Unification without Doublet-Triplet Splitting — SUSY Exotics at the LHC

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W. Kilian, J. Reuter, PLB **B642** (2006), 81, and work in progress (with F. Deppisch)

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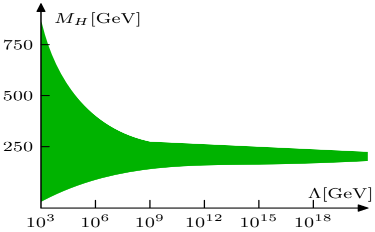
The Standard Model (SM) – Theorist's View

Renormalizable Quantum Field Theory (only with Higgs!) based on $SU(3)_c \times SU(2)_L \times U(1)_Y$ *non-simple* gauge group

Reducible representation:

$$\begin{aligned} & q\,(\mathbf{3},\mathbf{2})_{\frac{1}{3}} && \oplus && \ell\,(\mathbf{1},\mathbf{2})_{-1} \\ \oplus\; & u^c\,(\overline{\mathbf{3}},\mathbf{1})_{-\frac{4}{3}} && \oplus && d^c\,(\overline{\mathbf{3}},\mathbf{1})_{\frac{2}{3}} \\ \oplus\; & e^c\,(\mathbf{1},\mathbf{1}) && \oplus && H\,(\mathbf{1},\mathbf{2})_1 \end{aligned}$$



Incompleteness

- Electroweak Symmetry Breaking
- Higgs boson
- Origin of neutrino masses
- Dark Matter: $m_{DM} \sim 100\,\mathrm{GeV}$

Theoretical Dissatisfaction

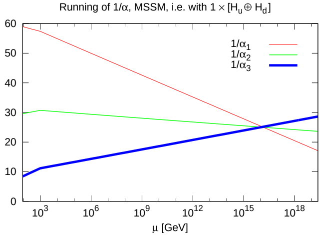
- 28 free parameters
- "strange" fractional $U(1)$ quantum numbers
- Hierarchy problem

Conventional and MSSM Unification

1971–74 Supersymmetry: consistent extrapolation to high scales

- $\Rightarrow$ unification quantitatively testable (assuming a given spectrum)
- $\Rightarrow$ two Higgs doublets H^u, H^d
- $\Rightarrow$ superpartners for all SM particles, presumably in the TeV range

Bottom-Up Approach: *just MSSM*



1973 Unification of leptons and quarks by Pati/Salam:

$$G_{\text{SM}} \subset G_{\text{PS}} = SU(4)_c \times SU(2)_L \times SU(2)_R \times Z_2$$

Each matter family in irreducible rep. (incl. ν_R, 2nd Higgs doublet):

1974 Unification of gauge couplings by Georgi/Glashow:

$$G_{\text{SM}} \subset G_{\text{GG}} = SU(5)$$

Matter representation for $SU(5)$ is reducible (classically)
Simple-group unification: partial unification of leptons/quarks

The prime example: (SUSY) $SU(5)$

$$SU(5) \underset{M_X}{\longrightarrow} SU(3)_c \times SU(2)_w \times U(1)_Y \underset{M_Z}{\longrightarrow} SU(3)_c \times U(1)_{em}$$

$SU(5)$ has $5^2 - 1 = 24$ generators:

$$\mathbf{24} \to \underbrace{(\mathbf{8},\mathbf{1})_0}_{G^\beta_\alpha} \oplus \underbrace{(\mathbf{1},\mathbf{3})_0}_{W} \oplus \underbrace{(\mathbf{1},\mathbf{1})_0}_{B} \oplus \underbrace{(\mathbf{3},\mathbf{2})_{\frac{5}{3}}}_{X,Y} \oplus \underbrace{(\bar{\mathbf{3}},\mathbf{2})_{-\frac{5}{3}}}_{\bar{X},\bar{Y}}$$

$$g A^a \frac{\lambda^a}{2} = \frac{g}{\sqrt{2}} \begin{pmatrix} \sqrt{2} G^a \frac{\lambda^a_{\text{GM}}}{2} & (\bar{X}, \bar{Y}) \\ (X, Y)^T & \sqrt{2} W^a \frac{\sigma}{2} \end{pmatrix} - \frac{g}{2\sqrt{15}} B \,\text{diag}(-2, -2, -2, 3, 3)$$

