Latest results on $t\bar{t}H (H \to bb)$ production at CMS

Daniel Salerno
on behalf of the CMS Collaboration

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ttH production

**Motivation**
- Provides a **direct probe** of the important top–Higgs coupling
  - Yukawa coupling $y_t \sim 1$
  - Indirect loop measurements can be influenced by BSM physics
- First measurement of Higgs coupling to up-type fermion
- Non-SM ttH rate could indicate presence of new physics

**Properties**
- Xsec: 0.5071 pb ±6.8/−9.9%
  - NLO QCD and NLO EW accuracy
- **Expect ~18,000 SM ttH events** in 2016 data at CMS
  - ~ 36 fb$^{-1}$
- LO Feynman diagram:
**ttH, H → bb**

### Comments

- Largest Higgs branching ratio
- Pure fermion production and decay
- Complicated final state
  - Large object combinatorics
- Large backgrounds
- Irreducible tt+bb background is not accurately known
  - Large theoretical uncertainties

### Feynman diagram

```
g --t --W --H --b
/g /q,\ /q,\ /q,\ /q,\ /b /b
```

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**Overview of analyses**

### Leptonic analysis
- ttH(bb) events with 1/2 leptons
  - One or two leptonically decaying tops
    - Muons or electrons
  - Kills QCD multijet background
- Categorize events based on jet and b-jet multiplicity
- Uses BDTs and MEM as final discriminants
- Completed with 12.9 fb⁻¹ at 13TeV
  - CMS PAS HIG-16-038

**Presented here today**

### Fully hadronic final state
- All hadronic ttH(bb) decay provides access to large number of events
  - BR AH = 46%
- Fully reconstructed final state
  - 8 jets: 4 b-jets and 4 light-jets
- Large QCD background
Data and event selection

- **Triggers:**
  - Single / double lepton ($\mu, e$) triggers

- **Signal / background:**
  - All simulated samples with corrections
    - Powheg Box V2 + Phythia 8 for signal and $tt+$jets

- **Jets:** anti-$k_T$ ($R=0.4$)
  - Lepton+jets: $\geq 4$, $p_T > 30$ GeV
  - Dilepton: $\geq 2$, $p_T > 30$ (20 subleading) GeV

- **Leptons:**
  - Leptons+jets: 1 $\mu(e)$, $p_T > 25(30)$ GeV
  - Dilepton: 2 OS $\mu/e$, $p_T > 25, 15$ GeV

2012 data: 19.5 fb$^{-1}$ at 8 TeV
CMS-PAS-HIG-13-019 / EPJC 75 (2015) 251

2015 data: 2.7 fb$^{-1}$ at 13 TeV
CMS-PAS-HIG-16-004

2016 data: 12.9 fb$^{-1}$ at 13 TeV
CMS-PAS-HIG-16-038
Event categories

**Lepton+Jets Channel**
- $\geq 6$ jet, $\geq 4$ b-tags: $S/B=0.035$, $S/N=0.973$
- $\geq 6$ jets, $\geq 3$ b-tags: $S/B=0.011$, $S/N=0.895$
- $4$ jets, $4$ b-tags: $S/B=0.015$, $S/N=0.242$
- $5$ jets, $\geq 4$ b-tags: $S/B=0.024$, $S/N=0.532$

**Dilepton Channel**
- $\geq 4$ jets, $\geq 4$ b-tags: $S/B=0.040$, $S/N=0.417$
- $\geq 4$ jets, $\geq 3$ b-tags: $S/B=0.012$, $S/N=0.453$
- $3$ jets, $3$ b-tags: $S/B=0.004$, $S/N=0.084$

**CMS Simulation**
ttH vs. tt+jets: BDT discrimination

Overview

- Stochastic Gradient Boost method
- Separate training in each category (total 7 BDTs)
  - ttH vs. tt+jets (50% events for training, 50% for analysis)
  - Different input variables for each category
- Particle Swarm algorithm
  - Variable selection and tree architecture
BDT: example input variables

