Searching for supersymmetric partners of top quarks at the CMS experiment

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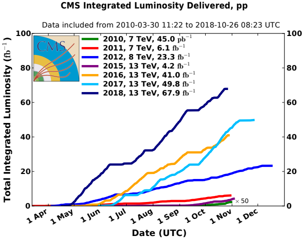
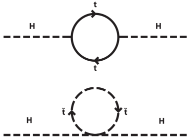
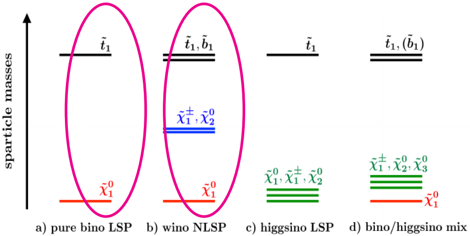
Introduction

- The LHC **performed very well** in Run-2.
- CMS recorded **137 fb^{-1}** of high quality data in **Run-2**.
- **Several SUSY searches** have been performed in various final states.
- The top squark sector serves as a probe to a wide variety of SUSY models and phase space scenarios.
- The tree level **Higgs mass** (in MSSM) receives **substantial correction involving top squark loops** – study of top squarks important for understanding the stability of the Higgs mass.





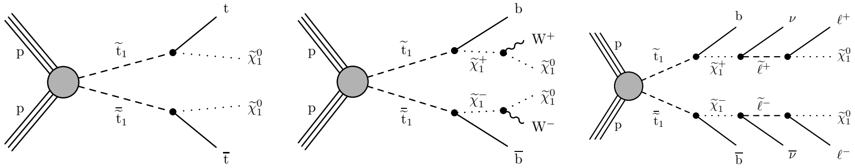


$$m_h^2 = m_Z^2 \cos^2 2\beta + \frac{3m_t^4}{2\pi^2 v^2 \sin^2\beta}\left[\log\frac{m_s^2}{m_t^2} + \frac{X_t^2}{2m_s^2}\left(1 - \frac{X_t^2}{6m_s^2}\right)\right]$$

- **I'll summarize the recent developments in top squark searches at the CMS experiment:**
  1. **$\tilde{t}_1$-pair production:** dilepton and single lepton + jets final states.
  2. **$\tilde{t}_2$-pair production:** same-sign (SS) leptons/multilepton+jets final state.

$\widetilde{t}_1$-pair production: dilepton final state [CMS-PAS-SUS-19-011]

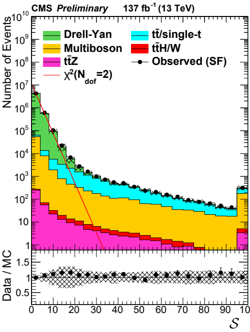
[$137\,fb^{-1}$]



- **Mass parameterization:**
  $m_{\tilde{\chi}_1^+} = (m_{\tilde{t}_1} + m_{\tilde{\chi}_1^0})/2$
  $m_{\tilde{\ell}} = m_{\tilde{\chi}_1^0} + x(m_{\tilde{\chi}_1^+} + m_{\tilde{\chi}_1^0}), \quad x \in [0.05, 0.5, 0.95]$
- Cross-sections normalized to **NNLO+NNLL** accuracy.
- The leptonic decays of the top quark and the W boson are considered.
- Decay assumed to be identical for all three flavors.
- The **leptons** in the final state and the presence of significant **missing transverse momentum (p_T^{miss})** helps to **reduce SM backgrounds**.

Search strategy

quantity	requirement
N_{leptons}	$= 2$ (e or μ), oppositely charged
$m(\ell\ell)$	>20 GeV **Suppresses bkg. from misidentified and non-prompt leptons**
$\lvert m_Z - m(\ell\ell)\rvert$	>15 GeV, same flavor only **Suppresses DY**
N_{jets}	≥ 2 } **Suppresses DY, and other vector boson bkg.**
$N_{\text{b jets}}$	≥ 1
$\mathcal{S}$	>12 **Suppresses events with no genuine missing energy**
$\cos\Delta\phi(p_{\mathrm{T}}^{\text{miss}}, j_1)$	<0.80 } **Suppresses DY with strongly mismeasured jets**
$\cos\Delta\phi(p_{\mathrm{T}}^{\text{miss}}, j_2)$	<0.96



- **Dilepton and single lepton triggers.**
- **New** $\mathcal{S}$ is the $p_{\mathrm{T}}^{\text{miss}}$ significance – reduces events where **detector effects and misreconstruction are the main sources of $p_{\mathrm{T}}^{\text{miss}}$.** Follows a χ^2-distribution with 2 degrees of freedom for events with no genuine $p_{\mathrm{T}}^{\text{miss}}$.

