Towards the identification of the SUSY flavour structure

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De Causmaecker, Fuks, Herrmann, Mahmoudi, O'Leary, Porod, Sekmen, Strobbe — JHEP 1511 (2015) 125 — arXiv:1509.05414 [hep-ph]
Chakraborty, Endo, Fuks, Herrmann, Nojiri, Pani, Polesello — PhysTeV Les Houches 2017 — arXiv:1803.10379 [hep-ph]
Chakraborty, Endo, Fuks, Herrmann, Nojiri, Pani, Polesello — *work to be published*
Bernigaud, Herrmann — *work to be published*

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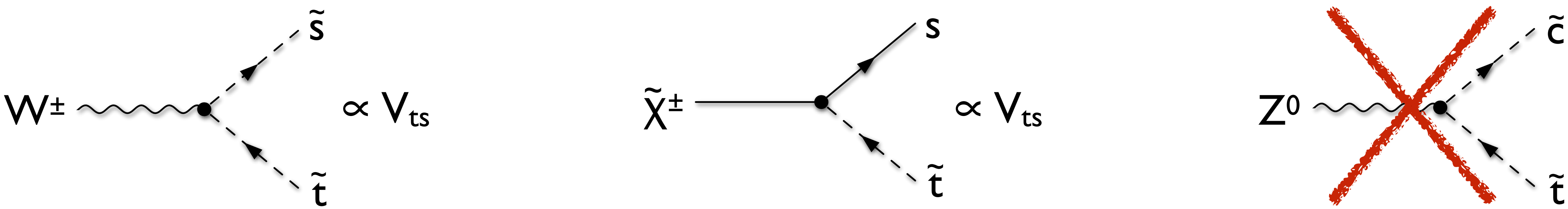
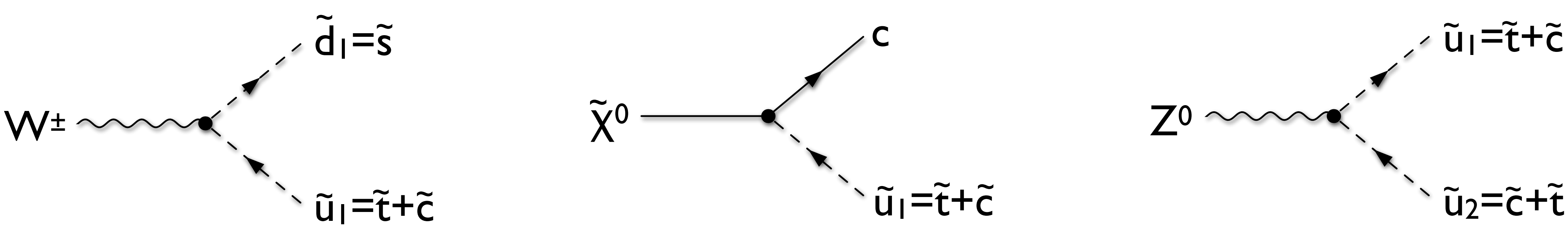
Squark flavour structure in the MSSM

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



MFV vs. NMFV…?
Disentangle flavour structure from LHC observations…?

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



The MSSM up-type squark sector

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

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

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

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

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

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

Quantity of interest for our analysis: **Stop-content of the lightest up-type squark**

$$x_{\tilde{t}} = (\mathcal{R}_{\tilde{u}})_{13}^2 + (\mathcal{R}_{\tilde{u}})_{16}^2$$

→

$x_{\tilde{t}} \approx 0\,,\; x_{\tilde{t}} \approx 1$ — **MFV**

$0 \lesssim x_{\tilde{t}} \lesssim 1$ — **NMFV**

Experimental constraints

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

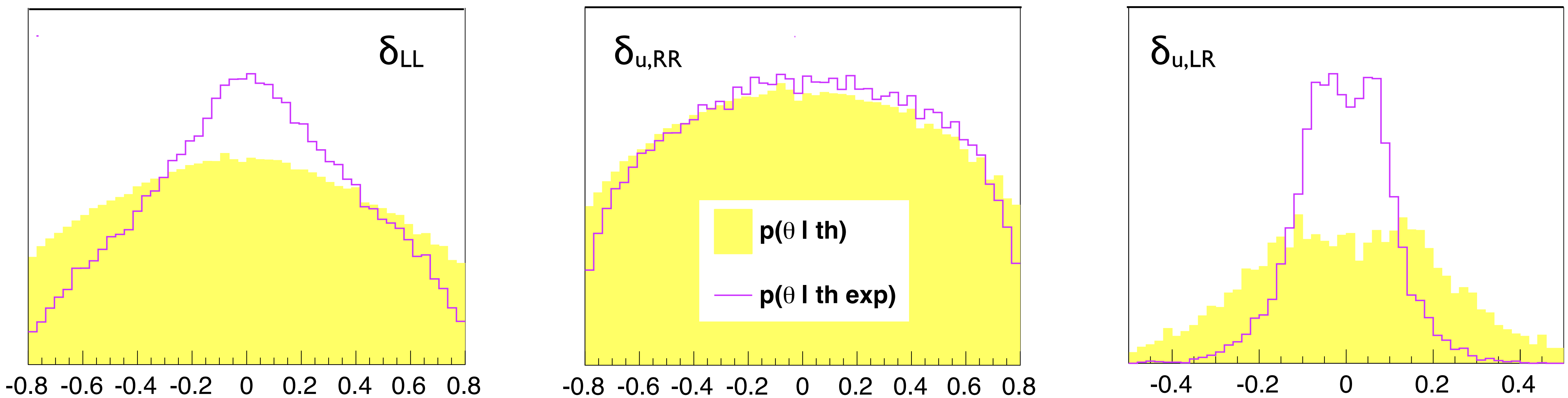
Observable	Exp. result and uncertainties	
m_h	(125.5 ± 2.5) GeV	ATLAS + CMS (2013)
$\text{BR}(B \to X_s \gamma)$	$(3.43 \pm 0.21^{\text{stat}} \pm 0.07^{\text{sys}} \pm 0.24^{\text{th}}) \cdot 10^{-4}$	HFAG (2013); Misiak et al. (2013), Mahmoudi (2007)
$\text{BR}(B_s \to \mu\mu)$	$(2.9 \pm 0.7^{\text{exp}}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

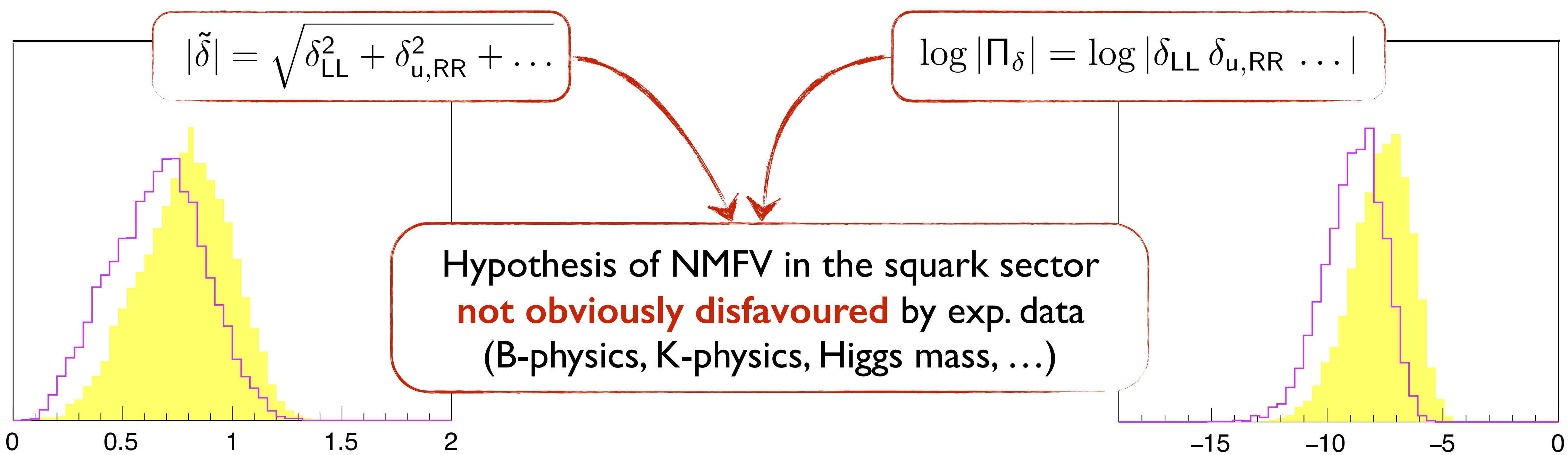
Consider only flavour mixing **between the 2nd and 3rd generations** of squarks (less constrained and most interesting) — seven independent NMFV-parameters

