



# Searches for 3<sup>rd</sup> Generation SUSY from CMS

Daryl Hare, Fermilab

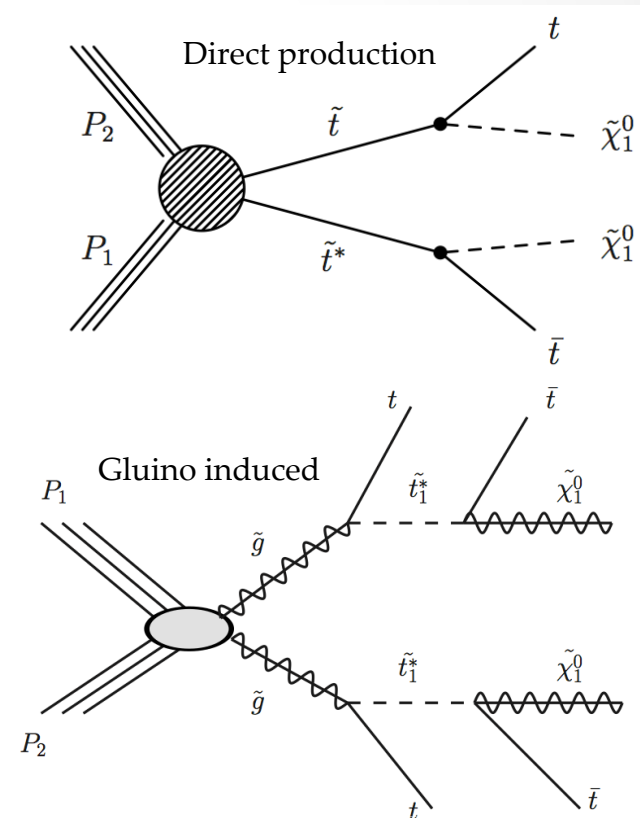
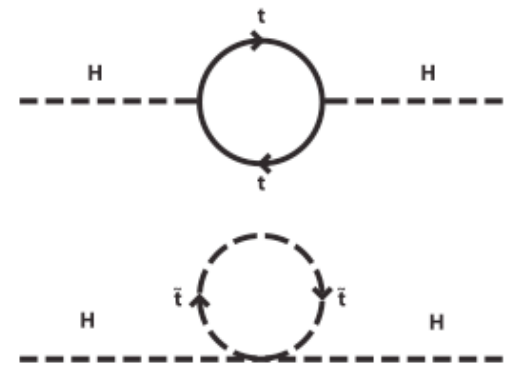
On behalf of the CMS Collaboration

# Outline

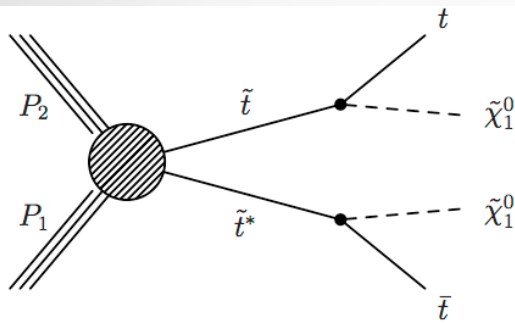
- Motivation
- Analyses:
  - Inclusive SUSY search with b's using razor variables
  - Gauge Mediated SUSY Breaking with Higgs
  - Single Lepton Direct Stop Search
  - Direct Stop Production with Higgs Bosons
- Summary & Conclusions

# Motivation

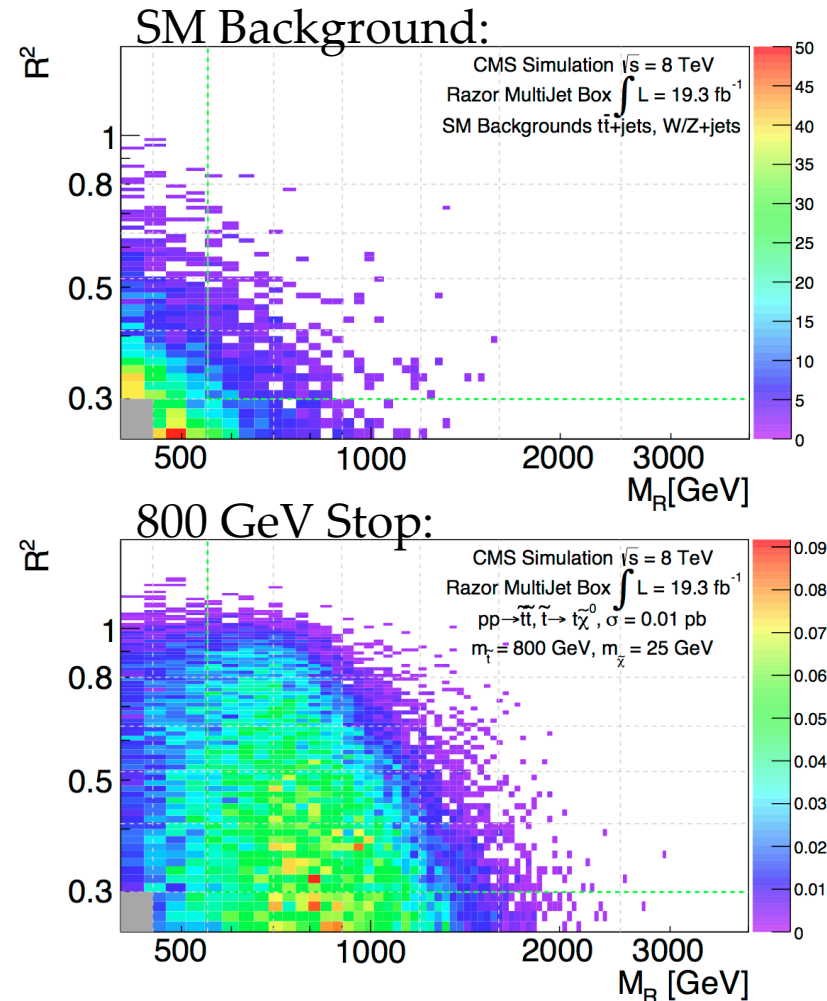
- Hierarchy problem of light Higgs mass solved by “Natural” SUSY
  - Particularly interesting given discovery of 125 GeV boson
  - Requires light top squark to cancel top quark radiative correction ( $< 1$  TeV)
- Light Higgs suggests Natural SUSY scenarios are within our reach
- Strong search program for 3<sup>rd</sup> generation SUSY at CMS
  - Direct top and bottom squark production
  - Gluino induced top or bottom squark production
  - Hadronic and leptonic final states
  - R Parity violating scenarios
- This talk focuses on stop production
  - See Sudan's talk later this session for inclusive SUSY searches



