Channels, Chases, & Challenges – New Physics at the LHC

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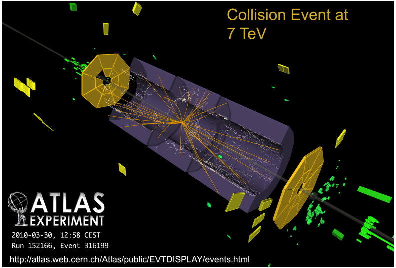
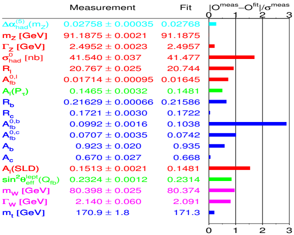


Talk, DESY, Hamburg, 23. June 2010

The Standard Model of Particle Physics – Doubts



– describes microcosm (too well?)

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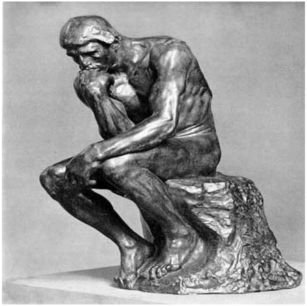
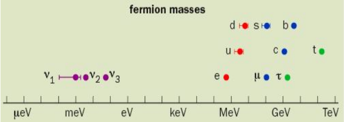
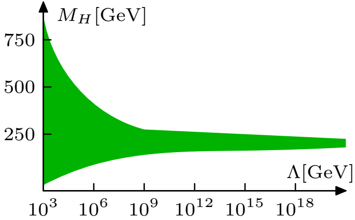


- describes microcosm (too well?)
- 28 free parameters



- Form of the Higgs potential ?



Hierarchy problem

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

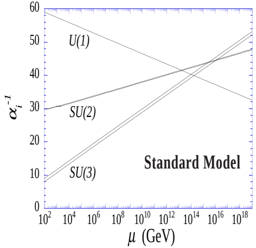
no symmetry protects Higgs from quantum corrections

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

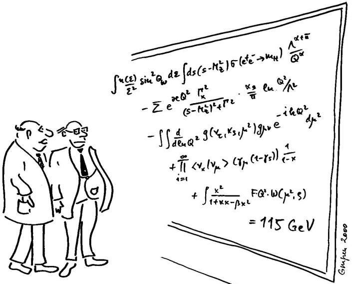
20000 GeV^2 = (100000000000000000000000000000000020000 –

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!"


NOT YET THOUGHT OF
NOT YET THOUGHT OF
NOT YET THOUGHT OF
bosonic TC
TC-TC
composite Higgs
hypercolor
supercolor
techni-GIM
extended TC
pseudo NGB
6th gen
5th gen
4th gen
S,T,U
vector-like family
lepto quark
sterile ν
heavy Majorana ν
fractionally charged
milli-charged
mono-pole
effective SUSY
SUSY
NMSSM
MSSM +νR
NMSSM
unnified SM
axigluon
Z'LR
Z'ψ
Z'SM
Z'χ
Z'η
WR
X Y
shadow matter
mirror symmetry
triplet Higgs
doubly charged Higgs
Type I
Type II
general 2HDSM
spontaneous CP
superweak
milli-weak
Weinberg's 3HD
Majoron
axion
familon
NGB
saxion
axino
quintessence
k-essence
4K λ
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) **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

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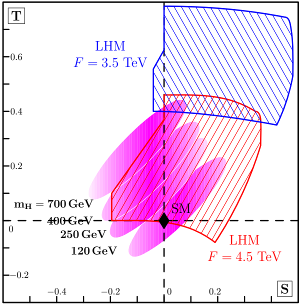
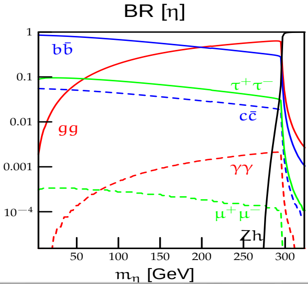
Little Higgs Models

Kilian/JRR **PRD 70** (2004), 015004; Kilian/Rainwater/JRR **PRD 71** (2005), 015008; **PRD 74** (2006), 095003; Butenuth/JRR, 2010