$SU(5)$ breaking: Higgs $\mathbf{\Sigma}$ in adjoint $\mathbf{24}$ rep.

$$\langle \mathbf{\Sigma} \rangle = w \times \text{diag}(1, 1, 1, -\tfrac{3}{2}, -\tfrac{3}{2}) \qquad M_X = M_Y = \frac{5}{2\sqrt{2}} g\, w$$

other breaking mechanisms possible (e.g. orbifold)

Quantum numbers

- Hypercharge: $\frac{\lambda_{12}}{2} = \sqrt{\frac{3}{5}}\frac{Y}{2}$ $\qquad Y = \frac{1}{3}\,\mathrm{diag}(-2,-2,3,3,3)$

  Quantized hypercharges are fixed by non-Abelian generator

- Weak Isospin: $T_{1,2,3} = \lambda_{9,10,11}/2$
- Electric Charge: $Q = T^3 + Y/2 = \mathrm{diag}(-\frac{1}{3},-\frac{1}{3},-\frac{1}{3},1,0)$
- Prediction for the weak mixing angle (with RGE running):

  $\alpha^{-1}(M_Z) = 128.91(2), \alpha_s(M_Z) = 0.1176(20), s_w^2(M_Z) = 0.2312(3)$

non-SUSY: $s_w^2(M_Z) \;=\; \frac{23}{134} + \frac{\alpha(M_Z)}{\alpha_s(M_Z)}\frac{109}{201} \;\approx 0.207$

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SUSY: $s_w^2(M_Z) = \frac{1}{5} + \frac{\alpha(M_Z)}{\alpha_s(M_Z)}\frac{7}{15} \approx 0.231$

New Gauge Bosons

Two colored EW doublets:

(X,Y), $(\bar{X},\bar{Y})$ with charges $\pm\frac{4}{3}, \pm\frac{1}{3}$

Fermions (Matter Superfields)

The only possible way to group together the matter:

$$\overline{\mathbf{5}} = \begin{array}{c}\Box\\\Box\\\Box\\\Box\end{array} : \quad \begin{pmatrix} d^c \\ d^c \\ d^c \\ \ell \\ -\nu_\ell \end{pmatrix} \qquad \mathbf{10} = \begin{array}{c}\Box\\\Box\end{array} : \quad \frac{1}{\sqrt{2}} \left(\begin{array}{ccc|cc} 0 & u^c & -u^c & -u & -d \\ -u^c & 0 & u^c & -u & -d \\ u^c & -u^c & 0 & -u & -d \\ \hline u & u & u & 0 & -e^c \\ d & d & d & e^c & 0 \end{array}\right)$$

$$\overline{\mathbf{5}} = (\overline{\mathbf{3}}, \mathbf{1})_{\frac{2}{3}} \oplus (\mathbf{1}, \mathbf{2})_{-1} \qquad \mathbf{10} = (\mathbf{3}, \mathbf{2})_{\frac{1}{3}} \oplus (\overline{\mathbf{3}}, \mathbf{1})_{-\frac{4}{3}} \oplus (\mathbf{1}, \mathbf{1})_{2}$$

Remarks

- $\mathbf{2} = \Box = \overline{\mathbf{2}}, \qquad (\mathbf{5} \otimes \mathbf{5})_a = \mathbf{10}, \quad (\mathbf{3} \otimes \mathbf{3})_a = \overline{\mathbf{3}}, \quad (\Box \otimes \Box)_a = \begin{array}{c}\Box\\\Box\end{array}$
- Quarks and leptons in the same multiplet
- Fractional charges from tracelessness condition (color!)
- $\overline{\mathbf{5}}$ and $\mathbf{10}$ have equal and opposite anomalies
- ν^c must be $SU(5)$ singlet

