Third generation SUSY searches in CMS

Eric Chabert
On behalf the CMS collaboration
### SUSY session on Tuesday:
- Squark/gluino searches in hadronic channels with CMS (*SAKUMA, Tai*)
- pMSSM studies with ATLAS and CMS (*FAWCETT, William James*)

### SUSY plenary session this morning:
- Inclusive searches for gluinos and squarks @LHC (*HODGKINSON, Mark*)
- SUSY searches in lepton and photon final states @LHC (*SCHULTE, Jan-Frederik*)
- Third generation SUSY searches at the LHC (*HOPKINS, Walter*)

### SUSY plenary session this morning:
- Squark/gluino in leptonic channels with CMS (*LOBANOV, Artur*)
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SUSY plenary session this morning:
- Squark/gluino in leptonic channels with CMS (LOBANOV, Artur)

I’m the last one 😞
I should have chosen an experiment whose name starts with an A not a C....

How could I be original ??
What’s in ?

Run 1 analyses
- Stop searches in 0/1/2 leptons
- Stop search in 2bs+MET
- Stop searches in RPV
- Gluino mediated stop production
- ...

Run II analyses
- Stop searches in multi-jets
- Stop searches in l+jets
- Stop search in 2bs+jets
- Sbottom search in 2bs+MET
- Sbottom search in OS -2l
- Gluino mediated stop production search
Physic processes considered

- Consider **Simplified Models Spectra with a limited number of sparticles**
- **Production modes of stop/sbottom**
  - Direct pair production
  - *Gluino induced pair production*

![Diagram showing simplified models](image)

- Example:
  - \( \tilde{t} \rightarrow c \tilde{\chi}_1^0 \)
  - \( \tilde{t} \rightarrow b f \tilde{f} \tilde{\chi}_1^0 \)
  - \( \tilde{t} \rightarrow b W \tilde{\chi}_1^0 \)
  - \( \Delta m = m(\tilde{t}_1) - m(\tilde{\chi}_1^0) \)

Not described in that talk
Physic processes considered

- **Stop searches**

  - Both decay $\tilde{t} \rightarrow t\tilde{\chi}_1^0$
  - Mixed decays where $BR \neq 100\%$
  - Both decay $\tilde{t} \rightarrow b\tilde{\chi}_1^+, \tilde{\chi}_1^+ \rightarrow W^*\tilde{\chi}_1^0b$

  - Top decays lead to 3 channels: 0, 1, 2 leptons

- **Sbottom searches**

  - Relevant in compressed spectra

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Stop searches: fully hadronic

Top $p_T$ OR $\Delta M(\tilde{t}, \tilde{\chi}_1^0)$

**High Efficiency Top Tagging (HPTT)**

- Use AK4 jets
- Combination of 3 jets with $\Delta R=1.5$
- Constraints on 2- and 3-body masses ($W$/top)
- Sensitivity to boosted topology:
  - 1- and 2-jets combination ($W$/top appearing as a single jet: mass constraints)

Optimized for low $\Delta m$, and mixed scenarios with T2tb decays

**High Purity Top Tagging (HPTT)**

- Boosted topology
  - Use Ak8 jets – CMS Top Tagging algo:
    - At least 3 subjets
    - Jet mass: [140-250] GeV
    - MinMass(3 highest $p_T$ subjets)>50 GeV
    - $p_T>$400 GeV

More efficient for T2tt models with medium and large $\Delta m$
Stop searches: fully hadronic

Top $p_T$ OR $\Delta M(\tilde{t}, \tilde{\chi}_1^0)$

High Efficiency Top Tagging (HPTT)

Performances measured in data
- Tag-and-probe method in $t\bar{t}-1l$ enriched sample
- MC/Data agreement: flat 5% uncertainty

High Purity Top Tagging (HPTT)

Performances measured in data
- Efficiency measured with $t\bar{t}-1\mu$ enriched sample: 10% uncertainty
- Fake rate measured a Control Sample with $H_T>1$ TeV & MET$>200$ GeV:
  - 30% overestimation in MC (corrected)
  - 10% uncertainty
Stop searches: fully hadronic

