Detecting light stop pairs in coannihilation scenarios at the LHC

Zhao-Huan YU (余钊焕)

Institute of High Energy Physics, CAS

with Xiao-Jun BI, Qi-Shu YAN and Peng-Fei YIN

arXiv:1211.2997

December 2012

Problem of Standard Model (SM)

A ∼125 GeV SM-like Higgs boson has been discovered

The quantum correction of SM Higgs boson mass Δm_H^2 suffers from quadratic divergence

$\Downarrow$

Hierarchy problem

$\Downarrow$

New physics at TeV scale

(supersymmetry, extra dimension, little Higgs, ...)

Stops in supersymmetric (SUSY) models

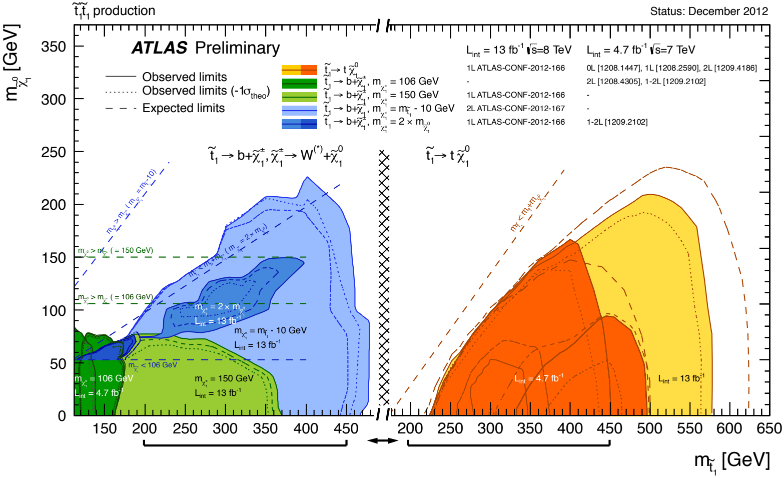
The lighter stop $\tilde{t}_1$ is probably reachable in early LHC searches.

- In order to cancel the large radiative corrections to m_H from the top quark loop without fine tuning, the stops $\tilde{t}_{1,2}$ need to be light enough.
- $\tilde{t}_1$ can be the lightest colored supersymmetric particle due to the large top Yukawa coupling and large mass splitting terms in many SUSY models.

In the following work, the direct production of $\tilde{t}_1 \tilde{t}_1^*$ pairs at the LHC is considered: $pp \to \tilde{t}_1 \tilde{t}_1^* + \text{jets}$

$m_{\tilde{t}_1}$ [GeV]	200	400	600
7 TeV, σ_{NLO} [fb]	11837	205	12
8 TeV, σ_{NLO} [fb]	17296	342	23

Current stop direct searches



Assuming some simplified models in which stops can be easily detected

Excluding stops up to $\sim 580\,\mathrm{GeV}$

Dark Matter (DM)

Not to violate baryon number B or lepton number L

(proton decay, flavor physics constraints)

$\Downarrow$

R-parity conserved SUSY $[P_R = (-1)^{3(B-L)+2s}]$

$\Downarrow$

The **lightest SUSY particle (LSP)** is stable.

$\Downarrow$

If the LSP is electrically neutral, such as $\tilde{\chi}_1^0$, it would be an attractive candidate for **non-baryonic dark matter**.

DM Relic density

ΛCDM model fitted by 7-year WMAP data: [Ap. J. Suppl. **192**, 16 (2011)]

$$\Omega_{\text{CDM}}h^2 = 0.1109,\ \Omega_{\text{baryon}}h^2 = 0.02258,\ \Omega_\Lambda = 0.734$$

(Cold DM $\sim$ 21.1%, baryons $\sim$ 4.3%, dark energy $\sim$ 74.6%)

For thermal produced DM, $\Omega_{\text{CDM}} \propto \langle \sigma_{\text{ann}} v \rangle^{-1}$.

In many SUSY models, most likely the lightest neutralino $\tilde{\chi}_1^0$ is the LSP.

However, the sfermion exchange process $\tilde{\chi}_1^0 \tilde{\chi}_1^0 \to f\bar{f}$ has the helicity suppression issue. The self-annihilation cross section σ_{ann} of $\tilde{\chi}_1^0$ is generally **not large enough** to yield the observed relic density Ω_{CDM}.

