
# Third generation squarks searches

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on behalf of the
**ATLAS** & **CMS** Collaborations

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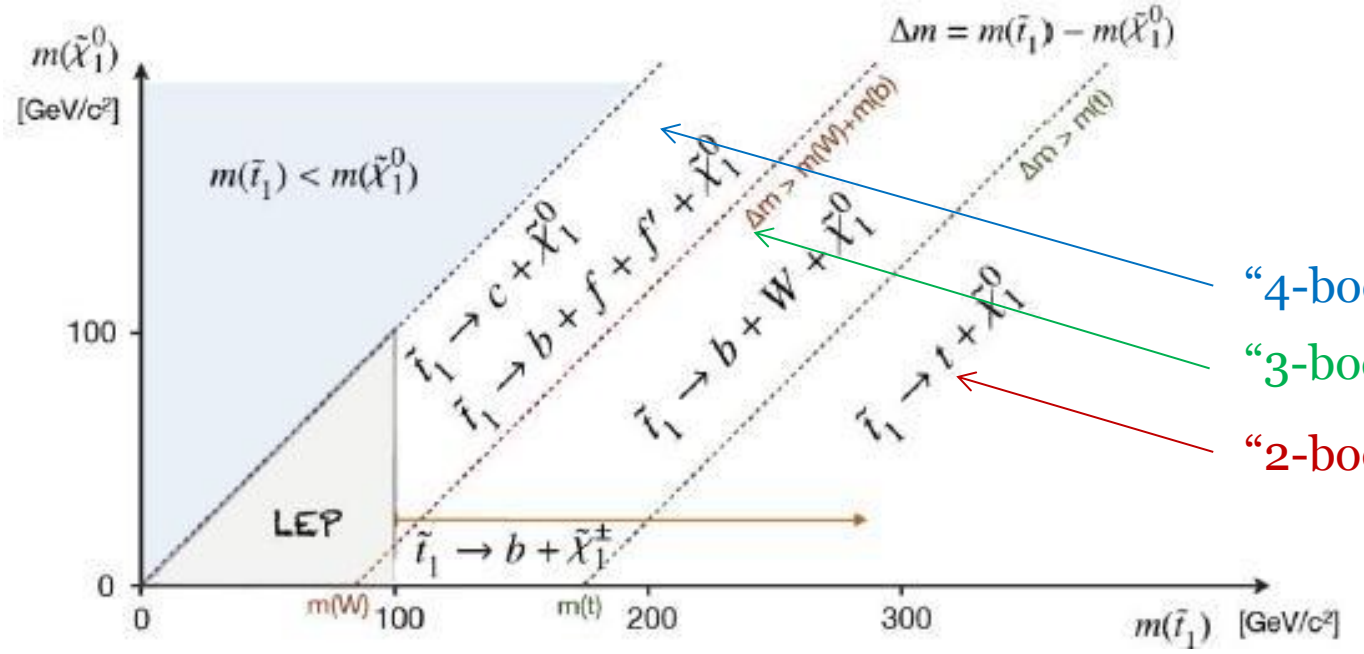
# Third generation squarks

- Supersymmetry (SUSY) offers a solution to the **hierarchy problem** in the Standard Model (SM)
- Light squarks can significantly contribute in **Higgs boson** mass loop corrections.
- Large mixing imply **lower masses** for third generation squarks $\tilde{t}$ (**stop**) and $\tilde{b}$ (**sbottom**) with respect to the first two generations.
- If R-parity is conserved, $\tilde{\chi}_1^0$ (lightest neutralino) remains a good candidate for **Dark Matter** (LSP)
- Many "natural" scenarios predict **light** third generation squarks to be lighter than ~1 TeV

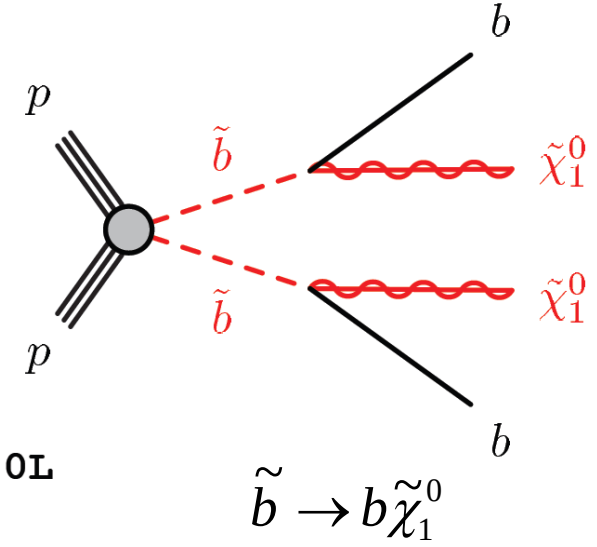
# Production and decays

- Here focus is on **direct** stop/sbottom **pair** production searches
- Few possible decay modes are possible for $\tilde{t}$ and $\tilde{b}$ depending on the sparticle masses of the point in the parameter space
- Simplified assumption is **100%** branching fraction for the given final state considered



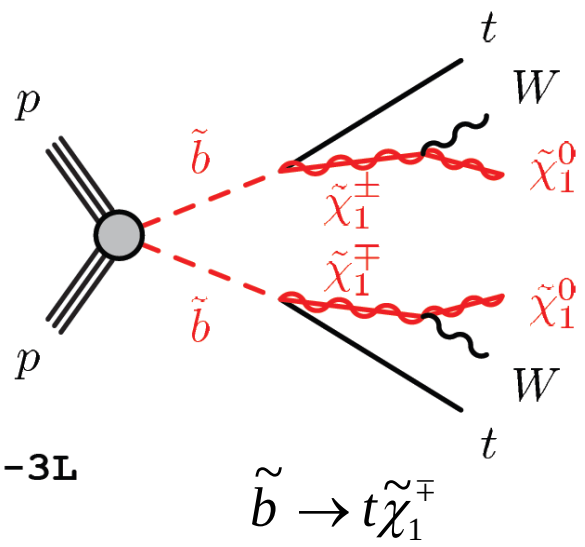

- Since 2011 ATLAS & CMS analyses are closing up the gaps with increasing sensitivity

# Direct production of sbottom pairs



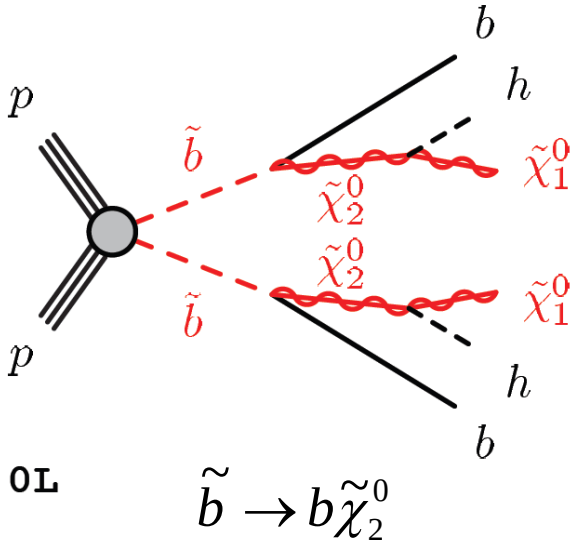

0L

$\tilde{b} \to b\tilde{\chi}_1^0$




2-3L

$\tilde{b} \to t\tilde{\chi}_1^{\mp}$




0L

$\tilde{b} \to b\tilde{\chi}_2^0$

- Signatures of interest can include 0 leptons or 2-3 leptons
- The last case considered can happen via Z instead of Higgs boson
- $\tilde{\chi}_1^0$ assumed to be the LSP, unless differently specified

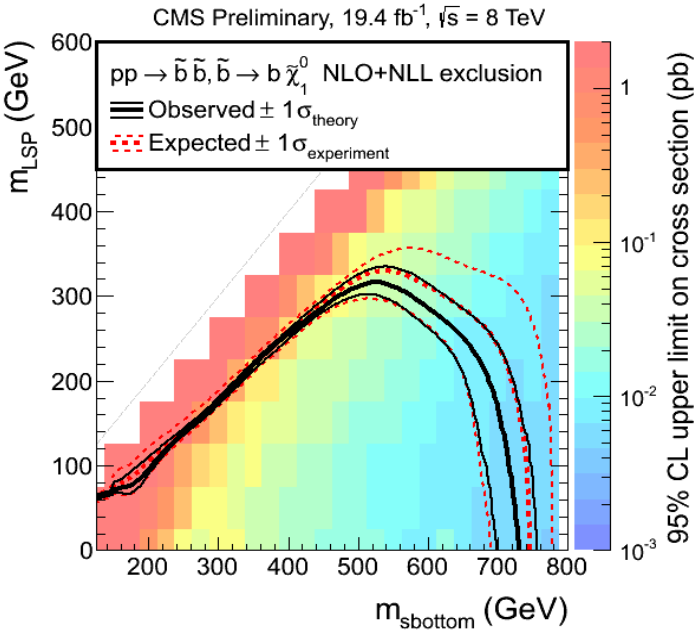
PAS-SUS-13-018

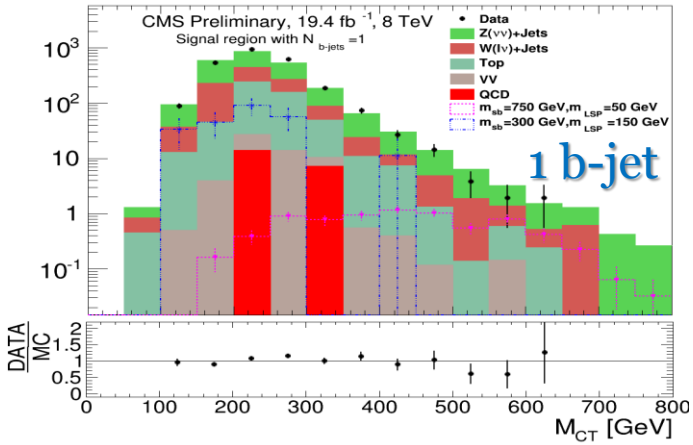
# 0 leptons + 2 (1 b-)jets + MET

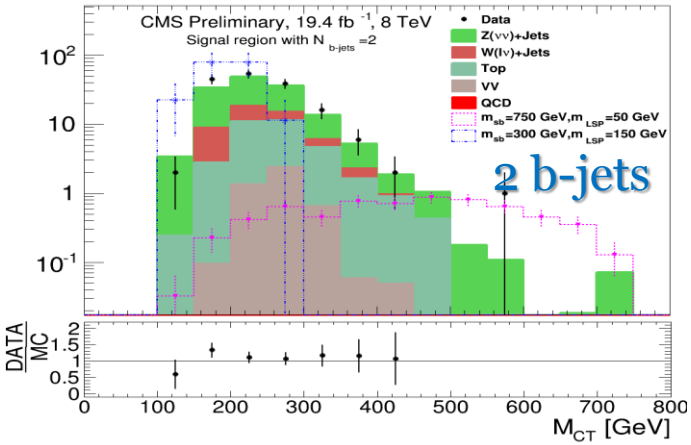
- Signal discriminant is $M_{CT}$ : $M_{CT}^2(J_1, J_2) = [E_T(J_1) + E_T(J_2)]^2 - [\mathbf{p}_T(J_1) - \mathbf{p}_T(J_2)]^2 = 2p_T(J_1)p_T(J_2)(1 + \cos\Delta\phi(J_1, J_2))$
- Eight exclusive signal regions (**SR**s):

| No. of b-jets | $M_{CT}$ | $M_{CT}$ | $M_{CT}$ | $M_{CT}$ |
|---|---|---|---|---|
| $N_{b-jets} = 1$ | < 250 GeV | 250 - 350 GeV | 350 - 450 GeV | > 450 GeV |
| $N_{b-jets} = 2$ | < 250 GeV | 250 - 350 GeV | 350 - 450 GeV | > 450 GeV |

- The production of bottom squarks with mass up to 700 GeV is excluded at 95% confidence level for neutralino masses less than 50 GeV.



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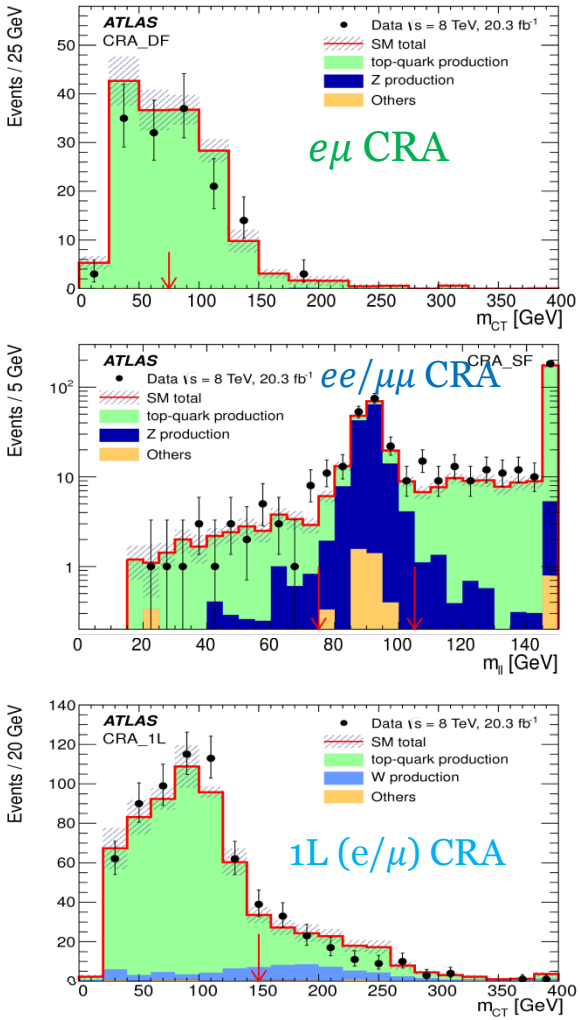
# 0 leptons + 2 b-jets + MET (1/2)

| Description | Signal Regions | |
|---|---|---|
| | SRA | SRB |
| | Event cleaning and lepton veto common to all SR | |
| $E_{\mathrm{T}}^{\mathrm{miss}}$ | $>$ 150 GeV | $>$ 250 GeV |
| Jet $p_{\mathrm{T}}$ | $j_1$ $>$130, $j_2$ $>$ 50GeV | $j_1$ $>$ 150, $j_2$ $>$ 30 GeV |
| Third jet $p_{\mathrm{T}}$ ($j_3$) | veto if $>$ 50 GeV | $>$ 30 GeV |
| $b$-tagging | Required on leading 2 jets | 2nd- and 3rd-leading jets |
| | $n_{b\text{-jets}} = 2$ | |
| $\Delta\phi(\boldsymbol{p}_{\mathrm{T}}^{\mathrm{miss}}, j_i)_{min}$ | $>$ 0.4 | $>$ 0.4 && $\Delta\phi(\boldsymbol{p}_{\mathrm{T}}^{\mathrm{miss}}, j_1) > 2.5$ |
| $E_{\mathrm{T}}^{\mathrm{miss}}/m_{\mathrm{eff}}$ ($k$) | $E_{\mathrm{T}}^{\mathrm{miss}}/m_{\mathrm{eff}}$ (2) $>$ 0.25 | $E_{\mathrm{T}}^{\mathrm{miss}}/m_{\mathrm{eff}}$ (3) $>$ 0.25 |
| $m_{\mathrm{CT}}$ | $>$ 150, 200, 250, 300, 350 GeV | - |
| $H_{\mathrm{T},3}$ | - | $<$ 50$GeV$ |
| $m_{bb}$ | $>$ 200$GeV$ | - |

