Searches for charged Higgs bosons at CMS

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for CMS experiment

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Beyond the SM Higgs sector

- Theoretical motivation for an extended Higgs sector is broad: coupling constant unification, CP violation, neutrino masses, hierarchy problem…

- Charged Higgs bosons \( (H^+) \) appear in many extensions → **sign of BSM physics**
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### Doublet models

- Add another doublet → **two Higgs-Doublet Models** (2HDM)
  - 5 scalar bosons: $h$, $H$, $A$, $H^+$, $H^-$
  - Classes of models (no FCNCs):

#### Type I (Fermiophobic)  Type II (MSSM-like)

\[
\Phi_1^d \Phi_2^u \\
\Phi_1^e \Phi_2^d
\]

#### Type X (Lepton-specific)  Type Y (Flipped)

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### Triplet models
- Addition of scalar triplet(s)
  - **Georgi-Machacek model:**
    - add one real and one complex \( SU(2) \) triplet
  - \( H^+ \) phenomenology different from the doublet models
  - **\( H^+WZ \) couplings** at tree level
  - Double-charged Higgs bosons \( H^{++} \)
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Experimental signatures for $H^+$

- $H^+$ production and decay are **model-dependent**
  - Different searches constrain different scenarios

![Graph showing BR as a function of $M_{H^+}$ for different decay modes and models]
H\(^+\) production and decay are model-dependent → Different searches constrain different scenarios
Experimental signatures for $H^+$

- $H^+$ production and decay are model-dependent.
  - Different searches constrain different scenarios.

*Type II (MSSM)*

$H^+ \rightarrow tb$

$H^+ \rightarrow \tau\nu$

$H^+ \rightarrow cs$

$H^+ \rightarrow \mu\nu$

$H^+ \rightarrow \nu\tau$

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$H^+ \rightarrow \nu\tau$

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Overview

Doublet models                  Triplet models

Run 1 legacy

Early Run 2

Recent results

\( H^+ \rightarrow \text{cs} \)

\( H^+ \rightarrow \text{cb} \)

\( H^+ \rightarrow \text{tb} \)

\( H^+ \rightarrow \text{τυ} \)

\( H^{++} \rightarrow \text{WW} \)

\( H^+ \rightarrow \text{WZ} \)

3VOMFHBDZ

&BSMZ3VO

3FDFOUSFTVMUT

%PVCMFUNPEFMT

5SJQMFUNPEFMT
Run 1 legacy

- Run 1 was fruitful in terms of $H^+$ results - some examples here
- Many exclusion limits still competitive
- **Model-independent limits** can be interpreted as constraints on parameter spaces of **specific scenarios**

### $H^+ \to cs$

**HIG-13-035**

*CMS* 19.7 fb$^{-1}$ (8 TeV)

- Observed
- Expected
- $t \to H^+b, H^+ \to cs$
- $B(H^+ \to cs) = 100\%$
- $95\%$ CL limit on $B(t \to H^+b)$

### $H^+ \to cb$

**HIG-16-030**

*CMS* Preliminary

- Combined $e+\mu$ channels
- $95\%$ CL limit on $\sigma(H^\pm)$

### $H^+ \to tb$

**HIG-14-023**

*CMS* $pp \to (t\bar{t})H^+, H^+ \to t\bar{b}$

- $l+\text{jets, } \tau\nu_{\tau}, ll$ final states
- Assuming $B(H^+ \to t\bar{b}) = 1$
- $95\%$ CL limit on $\sigma_{H^\pm}$ [pb]
Run 1 legacy

- Run 1 was fruitful in terms of $H^+$ results - some examples here
- Many exclusion limits still competitive
- Model-independent limits can be interpreted as constraints on parameter spaces of specific scenarios

Work on Run 2 dataset continues with improved analysis methods
- Decreasing stat. uncertainties require good control of systematic effects
Reconstruct the $\tau\nu$ transverse mass in the fully hadronic final state:

$$m_T = \sqrt{2p_T^{\tau_h} E_T^{\text{miss}} (1 - \cos(\Delta\phi(E_T^{\text{miss}}, \tau_h)))}$$
Reconstruct the $\tau\nu$ transverse mass in the fully hadronic final state:

$$m_T = \sqrt{2p_T^{\tau_h} E_{T\text{miss}}^h (1 - \cos(\Delta\phi(E_{T\text{miss}}^h, \tau_h)))}$$

