Flavour violation in SUSY GUTs
SU(5)×A₄ case study

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Flavour violation in SUSY GUTs
$SU(5)\times A_4$ case study

Flavour in the MSSM

Flavoured Grand Unification

$SU(5)\times A_4$ case study

Summary and perspectives

based mainly on work in collaboration with
Jordan Bernigaud, Stephen F. King, Samuel J. Rowley
to be published — arXiv:1812.01xyz

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	$1/2$	$(\tilde{H}_u^+ \;\; \tilde{H}_u^0)$	Higgsinos
	$(H_d^0 \;\; H_d^-)$	0	H_d	$1/2$	$(\tilde{H}_d^0 \;\; \tilde{H}_d^-)$	
W bosons	$W^0, W^\pm$	1		$1/2$	$\tilde{W}^0, \tilde{W}^\pm$	Winos
B boson	B^0	1		$1/2$	$\tilde{B}^0$	Bino
Gluon	g	1		$1/2$	$\tilde{g}$	Gluino
Graviton	G	2		$3/2$	$\tilde{G}$	Gravitino

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	$e_R^\dagger$	$1/2$	$\bar{e}$	0	$\tilde{e}_R^*$	
Higgs	$(H_u^+ \quad H_u^0)$	0	H_u			
	$(H_d^0 \quad H_d^-)$	0	H_d	$1/2$	$\tilde{\chi}^0_{1,2,3,4}$	Neutralinos
W bosons	$W^0, W^\pm$	1		$1/2$	$\tilde{\chi}^\pm_{1,2}$	Charginos
B boson	B^0	1				
Gluon	g	1		$1/2$	$\tilde{g}$	Gluino
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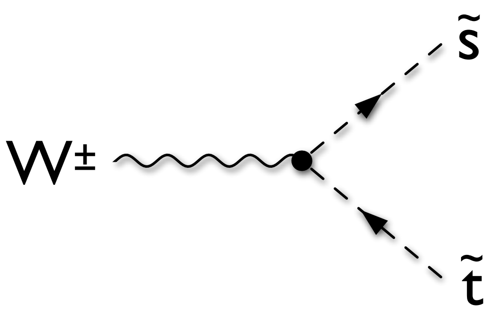
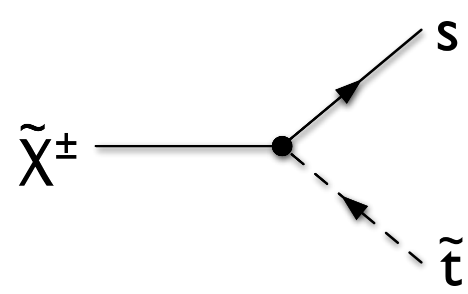
Flavour structure in the MSSM

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



$\propto V_{ts}$



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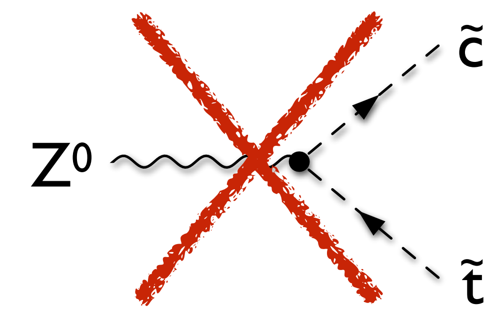

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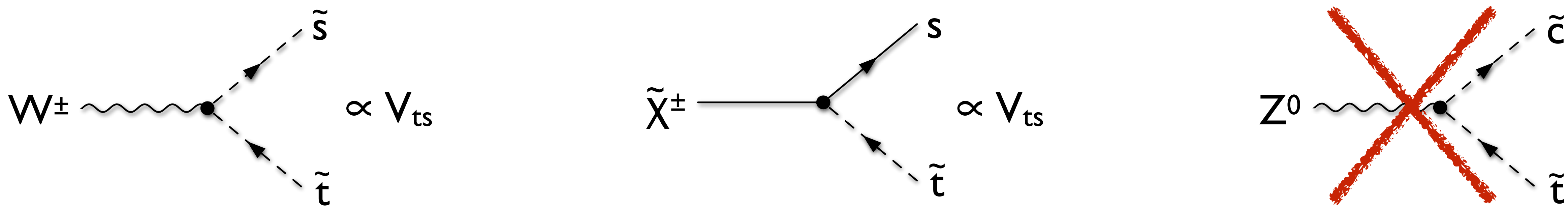
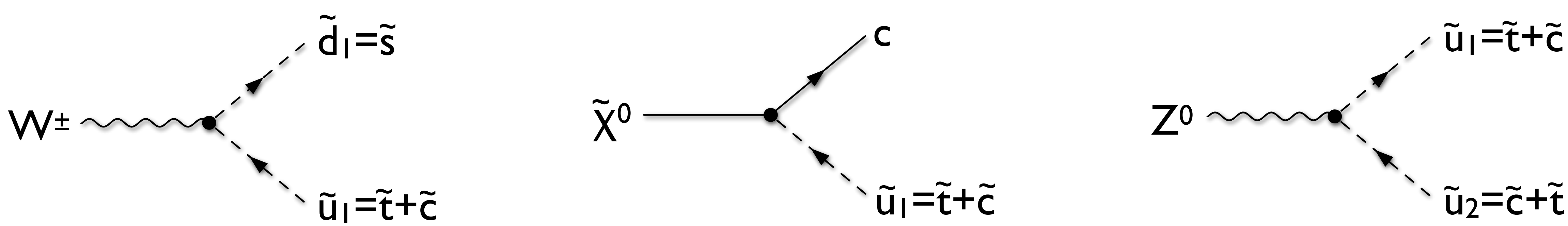


Allow for **new sources** of flavour violation: corresponding interactions not related to CKM/PMNS-matrices any more — **non-minimal flavour violation** (NMFV)



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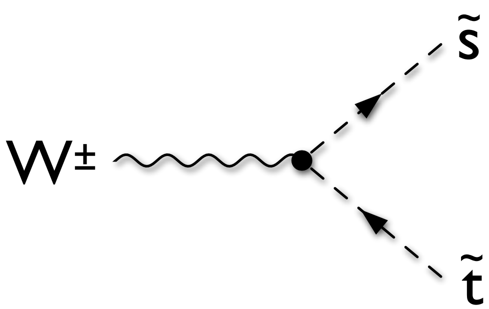
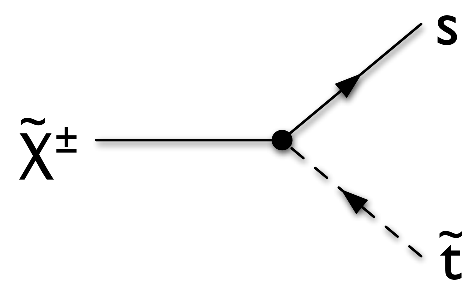


$\propto V_{ts}$



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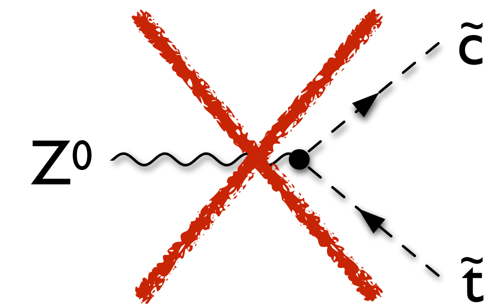

MFV vs. NMFV…?

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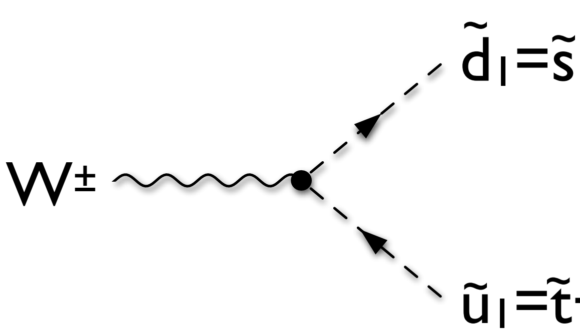

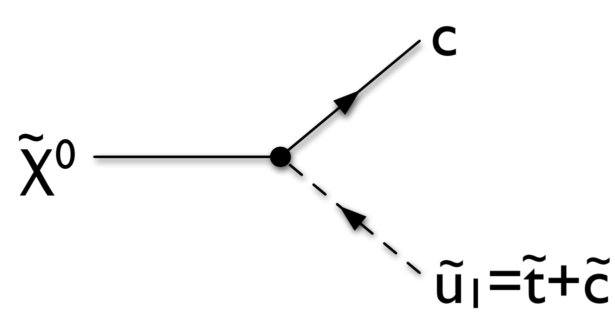

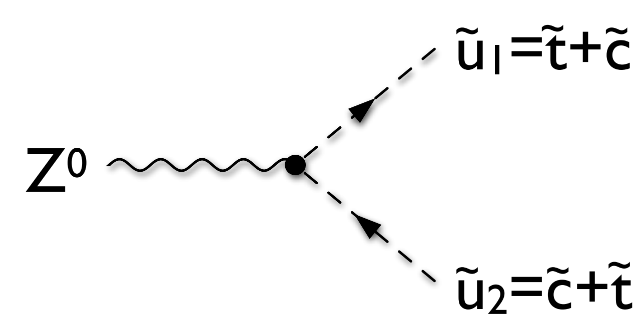

Sfermion sector in the MSSM

In the super-CKM basis, the sfermion sector is parametrized by four mass matrices:

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

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

$$\mathcal{M}^2_{\tilde{\ell}} = \begin{pmatrix} M^2_{\tilde{L}} + m_e^2 + D_{\tilde{\ell},L} & \frac{v_d}{\sqrt{2}} T_e - m_e \mu \tan\beta \\ \frac{v_d}{\sqrt{2}} T_e - m_e \mu^* \tan\beta & M^2_{\tilde{E}} + m_e^2 + D_{\tilde{\ell},R} \end{pmatrix}$$

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5 independent mass matrices and 3 trilinear coupling matrices

$$M^2_{\tilde{Q}}\,,\ M^2_{\tilde{U}}\,,\ M^2_{\tilde{D}}\,,\ M^2_{\tilde{L}}\,,\ M^2_{\tilde{E}} \qquad T_u\,,\ T_d\,,\ T_e$$

(3x3 matrices in flavour space — 48 independent parameters)

Sfermion sector in the MSSM

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

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

$$(\delta^D_{RR})_{ij} = \frac{(M^2_{\tilde{D}})_{ij}}{(M_{\tilde{D}})_{ii}(M_{\tilde{D}})_{jj}} \qquad (\delta^D_{RL})_{ij} = \frac{v_d}{\sqrt{2}}\frac{(T_d)_{ij}}{(M_{\tilde{Q}})_{ii}(M_{\tilde{D}})_{jj}}$$

$$(\delta^L_{RR})_{ij} = \frac{(M^2_{\tilde{L}})_{ij}}{(M_{\tilde{L}})_{ii}(M_{\tilde{L}})_{jj}} \qquad (\delta^E_{RR})_{ij} = \frac{(M^2_{\tilde{E}})_{ij}}{(M_{\tilde{E}})_{ii}(M_{\tilde{E}})_{jj}} \qquad (\delta^E_{RL})_{ij} = \frac{v_d}{\sqrt{2}}\frac{(T_e)_{ij}}{(M_{\tilde{L}})_{ii}(M_{\tilde{E}})_{jj}}$$

