# *Search for Supersymmetry at CMS

**Henning Flaecher**
**H.H. Wills Physics Laboratory**
**University of Bristol**

**for the CMS Collaboration**

# *Beyond Higgs? – Supersymmetry!

* Supersymmetry is a global symmetry of spin
  * each fermion has a bosonic partner, and vice versa
  * all other properties identical

* Supersymmetry is theoretically well motivated
  * it provides a solution to the hierarchy problem
  * unification of gauge couplings
  * can provide a candidate for Dark Matter

* Higher order corrections to Higgs mass
  * fermion and boson loops have opposite sign
  * hence the quadratic divergences cancel

* Next step in understanding of fundamental science, after Higgs boson discovery
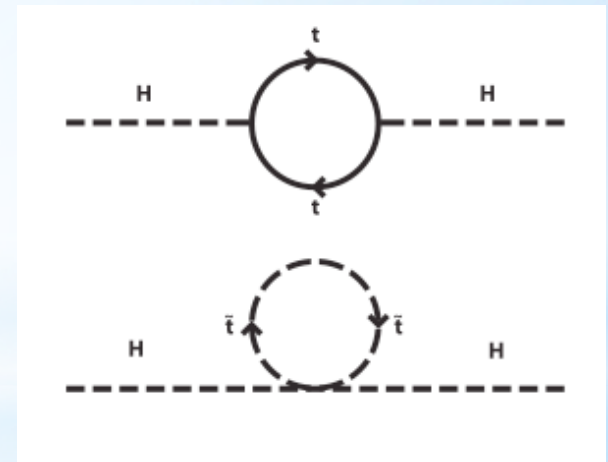
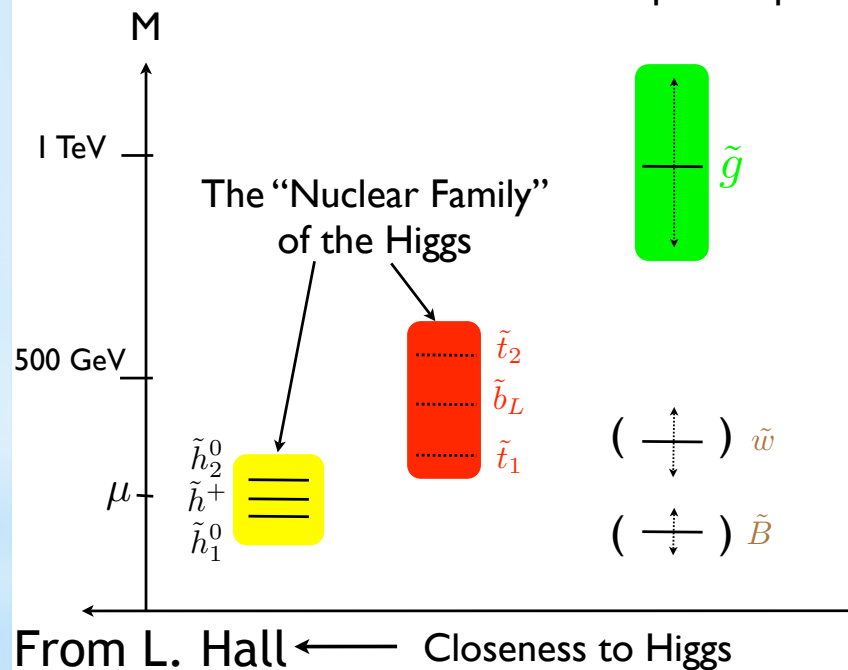# *Search for 3rd generation SUSY
## - stop and sbottom searches

### A Natural Spectrum

General "bottom-up" viewpoint

M

$\tilde{q}_{1,2}$ $\tilde{b}_R$ $\tilde{l}$

"Distant Cousins"

Mass hierarchies that avoid fine-tuning

1 TeV

$\tilde{g}$

The "Nuclear Family" of the Higgs

500 GeV

$\tilde{t}_2$
$\tilde{b}_L$
$\tilde{t}_1$

$(\,\dashv\,)\ \tilde{w}$

$\tilde{h}_2^0$
$\tilde{h}^+$
$\mu$
$\tilde{h}_1^0$

$(\,\dashv\,)\ \tilde{B}$

From L. Hall ← Closeness to Higgs

### Natural EWSB & SUSY *

* valid beyond MSSM

Do not want tuning in (Higgs mass)$^2$

$$\frac{m_{Higgs}^2}{2} = -|\mu|^2 + \ldots + \delta m_H^2$$

Higgsinos

1 loop $\quad \delta m_H^2|_{stop} = -\frac{3}{8\pi^2} y_t^2 \left( m_{U_3}^2 + m_{Q_3}^2 + |A_t|^2 \right) \log\left(\frac{\Lambda}{\text{TeV}}\right)$

stops, sbottom$_\mathbf{L}$

2 loop $\quad \delta m_H^2|_{gluino} = -\frac{2}{\pi^2} y_t^2 \left(\frac{\alpha_s}{\pi}\right) |M_3|^2 \log^2\left(\frac{\Lambda}{\text{TeV}}\right)$

gluino

From A. Weiler

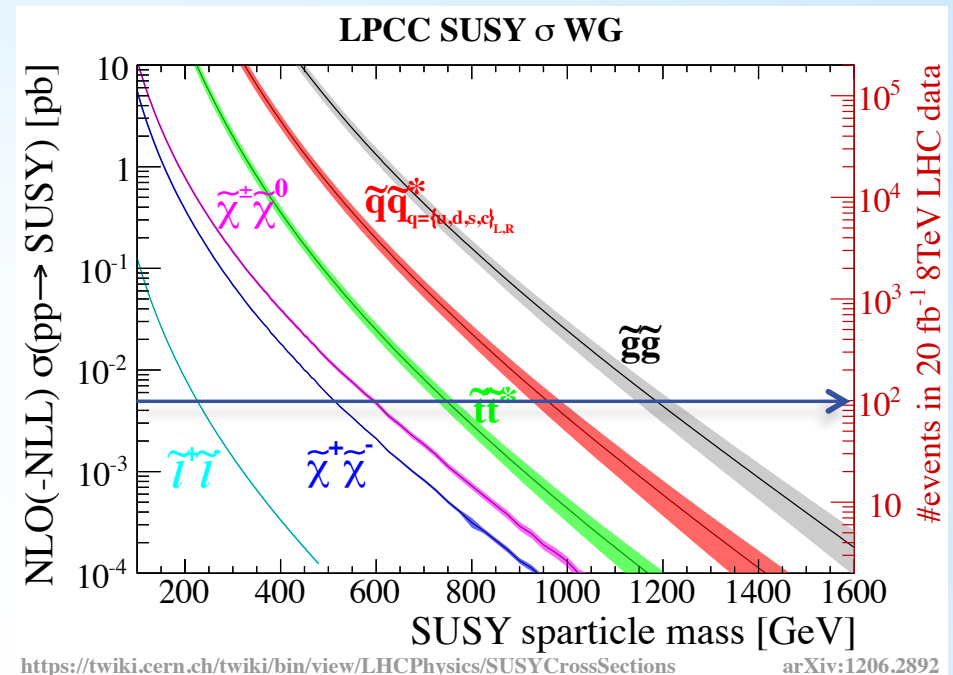# Focus of current searches

* stops and sbottoms

* gluinos and "light" squarks
  * search again for stop and sbottoms in gluino decays

* searches for Higgs in SUSY cascade

* charginos, neutralinos, sleptons

* RPV searches



**LPCC SUSY σ WG**

https://twiki.cern.ch/twiki/bin/view/LHCPhysics/SUSYCrossSections        arXiv:1206.2892

# *Focus of current searches

* stops and sbottoms
    * Direct stop pair production SUS-13-015
    * Monojet search for stop-> charm $\chi_1^0$ SUS-13-009

* gluinos and "light" squarks
    * search again for stop and sbottoms in gluino decays
    * Inclusive search with $M_{T2}$ SUS-13-019

* searches for Higgs in SUSY cascade
    * $stop_2$ -> $stop_1$ + higgs/Z search SUS-13-024
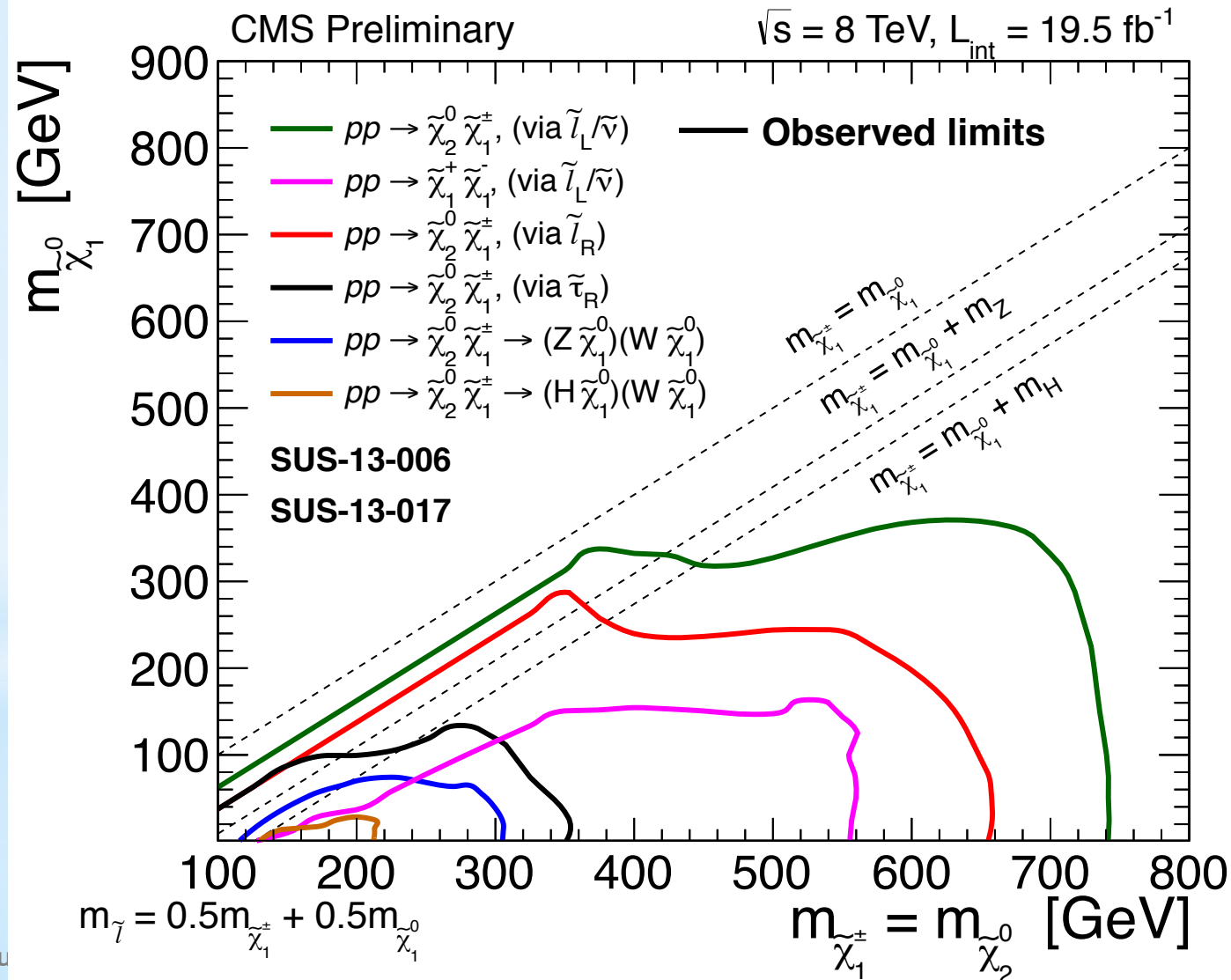    * $neutralino_1$ -> higgs + gravitino SUS-13-022

* charginos, neutralinos, sleptons

* RPV searches

* There are many many more results, please check:
* https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsSUS

# Searches for charginos, neutralinos & sleptons - Summary



CMS Preliminary · $\sqrt{s}$ = 8 TeV, $L_{int}$ = 19.5 fb$^{-1}$

- $pp \to \tilde{\chi}_2^0 \tilde{\chi}_1^\pm$, (via $\tilde{l}_L/\tilde{\nu}$)
- $pp \to \tilde{\chi}_1^+ \tilde{\chi}_1^-$, (via $\tilde{l}_L/\tilde{\nu}$)
- $pp \to \tilde{\chi}_2^0 \tilde{\chi}_1^\pm$, (via $\tilde{l}_R$)
- $pp \to \tilde{\chi}_2^0 \tilde{\chi}_1^\pm$, (via $\tilde{\tau}_R$)
- $pp \to \tilde{\chi}_2^0 \tilde{\chi}_1^\pm \to (Z \tilde{\chi}_1^0)(W \tilde{\chi}_1^0)$
- $pp \to \tilde{\chi}_2^0 \tilde{\chi}_1^\pm \to (H \tilde{\chi}_1^0)(W \tilde{\chi}_1^0)$

**Observed limits**

SUS-13-006

SUS-13-017

$m_{\tilde{\chi}_1^\pm} = m_{\tilde{\chi}_1^0}$

$m_{\tilde{\chi}_1^\pm} = m_{\tilde{\chi}_1^0} + m_Z$

$m_{\tilde{\chi}_1^\pm} = m_{\tilde{\chi}_1^0} + m_H$

$m_{\tilde{\chi}_1^0}$ [GeV]

$m_{\tilde{\chi}_1^\pm} = m_{\tilde{\chi}_2^0}$ [GeV]

$m_{\tilde{l}} = 0.5 m_{\tilde{\chi}_1^\pm} + 0.5 m_{\tilde{\chi}_1^0}$

# *direct production of stops

# Stop searches

* Dominant stop decay channel largely depends on available phase space
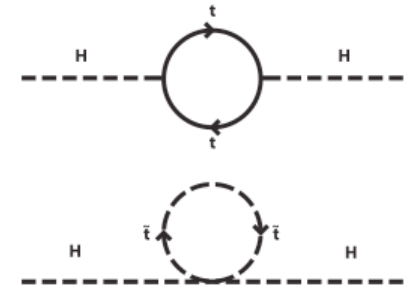
Decay modes in the $m(\tilde{t})$ vs. $m(\tilde{\chi}^0)$ plane

$\Delta m = m(\tilde{t}) - m(\tilde{\chi}^0)$

$\Delta m < m(W)$    $m(W) < \Delta m < m(t)$    $\Delta m > m(t)$

$m(\chi^0)$ [GeV]

not allowed
$m(stop) < m(LSP)$

Monojet searches

$\tilde{t} \to c\tilde{\chi}_1^0$

$\tilde{t} \to bW\tilde{\chi}_1^0$
(off-shell top)

$\tilde{t} \to t\tilde{\chi}_1^0$
(on-shell top)

LHC in the past
mainly looked here

$\tilde{t} \to bW^*\tilde{\chi}_1^0$

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

$0$    $m(W)$    $m(t)$    $m(\tilde{t})$ [GeV]
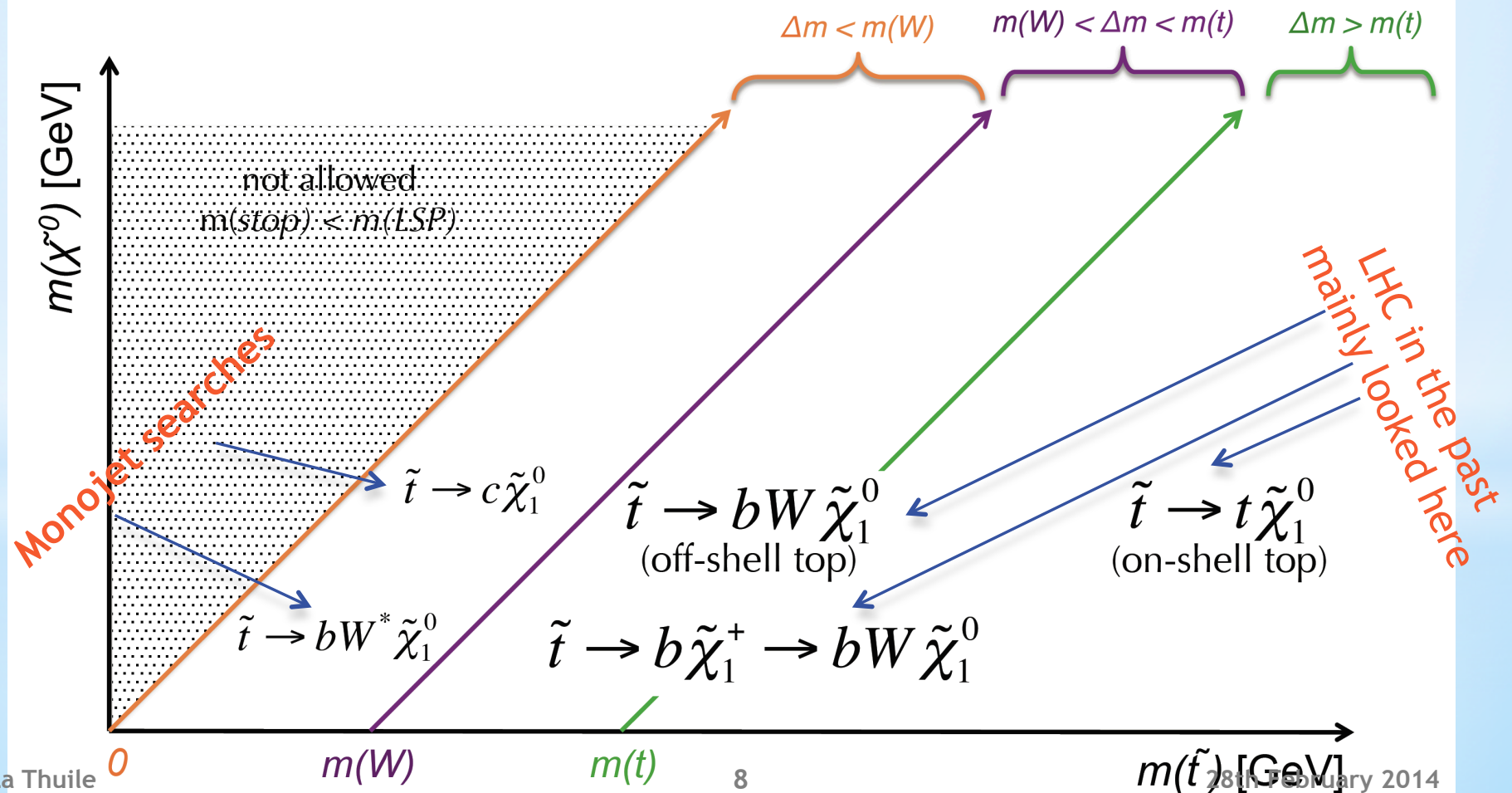
# Direct stop production – SUS-13-015