- SRA aims at large $\Delta m(\tilde{b},\tilde{\chi}_1^0)$ signal events
- SRB aims at small $\Delta m(\tilde{b},\tilde{\chi}_1^0)$ when there is a high-$p_{T_n}$ ISR jet in the event, boosting $b\bar{b}$
- $$H_{T,3} = \sum_{i=4} p_{T,i}$$
- Main backgrounds: $t\bar{t}$, Z+HF, W+HF: suitable CRs defined for each one of them



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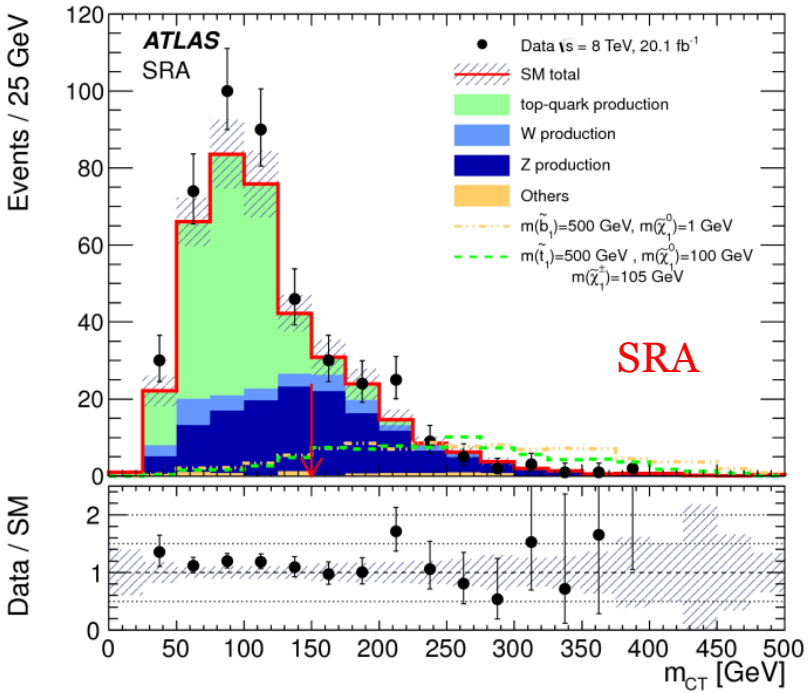
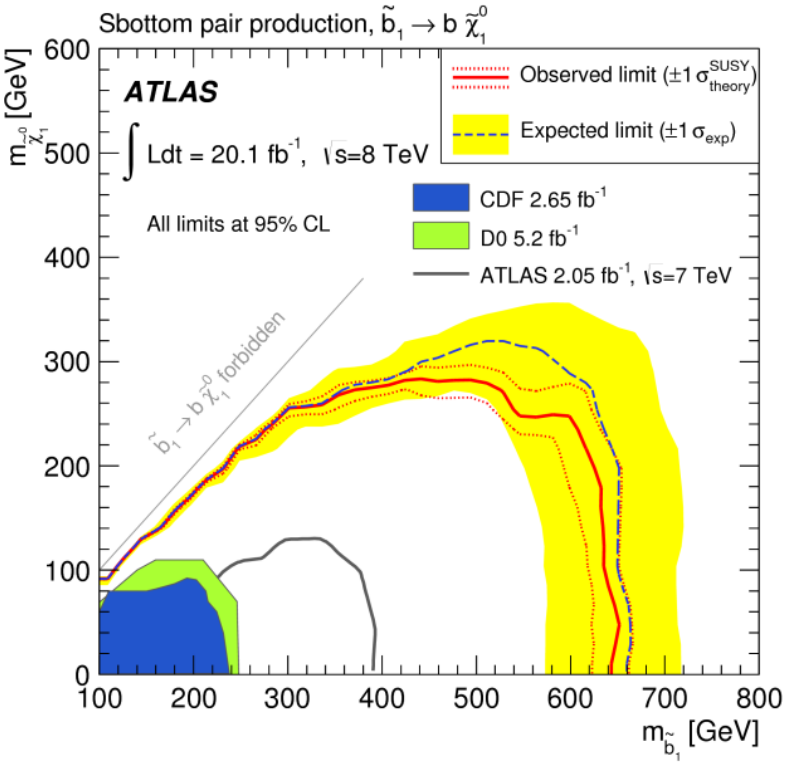
# 0 leptons + 2 b-jets + MET (2/2)

- No significant excess is observed in either SR
- The analysis is also sensitive to $\tilde{t} \rightarrow b + \tilde{\chi}_1^{\pm}$ scenarios with very low mass difference between $\tilde{\chi}_1^{\pm}$ and $\tilde{\chi}_1^{0}$.



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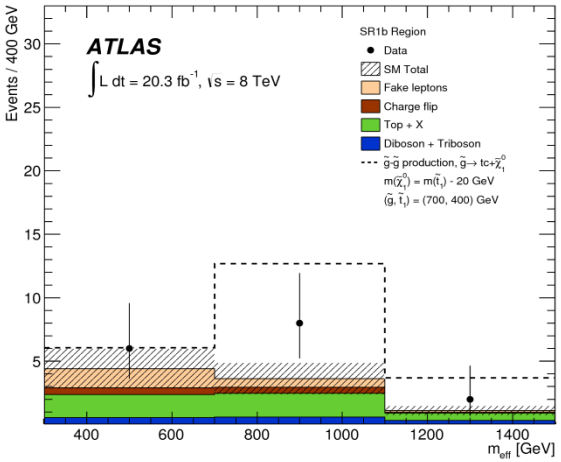
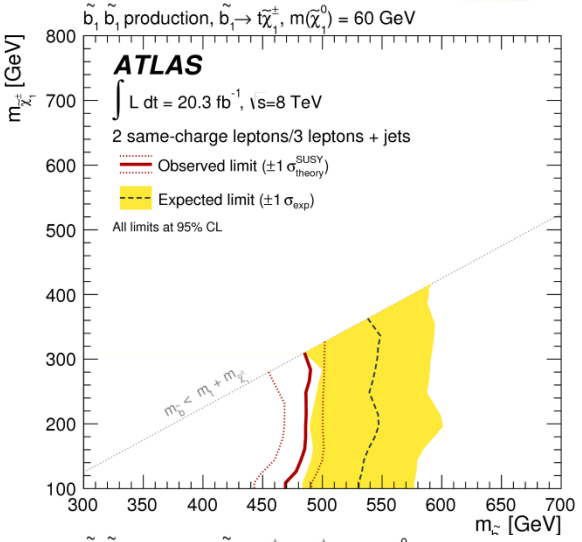
JHEP 06 (2014) 035 - arXiv:1404.2500

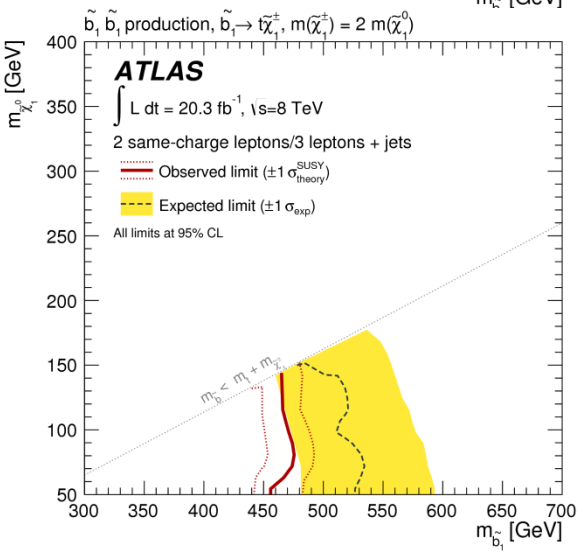
# 2 same-sign/3-leptons + 0-3 b-jets + MET

| SR | Leptons | $N_{b-\text{jets}}$ | Other variables | Additional requirement on $m_{\text{eff}}$ |
|---|---|---|---|---|
| SR3b | SS or 3L | $\geq 3$ | $N_{\text{jets}} \geq 5$ | $m_{\text{eff}}$ >350 GeV |
| SR1b | SS | $\geq 1$ | $N_{\text{jets}} \geq 3$, $E_{\text{T}}^{\text{miss}} > 150$ GeV, $m_{\text{T}}$ >100 GeV, SR3b veto | $m_{\text{eff}}$ >700 GeV |
| SR3Llow | 3L | - | $N_{\text{jets}} \geq 4$, $50 < E_{\text{T}}^{\text{miss}} < 150$ GeV, $Z$ boson veto, SR3b veto | $m_{\text{eff}}$ >400 GeV |
| SR3Lhigh | 3L | - | $N_{\text{jets}} \geq 4$, $E_{\text{T}}^{\text{miss}} > 150$ GeV, SR3b veto | $m_{\text{eff}}$ >400 GeV |

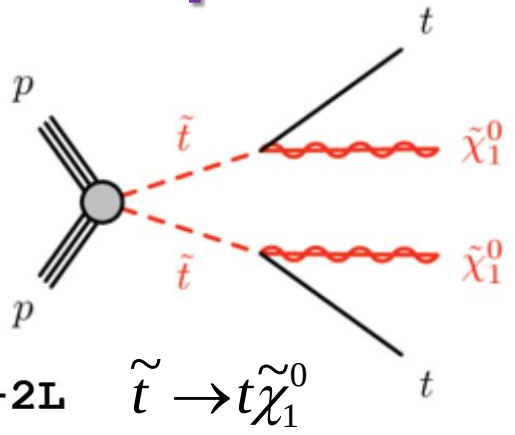
- Four SRs based on $E_T^{miss}$, $N_{jets}$, $M_T$, $m_{eff}$ sensitive to 3rd generation/direct squark searches
- Both **data-driven** and **MC** methods used to describe SM backgrounds: charge mis-measured leptons, fake leptons, prompt multi-leptons
- No significant excess of SUSY signal found with respect to SM



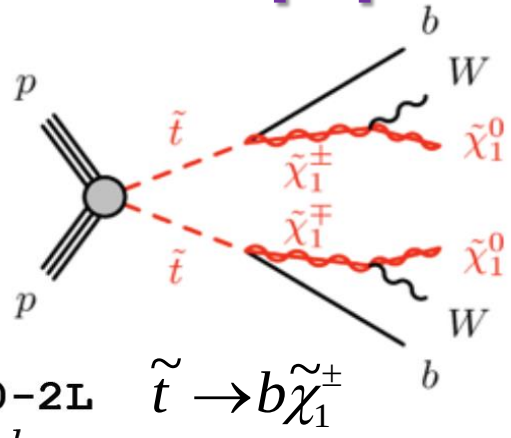



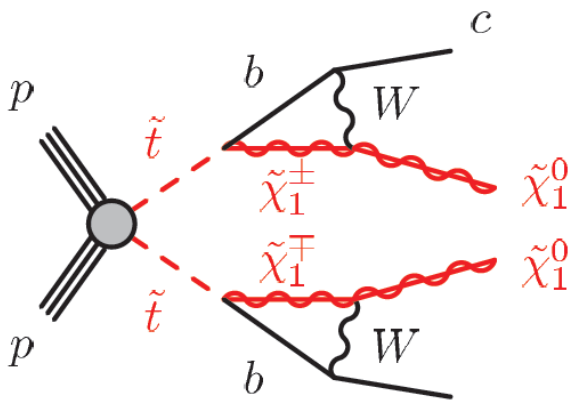
# Direct production of stop pairs



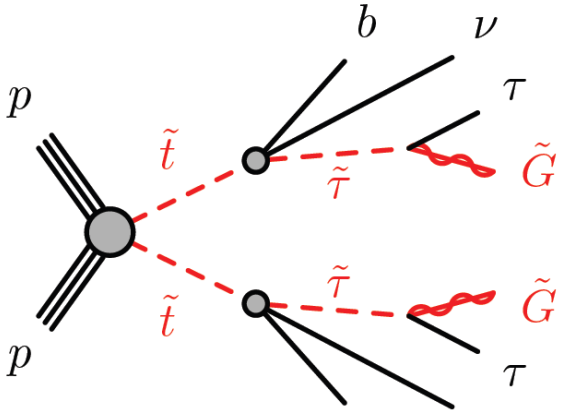

**0-2L** $\tilde{t} \to t\tilde{\chi}_1^0$



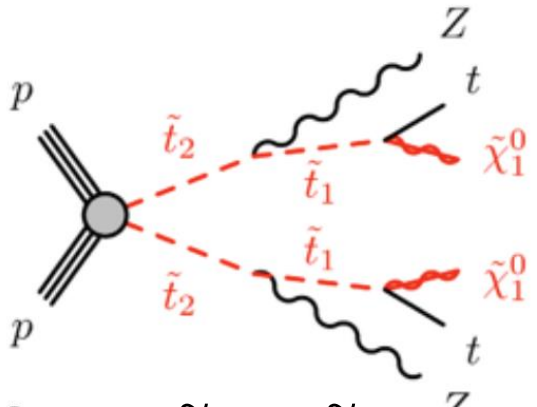

**0-2L** $\tilde{t} \to b\tilde{\chi}_1^{\pm}$




**0L** $\tilde{t} \to c\tilde{\chi}_1^0$




**2L** $\tilde{t} \to b\nu\tilde{\tau}$

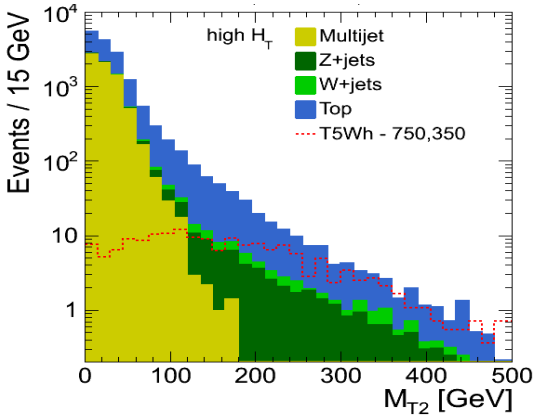


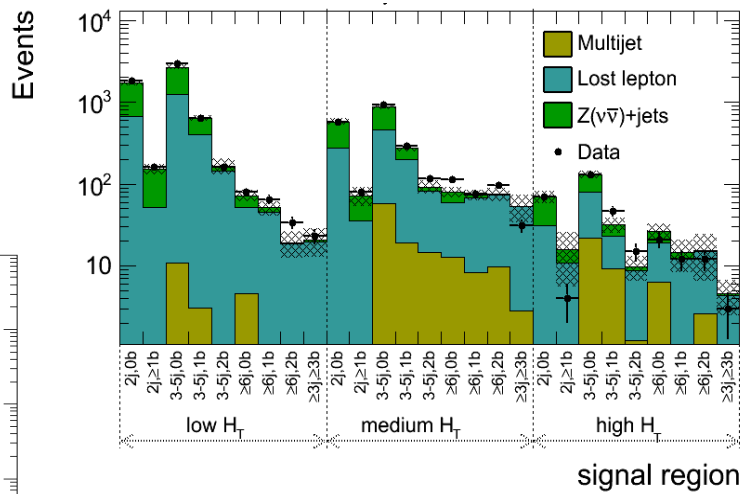

**2-3L** $\tilde{t}_2 \to Z\tilde{t}_1$

PAS-SUS-13-019

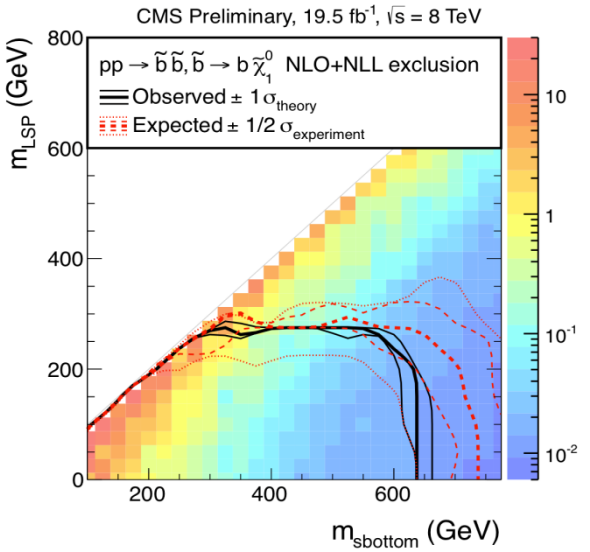
# 0 leptons + (b)jets + MET + large $M_{T2}$

