Hints for Exceptional Unification at the Large Hadron Collider

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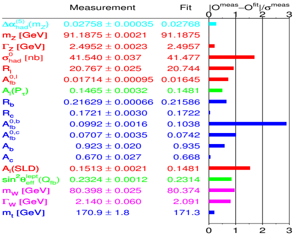
based on: hep-ph/0606277, 0709.4202, 0909.3081, 0909.3059; 1001.xxxx ($\sim$ Friday!); 1002.xxxx

MPI München, 20. January 2010

The Standard Model of Particle Physics – Doubts



– describes microcosm (too well?)

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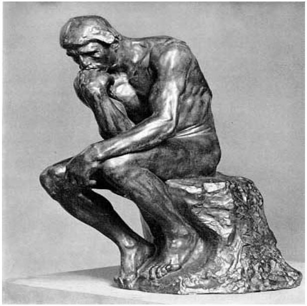
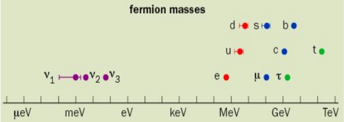
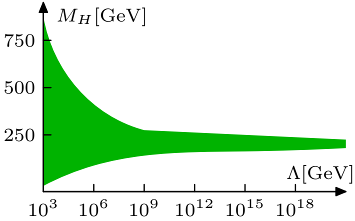


– describes microcosm (too well?)

– 28 free parameters



– Form of the Higgs potential ?



Hierarchy problem

chiral symmetry: $\delta m_f \propto v \ln(\Lambda^2/v^2)$

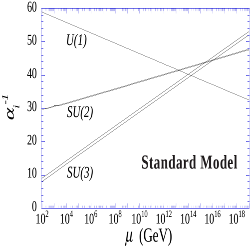
no symmetry protects Higgs from quantum corrections

$$\delta M_H^2 \propto \Lambda^2 \sim M_{\text{Planck}}^2 = (10^{19})^2 \text{ GeV}^2$$

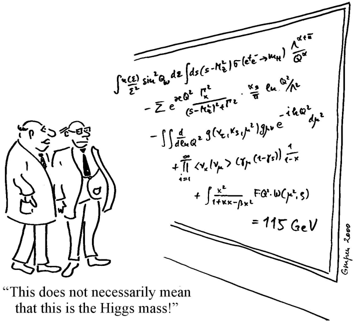
20000 GeV^2 = (100000000000000000000000000000000020000 –

100000000000000000000000000000000000000) GeV^2

Open Questions



- Unification of all forces (?)
- Baryon asymmetry $\Delta N_B - \Delta N_{\bar{B}} \sim 10^{-9}$
  missing CP violation
- Flavour: three generations
- Tiny neutrino masses: $m_\nu \sim \frac{v^2}{M}$
- Dark matter:
  - stable
  - weakly interacting
  - $m_{DM} \sim 100\,$GeV
- Quantum theory of gravity
- Cosmic inflation
- Cosmological constant



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

bosonic TC
composite Higgs
TC-TC
hypercolor
supercolor
techni-GIM
extended TC
pseudo NGB
NOT YET THOUGHT OF
effective SUSY
SUSY
NMSSM
MSSM +VR
unified SM
axigluon
sterile ν
6th gen
5th gen
4th gen
lepto quark
heavy Majorana
Z'
W'
X
Y
milli-charged
mono-pole
vector-like family
fractionally charged
S,T,U
shadow matter
mirror symmetry
triplet Higgs
doubly charged Higgs
Type I
Type II
general 2HDSM
spontaneous CP
superweak
milli-weak
Majoron
axion
familon
NGB
saxion
axino
Weinberg's 3HD
quintessence
k-essence
composite W,Z
contact int.
string
heterotic
matrix
IIB
IIA
F
I
M
N=2
N=4
N=8
Extra dim
worm-hole

Ideas for New Physics since 1970

(1) **New building blocks, sub structure**

- Technicolor/Topcolor: Higgs bound state of strongly interacting particles

(2) **Symmetry for the elimination of quantum corrections**

- Supersymmetry: Spin-statistics $\Rightarrow$ bosonic and fermionic corrections cancel each other
- Little-Higgs models: Global symmetries $\Rightarrow$ corrections from particles of like statistics cancel each other

(3) **Nontrivial space-time structure eliminates hierarchy**

- Additional space dimensions: Gravitation appears only weak
- Noncommutative space-time: Space-time coarse-grained

(4) **Ignoring the hierarchy**

- Anthropic Principle: Parameters are the way they are, *because* we observe them


Desperately
Seeking
SUSY

Anatomy of MSSM

- Yukawa couplings $\Rightarrow$ Superpotential:

$$\mathcal{W} = \hat{\Phi}_1 \hat{\Phi}_2 \hat{\Phi}_3 \equiv \Phi_1 \Phi_2 \Phi_3 \qquad \Longrightarrow \qquad (\phi_1 \phi_2)^2, \ldots, \left(\overline{\psi}_1 \psi_2\right) \phi_3$$

- NB: part of scalar potential from gauge kinetic terms (light Higgs)
- MSSM superpotential

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

- Ignorance about SUSY breaking shows up as “soft-breaking terms”: Gaugino and sparticle masses, trilinear scalar potential terms
- μ problem: EWSB demands $\mu \sim \mathcal{O}(100\,\text{GeV} - 1\,\text{TeV})$
- Additional SUSY degrees of freedom modify vacuum polarization
  $\Rightarrow$ Unification of gauge couplings possible

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:

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

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$$A = g\sum_{a=1}^{24} A^a \frac{\lambda^a}{2} = \frac{g}{\sqrt{2}} \left(\begin{array}{ccc|cc} \multicolumn{3}{c|}{\sqrt{2}G^a \frac{\lambda^a_{\text{GM}}}{2}} & \begin{array}{cc} \bar{X} & \bar{Y} \\ \bar{X} & \bar{Y} \\ \bar{X} & \bar{Y} \end{array} \\ \hline \begin{array}{ccc} X & X & X \\ Y & Y & Y \end{array} & & & \multicolumn{2}{c}{\sqrt{2}W^a \frac{\sigma}{2}} \end{array}\right)$$

$$- \frac{g}{2\sqrt{15}} B \left(\begin{array}{ccc|cc} -2 & & & & \\ & -2 & & \multicolumn{2}{c}{0} \\ & & -2 & & \\ \hline & 0 & & +3 & \\ & & & & +3 \end{array}\right)$$

