Exploring the flavour structure of the high-scale MSSM

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SUSY 2021

[G. Isidori, S.T.] 1904.12940

WANTED

FOR PLAUSIBLY EXTENDING THE SM

SUPERSYMMETRY

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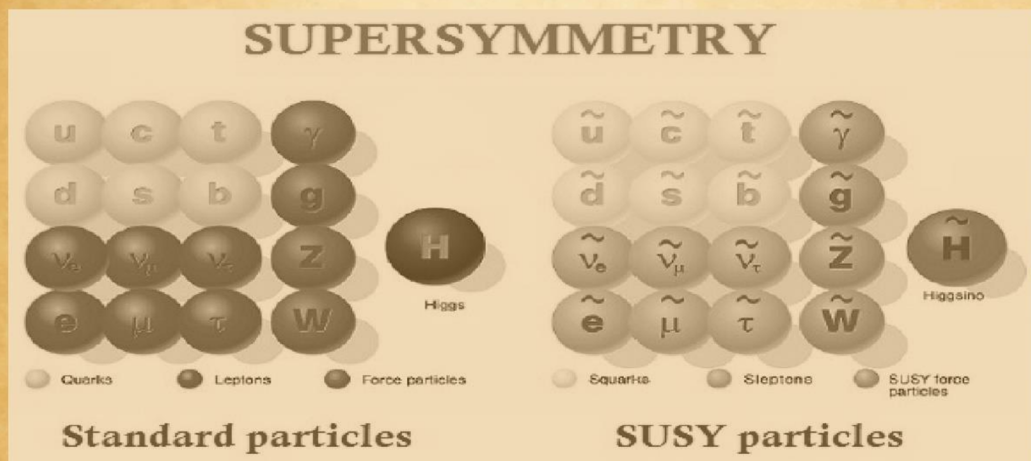


REWARD: NOBEL PRIZE

Where to look for SUSY traces???

- Evidently, there is no signal of SUSY in the LHC yet! (could be just around the TeV corner OR not…) Atlas – Public Results
- SUSY is still the most motivated BSM framework: *gauge coupling unification, natural DM candidate, embedding gravity in SUGRA etc.*
If realized at **high energies**, we have additionally: *successful prediction of Higgs mass, a-posteriori justification of top heaviness and partial alleviation of the flavour problem.*
- Yet, if the SUSY breaking scale lies in the 10-100 TeV domain, direct detection is out of reach for the HL-LHC.
- In the meantime, the only option to extract any indirect information is from low-energy probes.

Flavour obs

Addressing the Flavour Problem / Testing the MSSM

- Explaining the masses and mixing of fermions remains a fundamental open problem and SUSY makes it even more challenging by doubling the number of flavoured degrees of freedom without providing a mechanism to protect FCNCs.
- A residual flavour problem remains even at the **high-scale MSSM**.

  → problem or opportunity?
- We need to postulate additional, realistic hypotheses about the flavour structure.
- We need to identify the "optimal" set of flavour observables that remain sensitive to MSSM contributions.
- Do these observables remain interesting even in the long-term perspective, i.e. future colliders?

  → FCC-ee
  FCC-hh

Models of flavour: MFV & *U(2)*

- We consider four basic hypotheses about the flavour structure.

1. **Minimal Flavour Violation (MFV)**: The only quantities that break the SM flavour symmetry: $\mathcal{G}_F^{\rm SM} = \mathcal{G}_q \times \mathcal{G}_l$

$$\mathcal{G}_q = U(3)_Q \times U(3)_U \times U(3)_D, \quad \mathcal{G}_l = U(3)_L \times U(3)_E$$

are proportional to the SM Yukawa couplings.

[D'Ambrosio et al] 0207036 [Colangelo et al] 0807.0801

2. ***U*(2) flavour symmetry**: A theoretically well-motivated alternative is the following approximate flavour symmetry (for the quark sector):

$$\mathcal{G}_q = U(2)_Q \times U(2)_U \times U(2)_D$$

[Barbieri et al] 1105.2296

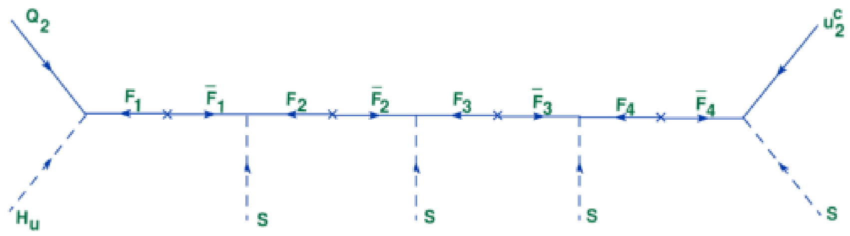
acting only on the first two generations. The symmetry is broken, in analogy to the MFV case (but the 3-1 and 3-2).

Special feature: The **effective** or **split-family SUSY** scenario is realizable.

