Stefano Zambito, Harvard - O.b.o ATLAS and CMS

A Dive Into Searches Involving Top Quarks
Top Quark(s)

3rd Generation
SUSY

Rare Production & Decays

Dark Matter

Vector-like Quarks

Heavy Resonances

A Dive Into Searches Involving Top Quarks

3rd Generation SUSY & Rare Top Decays

La Thuile, Mar 2nd ’18 - In this talk:

- Why $t$ so important in BSM searches?
- Prototype of stop search: 1L ATLAS
- Prototype of stop search: 0L CMS
- Sbottom searches, in a nutshell
- FCNC in $t$ production/decays

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Introduction

Why the top quark is so interesting - and all the searches involving it?

“Massive” and “point-like” at the same time - key source of fundamental information

Heaviest elementary particle discovered so far: mass close to that of gold nucleus!
It decays much faster than timescale for formation of strong bound states

Large Yukawa coupling (close to unity) - main contribution to virtual $m_H$ corrections:

Close connection to hierarchy problem (and its natural solution?)

$$\delta m_H^2 = \frac{3G_F}{4\sqrt{2}\pi^2} \left(2m_W^2 + m_Z^2 + m_H^2 - 4m_t^2\right) \Lambda^2 \approx -(0.2 \Lambda)^2$$

e.g. SUSY’s solution: (natural) cancellations given by the top’s superpartner, stop
Stop: Decays

stop-to-charm  4-body  3-body  2-body decays

\( \Delta m = m_{\tilde{t}_1} - m_{\tilde{\chi}_1^0} \)

- \( m_{\tilde{t}_1} < m_{\tilde{\chi}_1^0} \)
- \( \Delta m > 0 \)
- \( \Delta m > m_W + m_b \)
- \( \Delta m > m_t \)

\( \tilde{t}_1 \rightarrow c\tilde{\chi}_1^0 \)
\( \tilde{t}_1 \rightarrow bff\tilde{\chi}_1^0 \)
\( \tilde{t}_1 \rightarrow bW\tilde{\chi}_1 \)
\( \tilde{t}_1 \rightarrow t\tilde{\chi}_1 \)
Main Backgrounds

Typical signature involves large $E_T$, b-jets and 0, 1 or 2 leptons

Control (CR) and validation (VR) regions used to extract / x-check background predictions

- **$tt\ (0,1,2\ell)$**
  - $W_t \rightarrow tW$
  - b-jet
  - jets
  - fit MC to data in CR, “lepton replacement”

- **Single top (Wt mainly)**
  - $W_t \rightarrow tW$
  - b-jet
  - jets
  - fit MC to data in CR, “lepton replacement”

- **$Wj \rightarrow \ell\nu j$**
  - $W$ jets
  - fit MC to data in CR, “lepton replacement”

- **Multijets**
  - jets
  - fully data-driven

- **Z+jets (e.g. $Z_j \rightarrow \nu\nu j$)**
  - Z+jets
  - $Z$
  - use $Z_j \rightarrow \mu\nu j$ or $\gamma+jets$ events

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S. Zambito, Harvard University
Stop 1L, ATLAS: Strategy (I)

4-body decays

$E_T > 300$ GeV, at least one b-tagged jet
one soft lepton

3-body decays

Cut & count selection, shape fit to $p_T^{lep}/E_T^{miss}$

Events

<table>
<thead>
<tr>
<th>Events</th>
<th>ATLAS</th>
<th>Data</th>
<th>Total SM</th>
<th>$m(\tilde{t}, \tilde{\chi}_1^0) = (350, 330)$ GeV</th>
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<td>$\sqrt{s} = 13$ TeV, 36.1 fb$^{-1}$</td>
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$3$-body decays

Cut & count selection, shape fit to asymmetric-$m_{T2}$ (*)

Events

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(*) arXiv:1212.1720
Compressed, “diagonal” region

$m_t - m_\tilde{\chi} \approx m_t$ : signal kinematics very close to SM $t\bar{t}$

Need ISR activity to “misalign” $\chi\chi$
and get contribution to $E_T$

\[\chi \quad \chi \quad E_T\]

\[\chi \quad \chi \quad E_T\]

