Searches for supersymmetry in hadronic final states with the CMS experiment

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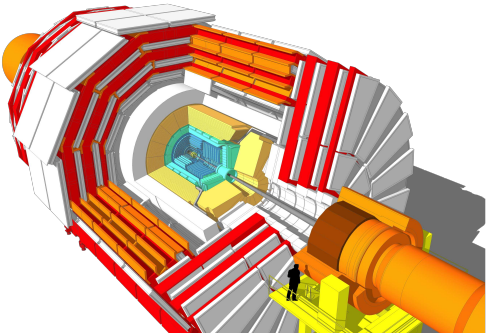
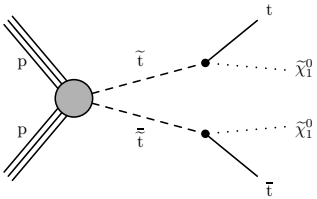
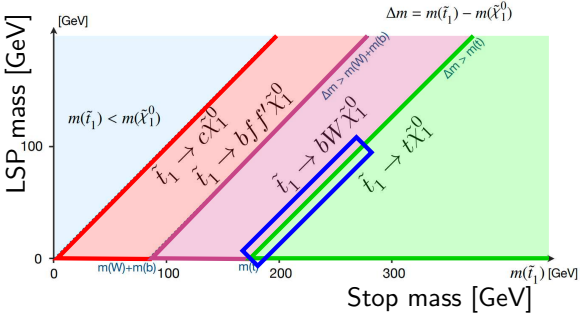
- SUSY has many variations and final states
- Low mass stop, charginos, or neutralinos well motivated
- Decay cascades often have top, W, Z, H
- Large branching ratios to jets
- Hadronic final states have good statistics
  - Backgrounds challenging, but surmountable
- Complementary to lepton final states, small backgrounds but small rates
- Focus today on Run 2 searches in hadronic final states for:
  - Stop squarks
  - Charginos or neutralinos
  - Higgsinos

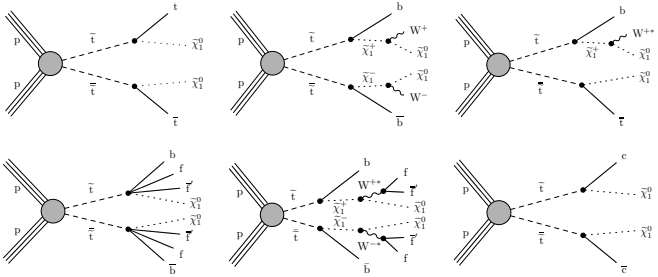


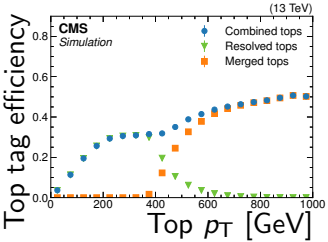


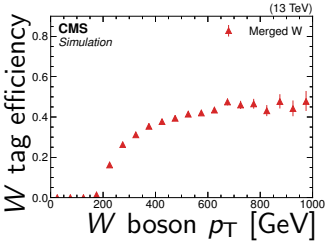


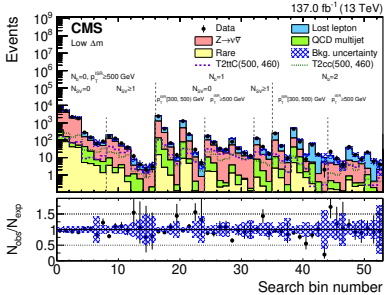
- Many models of stop production
- With R-parity conserved, LSP is stable, stop decays to LSP + SM particles
- LSP invisible in CMS—missing p_T
- Final state determined by Δm (mass difference between stop and LSP)
- For the model shown on the left:
  - Top + LSP when $\Delta m > m(t)$
  - Wb + LSP when $\Delta m > m(W) + m(b)$
  - Compressed region when $\Delta m < m(W) + m(b)$—many final states
  - Top corridor at $\Delta m \sim m(\text{top})$: signal very similar to SM
- Generally missing p_T, lots of jets
  - How much missing p_T depends on Δm

