Exceptional Grand Unification in the light of LHC data

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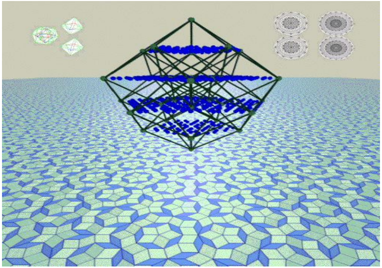


Brookhaven Forum 2011, BNL, 19. Oct. 2011

Why chiral exotics?

JRR/Kilian, PLB 642 (2006), 81, JRR 0709.4202

Proof of Unification only with megatons? What about colliders?

- SPA: Super precision accurately
- Alternative: Search for chiral exotics
- Physics beyond the MSSM as lever-arm to GUT scale

μ problem

- NMSSM trick
- Singlett Superfield with TeV-scale vacuum expectation value

Doublet-Triplet Splitting Problem; Longevity of the Proton

- Keep D, D^c superfields at the TeV scale
- New mechanism against proton decay
- Different unification scenario

Proton Decay

- Flavour symmetry can save the proton
- Discrete parity eliminates either LQ/DQ couplings

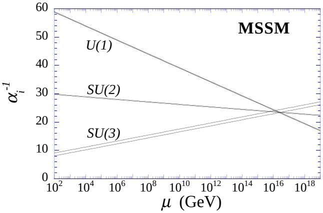
E_6 SUSY Grand Unification

Supersymmetry: allows consistent extrapolation to (very) high scales

$\Rightarrow$ Two Higgs doublets H^u, H^d

$\Rightarrow$ SM superpartners at the TeV scale

Bottom-Up approach: <u>only MSSM</u>



- Matter-Higgs unification
- Ansatz: all new particles at the TeV scale

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

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

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

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

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

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

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

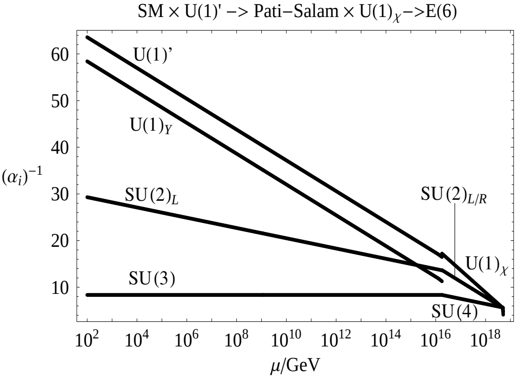
$$D^c = (\bar{\mathbf{3}},\mathbf{1})_{\frac{1}{3},-Q'_D}$$

Intermediate Pati-Salam/LR symmetry

JRR et al. 2006-9, King et al. 2008

- Additional particles destroy MSSM unification
- Unification below Λ_{Planck} with intermediate

$SU(4) \times SU(2)_L \times SU(2)_R \times U(1)_\chi$ Pati-Salam symmetry at $\sim 10^{15-16}$GeV



- $SU(2)_R$ and $SU(2)_L$: identical content/running
- Crossing of $SU(4)$ with $SU(2)_{L/R}$ couplings determines E_6 scale
- Lepton number: 4. colour
- $T^{15}_{SU(4)} \propto \frac{B-L}{2}$
- $Y = \frac{B-L}{2} + T^3_R$
- $U(1)$ Matching condition $\frac{1}{g_Y^2} = \frac{2}{5}\frac{1}{g_{B-L}^2} + \frac{3}{5}\frac{1}{g_R^2}$
- Integrating out ν^c: see-saw $\Rightarrow$ correct breaking

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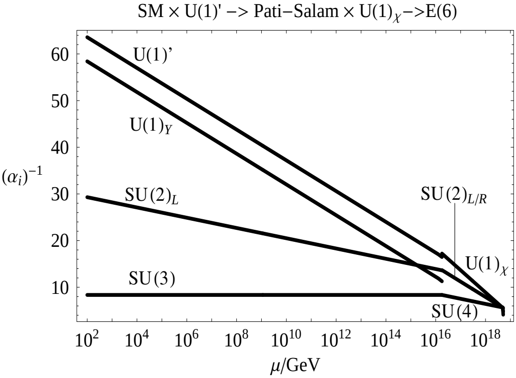

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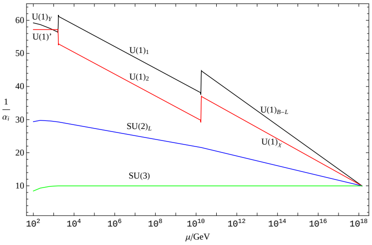
$U(1)$ Mixing

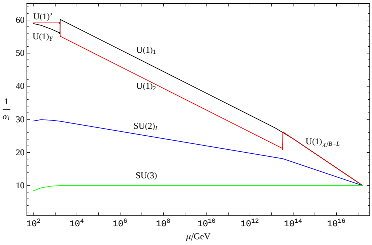
Braam/Knochel/JRR, JHEP 1006:013; Braam/JRR 1107.2806

