General squark mixing: Constraints and phenomenology

K. De Causmaecker *(Vreije Universiteit Brussel, Belgium)*; **B. Fuks** *(LPTHE, Sorbonne Universités / CNRS, Paris, France)*;
B. Herrmann *(LAPTh, Université Savoie Mont Blanc / CNRS, Annecy-le-Vieux, France)*; **F. Mahmoudi** *(CRAL, Université de Lyon / CNRS, Lyon, France)*;
B. O'Leary, W. Porod *(Universität Würzburg, Germany)*; **S. Sekmen** *(Kyongpook National University, Daegu, Korea)*;
N. Strobbe *(Fermi National Accelerator Laboratory, Batavia, USA)*

JHEP 1511 (2015) 125, arXiv:1509.05414 [hep-ph]

The squark sector of the MSSM

In the Standard Model, the Yukawa matrices are the only source of flavour-violation, leading to quark flavour-violating interactions related to the CKM-matrix. Considering new physics, there are two ways of modeling the flavour structure of the theory:

- Assume the same flavour structure as in the Standard Model: flavour-changing currents remain related to the CKM-matrix – **Minimal Flavour Violation (MFV)**
- Allow for new sources of flavour violation: corresponding interactions not related to CKM-matrix any more – **Non-Minimal-Flavour Violation (NMFV)**

In the Minimal Supersymmetric Standard Model (MSSM), the squark sector is, in the super-CKM basis, parametrized by two mass matrices according to

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

$$\mathcal{M}^2_{\tilde{d}} = \begin{pmatrix} M^2_{\tilde{Q}} + m^2_d + D_{\tilde{d},L} & \frac{v_d}{\sqrt{2}} T^\dagger_d - m_d \mu \tan\beta \\ \frac{v_d}{\sqrt{2}} T_d - m_d \mu^* \tan\beta & M^2_{\tilde{D}} + m^2_d + D_{\tilde{d},R} \end{pmatrix}$$

Non-minimally flavour-violating terms manifest as **non-diagonal entries** in the soft mass matrices ($M^2_{\tilde{Q}}$, $M^2_{\tilde{U}}$, and $M^2_{\tilde{D}}$) and trilinear coupling matrices (T_u and T_d).

The squark mass eigenstates are obtained via two 6x6 rotation matrices (generalized "mixing angles"):

$$\mathrm{diag}(m_{\tilde{q}_1}, \ldots, m_{\tilde{q}_6}) = \mathcal{R}_{\tilde{q}} \mathcal{M}^2_{\tilde{q}} \mathcal{R}^\dagger_{\tilde{q}} \qquad m_{\tilde{q}_1} < \cdots < m_{\tilde{q}_6} \qquad q = u, d$$

MCMC analysis of the parameter space

While previous studies of NMFV in the MSSM mainly were based on one of the NMFV parameters defined above being different from zero, the aim of the present analysis is to study the more general situation, where all flavour-violating entries of the Lagrangian are potentially sizeable. To this end, we employ the **Markov Chain Monte Carlo** technique in order to efficiently scan over the 22-dimensional parameter space of the phenomenological MSSM (including 3 Standard Model parameters):

