Searches for supersymmetric partner of top quark

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On behalf of the CMS and ATLAS collaborations

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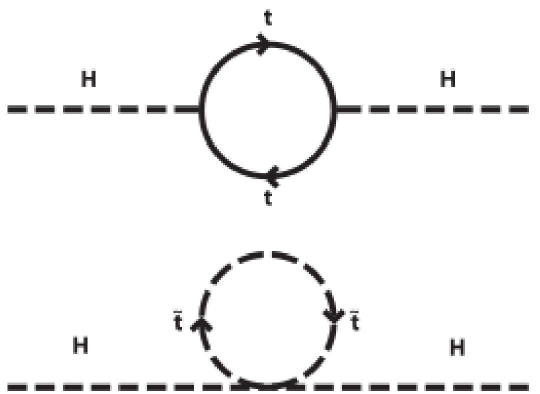
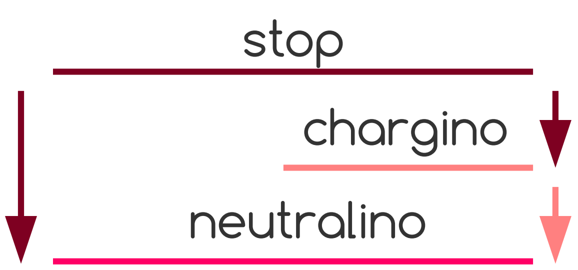
Motivation

- The **naturalness** problem can be solved by SUSY
  - Cancellation of the loop corrections to the Higgs mass

    → top squark is expected to be light
- SUSY predicts a **dark matter candidate**
  - SUSY scenario dependent – it can be a neutralino, a slepton or a gravitino

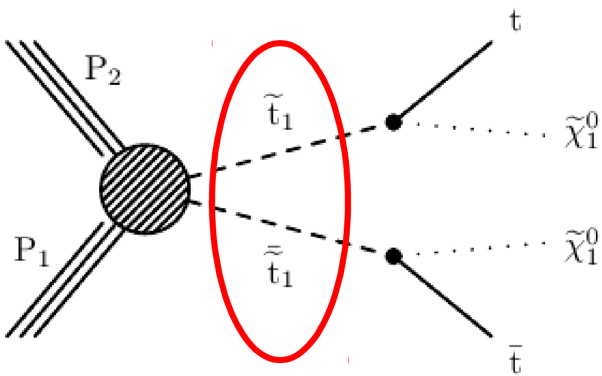
- Only Simplified Model Spectrum (SMS) is considered here
  - In considered models the lightest supersymmetric particle (LSP) is the neutralino





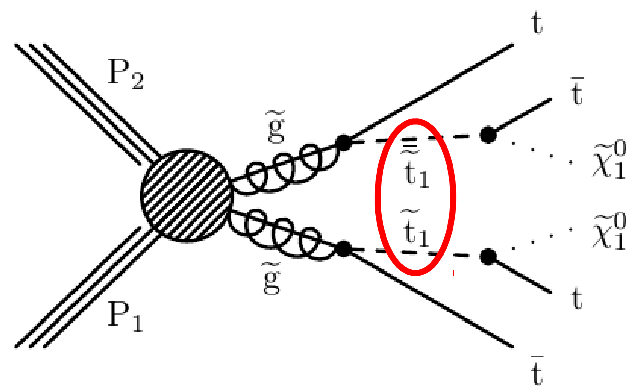
Production of the stop quarks

- Direct (e.g.)

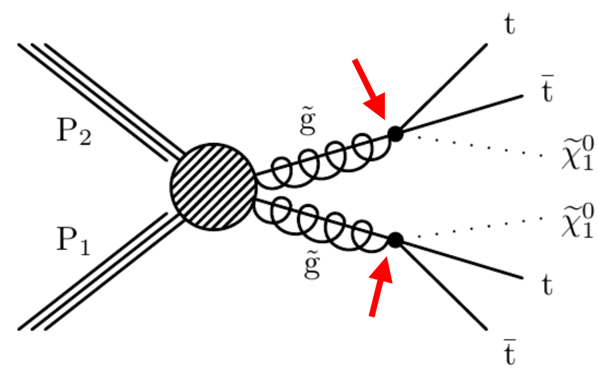


→ more in following slides

- Gluino mediated
  - On-shell stop



  - Off-shell stop

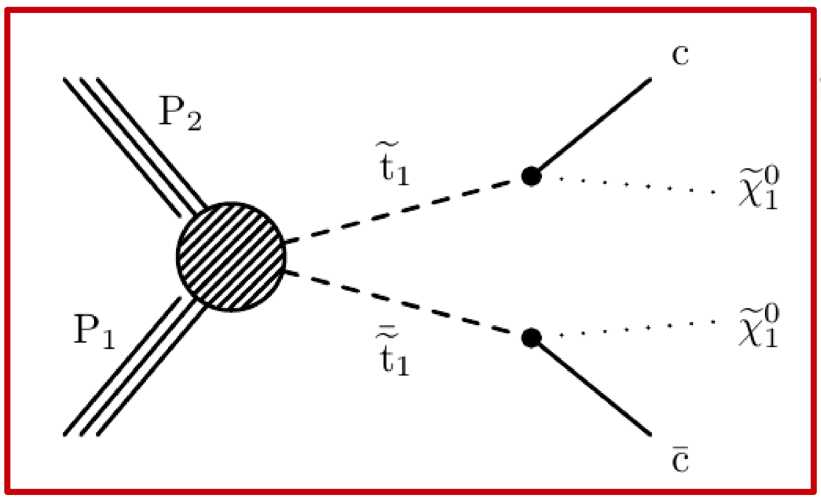


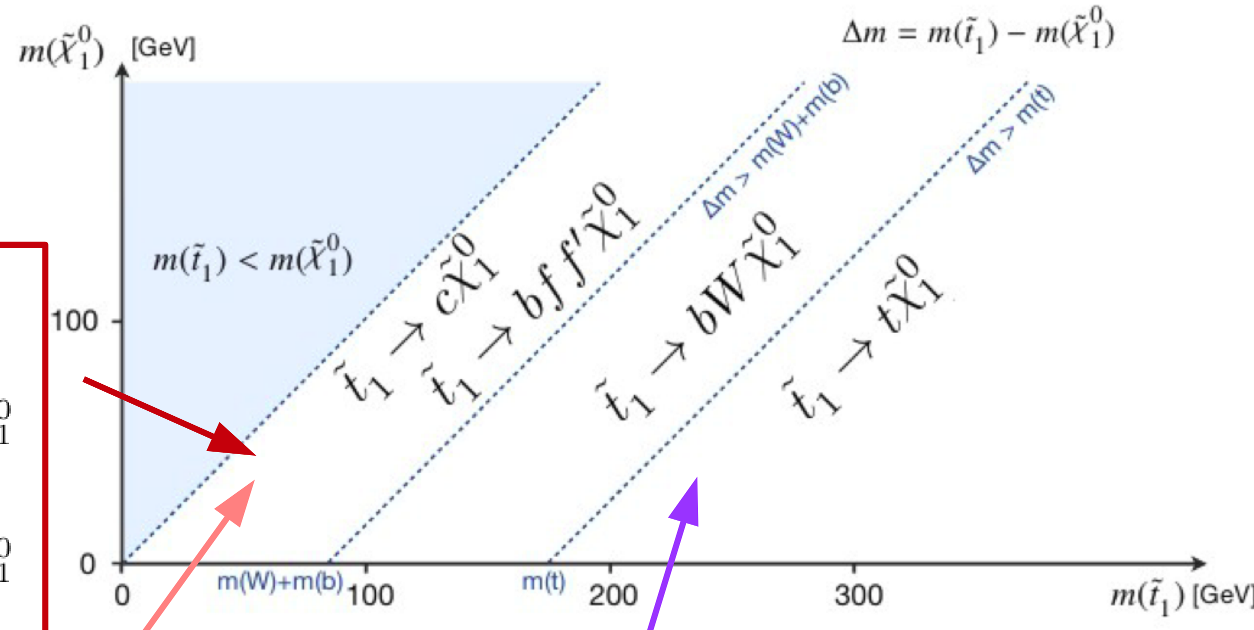
→ will not be presented here

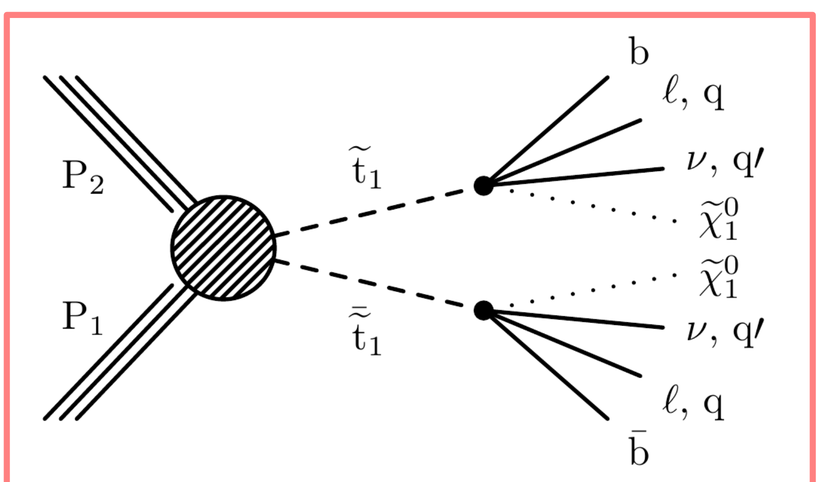
Stop decay channels: Basic

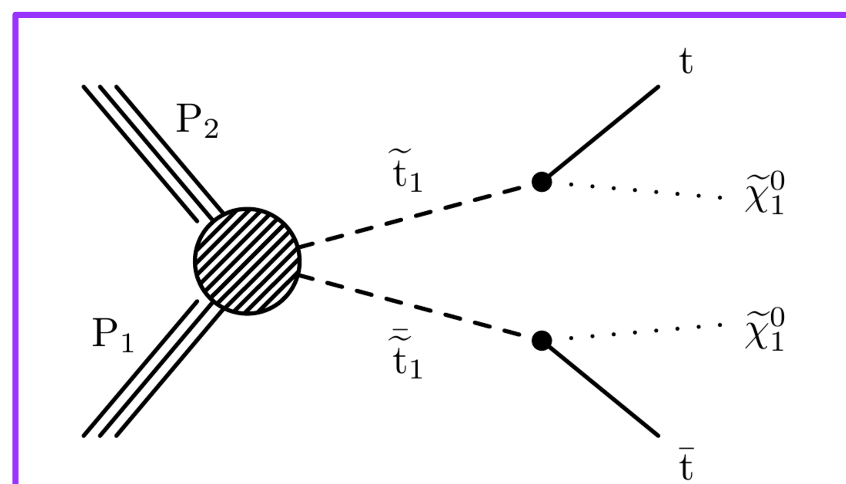
stop

neutralino

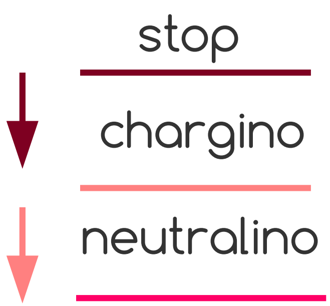


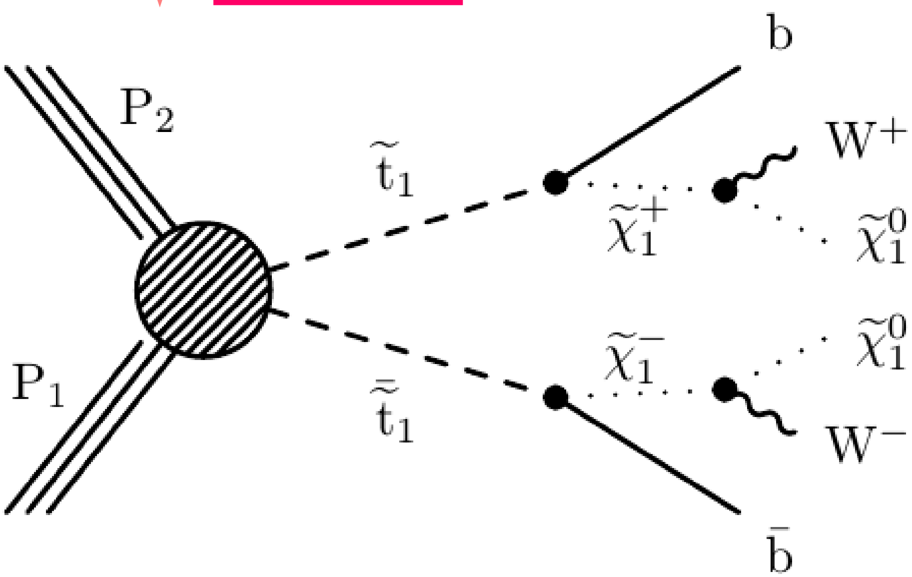


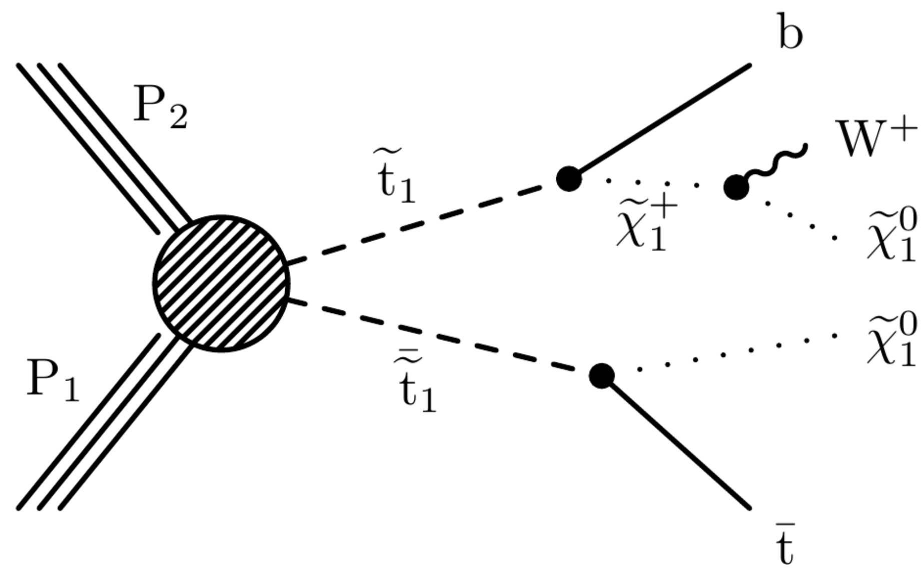




Stop decay channels: Adding intermediate chargino







Consider:
CMS: m(chargino) = 0.5(m(stop)-m(neutralino))
ATLAS: m(chargino) = 2m(neutralino)

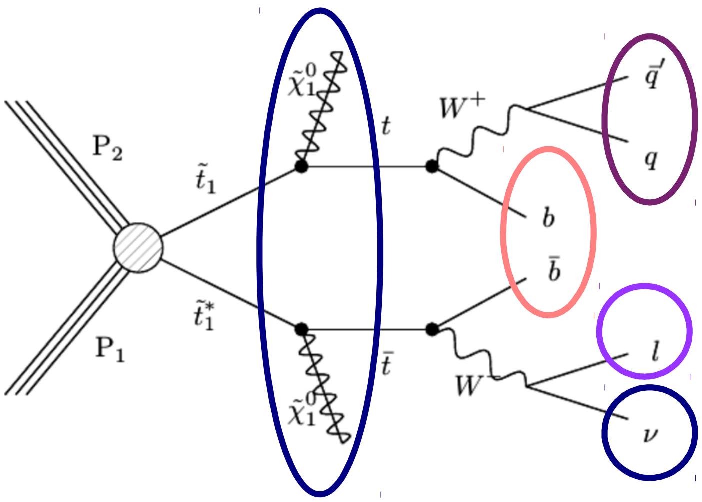
Consider:
CMS: m(chargino) = 5 GeV+m(neutralino))

