Flavour-violating decays of mixed top-charm squarks at LHC

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Chakraborty, Endo, Fuks, Herrmann, Nojiri, Pani, Polesello — PhysTeV Les Houches 2017 — arXiv:1803.10379 [hep-ph]
Chakraborty, Endo, Fuks, Herrmann, Nojiri, Pani, Polesello — arXiv:1808.07488 [hep-ph]

IRN Terascale — September 4-7, 2018 — Durham, United Kingdom

Reminder — Squark mass limits from ATLAS/CMS

Current squark and gaugino searches are very helpful and an important starting point…

CMS collaboration — Eur. Phys. J. C 77 (2017) 710 — arXiv:1705.04650 [hep-ex]

ATLAS collaboration — JHEP 09 (2017) 084 — arXiv:1706.03731 [hep-ex]

CMS collaboration — JHEP 10 (2017) 019 — arXiv:1706.04402 [hep-ex]

CMS collaboration — JHEP 10 (2017) 005 — arXiv:1707.03316 [hep-ex]

CMS collaboration — Phys. Lett. B 778 (2018) 263 — arXiv:1707.07274 [hep-ex]

ATLAS collaboration — Eur. Phys. J. C 77 (2017) 898 — arXiv:1708.03247 [hep-ex]

ATLAS collaboration — JHEP 11 (2017) 195 — arXiv:1708.09266 [hep-ex]

ATLAS collaboration — JHEP 12 (2017) 085 — arXiv:1709.04183 [hep-ex]

CMS collaboration — Phys. Rev. D 97 (2017) 012007 — arXiv:1710.11188 [hep-ex]

CMS collaboration — Phys. Rev. D 97 (2017) 032009 — arXiv:1711.00752 [hep-ex]

ATLAS collaboration — JHEP 01 (2018) 126 — arXiv:1711.03301 [hep-ex]

ATLAS collaboration — JHEP 06 (2018) 108 — arXiv:1711.11520 [hep-ex]

ATLAS collaboration — Phys. Rev. D 97 (2018) 112001 — arXiv:1712.02332 [hep-ex]

CMS collaboration — Phys. Rev. D 96 (2018) 032003 — arXiv:1704.07781 [hep-ex]

ATLAS collaboration — arXiv:1805.01649 [hep-ex]

(and many many more…)

Reminder — Squark mass limits from ATLAS/CMS

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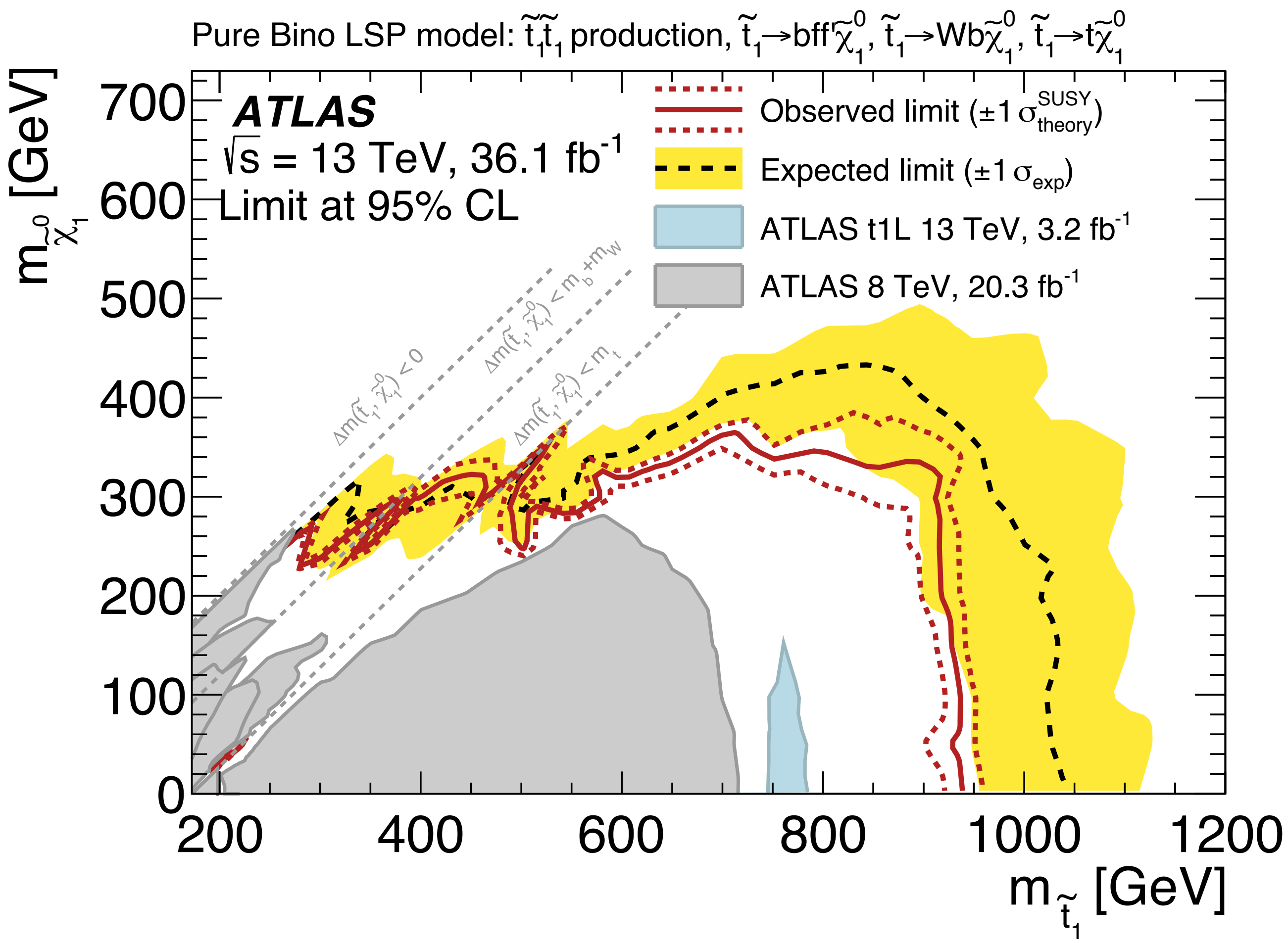
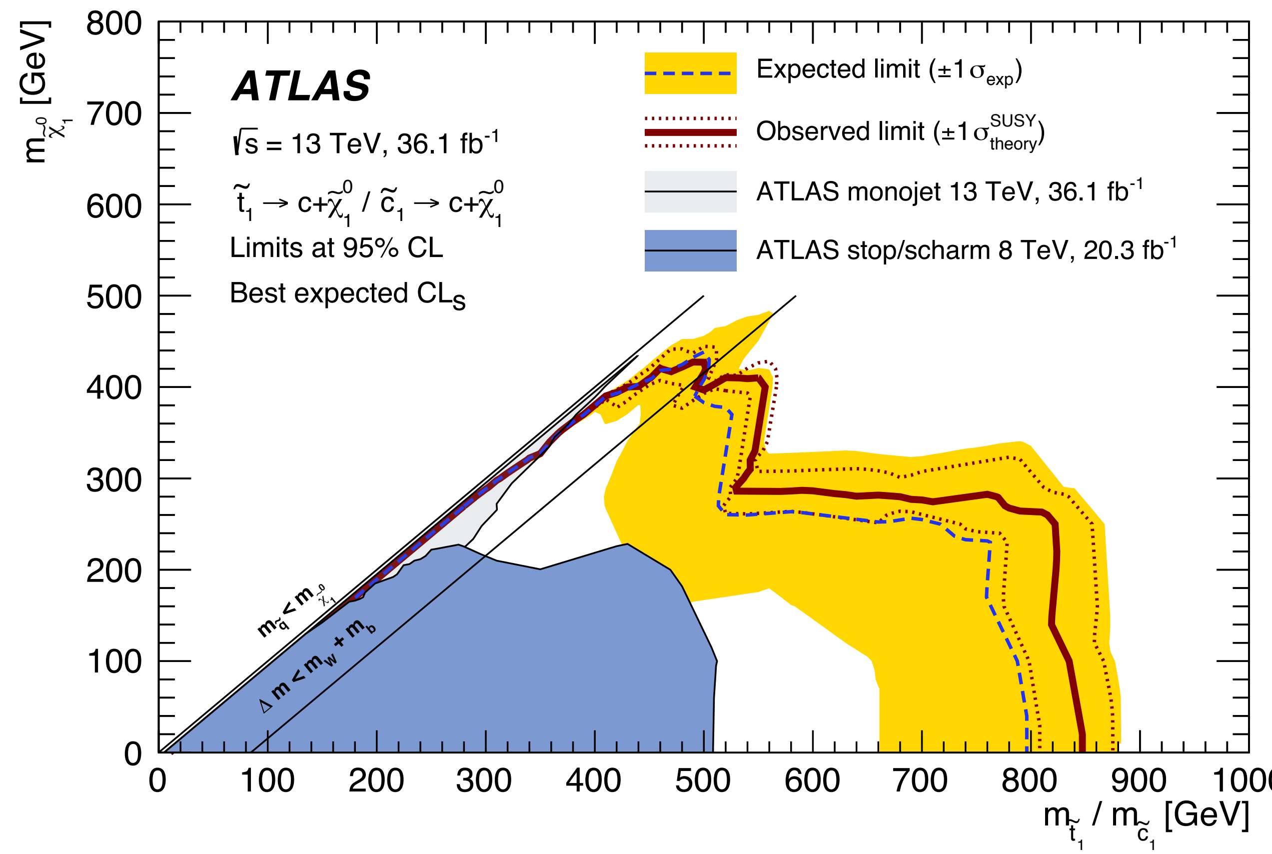


ATLAS coll. — JHEP 1806 (2018) 108 — arXiv: 1711.11530



ATLAS coll. — arXiv: 1805.01649

… but the obtained mass limits are based on (over-)simplifying assumptions
(mass hierarchy, squark and gaugino composition, decay pattern, …)