- "Little Big Higgs": Higgs boson heavy $(300 - 500\,\text{GeV})$
- Extensive low-energy constraints
- Tiny neutrino masses in LHM
- General search strategy at the LHC
- Proposal of methods to distinguish model classes





- Prediction of new scalar particles: Pseudoaxions
- Light electroweak singlets
- Good discovery prospects at LHC
- Model building aspects: T parity and dark matter in generalized models

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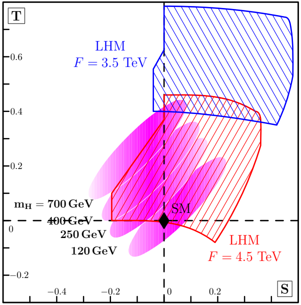

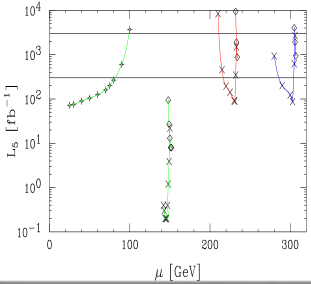

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Desperately
Seeking
SUSY

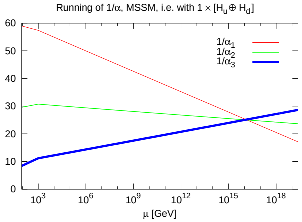
E_6 SUSY Grand Unification

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

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

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

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

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

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

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

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

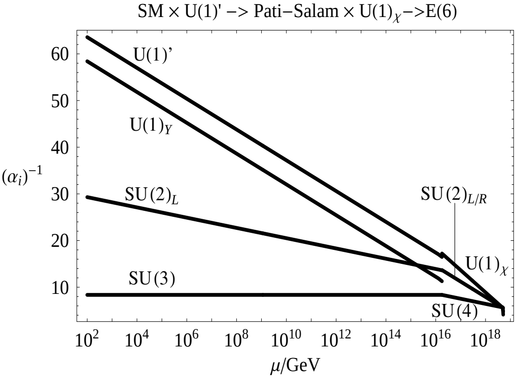
$$D^c = (\bar{\mathbf{3}},\mathbf{1})_{\frac{1}{3},-Q'_D}$$

Intermediate Pati-Salam symmetry

JRR/Kilian, **PLB 642** ('06), 81

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

$SU(3/4) \times SU(2)_L \times SU(2)_R[\times U(1)_\chi]$ Pati-Salam symmetry at $\sim 10^{15-16}$GeV



- $SU(2)_R$ and $SU(2)_L$: identical particle content ⇒ running
- Crossing of $SU(3/4)$ and $SU(2)_{L/R}$ couplings determines E_6 breaking scale
- $T^{15}_{SU(4)} \propto \frac{B-L}{2}$
- $Y = \frac{B-L}{2} + T^3_R$
- $U(1)$ Matching-Bedingung $\frac{1}{g_Y^2} = \frac{2}{5}\frac{1}{g_{B-L}^2} + \frac{3}{5}\frac{1}{g_R^2}$
- Integrating out ν^c (see-saw)
- Flavour symmetry forbids diquark couplings

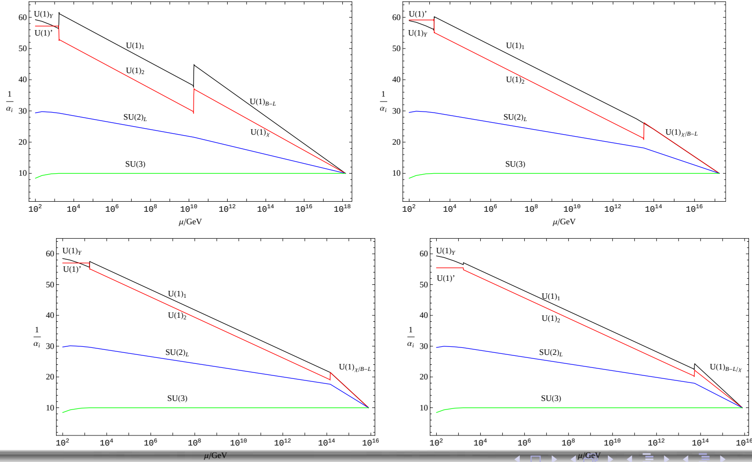
Effects by $U(1)$ mixing

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

- 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 through the running:



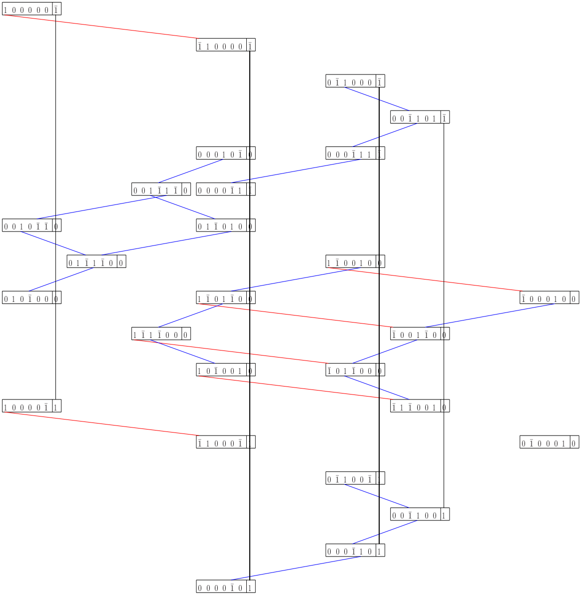
Problems and E_6/Pati-Salam breaking

JRR et al., 2010

- E_6 superpotential vanishes identically $\Rightarrow$ 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 irreps for PS breaking
  - $\mathbf{27}$, $\mathbf{351}$, and $\mathbf{351'}$ break E_6 to rank 5
    $U(1)_\chi$ broken, no quartic singlet potential
    But: construction of PS-NMSSM possible   Kilian/Knochel/JRR, 2010
  - No rank reduction: adjoint breaking
  - Breaking with $\langle(\mathbf{27})(\overline{\mathbf{27}})\rangle$ 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 irrep for $E_6 \to G_{PS}\times U(1)$
  - Possible to generate superpotential which does the breaking and allows for leptoquark couplings

Automatic Decomposition of Irreps

Horst/Mallot/JRR, 2010



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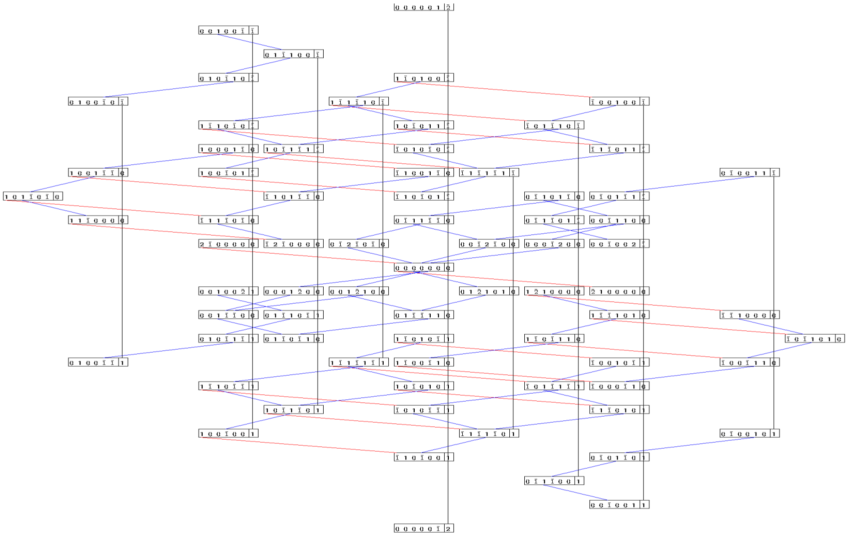

