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# Light Stop Decays and Implications for LHC Searches

arXiv:1408.4662, 1502.05935

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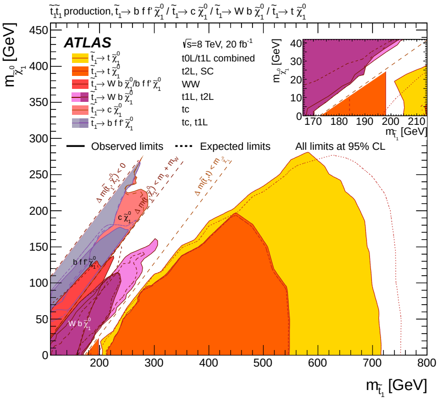
Eva Popenda | 2.9.2014

# Introduction

- SUSY searches at the LHC: Squarks of 1st & 2nd generation $> 1.5$ TeV
  Squarks of 3rd generation can still be light
- Light stop $\tilde{t}_1$ arises naturally: Large mixing between $\tilde{t}_L$ and $\tilde{t}_R$
- Light stops favoured by: Higgs data, reduced fine tuning, relic density




[arXiv:1506.0861]

- Lightest SUSY Particle: $\tilde{\chi}_1^0$
  Next-to-LSP: $\tilde{t}_1$
- Possible decay/search channels:

  If $m_{\tilde{t}_1} - m_{\tilde{\chi}_1^0} > m_W + m_b$:

  $\tilde{t}_1 \rightarrow b\,\tilde{\chi}_1^0 W$

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

  If $m_{\tilde{t}_1} - m_{\tilde{\chi}_1^0} < m_W + m_b$:

  $\tilde{t}_1 \rightarrow b\,\tilde{\chi}_1^0 f\,\bar{f}'$

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

# Theoretical Status: $\tilde{u}_1 \to c\,\tilde{\chi}_1^0$

- FCNC transition: Forbidden at tree level in SM
- Precision flavour measurements in agreement with CKM picture of SM
- MSSM: In general many new flavour-violating sources

$$\begin{pmatrix} \tilde{u}_1 \\ \vdots \\ \vdots \\ \tilde{u}_6 \end{pmatrix} = \begin{pmatrix} W_{11} & \dots & \dots & W_{16} \\ \vdots & \ddots & & \vdots \\ \vdots & & \ddots & \vdots \\ W_{61} & \dots & \dots & W_{66} \end{pmatrix} \begin{pmatrix} \tilde{u}_L \\ \tilde{c}_L \\ \tilde{t}_L \\ \tilde{u}_R \\ \tilde{c}_R \\ \tilde{t}_R \end{pmatrix}$$

- Solution to New Physics Flavour Puzzle:
  Minimal Flavour Violation: Based on flavour symmetry in quark sector of SM

$$U(3)_{\tilde{Q}_L} \times U(3)_{\tilde{u}_R} \times U(3)_{\tilde{d}_R}$$

  Smaller flavour symmetries: CKM-like pattern, fulfill constraints

$$U(2)_{\tilde{Q}_L} \times U(2)_{\tilde{u}_R} \times U(2)_{\tilde{d}_R}$$

*[Barbieri, Buttazzo, Sala & Straub, '14]*

➡ Lightest up-type squark $\tilde{u}_1$ mostly stop-like

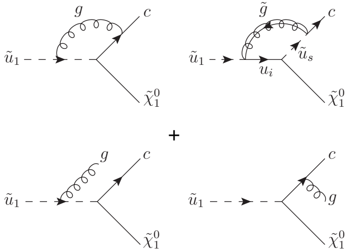
# Theoretical status: $\tilde{u}_1 \to c\,\tilde{\chi}_1^0$

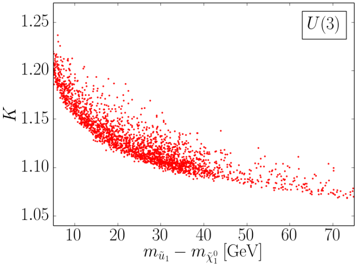
- Coupling $\tilde{t}_1 - c - \tilde{\chi}_1^0$ assumed to vanish at tree level *[Hikasa & Kobayashi, '87]*
  - ➡ Process realized at 1-loop with charged particles in loops
  - ➡ Calculation of 1-loop process in approximation
- Exact 1-loop calculation of charged loops *[Mühlleitner & Popenda, '11]*
  - ➡ Comparison to RGE-invariant MFV approach with tree level coupling