In the following: **Consider flavour structure beyond Minimal Flavour Violation…**

Outline

Introduction: MFV vs. NMFV in the squark sector

Recasting of existing LHC limits for NMFV squarks

Proposal for a dedicated NMFV search at LHC

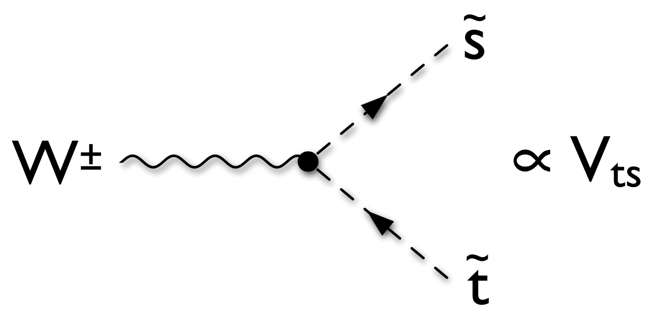
Conclusion

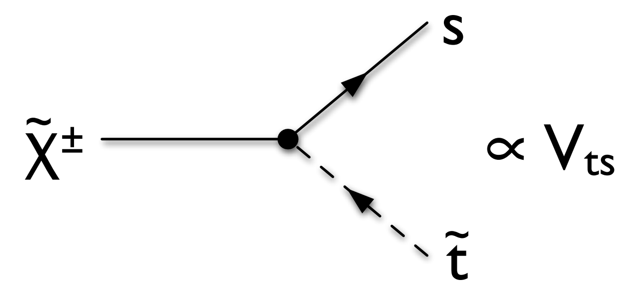
Disclaimer

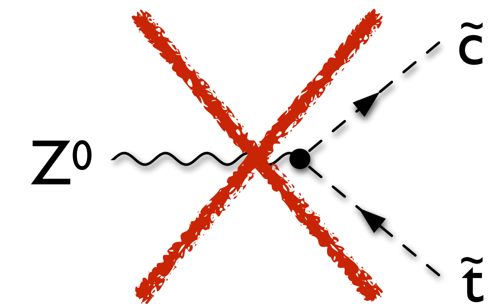
This work has been a collaboration of experimentalists and theorists initiated at the PhysTeV Les Houches workshop 2017.
I am a theorist — but I hope to cover all essential experimental points.

Squark flavour structure — MFV and beyond

Assume **same flavour structure** as in Standard Model: flavour-changing currents are related to CKM-matrix — <u>minimal flavour violation</u> (MFV)

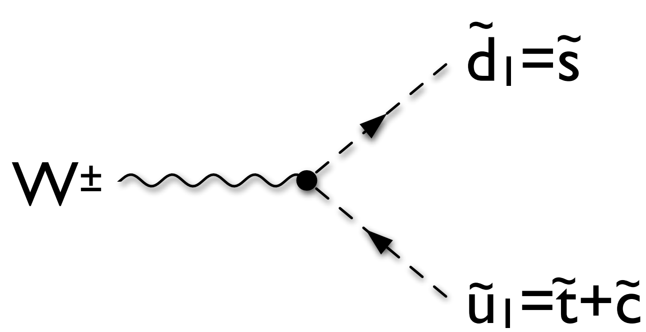


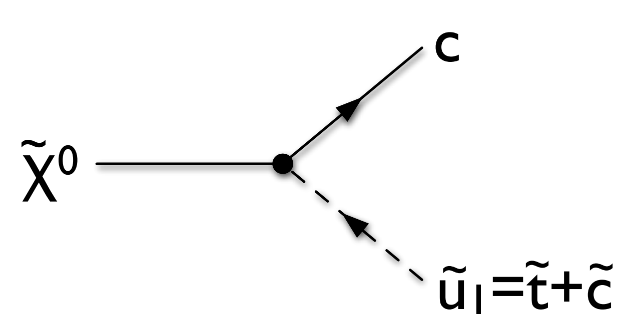


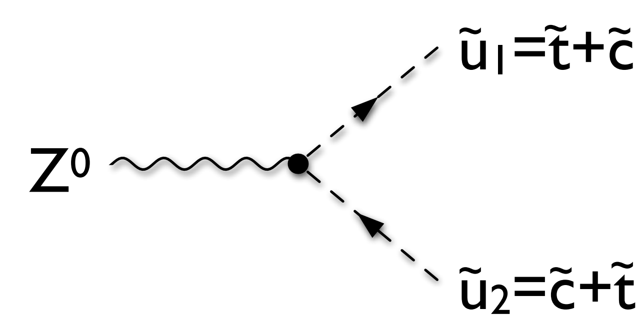


MFV vs. NMFV at LHC…?

Allow for **new sources** of flavour violation: corresponding interactions not related to CKM-matrix any more (no suppression!) — <u>non-minimal flavour violation</u> (NMFV)







The MSSM up-type squark sector

In the **super-CKM basis**, the up-type squark sector is parametrized by the **mass matrices**:

$$\mathcal{M}^2_{\tilde{u}} = \begin{pmatrix} V_{\rm CKM} M^2_{\tilde{Q}} V^\dagger_{\rm CKM} + m^2_u + D_{\tilde{u},L} & \frac{v_u}{\sqrt{2}} T^\dagger_u - m_u \frac{\mu}{\tan\beta} \\ \frac{v_u}{\sqrt{2}} T_u - m_u \frac{\mu^*}{\tan\beta} & M^2_{\tilde{U}} + m^2_u + D_{\tilde{u},R} \end{pmatrix}$$

Mass eigenstates are obtained via 6x6 rotation matrice (generalized "mixing angles"):

$$\mathrm{diag}\left(m^2_{\tilde{u}_1}, \ldots, m^2_{\tilde{u}_6}\right) = \mathcal{R}_{\tilde{u}} \mathcal{M}^2_{\tilde{u}} \mathcal{R}^\dagger_{\tilde{u}} \qquad m_{\tilde{u}_1} < \ldots < m_{\tilde{u}6}$$

NMFV terms manifest as **non-diagonal entries** in the soft-breaking matrices
— **dimensionless and scenario-independent parametrization**:

$$\delta_{LL} = \frac{(M^2_{\tilde{Q}})_{23}}{(M_{\tilde{Q}})_{22}(M_{\tilde{Q}})_{33}} \qquad \delta^u_{RR} = \frac{(M^2_{\tilde{U}})_{23}}{(M_{\tilde{U}})_{22}(M_{\tilde{U}})_{33}} \qquad \delta^u_{RL} = \frac{v_u}{\sqrt{2}} \frac{(T_u)_{23}}{(M_{\tilde{Q}})_{22}(M_{\tilde{U}})_{33}}$$

NMFV parameters can be considered as free parameters at the TeV scale (this talk…)
or motivated from larger frameworks such as GUTs with flavour symmetries
(see e.g. Jordan's talk after the coffee break…)

Experimental constraints

The flavour-violating elements may induce flavour-changing neutral currents (FCNC) or lift the CKM-suppression — severe **experimental constraints**

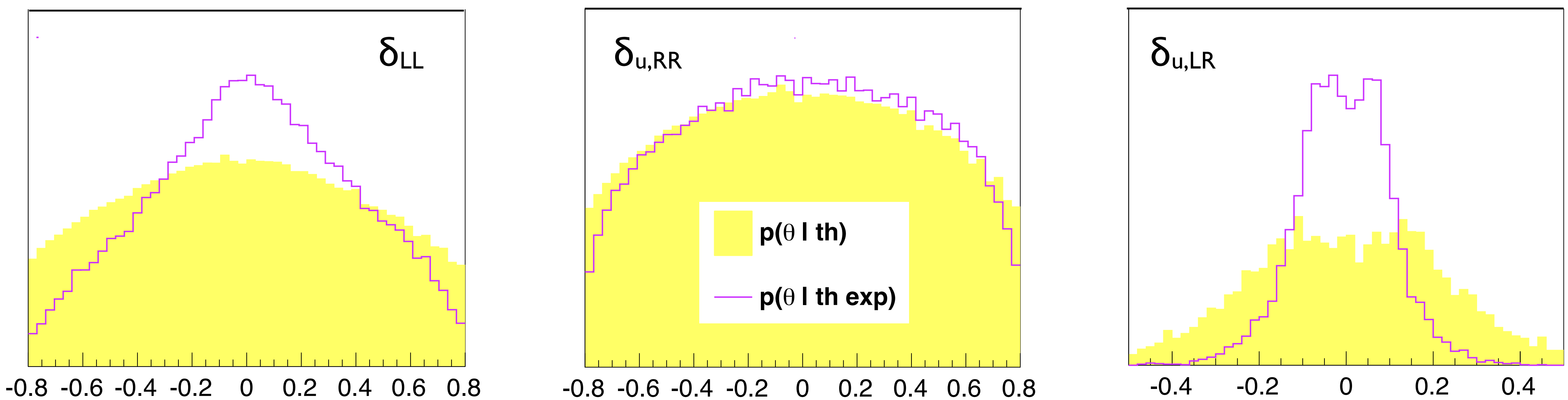
Observable	Exp. result and uncertainties	
m_h	(125.5 ± 2.5) GeV	ATLAS + CMS (2013)
$\mathrm{BR}(B \to X_s\gamma)$	$(3.43 \pm 0.21^{\mathrm{stat}} \pm 0.07^{\mathrm{sys}} \pm 0.24^{\mathrm{th}}) \cdot 10^{-4}$	HFAG (2013); Misiak et al. (2013), Mahmoudi (2007)
$\mathrm{BR}(B_s \to \mu\mu)$	$(2.9 \pm 0.7^{\mathrm{exp}} \pm 0.29^{\mathrm{th}}) \cdot 10^{-9}$	LHCb + CMS (2013), Mahmoudi *et al.* (2012)
$\mathrm{BR}(B \to X_s\mu\mu)$	$(1.60 \pm 0.68^{\mathrm{exp}} \pm 0.16^{\mathrm{th}}) \cdot 10^{-6}$	BaBar (2004); Belle (2005); Hurth *et al.* (2008, 2012)
$\mathrm{BR}(B_u \to \tau\nu)$	$(1.05 \pm 0.25^{\mathrm{exp}} \pm 0.29^{\mathrm{th}}) \cdot 10^{-4}$	PDG (2012); Mahmoudi (2008, 2009)
ΔM_{B_s}	$(17.719 \pm 0.043^{\mathrm{exp}} \pm 3.3^{\mathrm{th}})\ \mathrm{ps}^{-1}$	HFAG (2012); Ball *et al.* (2006)
ϵ_K	$(2.228 \pm 0.011) \cdot 10^{-3}$	PDG (2012)
$\mathrm{BR}(K_0 \to \pi_0\nu\nu)$	$\leq 2.6 \cdot 10^{-8}$	E391a (2010)
$\mathrm{BR}(K_+ \to \pi_+\nu\nu)$	$1.73^{+1.15}_{-1.05} \cdot 10^{-10}$	E949 (2008)