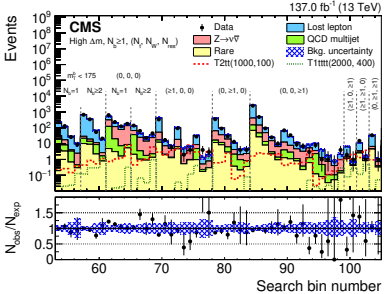
- Search for R-parity conserving stops in missing p_T + jets
- Many improvements over previous searches
- Require zero charged leptons, many jets, large missing p_T
- Cover all Δm except top corridor
- Many final states have multiple tops, W bosons, b jets
- Deep NN top, W taggers give sensitivity to different models
  - Resolved+merged top taggers cover wide range of top p_T
- Also use combination of low-p_T and high-p_T b taggers





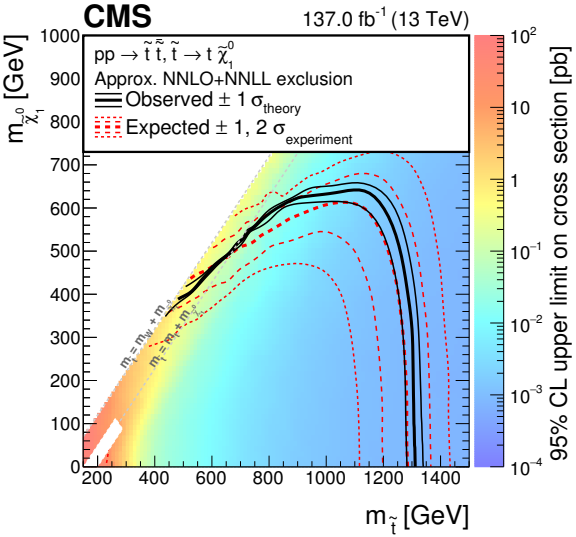




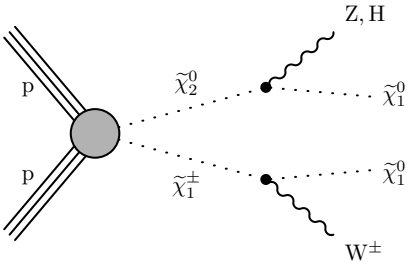


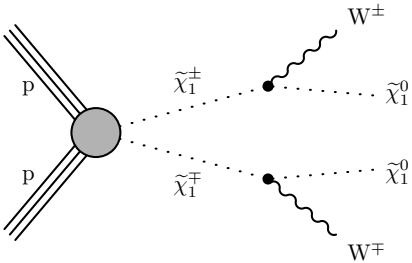
- Major backgrounds, data-driven methods:
  - "Lost lepton": SM backgrounds like $t\bar{t}$, $W+$jets that produce a lepton but it is not reconstructed
  - $Z+$jets with $Z \to \nu\bar{\nu}$
  - QCD multijet
- For each major background, define a control region enriched in that background, depleted of signal
- Use Monte Carlo to extrapolate control region data to search region
- Many search bins, based on number of tagged objects (b, t, W), number of jets, H_T, missing p_T, and others
- Some search bins more sensitive to low Δm models (upper plot), others to high Δm (lower plot)
- Only about half the 183 search bins shown here
- No excess of data above the SM prediction

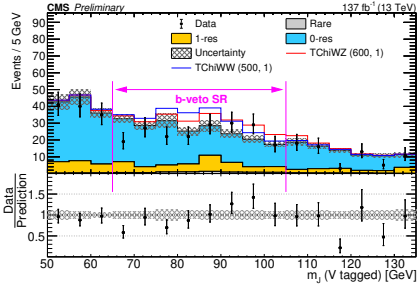
- Set limits on signal cross sections as function of sparticle masses
  - Top corridor not considered
- Only one model shown here, for high Δm
- Exclude parameter space where experimental cross section limit smaller than theoretical cross section
- Stop masses up to 1310 GeV excluded, depending on LSP mass
- Improvement over previous analyses ($\sim 200\,\mathrm{GeV}$ extension of excluded region) comes from
  - Additional data
  - Use of top and W taggers
  - Re-optimized search bins