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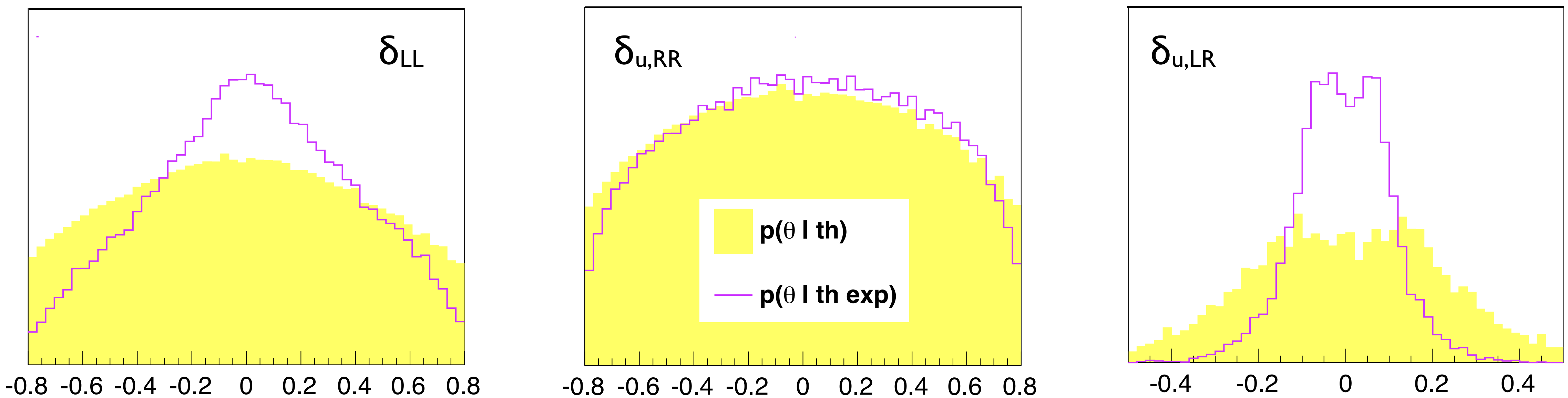
Mass eigenstates are obtained via 6x6 rotation matrices (generalized "mixing angles"):

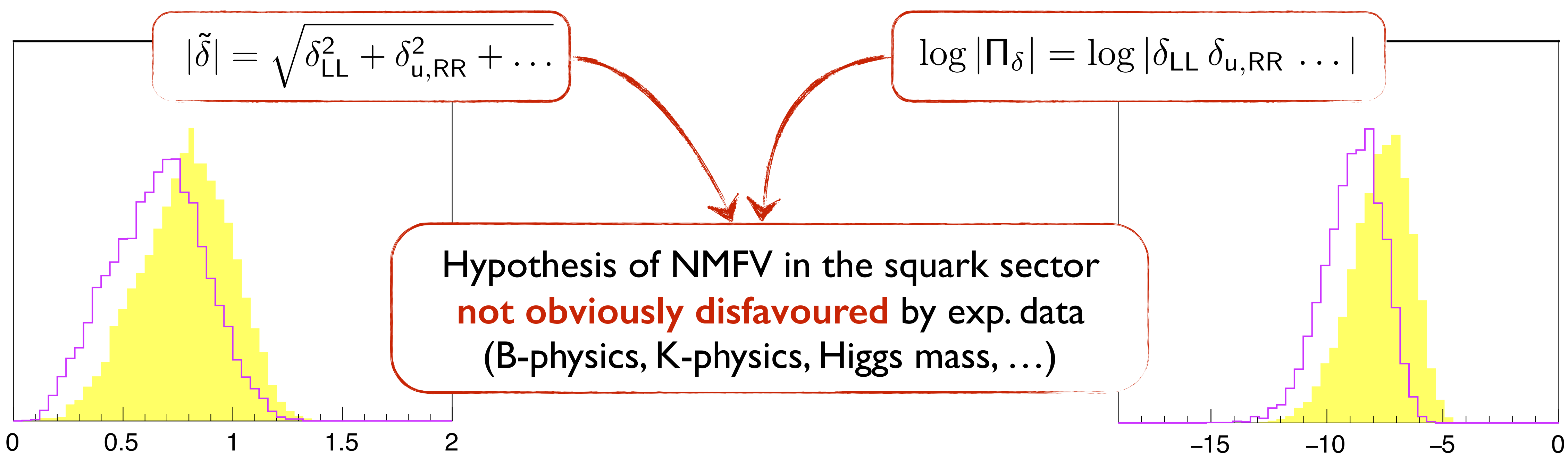
$$\mathrm{diag}\left(m^2_{\tilde{u}_1}, m^2_{\tilde{u}_2}, \dots, m^2_{\tilde{u}_6}\right) = \mathcal{R}_{\tilde{u}}\mathcal{M}^2_{\tilde{u}}\mathcal{R}^\dagger_{\tilde{u}} \qquad \mathrm{diag}\left(m^2_{\tilde{d}_1}, m^2_{\tilde{d}_2}, \dots, m^2_{\tilde{d}_6}\right) = \mathcal{R}_{\tilde{d}}\mathcal{M}^2_{\tilde{d}}\mathcal{R}^\dagger_{\tilde{d}}$$

$$\mathrm{diag}\left(m^2_{\tilde{\ell}_1}, m^2_{\tilde{\ell}_2}, \dots, m^2_{\tilde{\ell}_6}\right) = \mathcal{R}_{\tilde{\ell}}\mathcal{M}^2_{\tilde{\ell}}\mathcal{R}^\dagger_{\tilde{\ell}}$$

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**

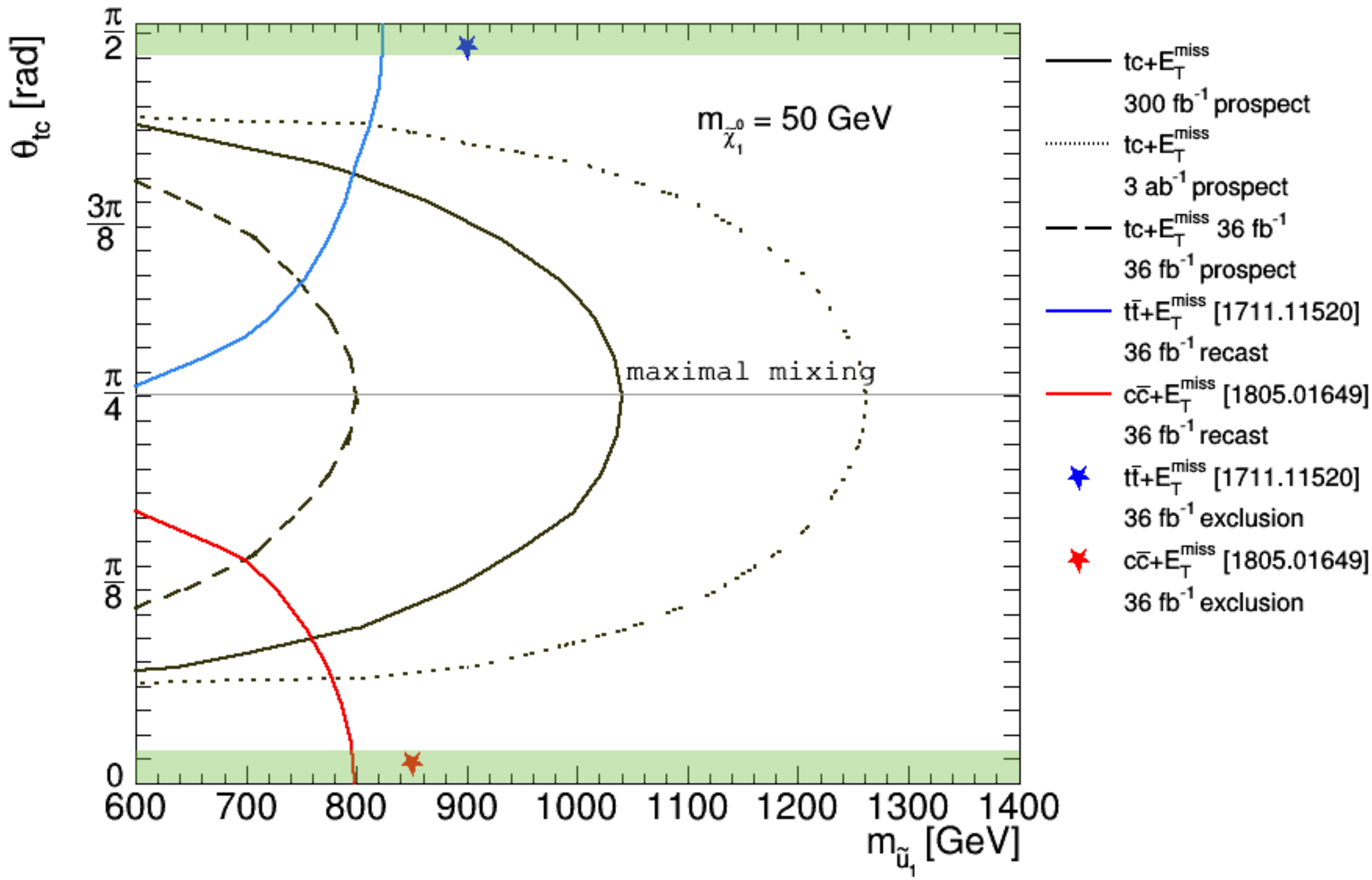




Hypothesis of NMFV in the squark sector **not obviously disfavoured** by exp. data (B-physics, K-physics, Higgs mass, …)

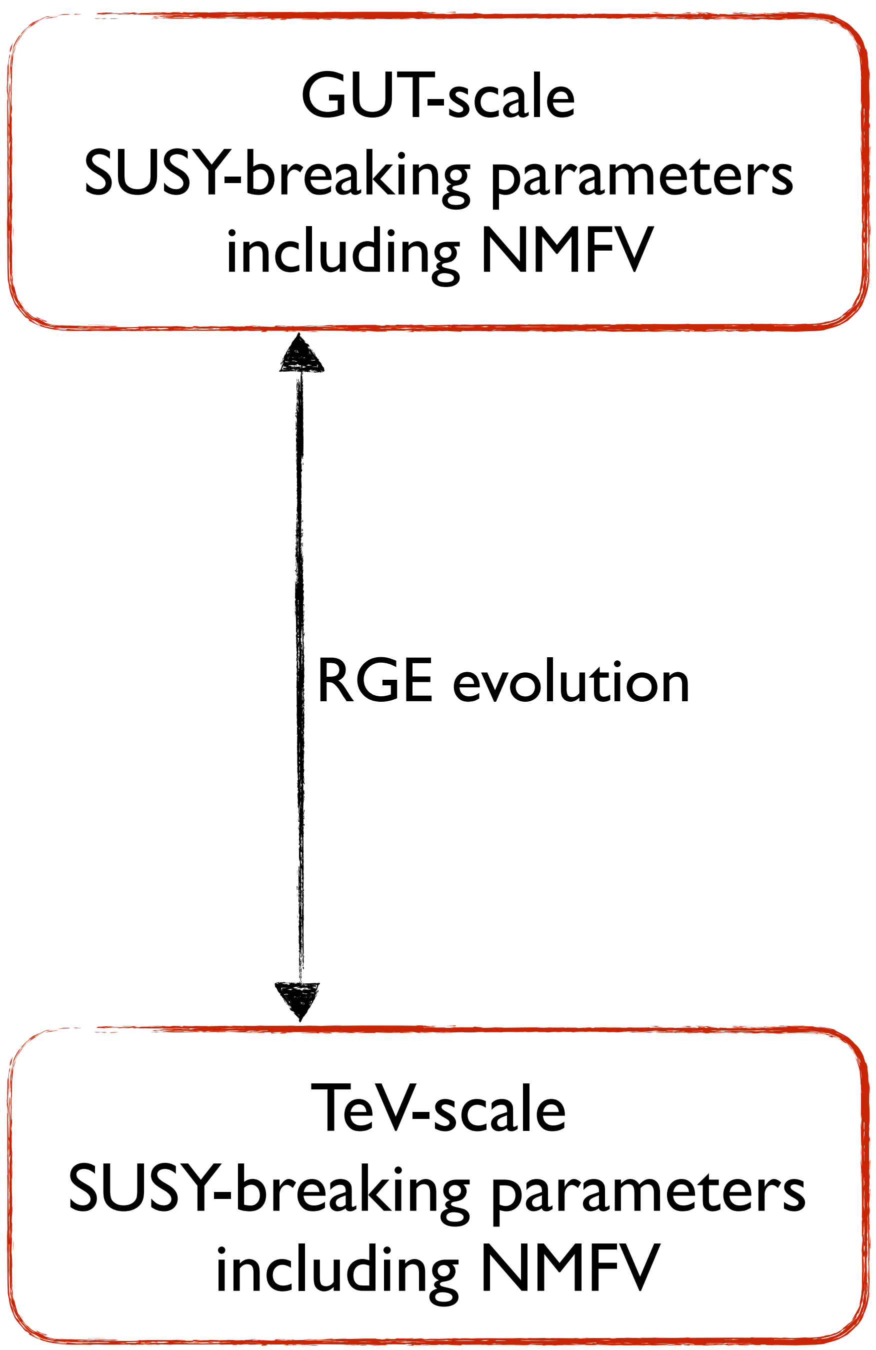
De Causmaecker, Fuks, Herrmann, Mahmoudi, O'Leary, Porod, Sekmen, Strobbe — JHEP 1511 (2015) 125 — arXiv:1509.05414 [hep-ph]

