



SEARCH FOR STOP PAIR PRODUCTION AT THE LHC USING THE CMS DETECTOR

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on behalf of the CMS Collaboration

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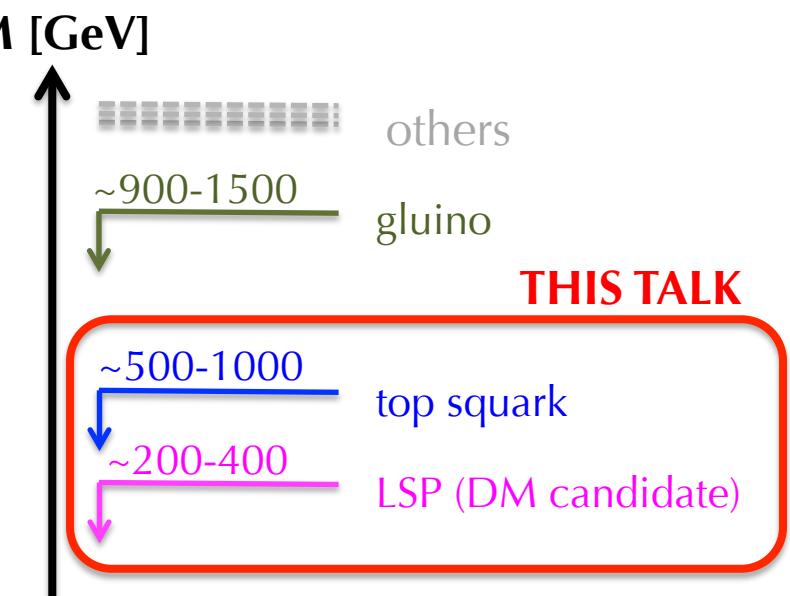
MOTIVATION

- Light Higgs particle is problematic because of large quantum effects from SM particles, **particularly from the top quark**
- In SUSY, **top squark cancels the top quark** contribution to the Higgs mass



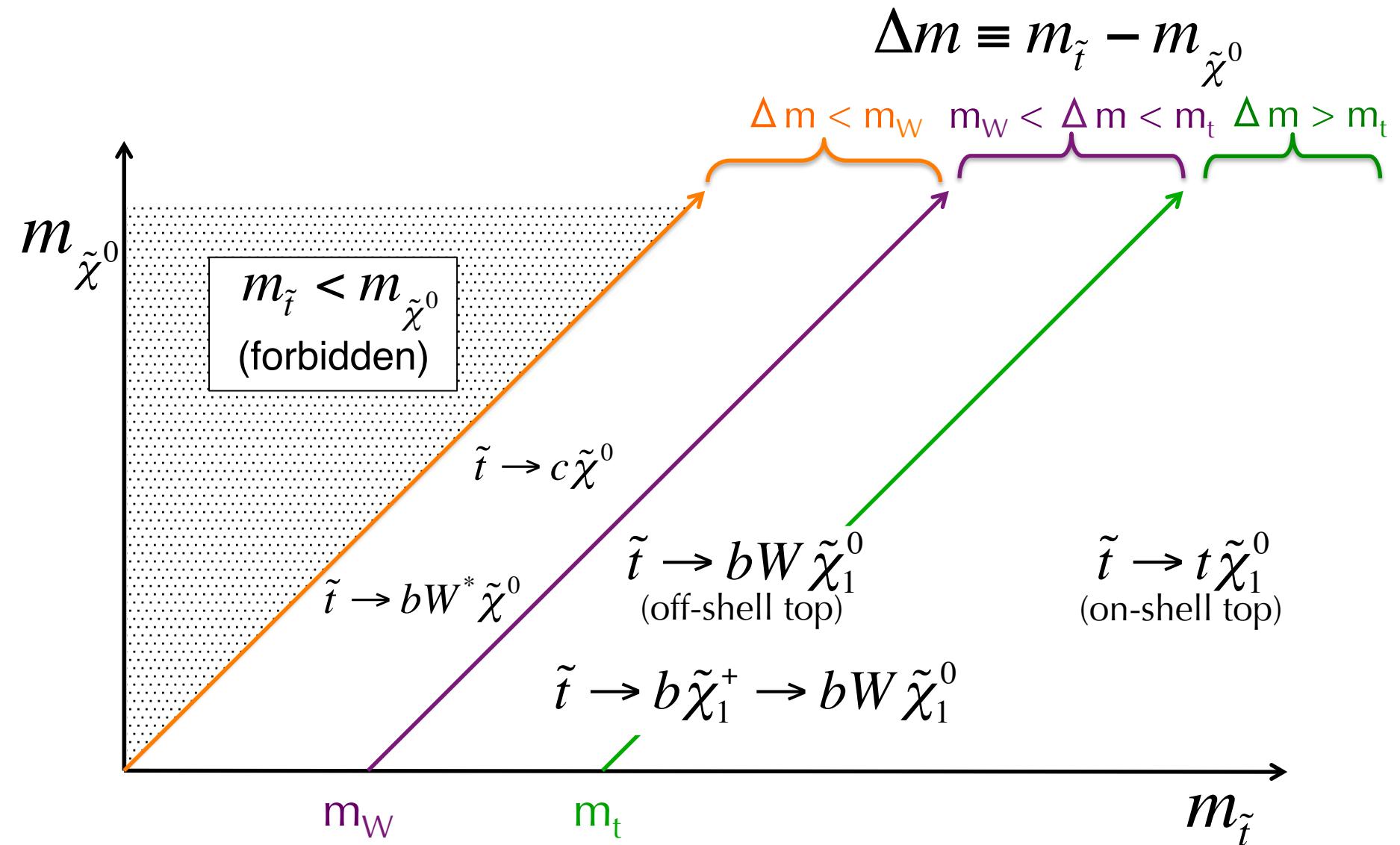
Top squarks are important for a SUSY solution to the hierarchy problem

- “Natural” (not fine-tuned) solution requires light top squarks $m(\tilde{t}) \lesssim$ few hundred GeV → direct production at LHC
- In scenario with R-parity, **top squarks** are pair produced and can decay to a **LSP** → stable dark matter candidate
- Production cross section σ at LHC
 - $\sigma(m(\tilde{t}) = 200 \text{ GeV}) \sim 20 \text{ pb}$
 - $\sigma(m(\tilde{t}) = 600 \text{ GeV}) \sim 0.02 \text{ pb}$