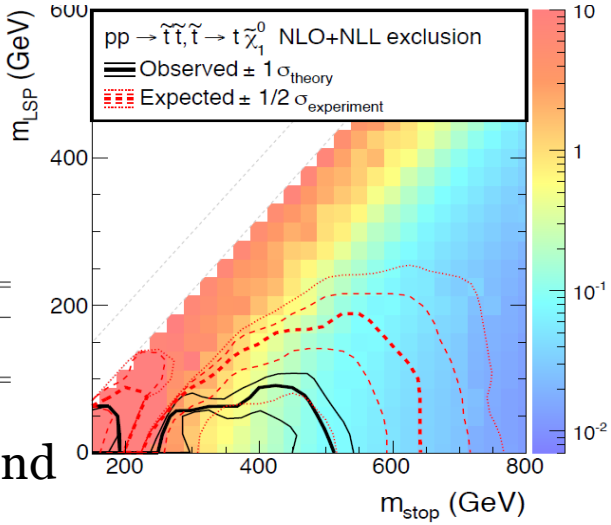
- Inclusive search for **fully hadronic** final states
- Several SRs defined according to jet , b-jet multiplicity, $H_T$ and $M_{T2}$
- Main backgrounds: $Z\to\nu\bar{\nu}$, $W$+jets or $t\bar{t}$+jets with a lost lepton
- A simplified signal model considered: T5Wh ($m_{\tilde{g}}$=750GeV, $M_{LSP}$=350GeV)




| Channel | Lost lepton | $Z(\nu\bar{\nu})$+jets | Total background | Data |
|---|---|---|---|---|
| low $H_T$ | $37.1 \pm 9.0$ | $6.9 \pm 6.9$ | $44.0 \pm 11.3$ | 55 |
| high $H_T$ | $64.8 \pm 16.4$ | $4.4 \pm 4.4$ | $69.2 \pm 17.0$ | 81 |




No significant excess of events over the expected background

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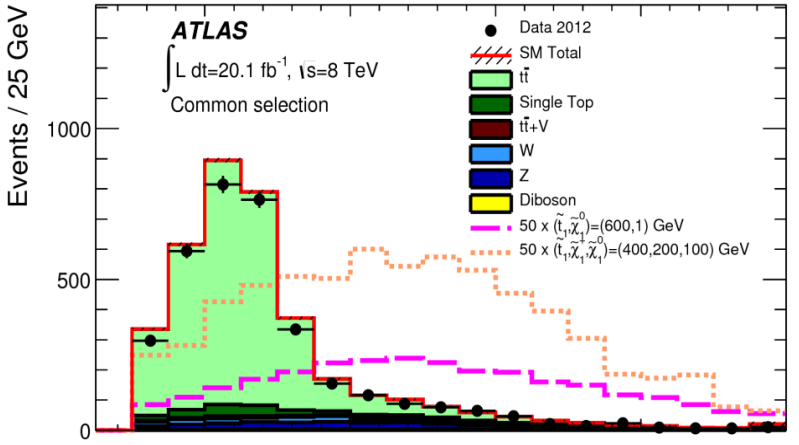
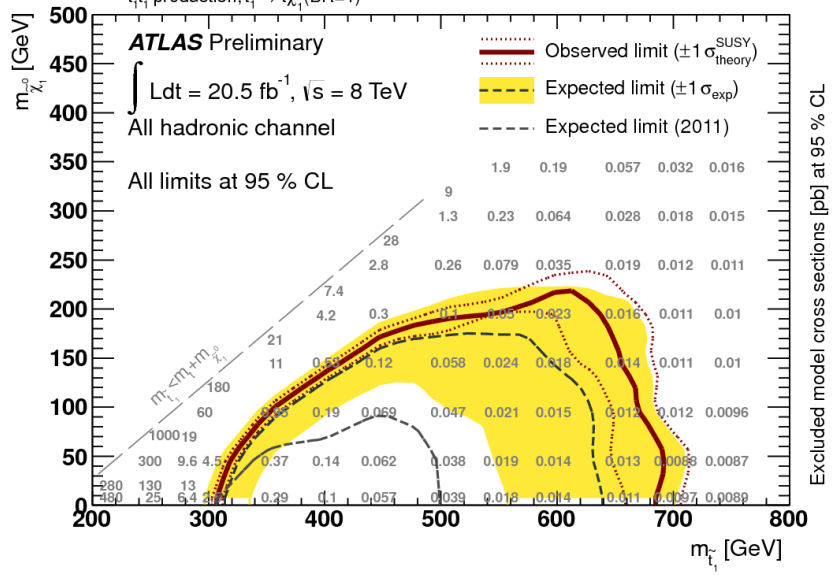
arXiv:1406.1122

# 0 leptons + 6 (2 b-)jets + MET

- Specific experimental signature different from 1st two generations
- ≥2 b-jets in final state
- Re-clustered fat jets used to enhance sensitivity for heavy stops
- Lepton veto
- MET > 150 GeV
- $m_T^{b,min}$ > 175 GeV
- Few SRs defined:
  - 4 SRs based on ≥6 jets with MET > 150/250/300/350 GeV
  - 2 SRs based on 4 or 5 jets with MET > 325/400 GeV
  - 3 SRs based on exactly 5 jets with MET > 160/160/215 GeV
- Stop here is searched to be heavy and very boosted: exclusion limits plot reaches stop masses up to 700 GeV

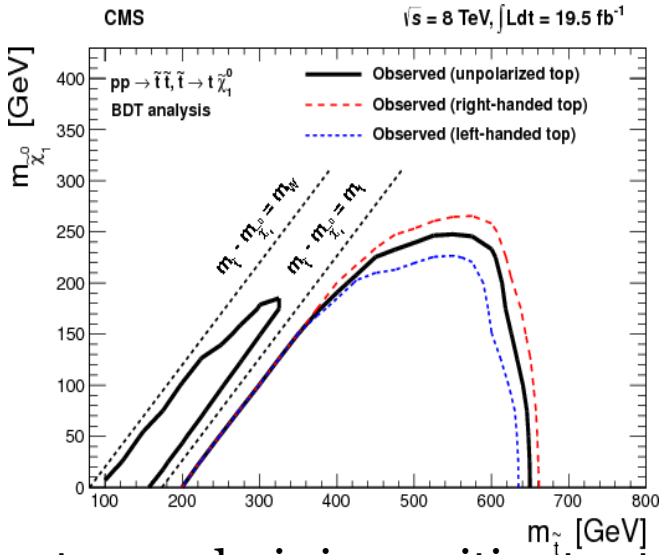


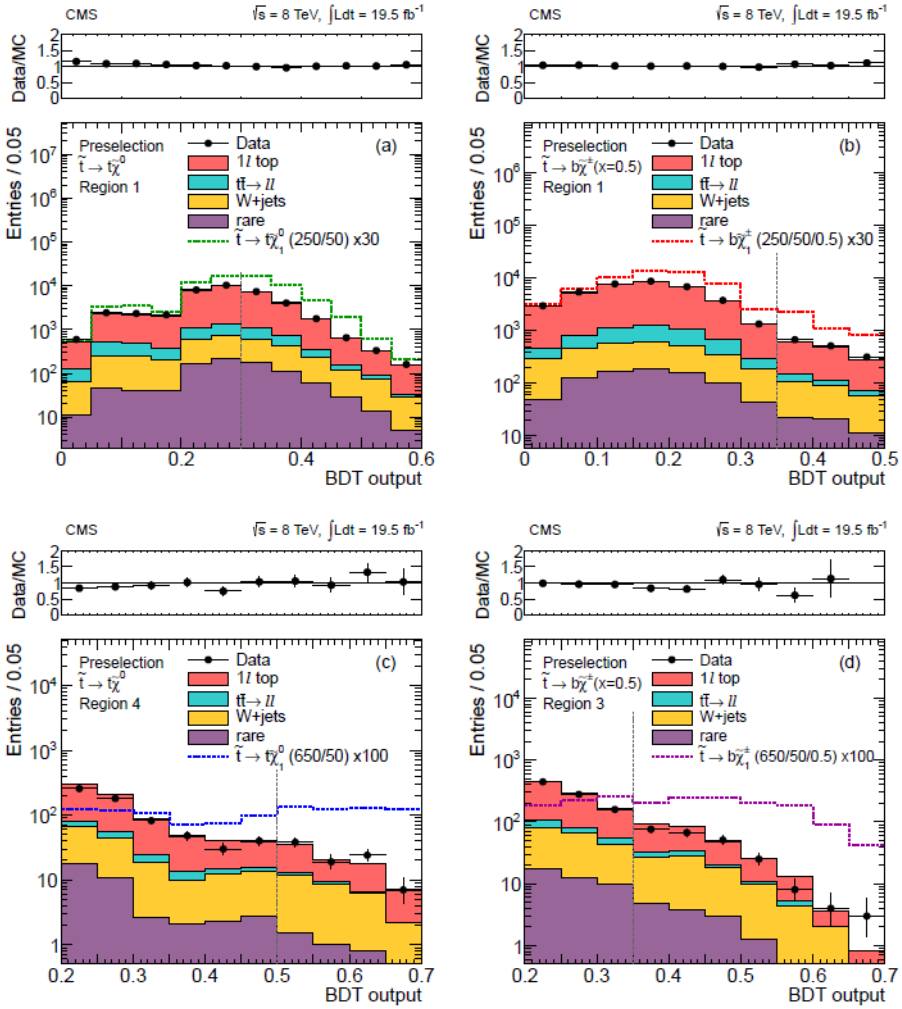



EPJC 73 (2013) 2677 - arXiv:1308.1586

# 1 lepton + jets + MET

- The goal is to look for direct stop **semi-leptonic decays**
- A cut-based approach and a multivariate (BDT) method are used
  - Input: $E_T^{miss}$, $m_T$, $\min\Delta\varphi$, $p_T^{b\text{-jet1}}$, …




1-lepton analysis is sensitive to stop polarization; CMS use various assumptions (ATLAS assumes almost $stop_R$-like $stop_1$)

PAS-SUS-14-011

# Inclusive razor & exclusive 1-lepton

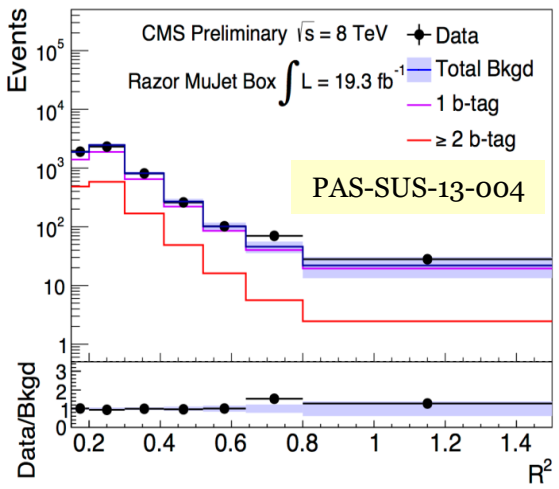
- Razor variables $M_R$ and $R$ are used to study the dijet topology resulting from the production of two squarks, each one decaying to a quark and a neutralino:
- Nine **razor boxes** are defined and compared with **exclusive single-lepton**
- $M_R$ and $R$ are functions smoothly falling for background and to peak for signal

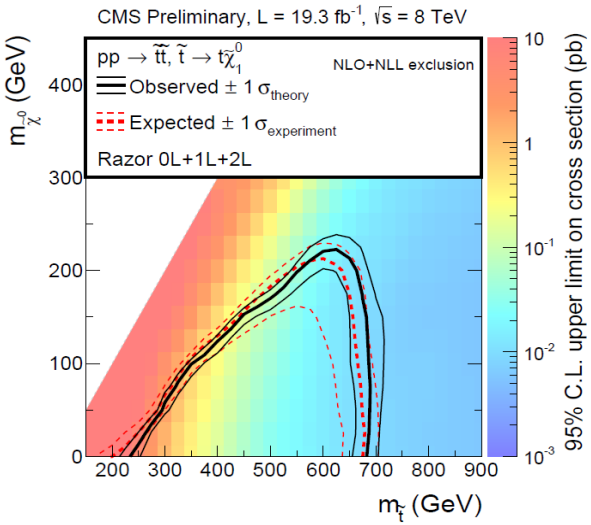
$$M_R \equiv \sqrt{(p_{j_1} + p_{j_2})^2 - (p_z^{j_1} + p_z^{j_2})^2}$$