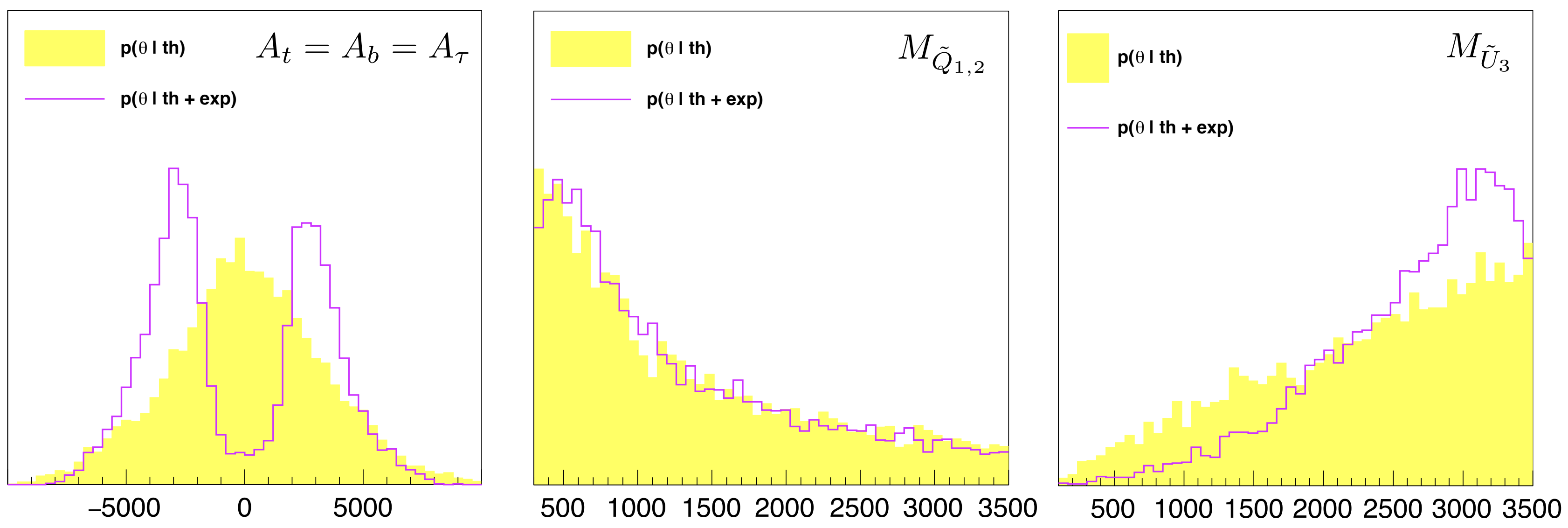
$$M_{\tilde{Q}_{1,2}},\ M_{\tilde{Q}_3},\ M_{\tilde{U}_{1,2}},\ M_{\tilde{U}_3},\ M_{\tilde{D}_{1,2}},\ M_{\tilde{D}_3},\ A_t = A_b = A_\tau,\ \tan\beta,\ \mu,\ m_A,\ M_1 = \frac{1}{2} M_2 = \frac{1}{6} M_3,\ M_{\tilde{\ell}},$$
$$\delta_{LL},\ \delta^u_{RR},\ \delta^d_{RR},\ \delta^u_{LR},\ \delta^u_{RL},\ \delta^d_{LR},\ \delta^d_{RL}, \qquad \alpha_s(m_Z),\ m_t^{\rm pole},\ m_b(m_b)$$

The figure below shows the obtained distributions of three flavour-conserving parameters affecting the squark sector. The constraints given above strongly influence the shape of the distribution of the **trilinear coupling featuring** two peaks around $|A_t| \sim 3000$ GeV. As in the case of MFV, this is explained by the Higgs-boson mass requiring a **relatively large mass splitting** between the squarks exhibiting the largest stop components, which is realized only for particular parameter combinations.

An interesting and somewhat unexpected feature concerns the squark soft mass parameters. As can be seen, **smaller values are preferred for the first and second generations, while the third generation prefers heavier masses**. This is also mostly caused by imposing the Higgs-boson mass. The corresponding corrections can be approximated by:

$$\Delta m^2_h = \frac{3 v_u^4}{8\pi^2 v^2} \left[\frac{(T_u)^2_{23}}{M^2_{1,2}} \left(\frac{y_t^2}{2} - \frac{(T_u)^2_{23}}{12 M^2_{1,2}} \right) \right] \qquad (T_u)_{23} = \frac{\sqrt{2}}{v_u} \delta^u_{LR} M_{\tilde{Q}_{1,2}} M_{\tilde{U}_3}$$

The third-generation mass parameters are **strongly constrained to be large** from the flavour sector. For a non-zero δ^u_{LR}, the Higgs boson becomes tachyonic if $M_{1,2} \simeq M_{\tilde{Q}_{1,2}} \simeq M_{\tilde{U}_{1,2}} \simeq M_{\tilde{D}_{1,2}}$ is too large. Note that physical solutions for the electroweak vacuum also favour lower values of these parameters.



