Very Light Stops at the LHC

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1212.4856

Why Light Stops?

- Third generation superpartners can be light in MSSM
- Large y_t
  - RGE running pushes down soft masses
  - Large L-R mixing $\rightarrow$ lighter eigenstate
- Electroweak Baryogenesis and MSSM Carena, Nardini, Quiros, Wagner
- Higgs and Naturalness - additional fields/gauge groups

Stop mass matrix

$$m_{\tilde{t}}^2 = \begin{pmatrix} M_{Q_3}^2 + m_t^2 + \Delta_L & m_t X_t \\ m_t X_t & M_{U_3}^2 + m_t^2 + \Delta_R \end{pmatrix}$$

- $m_{\tilde{t}}$ depends on $(M_{Q_3}^2, M_{U_3}^2, X_t)$
- $X_t = A_t - \mu / \tan\beta$ parametrizes $L-R$ mixing.
- $\tilde{t}_1 \sim \tilde{t}_R$: $M_{U_3}^2 \sim$ small or < 0
- $\tilde{t}_1 \sim \tilde{t}_L$: $M_{Q_3}^2 \sim$ small

MSSM spectrum

- $\tilde{t}_1$ is NLSP, $m_{\tilde{t}_1} \in [100\text{-}350]$ GeV, in particular $m_{\tilde{t}_1} < m_t$
- $\tilde{\chi}_1^0$ is LSP
- $\tilde{\chi}_1^\pm$ lightish
- Other squarks, sleptons, gluino $\sim$ TeV

Decay modes

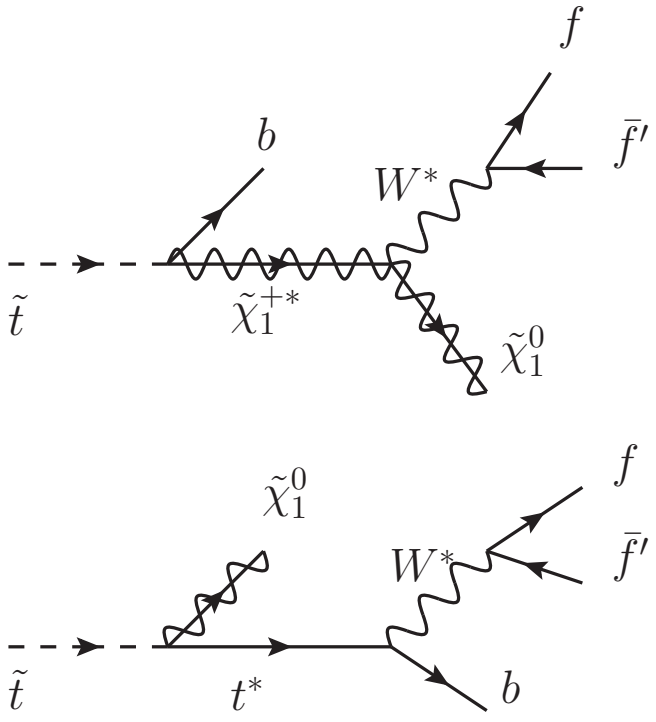
$$\left.\begin{array}{ll} \tilde{t}_1 \to t\tilde{\chi}_1^0 & m_{\tilde{t}_1} - m_t > 0 \\ \tilde{t}_1 \to b\tilde{\chi}_1^+ & m_{\tilde{t}_1} - m_{\tilde{\chi}_1^+} > m_b \end{array}\right\} \quad \text{LHC}$$

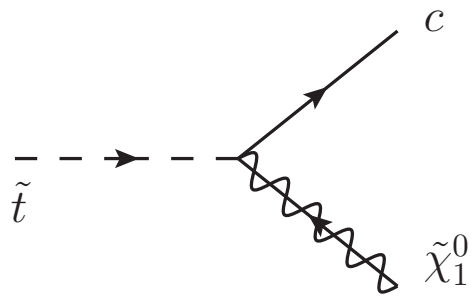
$$\tilde{t}_1 \to b\tilde{\chi}_1^0 W^+ \qquad \Delta m = m_{\tilde{t}_1} - m_{\tilde{\chi}_1^0} > m_W + m_b$$

$$\tilde{t}_1 \to b\tilde{\chi}_1^0 f\bar{f}' \qquad m_b < \Delta m < m_W + m_b$$

$$\tilde{t}_1 \to c\tilde{\chi}_1^0 \qquad \Delta m < m_b \qquad \text{CDF}$$

4B and FV mode





- 4B mode: SUSY-HIT

FV mode: Minimal Flavour Violation

Minimal Flavour Violation (MFV)

- If $Y_u = Y_d = 0$, then $G_F = SU(3)_{Q_L} \otimes SU(3)_{U_R} \otimes SU(3)_{D_R}$ (quarks)

$$\mathscr{L}_{yuk} = Y_u \bar{Q}_L H^* u_R + Y_d \bar{Q}_L H d_R$$

$$Q_L \sim (3,1,1) \qquad u_R \sim (1,3,1) \qquad d_R \sim (1,1,3)$$

- Impose G_F on $\mathscr{L}_{SM}$ by $Y_u \sim (3,\bar{3},1), Y_d \sim (3,1,\bar{3})$
- Y_u, Y_d spurions and $\not{G}_F \sim Y_{u,d}$
- MFV: NP is also invariant under G_F