Consider only flavour mixing **between the 2nd and 3rd generations** of squarks (less constrained and most interesting) — seven independent NMFV-parameters

$$\delta_{LL}, \quad \delta_{u,RR}, \quad \delta_{u,RL}, \quad \delta_{u,LR}, \quad \delta_{d,RR}, \quad \delta_{d,RL}, \quad \delta_{d,LR}$$

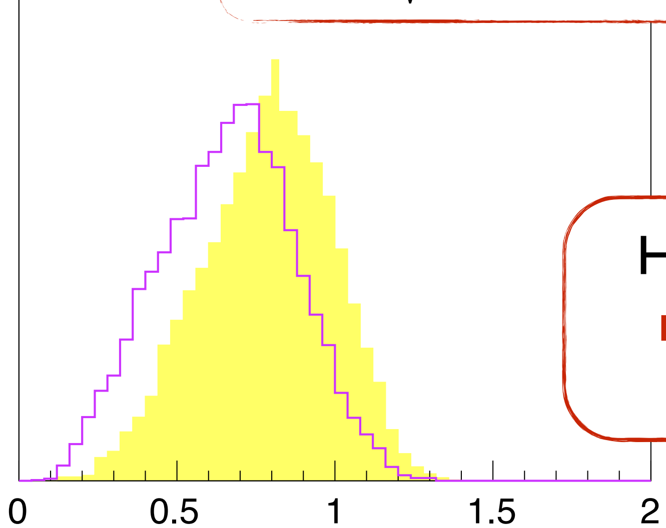
TeV scale MSSM — flavour-violating parameters

Extensive analysis of the MSSM with squark NMFV featuring 22 parameters at the TeV scale — **Markov Chain Monte Carlo (MCMC) study**

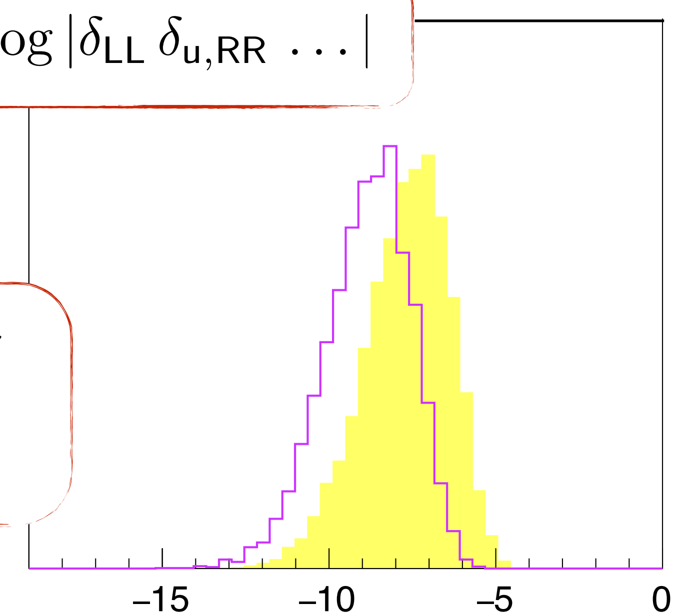


$$|\tilde{\delta}| = \sqrt{\delta^2_{\mathrm{LL}} + \delta^2_{\mathrm{u,RR}} + \dots}$$

$$\log|\Pi_\delta| = \log|\delta_{\mathrm{LL}}\,\delta_{\mathrm{u,RR}}\,\dots|$$



Hypothesis of NMFV in the squark sector
not obviously disfavoured by exp. data
(B-physics, K-physics, Higgs mass, …)



De Causmaecker, Fuks, Herrmann, Mahmoudi, O'Leary, Porod, Sekmen, Strobbe — JHEP 1511 (2015) 125 — arXiv:1509.05414 [hep-ph]

Recasting of existing LHC limits including NMFV in the squark sector

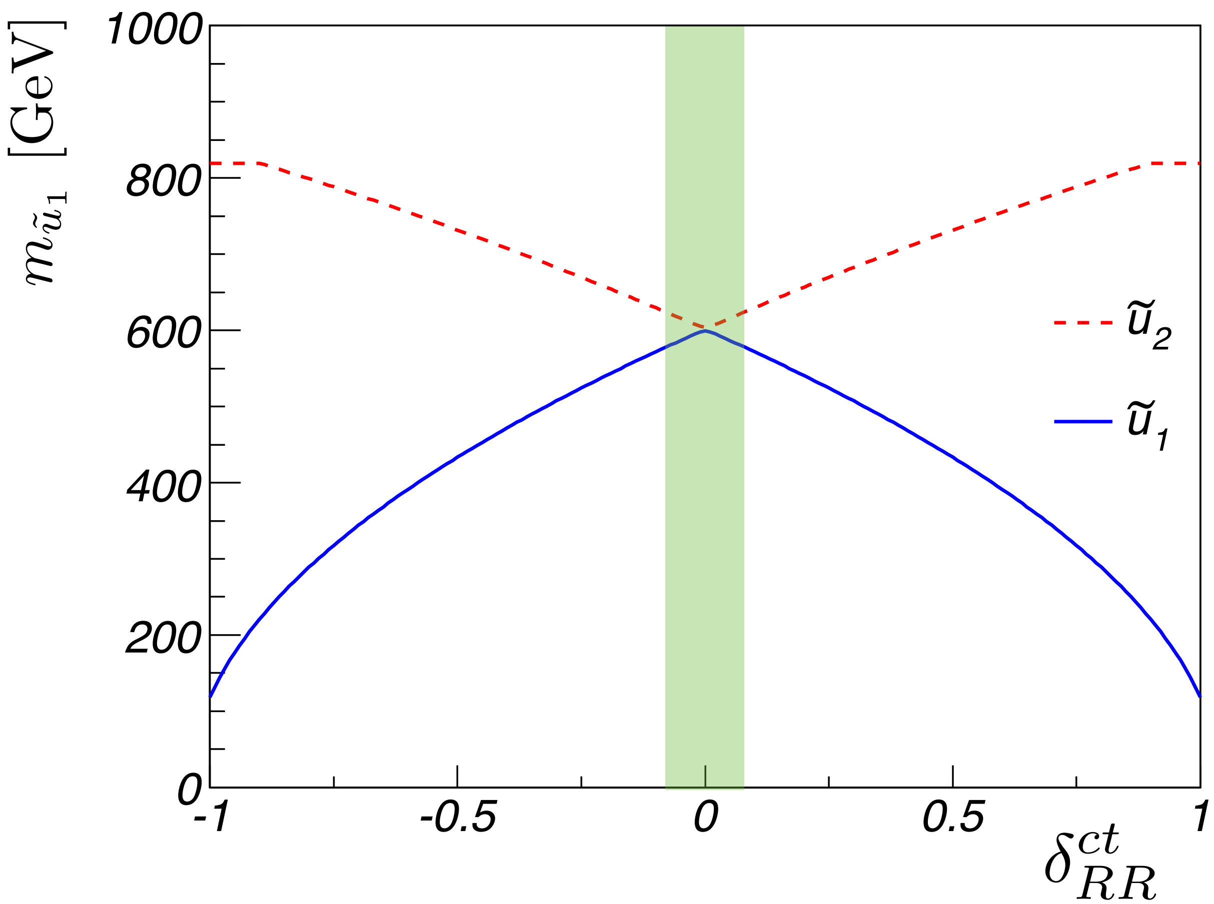
Chakraborty, Endo, Fuks, Herrmann, Nojiri, Pani, Polesello — PhysTeV Les Houches 2017 — arXiv:1803.10379 [hep-ph]
Chakraborty, Endo, Fuks, Herrmann, Nojiri, Pani, Polesello — arXiv:1808.07488 [hep-ph]

