Tasting SU(5) at the LHC

Sylvain Fichet
ICTP/SAIFR, Sao Paulo
17/01/15

based on 1403.3397 (PLB), 1501.05307 (JHEP),
with B. Herrmann and Y. Stoll

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1. Testing GUTs via accidental symmetries
2. Testing the supersymmetric SU(5) GUT
3. Heavy SUSY spectrum
4. Natural SUSY spectrum
5. Top-charm SUSY spectrum
6. Summary and outlook

Testing GUTs via accidental symmetries

Grand unification

- GUT: the Sandard Model interactions unify into a simple group at some higher scale

$$SU(3) \otimes SU(2)_L \otimes U(1)_Y \in G_{GUT}$$

Examples: $G_{GUT} = SU(5), SO(10), E_6$

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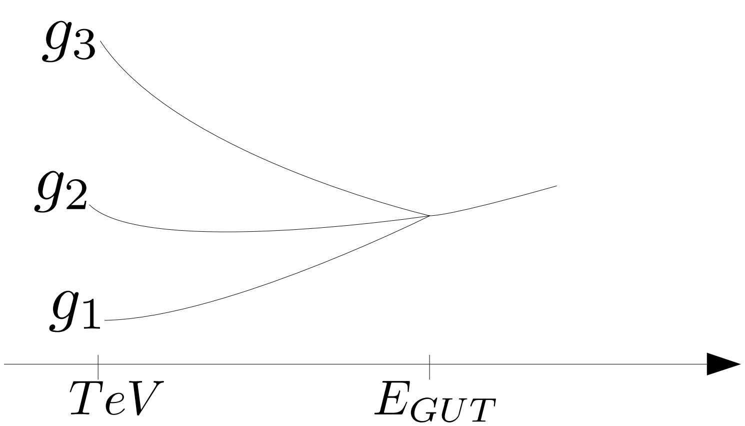
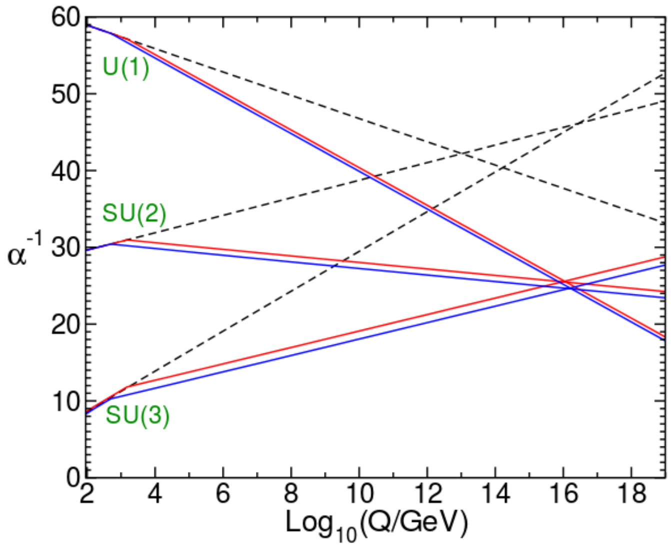
- Net prediction: gauge couplings unification



expected



observed

Matter unification

- Matter unification: SM fermions should fit complete representations of G_{GUT}
  (This is the most minimal/elegant choice for model-building)

$$\mathcal{R}_i \supset \psi_{i\,\mathrm{SM}}, \psi'_{i\,\mathrm{SM}} \cdots$$

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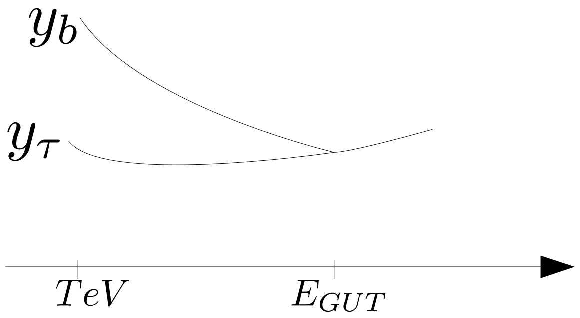
- Matter unification implies relations between couplings in the matter sector of the GUT-scale SM Lagrangian because

$$\mathcal{L} \supset \lambda_{ij}\mathcal{H}\mathcal{R}_i\mathcal{R}_j \supset \lambda_{ij} H \psi_i \psi'_j + \lambda_{ij} H \psi''_i \psi'''_j + \dots$$

- For example:



Matter unification

- In the past decades: a lot of model-building to reconciliate the GUT relations from matter unification with the observed fermion masses and mixings. (SUSY, family symmetries, higher dimensional operators...)
- See for example

[5] B. Ananthanarayan, G. Lazarides and Q. Shafi, "Top mass prediction from supersymmetric guts," Phys. Rev. D **44**, 1613 (1991).

[6] B. Ananthanarayan, G. Lazarides and Q. Shafi, "Radiative electroweak breaking and sparticle spectroscopy with tan Beta approximately = m(t) / m(b)," Phys. Lett. B **300**, 245 (1993).

[7] G. W. Anderson, S. Raby, S. Dimopoulos and L. J. Hall, "Precise predictions for m(t), V(cb), and tan Beta," Phys. Rev. D **47**, 3702 (1993) [hep-ph/9209250].

[8] G. Anderson, S. Raby, S. Dimopoulos, L. J. Hall and G. D. Starkman, "A Systematic SO(10) operator analysis for fermion masses," Phys. Rev. D **49**, 3660 (1994) [hep-ph/9308333].

[9] M. B. Einhorn and D. R. T. Jones, "The Weak Mixing Angle and Unification Mass in Supersymmetric SU(5)," Nucl. Phys. B **196**, 475 (1982).

[10] M. S. Carena, M. Olechowski, S. Pokorski and C. E. M. Wagner, "Electroweak symmetry breaking and bottom - top Yukawa unification," Nucl. Phys. B **426**, 269 (1994) [hep-ph/9402253].

