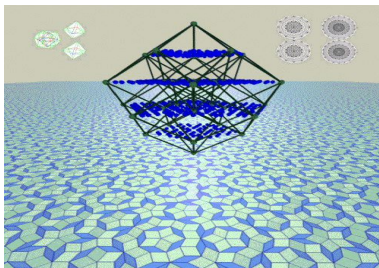


# Exceptional Grand Unification in the light of LHC data

Jürgen R. Reuter

DESY Hamburg



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

### $\mu$ 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

- ⇒ Two Higgs doublets  $H^u, H^d$
- ⇒ SM superpartners at the TeV scale

Bottom-Up approach: only MSSM

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

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

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

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

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

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

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

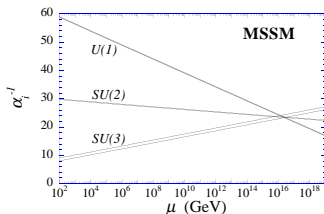
$$L_L = (\mathbf{1}, \mathbf{2})_{-\frac{1}{2}}, Q'_L$$

$$\nu^c = (\mathbf{1}, \mathbf{1})_{0}, Q'_\nu = 0$$

$$e^c = (\mathbf{1}, \mathbf{1})_{1}, Q'_e$$

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

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

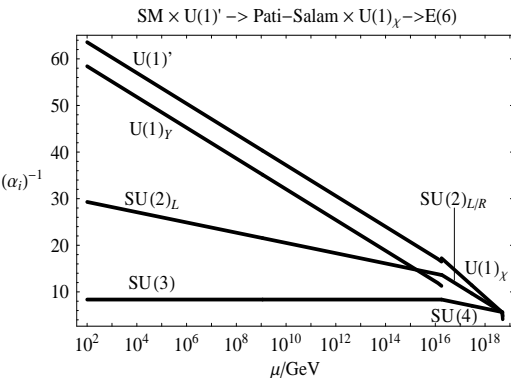


# Intermediate Pati-Salam/LR symmetry

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

- ▶ Additional particles destroy MSSM unification
- ▶ Unification below  $\Lambda_{Planck}$  with intermediate

$SU(4) \times SU(2)_L \times SU(2)_R \times U(1)_X$  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
- ▶  $T_{SU(4)}^{15} \propto \frac{B-L}{2}$
- ▶  $Y = \frac{B-L}{2} + T_R^3$
- ▶  $U(1)$  Matching condition  

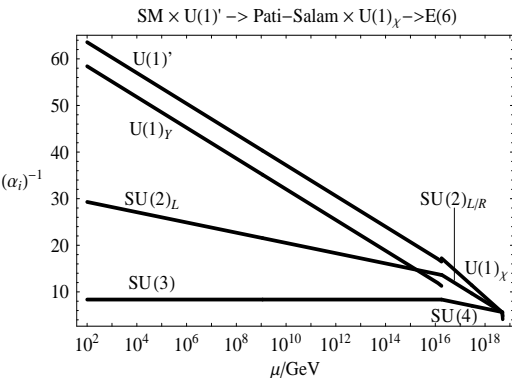
$$\frac{1}{g_Y^2} = \frac{2}{5} \frac{1}{g_{B-L}^2} + \frac{3}{5} \frac{1}{g_R^2}$$
- ▶ Integrating out  $\nu^c$ : see-saw  $\Rightarrow$  correct breaking

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

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$SU(3) \times SU(2)_L \times SU(2)_R \times U(1)_\chi \times U(1)_{B-L}$  LR symmetry at  $\sim 10^{15-16}$  GeV



- ▶  $SU(2)_R$  and  $SU(2)_L$ : identical content/running
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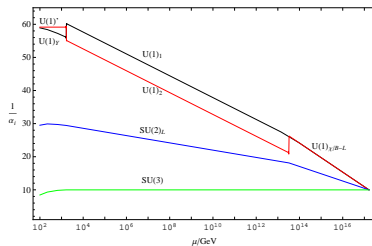
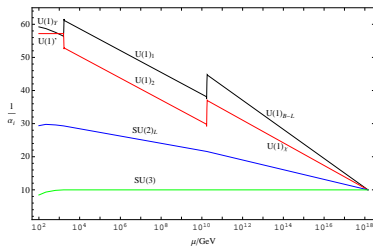
# $U(1)$ Mixing