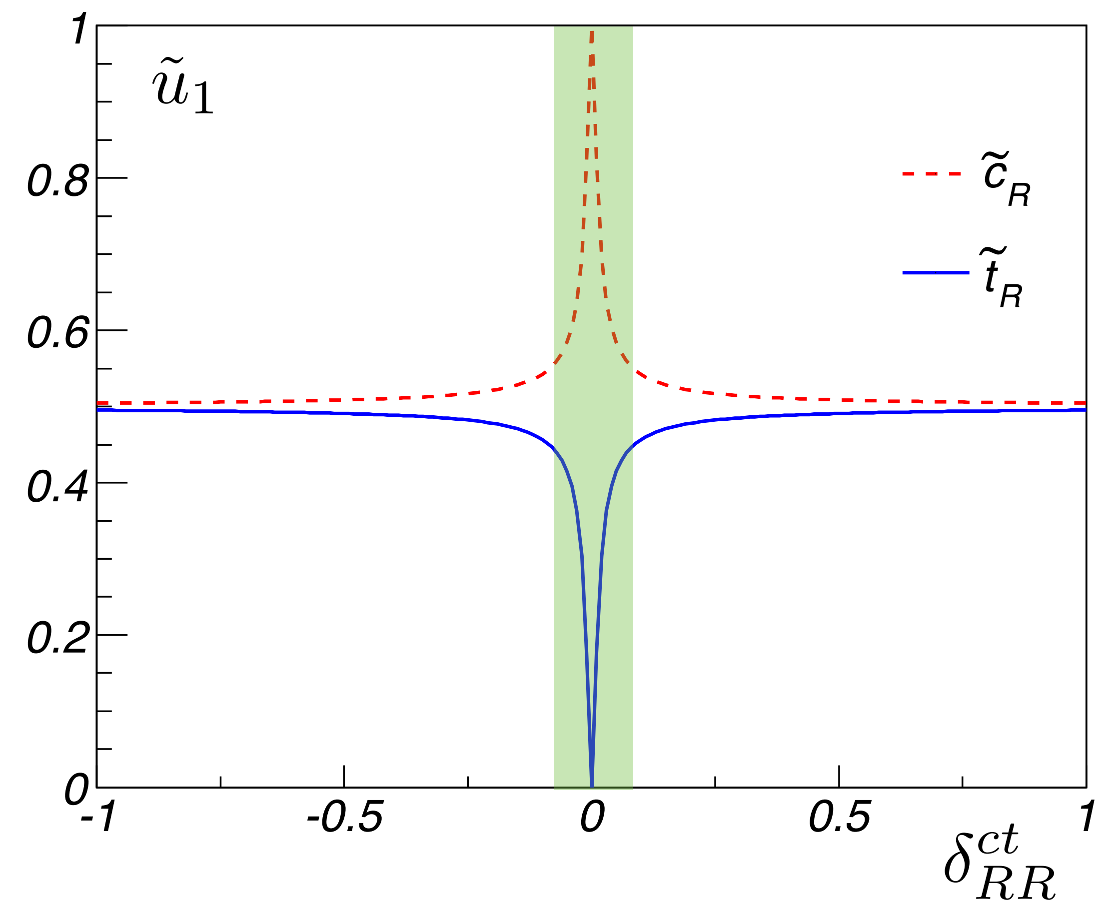
Simplified parameter setup featuring NMFV

Two active squark flavours — **bino-like neutralino** — all other states decoupled

$$\begin{pmatrix} \tilde{u}_1 \\ \tilde{u}_2 \end{pmatrix} = \begin{pmatrix} \cos\theta_{tc} & \sin\theta_{tc} \\ -\sin\theta_{tc} & \cos\theta_{tc} \end{pmatrix} \begin{pmatrix} \tilde{c}_R \\ \tilde{t}_R \end{pmatrix} \qquad m_{\tilde{\chi}_1^0} < m_{\tilde{u}_1} < m_{\tilde{u}_2}$$

This four-parameter setup captures the essential features of non-minimal flavour mixing

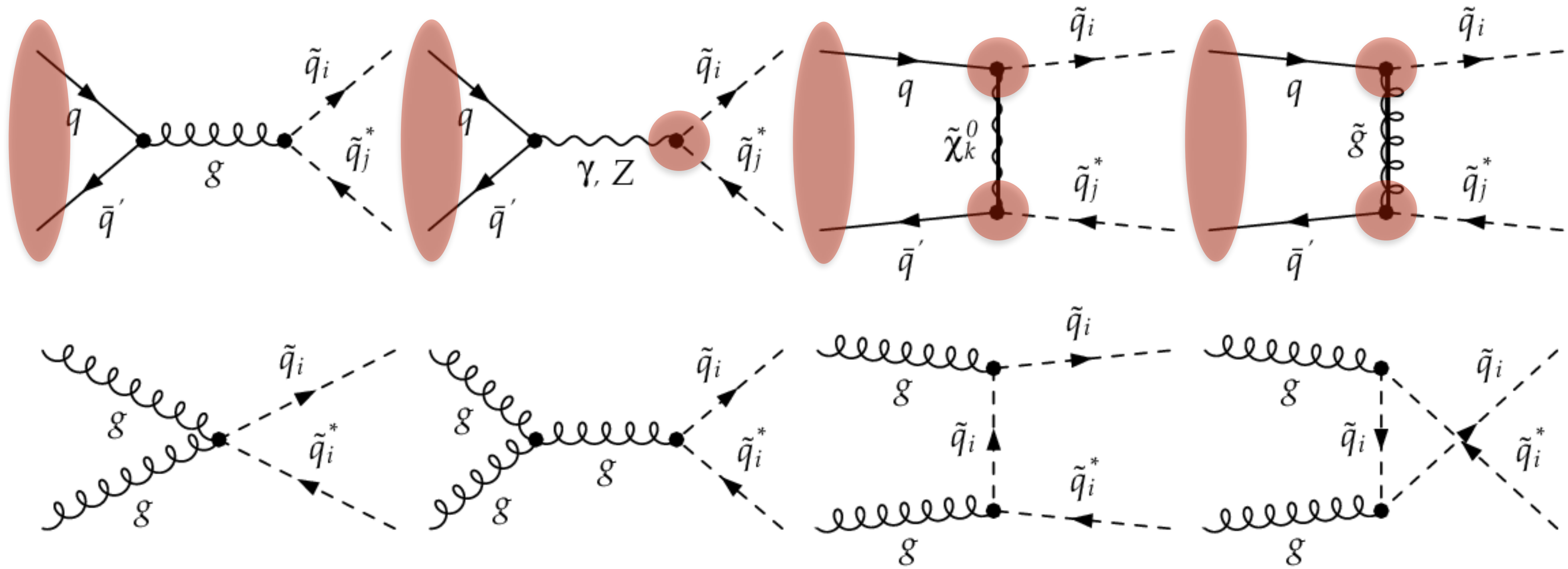




Chakraborty, Endo, Fuks, Herrmann, Nojiri, Pani, Polesello — PhysTeV Les Houches 2017 — arXiv:1803.10379 [hep-ph]
Chakraborty, Endo, Fuks, Herrmann, Nojiri, Pani, Polesello — arXiv:1808.07488 [hep-ph]

Squark production and decay in the NMFV-MSSM

The flavour-violating elements influence squark masses, flavour decomposition, production cross-sections and open new decay channels — characteristic NMFV signatures at LHC



Impact on production cross-section moderate — mainly squark mass dependence

Bruhnke, Herrmann, Porod — JHEP 09:006, 1-35 (2010) — arXiv:1007.2100 [hep-ph]
Bartl, Eberl, Herrmann, Hidaka, Majerotto, Porod — Phys. Lett. B 698: 380-388 (2011) — arXiv:1007.5483 [hep-ph]
Bartl, Eberl, Ginina, Herrmann, Hidaka, Majerotto, Porod — Phys. Rev. D 84: 115026 (2011) — arXiv:1107.2775 [hep-ph]
Bartl, Eberl, Ginina, Herrmann, Hidaka, Majerotto, Porod — Int.J.Mod.Phys. 29: 1450035 (2014) — arXiv:1212.4688 [hep-ph]
Bartl, Eberl, Ginina, Hidaka, Majerotto — Phys. Rev. D91: 015007 (2015) — arXiv:1411.2840 [hep-ph]
Chakraborty, Endo, Fuks, Herrmann, Nojiri, Pani, Polesello — PhysTeV Les Houches 2017 — arXiv:1803.10379 [hep-ph]
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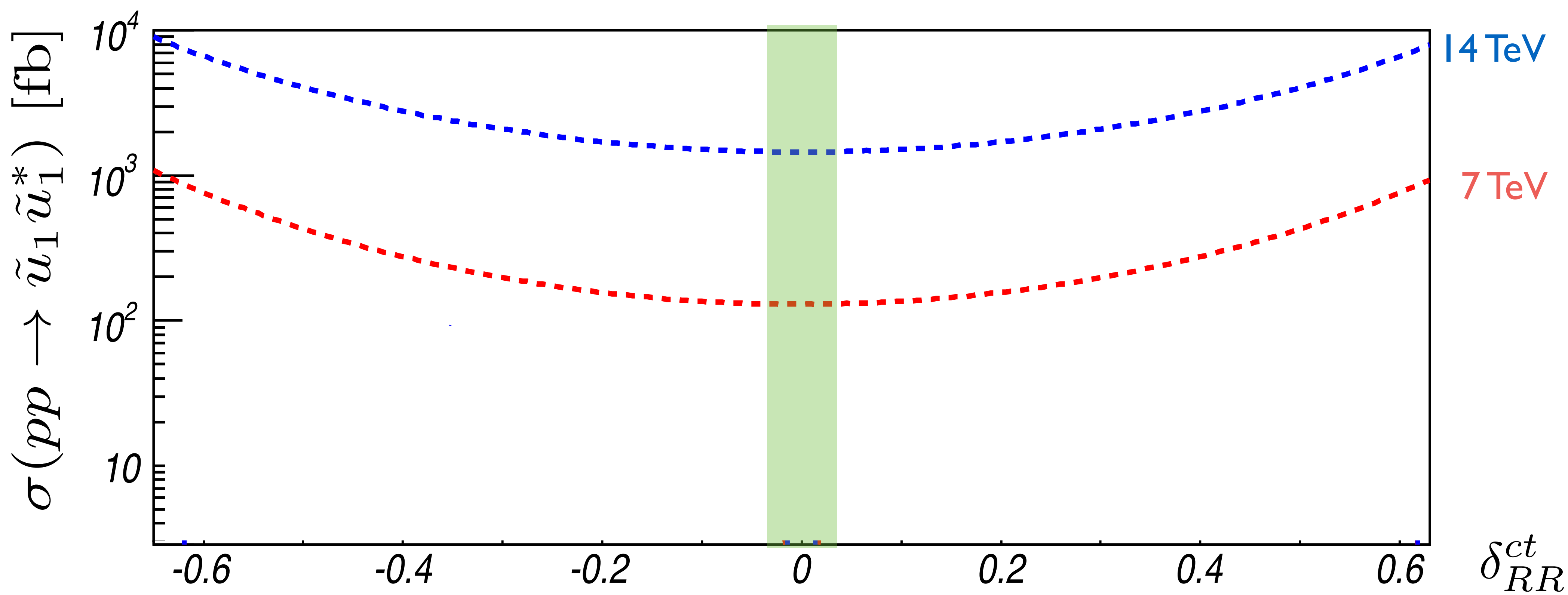