The Doublet-Triplet Splitting Problem

MSSM Higgses included in $\mathbf{5}_H \oplus \overline{\mathbf{5}}_H$

$$\mathbf{5}_H = (\mathbf{3},\mathbf{1})_{-\frac{2}{3}} \oplus (\mathbf{1},\mathbf{2})_1 : \begin{pmatrix} D \\ H_u \end{pmatrix} \qquad \overline{\mathbf{5}}_H = (\overline{\mathbf{3}},\mathbf{1})_{\frac{2}{3}} \oplus (\mathbf{1},\mathbf{2})_{-1} : \begin{pmatrix} D^c \\ \epsilon H_d \end{pmatrix}$$

D, D^c colored triplet Higgses with charges $\pm\frac{1}{3}$ (EW singlet)
colored Dirac fermion $\tilde{D}$ with charge $-1/3$ (EW singlet)

Unification requires omitting colored part of SU(5) Higgs $\mathbf{5}_H, \overline{\mathbf{5}}_H$

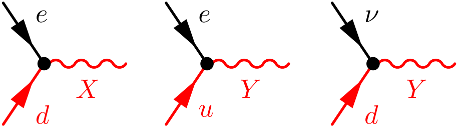
- **Doublet-triplet splitting problem** $(m_H \sim 100\,\text{GeV}, m_D \sim 10^{16}\,\text{GeV})$

Welcome, since $SU(5)$-symmetric Higgs interactions would read

$$\begin{aligned} \overline{\mathbf{5}}\,\mathbf{10}\,\overline{\mathbf{5}}_H &= \ell H_d e^c + q\epsilon H_d d^c + q\epsilon\ell D^c + d^c u^c D^c \\ \mathbf{10}\,\mathbf{5}_H\,\mathbf{10} &= q\epsilon H_u u^c + D u^c e^c + D q\epsilon q \end{aligned}$$

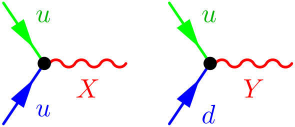
Generating SM masses $\Rightarrow$leptoquark *and* diquark coupl. for D, D^c
$\Rightarrow$ triggers **rapid proton decay**

Interactions



Leptoquark couplings

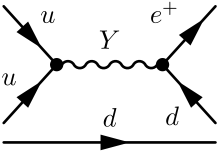
(and SUSY vertices)



Diquark couplings

(and SUSY vertices)

Vector bosons induce e.g. decay $p \to e^+ \pi^0$

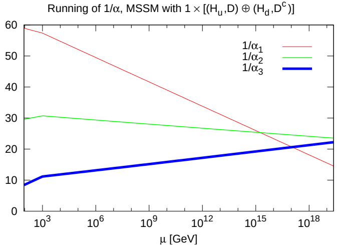


Doublet-Triplet Splitting

Possible scenarios:

1. Colored singlets are heavy (GUT scale) = doublet-triplet splitting
   - enables exact unification near 10^{16} GeV and excludes rapid proton decay
   - Proton decay may still be too fast (depending on the superpotential)
   - Doublet-triplet splitting is not trivially available

2. Colored singlets are light (TeV scale)
   - Simple unification no longer happens near 10^{16} GeV, nor elsewhere



   - Proton-decay coupl. must be excluded: consistent with GUT symmetry?

Further MSSM Issues

Even if doublet-triplet splitting is accepted,
the MSSM Higgs sector appears ad-hoc:

- **μ problem**
  μ-term $\mu H_u H_d$ is supersymmetric, in principle not related to soft-SUSY-breaking Lagrangian:

  Why is it $\mathcal{O}(100\,\text{GeV})$, not $\mathcal{O}(10^{16}\,\text{GeV})$?

  $\Rightarrow$ Possible extension as a solution: singlet Higgs S with superpotential

$$\lambda S H_u H_d \to \lambda \langle S \rangle H_u H_d = \mu H_u H_d$$

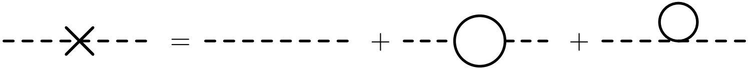
(does not change the unification prediction)

  $\Rightarrow$ NMSSM, where $\langle S \rangle$ should be somehow related to soft-breaking Lagrangian

  How?