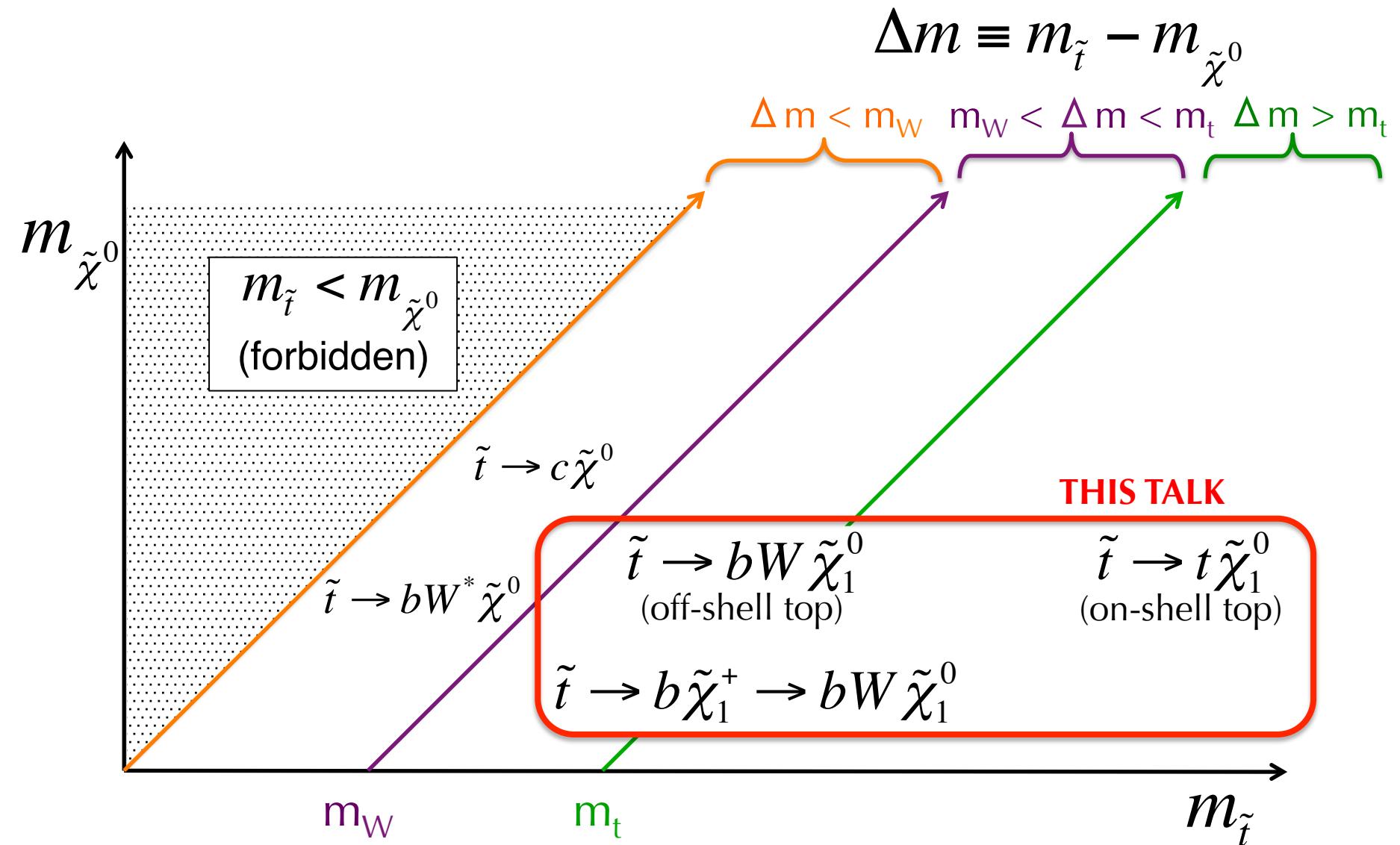


See for example
M. Papucci, J. T. Ruderman and A. Weiler
hep-ph/1110.6926v1

TOP SQUARK DECAYS



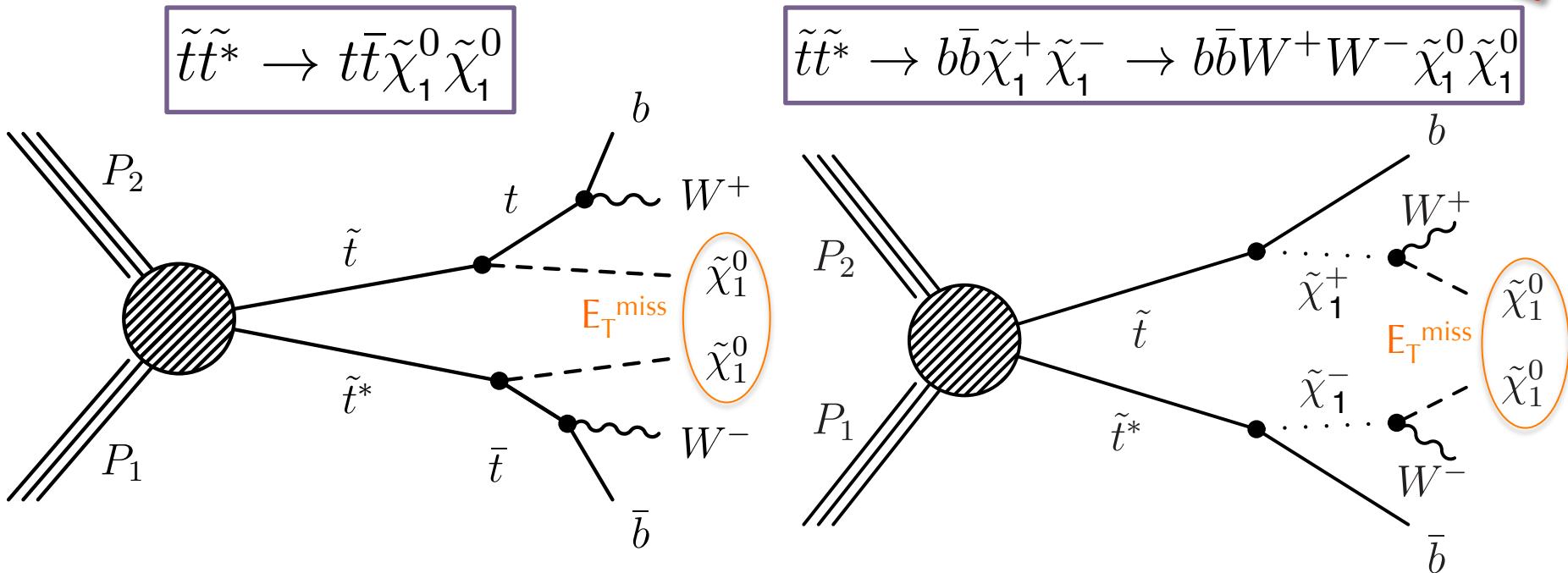
TOP SQUARK DECAYS



ANALYSIS SIGNATURES & STRATEGY

- Perform dedicated search for top squark pair production
- Focus on two decay modes

**NEW! LHCP result
19.5 fb⁻¹ 8 TeV data**



- **Signal looks like “ $t\bar{t} + E_T^{\text{miss}}$ ” from the invisible $\tilde{\chi}_1^0$ LSPs**
 - Use E_T^{miss} and kinematic variables to discriminate signal vs. background
 - Focus on 1ℓ channel → clean, large branching fraction

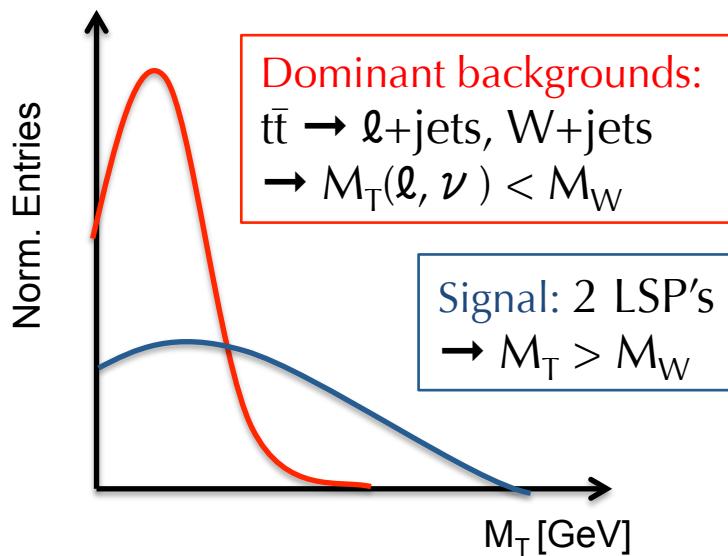
EVENT SELECTION AND BACKGROUNDS

■ Event pre-selection

- 1 high p_T isolated e or μ
- ≥ 4 jets with ≥ 1 b-jet
- Veto events with a second lepton
- Moderate E_T^{miss}

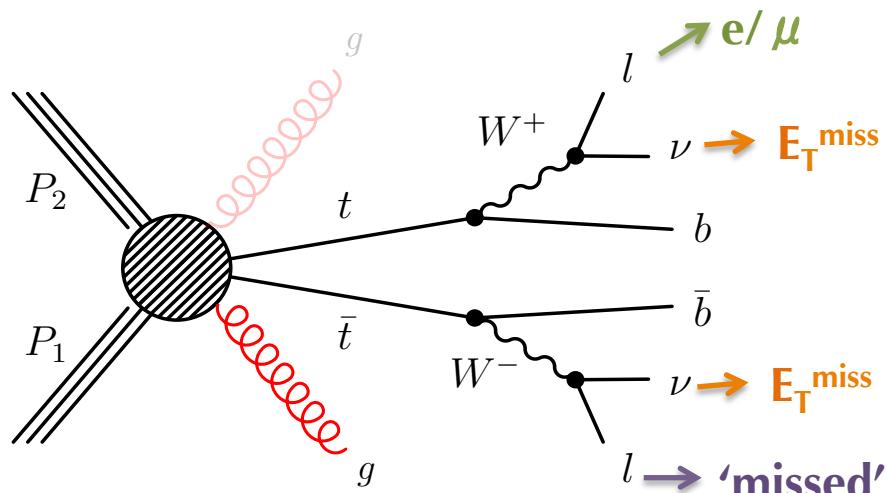
■ Search in M_T tail

$$M_T(\ell, E_T^{\text{miss}}) \gg M_W$$



■ Main backgrounds

- $t\bar{t} \rightarrow \ell\ell$ dominant in M_T tail

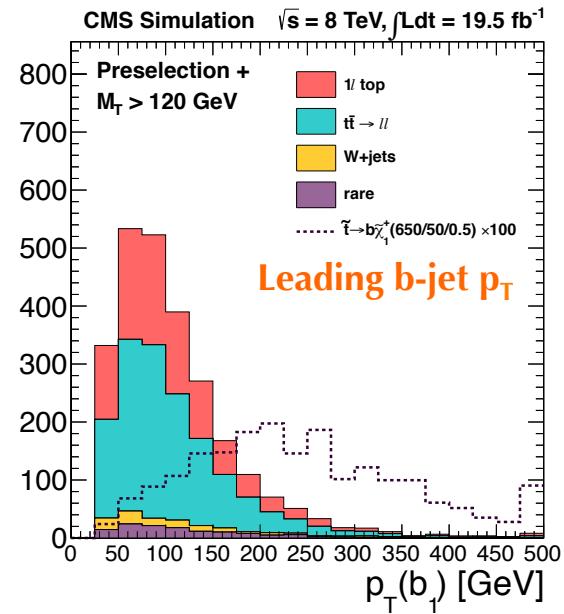
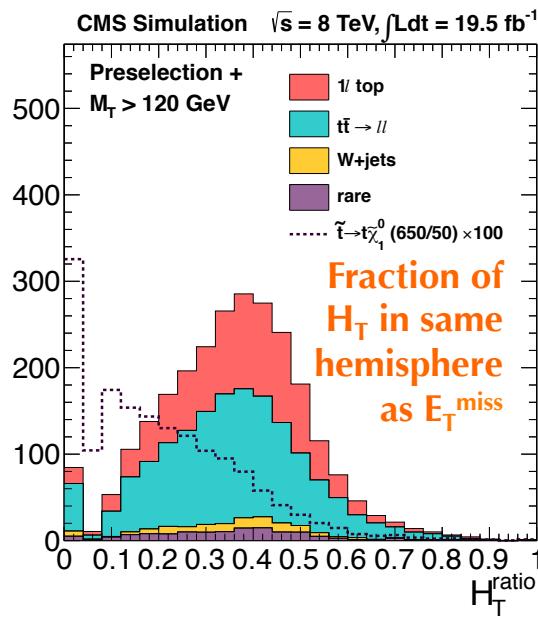
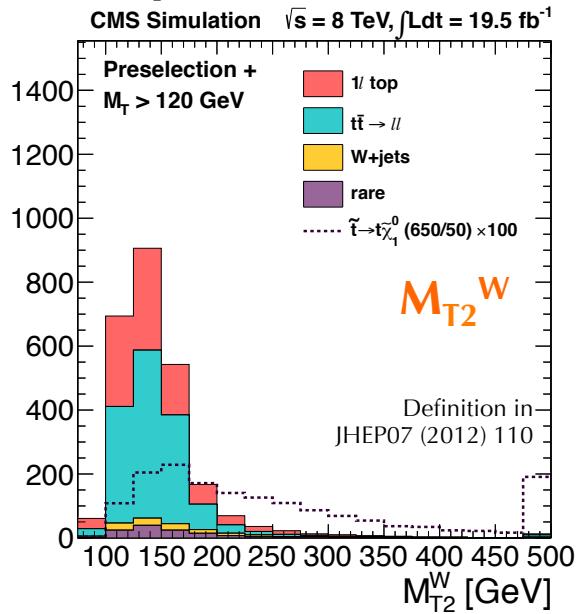