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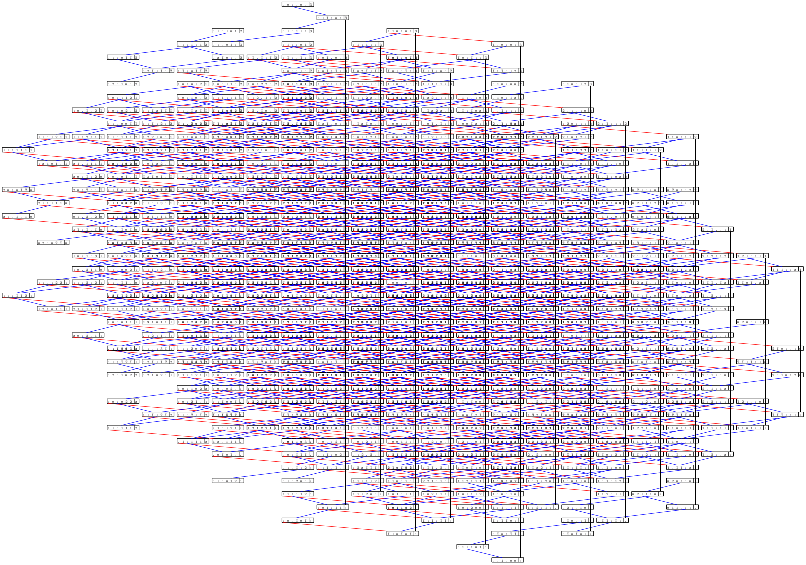
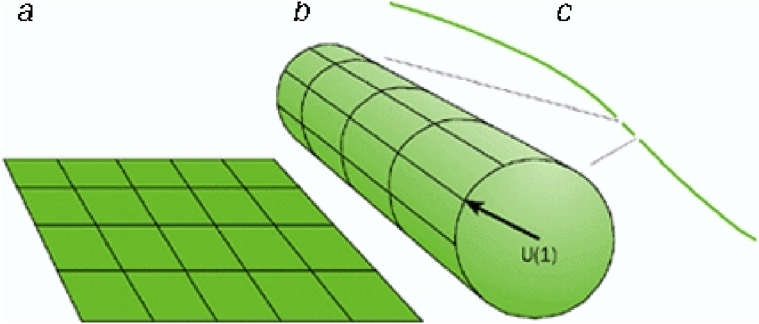


Alternative: Orbifold Breaking in Higher Dimensions



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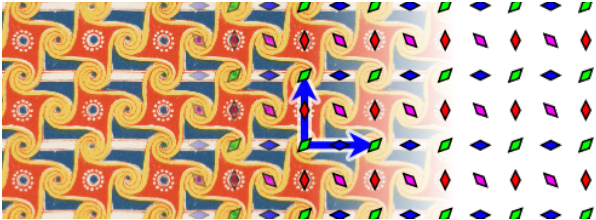

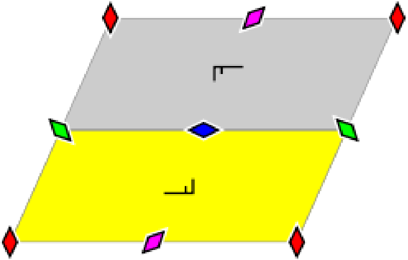

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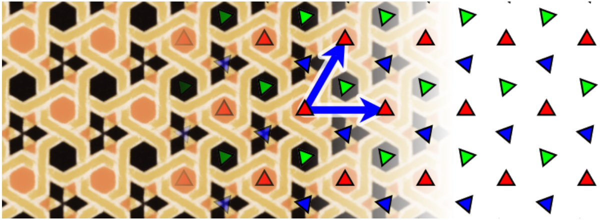

