C3a: New sources of flavour- and CP-violation at high transverse momenta

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Motivation

Why BSM flavour physics?

- flavour and CP are not good symmetries of nature, already violated in the SM (Yukawa couplings, CKM matrix)
- concrete BSM models typically introduce new sources of flavour and CP violation (e. g. squark mass matrices in SUSY)
- B meson anomalies provide the most promising experimental hints for breakdown of SM at the TeV scale

Motivation

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Questions to be addressed in C3a

➢ What is the impact of a non-trivial flavour structure on direct searches for new particles?

➢ Can high-p_T physics provide a complementary probe of the BSM flavour and CP structure?

Project goal

Study phenomenological implications of flavour and CP-violating interactions for high-p_T new physics (NP) searches by

- developing benchmark models with large flavour and/or CP-violating interactions, in agreement with available indirect search constraints
- re-evaluating existing high-p_T limits in the presence of flavour violation
- identifying new flavour and/or CP-violating signatures arising in these models
- supporting our predictions by precision calculations of cross-sections and differential distributions

Benchmark scenarios

1. **top partner models**
   generically lead to flavour violating signatures including top quarks
2. **top-flavoured dark matter**
   large flavour violating high-p_T signatures even in the absence of sizeable flavour mixing
3. **simplified models for the flavour anomalies**
   new TeV-scale particles with intrinsic quark flavour violation and lepton flavour univerality violation
4. **new sources of CP-violation**
   CP-asymmetries in new particle production and/or decay

Benchmark scenarios – in this talk

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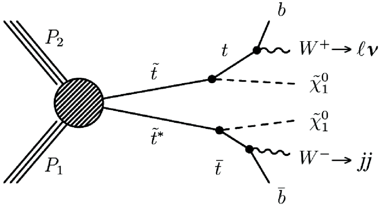
Top squarks at the LHC

Stop pair production $pp \to \tilde{t}\tilde{t}^*$

- flavour-conserving "vanilla" signature $t\bar{t} + \not{E}_T$ $(m_{\tilde{t}} > m_t + m_{\chi_1^0})$



- in the presence of sizable stop-scharm mixing the flavour-violating decay $\tilde{t} \to c\chi_1^0$ becomes relevant

  ➢ **impact on stop searches? new signatures?**

Hurth, Porod (2009); Bartl et al. (2010)
Blanke, Giudice, Paradisi, Perez, Zupan (2013)
Blanke, Fuks, Galon, Perez (2015)
...

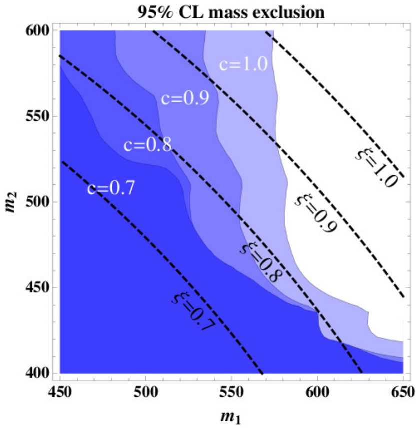
Heavy stops – reduced bounds

Stop-scharm mixing ➢ $\tilde{t} \to t\chi_1^0$ and $\tilde{t} \to c\chi_1^0$ allowed

- stops partly "hidden" in the less constrained $jj + \not{E}_T$ final state
  ➢ significantly weaker bounds for large stop-scharm mixing angle

- smoking gun signature $tc + \not{E}_T$
  ➢ recent detailed study

  Chakraborty et al. (2018)



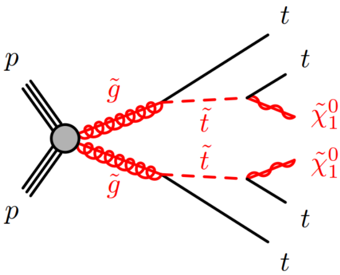
Blanke, Giudice, Paradisi, Perez, Zupan (2013)

$m_{1,2}$: mixed squark masses
$c = \cos\theta$: stop-scharm mixing angle
ξ : EW tuning measure