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

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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:

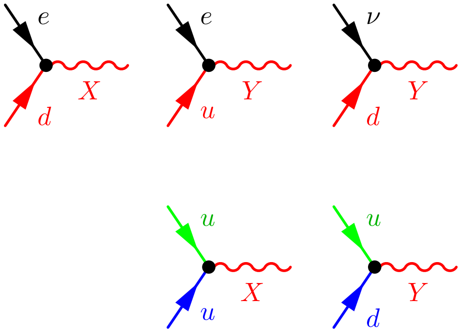
$$\overline{\mathbf{5}} = \begin{array}{|c|}\hline \\ \hline \\ \hline \\ \hline \\ \hline\end{array} : \quad \begin{pmatrix} d^c \\ d^c \\ d^c \\ \ell \\ -\nu_\ell \end{pmatrix} \qquad \mathbf{10} = \begin{array}{|c|}\hline \\ \hline \\ \hline\end{array} : \quad \frac{1}{\sqrt{2}} \left(\begin{array}{ccc|cc}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

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

Remarks

- $\mathbf{2} = \square = \overline{\mathbf{2}}, \qquad (\mathbf{5} \otimes \mathbf{5})_a = \mathbf{10}, \quad (\mathbf{3} \otimes \mathbf{3})_a = \overline{\mathbf{3}}, \quad (\square \otimes \square)_a = \begin{array}{|c|}\hline \\ \hline \\ \hline\end{array}$
- 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

Interactions



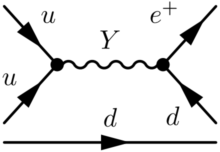
Leptoquark couplings

(and SUSY vertices)

Diquark couplings

(and SUSY vertices)

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



The doublet-triplet splitting problem

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

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

other breaking mechanisms possible (e.g. orbifold)

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other breaking mechanisms possible (e.g. orbifold)

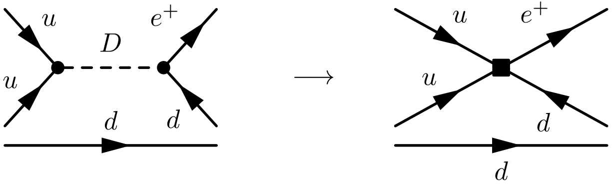
(MS)SM Higgs(es) included in $\mathbf{5} \otimes \overline{\mathbf{5}}$

$$\mathbf{5} = \square : \quad \begin{pmatrix} D \\ D \\ D \\ h^+ \\ h^0 \end{pmatrix} \qquad \overline{\mathbf{5}} = \begin{array}{|c|}\hline \; \\ \hline \; \\ \hline \; \\ \hline \; \\ \hline \end{array} : \quad \begin{pmatrix} D^c \\ D^c \\ D^c \\ h^- \\ -h^0 \end{pmatrix}$$

$$\mathbf{5} = \ (\mathbf{3}, \mathbf{1})_{-\frac{2}{3}} \oplus (\mathbf{1}, \mathbf{2})_1 \qquad \overline{\mathbf{5}} = \ (\overline{\mathbf{3}}, \mathbf{1})_{\frac{2}{3}} \oplus (\mathbf{1}, \mathbf{2})_{-1}$$

- D, D^c coloured triplet Higgses with charges $\pm\frac{1}{3}$
- also induces proton decay $\quad m_H \sim 100\,$GeV, $m_D \sim 10^{16}\,$GeV
- **Doublet-triplet splitting problem**

Naive estimate of proton lifetime



Effective 4-fermion operator (analogy to muon decay)

$$\mathcal{L}_F = \frac{4G_F}{\sqrt{2}}(\overline{\mu}\gamma_\kappa\nu_\mu)(\overline{\nu}_e\gamma^\kappa e) \qquad \mathcal{L}_{GUT} = \frac{4G_{GUT}}{\sqrt{2}}(\overline{u}\Gamma u)(\overline{e}\Gamma d)$$

$$\frac{G_F}{\sqrt{2}} = \frac{g_2^2}{8M_W^2} \qquad \frac{G_{GUT}}{\sqrt{2}} = \frac{g^2}{8M_{GUT}^2}$$

$$\tau(\mu \to e\nu_\mu\bar{\nu}_\mu) \sim \frac{192\pi^3}{G_F^2 m_\mu^5} \qquad \tau(p \to e^+\pi^0) \sim \frac{192\pi^3}{G_{GUT}^2 m_p^5}$$

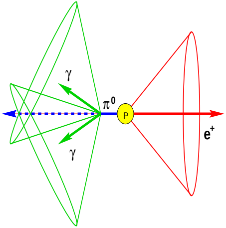
Proton lifetime for $\alpha(M_{GUT}) \sim 1/24$ and $M_{GUT} \sim 2 \times 10^{16}$ GeV:

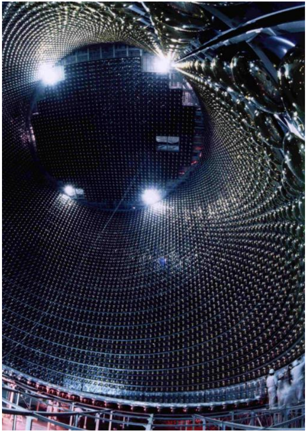
$\tau(p \to e^+\pi^0) \sim \frac{M_{GUT}^4}{[\alpha(M_{GUT})]^2 m_p^5} \to 10^{31\pm1}$ years

Compare: $\tau_p^{SM} \gtrsim 10^{150}$ years (gravity-induced)

Proton decay crucial for "GUT search"

- Tracking calorimeter (SOUDAN) or RICH Cherenkovs
- Super-Kamiokande: 50 kt water RICH
- measure change and time for reconstruction





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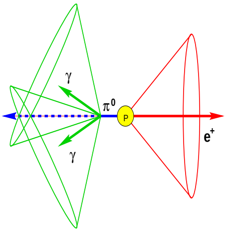


Channel	$\tau_p\,(10^{30}$ years)
$p \to$ invisible	0.21
$p \to e^+\pi^0$	1600
$p \to \mu^+\pi^0$	473
$p \to \nu\pi^+$	25
$p \to \nu K^+$	670
$p \to e^+\eta^0$	312
$p \to \mu^+\eta^0$	126
$p \to e^+\rho^0$	75
$p \to \mu^+\rho^0$	110
$p \to \nu\rho^+$	162
$p \to e^+\omega^0$	1000
$p \to \mu^+\omega^0$	117
$p \to e^+K^0$	150
$p \to \mu^+K^0$	1300
$p \to \nu K^+$	2300
$p \to e^+\gamma$	670
$p \to \mu^+\gamma$	478

New experiments:
HyperK (1 Mt), UNO (650 kt), European project Fréjus (1 Mt)

Precision: 10 years running $\Longrightarrow 10^{34} - 10^{35}$ years

Why chiral exotics?

