Tasting SUSY(-GUTs) at the LHC

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CP3 — Université Catholique de Louvain — Louvain-la-Neuve — 10 may 2017

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Introduction

Exploring the MSSM with non-minimal flavour violation at the TeV scale

Towards a test of SUSY-GUTs at the LHC

Conclusion

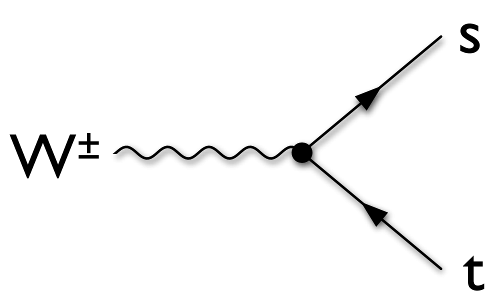
Flavour violation in the Standard Model

The Yukawa matrices are the only source of flavour violation, leading to quark-flavour violating interactions parametrized by the **CKM-matrix**:

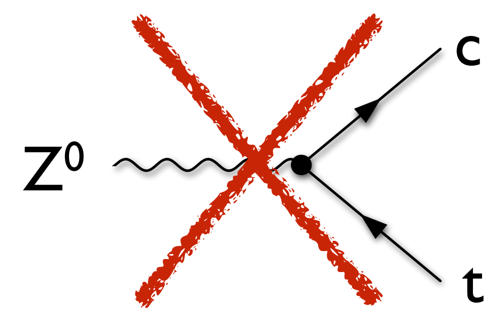
$$u_L^{(m)} = V_{u,L}\, u_L^{(i)}$$
$$u_R^{(m)} = V_{u,R}\, u_R^{(i)}$$
$$d_L^{(m)} = V_{d,L}\, d_L^{(i)}$$
$$d_R^{(m)} = V_{d,R}\, d_R^{(i)}$$

$$V_{\mathrm{CKM}} = V_{u,L}^{\dagger} V_{d,L} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$

Flavour-changing interactions proceed via charged currents (W-boson)
— **no flavour-changing neutral currents**!



$\propto V_{ts}$

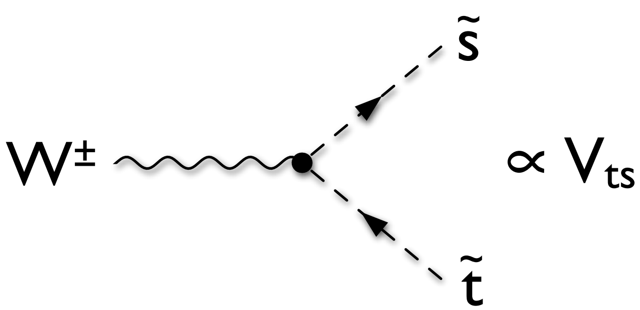


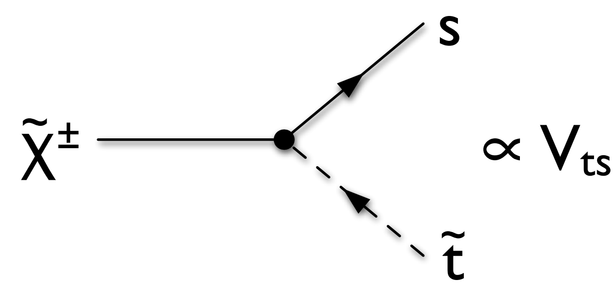
Similar situation and parametrization for lepton-flavour violation: **PMNS matrix**
(not discussed here…)

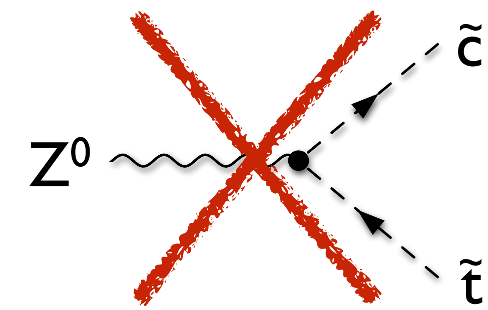
Flavour violation beyond the Standard Model

Two ways of dealing with physics beyond the Standard Model:

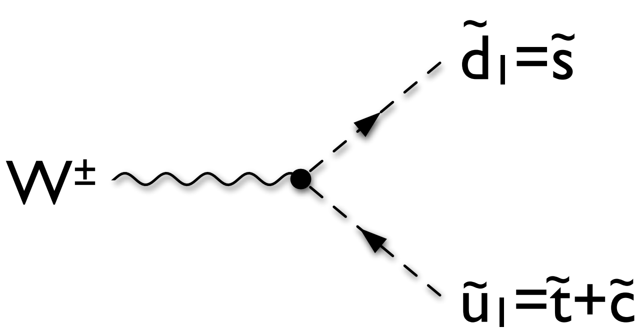
1. Assume **same flavour structure** as in Standard Model, flavour-changing currents remain related to CKM-matrix — minimal flavour violation (MFV)

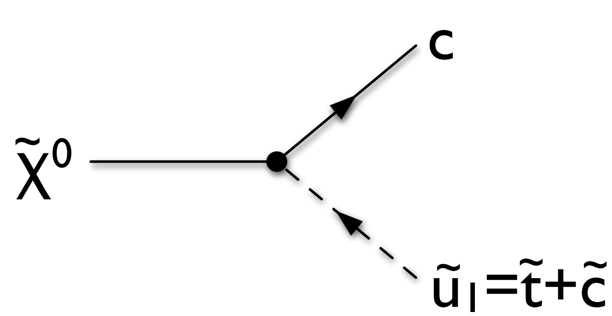


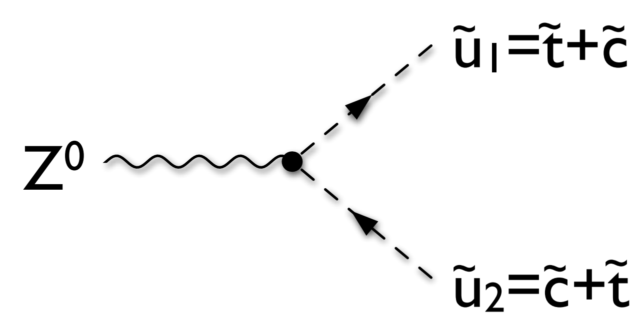




2. Allow for **new sources** of flavour violation: corresponding interactions not related to CKM-matrix any more (no suppression!) — non-minimal flavour violation (NMFV)







The Minimal Supersymmetric Standard Model

SM Particles		Spin		Spin		Superpartners
Quarks	$(u_L \;\; d_L)$	$1/2$	Q	0	$(\tilde{u}_L \;\; \tilde{d}_L)$	Squarks
	$u_R^\dagger$	$1/2$	$\bar{u}$	0	$\tilde{u}_R^*$	
	$d_R^\dagger$	$1/2$	$\bar{d}$	0	$\tilde{d}_R^*$	
Leptons	$(\nu \;\; e_L)$	$1/2$	L	0	$(\tilde{\nu} \;\; \tilde{e}_L)$	Sleptons
	$e_R^\dagger$	$1/2$	$\bar{e}$	0	$\tilde{e}_R^*$	
Higgs	$(H_u^+ \;\; H_u^0)$	0	H_u	$1/2$	$\tilde{\chi}^0_{1,2,3,4}$	Neutralinos
	$(H_d^0 \;\; H_d^-)$	0	H_d	$1/2$	$\tilde{\chi}^\pm_{1,2}$	Charginos
W bosons	$W^0, W^\pm$	1				
B boson	B^0	1				
Gluon	g	1		$1/2$	$\tilde{g}$	Gluino
Graviton	G	2		$3/2$	$\tilde{G}$	Gravitino

Flavour violation in the squark sector

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

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

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

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

$$\delta_{LL} = \frac{(M^2_{\tilde{Q}})_{23}}{(M_{\tilde{Q}})_{22}(M_{\tilde{Q}})_{33}} \,, \quad \delta^u_{RR} = \frac{(M^2_{\tilde{U}})_{23}}{(M_{\tilde{U}})_{22}(M_{\tilde{U}})_{33}}$$

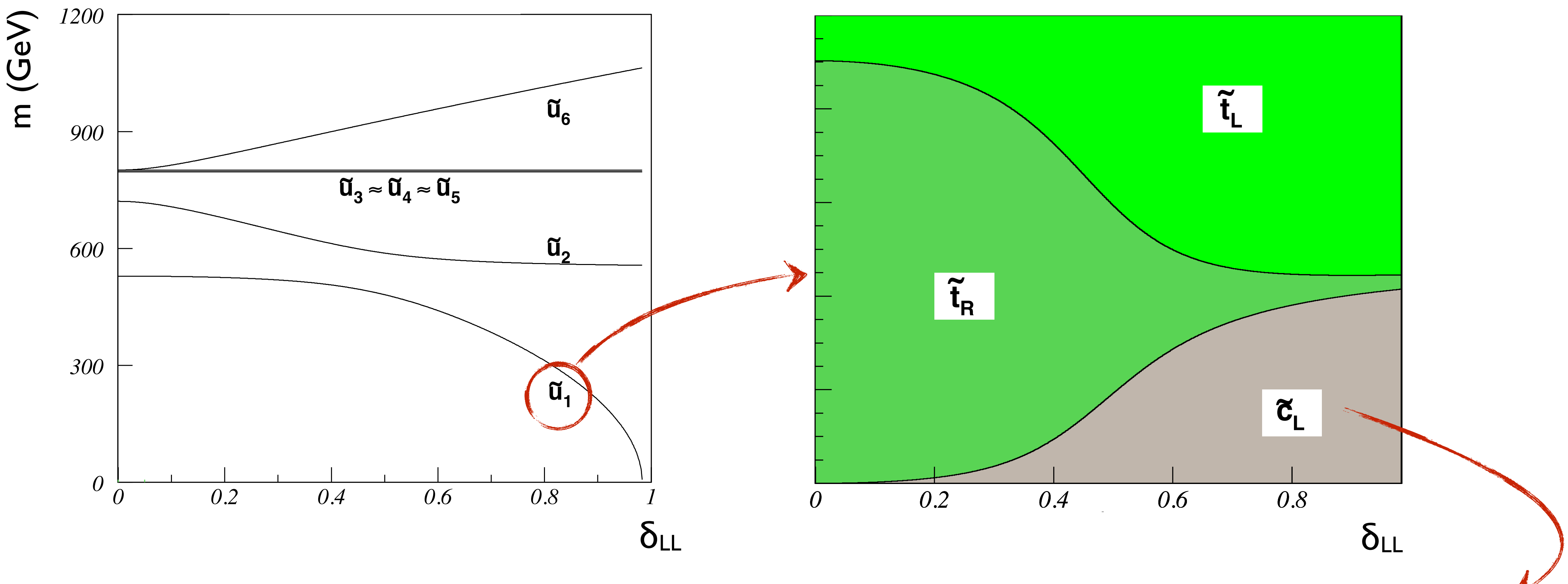
$$\delta^u_{RL} = \frac{v_u}{\sqrt{2}} \frac{(T_u)_{23}}{(M_{\tilde{Q}})_{22}(M_{\tilde{U}})_{33}} \,, \quad \delta^u_{LR} = \frac{v_u}{\sqrt{2}} \frac{(T_u)_{32}}{(M_{\tilde{Q}})_{33}(M_{\tilde{U}})_{22}} \quad \text{etc.}$$

