LHC Phenomenology of SUSY multi-step GUTs

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W. Kilian, JR, PL **B642** (2006), 81; arXiv:0709.4202;
work in progress (with F. Braam, K. Mallot, D. Wiesler)

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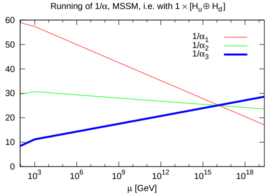
Motivation for (SUSY) Unification

Incompleteness/Theoretical Dissatisfaction

EWSB, H, m_ν, DM, hierarchy, ... , reducible representation:

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

Supersymmetry: consistent extrapolation to high scales



- $\Rightarrow$ unification quantitatively testable
- $\Rightarrow$ two Higgs doublets H^u, H^d
- $\Rightarrow$ TeV-scale SM-superpartners

Bottom-Up Approach: *just MSSM*

Unification verification only with megatons? What about colliders?

- SPA: super precision accurately
- Look for chiral exotics
- Physics beyond MSSM provides handle to GUT scale

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 $\mathbf{5}_H, \overline{\mathbf{5}}_H$

1) **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

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

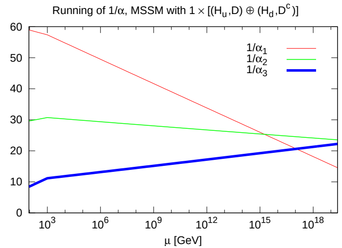
Generating SM masses $\Rightarrow$leptoquark *and* diquark coupl. for D, D^c
$\Rightarrow$ triggers **rapid proton decay**

Doublet-Triplet Splitting

Possible scenarios:

1. Colored singlets are heavy (GUT scale) = doublet-triplet splitting
   - enables exact unification near 10^{16} GeV, excludes rapid proton decay
   - Proton decay may still be too fast (depends on 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

2) μ **problem**: SUSY μ-term $\mu H_u H_d$, not related to soft breaking

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

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

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

$\Rightarrow$ NMSSM: $\langle S \rangle$ should be somehow related to soft-breaking

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

This mechanism may also be responsible for $\langle S \rangle$ in the NMSSM

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

3) **Higgs-matter unification:** Why only one family of Higgs matter? E_6 unifies Higgs fields with SM matter... 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., 2005/6
3. Different unification pattern

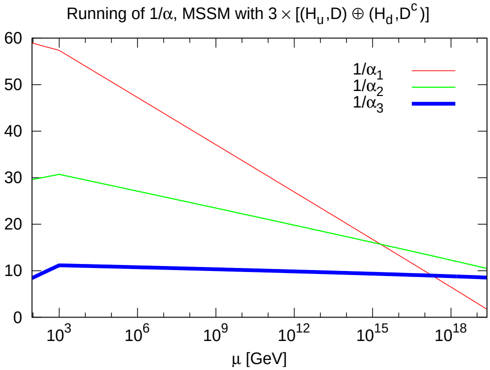
Running Couplings: PSSSM

[Braam/JR/W.Kilian, 2006/2009]

- Additional particles spoil simple unification
- Gauge couling unification below Λ_{Planck} due to intermediate Pati-Salam

$$SU(4) \times SU(2)_L \times SU(2)_R[\times U(1)_\chi]$$

symmetry at $\sim 10^{16}$ GeV



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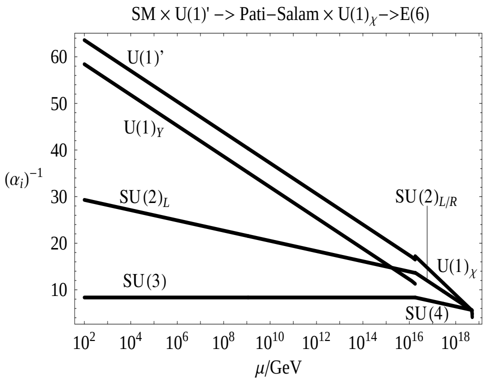


