SEARCHING FOR PAIR PRODUCTION OF TOP SQUARKS AT CMS EXPERIMENT

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**Supersymmetry** is an extension of the SM that assigns a new particle (supertpartner) to every SM particle differing only in ½ of spin.

This model can solve several shortcomings of the SM:

- **Unification.**
- If R-parity is conserved, the lightest supersymmetric particle (LSP) is stable and potentially massive, providing a good candidate for **Dark Matter**.
- The **hierarchy problem** since the quantum loop corrections to the Higgs mass, due mainly to the top quark, can be compensated by the effect of the top quark supertpartner.
The top quark plays an essential role in understanding the structure of the SM and SUSY.

**Simplified Model Spectra “T2tt”**
100% branching ratio assumed for the stop to top + neutralino decay.

Final states selected include 0, 1 and 2 leptons. But there are more decay modes possible also being investigated.

Several results with full Run 2 dataset have been published, and others are under way.

- **0 leptons**: SUS-19-005
- **1 lepton**: SUS-19-009
- **2 leptons** (eμ, “top corridor”): SUS-18-003*
- **2 leptons** (ττ): SUS-19-003 (2016+2017 datasets)

There are many more searches with partial datasets. *only 2016 dataset

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**SUS-19-005**

**SUS-19-009**

**SUS-18-003**

**SUS-19-003**
**Event selection and strategy**

- **All-hadronic** search: veto on leptons and isolated tracks.
- Events classified by $H_T$, $N_j$, $N_b$ and $M_{T2}$.
- Monojet regions binned in $N_b$ and jet $p_T$.

**Backgrounds estimated from data control regions**

- **Lost lepton**: genuine $p_T^{\text{miss}}$ from semi-leptonic W decay (W+jets, tt+jets).
- **Irreducible background**: Z+jets events where the Z boson decays to neutrinos.
- **QCD multijet**: fake $p_T^{\text{miss}}$ from mis-measured jets.

*M_{T2} bins for medium $H_T*
Interpret **results** in terms of **exclusion limits** on simplified models of SUSY.

$M_{T2}$ bins for medium $H_T$

Stop masses excluded up to 1.2 TeV
Event selection and strategy

- Exactly one isolated electron or muon, $N_j \geq 2$, $N_b \geq 1$ and $p_T^{\text{miss}} > 250\text{GeV}$.
- Events classified by $N_j$, $p_T^{\text{miss}}$, $M_{lb}$, $t_{\text{mod}}$ and 3 top quark tagging categories (untagged, merged and resolved).
- 2 additional regions: $\Delta m(\tilde{t}, \tilde{\chi}_0^1) \sim m_W$ and $\Delta m(\tilde{t}, \tilde{\chi}_0^1) \sim m_t$.

Backgrounds estimated using control samples and simulation

- **Lost lepton**: one bad lepton from a W boson decaying leptonically ($t\bar{t}$, single top).
- **$Z \to \nu\nu$**: events where the Z boson decays to neutrinos.
- **One lepton**: single W boson decaying leptonically without any additional genuine $p_T^{\text{miss}}$.
**TOP 1 LEPTON SEARCH**

- Interpret **results** in terms of **exclusion limits** on simplified models of SUSY.

- **Stop masses excluded up to 1.2 TeV**

- Standard search
- Top corridor search
- W corridor search
STOP 2 LEPTONS SEARCH: eµ CHANNEL IN TOP CORRIDOR

➢ Event selection and strategy
- Only 2016 dataset used, 36 fb⁻¹.
- OS eµ pair, \( N_j \geq 2 \) and \( N_b \geq 1 \).
- Search for degenerate stop pair production in 3 diagonals:
  \[ \Delta m(\tilde{t}, \tilde{\chi}_0^1) = m_t, m_t \pm 7.5 \text{ GeV} \]
- Main discriminating variable: \( M_{T2}(e\mu) \)

➢ Backgrounds
- The main background is \( t\bar{t} \) due to the similar kinematics with the signal process in this region. It is estimated from MC with an accurate knowledge coming from different comparisons of the MC with measured inclusive and differential cross-section.

\[ \Delta m(\tilde{t}, \tilde{\chi}_0^1) = m_t \]
No excess observed, then interpret **results** in terms of **exclusion limits** on simplified models of SUSY.