Lepton+Jets

Dilepton

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ttH vs. tt+bb: Matrix Element Method

Overview

- Provides optimal separation of signal and background
- Avoids wrong object assignment (sums over all combinations)
- Calculates the probability of an event being signal/background

Final discriminant

\[ P_{sb} = \frac{w_S}{w_S + k_{sb}w_B} \]
MEM discriminant

- Measured kinematical variables ($y$) used as input
  - Integration over poorly measured/missing variables ($E_{\text{jet}}$, neutrino direction)
- Sum over all possible permutations of object–particle matching

\[
 w_i(y) = \frac{1}{\sigma_i} \sum_{\text{perm}} \int_\Omega d\mathbf{x} \int dx_a dx_b \Phi(x_a, x_b) \delta^4 \left( x_a P_a + x_b P_b - \sum p(x) \right) |\mathcal{M}_i(x)|^2 W(y|x)
\]

- $\Omega$ = phase space volume of final particles $\mathbf{x}$
- $x_{a,b}$ = parton momentum fraction
- $\Phi$ = parton flux factor
- $\mathcal{M}_i$ = LO scattering amplitude of process $i$ ($i = \text{ttH, tt+bb}$)
- $W$ = transfer function: probability of measuring $y$ given $\mathbf{x}$
- $\sigma_i$ = normalisation factor such that $\int w_i(y) dy = 1$

Comparison to BDT
- No training => needs fewer MC statistics
- Easier interpretation
- Longer computation per event

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Subdivide each category into high/low BDT regions
- Take median of signal BDT score
  - Ensures sufficient events
- Optimal signal/background separation

Fit MEM discriminant
- Low BDT regions constrain backgrounds and systematics
- High BDT is signal enhanced
Subdivide each category into high/low BDT regions

Fit MEM discriminant
- Except 3 jet category (fit BDT discriminant)
  - Large number of events => better BDT training
Systematic uncertainties

- **Shape uncertainties**
  - Jet energy scale (JES)
  - Jet energy resolution (JER)
  - B-tag discriminator scale factors
  - Lepton ID/isolation
  - Trigger efficiency
  - Pile up uncertainty
  - Q^2 scale

- **Rate uncertainties**
  - tt+hf normalisation
  - PDF uncertainty
  - Parton shower scale
  - Luminosity

- **MC statistics uncertainties**

  Correction applied to reconstructed jet \( p_T \) in order to predict particle jet \( p_T \)
  - Depends on difference between reconstructed jet and generator jet \( p_T \)
  - Data / MC difference in b-tagging efficiency
  - Data / MC differences (\( \mu \) and e specific)
  - Minimum bias (p-p) cross section uncertainty
  - Renormalization and factorization scale for tt+jets
  - tt+bb, tt+2b, tt+b and tt+cc cross section uncertainty
  - gg, gg ttH, qq and qg initiated processes
  - tt+jets ISR/FSR uncertainty
  - LHC integrated luminosity uncertainty
  - Bin-by-bin
Pre-fit event yields

**CMS Preliminary**

12.9 fb⁻¹ (13 TeV)

- lepton+jets pre-fit expectation: $74 \pm 10$
- $4.0 \pm 0.7$
- $12 \pm 2$
- $27 \pm 6$

**Data/Bkg.**

<table>
<thead>
<tr>
<th>Lo</th>
<th>Hi</th>
</tr>
</thead>
<tbody>
<tr>
<td>≥6j,3b</td>
<td></td>
</tr>
<tr>
<td>4j,4b</td>
<td></td>
</tr>
<tr>
<td>5j, ≥4b</td>
<td></td>
</tr>
</tbody>
</table>

**CMS Preliminary**

11.4 - 12.9 fb⁻¹ (13 TeV)

- dilepton pre-fit expectation: $1.8 \pm 0.4$
- $17 \pm 3$
- $4.4 \pm 1.3$

**Data/Bkg.**

<table>
<thead>
<tr>
<th>3j,3b</th>
<th>Lo</th>
<th>Hi</th>
</tr>
</thead>
<tbody>
<tr>
<td>≥4j,3b</td>
<td></td>
<td></td>
</tr>
<tr>
<td>≥4j, ≥4b</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

