Hints of
Exceptional Grand Unification at the LHC

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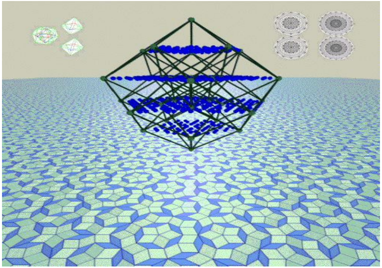
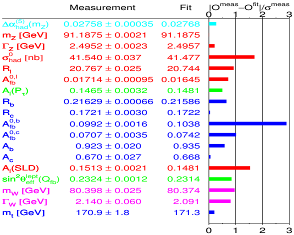
DESY Hamburg



Seminar, TU München, 20. Jan. 2012

The Standard Model of Particle Physics – Doubts



– describes microcosm (too well?)

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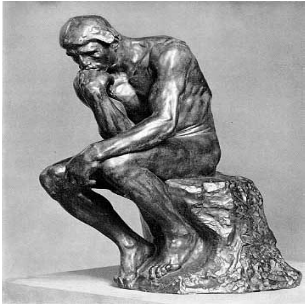
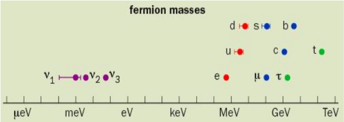
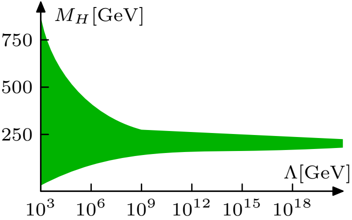


- describes microcosm (too well?)
- 28 free parameters



- Form of Higgs potential ?



Hierarchy Problem

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

no symmetry for quantum corrections to Higgs mass

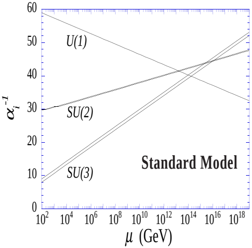
$$\delta M_H^2 \propto \Lambda^2 \sim M_{\text{Planck}}^2 = (10^{19})^2 \,\text{GeV}^2$$

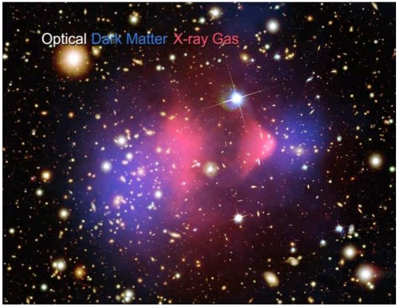
20000 GeV^2 = (100000000000000000000000000000000020000 –

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 gravitation
- Cosmic inflation
- Cosmological constant/ Dark Energy






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

Ideas for New Physics since 1970

(1) **Symmetry for Elimination of Quantum Corrections**

- Supersymmetry: Spin Statistics ⇒ corrections from bosons and fermions cancel each other
- Little-Higgs Models: Global symmetries ⇒ corrections from particles of like statistics cancel each other

(2) **New Building Blocks, Substructure**

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

(3) **Nontrivial Space-time Structure eliminates Hierarchy**

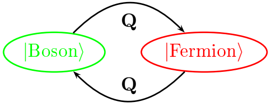
- Additional space dimensions: Gravitation appears only weak
- Noncommutative Space-time: Space-time coarse-grained

(4) **Ignoring the Hierarchy**

- Anthropic principle: Values are the way they are, because we measure them

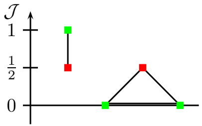
Supersymmetry (SUSY)

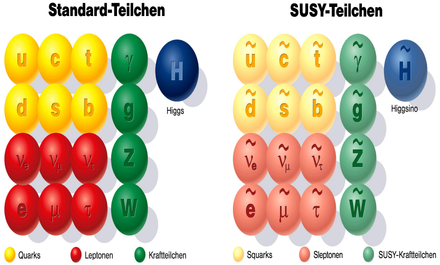
Gelfand/Likhtman, 1971; Akulov/Volkov, 1973; Wess/Zumino, 1974



- combines gauge and spacetime symmetries
- Multiplets of equal-mass fermions and bosons

⇒ SUSY broken in Nature





- Extend every particle by a superpartner
- Minimal Supersymmetric Standard Model (MSSM)
- Mass eigenstates:

Charginos: $\tilde{\chi}^{\pm} = \tilde{H}^{\pm}, \tilde{W}^{\pm}$

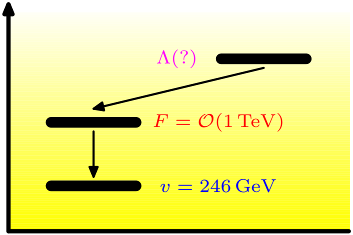
Neutralinos: $\tilde{\chi}^{0} = \tilde{H}, \tilde{Z}, \tilde{\gamma}$

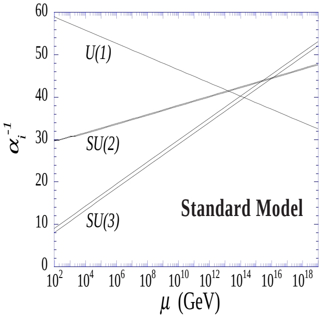
Hate-Love SUSY: Successes and By-Products

spontaneous SUSY breaking in the MSSM ↯
(MeV SUSY partners)

Breaking in "hidden sector", induces 100 free parameters

solves hierarchy problem:
$\delta M_H \propto F \log(\Lambda^2)$





- Existence of fundamental scalars
- Form of the Higgs potential
- Light Higgs ($M_H = 90 \pm 50$ GeV)
- discrete R parity
  - SM particles even, SUSY partners odd
  - prevents too rapid proton decay
  - lightest SUSY partner (LSP) stable
    Dark Matter $\tilde{\chi}_1^0$
- Unification of coupling constants

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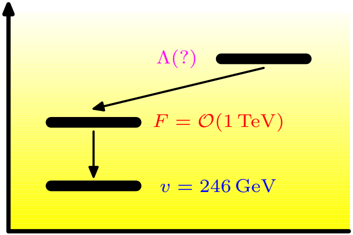

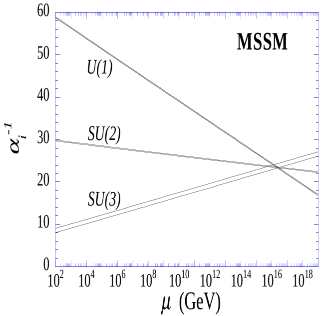

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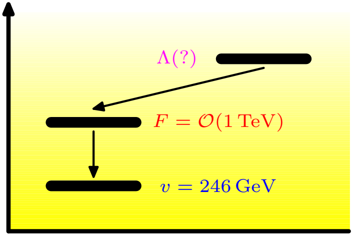

