ GeV
    - At least two jets with $|\eta| < 4.7$ and leading jet with $p_T > 50$ GeV
    - $\Delta R > 0.4$ between the jets and the selected eletrons/muons
- $W^{\pm}W^{\pm}$ requires a lepton with $p_T > 25$ GeV, other with $p_T > 20$ GeV; invariant mass of the pair greater than 20 GeV and more than 15 GeV away from m_Z
- $W^{\pm}Z$ requires a pair of same-flavoured leptons with opposite charges and $p_T > 25$ GeV, other with $p_T > 10$ GeV; invariant mass of the pair must be less than 15 GeV away from m_Z; if there are three same-flavoured leptons, the one that does not belong to the opposite signed pair with mass closest to m_Z must have $p_T > 20$ GeV; the total mass of the leptons must be greater than 100 GeV
- The two highest p_T jets must have a combined mass greater than 500 GeV and $|\Delta\eta_{jj}| > 2,5$
- Zeppenfeld Variable $z_l^* = |\eta_l - (\eta_{j1} - \eta_{j2})/2|/|\Delta\eta_{jj}|$ must be less than 0.75 ($W^{\pm}W^{\pm}$) or 1 ($W^{\pm}Z$)
- $p_T^{miss} > 30$ GeV

Background Estimation

- Select control regions by partially inverting the requirements for event selection
- Other estimation from simulation
- Events that pass the selection for $W^{\pm}W^{\pm}$ except for a looser criterion for one of the leptons allow estimation of the nonprompt lepton background. The efficiency for that loose selection is used to extrapolate the yield in the sample to the signal region.
- Control region for nonprompt leptons: $W^{\pm}W^{\pm}$ signal region except with the b-tagger being used to accept rather than reject
- Control region for tZq: $W^{\pm}Z$ signal region except with the b-tagger being used to accept rather than reject
- Control region for ZZ: events with lepton-antilepton pairs that otherwise respect all vector boson scattering requirements
- Control region for QCD: $W^{\pm}Z$ signal region except with a di-jet mass between 200 GeV and 500 GeV
- Electron sign mismeasurement estimated from simulation and comparison to $Z \longrightarrow e^{+}e^{-}$