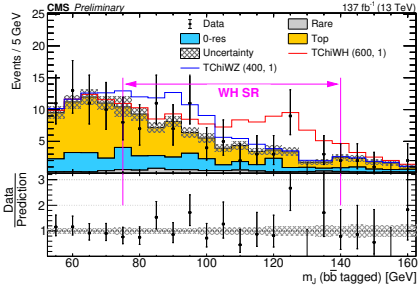


- Even if squarks too massive, still expect charginos/neutralinos at ~ 1 TeV
- Search for chargino-neutralino or chargino pair
- Assume:
  - R-parity conserved
  - LSP is lightest neutralino, bino-like
  - Lightest chargino is NLSP and is wino-like
  - In chargino-neutralino production, second lightest neutralino is mass-degenerate with lightest chargino and is wino-like
- Decay to WW, WZ, or WH plus two LSPs
- Hadronic decay of W, Z, H
- Lots of jets and missing p_T
- Try to identify boson decays using NNs



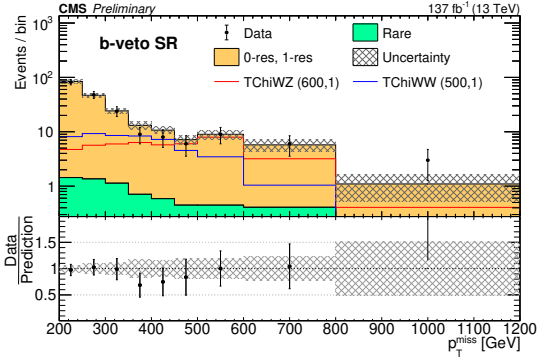


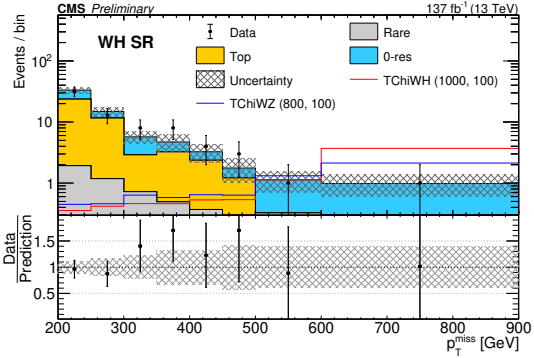




- Select events with missing p_T, at least two large-radius jets ("AK8"), and 2–6 normal-radius jets ("AK4")
- Intend to capture decay products of bosons in one AK8 jet each
- Employ three taggers for AK8 jets:
  - W tagger targets W decays
  - V tagger (upper figure) targets Z or W decays
  - $b\bar{b}$ tagger (lower figure) targets H or $Z \to b\bar{b}$
- Also use AK4 jet b tagger
- Many possible combinations of taggers
- Some used as search regions, others as control or validation regions
- Highest-level division based on AK4 b tagger

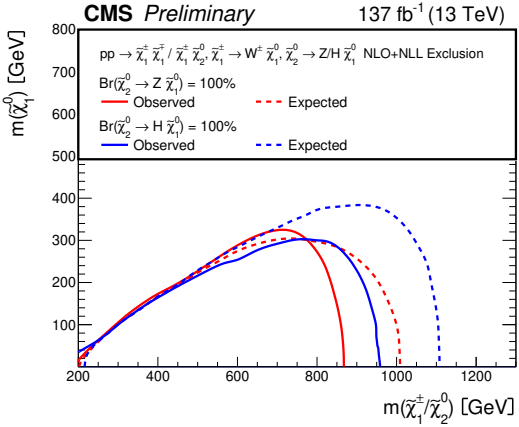
- b veto region requires zero AK4 b tags
- Sensitive to WW and WZ, but not WH
- Use W tagger and V tagger to define search region
- Backgrounds are events with zero or only one boson, called "0-res" and "1-res", plus rare events (e.g. triboson)
- 0-res and 1-res background estimates derived from control regions
- Control regions defined by vetoing W and V tags in various combinations
- Search region binned in missing p_T
- No excess in data above expected backgrounds



