HBSM at the LHC

Jahred Adelman
On behalf of the and collaborations
The state of the Higgs physics program

The ATLAS experiment has observed a Higgs boson with mass $m_H = 125.36$ GeV, which looks very much like the Standard Model (SM) Higgs boson. The data suggests that the signal strength, $\mu$, for the process $H \rightarrow \gamma\gamma$ is $1.17^{+0.27}_{-0.27}$ with a total uncertainty of $1.17^{+1.17}_{-1.17}$.

The process $H \rightarrow ZZ^* \rightarrow 4l$ has a signal strength of $1.44^{+0.40}_{-0.33}$, and the process $H \rightarrow WW^* \rightarrow l\nu l\nu$ has a signal strength of $1.09^{+0.23}_{-0.21}$.

The process $W,Z H \rightarrow b\bar{b}$ has a signal strength of $0.5^{+0.4}_{-0.4}$, and the process $H \rightarrow \tau\tau$ has a signal strength of $1.4^{+0.4}_{-0.4}$.

Looks very much like SM-Higgs boson. So where will we find new physics?
Why BSM Higgs?

- Nothing says there has to be only one Higgs boson
- Same Higgs boson leads to EWSB and also gives mass to fermions?
- Extra Higgs boson motivated by SUSY but other areas of physics too (models with axions, baryogenesis, neutrino masses)
- Haven’t seen new physics elsewhere yet
- Lots of reasons that SM needs extension
  - Hierarchy problem
  - Dark matter
  - …
How to use Higgs to find new physics

• Look for new Higgs bosons
  • General structure typically Two Higgs Doublet Model (2HDM)
  • Higgs boson + invisible/dark sector
    • Higgs $\rightarrow$ invisible and dark sector analyses
  • Higgs decays otherwise not allowed in SM
  • New physics in Higgs boson pair production
  • Discrepancies in couplings
    • production cross sections/branching ratios (not this talk)
  • Discrepancies in kinematics
    • not at that level yet except to confirm JP nature of Higgs (not this talk)
On the 2HDM

SM Higgs field: Complex scalar doublet
4 degrees of freedom of which:
• 3 provide longitudinal components of $W^\pm$, $Z$
• 1 CP-even Higgs boson ($h$)

2HDM Higgs field: Two complex scalar doublets
8 degrees of freedom (4 more than usual):
• 2 CP-even Higgs bosons ($h, H$), one of which is the observed 125 GeV resonance
• CP-odd pseudoscalar $A$
• Two charged Higgs bosons $H^\pm$
Parameters of the common 2HDM

- Four Higgs boson masses \((m_H, m_h, m_A, m_{H^\pm})\)
  - \(m_H\) or \(m_h = 125\) GeV
- Ratio of the vacuum expectation values of the two doublets, \(\tan \beta = v_2/v_1\)
- Mixing angle \(\alpha\) of \(h\) and \(H\)
- \(\cos(\beta - \alpha) \to 0 = \) alignment limit, \(H\) doesn’t couple to \(V\)

<table>
<thead>
<tr>
<th>2HDM Type</th>
<th>Up-type quarks couple to...</th>
<th>Down-type quarks couple to...</th>
<th>Charged leptons couple to...</th>
</tr>
</thead>
<tbody>
<tr>
<td>Type I</td>
<td>(\Phi_2)</td>
<td>(\Phi_2)</td>
<td>(\Phi_2)</td>
</tr>
<tr>
<td>Type II</td>
<td>(\Phi_2)</td>
<td>(\Phi_1)</td>
<td>(\Phi_1)</td>
</tr>
<tr>
<td>Lepton-specific</td>
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<td>(\Phi_1)</td>
</tr>
<tr>
<td>Flipped</td>
<td>(\Phi_2)</td>
<td>(\Phi_1)</td>
<td>(\Phi_2)</td>
</tr>
</tbody>
</table>
### MSSM and NMSSM

- **MSSM (Minimal Supersymmetric Standard Model)** is an instance of Type II 2HDM.
- **NMSSM (Next-to MSSM)** is an extension of MSSM that adds an extra gauge singlet.
- Solves $\mu$-problem (fine-tuning) of MSSM.
- Gain extra CP-even and CP-odd Higgs bosons.

#### 2HDM Type

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<tr>
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<tr>
<td>Type I</td>
<td>$\Phi_2$</td>
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<td>$\Phi_2$</td>
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<tr>
<td><strong>Type II</strong></td>
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<td>Flipped</td>
<td>$\Phi_2$</td>
<td>$\Phi_1$</td>
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</tr>
</tbody>
</table>

H/A→Zh→ll/νν + bb/ττ

• Look for decays of new, heavy Higgs bosons to 125 GeV Higgs + Z boson
• Take advantage of Z→ll and Z→νν decays
• Use highest branching ratio Higgs boson decays (bbbar / ditau)
• Typically use knowledge of masses of Z/h to select events, constrain the system (and improve 4-object mass resolution)
ATLAS search for $A \rightarrow Zh \rightarrow ll/\nu\nu + bb/\tau\tau$

1502.04478

- $h \rightarrow \tau\tau$, $Z \rightarrow ll$
  - Separate based on number of hadronic tau decays
  - Shape of hadronic tau fake from events with SS taus or taus failing ID cuts, normalized using mass sidebands
- $h \rightarrow bb$, $Z \rightarrow ll$ and $\nu\nu$
  - For neutrino decays of $Z$ boson, require large calorimeter and track MET, angular cuts to suppress multijet background, use transverse mass instead of $m_A$
  - Multijet backgrounds: $\mu\mu bb$ negligible, $ee bb$ estimated by fitting $m_{ll}$ to templates with inverted isolation, $\nu\nu bb$ estimated by inverting cuts on track vs calo MET, normalized by inverting angular cuts
  - $V+HF$ constrained with $V+0/1$ btag vs njet
• Non-zero widths larger than mass resolution up to 5% of $m_A$ taken into account
• No evidence for new physics (will be a common theme)
The CMS search for $A \rightarrow Zh \rightarrow ll + bb$ utilizes the following strategies:

- **Use loose+tight b-tagging**
- **Check Z+heavy flavor in regions with 0/1/2 btag but $m_{bb}$ far from $m_H$**
- **Multijet events negligible**
- **Kinematic fit to improve mass resolution (scale $p_T$ and angles of jets)**
- **Multivariate BDT trained separately for low/medium/high $m_A$ to discriminate S vs B**
- **Results from fit to 2D distribution of BDT and $m_{llbb}$**

The CMS Preliminary analysis shows significant data and background contributions from various sources, including SM Higgs, Z+jets, Z+b, Z+b(t), Z+b(t)+V, Single Top, W+jets, VV, and MC Stat. The $A \rightarrow Zh \rightarrow ll + bb$ events are categorized into $Z+bb$ Control Region, with data/bkg ratios clearly visible across different mass bins. The CMS statistics ($L = 19.7 fb^{-1}$ at 8 TeV) are highlighted in the presentation.
BDT adding significant additional information: Using 1D fits worsens limits by 10-20%
Other searches for new, neutral Higgs bosons

- Can use 2HDM as benchmark to search for other new resonances
- Often (but not always) searching for something heavier than 125 GeV
- Take advantage as always of many production modes
- Orthogonal to previous Z/A searches, helps to expand limits on 2HDM parameter space
CMS search for new $\gamma\gamma$ resonances

- Seeded by ~efficient loose diphoton triggers (look for ggF production)
- Require two high-$E_T$, isolated photons using various track- and calorimeter-based variables and different cone sizes
- Divide events based on photon quality and maximum photon $|\eta|$
- Fit diphoton mass distribution to $S+B$, background modeled with 5 analytic functions to check for spurious signal
- Fit range varied to minimize bias for each resonance mass hypothesis
CMS search for new $\gamma\gamma$ resonances

- Model signal with Crystal Ball, accounting for width up to 10% of resonance mass
- Separate limits on spin-0 and spin-2 resonances, plus 2HDM interpretation

ATLAS results (low and high mass): 1407.6583
ATLAS searches for new $H \rightarrow ZZ$

- Use $ZZ \rightarrow 4l$, $ll\nu\nu$, $llqq$ and $\nu\nuqq$ final states in ggF and VBF production modes (also $llqq$ boosted), use lepton or MET triggers
- $4l$: kinematic fit to Z hypothesis. Classify into VBF (forward jets w/large $m_{jj}$), VH (dijet mass or extra leptons) or ggF
  - $Z+$fake $\mu\mu$ estimated from data by fitting $m_{ll}$ with inverted $d0$ cut and no isolation
  - $Z+$fake $ee$ contribution estimated from data by relaxing calo ID, isolation and $d0$ cuts, and fitting to number of pixel and transition radiation hits
- $ll\nu\nu$: Classify into VBF or ggF, reject events with b-tags
  - $tt$ background estimated from $e\mu$ data
  - $Z+$jets estimated from ABCD method: $\Delta \Phi(II, \text{MET})$ and $\Delta \Phi(I,I)$
• **llqq**: Classify into VBF or ggF, as well as number of b-tags, reject events with high MET-significance
  • Scale dijet mass to Z mass
  • Merged jet ggF category requires high-$p_T$ Z
  • Z+jets normalization from dijet sidebands (tagged vs untagged, b vs c vs LF)
  • tt background cross-checked in $e\mu$ data
• **$\nu\nu qq$**: Divide into nb-tags < 2/== 2
  • V+jets normalized as in llqq, checked in signal region with one/two very loose muons
  • tt background as in llqq
ATLAS searches for new $H \rightarrow ZZ$