[Buckley et al] 1610.08059

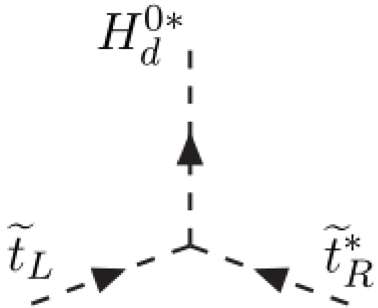
Models of flavour: *U*(1) & Disoriented A-terms

3. ***U*(1) Froggatt-Nielsen:** Representative example of a framework with larger flavour-violating terms. The quarks are assigned non-trivial charges and the symmetry is spontaneously broken via a SM singlet flavon field S.



[Lalak et al] 1006.2375

4. **Disoriented A-terms**: A scenario exclusive to SUSY where flavour violation occurs only due to the trilinear soft-breaking terms (L-R mixing):



These terms do not respect any proportionality to the CKM matrix.

[Giudice et al] 1201.6204

Flavour observables – Analysis strategy

- We focus on a set of representative observables that:

i. provide the most stringent contraints on the MSSM flavour space at the moment and

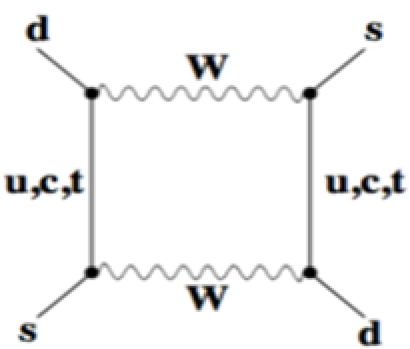
ii. could exhibit significant deviations from the SM, thanks to realistic improvements on the experimental and/or the theoretical side in the near future.

- We scrutinize the capability of each flavour model to provide a best-fit-point that improves over the SM, setting the observables (one at a time) to a future scenario corresponding to a possible 3σ deviation!
- The minimization processes is repeated from the lower present bounds to the point of decoupling as a function of an overall scale M (w.l.g. chosen to be the mass of the third generation squark).

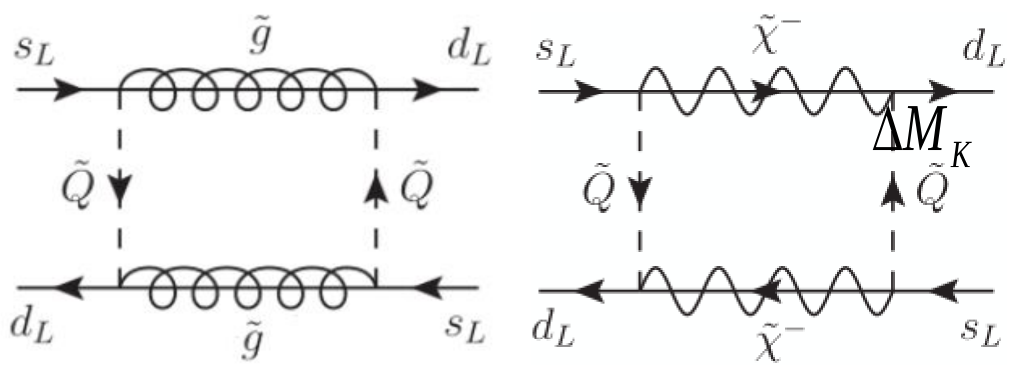
ΔF=2 processes

- $B_{d(s)} - \bar{B}_{d(s)}$ **system**: significant room for improvement on $\Delta M_{B_{d(s)}}$ due due Lattice-QCD, irreducible theory errors on the phases
- $K - \bar{K}$ & $D - \bar{D}$ **systems**: only the CPV mixing amplitudes are short-dinstance dominated and hence we consider $|\varepsilon_K|$ and $\Im(\Delta M_{12}^D)$, ΔM_K is kept only as a control-parameter

SM:



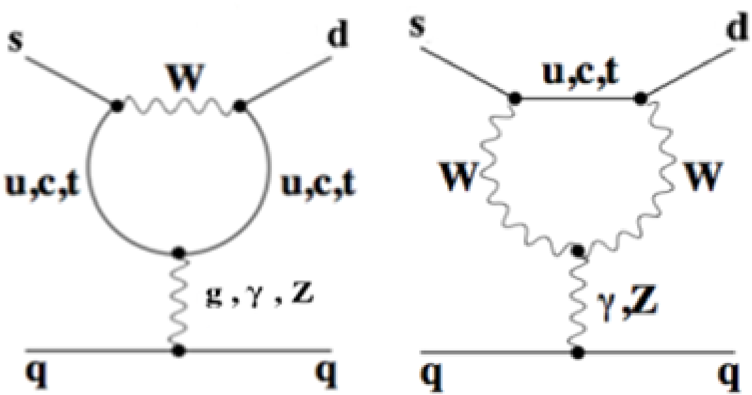
MSSM:



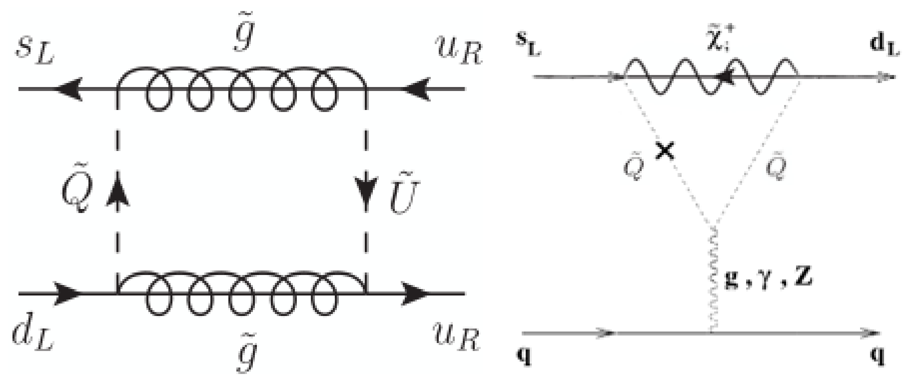
ΔF=1 processes

- $\varepsilon'_K/\varepsilon_K$ **: non-leptonic FCNC** sensitive to NP due to accidental cancellation in the SM ($\Delta I = 1/2$ rule), large uncertainty on the SM prediction
- $\mathcal{B}(K^+ \to \pi^+ \nu\bar{\nu})$ **: rare leptonic FCNC** that probes the *Z*-penguin, the dominant error is experimental
- $\mathcal{B}(B \to X_s \gamma)$ **: radiative FCNC** with theory error ≈ experimental error, irreducible uncertainties therefore kept as control-parameter

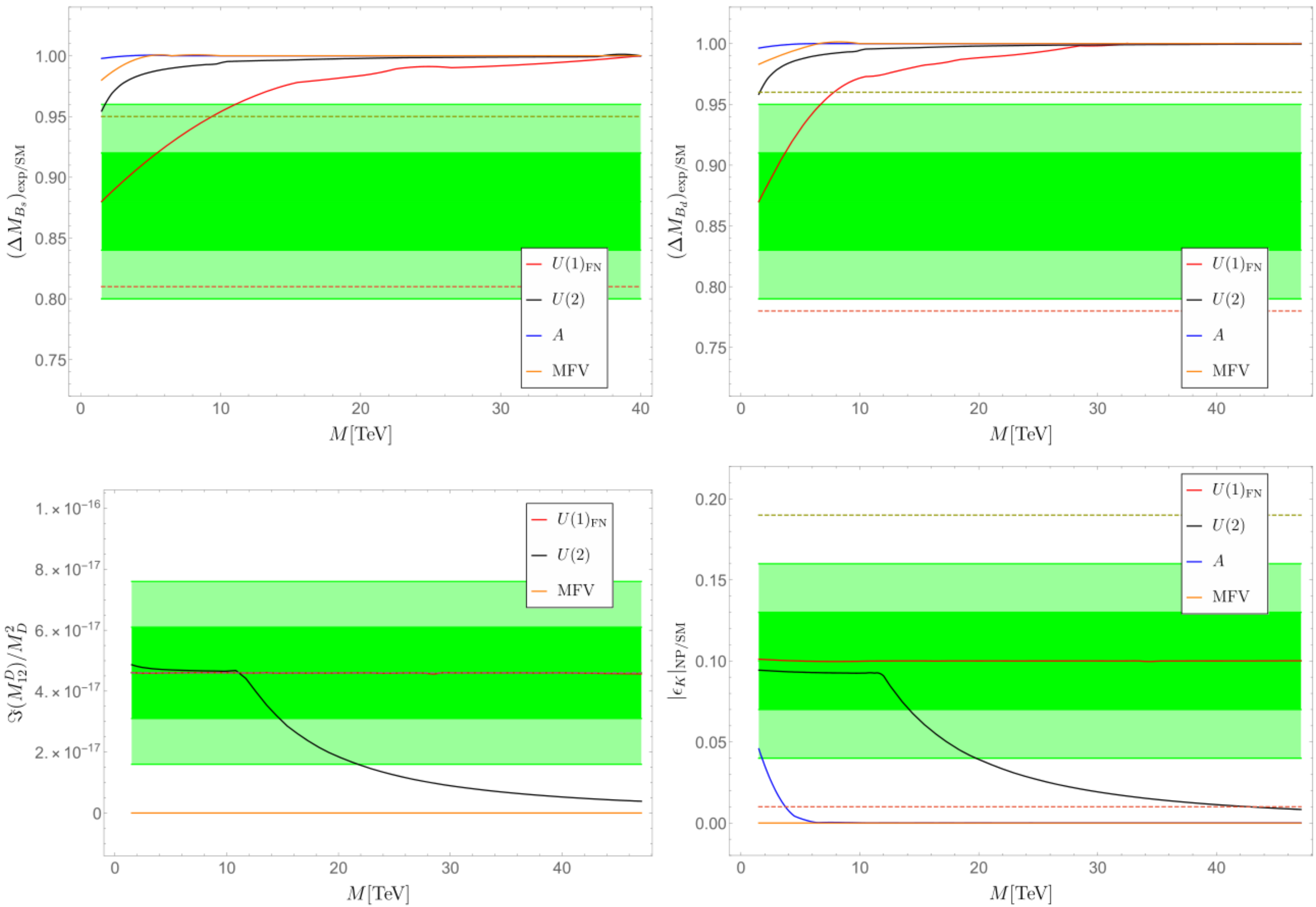
SM:



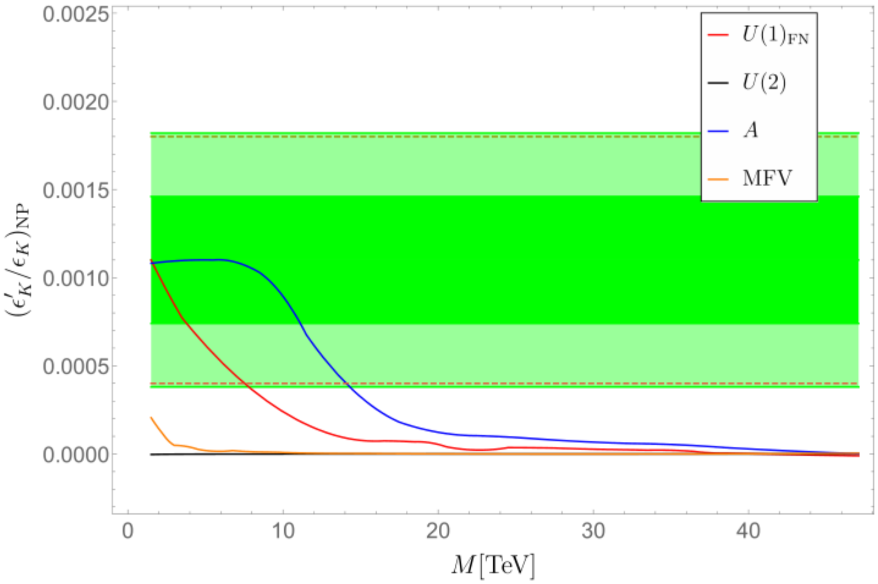
MSSM:

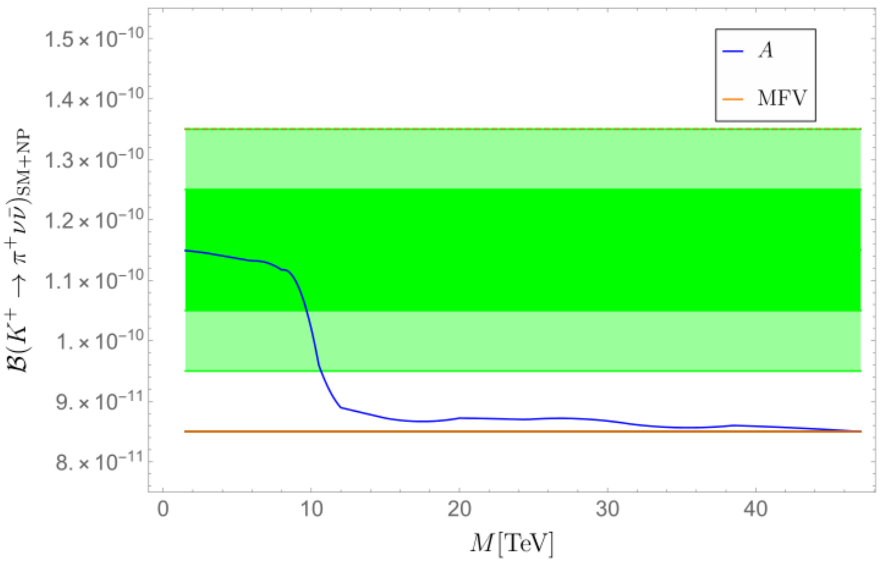


ΔF=2 processes



ΔF=1 processes



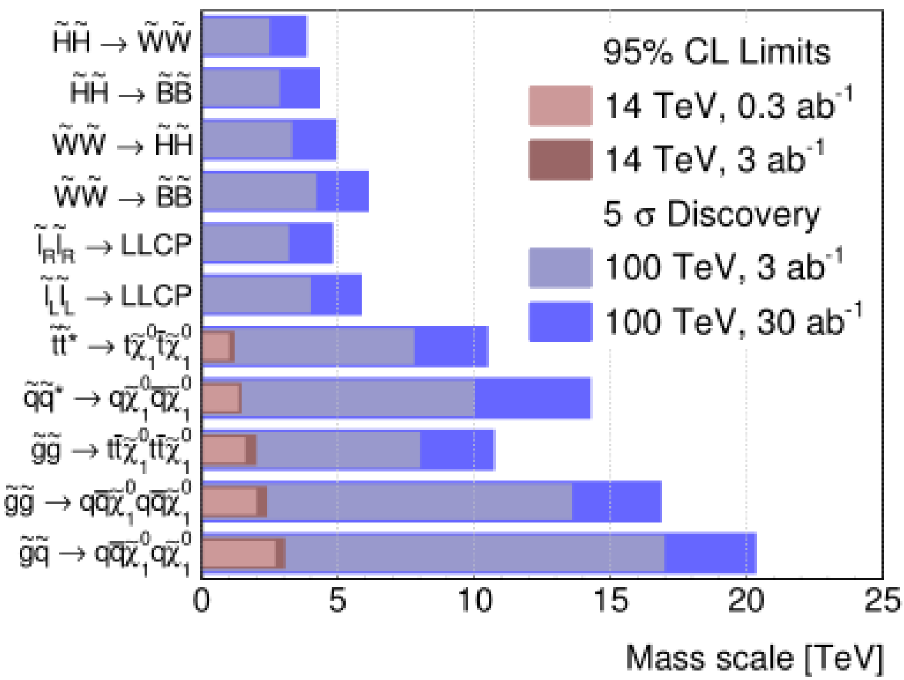


Discussion & Conclusions

- **Decoupling limit:** Below 50 TeV for all cases except $|\varepsilon_K|$ and $\Im(\Delta M_{12}^D)$ (sensitive up to several hundred TeV in the $U(1)_{\rm FN}$ case).
- **MFV vs *U*(2):** Both models follow the CKM paradigm, but MFV is much more rigid (= no sizeable effects). In contrast, $U(2)$ with decoupled first two generations can generate sizeable effects to 3-1 and 3-2 transitions. Yet, both scenarios fail to enhance ΔF=1 amplitudes.
- **$U(1)_{\rm FN}$:** Much more flexible, but with a caveat: tuning at low energies!
- **Disoriented A-terms:** Due to $SU(2)_L$-breaking nature of the A terms, ΔF=2 observables require dim-8 operators (= negligible contribution), BUT can accommodate the largest effects in ΔF=1!
- In each observable there is at least one flavour model able to accommodate a significant deviation from the SM for $M \leq 10$ TeV. Reversely, each model is associated to a characteristic signature at a given scale.

Future outlook

- Complimentarity in the regime of $\mathcal{O}(10)$ TeV , which can be probed at the FCC-hh. Models based on flavour symmetries ARE relevant at high energies and even more motivated than the flavour-anarchic case.



[Physics at a 100 TeV pp collider] 1606.00947

Thank you!!!!

Backup slides

Experimental Values / SM predictions

observable	experiment	$O_{\rm exp}/O_{\rm SM} - 1$	*future scenario* (3σ)
ΔM_{B_d}	$(0.5064 \pm 0.0019)\ \mathrm{ps}^{-1}$	-0.13 ± 0.09	-0.13 ± 0.04
ΔM_{B_s}	$(17.757 \pm 0.021)\ \mathrm{ps}^{-1}$	-0.12 ± 0.07	-0.12 ± 0.04
$\lvert\epsilon_K\rvert$	$(2.229 \pm 0.010) \times 10^{-3}$	0.10 ± 0.09	0.10 ± 0.03
$\mathcal{B}(B \to X_s\gamma)$	$(3.52 \pm 0.25) \times 10^{-4}$	0.11 ± 0.11	–
		$O_{\rm exp} - O_{\rm SM}$	
ϵ'_K/ϵ_K	$(16.6 \pm 2.3) \times 10^{-4}$	$(11 \pm 7) \times 10^{-4}$	$(11 \pm 3.6) \times 10^{-4}$
$\Im(M_{12}^D)/M_D^2$	$(0.0 \pm 4.6) \times 10^{-17}$	$(0.0 \pm 4.6) \times 10^{-17}$	$(4.6 \pm 1.5) \times 10^{-17}$
$\mathcal{B}(K^+ \to \pi^+\nu\bar{\nu})$	$(0.85 \pm 0.5) \times 10^{-10}$	$(0.0 \pm 0.5) \times 10^{-10}$	$(0.3 \pm 0.1) \times 10^{-10}$
$\Delta M_K/M_K$	7.0×10^{-16}	$(0 \pm 7) \times 10^{-16}$	–

Models of flavour: MFV

- We consider four basic hypotheses about the flavour structure.