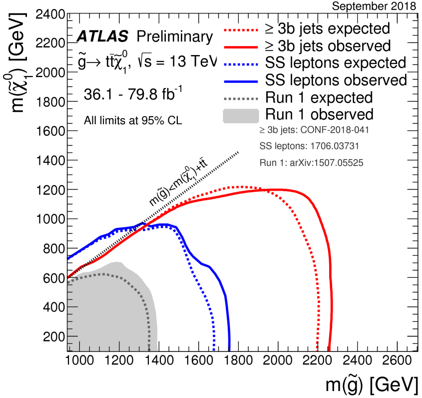
Including the gluino

Gluino decay via stops

flavour-conserving case well-studied



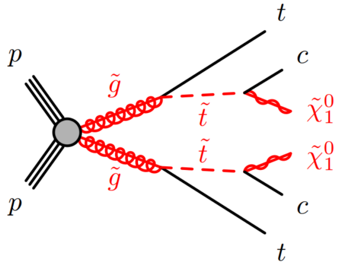
➢



Including the gluino

Gluino decay via stops

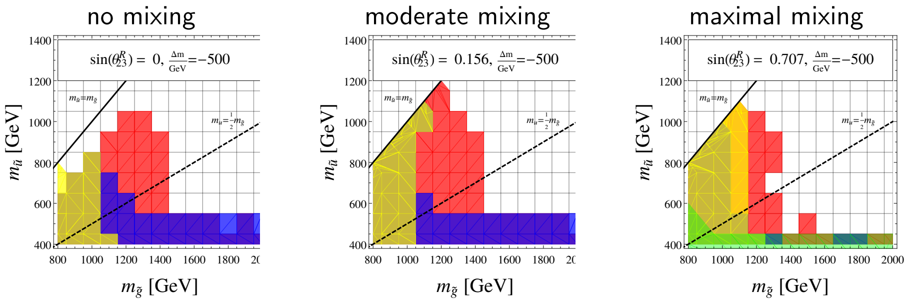
What about flavour-violating case?



➢

Example spectrum: $m_{\tilde{c}} = m_{\tilde{t}} + 500\,\text{GeV}$

Blanke, Fuks, Galon, Perez (2015)



recasted exp. searches:

ATLAS multijet+$\not\!\!E_T$ (2013)
CMS multijet+$\not\!\!E_T$ (2013)
CMS stop (2013)
ATLAS scharm (2014)

- **for individual searches:** significant impact on sensitivity
- **combined exclusion:** only mild change, mostly for large mixing

Light stops – a little goes a long way

For $m_{\tilde{t}} < m_t + m_{\chi_1^0}$, the decay $\tilde{t}_1 \to t + \chi_1^0$ is kinematically forbidden.

- **exactly flavour-conserving case**
  - depending on stop mass, three-body decay $\tilde{t}_1 \to b + W + \chi_1^0$ or even four-body decay $\tilde{t}_1 \to b + (W^* \to f f') + \chi_1^0$ dominant
  - long stop lifetime

- **Minimal Flavour Violation**
  - two-body decays $\tilde{t}_1 \to c + \chi_1^0$ and $\tilde{t}_1 \to u + \chi_1^0$ become accessible and usually even dominant
  - size of squark flavour violation impacts decay lengths

Mühlleitner, Popenda (2011)

Top partner models – future directions

Goals

- in-depth exploration of the (3-gen.) squark flavour structure in SUSY
- investigation of alternative top partner scenarios (e. g. composite)

Steps

- develop simplified models for scalar and fermionic top partners with flavour-violating couplings
- provide Monte-Carlo implementations, including higher-order corrections to ensure precise predictions
- reinterpret existing experimental limits
- investigate new flavour violating signatures
- identify patterns of observables that allow to pin down the underlying flavour structure and discriminate between models

Flavoured dark matter (DM)

Unknown DM properties

- coupling to SM particles?
- single particle or entire sector?
- analogy to ordinary SM matter

➢ **flavoured?**

Assumption:

dark matter carries flavour
and comes in multiple copies

➢ **New coupling to quarks:**

$$\lambda^{ij}\bar{q}_i\chi_j\phi$$

q_i	SM quarks
χ_j	DM particle, flavoured
ϕ	coloured scalar mediator
λ	coupling matrix

Flavoured DM beyond MFV

Agrawal, Blanke, Gemmler (2014)
Blanke, Kast (2017)
Blanke, Das, Kast (2017)