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Post-fit event yields

**CMS Preliminary**

**Events**

- **12.9 fb\(^{-1}\) (13 TeV)**

**Data/Bkg.**

<table>
<thead>
<tr>
<th></th>
<th>Lo</th>
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</tr>
</thead>
<tbody>
<tr>
<td>3j,3b</td>
<td>≥4j,3b</td>
<td>≥4j, ≥4b</td>
</tr>
</tbody>
</table>

**Negative best-fit signal strength**!
Final fit

- Combined fit across all categories
  - Binned maximum-likelihood
  - Considers all systematic uncertainties
- Systematics constrained

Lepton+Jets 5j, ≥4b
High BDT

Dilepton ≥4j, 3b
High BDT

Pre-fit vs Post-fit
Final results

11.4 - 12.9 fb$^{-1}$ at 13 TeV:

Obs. (Exp.) limit: 1.5 (1.7) x SM

Best fit $\mu = \sigma/\sigma_{\text{SM}} = -0.2 \pm 0.8$

1.5 sigma below SM expectation

Comparison to previous results

19.5 fb$^{-1}$ at 8 TeV:

Obs. (Exp.) limit
BDT: 5.2 (4.1) CMS-PAS-HIG-13-019
Matrix Element: 4.2 (3.3) EPJC 75 (2015) 251

2.7 fb$^{-1}$ at 13 TeV:

Obs. (Exp.) limit: 2.6 (3.6) x SM
Best fit $\mu = \sigma/\sigma_{\text{SM}} = -2.0 \pm 1.8$

CMS-PAS-HIG-16-004
What’s next?

New results with $\sim 36 \text{ fb}^{-1}$ coming soon!
- Full 2016 dataset

Future efforts being considered
- New machine learning techniques
- Re-incorporate boosted topologies (used in 2015)
  - Lower combinatorics
  - Different systematics
  - Good for high-lumi
- Better handle on systematics
- Constrain $t\bar{t}+hf$ uncertainty
  - Better cross section measurements and calculations

Stay tuned!
## Conclusion

### Summary
- **Strong results with only partial dataset (up to 12.9 fb\(^{-1}\))**
  - Observed (expected) 95% CL limit: 1.5 (1.7)
  - Best fit \(\mu = -0.2 \pm 0.8\)
- **Solid trend of improving performance**
  - \(2012 \rightarrow 2015 \rightarrow 2016\) part: 4.1/3.3 \rightarrow 3.6 \rightarrow 1.7 (expected limit)
- **Systematics becoming dominant**
  - Already contribute 60% to total uncertainty on best-fit-\(\mu\)
  - Long term efforts to constrain dominant systematics

### Outlook
- **New results for the leptonic and fully hadronic analyses**
  - How important will the systematic uncertainties be?
- **Combination with other ttH analyses**
  - Overall 5 sigma significance?
  - Or observation of new physics?

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See talk by Saranya Ghosh
Backup
## Triggers

### Lepton+jets

<table>
<thead>
<tr>
<th>Dataset</th>
<th>Trigger Name</th>
</tr>
</thead>
<tbody>
<tr>
<td>SingleMu</td>
<td>HLT_IsoMu22_v*</td>
</tr>
<tr>
<td>SingleMu</td>
<td>HLT_IsoTkMu22_v*</td>
</tr>
<tr>
<td>SingleEle</td>
<td>HLT_Ele27_eta2p1_WPTight_Gsf_v*</td>
</tr>
</tbody>
</table>

