The charming stop

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Probing the Standard Model and New Physics at Low and High Energies
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Outline

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talk based on **Flavoured Naturalness**, arXiv:1302.7232

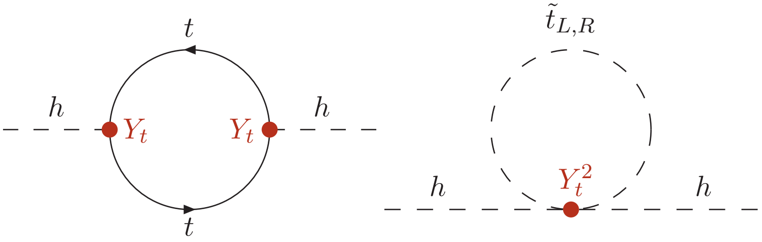
MB, Gian Giudice, Paride Paradisi, Gilad Perez, Jure Zupan





SUSY cancellation of quadratic divergences

- loop contributions of SM particles (e. g. tops) let the Higgs potential depend quadratically on the cut-off scale



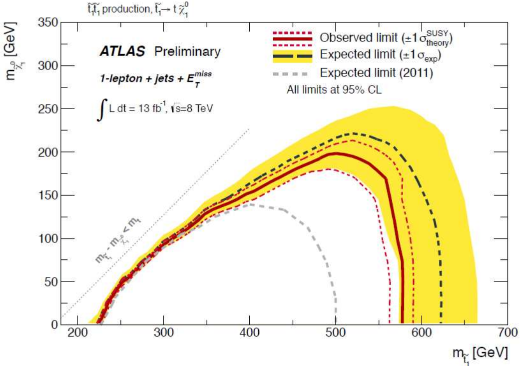
- logarithmic divergence is top squark mass dependent

$$\delta m_{Hu}^2 = -\frac{3Y_t^2}{8\pi^2}\left(m_{\tilde{t}_1}^2 + m_{\tilde{t}_2}^2 + |A_t|^2\right)\log\frac{\Lambda}{m_{\tilde{t}}}$$

➢ naturalness requires $m_{\tilde{t}_{L,R}} < \mathcal{O}(1\,\text{TeV})$

So where are the stops?

- no sign of stops seen so far at the LHC
- strongest bound* from ATLAS: $m_{\tilde{t}} > 585$ GeV for massless LSP



➢ constraint cuts deep into natural region

ATLAS-CONF-2012-166

* as of early March 2013 – more recent results not included in our analysis

A closer look at the constraints

- ATLAS stop mass limit based on simplified model
  - mostly right-handed stop decaying to almost purely right-handed tops
  - $Br(\tilde{t}_1 \to t\chi_1^0) = 100\%$

ATLAS-CONF-2012-166

- stop search from CMS assumes unpolarized tops in the final state

➢ much weaker bound $m_{\tilde{t}_1} > 430\,\text{GeV}$

CMS-PAS-SUS-2012-023

- both searches based on jets, single lepton and missing E_T

➢ **stronger constraint on right-handed (s)tops** due to more energetic lepton in the final state

see e. g. Perelstein, Weiler (2008), Gedalia, Lee, Perez (2009) Belanger et al. (2012), Almeida et al. (2008), Rehermann, Tweedie (2010)

Avoiding the right-handed stop bound

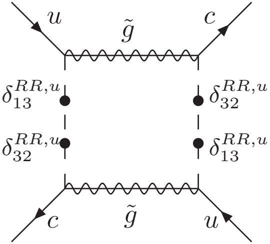
Stop mass bound can be softened by

- compressing spectrum (heavier LSP)
- introducing additional stop decays (e. g. $\tilde{t}_1 \to t\chi_2^0, b\chi_1^+, \ldots$)
- allowing for flavour mixing

for earlier related studies see e. g.
Han et al. (2003)
Cao et al. (2006)
Lopez-Val et al. (2007)
Hiller, Nir (2008)
Kribs et al. (2008)
Bartl et al. (2010)
Hurth, Porod (2009)
...

