Beyond Standard Model Physics

Search for direct top squark pair production in events with one lepton, jets, and missing transverse momentum at 13 TeV at CMS, on 137 fb^{-1} integrated luminosity

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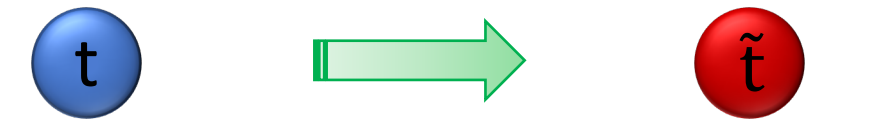
Purpose of the search

CMS PAS SUS-19-009

Find indications of the existence of particles consistent with SUSY models which extend the SM zoology

Stop or **top squark** ($\tilde{t}$)



fermion

sfermion
(scalar boson)

Would allow cancellation of quadratic divergences arising from quantum corrections to the Higgs boson mass

Exact cancellation → **several new states** and a **symmetry** to relate their couplings to the SM particles

Top squarks are one of those possible states

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sfermion
(scalar boson)

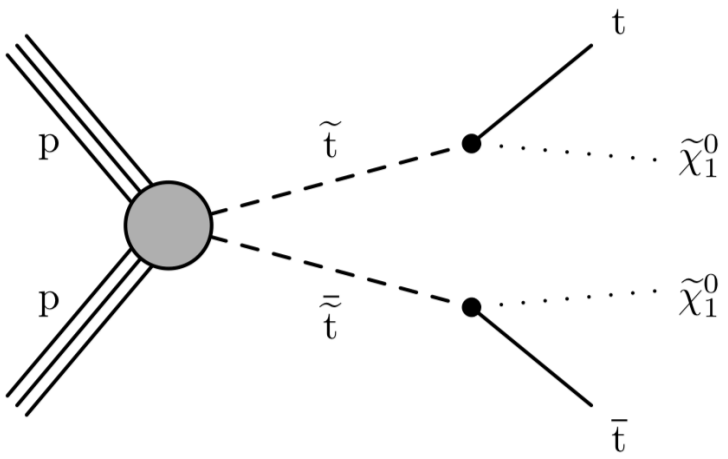
Top squark production should be accessible at the LHC, provided that $\tilde{t}$ mass is compatible with the electroweak symmetry breaking scale

The signal we are looking for

Direct top squark pair production in pp collisions at $\sqrt{s} = 13$ TeV at the LHC (in this search model)

Common experimental signature: $W^*W^* + bb + \tilde{\chi}_1^0\tilde{\chi}_1^0$

1 $\tilde{t} \rightarrow t\,\tilde{\chi}_1^0$



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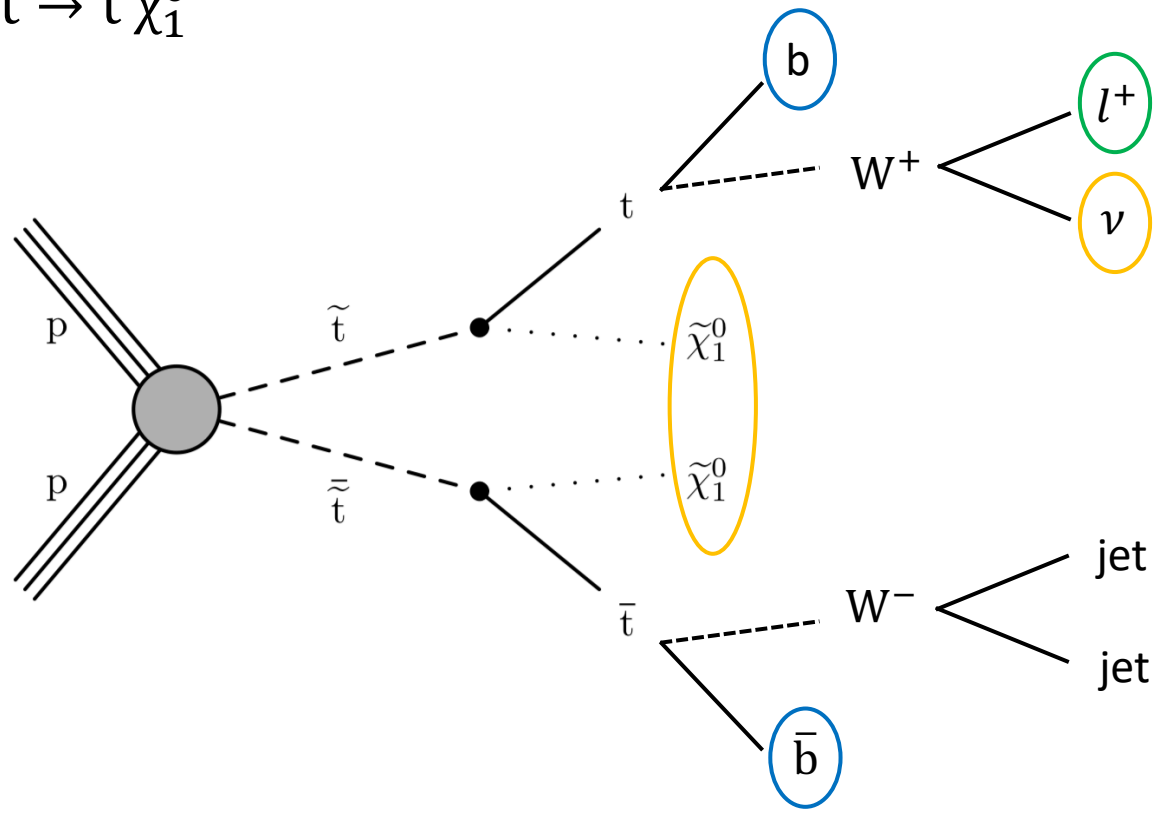

- 1 charged lepton (μ, e)
- 2 b-jets
- 2 additional non-b-tagged jets
- E_T^{miss}

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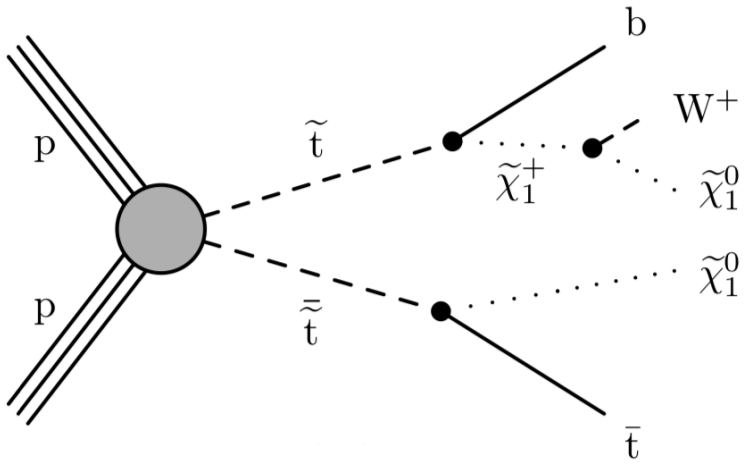
$\tilde{t} \to b\,\tilde{\chi}_1^+ \to bW^+\tilde{\chi}_1^0$



