# Light Stop Decays

[arXiv: 1408.4662, 1502.05935]

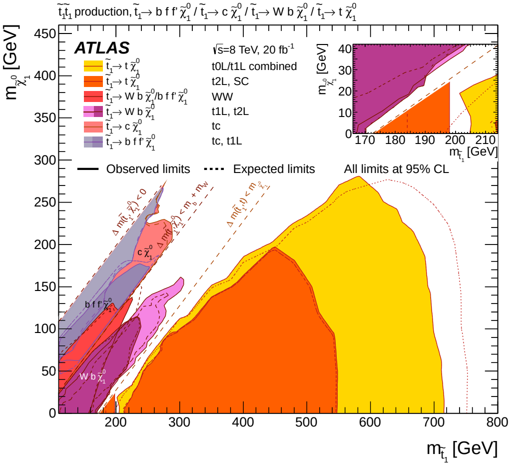
Ramona Gröber in coll. with Margarete Mühlleitner, Eva Popenda and Alexander Wlotzka | 01.07.2015

INFN Sezione di Roma Tre

# OUTLINE

1. Exclusion limits
2. Flavour-violating decays $\tilde{t}_1 \to c\tilde{\chi}_1^0/u\tilde{\chi}_1^0$
3. Four-body decay $\tilde{t}_1 \to b\tilde{\chi}_1^0 f\bar{f}'$
4. Three-body decay $\tilde{t}_1 \to bW\tilde{\chi}_1^0$
5. Results

# BOUNDS ON STOPS




In this talk:
Decays of light stops with
$m_{\tilde{t}_1} - m_{\tilde{\chi}_1^0} < m_t$
and
LSP: $\tilde{\chi}_1^0$ NLSP: $\tilde{t}_1$

Possible decays,
if $m_{\tilde{t}_1} < m_W + m_b + m_{\tilde{\chi}_1^0}$ :

- $\tilde{t}_1 \to (c/u)\tilde{\chi}_1^0$
- $\tilde{t}_1 \to b\tilde{\chi}_1^0 f\bar{f}'$

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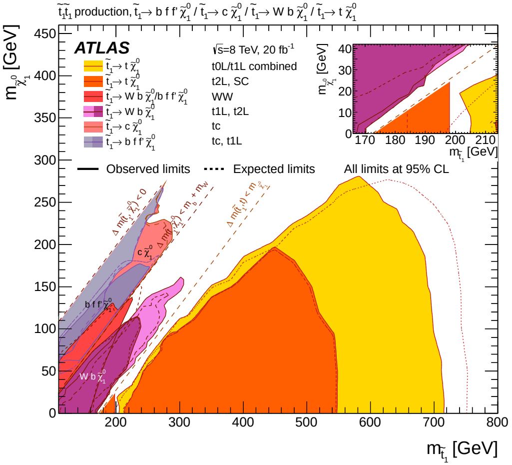


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## Earlier works:

[Hikasa, Kobayashi '87, Mühlleitner, Popenda '11]

- Computed one-loop process assuming a vanishing $(c/u) - \tilde{\chi}_1^0 - \tilde{t}_1$ coupling at tree-level
- But: Even if $(c/u) - \tilde{\chi}_1^0 - \tilde{t}_1$ coupling is zero at one scale, it is generated by RGE running of soft-SUSY breaking masses and couplings at any other scale.
- In [Hikasa, Kobayashi '87]: For $\Lambda_{Planck} = \Lambda_{noFV}$, the decay is dominated by $\log \Lambda_{Planck}/M_W$. Only these logarithmic terms were computed.
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## Here:

Computation of the decay widths $\tilde{t}_1 \to (c/u)\tilde{\chi}_1^0$ with one-loop sQCD corrections allowing for a flavour-violating $(c/u) - \tilde{\chi}_1^0 - \tilde{t}_1$ coupling at tree level.