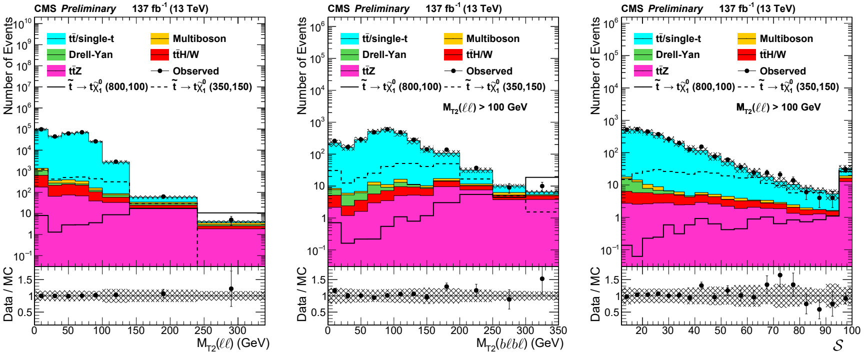
$$\mathcal{S} = 2\ln\left[\frac{\mathcal{L}(\vec{p}_{\mathrm{T}\,\text{true}}^{\,\text{miss}} = \vec{p}_{\mathrm{T}\,\text{obs}}^{\,\text{miss}})}{\mathcal{L}(\vec{p}_{\mathrm{T}\,\text{true}}^{\,\text{miss}} = 0)}\right]$$

Search region binning

$M_{\mathrm{T2}}(\mathrm{b}\ell\mathrm{b}\ell)$ (GeV)	$\mathcal{S}$	$100 < M_{\mathrm{T2}}(\ell\ell) < 140$ GeV	$140 < M_{\mathrm{T2}}(\ell\ell) < 240$ GeV	$M_{\mathrm{T2}}(\ell\ell) > 240$ GeV
0–100	12–50	SR0	SR6	
	>50	SR1	SR7	
100–200	12–50	SR2	SR8	SR12
	>50	SR3	SR9	
>200	12–50	SR4	SR10	
	>50	SR5	SR11	

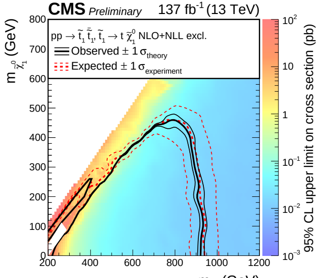
- Events from $t\bar{t}$ mostly populate $m_{\mathrm{T2}}(\ell\ell) < 100$ GeV. However, **the tails of m_{T2} can be populated due to:**
  1. Jet mom. resolution.
  2. Mismeasured jet mom.
  3. e/μ may fail ID, or W can decay to τ.

  These effects are checked in control regions – good closure b/w data and simulation.
- **Genuine $t\bar{t}$ bkg. normalization scale factor is extracted from a signal depleted CR ($m_{\mathrm{T2}}(\ell\ell) < 100$ GeV).**
- Correction factors for DY, multiboson, and top quark+X backgrounds are derived from fits in control regions.

