Why $t\bar{t}t\bar{t}t$

- Rare SM process on the edge of observation
  \[ \sigma (pp \rightarrow t\bar{t}t) = 12 \text{fb} \pm 20\% \text{ @ NLO (1711.02116)} \]

- Four top production is sensitive to interesting BSM models
  - Two Higgs Doublet Models (2HDM)
  - Simplified Dark Matter Theories
  - Effective Field Theory
Many Final States

- Signature defined by decay modes of the four W bosons
- Divide and Conquer by grouping similar signatures

- BR ~32%
- In progress

- BR ~56%
- Preliminary result using 36fb$^{-1}$ (PAS TOP-17-019)
  - $\sigma_{t\bar{t}t\bar{t}} < 48$fb @ 95%CL
- New analysis ongoing with more data and improved analysis techniques

- BR ~12%
- Published result with 2016 dataset (EPJC78 (2018) 140)
  - $\sigma_{t\bar{t}t\bar{t}} = 17^{+14}_{-11}$fb
- Preliminary result with full Run 2 137fb$^{-1}$ (PAS TOP-18-003)
Many Final States

- Signature defined by decay paths of the four W bosons
- Divide and Conquer by grouping similar signatures

High BR
Large SM bkg.
Syst. dominated

- BR ~32%
- In progress

- BR ~56%
- Preliminary result using 36fb $^{-1}$ (PAS TOP-17-019)
  - $\sigma_{t\bar{t}t\bar{t}} < 48$ fb @ 95%CL
- New analysis ongoing with more data and improved analysis techniques

Small BR
Small SM bkg.
Stat. dominated

- BR ~12%
- Published result with 2016 dataset (EPJC78 (2018) 140)
  - $\sigma_{t\bar{t}t\bar{t}} = 17^{+14}_{-11}$ fb
- Preliminary result with full Run 2 137fb $^{-1}$ (PAS TOP-18-003)
Baseline Event Selection

- Same-sign lepton pair, or $\geq 3$ leptons $|p_T| > 25 \, 20 \, 20 \text{GeV}$
- $\geq 2$ jets $|p_T| > 40 \text{GeV}$
- $\geq 2$ b-tagged jets $|p_T| > 25 \text{GeV}$
  - Neural Net based tagger ($\sim 70\%$ tag eff., $1\%$ mis. tag)
- $H_T > 300 \text{ GeV}$
- $E_T > 50 \text{ GeV}$
- Z-boson veto
  - $|m_Z - m_{\ell\ell}| < 15 \text{ GeV}$ for opposite sign, same flavor pair
  - If leptons pass tight ID, promote to separate $t\bar{t}Z$ control region, otherwise discard

![Event Selection Diagram](image-url)
Backgrounds

- Two types of backgrounds survive the Baseline Selection.
  - Processes which produce “fake” same-sign lepton pairs
    - Nonprompt leptons
    - Charge misidentified leptons
  - Processes with **genuine** prompt same-sign leptons
    - $t\bar{t}W$, $t\bar{t}Z$
      - Simulation normalized to data with dedicated control regions
    - $t\bar{t}H$, $t\bar{t}VV$, $X + \gamma$, Rare
      - Taken directly from simulation

![Graphs showing distribution of events](image)
Backgrounds: Nonprompt leps

- $t\bar{t}$ (for example) events can enter signal region through nonprompt leptons

- Not well described in simulation so estimate from data!
- This is the “tight-to-loose” ratio method.
Backgrounds: Nonprompt leps

- Define a measurement region that has many fakes and few prompt leptons
  - Single Lepton Selection
  - $E_T < 20 \text{GeV}, M_T < 20 \text{ GeV}$
- Measure the proportion of “loose” leptons that pass the “tight” selection
- Do this differentially in flavor, $p_T$, and $\eta$

$$P(\text{tight}|\text{loose}) = \frac{\#\text{tight}}{\#\text{loose}}$$
Backgrounds: Nonprompt leps

\[ P(tight | loose) = \frac{\#tight}{\#loose} \]

• Next, calculate a transfer factor that weights loose events to give the count of “fake” tight events.

\[ \varepsilon(f, p_T, \eta) = \frac{P}{1 - P} \]

\[ \#tight = \sum_{l!t\text{ leps}} \varepsilon(f_i, p_{T_i}, \eta_i) \]
Finally, in the signal region, the number of “fakes” that pass the tight selection can be estimated.