- The ggF and VBF relative ratio not fixed to SM
- Use $m_H$ (or $m_T$) as discriminating variable

See 1509.00389 for $H \rightarrow WW$ (EWS model)
CMS search for MSSM $h \rightarrow bb$

- Three neutral MSSM Higgs boson denoted by $\phi$, enhanced $bb$ decays at large $\tan \beta$
- Require two or more high-$p_T$ b-tagged jets are trigger level, 3 tight b-tags offline
- Dijet mass resolution $\rightarrow$ single mass search is enough for fits
- $tt\bar{t}$ expected to be tiny compared to QCD
- Use sum of secondary vertex masses within a jet for further categorization ($X_{123}$)
- Form templates for 2b, 1b, 2c, 1c, LF jets in two-tag data events depending on which of 3 jets is untagged, further binned by $X_{123}$ and leading dijet mass ($M_{12}$)
  - Merge templates where appropriate and shapes are similar
  - Take assumed flavor weight from simulation
- Binned $M_{12}$ and $X_{123}$ used to fit signal + background
CMS search for MSSM $h \rightarrow bb$

- Fit for generic cross section limits and also to various MSSM benchmarks for b-associated production
- Shown are 1D distributions unfolded after 2D fit
Searches for charged Higgs bosons

- 2HDM and other extensions predict Higgs bosons with electric charge
- Different types of decays than in neutral Higgs searches
ATLAS search for $H^+ \rightarrow \tau \nu$ in all-hadronic state

- Decay of charged Higgs boson to tau state grows with $\tan(\beta)$, look in state with no charged leptons
- Seed event with hadronic $\tau$ (27-29 GeV) + MET (40-50 GeV) trigger
- Require 4 (3) jets for low(high) signal selection, at least one b-tag, single high $p_T$ hadronic $\tau$, large MET and MET significance
- Data embedding used to model events with real $\tau$
- Multi-jet backgrounds estimate with matrix method, with fake and real probabilities parameterized in $p_T$, eta and ntrack
  - Fit multi-jet background to functional form to estimate high-$m_T$ tail
• $m_T$ is used as discriminating variable
• Set separate low-mass and high-mass limits
• Interpret in the context of various MSSM scenarios, but also set generic limits
CMS search for charged Higgs bosons 1508.07774

- Search for low-mass $H^+ \rightarrow \tau \nu$ in all-jets channel (low and high mass), $H^+ \rightarrow \tau \nu$ in $\mu \tau_h$ and $ll$ (high mass) and $H^+ \rightarrow tb$ in $\mu \tau_h$, $ll$ and single lepton channels
- Events seeded by hadronic $\tau$ (35 GeV)+MET (70 GeV) trigger, muon or dilepton triggers
- Data embedding used to model events with real $\tau$ in all-jets state
- Multi-jet backgrounds estimated by applying mis-ID rate to loose objects
- Most other backgrounds from simulation
- Single lepton $H^+ \rightarrow tb$: divide events based on number of jets, btags and lepton flavor to control and fit backgrounds
CMS search for charged Higgs bosons

- $H^+ \rightarrow \tau \nu$ all-jets: $m_T$ the observable
- $H^+ \rightarrow \tau \nu / t b$ in $l l / \mu \tau_h$: use n-btags
- $H^+ \rightarrow t b$ in single lepton: use $H_T$ distribution
- Need to assume model-dependent branching ratio, assume it is $\text{BR}(H^+ \rightarrow \tau \nu) = 1$ (all-jets) and $\text{BR}(H^+ \rightarrow t b) = 1$ (otherwise)
- Can combine analyses to set limits on variety of MSSM space

\[ T_{H^0} = \begin{array}{c|c|c|c|c|c|c|c|c|c} \hline \text{GeV} & 500 & 1000 & 1500 & 2000 & 2500 \hline \text{Events / GeV} & 2 \to 10 & 1 \to 10 & 1 \to 10 & 1 \to 10 & 1 \to 10 \hline \end{array} \]

\[ \sigma = 200 \text{ pb} \]

\[ \text{Data} / \text{Bkg.} = 0.5 \to 1 \]

\[ (8 \text{ TeV}) \]

\[ H^+ \rightarrow t b \]
ATLAS search for $H^+ \rightarrow W^+Z$ in VBF

- Higgs triplet model: Add additional triplets (not doublet) to SM Higgs sector
- Trigger with single- and di-lepton e and $\mu$ triggers
- Select $Z \rightarrow ll$ and $W \rightarrow qq$ decays, then require two forward jets separated in $\eta$ with large dijet mass
- Form $m_{\ell\ell qq}$ but first constrain $m_{qq}$ to $m_W$
- Require large $Z$ boson $p_T$ and small angle between charge leptons
- Multijet: Fit dilepton mass to templates formed with inverted electron isolation (negligible in muons)
- Reject ttbar by requiring less than 2 btags and low MET significance, e$\mu$ events with 2 btags used to normalize remainder
- $Z+$jets normalization left free to float in the fit (dominates)
• Set limits as a function of charged Higgs boson mass
• \((s_H)^2\) is the fraction of vector boson mass squared generated by triplet vev (free parameter)

ATLAS search for \(H^+ \rightarrow W^+Z\) in VBF

\[ \bar{s} = 8 \text{ TeV, 20.3 fb}^{-1} \]

\[ H^+ \rightarrow W^+Z \rightarrow q\bar{q}ll \]

\[ \sigma \times BR = 1 \text{ pb} \]

\[ m_H = 400 \text{ GeV} \]

\[ Z+\text{jets} \]

\[ \text{Multijet} \]

\[ \text{diboson} \]

\[ tt \]

\[ \text{Uncertainty} \]

\[ \text{Pre-fit background} \]

\[ \sigma_{\text{VBF}} \times BR(H^+ \rightarrow W^+Z) \text{ [fb]} \]

\[ \sigma_{\text{VBF}} \times BR(H^+ \rightarrow W^+Z) \text{ [fb]} \]

\[ m_{H^+} \text{ [GeV]} \]

\[ S_H \]

\[ H^+ \rightarrow W^+Z \rightarrow q\bar{q}ll \]

\[ \bar{s} = 8 \text{ TeV, 20.3 fb}^{-1} \]

\[ \Gamma_{H^+}/m_{H^+} > 15\% \]
Search for light new bosons

- In many models (NMSSM, hidden sector models), 125 GeV h can decay to lighter scalars (a), which then decays to light object (\(\mu\mu, \tau\tau, \gamma\gamma\))
- Very different backgrounds than standard Higgs analyses
- Reduced rate by asking for decays to muons or photons, to improve mass resolution
- Seeded by single and dimuon triggers
- Look for one tau to decay hadronically, the other to electron or muon back-to-back with dimuon candidate and potentially overlapping with $\tau_h$
- Other lepton and leading track in nearby cone required to have opposite sign
- Control region for light flavor: $\equiv 1$ jet and 0 b-tagged jets (DY, low-mass resonances)
- Control region for heavy flavor: at least two b-tagged jets (ttbar)
- Background pieces: $J/\Psi$ and $\Upsilon$, ttbar and continuum, estimated in signal region and control region
- Check background model in validation regions with same sign
- Use dimuon mass to look for signal
- Scan and set limits as a function of $m_a$
- Set limits for low-mass resonances (where analysis is optimized) and higher mass region as well
CMS $h \to aa \to \mu\mu\mu\mu$

- Seeded by dimuon triggers, require 4 muon candidates offline.
- Muons in a pair must have small invariant mass and either come from same vertex or have $dR<0.01$.
- Require dimuon masses to be compatible.
- Events with one dimuon pair plus third muon used to model backgrounds, normalization from events where dimuon masses not compatible.
- Validate backgrounds with non-isolated muons.
- Small J/Psi background estimated from non-isolated 4-muon events with at least one J/Psi candidates.
- 2.2 ± 0.7 events predicted, 1 event observed
- Set limits on various NMSSM models and on hidden sector models with kinetic mixing between dark photon and SM photon

CMS $h \rightarrow aa \rightarrow \mu\mu\mu\mu$

- Reference model: $\sigma(pp \rightarrow h_i \rightarrow a_1 a_1) = 0.008 \times \sigma_{SM}$
- $\mathcal{B}(a_1 \rightarrow 2\mu) = 7.7\%$

**Limit Graph**
- NMSSM 95% CL upper limits:
  - $m_{a_1} = 3.55\, \text{GeV}$
  - $m_{a_1} = 2\, \text{GeV}$
  - $m_{a_1} = 0.25\, \text{GeV}$
- CMS
  - $m_{h_1} < m_{h_2} = 125\, \text{GeV}$
  - $125\, \text{GeV} = m_{h_1} \leq m_{h_2}$

**Higgs Mass Plot**
- $m_{h_1} = 125\, \text{GeV}$
- $m_{h_2} = 125\, \text{GeV}$
- $m_{h_1} < m_{h_2}$

**Production Graph**
- $pp \rightarrow h \rightarrow n_1n_1 \rightarrow Y_D Y_D n_D n_D$
- $\mathcal{B}(h \rightarrow Y_D Y_D + X) = 0.1 - 40\%$