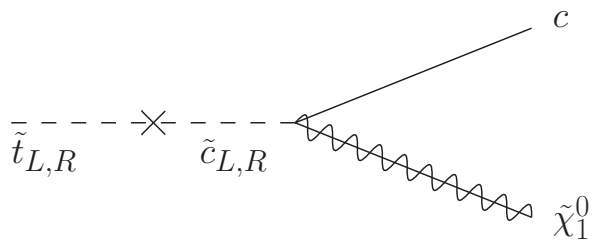
MFV in MSSM

- Soft masses are constrained by MFV

$$\mathbf{Y}_u = \lambda_u \qquad \mathbf{Y}_d = V_{CKM}\lambda_d \qquad (3\times 3 \text{ matrices})$$

$$\begin{aligned} \tilde{m}^2_{Q_L} &= \tilde{m}^2(a_1\mathbf{1} + b_1\mathbf{Y}_u\mathbf{Y}_u^\dagger + b_2\mathbf{Y}_d\mathbf{Y}_d^\dagger) \\ A_u &= A(a_4\mathbf{1} + b_7\mathbf{Y}_d\mathbf{Y}_d^\dagger)\mathbf{Y}_u \end{aligned}$$

- $a_i, b_i \sim \mathcal{O}(1)$

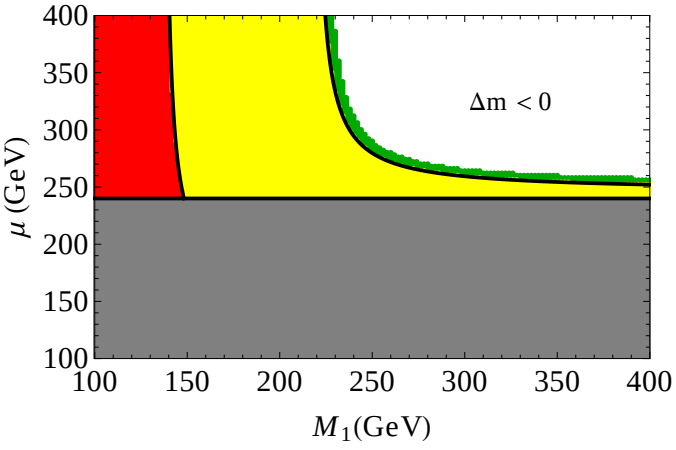


- FV width depends on stop L-R mixing, $\tilde{\chi}_1^0$ composition
- FV can dominate over 4B even when $\Delta m > m_b$

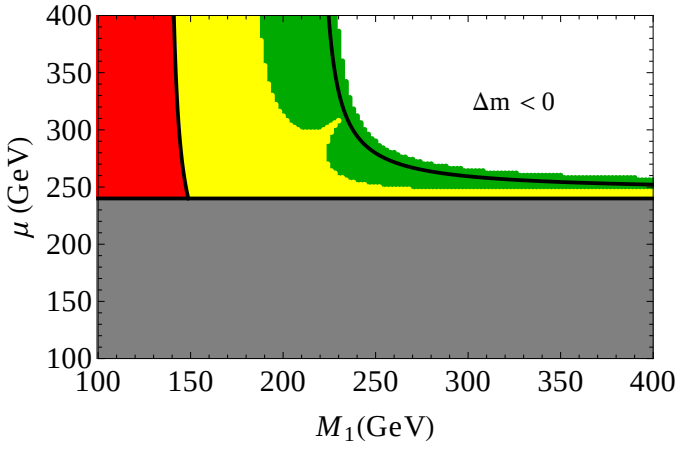
Phase Diagrams

- Fix $m_{\tilde{t}_1} = 225\,\text{GeV}, M_2 = 350\ \text{GeV}, \tan\beta = 10$
- $m_{\tilde{\chi}_1^0} \sim M_1, \mu$ and $m_{\tilde{\chi}_1^+} \sim M_2, \mu$

$\tilde{t}_1 \sim \tilde{t}_R$

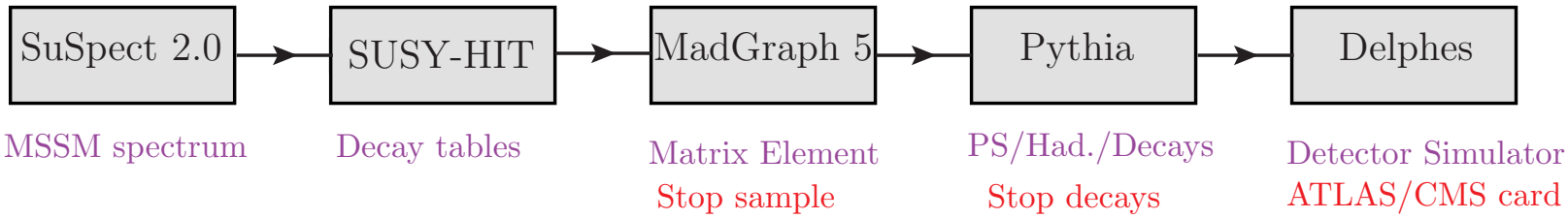


$\tilde{t}_1 \sim \tilde{t}_L$-$\tilde{t}_R$



- The regions are 2B (gray), 3B (red), 4B (yellow) and FV (green)
- $\tilde{\chi}_1 \sim$ Higgsino-like for small-μ, large-M_1 (large M_2)
- $\tilde{\chi}_1 \sim$ Bino-like for large-μ, small-M_1 (large M_2)
- Let's search for them!