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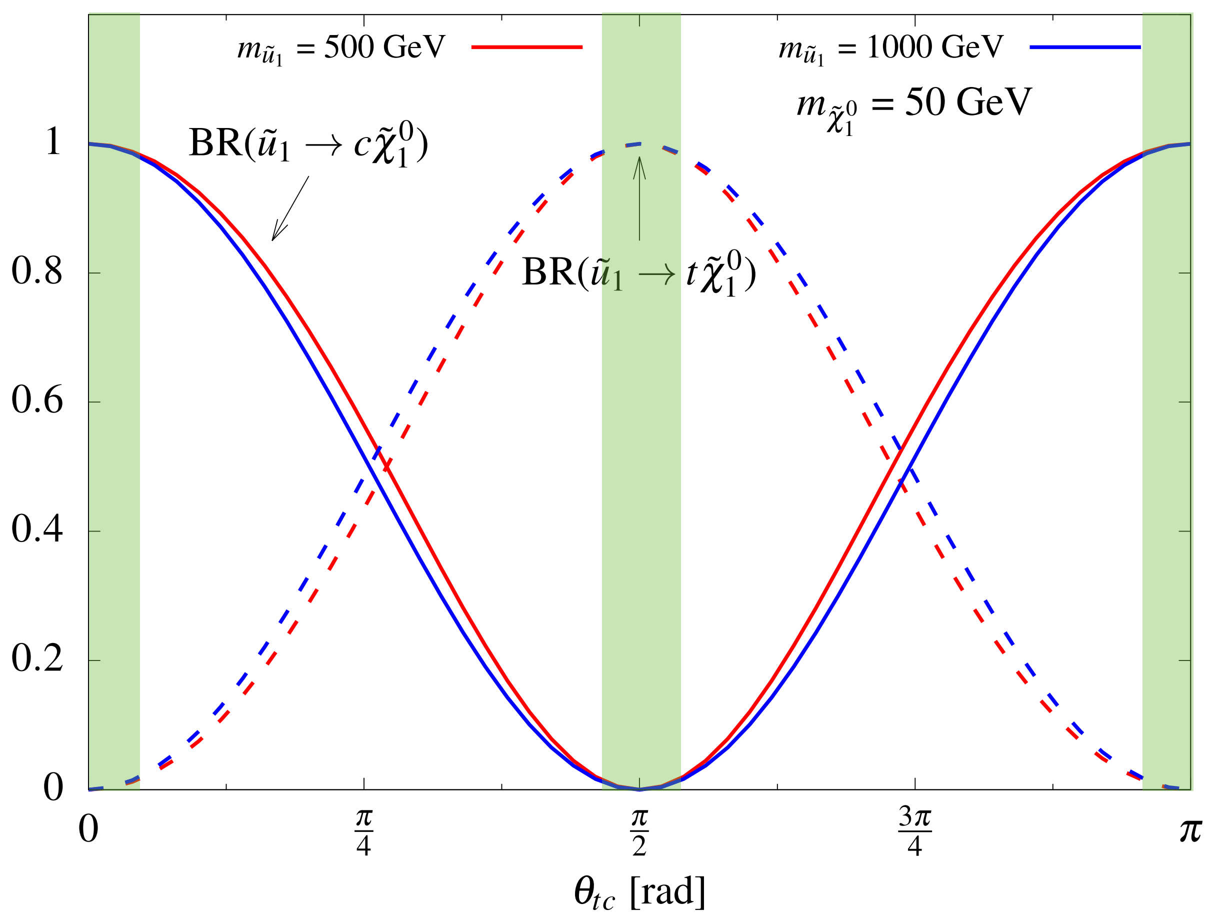

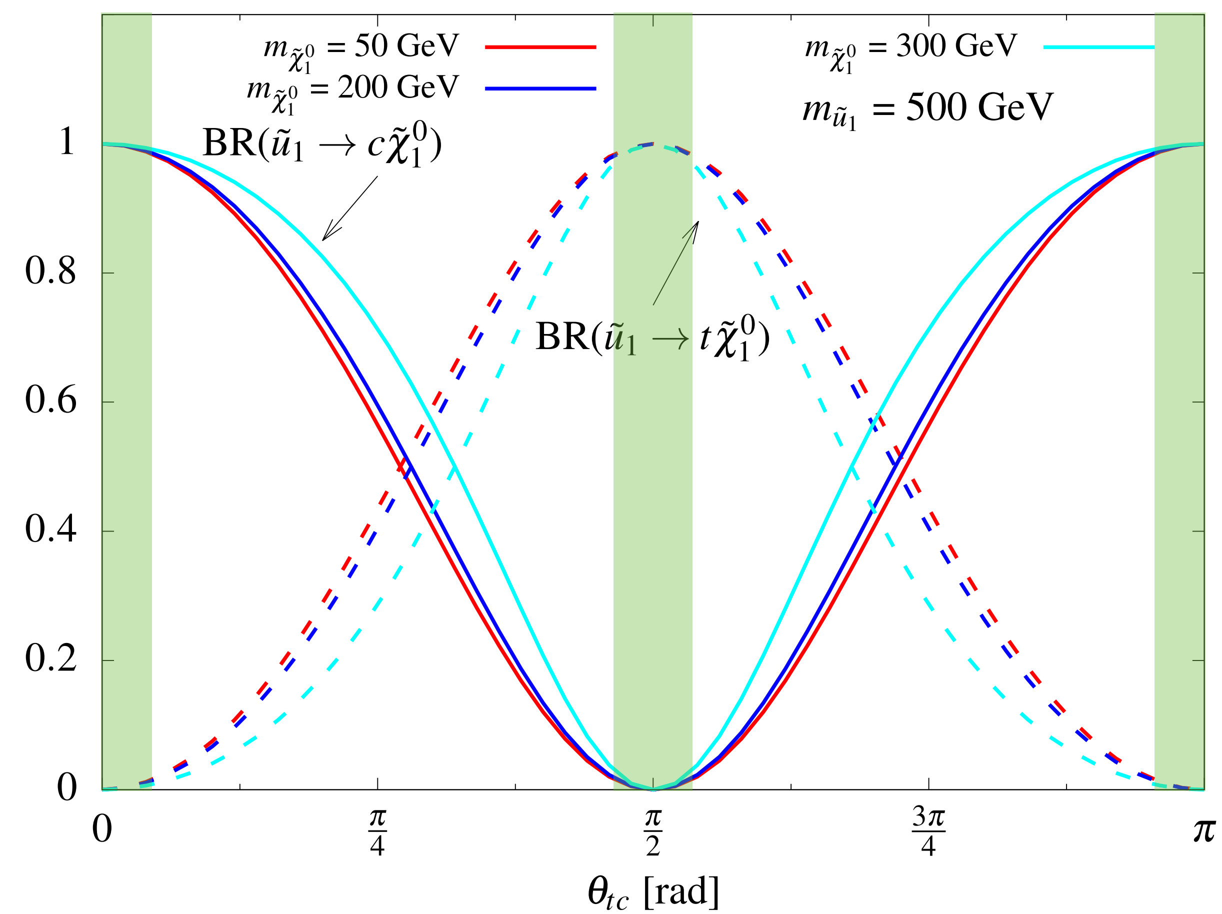

Both decay modes of a mixed squark can be equally important — **expect weaker limits!**
Impact of mass configuration on the branching ratio less important than flavour content…

Chakraborty, Endo, Fuks, Herrmann, Nojiri, Pani, Polesello — PhysTeV Les Houches 2017 — arXiv:1803.10379 [hep-ph]
Chakraborty, Endo, Fuks, Herrmann, Nojiri, Pani, Polesello — arXiv:1808.07488 [hep-ph]

Recasting LHC limits on squark searches

Evaluate sensitivity of the two relevant searches within the simplified setup…

$$pp \to t\bar{t} + E_T^{\rm miss}$$ ATLAS coll. — JHEP 1806 (2018) 108 — arXiv: 1711.11530

$$pp \to c\bar{c} + E_T^{\rm miss}$$ ATLAS coll. — arXiv: 1805.01649

… relying on the acceptances and efficiencies provided by the ATLAS collaboration

“discovery tN_med”

“discovery tN_high”

Estimate signal yields…

— NLO+NLL corrected stop pair production   Borschensky *et al.* – Eur.Phys.J. C74 (2014) 3174 – arXiv:1407.5066

— branching ratios (seen on previous slide)

… and compare to ATLAS model-independent upper limits

We cannot reproduce the ATLAS multi-bin fit — **our limits are more conservative**…