[11] B. Ananthanarayan, Q. Shafi and X. M. Wang, "Improved predictions for top quark, lightest supersymmetric particle, and Higgs scalar masses," Phys. Rev. D **50**, 5980 (1994) [hep-ph/9311225].

[12] R. Rattazzi and U. Sarid, "The Unified minimal supersymmetric model with large Yukawa couplings," Phys. Rev. D **53**, 1553 (1996) [hep-ph/9505428].

[13] T. Blazek and S. Raby, "Supersymmetric grand unified theories and global fits to low-energy data," Phys. Lett. B **392**, 371 (1997) [hep-ph/9611319].

[14] S. Profumo, "Neutralino dark matter, b tau Yukawa unification and nonuniversal sfermion masses," Phys. Rev. D **68**, 015006 (2003) [hep-ph/0304071].

[15] C. Pallis, "b tau unification with gaugino and sfermion mass nonuniversality," Nucl. Phys. B **678**, 398 (2004) [hep-ph/0304047].

[16] M. E. Gomez, G. Lazarides and C. Pallis, "Supersymmetric cold dark matter with Yukawa unification," Phys. Rev. D **61**, 123512 (2000) [hep-ph/9907261].

[17] M. E. Gomez, G. Lazarides and C. Pallis, "Yukawa quasi-unification," Nucl. Phys. B **638**, 165 (2002) [hep-ph/0203131].

[18] U. Chattopadhyay, A. Corsetti and P. Nath, "Supersymmetric dark matter and Yukawa unification," Phys. Rev. D **66**, 035003 (2002) [hep-ph/0201001].

[19] M. Badziak and K. Sakurai, "LHC constraints on Yukawa unification in SO(10)," JHEP **1202**, 125 (2012) [arXiv:1112.4796 [hep-ph]].

[20] M. Badziak, "Yukawa unification in SUSY SO(10) in light of the LHC Higgs data," Mod. Phys. Lett. A **27**, 1230020 (2012) [arXiv:1205.6232 [hep-ph]].

[21] A. S. Joshipura and K. M. Patel, "Yukawa coupling unification in $SO(10)$ with positive μ and a heavier gluino," Phys. Rev. D **86**, 035019 (2012) [arXiv:1206.3910 [hep-ph]].

[22] H. Baer, M. A. Diaz, J. Ferrandis and X. Tata, "Sparticle mass spectra from $SO(10)$ grand unified models with Yukawa coupling unification," Phys. Rev. D **61**, 111701 (2000) [hep-ph/9907211].

[23] D. Auto, H. Baer, C. Balazs, A. Belyaev, J. Ferrandis and X. Tata, "Yukawa coupling unification in supersymmetric models," JHEP **0306**, 023 (2003) [hep-ph/0302155].

[24] T. Blazek, R. Dermisek and S. Raby, "Yukawa unification in SO(10)," Phys. Rev. D **65**, 115004 (2002) [hep-ph/0201081].

[25] R. Dermisek, S. Raby, L. Roszkowski and R. Ruiz de Austri, "Dark matter and B(s) —¿ mu+ mu- with minimal SO(10) soft SUSY breaking II," JHEP **0509**, 029 (2005) [hep-ph/0507233].

[26] H. Baer, S. Kraml, S. Sekmen and H. Summy, "Dark matter allowed scenarios for Yukawa-unified SO(10) SUSY GUTs," JHEP **0803**, 056 (2008) [arXiv:0801.1831 [hep-ph]].

[27] W. Altmannshofer, D. Guadagnoli, S. Raby and D. M. Straub, "SUSY GUTs with Yukawa unification: A Go/no-go study using FCNC processes," Phys. Lett. B **668**, 385 (2008) [arXiv:0801.4363 [hep-ph]].

[28] I. Gogoladze, R. Khalid, S. Raza and Q. Shafi, "$t-b-\tau$ Yukawa unification for $\mu < 0$ with a sub-TeV sparticle spectrum," JHEP **1012**, 055 (2010) [arXiv:1008.2765 [hep-ph]].

[29] I. Gogoladze, R. Khalid, S. Raza and Q. Shafi, "Higgs and Sparticle Spectroscopy with Gauge-Yukawa Unification," JHEP **1106**, 117 (2011) [arXiv:1102.0013 [hep-ph]].

[30] G. Elor, L. J. Hall, D. Pinner and J. T. Ruderman, "Yukawa Unification and the Superpartner Mass Scale," JHEP **1210**, 111 (2012) [arXiv:1206.5301 [hep-ph]].

[31] H. Baer, S. Kraml and S. Kulkarni, "Yukawa-unified natural supersymmetry," JHEP **1212**, 066 (2012) [arXiv:1208.3039 [hep-ph]].

[32] M. Iskrzynski and K. Kowalska, "Exact SU(5) Yukawa matrix unification in the General Flavour Violating MSSM," arXiv:1412.8651 [hep-ph].

Are GUT mass relations the only prediction of matter unification?

Matter unification

- Consider again $\mathcal{L} \supset \lambda_{ij}\mathcal{H}\mathcal{R}_i\mathcal{R}_j$, and notice that

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  ⇨ Matter unification implies accidental permutation symmetries in flavour space.

- One expects such accidental symmetries to survive at low-energy:

$$16\pi^2 \beta_{y_u} = y_u (3\mathrm{tr}(y_u^\dagger y_u) + 3 y_u^\dagger y_u + \underbrace{y_d^\dagger y_d}_{\text{Only term that spoils the symmetry}} - \frac{16}{3} g_1^2 - 3 g_2^2 - \frac{15}{3} g_1^2)$$

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- Caution: the permutation symmetry should remain up to low-energy in this new sector

Matter unification

- These new degrees of freedom are heavy, so one can integrate them out. The subsequent effective Lagrangian
$$\mathcal{L}_{\rm eff} = \mathcal{L}_{\rm SM} + \mathcal{L}_5 + \mathcal{L}_6 + O\left(\Lambda^{-3}\right)$$
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- Thus dipole operators and Yukawa-like operators

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  1) Discover one of these operators

  2) Find observables to probe the non-diagonal elements of $\kappa_{ij},\ \mu_{ij}$

  $\Longrightarrow$ Will involve flavour violation and requires a sensitivity to chirality

Testing SU(5) SUSY GUTs

SU(5) unification

VOLUME 32, NUMBER 8 PHYSICAL REVIEW LETTERS 25 FEBRUARY 1974

Unity of All Elementary-Particle Forces

Howard Georgi* and S. L. Glashow
Lyman Laboratory of Physics, Harvard University, Cambridge, Massachusetts 02138
(Received 10 January 1974)

Strong, electromagnetic, and weak forces are conjectured to arise from a single fundamental interaction based on the gauge group SU(5).

