Hints of Exceptional Grand Unification at the LHC

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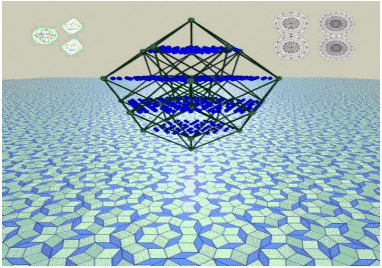
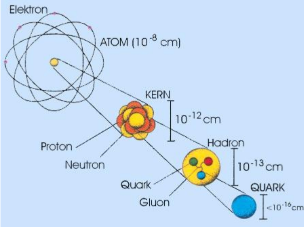


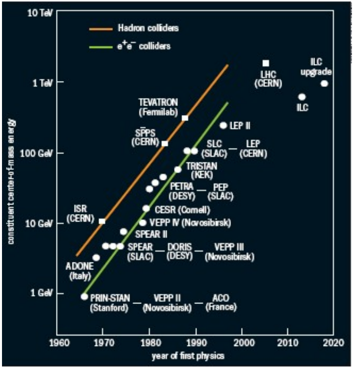
Talk, Hamburg, 23. November 2010

Particle Physics - “The High Energy Frontier”



System	Size	Energy
Molecules	10^{-8} m	$\sim 10^{-1}$ eV
Atoms	10^{-10} m	$\sim$ eV . . . . . . keV
Nuclei	10^{-14} m	~ 10 MeV
Nucleons	10^{-15} m	$\lesssim 1$ GeV

Resolution: $\Delta x \sim (\Delta E)^{-1} \Rightarrow$ High Energy Accelerators



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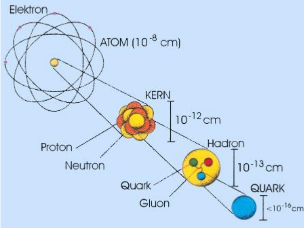

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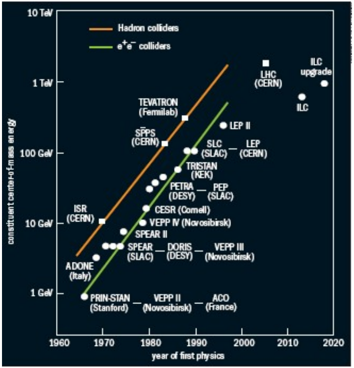
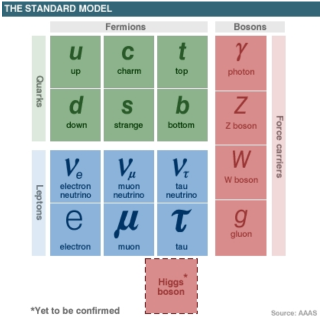
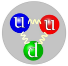
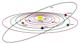
Tevatron 1.96 TeV $\rightarrow$ LHC 7 TeV



The Standard Model of Particle Physics – Successes



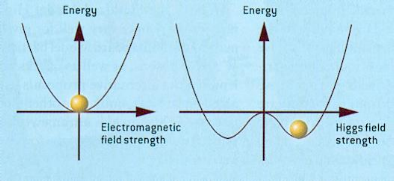
Interaction	Strength	Distance	Properties
strong	1	$\sim 10^{-15}$ m	
electromagnetic	10^{-2}	∞	
weak	10^{-12}	$\lesssim 10^{-17}$ m	
gravitation	10^{-39}	∞	

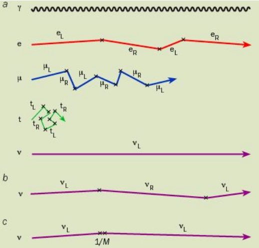
- Interactions: relativistic quantum field theories
- weak interaction: radioactive decays Fermi, 1934
- electroweak unification Glashow, Salam, Weinberg, 1967-1969
- strong interaction: asymptotic freedom Gross, Politzer, Wilczek, 1973
- Discovery of gluon DESY 1979 W, Z CERN, 1983
- Experimentally confirmed: better than 1%

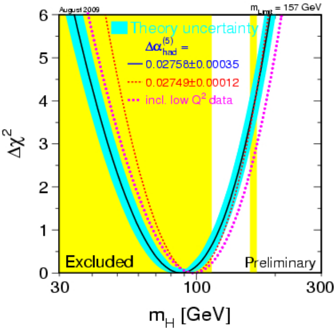
The Higgs Boson – A Long Expected Party

- Higgs: fundamental scalar field

  Anderson, Nambu, Brout, Englert, Guralnik, Hagen, Kibble, Higgs, 1961-1964
- vacuum expectat. value $v = 246$ GeV
- breaks electroweak symmetry to electromagnetism
- gives elementary particles their mass
- couples proportional to the mass

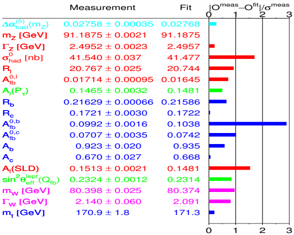






40 years search in vain

The Standard Model of Particle Physics – Doubts



– describes microcosm (too well?)