Additional mechanisms are needed (resonance, coannihilation, ...).

CMSSM case

① Higgs funnel region

$2m_{\tilde{\chi}_1^0} \simeq m_{A^0}$ or m_{h^0} or m_{H^0}

$\tilde{\chi}_1^0$ annihilates via a resonance

② Focus point region

$\tilde{\chi}_1^0$ is a bino-higgsino or bino-wino mixture

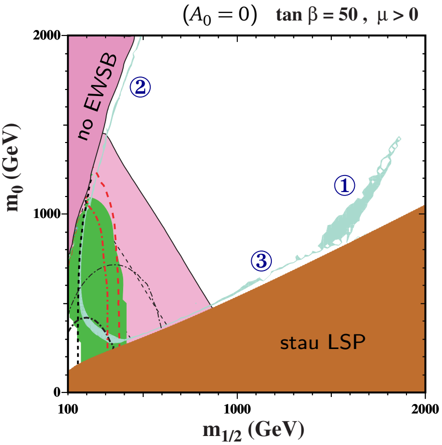
$m_{\tilde{\chi}_1^0} \sim m_{\tilde{\chi}_1^\pm}$ or $m_{\tilde{\chi}_2^0}$

$\tilde{\chi}_1^0$ coannihilates with $\tilde{\chi}_1^\pm$ or $\tilde{\chi}_2^0$

③ Sfermion coannihilation region

$m_{\tilde{\chi}_1^0} \sim m_{\tilde{\tau}_1}$ or $m_{\tilde{t}_1}$

$\tilde{\chi}_1^0$ coannihilates with $\tilde{\tau}_1$ or $\tilde{t}_1$



[Ellis, Olive, Sandick, arXiv:0704.3446]

Coannilation scenarios

In general, in order to yield the desired dark matter relic density by coannihilation mechanism, the mass of the next-to-lightest SUSY particle (NLSP) m_{NLSP} should satisfies

$$\frac{m_{\mathrm{NLSP}} - m_{\tilde{\chi}_1^0}}{m_{\tilde{\chi}_1^0}} \lesssim 20\%.$$

[Profumo, Yaguna, arXiv:hep-ph/0407036]

In this work, we study 3 coannihilation scenarios with a light stop.

1. $\tilde{t}_1$-$\tilde{\chi}_1^0$ coannihilation: $m_{\tilde{\chi}_1^0} \sim m_{\tilde{t}_1}$
2. $\tilde{\chi}_1^\pm$-$\tilde{\chi}_1^0$ coannihilation: $m_{\tilde{\chi}_1^0} \sim m_{\tilde{\chi}_1^\pm} < m_{\tilde{t}_1}$
3. $\tilde{\tau}_1$-$\tilde{\chi}_1^0$ coannihilation: $m_{\tilde{\chi}_1^0} \sim m_{\tilde{\tau}_1} < m_{\tilde{t}_1}$

