Habilitation à Diriger la Recherche — Université Grenoble Alpes

The Taste of New Physics —
Flavour Violation from TeV-scale Phenomenology to Grand Unification

Annecy — June 12, 2019

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Université Savoie Mont Blanc — CNRS

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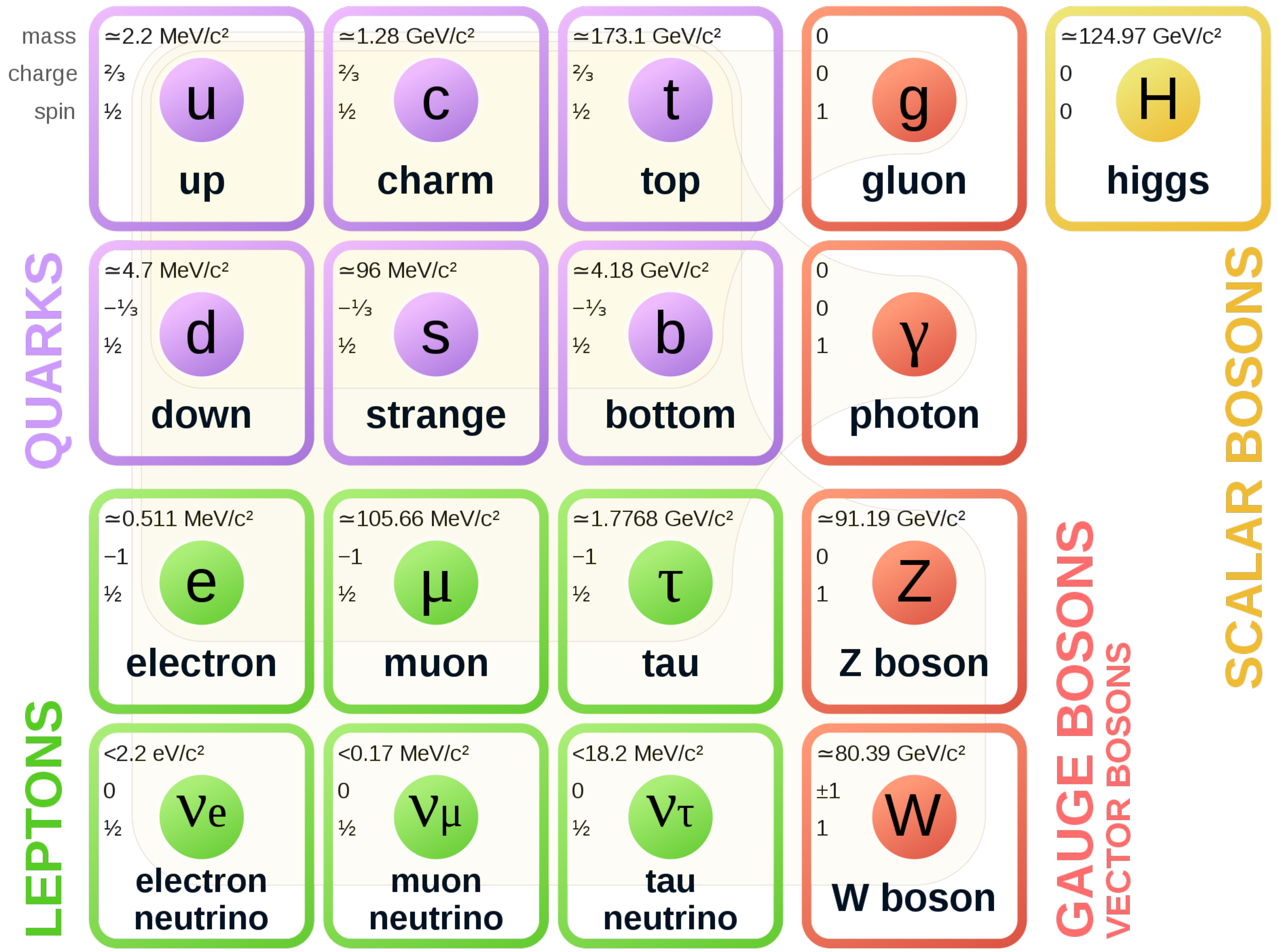
Introduction

Quark flavour in the Standard Model and the MSSM

The Standard Model of Particle Physics

Based on the gauge groupe *SU(3)xSU(2)xU(1)*, the Standard Model successfully describes a wide range of phenomena and has been tested to very good precision — however, **important questions remain unanswered… driving the exploration of new physics models!**



en.wikipedia.org/wiki/Standard_Model

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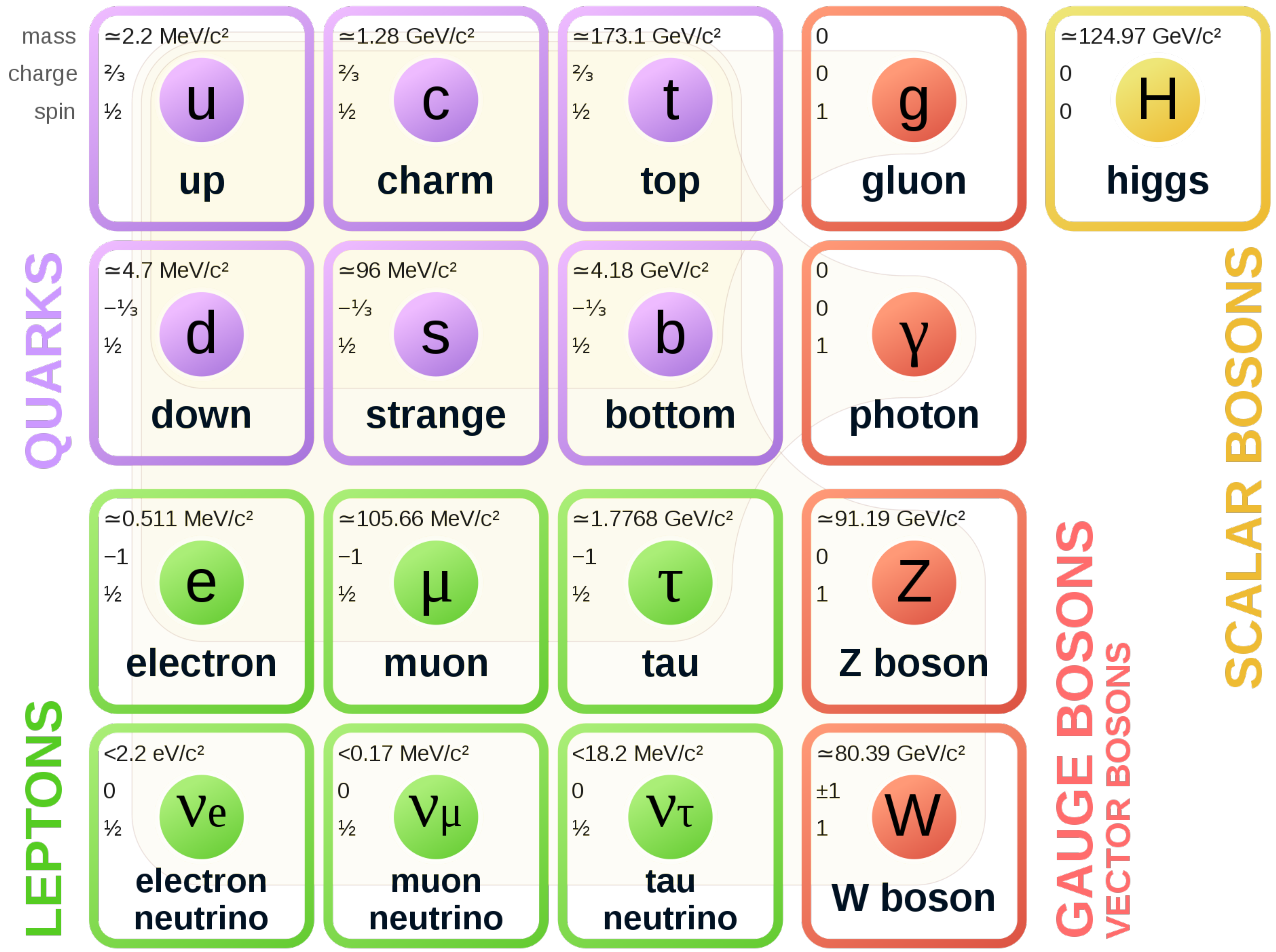

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Dark matter in the Universe…?

Neutrino masses…?

Hierarchy problem…?

Gauge coupling unification…?

Gravity…?

Lepton-flavour non-universality…?

Flavour problem…?

The Minimal Supersymmetric Standard Model

Supersymmetry relates bosonic and fermionic degrees of freedom — **superpartners** for all Standard Model particles
Supersymmetry must be broken at the TeV scale — introduce soft-breaking terms into the Lagrangian
Minimal Supersymmetric Standard Model ranks among the best studied new physics frameworks

$$\mathcal{Q}\,|\mathrm{boson}\rangle \quad\rightarrow\quad |\mathrm{fermion}\rangle$$
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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			
W bosons	$W^0, W^\pm$	1		$1/2$	$\tilde{\chi}^\pm_{1,2}$	Charginos
B boson	B^0	1				
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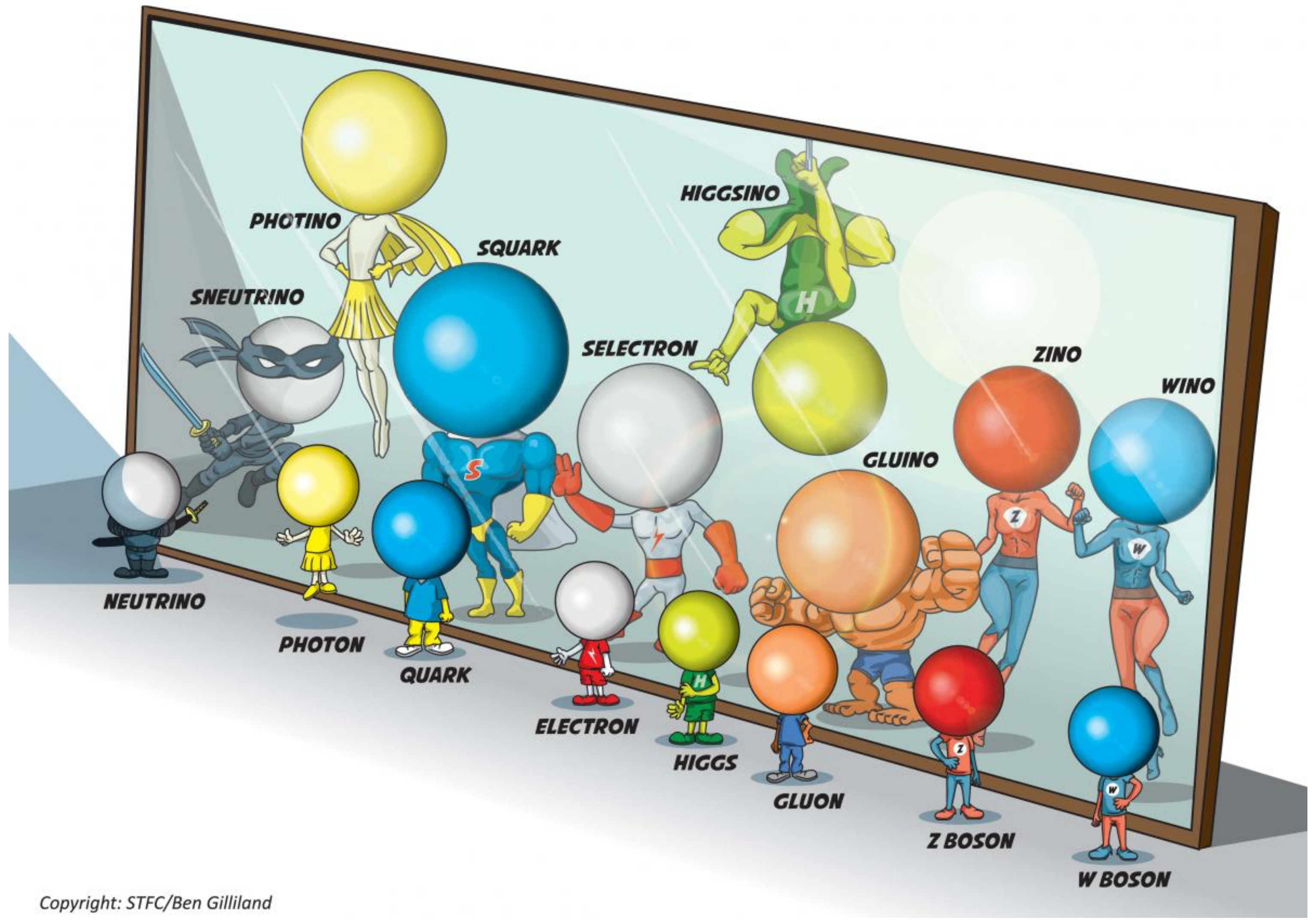

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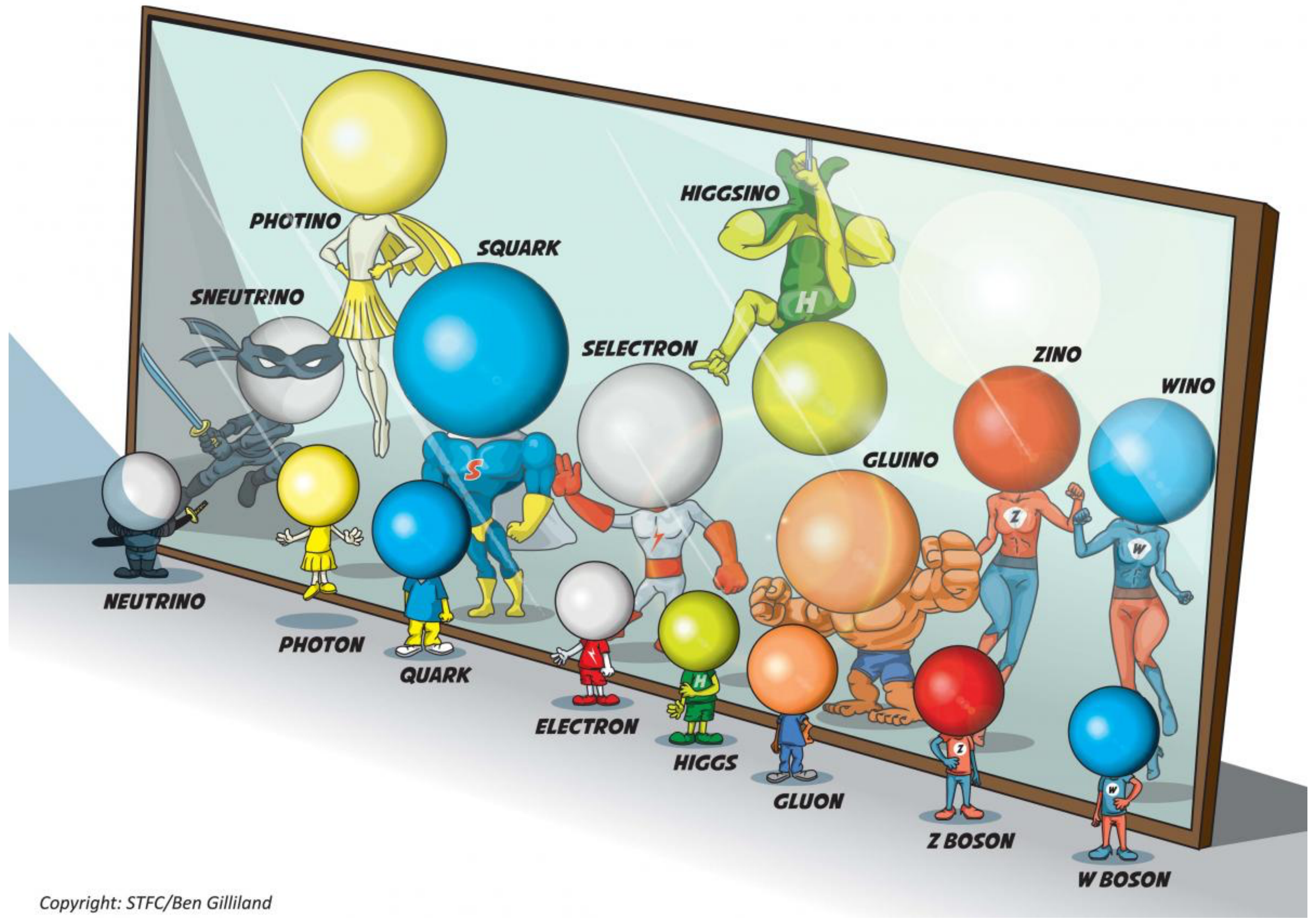

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Quark flavour in the Standard Model

Yukawa matrices are the only source of flavour violation

— flavour-violating interactions stem from the misalignment of up-type and down-type rotations

— parametrization through the **Cabbibo-Kobayashi-Maskawa (CKM) matrix**

$$u_L^{(i)} = V_{uL}\, u_L^{(m)}$$
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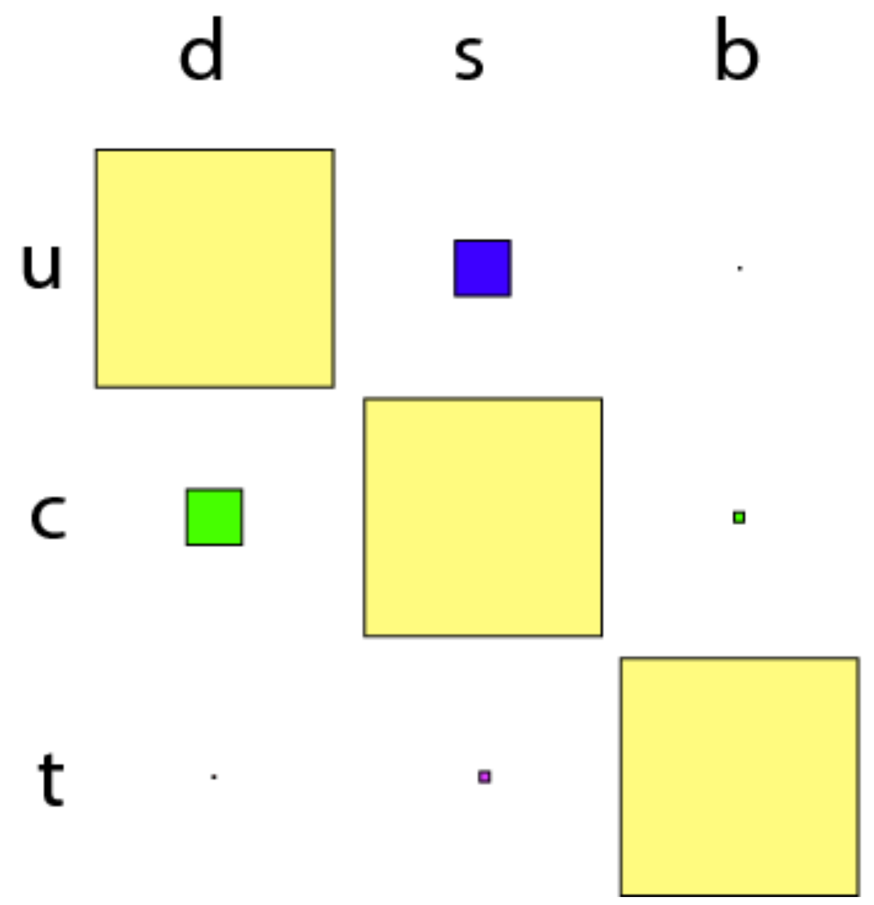

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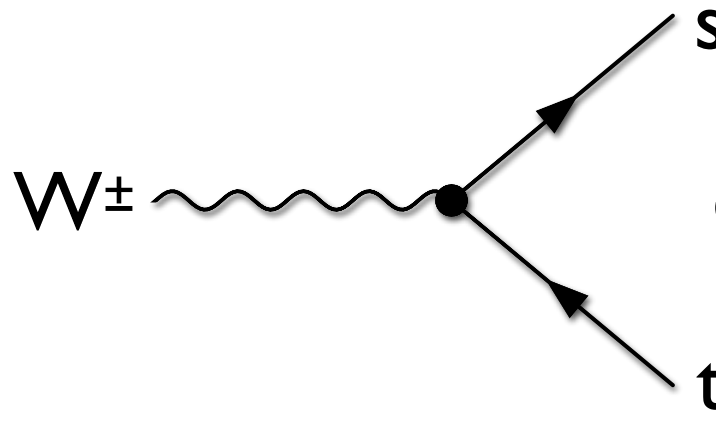
Flavour-changing interactions proceed through charged currents (W-boson)

— **no flavour-changing neutral currents (FCNCs)**



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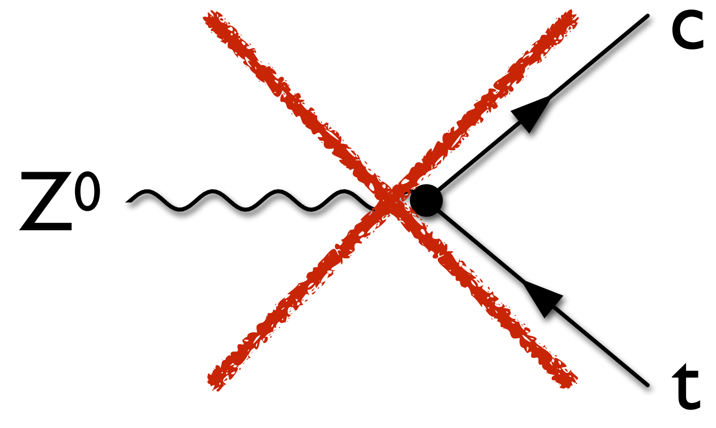

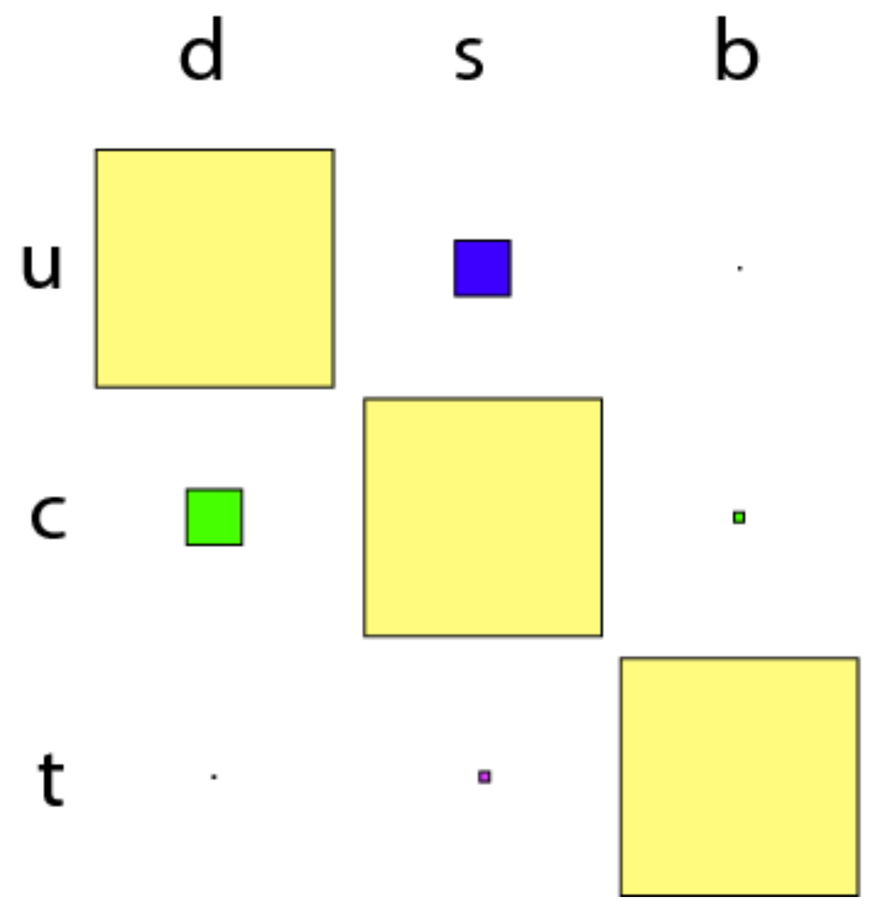

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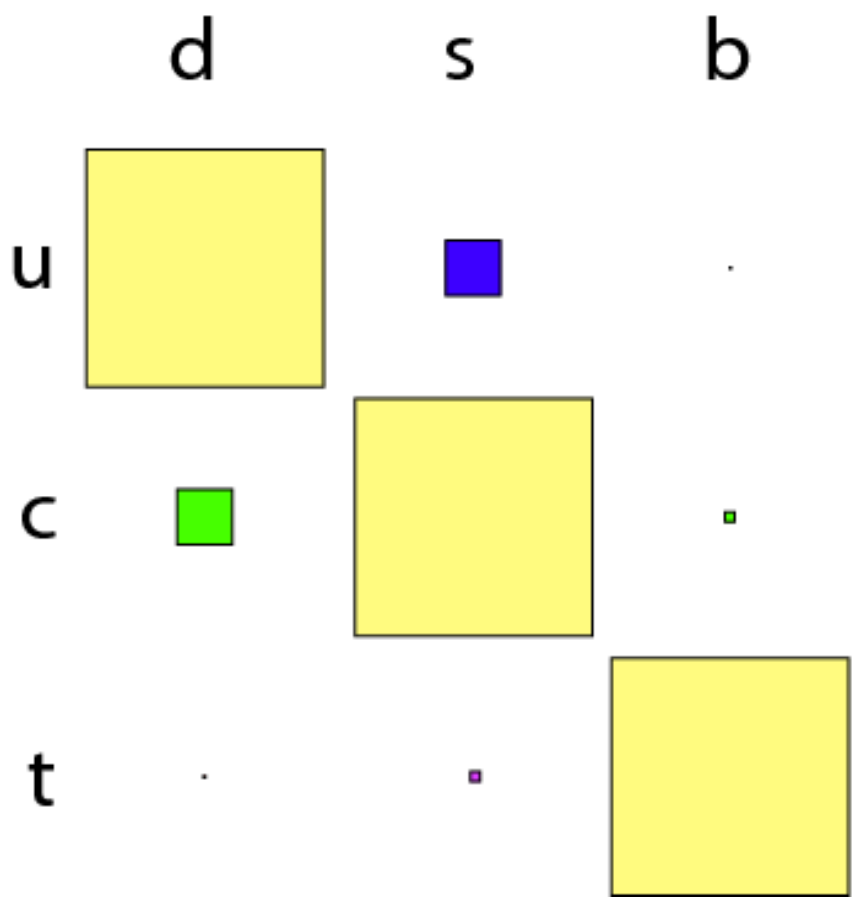

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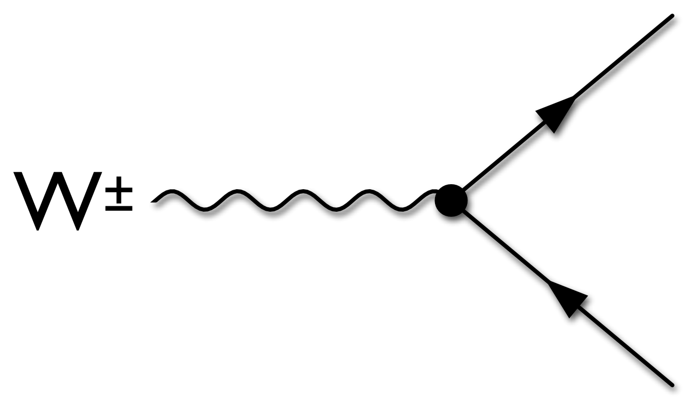

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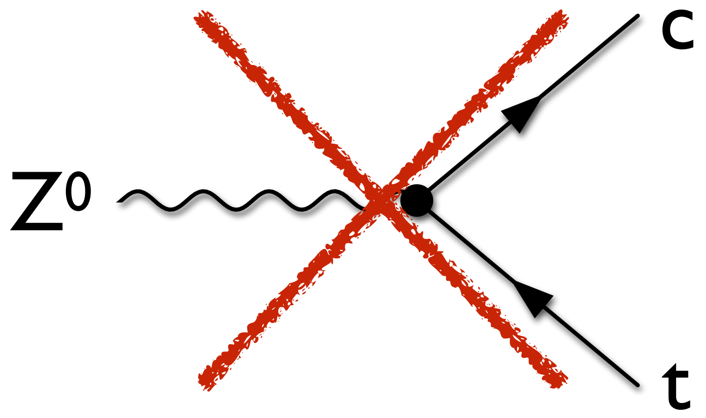


Similar description for the lepton and neutrino sectors involving the **PMNS matrix** (more later…)

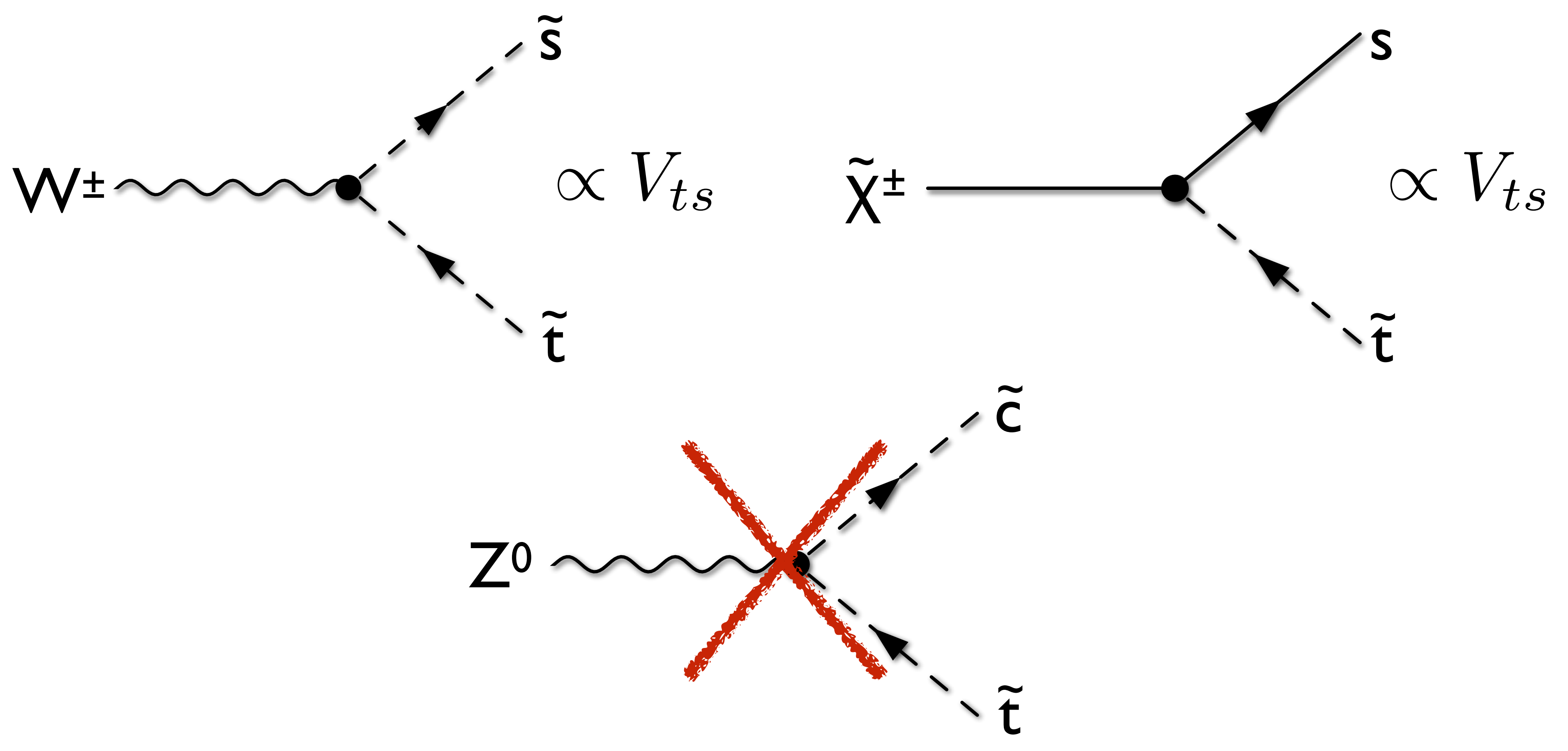
Quark flavour in the Standard Model... and beyond

