Flavored naturalness

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Particle and Astro-Particle Physics Seminar
CERN
February 1, 2013

Talk based on work done in collaboration with
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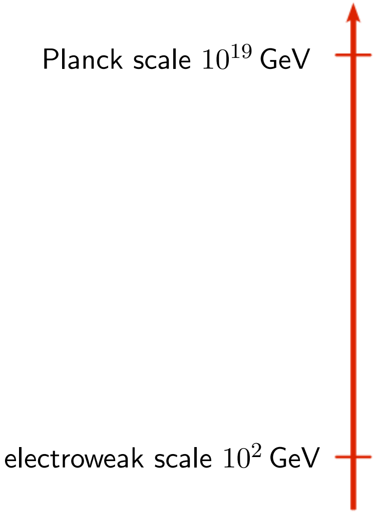
Paper in preparation, yet results still preliminary. . .
please don't scoop us! ☺

The hierarchy problem



The hierarchy problem

Planck scale 10^{19} GeV — decent glass of beer 

electroweak scale 10^{2} GeV — distance to nearest star Proxima Centauri

Stabilization of electroeak scale

Higgs potential in the Standard Model (SM)

$$V(H) = -\frac{\mu^2}{2} H^\dagger H + \frac{\lambda}{4!} (H^\dagger H)^2$$

Natural scale of electroweak symmetry breaking requires

$$\lambda \sim \mathcal{O}(1) \qquad \mu \sim \mathcal{O}(10^2\,\text{GeV})$$

μ is composed of its bare value and quantum corrections

$$\mu = \mu_0 + \delta\mu$$

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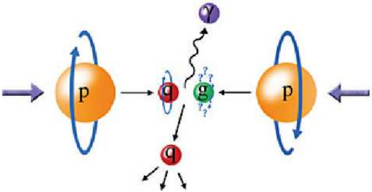
➢ In order to claim naturalness, we have to understand both the smallness of μ_0 and $\delta\mu$!

Can the LHC do the job?

Naturalness at the LHC?

LHC collides quarks and gluons



- excellent to produce colored new particles
- much less sensitive to weakly coupled physics ➢ Higgs sector

"easy" task: discover new colored particles that contribute to $\delta\mu$

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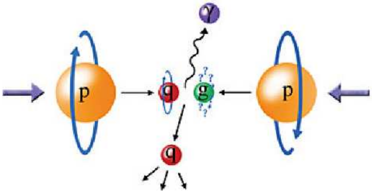

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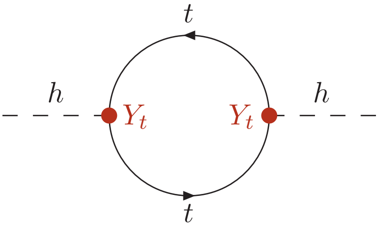
➢ Let's talk **SUSY** (just for the sake of simplicity)!

Cancellation of quadratic divergences

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



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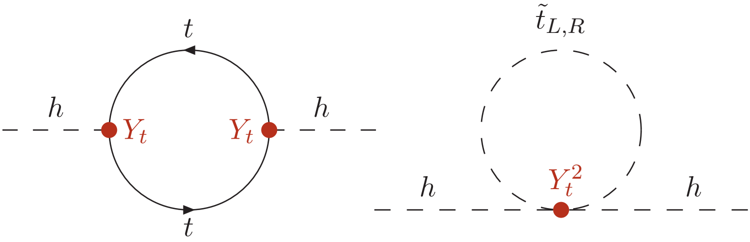


- new particles (stops) required to cancel these contributions
- independent of $m_{\tilde{t}}$
- couplings to the Higgs boson have to be equal

Cutting off the logarithmic divergence

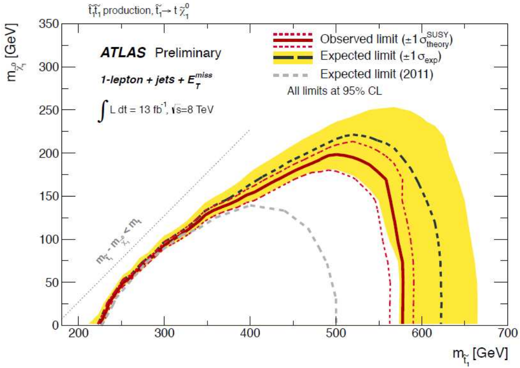
- logarithmic divergence is (s)quark mass dependent
  ➢ size of contribution depends on squark spectrum

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

- let's assume that tree level Higgs mass is raised w.r.t. to MSSM prediction (e. g. NMSSM)
  ➢ keep δm_{Hu}^2 as small as possible
  ➢ small trilinear coupling A_t
- fine-tuning controlled my stop masses $m_{\tilde{t}_{L,R}}$
  ➢ naturalness requires $m_{\tilde{t}_{L,R}} \lesssim 500\,\text{GeV}$

So where are the stops?

