Tasting the *SU(5)* nature of Supersymmetry at the LHC

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SU(5) relations in the up-squark sector

A fascinating feature of the Standard Model (SM) of particle physics is that the matter fields fit into a complete representation of *SU(5)*. This can be interpreted as a hint that the SM gauge group *SU(3)xSU(2)xU(1)* arises as the low-energy limit of a Grand Unified Theory (GUT) containing *SU(5)* at some higher scale. Unravelling whether or not nature is *SU(5)*-symmetric constitutes a challenging open problem of particle physics.

Within a supersymmetric *SU(5)* theory, interactions between the Higgs and the matter fields are given by the superpotential

$$\mathcal{W} \;=\; \lambda_d^{ij}\mathcal{H}_d 10_i\bar{5}_j + \lambda_u^{ij}\mathcal{H}_u 10_i 10_j \;\longrightarrow\; y_d^{ij}H_d Q_i D_j + y_\ell^{ij}H_d L_i E_j + y_u^{ij}H_u Q_i U_j$$

while the soft-breaking Lagrangian contains mass and trilinear terms of the form

$$\mathcal{L} \;\supset\; -\tilde{q}^* M_{\tilde{Q}}^2 \tilde{q} - \tilde{d}^* M_{\tilde{D}}^2 \tilde{d} - \tilde{u}^* M_{\tilde{U}}^2 \tilde{u} + a_d h_d \tilde{q}\tilde{d} + a_\ell h_d \tilde{\ell}\tilde{e} + a_u h_u \tilde{q}\tilde{u}$$

A first consequence of *SU(5)*-like unification of the matter fields are the relations

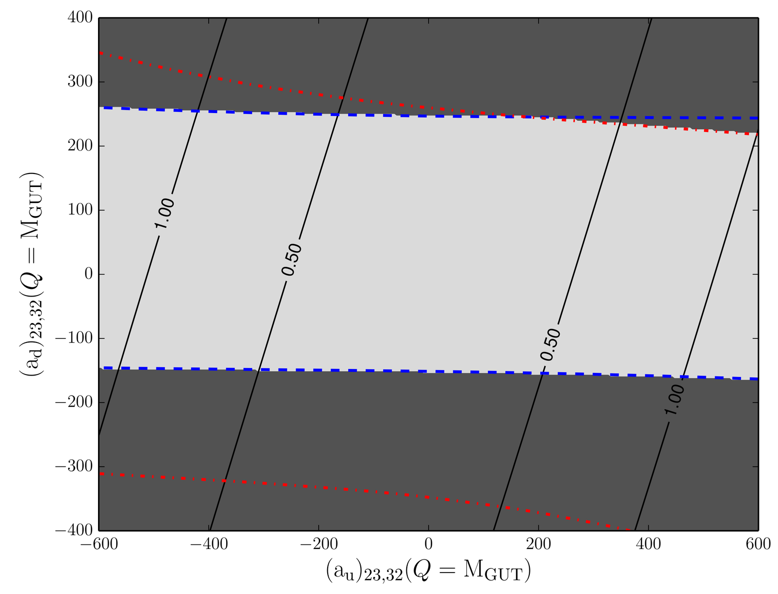
$$y_\ell = y_d^\dagger \quad\text{ and }\quad a_\ell = a_d^\dagger$$

between the Yukawa matrices of the down-type quarks and charged leptons, as well as for the corresponding trilinear terms. While these relations are exact at the GUT scale, they are modified when evolving them to the TeV scale through renormalization group (RG) running. In particular, the RG evolution of the second relation is highly model-dependent, and can therefore hardly constitute a generic test of the *SU(5)* GUT hypothesis.

The situation is different in the sector of up-type squarks. The $10_i 10_j$ term of the superpotential is symmetric, which enforces a symmetric top Yukawa coupling together with a corresponding symmetric trilinear coupling matrix at the GUT scale:

$$\boxed{y_u = y_u^\dagger \quad\text{ and }\quad a_u = a_u^\dagger}$$

As we will show in the following, this property provides a potential way to test the *SU(5)* GUT hypothesis, and is therefore the central point of our work.



The relevant one-loop beta-functions are dominated by symmetric terms, such that we can expect y_u and a_u to remain symmetric to a good precision at scales reachable at the LHC.

In order to quantify the effect of the RG running at the TeV scale, we define at the TeV scale:

$$\mathcal{A}_{ij} \;=\; \frac{\left|(a_u)_{ij} - (a_u)_{ji}\right|}{\mathrm{Tr}\{\mathcal{M}_{\tilde{u}}^2\}}$$

This asymmetry does generally not exceed a few percent, as can be seen in the Figure. We are thus interested in testing at the TeV scale the relations:

$$\boxed{y_u \approx y_u^t \quad\text{ and }\quad a_u \approx a_u^t}$$

Strategies for testing the *SU(5)* hypothesis at the TeV scale

Any strategy that can be set up to test the *SU(5)* relation necessarily relies on a comparison involving at least two up-type squarks. Some of the squarks can be light enough to be produced at the LHC, others may be too heavy such that they appear only virtually in intermediate processes. While the treatment of the eigenvalues of rotation matrices is rather technical, depending on the exact pattern of the up-squark mass matrix, two expansions can be used to in order to simplify the problem: the mass insertion approximation (MIA) or the effective field theory expansion (EFT). The feasability of the *SU(5)* tests, depends crucially on the amount of available data, whether they involve real or virtual squarks.