- Single lepton backgrounds: $t\bar{t} \rightarrow \ell + \text{jets}$ & single top s/t-channel (1ℓ top), $W + \text{jets}$
- Rare processes: mainly $t\bar{t} + W/Z/\gamma$, tW

SIGNAL DISCRIMINATION

- Signal regions target different decay modes and a range of signal kinematics

Example kinematic variables

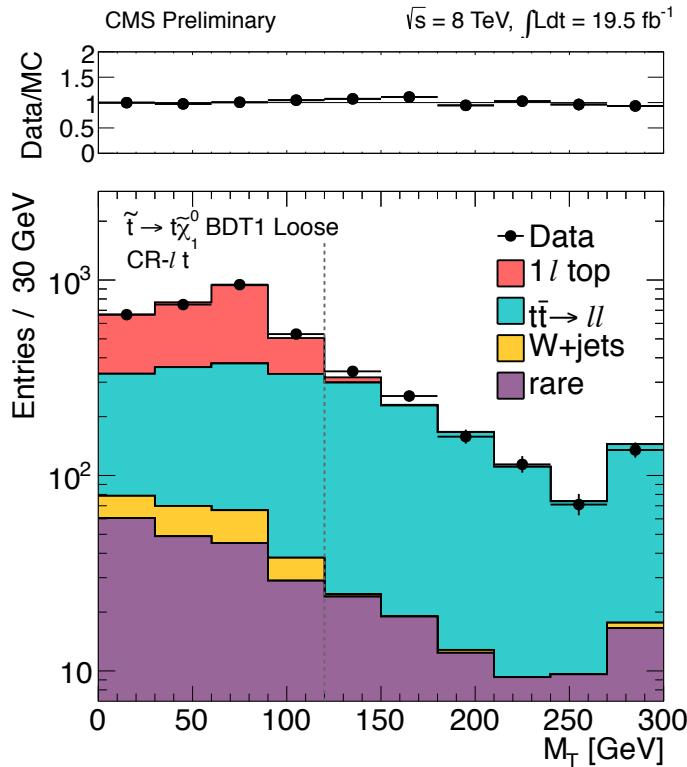


- **BDT analysis** (primary result): combine several kinematic variables in a BDT, perform cut-and-count analysis in signal regions defined by cuts on the BDT discriminant
- **Cut-based analysis** (cross-check): apply cuts on kinematic variables, perform cut-and-count analysis in signal regions with E_T^{miss} requirements

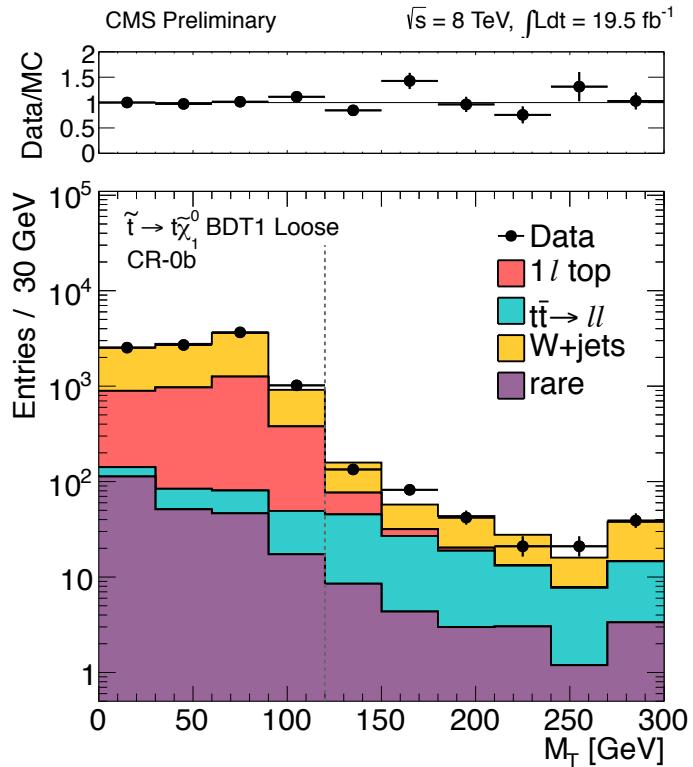
BACKGROUND ESTIMATION AND VALIDATION

- Estimate backgrounds from **simulation**, normalized using background-dominated data and validate predictions in **data control samples**

Control Sample $\ell + \text{isolated track or hadronic } \tau$ $t\bar{t}$ validation



Control Sample b-veto $W+\text{jets}$ validation

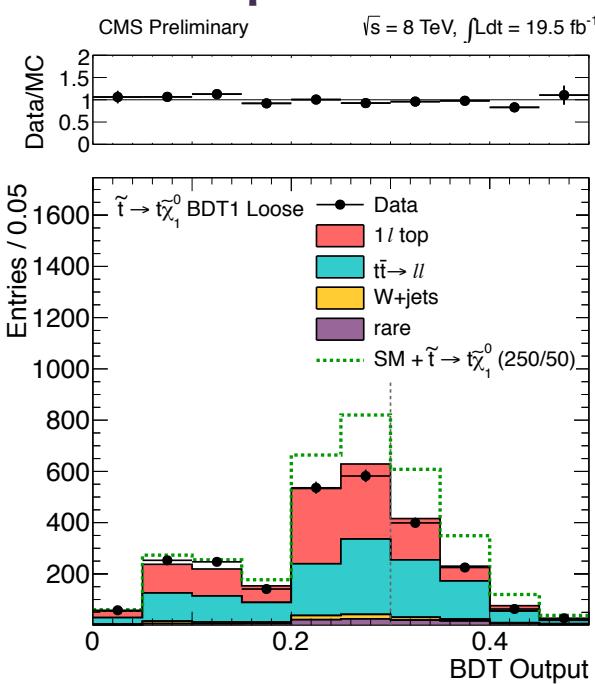
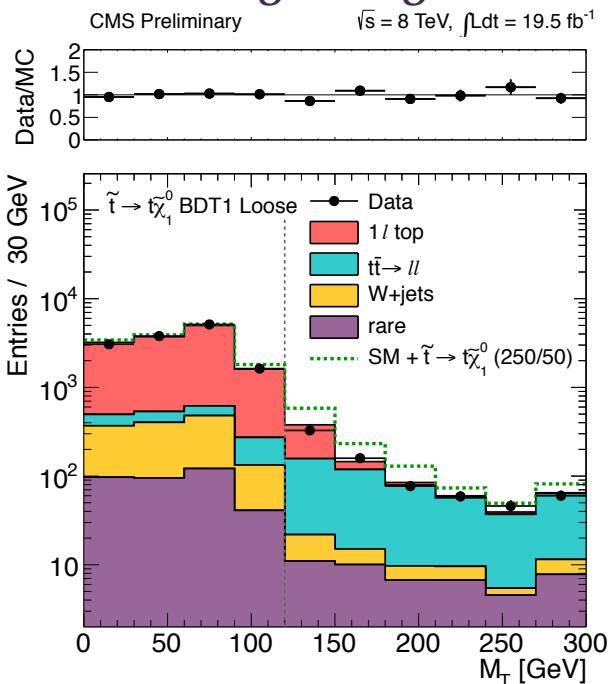


RESULTS: BDT ANALYSIS $t\tilde{\chi}^0$

- Background prediction accounts for observed yields in all signal regions
 - No evidence for top squarks**

Sample	BDT1 Loose	BDT1 Tight	BDT2	BDT3	BDT4	BDT5
$t\bar{t} \rightarrow ll$	438 ± 37	68 ± 11	46 ± 10	5 ± 2	0.3 ± 0.3	48 ± 13
$1l$ Top	251 ± 93	37 ± 17	22 ± 12	4 ± 3	0.8 ± 0.9	30 ± 12
W+jets	27 ± 7	7 ± 2	6 ± 2	2 ± 1	0.8 ± 0.3	5 ± 2
rare	47 ± 23	11 ± 6	10 ± 5	3 ± 1	1.0 ± 0.5	4 ± 2
Total	763 ± 102	124 ± 21	85 ± 16	13 ± 4	2.9 ± 1.1	87 ± 18
Data	728	104	56	8	2	76