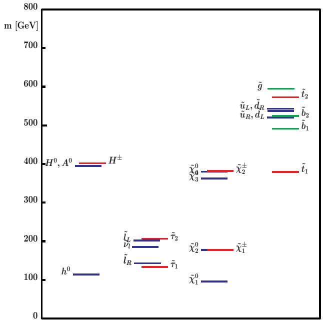

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Supersymmetric Grand Unification

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

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

Fermionen (Matter superfields)

Only possible way to combine matter:

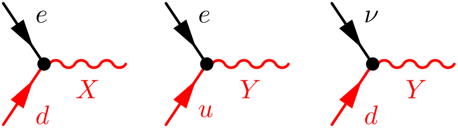
$$\overline{\mathbf{5}} = \begin{array}{|c|}\hline \\ \hline \\ \hline \\ \hline \\ \hline\end{array} : \quad \begin{pmatrix} d^c \\ d^c \\ d^c \\ \ell \\ -\nu_\ell \end{pmatrix} \qquad \mathbf{10} = \begin{array}{|c|}\hline \\ \hline \\ \hline\end{array} : \quad \frac{1}{\sqrt{2}} \left(\begin{array}{ccc|cc}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

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

Remarks

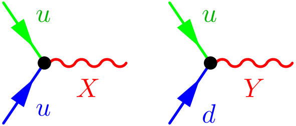
- $\mathbf{2} = \square = \overline{\mathbf{2}}, \qquad (\mathbf{5} \otimes \mathbf{5})_a = \mathbf{10}, \quad (\mathbf{3} \otimes \mathbf{3})_a = \overline{\mathbf{3}}, \quad (\square \otimes \square)_a = \begin{array}{|c|}\hline \\ \hline \\ \hline\end{array}$
- Quarks and leptons in the same multiplet
- Condition of tracelessness $\Rightarrow$ (color!)
- $\overline{\mathbf{5}}$ and $\mathbf{10}$ have equal and opposite anomalies
- ν^c must be $SU(5)$ singlet

Interactions



Leptoquark couplings

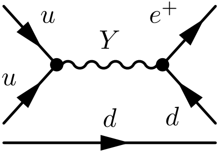
(and SUSY vertices)



Diquark couplings

(and SUSY Vertices)

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



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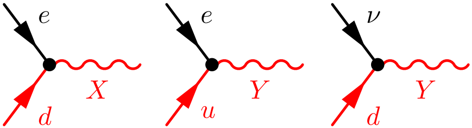

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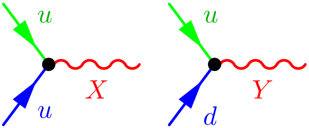

Diquark couplings

(and SUSY Vertices)

Proton Lifetime with $\alpha(M_{GUT}) \sim \frac{1}{24}$ 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

The Doublet-Triplet Splitting

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

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

other breaking mechanisms possible (e.g. orbifold)

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

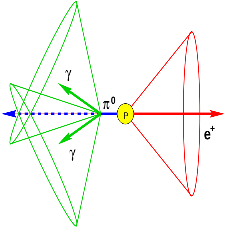
$$\mathbf{5} = \square : \quad \begin{pmatrix} D \\ D \\ D \\ h^+ \\ h^0 \end{pmatrix} \qquad \overline{\mathbf{5}} = \begin{matrix}\square\\\square\\\square\\\square\end{matrix} : \quad \begin{pmatrix} D^c \\ D^c \\ D^c \\ h^- \\ -h^0 \end{pmatrix}$$

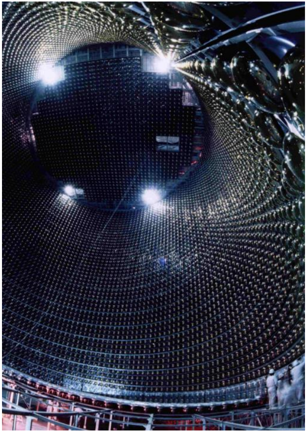
$$\mathbf{5} = \ (\mathbf{3},\mathbf{1})_{-\frac{2}{3}} \oplus (\mathbf{1},\mathbf{2})_1 \qquad \overline{\mathbf{5}} = \ (\overline{\mathbf{3}},\mathbf{1})_{\frac{2}{3}} \oplus (\mathbf{1},\mathbf{2})_{-1}$$

- D, D^c coloured triplets with charges $\pm\frac{1}{3}$
- induce proton decay, too $\qquad m_H \sim 100\,\text{GeV},\ m_D \sim 10^{16}\,\text{GeV}$
- **Doublet-Triplet Splitting Problem**

Proton Decay experimentum crucis for GUTs

- Tracking calorimeter (SOUDAN) or RICH Cerenkov counter
- Super-Kamiokande: 50 kt water RICH
- For reconstruction: measure time and location





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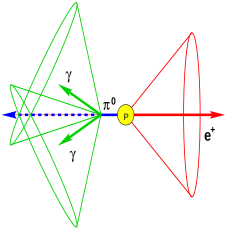


Kanal	$\tau_p (10^{30}$ years)
$p \to$ invisible	0.21
$p \to e^+\pi^0$	1600
$p \to \mu^+\pi^0$	473
$p \to \nu\pi^+$	25
$p \to \nu K^+$	670
$p \to e^+\eta^0$	312
$p \to \mu^+\eta^0$	126
$p \to e^+\rho^0$	75
$p \to \mu^+\rho^0$	110
$p \to \nu\rho^+$	162
$p \to e^+\omega^0$	1000
$p \to \mu^+\omega^0$	117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

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

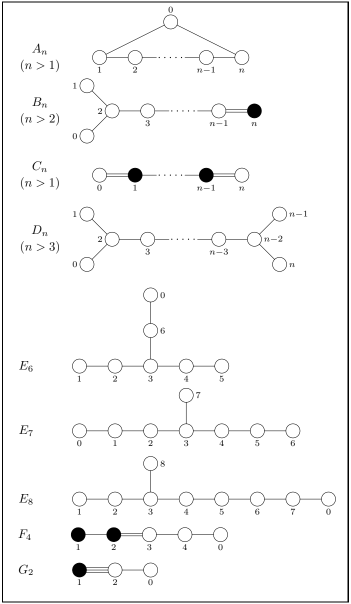
- Keep D, D^c superfields at the TeV scale
- New mechanism against proton decay
- Different unification scenario

Proton Decay

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

Exceptional Lie Algebras

Lie, 1881; Dynkin, 1957

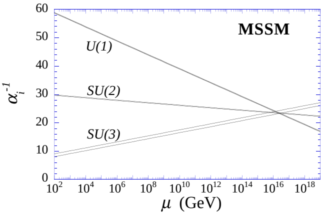


E_6 SUSY Grand Unification

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: only MSSM



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

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

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

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

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

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

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

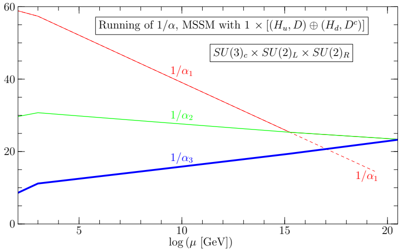
$$D = (\mathbf{3},\mathbf{1})_{-\frac{1}{3},\ Q'_D}$$