Signal signature (example)

- Multiple jets
- Multiple b-jets
- Large missing transverse energy (MET) from neutralinos and neutrino(s)
- 0/1/2 leptons from W bosons

  → **searches performed in 3 final states**
- (pre)selection also based on other topological/kinematical variables to reject the majority of background

1-lep example



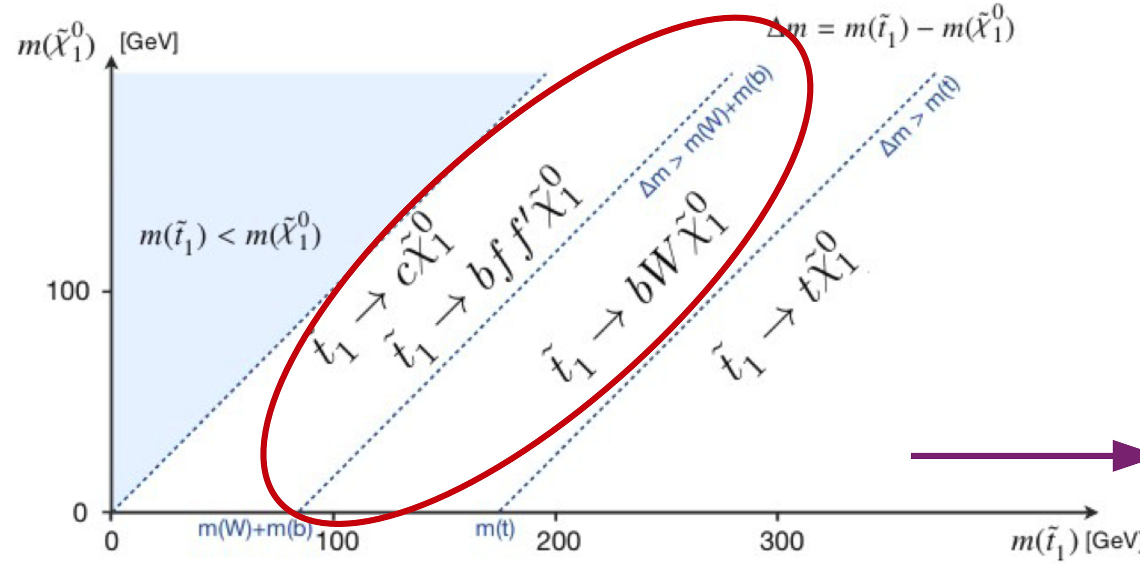
Coverage of different kinematics regimes

Low Δm

- Δm = m(t̃)-m(LSP) → compressed spectra
- Kinematics similar to bkg one
- Soft decay products → to have sufficient MET

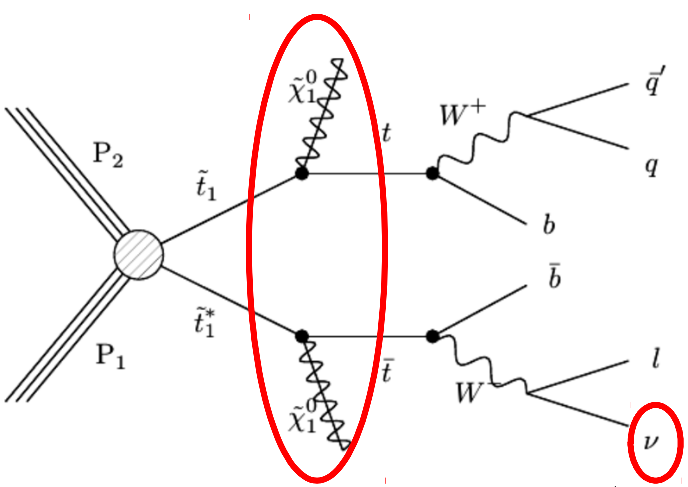
boost against ISR needed

→ **soft b-tagging (CMS)** – based on the presence of a secondary vertex

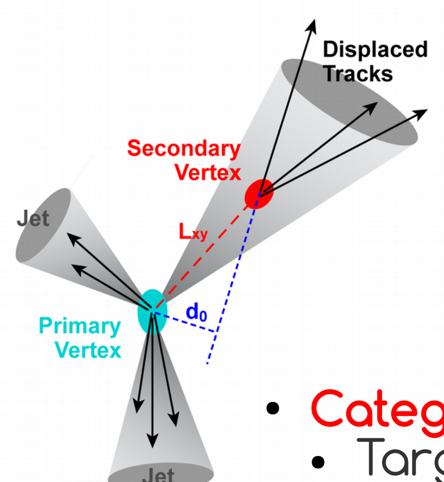


High Δm

- Boosted topologies → W/top tagging
- Different final state kinematics than in case of low Δm



ISR system   Boost of the stop system



- **Categorization** of events:
  - Target signals with different kinematics (and topology)
  - (Disentangle different backgrounds) → use of signal regions

Background estimation

- Data driven estimation
- Use of **Control Regions (CR)** to predict the background in **Signal Regions (SR)**
  - CRs and SRs are orthogonal
  - CRs formed by inverting one requirement (b-tag multiplicity, lepton multiplicity, …)
  - CRs as pure in 1 background as possible
- We can define **Validation Regions (VR)** to validate background estimation
  - Kinematically close to SRs

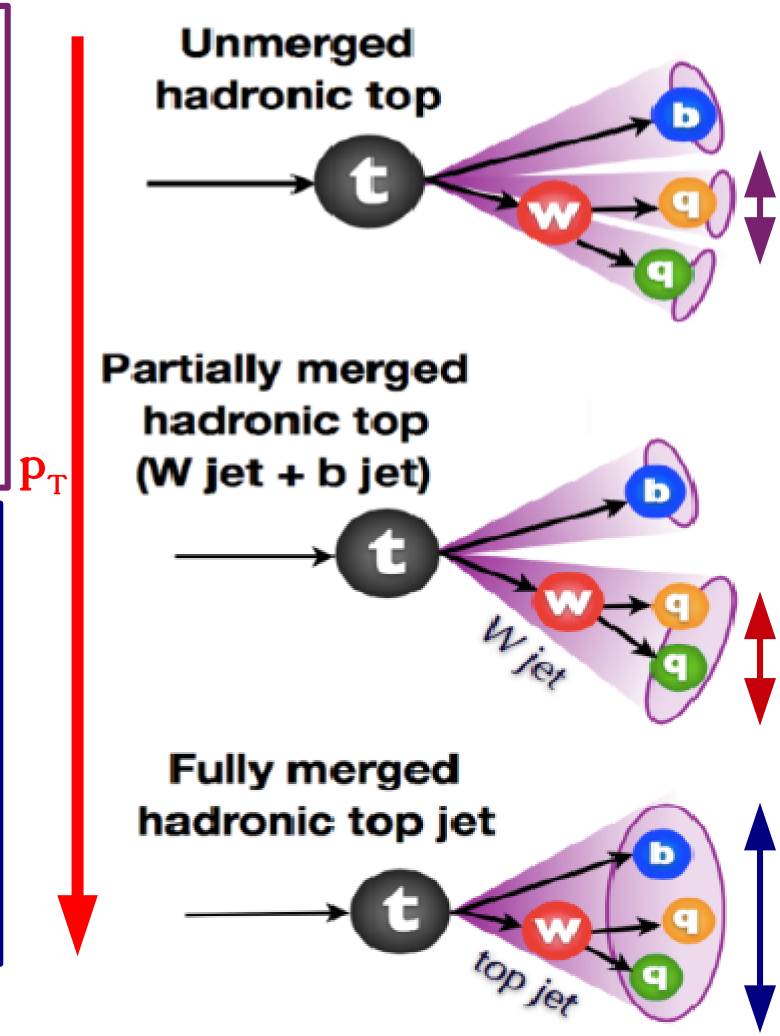
→ Observed yields in SRs compared to background prediction

CMS 0-lepton stop search:

top/W/resolved-top tagging (SUS-16-049)

- Use Multivariate analysis techniques (BDT) to distinguish 3-jet combination from top vs random combination
- Variables for BDT:
  - Kinematics of jets
  - Jet flavor discriminants
  - QG variables

- **Variables for BDT:**
  - **Fatjet:** Softdrop mass, N-subjettiness
  - **Softdrop subjets:** kinematic variables, b-tagging information, QuarkGluon variables



Resolved top tag: Standard R=0.4 jet

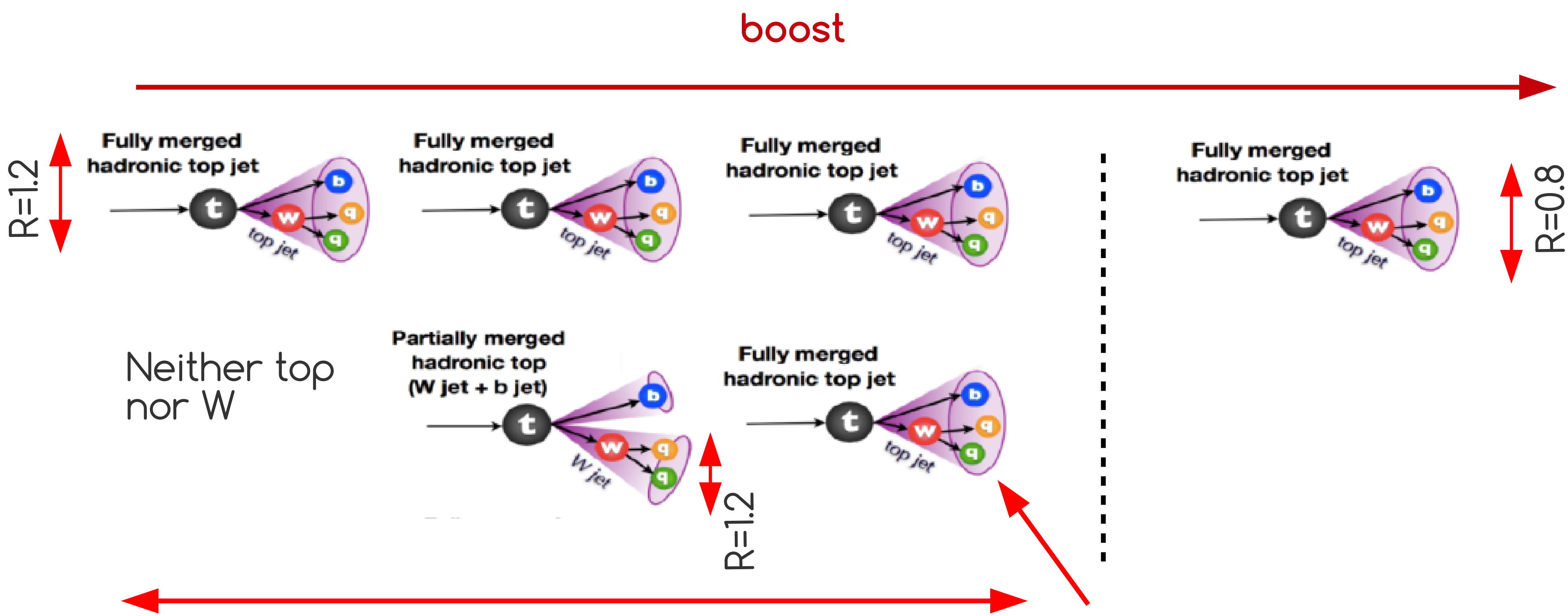
W-tag: Fat R=0.8 jet
- p_T>200 GeV
- 50<m_{SD}<110 GeV

Top-tag: Fat R=0.8 jet
- p_T>400 GeV
- m_{SD}>110 GeV

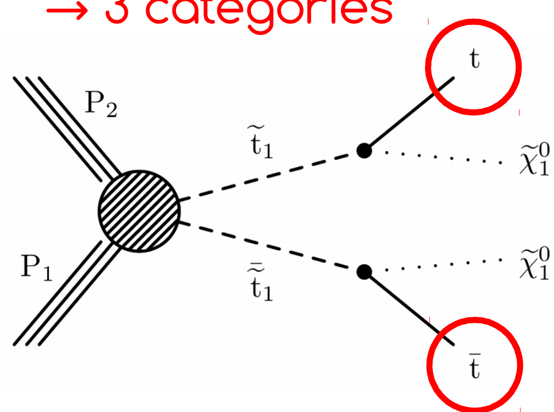
	Resolved-top tagger	W-tagger	Top-tagger
Efficiency/ mistag rate	Up to ~70% / 10%	Up to ~50% / 10%	Up to ~50% / 4%

m_{SD}- softdrop mass - wide-angle soft radiation removed from a jet (to mitigate ISR, pileup,…)

ATLAS 0-lepton stop search: top/W tagging (ATLAS-CONF-2017-020)



→ 3 categories

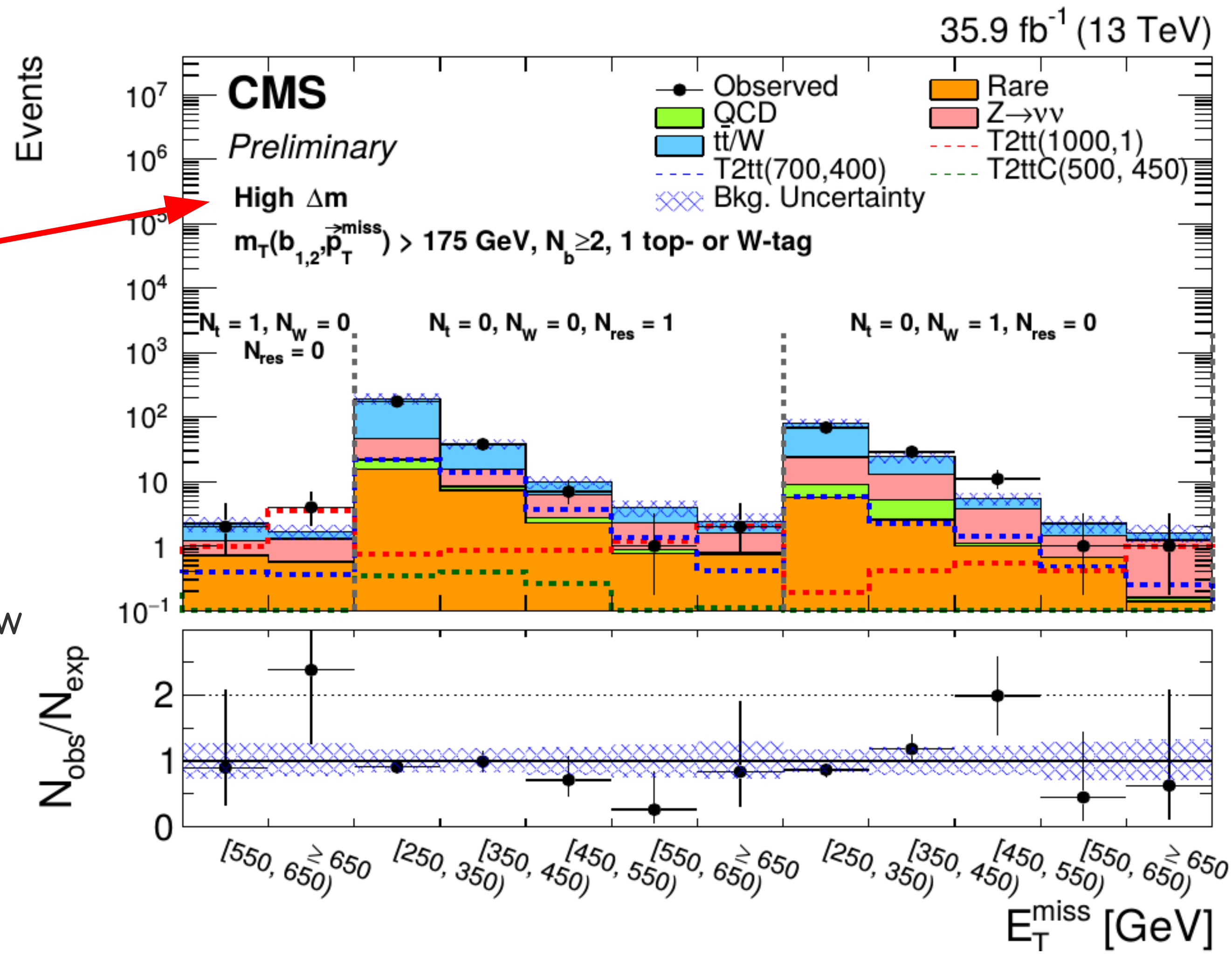


EXAMPLE OF FURTHER REQUIREMENTS:
reclustering with R=0.8
→ leading jet W candidate