Unification verification only with megatons? What about colliders?

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

μ problem

- NMSSM trick
- Singlet superfield with TeV-scale VEV

Doublet-triplet splitting problem, Longevity of the proton

- Try to keep D, D^c superfields at TeV scale
- Need mechanism to prevent rapid proton decay
- Need to rearrange running for unification

Flavour problem

- Flavour might help protecting the proton

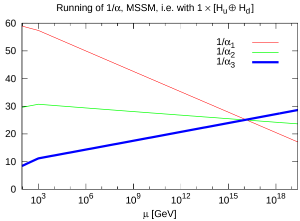
E_6 SUSY Grand Unification

JR/Kilian, PLB 642 (2006), 81

Supersymmetry: consistent extrapolation to high scales

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

Bottom-Up Approach: *just MSSM*



- Unifies Higgs and matter fields
- Ansatz: all new particles in the spectrum at TeV scale

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

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

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

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

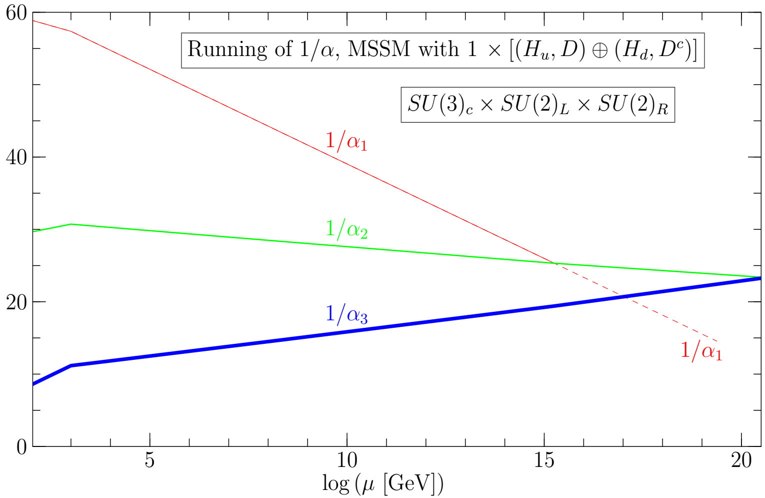
$$H^d = (\mathbf{1},\mathbf{2})_{-\frac{1}{2},Q'_{Hd}}$$

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

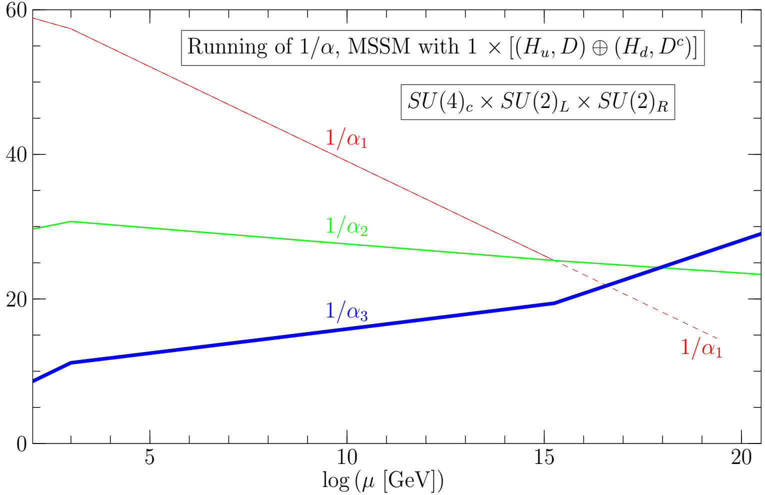
$$D = (\mathbf{3},\mathbf{1})_{-\frac{1}{3},\ Q'_D}$$

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

RGE running


60
40
20
0
Running of $1/\alpha$, MSSM with $1 \times [(H_u, D) \oplus (H_d, D^c)]$
$SU(3)_c \times SU(2)_L \times SU(2)_R$
$1/\alpha_1$
$1/\alpha_2$
$1/\alpha_3$
$1/\alpha_1$
5
10
15
20
$\log(\mu \text{ [GeV]})$

RGE running



Running of $1/\alpha$, MSSM with $1 \times [(H_u, D) \oplus (H_d, D^c)]$
$SU(4)_c \times SU(2)_L \times SU(2)_R$
$1/\alpha_1$
$1/\alpha_2$
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$1/\alpha_1$
0
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40
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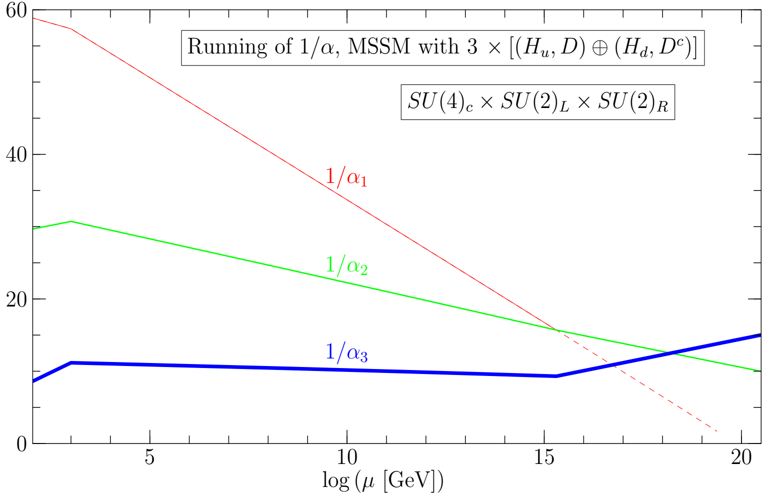
RGE running