**CMS Cross Section**
- $20.7\, \text{fb}^{-1}$ (8 TeV)
ATLAS $h \rightarrow aa \rightarrow \gamma\gamma\gamma\gamma$

- Look for 3 isolated photons final state
- Backgrounds with real photons and photons from electrons estimated from simulation
- Data-driven estimate of rate for jets to fake photons from isolation sidebands, final estimate from likelihood matrix method based on photon isolation, $p_T$ and $\eta$
- Fit all 3 distributions of diphoton masses, final limits from fits to second and third photons
Separate limits for 125 GeV and 600 GeV resonances

ATLAS Preliminary
\[ h \rightarrow aa \rightarrow \gamma\gamma\gamma\gamma \]
\[ m_h = 125 \text{ GeV} \]
\[ \sqrt{s} = 8 \text{ TeV}, 20.3 \text{ fb}^{-1} \]
95% C.L. upper limits
\[ m_{a_{23}} \] resonance search with \[ m_a \] dependent width

ATLAS Preliminary
\[ H \rightarrow aa \rightarrow \gamma\gamma \]
\[ m_H = 600 \text{ GeV} \]
\[ \sqrt{s} = 8 \text{ TeV}, 20.3 \text{ fb}^{-1} \]
95% C.L. upper limits
\[ m_{a_{23}} \] resonance search with \[ m_a \] dependent width
Conclusion

• Haven’t seen strong evidence of HBSM just yet, but Run 2 is ramping up
• Good reasons to expect that new physics is hiding just around the corner
• Time to keep probing and pushing and testing the Standard Model until it breaks
ATLAS search for $A \rightarrow Zh \rightarrow ll/\nu\nu + bb/\tau\tau$

$\sqrt{s} = 8$ TeV, 20.3 fb$^{-1}$

ATLAS

Events / 20 GeV

$m^{\text{rec}}_A$ [GeV]

Data 2012

$A \rightarrow Zh \rightarrow ll/\nu\nu + bb/\tau\tau$

$m^{\text{rec}}_A = 340$ GeV

$m^{\text{rec}}_A = 500$ GeV

$A \rightarrow Zh(bb)$

SM Zh

Diboson

Top

Multijet

Z+hf

Z+cl

Z+l

Uncertainty

Fake-$l/l$ background

$m_{Z'}$ [GeV]

Data 2012

$\sqrt{s} = 8$ TeV, 20.3 fb$^{-1}$

$A \rightarrow Zh \rightarrow ll/\nu\nu + bb/\tau\tau$

$m^{\text{rec}}_A = 340$ GeV

$m^{\text{rec}}_A = 500$ GeV

$A \rightarrow Zh(bb)$

SM Zh

Diboson

Top

Multijet

W+jets

Z+hf

Z+cl

Z+l

Uncertainty

Fake-$l/l$ background

$m_\ell$ [GeV]

Data 2012

$\sqrt{s} = 8$ TeV, 20.3 fb$^{-1}$

$A \rightarrow Zh \rightarrow ll/\nu\nu + bb/\tau\tau$

$m^{\text{rec}}_A = 340$ GeV

$m^{\text{rec}}_A = 500$ GeV

$A \rightarrow Zh(bb)$

SM Zh

Diboson

Top

Multijet

W+jets

Z+hf

Z+cl

Z+l

Uncertainty

Fake-$l/l$ background

$m_\ell$ [GeV]
Table 2
Predicted and observed number of events for the $\ell\ell bb$ and $\nu\nu bb$ final states shown after the profile likelihood fit to the data.

<table>
<thead>
<tr>
<th></th>
<th>$\ell\ell bb$</th>
<th>$\nu\nu bb$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$Z+$-jets</td>
<td>1443 ± 60</td>
<td>225 ± 11</td>
</tr>
<tr>
<td>$W+$-jets</td>
<td></td>
<td>55 ± 8</td>
</tr>
<tr>
<td>Top</td>
<td>317 ± 28</td>
<td>203 ± 15</td>
</tr>
<tr>
<td>Diboson</td>
<td>30 ± 5</td>
<td>10.8 ± 1.6</td>
</tr>
<tr>
<td>SM $Zh, Wh$</td>
<td>31.7 ± 1.8</td>
<td>22.5 ± 1.2</td>
</tr>
<tr>
<td>Multi-jet</td>
<td>20 ± 16</td>
<td>3.2 ± 3.1</td>
</tr>
<tr>
<td>Total background</td>
<td>1843 ± 34</td>
<td>521 ± 12</td>
</tr>
<tr>
<td>Data</td>
<td>1857</td>
<td>511</td>
</tr>
</tbody>
</table>

Table 1
The number of predicted and observed events for the $\ell\ell\tau\tau$ channels.

<table>
<thead>
<tr>
<th></th>
<th>Expected Background</th>
<th>Data</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\ell\ell\tau_{\text{had}}\tau_{\text{had}}$</td>
<td>28 ± 6</td>
<td>29</td>
</tr>
<tr>
<td>$\ell\ell\tau_{\text{lep}}\tau_{\text{had}}$</td>
<td>17 ± 4</td>
<td>18</td>
</tr>
<tr>
<td>$\ell\ell\tau_{\text{lep}}\tau_{\text{lep}}$ (SF)</td>
<td>9.5 ± 0.6</td>
<td>10</td>
</tr>
<tr>
<td>$\ell\ell\tau_{\text{lep}}\tau_{\text{lep}}$ (DF)</td>
<td>7.2 ± 0.7</td>
<td>7</td>
</tr>
</tbody>
</table>
ATLAS search for $A \rightarrow Z_h \rightarrow ll/\nu \nu + bb/\tau \tau$
ATLAS search for $A \rightarrow Zh \rightarrow ll/\nu\nu + bb/\tau\tau$

$\tan\beta$ vs $\cos(\beta-\alpha)$

$A \rightarrow Zh$ CMS, 20.3 fb$^{-1}$, $\sqrt{s} = 8$ TeV

- 2HDM Type I
- 2HDM Type II
- 2HDM Flipped

Obs 95% CL, Exp 95% CL, ±1σ band, ±2σ band, Excluded, by $A \rightarrow \tau\tau$

Jahred Adelman

PIC2015
Table 3: Summary of systematic uncertainties for backgrounds and signals. The top table shows uncertainties concerning shape, bottom normalization. The last column reports the increase in the expected limit when each single systematic source is frozen.

<table>
<thead>
<tr>
<th>Main backgrounds (Drell-Yan, tf)</th>
<th>Other electroweak (single-top, VV, Vh)</th>
<th>Signal</th>
<th>Effect on exp. limit after freezing</th>
</tr>
</thead>
<tbody>
<tr>
<td>Jet Energy Scale</td>
<td>0 – 4%</td>
<td>0 – 8%</td>
<td>0 – 1%</td>
</tr>
<tr>
<td>Jet Energy Resolution</td>
<td>0 – 2%</td>
<td>0 – 4%</td>
<td>0 – 1%</td>
</tr>
<tr>
<td>b-tagging</td>
<td>0 – 4%</td>
<td>0 – 8%</td>
<td>&lt; 1%</td>
</tr>
<tr>
<td>Factorization and renormalization scale</td>
<td>0 – 6%</td>
<td>6 – 10%</td>
<td>0 – 2%</td>
</tr>
<tr>
<td>Monte Carlo modeling</td>
<td>0 – 15%</td>
<td>-</td>
<td>0 – 6%</td>
</tr>
<tr>
<td>Monte Carlo statistics</td>
<td>1 – 4%</td>
<td>-</td>
<td>0 – 4%</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Normalization</th>
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</tr>
</thead>
<tbody>
<tr>
<td>Control region fit</td>
<td>0 – 2.4%</td>
<td>-</td>
<td>&lt; 1%</td>
</tr>
<tr>
<td>Extrapolation</td>
<td>2 – 13%</td>
<td>-</td>
<td>0 – 1%</td>
</tr>
<tr>
<td>Lepton and trigger efficiency</td>
<td>-</td>
<td>2.5%</td>
<td>2.5%</td>
</tr>
<tr>
<td>Jet Energy Scale</td>
<td>-</td>
<td>5.7%</td>
<td>3.8 – 0.2%</td>
</tr>
<tr>
<td>Jet Energy Resolution</td>
<td>-</td>
<td>3.2%</td>
<td>0.8 – 0.5%</td>
</tr>
<tr>
<td>b-tagging</td>
<td>-</td>
<td>4.9%</td>
<td>3.6 – 3.2%</td>
</tr>
<tr>
<td>Unclustered $E_T^{miss}$</td>
<td>-</td>
<td>1.9%</td>
<td>1.4 – 1.0%</td>
</tr>
<tr>
<td>Pile-up</td>
<td>-</td>
<td>0.9%</td>
<td>1.2%</td>
</tr>
<tr>
<td>PDF</td>
<td>-</td>
<td>4.3%</td>
<td>4.0 – 7.9%</td>
</tr>
<tr>
<td>Cross Section</td>
<td>-</td>
<td>9.2 – 15%</td>
<td>-</td>
</tr>
<tr>
<td>Luminosity</td>
<td>-</td>
<td>2.6%</td>
<td>2.6%</td>
</tr>
</tbody>
</table>
Table 2: List and description of all the variables included in the BDTs.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>CSV$_1$</td>
<td>highest CSV value between the two jets</td>
</tr>
<tr>
<td>CSV$_2$</td>
<td>second-highest CSV value</td>
</tr>
<tr>
<td>$m_{ll}$</td>
<td>invariant mass of the lepton pair</td>
</tr>
<tr>
<td>$p_T^Z$</td>
<td>$p_T$ of the Z candidate</td>
</tr>
<tr>
<td>$p_T^h$</td>
<td>$p_T$ of the dijet pair (h candidate)</td>
</tr>
<tr>
<td>$\Delta R_{bb}$</td>
<td>angular separation of the two jets in the $\eta - \phi$ space</td>
</tr>
<tr>
<td>$\tau_{bb}$</td>
<td>twist angle between the two jets $\tau \equiv \tan^{-1} \Delta \phi/\Delta \eta$</td>
</tr>
<tr>
<td>$E_T^{miss}$</td>
<td>Missing Energy Significance</td>
</tr>
<tr>
<td>$\chi^2$</td>
<td>$\chi^2$ of the kinematic fit</td>
</tr>
<tr>
<td>$S_T$</td>
<td>scalar sum of the $p_T$ of jets, leptons and $E_T^{miss}$ in the event</td>
</tr>
<tr>
<td>$n_{jets}$</td>
<td>number of jets with $p_T &gt; 20$ GeV in the event</td>
</tr>
<tr>
<td>Centrality</td>
<td>Centrality of the four decay products in the A rest frame</td>
</tr>
<tr>
<td>Aplanarity</td>
<td>event Aplanarity calculated with the four decay products</td>
</tr>
<tr>
<td>$\cos \theta^A$</td>
<td>production polar angle of the A candidate in its rest frame</td>
</tr>
<tr>
<td>$\cos \theta_1$</td>
<td>Z decay angle w.r.t. its flight direction in the Z rest frame</td>
</tr>
<tr>
<td>Pull Angle</td>
<td>angle of the pull vector of the highest-$p_T$ jet</td>
</tr>
</tbody>
</table>

