Top squarks searches &
connection to precision
top physics

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Top Quark Physics at the Precision Frontier
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Top squarks

- Superpartner of the top quark
  - Spin 0
  - Mass?
  - Top squarks can have large mixing because of large top Yukawa
- Naturalness arguments favor at least one top squark to be light enough to produce at the LHC
- Cross section depends strongly on mass
  - at the top mass, factor of ~5 smaller than $t\bar{t}$

![Graph showing cross section vs. mass](image-url)

- Cross section $\sigma$ at $\sqrt{s} = 13$ TeV
- $p\bar{p} \rightarrow t\bar{t}^*$ (NLL)
- $p\bar{p} \rightarrow t\bar{t}^*$ (NNLL)
- Gluinos/squarks decoupled
- NLO+NLL vs. NNLOapprox+NNLL

![Chart comparing cross sections](chart-url)
Top squark decays

- Different analysis techniques depending on $\Delta m$
Top squark searches

• “General purpose” searches split by lepton categories

• **0 lepton**
  • Largest branching fraction
  • Main background from lost lepton (t\(\bar{t}\) and W+jets)
  • Also Z→νν, t\(\bar{t}\)Z, QCD multijet

• **1 lepton (usually e/μ)**
  • Background from lost lepton from dilepton t\(\bar{t}\), no QCD multijet

• **2 lepton**
  • Smallest branching fraction, cleaner environment
  • Hard to compete with 0/1-lepton for most of phase space

\(t\bar{t}\) is almost always main background
• Key handle: **Missing transverse momentum** ($p_T^{\text{miss}}$) from undetected neutralinos

• Depending on top squark mass, the top quarks can have **large $p_T$**

• Can attempt to reconstruct (transverse) top squark mass, e.g. $M_{T2}$ variable etc
Top squark search in all-hadronic channel (CMS)

- Targets direct and gluino-mediated top squark production
- Suppress non-ttbar background by using top quark tagging
  - Custom 3-step algorithm
  - Maximize efficiency across top $p_T$ spectrum
- Construct 84 signal regions based on $N_b$, $N_t$, $p_T^{\text{miss}}$, $M_{T2}$, $H_T$
Background prediction

- $t\bar{t}$ is main background in all categories
  - lost lepton
  - hadronic tau
- Estimated using 1-lepton control region and MC transfer factors
- Prediction and observation agree

![Graph showing data and predictions](image)

**Validation in sideband region**

**Prediction for signal selection**
1-lepton example

- Main background is **lost leptons from dilepton tt̄**
- Predicted from an eμ control sample, using bin-by-bin transfer factors (from MC)
- Control region bins are aggregated in $p_T^{\text{miss}}$ to reduce statistical uncertainties
- $p_T^{\text{miss}}$ distribution in control region used as correction factor with half the difference as systematic uncertainty (25% at high MET)
Status last Summer

$\text{pp} \to \tilde{t}\tilde{t}, \tilde{t} \to t^{(*)} \tilde{\chi}^0_1$

July 2018

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

CMS

Dedicated searches for compressed region

Note greyed out region “Top corridor”

General searches
ISR modeling for compressed spectra

- For compressed signal models, analyses rely on initial state radiation to boost the top squarks and create larger $p_T^{\text{miss}}$ or higher $p_T$’s to pass the event selection.
- ISR modeling important signal systematic (up to 15%), and is validated using $t\bar{t}$ control sample.
- Madgraph (LO) + Pythia8 with MLM matching used.
- In 2016, reweighting needed to make $N_{j}^{\text{ISR}}$ spectrum agree (factor 0.92–0.51 for 1–6 extra jets), taking half the difference from 1 as uncertainty.
- For 2017, newer tune was used in MC, and reweighting is no longer needed.

Direct impact from precision top measurements.
Top corridor

\[ m_{\tilde{t}_1} - m_{\tilde{\chi}_1^0} \approx 175 \text{ GeV} \]

- Top quarks from squark decay produced \( \sim \) at rest, looks very much like SM \( t\bar{t} \)
- Needs precision approach — use \( e\mu \) final state
- ATLAS result using \( t\bar{t} \) spin correlations:
  - double-differential distributions of lepton \( \Delta \phi \) (uncorrelated \( t\bar{t} \) from top squarks) & \( \Delta \eta \) (scalar top squarks more central)
Top corridor

\[ m_{\tilde{t}_1} - m_{\tilde{\chi}_1^0} \approx 175 \text{ GeV} \]

- Top quarks from squark decay produced \( \sim \) at rest, looks very much like SM \( t\bar{t} \)
- Needs precision approach — use \( e\mu \) final state
- CMS result using **precise estimate of \( t\bar{t} \) (~6%)** and extra discrimination using \( M_{T2} \) variable

\[
M_{T2} = \frac{\min \left( \sum p_T^{\text{miss}_1} + \sum p_T^{\text{miss}_2}, \sum p_T^{\text{miss}} \right)}{p_T^{\text{miss}}}
\]

\[
\max \left[ m_T(p_T^{\ell_1}, p_T^{\text{miss}}), m_T(p_T^{\ell_2}, p_T^{\text{miss}}) \right]
\]