- no sign of stops seen so far at the LHC
- strongest bound from Atlas: $m_{\tilde{t}} > 560$ GeV for massless LSP



➢ tension with the naturalness constraint

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
  - $Br(\tilde{t}_1 \to t\chi_1^0) = 100\%$
- stop search from CMS assumes unpolarized tops in the final state

➢ much weaker bound $m_{\tilde{t}_1} > 430\,\text{GeV}$ for light χ_1^0

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

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Left-handed (s)tops are much less constrained than right-handed ones!

Right-handed stops $\tilde{t}_R \to t\chi_1^0$ at the LHC

see e. g. PERELSTEIN, WEILER (2008), CMS-PAS-SUS-12-023

Why are right-handed (s)tops so much more constrained?

- parity violation of weak interactions
  ➢ top rest frame: ℓ^+ momentum aligned with top spin

- decay of boosted right-handed top:
  boosts add up constructively to produce very energetic lepton
  ➢ passes p_T cuts more easily
  ➢ right-handed tops more visible in searches with final state leptons

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- assuming purely bino LSP:

right-handed tops arise from decay of right handed stops
➢ more strongly constrained than left-handed stops

Avoiding the right-handed stop bound

Stop mass bound can be softened by

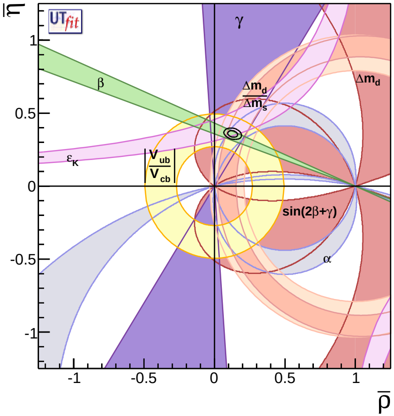
- compressing spectrum (heavier LSP)
- introducing additional stop decays (e. g. $\tilde{t}_1 \to t\chi_2^0, b\chi_1^+, \ldots$)

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 flavor mixing

Wait. . . I thought large squark flavor mixing is already ruled out by FCNC constraints?



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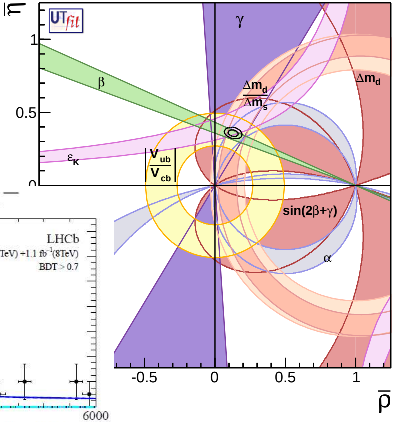

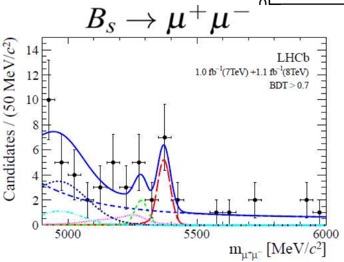

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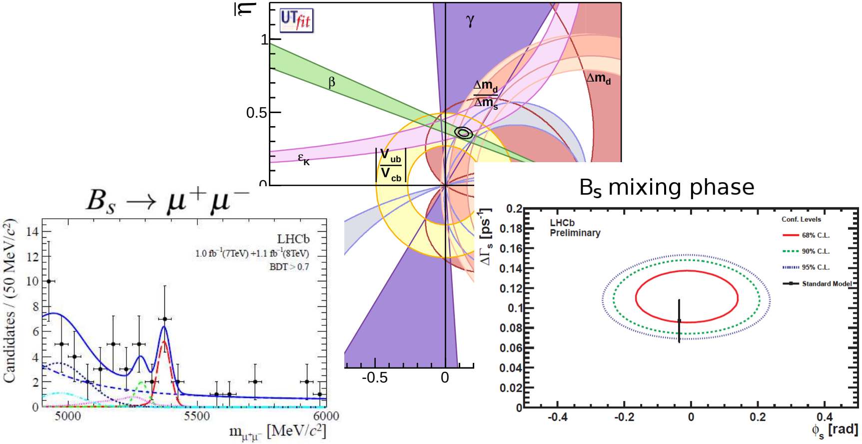