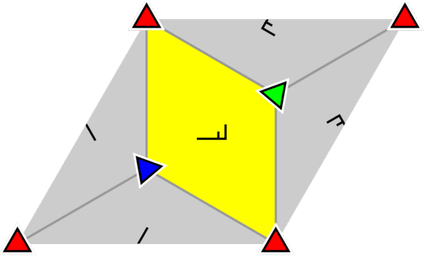

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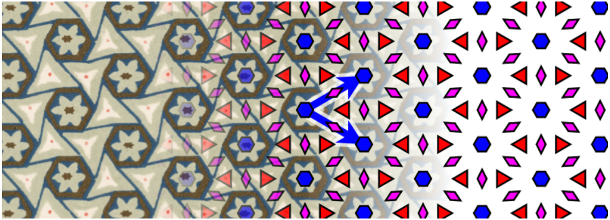
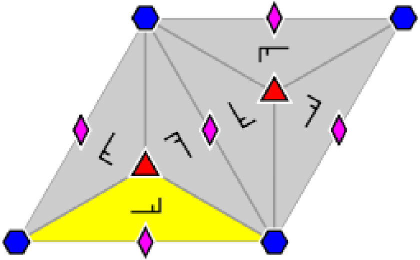
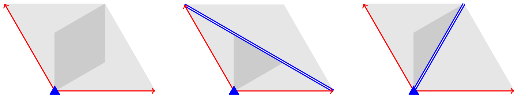




Alternative: Orbifold Breaking

Braam/Knochel/JRR, JHEP 1006:013

- 5D Orbifolds excluded:
  - either doublet-triplet splitting or no leptoquark pheno
  - or no protection against proton decay $\Rightarrow$ 6DOrbifolds
- Consider: $\mathbb{R}^4 \times (\mathbb{R}^2/\Gamma)$, Γ one of 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 by $\mathbb{Z}_2$, $\mathbb{Z}_3$, $\mathbb{Z}_4$.
- H parity: at least one fixed point, which distinguishes Higgs/matter
- use $\mathbb{Z}_3$ symmetry: simplest examples



- at least one fixed point ($SU(3)^3$) which splits lepto-/diquark couplings
- SUSY conserved by non-trivial embedding of $SU(2)$ R symmetry

Model Building ⇒ Phenomenology

Scan of PSSSM parameter space

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

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

  $\Rightarrow$ Reduction to 14 parameter
- Further constraints:
  (1) Experimental search limits for new particles
  (2) Running couplings perturbative up to Λ_{E_6}
  (3) Scalar (non-Higgs) mass terms positive
  (⇔ No false vacuum)

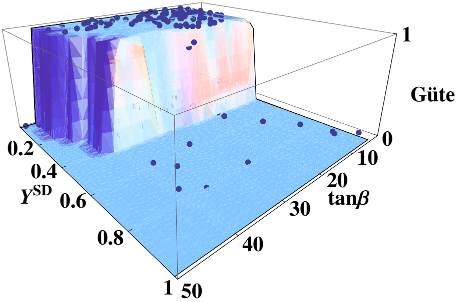
- 14-dim. parameter space

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

- Investigation per point (RGE, Higgs potential minimization, Calculation of masses) ~ 5 s

Lsg.: Monte-Carlo Markov chain through the parameter space

$\Rightarrow$ Effective search for relevant parameter tuples



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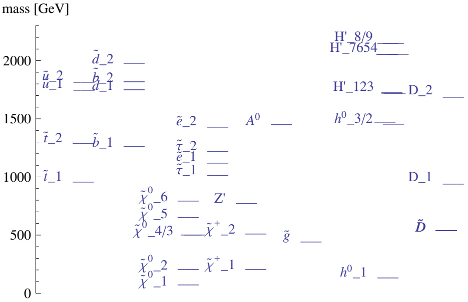
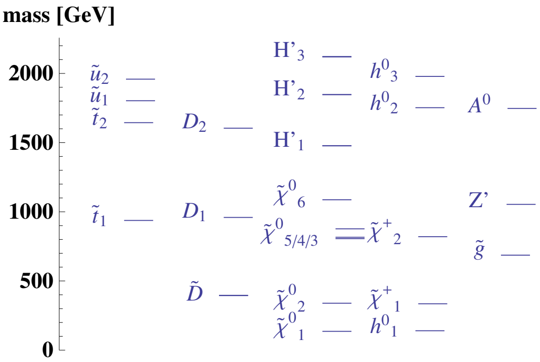