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)

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

- Effects for the running:



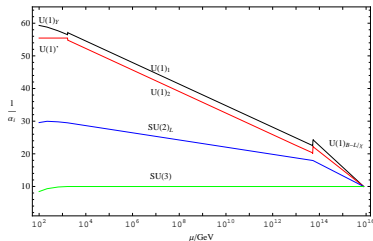
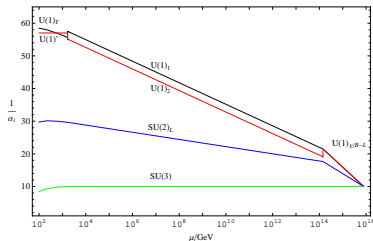
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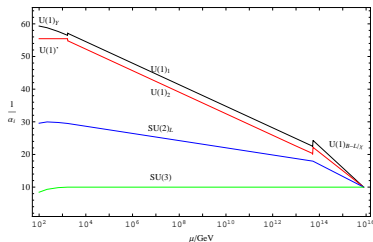
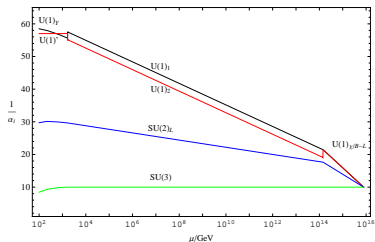
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- Effects for the running:



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



# The Superpotential / Sketch of a Model

Kilian/JR, 2006

Superpotential:

$$\mathcal{W} = \mathcal{W}_{\text{MSSM}} + \mathcal{W}_D + \mathcal{W}_N$$

$$\mathcal{W}_{\text{MSSM}} = Y^u u^c Q H_u + Y^d d^c Q H_d + Y^e e^c L H_d$$

$$\mathcal{W}_D = Y^D D u^c e^c + Y^{D^c} D^c Q L$$

$$\mathcal{W}_S = Y^{S_H} S H_u H_d + Y^{S_D} S D D^c$$

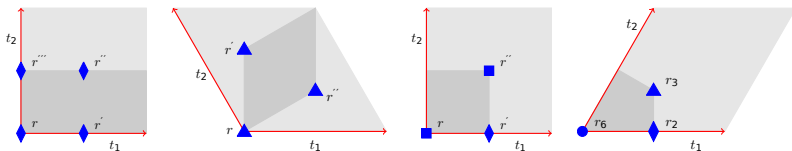
- Corresponding soft-breaking terms
- $t/\tilde{t}$  drive  $m_{H_u}^2$  negative
- $D/\tilde{D}$  drive  $m_S^2$  negative
- $U(1)'$   $D$ -terms provide large enough  $S$  quartics (and  $H$  quartics)
- Configuration drives system to large  $\langle S \rangle \sim 1 - 2 \text{ TeV}$
- $R$  parity 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/Knoche/JRR, JHEP 1006:013

- Consider:  $\mathbb{R}^4 \times (\mathbb{R}^2/\Gamma)$ ,  $\Gamma$  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  $(\xi_1, \bar{\xi}_2) \xrightarrow{\theta} (e^{-i\pi/n}\xi_1, e^{i\pi/n}\bar{\xi}_2)$
- 4D  $\mathcal{N} = 1$  SUSY conserved by either:
  - ▶ Using 10D Lorentz phases:

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

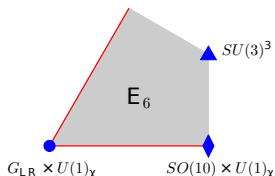
- ▶ Non-trivial embedding of  $SU(2)$  R symmetry