# Razor with b's

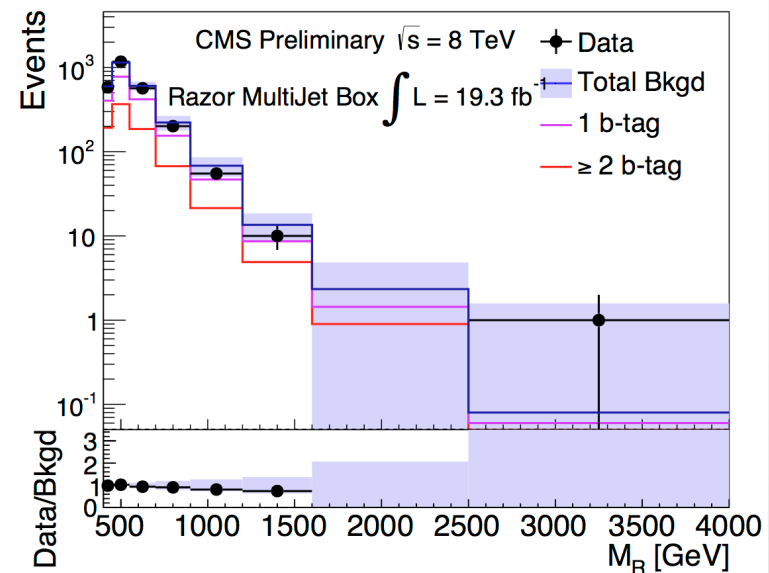
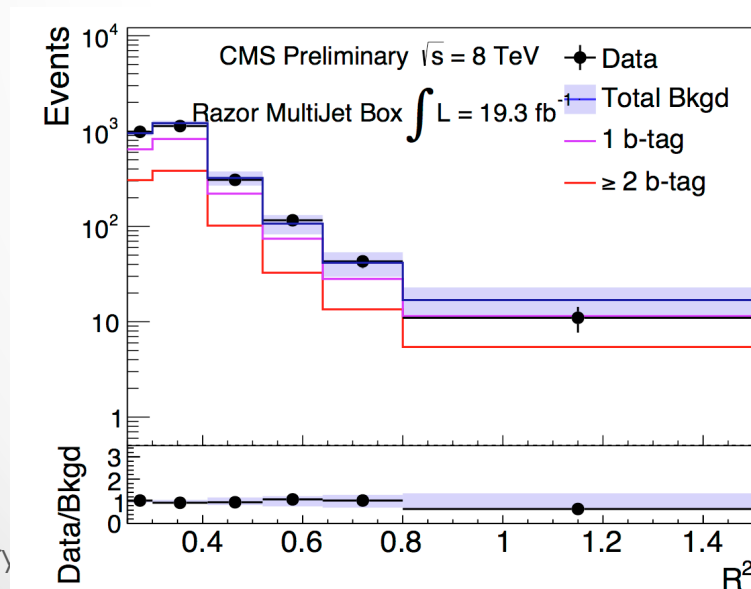
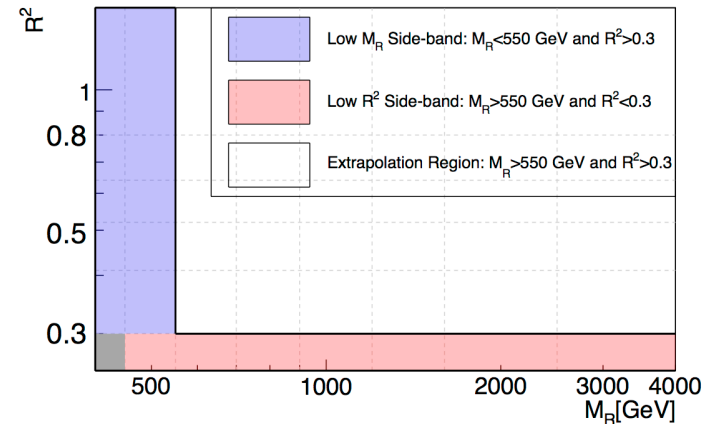


- Razor variables designed to ID two squarks each decaying to a quark and a stable neutralino
- Event is classified into two megajets
  - Chosen to minimize the invariant mass of the megajets summed in quadrature
- Look for a peaking signal in  $R^2$  vs  $M_R$



# Razor with b's

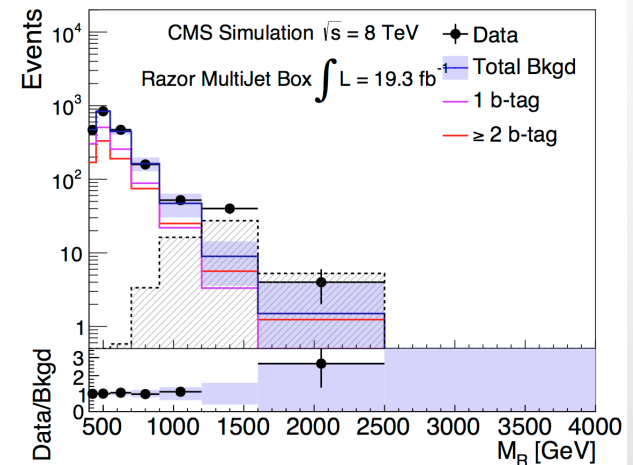
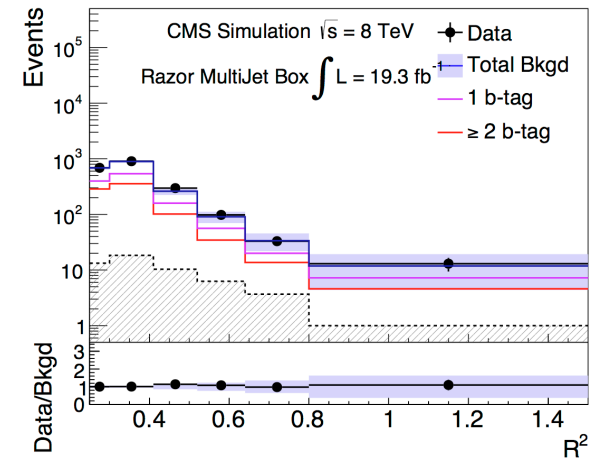
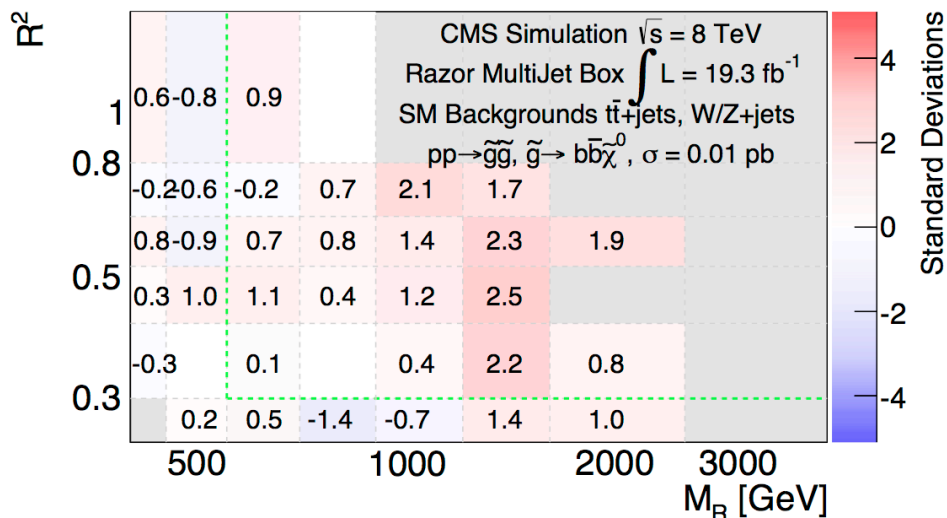
- Events sorted into exclusive signal boxes based on number of leptons and jets.
- Background estimated with a simultaneous fit of  $R^2$  and  $M_R$



# Razor with b's

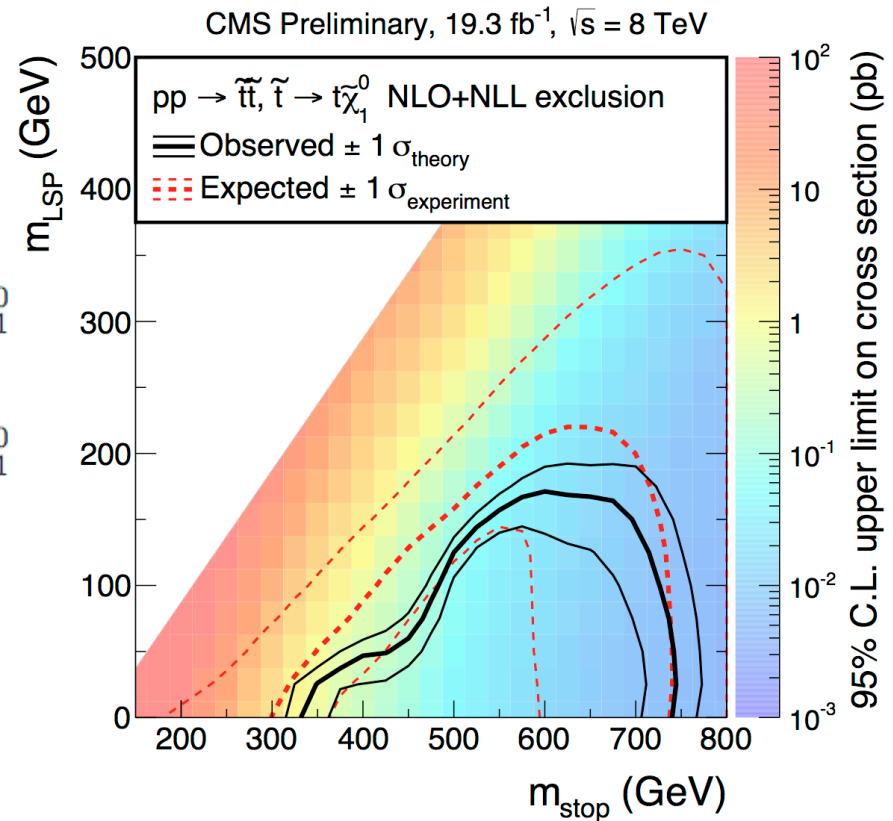
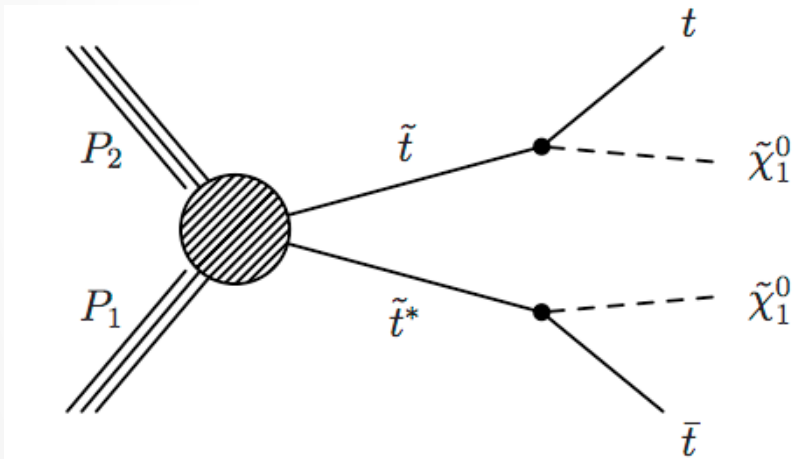
- Test background fit with injected signal ( $\sigma = 0.01$  pb)
  - $M_{\text{gluino}} = 1350$  GeV,  $M_{\text{neutralino}} = 50$  GeV
- Signal contamination in sideband has negligible effect on background shape
- Excess still observed near  $M_R \sim 1500$