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

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

Flavour violation in the squark sector

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

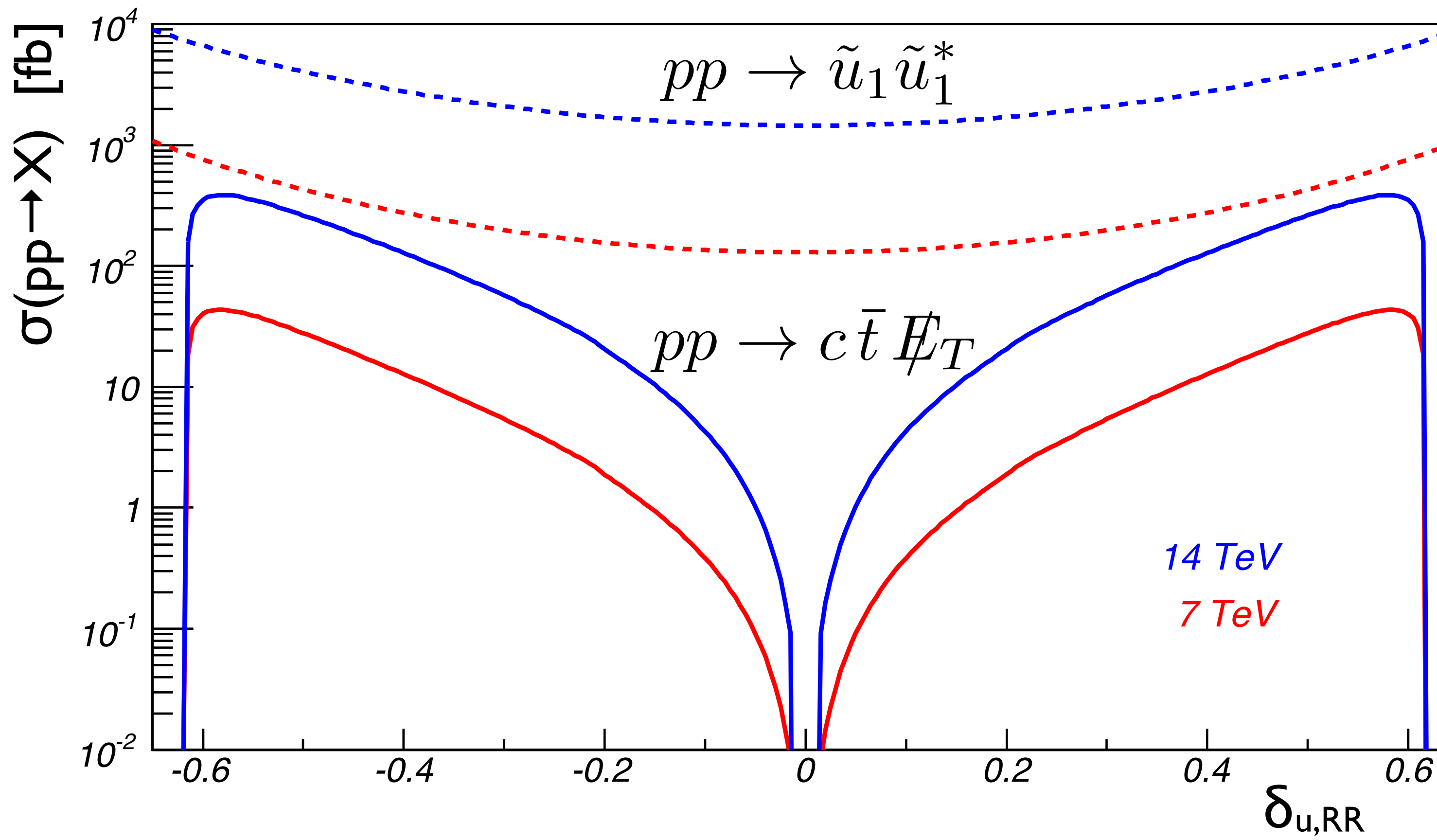


Decays $\tilde{u}_1 \to \tilde{\chi} t$ and $\tilde{u}_1 \to \tilde{\chi} c$ **simultaneously open**

Bozzi, Fuks, Herrmann, Klasen — Nucl. Phys. B 787: 1-54 (2007) — arXiv:0704.1826 [hep-ph]
Fuks, Herrmann, Klasen — Nucl. Phys. B 810: 266-299 (2009) — arXiv:0808.1104 [hep-ph]
Hurth, Porod — JHEP 0908 (2009) 087 — arXiv:0904.4574 [hep-ph]
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]
Fuks, Herrmann, Klasen — Phys. Rev. D 86: 015002 (2012) — arXiv:1112.4838 [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]

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**



Up to **10^4 events** at LHC
($\sqrt{s}$=14 TeV, 300 fb^{-1})

Bozzi, Fuks, Herrmann, Klasen — Nucl. Phys. B 787: 1-54 (2007) — arXiv:0704.1826 [hep-ph]
Fuks, Herrmann, Klasen — Nucl. Phys. B 810: 266-299 (2009) — arXiv:0808.1104 [hep-ph]
Hurth, Porod — JHEP 0908 (2009) 087 — arXiv:0904.4574 [hep-ph]
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Bartl, Eberl, Ginina, Herrmann, Hidaka, Majerotto, Porod — Phys. Rev. D 84: 115026 (2011) — arXiv:1107.2775 [hep-ph]
Fuks, Herrmann, Klasen — Phys. Rev. D 86: 015002 (2012) — arXiv:1112.4838 [hep-ph]
Bartl, Eberl, Ginina, Herrmann, Hidaka, Majerotto, Porod — Int.J.Mod.Phys. 29: 1450035 (2014) — arXiv:1212.4688 [hep-ph]
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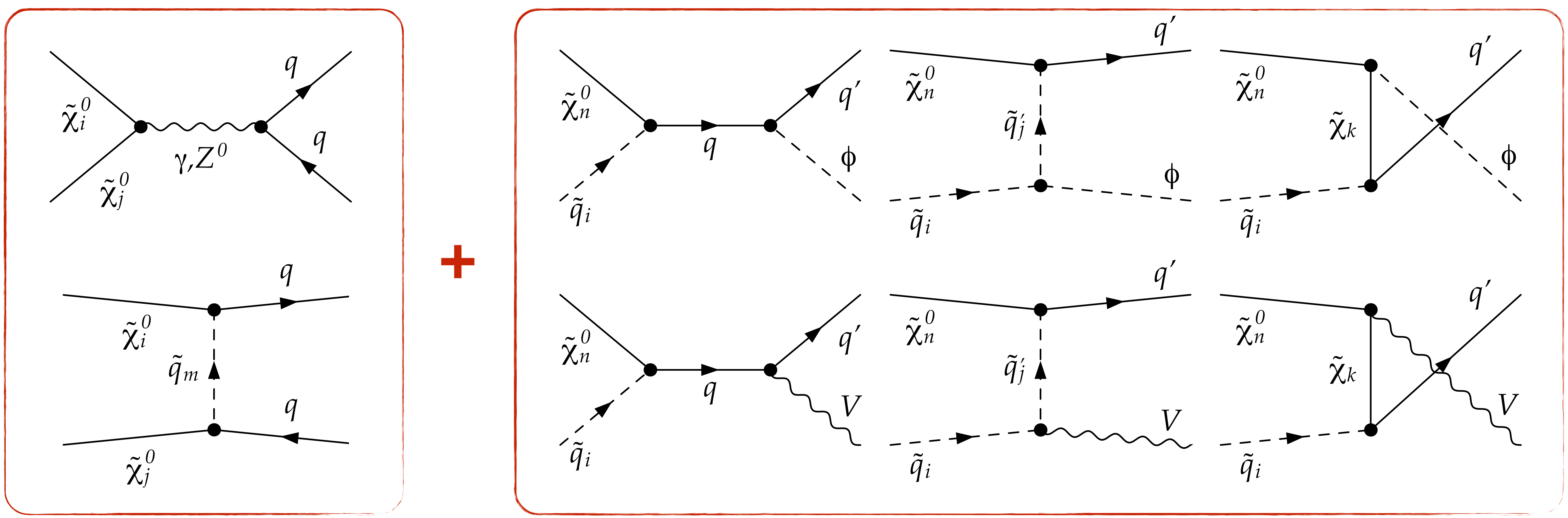
Impact on neutralino dark matter

Additional channels (and favoured co-annihilation) can increase annihilation cross-section — **mild impact on dark matter relic density and (co)annihilation channels**

$$\frac{\mathrm{d}n}{\mathrm{d}t} = -3Hn - \langle \sigma_{\mathrm{ann}} v \rangle \left(n^2 - n_{\mathrm{eq}}^2\right)$$

$$\langle \sigma_{\mathrm{ann}} v \rangle = \sum_{i,j=0}^{N} \langle \sigma_{ij} v_{ij} \rangle \frac{g_i g_j}{g_{\mathrm{eff}}^2} \left(\frac{m_i m_j}{m_0^2}\right)^{3/2} \exp\left\{-\frac{(m_i + m_j - 2m_0)}{T}\right\}$$

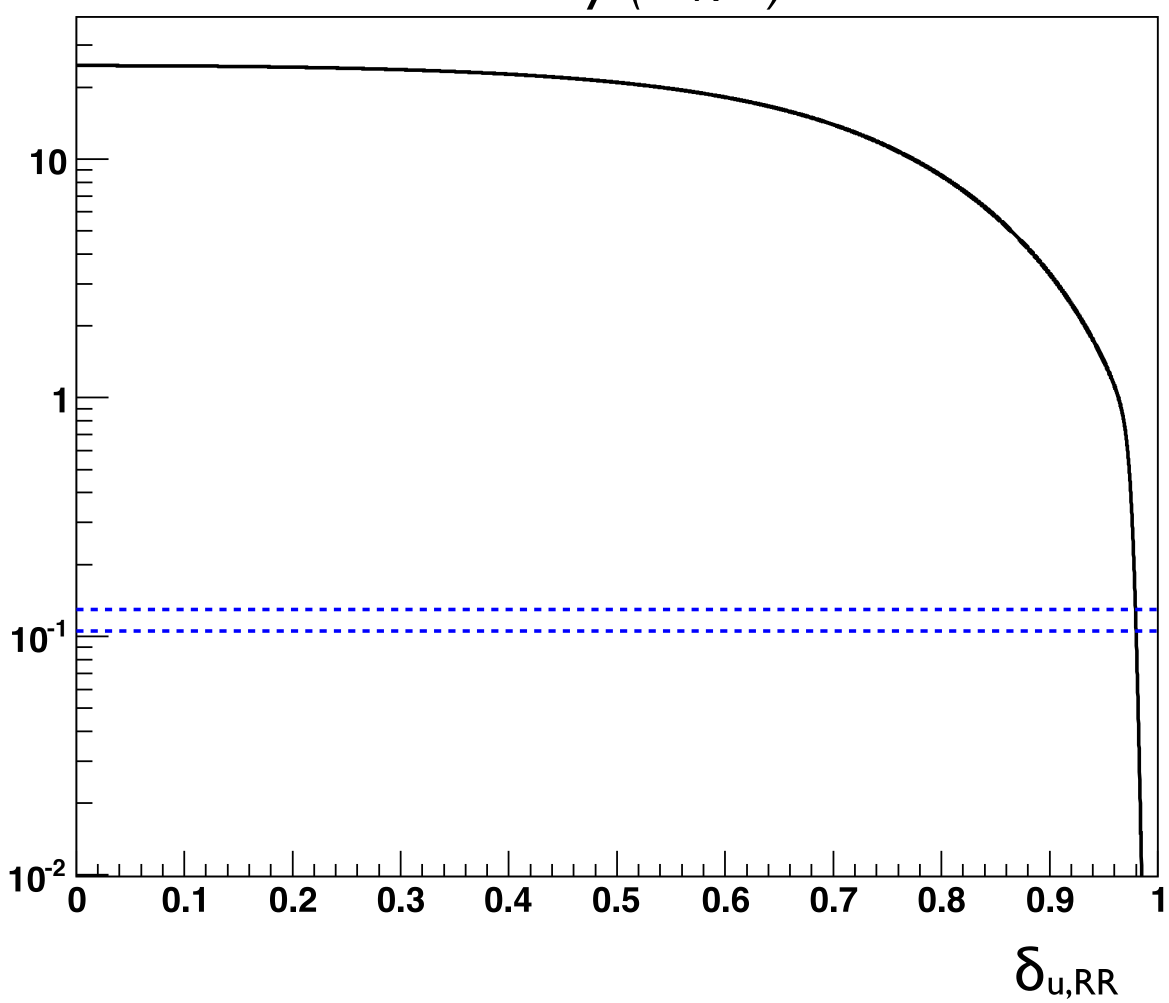


Herrmann, Klasen, Le Boulc'h — Phys. Rev. D84 (2011) 095007 — arXiv:1106.6229 [hep-ph]

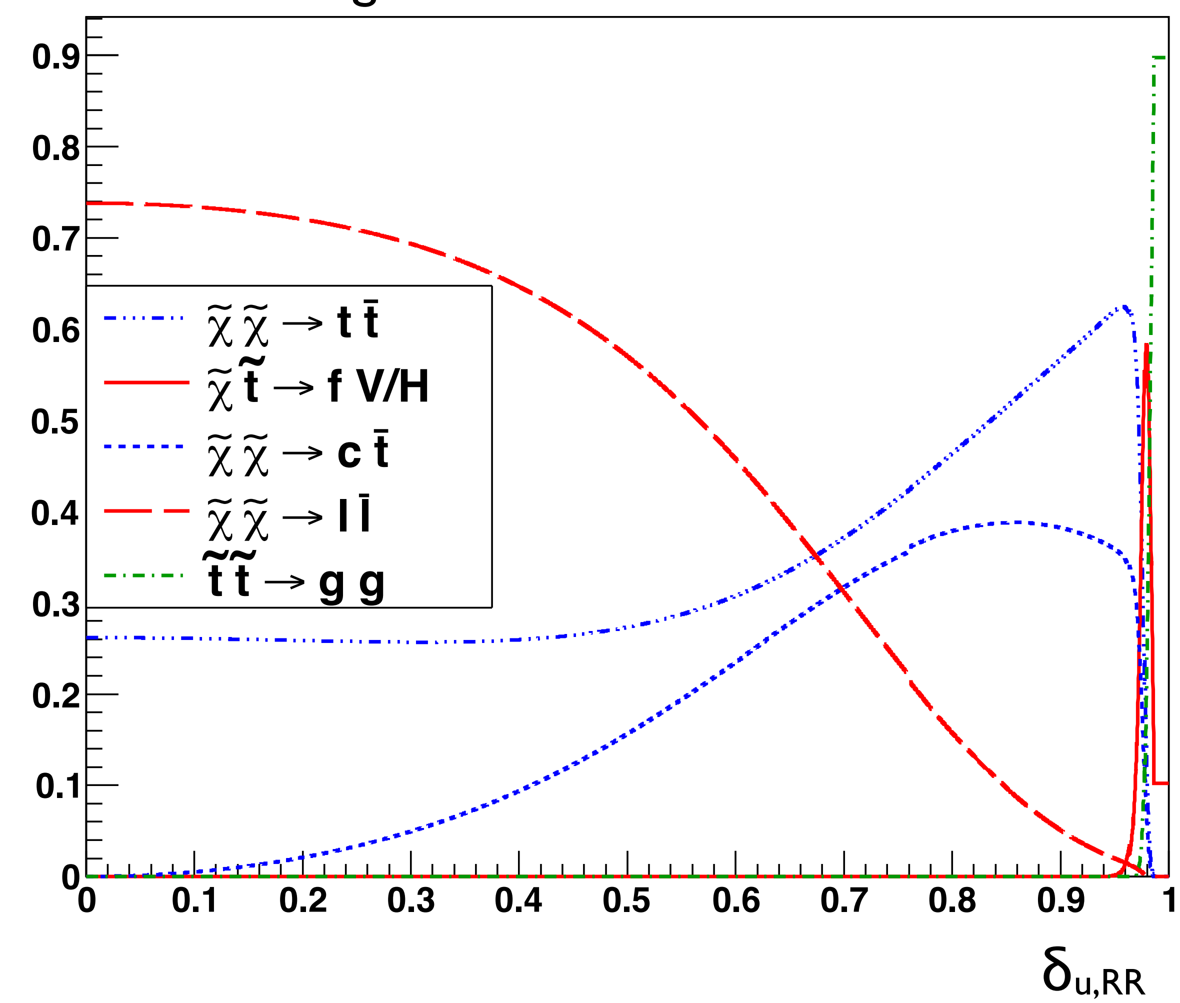
Impact on neutralino dark matter

Additional channels (and favoured co-annihilation) can increase annihilation cross-section — **mild impact on dark matter relic density and (co)annihilation channels**