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

# A specific Model

Braam/Knoche/JRR, JHEP 1006:013

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



- ▶ Anomalies from bulk **78** chiral modes after projection  
 $(\mathbf{16}_{-3/2} + \overline{\mathbf{16}}_{3/2}, (\bar{\mathbf{3}}, \mathbf{2}, \mathbf{1}) + (\bar{\mathbf{3}}, \mathbf{1}, \mathbf{2}), (\mathbf{3}, \mathbf{3}, \bar{\mathbf{3}}))$  cancel against **78** bulk hypermultiplet
- ▶ 3 gen. of **27** as brane-localized matter

$SU(3)^3 \setminus SO(10)_{Q_X}$	$\mathbf{16}_{\frac{1}{2}}$	$\mathbf{10}_{-1}$	$\mathbf{1}_2$
<b>A</b> = $(\bar{\mathbf{3}}, \mathbf{1}, \mathbf{3})$	$(\bar{\mathbf{3}}, \mathbf{1}, \mathbf{2})_{(-\frac{1}{3}, \frac{1}{2})}$	$(\bar{\mathbf{3}}, \mathbf{1}, \mathbf{1})_{(\frac{2}{3}, -1)}$	×
<b>B</b> = $(\mathbf{3}, \mathbf{3}, \mathbf{1})$	$(\mathbf{3}, \mathbf{2}, \mathbf{1})_{(\frac{1}{3}, \frac{1}{2})}$	$(\mathbf{3}, \mathbf{1}, \mathbf{1})_{(-\frac{2}{3}, -1)}$	×
<b>C</b> = $(\mathbf{1}, \bar{\mathbf{3}}, \bar{\mathbf{3}})$	$(\mathbf{1}, \mathbf{2}, \mathbf{1})_{(-1, \frac{1}{2})}$ $(\mathbf{1}, \mathbf{1}, \mathbf{2})_{(1, \frac{1}{2})}$	$(\mathbf{1}, \mathbf{2}, \mathbf{2})_{(0, -1)}$	$(\mathbf{1}, \mathbf{1}, \mathbf{1})_{(0, 2)}$

- ▶ Trinification FP  $SU(3)^3$  ( $H$ -even!) to discriminate LQ/DQ couplings (3rd gen.):  
 $\mathbf{27}^3 \rightarrow (\bar{\mathbf{3}}, \mathbf{1}, \mathbf{3})^3 + (\mathbf{3}, \mathbf{3}, \mathbf{1})^3 + (\mathbf{1}, \bar{\mathbf{3}}, \bar{\mathbf{3}})^3 + (\bar{\mathbf{3}}, \mathbf{1}, \mathbf{3})(\mathbf{3}, \mathbf{3}, \mathbf{1})(\mathbf{1}, \bar{\mathbf{3}}, \bar{\mathbf{3}})$
- ▶ 1.+2. gen. on  $SO(10)$  FP. (allows for LQ couplings)
- ▶ LR symmetry breaking by brane-localized matter:

- $L, l^c, \langle \nu^c \rangle + c.c. \sim (\mathbf{1}, \bar{\mathbf{3}}, \bar{\mathbf{3}}) \cap \mathbf{16} + c.c.$
- $L, l^c, \langle \nu^c \rangle, H_u, H_d, S + c.c. \sim (\mathbf{1}, \bar{\mathbf{3}}, \bar{\mathbf{3}}) + c.c.$

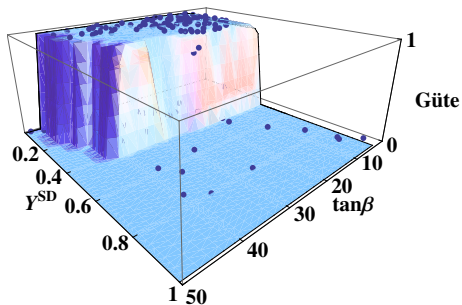
# Model Building $\Rightarrow$ Phenomenology