Loosest signal region \rightarrow targets low $m(\text{stop})$ and small ΔM

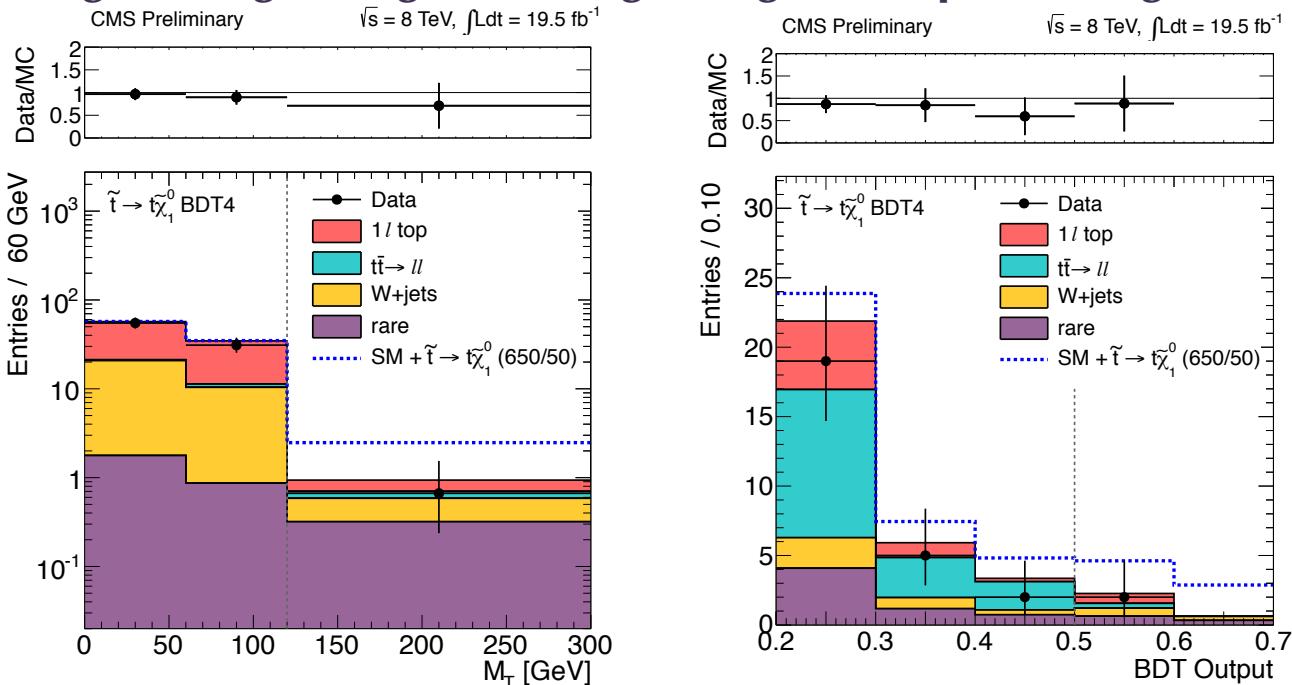


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Total	763 ± 102	124 ± 21	85 ± 16	13 ± 4	2.9 ± 1.1	87 ± 18
Data	728	104	56	8	2	76

Tightest signal region \rightarrow targets high $m(\text{stop})$ and large ΔM

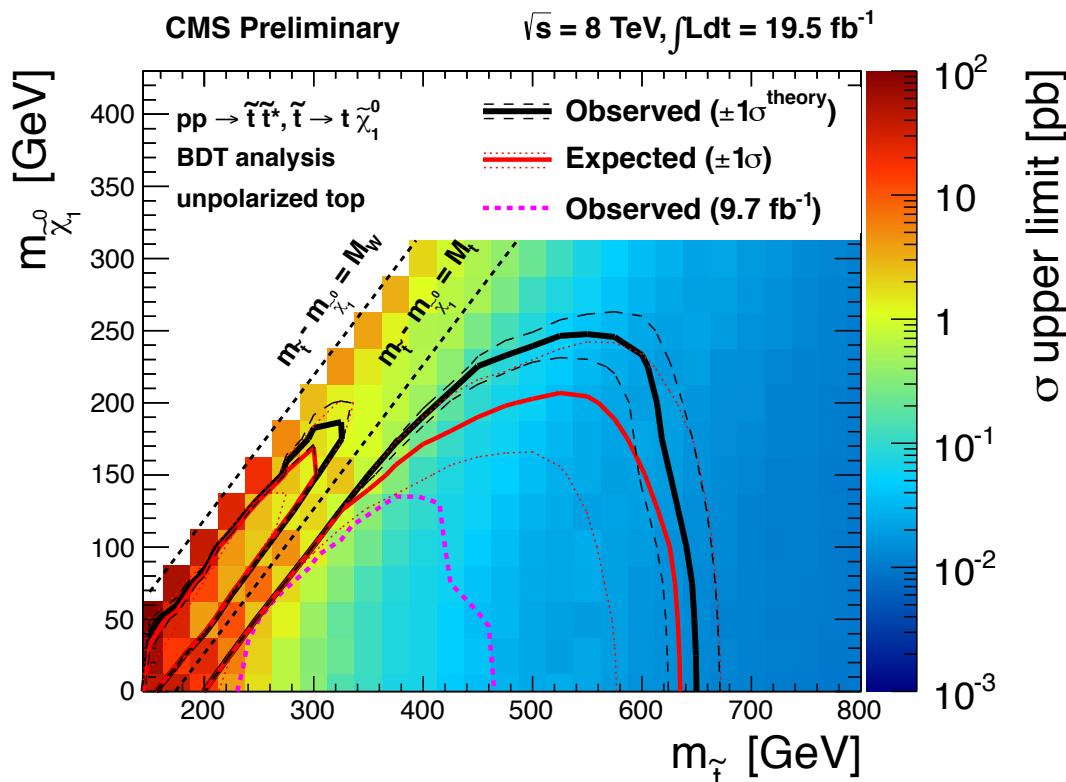


More signal regions in backup

INTERPRETATION: BDT ANALYSIS $t\tilde{\chi}^0$

- Set limits using cut-and-count results from **6 BDT signal regions**
 - For each model point, use results from most sensitive signal region

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

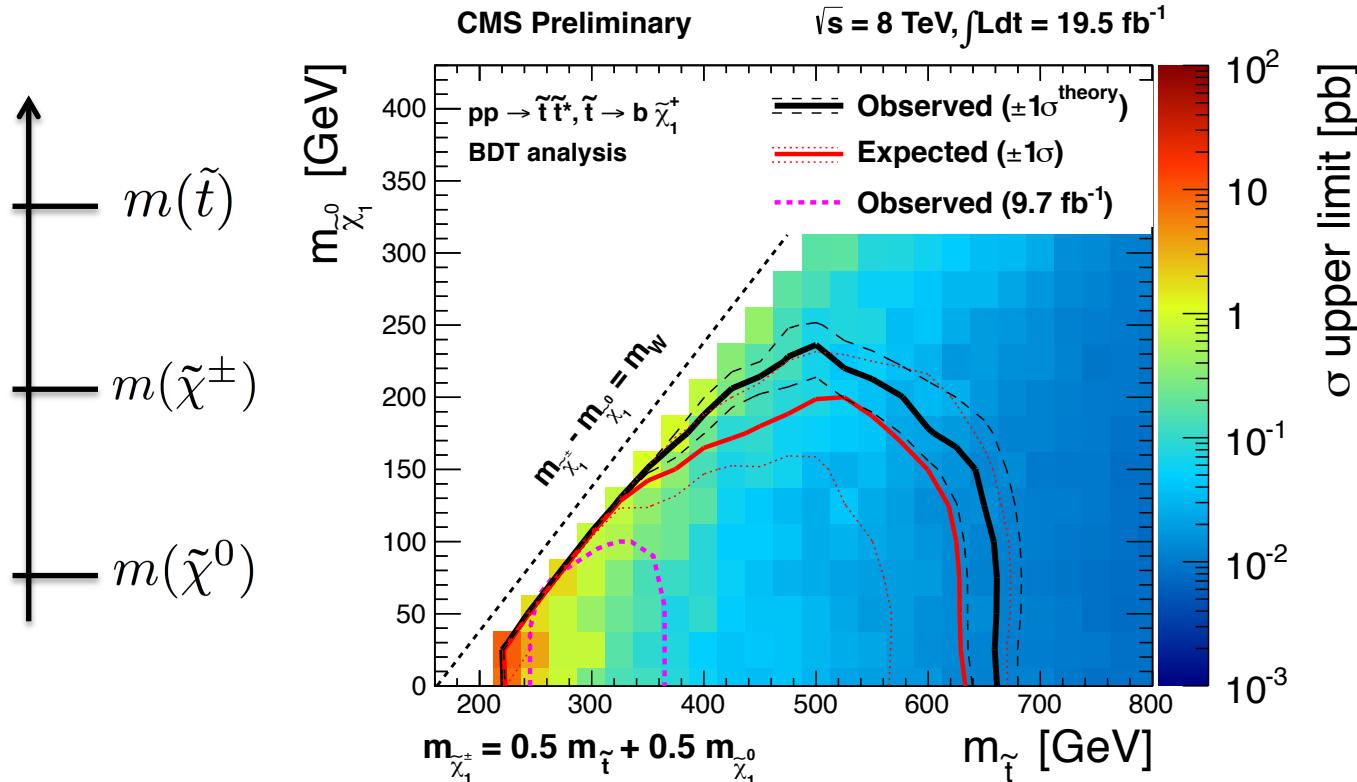


Results probe $m(\tilde{t}) \lesssim 650$ GeV for $m(\tilde{\chi}^0) \lesssim 250$ GeV
Sensitive to the $\Delta M < m_{\text{top}}$ and $m_{\text{stop}} < m_{\text{top}}$ regions