Radiative Symmetry Breaking

MSSM with cutoff $\Lambda \sim 10^{16}$ GeV: major contribution to Higgs potential comes through Coleman-Weinberg mechanism:



$\Rightarrow$ Large top Yukawa coupl. drives effective H_u mass squared negative:

$$m^2_{\text{eff}} = (m^2_{H,\text{soft}} + \mu^2) \quad + \quad (\Lambda^2 \cdot 0) + m^2_{t,\text{soft}} \frac{\lambda^2}{16\pi^2} \ln \frac{m^2_{t,\text{soft}}}{\Lambda^2}$$

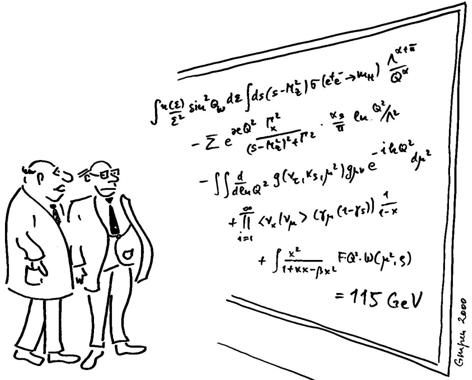
Such a mechanism may also be responsible for a S vev in the NMSSM

- requires the existence of a vectorlike pair of chiral superfields
  - for instance, D and D^c (colored) with coupling SDD^c
  - ... as required by $SU(5)$, if SH_uH_d is present
    ...... would simultaneously give a Dirac mass to D.
- Without tree-level quartic coupling, the CW mechanism implies $\langle S \rangle \sim 4\pi m_{\text{soft}}$, so $\langle S \rangle \gg \langle H \rangle$.

Further MSSM Issues

Even if doublet-triplet splitting is accepted,
the MSSM Higgs sector appears ad-hoc:

- Why is there only one family of Higgs matter? Neither $SU(5)$, nor G_{PS} (nor $SO(10)$) does unify Higgs fields with SM matter. . .



"This does not necessarily mean
that this is the Higgs mass!"

Higgs-Matter Unification

1976: Trinification: Treat all interactions equally

$$G_{\text{Tri}} = SU(3)_c \times SU(3)_L \times SU(3)_R \times Z_3$$

Multiplets:

$$L(1,3,\bar{3}) = \begin{pmatrix} H_u^+ & H_d^0 & \nu_L \\ H_u^0 & H_d^- & e_L \\ e_R^c & \nu_R^c & S \end{pmatrix} \qquad \begin{pmatrix} u_L \\ d_L \\ D_L \end{pmatrix} = Q_L(3,\bar{3},1)$$

$$Q_R(\bar{3},1,3) = \begin{pmatrix} u_R^c & d_R^c & D_R^c \end{pmatrix}$$

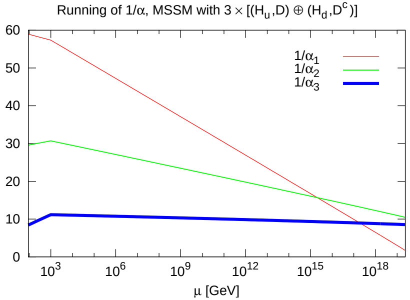
1976: E_6 as superset of trinification (and $SO(10)$) with additional gauge bosons $X(3,3,3)$ and $\bar{X}(\bar{3},\bar{3},\bar{3}) \Rightarrow \mathbf{78}$

$\Rightarrow$ irreducible multiplet ($\mathbf{27}$) unifies all matter, Higgs, colored and neutral singlets (within each family)

$\Rightarrow$ contains NMSSM, allows for radiative symmetry breaking in both singlet and doublet sectors