Table 1: Control regions definition (top) and scale factors (bottom) derived for the four main backgrounds. Uncertainties are statistical only.

<table>
<thead>
<tr>
<th>Control Region</th>
<th>Z mass [GeV]</th>
<th>h mass [GeV]</th>
<th>CSV$_1$</th>
<th>CSV$_2$</th>
<th>$E_T^{miss}$ [GeV]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Z+0 b-jets</td>
<td>80 &lt; $m_{ll}$ &lt; 100</td>
<td>$m_{bb} &lt; 90, m_{bb} &gt; 140$</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Z+1 b-jets</td>
<td>80 &lt; $m_{ll}$ &lt; 100</td>
<td>$m_{bb} &lt; 90, m_{bb} &gt; 140$</td>
<td>Tight</td>
<td>not Loose</td>
<td>&lt; 40</td>
</tr>
<tr>
<td>Z+2 b-jets</td>
<td>80 &lt; $m_{ll}$ &lt; 100</td>
<td>$m_{bb} &lt; 90, m_{bb} &gt; 140$</td>
<td>Tight</td>
<td>Loose</td>
<td>&lt; 40</td>
</tr>
<tr>
<td>Top</td>
<td>$m_{ll} &lt; 80, m_{ll} &gt; 100$</td>
<td>-</td>
<td>-</td>
<td>Tight</td>
<td>Loose</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Scale Factors</th>
<th>Z+jets</th>
<th>Z+b</th>
<th>Z + bb</th>
<th>$t\bar{t}$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1.069 ± 0.002</td>
<td>0.945 ± 0.012</td>
<td>1.008 ± 0.020</td>
<td>0.984 ± 0.010</td>
</tr>
</tbody>
</table>

Table 4: Observed and expected 95% CL upper limit on $\sigma \times B(A \rightarrow Zh \rightarrow \ell\ell bb)$ as a function of $m_A$, including all statistical and systematic uncertainties.

<table>
<thead>
<tr>
<th>$m_A$ [GeV]</th>
<th>225</th>
<th>250</th>
<th>275</th>
<th>300</th>
<th>325</th>
<th>350</th>
<th>400</th>
<th>500</th>
<th>600</th>
</tr>
</thead>
<tbody>
<tr>
<td>Observed [fb]</td>
<td>17.9</td>
<td>16.8</td>
<td>14.8</td>
<td>19.5</td>
<td>10.1</td>
<td>8.84</td>
<td>3.29</td>
<td>3.35</td>
<td>2.61</td>
</tr>
<tr>
<td>Expected [fb]</td>
<td>17.9</td>
<td>18.1</td>
<td>16.4</td>
<td>13.6</td>
<td>10.0</td>
<td>7.84</td>
<td>5.27</td>
<td>2.79</td>
<td>1.93</td>
</tr>
</tbody>
</table>
CMS search for $A \rightarrow Zh \rightarrow ll + bb/\tau\tau$

$H \rightarrow ZA$

2HDM type-II

$\tan(\beta) = 1.5 \ ; \ \cos(\beta - \alpha) = 0.01$

$H \rightarrow ZA$

2HDM type-II

$\tan(\beta) = 1.5 \ ; \ \cos(\beta - \alpha) = 0.01$

$A \rightarrow ZH$

Kinematically forbidden

$\pm 1\sigma$ Exp. Excl.

Obs. Excl.

$\frac{\sigma}{\sigma_{TH}}$

$10^5$

$10^4$

$10^3$

$10^2$

$10^1$

$10^{-1}$

$\sigma_{95\%}$

$\sigma_{95\%}$

$19.8 \text{ fb}^{-1} (8 \text{ TeV})$

$M_A$ (GeV)

$M_H$ (GeV)
CMS search for new $\gamma \gamma$ resonances

$\Gamma_x = 0.1 \text{ GeV}; \text{spin-2}$

$\Gamma_x = 0.1 \text{ GeV}; \text{spin-0}$

$\Gamma_x = 10\% \text{ of } m_x; \text{spin-0}$

$\Gamma_x = 840 \text{ GeV}; \text{spin-0}$
CMS search for new $\gamma \gamma$ resonances

CMS

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

\[ \tan \beta \]

Type I 2HDM: $A \to \gamma \gamma$

$m_A = 300$ GeV; $m_\ell = 300$ GeV

- Observed
- NLO expected
- NLO expected $\pm 1 \sigma$
- NLO expected $\pm 2 \sigma$

\[ \cos(\beta - \alpha) \]

$\sigma$(barn)

CMS

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

All classes combined - Observed

- 0.002 pb
- 0.003 pb
- 0.004 pb
- 0.010 pb
- 0.020 pb

CMS

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

All classes combined - Expected

- 0.002 pb
- 0.003 pb
- 0.004 pb
- 0.010 pb
- 0.020 pb

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## CMS search for new $\gamma\gamma$ resonances

### Sources of systematic uncertainty

<table>
<thead>
<tr>
<th>Sources of systematic uncertainty</th>
<th>Uncertainty</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Per photon</strong></td>
<td></td>
</tr>
<tr>
<td>Energy resolution, $R_9 &gt; 0.94$ (low $\eta$, high $\eta$)</td>
<td>0.10%, 0.20%</td>
</tr>
<tr>
<td>Energy resolution, $R_9 &lt; 0.94$ (low $\eta$, high $\eta$)</td>
<td>0.10%, 0.18%</td>
</tr>
<tr>
<td>Photon energy scale</td>
<td>0.5%</td>
</tr>
<tr>
<td>Photon identification efficiency</td>
<td>1.0%</td>
</tr>
<tr>
<td><strong>Per event</strong></td>
<td></td>
</tr>
<tr>
<td>Integrated luminosity</td>
<td>2.6%</td>
</tr>
<tr>
<td>Vertex finding efficiency</td>
<td>0.2%</td>
</tr>
<tr>
<td>Trigger efficiency</td>
<td>1.0%</td>
</tr>
<tr>
<td>$R_9$ class migration</td>
<td>2.3%</td>
</tr>
<tr>
<td><strong>Additional normalization uncertainty</strong></td>
<td>5%</td>
</tr>
<tr>
<td><strong>Breit–Wigner model</strong></td>
<td>0.01–10%</td>
</tr>
</tbody>
</table>

### Class and criteria

<table>
<thead>
<tr>
<th>Class</th>
<th>$\eta$ criterion</th>
<th>$R_9$ criterion</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>$\max(</td>
<td>\eta</td>
</tr>
<tr>
<td>1</td>
<td>$\max(</td>
<td>\eta</td>
</tr>
<tr>
<td>2</td>
<td>$1.57 &lt; \max(</td>
<td>\eta</td>
</tr>
<tr>
<td>3</td>
<td>$1.57 &lt; \max(</td>
<td>\eta</td>
</tr>
</tbody>
</table>
ATLAS searches for new H → ZZ

ATLAS (8 TeV, 20.3 fb⁻¹)
H → ZZ → llll, ggF

ATLAS (8 TeV, 20.3 fb⁻¹)
H → ZZ → llll, VBF

ATLAS (8 TeV, 20.3 fb⁻¹)
H → ZZ → llll, VH

Events / 10 GeV

Data

ggF H (200 GeV)
5 × obs. limit
qq → ZZ
gg → ZZ
Z+jets, tt
Uncertainty

VBF H (200 GeV)
5 × obs. limit
VH (200 GeV)
5 × obs. limit
qq → ZZ
gg → ZZ
Z+jets, tt
Uncertainty