- $SU(2)_R$ and $SU(2)_L$: identical particle content

$\Rightarrow$ Identical running

- Crossing of $SU(4)$ and $SU(2)_{L/R}$ couplings determines E_6 breaking scale

E_6 unification with intermediate Pati-Salam Symmetry

The quantum numbers of the **27** under the Pati-Salam gauge group are

$$\begin{aligned}
\mathbf{Q}_R &= ((u^c, d^c), (\nu^c, e^c)) = (\bar{\mathbf{4}}, \mathbf{1}, \mathbf{2})_{\frac{1}{2}} \\
\mathbf{Q}_L &= ((Q, L)) = (\mathbf{4}, \mathbf{2}, \mathbf{1})_{\frac{1}{2}} \\
\mathbf{H} &= (H^u, H^d) = (\mathbf{1}, \mathbf{2}, \mathbf{2})_{-1} \\
\mathbf{D} &= (D, D^c) = (\mathbf{6}, \mathbf{1}, \mathbf{1})_{-1} \\
\mathbf{S} &= (\mathbf{1}, \mathbf{1}, \mathbf{1})_2
\end{aligned}$$

- Lepton number becomes 4^{th} color
- $T^{15}_{SU(4)} \propto \frac{B-L}{2}$
- $Y = \frac{B-L}{2} + T^3_R$
- Integrating out ν^c

⇒ appropriate breaking

⇒ see-saw mechanism (i.e. naturally small neutrino masses)

Flavor Symmetry

Proton decay?

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

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
- baryon number as low-energy symmetry, flavor symmetry not (necessarily)

The LHC phenomenology

[Braam/JR/Wiesler]

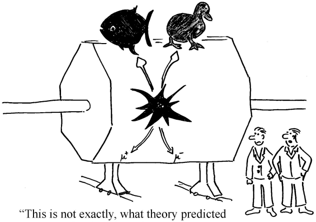
Next step: Provide a viable low-energy spectrum

At LHC:

1) $1-3$ pairs of scalar leptoquarks D_L, D_R.
   - probably heavy $\lesssim 1$ 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

Investigation Of The Parameter Space

- # free parameters $\sim \mathcal{O}(100)$, additional assumptions:
  - Unified SSB-parameters - Flavor structur

  $\Rightarrow$ Limitation on 14 free parameters
- Constraints:
  1. Experimental lower bounds on masses of new particles
  2. Running parameters perturbative up to Λ_{E_6}
  3. Scalar (non-Higgs) mass terms have to remain positive
     (⇔ No unwanted symmetry breaking)

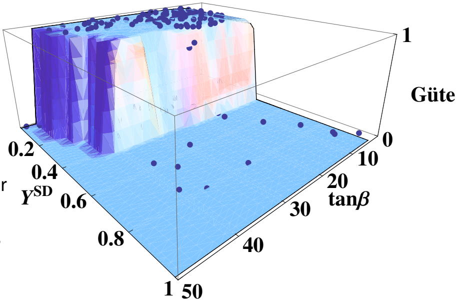
- 14-dim parameter space

$\Rightarrow$ grid scanning $\rightarrow 10^{28}$ points

- Investigation per point (RGE, Higgs potential minimization, calculation of masses) ~ 5 s

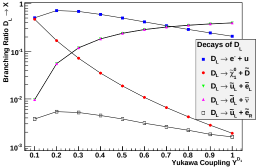
Sol: Monte-Carlo Markov-Chain through parameter space

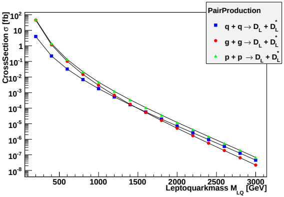
$\Rightarrow$ Effective search for sensible parameter tupels

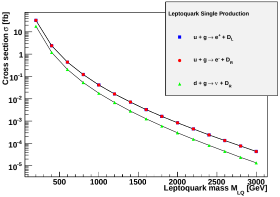


Predictions for Collider Experiments

- Collider phenomenology with event generator `WHIZARD` [Kilian/Ohl/JR]
- Implementation of leptoquark/leptoquarkino + Higgs/weak ino sector
- First analyses: BRs, cross sections for scalar leptoquarks, S/B
- In progress: leptoquarkino pheno







Cuts		Background	$m_D = 0.6$ TeV		$m_D = 0.8$ TeV		$m_D = 1.0$ TeV	
p_T	$M_{\ell\ell}$	N_{BG}	N_1	$S_1/\sqrt{B}$	N_2	$S_2/\sqrt{B}$	N_3	$S_3/\sqrt{B}$
50	10	413274	64553	**93**	14823	**23**	4819	**7**
100	150	3272	40749	**194**	10891	**92**	3767	**45**
200	150	198	12986	**113**	5678	**74**	2405	**47**