### Dilepton

<table>
<thead>
<tr>
<th>Channel</th>
<th>Trigger Name</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\mu^+\mu^-$</td>
<td>HLT_Mu17_TrkIsoVVL_TkMu8_TrkIsoVVL_v*</td>
</tr>
<tr>
<td>$\mu^+\mu^-$</td>
<td>HLT_Mu17_TrkIsoVVL_Mu8_TrkIsoVVL_v*</td>
</tr>
<tr>
<td>$e^+e^-$</td>
<td>HLT_Ele23_Ele12_CaloIdL_TrackIdL_IsoVL_DZ_v*</td>
</tr>
<tr>
<td>$\mu^\pm e^\mp$</td>
<td>HLT_Mu23_TrkIsoVVL_Ele12_CaloIdL_TrackIdL_IsoVL_v*</td>
</tr>
<tr>
<td>$\mu^\pm e^\mp$</td>
<td>HLT_Mu8_TrkIsoVVL_Ele23_CaloIdL_TrackIdL_IsoVL_v*</td>
</tr>
</tbody>
</table>
Particle Swarm algorithm

- An optimization algorithm
- Different BDT settings (i.e. tree structure and variables) form the search-space
  - A specific setting corresponds to one point in this search space

Algorithm

- Create a swarm of candidate BDTs
- Initialize each BDT with a random set of input variables and a random position in parameter-space
- Do N iterations
  - Repeatedly train/test at current position
  - Vary input variables to maximize ROC while KS>threshold
- Then the BDTs move to new positions, based on their own position and the swarm’s best previous position

## BDT input variables

### Lepton+jets

<table>
<thead>
<tr>
<th>Object and event kinematics</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>( p_T^{\text{jet}} )</td>
<td>Transverse momentum of ( i )-th jet, jets ordered in ( p_T )</td>
</tr>
<tr>
<td>HT</td>
<td>Scalar sum of transverse momenta for all jets with ( p_T &gt; 30 \text{ GeV/c} )</td>
</tr>
<tr>
<td>MET</td>
<td>Missing transverse energy</td>
</tr>
<tr>
<td>( \sum \Delta p_T^{\text{jet}, \text{lepton}, \text{MET}} )</td>
<td>Sum of the ( p_T ) of all jets, leptons, and MET</td>
</tr>
<tr>
<td>( \Delta \eta^{\text{jet}, \text{lepton}} )</td>
<td>Invariant mass of the 4-vector sum of all jets, leptons, and MET</td>
</tr>
<tr>
<td>( \Delta \eta^{\text{jet}, \text{lepton}} )</td>
<td>Average ( \Delta \eta ) between b-tagged jets</td>
</tr>
<tr>
<td>( \Delta \eta^{\text{jet}, \text{lepton}} )</td>
<td>Average ( \Delta \eta ) between jets</td>
</tr>
<tr>
<td>( \Delta \eta^{\text{jet}, \text{lepton}} )</td>
<td>Maximal ( \Delta \eta ) between any jet and the average (</td>
</tr>
<tr>
<td>( \Delta \eta^{\text{jet}, \text{lepton}} )</td>
<td>Maximal ( \Delta \eta ) between any b-tagged jet and the average (</td>
</tr>
<tr>
<td>( \Delta \eta^{\text{jet}, \text{lepton}} )</td>
<td>Maximal ( \Delta \eta ) between any b-tagged jet and the average (</td>
</tr>
<tr>
<td>( \Delta R^{\text{tag}, \text{tag}} )</td>
<td>Average ( \Delta R ) between the two closest b-tagged jets</td>
</tr>
<tr>
<td>(</td>
<td>\Delta R^{\text{tag}, \text{tag}}</td>
</tr>
<tr>
<td>( M_{\text{min}} )</td>
<td>Invariant mass of the two b-tagged jets that are closest in ( \Delta R )</td>
</tr>
<tr>
<td>( M_{\text{max}} )</td>
<td>Invariant mass of the two b-tagged jets with an invariant mass closest to ( 125 \text{ GeV/c}^2 )</td>
</tr>
<tr>
<td>( M_1 )</td>
<td>A minimum-chi-squared fit to event kinematics is used to select two b-tagged jets as top-decay products. Of the remaining b-tagged jets, the invariant mass of the two with highest ( E_T ) is saved as this quantity</td>
</tr>
<tr>
<td>( \sqrt{\Delta \eta^{\text{bb}}}, \Delta \eta^{\text{bb}} )</td>
<td>Square root of the product of (</td>
</tr>
<tr>
<td>( \Sigma )</td>
<td>Ratio of the likelihood that the transverse momentum of all jets and the sum of the energies of all jets</td>
</tr>
<tr>
<td>CSVv2 b-tag</td>
<td>First- to fifth-highest b-tag discriminant value of all jets</td>
</tr>
<tr>
<td>CSVv2 b-tag</td>
<td>Average b-tag discriminant value of all b-tagged jets</td>
</tr>
<tr>
<td>CSVv2 b-tag</td>
<td>Squared difference between the b-tag discriminant value of a given b-tagged jet and the average CSVv2 discriminant value of all b-tagged jets, summed over all b-tagged jets</td>
</tr>
<tr>
<td>CSVv2 b-tag</td>
<td>Ratio of the likelihood that the event contains four b-jets to the likelihood that it contains two b-jets. The likelihoods are constructed from the b-tag discriminant, the ( p_T ) and the ( \eta ) of the jets.</td>
</tr>
</tbody>
</table>