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

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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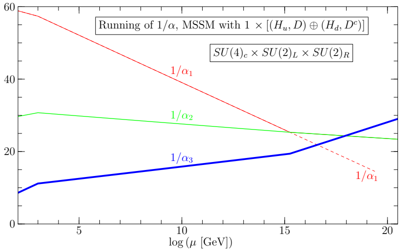

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$SU(3)_c$ crosses at 10^{21} GeV: too high

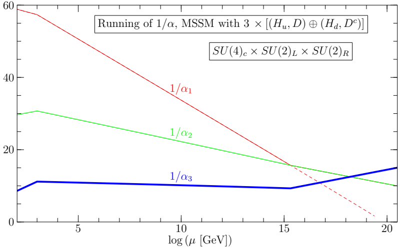
$\Rightarrow$ extend to $SU(4)_C$: unification possible at 10^{18} GeV

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

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

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

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

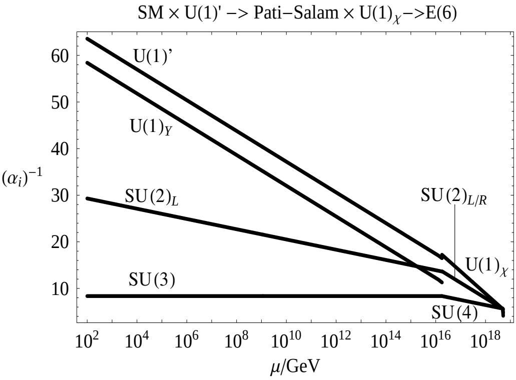
- E_6 symmetry (and possibly extra fields) at 10^{18} GeV

Intermediate Pati-Salam 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

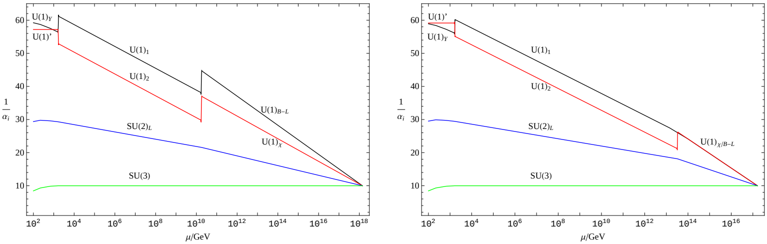
$U(1)$ Mixing

Braam/Knochel/JRR, JHEP 1006:013; King et al., 2009, 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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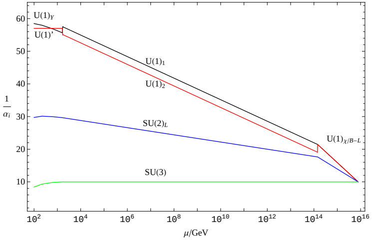

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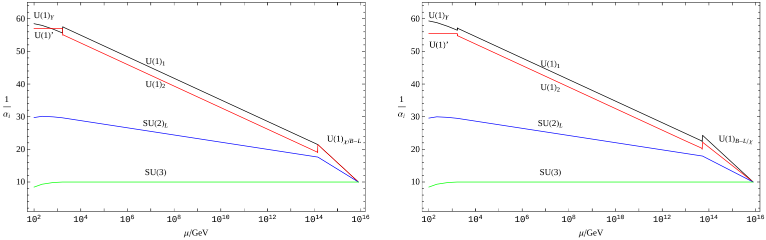

- Same effect for soft-breaking terms: interesting singlino mixing

The Superpotential / Sketch of a Model

Kilian/JR, 2006

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

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

- Corresponding soft-breaking terms
- $t/\tilde{t}$ drive $m^2_{H_u}$ 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

Problems and E_6/Pati-Salam breaking

JRR et al., 2012

- 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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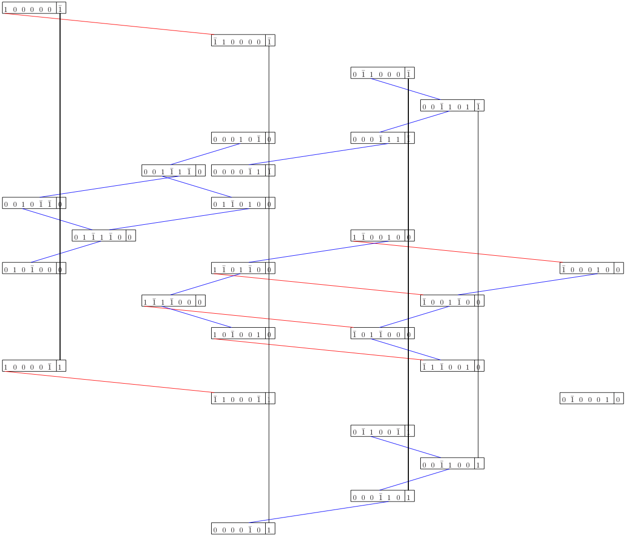
Automatic Irrep Decomposition