# Scan of Parameter Space

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

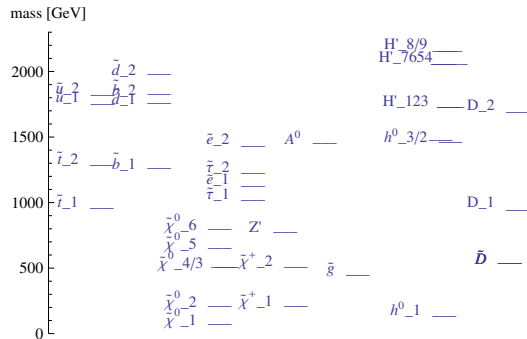
- ▶ # free parameters  $\sim \mathcal{O}(100)$ , additional assumptions:
  - Unified Soft-Breaking terms
  - Flavour structure
 ⇒ Restriction to 14 parameters
- ▶ Constraints:
  - (1) Experimental search limits for new particles
  - (2) Running couplings perturbative up to  $\Lambda_{E_6}$
  - (3) Scalar (non-Higgs) mass terms positive  
( $\Leftrightarrow$  No false vacua)



- ▶ 14-dim. parameter space
  - ⇒ 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
- ⇒ Effective search for relevant parameter tuples

# Generic Properties of Spectra

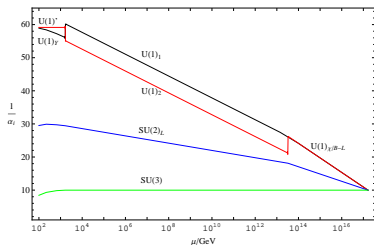
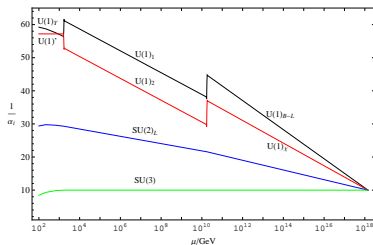
EXSPECT: Braam/JRR, 2011



- Vanishing 1-loop QCD  $\beta$  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

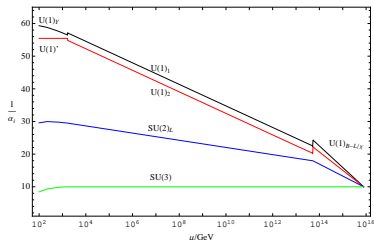
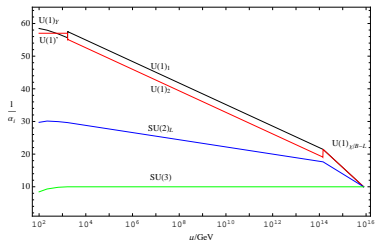
# Sample Spectra

$H_{\text{int}}, \bar{H}_{\text{int}}$	$i)$	$ii)$	$3ii)$	$i) + 2ii)$
$\Lambda_{\text{int}}/\text{GeV}$	$1.6 \times 10^{10}$	$3.0 \times 10^{13}$	$1.3 \times 10^{14}$	$4.9 \times 10^{13}$
$\Lambda_{\text{GUT}}/\text{GeV}$	$1.3 \times 10^{18}$	$1.5 \times 10^{17}$	$7.2 \times 10^{15}$	$7.2 \times 10^{15}$
$g'   M_{Z'}$	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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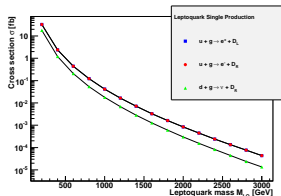
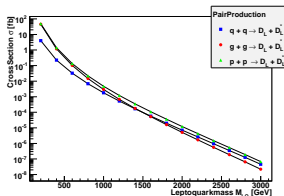
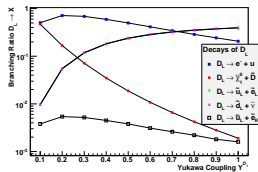




# Predictions from $E_6$ GUTs for LHC

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

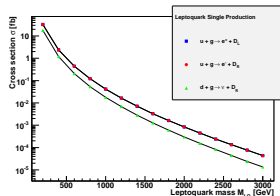
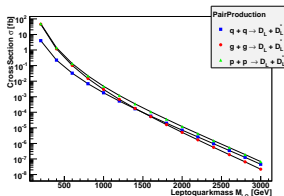
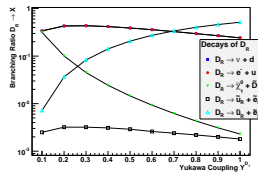