For dilepton events, the sum is over events with 1 tight lepton and one loose-not-tight lepton.

~17% background contribution.

\[
\#fakes = \sum_{\text{l!t leps}} \varepsilon(f_i, p_{T_i}, \eta_i)
\]
**Backgrounds:** $t\bar{t}W, t\bar{t}Z$

- Regions **CRW** and **CRZ** show 20-30% scale factor for $t\bar{t}W$, and $t\bar{t}Z$.
- Consistent with dedicated 2016 measurements being 20% (25%) higher than NLO calculations for $t\bar{t}W$ ($t\bar{t}Z$).
• Pre-fit signal region kinematic distributions show good agreement when including signal.
Signal Extraction

- A 19-variable xgboost BDT is trained with kinematic information to separate signal from background
  - $N_{jet}, N_b, N_{lep}, H_T, \text{Jet } p_T, \text{Lepton } p_T, \Delta \varphi, \Delta \eta, …$

- Along with a separate control region for $t\bar{t}Z$ ("CRZ"), 17 bins of the BDT discriminant are used in a maximum likelihood fit

- Cut based approach used as a cross check
  - 16 bins based on $N_{jet}, N_b$, and $N_{lep}$
  - In addition to CRZ, include a control region for $t\bar{t}W$ ("CRW")
Results

- Full Run 2 BDT analysis (137 fb$^{-1}$)
  - 2.6σ obs. (2.7σ exp.) $\rightarrow \sigma_{t\ell t\ell} = 12.6^{+5.8}_{-5.2}$ fb

- Consistent with cut-based cross-check
  - 1.7σ obs. (2.5σ exp.) $\rightarrow \sigma_{t\ell t\ell} = 9.4^{+6.2}_{-6.6}$ fb
Interpretations: Top Yukawa

- Higgs-mediated contribution grows with $y_t$.
- Sloped $\sigma_{t\bar{t}t\bar{t}}$ from growing $t\bar{t}H$ background ($\propto y_t^2$)

$$\sigma(t\bar{t}t\bar{t}) = \sigma_{g+Z/\gamma}^{SM}(t\bar{t}t\bar{t}) + \kappa_t^2 \sigma_{int}^{SM} + \kappa_t^4 \sigma_{(t\bar{t}t\bar{t})_H}^{SM}$$

$|y_t/y_t^{SM}| < 1.7$ @ 95% CL
Interpretations: 2HDM

- General 2HDM predict an additional Higgs doublet → four new particles
  - Type-II, \( \tan \beta = 1 \) – prefer decays of H/A → \( tt \)
  - \( \sin \beta - \alpha = 1 \), “alignment condition”, makes light CP-even higgs h SM-like

- Probe **associated production** modes giving 3 and 4 top final states
  - Consider H and A separately, decoupling other particles

- Exclude heavy (\( m > 2m_t \)) scalar (pseudoscalar) bosons up to ~470 (550) GeV
Summary

• Latest CMS measurement of $t\bar{t}t\bar{t}$ cross-section with 2L SS and ≥ 3L final state

\[ \sigma_{t\bar{t}t\bar{t}} = 12.6^{+5.8}_{-5.2} \text{fb (2.6\sigma obs.)} \]

• Rich Phenomenology – Can constrain Top Yukawa coupling, exotic mediators, …

• Exciting prospects for Run 2/3 – Larger dataset, all final states
Backup
# Systematic Uncertainties

