Searches for third generation SUSY particles with the CMS experiment

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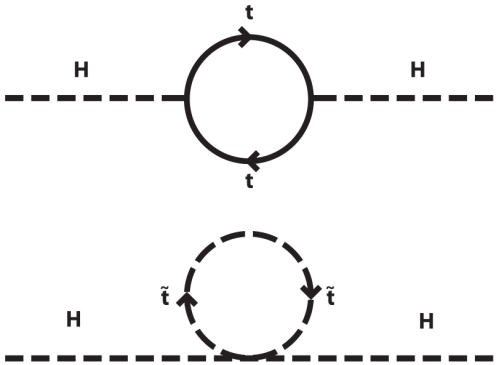
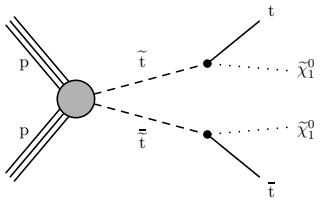
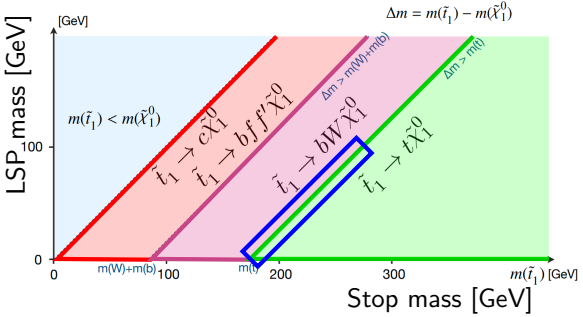
- Third generation SUSY partners: stop, sbottom, stau, tau sneutrino
- Focus on stop today
- Stop quark could help solve hierarchy problem
- Top quark loop makes quadratic correction to Higgs mass
- Cancelled by stop loop, if stop mass close to top mass
- Low mass stops well-motivated and accessible at LHC

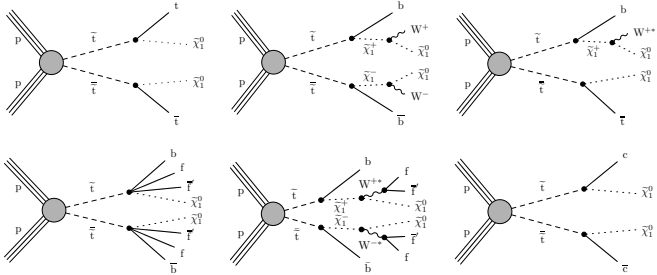


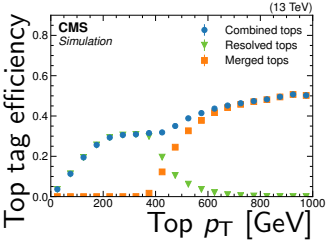


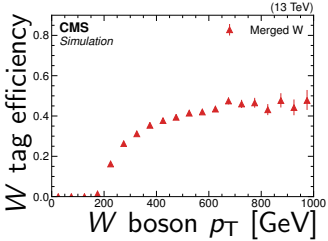


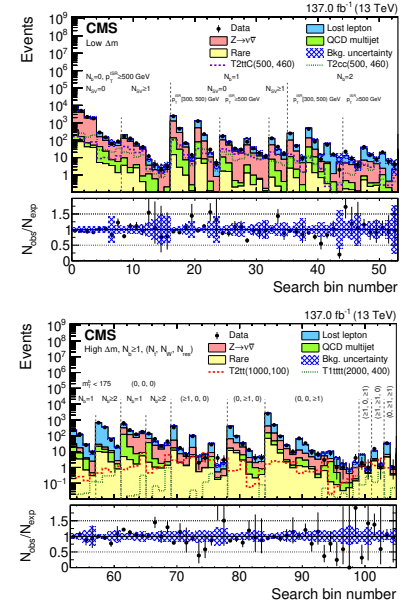
- Many models of stop production
- With R-parity conserved, LSP is stable, stop decays to LSP + SM particles
- LSP invisible in CMS—missing p_T
- Final state determined by Δm (mass difference between stop and LSP)
- For the model shown on the left:
  - Top + LSP when $\Delta m > m(t)$
  - Wb + LSP when $\Delta m > m(W) + m(b)$
  - 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, sometimes one or a few charged leptons
  - 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