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

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**





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

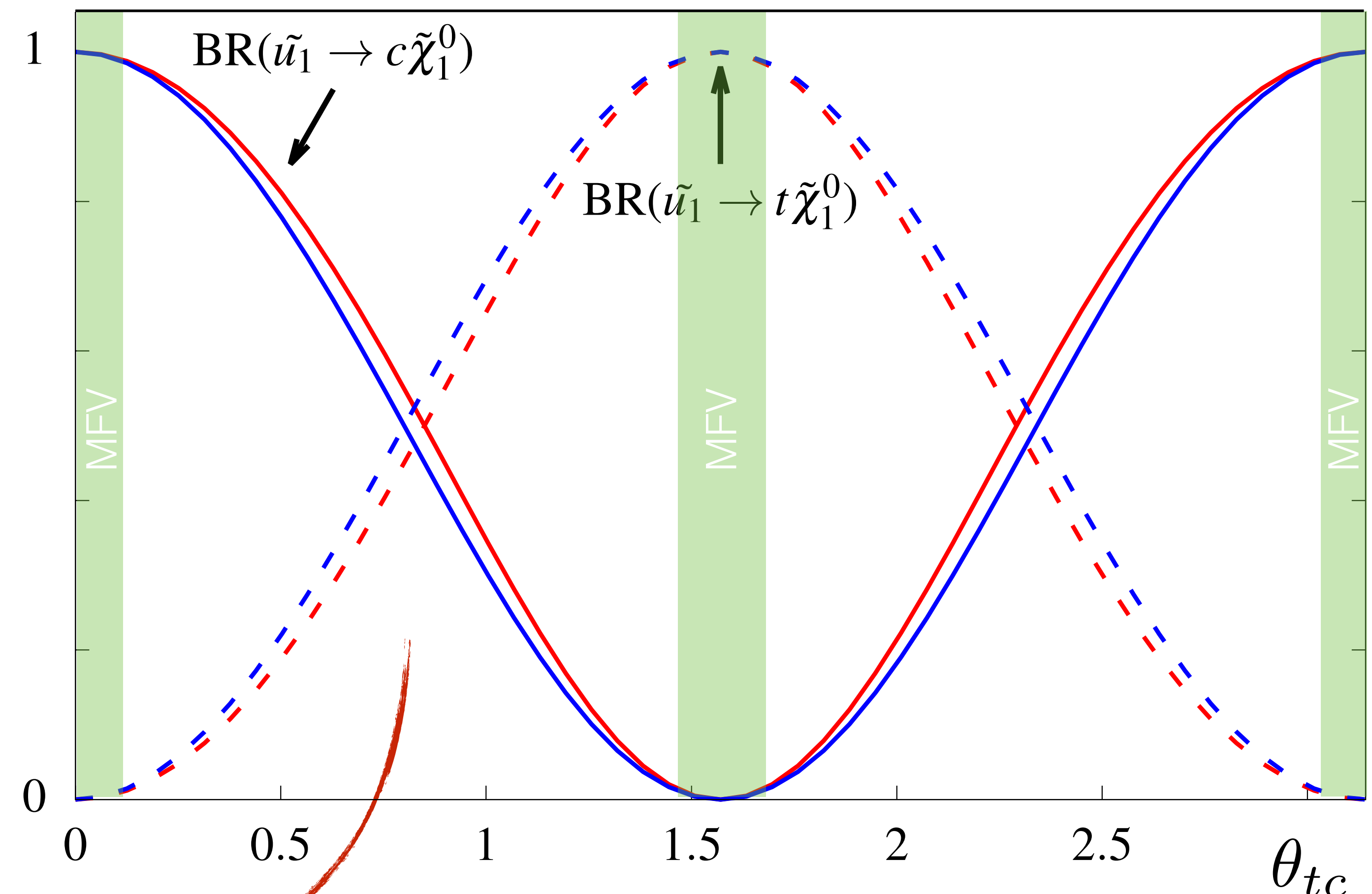
Signatures of squark flavour violation at the LHC

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

Simplified parameter space:

$$\begin{pmatrix} \tilde{u}_1 \\ \tilde{u}_2 \end{pmatrix} = \begin{pmatrix} \cos\theta_{tc} & \sin\theta_{tc} \\ -\sin\theta_{tc} & \cos\theta_{tc} \end{pmatrix} \begin{pmatrix} \tilde{c}_R \\ \tilde{t}_R \end{pmatrix}$$

$$pp \to \tilde{u}\tilde{u}^* \to t\bar{t}\, E_T^{\rm miss}$$
$$pp \to \tilde{u}\tilde{u}^* \to c\bar{c}\, E_T^{\rm miss}$$
$$pp \to \tilde{u}\tilde{u}^* \to t\bar{c}\, E_T^{\rm miss}$$



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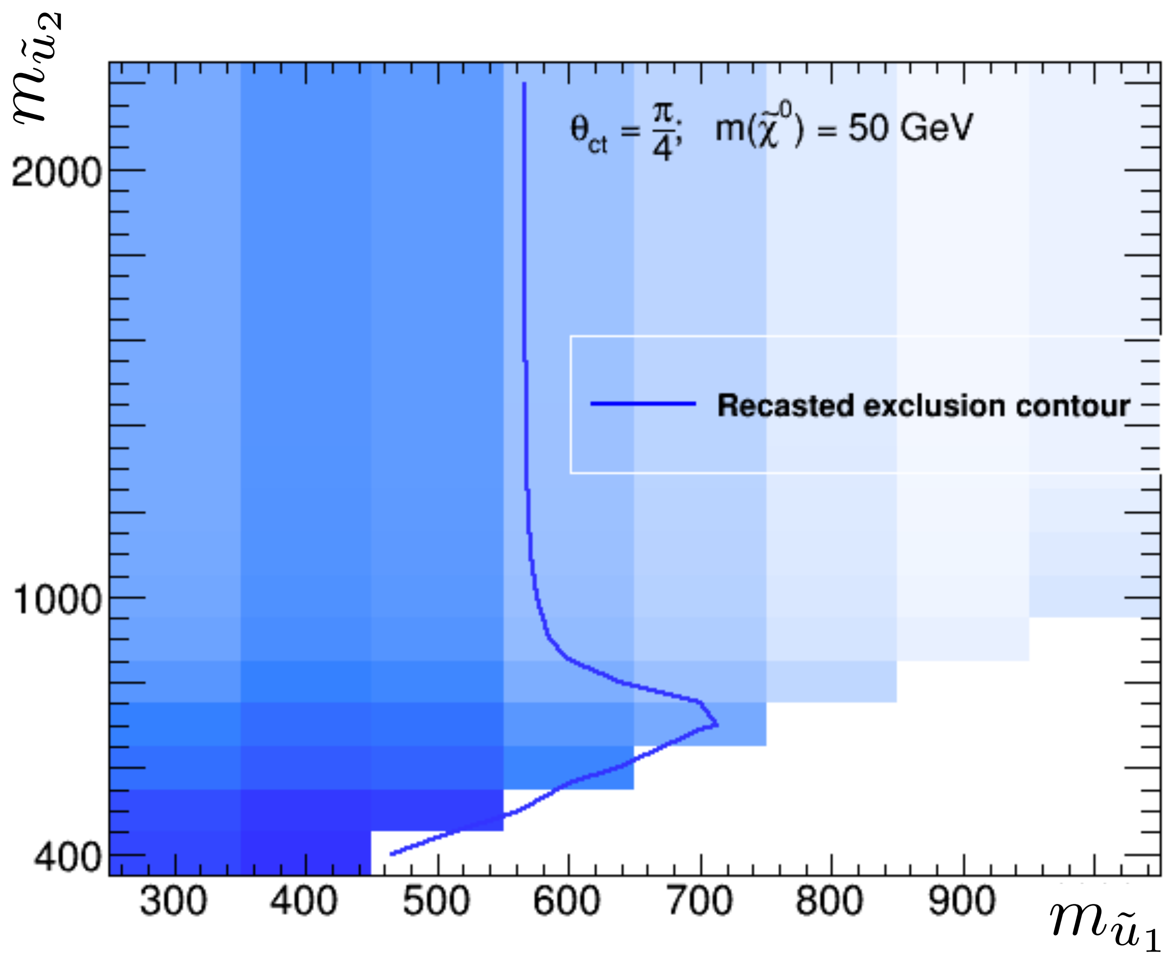
Chakraborty, Endo, Fuks, Herrmann, Nojiri, Pani, Polesello — PhysTeV Les Houches 2017 — arXiv:1803.10379 [hep-ph]
Chakraborty, Endo, Fuks, Herrmann, Nojiri, Pani, Polesello — *work to be published…*

