CMS Higgs physics results

Martin Flechl (HEPHY Vienna)  
for the CMS Collaboration  
La Thuile, Moriond 2019,  
March 23rd, 2019
CMS Higgs results released in March 2019

- $h_{125} \rightarrow \gamma \gamma$
- $h_{125} \rightarrow 4\ell$
- $h_{125} \rightarrow \tau\tau$
- $A \rightarrow Zh_{125}$, $h_{125} \rightarrow bb$
- Heavy $H \rightarrow WW$
- $tth_{125}$, $h_{125} \rightarrow inv$
- $h_{125} \rightarrow inv$ combination
- $h_{125} \rightarrow J/\psi J/\psi$ & $YY$
- $h_{125} \rightarrow a_{1}a_{1} \rightarrow 4\tau$
- Heavy $H \rightarrow ttbar$
- $A \rightarrow Zh_{125} \rightarrow \ell\ell\tau\tau$
- $H^{+} \rightarrow \tau\nu$
- $H^{+} \rightarrow tb$
- $H^{+} \rightarrow AW$

=> Meng‘s talk
=> Meng‘s talk
=> Meng‘s talk
=> Stephanie‘s talk
=> Stephanie‘s talk

Rare $h_{125}$ decays

Heavy neutral Higgs bosons

Charged Higgs bosons
**tth\(^{125}\), h\(^{125}\) → invisible**

**First h → invisible bounds using tth topology**

- **Reinterpretation of stop searches**
  - Combines three analyses:
    
    | Analysis | Backgrounds                                      |
    |----------|-------------------------------------------------|
    | 0L       | tt(1L), Z→vv and ttZ(→vv)                       |
    | 1L       | tt(2L), W+jets and ttZ(→vv)                     |
    | 2L       | tt(2L), ttZ(→vv) and DY/VV                      |

→ 0L/1L/2L + (b) jets + MET

B(H→inv)<0.46 (exp: 0.48)

**Boosted W/top: jets**

**Modified topness**
$h_{125} \rightarrow$ invisible combination

**Motivation: dark matter**

- New: combination with run 1 & 2015 results (VBF, VH, gg→H+jet)
- $B(H \rightarrow \text{inv}) < 0.19$ (exp: 0.15)
  [previous, CMS 2016: 0.26 (0.20)]
- Higgs portal interpretation

**Best LHC limit!**

See Deborah Pinna’s talk (Tuesday)
h_{125} \rightarrow J/\psi \ J/\psi \ and \ YY

Almost background-free \rightarrow sensitivity \ scales \ with \ luminosity

- SM prediction small & uncertain
  - BSM enhancement (new amplitudes)?
- Dedicated trigger: 2\mu – m(J/\psi) \quad 3\mu – m(Y)
- Low-p_T muons: p_T > 3 \text{ GeV}

<table>
<thead>
<tr>
<th>Limit</th>
<th>observed</th>
<th>expected</th>
</tr>
</thead>
<tbody>
<tr>
<td>\mathcal{B}(H \rightarrow J/\psi J/\psi) \times 10^3</td>
<td>1.8</td>
<td>1.8^{+0.2}_{-0.1}</td>
</tr>
<tr>
<td>\mathcal{B}(H \rightarrow YY) \times 10^3</td>
<td>1.4</td>
<td>1.4 \pm 0.1</td>
</tr>
<tr>
<td>\mathcal{B}(Z \rightarrow J/\psi J/\psi) \times 10^6</td>
<td>2.2</td>
<td>2.8^{+1.2}_{-0.7}</td>
</tr>
<tr>
<td>\mathcal{B}(Z \rightarrow YY) \times 10^6</td>
<td>1.5</td>
<td>1.5 \pm 0.1</td>
</tr>
</tbody>
</table>

SM: \mathcal{B}(H \rightarrow J/\psi \ J/\psi) \approx 1.5 \times 10^{-10}
\mathcal{B}(H \rightarrow YY) \approx 2 \times 10^{-9}

PRD 79 (2009) 114015
\[ h_{125} \rightarrow a_1 a_1 \rightarrow 4\tau / 2\tau 2\mu \]

**Motivation: 2HDM+singlet [NMSSM]**

- Range: \( m(a_1) = 4\text{–}15 \text{ GeV}, m(h) = 125 \text{ GeV} \)
- Highly boosted \( a_1 \) boson, non-isolated muons
- Selection: SS \( \mu \) pair + two 1-prong \( \tau \) decays (OS wrt nearest \( \mu \))
- 2D observable \( m(\mu_1, \text{trk}_1) \) vs \( m(\mu_2, \text{trk}_2) \)
- Improves Run-1 CMS limits by up to a factor 10 \([\rightarrow \text{more than lumi scaling}]\)
Heavy H→ttbar

MSSM, low tan β, m(H)>2m(t): B(H→ttbar)≈1

- Search for gg→A/H→ttbar
  - Strong interference with SM ttbar:
    - Peak-dip structure
  - ℓ+jets and ℓℓ channel
  - ttbar kinematic reconstruction