Extract 95\% CL limits by binned ML fit.
Triplet models: \( H^+ \rightarrow WZ \)

**VBF \( H^+ \) production predicted by Georgi Machacek model**

**Event selection**
- **Z**: \( l^+l^- \) pair: \( p_T > 25 \text{ GeV} \) (15 GeV), \( |m_{l^-l^+}-m_Z| < 15 \text{ GeV} \)
- **W**: 3rd lepton \( l' \), \( p_T > 20 \text{ GeV} \) and \( p_T^{\text{miss}} > 30 \text{ GeV} \)
- **Two AK4 jets**: \( p_T > 30 \text{ GeV}, |\eta|<4.7, \Delta R_{j,i}>0.4, m_{jj} > 500 \text{ GeV}, \Delta \eta_{j1,j2}>2.5, \)
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**Additional selections to suppress backgrounds**
- 4th lepton veto (\( p_T > 10 \text{ GeV} \))
- b jet veto (\( p_T > 30 \text{ GeV}, |\eta|<4.7 \)) against \( t\bar{t} \)
- \( m_{\ell\ell} > 4 \text{ GeV} \) (for all lepton pairs), against coll. emission and low-\( m_{\ell\ell} \) resonances
- \( m_{3\ell} > 100 \text{ GeV} \) against Z+FSR

Irreducible backgrounds: SM WZjj
Reconstruct WZ transverse mass \( m_T^2(WZ) = (E_T(W) + E_T(Z))^2 - (\vec{p}_T(W) + \vec{p}_T(Z))^2 \) → ML fit to extract limits on \( H^+ \) production cross section

\[
m_T^2(WZ) = (E_T(W) + E_T(Z))^2 - (\vec{p}_T(W) + \vec{p}_T(Z))^2
\]

Background estimation

- Prompt lepton backgrounds (EW/QCD WZjj, top, VV, Zγ) estimated from simulation
- QCD WZjj: normalization from a control region (mjj > 100 GeV and invert mjj or Δη₁,₂ cut)
- Nonprompt lepton background estimated from data

Limits also set on anomalous quartic gauge couplings in terms of effective field theory (EFT) operators.
95% upper limits on $\sigma_{VBF} \times B(H^+ \rightarrow WZ)$ extracted using CL$_S$ criterion

- $H^+$ assumed to have a **narrow intrinsic width**

- Limits interpreted in **Georgi-Machacek model**, as a function of $m_{H^+}$ and $s_H$
  - $s_H^2$ is the W/Z mass fraction generated by VEV of the triplets

- **Blue region** not allowed theoretically
**Triplet models:** $H^{++} \rightarrow WW$

**VBF $H^{++}$ production predicted by Georgi Machacek model**

**Event selection**

- Two isolated same-sign leptons
- $p_T > 25$ GeV or $p_T > 20$ GeV
- $|\eta| < 2.5$ (2.4) for electrons (muons)
- $p_T^{\text{miss}} > 40$ GeV
- Two AK4 jets ($p_T > 30$ GeV, $|\eta| < 5$) and $m_{jj} > 500$ GeV
- $\max(z^*_i) < 0.75$, $z^*_i = |\eta_j-(\eta_{j1}+\eta_{j2})/2|/|\Delta\eta_{j1j2}|$

**Irreducible background:**
SM $W^+W^+$ production
VBF $H^{++}$ production predicted by Georgi Machacek model

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- $\max(z_i^*) < 0.75$, $z_i^* = |\eta_{i-}(\eta_{j1} + \eta_{j2})|/2l/|\Delta\eta_{j1j2}|$