## PSUEDODATA



# Razor with b's

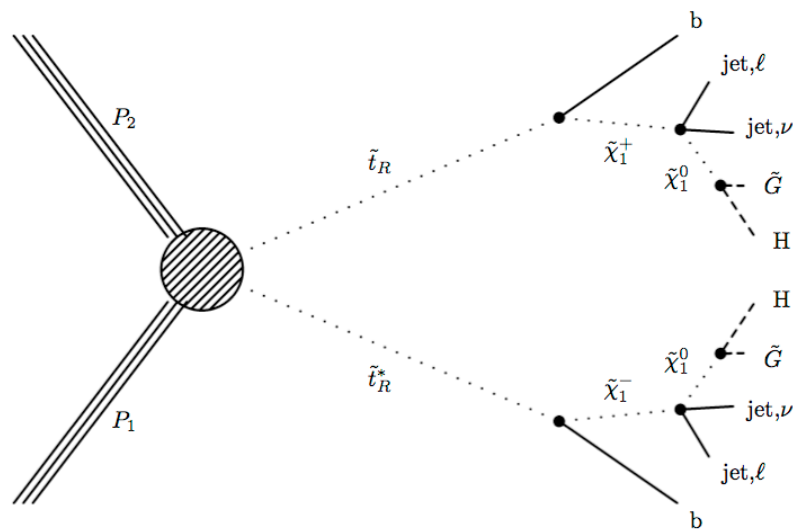
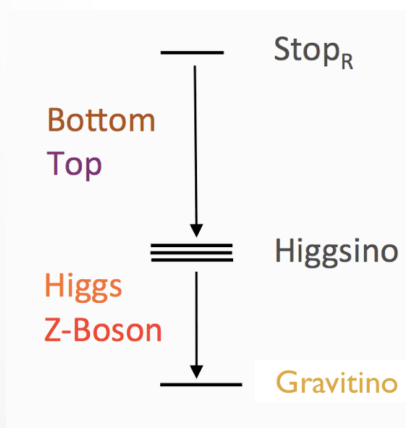
- Inclusive search.
  - Showing the limit for the stop interpretation (see Sudan's talk later today for more):



# Gauge Mediated SUSY Breaking

CMS collaboration  
PAS SUS-13-014  
19.5 fb<sup>-1</sup>

- In this model, SUSY breaking is mediated by gauge interactions rather than supergravity
- Scale of SUSY breaking can be 10's of TeV's rather than  $O(10^{11} \text{ GeV})$
- Cascade decay ending with b's, 2 Higgs, and  $E_{\text{miss}}$  from gravitinos

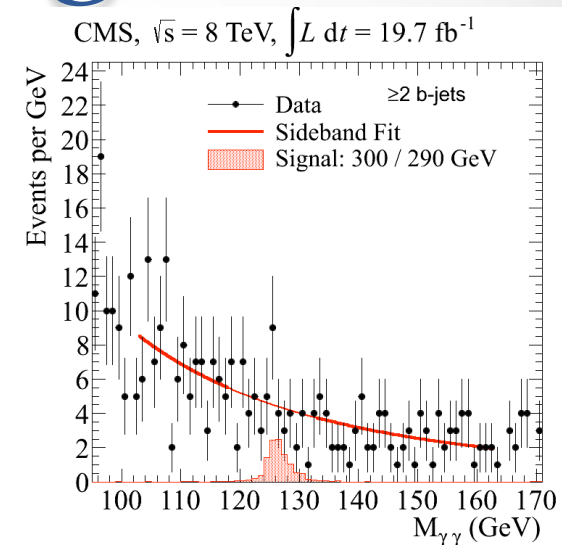




# Gauge Mediated SUSY Breaking

CMS collaboration  
PAS SUS-13-014  
19.5 fb<sup>-1</sup>

- Require 1 Higgs to decay to  $\gamma\gamma$
- Higgs  $\rightarrow \gamma\gamma$  allows us to use Higgs mass sidebands for data-driven background estimate
- Search:
  - $\geq 2$  b-tagged jets ( $\geq 30$  GeV)
  - $\geq 2$  photons ( $\geq 40$  and  $25$  GeV)
- Main background is QCD production of  $\gamma\gamma bb$  or  $\gamma\gamma b+j$  where  $j$  is misidentified as a  $\gamma$ 
  - SM Higgs production and  $e$  faking  $\gamma$  are negligible
- 3 search regions:
  - Additional b-tagged jet
  - $bb$  pair in the Higgs mass window of 95 to 155 GeV
  - All other events



