LABORATÓRIO DE INSTRUMENTAÇÃO
E FÍSICA EXPERIMENTAL DE PARTÍCULAS
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CMS
Compact Muon Solenoid

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

https://arxiv.org/abs/2104.04762

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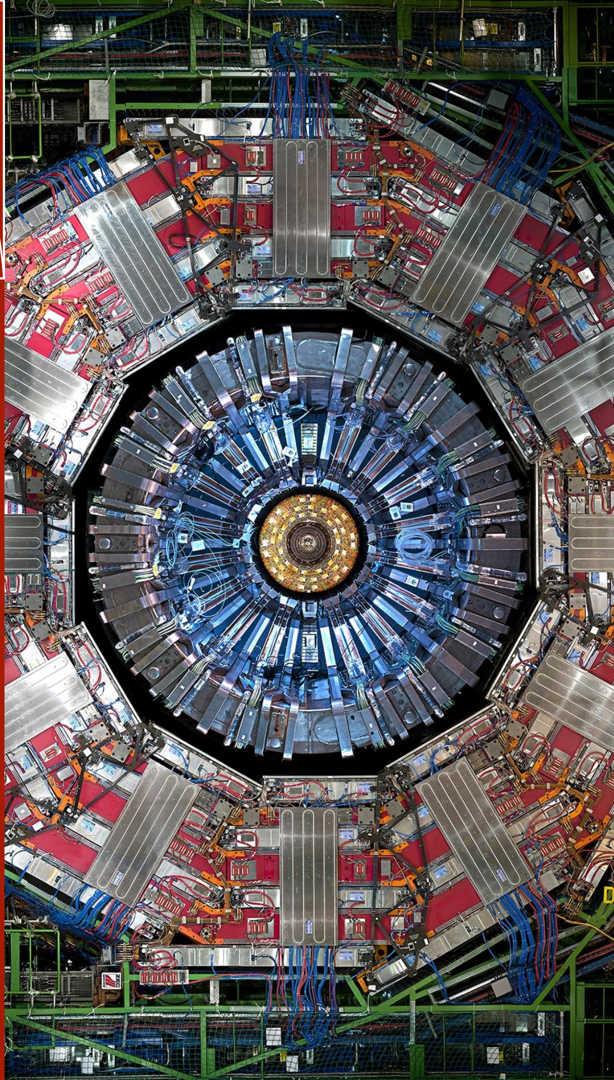

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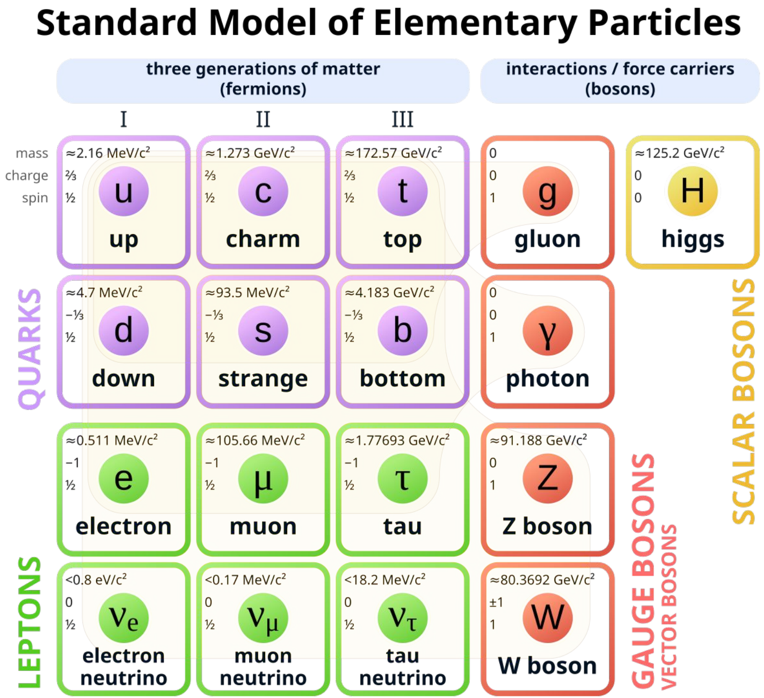
Introduction

- Higgs bosons was introduced in 1964 by P. HIGGS, F. ENGLERT, R. BROUT to enable electroweak symmetry breaking, providing mass to the W and Z bosons and to fermions

- In 2012 the Higgs bosons was discovered by the ATLAS and CMS experiments at the Large Hadron Collider (LHC)