LHC squark mass limits and search proposal



Chakraborty, Endo, Fuks, Herrmann, Nojiri, Pani, Polesello — PhysTeV Les Houches 2017 — arXiv:1803.10379 [hep-ph]
Chakraborty, Endo, Fuks, Herrmann, Nojiri, Pani, Polesello — Eur. Phys. J. C78 (2018) 10: 844 — arXiv:1808.07488 [hep-ph]

Implementation in a (flavoured) GUT framework



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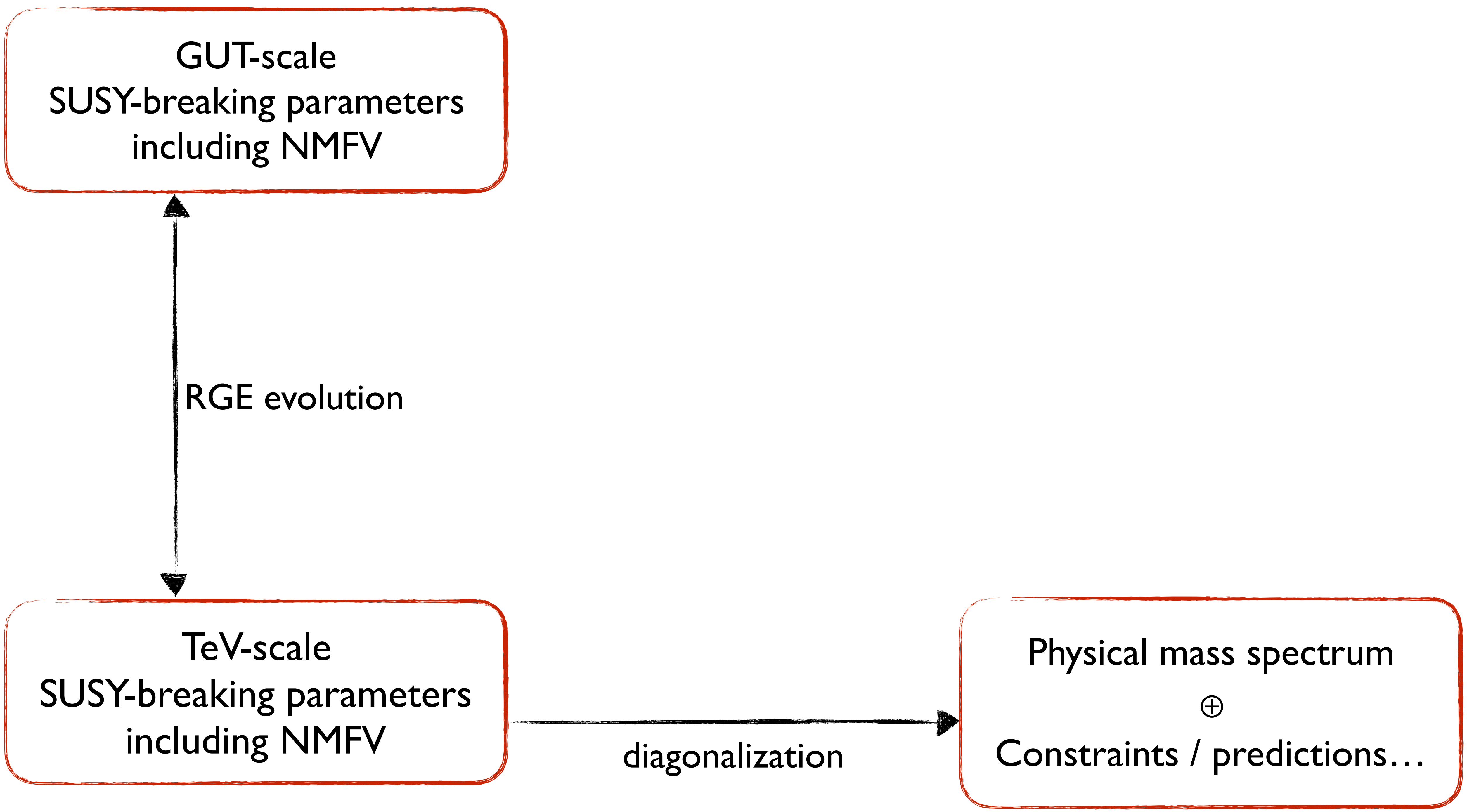

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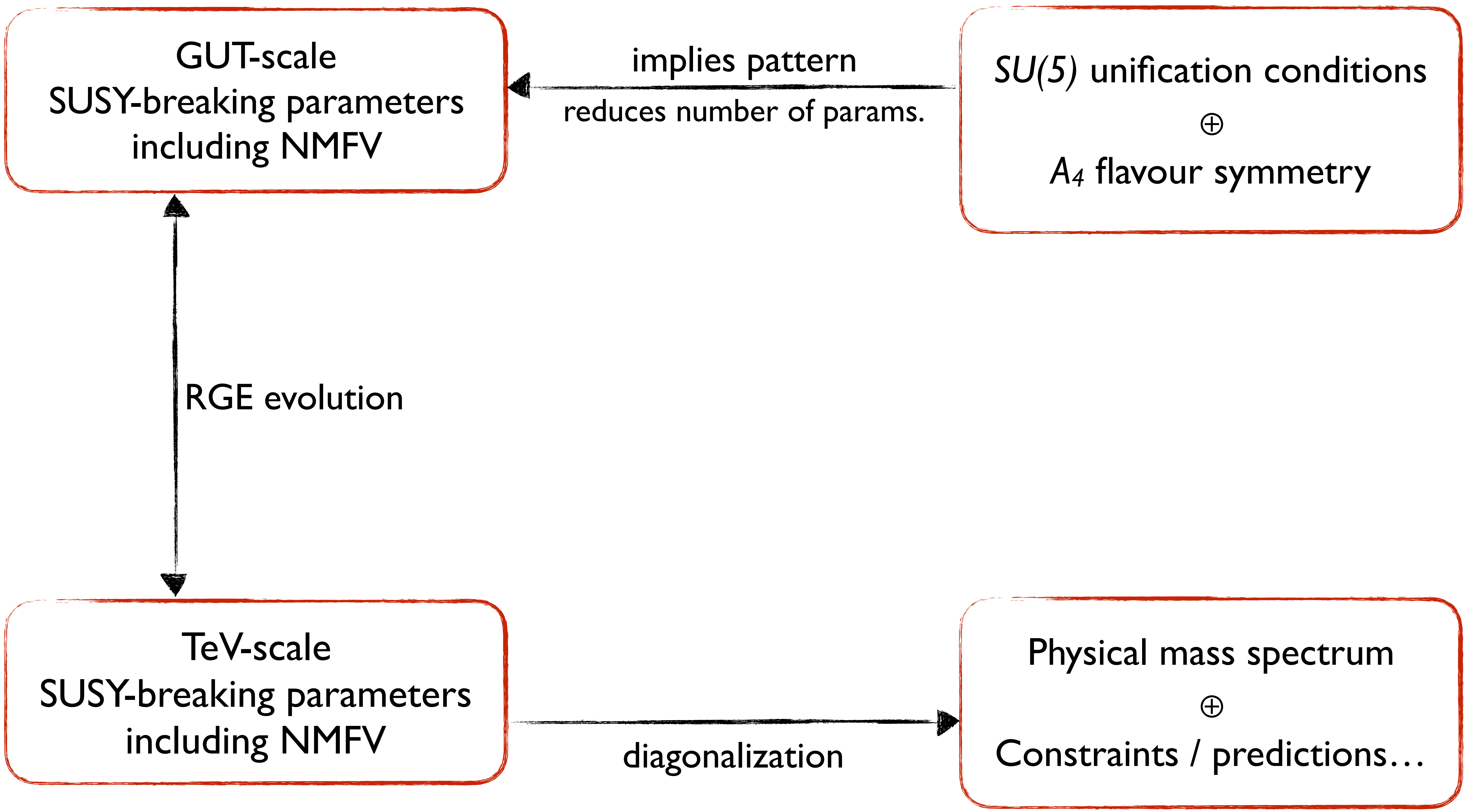

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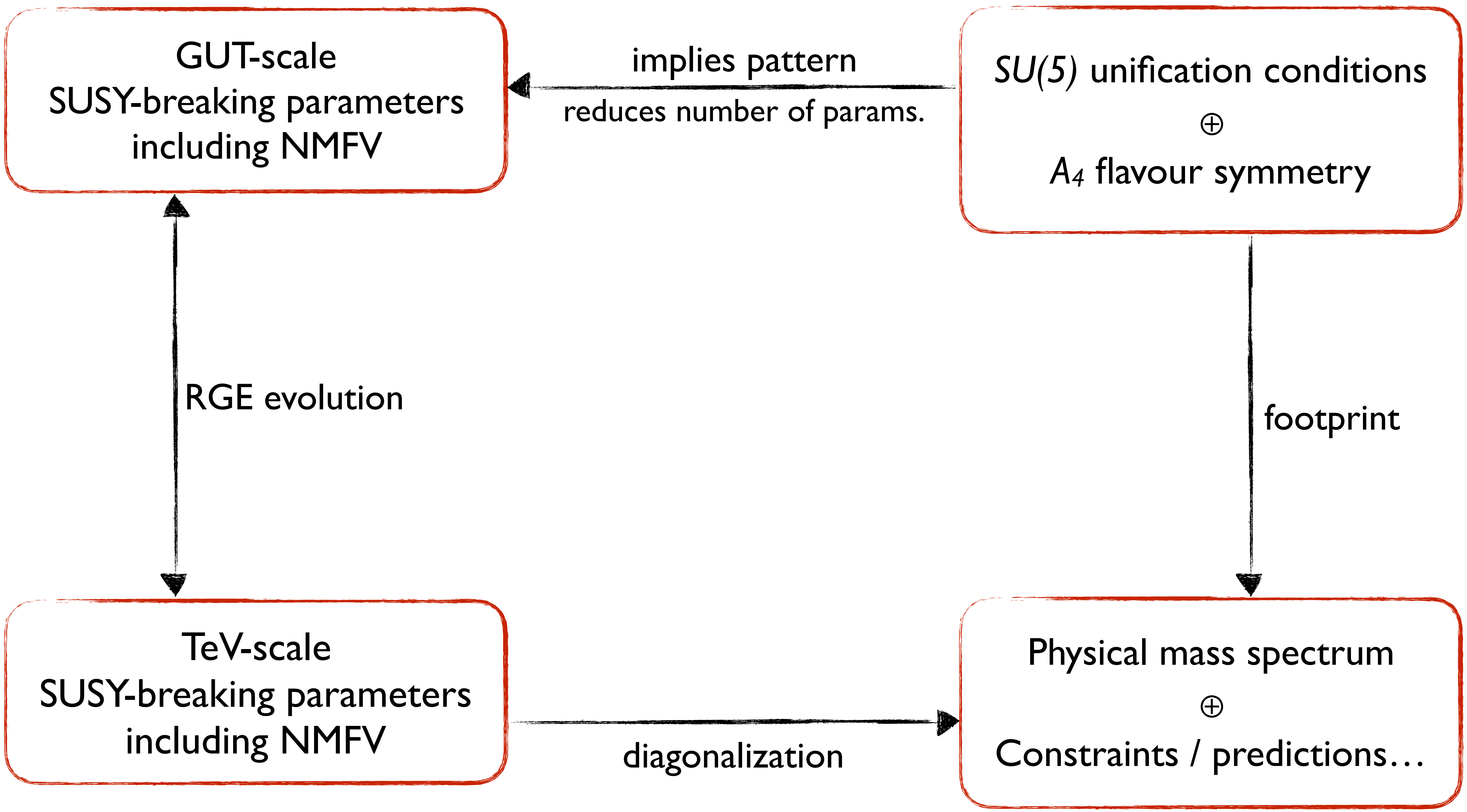

