Searches for Top Squark Pairs
at the LHC

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U. of Chicago HEP Seminar, November 10th, 2014

Art courtesy of Xavier Cortada (with the participation of physicist Pete Markowitz)
Why search for top squarks (stops)?

Top squark production and decay

Inclusive search in $1\ell + \text{jets}$ mode in CMS

Limitations

Prospects and conclusions
SUSY
Enormous radiative corrections to $m_{\text{higgs}}$ in SM: $\Delta m^2 \sim \Lambda_{\text{UV}}^2$
Enormous radiative corrections to $m_{\text{higgs}}$ in SM: $\Delta m^2 \sim \Lambda^2_{\text{UV}}$

Top squarks cancel the $\Lambda^2_{\text{UV}}$ term, remainder depends on difference between $m_t^2$ and $m^2_{\text{stop}}$

Light stops needed for “natural” (not fine-tuned) solution to the hierarchy problem
Stop Production & Decay
Top Squark Production at the LHC

\[ \sigma(pp \rightarrow \tilde{t} \tilde{t}^*) \] [pb]

\[ \sqrt{s} = 8 \text{ TeV} \]
NLO-NLL
LPCC SUSY \( \sigma \) WG

Example production modes:
- \( t \bar{t} \)
- \( \tilde{t} \tilde{t} \)
- \( \tilde{t} \tilde{t}^* \)

Stop mass [GeV]
Top Squark Production at the LHC

\[ \sigma = \sigma \cdot \mathcal{L} \]

Events in 2012

- \( t \bar{t} \) events
- \( \tilde{t} \tilde{t} \) events
- \( \tilde{t} \tilde{t}^* \) events

\( \sqrt{s} = 8 \text{ TeV} \)
NLO-NLL
LPCC SUSY \( \sigma \) WG

Sensitive up to \( m_{\text{stop}} \sim 700 \text{ GeV} \)

SM \( tt \) is \( \sim 10-10000 \) more likely to be produced in LHC collisions
Top Squark Decays

\[ \Delta m > m_{\text{top on-shell top}} \]

\[ \tilde{t} \rightarrow t \tilde{\chi}_1^0 \rightarrow bW \tilde{\chi}_1^0 \]
Top Squark Decays

\[ \Delta m < m_{\text{top}} \text{ off-shell top} \]
\[ \Delta m < m_W \text{ off-shell W} \]

\[ \tilde{t} \rightarrow t \tilde{\chi}_1^0 \rightarrow bW^*(\tilde{\chi}_1^0) \]
Alternative Top Squark Decays

\[ \tilde{t} \rightarrow b\tilde{\chi}_1^+ \rightarrow bW\tilde{\chi}_1^0 \]

Same objects in the final state as

\[ \tilde{t} ightarrow t\tilde{\chi}_1^0 \rightarrow bW\tilde{\chi}_1^0 \]
Top Squark Decays

$$\Delta m \equiv m_{\tilde{t}} - m_{\tilde{\chi}^0}$$

$$m_{\tilde{t}} < m_{\tilde{\chi}^0}$$

(forbidden)
Top Squark Decays

\[ \Delta m = m_{\tilde{t}} - m_{\tilde{\chi}^0} \]

- \( \Delta m < m_W \)
- \( m_W < \Delta m < m_t \)
- \( \Delta m > m_t \)

- \( m_{\tilde{t}} < m_{\tilde{\chi}^0} \) (forbidden)
- \( \tilde{t} \rightarrow bW^{*} \tilde{\chi}^0 \) (off-shell W)
- \( \tilde{t} \rightarrow bW \tilde{\chi}^0_1 \) (off-shell top)
- \( \tilde{t} \rightarrow t \tilde{\chi}^0_1 \rightarrow bW \tilde{\chi}^0_1 \) (on-shell top)
- \( \tilde{t} \rightarrow b \tilde{\chi}^+_1 \rightarrow bW \tilde{\chi}^0_1 \)
Top Squark Decays

\[ \Delta m \equiv m_{\tilde{t}} - m_{\tilde{\chi}^0} \]

\[ \Delta m < m_W \quad m_W < \Delta m < m_t \quad \Delta m > m_t \]