Selection

- $N_j \geq 4$ ($p_T \geq 30$ (20) GeV) [suppress QCD]
- $N_b \geq 1$ ($N_b^l \geq 2$) [suppress EW]
- Isolated Lepton veto ($e/\mu/\tau_h$) [suppress 1l processes]
- Min $\Delta\phi$ ($j,MET$) > 0.5 (among 3 or 4 leading jets) [suppress QCD]
- $MET > 200$ (250) GeV [suppress $tt$] (+ HT > 500 GeV)

Introduce discriminating variables

$M_T(b_{1,2},E_T) \equiv \text{Min}[M_T(b_1,E_T), M_T(b_1,E_T)]$

$M_{T2} \equiv \min_{\tilde{q}^{(1)},\tilde{q}^{(2)} = \tilde{p}_T^\text{miss}} \{\max\{m_T^2(p_T^{(1)};m_p^{(1)},\tilde{q}^{(1)};m_{\tilde{\chi}_1}^0), m_T^2(p_T^{(2)};m_p^{(2)},\tilde{q}^{(2)};m_{\tilde{\chi}_1}^0)\}\}$

$M(\tilde{\chi}_1^0) = 0$

MET is coming from $\tilde{\chi}_1^0$

End-shape at top mass for $tt$

Estimator of stop mass for signal
Stop searches: fully hadronic

**High Efficiency Top Tagging (HPTT)**

**Binning:**
- $N_{\text{top}}$, $N_b$, MET, $M_{T2}$
- 37 exclusives search regions

**High Purity Top Tagging (HPTT)**

**Binning:**
- $N_{\text{top}}$, $N_b$, $N_{\text{jets}}$, $M_T(b,\text{MET})$
- 50 exclusives search regions

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**CMS Preliminary**

**Data**
- $t\bar{t}$
- $W$(inv)+jets
- Single top
- $Z$(nu)v)+jets
- QCD
- tZ
- Rare

Events:
- $N_{\text{top}}$ (vertical axis)
- $N_b$, $N_{\text{jets}}$ (horizontal axis)

**Observed**
- $M_{T}(b,\text{MET}) > 175$ GeV
- $\geq 5$ jets, $N_t \geq 1$

**HPTT**
- $N_b = 1$
- $N_b \geq 2$

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This is just a subset of the Signal regions
Stop searches: fully hadronic

**Generalities:**

- Major backgrounds estimated from **orthogonal control regions (CR)**
  - Define to be as close as possible to the signal regions (~ same binning)
  - **Integration over some variables** done to increase the statistical power of the estimation when no dependencies are observed
  - Make use of **Transfer Factors** (Control -> Signal region)

- Rare backgrounds taken from simulation
  - **Reweighted** to the most accurate x-section and to known mis-modeling of the simulation (ex: PU)
  - all uncertainties (theory – experimental) are taken into account

- Signal is taken from simulation in similar way to the MC background (reweighting + uncertainties)

**Background estimation strategy for fully hadronic stop searches**

- **Lost lepton background:** from 1l CR. MT < 100 GeV.
- **Z\rightarrow\nu\nu:** Use an enriched 2l CR as well as a γ +jets CR
- **Multi-jet background:** estimated from a CR defined by inverting the cut on Δφ (jets, MET)
- **ttZ:** from simulation
Stop search: one lepton

Selection

- 1 lepton (e/μ)
- MET > 250 GeV
- At least one b-tagged jet (against EWK)
- $M_T > 150$ GeV (against W+jets & tt →1l)
- No extra e/μ/τ (against tt → 2l)