CMS 0-lepton stop search: SRs

Different optimizations:

- Low Δm
  - Soft b-tagging, ISR tagging and veto W/top tagging
- High Δm
  - W/top/resolved-top tagger



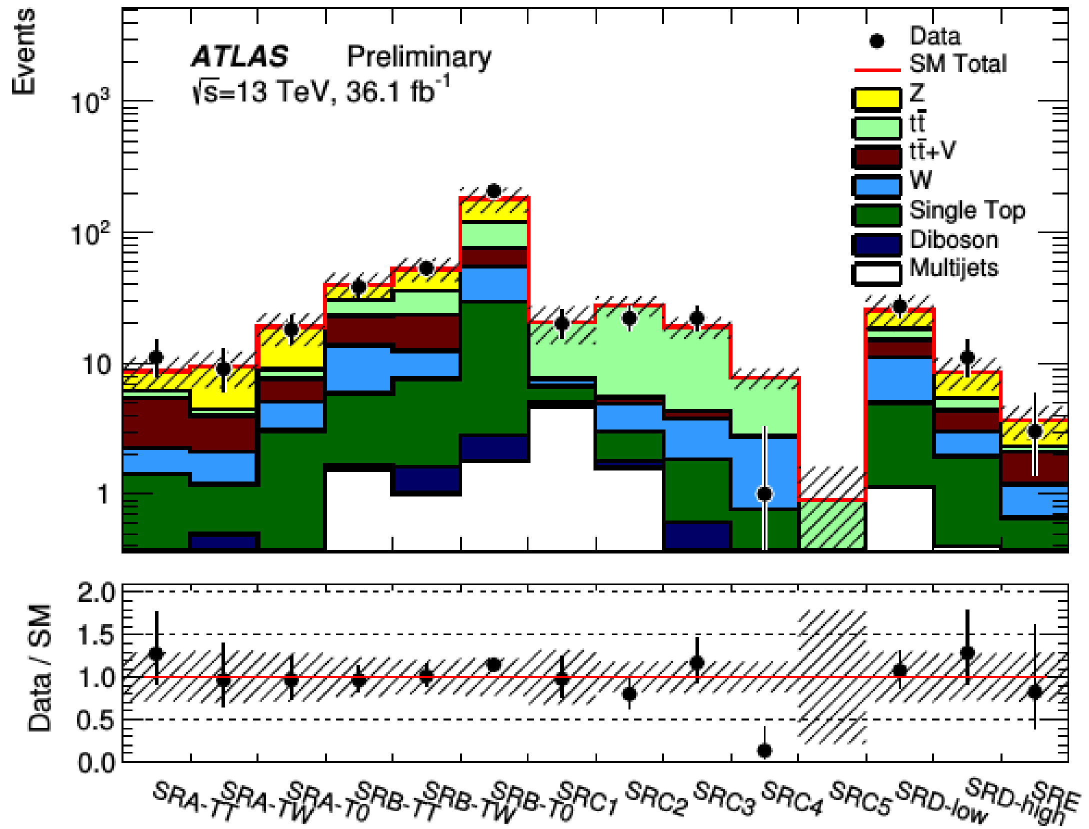
Powerful variable:

- M_T(b,MET)
  - Used to discriminate between low and high Δm signal signature and/or reject SM background (CMS,ATLAS)

M_T(object,MET) = sqrt($2p_T^{object}$MET(1-cos($\Delta\varphi_{ojbect,MET}$)))

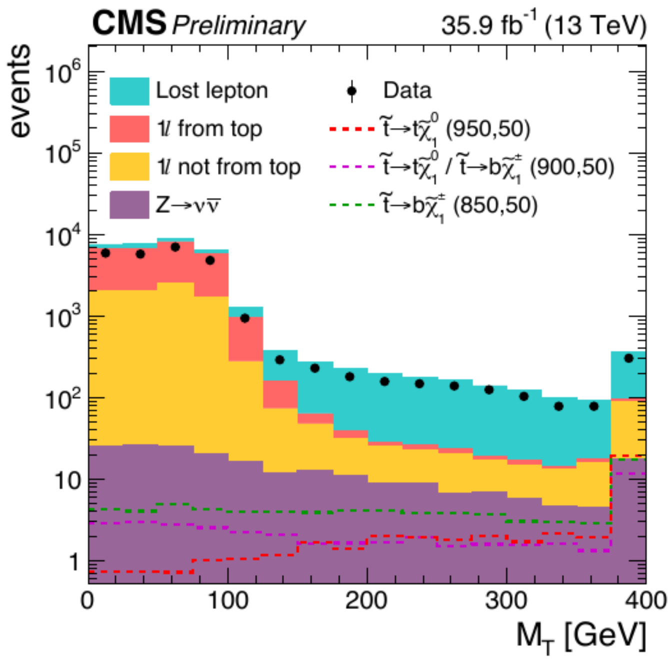
ATLAS 0-lepton stop search: SRs

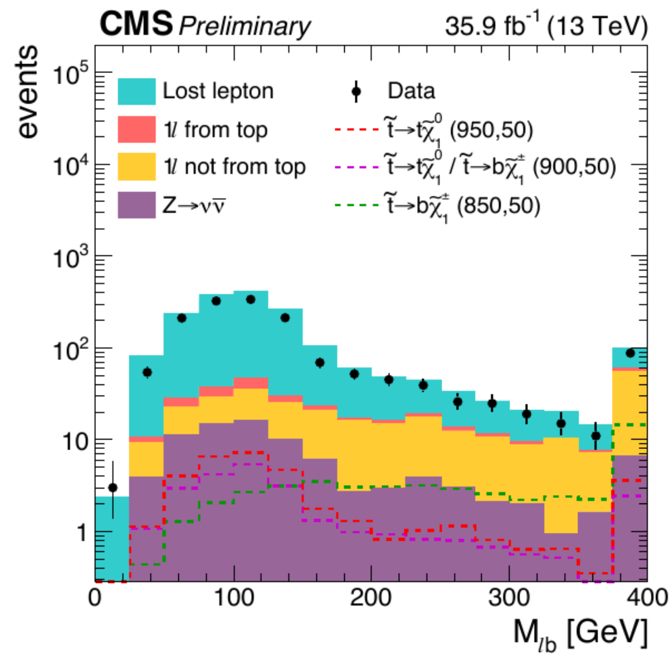
SRs	Targeted kinematic regime	Techniques
A	High stop mass Large Δm	W/top tagging with two R=1.2 jets
B	High stop mass Intermediate Δm	
C	Low Δm (~m_t)	Boost against ISR - assume a specific decay topology
D	Stop→ b+chargino	
E	Highly boosted tops	Top tagging with R=0.8 jets

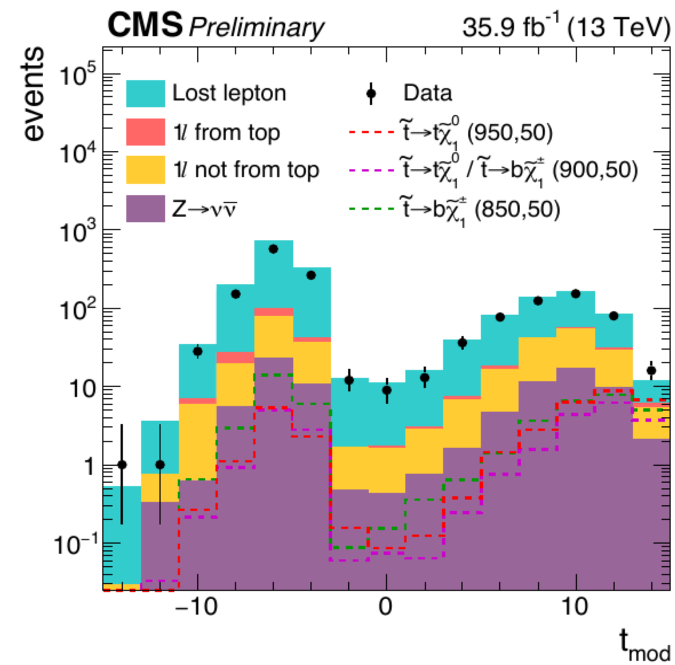


CMS 1-lepton stop search: Variables

(SUS-16-051)







M_T(lep,MET)>150 GeV

- Powerful variable for selection
- Helps to suppress mainly W+jets and ttbar→1l, due to its endpoint at W mass

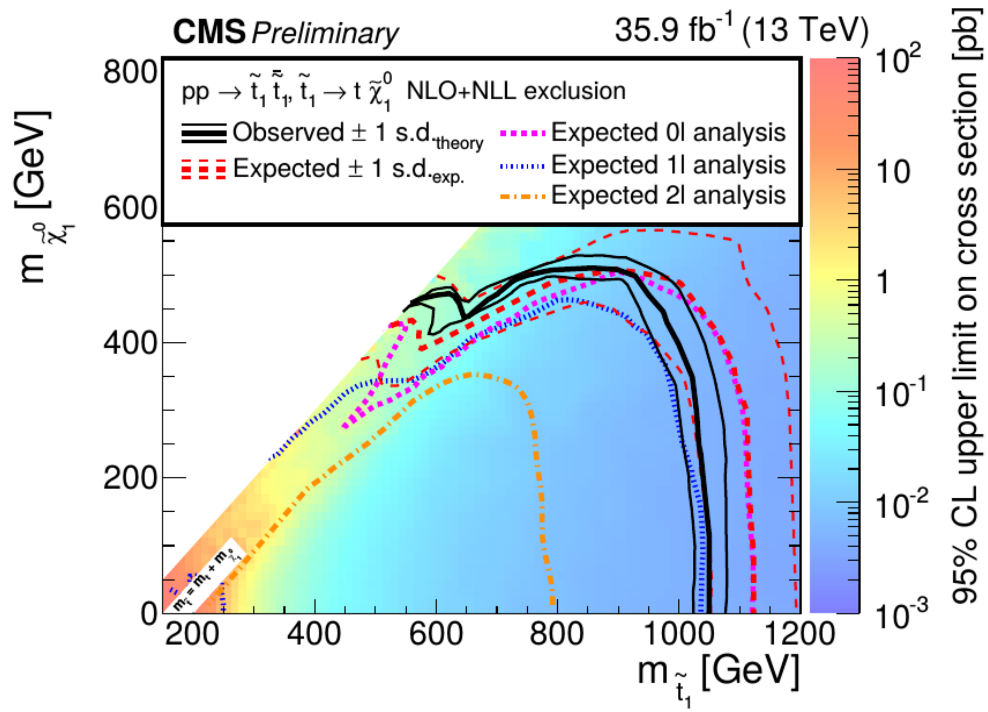
M_{lb}

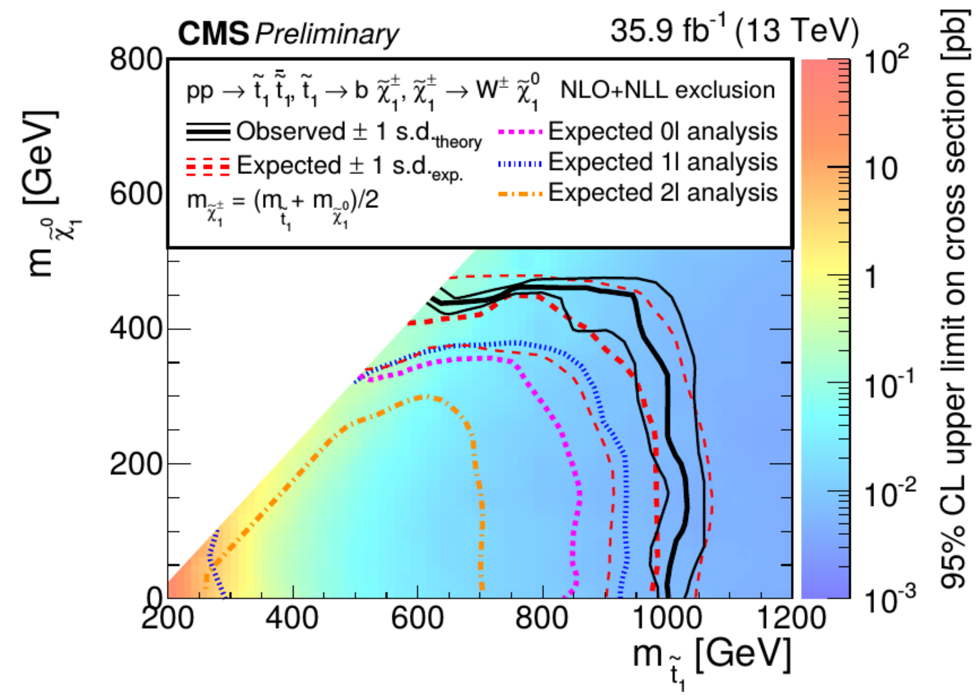
- Invariant mass of the reconstructed lepton and closest b-quark

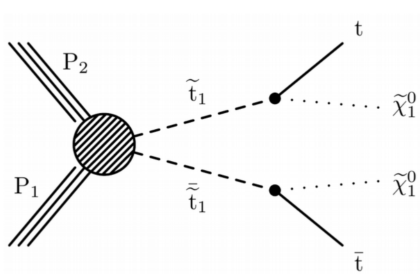
Modified topness

- Variable telling how well the event agrees with ttbar→ 2l hypothesis

CMS interpretations (SUS-16-049, SUS-16-051, SUS-17-001)