# General flavour structure of the MSSM

In general: MSSM has many new sources of flavour violation
$\rightarrow$ all squark flavour eigenstates can mix

$$\begin{pmatrix} \tilde{u}_1 \\ \tilde{u}_2 \\ \tilde{u}_3 \\ \tilde{u}_4 \\ \tilde{u}_5 \\ \tilde{u}_6 \end{pmatrix} = \begin{pmatrix} W^{\tilde{u}}_{11} & \cdots & \cdots & W^{\tilde{u}}_{16} \\ \vdots & \ddots & & \vdots \\ \vdots & & \ddots & \vdots \\ W^{\tilde{u}}_{61} & \cdots & \cdots & W^{\tilde{u}}_{66} \end{pmatrix} \begin{pmatrix} \tilde{u}_L \\ \tilde{c}_L \\ \tilde{t}_L \\ \tilde{u}_R \\ \tilde{c}_R \\ \tilde{t}_R \end{pmatrix}$$

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mostly stop-like $\longrightarrow$

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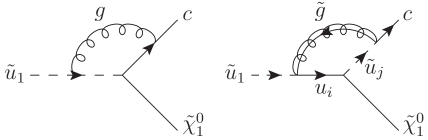
$\Longrightarrow$ But: Flavour observables tell us that these new sources must be strongly restricted

Ways out:

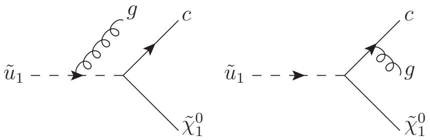
Minimal flavour violation [Chivukula, Georgi, Randall '87; Hall, Randall '90; D'Ambrosio, Giudice, Isidori, Strumia '02]
based on $SU(3)_{Q_L} \times SU(3)_{U_R} \times SU(3)_{D_R}$ flavour symmetry

smaller flavour symmetries, e.g. $SU(2)_{Q_L} \times SU(2)_{U_R} \times SU(2)_{D_R}$, can still be consistent with flavour observables [Barbieri, Buttazzo, Sala, Straub '14; ...]

Virtual corrections:




Real corrections:




Renormalization of mixing matrix and masses in on-shell scheme. (For $\overline{\mathrm{DR}}$ scheme see [Aebischer, Crivellin, Greub '14])

# RENORMALIZATION

Lagrangian:

$$\mathcal{L}^R_{f\tilde{f}\tilde{\chi}_0} = \bar{u}_i \left( \frac{2\sqrt{2}}{3} g_1 Z_{l1} \sum_{j=1}^{3} W^{\tilde{u}*}_{js} U^L_{ji} - \frac{\sqrt{2}}{v \sin\beta} m_{u_i} Z^*_{l4} \sum_{j=1}^{3} W^{\tilde{u}*}_{j+3s} U^L_{ji} \right) P_L \tilde{u}^\dagger_s \tilde{\chi}^0_l + h.c.$$

- Mass counterterm

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

- The bare fields can be expressed by

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

- Renormalization of mixing matrices

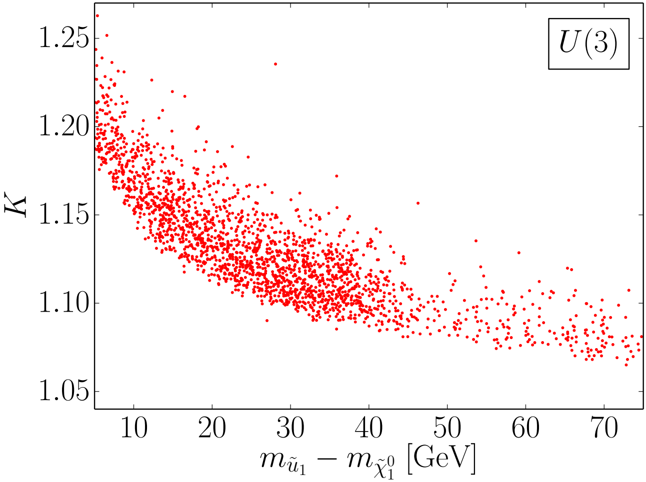
$$U^{L/R}_{ij} = (\delta_{in} + \delta u^{L/R}_{in}) U^{L/R}_{nj}\ , \qquad W^{(0)}_{ij} = (\delta_{in} + \delta w_{in}) W_{nj}$$

The counterterm can be expressed by [Denner, Sack; Yamada; Degrassi, Gambino, Slavich '06; ...]