Neutralino relic density ($\Omega_\chi h^2$)



Contributing channels



Herrmann, Klasen, Le Boulc'h — Phys. Rev. D84 (2011) 095007 — arXiv:1106.6229 [hep-ph]

Exploring the MSSM with non-minimal flavour violation

K. De Causmaecker, B. Fuks, B. Herrmann, F. Mahmoudi, B. O'Leary, W. Porod, N. Strobbe, S. Sekmen

JHEP 1511 (2015) 125 — arXiv:1510.01159 [hep-ph]

Experimental constraints on squark mixing

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

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

Exploring the full parameter space

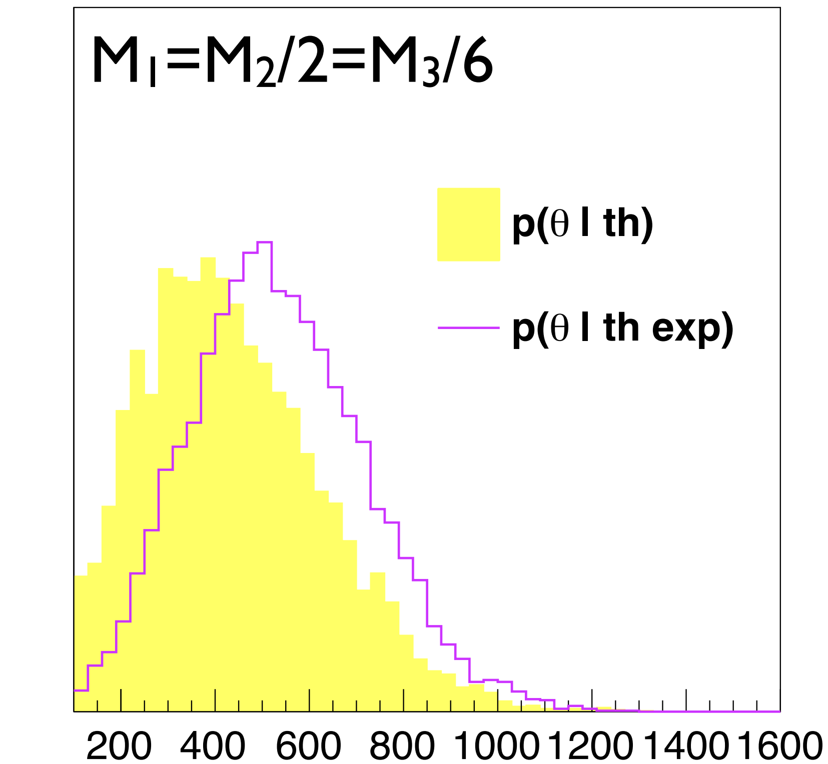
TeV-scale MSSM with additional NMFV-parameters governed by 19+3 parameters
— efficient study of the full parameter space: **Markov-Chain Monte-Carlo (MCMC)**

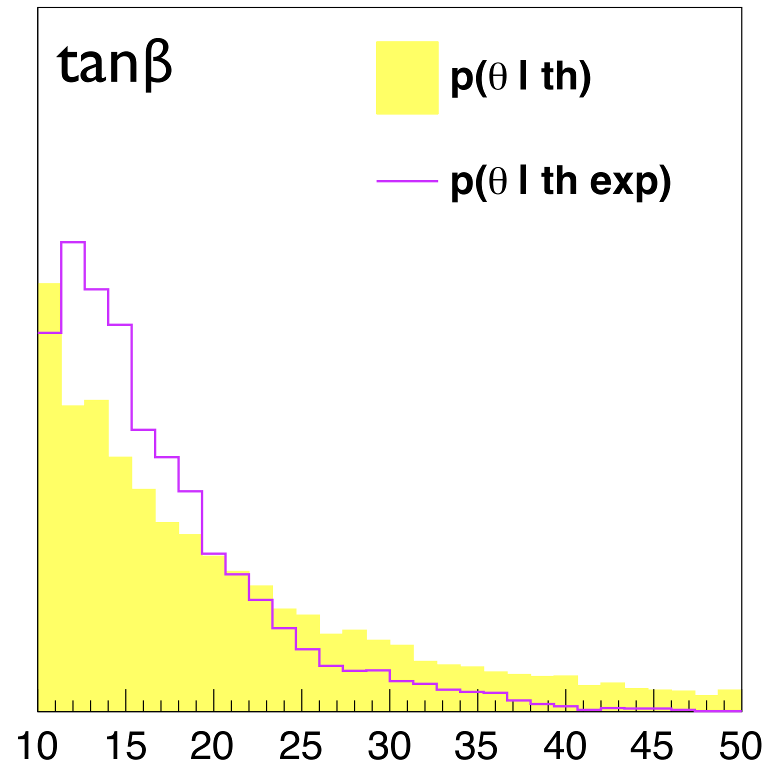
Parameter	Scanned range
$\alpha_s(m_Z)$	$\mathcal{N}(0.1184, 0.0007)$
$m_t^{\rm pole}$	$\mathcal{N}(173.3, 1.3928)$ GeV
$m_b(m_b)$	$\mathcal{N}(4.19, 0.12)$ GeV
$M_{\tilde{Q}_{1,2}}$	[300, 3500] GeV
$M_{\tilde{Q}_3}$	[100, 3500] GeV
$M_{\tilde{U}_{1,2}}$	[300, 3500] GeV
$M_{\tilde{U}_3}$	[100, 3500] GeV
$M_{\tilde{D}_{1,2}}$	[300, 3500] GeV
$M_{\tilde{D}_3}$	[100, 3500] GeV
A_f	[-10000, 10000] GeV or $\lvert A_f \rvert < 4 \max\{M_{\tilde{q}}, M_{\tilde{\ell}}\}$

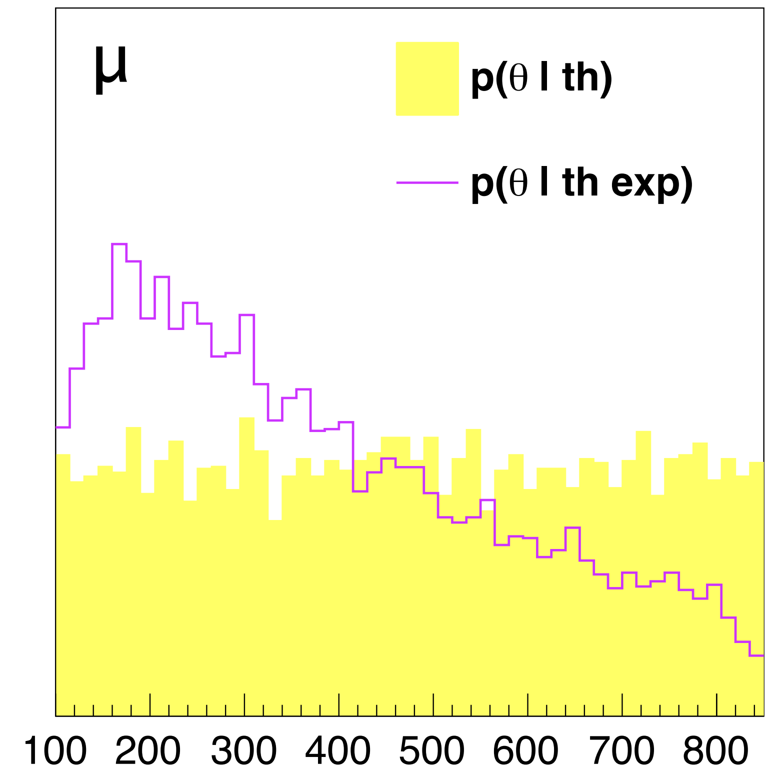
Parameter	Scanned range
$\tan\beta$	[10, 50]
μ	[100, 850] GeV
m_A	[100, 1600] GeV
M_1	[100, 1600] GeV
$M_{\tilde{\ell}}$	[100, 3500] GeV
δ_{LL}	[-0.8, 0.8]
δ^u_{RR}	[-0.8, 0.8]
δ^d_{RR}	[-0.8, 0.8]
δ^u_{LR}	[-0.5, 0.5]
δ^u_{RL}	[-0.5, 0.5]
δ^d_{LR}	[-0.05, 0.05]
δ^d_{RL}	[-0.05, 0.05]

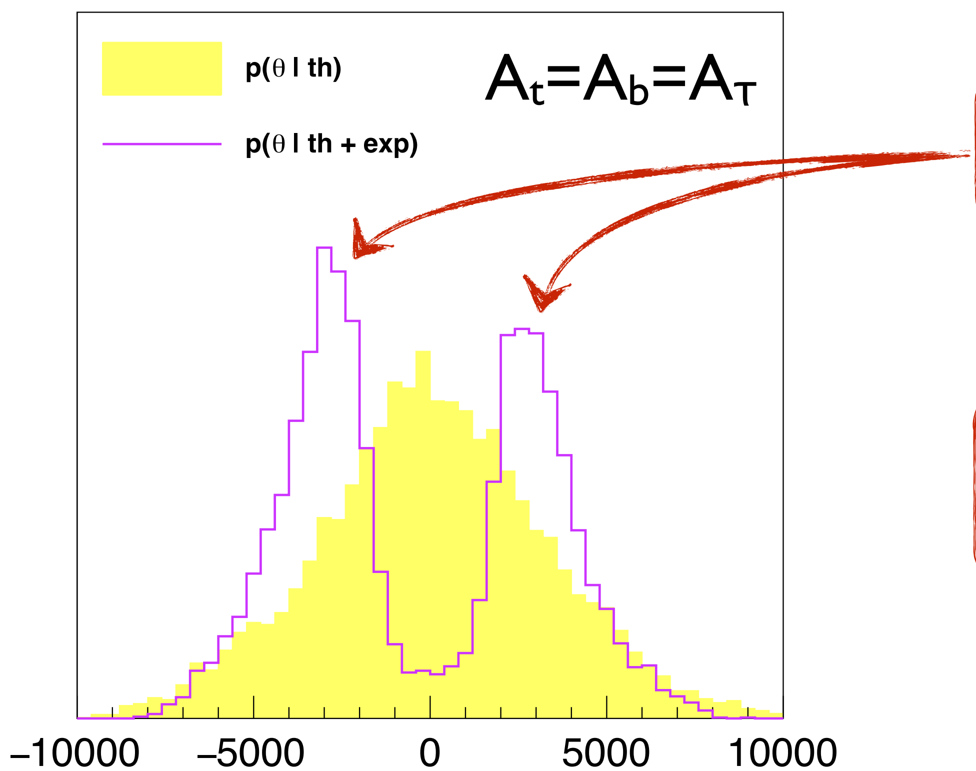
Impose Higgs mass and flavour constraints (SPHENO W. Porod, SUPERISO N. Mahmoudi)
In addition, require neutralino LSP plus vacuum stability (VEVACIOUS B. O'Leary)
— study **distributions of input parameters and physical quantities**