Analysis



- Generate NP signal, not SM background
- Study FV, 4B and 3B mode separately (BR=100%) in $m_{\tilde{t}_1} - m_{\tilde{\chi}_1^0}$ plane
- Apply model-independent upper bounds to constrain NP

Generating a signal

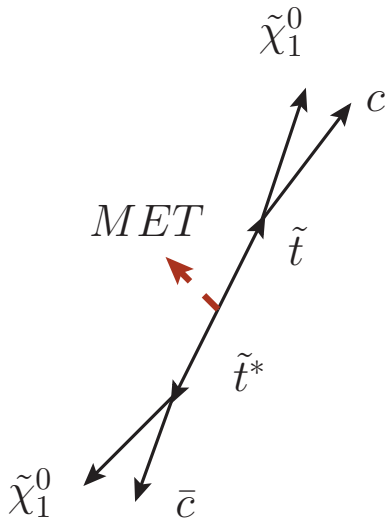
- $N = \sigma \times A$, where $A = \frac{\#\ events\ passing\ cuts}{total\ events}$

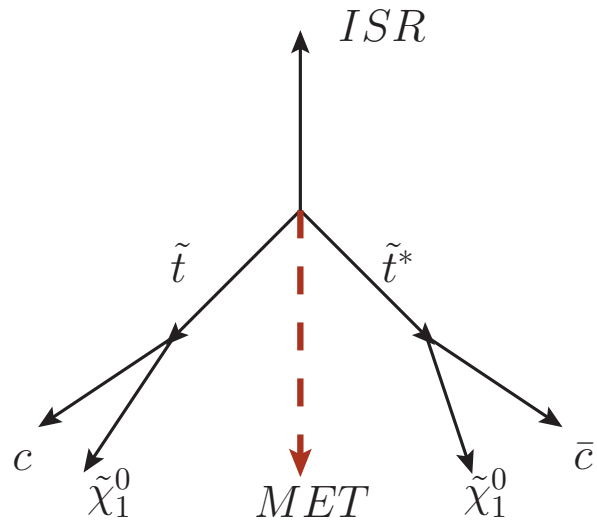
- Many SUSY searches have high MET requirement (*e.g.* ATLAS jets+$\not{E}_T$ with $m_{eff} = \Sigma_j p_T + \not{E}_T > 1\,\text{TeV}$)
- Small Δm region - soft jets
- Very low acceptance for a pure stop sample

- Important effects from QCD initial state radiation

Initial State Radiation (ISR)

Alwall, Le, Lisanti, Wacker



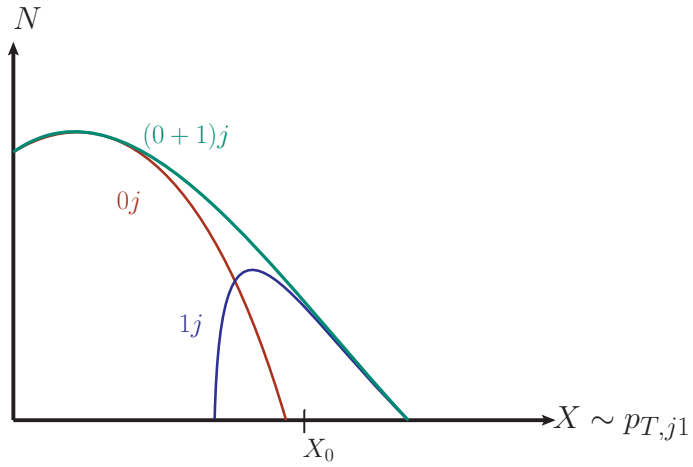


- Boosted stops (back-to-back) give small MET
- $\tilde{\chi}_1^0$s momenta unbalanced due to ISR $\rightarrow$ large MET

The stop sample

- Indirect LHC searches probe various kinematic variables
- Want to constrain light stop decays for all relevant searches
- Generate search specific stop samples *or* find an optimal stop sample