Testing SU(5)

- Matter unification: Matter fields embedded into SU(5) as

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  New degrees of freedom are needed

- Let us assume supersymmetry. New d.o.f's are the superpartners.

A new SUSY SU(5) relation

- Assume SUSY is broken by a SU(5) singlet. The SU(5) relations are transmitted to the squark and slepton sectors,

$$\mathcal{L}_{\rm soft} \supset a_u^{ij} h_u \tilde{q}_i \tilde{u}_j + a_d^{ij} h_d \tilde{q}_i \tilde{d}_j + a_\ell^{ij} h_{d\,i} \tilde{\ell}_j \tilde{e}$$

(+ soft masses...)

$$a_u = a_u^t \qquad\qquad a_d = a_\ell^t$$

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- The relation is confined to the up-(s)quark sector. SU(5) tests will be based on observables related to chirality flips and/or flavour violation.

$$\mathcal{M}_{\tilde{u}}^2 = \begin{pmatrix} \hat{M}_Q^2 + O(v_u^2)\mathbf{1}_3 & \frac{v_u}{\sqrt{2}}\,\hat{a}_u\,(1 + c_\alpha \frac{h}{v_u} + \ldots) + O(v_u M_{\text{SUSY}})\mathbf{1}_3 \\ \frac{v_u}{\sqrt{2}}\,\hat{a}_u^\dagger\,(1 + c_\alpha \frac{h}{v_u} + \ldots) + O(v_u M_{\text{SUSY}})\mathbf{1}_3 & \hat{M}_U^2 + O(v_u^2)\mathbf{1}_3 \end{pmatrix}$$

Heavy supersymmetry

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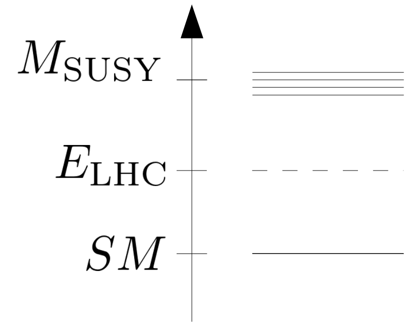
- Assume that the whole SUSY spectrum is too heavy to be produced on-shell. Its low-energy effects are captured into an EFT. The up squark matrix induces flavour-changing top dipoles.



$$
\begin{aligned}
\mathcal{L}^{(6)}_{1-\mathrm{loop}} \supset\ & \frac{\alpha^G_{3i}}{M^2_{\rm SUSY}}\,\bar{t}_L \sigma^{\mu\nu} T^a u_{R\,i} H_u G^a_{\mu\nu} + \frac{\alpha^G_{i3}}{M^2_{\rm SUSY}}\,\bar{u}_{L\,i} \sigma^{\mu\nu} T^a t_R H_u G^a_{\mu\nu} \\
& + \frac{\alpha^W_{3i}}{2\,M^2_{\rm SUSY}}\,\bar{t}_L \sigma^{\mu\nu} u_{R\,i} H_u W^3_{\mu\nu} + \frac{\alpha^W_{i3}}{2\,M^2_{\rm SUSY}}\,\bar{u}_{L\,i} \sigma^{\mu\nu} T^I t_R H_u W^3_{\mu\nu} \\
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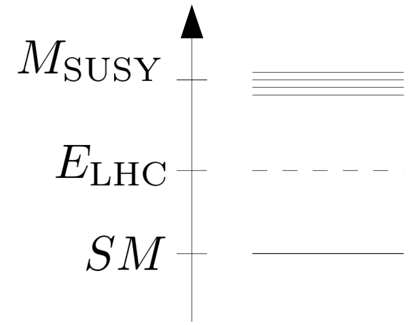

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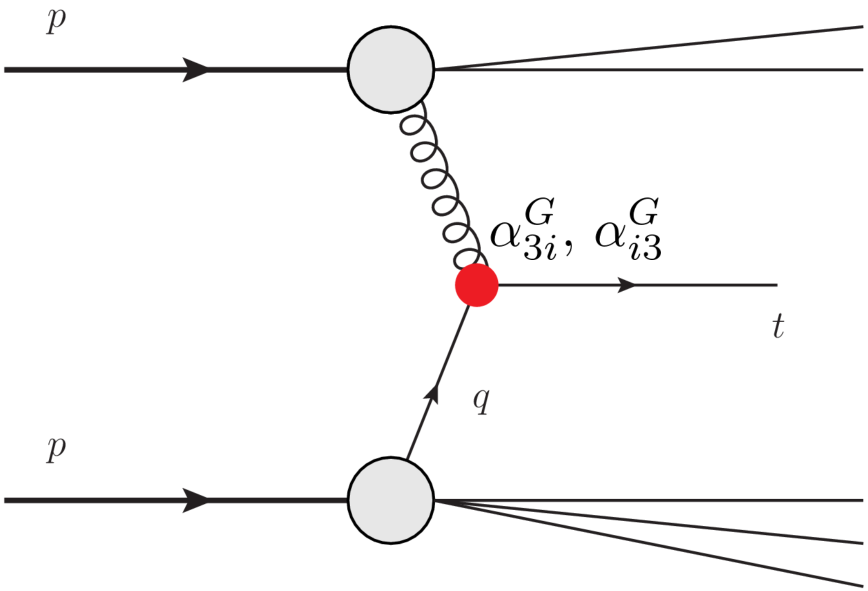
- If the SU(5) hypothesis is true, $a_u \approx a_u^t$ implies

$$\alpha^G_{3i} \approx \alpha^G_{i3}\,, \quad \alpha^W_{3i} \approx \alpha^W_{i3} \quad \alpha^B_{3i} \approx \alpha^B_{i3}$$