INTERPRETATION: BDT ANALYSIS $b\tilde{\chi}^\pm$

- Set limits using cut-and-count results from 4 BDT signal regions

$$\tilde{t}\tilde{t}^* \rightarrow b\bar{b}\tilde{\chi}_1^+\tilde{\chi}_1^- \rightarrow b\bar{b}W^+W^-\tilde{\chi}_1^0\tilde{\chi}_1^0$$

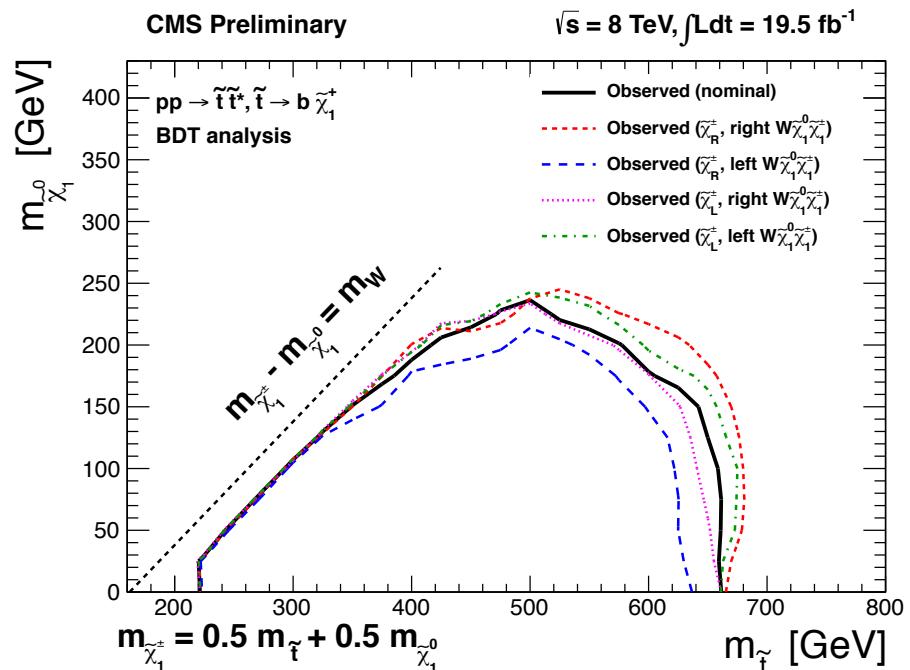
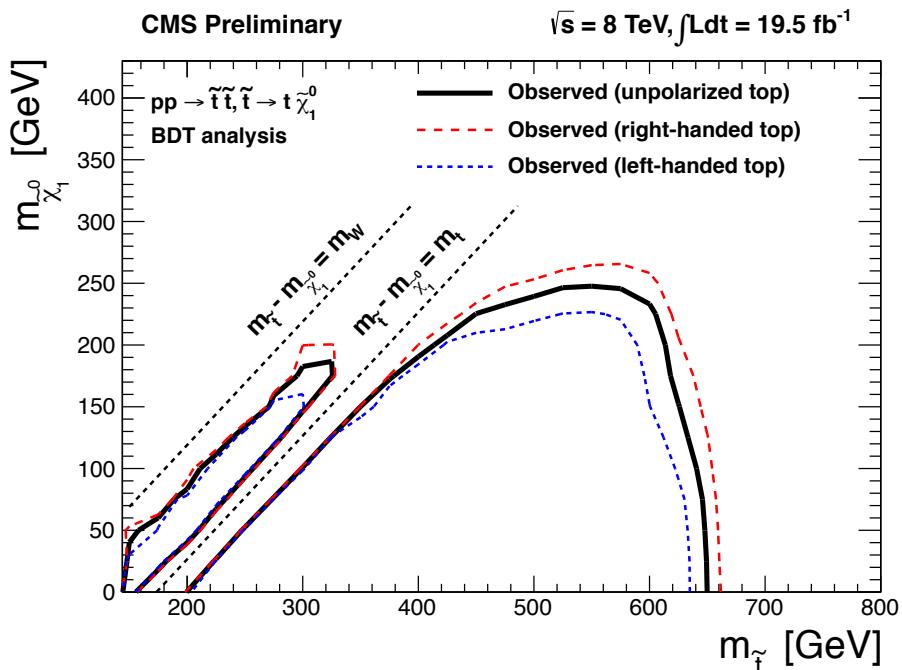


Results probe $m(\tilde{t}) \lesssim 660$ GeV for $m(\tilde{\chi}^0) \lesssim 225$ GeV

See backup
for other
choices
of $m(\tilde{\chi}^\pm)$

POLARIZATION DEPENDENCE

- Signal acceptance depends on the polarization of the intermediate decay particles, the top quark in the $t\tilde{\chi}^0$ case and the $\tilde{\chi}^\pm$ and W^\pm for the $b\tilde{\chi}^\pm$ case



Impact of polarization of intermediate particles on mass limits typically within $\pm 20 \text{ GeV}$

SUMMARY & OUTLOOK

- **Searched for signatures of top squarks in several decay modes**
 - Dedicated search in 1ℓ final state using full 8 TeV dataset
 - No excesses observed → **results probe top squarks up to masses ~ 650 GeV, interesting range from naturalness considerations**
- **Despite current exclusions, there are several scenarios where top squarks may have eluded detection in existing searches**
 - Top squarks with $\Delta m \sim m_{top}$ or large mass
 - “Compressed spectra” e.g. $\tilde{t} \rightarrow t\tilde{\chi}^0$ with small $\Delta m = m_{\tilde{t}} - m_{\tilde{\chi}^0}$
 - Experimentally difficult channels, e.g. $\tilde{t} \rightarrow c\tilde{\chi}^0$
- **Current and future LHC runs provide unique opportunity to search for top squarks**
 - Improve analysis, larger dataset and higher energy → next few years key to probe top squarks with masses favored by naturalness

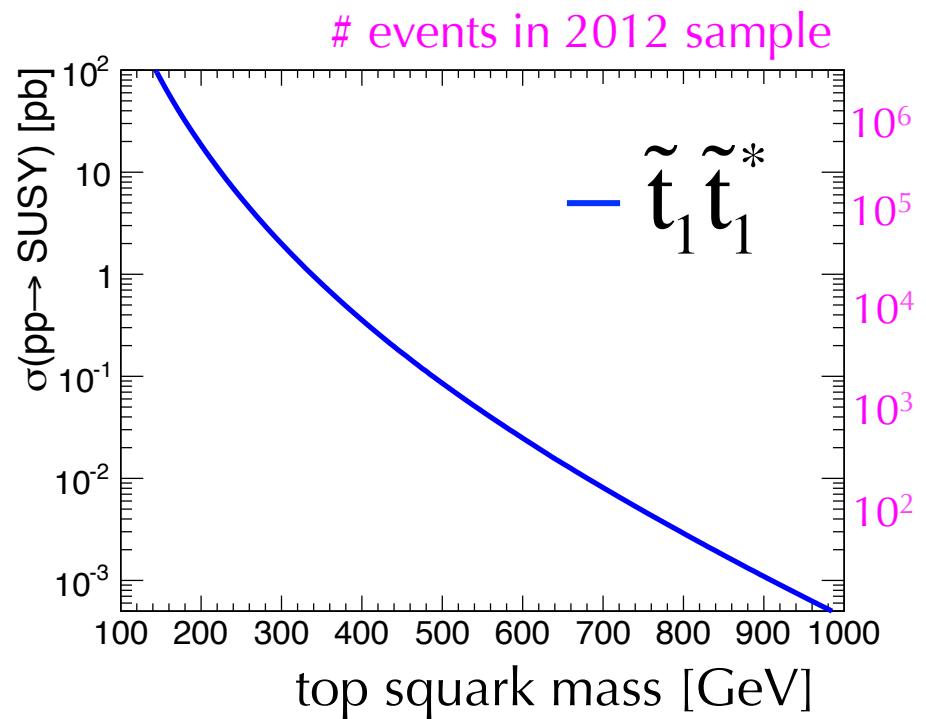
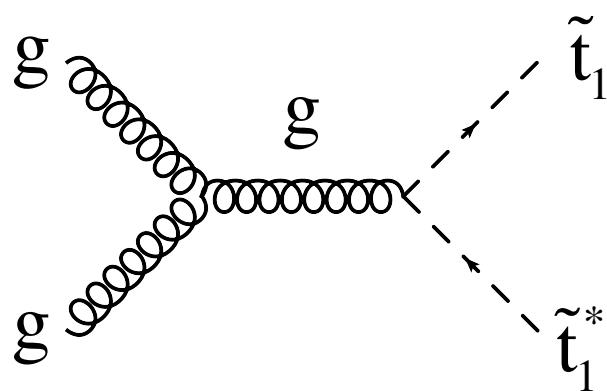
More details CMS Physics Analysis Summary SUS-13-011