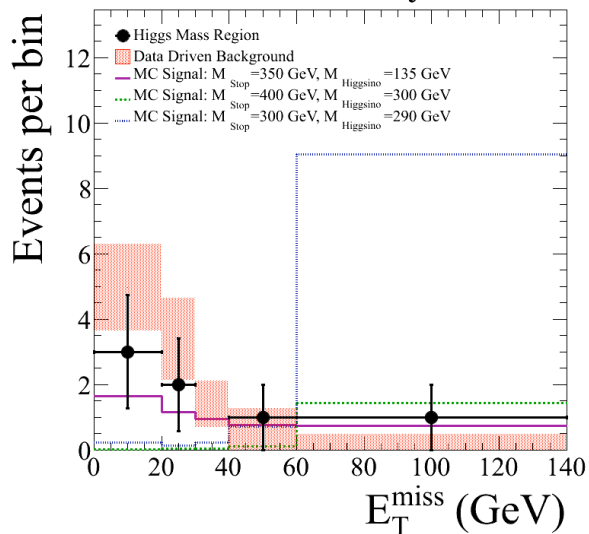
# Gauge Mediated SUSY Breaking

CMS collaboration  
PAS SUS-13-014  
19.5 fb<sup>-1</sup>

- Data vs Background comparison of  $E_T^{\text{miss}}$  in all 3 search regions

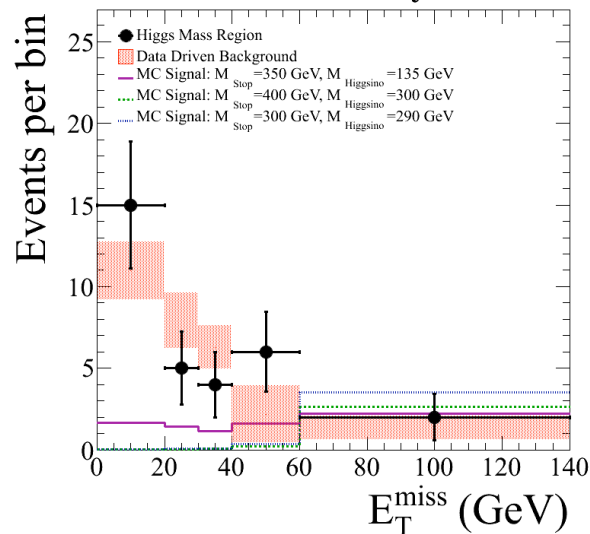
## 2 b's, On Higgs Mass

CMS Preliminary,  $\sqrt{s} = 8$  TeV,  $\int L dt = 19.5$  fb<sup>-1</sup>



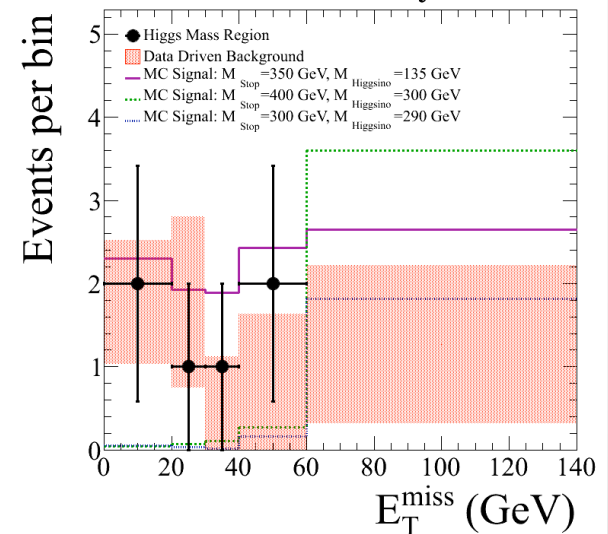
## 2 b's, Off Higgs Mass

CMS Preliminary,  $\sqrt{s} = 8$  TeV,  $\int L dt = 19.5$  fb<sup>-1</sup>



## ≥3 b's

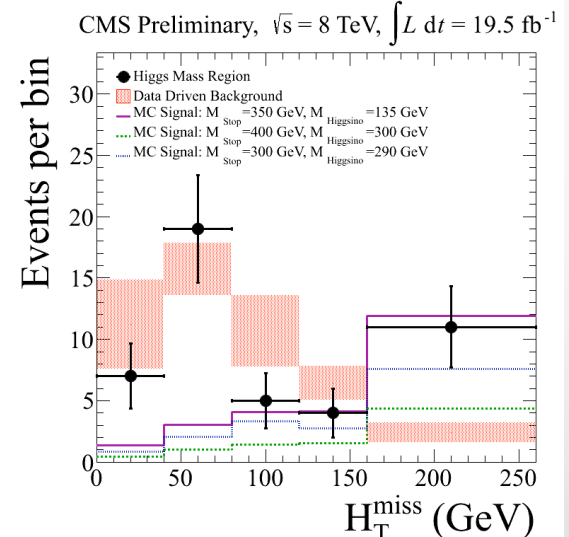
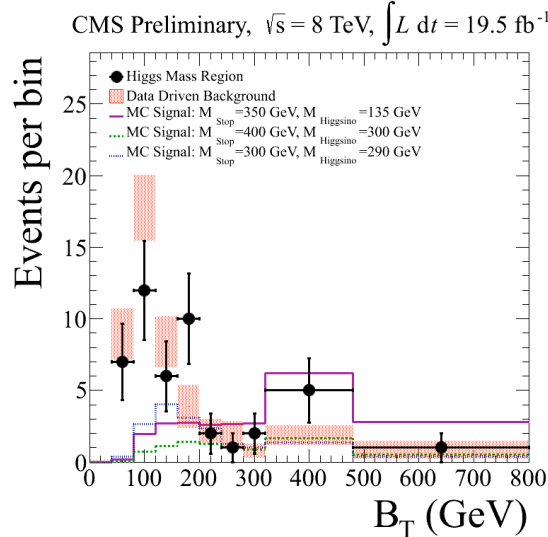
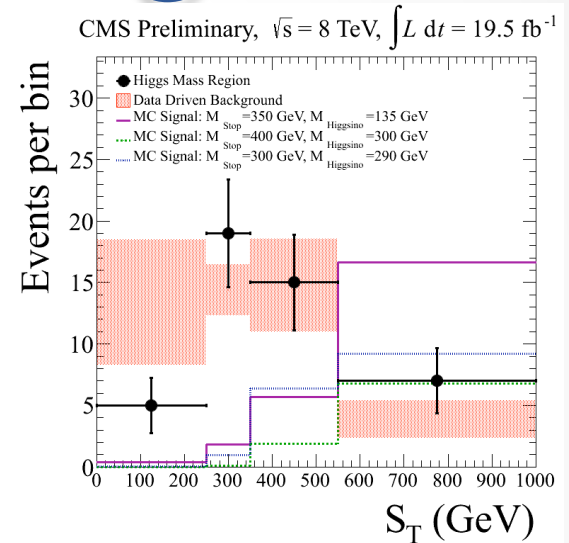
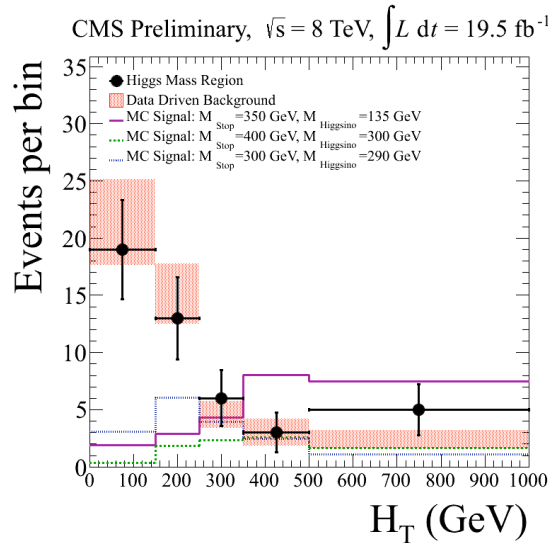
CMS Preliminary,  $\sqrt{s} = 8$  TeV,  $\int L dt = 19.5$  fb<sup>-1</sup>



# Gauge Mediated SUSY Breaking

CMS collaboration  
PAS SUS-13-014  
19.5 fb<sup>-1</sup>

- Event variable comparison:
  - $H_T$ : Scale sum of jet  $p_T$
  - $S_T$ : Scalar sum of  $E_T^{\text{miss}}$ ,  $H_T$ , and  $p_T$  of  $\gamma$
  - $B_T$ : Scalar sum of  $p_T$  of b-tagged jets
  - $H_T^{\text{miss}}$ : vector sum of all jets  $p_T$



# Gauge Mediated SUSY Breaking

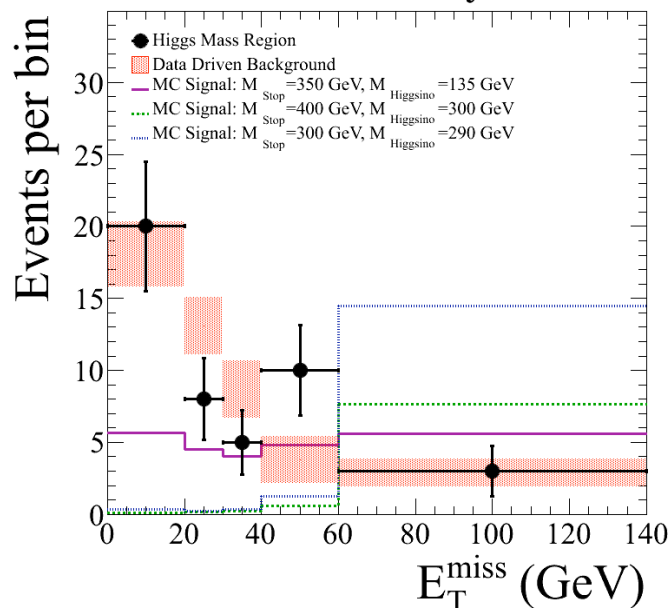
CMS collaboration  
PAS SUS-13-014  
19.5 fb<sup>-1</sup>

- Results:

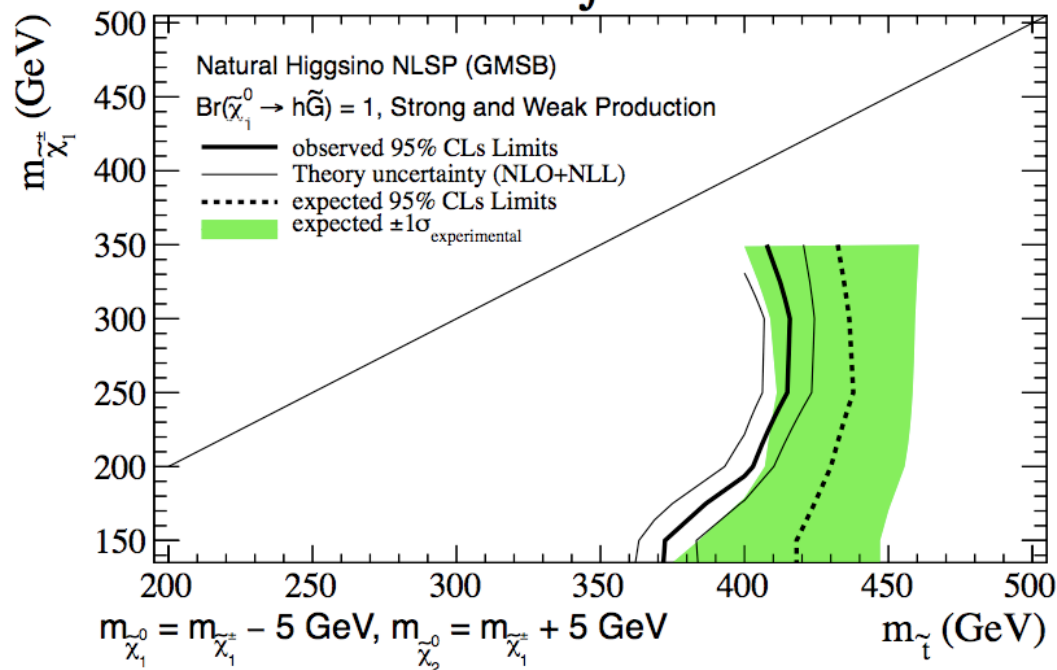
	On H mass	Off H mass	3+ b-jets
SM Background	10.8 ± 2.1	28.7 ± 3.0	6.3 ± 1.5
Observed	7	33	6

## 3 signal regions combined

CMS Preliminary,  $\sqrt{s} = 8$  TeV,  $\int L dt = 19.5$  fb<sup>-1</sup>

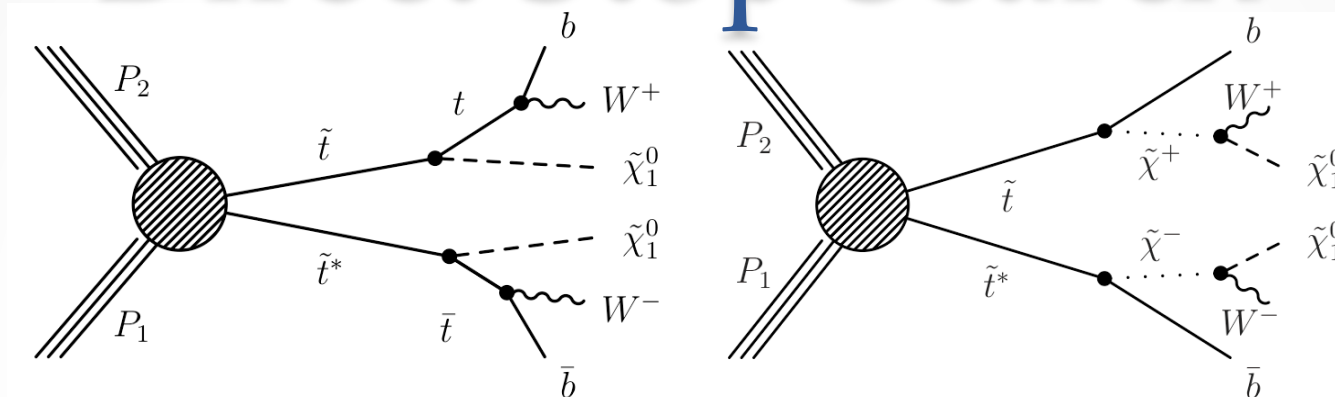


CMS Preliminary,  $\sqrt{s} = 8$  TeV,  $\int L dt = 19.5$  fb<sup>-1</sup>



# Single Lepton Direct Stop Search

CMS collaboration  
PAS SUS-13-011  
hep-ex/1308.1586  
19.5 fb<sup>-1</sup>



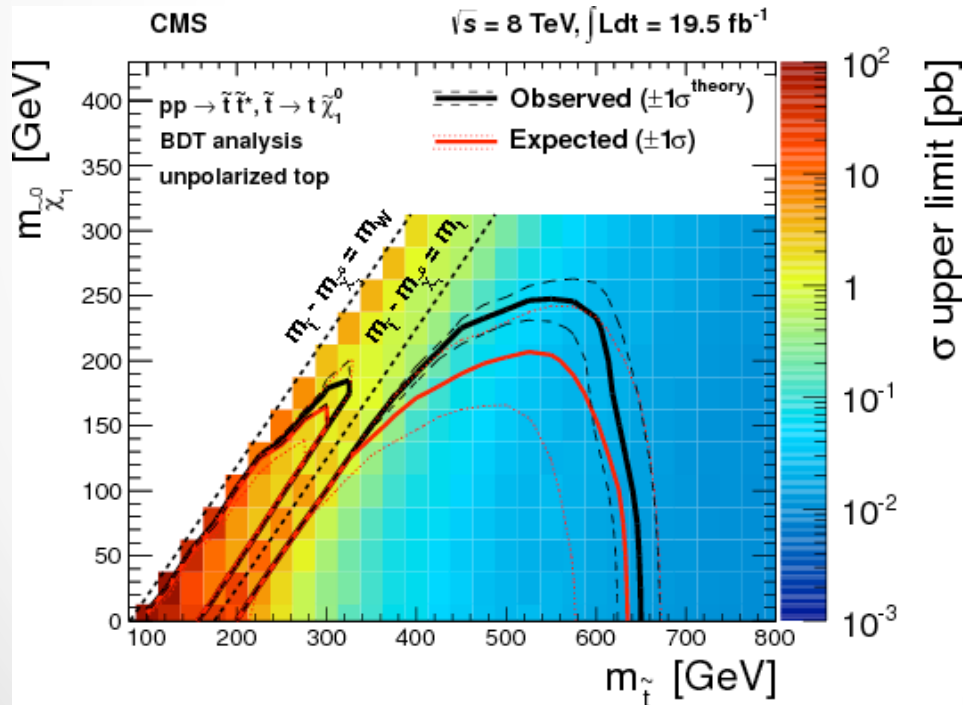
- Again, signal looks like:  $t\bar{t} + E_{\text{T}}^{\text{miss}}$
- **Require:**
  - 1 high  $p_{\text{T}}$  isolated e or  $\mu$  (veto other leptons)
  - $\geq 4$  jets with  $\geq 1$  b-tagged jet
  - Moderate  $E_{\text{T}}^{\text{miss}}$
- Use a BDT combining variables like  $E_{\text{T}}^{\text{miss}}$ ,  $M_{\text{T}2}$ , etc.
- Several different BDT's each focus on different area of 2D stop-neutralino space

# Single Lepton Direct Stop Search

CMS collaboration  
PAS SUS-13-011  
hep-ex/1308.1586  
19.5 fb<sup>-1</sup>

$$\tilde{t} \rightarrow t \tilde{\chi}_1^0$$

Sample	BDT1 Loose	BDT1 Tight	BDT2	BDT3	BDT4	BDT5
Expected	763 ± 102	124 ± 21	85 ± 16	13 ± 4	2.9 ± 1.1	87 ± 18
Data	728	104	56	8	2	76