Stop decay to charm may dominate for a very light and low \( \Delta m \) stop

\[ \tilde{t} \rightarrow bW^* \tilde{\chi}^0 \quad \text{(off-shell W)} \]

\[ \tilde{t} \rightarrow bW \tilde{\chi}_1^0 \quad \text{(off-shell top)} \]

\[ \tilde{t} \rightarrow t \tilde{\chi}_1^0 \rightarrow bW \tilde{\chi}_1^0 \quad \text{(on-shell top)} \]

\[ \tilde{t} \rightarrow b \tilde{\chi}_1^+ \rightarrow bW \tilde{\chi}_1^0 \]

\[ m_{\tilde{t}} < m_{\tilde{\chi}^0} \quad \text{(forbidden)} \]
Top Squark Decays

\[ \Delta m \equiv m_{\tilde{t}} - m_{\tilde{\chi}^0} \]

\[ m_{\tilde{t}} < m_{\tilde{\chi}^0} \quad \text{(forbidden)} \]

\[ \tilde{t} \rightarrow c\tilde{\chi}_1^0 \]

\[ \tilde{t} \rightarrow bW^*\tilde{\chi}^0 \quad \text{(off-shell W)} \]

\[ \tilde{t} \rightarrow b\tilde{\chi}_1^+ \rightarrow bW\tilde{\chi}_1^0 \]

\[ \tilde{t} \rightarrow bW\tilde{\chi}_1^0 \quad \text{(off-shell top)} \]

\[ \tilde{t} \rightarrow t\tilde{\chi}_1^0 \rightarrow bW\tilde{\chi}_1^0 \quad \text{(on-shell top)} \]

Search for pairs of \( bW+\text{LSP} \)

\[ \Delta m < m_W \quad m_W < \Delta m < m_t \quad \Delta m > m_t \]
Search in 1\ell + jets mode in CMS
Top Squark Search

Signal is $tt$ with extra missing energy

**stop signal**

**top background**
Top Squark Signature
Top Squark Signature

Signature depends on W decay modes

lepton $\ell = e$ or $\mu$

tau 20%
dileptons 4%
alldjets 46%
$\ell$+jets 30%

Kinematics: Transverse Mass

\[ M_T^W (\ell, \nu)^2 = (E_T(\ell) + E_T(\nu))^2 - (p_T(\ell) + p_T(\nu))^2 \]

\[ \rightarrow 2E_T(\ell)E_T(\nu)(1 - \cos(\Delta \phi)) \]

Fractions Entries

Backgrounds with MET from \( \nu \)

\[ \rightarrow M_T(\ell, \nu) < M_W \]

Also other backgrounds: W+jets, single top, rare processes (e.g. \( ttZ \))
Kinematics: Transverse Mass

\[ M_T^W(\ell, \nu)^2 = (E_T(\ell) + E_T(\nu))^2 - (p_T^\ell(\ell) + p_T^\nu(\nu))^2 \]

\[ \rightarrow 2E_T(\ell)E_T(\nu)(1 - \cos(\Delta\phi)) \]

\text{MET}

Suppress backgrounds by requiring large \( M_T \)
The Transverse Mass

Predictions from Monte Carlo simulation

$1\ell + \text{jets signature}$

Search for an excess of events at large $M_T$
The SM at High Transverse Mass

Predictions from Monte Carlo simulation

1\ell + jets signature

\[t\bar{t} \rightarrow \ell\ell\] dominant
\[\sim 60\ %\]

Aggressive 2\(^{nd}\) lepton veto does not completely solve problem!
Use kinematical information in addition to $E_T^{\text{miss}}$ and $M_T$ to reduce $tt$.
Use kinematical information in addition to $E_T^{miss}$ and $M_T$ to reduce tt
Kinematic Variables

Use kinematical information in addition to $E_T^{miss}$ and $M_T$ to reduce tt

$M_{T2}^W$ is minimum mother particle mass consistent with kinematic constraints

$$M_{T2}^W = \min \left\{ m_y \text{ consistent with:} \begin{align*} \vec{p}_1^{T} + \vec{p}_2^{T} &= \vec{E}_T^{miss}, \ p_1^2 = 0, \ (p_1 + p_\ell)^2 &= p_2^2 = M_W^2, \\ (p_1 + p_\ell + p_{b_1})^2 &= (p_2 + p_{b_2})^2 = m_y^2 \end{align*} \right\}$$

Gallichio et al. hep-ph/1203.4813
Use kinematical information in addition to $E_T^{\text{miss}}$ and $M_T$ to reduce $tt$.