Heavy supersymmetry

- LHC:



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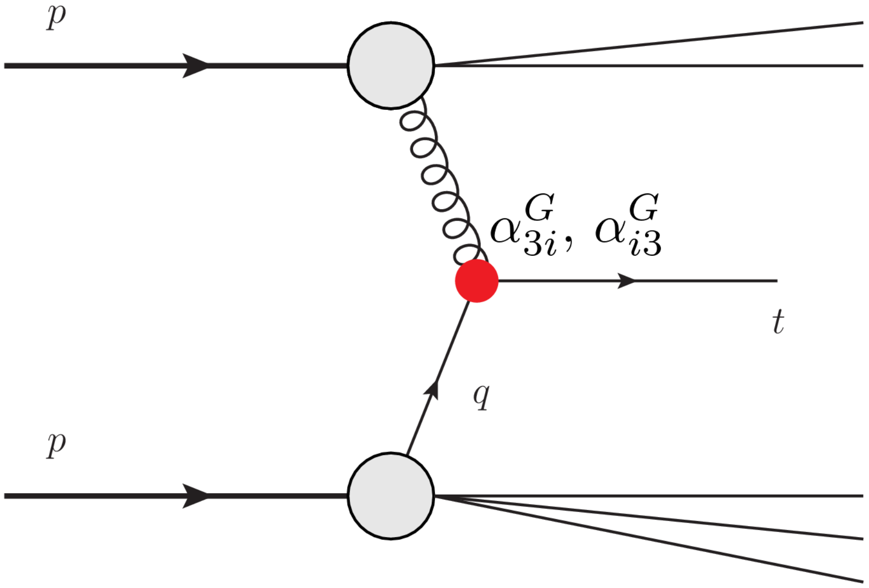


- Using top polarimetry in single top searches, one disentangles between α^G_{3i} and α^G_{i3} . ⇨ SU(5) test doable at the LHC !

Heavy supersymmetry

- Consider a spin-analysing variable z such that $\frac{dN}{N\,dz} = 1 + \kappa P_t z$
- Example: forward-backward assymetry using the lepton-top angle.
- Define the test $R = \frac{2}{\kappa} \frac{|N_+ - N_-|}{N_+ + N_-}$ which satisfies

$$\mathrm{E}(R) = \frac{\left||\alpha_{3i}|^2 - |\alpha_{i3}|^2\right|}{|\alpha_{3i}|^2 + |\alpha_{i3}|^2}$$

Heavy supersymmetry

- A correct evaluation of the power of the test has to involve statistics. Details on the statistical setup are shown in backup slides.

- A benchmark result:

Assessing $$\frac{\left||\alpha_{3i}|^2 - |\alpha_{i3}|^2\right|}{|\alpha_{3i}|^2 + |\alpha_{i3}|^2} > 50\%$$

with a 3 sigma significance and spin-analysing power $\kappa \approx 1$ requires ~144 events.

Heavy supersymmetry

- But dipole coefficients from SUSY are small ! The current LHC searches might not be good enough to even detect SUSY dipoles.

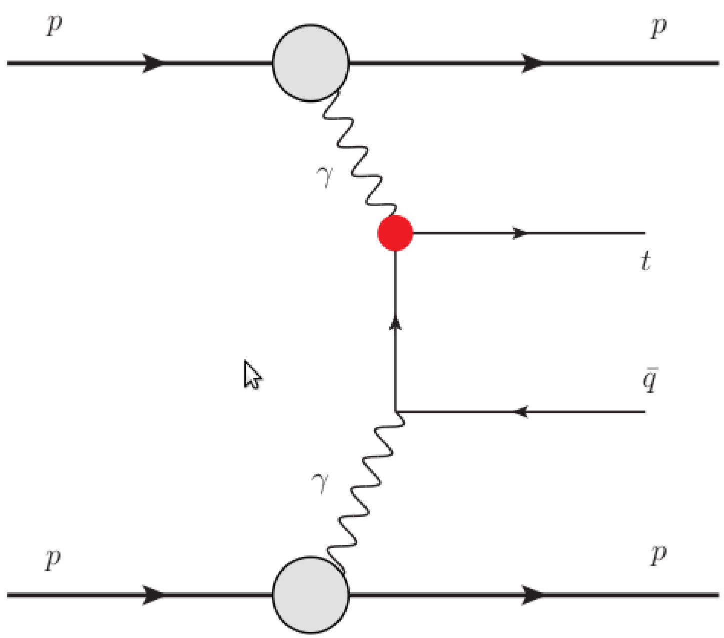
Dipole coefficients combinations	95% CL limits	SUSY
$\left(\lvert\alpha^{\gamma}_{31}\rvert^2 + \lvert\alpha^{\gamma}_{13}\rvert^2\right)^{1/2} M_{\mathrm{SUSY}}^{-2}$	$< 0.19\ \mathrm{TeV}^{-2}$ [58] (CMS)	$7 \cdot 10^{-5}\ \mathrm{TeV}^{-2}$
$\left(\lvert\alpha^{\gamma}_{32}\rvert^2 + \lvert\alpha^{\gamma}_{23}\rvert^2\right)^{1/2} M_{\mathrm{SUSY}}^{-2}$	$< 0.65\ \mathrm{TeV}^{-2}$ [58] (CMS)	$7 \cdot 10^{-5}\ \mathrm{TeV}^{-2}$
$\left(\lvert\alpha^{Z}_{31}\rvert^2 + \lvert\alpha^{Z}_{13}\rvert^2\right)^{1/2} M_{\mathrm{SUSY}}^{-2}$	$< 0.68\ \mathrm{TeV}^{-2}$ [59] (CMS)	$1 \cdot 10^{-4}\ \mathrm{TeV}^{-2}$
$\left(\lvert\alpha^{Z}_{32}\rvert^2 + \lvert\alpha^{Z}_{23}\rvert^2\right)^{1/2} M_{\mathrm{SUSY}}^{-2}$	$< 3.44\ \mathrm{TeV}^{-2}$ [59] (CMS)	$1 \cdot 10^{-4}\ \mathrm{TeV}^{-2}$
$\left(\lvert\alpha^{G}_{31}\rvert^2 + \lvert\alpha^{G}_{13}\rvert^2\right)^{1/2} M_{\mathrm{SUSY}}^{-2}$	$< 0.029\ \mathrm{TeV}^{-2}$ [60] (ATLAS)	$3 \cdot 10^{-4}\ \mathrm{TeV}^{-2}$
$\left(\lvert\alpha^{G}_{32}\rvert^2 + \lvert\alpha^{G}_{23}\rvert^2\right)^{1/2} M_{\mathrm{SUSY}}^{-2}$	$< 0.063\ \mathrm{TeV}^{-2}$ [60] (ATLAS)	$3 \cdot 10^{-4}\ \mathrm{TeV}^{-2}$