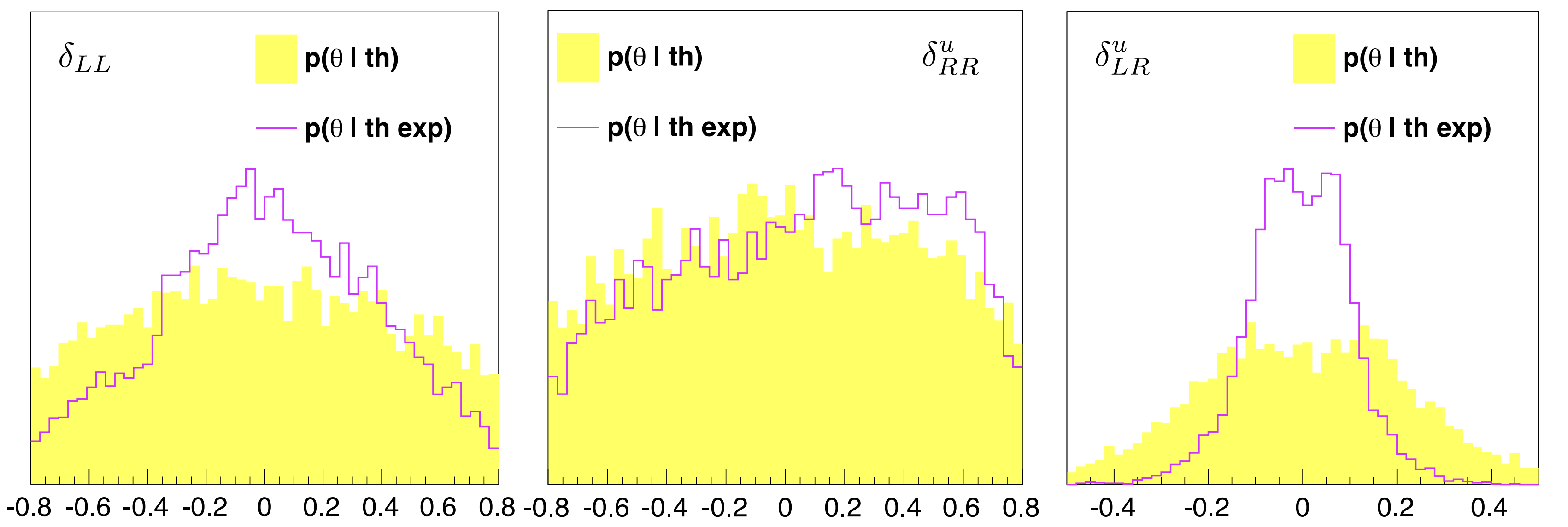
Experimental constraints

The flavour-violating elements may induce flavour-changing neutral currents (FCNC) or lift the CKM-suppression, they are thus heavily **constrained by a large variety of experimental data**.

Observable	Exp. result and uncertainties	
m_h	(125.5 ± 2.5) GeV	ATLAS + CMS (2013)
$\mathrm{BR}(B \to X_s\gamma)$	$(3.43 \pm 0.21^{\rm stat} \pm 0.07^{\rm sys} \pm 0.24^{\rm th}) \cdot 10^{-4}$	HFAG (2013); Misiak et al. (2013), Mahmoudi (2007)
$\mathrm{BR}(B_s \to \mu\mu)$	$(2.9 \pm 0.7^{\rm exp} \pm 0.29^{\rm th}) \cdot 10^{-9}$	LHCb + CMS (2013), Mahmoudi et al. (2012)
$\mathrm{BR}(B \to X_s\mu\mu)$	$(1.60 \pm 0.68^{\rm exp} \pm 0.16^{\rm th}) \cdot 10^{-6}$	BaBar (2004); Belle (2005); Hurth et al. (2008, 2012)
$\mathrm{BR}(B_u \to \tau\nu)$	$(1.05 \pm 0.25^{\rm exp} \pm 0.29^{\rm th}) \cdot 10^{-4}$	PDG (2012); Mahmoudi (2008, 2009)
ΔM_{B_s}	$(17.719 \pm 0.043^{\rm exp} \pm 3.3^{\rm th})$ 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)

We consider only additional mixing between squarks of the **second and third generations**, which is less constrained and phenomenologically most interesting. In order to obtain a scenario-independent description, we define seven **dimensionless NMFV-parameters**:

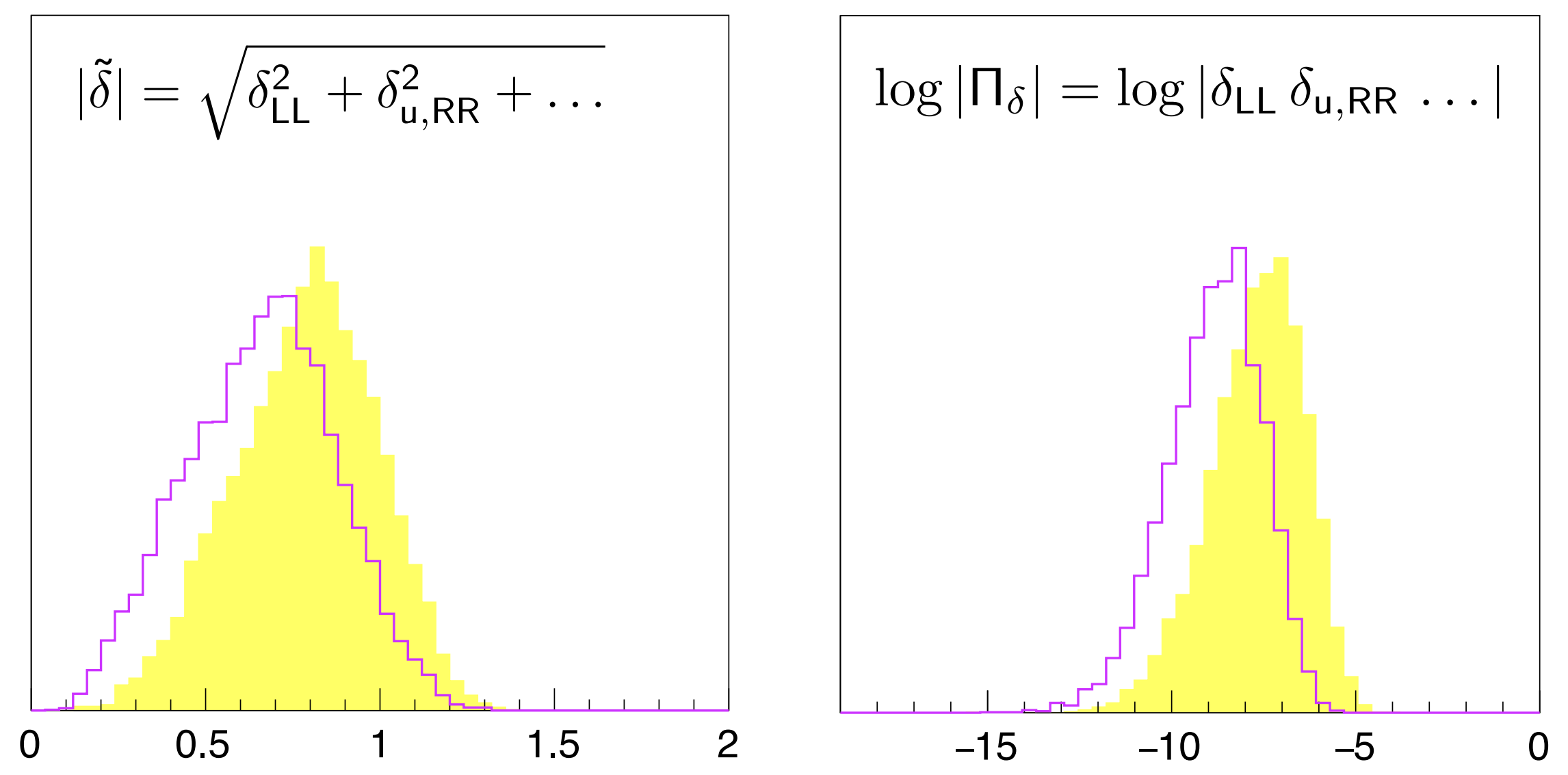
$$\delta_{LL} = \frac{(M^2_{\tilde{Q}})_{23}}{(M_{\tilde{Q}})_{22}(M_{\tilde{Q}})_{33}} \qquad \delta^u_{LL} = \frac{(M^2_{\tilde{U}})_{23}}{(M_{\tilde{U}})_{22}(M_{\tilde{U}})_{33}} \qquad \delta^u_{RL} = \frac{v_u}{\sqrt{2}} \frac{(T_u)_{23}}{(M_{\tilde{U}})_{22}(M_{\tilde{Q}})_{33}} \qquad \text{etc.}$$



Our study shows that most of the seven flavour-violating parameters can be **sizeable in wide regions of the allowed parameter space**. In addition to the Higgs-boson mass, the most important constraints are the **meson-oscillation parameter** ΔM_{B_s} and the **decay** $B_s \to \mu\mu$. The distribution of δ^u_{LR} featuring two peaks at $|\delta^u_{LR}| \sim 0.05$ is expected from the corrections to the Higgs-boson mass discussed above. In the down-type sector, the distributions of δ^d_{RL} and δ^d_{LR} show clear peaks around zero as large values mostly lead to tachyons, but are hardly constrained from the imposed flavour observables.