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

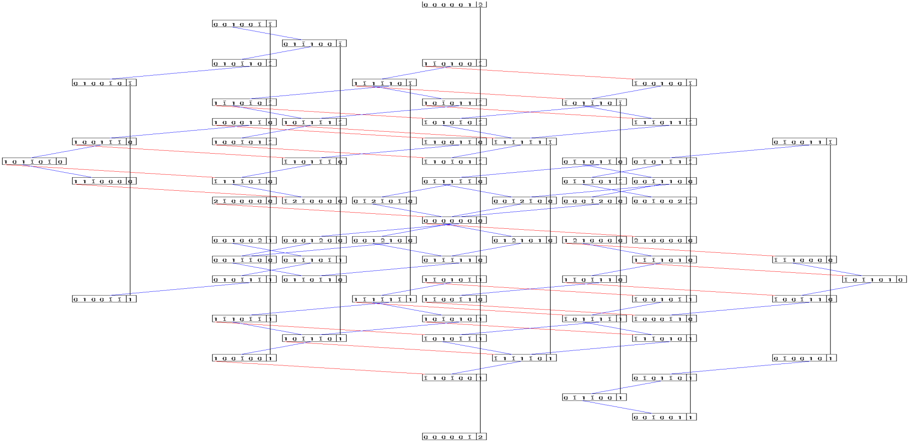
27



Automatic Irrep Decomposition

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

78



Automatic Irrep Decomposition

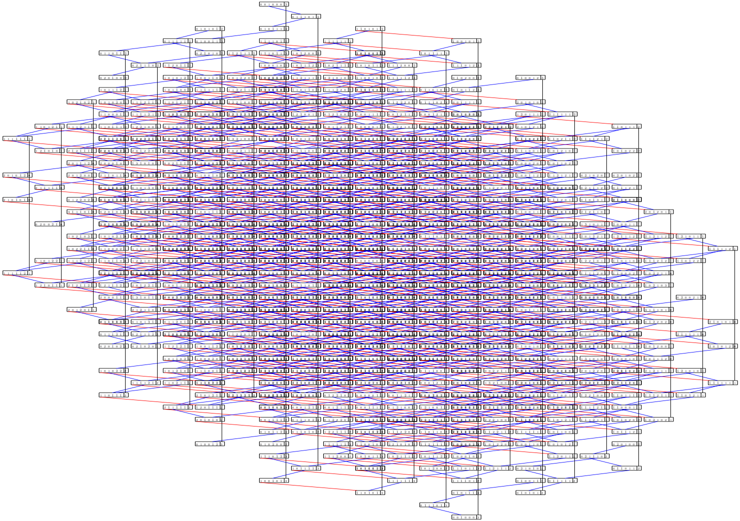
Mallot/JRR; Horst/JRR: CleGo, CPC (2011)

351′

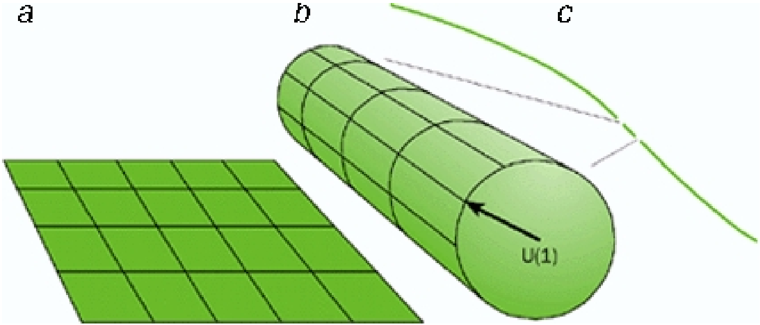
Automatic Irrep Decomposition

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

2925



Alternative: Orbifold Breaking in Extra Dimensions



Asaki/Buchmüller/Covi, 01-02; Hebecker/Ratz, 03; Kobayashi/Raby/Zhang, 04; Förste/Nilles/Wingerter, 05; Buchmüller/Hamaguchi/Lebedev/Ratz, 07; Lebedev/Nilles/Raby/Ramos-Sanchez/Ratz/Vaudrevange, 07-08; Groot Nibbelink/Held/Ruehle/Trapletti/Vaudrevange, 09

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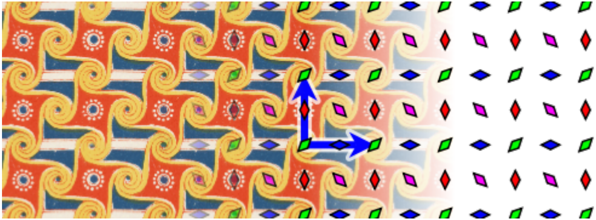

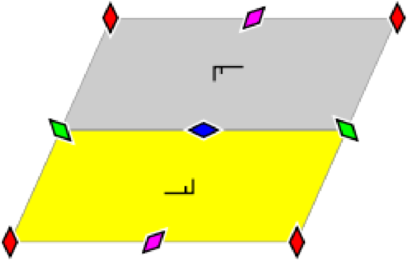

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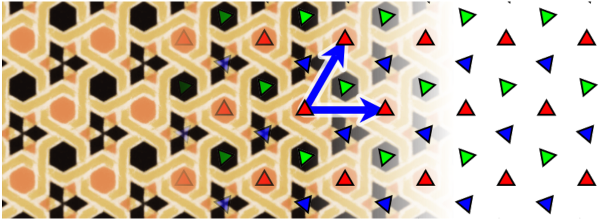

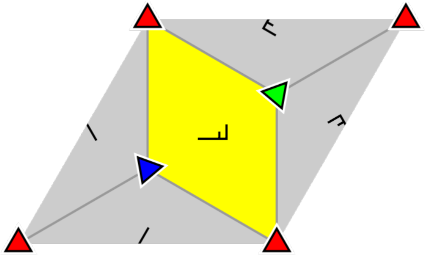

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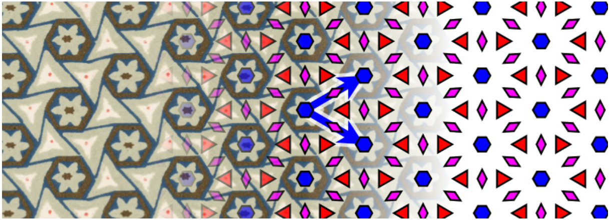
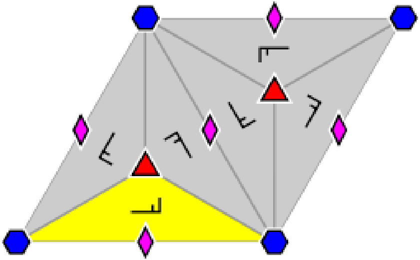
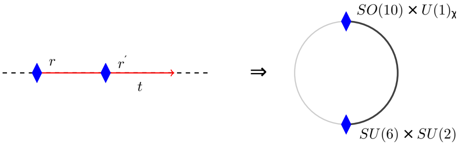




PS models from 5D orbifolds

Braam/Knochel/JRR, JHEP 1006:013

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



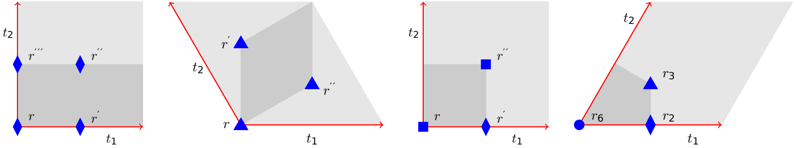
$SU(6)\times SU(2)_L$ \ $SO(10)_{\sqrt{6}Q\chi}$	$\mathbf{16}_{\frac{1}{2}}$	$\mathbf{10}_{-1}$	$\mathbf{1}_{2}$
$(\overline{\mathbf{15}},\mathbf{1})$	$(\overline{\mathbf{4}},\mathbf{1},\mathbf{2})_{1/2}$	$(\mathbf{6},\mathbf{1},\mathbf{1})_{-1}$	$(\mathbf{1},\mathbf{1},\mathbf{1})_{2}$
$(\mathbf{6},\mathbf{2})$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

