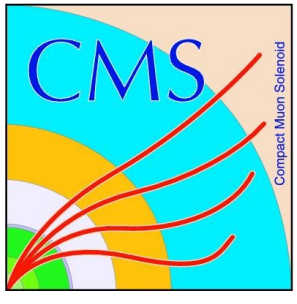
# Searches for supersymmetric partners of third-generation quarks with CMS

Markéta Jansová
(IPHC Strasbourg)

On behalf of the CMS collaboration




DIS 2017, Birmingham

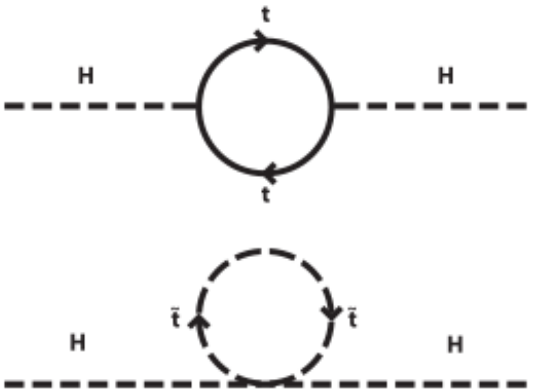
# Outline

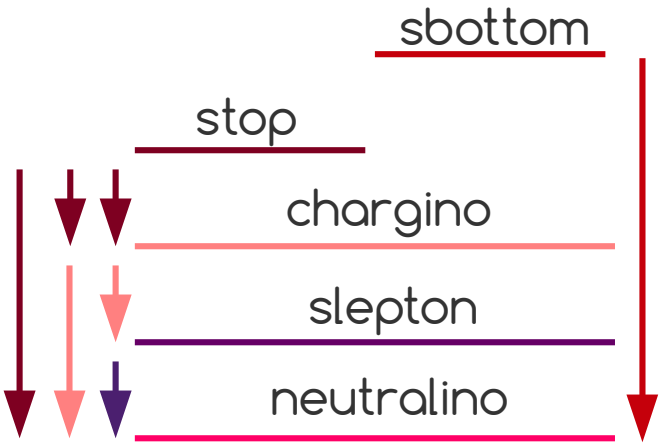
1. Motivation
2. Stop searches
   i. 0-lep stop search
   ii. 1-lep stop search
   iii. 2-leps stop search
   iv. Interpretations
3. Sbottom searches
   i. Sbottom and stop 0-lep search
4. Conclusion

# Motivation

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

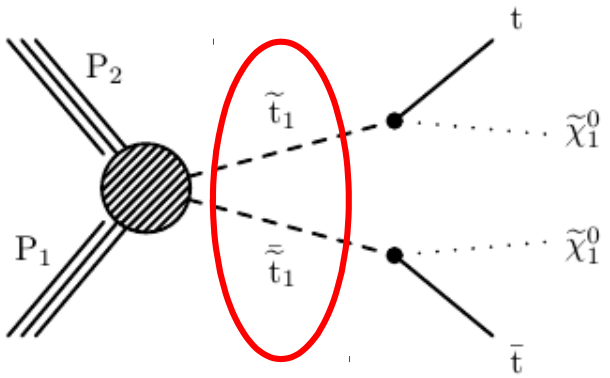
    → third-generation squarks are expected to be light
- SUSY predicts a dark matter candidate
  - SUSY scenario dependent – it can be a neutralino, a slepton or a gravitino
- Only Simplified Model Spectrum (SMS) is considered here
  - In considered models the lightest supersymmetric particle (LSP) is the neutralino



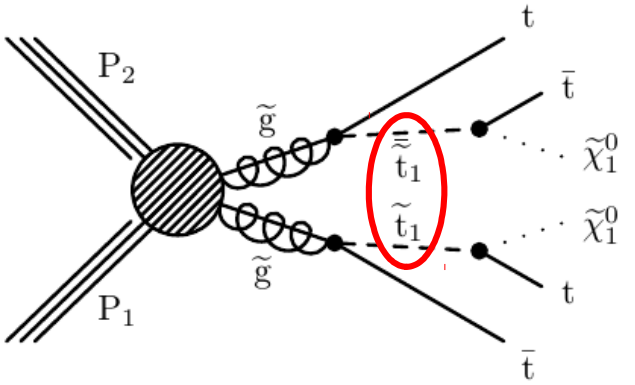
# Production of the stop quarks

- Direct (e.g.)