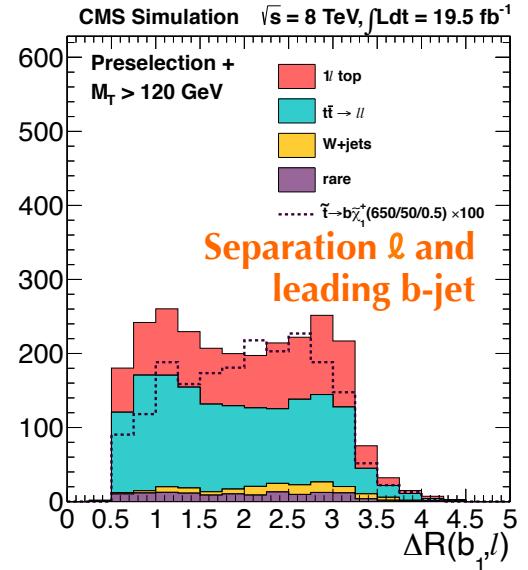
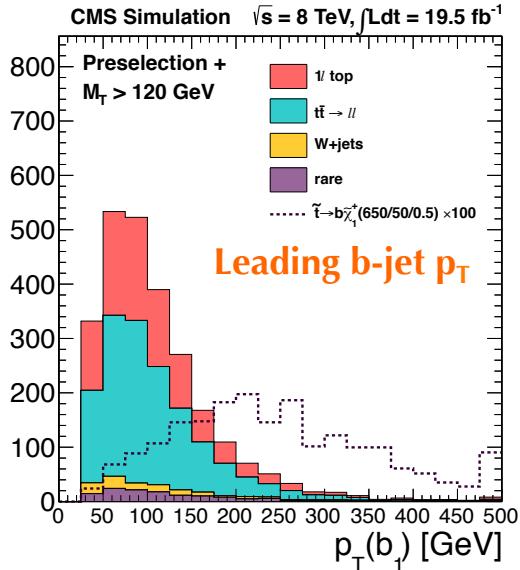
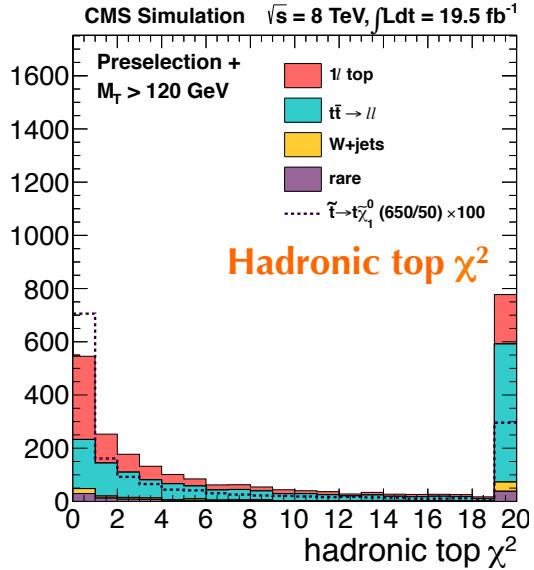
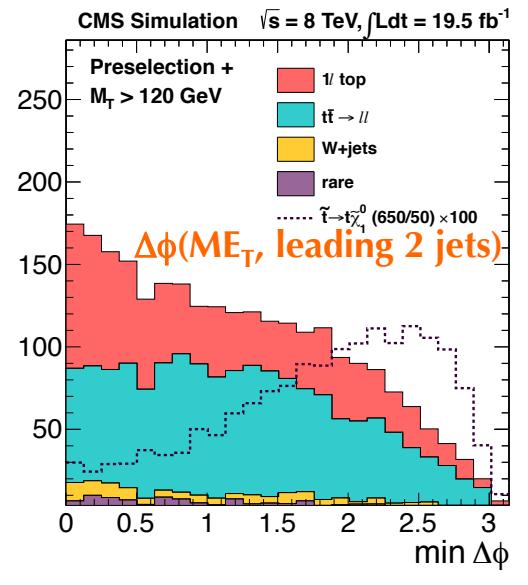
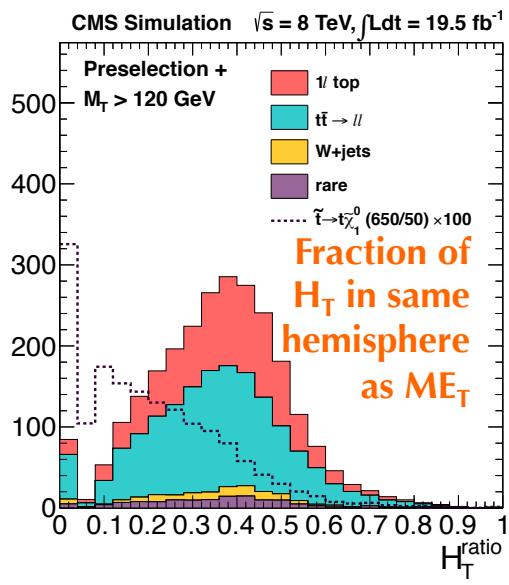
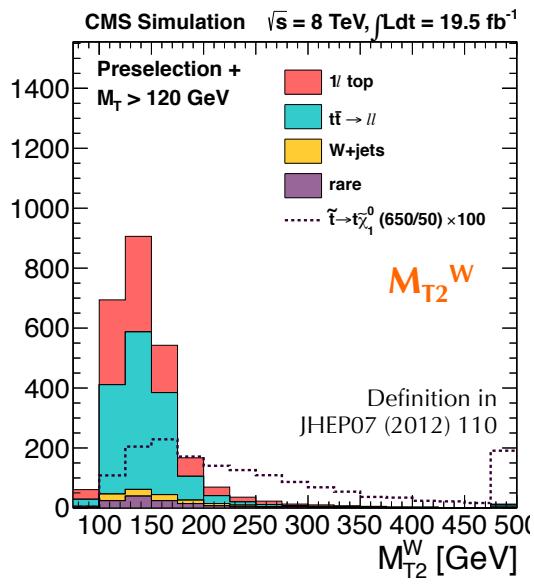
BACKUP

TOP SQUARK PAIR PRODUCTION

- Top squark pair production mostly via gg (dominant) and q \bar{q}
- **Critical challenge**
 - Small stop mass: large cross section, but signal looks similar to background
 - Large stop mass: different kinematics, but small cross section



KINEMATIC VARIABLES



SIGNAL REGION DEFINITIONS

- Signal regions target different decay modes and a range of signal kinematics

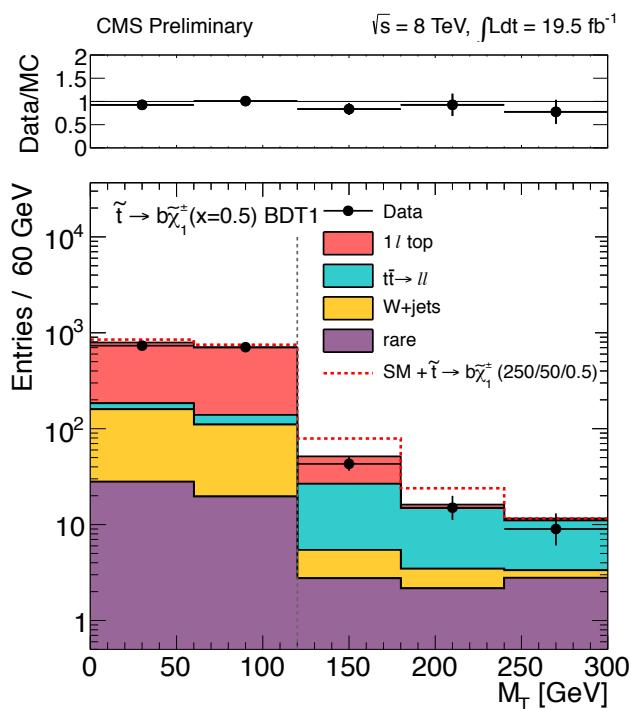
$t\chi^0$

$b\chi^\pm$

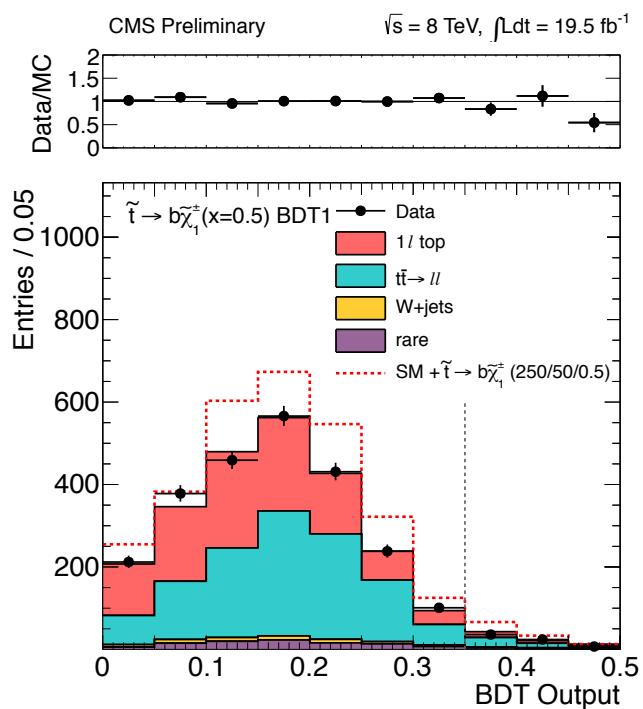
Selection	$\tilde{t} \rightarrow t\tilde{\chi}_1^0$ cut-based Low ΔM	$\tilde{t} \rightarrow t\tilde{\chi}_1^0$ High ΔM	$\tilde{t} \rightarrow t\tilde{\chi}_1^0$ BDT	$\tilde{t} \rightarrow b\tilde{\chi}_1^+$ cut-based Low ΔM	$\tilde{t} \rightarrow b\tilde{\chi}_1^+$ High ΔM	$\tilde{t} \rightarrow b\tilde{\chi}_1^+$ BDT
$E_T^{\text{miss}} (\text{GeV})$	> 150,200, 250,300	> 150,200, 250,300	yes	> 100,150, 200,250	> 100,150, 200,250	yes
$M_{\text{T2}}^W (\text{GeV})$		> 200	yes		> 200	yes
$\min \Delta\phi$	> 0.8	> 0.8	yes	> 0.8	> 0.8	yes
H_T^{ratio}			yes			yes
χ^2	<5	<5	(on-shell top) (off-shell top)			
leading b-jet p_T (GeV)					> 100	yes
$\Delta R(\ell, \text{leading b-jet})$						yes