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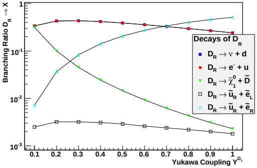

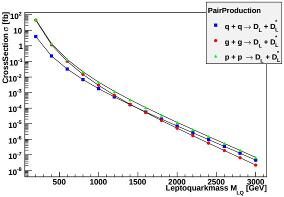

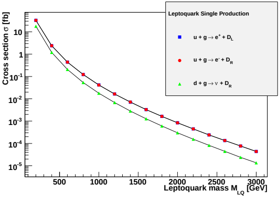

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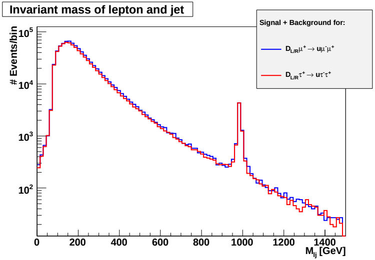
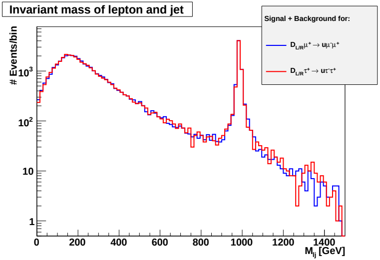

Invariant mass of lepton and jet
Signal + Background for:
$D_{L/R}\mu^+ \to u\mu^-\mu^+$
$D_{L/R}\tau^+ \to u\tau^-\tau^+$
Events/bin
M_{lj} [GeV]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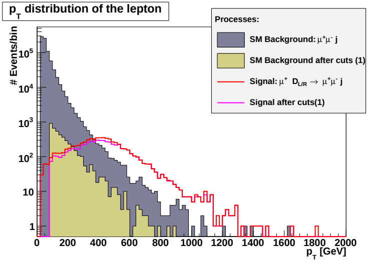
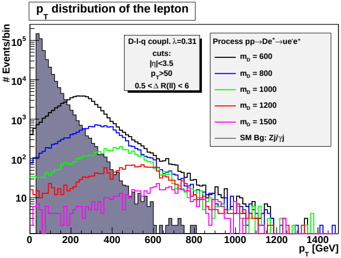

p_T distribution of the lepton
Processes:
SM Background: $\mu^+\mu^-$ j
SM Background after cuts (1)
Signal: μ^+ $D_{L/R}$ $\to$ $\mu^+\mu^-$ j
Signal after cuts(1)
Events/bin
p_T [GeV]


p_T distribution of the lepton
D-l-q coupl. λ=0.31
cuts:
$|\eta|<3.5$
$p_T>50$
$0.5 < \Delta R(ll) < 6$
Process $pp \to De^+ \to ue^-e^+$
m_D = 600
m_D = 800
m_D = 1000
m_D = 1200
m_D = 1500
SM Bg: Zj/γj
Events/bin
p_T [GeV]

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" Ellis et al., 1985; Campbell et al., 1986

  (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!)

Summary/Outlook

3 independent building blocks for exotic SUSY phenomenology

Color-triplet leptoquark/inos are present in the low-energy spectrum

- multi-step unification (PSSSM: E_6 with PS symmetry)
- 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

Investigation of the parameter space $\Rightarrow$ Input for `WHIZARD`

Leptoquark phenomenology could hint toward GUT

Further Studies:

- PS-symmetry breaking, $U(1)$-mixing, threshold corrections
- More LHC pheno (leptoquarkinos, Higgs, weak inos, Z' ...)