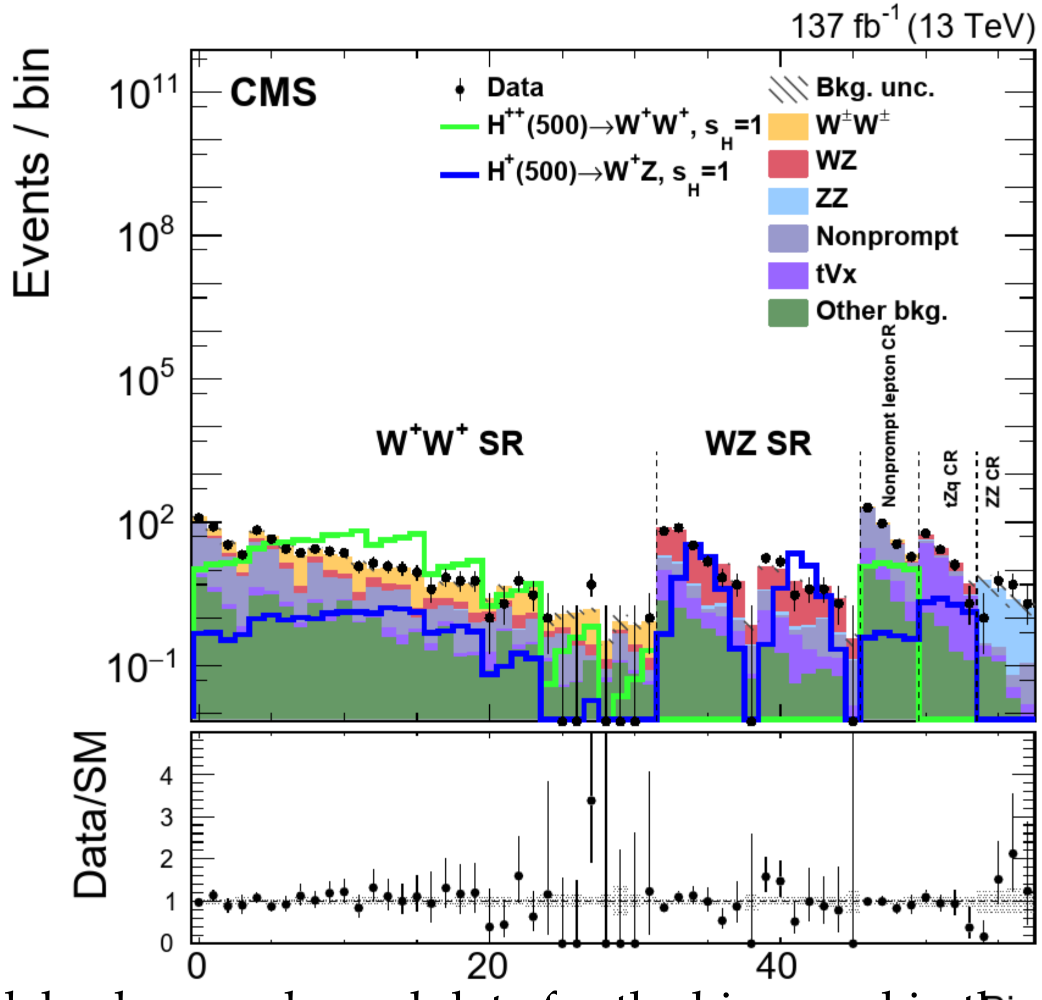
Signal Extraction

- Binned maximum-likelihood fit for the signal and control regions
- Signal strength and normalization factors for tZq and ZZ backgrounds are free parameters
- Contributions from the Standard Model also take into account interference contributions between EW and QCD
- Di-boson transverse mass: $m_T^{VV} = \sqrt{\left(\sum_i E_i\right)^2 - \left(\sum_i p_{z,i}\right)^2}$ with i iterating over the leptons and neutrinos from the decay of the gauge bosons in the event; distinguishes resonant signal and non-resonant background
- The di-jet mass, m_{jj}, distinguishes between events that are not vector boson scattering and the signal and vector-vector electro-weak background due to the latter having large masses
- Fit done in a distribution binned in intervals of m_T^{VV} and m_{jj}
- Systematic uncertainties are used as nuisance parameters in a profile likelihood technique
- Normalization uncertainties are log-normal nuisance parameters
- Uncertainties in the shape of the distributions are nuisance parameters with external Gaussian constraints
- Dominant nuisance parameters are not significanly constrained by data due to normalized nuisance parameters being close to 1

Systematic Uncertainties

Source of uncertainty	$\Delta\mu$ background-only	$\Delta\mu$ $s_{\mathrm{H}} = 1.0$ and $m_{\mathrm{H}_5} = 500\,\mathrm{GeV}$
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
$\mathrm{W}^{\pm}\mathrm{W}^{\pm}/\mathrm{WZ}$ rate	0.014	0.015
Other prompt background rate	0.002	0.015
Signal rate	—	0.064
Limited 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

Results



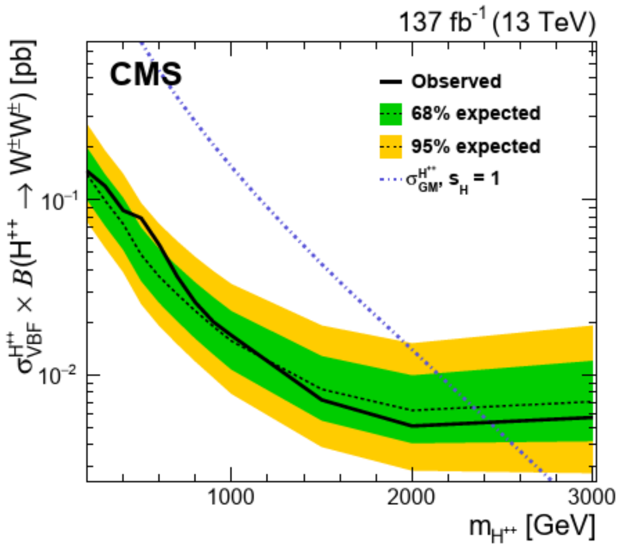
Distributions for signal, backgrounds, and data for the bins used in the simultaneous fit