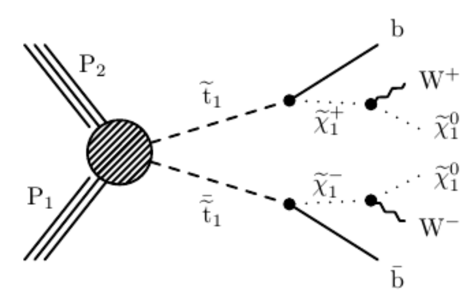




Exclude:
Stop~1050 GeV
Neutralino~500 GeV

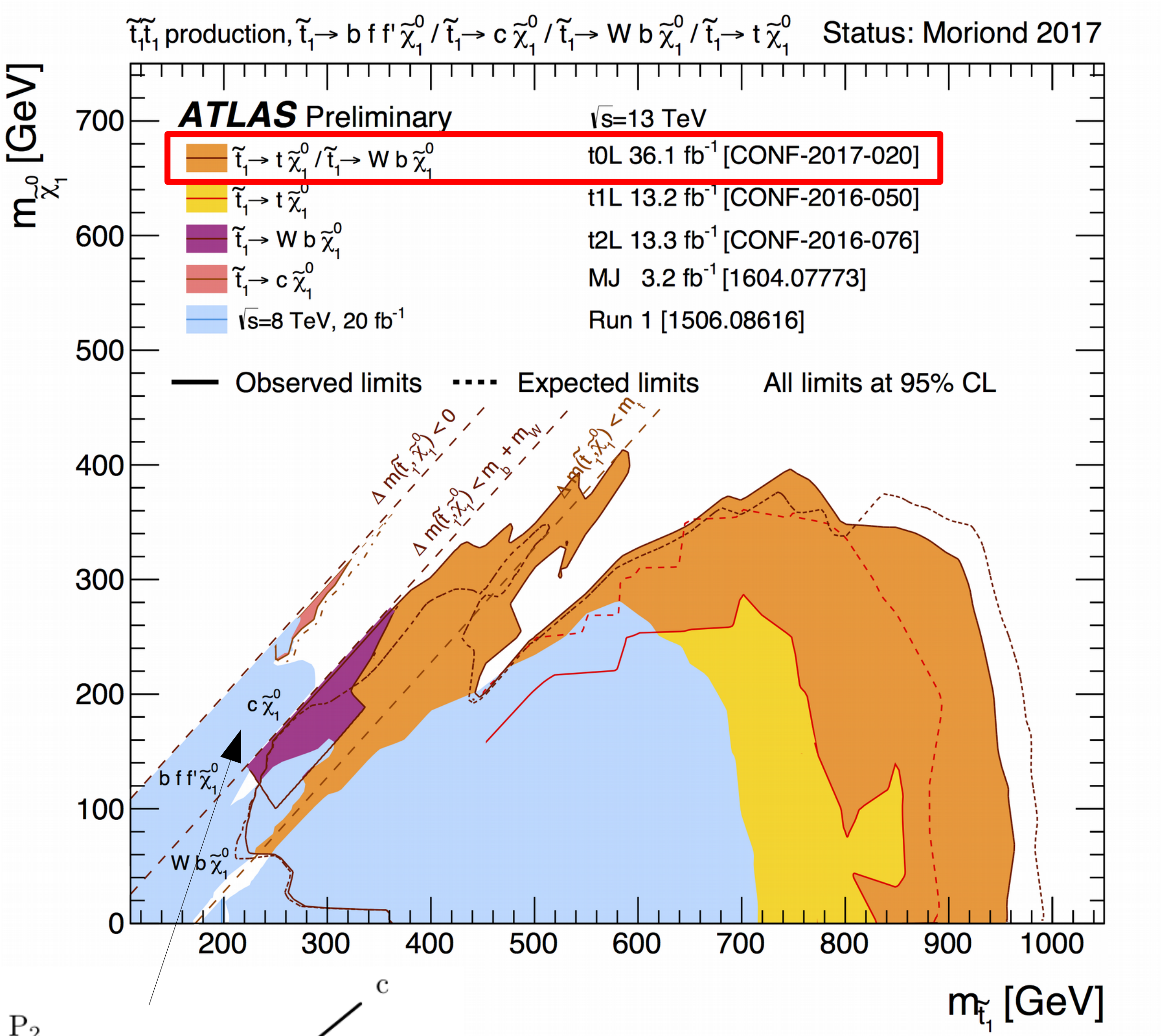
Most sensitivity from 0-lep

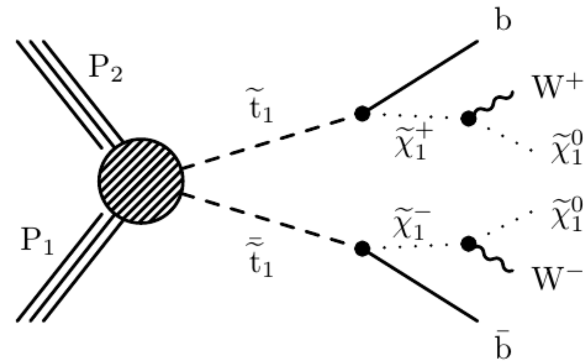
Most sensitivity from 1-lep

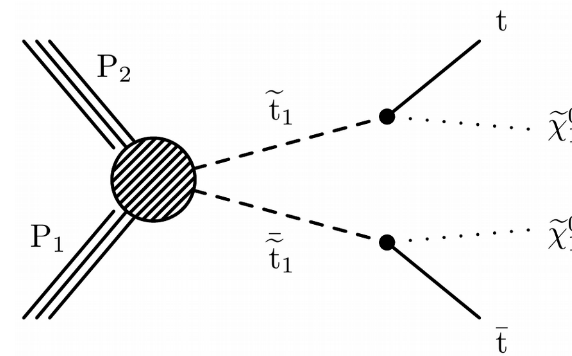


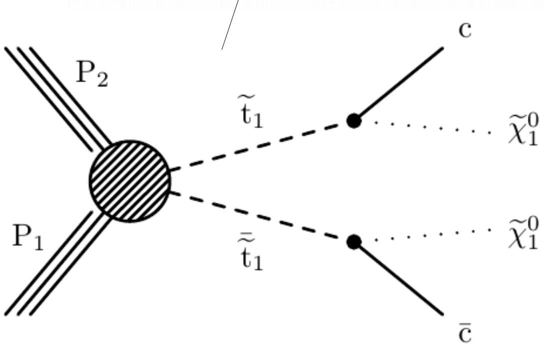
Exclude:
Stop~1000 GeV
Neutralino~450 GeV

ATLAS interpretations



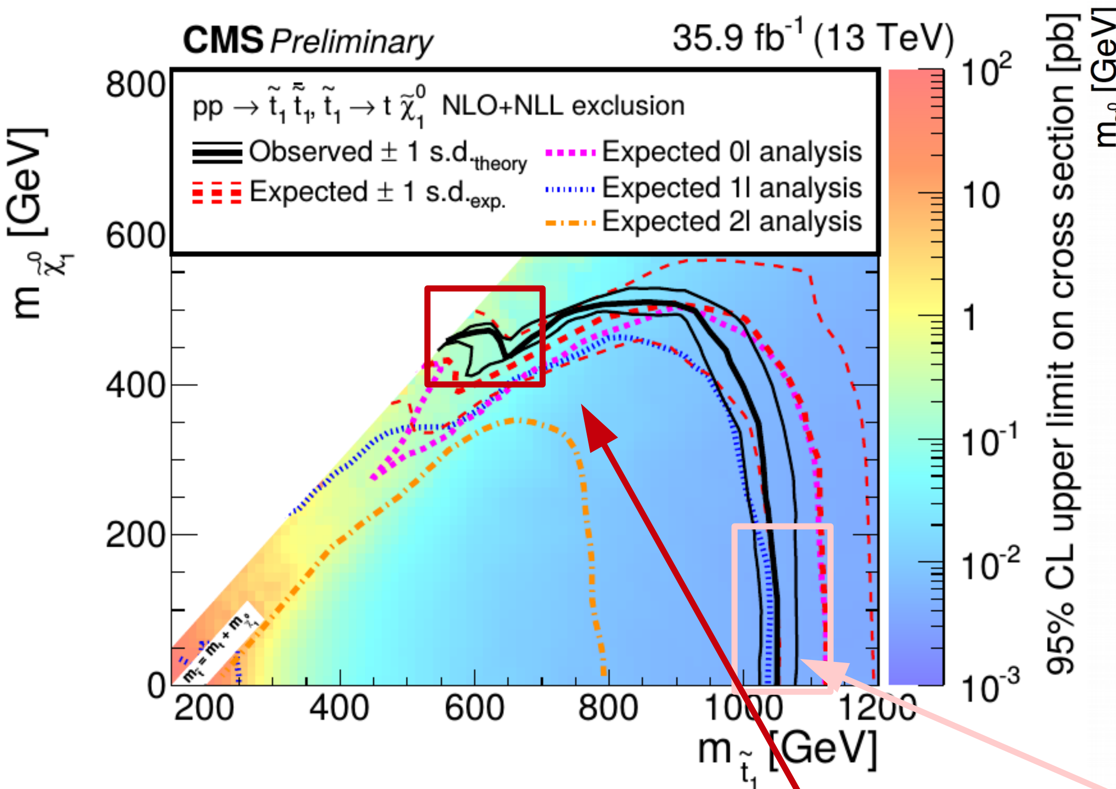


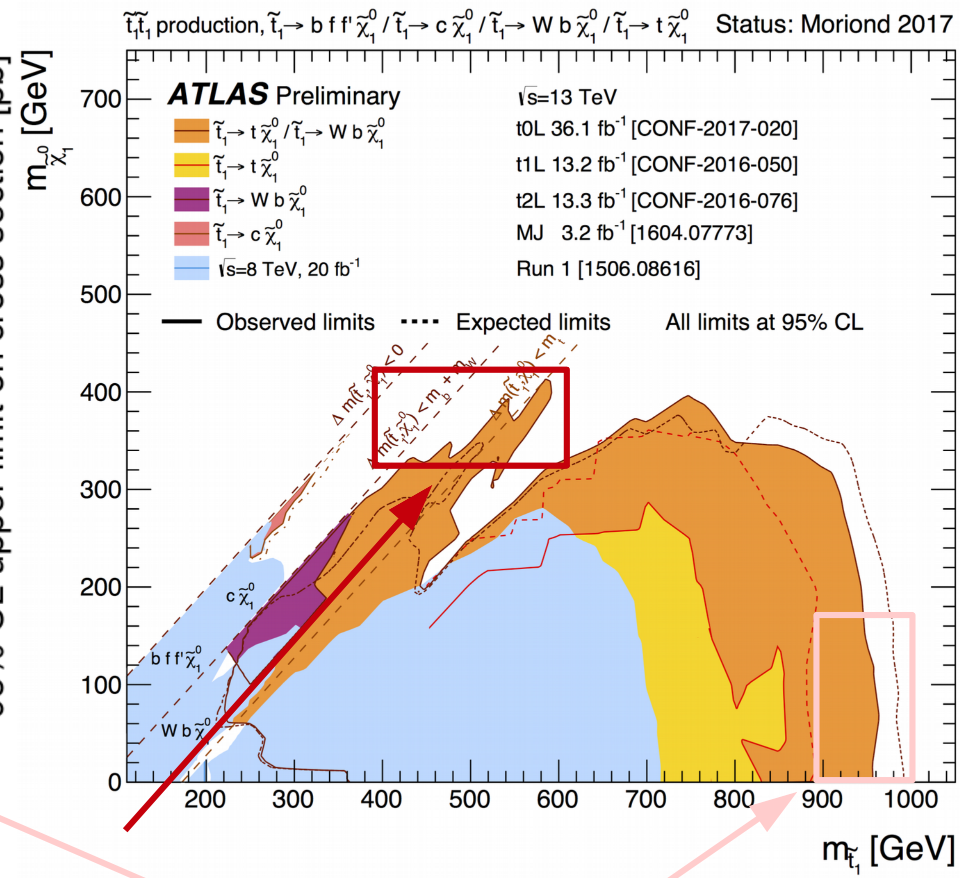




Exclude:
Stop~950 GeV

Improvements of limits





Compressed spectra

Boosted objects

Conclusion

- Presented **latest results of SUSY stop searches** in hadronic and leptonic final states with 35.9 fb^{-1} (CMS) and 36.1 fb^{-1} (ATLAS) of 13 TeV data
- Unfortunately no sign of SUSY so far

  → limits were set in terms of Simplified Model Spectra

- But **rapid improvement in sensitivity**
  - Observed limits on the sparticle masses up to: **stop**~1 TeV, **neutralino**~0.5 TeV

    → Observed limit of stop mass extended by ~250 GeV with respect to Run I

  - **Not only scaling results with luminosity!**
    - Use of new techniques such as soft b-tagging (CMS) or tagging of boosted objects
    - Design of dedicated searches for compressed spectra
    - Exploring new discriminating variables

- More SUSY public results available at:
  https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsSUS
  https://twiki.cern.ch/twiki/bin/view/AtlasPublic/SupersymmetryPublicResults

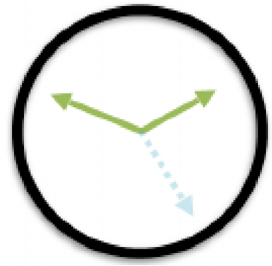
BACKUP

2-lepton stop search: Introduction (SUS-17-001)

CATEGORIZATION:

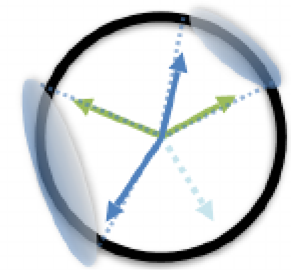
- Splitting in same and opposite flavor leptons
- MET
- $M_{T2}(ll)$
- $M_{T2}(lblb)$