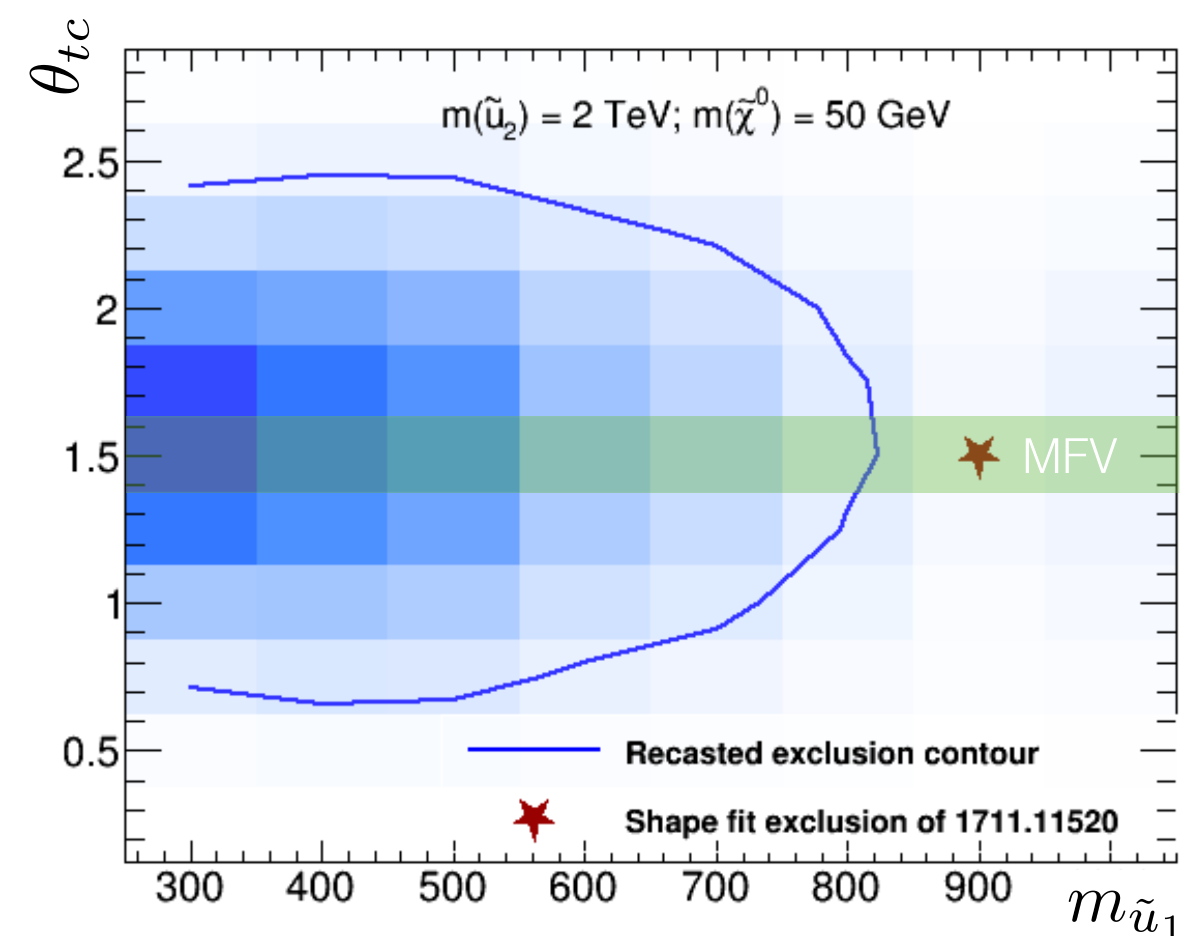
Recasting LHC limits on squark searches

Dedicated searches by ATLAS (and CMS): $\tilde{t}\tilde{t}^* \to t\bar{t}\,E_T^{\rm miss}$ $\tilde{c}\tilde{c}^* \to c\bar{c}\,E_T^{\rm miss}$

ATLAS Collaboration — arXiv:1711.11520 [hep-ex]

Recasting of the observed limits in the simplified parameter space $(m_{\tilde{u}_1}, m_{\tilde{u}_2}, \theta_{tc})$





Non-negligible mixing has important impact on the current exclusion limits

Obtained limits more conservative than original limits due to less complete analysis

(in particular: missing multi-bin information)