$M_{T2}^W$ is minimum mother particle mass consistent with kinematic constraints

$$M_{T2}^W = \min \left\{ m_y \text{ consistent with: } \begin{bmatrix} \vec{p}_1^T + \vec{p}_2^T = \vec{E}_T^{\text{miss}}, & p_1^2 = 0, & (p_1 + p_\ell)^2 = p_2^2 = M_W^2, \\ (p_1 + p_\ell + p_{b1})^2 = (p_2 + p_{b2})^2 = m_y^2 \end{bmatrix} \right\}$$

Gallichio et al. hep-ph/1203.4813
Kinematic Variables

Use kinematical information in addition to $E_T^{\text{miss}}$ and $M_T$ to reduce $t\bar{t}$

**Diagram:**

- **Signal**:
  - $\tilde{\chi}_1^0$
  - $E_T^{\text{miss}}$
  - $\tilde{\chi}_1^0$

- **Background**:
  - $E_T^{\text{miss}}$
  - $\bar{t}$
  - $t$
Use kinematical information in addition to $E_T^{\text{miss}}$ and $M_T$ to reduce $t\bar{t}$
Kinematic Variables

Use kinematical information in addition to $E_T^{\text{miss}}$ and $M_T$ to reduce $t\bar{t}$

$$\Delta \phi > 0.8$$

**signal**

**background**

$\chi_1^0 \rightarrow t\bar{t}$

$\Delta \phi$: minimum $\Delta \phi$ between either of 2 leading jets and $E_T^{\text{miss}}$
Kinematic Variables

Use kinematical information in addition to $E_T^{\text{miss}}$ and $M_T$ to reduce $tt$

Signal has hadronically decaying top while $tt \rightarrow \ell^+\ell^-$ does not

Construct 3-jet hadronic top $\chi^2$ hypothesis
Kinematic Variables

Use kinematical information in addition to $E_T^{\text{miss}}$ and $M_T$ to reduce $tt$

Signal has hadronically decaying top while $tt\rightarrow \ell^{+}\ell^{-}$ does not

Construct 3-jet hadronic top $\chi^2$ hypothesis
Use kinematical information in addition to $E_T^{\text{miss}}$ and $M_T$ to reduce $tt$
1ℓ Top Squark Selection

1ℓ signature:
1 e/ μ $p_T > 30$ GeV
2$^{nd}$ lepton veto
≥4 jets $p_T > 30$ GeV
≥1 b-jet
$E_T^{miss} > 100$ GeV

stop signal

additional jets

MET

1ℓ signature:
1 e/ μ $p_T > 30$ GeV
2$^{nd}$ lepton veto
≥4 jets $p_T > 30$ GeV
≥1 b-jet
$E_T^{miss} > 100$ GeV
Second Lepton Rejection

**Veto on events with an isolated track**

Isolated track catches leptons or hadrons from τ-decay

\[ p_T > 10 \text{ GeV} \]

If e or μ \( p_T > 5 \text{ GeV} \) and loosen isolation

**Main tau branching fractions**

- 1-charged particle ('1-prong')
  - e or μ \( \sim 32\% \)
- 3-charged particles ('3-prong') \( \sim 15\% \)
- Hadrons from τ-decay \( \sim 53\% \)

**Veto hadronic τ candidates with \( p_T > 20 \text{ GeV} \)**

Catches multiprong decays
Kinematical Quantities

At preselection

![Graphs showing kinematical quantities at preselection.]
Main analysis combines several variables in BDTs ↦ signal regions defined by cuts on BDT output

Cross checked with cut-based analysis ↦ less sensitivity to model details

Do both in parallel ↦ 18 BDT and 16 cut-based signal regions!
Signal Region Selection

\[ \tilde{t} \rightarrow t\tilde{\chi}_1^0 \]

\[ \Delta M = m_{\tilde{t}} - m_{\tilde{\chi}_1^0} \]

\[ \Delta M = m_{\text{top}} \]
Signal Region Selection

\[ \Delta M = m_{\tilde{t}} - m_{\tilde{\chi}^0} \]