- LQ/DQ couplings from: $\mathbf{10}\ \mathbf{16}\ \mathbf{16}$, $\mathbf{6}\ \mathbf{6}\ \overline{\mathbf{15}}$, $\overline{\mathbf{15}}\ \overline{\mathbf{15}}\ \overline{\mathbf{15}}$ ⇒ 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 $\longrightarrow \mathbf{16}_{-3/2} + \overline{\mathbf{16}}_{3/2}$, $(\mathbf{20},\mathbf{2})$
- 4 bulk 5D E_6 $\mathbf{27}$ hypermultiplet with $\mathbb{Z}_2\times\mathbb{Z}_2'$ parities $(++),(--),(-+),(+-) \longrightarrow$ $(\mathbf{6},\mathbf{1},\mathbf{1})_{-1} + (\mathbf{1},\mathbf{1},\mathbf{1})_{2}$, $(\mathbf{4},\mathbf{2},\mathbf{1})_{\frac{1}{2}}$, $(\overline{\mathbf{4}},\mathbf{1},\mathbf{2})_{\frac{1}{2}}$, $(\mathbf{1},\mathbf{2},\mathbf{2})_{-1}$
- 3rd gen. from 2 bulk hypermultiplets + a brane-localized $\mathbf{16}'_{\frac{1}{2}} + \mathbf{16}^{3}_{\frac{1}{2}}$
- LQ-/DQ couplings generated (only simultaneously), but must be rendered small by hand

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

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

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 $3\overline{V}$
	$SU(3)_C \times SU(3)_L \times SU(3)_R$	$(0, 0, 1, -1, 0, 0)$

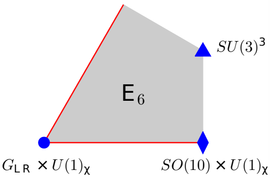
$\mathbb{Z}_4$	Subgroup H	Shift $4\overline{V}$
	$SU(3)_C \times SU(3)_L \times SU(2)_R \times U(1)$	$(0, 0, 1, 2, 0, 0)$
	$SU(3)_C \times SU(3)_R \times SU(2)_L \times U(1)$	$(-1, 1, 1, 1, 1, 0)$

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

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

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 $(\mathbf{16}_{-3/2} + \overline{\mathbf{16}}_{3/2}, (\bar{\mathbf{3}}, \mathbf{2}, \mathbf{1}) + (\bar{\mathbf{3}}, \mathbf{1}, \mathbf{2}), (\mathbf{3}, \mathbf{3}, \bar{\mathbf{3}}))$ cancel against $\mathbf{78}$ bulk hypermultiplet

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

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

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

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

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

▶ LR symmetry breaking by brane-localized matter:

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

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

Model Building ⇒ Phenomenology

Scan of Parameter Space

Braam/JRR/Wiesler, 0909.3081; JRR et al., 2012

- # 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)

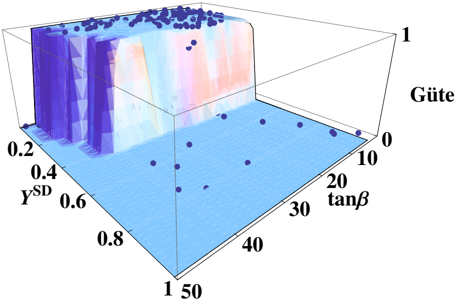
- 14-dim. parameter space

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

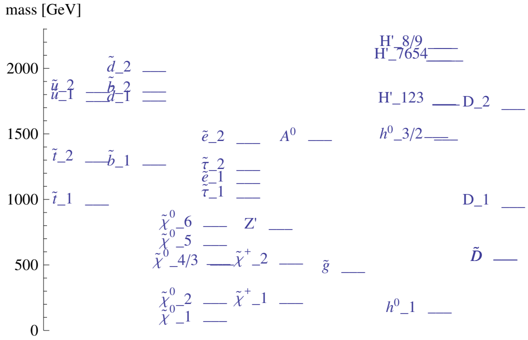
- Investigation per point (RGE, Higgs potential minimisation, Calculation of masses) $\sim 10 - 100$ ms

Lsg.: Monte-Carlo Markov chain through parameter space

$\Rightarrow$ Effective search for relevant parameter tuples



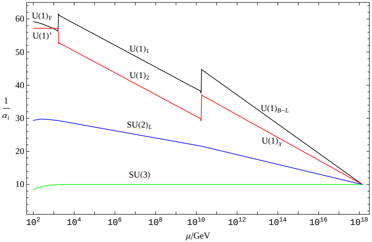
Generic Properties of Spectra

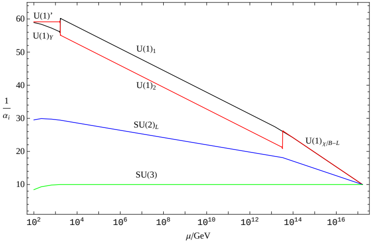


- Vanishing 1-loop QCD β function $\Rightarrow$ Light Gluino
- Higgs- and neutralino sector different because of singlet superfield admixture
- light Z' (peculiar asymmetries)
- Flavoured Higgs sector: Unhiggses, Unhiggsinos
- Leptoquarks/Leptoquarkinos

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}
$g' \vert M_{Z'}$	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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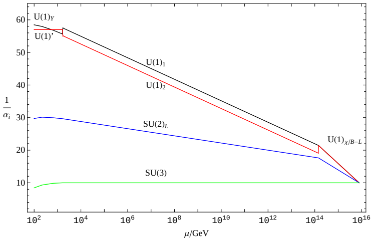
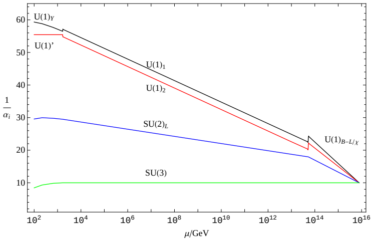




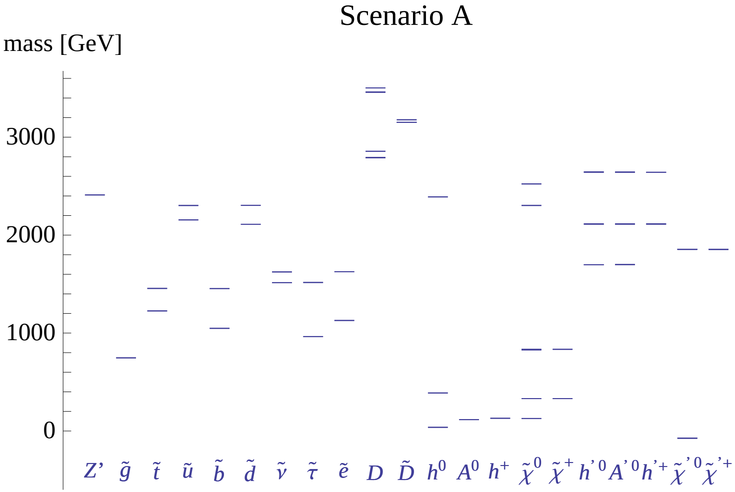
Sample Spectra

	Scenario A	Scenario B	Scenario C
y_lq	0.106	0.145	0.210
y_lqc	0.082	0.075	0.230
y_sd	0.397	0.856	0.655
y_sh	0.214	0.321	0.052
y_nmssm	0.173	0.145	0.150
M_g	1105	-1452	-1359
M_gluino	-820	-875	-841

h_sm	-764	-1261	-749
h_lq	372	-446	-376
h_lqc	-224	-0.9	-897
h_sd	-264	500	307
h_sh	351	-767	19
h_nmssm	22.5	-185	73
m_sfer	1689	814	1690
m_dh	1234	1154	1936
m_H	1959	1921	1465
m_D	816	805	826
m_S	1201	1921	1357
m_int	-1459	-1050	-845