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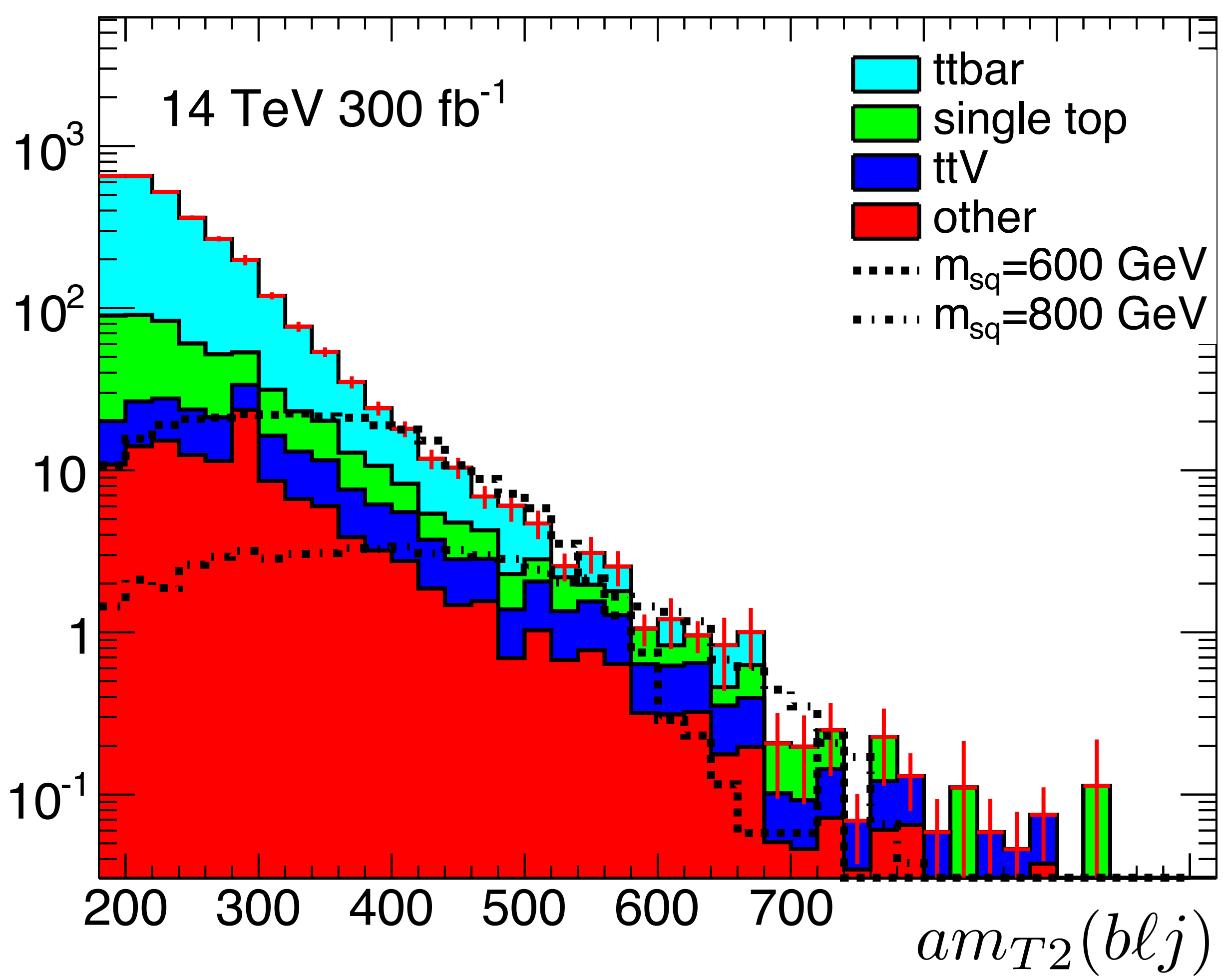
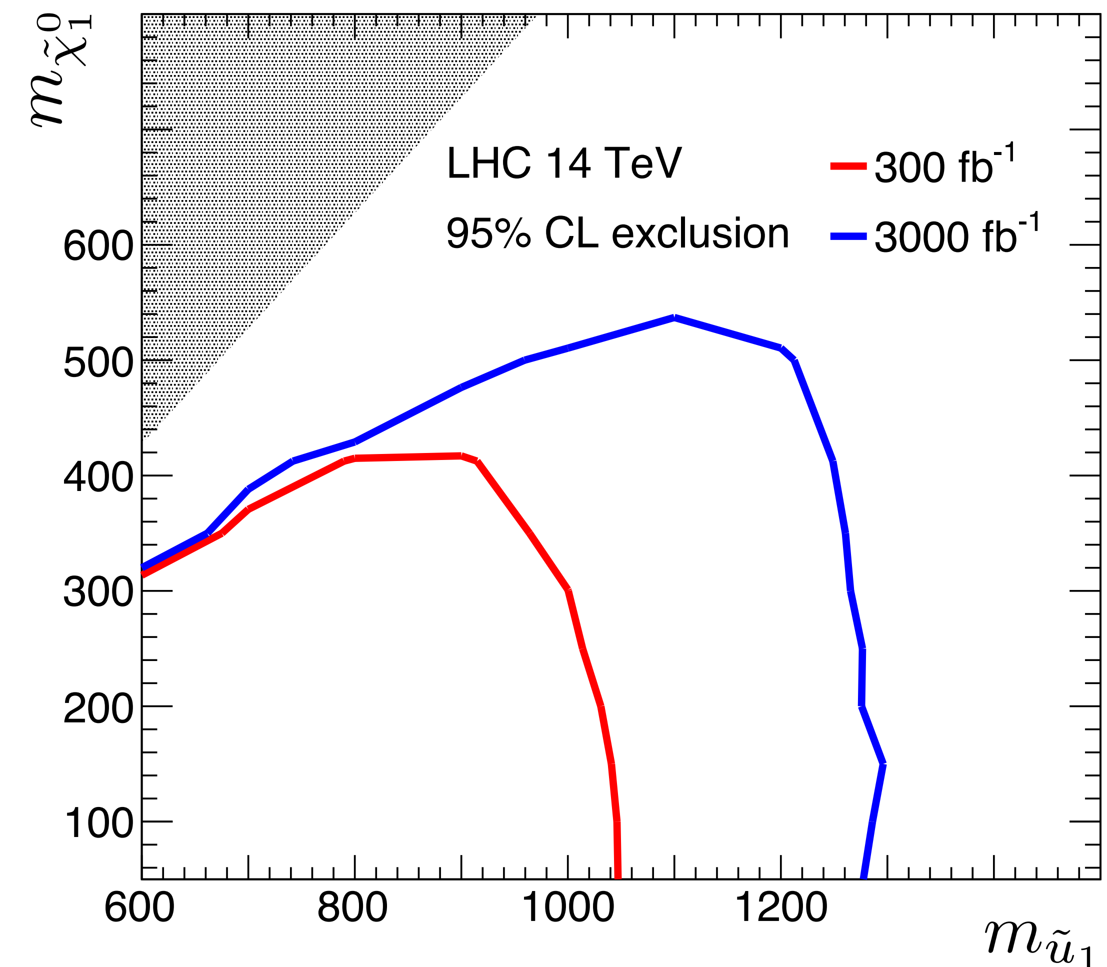
Chakraborty, Endo, Fuks, Herrmann, Nojiri, Pani, Polesello — *work to be published…*

Reach of a dedicated NMFV search at LHC

Defining dedicated kinematic variables allows signal-background discrimination such that **mixed stop scenarios with squark masses up to about 1 TeV would yield a 2σ excess at the LHC with 300 fb^{-1}** (this range being extended to about 1.3 TeV for 3000 fb^{-1})