* Hadronic decay channel, aims at reconstructing tops
* Uses $p_{Tmiss}$, $M_{T2}$, $M_T^{Rsys}$ and $M_T^{3jet}$ distributions as discriminating variables
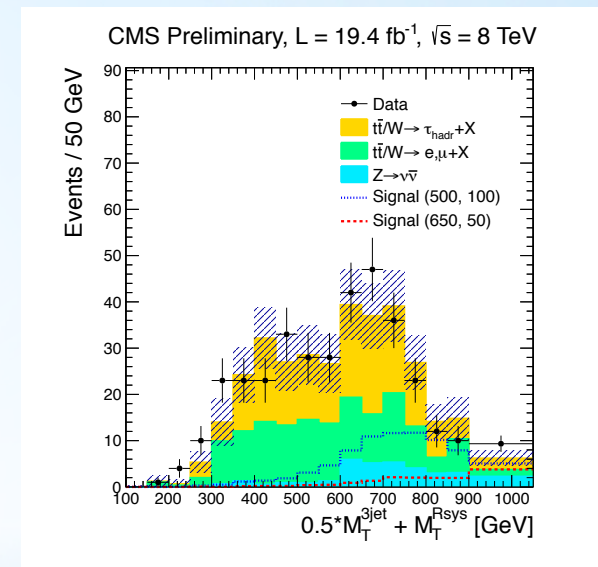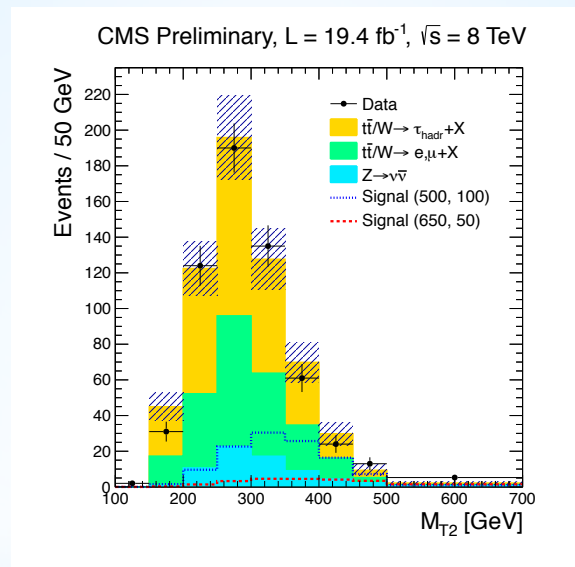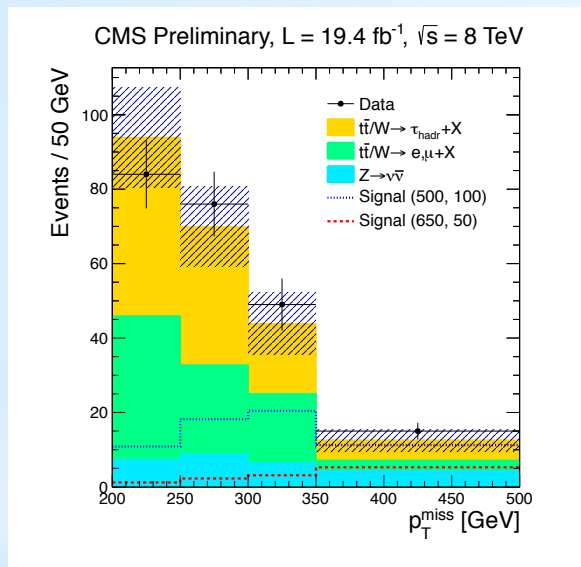


| Search region | $Z \to \nu\bar{\nu}$ | $t\bar{t}/W \to e, \mu + X$ | $t\bar{t}/W \to \tau_h + X$ | QCD | Rare processes | Total background | Obs. data |
|---|---|---|---|---|---|---|---|
| $p_T^{miss} > 200\,\text{GeV}$, $N_{\text{b-jets}} \geq 1$ | $35.8\,^{+16.3}_{-19.0}$ | $89.3\,^{+21.9}_{-21.0}$ | $120.2\,^{+11.8}_{-11.9}$ | $3.2\,^{+18.2}_{-3.2}$ | $5.8\,^{+2.9}_{-2.9}$ | $254.3\,^{+35.0}_{-31.0}$ | 254 |
| $p_T^{miss} > 350\,\text{GeV}$, $N_{\text{b-jets}} \geq 1$ | $13.2\,^{+6.5}_{-7.9}$ | $8.2\,^{+4.0}_{-4.0}$ | $16.5\,^{+3.4}_{-3.4}$ | $1.0\,^{+1.9}_{-1.0}$ | $2.0\,^{+1.0}_{-1.0}$ | $40.9\,^{+8.6}_{-9.6}$ | 45 |
| $p_T^{miss} > 200\,\text{GeV}$, $N_{\text{b-jets}} \geq 2$ | $6.1\,^{+15.3}_{-5.5}$ | $33.8\,^{+10.3}_{-10.0}$ | $45.3\,^{+7.0}_{-7.0}$ | $0.1\,^{+0.6}_{-0.1}$ | $3.1\,^{+1.6}_{-1.6}$ | $88.4\,^{+19.8}_{-13.5}$ | 83 |
| $p_T^{miss} > 350\,\text{GeV}$, $N_{\text{b-jets}} \geq 2$ | $1.8\,^{+6.8}_{-1.6}$ | $1.2\,^{+1.0}_{-1.0}$ | $4.3\,^{+1.7}_{-1.8}$ | $0.1\,^{+0.5}_{-0.1}$ | $1.2\,^{+0.6}_{-0.6}$ | $8.6\,^{+7.1}_{-2.7}$ | 15 |

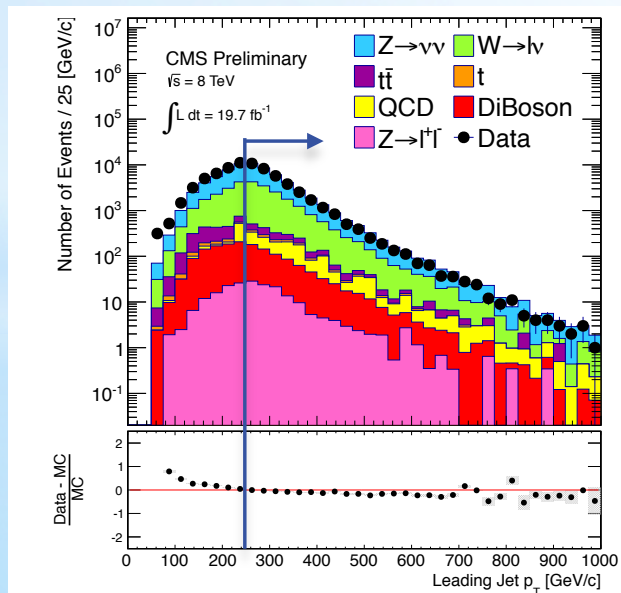# *Limit in stop-neutralino mass plane
# SUS-13-015
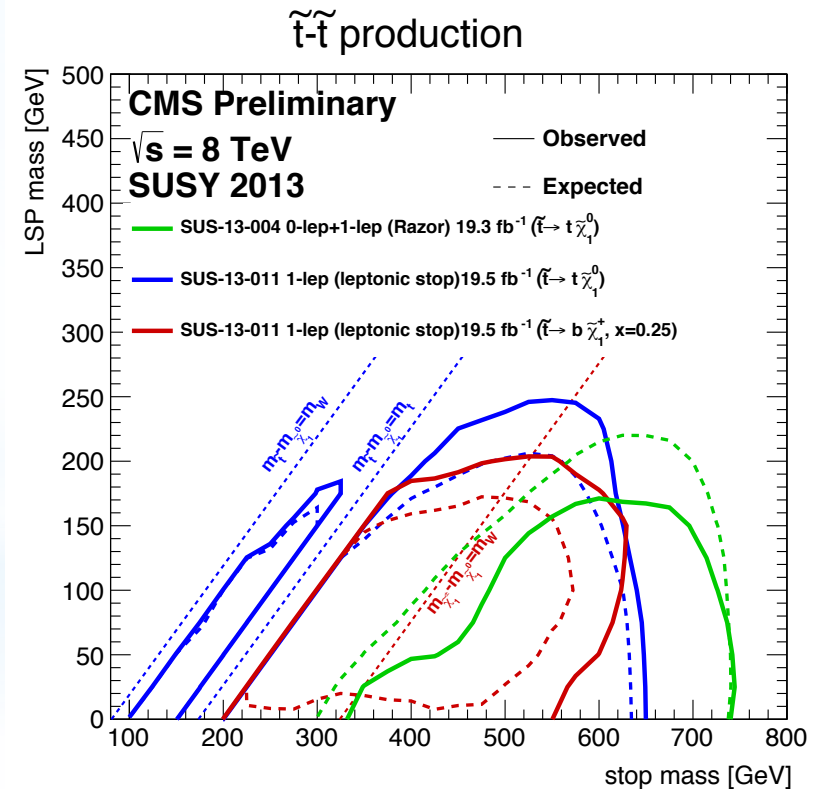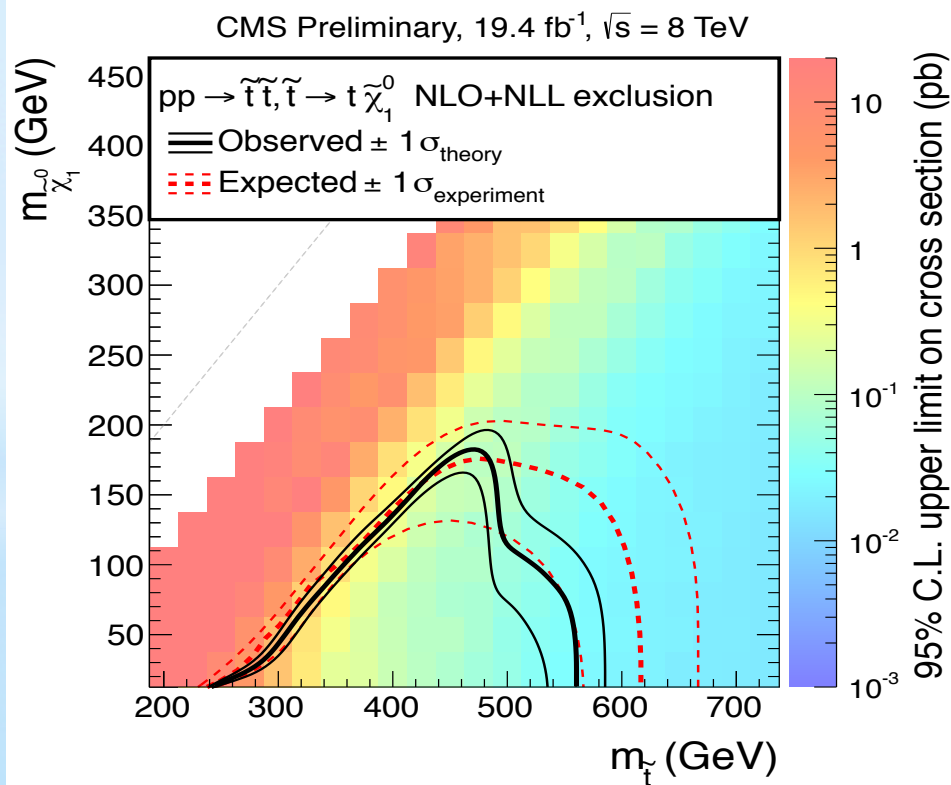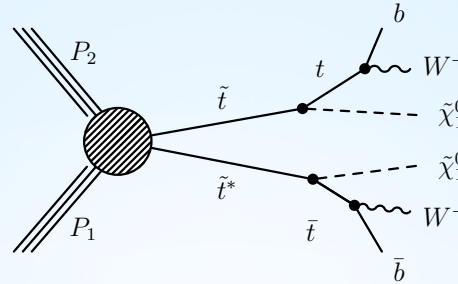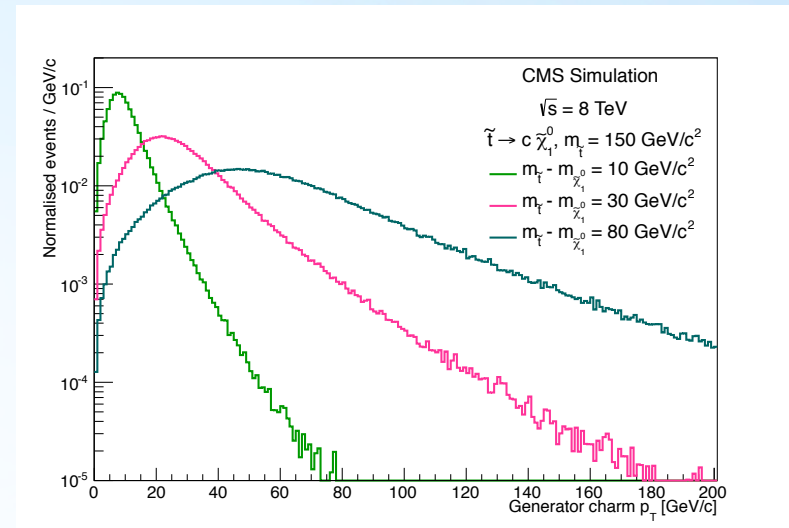
# *Limit in stop-neutralino mass plane