### Dilepton

<table>
<thead>
<tr>
<th>Event variable</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>( (\Delta \eta^{\text{tag}, \text{tag}}) )</td>
<td>Average ( \Delta \eta ) between b-tagged jets</td>
</tr>
<tr>
<td>( \Delta \eta^{\text{tag}, \text{tag}} )</td>
<td>Sum of the ( p_T ) of all jets and leptons</td>
</tr>
<tr>
<td>( \Delta \eta^{\text{tag}, \text{tag}} )</td>
<td>Twisted angle between jet pair</td>
</tr>
<tr>
<td>( \Delta \eta^{\text{tag}, \text{tag}} )</td>
<td>( \Delta \eta ) between the two closest b-tagged jets</td>
</tr>
<tr>
<td>( \Delta \eta^{\text{tag}, \text{tag}} )</td>
<td>( \Delta \eta ) between the two furthest b-tagged jets</td>
</tr>
<tr>
<td>( M_{\text{min}} )</td>
<td>Invariant mass of jet pair with minimum ( \Delta R )</td>
</tr>
<tr>
<td>( M_{\text{max}} )</td>
<td>Invariant mass of a jet pair ordered in closeness to the Higgs mass</td>
</tr>
<tr>
<td>( M_{\text{b-tag}, \text{b-tag}} )</td>
<td>Mass of b-tagged jet pair with minimum ( \Delta R )</td>
</tr>
<tr>
<td>( M_{\text{min}} )</td>
<td>Sum of the ( p_T ) of b-tagged jet pair with minimum ( \Delta R )</td>
</tr>
<tr>
<td>(</td>
<td>\Delta \eta^{\text{tag}, \text{tag}}</td>
</tr>
<tr>
<td>(</td>
<td>\Delta \eta^{\text{tag}, \text{tag}}</td>
</tr>
<tr>
<td>( \Delta \eta^{\text{tag}, \text{tag}} )</td>
<td>Scalar sum of transverse momentum for all jets</td>
</tr>
<tr>
<td>( \Delta \eta^{\text{tag}, \text{tag}} )</td>
<td>( \Delta \eta ) between the two closest jets</td>
</tr>
<tr>
<td>( \Delta \eta^{\text{tag}, \text{tag}} )</td>
<td>Median invariant mass of all combinations of jet pairs</td>
</tr>
<tr>
<td>( \Delta \eta^{\text{tag}, \text{tag}} )</td>
<td>Mass for b-tagged jet pair with maximum invariant mass combination</td>
</tr>
<tr>
<td>( \Delta \eta^{\text{tag}, \text{tag}} )</td>
<td>Average ( \Delta \eta ) between jets (with at least one b-tagged jet)</td>
</tr>
<tr>
<td>( \Delta \eta^{\text{tag}, \text{tag}} )</td>
<td>Sum of the ( p_T ) of jet pair with minimum ( \Delta R ) (with at least one b-tagged jet)</td>
</tr>
<tr>
<td>( \Delta \eta^{\text{tag}, \text{tag}} )</td>
<td>Twisted angle between jet pair (with at least one b-tagged jet)</td>
</tr>
<tr>
<td>( \Delta \eta^{\text{tag}, \text{tag}} )</td>
<td>Invariant mass of the 3-jet system with the largest transverse momentum</td>
</tr>
<tr>
<td>( \Delta \eta^{\text{tag}, \text{tag}} )</td>
<td>Invariant mass of a jet pair (with at least one b-tagged jet) ordered in closeness to the Higgs mass</td>
</tr>
</tbody>
</table>