Running of $1/\alpha$, MSSM with $3 \times [(H_u, D) \oplus (H_d, D^c)]$
$SU(4)_c \times SU(2)_L \times SU(2)_R$
$1/\alpha_1$
$1/\alpha_2$
$1/\alpha_3$
60
40
20
0
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10
15
20
$\log(\mu\ [\mathrm{GeV}])$

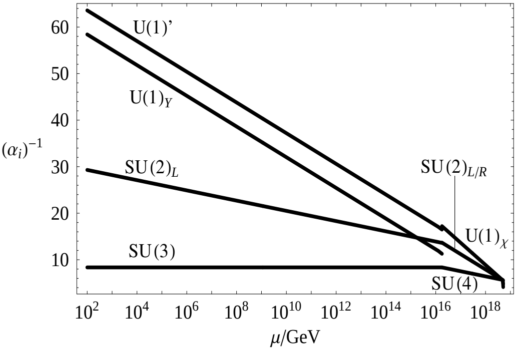
Intermediate Pati-Salam symmetry

JR/Kilian 2006, King et al. 2008

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

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

SM × U(1)' –> Pati–Salam × U(1)$_\chi$–>E(6)



- $SU(2)_R$ and $SU(2)_L$: identical content/running
- Crossing of $SU(4)$ and $SU(2)_{L/R}$ couplings determines E_6 scale
- Lepton number: 4^{th} color
- $T^{15}_{SU(4)} \propto \frac{B-L}{2}$
- $Y = \frac{B-L}{2} + T^3_R$
- $U(1)$ 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)

$\Rightarrow$ appropriate breaking

Matter-Higgs unification: E_6 in PS framework (PSSSM)

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

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

At M_ν left-right symmetric model: $SU(2)_L \times SU(2)$

$$Q_R = \begin{pmatrix} u^c \\ d^c \end{pmatrix}, \qquad L_R = \begin{pmatrix} \nu^c \\ \ell^c \end{pmatrix} \qquad H = \begin{pmatrix} H_u \\ H_d \end{pmatrix} \qquad D \qquad D^c$$

Pati-Salam group $SU(4)_c \times SU(2)_L \times SU(2)_R$

$$\begin{aligned} \mathbf{Q}_L = (Q, L) &= (\mathbf{4}, \mathbf{2}, \mathbf{1}) \\ \mathbf{Q}_R = ((u^c, d^c), (\nu^c, \ell^c)) &= (\overline{\mathbf{4}}, \mathbf{1}, \mathbf{2}) \\ \mathbf{H} = (H_u, H_d) &= (\mathbf{1}, \mathbf{2}, \mathbf{2}) \\ \mathbf{D} = (D, D^c) &= (\mathbf{6}, \mathbf{1}, \mathbf{1}) \\ \mathbf{S} &= (\mathbf{1}, \mathbf{1}, \mathbf{1}) \end{aligned}$$

Flavour Symmetry and proton decay

Assume $SU(3)_F$ **or** $SO(3)_F$ **flavour symmetry**

- Left-right symmetry: $SU(2)_L \times SU(2)_R$, $SU(3)_c$, $SU(3)_F$
- Diquark couplings vanish identically:

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

- Baryon number is symmetry of the superpotential
- $SU(2)_R$ and $SU(3)_F$ breaking spurions?
  symmetry breaking by condensates linear/bilinear in fundamental reps.:
  D, D^c *couple to other quarks only as singlets*
- Integrating out heavy fields: baryon number emerges as low-energy symmetry, flavour symmetry not
- Leptoquark couplings possible

Model-building set-up

Toy Model (no dynamics!)

1. 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)

Model-building set-up

1. Somewhat below M_{Planck}
   - $N=2 \to 1$ breaking removes mirror matter: $\langle (\mathbf{27}_3)^a_i (\overline{\mathbf{27}}_{\bar{3}})^b_j \rangle = \delta^{ab}\delta_{j,i+1}$
   - 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):

$$\mathbf{27}_3\, \mathbf{27}_3\, \mathbf{27}_3 = 0 \qquad (\mathbf{27}_3\, \mathbf{78}_1\, \overline{\mathbf{27}}_{\bar{3}}),\ (\mathbf{78}_1\, \mathbf{78}_1\, \mathbf{78}_1),\ (\mathbf{27}_3\, \mathbf{1}_8\, \overline{\mathbf{27}}_{\bar{3}}),\ \mathbf{1}_8\, \mathbf{1}_8\, \mathbf{1}_8$$

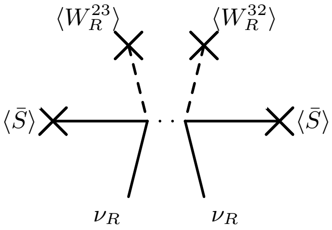
- Flavor dynamics in higher-dim. superpotential due to $\mathbf{1_8}$ matter exchange

Model-building set-up

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

Model-building set-up

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

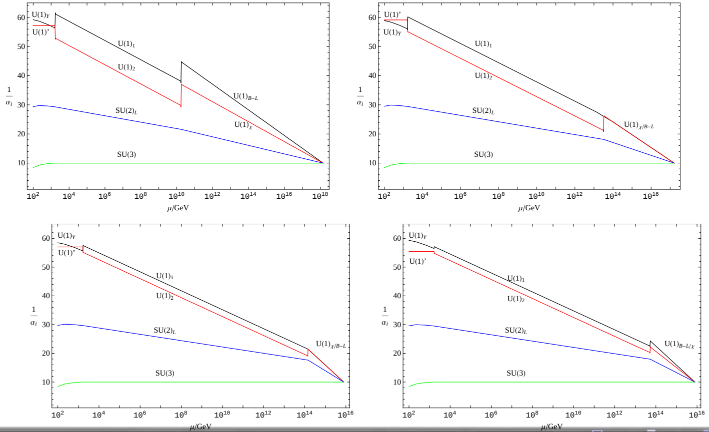
Effects from $U(1)$ mixing

Braam/Knochel/JR, 2009; King et al., 2009

- Two $U(1)$ factors present below the intermediate scale
- Kinetic mixing: non-rational coefficients because of 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 on running:



Problems and E_6/Pati-Salam breaking

- E_6 superpotential identically vanishes $\Rightarrow$ higher-dim. E_6 op. generate PS superpotential power suppression: top Yukawa ?
- discrete symmetry to discriminate lepto- and diquark couplings/H parity violates GUT multiplet structure
- severe constraints from perturbativity above Λ_{PS}
- Difficulty to find representations for PS breaking
  - $\mathbf{27}$, $\mathbf{351}$, and $\mathbf{351'}$ break E_6 to rank 5
    $U(1)_\chi$ is lost, quartic singlet potential absent!
    But: construction of PS-NMSSM possible   Kilian/Knochel/JR, 2010
  - No rank reduction: adjoint breaking VEV: $V = V_i H_i \qquad M_j^2 \sim (\alpha_i^j V_i)^2$
    Three options (mostly smaller groups):
    1. $V \propto U(1)_\chi$: $\qquad E_6 \to SO(10) \times U(1)_\chi$
    2. $V \propto U(1)_{B-L}$: $\qquad E_6 \to G_{LR} \times U(1)_\chi$
    3. Special combination: $\qquad E_6 \to SU(3)_c \times SU(3) \times SU(2) \times U(1)_\chi$

Breaking E_6 to Pati-Salam

Braam/Kilian/Knochel/JR, 2010

- Breaking by $\langle(\mathbf{27})(\overline{\mathbf{27}})\rangle$ or $\langle\mathbf{27}\rangle\,\langle\overline{\mathbf{27}}\rangle$
  $\mathbf{27}\times\overline{\mathbf{27}} = \mathbf{1}+\mathbf{78}+\mathbf{650}$
- $\mathbf{650}$ smallest rep. that does $E_6 \to G_{PS}\times U(1)$
- No rank reduction $\Rightarrow$ restricted to zero weights
- Easier description: use decomposition of $E_6 \to SU(6)\times SU(2)$:
  $\mathbf{27}\to(\mathbf{15},\mathbf{1})+(\overline{\mathbf{6}},\mathbf{2})$

$$\mathbf{27}\times\overline{\mathbf{27}} \quad\to\quad \underbrace{(\mathbf{1},\mathbf{1})}_{\mathbf{1}}+\underbrace{(\mathbf{35},\mathbf{1})+(\mathbf{20},\mathbf{2})+(\mathbf{1},\mathbf{3})}_{\mathbf{78}}+ \underbrace{(\mathbf{189},\mathbf{1})+(\mathbf{70},\mathbf{2})+(\overline{\mathbf{70}},\mathbf{2})+(\mathbf{20},\mathbf{2})+(\mathbf{35},\mathbf{1})+(\mathbf{35},\mathbf{3})+(\mathbf{1},\mathbf{1})}_{\mathbf{650}}$$

Terms that do not break $SU(2)_L\times SU(2)_R$:

$$(\mathbf{1},\mathbf{1})_{\mathbf{1}},\quad(\mathbf{1},\mathbf{1})_{\mathbf{650}},\quad(\mathbf{35},\mathbf{1})_{\mathbf{78}},\quad(\mathbf{35},\mathbf{1})_{\mathbf{650}},\quad(\mathbf{189},\mathbf{1})_{\mathbf{650}}$$

- 20 zero weights, 9 of them in $\mathbf{189}$
- Possible to construct a superpotential which does the breaking and allows leptoquark couplings

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Braam/Kilian/Knochel/JR, 2010

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$$\mathbf{27}\times\overline{\mathbf{27}} \quad \to \quad \underbrace{(\mathbf{1},\mathbf{1})}_{\mathbf{1}} + \underbrace{(\mathbf{35},\mathbf{1}) + (\mathbf{20},\mathbf{2}) + (\mathbf{1},\mathbf{3})}_{\mathbf{78}} +$$
$$\underbrace{(\mathbf{189},\mathbf{1}) + (\mathbf{70},\mathbf{2}) + (\overline{\mathbf{70}},\mathbf{2}) + (\mathbf{20},\mathbf{2}) + (\mathbf{35},\mathbf{1}) + (\mathbf{35},\mathbf{3}) + (\mathbf{1},\mathbf{1})}_{\mathbf{650}}$$

Terms that do not break $SU(2)_L \times SU(2)_R$:

$$(\mathbf{1},\mathbf{1})_{\mathbf{1}}, \quad (\mathbf{1},\mathbf{1})_{\mathbf{650}}, \quad (\mathbf{35},\mathbf{1})_{\mathbf{78}}, \quad (\mathbf{35},\mathbf{1})_{\mathbf{650}}, \quad (\mathbf{189},\mathbf{1})_{\mathbf{650}}$$

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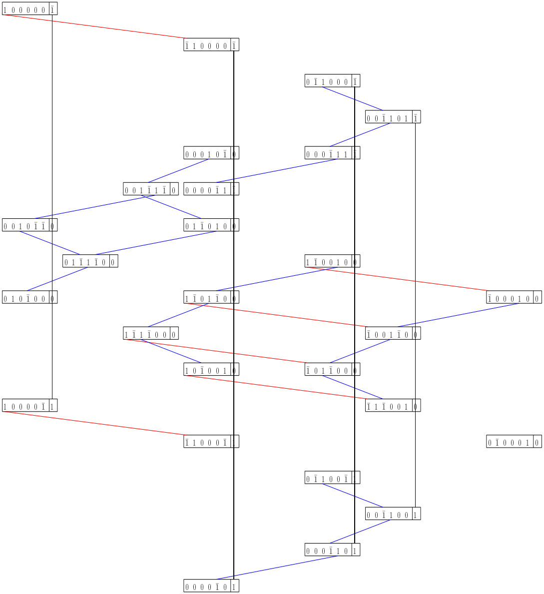
- Possible to construct a superpotential which does the breaking and allows leptoquark couplings