**Looser selections** → more signal due to larger \( \sigma \) but larger backgrounds

**Tighter selections** → smaller backgrounds but less signal due to lower \( \sigma \)
Train 5 BDTs to target different regions of parameter space

\[ \Delta M = m_{\tilde{t}} - m_{\tilde{\chi}^0} \]

BDT1 Loose | BDT1 Tight | BDT2 | BDT3 | BDT4 | BDT5
--- | --- | --- | --- | --- | ---
Sample: small \( m_{\text{stop}} \) | small \( \Delta M \) | large \( \Delta M \) | off-shell top

More BDTs to target \( b\chi^\pm \) mode
Background Estimation

Backgrounds from Monte Carlo → Calibrate/correct with “control regions”

Signal sample

CMS

$\sqrt{s} = 8$ TeV, $\int L dt = 19.5$ fb$^{-1}$

Data/MC

$\tilde{t} \to t\chi_1^0$ BDT1 Loose

- Data
- $t\bar{t}$ / top
- $t\bar{t} \to ll$
- W+jets
- rare
- SM + $\tilde{t} \to t\chi_1^0 (250/50)$

$M_T > 120$ GeV
Background Estimation

Backgrounds from Monte Carlo → Calibrate/correct with “control regions”

Signal sample

$\tilde{t} \rightarrow t\chi_1^0$ BDT1 Loose

Data

1/ top

$tt \rightarrow l^+l^-$

entries / 30 GeV

$MT > 120$ GeV

$\chi \rightarrow t\tilde{t}$

Data/MC

$\sqrt{s} = 8$ TeV, $\int L dt = 19.5$ fb$^{-1}$

$t\rightarrow t\tilde{t}$

BDT1 Loose

Data

1/ top

$tt \rightarrow l^+l^-$

Invert 2nd lepton veto

Entries / 30 GeV

$MT > 120$ GeV

$\chi \rightarrow t\tilde{t}$

Data/MC

$\sqrt{s} = 8$ TeV, $\int L dt = 19.5$ fb$^{-1}$
Background Estimation

Backgrounds from Monte Carlo → Calibrate/correct with “control regions”

Signal sample

W+Jets sample: Invert b-tagging

$\tilde{t} \rightarrow \tilde{t}_1^0$ BDT1 Loose

$M_T > 120$ GeV

$\sqrt{s} = 8$ TeV, $\int L dt = 19.5$ fb$^{-1}$

$\tilde{t} \rightarrow t\chi_1^0$ (250/50)

Preselection CR-0b

$M_T > 120$ GeV

Background Estimation

Backgrounds from Monte Carlo $\rightarrow$ Calibrate/correct with “control regions”

Issue with $E_T^{\text{miss}}$ resolution affecting $M_T$
  $\rightarrow$ measured in W+jets, corrected via scale factor $1.2 \pm 0.3$
  $\rightarrow$ transfer to $t\bar{t} \rightarrow \ell+\text{jets}$ not straightforward
Single Lepton Backgrounds

Two contributions to high $M_T$ tail

$W+\text{jets}$: dominated by off-shell $W$ production

$M_T(\ell, \nu) > m_W$

$W \rightarrow l\nu$

$1\ell\text{ top}$: $M_T$ is bounded

$M_T(\ell, \nu) < m_{\text{top}} - m_b$

$\rightarrow$ detector resolution effects dominate

$t \rightarrow Wb \rightarrow l\nu b$

$1\ell\text{ top} \sim 25\%$ & $W+\text{jets} \sim 5\%$ of total background
Looser signal regions target low $m_{stop}$ and low $\Delta m$

$\Delta M = m_{top}$

Limited by systematic uncertainty (13%) largest contribution from estimate of 1-lepton background
Signal and Background Expectations

Tighter signal regions target high $m_{\text{stop}}$ and large $\Delta m$

$\Delta M = m_{\text{top}}$

Total Background $\quad 2.9 \pm 1.1$

Signal (650/50) $\quad 4.3 \pm 0.1$

Limited by statistics
The Results

CMS \( \sqrt{s} = 8 \text{ TeV}, \int L dt = 19.5 \text{ fb}^{-1} \)