Cuts		Background	$m_D = 0.6$ TeV		$m_D = 0.8$ TeV		$m_D = 1.0$ TeV	
$p_T$	$M_{\ell\ell}$	$N_{BG}$	$N_1$	$S_1/\sqrt{B}$	$N_2$	$S_2/\sqrt{B}$	$N_3$	$S_3/\sqrt{B}$
50	10	413274	64553	<b>93</b>	14823	<b>23</b>	4819	<b>7</b>
100	150	3272	40749	<b>194</b>	10891	<b>92</b>	3767	<b>45</b>
200	150	198	12986	<b>113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

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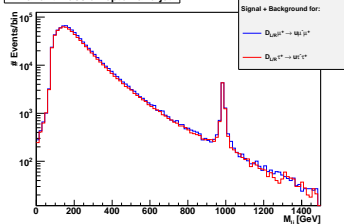
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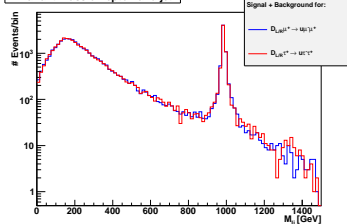
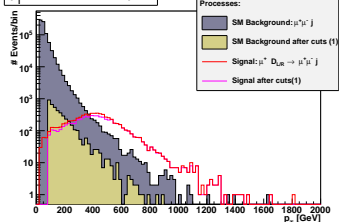
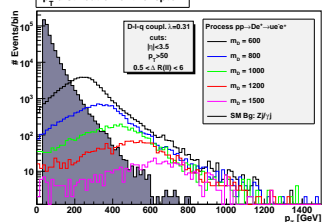
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Braum/JRR/Wiesler, 0909.3081; Braam/Horst/Knochel/JRR/Wiesler, 2011

Invariant mass of lepton and jet



Invariant mass of lepton and jet

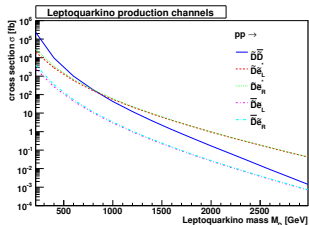
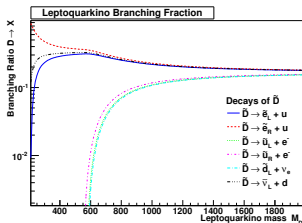
 $p_T$  distribution of the lepton $p_T$  distribution of the lepton

- Backgrounds:  $tt + n_j$ ,  $W/Z + n_j$
- Cuts:  $p_T > 150$  GeV,  $-1.0 < \cos \theta_{lj} < 0.7$

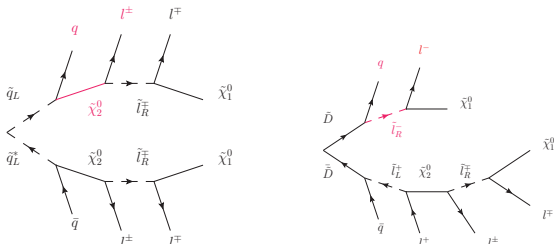
# Mass Edges for Leptoquarkinos

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

## ► Properties of Leptoquarkinos:



## ► Identical exclusive final states

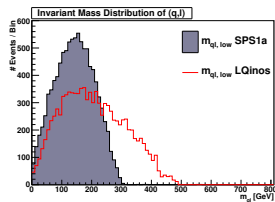
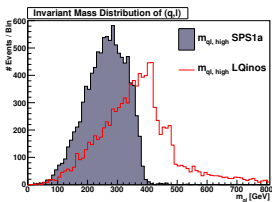