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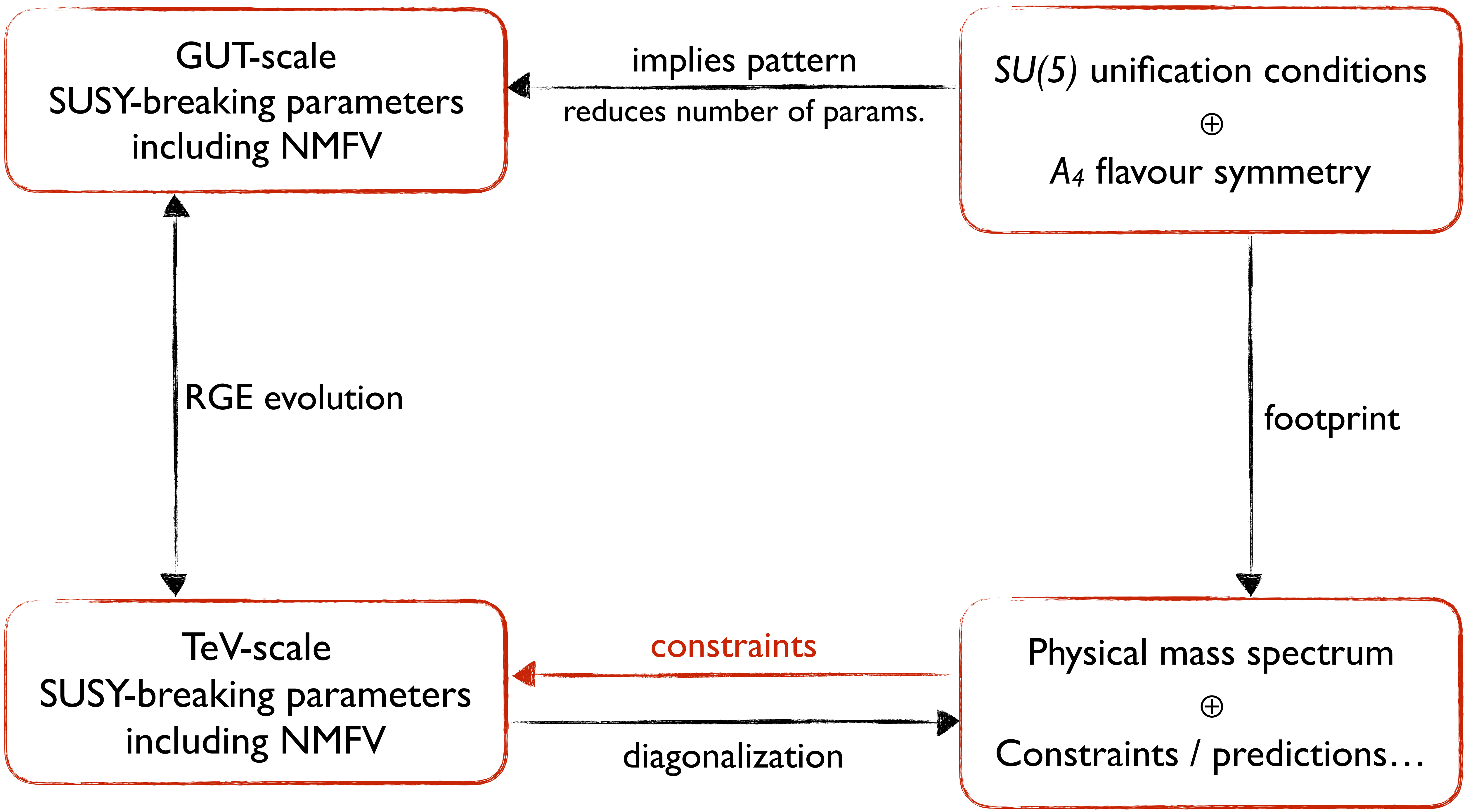

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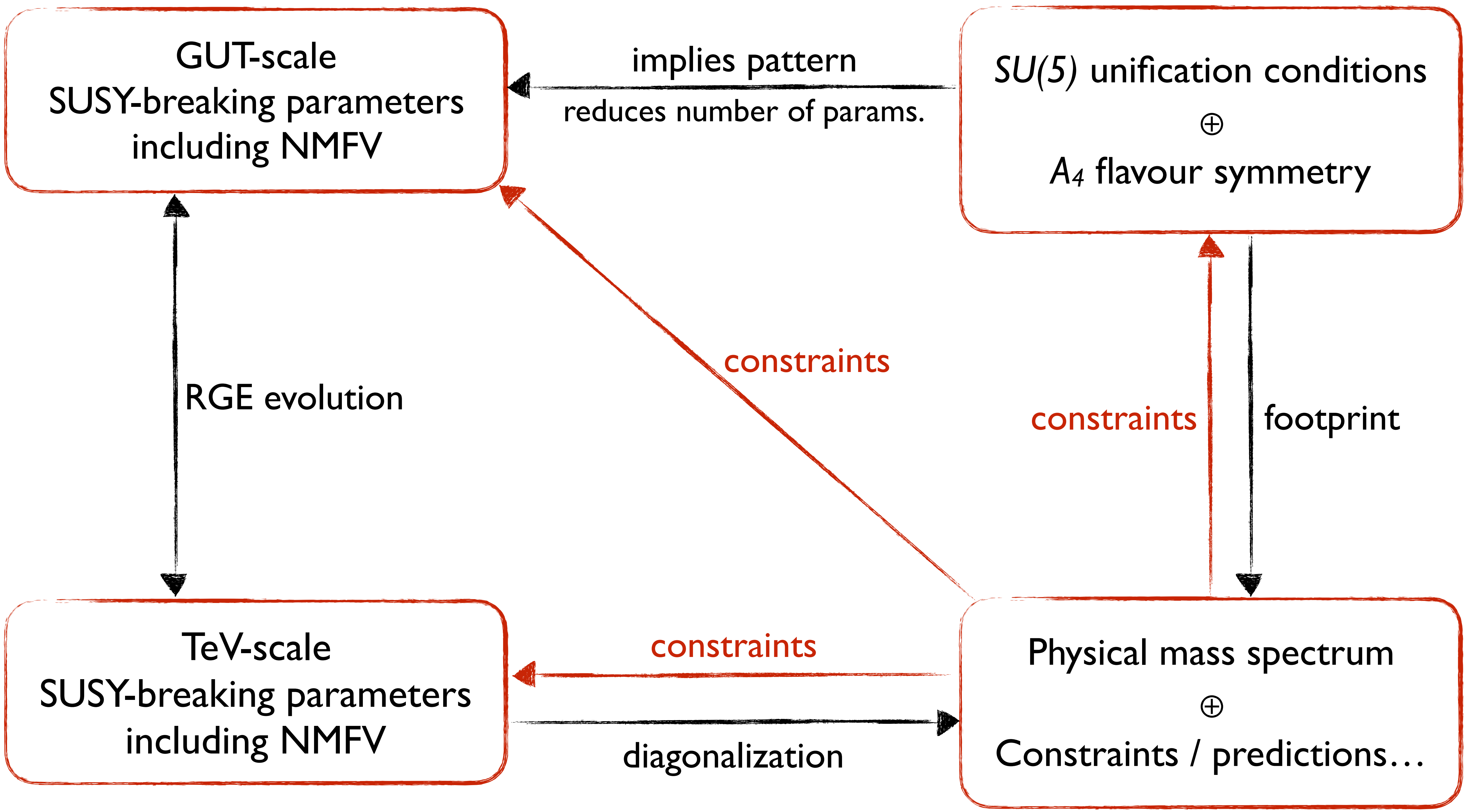

SU(5)-like Grand Unification

Standard-Model fields are neatly accommodated into the $\overline{\mathbf{5}}$ and **10** representations of *SU(5)*

$$F = \overline{\mathbf{5}} = \begin{pmatrix} d_r^c \\ d_b^c \\ d_g^c \\ e^- \\ -\nu_e \end{pmatrix}_L \qquad T = \mathbf{10} = \begin{pmatrix} 0 & u_g^c & -u_b^c & u_r & d_r \\ . & 0 & u_r^c & u_b & d_b \\ . & . & 0 & u_g & d_g \\ . & . & . & 0 & e^c \\ . & . & . & . & 0 \end{pmatrix}_L$$

The *SU(5)* gauge group may be broken into the Standard-Model gauge group according to

$$SU(5) \rightarrow SU(3)_C \times SU(2)_L \times U(1)_Y$$

$$\begin{aligned} \overline{\mathbf{5}} &= d^c(\overline{\mathbf{3}}, \mathbf{1}, 1/3) \oplus L(\mathbf{1}, \overline{\mathbf{2}}, -1/2)\,, \\ \mathbf{10} &= u^c(\overline{\mathbf{3}}, \mathbf{1}, -2/3) \oplus Q(\mathbf{3}, \mathbf{2}, 1/6) \oplus e^c(\mathbf{1}, \mathbf{1}, 1) \end{aligned}$$

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Extending to Supersymmetry, *SU(5)* symmetry provides the following relationships between soft terms at the Grand Unification scale:

$$\begin{aligned} M^2_{\tilde{D}} &= M^2_{\tilde{L}} \equiv M^2_F & \qquad A_d = A_e^t &\equiv A_{FT} \\ M^2_{\tilde{Q}} = M^2_{\tilde{U}} &= M^2_{\tilde{E}} \equiv M^2_T & A_u &\equiv A_{TT} \end{aligned}$$

Adding the A_4 flavour symmetry

Unify three families of $\bar{\mathbf{5}} = F = \left(d^c, L\right)$ into the triplet of A_4
while the three $\mathbf{10}_i = T_i = \left(Q, u^c, e^c\right)_i$ representations are singlets of A_4

$$M_F^2 = \begin{pmatrix} m_F^2 & 0 & 0 \\ 0 & m_F^2 & 0 \\ 0 & 0 & m_F^2 \end{pmatrix} \qquad M_T^2 = \begin{pmatrix} m_{T_1}^2 & 0 & 0 \\ 0 & m_{T_2}^2 & 0 \\ 0 & 0 & m_{T_3}^2 \end{pmatrix}$$

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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 — Phys. Rev. D 87 (2013) 096018 — arXiv:1301.6764 [hep-ph]
M. Dimou, S. F. King, C. Luhn — JHEP 1602 (2016) 118 — arXiv:1511.07886 [hep-ph]
M. Dimou, S. F. King, C. Luhn — Phys. Rev. D 93 (2016) 075026 — arXiv:1512.09063 [hep-ph]

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

Muon $g-2$ and dark matter suggest nonuniversal gaugino masses: $SU(5) \times A_4$ case study at the LHC

Alexander S. Belyaev,[1,2,*] Steve F. King,[1,†] and Patrick B. Schaefers[1,‡]

arXiv:1801.00514 [hep-ph]

$$a_\mu^{\rm exp} - a_\mu^{\rm SM} = (28.8 \pm 8.0) \cdot 10^{-10}$$

$$\Omega_{\rm CDM} h^2 \lesssim 0.1224$$

$$\sigma_{\rm DD}^{\rm SI} \lesssim 7.64 \cdot 10^{-11}\ {\rm pb}$$

$$m_h = (125.09 \pm 1.50)\ {\rm GeV}$$

$$\mathrm{BR}(b \to s\gamma) = (3.29 \pm 0.52) \cdot 10^{-4}$$

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specific MFV mass spectrum:

$$m_{\tilde\chi_1^0} \sim m_{\tilde\mu_R} \sim 100...200\ {\rm GeV}$$

all other states heavy (>3 TeV)

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

Muon $g-2$ and dark matter suggest nonuniversal gaugino masses: $SU(5)\times A_4$ case study at the LHC

Alexander S. Belyaev,[1,2,*] Steve F. King,[1,†] and Patrick B. Schaefers[1,‡]

arXiv:1801.00514 [hep-ph]

$$a_\mu^{\rm exp} - a_\mu^{\rm SM} = (28.8 \pm 8.0)\cdot 10^{-10}$$

$$\Omega_{\rm CDM} h^2 \lesssim 0.1224$$

$$\sigma_{\rm DD}^{\rm SI} \lesssim 7.64\cdot 10^{-11}\ {\rm pb}$$

$$m_h = (125.09 \pm 1.50)\ {\rm GeV}$$

$${\rm BR}(b\to s\gamma) = (3.29 \pm 0.52)\cdot 10^{-4}$$

$${\rm BR}(B_s\to \mu^+\mu^-) = 3.0^{+1.0}_{-0.9}\cdot 10^{-9}$$

specific MFV mass spectrum:

$m_{\tilde\chi_1^0} \sim m_{\tilde\mu_R} \sim 100 \ldots 200$ GeV

all other states heavy (>3 TeV)

What about NMFV effects in this setup…?