$M_{T2}(ll)$

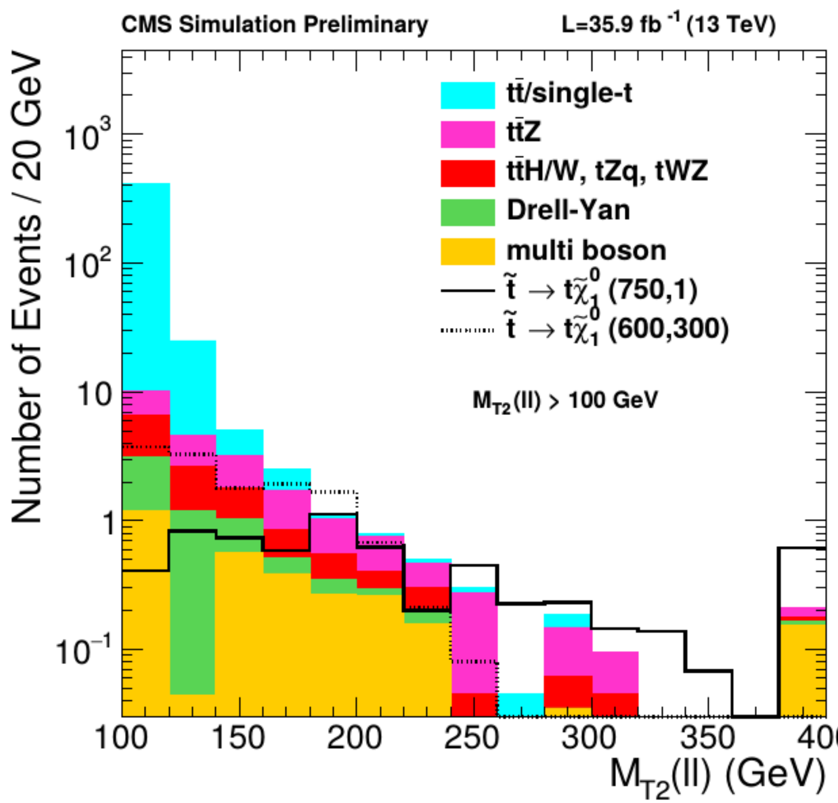


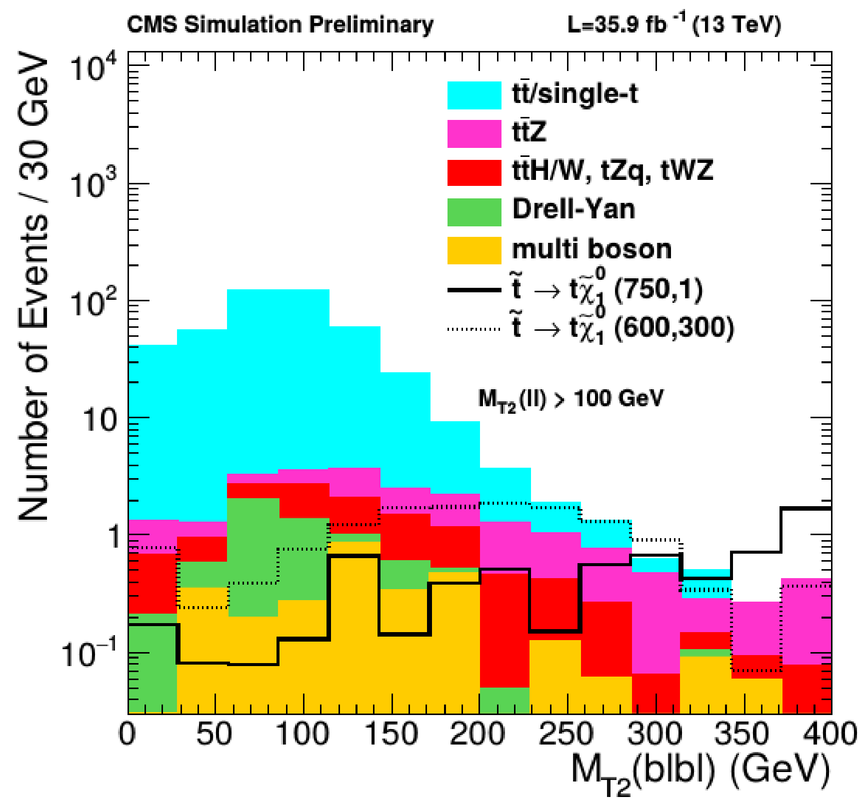
leptons+MET
→ endpoint at W mass

$M_{T2}(lblb)$



leptons+MET+bjets
→ endpoint at top mass

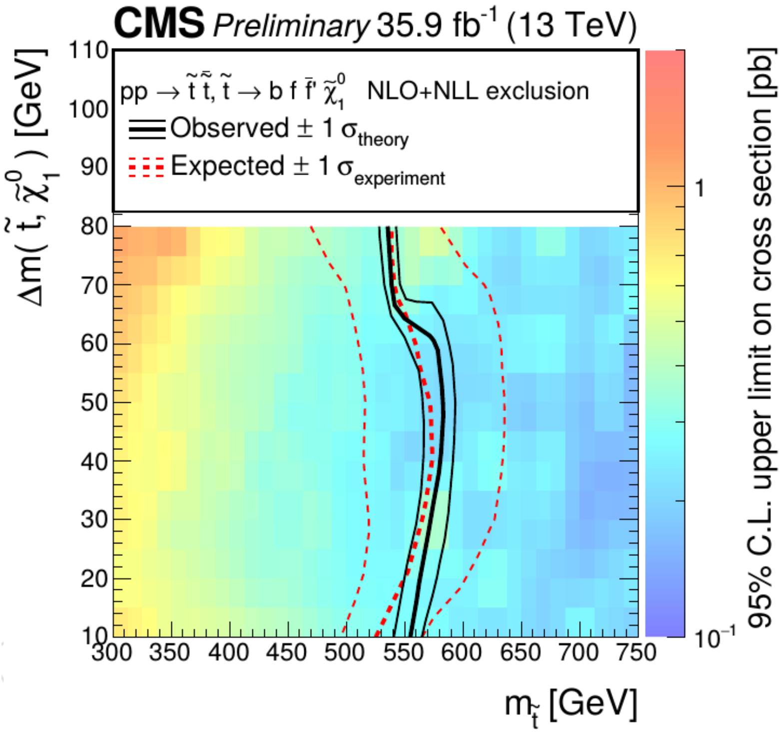


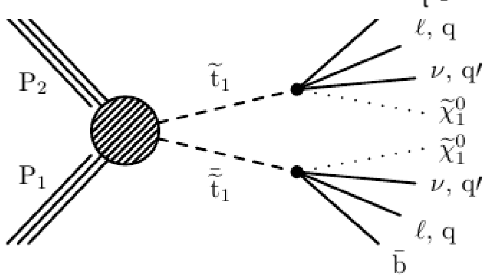


$$M_{T2}(\ell\ell) = \min_{\vec{p}_{T1}^{\,\text{miss}}+\vec{p}_{T2}^{\,\text{miss}}=\vec{p}_{T}^{\,\text{miss}}} \left(\max \left[M_T(\vec{p}_{T}^{\,\text{vis1}}, \vec{p}_{T1}^{\,\text{miss}}), M_T(\vec{p}_{T}^{\,\text{vis2}}, \vec{p}_{T2}^{\,\text{miss}}) \right] \right); \quad \vec{p}_{T}^{\,\text{vis1,2}} = \vec{p}_{T}^{\,\ell 1,2}$$

Other processes

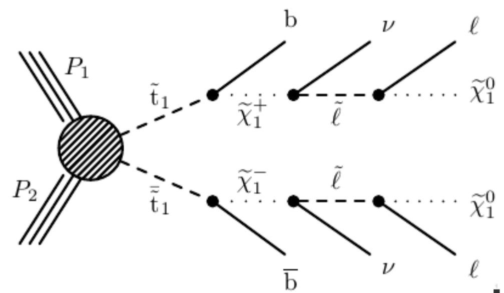
SUS-16-049



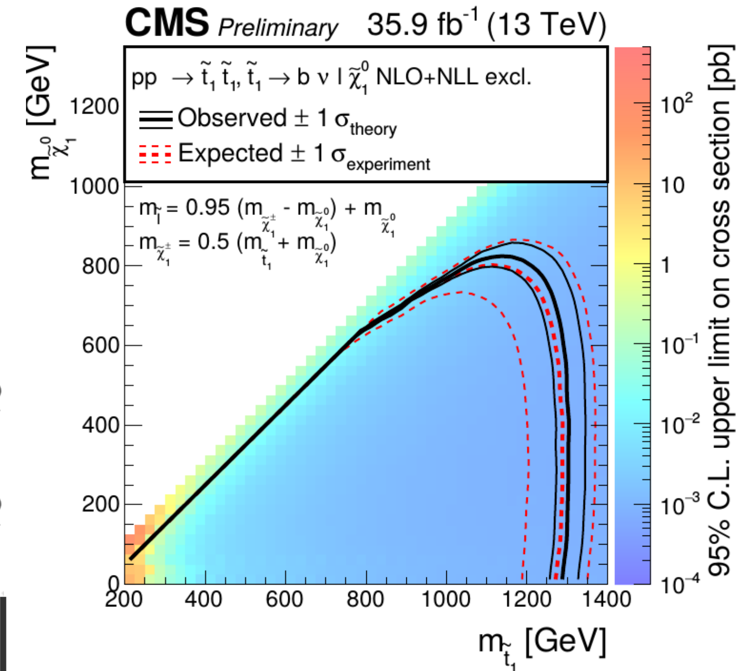


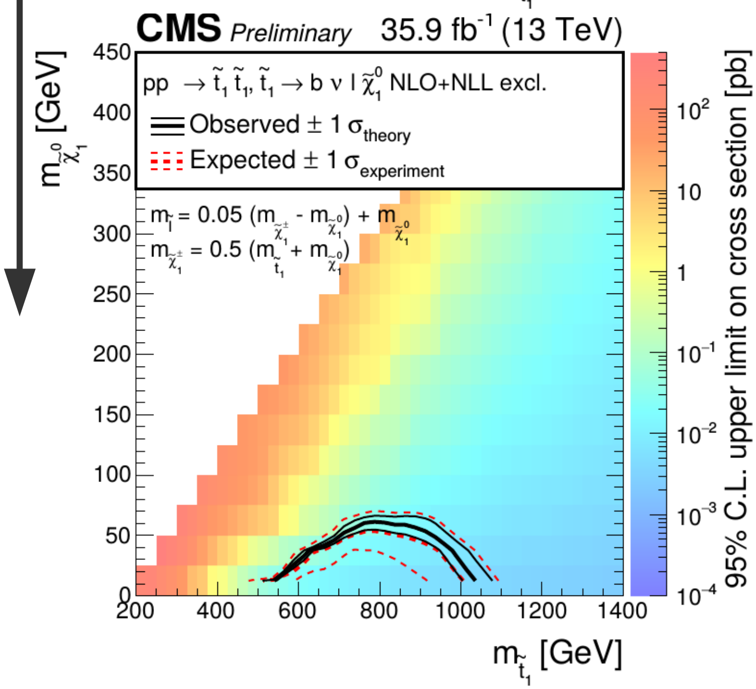
Exclude:
Stop~580 GeV
Neutralino~540 GeV

SUS-17-001
Cascade decay:



Different masses of intermediate particles (chargino,slepton)
→ much **weaker limits**

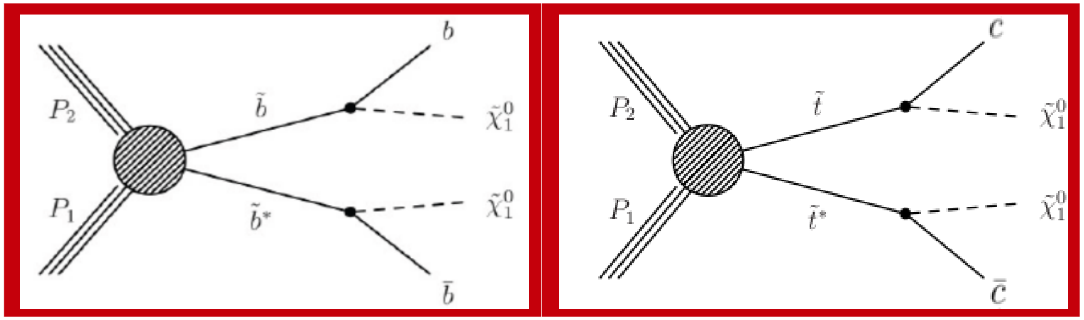




Sbottom searches

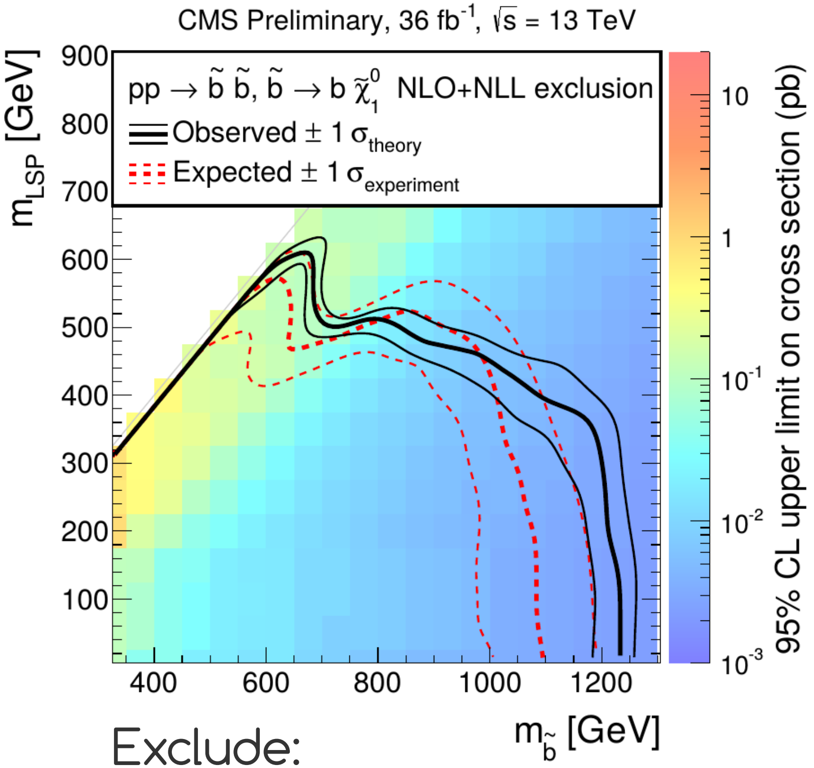
- Several decay channels of sbottom are studied in CMS
- In this talk focus only on:

  sbottom → b + neutralino



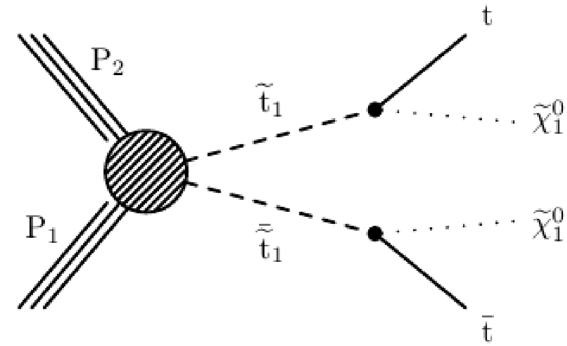
0-lepton sbottom/stop search (SUS-16-032)

- Search for direct bottom/top squarks production in final states with b/c jets and no leptons
- Heavy flavor jets tagging – first time the c-tagger is used in an analysis in CMS
- Separate optimizations
  - Low Δm
    - Δm(sbottom/stop,neutralino)<100 GeV
    - ISR, soft b-tagging
  - High Δm
    - Δm(sbottom,neutralino)>100 GeV

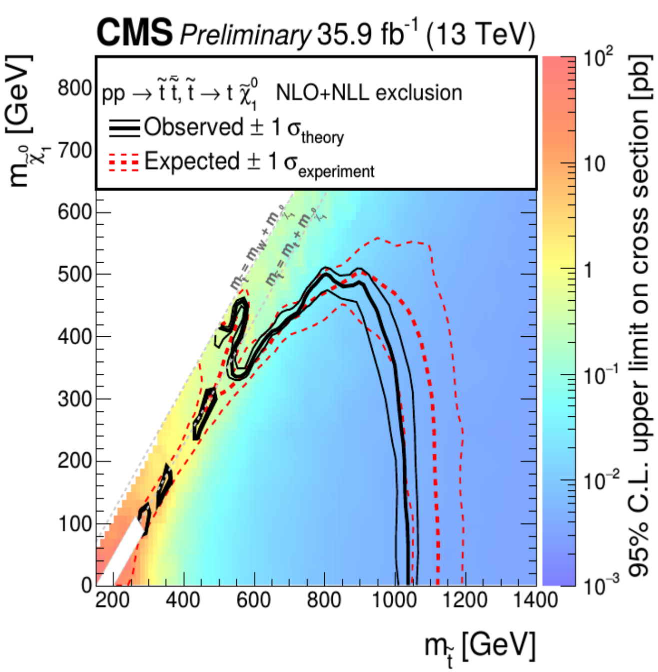


Exclude:
Sbottom~1225GeV
Neutralino~600GeV

Interpretations

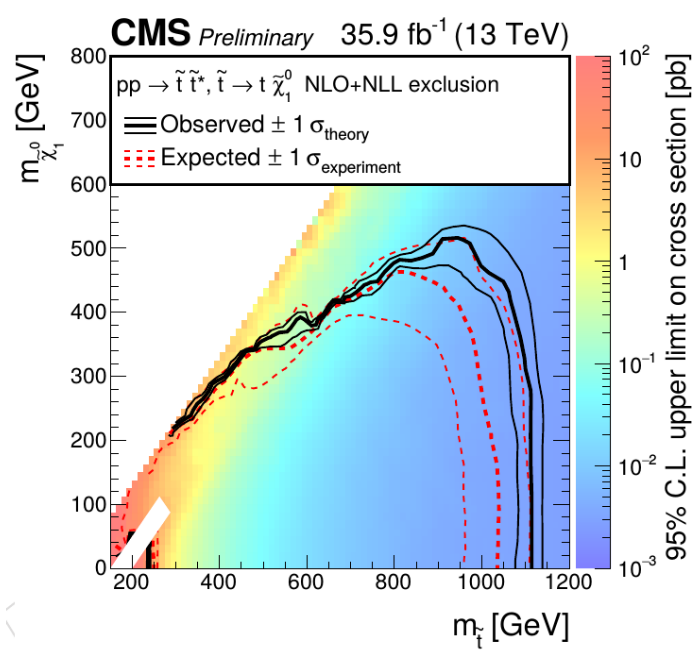


0-lep SUS-16-049



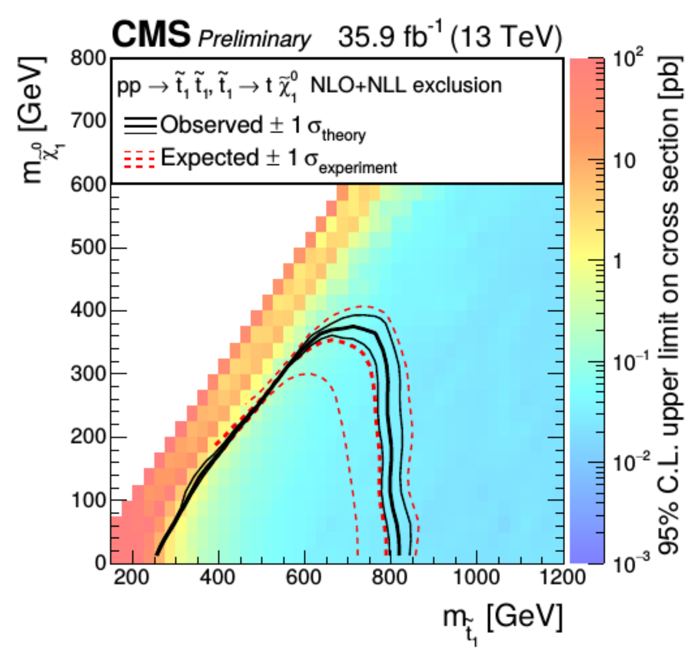
Exclude:
Stop~1040 GeV
Neutralino~500 GeV