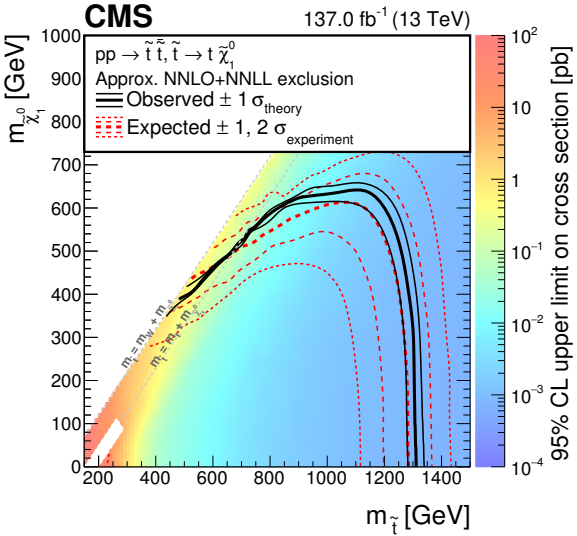


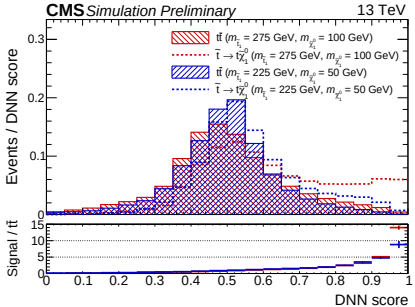


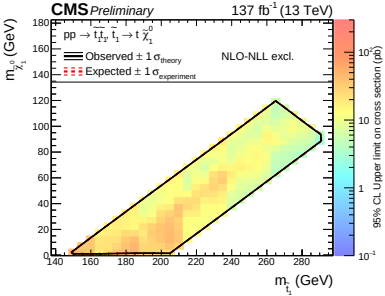


- Major backgrounds, data-driven methods:
  - "Lost lepton": SM backgrounds like $t\bar{t}$, W + jets that produce a lepton but it is not reconstructed
  - Z + jets with $Z \to \nu\bar{\nu}$
  - QCD multijet
- For each major background, define a control region enriched in that background, depleted of 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 larger than theoretical cross section
- Stop masses up to 1310 GeV excluded, depending on LSP mass
- Improvement over previous analyses ($\sim$ 200 GeV extension of excluded region) comes from
  - Additional data
  - Use of top and W taggers
  - Re-optimized search bins

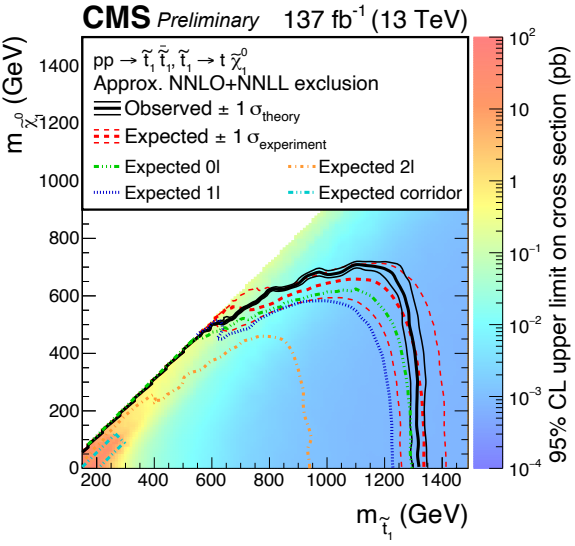


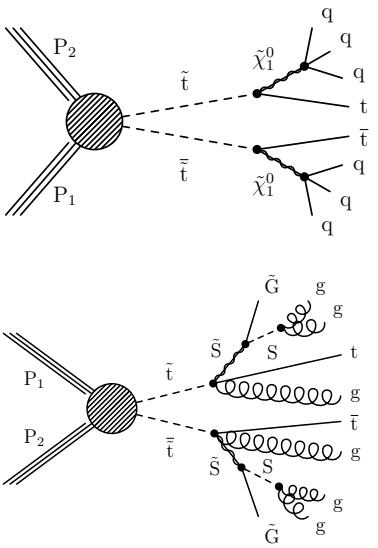




- Dedicated top corridor study
- Signal models depend sensitively on sparticle masses in top corridor
- Require two opposite-charge leptons, at least two jets, missing $p_{\mathrm{T}} > 50\,\mathrm{GeV}$, and additional cuts to suppress $t\bar{t}$ background
- Backgrounds estimated from Monte Carlo
- Train parametric deep neural network to discriminate signals from background
- NN depends on assumed sparticle masses to maximize sensitivity throughout top corridor
- Entire top corridor region excluded by dedicated analysis

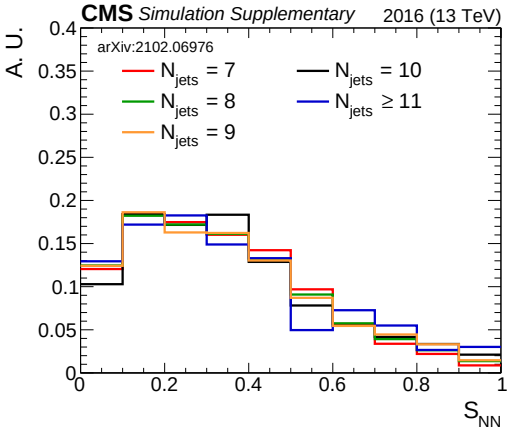
- Combine CMS stop searches including:
  - All-hadronic search, arXiv:2103.01290
  - One-lepton search, JHEP 05 (2020) 032
  - Two-lepton search, EPJ C 81, 3 (2021)
  - Corridor study, CMS-PAS-SUS-20-002
- Coordination among analyses to avoid overlap among search or control regions
- Each analysis important in different parameter spaces, e.g.:
  - All-hadronic dominates large Δm
  - One-lepton and resolved taggers important at small Δm
- Stop masses up to 1325 GeV excluded, depending on LSP mass
- First CMS exclusion of top corridor region