Chakraborty, Endo, Fuks, Herrmann, Nojiri, Pani, Polesello — PhysTeV Les Houches 2017 — arXiv:1803.10379 [hep-ph]
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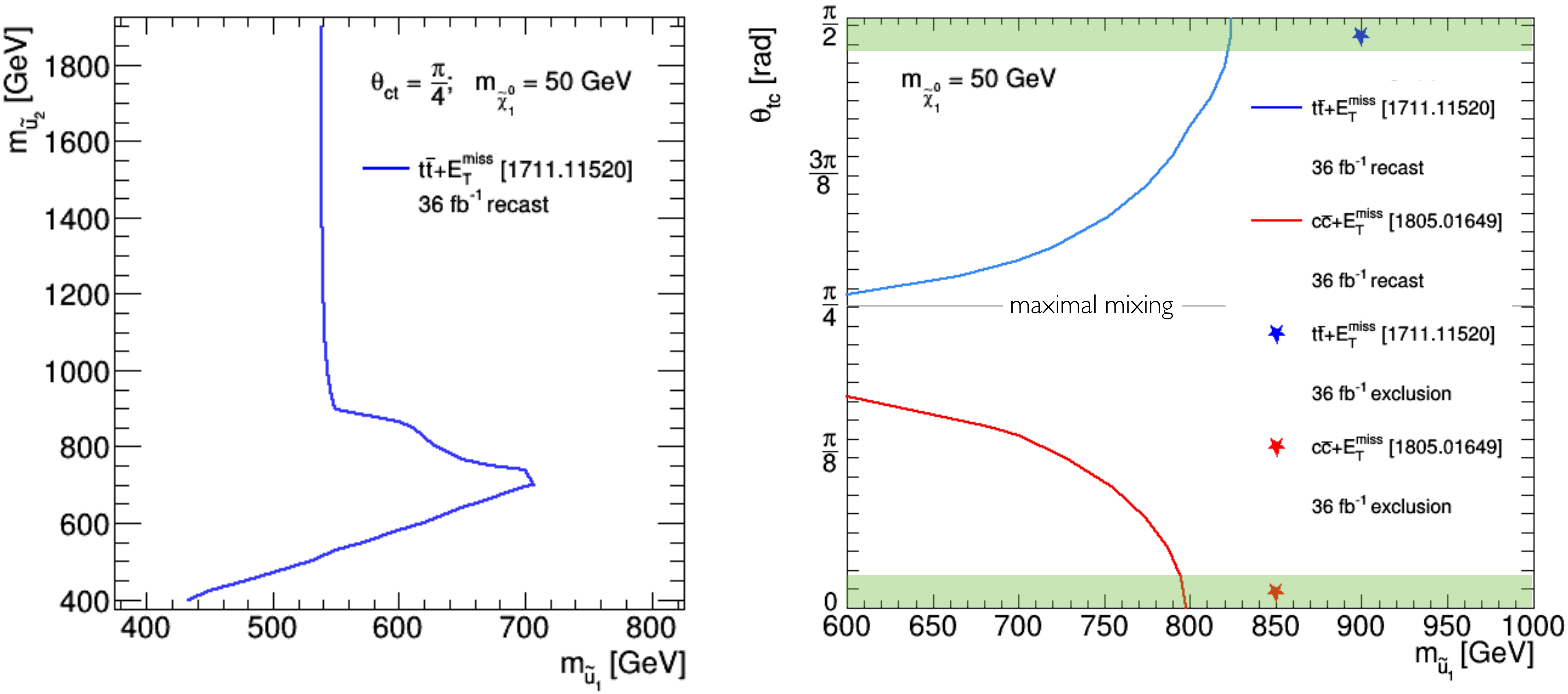


For maximal mixing, the "MFV limits" are weakened by up to around 500 GeV

(less weakened for $m_1 \sim m_2$ since the higher cross-section compensates the smaller branching ratio)

Relaxing the MFV-hypothesis has important impact on the obtained limits

Current searches have significantly reduced sensitivity in case of sizeable flavour mixing…

Chakraborty, Endo, Fuks, Herrmann, Nojiri, Pani, Polesello — PhysTeV Les Houches 2017 — arXiv:1803.10379 [hep-ph]
Chakraborty, Endo, Fuks, Herrmann, Nojiri, Pani, Polesello — arXiv:1808.07488 [hep-ph]

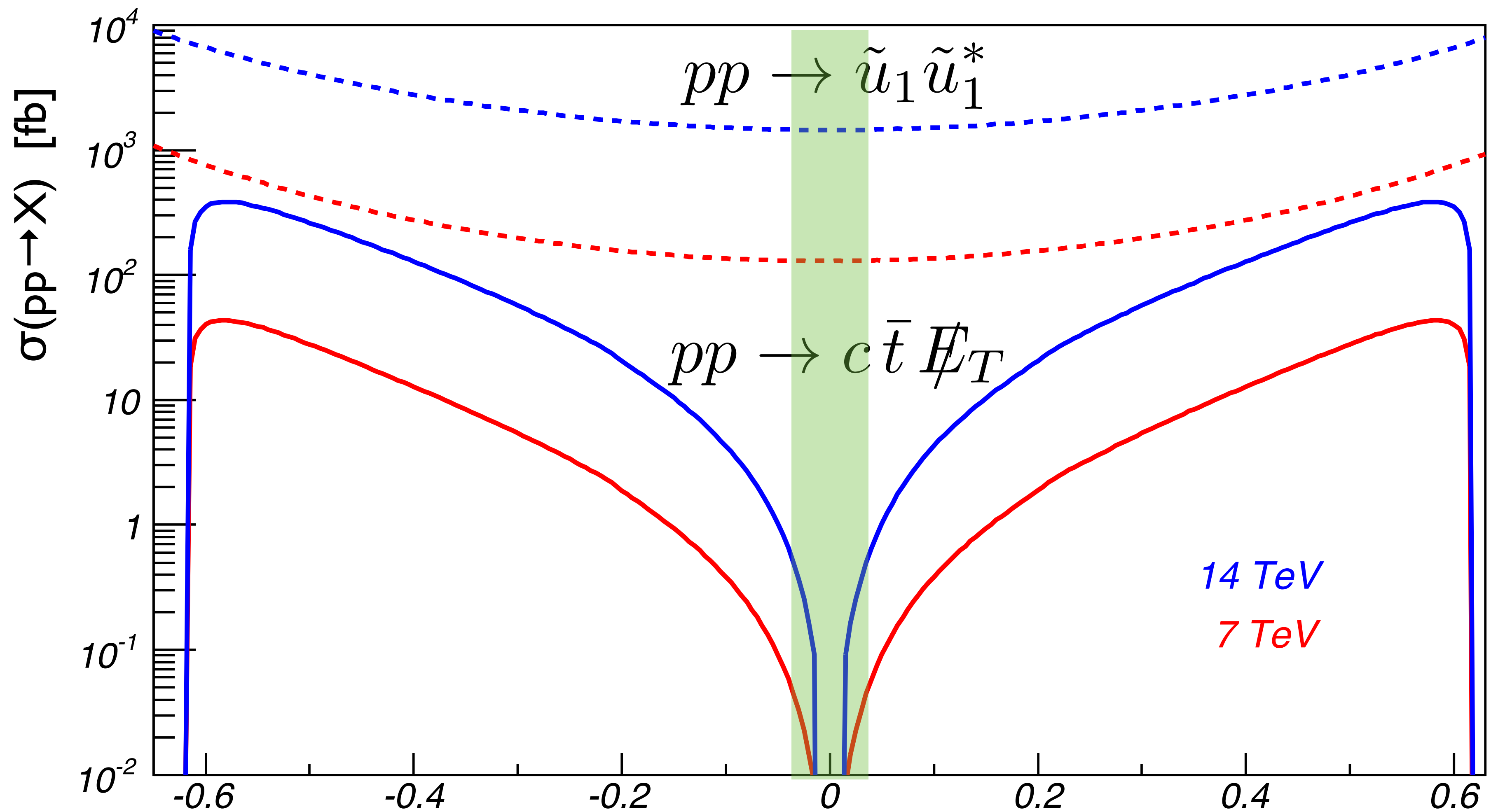
Proposal for a dedicated LHC search for NMFV in the squark sector

Chakraborty, Endo, Fuks, Herrmann, Nojiri, Pani, Polesello — PhysTeV Les Houches 2017 — arXiv:1803.10379 [hep-ph]
Chakraborty, Endo, Fuks, Herrmann, Nojiri, Pani, Polesello — arXiv:1808.07488 [hep-ph]

Dedicated NMFV search at LHC — proposal

Shortcomings of previous analyses may be addressed by taking into account the **"*tc*-channel"**

$$pp \;\to\; \tilde{u}_1\,\tilde{u}_1^* \;\to\; t\,c\,\tilde{\chi}_1^0\,\tilde{\chi}_1^0 \;\to\; \ell\,b\,c\,E_T^{\rm miss}$$



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$$pp \to \tilde{u}_1 \tilde{u}_1^* \to t\, c\, \tilde{\chi}_1^0 \tilde{\chi}_1^0 \to \ell\, b\, c\, E_T^{\text{miss}}$$

Event preselection

exactly one isolated electron or muon with $p_T > 25$ GeV and $|\eta| < 2.5$

at least one *b*-tagged jet with $p_T > 50$ GeV and $|\eta| < 2.5$

invariant mass of the *b*-lepton system $m_{b\ell} < 160$ GeV (from top decay)

Case A

veto additional *b*-jets

extra light jet with $p_T > 100$ GeV

Case B

only one *b*-tagged jet with $m_{b\ell} < 160$ GeV

c-tagged leading jet $m_{j\ell} > 160$ GeV

failing *b*-tagging for remaining jets $m_{j\ell} > 160$ GeV

Use asymmetric m_{T2} variable to reduce dilepton background: $am_{T2} > 200$ GeV

Further background reduction by constructing another transverse m_{T2} variable: m_{T2blj}

Chakraborty, Endo, Fuks, Herrmann, Nojiri, Pani, Polesello — PhysTeV Les Houches 2017 — arXiv:1803.10379 [hep-ph]