- Higgs boson: A,C $m_h \approx 110$ GeV B $m_h \approx 107$ GeV
- Z': A, B $m_{Z'} \approx 2480$ GeV C $m_{Z'} \approx 2090$ GeV (R-odd and H-odd)
- Dark Matter: lightest dark Higgsino, $m_{\chi^\pm} \sim \mathcal{O}(.1 - 1\text{GeV})$

Sample Spectra



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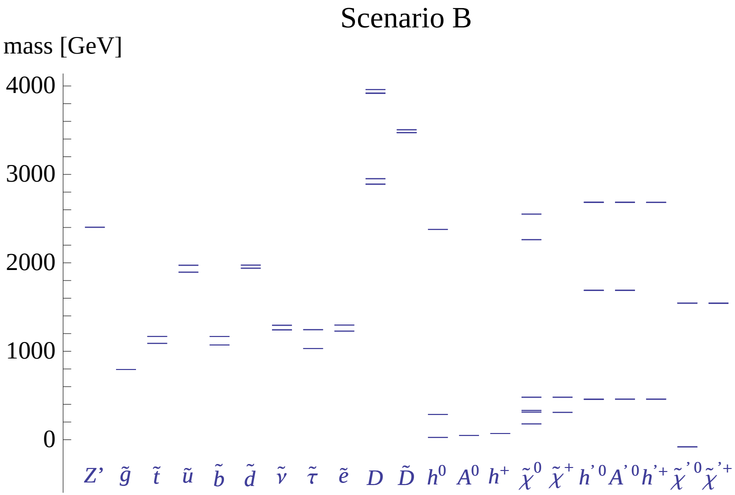

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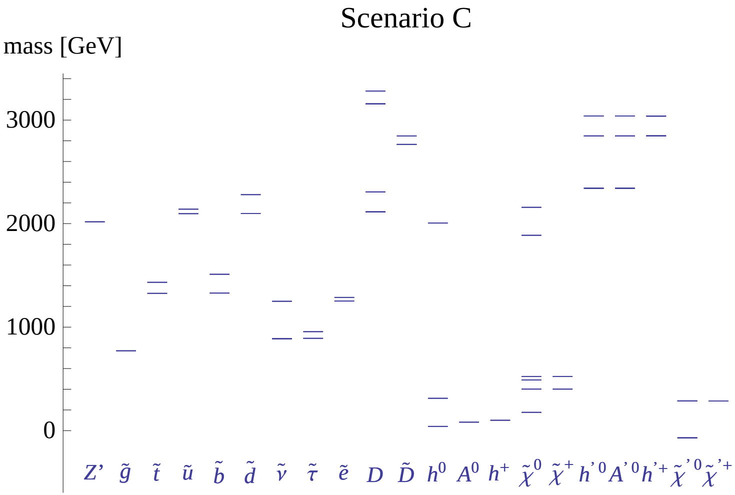
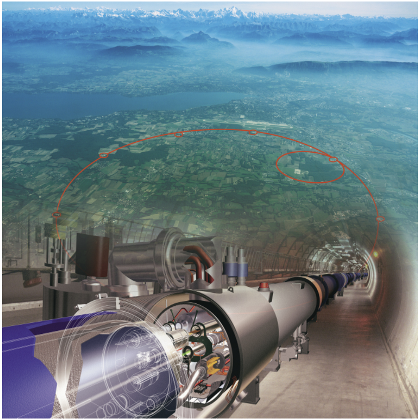
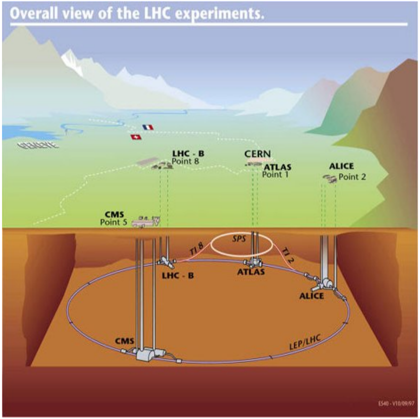


New Particles at the Large Hadron Collider

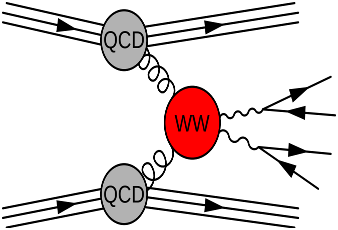
LHC @ CERN: from March 2010 7 TeV

pp-Collider $\sqrt{s} = 14$ TeV



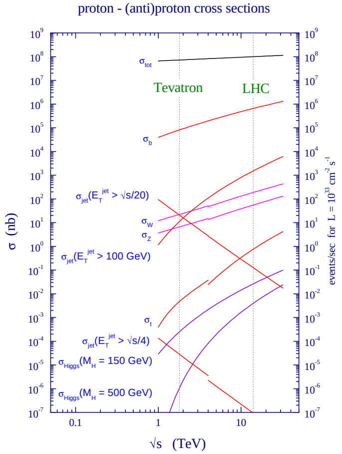


The Challenge of LHC



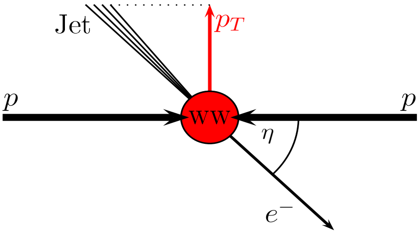
Partonic subprocesses qq, qg, gg

No fixed partonic energy



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

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



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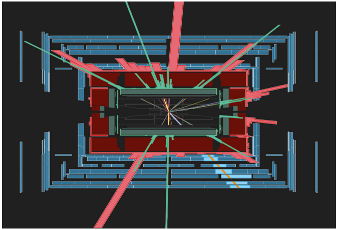

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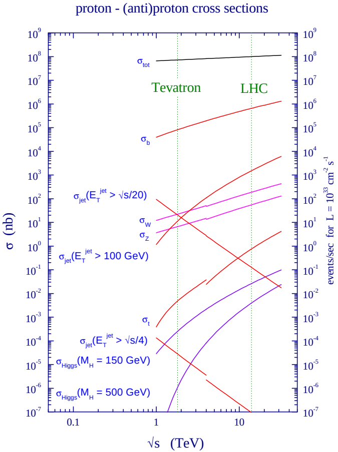