# Mass Edges for Leptoquarkinos

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

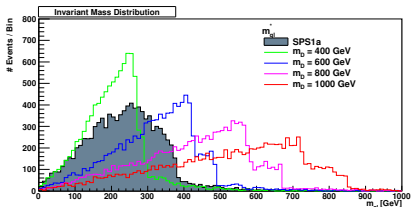
- ▶ Mass edges more dominant because of missing spin correlations

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



- ▶ Combinatorial backgrounds, combine softest jet and hardest lepton:

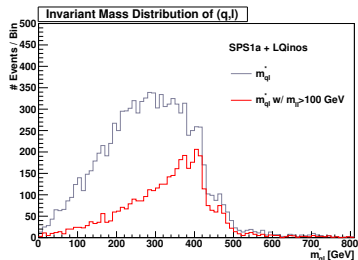
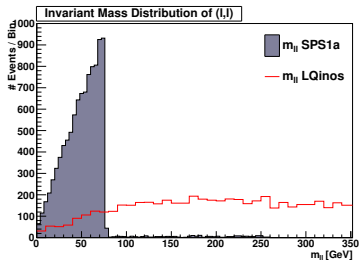
$$m_{ql}^* = m(\min_E\{q_1, q_2\}, \max_E\{l^+, l^-\})$$



# Discrimination from standard SUSY

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

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



- S/B estimate,  $100 \text{ fb}^{-1}$ , 2 OSSF, 2 hard jets,  $\cancel{E}_T$

$m_{\tilde{D}}$	# 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:  $E_6 \rightarrow SU(3/4) \times SU(2)_L \times SU(2)_R \times U(1)^2$
- 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

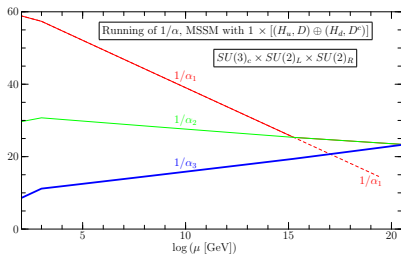
# Backup Slides



# Running With Triplets

Kilian/JR, 2006

Bottom-up approach: MSSM with one generation of triplets

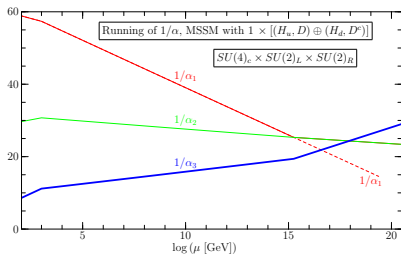


$10^{15}$  GeV: crossing of  $SU(2)_L$  and  $U(1)_Y$   
 $\Rightarrow$  unification to LR symmetry  $SU(2)_L \times SU(2)_R$ , requires  $\nu_R^c$   
 $SU(3)_c$  crosses at  $10^{21}$  GeV: too high

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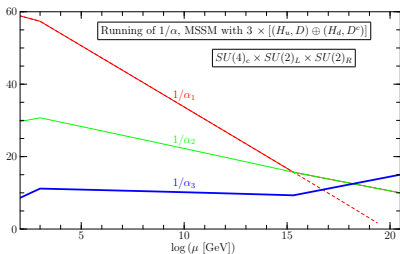
$\Rightarrow$  extend to  $SU(4)_C$ : unification possible at  $10^{18}$  GeV

# Running With Triplets

Kilian/JR, 2006

Complete Model:

- ▶ Full SUSY  $E_6/G_{\text{Tri}}$  matter spectrum above  $10^3$  GeV, except  $\nu^c$



- ▶ PS symmetry with  $\nu_R$  above  $10^{15}$  GeV

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

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

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

- ▶  $E_6$  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  $\Lambda_{\text{GUT}}$
  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**:

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

# 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  $\Lambda_{PS}$
- Difficulties to find representations for PS breaking
  - ▶ **27, 351, and 351'** break  $E_6$  to rank 5  
 $U(1)_X$  broken, no quartic singlet potential
  - ▶ No rank reduction: **adjoint breaking**
  - ▶ Breaking through  $\langle (27)(\overline{27}) \rangle$  or  $\langle 27 \rangle \langle \overline{27} \rangle$        $27 \times \overline{27} = 1 + 78 + 650$
  - ▶ **650** smallest rep for  $E_6 \rightarrow G_{PS} \times U(1)$
  - ▶ Possible to construct superpotential which does the breaking and allows leptoquark couplings