- Two $U(1)$ factors below the intermediate scale
- Kinetic mixing: non-rational coefficients (gauge couplings)

$$\mathcal{L} = i\, g_i\, Q_i^a\, A_i^\mu\, \bar{\psi}^a\, \gamma_\mu\, \psi^a - \frac{1}{4}\, F_i^{\mu\nu}\, \delta_{ij}\, F_{\mu\nu,j} - \frac{1}{4}\, F_i^{\mu\nu}\, \Delta Z_{ij}\, F_{\mu\nu,j}\,.$$

- Effects for the running:





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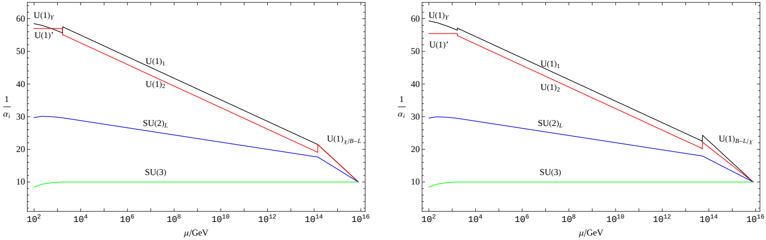

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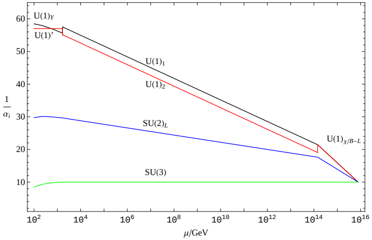
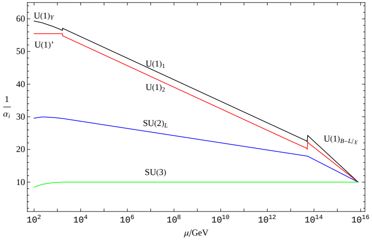




- Same effect for soft-breaking terms: interesting singlino mixing

The Superpotential / Sketch of a Model

Kilian/JR, 2006

Superpotential: $\mathcal{W} = \mathcal{W}_{\mathrm{MSSM}} + \mathcal{W}_D + \mathcal{W}_N$

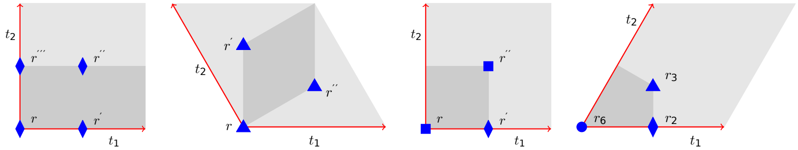
$$\begin{aligned} \mathcal{W}_{\mathrm{MSSM}} &= Y^u u^c Q H_u + Y^d d^c Q H_d + Y^e e^c L H_d \\ \mathcal{W}_D &= Y^D D u^c e^c + Y^{D^c} D^c Q L \\ \mathcal{W}_S &= Y^{S_H} S H_u H_d + Y^{S_D} S D D^c \end{aligned}$$

- Corresponding soft-breaking terms
- $t/\tilde{t}$ drive $m^2_{H_u}$ negative
- $D/\tilde{D}$ drive m^2_S negative
- $U(1)'$ D-terms provide large enough S quartics (and H quartics)
- Configuration drives system to large $\langle S \rangle \sim 1 - 2$ TeV
- R parity is not sufficient to protect proton: discrete parity to distinguish LQ/DQ couplings (or flavor symmetry)
- Flavored Higgs sector: additional parity to beware of FCNCs $\Rightarrow$ H parity Griest/Sher, 1989

LR Models from 6D Orbifolds

Braam/Knochel/JRR, JHEP 1006:013

- Consider: $\mathbb{R}^4 \times (\mathbb{R}^2/\Gamma)$, Γ one of the 17 crystallographic groups
- Use shifts of the bulk E_6 root lattice + discrete Wilson lines on the tori
- $E_6 \supset SU(3) \times SU(2)^2 \times U(1)^2$ breakings through $\mathbb{Z}_2, \mathbb{Z}_3, \mathbb{Z}_4, \mathbb{Z}_6$:



- H Parity: at least one fixed point to distinguish Higgs/Matter
- at least one fixed point to discriminate LQ/DQ couplings
- $\mathbb{Z}_n$ Orbifold compactification breaks SUSY $\left(\xi_1, \bar{\xi}_2\right) \xrightarrow{\theta} \left(e^{-i\pi/n}\xi_1, e^{i\pi/n}\bar{\xi}_2\right)$
- 4D $\mathcal{N} = 1$ SUSY conserved by either:
  - Using 10D Lorentz phases:

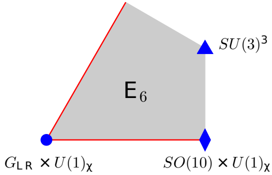
$$\theta = \exp\left[\frac{A}{4}[\Gamma^5, \Gamma^6] + \frac{B}{4}[\Gamma^7, \Gamma^8] + \frac{C}{4}[\Gamma^9, \Gamma^{10}]\right]$$