Stop masses excluded up to:
- **208 GeV** in $\Delta m(\tilde{t}, \tilde{\chi}_0^1) = m_t$
- **235 GeV** in $\Delta m(\tilde{t}, \tilde{\chi}_0^1) = m_t - 7.5$ GeV
- **242 GeV** in $\Delta m(\tilde{t}, \tilde{\chi}_0^1) = m_t + 7.5$ GeV
**STOP 2 LEPTONS SEARCH: \( \tau \tau \) CHANNEL**

- **Event selection and strategy**
  - Only **2016-2017 datasets** used, 77.2 fb\(^{-1}\).
  - OS hadronically decaying \( \tau_h \) pair \( N_j \geq 2, N_b \geq 1, p_{T\text{miss}} > 50\text{GeV} \) and \( H_T > 100\text{GeV} \).
  - Events classified by \( p_{T\text{miss}}, M_{T^2} \) and \( H_T \).

- **Backgrounds, evaluated in control regions**
  - **Prompt \( tt \):** \( t\bar{t} \) events with two genuine \( \tau_h \) decays.
  - **Fake taus:** mostly from hadronic and semi-leptonic \( t\bar{t} \) events with jets being misidentified as \( \tau_h \) candidate.
  - **DY + others SM:** minor backgrounds.

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Interpret **results** in terms of **exclusion limits** on simplified models of SUSY.

Stop masses excluded up to 1.1 TeV
First analyses with **full Run 2 in CMS** achieve excellent exclusion limits, excluding stop quarks with masses up to 1.2 TeV.

Several channels have been explored with partial luminosity and are being studied with the full Run 2.

There are many more results on the way!

Stay tuned!

CMS Public SUSY Results:
BACK UP
**$M_{T2}$ variable**

- **Stop 0 leptons:**

  $$M_{T2} = \min_{\not{p}_T^{\text{miss}}{X(1)} + \not{p}_T^{\text{miss}}{X(2)} = \not{p}_T^{\text{miss}}} \left[ \max \left( M_T^{(1)}, M_T^{(2)} \right) \right]$$

  $\not{p}_T^{\text{miss}}{X(i)}$ (i = 1, 2) are trial vectors obtained by decomposing $\not{p}_T^{\text{miss}}$, and $M_T^{(i)}$ are the transverse masses obtained by pairing either of the trial vectors with one of the two pseudojets.

- **Stop 2 leptons:**

  $$M_{T2} = \min_{\not{p}_T^{\text{miss}}{T,1} + \not{p}_T^{\text{miss}}{T,2} = \not{p}_T^{\text{miss}}} \left( \max \left[ m_T(\not{p}_T^{\ell 1}, \not{p}_T^{\text{miss}}{1}), m_T(\not{p}_T^{\ell 2}, \not{p}_T^{\text{miss}}{2}) \right] \right)$$
**STOP 2 LEPTONS SEARCH: \(\tau\tau\) CHANNEL**

- The Minimal Supersymmetric Standard Model (MSSM) is one of the most promising BSM candidates currently.
- MSSM: SM + \(\tilde{S}M\) + 2 Higgs doublets. **MSSM has five Higgs bosons**: \(h, H, A, H^\pm\).
- The tree level CP-even \(h\) receives substantial correction involving top squark loops:

\[
m_h = m_Z |\cos 2\beta| + \frac{3m_t^4}{2\pi^2 v^2 \sin^2 \beta} \left[ \log \frac{m_s^2}{m_t^2} + \frac{X_t^2}{2m_s^2} \left(1 - \frac{X_t^2}{6m_s^2}\right) \right]
\]

\[
X_t = A_t - \mu \cot \beta
\]

\[
m_s = \sqrt{m_{t_1} m_{t_2}}
\]

- \(h\) is the SM-like Higgs with \(m_h = 125\) GeV.