# Problems and $E_6$ /Pati-Salam breaking

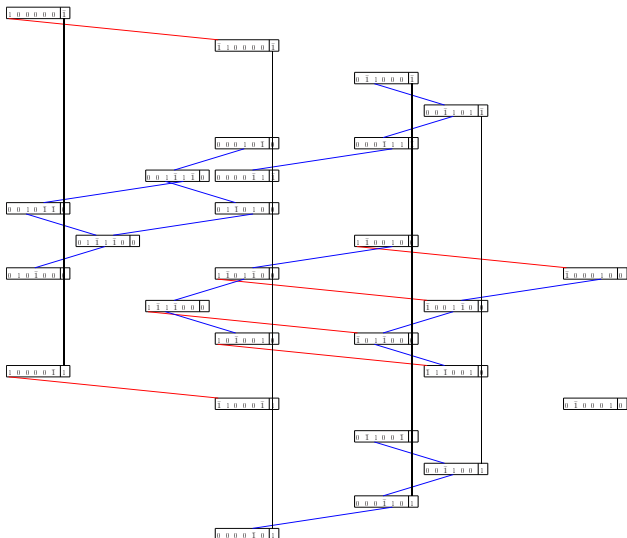
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# Automatic Irrep Decomposition

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

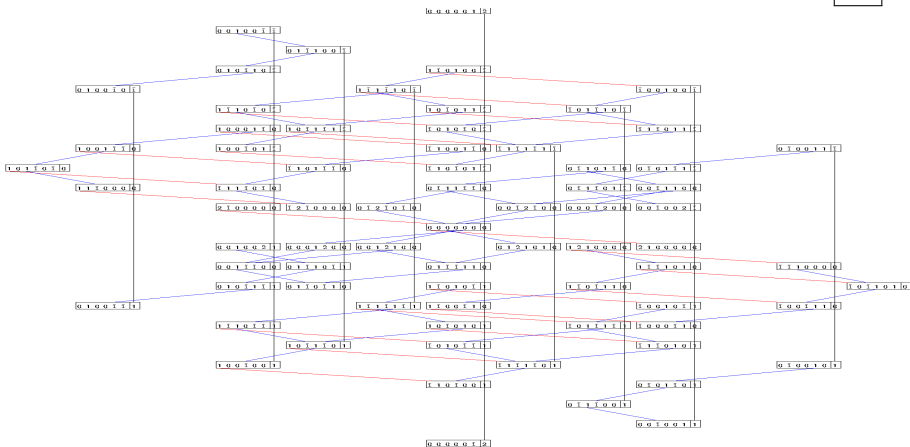
27



# Automatic Irrep Decomposition

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

78

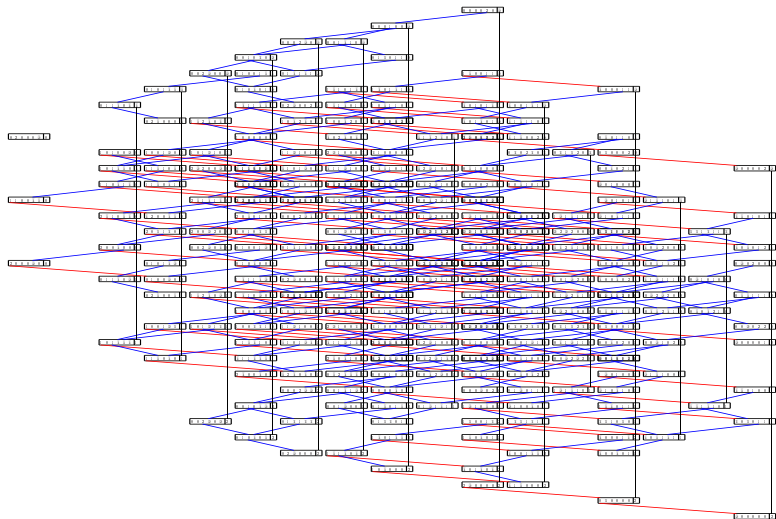




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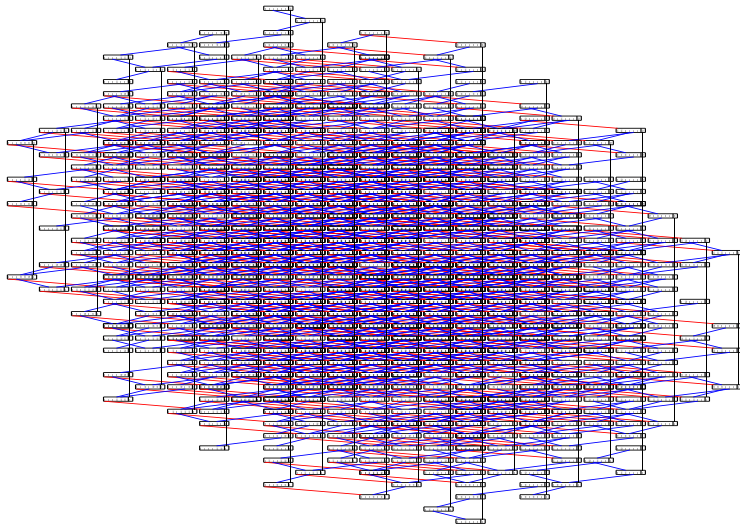
351'



# Automatic Irrep Decomposition

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

2925



# PS models from 5D orbifolds

Braam/Knoche/JRR, JHEP 1006:013

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



$SU(6) \times SU(2)_L$	$SO(10)_{\sqrt{6}Q_X}$	$16_{\frac{1}{2}}$	$10_{-1}$	$1_2$
$(\overline{15}, 1)$		$(\overline{4}, 1, 2)_{1/2}$	$(6, 1, 1)_{-1}$	$(1, 1, 1)_2$
$(6, 2)$		$(4, 2, 1)_{1/2}$	$(1, 2, 2)_{-1}$	$\times$

- ▶ LQ/DQ couplings from:  $10 \ 16 \ 16, 6 \ 6 \ \overline{15}, \overline{15} \ \overline{15} \ \overline{15} \Rightarrow$  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  $E_6$  **78** vector multiplet  $\rightarrow 16_{-3/2} + \overline{16}_{3/2}, (20, 2)$