ISR jet(s)
Compressed, “diagonal” region

\[ m_t - m_{\tilde{\chi}} \approx m_t \]: signal kinematics very close to SM \( t\bar{t} \)

3 BDTs targeting different \( m_{\text{stop}} \),
exploiting correlation between ISR and \( E_T \):

\( \text{BDT}_\text{low}, \text{BDT}_\text{med}, \text{BDT}_\text{high} \)

Need ISR activity to “misalign” \( \chi\chi \)
and get contribution to \( E_T \)

\[ R_{\text{ISR}} = E_T / p_{T,\text{ISR}} \text{ (in CM)} \]
2-body decays

Two signal regions, simple requirements on powerful variables

Targeting, respectively, intermediate and high stop masses

- shape fit in $E_T$: 5 bins above 250 GeV

\[ \Delta m_{T2} \] variable targets

$H_{T,\text{sig}} = \frac{|\tilde{H}_{T}\text{miss}| - M}{\sigma |\tilde{H}_{T}\text{miss}|}$

Obtained from per-event jet energy uncertainties

Negative vector sum of all jets momenta

Offset (100 GeV)
Reconstructing kinematics of stop decay products key to reject backgrounds

Low $\Delta m (< m_W)$: reconstruct ISR from large-R jets; soft b-tagging via $N_{sv}$ (secondary vertices)

High $\Delta m$: reconstruct hadronic $t$ and $W$ candidates (from stop decays)

one R=0.8 jet with 2 substructures

+ BDT

3 resolved R=0.4 jets

+ BDT

Simulation corrected to match $t$ and $W$ tagging eff. measured in data

JHEP 10 (2017) 005
Stop 0L, CMS: Strategy (II)

Trigger on $E_T$ (offline: >250 GeV), veto events with isolated leptons

**Low $\Delta m$**

- $N_{\text{jets}} \geq 2$, $N_t=N_W=0$, $m_T(\not{E}_T, b\text{-jet}) < 175$ GeV
- one ISR jet, $p_{T,\text{ISR}} > 300$ GeV, $\Delta \phi(\not{E}_T, \text{ISR}) > 2$, ...

**High $\Delta m$**

- $N_{\text{jets}} \geq 5$, $N_{\text{b-tag}} \geq 1$, $\Delta \phi(\not{E}_T, j_{1..4}) \geq 0.5$

53 search regions slicing:
- $N_{\text{jets}}, N_{\text{b-tag}}, N_{\text{SV}}, p_{T,\text{ISR}}, p_{T,b}, \not{E}_T$
Stop: Exclusion Limits

Simplified models: excluded up to \( m_{\tilde{t}} \sim 1.1 \text{ TeV} \) (and up to \( m_{\tilde{\chi}_0} \sim 500 \text{ GeV} \))

However, interesting holes at light stop mass: very challenging region!
Simplified models: excluded up to $m_{\tilde{t}} \sim 1.1$ TeV (and up to $m_{\tilde{\chi}^0} \sim 500$ GeV)

However, interesting holes at light stop mass: very challenging region!

pMSSM-inspired models show weaker limits: $m_{\tilde{t}} \sim 600$ GeV + light LSP allowed
Sbottom: Strategy

\( \tilde{t}_L \) and \( \tilde{b}_L \) in same weak isospin multiplet

\( \tilde{b}\tilde{b} \) less “jetty” than \( \tilde{t}\tilde{t} \) events; harder b-jets

select events with 2 energetic b-jets and large \( E_T \)

CMS: (soft*) c-/b-tagging

\( M_{CT} \): endpoint at \((m_{\tilde{b}}^2 - m_{\tilde{\chi}^0})/m_{\tilde{b}}^2\)

ATLAS: tailored kinematic variables

\( m_T(\ell,E_T) \): endpoint at \( m_W \) for \( \tilde{t}\tilde{t} \) and \( W+jets \)

\( 0L \)

\( 1L \)

[Diagrams showing event selections and mass spectra for CMS and ATLAS]