Sfermion sector in the MSSM — revisited

In the **super-CKM/PMNS basis**, the sfermion sector is parametrized by **four mass matrices**:

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

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

$$\mathcal{M}^2_{\tilde{\ell}} = \begin{pmatrix} M^2_{\tilde{L}} + m_e^2 + D_{\tilde{\ell},L} & \frac{v_d}{\sqrt{2}} T_e - m_e \mu \tan\beta \\ \frac{v_d}{\sqrt{2}} T_e - m_e \mu^* \tan\beta & M^2_{\tilde{E}} + m_e^2 + D_{\tilde{\ell},R} \end{pmatrix}$$

↓

5 independent mass matrices and 3 trilinear coupling matrices

$$M^2_{\tilde{Q}}\,,\ M^2_{\tilde{U}}\,,\ M^2_{\tilde{D}}\,,\ M^2_{\tilde{L}}\,,\ M^2_{\tilde{E}} \qquad T_u\,,\ T_d\,,\ T_e$$

(3x3 matrices in flavour space — 48 independent parameters)

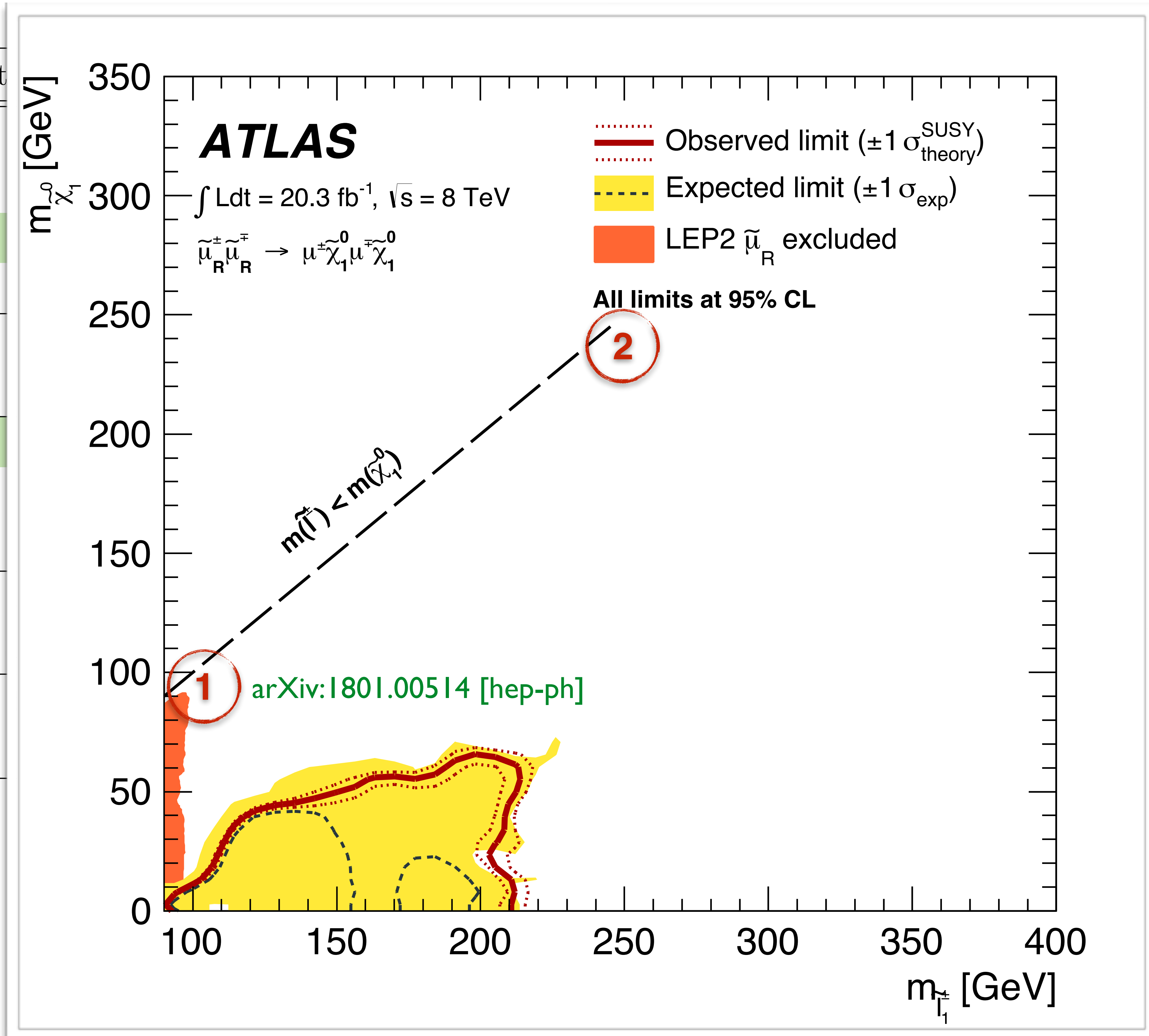
MFV Reference points

	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

	Parameter/Observable	Scenario 1	Scenario 2
Physical masses	m_h	126.7	127.3
	$m_{\tilde{g}}$	5570.5	5625.7
	$m_{\tilde{\mu}_L}$	4996.7	4997.5
	$m_{\tilde{\mu}_R}$	102.1	254.4
	$m_{\tilde{\chi}_1^0}$	94.6	250.4
	$m_{\tilde{\chi}_2^0}$	323.6	322.0
	$m_{\tilde{\chi}_3^0}$	2248.8	2331.1
	$m_{\tilde{\chi}_4^0}$	2248.8	2331.2
	$m_{\tilde{\chi}_1^\pm}$	323.8	322.2
	$m_{\tilde{\chi}_2^\pm}$	2249.8	2332.2

MFV Reference points

	Paramet…
MFV Parameters at GUT scale	



Scenario 2
127.3
5625.7
4997.5
254.4
250.4
322.0
2331.1
2331.2
322.2
2332.2

NMFV parameter study

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	$[-1.49, 1.49] \times 10^{-4}$

parameters at GUT scale

$$\left(\delta^T\right)_{ij} = \frac{\left(M_T^2\right)_{ij}}{\left(M_T\right)_{ii}\left(M_T\right)_{jj}}$$

$$\left(\delta^F\right)_{ij} = \frac{\left(M_F^2\right)_{ij}}{\left(M_F\right)_{ii}\left(M_F\right)_{jj}}$$

$$\left(\delta^{TT}\right)_{ij} = \frac{v_u}{\sqrt{2}} \frac{\left(T_u\right)_{ij}}{\left(M_T\right)_{ii}\left(M_T\right)_{jj}}$$

$$\left(\delta^{FT}\right)_{ij} = \frac{v_u}{\sqrt{2}} \frac{\left(T_d\right)_{ij}}{\left(M_T\right)_{ii}\left(M_F\right)_{jj}}$$

Experimental constraints

Observable	Constraint
m_h	(125.2 ± 2.5) GeV
$\mathrm{BR}(\mu \to e\gamma)$	$< 4.2 \times 10^{-13}$
$\mathrm{BR}(\mu \to 3e)$	$< 1.0 \times 10^{-12}$
$\mathrm{BR}(\tau \to e\gamma)$	$< 3.3 \times 10^{-8}$
$\mathrm{BR}(\tau \to \mu\gamma)$	$< 4.4 \times 10^{-8}$
$\mathrm{BR}(\tau \to 3e)$	$< 2.7 \times 10^{-8}$
$\mathrm{BR}(\tau \to 3\mu)$	$< 2.1 \times 10^{-8}$
$\mathrm{BR}(\tau \to e^-\mu\mu)$	$< 2.7 \times 10^{-8}$
$\mathrm{BR}(\tau \to e^+\mu\mu)$	$< 1.7 \times 10^{-8}$
$\mathrm{BR}(\tau \to \mu^- ee)$	$< 1.8 \times 10^{-8}$
$\mathrm{BR}(\tau \to \mu^+ ee)$	$< 1.5 \times 10^{-8}$
$\mathrm{BR}(B \to X_s\gamma)$	$(3.32 \pm 0.18) \times 10^{-4}$
$\mathrm{BR}(B_s \to \mu\mu)$	$(2.7 \pm 1.2) \times 10^{-9}$
ΔM_{B_s}	$(17.757 \pm 0.042 \pm 2.7)$ ps^{-1}
ΔM_K	$(3.1 \pm 1.2) \times 10^{-15}$ GeV
ϵ_K	2.228 ± 0.29
$\Omega_{\mathrm{CDM}} h^2$	0.1198 ± 0.0042

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$\mathrm{BR}(\tau \to e^-\mu\mu)$	$< 2.7 \times 10^{-8}$
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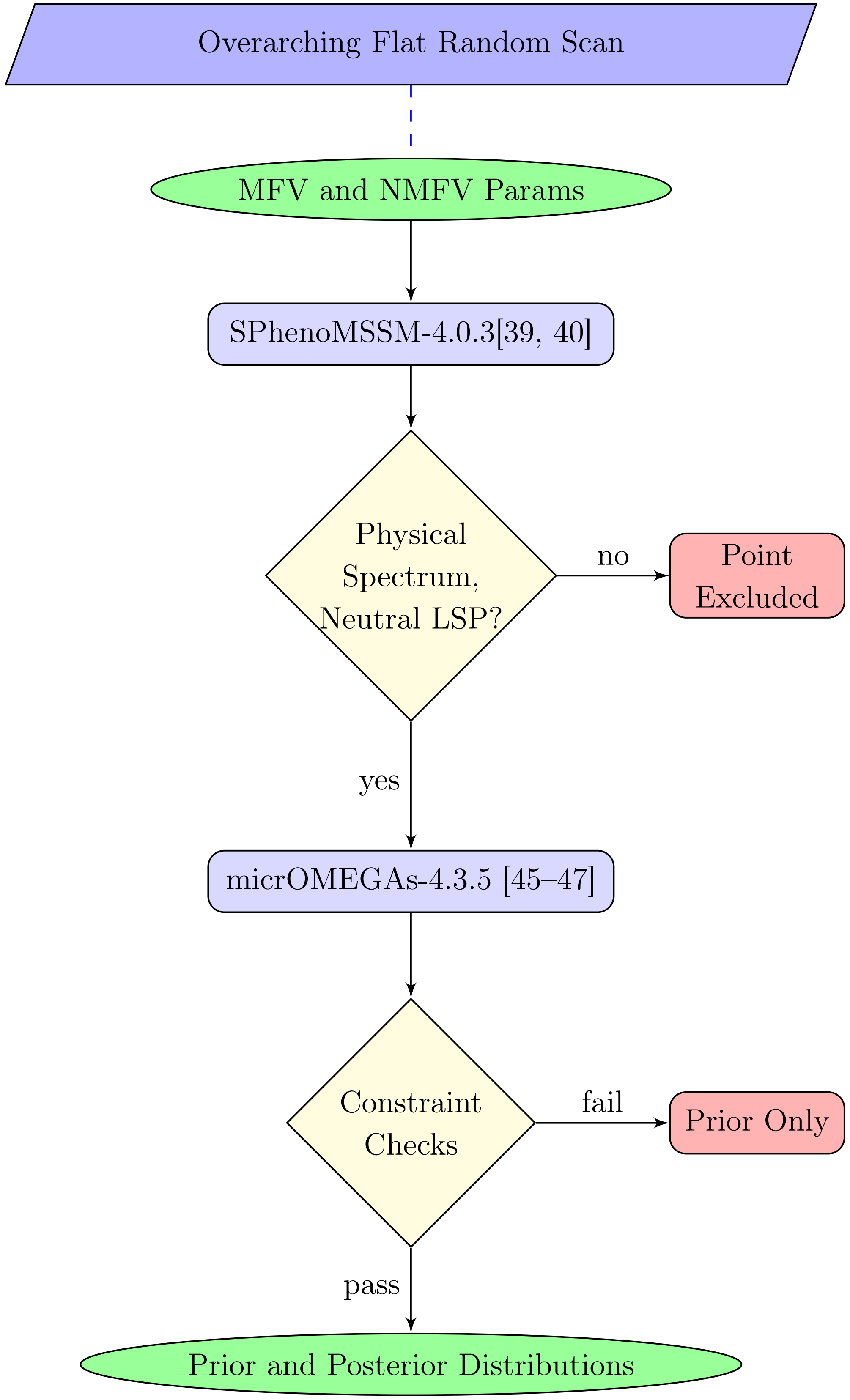