For more information go to the **approval talk** of the analysis.

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**MSSM Higgs Mass**

- No mixing scenario \((X_t = 0)\): stop mass needs to very high (~ 3 TeV) to get a 125 GeV Higgs.
- Maximal mixing scenario: Can get a lighter stop (~ 500 GeV) – interesting in the LHC scenario.
- This motivates us to look for top squarks at the LHC to establish Supersymmetry.

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**Figure: Ref: A. Djouadi et al. 1112.3028**
**STOP 2 LEPTONS SEARCH: $\tau\tau$ CHANNEL**

- The chargino/neutralino has a gaugino and higgsino-like component:
  \[
  \tilde{\chi}_i^\pm = C_{1i} \tilde{W}^\pm + C_{2i} \tilde{H}^\pm \\
  \tilde{\chi}_i^0 = N_{1i} \tilde{\gamma} + N_{2i} \tilde{Z} + N_{3i} \tilde{H}_1^0 + N_{4i} \tilde{H}_2^0
  \]

- The chargino/neutralino couples to sleptons as $\sim m_1 / \cos \beta$ with the higgsino component.

- A higgsino like scenario implies:
  \[
  |C_{2i}|^2 >> |C_{1i}|^2 \text{ and } |N_{3i}|^2 + |N_{4i}|^2 >> |N_{1i}|^2 + |N_{2i}|^2.
  \]

- $\tan \beta >> 1$ implies $1 / \cos \beta >> 1$.

- Hence in a **higgsino-like scenario and/or high $\tan \beta$ region**, chargino/neutralino will preferably decay to a $\tau$ final state because $m_\tau >> m_e, m_\mu$:
  \[
  \tilde{\chi}_1^\pm \rightarrow \tilde{\tau}_1 \nu_\tau + \tilde{\nu}_\tau \tau \rightarrow \tau \nu_\tau \chi_1^0 \\
  \tilde{\chi}_2^0 \rightarrow \tilde{\tau}_1 \tau \rightarrow \tau \tau \tilde{\chi}_1^0
  \]

- **Such SUSY cascade decays lead to final states with lots of taus.**

- The existing exclusions (hadronic/leptonic) are not applicable for a **higgsino-like and/or high $\tan \beta$ scenario** where the chargino/neutralino will preferably decay to a $\tau$ final state, and hence the need to search for tau lepton final states.
Event selection and strategy
- Only 2016 dataset used, 36 fb$^{-1}$.
- Two OS electron or muon, $N_j \geq 2$, $N_b \geq 1$, $p_T^{miss} > 80\text{GeV}$ and $M_{T2}(ll) > 100\text{GeV}$.
- Main discriminating variable: $M_{T2}(ll)$.
- Events classified by $p_T^{miss}$, $M_{T2}(ll)$ and $M_{T2}(blbl)$.

Backgrounds, validated in several control regions
- Main backgrounds are $t\bar{t}$ and single top quark events with either severely mismeasured $p_T^{miss}$ or misidentified leptons.
Interpret results in terms of exclusion limits on simplified models of SUSY.

Stop masses excluded up to 800 GeV
**TOP 2 LEPTONS SEARCH: compressed stop**

- **Event selection and strategy**
  - Only **2016 dataset** used, 36 fb$^{-1}$.
  - OS electron or muon pair and $p_T^{miss} > 140 GeV$.
  - Search for compressed stop: $m_W \leq \Delta m (\tilde{t}, \tilde{\chi}_0^1) \leq m_t$.
  - Main discriminating variable: $M_{T2}(ll)$.
  - Events classified by $N_j, N_b, ISR_{jets}, channels$ and $M_{T2}(ll)$.

- **Backgrounds**
  - Main backgrounds: $t\bar{t}, tW$ and $WW$.

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**Combination of 12 signal region distributions**

**Stop masses excluded up to 420GeV**