ℓ+jets 2D observable:

\[ m_{tt}, \cos \theta(t_ℓ)^* \]

angle: leptonic top in ttbar frame, ttbar system in lab frame

SM ttbar A(500)
Heavy H→ttbar

- Non-linear model; signal would actually be a deficit in some bins
  \[ \lambda_i(\mu, p, \nu) = \mu \sum_{\Phi=H, A} \left( g_{\Phi H}^4 \cdot s_{R,i}(p, \nu) + g_{\Phi H}^2 \cdot s_{I,i}(p, \nu) \right) + b_i(\nu) \]

- Model-independent limits interpreted in the hMSSM

- Event excess/deficit at 
  \[ A(m=400 \text{ GeV}; \Gamma=4\%) : \]
  - local 3.8\(\sigma\), global 2\(\sigma\).
    - driven by the (less sensitive) \(\ell\ell\) channel
What if $A$ is too light to decay to $\text{ttbar}$?

**MSSM:** $B(A \to Zh) \approx 1$ [low $\tan \beta$, $m_A \approx 200-350$ GeV]

- **Target:** $gg \to A$, with $m(h) = 125$ GeV
- **$m(A)$:** SVFit (likelihood-based) estimator with $m(h) = 125$ GeV constraint
- **Cross section limits also interpreted in MSSM context**
Main motivation: MSSM, high tan $\beta$

- Channels: $\tau+$jets, $\tau+1l$, $0\tau+1l$
  - 36 categories, e.g. #jets & polarisation estimate $R_\tau = \frac{p_T^{\tau,\text{track}}}{p_T^{\tau,\text{gen}}}$
- Low-mass ($t\to bH^+$), high-mass ($gg\to tbH^+$), and intermediate-mass (interference, 1$^{\text{st}}$ time in CMS)
- Cross section limits from 80-3000 GeV
H+ → tb

Main motivation: MSSM, low tan β

- Channels: 1ℓ, 2ℓ
  - Categorized by #jets and #b-jets
- ML-driven final discriminants, primarily vs ttbar
  - 1ℓ: BDT [13 input variables]
  - 2ℓ: DNN, parametrized wrt m(H+) [16 input variables]
- Mass range: 200 – 3000 GeV
$H^+ \rightarrow AW, \ A \rightarrow \mu\mu$

Main motivation: 2HDM, light $H^+$, low tan $\beta$

- $t \rightarrow bH^+$, in type I/II 2HDM: $B(H^+\rightarrow AW) \approx 1$ possible
- Channels: $3\mu$, $1e2\mu$
- $B(t \rightarrow bH^+)<0.6%-2.9\%$, [\(B(H^+\rightarrow AW)=1\), \(B(A\rightarrow \mu\mu)=3\times10^4\)]

First time since LEP!
Conclusions

- This month, a wealth of Higgs results pushing the boundaries of various BSM models has been released – with just a quarter of the full Run-2 data for most analyses, and analysis improvements still in the pipeline!

- Stay tuned for the full Run 2 results...
References

- $H \rightarrow \gamma\gamma\gamma$ CMS-PAS-HIG-18-029 => Meng
- $H \rightarrow 4\ell$ CMS-PAS-HIG-19-001 => Meng
- $H \rightarrow \tau\tau$ CMS-PAS-HIG-18-032 => Meng
- $A \rightarrow Zh, h \rightarrow bb$ arXiv:1903.00941, EPJC => Stephanie
- Heavy $H \rightarrow WW$ CMS-PAS-HIG-17-033 => Stephanie
- $H^+ \rightarrow \tau\nu$ arXiv:1903.04560, JHEP
- $H^+ \rightarrow tb$ CMS-PAS-HIG-18-004
- $H^+ \rightarrow AW$ CMS-PAS-HIG-18-020
- $H \rightarrow J/\psi J/\psi$ and YY CMS-PAS-HIG-18-025
- $H \rightarrow t\bar{t}b$ CMS-PAS-HIG-17-027
- $H \rightarrow aa \rightarrow 4\tau$ CMS-PAS-HIG-18-006
- $A \rightarrow Zh \rightarrow l\ell\tau\tau$ CMS-PAS-HIG-18-023
- LFV $H$, high-mass CMS-PAS-HIG-18-017
- $ttH, H \rightarrow inv$ CMS-PAS-HIG-18-008
- $H \rightarrow inv$ combination arXiv:1809.05937, PLB
**ttH inv 0L**

- **Cornerstone of the search:**
  Identification of hadronically decaying top and W using multivariate methods [i.e. BDT]
  - “Merged top and W”:
    - Highly boosted top/W: Jet substructure methods, flavour tagging... on R=0.8 jets
  - “Resolved top”:
    - Moderately boosted tops
    - Use of standard jets with R=0.4

**Search carried out on all possible combinations of merged top/W & resolved top**

- Events are further categorized by:
  - $N_j$, $N_b$, $m_T^{b,\text{min}}$ & $M_{E_T}$ [all SR are orthogonal]

- Main backgrounds: ttbar (1L), Z-$\to$vv, ttZ-$\to$vv
ttH inv 1L

- Baseline selection: 1L, $N_j>=2$, $N_b>=1$, $ME_T>250$ GeV
  
  $M_T(L, ME_T)>150$ GeV

- Key players: tt(2L) killers

- Events further categorized based on:
  $N_j$, $M_{Lb}$ and $ME_T$

- Main backgrounds: ttbar(2L), W+jets, ttZ(->vv)