**Low Mass**

- Data
- SM \( t \bar{t} \rightarrow t \chi_1^0 \) (250/50)
- \( t \bar{t} \rightarrow t \chi_1^0 \) signal region

**High Mass**

- Data
- SM + \( t \bar{t} \rightarrow t \chi_1^0 \) (650/50)

**Signal Kinematics**

\[ m_{\tilde{t}} - m_{\chi_1^0} = \Delta M = m_{\text{top}} \]

<table>
<thead>
<tr>
<th>Region</th>
<th>Data</th>
<th>Total Background</th>
<th>Signal</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low Mass</td>
<td>728</td>
<td>763 ± 102</td>
<td>285 ± 8.5 ((250/50))</td>
</tr>
<tr>
<td>High Mass</td>
<td>2</td>
<td>2.9 ± 1.1</td>
<td>4.3 ± 0.1 ((650/50))</td>
</tr>
</tbody>
</table>

4 other signal regions in backup
What does this search tell us?

Set limits using results from the signal region with the best expected sensitivity

Results probe $m(\tilde{t}) \lesssim 650$ GeV for $m(\tilde{\chi}_1^0) \lesssim 225$ GeV

Sensitive to the $\Delta M < m_{\text{top}}$ and $m_{\text{stop}} < m_{\text{top}}$ regions
Multivariate vs. Cut Based

**Multivariate**

CMS

$\sqrt{s} = 8$ TeV, $\mathbf{Ldt} = 19.5$ fb$^{-1}$

$pp \to \tilde{t}\tilde{t}, \tilde{t} \to t\tilde{\chi}_1^0$

Unpolarized top

BDT analysis

**Cut-based**

CMS

$\sqrt{s} = 8$ TeV, $\mathbf{Ldt} = 19.5$ fb$^{-1}$

$pp \to \tilde{t}\tilde{t}, \tilde{t} \to t\tilde{\chi}_1^0$

Unpolarized top

Cut-based analysis

Limits from cut-based analysis a little worse
1\ell + 0\ell Comparison of Stop Results

All jets search extends sensitivity to higher top squark mass

CMS Preliminary, \( \sqrt{s} = 8 \) TeV

pp \( \rightarrow \tilde{t} \tilde{t}, \tilde{t} \rightarrow t\tilde{\chi}_1^0 \)

- NLO+NLL exclusion
- MVA 1L, L = 19.5 fb\(^{-1}\) Observed ± 1 \( \sigma_{\text{theory}} \)
- Razor 0L, L = 19.3 fb\(^{-1}\)

All jets result
SUS-13-004
SUS-14-011
$1\ell + 0\ell$ Combination of Stop Results

Results sensitive to top squarks to $m_{\text{stop}} \sim 750$ GeV

CMS Preliminary, $L = 19.5$ fb$^{-1}$, $\sqrt{s} = 8$ TeV

$pp \to \tilde{t}\tilde{t}, \tilde{t} \to t\chi_1^0$  
NLO+NLL exclusion

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

MVA 1L Razor 0L

95% C.L. upper limit on cross section (pb)
Results probe $m_{\text{stop}} \sim 100 - 650$ GeV
For $m(\tilde{\chi}^{\pm}) \sim m(\tilde{\chi}^0)$, strong dependence on $BF(\text{stop} \rightarrow t + \tilde{\chi}^0)$
1\ell + 0\ell Combination: Branching Fraction

Combination with low jet multiplicity fully hadronic search is sensitive to a wider range of possible branching fractions

CMS Preliminary, L = 19.5 fb⁻¹, √s = 8 TeV

pp → \tilde{t}\tilde{\ell}, \tilde{t} → t\chi_1^0 / b\chi_1^\pm, NLO+NLL exclusion

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

MVA 1L Razor 0L
BR(\tilde{t} → t\chi_1^0) = 50%

\begin{align*}
\tilde{t} & \quad \tilde{\ell} \\
t^{(*)} & \quad b \\
\tilde{\chi}_1^\pm & \quad W^* \quad \text{\{5 GeV\}} \\
\tilde{\chi}_1^0 & \quad W^* \quad \text{\{5 GeV\}}
\end{align*}