Higgs-Matter Unification

Complete $G_{\rm Tri}$ or E_6 multiplet: no unification

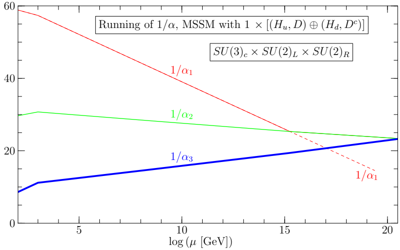


Possible scenarios:

1. Omit one bi-triplet D, D^c family $\Rightarrow$ doublet-triplet splitting
2. Add one extra MSSM Higgs family $\Rightarrow$ ESSM (S.King et al.)
3. Different unification pattern

Running With Triplets

Bottom-up approach: MSSM with one generation of triplets



10^{15} GeV: crossing of $SU(2)_L$ and $U(1)_Y$
$\Rightarrow$ unification to LR symmetry $SU(2)_L \times SU(2)_R$, requires ν_R^c
$SU(3)_c$ crosses at 10^{21} GeV: too high

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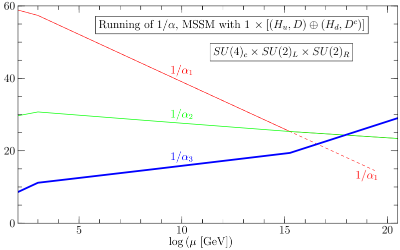

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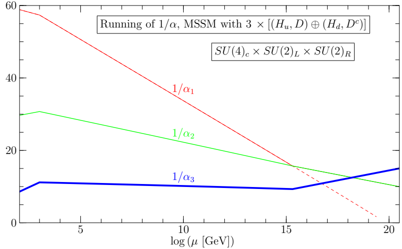
$SU(3)_c$ crosses at 10^{21} GeV: too high

$\Rightarrow$ extend to $SU(4)_C$: unification possible at 10^{18} GeV

Running With Triplets

Complete Model:

- Full SUSY E_6/G_{Tri} matter spectrum above 10^3 GeV, except ν^c



- PS symmetry with ν_R above 10^{15} GeV

$$\mathbf{Q}_L = (Q, L) = (\mathbf{4}, \mathbf{2}, \mathbf{1}) \qquad \mathbf{D} = (D, D^c) = (\mathbf{6}, \mathbf{1}, \mathbf{1})$$

$$\mathbf{Q}_R = ((u^c, d^c), (\nu^c, \ell^c)) = (\overline{\mathbf{4}}, \mathbf{1}, \mathbf{2}) \qquad \mathbf{S} = (\mathbf{1}, \mathbf{1}, \mathbf{1})$$

$$\mathbf{H} = (H_u, H_d) = (\mathbf{1}, \mathbf{2}, \mathbf{2})$$

- E_6 symmetry (and possibly extra fields) at 10^{18} GeV

Flavor Symmetry

Proton decay?

- Once triplets are included, a PS-symmetric superpotential contains leptoquark and diquark couplings simultaneously:
  $DQ_RQ_R = \epsilon_{\alpha\beta\gamma}\epsilon_{jk}D_\alpha(Q_R)_{\beta j}(Q_R)_{\gamma k}$

Possible solution: extra flavor symmetry $SU(3)_F$ (or $SO(3)_F$)

$\Rightarrow$ D diquark coupling with $SU(2)_R, SU(3)_c, SU(3)_F$:

$$DQ_RQ_R = \epsilon^{abc}\epsilon_{\alpha\beta\gamma}\epsilon_{jk}D^a_\alpha(Q_R)^b_{\beta j}(Q_R)^c_{\gamma k}$$

Vanishes due to total antisymmetry $\Rightarrow$ **no proton decay**

Analogous for $\epsilon^{abc}\epsilon_{\alpha\beta\gamma}\epsilon_{jk}(D^c)^a_\alpha(Q_L)^b_{\beta j}(Q_L)^c_{\gamma k}$

- Leptoquark coupling of D not affected

Eff. superpotential from (spontan.) breaking of LR and/or flavor symm.:

- Exclude spurions $\propto \epsilon_{\alpha\beta\gamma}$ (color space) $\Rightarrow$ diquark couplings absent
- Integrating out heavy fields: baryon number as low-energy symmetry, flavor symmetry not

Sample Implementation

Toy Model (no dynamics!)