$$\delta u^{L/R}_{ij} = \frac{1}{4}\left(\delta Z^{L/R}_{ij} - \delta Z^{L/R\dagger}_{ij}\right)\ , \qquad \delta w_{ij} = \frac{1}{4}\left(\delta Z^{\tilde{q}}_{ij} - \delta Z^{\tilde{q}\dagger}_{ij}\right)$$

$K = \frac{\Gamma_{NLO}}{\Gamma_{LO}}$

[RG, Mühlleitner, Popenda, Wlotzka '14]



# FOUR-BODY DECAYS $\tilde{u}_1 \to \tilde{\chi}_1^0 d_i f \bar{f}'$

Previous work:

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

available in SUSY-HIT [Djouadi, Mühlleitner, Spira '06]

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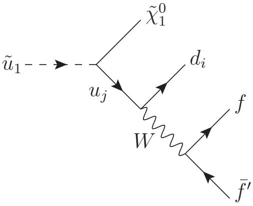
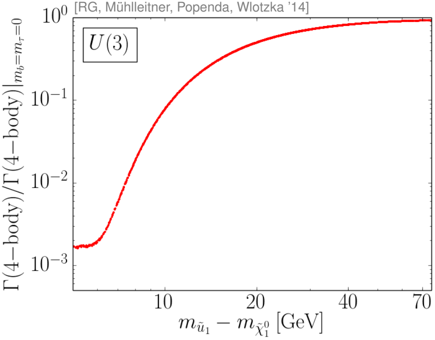
Here:

- Computation of $\tilde{u}_1 \to \tilde{\chi}_1^0 d_i f \bar{f}'$ with $d_i = b, s, d$ and $f, f' = b, s, d, c, u, \tau, \mu, e, \nu_\tau, \nu_\mu, \nu_e$ allowing for flavour violation
- Full dependence on masses of third generation fermions
- Implemented in SUSY-HIT



# Above $W$ boson threshold: $\tilde{u}_1 \to d_i W \tilde{\chi}_1^0$ decays

If $m_{\tilde{u}_1} - m_{\tilde{\chi}_1^0} > m_W$:

$W$ boson can be on-shell, three-body decay $\tilde{u}_1 \to d_i W \tilde{\chi}_1^0$

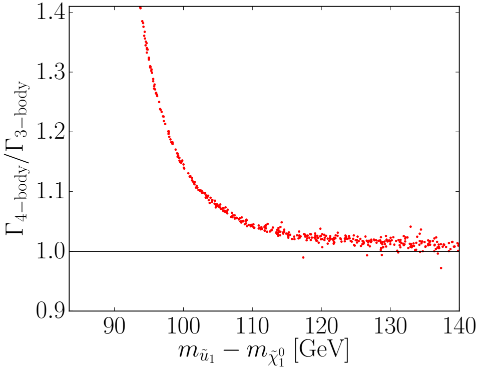
[Porod, Wohrmann '97, Porod '99, Djouadi, Mambrini '00]

- $W$ boson width in 4-body decay
  "Overall-factor scheme" for gauge independent result: multiply tree-level amplitude by

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

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

- In SUSY-HIT: $\tilde{u}_1 \to d_i W \tilde{\chi}_1^0$ decays extended to general flavour structure, for $m_{\tilde{u}_1} - m_{\tilde{\chi}_1^0} < m_W + 30$ GeV 4-body decays are computed



## Scan over parameter space

- Spectrum generated with SPHENO [Porod '03; Porod, Staub '11]
- Light stop decays implemented into SUSY-HIT [RG, Mühlleitner, Popenda, Wlotzka '14 & '15]

Compatibility checks:

- Higgs results: Checked with HiggsBounds and HiggsSignals [Bechtle, Brein, Heinemeyer, Stal, Stefaniak, Weiglein, Williams '08, '11, '13]