- Completed the particle content of the Standard Model



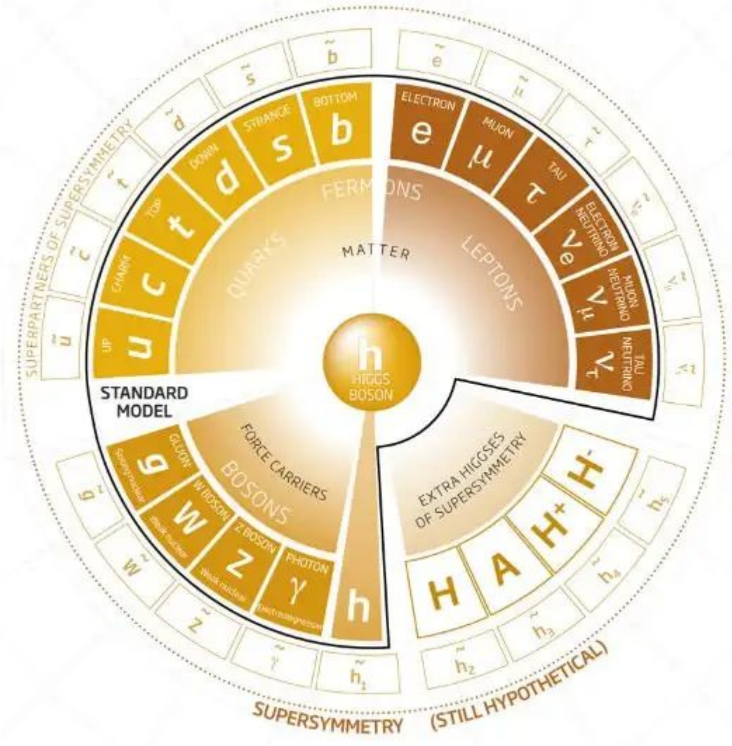
The Standard Model is a successful theory that accurately describes many phenomena, yet it still has limitations and unresolved questions.

- Why do neutrinos have mass?
- What is dark matter?
- Why there is a matter-antimatter asymmetry ?
- Why is the expansion of the universe accelerating?
- Is there a boson associated with the gravity force ?
- ...

Beyond standard model theory

- **SuperSymmetry principle**
  - **The Georgi–Machacek (GM) model** extends the Higgs sector by introducing scalar triplets, which predict additional Higgs bosons:
    - **singly charged (H±)** and **doubly charged (H±±)** called H5 that decay to boson exclusively.
    - Additional charged Higgs bosons H± predicted in the GM model only have fermonic decay and are not considered in this study

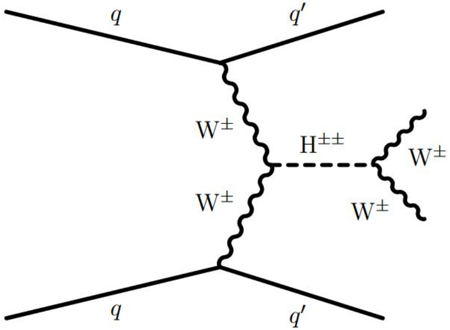
- A good way to look at this windows is through **VBS study**
  - VBF directly probes the coupling between vector bosons (W/Z) and scalars.
    - Charged Higgs bosons in the GM model can into boson pairs making VBF the ideal channel to study them.
      - **H±→W±Z**
      - **H±±→W±W±**



Signals

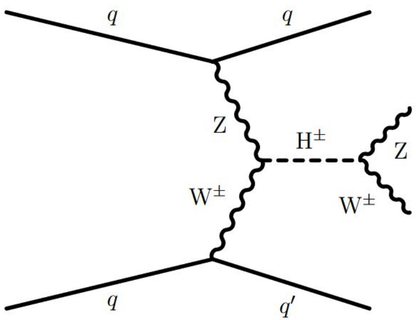
Candidate events contain either two identified leptons of the same charge or three identified charged leptons with the total charge of ±1, moderate missing transverse momentum (pmiss T), and two jets with large values of |Δηjj| and mjj

$$W^{\pm}W^{\pm} \rightarrow \ell^{\pm}\nu\ell'^{\pm}\nu$$



where $\ell, \ell' = e, \mu$

$$W^{\pm}Z \rightarrow \ell^{\pm}\nu\ell'^{\pm}\ell'^{\mp}$$



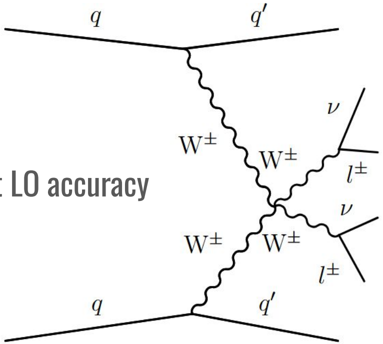
Final state :

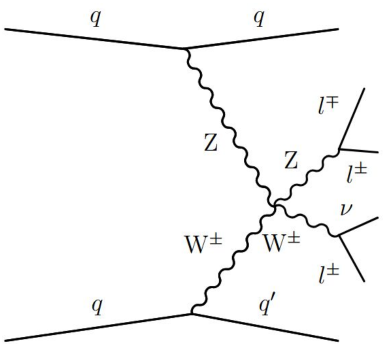
- **Two gauge bosons**
- **Two forward jets with a large pseudorapidity separation (|Δηjj|) and a large dijet invariant mass (mjj)**

The signal is simulated using MADGRAPH5 aMC@NLO 2.4.2 at leading order (LO) accuracy. The predicted signal cross sections are taken at next-to-next-to-LO (NNLO) accuracy from the GM model

