Search for Top Squarks Using Top Tagging at CMS

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On behalf of the CMS Collaboration
Analysis strategy

- All-hadronic analysis using top tagging
  - Custom tagging algorithm
  - Designed for good efficiency for large range of top $p_T$
- Search regions binned in $N_t$, $N_b$, $p_T^{\text{miss}}$, $M_{T2}/H_T$
- Interpret results using Simplified Model Spectrum (SMS)
- Link to full results
Top Tagger: Overview

Top tagging algorithm

- **First tag fully merged tops**
  - Using AK8 boosted top tagging
  - Discriminates using soft-drop mass and sub-jettiness variables
- **Tag medium $p_T$ tops with W+jet category**
  - AK8 as a boosted W (loose working point)
  - Combine with a nearby AK4 jet
  - Require combined mass consistent with top and AK8 mass to combined mass ratio to be consistent with $M_W/M_t$
- **Tag low $p_T$ tops with combinations of 3 resolved AK4 jets with MVA**

These three categories are combined

- Fully merged are tagged first, then W+jet, then resolved, removing jets from consideration form subsequent steps
To avoid overlap: AK4 jets that are $\Delta R < 0.4$ matched to an AK8 jet subjet are removed as input of resolved top tagger.

Resolved Top – All combinations of 3 AK4 jets
- $p_T > 30$ GeV and $|\eta| < 5$
- $\Delta R < 1.5$
- Trijet mass between 110 and 250 GeV

MVA training on jet properties (Input variables: tri-jet mass, restframe angular separations, $p$, b-tagging discriminator, quark-gluon discriminator)

Boosted top
De-boost by trijet $p_T$
Rest-frame top
Direction of trijet system boost

The sub-leading jets are from W decay
Largest $p_T$ jet is usually the b jet

MVA cut > 0.85
Top Tagger: Performance

Similar efficiencies compare with 2016 ICHEP Tagger, but much lower mistag rate
**Baseline Selection**

- **Jets and \( p_T^{\text{miss}} \):**
  - \( N_{\text{jets}}(p_T > 50) \geq 2 \) (AK4 jets)
  - \( N_{\text{jets}}(p_T > 30) \geq 4 \) (AK4 jets)
  - \( p_T^{\text{miss}} > 250 \) GeV
  - \( H_T > 300 \) GeV
  - \( \Delta \phi(j_{1,2,3}, p_T^{\text{miss}}) > 0.5, 0.3, 0.3 \)
  - \( N_b \geq 1 \)

- **Veto** \( e, \mu, \) and tracks consistent with \( \tau \)

- **Top reconstruction:**
  - \( N_t \geq 1 \) with top tagger
  - \( M_{T2} > 200 \) GeV

### Binning variables

<table>
<thead>
<tr>
<th>( N_b )</th>
<th>( 1 )</th>
<th>( 2 )</th>
<th>( \geq 3 )</th>
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</thead>
<tbody>
<tr>
<td>( N_t )</td>
<td>( p_T^{\text{miss}}, M_{T2} )</td>
<td>( p_T^{\text{miss}}, M_{T2} )</td>
<td>( p_T^{\text{miss}}, H_T )</td>
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<td>( \geq 3 )</td>
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</tbody>
</table>

\[
M_{T2} = \min_{p_T^{\text{miss}(1)} + p_T^{\text{miss}(2)} = p_T^{\text{miss}}} \left[ \max \left( M_T^{(1)}, M_T^{(2)} \right) \right]
\]
Background Estimations

- **Main Backgrounds**
  - $t\bar{t}/t/W + jets$
    - Estimated by data driven approach using translation factors
  - $Z \rightarrow \nu\nu$
    - Estimated by data corrected MC
  - QCD
    - Estimated in data sideband with data-normalized translation factors derived from MC

- **Sub-dominant backgrounds**
  - $t\bar{t}Z$
  - Diboson
  - Triboson
  - Estimated from MC
Estimated using single lepton (e & μ) data side band
- Matches baseline selection but with lepton veto replaced with explicit selection of one e or μ
- $m_T(p_T^{\text{miss}}, \ell) < 100$ GeV

Translation factors are derived per search bin
- Derived using MC
- Move estimate from single lepton control samples to signal sample

The estimate is derived separately using the e and μ control regions and both are used to constrain the final estimate

The dominant systematic uncertainty comes from the statistics of the translation factor

Single lepton control sample
- 1 e or μ
- $m_T(p_T^{\text{miss}}, \ell) < 100$ GeV

Signal Sample - Baseline selection

$$\hat{N}_{SS}^B = T^B \hat{N}_{CS}^B$$

$$T^B = \frac{\hat{N}_{SS}^{MC:B}}{\hat{N}_{CS}^{MC:B}}$$
**Z → νν Background Estimate**

- MC base estimate, validated in $Z\to\mu\mu$ control sample
  - Require 2 opposite sign muons
  - $81 < M_{\mu\mu} < 101$ GeV