Assume same flavour structure as in the Standard Model

— Yukawa matrices remain only source of flavour violation

— all quark flavour violation related to CKM matrix

— **Minimal Flavour Violation (MFV)**



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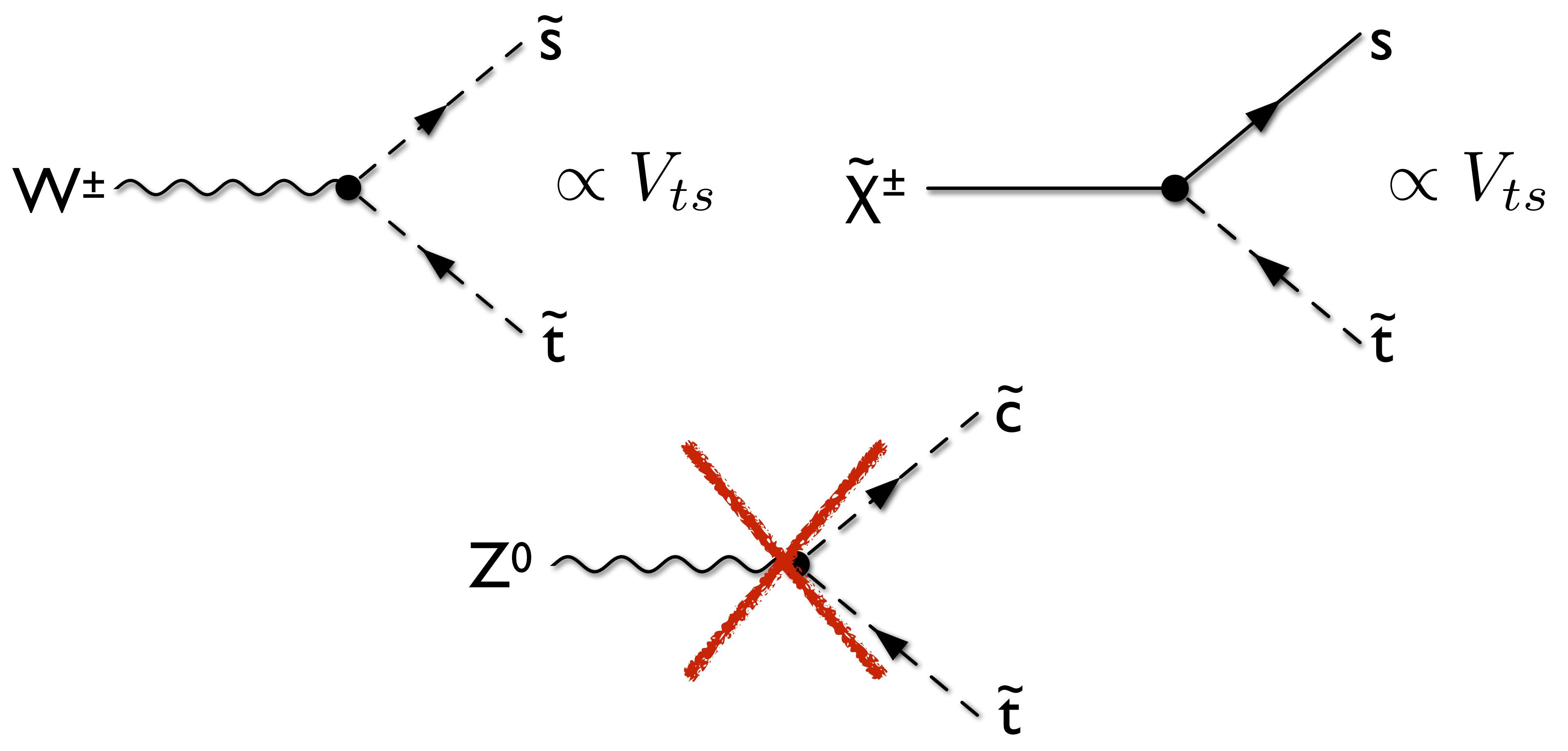
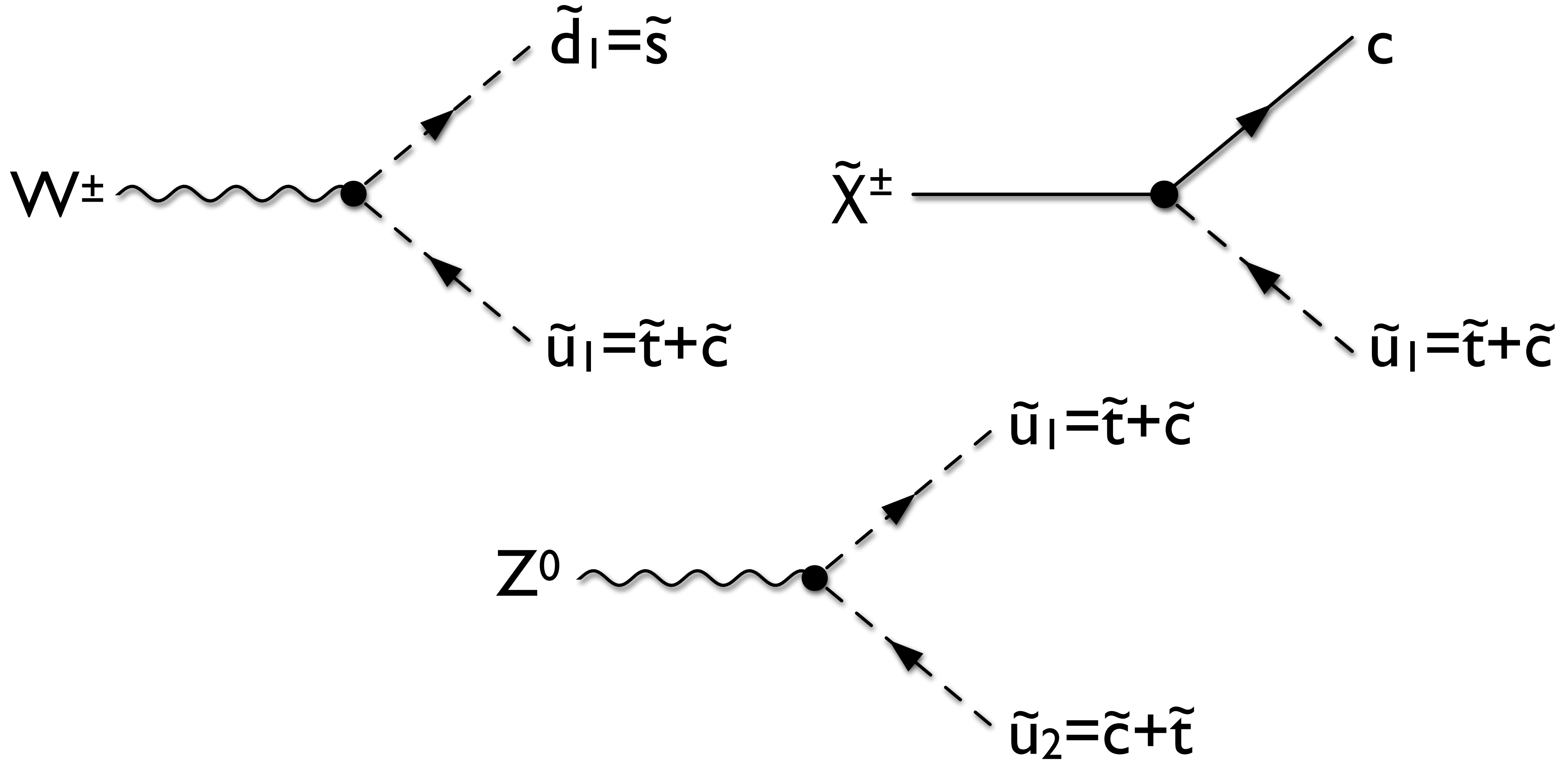


Allow for additional sources of flavour violation

— corresponding interactions not related to CKM matrix
— may allow for flavour-changing neutral currents (FCNCs)
— **Non-Minimal Flavour Violation (NMFV)**



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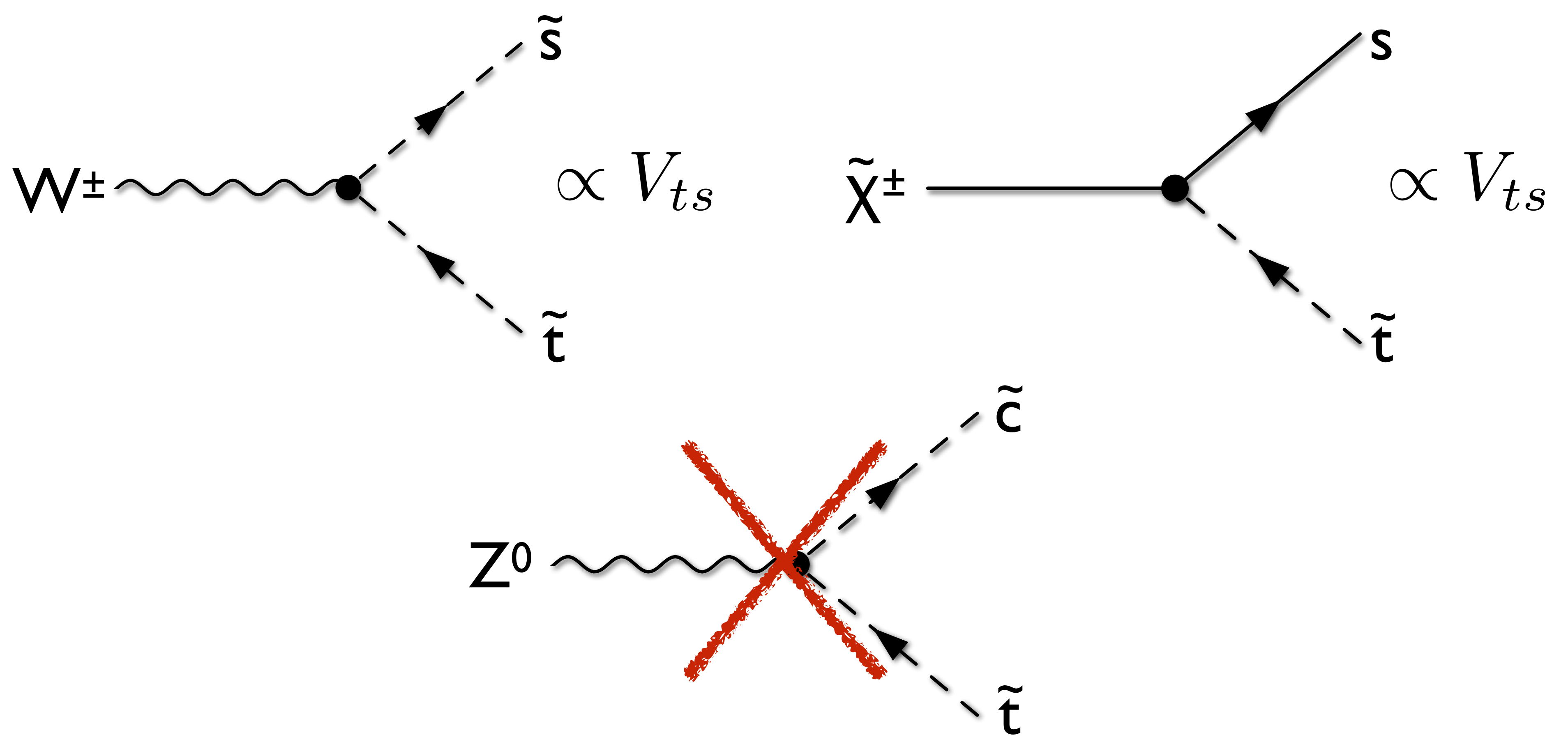

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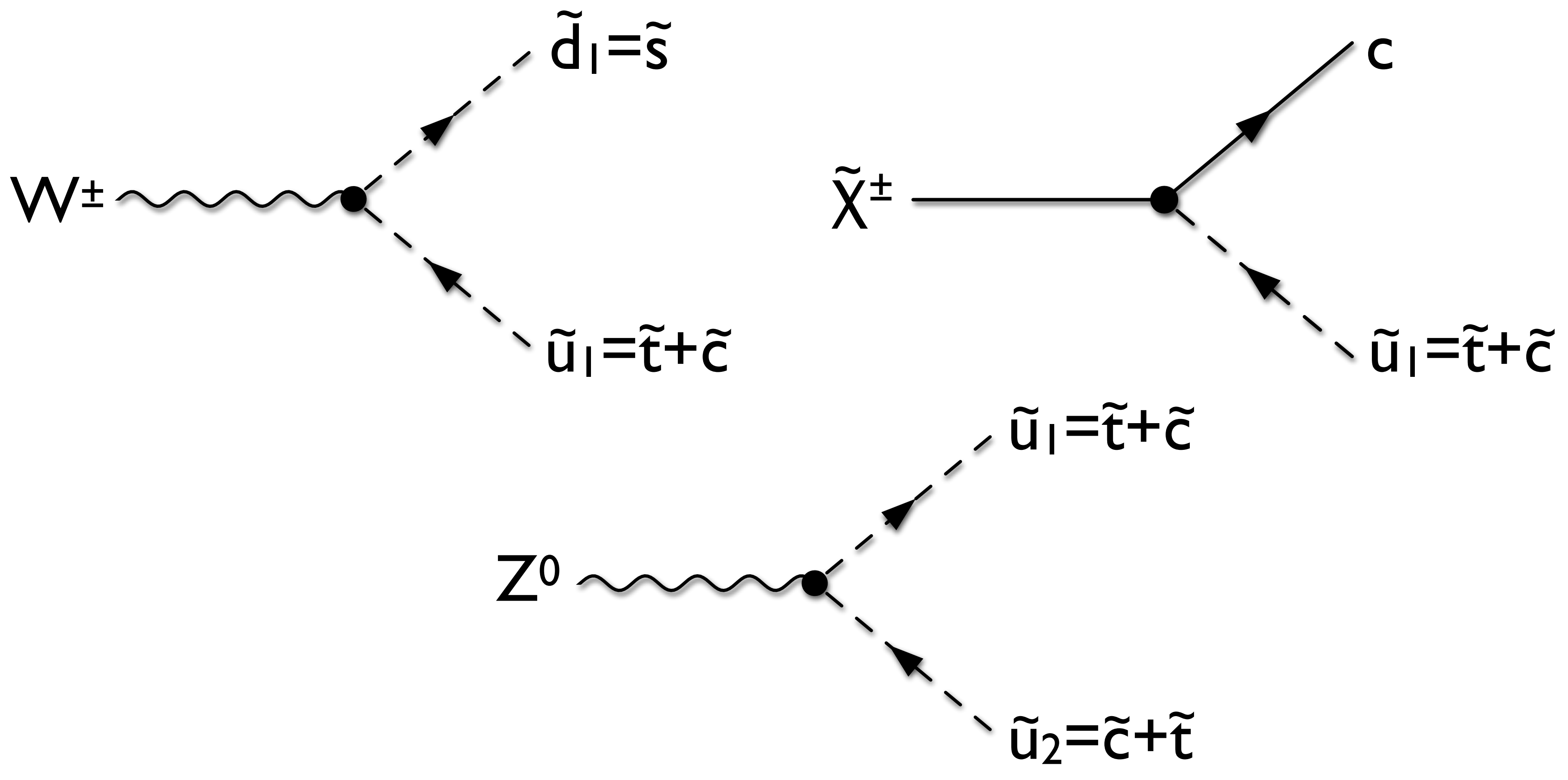

Experimental constraints on such terms…?
LHC signatures stemming from such couplings…?
Distinguish MFV and NMFV experimentally…?
Implementation in Grand Unification frameworks…?

The squark sector of the MSSM with NMFV

In the **super-CKM basis**, and in the most general case, the squark sector is parametrized by two 6x6 mass matrices
— diagonalization through two **6x6 rotation matrices** carrying all information about flavour content (generalized "mixing angles")

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

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$$(\tilde{u}_1, \tilde{u}_2, \ldots, \tilde{u}_6)^T = \mathcal{R}_{\tilde{u}} (\tilde{u}_L, \tilde{c}_L, \tilde{t}_L, \tilde{u}_R, \tilde{c}_R, \tilde{t}_R)^T$$

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Non-Minimally Flavour Violating terms manifest as **off-diagonal entries in the soft mass and trilinear matrices**
— **dimensionless and scenario-independent parametrization** by normalizing w.r.t. the corresponding diagonal elements

$$\big(\delta_{LL}\big)_{ij} = \frac{\big(M^2_{\tilde{Q}}\big)_{ij}}{\big(M_{\tilde{Q}}\big)_{ii}\big(M_{\tilde{Q}}\big)_{jj}} \qquad \big(\delta^u_{LR}\big)_{ij} = \frac{v_u}{\sqrt{2}} \frac{\big(T_u\big)_{ij}}{\big(M_{\tilde{U}}\big)_{ii}\big(M_{\tilde{Q}}\big)_{jj}}$$

$$\big(\delta^u_{RL}\big)_{ij} = \frac{v_u}{\sqrt{2}} \frac{\big(T_u\big)_{ij}}{\big(M_{\tilde{Q}}\big)_{ii}\big(M_{\tilde{U}}\big)_{jj}} \qquad \big(\delta^u_{RR}\big)_{ij} = \frac{\big(M^2_{\tilde{U}}\big)_{ij}}{\big(M_{\tilde{U}}\big)_{ii}\big(M_{\tilde{U}}\big)_{jj}}$$

Outline

Experimental constraints on quark flavour violation

LHC phenomenology of the MSSM with NMFV

NMFV within Grand Unification frameworks — A4xSU(5) case study

Part I

Experimental constraints on quark flavour violation

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

"General squark flavour mixing: constraints, phenomenology and benchmarks"

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

G. Brooijmans *et al.*

"Les Houches 2013 — Physics at TeV Colliders: New Physics Working Group Report"

arXiv:1405.1617 [hep-ph]

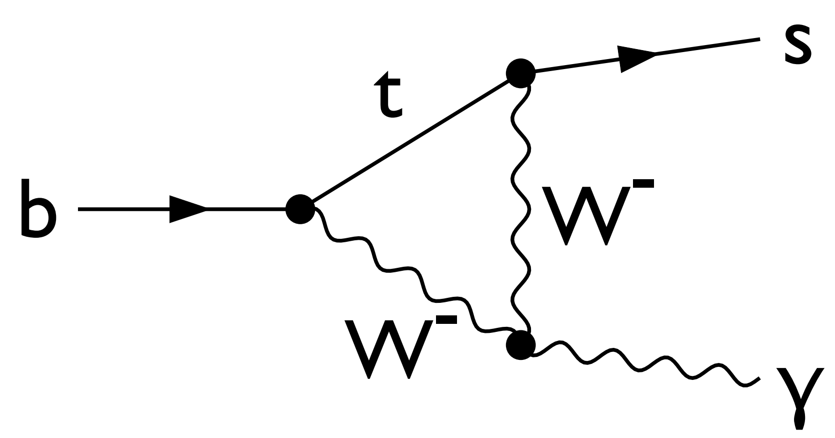
B. Herrmann, Q. Le Boulc'h, M. Klasen

"Impact of squark flavour violation on neutralino dark matter"

Phys. Rev. D84 (2011) 095007 — arXiv:1106.6229 [hep-ph]

Flavour constraints on new physics

New particles affect predictions of any observable through their **loop contributions**
— a large variety of **precision observables** can serve as test for new physics, especially through **flavour-violating effects**



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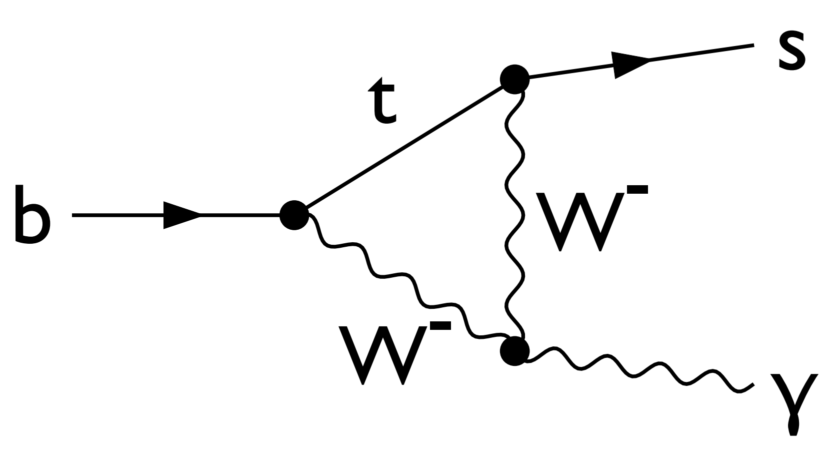

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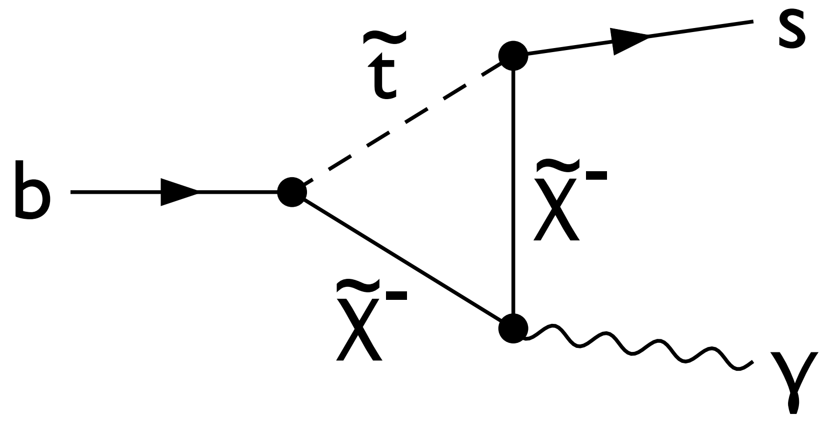

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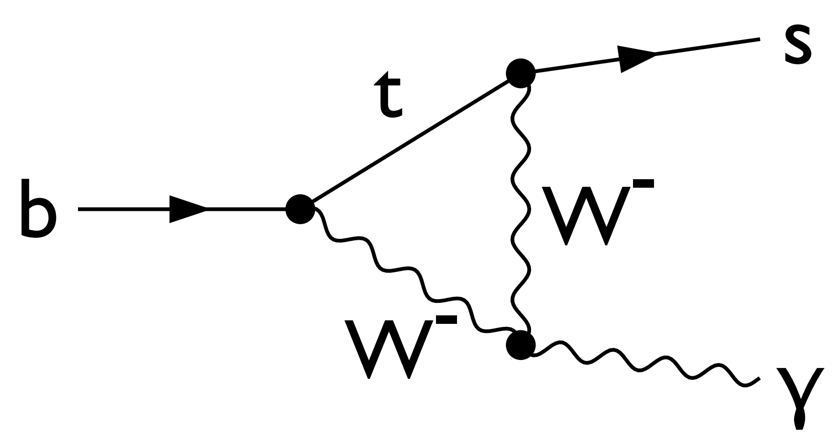

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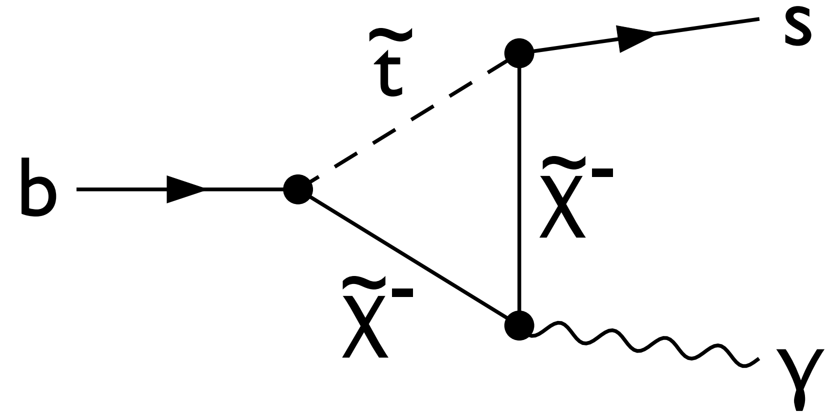

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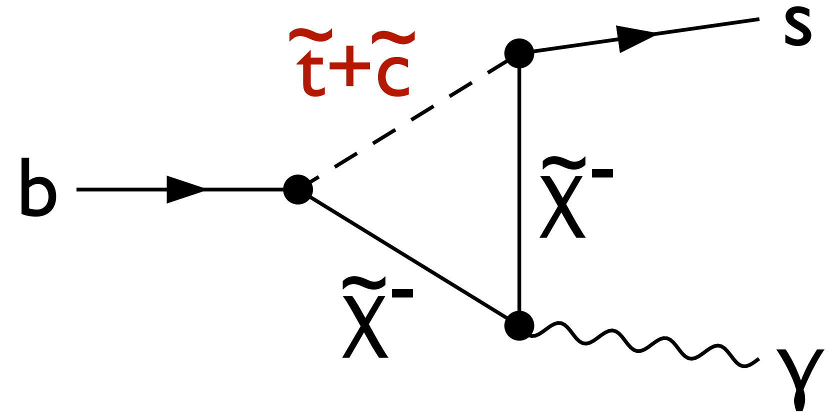

$\propto V_{tb} V_{cs} \sim 1$

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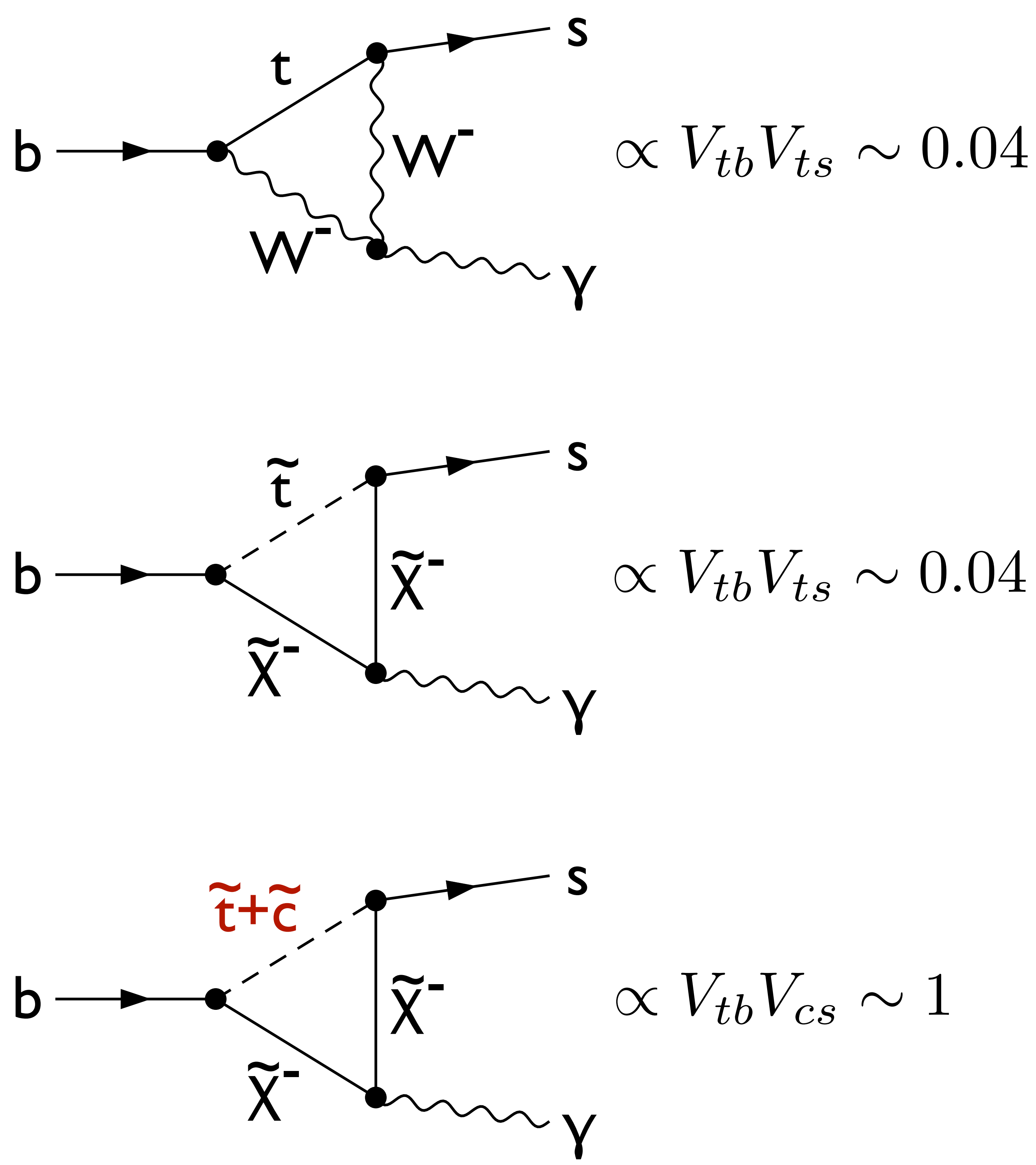
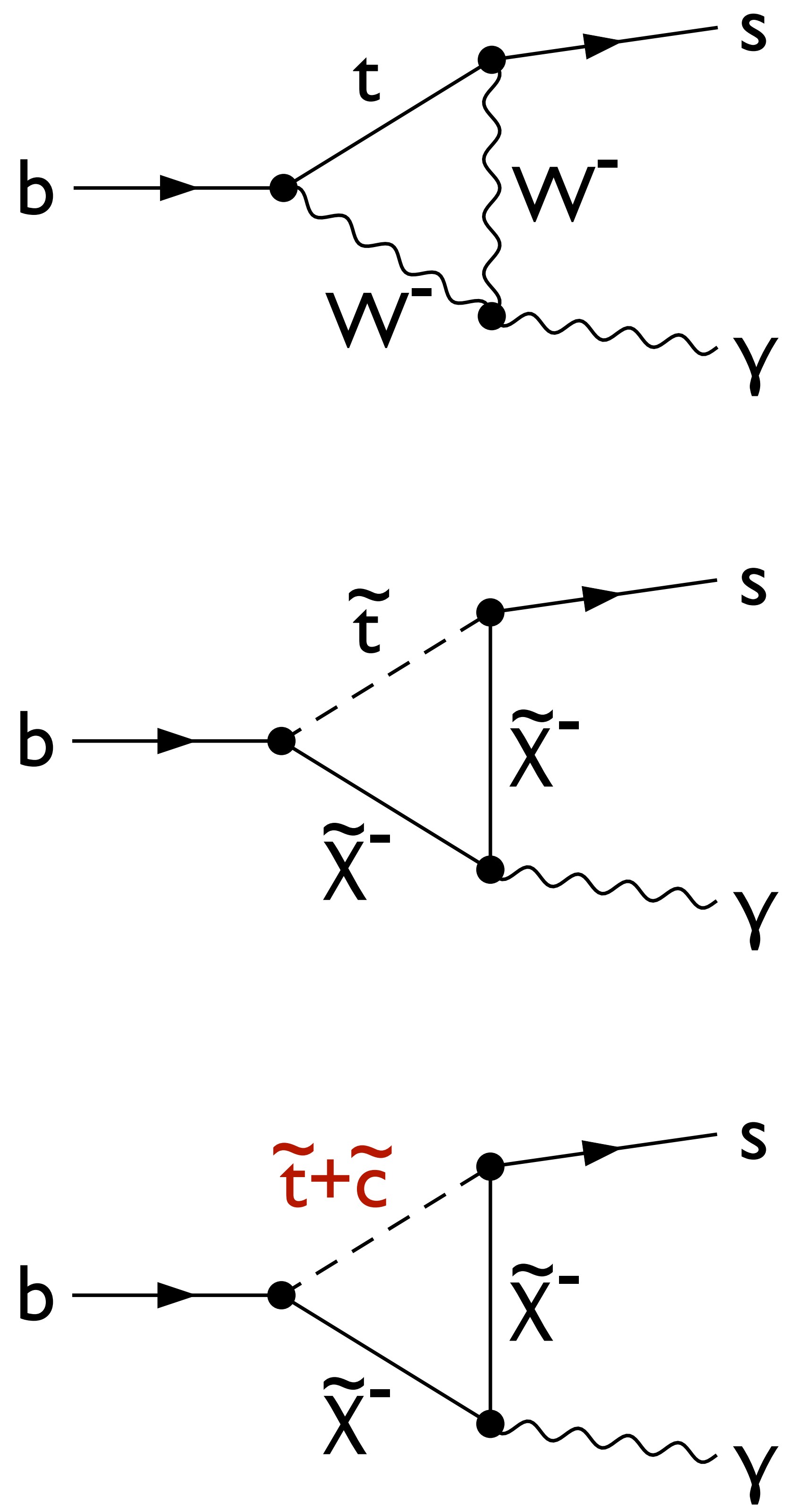