* Dependence on stop BF
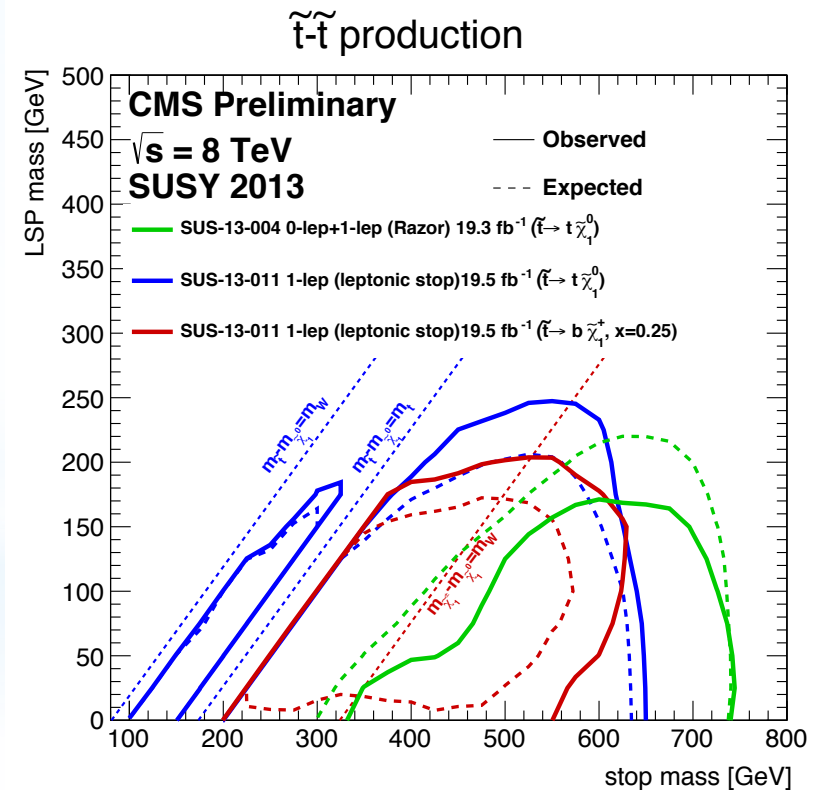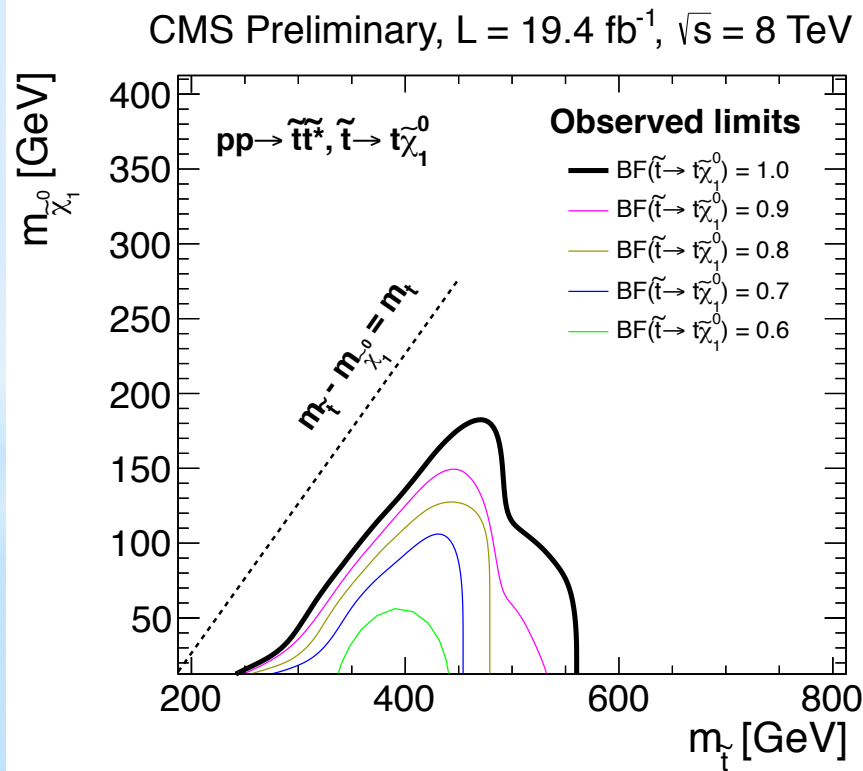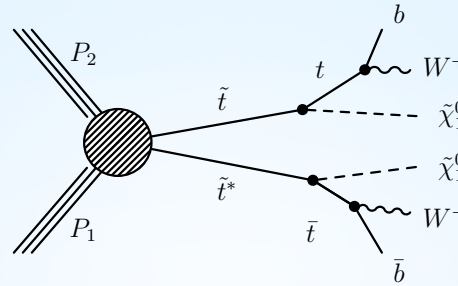
# Monojet search for stop->charm $\chi_1^0$
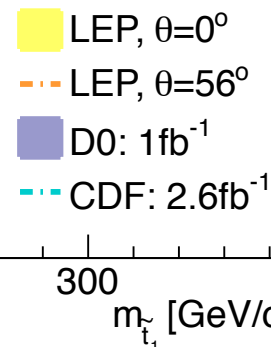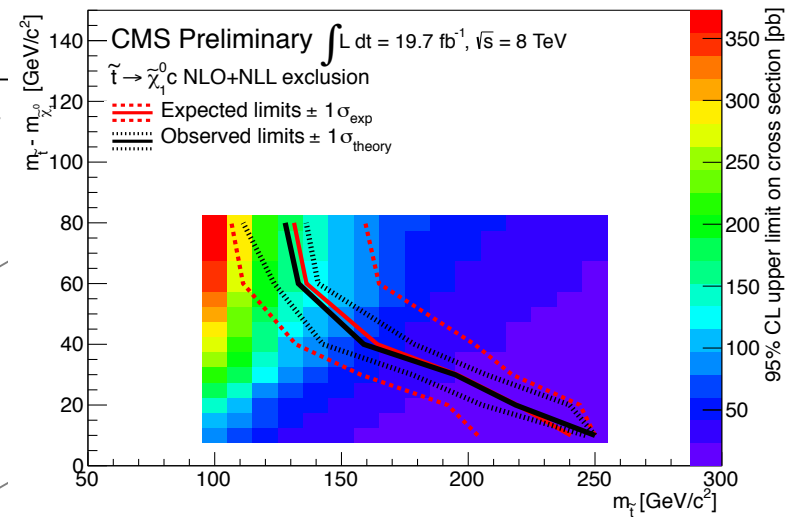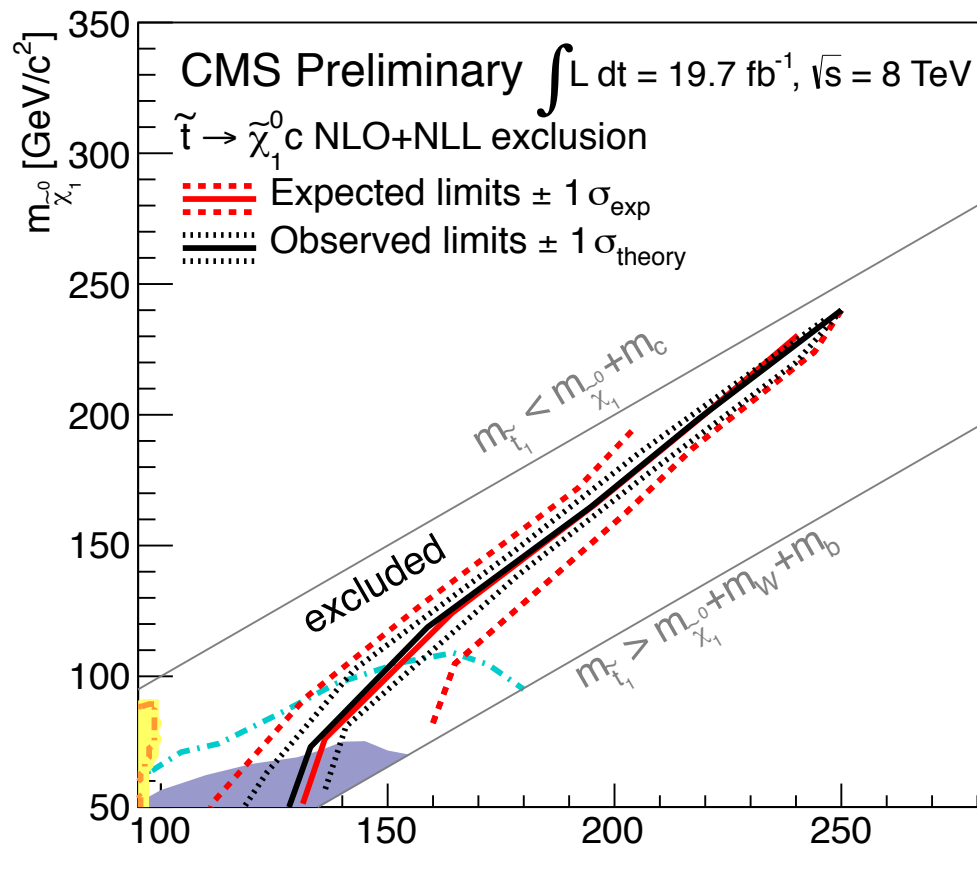# SUS-13-009

* Monojet search as function of leading jet $p_T$ (> 250 GeV, ... , >550GeV)
  * MET > 250 GeV
* Allow for second jet with $p_T$ > 60 GeV, veto 3rd jet
* Stop decay "invisible"
  * only soft decay products
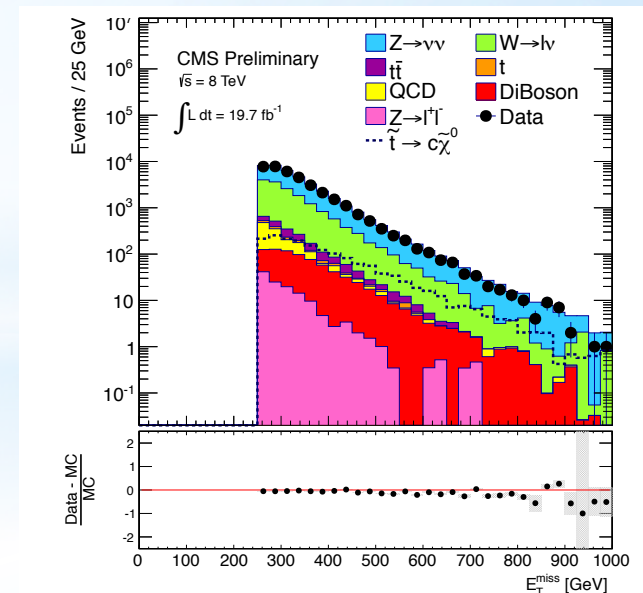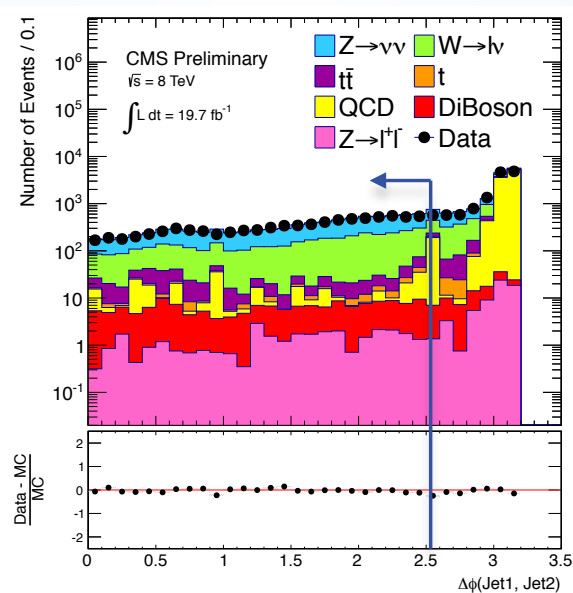
# Interpretation - SUS-13-009

| $p_{\mathrm{T}}(j_1)$ (GeV/$c$) | $> 250$ | $> 300$ | $> 350$ | $> 400$ | $> 450$ | $> 500$ | $> 550$ |
|---|---|---|---|---|---|---|---|
| Total SM | $35862 \pm 1474$ | $17409 \pm 803$ | $8064 \pm 437$ | $3907 \pm 250$ | $2098 \pm 160$ | $1096 \pm 106$ | $563 \pm 71$ |
| Data | 36582 | 17646 | 8119 | 3896 | 1898 | 1003 | 565 |

# *inclusive searches

* Search for excess in $M_{T2}$ distribution in data binned by HT and number of b-tags

$$M_{T2}(m_{\tilde{\chi}}) = \min_{\vec{p}_T^{\tilde{\chi}(1)} + \vec{p}_T^{\tilde{\chi}(2)} = \vec{p}_T^{miss}} \left[ \max\left( M_T^{(1)}, M_T^{(2)} \right) \right]$$