ALTERNATIVE $b\chi^\pm$ SIGNAL REGION

- Signal region distributions for loosest BDT $b\chi^\pm$ signal region with χ^\pm mass parameter $x=0.5$
 - No evidence for top squarks**

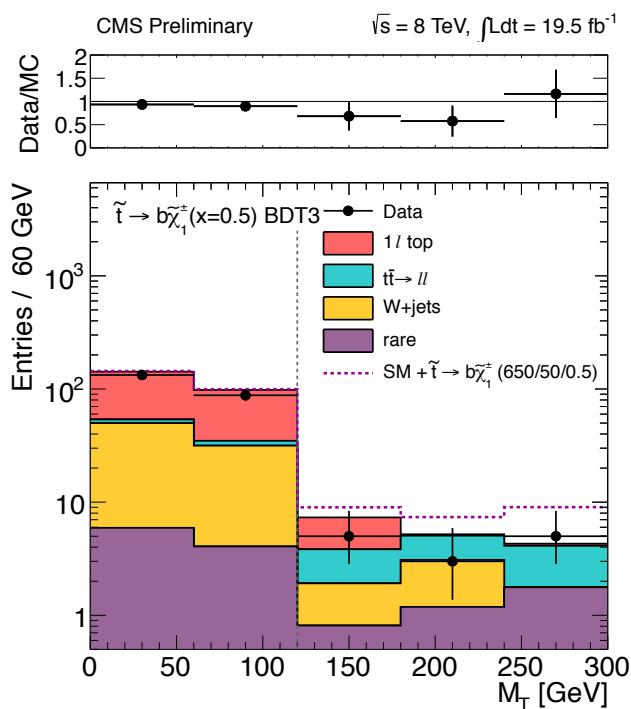


Sample	$\tilde{t} \rightarrow b\tilde{\chi}_1^\pm x=0.5$			
	BDT1	BDT2 Loose	BDT2 Tight	BDT3
$t\bar{t} \rightarrow ll$	40 ± 5	21 ± 4	4 ± 2	6 ± 2
1l Top	24 ± 10	15 ± 7	4 ± 3	4 ± 2
W+jets	5 ± 1	5 ± 1	2 ± 1	3 ± 1
Rare	8 ± 4	8 ± 4	3 ± 1	4 ± 2
Total	77 ± 12	50 ± 9	13 ± 4	17 ± 4
Data	67	35	12	13

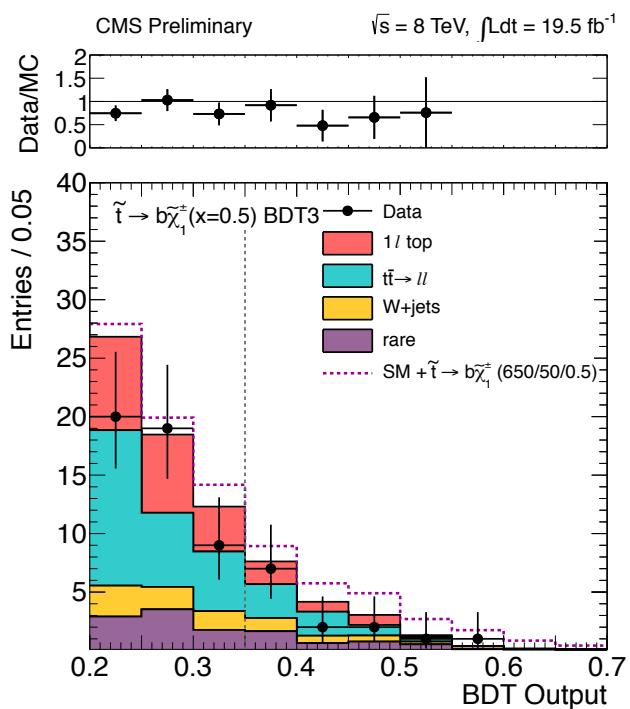


ALTERNATIVE $b\chi^\pm$ SIGNAL REGION

- Signal region distributions for tightest BDT $b\chi^\pm$ signal region with χ^\pm mass parameter $x=0.5$
 - No evidence for top squarks**



Sample	$\tilde{t} \rightarrow b\tilde{\chi}_1^\pm$ $x=0.5$			
	BDT1	BDT2 Loose	BDT2 Tight	BDT3
$t\bar{t} \rightarrow ll$	40 ± 5	21 ± 4	4 ± 2	6 ± 2
1l Top	24 ± 10	15 ± 7	4 ± 3	4 ± 2
W+jets	5 ± 1	5 ± 1	2 ± 1	3 ± 1
Rare	8 ± 4	8 ± 4	3 ± 1	4 ± 2
Total	77 ± 12	50 ± 9	13 ± 4	17 ± 4
Data	67	35	12	13



RESULTS: $t\tilde{\chi}^0$ SIGNAL REGIONS

BDT analysis

Sample	$\tilde{t} \rightarrow t\tilde{\chi}_1^0$					
	BDT1 Loose	BDT1 Tight	BDT2	BDT3	BDT4	BDT5
$t\bar{t} \rightarrow \ell\ell$	438 ± 37	68 ± 11	46 ± 10	5 ± 2	0.3 ± 0.3	48 ± 13
1ℓ Top	251 ± 93	37 ± 17	22 ± 12	4 ± 3	0.8 ± 0.9	30 ± 12
$W + \text{jets}$	27 ± 7	7 ± 2	6 ± 2	2 ± 1	0.8 ± 0.3	5 ± 2
Rare	47 ± 23	11 ± 6	10 ± 5	3 ± 1	1.0 ± 0.5	4 ± 2
Total	763 ± 102	124 ± 21	85 ± 16	13 ± 4	2.9 ± 1.1	87 ± 18
Data	728	104	56	8	2	76

cut-based analysis

Sample	$E_T^{\text{miss}} > 150 \text{ GeV}$	$E_T^{\text{miss}} > 200 \text{ GeV}$	$E_T^{\text{miss}} > 250 \text{ GeV}$	$E_T^{\text{miss}} > 300 \text{ GeV}$
Low ΔM Selection				
$t\bar{t} \rightarrow \ell\ell$	131 ± 15	42 ± 7	17 ± 5	5.6 ± 2.5
1ℓ Top	94 ± 47	30 ± 19	9 ± 6	3.1 ± 2.4
$W + \text{jets}$	10 ± 3	5 ± 1	2 ± 1	1.0 ± 0.4
Rare	16 ± 8	7 ± 4	4 ± 2	1.8 ± 0.9
Total	251 ± 50	83 ± 21	31 ± 8	11.5 ± 3.6
Data	227	69	21	9
High ΔM Selection				
$t\bar{t} \rightarrow \ell\ell$	8 ± 2	5 ± 2	3.2 ± 1.4	1.4 ± 0.9
1ℓ Top	13 ± 6	6 ± 4	3.0 ± 2.2	1.4 ± 1.0
$W + \text{jets}$	4 ± 1	2 ± 1	1.5 ± 0.5	0.9 ± 0.3
Rare	4 ± 2	3 ± 1	1.8 ± 0.9	1.0 ± 0.5
Total	29 ± 7	17 ± 5	9.5 ± 2.8	4.7 ± 1.4
Data	23	11	3	2

- Data consistent with predicted bkg
- No evidence for top squarks

RESULTS: $t\bar{t}\chi^\pm$ SIGNAL REGIONS

BDT analysis

$\tilde{t} \rightarrow b\tilde{\chi}_1^+ x=0.75$

Sample	BDT1	BDT2	BDT3	BDT4
$t\bar{t} \rightarrow \ell\ell$	37 ± 5	9 ± 2	3.1 ± 1.3	248 ± 22
1ℓ Top	17 ± 9	6 ± 5	1.6 ± 1.6	188 ± 70
$W+jets$	4 ± 1	4 ± 1	1.6 ± 0.6	22 ± 6
Rare	4 ± 2	4 ± 2	1.8 ± 0.9	20 ± 10
Total	61 ± 10	22 ± 6	8.1 ± 2.3	478 ± 74
Data	50	13	5	440

$\tilde{t} \rightarrow b\tilde{\chi}_1^+ x=0.5$

Sample	BDT1	BDT2 Loose	BDT2 Tight	BDT3
$t\bar{t} \rightarrow \ell\ell$	40 ± 5	21 ± 4	4 ± 2	6 ± 2
1ℓ Top	24 ± 10	15 ± 7	4 ± 3	4 ± 2
$W+jets$	5 ± 1	5 ± 1	2 ± 1	3 ± 1
Rare	8 ± 4	8 ± 4	3 ± 1	4 ± 2
Total	77 ± 12	50 ± 9	13 ± 4	17 ± 4
Data	67	35	12	13

$\tilde{t} \rightarrow b\tilde{\chi}_1^+ x=0.25$

Sample	BDT2	BDT3
$t\bar{t} \rightarrow \ell\ell$	2.2 ± 1.3	1.2 ± 1.0
1ℓ Top	4.0 ± 1.8	1.5 ± 0.8
$W+jets$	2.0 ± 0.7	0.7 ± 0.3
Rare	1.6 ± 0.8	1.0 ± 0.5
Total	9.8 ± 2.4	4.4 ± 1.4
Data	7	2