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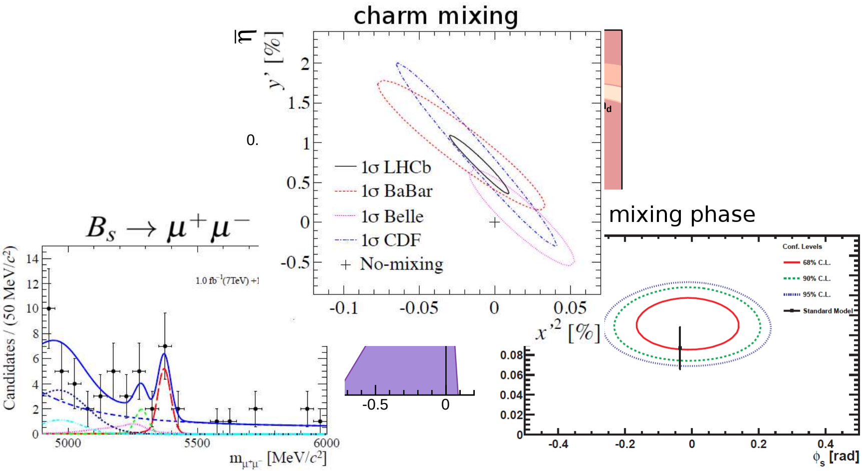

A closer look

- K and B meson decays constrain flavor 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

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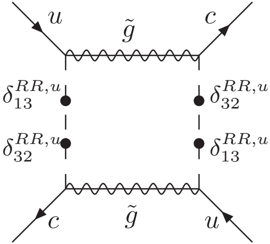
- K and B meson decays constrain flavor violation in the down (s)quark system
  ➢ $SU(2)_L$: constraints also on left-handed up squark mixing
- "direct" constraint on up squark mixing only from charm physics
  ➢ $D - \bar{D}$ mixing constrains product $\delta_{13}^{RR,u}\delta_{32}^{RR,u}$



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

Flavored naturalness

squark flavor mixing modifies the squark Higgs couplings

- impact on naturalness

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

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

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

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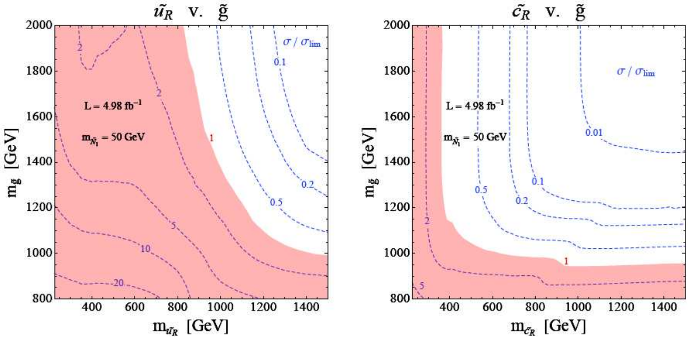
improvement on naturalness in the right-handed sector

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

($m_{\tilde{t}_R} = 560$ GeV Atlas bound)

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)

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, $m_{\chi_1^0} = 0$
- 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 $t\bar{t}$ + MET and $c\bar{c}$ + MET final states
  ➢ cannot be treated independently

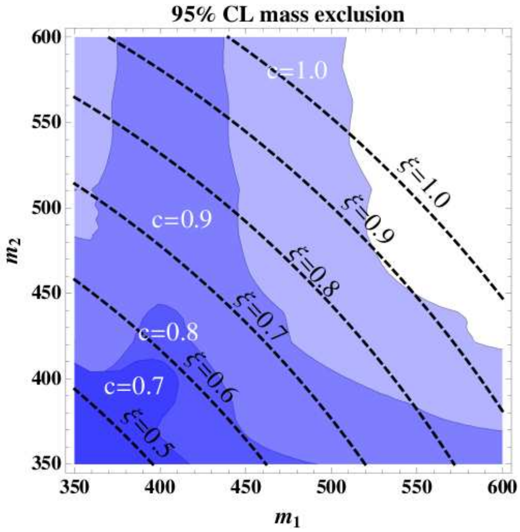
A naive χ^2 function

define χ^2 function

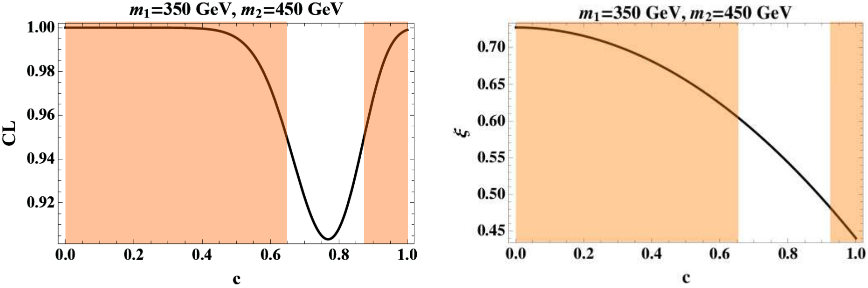
$$\chi^2 = \left(\frac{c^4\sigma(m_1) + r_{t\bar{t}}s^4\sigma(m_2)}{\Delta\sigma_{t\bar{t}}(m_1)}\right)^2 + \left(\frac{s^4\sigma(m_1) + r_{jets}c^4\sigma(m_2)}{\Delta\sigma_{jets}(m_1)}\right)^2$$