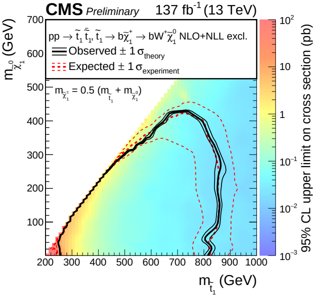


- **No significant excess is observed.**

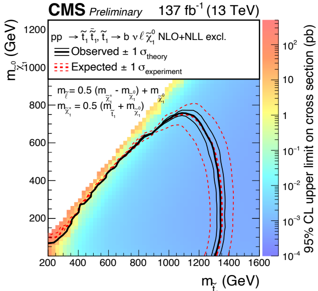
(a) $\tilde{t}_1 \to t\tilde{\chi}_1^0$



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



(c) $\tilde{t}_1 \to b\tilde{\chi}_1^+ \to \nu\tilde{l}^+$ ($x = 0.5$)

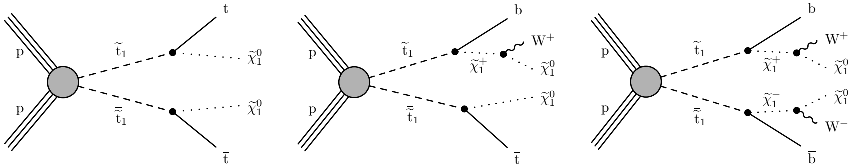


- **(a)** $m_{\tilde{t}_1}$ excluded up to 900 GeV for nearly massless LSP.
- **(b)** $m_{\tilde{t}_1}$ excluded up to 800 GeV for nearly massless LSP.
- **(c)** $m_{\tilde{t}_1}$ excluded up to 1300 GeV for nearly massless LSP.

$\widetilde{t}_1$-pair production: single lepton + jets final state [hep-ex 1912.08887]

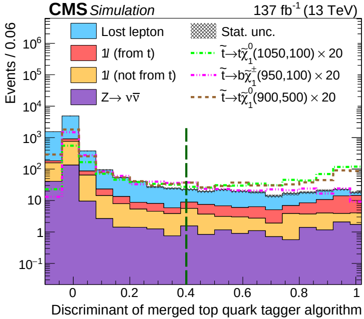
[137 fb^{-1}]

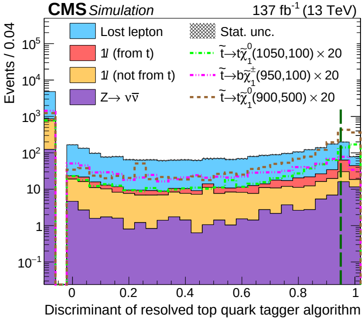
Signal and final state (single lepton + jets)



- Chargino mass parameterization same as before.
- One W boson decays to a lepton, and the other to hadrons.

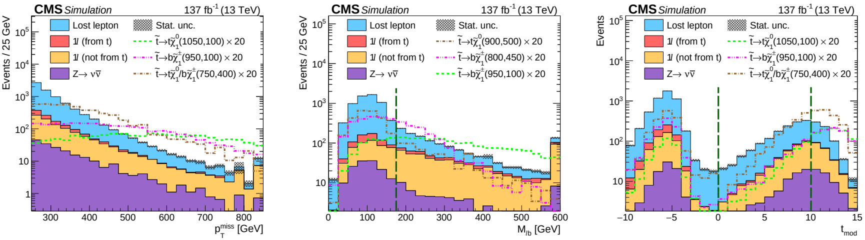
- **p_T^{miss}, H_T, and single lepton triggers.**
- Exactly one isolated lepton (e/μ).
- At least 2 jets ($N_j \geq 2$). At least 1 b-tagged jet.
- $p_T^{miss} > 250$ GeV, $m_T > 150$ GeV.
  Reduces $t\bar{t}$ and W +jets backgrounds.
- min $\Delta\phi(j_{12}, \vec{p}_T^{miss}) > 0.8$ (standard), 0.5 (compressed).
  Suppresses bkg. from two leptonically decaying W bosons (tW, $t\bar{t}$).
- Top tagger (using DNN) used to tag the hadronically decaying top quark: three categories (untagged, resolved, merged).
- **Search region** divided into **39 bins** in terms of N_j, t_{mod} (topness), $m_{\ell b}$, p_T^{miss}, and top-tagging category.
- **New** **Soft ($p_T > 1$ GeV) b-tagging using a secondary vertex not associated to jets or leptons.**
  This improves sensitivity in the compressed region $m_{\tilde{t}_1} - m_{\tilde{\chi}_1^0} \sim m_W$.