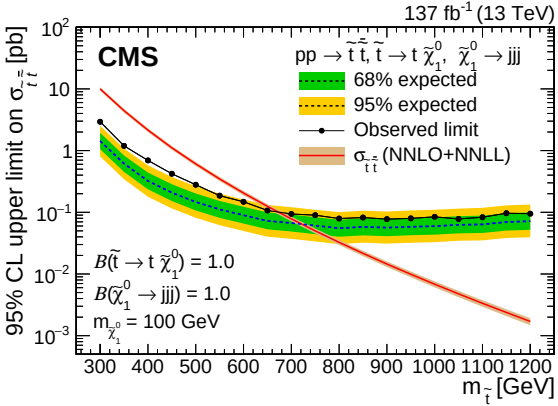




- If R-parity not conserved, LSP not stable, and final state may have no missing p_T
- Similarly, "stealth" models with hidden sectors have small mass splitting and little to no missing p_T
- Common final state: two top quarks, lots of jets, little or no missing p_T
- Need novel technique for stop search without missing p_T
- Important feature is high jet multiplicity

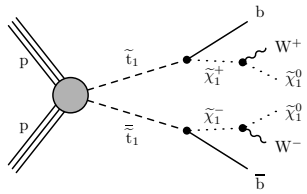
- Require at least seven jets, exactly one charged lepton
- Train neural network to discriminate signal from $t\bar{t}$ + jets background
- Use gradient reversal to make NN output independent of number of jets
- Look at NN score vs. number of jets
- Signal would appear in data as change in shape of NN output as number of jets increases
- Model $t\bar{t}$ + jets background with functional form based on QCD prediction of jet scaling
  - Enabled by NN independence from jet multiplicity

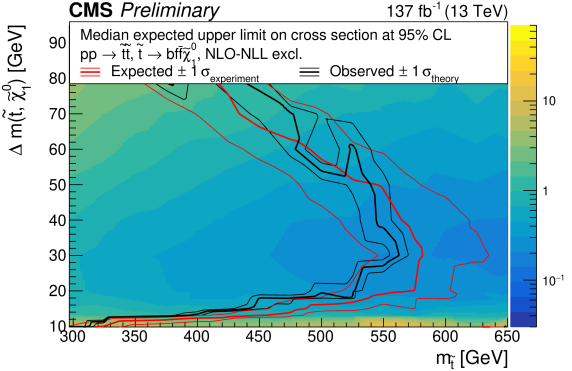




- Set limits for R-parity violating and stealth models (RPV shown here)
- Exclude stop masses up to 670 (870) GeV for RPV (stealth) model
- Modest excess seen in excluded region
- Local significance less than 3σ everywhere
- With look-elsewhere effect, global significance even smaller
- Novel techniques provide sensitivity to previously inaccessible scenarios

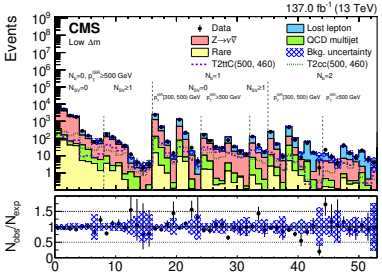
- Primarily an electroweakino search in compressed scenario
- Also interpret as search for stops with in compressed region
- Same models and parameter space also constrained by all-hadronic stop search described previously
- Require two or three charged leptons with low p_T: $5 < p_T < 30\,\text{GeV}$
- Also require missing $p_T > 125\,\text{GeV}$
- Exclude stop masses up to 550 GeV, depending on the model and on Δm

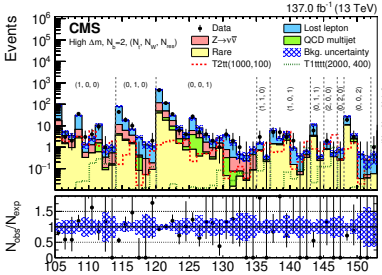


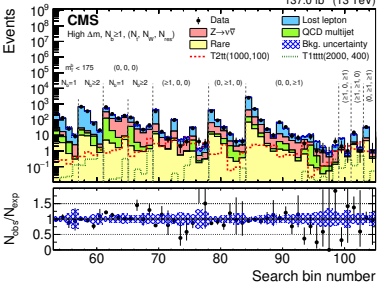


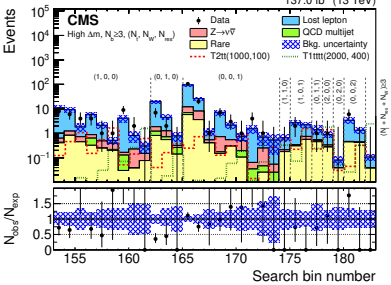
- LHC Run 2 stop searches extend stop exclusion by $\sim 200\,\text{GeV}$
- Cover top corridor region with dedicated study for first time
- CMS combination excludes stop masses up to 1325 GeV
- Novel techniques provide sensitivity to R-parity violating and stealth scenarios
- Soft lepton study interpreted as stop search in compressed region
- Other third-generation sparticles also searched for at CMS:
  - Sbottom masses up to 1600 GeV excluded by inclusive searches
  - Run 2 stau searches are in the pipeline