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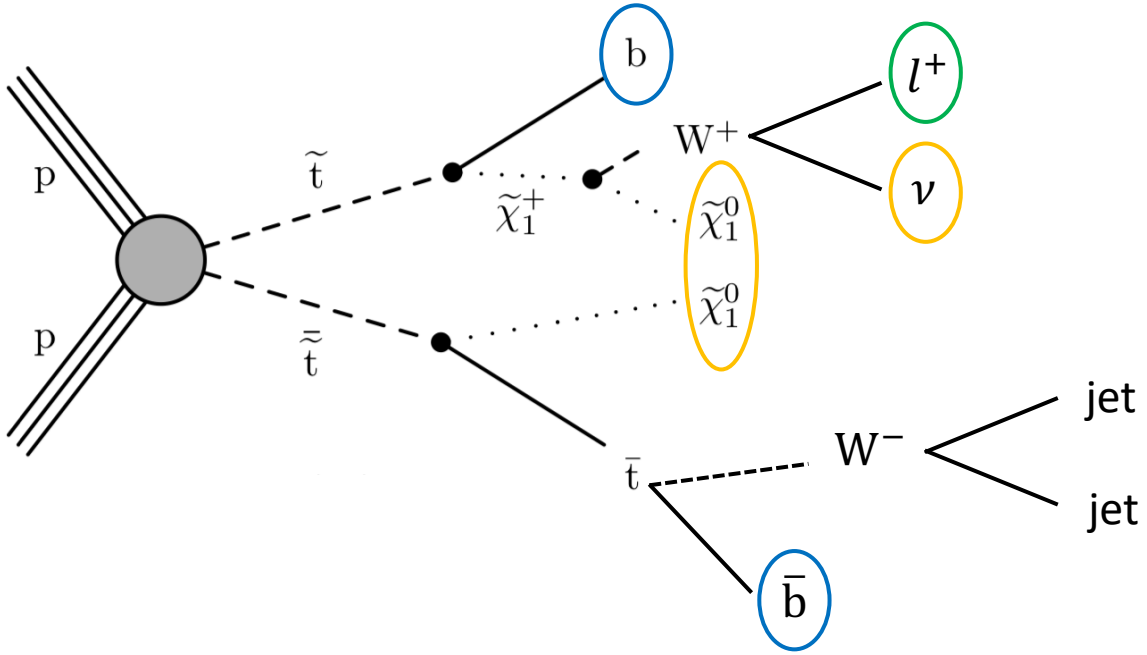

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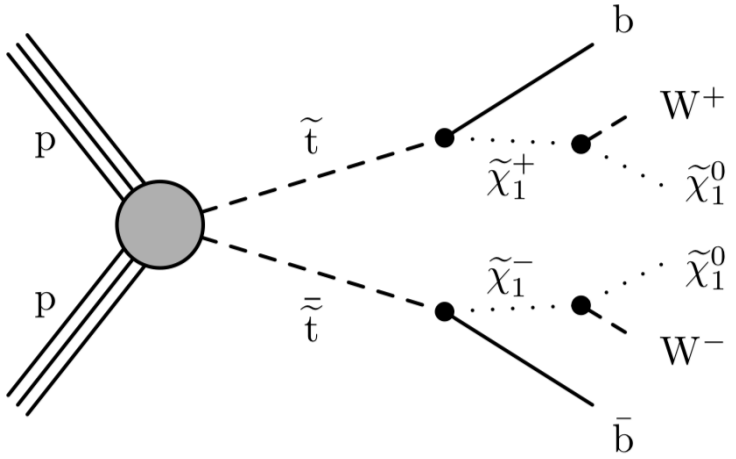

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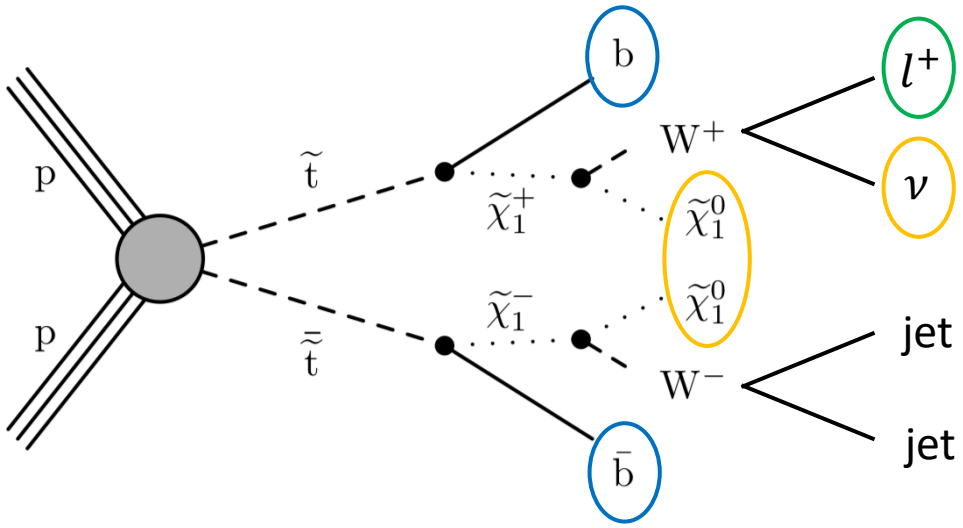

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Analysis ingredients

- 3 categories of search regions, designed to be sensitive to top squark production scenarios with:

$\Delta m\,(\tilde{t}, \tilde{\chi}_1^0) > m_t$ $\Delta m\,(\tilde{t}, \tilde{\chi}_1^0) \sim m_t$ $\Delta m\,(\tilde{t}, \tilde{\chi}_1^0) \sim (m_W + m_b)$

Compressed mass spectrum scenario

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Compressed mass spectrum scenario

- Trigger event selection:

$p_T^{miss} > 120$ GeV OR SingleMu(Ele) $24 - 27\ (27 - 35)$ GeV

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- Preselection:
  - *Exactly* one lepton (μ, e), isolated and coming from the PV
  - $N_{jets} \geq 2,\ p_T > 30$ GeV
  - $N_{b-jets} \geq 1$ for $\Delta m\,(\tilde{t}, \tilde{\chi}_1^0) > m_t$ and $\Delta m\,(\tilde{t}, \tilde{\chi}_1^0) \sim m_t$
  - $N_{b-jets,\,soft} \geq 1$ for $\Delta m\,(\tilde{t}, \tilde{\chi}_1^0) \sim (m_W + m_b)$. "Soft" $\rightarrow p_T^{jet} < 20$ GeV
  - $p_T^{miss} > 250$ GeV
  - $M_T = \sqrt{2 p_T^l E_T^{miss} [1 - cos\Delta\phi(l, \vec{p}_T^{miss})]} > 150$ GeV
  - $\Delta\phi(j_{1,2}, \vec{p}_T^{miss}) > 0.8 - 0.5$
  - Reject events with extra *loose* lepton or isolated PF candidate

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} Heavily suppress semileptonic $t\bar{t}$ and W+jets

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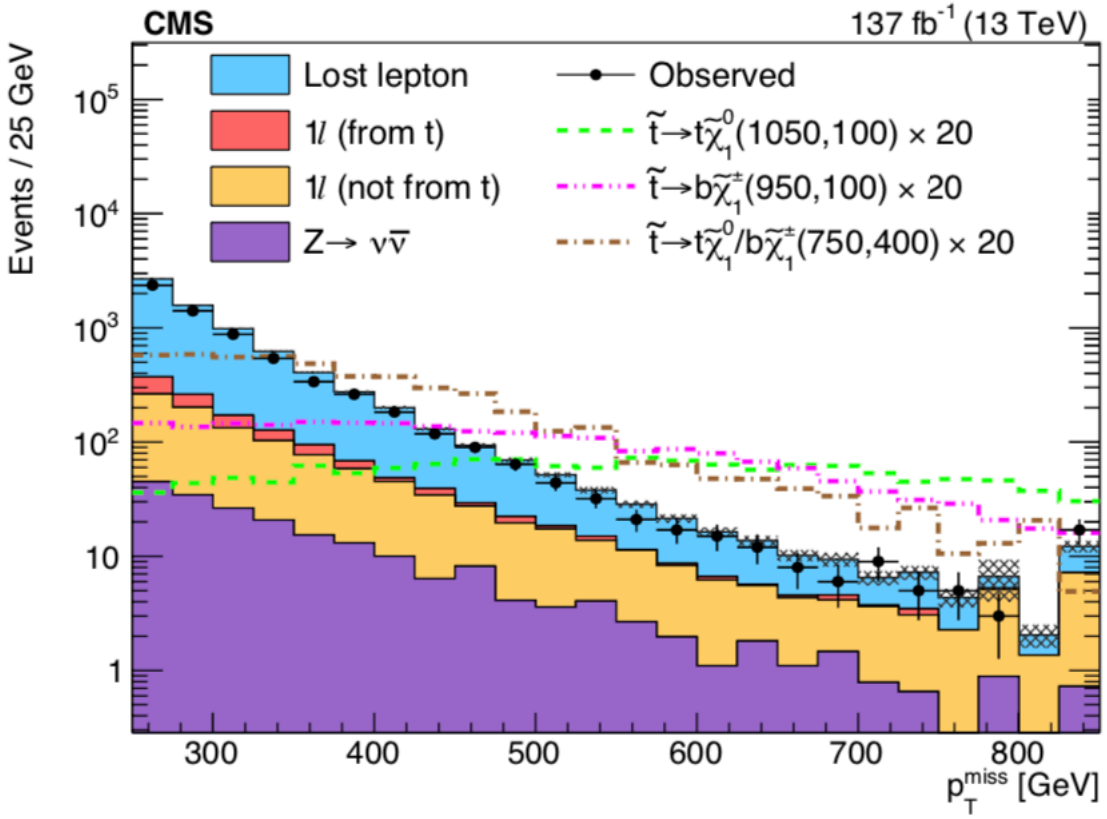
} Suppress backgrounds with 2 leptonically decaying Ws (primarily $t\bar{t}$ and tW)

Background classification

Three categories of background remain after the preselection cuts



1. **Lost lepton**: events with two W bosons decaying leptonically, where one of the two leptons is not reconstructed or not identified
   Source: $t\bar{t}$, Single t (small)

2. **One-lepton**: events with a single W boson decaying leptonically and no other additional source of p_T^{miss}
   Source: Single t, direct W production

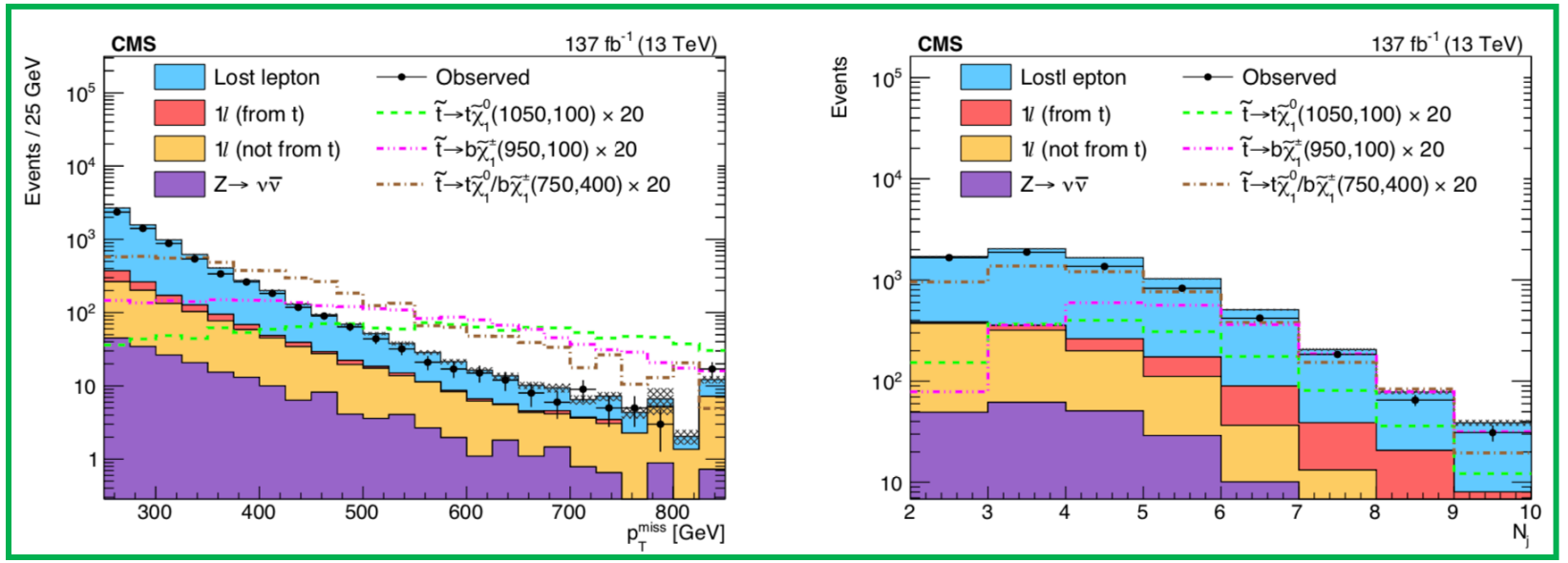
3. $\mathbf{Z \to \nu\bar{\nu}}$: events with a single leptonically decaying W boson and a Z boson decaying to a pair of neutrinos
   Source: $t\bar{t}Z$, WZ etc