BF=50%
Summary of Stop Mass Limits

$\tilde{t}\tilde{t}$ production, $\tilde{t} \rightarrow t \tilde{\chi}_1^0 / c \tilde{\chi}_1^0$

CMS Preliminary

$\sqrt{s} = 8$ TeV

ICHEP 2014

Similar results from ATLAS

https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsSUS
Limitations
Results probe $m_{\text{stop}} \sim 100 - 650$ GeV
BUT $m_{\text{stop}} \lesssim 650$ GeV is not conclusively ruled out because of gaps!
The Gap around $m_{\text{top}}$

CMS, pp→$\tilde{t}_{1}\tilde{t}_{1}^{*}$ production

$\sqrt{s} = 8$ TeV, $\int L dt = 19.5$ fb$^{-1}$

Gap in sensitivity at $m_{\text{stop}} - m_{\text{LSP}} \sim m_{\text{top}}$

How can we target this region?
Kinematics around $m_{\text{top}}$

Inset from exclusion plot

$	ilde{\chi}^0$ momentum in stop rest frame

CMS Simulation

$\sqrt{s} = 8$ TeV

off-shell

on-shell

$\Delta M \sim m_{\text{top}} \rightarrow$ low momentum LSP
Sensitivity around $m_{\text{top}}$

CMS Preliminary

$\sqrt{s} = 8$ TeV, $\int L dt = 19.5$ fb$^{-1}$

Entries / 30 GeV

- Background, evts$(M_M > 120$ GeV) = 251 ± 50
- $\tilde{t} \rightarrow t\tilde{\chi}^0$ $(250/50)$, evts$(M_M > 120$ GeV) = 124
- $\tilde{t} \rightarrow t\tilde{\chi}^0$ $(250/75)$, evts$(M_M > 120$ GeV) = 39
- $\tilde{t} \rightarrow t\tilde{\chi}^0$ $(250/100)$, evts$(M_M > 120$ GeV) = 106

$\tilde{t} \rightarrow t\tilde{\chi}^0$ Cut-based
Low $\Delta M E_T^{\text{miss}} > 150$ GeV

CMS Simulation

$\sqrt{s} = 8$ TeV

- $\tilde{t} \rightarrow t\tilde{\chi}^0$ $(250/50)$
- $\tilde{t} \rightarrow t\tilde{\chi}^0$ $(250/75)$
- $\tilde{t} \rightarrow t\tilde{\chi}^0$ $(250/100)$

$\Delta M \sim m_{\text{top}}$

on-shell

Off-shell

$\Delta M \sim m_{\text{top}}$

Low momentum LSP $\rightarrow$ low $E_T$

$\rightarrow$ low $M_T$ acceptance
Recoiling Signals

Inset from exclusion plot

Design event selection for stops recoiling against ISR jets
   → increase LSP momentum
   → gain sensitivity

\[ m_{\chi_1^0} [\text{GeV}] \]

\[ m_{\tilde{t}} [\text{GeV}] \]

\[ \tilde{t} \]

\[ \tilde{t}^* \]
Revisiting the Gap around $m_{\text{top}}$

Gap in sensitivity at $m_{\text{stop}} - m_{\text{LSP}} \sim m_{\text{top}}$

Other ways to target the gap region:
Search for top squarks produced in decay of other SUSY particles
Stop in Gluino Cascade Decays

If the lightest stop is hiding in the top, could see it in the decay of the gluino

Hole closed for 100% BF if $m_{\text{gluino}}$ below ~1.3 TeV
Stop$_1$ in Stop$_2$ Cascade Decays

If the lightest stop is hiding in the top, could see it in the decay of a heavier stop

\[ \Delta m = m_{\text{top}} \]

\[
\begin{pmatrix}
\tilde{t}_1 \\
\tilde{t}_2
\end{pmatrix} = \begin{pmatrix}
\cos \theta_t & \sin \theta_t \\
-\sin \theta_t & \cos \theta_t
\end{pmatrix} \begin{pmatrix}
\tilde{t}_L \\
\tilde{t}_R
\end{pmatrix}
\]
Stop$_2$ Signature