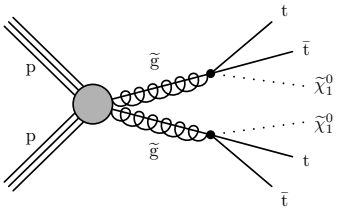
- Diagram of Higgs mass loop cancellation by VermillionBird - Own work, CC BY 3.0, https://commons.wikimedia.org/w/index.php?curid=3429162
- stop mass vs LSP mass from arXiv:1407.0583
- All-hadronic stop search: arXiv:2103.01290
- One-lepton stop search: JHEP 05 (2020) 032
- Two-lepton stop search: EPJ C 81, 3 (2021)
- Corridor study and combination: CMS-PAS-SUS-20-002
- Stealth stop search: arXiv:2102.06976
- Soft leptons: CMS-PAS-SUS-18-004
- Sbottom inclusive search: arXiv:2012.08600

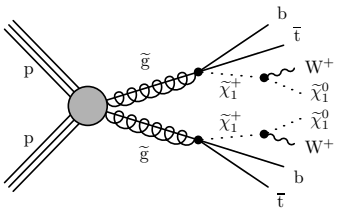

137.0 fb-1 (13 TeV)
CMS
Low Δm
Data
Z→νν̄
Rare
T2tt(500, 460)
Lost lepton
QCD multijet
Bkg. uncertainty
T2cc(500, 460)
Events
Search bin number
Nobs/Nexp

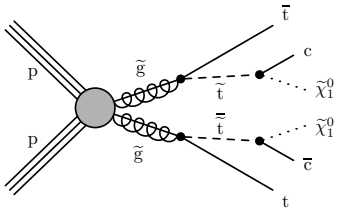

137.0 fb-1 (13 TeV)
CMS
High Δm, Nc=2, (Nl, Nw, Nres)
Data
Z→νν̄
Rare
T2tt(1000,100)
Lost lepton
QCD multijet
Bkg. uncertainty
T1tttt(2000, 400)
Events
Search bin number
Nobs/Nexp

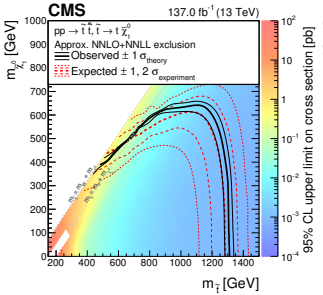

137.0 fb-1 (13 TeV)
CMS
High Δm, Nc≥1, (Nl, Nw, Nres)
Data
Z→νν̄
Rare
T2tt(1000,100)
Lost lepton
QCD multijet
Bkg. uncertainty
T1tttt(2000, 400)
Events
Search bin number
Nobs/Nexp

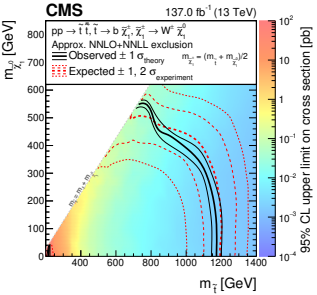

137.0 fb-1 (13 TeV)
CMS
High Δm, Nc≥3, (Nl, Nw, Nres)
Data
Z→νν̄
Rare
T2tt(1000,100)
Lost lepton
QCD multijet
Bkg. uncertainty
T1tttt(2000, 400)
Events
Search bin number
Nobs/Nexp

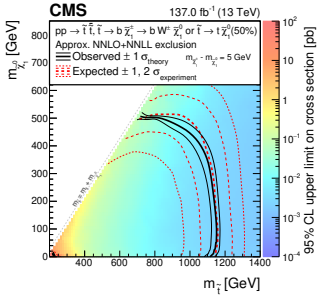

p
p
$\widetilde{g}$
$\widetilde{g}$
t
$\bar{t}$
$\widetilde{\chi}_1^0$
$\widetilde{\chi}_1^0$
t
$\bar{t}$

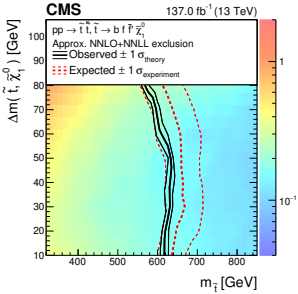

p
p
$\widetilde{g}$
$\widetilde{g}$
b
$\bar{t}$
$\widetilde{\chi}_1^+$
$\widetilde{\chi}_1^+$
W+
$\widetilde{\chi}_1^0$
$\widetilde{\chi}_1^0$
W+
b
$\bar{t}$

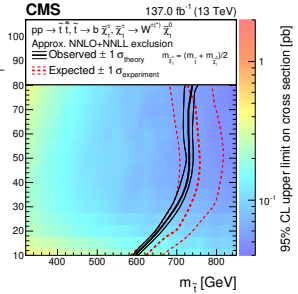

p
p
$\widetilde{g}$
$\widetilde{g}$
$\bar{t}$
$\widetilde{t}$
$\bar{t}$
c
$\widetilde{\chi}_1^0$
$\widetilde{\chi}_1^0$
$\bar{c}$
t