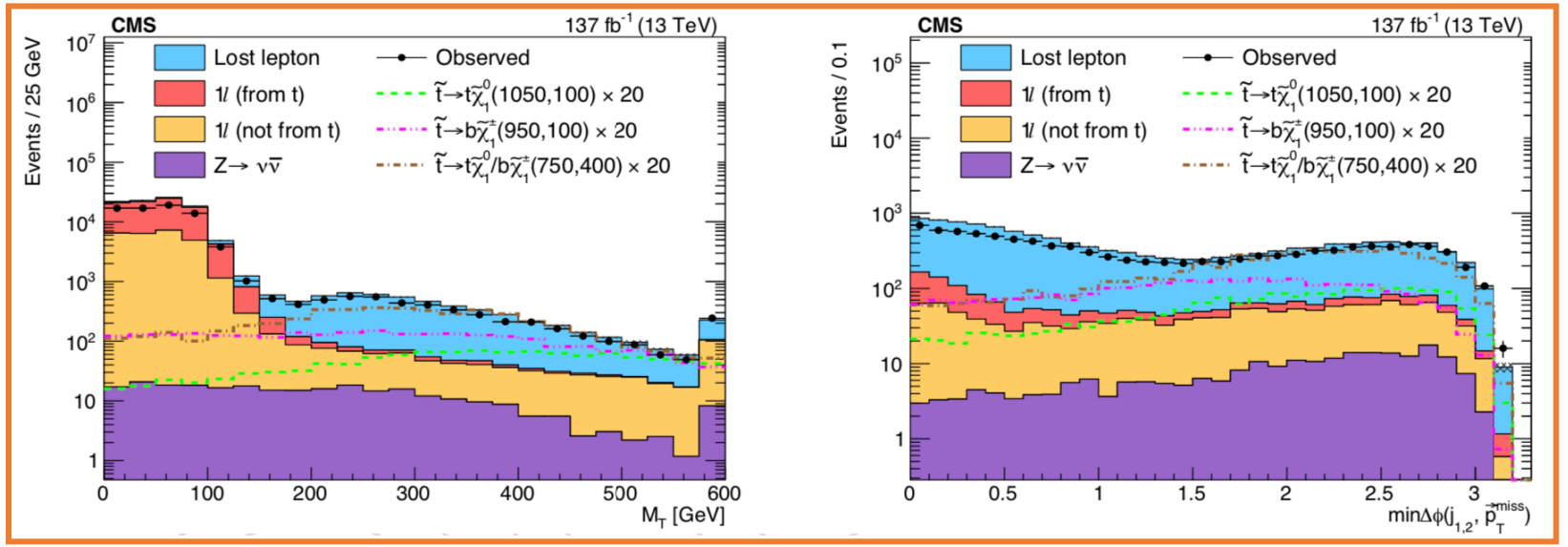
Such background contributions are estimated either from **simulation** or from **data control regions**

After preselection...

All cuts applied, **included** the ones on the plotted variables

All cuts applied, **excluded** the ones on the plotted variables





Search strategy

Categorize events passing the preselection, based on their behavior with respect to a few variables

N_j

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N_j

top tagging category

Use two DNNs to categorize events based on ID of hadronically decaying top quarks

- Tag 3 resolved jets
- Tag merged top quark decays

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N_{j}

top
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$p_{\mathrm{T}}^{\mathrm{miss}}$

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$M_{l\mathrm{b}}$ → Invariant mass of the lepton and the closest b-tagged jet in ΔR.

In events containing leptonic decay of top quark:

$$M_{l\mathrm{b}} \leq m_{\mathrm{t}} \sqrt{1 - \frac{m_{\mathrm{W}}^2}{m_{\mathrm{t}}^2}}$$

Two categories:

- $M_{l\mathrm{b}} < 175$ GeV
- $M_{l\mathrm{b}} > 175$ GeV && $N_{\mathrm{b-jets}}^{tight} \geq 1$ to suppress W+jets

Does not apply to W+jets or Signal where $\tilde{\mathrm{t}} \rightarrow \mathrm{b}\, \tilde{\chi}_1^+$

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$p_{\mathrm{T}}^{\mathrm{miss}}$

$M_{l\mathrm{b}}$

Modified topness (t_{mod})

χ^2-like variable to discriminate signal from leptonically decaying $t\bar{t}$

$$t_{\mathrm{mod}} = \ln(\min S), \text{ with } S = \frac{\left(m_{\mathrm{W}}^2 - (p_\nu + p_l)^2\right)^2}{(5\ \mathrm{GeV})^4} + \frac{(m_{\mathrm{t}}^2 - (p_{\mathrm{b}} + p_{\mathrm{W}})^2)^2}{(15\ \mathrm{GeV})^4}$$

wrt to $\vec{p}_{\mathrm{W}}$ and p_ν^z

$\vec{p}_{\mathrm{T}}^{\,\mathrm{miss}} = \vec{p}_{\mathrm{T,W}} + \vec{p}_{\mathrm{T},\nu}$ and $p_{\mathrm{W}}^2 = m_{\mathrm{W}}^2$