1. **Minimal Flavor Violation (MFV)**: The only quantities that break the SM flavour symmetry: $\mathcal{G}_F^{\mathrm{SM}} = \mathcal{G}_q \times \mathcal{G}_l$

$$\mathcal{G}_q = U(3)_Q \times U(3)_U \times U(3)_D, \quad \mathcal{G}_l = U(3)_L \times U(3)_E$$

are spurion fields proportional to the SM Yukawa couplings. The soft-breaking terms can be reconstructed as (convergent) series of spurions.

$$(\tilde{M}_Q^2)_{IJ} = \tilde{m}_Q^2 \left[\delta_{IJ} + b_1 (Y_U^\dagger Y_U)_{IJ} + b_2 (Y_D^\dagger Y_D)_{IJ} + \ldots \right]$$

$$(\tilde{M}_U^2)_{IJ} = \tilde{m}_U^2 \left[\delta_{IJ} + b_3 (Y_U^\dagger Y_U)_{IJ} + \ldots \right]$$

$$(\tilde{M}_D^2)_{IJ} = \tilde{m}_D^2 \left[\delta_{IJ} + b_4 (Y_D^\dagger Y_D)_{IJ} + \ldots \right]$$

[D'Ambrosio et al] 0207036
[Colangelo et al] 0807.0801

and similarly for the slepton mass matrices and the A-terms.
Keeping only the leading LFV terms, the MFV minimal version of the MSSM contains a total of 15 parameters.

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Models of flavour: $U(2)$ & $U(1)_{\text{FN}}$

2. ***U*(2) chiral flavour symmetry**: A theoretically well-motivated alternative is the following approximate flavour symmetry (for the quark sector):

$$\mathcal{G}_q = U(2)_Q \times U(2)_U \times U(2)_D$$

[Barbieri et al] 1105.2296

acting only on the first two generations. The symmetry is broken, in analogy to the MFV case, by the Yukawa matrices:

$$Y_U = y_t \begin{pmatrix} \Delta Y_U & x_t V_Q \\ 0 & 1 \end{pmatrix} \quad \text{and} \quad Y_D = y_b \begin{pmatrix} \Delta Y_D & x_b V_Q \\ 0 & 1 \end{pmatrix}$$

[Buckley et al] 1610.08059

Special feature: The **effective** or **split-family SUSY** scenario is realizable.

3. **Holomorphic *U*(1) Froggatt-Nielsen:** Representative example of a framework with larger flavour-violating terms. The quarks are assigned non-trivial charges and the symmetry is spontaneously broken via a SM singlet flavon field S.

[Lalak et al] 1006.2375

Models of flavour: Disoriented A-terms

For instance, the up-Yukawa takes the form:

$$\epsilon_{ij} Y_U^{IJ} H_i^U Q_j^I u_R^{J*} = \epsilon_{ij} \left[a_{IJ} \left(\frac{\langle S \rangle}{M} \right)^{|u_J + q_I|} \right] H_i^U Q_j^I u_R^{J*}$$

Proceeding in a similar manner we obtain the soft-breaking terms.

4. **Disoriented A-terms**: A scenario exclusive to SUSY where flavour violation occurs only in the L–R mixing, hence the trilinear soft-breaking terms:

$$(A_F)_{IJ} = A_0 \theta_{IJ}^F y_{F_J}, \quad F = U, D$$

$$(A_E)_{IJ} = A_0 \theta_{IJ}^E y_{E_J}$$

[Giudice et al] 1201.6204

The generic mixing angles θ do not respect exact proportionality to the CKM matrix elements.

Generalities: MSSM mass terms

The R-parity conserving **superpotential of the MSSM** takes the form:

$$W = \mu\epsilon_{ij} H_i^U H_j^D + \epsilon_{ij} Y_L^{IJ} H_i^D \tilde{L}_j^I \tilde{e}_R^{+J} + \epsilon_{ij} Y_D^{IJ} H_i^D \tilde{Q}_j^I \tilde{d}_R^{J*} + \epsilon_{ij} Y_U^{IJ} H_i^U \tilde{Q}_j^I \tilde{u}_R^{J*}$$

The soft breaking terms are divided into the following classes:

1. Mass terms for the scalar fields:

$$-m_{H_U}^2 H_i^{U*} H_i^U - m_{H_D}^2 H_i^{D*} H_i^D - (\tilde{M}_L^2)_{IJ} \tilde{L}_i^{I*} \tilde{L}_i^J - (\tilde{M}_E^2)_{IJ} \tilde{e}_R^{+I*} \tilde{e}_R^{+J}$$

$$-(\tilde{M}_Q^2)_{IJ} \tilde{Q}_i^{I*} \tilde{Q}_i^J - (\tilde{M}_D^2)_{IJ} \tilde{d}_R^{J*} \tilde{d}_R^I - (\tilde{M}_U^2)_{IJ} \tilde{u}_R^{J*} \tilde{u}_R^I$$