Extend $E_6 \times SU(3)_F$ to E_8

. . . by implementing $N = 2$ supersymmetry:

- We have: matter $\mathbf{27_3}$ and gauge $\mathbf{78_1} + \mathbf{1_8}$.
- Add: mirror matter $\overline{\mathbf{27}}_{\bar{\mathbf{3}}}$
- supersymmetrize by adding *matter* $\mathbf{78_1} + \mathbf{1_8}$ and *gauge* $\mathbf{27_3} + \overline{\mathbf{27}}_{\bar{\mathbf{3}}}$.

Decomposition of reps. in $E_8 \to E_6 \times SU(3)_F$:

$$\mathbf{248} = \mathbf{27_3} \oplus \overline{\mathbf{27}}_{\overline{\mathbf{3}}} \oplus \mathbf{78_1} \oplus \mathbf{1_8}$$

Result: matter $\mathbf{248}$ and gauge $\mathbf{248}$ (fundamental = adjoint)

Sample Implementation

Top-down

1. Somewhat below M_{Planck}
   - $N = 2 \rightarrow N = 1$ breaking removes mirror matter, leaving E_6 zero mode of chiral matter $\mathbf{27_3}$, maybe adjoint matter $\mathbf{78_1}$ and $\mathbf{1_8}$
   - Flavor $SU(3)$ on the zero modes (would be anomalous) is broken by colorless spurions, e.g., condensate $\langle \mathbf{1_8} \rangle$.
   - E_6 is broken to G_{PS} by colorless spurions, e.g., bilinear = Higgs 'μ term' $\langle \bar{H}_u \bar{H}_d \rangle$ in the $\overline{\mathbf{27}}_{\bar{\mathbf{3}}}$ mirror representation
   - Additional allowed spurion = Singlet $\langle \mathbf{1_1}, \mathbf{1} \rangle = \langle \bar{S} \rangle$ (3. gen.)

   Note: all spurions so far break flavor as well

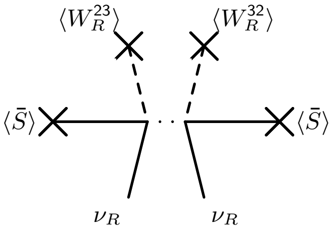
Result:

- PS symmetry
- all MSSM superpotential terms allowed, but subject to PS symmetry and flavor constraints (no quark mixing)
- Flavor dynamics in higher-dim. superpotential due to $\mathbf{1_8}$ matter exchange

Sample Implementation

2. At 10^{15} GeV

Condensate in adjoint matter representation: $\langle \mathbf{78_1} \rangle = \langle W_R^{23} \rangle$
+ higher-dimensional terms $(\mathbf{27}\,\mathbf{78}\,\overline{\mathbf{27}})^2$



$\Rightarrow$ ν_R Majorana mass

$\Rightarrow$ PS symmetry broken to SM

$\Rightarrow$ Leptoquark couplings possible for D, D^c, but no diquark couplings

Sample Implementation

3. At 10^3 GeV

Soft-breaking terms (hidden sector) induce radiative symmetry breaking $\langle S \rangle$ via D/D^c loops

- $\Rightarrow$ μ_D-term $D^c \langle S \rangle D$ (Dirac masses)
- $\Rightarrow$ μ_H-term $H_u \langle S \rangle H_d$
- $\Rightarrow$ Z' mass if the extra $U(1)$ broken by $\langle S \rangle$ was gauged

... with flavor mixing

4. At 10^2 GeV

Soft-breaking + effective μ-term induce radiative symmetry breaking $\langle H_u \rangle$ via t/t^c loops

- $\Rightarrow$ $\langle H_d \rangle$ due to Higgs superpotential + soft-breaking terms
- $\Rightarrow$ Dirac masses for all charged MSSM matter
- $\Rightarrow$ Majorana masses (see-saw) for ν_L