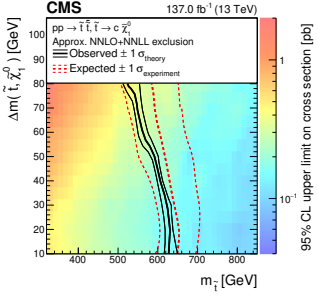

CMS
137.0 fb^{-1} (13 Ev)
pp → t t̄, t → t χ$_1^0$
Approx. NNLO+NNLL exclusion
Observed ± 1 σ$_{theory}$
Expected ± 1, 2 σ$_{experiment}$
m$_{\chi_1^0}$ [GeV]
m$_{\tilde{t}}$ [GeV]
95% CL upper limit on cross section [pb]

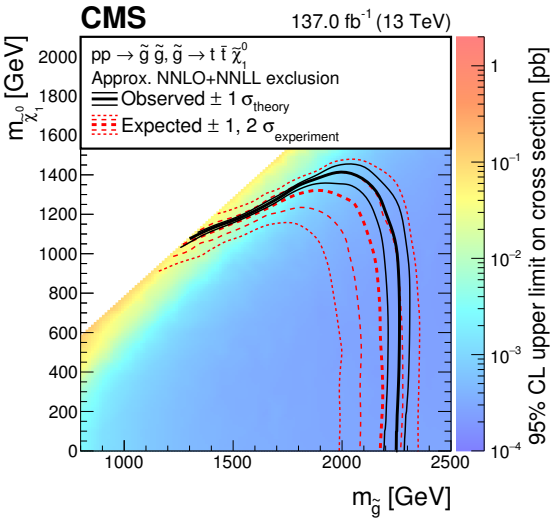

CMS
137.0 fb^{-1} (13 Ev)
pp → t t̄, t → b χ$_1^±$, χ$_1^±$ → W$^±$ χ$_1^0$
Approx. NNLO+NNLL exclusion
Observed ± 1 σ$_{theory}$
Expected ± 1, 2 σ$_{experiment}$
m$_{\chi_1^±}$ [GeV]
m$_{\tilde{t}}$ [GeV]
95% CL upper limit on cross section [pb]

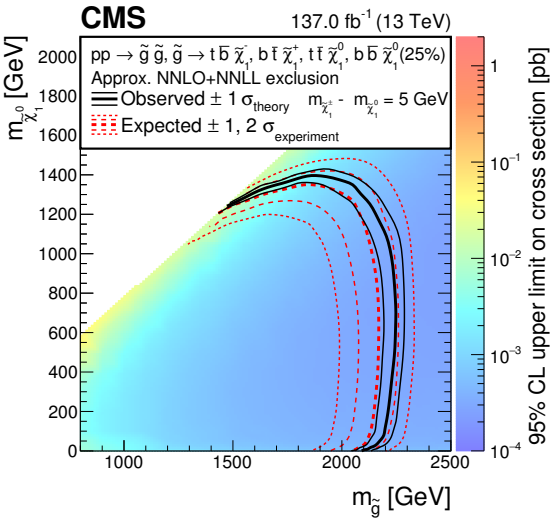

CMS
137.0 fb^{-1} (13 Ev)
pp → t t̄, t → b χ$_1^±$ → b W$^±$ χ$_1^0$ or t → t χ$_1^0$(50%)
Approx. NNLO+NNLL exclusion
Observed ± 1 σ$_{theory}$
Expected ± 1, 2 σ$_{experiment}$
m$_{\chi_1^0}$ [GeV]
m$_{\tilde{t}}$ [GeV]
95% CL upper limit on cross section [pb]

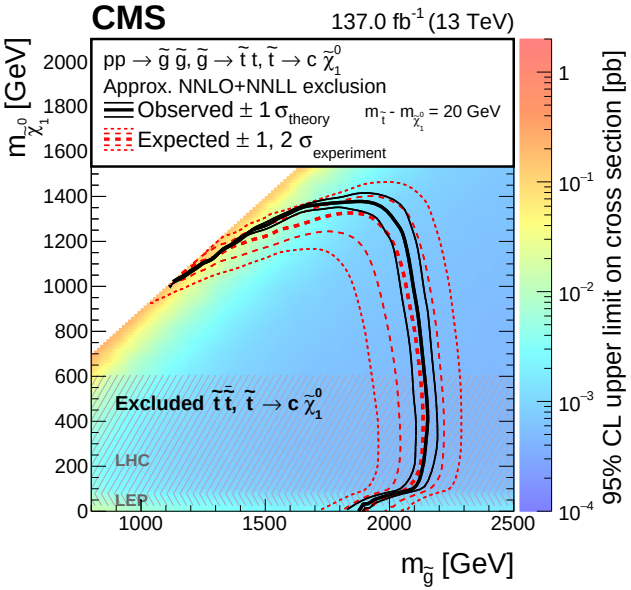

CMS
137.0 fb^{-1} (13 TeV)
pp → t̃ t̃*, t̃ → b f f̄' χ̃$_1^0$
Approx. NNLO+NNLL exclusion
Observed ± 1 σ$_{theory}$
Expected ± 1 σ$_{experiment}$
Δm(t̃, χ̃$_1^0$) [GeV]
m$_{t̃}$ [GeV]
95% CL upper limit on cross section [pb]