Observable	Experimental result	
m_{h^0}	(125.2 ± 2.1) GeV	ATLAS/CMS 2018
$\mathrm{BR}\,(B \to X_s\gamma)$	$(3.32 \pm 0.15) \cdot 10^{-4}$	HFLAV 2018
$\mathrm{BR}\,(B \to X_s\mu\mu)_{q^2\in[1;6]\ \mathrm{GeV}^2}$	$(0.66 \pm 0.55) \cdot 10^{-6}$	BaBar 2014
$\mathrm{BR}\,(B \to X_s\mu\mu)_{q^2>14.4\ \mathrm{GeV}^2}$	$(0.60 \pm 0.26) \cdot 10^{-6}$	BaBar 2014
$\mathrm{BR}\,(B_s \to \mu\mu)$	$(2.7 \pm 1.0) \cdot 10^{-9}$	PDG 2018
$\mathrm{BR}\,(B \to K^*\mu\mu)_{q^2\in[1;6]\ \mathrm{GeV}^2}$	$(1.7 \pm 0.26) \cdot 10^{-7}$	LHCb 2013
$\mathrm{AFB}\,(B \to K^*\mu\mu)_{q^2\in[1.1;6]\ \mathrm{GeV}^2}$	$(-0.075 \pm 0.030) \cdot 10^{-7}$	LHCb 2015
$\mathrm{BR}\,(B_u \to \tau\nu)\,/\mathrm{BR}\,(B_u \to \tau\nu)_{\mathrm{SM}}$	1.04 ± 0.34	PDG 2018
$\mathrm{BR}\left(K^0 \to \pi^0\nu\nu\right)$	$\leq 2.6 \cdot 10^{-8}$	PDG 2018
$\mathrm{BR}\,(K^+ \to \pi^+\nu\nu)$	$1.73^{+0.97}_{-0.88} \cdot 10^{-10}$	PDG 2018
ΔM_{B_s}	$(17.757 \pm 2.266)\ \mathrm{ps}^{-1}$	PDG 2018
ϵ_K	2.228 ± 0.243	PDG 2018
$\Delta a_\mu = a_\mu^{\mathrm{exp}} - a_\mu^{\mathrm{SM}}$	$(26.1 \pm 10.74) \cdot 10^{-10}$	PDG 2018
$\Omega_{\mathrm{CDM}}h^2$	(0.1200 ± 0.0020)	Planck 2018

Flavour constraints on new physics

New particles affect predictions of any observable through their **loop contributions**
— a large variety of **precision observables** can serve as test for new physics, especially through **flavour-violating effects**



$\propto V_{tb}V_{ts} \sim 0.04$

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$\propto V_{tb}V_{cs} \sim 1$

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An MCMC study of the NMFV-MSSM parameter space — Setup

Study the parameter space of NMFV in the squark sector of the MSSM w.r.t. experimental constraints
— consider only **mixing between 2nd and 3rd generation** squarks (1st generation mixing heavily constrained by meson mixing)
— use **Markov Chain Monte Carlo** algorithm to efficiently scan the **19-dimensional parameter** space under consideration

Parameter	Scanned range
$\tan\beta$	[10, 50]
μ	[100, 850]
m_A	[100, 1600]
M_1	[100, 1600]
$M_{\tilde{\ell}}$	[100, 3500]
δ_{LL}	[-0.8, 0.8]
δ^u_{RR}	[-0.8, 0.8]
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δ^u_{LR}	[-0.5, 0.5]
δ^u_{RL}	[-0.5, 0.5]
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$M_{\tilde{U}_{1,2}}$	[300, 3500]
$M_{\tilde{U}_3}$	[100, 3500]
$M_{\tilde{D}_{1,2}}$	[300, 3500]
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A_f	[-10000, 10000]

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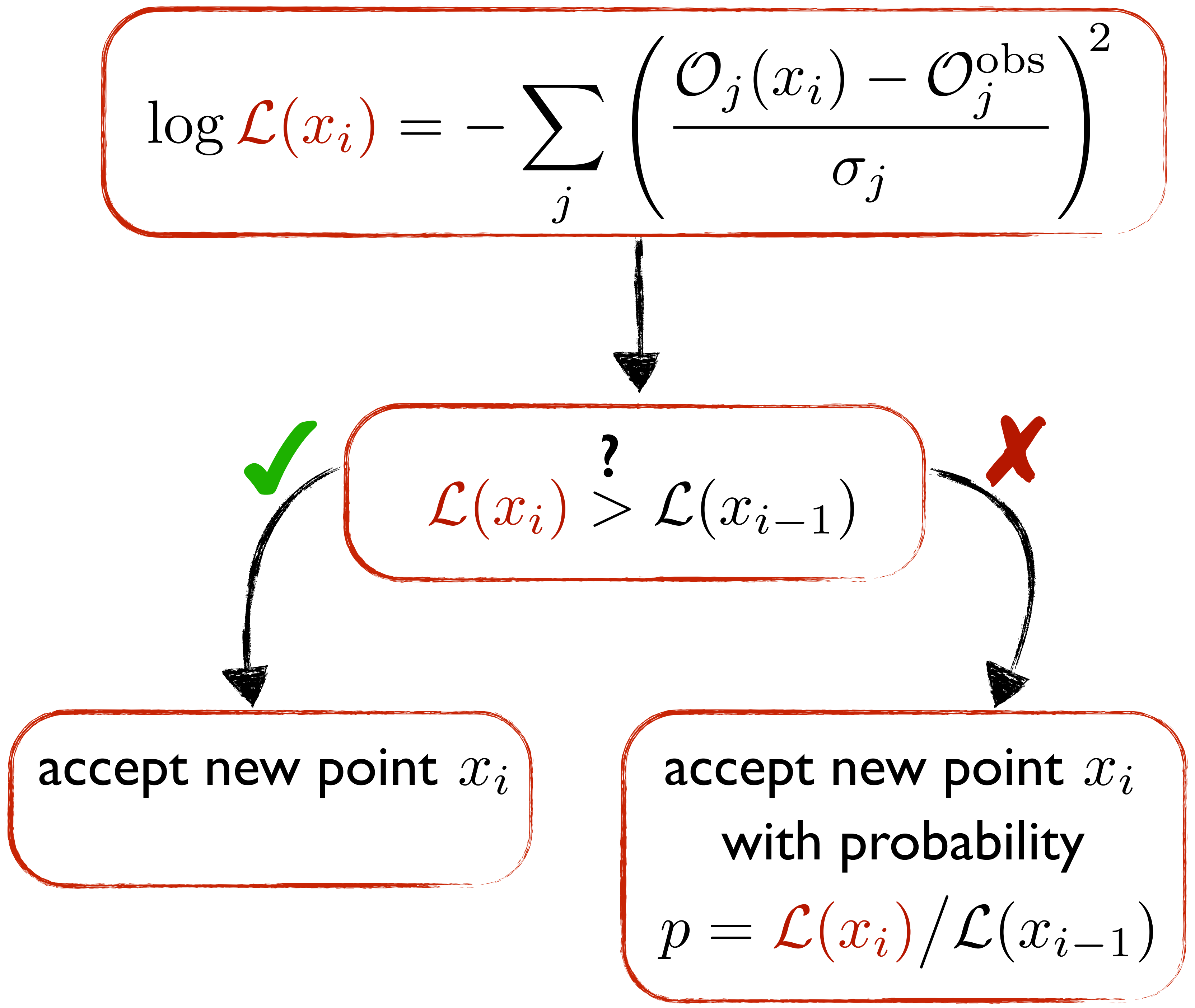

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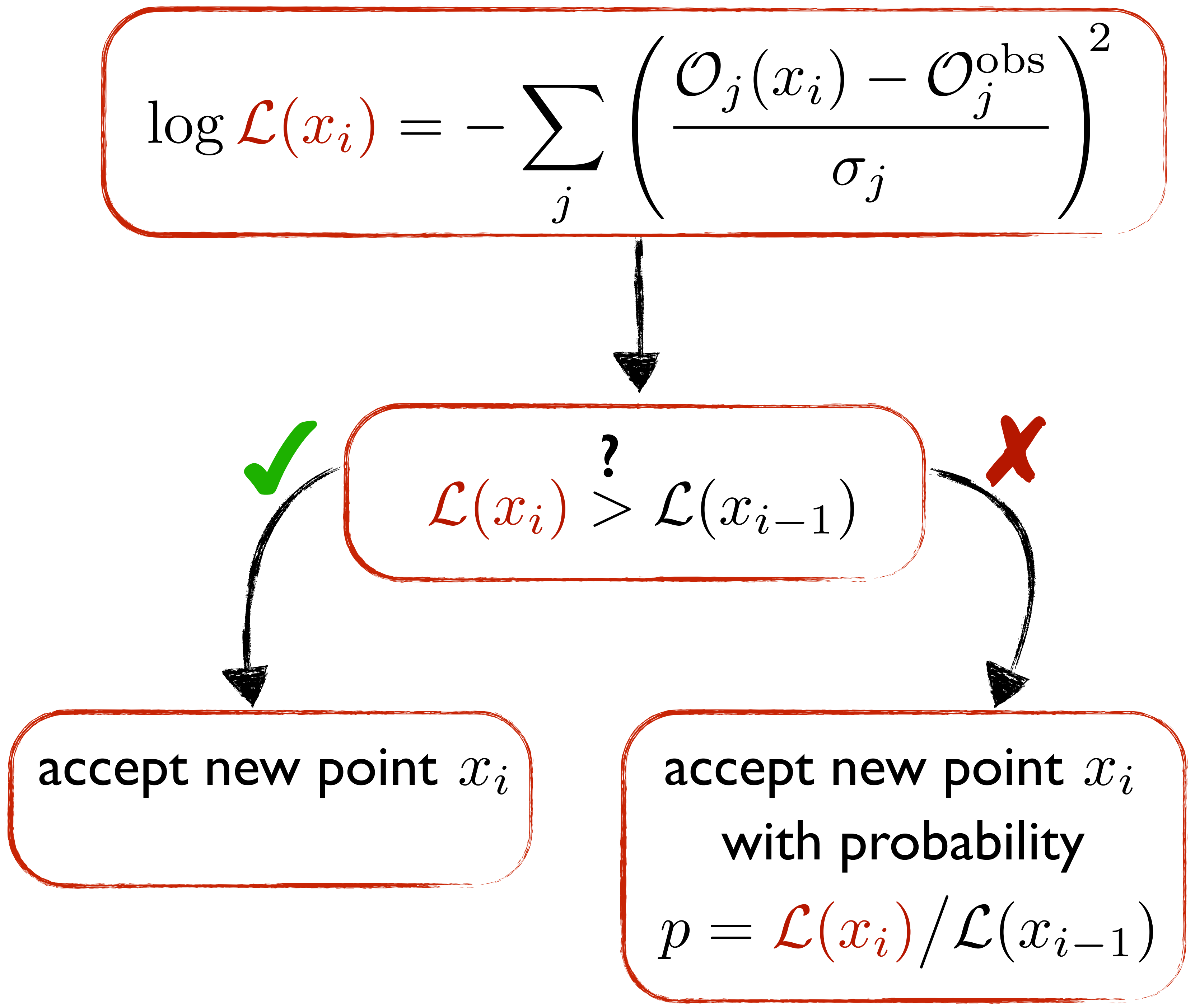
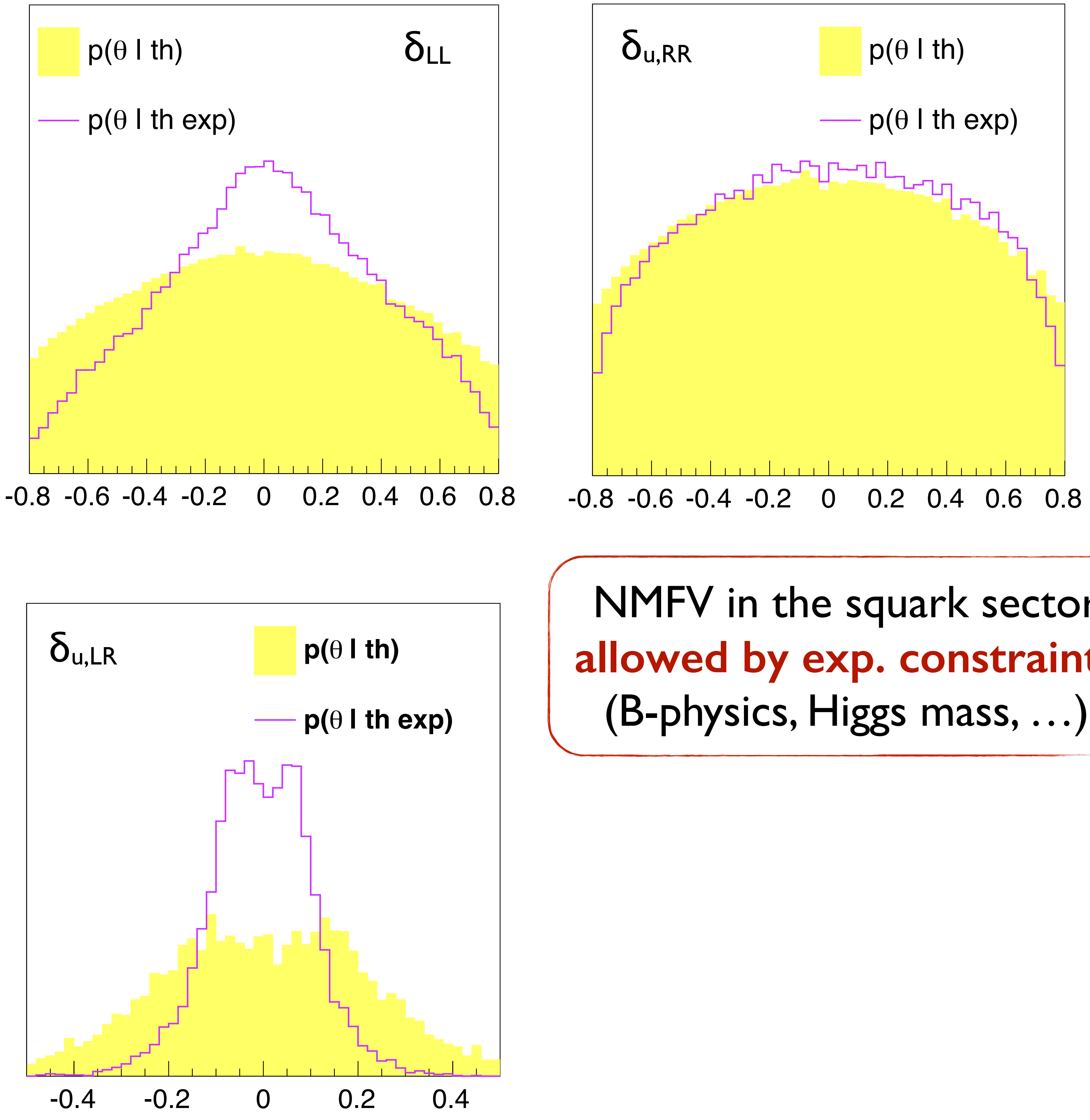


Flavour and mass constraints evaluated using SPheno Porod 2003-2019 and SuperIso Mahmoudi 2008-2019
— in addition, require neutralino dark matter plus vacuum stability (Vevacious O'Leary 2013)

An MCMC study of the NMFV-MSSM parameter space — Selected results



NMFV in the squark sector
allowed by exp. constraints
(B-physics, Higgs mass, …)

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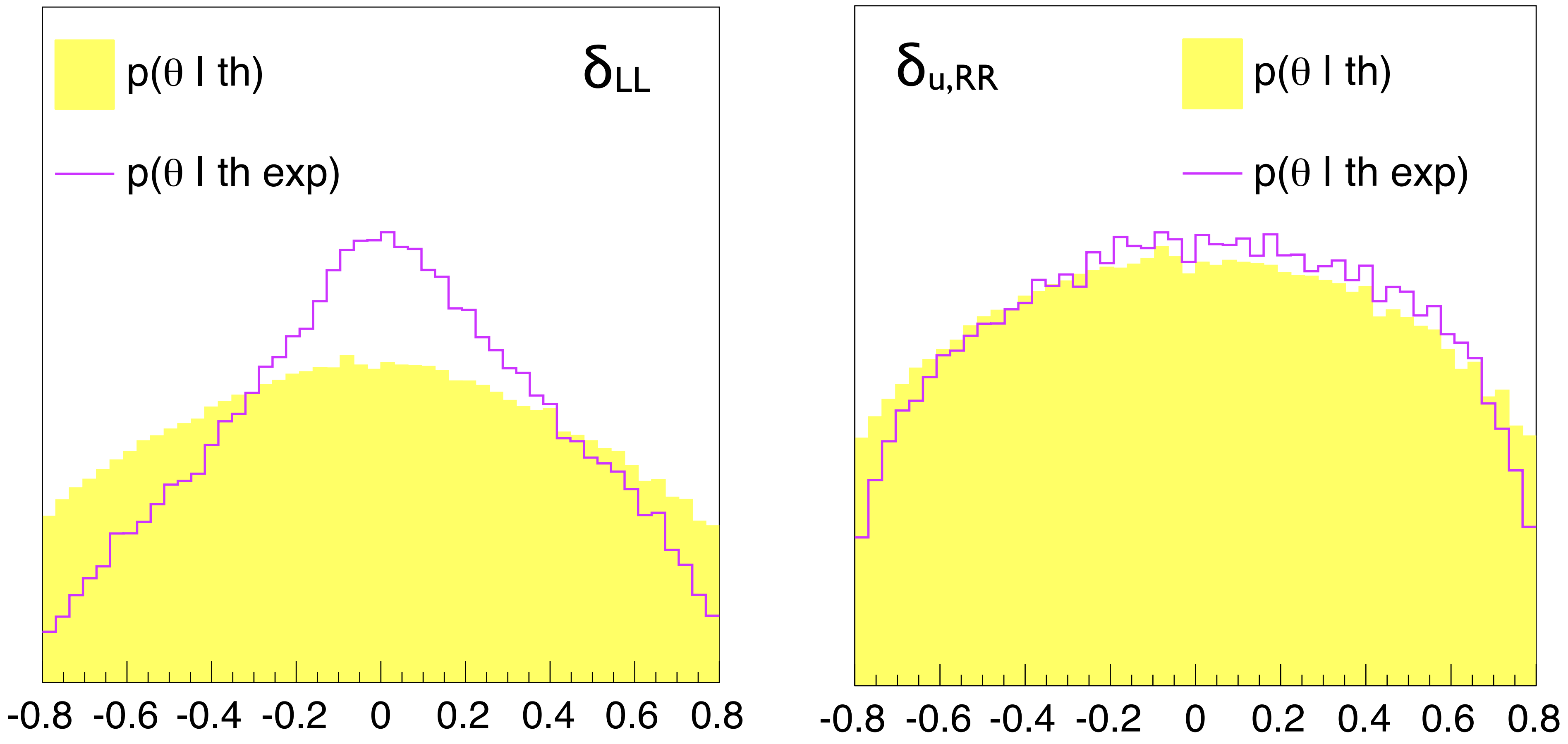

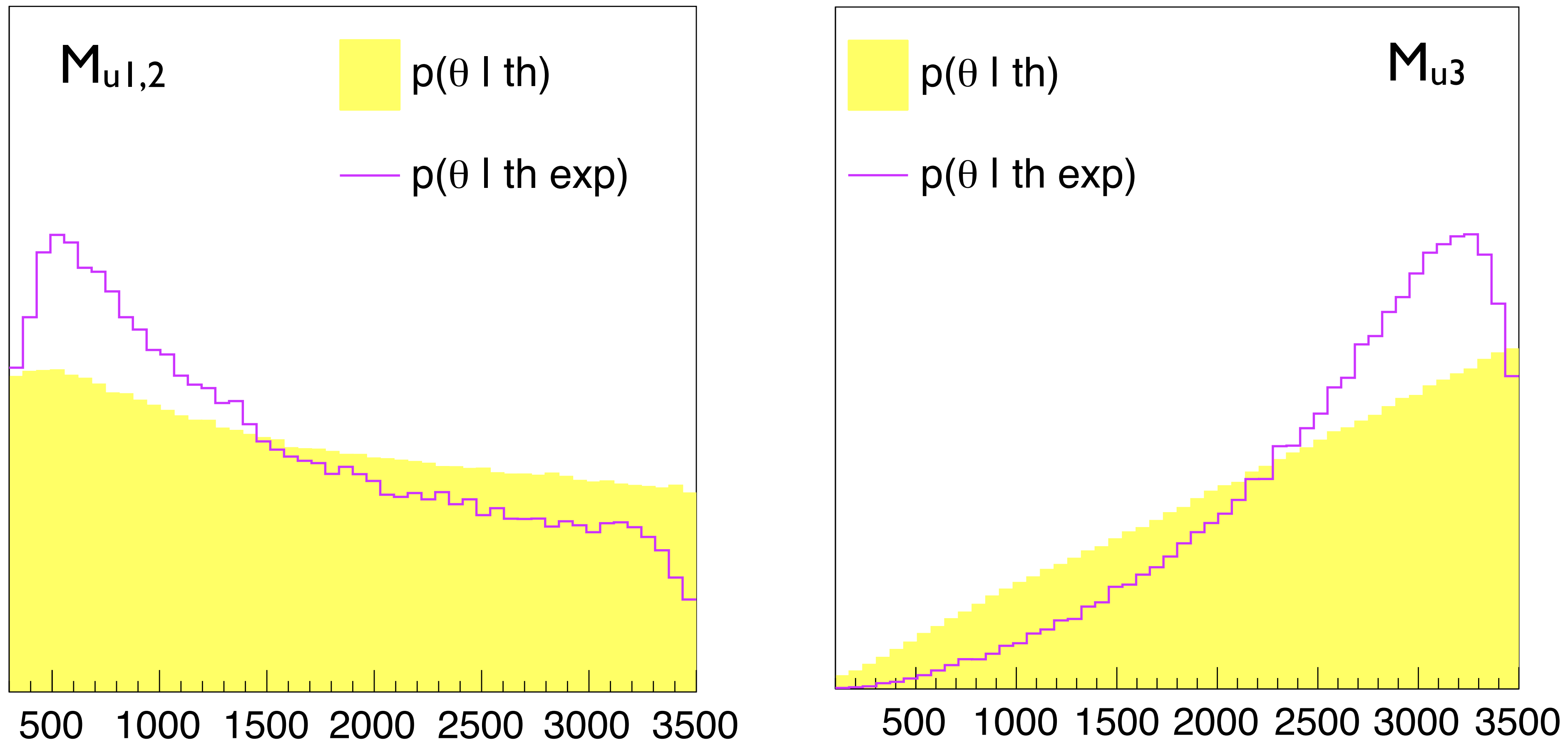

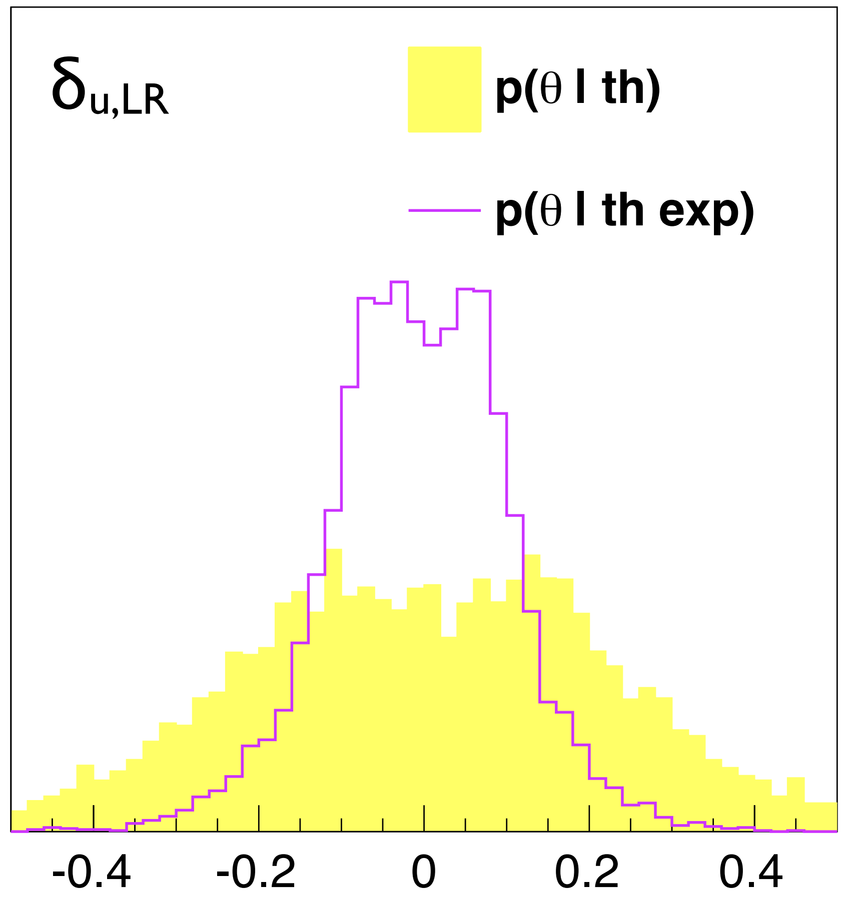

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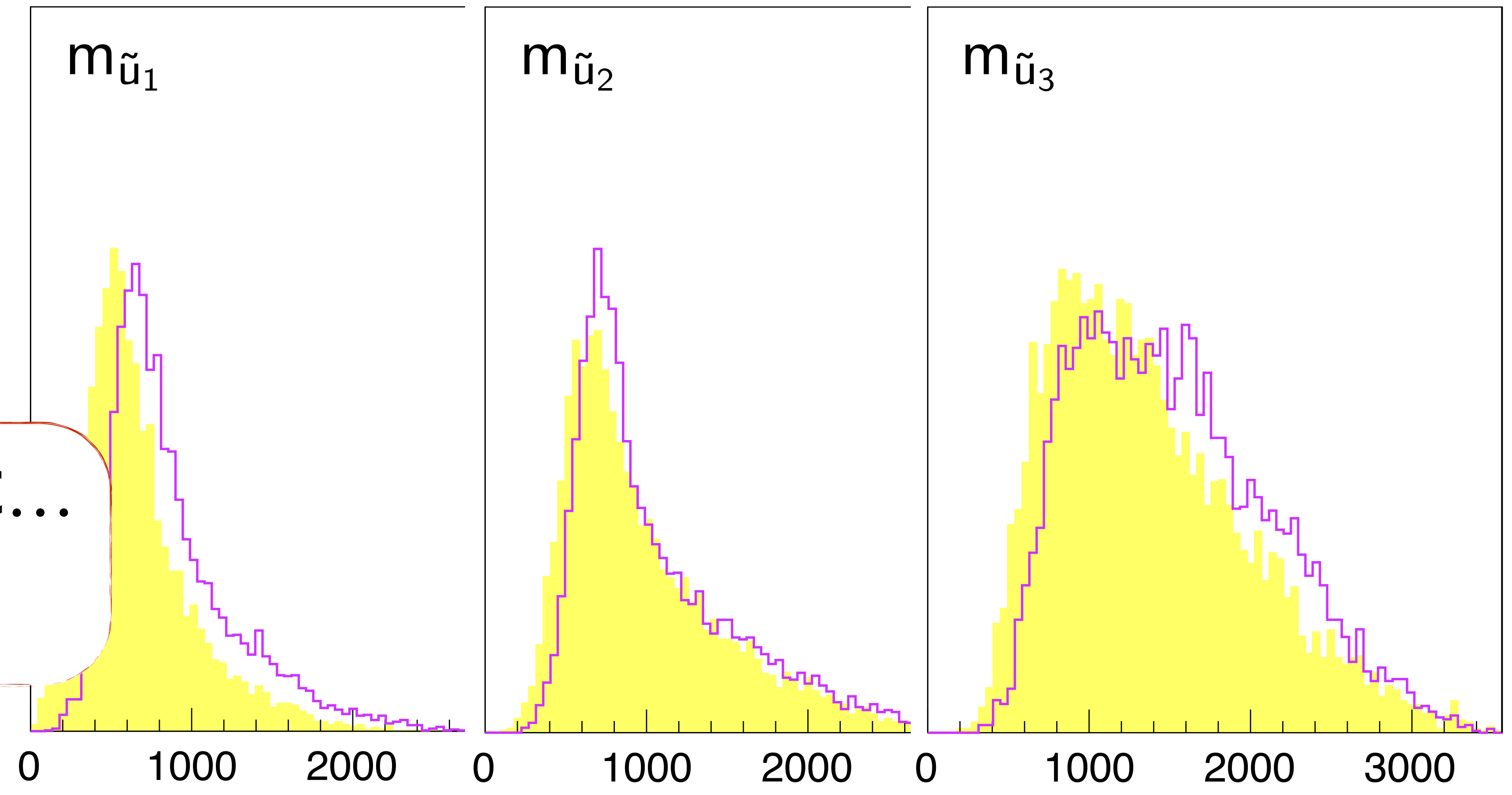
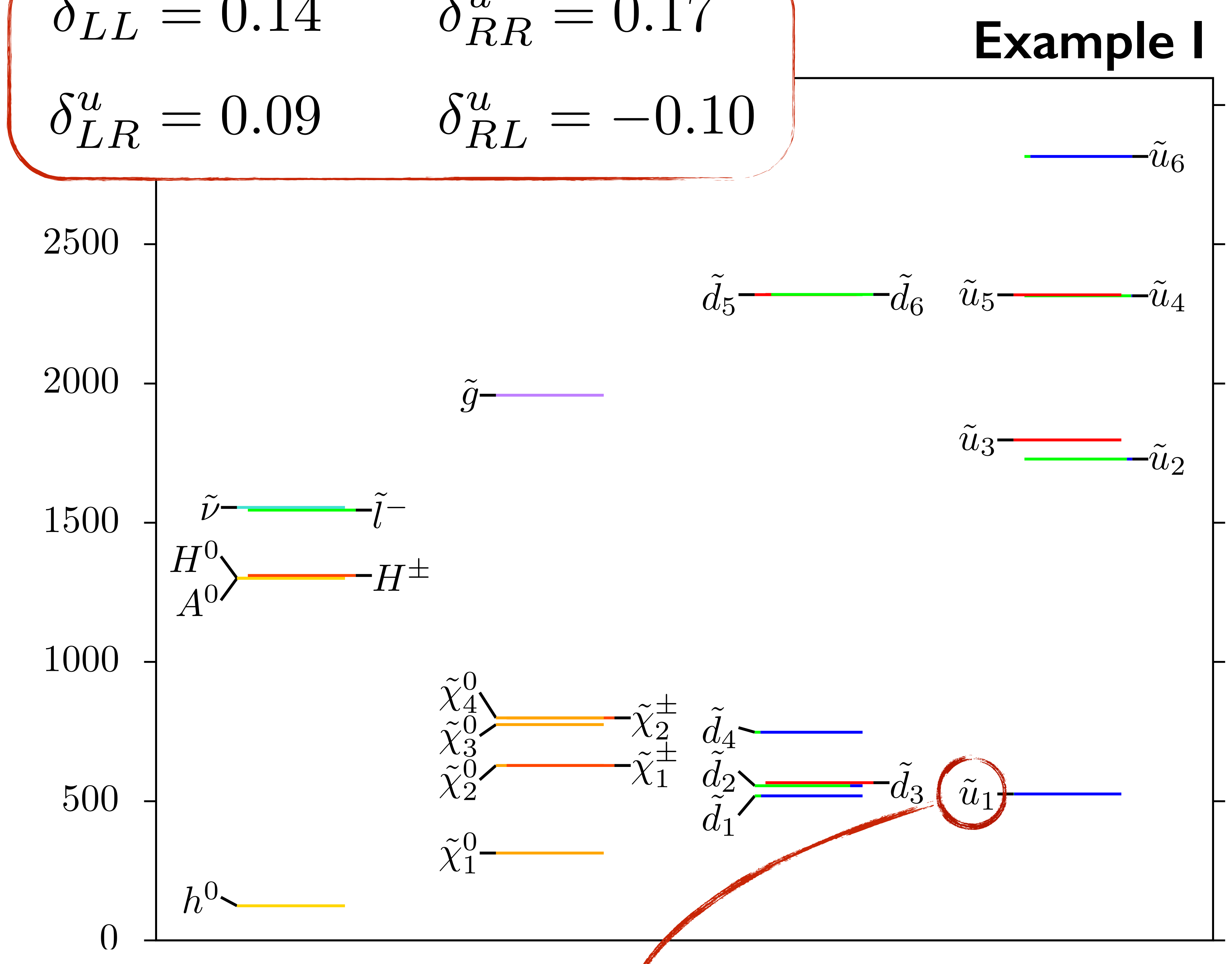