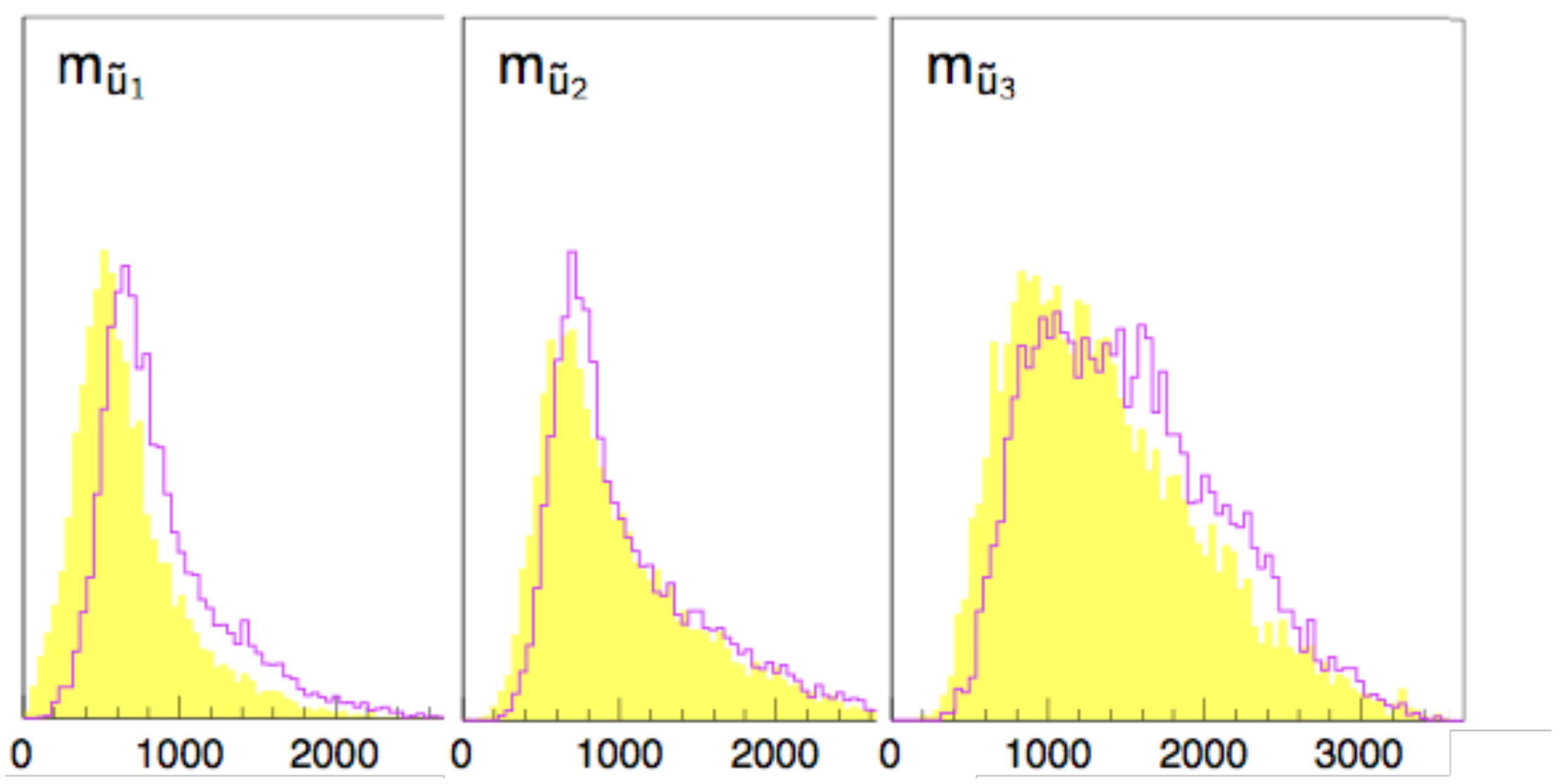
In order to display the overall distribution of NMFV entries present in the Lagrangian, we introduce the quantities $|\vec{\delta}|$ and $\log|\Pi_\delta|$. As can be seen in the figures below, for essentially all scenarios, **at least one NMFV-parameter is sizeable** and non-vanishing, while at least one of the NMFV parameters has to be small. However, a large fraction of the scanned points exhibit **several non-vanishing flavour-violating elements**.