Results — flavour-conserving parameters







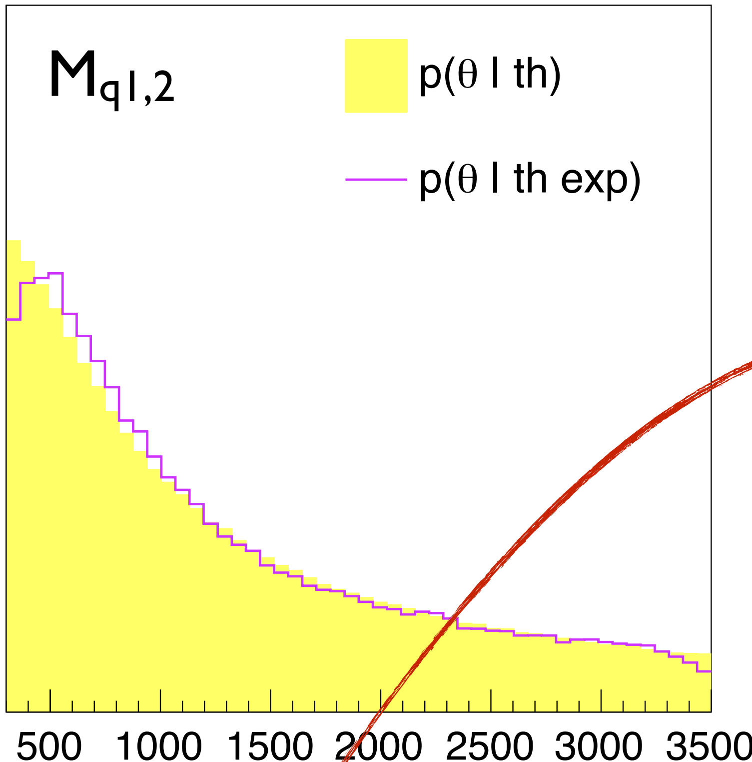


$$|X_t| = |A_t - \mu/\tan\beta| \sim \sqrt{6}\, M_{SUSY}$$

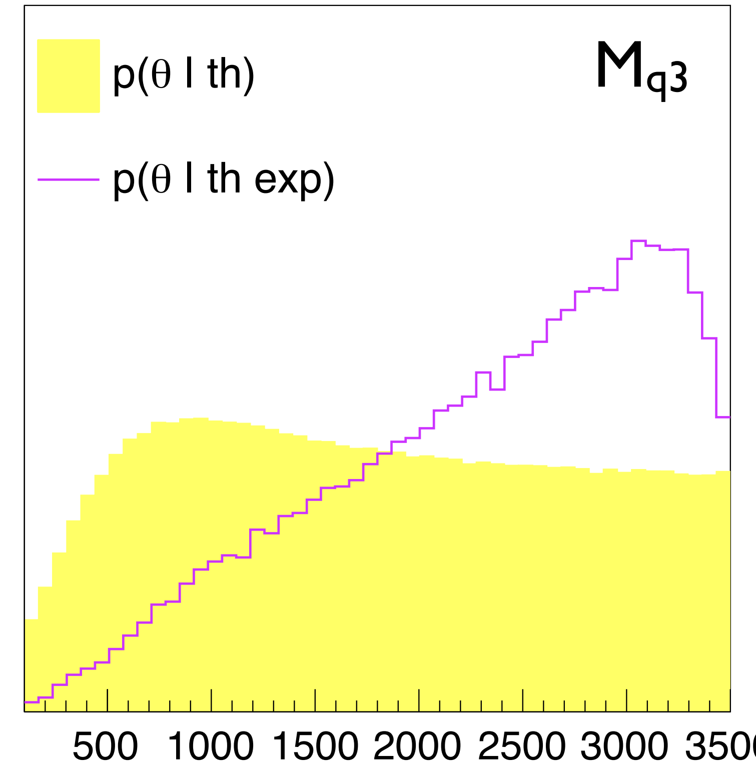
$m_h \sim 125$ GeV

$$m_h^2 = m_Z^2 \cos^2 2\beta + \frac{3g^2 m_t^4}{8\pi m_W^2}\left[\log\frac{M_{SUSY}^2}{m_t^2} + \frac{X_t^2}{M_{SUSY}^2}\left(1 - \frac{X_t^2}{12 M_{SUSY}^2}\right)\right]$$

Results — flavour-conserving parameters



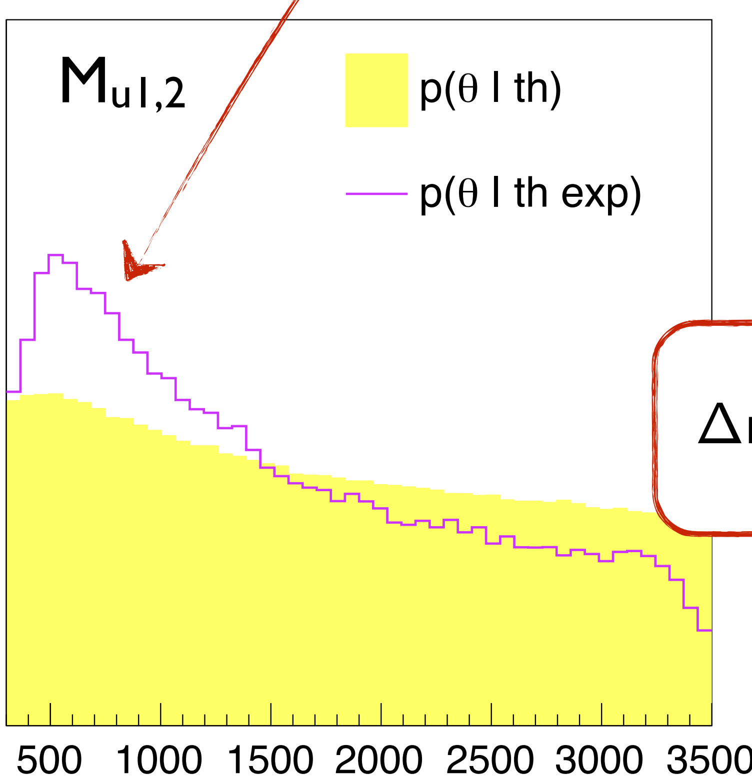
compensate non-zero $\delta_{u,LR}$



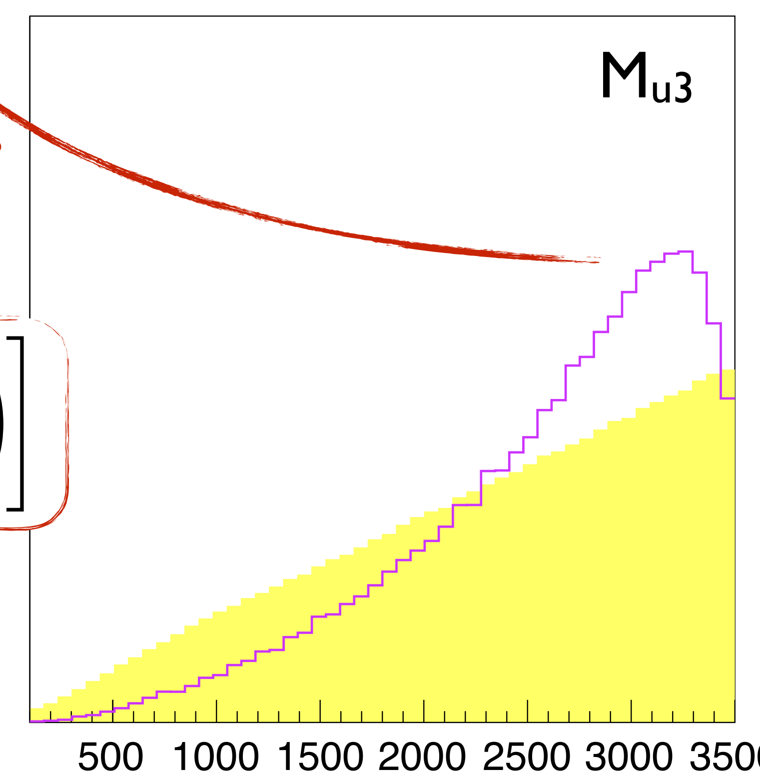
$$(T_u)_{23} = \frac{\sqrt{2}}{v_u}\, \delta^u_{LR}\, M_{Q_{1,2}}\, M_{U_3}$$

$m_h \sim 125$ GeV

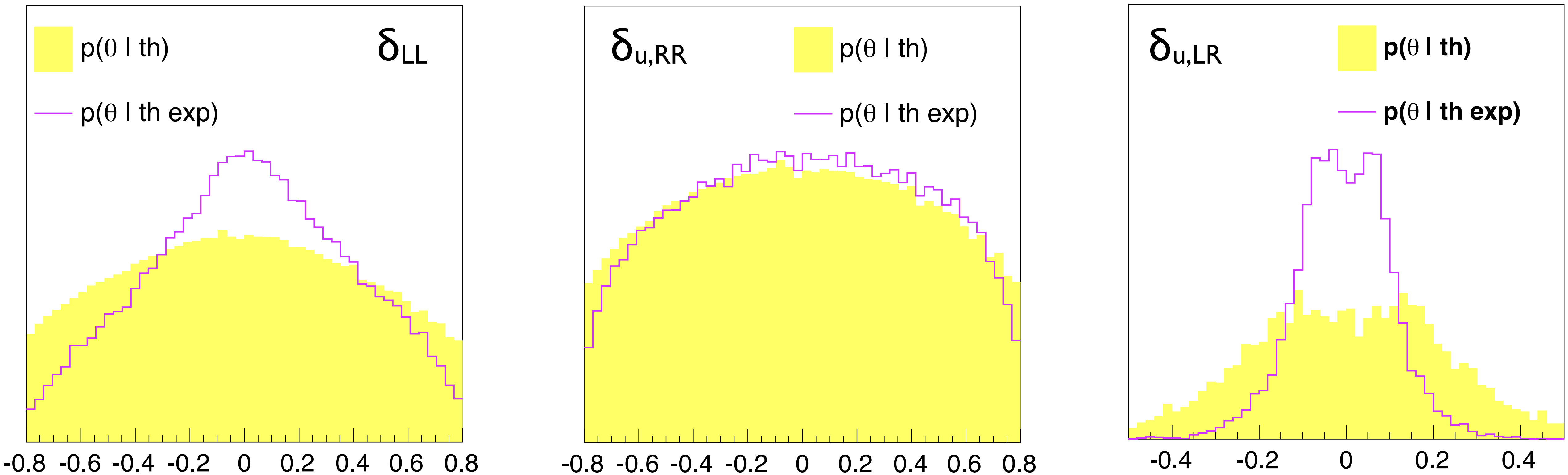
flavour constraints



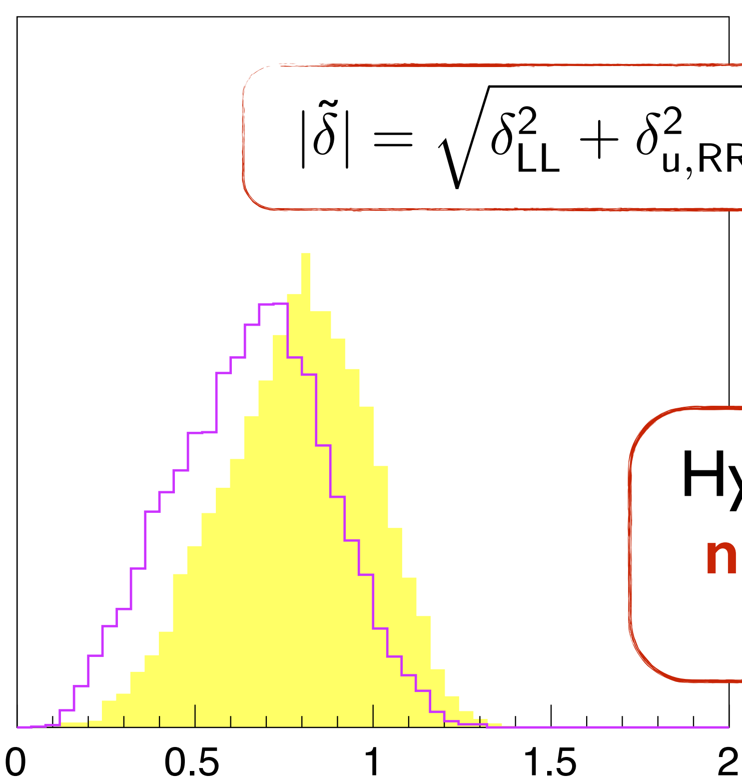
$$\Delta m_h^2 = \frac{3v_u^4}{8\pi^2 v^2}\left[\frac{(T_U)^2_{23}}{M^2_{SUSY}}\left(\frac{Y_t^2}{2} - \frac{(T_U)^2_{23}}{12 M^2_{SUSY}}\right)\right]$$