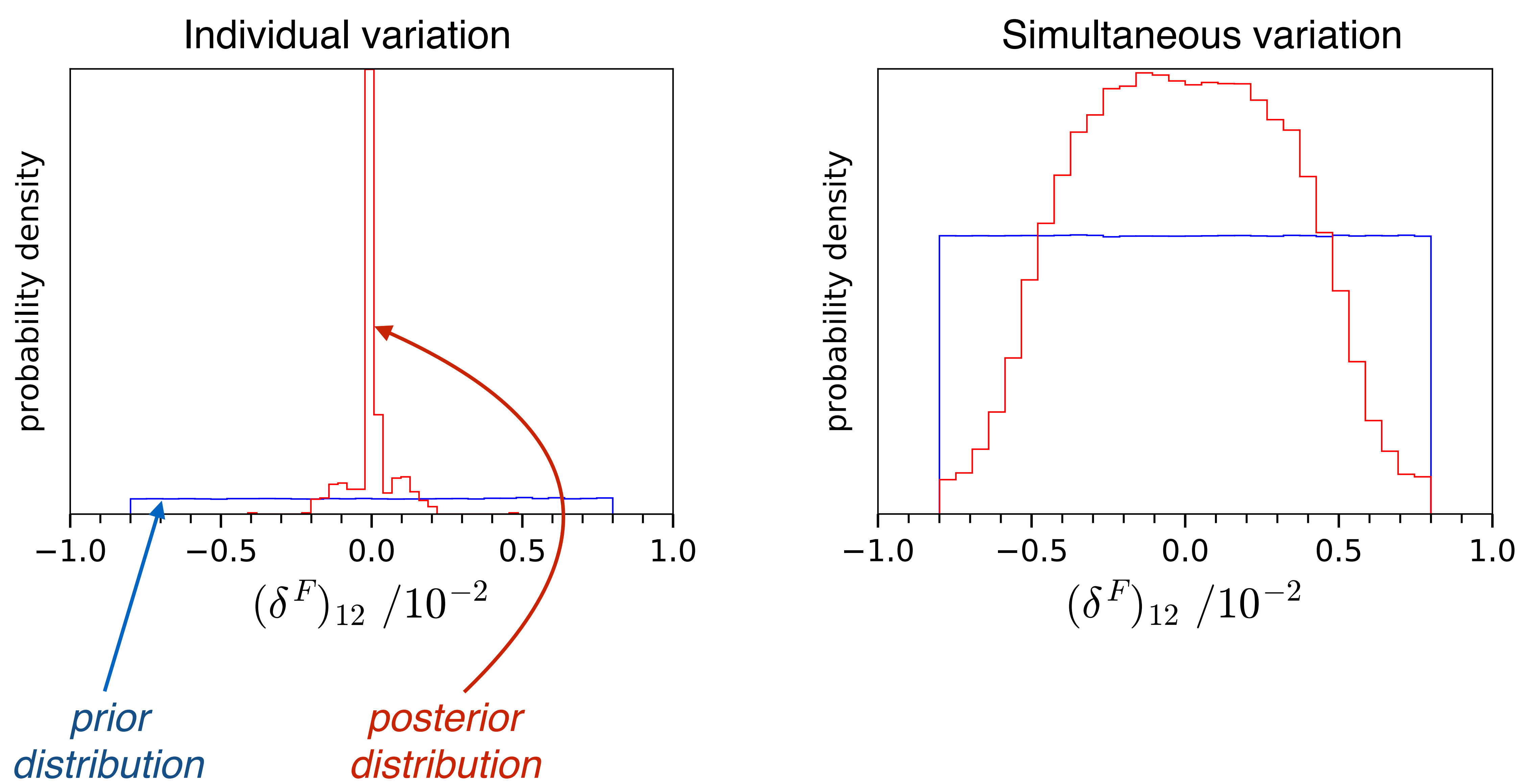
Results — Overview

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

* parameter not varied

† extrapolated range

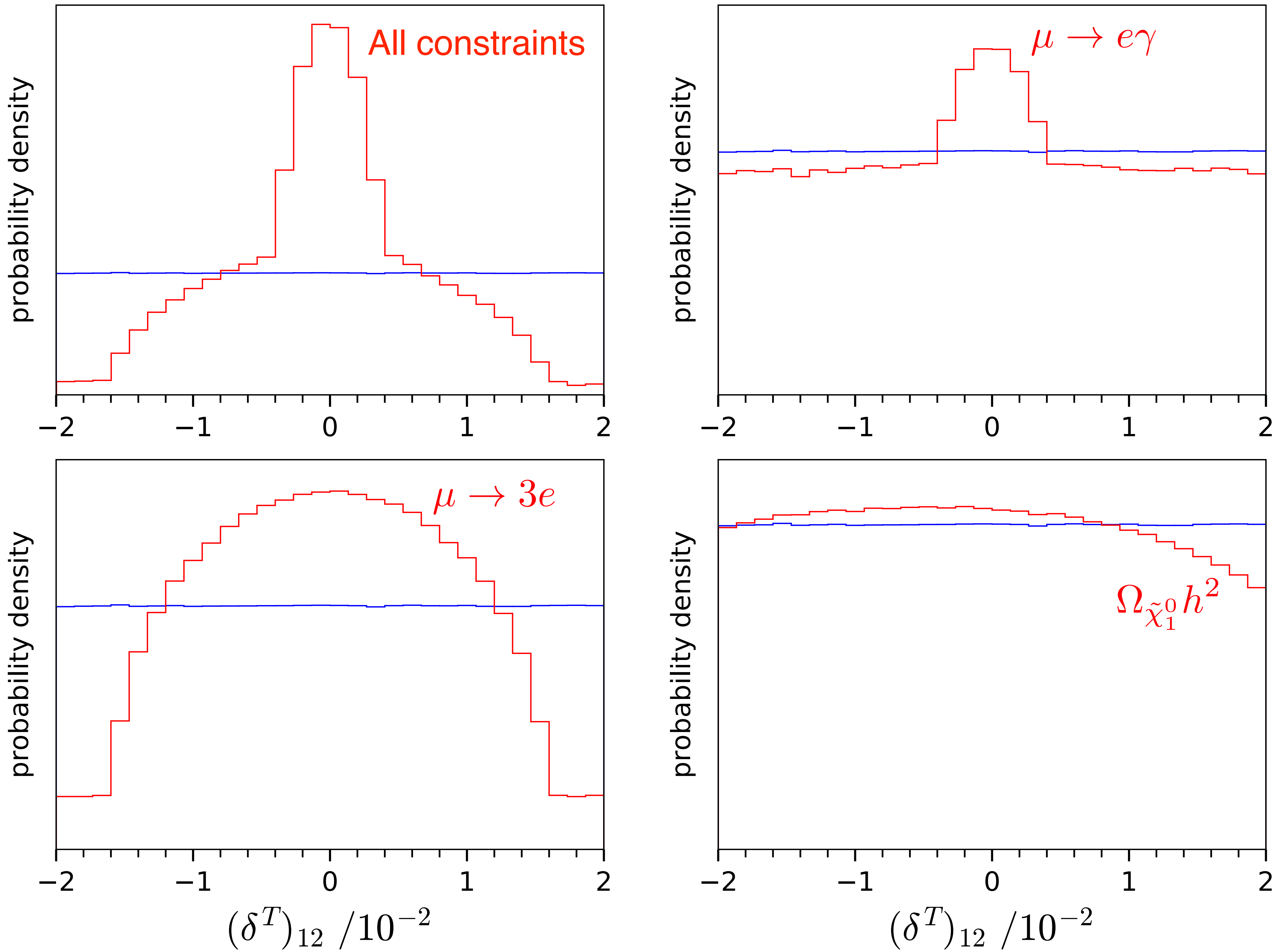
Individual vs. simultaneous variation



In a multi-dimensional parameter space, it is clearly not enough to scan each parameter individually…

→ **interference or cancellation effects in simultaneous study can be very important!**

Interplay of different constraints



μ→eγ vs. μ→3e

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

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

???

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

μ→eγ vs. μ→3e

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

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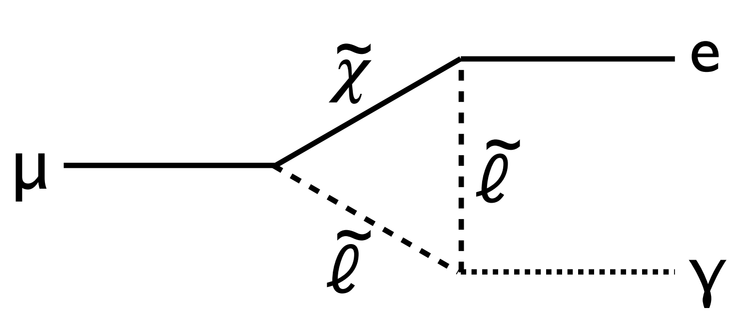
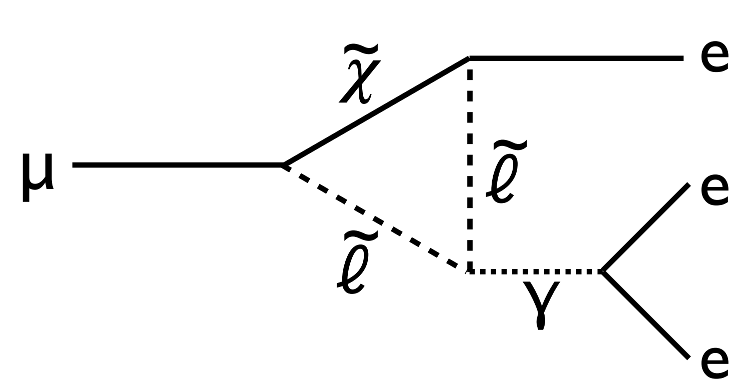
???

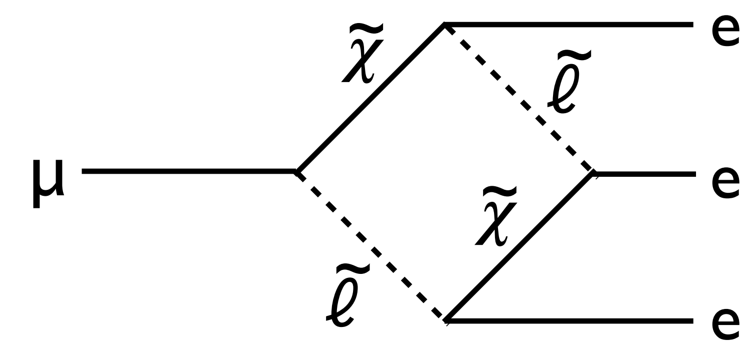
$(\delta^F)_{12}$	$\mu \to 3e,\ \mu \to e\gamma$
$(\delta^F)_{13}$	$\mu \to 3e,\ \mu \to e\gamma$



$$\propto \frac{m_e}{m_\mu}\,\delta_{12}\,\alpha^3$$



$$\propto \frac{m_e}{m_\mu}\,\delta_{12}\,\alpha^4$$



$$\propto \delta_{12}\,\alpha^4$$

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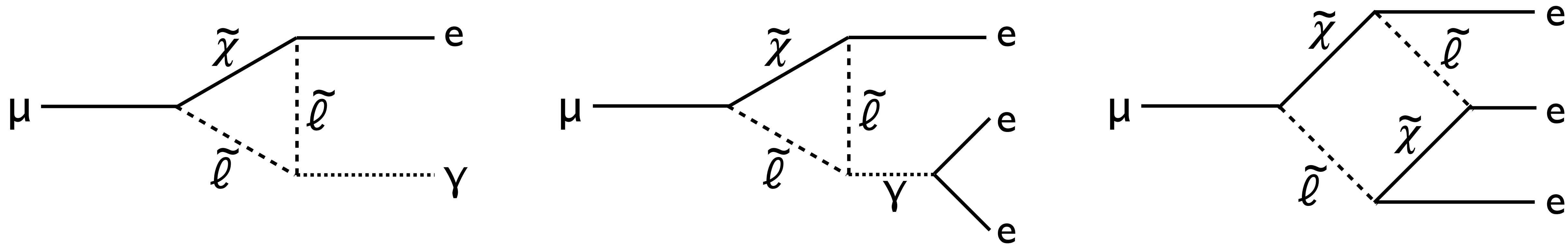
$\mathrm{BR}(\mu \to e\gamma) < 4.2 \times 10^{-13}$

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

???