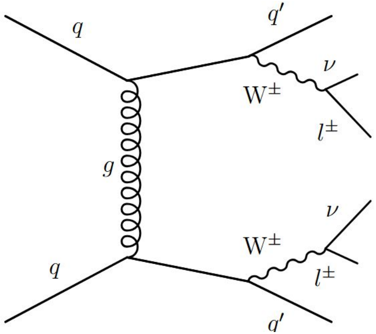
EW-induced

simulated using MADGRAPH5 aMC@NLO at LO accuracy with six EW (O(α6)) and zero QCD vertices

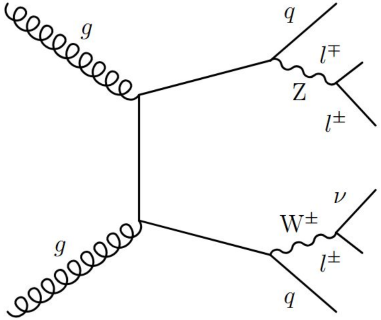




QCD-induced



Simulated using MADGRAPH5 aMC@NLO at LO accuracy with four EW and two QCD vertices.

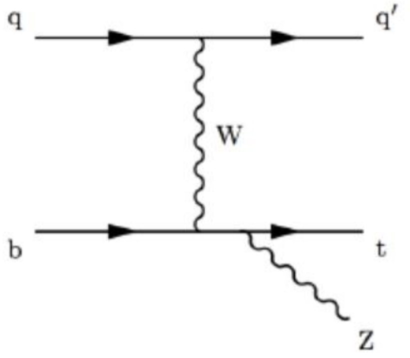


simulated at LO using the MADGRAPH5 aMC@NLO generator with at least one QCD vertex at tree level.

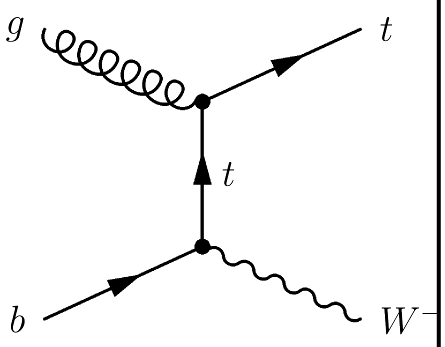
The interference between the EW and QCD diagrams is also accounted for with MADGRAPH5 aMC@NLO.