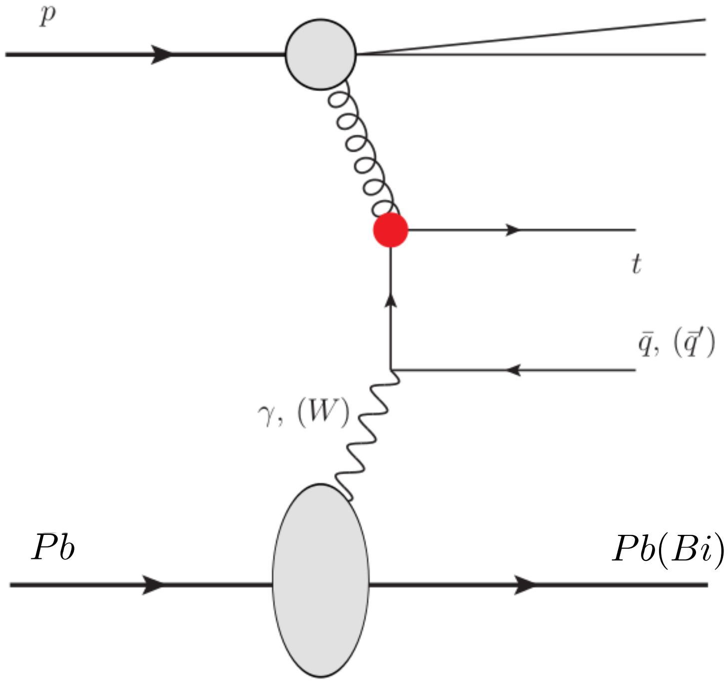
[SF/Herrmann/Stoll '15]

Heavy supersymmetry

- Proposal : dipole searches in ultraperipheral collisions.

- Examples :



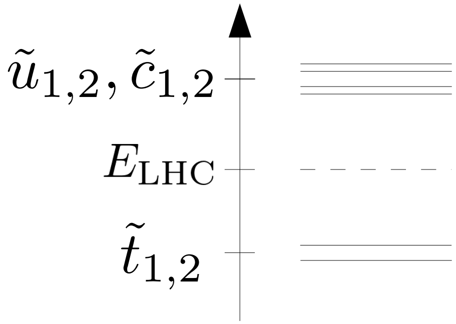


- Never considered before, potentially competes with standard CMS/ATLAS searches. Simulations will be done with the ATLAS Forward Physics group.

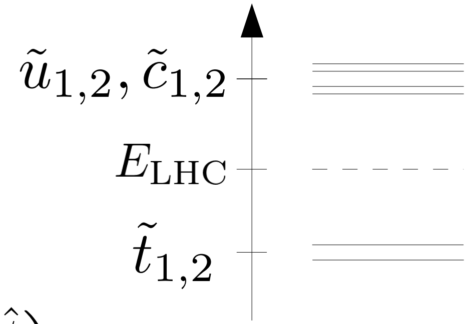
Natural supersymmetry

Natural supersymmetry

- Consider natural supersymmetry spectrum (motivated from naturalness and UV constructions)



Natural supersymmetry



- Consider natural supersymmetry spectrum
  (motivated from naturalness and UV constructions)

- Integrate out heavy squarks:

$$\mathcal{L} \supset \tilde{u}^\dagger \mathcal{M}^2_{\tilde{u}} \tilde{u} \equiv \Phi^\dagger \mathcal{M}^2 \Phi = \left(\hat{\phi}^\dagger, \phi^\dagger\right) \begin{pmatrix} \hat{M}^2 & \tilde{M}^2 \\ \tilde{M}^{2\dagger} & M^2 \end{pmatrix} \begin{pmatrix} \hat{\phi} \\ \phi \end{pmatrix} ,$$

$$\mathcal{L} \supset \left|D\Phi\right|^2 - \Phi^\dagger \mathcal{M}^2 \Phi + \left(\mathcal{O}\phi + \hat{\mathcal{O}}\hat{\phi} + \text{h.c.}\right) ,$$

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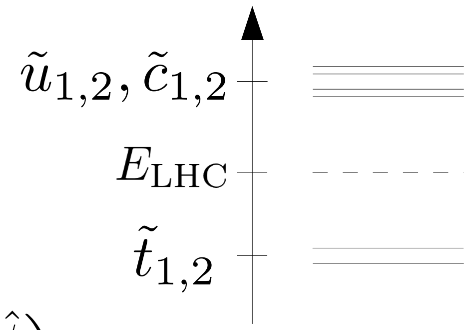

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$$||\hat{M}|| \ll E \quad \Downarrow$$

$$\mathcal{L}_{\rm eff} = \left|D\phi\right|^2 + \Big(\mathcal{O} - \overbrace{\hat{\mathcal{O}}(\hat{M}^{-2} - \hat{M}^{-4}D^2)\tilde{M}^2}^{\text{FV interactions}} - \frac{\mathcal{O}}{2}\overbrace{\tilde{M}^{2\dagger}\hat{M}^{-4}\tilde{M}^2}^{\text{FC corrections}}\Big)\phi + \text{h.c.}$$
$$-\phi^\dagger\left(M^2 - \tilde{M}^{2\dagger}\hat{M}^{-2}\tilde{M}^2 - \frac{1}{2}\left\{\tilde{M}^{2\dagger}\hat{M}^{-4}\tilde{M}^2, M^2\right\}\right)\phi\,.$$

Natural supersymmetry

- Example: Flavour changing test. Assume $m_{\tilde{t}_{1,2}} > m_{\tilde{W}} > m_{\tilde{B}}$, as motivated by typical GUT spectrum.