Additional selections to suppress backgrounds

- $m_{ll} > 20$ GeV against nonprompt leptons
- $b$ jet veto against $t\bar{t}$
- $Z$ veto ($m_{ll} - m_Z > 15$ GeV) against Drell-Yan
- 3rd lepton veto ($p_T > 10$ GeV) against $WZ$
- $\tau_h$ veto ($p_T > 18$ GeV) against $WZ$

Irreducible background:
SM $W^+W^+$ production
**Triplet models:** $H^{++} \rightarrow WW$

- Simultaneous fit to $(m_{ll}, m_{jj})$ 2D distribution and $m_{jj}$ in WZ control region
- Non-prompt lepton background estimated from data
- WW, WZ and other backgrounds from simulation (corrections from data)
  - WZ normalized using WZ control region (3 leptons, $|m_{ll} - m_{ll}| < 15$ GeV)
**Triplet models:** $H^{++} \rightarrow WW$

- **VBF $H^{±±} \rightarrow W^{±}W^{±}$**
  - Observed
  - Median expected
  - Expected ± 1σ
  - Expected ± 2σ

- **95% model-independent limits extracted using CL$_{S}$ criterion**

- **Limits interpreted in Georgi–Machacek model, as a function of $m_{H^{±±}}$ and $s_{H}$**

- **Blue region** not allowed theoretically
Table 11: Expected and observed 95% CL upper limits on $H^+\rightarrow c\bar{s}$.

**Summary**

**Doublet models**

- $H^+\rightarrow c\bar{s}$
- $H^+\rightarrow c\bar{b}$
- $H^+\rightarrow t\bar{b}$
- $H^+\rightarrow WZ$
- $H^+\rightarrow \tau^+\tau^-$

**Triplet models**

- Expected and observed 95% CL upper limits on $H^+\rightarrow WW$ (13 TeV)
  - Observed
  - Expected
  - Expected $\pm 1\sigma$
  - Expected $\pm 2\sigma$

- Expected and observed 95% CL upper limits on $H^+\rightarrow c\bar{s}$ (13 TeV)
  - Observed
  - Expected
  - Expected $\pm 1\sigma$
  - Expected $\pm 2\sigma$

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  - Observed
  - Expected
  - Expected $\pm 1\sigma$
  - Expected $\pm 2\sigma$

- Expected and observed 95% CL upper limits on $H^+\rightarrow t\bar{b}$ (13 TeV)
  - Observed
  - Expected
  - Expected $\pm 1\sigma$
  - Expected $\pm 2\sigma$

- Expected and observed 95% CL upper limits on $H^+\rightarrow WZ$ (13 TeV)
  - Observed
  - Expected
  - Expected $\pm 1\sigma$
  - Expected $\pm 2\sigma$

- Expected and observed 95% CL upper limits on $H^+\rightarrow \tau^+\tau^-$ (13 TeV)
  - Observed
  - Expected
  - Expected $\pm 1\sigma$
  - Expected $\pm 2\sigma$

**Figure 10**: Expected and observed 95% CL upper limits on $H^+\rightarrow WW$ (13 TeV).
Table 11: Expected and observed 95% CL upper limits on the production of the

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<th>Mass (GeV)</th>
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<th>Observed</th>
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<td>200</td>
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</table>

Combined limits on $B(t \to H b)$ with $B(H \to c) = 1$

$|\tan \beta| < 0.015$

More $H^+$ results will follow!
Back-up slides
CMS DETECTOR

- Total weight: 14,000 tonnes
- Overall diameter: 15.0 m
- Overall length: 28.7 m
- Magnetic field: 3.8 T

STEEL RETURN YOKE
- 12,500 tonnes

SILICON TRACKERS
- Pixel (100x150 μm) ~16m² ~66M channels
- Microstrips (80x180 μm) ~200m² ~9.6M channels

SUPERCONDUCTING SOLENOID
- Niobium titanium coil carrying ~18,000A

MUON CHAMBERS
- Barrel: 250 Drift Tube, 480 Resistive Plate Chambers
- Endcaps: 468 Cathode Strip, 432 Resistive Plate Chambers

PRESHOWER
- Silicon strips ~16m² ~137,000 channels

FORWARD CALORIMETER
- Steel + Quartz fibres ~2,000 Channels

CRYSTAL ELECTROMAGNETIC CALORIMETER (ECAL)
- ~76,000 scintillating PbWO₄ crystals