Generic properties of spectra

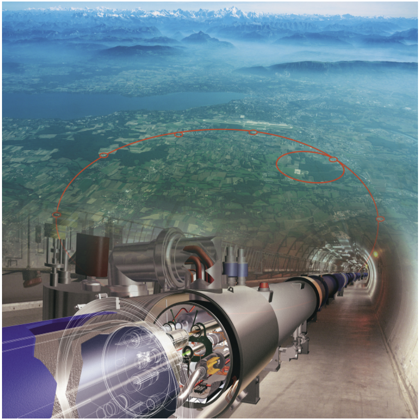


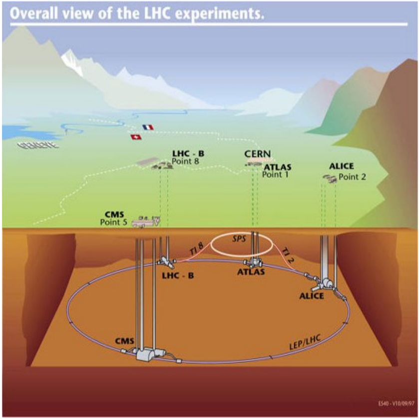
- Vanishing 1-loop QCD β function $\Rightarrow$ light gluino
- Higgs-/neutralino sector different because of admixture of singlet superfield
- TeV-scale Z'
- Flavoured Higgs sector: Unhiggses, Unhiggsinos
- Leptoquarks/Leptoquarkinos

New particles at the Large Hadron Collider

LHC @ CERN: since march 2010 7 TeV

pp collider $\sqrt{s} = 14$ TeV





WHIZARD

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

- 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 matrix elements
- Recent version: 2.0.2 (18.5.2010)
  `http://projects.hepforge.org/whizard` und
  `http://whizard.event-generator.org`
- Parton shower ($k^\perp$ ordered and analytic)
- no hadronization
- Underlying Event: pre-release (for 2.1)
- Arbitrary processes: matrix element generator (O'Mega)
- BSM: see next page
- New features: ME/PS matching, cascades, versatile new steering syntax, WHIZARD as 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 + flavours)
- $pp \to \tilde{\chi}_1^0\tilde{\chi}_1^0 bbbb$ (32,000 diagrams, 22 color flows, $\sim 10,000$ PS channels)
- $pp \to VVjj \to jj\ell\ell\nu\nu$ incl. anom. TGC/QGC
- Test case $gg \to 9g$ (224,000,000 diagrams)

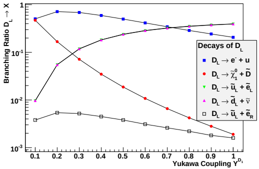
MODEL TYPE	with CKM matrix	trivial CKM
QED with e, μ, τ, γ	–	QED
QCD with d, u, s, c, b, t, g	–	QCD
Standard model	SM_CKM	SM
SM with anomalous couplings	SM_ac_CKM	SM_ac
SM with anomalous top couplings	—	SM_top
SM with K matrix	—	SM_KM
MSSM	MSSM_CKM	MSSM
MSSM with gravitinos	—	MSSM_Grav
NMSSM	—	NMSSM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

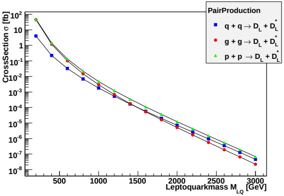
easy to implement new models (FeynRules interface)

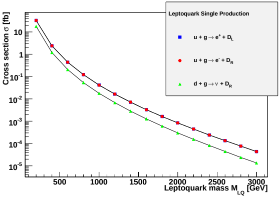
Predictions from E_6 GUTs for LHC

Braam/JRR/Wiesler, 0909.3081

- Simulations for the E_6 model with `WHIZARD`
- Implementation of leptoquark/leptoquarkino + Higgs/weak ino sector
- 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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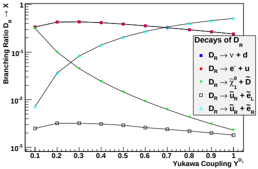
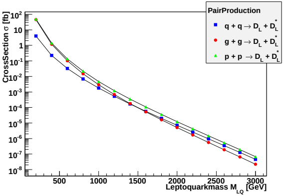
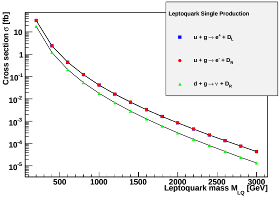
- First analyses: BRs, cross sections for scalar leptoquarks, S/B
- In progress: leptoquarkino pheno