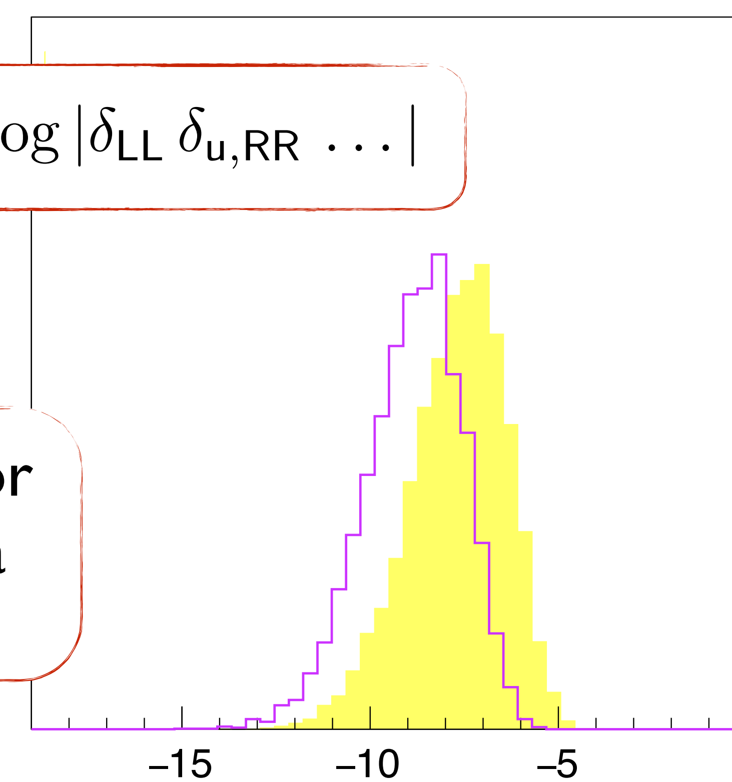
Results — flavour-violating parameters



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

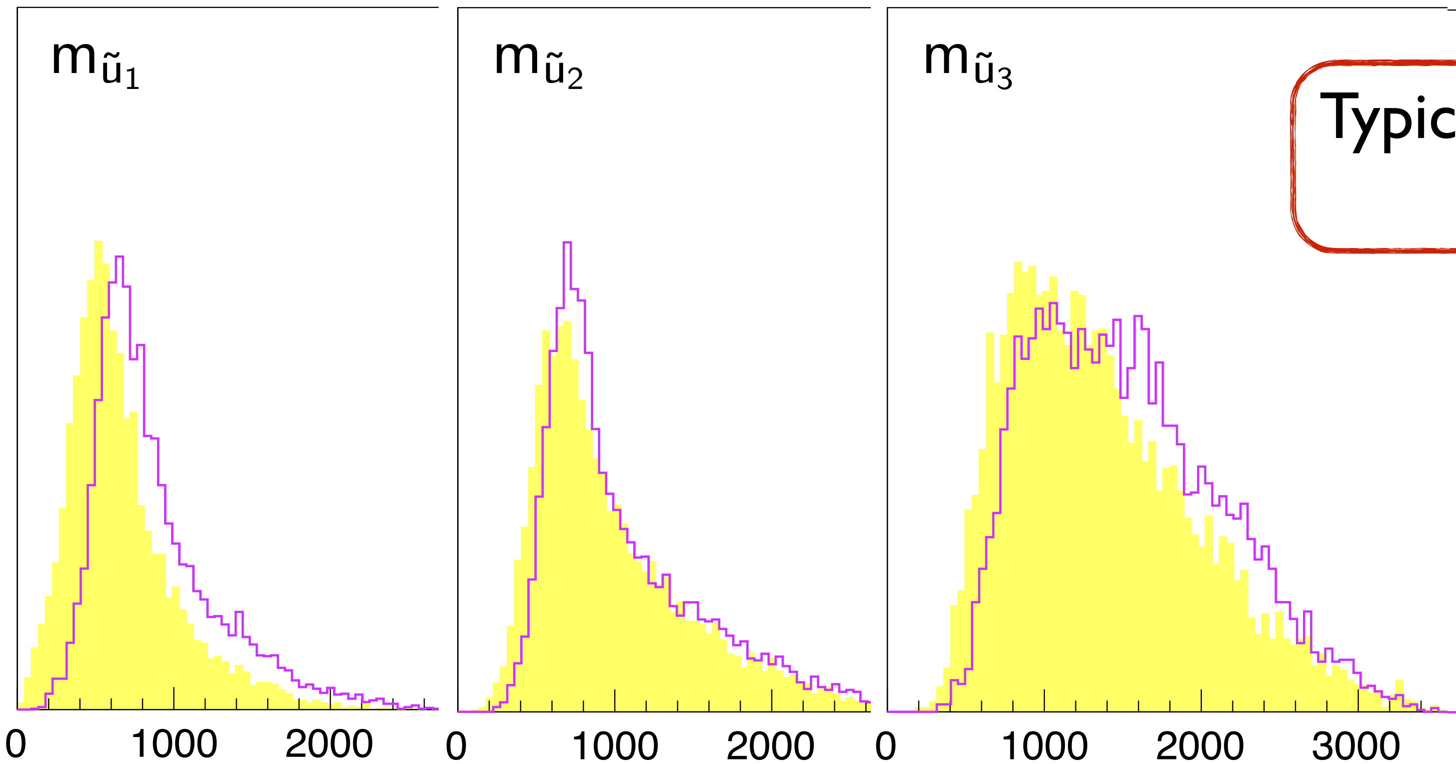


$$\log|\Pi_\delta| = \log|\delta_{\mathrm{LL}}\,\delta_{\mathrm{u,RR}}\;\ldots|$$

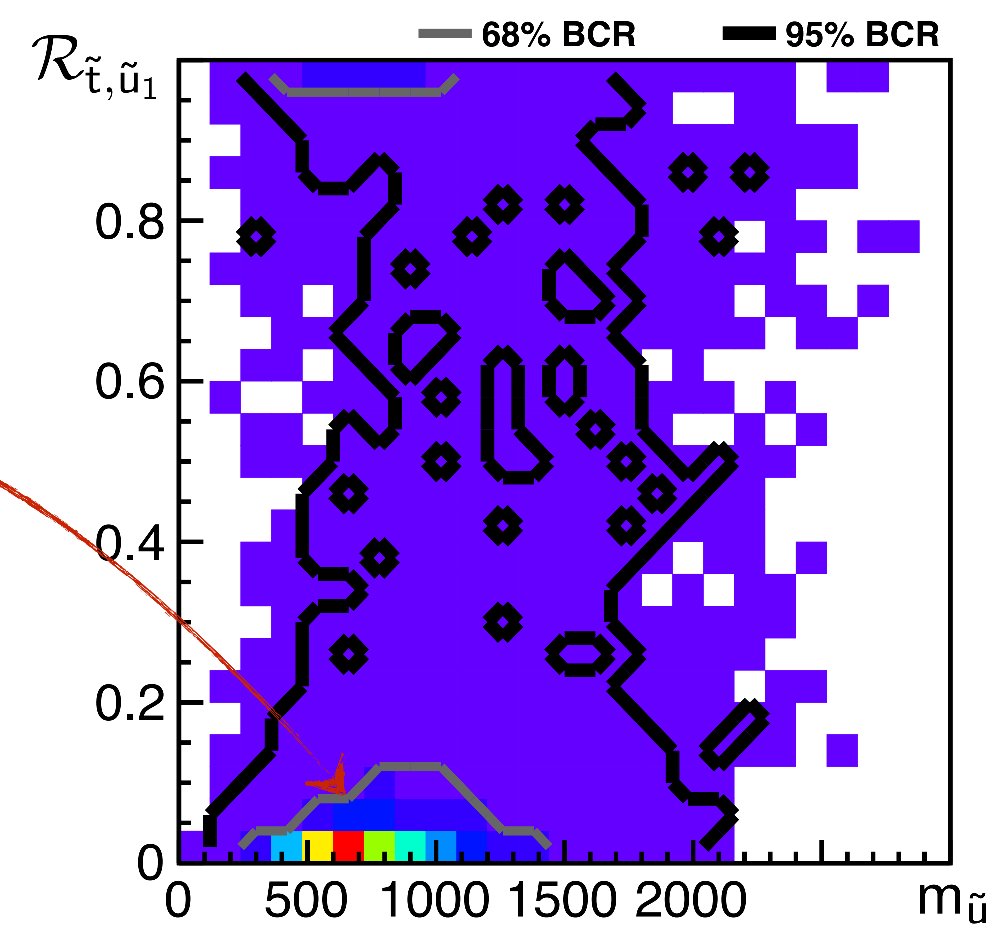


Hypothesis of NMFV in the squark sector
not obviously disfavoured by exp. data
(B-physics, K-physics, Higgs mass, …)

Results — physical squark masses



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



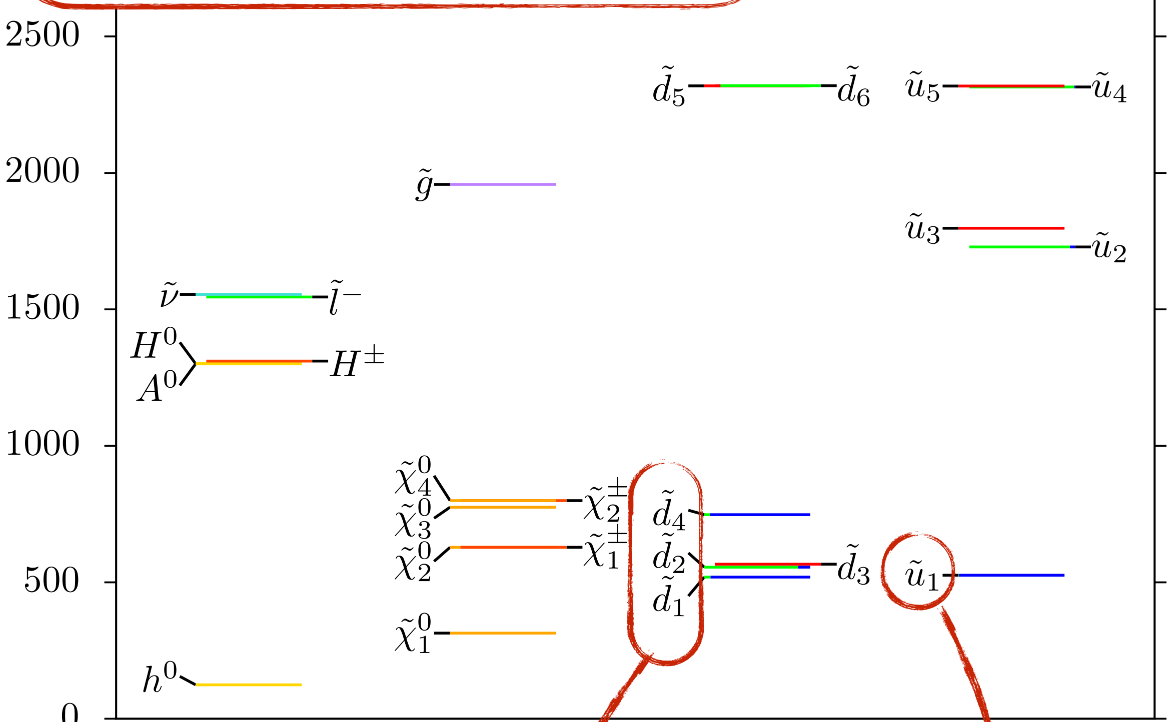
Lightest up-type states mainly **not stop-like**

Benchmark scenarios for future studies

In total, typical features of NMFV captured in four benchmark scenarios

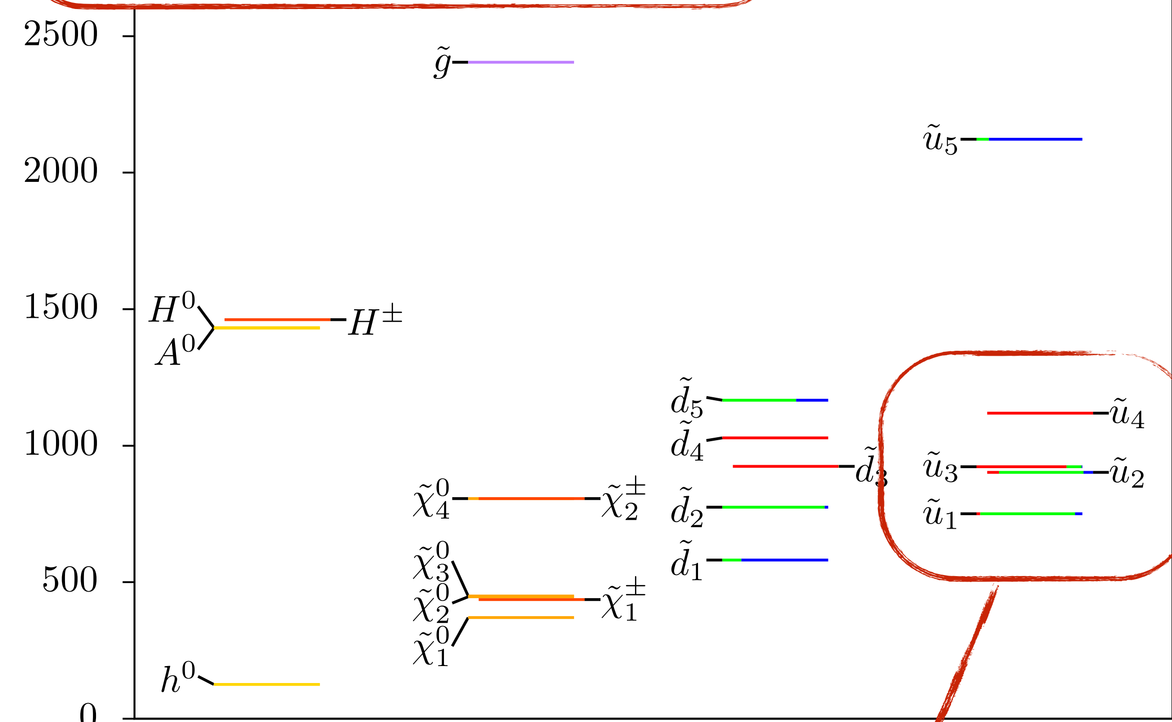
$\delta_{LL} = 0.14 \quad \delta^{u}_{RR} = 0.17$