  - Non-trivial embedding of $SU(2)$ R symmtry

$$\theta = \exp\left[\frac{2\pi}{n}\frac{1}{4}([\Gamma^5, \Gamma^6] + c_R i I^{3R})\right]$$

A specific Model

Braam/Knochel/JRR, JHEP 1006:013



- Use $T^2/\mathbb{Z}_6$ (a.k.a. $\mathbb{R}^2/\mathbf{632}$ or p6)
- Shift vector $\overline{V}(r_6) = (\frac{1}{6}, -\frac{1}{6}, -\frac{1}{3}, -\frac{1}{2}, -\frac{1}{6}, 0)$ (in $\overline{Q}_{B-L}$ direction)
- No discrete Wilson lines allowed

▸ Anomalies from bulk $\mathbf{78}$ chiral modes after projection $(\mathbf{16}_{-3/2} + \overline{\mathbf{16}}_{3/2}, (\overline{\mathbf{3}}, \mathbf{2}, \mathbf{1}) + (\overline{\mathbf{3}}, \mathbf{1}, \mathbf{2}), (\mathbf{3}, \mathbf{3}, \overline{\mathbf{3}}))$ cancel against $\mathbf{78}$ bulk hypermultiplet

▸ 3 gen. of $\mathbf{27}$ as brane-localized matter

$SU(3)^3 \backslash SO(10)_{Q_\chi}$	$\mathbf{16}_{\frac{1}{2}}$	$\mathbf{10}_{-1}$	$\mathbf{1}_{2}$
$\mathbf{A} = (\overline{\mathbf{3}}, \mathbf{1}, \mathbf{3})$	$(\overline{\mathbf{3}}, \mathbf{1}, \mathbf{2})_{(-\frac{1}{3}, \frac{1}{2})}$	$(\overline{\mathbf{3}}, \mathbf{1}, \mathbf{1})_{(\frac{2}{3}, -1)}$	×
$\mathbf{B} = (\mathbf{3}, \mathbf{3}, \mathbf{1})$	$(\mathbf{3}, \mathbf{2}, \mathbf{1})_{(\frac{1}{3}, \frac{1}{2})}$	$(\mathbf{3}, \mathbf{1}, \mathbf{1})_{(-\frac{2}{3}, -1)}$	×
$\mathbf{C} = (\mathbf{1}, \overline{\mathbf{3}}, \overline{\mathbf{3}})$	$(\mathbf{1}, \mathbf{2}, \mathbf{1})_{(-1, \frac{1}{2})}$ $(\mathbf{1}, \mathbf{1}, \mathbf{2})_{(1, \frac{1}{2})}$	$(\mathbf{1}, \mathbf{2}, \mathbf{2})_{(0, -1)}$	$(\mathbf{1}, \mathbf{1}, \mathbf{1})_{(0, 2)}$

▸ Trinification FP $SU(3)^3$ (H-even!) to discriminate LQ/DQ couplings (3rd gen.):

$$\mathbf{27}^3 \to (\overline{\mathbf{3}}, \mathbf{1}, \mathbf{3})^3 + (\mathbf{3}, \mathbf{3}, \mathbf{1})^3 + (\mathbf{1}, \overline{\mathbf{3}}, \overline{\mathbf{3}})^3 + (\overline{\mathbf{3}}, \mathbf{1}, \mathbf{3})(\mathbf{3}, \mathbf{3}, \mathbf{1})(\mathbf{1}, \overline{\mathbf{3}}, \overline{\mathbf{3}})$$

▸ 1.+2. gen. on $SO(10)$ FP. (allows for LQ couplings)

▸ LR symmetry breaking by brane-localized matter:

$$i) \qquad L, l^c, \langle \nu^c \rangle + c.c. \sim (\mathbf{1}, \overline{\mathbf{3}}, \overline{\mathbf{3}}) \cap \mathbf{16} + c.c.$$

$$ii) \qquad L, l^c, \langle \nu^c \rangle, H_u, H_d, S + c.c. \sim (\mathbf{1}, \overline{\mathbf{3}}, \overline{\mathbf{3}}) + c.c.$$

Model Building ⇒ Phenomenology

Scan of Parameter Space

Braam/JRR/Wiesler, 0909.3081; JRR et al., 2010

- $\#$ free parameters $\sim \mathcal{O}(100)$, additional assumptions:
  - Unified Soft-Breaking terms - Flavour structure

  $\Rightarrow$ Restriction to 14 parameters
- Constraints:
  (1) Experimental search limits for new particles
  (2) Running couplings perturbative up to Λ_{E_6}
  (3) Scalar (non-Higgs) mass terms positive
  ($\Leftrightarrow$ No false vacua)

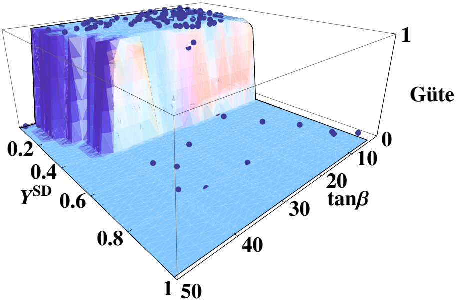
- 14-dim. parameter space

$\Rightarrow$ Grid Scan: $\rightarrow 10^{28}$ points

- Investigation per point (RGE, Higgs potential minimisation, Calculation of masses) $\sim 10 - 100$ ms