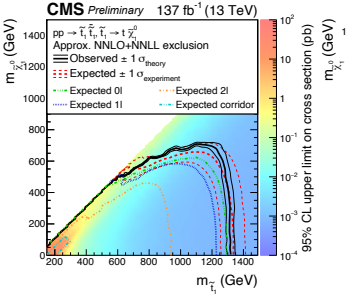

CMS
137.0 fb^{-1} (13 TeV)
pp → t̃ t̃*, t̃ → b χ̃$_1^±$, χ̃$_1^±$ → W$^{(*)}$ χ̃$_1^0$
Approx. NNLO+NNLL exclusion
Observed ± 1 σ$_{theory}$
Expected ± 1 σ$_{experiment}$
m$_{χ̃_1^±}$ = (m$_{t̃}$ + m$_{χ̃_1^0}$)/2
Δm(t̃, χ̃$_1^0$) [GeV]
m$_{t̃}$ [GeV]
95% CL upper limit on cross section [pb]

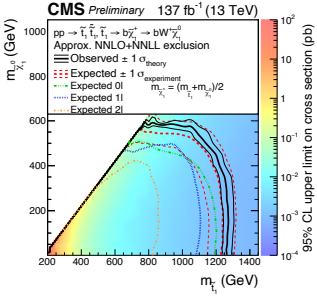

CMS
137.0 fb^{-1} (13 TeV)
pp → t̃ t̃*, t̃ → c χ̃$_1^0$
Approx. NNLO+NNLL exclusion
Observed ± 1 σ$_{theory}$
Expected ± 1 σ$_{experiment}$
Δm(t̃, χ̃$_1^0$) [GeV]
m$_{t̃}$ [GeV]
95% CL upper limit on cross section [pb]

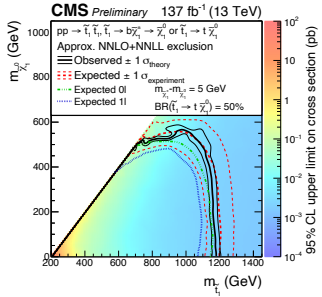

CMS
137.0 fb^{-1} (13 TeV)
pp → g̃ g̃, g̃ → t t̄ χ̃$_1^0$
Approx. NNLO+NNLL exclusion
Observed ± 1 σ$_{theory}$
Expected ± 1, 2 σ$_{experiment}$
m$_{\tilde{\chi}_1^0}$ [GeV]
m$_{\tilde{g}}$ [GeV]
95% CL upper limit on cross section [pb]

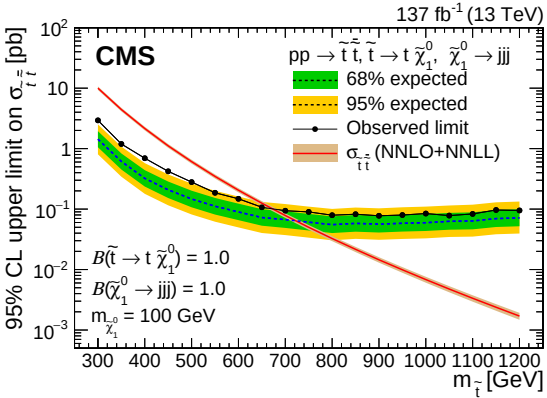

CMS
137.0 fb^{-1} (13 TeV)
pp → g̃ g̃, g̃ → t b̄ χ̃$_1^-$, b b̄ χ̃$_1^+$, t t̄ χ̃$_1^0$, b b̄ χ̃$_1^0$(25%)
Approx. NNLO+NNLL exclusion
Observed ± 1 σ$_{theory}$ m$_{\tilde{\chi}_1^\pm}$ - m$_{\tilde{\chi}_1^0}$ = 5 GeV
Expected ± 1, 2 σ$_{experiment}$
m$_{\tilde{\chi}_1^0}$ [GeV]
m$_{\tilde{g}}$ [GeV]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

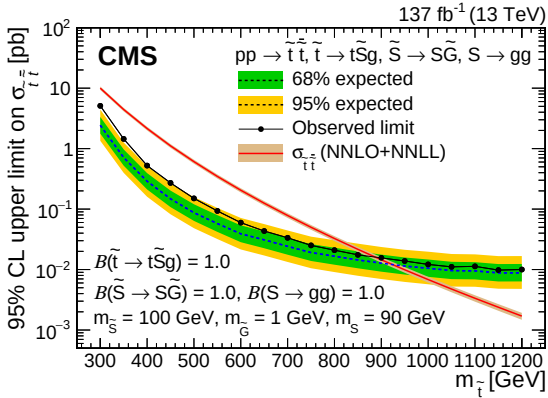

CMS
137.0 fb-1 (13 TeV)
pp → g̃ g̃, g̃ → t̃ t, t̃ → c χ̃10
Approx. NNLO+NNLL exclusion
Observed ± 1 σtheory
Expected ± 1, 2 σexperiment
mt̃ - mχ̃10 = 20 GeV
Excluded t̃ t̃*, t̃ → c χ̃10
LHC
LEP
mχ̃10 [GeV]
mg̃ [GeV]
95% CL upper limit on cross section [pb]