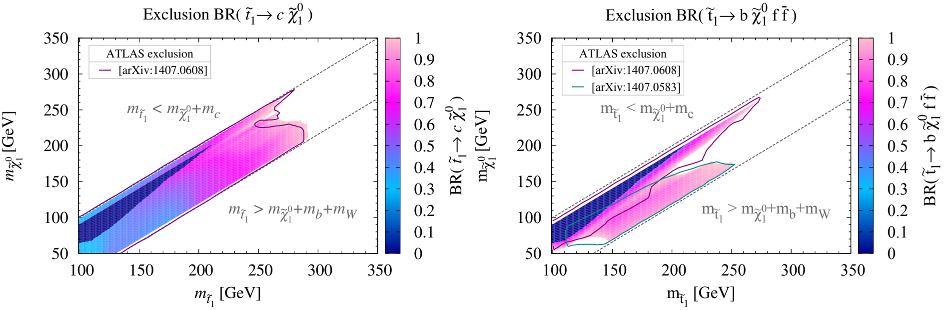
  For Higgs branching ratios: HDECAY [Djouadi, Kalinowski, Mühlleitner, Spira '97]
- Relic density $\Omega_c h^2 < 0.12$ [Planck Collaboration '13] with SuperIsoRelic [Arbey, Mahmoudi '09,'11]
- Some *B* flavour observables with SuperIsoRelic
- Masses of sparticles are chosen such that they evade direct searches by ATLAS and CMS

# Exclusions due to direct searches

ATLAS and CMS results: Exclusions assume BRs of 100% in either decay into $c\tilde{\chi}_1^0$ [ATLAS-CONF-2013-068, ATLAS 1407.0608, CMS-PAS-SUS-13-009] or 4-body decay [ATLAS 1407.0583]
Monday's exclusion paper of ATLAS [ATLAS 1506.08616] also for reduced BRs!

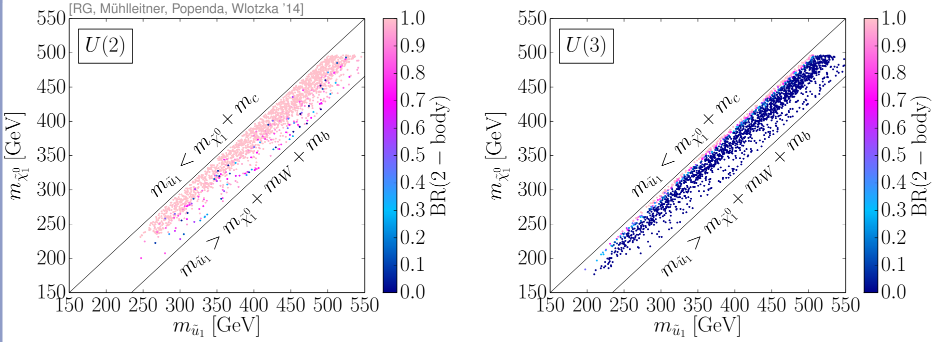
Here: reinterpretation necessary to give exclusions for different BRs.

[RG, Mühlleitner, Popenda, Wlotzka '14]




- BRs with values above the associated color are excluded
- For BRs smaller than 1 the exclusions can be weakened
- For compatiblity with the searches [ATLAS 1407.0583, 1403.4853, CMS 1308.1586 ] for $\tilde{t}_1 \to Wb\tilde{\chi}_1^0$ decays: `SModelS` [Kraml, Kulkarni, Laa, Lessa, Magerl, Proschofsky, Waltenberger '13]

# Results: Below $W$ boson threshold

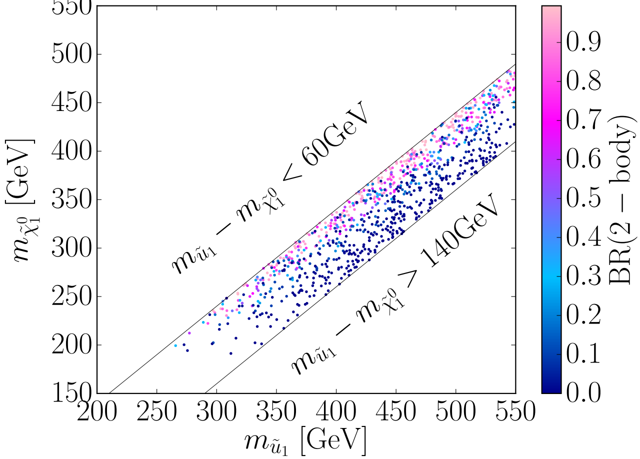



$\Longrightarrow$ Assumption of BRs of 100% wrong in large parts of the parameter space.

$\Longrightarrow$ Points with lower masses than the exclusion still viable, if they have reduced BRs.

$\Longrightarrow$ Decay channels depend on flavour model.