Additional backgrounds

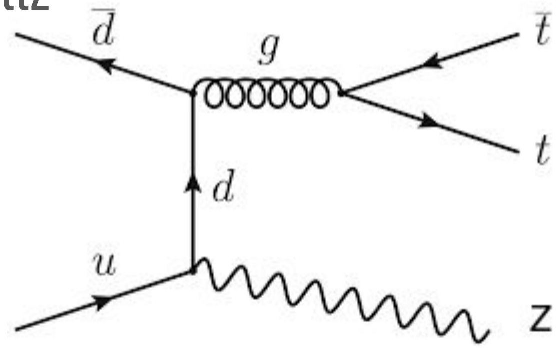
tZq



tW



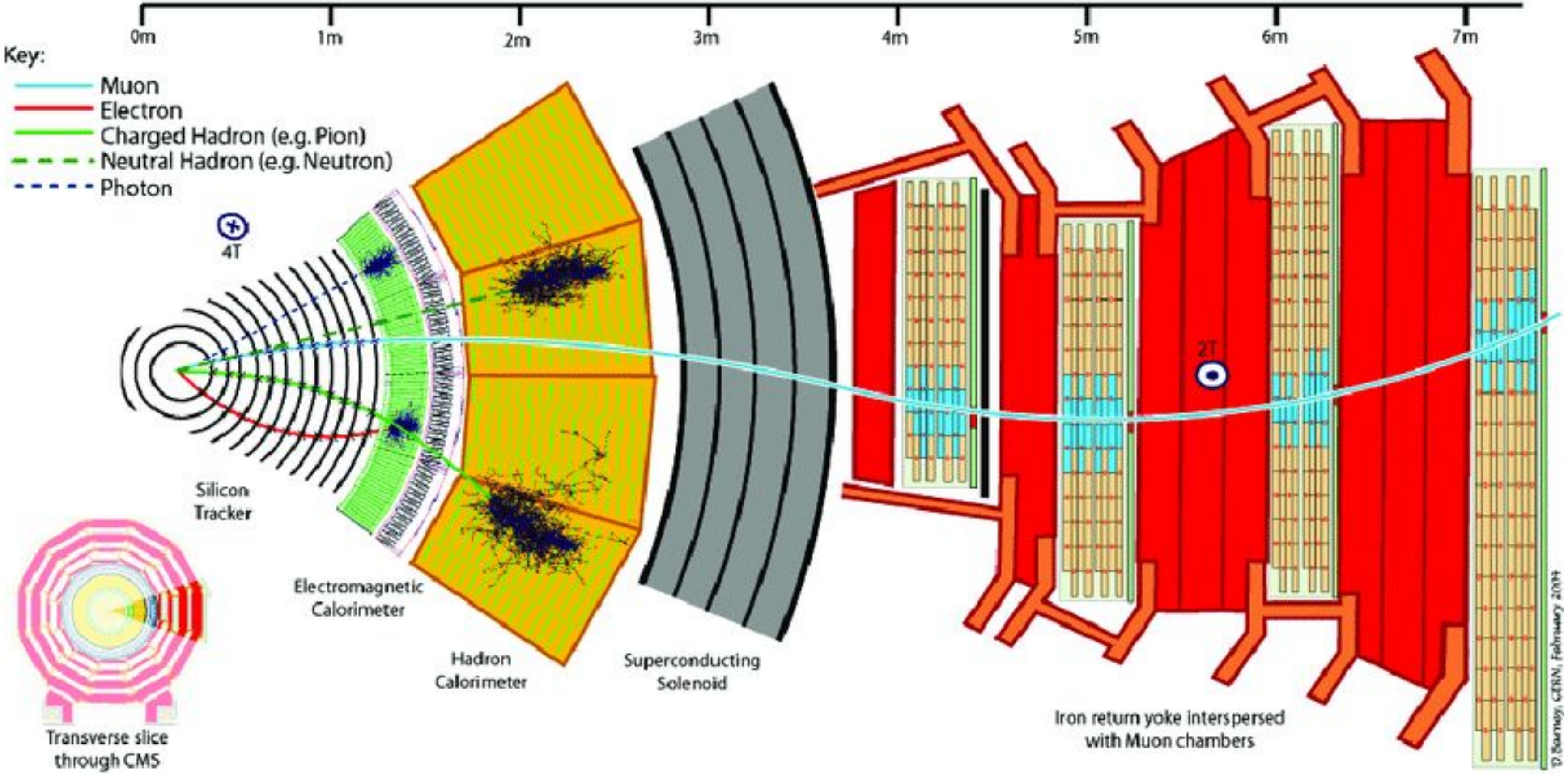
ttZ



ttW, ttγ, VVV, ZZ,...

- tt, tW, ZZ : POWHEG generator
- tZq, ttW, ttZ, tt γ, and VVV : MADGRAPH5 at NLO accuracy in QCD

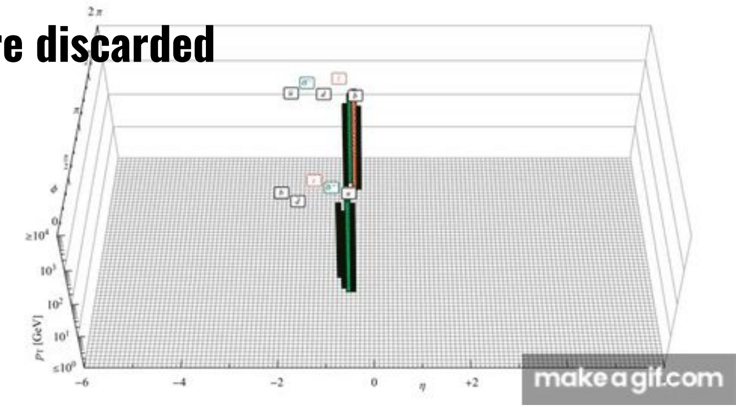
CMS detector



- **Particle-flow (PF) algorithm :**
  - Combine information from the tracker, calorimeters, and muon systems
  - Reconstruct and identify charged and neutral hadrons, photons, muons, and electrons.

- **Jets are reconstructed by clustering PF candidates using the anti-kT algorithm**
  - Jet energy corrections are derived from simulation studies so that the average measured energy of jets becomes identical to that of particle level jets.
  - Jets with transverse momentum pT > 30 GeV and $|\eta| < 4.7$ are included in the analysis.

- **Tracks identified to be originating from pileup vertices are discarded**



Events reconstruction and selection

- **Trigger Strategy**
  - Use single-lepton triggers (e/mu) and dilepton triggers with lower thresholds to maximize efficiency (>99%).

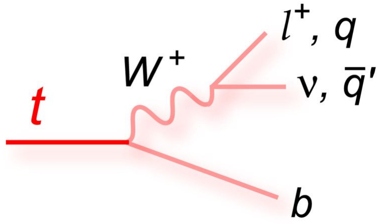
- **Lepton selection**
  - Require isolated electrons/muons to reduce contamination from nonprompt leptons.
  - Leading lepton pT thresholds:
    - Electrons: > 27 GeV (trigger)
    - Muons: > 24 GeV (trigger)

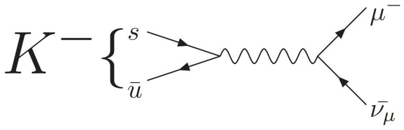
- **b jet and Tau Veto**
  - <u>b-jet veto:</u> Reject events with ≥1 jet (pT > 20 GeV, $|\eta| < 2.4$) tagged as bottom quark using DEEPCSV algorithm to suppresses top quark backgrounds.
  - <u>τh veto:</u> Reject events with ≥1 hadronic τ decay (τh) with pT > 18 GeV and $|\eta| < 2.3$, reconstructed via hadrons-plus-strips to reduces diboson backgrounds.
- **Missing Transverse Momentum**
  - Require pTmiss > 30 GeV to capture neutrinos from W/Z decays.