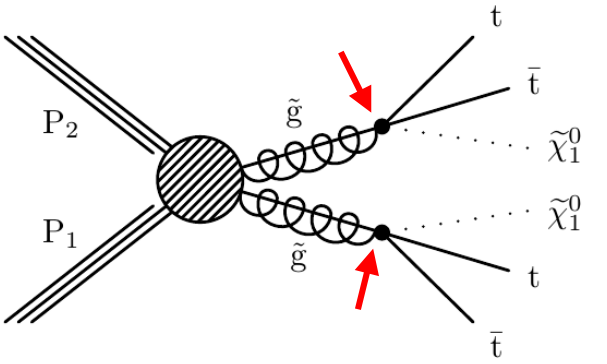



→ more in following slides

- Gluino mediated
  - On-shell stop




  - Off-shell stop

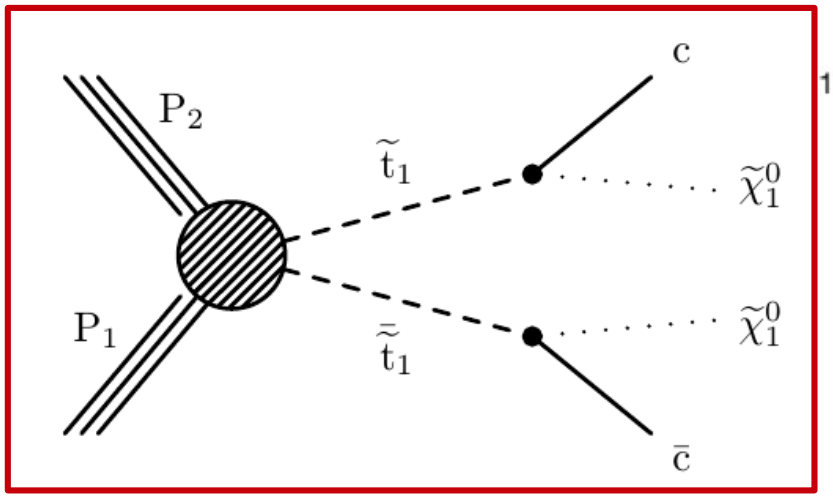


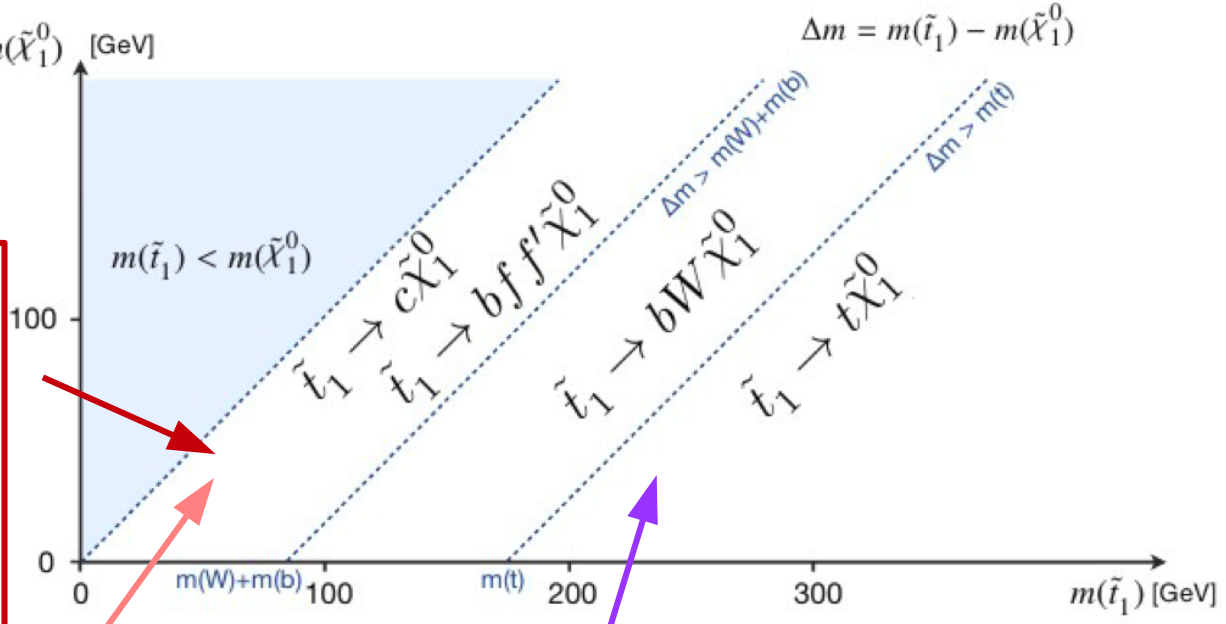

→ will not be presented here

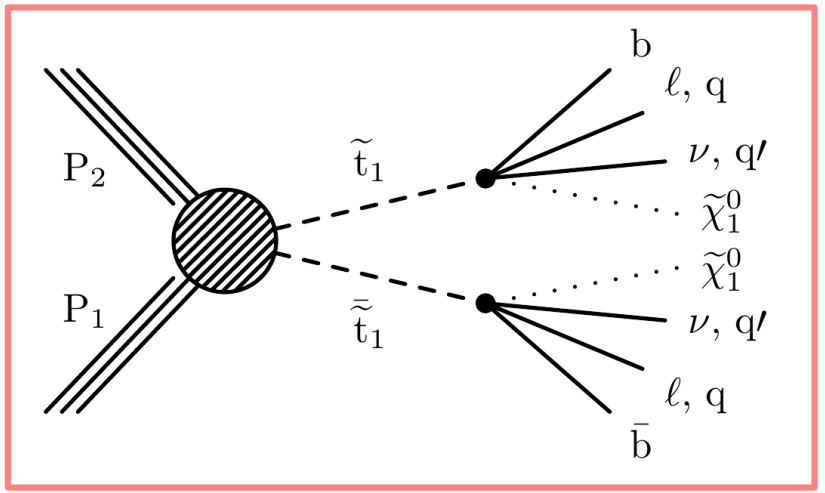
# Stop decay channels: Basic

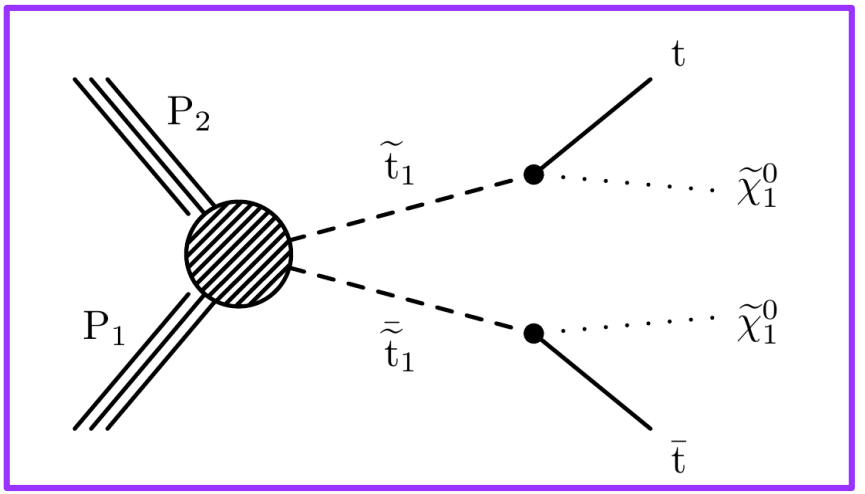
stop

neutralino

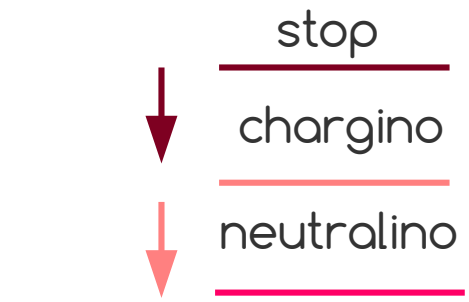


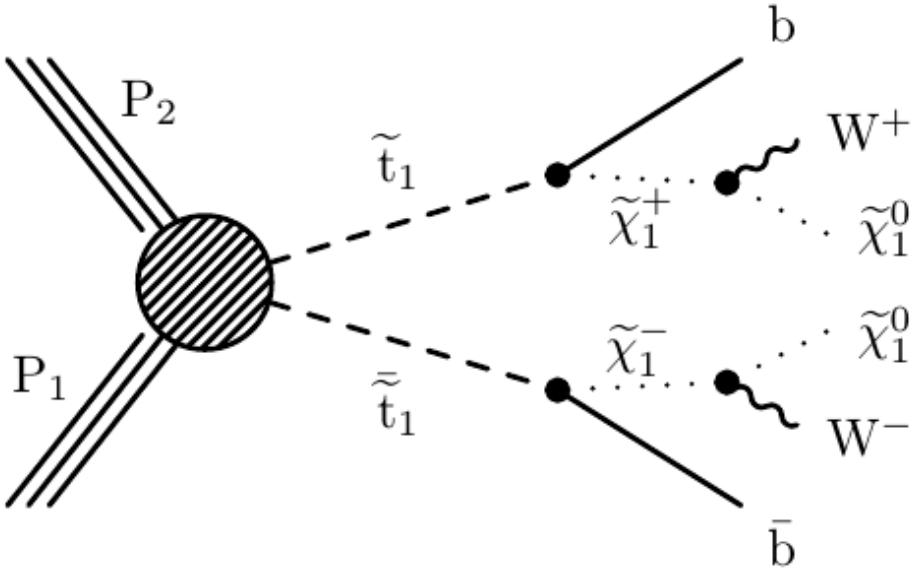



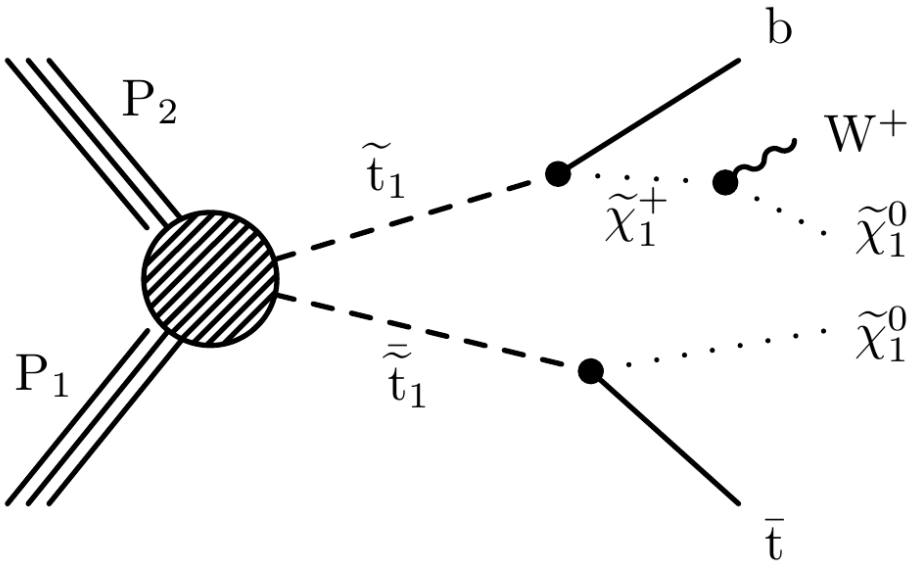



# Stop decay channels: Adding intermediate chargino




**Consider:**
m(chargino) = 0.5(m(stop)-m(neutralino))



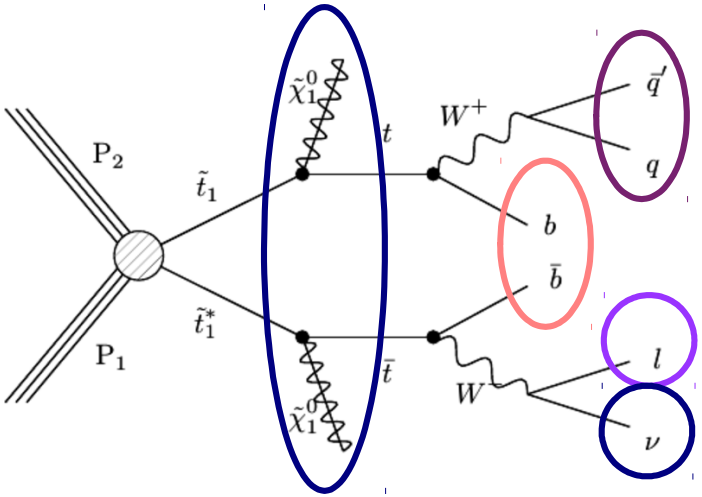

**Consider:**
m(chargino) = 5 GeV+m(neutralino))

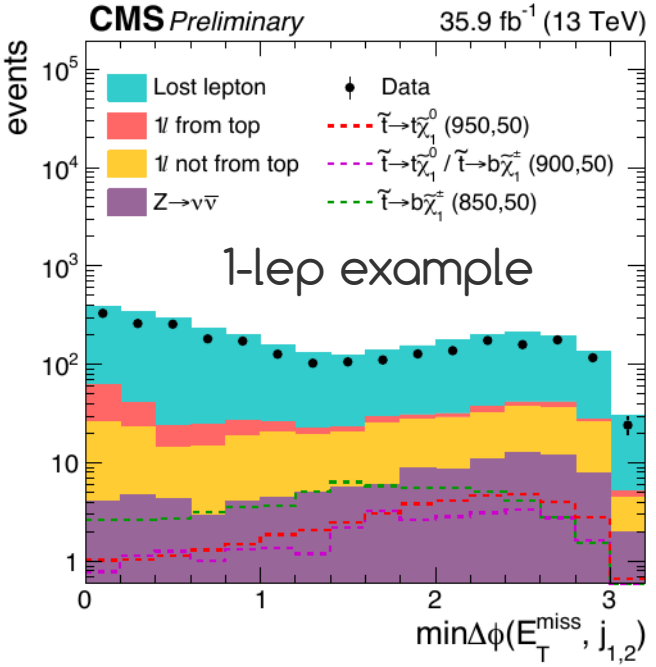
# Signal signature (example)

- 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
  - Example: min Δφ (jets,MET) shape different for signal and some backgrounds

1-lep example



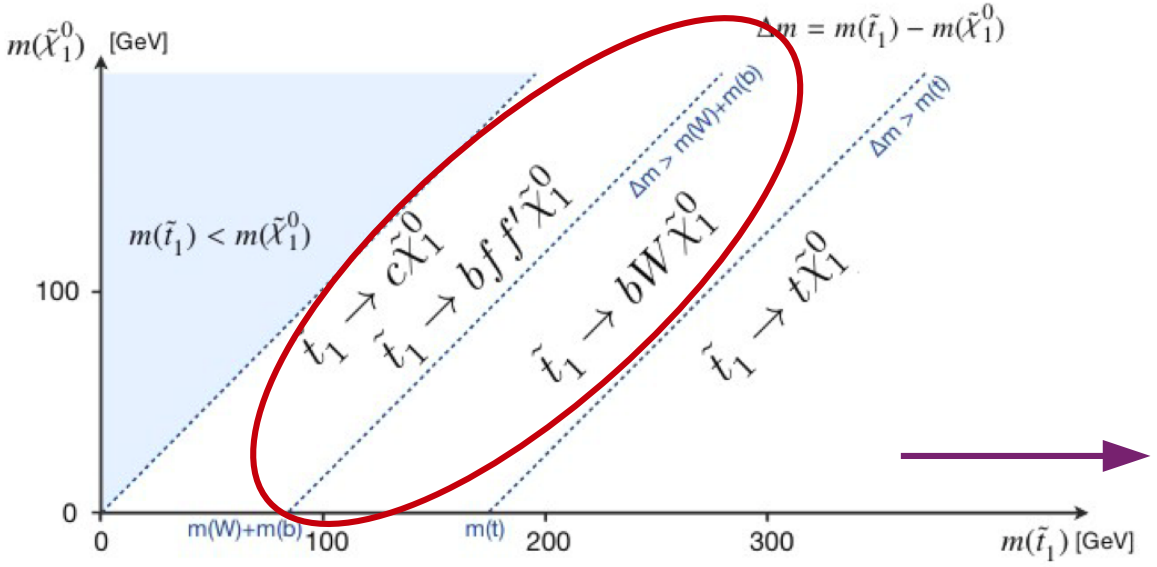
# Coverage of different kinematics regimes

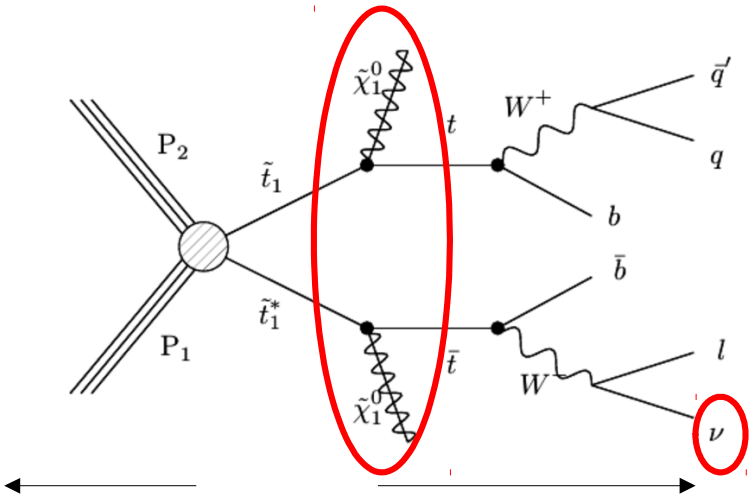
**Low Δm**

- Δm = m($\tilde{t}$)-m(LSP)
  → compressed spectra
- Kinematics similar to bkg one
- Soft decay products
  → to have sufficient MET

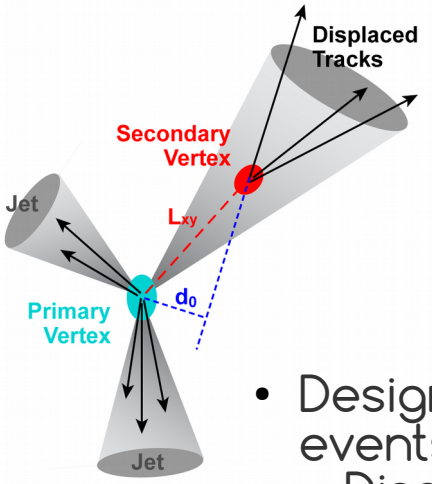
**boost against ISR** needed – additional not b-tagged jet

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




ISR system Boost of the stop system




**High Δm**

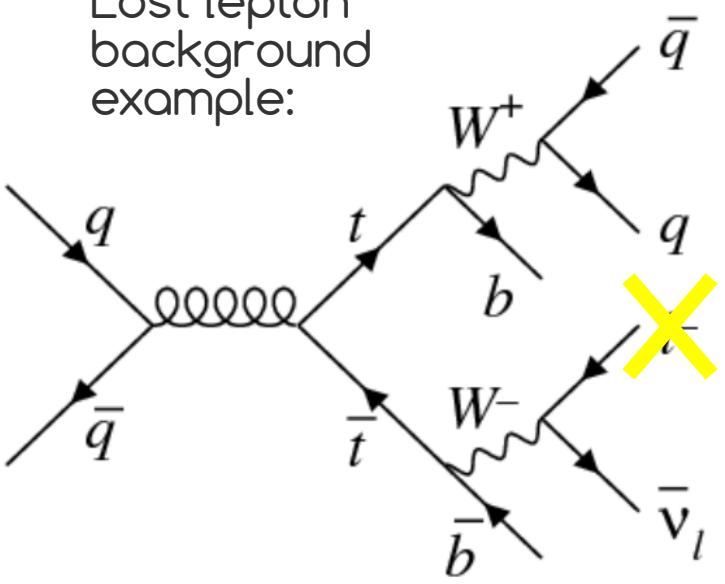
- Boosted topologies
  → W/top tagging
- Different final state kinematics than in case of low Δm

- Design variables for **categorization** of events:
  - Disentangle signals with different kinematics
  - Disentangle different backgrounds
    → use of various signal regions

# Background composition

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

Lost lepton background example:



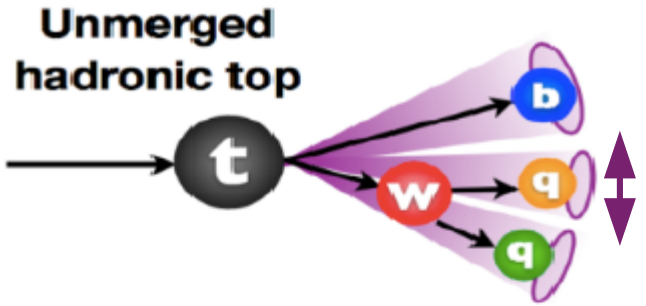

| Background | Typically estimated → in majority of cases data driven methods |
|---|---|
| Lost lepton | Data driven; CR with **additional lepton** w.r.t. SR |
| Z→vv+jets | Data driven; **Z→ll** and/or **γ+jets** samples |
| QCD | Data driven; **low Δφ** CR |
| ttZ (WZ) | From MC with normalization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

# 0-lepton stop search: top/W/resolved-top tagging (SUS-16-049)

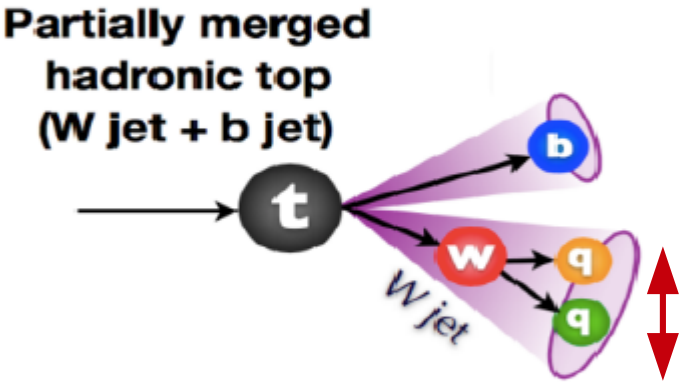
- Use Multivariate analysis techniques (BDT) to distinguish 3-jet combination from top vs random combination
- Variables for BDT:
  - Kinematics of jets
  - Jet flavor discriminants
  - QG variables

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

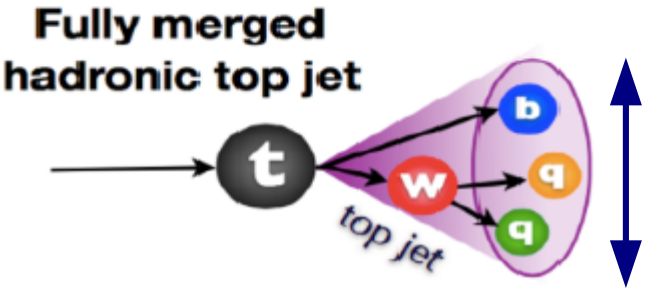
$p_T$




Resolved top tag: Standard ak4 jet




W-tag: Fat ak8 jet
- $p_T$>200 GeV
- 50<$m_{SD}$<110 GeV




Top-tag: Fat ak8 jet
- $p_T$>400 GeV
- $m_{SD}$>110 GeV

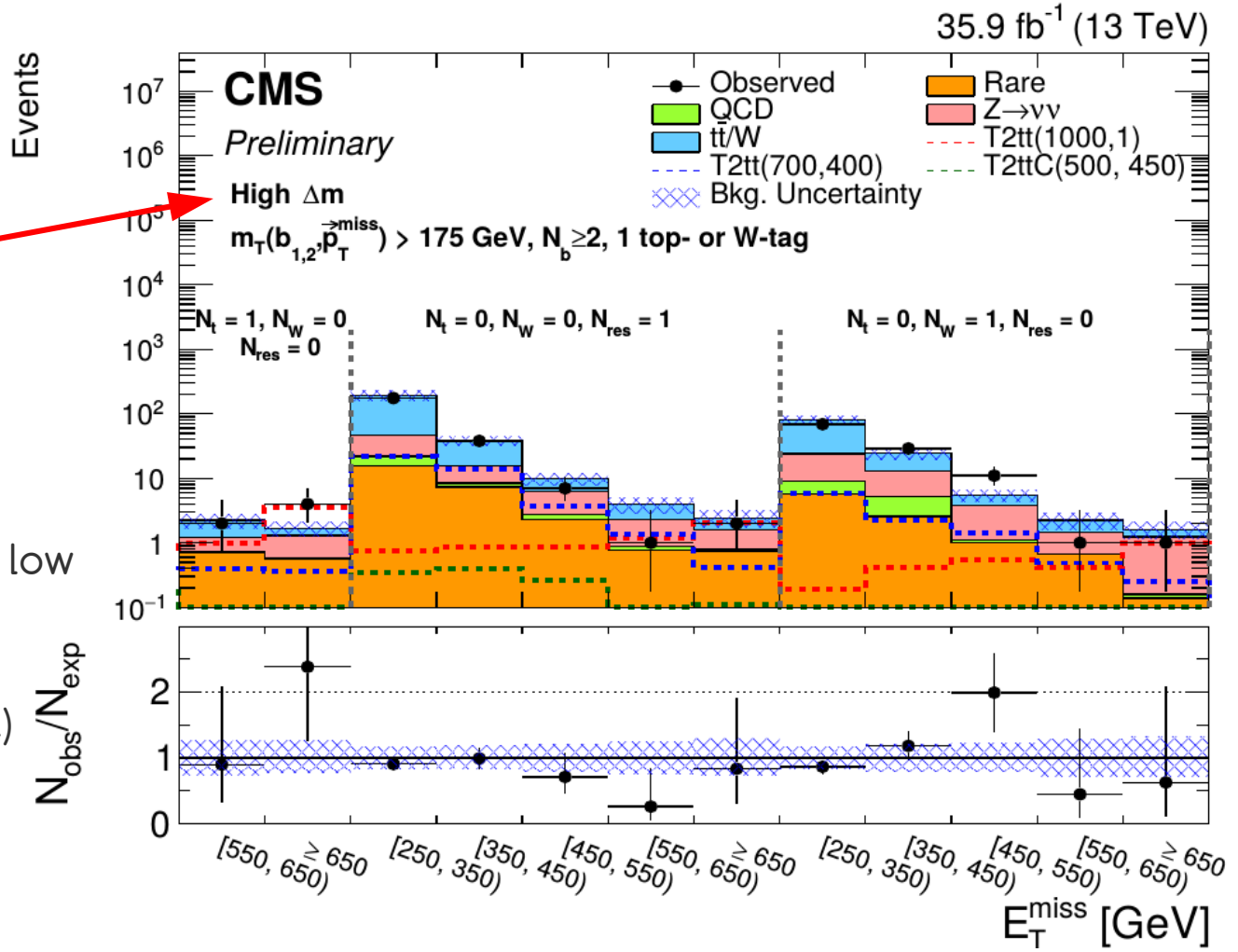
| | Resolved-top tagger | W-tagger | Top-tagger |
|---|---|---|---|
| Efficiency/ mistag rate | Up to ~70% / 10% | Up to ~50% / 10% | Up to ~50% / 4% |

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

# 0-lepton stop search: Categorization

Different optimizations:

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

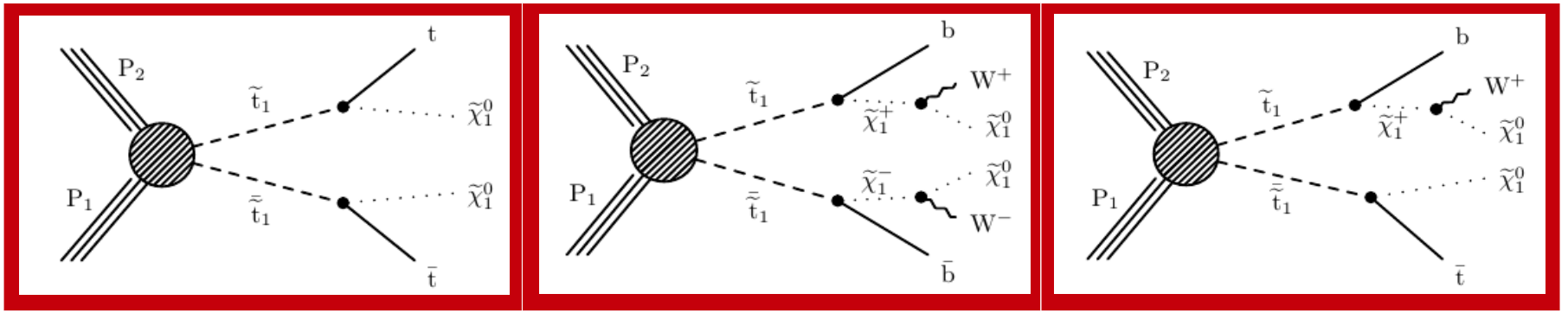



CATEGORIZATION:

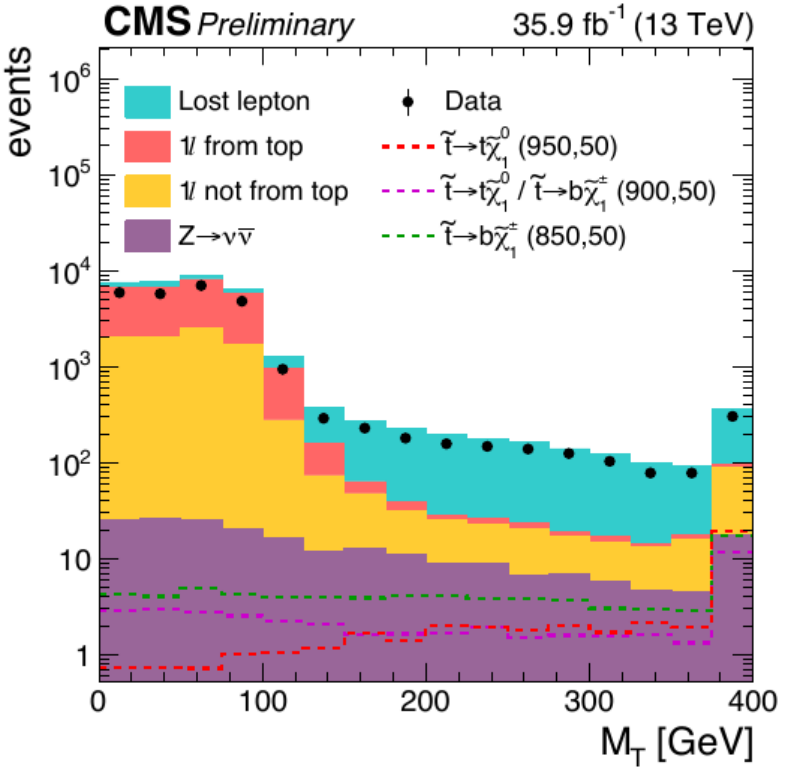
- $M_T$(b,MET) – discriminates between low and high Δm signal signature
- Low Δm
  - $N_{jets}$, $N_{bjets}$, $p_T$(b), MET, $N_{soft\text{-}btags}$, $p_T$(ISR)
- High Δm
  - $N_{jets}$, $N_{bjets}$, MET, $N_{top}$, $N_W$, $N_{resolved\text{-}top}$

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

# 1-lepton stop search: Introduction (SUS-16-051)




- Separate analysis in the compressed region for the stop→t+LSP → increase of the sensitivity
  - Used for 100<Δm($\tilde{t}$,LSP)<225 GeV
  - Additional jet requirement → ISR



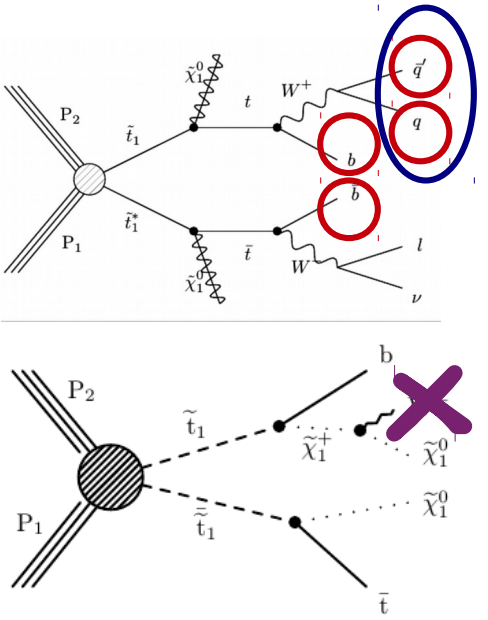

$M_T$(lep,MET)>150 GeV
- Powerful variable for selection
- Helps to suppress mainly W+jets and ttbar→1ℓ, due to its endpoint at W mass