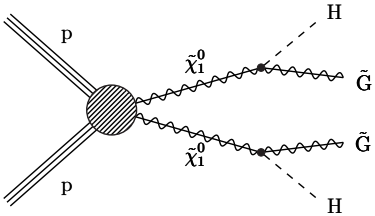


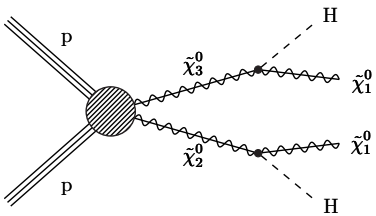
- b tag search region requires at least one AK4 b tag
- Sensitive to WH and to WZ
- Use W tagger and $b\bar{b}$ tagger to define search regions
- Background from top production becomes important here
- Use tagger veto to define control regions, and also use events with one charged lepton for more control regions
- Lepton control regions constrain top backgrounds, tag-veto control regions constrain 0-res backgrounds

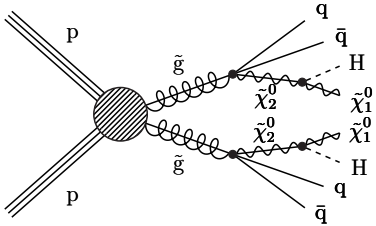
- No excess observed above expected SM backgrounds
- Establish 95% CL limits on all considered models as functions of LSP and NLSP masses
- Showing limits combining chargino pair and chargino-neutralino production, assuming NLSP neutralino decays to Z or to H
- For very light LSP, NLSP masses up to 870 (960) GeV are excluded for the Z (H) case



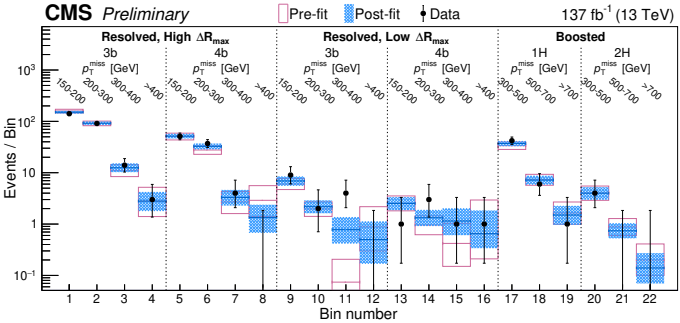
HH + MET: CMS-PAS-SUS-20-004







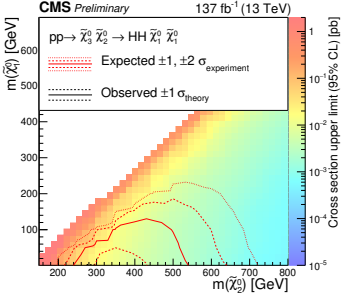
- Search for higgsino pair production
- Two Higgs bosons decaying to $b\bar{b}$, plus missing p_T
- Divide search according to H boson p_T
  - low p_T: resolved b jets (AK4 b jets)
  - high p_T: merged $b\bar{b}$ AK8 jet
- H boson p_T determined by mass splitting between higgsino and daughter sparticle (Goldstino or lightest neutralino)
- Select events with missing p_T, zero charged leptons and jets:
  - low p_T: 4 or 5 AK4 jets
  - high p_T: 2 AK8 jets
- Apply b-tagging algorithms to AK4 and AK8 jets
- Attempt to reconstruct two H boson candidates