Summary of the selection requirements

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

- Nonprompt Leptons (fake leptons)
  - Source: heavy-flavor decays, misidentified hadrons, photon conversions.
    - One lepton passes a loose ID, the other passes tight.
    - Efficiency to pass tight selection measured in dijet-enriched samples.
    - ~20% uncertainty included due to sample composition.





- The nonpromptlepton CR is defined by requiring the same selection as for the W±W± SR, but with the b jet veto requirement inverted.

Background estimation

- Electron sign mismeasurement
  - Estimated from simulation, corrected using $Z \to ee$ data.
  - Mismeasurement rate:
    - Barrel: ~0.01%
    - Endcap: up to 0.3%

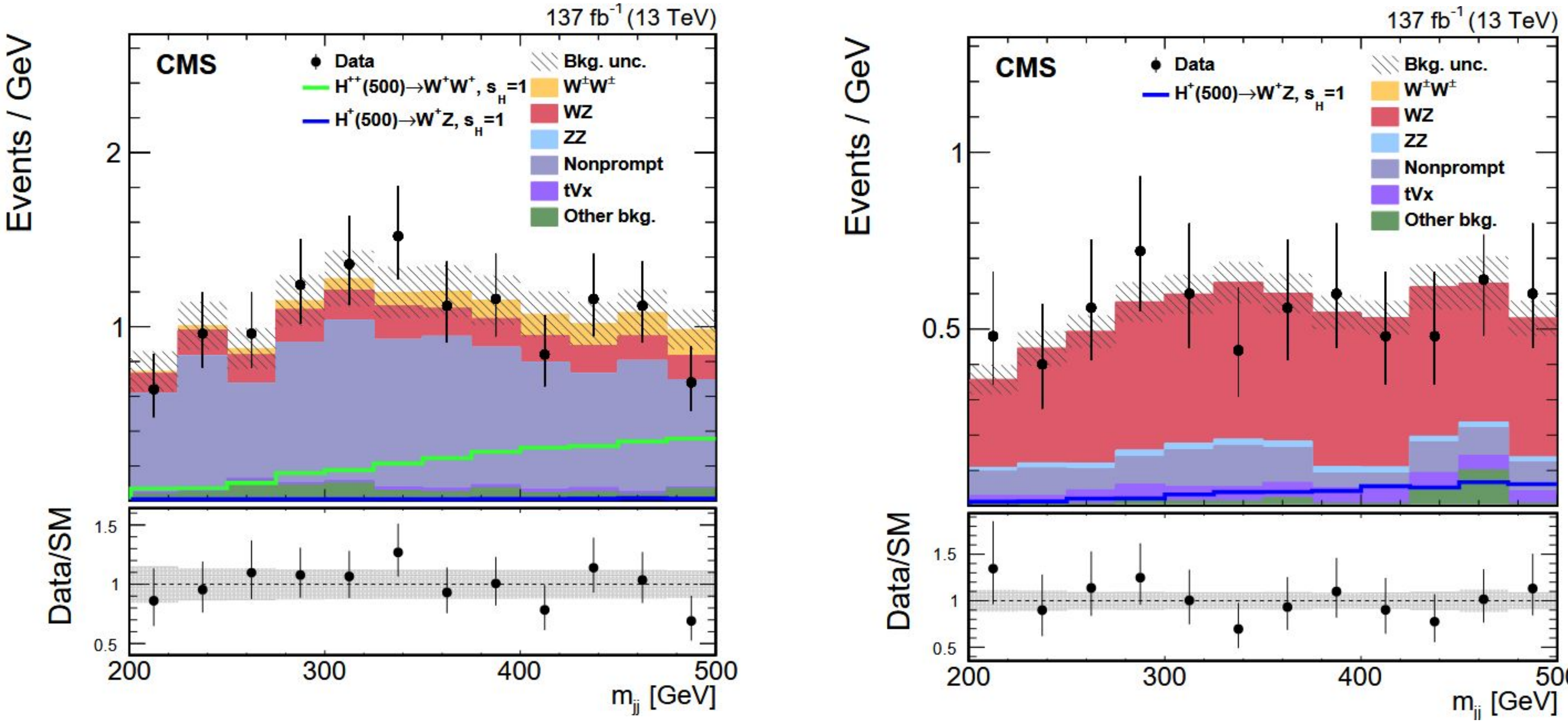
- tZq, ZZ, ttV, tribosons, QCD WZ/WW, etc.
  - The tZq CR is defined by requiring the same selection as for the WZ SR, but with the b jet veto requirement inverted. The selected events are dominated by the tZq background process.
  - The ZZ CR selects events with two opposite-sign same-flavor lepton pairs with the same VBS-like requirements
  - Shapes of the tZq and ZZ background processes : from simulation
  - Normalization of tZq, and ZZ background processes : from the data.
  - QCD WZ/WW, tribosons are estimated from simulation

Signal extraction

- Use binned maximum likelihood fit over multiple regions:
  - Signal Regions : W±W± and WZ
  - Control Regions : tZq, ZZ, nonprompt leptons