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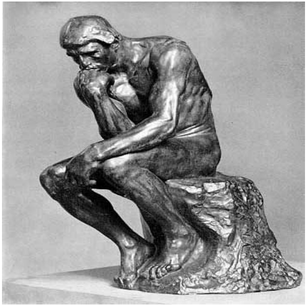
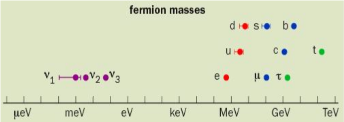
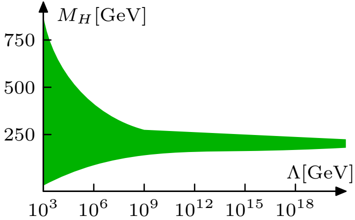


- describes microcosm (too well?)
- 28 free parameters



- 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

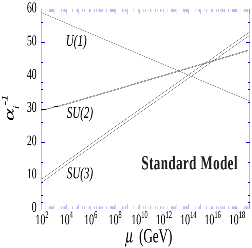
– Tiny neutrino masses $m_\nu \sim \frac{v^2}{M}$

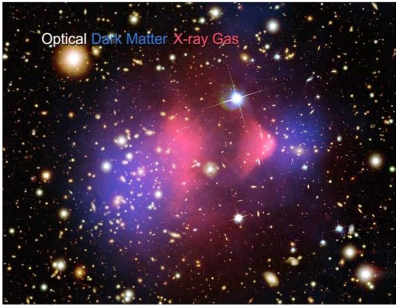
– Dark matter:
  - stable
  - weakly interacting
  - $m_{DM} \sim 100\,$GeV

– 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
6th gen
5th gen
4th gen
vector-like family
lepto quark
sterile ν
heavy Majorana
fractionally charged
milli-charged
mono-pole
S,T,U
effective SUSY
SUSY
NMSSM
nMSSM
un-unified SM
axigluon
W_R
X Y
shadow matter
mirror symmetry
triplet Higgs
doubly charged Higgs
Type I
Type II
general 2HDSM
spontaneous CP
superweak
Weinberg's 3HD
milli-weak
Majoron
axion
familon
NGB
saxion
axino
quintessence
k-essence
composite W,Z
contact int.
string
heterotic
IIB
matrix M
F
IIA
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

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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:

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

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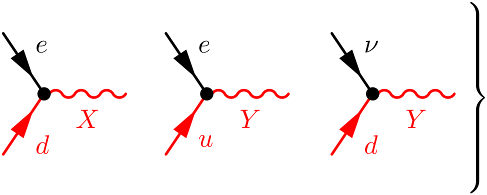
$$A = g \sum_{a=1}^{24} A^a \frac{\lambda^a}{2} = \frac{g}{\sqrt{2}} \left(\begin{array}{ccc|cc} \multicolumn{3}{c|}{\multirow{3}{*}{$\sqrt{2} G^a \frac{\lambda^a_{\text{GM}}}{2}$}} & \bar{X} & \bar{Y} \\ & & & \bar{X} & \bar{Y} \\ & & & \bar{X} & \bar{Y} \\ \hline X & X & X & \multicolumn{2}{c}{\multirow{2}{*}{$\sqrt{2}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

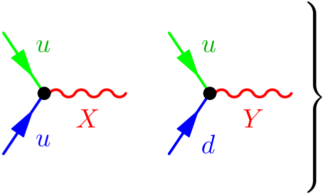
$$- \frac{g}{2\sqrt{15}} B \left(\begin{array}{ccc|cc} -2 & & & & \\ & -2 & & \multicolumn{2}{c}{0} \\ & & -2 & & \\ \hline \multicolumn{3}{c|}{\multirow{2}{*}{0}} & +3 & \\ & & & & +3 \end{array} \right)$$

Interactions



Leptoquark couplings

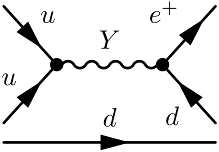
(and SUSY vertices)



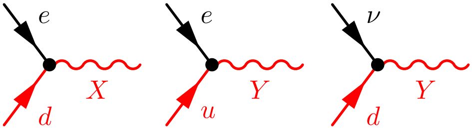
Diquark couplings

(and SUSY Vertices)

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



Interactions



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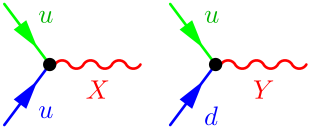

Diquark couplings

(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 $\mathbf{5} \oplus \overline{\mathbf{5}}$

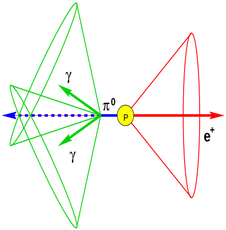
$$\mathbf{5} = \square : \quad \begin{pmatrix} D \\ D \\ D \\ h^+ \\ h^0 \end{pmatrix} \qquad \overline{\mathbf{5}} = \begin{array}{c} \square \\ \square \\ \square \\ \square \end{array} : \quad \begin{pmatrix} D^c \\ D^c \\ D^c \\ h^- \\ -h^0 \end{pmatrix}$$

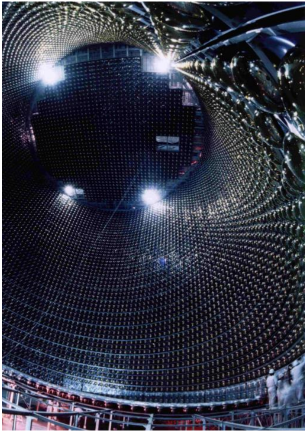
$$\mathbf{5} = \ (\mathbf{3},\mathbf{1})_{-\frac{2}{3}} \oplus (\mathbf{1},\mathbf{2})_1 \qquad \overline{\mathbf{5}} = \ (\overline{\mathbf{3}},\mathbf{1})_{\frac{2}{3}} \oplus (\mathbf{1},\mathbf{2})_{-1}$$