Binning

- $N_{\text{jet}}$ (2, 3 or ≥ 4 jets)
- MET bins
- $MT_{2W} [</>] 200$ GeV

$M_{T2}^W = \min \{ m_y \text{ consistent with } p_1^2 = 0, \left( p_1 + p_\ell \right)^2 = p_2^2 = M_W, \bar{p}_T^1 + \bar{p}_T^2 = \vec{E}_T^{\text{miss}}, \left( p_1 + p_\ell + p_{b1} \right)^2 = \left( p_2 + p_{b2} \right)^2 = m_y^2 \}$
Stop search: one lepton

**3- >=4 jets selection**

- Events / 25 GeV
- $2.3 \text{ fb}^{-1}$ (13 TeV)

**Low $\Delta M$**
- $t\to t\tilde{\chi}_1^0$ (300,150)
- $t\to t\tilde{\chi}_2^0$ (500,200)
- $t\to t\tilde{\chi}_3^0$ (600,50)

**MT2W**

**2 jets selection**

- Events / 1
- $2.3 \text{ fb}^{-1}$ (13 TeV)

**Modified topness**

- Use $t^{\text{mod}}$ instead of $MT2W$ to suppress $tt-2l$ background:
  - $X^2$ with $W^l$ mass and $top^{\text{lost lepton mass}}$

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Stop search: one lepton

- **2 jets**
  - Soft /invisible decay
  - Small $\Delta M(\tilde{\chi}_1^+, \tilde{\chi}_1^0)$

- **3 jets**
  - Boosted hadronic W
  - V.Large $\Delta M(\tilde{t}, \tilde{\chi}_1^0)$

- **≥ 4 jets**
  - MT2W used to discriminate
  - Small and high $\Delta M(\tilde{t}, \tilde{\chi}_1^0)$

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**Introduction**

**Stop searches**

**Sbottom search**

**Conclusion**

**CMS Preliminary**

- 2.3 fb⁻¹ (13 TeV)

- Events
  - Compressed: $\tilde{\chi}_1^\pm - \tilde{\chi}_1^0$
  - Boosted High $\Delta M$
  - Low $\Delta M$
  - High $\Delta M$

- Data
  - Lost Lepton
  - $t\bar{t} \rightarrow \nu$
  - $\nu$ (not from t)
  - $Z \rightarrow \nu\bar{\nu}$

- $\tilde{t} \rightarrow t\tilde{\chi}_1^0$ (700,50)
  - $\tilde{t} \rightarrow t\tilde{\chi}_1^0 / \tilde{b}\tilde{\chi}_1^\pm$ (600,200)
  - $\tilde{t} \rightarrow t\tilde{\chi}_1^0$ (300,150)

**$E_T^{miss}$ [GeV]**

- 250 – 350
- 350
- 250 – 325
- 325
- 350
- 450
- ≥ 450
Stop search: one lepton

- Background estimation
  - **Lost lepton**: taken from a 2l CR
  - **W+Jets**: estimated from 0 b-tag CR
  - **Minor backgrounds**: from simulation

![MET distribution in CR](image)

**W+j enriched**  
**tt-2l enriched**

![Njet distribution in an enriched tt-2l CR](image)

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Stop searches: Combination

First 13 TeV results (2.3 fb\(^{-1}\)) already supersede the limits at 8 TeV (19 fb\(^{-1}\))

BR=100%
Assume BR = 50% for both channels
Selection: veto $\ell$ or isolated track, **two or three jets** with $p_T>50$ GeV, MET>250 GeV (MET trigger), $\Delta \phi (j_{123}, \text{MET}) > 0.4$

### Non-compressed

**Selection:**
- $p_T(j_1)>100$ GeV, $p_T(j_2)>75$ GeV
- both are **b-tagged**
- $H_T>200$ GeV, $m_{CT}>250$ GeV

### Compressed

**Selection:**
- $p_T(j_1)>250$ GeV - NOT b-tagged
  - Require a ISR jet to boost the system
- $p_T(j_2)>60$ GeV, **b-tagged**
- $\Delta \phi (j_1, \text{MET}) > 2.3$
Sbottom search