Hard process

⇑

MadGraph5

⇕

MLM matching

⇕

Parton shower

⇑

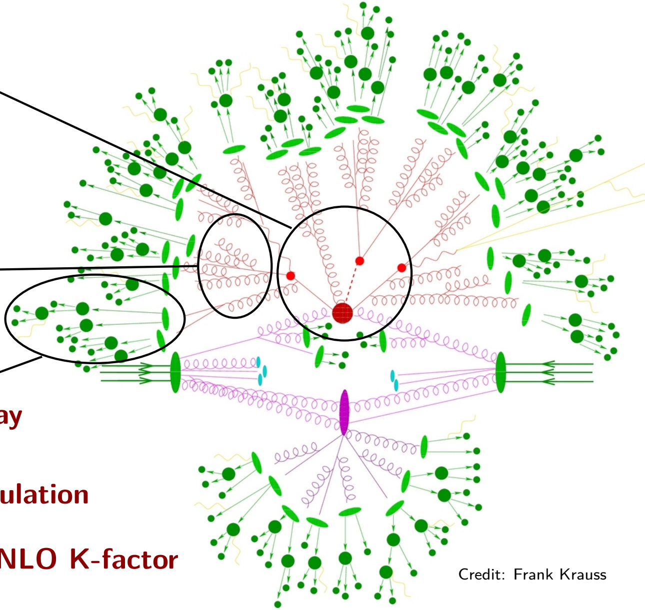
Pythia 6.4

⇓

Hadronization & decay

PGS4 ⇒ **Detector simulation**

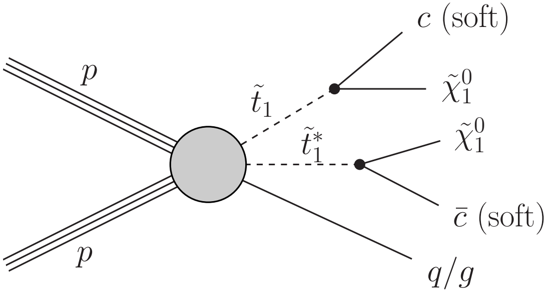
Prospino2, MCFM ⇒ **NLO K-factor**



Credit: Frank Krauss

Scenario 1: $\tilde{t}_1$-$\tilde{\chi}_1^0$ coannihilation

The lighter stop $\tilde{t}_1$ is the NLSP: $m_{\tilde{\chi}_1^0} \sim m_{\tilde{t}_1}$
$\tilde{t}_1$ decay channels: $\tilde{t}_1 \to t\tilde{\chi}_1^0,\ bW\tilde{\chi}_1^0,\ c\tilde{\chi}_1^0,\ ff'b\tilde{\chi}_1^0$
For $m_{\tilde{\chi}_1^0} + m_c < m_{\tilde{t}_1} < m_{\tilde{\chi}_1^0} + m_b + m_W$, assume $\tilde{t}_1 \to c\tilde{\chi}_1^0$ (100%).



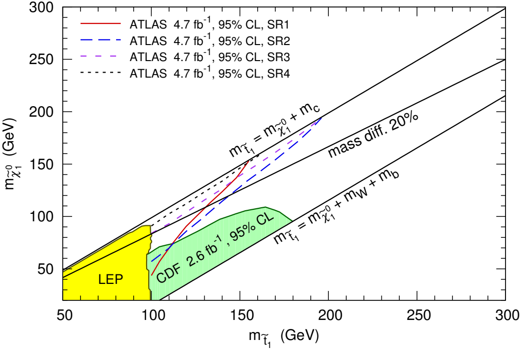
LHC searching channel: monojet + $\not{E}_T$
SM backgrounds: $Z(\to \nu\bar{\nu})$ + jets, $W(\to \ell\nu)$ + jets, ...

$\tilde{t}_1$-$\tilde{\chi}_1^0$ coannihilation: $\tilde{t}_1 \to c\,\tilde{\chi}_1^0$

Analysis instance:
(ATLAS Signal Region 2)
Lepton veto
$\not\!\!E_{\mathrm{T}} > 220\,\mathrm{GeV}$
Jet 1: $p_{\mathrm{T}} > 220\,\mathrm{GeV}$, $|\eta| < 2$
Jet 3: $p_{\mathrm{T}} < 30\,\mathrm{GeV}$
$\Delta\phi(j_2, \not\!\!E_{\mathrm{T}}) > 0.5$

$\Downarrow$

SM bkg: 8800 ± 400
Observed: 8631
$\sigma_{\mathrm{vis}}^{\mathrm{BSM}} < 170\,\mathrm{fb}$ (95% CL)



ATLAS 7 TeV, $4.7\,\mathrm{fb}^{-1}$, monojet + $\not\!\!E_{\mathrm{T}}$
[arXiv:1210.4491]

($\sigma_{\mathrm{vis}} \equiv \sigma \cdot A \cdot \epsilon =$ production cross section $\times$ acceptance $\times$ efficiency)

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

LHC 8 TeV, 20 fb^{-1}

Kinematic cuts:

Lepton veto

$\not{E}_T > 300\,\mathrm{GeV}$

Jet 1: $p_T > 150\,\mathrm{GeV}$, $|\eta| < 2.4$

Jet 3: $p_T < 50\,\mathrm{GeV}$

$\Delta\phi(j_1, j_2) < 2.5$

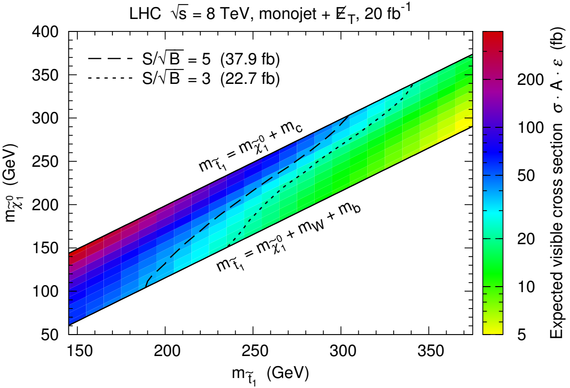
$\Downarrow$

SM bkg: 22944

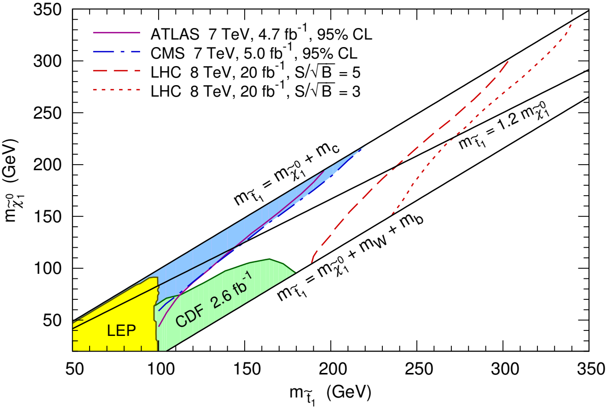
(13939 $Z(\to \nu\bar{\nu})$ + jets, 9005 $W(\to \ell\nu)$ + jets)

$\Downarrow$

$\sigma_{\mathrm{vis}}^{\mathrm{BSM}} < 22.7\,\mathrm{fb}$ for $S/\sqrt{B} < 3$, $\sigma_{\mathrm{vis}}^{\mathrm{BSM}} < 37.9\,\mathrm{fb}$ for $S/\sqrt{B} < 5$



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



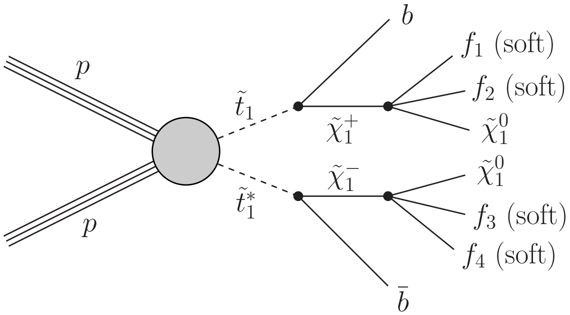
For "coannihilation region" $(m_{\tilde{t}_1} < 1.2 m_{\tilde{\chi}_1^0})$,

$$7\,\text{TeV},\ \sim 5\,\text{fb}^{-1} \quad \to \quad m_{\tilde{t}_1} \gtrsim 150 - 220\ \text{GeV}\ (95\%\ \text{CL})$$

$$8\,\text{TeV},\ 20\,\text{fb}^{-1} \quad \to \quad m_{\tilde{t}_1} \gtrsim 270 - 340\ \text{GeV}\ (S/\sqrt{B} < 3)$$

Scenario 2: $\tilde{\chi}_1^\pm$-$\tilde{\chi}_1^0$ coannihilation

The lighter chargino $\tilde{\chi}_1^\pm$ is the NLSP: $m_{\tilde{\chi}_1^0} \sim m_{\tilde{\chi}_1^\pm} < m_{\tilde{t}_1}$
Fixing $(m_{\tilde{\chi}_1^\pm} - m_{\tilde{\chi}_1^0})/m_{\tilde{\chi}_1^0} = 10\%$, for $m_b + m_{\tilde{\chi}_1^\pm} < m_{\tilde{t}_1} < m_{\tilde{\chi}_1^0} + m_t$,
assume $\tilde{t}_1 \to b\tilde{\chi}_1^\pm$ (100%) and $\tilde{\chi}_1^\pm \to f f' \tilde{\chi}_1^0$ (100%).



LHC searching channel: 1-2 b-jets + $\not{E}_T$
SM backgrounds: top pair, Z/W + heavy flavors, single top, ...