Typically several squarks accessible at the LHC…
— **lightest squark mostly not stop-like…**

Example scenarios within the NMFV-MSSM

$\delta_{LL} = 0.14 \qquad \delta^u_{RR} = 0.17$

$\delta^u_{LR} = 0.09 \qquad \delta^u_{RL} = -0.10$



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

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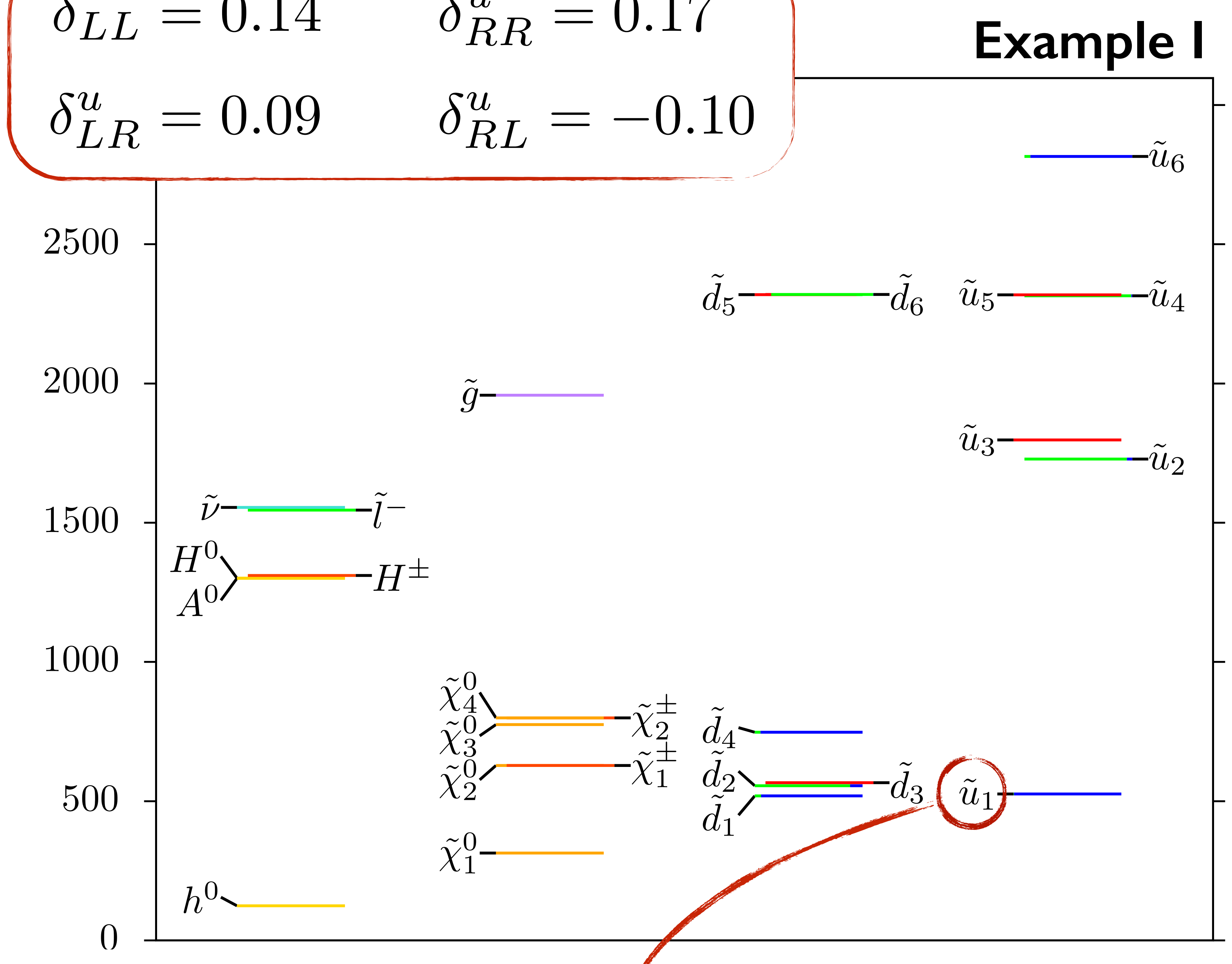

$\mathrm{BR}(\tilde{u}_1 \to t\tilde{\chi}^0_1) = 0.99$

$\delta_{LL} = 0.59 \qquad \delta^u_{RR} = 0.60$

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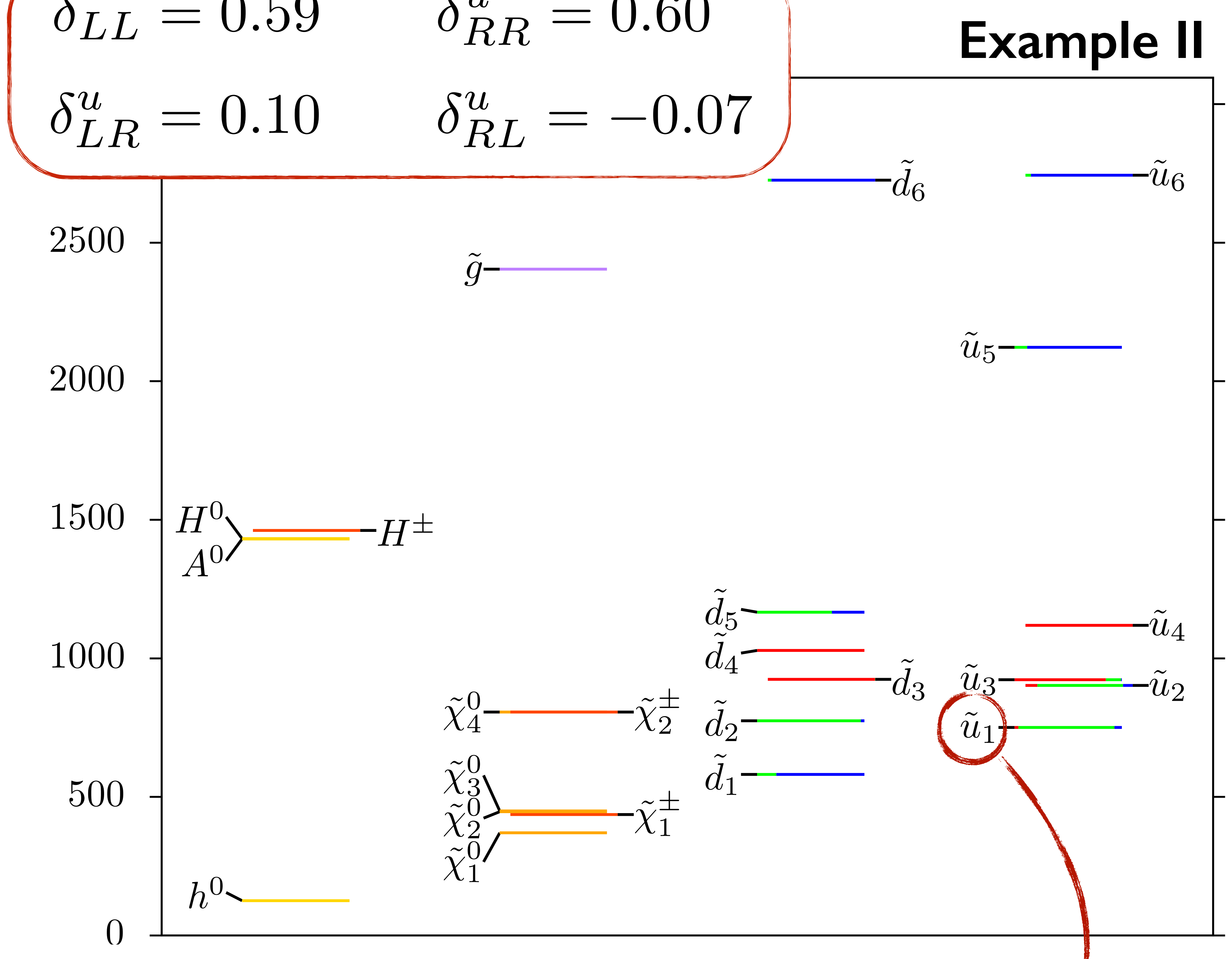

$\mathrm{BR}(\tilde{u}_1 \to t\tilde{\chi}^0_1) \approx 0.12$

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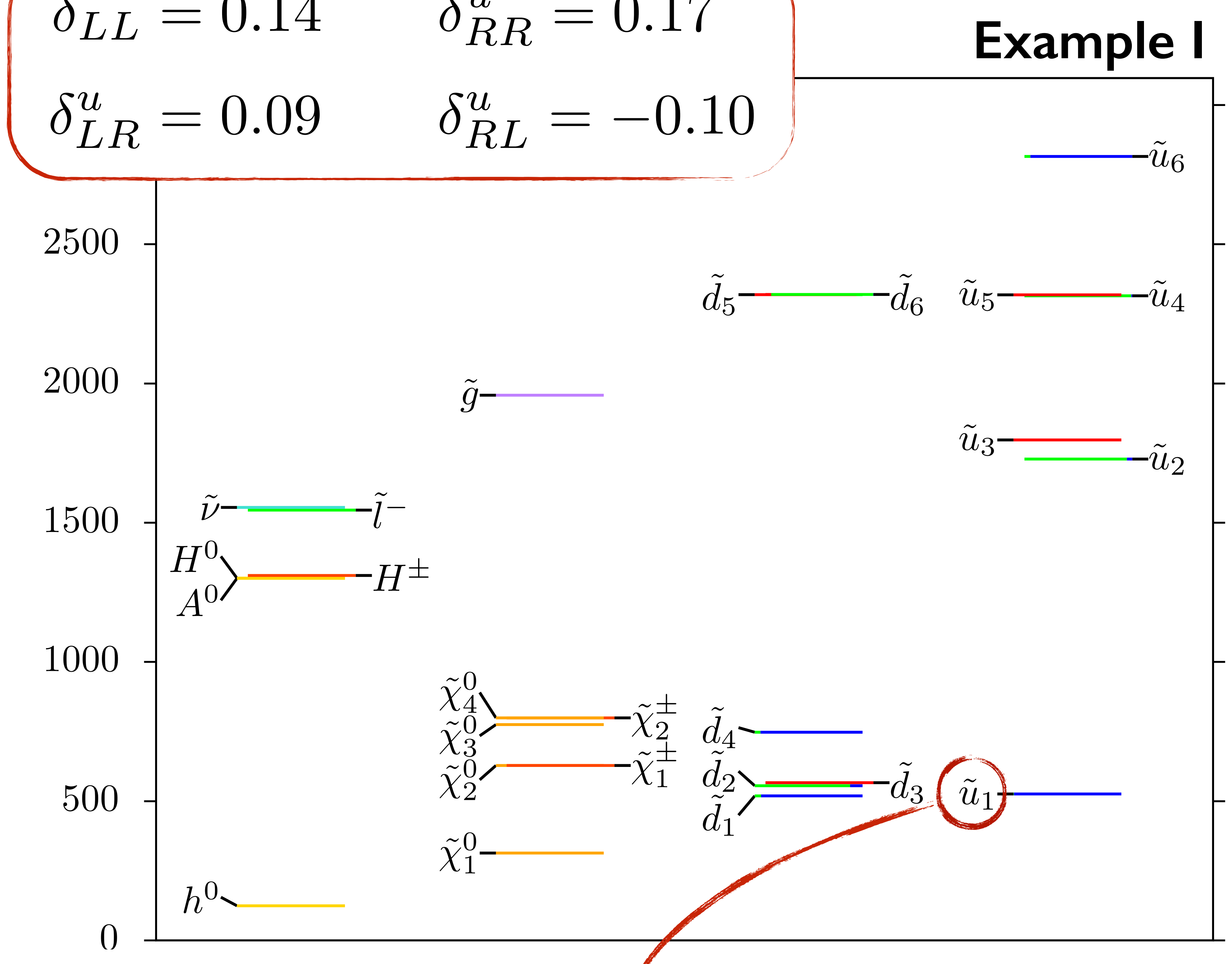

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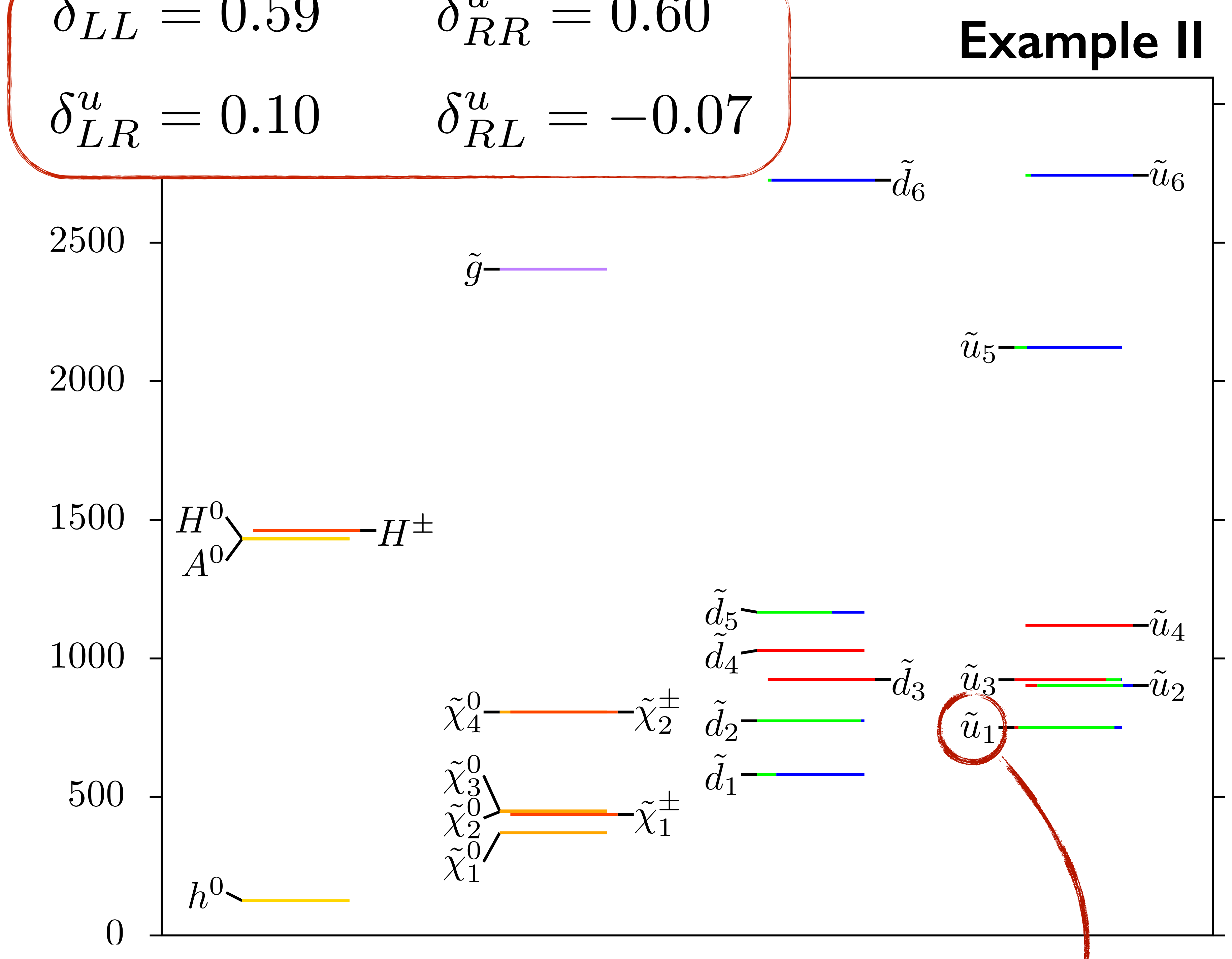

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Limits on squark masses…?
Identification of flavour structure…?

Part II

LHC phenomenology of the squark sector with NMFV

A. Chakraborty, M. Endo, B. Fuks, B. Herrmann, M. M. Nojiri, G. Polesello, P. Pani

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

Eur. Phys. J. C78 (2018) 10, 844 — arXiv:1808.07488 [hep-ph]

G. Brooijmans *et al.*

"Les Houches 2017 — Physics at TeV Colliders: New Physics Working Group Report"

arXiv:1803.10379 [hep-ph]

J. Bernigaud, B. Herrmann

"First steps towards to the reconstruction of the squark flavour structure"

SciPost Phys. 6 (2019) 66 — arXiv:1809.04370 [hep-ph]

LHC signatures of NMFV in the squark sector

The flavour-violating elements influence squark masses, flavour decomposition, production cross-sections and open new decay channels
— **characteristic NMFV signatures at colliders, e.g. the LHC**
— consider **simple two-generation squark model including flavour mixing** (parametrized through one mixing angle)

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

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$$\delta_{tc} = \frac{M^2_{tc}}{M_{\tilde{c}_R} M_{\tilde{t}_R}}$$

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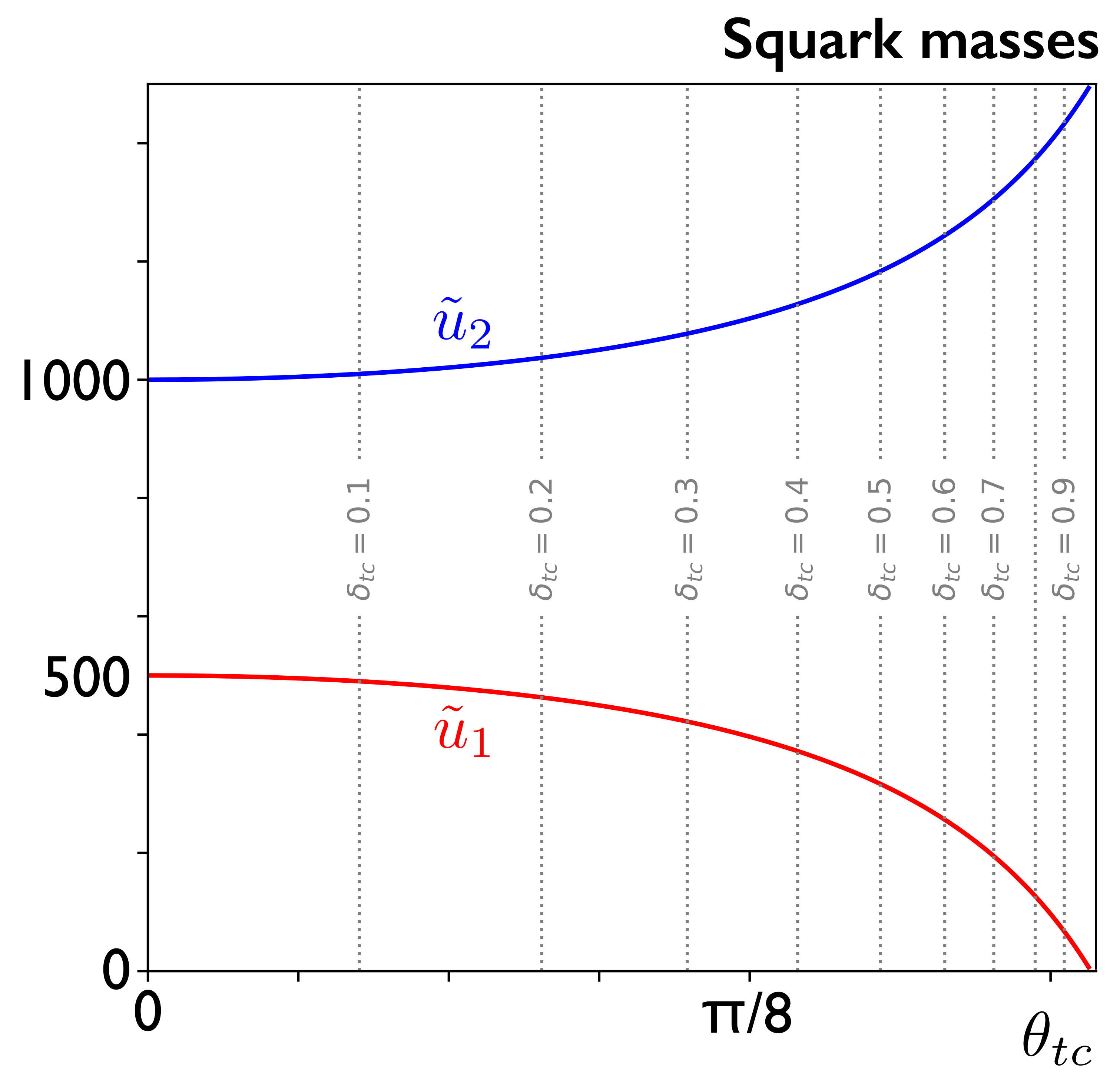

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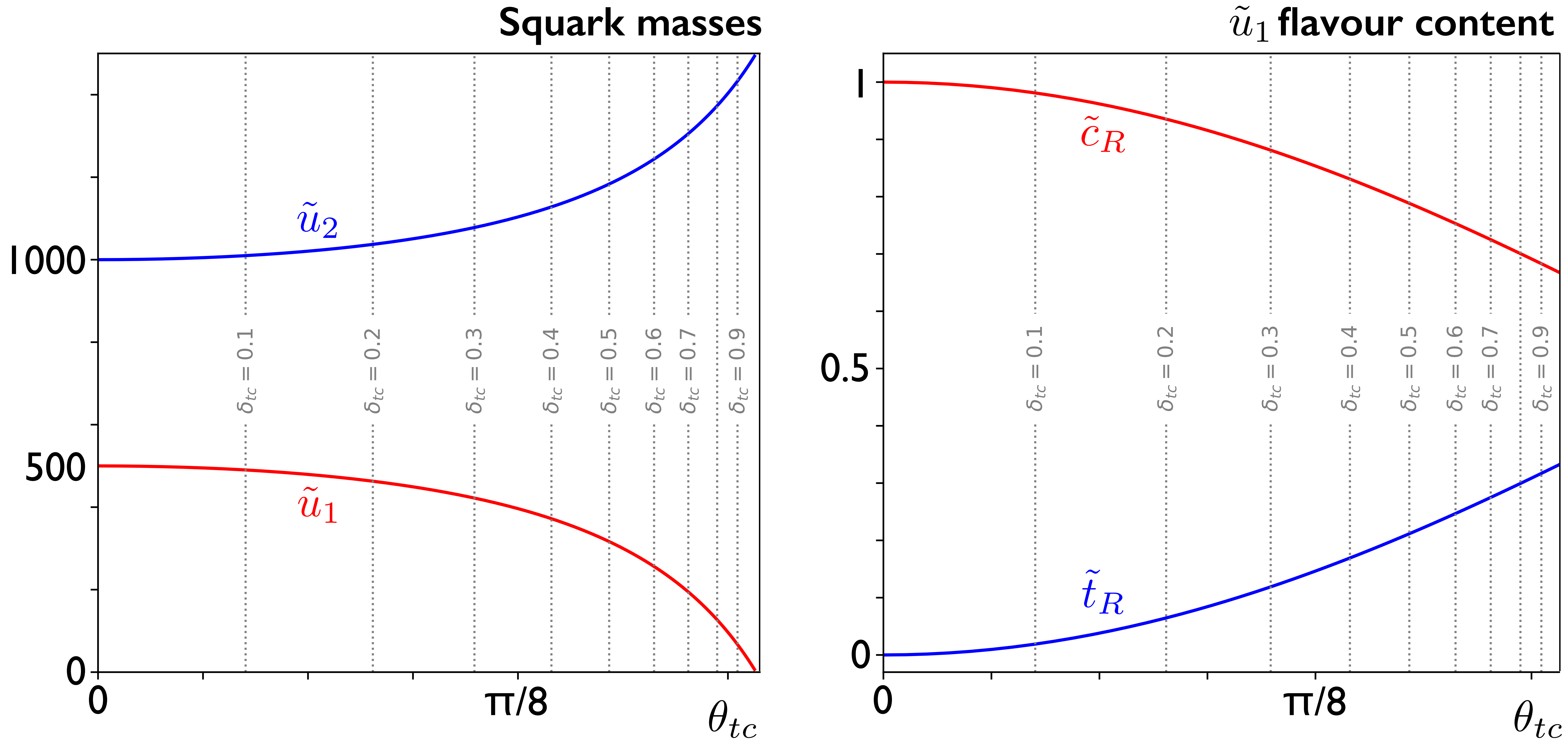

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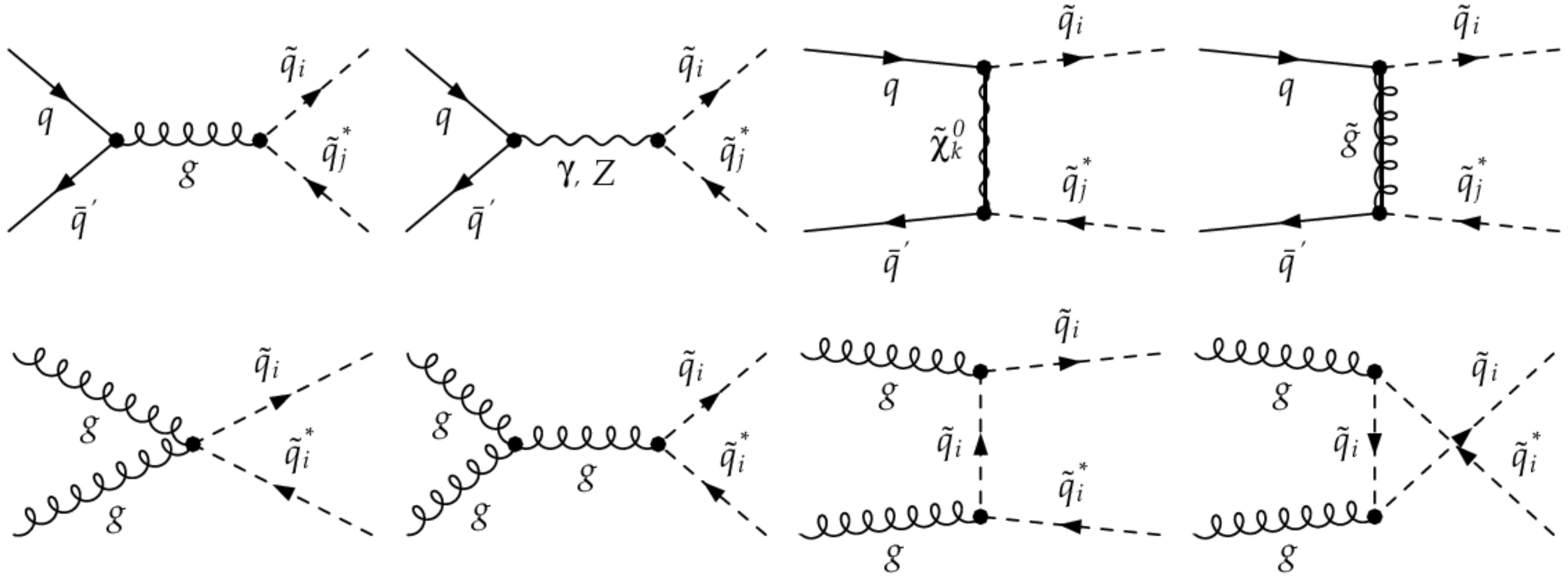

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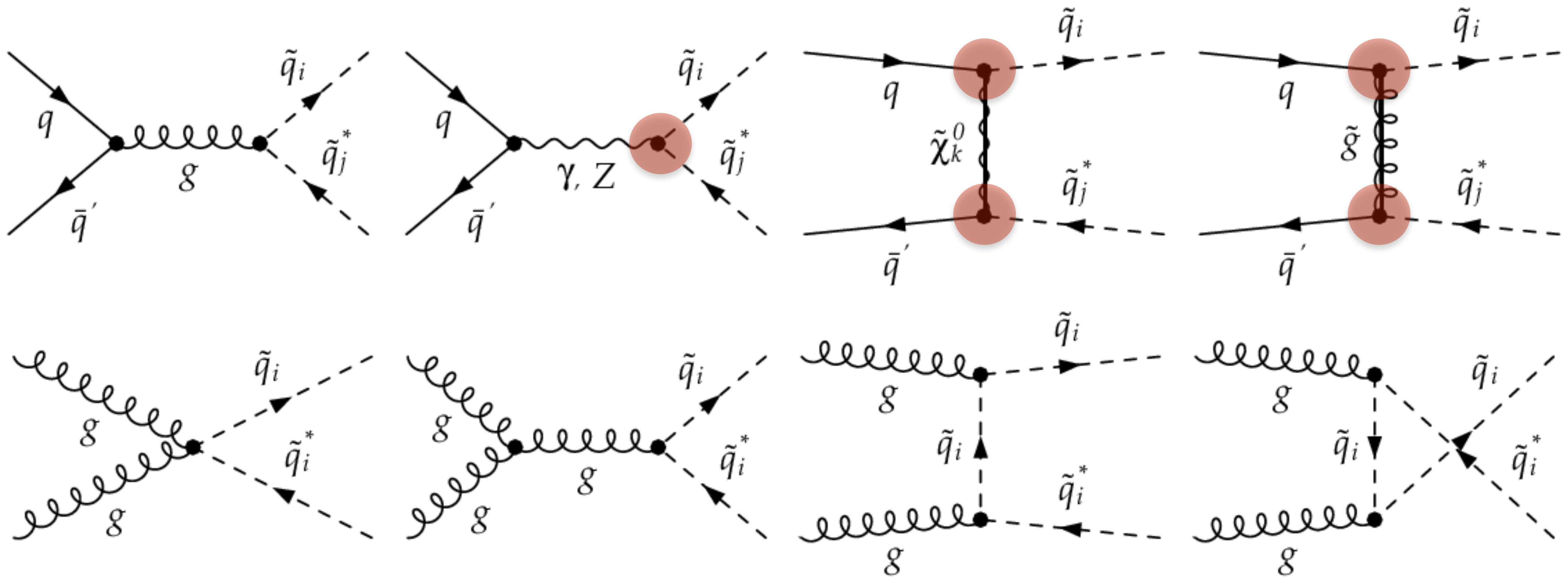