Here: SUSY-QCD corrections to $\tilde{u}_1 \to c\tilde{\chi}_1^0$ *[Gröber, Mühlleitner, Popenda & Wlotzka, '14]*

$$\Gamma^{\text{NLO}} = \Gamma^{\text{LO}} + \Gamma^{\text{virt}} + \Gamma^{\text{real}}$$

$$K = \Gamma^{\text{NLO}}/\Gamma^{\text{LO}}$$



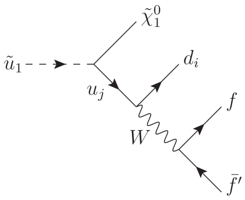



# Theoretical status: $\tilde{u}_1 \to q\, \tilde{\chi}^0_1\, f\, \bar{f}'$

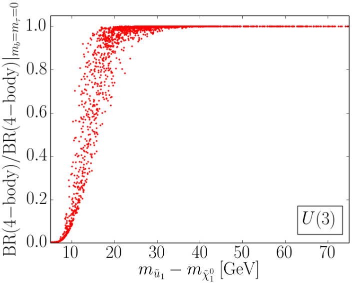
- Four-body decays $\tilde{t}_1 \to b\, \tilde{\chi}^0_1\, f\, \bar{f}'$ [Böhm, Djouadi & Mambrini, '99]

Here:

- Allow for FCNC couplings at tree level: $\tilde{u}_1 \to q\tilde{\chi}^0_1 f\bar{f}'$
  with $q = d, s, b$ and $f, f' = d, s, b, u, c, e, \mu, \tau, \nu_e, \nu_\mu, \nu_\tau$
- Take into account mass dependence of 3rd generation fermions




- Dominating Feynman diagram
- FV effects negligible



# Theoretical status: $\tilde{u}_1 \to q\,\tilde{\chi}_1^0\,W$

- Three-body decays $\tilde{t}_1 \to b\,\tilde{\chi}_1^0\,W$

*[Porod & Wohrmann '96, Porod '98]*
*[Djouadi & Mambrini '00]*

Here:

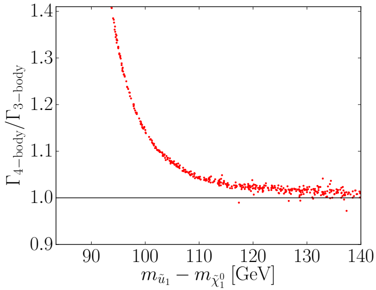
- Allow for FCNC couplings at tree level: $\tilde{u}_1 \to q\,\tilde{\chi}_1^0\,W$ with $q = d, s, b$
- Take into account mass dependence of b quark

- Off-shell effects in threshold region: Include W boson width in 4-body decay in gauge independent way

  Overall factor scheme:
  Multiply whole tree level amplitude by

$$\prod_{W\text{propagators}} \frac{p_W^2 - m_W^2}{p_W^2 - m_W^2 + i m_W \Gamma_W}$$

*[Baur, Vermaseren & Zeppenfeld '92, Baur & Zeppenfeld '95]*
*[Denner, Dittmaier, Roth & Wackeroth '99]*



# Implementation and Constraints

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- Light stop decays implemented in `SUSY-HIT` [http://www.itp.kit.edu/∼maggie/SUSY-HIT]
- Spectrum from `SPheno` [Porod '03, Porod & Straub '12]
- No strict MFV but

$$300 \text{ GeV} < M_{\tilde{t}_R} < 600 \text{ GeV} \qquad 1 \text{ TeV} < A_t < 2 \text{ TeV}$$

Constraints on points of random scan:

- Higgs data: [Bechtle, Brein, Heinemeyer, Stal, Stefaniak, Weiglein, Williams, '08-'13]
  `HiggsBounds`: Compatibility with non-observation of SUSY Higgs bosons
  `HiggsSignals`: Compatibility of SM-like Higgs Boson with data
  `HDECAY`: Effective couplings & decay widths [Djouadi, Kalinoswki, Spira & Zerwas, '91-'98]
- Relic density: $\Omega_c h^2(\tilde{\chi}_1^0) < 0.12$ [Planck collaboration, '13]
  Calculated with `SuperIsoRelic` [Arbey & Mahmoudi, '09,'11]
- B meson branching ratios
  Calculated with `SuperIso` [Mahmoudi, '07,'08]
- SUSY searches

$$m_{\tilde{g}} = 1450 \text{ GeV} \qquad m_{\tilde{q}_{1,2}} > 900 \text{ GeV}$$

[ATLAS, 1405.7875; CMS-PAS-SUS-13-019]