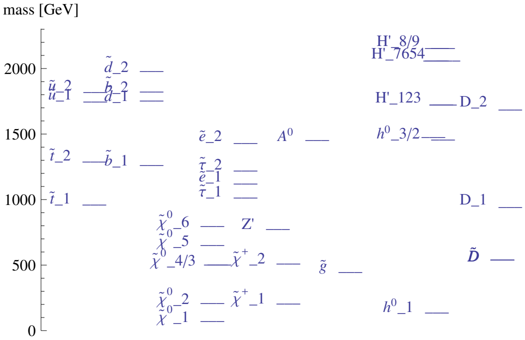
Lsg.: Monte-Carlo Markov chain through parameter space

$\Rightarrow$ Effective search for relevant parameter tuples



Generic Properties of Spectra

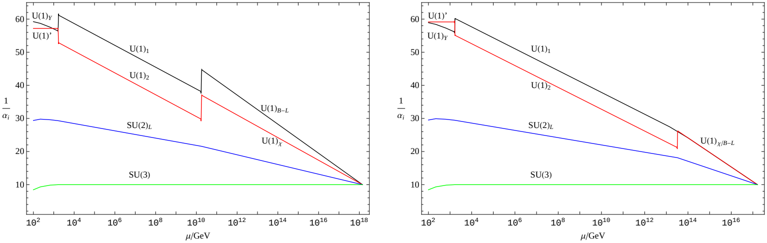
EXSPECT: Braam/JRR, 2011



- Vanishing 1-loop QCD β function $\Rightarrow$ Light Gluino
- Higgs- and neutralino sector different because of singlet superfield admixture
- light Z' (peculiar asymmetries)
- Flavoured Higgs sector: Unhiggses, Unhiggsinos
- Leptoquarks/Leptoquarkinos

Sample Spectra

$H_{\text{int}}, \bar{H}_{\text{int}}$	$i)$	$ii)$	$3ii)$	$i) + 2ii)$
Λ_{int} / GeV	1.6×10^{10}	3.0×10^{13}	1.3×10^{14}	4.9×10^{13}
Λ_{GUT} / GeV	1.3×10^{18}	1.5×10^{17}	7.2×10^{15}	7.2×10^{15}
$g' \mid M_{Z'}$	0.471	0.467	0.476	0.482
Q'_X				
Q	0.224	0.231	0.234	0.232
u^c	0.283	0.261	0.250	0.257
d^c	0.055	0.067	0.073	0.069
D	-0.449	-0.462	-0.468	-0.464
D^c	-0.339	-0.328	-0.322	-0.326
L	0.114	0.097	0.089	0.094
e^c	0.165	0.201	0.218	0.208
H^u	-0.508	-0.492	-0.484	-0.489
H^d	-0.279	-0.298	-0.307	-0.301
S	0.787	0.790	0.790	0.790



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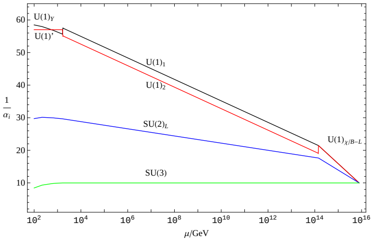
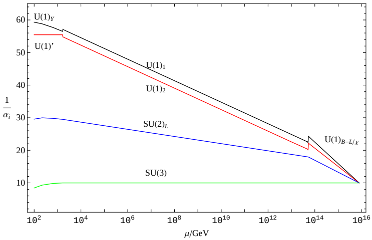
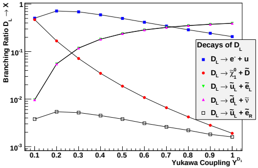


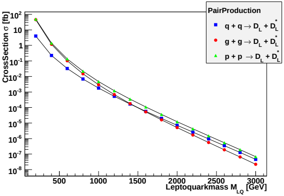


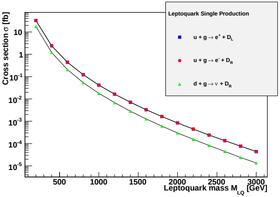
Predictions from E_6 GUTs for LHC

Braam/JRR/Wiesler, 0909.3081

- Simulations for the E_6 model with `WHIZARD`
- Implementation of Leptoquark/Leptoquarkino + Higgs/weak ino sector (now FeynRules impl.)
- Analyses: BRs, cross sections for scalar leptoquarks, S/B
- Leptoquarkino phenomenology







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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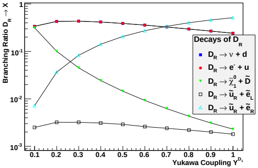