FCNC constraints on squark flavour mixing

- K and B meson decays constrain flavour violation in the down (s)quark system
  - ➢ $SU(2)_L$: constraints also on left-handed up squark mixing
- "direct" constraint on up squark mixing only from charm physics
  - ➢ $D - \bar{D}$ mixing constrains product $\delta_{13}^{RR,u}\delta_{32}^{RR,u}$



➢ 13 and **23 mixing in the right-handed up squark sector** are still **allowed to be large** *individually*

Flavoured naturalness

squark flavour mixing modifies the squark Higgs couplings

- impact on naturalness

$$\delta m_{Hu}^2 = -\frac{3Y_t^2}{8\pi^2}\left(m_{\tilde{t}_L}^2 + c^2 m_1^2 + s^2 m_2^2\right)\log\frac{\Lambda}{m_{\tilde{t}}}$$

- naturalness depends on both masses m_1, m_2 of the mixed $\tilde{c}_R, \tilde{t}_R$ states and the mixing angle $s = \sin\theta, c = \cos\theta$ *

  * for $c = 1, s = 0$: $m_1 = m_{\tilde{t}_R}$, $m_2 = m_{\tilde{c}_R}$

impact on naturalness from stop-scharm mixing

$$\xi = \frac{c^2 m_1^2 + s^2 m_2^2}{m_{\tilde{t}_R}^2}$$

($m_{\tilde{t}_R} = 585$ GeV ATLAS bound)

LHC constraints in the presence of $\tilde{t}_R - \tilde{c}_R$ mixing

- assumptions:
  - only $\tilde{q}_i \to t\chi_1^0, c\chi_1^0$ kinematically allowed
  - gaugino LSP with $m_{\chi_1^0} = 0$
  - negligible mixing between left- and right-handed squarks

- modified branching fractions

$$Br(\tilde{q}_1 \to t\chi_1^0) \approx c^2 \qquad Br(\tilde{q}_2 \to t\chi_1^0) \approx s^2$$
$$Br(\tilde{q}_1 \to c\chi_1^0) \approx s^2 \qquad Br(\tilde{q}_2 \to c\chi_1^0) \approx c^2$$

- both $\tilde{q}_1$ and $\tilde{q}_2$ contribute to $t\bar{t} + \not{E}_T$ and jets $+ \not{E}_T$ final states

  ➢ cannot be treated independently

- new signal $t\bar{c} + \not{E}_T$ – has not yet been searched for

Two (naive) approaches

$$\chi^2 = \left(\frac{c^4\sigma(m_1) + r_{t\bar{t}} s^4 \sigma(m_2)}{\Delta\sigma_{t\bar{t}}(m_1)}\right)^2 + \left(\frac{A\sigma(m_1) + r_{jets} B\sigma(m_2)}{\Delta\sigma_{jets}(m_1)}\right)^2$$

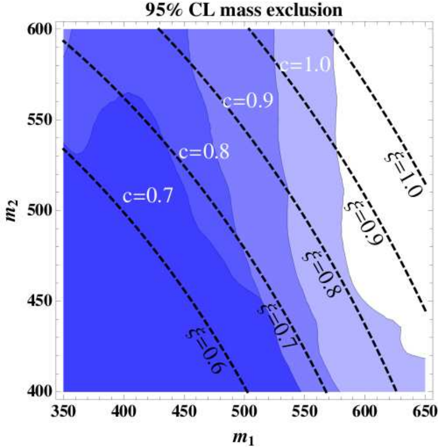
$\sigma(m)$	production cross-section for squark with mass m
$\Delta\sigma_f(m)$	1σ level exp. upper bound for squark of mass m that decays exclusively to f
$r_f = \frac{\Delta\sigma_f(m_1)}{\Delta\sigma_f(m_2)}$	correction factor for different exp. efficiencies for detection of squark with mass m_2 in final state f

Two approaches for treatment of $t\bar{c} + \not{E}_T$ final state

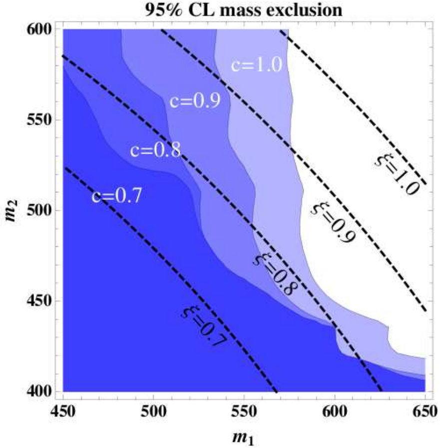
1. aggressive approach: ignore it ➢ $A = s^4$, $B = c^4$
2. conservative approach: assume it fully contributes to jets $+ \not{E}_T$
   ➢ $A = s^4 + 2s^2c^2 Br(W \to \text{jets})$, $B = c^4 + 2s^2c^2 Br(W \to \text{jets})$