- Measure $\underset{(N_Y)}{\tilde{t} \to \tilde{B}\, u/c}$ $\quad \tilde{t} \to \underset{(N_L)}{\tilde{W}\, u/c} \to \tilde{B}\, Z/h\, u/c\,,$

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- If the SU(5) hypothesis is verified, then

$$\mathrm{E}\left[\frac{N_Y^c}{N_L^c}\right] = \mathrm{E}\left[\frac{N_Y^{\not{c}}}{N_L^{\not{c}}}\right]$$

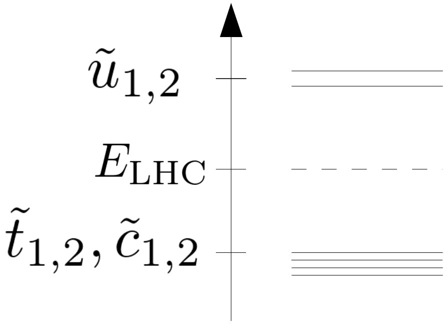
- A benchmark result:

  Testing a 50% discrepancy in this relation within 3 sigma significance, assuming a true charm fraction of 0.5 and a charm-tagging efficiency of 0.5 requires ~72 events.

Top-charm supersymmetry

Top-charm supersymmetry

- We advocate the top-charm spectrum. Known to improve stop bounds, flavour constraints, fine-tuning. [Blanke/Giudice/Paradisi/Perez/Zupan '13]



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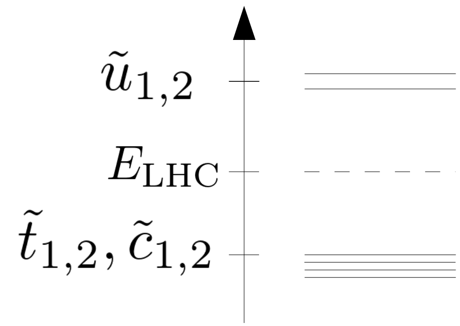
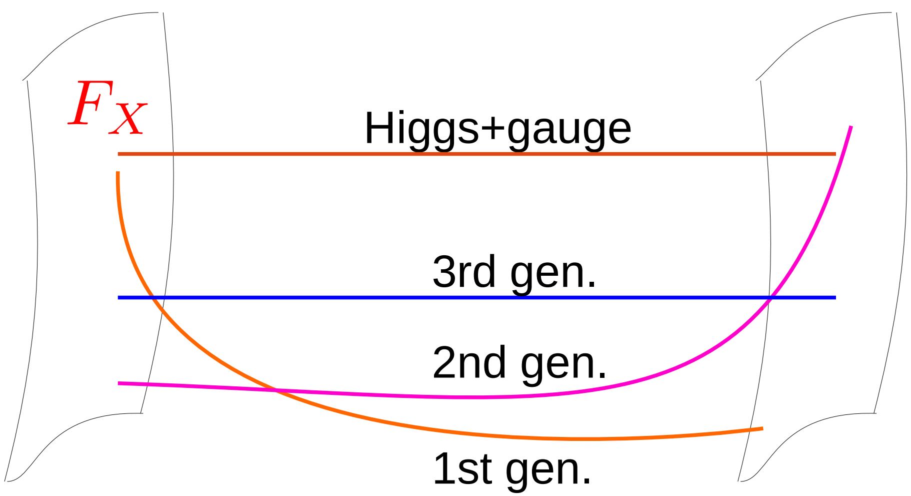


- Motivated from 5d GUTs [SF/Herrmann/Stoll '15]
  Example: a flat $O(M_{GUT})$ extradimension with gauge-Higgs unification, with Scherk-Schwarz SUSY breaking and a brane source F_X



Bulk masses :

$a_1/R > 0$

$a_2/R < 0$

$a_3/R \sim 0$

$\approx m^2_{Q,U,3}$

$$m_Q^2 = m_U^2 \approx \mathrm{diag}\left[\left(\frac{F_X}{M_*^2}\right)^2 \frac{a_1}{\pi R M_*},\ 0\ ,\ \left(\frac{F_T}{2R}\right)^2 + \left(\frac{F_X}{M_*^2}\frac{1}{\pi R M_*}\right)^2\right] + K_3 M_{1/2}$$

Top-charm supersymmetry

- The four stops and scharms are in general mixed. How to extract the relevant information about SU(5) ? Crucial observation : observing a Higgs in final state gives direct access to the LR mixing.

$$\mathcal{M}^2_{\tilde{u}} = \begin{pmatrix} \hat{M}^2_Q + O(v_u^2)\mathbf{1}_3 & \frac{v_u}{\sqrt{2}}\,\hat{a}_u\,(1 + c_\alpha \frac{h}{v_u} + \ldots) + O(v_u M_{\mathrm{SUSY}})\mathbf{1}_3 \\ \frac{v_u}{\sqrt{2}}\,\hat{a}_u^\dagger\,(1 + c_\alpha \frac{h}{v_u} + \ldots) + O(v_u M_{\mathrm{SUSY}})\mathbf{1}_3 & \hat{M}^2_U + O(v_u^2)\mathbf{1}_3 \end{pmatrix}. \quad (2.5)$$