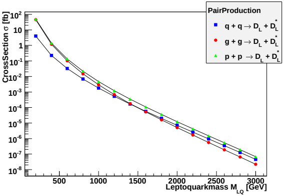

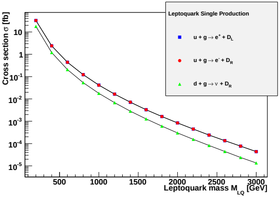

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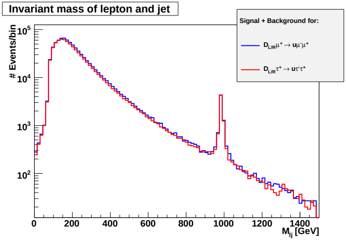
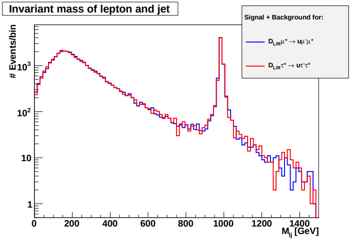
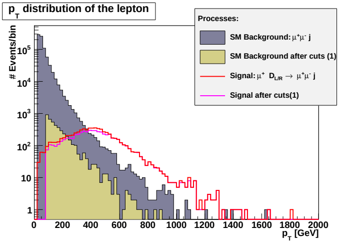
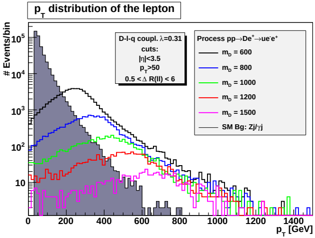
Braam/JRR/Wiesler, 0909.3081; Braam/Horst/Knochel/JRR/Wiesler , 2011







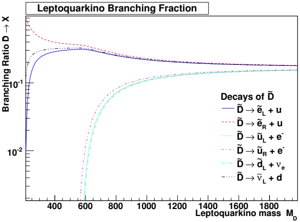


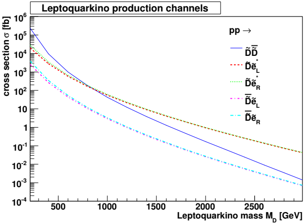
- Backgrounds: $tt + nj$, $W/Z + nj$
- Cuts: $\not{p}_T > 150$ GeV, $\quad -1.0 < \cos\theta_{\ell j} < 0.7$

Mass Edges for Leptoquarkinos

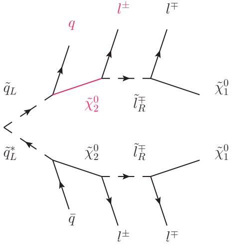
JRR/Wiesler, PRD **84** (2011) 015012

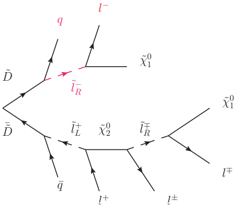
- Properties of Leptoquarkinos:





- Identical exclusive final states



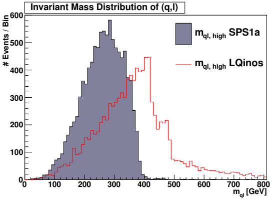


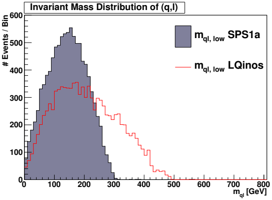
Mass Edges for Leptoquarkinos

JRR/Wiesler, PRD **84** (2011) 015012

- Mass edges more dominant because of missing spin correlations

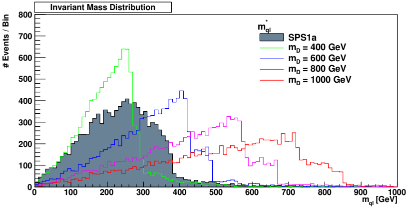
$$m_{ql,high} = \max\{m_{ql+}, m_{ql-}\} \qquad m_{ql,low} = \min\{m_{ql+}, m_{ql-}\}$$





- Combinatorial backgrounds, combine softest jet and hardest lepton:

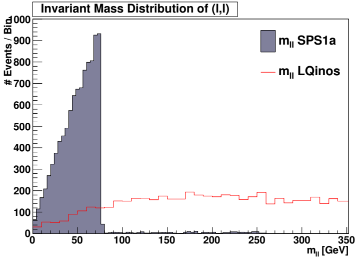
$$m^*_{ql} = m(\min_E\{q_1, q_2\}, \max_E\{l^+, l^-\})$$

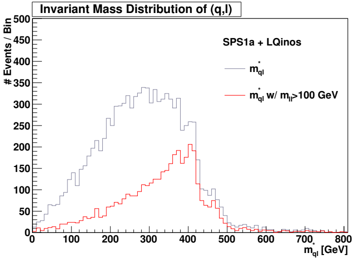


Discrimination from standard SUSY

JRR/Wiesler, PRD **84** (2011) 015012

- Look at dilepton spectrum: standard SUSY ⇒ same cascade, Leptoquarkinos ⇒ different cascades
- Cut on kinematic edge in standard dilepton spectra