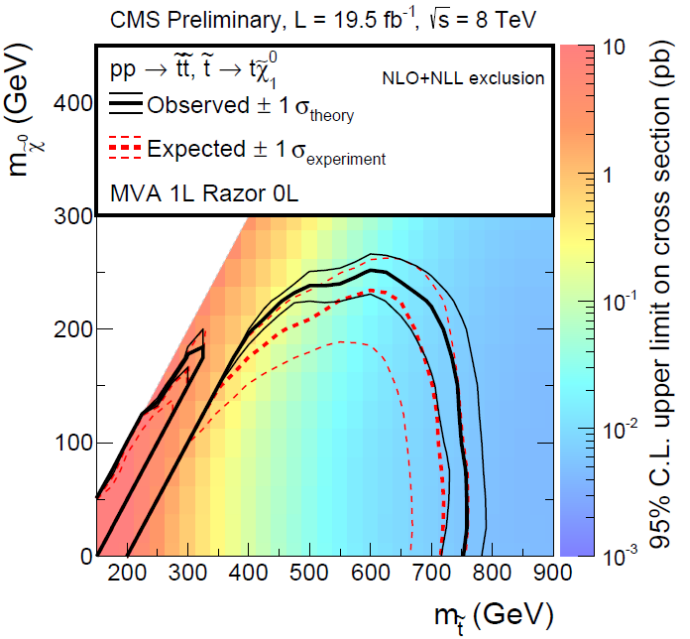
$$M_T^R \equiv \sqrt{\frac{E_T^{miss}(p_T^{j1} + p_T^{j2}) - \vec{E}_T^{miss} \cdot (\vec{p}_T^{\,j1} + \vec{p}_T^{\,j2})}{2}}$$

$$R \equiv \frac{M_T^R}{M_R}$$

After combination with 1-lepton exclusive analysis



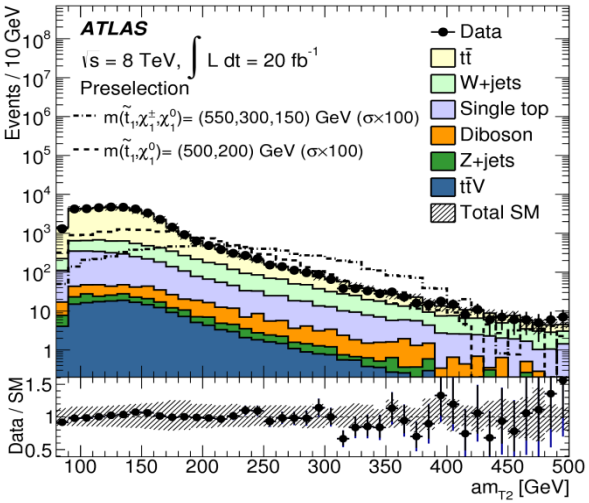



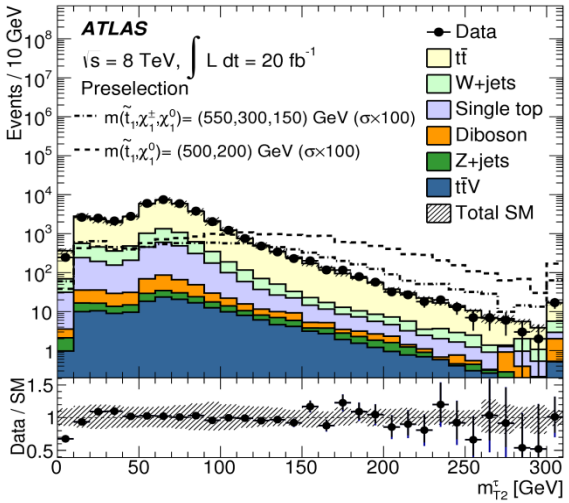



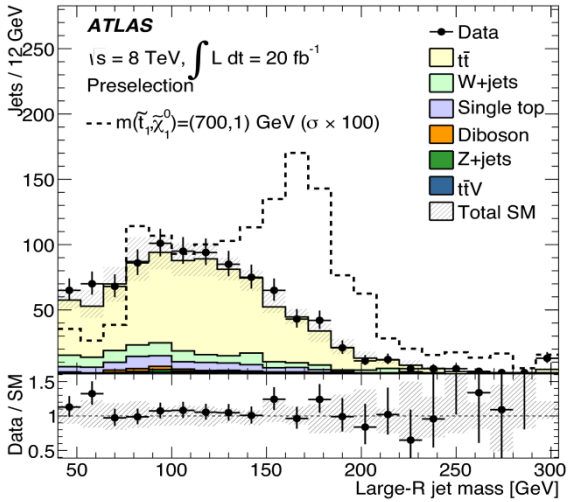
arXiv:1407.0583

# 1 lepton + 4 (1 b-)jets + MET (1/2)

- Wide range of scenarios considered with different sets of $\tilde{t}_1$, $\tilde{\chi}_1^{\pm}$, $\tilde{\chi}_1^0$ masses
- Different approaches used for a total of 15 SRs with $E_T^{miss}$ > 100 GeV:
  - b-tagged jets to build kinematic variables, single large-radius jets for heavy stop;
  - low-$p_T$ leptons to improve sensitivity for $\tilde{t}_1 \to b\tilde{\chi}_1^{\pm}$ decays for small $\Delta m(\tilde{\chi}_1^{\pm}, \tilde{\chi}_1^0)$
- Both **cut-and-count** and **shape-fit** methods used to estimate expected and observed exclusion limits
- Largest SM background for large-R jets is dileptonic $t\bar{t}$ events with one lost lepton
  - Also $W$+jets is relevant: both sources are estimated with data-driven CRs



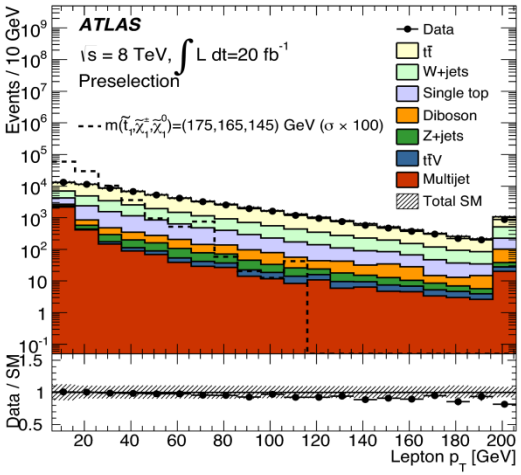



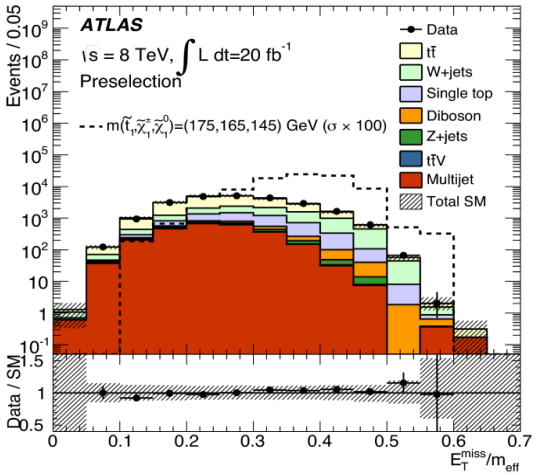



arXiv:1407.0583

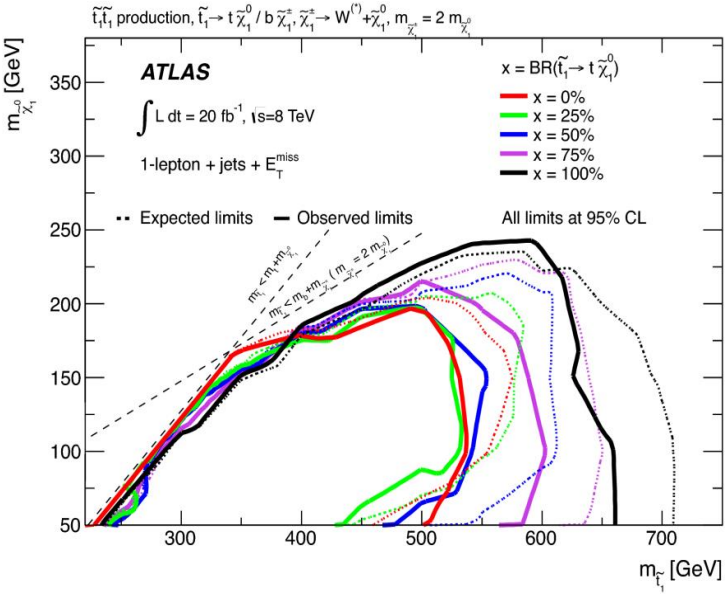
# 1 lepton + 4 (1 b-)jets + MET (2/2)

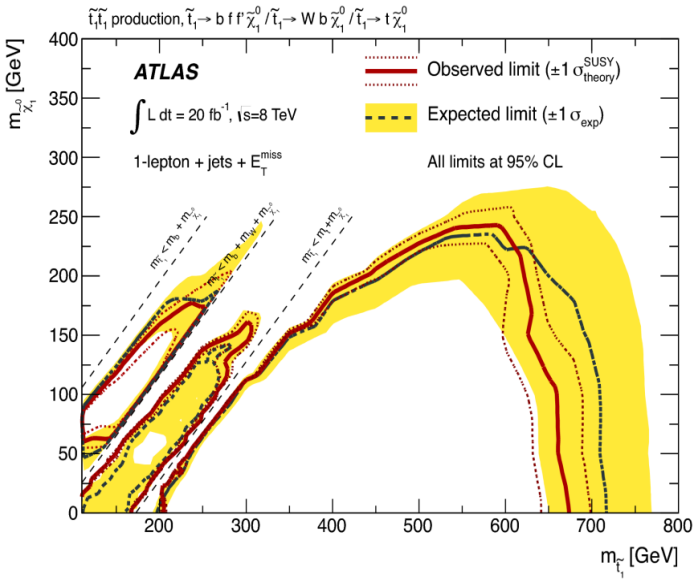
- The soft-lepton analysis is based on 6(7) GeV < $p_T^l$ < 25 GeV for muons(electrons)
  - Specific track-isolation criteria are applied to leptons, looser than for large-R jets analysis




- Expected and observed 95% CL excluded regions assuming **BR($\tilde{t}_1 \to t\tilde{\chi}_1^0$) =100%**



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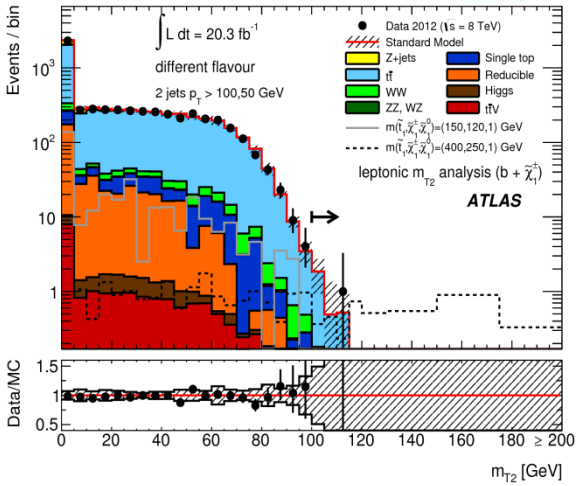
JHEP 06 (2014) 124 - arXiv:1403.4853

# 2 leptons + (b-)jets + MET (1/2)

- Three separate approaches followed, based on $\mathbf{m_{T2}}$

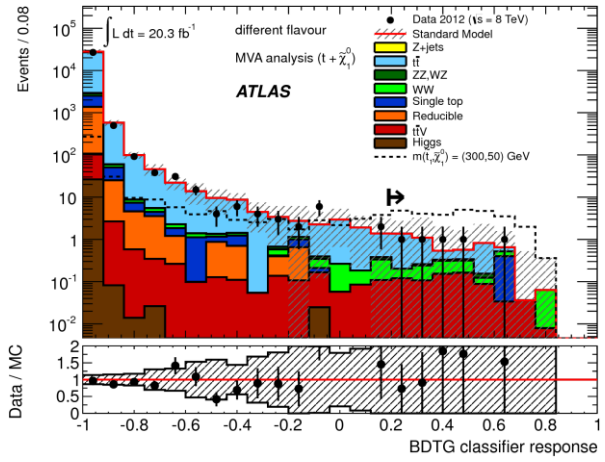
$$m_{T2}(\vec{p}_T^{\,\alpha}, \vec{p}_T^{\,\beta}, \vec{p}_T^{\,miss}) = min_{\vec{q}_T^{\,1}+\vec{q}_T^{\,2}=\vec{p}_T^{\,miss}}\{max(m_T^2(\vec{p}_T^{\,\alpha}, \vec{q}_T^{\,1}), m_T^2(\vec{p}_T^{\,\beta}, \vec{q}_T^{\,2}))\}$$

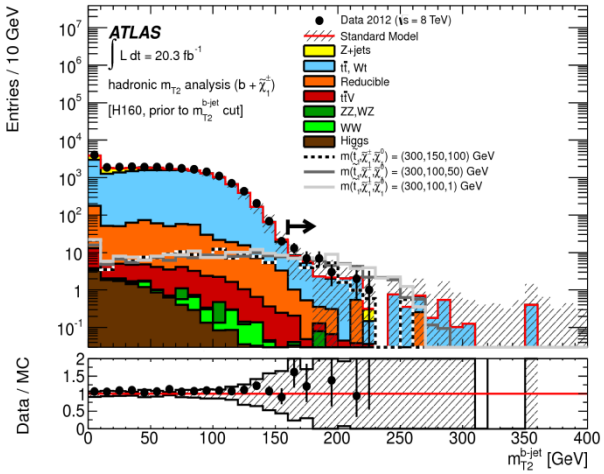
  - $\tilde{t} \to b\tilde{\chi}_1^{\pm}$ using leptonic $m_{T2}$ for $\Delta m(\tilde{\chi}_1^{\pm}, \tilde{\chi}_1^0) > m_W$
  - $\tilde{t} \to b\tilde{\chi}_1^{\pm}$ using hadronic $m_{T2}$ for $\Delta m(\tilde{\chi}_1^{\pm}, \tilde{\chi}_1^0) < m_W$
  - $\tilde{t} \to t\tilde{\chi}_1^0$ using multivariate analysis (MVA) including $m_{T2}$




The **MVA** is based on 5 DF and 4 SF SRs defined according to 5+4 Boosted Decision Trees with Gradient boost (**BDTG**) classifier responses.