Automatic decomposition of irreps

Horst/Mallot/JR, 2010



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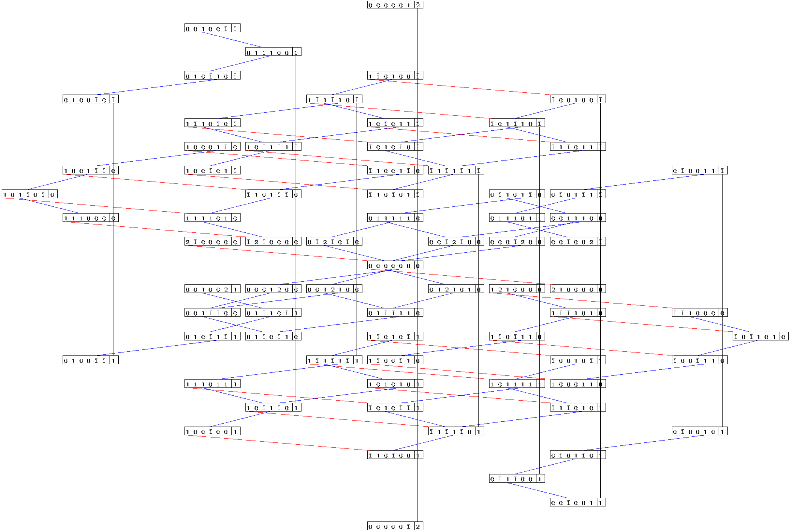

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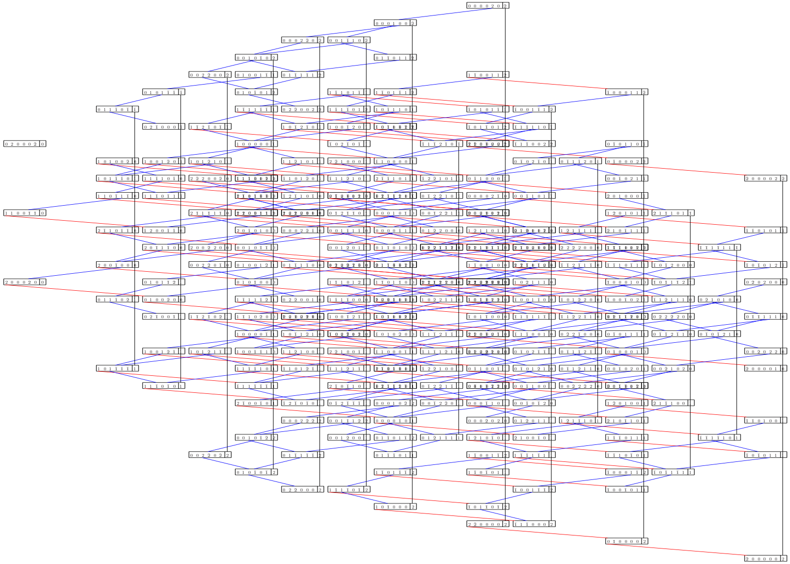

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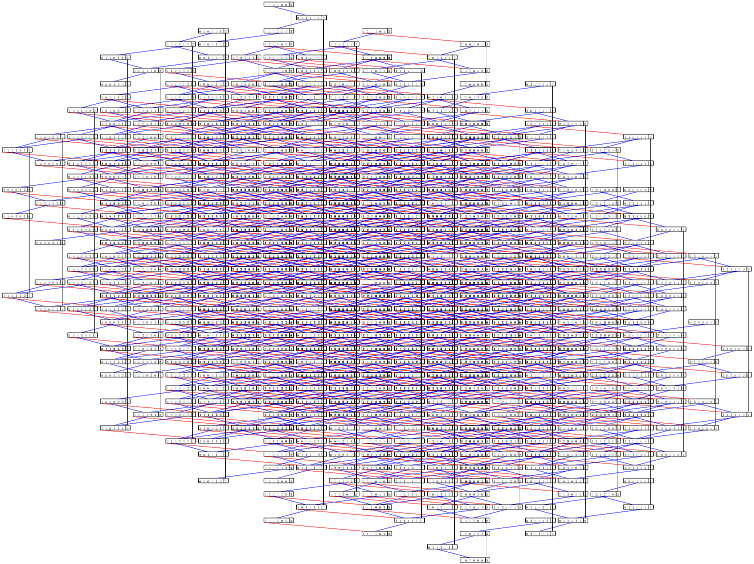


Alternative: Orbifold Breaking

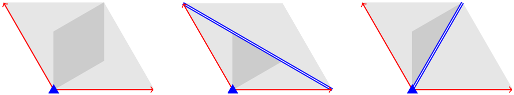
Braam/Knochel/JR, 2010

- 5D Orbifolds not viable:
  - either doublet-triplet splitting and no LQ pheno
  - or no proton protection mechanism at hand

$\Rightarrow$ 6D Orbifolds

- Consider: $\mathbb{R}^4 \times (\mathbb{R}^2/\Gamma)$, Γ one of 17 plane crystallographic groups
- Use shifts on the root lattice of bulk E_6 and discrete Wilson lines on the tori
- Goal: intermediate $SU(3)_c \times SU(2)_L \times SU(2)_R \times U(1)^2$
- H parity: at least one fixed point which splits Higgs/matter

- Using $\mathbb{Z}_3$ symmetries: simplest examples



- Because 4D SUSY from 6D orbifolds is difficult: study also 10D models

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

$\mathbb{Z}_2$	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 $4\overline{V}$
	$SU(3)_C \times SU(3)_L \times SU(2)_R \times U(1)$	$(0,0,1,2,0,0)$
	$SU(3)_C \times SU(3)_R \times SU(2)_L \times U(1)$	$(-1,1,1,1,1,0)$

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

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

- Use one trinification fixed point $SU(3)^3$ to distinguish lepto-/diquark couplings:

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

Investigation Of The Parameter Space

Braam/JR, 2009

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

  $\Rightarrow$ Limitation on 14 free parameters
- Constraints (more below):
  (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

  ($\Leftrightarrow$ No unwanted symmetry breaking)

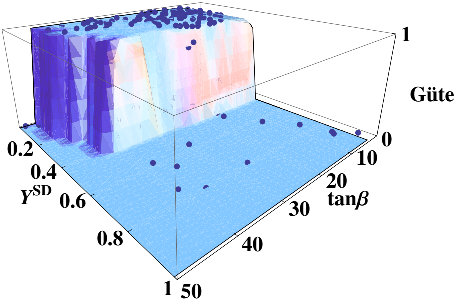
- 14-dim parameter space

$\Rightarrow$ 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



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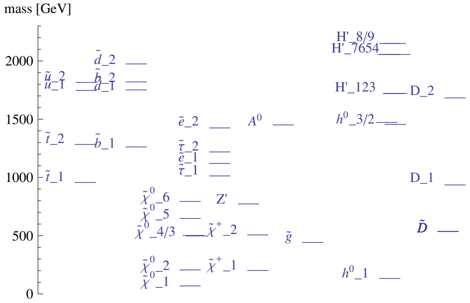