- S/B estimate, 100 fb^{-1}, 2 OSSF, 2 hard jets, $\not{E}_T$

$m_{\tilde{D}}$	# N(LQino) & N(SUSY)	# N_{cut}	S / $\sqrt{S+B}$
400	8763	5061	54
600	1355	540	15
800	684	102	4
1000	594	24	1

- **More pheno to come..... stay tuned...**

Summary & Outlook

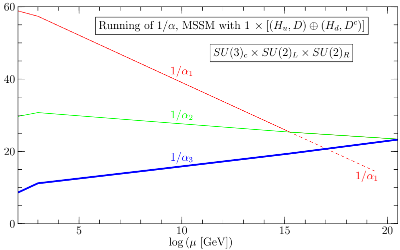
- Grand Unified Theories with intermediate breaking
- Viable scenarios: $E_6 \to SU(3/4) \times SU(2)_L \times SU(2)_R \times U(1)^2$
- Possible breaking mechanisms: Higgs vs. Orbifold boundary conditions
- Proton decay beyond experimental reach $(10^{40} - 10^{46}$ yrs.)
- Direct hints through chiral exotics at LHC
- Interesting, but intricate phenomenology at LHC
- Embedding into heterotic string/F theory Hebecker/Knochel/Ratz/JRR/Vaudrevange
- Flavour plays important role: continuous vs. discrete symmetries
- Open questions: flavour, dark matter, SUSY breaking mechanisms

Backup Slides

Running With Triplets

Kilian/JR, 2006

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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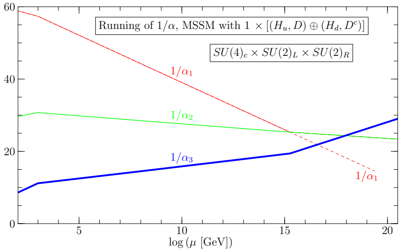

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$SU(3)_c$ crosses at 10^{21} GeV: too high

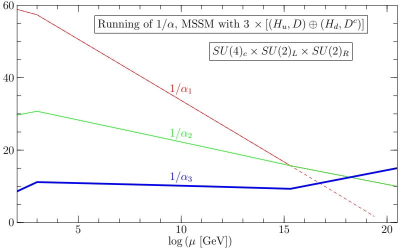
$\Rightarrow$ extend to $SU(4)_C$: unification possible at 10^{18} GeV

Running With Triplets

Kilian/JR, 2006

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

Proton Decay in the PSSSM

Mallot/JRR, 2010

- Superpotential (and soft breaking) do not induce proton decay
- Investigate exchange of E_6 gauge bosons/gauginos
- Steps from top down:
  1. Group-theoretical weights from Clebsch-Gordan decomposition
     Horst/Mallot/JRR, 2009
  2. Calculation of proton-decay Wilson coefficients at Λ_{GUT}
  3. Short-distance (SUSY) renormalisation group factor
  4. Matching to SM dimension-6 Fermi operators
  5. Long-distance (SM/QCD) renormalisation group factor
  6. Matching to mesonic/baryonic operators (analogue to chiral perturbation theory)
  7. Calculation of baryon decay matrix element and width
- Yields very conservative estimate:

$$1/\Gamma_{tot}(p \to X) \quad \approx \quad 10^{40} - 10^{46} \text{ Jahre}$$

Problems and E_6/Pati-Salam breaking

JRR et al., 2010

- E_6 superpotential vanishes $\Rightarrow$ E_6 operators generate PS superpotential Power suppression: top Yukawa?
- discrete symmetry to discriminate lepto-/diquark couplings/H-Parity violate GUT multiplet structure
- strong constraints from perturbativity above Λ_{PS}
- Difficulties to find representations for PS breaking
  - $\mathbf{27}$, $\mathbf{351}$, and $\mathbf{351'}$ break E_6 to rank 5
    $U(1)_\chi$ broken, no quartic singlet potential
  - No rank reduction: adjoint breaking
  - Breaking through $\langle(\mathbf{27})(\overline{\mathbf{27}})\rangle$ or $\langle\mathbf{27}\rangle\,\langle\overline{\mathbf{27}}\rangle$ $\qquad \mathbf{27}\times\overline{\mathbf{27}} = \mathbf{1}+\mathbf{78}+\mathbf{650}$
  - $\mathbf{650}$ smallest rep for $E_6 \to G_{PS}\times U(1)$
  - Possible to construct superpotential which does the breaking and allows leptoquark couplings