Bounds on the mixed squark masses

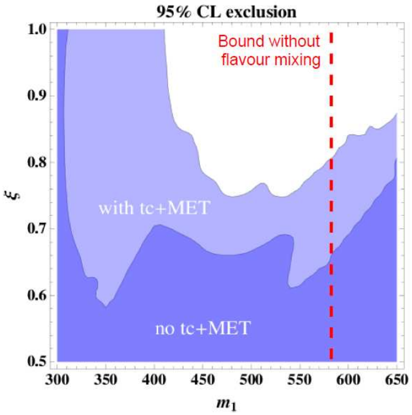
aggressive approach



conservative approach



How much do we gain?



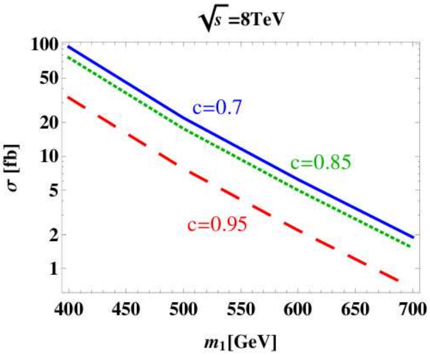
effects of stop-scharm mixing

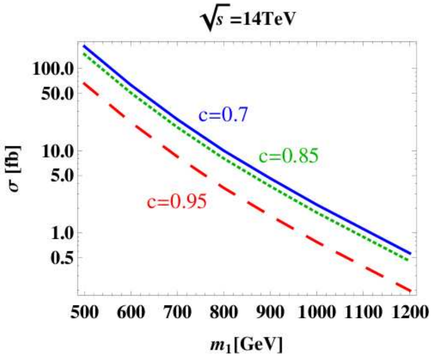
- mass of stop-like state can be lowered significantly
- mild improvement of naturalness

Dedicated searches for $t\bar{c} + \not{E}_T$ ($\bar{t}c + \not{E}_T$)

see also Bartl, Eberl, Herrmann, Hidaka, Majerotto, Porod (2010)

large cross-section predicted for flavour violating signal $t\bar{c} + \not{E}_T$





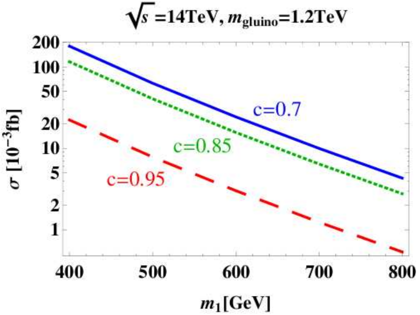
➢ **dedicated search should be promising**

Same sign tops – a smoking gun?

model gives rise to same sign tops via t-channel gluino exchange

$$pp(cc) \to \tilde{q}_i \tilde{q}_j \to tt\chi_1^0\chi_1^0$$

observation would be a smoking gun signature



cross section strongly suppressed

- small charm quark PDF
- flavour mixing $c^4 s^4 \leq 1/16$

leptonic tops needed

➢ **requires LHC luminosity upgrade**

Conclusions

Large flavour mixing between the right-handed stop and scharm

- is in perfect agreement with present flavour data
- can significantly lower the direct bounds from ATLAS and CMS
- leads to a modest improvement of naturalness
- induces $t\bar{c} + \not{E}_T$ as a promising channel to discover (or further constrain) this set-up

Back-up slides

Trilinear coupling A_t

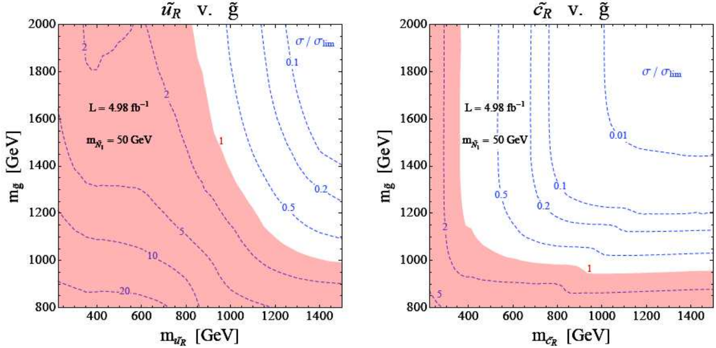
$$\delta m_{Hu}^2 = -\frac{3Y_t^2}{8\pi^2}\left(m_{\tilde{t}_1}^2 + m_{\tilde{t}_2}^2 + |A_t|^2\right)\log\frac{\Lambda}{m_{\tilde{t}}}$$