1-lep SUS-16-051



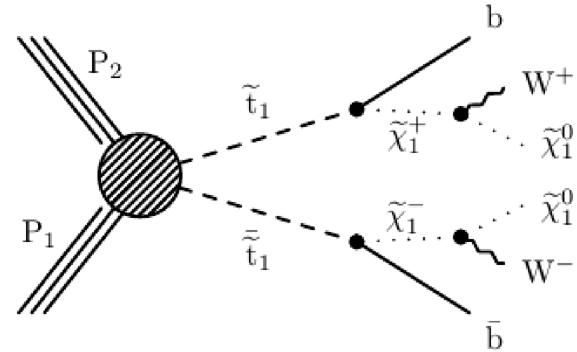
Exclude:
Stop~1120 GeV
Neutralino~515 GeV

2-lep SUS-17-001

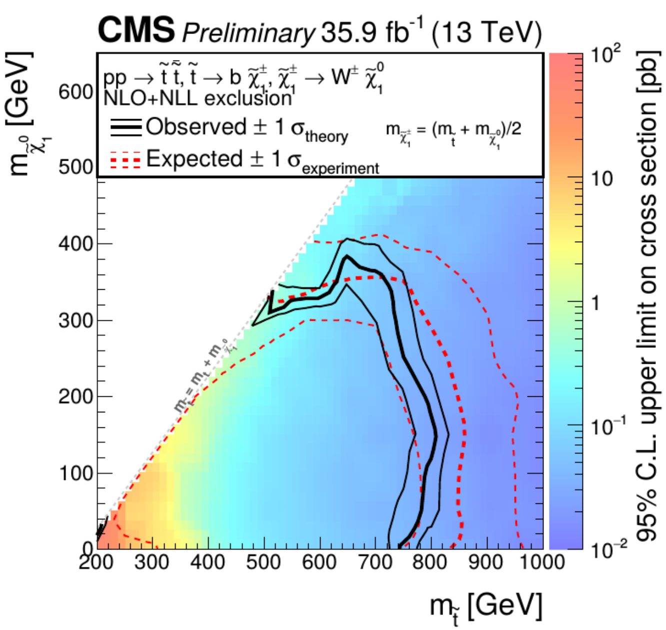


Exclude:
Stop~850 GeV
Neutralino~380 GeV

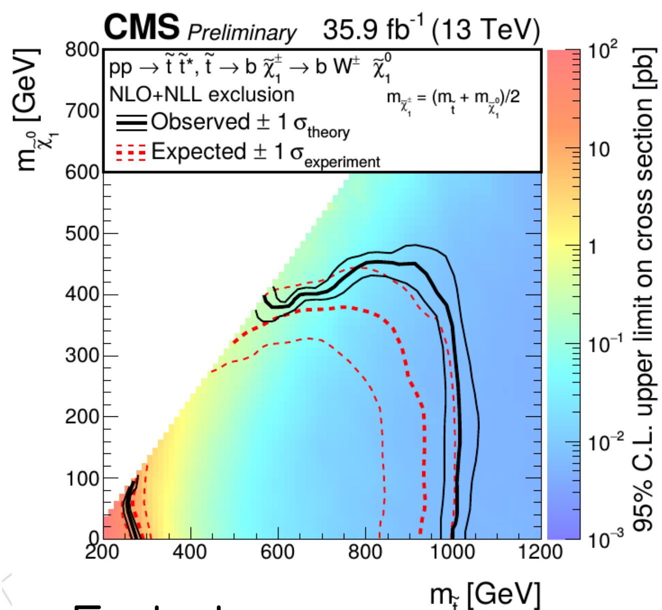
Interpretations



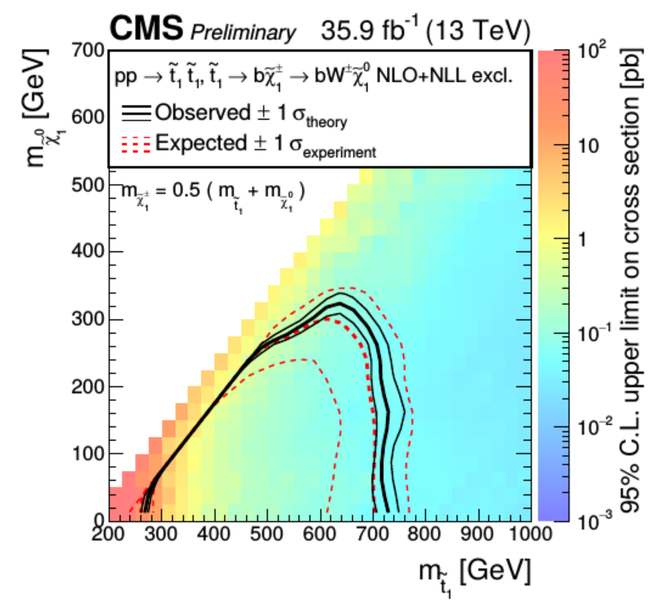
0-lep SUS-16-049



1-lep SUS-16-051



2-lep SUS-17-001

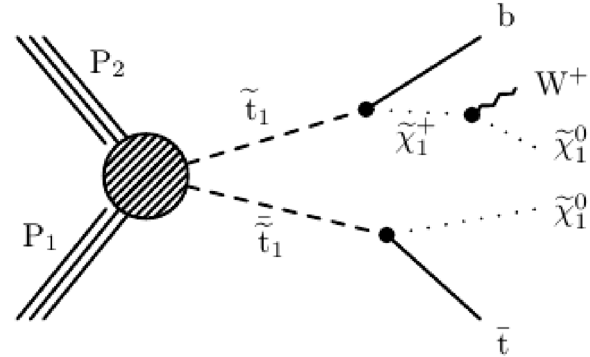


Exclude:
Stop~800 GeV
Neutralino~360 GeV

Exclude:
Stop~1025 GeV
Neutralino~460 GeV

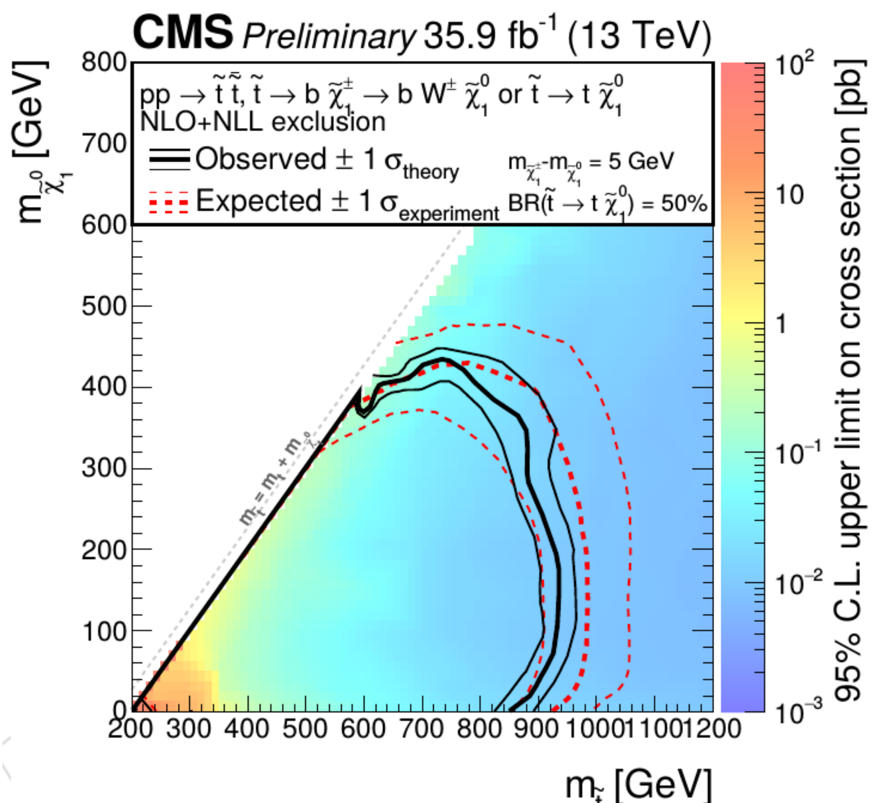
Exclude:
Stop~750 GeV
Neutralino~300 GeV

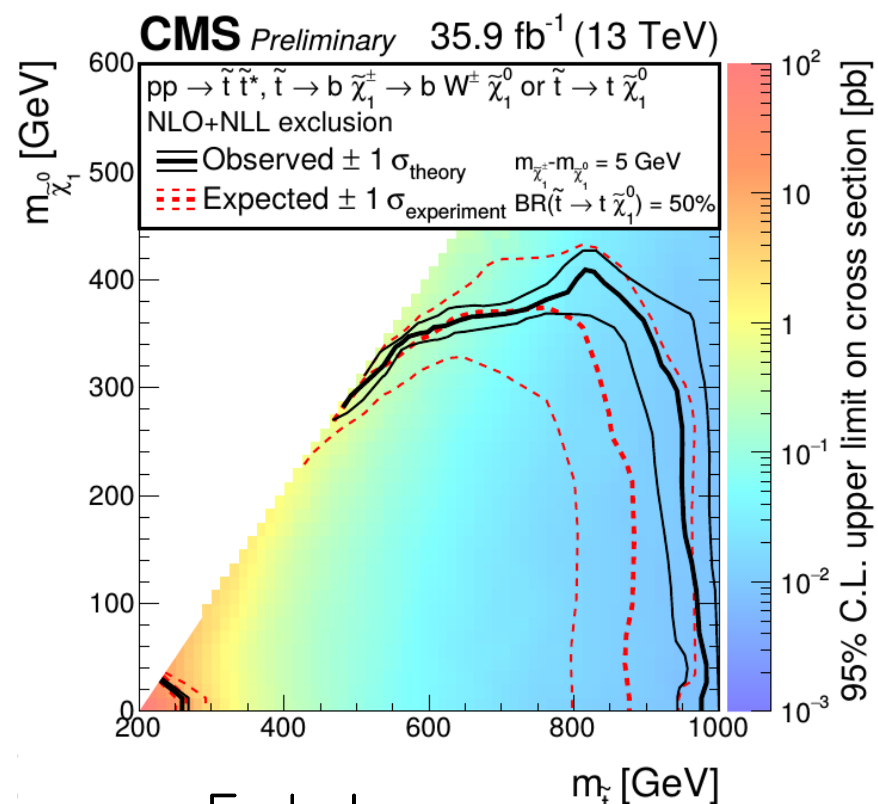
Interpretations



0-lep SUS-16-049

1-lep SUS-16-051

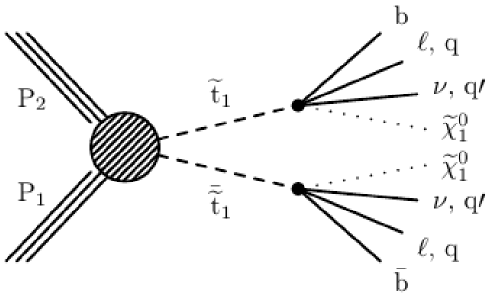




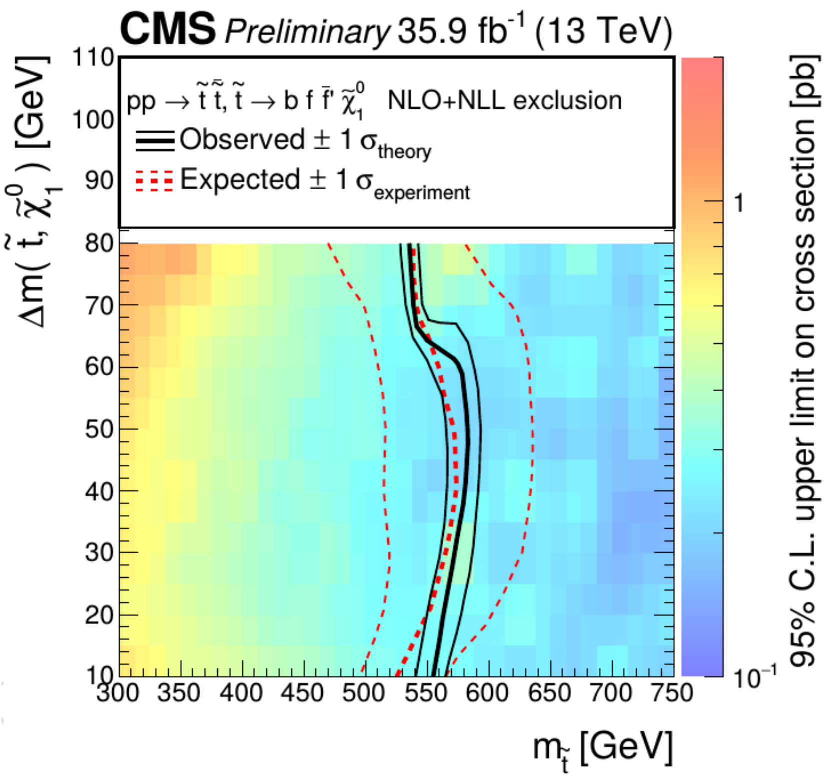
Exclude:
Stop~940 GeV
Neutralino~440 GeV