BDT5 is for mass splitting  
below top mass

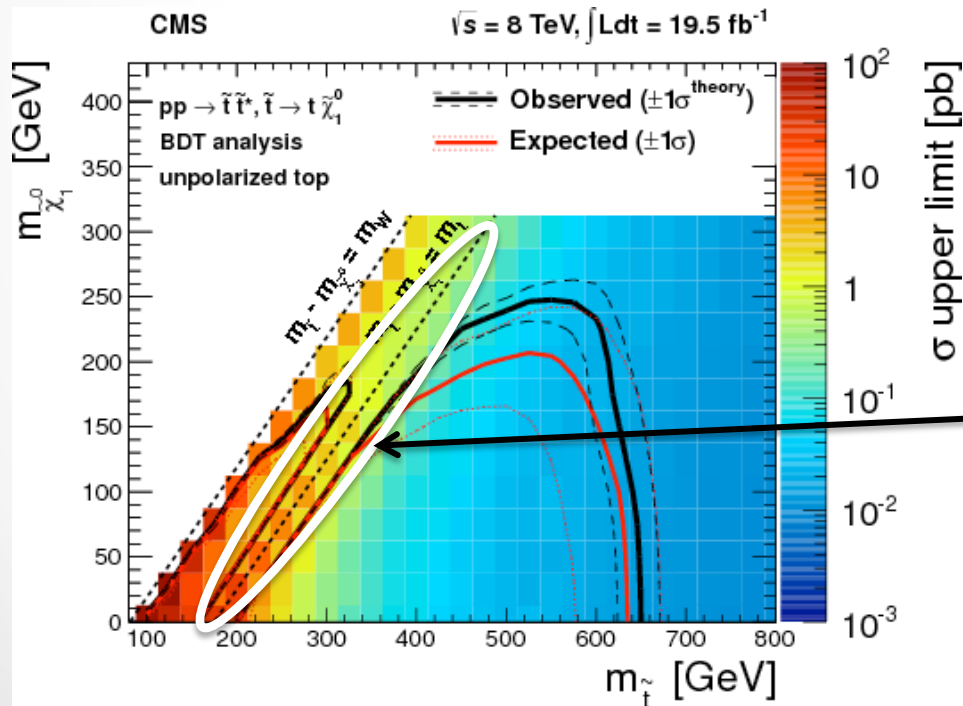


# Single Lepton Direct Stop Search

CMS collaboration  
PAS SUS-13-011  
hep-ex/1308.1586  
19.5 fb<sup>-1</sup>

$$\tilde{t} \rightarrow t \tilde{\chi}_1^0$$

Sample	BDT1 Loose	BDT1 Tight	BDT2	BDT3	BDT4	BDT5
Expected	763 ± 102	124 ± 21	85 ± 16	13 ± 4	2.9 ± 1.1	87 ± 18
Data	728	104	56	8	2	76



BDT5 is for mass splitting below top mass

What if Stop is hiding here?

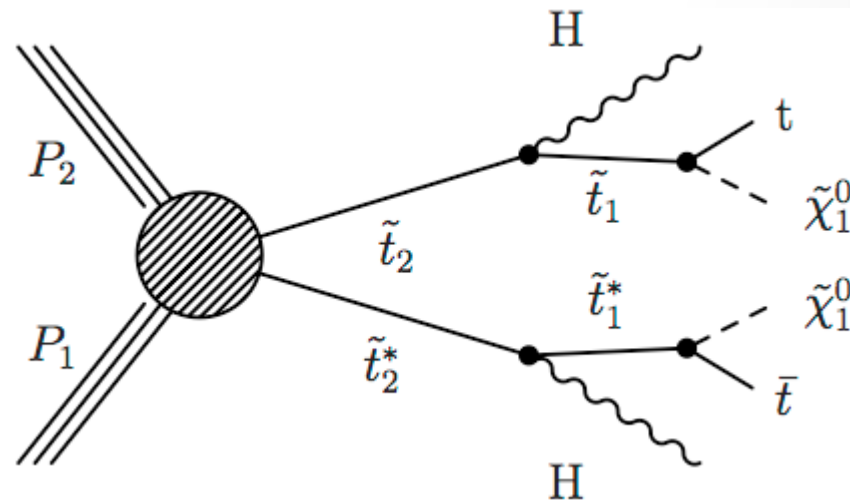
Mass splitting equal to top quark means decay products are produced at rest and signal looks like  $t\bar{t}$

# NEW Direct Stop Production with Higgs

CMS collaboration  
PAS SUS-13-021  
19.5 fb<sup>-1</sup>

- $\tilde{t}_1$  and  $\tilde{t}_2$  are eigenstates of  $\tilde{t}_{L/R}$
- Usually search for the lighter eigenstate  $\tilde{t}_1$
- If Stop-Neutralino mass splitting is equal to the top mass, can search for it with  $\tilde{t}_2$  decay:  $\tilde{t}_2 \rightarrow \tilde{t}_1 + H$ 
  - Assume this mass splitting and H is SM Higgs

- Search for:
  - 1 or 2 leptons
  - $\geq 4$  jets
  - $\geq 2$  b-tagged jets
    - With evidence of  $H \rightarrow b\bar{b}$  decay
  - $E_{\text{miss}} > 50$  GeV
    - Suppress SM W+jets





# NEW

# Direct Stop Production with Higgs

CMS collaboration  
PAS SUS-13-021  
19.5 fb<sup>-1</sup>

N(lep)	Lep. veto	N(b-tags)	Signal region		Sideband region	
			N(jets)	Kinematic requirement	N(jets)	Kinematic requirement
1	track or $\tau_h$	= 3b	$\geq 5$	$M_T > 150$ GeV	= 5	$50 \leq M_T \leq 100$ GeV
		$\geq 4b$	$\geq 4$	$M_T > 120$ GeV	= 4	
2 OS	extra $e/\mu$	= 3b	$\geq 5$	$100 \leq M(b,b) \leq 150$ GeV	= 5	$N(b,b) = 0$
		$\geq 4b$	$\geq 4$	$N(b,b) = 1, 100 \leq M(b,b) \leq 150$ GeV or $N(b,b) \geq 2$	= 4	or $N(b,b) = 1, (M(b,b) \leq 100$ or $M(b,b) \geq 150$ GeV)

- Single lepton channels require large  $M_t$
- Dilepton channels select  $bb$  pairs consistent with Higgs decay
- Dominant background from  $tt$  pair production
  - Estimated by extrapolating from simulation which is validated using data in the sidebands
- Rare processes are derived from simulation with 50% uncertainty
  - $ttH/W/Z/\gamma^*$ , triboson, diboson,  $W/Z/\gamma^* +$  jets, and single top
  - All have much smaller expected cross sections than dominant  $tt$  background

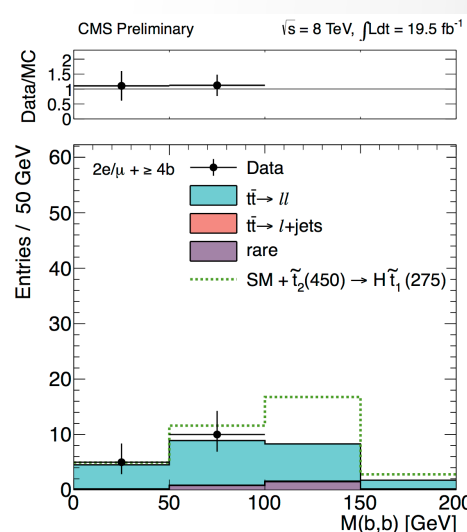
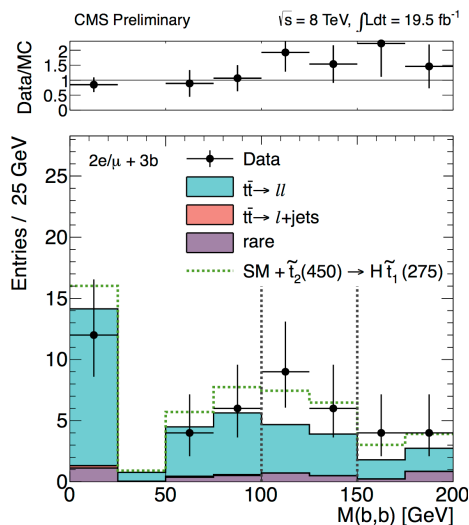
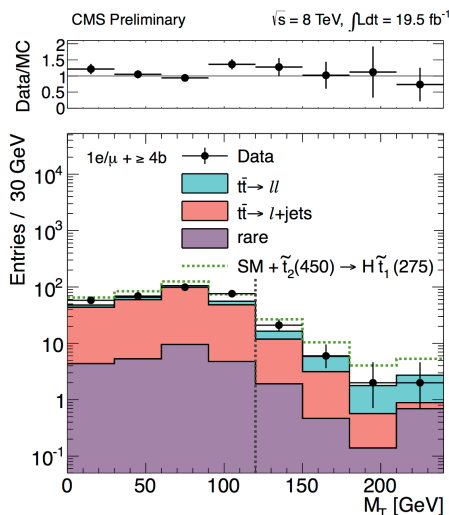
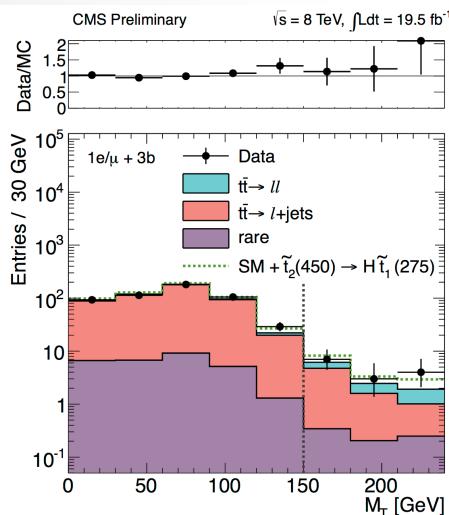
**NEW**