- MSSM requires large A_t or multi-TeV stop for $m_H \sim 125\,\text{GeV}$
- increased tree level Higgs mass in straightforward extensions, e. g. λSUSY see e. g. Hall, Pinner, Ruderman (2012)
  - ➢ keep δm_{Hu}^2 as small as possible
  - ➢ assume small trilinear coupling A_t

Constraints on the first two generation squarks

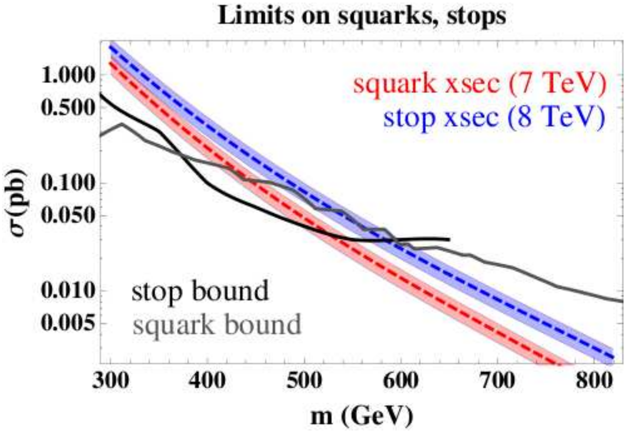
- strong exp. limits on first two generation squarks usually assume 8-fold degeneracy
- bounds on second generation much weaker because of smaller PDFs

Mahbubani, Papucci, Perez, Ruderman, Weiler (2012)



➢ right-handed scharm can be as light as 450 GeV (w/o mixing)

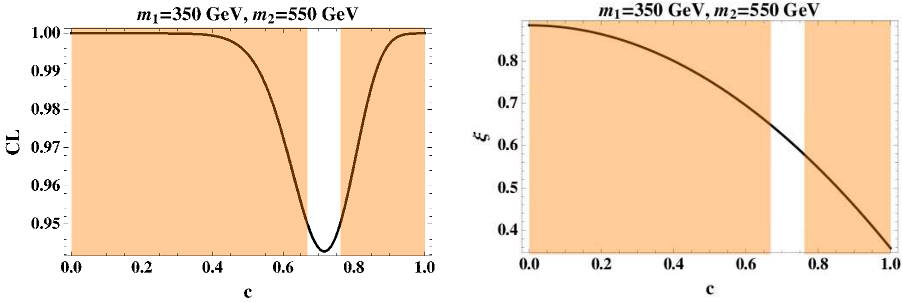
Upper bounds on stop and scharm pair production



NLO+NLL prediction:
Beenakker et al. (2011)

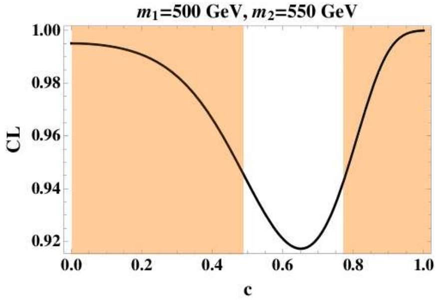
exp. bounds
ATLAS, CMS (2012)

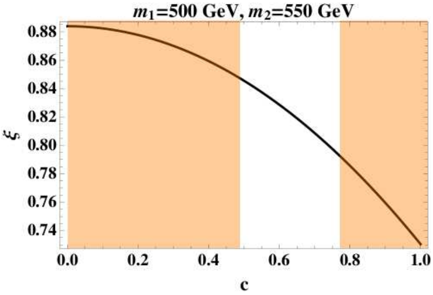
Example spectrum – aggressive approach



- masses as low as 350 GeV and 550 GeV possible if mixing is large
- modest improvement of fine-tuning

Example spectrum – conservative approach





- stronger bounds than in the naive fit
- still masses around $520\,$GeV are allowed and lead to slight improvement of naturalness