<table>
<thead>
<tr>
<th>Source</th>
<th>Uncertainty (%)</th>
<th>Impact on $\sigma(tt\bar{t})$ (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Integrated luminosity</td>
<td>2.3–2.5</td>
<td>3</td>
</tr>
<tr>
<td>Pileup</td>
<td>0–5</td>
<td>1</td>
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<tr>
<td>Trigger efficiency</td>
<td>2–7</td>
<td>2</td>
</tr>
<tr>
<td>Lepton selection</td>
<td>2–10</td>
<td>2</td>
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<tr>
<td>Jet energy scale</td>
<td>1–15</td>
<td>9</td>
</tr>
<tr>
<td>Jet energy resolution</td>
<td>1–10</td>
<td>6</td>
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<tr>
<td>$b$ tagging</td>
<td>1–15</td>
<td>6</td>
</tr>
<tr>
<td>Size of simulated sample</td>
<td>1–25</td>
<td>&lt;1</td>
</tr>
<tr>
<td>Scale and PDF variations †</td>
<td>10–15</td>
<td>2</td>
</tr>
<tr>
<td>ISR/FSR (signal) †</td>
<td>5–15</td>
<td>2</td>
</tr>
<tr>
<td>$t\bar{t}H$ (normalization) †</td>
<td>25</td>
<td>5</td>
</tr>
<tr>
<td>Rare, $X\gamma$, $t\bar{t}VV$ (norm.) †</td>
<td>11–20</td>
<td>&lt;1</td>
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<tr>
<td>$t\bar{t}Z$, $t\bar{t}W$ (norm.) †</td>
<td>40</td>
<td>3–4</td>
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<tr>
<td>Charge misidentification †</td>
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<tr>
<td>Nonprompt leptons †</td>
<td>30–60</td>
<td>3</td>
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<tr>
<td>$N_{\text{ISR/FSR}}$ †</td>
<td>1–30</td>
<td>2</td>
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<tr>
<td>$N_{\text{jets}}$ †</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\sigma(tt\bar{b})/\sigma(tt\bar{j})$ †</td>
<td>35</td>
<td>11</td>
</tr>
</tbody>
</table>

†Correlated across years
Backgrounds: Charge misid.

- Charge mismeasurement in dilepton OS events fakes a SS event.
  - Measure flip probability in simulated SR events
  - Verify normalization closure in Z-dominated CR
  - Reweight OS ee events to predict SS region contribution
Interpretations: Higgs Oblique Parameter

“…The Higgs boson oblique parameter $\hat{H}$ [is] the hallmark of off-shell Higgs physics. $\hat{H}$ is defined as the Wilson coefficient of the sole dimension-6 operator that modifies the Higgs boson propagator, within a Universal EFT”

\[
\delta \sigma_{t\bar{t}t\bar{t}} = \frac{\sigma_{\hat{H}} - \sigma_{SM}}{\sigma_{SM}} \approx 0.03 \left( \frac{\hat{H}}{0.04} \right) + 0.15 \left( \frac{\hat{H}}{0.04} \right)^2
\]

• We generate $t\bar{t}t\bar{t}$ with different values of $\hat{H}$ to account for changes in acceptance

• Scale $t\bar{t}H$ cross section by $(1 - \hat{H})^2$ to account for its $\hat{H}$ dependency.

• Combining this with the BDT analysis results yields a limit of

$\hat{H} < 0.16 \ @ \ 95\% \ CL$
Interpretations: Dark Matter

• $t\bar{t} + DM(1807.06522)$ and $t + DM(1901.01553)$ can potentially give rise to multi-top final states
  - Complements traditional MET-based searches with $t\bar{t}t\bar{t}$ above (and slightly past) the $m_{\text{mediator}} = 2m_{DM}$ diagonal.

• Parameters
  - Mediator mass (scalar $\phi$ or pseudoscalar $A$)
  - DM particle $\chi$ mass
  - DM-mediator coupling, fermion-mediator coupling

• Simplified model assumes the two couplings to be unity
Interpretations: Off-Shell Mediators

- New neutral particles with $m < 2m_t$?
- Consider scalar $\phi$ and vector $Z'$ that are top-philic (1611.05032)
  - Constrain couplings above 1.1 (0.1-0.9) for scalar (vector) mediators