$$\left(M_T^{(i)}\right)^2 = \left(m^{vis(i)}\right)^2 + m_{\tilde{\chi}}^2 + 2\left( E_T^{vis(i)} E_T^{\tilde{\chi}(i)} - \vec{p}_T^{vis(i)} \cdot \vec{p}_T^{\tilde{\chi}(i)} \right)$$
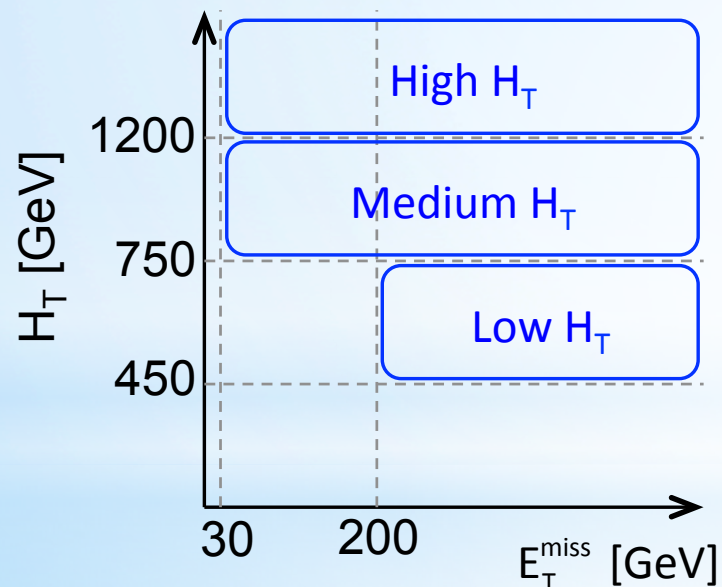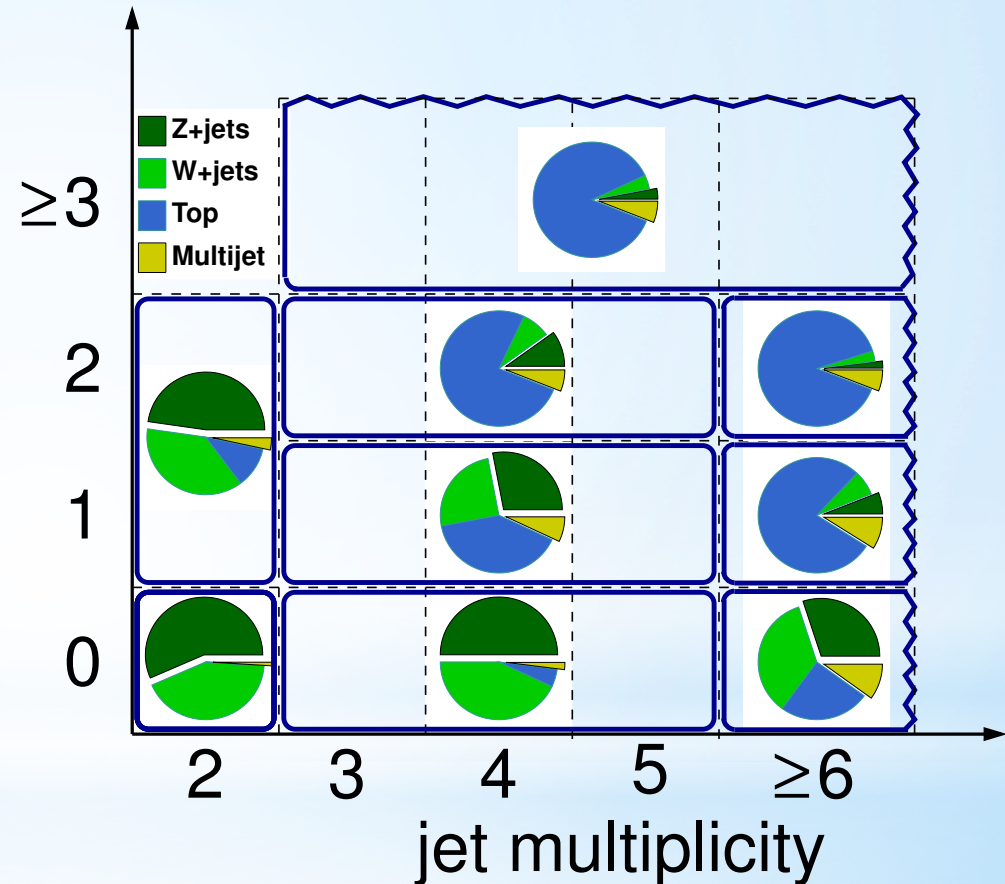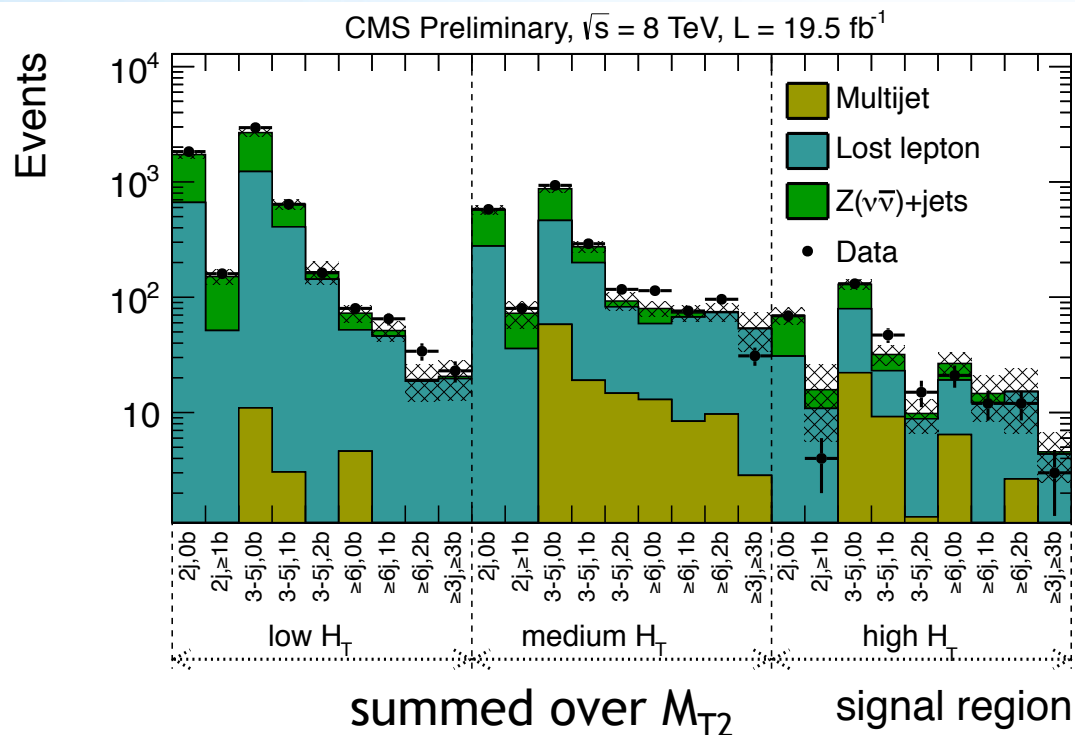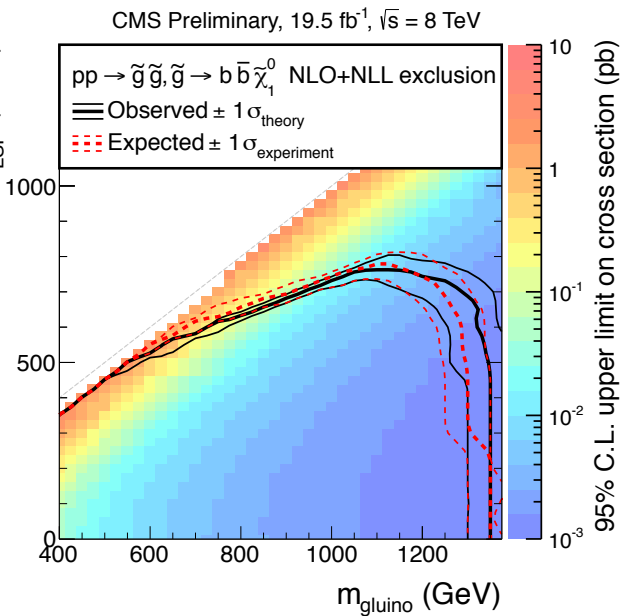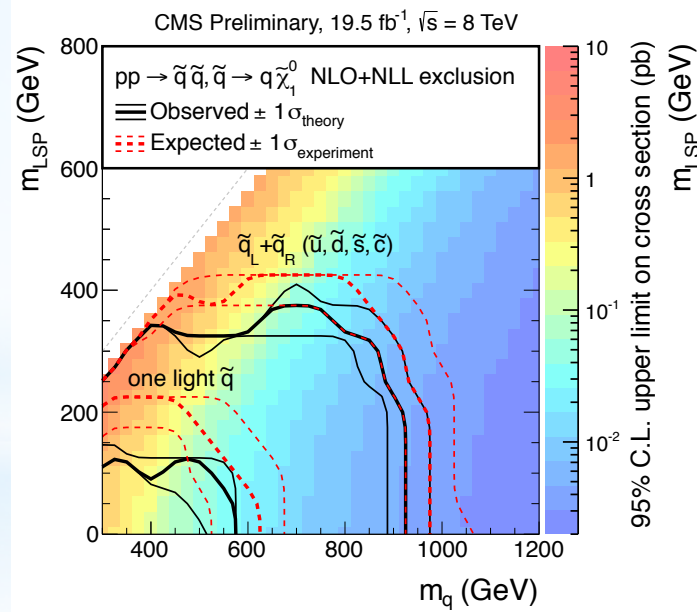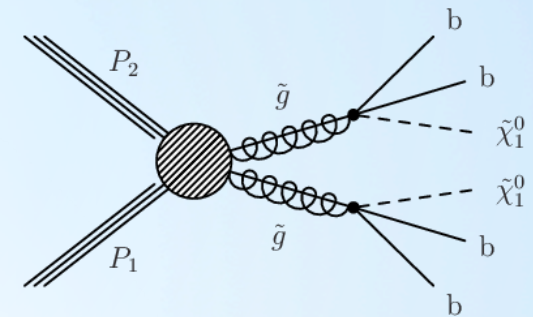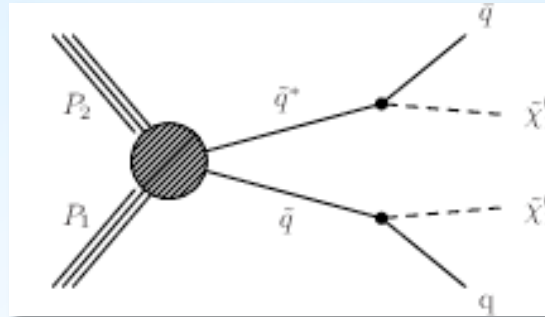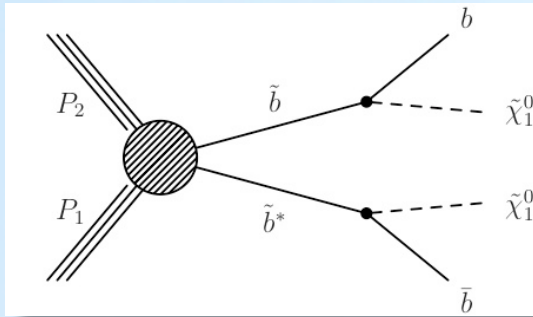
# Inclusive search with $M_{T2}$ – SUS-13-019

* data-driven background estimations
  * single muon sample for W+jets and tt+jets
  * photon + jets and di-muon sample for Z+jets
  * QCD from $M_{T2}$ sideband extrapolation
* Search in bins of $M_{T2}$ with $M_{T2}$ > 200 GeV
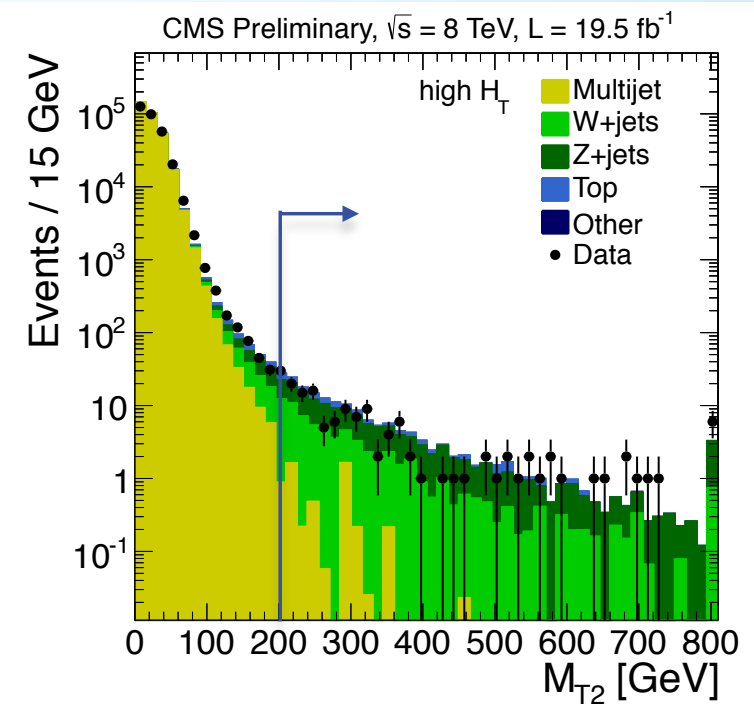
# Inclusive search with $M_{T2}$ – SUS-13-019
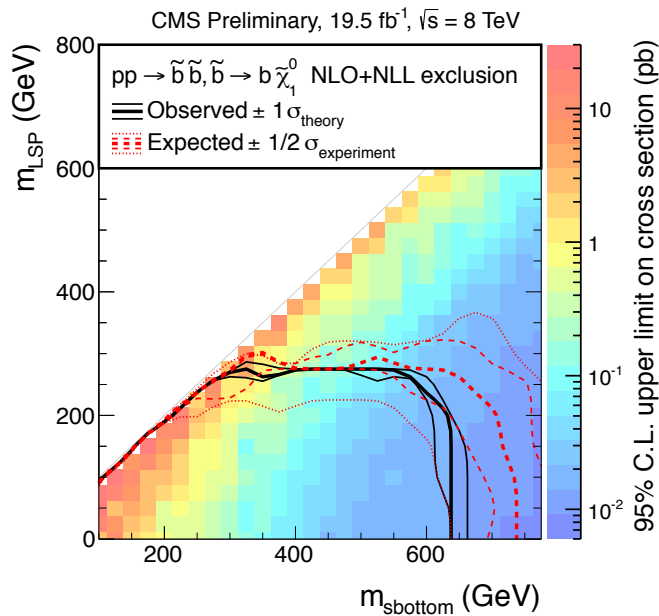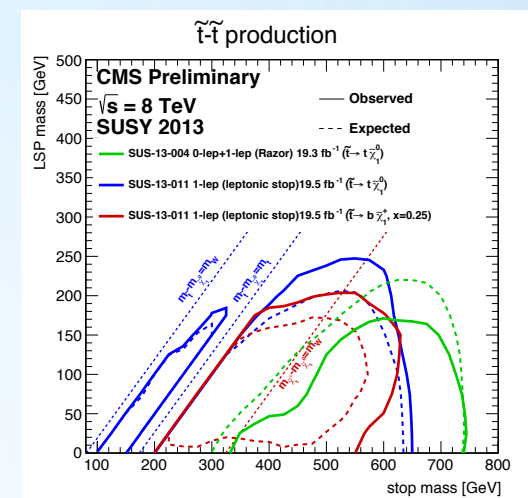
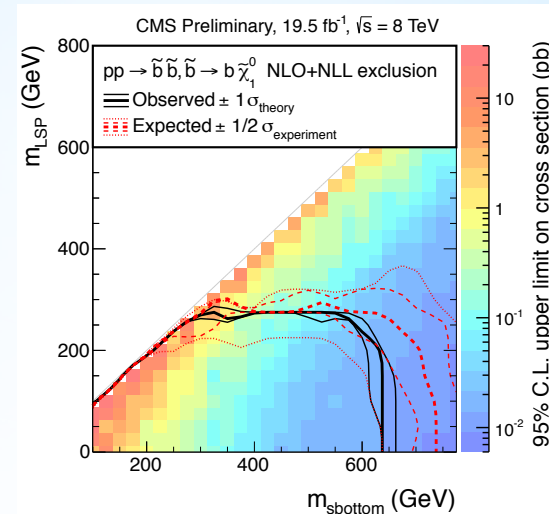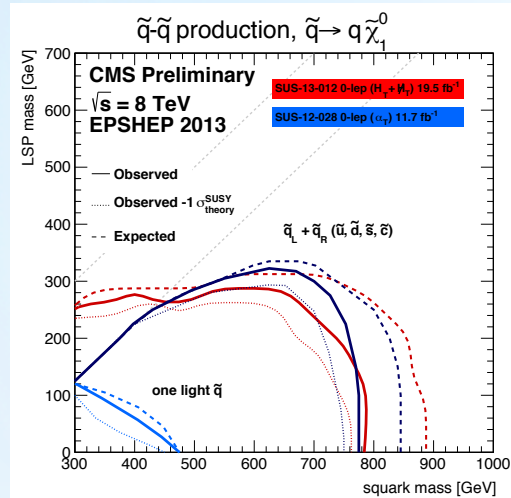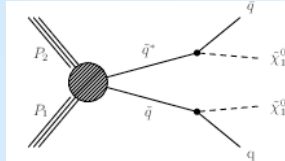*additional interpretations available

# Overview of squark & gluino searches
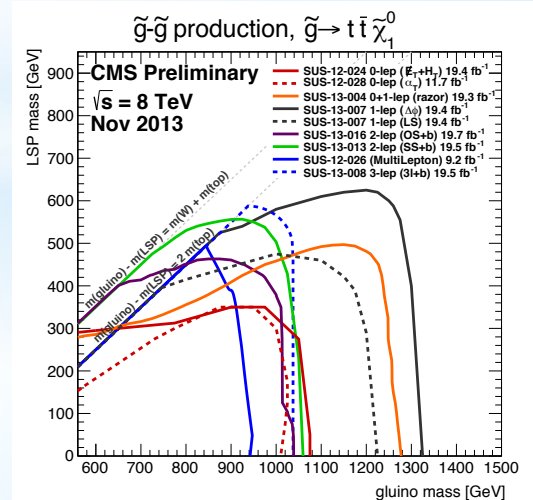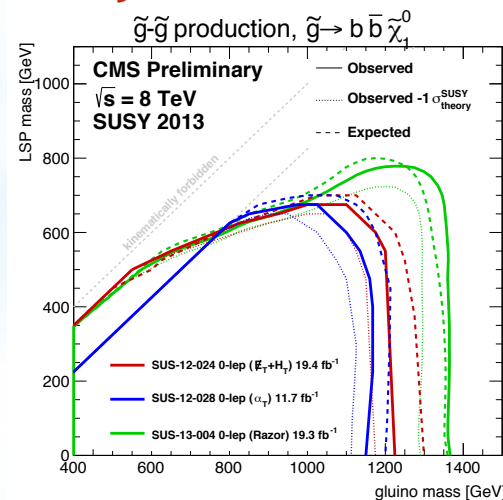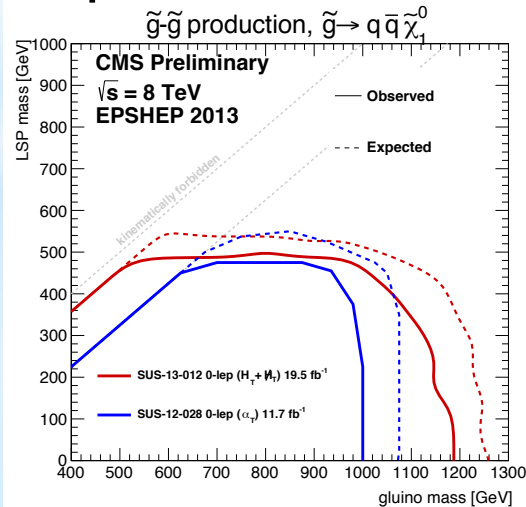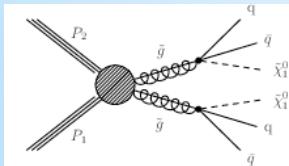
## Direct squark production: sensitivity around 600-700 GeV
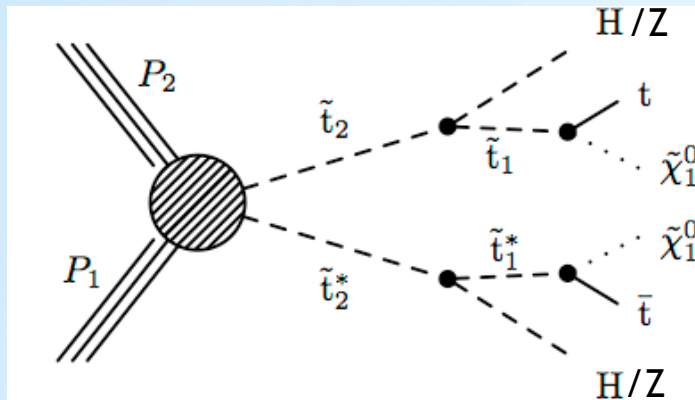


## Gluino pair production: sensitivity around 1.0-1.3 TeV



La Thuile

# *Higgs in SUSY cascade
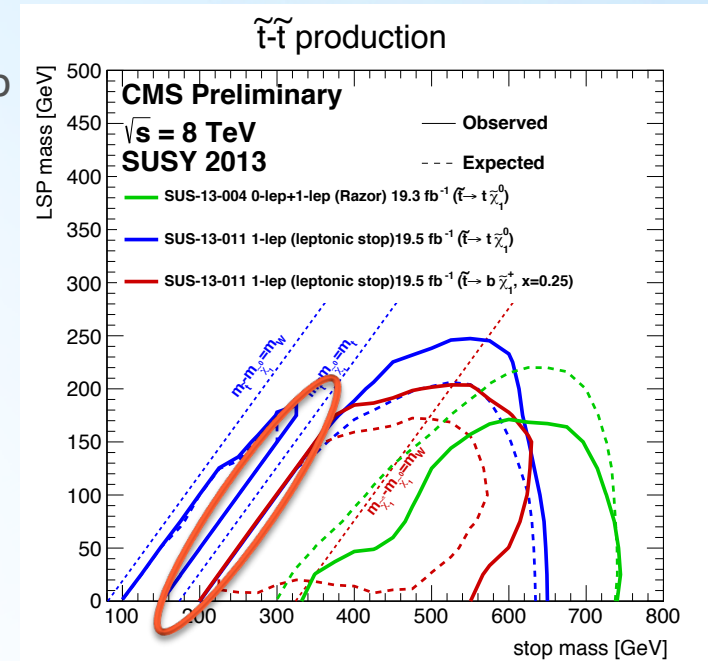
# * $Stop_2$ search with decay via Z and H - SUS-13-024