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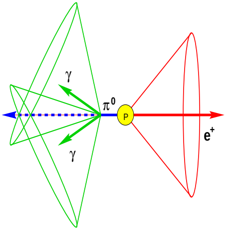


Kanal	$\tau_p\,(10^{30}$ years$)$
$p \to$ invisible	0.21
$p \to e^+\pi^0$	1600
$p \to \mu^+\pi^0$	473
$p \to \nu\pi^+$	25
$p \to \nu K^+$	670
$p \to e^+\eta^0$	312
$p \to \mu^+\eta^0$	126
$p \to e^+\rho^0$	75
$p \to \mu^+\rho^0$	110
$p \to \nu\rho^+$	162
$p \to e^+\omega^0$	1000
$p \to \mu^+\omega^0$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

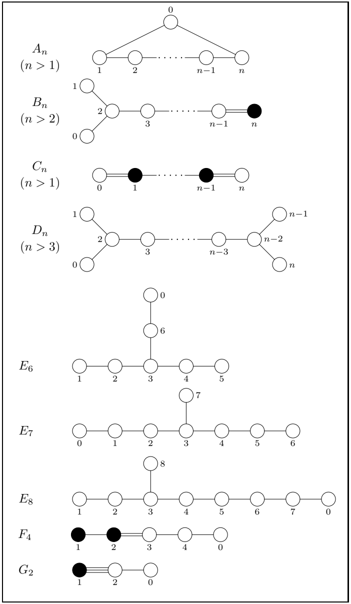
- Keep D, D^c superfields at the TeV scale
- New mechanism against proton decay
- Different unification scenario

Proton Decay

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

Exceptional Lie Algebras

Lie, 1881; Dynkin, 1957



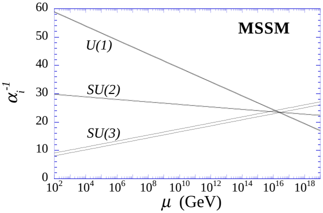
E_6 SUSY Grand Unification

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

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

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

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

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

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

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

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

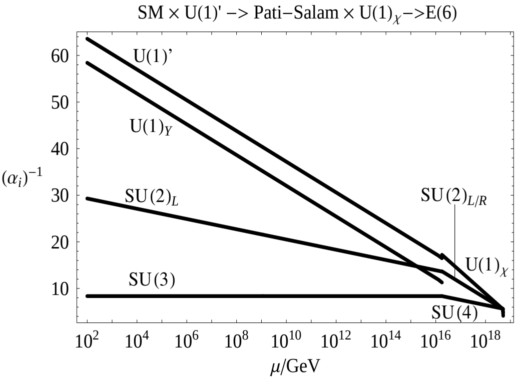
$$D^c = (\bar{\mathbf{3}},\mathbf{1})_{\frac{1}{3},-Q'_D}$$

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 $\frac{1}{g_Y^2} = \frac{2}{5}\frac{1}{g^2_{B-L}} + \frac{3}{5}\frac{1}{g_R^2}$
- Integrating out ν^c: (see-saw)

$\Rightarrow$ correct breaking

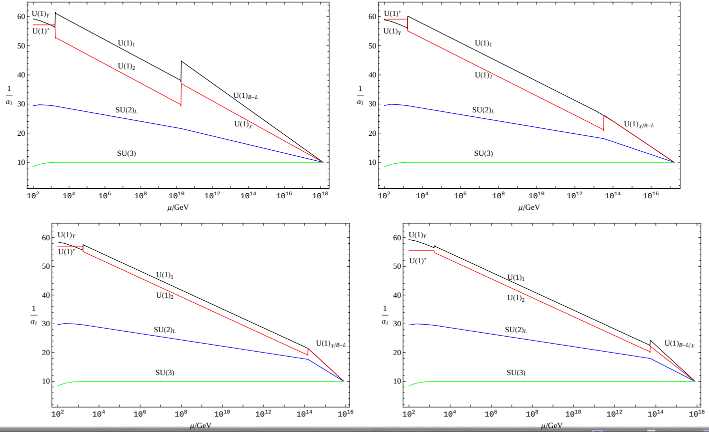
$U(1)$ Mixing

Braam/Knochel/JRR, JHEP 1006:013; King et al., 2009, JRR et al., 2010

- 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:



Problems and E_6/Pati-Salam breaking

JRR et al., 2010

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

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Automatic Decomposition of Irreps

Mallot/JRR; Horst/JRR: CleGo, 2010

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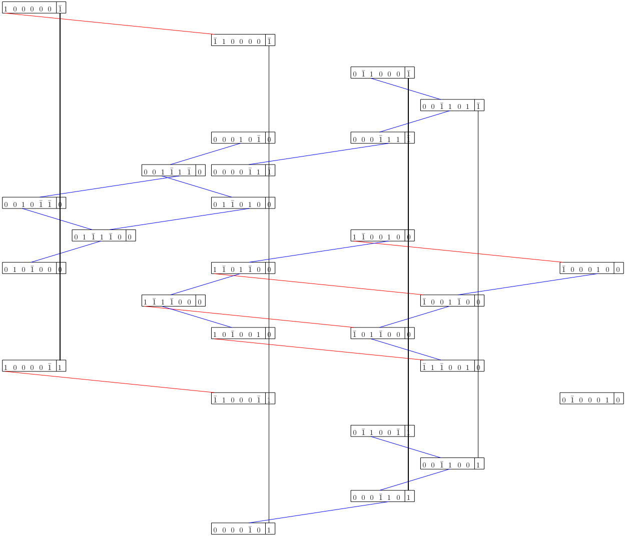