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



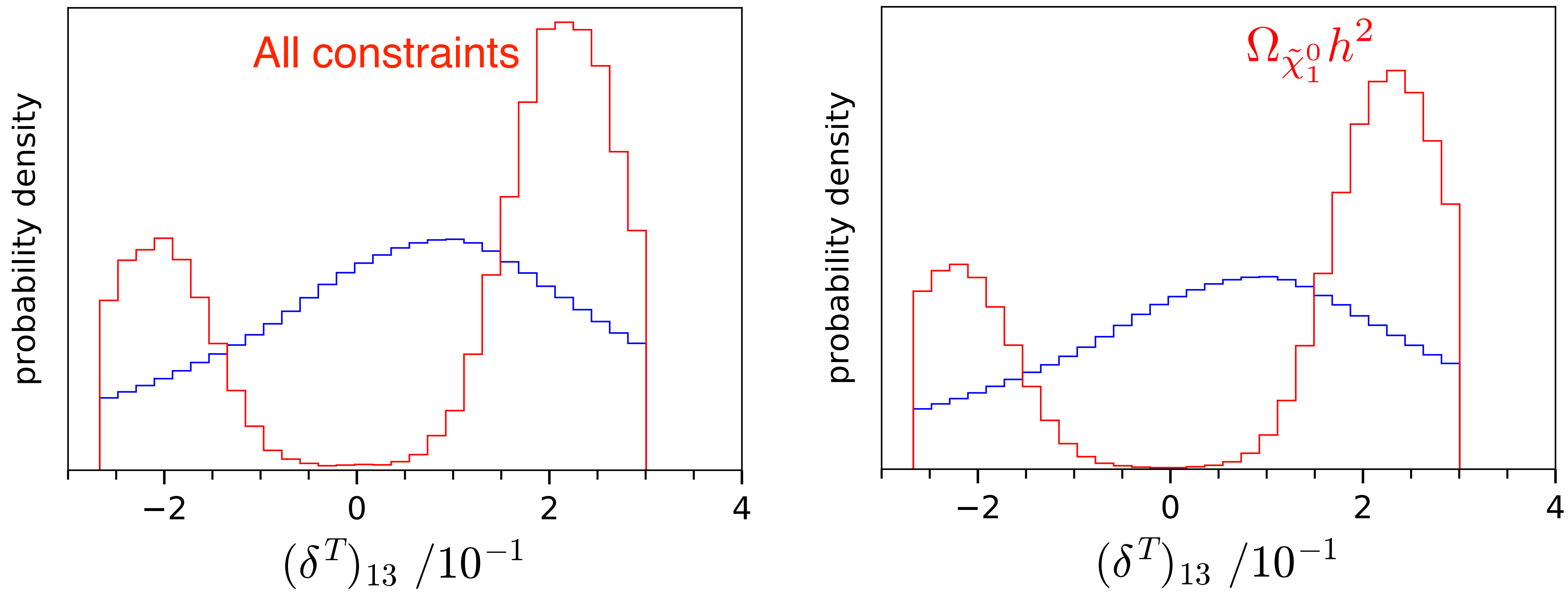
$\propto \frac{m_e}{m_\mu}\,\delta_{12}\,\alpha^3$

~~$\propto \frac{m_e}{m_\mu}\,\delta_{12}\,\alpha^4$~~

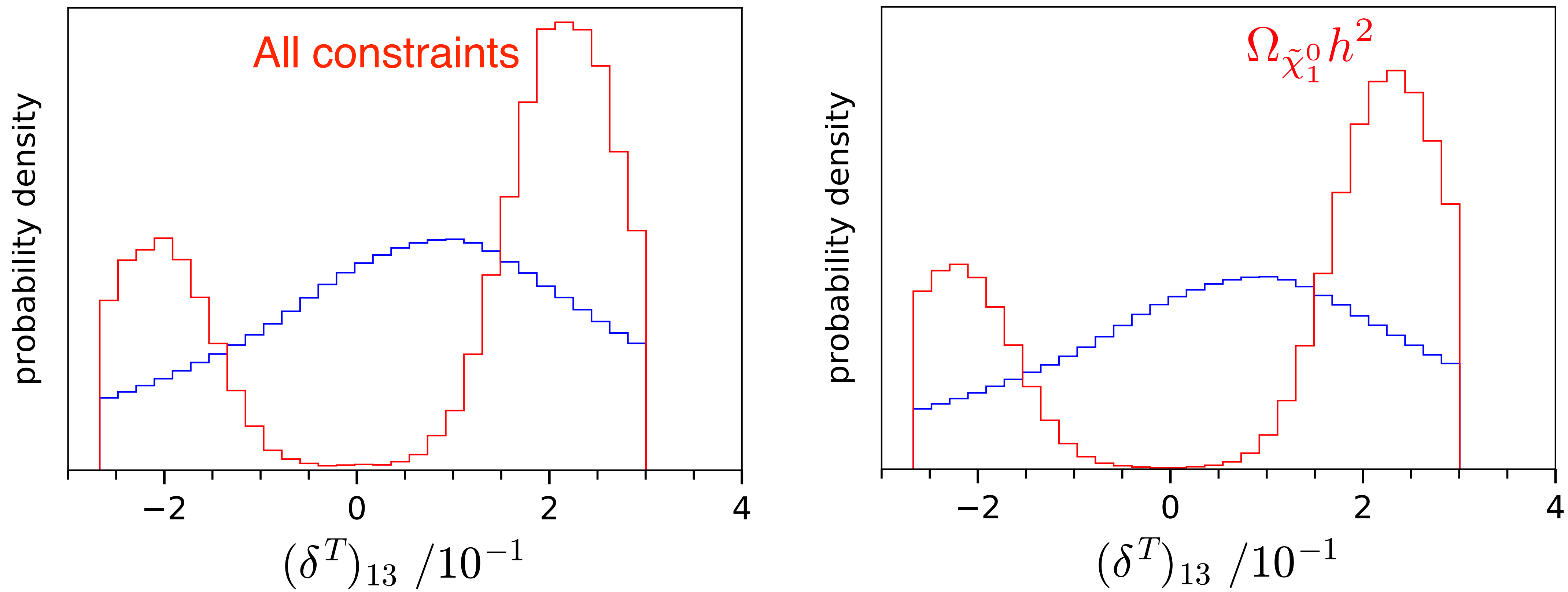
$\propto \delta_{12}\,\alpha^4$

$\mathcal{A}(\mu \to 3e) \sim \mathcal{A}(\mu \to e\gamma)$

Interplay of different constraints



Interplay of different constraints

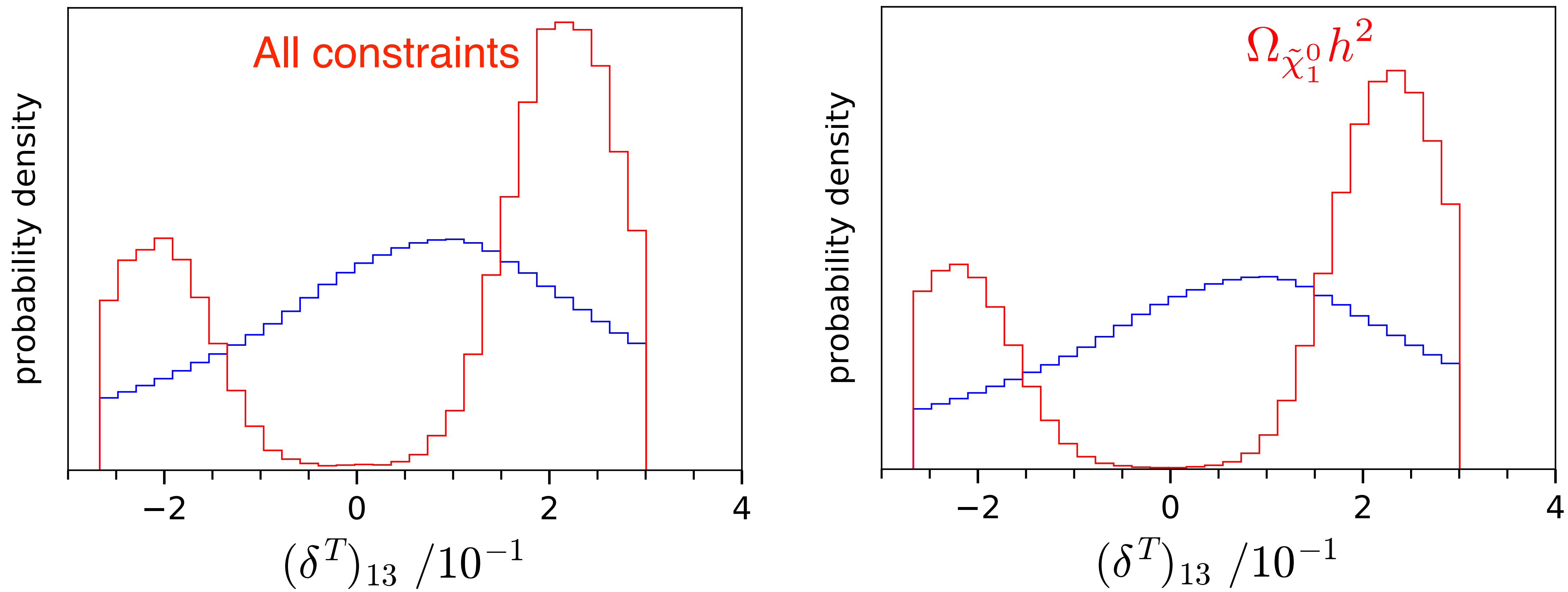


$\left(\delta^T\right)_{13}$ not constrained by flavour observables

other NMFV parameters driven away from zero by flavour observables,

$\longrightarrow$ **decrease in lightest smuon mass…**

Interplay of different constraints



$\left(\delta^T\right)_{13}$ not constrained by flavour observables

other NMFV parameters driven away from zero by flavour observables,

$\longrightarrow$ **decrease in lightest smuon mass…**

$\left(\delta^T\right)_{13}$ **increases lightest smuon mass** (due to specific pattern of mass matrix)

$\longrightarrow$ **compensation of effect of other NMFV parameters w.r.t. to the relic density**