**Event shape**

- Sphericity
- Aplanarity
- \( H_{1-4} \)

**Fox-Wolfram moments**

\[
3 (\lambda_1 \lambda_2 + \lambda_1 \lambda_3 + \lambda_2 \lambda_3) [80]
\]
### BDT variables by category

**Lepton+jets**

<table>
<thead>
<tr>
<th>4 jets, 4 tags</th>
<th>5 jets, ≥ 4 tags</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \sum p_T(\text{jets, lepton, MET}) )</td>
<td>( \sum p_T(\text{jets, lepton, MET}) )</td>
</tr>
<tr>
<td>avg. CSVv2 of b-tagged jets</td>
<td>avg. CSVv2 of b-tagged jets</td>
</tr>
<tr>
<td>aplanarity ( H_3 )</td>
<td>aplanarity ( H_3 )</td>
</tr>
<tr>
<td>( (\sum p_T(\text{jet})) / (\sum E(\text{jet})) )</td>
<td>( (\sum p_T(\text{jet})) / (\sum E(\text{jet})) )</td>
</tr>
<tr>
<td>( M_2 ) of min ( \Delta R(\text{tag, tag}) )</td>
<td>( M_2 ) of min ( \Delta R(\text{tag, tag}) )</td>
</tr>
<tr>
<td>≥ 6 jets, 3 tags</td>
<td>≥ 6 jets, ≥ 4 tags</td>
</tr>
<tr>
<td>aplanarity ( \sqrt{\Delta \eta(t^{\text{lep}}, bb) \times \Delta \eta(t^{\text{had}}, bb)} )</td>
<td>best Higgs mass</td>
</tr>
<tr>
<td>( (\sum p_T(\text{jet})) / (\sum E(\text{jet})) )</td>
<td>( \sum p_T(\text{jets, lepton, MET}) )</td>
</tr>
<tr>
<td>( \text{min} \Delta R(\text{tag, tag}) )</td>
<td>( \text{min} \Delta R(\text{tag, tag}) )</td>
</tr>
<tr>
<td>2nd moment of b-tagged jets’ CSVv2</td>
<td>( \sum p_T(\text{jets, lepton, MET}) )</td>
</tr>
<tr>
<td>( \sum p_T(\text{jets, lepton, MET}) )</td>
<td>( \sum p_T(\text{jets, lepton, MET}) )</td>
</tr>
<tr>
<td>b-tagging likelihood ratio</td>
<td>b-tagging likelihood ratio</td>
</tr>
</tbody>
</table>