... again, with flavor mixing

Dark Matter

MSSM Higgses: H_u^f, H_d^f with $f = 1, 2, 3$

- $*$ VEV selects single direction (taken as $f = 3$) in family space
  $\Rightarrow$ 1 gen. MSSM Higgses, 2 gen. "unhiggses"

(2 bi-doublets = 8 charged and 8 neutral scalars + fermion superpartners)

In gauge interactions, unhiggses are pair-produced, thus suppressed in precision data, ... but also Yukawa interactions

1) FCNC 2) resonant single production in $q\bar{q}$ or e^+e^- annihilation

Unhiggses very heavy *or* artificially aligned *or* suppressed

$\Rightarrow$ (approximate?) H parity: odd for unhiggses, even otherwise

And why not? Flavor symmetry removes the need for R parity anyway.

If H parity is exact:

- lightest unhiggs: H parity protected dark matter
- Pair production of unhiggses/unhiggsinos, cascade decays

. . . *and* R parity is exact:

- dark matter mix: interesting relic abundance
  (relaxes all neutralino bounds!)

A little bit of Pheno

Deppisch/Kilian/JR

Next step: Provide a viable low-energy spectrum

At LHC:

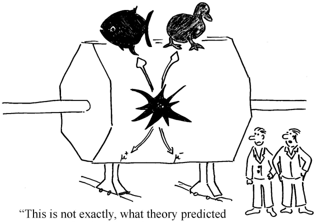
1) $1-3$ pairs of scalar leptoquarks D_L, D_R.

- probably heavy $\gtrsim 1$ TeV (but hierarchy is possible)
- pair-produced in gg fusion at LHC
- decay into ℓu and νd:
  - generation-diagonal, or just third-generation: τt and νb or
  - generation-crossed (flavor symmetry!): ec, eb, μd,te, $t\mu$ ...
    $gq \to D\ell$ production enhanced
  - or, if R-parity is violated, may mix with down-type squarks.

2) $1-3$ fermionic leptoquarkinos $\tilde{D}$

- are probably heavy as well, but somewhat lighter than scalars (because $m^2 = \lambda\langle S\rangle^2 + m^2_{\text{soft}}$)
- are also pair produced (maybe singly if R-parity is violated)
- decay into $\tilde{\ell}j$, or $\ell\tilde{q}$, or $\nu\tilde{q}$
  - rich signatures!
  - spin measurement distinguishes from ordinary squarks

A little bit of Pheno


"This is not exactly, what theory predicted for the Higgs decay!"

3) (non)"standard" MSSM Higgs
   - Relaxed Higgs bounds (like in NMSSM)
   - Possibly large invisible decay ratio ($\tilde{\chi}^0, a$)

4) $2 - 4$ doublets of unhiggses
   - probably only pair-produced: Drell-Yan, maybe Higgs decays (singlets involved)
   - missing-energy signatures, unique identification could be difficult: ILC?

5) $1 - 3$ singlet scalars + pseudoscalars
   - masses, properties?

6) and all associated neutralinos (≤ 11) and charginos (≤ 4)
   - large and complicated chargino/neutralino mixing matrices. Decay chains at LHC become difficult to understand.

7) Either heavy Z' (gauged NMSSM) or light pseudo-axion(s) η corresponding to extra $U(1)$

Conclusion: LHC phenomenology rich . . . and confusing

Summary

3 independent building blocks for exotic SUSY phenomenology

Color-triplet 'leptoquark' scalars/fermions are present in the low-energy spectrum

- leads to a different unification pattern
- favoring PS symmetry above the R-neutrino mass scale

Flavor symmetry prohibits proton decay

- instead of (or in addition to) R parity
- Superpotential terms are due to GUT- and flavor-breaking
- . . . . . . therefore do not exhibit GUT relations

Higgs sector is flavored

- Unhiggses (1st and 2nd generation) carry conserved quantum number
- Unhiggses dark matter candidates
- Ordinary MSSM stuff might decay via R-parity violation

Confusing LHC pheno, but handle to GUT scale

Some Unification needs time