2. Mass terms for the gauginos:

$$\frac{1}{2} M_1 \lambda_B \lambda_B + \frac{1}{2} M_2 \lambda_A \lambda_A + \frac{1}{2} M_3 \lambda_G^\alpha \lambda_G^\alpha + \text{h.c.}$$

3. Trilinear couplings (A-terms) of the scalar fields:

$$\epsilon_{ij} (A_L)_{IJ} H_i^D \tilde{L}_j^I \tilde{e}_R^{+J} + \epsilon_{ij} (A_D)_{IJ} H_i^D \tilde{Q}_j^I \tilde{d}_R^{J*} + \epsilon_{ij} (A_U)_{IJ} H_i^U \tilde{Q}_j^I \tilde{u}_R^{J*} + \text{h.c.}$$

Generalities: Diagonalization – Mass insertions δ

For instance, the down-squark mass matrix may be written as:

$$\tilde{M}_D^2 = \begin{pmatrix} (\tilde{M}_D^2)_{LL} & (\tilde{M}_D^2)_{LR} \\ (\tilde{M}_D^2)_{RL} & (\tilde{M}_D^2)_{RR} \end{pmatrix} \cong \begin{pmatrix} \tilde{M}_Q^2 & v_D A_D \\ v_D A_D & \tilde{M}_D^2 \end{pmatrix},$$

where the mass matrices are in general non-diagonal 3×3 block matrices. The fields $\tilde{Q}$ and $\tilde{d}_R$ mix to give six squark mass eigenstates $\tilde{D}$:

$$Z_D \begin{pmatrix} (\tilde{M}_D^2)_{LL} & (\tilde{M}_D^2)_{LR} \\ (\tilde{M}_D^2)_{LR} & (\tilde{M}_D^2)_{RR} \end{pmatrix} (Z_D)^\dagger = \begin{pmatrix} \tilde{m}_{D_1}^2 & & 0 \\ & \ddots & \\ 0 & & \tilde{m}_{D_6}^2 \end{pmatrix}$$

We parametrize the (very) small off-diagonal corrections by defining:

$$(\delta_{LL}^q)^{IJ} = \frac{(\tilde{M}_Q^2)_{IJ}}{\left|(\tilde{M}_Q^2)_{II}\right|^{1/2} \left|(\tilde{M}_Q^2)_{JJ}\right|^{1/2}}, \quad (\delta_{LR}^D)^{IJ} = \frac{v_D (A_D)_{IJ}}{\left|(\tilde{M}_Q^2)_{II}\right|^{1/2} \left|(\tilde{M}_D^2)_{JJ}\right|^{1/2}}, \quad (\delta_{RR}^D)^{IJ} = \frac{(\tilde{M}_D^2)_{IJ}}{\left|(\tilde{M}_D^2)_{II}\right|^{1/2} \left|(\tilde{M}_D^2)_{JJ}\right|^{1/2}}$$

Any function of the diagonal masses can be then extended as follows:

$$Z_{ik}^\dagger f(\tilde{m}_{D_k}) Z_{kj} = \delta_{ij} f(\tilde{m}_i^0) + (\mathcal{N}^{ij}\delta^{ij}) f(\tilde{m}_i^0, \tilde{m}_j^0) + \sum_{k=1}^{6} (\mathcal{N}^{ik}\delta^{ik})(\mathcal{N}^{kj}\delta^{kj}) f(\tilde{m}_i^0, \tilde{m}_j^0, \tilde{m}_k^0) + \mathcal{O}(\delta^3)$$

[Colangelo et al] 9808487v1

I. MFV mass insertions

Keeping only the leading LFV terms, the MFV minimal version of the MSSM contains a total of 15 parameters:

$$M_1,\ M_2,\ M_3,\ \mu,\ M_A,\ \tan\beta$$

$$\tilde{m}_Q^2,\ \tilde{m}_U^2,\ \tilde{m}_D^2,\ \tilde{m}_L^2,\ \tilde{m}_E^2,\ \tilde{a}_0,\ x_1,\ x_2,\ y_5$$

The model contains then the following non-vanishing mass insertions:

$$(\delta_{LL}^q)^{12} = V_{ts} V_{td}^* x_1, \quad (\delta_{LL}^q)^{23} = V_{tb} V_{ts}^* \frac{x_1}{|1+x_1|^{1/2}} = \frac{V_{tb} V_{ts}^*}{V_{tb} V_{td}^*} (\delta_{LL}^q)^{13}, \quad (\delta_{LL}^q)^{IJ} = (\delta_{LL}^q)^{JI*},$$

$$(\delta_{LR}^U)^{32} = V_{ts} \frac{v_U \tilde{a}_0}{|\tilde{m}_Q^2(1+x_1)|^{1/2} |\tilde{m}_U^2|^{1/2}} = \frac{V_{ts}}{V_{td}} (\delta_{LR}^U)^{31},$$

$$(\delta_{LR}^D)^{32} = V_{ts} \frac{v_D \tilde{a}_0 y_5}{|\tilde{m}_Q^2(1+x_1)|^{1/2} |\tilde{m}_D^2|^{1/2}} = \frac{V_{ts}}{V_{td}} (\delta_{LR}^D)^{31}$$