# Constraints from direct searches

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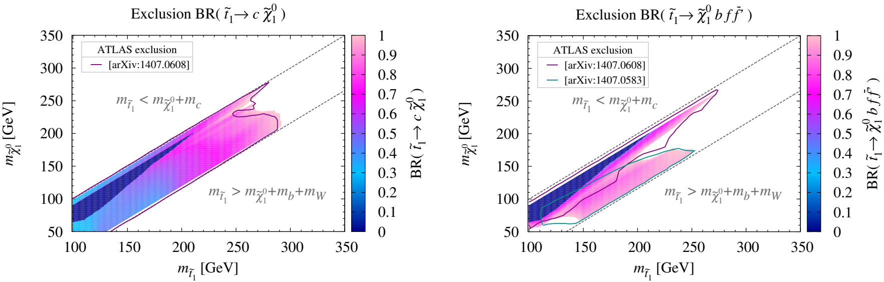
$\tilde{t}_1 \to c\,\tilde{\chi}_1^0$ and $\tilde{t}_1 \to b\tilde{\chi}_1^0 f\bar{f}'$ [ATLAS-CONF-2013-068, ATLAS 1407.0608, CMS-PAS-SUS-13-009; ATLAS 1407.0583]

- Exclusion limits from ATLAS and CMS assumed BRs of 100% for either decay
- Just recently exclusions for certain, reduced BRs [ATLAS 1506.0861]
- Re-interpretation of exclusion bounds:




➡ Stop masses with a BR above the one associated with colour code are excluded

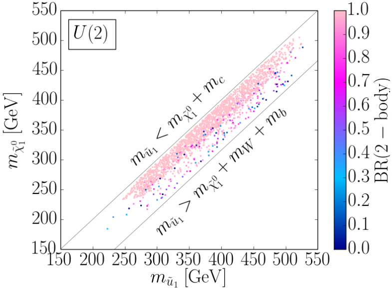
$\tilde{t}_1 \to b\tilde{\chi}_1^0 W$ [ATLAS 1407.0583, 1403.4853, CMS 1308.1586]

- Compatibility of parameter points above threshold with searches by using SModelS [Kraml, Kulkarni, Laa, Lessa, Magerl, Proschofsky, Waltenberger 13]

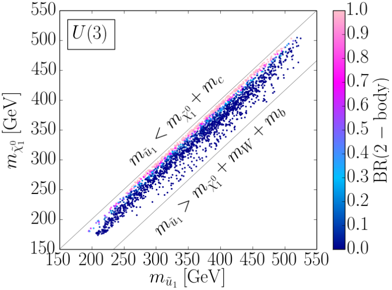
# Results: Below $b + \tilde{\chi}_1^0 + W$ threshold

2 different symmetries in squark sector

$U(2)_{\tilde{Q}_L} \times U(3)_{\tilde{u}_R} \times U(3)_{\tilde{d}_R}$




$U(3)_{\tilde{Q}_L} \times U(3)_{\tilde{u}_R} \times U(3)_{\tilde{d}_R}$




$$M_{\tilde{Q}_{L,11}} = M_{\tilde{Q}_{L,22}} = 1.5 \text{ TeV}$$
$$M_{\tilde{Q}_{L,33}} \in [1, 1.5] \text{ TeV}$$

$$M_{\tilde{Q}_{L,11}} = M_{\tilde{Q}_{L,22}} = M_{\tilde{Q}_{L,33}} \in [1, 1.5] \text{ TeV}$$

➡ Assumption of $BR = 1$ is wrong for both decays over large parts of parameter space

# Results: Above $b + \tilde{\chi}_1^0 + W$ threshold

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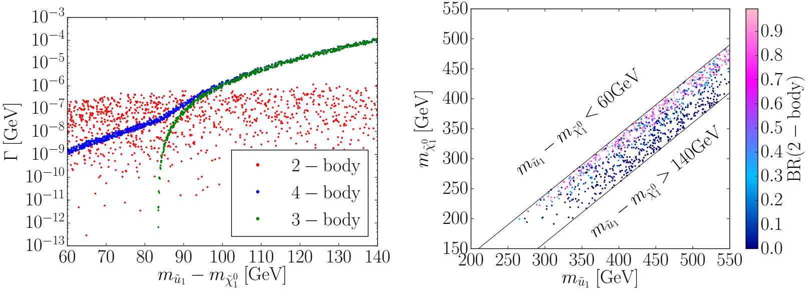
For $U(2)$-inspired flavour symmetry:




- Close to threshold 2-body decay, $\tilde{t}_1 \to c\, \tilde{\chi}_1^0$, of similar size as other decays: BRs of 40 % possible at 20 GeV above threshold
- Offers new discovery perspective for light stops, as charm tagging could be used efficiently [ATLAS 1501.01325]