Seven input variables used in each of the 5+4 trainings:
$E_T^{miss}, m_{\ell\ell}, m_{T2}, \Delta\varphi_{\ell\ell}, \Delta\vartheta_{\ell\ell}, \Delta\varphi_{\ell j}, \Delta\varphi_{\ell E_T^{miss}}$

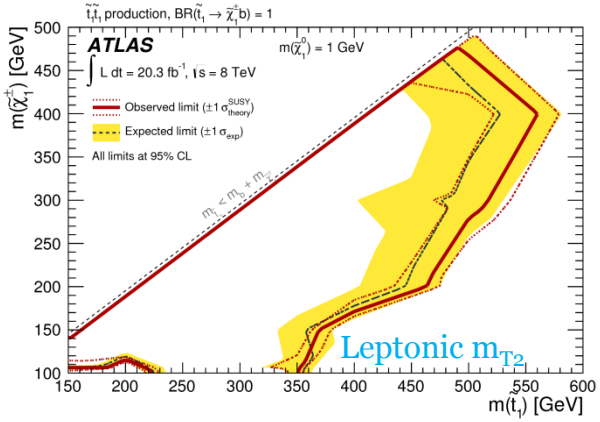


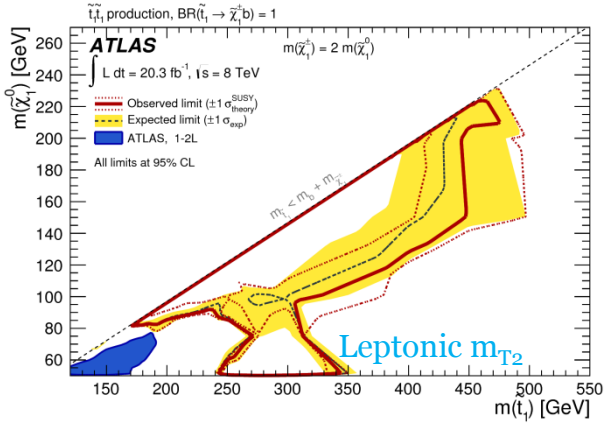



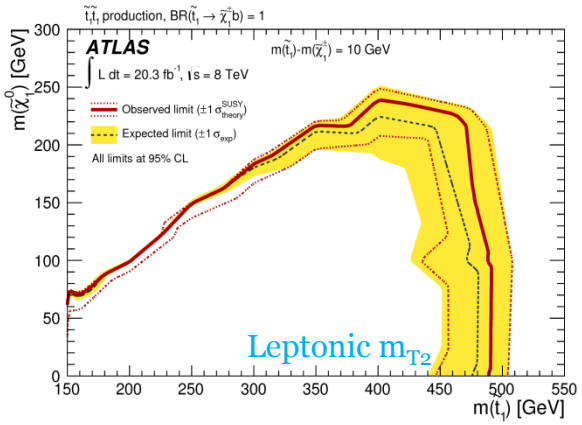
JHEP 06 (2014) 124 - arXiv:1403.4853

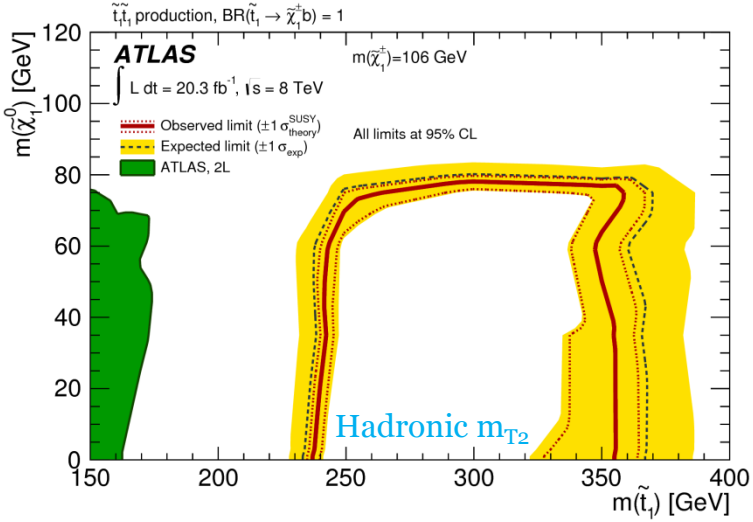
# 2 leptons + (b-)jets + MET (2/2)

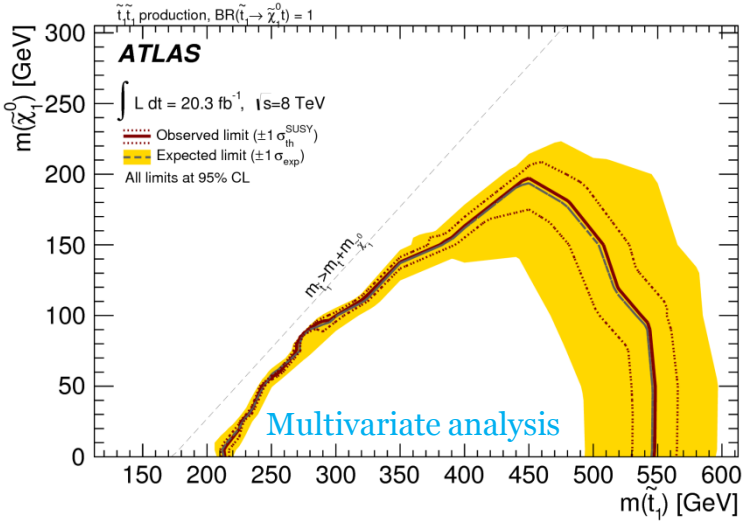
- Each analysis determines improvements in 95% CL exclusion limits plots



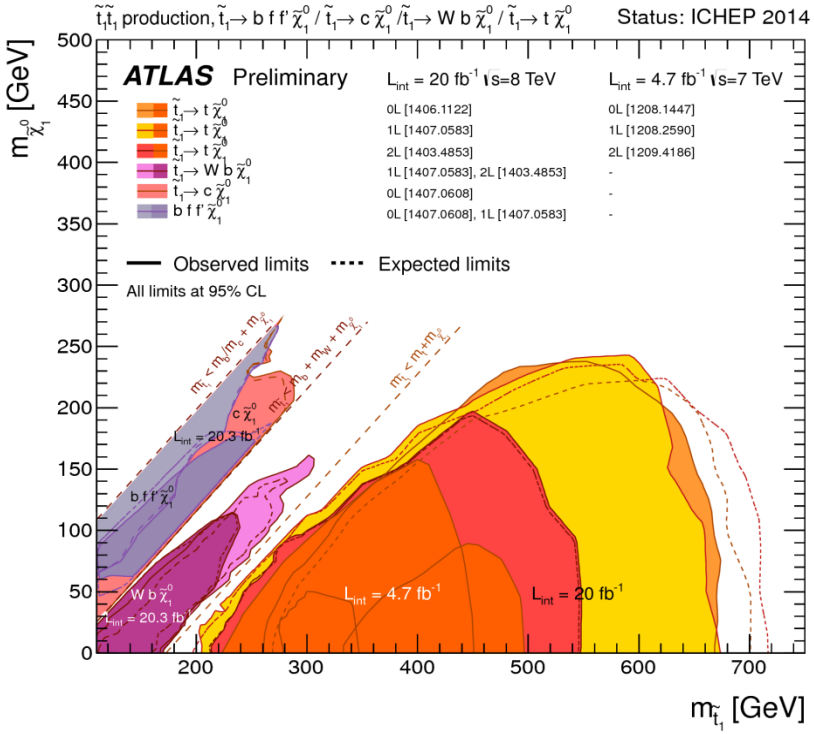



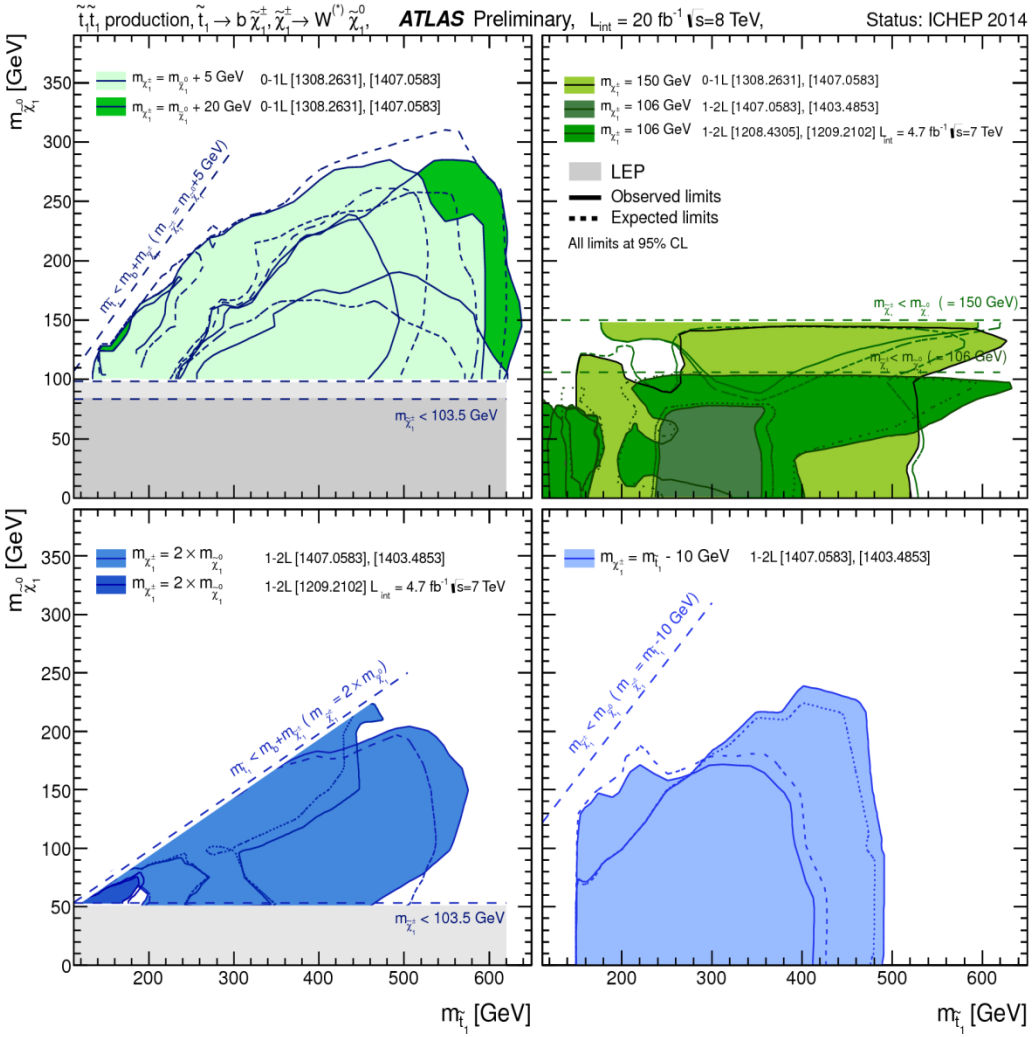



# ATLAS summary plots

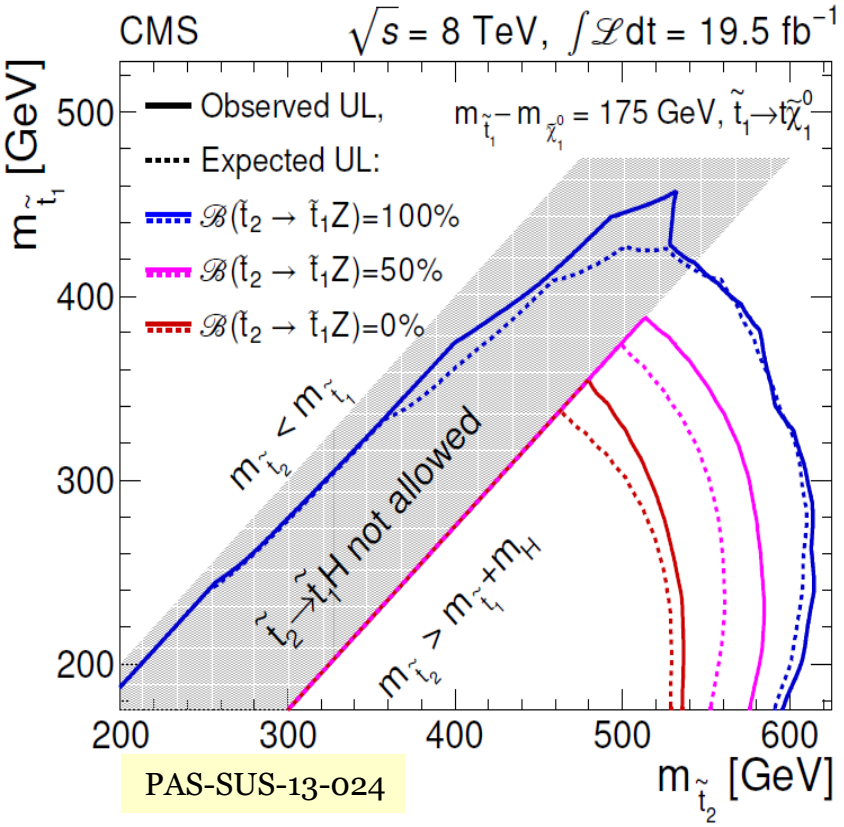
- ATLAS analyses with 7 TeV and 8 TeV data selecting 0,1,2 leptons in the final state are used to obtain top squark exclusion limits at 95% CL