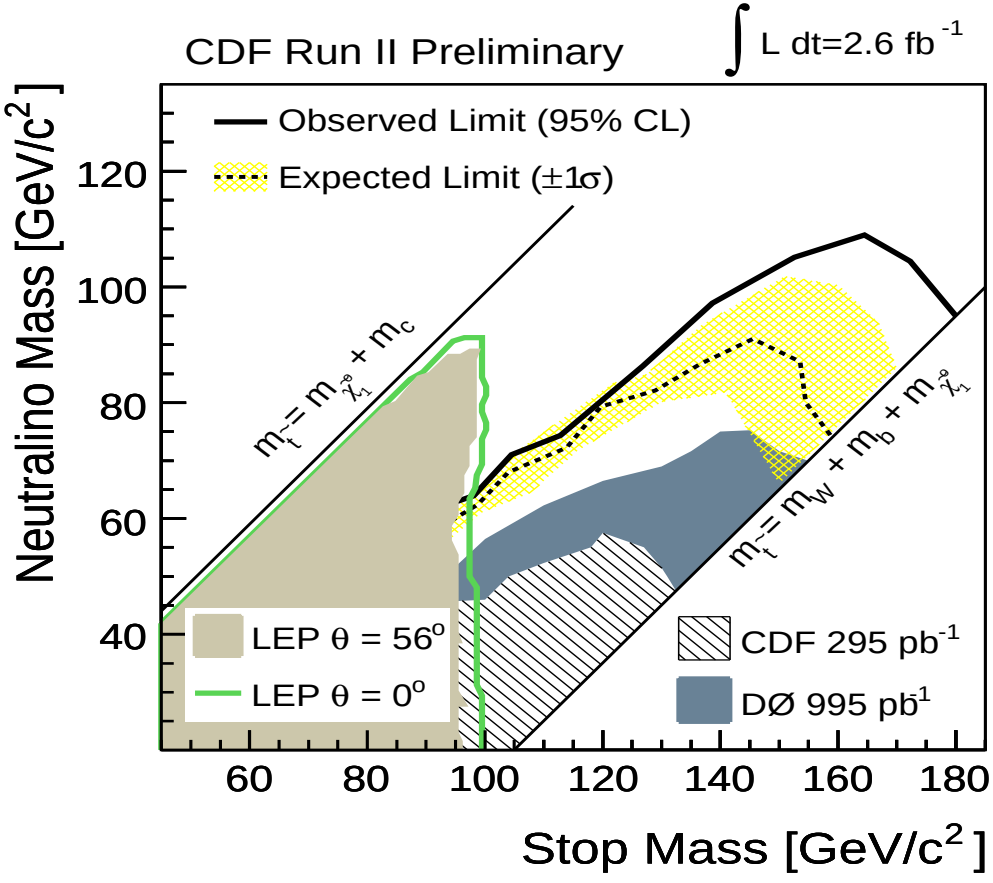
- Considered $\tilde{t}\tilde{t}^*, \tilde{t}\tilde{t}^*(0+1)j, \tilde{t}\tilde{t}^* + 1j$ for a range of $p_{T,j1}$ and representative variables $(p_{T,j}, \not{E}_T, H_T, m_{eff})$
- Optimal sample: $\tilde{t}\tilde{t}^* j$ with $p_{T,j1} = 150\,\text{GeV}$



Production cross-section

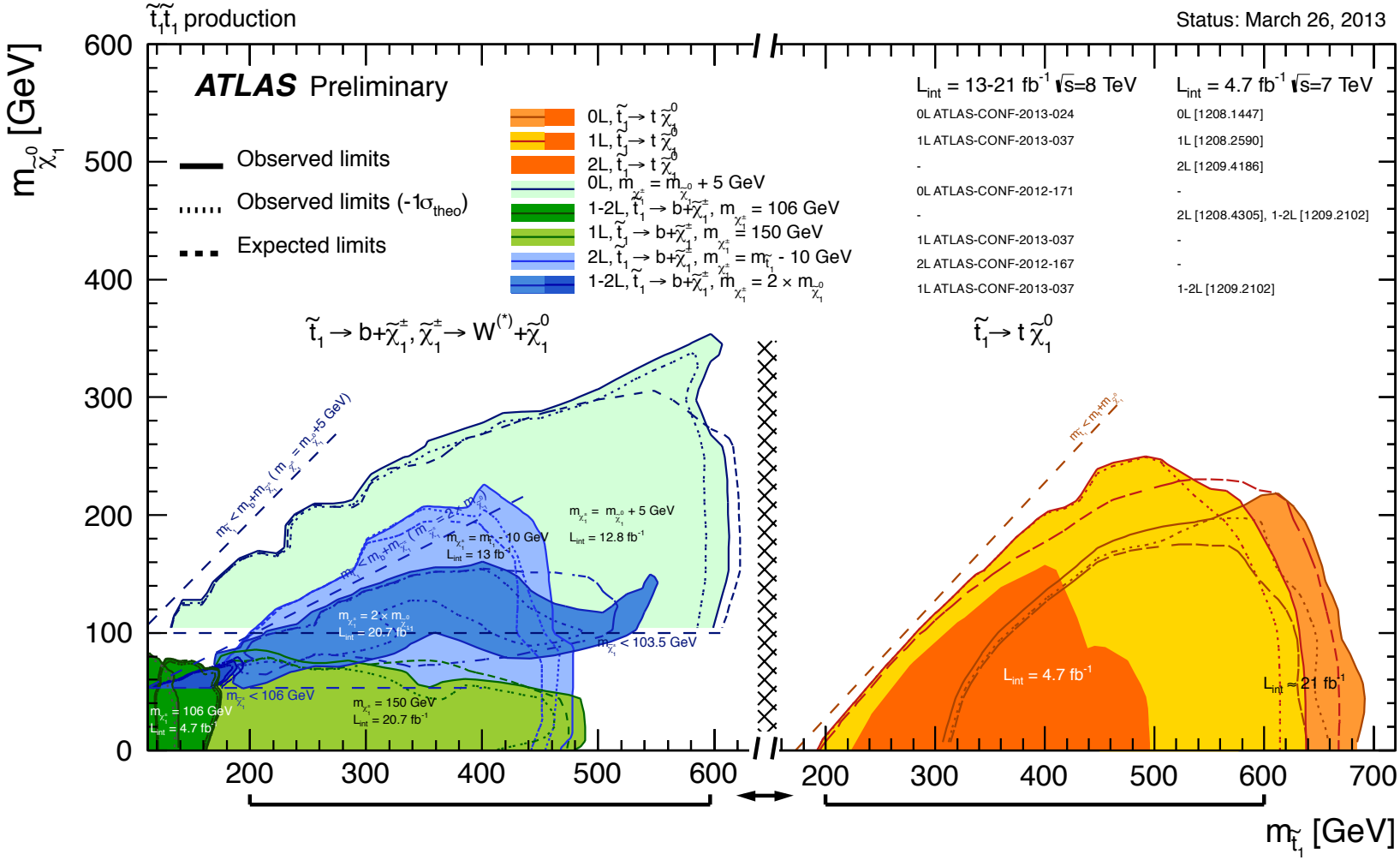
- $\tilde{t}\bar{t}^{*}j$ cross-section at NLO
- $\sigma_{\tilde{t}\bar{t}^{*}j}$ $\sim$7 pb - 0.05 pb
- Allow $\pm$50% variation for higher-order effects
- Generate separate samples with BR=100% for FV, 4B and 3B mode