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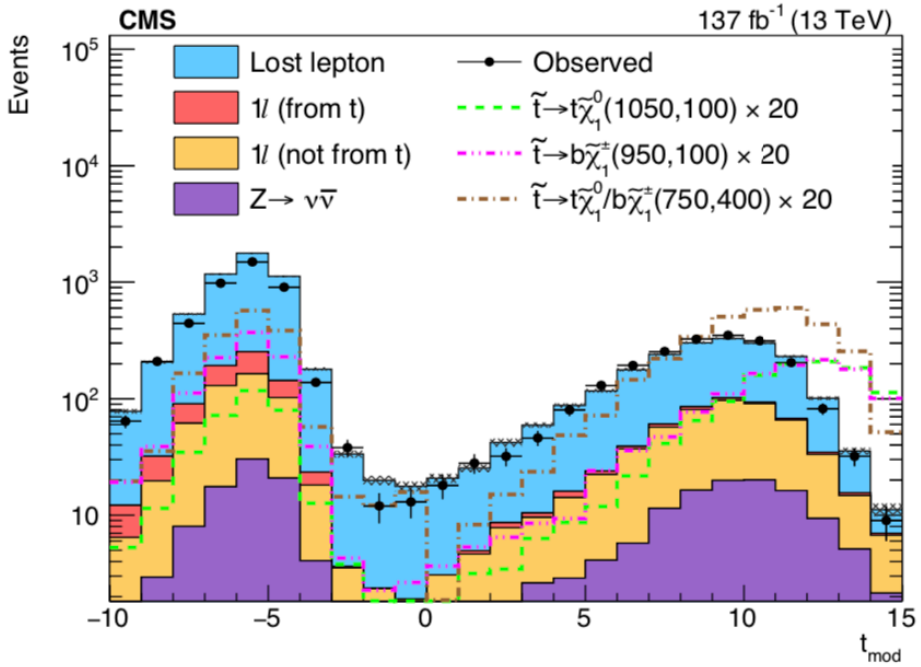
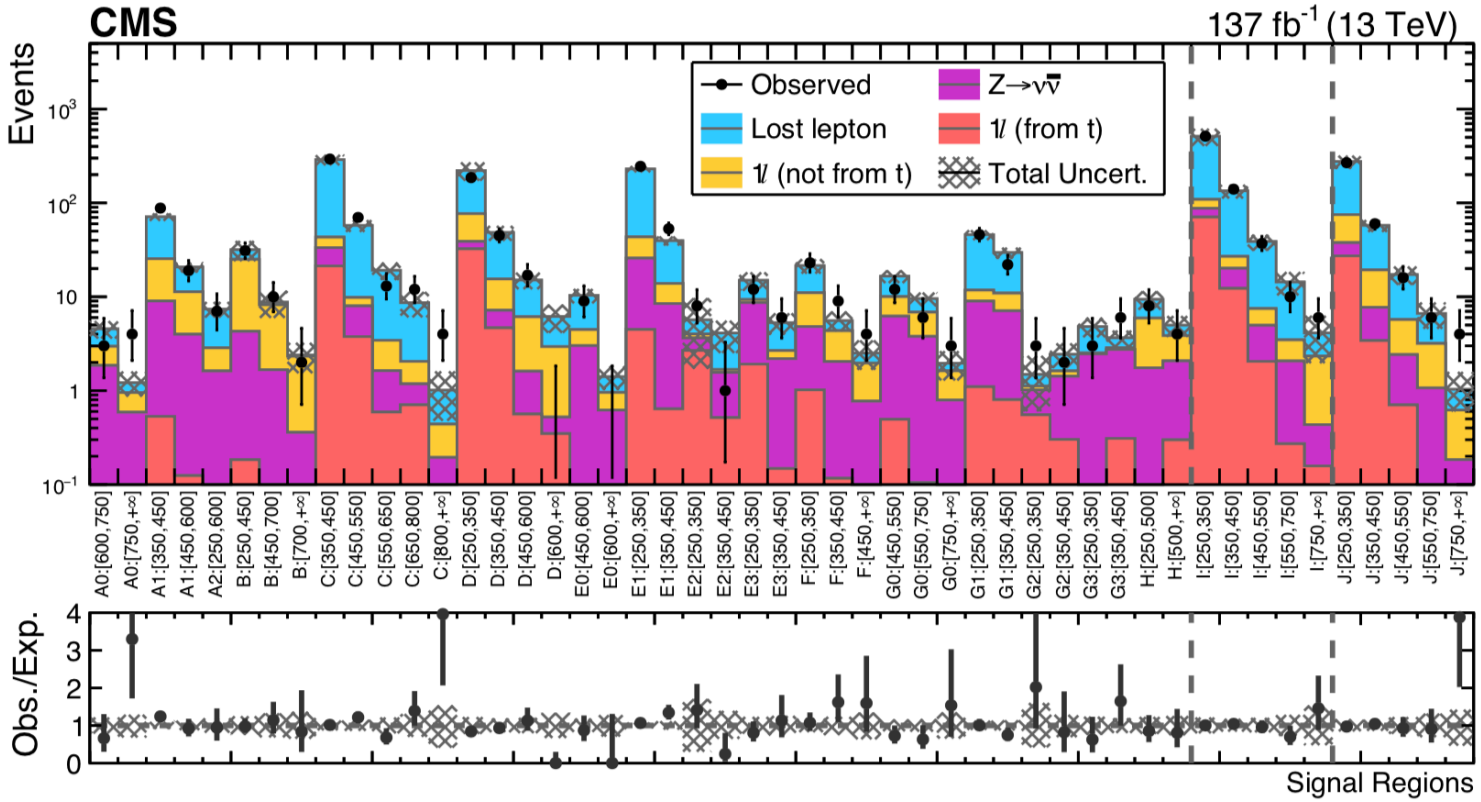


Low values → background like

Higher values → signal like

Results

Yield comparison in 39 categories



	N_J	t_{mod}	M_{lb} [GeV]
A	2–3	> 10	≤ 175
B	2–3	> 10	> 175
C	≥ 4	≤ 0	≤ 175
D	≥ 4	≤ 0	> 175
E	≥ 4	0–10	≤ 175
F	≥ 4	0–10	> 175
G	≥ 4	> 10	≤ 175
H	≥ 4	> 10	> 175