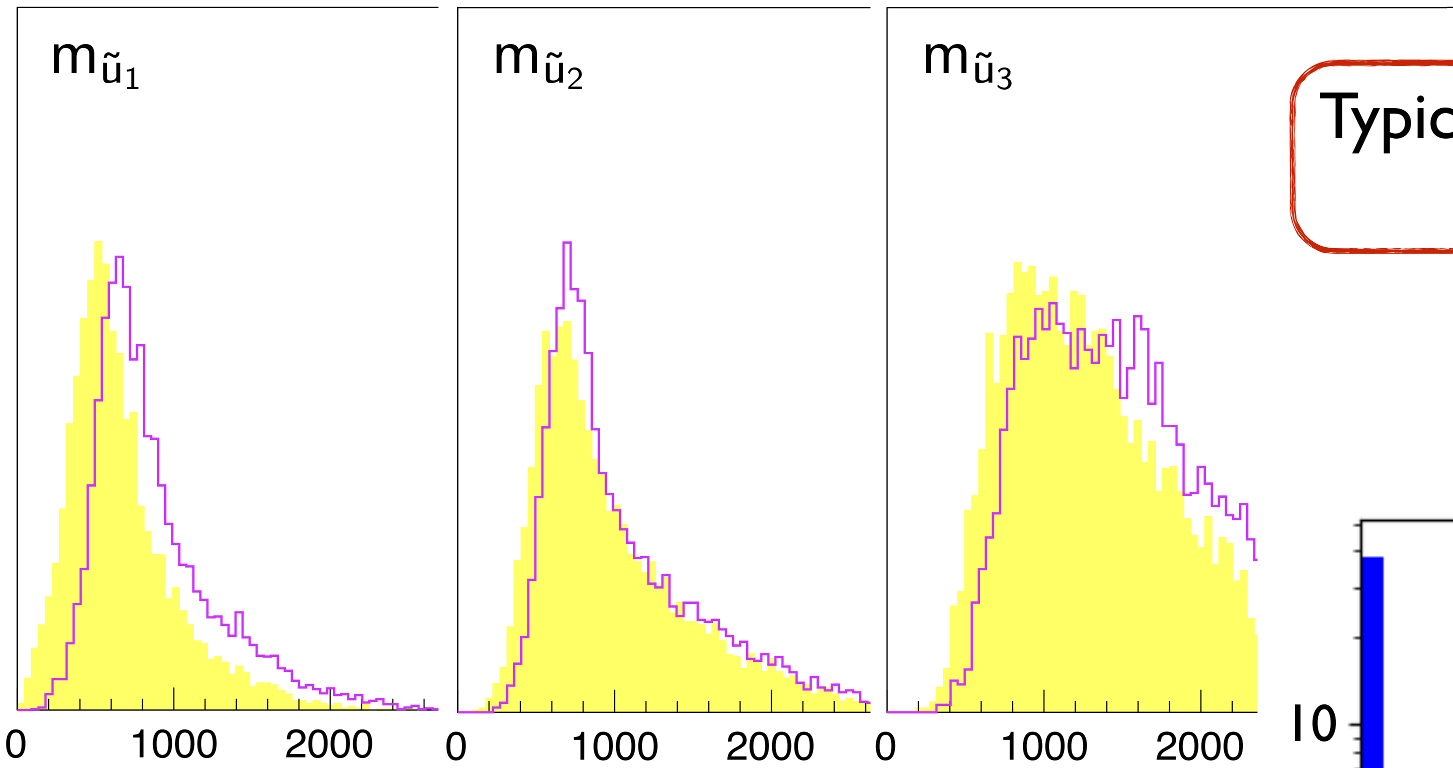




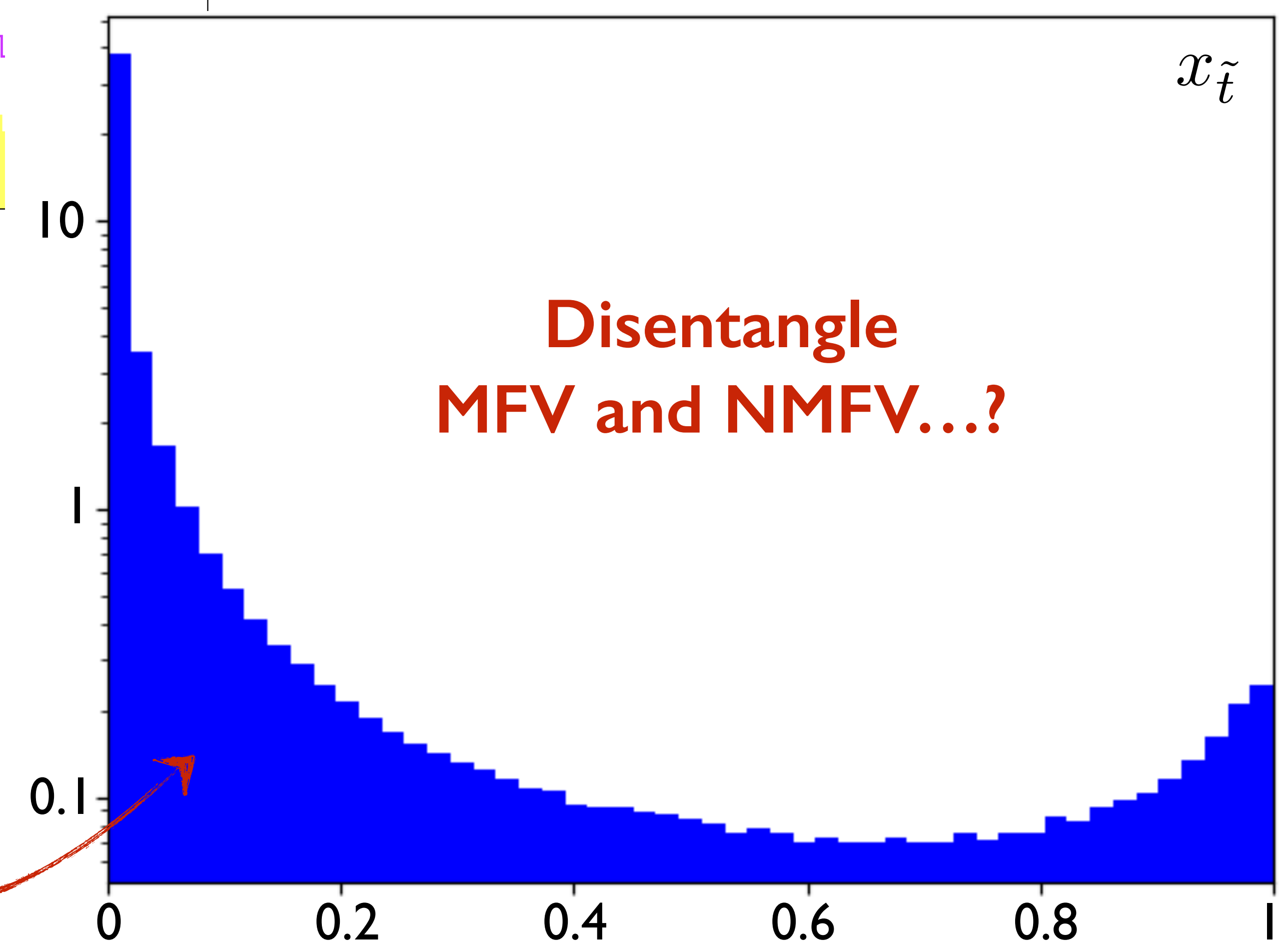
It is crucial to include analyses dedicated to the decay of top-partners into a single top quark and a lighter jet $pp \to tc + E_T^{\rm miss} \to \ell bc + E_T^{\rm miss}$

Chakraborty, Endo, Fuks, Herrmann, Nojiri, Pani, Polesello — PhysTeV Les Houches 2017 — arXiv:1803.10379 [hep-ph]
Chakraborty, Endo, Fuks, Herrmann, Nojiri, Pani, Polesello — *work to be published…*

Typical scenarios with squark flavour violation



Typically several (up- and down-type) states **accessible at LHC**



Disentangle MFV and NMFV…?

Lightest up-type states mainly **not stop-like** (contrary to the "usual" MFV-like MSSM !)

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

Likelihood inference of flavour decomposition

“observed” data
(or test scenario…)

D_i, σ_i

Model database
(e.g. MCMC study, simplified scan,…)

θ_i

$$\ln \mathcal{L}(\theta) \;=\; -\sum_i \left(\frac{\theta_i - D_i}{\sigma_i}\right)^2$$

Observables from LHC

$m_{\tilde{u}_1}, \quad m_{\tilde{\chi}_1^0}, \quad m_{\tilde{\chi}_1^+}$

$$R_{c/t} = \frac{\mathrm{BR}(\tilde{u}_1 \to c\chi_1^0)}{\mathrm{BR}(\tilde{u}_1 \to t\chi_1^0)};$$

$$R_{b/t} = \frac{\mathrm{BR}(\tilde{u}_1 \to b\chi_1^+)}{\mathrm{BR}(\tilde{u}_1 \to t\chi_1^0)}$$