- Modified topness

  Inspired from: arXiv: 1212.4495

  $$S(\bar{p}_W, p_{WZ}) = \frac{(m_W^2 - (p_W + p_T)^2)^2}{a_W^2} + \frac{(m_T^2 - (p_b + p_W)^2)^2}{a_t^4}$$
**ttH inv 2L**

- **Search with opposite charge e/μ**
  - Main discriminating variables: $M_{T2}$ and different flavors of $M_{T2}$

  $$M_{T2}^2(ll) = \min_{p_1+p_2=p_f} \left[ \max \left\{ m_T^2(p_{11}, p_{1}), m_T^2(p_{22}, p_{2}) \right\} \right]$$

- **Main backgrounds:** tt(2L), ttZ(-v v) and DY/VV

- **CMS Simulation**
  - L = 36.4 fb⁻¹ (13 TeV)
  - ttH/W, tZq, twZ
  - DY (LO, HT)
  - multiboson
  - ttZ
  - tt(2L): end point in mass of W
  - $M_{T2}^2(ll) > 100$ GeV

- **M_{T2}bll:** Similar to $M_{T2}ll$ with the use of bs

- **CMS Simulation**
  - 35.9 fb⁻¹ (13 TeV)
  - ttH/W, tZq, twZ
  - Drell-Yan
  - multiboson
  - ttH, H→invisible
  - $M_{T2}^2(ll)$ (GeV)
  - tt(2L): end point in mass of top
  - $M_{T2}^2(ll)$ (GeV)
ttH inv

CMS Preliminary

Events

A: $N_j \leq 3$, $t_{mod} > 10$, $M_{tb} \leq 175$ GeV
B: $N_j \leq 3$, $t_{mod} > 10$, $M_{tb} > 175$ GeV
C: $N_j \geq 4$, $t_{mod} \leq 0$, $M_{tb} \leq 175$ GeV
D: $N_j \geq 4$, $t_{mod} \leq 0$, $M_{tb} > 175$ GeV
E: $N_j \geq 4$, $0 < t_{mod} \leq 10$, $M_{tb} \leq 175$ GeV
F: $N_j \geq 4$, $0 < t_{mod} \leq 10$, $M_{tb} > 175$ GeV
G: $N_j \geq 4$, $t_{mod} > 10$, $M_{tb} \leq 175$ GeV
H: $N_j \geq 4$, $t_{mod} > 10$, $M_{tb} > 175$ GeV

Lost Lepton
$1'$ (not from t)
ttH, H\rightarrow invisible
Z\rightarrow \nu\nu
Total uncertainty
B(H\rightarrow invisible) = 100%

Data
ttH inv

- 0L

- 1L/2L
ttH inv combi systematics

<table>
<thead>
<tr>
<th>Source</th>
<th>All-hadronic</th>
<th>Semi-leptonic</th>
<th>Di-leptonic</th>
</tr>
</thead>
<tbody>
<tr>
<td>QCD scale cross section</td>
<td>+5.8/-9.2%</td>
<td>+5.8/-9.2%</td>
<td>+5.8/-9.2%</td>
</tr>
<tr>
<td>QCD scale acceptance</td>
<td>0.7–14.0%</td>
<td>0.8–30.0%</td>
<td>1.0–7.0%</td>
</tr>
<tr>
<td>PDF cross section</td>
<td>3.6%</td>
<td>3.6%</td>
<td>3.6%</td>
</tr>
<tr>
<td>PDF acceptance</td>
<td>0.6–3.7%</td>
<td>0.5–4.0%</td>
<td>1.0–1.9%</td>
</tr>
<tr>
<td>Sample statistics</td>
<td>1.0–10.0%</td>
<td>1.6–11.2%</td>
<td>3.3–26.4%</td>
</tr>
<tr>
<td>Luminosity</td>
<td>2.5%</td>
<td>2.5%</td>
<td>2.5%</td>
</tr>
<tr>
<td>Trigger</td>
<td>2.0%</td>
<td>2.0%</td>
<td>0.2–0.5%</td>
</tr>
<tr>
<td>Pileup</td>
<td>0.2–2.0%</td>
<td>0.1–2.5%</td>
<td>0.0–3.0%</td>
</tr>
<tr>
<td>Jet energy scale</td>
<td>2.8–7.6%</td>
<td>2.8–9.7%</td>
<td>0.0–9.0%</td>
</tr>
<tr>
<td>B-tagging scale factor</td>
<td>0.3–3.3%</td>
<td>1.2–1.6%</td>
<td>0.1–1.3%</td>
</tr>
<tr>
<td>Lepton efficiency</td>
<td>0.0–0.7%</td>
<td>3.0–3.1%</td>
<td>3.8–5.5%</td>
</tr>
<tr>
<td>Unclustered $p_T^{miss}$</td>
<td>0.2–1.8%</td>
<td>0.1–12.3%</td>
<td></td>
</tr>
<tr>
<td>Top/W tagging</td>
<td>1.0 – 20%</td>
<td>–</td>
<td>–</td>
</tr>
</tbody>
</table>
Within 95% CL of Run 1 combination: BR < 0.14–0.24 (0.11–0.19)
**h → mesons**