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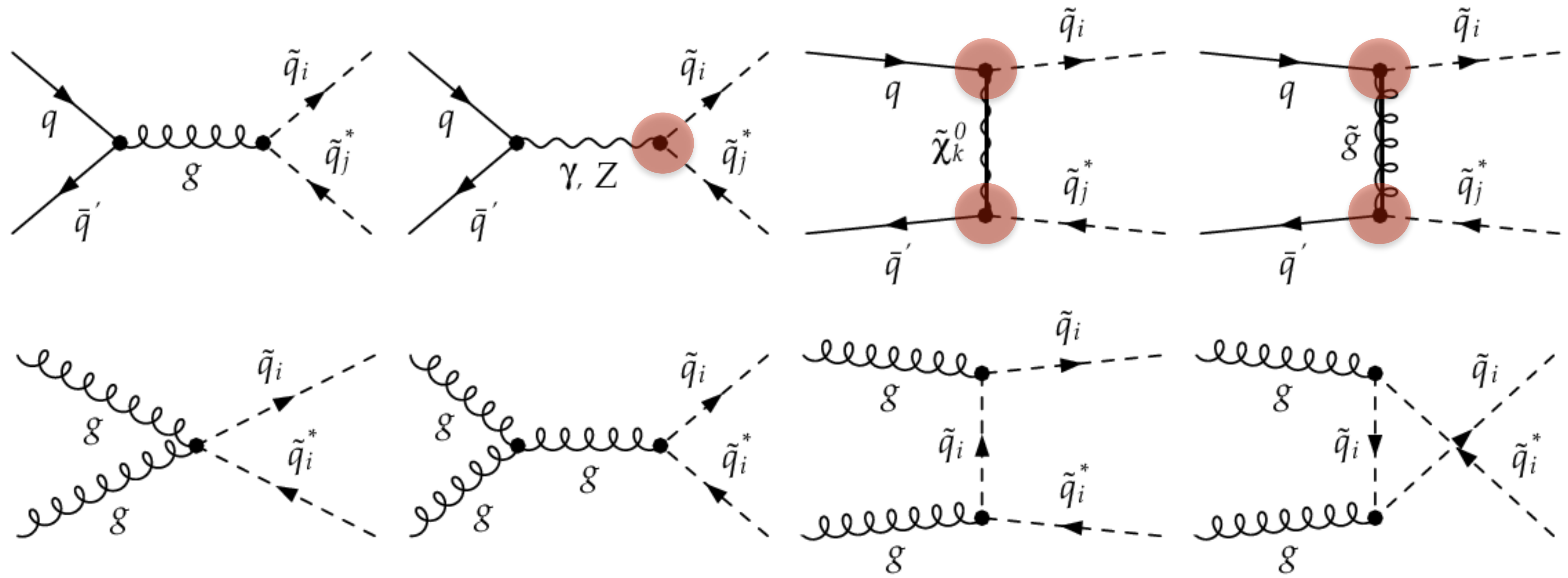

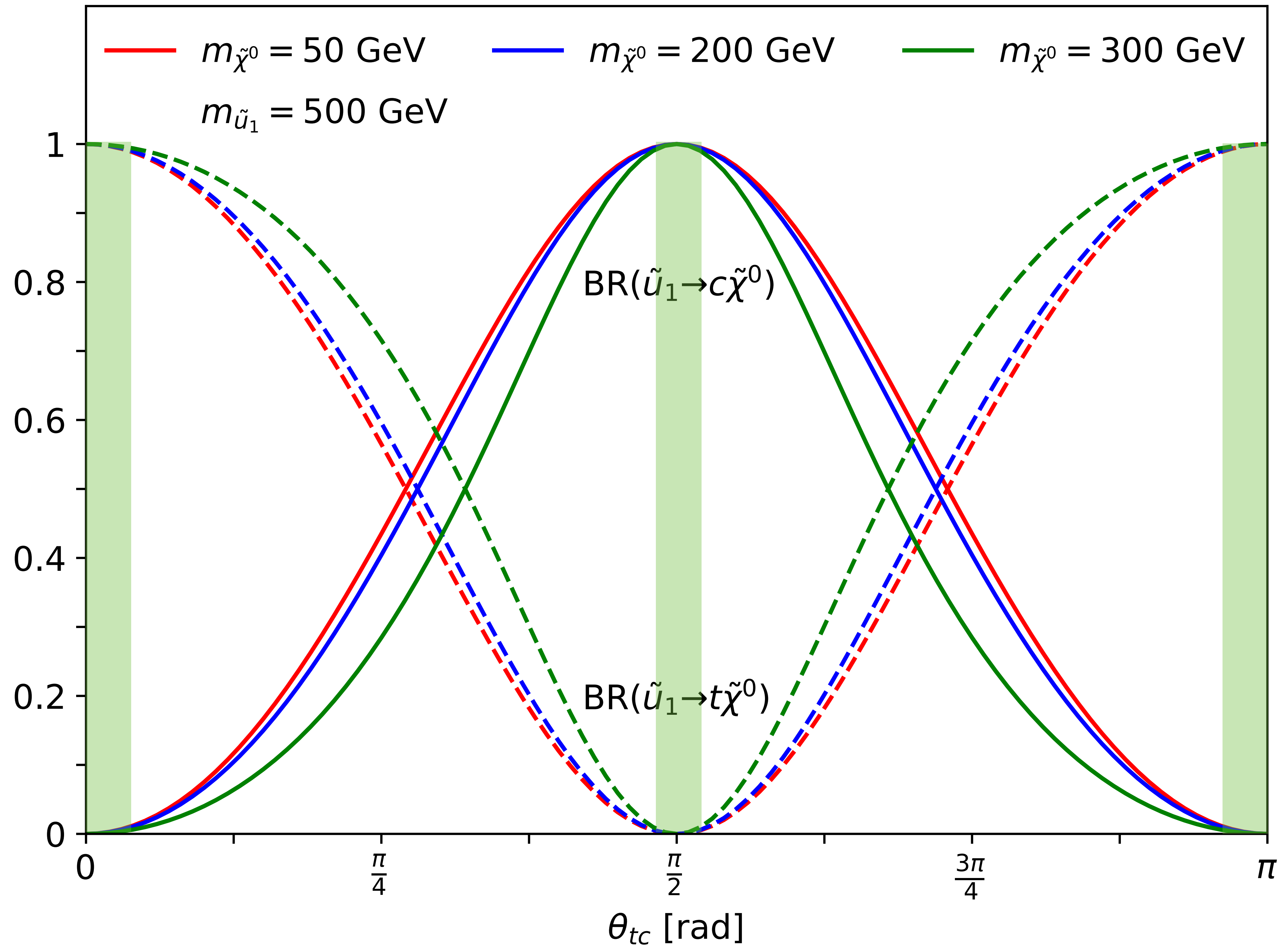

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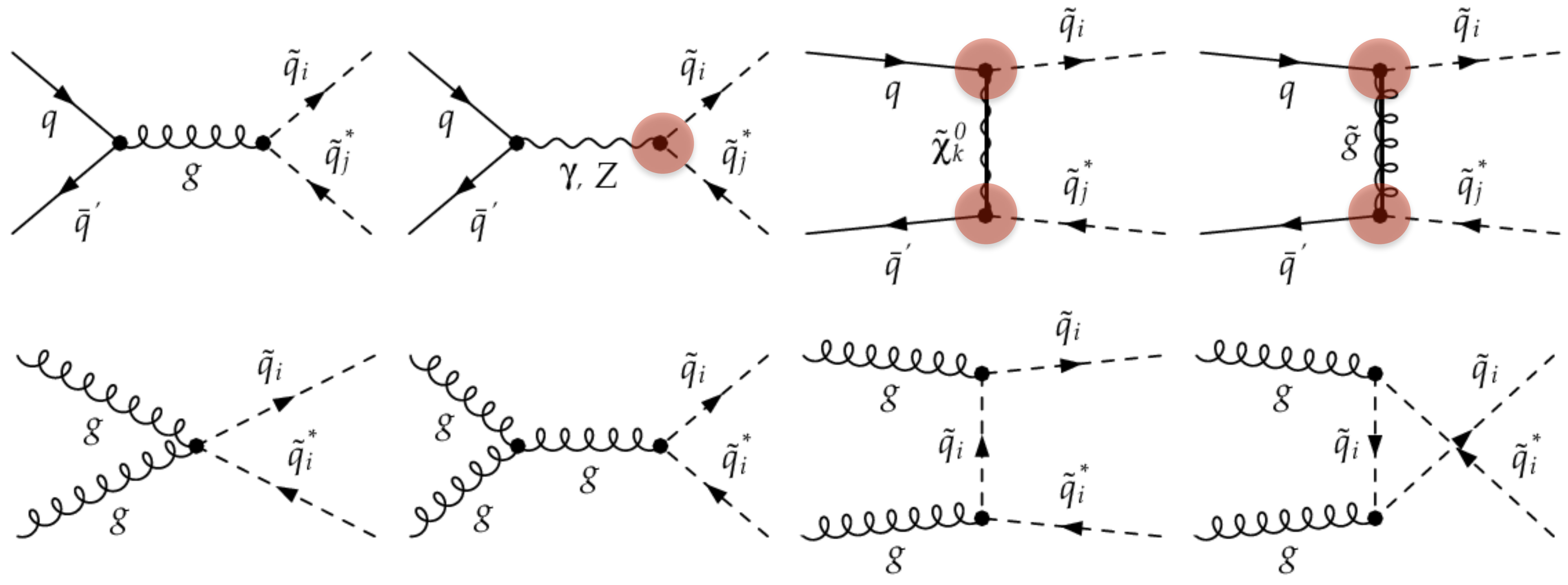
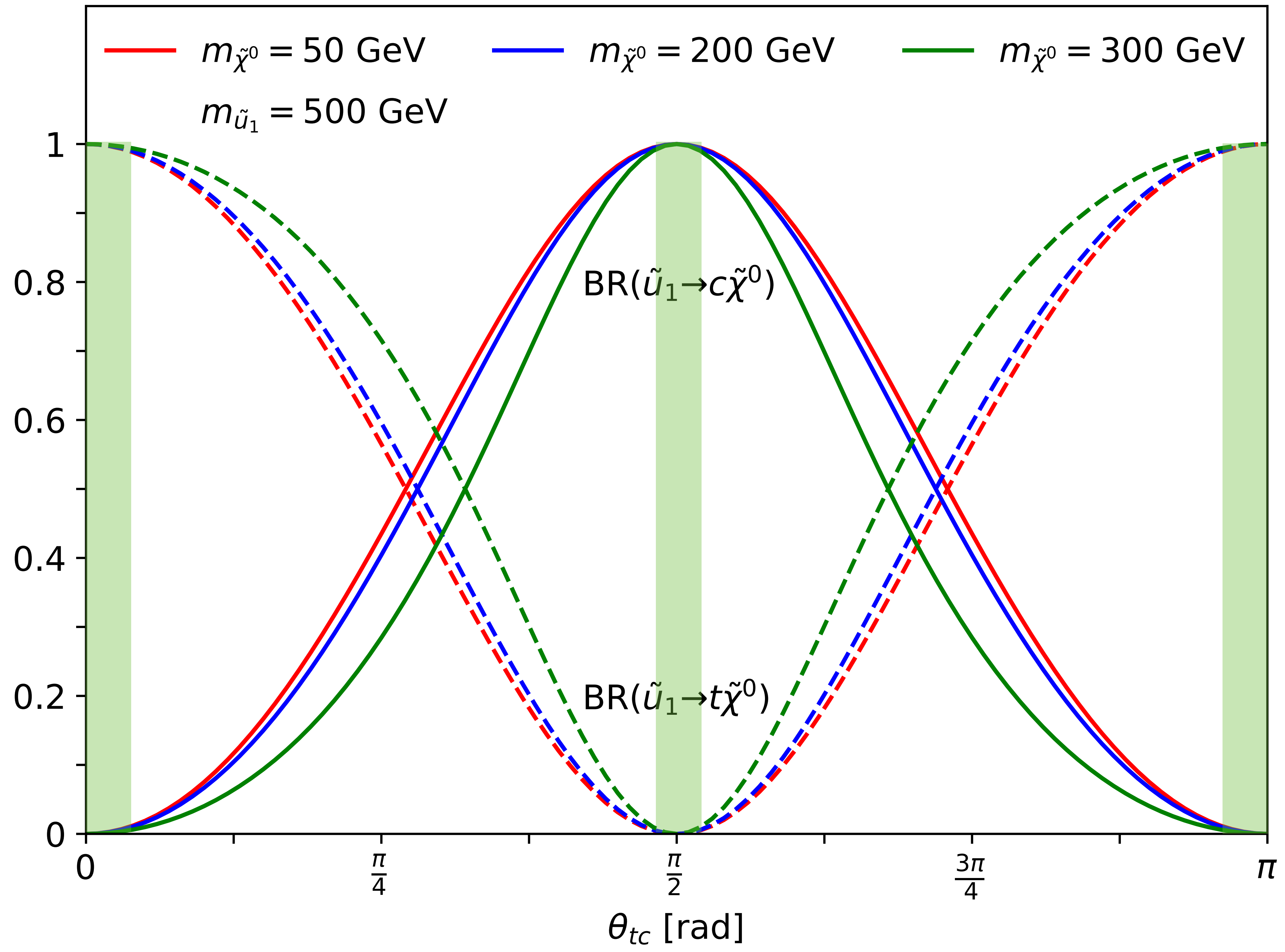
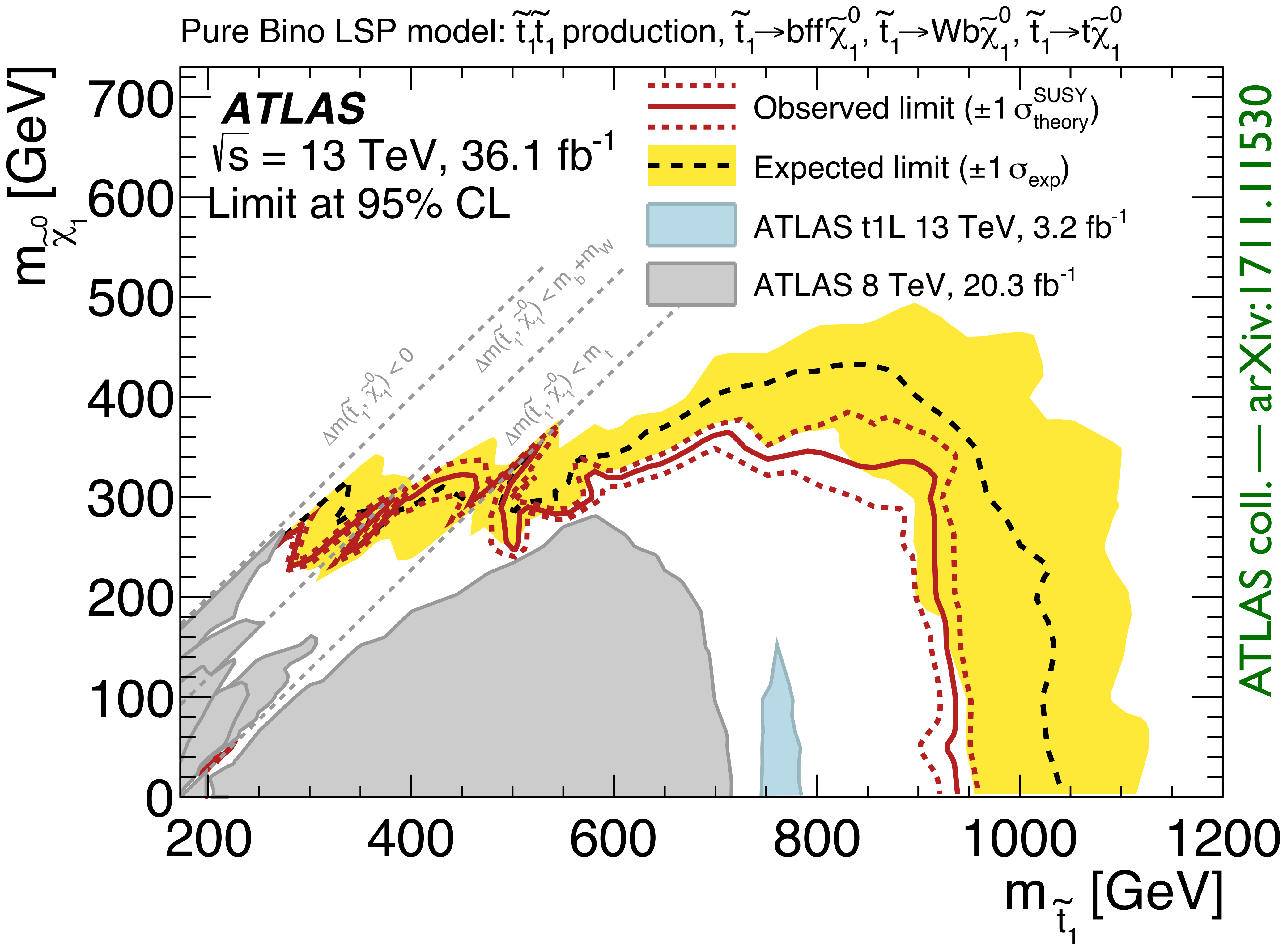
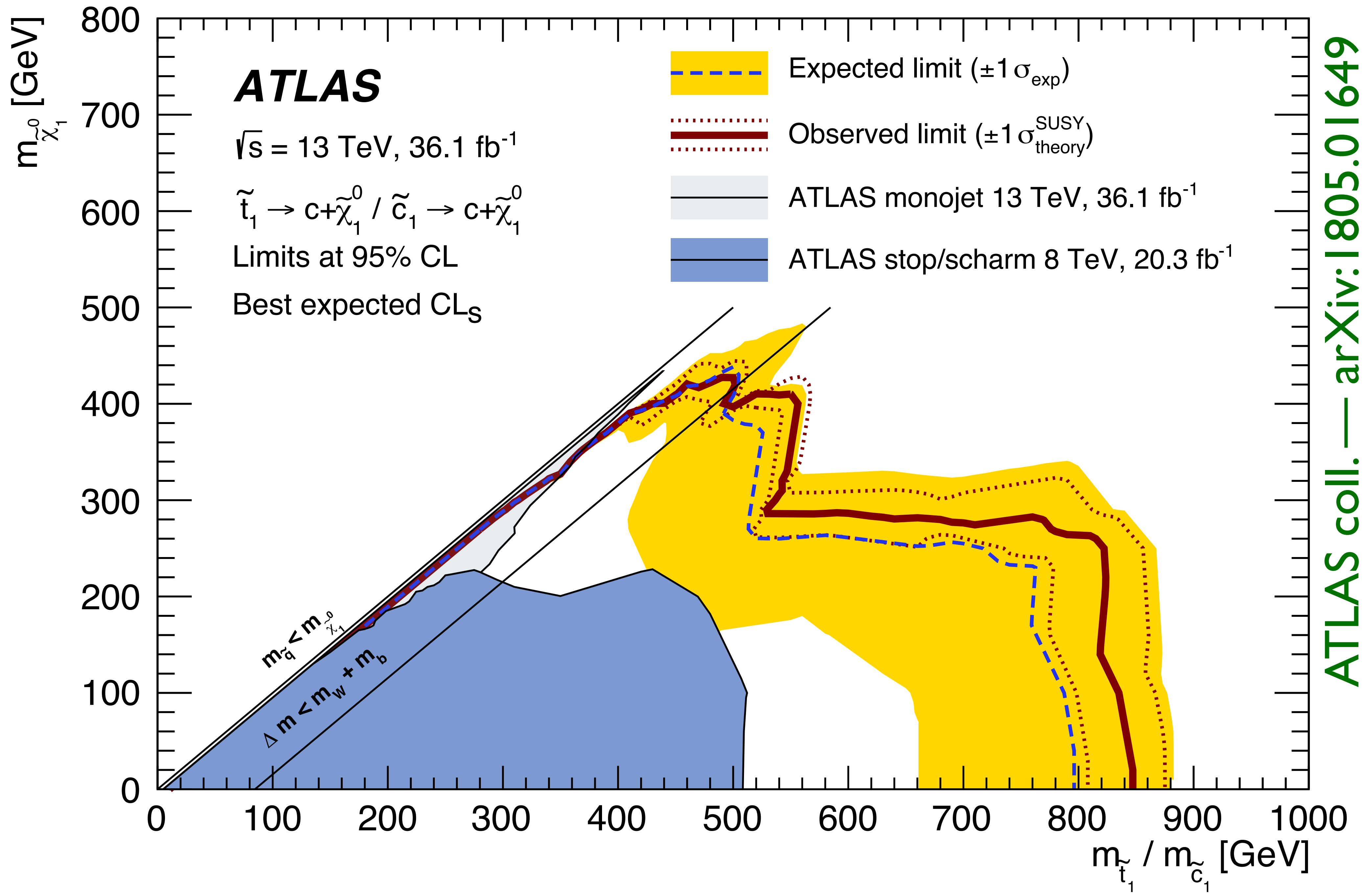


Expect weaker mass limits in the NMFV case…!



Experimental limits on squark masses by ATLAS and CMS





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

— based on (over-)simplifying assumptions such as **specific decay patterns, often involving one single decay channel…**

— such limits are **expected to be weakened** when more complex decay patterns are considered

Recasting limits on squark masses including NMFV

Evaluate the sensitivity of the two relevant searches (tt and cc channels) within the simplified setup
— relying on the acceptances and efficiencies provided by the ATLAS collaboration (“`discovery tN_med`” and “`discovery tN_high`”)
— **estimate signal yields and compare to ATLAS model-independent upper limits**

$pp \to t\bar{t} + \not{E}_T$ ATLAS coll. — arXiv:1711.11530

$pp \to c\bar{c} + \not{E}_T$ ATLAS coll. — arXiv:1805.01649

NLO+NLL corrected stop pair production
Borschensky *et al.* — arXiv:1407.5066
combined with relevant branching ratios
(seen on previous slide)

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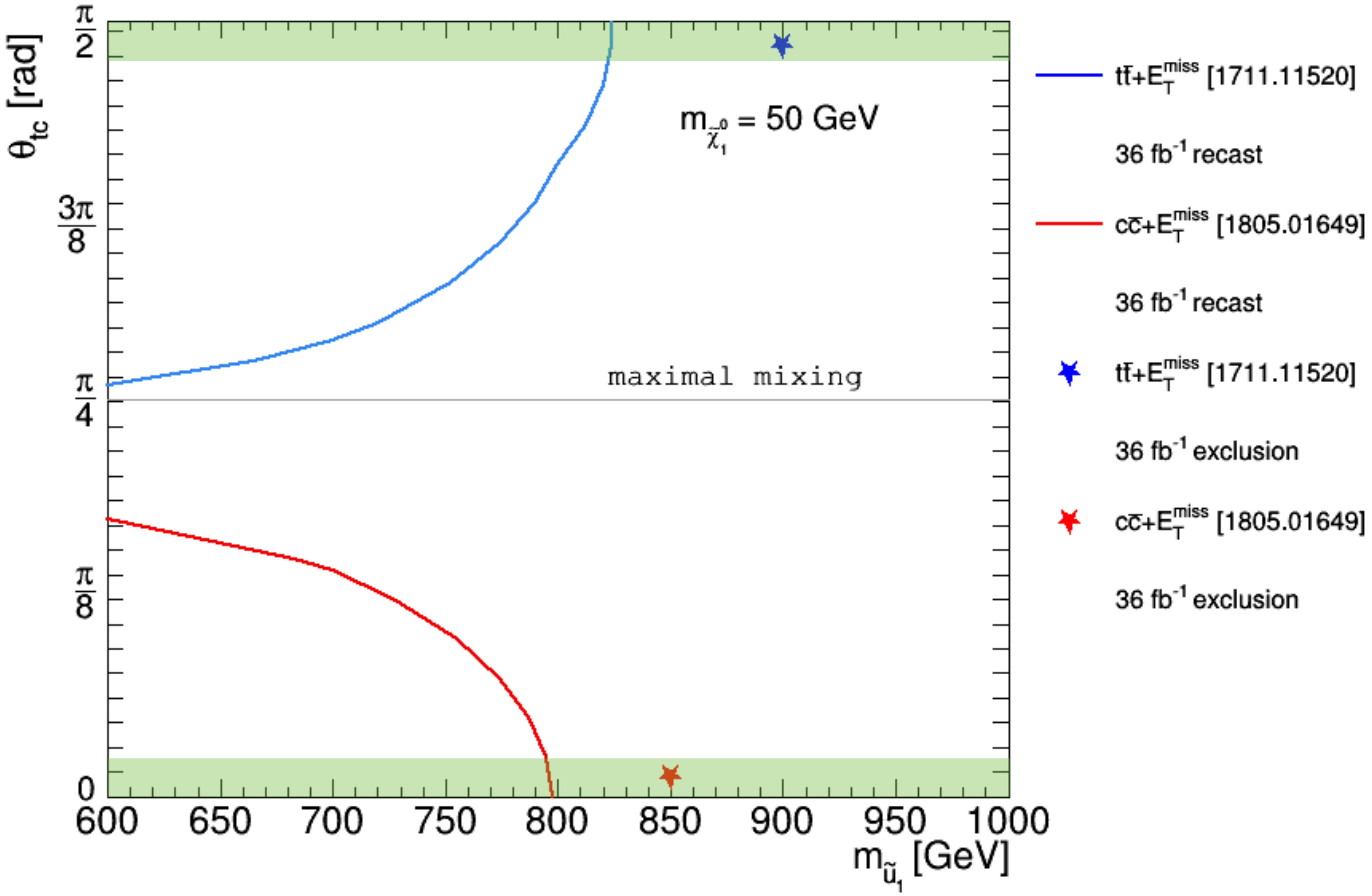

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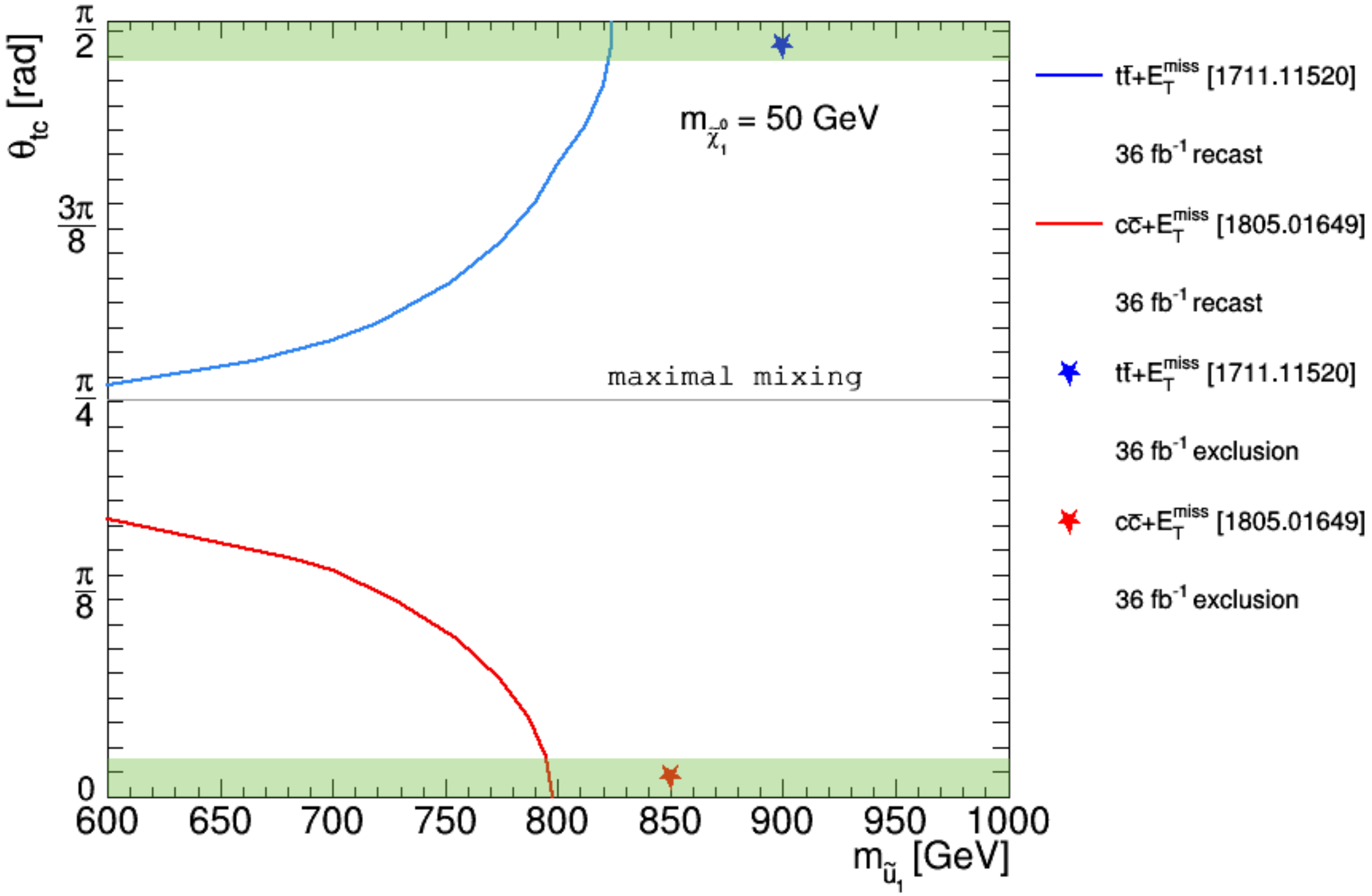
This method cannot reproduce the ATLAS multi-bin fit
— **obtained limits are more conservative…**
— but **impact of modified decay pattern clearly visible**



Proposal for a dedicated squark search including NMFV

Shortcomings of previous analyses may be overcome by taking into account the **specific signature** stemming from NMFV
— **expected reach at the LHC** for a dedicated search for the **"top-charm" final state** shows importance of "non-standard" searches

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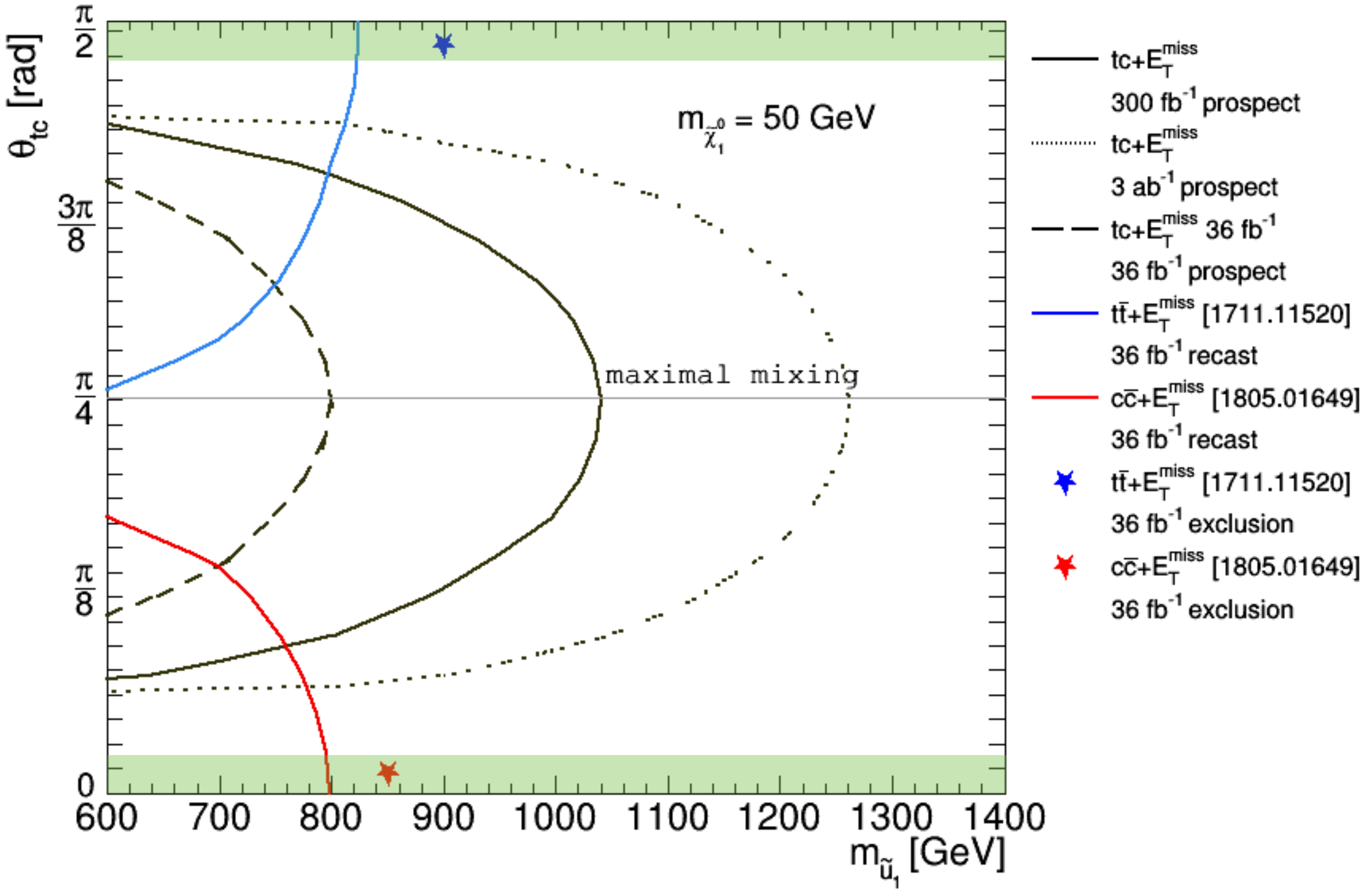

Towards the reconstruction of the flavour structure

Study the possibility to infer the flavour content after discovery of "squark-like" particle at the LHC
— **Distinguish Minimal and Non-Minimal Flavour Violation…?**
— Focus here on the **stop-content of the lightest up-type squark** (supposed to be observed)

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

$x_{\tilde{t}} \approx 0\,, \quad x_{\tilde{t}} \approx 1$ MFV-like situation

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Likelihood inference (value of $x_{\tilde{t}}$)
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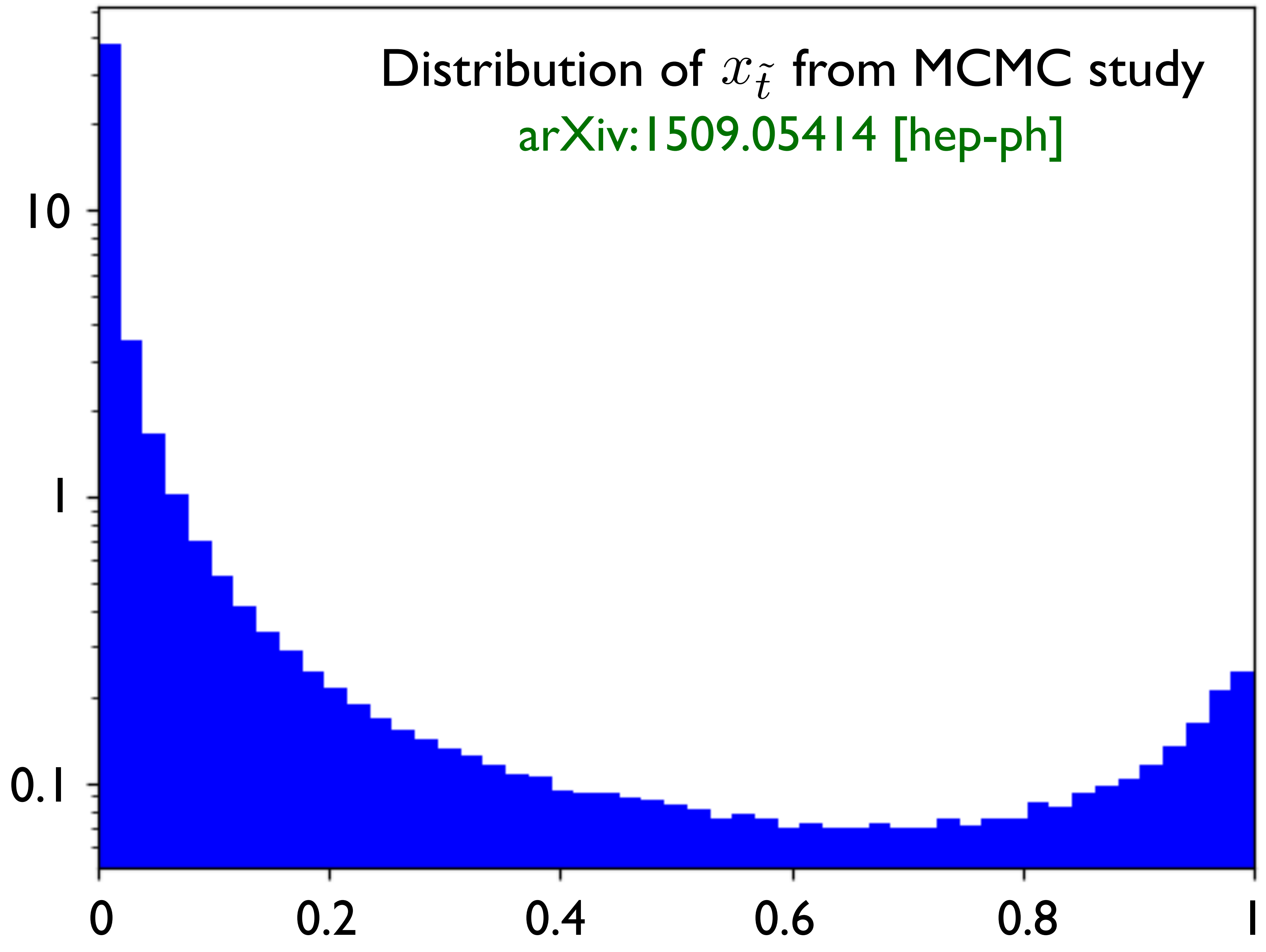

Note that stop-content distribution may be expected to peak at the “MFV-like” extremities!