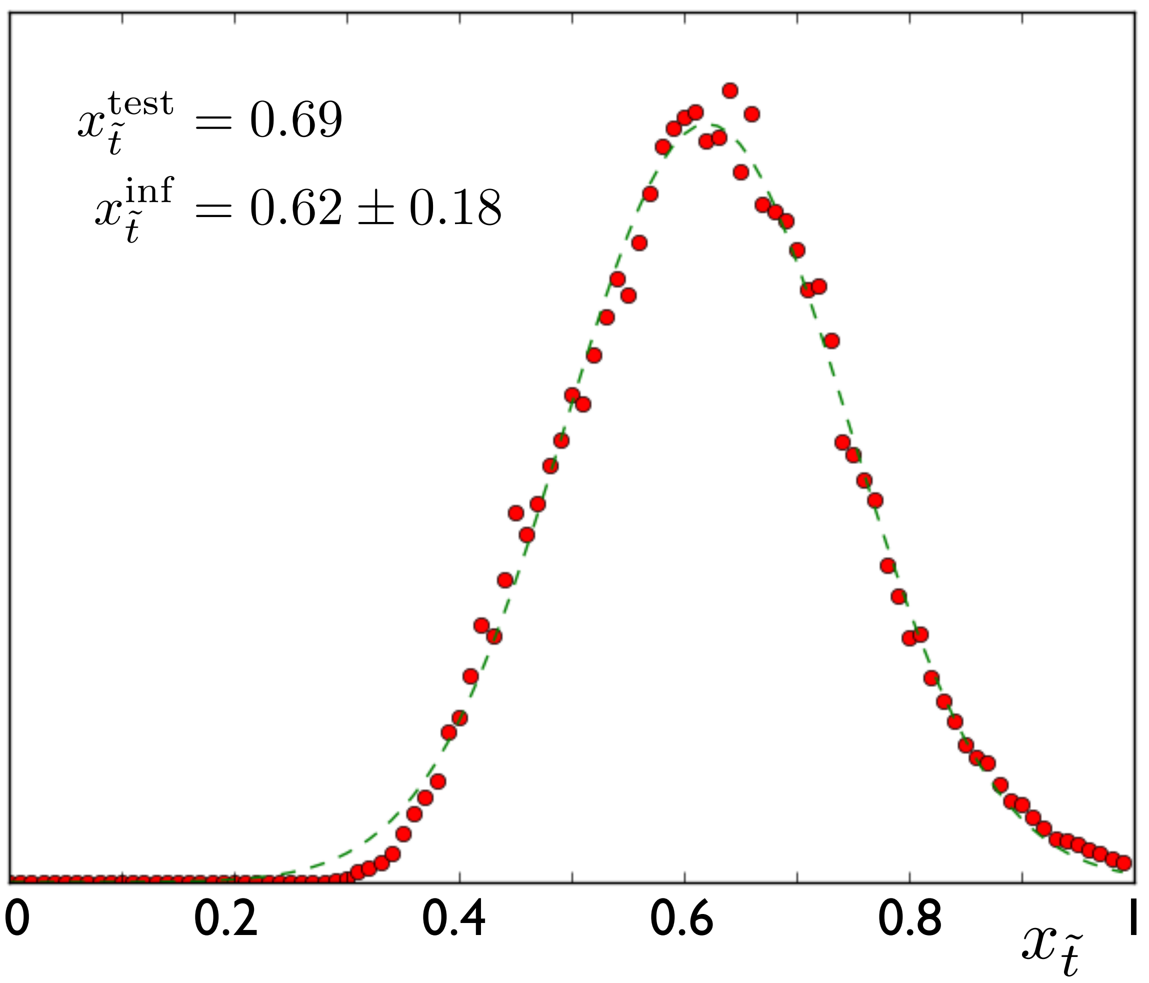
Average likelihood for distinct bins in $x_{\tilde{t}}$

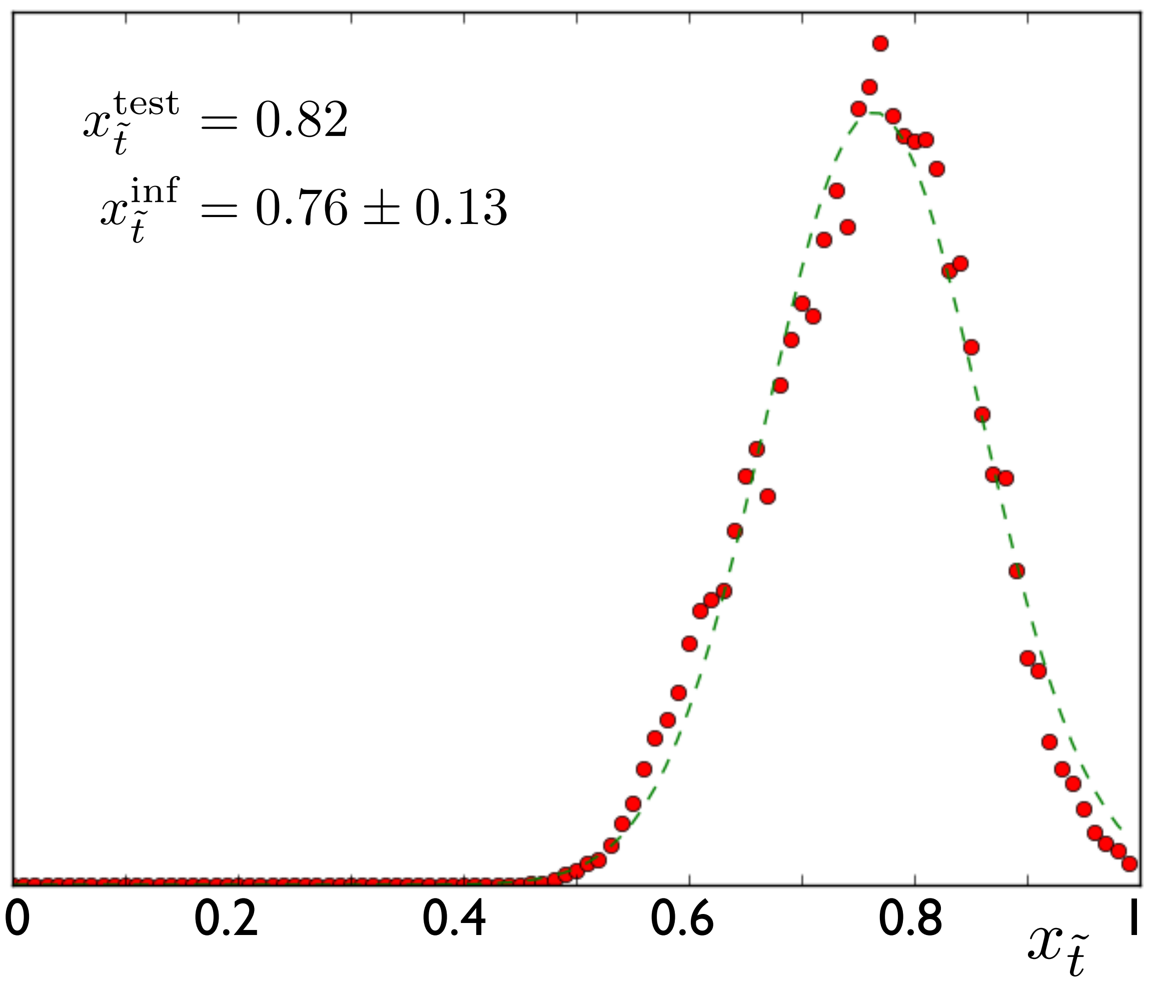
$$\hat{\mathcal{L}}_j(x_{\tilde{t}}) \;=\; \frac{1}{N_j}\sum_{k=1}^{N_j} \mathcal{L}(\theta)$$

Inference of stop component $x_{\tilde{t}}$ by fitting a Gaussian likelihood…

Bernigaud, Herrmann — *work to be published…*

Likelihood inference: Selected results





This analysis basically allows to recover the actual stop component of the squark

Limitations arise from the large number of parameter points required to perform the fit and the evaluation of the uncertainty entering the likelihood…

A similar study of the full model suffers from the **non-flat prior of the stop component…**