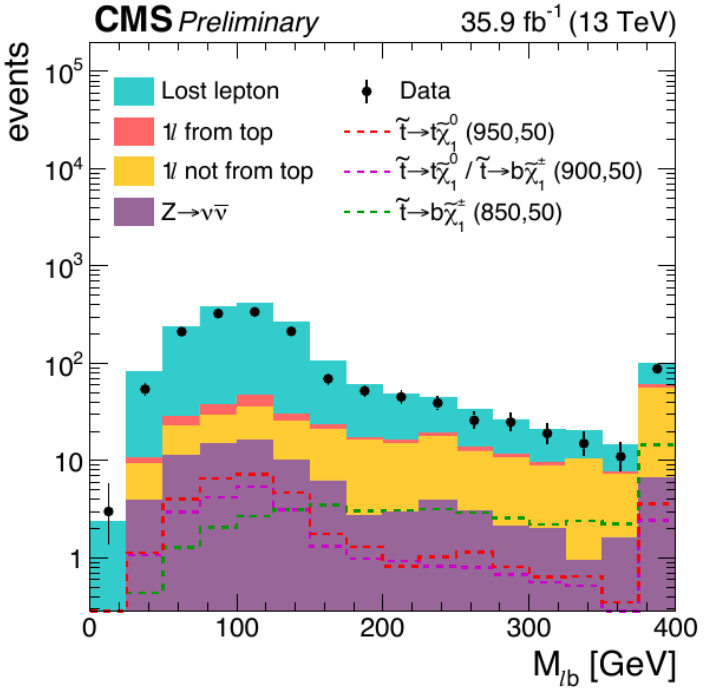
# 1-lepton stop search: Categorization

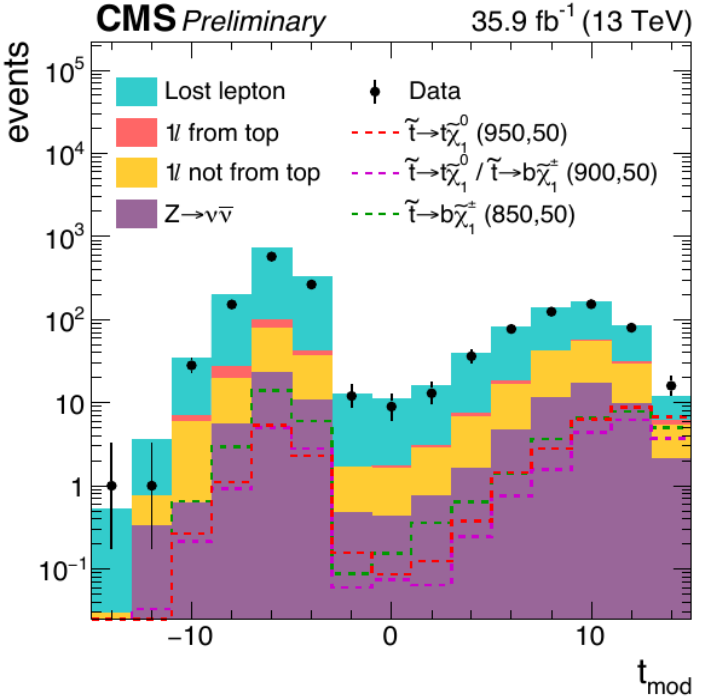
CATEGORIZATION:

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

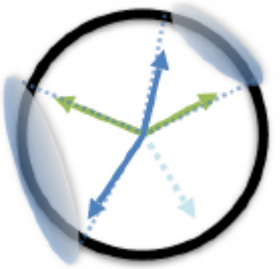
- 2-3 jets
  - boosted topologies → merged jets
  - chargino and neutralino almost mass degenerated → soft jets
- ≥4 jets



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



CATEGORIZATION:

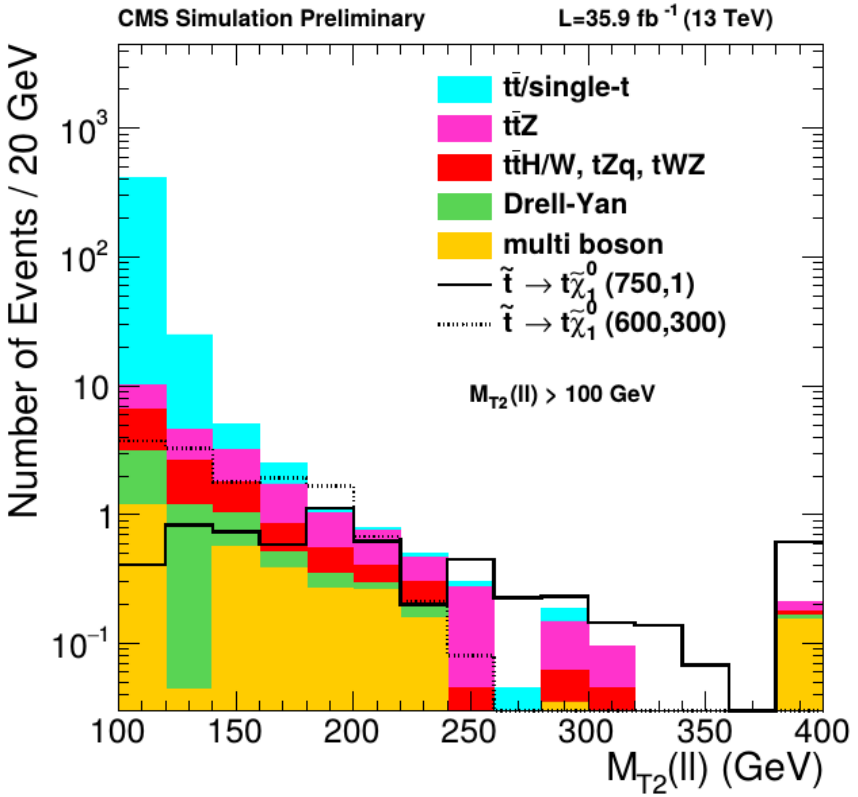
- Splitting in same and opposite flavor leptons
- MET
- $M_{T2}(ll)$
- $M_{T2}(lblb)$

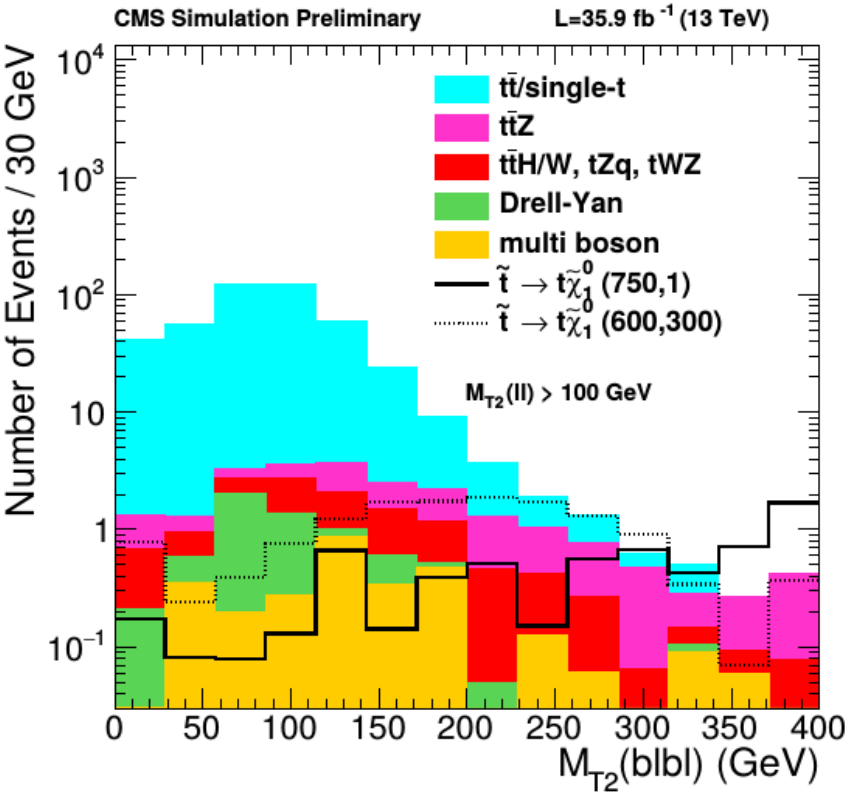
$M_{T2}(ll)$

leptons+MET
→ endpoint at W mass

$M_{T2}(lblb)$

leptons+MET+bjets
→ endpoint at top mass

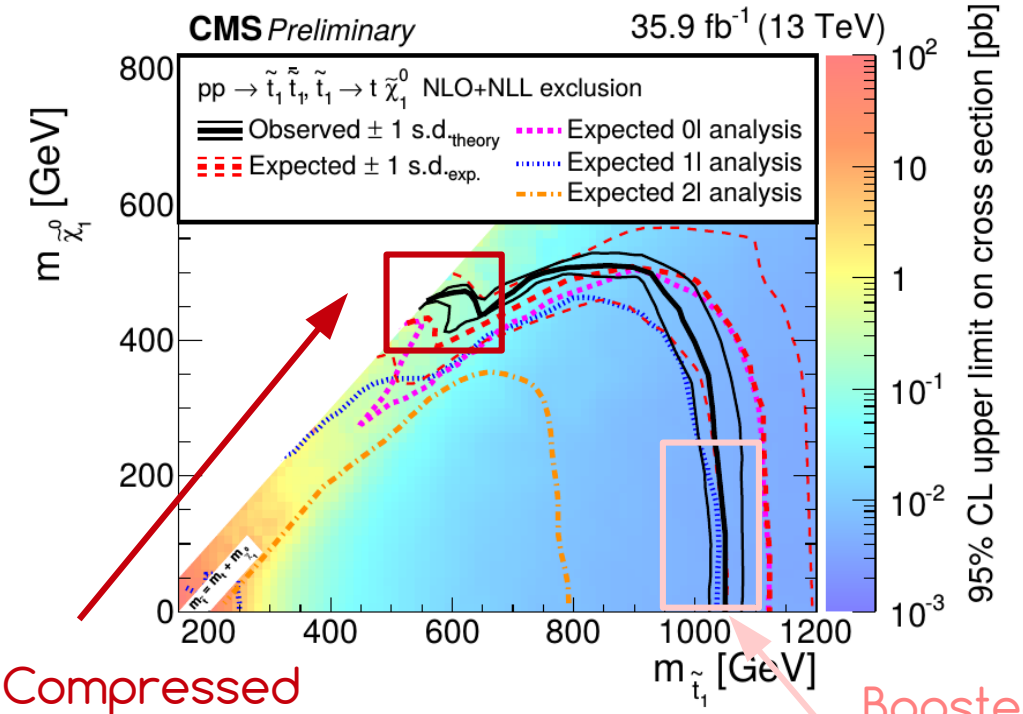


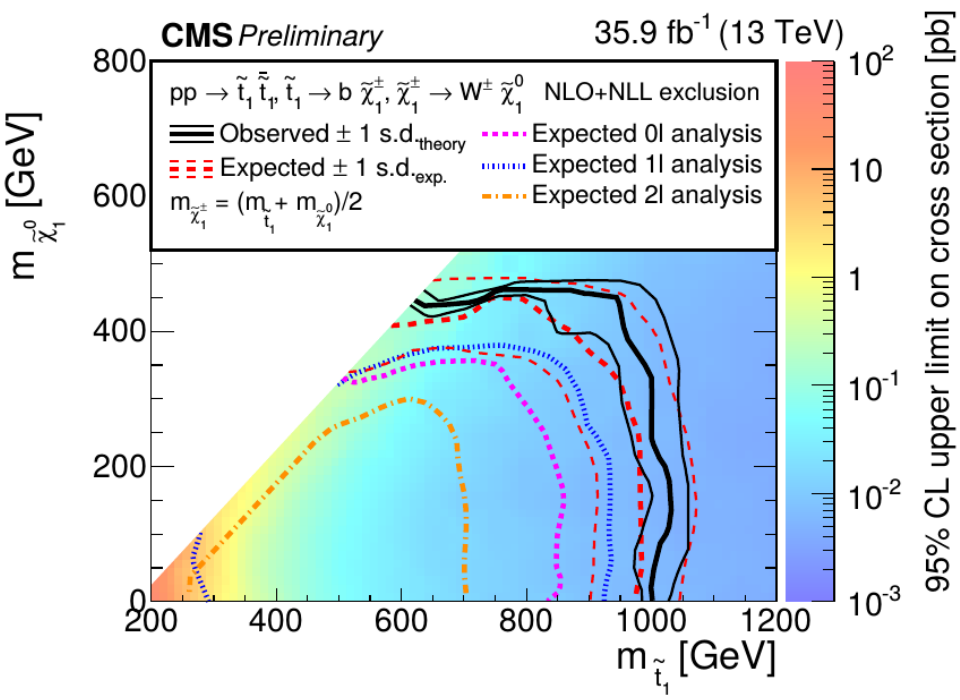




$$M_{T2}(\ell\ell) = \min_{\vec{p}_{T1}^{\,miss}+\vec{p}_{T2}^{\,miss}=\vec{p}_{T}^{\,miss}} \left(\max\left[M_T(\vec{p}_T^{\,vis1}, \vec{p}_{T1}^{\,miss}), M_T(\vec{p}_T^{\,vis2}, \vec{p}_{T2}^{\,miss})\right]\right); \quad \vec{p}_T^{\,vis1,2} = \vec{p}_T^{\,\ell 1,2}$$