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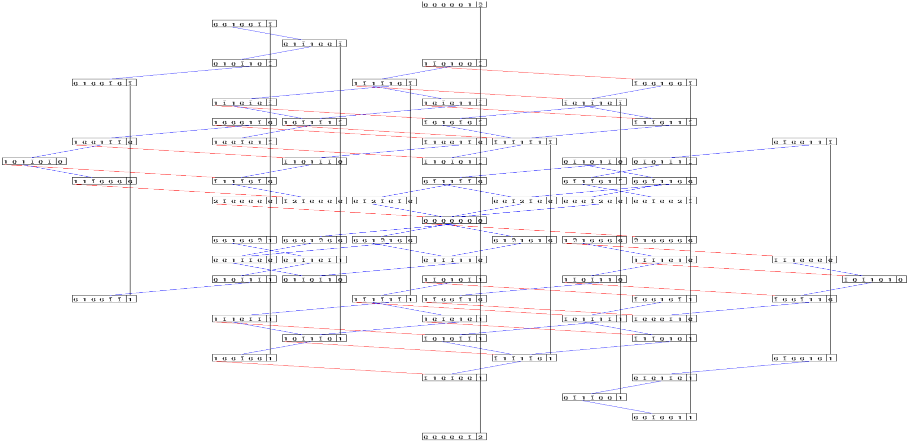


Automatic Decomposition of Irreps

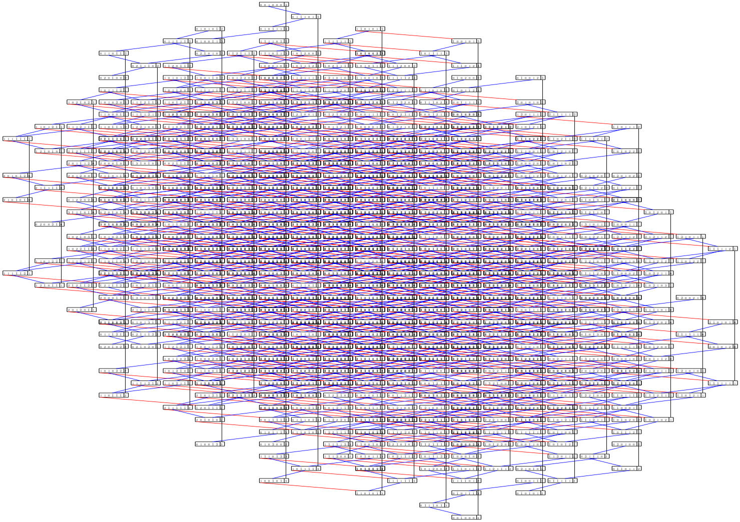
Mallot/JRR; Horst/JRR: CleGo, 2010

351′

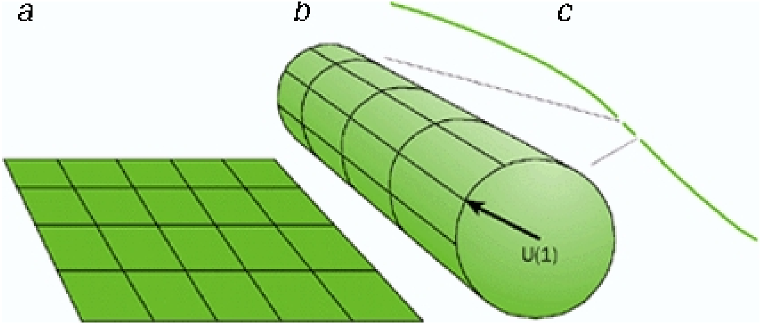
Automatic Decomposition of Irreps

Mallot/JRR; Horst/JRR: CleGo, 2010

2925



Alternative: Orbifold Breaking in Extra Dimensions



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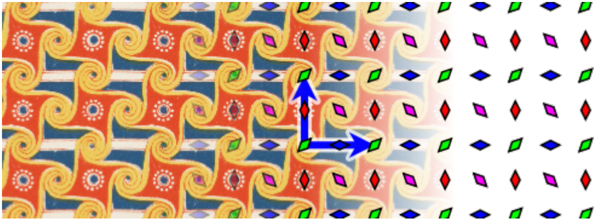

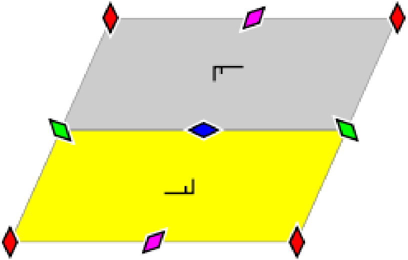

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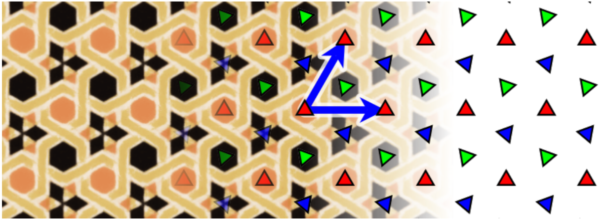