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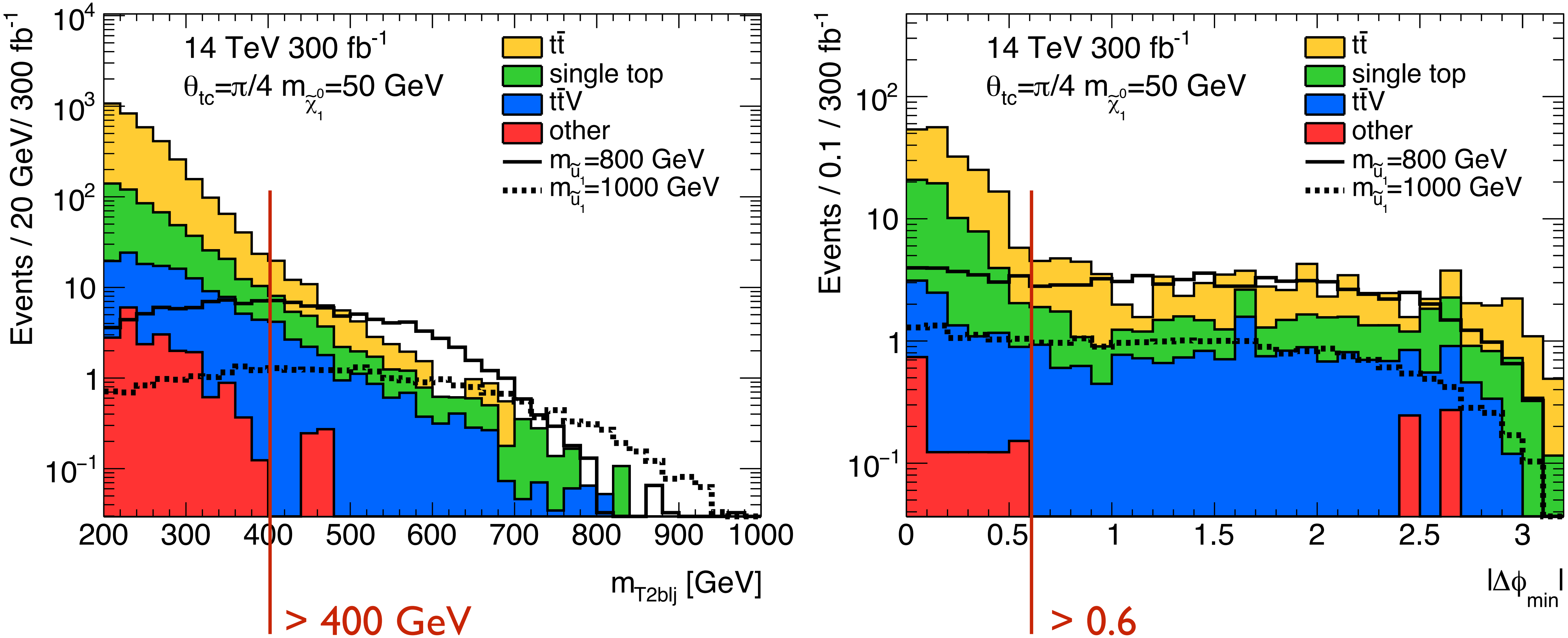
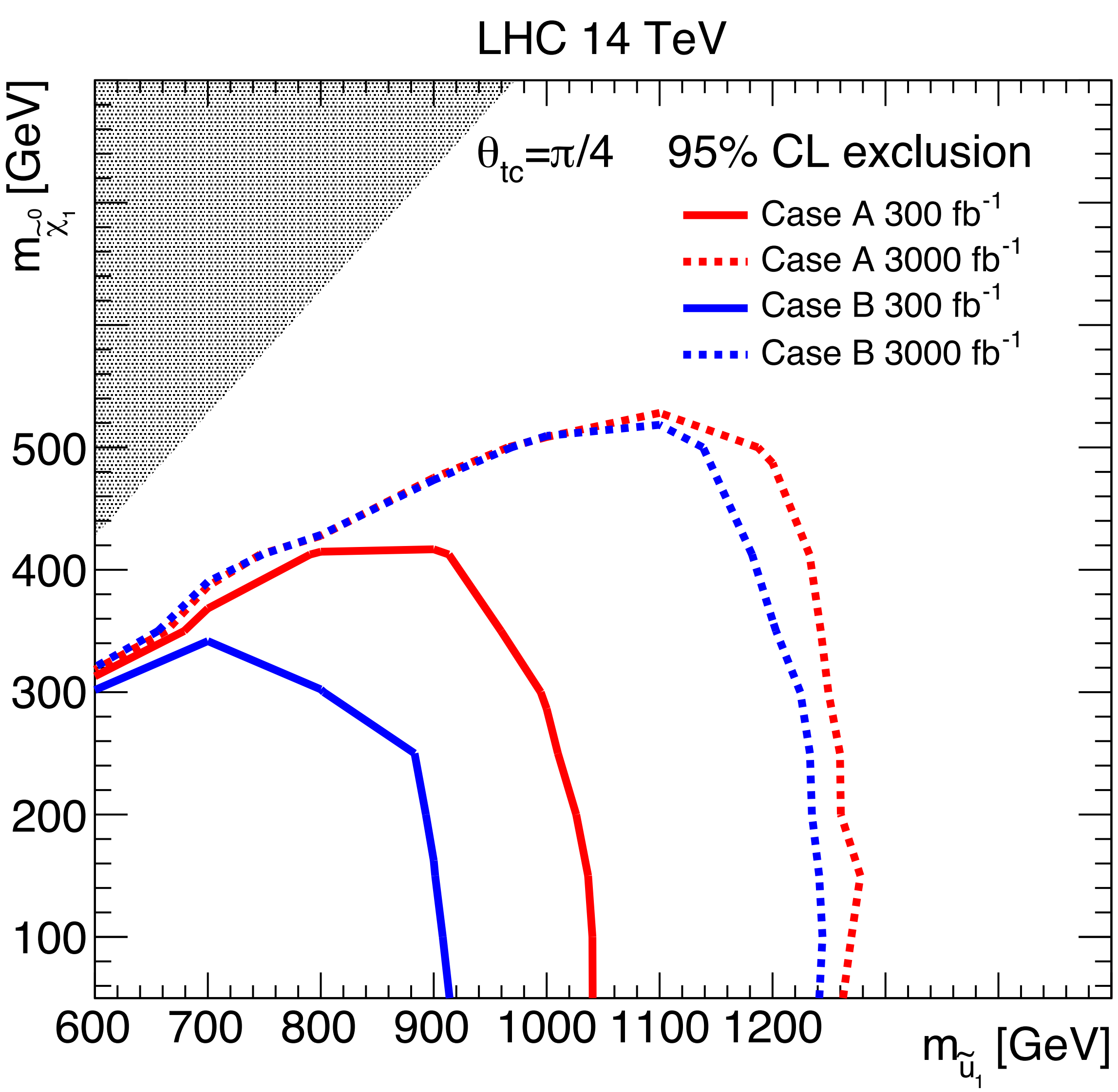
Dedicated NMFV search at LHC — event selection

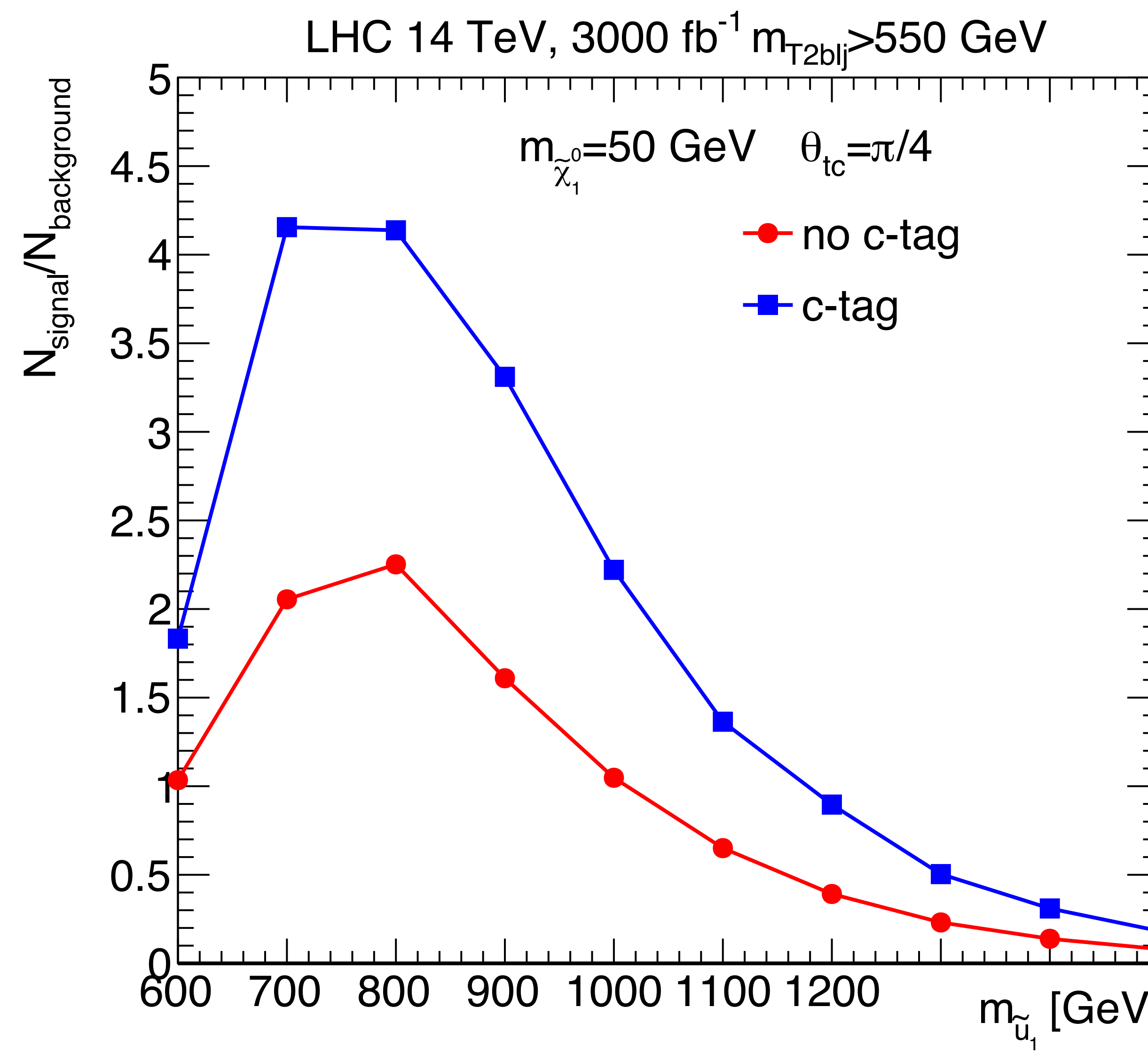


Simplified NMFV model implemented in `FeynRules 2.0` and `MadGraph5_aMC@NLO`
Generate LO matrix elements convoluted with `NNPDF 3.0` parton distribution functions
Parton showering and hadronisation using `PYTHIA 8.2`
Reweight each event to match the production cross-section estimated at NLO+NLL accuracy
Jet reconstruction using `FASTJET` and compared to `DELPHES`