Background estimation

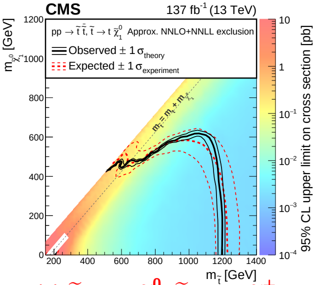
- **Lost lepton bkg.:** Events with two W bosons decaying leptonically where **one of the leptons is not reconstructed/identified.**
  Estimated using a di-lepton data control sample.
- **Single lepton bkg.:** Single W bosons decaying leptonically.
  Estimated using a data control sample with no b-jets.
- **$Z \rightarrow \nu\bar{\nu}$ bkg.**: Events with a leptonically decaying W boson and a Z boson decaying to neutrinos.
  Estimated using simulation.



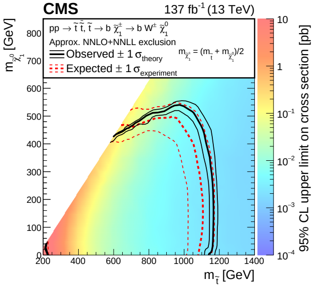
Results

- **No significant excess is observed.**

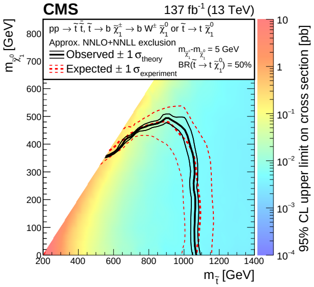
(a) $\tilde{t}_1 \to t\tilde{\chi}_1^0$



(b) $\tilde{t}_1 \to b\tilde{\chi}_1^+$



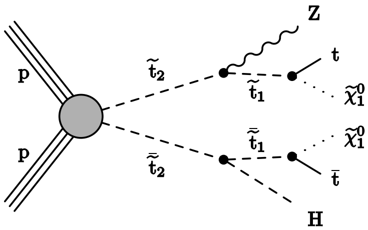
(c) $\tilde{t}_1 \to t\tilde{\chi}_1^0$, $\tilde{t}_1 \to b\tilde{\chi}_1^+$,



- **(a)** $m_{\tilde{t}_1}$ excluded up to 1200 GeV for nearly massless LSP.
- **(b)** $m_{\tilde{t}_1}$ excluded up to 1150 GeV for nearly massless LSP.
- **(c)** $m_{\tilde{t}_1}$ excluded up to 1050 GeV for nearly massless LSP.

$\widetilde{t}_2$-pair production:
same-sign dilepton/multilepton + jets final state
[hep-ex 2001.10086]

[137 $\mathbf{fb^{-1}}$]

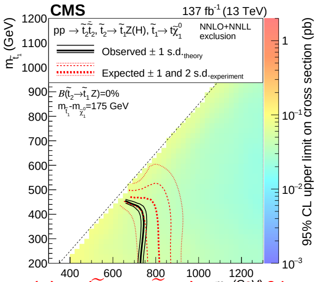


- $m_{\tilde{t}_1} - m_{\tilde{\chi}_1^0} = 175\,\text{GeV}\ (\approx m_t)$.
- **Signature contains two Higgs bosons, two Z bozons, or one of each.**
- Three different values of the branching fraction $\mathcal{B}(\tilde{t}_2 \to \tilde{t}_1 Z)$ are considered: 0%, 50%, and 100%.
- **More details on search strategy and bkg. estimation in Ashraf's talk.**

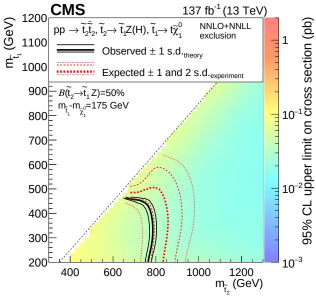
Results

- **No significant excess is observed.**

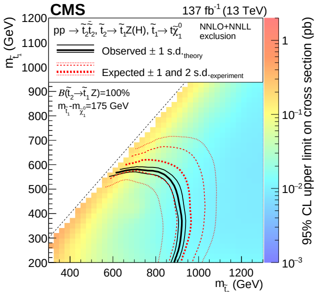
(a) $\mathcal{B}(\tilde{t}_2 \to \tilde{t}_1 H) = 100\%$