* for compressed signal mass spectra

15 - 3rd generation SUSY & rare top processes/decays
Sbottom: Exclusion Limits

Exclusions reaching $m_{\tilde{b}} \sim 1.25$ TeV, and:

- ~600 GeV in neutralino mass for direct decays
- ~350 GeV for decays with intermediate chargino

Bottom squark pair production, $\tilde{b}_1 \rightarrow b \tilde{\chi}_1^0 / t \tilde{\chi}_1^0$ at 50% BR

JHEP 11 (2017) 195

16 - 3rd generation SUSY & rare top processes/decays

S. Zambito, Harvard University
Rare Top Processes/Decays

FCNC highly suppressed in SM $\rightarrow$ enhanced rates signal of new physics

$t\bar{t}$ with FCNC decays (ATLAS+CMS)

FCNC single-top production (CMS)

SM: $\mathcal{B}(t \rightarrow qH) \sim 10^{-14}$; $\mathcal{B}(t \rightarrow qZ) \sim 3 \times 10^{-15}$; can go up to $\sim 10^{-3}$ in some BSM scenarios: non-minimal $H$ sector, SUSY, warped extra dimensions, composite $H$ models, etc...
Rare Top Processes/Decays

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**FCNC $tqH$ vertices (ATLAS: $H \rightarrow \gamma\gamma$, CMS: $H \rightarrow bb$)**

- Main backgrounds: $\gamma\gamma+\text{jets}$, $t\bar{t}\gamma$ and $V\gamma$ (ATLAS); $t\bar{t}$, single-top (CMS)
- Largest uncertainties: $t\bar{t}$ hard-process generation (ATLAS) and $b$-tagging (CMS)

**FCNC $tqZ$ vertices (3L final state, ATLAS+CMS)**

- Main backgrounds: diboson, $t\bar{t}Z$, $tZ$, $t\bar{t}H$
- Largest uncertainties: background modeling
**FCNC: t → qH, H → γγ**

### Hadronic $t\bar{t}$ selection

- **$N_{jets} \geq 4$, $N_{b-tag} \geq 1$**
- $152 < m(t_1) < 190$ GeV
- $120 < m(t_2) < 220$ GeV

**Signal from fit to $m(\gamma\gamma)$**

**Bkg. from sidebands**

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### Semileptonic $t\bar{t}$ selection

- **$N_{jets} \geq 1$, 1 isolated lepton**
- $152 < m(t_1) < 190$ GeV
- $130 < m(t_2) < 210$ GeV

**Signal form fit to $m(\gamma\gamma)$**

**Bkg. from sidebands**

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**ATLAS**

- $\sqrt{s} = 13$ TeV, 36.1 fb$^{-1}$
- **Hadronic selection**
  - Data
  - $t \rightarrow cH(\gamma\gamma)$ B = 5%
  - SHERPA $\gamma\gamma j$ (scaled)
  - $t\gamma$

**ATLAS**

- **Leptonic selection**
  - Data
  - $t \rightarrow cH(\gamma\gamma)$ B = 1%
  - SHERPA $\gamma\gamma j$ (scaled)
  - $W_{\gamma\gamma} + Z\gamma\gamma$
  - $t\gamma$

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19 - 3$^{rd}$ generation SUSY & rare top processes/decays
FCNC: $t \rightarrow qH$, $H \rightarrow bb$

Events with 1L, $N_{\text{jets}} \geq 3$ and $N_{\text{b-tag}} \geq 2$ are split into 5 $N_{\text{jets}}+N_{\text{b-tag}}$ categories

Full event kinematics reconstruction: all possible lepton, $\nu$ and (b-)jets combinations

$\text{BDT}_{\text{RECO}}$ trained on simulation to select the correct b-jet assignment: 75% success rate

1 $\text{BDT}$ per $N_{\text{jets}}+N_{\text{b-tag}}$ category, maximizing S/B separately for $t \rightarrow uH$ and $t \rightarrow cH$

Main variables in training are $\text{BDT}_{\text{RECO}}$, lepton charge, b-tagging discriminant score, $m_{bb}$
Simultaneous fit to 5 regions
Constrain bkg., isolate signal
Mainly defined by $N_{\text{jets}}, N_{\text{b-tag}}$ requirements