In many classes of physical models, the squark masses exhibit some hierarchy. The physics of the light squarks can then be captured in an effective Lagrangian, where heavy squarks are integrated out. The higher-dimensional operators present in this tree-level Lagrangian will serve as a basis for the *SU(5)* tests based on both virtual and real squarks.

When all up-type squarks are heavier than the typical LHC scale, they can only appear off-shell. Potential tests of the *SU(5)* hypothesis are thus based on virtual squarks only. All squarks can be integrated out and the effective Lagrangian contains the SM plus possibly other light SUSY particles. If the whole SUSY spectrum is heavy, operators of interest are stemming from one-loop diagrams involving at least one Higgs-squark-squark vertex together with fermions on the outgoing legs in order to access information on the flavour structure. We propose *SU(5)* tests for this scenario in the publications indicated above. Moreover, tests involving ultrapheripheral searches are proposed.

If the relative mass difference of the squarks is small, the mass insertion approximation (MIA) can be applied. The *SU*(5) relation of our interest then translates into a relation between the corresponding mass insertions. Note that the MIA is valid also in the case where only a subset of the squark mass eigenstates is nearly degenerate.

Finally, if the *SU(5)* test consists of a simple relation, e.g. between event rates at the LHC, a frequentist *p*-value can be used to evaluate the potential of the test. For the tests proposed in the publications above, we systematically report the power of the test based on this *p*-value analysis.

Natural Supersymmetry

As an example, let us consider the case of natural Supersymmetry. The mass spectrum of this scenario features a first and second generation of squarks that are considerably heavier than those of the third generation. Here, the effective theory will contain two mostly stop-like squarks. Their mixing is not constrained and can potentially be large, which is often needed to satisfy the Higgs-mass constraint. The effective operators that appear when integrating out the heavier squarks can potentially induce flavour-changing stop decays. We assume that both stops are produced at the LHC.

In the case where $m_{\tilde{t}_{1,2}} > m_{\tilde{W}} > m_{\tilde{B}}$, the stops may decay either into the lightest ($\tilde{B}$) and the second-lightest neutralino ($\tilde{W}$). In order to build a *SU(5)* test, we are interested in the flavour-changing decays

$$\boxed{\tilde{t} \;\rightarrow\; \tilde{W}\; u/c \;\rightarrow\; \tilde{B}\; Z/h\; u/c} \quad\text{ and }\quad \boxed{\tilde{t} \;\rightarrow\; \tilde{B}\; u/c}.$$

We assume that the stop masses are unknown and that only the event rates of the above processes, respectively denoted by N_Y and N_L, are experimentally accessible. Moreover, we assume that a certain fraction, denoted by N_Y^c and N_L^c can be charm-tagged. Assuming the same charm-tagging efficiency, the relation constituting the *SU(5)* test is:

$$\boxed{\frac{N_Y^c}{N_L^c} = \frac{N_Y^{\not c}}{N_L^{\not c}}}$$

The expected precision associated to this test has been evaluated. Testing the relation with 50% (10%) precision at 3σ requires $N_Y \sim N_L \sim 110\ (2700)$ events. For comparison, assuming flavour-violating branching ratios of 0.05 and 300 fb^{-1}, we expect 1340 (11) events for $m_{\tilde{t}}$=700 (1400) GeV.

For the case $m_{\tilde{W}} > m_{\tilde{t}_{1,2}} > m_{\tilde{B}}$, the stops decay only into the bino according to $\tilde{t} \;\rightarrow\; t_{L,R}\tilde{B}$. Performing top polarimetry on a decaying stop pair potentially gives access to the stop mixing angle. The same kind of procedure also provides a *SU(5)* test. Let us assume that the spin of the tops is analyzed through distributions of the form $(1+\kappa P_t z)$ with $z \in [-1,1]$. The decays of the stops $\tilde{t}_a$ and $\tilde{t}_b$ leading to the event rates N_a and N_b are then splitted over $D_- = [-1,0]$ and $D_+ = [0,1]$ such that

$$\boxed{N_a = N_{a+} + N_{a-} \quad\text{ and }\quad N_b = N_{b+} + N_{b-}}$$

These event rates satisfy a non-trivial relation if the *SU(5)* hypothesis is verified. With a spin analyzer of efficiency $\kappa = 0.5$ and $N_a = 20$, $N_b \gtrsim 137$ events are needed to probe the relation at 3σ. Testing the relation with 50% (20%) precision requires $N_b \approx 589\ (7560)$. For comparison, for 300 fb^{-1} one expects about 26700 (213) events for stop masses of 700 (1400) GeV.