* close the gap where

$$m_{stop} - m_{\chi_1^0} = m_{top}$$

Sensitive to H->bb,
H->ZZ & H->WW decays

**NEW!!**

* Search regions:

| $N_\ell$ | Veto | $N_{b\ jets}$ | $N_{jets}$ | $E_T^{miss}$ [GeV] | Additional requirements [GeV] |
|---|---|---|---|---|---|
| 1 | track or $\tau_h$ | $= 3$ | $\geq 5$ | $\geq 50$ | $m_T > 150$ |
| | | $\geq 4$ | $\geq 4$ | | $m_T > 120$ |
| 2 OS | extra e/$\mu$ | $= 3$ | $\geq 5$ | $\geq 50$ | ($N_{bb} = 1$ with $100 \leq m_{bb} \leq 150$), $N_{bb} \geq 2$ |
| | | $\geq 4$ | $\geq 4$ | | |
| 2 SS | extra e/$\mu$ | $= 1$ | $[2,3], \geq 4$ | $[50,120], \geq 120$ | for low/high-$p_T$: $H_T \in [200, 400], \geq 400$ |
| | | $\geq 2$ | | | |
| $\geq 3$ | — | $= 1$ | $[2,3], \geq 4$ | $[50,100], [100,200], \geq 200$ | for on/off-Z: $H_T \in [60, 200], \geq 200$ |
| | | $= 2$ | | | |
| | | $\geq 3$ | $\geq 3$ | | |

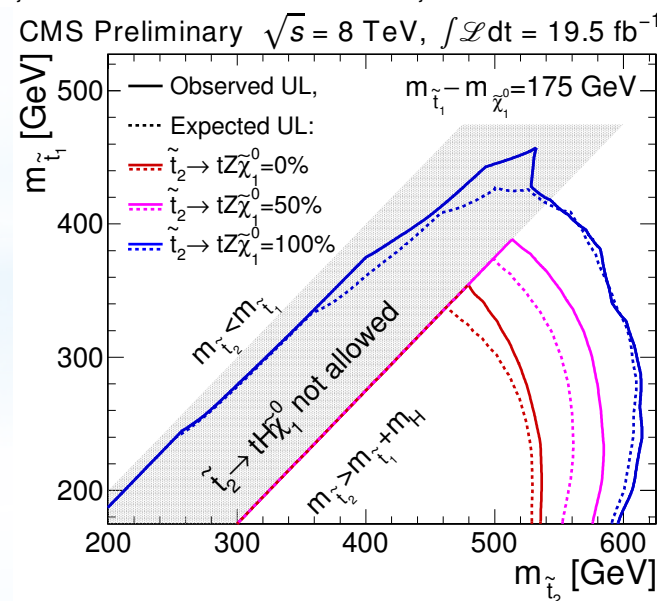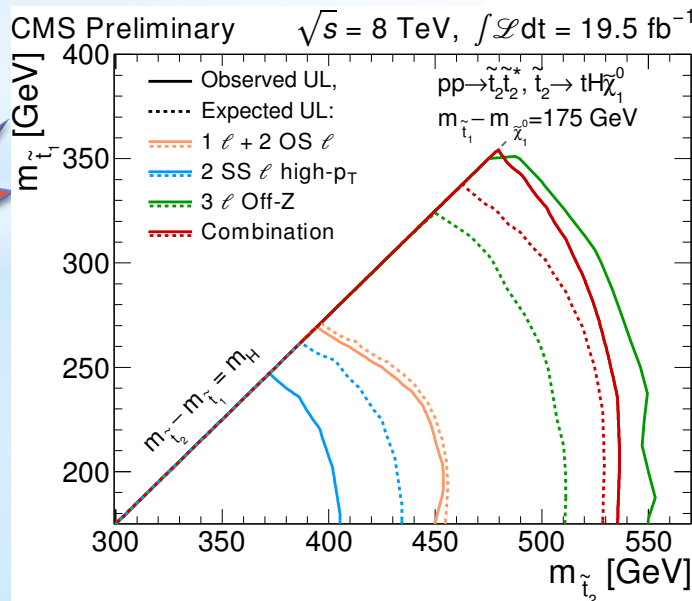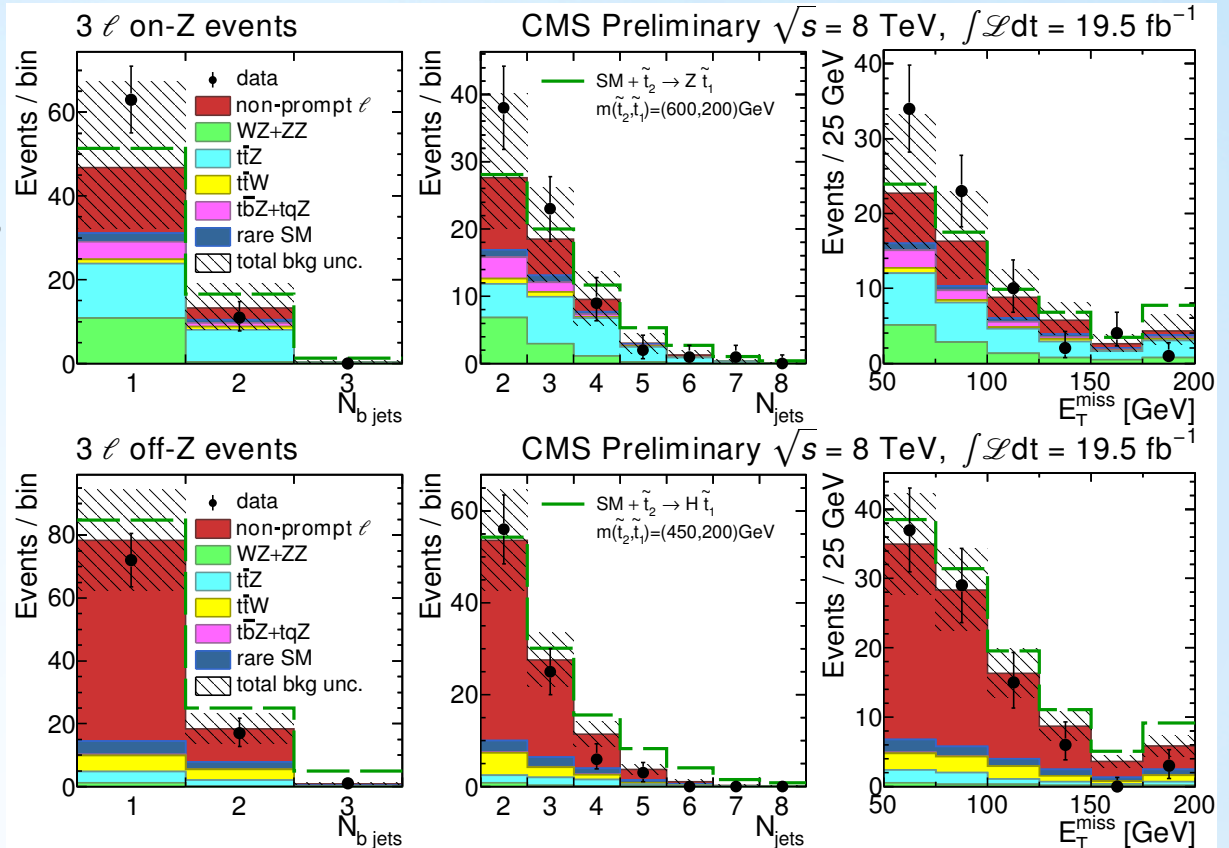La                                                                                          014

# SUS-13-024

* >=3 lepton selection is the most sensitive
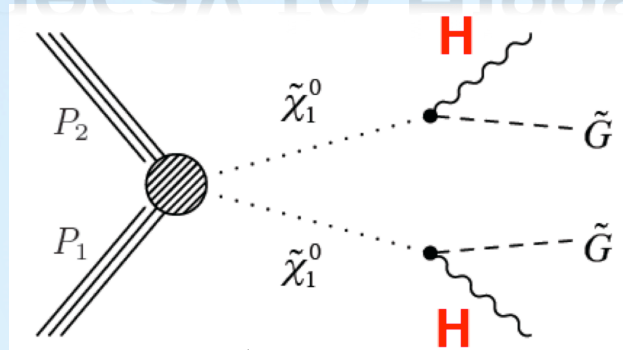  * divided by

    on Z and off Z

* For all points:
  * $m_{stop1} - m_{\chi_1^0} = m_{top}$

NEW!!

# EWK production of Higgsinos with decay to Higgs -SUS-13-022

**NEW!!!**



$\tilde{\chi}_1^0$, $\tilde{\chi}_2^0$, and $\tilde{\chi}_1^\pm$ states are pure higgsinos

$\tilde{\chi}_1^0$, $\tilde{\chi}_2^0$, and $\tilde{\chi}_1^\pm$ mass degenerate

* 4 b-jet final state

* Uses MET significance $S_{MET}$ as discriminating variable as well as $\Delta R$ between b-jets of H candidates and

$$|\Delta m_{jj}| \equiv |m_{jj,1} - m_{jj,2}|$$

$$\langle m_{jj} \rangle \equiv (m_{jj,1} + m_{jj,2})/2.$$

of Higgs candidates



Example distributions for 4-b events

# *Interpretation in GMSB model- SUS-13-022

$S_{MET}$ = [30-50], [50-100], [100-150], [>150]
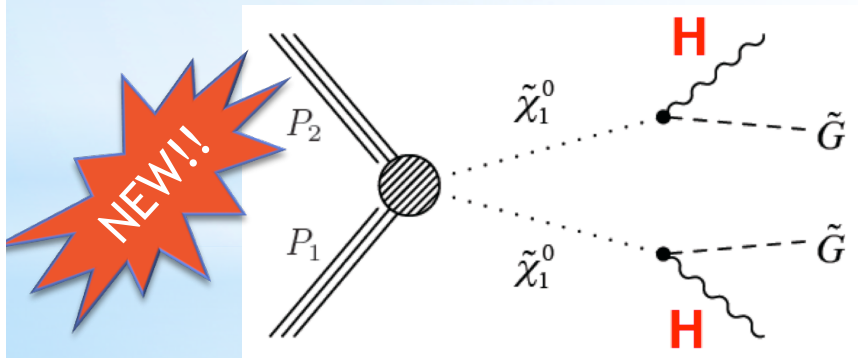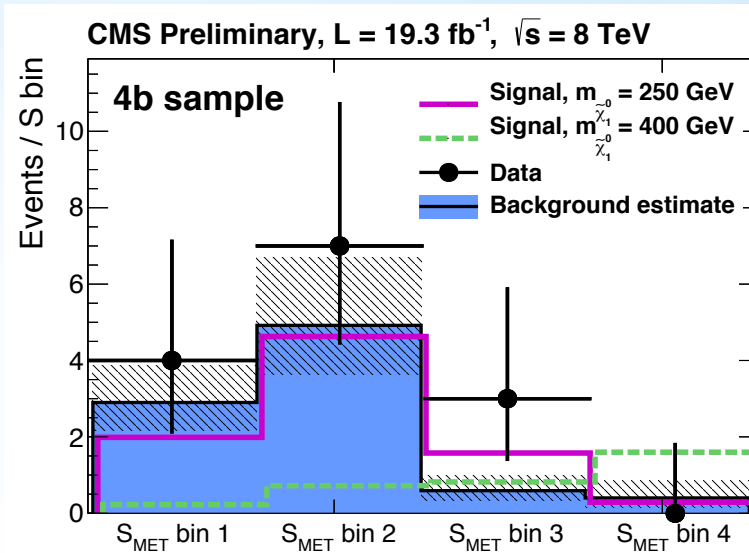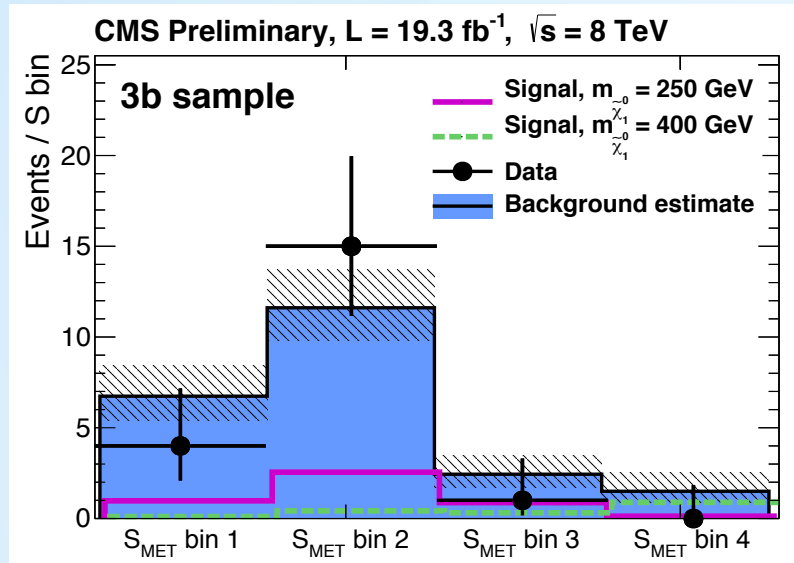


$\tilde{\chi}_1^0$, $\tilde{\chi}_2^0$, and $\tilde{\chi}_1^\pm$ states are pure higgsinos,

$\tilde{\chi}_1^0$, $\tilde{\chi}_2^0$, and $\tilde{\chi}_1^\pm$ mass degenerate
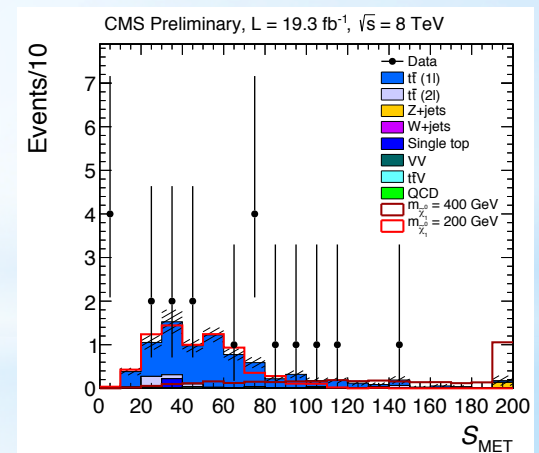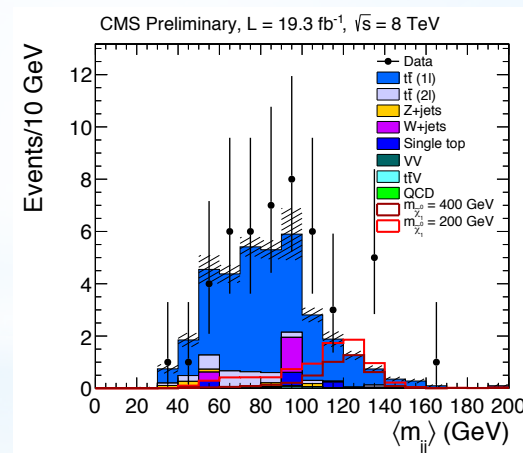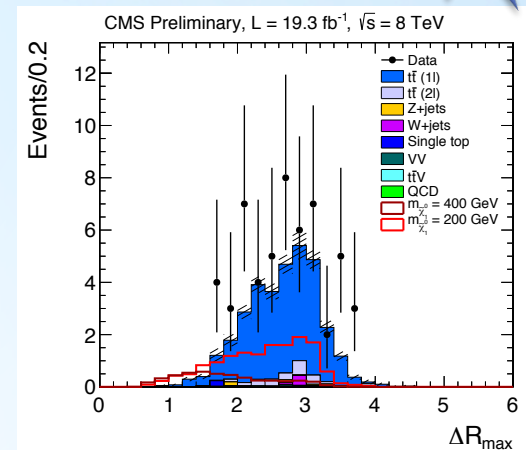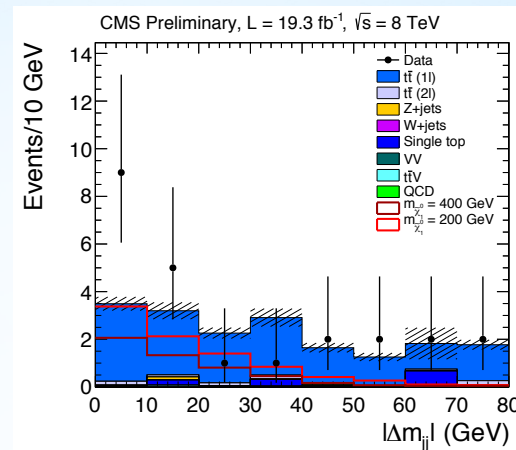
K. Matchev & S. Thomas,
Phys. Rev. D 62 (2000) 077702