Chakraborty, Endo, Fuks, Herrmann, Nojiri, Pani, Polesello — PhysTeV Les Houches 2017 — arXiv:1803.10379 [hep-ph]
Chakraborty, Endo, Fuks, Herrmann, Nojiri, Pani, Polesello — arXiv:1808.07488 [hep-ph]

Dedicated NMFV search at LHC — expected reach





Analysis statistics dominated at low luminosity — large difference between Case A and Case B
Difference between two methods reduced at higher luminosity

Signal-background ratio higher when incorporating *c*-tagging

Chakraborty, Endo, Fuks, Herrmann, Nojiri, Pani, Polesello — PhysTeV Les Houches 2017 — arXiv:1803.10379 [hep-ph]
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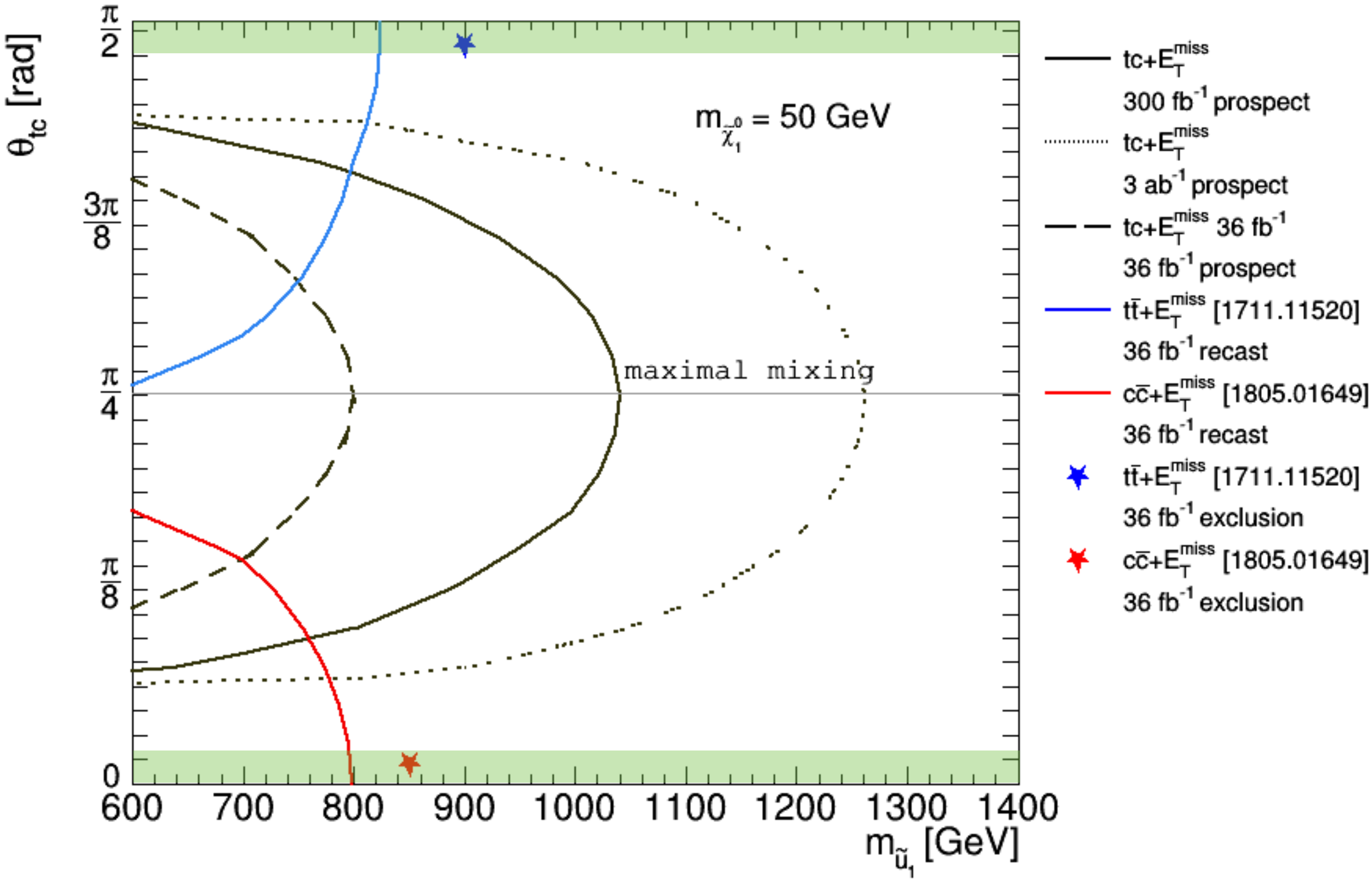

Chakraborty, Endo, Fuks, Herrmann, Nojiri, Pani, Polesello — PhysTeV Les Houches 2017 — arXiv:1803.10379 [hep-ph]
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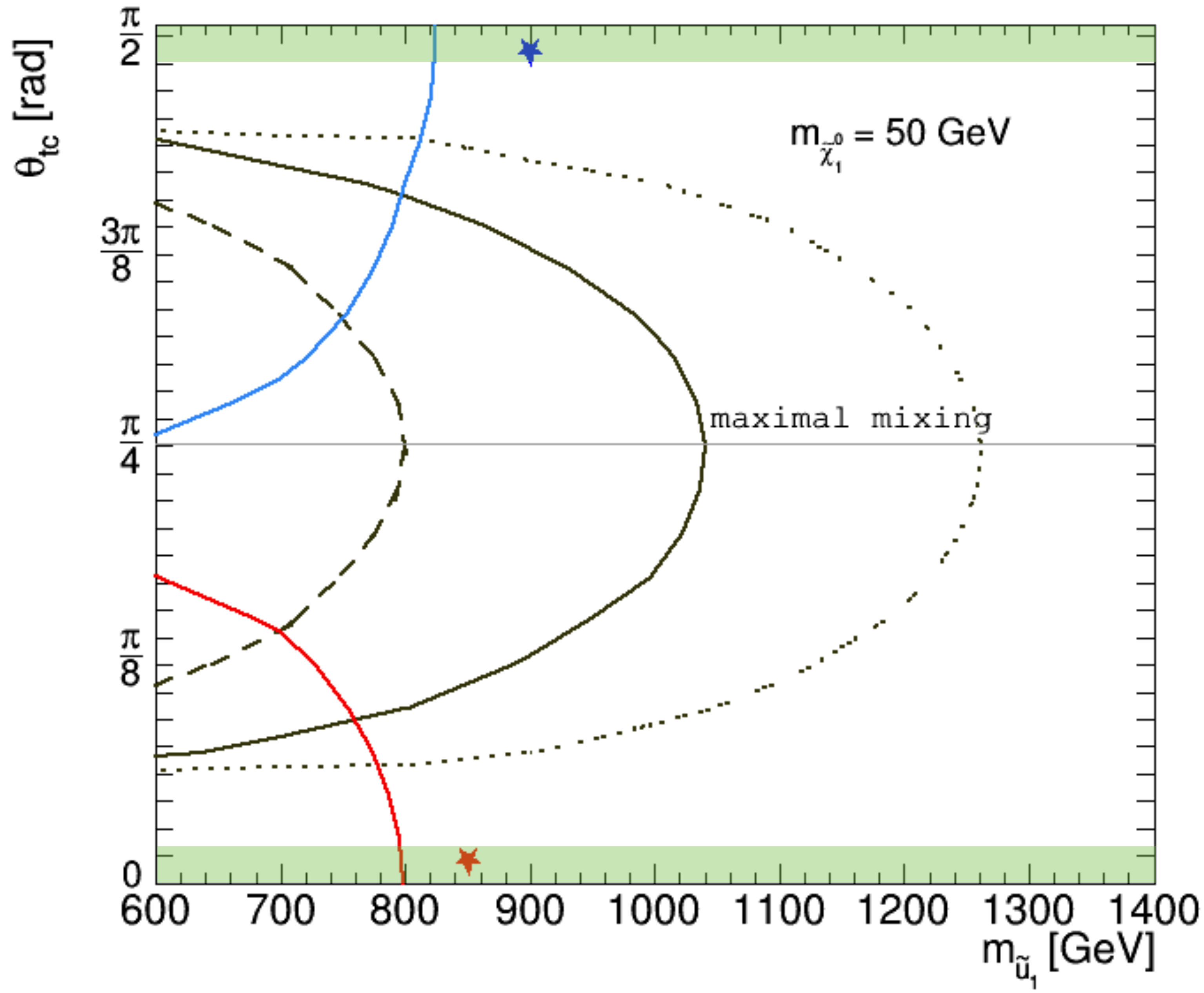
Conclusions



"SUSY is not dead…!"

New physics might be hiding in (so far) **unexplored corners of parameter space, beyond the** (sometimes too simple) **assumptions and thus not covered by exp. searches**

Taking into account flavour mixing and "mixed signatures" would be very interesting and open the searches to interesting physics cases…

Physics at TeV Colliders — Les Houches 2019

Session 1 (SM): 10-19 june 2019
Working groupes: Higgs / Loops and multilegs / Tools and Monte-Carlos

Session 2 (BSM): 19-28 june 2019
Working groupes: Higgs / New physics / Tools and Monte-Carlos

Save the dates! More information soon… http://phystev.cnrs.fr