Predictions for:

A.K. Likhoded, A.V. Luchinsky,
Double Charmonia Production in Exclusive Z Boson Decays,

- Applies Same Formalism as Higgs
  \[ B(Z \to J/\psi \ J/\psi) \approx 10^{-12} \]

Naïve:

\[ Z \to \gamma \ J/\psi \Rightarrow B(Z \to J/\psi J/\psi) \approx 6 \cdot 10^{-11} \]

\[ B(Z \to Y \ Y) \approx ? \]

strongly suppressed in SM

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**2017 Data**

- CMS Preliminary
- 37.5 fb⁻¹ (13 TeV)

- Data
- Background
- Model Boson Signals

**Simulation: Background**

Non Prompt Non resonant \(J/\psi\) pairs
Production model
- Dominantly produced via ggF [1-4]
- \(J/\psi\) are color octet bound states that radiate soft gluon decaying into real \(J/\psi\)
- generated with this [3]

For Non Prompt Non resonant \(Y\) Pairs
- Same production model with \(Y\) mass

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**2017 Datasets**

- Run2017C-17Nov2017-v1/AOD
- Run2017D-17Nov2017-v1/AOD
- Run2017E-17Nov2017-v1/AOD
- Run2017F-17Nov2017-v1/AOD

**Luminosity**

- 37.5 fb⁻¹

**Higgs**

MC Event Generator
- POWHEG v2.0 (includes ggF and VBF)
- NNPDF3.1

To decay
- JHUGen generator 7.1.4

Hadronization and Fragmentation
- PYTHIA 8.226, tune CUETP8M1

---

References:

**h → mesons**

- **Unbinned ML fit to data**

  - **Data J/ψ J/ψ**
    - #189 Candidate Events
    - Acceptance x Efficiency: 23%

  - **Background Model**
    - \( F_{bkg}(x) = e^{c \cdot x} + \text{Uniform} \)

  - **Signal Model**
    - (2 events shown for demonstration)
    - Higgs-Signal - Double Gaussian
    - Z-Signal - Voigtian

  - **RooFit** - Extended ML Fit [1]

  - Muon Criteria
    - \( \geq 4 \) soft muons, each \( p_T > 3 \text{ GeV} \) and \( |\eta| < 2.4 \)
    - Isolation: \( \Delta R = 0.3 \quad \text{Sum}(p_T)/p_T < 0.5 \)

  - **Data YY**
    - #106 Event Candidates
    - Acceptance x Efficiency: 27%

  - **Background Model**
    - \( F_{bkg}(x) = e^{c \cdot x} \)

  - **Signal Model**
    - (for demonstration 2 signal events)
    - Higgs-Signal - Double Gaussian
    - Z-Signal - Voigtian

  - **RooFit** - Extended ML Fit [1]

- **Di-Muon Criteria**

  - \( \text{Di-muon candidate, P vtx}(\mu^+ \mu^-) > 0.5\% \quad \geq 2 \text{ di-muon candidates, } m(J/\psi) \in [3.0, 3.2], [2.95,3.25] \text{GeV} \)
  - \( m(Y) \in [8.5, 11] \text{ GeV} \)
  - \( p_T(J/\psi) > 3.5 \text{ GeV} \)
  - \( p_T(Y) > 5 \text{ GeV} \)

- **4-Muon Criteria**

  - \( 4 \text{ muon Vtx Prob}(J/\psi) > 5\% \)
  - \( \text{Prob}(Y) > 1\% \quad |\Delta y| < 3.0 \)
MC event generator PYTHIA 8.2 used to model the NMSSM Higgs boson signal $H(125) \to 2a_1 \to 4\tau$ produced via ggF, VBF, VH and $t\bar{t}H$ for different $a_1$ mass points

- Samples created within the official production campaigns in summer 2016

MC event generator MADGRAPH5_aMC@NLO2.2.2 used to model the NMSSM Higgs boson signal $H(125) \to 2a_1 \to 2\tau 2\mu$ produced via ggF for different $a_1$ mass points

- Samples were privately produced and approved by MC generator group

**MUONS:**

- Two muons are selected if they are identified as muons by the particle-flow (PF) algorithm while they are reconstructed by the Global reconstruction algorithm, also if:
  - $p_T > 9$ GeV, $|\eta| < 2.4$, matches Mu8 leg
  - $p_T > 18$ GeV, $|\eta| < 2.4$, matches Mu17 leg
  - Pass HIP-safe Medium (Medium) ID formulated by the Muon POG for the Run2016 B-F (Run2016 G-H) data-taking period
  - no isolation requirement imposed
  - impact parameter w.r.t. primary vertex
    - $|d_0| < 0.5$ mm
    - $|d_z| < 1.0$ mm
    - $\Delta R(\mu_1, \mu_2) > 2$ & Same sign requirement
    - If # same-sign muon pair $>1$ → pair with the largest sum of muons $p_T$ chosen