Likelihood fit — Selected results

Model database
(here: MCMC study)

θ_i

"observed data" (here: test scenario…)

$m_{\tilde{u}_1}$

$m_{\tilde{\chi}_1^0}$

$m_{\tilde{\chi}_1^\pm}$

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

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D_i, σ_i

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

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distinct bins in $x_{\tilde{t}}$

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

**Inference of stop component
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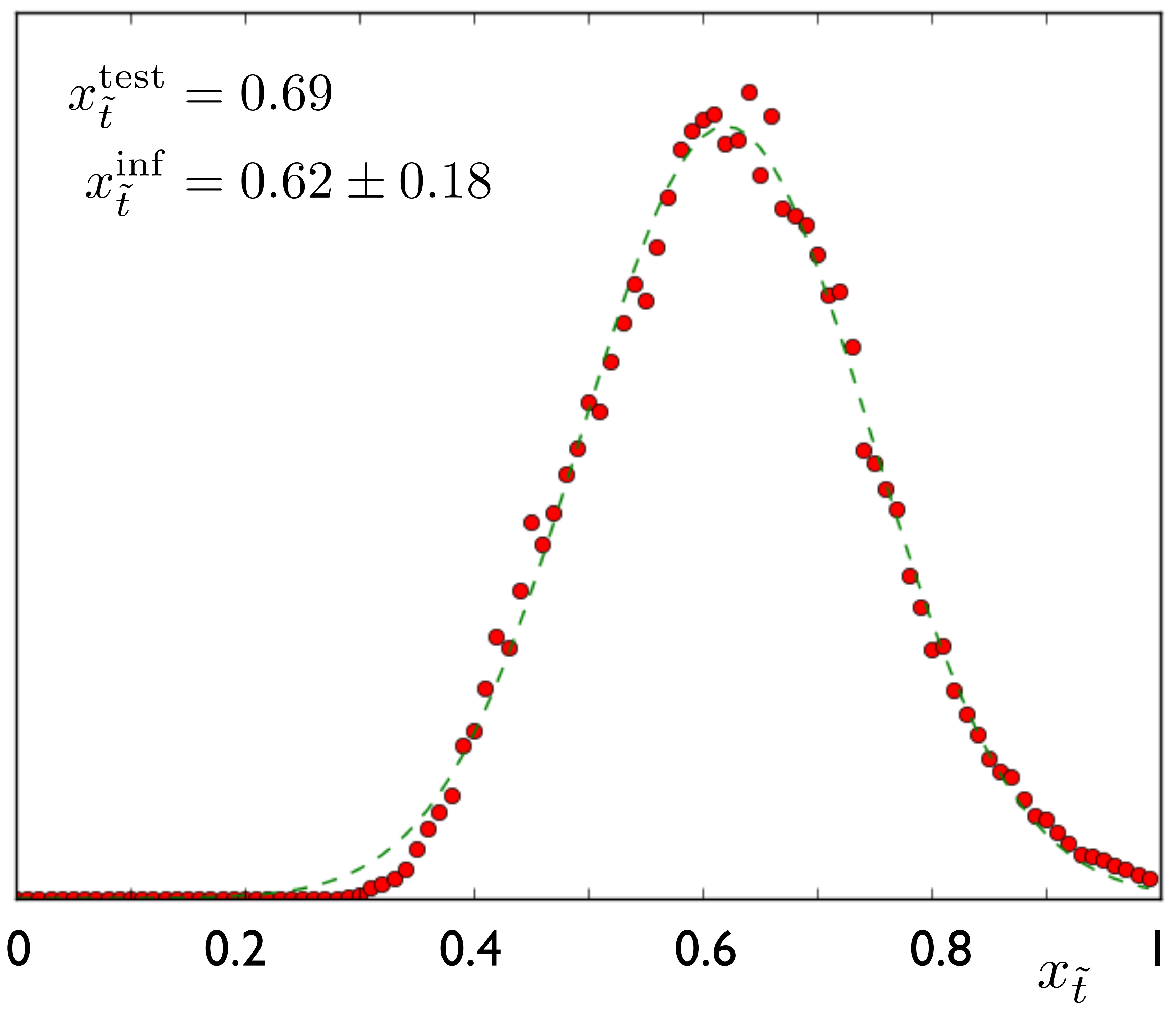

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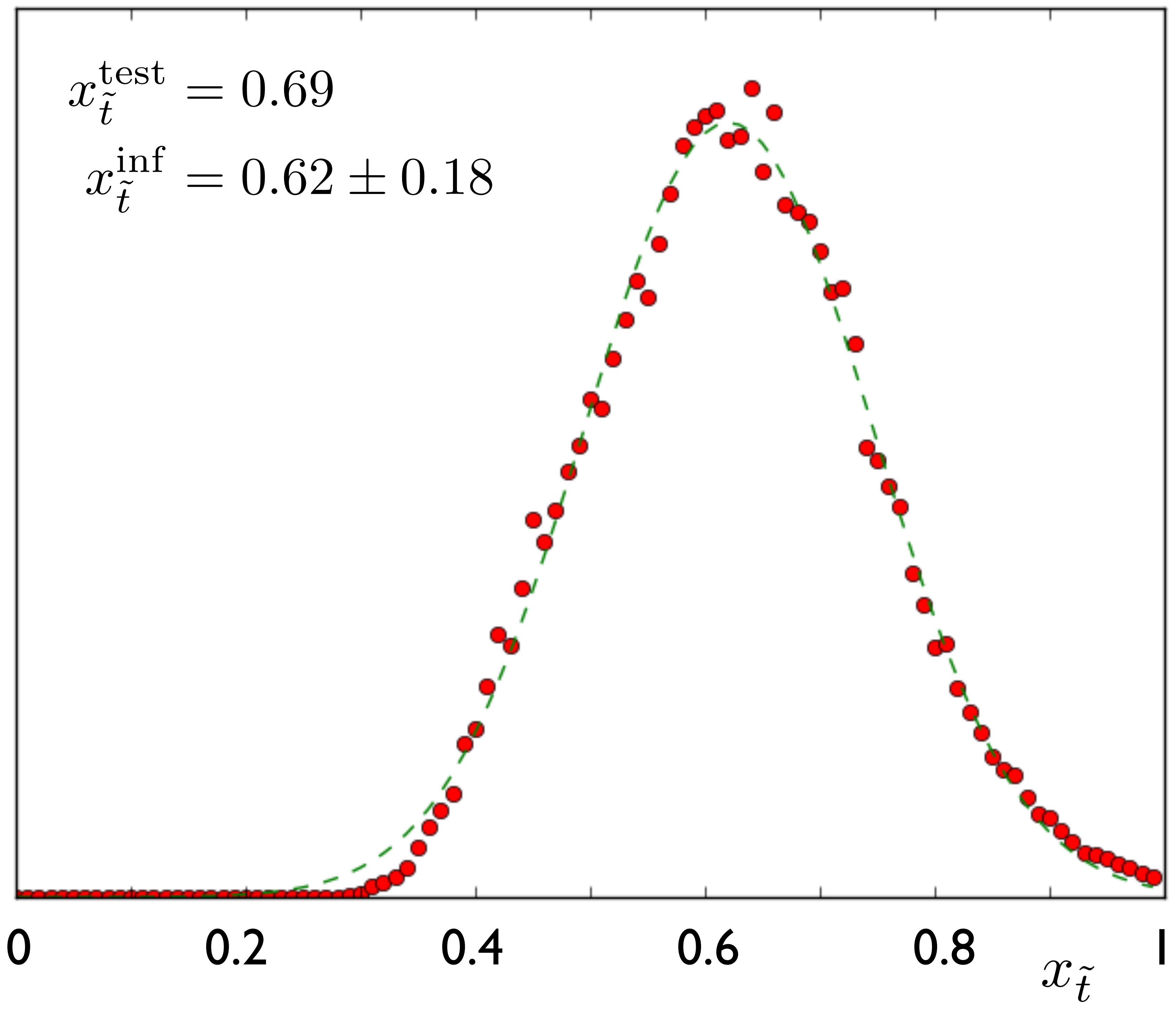
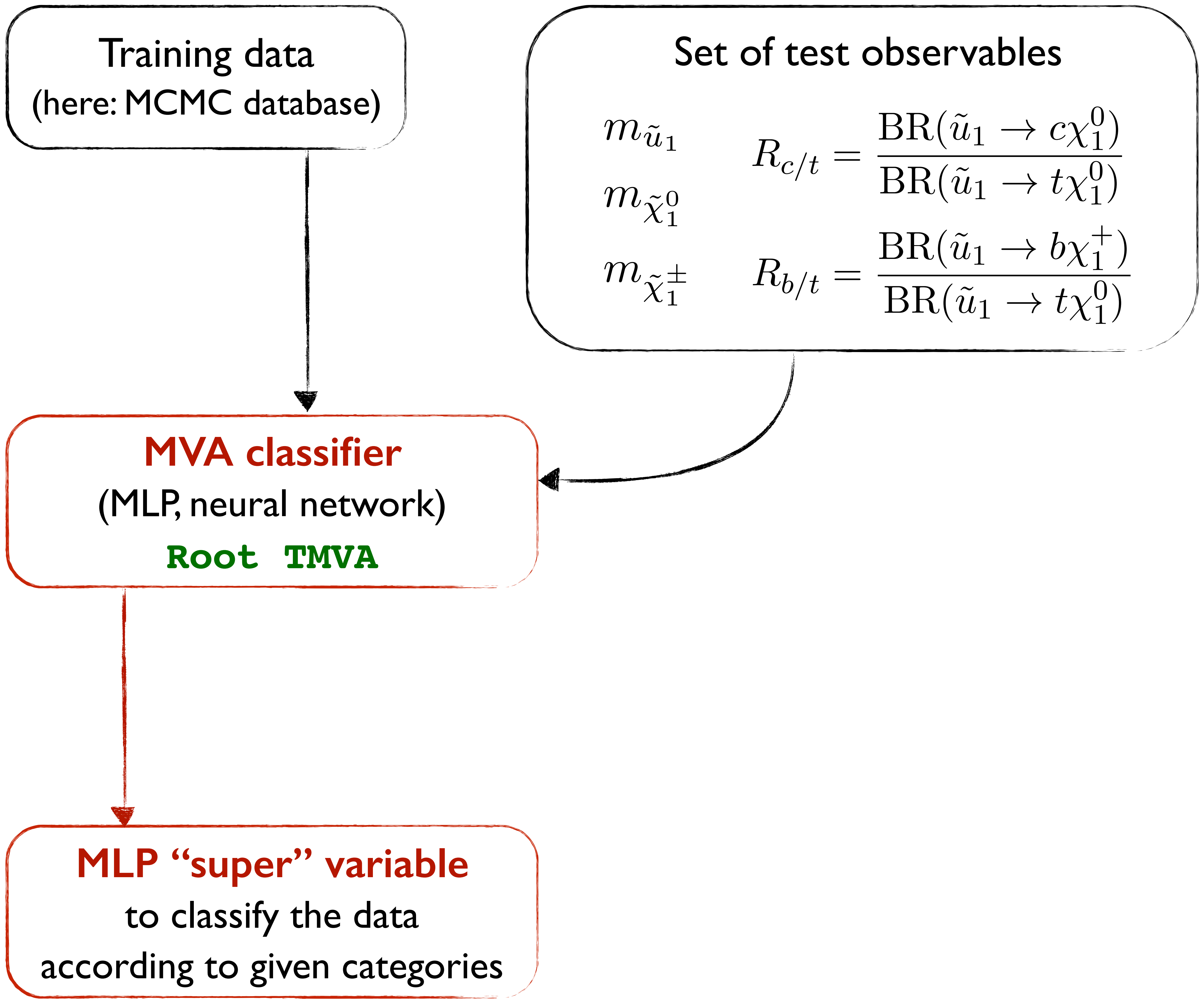


Interesting approach **managing to reconstruct stop content** in certain cases…
— but **requires additional information** on other sectors (especially gauginos)
— suffers from **dependence on the prior**…

Multivariate analysis — Selected results



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MVA classifier
(MLP, neural network)
Root TMVA

Test categories for the NMFV-MSSM:

"charm" MFV	$0.00 \leq x_{\tilde{t}} < 0.05$
"charm" NMFV	$0.05 < x_{\tilde{t}} < 0.50$
"top" NMFV	$0.50 < x_{\tilde{t}} < 0.95$
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MLP "super" variable
to classify the data
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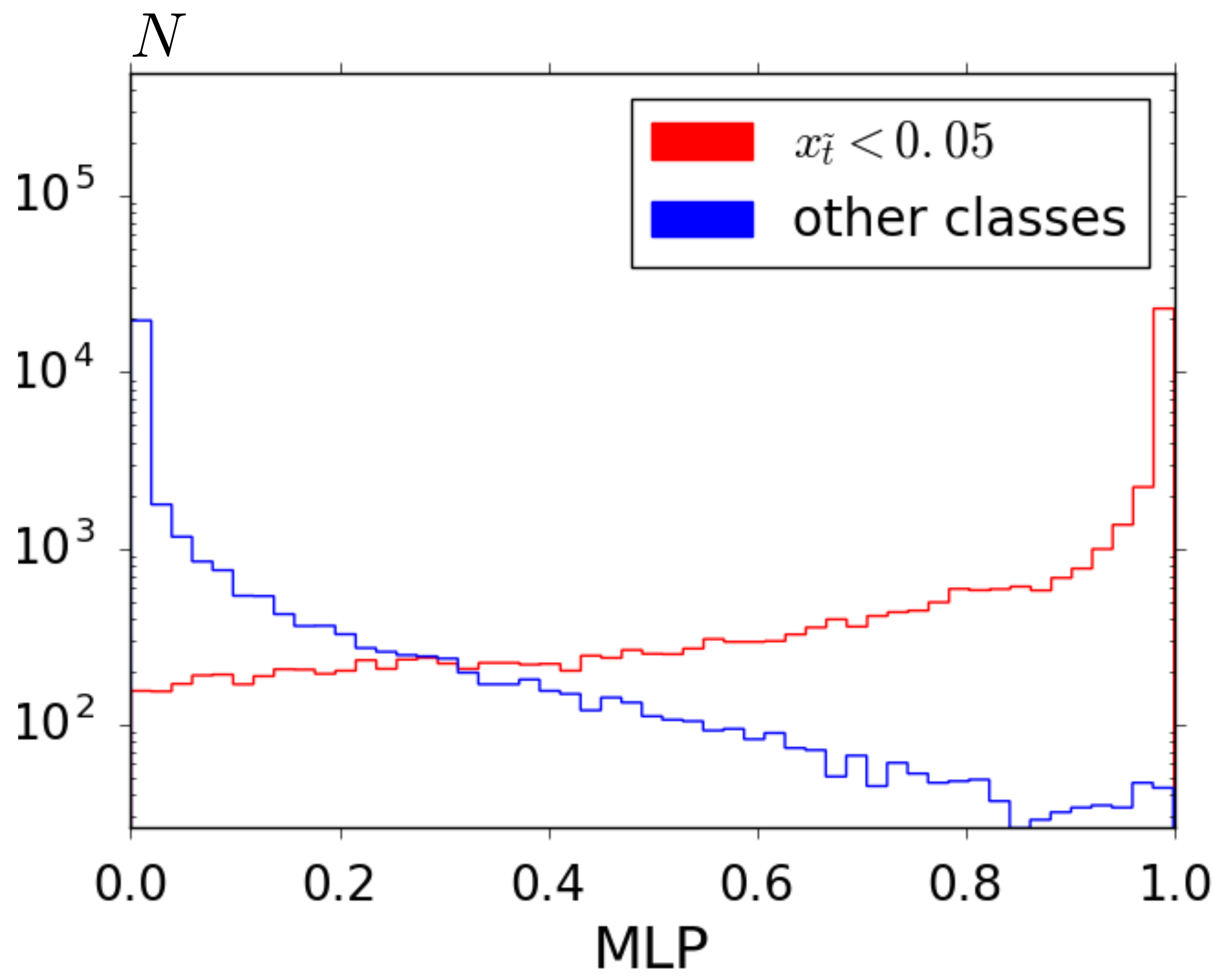

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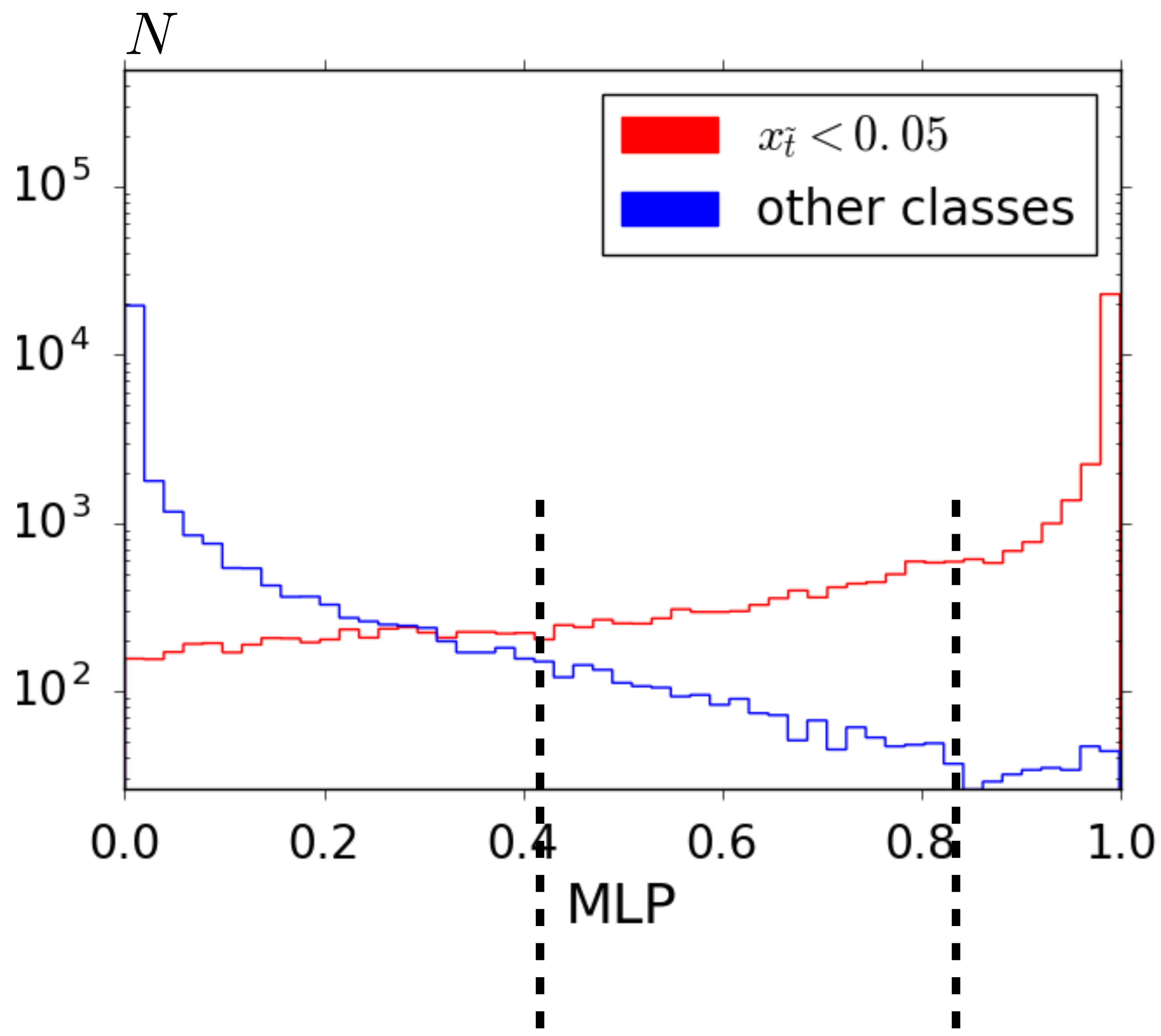
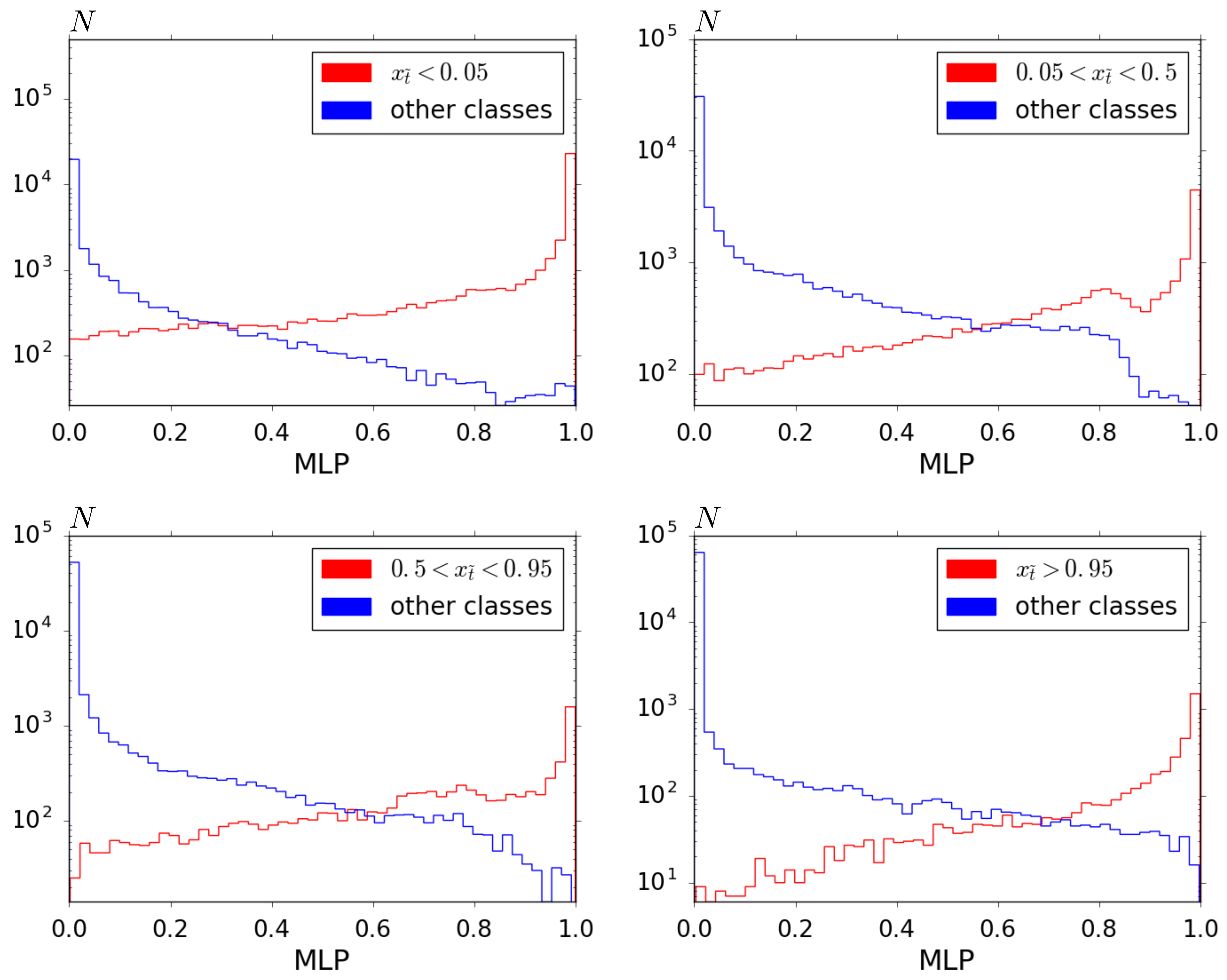


Efficiency 89%
misid. rate 5%

Efficiency 72%
misid. rate 1%

Multivariate analysis — Selected results



Efficiencies for 10% misidentification rate:

Categories		Efficiency
"charm" MFV	$0.00 \leq x_{\tilde{t}} < 0.05$	95%
"charm" NMFV	$0.05 < x_{\tilde{t}} < 0.50$	51%
"top" NMFV	$0.50 < x_{\tilde{t}} < 0.95$	41%
"top" MFV	$0.95 < x_{\tilde{t}} \leq 1.00$	69%

MVA classifier less efficient for stop-like cases…
mainly due to prior!

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

Part III

NMFV within Grand Unification Frameworks
— $A_4 \times SU(5)$ case study —

J. Bernigaud, B. Herrmann, S. F. King, S. J. Rowley

"Non-minimal flavour violation in $A_4 \times SU(5)$ SUSY GUTs with smuon assisted dark matter"

JHEP 1903 (2019) 067 — arXiv:1812.07463 [hep-ph]

The MSSM with *SU(5)* unification conditions and an A_4 flavour symmetry

Standard Model matter fields neatly fit into **complete representations of *SU(5)***:

$$SU(5) \to SU(3) \times SU(2) \times U(1)$$

$$\bar{\mathbf{5}} = F = d^c \otimes L \qquad \mathbf{10} = T = u^c \otimes Q \otimes e^c$$

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Unify three families of $\bar{\mathbf{5}}$ into the **triplet** of A_4 while the three $\mathbf{10}$ are **singlets** of A_4

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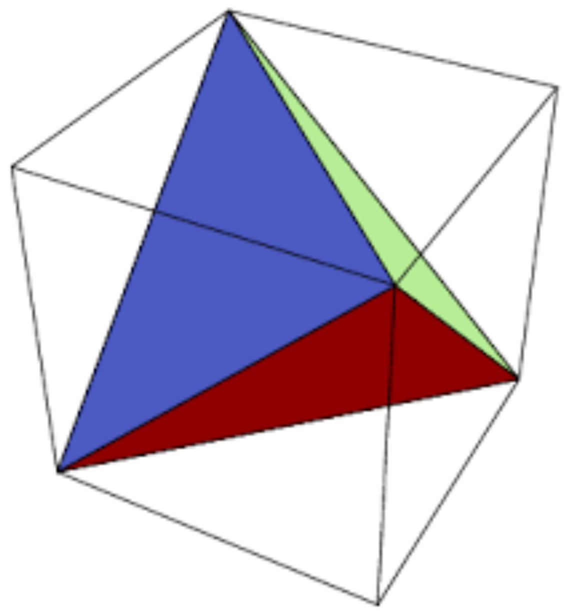

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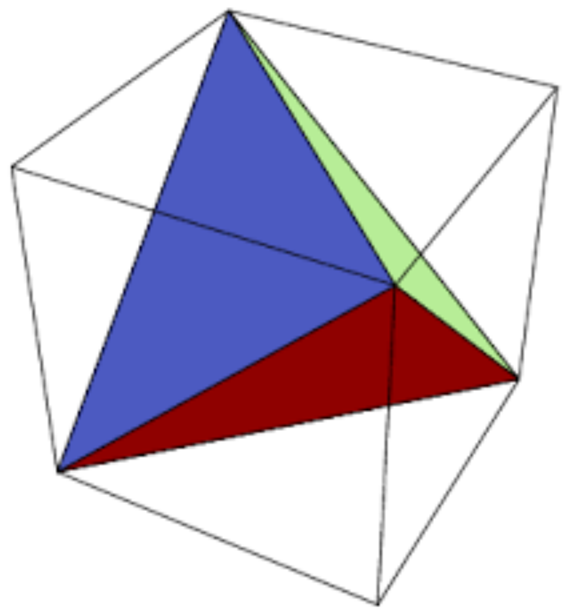

Generally, **non-minimal flavour violation is expected in this type of setup** (presence of flavons related to the breaking of A_4…)

S. Antusch, S. F. King, M. Spinrath — arXiv:1301.6764 [hep-ph]
M. Dimou, S. F. King, C. Luhn — arXiv:1511.07886 [hep-ph]
M. Dimou, S. F. King, C. Luhn — arXiv:1512.09063 [hep-ph]

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PHYSICAL REVIEW D **97**, 115002 (2018)

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More generally, NMFV in flavoured GUT frameworks…?