- ▶ 4 bulk 5D  $E_6$  **27** hypermultiplet with  $\mathbb{Z}_2 \times \mathbb{Z}'_2$  parities  $(++), (--), (-+), (+-)$   $\rightarrow (6, 1, 1)_{-1} + (1, 1, 1)_2, (4, 2, 1)_{\frac{1}{2}}, (\overline{4}, 1, 2)_{\frac{1}{2}}, (1, 2, 2)_{-1}$
- ▶ 3rd gen. from 2 bulk hypermultiplets + a brane-localized  $16'_{\frac{1}{2}} + 16^3_{\frac{1}{2}}$
- ▶ **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 $2\bar{V}$
	$SO(10) \times U(1)_X$	$(1, 1, 0, 1, 1, 0)$
	$SU(6) \times SU(2)_R$	$(0, 0, 1, 0, 0, 0)$
	$SU(6) \times SU(2)_L$	$(1, 1, 1, 1, 1, 0)$
$\mathbb{Z}_3$	Subgroup $H$	Shift $3\bar{V}$
	$SU(3)_C \times SU(3)_L \times SU(3)_R$	$(0, 0, 1, -1, 0, 0)$
$\mathbb{Z}_4$	Subgroup $H$	Shift $4\bar{V}$
	$SU(3)_C \times SU(3)_L \times SU(2)_R \times U(1)$	$(0, 0, 1, 2, 0, 0)$
	$SU(3)_C \times SU(3)_R \times SU(2)_L \times U(1)$	$(-1, 1, 1, 1, 1, 0)$

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

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