X0: Inclusive
X1: Untagged
X2: Merged t quark tag
X3: Resolved t quark tag

I: $N_J \geq 5$, $N_{b,med} \geq 1$
J: $N_J \geq 3$, $N_{b,soft} \geq 1$

The observed yields are compatible with the estimated SM backgrounds

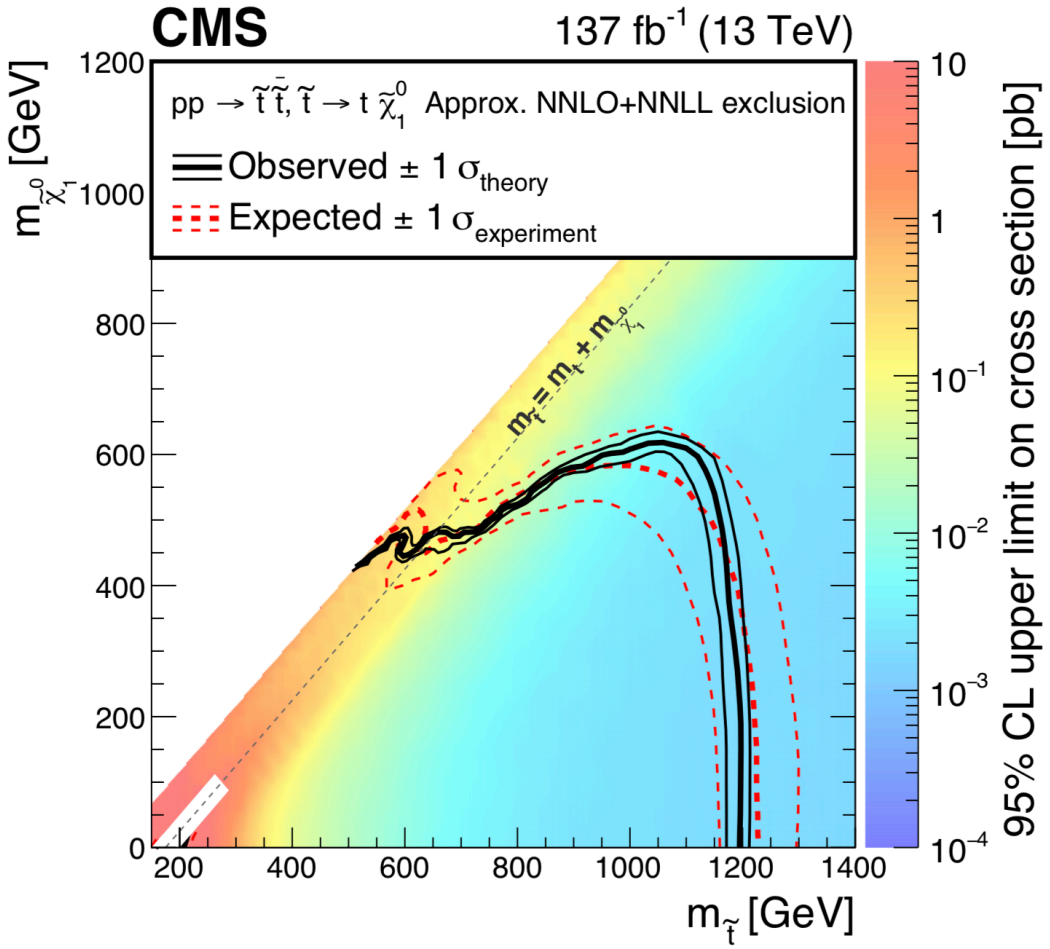
Upper Limits

Limits on the production cross sections are derived as a function of the mass of the SUSY particles

Search regions combined:

$\Delta m\,(\tilde{t}, \tilde{\chi}_1^0) \sim m_W \qquad 100 \leq \Delta m\,(\tilde{t}, \tilde{\chi}_1^0) \leq 150$ GeV

$\Delta m\,(\tilde{t}, \tilde{\chi}_1^0) \sim m_t \qquad 150 \leq \Delta m\,(\tilde{t}, \tilde{\chi}_1^0) \leq 225$ GeV



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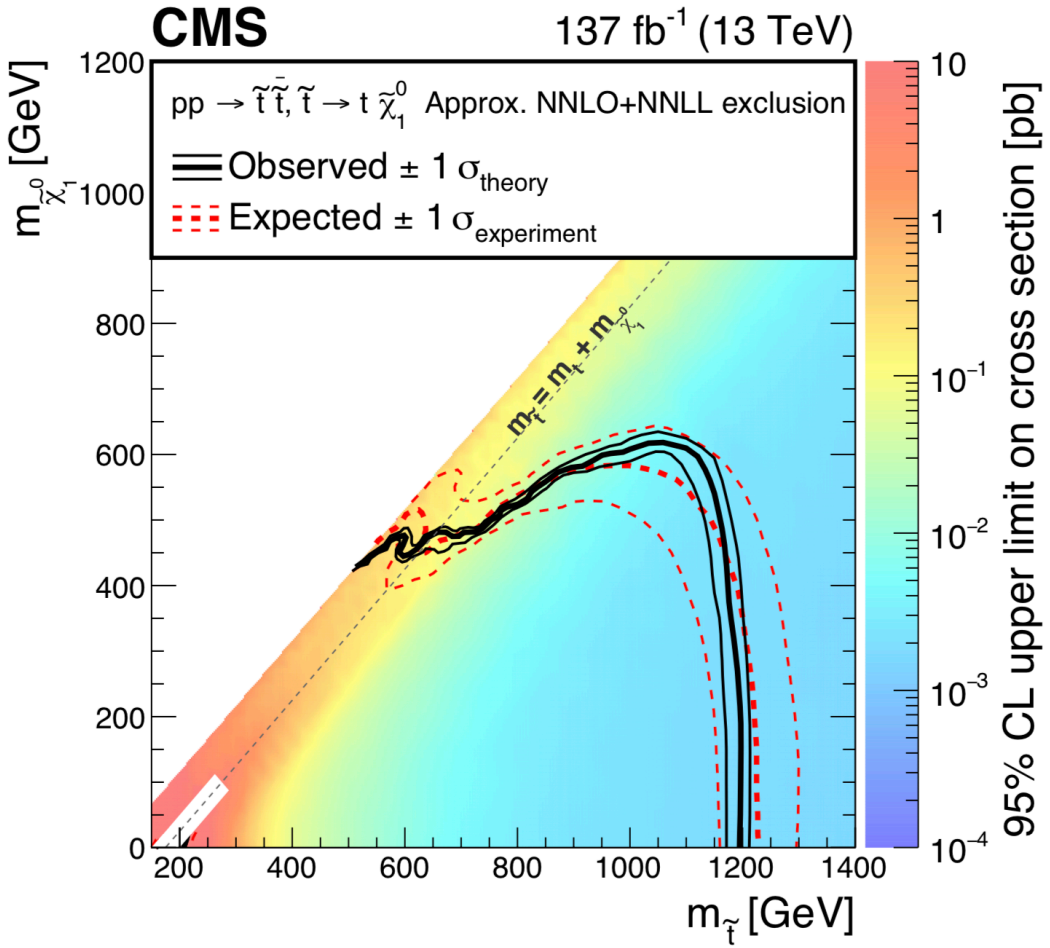
Improvement up to a factor 5 in cross section sensitivity wrt to the standard search regions