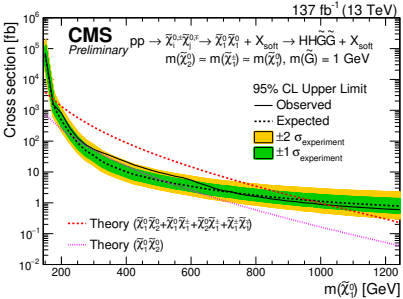


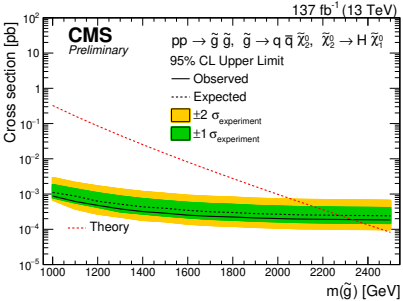
- Split events according to H boson p_T, missing p_T, number of reconstructed candidates, and (for low p_T case) largest dijet separation
- Estimate backgrounds using control regions and simulation
- Low p_T backgrounds dominated by top pair production
- High p_T backgrounds dominated by QCD and top
- No more than modest excess in one or two bins

HH + MET: CMS-PAS-SUS-20-004

- Set 95% CL limits
- For electroweak production (left), no exclusion possible
- For gauge-mediated model (upper right), higgsino masses between 175 and 1025 GeV excluded
- For strong production of gluino pairs (lower right), exclude higgsino masses below 2330 GeV
- Strongest constraints on higgsino production from CMS to date





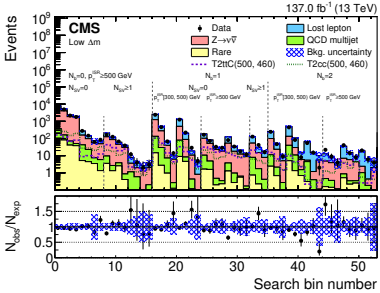


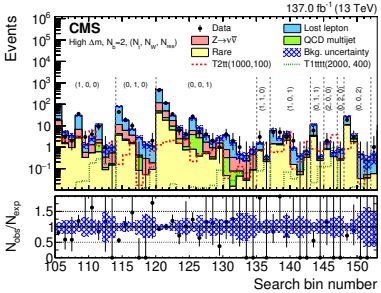
Summary

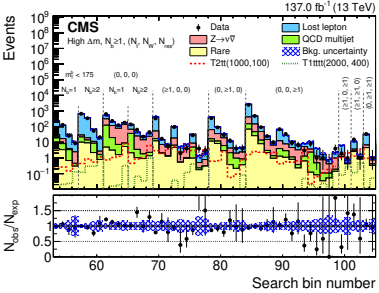
- Hadronic stop search extends stop exclusion by $\sim 200\,\mathrm{GeV}$
- Chargino/neutralino search most sensitive to date for boosted phase space, uses deep NN taggers
- Higgsino pair search combines resolved and boosted phase spaces, obtains strong constraints on gauge-mediated models and gluino production models
- Hadronic final states are a critical part of the hunt for SUSY

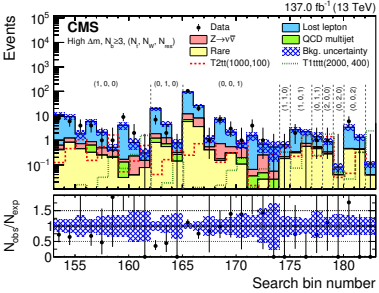
References

- stop mass vs LSP mass figure taken from arXiv:1407.0583
- All-hadronic stop search: PRD 104 052001 (2021)
- WW, WZ, WH: CMS-PAS-SUS-21-002
- Di-Higgs plus MET: CMS-PAS-SUS-20-004


137.0 fb^{-1} (13 TeV)
CMS
Low Δm
Data
Z→νν̄
Rare
T2tt(500, 460)
Lost lepton
QCD multijet
Bkg. uncertainty
T2cc(500, 460)
Events
N_{obs}/N_{exp}
Search bin number


137.0 fb^{-1} (13 TeV)
CMS
High Δm, N_e=2, (N_j, N_b, N_{res})
Data
Z→νν̄
Rare
T2tt(1000,100)
Lost lepton
QCD multijet
Bkg. uncertainty
T1ttt(2000, 400)
Events
N_{obs}/N_{exp}
Search bin number


137.0 fb^{-1} (13 TeV)
CMS
High Δm, N_e≥1, (N_j, N_b, N_{res})
Data
Z→νν̄
Rare
T2tt(1000,100)
Lost lepton
QCD multijet
Bkg. uncertainty
T1tttt(2000, 400)
Events
N_{obs}/N_{exp}
Search bin number