VH (200 GeV)

Data

Z+jets
Z + jets CR
Diboson
Top
Multijet
Uncertainty

Pre-fit background

Data/Pred

0.5
1.5
2
2.5
3
3.5
4
4.5
5
6
7
8
9
10

Z + jets CR

Z + jets CR

Merged

Z + jets CR

Data

Z+jets
Z+bl
Z+cl
Z+l
Diboson
Top
Multijet
Uncertainty

Pre-fit background
ATLAS searches for new $H \rightarrow ZZ$

**ATLAS**

$p_p = 8$ TeV, 20.3 fb$^{-1}$

$H \rightarrow ZZ \rightarrow$ llq tagged

Top $e\mu$ CR

**ATLAS**

$p_p = 8$ TeV, 20.3 fb$^{-1}$

$H \rightarrow ZZ \rightarrow$ $qq$ untagged

W$+hf$

W$+cl$

W$+l$

Z$+hf$

Z$+bl$

Z$+cl$

Z$+l$

Diboson

Top

Uncertainty

Pre-fit background

**ATLAS**

$p_p = 8$ TeV, 20.3 fb$^{-1}$

$H \rightarrow ZZ \rightarrow$ $vvqq$ tagged

W$+hf$

W$+cl$

W$+l$

Z$+hf$

Z$+bl$

Z$+cl$

Z$+l$

Diboson

Top

Uncertainty

Pre-fit background

**ATLAS**

$p_p = 8$ TeV, 20.3 fb$^{-1}$

$H \rightarrow ZZ \rightarrow$ $vvqq$ 0 tags

Z$+jets$ CR

**ATLAS**

$p_p = 8$ TeV, 20.3 fb$^{-1}$

$H \rightarrow ZZ \rightarrow$ $llqq$ tagged

Top $e\mu$ CR

**ATLAS**

$p_p = 8$ TeV, 20.3 fb$^{-1}$

$H \rightarrow ZZ \rightarrow$ $llqq$ untagged

W$+hf$

W$+cl$

W$+l$

Z$+hf$

Z$+bl$

Z$+cl$

Z$+l$

Diboson

Top

Uncertainty

Pre-fit background
ATLAS searches for new H→ZZ

1507.05930

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ATLAS searches for new H → ZZ

ATLAS

\( \sqrt{s} = 8 \text{ TeV}, 20.3 \text{ fb}^{-1} \)

H → ZZ \rightarrow \nu \nu\, \nu \nu q q \ tags

W + jets CR

MV1c b-tagging event category

Data/Pred

0% 50% 60% 70% 80% 100%

ATLAS

\( \sqrt{s} = 8 \text{ TeV}, 20.3 \text{ fb}^{-1} \)

H → ZZ \rightarrow l l q q \ tags

Z + jets CR

MV1c b-tagging event category

Data/Pred

0% 50% 60% 70% 80% 100%
Table 1: Separate sources of systematic uncertainties accounted for in the analysis. The magnitude of the variation of the source that has been applied to the signal model is shown.

<table>
<thead>
<tr>
<th>Source</th>
<th>Magnitude</th>
</tr>
</thead>
<tbody>
<tr>
<td>Integrated luminosity</td>
<td>2.6%</td>
</tr>
<tr>
<td>Acceptance (PDF)</td>
<td>3.0%</td>
</tr>
<tr>
<td>Trigger Efficiency</td>
<td></td>
</tr>
<tr>
<td>- Electron</td>
<td>2%</td>
</tr>
<tr>
<td>- Muon</td>
<td>3.5%</td>
</tr>
<tr>
<td>Selection Efficiency</td>
<td></td>
</tr>
<tr>
<td>- Photon</td>
<td>1.0–2.6%</td>
</tr>
<tr>
<td>- Electron</td>
<td>5.0%</td>
</tr>
<tr>
<td>- Muon</td>
<td>2.0%</td>
</tr>
<tr>
<td>Signal</td>
<td></td>
</tr>
<tr>
<td>- Mass Scale</td>
<td>1.0%</td>
</tr>
<tr>
<td>- Mass Resolution</td>
<td>10.0%</td>
</tr>
<tr>
<td>Pileup</td>
<td>1.3%</td>
</tr>
</tbody>
</table>
CMS search for MSSM $h \rightarrow bb$

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

$M_{12}$ [GeV]

CMS Simulation (8 TeV)

$X_{123}$

$M_{12}$ [GeV]
CMS search for MSSM h→bb

\[ m_A \text{ [GeV]} \]

95% CL limit
- Expected
- ±1σ expected
- ±2σ expected
- Observed

\[ m_{A,\text{max}} \text{ scenario} \]
- \( \mu = +200 \text{ GeV} \)
- \( m_{h,\tau} = 125\pm3 \text{ GeV} \)

\[ m_A \text{ [GeV]} \]

CMS, 19.7 fb\(^{-1}\) (8 TeV) + 4.9 fb\(^{-1}\) (7 TeV)

\[ m_A \text{ [GeV]} \]

CMS, 19.7 fb\(^{-1}\) (8 TeV)

\[ m_A \text{ [GeV]} \]

CMS, 19.7 fb\(^{-1}\) (8 TeV) + 4.9 fb\(^{-1}\) (7 TeV)

\[ m_A \text{ [GeV]} \]

CMS, 19.7 fb\(^{-1}\) (8 TeV)

\[ m_A \text{ [GeV]} \]

CMS, 19.7 fb\(^{-1}\) (8 TeV) + 4.9 fb\(^{-1}\) (7 TeV)

\[ m_A \text{ [GeV]} \]

CMS, 19.7 fb\(^{-1}\) (8 TeV)

\[ m_A \text{ [GeV]} \]

CMS, 19.7 fb\(^{-1}\) (8 TeV) + 4.9 fb\(^{-1}\) (7 TeV)
CMS search for MSSM h -> bb

$\alpha(pp \rightarrow (q\bar{q}) \rightarrow (q\bar{q}b\bar{b}) \times B(q\bar{q} \rightarrow b\bar{b}) [pb]$

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

95% CL limit
- Expected
- $\pm 1\sigma$ expected
- $\pm 2\sigma$ expected
- Observed

$\beta, \tan(10, 20, 30, 40, 50, 60)$

(7 TeV)

$\pm 500$ GeV

CMS, 19.7 fb$^{-1}$ (8 TeV) + 4.9 fb$^{-1}$ (7 TeV)

$\pm 200$ GeV

$\pm 500$ GeV

$\beta, \tan(10, 20, 30, 40, 50, 60)$

(7 TeV)

$\pm 500$ GeV

CMS, 19.7 fb$^{-1}$ (8 TeV) + 4.9 fb$^{-1}$ (7 TeV)

$\pm 200$ GeV

$\pm 500$ GeV

$\beta, \tan(10, 20, 30, 40, 50, 60)$

(7 TeV)
ATLAS search for $H^+ \rightarrow \tau \nu$ in all-hadronic state

- 1-track $\tau$
- 3-track $\tau$

$\int L dt = 19.5 \text{ fb}^{-1}$

$\sqrt{s} = 8 \text{ TeV}$

ATLAS

Jet-to-$\tau$ misidentification probability

$\sigma_{\text{iso}}$ track

$N_{\text{iso}} \text{ track}$

$N_{\text{iso}} \text{ track}$

$\tau$ 1-track

$\tau$ 3-track

ATLAS

Events / 20 GeV

$\int L dt = 19.5 \text{ fb}^{-1}$

$\sqrt{s} = 8 \text{ TeV}$

$\tau$ 1-track

$\tau$ 3-track

ATLAS

Simulation

- Single top
- W+jets
- Z+jets
- $t\bar{t}$
- $H^+(130)$ (arbitrary normalization)
- $H^+(250)$ (arbitrary normalization)
- $H^+(500)$ (arbitrary normalization)

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ATLAS search for H$^+ \to \tau \nu$ in all-hadronic state

**ATLAS**

$\int L dt = 19.5 \text{ fb}^{-1}$

$\sqrt{s} = 8 \text{ TeV}$

Data 2012

MSSM Light top squark scenario

$\tan \beta$ vs $m_H$ [GeV]

**MSSM Tauphobic scenario**

$\int L dt = 19.5 \text{ fb}^{-1}$

$\sqrt{s} = 8 \text{ TeV}$

Data 2012

MSSM Light stau scenario

$\tan \beta$ vs $m_H$ [GeV]

**MSSM Light stau scenario**

$\int L dt = 19.5 \text{ fb}^{-1}$

$\sqrt{s} = 8 \text{ TeV}$

Data 2012

MSSM Light stau scenario

$\tan \beta$ vs $m_H$ [GeV]

**MSSM Light stau scenario**

$\int L dt = 19.5 \text{ fb}^{-1}$

$\sqrt{s} = 8 \text{ TeV}$

Data 2012

MSSM Light stau scenario

$\tan \beta$ vs $m_H$ [GeV]

**MSSM Light stau scenario**
ATLAS search for $H^+ \rightarrow \tau \nu$ in all-hadronic state

**Data** (embedded) ~ 1412.6663

**Events**

- $p_T^{\tau}$ [GeV]
- $E_T^{miss}$ [GeV]