- Variables
  - W±W± channel:
    - Use mjj (dijet mass) and mT (transverse mass of lepton + pTmiss)
  - WZ channel:
    - Use mT(WZ) of the WZ system (3-lepton + pTmiss)

The mjj distributions after requiring the same selection as for the WW (left) and WZ (right) SRs, but with a requirement of **200 < mjj < 500 GeV**

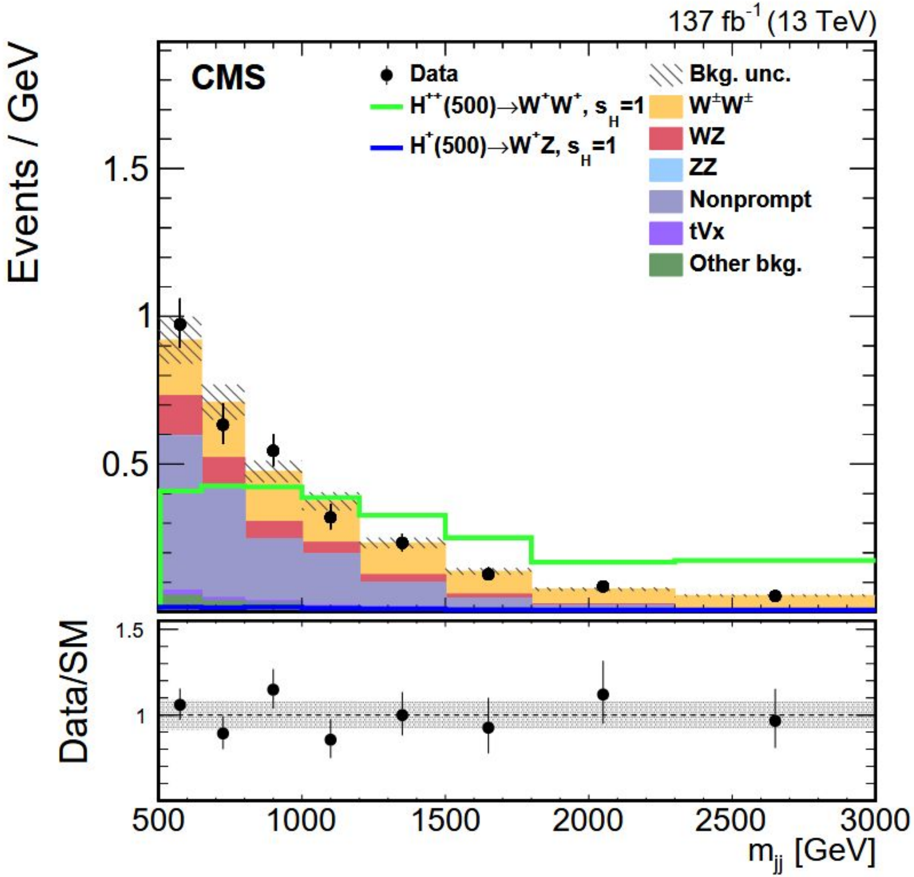


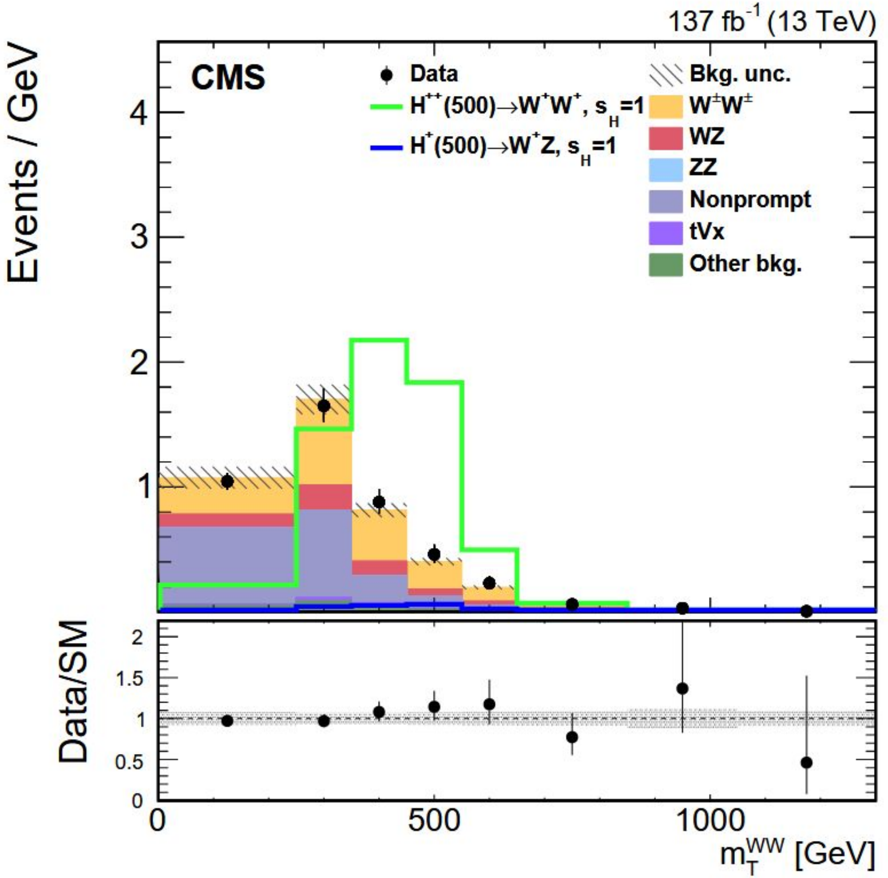
Systematic uncertainties