137.0 fb^{-1} (13 TeV)
CMS
High Δm, N_e≥3, (N_j, N_b, N_{res})
Data
Z→νν̄
Rare
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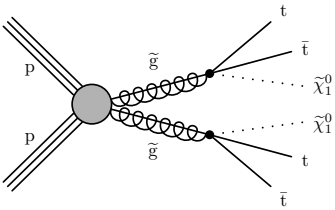
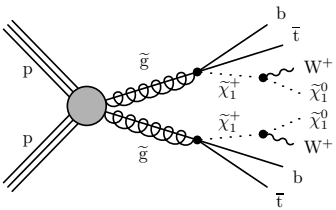
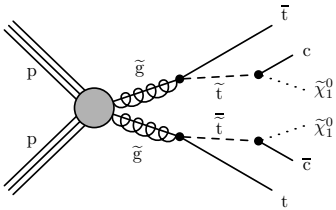
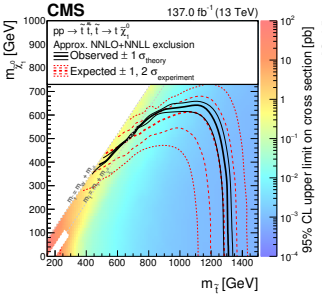
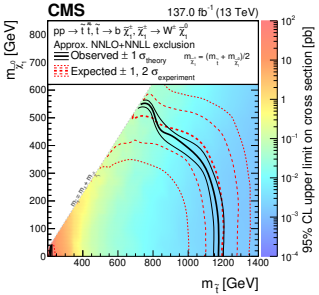
Lost lepton
QCD multijet
Bkg. uncertainty
T1tttt(2000, 400)
Events
N_{obs}/N_{exp}
Search bin number

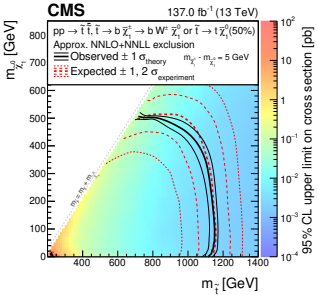

p
p
$\tilde{g}$
$\tilde{g}$
t
$\bar{t}$
$\tilde{\chi}_1^0$
$\tilde{\chi}_1^0$
t
$\bar{t}$

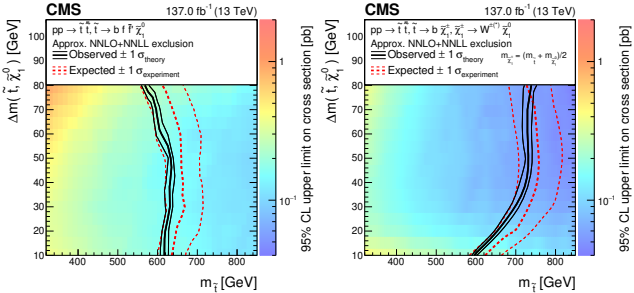

p
p
$\tilde{g}$
$\tilde{g}$
b
$\bar{t}$
W^+
$\tilde{\chi}_1^+$
$\tilde{\chi}_1^0$
$\tilde{\chi}_1^+$
$\tilde{\chi}_1^0$
W^+
b
$\bar{t}$

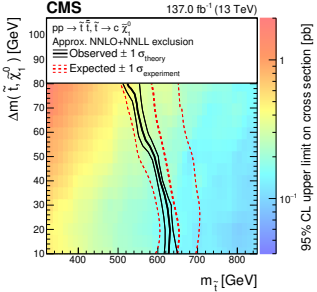

p
p
$\tilde{g}$
$\tilde{g}$
$\bar{t}$
c
$\tilde{t}$
$\tilde{\chi}_1^0$
$\bar{\tilde{t}}$
$\tilde{\chi}_1^0$
$\bar{c}$
t