# Interpretations: combination of 0,1 and 2 lepton stop analyses

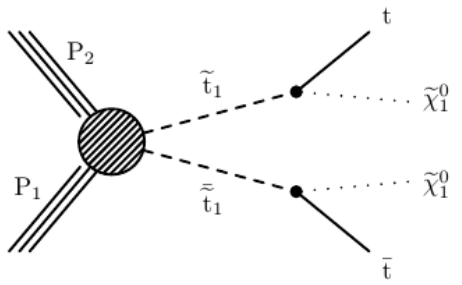
(SUS-16-049, SUS-16-051, SUS-17-001 )




Compressed spectra

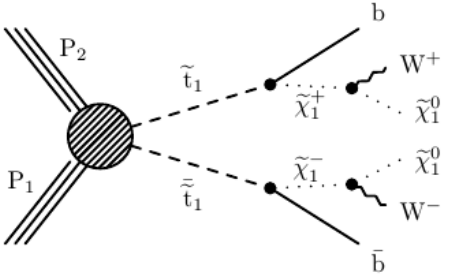
Boosted objects




Exclude:
Stop~1050 GeV
Neutralino~500 GeV

Most sensitivity from 0-lep

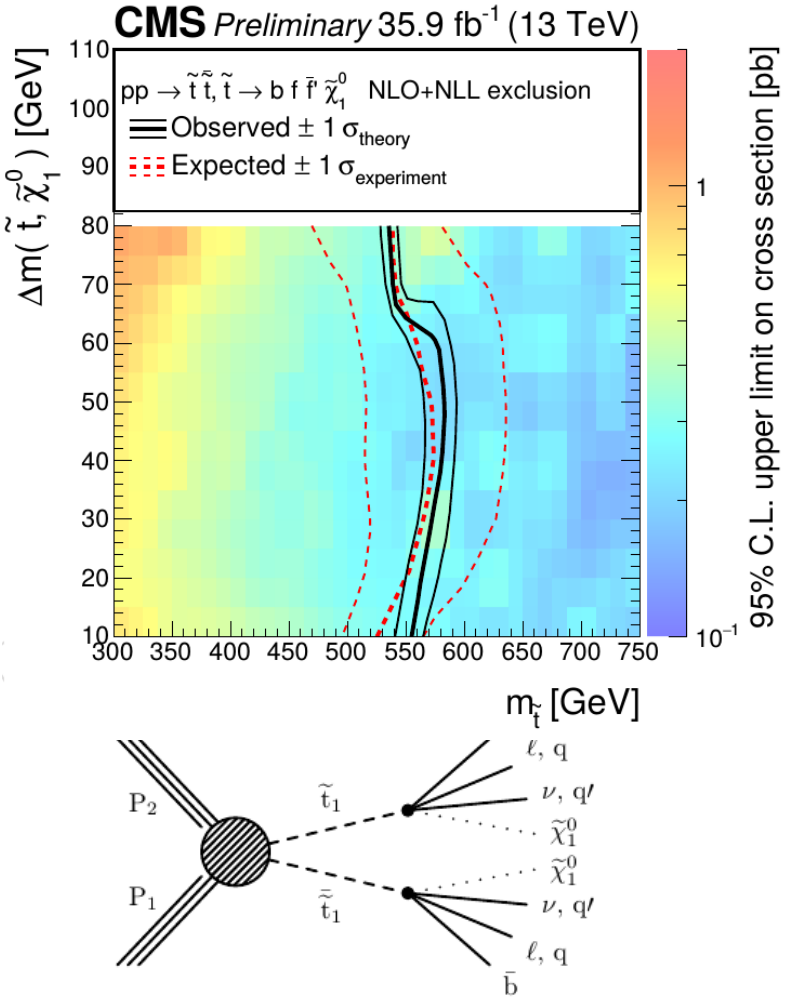
Most sensitivity from 1-lep




Exclude:
Stop~1000 GeV
Neutralino~450 GeV

# Other processes

SUS-16-049

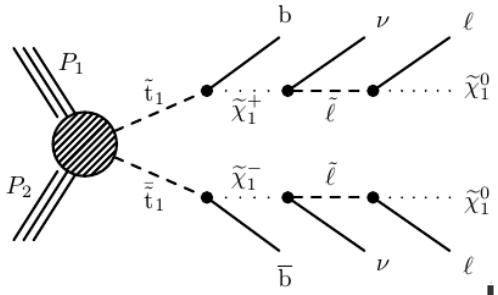




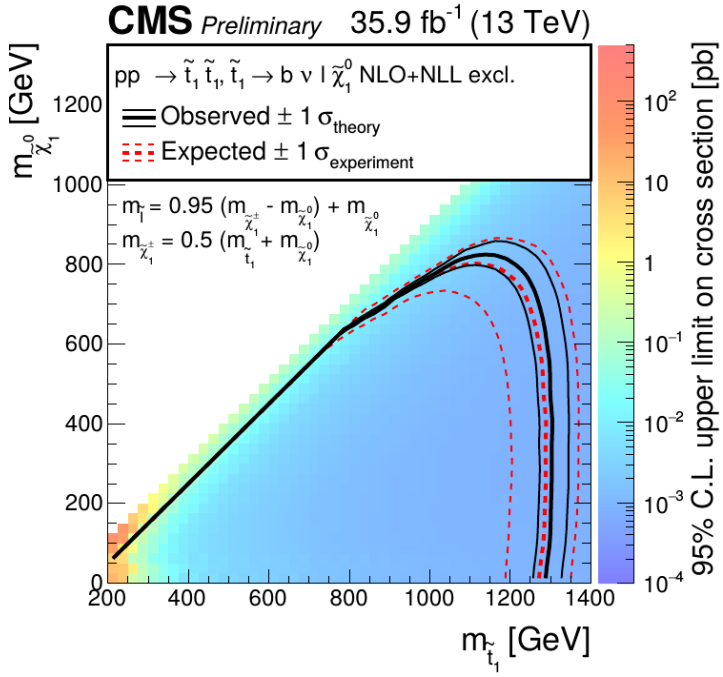


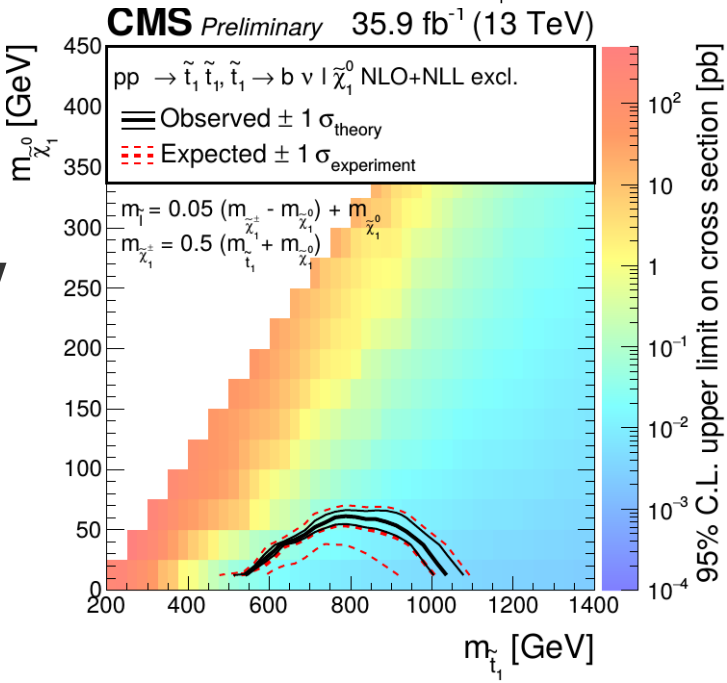
Exclude:
Stop~580 GeV
Neutralino~540 GeV

SUS-17-001
Cascade decay:




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

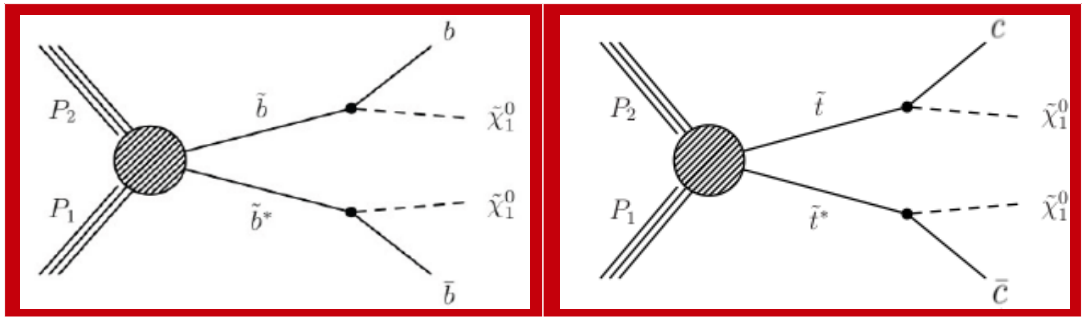


# Sbottom searches

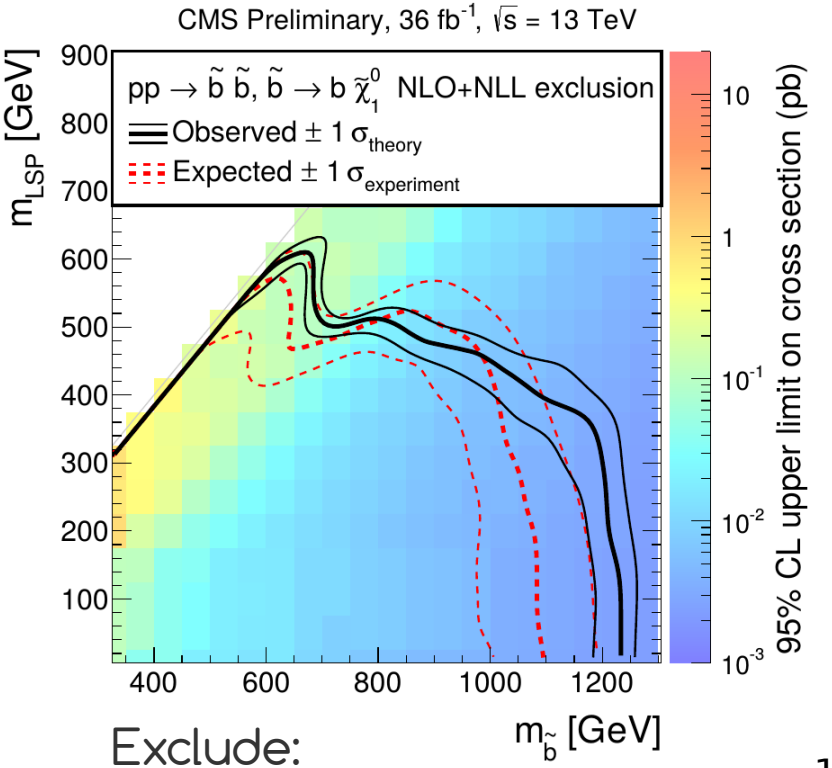
- Several decay channels of sbottom are studied in CMS
- In this talk focus only on:

  **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

# Conclusion

- Presented **latest results of 3rd generation SUSY searches** in hadronic and leptonic final states with 35.9 $fb^{-1}$ of 13 TeV CMS 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**~1.1 TeV, **sbottom**~1.2 TeV, **neutralino**~0.6 TeV

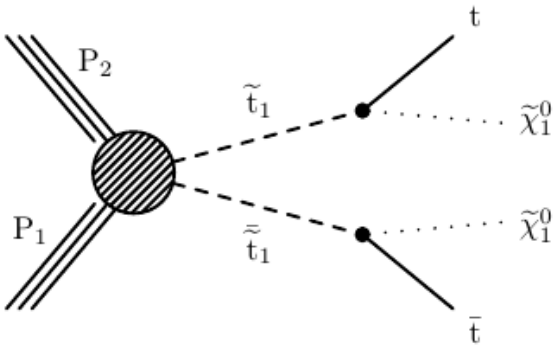
    **→ Observed limit of stop mass extended by ~100 GeV with respect to ICHEP 2016**
  - **Not only scaling results with luminosity!**
    - Use of new techniques such as soft b-tagging or boosted objects tagging
    - Design of dedicated searches for compressed spectra
    - Exploring new discriminating variables

- Limits are **touching the naturalness bound** → depending on the realization of SUSY model (cascade model example) the limits can be weaker

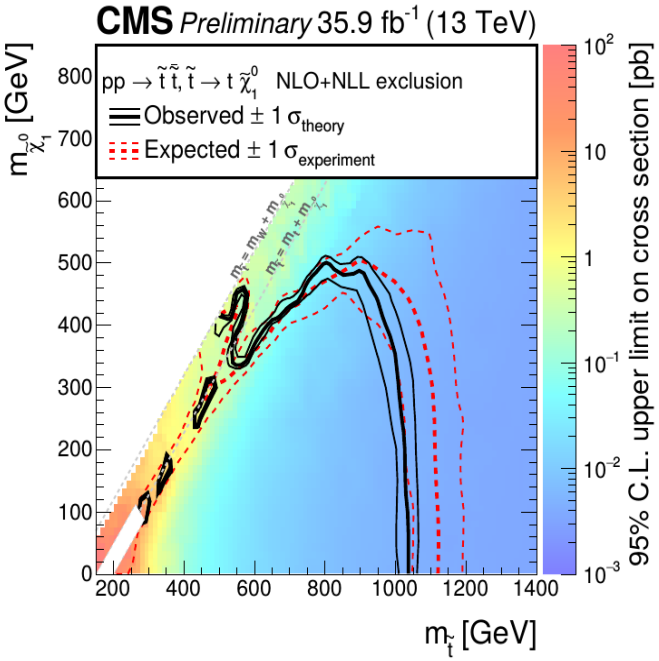
- SUSY public results available at:
  https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsSUS

# BACKUP

# Interpretations

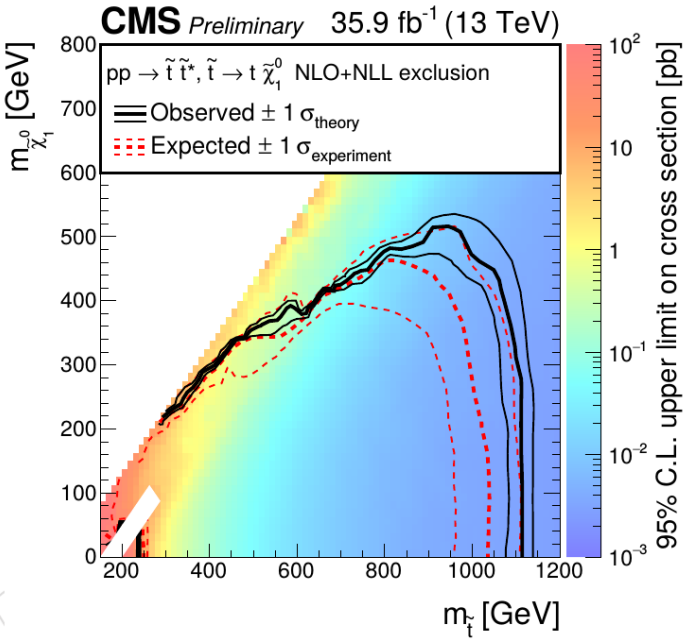



0-lep SUS-16-049



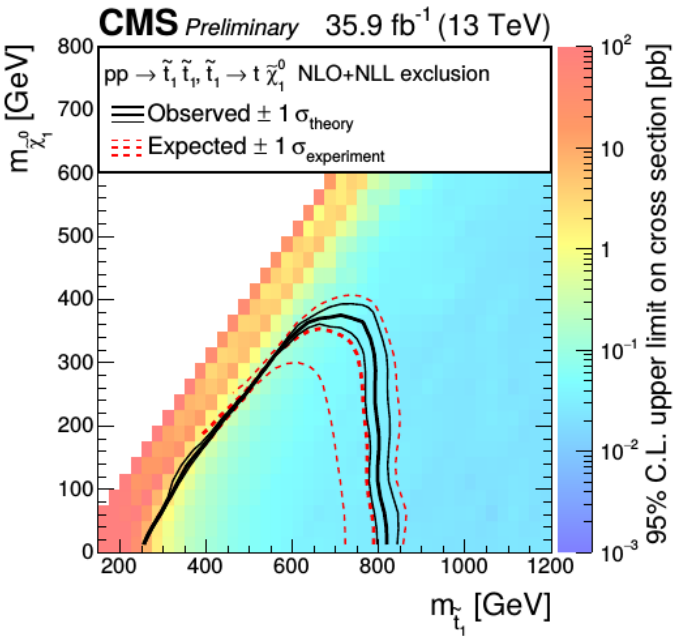

Exclude:
Stop-1040 GeV
Neutralino-500 GeV

1-lep SUS-16-051



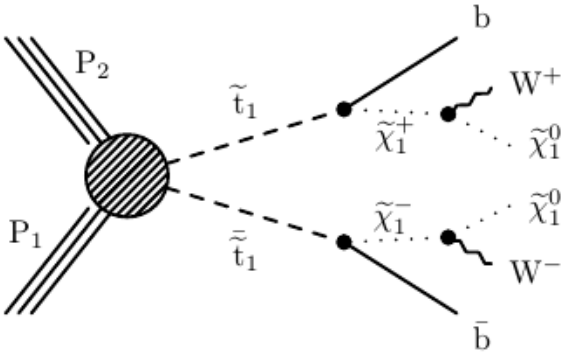

Exclude:
Stop-1120 GeV
Neutralino-515 GeV

2-lep SUS-17-001

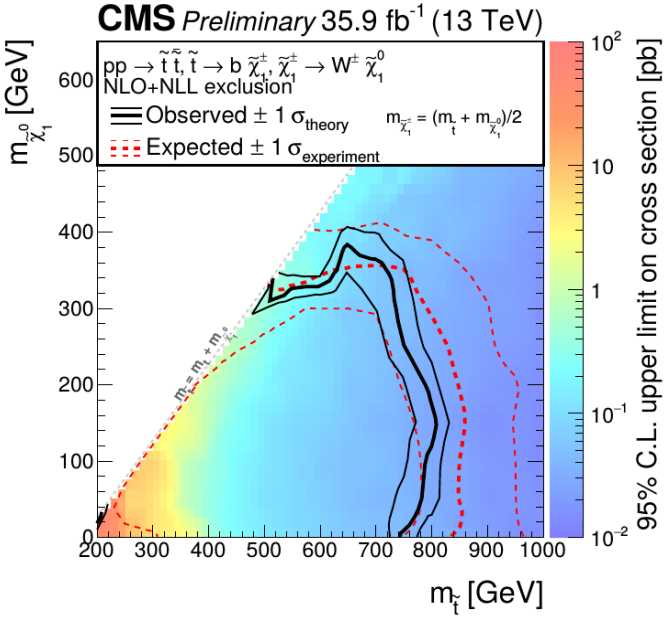



Exclude:
Stop-850 GeV
Neutralino-380 GeV

# Interpretations

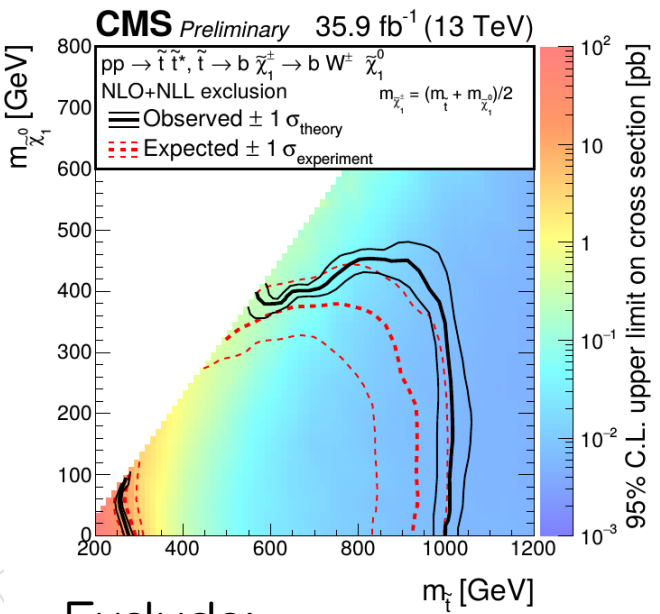



## 0-lep SUS-16-049



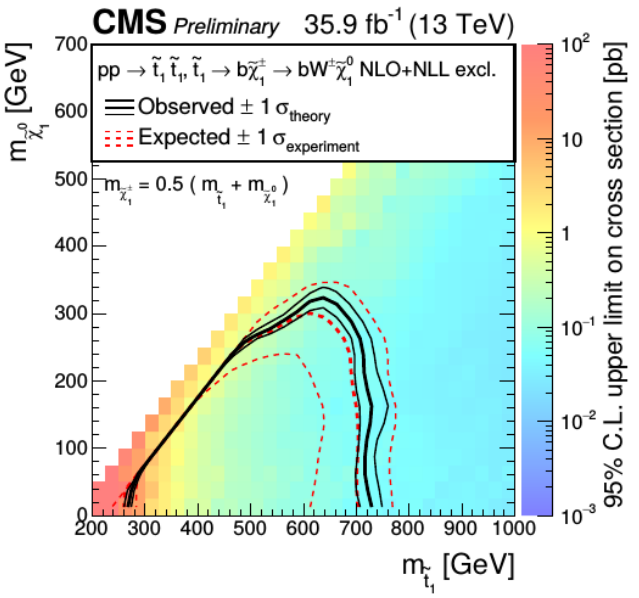

Exclude:
Stop~800 GeV
Neutralino~360 GeV

## 1-lep SUS-16-051



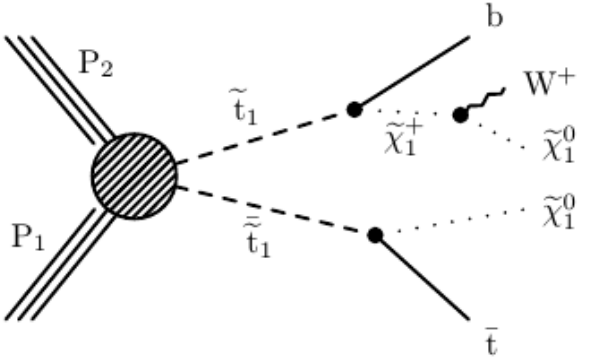

Exclude:
Stop~1025 GeV
Neutralino~460 GeV

## 2-lep SUS-17-001

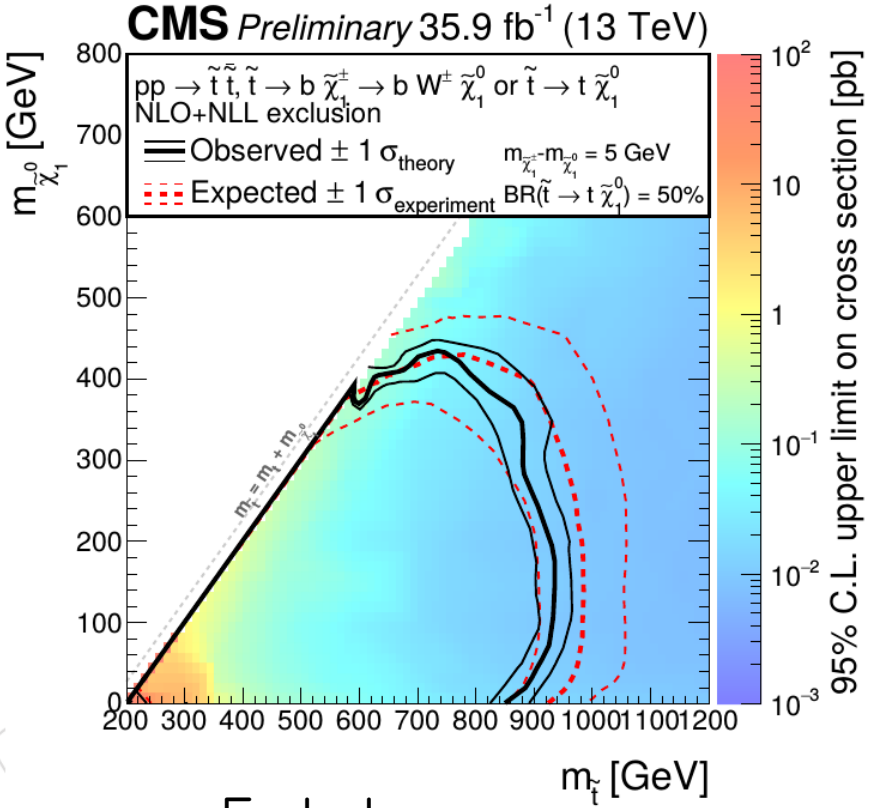



Exclude:
Stop~750 GeV
Neutralino~300 GeV

# Interpretations

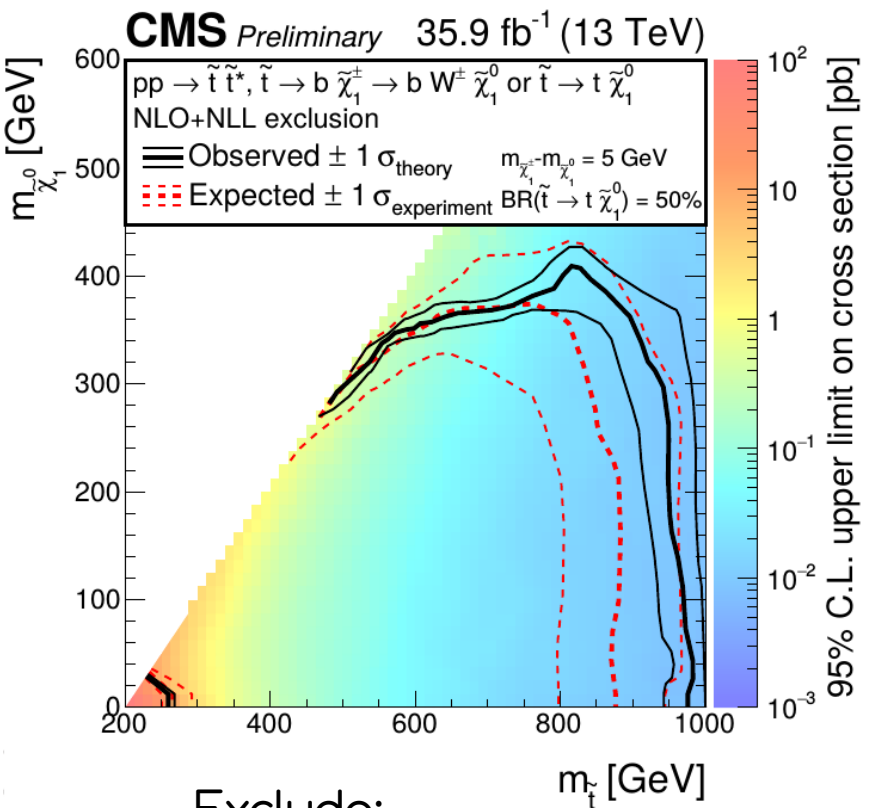



0-lep SUS-16-049



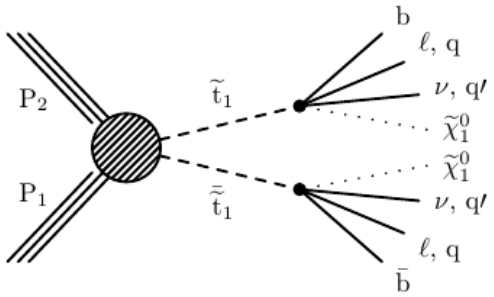

Exclude:
Stop~940 GeV
Neutralino~440 GeV

1-lep SUS-16-051

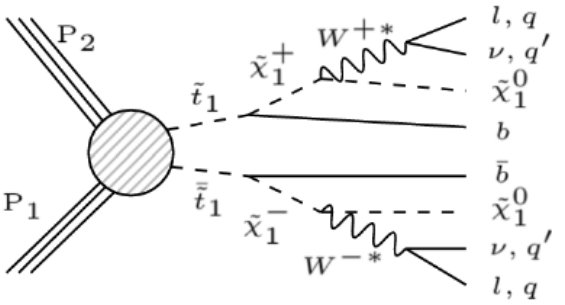



Exclude:
Stop~980 GeV
Neutralino~400 GeV

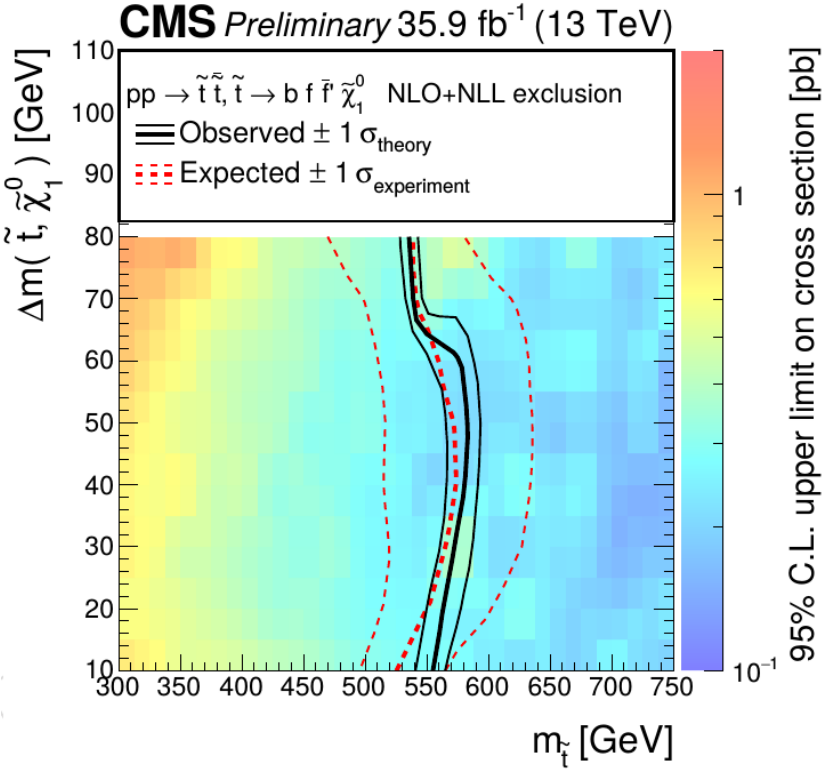
# Interpretations



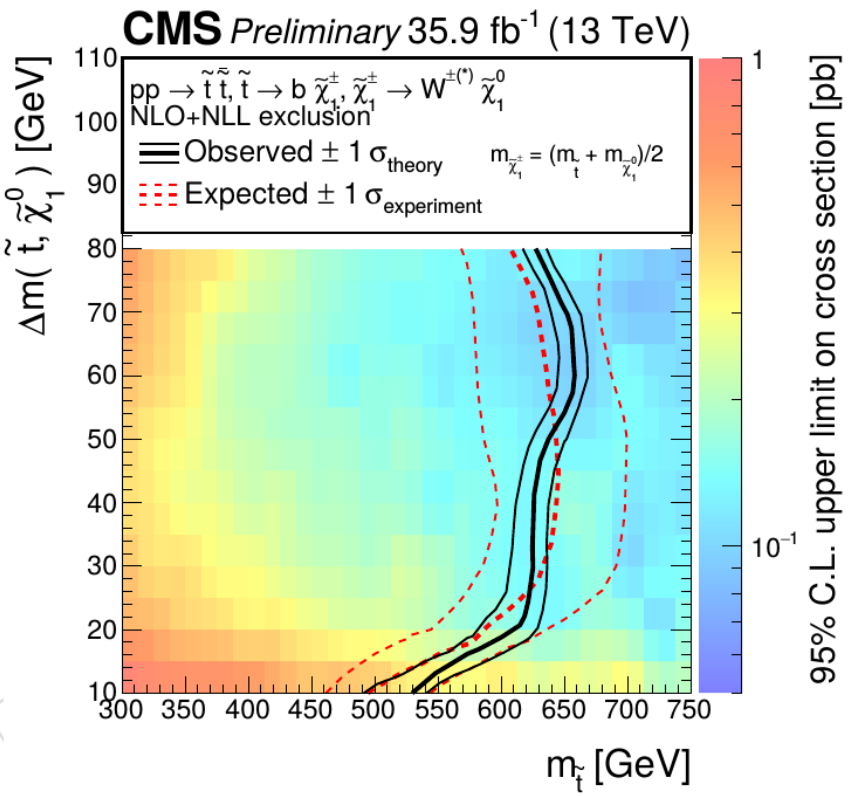

0-lep SUS-16-049




0-lep SUS-16-049



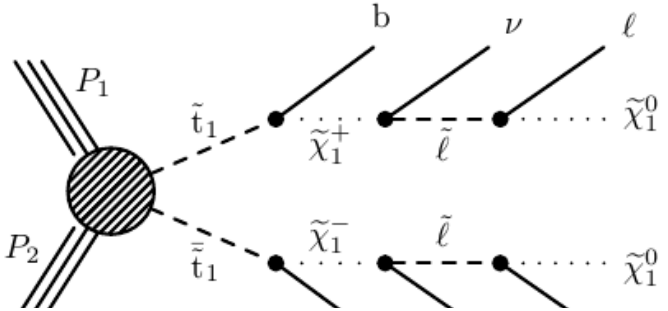

Exclude:
Stop-580 GeV
Neutralino-540 GeV

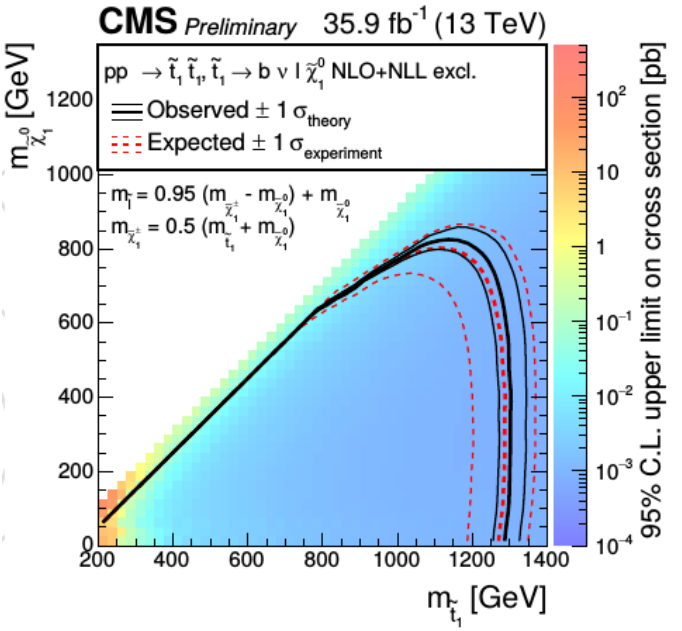


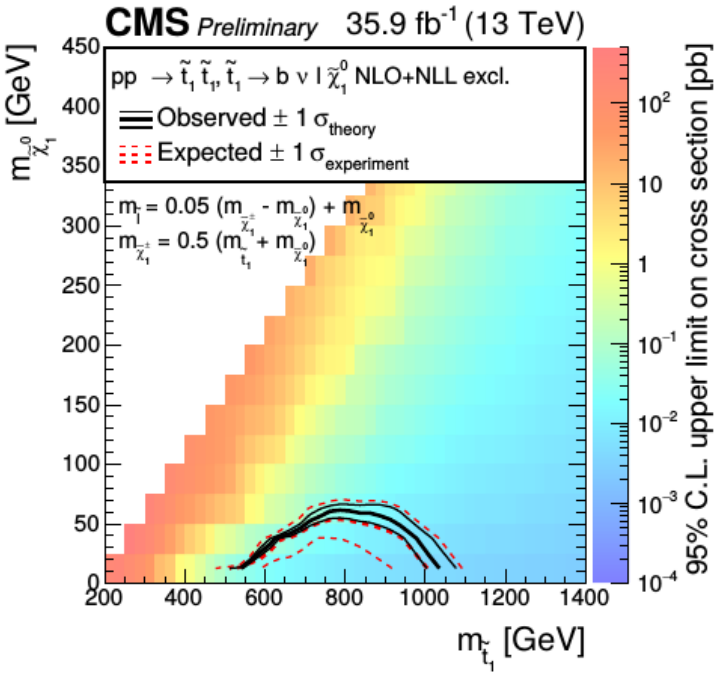

Exclude:
Stop-660 GeV
Neutralino-610 GeV

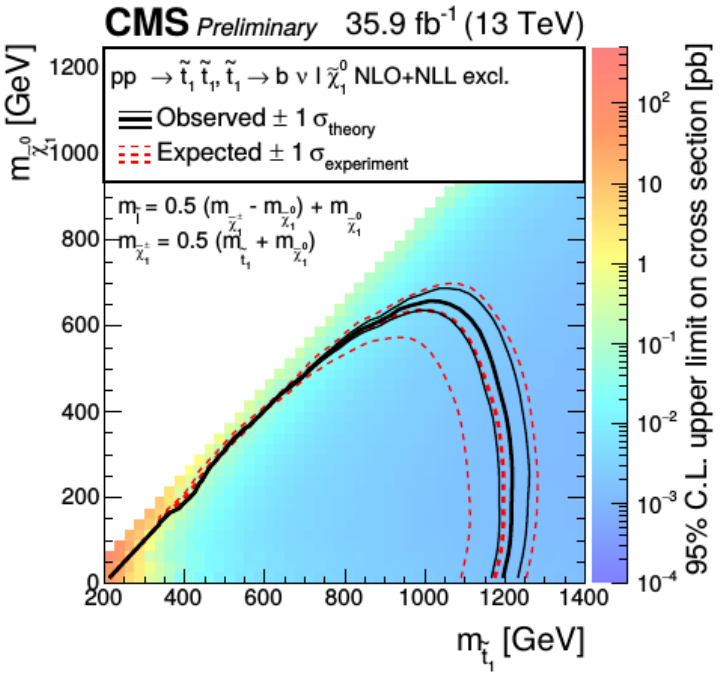
# Interpretations - Cascade decay to two leptons

2-lep SUS-17-001



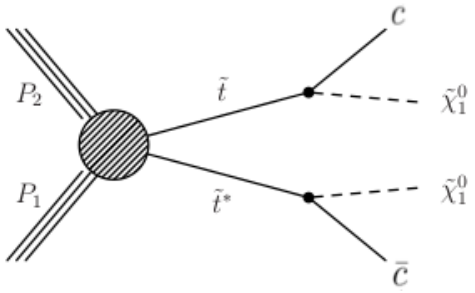



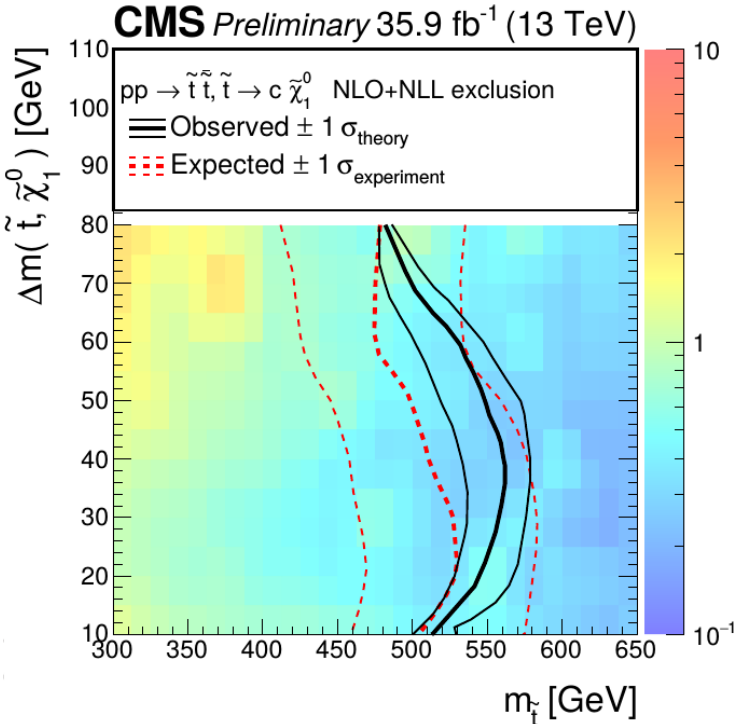



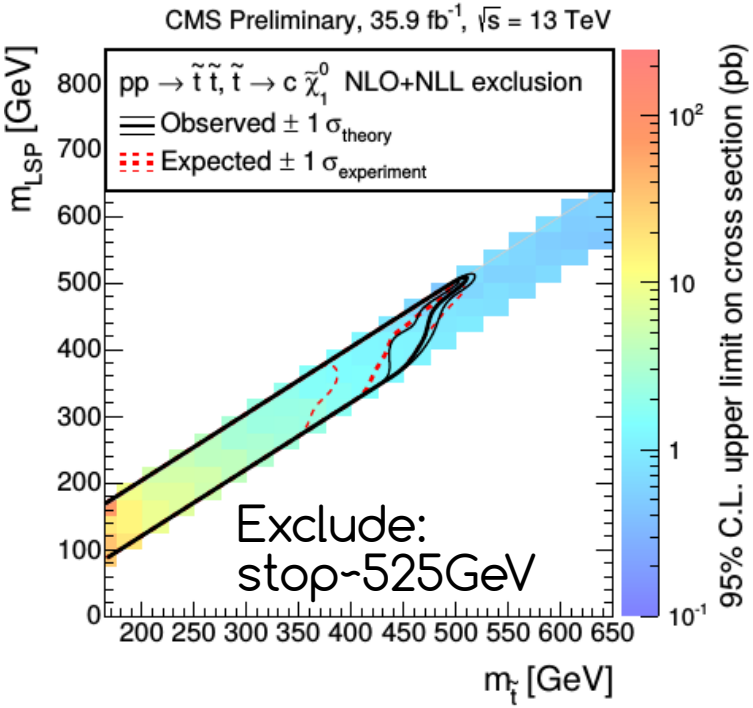
Exclude:
Stop-560 GeV
Neutralino-510 GeV

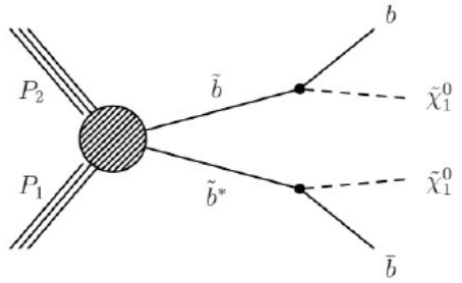
0-lep SUS-16-049



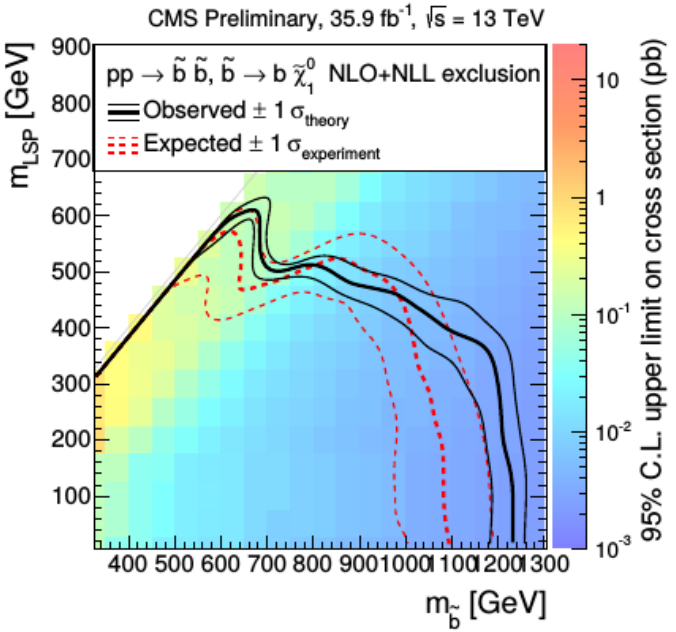




0-lep SUS-16-032




0-lep SUS-16-032




Exclude:
sbottom~1225GeV
neutralino~600GeV

# 0-lepton stop search: low vs high Δm

| | Low Δm category | High Δm category |
|---|---|---|
| Preselection | MET>250 GeV, $\Delta\varphi(j_1,\text{MET})>0.5$, $\Delta\varphi(j_{2,3},\text{MET})>0.15$ MET/sqrt(HT)>10 | MET>250 GeV, $\Delta\varphi(j_{1,2,3},\text{MET})>0.5$ |
| $N_{jets}$ | ≥2 | ≥5 |
| $N_{bjets}$ | ≥0 | ≥1 |
| $M_T$(b,MET) [GeV] | <175 | >175 |
| Tagging | ISR tagging ($\lvert\Delta\varphi(\text{ISR,MET})\rvert>2$), 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)** = $\text{sqrt}(2p_T^{\text{object}}\text{MET}(1-\cos(\Delta\varphi_{\text{ojbect,MET}})))$

Top/W veto helps significantly to reduce ttbar background

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

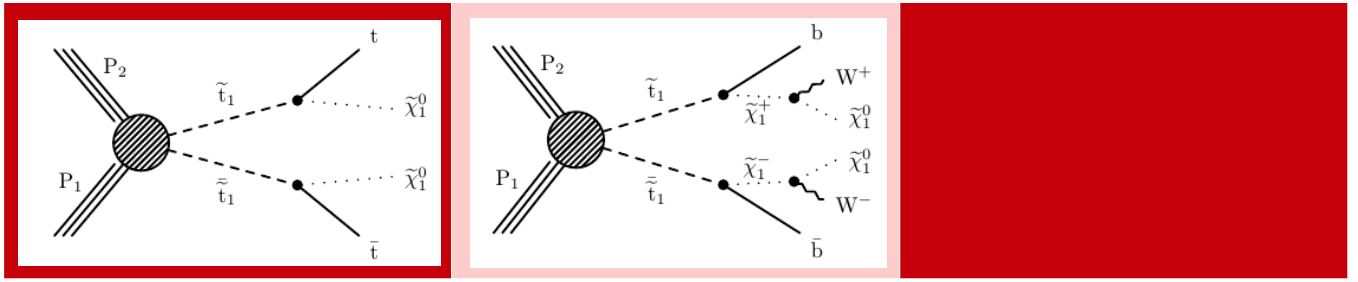
# 1-lepton stop search

Nominal analysis:

- PRESELECTION:
- ≥2 jets
- ≥1 medium btag (or tight to gain more sensitivity in regions dominated by W+jets)
- MET>250 GeV
- $\Delta\varphi\ (j_{1,2,3}, MET)>0.8$
- $M_T>150$ 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)
- $\Delta\varphi(lep,MET)<2$ (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
- $\Delta\varphi(j_{1,2,3},MET)>0.5$

# 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 $\Delta\varphi(j_{1,2,3},\text{MET})>0.4$, $(p_T(\text{ISR})+\text{MET})/\text{MET}<0.5$ | MET>250 GeV, min $\Delta\varphi(j_{1,2,3},\text{MET})>0.4$, min $m_T(j_{1,2},\text{MET})>250$ 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) |