(b) $\mathcal{B}(\tilde{t}_2 \to \tilde{t}_1 Z) = 50\%$, $\mathcal{B}(\tilde{t}_2 \to \tilde{t}_1 H) = 50\%$



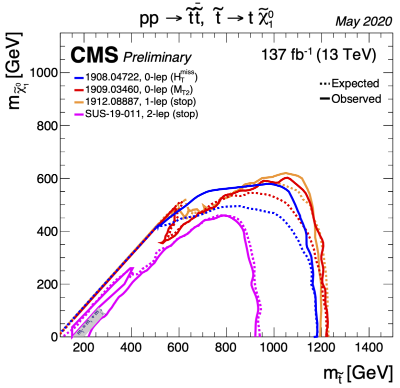
(c) $\mathcal{B}(\tilde{t}_2 \to \tilde{t}_1 Z) = 100\%$



- **(a)** $m_{\tilde{t}_2}$ excluded up to 700 GeV for $m_{\tilde{t}_1} = 200$ GeV.
- **(b)** $m_{\tilde{t}_2}$ excluded up to 750 GeV for $m_{\tilde{t}_1} = 200$ GeV.
- **(c)** $m_{\tilde{t}_2}$ excluded up to 900 GeV for $m_{\tilde{t}_1} = 200$ GeV.

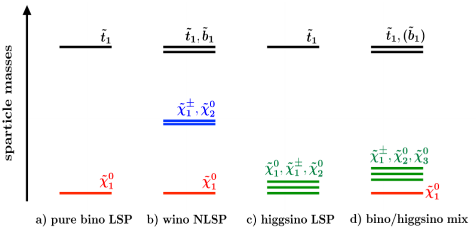
Summary

Summary



- The recent results of top squark searches at CMS have been presented.
- **Full Run-2** (137 fb^{-1}) of other searches **in the pipeline**.
- LHC now in LS-2, gearing for Run-3.
- **Stay tuned for more results!**

Typical benchmark scenarios



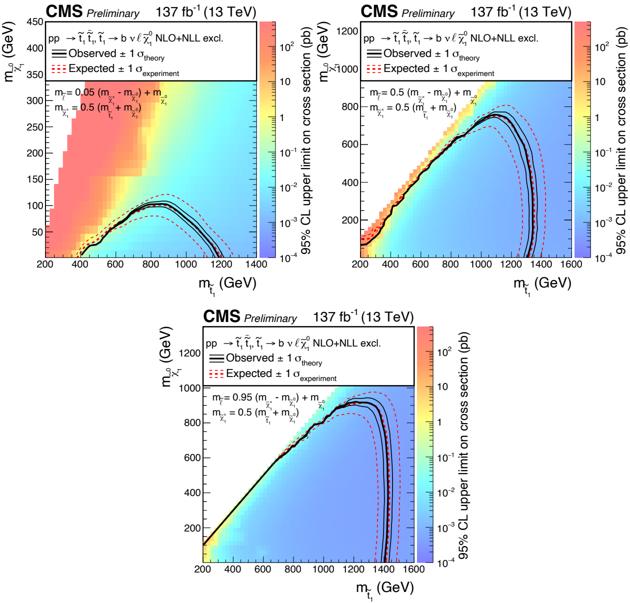
[image source]

- (a) **2001.10086** (SS dilepton/multilepton+jets, 137 fb^{-1}), **CMS-PAS-SUS-19-011** (dilepton, 137 fb^{-1}), **1912.08887** (one lepton+jets, 137 fb^{-1}), **1908.04722** (jets, 137 fb^{-1}), **1909.03460** (disappearing tracks, 137 fb^{-1}), **1901.06726** (*GMSMB*, photons+jets, 35.9 fb^{-1})
- (b) **CMS-PAS-SUS-19-011** (dilepton, 137 fb^{-1}), **1912.08887** (one lepton+jets, 137 fb^{-1}), **1909.03460** (disappearing tracks, 137 fb^{-1})
- (d) **1910.12932** (ditau, 77 fb^{-1})
- **Results from top-corridor and dedicated fully hadronic searches soon.**