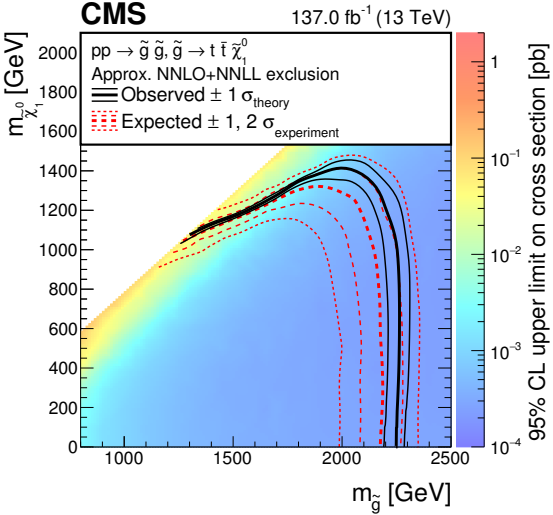

CMS
137.0 fb^{-1} (13 TeV)
pp → t t̄, t̄ → t $\tilde{\chi}_1^0$
Approx. NNLO+NNLL exclusion
Observed ± 1 σ_{theory}
Expected ± 1, 2 $\sigma_{experiment}$
$m_{\tilde{\chi}_1^0}$ [GeV]
$m_{\tilde{t}}$ [GeV]
95% CL upper limit on cross section [pb]

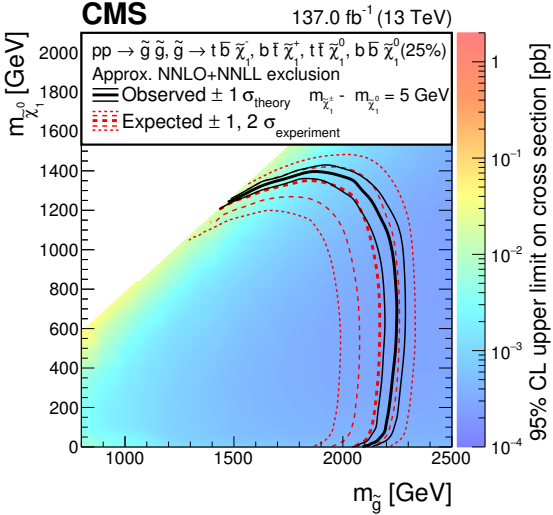

CMS
137.0 fb^{-1} (13 TeV)
pp → t t̄, t̄ → b $\tilde{\chi}_1^\pm$, $\tilde{\chi}_1^\pm$ → W$^\pm$ $\tilde{\chi}_1^0$
Approx. NNLO+NNLL exclusion
Observed ± 1 σ_{theory}
$m_{\tilde{\chi}_1^\pm} = (m_{\tilde{t}} + m_{\tilde{\chi}_1^0})/2$
Expected ± 1, 2 $\sigma_{experiment}$
$m_{\tilde{\chi}_1^0}$ [GeV]
$m_{\tilde{t}}$ [GeV]
95% CL upper limit on cross section [pb]