**ATLAS**

- L$dt = 19.5$ fb$^{-1}$
- $\mathcal{E} = 8$ TeV

**Event Cuts**

- High-mass $H^+$ selection
- Low-mass $H^+$ selection

**Graphs**

- Single top + $W/Z$ and jets
- Single top + $H$
ATLAS search for $H^+ \rightarrow \tau \nu$ in all-hadronic state

\[ \int \text{Ldt} = 19.5 \text{ fb}^{-1} \]
\[ \sqrt{s}=8 \text{ TeV} \]
\[ \text{Data 2012} \]
\[ \text{MSSM } m_h^{\text{mod}} \text{ scenario} \]

Median expected exclusion
Observed exclusion 95% CL
Observed +1σ theory
Observed -1σ theory

$\tan \beta$ vs. $m_H$ [GeV]

$\beta$ vs. $m_H$ [GeV]
ATLAS search for $H^+ \rightarrow \tau \nu$ in all-hadronic state

\[ \int L dt = 19.5 \text{ fb}^{-1} \]

- High-mass $H^+$ selection
- Low-mass $H^+$ selection
ATLAS search for $H^+ \rightarrow \tau \nu$ in all-hadronic state 1412.6663
ATLAS search for $H^+ \rightarrow \tau \nu$ in all-hadronic state

\[ \frac{\Delta \hat{\mu}}{\Delta \hat{\mu}_\text{tot}} \]

-2 -1 0 1 2

Pull

(ATLAS)

\[ \int L dt = 19.5 \text{ fb}^{-1} \]

$\sqrt{s} = 8 \text{ TeV}$

$m_{\mu^+} = 130 \text{ GeV}$

Post-fit Impact on $\hat{\mu}$

\[ (\theta - \theta_0)/\Delta \theta \]

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ATLAS search for $H^+ \rightarrow \tau \nu$ in all-hadronic state

$\frac{d^2 \sigma}{d m_{H^+} \cdot d m_{\tau \nu}} \cdot B[H^+ \rightarrow \tau \nu]$ vs. $m_{H^+}$ [GeV]

$\sigma_{H^+} \times B[H^+ \rightarrow \tau \nu]$ [pb] vs. $m_{H^+}$ [GeV]
<table>
<thead>
<tr>
<th>$m_H$ (GeV)</th>
<th>Expected limit [fb] for given $\Gamma_{Hb}/m_H$ [%]</th>
<th>0</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
<th>9</th>
<th>10</th>
<th>11</th>
<th>12</th>
</tr>
</thead>
<tbody>
<tr>
<td>200</td>
<td>667</td>
<td>765</td>
<td>869</td>
<td>953</td>
<td>1.08 $\times 10^3$</td>
<td>1.18 $\times 10^3$</td>
<td>1.29 $\times 10^4$</td>
<td>1.71 $\times 10^3$</td>
<td>2.16 $\times 10^3$</td>
<td>2.41 $\times 10^3$</td>
<td>2.71 $\times 10^3$</td>
<td>3.00 $\times 10^3$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>250</td>
<td>745</td>
<td>830</td>
<td>923</td>
<td>1.02 $\times 10^3$</td>
<td>1.12 $\times 10^3$</td>
<td>1.22 $\times 10^3$</td>
<td>1.33 $\times 10^3$</td>
<td>1.79 $\times 10^3$</td>
<td>2.14 $\times 10^3$</td>
<td>2.56 $\times 10^3$</td>
<td>3.00 $\times 10^3$</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>300</td>
<td>667</td>
<td>773</td>
<td>878</td>
<td>953</td>
<td>1.08 $\times 10^3$</td>
<td>1.18 $\times 10^3$</td>
<td>1.29 $\times 10^4$</td>
<td>1.71 $\times 10^3$</td>
<td>2.16 $\times 10^3$</td>
<td>2.41 $\times 10^3$</td>
<td>2.71 $\times 10^3$</td>
<td>3.00 $\times 10^3$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>350</td>
<td>436</td>
<td>530</td>
<td>634</td>
<td>728</td>
<td>1.02 $\times 10^3$</td>
<td>1.12 $\times 10^3$</td>
<td>1.22 $\times 10^3$</td>
<td>1.33 $\times 10^3$</td>
<td>1.79 $\times 10^3$</td>
<td>2.14 $\times 10^3$</td>
<td>2.56 $\times 10^3$</td>
<td>3.00 $\times 10^3$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>400</td>
<td>334</td>
<td>437</td>
<td>541</td>
<td>645</td>
<td>1.02 $\times 10^3$</td>
<td>1.12 $\times 10^3$</td>
<td>1.22 $\times 10^3$</td>
<td>1.33 $\times 10^3$</td>
<td>1.79 $\times 10^3$</td>
<td>2.14 $\times 10^3$</td>
<td>2.56 $\times 10^3$</td>
<td>3.00 $\times 10^3$</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Source of uncertainty**

**Impact (%)**

- Total: 20
- Statistical: 14
- Systematic: 14

**Experimental Uncertainties**

- Jets+$E_T^{miss}$: 8.8
- Luminosity: 2.8
- Leptons: 0.9
- $b$-tagging: 0.2

**Theoretical and Modeling Uncertainties**

- Signal: 10
- Top: 3.8
- $Z$+jets: 3.7
- Multijet: 0.1
ATLAS search for $H^+ \rightarrow W^+ Z$ in VBF

ATLAS
\[ \bar{\beta} = 8 \text{ TeV}, 20.3 \text{ fb}^{-1} \]

$H^+ \rightarrow W^+ Z \rightarrow q\bar{q}l\bar{l}$
\[ \sigma \times \text{BR} = 1 \text{ pb} \]

Events / GeV

$E_T^{miss}/|H_T| \text{ [GeV}^{0.5}]$

Events / 10 GeV

$p_T$ [GeV]

Events / 16 GeV

$p_T^Z$ [GeV]

Data
$H^+ \rightarrow W^+ Z \rightarrow q\bar{q}l$
$\sigma \times \text{BR} = 1 \text{ pb}$

$\sqrt{s} = 8 \text{ TeV}, 20.3 \text{ fb}^{-1}$

$H^+ \rightarrow W^+ Z \rightarrow q\bar{q}l$
$\sigma \times \text{BR} = 1 \text{ pb}$

$\sqrt{s} = 8 \text{ TeV}, 20.3 \text{ fb}^{-1}$

$H^+ \rightarrow W^+ Z \rightarrow q\bar{q}l$
$\sigma \times \text{BR} = 1 \text{ pb}$
Jahred Adelman

**ATLAS h → aa → µµττ**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>fT</th>
<th>( \frac{Y}{\psi^+ Y} ) (%)</th>
<th>fRes ( \frac{Y^+ Y}{\text{Total}} ) (%)</th>
<th>fT ( \text{Total} ) (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CRj</td>
<td>32.6±0.3</td>
<td>14.7±0.1</td>
<td>6.1±0.9</td>
<td></td>
</tr>
<tr>
<td>CRb</td>
<td>N/A N/A</td>
<td>87.2±5.1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>VRµ</td>
<td>35.8±6.0</td>
<td>18.8±2.3</td>
<td>28.2±3.2</td>
<td></td>
</tr>
<tr>
<td>VRe</td>
<td>36.3±9.2</td>
<td>12.2±2.3</td>
<td>34.2±3.6</td>
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</tr>
<tr>
<td>SRµ</td>
<td>25.8±4.9</td>
<td>15.2±1.6</td>
<td>20.4±4.1</td>
<td></td>
</tr>
<tr>
<td>SRe</td>
<td>24.5±6.6</td>
<td>11.8±1.6</td>
<td>23.5±5.0</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \mu )</td>
<td>(99.86 ± 0.01)%</td>
<td>(60.7 ± 3.8) GeV</td>
</tr>
<tr>
<td>( \sigma )</td>
<td>(1.68 ± 0.02)% ( g_z \left( \frac{2}{S+Z} \right) )</td>
<td>(23.4 ± 0.5)%</td>
</tr>
<tr>
<td>( \alpha_{CB} )</td>
<td>1.49±0.03 ( f_{\psi'} \left( \frac{2S+Z}{2S+3Z} \right) )</td>
<td>(6.3 ± 0.3)%</td>
</tr>
<tr>
<td>( \alpha_{\gamma^*} )</td>
<td>( -31 ± 3 ) TeV(^{-1} ) ( f_{T3S} \left( \frac{3S}{2S+3S} \right) )</td>
<td>(46.8 ± 1.4)%</td>
</tr>
<tr>
<td>( n_{\gamma^*} )</td>
<td>-0.75±0.02 ( f_{T2S} \left( \frac{2S+3S}{1S+2S+3S} \right) )</td>
<td>(49.9 ± 0.6)%</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Selection</th>
<th>Relative efficiency (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Generator-level</td>
<td>0.41±0.00</td>
</tr>
<tr>
<td>Pass trigger</td>
<td>67.6±0.3</td>
</tr>
<tr>
<td>Two selected muons</td>
<td>77.8±0.3</td>
</tr>
<tr>
<td>Opposite charge ( (\mu, \mu) )</td>
<td>100.0±0.0</td>
</tr>
<tr>
<td>( p_T (\mu, \mu) &gt; 40 ) GeV</td>
<td>98.1±0.1</td>
</tr>
<tr>
<td>( 2.8 ) GeV ( &lt; m_{\mu\mu} &lt; 70 ) GeV</td>
<td>100.0±0.0</td>
</tr>
<tr>
<td>Third lepton</td>
<td>18.2±0.3 ( \Delta \phi (\mu, \mu) )</td>
</tr>
<tr>
<td>Opposite charge ( (\ell, \mu, \mu) )</td>
<td>95.5±0.4 ( 93.7±0.7 )</td>
</tr>
<tr>
<td>1 or 3 nearby tracks</td>
<td>91.4±0.5 ( 82.8±1.1 )</td>
</tr>
<tr>
<td>Opposite charge ( (\ell, \mu, \mu) )</td>
<td>91.2±0.9 ( 88.1±1.1 )</td>
</tr>
<tr>
<td>Lepton isolation</td>
<td>75.5±0.9 ( 84.6±1.3 )</td>
</tr>
</tbody>
</table>
ATLAS $h \rightarrow aa \rightarrow \mu\mu\tau\tau$
Table 1: Event selection efficiencies $\epsilon_{\text{sim}}(m_{h_1}, m_{a_1})$ and $\epsilon_{\text{sim}}(m_{\gamma D}, c\tau_{\gamma D})$, as obtained from simulation, the geometric and kinematic acceptances $\alpha_{\text{gen}}(m_{h_1}, m_{a_1})$ and $\alpha_{\text{gen}}(m_{\gamma D}, c\tau_{\gamma D})$, calculated using only generator-level information, and their ratios (with statistical uncertainties), for a few representative NMSSM and dark SUSY benchmark samples. The experimental data-to-simulation scale factor ($\epsilon_{\text{data}} / \epsilon_{\text{sim}}$, described later) is not applied.