$\tilde{t}_2$ $\rightarrow$ H or Z

$\tilde{t}_1$ $\rightarrow$ t

$\Delta m = m_{top}$

Signature $tt$ with Higgs or Z bosons

$Z$ signature
$\rightarrow$ additional leptons

$H$ signature
$\rightarrow$ additional b-jets

$P_2$ $P_1$
Interpretation

Set limits combining results from searches with multiple b-jets and multiple leptons

Consider all possible branching fractions to H or Z

Hole closed for $m_{\text{stop2}}$ below $\sim 550-600$ GeV

CMS $\sqrt{s} = 8$ TeV, $\int \mathcal{L} dt = 19.5$ fb$^{-1}$

- $\mathcal{B}(\tilde{t}_2 \to \tilde{t}_1 Z) = 100\%$
- $\mathcal{B}(\tilde{t}_2 \to \tilde{t}_1 Z) = 50\%$
- $\mathcal{B}(\tilde{t}_2 \to \tilde{t}_1 Z) = 0\%$

Hole closed for $m_{\tilde{t}_2}$ below $\sim 550-600$ GeV

PLB 736 (2014) 371
hep-ex/1405.3886
Revisiting the Gap around $m_{\text{top}}$

CMS, $pp\rightarrow\tilde{t}_1\tilde{t}_1^*$ production

$\sqrt{s} = 8 \text{ TeV}, \int L dt = 19.5 \text{ fb}^{-1}$

1L, SUS-13-011, $\tilde{t}\rightarrow t\tilde{\chi}_1^0$

Other ways to target the gap region:

Precision $\sigma(t\bar{t})$ measurement

Gap in sensitivity at $m_{\text{stop}} - m_{\text{LSP}} \sim m_{\text{top}}$
Stops hiding in the Top

Consider the impact of a light stop on the measured $t\bar{t}$ cross section

Stop would increase observed \( \sigma (tt) \sim 15\% \)

Experiment \( \Delta \sigma \sim 4\% \)

NNLO theory \( \Delta \sigma \sim 6\% \)

<table>
<thead>
<tr>
<th>$\sqrt{s}$ [TeV]</th>
<th>7</th>
<th>8</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Experiment $\sigma (tt)$ [pb]</strong></td>
<td>182.9 ± 7.1</td>
<td>242.4 ± 10.3</td>
</tr>
<tr>
<td><strong>Theory $\sigma (tt)$ [pb]</strong></td>
<td>177.3 $^{+11.5}_{-12.0}$</td>
<td>252.9 $^{+15.3}_{-16.3}$</td>
</tr>
</tbody>
</table>

Constrain $m_{\text{stop}} \sim m_t$ for 100\% BR $t\chi^0$

\[ \text{ATLAS} \]

\( \sqrt{s} = 7 \text{ TeV}, 4.6 \text{ fb}^{-1} \)

\( \sqrt{s} = 8 \text{ TeV}, 20.3 \text{ fb}^{-1} \)

Expected limit $\pm 1 \sigma_{\text{exp SUSY}}$

Observed limit $\pm 1 \sigma_{\text{theory}}$

$\tilde{t}_1 \rightarrow t \tilde{\chi}_1^0$, $m(\tilde{\chi}_1^0) = 1 \text{ GeV}$

hep-ex/1406.5375
Submitted to EPJC
Stops hiding in the Top

$\Delta \phi(l_1, l_2)$ in $tt\rightarrow \ell^+\ell^-$ affected by presence of stops (spin 0)

**ATLAS Preliminary**

$\int Ldt = 20.3fb^{-1}$

$\sqrt{s} = 8\text{ TeV}$
Stops hiding in the Top

$\Delta \phi(l_1, l_2)$ in $tt \rightarrow l^+ l^-$ affected by presence of stops (spin 0)

Measurement can be used to constrain stops with $m_{\text{stop}} \sim m_t$
Prospects & Conclusions
Summary of Run1 Stop Mass Limits

CMS Preliminary

\( \sqrt{s} = 8 \) TeV

ICHEP 2014

\( \tilde{t}\tilde{t} \) production, \( \tilde{t} \rightarrow t \tilde{\chi}_1^0 / c \tilde{\chi}_1^0 \)