# Direct Stop Production with Higgs

CMS collaboration  
PAS SUS-13-021  
19.5 fb<sup>-1</sup>

- Result:

Sample	1l + 3b	1l + ≥4b	2l + 3b	2l + ≥4b
$t\bar{t} \rightarrow \ell + \text{jets}$	$6.1 \pm 1.1$	$13.2 \pm 3.2$	$0.0 \pm 0.1$	$0.1 \pm 0.1$
$t\bar{t} \rightarrow \ell\ell + \text{jets}$	$3.2 \pm 0.9$	$10.4 \pm 4.3$	$7.2 \pm 2.1$	$8.8 \pm 3.8$
Rare	$0.8 \pm 0.1$	$3.2 \pm 0.8$	$1.2 \pm 0.2$	$1.7 \pm 0.6$
Total background prediction	$10.0 \pm 1.8$	$26.8 \pm 5.6$	$8.4 \pm 2.7$	$10.6 \pm 5.1$
Total relative uncertainty [%]	17.5	20.9	31.7	48.2
Data	14	31	15	3

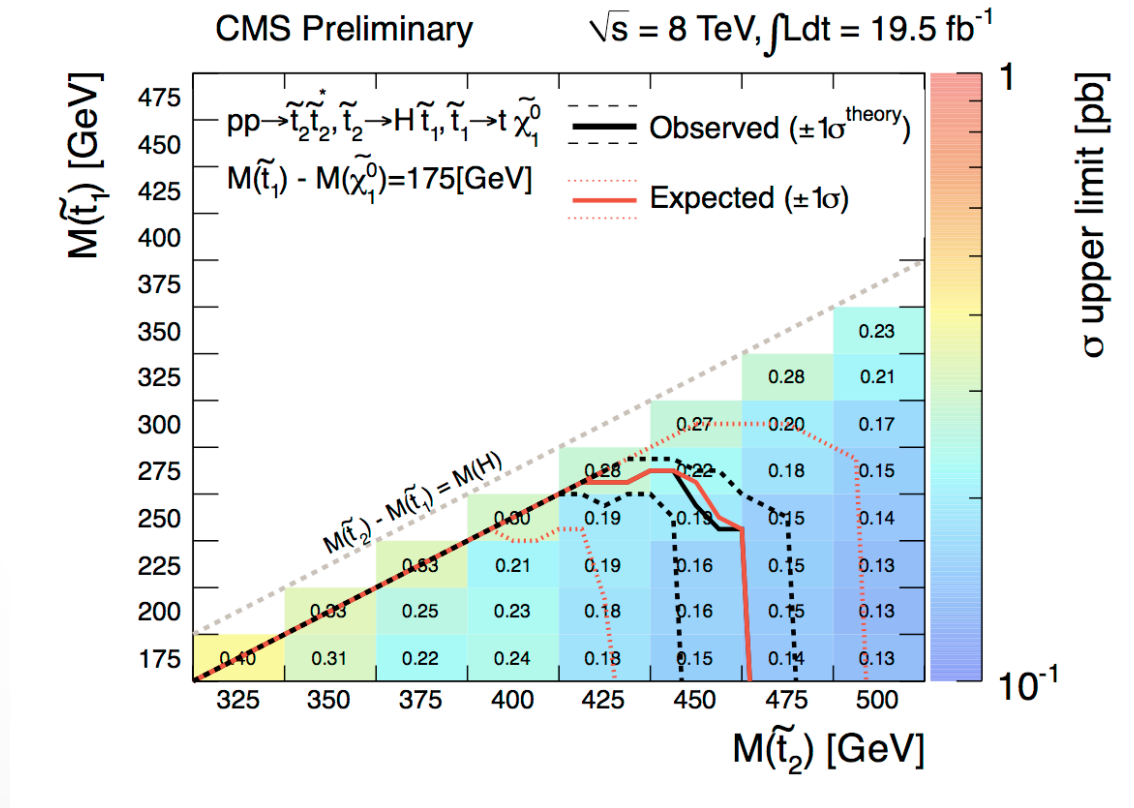


**NEW**

# Direct Stop Production with Higgs

CMS collaboration  
PAS SUS-13-021  
19.5 fb<sup>-1</sup>

- Limits:
  - Neutralino mass is restricted to be  $M_{\text{stop}} - M_{\text{top}}$



# Conclusions

- Strong program of third generation SUSY searches at CMS
  - Several different final states being examined
  - Focused on stop production here. You will see more in Sudan's talk later this session.
  - No significant excess over the Standard Model prediction has been observed so far
- Natural SUSY is being put to the test
  - Stop mass limits extending above 700 GeV
  - New analyses exploring areas SUSY can hide in
  - Run II starting in 2015 should cover Natural SUSY range

# Backup

...

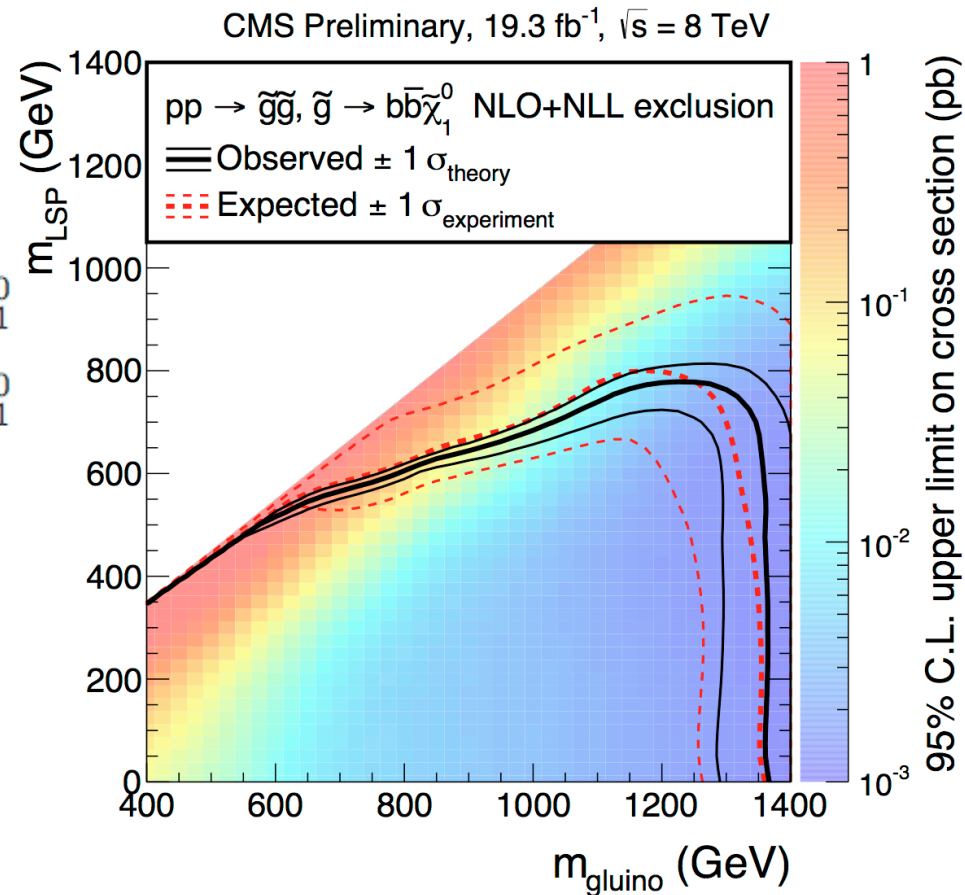
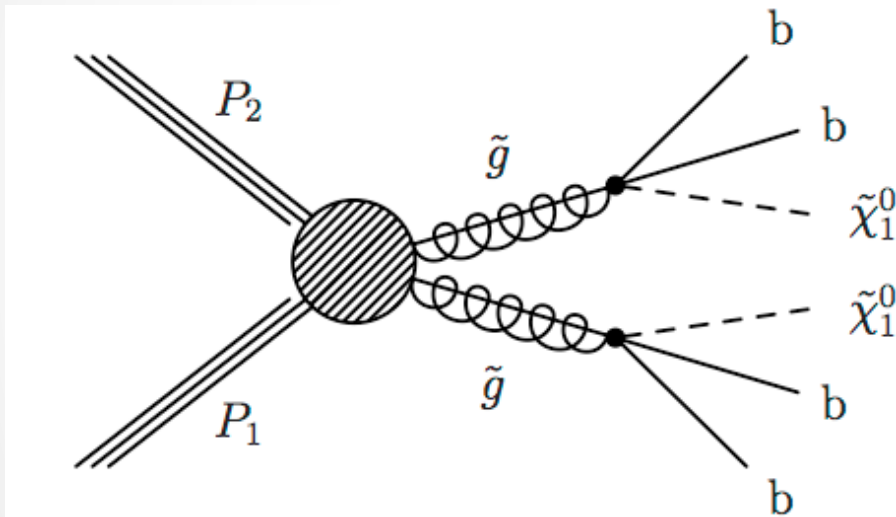
# Razor with b's