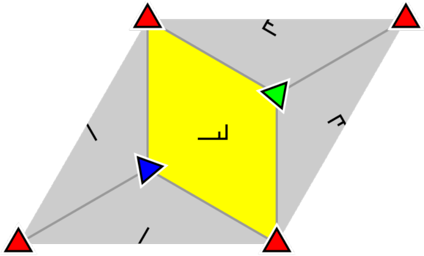

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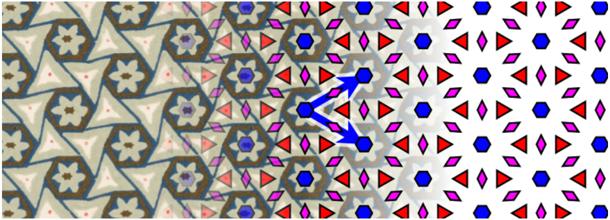
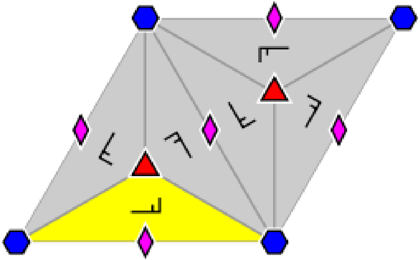
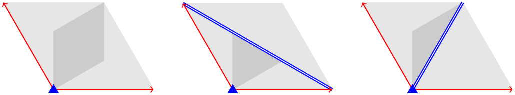




Alternative: Orbifold Breaking

Braam/Knochel/JRR, JHEP 1006:013

- 5D-Orbifolds not possible:
  - either doublet-triplet splitting or no LQ pheno
  - or no mechanism against proton decay $\Rightarrow$ 6D Orbifolds
- Consider: $\mathbb{R}^4 \times (\mathbb{R}^2/\Gamma)$, Γ one of the 17 crystallographic groups
- Use shifts of the root lattice of the bulk E_6 and discrete Wilson lines on the tori
- $E_6 \supset SU(3) \times SU(2)^2 \times U(1)^2$ breakings through $\mathbb{Z}_2$, $\mathbb{Z}_3$, $\mathbb{Z}_4$.
- H Parity: at least one fixed point distinguishes Higgs/Matter
- Use $\mathbb{Z}_3$ symmetries: simplest examples



- at least one fixed point ($SU(3)^3$), which discrimates LQ/DQ couplings
- SUSY conserved by non-trivial embedding of $SU(2)$ R symmtry

$E_6 \supset H \supset SU(3) \times SU(2)^2 \times U(1)^2$ 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

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

- Use trinification fixed point $SU(3)^3$, to discriminate LQ/DQ couplings:

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

Model Building ⇒ Phenomenology

Scan of Parameter Space

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

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

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

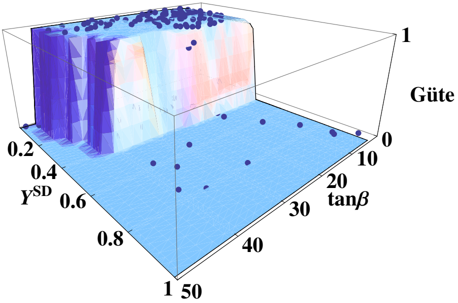
- 14-dim. parameter space

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

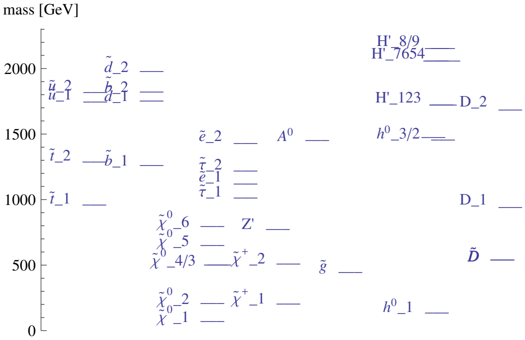
- Investigation per point (RGE, Higgs potential minimisation, Calculation of masses) $\sim 10 - 100$ ms

Lsg.: Monte-Carlo Markov chain through parameter space

$\Rightarrow$ Effective search for relevant parameter tuples



Generic Properties of Spectra

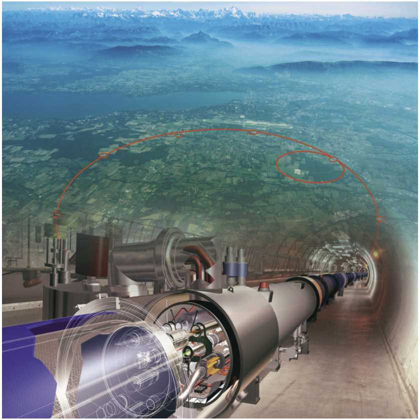


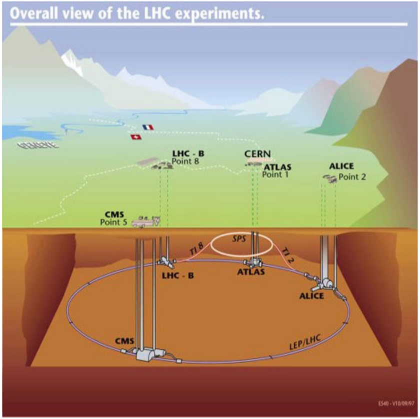
- Vanishing 1-loop QCD β function $\Rightarrow$ Gluino
- Higgs- and neutralino sector different because of singlet superfield admixture
- light Z'
- Flavoured Higgs sector: Unhiggses, Unhiggsinos
- Leptoquarks/Leptoquarkinos