$\delta^{u}_{LR} = 0.09 \quad \delta^{u}_{RL} = -0.10$



$\delta_{LL} = 0.59 \quad \delta^{u}_{RR} = 0.60$

$\delta^{u}_{LR} = 0.10 \quad \delta^{u}_{RL} = -0.07$



$\mathrm{BR}(\tilde{d}_1 \to b\,\tilde{\chi}^0_1) = 0.84$

$\mathrm{BR}(\tilde{d}_1 \to s\,\tilde{\chi}^0_1) = 0.16$

$\mathrm{BR}(\tilde{d}_4 \to b\,\tilde{\chi}^0_1) = 0.42$

$\mathrm{BR}(\tilde{d}_4 \to W^-\,\tilde{u}_1) = 0.27$

$\mathrm{BR}(\tilde{d}_4 \to h^0/Z^0\,\tilde{d}_1) = 0.13$

$\mathrm{BR}(\tilde{u}_1 \to t\,\tilde{\chi}^0_1) = 0.99$

$\tilde{u}_1 = 0.07\,\tilde{t} + 0.84\,\tilde{c} + 0.09\,\tilde{u}$

$\tilde{u}_2 = 0.09\,\tilde{t} + 0.80\,\tilde{c} + 0.11\,\tilde{u}$

$\tilde{u}_3 = 0.01\,\tilde{t} + 0.14\,\tilde{c} + 0.85\,\tilde{u}$

Towards a test of SUSY-GUTs at the LHC — the example of *SU(5)*

S. Fichet, B. Herrmann, Y. Stoll — Phys. Lett. B 742 (2015) 69-73 — arXiv:1403.3397 [hep-ph]
S. Fichet, B. Herrmann, Y. Stoll — JHEP 05 (2015) 091 — arXiv:1501.05307 [hep-ph]
B. Herrmann, S. Fichet — *to be published*…

Motivation

Assumption (optimistic!): **A new state is observed at LHC** — e.g. squark…

Question: What can we learn from it…?

In particular: **What can we learn about grand unification…?**

Matter unification — **accidental permutation symmetries** at high scale

↓ potentially (almost) **insensitive to quantum corrections**

Possibility to set up **tests at the TeV scale** — Large Hadron Collider

In the following: Consider the example of *SU(5)*-like unification in Supersymmetry…

SU(5) — Standard Model and MSSM

Matter (super)fields fit into complete representations of the *SU(5)* gauge group

$$\mathbf{10} = (Q, U, E) \qquad \bar{\mathbf{5}} = (L, D)$$

↓

Hint towards Grand Unified Theory (GUT) containing *SU(5)* as a subgroup

SU(5) → *SU(3)* × *SU(2)* × *U(1)*

↓

Is Nature *SU(5)*-symmetric at short distance...?

Sfermions belonging to same representations share common soft mass matrices

$$M^2_{\mathbf{10}} \equiv M^2_{\tilde{Q}} = M^2_{\tilde{U}} = M^2_{\tilde{E}}$$
$$M^2_{\mathbf{5}} \equiv M^2_{\tilde{D}} = M^2_{\tilde{L}}$$

SU(5)-specific relations — GUT scale

Requiring the superpotential to be invariant implies:

$$(Y_d)_{ij} = (Y_\ell)_{ji} \iff \boxed{Y_d = Y_\ell^t}$$
$$(Y_u)_{ij} = (Y_u)_{ji} \iff \boxed{Y_u = Y_u^t}$$

at GUT scale

If SUSY-breaking mediated by *SU(5)* singlet, these relations propagate into soft sector:

$$(T_d)_{ij} = (T_\ell)_{ji} \iff \boxed{T_d = T_\ell^t}$$
$$(T_u)_{ij} = (T_u)_{ji} \iff \boxed{T_u = T_u^t}$$

at GUT scale

Renormalization group evolution — **we expect at the TeV scale:**

$$\boxed{Y_d \neq Y_\ell^t \quad T_d \neq T_\ell^t}$$

↓

not very useful…

$$\boxed{Y_u \approx Y_u^t \quad T_u \approx T_u^t}$$

↓

test *SU(5)* hypothesis…

$SU(5)$-specific relations — TeV scale

Renormalization group equations (one-loop) of up-type Yukawa and trilinear couplings

$$16\pi^2\ \beta_{Y_u} = Y_u\left[3\,\mathrm{Tr}\{Y_u^\dagger Y_u\} + 3\,Y_u^\dagger Y_u + Y_d^\dagger Y_d - \frac{16}{3}g_3^2 - 3g_2^2 - \frac{13}{15}g_1^2\right]$$

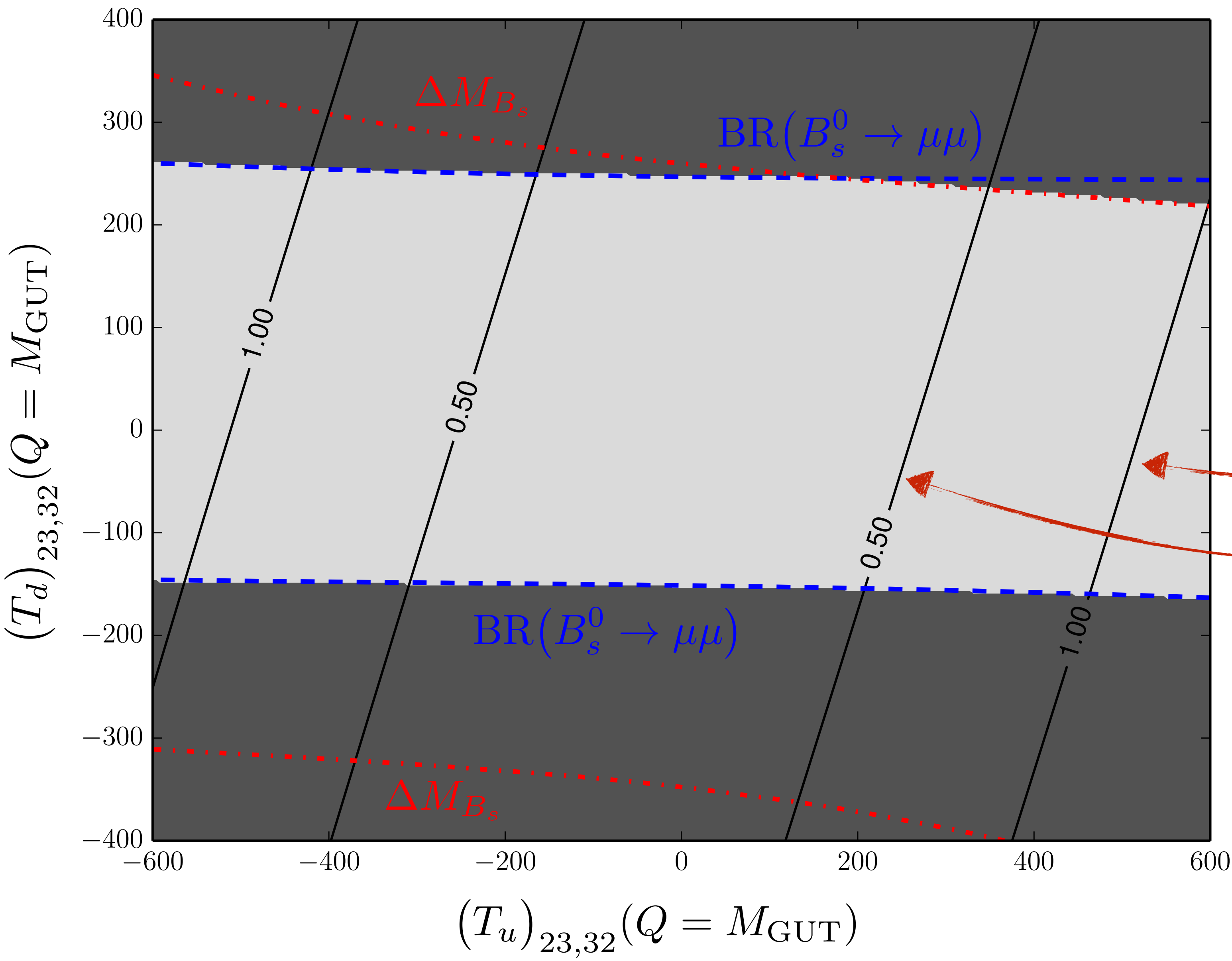
$$16\pi^2\ \beta_{T_u} = T_u\left[3\,\mathrm{Tr}\{Y_u^\dagger Y_u\} + 5\,Y_u^\dagger Y_u + Y_d^\dagger Y_d - \frac{16}{3}g_3^2 - 3g_2^2 - \frac{13}{15}g_1^2\right] + Y_u\left[6\,\mathrm{Tr}\{T_u Y_u^\dagger\} + 4\,Y_u^\dagger T_u + 2Y_d^\dagger T_d + \frac{32}{3}M_3 g_3^2 + 6M_2 g_2^2 + \frac{26}{15}M_1 g_1^2\right]$$

Beta-functions mostly dominated by symmetric contributions,
while non-symmetric terms are suppressed…

$$\Big\{SU(5)\text{–type SUSY GUT}\Big\} \Longrightarrow \Big\{T_u \approx T_u^t \text{ at TeV scale}\Big\}$$

Related observables at LHC….?

SU(5)-specific relations — TeV scale



$$\mathcal{A}_{23} = \frac{\left|(T_u)_{23} - (T_u)_{32}\right|}{\mathrm{Tr}\{\mathcal{M}^2_{\tilde{u}}\}^{1/2}}$$

$(Q = 1\ \mathrm{TeV})$

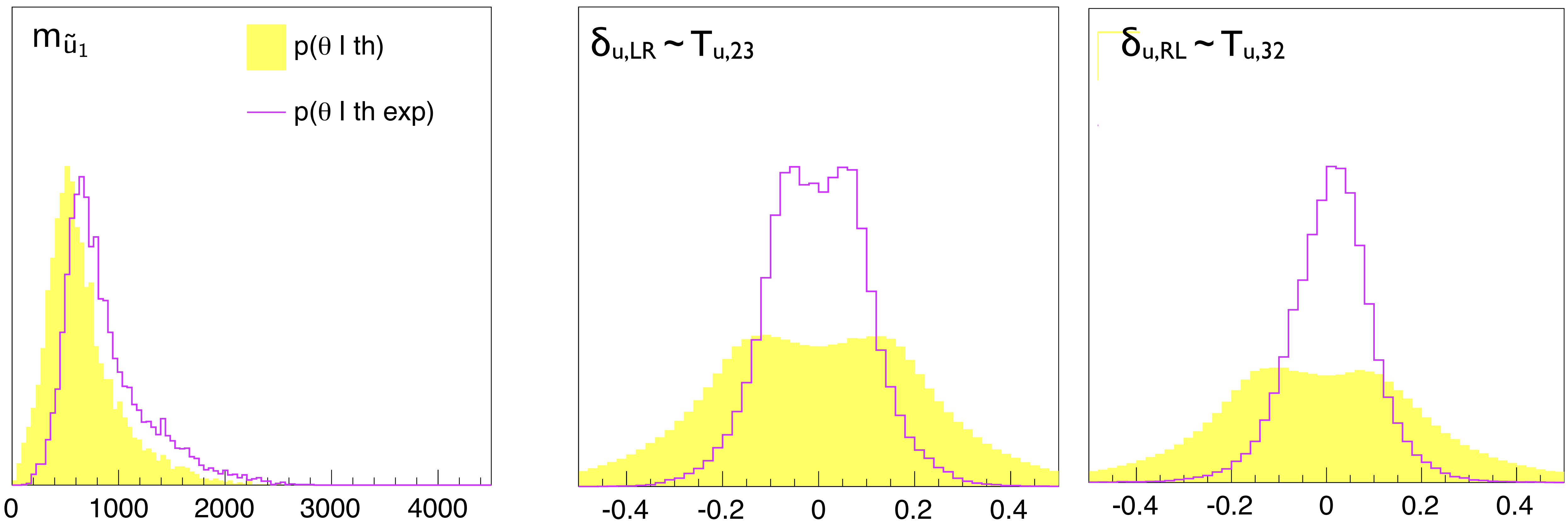
$\mathcal{A}_{23} \lesssim 2\%$ $\qquad \tan\beta = 10$

$\mathcal{A}_{23} \lesssim 5\%$ $\qquad \tan\beta = 40$

Asymmetry at the TeV scale **does not exceed a few percent** for typical scenarios — such a precision difficult to reach at LHC…

Flavour violation in the squark sector

Hypothesis of non-minimal flavour violation in the squark sector **not obviously disfavoured by experimental data** (B-physics, K-physics, Higgs mass…)



Lightest squark states (mixtures of stop and charm) **accessible at the LHC**

— and not completely ruled out (yet…?)