Bernigaud, Herrmann — *work to be published…*

Multi-variate analysis: MFV vs. NMFV

Training data
(e.g. MCMC study, simplified scan,…)

MVA classifier (MLP, neural network)
`Root TMVA`

MLP "super" variable
to classify the data

Observables from LHC

$$m_{\tilde{u}_1}, \quad m_{\tilde{\chi}_1^0}, \quad m_{\tilde{\chi}_1^+}$$

$$R_{c/t} = \frac{\mathrm{BR}(\tilde{u}_1 \to c\chi_1^0)}{\mathrm{BR}(\tilde{u}_1 \to t\chi_1^0)},$$

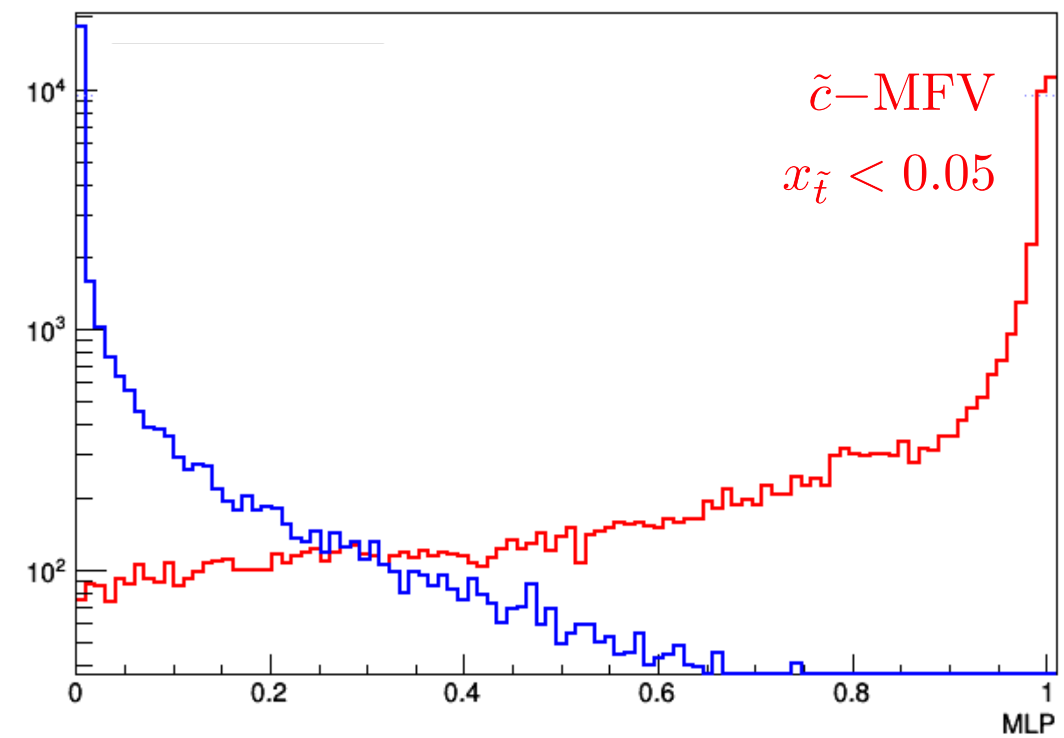
$$R_{b/t} = \frac{\mathrm{BR}(\tilde{u}_1 \to b\chi_1^+)}{\mathrm{BR}(\tilde{u}_1 \to t\chi_1^0)}$$

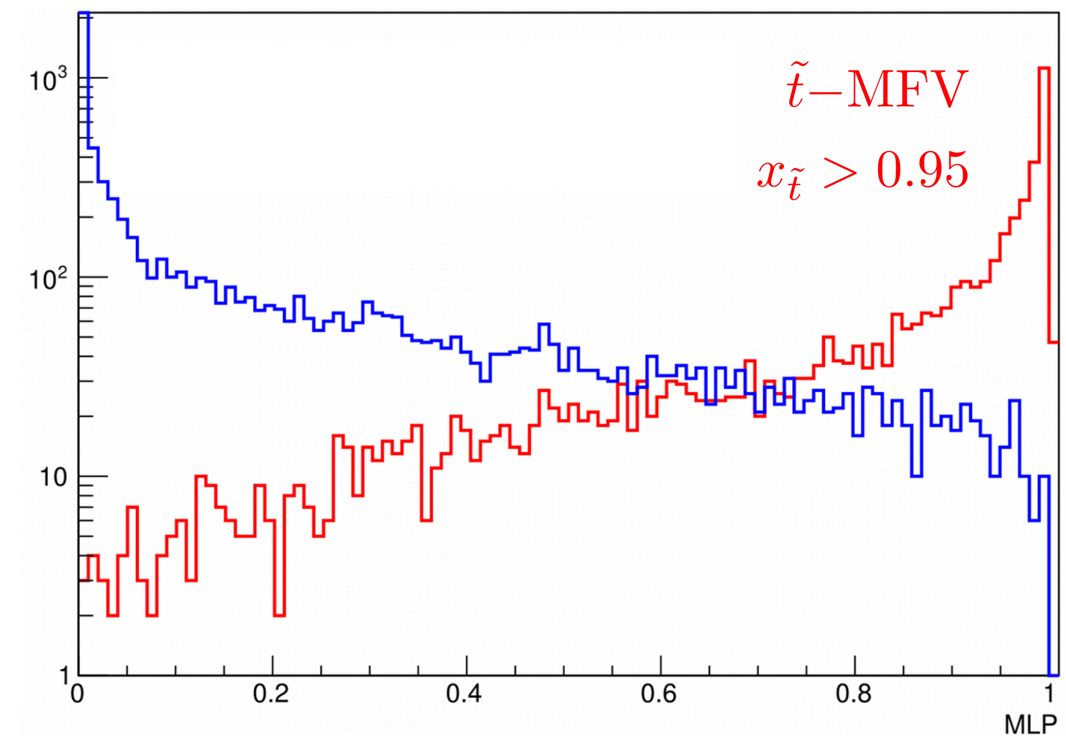
Test categories:

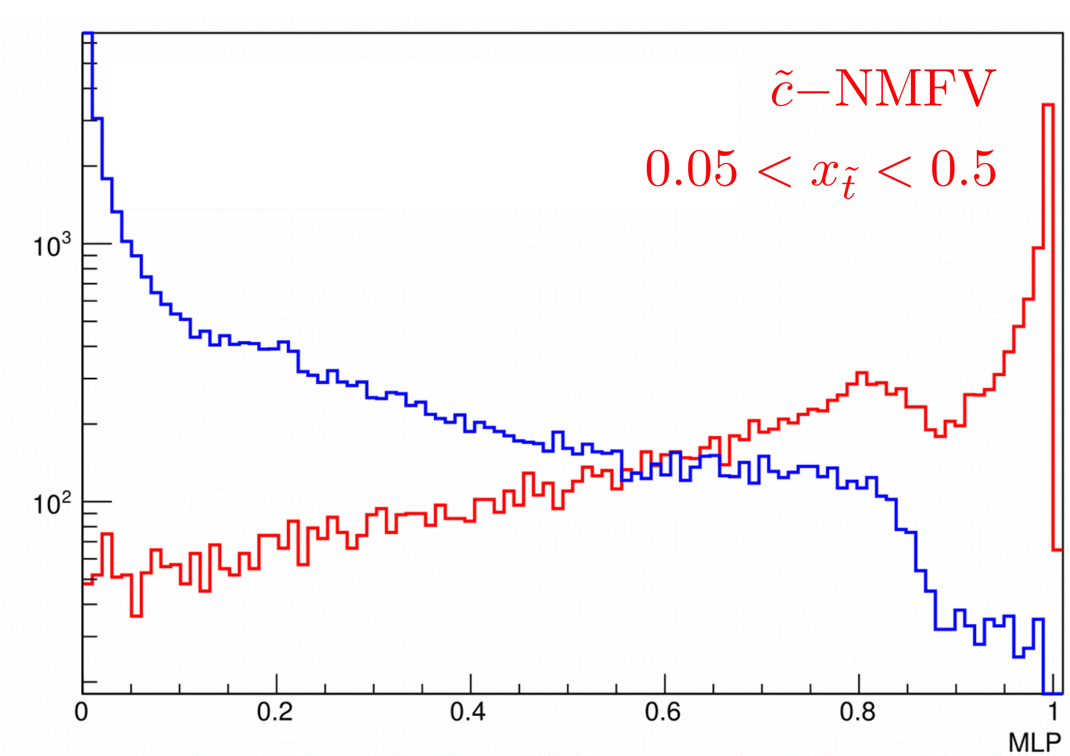
$x_{\tilde{t}} < 0.05$	$\tilde{c}$ – MFV
$0.05 < x_{\tilde{t}} < 0.50$	$\tilde{c}$ – NMFV
$0.50 < x_{\tilde{t}} < 0.95$	$\tilde{t}$ – NMFV
$x_{\tilde{t}} > 0.95$	$\tilde{t}$ – MFV