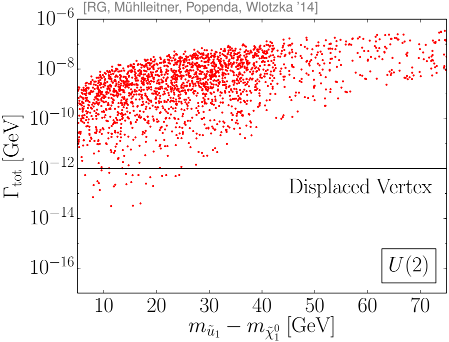
[RG, Mühlleitner, Popenda, Wlotzka '15]

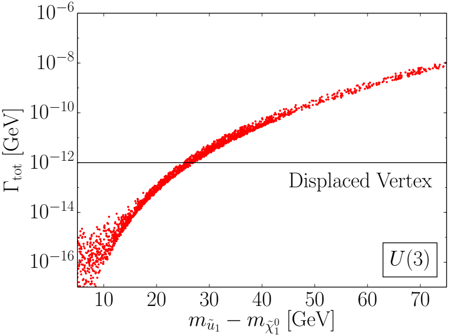


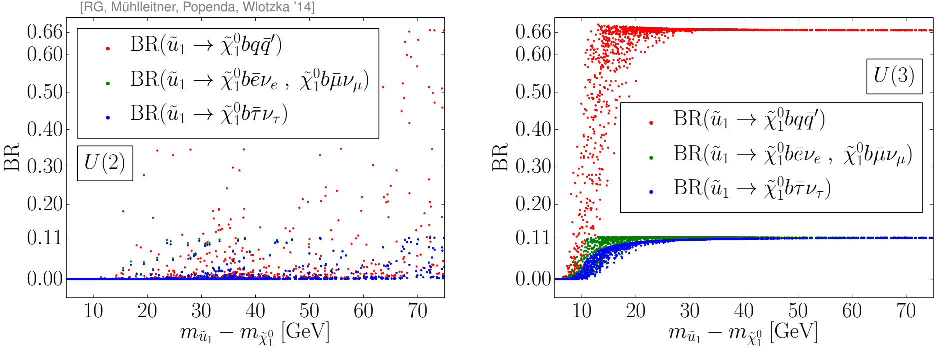

$\Longrightarrow$ For $U(2)$ flavour model: $\tilde{u}_1 \to c\tilde{\chi}_1^0$ can still be dominant decay channel above $W$ threshold

# TOTAL DECAY WIDTH

[RG, Mühlleitner, Popenda, Wlotzka '14]






- BRs in the different 4-body decay final states correspond to the *W* decay
- Slepton exchange diagrams negligibly small $\Longrightarrow$ $\tilde{\chi}_1^0 b\bar{\mu}\nu_\mu$ and $\tilde{\chi}_1^0 b\bar{e}\nu_e$ final states have the same BRs
- $\tilde{\chi}_1^0 b\bar{\tau}\nu_\tau$ nearly same BRs as $\tilde{\chi}_1^0 b(\bar{\mu}/\bar{e})(\nu_\mu/\nu_e)$ final states, differences only from inclusion of mass for $\tau$
- Final states in 4-body decay only possible due to FV give very small contribution

## Conclusions

- Stop decays into
  - $c\tilde{\chi}_1^0$, $u\tilde{\chi}_1^0$ (with SUSY-QCD corrections)
  - $\tilde{\chi}_1^0 d_i f\bar{f}'$ (with full dependence on masses of 3rd generation fermions)
  - $\tilde{\chi}_1^0 d_i W$ (including off-shell effects)

  included in `SUSY-HIT` allowing for FV couplings.
- Simplified assumptions of BRs of 100% in large parameter space not true $\Rightarrow$ Weaker exclusion limits.
  Since Monday's ATLAS paper this is also taken into account in the experimental analysis.
- Above $W$ boson threshold also decay into $\tilde{u}_1 \to c\tilde{\chi}_1^0$ can be sizeable. Has to be considered by experiments.

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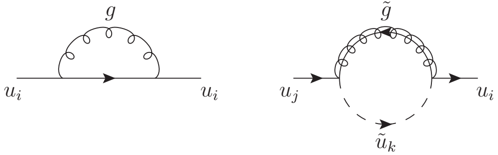
Thanks for your attention!