La Thuile
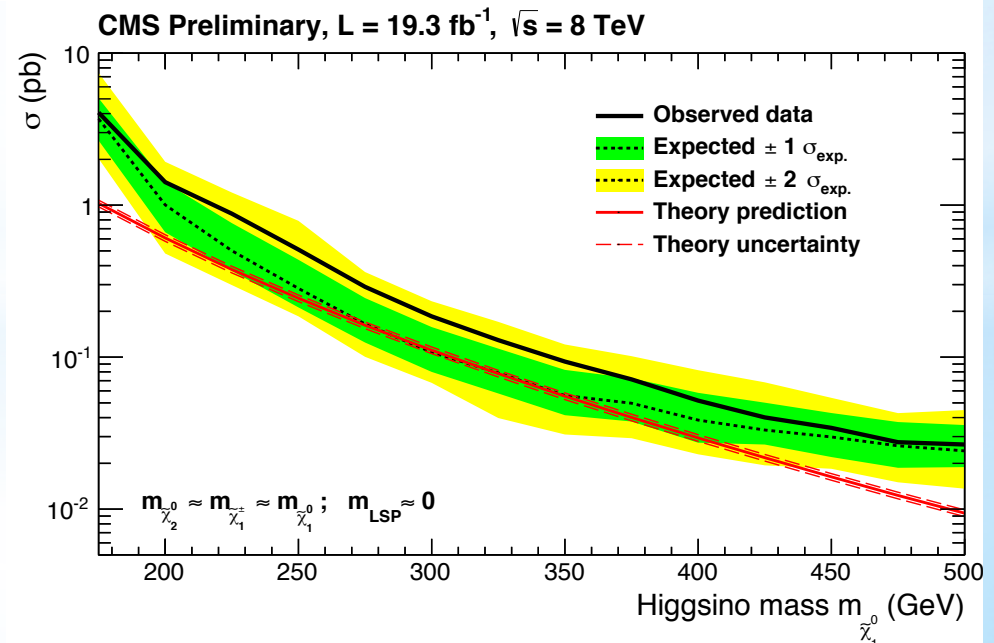
# *Outlook

*Good prospects for SUSY from energy increase from 8->13 TeV

*much larger than just ratio of CM energies

*up to factor ~50 for pair production of 1.5 TeV gluinos

*factor 6 for stop pairs of 500 GeV

*Not only good for SUSY but also Z' etc.



ratios of LHC parton luminosities: 13 TeV / 8 TeV

gg
$\Sigma q\bar{q}$
qg

stop pair @ 500 GeV

gluino pair @ 1500 GeV

luminosity ratio

$M_X$ (GeV)

WJS2013

MSTW2008NLO
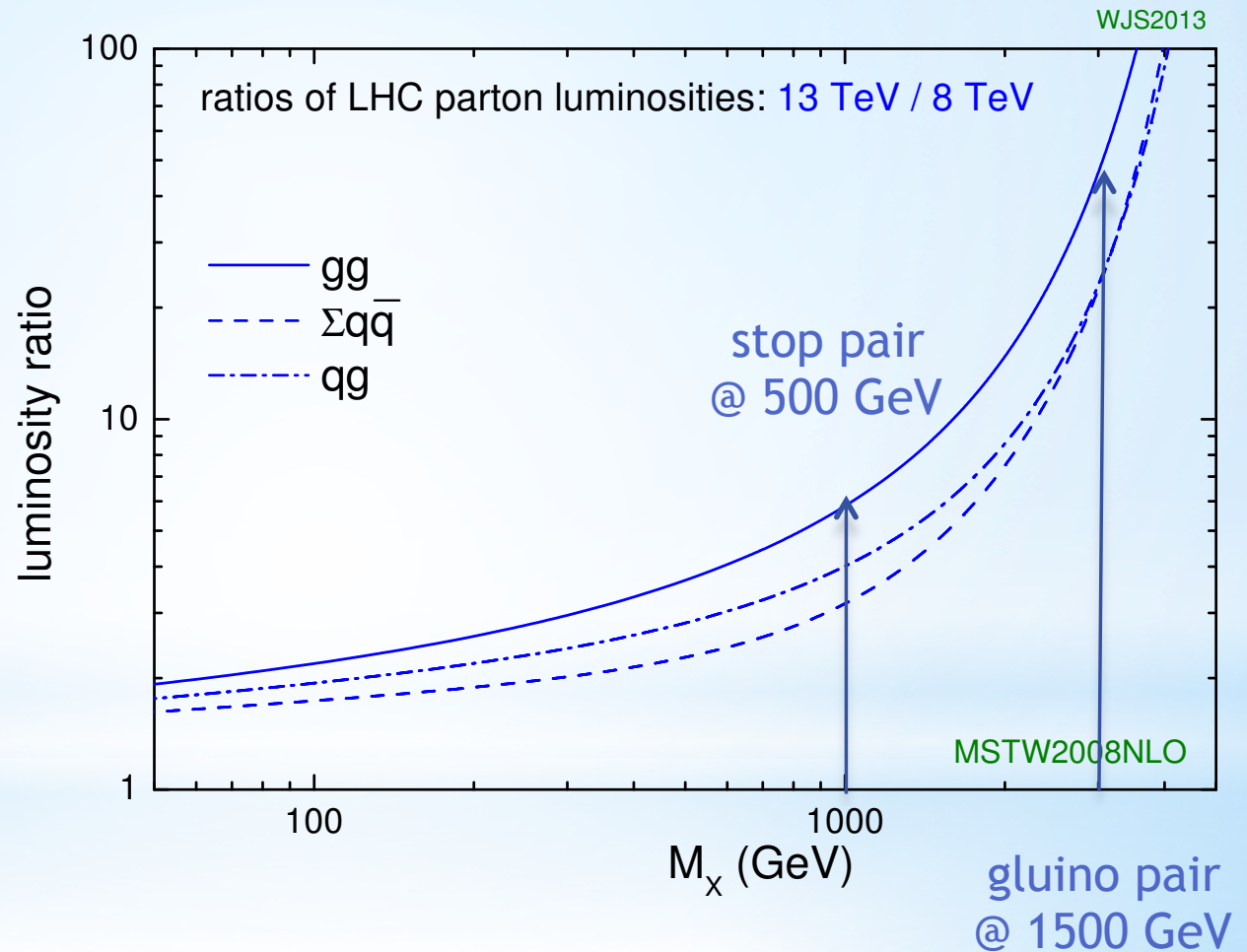
# *Projections for 300/fb @ 14 TeV

Exclusion with 20/fb @ 8 TeV
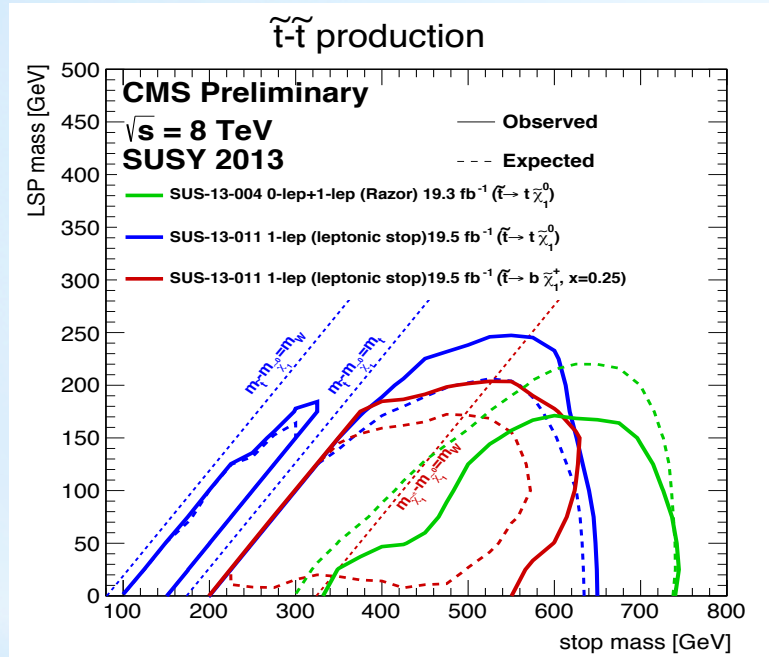
Discovery with 300/fb @ 14 TeV
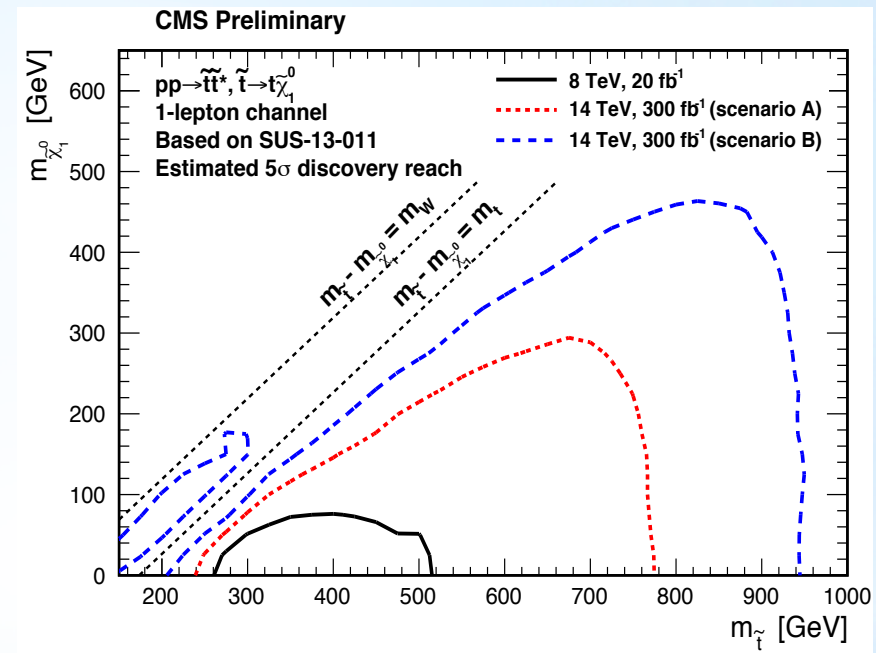


* Searches will cover the interesting region of stop masses up to 1 TeV with 300/fb @ 13 TeV

* Neutralino masses up to 500 GeV

* In gluino mediated models, reach up to $m_{gl}$ of 2 TeV

# *Summary

* Supersymmetry proves to be elusive
  * Searches focus on stops and sbottoms because of special role for Higgs boson
  * Sensitivity for charginos/neutralino/slepton production is becoming interesting
  * very broad search programme for gluinos and squark production

* Discovery of a Higgs has led to several analyses searching for Higgs in SUSY decay chain

* Degenerate mass spectra prove to be difficult but accessible through monojet searches

* LHC @ 13 TeV will open up a large region of so far unexplored parameter space

* Check here:
* https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsSUS

Thank you!

# *backup

# *from 2010 -> 2012

**13 candidate events**
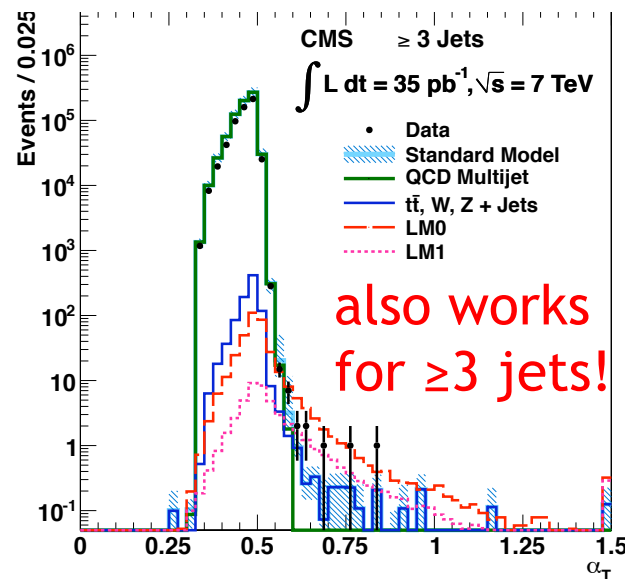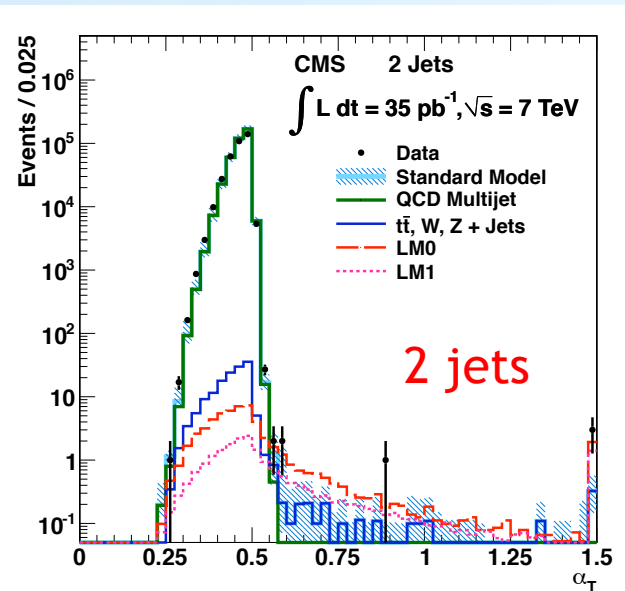
**1000's of candidate events, split by HT, $N_{jets}$ and $N_{b\text{-}jets}$**
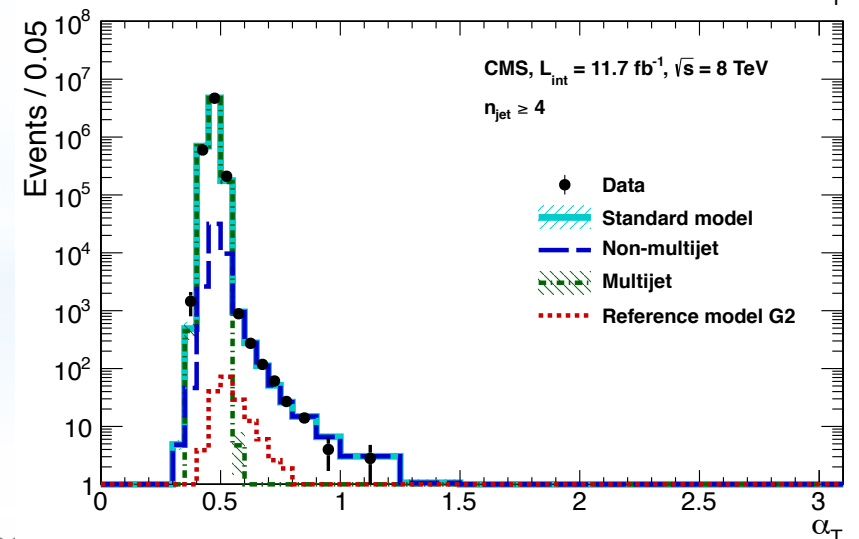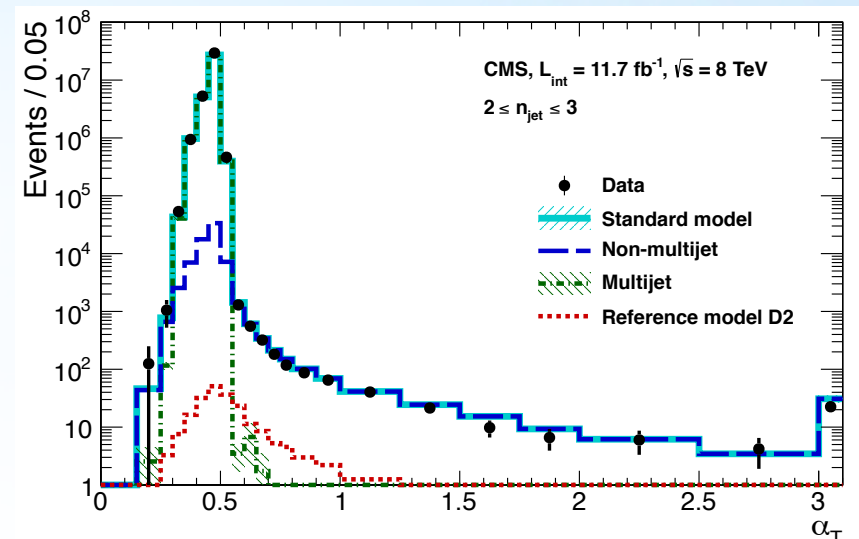
# *(no) SUSY - Big picture - RPC