<table>
<thead>
<tr>
<th>WZ control region (WZCR)</th>
<th>single top quark signal region (STSR)</th>
<th>top quark pair signal region (TTSR)</th>
<th>single top quark control region (STCR)</th>
<th>top quark pair control region (TTCR)</th>
</tr>
</thead>
</table>

BDT to improve S/B

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

**FCNC: $t\rightarrow qZ$ (3L Final State)**

$\chi^2$-based $t\bar{t}$ reconstruction

$$\chi^2 = \frac{(m_{\text{reco}} - m_{\text{FCNC}})^2}{\sigma_{\text{FCNC}}} + \frac{(m_{\text{reco}} - m_{\text{bW}})^2}{\sigma_{\text{bW}}} + \frac{(m_{\text{reco}} - m_{\text{W}})^2}{\sigma_{\text{W}}}.$$
$\mathcal{B}(t \rightarrow uZ) < 0.017$ (0.024) %
$\mathcal{B}(t \rightarrow cZ) < 0.023$ (0.032) %
$\mathcal{B}(t \rightarrow uH) < 0.22$ (0.16) %
$\mathcal{B}(t \rightarrow cH) < 0.24$ (0.17) %  
($H \rightarrow \gamma \gamma$)

$\mathcal{B}(t \rightarrow uZ) < 0.024$ (0.015) %
$\mathcal{B}(t \rightarrow cZ) < 0.045$ (0.037) %
$\mathcal{B}(t \rightarrow uH) < 0.47$ (0.34) %
$\mathcal{B}(t \rightarrow cH) < 0.47$ (0.44) %  
($H \rightarrow bb$)

**Limits on off-diagonal Yukawa couplings:**

$$\lambda_{tqH} = (1.92 \pm 0.02) \times \sqrt{\mathcal{B}} \Rightarrow \sqrt{\lambda_{tCH}^2 + 0.92\lambda_{tuH}^2} < 0.090$$

**Limits on FCNC couplings @ scale $\Lambda$:**

$$L^{\Lambda}_{FCNC} = \sum_{q=u,c} \left[ \frac{\sqrt{2}}{4} \frac{g}{\cos \theta_W} \lambda^{\Lambda}_{tqZ} \left( f_{Zq}^{L} P_{L} + f_{Zq}^{R} P_{R} \right) qZ_{\mu\nu} \right] + h.c.$$
Top quark plays a key role in many BSM searches

- Great deal of efforts in ATLAS+CMS to look for $t$- and $b$-quark super-partners
  - a small fraction presented today, through the 0L and 1L workhorses
  - only stringent limits so far, but we’re not yet at the end of the journey…
- Limits on DM+HF models nicely complement direct-detection experiments
- Searches for rare top processes/decays start to show sensitivity for BSM rates
Spares
The ‘well-tempered neutralino’ [69] scenario seeks to provide a viable dark-matter candidate while simultaneously addressing the problem of naturalness by targeting an LSP that is an admixture of bino and higgsino. The mass spectrum of the electroweakinos (higgsinos and bino) is expected to be slightly compressed, with a typical mass-splitting between the bino and higgsino states of 20–50 GeV. A pMSSM signal model is designed such that only a low level of fine-tuning [70, 71] of the pMSSM parameters is needed and the annihilation rate of neutralinos is consistent with the observed dark-matter relic density $^5$ ($0.10 < \Omega h^2 < 0.12$) [72].
Stop 0L, CMS: Strategy (II)

Trigger on $\vec{E}_T$ (offline: $>250$ GeV), veto events with isolated leptons

**Low $\Delta m$**

$N_{\text{jets}} \geq 2$, $N_t = N_W = 0$, $m_T(b, \text{b-jet}) < 175$ GeV

one ISR jet, $p_{T,\text{ISR}} > 300$ GeV, $\Delta\phi(\vec{E}_T, \text{ISR}) > 2$, ...