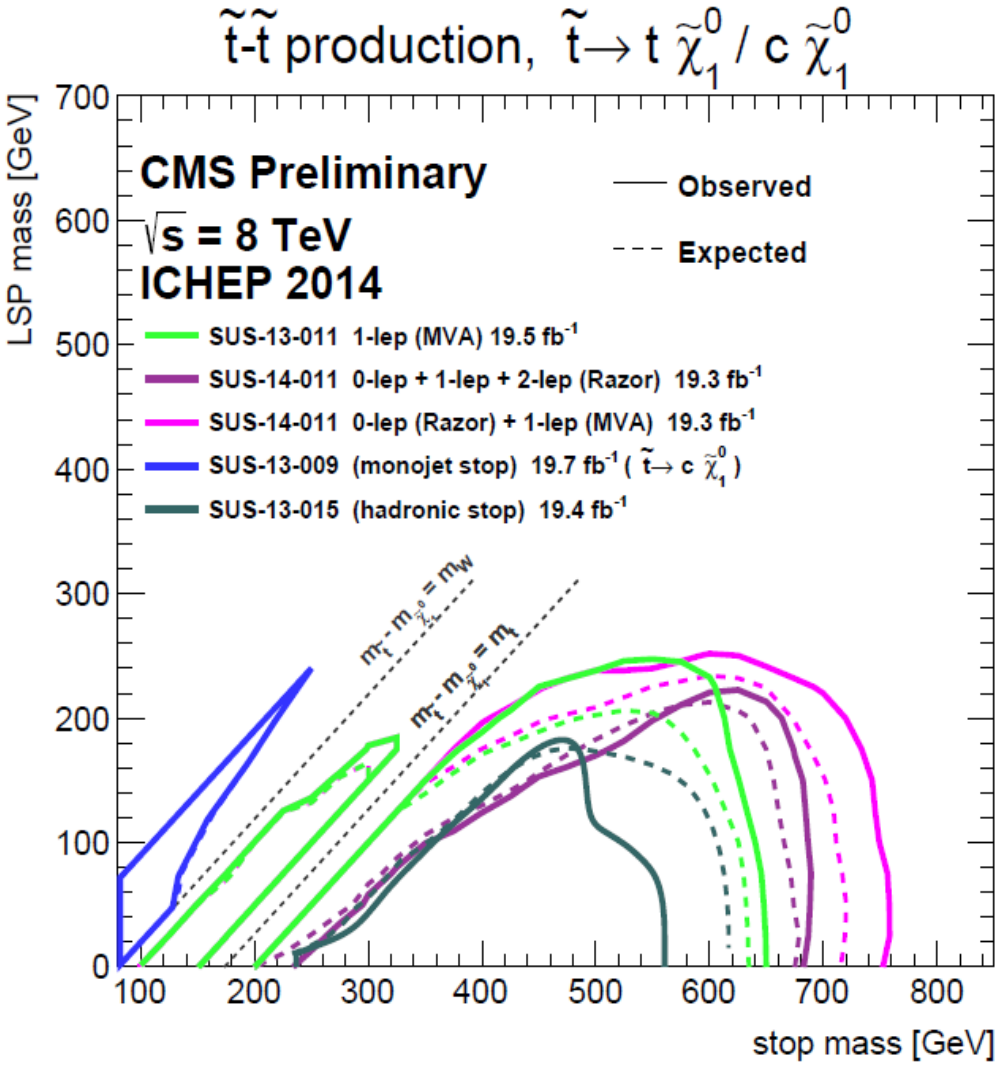


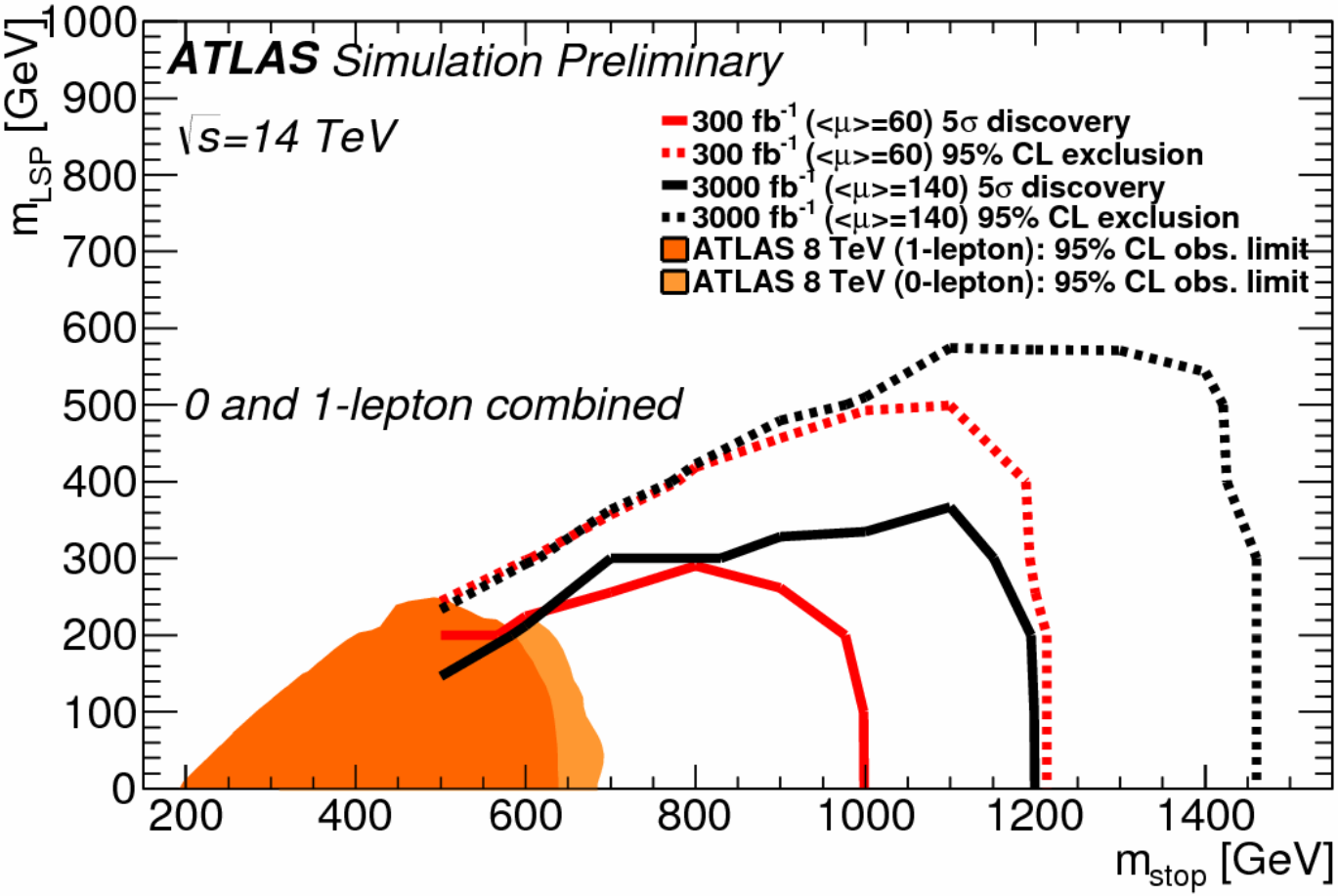
# CMS summary plots

- Summary of CMS exclusion limits for direct top squarks searches



# Expected 14 TeV ATLAS coverage



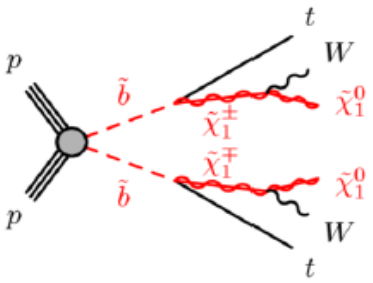
# Conclusions

- The status of third generation squarks searches at the **LHC** has been presented
- Only few relevant channels have been shown here, while many more interesting analyses are ongoing in both **ATLAS** and **CMS** Collaborations, including:
  - RPV stop decays
  - Very compressed spectra
  - Gluino decays via virtual squark exchange
- No significant excess over the Standard Model background has been observed so far in any analysis
- The next LHC run at $\sqrt{s}$ = 13 TeV will improve knowledge in the uncovered parts of phase space

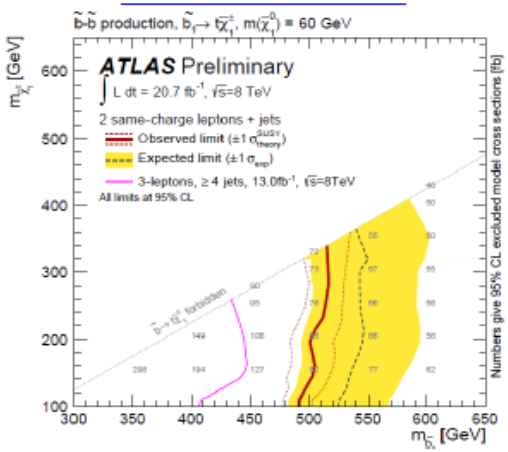
# Backup material

# Other sbottom searches

- 2 same sign lepton analysis can be interpreted in other scenarios such as sbottom pair production.




ATLAS-CONF-2013-007

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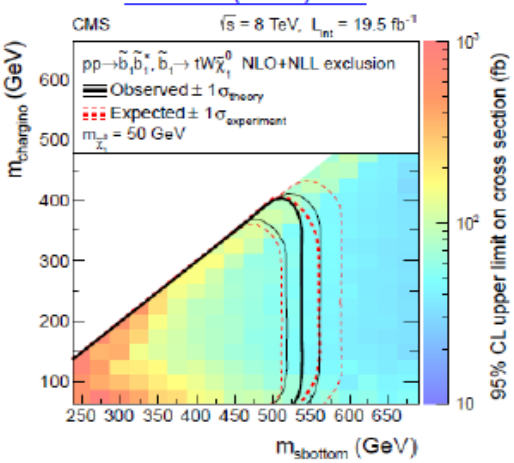
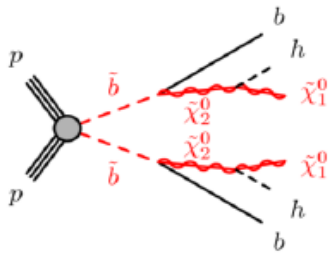
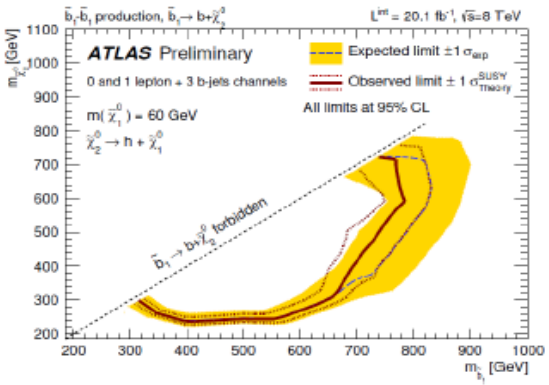



- The models in which the sbottom decaying to the neutralino2 are also considered.
  - Then the neutralino2 decays to a Higgs or Z.

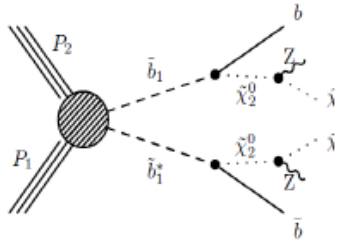
ATLAS-CONF-2013-061

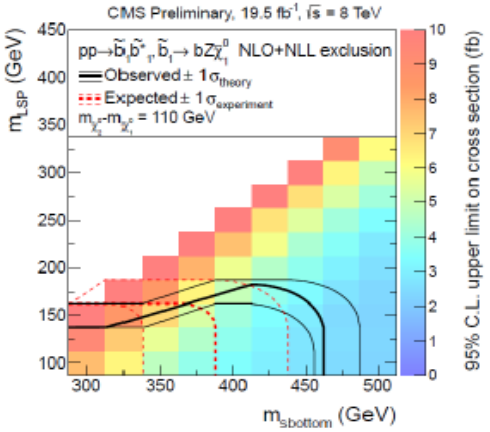



Interpretation of the high b-jet multiplicity analyses

CMS-PAS-SUS-13-004



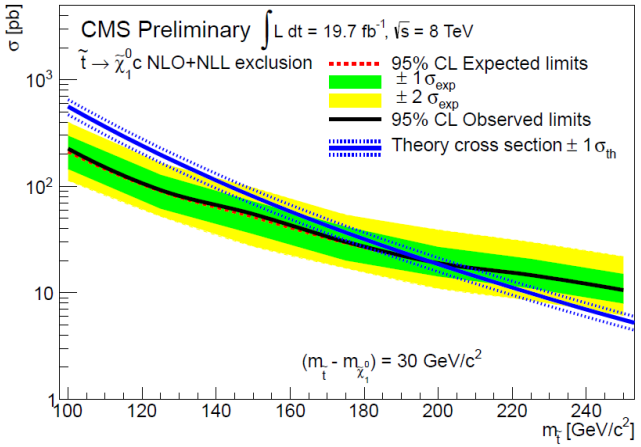



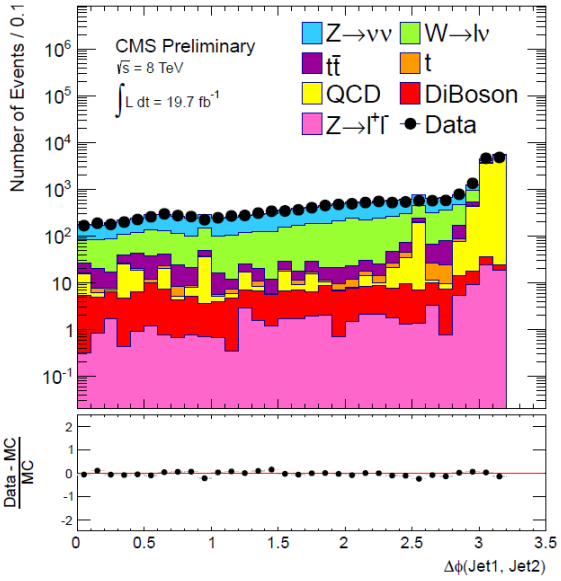

Interpretation of 3-lepton b-jets analyses

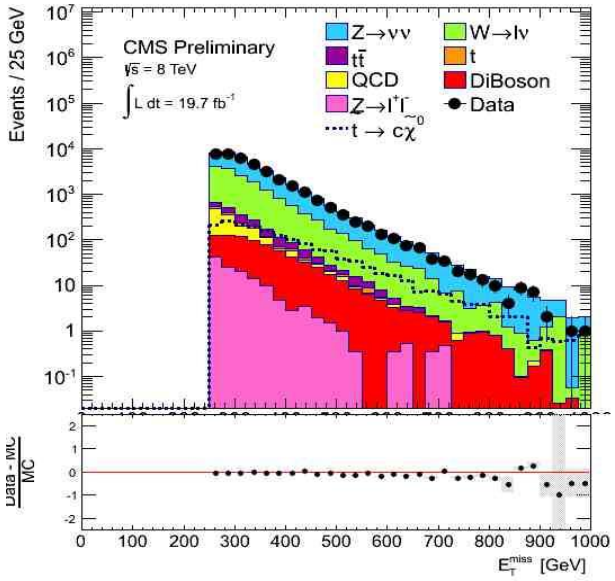
PAS-SUS-13-009

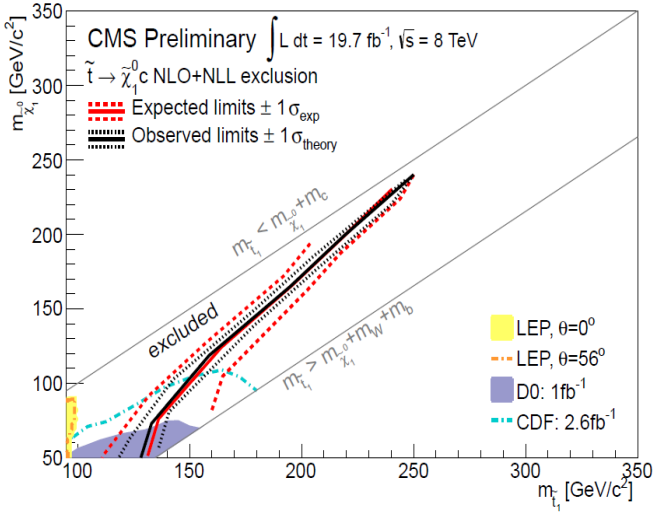
# 0 leptons + soft c-jets + MET

- The purpose is to select a possible decay $\tilde{t} \to c\tilde{\chi}_1^0$ assuming negligible $\tilde{t} \to bW\tilde{\chi}_1^0$ and $\tilde{t} \to bf\bar{f}\tilde{\chi}_1^0$
- Two triggers are used, based on $E_T^{miss}$ and on jets
- Main backgrounds: ***W*** and ***Z*** production, $t\bar{t}$
- Seven inclusive SRs: $p_T(j_1)$>250,300,…,550 GeV
- No excess of signal with respect of SM was found



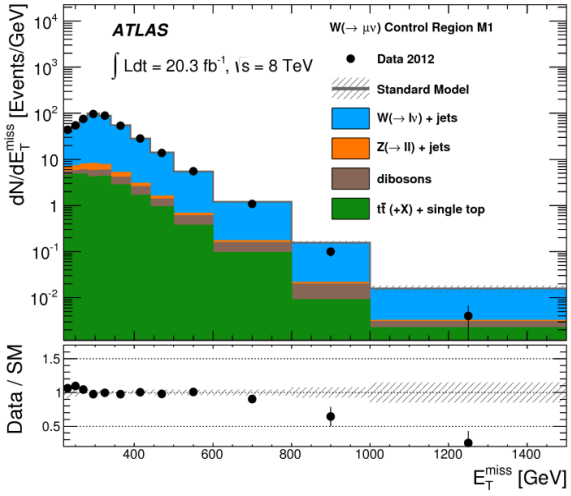



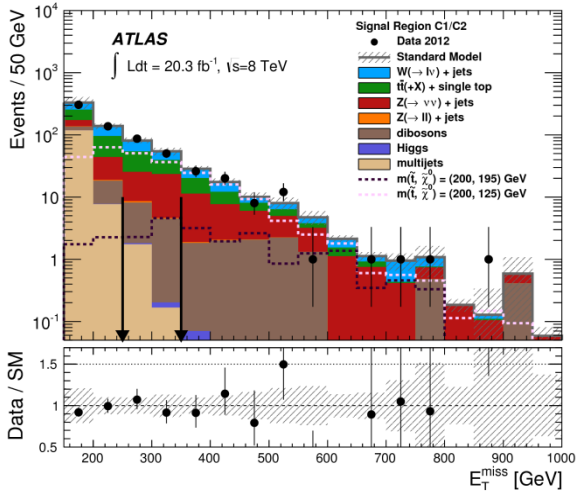
A. Ventura - Third generation squark searches