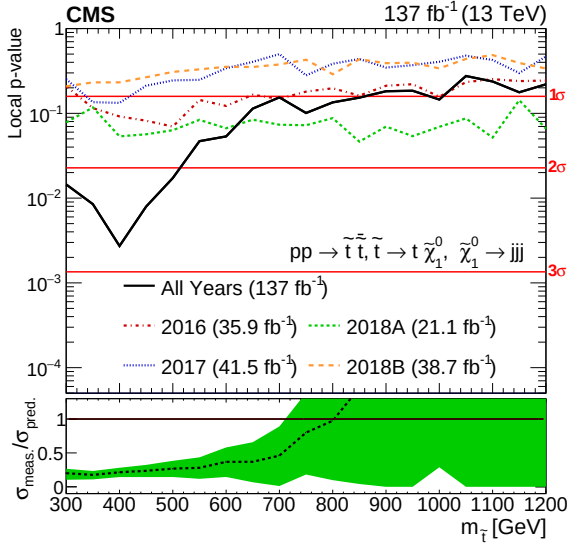

CMS Preliminary 137 fb-1 (13 TeV)
pp → t̃1 t̃1*, t̃1 → t χ̃10
Approx. NNLO+NNLL exclusion
Observed ± 1 σtheory
Expected ± 1 σexperiment
Expected 0l
Expected 1l
Expected 2l
Expected corridor
mχ̃10 (GeV)
mt̃1 (GeV)
95% CL upper limit on cross section (pb)

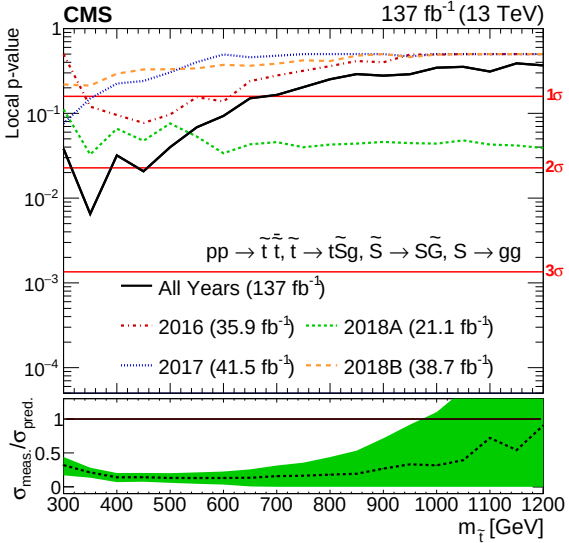

CMS Preliminary 137 fb-1 (13 TeV)
pp → t̃1 t̃1*, t̃1 → b χ̃1± → bW* χ̃10
Approx. NNLO+NNLL exclusion
Observed ± 1 σtheory
Expected ± 1 σexperiment
Expected 0l
Expected 1l
Expected 2l
mχ̃1± = (mt̃1+mχ̃10)/2
mχ̃1± (GeV)
mt̃1 (GeV)
95% CL upper limit on cross section (pb)

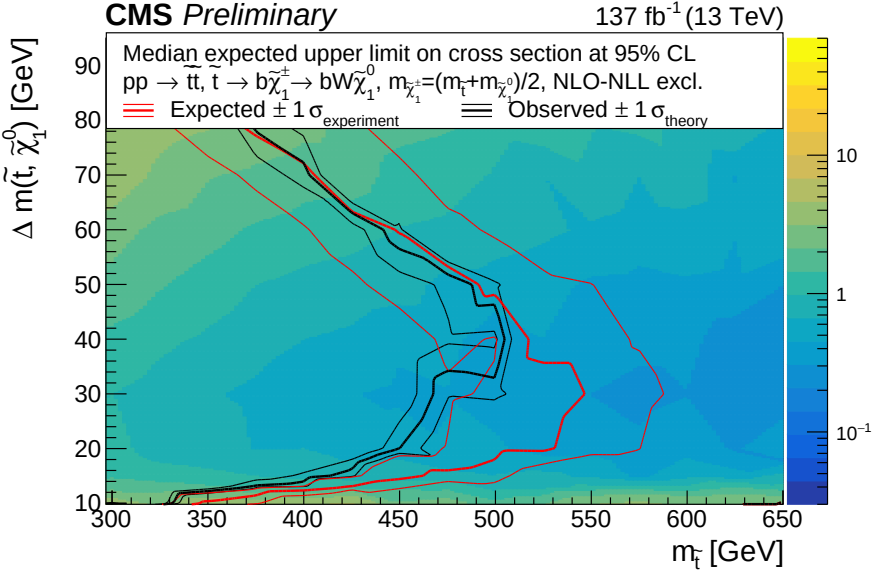

CMS Preliminary 137 fb-1 (13 TeV)
pp → t̃1 t̃1*, t̃1 → b χ̃1± → χ̃10 or t̃1 → t χ̃10
Approx. NNLO+NNLL exclusion
Observed ± 1 σtheory
Expected ± 1 σexperiment
Expected 0l
Expected 1l
mχ̃1± - mχ̃10 = 5 GeV
BR(t̃1 → t χ̃10) = 50%
mχ̃1± (GeV)
mt̃1 (GeV)
95% CL upper limit on cross section (pb)