53 search regions

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**High $\Delta m$**

$N_{\text{jets}} \geq 5$, $N_b - \text{tag} \geq 1$, $\Delta\phi(\vec{E}_T, j_1 ... 4) \geq 0.5$

51 search regions

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Table 1: Summary of the 51 non-overlapping search regions that mainly target high $\Delta m$ signal. The high $\Delta m$ baseline selection is $N_j \geq 5$, $p_{T,\text{miss}} \geq 250$ GeV, no leptons, $N_b \geq 1$, and $\Delta\phi_{1234} \geq 0.5$.

<table>
<thead>
<tr>
<th>$N_j$</th>
<th>$N_b$</th>
<th>$N_W$</th>
<th>$N_{\text{res}}$</th>
<th>$p_{T,\text{miss}}$ [GeV]</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\geq 7$</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>$\geq 1$</td>
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<tr>
<td>$\geq 5$</td>
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<td>$\geq 1$</td>
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<td>0</td>
<td>$\geq 1$</td>
<td>0</td>
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</tbody>
</table>

Table 2: Summary of the 53 non-overlapping search regions that mainly target low $\Delta m$ signal. The low $\Delta m$ baseline selection is $N_j \geq 2$, $p_{T,\text{miss}} \geq 250$ GeV, no leptons, $N_t = N_W = N_{\text{res}} = 0$, $m_T < 175$ GeV (when applicable), $|\Delta\phi(j, p_{T,\text{miss}})| \geq 0.5$, $|\Delta\phi_{123, p_{T,\text{miss}}}| \geq 0.15$, and an ISR jet with $p_{T,\text{ISR}} \geq 300$ GeV, $|\eta| \leq 2.4$, $|\Delta\phi(\text{ISR}, p_{T,\text{miss}})| \geq 2$, and $S_{E_t} \geq 10 \sqrt{\text{GeV}}$.

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<th>$N_W$</th>
<th>$N_{\text{res}}$</th>
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<th>$p_{T,\text{miss}}$ [GeV]</th>
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<tr>
<td>$\geq 7$</td>
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<td>0</td>
<td>0</td>
<td>1</td>
<td>250-300, 300-400, 400-500, $\geq 500$</td>
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<tr>
<td>$\geq 5$</td>
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<td>0</td>
<td>$\geq 1$</td>
<td>1</td>
<td>550-650, $\geq 650$</td>
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<td>$\geq 1$</td>
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26 - 3rd generation SUSY & rare top processes/decays

S. Zambito, Harvard University
DM+Heavy Flavor(s) (HF)

WIMP(s) via mediators: spin-0 $\phi/a$ or vector $V$

Minimal Flavor Violation: Yukawa-type $\phi/a$-SM couplings

Monotop: flavor-violating V-quark couplings

ATLAS: tailored kinematic variables

$$\xi^+ = m_{T2} + 0.2 \cdot E_T^{\text{miss}}$$

large tail created by $\chi\chi$

**CMS:** exploit top reconstruction

**ATLAS**

- $\sqrt{s} = 13$ TeV, 36.1 fb$^{-1}$
- SRt3

**Events / 50 GeV**

- Data
- Standard Model
- $t\bar{t}$
- Wt
- $t\bar{t}+Z$
- Fakes/NP
- $V+V$
- Others

**Normalized distribution**

- CMS Simulation
  - 110 $< m_{SD} < 210$ GeV
- $q/g$ jets

27 - 3rd generation SUSY & rare top processes/decays

S. Zambito, Harvard University
95% CL exclusion limits on Dirac DM and (pseudo)scalar mediators

Scalar mediators $\phi$ masses excluded between 10-50 GeV ($g=1$, $m(\chi)=1$ GeV)

Vector mediators with flavor-violating couplings excluded up to 1.8 TeV ($g_{q,V}=0.25$, $g_{\chi,V}=1$)

DM + $t\bar{t}$ ($b\bar{b}$)

CMS

Monotop

$36fb^{-1}$ (13 TeV)
DM+HF: Limits

95% CL exclusion limits on Dirac DM and (pseudo)scalar mediators
Scalar mediators $\phi$ masses excluded between 10-50 GeV ($g=1$, $m(\chi)=1$ GeV)
Vector mediators with flavor-violating couplings excluded up to 1.8 TeV ($g_{q,V}=0.25$, $g_{\chi,V}=1$)