Backup

Systematic uncertainty	typical (%)	max (%)	Systematic uncertainty	typical (%)	max (%)
Integrated luminosity	2	2	Pileup modeling	5	7
Jet energy scale	4	20	Jet energy resolution	3	4
btagging efficiency	2	3	btagging mistage rate	1	7
Trigger efficiency	1	2	Modeling of unclustered energy	3	7
$t\bar{t}$ normalisation	9	9	Fake/non-prompt leptons	5	5
$t\bar{t}Z$ normalisation	10	14	Non-gaussian jet mismeasurements	6	6
Multiboson background normalisation	4	8	Rare background normalisation	5	8
Drell-Yan normalisation	3	8	Parton distribution functions	2	4
Lepton identification efficiency	3	5	μ_R and μ_F choice	7	11

CMS-PAS-SUS-19-011: Limits



through a technique called domain adaption via gradient reversal [88]. With this method, an additional output is added to the neural network to distinguishing between trijet candidates from QCD simulation and a QCD-enriched data sample. The main network is then restricted to minimize its ability to discriminate simulation from data. This yields a network with good separation between signal and background while minimizing over-fitting on features that exist only in simulation. Before the final selection of trijets as top quarks can be made, any trijet candidates that may share the jets with another candidate must be removed. This is achieved by always favoring the candidate with a higher top discriminator value as determined by the neural network. The reconstructed candidates are identified as hadronic tops when the neural network discriminator is above the threshold corresponding to an efficiency of 45% and the mistagging rate is 10% for dileptonic $\mathrm{t\bar{t}}$ events.

The second DNN, referred to as a merged tagger, uses the DeepAK8 [89] algorithm to identify top quarks with large boost, where the decay products are merged into a single jet (merged top quark decay). The identification of this boosted top quark signature is based on anti-k_{T} jets clustered with a distance parameter of 0.8. The efficiency for lepton + hadronic-top events is 40% and the mistagging rate is 5% for dileptonic $\mathrm{t\bar{t}}$ events.

4.2 Search strategy

The signal regions for the standard search are summarized in Table 2, and are defined by categorizing events passing the preselection requirements based on N_{j}, the number of identified hadronic top quarks, $p_{\mathrm{T}}^{\text{miss}}$, the invariant mass ($M_{\ell\mathrm{b}}$) of the lepton and the closest b-tagged jet in ΔR, and a modified version of the topness variable [90], t_{mod} [27], which is defined as:

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

with resolution parameters $a_{\mathrm{W}} = 5\,\text{GeV}$ and $a_{\mathrm{t}} = 15\,\text{GeV}$. The t_{mod} variable is a χ^2-like variable that discriminates signal from leptonically decaying $\mathrm{t\bar{t}}$ events: an event with a small value of t_{mod} is likely to be a dilepton $\mathrm{t\bar{t}}$ event, while signal events tend to have larger t_{mod} values. The first term in its definition corresponds to the top quark decay containing the reconstructed lepton, and the second term corresponds to the top quark decay containing the missing lepton. The p_{W} in the second term symbolizes the momentum of the missing lepton and neutrino from the W decay. The minimization of the variable S is done with respect to all components of the three momentum $\vec{p}_{\mathrm{W}}$ and the component of the three momentum $\vec{p}_\nu$ along the beam line with the constraints that $\vec{p}_{\mathrm{T}}^{\text{miss}} = \vec{p}_{\mathrm{T,W}} + \vec{p}_{\mathrm{T},\nu}$ and $p_{\mathrm{W}}^2 = m_{\mathrm{W}}^2$. The distribution of t_{mod} for events passing the preselection is shown in Fig. 3 (upper left). The t_{mod} distribution is split into three bins, each sensitive to a different mass splitting of the top squark and neutralino.