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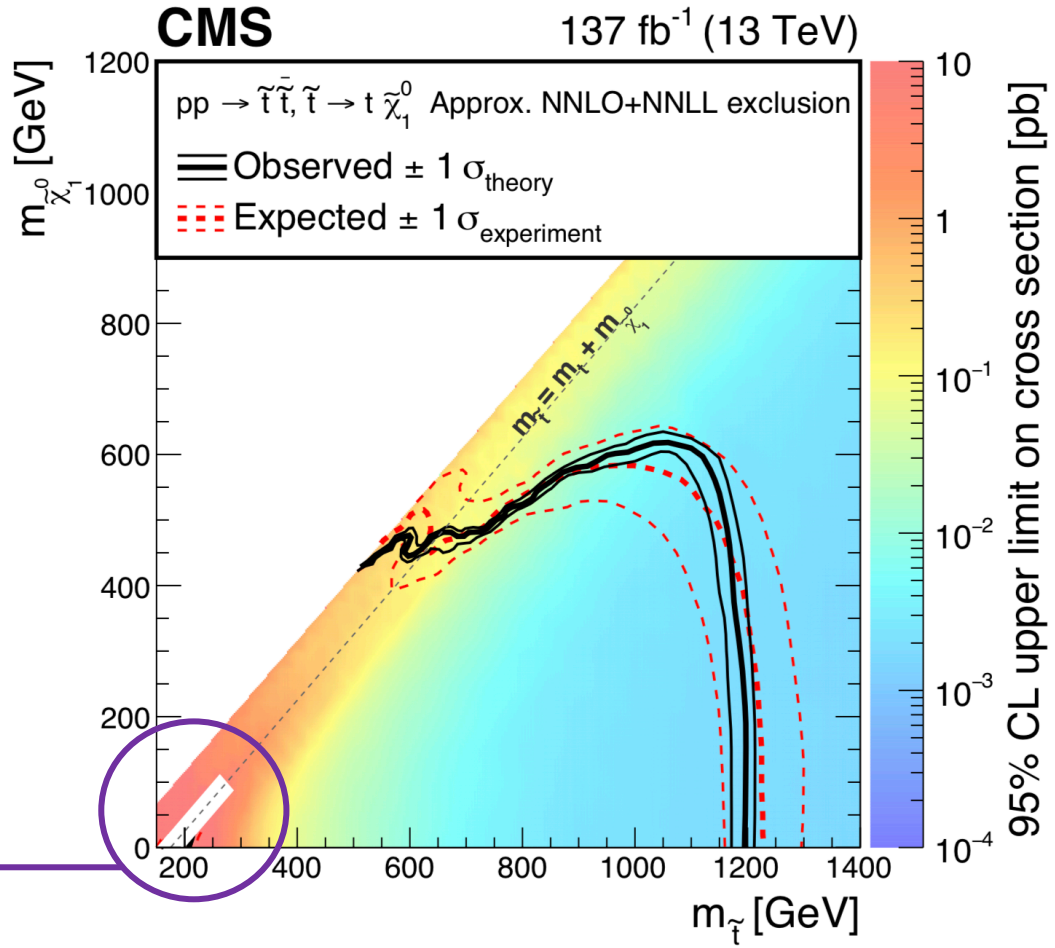
Selection acceptance for top squarks changes rapidly and is very sensitive to the details of the simulation

No interpretation performed

$$\left|m_{\tilde{t}} - m_t - m_{\tilde{\chi}_1^0}\right| < 25\ \text{GeV} \quad \&\& \quad m_{\tilde{t}} < 275\ \text{GeV}$$



Uncertainties

Statistical

Dominant in all background categories

• Data control regions (used to estimate lost lepton and one-lepton bkg)	4-50%
• Simulation (used for all bkg and for sig estimation)	3-70%

Systematic

Arising from:

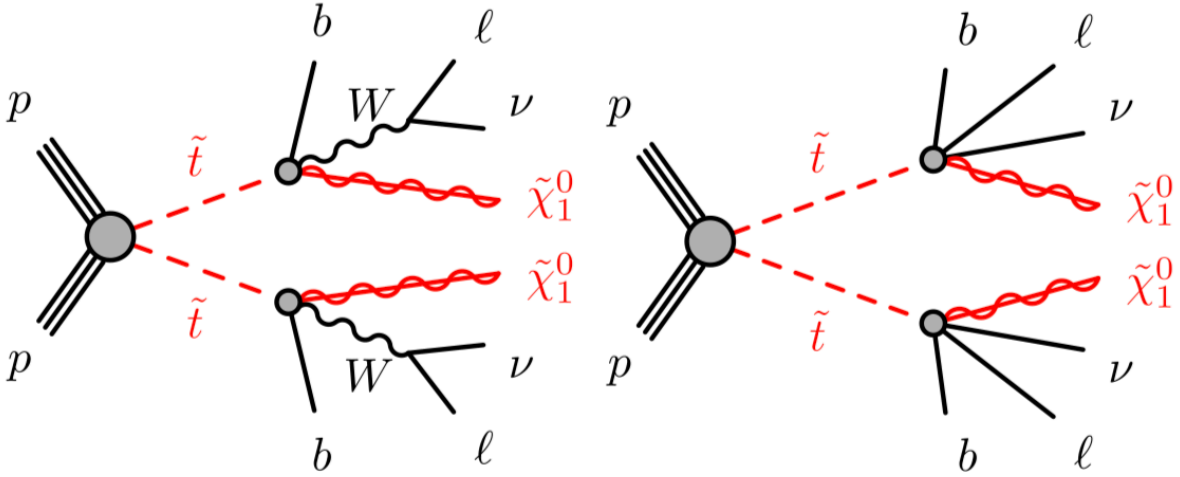
• $t\bar{t}$ p_T^{miss} modeling (lost lepton)	3-50%
• Jet energy scale	1-34%
• t tagging efficiency	3-10%
• b tagging efficiency	0-10%

The overall uncertainty is generally larger at high p_T^{miss} or when yields in the control regions become small

Similar searches

Several searches for top squarks have been performed by both ATLAS and CMS, looking at different final states