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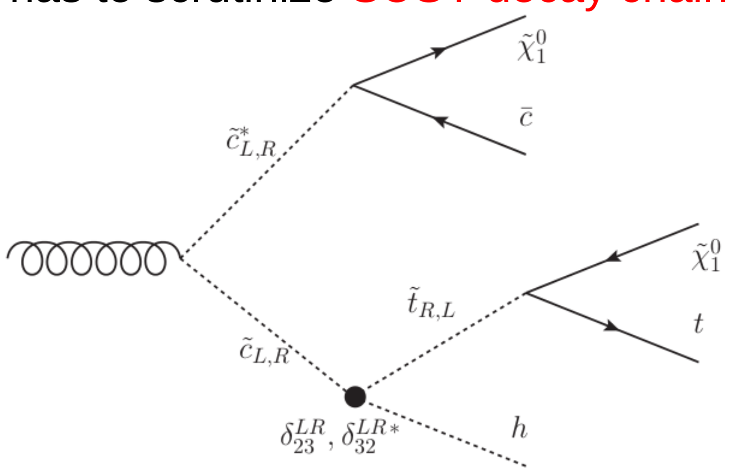
- Therefore one has to scrutinize SUSY decay chains with flavour violation and a Higgs, such like



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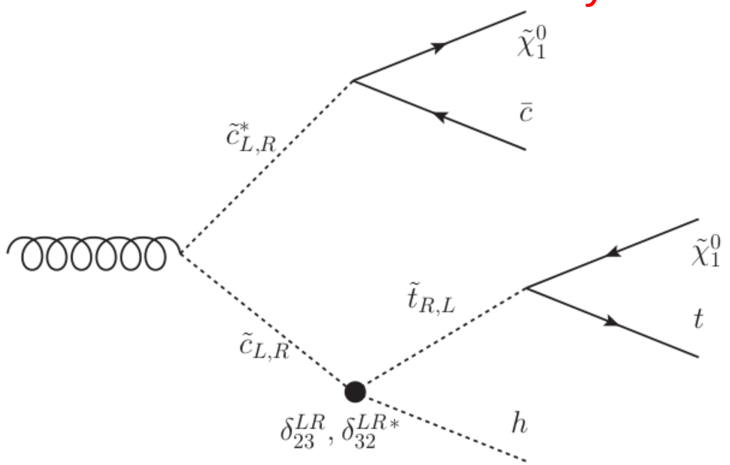


- Not so easy to find tests based on simple relations.

⇨ Good playground for global tests. [SF/Herrmann/Stoll, in progress]

Summary

- Grand unification is a major idea of high-energy physics, but is hard to test.
- We point out that accidental permutation symmetries in flavour space implied by matter unification can remain at low-energy, and can be tested if new dof's are present.
- Such tests can be done via dimension-6 effective operators (dipoles and Yukawa-like).
  ⇨ STAY TUNED

Summary

- Focus on SUSY SU(5). The tests involve up squarks, with observables sensitive to flavour violation and chirality.

- We work out some SU(5) tests in typical SUSY spectra.

	Heavy SUSY	Natural SUSY		Top-charm 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

- Tests based on simple relations. Easy to implement in a SUSY pheno study. Other simple tests can be found – just try!

- More generally a global hypothesis test has to be performed. A work using Bayesian techniques is ongoing. [SF, Herrmann, Stoll, in progress]

Thank you !

Search strategies

- Any SU(5) test relying on $a_u = a_u^t$ requires to measure the effects of at least two squarks (could be either virtual or real squarks).
- The low-energy SUSY spectrum is in principle arbitrary. We will focus on typical cases. We search for exact relations (we do not pursue in the direction of global tests in this talk)
- Useful tools:

If hierarchical mass eigenvalue: E/M expansion (EFT)

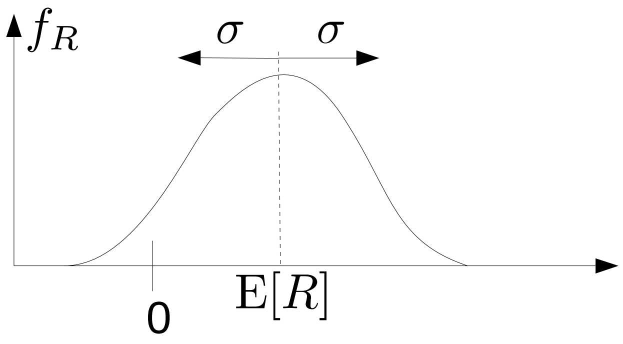
Close mass eigenvalues hierarchy: $\Delta M/M$ expansion (MIA)

Evaluating the potential of a test

- Assume some projected data (say 13 TeV LHC with 300 fb^-1), and a given SU(5) test. How to properly quantify the power of the test ?

- The evaluation has to involve both a statistical significance and the precision at which the SU(5) relation is tested.

- Consider a relation $R(O)$ among some observables. If the SU(5) hypothesis is true, then $\mathrm{E}[R(O)] = 0$. Assume a variance σ^2 and a nearly Gaussian statistics for R .



- Compatibility of $\hat{R}$ with zero is given by $Z = \hat{R}/\sigma$

Evaluating the potential of a test

- The quantity $Z\sigma$ contains all the information about the compatibility with zero.

- Define $P_Z = Z\sigma$ as the expected precision of the test. One can compute it analytically for a given test, from $\sigma = V[R[O]]^{1/2}$.

- For example:

$P_Z = 20\%$ means that a violation of the relation $\mathrm{E}[R] = 0$ by 20% or more (i.e. $\mathrm{E}[R] > 20\%$) can be assessed with a significance of $Z\sigma$.