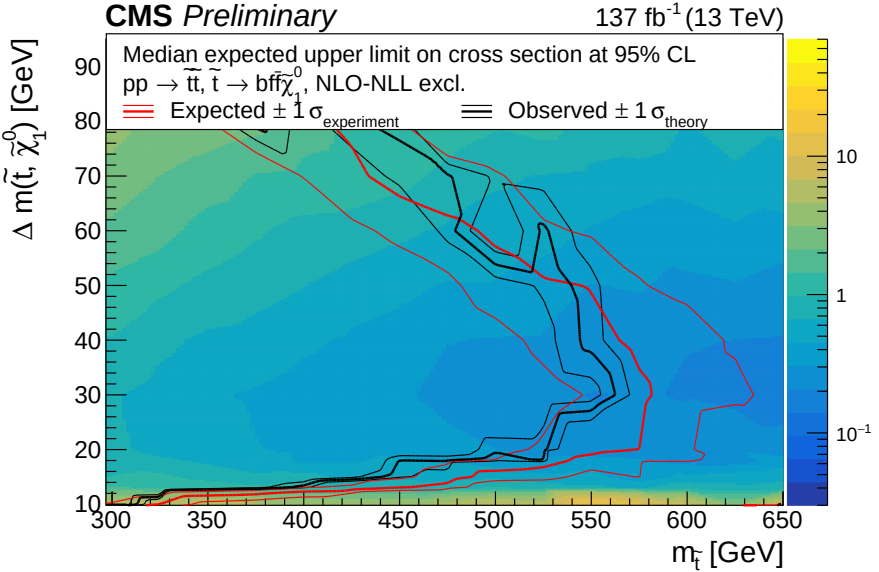

137 fb^{-1} (13 TeV)
CMS
pp → t̃ t̃*, t̃ → t χ̃$_1^0$, χ̃$_1^0$ → jjj
68% expected
95% expected
Observed limit
σ$_{t̃ t̃*}$ (NNLO+NNLL)
B(t̃ → t χ̃$_1^0$) = 1.0
B(χ̃$_1^0$ → jjj) = 1.0
m$_{χ̃_1^0}$ = 100 GeV
95% CL upper limit on σ$_{t̃ t̃*}$ [pb]
m$_{t̃}$ [GeV]


137 fb^{-1} (13 TeV)
CMS
pp → t̃ t̃*, t̃ → tS̃g, S̃ → SG̃, S → gg
68% expected
95% expected
Observed limit
σ$_{t̃ t̃*}$ (NNLO+NNLL)
B(t̃ → tS̃g) = 1.0
B(S̃ → SG̃) = 1.0, B(S → gg) = 1.0
m$_{S̃}$ = 100 GeV, m$_{G̃}$ = 1 GeV, m$_S$ = 90 GeV
95% CL upper limit on σ$_{t̃ t̃*}$ [pb]
m$_{t̃}$ [GeV]


CMS
137 fb^{-1} (13 TeV)
Local p-value
1σ
2σ
3σ
pp → t̃ t̃̄, t̃ → t χ̃$_1^0$, χ̃$_1^0$ → jjj
All Years (137 fb^{-1})
2016 (35.9 fb^{-1})
2018A (21.1 fb^{-1})
2017 (41.5 fb^{-1})
2018B (38.7 fb^{-1})
σ$_{meas.}$/σ$_{pred.}$
m$_{t̃}$ [GeV]


CMS
137 fb^{-1} (13 TeV)
Local p-value
1σ
2σ
3σ
pp → t̃ t̃̄, t̃ → tS̃g, S̃ → SG̃, S → gg
All Years (137 fb^{-1})
2016 (35.9 fb^{-1})
2018A (21.1 fb^{-1})
2017 (41.5 fb^{-1})
2018B (38.7 fb^{-1})
σ$_{meas.}$/σ$_{pred.}$
m$_{t̃}$ [GeV]


CMS Preliminary
137 fb-1 (13 TeV)
Median expected upper limit on cross section at 95% CL
pp → t̃t̃, t̃ → bχ̃1± → bWχ̃10, mχ̃1±=(mt̃+mχ̃10)/2, NLO-NLL excl.
Expected ± 1 σexperiment
Observed ± 1 σtheory
Δ m(t̃, χ̃10) [GeV]
mt̃ [GeV]
10
1
10−1


CMS Preliminary
137 fb-1 (13 TeV)
Median expected upper limit on cross section at 95% CL
pp → t̃t̃, t̃ → bff̄χ̃10, NLO-NLL excl.
Expected ± 1 σexperiment
Observed ± 1 σtheory
Δ m(t̃, χ̃10) [GeV]
mt̃ [GeV]
10
1
10−1