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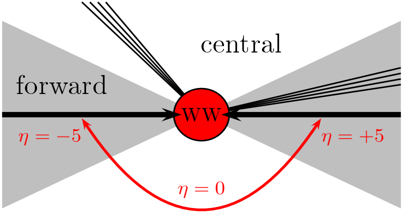
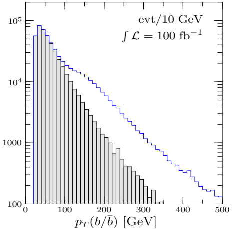


Search & Model Discrimination



Decay products of heavy particles

- high-p_T jets, many hard leptons

Production of coloured particles

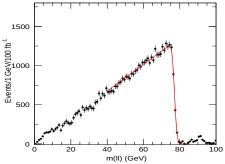
weakly interacting particles only in decays

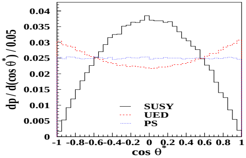
Dark Matter ⇔ discrete parity (R, T, KK)

- new particles only in pairs ⇒ high energies, long decay chains
- Dark Matter ⇒ large missing energy in the detector ($\not{E}_T$)

Different models/decay chains — identical signatures

- Mass of new particles: endpoints of decay spectra





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- Model discrimination: Measuring coupling constants

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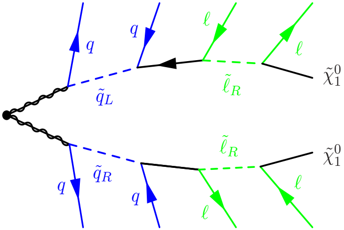

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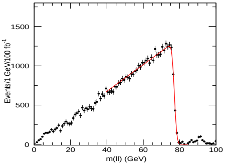

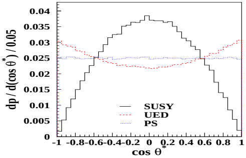

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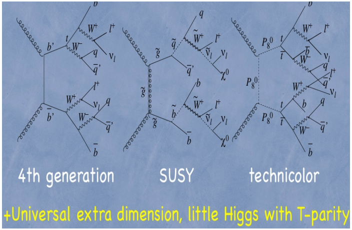

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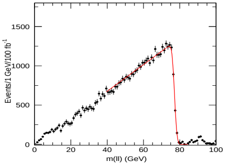

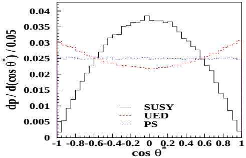

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WHIZARD

Kilian/Ohl/JRR: DESY/Freiburg/Siegen/Würzburg, hep-ph/0102195, 0708.4233

- Multi-Purpose event generator for collider and astroparticle physics
- Acronym: **W**, **HI**ggs, **Z**, **A**nd **R**espective **D**ecays (deprecated)
  - Fast adaptive multi-channel Monte-Carlo integration
  - Very efficient phase space and event generation
  - Optimized/-al matrix elements
  - Recent version: 2.0.6 (07.12.2011)
    `http://projects.hepforge.org/whizard` und
    `http://whizard.event-generator.org`
  - Parton shower ($k^\perp$-ordered and analytical)
  - Underlying Event: preliminary (for 2.1)
  - Arbitrary processes: matrix element generator (O'Mega)
  - 2.0 Features: ME/PS matching, cascades, versatile new steering syntax, WHIZARD as shared library
- Interface to `FeynRules` Christensen/Duhr/Fuks/JRR/Speckner, 1010.3215
- Prime example: LHC pheno of HEIDI models Fuks/JRR/Speckner/van der Bij

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- Multi-Purpose event generator for collider and astroparticle physics
- Focus: LHC, ILC, CLIC, SM, QCD, BSM

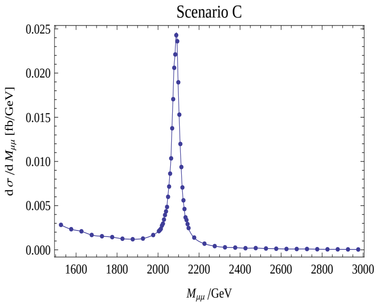
MODEL TYPE	with CKM matrix	trivial CKM
QED with e, μ, τ, γ	–	`QED`
QCD with d, u, s, c, b, t, g	–	`QCD`
Standard model	`SM_CKM`	`SM`
SM with anomalous couplings	`SM_ac_CKM`	`SM_ac`
SM with anomalous top couplings	—	`SM_top`
SM with K matrix	—	`SM_KM`
MSSM	`MSSM_CKM`	`MSSM`
MSSM with Gravitinos	—	`MSSM_Grav`
NMSSM	`NMSSM_CKM`	`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`

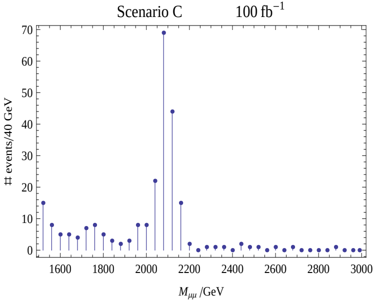
easy to
implement new models

- Interface to `FeynRules` Christensen/Duhr/Fuks/JRR/Speckner, 1010.3215
- Prime example: LHC pheno of HEIDI models Fuks/JRR/Speckner/van der Bij

Z': Drell-Yan and Asymmetry

- Z', typical mass: 2-2.5 TeV, typical width: ~ 40 GeV
- Drell-Yan cross section: $\sigma(pp \to Z' \to \mu\mu; 14\,\text{TeV}) = 1.5 - 2.5$ fb
  Cuts: $|\eta| < 2.5$ (acceptance), $p_T(\mu) > 50$ GeV, $M_{\mu\mu} > 1.5$ TeV
  Z' line shape; simulation with WHIZARD for 100 fb^{-1}:





- Forward-backward Asymmetry: $A_{FB} \equiv \frac{\sigma_F - \sigma_B}{\sigma_F + \sigma_B}$
  where

$$\sigma_F \equiv \int_0^1 \frac{d\sigma(q\bar{q} \to \mu^+\mu^-)}{d\cos\theta^*} d\cos\theta^* \qquad \sigma_B \equiv \int_{-1}^0 \frac{d\sigma(q\bar{q} \to \mu^+\mu^-)}{d\cos\theta^*} d\cos\theta^*$$

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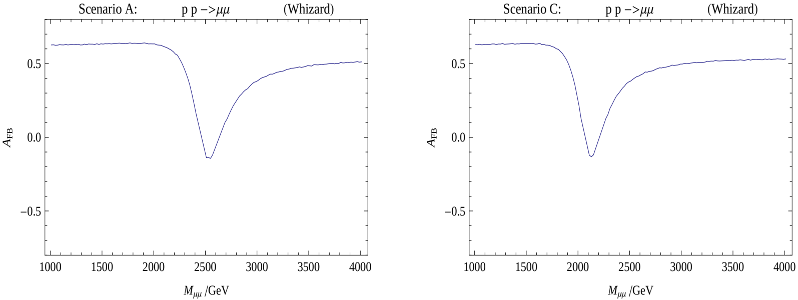