- Observed
- Expected

- SUS-13-011 1-lep (MVA) 19.5 fb\(^{-1}\)
- SUS-14-011 0-lep + 1-lep + 2-lep (Razor) 19.3 fb\(^{-1}\)
- SUS-14-011 0-lep (Razor) + 1-lep (MVA) 19.3 fb\(^{-1}\)
- SUS-13-009 (monojet stop) 19.7 fb\(^{-1}\) (\( \tilde{t} \rightarrow c \tilde{\chi}_1^0 \))
- SUS-13-015 (hadronic stop) 19.4 fb\(^{-1}\)

https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsSUS
Summary of Run1 Stop Mass Limits

- \( \tilde{t} \tilde{t} \) production, \( \tilde{t} \rightarrow t \tilde{\chi}^0_1 / c \tilde{\chi}^0_1 \)

- Soft decay products, low efficiency, difficult to trigger (e.g. high-\( p_T \) monojet-like ISR jet)

- Events ~ SM WW

- Events ~ SM tt

- SUS-13-009 (monojet stop) 19.7 fb
- SUS-13-015 (hadronic stop) 19.4 fb

https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsSUS
Summary of ATLAS Results

\[ \tilde{t}, \tilde{b}, \tilde{c}, \tilde{\chi}_1^0 \]

\[ \tilde{t} \rightarrow t \tilde{\chi}_1^0, \tilde{b} \rightarrow b \tilde{\chi}_1^0, \tilde{c} \rightarrow c \tilde{\chi}_1^0, \tilde{\chi}_1^0 \rightarrow W b, \tilde{\chi}_1^0 \rightarrow t \tilde{\chi}_1^0 \]

Status: ICHEP 2014

ATLAS Preliminary

- \( L_{\text{int}} = 20 \text{ fb}^{-1}, \sqrt{s} = 8 \text{ TeV} \)
- \( L_{\text{int}} = 4.7 \text{ fb}^{-1}, \sqrt{s} = 7 \text{ TeV} \)

Observed limits

- \( 0L \ [1408.1122] \)
- \( 1L \ [1407.0583] \)
- \( 2L \ [1403.4853] \)

Expected limits

- \( 0L \ [1408.1447] \)
- \( 1L \ [1408.2590] \)
- \( 2L \ [1409.4186] \)

All limits at 95% CL

https://twiki.cern.ch/twiki/bin/view/AtlasPublic/SupersymmetryPublicResults
Extending to Higher Masses

CMS, $pp\rightarrow \tilde{t}_{1}\tilde{t}_{1}^*$ production

$\sqrt{s} = 8$ TeV, $\int L dt = 19.5$ fb$^{-1}$

$1L$, SUS-13-011, $\tilde{t}\rightarrow t\tilde{\chi}^0_1$

- Observed
- Expected

Limited by statistics ➔ need more data!
Top Squarks at LHC Run 2

LHC Run2 (~2015-2021) expect ~300 fb⁻¹ of data at \( \sqrt{s} = 13-14 \) TeV

Expect *discovery* reach up to \( m_{\text{stop}} \sim 750-950 \) GeV
Analysis Updates

Revisit analysis for large $m_{stop} \rightarrow$ boosted decay products
Summary of Searches and Outlook

In the next years can cover a lot of the gaps!

Lower masses
→ more precise background estimates & targeted analyses

Higher masses
→ use higher energy data

Dedicated searches

tt + MET

Observed

Expected

L_{tt} = 19.5 \text{ fb}

\int = 8 \text{ TeV}, s_{\ast} \text{ production}

\chi \sim t \rightarrow t \sim m_{W} = m_{0}1 \chi \sim - m_{t} \sim m_{W}
Conclusion

Light stops are a powerful signature of new physics to search for at the LHC

Searches for stops at the LHC are the first to explore significant regions of interesting parameter space. No signs of stops, but understanding of SM backgrounds is the key to any future discovery.

There are loopholes, even for light stops, some are currently being addressed → need to cover the gaps in sensitivity.

The next years are going to be crucial to discover light stops or to set severe constraints on Natural SUSY → the higher energy data will extend the sensitivity to close to 1 TeV.
Thank you

Art courtesy of Xavier Cortada (with the participation of physicist Pete Markowitz)