Stop limits: Tevatron



- Cuts:
  - $\not{E}_T \geq 50$ GeV
  - $\geq 2j$ with $p_T \geq 35, 25, \ldots$ GeV
  - No constraints for $\Delta m < 30\,\text{GeV}$

Stop limits: LHC



Relevant LHC searches

- FV ($j + 0l + \not{E}_T$):
  - Monojet
  - Jets+$\not{E}_T$
  - b-jet searches (c mistag $\sim 10\%$)
  - Razor and m_{T2}

- 4B ($j + b + \geq 0l + \not{E}_T$):
  - Monojet
  - Jets+$\not{E}_T$
  - b-jet searches
  - Razor and m_{T2}

- 3B ($j + b + \geq 0l + \not{E}_T$):
  - b-jet searches
  - Razor and m_{T2}

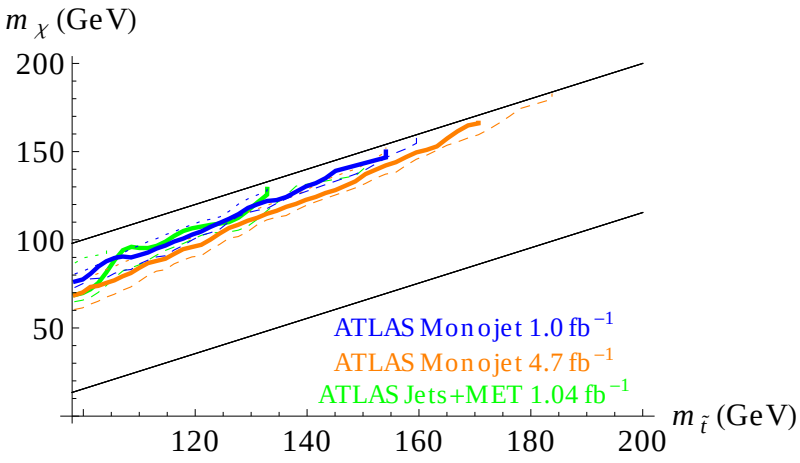
ATLAS searches ($\sqrt{s} = 7\,\text{TeV}$)

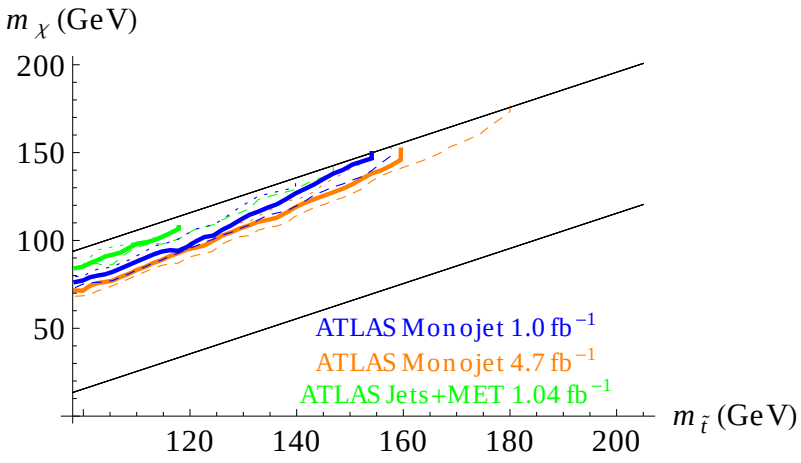
ATLAS Analysis ($\mathscr{L}/fb^{-1}$)	Final states	Decay channel
Monojet (1.00)	$\leq$ 1-3j, 0l	FV, 4B
Jets+$\not{E}_T$ (1.04)	$\geq$ 2-4j, 0l	FV, 4B
Monojet (4.7)	$\leq 2j, 0l$	FV, 4B
$j+b+\not{E}_T$ (0.83)	$\geq 3j, \geq 1b, 0l$	-
$j+l+\not{E}_T$ (1.04)	$\geq$3-4j, 1l	-
$j+b+l+\not{E}_T$ (1.03)	$\geq 4j, \geq 1b, 1l$	-
$j+b+l+\not{E}_T$ (2.05)	$\geq$ 3-4$j \geq 1b$, 0-1l	-
$\tilde{t}\tilde{t}^* \rightarrow ll$ (4.7)	$\geq 1j, 1l$	-
$j+l+b+\not{E}_T$ (4.7)	$\geq 4j, 1b, 1l$	-
$j+b+\not{E}_T$ (4.7)	$\geq 4j, \geq 2b, 1l$	-