New Particles at the Large Hadron Collider

LHC @ CERN: from March 2010 7 TeV

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

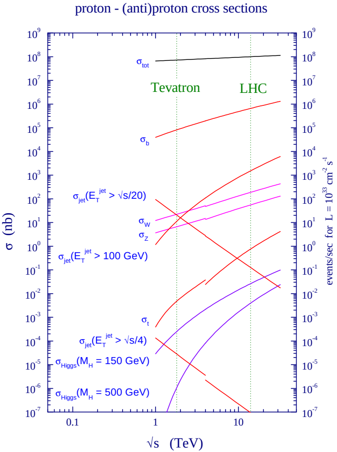


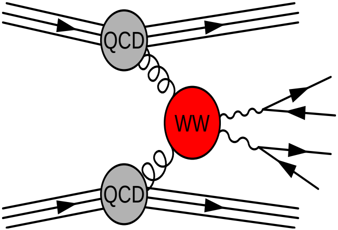


the Challenge of LHC

Partonic subprocesses qq, qg, gg

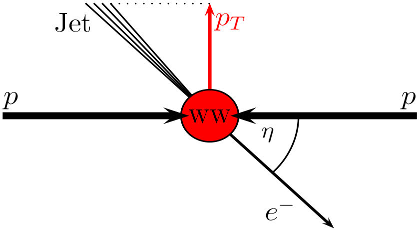
No fixed partonic energy





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

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



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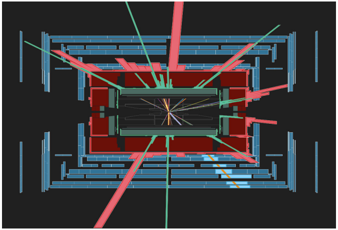

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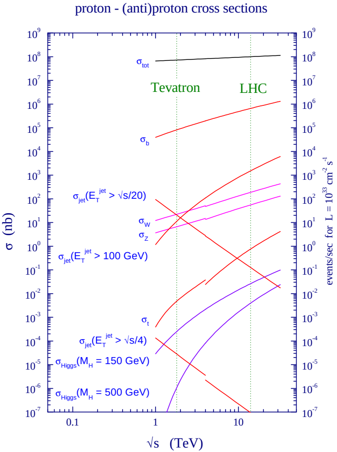

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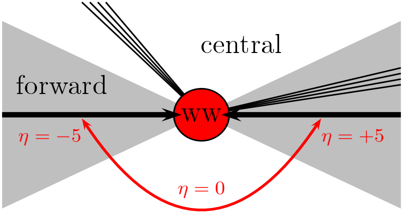
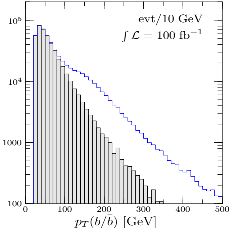


Search & Model Discrimination



Decay products of heavy particles

- high-p_T jets, many hard leptons

Production of coloured particles

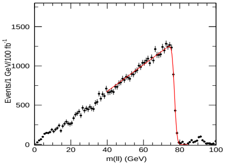
weakly interacting particles only in decays

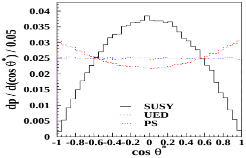
Dark Matter $\Leftrightarrow$ discrete parity (R, T, KK)

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

Different models/decay chains — identical signatures

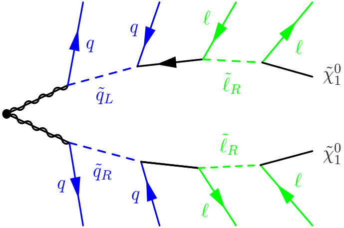
- Mass of new particles: endpoints of decay spectra





- Spin of new particles: Angular correlations, asymmetries, . . .
- Model discrimination: Measuring coupling constants

Search & Model Discrimination



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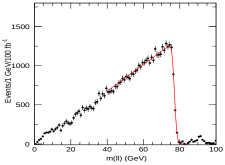

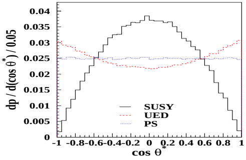

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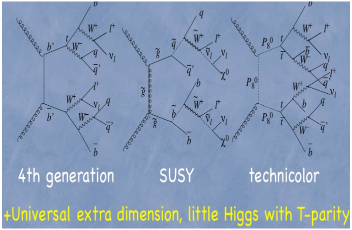

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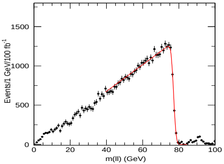

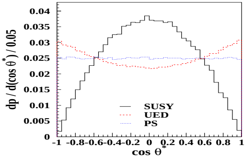

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WHIZARD

Kilian/Ohl/JRR: Edinburgh/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: 2.0.4 (26.10.2010)
    `http://projects.hepforge.org/whizard` und
    `http://whizard.event-generator.org`
  - Parton shower ($k^{\perp}$-geordnet und analytisch)
  - 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
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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
- Analyses: BRs, cross sections for scalar leptoquarks, S/B
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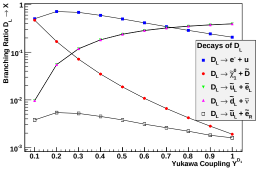