**TRACKS:**

- Charged PF objects
  - Good quality tracks following Tracking POG recommendations
  - $p_T(trk) > 1$ GeV, $|\eta| < 2.4$
  - Loose impact parameter requirements on the tracks: $|d_{xy}| < 1.0$ cm, $|d_z| < 1.0$ cm
Main differences of HIG-18-006 w.r.t HIG-14-019:

- 13 TeV & 35.9 fb⁻¹
- Mass range extended up to 15 GeV
- All production modes (ggH, VBF, VH, ttH) and \( H(125) \rightarrow a_1 a_1 \rightarrow 2\mu 2\tau \) channel included
- More robust and reliable background model
## aa→4tau systematics

<table>
<thead>
<tr>
<th>Source</th>
<th>Value</th>
<th>Affected sample</th>
<th>Type</th>
<th>Effect on the total yield</th>
</tr>
</thead>
<tbody>
<tr>
<td>Statistical uncertainties in C(i,j)</td>
<td>3–60%</td>
<td>bkg.</td>
<td>bin-by-bin</td>
<td>¬</td>
</tr>
<tr>
<td>Uncertainty in the ID template ( f_{ID}(i) )</td>
<td>–</td>
<td>bkg.</td>
<td>shape</td>
<td>¬</td>
</tr>
<tr>
<td>Integrated luminosity</td>
<td>2.5%</td>
<td>signal</td>
<td>norm.</td>
<td>2.5%</td>
</tr>
<tr>
<td>Muon ID and trigger efficiency</td>
<td>2% per muon</td>
<td>signal</td>
<td>norm.</td>
<td>4%</td>
</tr>
<tr>
<td>Track selection and isolation efficiency</td>
<td>4–12% per track</td>
<td>signal</td>
<td>shape</td>
<td>10–18%</td>
</tr>
<tr>
<td>MC stat. uncertainties in signal yields</td>
<td>8–100%</td>
<td>signal</td>
<td>bin-by-bin</td>
<td>5–20%</td>
</tr>
</tbody>
</table>

### Theory uncertainties in the signal acceptance

- \( \mu_F \) and \( \mu_f \) variations: 0.8–2%
- PDF: 1–2%

### Theory uncertainties in the signal cross sections

<table>
<thead>
<tr>
<th>Source</th>
<th>Value</th>
<th>Affected sample</th>
<th>Type</th>
<th>Effect on the total yield</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \mu_F ) and ( \mu_f ) variations (gg → H(125))</td>
<td>–</td>
<td>signal</td>
<td>norm.</td>
<td>+4.6%</td>
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<tr>
<td>( \mu_F ) and ( \mu_f ) variations (VBF)</td>
<td>–</td>
<td>signal</td>
<td>norm.</td>
<td>-6.7%</td>
</tr>
<tr>
<td>( \mu_F ) and ( \mu_f ) variations (VH)</td>
<td>–</td>
<td>signal</td>
<td>norm.</td>
<td>-0.3%</td>
</tr>
<tr>
<td>( \mu_F ) and ( \mu_f ) variations (ttH)</td>
<td>–</td>
<td>signal</td>
<td>norm.</td>
<td>+1.8%</td>
</tr>
<tr>
<td>PDF (gg → H(125))</td>
<td>–</td>
<td>signal</td>
<td>norm.</td>
<td>-1.8%</td>
</tr>
<tr>
<td>PDF (VBF)</td>
<td>–</td>
<td>signal</td>
<td>norm.</td>
<td>-5.8%</td>
</tr>
<tr>
<td>PDF (VH)</td>
<td>–</td>
<td>signal</td>
<td>norm.</td>
<td>-0.2%</td>
</tr>
<tr>
<td>PDF (ttH)</td>
<td>–</td>
<td>signal</td>
<td>norm.</td>
<td>3.1%</td>
</tr>
<tr>
<td>PDF (gg → VH)</td>
<td>–</td>
<td>signal</td>
<td>norm.</td>
<td>2.1%</td>
</tr>
<tr>
<td>PDF (ttH)</td>
<td>–</td>
<td>signal</td>
<td>norm.</td>
<td>1.8%</td>
</tr>
<tr>
<td>PDF (ttH)</td>
<td>–</td>
<td>signal</td>
<td>norm.</td>
<td>3.6%</td>
</tr>
</tbody>
</table>

QCD multijet events dominate the final selected sample.

Contribution from other backgrounds sources constitutes \( \sim 1\% \) of all selected events.

Modeling of background shape done with data and modeling of signal done with simulation.

**Modeling of the background shape derived from 2D probability density function → explanation given in next slide**
h→aa run 1 summary
$A \rightarrow t\bar{t}b$  

**ATLAS:**  
*Phys. Rev. Lett. 119, 191803*

**FIG. 3.**

The 95% C.L. observed and expected exclusion regions for the type-II 2HDM ($\mu = 1$) considering only a pseudoscalar $A$ (left), only a scalar $H$ (middle), and the mass-degenerate scenario $m_A = m_H$ (right). Blue points indicate parameter values at which signal samples are produced.