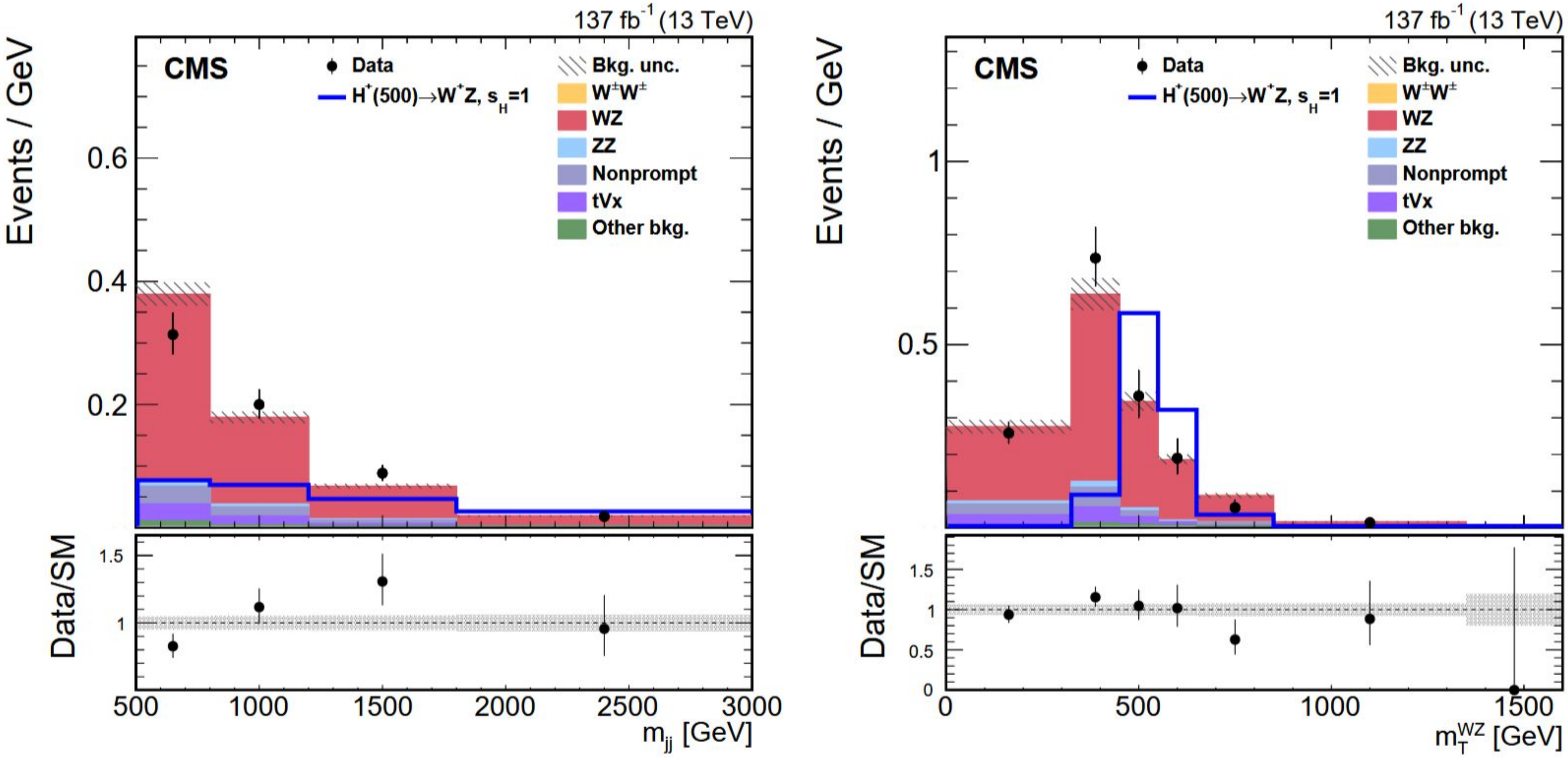
- Experimental
  - Integrated luminosity: ±1.8%
  - Pileup modeling
  - Jet energy scale/resolution, lepton ID, b-tagging, τ_h veto
  - Trigger efficiency uncertainties
- Theoretical
  - PDF and scale variations (μ_R, μ_F)
  - Electroweak corrections to VBF
  - Signal modeling: QCD scale, PDF, parton showering
- Simulation
  - Nonprompt lepton fake rate: ±20%
  - Charge mis-ID corrections