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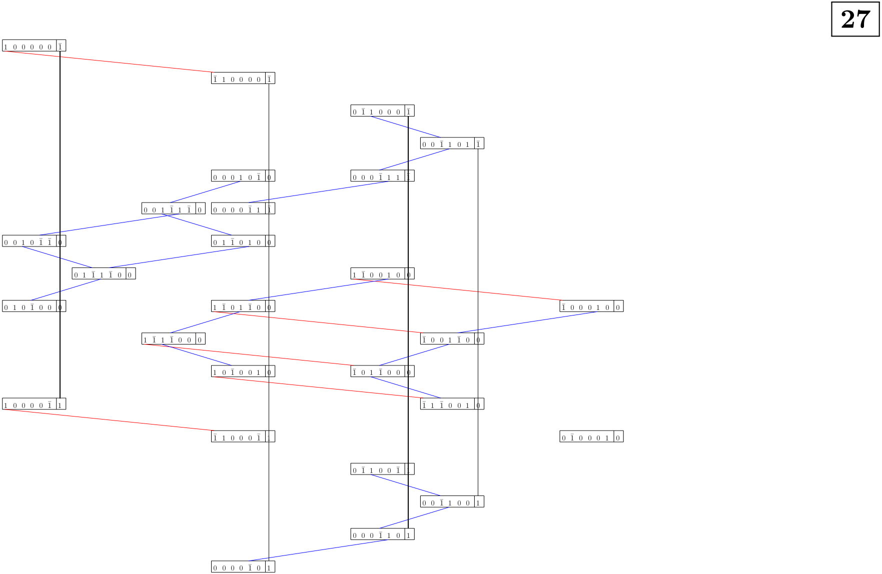
Automatic Irrep Decomposition

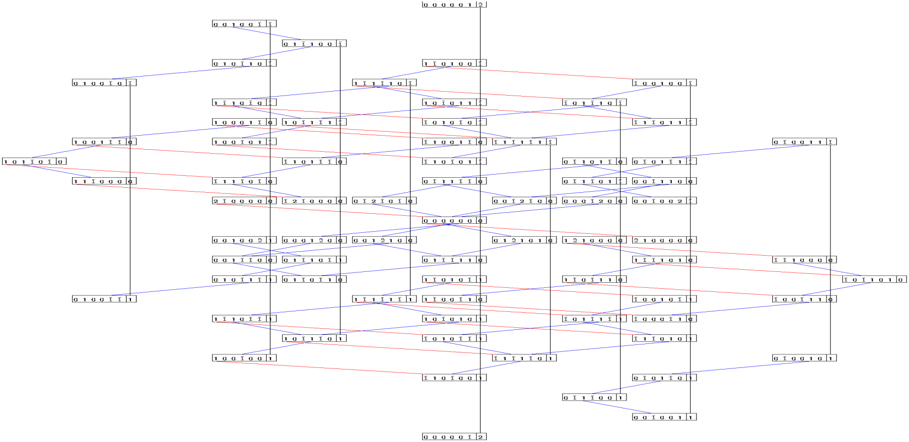
Mallot/JRR; Horst/JRR: CleGo, CPC (2011)



Automatic Irrep Decomposition

Mallot/JRR; Horst/JRR: CleGo, CPC (2011)

78



Automatic Irrep Decomposition

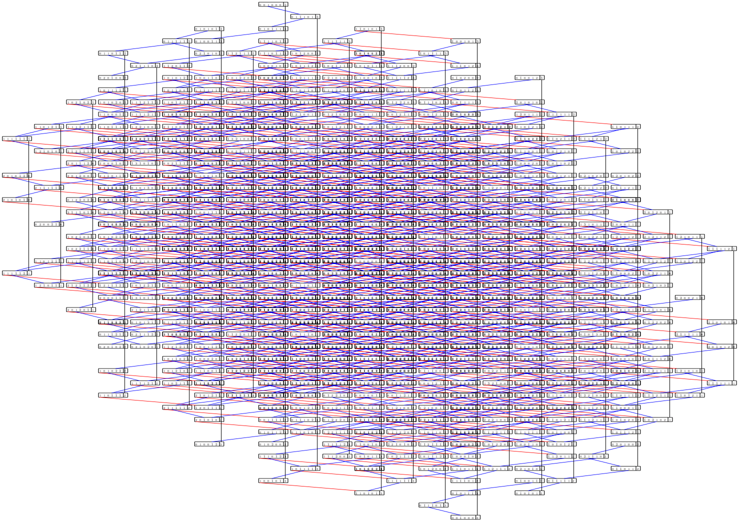
Mallot/JRR; Horst/JRR: CleGo, CPC (2011)

351′

Automatic Irrep Decomposition

Mallot/JRR; Horst/JRR: CleGo, CPC (2011)

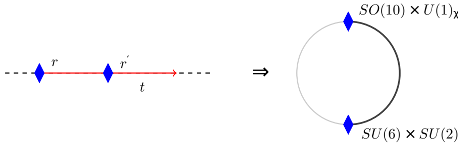
2925



PS models from 5D orbifolds

Braam/Knochel/JRR, JHEP 1006:013

$E_6 \;\rightarrow\; PS \times U(1)$ breaking on $S^1/(\mathbb{Z}_2 \times \mathbb{Z}_2')$