<table>
<thead>
<tr>
<th>$m_{h_1}$ [GeV]</th>
<th>90</th>
<th>125</th>
<th>125</th>
</tr>
</thead>
<tbody>
<tr>
<td>$m_{a_1}$ [GeV]</td>
<td>2</td>
<td>0.5</td>
<td>3.55</td>
</tr>
<tr>
<td>$\epsilon_{\text{sim}}$ [%]</td>
<td>11.0 ± 0.1</td>
<td>21.1 ± 0.1</td>
<td>17.3 ± 0.1</td>
</tr>
<tr>
<td>$\alpha_{\text{gen}}$ [%]</td>
<td>15.9 ± 0.1</td>
<td>32.0 ± 0.1</td>
<td>26.3 ± 0.1</td>
</tr>
<tr>
<td>$\epsilon_{\text{sim}} / \alpha_{\text{gen}}$</td>
<td>0.69 ± 0.01</td>
<td>0.66 ± 0.01</td>
<td>0.66 ± 0.01</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>$m_{\gamma D}$ [GeV]</th>
<th>0.25</th>
<th>0.5</th>
<th>2</th>
<th>0.25</th>
<th>0.5</th>
<th>2</th>
</tr>
</thead>
<tbody>
<tr>
<td>$c\tau_{\gamma D}$ [mm]</td>
<td>0</td>
<td>0.5</td>
<td>2</td>
<td>0</td>
<td>0.5</td>
<td>2</td>
</tr>
<tr>
<td>$\epsilon_{\text{sim}}$ [%]</td>
<td>8.85 ± 0.12</td>
<td>1.76 ± 0.05</td>
<td>0.23 ± 0.03</td>
<td>6.13 ± 0.23</td>
<td>4.73 ± 0.07</td>
<td>1.15 ± 0.04</td>
</tr>
<tr>
<td>$\alpha_{\text{gen}}$ [%]</td>
<td>14.32 ± 0.14</td>
<td>2.7 ± 0.06</td>
<td>0.31 ± 0.03</td>
<td>8.89 ± 0.28</td>
<td>6.98 ± 0.09</td>
<td>1.68 ± 0.05</td>
</tr>
<tr>
<td>$\epsilon_{\text{sim}} / \alpha_{\text{gen}}$</td>
<td>0.62 ± 0.01</td>
<td>0.65 ± 0.02</td>
<td>0.74 ± 0.13</td>
<td>0.69 ± 0.03</td>
<td>0.68 ± 0.01</td>
<td>0.68 ± 0.03</td>
</tr>
</tbody>
</table>
Scenarios

- mhmax: the mass of the lightest CP-even Higgs boson is maximized
- Interpret 125 GeV as lightest CP-even Higgs boson but drop maximal requirement: \( mh_{mod+} \) and \( mh_{mod-} \), differing in sign of mixing in stop sector
CMS search for charged Higgs bosons 1508.07774

\begin{align*}
\text{g} & \rightarrow \text{t} \\
\text{t} & \rightarrow \text{b} \\
\text{g} & \rightarrow \text{t} \\
\text{t} & \rightarrow \text{b} \\
\text{g} & \rightarrow \text{t} \\
\text{t} & \rightarrow \text{b} \\
\text{g} & \rightarrow \text{t} \\
\text{t} & \rightarrow \text{b} \\
\end{align*}
CMS search for charged Higgs bosons

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

Events

Data/Bkg.

CMS

$\mu^+\mu^-$ final state

Events

$10^0$ to $10^7$

Data/Bkg.

CMS

$\tau^+\tau^-$ final state

Events

$10^3$ to $10^6$

Data/Bkg.

CMS

$\tau^+\tau^-$ final state

Events

$10^0$ to $10^4$

Data/Bkg.

CMS

$\tau^+\tau^-$ final state

Events

$10^3$ to $10^6$

Data/Bkg.
CMS search for charged Higgs bosons

1508.07774

Jahred Adelman

PIC2015
CMS search for charged Higgs bosons

$19.7 \text{ fb}^{-1} (8 \text{ TeV})$

\[ \sigma_{H^+} \] limit on $m_H^+$ [GeV]

---

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

$\ell^+$jets, $\ell^\pm \ell^\mp$ final states

Assuming $B(H^+ \rightarrow t\bar{b}) = 1$

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

---

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

$\ell^+$jets final states

Assuming $B(H^+ \rightarrow t\bar{b}) = 1$

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

---

CMS $t \rightarrow H^+b$, $H^+ \rightarrow \ell^+\nu\tau$, $\ell^\pm\nu\tau\ell^\mp$ final state

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

---

CMS $\nu\tau \rightarrow \ell^+H$, $H \rightarrow t\bar{b}$

$\ell^+$jets final state

- **Observed**
- **Expected median $\pm 1\sigma$**
- **Expected median $\pm 2\sigma$**
CMS search for charged Higgs bosons

1508.07774

Jahred Adelman

PIC2015
# CMS search for charged Higgs bosons

**Source**: $N_{\text{events}} (\pm \text{stat} \pm \text{syst})$

<table>
<thead>
<tr>
<th>Process</th>
<th>$N_{\text{events}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$H^+ \rightarrow \tau^+ \nu_\tau$, $m_{H^+} = 250$ GeV</td>
<td>176 ± 10 ± 13</td>
</tr>
<tr>
<td>$H^+ \rightarrow t\bar{b}$, $m_{H^+} = 250$ GeV</td>
<td>37 ± 2 ± 3</td>
</tr>
<tr>
<td>$t\bar{t} \rightarrow \mu^+ \nu_\mu + X$</td>
<td>2913 ± 14 ± 242</td>
</tr>
<tr>
<td>Misidentified $\tau_\mu$</td>
<td>1544 ± 14 ± 175</td>
</tr>
<tr>
<td>$t\bar{t}$ dijeton</td>
<td>101 ± 27</td>
</tr>
<tr>
<td>$Z/\gamma^* \rightarrow ee, \mu\mu$</td>
<td>12 ± 3 ± 4</td>
</tr>
<tr>
<td>$Z/\gamma^* \rightarrow \tau\tau$</td>
<td>162 ± 40 ± 162</td>
</tr>
<tr>
<td>Single top quark</td>
<td>150 ± 12 ± 18</td>
</tr>
<tr>
<td>Dibosons</td>
<td>20 ± 3 ± 2</td>
</tr>
<tr>
<td>Total SM backgrounds</td>
<td>4903 ± 45 ± 341</td>
</tr>
<tr>
<td>Data</td>
<td>4839</td>
</tr>
</tbody>
</table>

## Signal

<table>
<thead>
<tr>
<th>Signal</th>
<th>$t\bar{t} \rightarrow \mu^+ \nu_\mu + X$</th>
<th>$t\bar{t}$ dijeton</th>
<th>$\tau_\mu$ mis-id</th>
<th>Single top quark</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\mu$ trigger</td>
<td>2.0</td>
<td>2.0</td>
<td>2.0</td>
<td>2.0</td>
</tr>
<tr>
<td>$\mu$ identification</td>
<td>1.0</td>
<td>1.0</td>
<td>1.0</td>
<td>1.0</td>
</tr>
<tr>
<td>$\tau_\mu$ identification</td>
<td>6.0</td>
<td>6.0</td>
<td>6.0</td>
<td>6.0</td>
</tr>
</tbody>
</table>