Testing the *SU(5)* hypothesis at the LHC

Any test of the *SU(5)* relation relies on a comparison involving at least two (up-type) squarks

The mass spectrum may exhibit different features:

Natural supersymmetry	→ **Effective theory approach…**
Heavy supersymmetry	→ **Effective theory approach…**
Top-charm supersymmetry	→ **Mass insertion approximation…**

S. Fichet, B. Herrmann, Y. Stoll — Phys. Lett. B 742 (2015) 69-73, arXiv:1403.3397 [hep-ph]
S. Fichet, B. Herrmann, Y. Stoll — JHEP 05 (2015) 091, arXiv:1501.05307 [hep-ph]

Need for a more general analysis not relying on specific mass hierarchies:

Arbitrary mass spectra → **Bayesian analysis…**

Y. Stoll — PhD Thesis — Université Grenoble-Alpes
S. Fichet, B. Herrmann — *to be published…*

Bayesian statistics (on one slide...)

Probability = "measurement of the **degree of belief** about a proposition"

Important application: Comparison of two models with respect to given data

$$B_{01} = \frac{p(d|\mathcal{M}_0)}{p(d|\mathcal{M}_1)}$$

Bayes factor

Here: **nested models**

$$\text{SDDR} = \frac{p(\mathcal{A}_{23}|d)}{p(\mathcal{A}_{23})}\bigg|_{\mathcal{A}_{23}=0}$$

Savage Dickey density ratio

$\lvert\log B_{01}\rvert$	Odds	Probability	Strength of evidence
< 1.0	$\lesssim 3:1$	< 0.750	Inconclusive
1.0	$\sim 3:1$	≈ 0.750	Weak evidence
2.5	$\sim 12:1$	≈ 0.923	Moderate evidence
5.0	$\sim 150:1$	≈ 0.993	Strong evidence

Jeffreys scale

In practice, the probability densities (and thus the SDDR) can be evaluated by using **Markov Chain Monte Carlo** methods…

Test scenario — derived from *SU(5)* boundary conditions

$(M^2_{\mathbf{10}})_{ij}$	$j=1$	$j=2$	$j=3$
$i=1$	$(10000)^2$	0	0
$i=2$	0	$(609)^2$	$(841)^2$
$i=3$	0	$(841)^2$	$(1564)^2$

$(M^2_{\bar{\mathbf{5}}})_{ij}$	$j=1$	$j=2$	$j=3$
$i=1$	$(8600)^2$	0	0
$i=2$	0	$(1180)^2$	0
$i=3$	0	0	$(1317)^2$

$(T_u)_{ij}$	$j=1$	$j=2$	$j=3$
$i=1$	0	0	0
$i=2$	0	0	-575
$i=3$	0	-575	-1055

$(T_d)_{ij}$	$j=1$	$j=2$	$j=3$
$i=1$	0	0	0
$i=2$	0	0	0
$i=3$	0	0	-70

$M_{1/2}$	962
$M^2_{H_{u,d}}$	$(1343)^2$
$\tan\beta$	10
$\text{sign}(\mu)$	$+1$

Renormalisation group evolution
and spectrum calculation: **SPHENO** [W. Porod 2003-2015]

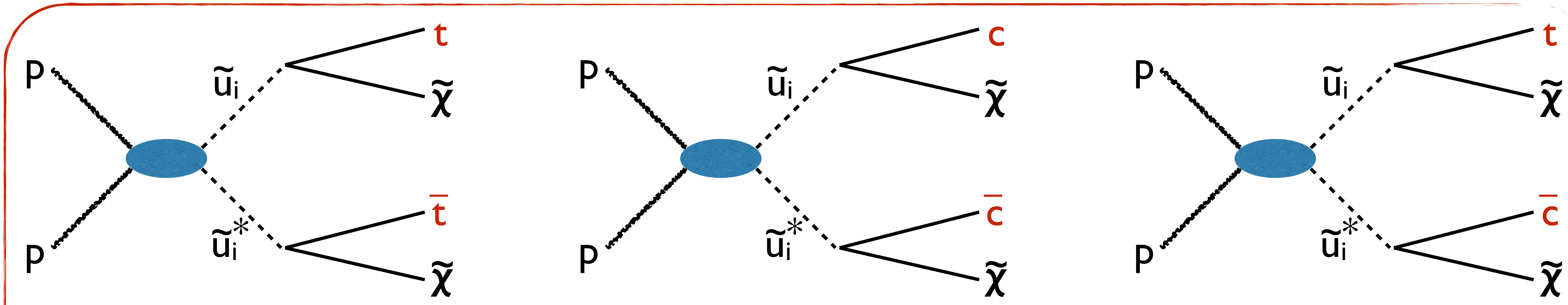
	$m_{\tilde{u}_1}$	$m_{\tilde{u}_2}$	$m_{\tilde{u}_3}$	$m_{\tilde{u}_4}$	m_{h^0}	$m_{\tilde{\chi}^0_1}$	$(T_u)_{33}$	$(T_u)_{23}$	$(T_u)_{32}$
R	1144.6	1405.4	1468.8	1786.5	122.6	419.3	-2017.0	-810.6	-884.3
C	1153.9	1381.1	1471.3	1792.5	121.4	419.2	-1965.2	1199.1	-1252.7

Counter example at TeV scale

$$(T_u)_{23} \approx -(T_u)_{32}$$

Test observables — Large Hadron Collider

Consider production of up-type squarks and subsequent decay into top and charm jets



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]

Cross-sections and branching ratios numerical evaluated using **XSUSY** [Fuks, Herrmann 2007]

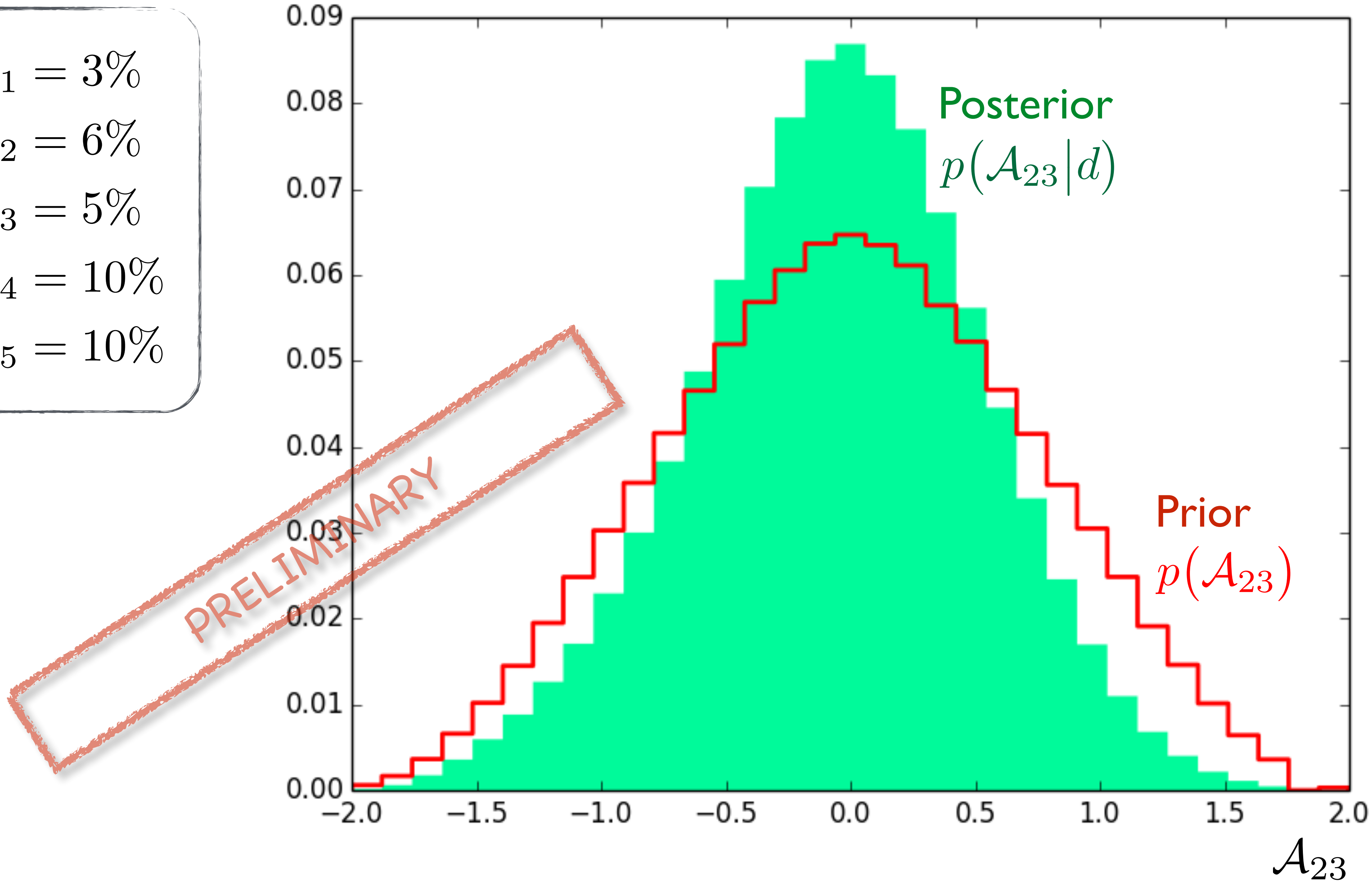
Test scenario: $N_{tt} = 328, \quad N_{cc} = 51, \quad N_{ct} = 26$

Statistical errors evaluated assuming Gaussian distributions for these observables

Minimal scenario — *SU(5)* case

$$\mathcal{O}_1 = N_{cc}/N_{tt} \qquad \sigma_1 = 3\%$$
$$\mathcal{O}_2 = N_{ct}/N_{tt} \qquad \sigma_2 = 6\%$$
$$\mathcal{O}_3 = m_{\tilde{u}_1}/m_{\tilde{u}_2} \qquad \sigma_3 = 5\%$$
$$\mathcal{O}_4 = \mathcal{R}_{\tilde{u}_1\tilde{t}_L}/\mathcal{R}_{\tilde{u}_1\tilde{t}_R} \qquad \sigma_4 = 10\%$$
$$\mathcal{O}_5 = \mathcal{R}_{\tilde{u}_1\tilde{c}_L}/\mathcal{R}_{\tilde{u}_1\tilde{c}_R} \qquad \sigma_5 = 10\%$$

$$\mathcal{L} = 300\ \text{fb}^{-1}$$
$$\sqrt{s} = 14\ \text{TeV}$$



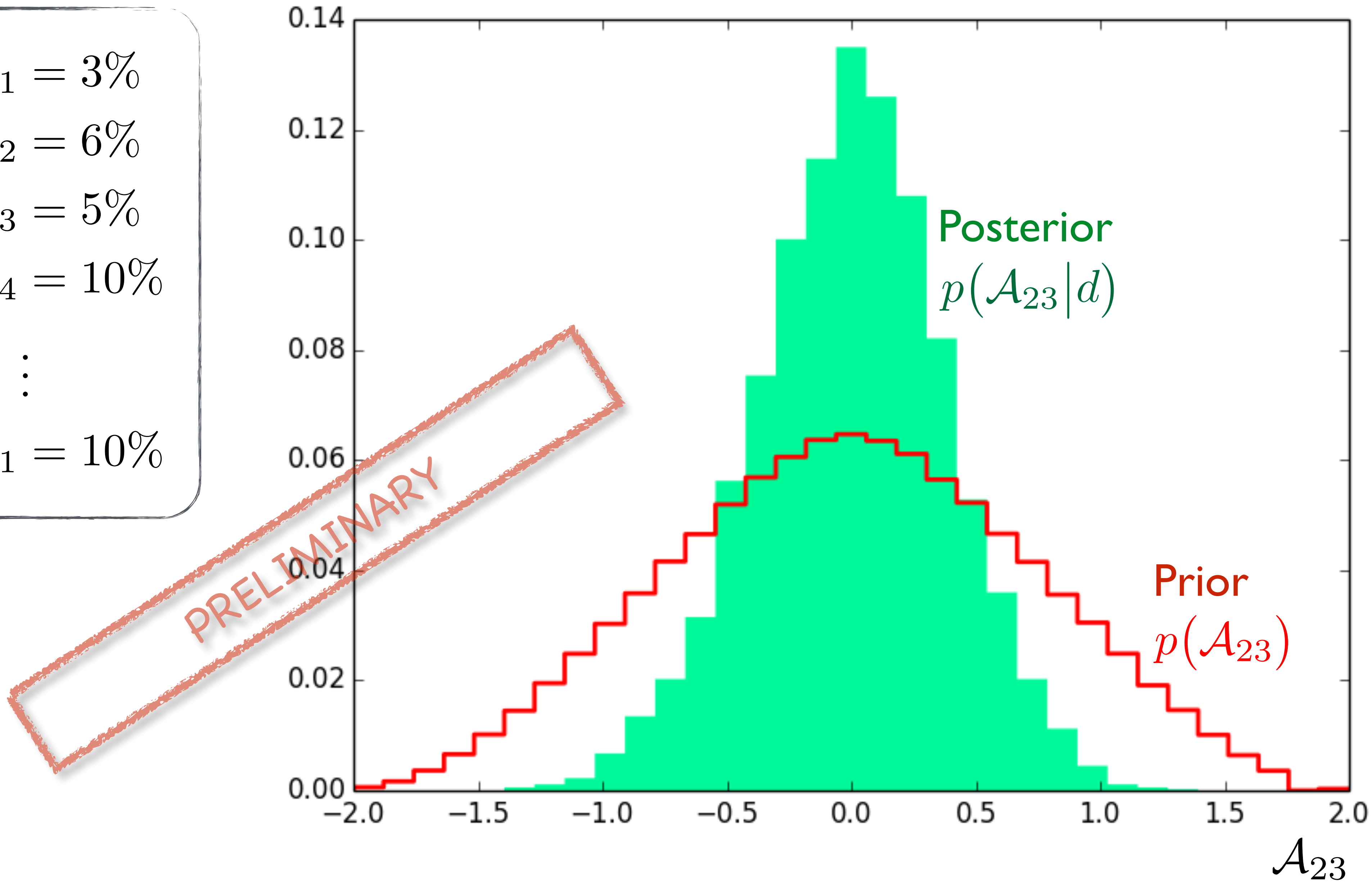
$$\text{SDDR} = \left.\frac{p(\mathcal{A}_{23}|d)}{p(\mathcal{A}_{23})}\right|_{\mathcal{A}_{23}=0} = 1.35 < 3.0$$