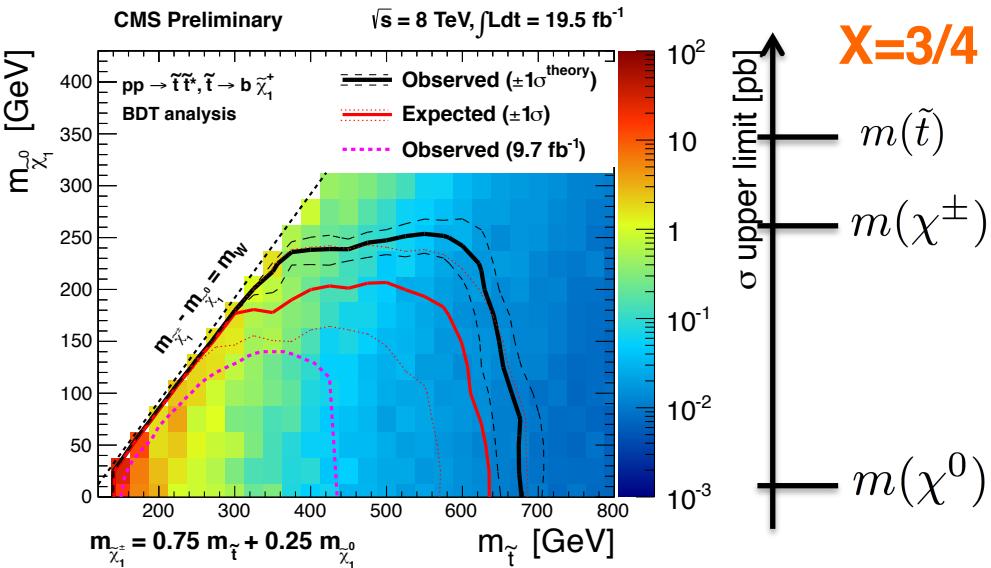
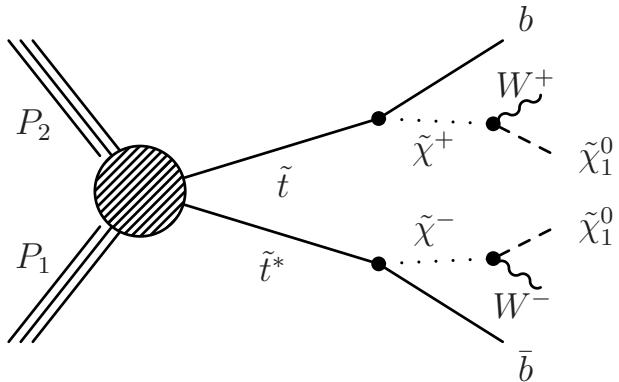
cut-based analysis

Sample	$E_T^{\text{miss}} > 100 \text{ GeV}$	$E_T^{\text{miss}} > 150 \text{ GeV}$	$E_T^{\text{miss}} > 200 \text{ GeV}$	$E_T^{\text{miss}} > 250 \text{ GeV}$
Low ΔM Selection				
$t\bar{t} \rightarrow \ell\ell$	875 ± 57	339 ± 23	116 ± 14	40 ± 9
1ℓ Top	658 ± 192	145 ± 70	41 ± 24	14 ± 9
$W+jets$	59 ± 15	21 ± 5	8 ± 2	4 ± 1
Rare	70 ± 35	33 ± 17	16 ± 8	8 ± 4
Total	1662 ± 203	537 ± 75	180 ± 28	66 ± 13
Data	1624	487	151	52
High ΔM Selection				
$t\bar{t} \rightarrow \ell\ell$	25 ± 5	12 ± 3	7 ± 2	2.9 ± 1.5
1ℓ Top	35 ± 10	15 ± 6	6 ± 3	2.7 ± 1.8
$W+jets$	9 ± 2	5 ± 1	2 ± 1	1.8 ± 0.6
Rare	9 ± 5	7 ± 3	4 ± 2	2.4 ± 1.2
Total	79 ± 12	38 ± 7	19 ± 5	9.9 ± 2.7
Data	90	39	18	5

- Data consistent with predicted bkg \rightarrow no evidence for top squarks

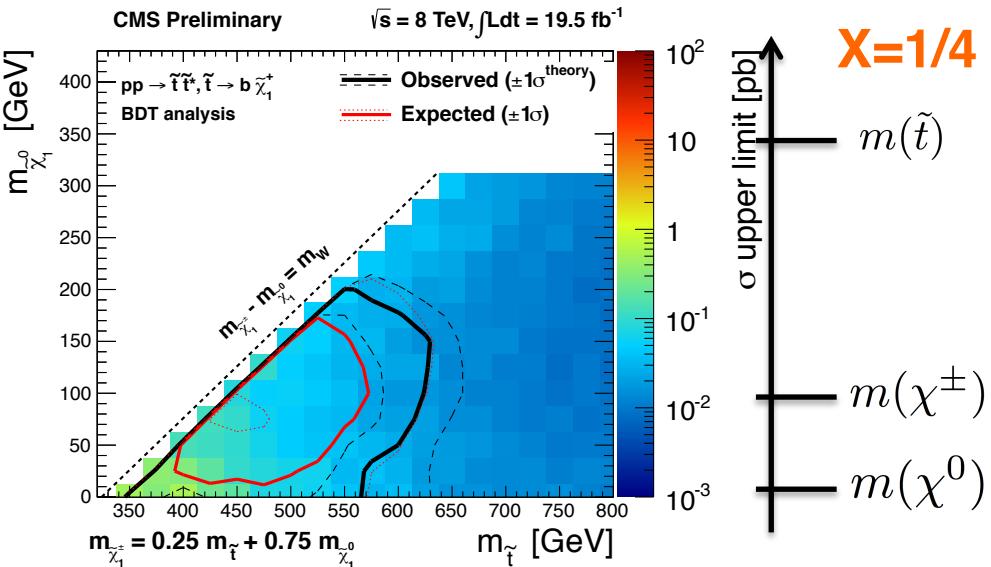
INTERPRETATION $b\chi^\pm$

$$\tilde{t}\tilde{t}^* \rightarrow b\bar{b}\tilde{\chi}^+\tilde{\chi}^- \rightarrow b\bar{b}W^+W^-\tilde{\chi}_1^0\tilde{\chi}_1^0$$



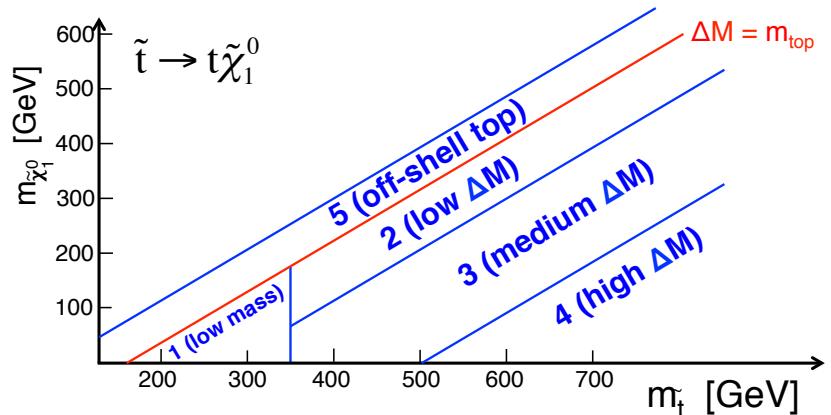
- Two scenarios for chargino mass
- $$m(\tilde{\chi}^\pm) = x \, m(\tilde{t}) + (1-x) \, m(\tilde{\chi}^0)$$
- $$X=3/4 \text{ and } x=1/4$$

Results probe
 $m(\tilde{t}) \lesssim 160 - 420 \text{ GeV}$
for $m(\tilde{\chi}^0) \lesssim 150-200 \text{ GeV}$



SYSTEMATIC UNCERTAINTIES

- Example: breakdown of sources of systematic uncertainty for $t\tilde{\chi}_1^0$ BDT analysis



Relative uncertainty on the total background prediction [%]

		$\tilde{t} \rightarrow t\tilde{\chi}_1^0$					
Sample		BDT1 Loose	BDT1 Tight	BDT2	BDT3	BDT4	BDT5
M _T SF	M_T peak data and MC (stat)	1.0	2.1	2.7	5.3	8.7	3.0
$t\bar{t} \rightarrow \ell^+ \ell^-$	N_{jets} modeling	1.7	1.6	1.6	1.1	0.4	1.7
$t\bar{t} \rightarrow \ell^+ \ell^-$	(CR- ℓt and CR- 2ℓ tests)	4.0	8.2	11.0	12.5	7.2	13.8
$t\bar{t}$	2nd lepton veto	1.5	1.4	1.4	0.9	0.3	1.4
$t\bar{t} \rightarrow \ell^+ \ell^-$	(stat)	1.1	2.8	3.4	7.0	7.4	3.3
$W + \text{jets}$	$W + \text{jets}$ cross section	1.6	2.2	2.8	1.7	2.7	2.2
$W + \text{jets}$	(stat)	1.1	1.9	2.0	4.6	10.8	5.2
$W + \text{jets}$ SF uncertainty		8.3	7.7	6.8	8.1	9.7	8.6
1ℓ bkg	1ℓ Top (stat)	0.4	0.8	0.8	1.4	4.4	1.2
1ℓ bkg	1ℓ Top tail-to-peak ratio	9.0	11.4	12.4	19.6	28.5	9.1
Rare bkg	rare cross sections	1.8	3.0	4.0	8.1	15.7	0.7
13-38%	Total	13.4	17.1	19.3	27.8	38.4	20.2

SENSITIVITY AROUND m_{top}

- Reduced sensitivity in region $\Delta m = m_t - m_{\chi^0} \sim m_{\text{top}}$
 - Momentum of the χ^0 is reduced in the ‘compressed’ region → reduced source of ME_T which is the main discriminator from background
 - Results in a reduced M_T acceptance