$\tilde{\chi}_1^\pm$-$\tilde{\chi}_1^0$ coannihilation: $\tilde{t}_1 \to b\tilde{\chi}_1^+$, $\tilde{\chi}_1^+ \to f f' \tilde{\chi}_1^0$

Analysis instance:

(ATLAS Signal Region 2)

Lepton veto

$\not{E}_T > 200\,\text{GeV}$

$n_{\text{b-jet}} = 2$ ($p_T > 60\,\text{GeV}$)

Jet 3: $p_T < 50\,\text{GeV}$

$\not{E}_T / m_{\text{eff}} > 0.25$

$m_{CT} > 100\,\text{GeV}$

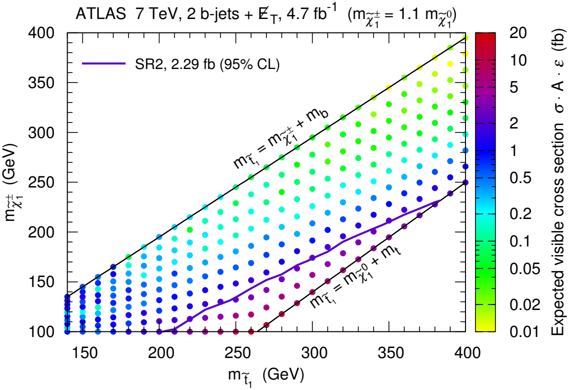
$\Delta\phi(j_{1,2}, \not{E}_T) > 0.4$

$\Downarrow$

SM bkg: 27 ± 7

Observed: 20

$\sigma_{\text{vis}}^{\text{BSM}} < 2.29\,\text{fb}$ (95% CL)



ATLAS 7 TeV, $4.7\,\text{fb}^{-1}$, 2b-jets + $\not{E}_T$

[ATLAS-CONF-2012-106]

(The contransverse mass m_{CT} defined as $m_{CT}^2 = (E_T^{j_1} + E_T^{j_2})^2 - (\mathbf{p}_T^{j_1} - \mathbf{p}_T^{j_2})^2$)

$\tilde{\chi}_1^\pm$-$\tilde{\chi}_1^0$ coannihilation: $\tilde{t}_1 \to b\tilde{\chi}_1^+$, $\tilde{\chi}_1^+ \to f f' \tilde{\chi}_1^0$

Analysis instance:

(CMS Signal Region 1BL)

Lepton veto

$\not{E}_T > 250\,\text{GeV}$

$H_T > 400\,\text{GeV}$

$n_{\text{jet}} \geq 3$ $(p_T > 50\,\text{GeV})$

$n_{\text{b-jet}} \geq 1$ $(p_T > 30\,\text{GeV})$

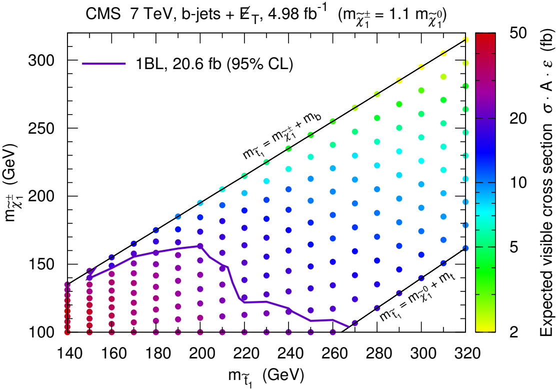
$\Delta\hat{\phi}_{\min} > 4.0$

$\Downarrow$

SM bkg: $477 \pm 26 \pm 38$

Observed: 478

$\sigma_{\text{vis}}^{\text{BSM}} < 20.6\,\text{fb}$ (95% CL)



CMS $7\,\text{TeV}$, $4.98\,\text{fb}^{-1}$, b-jets + $\not{E}_T$

[arXiv:1208.4859]

$\tilde{\chi}_1^\pm$-$\tilde{\chi}_1^0$ coannihilation: $\tilde{t}_1 \to b\tilde{\chi}_1^+$, $\tilde{\chi}_1^+ \to f f' \tilde{\chi}_1^0$

LHC 8 TeV, 20 fb^{-1}

Kinematic cuts:

Lepton veto

$\not{E}_T > 200\,\text{GeV}$

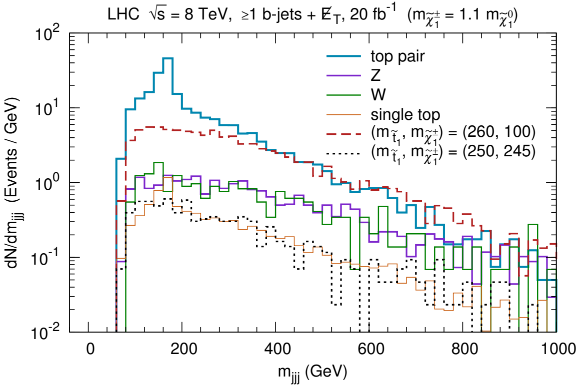
$H_T > 300\,\text{GeV}$

$n_{\text{jet}} \geq 3\ (p_T > 60\,\text{GeV})$

$n_{\text{b-jet}} \geq 1\ (p_T > 30\,\text{GeV})$

$\Delta\phi(j_{1,2,3}, \not{E}_T) > 0.4$

$m_{jjj} \notin (130, 200)$ GeV

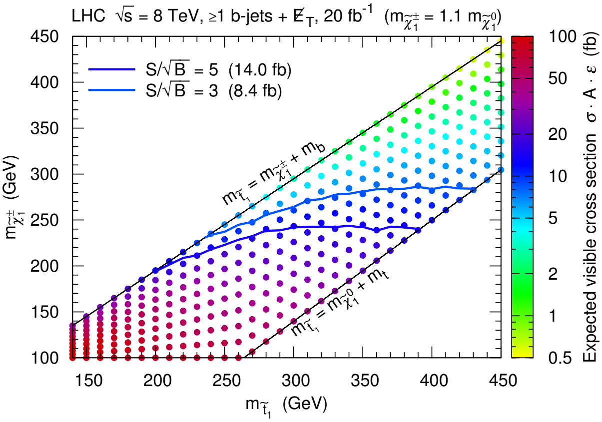


(Pick up a pair of jets with $m_{jj} > 60$ GeV and smallest ΔR, and m_{jjj} is the invariant mass of this pair of jets and a third jet which is closest to them.)

$m_{jjj} \notin (130, 200)$ GeV rejects 47% (31%) of top pair (single top) events, while only rejects 20% of stop events for $(m_{\tilde{t}_1}, m_{\tilde{\chi}_1^\pm}) = (260, 100)$ GeV.

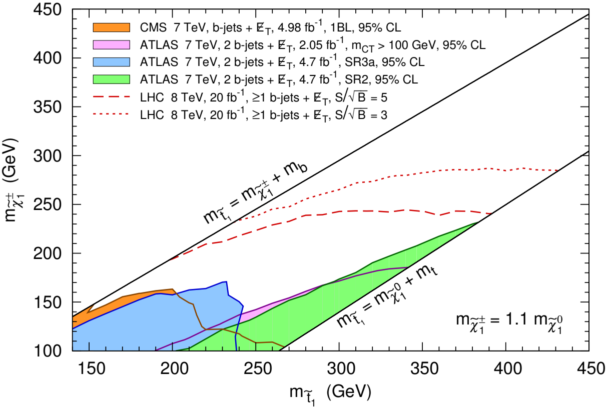
$\tilde{\chi}_1^\pm$-$\tilde{\chi}_1^0$ coannihilation: $\tilde{t}_1 \to b\tilde{\chi}_1^+$, $\tilde{\chi}_1^+ \to f f' \tilde{\chi}_1^0$

SM bkg: 3132
(2269 top pair
390 Z + heavy flavor
353 W + heavy flavor
120 single top)



$$\sigma_{\rm vis}^{\rm BSM} < 8.4\,\text{fb for } S/\sqrt{B} < 3, \quad \sigma_{\rm vis}^{\rm BSM} < 14.0\,\text{fb for } S/\sqrt{B} < 5$$

$\tilde{\chi}_1^\pm$-$\tilde{\chi}_1^0$ coannihilation: $\tilde{t}_1 \to b\tilde{\chi}_1^+$, $\tilde{\chi}_1^+ \to f f' \tilde{\chi}_1^0$