Test inconclusive…
(idem for counter-example)

Optimistic scenario — *SU(5)* case

$$\mathcal{O}_1 = N_{cc}/N_{tt} \qquad \sigma_1 = 3\%$$
$$\mathcal{O}_2 = N_{ct}/N_{tt} \qquad \sigma_2 = 6\%$$
$$\mathcal{O}_3 = m_{\tilde{u}_1}/m_{\tilde{u}_2} \qquad \sigma_3 = 5\%$$
$$\mathcal{O}_4 = \mathcal{R}_{\tilde{u}_1 \tilde{t}_L} \qquad \sigma_4 = 10\%$$
$$\vdots \qquad \vdots$$
$$\mathcal{O}_{11} = \mathcal{R}_{\tilde{u}_2 \tilde{c}_R} \qquad \sigma_{11} = 10\%$$

$$\mathcal{L} = 300 \text{ fb}^{-1}$$
$$\sqrt{s} = 14 \text{ TeV}$$



$$\text{SDDR} = \left.\frac{p(\mathcal{A}_{23}|d)}{p(\mathcal{A}_{23})}\right|_{\mathcal{A}_{23}=0} = 2.08 < 3.0$$

Test inconclusive…

(but **weak evidence against** *SU(5)* for counter-exemple!)

High-luminosity scenario — *SU(5)* case

$\mathcal{O}_1 = N_{cc}/N_{tt}$ $\sigma_1 = 0.3\%$

$\mathcal{O}_2 = N_{ct}/N_{tt}$ $\sigma_2 = 0.6\%$

$\mathcal{O}_3 = m_{\tilde{u}_1}/m_{\tilde{u}_2}$ $\sigma_3 = 1\%$

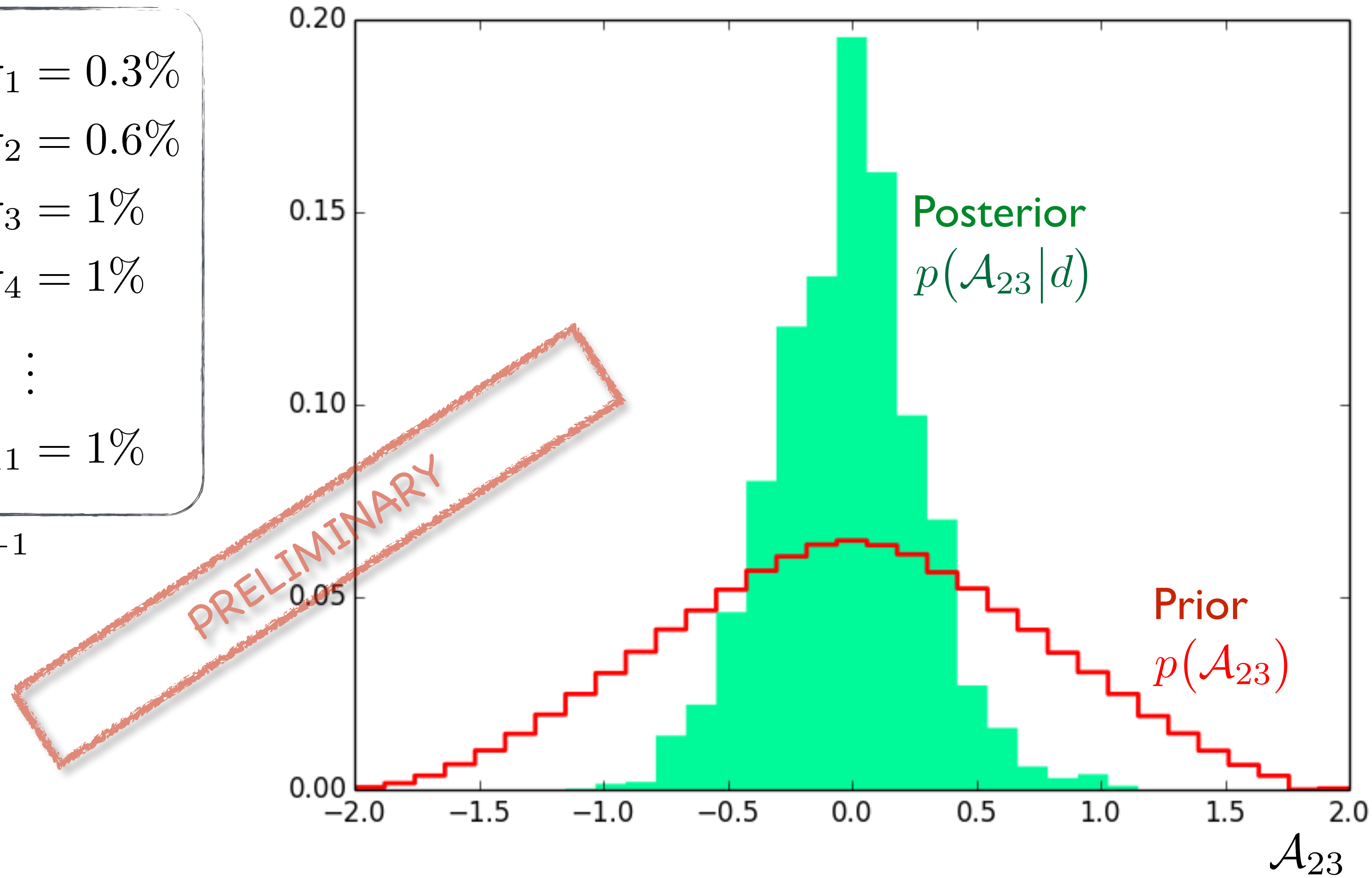
$\mathcal{O}_4 = \mathcal{R}_{\tilde{u}_1 \tilde{t}_L}$ $\sigma_4 = 1\%$

$\vdots$ $\vdots$

$\mathcal{O}_{11} = \mathcal{R}_{\tilde{u}_2 \tilde{c}_R}$ $\sigma_{11} = 1\%$

$\mathcal{L} = 3000 \text{ fb}^{-1}$

$\sqrt{s} = 14 \text{ TeV}$



$$\text{SDDR} = \left.\frac{p(\mathcal{A}_{23}|d)}{p(\mathcal{A}_{23})}\right|_{\mathcal{A}_{23}=0} = 3.02 \gtrsim 3.0$$

Weak evidence in favour of *SU(5)* hypothesis

High-luminosity scenario — Counter example

$\mathcal{O}_1 = N_{cc}/N_{tt}$ $\sigma_1 = 0.3\%$

$\mathcal{O}_2 = N_{ct}/N_{tt}$ $\sigma_2 = 0.6\%$

$\mathcal{O}_3 = m_{\tilde{u}_1}/m_{\tilde{u}_2}$ $\sigma_3 = 1\%$

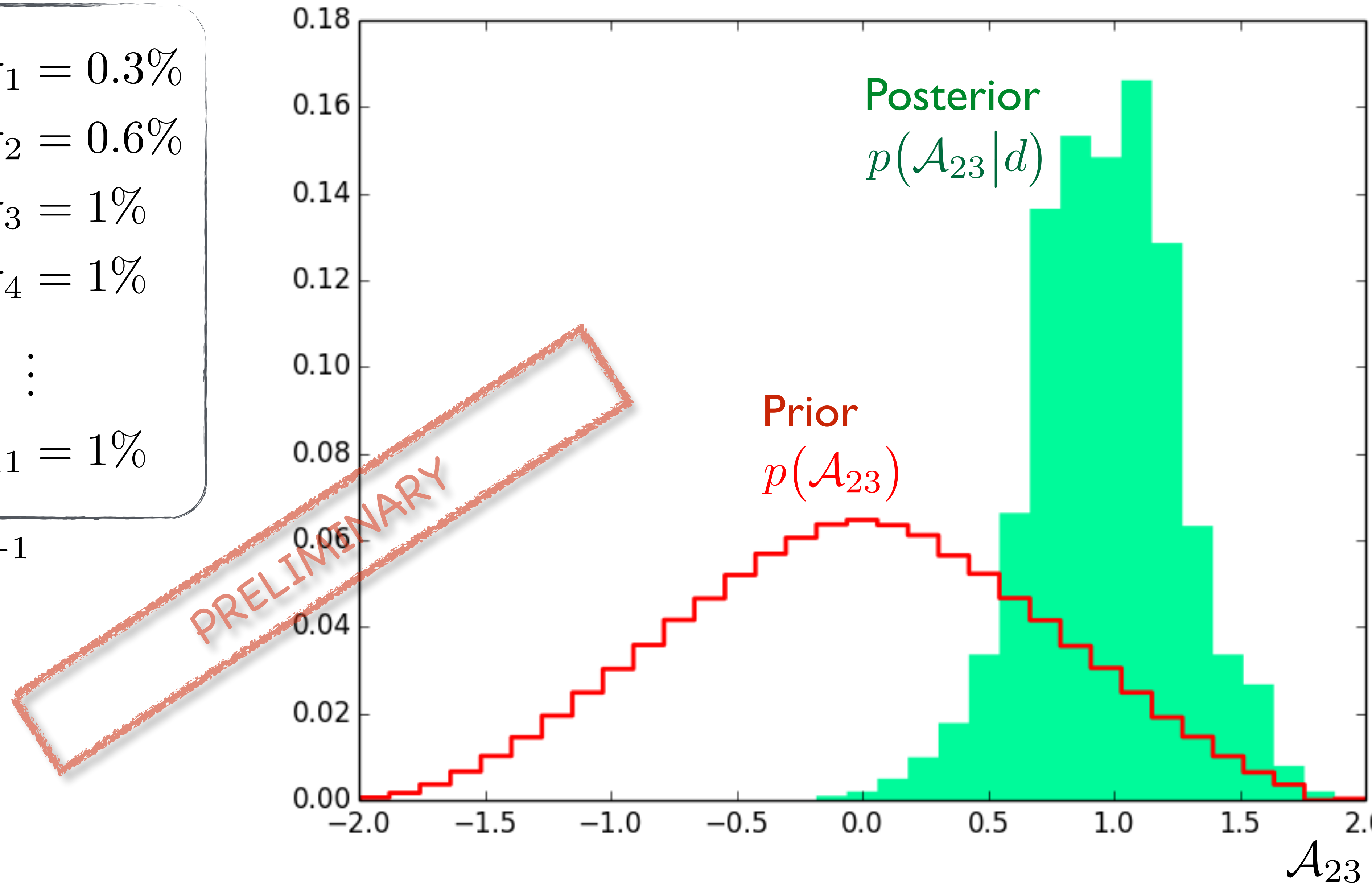
$\mathcal{O}_4 = \mathcal{R}_{\tilde{u}_1 \tilde{t}_L}$ $\sigma_4 = 1\%$

$\vdots$ $\vdots$

$\mathcal{O}_{11} = \mathcal{R}_{\tilde{u}_2 \tilde{c}_R}$ $\sigma_{11} = 1\%$

$\mathcal{L} = 3000 \text{ fb}^{-1}$

$\sqrt{s} = 14 \text{ TeV}$



$$\text{SDDR} = \left. \frac{p(\mathcal{A}_{23}|d)}{p(\mathcal{A}_{23})} \right|_{\mathcal{A}_{23}=0} = 0.03 < 1/12$$

Moderate evidence against *SU(5)* hypothesis

Conclusion

Conclusion

Non-minimally flavour-violating terms may be present in the Lagrangian of a supersymmetric theory — **interesting signatures at colliders** (but rather mild impact w.r.t. dark matter)

Several non-minimally flavour violating terms can be **simultaneously sizeable**

Flavour-violating couplings may open **windows towards GUT physics**
— effective theory and MCMC approaches in order to test *SU(5)* hypothesis