## Single $\tau$ trigger: data

<table>
<thead>
<tr>
<th>Signal</th>
<th>$H^+ H^-$</th>
<th>$H^+ H^+$</th>
<th>$H^+ H^+$</th>
<th>Multi-jets</th>
<th>EW$++t\tau$</th>
<th>EW$++t\tau$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\tau$ part of trigger; data</td>
<td>1.5–1.8</td>
<td>1.3–1.5</td>
<td>1.8–3.0</td>
<td>-0.5</td>
<td>1.2</td>
<td>1.4</td>
</tr>
<tr>
<td>$\tau$ part of trigger; simulation</td>
<td>0.7–0.8</td>
<td>0.6–0.7</td>
<td>0.8–1.1</td>
<td>-0.2</td>
<td>0.8</td>
<td></td>
</tr>
<tr>
<td>$\bar{t}\bar{b}$ part of trigger; data</td>
<td>2.6–3.3</td>
<td>2.5–2.8</td>
<td>2.9–3.2</td>
<td>-1.2</td>
<td>2.5</td>
<td>2.8</td>
</tr>
<tr>
<td>$\bar{t}\bar{b}$ part of trigger; simulation</td>
<td>0.1</td>
<td>0.1</td>
<td>0.1</td>
<td>-0.1</td>
<td>0.4</td>
<td></td>
</tr>
</tbody>
</table>

## Approximation in $\bar{t}\bar{b}$ part of trigger

| $\lambda$ part of trigger | 12 |

## Single $\mu$ trigger: data

| Veto of events with $e$ | 0.1–0.2 | 0.2–0.3 | 0.2–0.3 | < -0.1 | 0.4 |
| Veto of events with $\mu$ | 0.1 | 0.1–0.2 | 0.1 | < -0.1 | 0.5 |
| $\tau_\mu$ identification (S) | 6.0 | 6.0 | 5.9–6.0 | -0.8 | 6.0 |
| $\mu$ identification as $\tau_\mu$ (S) | < 0.1 | < 0.1 | < 0.1 | < -0.1 | 3.3 |
| $\mu$ misidentification as $\tau_\mu$ (S) | < 0.1 | < 0.1 | < 0.1 | < -0.1 | 1.1 |
| Jet misidentification as $\tau_\mu$ (S) | 0.1 | 0.1–0.3 | 0.1 | -6.9 | 17 |
| $\tau_\mu$ energy scale (S) | 0.3–2.6 | 2.7–5.2 | 0.3–2.7 | -1.8 | 5.8 | 2.0 |
| Jet energy scale | 2.6–5.2 | 2.0–3.0 | 1.6–2.1 | -1.4 | 3.2 |
| Jet energy resolution | 1.1–1.8 | 0.5–1.3 | 0.7–1.5 | -0.2 | 3.2 |
| Unclustered $\bar{t}\bar{b}$ energy scale | 0.1–0.4 | 0.1–0.9 | 0.1–0.4 | -0.5 | 1.5 |
| b-tagging (S) | 5.9–20 | 4.7–5.3 | 4.6–5.4 | -3.5 | 5.0 |
| Top quark $p_T$ modelling (S) | 0.1 | 0.1 | 0.1 | -0.1 | 0.2 |
| $\bar{t}\bar{b}$ energy scale (S) | 0.1 | 0.1 | 0.1 | -0.1 | 0.2 |

## Integrated luminosity

| Value | 2.6 | 2.6 | 2.6 | 2.6 |

## CMS search for charged Higgs bosons

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
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<td>Data</td>
<td>4839</td>
</tr>
</tbody>
</table>
### CMS search for charged Higgs bosons

**1508.07774**

<table>
<thead>
<tr>
<th>Decay mode</th>
<th>Signatures for ( m_{H^+} &lt; m_t - m_b )</th>
<th>Signatures for ( m_{H^+} &gt; m_t - m_b )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( H^+ \rightarrow \tau^+ \nu_\tau )</td>
<td>( \tau_\nu + \text{jets}^{(5)} )</td>
<td>( \tau_\nu + \text{jets}^{(5)} ), ( \mu \nu^{(6)} ), ( \ell \ell^{(7)} )</td>
</tr>
<tr>
<td>( H^+ \rightarrow t\bar{b} )</td>
<td>—</td>
<td>( \mu \nu^{(6)} ), ( \ell \ell^{(7)} ), ( \ell + \text{jets}^{(8)} )</td>
</tr>
</tbody>
</table>

### Table

<table>
<thead>
<tr>
<th>Source</th>
<th>Signal</th>
<th>tt dilepton</th>
<th>Z/( \gamma ) ( \rightarrow \ell \ell )</th>
<th>Single top quark</th>
</tr>
</thead>
<tbody>
<tr>
<td>e(\mu) trigger efficiency</td>
<td>3.0</td>
<td>3.0</td>
<td>3.0</td>
<td>3.0</td>
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<td>e identification</td>
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<tr>
<td>(\mu) identification</td>
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<td>1.0</td>
<td>1.0</td>
<td>1.0</td>
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<tr>
<td>Jet energy scale (S)</td>
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<td>1.1</td>
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<tr>
<td>Jet energy resolution (S)</td>
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<td>0.3</td>
<td>0.4</td>
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<tr>
<td>Unclustered (E_T^{miss}) energy scale (S)</td>
<td>1.3</td>
<td>2.1</td>
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<td>2.6</td>
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<tr>
<td>b tagging (S)</td>
<td>2.4</td>
<td>3.7</td>
<td>10</td>
<td>4.3</td>
</tr>
<tr>
<td>uds(\rightarrow)b mistagging (S)</td>
<td>2.3</td>
<td>3.6</td>
<td>10</td>
<td>4.4</td>
</tr>
<tr>
<td>Top quark (p_T) modelling (S)</td>
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<td>—</td>
<td>—</td>
<td>—</td>
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<tr>
<td>Pileup modelling</td>
<td>0.6</td>
<td>0.4</td>
<td>1.2</td>
<td>1.2</td>
</tr>
<tr>
<td>Cross sections</td>
<td>(23 \pm 4.6)</td>
<td>4.0</td>
<td>8.0</td>
<td>—</td>
</tr>
<tr>
<td>Matching scale (S)</td>
<td>7.7</td>
<td>—</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>Fact./renorm. scale (S)</td>
<td>8.4</td>
<td>—</td>
<td>—</td>
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</tr>
<tr>
<td>PDF shape</td>
<td>shape only</td>
<td>—</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>Heavy flavours (S)</td>
<td>&lt;0.1</td>
<td>—</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>Integrated luminosity</td>
<td>2.6</td>
<td>2.6</td>
<td>2.6</td>
<td>2.6</td>
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</tbody>
</table>

<table>
<thead>
<tr>
<th>Source</th>
<th>(N_{\text{events}}) ((\pm) stat (\pm) syst)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Signal, (m_{H^+} = 120) GeV</td>
<td>151 (\pm) 12 (\pm) 18</td>
</tr>
<tr>
<td>Signal, (m_{H^+} = 300) GeV</td>
<td>168 (\pm) 2 (\pm) 16</td>
</tr>
<tr>
<td>EW+t(t) with (\tau_h) (data)</td>
<td>283 (\pm) 12 (\pm) 55</td>
</tr>
<tr>
<td>Multijet background (data)</td>
<td>80 (\pm) 3 (\pm) 9</td>
</tr>
<tr>
<td>EW+t(t) no (\tau_h) (sim.)</td>
<td>47 (\pm) 2 (\pm) 10</td>
</tr>
<tr>
<td>Total expected</td>
<td>410 (\pm) 12 (\pm) 57</td>
</tr>
<tr>
<td>Data</td>
<td>392</td>
</tr>
</tbody>
</table>

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<table>
<thead>
<tr>
<th>$m_{H^+}$ [GeV]</th>
<th>$-2\sigma$</th>
<th>$-1\sigma$</th>
<th>median</th>
<th>$+1\sigma$</th>
<th>$+2\sigma$</th>
</tr>
</thead>
<tbody>
<tr>
<td>95% CL upper limit on $\sigma(pp \to t(b)H^+)$ with $B(H^+ \to tb) = 1$</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>180</td>
<td>1.07</td>
<td>1.43</td>
<td>2.01</td>
<td>2.81</td>
<td>3.78</td>
</tr>
<tr>
<td>200</td>
<td>0.87</td>
<td>1.16</td>
<td>1.62</td>
<td>2.27</td>
<td>3.07</td>
</tr>
<tr>
<td>220</td>
<td>0.62</td>
<td>0.83</td>
<td>1.16</td>
<td>1.64</td>
<td>2.20</td>
</tr>
<tr>
<td>250</td>
<td>0.49</td>
<td>0.66</td>
<td>0.93</td>
<td>1.31</td>
<td>1.78</td>
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<tr>
<td>300</td>
<td>0.33</td>
<td>0.45</td>
<td>0.62</td>
<td>0.88</td>
<td>1.18</td>
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<tr>
<td>400</td>
<td>0.22</td>
<td>0.29</td>
<td>0.40</td>
<td>0.57</td>
<td>0.76</td>
</tr>
<tr>
<td>500</td>
<td>0.15</td>
<td>0.20</td>
<td>0.28</td>
<td>0.39</td>
<td>0.52</td>
</tr>
<tr>
<td>600</td>
<td>0.10</td>
<td>0.14</td>
<td>0.19</td>
<td>0.27</td>
<td>0.36</td>
</tr>
</tbody>
</table>

CMS search for charged Higgs bosons

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