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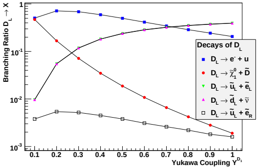
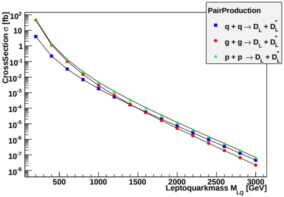
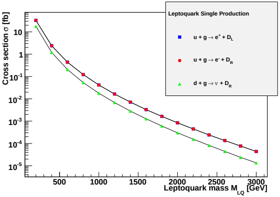
Predictions from E_6 GUTs for LHC

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**
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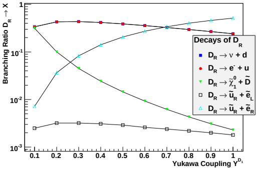

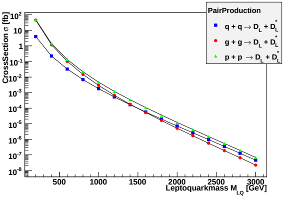

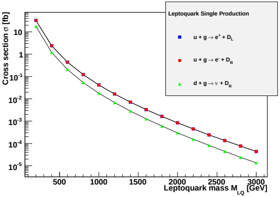

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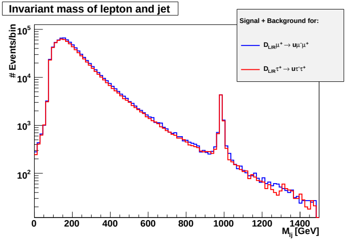
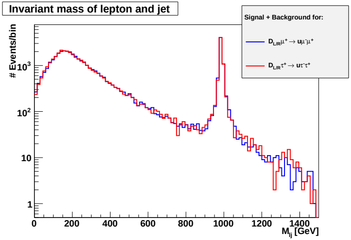
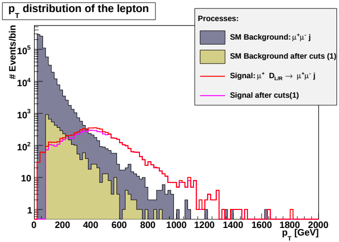
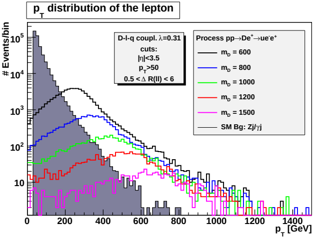
Braam/JRR/Wiesler, 0909.3081; Braam/Horst/Knochel/JRR/Wiesler , 2010/11







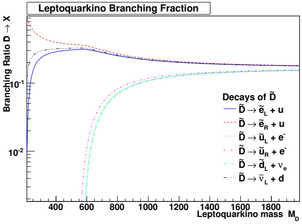


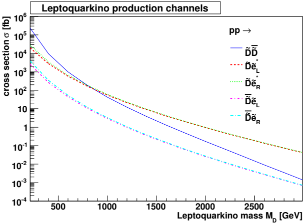
- Backgrounds: $tt + nj$, $W/Z + nj$
- Cuts: $\not{p}_T > 150$ GeV, $\quad -1.0 < \cos\theta_{\ell j} < 0.7$

Mass Edges for Leptoquarkinos

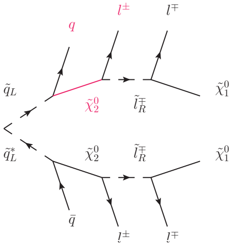
JRR/Wiesler, 1010.4215

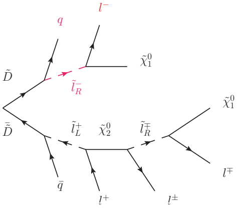
- Properties of Leptoquarkinos:





- Identical exclusive final states



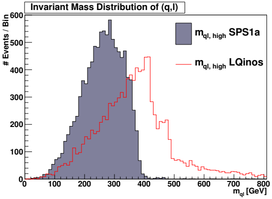


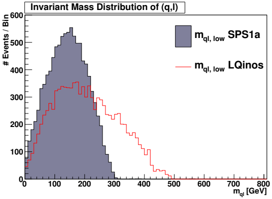
Mass Edges for Leptoquarkinos

JRR/Wiesler, 1010.4215

- Mass edges more dominant because of missing spin correlations

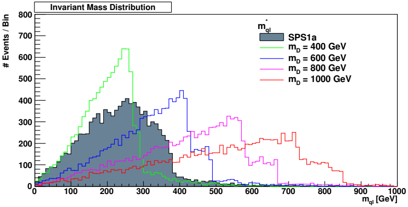
$$m_{ql,high} = \max\{m_{ql+}, m_{ql-}\} \qquad m_{ql,low} = \min\{m_{ql+}, m_{ql-}\}$$





- Combinatorial backgrounds, combine softest jet and hardest lepton:

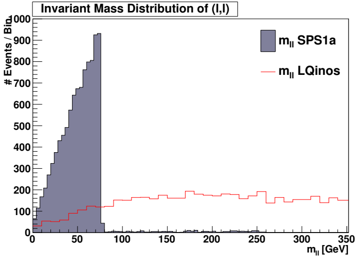
$$m^*_{ql} = m(\min_E\{q_1, q_2\}, \max_E\ \{l^+, l^-\})$$

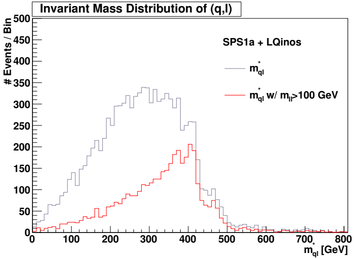


Discrimination from standard SUSY

JRR/Wiesler, 2010/11

- 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 / $\sqrt{\text{S+B}}$
400	8763	5061	54
600	1355	540	15
800	684	102	4
1000	594	24	1

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

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:

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

Summary SUSY GUTs

- 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
- Direct hints through chiral exotics at LHC
- Interesting, but intricate phenomenology at LHC
- Embedding into heterotic string/F theory (if someone is interested)
- Flavour plays important role: continuous vs. discrete symmetries
- Open questions: flavour, dark matter, SUSY breaking mechanisms

Outlook

- LHC: new era of physics
- New particles, new symmetries, new interactions, dark matter
- Model Building, Phenomenology, Tools
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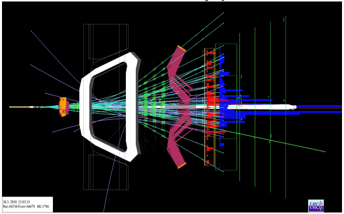
LHCb Event Display



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