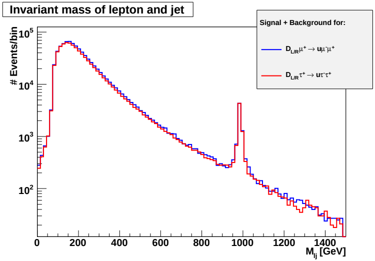


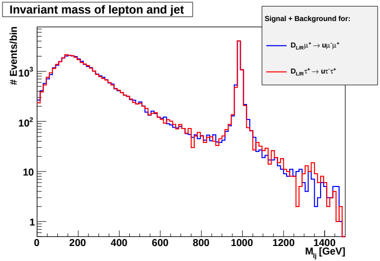


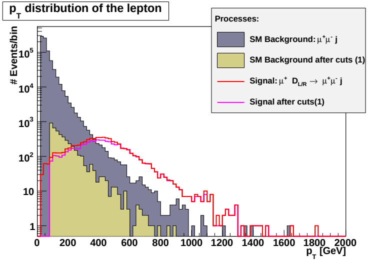


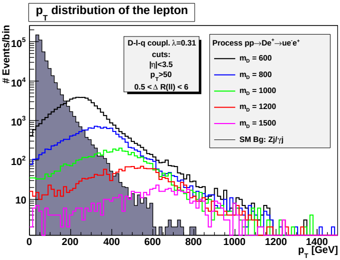
Cuts		Background	$m_D = 0.6$ TeV		$m_D = 0.8$ TeV		$m_D = 1.0$ TeV	
p_T	$M_{\ell\ell}$	N_{BG}	N_1	$S_1/\sqrt{B}$	N_2	$S_2/\sqrt{B}$	N_3	$S_3/\sqrt{B}$
50	10	413274	64553	**93**	14823	**23**	4819	**7**
100	150	3272	40749	**194**	10891	**92**	3767	**45**
200	150	198	12986	**113**	5678	**74**	2405	**47**

Braam/JRR/Wiesler, 0909.3081









Proton Decay in the PSSSM

Mallot/JRR, 2010

- Superpotential (and soft breaking) do not induce proton decay
- Study exchange of E_6 gauge bosons/gauginos
- Technical steps (top-down):
  1. Group-theoretical weights from Clebsch-Gordan decomposition
     Horst/Mallot/JRR, 2010
  2. Calculation of the proton decay Wilson coefficients at Λ_{GUT}
  3. Short-distance (SUSY) RG factor
  4. Matching to SM dim. 6 Fermi operators
  5. Long-distance (SM/QCD) RG factor
  6. Matching to mesonic/baryonic operators (similar to chiral pert. theory)
  7. Calculation of the baryon decay matrix element and the width
- $\Rightarrow$ very conservative estimate:

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

Summary/Outlook SUSY GUTs

- Grand Unified Theories with intermediate breaking
- Viable paths: $E_6 \to SU(3/4) \times SU(2)_L \times SU(2)_R \times U(1)^2$
- Possible breaking scenarios: Higgs vs. Orbifold boundary conditions
- Proton decay beyond experimental reach
- Direct detection through chiral exotics at LHC
- Interesting, but intricate pheno at LHC
- Embedding in heterotic string theory
- Flavour important: continous vs. discrete symmetries
- Dark matter cocktail: complex pheno
- Open questions: SUSY breaking mechanism, flavour, see-saw

ALTERNATIVE ELECTROWEAK SYMMETRY BREAKING

Resonances in VV scattering

Alboteanu/Kilian/JRR, JHEP 0811:010

Model-independent description for LHC, respect weak isospin ($\rho \approx 0$):