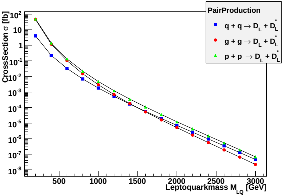

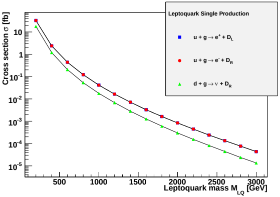

Cuts		Background	$m_D = 0.6$ TeV		$m_D = 0.8$ TeV		$m_D = 1.0$ TeV	
p_T	$M_{\ell\ell}$	N_{BG}	N_1	$S_1/\sqrt{B}$	N_2	$S_2/\sqrt{B}$	N_3	$S_3/\sqrt{B}$
50	10	413274	64553	**93**	14823	**23**	4819	**7**
100	150	3272	40749	**194**	10891	**92**	3767	**45**
200	150	198	12986	**113**	5678	**74**	2405	**47**

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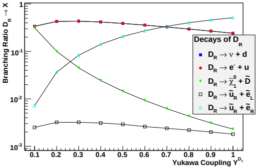

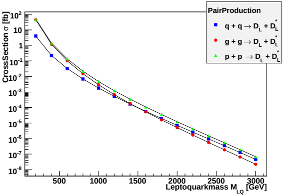

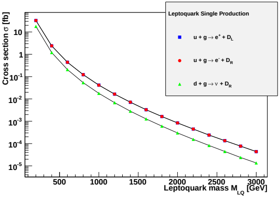

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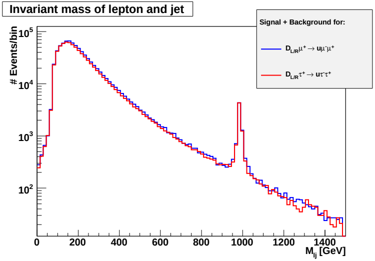
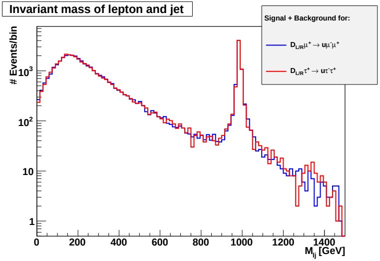
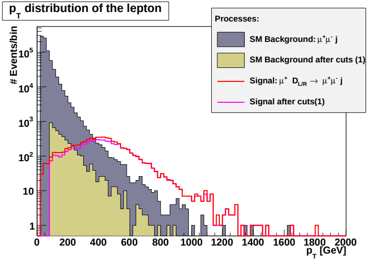
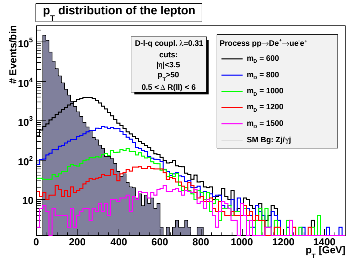
Braam/JRR/Wiesler, 0909.3081; Braam/Horst/Knochel/JRR/Wiesler , 2010/11





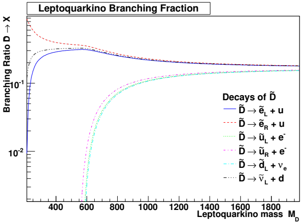


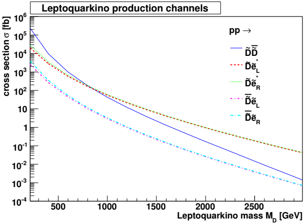


Mass Edges for Leptoquarkinos

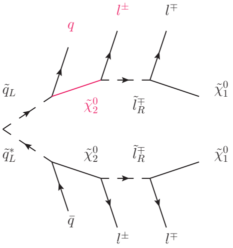
JRR/Wiesler, 1010.4215

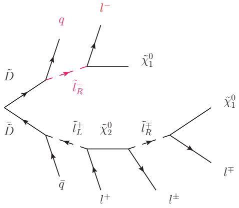
- Properties of Leptoquarkinos:





- Identical exclusive final states



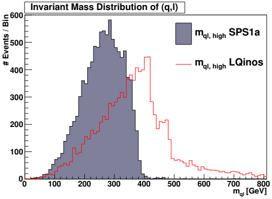


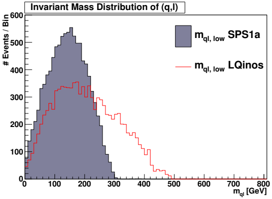
Mass Edges for Leptoquarkinos

JRR/Wiesler, 1010.4215

- Mass edges more dominant because of missing spin correlations

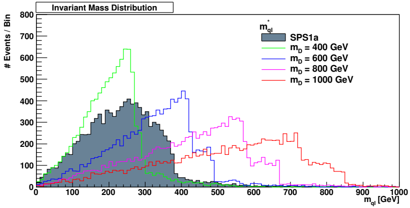
$$m_{ql,high} = \max\{m_{ql+}, m_{ql-}\} \qquad m_{ql,low} = \min\{m_{ql+}, m_{ql-}\}$$





- Combinatorial backgrounds, combine softest jet and hardest lepton:

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



- New mass variable for subtraction of comb. backgrounds

JRR/Wiesler

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:

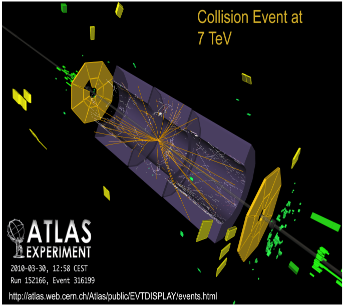
$$1/\Gamma_{tot}(p \to X) \quad \approx \quad 10^{40} - 10^{46} \text{ Jahre}$$

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 Hebecker/Knochel/Ratz/JRR/Vaudrevange
- 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
- Interesting times!