**Search for $A/H \rightarrow t\bar{t}b$ produced through gluon fusion**
- Simulation with MG5 at LO scaled to N$^3$LO
- No BSM particles are allowed in the loop
- Signal points form a grid in $m_A/H \times \Gamma_A/H$ space
- Consider only pure $A$ or pure $H$

**SM $t\bar{t}b$ is the dominant bkg by far**

Set limits on coupling strength modifier $g_{A/H}$
- $A/H$ production interferes strongly with SM
- Resonance scales as $g_{A/H}^4$, interference $g_{A/H}^2$
- Leads to a peak-dip structure in $\frac{d\sigma_{t\bar{t}}}{dm_{t\bar{t}}}$ spectrum

**Yukawa-like coupling means large top contributions**
- Direct $A \rightarrow WW$ is forbidden
- $H \rightarrow WW$ is suppressed in the alignment limit $h = h(125)$
- $BR(A/H \rightarrow t\bar{t}) \sim 1$ if $m_{A/H} \gtrsim 2m_t$
A → ttbar

**l + jets channel:**
- Single lepton triggers
- Exactly 1 tight e or μ
- ≥ 4 jets, ≥ 2 b-tagged
- $m_T > 50$ GeV
- In-house single e trigger SFs
- Data-driven multijet bkg (ABCD method)

**ll channel:**
- Double + single lepton triggers
- Exactly 2 tight e or μ
- ≥ 2 jets, ≥ 1 jet b-tagged
- $m_{ll} > 20$ GeV
- In ee and $\mu\mu$: DY-veto cuts
- Trigger SFs from AN-2016-392
- Lepton scale corrections and smearing
- Data-driven DY bkg ($R_{\text{out/in}}$ method)

*tt* kinematic reconstruction is the same as in TOP-16-008 (*l + jets*) and TOP-16-011 (ll)
- Events not passing this reconstruction are rejected

<table>
<thead>
<tr>
<th>Process</th>
<th>Muon channel</th>
<th>Electron channel</th>
</tr>
</thead>
<tbody>
<tr>
<td>Observed</td>
<td>416254</td>
<td>274821</td>
</tr>
<tr>
<td>Signal $A \to t\bar{t}$ ($m_A = 500$ GeV, $\Gamma_A/m_A = 5%$)</td>
<td>$(1.5^{+0.9}_{-0.8}) \times 10^3$</td>
<td>$(0.9^{+0.6}_{-0.5}) \times 10^3$</td>
</tr>
<tr>
<td>Total background</td>
<td>$(416.3^{+1.1}_{-1.2}) \times 10^3$</td>
<td>$(274.8^{+0.8}_{-0.9}) \times 10^3$</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Process</th>
<th>Event yield</th>
</tr>
</thead>
<tbody>
<tr>
<td>Observed</td>
<td>230233</td>
</tr>
<tr>
<td>Signal $A \to t\bar{t}$ ($m_A = 500$ GeV, $\Gamma_A/m_A = 5%$)</td>
<td>$(0.7^{+0.5}_{-0.4}) \times 10^3$</td>
</tr>
<tr>
<td>Total background</td>
<td>$(231.1 \pm 0.8) \times 10^3$</td>
</tr>
</tbody>
</table>
A → ttbar, l+jets

Search observables

- Exploit 2D distribution of $m_{t\bar{t}}$ and the angle $|\cos \theta^*_{t, \ell}|$ probing the spin of s-channel propagator
- 25 $m_{t\bar{t}}$ bins based on resolution and statistical power
- $|\cos \theta^*_{t, \ell}|$ is the angle between leptonic top in $t\bar{t}$ ZMF and $t\bar{t}$ system in lab frame
- Flat for A/H resonance, peaks at 1 for SM at parton level, full phase space
- 5 $|\cos \theta^*_{t, \ell}|$ bins with non-uniform edges based on signal vs SM shapes
- Analysis template has 25 × 5 bins each in e and $\mu$ channels
Search observables

- Exploit 2D distribution of $m_{t\bar{t}}$ and the angle $c_{\text{hel}}$
  probing the spin of s-channel propagator
- 23 $m_{t\bar{t}}$ bins based resolution and statistical power
- $c_{\text{hel}}$ is the angle between the leptons in their parent top helicity frames in $t\bar{t}$ ZMF
- Discriminates both $A/H$ vs SM and $A$ vs $H$
- Use 5 equidistant $c_{\text{hel}}$ bins
- Analysis template has $23 \times 5$ bins in combined $ee + \mu\mu + e\mu$ channel
A→ttbar, A limits
A → ttbar, H limits
A→Zh, lltautau

AZh signal samples targeting gluon fusion production of A boson

- Based on mhmod" model, with low tanβ (~ 2)
- Cover nine mass points: 220, 240, 260, 280, 300, 320, 340, 350, and 400 GeV

Background measurements

- **Irreducible background** (ZZ→4l, WWZ, WZZ, ZZZ, ttZ...) contribution taken from MC
  - Contributes to ~50% of the total background yield
- **Reducible background** (WZ+jets, Z+jets, ttbar) estimated by the fake rate method

This analysis uses 2016 data corresponding to 35.9 fb⁻¹

- Double electron, single electron, double muon, and single muon data sets
- Follows closely the standard model VH analysis ([HiG-16-007](#))
  - For example, the trigger selection is identical
- Multiple changes compared to the 8 TeV analysis ([HiG-14-034](#))
  - The most important change in the analysis strategy:
    - constrain mass of the Higgs boson h to 125 GeV when reconstructing the 4-vect
      - a notable improvement in the performance is achieved!