Exclude:
Stop~980 GeV
Neutralino~400 GeV

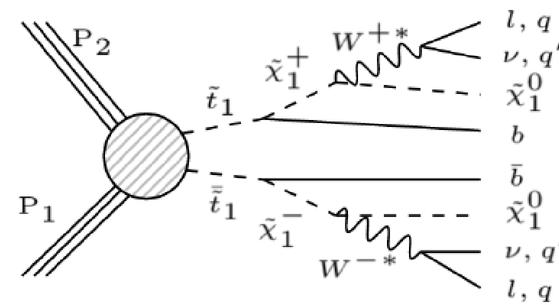
Interpretations



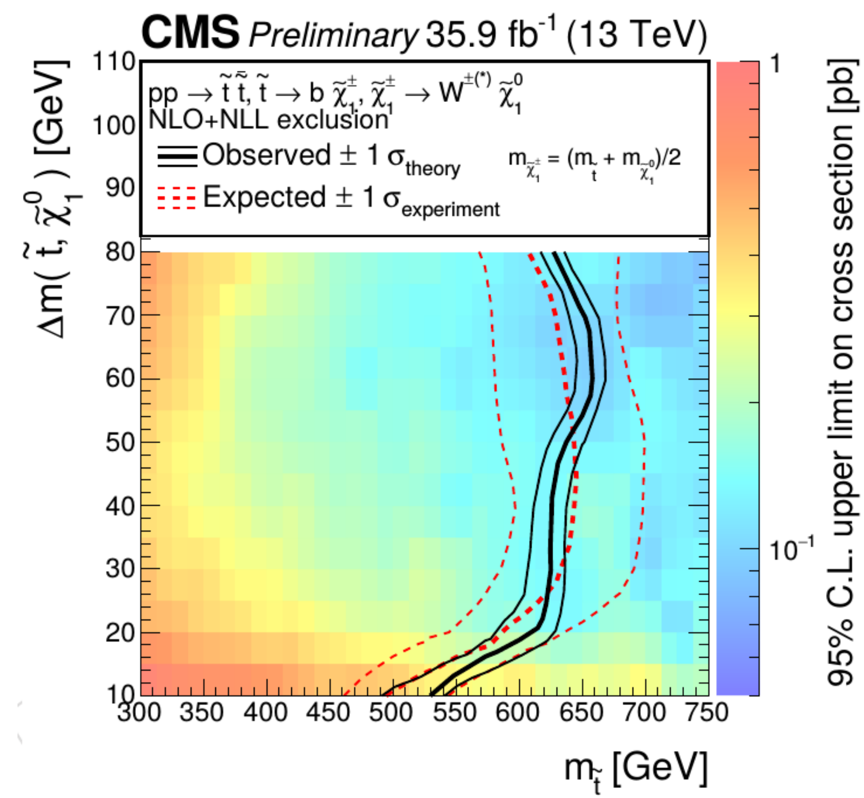
0-lep SUS-16-049



Exclude:
Stop~580 GeV
Neutralino~540 GeV



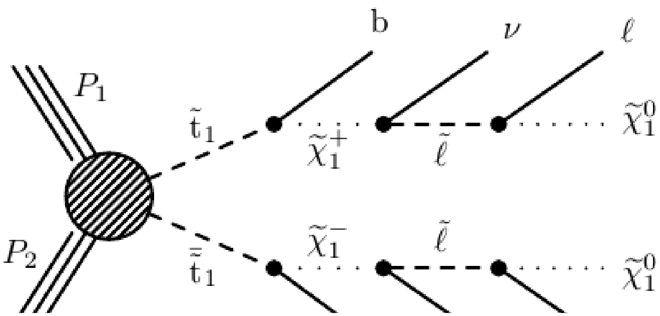
0-lep SUS-16-049

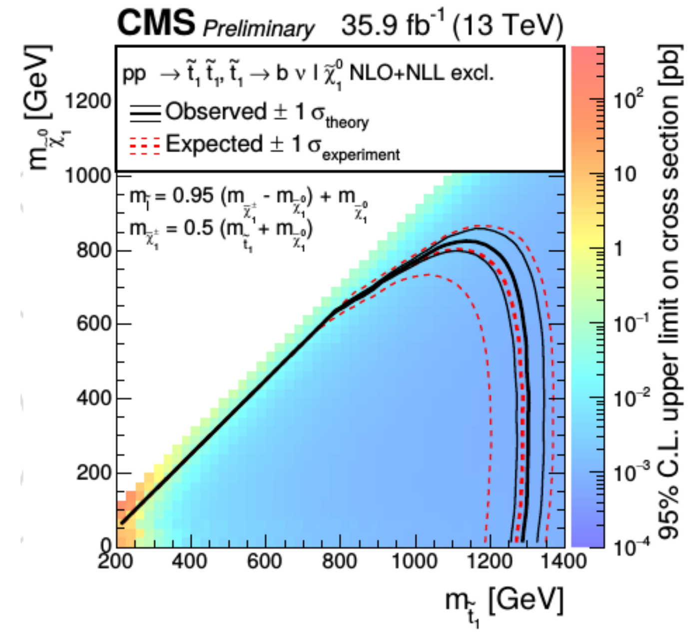


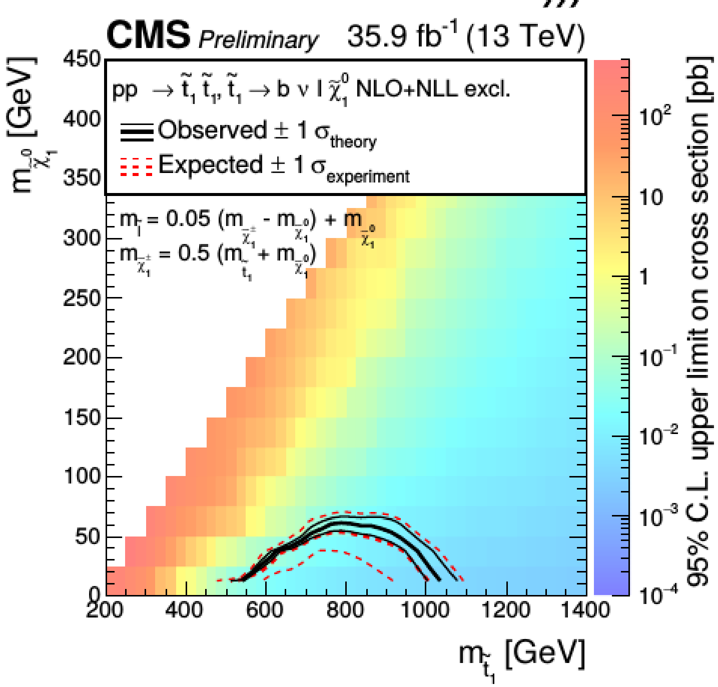
Exclude:
Stop~660 GeV
Neutralino~610 GeV

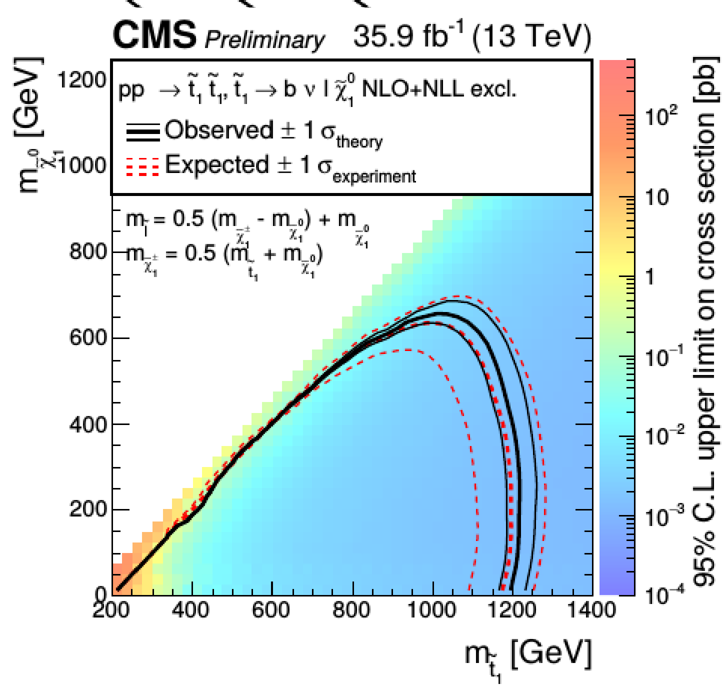
Interpretations - Cascade decay to two leptons

2-lep SUS-17-001

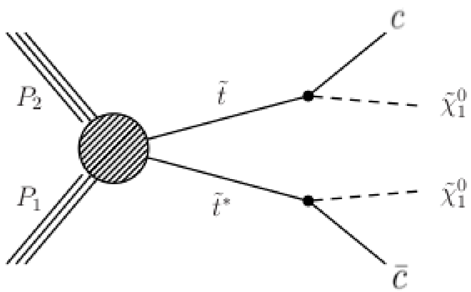




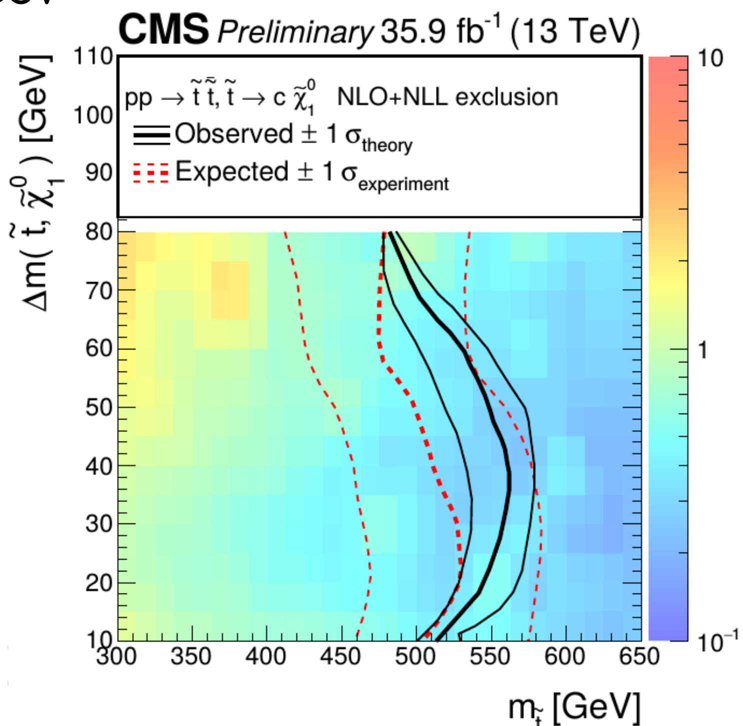




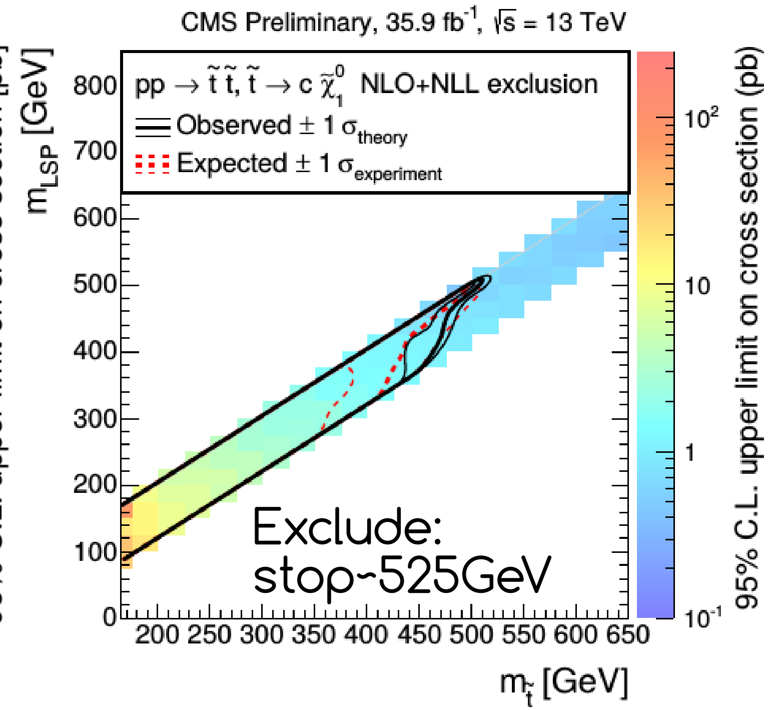
Exclude:
Stop~560 GeV
Neutralino~510 GeV

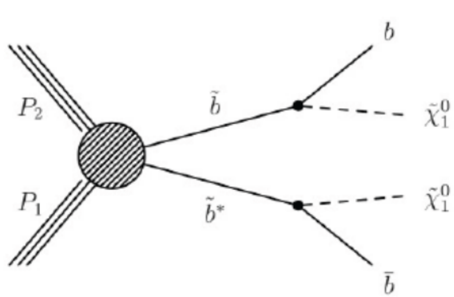


0-lep SUS-16-049

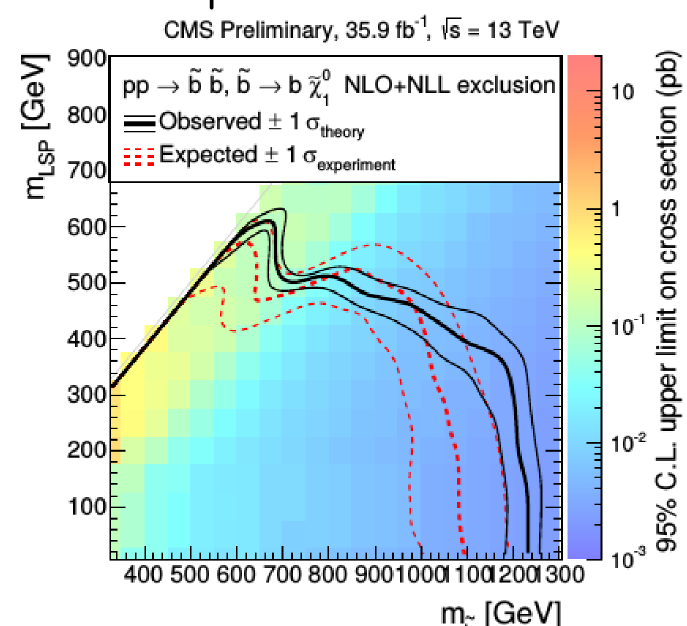


0-lep SUS-16-032





0-lep SUS-16-032

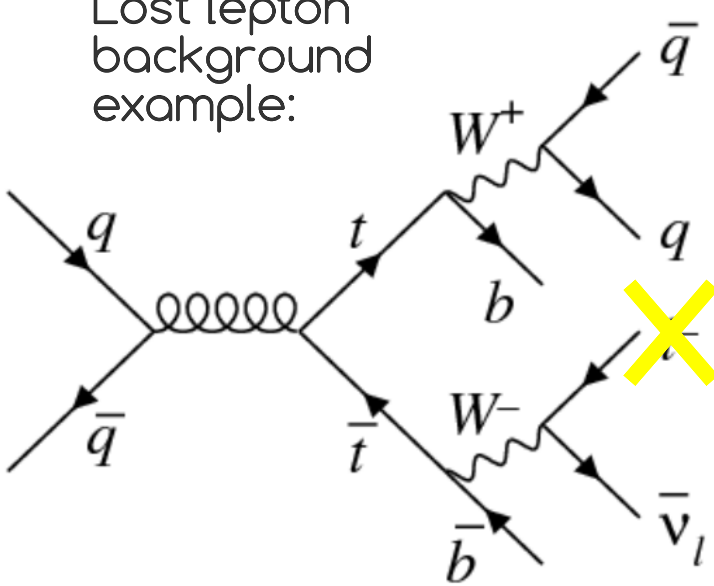


Exclude:
sbottom~1225GeV
neutralino~600GeV

Background composition

Final state	Typical background (ordered)				
0 lepton	Lost lepton (ttbar→1l, W+jets, single top) or Z→nunu for Atlas	Z+jets(Z→νν)	QCD	Rare (ttZ, diboson)	
1 lepton	Lost lepton (ttbar→2l,tW)	W+jets	Z→νν (ttZ,WZ)	ttbar→1l	
2 leptons	ttZ	Top backgroud (ttbar/single top→2l)	ttH/W,tZq,WZ	multiboson	DY

Lost lepton background example:



Background	Typically estimated → in majority of cases data driven methods
Lost lepton	Data driven; CR with **additional lepton** w.r.t. SR
Z→νν+jets	Data driven; **Z→ll** and/or **γ+jets** samples
QCD	Data driven; **low Δφ** CR
ttZ (WZ)	From MC with normalization derived from data
W+jets→1l	Data driven; **reverted b-tag** CR
Rare	Usually taken **from MC**

0-lepton stop search: low vs high Δm

	Low Δm category	High Δm category
Preselection	MET>250 GeV, $\Delta\varphi$ (j_1,MET)>0.5, $\Delta\varphi$ ($j_{2,3}$,MET)>0.15 MET/sqrt(HT)>10	MET>250 GeV, $\Delta\varphi(j_{1,2,3}$,MET)>0.5
N_{jets}	≥2	≥5
N_{bjets}	≥0	≥1
M_T(b,MET) [GeV]	<175	>175
Tagging	ISR tagging (|$\Delta\varphi$(ISR,MET)|>2), soft-b tagging, veto top/W tags	Top/W tagging
Categorization	N_{jets}, N_{bjets}, p_T(b), MET, $N_{soft\text{-}btags}$, p_T(ISR)	N_{jets}, N_{bjets}, MET, N_{top}, N_W, $N_{resolved\text{-}top}$

H_T - sum of the pT of jets

For the background with one source of MET, the Δφ between MET and jet should be small (e.g. MET and jet originate from one top)

M_T(object,MET) = $\text{sqrt}(2p_T^{object}\text{MET}(1-\cos(\Delta\varphi_{ojbect,MET})))$

Top/W veto helps significantly to reduce ttbar background

Low and high Δm regions are orthogonal and statistically combined for interpretation

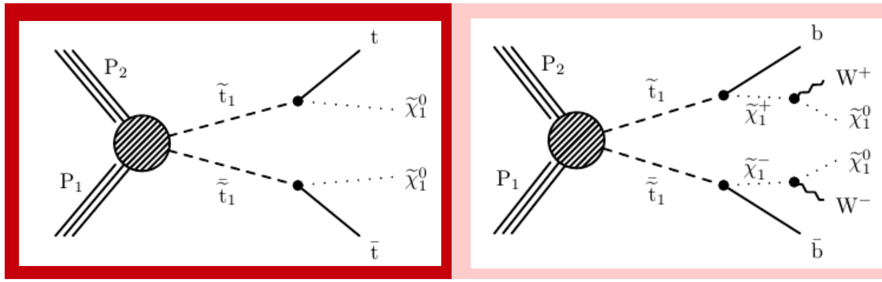
1-lepton stop search

Nominal analysis:

- PRESELECTION:
- **≥2 jets**
- **≥1 medium btag** (or tight to gain more sensitivity in regions dominated by W+jets)
- **MET>250 GeV**
- **Δφ ($j_{1,2,3}$,MET)>0.8**
- **M_T>150 GeV** (helps to suppress mainly W+jets and ttbar→1l, due to its endpoint at W mass)

CATEGORIZATION:

- **2-3 jets, ≥4 jets**
- **MET**
- **M_{lb}** (Invariant mass of reconstructed lepton and closest b-quark)
- **Modified topness** (variable telling how well the event agrees with ttbar→ 2l hypothesis)



Compressed analysis:

- Additional jet requirement → **ISR**
- **Leading jet not b-taged** (ISR is not b)
- **p_T(lep)<150 GeV** (lepton relatively soft)
- **Δφ(lep,MET)<2** (system boosted in one direction)
- **≥1 medium btag**
- **M_T(lep,MET)>150 GeV** (endpoint at W mass if the only source of MET is one neutrino)
- **MET>250 GeV**
- **Δφ($j_{1,2,3}$,MET)>0.5**

2-lepton stop search

PRESELECTION:

- $M_{T2}(ll)$>100GeV, MET>80GeV
- 2 leptons, at least 1 bjet and 2 jets

CATEGORIZATION:

- **$M_{T2}(ll)$** = min ($M_T(l1)$,$M_T(l2)$) → endpoint at W mass if no additional MET in event
- **$M_{T2}(lblb)$** – endpoint at top mass
- **MET**

BACKGROUND ESTIMATION:

- **Top background**
  - Normalize to $M_{T2}(ll)$<100GeV control region
- One global fit is used to constrain **DY, diboson and ttZ**
  - Fit of DY and dibosons in 13 CR
  - Fit of ttZ in 5 CR
- Other **(ttH, ttW, tZq, ...)** taken from simulations with 25% uncertainty

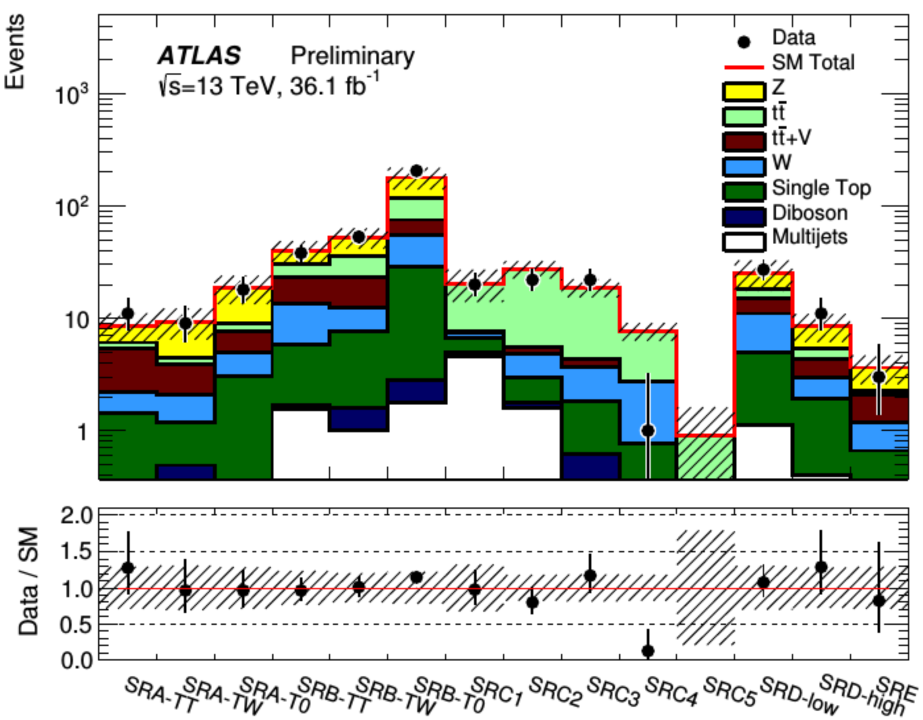
0-lepton sbottom/stop search

MET enhanced due to ISR

Contransverse mass
$m_{CT} = 2p_T(j_1)p_T(j_2)(1+\cos\Delta\varphi(j_1,j_2))$

	Low Δm category	High Δm category
Used in	Δm(sbottom/stop,neutralino)<100 GeV	Δm(sbottom,neutralino)>100 GeV
Preselection	MET>250 GeV, min $\Delta\varphi(j_{1,2,3}$,MET)>0.4, (p_T(ISR)+MET)/MET<0.5	MET>250 GeV, min $\Delta\varphi(j_{1,2,3}$,MET)>0.4, min $m_T(j_{1,2}$,MET)>250 GeV, m_{CT}>150 GeV
N_{jets}	2,3 or 4	2,3 or 4
N_{bjets}	≥0	2 leading jets must be b-tagged
Tagging	ISR tagging, soft-b tagging	-
Categorization	N_{bjets}, N_{cjets}, $N_{soft\text{-}btags}$, MET, H_T(of bjets)	MET, m_{CT}, H_T(of two leading jets)

Results



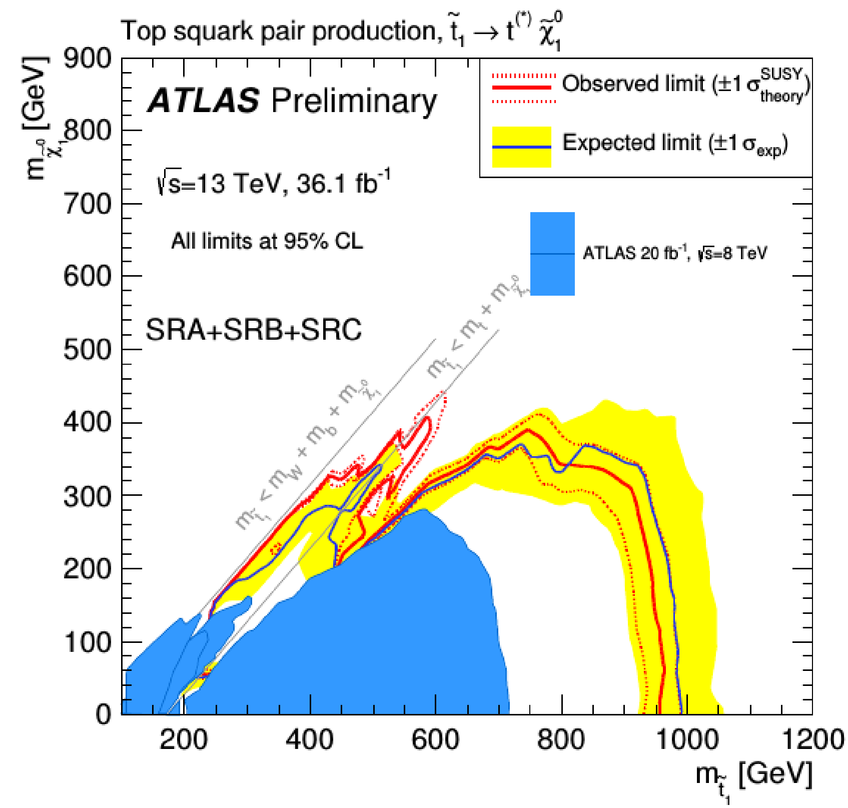
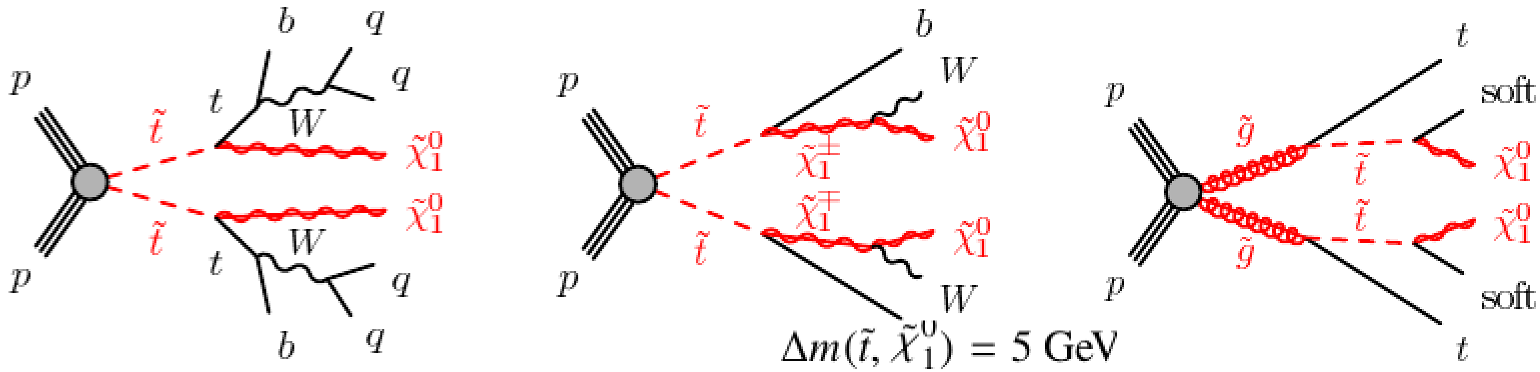


Figure 8 shows the observed (solid red line) and expected (solid blue line) exclusion limits at 95% CL in the $\tilde{t}$ - $\tilde{\chi}_1^0$ mass plane for $\int \mathcal{L}\, dt = 36.1\ \mathrm{fb}^{-1}$ for SRA, SRB, and SRC. The data excludes top-squark masses between 450 and 950 GeV for $\tilde{\chi}_1^0$ masses below 160 GeV extending Run 1 limits from the combination of

Atlas all hadronic

ATLAS-CONF-2017-020



(a) $\tilde{t} \to t^{(*)} \tilde{\chi}_1^0$ (b) $\tilde{t} \to b\tilde{\chi}_1^{\pm} \to bW^{(*)}\tilde{\chi}_1^0$ (c) $\tilde{g} \to t\tilde{t} \to t\tilde{\chi}_1^0$+soft

at least four jets and large missing transverse momentum

Sensitivity to the region where $m_{\tilde{t}} - m_{\tilde{\chi}_1^0} \sim m_t$, which typically has relatively low-p_{T} final state objects and low $E_{\mathrm{T}}^{\mathrm{miss}}$, is achieved by exploiting events in which high-p_{T} jets from initial-state radiation (ISR) boosts the di-top-squark system in the transverse plane. For this regime, $t\bar{t}$ production makes up the dominant

Five sets of signal regions (SRA-E) are defined to target each topology and kinematic regime. SRA (SRB) is sensitive to production of high-mass $\tilde{t}$ pairs with large (intermediate) $\Delta m(\tilde{t}, \tilde{\chi}_1^0)$. Both SRA and SRB employ top-mass reconstruction techniques to reject background. SRC is designed for the highly compressed region with $\Delta m(\tilde{t}, \tilde{\chi}_1^0) \sim m_t$. In this signal region, initial-state radiation (ISR) is used to improve sensitivity to these decays. SRD is targeted at $\tilde{t} \to b\tilde{\chi}_1^{\pm}$ decays, where no top-quark candidates are reconstructed. SRE is optimized for scenarios with highly-boosted top quarks that can occur in gluino-mediated top-squark production.

(36.1 ± 1.2) fb^{-1}

A,B

The decay products of the $t\bar{t}$ system in the all-hadronic decay mode can often be reconstructed as six distinct $R = 0.4$ jets. The transverse shape of these jets is typically circular with a radius equal to this distance parameter, but when two of the jets are less than $2R$ apart in $\eta - \phi$ space, the one-to-one correspondence of a jet with a top daughter may no longer hold. Thus, the two hadronic top candidates are reconstructed by applying the anti-k_t clustering algorithm [52] to the $R = 0.4$ jets, using reclustered distance parameters of $R = 0.8$ and $R = 1.2$. Two $R = 1.2$ reclustered jets are required; the mass of the highest-p_{T} $R = 1.2$ reclustered jet is shown in Fig. 2 (a). The events are divided into three categories based on the resulting $R = 1.2$ reclustered jet masses ordered in p_{T}, as illustrated in Fig. 3: the “TT” category includes events with two top candidates i.e. with masses $m^{0}_{\mathrm{jet},R=1.2} > 120$ GeV and $m^{1}_{\mathrm{jet},R=1.2} > 120$ GeV, the “TW” category contains events with one top candidate and a W candidate i.e. where $m^{0}_{\mathrm{jet},R=1.2} > 120$ GeV and $60 < m^{1}_{\mathrm{jet},R=1.2} < 120$ GeV, and the “T0" category represents events with only one top candidate, i.e. where $m^{0}_{\mathrm{jet},R=1.2} > 120$ GeV and $m^{1}_{\mathrm{jet},R=1.2} < 60$ GeV. Since the signal-to-background ratio is quite different in each of these categories, they are optimized individually for both SRA and SRB.

$$m_{\mathrm{T}}^{b,\mathrm{min}} = \sqrt{2\, p_{\mathrm{T}}^{b}\, E_{\mathrm{T}}^{\mathrm{miss}} \left[1 - \cos\Delta\phi\left(\mathbf{p}_{\mathrm{T}}^{b}, \mathbf{p}_{\mathrm{T}}^{\mathrm{miss}}\right)\right]} > 200\ \mathrm{GeV},$$

is made on the mass of the leading (in p_{T}) R=0.8 reclustered jet to be consistent with a W candidate: $m^{0}_{\mathrm{jet},R=0.8} > 60$ GeV. Additionally, requirements on the stransverse mass ($m_{\mathrm{T2}}^{\chi^2}$) [64, 65] are made which

C

signal topology is very similar to SM $t\bar{t}$ production. In the presence of high-momentum ISR, which can be reconstructed as multiple jets and form an ISR system, the di-top-squark system is boosted in the transverse plane. The ratio of the $E_{\mathrm{T}}^{\mathrm{miss}}$ to the p_{T} of the ISR system in the centre-of-mass (CM) frame ($p_{\mathrm{T}}^{\mathrm{ISR}}$), defined as R_{ISR}, is proportional to the ratio of the $\tilde{\chi}_1^0$ and $\tilde{t}$ masses [66, 67]:

$$R_{\mathrm{ISR}} \equiv \frac{E_{\mathrm{T}}^{\mathrm{miss}}}{p_{\mathrm{T}}^{\mathrm{ISR}}} \sim \frac{m_{\tilde{\chi}_1^0}}{m_{\tilde{t}}}. \tag{2}$$

A recursive jigsaw reconstruction technique, as described in Ref. [68], is used to divide each event into an ISR hemisphere and a sparticle hemisphere, where the latter consists of the pair of candidate top squarks, each of which decays via a top quark and a $\tilde{\chi}_1^0$. Objects are grouped together based on their proximity in the lab frame's transverse plane by minimizing the reconstructed transverse masses of the ISR system and sparticle system simultaneously over all choices of object assignment. Kinematic variables are then defined based on this assignment of objects to either the ISR system or the sparticle system. This method

D,E

SRD is optimized for direct top-squark pair production where both top squarks decay via $\tilde{t} \rightarrow b\tilde{\chi}_1^{\pm}$ where $m_{\tilde{\chi}_1^{\pm}} = 2m_{\tilde{\chi}^0}$. In this signal region, at least five jets are required, two of which must be b-tagged. The

SRE is designed for models which have highly-boosted top quarks. Such signatures can arise from direct pair production of high-mass top partners, or from the gluino-mediated compressed $\tilde{t}$ scenario with large $\Delta m(\tilde{g}, \tilde{t})$. In this regime, reclustered jets with $R = 0.8$ are utilized to optimize experimental sensitivity to these highly-boosted top quarks. In this signal region, at least four jets are required, two of which must be b-tagged. Additional discrimination is provided by a measure of the $E_{\mathrm{T}}^{\mathrm{miss}}$ significance: $E_{\mathrm{T}}^{\mathrm{miss}}/\sqrt{H_{\mathrm{T}}}$,