Systematic uncertainties

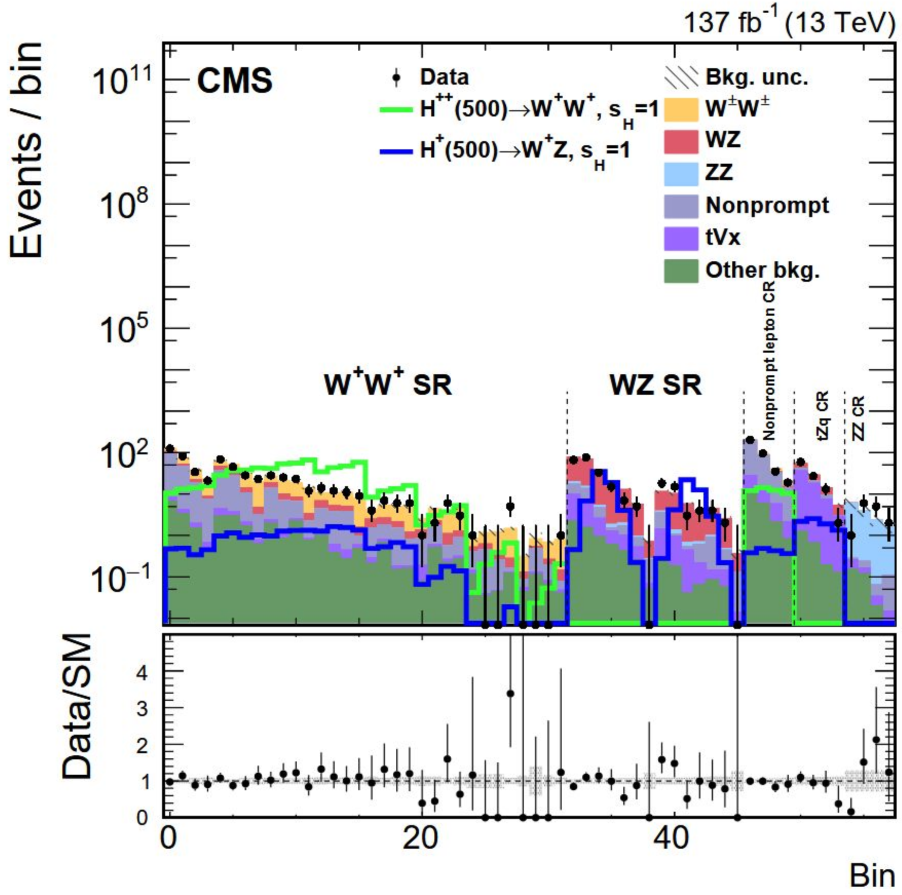
Source of uncertainty	$\Delta\mu$ background-only	$\Delta\mu$ $s_H = 1.0$ and $m_{H_5} = 500\,GeV$
Integrated luminosity	0.002	0.019
Pileup	0.001	0.001
Lepton measurement	0.003	0.033
Trigger	0.001	0.007
JES and JER	0.003	0.006
b tagging	0.001	0.006
Nonprompt rate	0.002	0.002
$W^{\pm}W^{\pm}/WZ$ rate	0.014	0.015
Other prompt background rate	0.002	0.015
Signal rate	—	0.064
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


137 fb^{-1} (13 TeV)
CMS
Data
$H^{++}(500)\rightarrow W^+W^+$, s_H=1
$H^+(500)\rightarrow W^+Z$, s_H=1
Bkg. unc.
$W^\pm W^\pm$
WZ
ZZ
Nonprompt
tVx
Other bkg.
Events / GeV
Data/SM
m_{jj} [GeV]


137 fb^{-1} (13 TeV)
CMS
Data
$H^{++}(500)\rightarrow W^+W^+$, s_H=1
$H^+(500)\rightarrow W^+Z$, s_H=1
Bkg. unc.
$W^\pm W^\pm$
WZ
ZZ
Nonprompt
tVx
Other bkg.
Events / GeV
Data/SM
m_T^{WW} [GeV]


137 fb-1 (13 TeV)
CMS
Data
H+(500)→W+Z, sH=1
Bkg. unc.
W±W±
WZ
ZZ
Nonprompt
tVx
Other bkg.
Events / GeV
Data/SM
mjj [GeV]
137 fb-1 (13 TeV)
CMS
Data
H+(500)→W+Z, sH=1
Bkg. unc.
W±W±
WZ
ZZ
Nonprompt
tVx
Other bkg.
Events / GeV
Data/SM
mTWZ [GeV]

Results



The bins 1–32 (4×8) show the events in the WW SR (mjj × mT), the bins 33–46 (2×7) show the events in the WZ SR (mjj × mT), the 4 bins 47–50 show the events in the nonprompt lepton CR(mjj), the 4 bins 51–54 show the events in the tZq CR (mjj), and the 4 bins 55–58 show the events in the ZZ CR (mjj).

Conclusion

- 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 decaying into vector bosons as a function of mass from 200 to 3000 GeV.
- The observed 95% confidence level limits exclude GM sH parameter values greater than 0.20–0.35 for the mass range from 200 to 1500 GeV.

Thanks for your attention