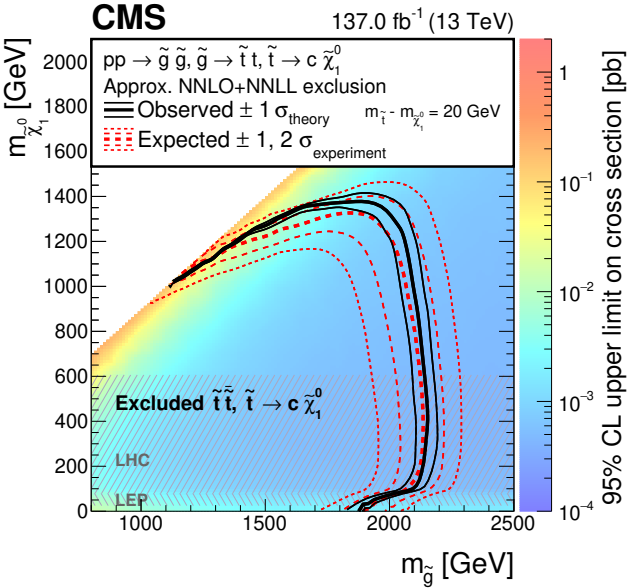

CMS
137.0 fb^{-1} (13 TeV)
pp → t̄ t, t̄ → b $\tilde{\chi}_1^\pm$ → b W$^\pm$ $\tilde{\chi}_1^0$ or t̄ → t $\tilde{\chi}_1^0$(50%)
Approx. NNLO+NNLL exclusion
Observed ± 1 σ_{theory}
$m_{\tilde{\chi}_1^\pm} - m_{\tilde{\chi}_1^0} = 5$ GeV
Expected ± 1, 2 $\sigma_{experiment}$
$m_{\tilde{\chi}_1^0}$ [GeV]
$m_{\tilde{t}}$ [GeV]
95% CL upper limit on cross section [pb]


CMS
137.0 fb^{-1} (13 TeV)
pp → t̃ t̃, t̃ → b f f̄ $\tilde{\chi}_1^0$
Approx. NNLO+NNLL exclusion
Observed ± 1 σ_{theory}
Expected ± 1 $\sigma_{experiment}$
$\Delta m(\tilde{t}, \tilde{\chi}_1^0)$ [GeV]
$m_{\tilde{t}}$ [GeV]
95% CL upper limit on cross section [pb]
CMS
137.0 fb^{-1} (13 TeV)
pp → t̃ t̃, t̃ → b $\tilde{\chi}_1^\pm$, $\tilde{\chi}_1^\pm$ → W$^{(*)}$ $\tilde{\chi}_1^0$
Approx. NNLO+NNLL exclusion
Observed ± 1 σ_{theory}
$m_{\tilde{\chi}_1^\pm} = (m_{\tilde{t}} + m_{\tilde{\chi}_1^0})/2$
Expected ± 1 $\sigma_{experiment}$
$\Delta m(\tilde{t}, \tilde{\chi}_1^0)$ [GeV]
$m_{\tilde{t}}$ [GeV]
95% CL upper limit on cross section [pb]


CMS
137.0 fb^{-1} (13 TeV)
pp → t̃ t̃, t̃ → c $\tilde{\chi}_1^0$
Approx. NNLO+NNLL exclusion
Observed ± 1 σ_{theory}
Expected ± 1 $\sigma_{experiment}$
$\Delta m(\tilde{t}, \tilde{\chi}_1^0)$ [GeV]
$m_{\tilde{t}}$ [GeV]
95% CL upper limit on cross section [pb]


CMS
137.0 fb^{-1} (13 TeV)
pp → g̃ g̃, g̃ → t t̄ χ̃$^0_1$
Approx. NNLO+NNLL exclusion
Observed ± 1 σ$_{theory}$
Expected ± 1, 2 σ$_{experiment}$
m$_{\tilde{\chi}^0_1}$ [GeV]
m$_{\tilde{g}}$ [GeV]
95% CL upper limit on cross section [pb]


CMS
137.0 fb^{-1} (13 TeV)
pp → g̃ g̃, g̃ → t b̄ χ̃$^-_1$, b t̄ χ̃$^+_1$, t t̄ χ̃$^0_1$, b b̄ χ̃$^0_1$(25%)
Approx. NNLO+NNLL exclusion
Observed ± 1 σ$_{theory}$
m$_{\tilde{\chi}^\pm_1}$ - m$_{\tilde{\chi}^0_1}$ = 5 GeV
Expected ± 1, 2 σ$_{experiment}$
m$_{\tilde{\chi}^0_1}$ [GeV]
m$_{\tilde{g}}$ [GeV]
95% CL upper limit on cross section [pb]


CMS
137.0 fb-1 (13 TeV)
pp → g̃ g̃, g̃ → t̃ t, t̃ → c χ̃01
Approx. NNLO+NNLL exclusion
Observed ± 1 σtheory
Expected ± 1, 2 σexperiment
mt̃ - mχ̃01 = 20 GeV
Excluded t̃t̃, t̃ → c χ̃01
LHC
LEP
mχ̃01 [GeV]
mg̃ [GeV]
95% CL upper limit on cross section [pb]