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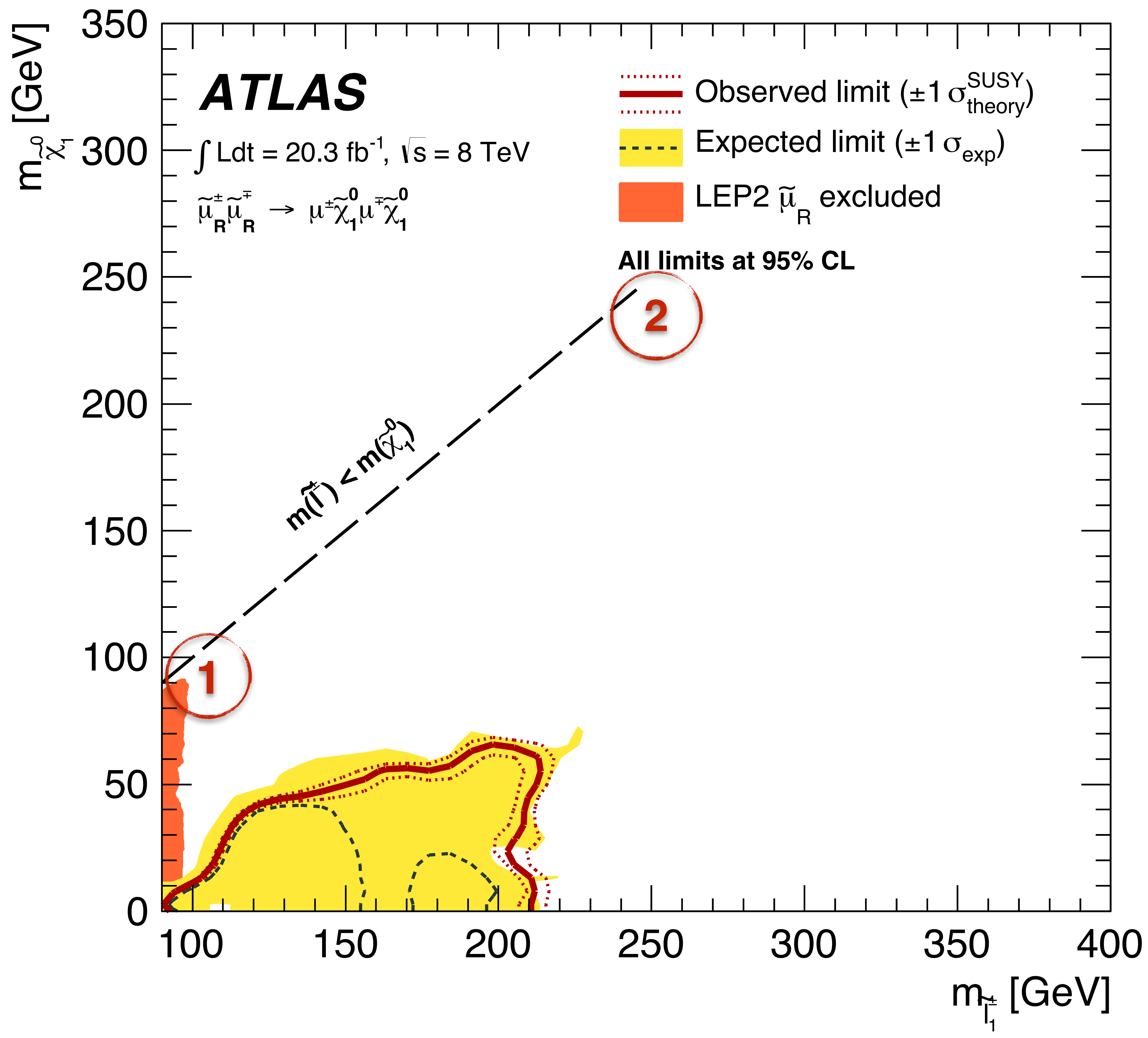

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— impose **hadronic and leptonic** constraints using SPheno Porod 2003-2019 and SARAH Staub 2007-2018
— impose neutralino dark matter and relic density using micrOMEGAs Bélanger *et al.* 2003-2019

Observable	Constraint
m_h	(125.2 ± 2.5) GeV
$\mathrm{BR}(\mu \to e\gamma)$	$< 4.2 \times 10^{-13}$
$\mathrm{BR}(\mu \to 3e)$	$< 1.0 \times 10^{-12}$
$\mathrm{BR}(\tau \to e\gamma)$	$< 3.3 \times 10^{-8}$
$\mathrm{BR}(\tau \to \mu\gamma)$	$< 4.4 \times 10^{-8}$
$\mathrm{BR}(\tau \to 3e)$	$< 2.7 \times 10^{-8}$
$\mathrm{BR}(\tau \to 3\mu)$	$< 2.1 \times 10^{-8}$
$\Omega_{\mathrm{CDM}}h^2$	0.1198 ± 0.0042

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$\Omega_{\mathrm{CDM}} h^2$	0.1198 ± 0.0042

The MSSM with *SU(5)xA₄* unification conditions including NMFV

Introduce NMFV elements in the Lagrangian **at the GUT scale around two reference scenarios** based on previous study
— impose **hadronic and leptonic** constraints using SPHENO Porod 2003-2019 and SARAH Staub 2007-2018
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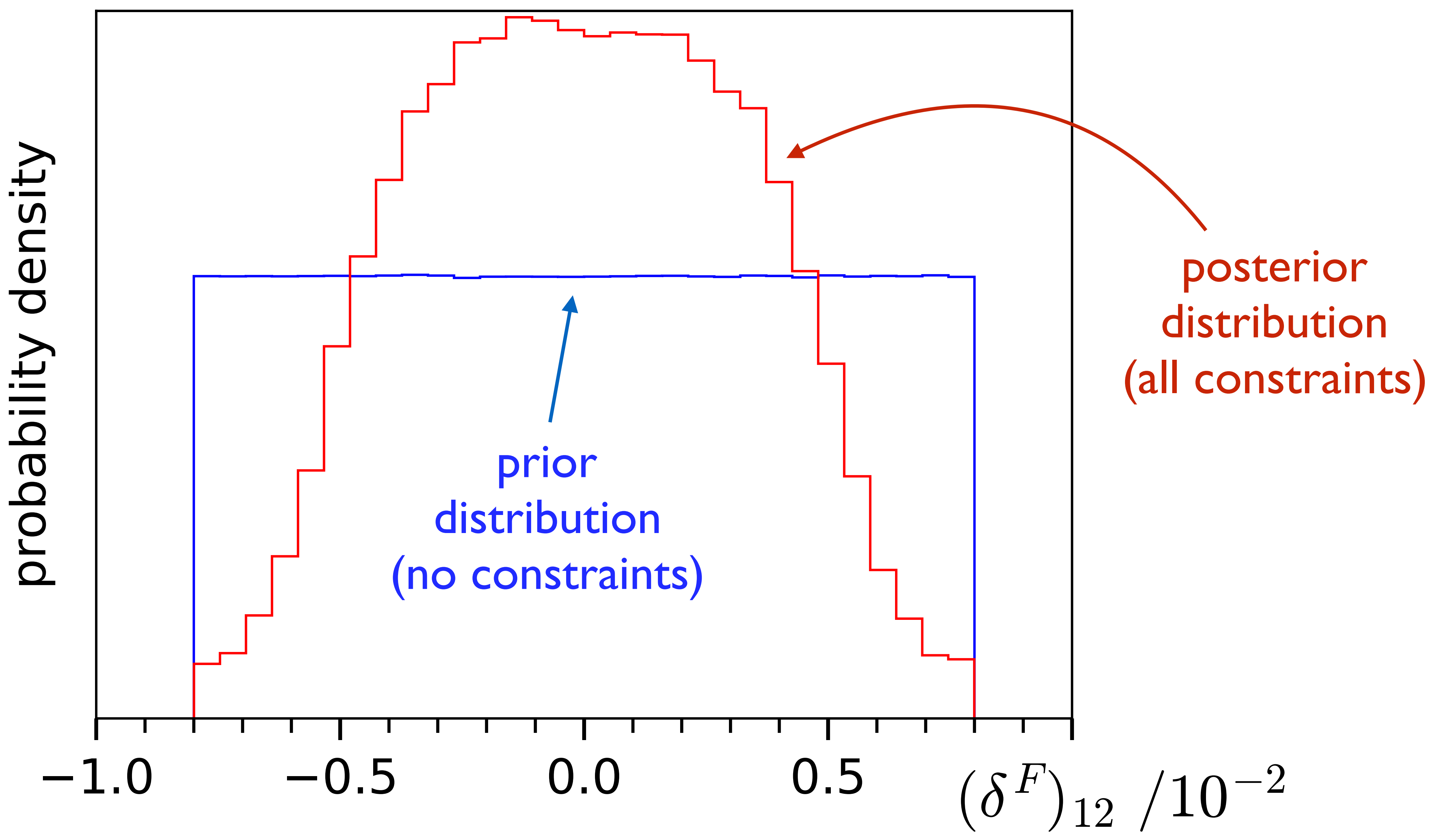

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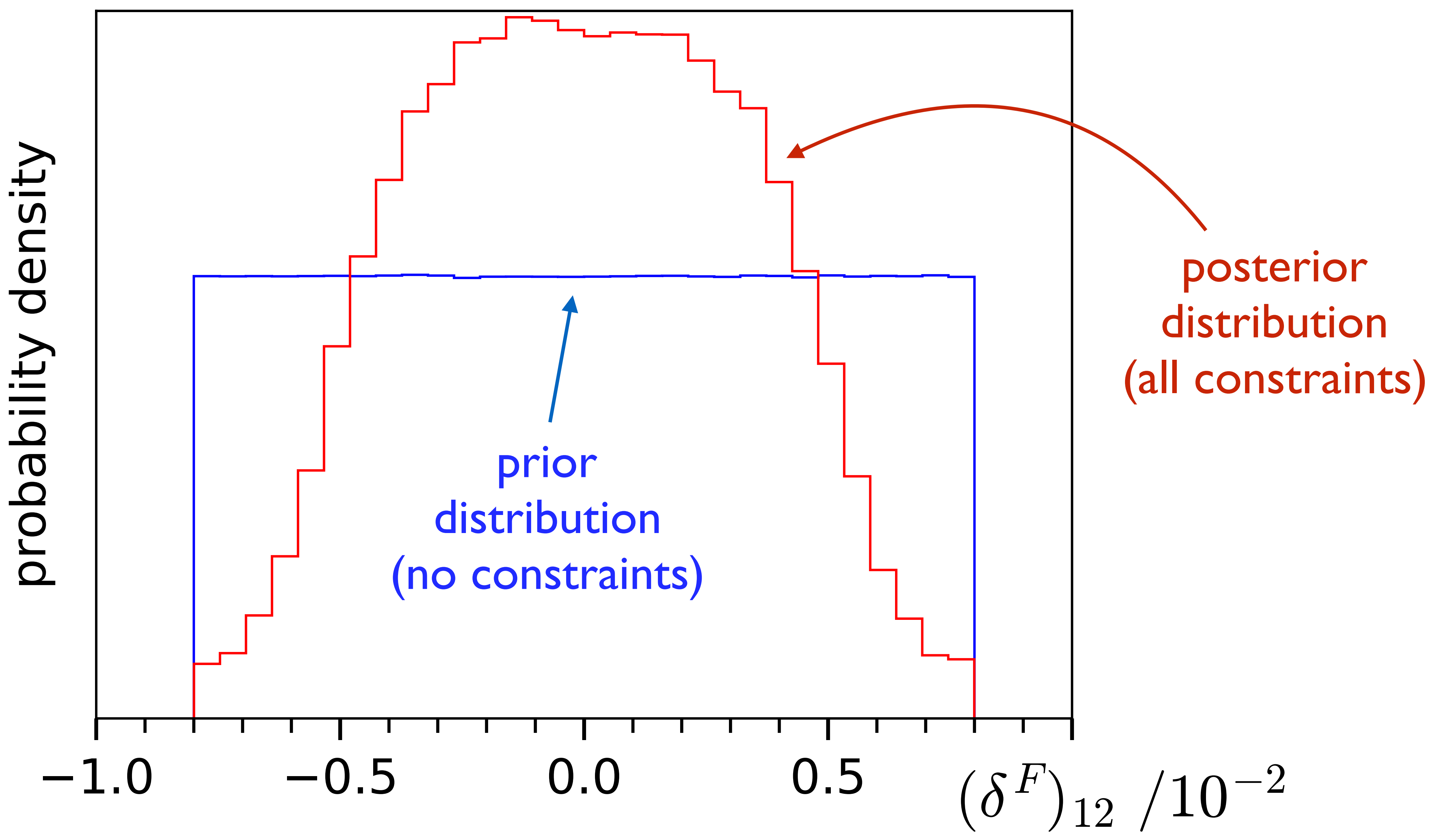
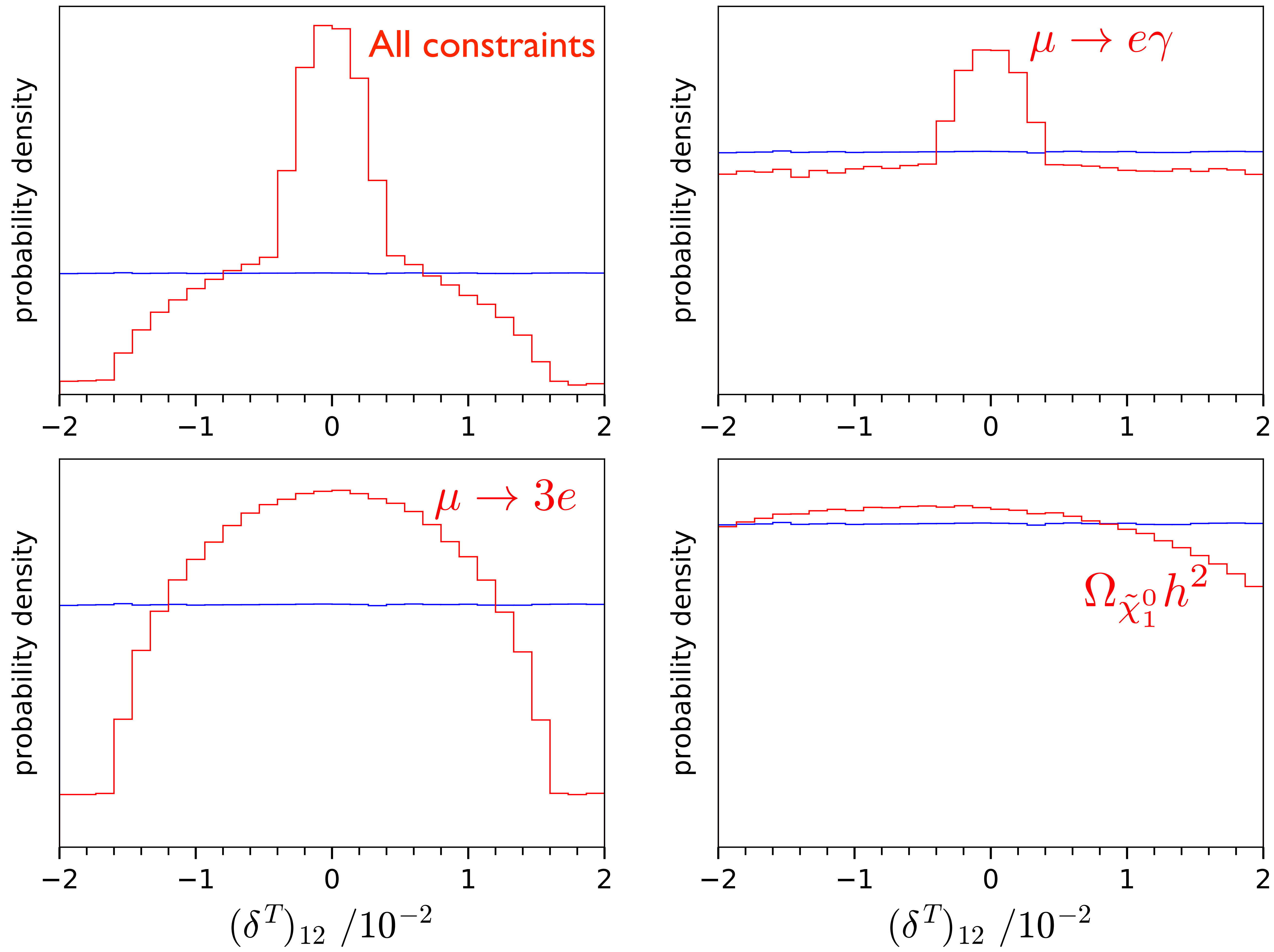
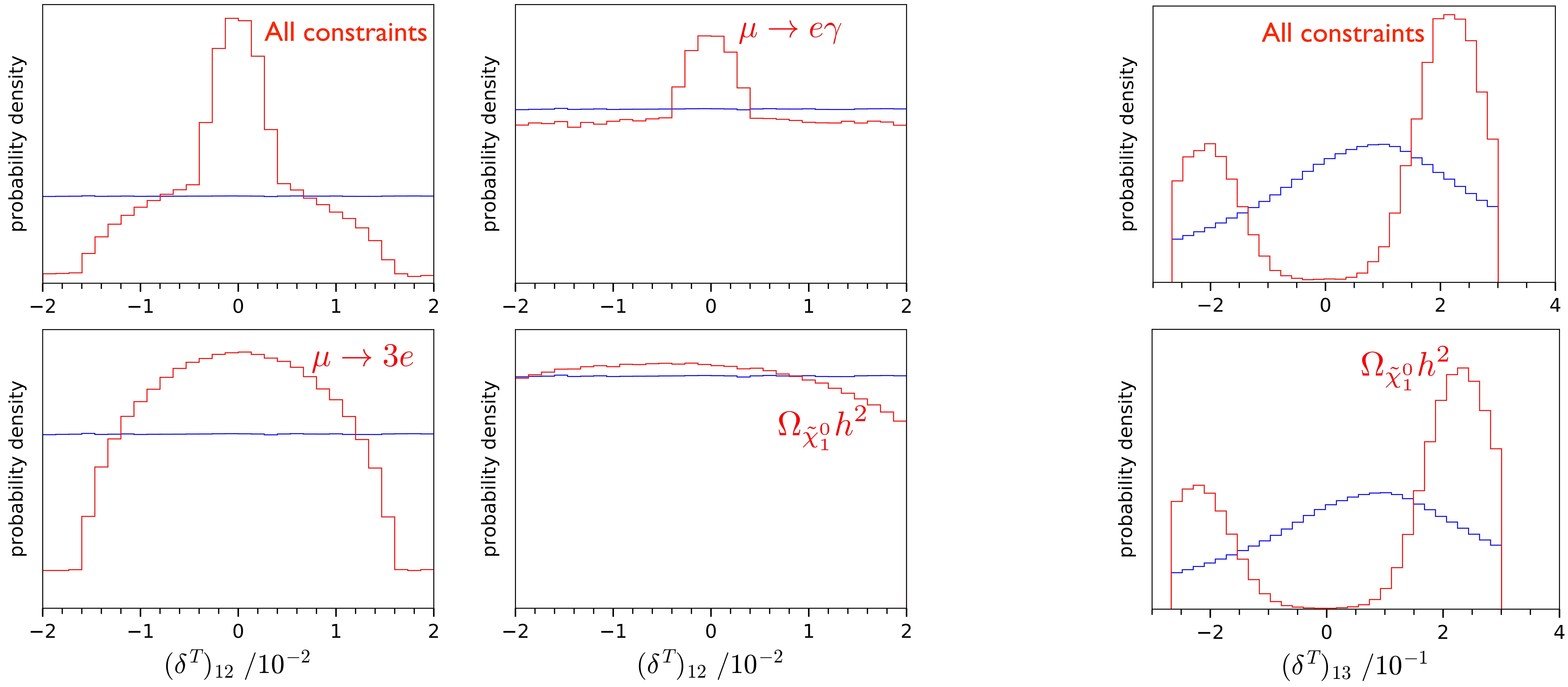


In a multi-dimensional parameter space, it is not enough to study each parameter individually…
— **interference effects in simultaneous analysis are important** and lead to larger allowed intervals!

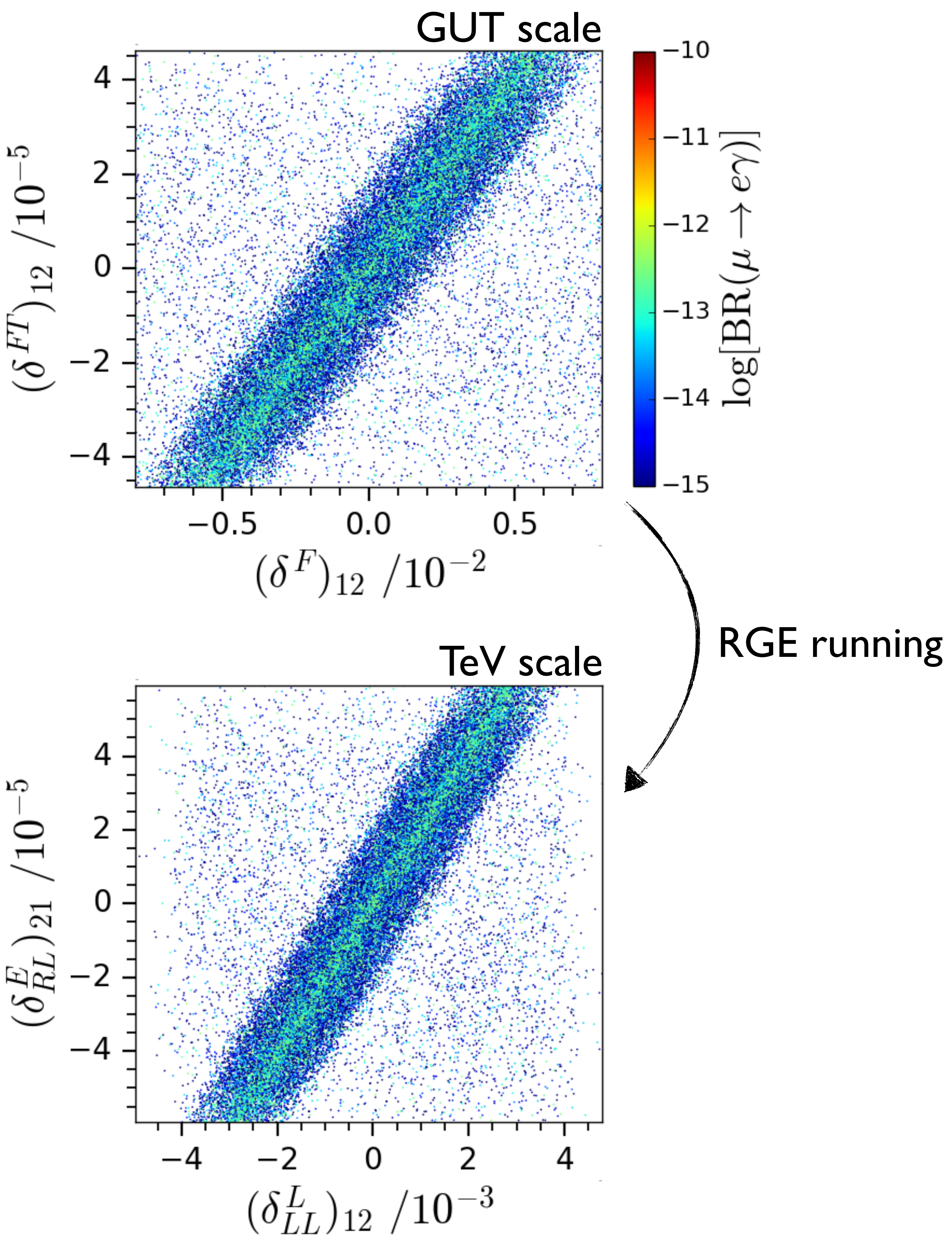
Interplay and importance of different constraints



Interplay and importance of different constraints



Correlations and TeV-scale phenomenology



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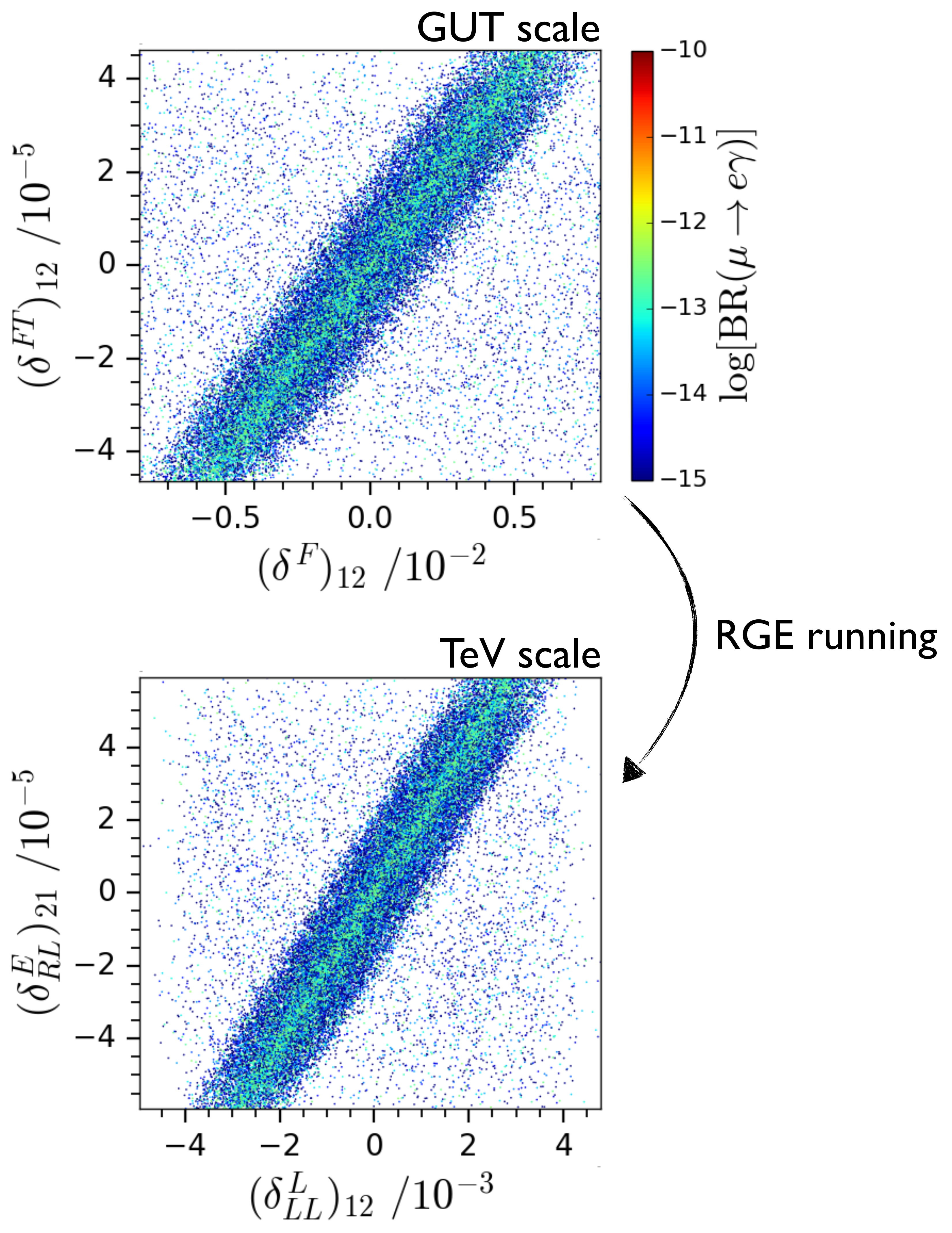
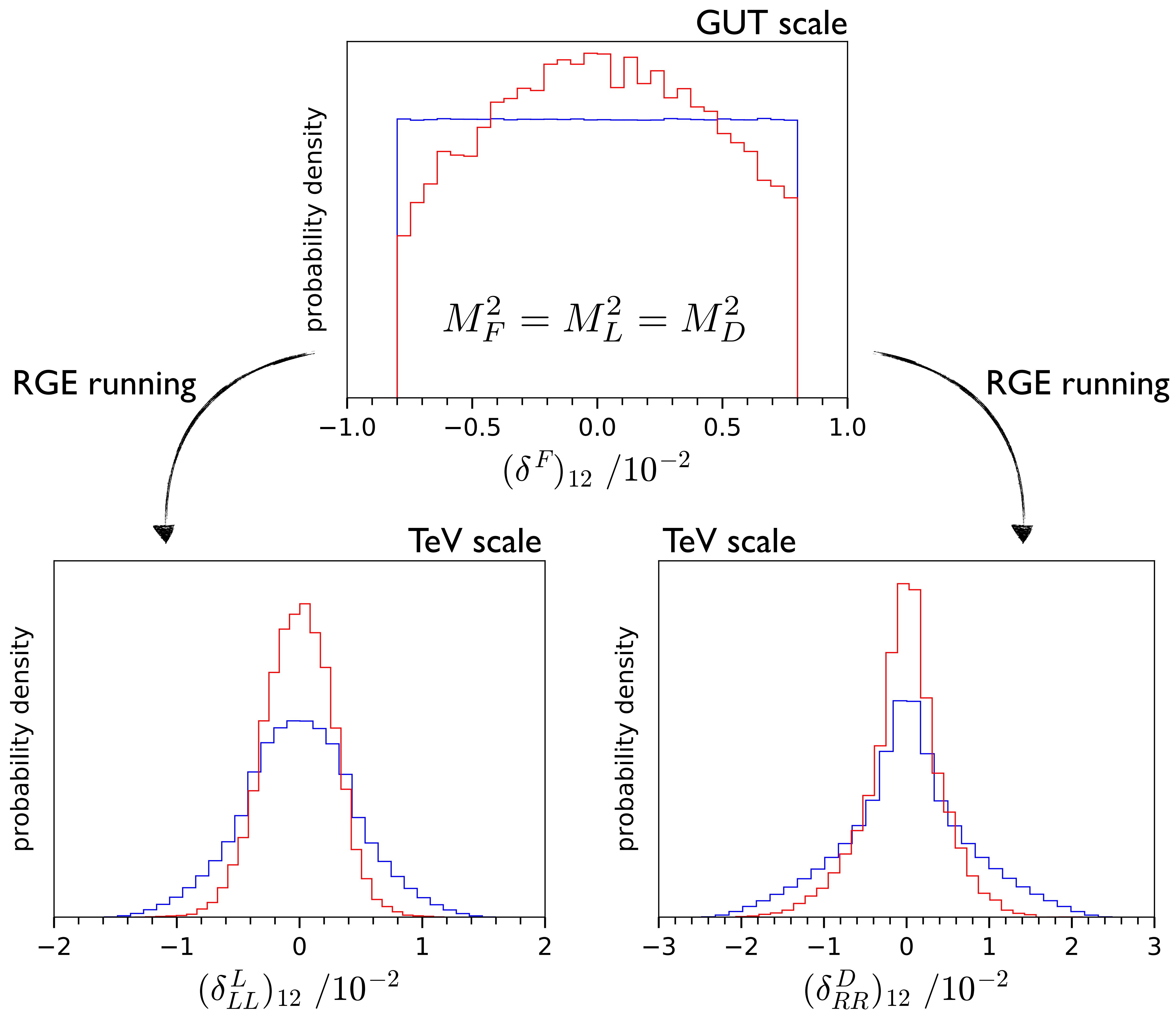




Part IV

Conclusions and Outlook

Summary and perspectives: Supersymmetric models

Additional sources of flavour violation w.r.t. Yukawa matrices may be present in new physics models
— **Non-Minimal Flavour Violation** (NMFV) in the squark sector not related to CKM-matrix
Here: **Minimal Supersymmetric Standard Model** (MSSM) **with most general flavour mixing** (NMFV in the squark sector)

TeV-scale phenomenology

Experimental constraints (mostly related to flavour observables) leave room for **sizeable NMFV elements in the MSSM Lagrangian**

LHC **limits on squark masses are considerably weakened** when introducing squark flavour mixing

Dedicated search **for "mixed top-charm" final states** required to improve the situation

Multivariate analysis techniques seem interesting to identify the flavour structure of an observed squark

→ Understand treatment of **uncertainties in this framework…** Bernigaud, Herrmann *(future project)*

GUT-scale implementation

Study of ***SU(5)xA$_4$* framework** reveals interesting phenomenology…

→ **Pursue studies in a more complete framework, e.g. *SU(5)xA$_4$***

Bernigaud, Forster, Herrmann, King, Rowley *(ongoing work)*

Use flavour-related observables to test *SU(5)* hypothesis based on LHC observables…

Fichet, Herrmann, Stoll — JHEP 1505 (2015) 091

→ **Propose tests for arbitrary mass configurations** (Bayesian statistics, multivariate analysis,…?)