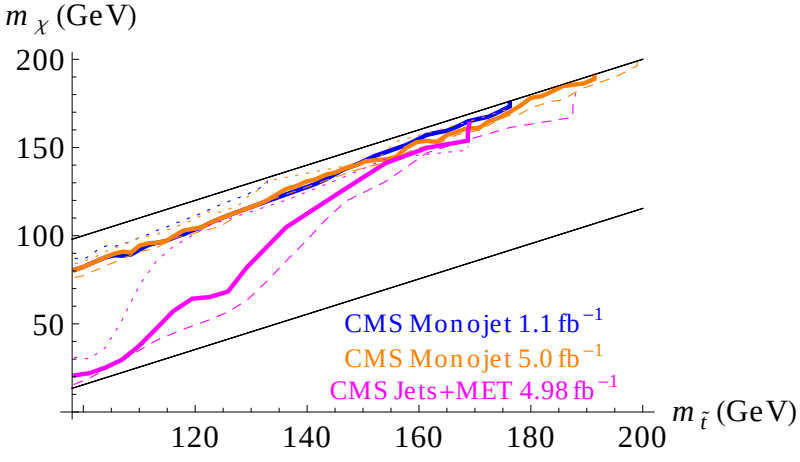
CMS searches ($\sqrt{s} = 7\,\text{TeV}$)

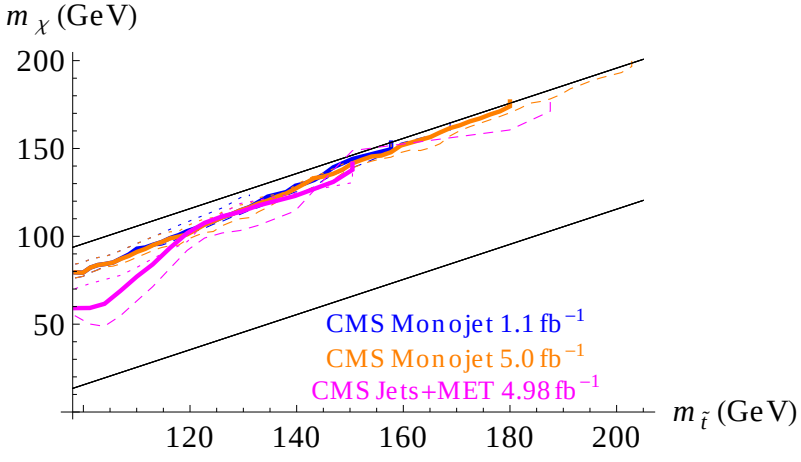
CMS Analysis ($\mathscr{L}/fb^{-1}$)	Final states	Decay channel
Monojet (1.1)	$\leq 2j, 0l$	FV, 4B
$j + \not{E}_T$ (1.1)	$\geq 3j, 0l$	-
α_T (1.14)	$\geq 2j$, 0-1$l(\mu)$, 0-1γ	-
$j + b + \not{E}_T$ (1.1)	$\geq$ 3-4$j, \geq 1b1l, \geq 1b$	FV, 4B
Razor (4.4)	$\geq 2j$, 0-2l	FV, 4B, 3B
$j + l + \not{E}_T$ (1.1)	$\geq$ 3-4j, 1l	-
M_{T2} (1.1)	$\geq$ 3-4$j, \geq$ 0-1$b, 0l$	FV, 4B, 3B
Monojet (5.0)	$\leq 2j, 0l$	FV, 4B
$j + \not{E}_T$ (4.98)	$\geq 3j, 0l$	FV, 4B
α_T (4.98)	$\geq 2j$, 0-3$b, 0l$,	-
$j + b + \not{E}_T$ (4.98)	$\geq 3j$, 1-3$b, 0l$	FV, 4B, 3B
Razor (4.7)	$\geq 2j, \geq 1b$, 0-2l	FV, 4B, 3B
M_{T2} (4.73)	$\geq$ 3-4$j, \geq$ 0-1$b, 0l$	FV, 4B, 3B