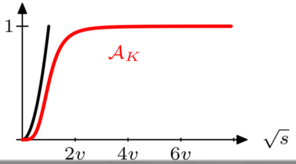
	$J = 0$	$J = 1$	$J = 2$
$I = 0$	σ^0 (Higgs ?)	ω^0 $(\gamma'/Z'\ ?)$	a^0 (Graviton ?)
$I = 1$	$\pi^\pm, \pi^0$ (2HDM ?)	$\rho^\pm, \rho^0$ $(W'/Z'\ ?)$	$t^\pm, t^0$
$I = 2$	$\phi^{\pm\pm}, \phi^\pm, \phi^0$ (Higgs triplet ?)	—	$f^{\pm\pm}, f^\pm, f^0$

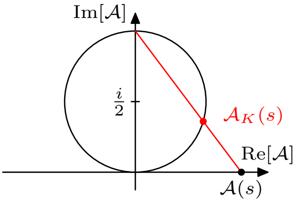
LHC access limited: 1. resonance correct, guarantee unitarity

K-Matrix unitarization

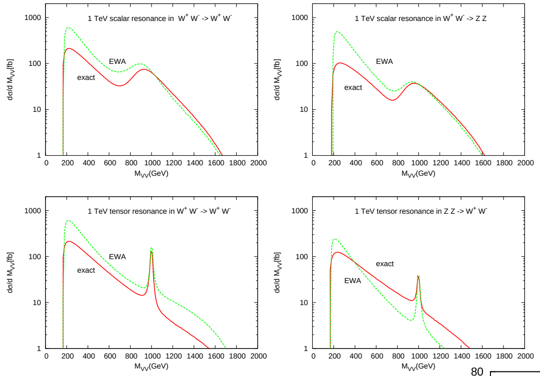
$$\mathcal{A}_K(s) = \mathcal{A}(s)/(1 - i\mathcal{A}(s))$$

- Low-energy theorem (LET): $\frac{s}{v^2}$
- K-matrix ampl.: $|\mathcal{A}(s)|^2 \overset{s\to\infty}{\to} 1$
- Poles $\pm iv$: M_0, Γ large



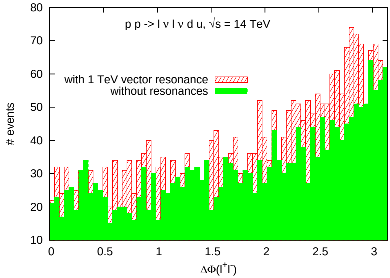


- Unitarization in each spin-isospin eigen-channel
- breaks crossing invariance
- Explicit “time arrow” in WHIZARD



- Effective W approx. vs. WHIZARD full matrix elements
- Shapes/normalization of distributions heavily affected
- EWA: Sideband subtraction completely screwed up!

- Example: 850 GeV vector resonance
- coupling $g_\rho = 1$
- Discriminator: angular correlations
- Ongoing ATLAS study



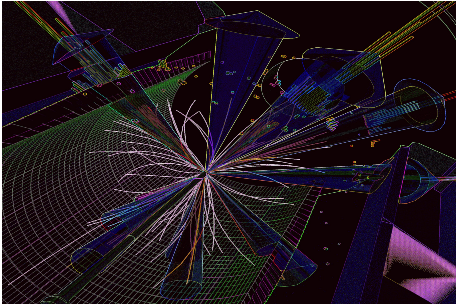
Outlook (I)

ONGOING/FUTURE PROJECTS

- SUSY GUTs (we had this)
- LHC Pheno / WHIZARD
  - QCD features: BLHA, automatic dipole subtraction, FeynArts/LoopTools Interface, CKKW matching, parton shower development, GOLEM interface
  - SM/BSM projects: new model implementation/validation, LHC searches
  - LHC cascades: strategies for mass/spin determination
  - highly-boosted particles at LHC
- Pheno-driven model building
  - Theoretical aspects of Little Higgs/Technicolor models
  - Dark matter models

Outlook (II)

- LHC: new era of physics is beginning
- New particles, new symmetries, new interactions
- A lot to do: Model building and phenomenology
- Interesting times ahead!



Outlook (II)

- LHC: new era of physics is beginning
- New particles, new symmetries, new interactions
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"Though this be madness, yet there is method in 't.". - (Hamlet, Act II, Scene II).