- DY loose region:
  - $N_j \geq 4$, elec veto, $\Delta\phi$
  - $p_T^{\text{miss}} > 100$ GeV
  - $H_T > 300$ GeV,
  - $N_T \geq 1$

- Tight region adds:
  - $p_T^{\text{miss}} > 250$ GeV
  - $M_{T2} > 200$ GeV

- Dominant uncertainty from residual Data/MC disagreement in Loose region

**Mathematical Expressions**

- Tight Normalization
  - $\hat{N}_B = R_{\text{norm}} \sum_{\text{events} \in B} S_{DY}(N_{\text{jet}}) w_{MC}$

- $w_{MC} = (\sigma \times \mathcal{L}) \epsilon_{\text{trig}} w_{\text{btag}} w_{\text{pileup}}$
Background predictions compared with observed data

No significant excess observed
Final Limits

CMS Preliminary 35.9 fb⁻¹ (13 TeV)

pp \rightarrow \tilde{t} \tilde{\ell}, \tilde{\ell} \rightarrow t \tilde{\chi}^0 \_ NLO+NLL exclusion

- Observed ± 1 \sigma_{\text{theory}}
- Expected ± 1 \sigma_{\text{experiment}}

m_{\tilde{t}} [GeV]

m_{\tilde{\chi}^0} [GeV]

m_{\tilde{\ell}} [GeV]

m_{\tilde{\chi}^0} [GeV]

pp \rightarrow \tilde{g}, \tilde{\ell}, \tilde{\ell} \rightarrow t \tilde{\chi}^0 \_ NLO+NLL exclusion

- Observed ± 1 \sigma_{\text{theory}}
- Expected ± 1 \sigma_{\text{experiment}}

m_{\tilde{g}} [GeV]

m_{\tilde{\chi}^0} [GeV]

m_{\tilde{\ell}} [GeV]

m_{\tilde{\chi}^0} [GeV]

T1tttt

T5ttcc

T2tt

7/31/2017
Top tagging particularly helps at high $M_{\chi}$

More CMS limits

$$pp \rightarrow \tilde{g}\tilde{g}, \tilde{g} \rightarrow t\bar{t} \tilde{\chi}_1^0$$

Moriond 2017

CMS Preliminary 35.9 fb$^{-1}$ (13 TeV)

- SUS-16-033, 0-lep ($H_T^{\text{miss}}$)
- SUS-16-036, 0-lep ($M_{T2}$)
- SUS-16-037, 1-lep ($M_{1j}$)
- SUS-16-042, 1-lep ($\Delta \phi$)
- SUS-16-035, $\geq$2-lep (SS)
- SUS-16-041, $\geq$3-lep

CMS Preliminary 35.9 fb$^{-1}$ (13 TeV)

pp $\rightarrow \tilde{g} \tilde{g}, \tilde{g} \rightarrow t\bar{t} \tilde{\chi}_1^0$ NLO+NLL exclusion

- Observed $\pm 1 \sigma_{\text{theory}}$
- Expected $\pm 1 \sigma_{\text{experiment}}$

95% CL upper limit on cross section [pb]
We have designed an updated top tagging algorithm
- Similar efficiency as past tagger but ~50% of its mistag rate
- Tagger code released as standalone package

We have excluded T2tt models up to ~1000 GeV in stop mass and ~400 GeV in LPS mass
We have excluded T1tttttt models up to ~2000 GeV in stop mass and ~1100 GeV in LPS mass
Backup Slides
84 search bins in $N_b, N_t, p_T^{miss}, M_{T2}/H_T$

- $N_b, N_t = 1, 2$: Targeting T2tt, each block is binned in $p_T^{miss}, M_{T2}$
- $N_b$ or $N_t \geq 3$: Targeting T1tttt, each block is binned in $p_T^{miss}, H_T$ only
Search Bins
Data sideband selected using full baseline selection except $N_b \geq 2$, $N_t = 0$, and a stricter cut to reduce QCD of $\Delta \phi(p_T^{\text{miss}}, j_1,2,3,4) > 0.5$

Cross-check shows good agreement in both electron and muon channel
The loose DY control region with $N_b \geq 1$ after all weights are applied.
Use inverted $\Delta\phi$ control sample to predict the number of QCD events, using a translation factor ($T$-factor)

$$N_{QCD}^{SR} = N_{QCD}^{\Delta\phi} \times T_{QCD}$$

- The $T$-factor is measured in data in a sideband region ($200 < E_T^{miss} < 250$ GeV), and extrapolate in higher $E_T^{miss}$ region using MC results
- MC gives the shape and systematics and data sideband gives the normalization

- $N_t \leq 2$ and $N_b \leq 2$: 2D in $(M_{T2}, E_T^{miss})$

- $N_t \geq 3$ or $N_b \geq 3$: 1D in $E_T^{miss}$

- Red circled numbers are compared to measurement directly from data \(\rightarrow\) determine normalization to the $T$-factor numbers for the higher $E_T^{miss}$ bins