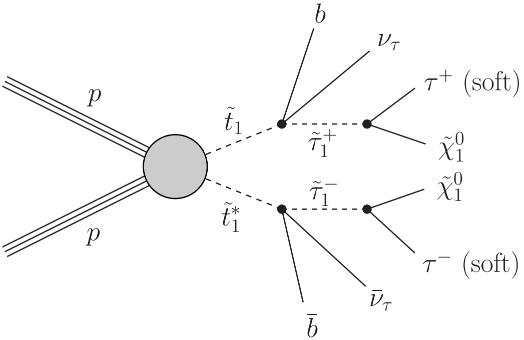


$7\,\text{TeV},\ \sim 5\,\text{fb}^{-1}$ $\rightarrow$ exclusion up to $m_{\tilde{t}_1} \simeq 380$ GeV (95% CL)

$8\,\text{TeV},\ 20\,\text{fb}^{-1}$ $\rightarrow$ exclusion up to $m_{\tilde{t}_1} \simeq 430$ GeV ($S/\sqrt{B} > 3$)

Scenario 3: $\tilde{\tau}_1$-$\tilde{\chi}_1^0$ coannihilation

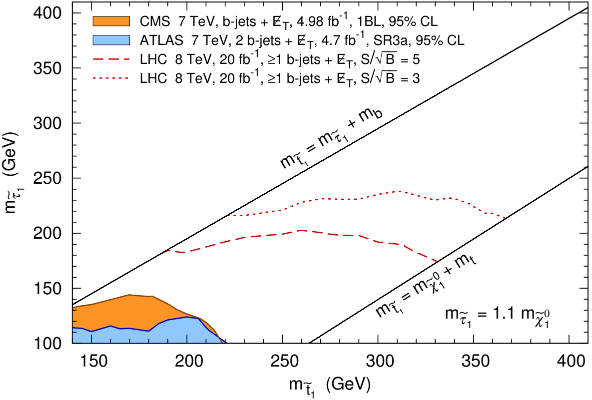
The lighter stau $\tilde{\tau}_1^\pm$ is the NLSP: $m_{\tilde{\chi}_1^0} \sim m_{\tilde{\tau}_1} < m_{\tilde{t}_1}$
Fixing $(m_{\tilde{\tau}_1} - m_{\tilde{\chi}_1^0})/m_{\tilde{\chi}_1^0} = 10\%$, for $m_b + m_{\tilde{\tau}_1} < m_{\tilde{t}_1} < m_{\tilde{\chi}_1^0} + m_t$,
assume $\tilde{t}_1 \to b\tilde{\tau}_1^+ \nu_\tau$ (100%) and $\tilde{\tau}_1^\pm \to \tau^\pm \tilde{\chi}_1^0$ (100%).



LHC searching channel: 1-2 b-jets + $\not{E}_T$

$\tilde{\tau}_1$-$\tilde{\chi}_1^0$ coannihilation: $\tilde{t}_1 \to b\tilde{\tau}_1^+\nu_\tau$, $\tilde{\tau}_1^+ \to \tau^+\tilde{\chi}_1^0$

The neutrinos $\nu_\tau(\bar{\nu}_\tau)$ take away some energy so that b-jets become soft.



$7\,\text{TeV},\ \sim 5\,\text{fb}^{-1} \quad \to \quad$ exclusion up to $m_{\tilde{t}_1} \simeq 220$ GeV (95% CL)

$8\,\text{TeV},\ 20\,\text{fb}^{-1} \quad \to \quad$ exclusion up to $m_{\tilde{t}_1} \simeq 370$ GeV ($S/\sqrt{B} > 3$)

Conclusions and discussions

1. We focus on the possible connections between light stops and dark matter in the context of supersymmetry.
2. The three coannihilation scenarios considered here are very general DM coannihilation scenarios in many SUSY models. It is important to study their impacts on the light stop searches at the LHC.
3. In these three coannihilation scenarios, the constraints on stop given by current LHC data are **not so strong**.
   $\tilde{t}_1/\tilde{\chi}_1^{\pm}/\tilde{\tau}_1$-$\tilde{\chi}_1^0$ coanni. scenario: up to $m_{\tilde{t}_1} \sim 220/380/220\,\mathrm{GeV}$
4. For the dataset of 20 fb^{-1} at 8 TeV, the LHC can be expected to explore larger regions in parameter spaces.
   $\tilde{t}_1/\tilde{\chi}_1^{\pm}/\tilde{\tau}_1$-$\tilde{\chi}_1^0$ coanni. scenario: up to $m_{\tilde{t}_1} \sim 340/430/370\,\mathrm{GeV}$

Thanks for your attention!