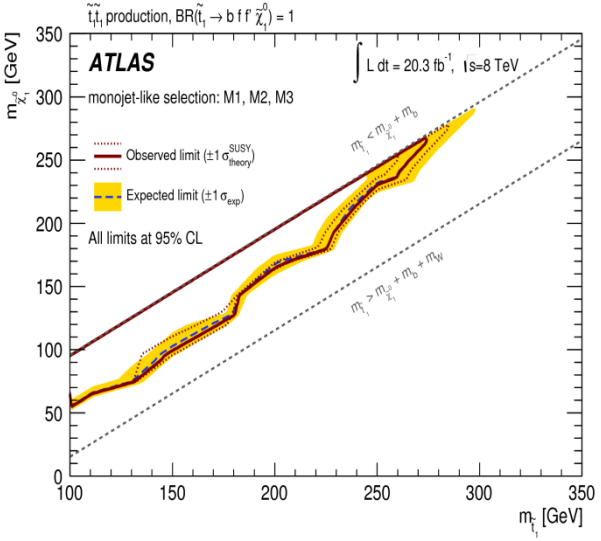
arXiv:1407.0608

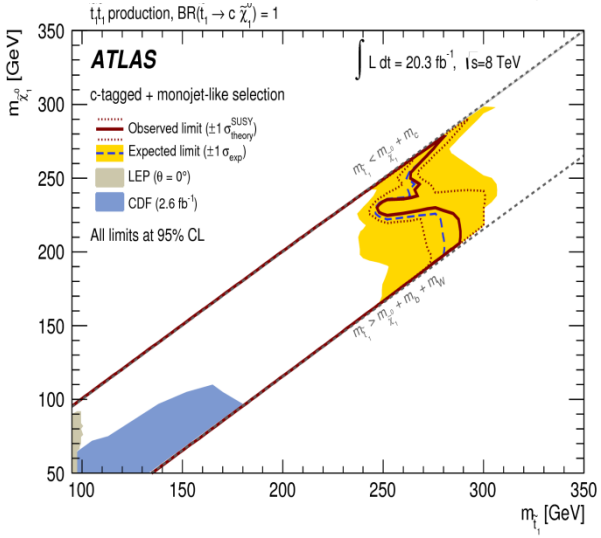
# 0 leptons + mono-jet/c-jets + MET

- Searching for $\tilde{t}_1 \to c\tilde{\chi}_1^0$ across $(m_{\tilde{t}_1}, m_{\tilde{\chi}_1^0})$ parameter space or compressed SUSY scenarios: $\tilde{t}_1 \to b + ff' + \tilde{\chi}_1^0$
- **Mono-jet** selection to target small Δm regions
- **Charm-tagged** selection in case of large Δm providing boost to *c*-quark



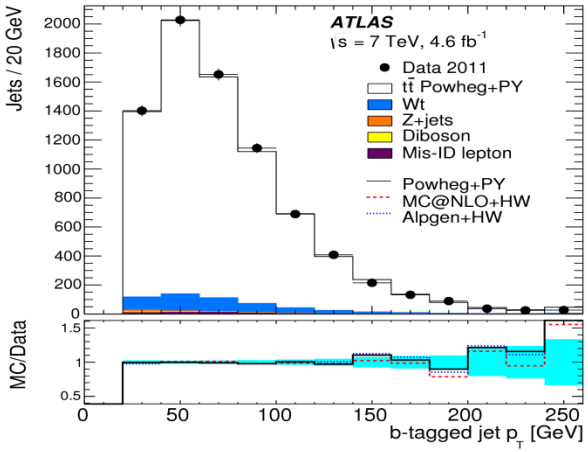



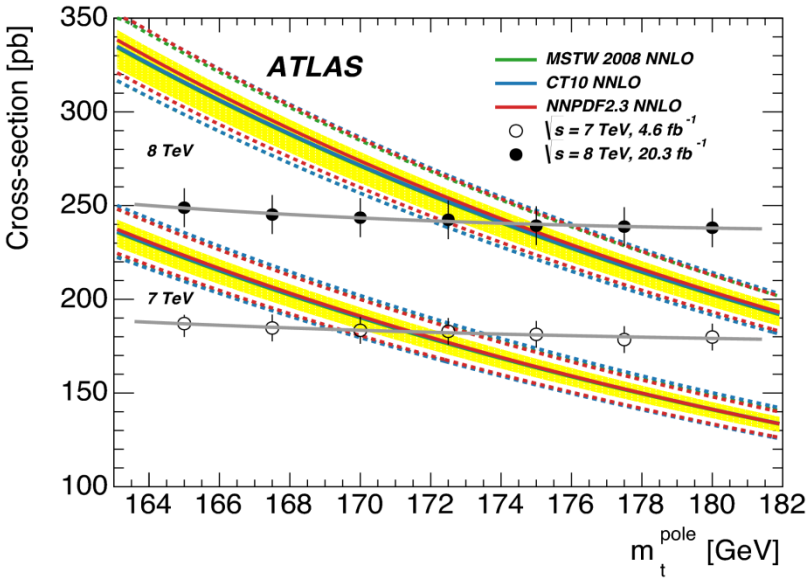

- No statistically relevant excess in any considered SR
- 95% CL limits for both mono-jet selection and combination with *c*-tagged signal regions

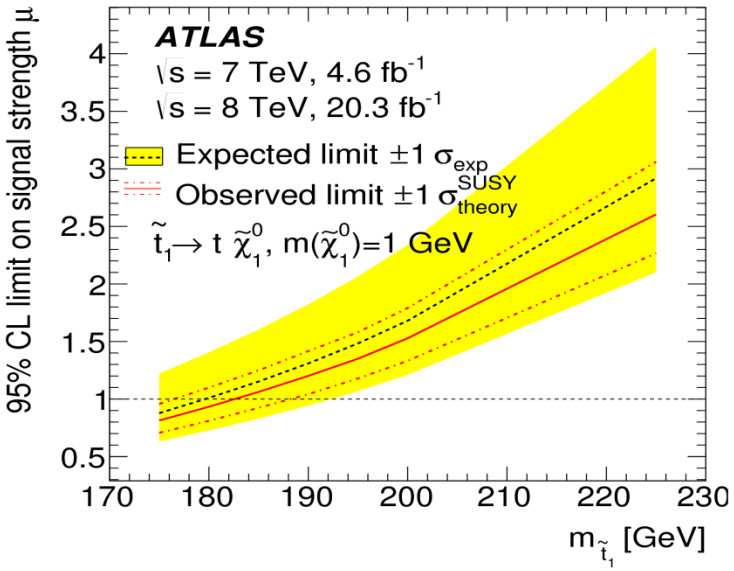
# Reinterpretation from ttbar cross-section measurements

arXiv:1406.5375

- By comparing precise measurements of $t\bar{t}$ cross section at $\sqrt{s}$ = 7 and 8 TeV with QCD predictions, limits are placed on the pair-production of stop squarks with masses close to $m_t$ decaying to mostly right-handed top quarks and a light neutralino
- Exclusion at 95% CL in [$m_t$ , 177 GeV]



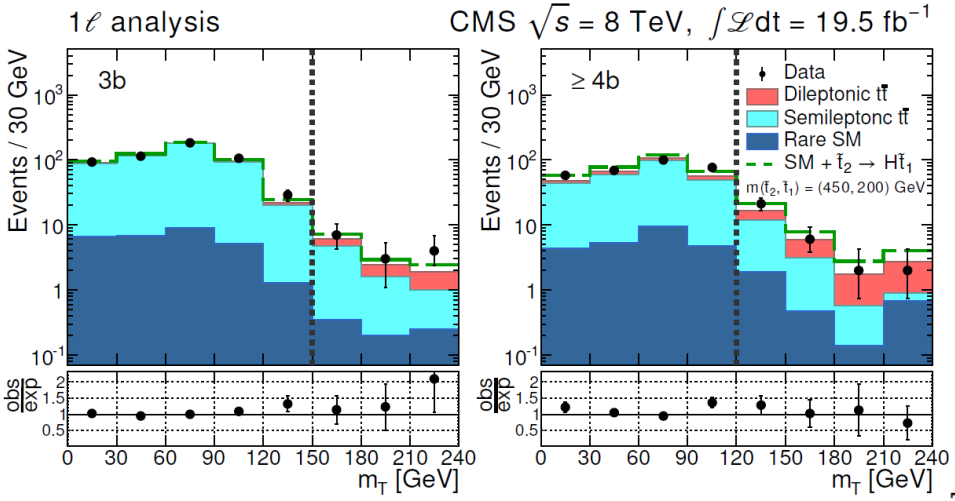



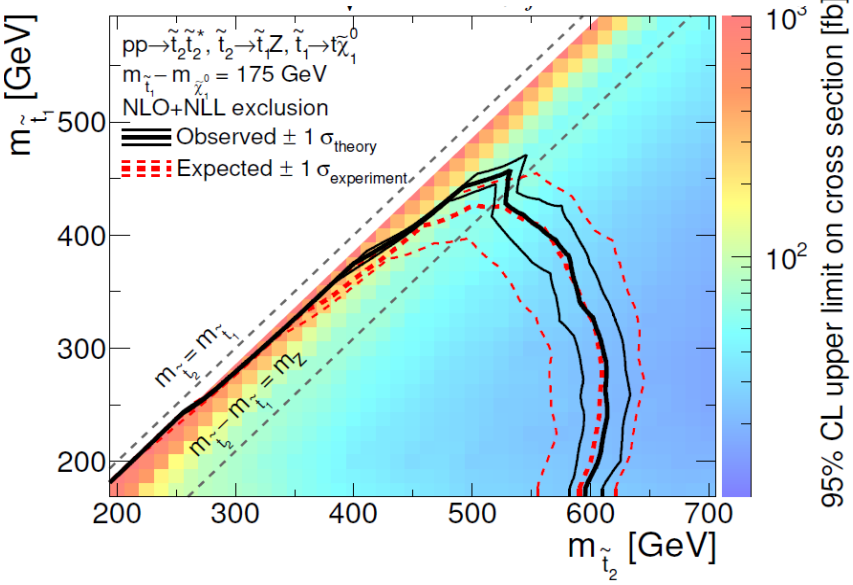



PAS-SUS-13-024 - arXiv:1405.3886

# Stop search with H or Z bosons

- Search for SUSY through the direct pair production of top squarks, with Higgs (H) or Z bosons in the decay chain: either $\tilde{t}_2 \rightarrow H\,\tilde{t}_1$ or $\tilde{t}_2 \rightarrow Z\,\tilde{t}_1$, followed in both cases by $\tilde{t}_1 \rightarrow t\tilde{\chi}^0$, being $\tilde{\chi}^0$ the LSP
- The search is performed using a selection of events containing leptons and bottom-quark jets
- No evidence for a significant excess of events over the standard model background prediction is observed



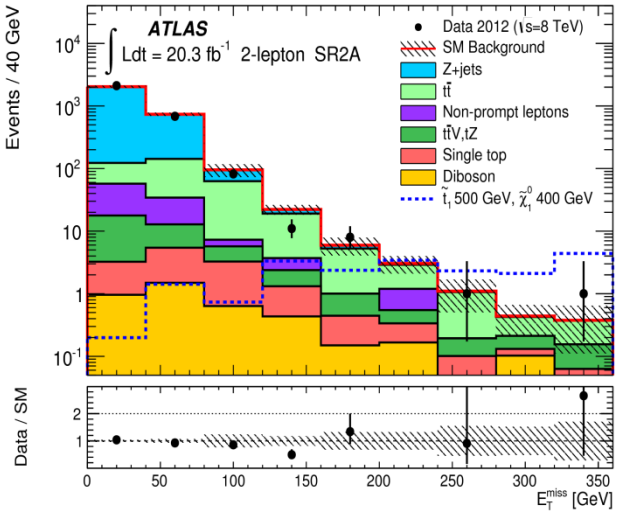



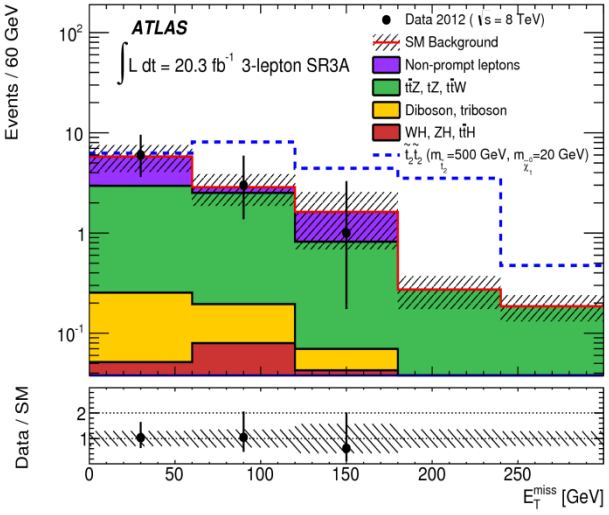
A. Ventura - Third generation squark searches

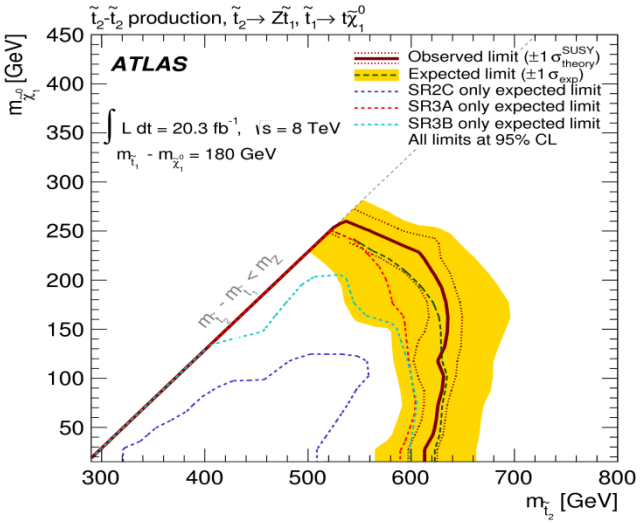
EPJC 74 (2014) 2883 - arXiv:1403.5222

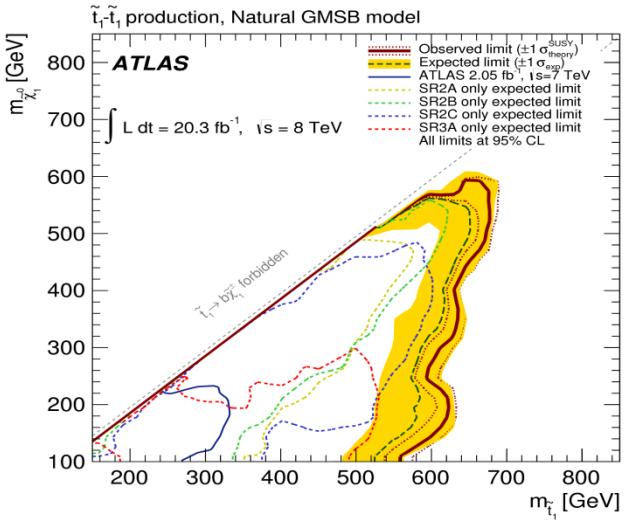
# Z + b-jet + jets + MET

- Possible decay of $\tilde{t}_2 \rightarrow Z\,\tilde{t}_1$ with $\tilde{t}_1 \rightarrow t\,\tilde{\chi}_1^0$
- Also $\tilde{\chi}_1^0 \rightarrow Z\,\tilde{G}$ considered in GMSB scenario
- Five **SRs** defined depending on the number of leptons in final state to cover full phase space
- Main backgrounds: $t\bar{t}$ in 2-lepton channel and $t\bar{t}Z$ in 3-lepton channel