Passes conversion veto, missing hits < 2

\[
\text{e: } p_T > 10 \text{ GeV, } |\eta| < 2.5 \\
\text{dR between light leptons} > 0.3 \\
\text{dXY < 0.045, } dZ < 0.2 \\
\text{Trigger matching within } dR<0.5
\]

Selection of hadronic taus

\[
\begin{align*}
\tau_h: & \quad p_T > 20 \text{ GeV, } |\eta| < 2.3 \\
\text{id, 95% efficiency} & \quad \text{Passing Old Decay Mode Finding} \\
\text{dR between tau and any lepton} > 0.5 \\
dZ < 0.2
\end{align*}
\]

Consider all tau decays (leptonic and hadronic): \(\tau\nu \rightarrow \tau_h\tau_h, \, \mu\tau_h, \, e\tau_h, \, e\mu\)
(no \(\tau\nu\rightarrow\mu\mu\) and \(\tau\nu\rightarrow\eta\eta\))
\textbf{H}^+ \rightarrow \text{\(\text{\(\tau\))} \nu}

- \(\tau_h + \text{jets: hadronic final state (events with an electron or muon are vetoed);}
- \(\ell + \tau_h: \text{leptonic final state with a hadronically decaying tau lepton (events with additional electrons or muons are vetoed); and}
- \(\ell + \text{no } \tau_h: \text{leptonic final state without a hadronically decaying tau lepton (events with a } \tau_h \text{ or additional electrons or muons are vetoed).}

The selected events are classified into two categories based on the value of the variable \(R_\tau = p_T^\text{track} / p_T^\tau\), reflecting the helicity correlations emerging from the opposite polarization states of the tau leptons originating from \(W^\pm\) and \(H^\pm\) decays [79]. The distribution of the \(R_\tau\) variable is

The selected events are classified into several categories for statistical analysis. Three categories are defined based on the jet multiplicity and the number of jets passing the b jet identification: \(1j1b\) (one jet, also identified as a b jet), \(\geq2j1b\), and \(\geq2j2b\). A second categorization is performed in bins of \(p_T^\text{miss}\): 70–100, 100–150, and >150 GeV. Together with the separate electron and muon final states, this results in 18 categories. The signal-to-background ratio in different as in the \(\ell + \tau_h\) final state is established. Four categories are used based on jet multiplicity and the number of jets passing the b jet identification: \(2j1b\), \(2j2b\), \(3j1b\), and \(3j\geq2b\), followed by two categories in \(p_T^\text{miss}\): 100–150 and >150 GeV. Together with the separate electron and muon final states, this results in 16 categories.
The signal samples for the light $H^\pm$ mass values from 80 to 160 GeV are generated at next-to-leading order (NLO) with the MadGraph5_aMC@NLO v2.3.3 [44] generator, assuming $H^\pm$ production via top quark decay ($pp \to H^\pm W^\mp b\bar{b}$). For the heavy $H^\pm$ mass range from 180 GeV to 3 TeV, the same approach is used except that $H^\pm$ production via $pp \to tbH^\pm$ is assumed. For the intermediate mass range from 165 to 175 GeV, the samples are generated at LO using the MadGraph5_aMC@NLO v2.3.3 with the model described in Ref. [20], which is available only at LO.
**H+ → taunu**

**Electrons:**
- tight: MVA with 88% signal eff. (custom), $p_T > 35 \text{ GeV}$, $|\eta| < 2.1$ (trg.), mini-iso < 0.1
- loose (for veto): MVA with 95% signal eff. (custom), $p_T > 10 \text{ GeV}$, $|\eta| < 2.1$, mini-iso < 0.4

**Muons:**
- tight: POG medium cut-based, $p_T > 30 \text{ GeV}$, $|\eta| < 2.4$, mini-iso < 0.1
- loose (for veto): POG loose cut-based, $p_T > 30 \text{ GeV}$, $|\eta| < 2.4$, mini-iso < 0.4

**Taus:**
- old decay mode finding, loose MVA isolation, discriminator against electrons and muons
- hadronic final state: $p_T > 50 \text{ GeV}$ (trg.), $|\eta| < 2.1$, leading track $p_T > 30 \text{ GeV}$ (trg), 1-prong only
- leptonic final state: $p_T > 20 \text{ GeV}$, $|\eta| < 2.3$, separated from leptons by $\Delta R > 0.4$

**Jets:**
- $p_T > 30 \text{ GeV}$, $|\eta| < 4.7$ for hadronic, $|\eta| < 2.4$ for leptonic
- separated from leptons by $\Delta R > 0.5/0.4$ (hadronic/leptonic)