Table 1: Lepton, b-tag, kinematic, and jet multiplicity requirements for each of the ten boxes in the razor analysis. The boxes are listed in decreasing hierarchy rank. The ranking is introduced to unambiguously associate an event to a box.

Requirements				
Box	lepton	b-tag	kinematic	jet
Dilepton Boxes				
MuEle	$\geq 1$ tight electron and $\geq 1$ loose muon	$\geq 1$ b-tag	$(M_R > 300 \text{ GeV and } R^2 > 0.15)$ and $(M_R > 450 \text{ GeV or } R^2 > 0.2)$	$\geq 2$ jets
MuMu	$\geq 1$ tight muon and $\geq 1$ loose muon	$\geq 1$ b-tag	$(M_R > 300 \text{ GeV and } R^2 > 0.15)$ and $(M_R > 450 \text{ GeV or } R^2 > 0.2)$	$\geq 2$ jets
EleEle	$\geq 1$ tight electron and $\geq 1$ loose electron	$\geq 1$ b-tag	$(M_R > 300 \text{ GeV and } R^2 > 0.15)$ and $(M_R > 450 \text{ GeV or } R^2 > 0.2)$	$\geq 2$ jets
Single Lepton Boxes				
MuMultiJet	$\geq 1$ tight muon	$\geq 1$ b-tag	$(M_R > 300 \text{ GeV and } R^2 > 0.15)$ and $(M_R > 450 \text{ GeV or } R^2 > 0.2)$	$\geq 4$ jets
MuJet	$\geq 1$ tight muon	$\geq 1$ b-tag	$(M_R > 300 \text{ GeV and } R^2 > 0.15)$ and $(M_R > 450 \text{ GeV or } R^2 > 0.2)$	2 or 3 jets
EleMultiJet	$\geq 1$ tight electron	$\geq 1$ b-tag	$(M_R > 300 \text{ GeV and } R^2 > 0.15)$ and $(M_R > 450 \text{ GeV or } R^2 > 0.2)$	$\geq 4$ jets
EleJet	$\geq 1$ tight electron	$\geq 1$ b-tag	$(M_R > 300 \text{ GeV and } R^2 > 0.15)$ and $(M_R > 450 \text{ GeV or } R^2 > 0.2)$	2 or 3 jets
Hadronic Boxes				
MultiJet	none	$\geq 1$ b-tag	$(M_R > 400 \text{ GeV and } R^2 > 0.25)$ and $(M_R > 550 \text{ GeV or } R^2 > 0.3)$	$\geq 4$ jets
2b-Jet	none	$\geq 2$ b-tag	$(M_R > 400 \text{ GeV and } R^2 > 0.25)$ and $(M_R > 550 \text{ GeV or } R^2 > 0.3)$	2 or 3 jets

# Razor with b's

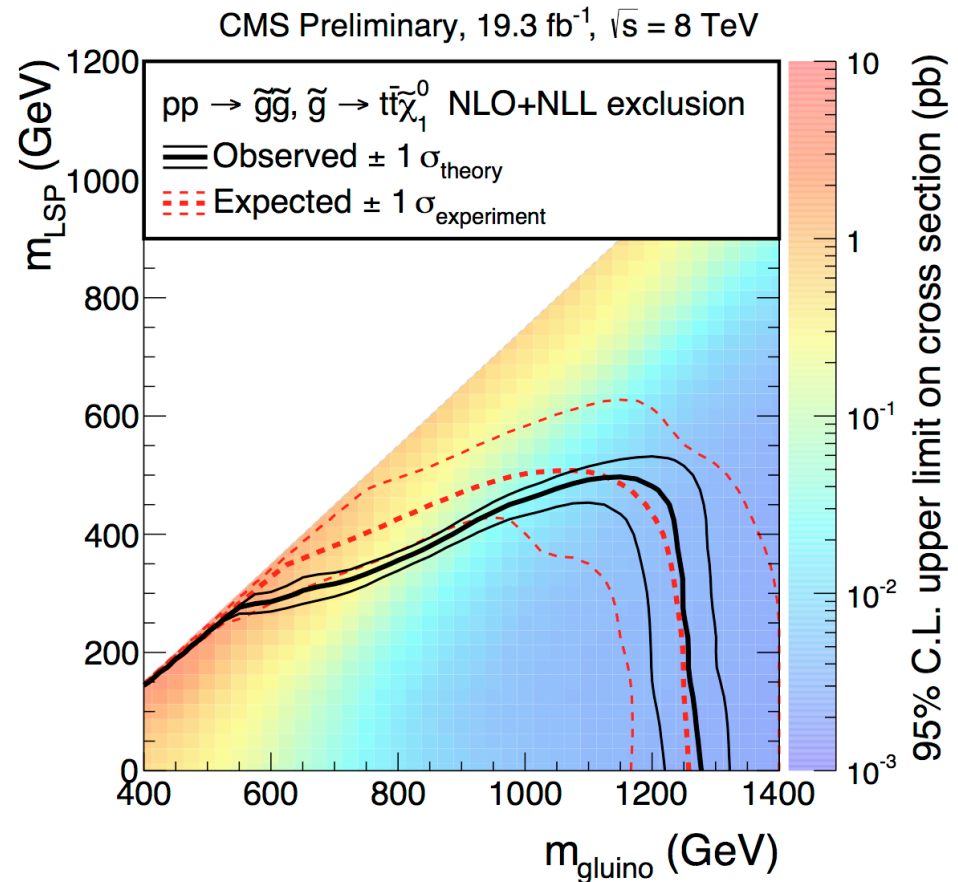
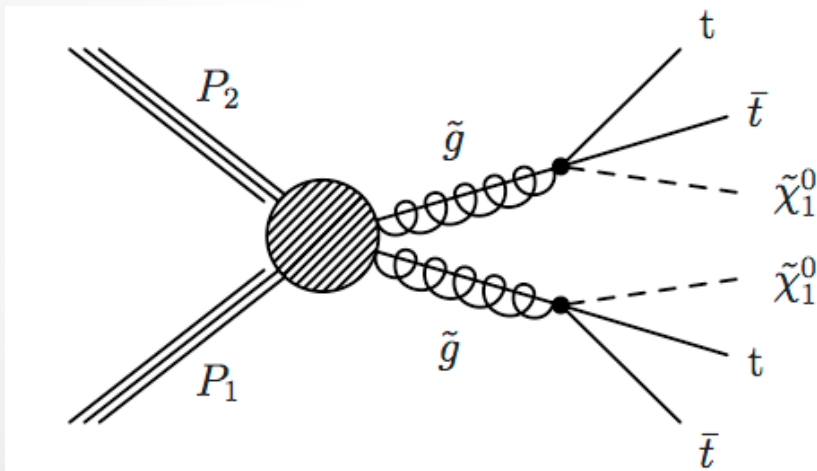
- Limit for Gluino to 4 b's





# Razor with b's

- Razor limit for Gluino to 4 tops:





# Single Lepton Direct Stop Search

CMS collaboration  
PAS SUS-13-011  
hep-ex/1308.1586  
19.5 fb<sup>-1</sup>

$$\tilde{t} \rightarrow t \tilde{\chi}_1^0$$