Quark self-energy:

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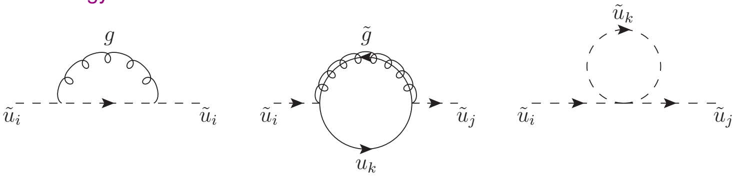
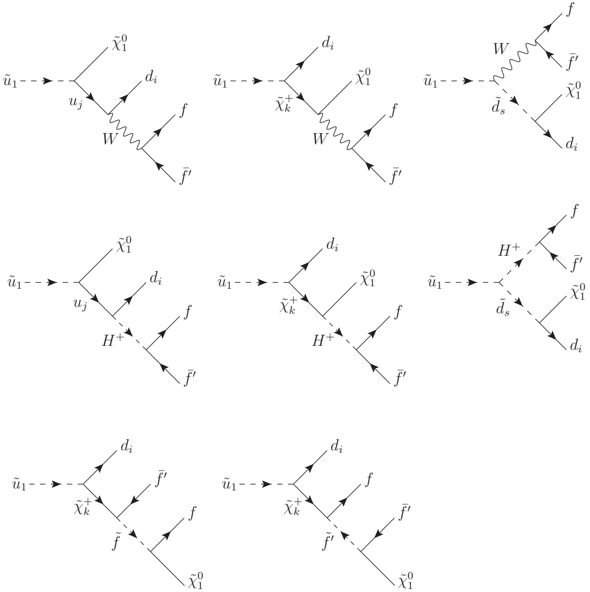
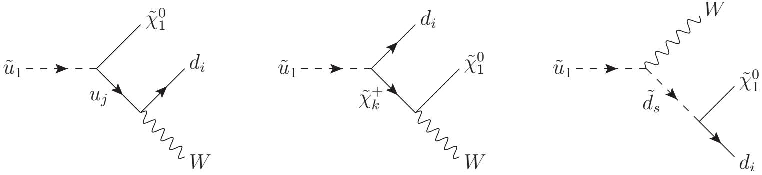


## SCAN OVER PARAMETER SPACE

$$
\begin{aligned}
75\ \text{GeV} \geq m_{\tilde{u}_1} - m_{\tilde{\chi}_1^0} &\geq 5\ \text{GeV} \\
\tilde{m}_{\tilde{Q}_3} &\in [1000, 1500]\ \text{GeV} \\
\tilde{m}_{\tilde{u}_3} &\in [300, 600]\ \text{GeV} \\
A_t &\in [1000, 2000]\ \text{GeV} \\
M_1 &\in [75, 500]\ \text{GeV} \\
m_A &\in [150, 1000]\ \text{GeV} \\
\tan\beta &\in [1, 15] \\
\mu &= 900\ \text{GeV} \\
M_2 &= 650\ \text{GeV} \\
M_3 &= 1530\ \text{GeV} \\
A_u = A_c = A_d = A_s = A_b &= 0 \\
(\tilde{m}_{\tilde{Q}})_{11} = (\tilde{m}_{\tilde{Q}})_{22} = (\tilde{m}_{\tilde{u}})_{11} = (\tilde{m}_{\tilde{u}})_{22} &= 1500\ \text{GeV} \\
(\tilde{m}_{\tilde{d}})_{ii} &= 1500\ \text{GeV} \\
(\tilde{m}_{\tilde{L},\tilde{e}})_{ii} &= 1000\ \text{GeV}
\end{aligned}
$$

# FOUR-BODY DECAY: ALL CONTRIBUTIONS




$\tilde{u}_1$
$\tilde{\chi}_1^0$
$d_i$
$u_j$
$W$
$\tilde{u}_1$
$d_i$
$\tilde{\chi}_1^0$
$\tilde{\chi}_k^+$
$W$
$\tilde{u}_1$
$W$
$\tilde{\chi}_1^0$
$\tilde{d}_s$
$d_i$

# ATLAS EXCLUSION [ARXIV: 1506.08616]