Backup: E_6 Particle Content

- Unifies Higgs and matter fields
- Contains $SU(3)_c \times SU(2)_L \times U(1)_Y\ [\times U(1)'] \Rightarrow$ additional Z'
- Ansatz: all new particles in the spectrum at TeV scale
- SM $\times U(1)'$ quantum numbers of the fundamental $\mathbf{27}$:

Notation: $(SU(3), SU(2))_{Y,Q'}$

$$Q_L = (\mathbf{3},\mathbf{2})_{\frac{1}{6},Q'_Q} \qquad L_L = (\mathbf{1},\mathbf{2})_{-\frac{1}{2},Q'_L}$$

$$u^c = (\bar{\mathbf{3}},\mathbf{1})_{-\frac{2}{3},Q'_u} \qquad \nu^c = (\mathbf{1},\mathbf{1})_{0,Q'_\nu=0}$$

$$d^c = (\bar{\mathbf{3}},\mathbf{1})_{\frac{1}{3},Q'_d} \qquad e^c = (\mathbf{1},\mathbf{1})_{1,Q'_e}$$

$$H^u = (\mathbf{1},\mathbf{2})_{\frac{1}{2},Q'_{Hu}}$$

$$H^d = (\mathbf{1},\mathbf{2})_{-\frac{1}{2},Q'_{Hd}}$$

$$S = (\mathbf{1},\mathbf{1})_{0,Q'_S \neq 0}$$

$$D = (\mathbf{3},\mathbf{1})_{-\frac{1}{3},\ Q'_D}$$

$$D^c = (\bar{\mathbf{3}},\mathbf{1})_{\frac{1}{3},-Q'_D}$$

Backup: 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 $E_8 \to E_6 \times SU(3)_F$:

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

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

Backup: Sample Implementation — Top Down

1. Somewhat below M_{Planck}
   - $N = 2 \to 1$ breaking removes mirror matter: $\langle (\mathbf{27}_3)_i^a (\overline{\mathbf{27}}_{\bar{3}})_j^b \rangle = \delta^{ab} \delta_{j,i+1}$
   - 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" $\langle \overline{\mathbf{1}}_{2,2} \overline{\mathbf{1}}_{2,2} \rangle$ in the $\overline{\mathbf{27}}_{\bar{3}} \overline{\mathbf{27}}_{\bar{3}}$ mirror representation
   - Additional allowed spurion = Singlet $\langle \overline{\mathbf{1}}_{\mathbf{1},\mathbf{1}} \rangle = \langle \bar{S} \rangle$ (3. gen.)

   Note: all spurions so far break flavor as well

Result:

- PS symmetry
- all MSSM superpotential terms allowed, subject to PS symmetry/flavor constraints (no quark mixing):

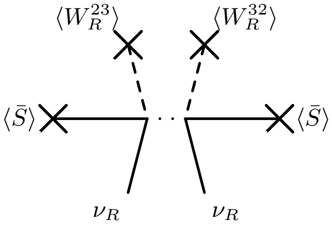
  $$\mathbf{27}_3\,\mathbf{27}_3\,\mathbf{27}_3 = 0 \qquad (\mathbf{27}_3\,\mathbf{78}_1\,\overline{\mathbf{27}}_{\bar{3}}),\ (\mathbf{78}_1\,\mathbf{78}_1\,\mathbf{78}_1),\ (\mathbf{27}_3\,\mathbf{1}_8\,\overline{\mathbf{27}}_{\bar{3}}),\ \mathbf{1}_8\,\mathbf{1}_8\,\mathbf{1}_8$$
- Flavor dynamics in higher-dim. superpotential due to $\mathbf{1_8}$ matter exchange

Backup: Sample Implementation

only potentially dangerous term for proton decay: $\mathbf{78}_1\,\mathbf{78}_1\,\mathbf{78}_1$,
because inserting (colorless) condensates into $\mathbf{27}_3\,\mathbf{78}_1\,\overline{\mathbf{27}}_{\bar{3}}$,
integrating out $\mathbf{78}_1$
color-triplet leptoquark self-coupling $XXX = 0$ (antisymmetry)

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

Backup: 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

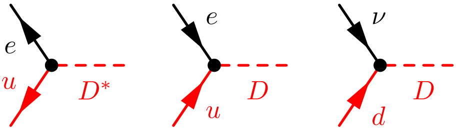
4. At 10^2 GeV

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

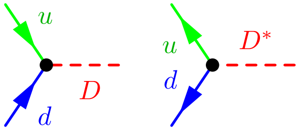
... again, with flavor mixing

Backup: Interactions



Leptoquark couplings

(and SUSY vertices)



Diquark couplings

(and SUSY vertices)

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

experimentally: $\tau(p) > 10^{33}$ yrs