Summary of CMS SUSY Results* in SMS framework — SUSY 2013
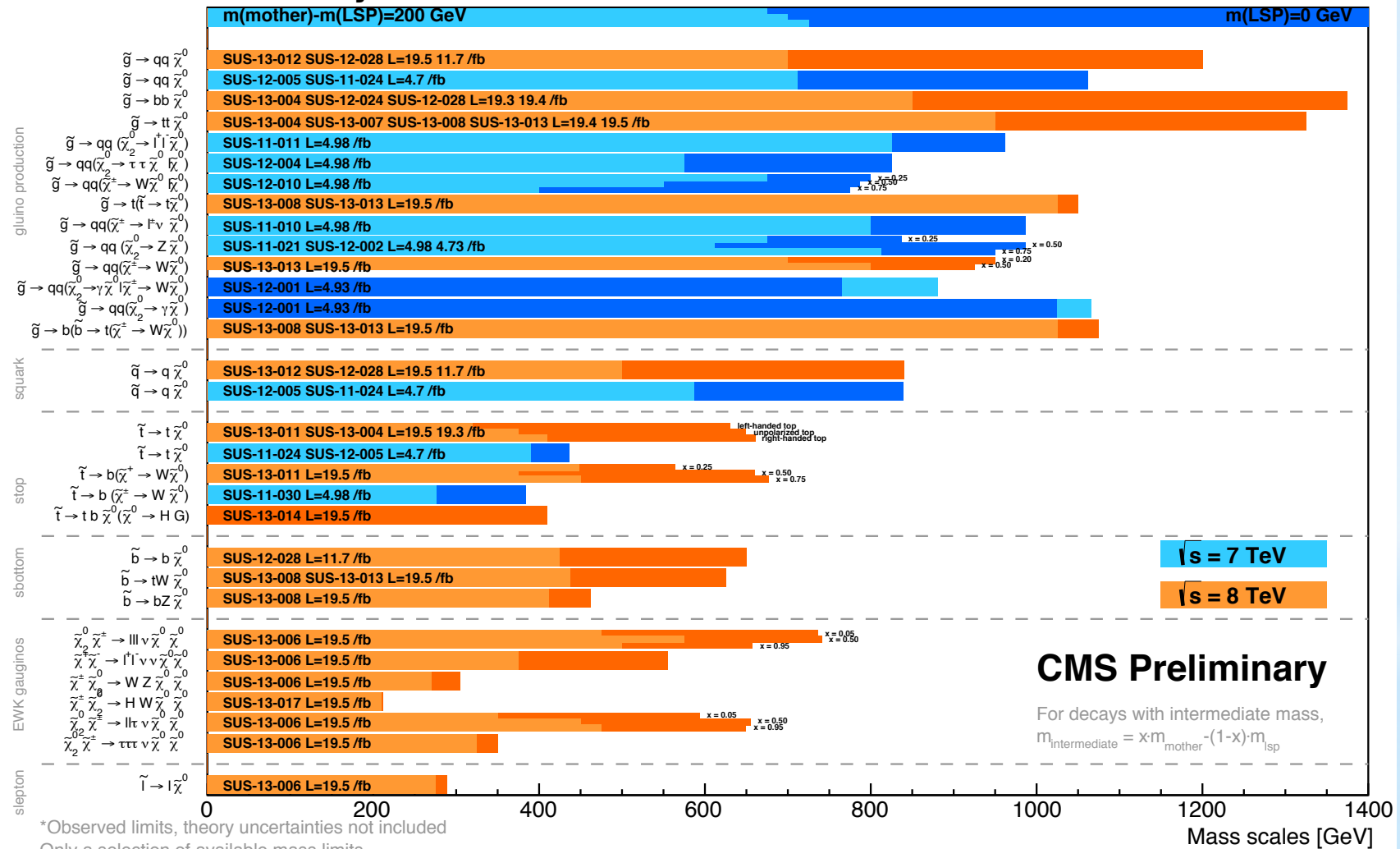
CMS Preliminary

For decays with intermediate mass, $m_{intermediate} = x \cdot m_{mother} - (1-x) \cdot m_{lsp}$

$\sqrt{s} = 7$ TeV
$\sqrt{s} = 8$ TeV

*Observed limits, theory uncertainties not included
Only a selection of available mass limits
Probe *up to* the quoted mass limit

Mass scales [GeV]

# *RPV searches



**Summary of CMS RPV SUSY Results\***                              **EPSHEP 2013**

| | |
|---|---|
| $\tilde{g} \to qll\nu$ $\lambda_{122}$ | SUS-12-027 L=9.2 /fb |
| $\tilde{g} \to qll\nu$ $\lambda_{123}$ | SUS-12-027 L=9.2 /fb |
| $\tilde{g} \to qll\nu$ $\lambda_{233}$ | SUS-12-027 L=9.2 /fb |
| $\tilde{g} \to qbt\mu$ $\lambda'_{231}$ | SUS-12-027 L=9.2 /fb |
| $\tilde{g} \to qbt\mu$ $\lambda'_{233}$ | SUS-12-027 L=9.2 /fb |
| $\tilde{g} \to qqb$ $\lambda''_{113/223}$ | EXO-12-049 L=19.5 /fb |
| $\tilde{g} \to qqq$ $\lambda''_{112}$ | EXO-12-049 L=19.5 /fb |
| $\tilde{g} \to tbs$ $\lambda''_{323}$ | SUS-13-013 L=19.5 /fb |
| $\tilde{g} \to qqqq$ $\lambda''_{112}$ | SUS-12-027 L=9.2 /fb |
| $\tilde{q} \to qll\nu$ $\lambda_{122}$ | SUS-12-027 L=9.2 /fb |
| $\tilde{q} \to qll\nu$ $\lambda_{123}$ | SUS-12-027 L=9.2 /fb |
| $\tilde{q} \to qll\nu$ $\lambda_{233}$ | SUS-12-027 L=9.2 /fb |
| $\tilde{q} \to qbt\mu$ $\lambda'_{231}$ | SUS-12-027 L=9.2 /fb |
| $\tilde{q} \to qbt\mu$ $\lambda'_{233}$ | SUS-12-027 L=9.2 /fb |
| $\tilde{q}_R \to qqqq$ $\lambda''_{112}$ | SUS-12-027 L=9.2 /fb |
| $\tilde{t}_R \to \mu e\nu t$ $\lambda_{122}$ | SUS-13-003 L=19.5 9.2 /fb |
| $\tilde{t}_R \to \mu\tau\nu t$ $\lambda_{123}$ | SUS-12-027 L=9.2 /fb |
| $\tilde{t}_R \to \mu\tau\nu t$ $\lambda_{233}$ | SUS-13-003 L=19.5 9.2 /fb |
| $\tilde{t}_R \to tbt\mu$ $\lambda'_{233}$ | SUS-13-003 L=19.5 /fb |
| $\tilde{t} \to b\tau$ $\lambda'_{333}$ | EXO-12-002 L=4.8 /fb |

Prompt LSP decays

$\sqrt{s}$ = 7 TeV
$\sqrt{s}$ = 8 TeV
**CMS Preliminary**
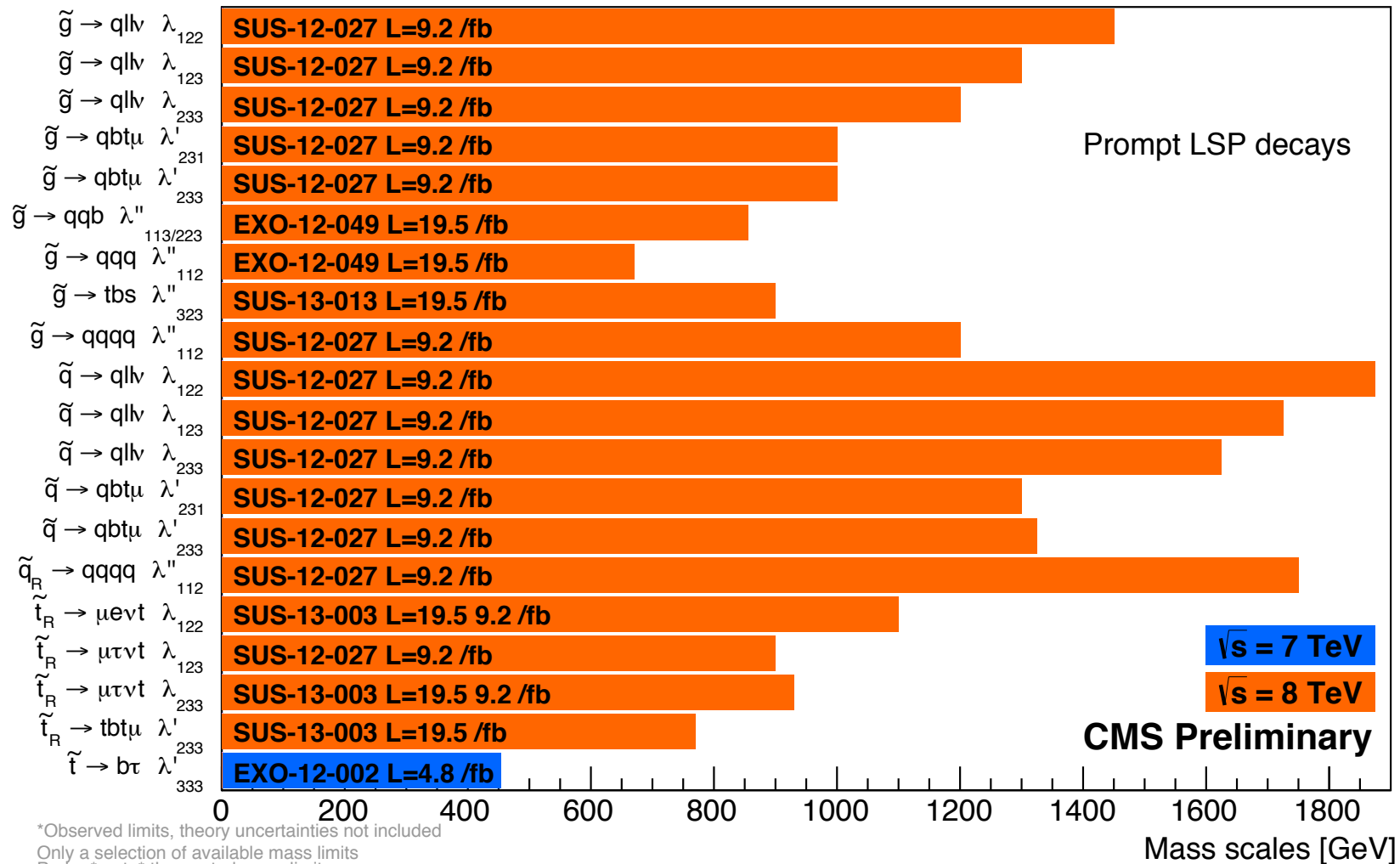
0   200   400   600   800   1000   1200   1400   1600   1800

\*Observed limits, theory uncertainties not included
Only a selection of available mass limits
Probe *up to* the quoted mass limit

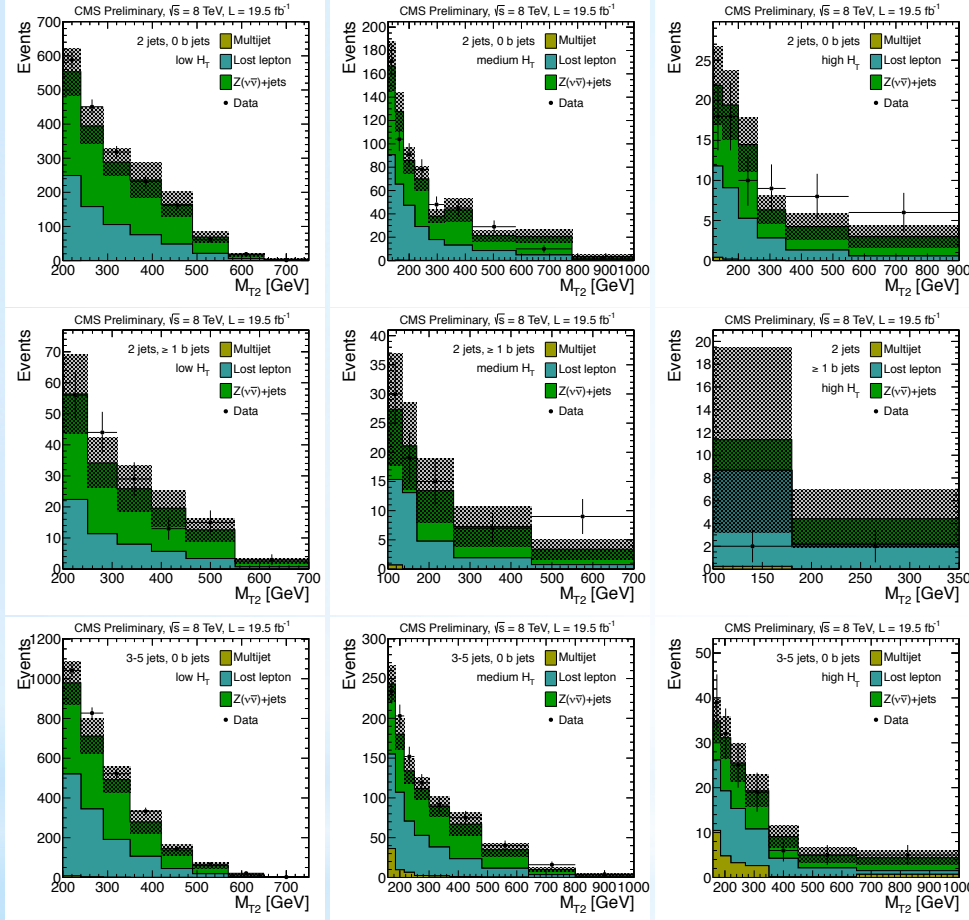Mass scales [GeV]