Constraints and Low-Energy Spectra

CONSTRAINTS USED FOR THE PARAMETER SCAN:

- LSP is the lightest neutralino (can be singlino/unhiggsino!)
- No tachyons, CCB
- Higgs potential bounded from below
- LSP does not overclose the universe
- Sparticles evade LEP and Tevatron direct search limits
- Contribution to invisible Z width ≤ 2 MeV (LEP)
- $-0.0007 < \Delta\rho < 0.0026$ (PDG '08)

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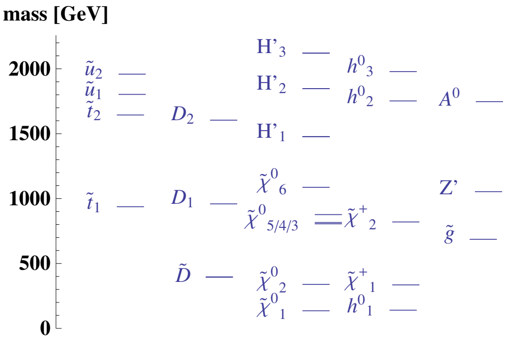
WORK IN PROGRESS: FLAVOR CONSTRAINTS

- BR$(B \to s\gamma) \sim (2.5 - 4.1) \times 10^{-4}$ (HFAG, Misiak et al., Becher/Neubert)
- BR$(B_s \to \mu\mu) \lesssim 4.5 \times 10^{-8}$ (CDF/D)
- SUSY contrib. to $(g-2)_\mu$: $(-10 \lesssim (g-2)_\mu \lesssim 40) \times 10^{-10}$
- BR$(B \to \tau\nu) \sim (50 - 227) \times 10^{-6}$ (HFAG, ICHEP '08, Isidori/Paradisi, Erikson/Mahmoudi/Stal)
- Meson-Antimeson-Mixing: constraints on sfermion mass ratios

Generic Properties of Spectra

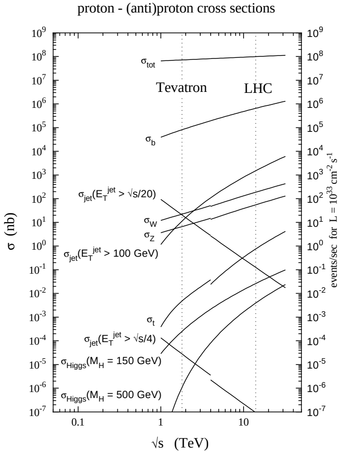


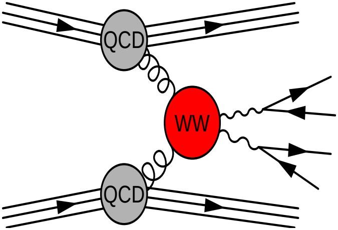
- Vanishing 1-loop QCD $beta$ function $\Rightarrow$ gluino
- Higgs and neutralino sector relations get disturbed by singlet superfield admixture
- Possibility for an additional (quite light) Z'
- Flavored Higgs sector: Unhiggses, Unhiggsinos
- Leptoquarks/Leptoquarkinos

The challenge of the LHC

Partonic subprocesses: qq, qg, gg

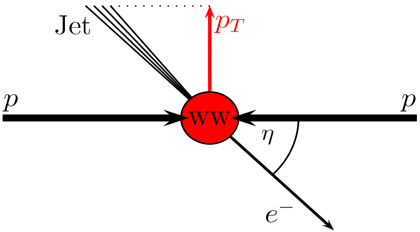
No fixed partonic energy



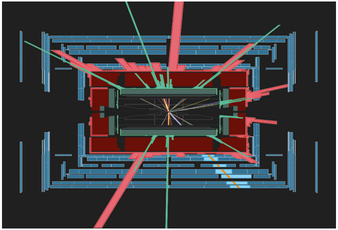


$R = \sigma \mathcal{L}$ $\quad \mathcal{L} = 10^{34}\,\mathrm{cm}^{-1}\mathrm{s}^{-1}$

High rates for t, W/Z, H, $\Rightarrow$ **huge backgrounds**



The challenge of the LHC



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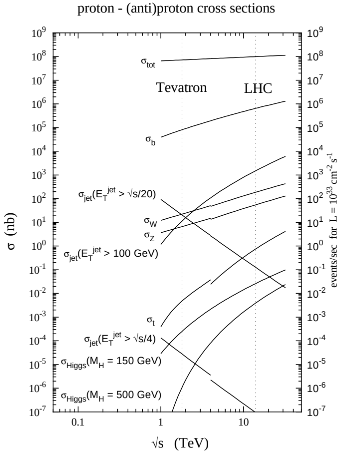

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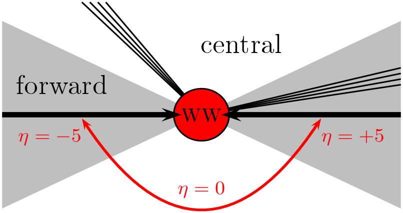


WHIZARD

Kilian/Ohl/JR + PhDs, hep-ph/0102195, 0708.4233

- Acronym: **W**, **HI**ggs, **Z**, **A**nd **R**espective **D**ecays (deprecated)
- Fast Multi-Channel Monte-Carlo integration
- Very efficient phase space and event generation
- Optimized matrix elements
- Current version: 2.0.0β (2.0.0_rc1 next Sunday)
  `http://projects.hepforge.org/whizard` and
  `http://whizard.event-generator.org`
- parton shower ($p_\perp$ ordered) and analytic (v2.0)
- no hadronization yet
- underlying event: preliminary version for v2.1
- Arbitrary processes: a generator generator (O'Mega)
- BSM: cf. next page
- 2.0 features: ME/PS matching, cascades, new versatile user interface and syntax, WHIZARD as a shared library

WHIZARD – Overview over BSM Models

Very high level of Complexity:

- $e^+e^- \to t\bar{t}H \to b\bar{b}b\bar{b}jj\ell\nu$ (110,000 diagrams)
- $e^+e^- \to ZHH \to ZWWWW \to bb + 8j$ (12,000,000 diagrams)
- $pp \to \ell\ell + nj, n = 0, 1, 2, 3, 4, \ldots$ (2,100,000 diagrams with 4 jets + flavors)
- $pp \to \tilde{\chi}_1^0 \tilde{\chi}_1^0 bbbb$ (32,000 diagrams, 22 color flows, $\sim 10,000$ PS channels)
- $pp \to VVjj \to jj\ell\ell\nu\nu$ incl. anomalous TGC/QGC
- Test case $gg \to 9g$ (224,000,000 diagrams)

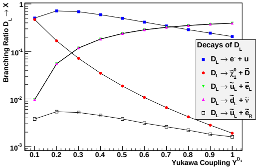
MODEL TYPE	with CKM matrix	trivial CKM
QED with e, μ, τ, γ	–	QED
QCD with d, u, s, c, b, t, g	–	QCD
Standard Model	SM_CKM	SM
SM with anomalous couplings	SM_ac_CKM	SM_ac
SM with anomalous top couplings	—	SM_top
SM with K matrix	—	SM_KM
MSSM	MSSM_CKM	MSSM
MSSM with gravitinos	—	MSSM_Grav
NMSSM	—	NMSSM
extended SUSY models	—	PSSSM
Littlest Higgs	—	Littlest
Littlest Higgs with ungauged $U(1)$	—	Littlest_Eta
Littlest Higgs with T parity	—	Littlest_Tpar
Simplest Little Higgs (anomaly-free)	—	Simplest
Simplest Little Higgs (universal)	—	Simplest_univ
UED	—	UED
3-Site Higgsless Model	—	Threeshl
Noncommutative SM (inoff.)	—	NCSM
SM with Z'	—	Zprime
SM with gravitino and photino	—	GravTest
Augmentable SM template	—	Template

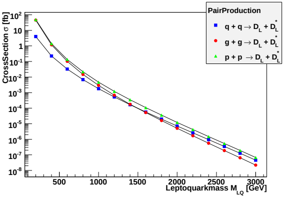
easy to
implement new models

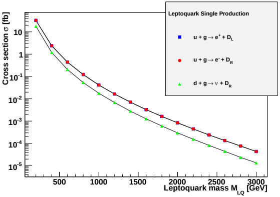
Predictions from E_6 GUTs for LHC

Braam/JR/Wiesler, 0909.3081

- Simulations for the E_6 model with WHIZARD
- 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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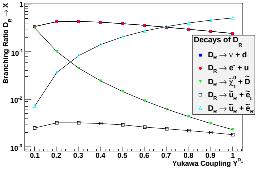
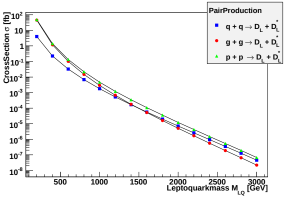
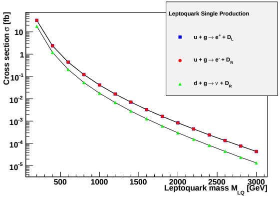
- First analyses: BRs, cross sections for scalar leptoquarks, S/B
- In progress: leptoquarkino pheno

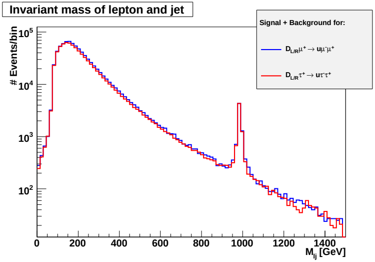


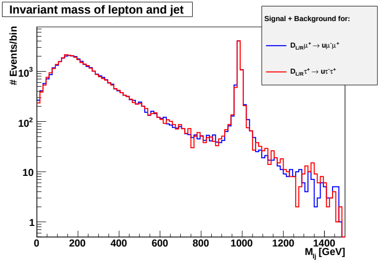


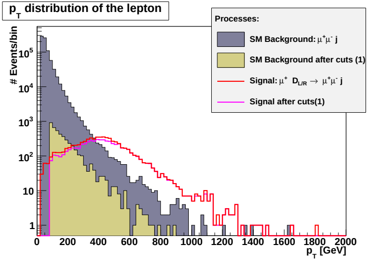


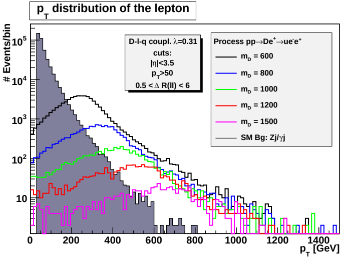
Cuts		Background	$m_D = 0.6$ TeV		$m_D = 0.8$ TeV		$m_D = 1.0$ TeV	
p_T	$M_{\ell\ell}$	N_{BG}	N_1	$S_1/\sqrt{B}$	N_2	$S_2/\sqrt{B}$	N_3	$S_3/\sqrt{B}$
50	10	413274	64553	**93**	14823	**23**	4819	**7**
100	150	3272	40749	**194**	10891	**92**	3767	**45**
200	150	198	12986	**113**	5678	**74**	2405	**47**

Braam/JR/Wiesler, 0909.3081









Dark Matter, Family Symmetries

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!)

Proton decay in the PSSSM

Mallot/JR, 2009

- Superpotential (and soft-breaking) terms do not induce proton decay
- Investigate exchange from E_6 gauge bosons/gauginos
- Calculational way from top to bottom
  1. Group-theoretical weights from Clebsch-Gordan decomposition
     Horst/Mallot/JR, 2009
  2. Calculational of proton-decay Wilson coefficients at Λ_{GUT}
  3. Short-distance (SUSY) renormalization-group factor
  4. Matching to SM dimension-six Fermi operators
  5. Long-distance (SM/QCD) renormalization-group factor
  6. Matching to operators of chiral perturbation theory
  7. Simple calculation of the baryon decay matrix element and width
- This yields a very conservative estimate:

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

Summary/Conclusions

- GUTs with intermediate breaking steps
- viable ways: $E_6 \to SU(3/4) \times SU(2)_L \times SU(2)_R \times U(1)^2$
- Possible breaking scenarios: Higgs vs. orbifold boundary conditions
- Proton decay out of experimental reach
- Allow for direct hints as chiral exotics at the LHC
- Interesting, but intricate phenomenology at the LHC
- Important role of flavor: continuous vs. discrete symmetries
- Open questions: SUSY breaking mechanism, flavour

Grand Unification: Long and difficult business

Grand Unification: Long and difficult business