Top-charm Supersymmetry

As second example, let us consider the case where only the first generation of squarks is heavy, while stop and scharm states are potentially accessible at the LHC. Phenomenologically, this framework constitutes an ideal playground to gain knowledge about how to test the *SU(5)* hypothesis.

We first consider a case where all stop and scharm masses are nearly degenerate. This implies that the mass insertion approximation (MIA) is valid for the sector of stops and scharms, and that these states should be produced in equally abundant way at the LHC. The off-diagonal elements of the trilinear up-type matrix are identified with mass insertions $(\delta_u^{LR})_{ij}$ and the *SU(5)* hypothesis implies:

$$\boxed{(\delta_u^{LR})_{23} \approx (\delta_u^{LR})_{32}}$$

These mass insertions are related to the squark-Higgs scalar coupling, such that one may use the Higgs as a probe of the squark mass eigenstates. The LHC processes of interest are thus stop and scharm production, followed by a flavour-violating decay into a squark and a Higgs in one of the decay chains. We further assume that the squarks decay into the bino. These processes can be identified requiring a single top, a hard jet, a Higgs, and large missing energy. This test has to rely on a distinction between the chiralities, which is possible only for the top quark. Provided that the cascade decay with $\tilde{c}_L \rightarrow h\tilde{t}_R$ can be isolated, top polarimetry then readily provides a *SU(5)* test, since

$$\boxed{\mathrm{BR}(\tilde{c}_L \rightarrow h\tilde{t}_R) \propto |\delta_{23}^{LR}|^2 \quad\text{ and }\quad \mathrm{BR}(\tilde{c}_R \rightarrow h\tilde{t}_L) \propto |\delta_{32}^{LR}|^2}$$

In the case of large stop mixing, while the scharm masses are still nearly degenerate, the MIA applies to the scharm sector only, while the stops have to be rotated in their mass eigenbasis. Assuming the mass hierarchy $m_{\tilde{t}_2} > m_{\tilde{c}} > m_{\tilde{t}_1}$, the SUSY cascade decays are rather different from the situation discussed above. Flavour changing scharm decays going through $\tilde{t}_2$ are now suppressed such that top polarimetry is not useful anymore. Real decays

$$\boxed{\tilde{t}_2 \rightarrow h\tilde{c} \quad\text{ and }\quad \tilde{c} \rightarrow h\tilde{t}_1}$$

are now opened. We require again a single top, a hard jet, a Higgs, and large missing energy from both sides of the decay chains. The *SU(5)* test can then be build from the numbers N_{hj} and N_{ht} of events corresponding to the two above decay modes. Assuming $N_{hj} \ll N_{ht}$ and $\theta_{\tilde{t}} = 0.4$, testing the relation with 50% (10%) precision at 3σ requires $N_{hj} \gtrsim 19\ (464)$ events, respectively. Roughly twice less events are needed for $\theta_{\tilde{t}} = 0$. For comparison, assuming flavour-violating branching ratios of 0.05 and 300 fb^{-1}, one expects about 1340 (11) events for squark masses of 700 (1400) GeV.

Conclusions and outlook

We elaborate on the relation $a_u = a_u^\dagger$, indicating that the up-squark trilinear coupling matrix is symmetric at the GUT scale if one assumes an SU(5)-like grand unification. This relation is found to survive to good approximation through the MSSM renormalization group running, such that it is spoiled by O(1%) of relative error at the TeV scale. This relation can thus be taken as a window to GUT physics. All *SU(5)* tests based on this property have to rely on either flavour violation or chirality flip in the up-type sector. We propose several tests for the LHC.

In many cases, the tests we find consist in determining whether a relation among certain observables (e.g. event rates) is satisfied or not. In order to quantify the feasibility of the test, we introduce a systematic procedure relying on a frequentist *p*-value. The associated expected precision tells, for a given amount of data, up to which magnitude a violation of the *SU(5)* relation can be assessed within a given statistical significance.

The *SU(5)* tests proposed in the above publications are summarized in the Table beneath. The typical amount of events needed to reach an expected precision of 50% at 3σ is also shown for each test. The number of needed events ranges roughly from 10 to 100. In cases where no simple relation between certain observables can be defined, a more global hypothesis testing has to be performed. This is subject to ongoing work.

	Heavy	Natural SUSY		Top-charm SUSY	
	SUSY	$m_{\tilde{t}_{1,2}} > m_{\tilde{B},\tilde{W}}$	$m_{\tilde{W}} > m_{\tilde{t}_{1,2}} > m_{\tilde{B}}$	$m_{\tilde{t}_{L,R}} \sim m_{\tilde{c}_{L,R}}$	$m_{\tilde{t}_2} > m_{\tilde{c}_{L,R}} > m_{\tilde{t}_1}$
Squarks involved	virtual	virtual/real		real	
Top polarimetry	yes	no	yes	yes	no
Charm-tagging	no	yes	no	no	no
Higgs detection	no	no	no	yes	yes
θ_t-dependence	no	no	yes	no	yes
$P_3 = 50\%$	144	72	108	144	10