II. $U(2)$ mass insertions

In first approximation, one discards the subleading $\Delta Y_{U/D}$ spurions, the first two generations become degenerate and the squark mass matrices can be expressed in terms of a CKM-like parametrization:

$$\tilde{M}_Q^2 = W_L^d \,\mathrm{diag}(\tilde{m}_{Q_h}^2, \tilde{m}_{Q_h}^2, \tilde{m}_{Q_l}^2) W_L^{d\dagger}$$

$$\tilde{M}_U^2 = \mathrm{diag}(\tilde{m}_{u_h}^2, \tilde{m}_{u_h}^2, \tilde{m}_{u_l}^2), \quad \tilde{M}_D^2 = \mathrm{diag}(\tilde{m}_{d_h}^2, \tilde{m}_{d_h}^2, \tilde{m}_{d_l}^2)$$

$$A_U = a_0, \quad A_D = a_0 y_b$$

In the limit $\tilde{m}_{Q_h}^2 >> \tilde{m}_{Q_l}^2$, the model contains only LL mass insertions:

$$(\delta_{LL}^q)^{IJ} = \sum_{K=1}^{2} (W_L^d)_{IK} (W_L^{d*})_{JK} = -(W_L^d)_{I3} (W_L^{d*})_{J3}$$

[Barbieri et al] 1105.2296

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III. $U(1)_{\text{FN}}$ mass insertions

One can then write down the following soft breaking up to their respective order $\mathcal{O}(1)$ coefficients:

$$\tilde{M}_Q^2 = \tilde{m}_Q^2 \begin{pmatrix} 1 & \epsilon & \epsilon^3 \\ \epsilon & 1 & \epsilon^2 \\ \epsilon^3 & \epsilon^2 & 1 \end{pmatrix}, \quad \tilde{M}_U^2 = \tilde{m}_U^2 \begin{pmatrix} 1 & \epsilon & \epsilon^3 \\ \epsilon & 1 & \epsilon^2 \\ \epsilon^3 & \epsilon^2 & 1 \end{pmatrix}, \quad \tilde{M}_D^2 = \tilde{m}_D^2 \begin{pmatrix} 1 & \epsilon & \epsilon \\ \epsilon & 1 & 1 \\ \epsilon & 1 & 1 \end{pmatrix},$$

$$A_U = a_0 \begin{pmatrix} \epsilon^6 & \epsilon^5 & \epsilon^3 \\ \epsilon^5 & \epsilon^4 & \epsilon^2 \\ \epsilon^3 & \epsilon^2 & 1 \end{pmatrix}, \quad A_D = a_0 \begin{pmatrix} \epsilon^4 & \epsilon^3 & \epsilon \\ \epsilon^3 & \epsilon^2 & \epsilon^2 \\ \epsilon & \epsilon^2 & 1 \end{pmatrix}$$

[Lalak et al] 1006.2375

Depending on the choice of the accuracy, we may drop higher powers of ε and calculate the leading order mass insertions:

$$(\delta^q_{LL})^{12} = (\delta^q_{LL})^{21} = (\delta^q_{RR})^{12} = (\delta^q_{RR})^{21} = c^{q12}_{RR}\epsilon, \quad (\delta^D_{LR})^{13} = (\delta^D_{LR})^{31} = c^{D13}_{LR} \frac{a_0}{\sqrt{\tilde{m}_Q^2 \tilde{m}_D^2}} \epsilon$$

ΔI=1/2 rule

➢ In the SM, we have:

$$\frac{\varepsilon'_K}{\varepsilon_K} = -\frac{\omega}{\sqrt{2}\left|\varepsilon_K\right|_{\exp} \mathrm{Re}\, A_0}\left(\mathrm{Im}\, A_0 - \frac{1}{\omega}\mathrm{Im}\, A_2\right)$$

$$\mathcal{O}_6 = \left(\overline{b_L^\alpha}\gamma^\mu d_L^\beta\right)\left(\sum_q \overline{q_R^\beta}\gamma_\mu q_R^\alpha\right)$$

$$\mathcal{O}_8 = \frac{3}{2}\left(\overline{b_L^\alpha}\gamma^\mu d_L^\beta\right)\left(\sum_q e_q \overline{q_R^\beta}\gamma_\mu q_R^\alpha\right)$$

➢ While both $\langle \mathcal{O}_6(\mu)\rangle_0$ and $\langle \mathcal{O}_8(\mu)\rangle_2$ receive chiral enhancement, NP is favored as a modification of the coefficient of $\mathcal{O}_8$ due to the additional $1/\omega \approx 22$.