**B-jets:** CSVv2 medium working point, $|\eta| < 2.4$

**MET:** PF MET + Type-I corrections
$H^+ \rightarrow \tau \nu$ 

Analysis strategy: hadronic final state

- BR 44%, sensitivity in light $H^+$ regime constrained due to trigger thresholds
- optimized event selection to enhance signal sensitivity

**Baseline selection**

- hadronic tau matched with HLT
- MET > 90 GeV
- at least 3 jets, one b-tagged jet
- veto on loose electrons or muons
- angular cut to suppress jet $\rightarrow$ fake $\tau_h$

\[ R_{bb}^{\text{min}} = \min_{j_{1} \neq j_{2} \neq j_{3}} \sqrt{\Delta \phi(j_{1}, j_{2})^2 + (\pi - \Delta \phi(j_{1}, E_T))^2} > 40 \text{ deg} \]

recoiling jet back to back with $\tau$ jet

MET from over-estimation of $\tau_p T$ (back to back)
H+ → taunu

Analysis strategy: hadronic final state

→ BR 44%, sensitivity in light H± regime constrained due to trigger thresholds
→ optimized event selection to enhance signal sensitivity

Categorization based on $R_{\tau}$

- $H^\pm$ is a scalar, $W^\pm$ is a vector boson → opposite polarization states of $\tau$
- helicity correlations reflected in variable

$$R_{\tau} = \frac{p_{\tau}(\text{leading track})}{p_{\tau}(T_{\tau})}$$

→ high $R_{\tau}$ signal abundant
→ low $R_{\tau}$ also used to behouden statistical pc

- categorization based on $R_{\tau} > 0.75$ and $R_{\tau} < 0.75$
→ optimized across entire mass range
H+ → taunu

Analysis strategy: leptonic final state

→ BR 45 %, limited sensitivity in heavy H± regime due to jet multiplicity constraints
→ loose event selection, categorize to enhance signal sensitivity and constrain backgrounds

1l + T_h: leptonic final state w/ hadronic T
- tight lepton + trigger + hadronic T
- MET > 70 GeV
- one, two or three jets, one b-tagged jet
- veto on additional loose electrons or muons

1l + no T_h: leptonic final state w/o hadronic T
- tight lepton + trigger + veto hadronic T
- MET > 100 GeV (suppress QCD)
- two or three jets, one b-tagged jet
- veto on additional loose electrons or muons

High MET cuts to suppress QCD multijet events and fakes. Further suppression to a negligible amount by applying the following angular cuts:
- Δφ(MET, lepton) > 0.5 → suppress non prompt leptons (muonic b-hadron decays)
- Δφ(MET, leading jet) > 0.5 → suppress fake leptons (1l + no T_h only)
- min(Δφ(lepton, jet)) < π - 0.5 → suppress jet mismeasurements (1l + no T_h only)
H+ → taunu

Analysis strategy: leptonic final state

Categorization performed in four dimensions: final state (e/μ), jet multiplicity, b-jet multiplicity and MET

Jet and b-jet multiplicity
- sensitive for different mass hypotheses
- constrain dominant systematics
- 3 categories for 1l + T_h:
  - 1j/1b | 2-3j/1b | 2-3j/2-3b
- 4 categories for 1l + no T_h:
  - 2j/1b | 2j/2b | 3j/1b | 3j/2-3b

Categorization in MET bins
- low MET to constrain systematics, high MET for improved signal sensitivity
- 3 categories for 1l + T_h:
  - 70 < MET < 100 GeV | 100 < MET < 150 | MET > 150 GeV
- 2 categories for 1l + no T_h:
  - 100 < MET < 150, MET > 150 GeV

→ total categories: 34
H$^+ \rightarrow$ taunu
MultiVariate Analysis: 1L

- Technology: BDT with adaptive boosting
- 13 input variables: optimized from N+1 and N-1 studies, link
- Randomly split signal and background
  - training/testing/application
    - $1/3 \times 1/3 \times 1/3$ of signal samples and separate ttbar samples as described before
  - trained at each signal mass in the inclusive 4 signal regions against ttbar background
- improved discriminating power compared to HT
- consistent BDT response from other SM backgrounds

MultiVariate Analysis: 2L

- Technology: DNN
  - Keras platform with TensorFlow backend
- 16 input variables
- Randomly split signal and background
  - training/testing/application
    - $1/3 \times 1/3 \times 1/3$ of signal samples and separate ttbar samples
  - parametrized as function of the charged higgs mass
  - training in the inclusive $\geq 3$ jets and $\geq 1$ b-jets region against ttbar, ST, TT+X(X=Z/W/h)
- better performance over HT
- consistent DNN response from different ttbar heavy flavour process
H+ → AW

- Local linear bkg model

- Baseline selection for signal
  - 3 tight leptons (1e2μ, 3μ), no additional loose lepton
  - due to trigger threshold, $P_T(\mu) > 20$ GeV for leading muon in 3μ
  - includes at least 1 opposite-sign (OS) muon pair
  - $m_{\mu\mu} > 12$, $|m_{\mu\mu} - 91.2| > 10$ GeV for all OS muon pair
  - $\geq 2j(\geq 1b)$
H^+ \rightarrow AW