$SU(6)\times SU(2)_L$ \ $SO(10)_{\sqrt{6}Q\chi}$	$\mathbf{16}_{\frac{1}{2}}$	$\mathbf{10}_{-1}$	$\mathbf{1}_{2}$
$(\overline{\mathbf{15}},\mathbf{1})$	$(\overline{\mathbf{4}},\mathbf{1},\mathbf{2})_{\mathbf{1/2}}$	$(\mathbf{6},\mathbf{1},\mathbf{1})_{-\mathbf{1}}$	$(\mathbf{1},\mathbf{1},\mathbf{1})_{\mathbf{2}}$
$(\mathbf{6},\mathbf{2})$	$(\mathbf{4},\mathbf{2},\mathbf{1})_{\mathbf{1/2}}$	$(\mathbf{1},\mathbf{2},\mathbf{2})_{-\mathbf{1}}$	×

- LQ/DQ couplings from: $\mathbf{10}\;\mathbf{16}\;\mathbf{16}$, $\mathbf{6}\;\mathbf{6}\;\overline{\mathbf{15}}$, $\overline{\mathbf{15}}\;\overline{\mathbf{15}}\;\overline{\mathbf{15}}$ $\Rightarrow$ no way to forbid either of them
- Anomalies: $SU(6)\times SU(2)$ fixed point only vector-like matter
- Gauge shifts: $\overline{V} = (\frac{1}{2},\frac{1}{2},0,\frac{1}{2},\frac{1}{2},0)$, $\quad \overline{V}' = (\frac{1}{2},\frac{1}{2},\frac{1}{2},\frac{1}{2},\frac{1}{2},0)$
- 5D E_6 $\mathbf{78}$ vector multiplet $\longrightarrow \mathbf{16}_{-\mathbf{3/2}} + \overline{\mathbf{16}}_{\mathbf{3/2}}$, $(\mathbf{20},\mathbf{2})$
- 4 bulk 5D E_6 $\mathbf{27}$ hypermultiplet with $\mathbb{Z}_2 \times \mathbb{Z}_2'$ parities $(++), (--), (-+), (+-) \longrightarrow$ $(\mathbf{6},\mathbf{1},\mathbf{1})_{-\mathbf{1}} + (\mathbf{1},\mathbf{1},\mathbf{1})_{\mathbf{2}}$, $(\mathbf{4},\mathbf{2},\mathbf{1})_{\frac{1}{2}}$, $(\overline{\mathbf{4}},\mathbf{1},\mathbf{2})_{\frac{1}{2}}$, $(\mathbf{1},\mathbf{2},\mathbf{2})_{-\mathbf{1}}$
- 3rd gen. from 2 bulk hypermultiplets + a brane-localized $\mathbf{16}'_{\frac{1}{2}} + \mathbf{16}^{\mathbf{3}}_{\frac{1}{2}}$
- LQ-/DQ couplings generated (only simultaneously), but must be rendered small by hand

Classification of Models

- $E_6 \supset H \supset SU(3) \times SU(2)^2 \times U(1)^2$ Breaking through $\mathbb{Z}_2$, $\mathbb{Z}_3$, $\mathbb{Z}_4$.

$\mathbb{Z}_2$	Subgroup H	Shift $2\overline{V}$
	$SO(10) \times U(1)_\chi$	$(1,1,0,1,1,0)$
	$SU(6) \times SU(2)_R$	$(0,0,1,0,0,0)$
	$SU(6) \times SU(2)_L$	$(1,1,1,1,1,0)$

$\mathbb{Z}_3$	Subgroup H	Shift $3\overline{V}$
	$SU(3)_C \times SU(3)_L \times SU(3)_R$	$(0,0,1,-1,0,0)$

$\mathbb{Z}_4$	Subgroup H	Shift $4\overline{V}$
	$SU(3)_C \times SU(3)_L \times SU(2)_R \times U(1)$	$(0,0,1,2,0,0)$
	$SU(3)_C \times SU(3)_R \times SU(2)_L \times U(1)$	$(-1,1,1,1,1,0)$

- non-trivial ($H_i \not\subseteq H_j$) common invariant subgroups $H_i \cap H_j$ under two combined shifts

$\mathbb{Z}_2 \times \mathbb{Z}_2$	$SU(4)_C \times SU(2)_L \times SU(2)_R \times U(1)_\chi$
$\mathbb{Z}_2 \times \mathbb{Z}_3$	$SU(3)_C \times SU(2)_L \times SU(2)_R \times U(1)_{B-L} \times U(1)_\chi$ $SU(3)_C \times SU(3)_L \times SU(2)_R \times U(1)$ $SU(3)_C \times SU(3)_R \times SU(2)_L \times U(1)$
$\mathbb{Z}_2 \times \mathbb{Z}_4$	$SU(4)_C \times SU(2)_L \times SU(2)_R \times U(1)_\chi$ $SU(3)_C \times SU(2)_L \times SU(2)_R \times U(1)_{B-L} \times U(1)_\chi$
$\mathbb{Z}_3 \times \mathbb{Z}_4$	$SU(3)_C \times SU(3)_L \times SU(2)_R \times U(1)$ $SU(3)_C \times SU(3)_R \times SU(2)_L \times U(1)$
$\mathbb{Z}_4 \times \mathbb{Z}_4$	$SU(3)_C \times SU(2)_L \times SU(2)_R \times U(1)_{B-L} \times U(1)_\chi$