Heavy supersymmetry

- Coming back to heavy SUSY : consider the SU(5) relation $\alpha_{3i} = \alpha_{i3}$
- Consider a spin-analysing variable z such that $\dfrac{dN}{N\,dz} = 1 + \kappa P_t z$
- Define the test $R = \dfrac{2}{\kappa} \dfrac{|N_+ - N_-|}{N_+ + N_-}$ which satisfies

$$\mathrm{E}(R) = \frac{\left||\alpha_{3i}|^2 - |\alpha_{i3}|^2\right|}{|\alpha_{3i}|^2 + |\alpha_{i3}|^2}$$

- Computing the variance of R, one gets the expected precision

$$P_Z = Z \frac{2}{\kappa} \frac{(N+B)^{1/2}}{N}$$

Heavy supersymmetry

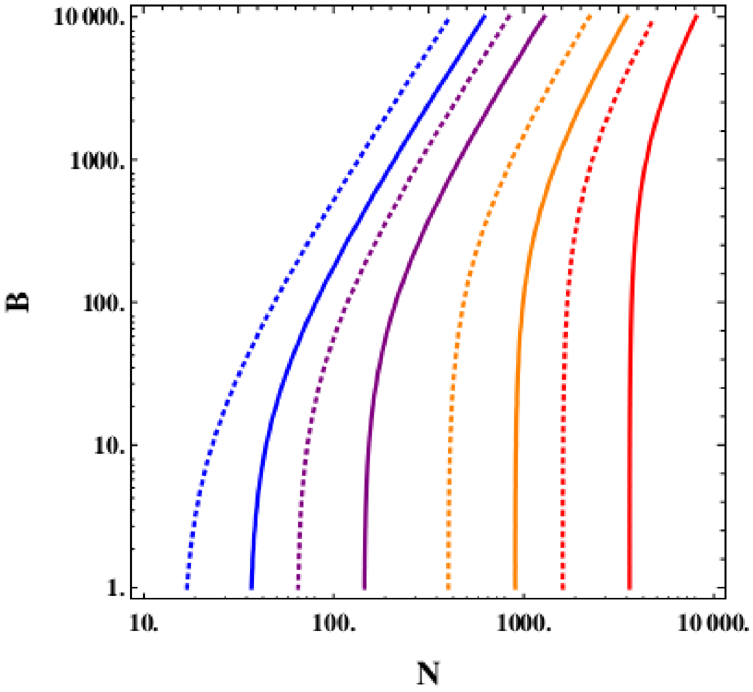


Figure 3. Expected precision P_Z for top-polarization based $SU(5)$-tests as a function of the total number of signal and background events N and B. The spin-analyzing power is fixed to $\kappa = 1$. Plain (dotted) lines denote 2σ (3σ) significance, respectively. Blue, purple, orange, and red lines respectively show $P_{2,3} = 100\%,\ 50\%,\ 20\%,\ 10\%$ isolines of expected precision.

Natural supersymmetry

- Example: Flavour changing test. Assume $m_{\tilde{t}_{1,2}} > m_{\tilde{W}} > m_{\tilde{B}}$, as motivated bu typical GUT spectrum.

- Measure $\underset{(N_Y)}{\tilde{t} \rightarrow \tilde{B}\, u/c}$ $\quad \underset{(N_L)}{\tilde{t} \rightarrow \tilde{W}\, u/c} \rightarrow \tilde{B}\, Z/h\, u/c\,,$

- If the SU(5) hypothesis is verified, then

$$\mathrm{E}\left[\frac{N_Y^c}{N_L^c}\right] = \mathrm{E}\left[\frac{N_Y^{\not c}}{N_L^{\not c}}\right]$$

- Expected precision is

$$P_Z = \frac{Z}{2\epsilon_c^{1/2}}\left(\frac{1}{N_Y}+\frac{1}{N_L}\right)^{1/2}\left(\frac{1}{\gamma}+\frac{1}{\gamma-1}-\frac{(1-\epsilon_c)\gamma}{(\gamma-1)^2}\right)^{1/2}.$$

with $\mathrm{E}[N_Y^c] = \epsilon_c \gamma_Y \mathrm{E}[N_Y]\,, \qquad \mathrm{E}[N_L^c] = \epsilon_c \gamma_L \mathrm{E}[N_L]\,,$

Natural supersymmetry

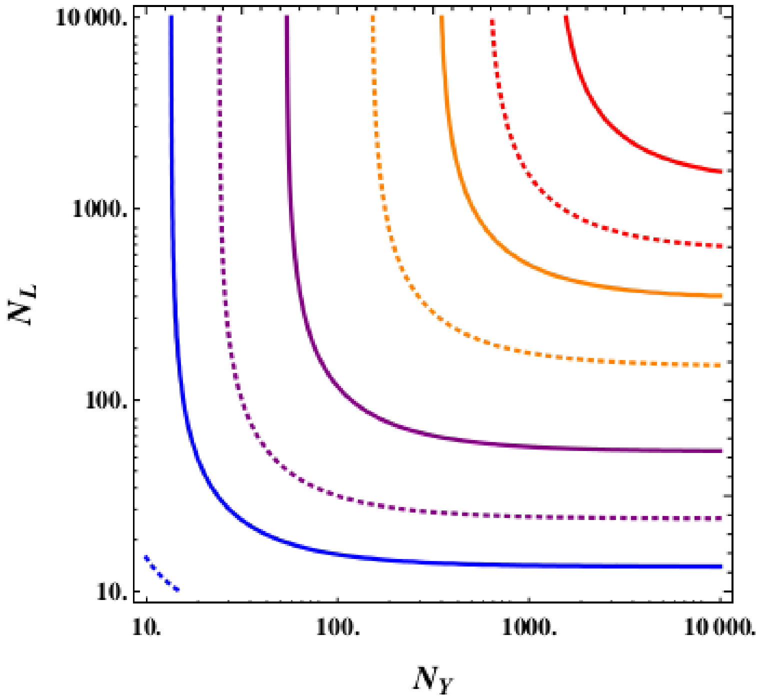


Figure 5. Expected precision P_Z for the $SU(5)$ test on flavour-changing stop decays Eq. (6.3). N_Y and N_L are the numbers of observed stop decays to bino and wino, respectively. The charm fraction is fixed to $\gamma = 0.5$ and the charm-tagging efficiency to $\epsilon_c = 0.5$. Plain (dotted) lines denote 2σ (3σ) significance respectively. Blue, purple, range and red lines respectively show $P_{2,3} = (100\%, 50\%, 20\%, 10\%)$ isolines of the expected precision.