FV and 4B: Monojets and Jets+$\not{E}_T$

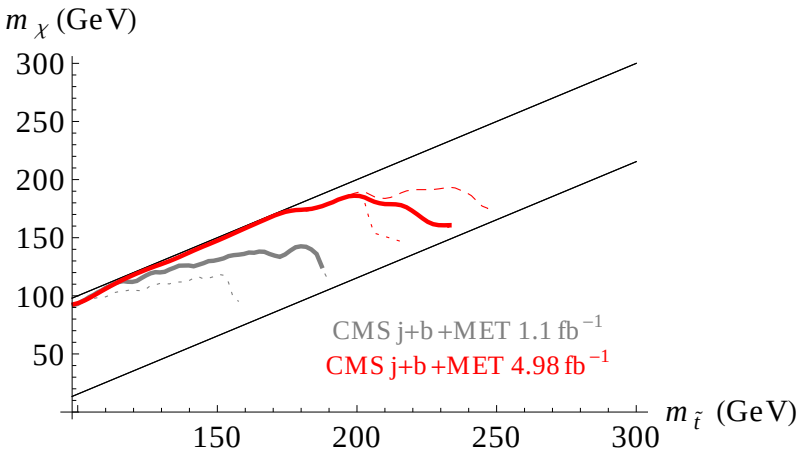


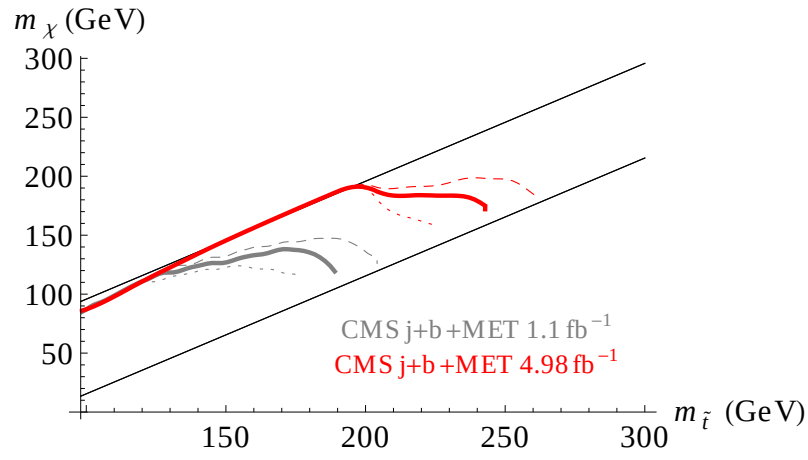


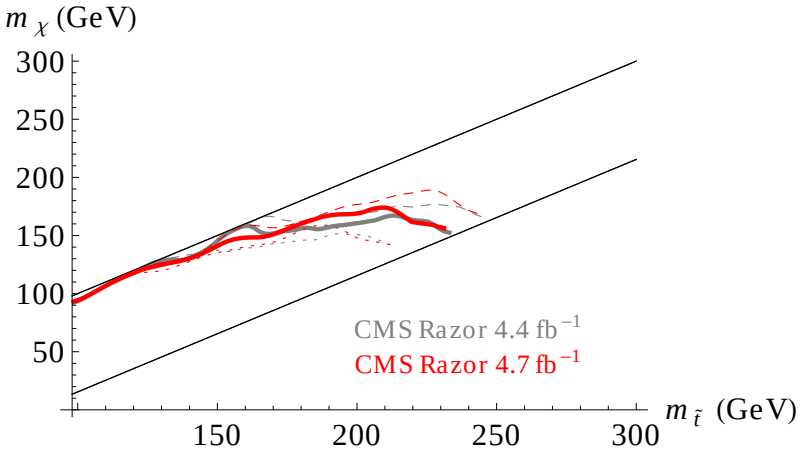


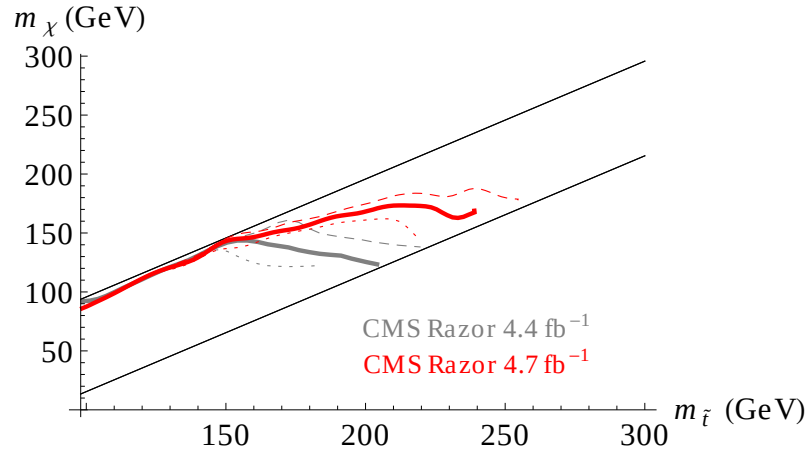


FV and 4B: *b*-jet searches

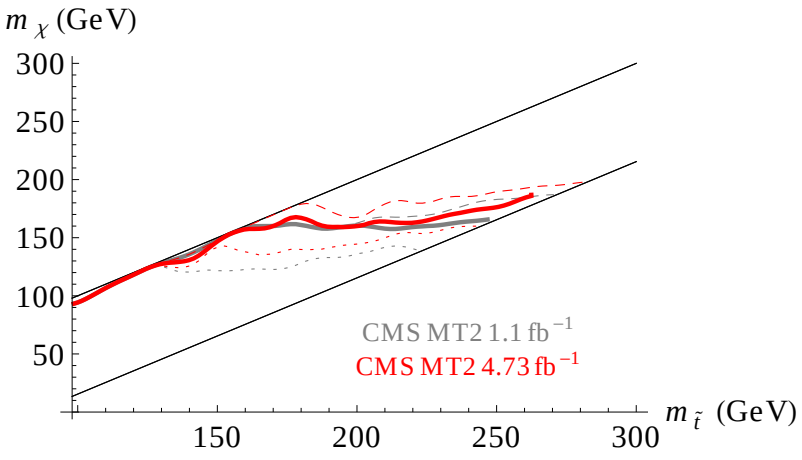


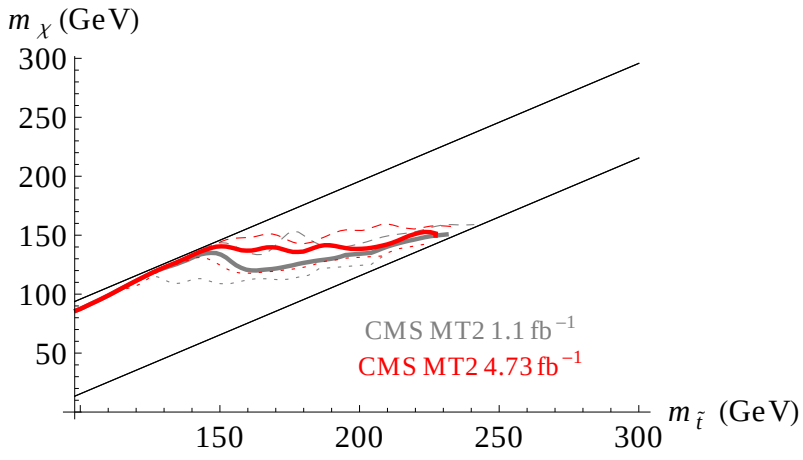






FV and 4B: m_{T2}


m_{χ} (GeV)
300
250
200
150
100
50
150
200
250
300
$m_{\tilde{t}}$ (GeV)
CMS MT2 1.1 fb^{-1}
CMS MT2 4.73 fb^{-1}


m_{χ} (GeV)
300
250
200
150