A simplified model of top-flavoured dark matter

Flavoured Dirac-fermionic DM χ_j and couples to up-type quarks via a coloured scalar mediator Blanke, Kast (2017)

$$\mathcal{L}_{\rm NP} = i\bar\chi\not\partial\chi - m_\chi\bar\chi\chi + (D_\mu\phi)^\dagger(D^\mu\phi) - m_\phi^2\phi^\dagger\phi - \lambda^{ij}\bar{u_{Ri}}\chi_j\phi$$
$$+\lambda_{H\phi}\,\phi^\dagger\phi\,H^\dagger H + \lambda_{\phi\phi}\,\phi^\dagger\phi\,\phi^\dagger\phi$$

Assumptions:

- λ constitutes the *only* new source of flavour violation
- DM is top-flavoured: $m_{\chi_t} < m_{\chi_u}, m_{\chi_c}$

Parametrisation of DM-quark coupling: $\lambda = U_\lambda D_\lambda$

U_λ unitary matrix, 3 mixing angles θ_{12}, θ_{13}, θ_{23} and 3 phases

D_λ real diagonal matrix, e.g. $D_\lambda = \mathrm{diag}(D_{\lambda,11}, D_{\lambda,22}, D_{\lambda,33})$

LHC constraints on top-flavoured dark matter

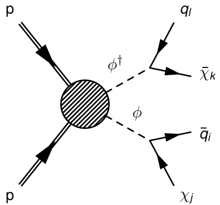
- most stringent constraints from mediator pair production
- signatures similar to SUSY squarks
  - $t\bar{t} + \not{E}_T$, $jj + \not{E}_T$
  - also $tj + \not{E}_T$ even for $U_\lambda \equiv \mathbb{1}$

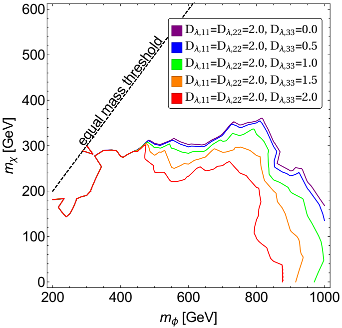
  rel. rates depend on flavour structure
- naive recast of ATLAS run 1 cross-section limits:

$$m_\phi \gtrsim 850\,\text{GeV}$$

for DM couplings $D_{\lambda,ii} \leq 2$

Blanke, Kast (2017)





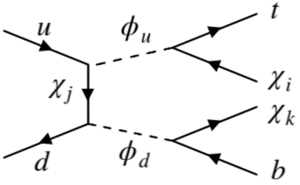
Flavoured dark matter moving left

Blanke, Das, Kast (2017)

- introducing an $SU(2)_L$-doublet mediator Φ allows to couple the DM flavour triplet χ_j to left-handed quarks Q_{Li}

$$\lambda^{ij}\bar{Q}_{Li}\chi_j\Phi$$

- richer phenomenology than for DM couplings to right-handed quarks, e. g. direct connection between top and B physics
- novel collider signature $tb + \not{E}_T$ – yet to be investigated!



Flavoured dark matter – future directions

Goals

- include scenarios with different spin-statistics
- detailed analysis of their LHC phenomenology

Steps

- extend the flavoured-dark matter toolbox of simplified models
- provide limits on dark matter and mediator masses from LHC searches
- study predicted flavour violating signatures, like $tj + \not{E}_T$ and $tb + \not{E}_T$
- investigate how to distinguish the various underlying models, based on p_T and $\not{E}_T$ distributions, angular observables etc.

The need for precision

flavour- and CP-violating interactions provide subtle signatures that need to be discriminated from often large backgrounds

➢ precise knowledge of signal cross sections and kinematic features indispensable to fully exploit their NP discovery potential

Goals

- address theoretical consistency of simplified models (gauge invariance, perturbative unitarity etc.)
- provide publicly available implementations of flavour-violating models in UFO format
- full Monte-Carlo implementations, including higher-order corrections and matching to parton showers Beenakker, Krämer et al. (2010) Gavin, Krämer, Mühlleitner et al. (2015)
- make use of modern analysis techniques, like machine learning, to optimise the LHC reach Blanke, Kast, Thompson, Westhoff, Zurita (2019)

Summary

Adding flavour to LHC physics

- has important implications for existing NP searches
- induces striking signatures not yet being looked for
- needs high precision for accurate predictions