In events containing a leptonically decaying top quark, the invariant mass of the lepton and the bottom quark jet from the same top quark decay is bound by

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

This bound does not apply to either W + jets events or signal events, where the top squark decays to a bottom quark and a chargino. To maintain acceptance to a broad range of signal scenarios, rather than requiring a selection on $M_{\ell\mathrm{b}}$, events are placed into low- or high-$M_{\ell\mathrm{b}}$ categories if the value of $M_{\ell\mathrm{b}}$ is less or greater than 175 GeV, respectively. In signal regions

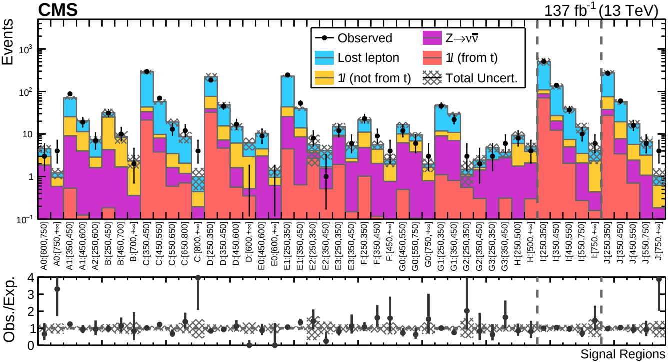
1912.08887 (SUS-19-009): SR binning

Label	N_j	t_{mod}	$M_{\ell b}$ [GeV]	ttagging category	p_T^{miss} bins [GeV]
A0				—	[600, 750, +∞]
A1	2–3	>10	≤175	U	[350, 450, 600]
A2				M	[250, 600]
B	2–3	>10	>175	—	[250, 450, 700, +∞]
C	≥4	≤0	≤175	—	[350, 450, 550, 650, 800, +∞]
D	≥4	≤0	>175	—	[250, 350, 450, 600, +∞]
E0				—	[450, 600, +∞]
E1	≥4	0–10	≤175	U	[250, 350, 450]
E2				M	[250, 350, 450]
E3				R	[250, 350, 450]
F	≥4	0–10	>175	—	[250, 350, 450, +∞]
G0				—	[450, 550, 750, +∞]
G1	≥4	>10	≤175	U	[250, 350, 450]
G2				M	[250, 350, 450]
G3				R	[250, 350, 450]
H	≥4	>10	>175	—	[250, 500, +∞]

1912.08887 (SUS-19-009): SR binning (compressed)

Compressed spectra with $\Delta m\left(\widetilde{t},\widetilde{\chi}^0_1\right) \sim m_t$		
Label I	Selection criteria	$N_j \geq 5$, leading-p_T jet not b-tagged, $N_{b,\,med} \geq 1$, $p^{\ell}_T < \max\left(50,\ 250 - 100 \times \Delta\phi(\vec{p}^{\,miss}_T, \vec{p}^{\,\ell}_T)\right)$ GeV,
	p^{miss}_T bins [GeV]	[250, 350, 450, 550, 750, $+\infty$]
Compressed spectra with $\Delta m\left(\widetilde{t},\widetilde{\chi}^0_1\right) \sim m_W$		
Label J	Selection criteria	$N_j \geq 3$, leading-p_T jet not b-tagged, $N_{b,\,soft} \geq 1$, $p^{\ell}_T < \max\left(50,\ 250 - 100 \times \Delta\phi(\vec{p}^{\,miss}_T, \vec{p}^{\,\ell}_T)\right)$ GeV,
	p^{miss}_T bins [GeV]	[250, 350, 450, 550, 750, $+\infty$]

Source	Signal	Lost lepton	1ℓ (not from t)	$Z \to \nu\bar{\nu}$
Data statistical uncertainty	—	5–50%	4–30%	—
Simulation statistical uncertainty	6–36%	3–68%	5–70%	4–41%
$t\bar{t}$ p_T^{miss} modeling	—	3–50%	—	—
Signal p_T^{miss} modeling	1–25%	—	—	—
QCD scales	1–5%	0–3%	2–5%	1–40%
Parton distribution	—	0–4%	1–8%	1–12%
Pileup	1–5%	1–8%	0–5%	0–7%
Luminosity	2.3–2.5%	—	—	2.3–2.5%
$W + b(\bar{b})$ cross section	—	—	20–40%	—
$t\bar{t}Z$ cross section	—	—	—	5–10%
System recoil (ISR)	1–13%	0–3%	—	—
Jet energy scale	2–24%	1–16%	1–34%	1–28%
p_T^{miss} resolution	—	1–10%	1–5%	—
Trigger	2–3%	1–3%	—	2–3%
Lepton efficiency	3–4%	2–12%	—	1–2%
Merged t tagging efficiency	3–6%	—	—	5–10%
Resolved t tagging efficiency	5–6%	—	—	3–5%
b tagging efficiency	0–2%	0–1%	1–7%	1–10%
Soft b tagging efficiency	2–3%	0–1%	0–1%	0–5%