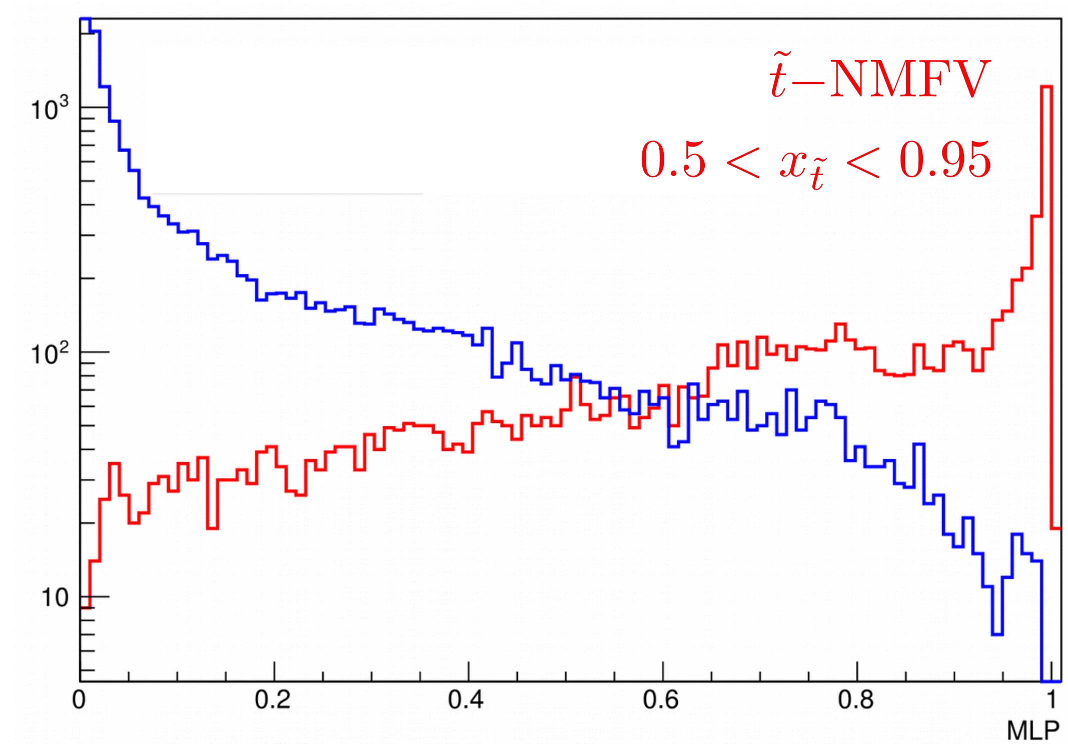
Bernigaud, Herrmann — *work to be published…*

Multi-variate analysis: Selected results



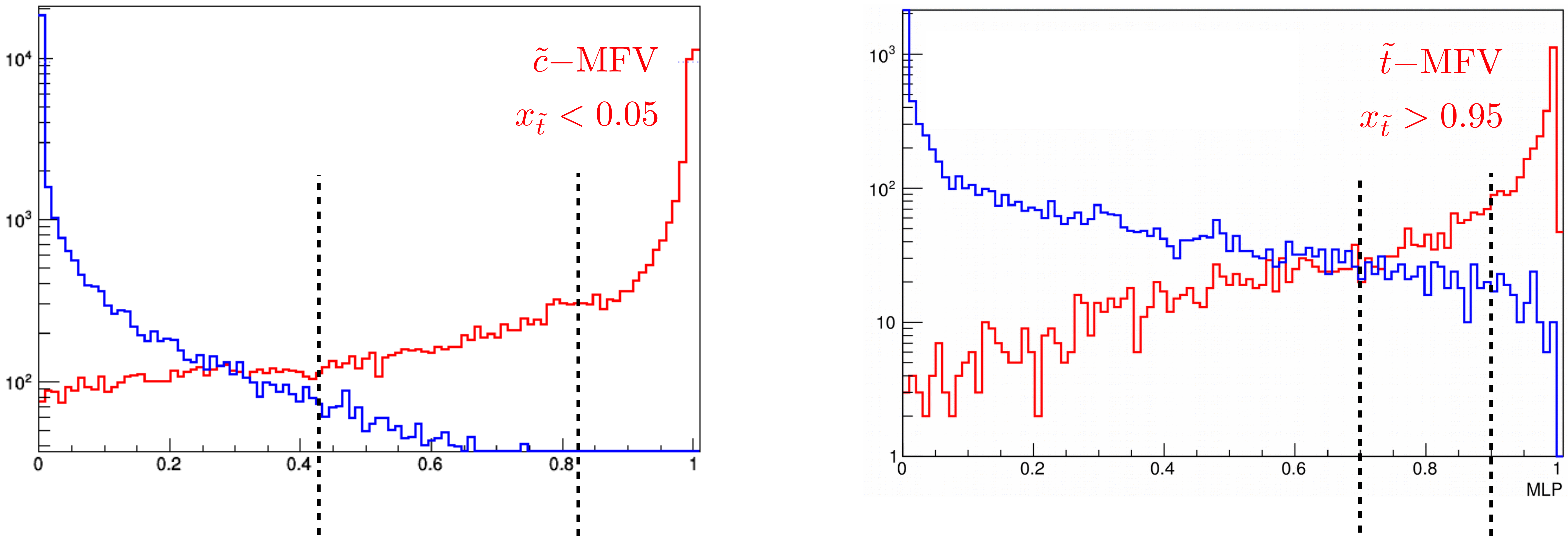






Bernigaud, Herrmann — *work to be published…*

Multi-variate analysis: Selected results



Eff. 89%
misid. 5%

Eff. 72%
misid. 1%

Eff. 57%
misid. 20%

Eff. 34%
misid. 5%

MVA classifier less efficient for stop-like cases… partly due to prior (again), but more features to be understood…

MVA classifier works better for the full NMFV-MSSM than for the simplified setup (the opposite holds for the likelihood inference approach)

Bernigaud, Herrmann — *work to be published…*

Summary

Non-minimal flavour violation in Supersymmetry is well motivated both from the theoretical and phenomenological point of view — **rich phenomenology at the TeV scale…**

NMFV terms can be motivated from GUT theories / flavour symmetries (not discussed here)…

<u>Identification of the flavour structure based on observations at the TeV scale</u>

- **Likelihood inference** interesting approach, but suffers from dependence on the prior…
- **Multivariate analysis** needs less information, but difficult to handle uncertainties and difficult to "really" interpret results… Dependence on prior to be clarified!

Need for dedicated searches for NMFV final states at LHC…