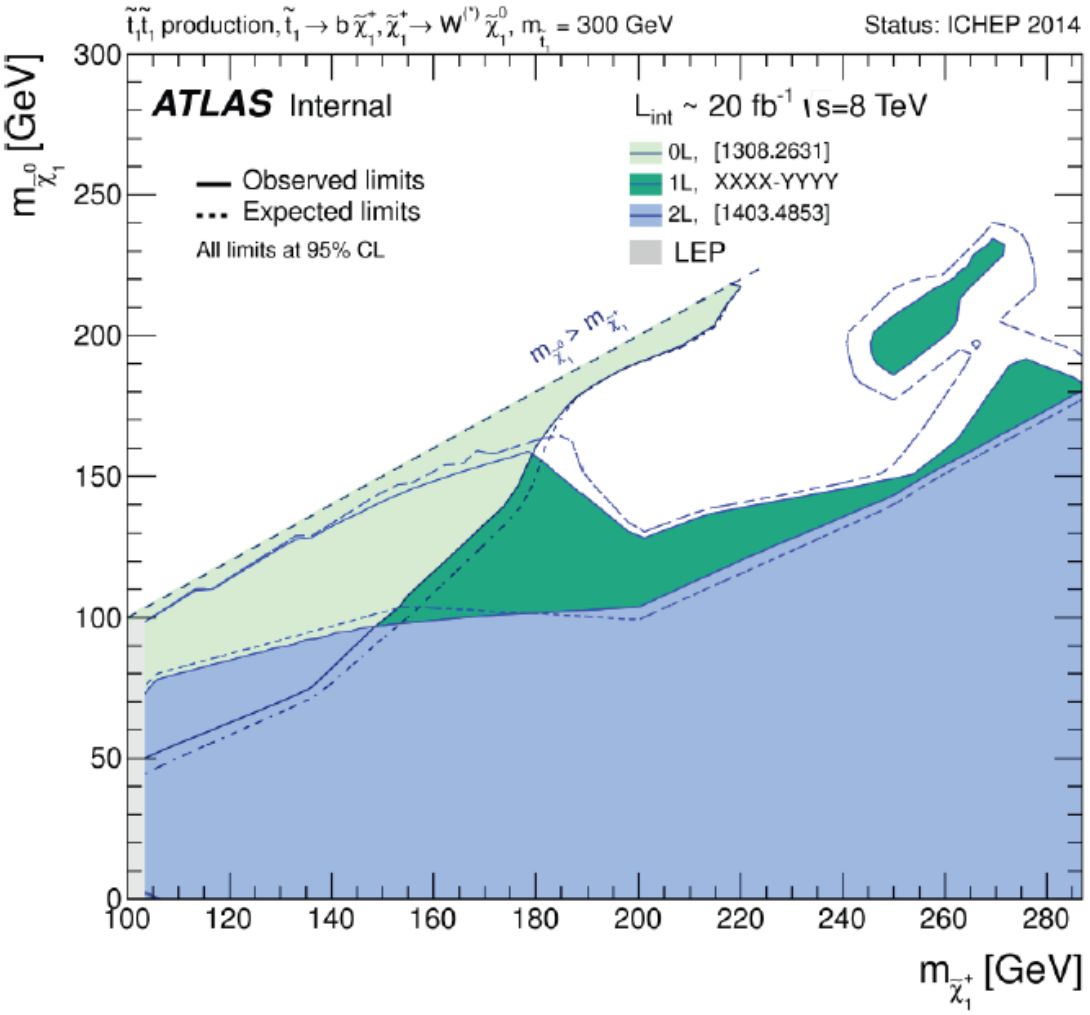




- 95% CL limits on top squarks pairs production

# ATLAS direct stop pairs production stop → b chargino



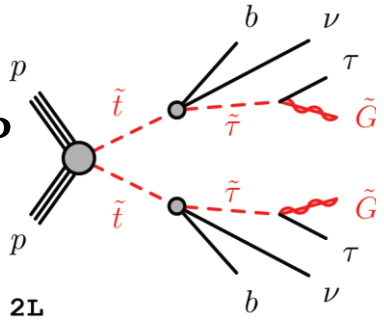

This plot display limits in the chargino1—neutralino1 (LSP) plane for a fixed stop mass of 300 GeV

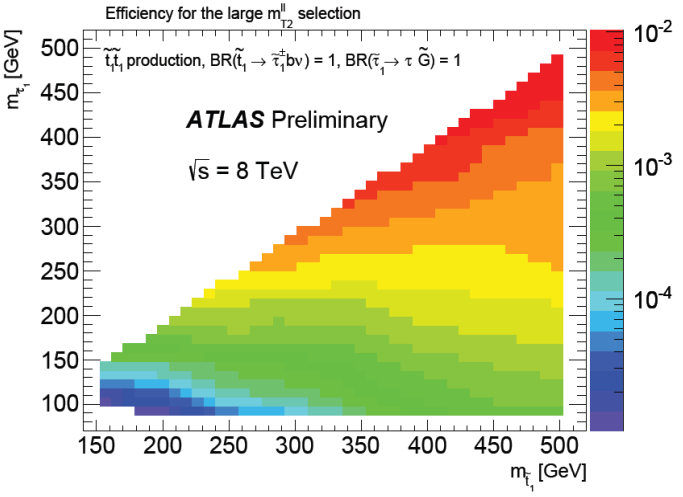
It further illustrates the complementarity of the analyses, and where the particular challenges lie

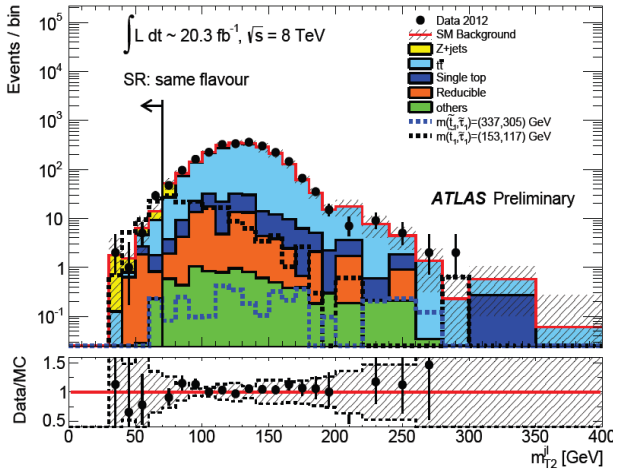
ATLAS-CONF-2014-014

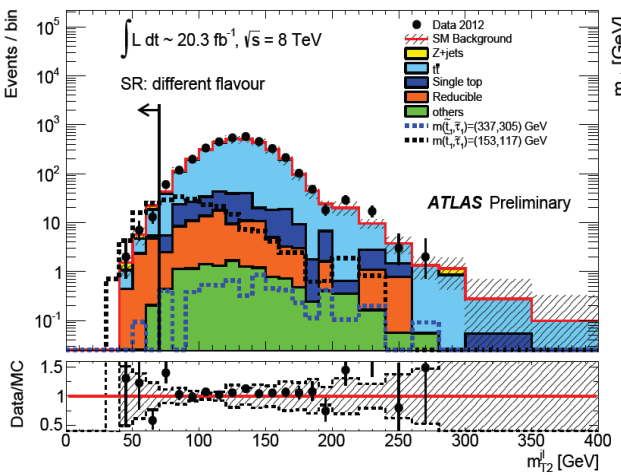
# Stop in b, tau and gravitino

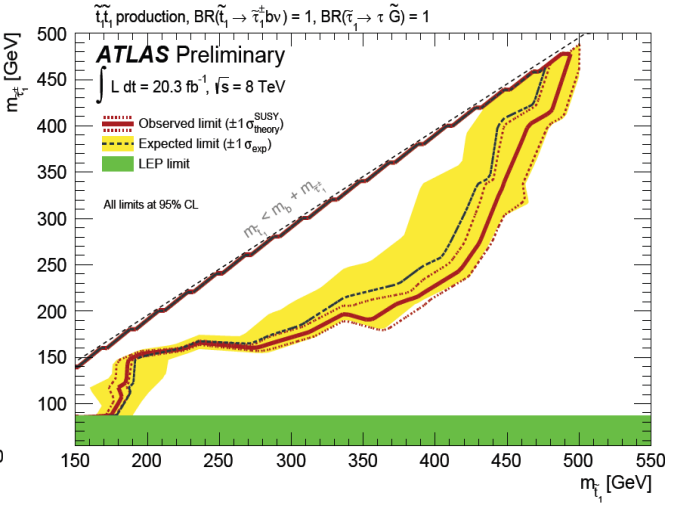
- Search considers decays via $\tilde{t} \to b\nu\tilde{\tau}$ with $\tilde{\tau} \to \tau \tilde{G}$
- Here $\tilde{G}$ is assumed to be the LSP
- Seven SRs are defined based on jet and $m_{T2}{}^{ll}$ selection
- Dominant backgrounds: $t\bar{t}$ and *Z+jets* events



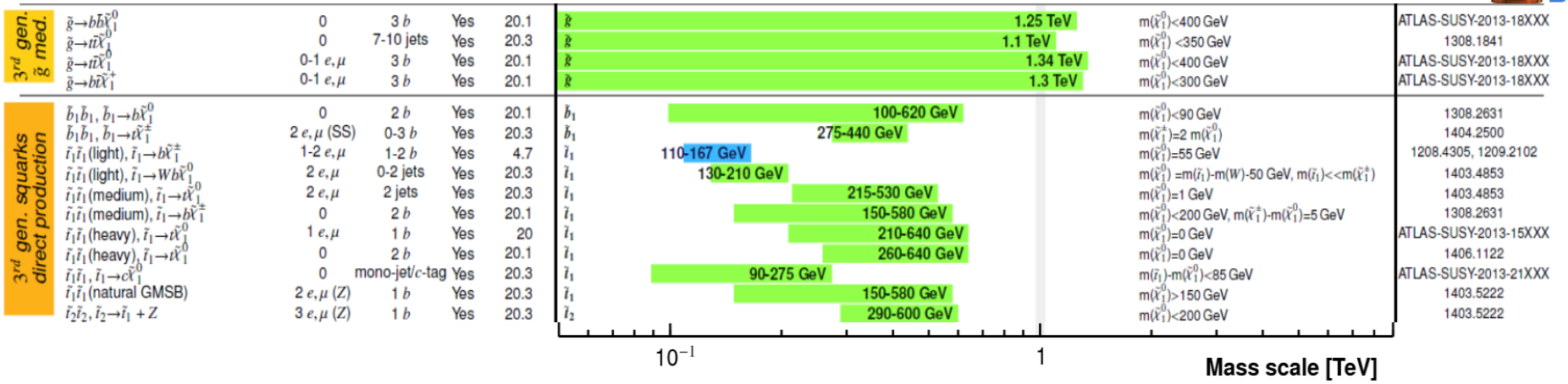



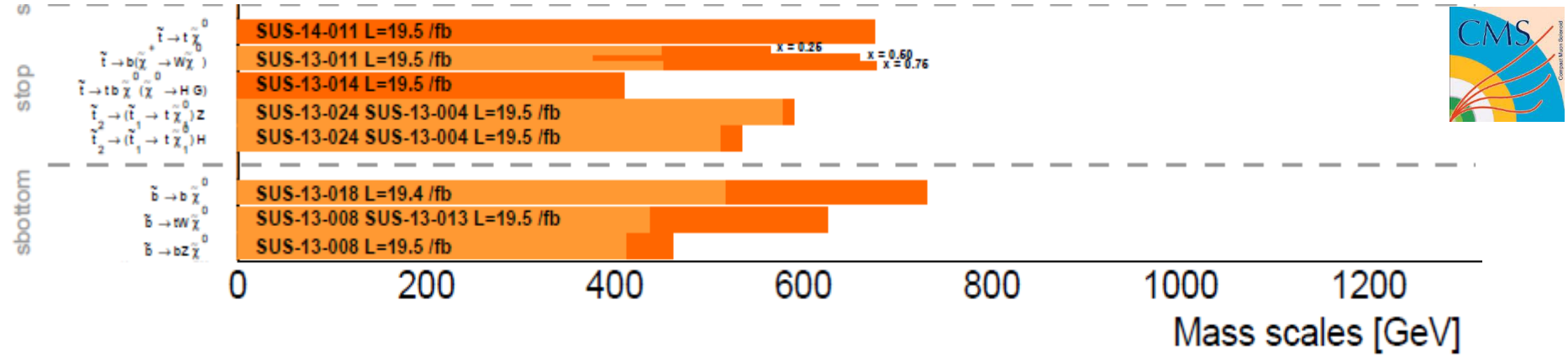



# ATLAS and CMS 95% CL exclusion limits



# Recent ATLAS papers

- 0 lepton + 6 (2 b-)jets + Etmiss [Heavy stop] – Submitted to JHEP – 1406.1122
- Z + b-jet + jets + Etmiss [Stop in GMSB, stop2] – Accepted by EPJC – 1403.5222
- 2 leptons + (b)jets + Etmiss [stop] – JHEP 06 (2014) 124 – 1403.4853
- 0 leptons + 2 b-jets + Etmiss [Sbottom/stop] – JHEP 10 (2013) 189 – 1308.2631
- Stop in b, tau and gravitino – ATLAS-CONF-2014-014
- 0 leptons + mono-jet/c-jets + Etmiss [Stop in charm+LSP] – ATLAS-CONF-2013-068
- 0-1 leptons + >=3 b-jets + Etmiss [3rd gen. squarks] – ATLAS-CONF-2013-061
- 0 lepton + 6 (2 b-)jets + Etmiss [Heavy stop] – ATLAS-CONF-2013-024
- 1 lepton + 4(1 b-)jets + Etmiss [Medium / heavy stop] – ATLAS-CONF-2013-037
- Z + b-jet + jets + Etmiss [Stop in GMSB, stop2] – ATLAS-CONF-2013-025

# Recent CMS papers

- Search for top-squark pair production with Higgs and Z bosons in the final state in pp collisions at 8 TeV – Submitted to PLB arXiv:1405.3886
- Search for top-squark pair production in the single lepton final state in pp collisions at 8 TeV – EPJC 73 (2013) 2677 arXiv:1308.1586
- Search for stop in R-parity-violating supersymmetry with three or more leptons and b-tags – PRL 111, 221801 (2013), arXiv:1306.6643
- Search for direct production of a pair of bottom squarks – PAS-SUS-13-018
- Search for direct production of stops decaying to a charm and LSP using the monojet + MET final state – PAS-SUS-13-009
- Search for top squarks in multijet events with large missing momentum in pp collisions at 8 TeV – PAS-SUS-13-015
- Search for Direct Top Squark Pair Production with Higgs bosons in the Final State in pp collisions at 8 TeV – PAS-SUS-13-021
- Search for direct top squark pair production in events with a single isolated lepton, jets and missing transverse energy at $\sqrt{s}$ = 8 TeV – PAS-SUS-12-023