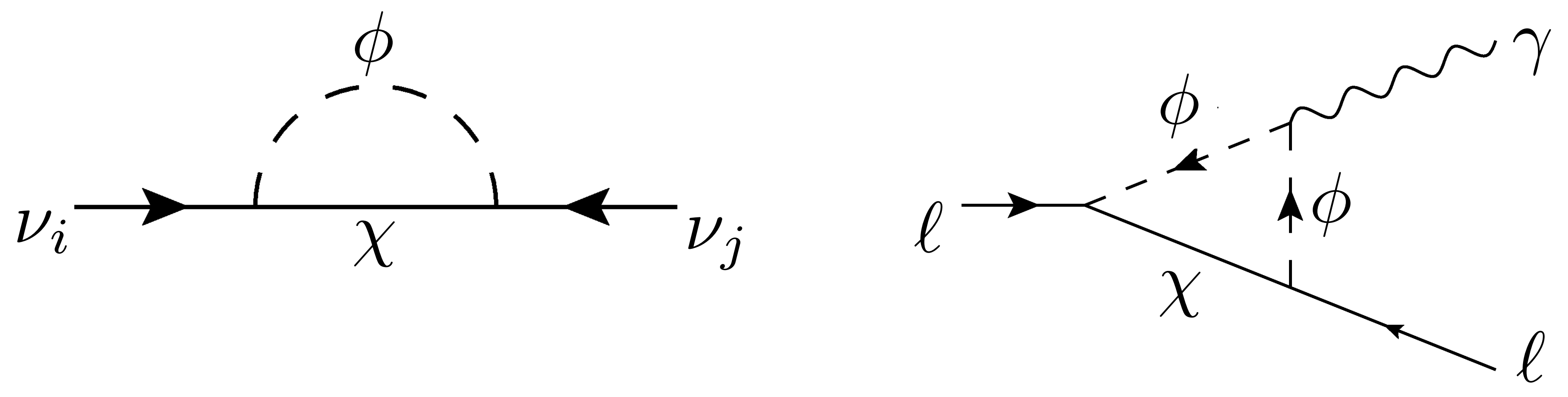
Fichet, Herrmann *(preliminary studies to be completed)*

Perspectives: Non-supersymmetric models — Lepton flavour violation

Lepton flavour violating decays experimentally more constraining than hadronic observables
Recent measurements (R_K and R_{K^*}) point towards **lepton flavour violation and non-universality**
Lepton flavour violation related to the generation of **neutrino masses** via the **PMNS matrix**

New physics effects on leptonic observables

Extend Standard Model by a number of fermions and scalars,
impose Z_2 symmetry to ensure stable dark matter candidate



Phenomenology of such classes of models

→ Interplay of lepton-flavour violation ($\ell \to \ell\gamma$, $\ell \to \ell\gamma\gamma$, $\ell \to 3\ell$) and dark matter

Herrmann, Klasen, Sarazin, Zeinstra *(future project)*

→ Differences w.r.t. to Seesaw mechanism

→ Constraints from anomalous magnetic moments (and more…)

Herrmann, Sarazin *(future projects)*


thank you
danke
謝謝
ngiyabonga
teşekkür ederim
спасибо
gracias
tapadh leat
mochchakkeram
bedankt
dziękuję
hvala
mauruuru
dank je
go raibh maith agat
obrigado
sukriya
kop khun krap
sağolun
arigatò
takk
dakujem
grazie
terima kasih
мерси
merci
감사합니다
ありがとう

Backup

The MSSM with *SU(5)xA4* unfication — Reference scenarios and scan boundaries

	Parameter/Observable	Scenario 1	Scenario 2
MFV Parameters at GUT scale	m_F	5000	5000
	m_{T_1}	5000	5000
	m_{T_2}	200	233.2
	m_{T_3}	2995	2995
	a_{33}^{TT}	-940	-940
	a_{33}^{FT}	-1966	-1966
	M_1	250.0	600.0
	M_2	415.2	415.2
	M_3	2551.6	2551.6
	M_{H_u}	4242.6	4242.6
	M_{H_d}	4242.6	4242.6
	$\tan\beta$	30	30
	μ	-2163.1	-2246.8

Parameters	Scenario 1	Scenario 2
$(\delta^T)_{12}$	$[-2.00, 2.00] \times 10^{-2}$	$[-5.57, 5.15] \times 10^{-2}$
$(\delta^T)_{13}$	$[-8.01, 8.01] \times 10^{-2}$	$[-0.267, 0.301]$
$(\delta^T)_{23}$	0.0	$[-5.73, 5.73] \times 10^{-2}$
$(\delta^F)_{12}$	$[-8.00, 8.00] \times 10^{-3}$	$[-8.00, 8.00] \times 10^{-3}$
$(\delta^F)_{13}$	$[-1.00, 1.00] \times 10^{-2}$	$[-8.00, 8.00] \times 10^{-2}$
$(\delta^F)_{23}$	$[-1.60, 1.60] \times 10^{-2}$	$[-8.00, 8.00] \times 10^{-2}$
$(\delta^{TT})_{12}$	$[-8.69, 10.43] \times 10^{-4}$	$[-7.46, 8.95] \times 10^{-4}$
$(\delta^{TT})_{13}$	$[-1.74, 1.74] \times 10^{-3}$	$[-3.48, 1.74] \times 10^{-3}$
$(\delta^{TT})_{23}$	$[-0.0174, 0.145]$	$[-0.0871, 0.124]$
$(\delta^{FT})_{12}$	$[-4.64, 4.64] \times 10^{-5}$	$[-5.47, 5.47] \times 10^{-5}$
$(\delta^{FT})_{13}$	$[-7.74, 7.74] \times 10^{-5}$	$[-3.87, 3.87] \times 10^{-4}$
$(\delta^{FT})_{21}$	0.0	$[-1.04, 1.04] \times 10^{-4}$
$(\delta^{FT})_{23}$	$[-1.16, 1.16] \times 10^{-4}$	$[-2.32, 2.32] \times 10^{-4}$
$(\delta^{FT})_{31}$	$[-1.39, 1.39] \times 10^{-5}$	$[-8.81, 8.81] \times 10^{-5}$
$(\delta^{FT})_{32}$	0.0	$[-1.49, 1.49] \times 10^{-4}$

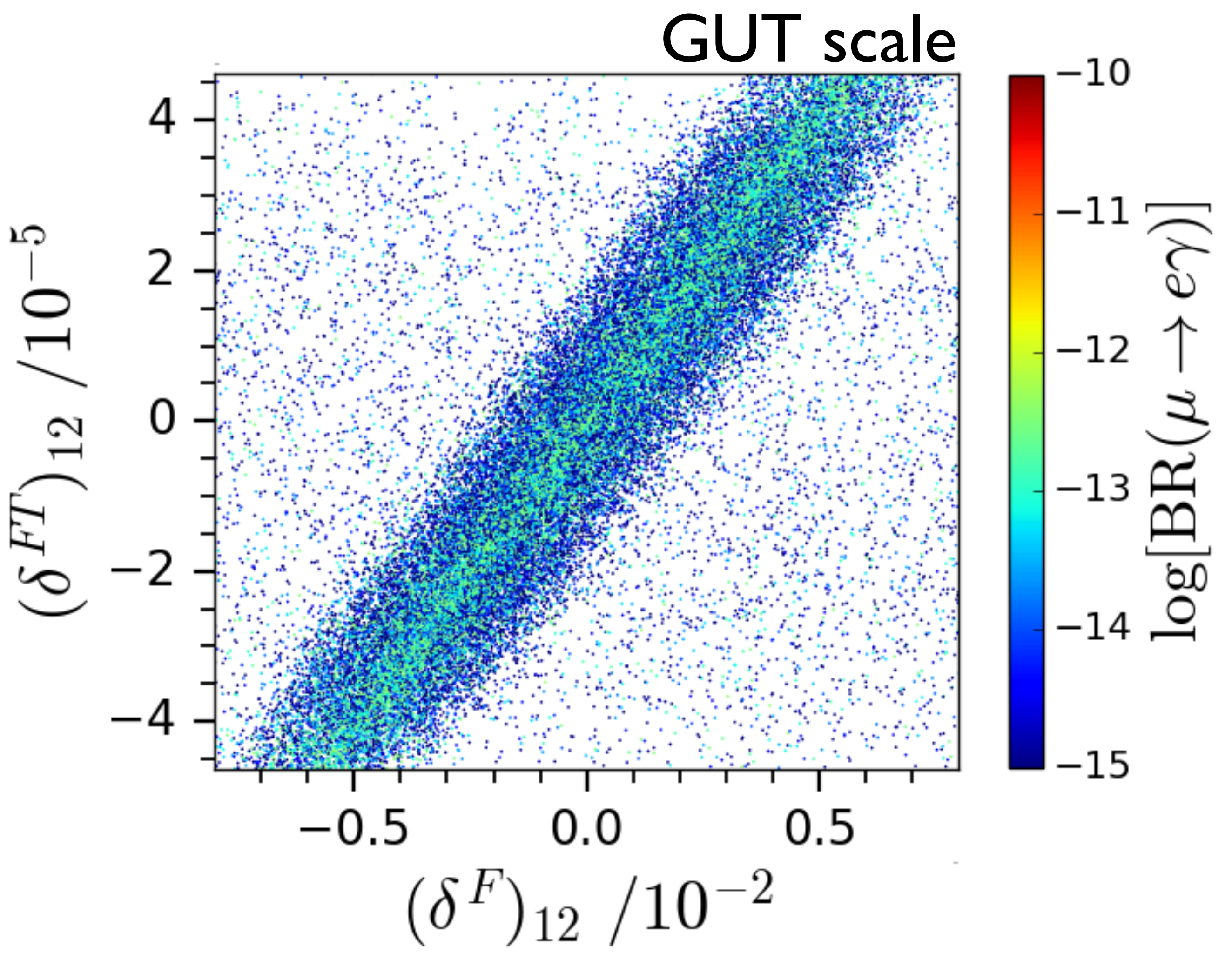
The MSSM with *SU(5)xA4* unification — Results overview

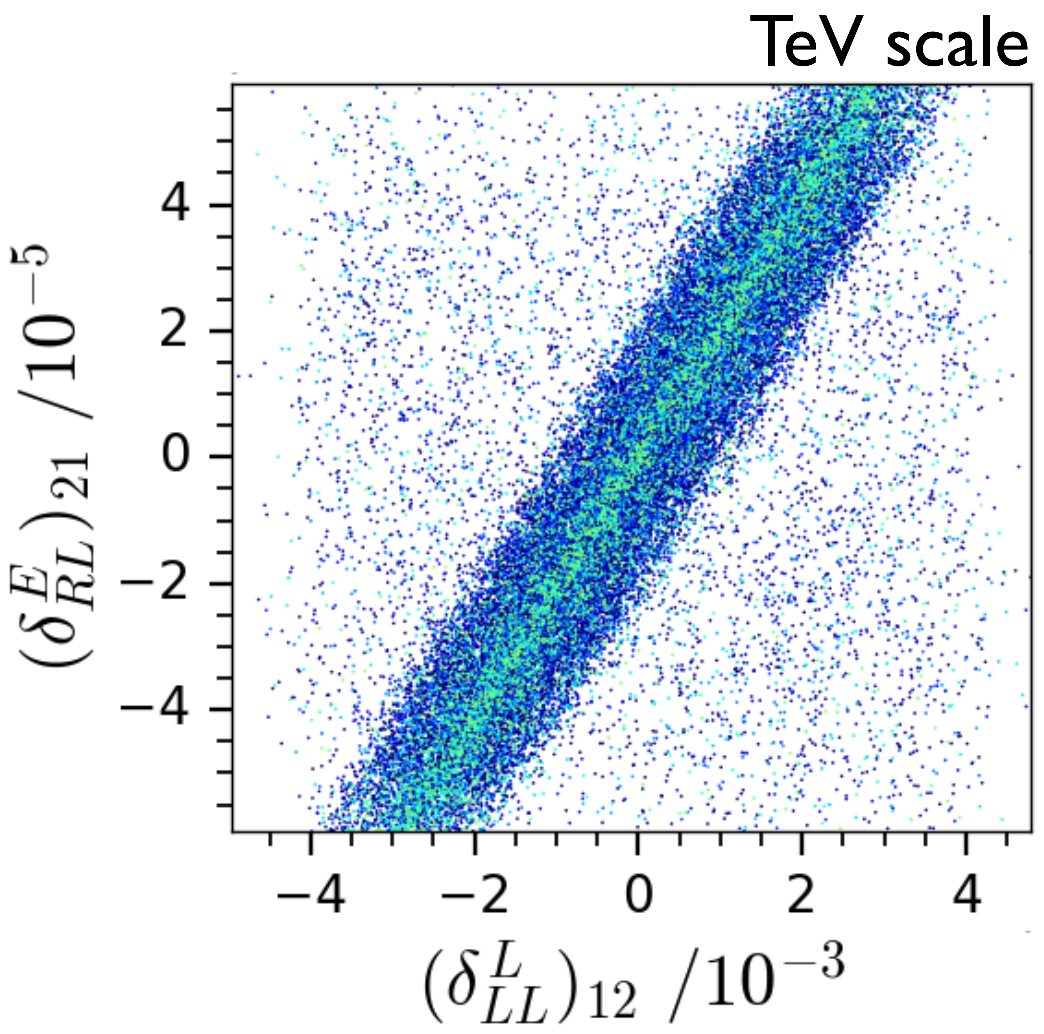
Parameters	Scenario 1	Most constraining obs. 1	Scenario 2	Most constraining obs. 2
$(\delta^T)_{12}$	[-0.015, 0.015]	$\mu \to 3e$, $\mu \to e\gamma$, $\Omega_{\tilde{\chi}^0_1}h^2$	[-0.12, 0.12]†	$\Omega_{\tilde{\chi}^0_1}h^2$, $\mu \to e\gamma$
$(\delta^T)_{13}$	]-0.06, 0.06[	$\Omega_{\tilde{\chi}^0_1}h^2$	[-0.3, 0.3]†	$\Omega_{\tilde{\chi}^0_1}h^2$
$(\delta^T)_{23}$	[0, 0]*	$\Omega_{\tilde{\chi}^0_1}h^2$, $\mu \to 3e$, $\mu \to e\gamma$	[-0.1, 0.1†]	$\Omega_{\tilde{\chi}^0_1}h^2$, $\mu \to 3e$, $\mu \to e\gamma$,
$(\delta^F)_{12}$	[-0.008, 0.008]	$\mu \to 3e$, $\mu \to e\gamma$	[-0.015, 0.015]†	$\mu \to 3e$, $\mu \to e\gamma$
$(\delta^F)_{13}$	]-0.01, 0.01[	$\mu \to e\gamma$	[-0.15, 0.15]†	$\mu \to 3e$, $\mu \to e\gamma$
$(\delta^F)_{23}$	]-0.015, 0.015[	$\mu \to e\gamma$, $\Omega_{\tilde{\chi}^0_1}h^2$	[-0.15, 0.15]†	$\Omega_{\tilde{\chi}^0_1}h^2$, $\mu \to e\gamma$, $\mu \to 3e$
$(\delta^{TT})_{12}$	[-3, 3.5] $\times 10^{-5}$	prior	[-1, 1.5]† $\times 10^{-3}$	prior, $\Omega_{\tilde{\chi}^0_1}h^2$
$(\delta^{TT})_{13}$	]-6, 7[$\times 10^{-5}$	prior, $\Omega_{\tilde{\chi}^0_1}h^2$	[-4, 2.5]† $\times 10^{-3}$	prior, $\Omega_{\tilde{\chi}^0_1}h^2$
$(\delta^{TT})_{23}$	]-0.5, 4[$\times 10^{-5}$	prior, $\Omega_{\tilde{\chi}^0_1}h^2$	[-0.25, 0.2]†	prior, $\Omega_{\tilde{\chi}^0_1}h^2$
$(\delta^{FT})_{12}$	[-0.0015, 0.0015]	$\Omega_{\tilde{\chi}^0_1}h^2$	[-1.2, 1.2]† $\times 10^{-4}$	$\mu \to 3e$, $\Omega_{\tilde{\chi}^0_1}h^2$, $\mu \to e\gamma$
$(\delta^{FT})_{13}$	]-0.002, 0.002[	$\Omega_{\tilde{\chi}^0_1}h^2$	[-5, 5] $\times 10^{-4}$	$\Omega_{\tilde{\chi}^0_1}h^2$, $\mu \to 3e$, $\mu \to e\gamma$
$(\delta^{FT})_{21}$	[0,0]*	prior	[-1.2, 1.2]† $\times 10^{-4}$	$\Omega_{\tilde{\chi}^0_1}h^2$, prior
$(\delta^{FT})_{23}$	]-0.0022, 0.0022[	$\Omega_{\tilde{\chi}^0_1}h^2$	[-6, 6]† $\times 10^{-4}$	$\mu \to 3e$, $\Omega_{\tilde{\chi}^0_1}h^2$, $\mu \to e\gamma$
$(\delta^{FT})_{31}$	]-0.0004, 0.0004[	$\Omega_{\tilde{\chi}^0_1}h^2$	[-2, 2]† $\times 10^{-4}$	$\Omega_{\tilde{\chi}^0_1}h^2$
$(\delta^{FT})_{32}$	[0,0]*	prior	[-1.5, 1.5] $\times 10^{-4}$	$\Omega_{\tilde{\chi}^0_1}h^2$

* parameter not varied

† extrapolated range

The MSSM with *SU(5)xA4* unification — constraints





$$\mathrm{BR}(\mu\to e\gamma) < 4.2\times 10^{-13}$$
$$\mathrm{BR}(\mu\to 3e) < 1.0\times 10^{-12}$$

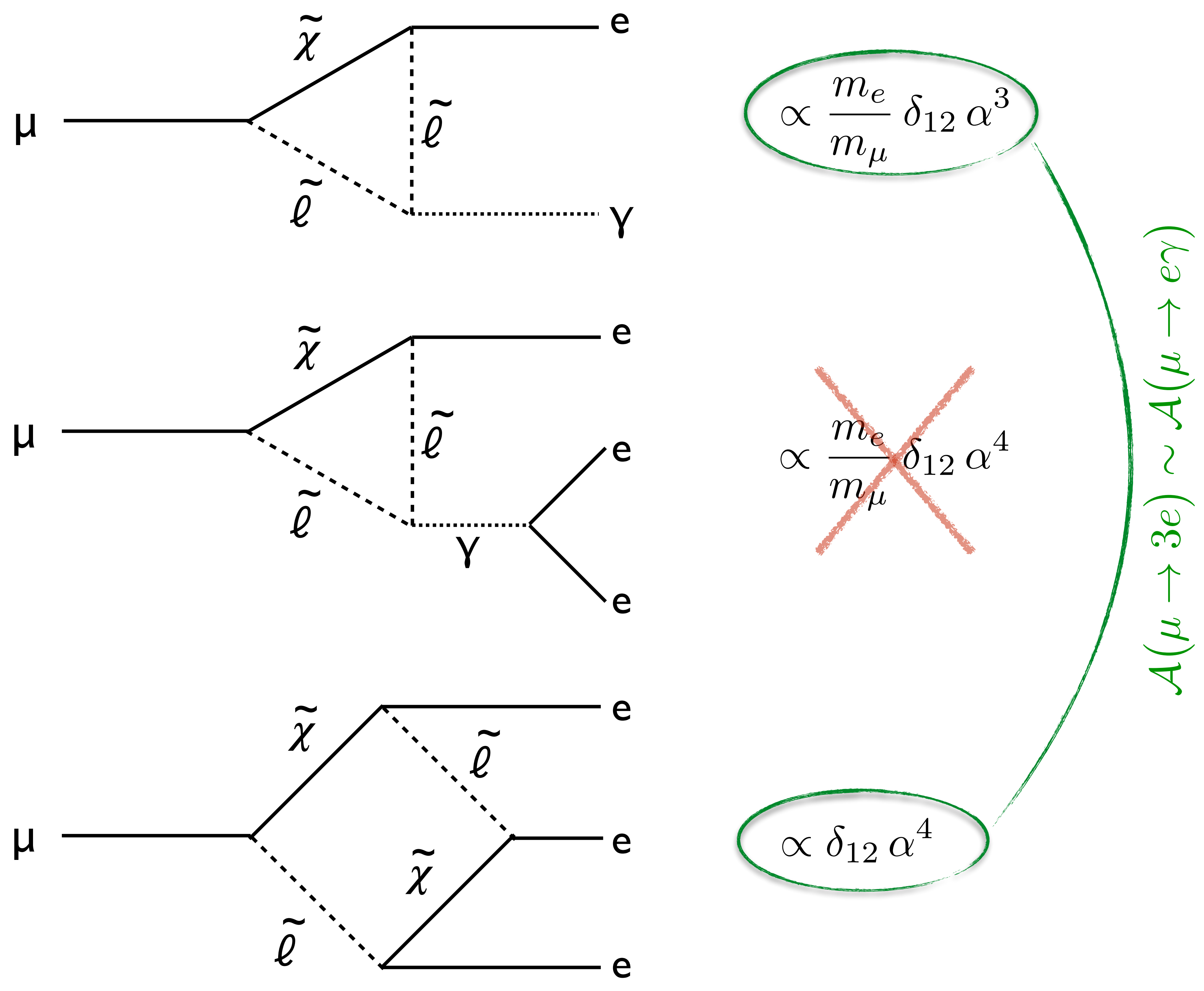
???

$(\delta^F)_{12}$	$\mu\to 3e,\ \mu\to e\gamma$
$(\delta^F)_{13}$	$\mu\to 3e,\ \mu\to e\gamma$

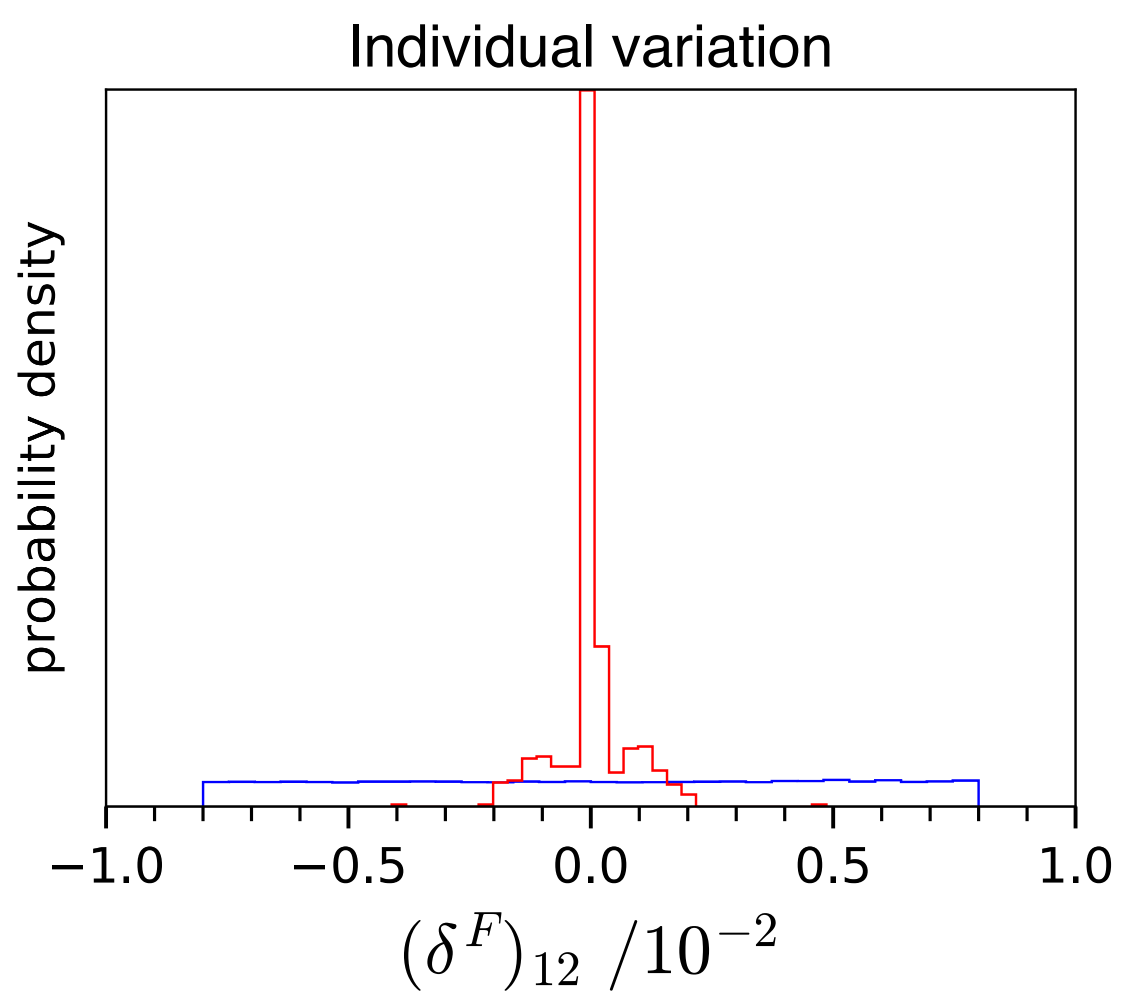
$$\mathrm{BR}(\mu\to e\gamma) \propto \frac{\alpha}{G_F}\Big(|A_L|^2+|A_R|^2\Big)$$

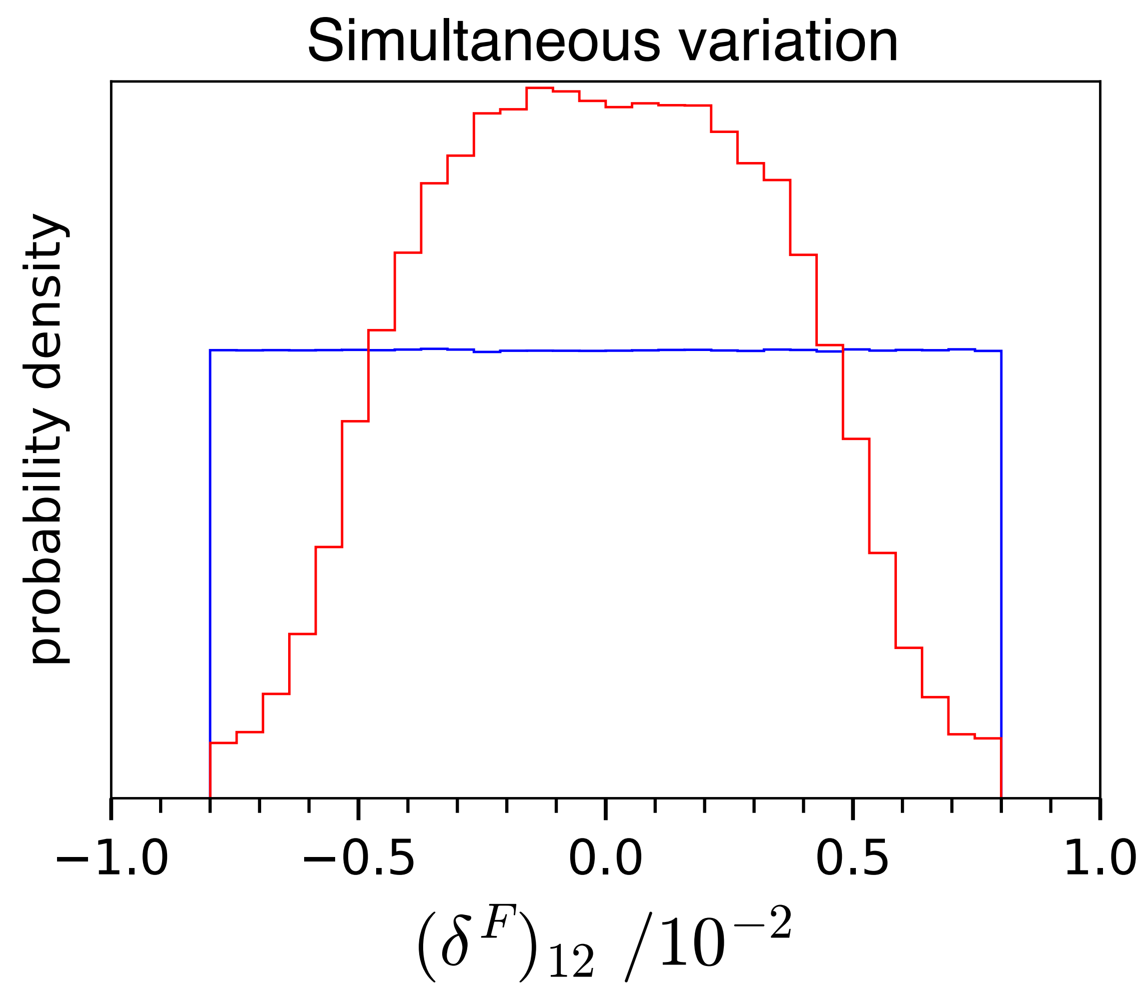
$$A_L = C_1(\delta^L_{LL})_{12} + C_2(\delta^E_{RL})_{12}$$
$$A_R = C_3(\delta^L_{RR})_{12} + C_4(\delta^E_{RL})_{12}$$

$$\Longrightarrow\quad (\delta^L_{LL})_{12} = \frac{2C_2}{C_1}(\delta^E_{RL})_{12}$$
$$(\delta^L_{RR})_{12} = \frac{2C_4}{C_3}(\delta^E_{RL})_{12}$$



The MSSM with *SU(5)xA4* unification — constraints





Soft SUSY Breaking Grand Unification: Leptons vs Quarks on the Flavor Playground

M. Ciuchini,[1] A. Masiero,[2] P. Paradisi,[3,4,5] L. Silvestrini,[6] S. K. Vempati,[7,8] and O. Vives[4]

Nucl. Phys. B 783 (2007) 112-142 — arXiv:hep-ph/0702144

Bounds on leptonic mass

Type of δ^l_{12}	$\mu \to e\,\gamma$	$\mu \to e\,e\,e$	$\mu \to e$ conversion in Ti
LL	6×10^{-4}	2×10^{-3}	2×10^{-3}
RR	-	0.09	-
LR/RL	1×10^{-5}	3.5×10^{-5}	3.5×10^{-5}

Type of δ^l_{13}	$\tau \to e\,\gamma$	$\tau \to e\,e\,e$	$\tau \to e\mu\mu$
LL	0.15	–	-
RR	-	-	-
LR/RL	0.04	0.5	-

Type of δ^l_{23}	$\tau \to \mu\,\gamma$	$\tau \to \mu\,\mu\,\mu$	$\tau \to \mu\,e\,e$
LL	0.12	-	-
RR	-	-	-
LR/RL	0.03	-	0.5

Bounds on hadronic mass

$ij\backslash AB$	LL	LR	RL	RR
12	1.4×10^{-2}	9.0×10^{-5}	9.0×10^{-5}	9.0×10^{-3}
13	9.0×10^{-2}	1.7×10^{-2}	1.7×10^{-2}	7.0×10^{-2}
23	1.6×10^{-1}	4.5×10^{-3}	6.0×10^{-3}	2.2×10^{-1}

Imposing *SU(5)* unification conditions, hadronic mass insertions supposed to be smaller than leptonic ones, e.g.

$$|(\delta^d_{ij})_{\rm RR}| \quad \leq \quad \frac{m_L^2}{m_{d^c}^2}|(\delta^l_{ij})_{\rm LL}|$$