HADRON CALORIMETER (HCAL)
- Brass + Plastic scintillator ~7,000 channels
Introduction

Modern general-purpose detectors at high-energy colliders are based on the concept of cylindrical detection layers, nested around the beam axis. Starting from the beam interaction region, particles first enter a tracker, in which charged-particle trajectories (tracks) and origins (vertices) are reconstructed from signals (hits) in the sensitive layers. The tracker is immersed in a magnetic field that bends the trajectories and allows the electric charges and momenta of charged particles to be measured. Electrons and photons are then absorbed in an electromagnetic calorimeter (ECAL). The corresponding electromagnetic showers are detected as clusters of energy recorded in neighbouring cells, from which the energy and direction of the particles can be determined. Charged and neutral hadrons may initiate a hadronic shower in the ECAL as well, which is subsequently fully absorbed in the hadron calorimeter (HCAL). The corresponding clusters are used to estimate their energies and directions. Muons and neutrinos traverse the calorimeters with little or no interactions. While neutrinos escape undetected, muons produce hits in additional tracking layers called muon detectors, located outside the calorimeters. This simplified view is graphically summarized in Fig. 1, which displays a sketch of a transverse slice of the CMS detector [1].

Figure 1: A sketch of the specific particle interactions in a transverse slice of the CMS detector, from the beam interaction region to the muon detector. The muon and the charged pion are positively charged, and the electron is negatively charged.
Georgi-Machacek model

- Scalar sector of the Standard Model (SM) is extended by **addition of one complex and one real SU(2) triplet**


- **A custodial SU(2) symmetry** is imposed upon the scalar potential, so that $\rho=1$ is **at tree level**
  → agreement with EWK precision data

- Model used as **implemented in MG5_aMC**

- Doublet and triplet VEVs constrained to obtain the observed W and Z masses

\[ \rho \equiv \frac{m_W^2}{m_Z^2 \cos^2 \theta_W} = 1 + \ldots \]
**Trigger:** OR of single lepton and dilepton triggers, ~100% efficiency

**Normalization of QCD WZjj background**
- Normalization from **control region**, (10% syst. uncert)

**Nonprompt lepton background measurement**
- ”Nonprompt lepton” = a **lepton inside jets** or a **jet mis-id. as an isol. lepton**
- Tight-to-loose method:
  - Select control sample of leptons with loose ID/isolation requirements
  - **Estimate the probability** that a loose lepton is misidentified as a tight one using a **dijet sample enriched in nonprompt leptons**
  - **Apply** this probability (as a function of **lepton flavor**, $p_T$, $\eta$) to control sample to estimate the resulting contribution to the signal region
- Method **validated** in tt and Drell-Yan enriched control regions → 30% syst. uncertainty
H$^+$ → WZ: Systematic uncertainties

- Jet energy scale and jet energy resolution
- QCD RF scale & PDF uncertainties for simulated (prompt lepton) backgrounds
- QCD WZjj normalization (10%)
- Nonprompt lepton background normalization (30%)
- Statistical uncertainty of control sample for nonprompt lepton background estimation
- Lepton energy scale and efficiency (~3%)
- Luminosity (2.5%)
- b mistagging probability
- $p_T^{\text{miss}}$ energy scale
- Pileup reweighting
- Lepton ID/isolation efficiency
- Trigger efficiency
**Trigger:** OR of single lepton and dilepton triggers, ~100% efficiency

**Nonprompt lepton background measurement**
- Using tight-to-loose method

**Charge misassignment background**
- Probability from simulation + scale factors to data

**Normalization of (simulated) WZ background**
- Using the WZ control region, derive scale factors as a function of \( m_{jj} \)
### H\(^{++}\) → WW: Systematic uncertainties

<table>
<thead>
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<th>source</th>
<th>EW WW</th>
<th>QCD WW</th>
<th>DPS WW</th>
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<th>WZ</th>
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<th>VVV</th>
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Ranges indicate minimum and maximum over all bins.