# Summary

- Light stop decays with FV couplings implemented in `SUSY-HIT`

  $\tilde{u}_1 \to c\, \tilde{\chi}_1^0$: SUSY-QCD corrections
  $\tilde{u}_1 \to q\, \tilde{\chi}_1^0\, f\, \bar{f}'$: 3rd generation masses
  $\tilde{u}_1 \to q\, \tilde{\chi}_1^0\, W$: off-shell effects, b quark mass

- BRs are likely to deviate from 1:
  Exclusion bounds derived for assumption of BR=100% are weakened
  ➡ Recently taken into account in experimental analyses

- FV 2-body decay, $\tilde{u}_1 \to c\, \tilde{\chi}_1^0$, can be competitive with other decay modes above the W threshold
  ➡ Should be taken into account in experimental analyses

# On-shell Renormalization

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- Quark mass counterterm:

$$m^0_{u_i} = m_{u_i} + \delta m_{u_i}$$

- Quark and squark field counterterms:

$$q^{L/R}_{(0)i} = (\delta_{ij} + \delta Z^{L/R}_{ij})\, q^{L/R}_j \qquad \tilde{q}^{(0)}_i = (\delta_{ij} + \delta Z^{\tilde{q}}_{ij})\, \tilde{q}_j$$

- Quark and squark mixing matrices counterterms:

$$U^{L/R}_{(0)ij} = (\delta_{in} + \delta u^{L/R}_{in})\, U^{L/R}_{nj} \qquad \tilde{W}^{(0)}_{ij} = (\delta_{in} + \delta \tilde{w}_{in})\, \tilde{W}_{nj}$$

Bare and renormalized matrices unitary ➡ Counterterms anti-hermitian

$$\delta u^{L/R} = \frac{1}{4}(\delta Z^{L/R} - \delta Z^{L/R\dagger}) \qquad \delta \tilde{w} = \frac{1}{4}(\delta Z^{\tilde{q}} - \delta Z^{\tilde{q}\dagger})$$

[Denner & Sack, '90]
[Degrassi, Gambino & Slavich, '06]

Feynman-'t Hooft gauge: Coincides with gauge independent result

[Yamada, '01]

# Parameter choice and Random scan

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$$1 \leq \tan\beta \leq 15 \qquad 150\text{ GeV} \leq M_A \leq 1\text{ TeV}$$

$$75\text{ GeV} \leq M_1 \leq 500\text{ GeV} \qquad M_2 = 650\text{ GeV} \qquad M_3 = 1530\text{ GeV}$$

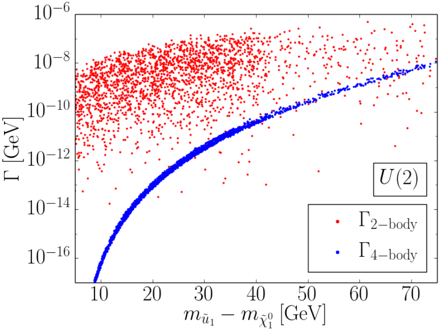
$$\mu = 900\text{ GeV}$$

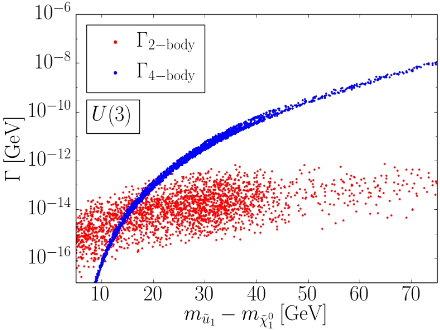
$$\begin{aligned} M_{\tilde{E}_R} &= M_{\tilde{L}_{1,2,3}} = 1\text{ TeV} \qquad A_E = 0\text{ TeV} \\ M_{\tilde{U}_R} &= M_{\tilde{D}_R} = 1.5\text{ TeV} \qquad A_U = A_D = 0\text{ TeV} \end{aligned}$$

$$300\text{ GeV} \leq M_{\tilde{t}_R} \leq 600\text{ GeV} \qquad 1\text{ TeV} \leq A_t \leq 2\text{ TeV}$$