Non-compressed

Binning: $H_T$ and $m_{CT}$

\[
m_{CT}^2(j_1,j_2) = \left[ E_T(j_1) + E_T(j_2) \right]^2 - \left[ p_T(j_1) - p_T(j_2) \right]^2
= 2p_T(j_1)p_T(j_2)(1 + \cos \Delta \phi(j_1,j_2)),
\]

Compressed

Binning: $N_{b-jets}$, MET
Main backgrounds estimation:

- **Z\rightarrow\mu\mu:**
  from a Z\rightarrow\mu\mu enriched sample
  μ’s are removed to recompute all the kinematic variables

- **Lost lepton backgrounds:**
  from a enriched e/μ single control sample

- **QCD multijets:**
  from control region defined by the inversion of the Δ\phi(j,MET) cut and at lower MET values

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**Events**

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**Conclusion**

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**Sbottom search**

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**Introduction**

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**Stop searches**

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Sbottom searches: exclusion limits

Introduc0n

Stop searches

Sbottom search

Conclusion
Conclusion

- Targeted searches for third generation squarks
  - Covering **broad range of signatures** with dedicated tools
  - Use **dedicated approaches** to cover the different kinematics (compressed, moderate, boosted): top-taggers, specific variables

- No evidence yet, results interpreted in terms of limits in SMS

- Stop searches with 2015 data beginning to surpass 8 TeV limits
  \[ m_{\text{stop}} > 800 \text{ GeV for low } m_{\text{LSP}} \]

- Run2 will boost the reach
  - Focus on compressed scenarios, and \( \Delta m \approx m_t \)
  - Work on isolation, boosted objects, high pileup
  - Expand interpretations
Diversity is the keyword

we don’t know where the SUSY could be (if...) and we should try to cover as much possibilities as we can
Partial cancelation of the top quark radiative corrections to the Higgs mass \(\Rightarrow\) natural SUSY models

- Stop expected to be “light”
- IF lowest color-charged SUSY particle \(\Rightarrow\) highest cross-section

Link with Dark Matter (DM)

- In RP-conserved models, LSP is stable. In most of the models it is the neutralino (WIMP candidate)
- Stop-neutralino co-annihilation could contribute to the relic DM density: favors low mass difference
Perspectives

As a reminder, these are some simple extrapolation made for Snowmass
Latest results:
https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsSUS

Covered analysis:
- SUS-16-001
- SUS-16-002
- SUS-16-007
Simulation

Generations
- MADGRAPH5: tt, W+jets, Z+jets, gamma+jets [with NNPDF3.0]
- POWHEGv1.0:
  - MAGRHAPH5_AMC@NLO: single top, ttZ, ttW

PDF: NNPDF3.0

PS+Hadronization: PYTHIA8.1

Simulation: GEANT4 based

Cross-section normalization: (N)NLO+NLL (when possible)

Monte-Carlo correction
- Lepton efficiencies (estimated from Z+jets) [param: kinematics]
- B-tagging efficiencies (di-jets+tt) [param: kinematics & flavor]
- PileUp reweighing [data/MC ratios]
Stop search: 8/13 TeV comparison

**Stop production, \( \tilde{t} \to t \tilde{\chi}_1^0 / c \tilde{\chi}_1^0 \)**

**Introduction**

**Stop searches**

**Sbottom search**

**Conclusion**

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**CMS**

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

- **Observed UL:** \( m_{\tilde{t}_1} - m_{\tilde{\chi}_1^0} = 175 \text{ GeV} \)
- **Expected UL:**
  - 100% \( \mathcal{B}(\tilde{t}_2 \to \tilde{t}_1 Z) = 100\% \)
  - 50% \( \mathcal{B}(\tilde{t}_2 \to \tilde{t}_1 Z) = 50\% \)
  - 0% \( \mathcal{B}(\tilde{t}_2 \to \tilde{t}_1 Z) = 0\% \)

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**Stop searches**

**Sbottom search**

**Conclusion**

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Eric Chabert  Third generation SUSY searches in CMS  LHCP2016 - June 17, 2016  29