# *MT2 - SUS-13-19



Figure 7: $M_{T2}$ distributions from data-driven background estimates compared to data for low $H_T$ (left), medium $H_T$ (middle), and high $H_T$ (right). The topological region in the jet − b-jet multiplicity is given in each plot. They are from top to bottom: $N_j = 2$ and $N_b = 0$, $N_j = 2$ and $N_b \geq 1$, $3 \leq N_j \leq 5$ and $N_b = 0$. The data correspond to an integrated luminosity of 19.5 fb$^{-1}$. All selection cuts are applied. The uncertainty band drawn in this figure does not contain shape uncertainties of the lost-lepton estimate.
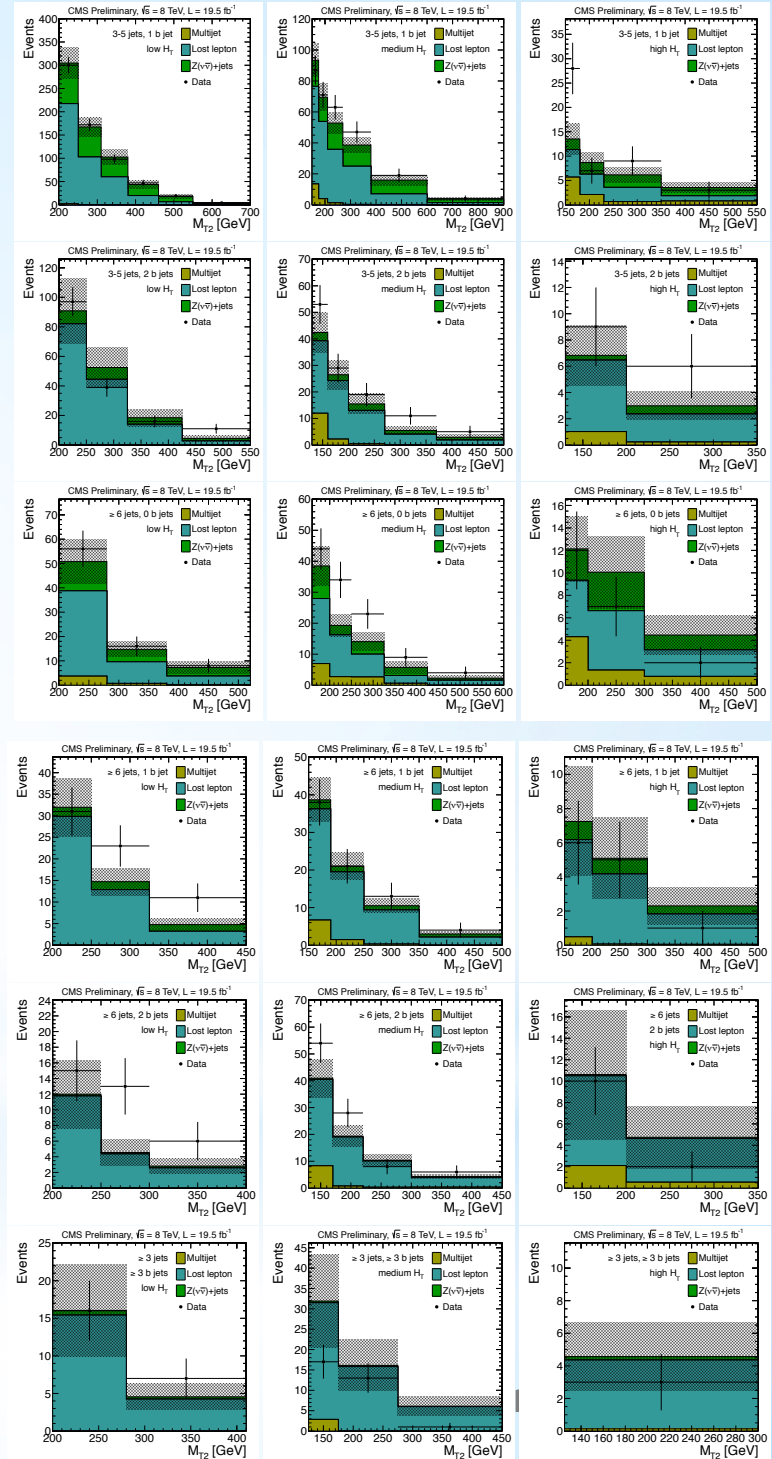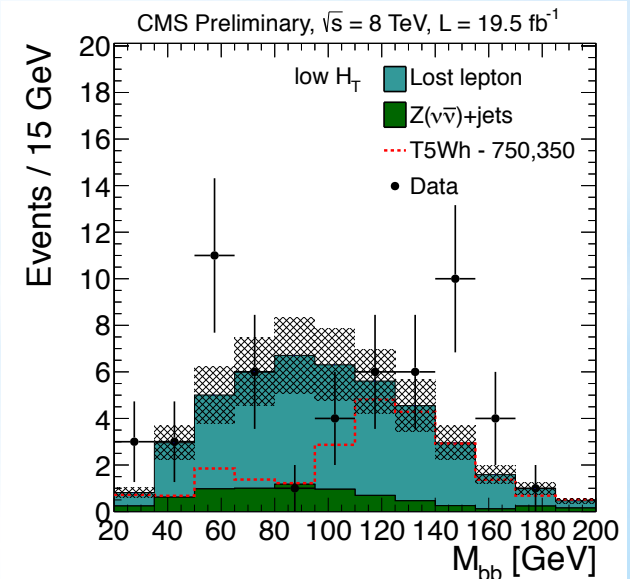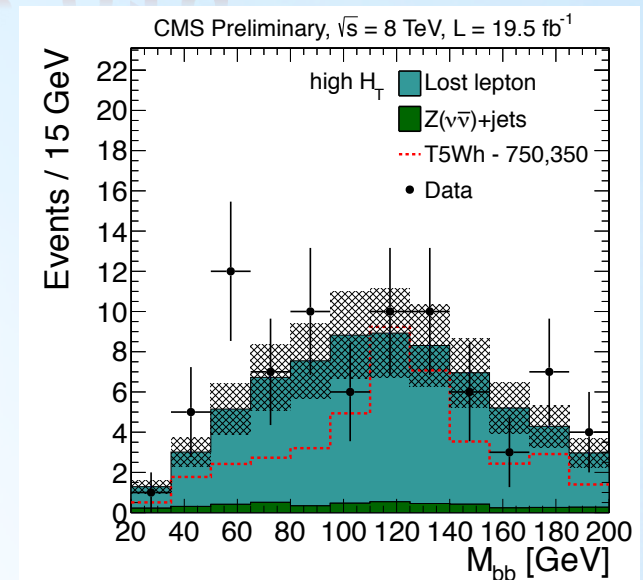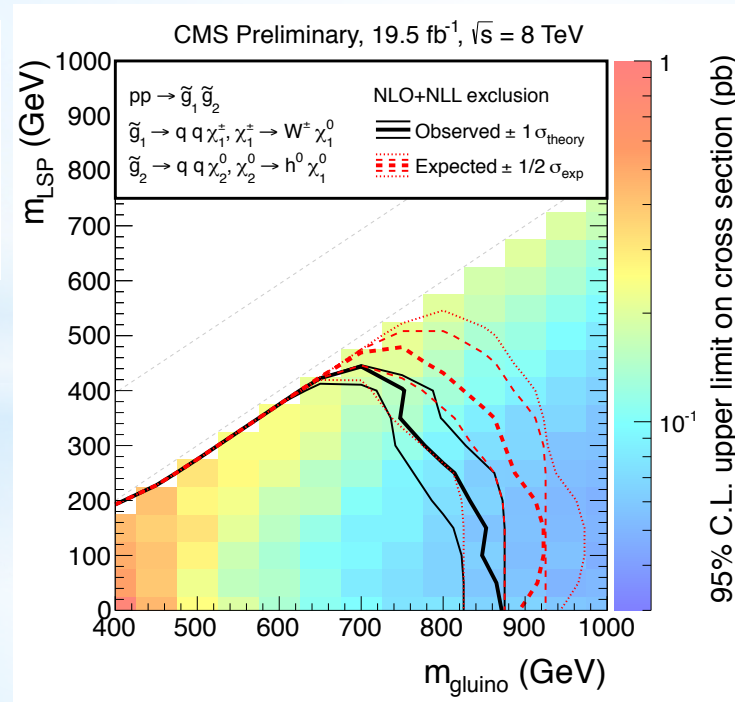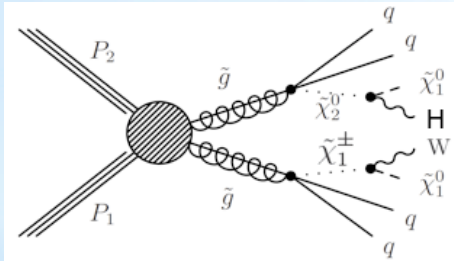
# $M_{T2}$ Higgs search – SUS-13-019
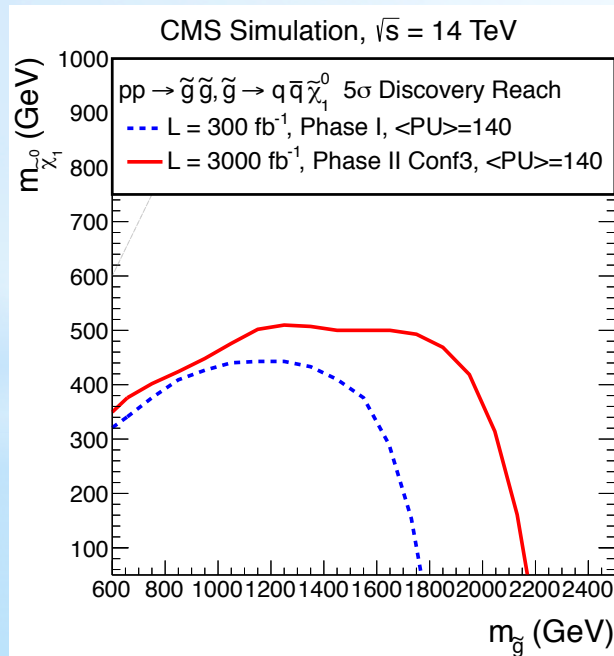
## *Slightly modified search cuts:
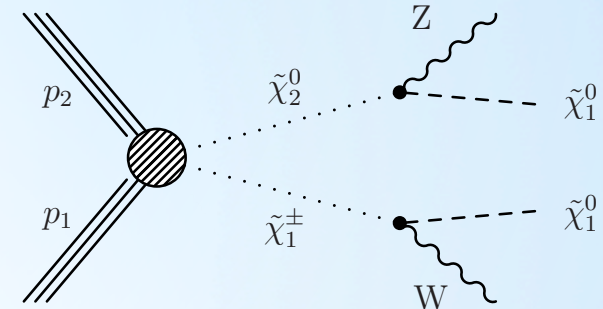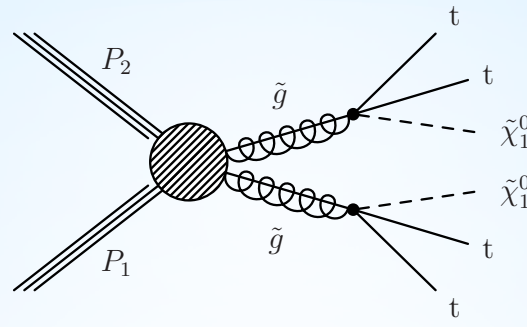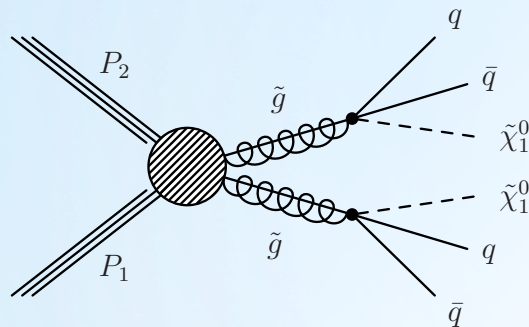
- $N_j \geq 4$,
- $N_b \geq 2$, with $p_T \geq 20\,\text{GeV}$[1],
- $450 \leq H_T < 750\,\text{GeV}$, $E_T^{\text{miss}} > 200\,\text{GeV}$, and $M_{T2} > 200\,\text{GeV}$ - called the low $H_T$ region,
- $H_T \geq 750\,\text{GeV}$, $E_T^{\text{miss}} > 30\,\text{GeV}$, and $M_{T2} > 125\,\text{GeV}$ - called the high $H_T$ region.

## *Look for excess in invariant mass distribution of two b-jets



CMS Preliminary, $\sqrt{s}$ = 8 TeV, L = 19.5 fb$^{-1}$

high $H_T$
Lost lepton
$Z(\nu\bar{\nu})$+jets
T5Wh - 750,350
Data



CMS Preliminary, 19.5 fb$^{-1}$, $\sqrt{s}$ = 8 TeV

$pp \rightarrow \tilde{g}_1 \tilde{g}_2$

$\tilde{g}_1 \rightarrow q\,q\,\chi_1^{\pm}$, $\chi_1^{\pm} \rightarrow W^{\pm}\chi_1^0$
$\tilde{g}_2 \rightarrow q\,q\,\chi_2^0$, $\chi_2^0 \rightarrow h^0\chi_1^0$

NLO+NLL exclusion
Observed $\pm\, 1\,\sigma_{\text{theory}}$
Expected $\pm\, 1/2\,\sigma_{\text{exp}}$

95% C.L. upper limit on cross section (pb)



CMS Preliminary, $\sqrt{s}$ = 8 TeV, L = 19.5 fb$^{-1}$

low $H_T$
Lost lepton
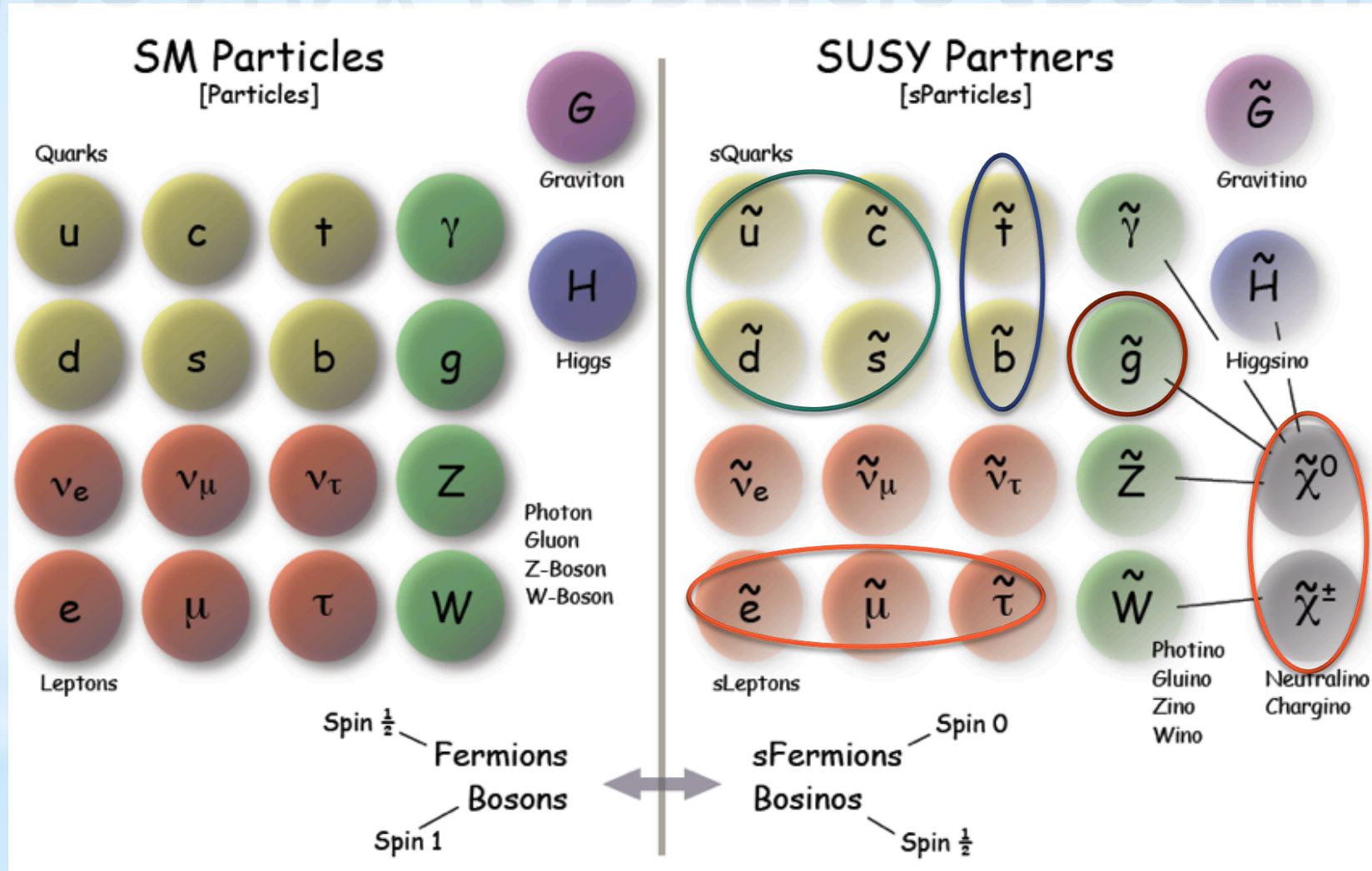$Z(\nu\bar{\nu})$+jets
T5Wh - 750,350
Data

# *Expected sensitivity @ 14 TeV

## CMS contribution to ECFA workshop
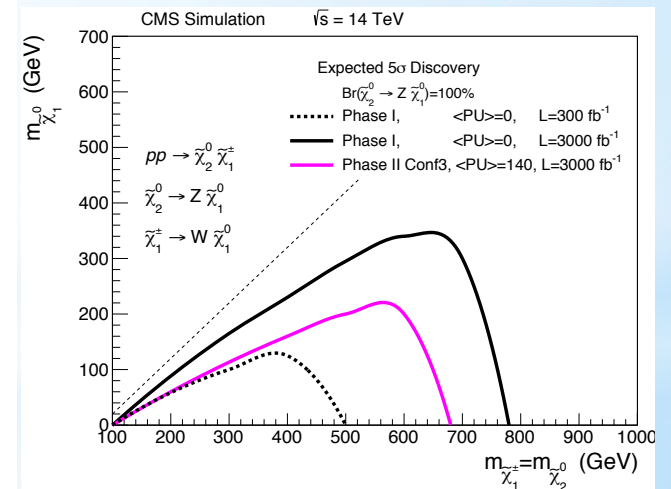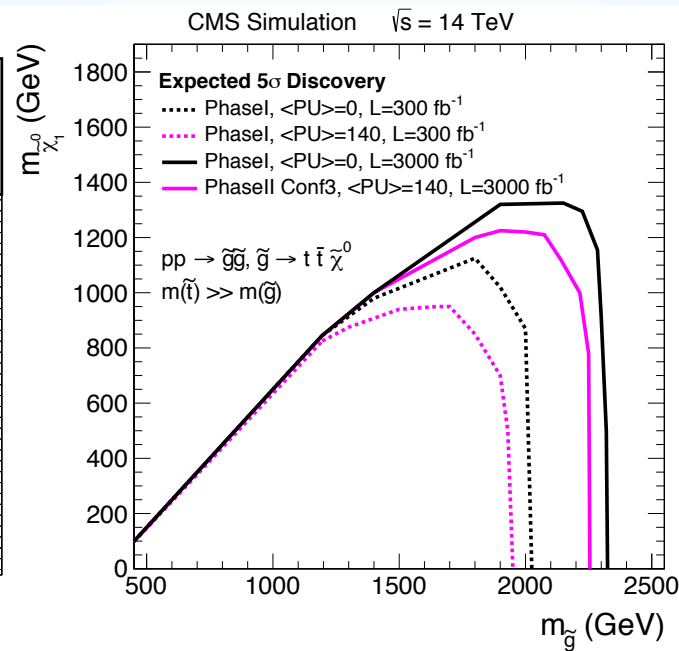


SMS assume 100% BF for these decays!

# The SUSY (s)particle spectrum



*Search for ~all of these, produced either directly or in cascades