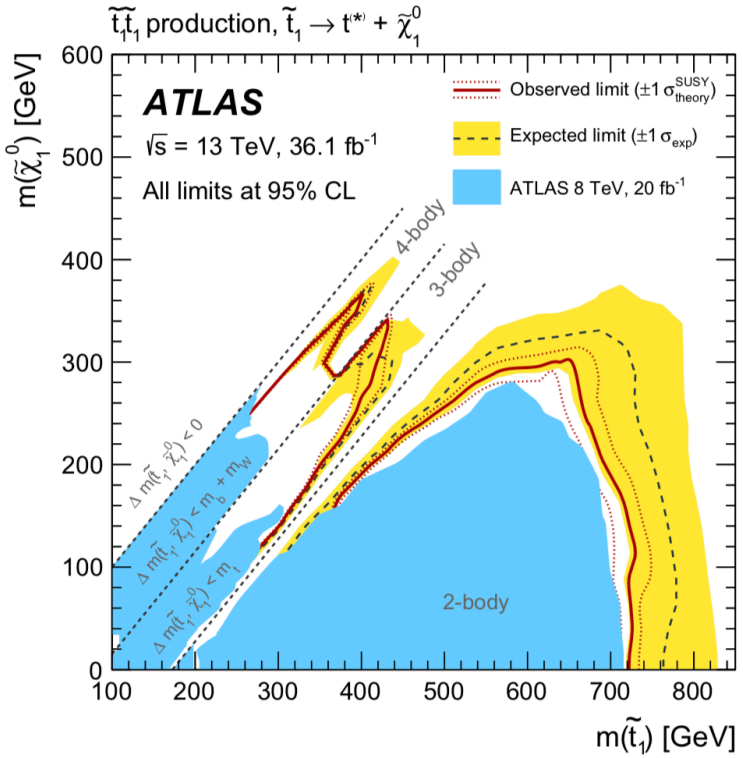
ATLAS doi:10.1103/PhysRevD.94.052009



Three and four-body decays included in the signal

Targeting the double-lepton final states

clearer signature, suppressed cross section



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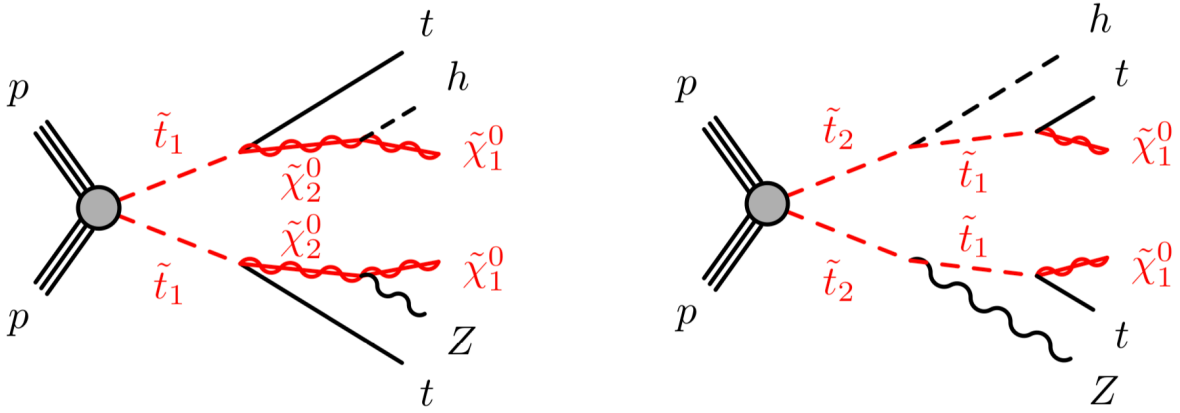
ATLAS doi:10.1007/JHEP08(2017)006



Z and Higgs production included

Targeting double, same-sign lepton / $b\bar{b}$ final states

Clear event reconstruction, bounding m_{ll} and $m_{b\bar{b}}$ to Z and h mass values respectively

+

$\tilde{t}_2 \to h/Z\tilde{t}_1$, $\tilde{t}_1 \to t, \tilde{\chi}_1^0$
offers a much more distinguishable signature from $t\bar{t}$ than just $\tilde{t}_1 \to t, \tilde{\chi}_1^0$

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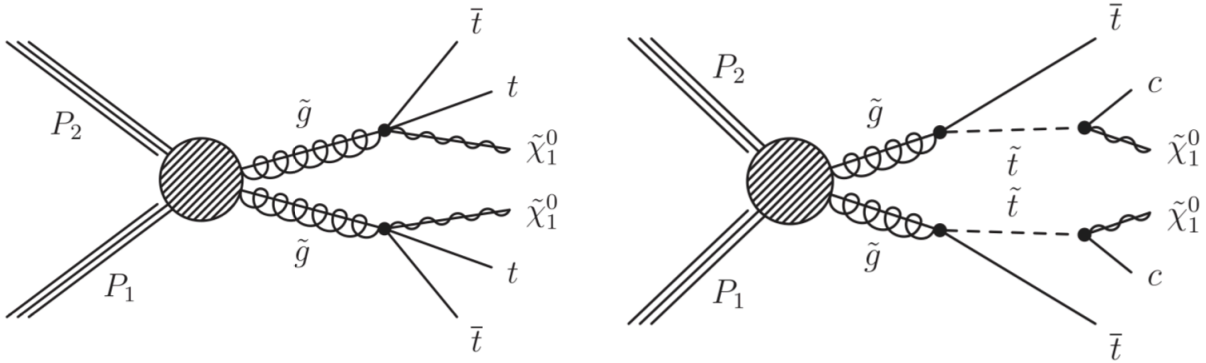
CMS

doi:10.1103/PhysRevD.96.012004



Gluino-mediated processes are also considered

Targeting the all-hadronic final state

Higher cross-section, harder reconstruction

Conclusions

HEP landscape is now quite rich of searches for NP. Among those, SUSY searches are strongly motivated by the need to answer those questions which the SM leaves unsolved

- Searches for top squark pair production have been performed by ATLAS and CMS (and Tevatron, etc)

- Different models have been probed, resulting in diverse final states

- The search for top squark pair production we examined has set exclusion limits at 95% CL for:
  - top squark masses up to 1.2 TeV for a massless neutralino
  - neutralino masses up to 600 GeV for a 1 TeV stop quark mass

- The full LHC integrated luminosity in Run2 at 13 TeV was exploited, so as improved strategies for event categorization wrt the previous searches in the same channels

- The search can be improved in the future: statistical uncertainty is still dominant for both data and simulation (in all the background categories). Furthermore, the search can be improved in sensitivity to a signal given by both top squarks decaying to charginos, in those models with a compressed neutralino-chargino mass spectrum

BACKUP

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