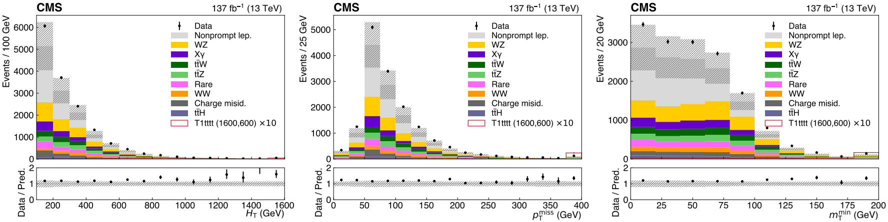
	N_J	t_{mod}	M_{lb} [GeV]
A	2–3	> 10	≤ 175
B	2–3	> 10	> 175
C	≥ 4	≤ 0	≤ 175
D	≥ 4	≤ 0	> 175
E	≥ 4	0–10	≤ 175
F	≥ 4	0–10	> 175
G	≥ 4	> 10	≤ 175
H	≥ 4	> 10	> 175

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: $N_J \geq 3$, $N_{b,soft} \geq 1$

2001.10086 (SUS-19-008): search strategy

- **Dilepton triggers.**
- At least two **(same-sign)** leptons (e/μ).
- At least two jets.
- Reject events with $m_{\ell\ell} < 12\,\text{GeV}$ (same flavor).
  Reject events with $m_{\ell\ell} < 8\,\text{GeV}$ (any charge/flavor).
- The search covers leptons with both high (H, $p_{\mathrm{T}} > 25\,\text{GeV}$) and low (L, $p_{\mathrm{T}} < 25\,\text{GeV}$).
  This improves sensitivity in the compressed region where the leptons are soft.
  1. HH, HL, LL: Exactly two leptons, $p_{\mathrm{T}}^{\text{miss}} > 50\,\text{GeV}$.
  2. LM (low $p_{\mathrm{T}}^{\text{miss}}$): Exactly two leptons, $p_{\mathrm{T}}^{\text{miss}} < 50\,\text{GeV}$.
  3. ML (multilepton): ≥ 3 leptons, $p_{\mathrm{T}}^{\text{miss}} < 50\,\text{GeV}$.
- Each of these categories is **subdivided** in terms of N_j, N_b, H_{T}, SS pair sign, $p_{\mathrm{T}}^{\text{miss}}$, and $m_{\mathrm{T}}^{\text{min}}$.



- Events with two or more **prompt leptons**, including an SS pair.
  Estimated from simulation (with various correction factor applied).

- Events with at least one **nonprompt lepton**.
  Estimated by evaluating the rate of nonprompt leptons being identified as prompt, in data ("tight-to-loose").

- Events with a pair of opposite-sign leptons, one of which is **reconstructed with the wrong charge**.
  The electron charge mis-ID rate is parameterized as a function of the lepton p_{T} and η (10^{-5} to 5×10^{-3}); negligible for muons.

Source	Typical uncertainty (%)	Correlation across years
Integrated luminosity	2.3–2.5	Uncorrelated
Lepton selection	2–10	Uncorrelated
Trigger efficiency	2–7	Uncorrelated
Pileup	0–6	Uncorrelated
Jet energy scale	1–15	Uncorrelated
b tagging	1–10	Uncorrelated
Simulated sample size	1–20	Uncorrelated
Scale and PDF variations	10–20	Correlated
Theoretical background cross sections	30–50	Correlated
Nonprompt leptons	30	Correlated
Charge misidentification	20	Uncorrelated
N_J^{ISR}	1–30	Uncorrelated