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 insertions

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

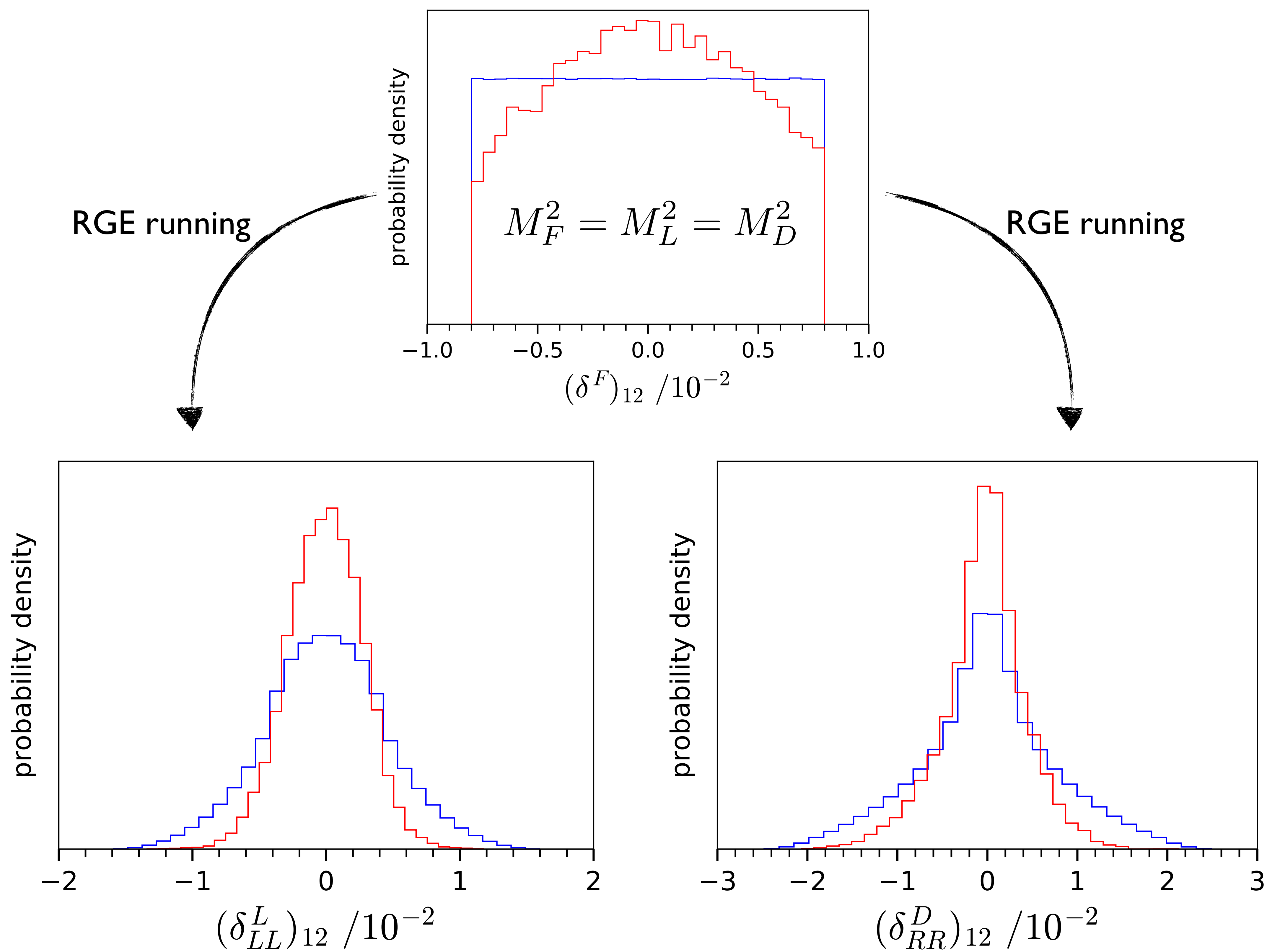
Bounds on hadronic mass insertions

$ij\backslash AB$	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}

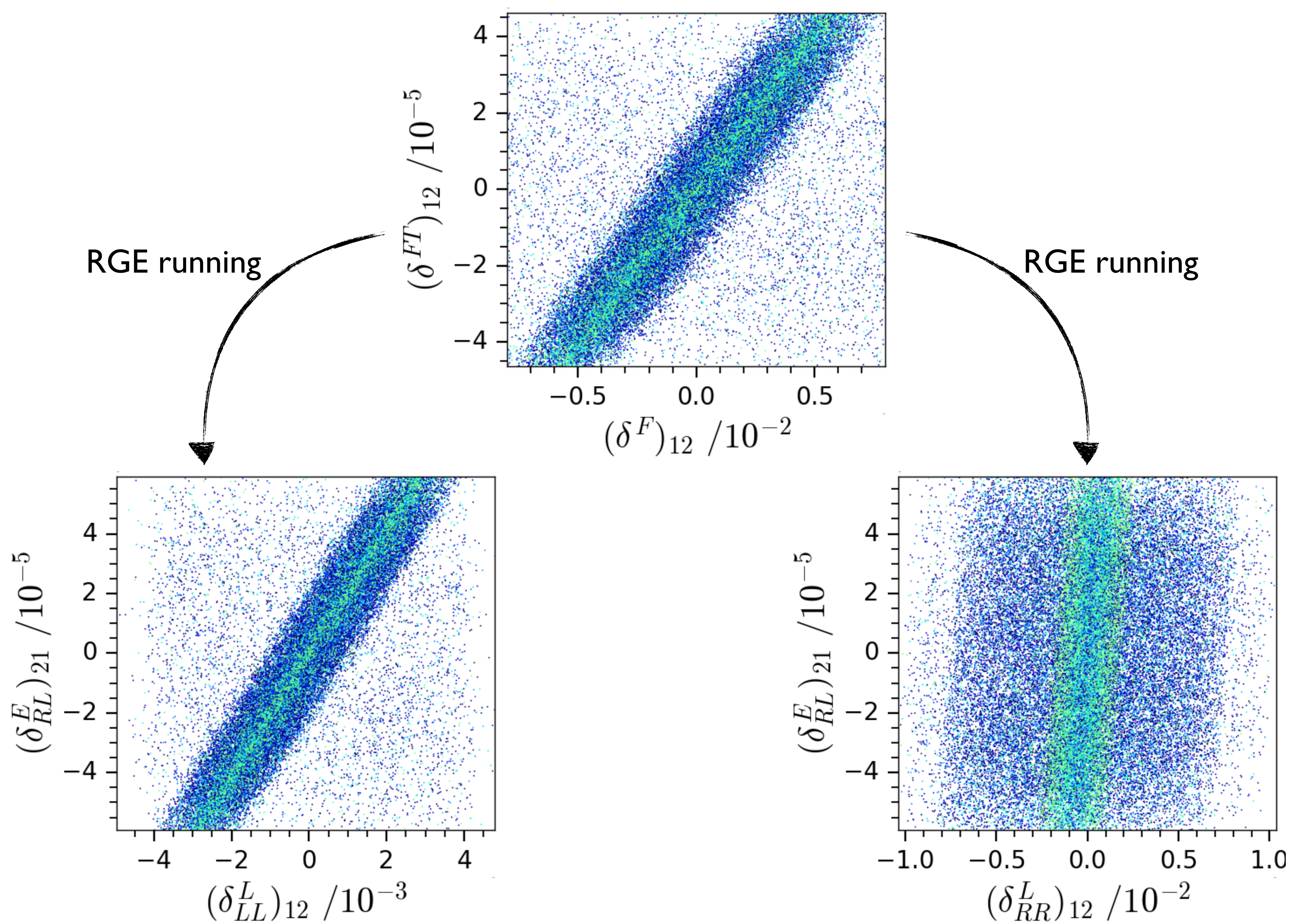
Imposing *SU(5)* unification conditions, hadronic mass insertions supposed to be smaller than leptonic ones, e.g.

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

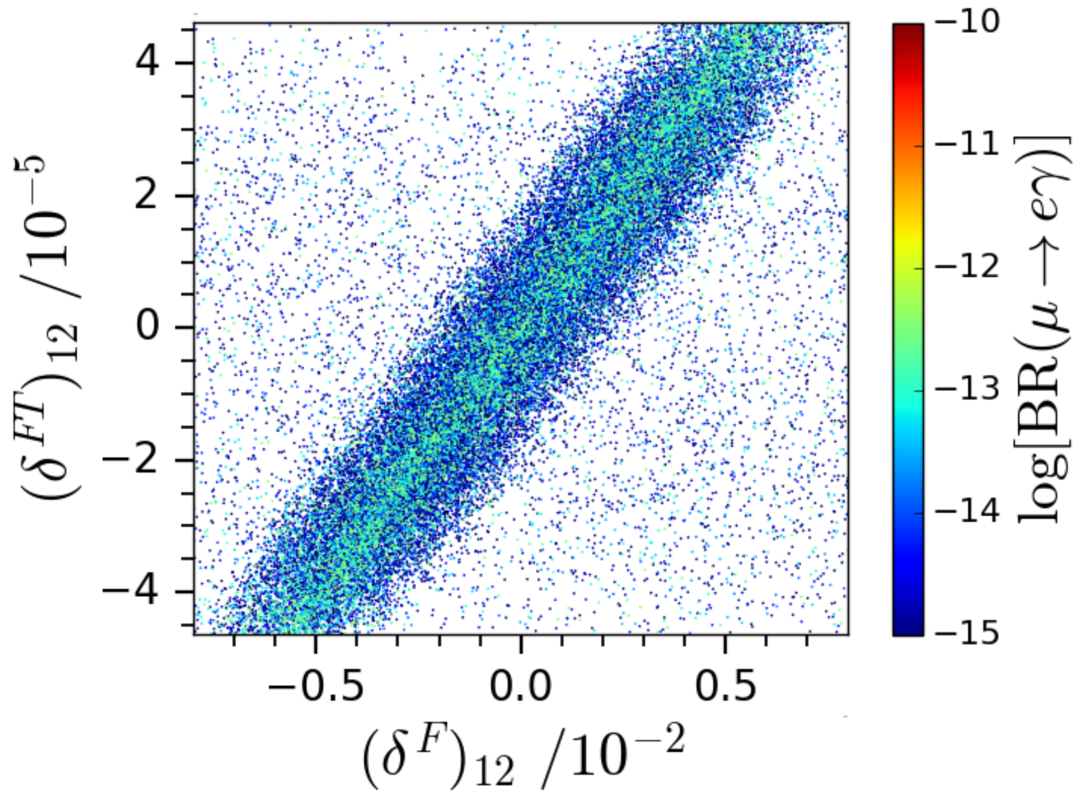
Leptonic vs. hadronic NMFV at TeV scale



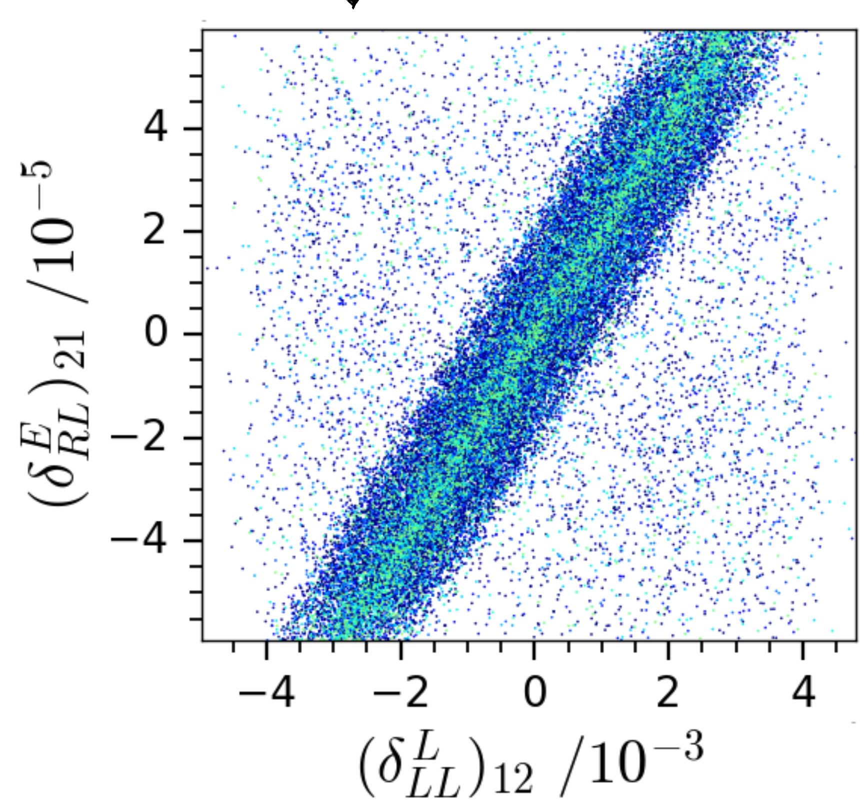
Parameter correlations



Parameter correlations



RGE running



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

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

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

Results — Summary

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

* parameter not varied

† extrapolated range

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