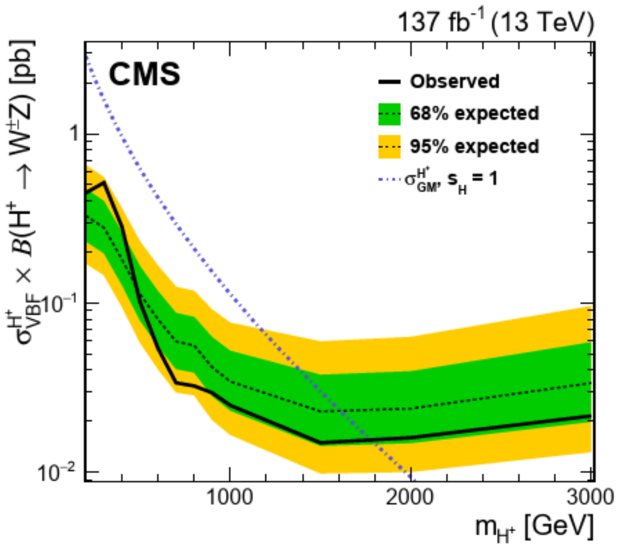
Results

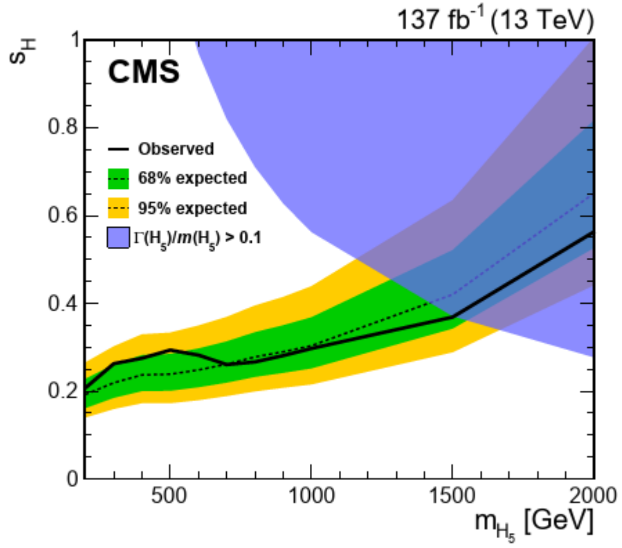
Process	WW SR	WZ SR	Nonprompt CR	tZq CR	ZZ CR
$H^{\pm\pm}(500) \to W^{\pm}W^{\pm}$	666 ± 68	—	48.9 ± 5.1	—	—
$H^{\pm}(500) \to WZ$	19.2 ± 2.4	107 ± 11	1.7 ± 0.2	8.0 ± 0.9	—
$W^{\pm}W^{\pm}$	230 ± 16	—	28.2 ± 1.8	—	—
WZ	67.8 ± 5.8	196 ± 15	10.3 ± 1.0	27.2 ± 2.4	—
ZZ	0.7 ± 0.2	6.4 ± 2.0	0.1 ± 0.1	1.1 ± 0.3	13.3 ± 4.0
Nonprompt	262 ± 36	22.3 ± 7.7	263 ± 21	8.4 ± 3.1	0.2 ± 0.2
tVx	8.4 ± 1.9	17.7 ± 3.3	28.8 ± 5.6	62 ± 11	0.2 ± 0.1
Other background	31.1 ± 7.3	6.8 ± 1.4	21.1 ± 4.2	2.2 ± 0.4	0.3 ± 0.1
Total background	600 ± 40	249 ± 18	352 ± 22	101 ± 12	14.0 ± 4.0
Data	602	249	352	101	14

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

Results







Values above the curves are excluded.

Conclusions

- No excess of events with respect to the Standard Model prediction is observed.

- Limits for the Georgi-Machacek model: 95% confidence level limits exclude $s_H > 0.2{\sim}0.35$ for $200\ \mathrm{GeV}\ \leq m_{H_5} \leq 1500\ \mathrm{GeV}$

Thank you for your attention!