$\sigma(m)$	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

Bounds on the mixed squark masses



Naturalness improvement – example spectrum



- masses as low as 350 GeV and 450 GeV possible if mixing is large
- significant improvement of fine-tuning

A bit too naive?

- $\tilde{q}_i$ pair production also leads to $t\bar{c}(\bar{t}c)+$ MET final state
- enters jets+MET search if top decays hadronically
- ideally: do a full Monte-Carlo

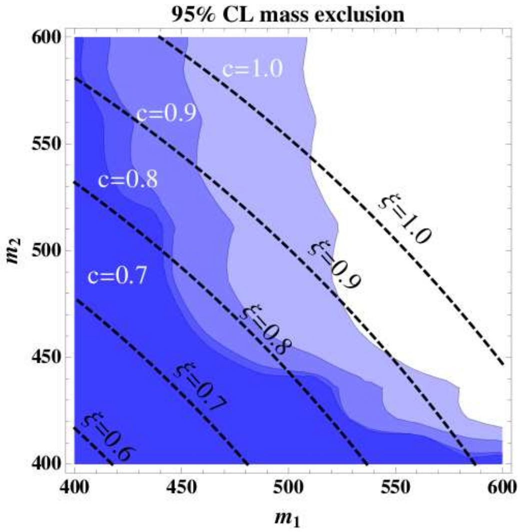
A bit too naive?

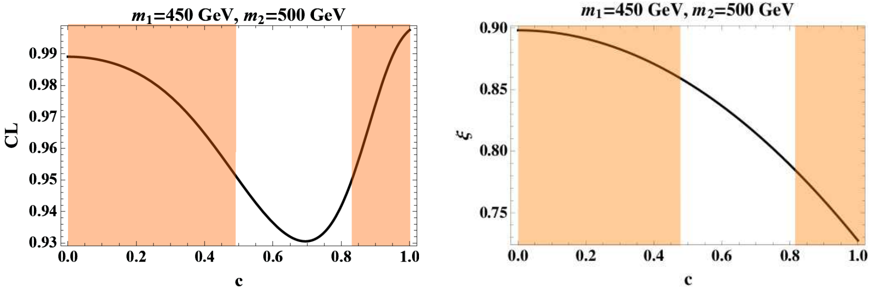
- $\tilde{q}_i$ pair production also leads to $t\bar{c}(\bar{t}c)$ + MET final state
- enters jets+MET search if top decays hadronically
- ideally: do a full Monte-Carlo
- even more ideally: let the experimentalists do the search
- in the meantime: estimate effect by modifying the χ^2 function to

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

$$A = s^4 + 2s^2c^2 Br(W \to \text{jets}) \qquad B = c^4 + 2s^2c^2 Br(W \to \text{jets})$$

A conservative χ^2 fit





- stronger bounds than in the naive fit
- still masses below $500\,\mathrm{GeV}$ are allowed and lead to significant improvement of naturalness

Dedicated searches for $t\bar{c}$ + MET ($\bar{t}c$ + MET)

see also BARTL, EBERL, HERRMANN, HIDAKA, MAJEROTTO, POROD (2010)

large cross-section predicted for flavor violating signal $t\bar{c}$ + MET

➢ dedicated search should be promising

possible strategies

- top-tagger
- b tag + isolated lepton
- charm tag
- ...

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

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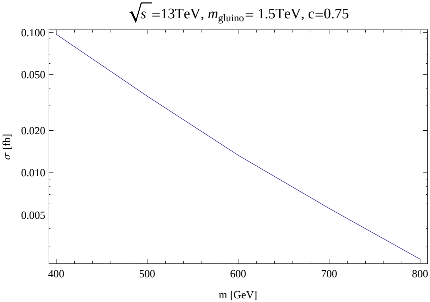

small cross section + leptonic tops needed ➢ hopeless at the LHC

Conclusions

Large flavor mixing between the right-handed stop and scharm

- is in perfect agreement with present flavor data
- can significantly lower the direct bounds from Atlas and CMS
- leads to a sizable improvement of naturalness
- induces $t\bar{c} + \text{MET}$ as a promising channel to discover (or further constrain) this setup