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[arXiv:1901.01288]
Top corridor

\[ m_{\tilde{t}_1} - m_{\tilde{\chi}_1^0} \approx 175 \text{ GeV} \]

Slightly worse sensitivity compared to spin correlation measurement

<table>
<thead>
<tr>
<th>Source</th>
<th>Range (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \mu_F ) and ( \mu_R ) scales</td>
<td>0.3–1.0</td>
</tr>
<tr>
<td>PDF</td>
<td>( \approx 0.6 )</td>
</tr>
<tr>
<td>Initial-state radiation</td>
<td>0.5–1.0</td>
</tr>
<tr>
<td>Final-state radiation</td>
<td>0.6–1.2</td>
</tr>
<tr>
<td>ME/PS matching (( h_{\text{damp}} ))</td>
<td>0.3–2.0</td>
</tr>
<tr>
<td>Underlying event</td>
<td>( \approx 0.8 )</td>
</tr>
<tr>
<td>Colour reconnection</td>
<td>( \approx 1.5 )</td>
</tr>
<tr>
<td>Top quark ( p_T ) reweighting</td>
<td>0.1–0.5</td>
</tr>
<tr>
<td>Top quark mass (acceptance)</td>
<td>( \approx 1.0 )</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Source</th>
<th>Range for ( \bar{t}t ) and signal (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Muon efficiencies</td>
<td>( \approx 1.4 )</td>
</tr>
<tr>
<td>Electron efficiencies</td>
<td>( \approx 1.5 )</td>
</tr>
<tr>
<td>Trigger efficiency</td>
<td>( \approx 0.6 )</td>
</tr>
<tr>
<td>Lepton energy scale</td>
<td>0.5–2.0</td>
</tr>
<tr>
<td>Jet energy scale</td>
<td>1.5–3.0</td>
</tr>
<tr>
<td>Jet energy resolution</td>
<td>0.3–3.5</td>
</tr>
<tr>
<td>btagging efficiency</td>
<td>1.2–2.0</td>
</tr>
<tr>
<td>Mistag efficiency</td>
<td>0.2–0.6</td>
</tr>
<tr>
<td>Unclustered energy</td>
<td>0.5–1.5</td>
</tr>
<tr>
<td>Pileup</td>
<td>0.5–3.5</td>
</tr>
</tbody>
</table>
What about RPV?

- Standard SUSY searches assume R-parity is conserved
  - Neutralino is stable → Missing transverse momentum
- With R-parity violation, other decay options become possible
  - Usually results in extra leptons or jets, instead of missing transverse momentum

<table>
<thead>
<tr>
<th>Decay</th>
<th>Coupling</th>
<th>Topology</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\tilde{t} \to \ell j$</td>
<td>LQD</td>
<td>2l+2j, cf. leptoquarks</td>
</tr>
<tr>
<td>$\tilde{t} \to jj$</td>
<td>UDD</td>
<td>4j, paired dijets</td>
</tr>
<tr>
<td>$\tilde{t} \to t\tilde{\chi}_0^0, \tilde{\chi}_0^0 \to \ell jj$</td>
<td>LQD</td>
<td>ttbar + lepton(s) + jets</td>
</tr>
<tr>
<td>$\tilde{t} \to t\tilde{\chi}_0^0, \tilde{\chi}_0^0 \to jjj$</td>
<td>UDD</td>
<td>ttbar + 6 jets</td>
</tr>
<tr>
<td>$\tilde{t} \to b\tilde{\chi}_0^+, \tilde{\chi}_0^+ \to \ell \ell \ell$</td>
<td>LLE</td>
<td>6 leptons + 2 bjets</td>
</tr>
<tr>
<td>$\tilde{t} \to b\tilde{\chi}_0^+, \tilde{\chi}_0^+ \to jjj$</td>
<td>UDD</td>
<td>8 jets</td>
</tr>
</tbody>
</table>
Impact from precision top quark measurements

- $tt$ is main background for almost all top squark searches
- Differential $tt$ cross section measurements very valuable! Especially as a function of variables often used in SUSY searches
  - Missing transverse momentum
  - $M_{T2}$
  - Number of jets
  - Transverse mass $M_T(l,\text{MET})$
  - Hadronic activity, $H_T$
  - …
Word of caution

• Please keep in mind the possibility that there might be SUSY/other BSM in your $t\bar{t}$ signal selection!

• This is especially possible for tricky corners of parameter space, e.g. “stealthy stops”, or certain RPV scenarios, that have no extra $p_T^{\text{miss}}$

• Small top squark cross section means that this could be a small effect in your measurement

• Be careful when tuning SM $t\bar{t}$ MC, since that MC will also be used by new physics searches
Summary

• **t\(\bar{t}\)** is main background for most top squark searches
• Often estimated using data control regions with MC transfer factors
• Transfer factor need to be modeled well
• In addition, correction factors are derived from Data/MC agreement in control regions
• **Better modeling of t\(\bar{t}\) helps reduce systematic uncertainties**
  • Important for tricky corners of phase space
  • Will be more important for large data sets at HL-LHC
• **Keep up the good work! :-)**