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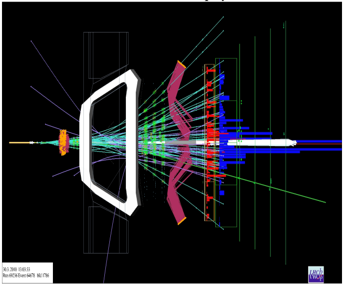
LHCb Event Display



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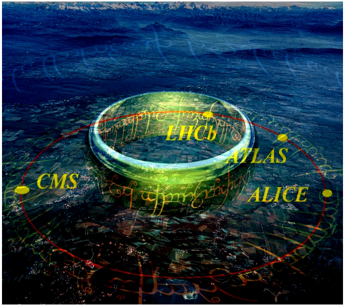


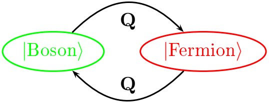
"Though this be madness, yet there is method in 't.". - (Hamlet, Act II, Scene II).

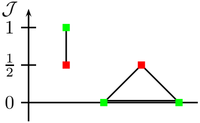
Supersymmetry (SUSY)

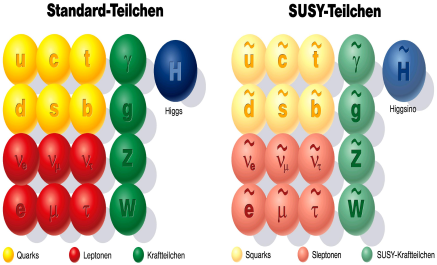
Gelfand/Likhtman, 1971; Akulov/Volkov, 1973; Wess/Zumino, 1974

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

⇒ SUSY broken in Nature







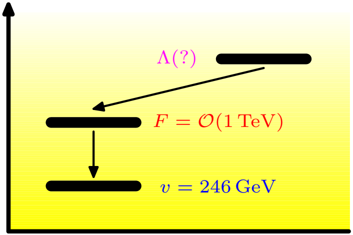
- Extend every particle by a superpartner
- Minimal Supersymmetric Standard Model (MSSM)
- Mass eigenstates:
  Charginos: $\tilde{\chi}^{\pm} = \tilde{H}^{\pm}, \tilde{W}^{\pm}$
  Neutralinos: $\tilde{\chi}^{0} = \tilde{H}, \tilde{Z}, \tilde{\gamma}$

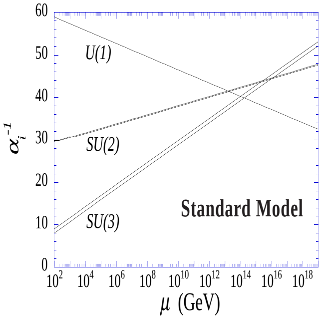
Hate-Love SUSY: Successes and By-Products

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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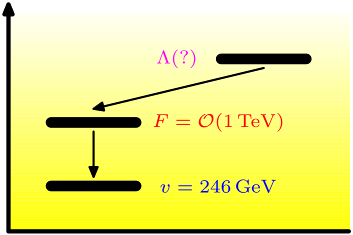

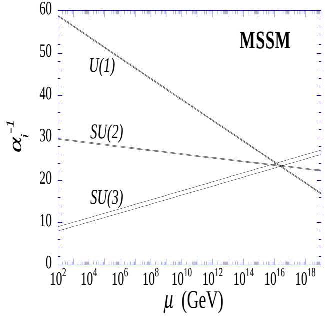

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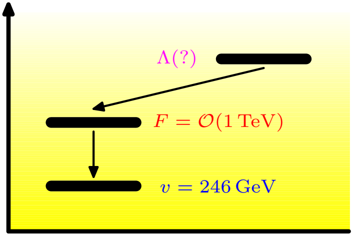

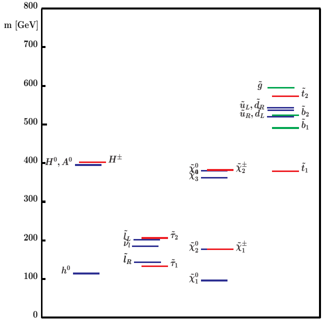

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Supersymmetric Grand Unification

Fermionen (Materie-Superfelder)

Einzig möglicher Weg, Materie zu kombinieren:

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

$$\overline{\mathbf{5}} = (\overline{\mathbf{3}}, \mathbf{1})_{\frac{2}{3}} \oplus (\mathbf{1}, \mathbf{2})_{-1} \qquad \mathbf{10} = (\mathbf{3}, \mathbf{2})_{\frac{1}{3}} \oplus (\overline{\mathbf{3}}, \mathbf{1})_{-\frac{4}{3}} \oplus (\mathbf{1}, \mathbf{1})_2$$

Bemerkungen

- Quarks und Leptonen im selben Multiplett
- Rationale Ladungen von der Spurfreiheits-Bedingung (Farbe!)
- $\overline{\mathbf{5}}$ und $\mathbf{10}$ haben gleiche und entgegengesetzte Anomalien
- ν^c muss ein $SU(5)$-Singlett sein