**Dilepton**

<table>
<thead>
<tr>
<th>3 jets, 3 tags</th>
<th>≥ 4 jets, 3 tags</th>
<th>≥ 4 jets, ≥ 4 tags</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \langle d \rangle_{\text{tagged}} )</td>
<td>Centrality(jets &amp; leptons)</td>
<td>Centrality(tags)</td>
</tr>
<tr>
<td>( H_1(\text{jets}) )</td>
<td>C(jets)</td>
<td>( H_T^{\text{tags}} )</td>
</tr>
<tr>
<td>( M_{\text{higgs-like}} )</td>
<td>( H_2(\text{tags}) )</td>
<td>( M_{\text{higgs-like}} )</td>
</tr>
<tr>
<td>( M_{\text{tag, tag}}^{\text{max mass}} )</td>
<td>( M_{\text{j}, \text{j}, \text{jet}}^{\text{max }} )</td>
<td>( M_{\text{j}, \text{j}, \text{jet}}^{\text{max }} )</td>
</tr>
<tr>
<td>( \text{min} \Delta R_{\text{tag, tag}} )</td>
<td>( M_{\text{min} \Delta R}^{\text{tag, tag}} )</td>
<td>( M_{\text{min} \Delta R}^{\text{tag, tag}} )</td>
</tr>
<tr>
<td>( \text{max} \Delta \eta_{\text{jet, jet}} )</td>
<td>( M_{\text{tag, tag}}^{\text{max mass}} )</td>
<td>( \text{max} \Delta \eta_{\text{jet, jet}} )</td>
</tr>
<tr>
<td>( \sum p_T(\text{jets, leptons}) )</td>
<td>( \text{median} M_{\text{j}, \text{j}, \text{jet}} )</td>
<td>median ( M_{\text{j}, \text{j}, \text{jet}} )</td>
</tr>
<tr>
<td>( H_4 / H_0(\text{tags}) )</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Extra variables: Lepton+Jets
Extra variables: Dilepton
Lepton+Jets pre-fit discriminant
Dilepton pre-fit discriminant

3j,3b
BDT only

Low BDT

≥4j,3b
MEM discriminant

High BDT

≥4j,≥4b
MEM discriminant
Lepton+Jets post-fit discriminant

CMS Preliminary data (Run 2016)

4 jets, 4 b-tags
BDT>0.26

5 jets, 4 b-tags
BDT>0.26

≥6 jets, 3 b-tags
BDT>0.26

≥6 jets, 4 b-tags
BDT>0.26

Low BDT

High BDT

Data/Bkg.

Events

MEM discriminant

CMS

Preliminary

4j,4b

5j,≥4b

≥6j,3b

≥6j,≥4b

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28
Dilepton post-fit discriminant

3j,3b
BDT only

Low BDT

High BDT
High BDT categories provide best sensitivity (as expected)
Yields from the bins of the final discriminants plotted in terms of pre-fit S/B

Standard model signal expectation

Fitted signal

Fitted background

11.4 – 12.9 fb$^{-1}$ (13 TeV)

CMS Preliminary

- data
- \( \tilde{t}\tilde{H} (\mu_{SM} = 1.0) \)
- \( \tilde{t}\tilde{H} (\mu = -0.19) \)
- Background
- Bkgd. Unc
Run I results

Analysis overview

- Major backgrounds: tt+jets (including tt+bb), single-top, V+jets, VV, tt+V (simulated)
- 1 or 2 opposite sign leptons
- At least 4 (l+jets) or 3 (DL) jets
  - Including at least 2 b-tags
  - Boosted top and Higgs in Run II
- Several event categories
  - Based on N_{jets} and N_{b-jets}
- Major systematics: JES, b-tagging, theory uncertainty on tt+hf
- BDT and Matrix Element discriminants used separately

Results: 19.5 fb^{-1}

- **BDT**
  - Post-Fit (S+B)
  - [8 TeV, L = 19.5 fb^{-1}]

- **Matrix Element**

Best fit \( \mu = 0.9 +2.5/-2.4 \)

Best fit \( \mu = 1.2 +1.6/-1.5 \)
Run II results

Analysis overview
- 2 channels: SL and DL
- BDT and Matrix Element discriminants combined

Results: 2.7 fb⁻¹

Lepton+Jets
- 1 lepton, all jets, 3 b-tags
- BDT > 0.1

Dilepton
- 2D MEM discriminant
- Boosted top and Higgs

Data/MC
- 33
- 2.7 fb⁻¹ (13 TeV)

Obs. (Exp.): 2.6 (3.6)

95% CL limit on $\mu = \alpha/\alpha_{SM}$ at $m_H = 125$ GeV