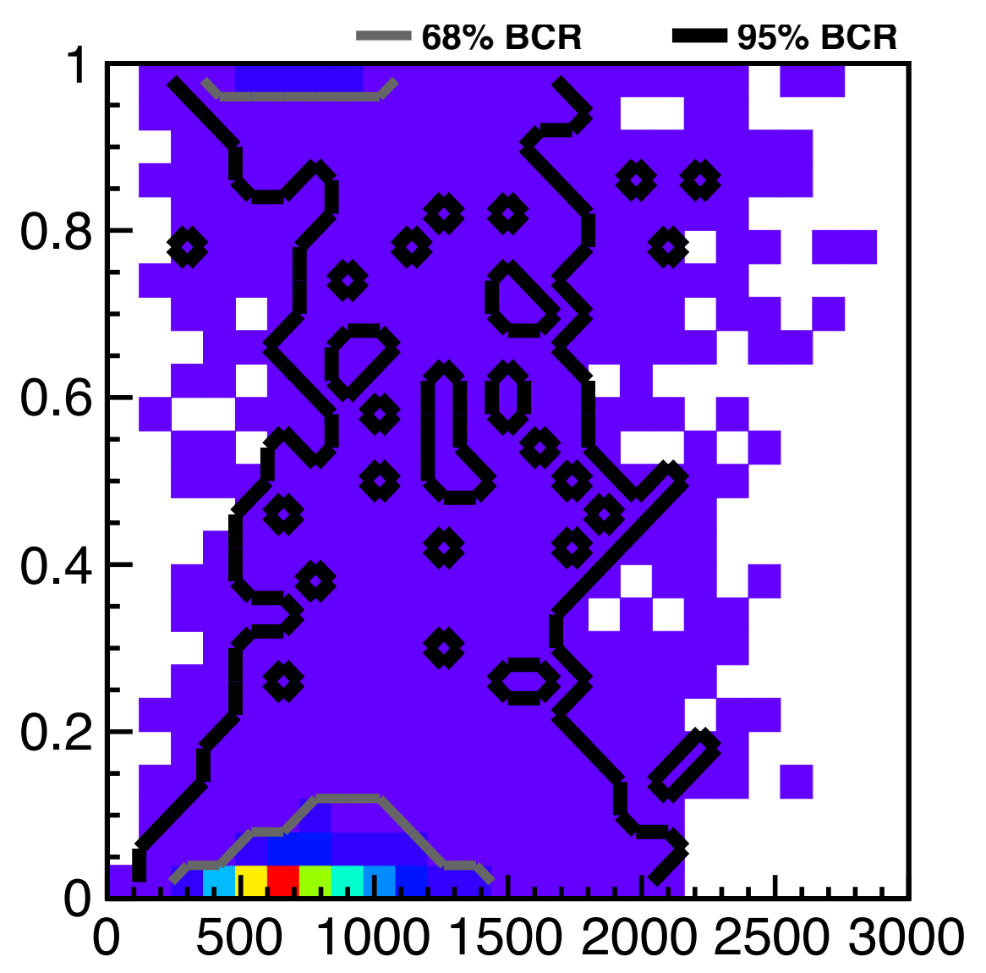
Let us finally mention that we **did not find any strong correlations** between the different NMFV quantities under consideration.



Phenomenology at the LHC

Our analysis shows that, despite the strong constraints on the parameter space, the three lightest up-type squarks are likely to have **masses of around 1 TeV** or less, and should therefore be **accessible at the LHC** (see figure below). As a consequence of the distributions of the soft mass parameters discussed above, the lightest state is, however, **mostly not "stop-like", but rather "scharm-like"**.





Benchmark points for future studies

Finally, we propose **four benchmark scenarios** within the MSSM with non-minimal flavour violation in the squark sector. These four scenarios capture **typical features**, such as flavour decompositions or branching fractions, identified in the results of the MCMC study. The mass spectra of two benchmark points are shown below, all details about the MCMC analysis and further scenarios are given in our publication cited above.