100
50
150
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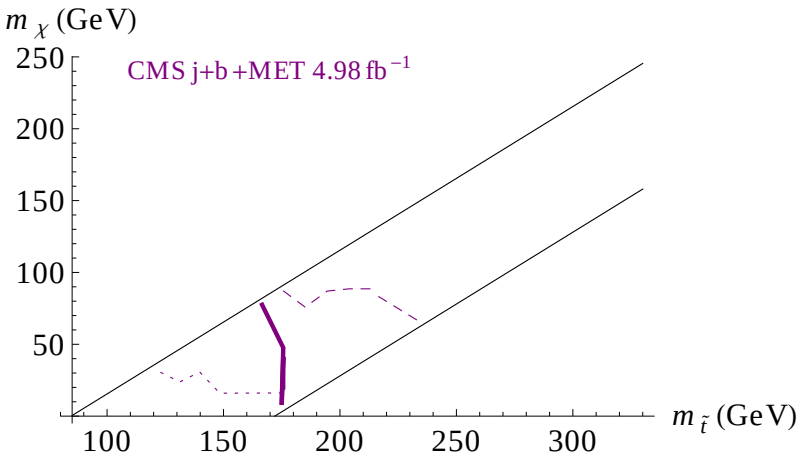
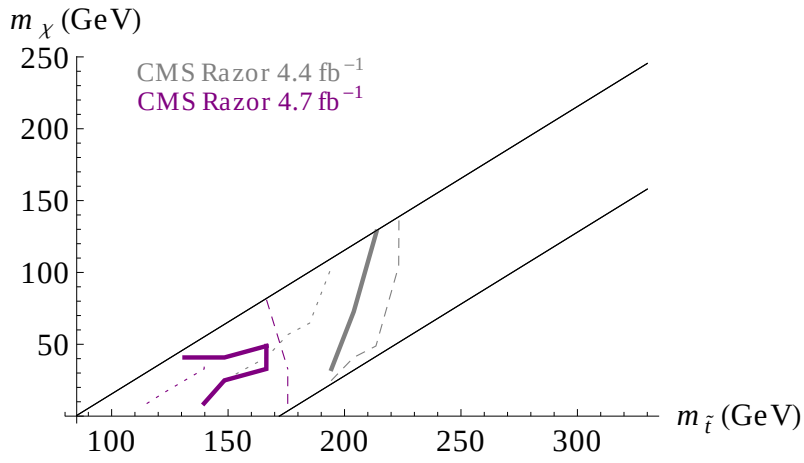
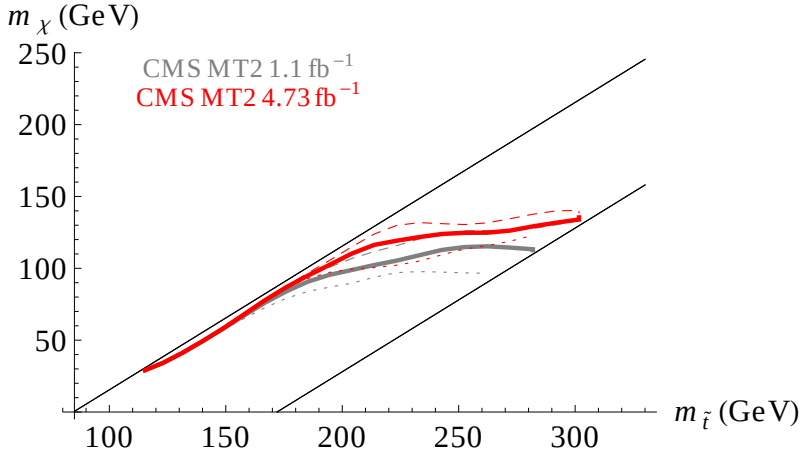
250
300
$m_{\tilde{t}}$ (GeV)
CMS MT2 1.1 fb^{-1}
CMS MT2 4.73 fb^{-1}

3B: *b*-jet searches







Conclusions

- 3rd generation superpartners can be light (and interesting) in MSSM
- Current LHC searches put strong limits on light stops (theorist-level)
- Hopefully LHC will constrain these decay modes soon