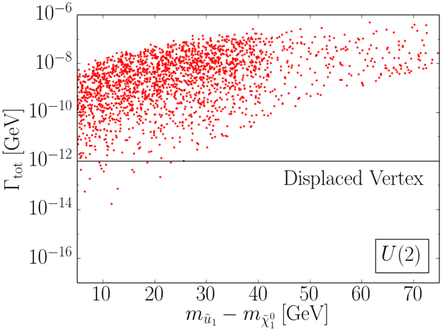
$$\begin{aligned} \mathcal{B}(B_s^0 \to \mu^+\mu^-) &= (2.9 \pm 0.7) \times 10^{-9} \\ \mathcal{B}(B^0 \to \mu^+\mu^-) &< 8.1 \times 10^{-10} \text{ at } 95\% \text{ CL} \\ \mathcal{B}(B^+ \to \tau^+\nu_\tau) &= (1.05 \pm 0.25) \times 10^{-4} \\ \mathcal{B}(B \to X_s\gamma) &= (355 \pm 24 \pm 9) \times 10^{-6} \end{aligned}$$

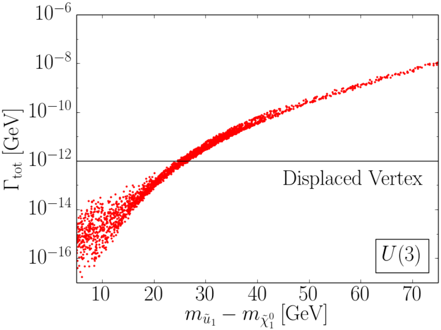
# Partial decay widths



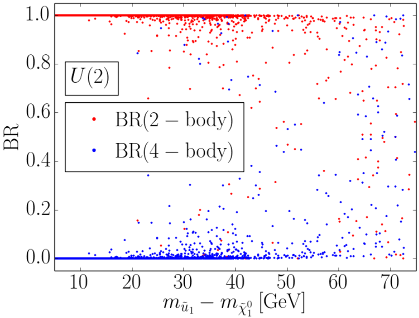
# Total decay widths

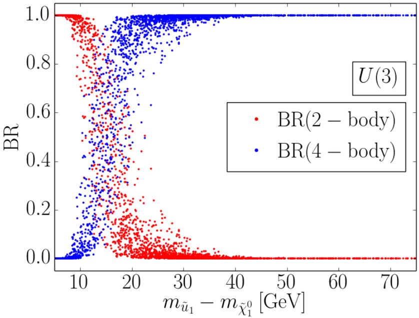


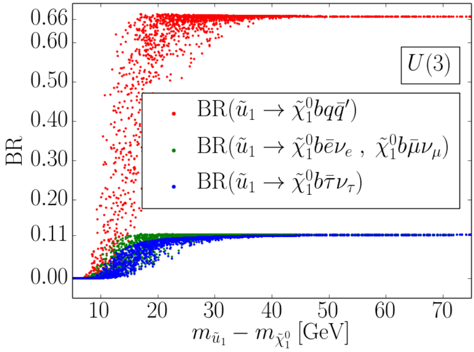

- Observation of displaced vertices allows for conclusions on the flavour symmetry of the model
- Below $10^{-12}$ GeV: two displaced vertices could be possible, one from the $\tilde{u}_1$ decay and the second from the b-quark final state (see BRs on next slide)

# Branching ratios



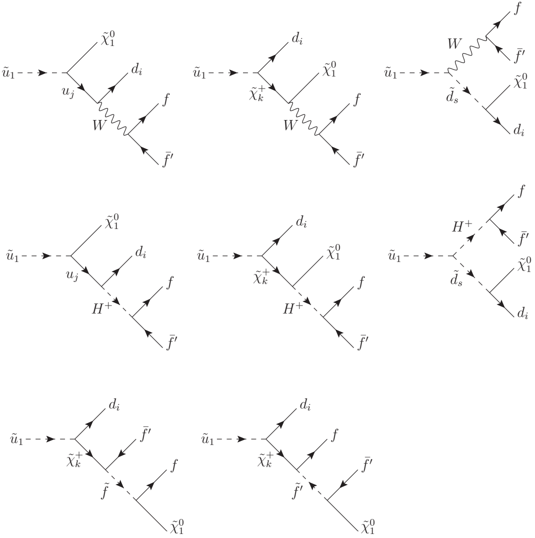



# Final states in 4-body decay



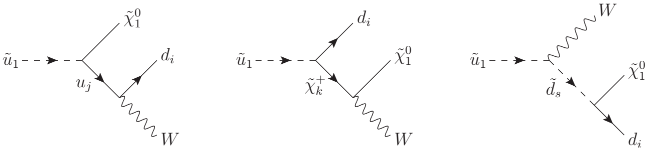

- BRs in the different 4-body decay final states correspond to the W decay (66 % quark, 11% each lepton)

# Feynman diagrams of 4-body decay



# Feynman diagrams of 3-body decay





# ATLAS results for reduced BRs

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